(BSM) Higgs Physics at Hadron Colliders

pre-SUSY 2024

School

Madrid
3-7 June 2024
(the week before SUSY!)

Margarete Mühlleitner, KIT

Pre-SUSY school 2024: School on Supersymmetry and Unification of Fundamental forces

3.–7. Juni 2024
IFT (Madrid, Spain)
Europe/Madrid Zeitzone

pre-SUSY 204
IFT (Madrid, Spain)
3-7 June 2024

Geben Sie Ihren Suchbegriff ei

- Übersicht
- Wissenschaftliches Programm
- Tagesordnung
- Anmeldung
- Teilnehmerliste
- Code of Conduct
- SUSY 2024

Pre-SUSY School 2024

A pre-SUSY pedagogical lecture school which will precede the SUSY2024 conference from Monday 3 June to Friday 7 June, 2024 at IFT, Madrid.

The aim of the school is to introduce advanced undergraduate, graduate, PhD students and postdocs into specialised topics of particle physics, cosmology, mathematical physics and programming skills related to supersymmetry.

Registration will open on 15/February and close on 15/May for the pre-SUSY school.

Outline

- The SM in a nutshell

- Experimental test of the Higgs mechanism
  - Role of the Higgs boson mass
  - Higgs quantum numbers
  - Coupling measurements
  - Higgs pair production

- BSM Higgs Physics / Extended Higgs Sectors
  - EFT
  - UV-complete models
  - Experimental and Theoretical Constraints

- Strongly-Interacting Higgs Sectors
  - SMEFT, EWChL, MCHM4&5, Composite 2HDM

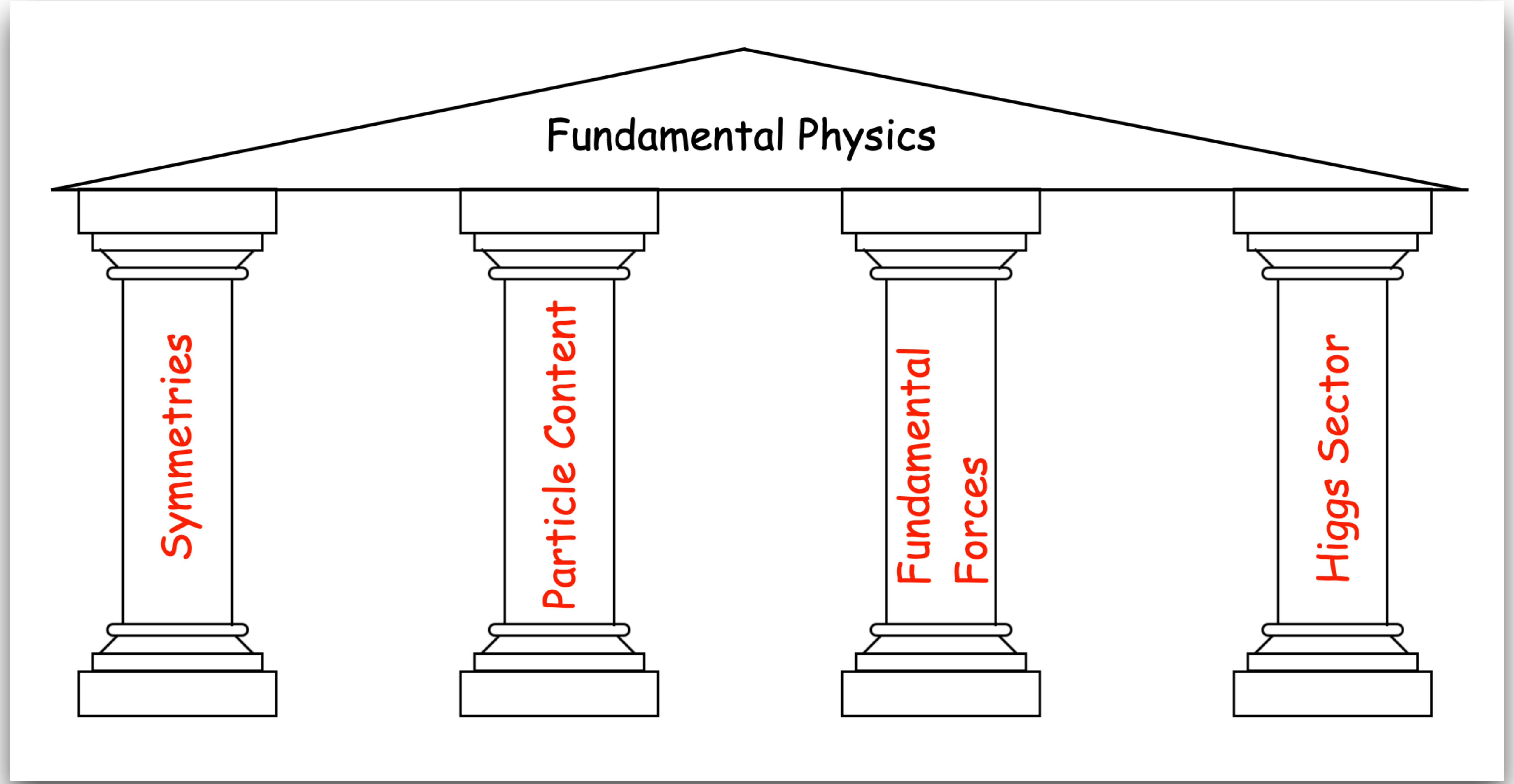
- UV-complete Models
  - 2HDM, C2HDM, N2HDM, MSSM, NMSSM

- Measuring EWSB
  - BSM di-Higgs production
  - di-Higgs beats single-Higgs
  - EFT in di-Higgs production
  - Measuring BSM λ_{3H} HO, interference effects

- Conclusions

The SM in a Nutshell

The Standard Model of Particle Physics in a Nutshell

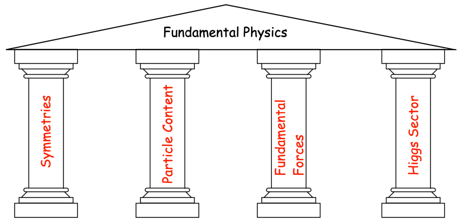


Particle Content

❖ Particle Content: Matter particles and interaction particles

Matter Particles

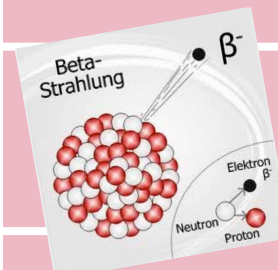
u	c	t	Quarks
d	s	b	
ν(e)	ν(μ)	ν(τ)	Leptons
e	μ	τ	
1	2	3	Families

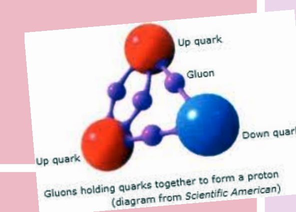


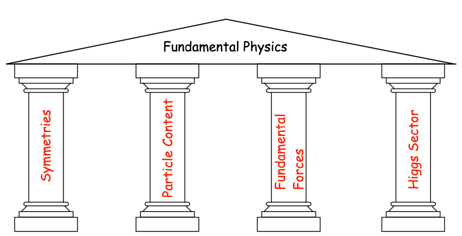
Fundamental Forces

❖ Fundamental Forces interaction particles:

Fundamental Force	Mediator/Interaction Particle
Electromagnetic Force	Photon γ
Weak Force	W and Z Bosons
Strong Force	Gluons g
Not in the Standard Model:	
Gravity	Graviton

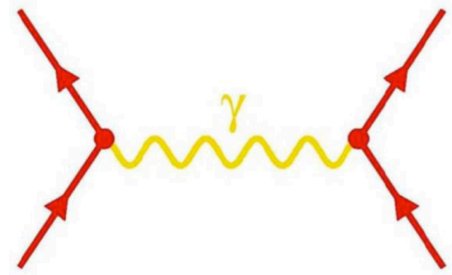






Gauge Symmetries

- Description of fundamental interactions: with quantum field theories
  fields are quantized, e.g. photon: electromagnetic field quantum



interaction: exchange of field quanta

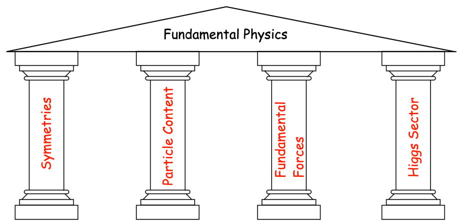
- Relativistic quantum field theories: invariant under space-time transformations: Lorentz transformations + space-time translations (Poincaré group)

- Construction principle: requirement of local gauge invariance (internal symmetry)

- Gauge symmetries of the Standard Model:

$U(1)_Y \times SU(2)_L \times SU(3)_C$

electroweak (U(1)$_Y$ × SU(2)$_L$) strong (SU(3)$_C$) interaction



Higgs Mechanism

❖ The problem with the masses:

✏ Fermion Lagrangian $\mathcal{L}_f = \bar{\Psi}(i\gamma^\mu D_\mu - m)\Psi$ for fermion field $\Psi = \begin{pmatrix} \chi \\ \varphi \end{pmatrix}$

Kinetic term is invariant under chiral transformations $\Psi'_L = U_L \Psi_L$ and $\Psi'_R = U_R \Psi_R$

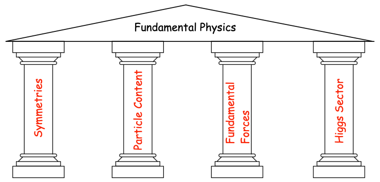
but not the mass term: $m\bar{\Psi}\Psi = m(\varphi^\dagger, \chi^\dagger)\begin{pmatrix} \chi \\ \varphi \end{pmatrix} = m(\varphi^\dagger \chi + \chi^\dagger \varphi) = m(\bar{\Psi}_L \Psi_R + \bar{\Psi}_R \Psi_L)$

✏ Gauge boson Lagrangian $\mathcal{L} = -\frac{1}{4} \underbrace{F^{\mu\nu}F_{\mu\nu}}_{\text{gauge invariant}} + \frac{m^2}{2} \underbrace{A^\mu A_\mu}_{\text{not gauge invariant}}$

U(1) gauge transformation $A_\mu \to A'_\mu = A_\mu + \partial_\mu \theta$.

Mass term breaks gauge invariance:

$$(A_\mu A^\mu)' = (A_\mu + \partial_\mu \theta)(A^\mu + \partial^\mu \theta) = A_\mu A^\mu + 2A_\mu \partial^\mu \theta + (\partial_\mu \theta)(\partial^\mu \theta)$$



- Higgs Mechanism:

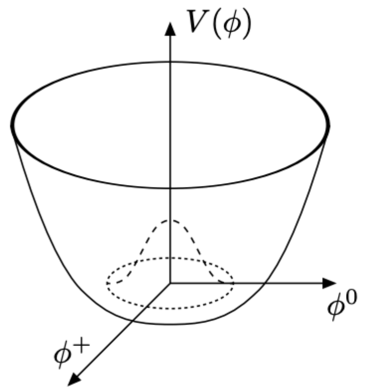
  Generation of particle masses through spontaneous symmetry breaking (SSB)

- Higgs Lagrangian: $\mathcal{L}_{\text{Higgs}} = (D_\mu \Phi)(D^\mu \Phi)^\dagger - V(\Phi)$

  with the Higgs potential $V(\Phi) = \mu^2(\Phi^\dagger \Phi) + \lambda(\Phi^\dagger \Phi)^2$ and $<\Phi> = \frac{1}{\sqrt{2}}(0,v)^T$

The Higgs potential has a non-vanishing vacuum expectation value (VEV) v for $\mu^2 < 0$

$|\Phi|^2 = v^2 = -(\mu^2)/(2\lambda)$, v=246 GeV



- SSB: Lagrangian preserves the gauge symmetry, but the ground state breaks it

- Generation of particle masses: through particle interactions with Higgs in the ground state

Example Fermion Mass Generation

- **Fermion masses**

  generated through the Yukawa interactions; e.g. for electrons

$$\mathcal{L}^e_{\text{Yuk}} = -\frac{h_e}{\sqrt{2}} \left(\begin{array}{c} \bar{\nu}_L \\ \bar{e}_L \end{array} \right)^T \left(\begin{array}{c} 0 \\ v+H \end{array} \right) e_R + \text{h.c.}$$

⇝ electron mass term

$$\mathcal{L}^e_{\text{Yuk,mass}} = -\frac{h_e v}{\sqrt{2}} (\bar{e}_L e_R + \bar{e}_R e_L) = \frac{h_e v}{\sqrt{2}} \bar{e} e$$

The Yukawa coupling h_e is related to the electron mass by

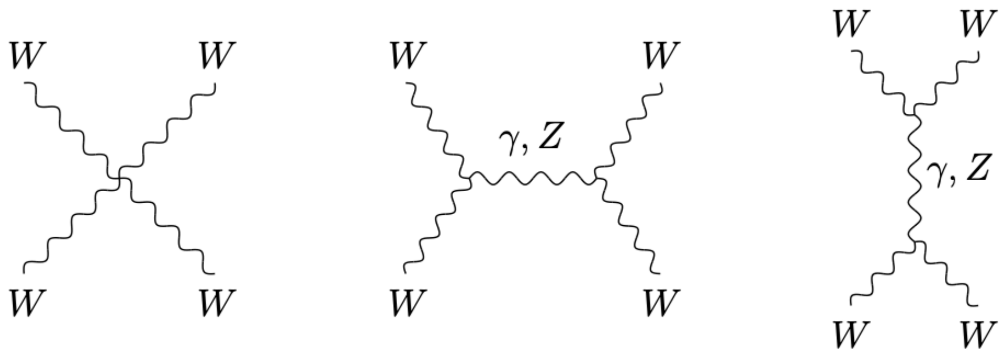
$$h_e = g \frac{m_e}{\sqrt{2} M_W}$$

We also have an interaction between the electron and the Higgs boson

$$\mathcal{L}_{\text{int}} = -g \frac{m_e}{2 M_W} \bar{e} H e$$

Unitarity Restoration

- Scattering of longitudinally polarized W bosons:



$$\mathcal{A} = \frac{G_F s}{8\pi\sqrt{2}}$$

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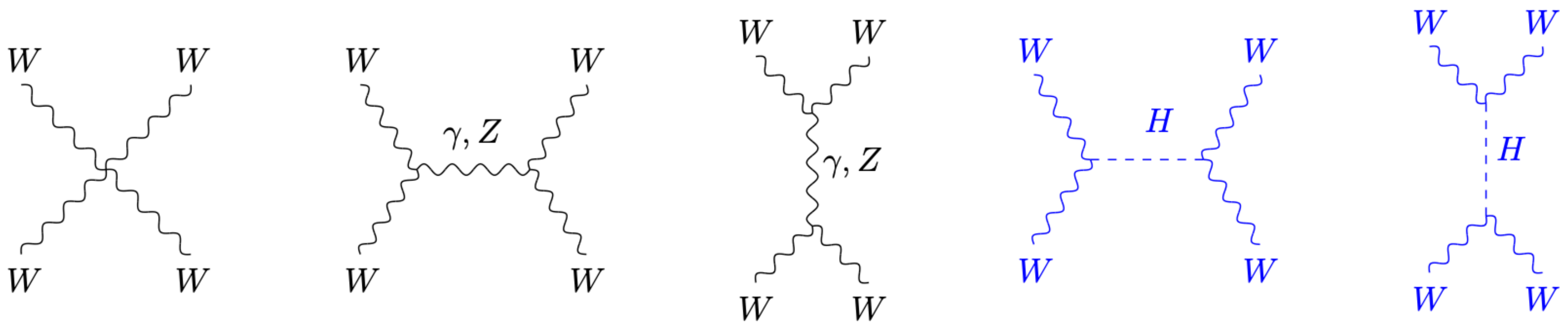


$$\mathcal{A} = \frac{G_F M_H^2}{4\sqrt{2}\pi}$$

Higgs ensures unitarity of W boson scattering if HWW coupling proportional m_W^2

Experimental Test of the Higgs Mechanism

Establishing the Higgs Mechanism

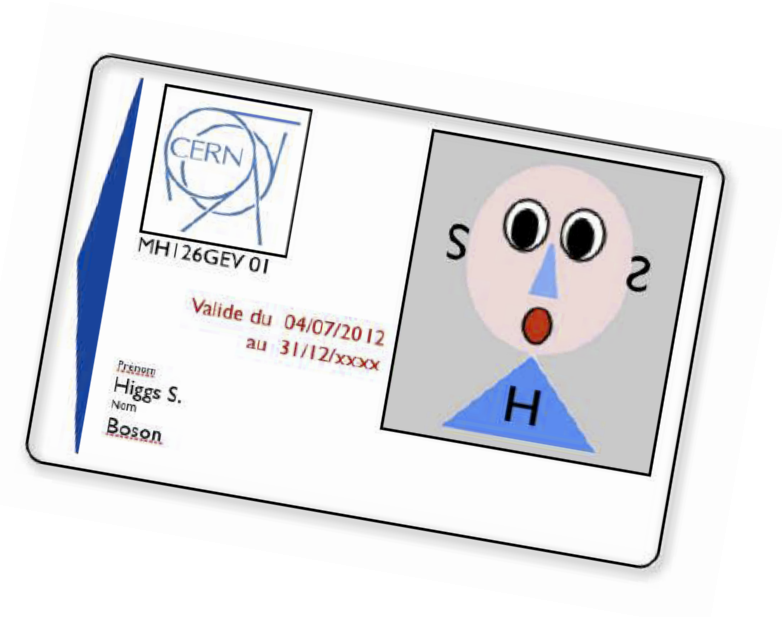
4th July 2012

Discovery of new particle announced by CERN!!

But how can we be sure that it is a Higgs? We must

- Measure its couplings to the other SM particles
- We must determine its spin and CP quantum numbers
- We must measure the Higgs potential, I.e. its self-couplings

My Diary



The Role of the Higgs Boson Mass

✦ Present Accuracy: [ATLAS,CMS]

M_H = 125.09 ± 0.21 (stat) ± 0.11 (syst) GeV

✦ Why precision?

∗ Self-consistency test of SM at quantum level
(e.g.: Higgs loop corrections to W boson mass)

∗ $M_H \leftrightarrow$ stability of the electroweak vacuum [Degrassi eal;Bednyakov eal]

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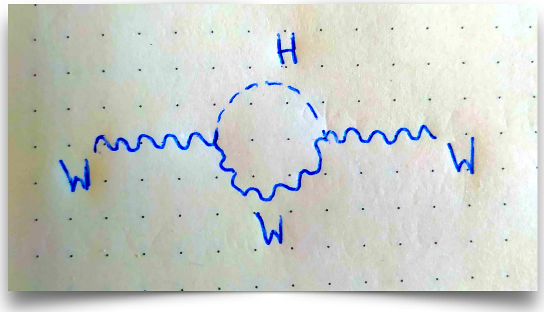
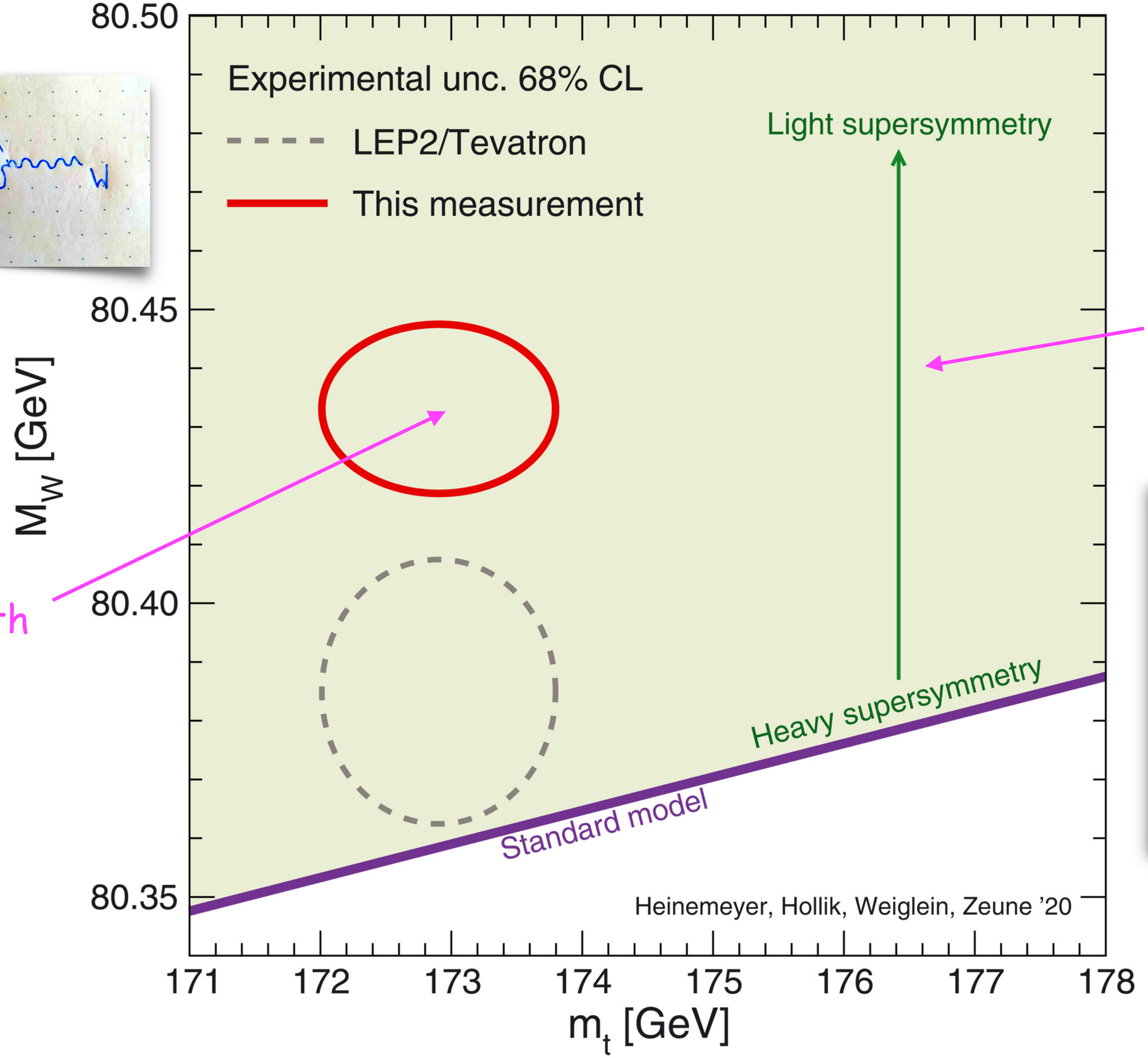
The W Boson Mass





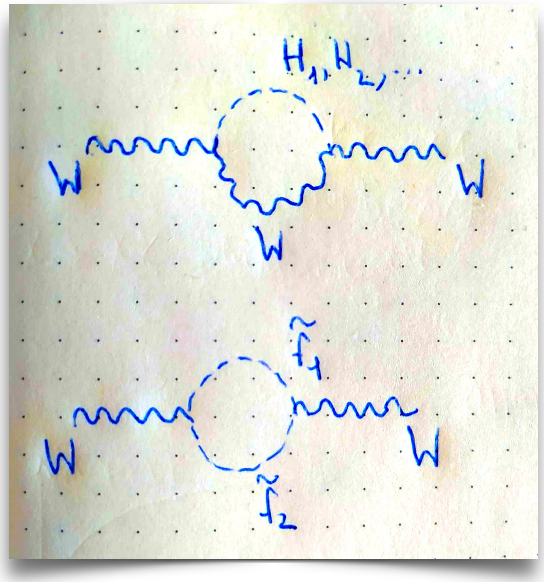
[CDF,2022]

tension with

SM at 7σ

new physics ->

compatibility



The W Boson Mass

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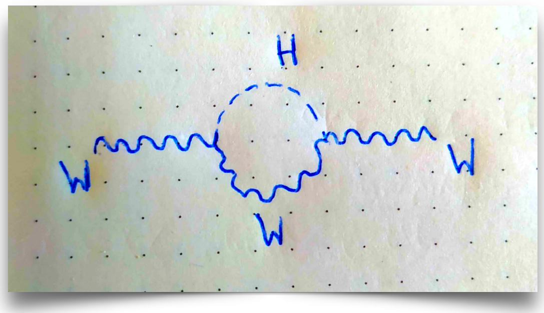

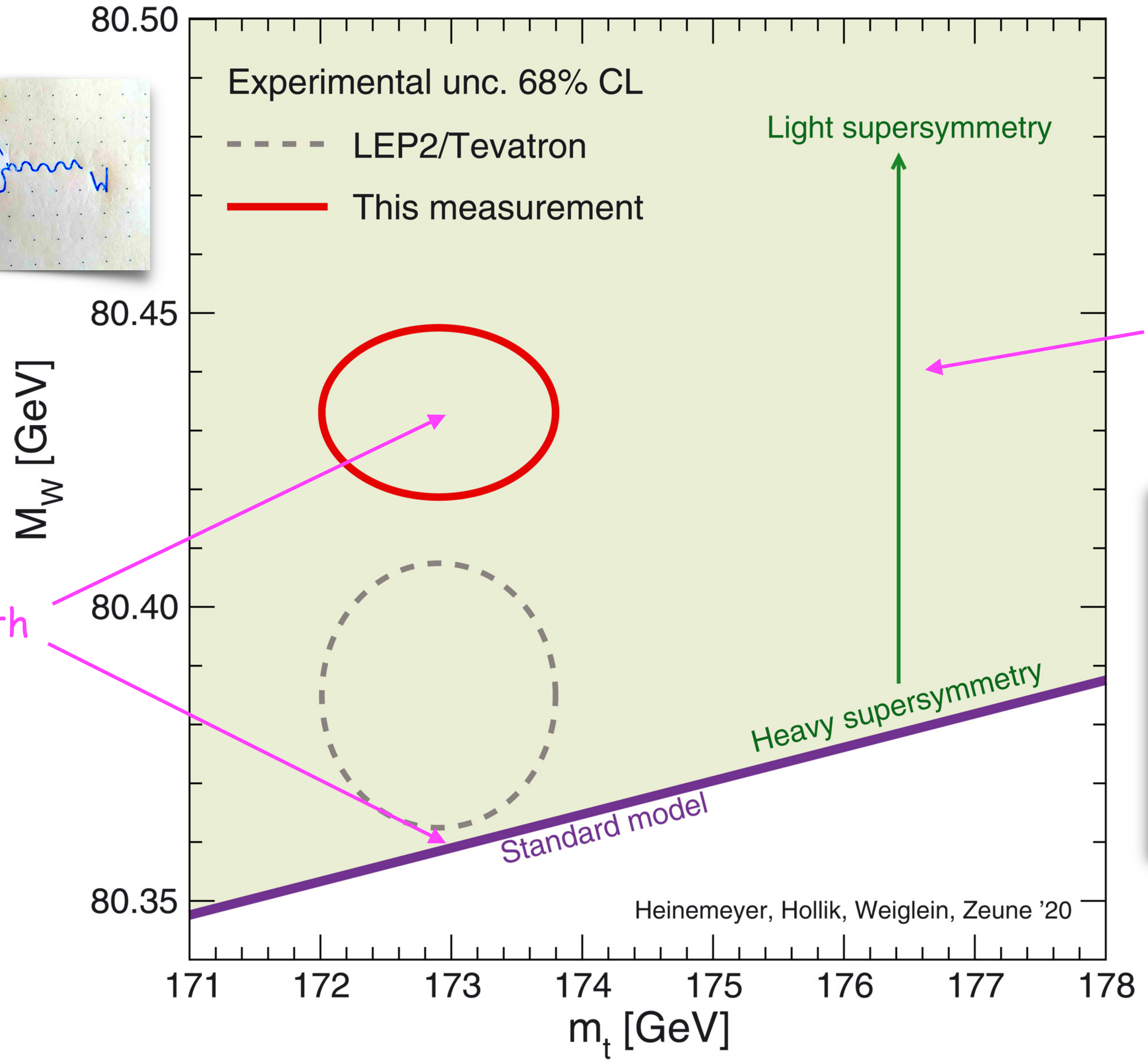

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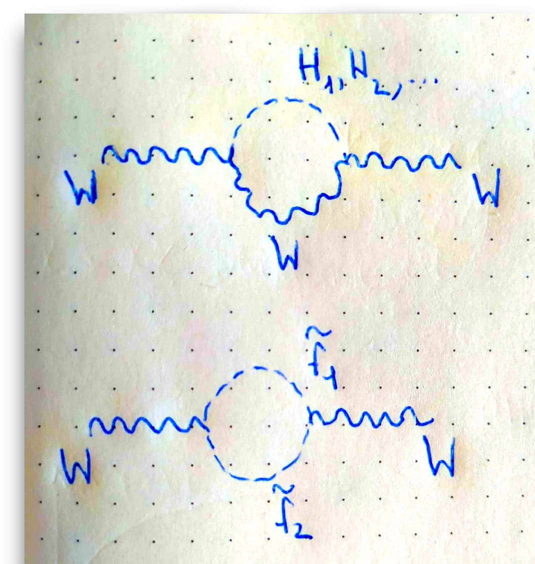

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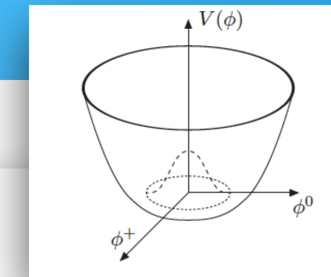
Stability of the Electroweak Vacuum

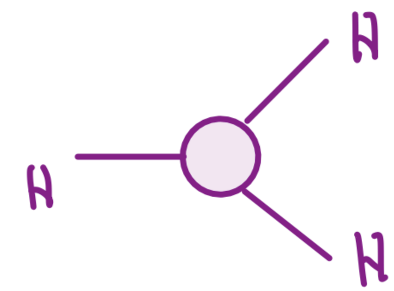


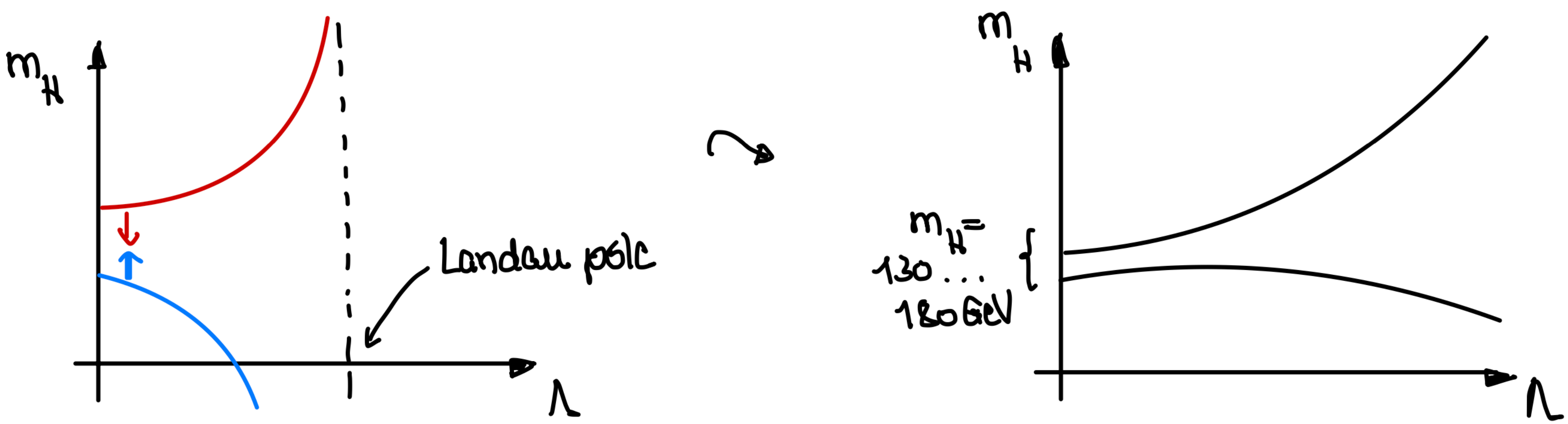
$$V(H) = \frac{1}{2} M_H^2 H^2 + \frac{1}{3!} \lambda_{HHH} H^3 + \frac{1}{4!} \lambda_{HHHH} H^4$$

$$\lambda_{HHH} = 3 \frac{M_H^2}{v}$$

quantum corrections to self-coupling from all SM particles

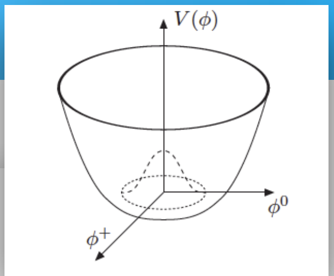
top : negative contribution ; all others positive





if SM valid until Planck scale

Stability of the Electroweak Vacuum



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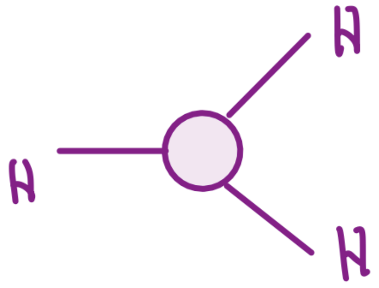

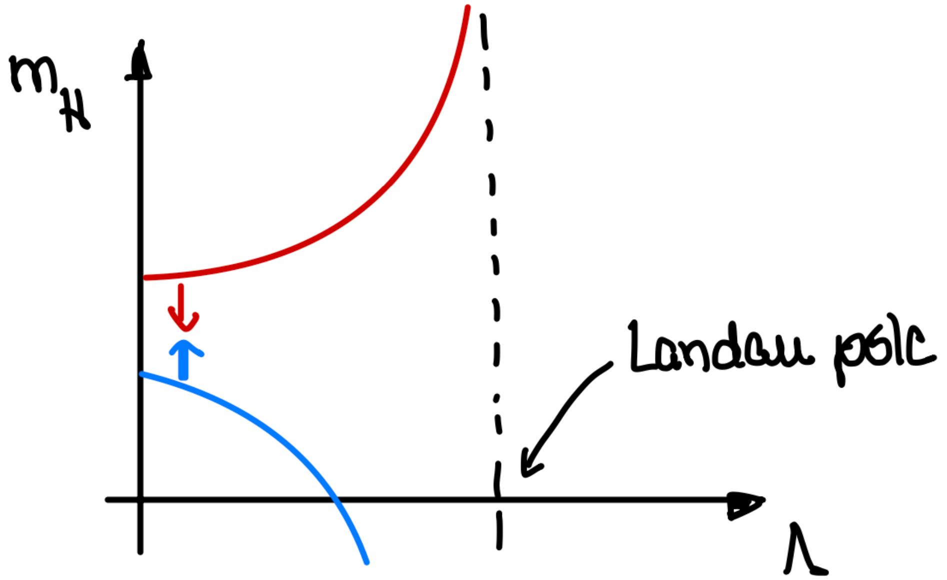

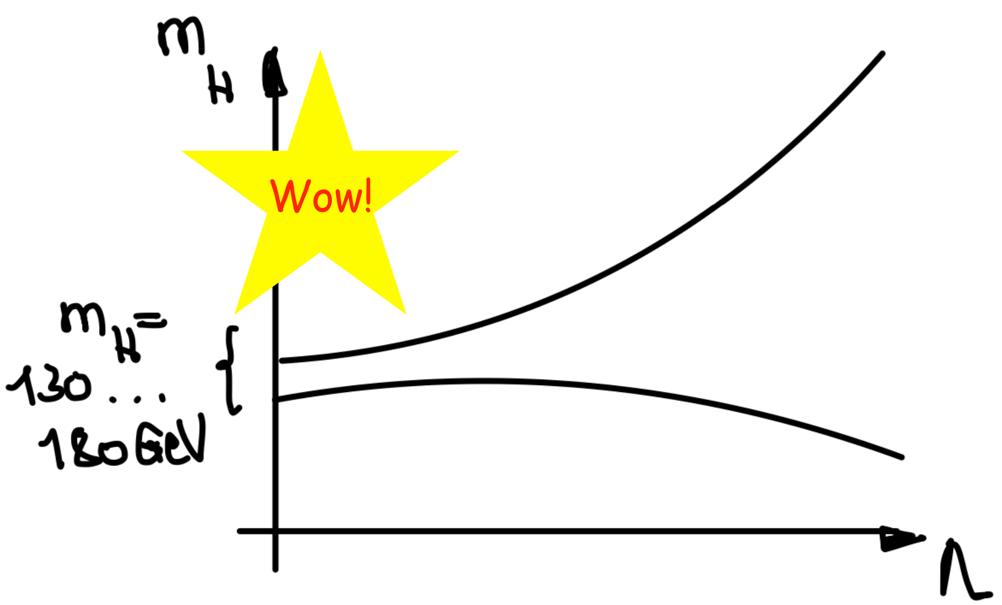

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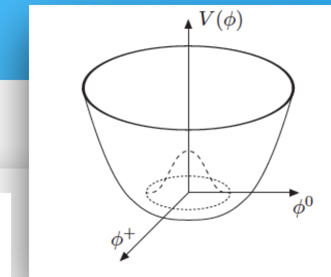
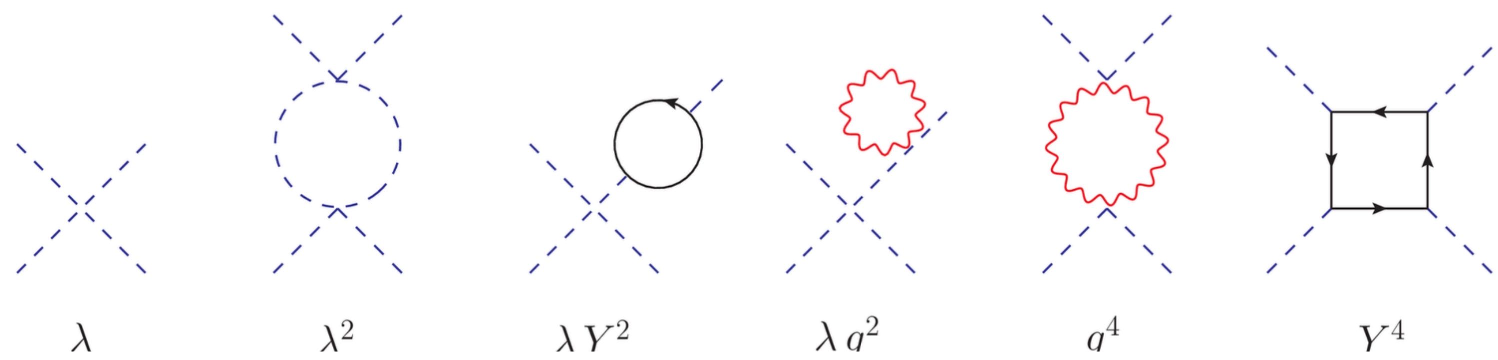
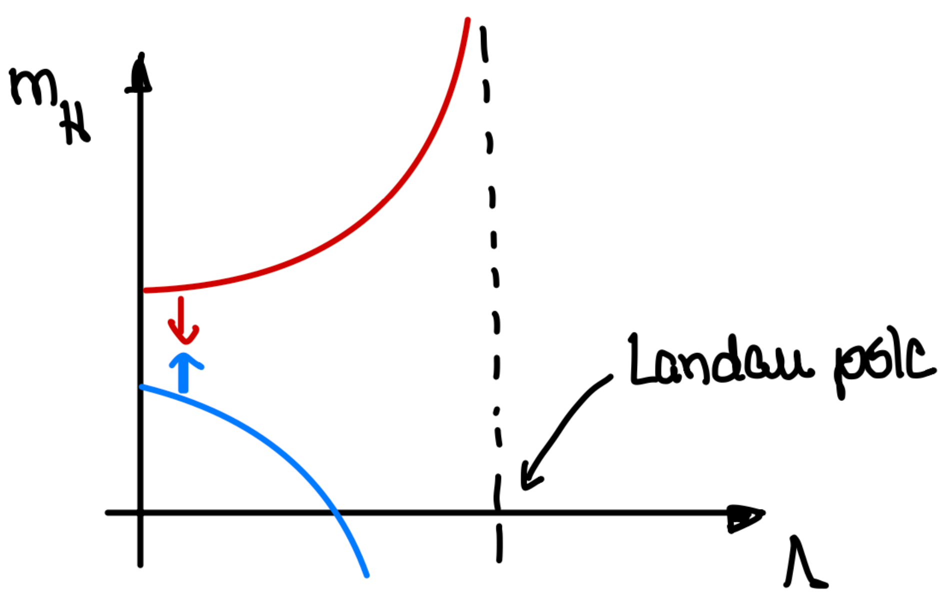
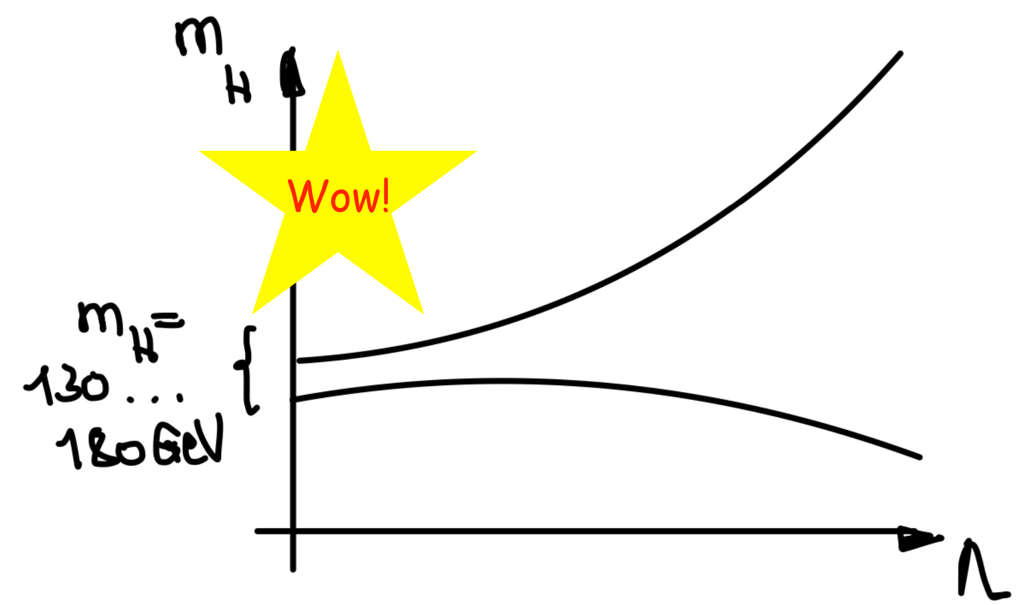




$$\frac{d\lambda}{d\ln\mu} = \frac{1}{16\pi^2}\left[+24\lambda^2 + \lambda\left(4N_cY_t - 9g^2 - 3g'^2\right) - 2N_cY_t^4 + \frac{9}{8}g^4 + \frac{3}{8}g'^4 + \frac{3}{4}g^2g'^2 + \ldots\right]$$





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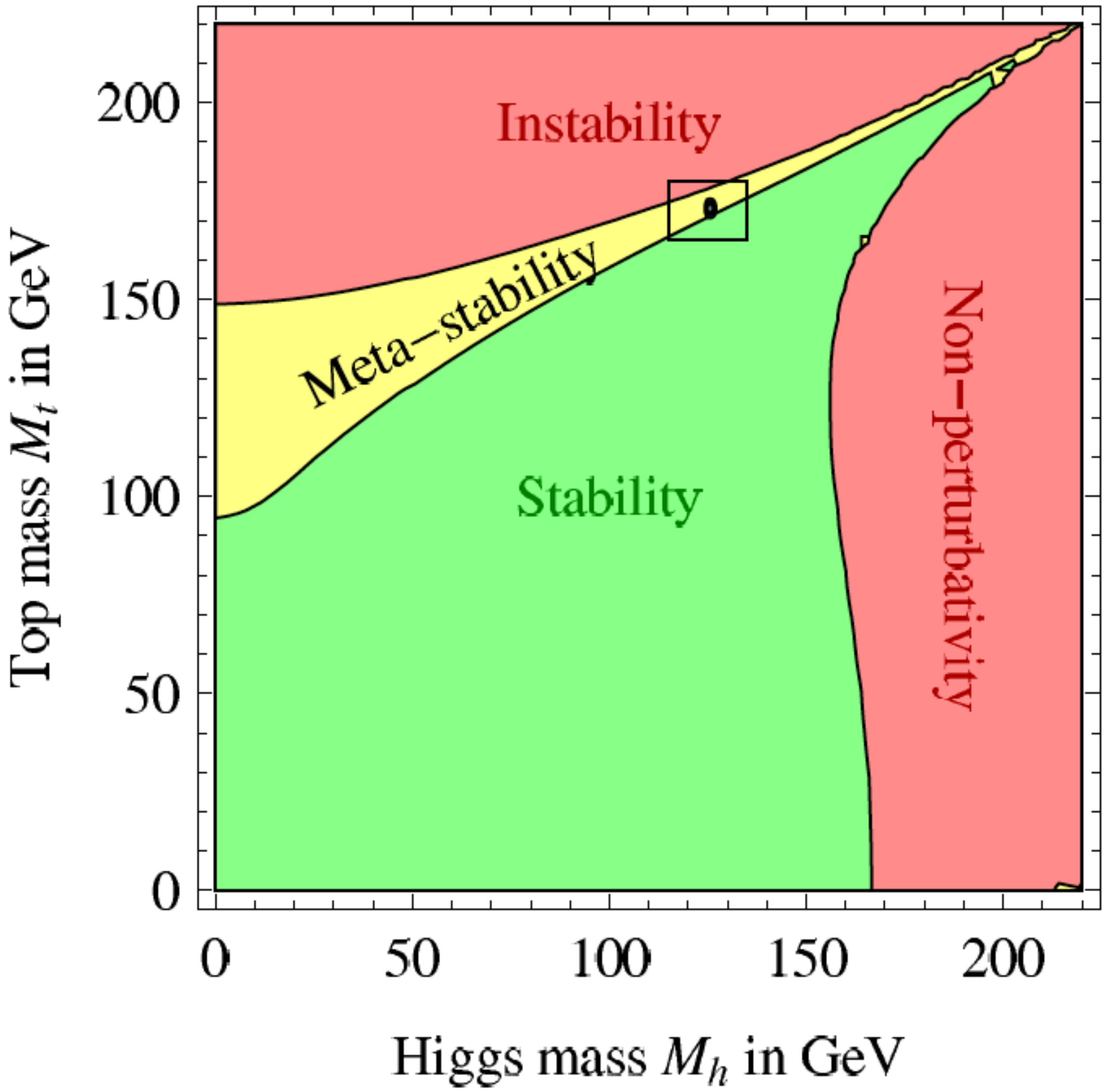
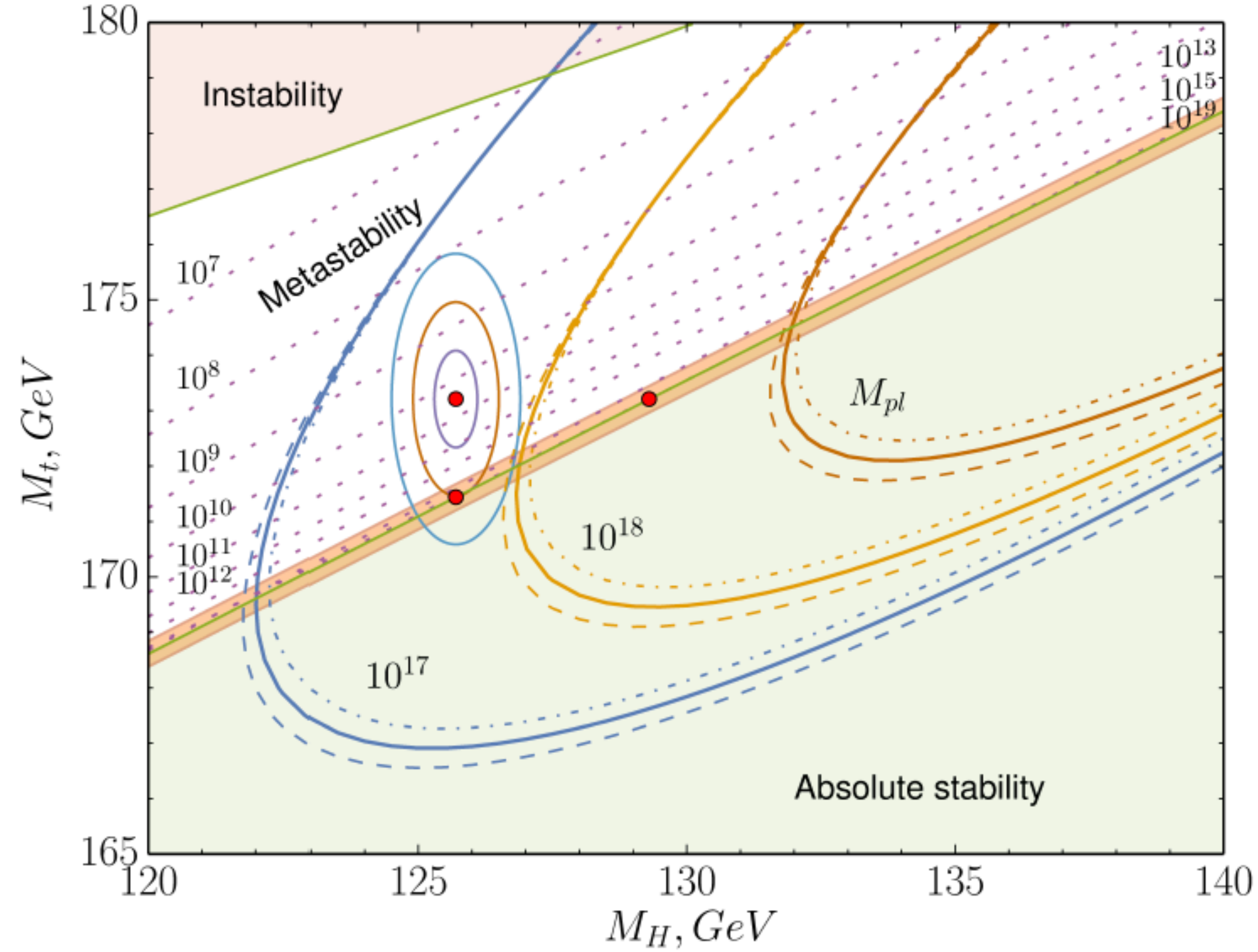
Stability of the Electroweak Vacuum

[Degrassi,Di Vita,Elias-Miro,Espinosa,'12]



[Bednyakov,Kniehl,Pikelner,Veretin,'15]



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* Self-consistency test of SM at quantum level
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Precision measurements of SM parameters (m_W, m_{top}) crucial

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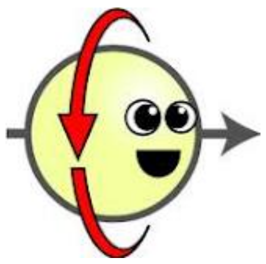
indirect constraints on viable BSM parameter space

*(will come back to this)

Higgs Spin and CP Quantum Numbers

❖ Quantum numbers of the Higgs boson: J^{PC}
- J spin
- P parity
- C charge conjugation



✻ γγ→H or H→γγ ~> J ≠ 1

❖ CP properties:

✻ SM Higgs $J^{CP} = 0^{++}$; beyond the SM (BSM)

- more than one spin-0 particle possible
- CP-even, CP-odd, CP-violating Higgs states

✻ Study of CP properties ~> insights in beyond-SM (BSM) physics

✻ existing and future colliders:
establish CP properties, determine amount of CP-mixing

Determination of Higgs Quantum Numbers

- **Spin and CP quantum numbers: threshold effects and angular correlations in**

  - angular correlations in production: Hjj in vector boson fusion, — Plehn,Rainwater,Zeppenfeld; Hankele,Klämke,Zeppenfeld

    gluon gluon fusion — Odagiri; Klamke,Zeppenfeld; Campanario eal; Del Duca eal; Andersen eal

  - Higgs decays into W and Z pairs — Dell'Aquila,Nelson; Barger eal; Kramer,Kühn,Stong,Zerwas; Skjold,Osland; Choi,Kalinowski,Liao,Zerwas Miller,MMM,Zerwas;Bluj; Dova eal; Buszello,Fleck,Marquard,van der Bij; Gao eal:Englert eal: Sancti eal

    observables sensitive to CP-violation — Chang eal; Skjold,Osland; Choi eal; Niezurawski,Zarnecki,Krawczyk; Godbole,Kraml;Rindani,Singh Godbole,Miller,MMM; De Rujula eal

  - $\gamma\gamma$ collisions — Grzadkowski,Gunion; Asakawa,Choi,Hagiwara; Godbole,Rindani,Singh; Godbole,Kraml,Rindani,Singh

  - Higgs-radiation & VBF at e^+e^- colliders, also Higgs-ZZ coupling

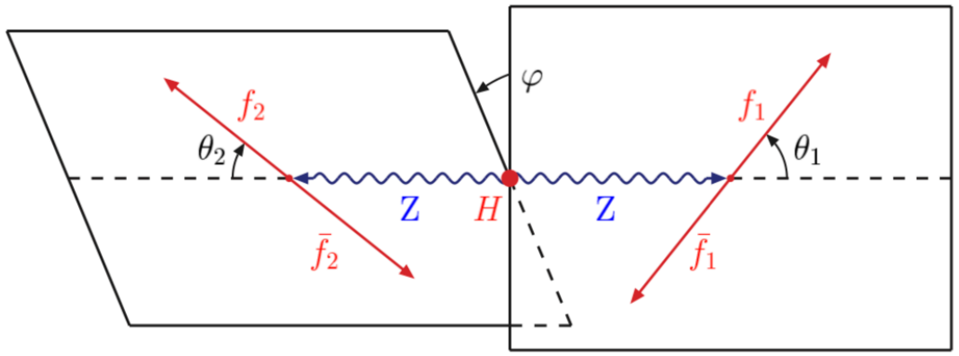
    Godbole,Roy; Hagiwara,Stong; Gounaris,Renard; Rao,Rindani Miller,Choi,Eberle,MMM,Zerwas; Skjold,Osland; Hagiwara eal; Han,Jiang; Biswal, Godbole, Singh; Biswal, Choudhury, Godbole eal

Example for Spin and CP Determination

❖ Higgs Decay into Z boson pair: $H \to ZZ^{(*)} \to (f_1\bar{f}_1)(f_2\bar{f}_2)$

SM Double polar angle distribution

$$\frac{1}{\Gamma'}\frac{d\Gamma'}{d\cos\theta_1 d\cos\theta_2} = \frac{9}{16}\frac{1}{\gamma^4+2}\Big[\gamma^4\sin^2\theta_1\sin^2\theta_2 + \frac{1}{2}(1+\cos^2\theta_1)(1+\cos^2\theta_2)\Big]$$



SM Azimuthal angular distribution

$$\frac{1}{\Gamma'}\frac{d\Gamma'}{d\phi} = \frac{1}{2\pi}\Big[1+\frac{1}{2}\frac{1}{\gamma^4+2}\cos 2\phi\Big]$$

❖ Angular distributions for particle w/ arbitrary spin and parity:
helicity analyses & operator expansion

✏ Azimuthal angular distribution differs for scalar and pseudoscalar particle:

$$\begin{array}{lcl} 0^+ & : & d\Gamma/d\phi \sim 1 + 1/(2\gamma^4+4)\cos 2\phi \\ 0^- & : & d\Gamma/d\phi \sim 1 - 1/4\cos 2\phi \end{array}$$

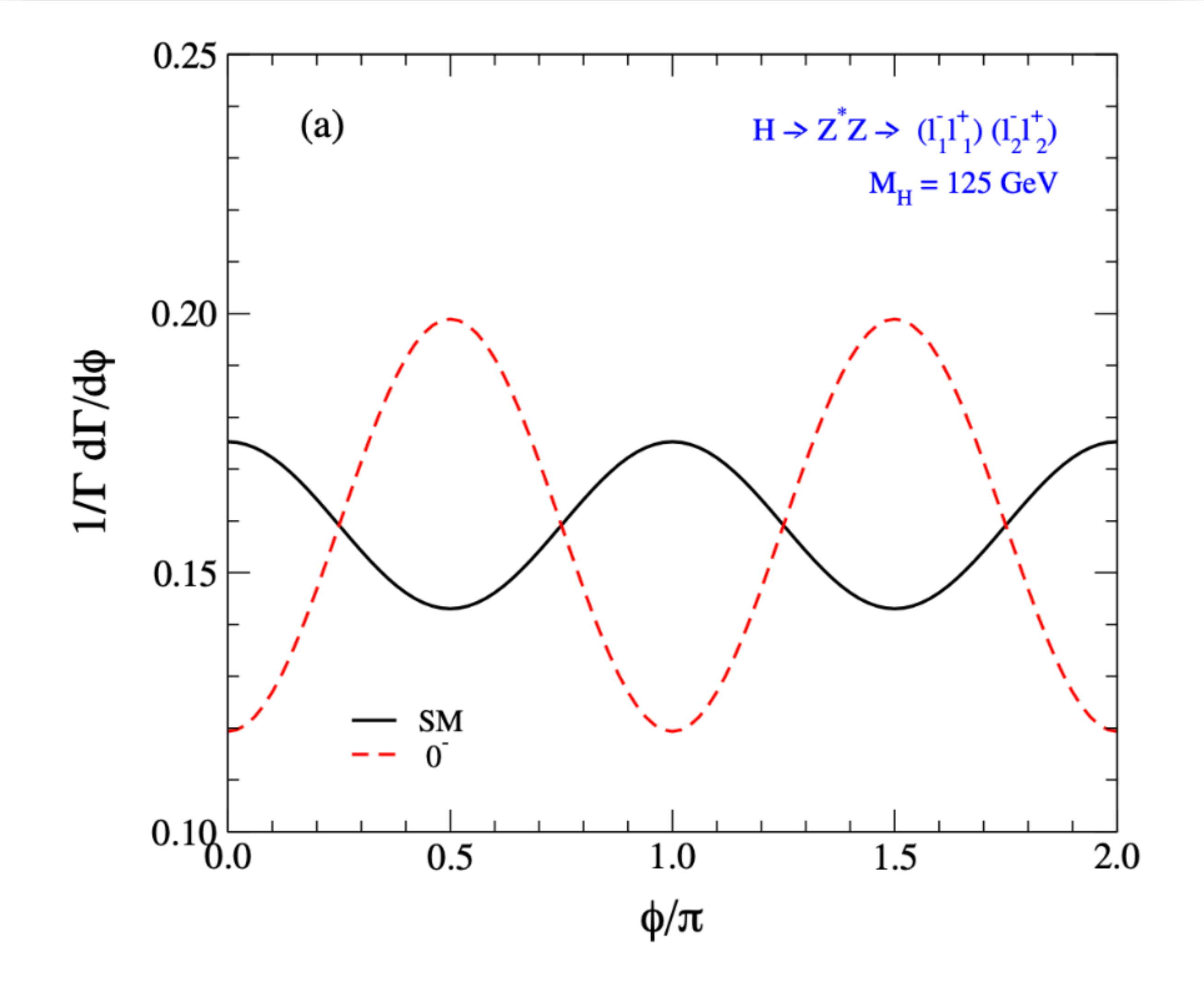
✏ Threshold behavior allows to determine the spin of the particle:

spin 0: linear rise w/ β
spin 1 (2) particle ~ β^3 (~ β^5)

$$\frac{d\Gamma[H\to Z^*Z]}{dM_*^2} \sim \beta = \sqrt{(M_H-M_Z)^2 - M_*^2}/M_H$$

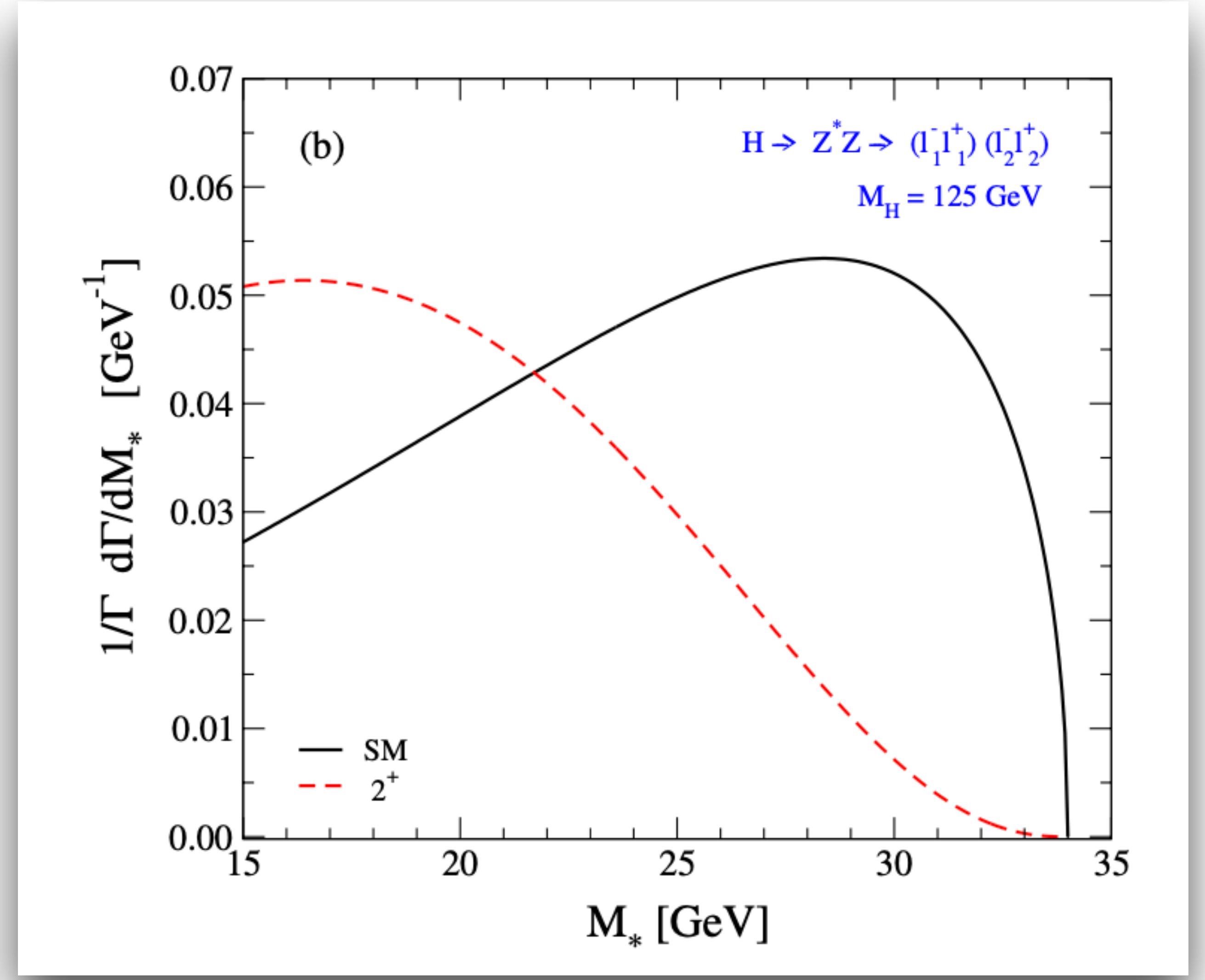
Extraction of Higgs Quantum Numbers

CP-even or CP-odd



[Adapted from Choi,Miller,MM,Zerwas,´03]

Spin 0 or Spin 2



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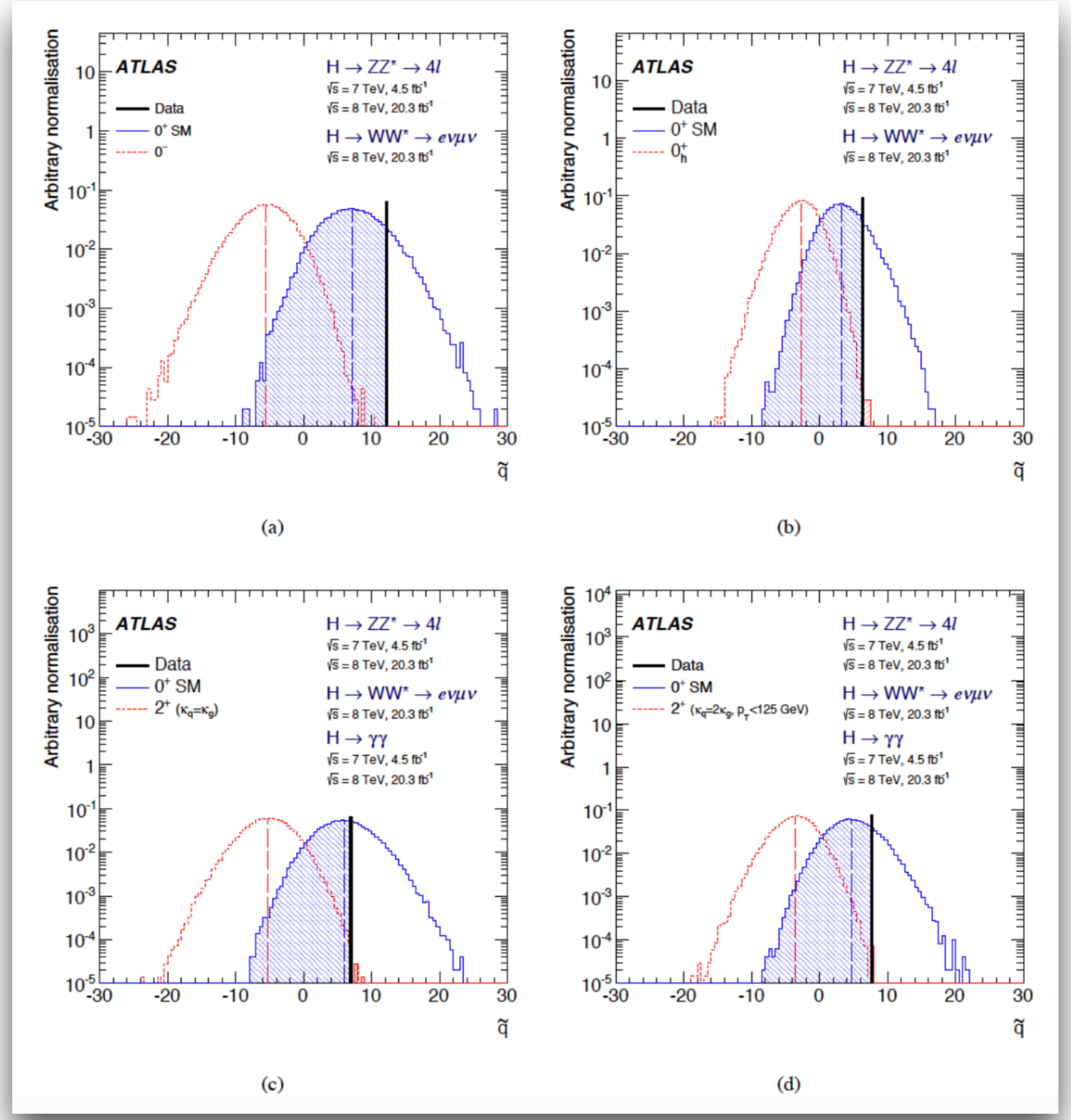
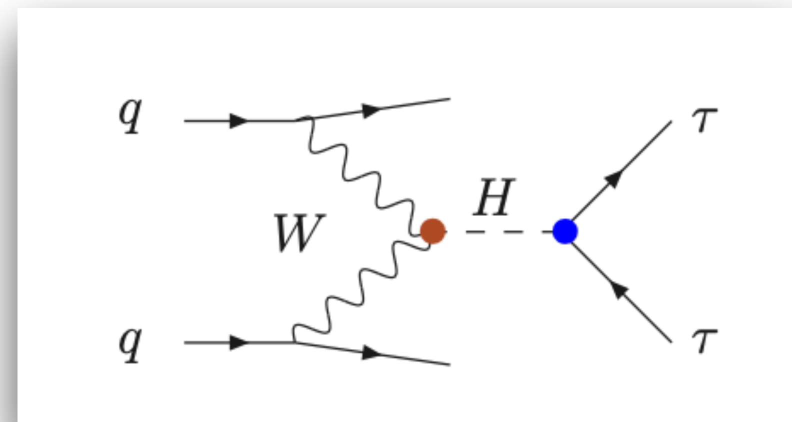
Experiment: Hypothesis Test

[ATLAS,1506.05669]



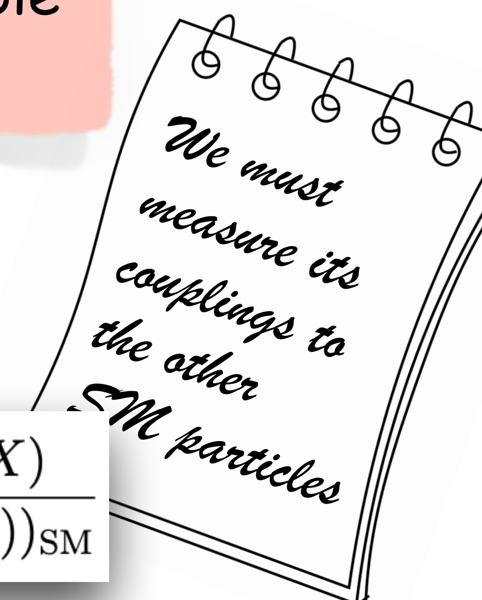
Higgs Coupling Measurements

- **Higgs mechanism:** Higgs couplings to SM particles ~ to masses of the particles
- **Experimental test:** various production and decay channels ~> extract couplings



~ Γ_{WW} x BR(H->ττ) ~ Γ_{WW} x Γ(H->ττ)/Γ_{tot}

at LHC: not all final states are accessible
small SM Γ_{tot} non measurable



- Experimental provide best fit values on mu-values (signal strength parameters):

$$\mu = \frac{\sigma_{\text{prod}} \times BR(H \to XX)}{(\sigma_{\text{prod}} \times BR(H \to XX))_{\text{SM}}}$$

For extraction of coupling values, a Lagrangian parametrizing possible new physics couplings needs to be defined ~> kappa framework

The Kappa Framework

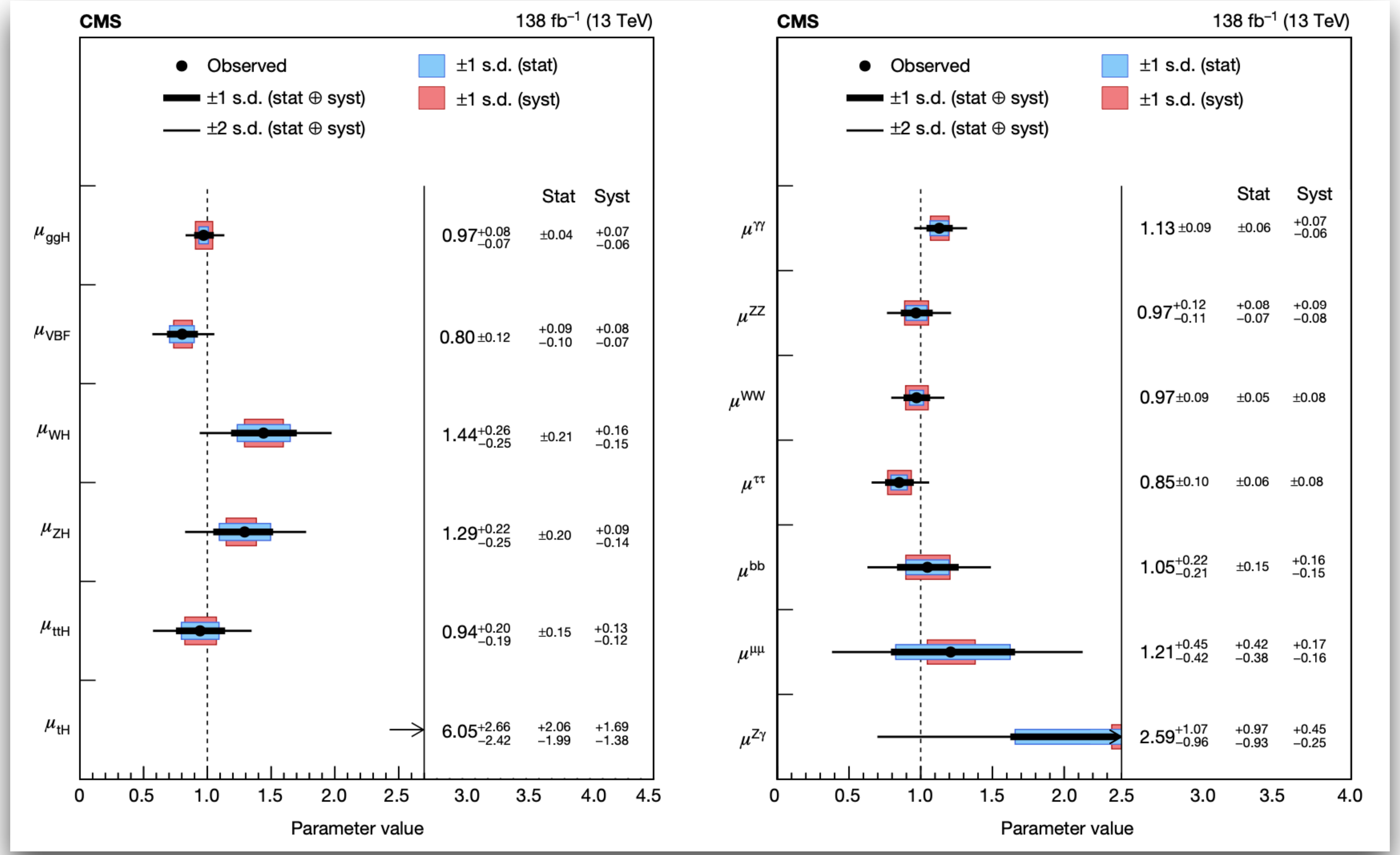
❖ Kappa Framework: Simplest approach

$$\mathcal{L} = \mathcal{L}_h - (M_W^2 W_\mu^+ W^{\mu-} + \frac{1}{2} M_Z^2 Z_\mu Z^\mu)[1 + 2\,\kappa_V\,\frac{h}{v} + \mathcal{O}(h^2)]$$
$$-m_{\psi_i} \bar{\psi}_i \psi_i [1 + \kappa_F\,\frac{h}{v} + \mathcal{O}(h^2)] + \ldots$$

- $\kappa_W = \kappa_Z \equiv \kappa_V$ justified by assumed custodial symmetry
- assumes that there are no flavor-changing neutral couplings (FCNCs)
- loop induced couplings ($H\gamma\gamma$, $HZ\gamma$, Hgg) parametrized in terms of fundamental couplings
- assumes that there are no invisible or undetected Higgs decays beyond the SM
- with more data, higher precisions take individual κ_F for the different fermions
- distributions are also sensitive to the Lorentz structure of the couplings, which is taken to be SM-like in the kappa framework
- For Γ_{tot} model assumptions have to be made (e.g. Γ_{tot} dominated by partial widths into $WW, ZZ, bb, \tau\tau, gg, \gamma\gamma$)

Signal Strength Fit

[Tumasyan eal,2207.00043]

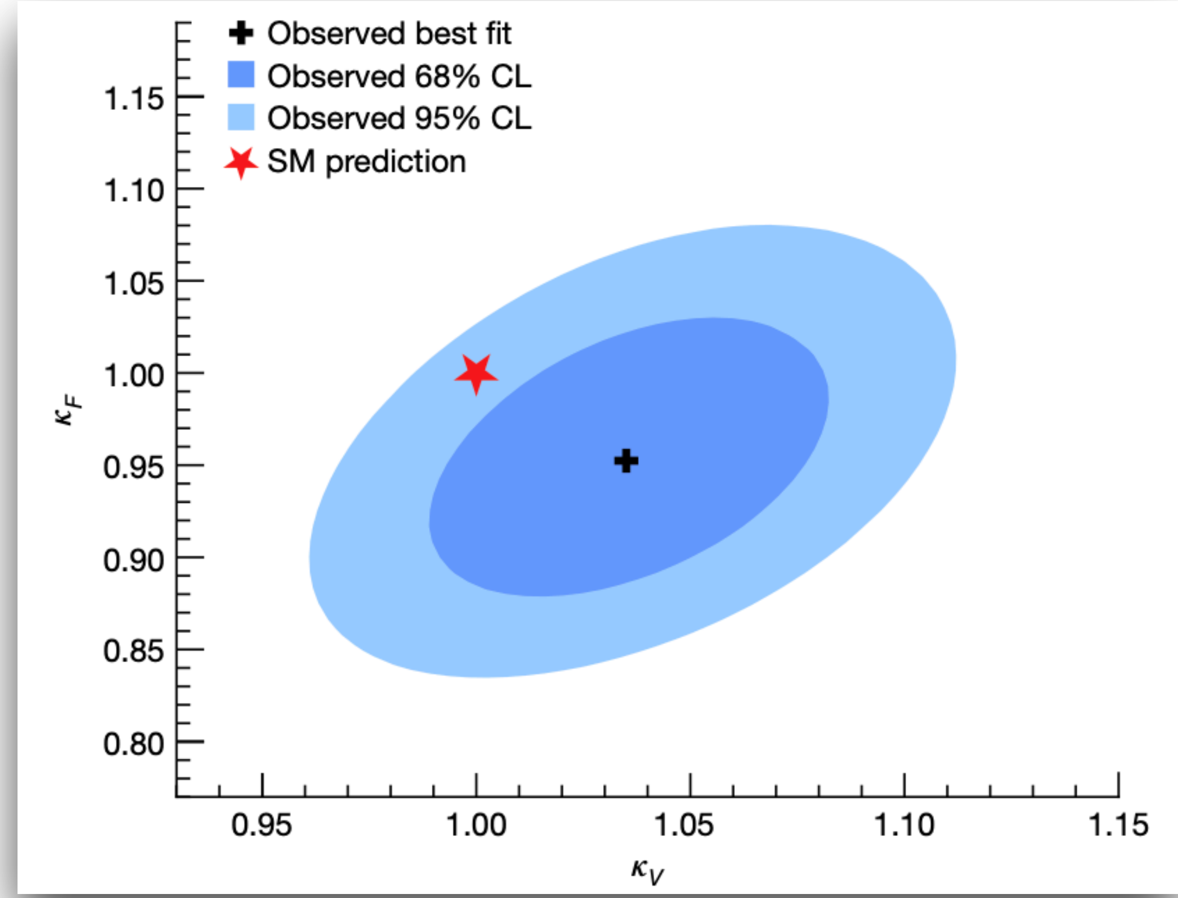


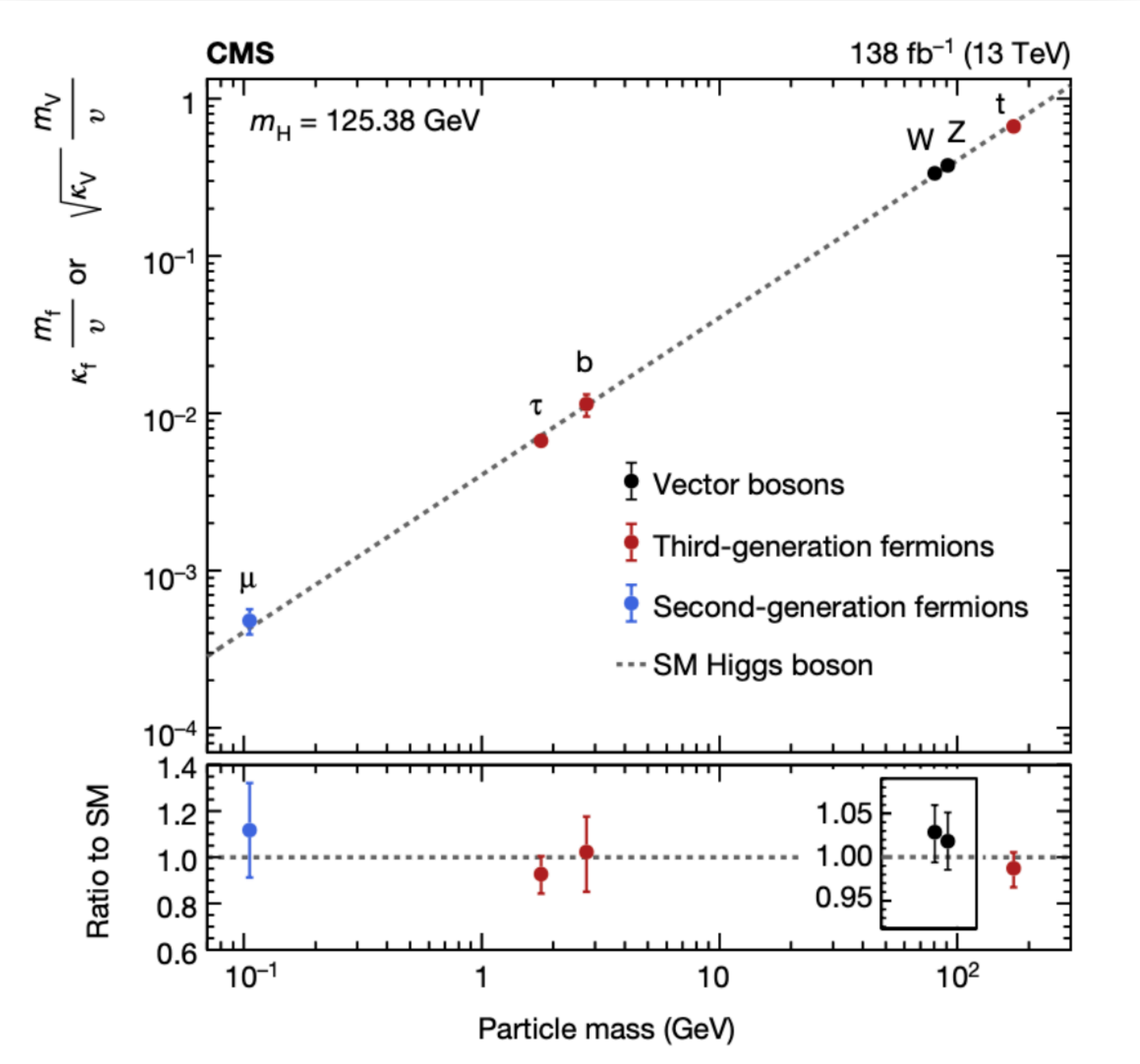
assumes $\mathrm{BR}^f = (\mathrm{BR}^f)^{\mathrm{SM}}$ assumes $\sigma_i = (\sigma_i)^{\mathrm{SM}}$

Coupling Modifiers

[Tumasyan eal,2207.00043]

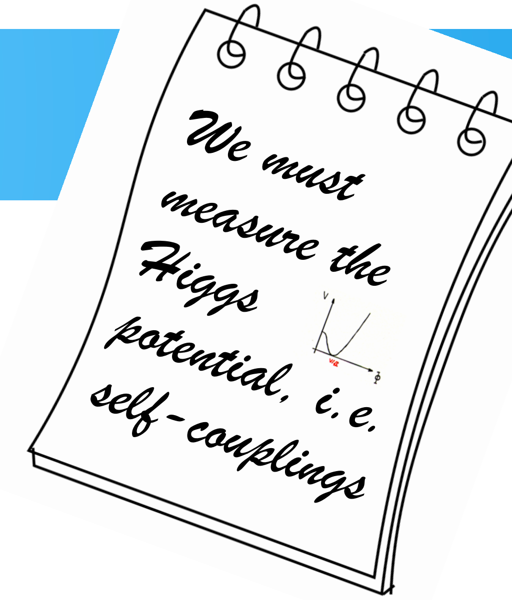
[Aad eal,2207.00092]





The discovered Higgs boson looks very SM-like

Trilinear Higgs Self-Coupling



❖ SM Higgs potential: in physical gauge

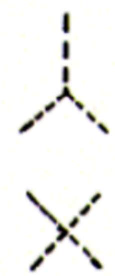
$$V(H) = \frac{1}{2} M_H^2 H^2 + \frac{M_H^2}{2v} H^3 + \frac{M_H^2}{8v^2} H^4$$

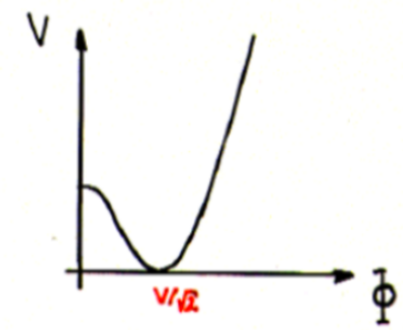
Higgs mass : $M_H = \sqrt{2\lambda}\, v$

trilinear Higgs self-coupling : $\lambda_{HHH} = 3 M_H^2 / M_Z^2$

quadrilinear Higgs self-coupling : $\lambda_{HHHH} = 3 M_H^2 / M_Z^4$

(units $\lambda_0 = 33.8\,\mathrm{GeV}/\lambda_0^2$)

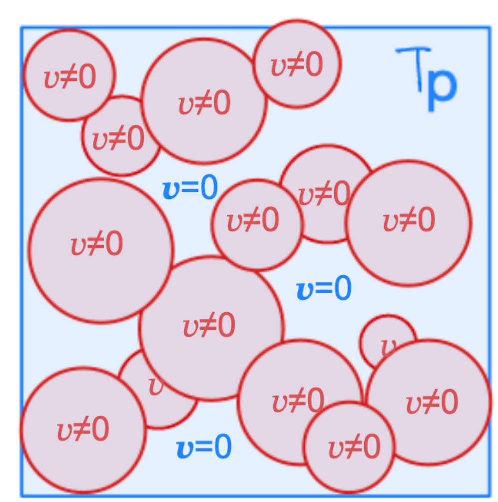




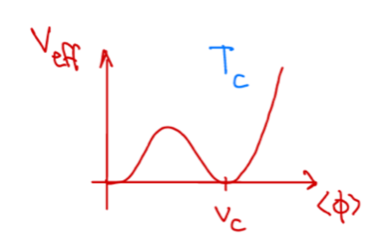
Measurement of the scalar boson self-couplings and Reconstruction of the EWSB potential	Experimental verification Of the scalar sector of the EWSB mechanism

❖ Importance of the trilinear Higgs self-coupling:

- Determines shape of the Higgs potential
- Sensitive to beyond-SM physics
- Important input for electroweak phase transition*

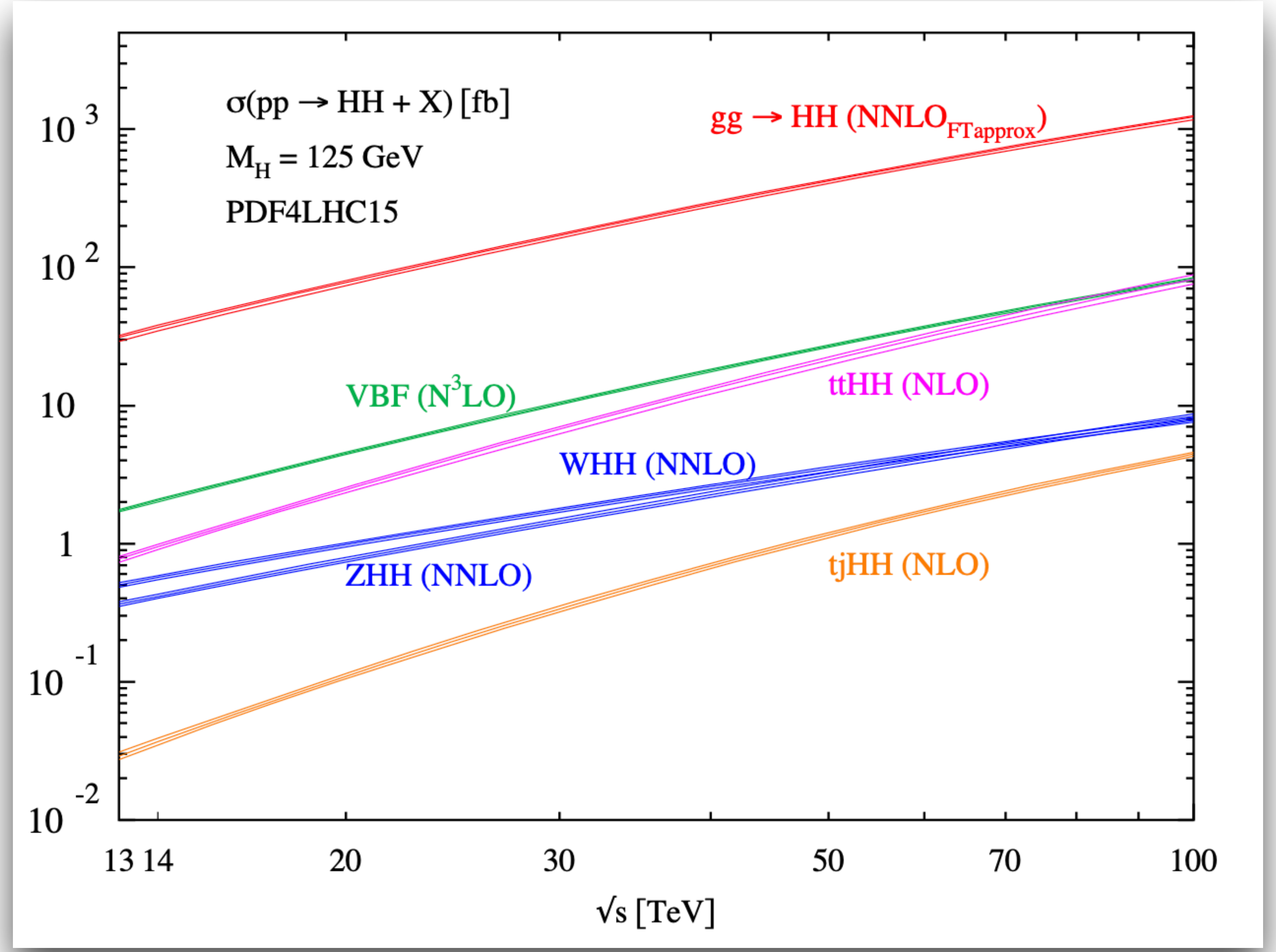


*matter-asymmetry through electroweak baryogenesis



Double Higgs Production at the LHC

[HH, White paper]



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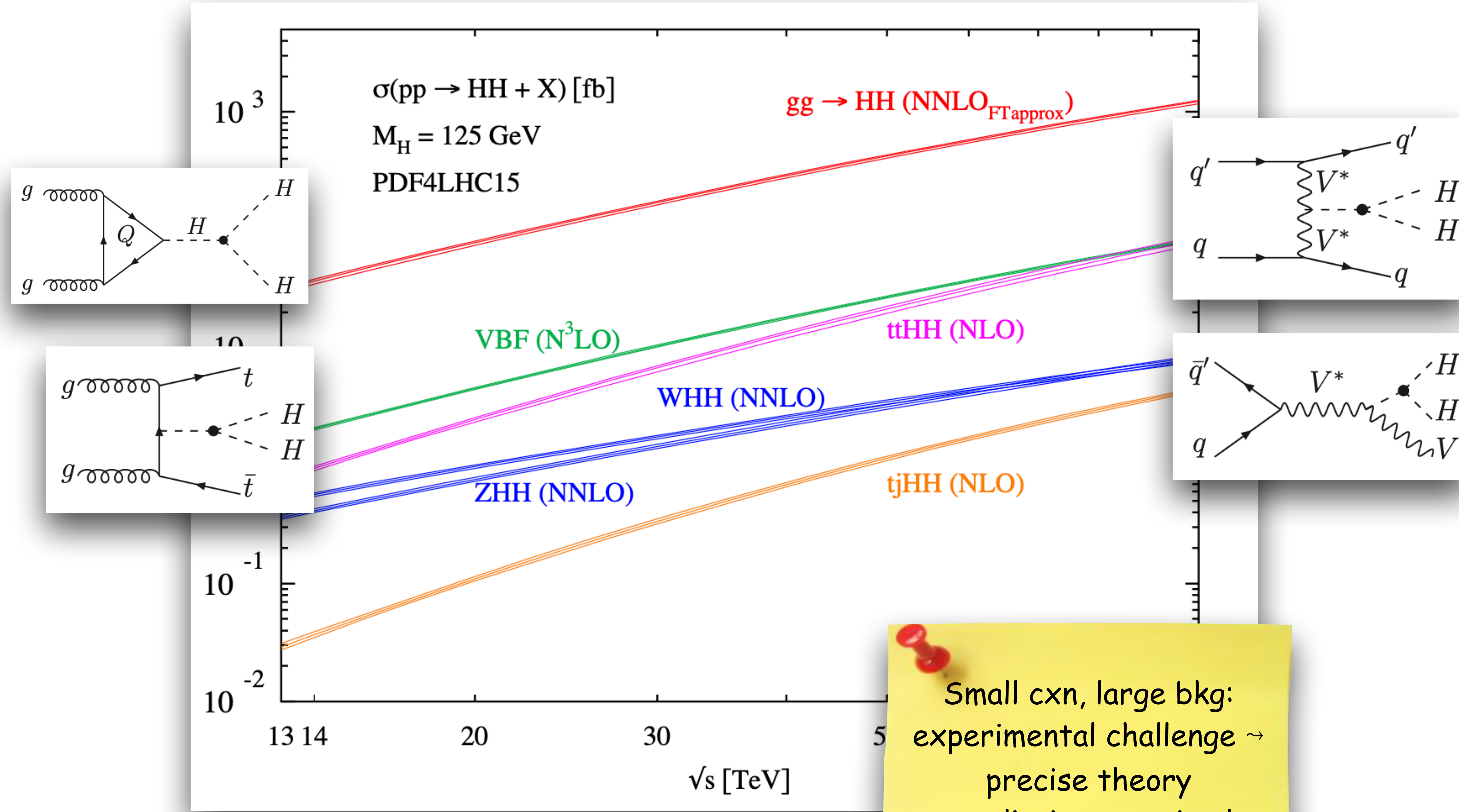
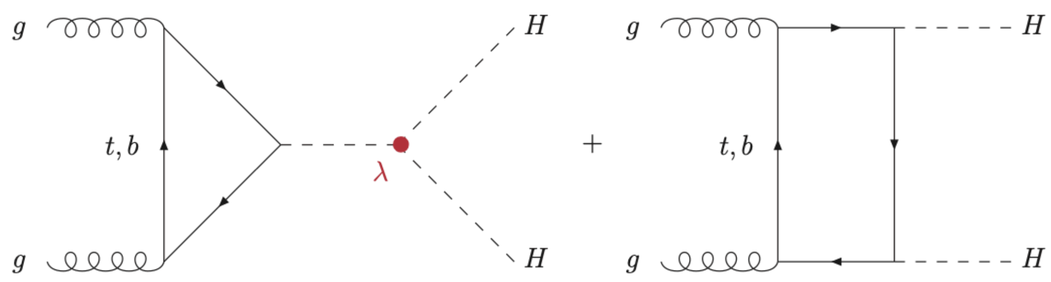


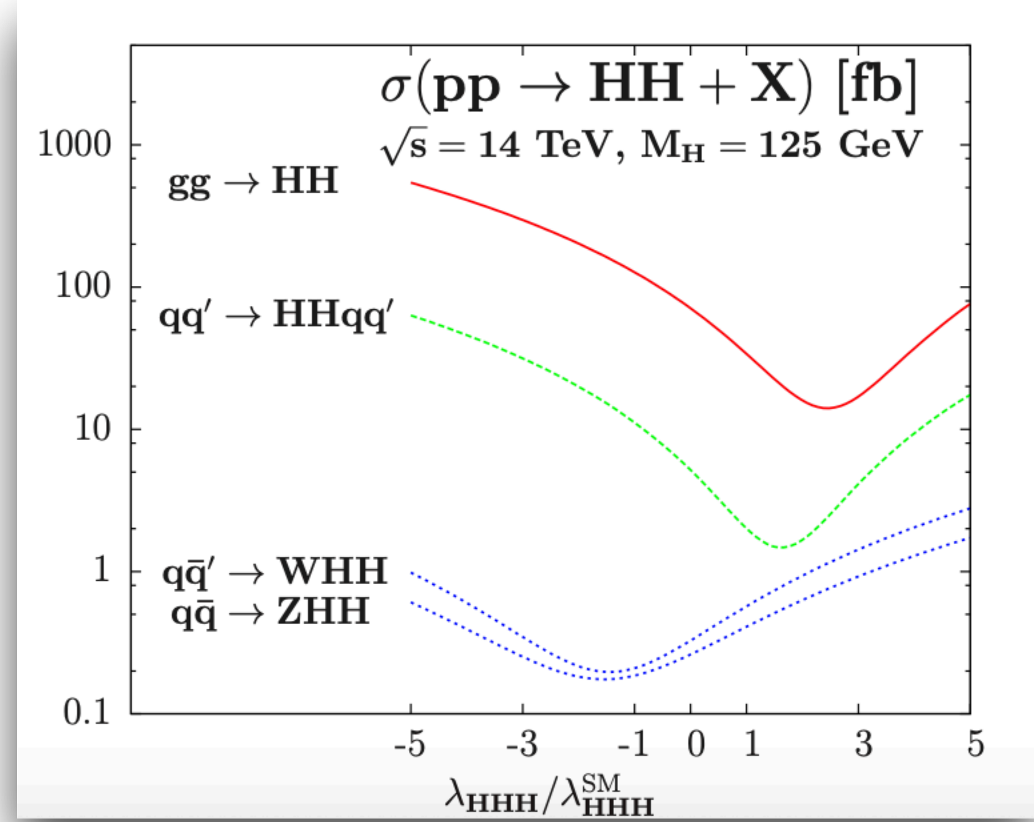
Small cxn, large bkg: experimental challenge → precise theory predictions required

Higgs Pair Production through Gluon Fusion

- Loop mediated at leading order - SM: third generation dominant



- Threshold region sensitive to λ; large M_{HH}: sensitive to c_{tt}/c_{bb} [e.g. boosted Higgs pairs]

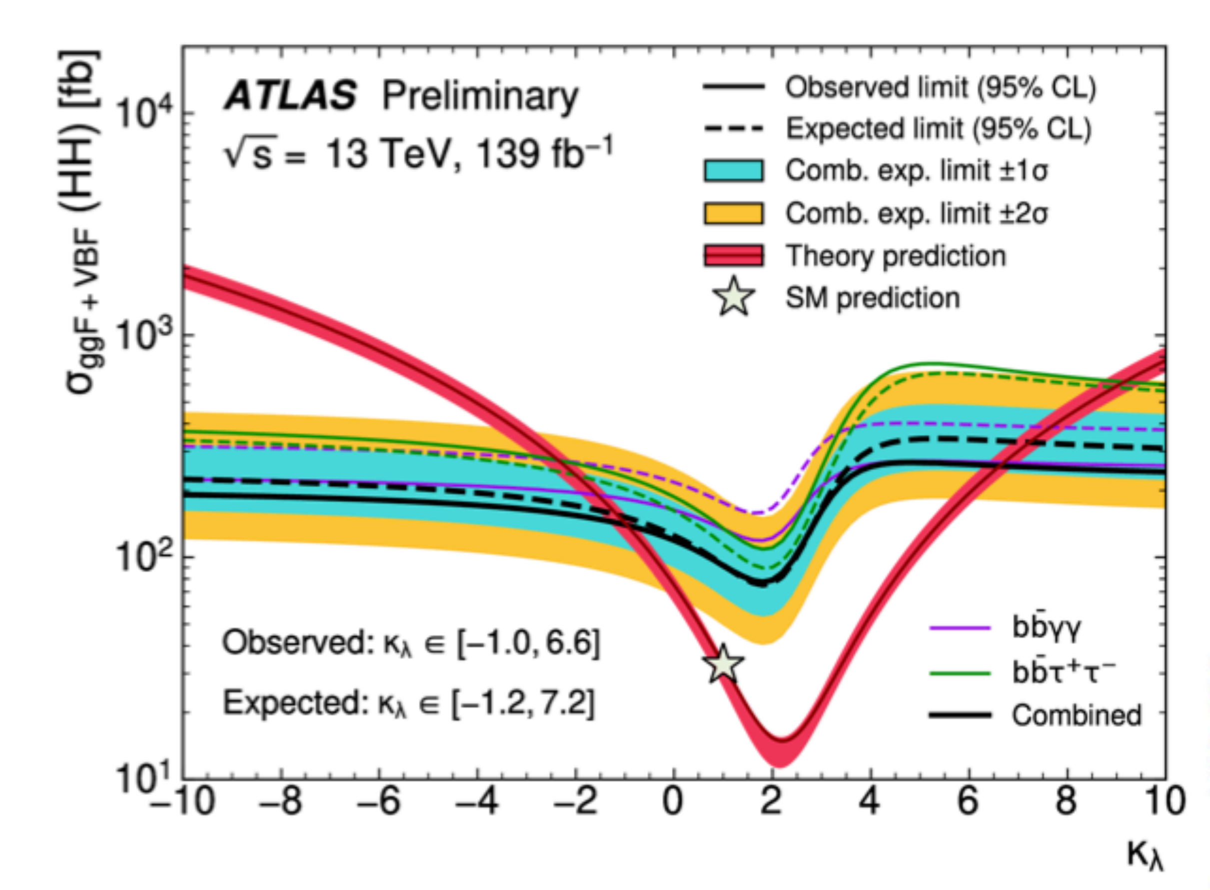


[Baglio,Djouadi,Gröber,MM,Quévillon,Spira]

$$gg \to HH : \frac{\Delta\sigma}{\sigma} \sim -\frac{\Delta\lambda}{\lambda}$$

decreasing with M_{HH}

Experimental Limits

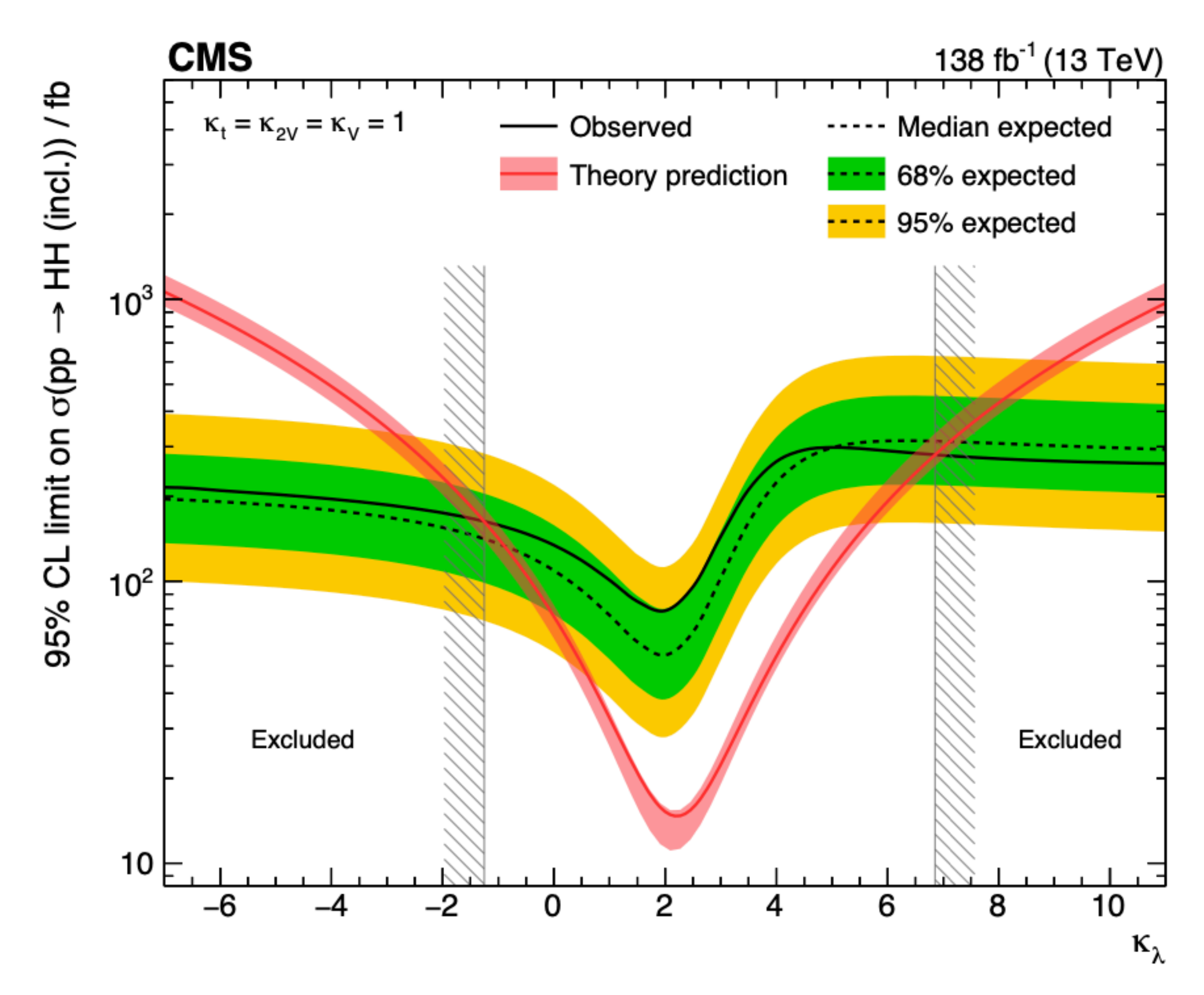


[Rui Zhang, ATLAS, HH Workshop´22]

Observed: $\kappa_\lambda \in [-1.0, 6.6]$

Expected: $\kappa_\lambda \in [-1.2, 7.2]$

[CMS,2207.00043]



$-1.24 \leq \boldsymbol{\kappa_\lambda} \leq 6.49$

Higher-Order QCD Corrections

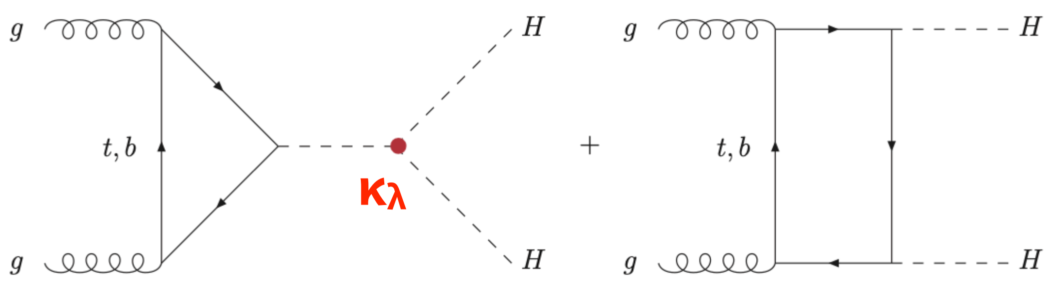
- 2-loop QCD corrections: $\lesssim$ 70% [HTL, $\mu = M_{HH}/2$] [Dawson,Dittmaier,Spira]
- 2-loop QCD corrections: $\sigma = \sigma_0 + \sigma_1/m_t^2 + \ldots + \sigma_4/m_t^8$
  [refinement: full LO at differential level] [Grigo,Hoff,Melnikov,Steinhauser]
- Mass effects @ NLO in real corrections: ~ - 10%
  [Frederix,Frixione,Hirschi,Maltoni,Mattelaer,Torrielli,Vryonidou,Zaro]
- NNLO QCD corrections: ~ 20% [HTL] [de Florian,Mazzitelli; Grigo,Melnikov,Steinhauser]
- N^{3}LO QCD corrections: ~ 5% [HTL] [Chen,Li,Shao,Wang]
- NNLO Monte Carlo: inclusion of full top-mass effects @ NLO [partly at NNLO]
  [Grazzini,Heinrich,Jones,Kallweit,Kerner,Lindert,Mazzitelli]
- NLO: matching to parton showers [Heinrich,Jones,Kerner,Luisoni,Vryonidou]
- New expansion/extrapolation methods:
  (i) $1/m_t^2$ expansion + conformal mapping + Padé approximants [Gröber,Maier,Rauh]
  (ii) p_T^2 expansion [Bonciani,Degassi,Giardino,Gröber]
- NLO: small mass expansion [$Q^2 \gg m_t^2$] [Davies,Mishima,Steinhauser,Wellmann]
- Combination of full NLO and small mass expansion
  [Davies,Heinrich,Jones,Kerner,Mishima, Steinhauser,Wellmann]

Higher-Order QCD Corrections

Complete list, see e.g. twiki of LHC Higgs Working Subgroup HH and recent reviews

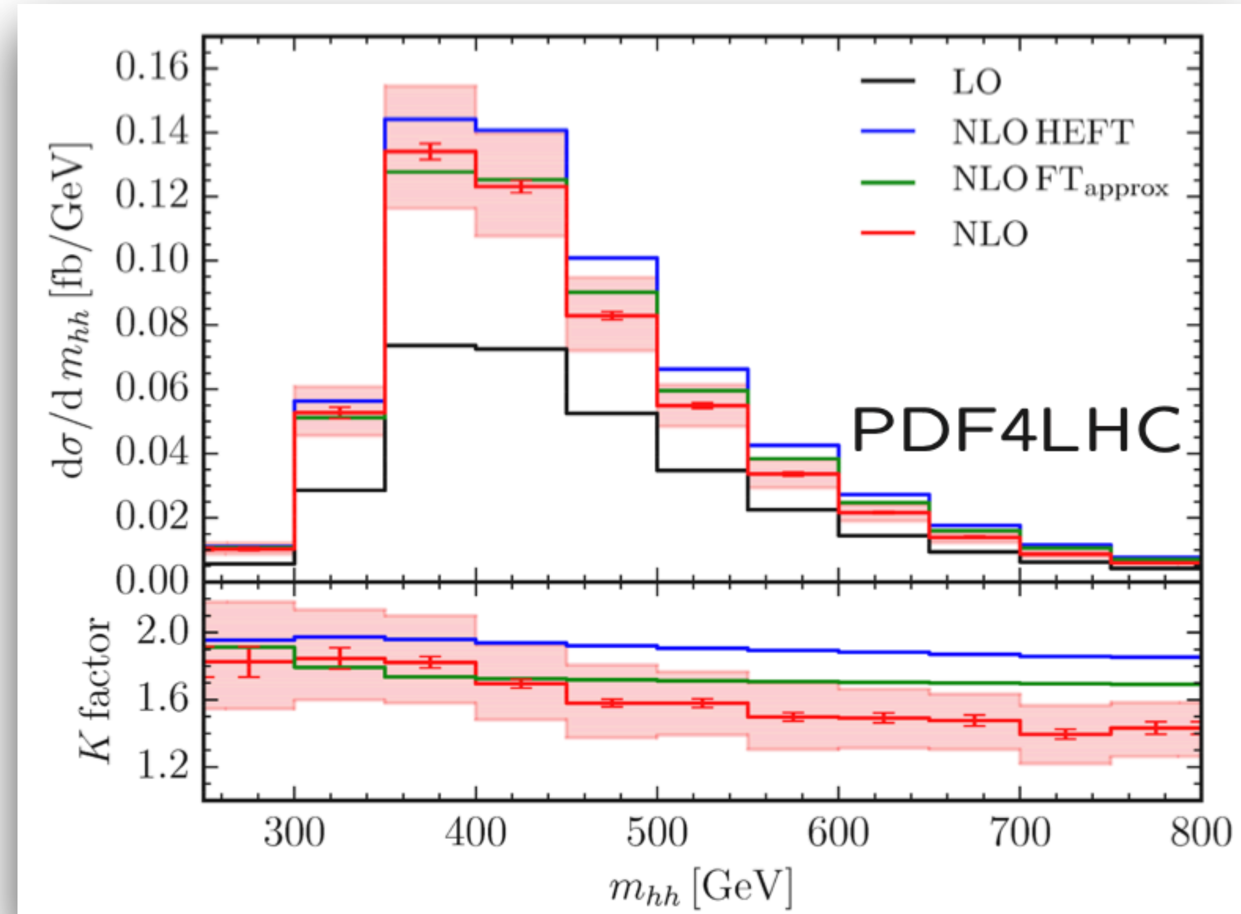
-> recommendations for cross sections to be used given for
- different c.m. energies
- different coupling modifiers

-> uncertainties on di-Higgs cross sections

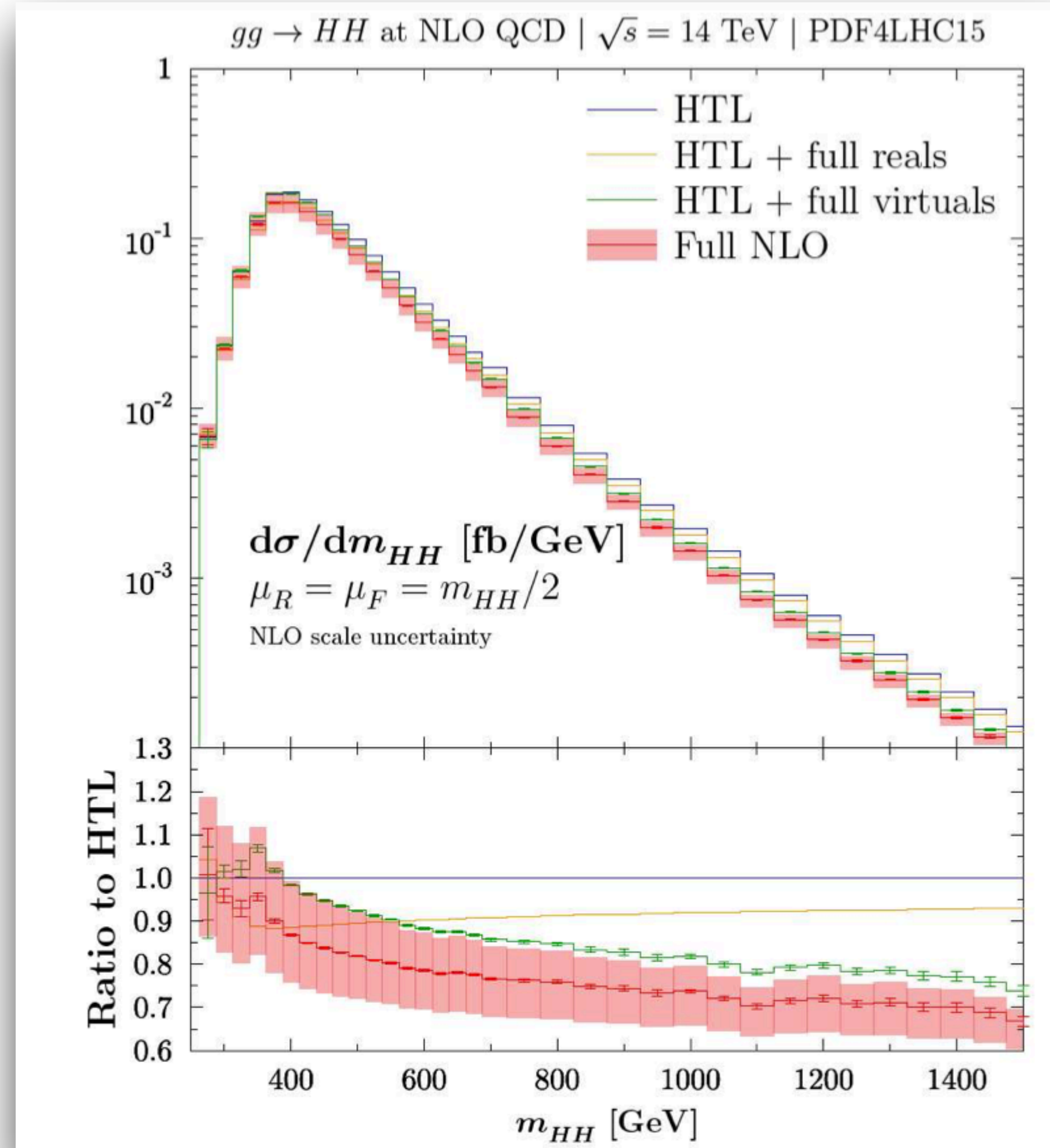


NLO QCD Including the Full Top Mass Dependence

[Borowka,Greiner,Heinrich,Jones,Kerner, Schlenk,Schubert,Zirke]



[Baglio,Campanario,Glaus,MM,Ronca,Spira,Streicher]



$\sigma_{NLO} =$	$32.91(10)^{+13.8\%}_{-12.8\%}\ fb$	$32.81(7)^{+13.5\%}_{-12.5\%}\ fb$
$\sigma^{HTL}_{NLO} =$	$38.75^{+18\%}_{-15\%}\ fb$	$38.66^{+18\%}_{-15\%}\ fb$
$m_t =$	173 GeV	172.5 GeV

$\Rightarrow$ -15% mass effects on top of LO

Uncertainties due to m_t

- Use m_t, $\overline{m}_t(\overline{m}_t)$ and scan $Q/4 < \mu < Q$ $\rightarrow$ uncertainty = envelope:

$$\frac{d\sigma(gg \to HH)}{dQ}\Big|_{Q=300\ \text{GeV}} = 0.02978(7)^{+6\%}_{-34\%}\ \text{fb/GeV},$$

$$\frac{d\sigma(gg \to HH)}{dQ}\Big|_{Q=400\ \text{GeV}} = 0.1609(4)^{+0\%}_{-13\%}\ \text{fb/GeV},$$

$$\frac{d\sigma(gg \to HH)}{dQ}\Big|_{Q=600\ \text{GeV}} = 0.03204(9)^{+0\%}_{-30\%}\ \text{fb/GeV},$$

$$\frac{d\sigma(gg \to HH)}{dQ}\Big|_{Q=1200\ \text{GeV}} = 0.000435(4)^{+0\%}_{-35\%}\ \text{fb/GeV}$$

- Bin-by-bin interpolation:

$$\sigma(gg \to HH) = 32.81^{+4\%}_{-18\%}\ \text{fb}$$

Why a Dynamical Scale

- Large momentum expansion ($\hat{s} = Q^2 \gg m_t^2$), two form factors:

[Davies,Mishima,Steinhauser,Wellmann]

pole mass m_t:

$$\Delta F_{1,mass} \to \frac{\alpha_s}{\pi}\left\{2F_{1,LO}\log\frac{m_t^2}{\hat{s}} + \frac{m_t^2}{\hat{s}}G_1(\hat{s},\hat{t})\right\},$$

$$\Delta F_{2,mass} \to \frac{\alpha_s}{\pi}\left\{2F_{2,LO}\log\frac{m_t^2}{\hat{s}} + \frac{m_t^2}{\hat{s}}G_2(\hat{s},\hat{t})\right\}$$

$\overline{\text{MS}}$ mass $\overline{m}_t(\mu_t)$:

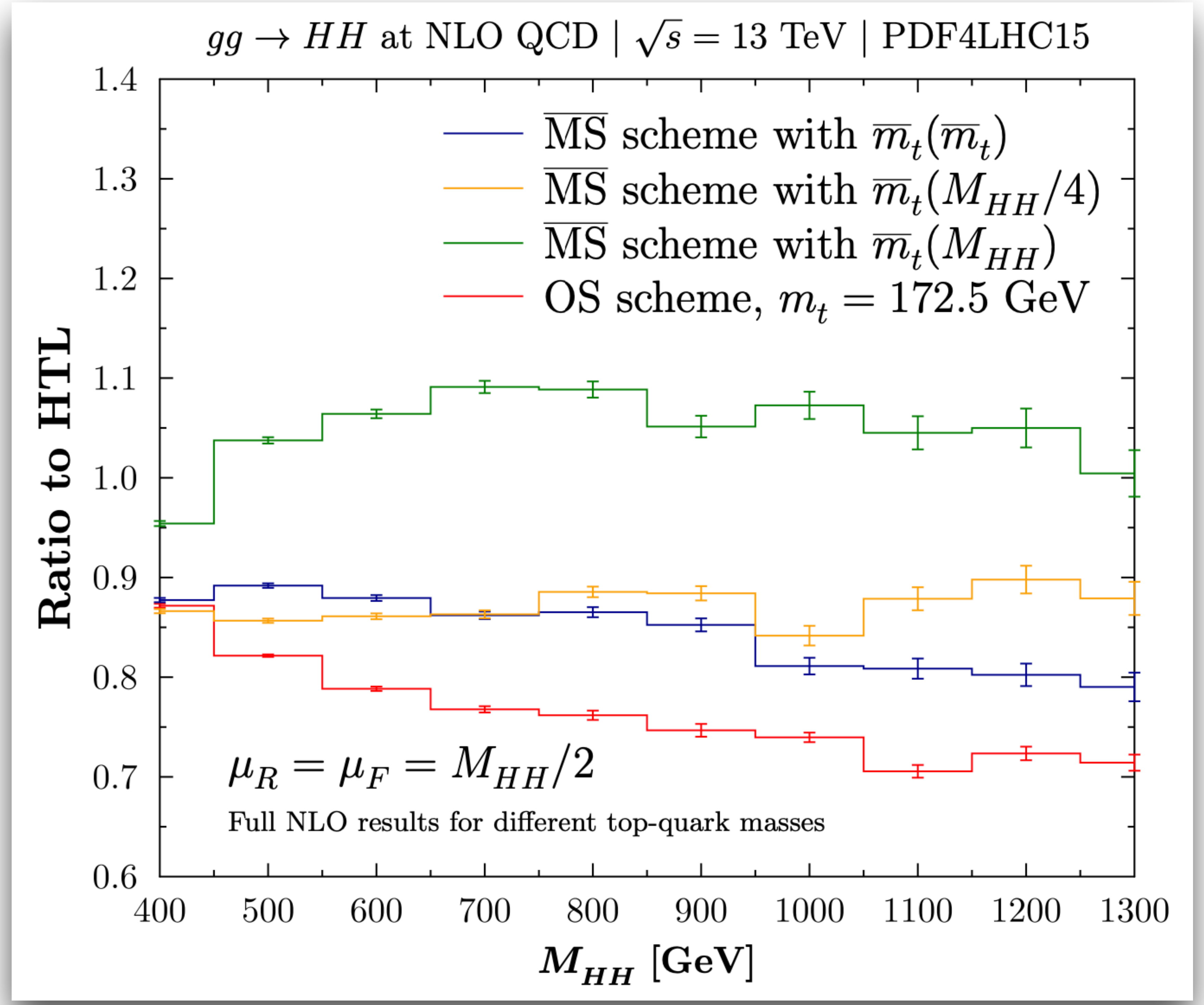
$$\Delta F_{1,mass} \to \frac{\alpha_s}{\pi}\left\{2F_{1,LO}\left[\log\frac{\mu_t^2}{\hat{s}} + \frac{4}{3}\right] + \frac{\overline{m}_t^2(\mu_t)}{\hat{s}}G_1(\hat{s},\hat{t})\right\},$$

$$\Delta F_{2,mass} \to \frac{\alpha_s}{\pi}\left\{2F_{2,LO}\left[\log\frac{\mu_t^2}{\hat{s}} + \frac{4}{3}\right] + \frac{\overline{m}_t^2(\mu_t)}{\hat{s}}G_2(\hat{s},\hat{t})\right\}$$

- $\Rightarrow$ scale $\mu_t \sim Q$ preferred at large Q

Scale Choice

[Baglio,Campanario,Glaus,MM,Ronca,Spira]



Uncertainties at NLO

[Baglio,Campanario,Glaus,MM,Ronca,Spira]

- Renormalization and factorization scale uncertainties at NLO:

$$\begin{aligned}
\sqrt{s} = 13\ \text{TeV}: \quad & \sigma_{tot} = 27.73(7)^{+13.8\%}_{-12.8\%}\ \text{fb} \\
\sqrt{s} = 14\ \text{TeV}: \quad & \sigma_{tot} = 32.81(7)^{+13.5\%}_{-12.5\%}\ \text{fb} \\
\sqrt{s} = 27\ \text{TeV}: \quad & \sigma_{tot} = 127.0(2)^{+11.7\%}_{-10.7\%}\ \text{fb} \\
\sqrt{s} = 100\ \text{TeV}: \quad & \sigma_{tot} = 1140(2)^{+10.7\%}_{-10.0\%}\ \text{fb}
\end{aligned}$$

- m_t scale/scheme uncertainties at NLO:

$$\begin{aligned}
\sqrt{s} = 13\ \text{TeV}: \quad & \sigma_{tot} = 27.73(7)^{+4\%}_{-18\%}\ \text{fb} \\
\sqrt{s} = 14\ \text{TeV}: \quad & \sigma_{tot} = 32.81(7)^{+4\%}_{-18\%}\ \text{fb} \\
\sqrt{s} = 27\ \text{TeV}: \quad & \sigma_{tot} = 127.8(2)^{+4\%}_{-18\%}\ \text{fb} \\
\sqrt{s} = 100\ \text{TeV}: \quad & \sigma_{tot} = 1140(2)^{+3\%}_{-18\%}\ \text{fb}
\end{aligned}$$

- Linear sum of uncertainties ~>

Final Uncertainties at FT_{approx}

[Baglio,Campanario,Glaus,MM,Ronca,Spira]

- Final combined renormalization/factorization scale and m_t scale/scheme uncertainties at $NNLO_{FTapprox}$*:

$$\sqrt{s} = 13 \text{ TeV}: \quad \sigma_{tot} = 31.05^{+6\%}_{-23\%} \text{ fb}$$
$$\sqrt{s} = 14 \text{ TeV}: \quad \sigma_{tot} = 36.69^{+6\%}_{-23\%} \text{ fb}$$
$$\sqrt{s} = 27 \text{ TeV}: \quad \sigma_{tot} = 139.9^{+5\%}_{-22\%} \text{ fb}$$
$$\sqrt{s} = 100 \text{ TeV}: \quad \sigma_{tot} = 1224^{+4\%}_{-21\%} \text{ fb}$$

*FT_{approx}: full NNLO QCD in the heavy-top-limit with full LO and NLO mass effects and full mass dependence in the one-loop double real corrections at NNLO QCD

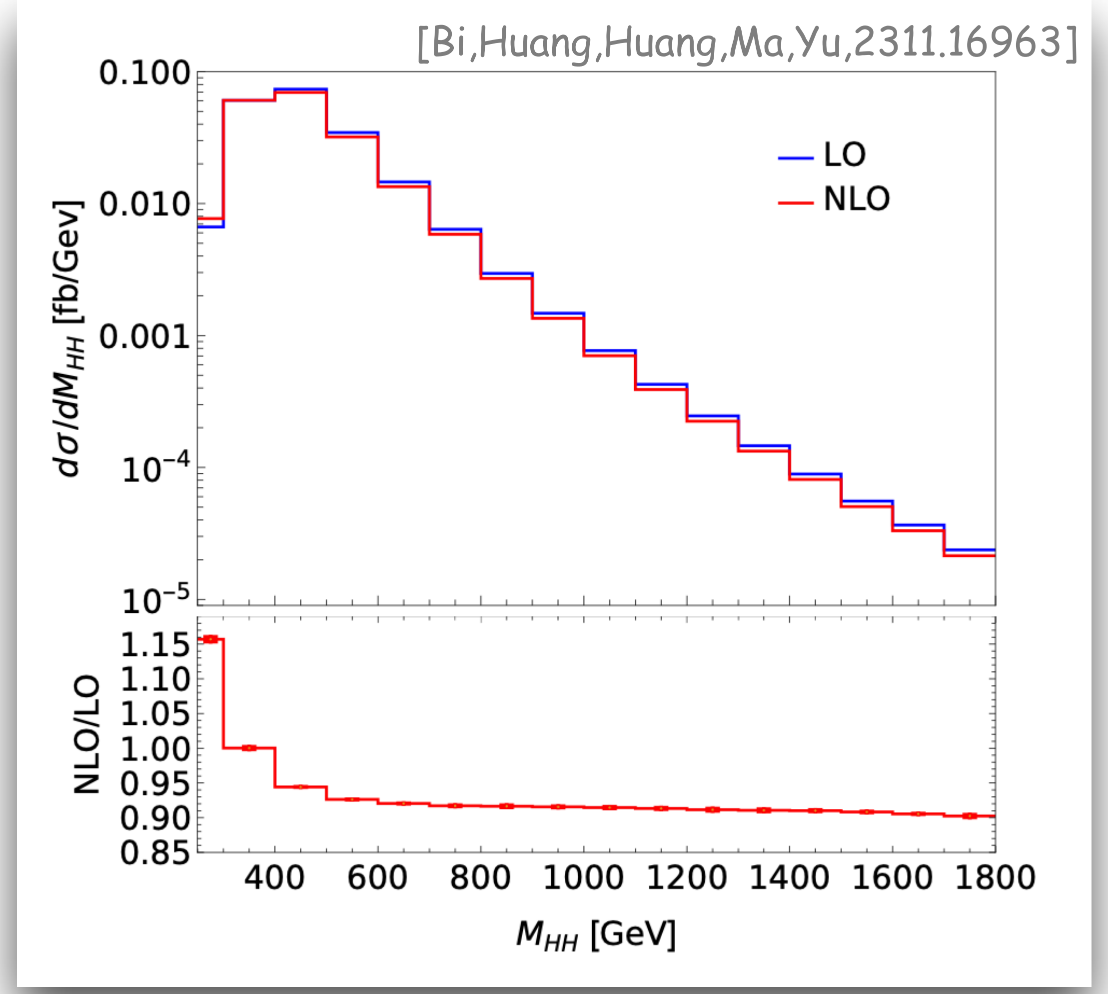
Uncertainties for Different Higgs Self-Coupling Values

- Final combined uncertainties at $\text{NNLO}_{\text{FTapprox}}$: [Baglio,Campanario,Glaus,MM,Ronca,Spira]

$$\kappa_\lambda = -10: \quad \sigma_{tot} = 1680^{+13\%}_{-14\%} \text{ fb}$$
$$\kappa_\lambda = -5: \quad \sigma_{tot} = 598.9^{+13\%}_{-15\%} \text{ fb}$$
$$\kappa_\lambda = -1: \quad \sigma_{tot} = 131.9^{+11\%}_{-16\%} \text{ fb}$$
$$\kappa_\lambda = 0: \quad \sigma_{tot} = 70.38^{+8\%}_{-18\%} \text{ fb}$$
$$\kappa_\lambda = 1: \quad \sigma_{tot} = 31.05^{+6\%}_{-23\%} \text{ fb}$$
$$\kappa_\lambda = 2: \quad \sigma_{tot} = 13.81^{+3\%}_{-28\%} \text{ fb}$$
$$\kappa_\lambda = 2.4: \quad \sigma_{tot} = 13.10^{+6\%}_{-27\%} \text{ fb}$$
$$\kappa_\lambda = 3: \quad \sigma_{tot} = 18.67^{+12\%}_{-22\%} \text{ fb}$$
$$\kappa_\lambda = 5: \quad \sigma_{tot} = 94.82^{+18\%}_{-13\%} \text{ fb}$$
$$\kappa_\lambda = 10: \quad \sigma_{tot} = 672.2^{+16\%}_{-13\%} \text{ fb}$$

Electroweak Corrections to SM Higgs Pair Production

- Top-Yukawa-induced corrections to Higgs pair production [MM,Schlenk,Spira,` 22]
- NLO EW corrections to gg->HH and gg->gH in the large mt limit [Davies,Schönwald,Steinhauser,Zhang,'23]
- Higgs boson contribution to the leading 2-loop Yukawa corrections to gg->HH [Davies,Mishima,Schönwald,Steinhauser,Zhang,´ 22]
- Complete NLO EW corrections [Bi,Huang,Huang,Ma,Yu,´ 23]

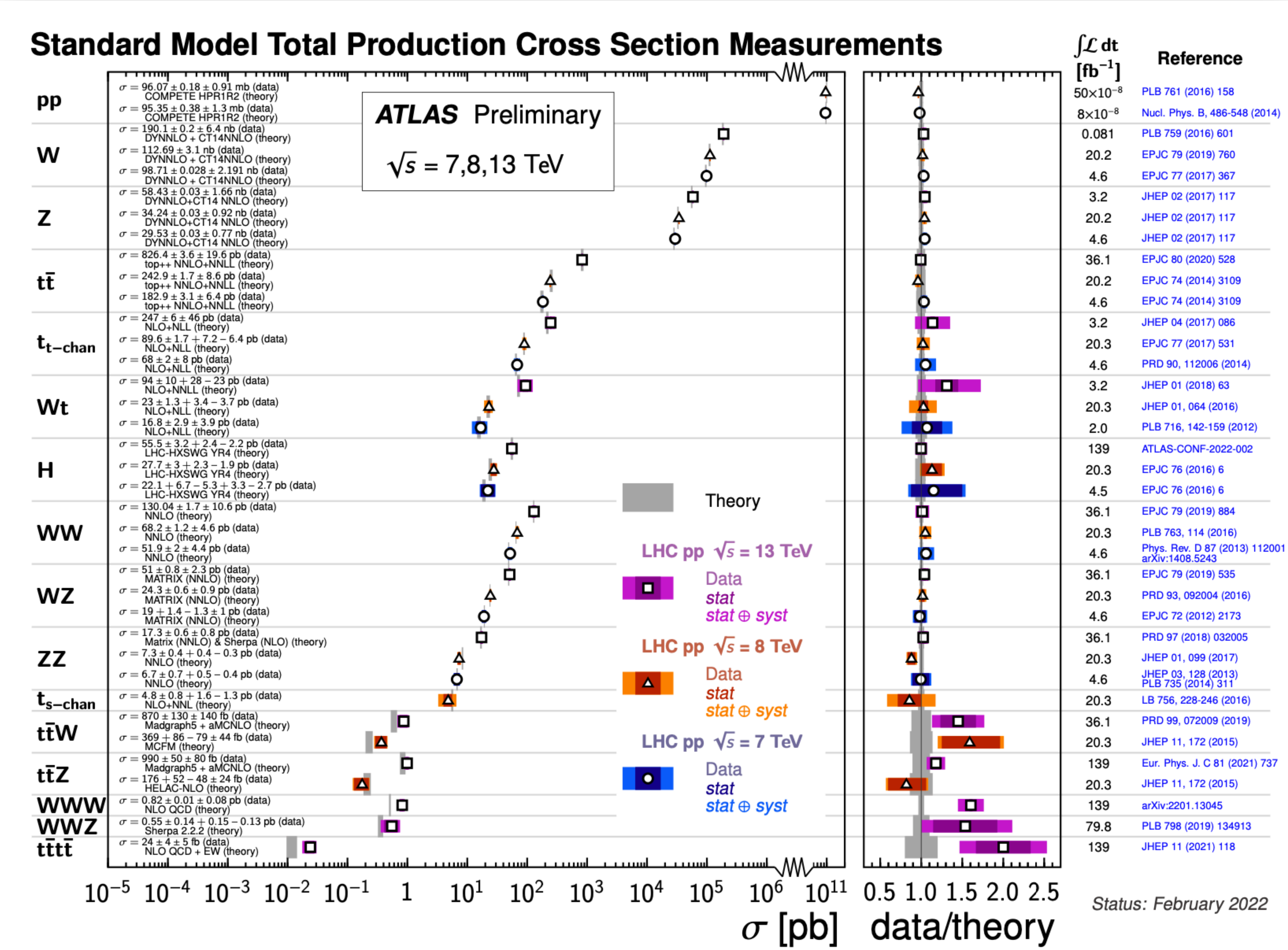


Impact of EW corrections on total cxn: -4%

Impact on differential distributions can be +15%...-10%

Significantly reduced theoretical uncertainty

10 Years LHC at the Energy Frontier

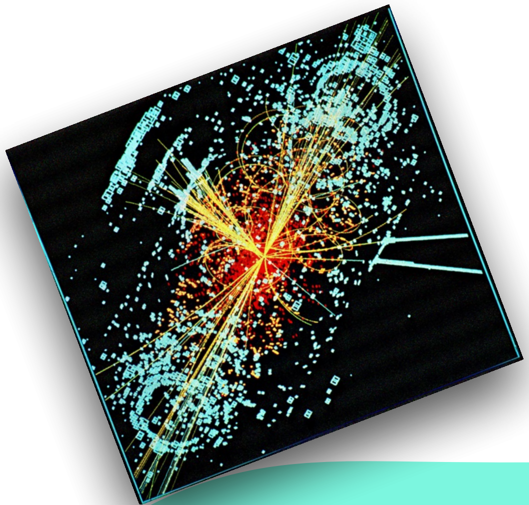


Success of experiment and theory

SM provides consistent description of the data at the quantum level

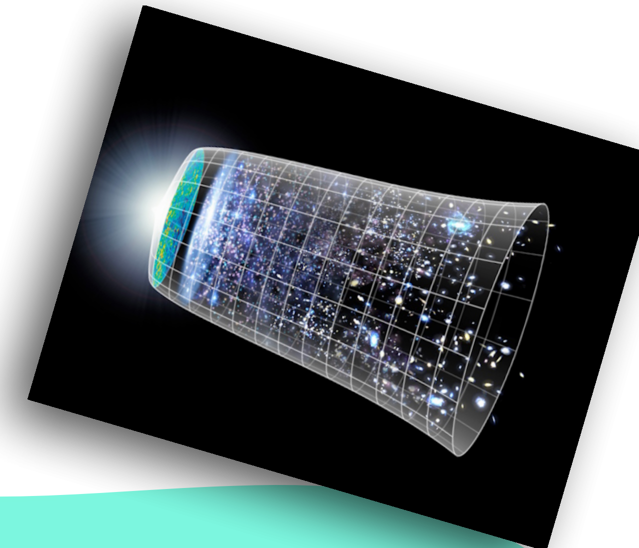
Still! there are many open questions left!

Open Questions



Particle physics

Cosmology



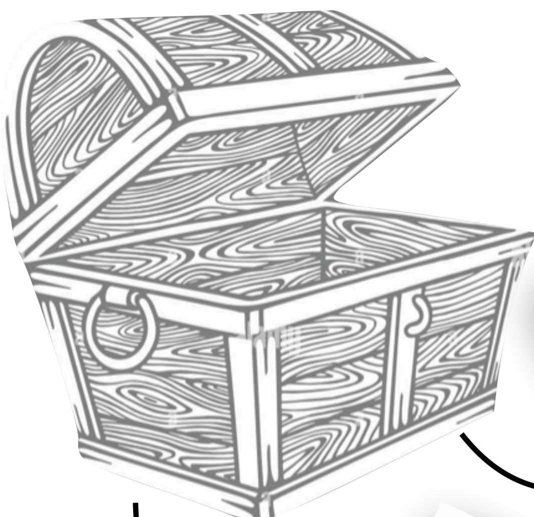
- ❖origin of electroweak symmetry breaking
- ❖hierarchy problem
- ❖nature of the Higgs boson
- ❖fermion mass and flavor puzzle
- ❖origin of neutrino masses

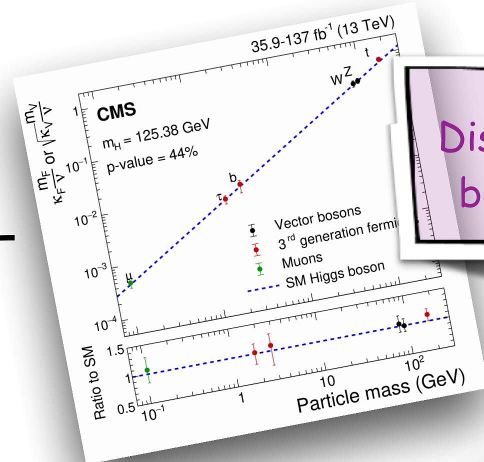
- ❖nature of Dark Matter
- ❖matter-antimatter asymmetry
- ❖dark energy
- ❖inflation
- ❖how to incorporate gravity

Decipherment of fundamental laws of nature:
judicious combination of
theoretical methods/interpretation
and experimental input/scrutiny

New physics is required, but there is no clear indication at which energy scale

The Challenge





Discovered Higgs Boson behaves very SM-like

Consistency Test of the SM at the quantum level

No direct discovery of New Physics so far

New physics may be heavy, with new particles at a large mass scale

New physics may be light, but with small couplings

=> New physics is subtle:
small cross sections
novel signatures

Strategy for the Exploration of the New Physics Landscape

Reach out for:
- Precision
- Diversity
- Model Independence

Ensure close interaction:
- theory and experiment
- energy and intensity frontiers
- collider physics, low-energy physics, astroparticle physics, cosmology

Strategy for the Exploration of the New Physics Landscape

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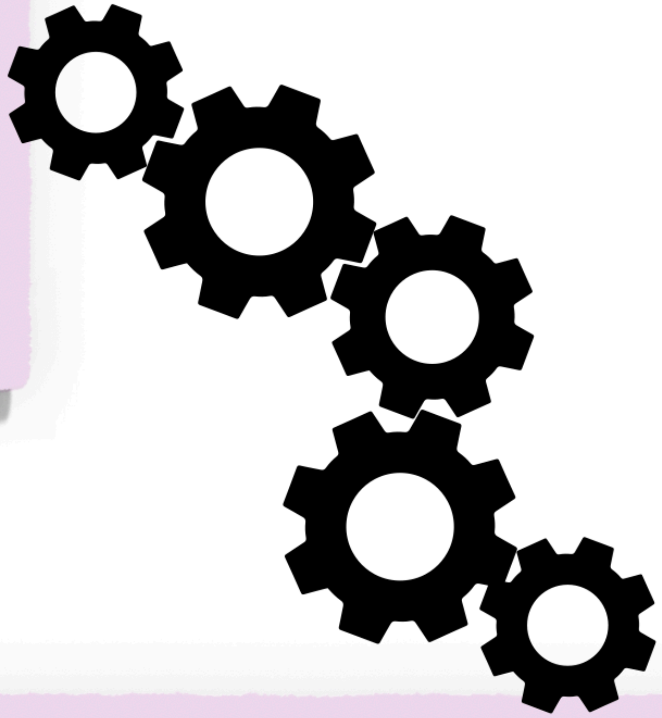


Now: We have the Higgs boson - What do we learn from the Higgs boson?

Ensure close interaction:
- theory and experiment
- energy and intensity frontiers
- collider physics, low-energy physics, astroparticle physics, cosmology

What do we Learn from Higgs Physics?

$$\mathcal{L}_{Higgs} = (\mathcal{D}_\mu \Phi_i)(\mathcal{D}^\mu \Phi_i)^\dagger - V(\Phi_i) + \mathcal{L}_{Yukawa}$$

- anomalous Higgs gauge couplings δ_{cZ}, $c_{ZZ}, c_{Z\square}, c_{\gamma\gamma}, c_{Z\gamma}, c_{gg}$
- CP violation

✏ **New Physics & DM**
✏ **Baryogenesis**

- coupling relations $g_X \sim m_X^{(2)}$

✏ **Establish Higgs mechanism**

- Higgs mass
- Higgs self-interaction $\lambda_{HHH} + \delta\kappa_\lambda$
- vacuum structure
- CP violation
- portal to hidden sector

✏ **Self-consistency SM**
✏ **Ultimate test Higgs mechanism**
✏ **Vacuum stability**
✏ **New Physics&DM**
✏ **Matter asymmetry**
✏ **Cosmological evolution**

- anomalous couplings δy_t, δy_c, δy_b, δy_τ, δy_μ, δy_e
- CP violation

✏ **Flavor/Matter puzzle**
✏ **New Physics**
✏ **Baryogenesis**

Establish Higgs Mechanism

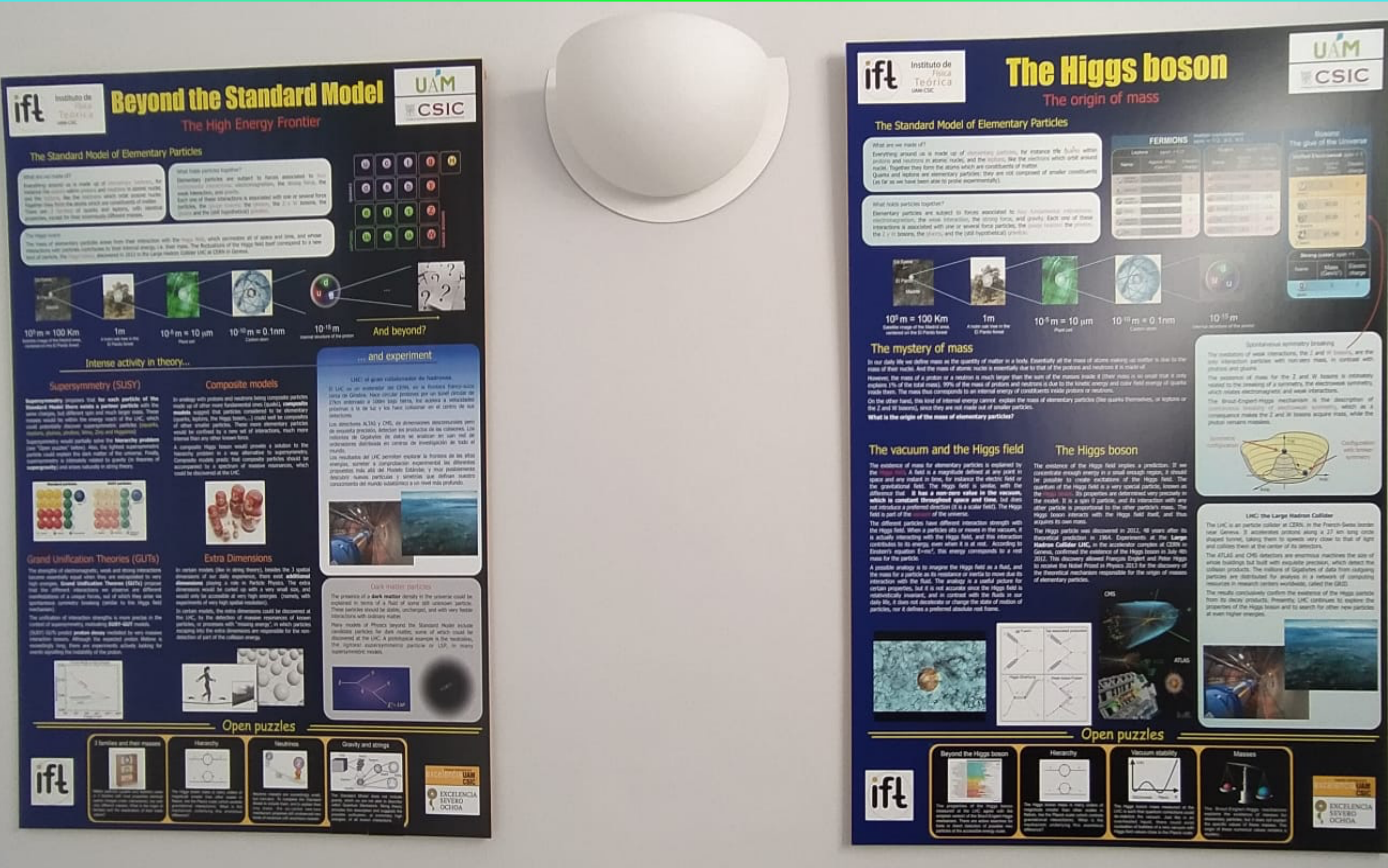
New Physics

Matter-Antimatter Asymmetry

Flavor Matter Puzzle

Evolution of Cosmos

BSM Higgs Physics - Extended Higgs Sectors



Vast New Physics Landscape

Extended Higgs Sectors

Why extended Higgs sectors?

* fermion/gauge sectors not minimal - why should the Higgs sector be minimal?

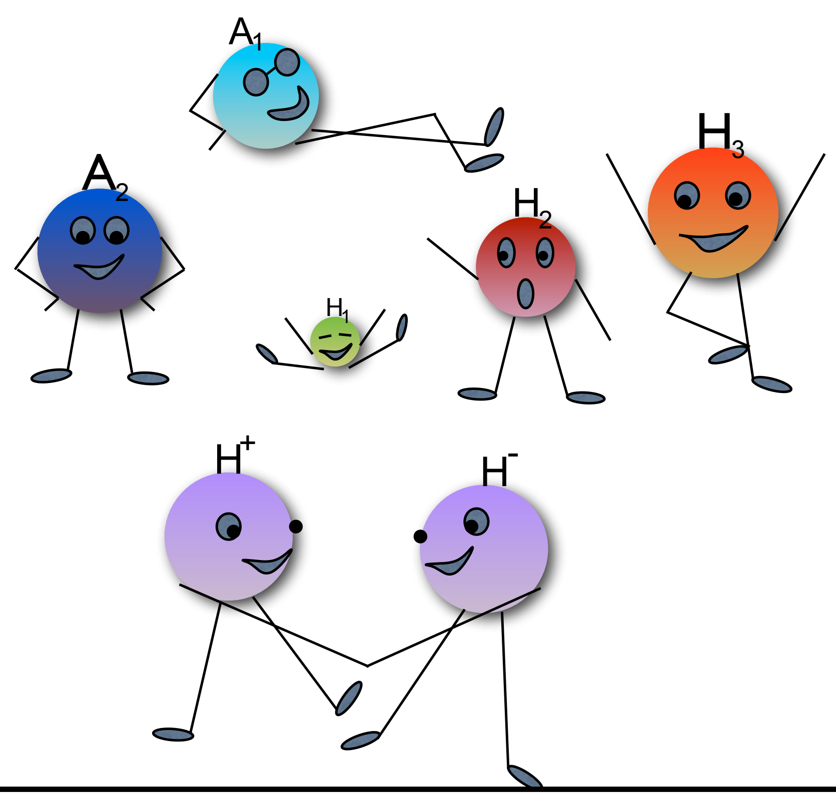
* extended Higgs sectors:
  alleviate metastability, DM candidate, additional sources of CP-violation ← baryogenesis

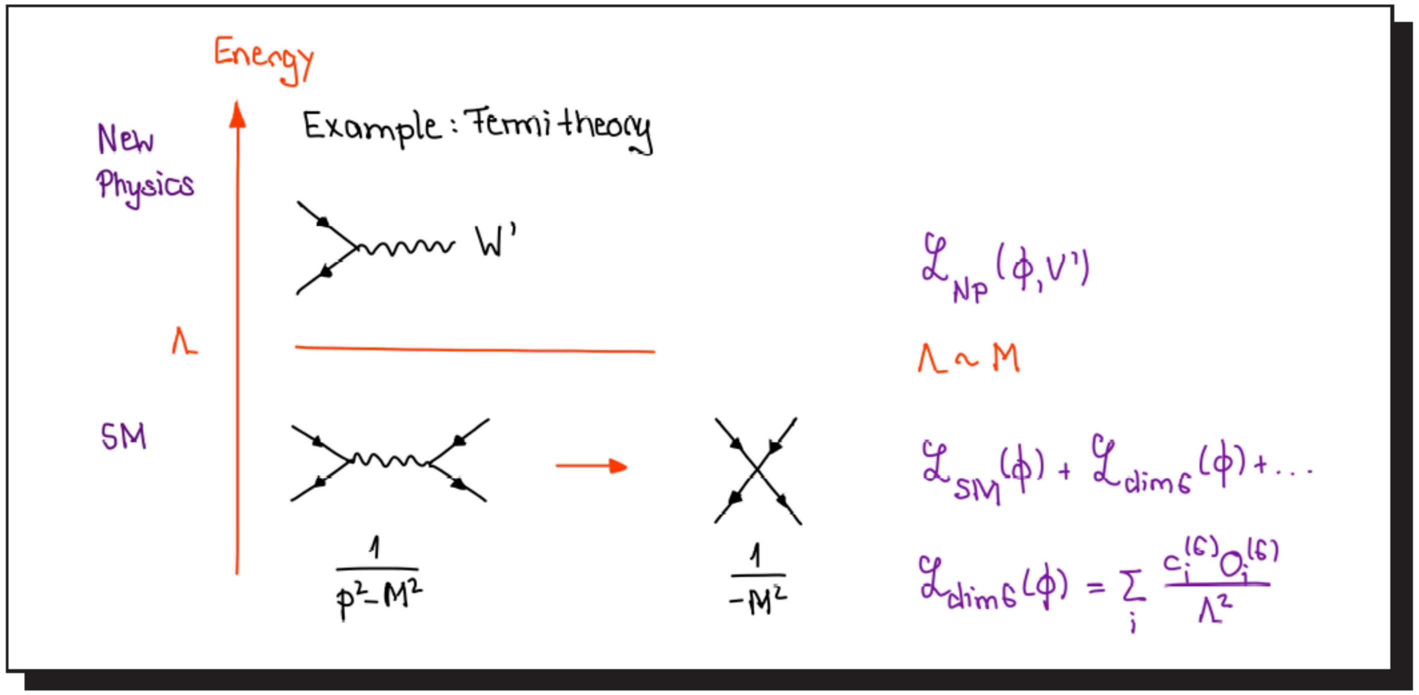
* many new physics models require extended Higgs models ← supersymmetry!

How systemize approach not to miss any new physics sign?

* effective theory (rather model-independent, new physics effects at high energy scales)

* specific well-motivated UV-complete models



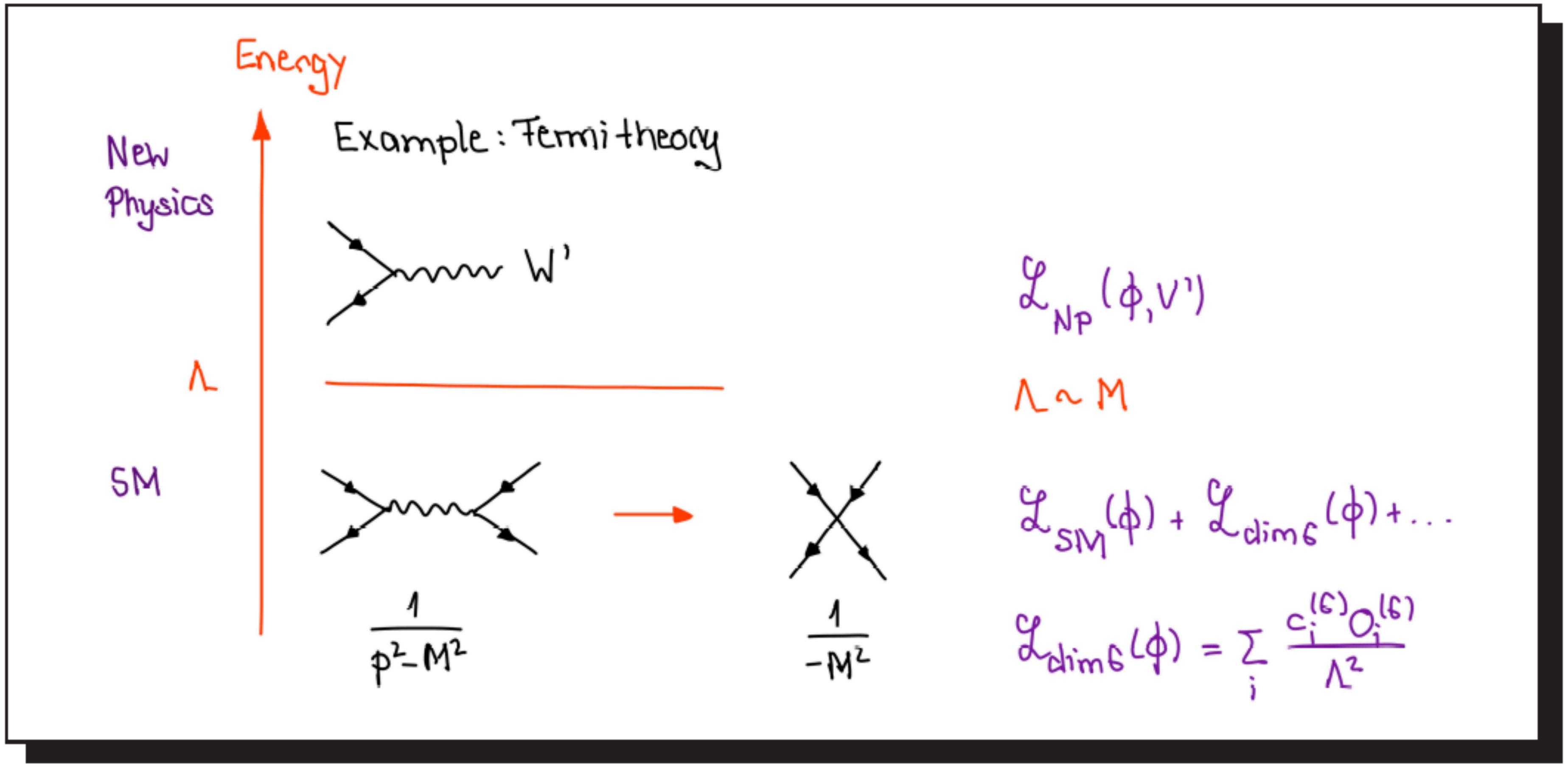


SM Effective Theory (SMEFT)

◆ SMEFT approach:

[Burgess,Schnitzer;Leung eal;Buchmüller,Wyler;Grzadkowski eal; Hagiwara,Ishihara,Szalapski;Zeppenfeld;Giudice eal]

* SM field content and SM gauge symmetries, no New Physics at E < Λ
* SM deviations: higher-dimensional operators built from SM fields
* Operators = low-energy remnants of heavy new physics integrated out at Λ =>
* Operators suppressed by scale Λ



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◆ New interactions of SM particles: Higgs part of a doublet field (EWSB linearly realized) ~> leading new physics (NP) effects described by D=6 operators

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i^{(6)} O_i^{(6)}}{\Lambda^2} + \mathcal{O}(\Lambda^{-4})$$

Electroweak Chiral Lagrangian (EWChL)

◆ SMEFT approach:

[Burgess,Schnitzer;Leung eal;Buchmüller,Wyler;Grzadkowski eal; Hagiwara,Ishihara,Szalapski;Zeppenfeld;Giudice eal]

✻ EWSB linearly realized: Higgs boson part of a weak doublet

✻ Additional expansion in $g_* v/\Lambda \ll 1$ (g_* typical coupling of the NP sector)

◆ EW Chiral Lagrangian (EWChL):

[Contino eal; Azatov eal; Alonso eal; Brivio eal; Elias-Miró eal; Buchada eal]

✻ EWSB non-linearly realized: Higgs treated as singlet

✻ Chiral expansion

Global SMEFT Fit

◆ SMEFT analysis:

✻ Model and basis independence: **All** relevant operators need to be included

✻ Number of non-redundant dim-6 operators for 3 generations: 2499, 59 for 1 generation

[Grzadkowski eal;Alonso eal]

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$	Q_{ee}	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$	Q_{le}	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$	Q_{uu}	$(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$	Q_{lu}	$(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar d_p \gamma_\mu d_r)(\bar d_s \gamma^\mu d_t)$	Q_{ld}	$(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$	Q_{eu}	$(\bar e_p \gamma_\mu e_r)(\bar u_s \gamma^\mu u_t)$	Q_{qe}	$(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p \gamma_\mu \tau^I l_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$

$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating	
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$		

Global SMEFT Fit

◆ SMEFT analysis:

✻ Model and basis independence: **All** relevant operators need to be included

✻ Number of non-redundant dim-6 operators for 3 generations: 2499, 59 for 1 generation

[Grzadkowski eal;Alonso eal]

✻ Global fit: complicated parameter space w/ many degenerate/flat directions and local minima ~>

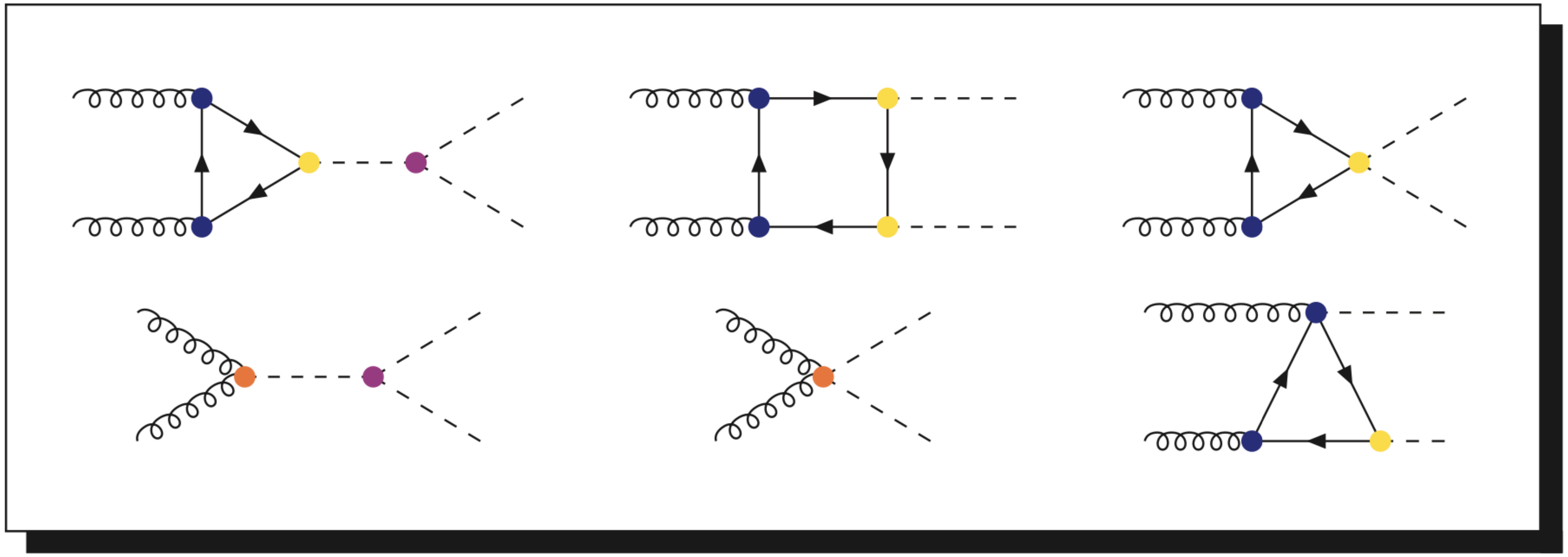
◆ Practical approach - reduce number of operators by:

✻ Symmetry assumptions, e.g. flavor, CP conservation

✻ focus on subsectors: Higgs, electroweak, top, Higgs-electroweak, top-Higgs, ...:

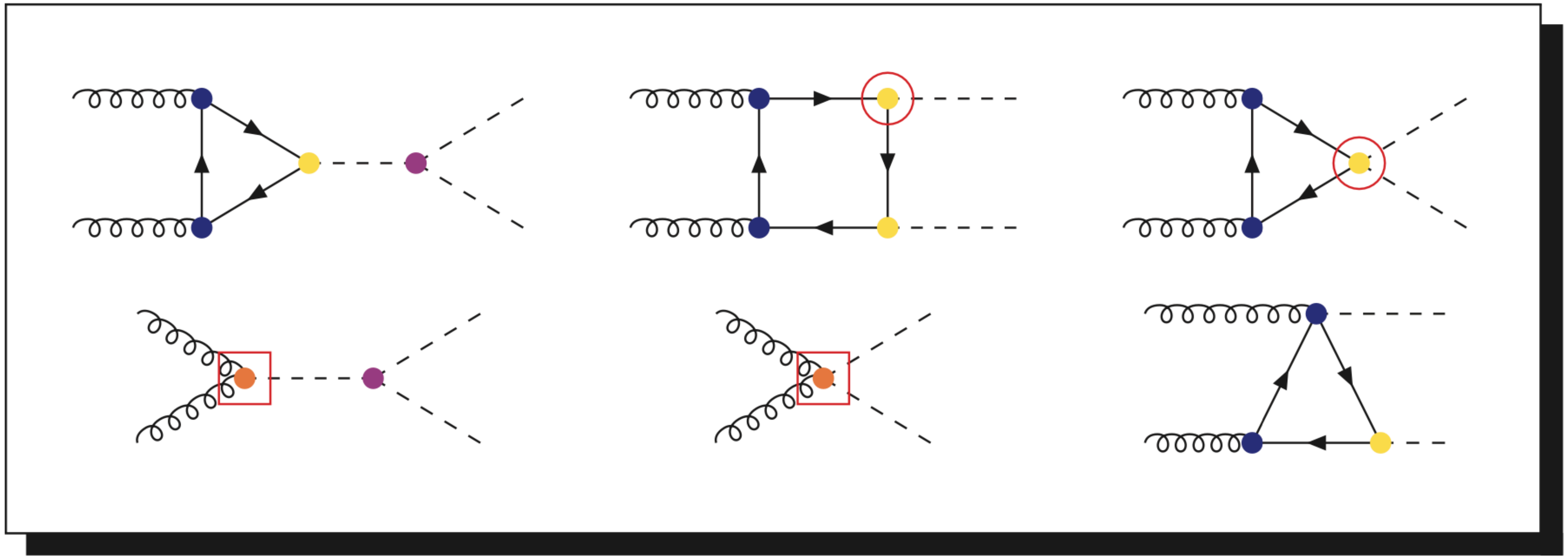
- ◇ include only operators relevant to the considered particle(s)/processes
- ◇ assume other operators well constrained from different processes
- ◇ note: not always justified!

Example EFT Operators Contributing to Higgs Pair Production



$\mathcal{O}_H$	$=$	$\frac{1}{2}(\partial_\mu(\phi^\dagger\phi))^2$	$\longrightarrow$	overall shift of couplings
$\mathcal{O}_6$	$=$	$-(\phi^\dagger\phi)^3$	$\longrightarrow$	shifts Higgs self-coupling
$\mathcal{O}_{t\phi}$	$=$	$(\phi^\dagger\phi)(\bar{Q}\tilde{\phi}t) + h.c.$	$\longrightarrow$	shifts top Yukawa coupling; $t\bar{t}HH$
$\mathcal{O}_{\phi G}$	$=$	$(\phi^\dagger\phi)G^a_{\mu\nu}G^{a\mu\nu}$	$\longrightarrow$	pointlike Higgs to gluon couplings
$\mathcal{O}_{tG}$	$=$	$(\bar{Q}\sigma^{\mu\nu}T^a t)\phi G^a_{\mu\nu} + h.c.$	$\longrightarrow$	chromomagnetic dipole operator

Example EFT Operators Contributing to Higgs Pair Production



Non-linear EFT:

couplings of one/two Higgs bosons to gluons become linear independent

couplings of one/two Higgs bosons to fermions become linear independent

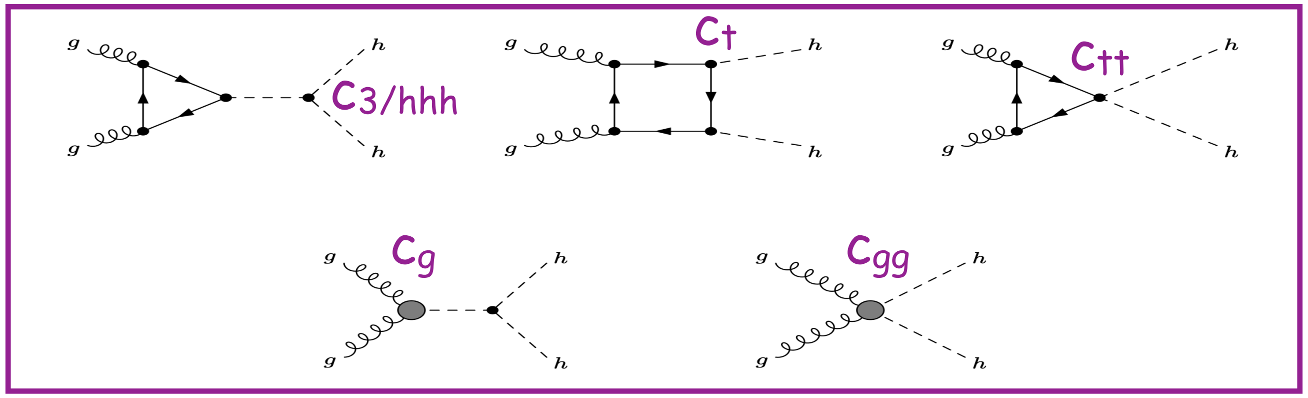
can be probed directly in di-Higgs productions

Processes w/ 0,1,2 Higgs boson need to be connected to disentangle linear/non-linear dynamics

Note: EFT operators destroy SM cancellation between triangle and box diagrams

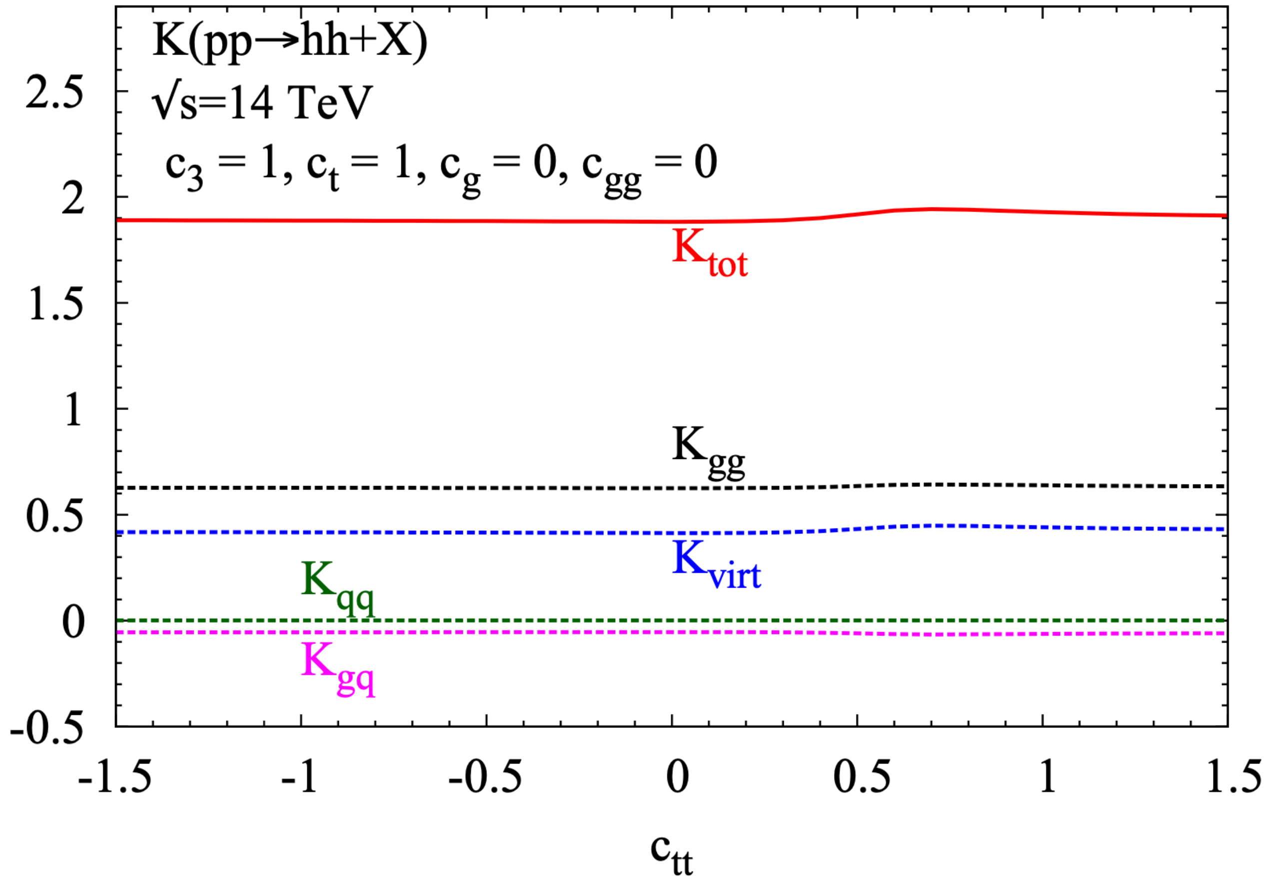
$\leadsto$ limits derived on λ_{HHH} depend on EFT description

EFT Effect at NLO QCD in HH

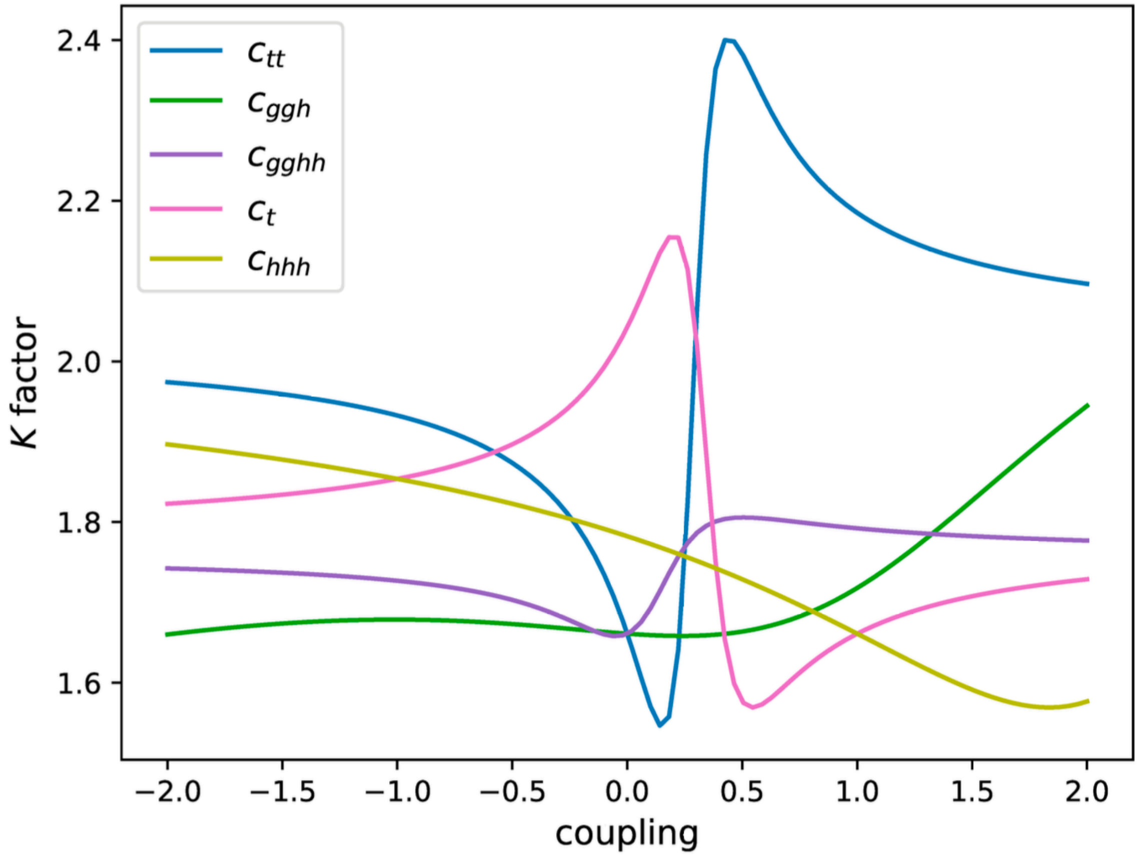


K-factor:
ratio of NLO
to LO observable

[Gröber,MM,Spira,Streicher,'15]



[Buchalla,Capozi,Celis,Heinrich,Scyboz,'18]



Tops integrated out at NLO:
- flat dependence of K-factors

[see also de Florian,Fabre,Mazzitelli,´17]

Inclusion of full top dependence at NLO:
- non-uniform K-factors

Specific UV-Complete New Physics Models

Investigations of specific UV-complete models:

* Indisponible: complement EFT approach
* EFT approach cannot capture new physics effects due to new light particles

Guidelines for model selection

* simplicity
* compatibility with relevant experimental and theoretical constraints
* solve (some of the) flaws of the SM
* testable in experiment

Validity of the models: they have comply with

* experimental constraints
* theoretical constraints

Experimental Constraints on Extended Higgs Sectors

✏ Electroweak rho parameter very close to 1: $\rho = \frac{M_W^2}{M_Z^2 \cos^2\theta_W} \approx 1$ (in SM automatically fulfilled)

* model with n scalar multiplets ϕ_i with weak isospin I_i, weak hypercharge Y_i and VEVs v_i of the neutral components: rho parameter at tree level

$$\rho_i = \frac{\sum_{i=1}^{n} [I_i(I_i+1) - \frac{1}{4}Y_i^2]v_i}{\sum_{i=1}^{n} \frac{1}{2} Y_i^2 v_i}$$

* SU(2) singlets with $Y=0$ and SU(2) doublets with $Y=\pm 1$ satisfy

$$I(I+1) = \frac{3}{4}Y^2$$

and hence $\rho = 1$

✏ Flavor-changing neutral currents (FCNCs): very stringent constraints from experiment

solution for multi-Higgs models: apply symmetries such that all right-handed fermions of a given electric charge couple to exactly one Higgs doublet (cf. e.g.(N)2HDM type I...IV); minimal flavor violation (flavor violation only arises from CKM matrix)

Experimental Constraints on Extended Higgs Sectors

✏ Further constraints:

* Electroweak precision tests (EWPTs): Peskin-Takeuchi resp. S,T,U parameters parametrize potential NP contributions to EW radiative corrections; S,T,U are zero for SM ref. point; assumptions:

  - EW gauge group is $SU(2)_L \times U(1)_Y$ ~> no additional gauge bosons beyond $Z, W^\pm, \gamma$, e.g. no Z´
  - New physics couplings from light fermions are suppressed ~> only oblique corrections (= vacuum polarization), no box and vertex corrections need to be considered
  - NP energy scale is large compared to the EW scale ~> expansion in q^2/M^2, M = NP scale

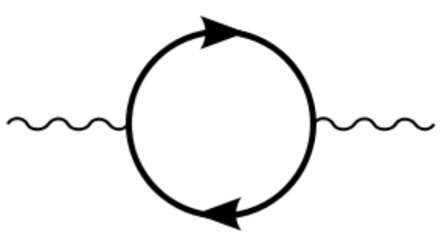
  => parametrization in terms of four vacuum polarization functions: self-energies of the $Z, W^\pm, \gamma$ and mixing between Z and γ induced by loop diagrams

$$\Pi_{\gamma\gamma}(q^2) = q^2\Pi'_{\gamma\gamma}(0) + \ldots$$

$$\Pi_{Z\gamma}(q^2) = q^2\Pi'_{Z\gamma}(0) + \ldots$$

$$\Pi_{ZZ}(q^2) = \Pi_{ZZ}(0) + q^2\Pi'_{ZZ}(0) + \ldots$$

$$\Pi_{WW}(q^2) = \Pi_{WW}(0) + q^2\Pi'_{WW}(0) + \ldots$$



$$\alpha S = 4s_w^2c_w^2\left[\Pi'_{ZZ}(0) - \frac{c_w^2 - s_w^2}{s_w c_w}\Pi'_{Z\gamma}(0) - \Pi'_{\gamma\gamma}(0)\right]$$

$$\alpha T = \frac{\Pi_{WW}(0)}{M_W^2} - \frac{\Pi_{ZZ}(0)}{M_Z^2}$$

$$\alpha U = 4s_w^2\left[\Pi'_{WW}(0) - c_w^2\Pi'_{ZZ}(0) - 2s_wc_w\Pi'_{Z\gamma}(0) - s_w^2\Pi'_{\gamma\gamma}(0)\right]$$

Experimental Constraints on Extended Higgs Sectors

✏ Further constraints:

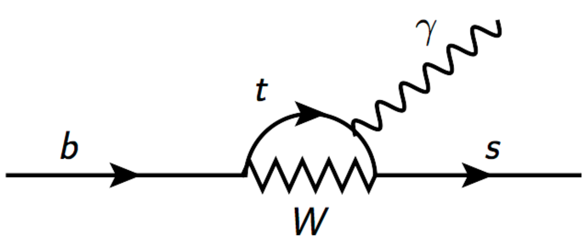
* Electroweak precision tests S,T,U parameters

  - S parameter: measures difference between left-handed & right-handed fermions w/ weak isospin ~> tightly constrains number of new fourth-generation chiral fermions
  - T parameter: measures isospin violation (<- sensitive to loop corrections to Z and W vacuum polarization)
  - S and T parameter: affected by varying the Higgs boson mass
    Before discovery: mass of Higgs boson constrained by EWPTs to lie within close to LEP lower bound (114 GeV) and 200 GeV.
  - U parameter: not very useful in practice, parametrizes dim-8 effects

* Flavour constraints: NP effects to flavor observables from loop corrections
  - Example: $B \to X_s \gamma$ receives NP contributions from $H^\pm$ exchange;
    sets lower bound of about 800 GeV on $m_{H^\pm}$ in the 2HDM type II

[Deschamps eal,'09;Mahmoudi,Stal,'09;Hermann eal,'12;Misiak eal,'15; Misiak,Steinhauser,'17;Misiak,Rehman,Steinhauser,'20]

SM diagram:



Experimental Constraints on Extended Higgs Sectors

✏ Further constraints:

* Higgs data:
  - one of the Higgs bosons has to have a mass of 125 GeV and behave very SM-like, i.e. comply with LHC Higgs data
  - remaining Higgs bosons have to comply with LHC exclusion limits from searches for additional Higgs bosons

* Direct searches for new particles predicted by the model:
  - model has to respect exclusion limits on these particles (e.g. lower bounds on stop or gluino masses in supersymmetric models)

* Low-energy observables like the anomalous magnetic moment

* Electric Dipole Moment (EDM) constraints: stringent constraints on CP violation in CP-violating models

* Dark Matter (DM) observables (relic density, direct and indirect detection limits): constrains models w/ DM candidate

Theory Constraints on Extended Higgs Sectors

✏ Theory constraints: (will be discussed in detail below)

* Higgs potential bounded from below
* EW vacuum with v=246 GeV is the global minimum
* Perturbative unitarity

Parameter Scans of the Models

Parameter scans w/ constraints:
Reduction of the parameter space
to the still allowed parameter space
~> sharpens predictions of the models

✏ Parameter scans performed with ScannerS: [Coimbra,Sampaio,Santos;MM,Sampaio,Santos,Wittbrodt]

ScannerS: Tool for performing scans in models with extended Higgs sectors
checking for the theoretical and experimental constraints

- link to HiggsTools to check for Higgs constraints

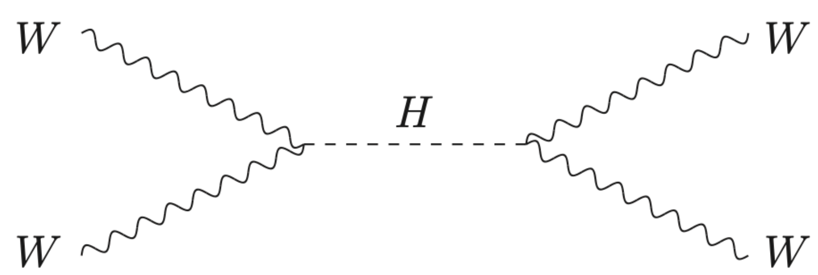
[Bahl,Biekötter,Bechtle,Heinemeyer,Li,Paasch,Weiglein,Wittbrodt]

- link to MicrOMEGAs to check for Dark Matter constraints [Bélanger,Boudjema,Pukhov eal]

Strongly-Interacting Higgs

Higgs Realization

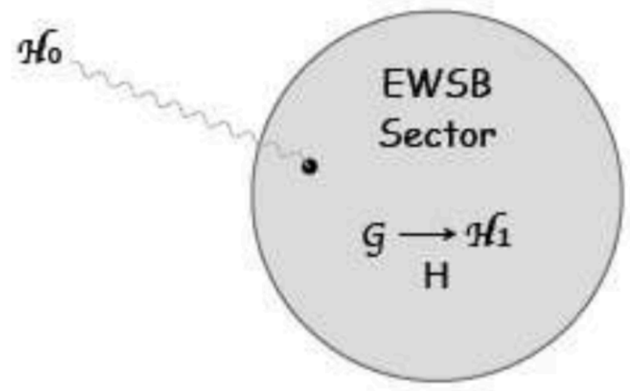
Weakly coupled models



SM and its singlet, doublet, triplet extensions, SUSY

New particles necessary to stabilize the Higgs mass

Strongly-interacting dynamics



Composite Higgs Models

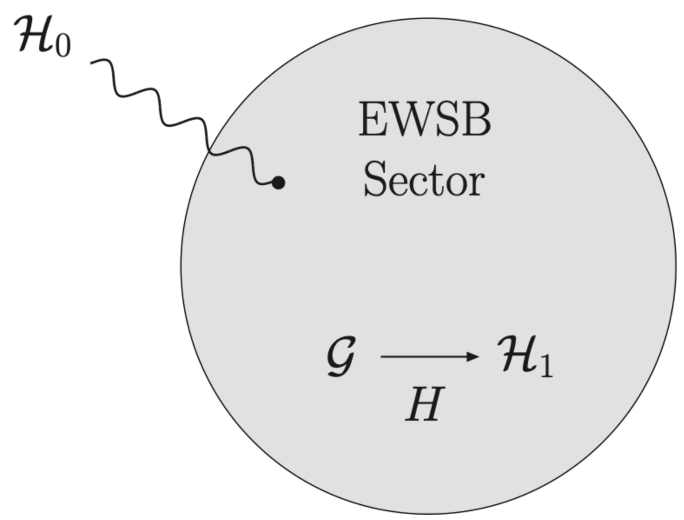
Resonances for unitarity
Higgs boson composite object

Composite Higgs Boson

Kaplan,Georgi; Dimopoulos eal; Dugan eal

- **Bound state from a Strongly Interacting Sector not much above weak scale**

- **How can we obtain a light composite Higgs?**



Higgs: Pseudo-Goldstone boson of strongly interacting sector

Global symmetry of strong sector $\mathcal{G}$ $\xrightarrow{\text{spontaneously broken at } f}$ subgroup $\mathcal{H}_1$

$\mathcal{G}/\mathcal{H}_1$: contains Higgs boson as Nambu-Goldstone Boson

- **SM Gauge Group**
  - $\mathcal{H}_0 \subset \mathcal{G}$ gauged by external vector bosons
  - Identify $\mathcal{H}_0 = G_{\mathrm{SM}} = SU(2)_L \times U(1)_Y$; $\mathcal{G} \to \mathcal{H}_1 \supset G_{\mathrm{SM}}$
  - $\mathcal{H}_1$ contains 'custodial' $SO(4) \cong SU(2)_L \times SU(2)_R$ (protect T parameter)
  - SM fields are external to strong sector $\rightsquigarrow$ elementary

[Cartoon taken from R.Contino, 1005.4269]

Composite Higgs Boson

- **Possible symmetry patterns**

  Examples:

  - $SO(5)/SO(4)$: 4 PGBs $= W_L^\pm, Z_L, h \to$ Minimal Comp. Higgs Model — Agashe, Contino, Pomarol
  - $SO(6)/SO(5)$: 5 PGBs $= W_L^\pm, Z_L, h, a \to$ Next MCHM — Gripaios, Pomarol, Riva, Serra
  - $SO(6)/[SO(4) \times SO(2)]$: 8 PGBs $= W_L^\pm, Z_L, h, H, A, H^\pm \to$ Composite 2HDM — De Curtis, Delle Rose, Moretti, Yagyu
  - ... — For a list: Bellazzini, Csáki, Serra

- **Higgs Boson Mass protected** $\leftarrow$ quantum corrections saturated at composite scale

- **Higgs Potential generated radiatively**
  - ◇ By gauge boson and top quark loops
  - ◇ EWSB triggered by top loops

- **Partial Compositeness**

Kaplan;
Contino,Kramer,Son,Sundrum

◇ Elementary fermions couple linearly to heavy states of strong sector w/ same quantum numbers

$$\mathcal{L}_{pc} = -\Delta_L \bar{q}_L Q_R - \Delta_R \bar{T}_L t_R + h.c.$$

◇ Fermions acquire mass through mixing with new vector-like strong sector fermions

◇ Linear couplings violate $\mathcal{G}$ explicitly $\rightsquigarrow$ Higgs potential induced

◇ Large top Yukawa couplings $\rightsquigarrow$ top largely composite

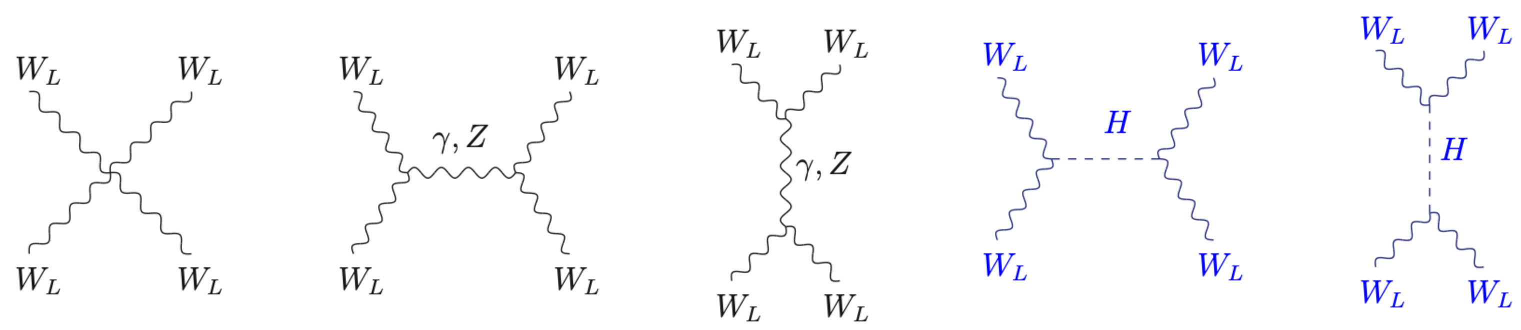
◇ Light Higgs boson requires light top partners

Matsedonskyi,Panico,Wulzer;
Redi,Tesi; Marzocca,Serone,Shu;
Pomarol,Riva

▷ Modified Higgs couplings to SM gauge bosons and fermions

∗ Unitarity not restored any more in $V_L V_L$ — Giudice eal; Contino eal '10,'13

- **Longitudinal W boson scattering**



$$\mathcal{A} = \frac{1}{v^2}\left(s - \frac{\kappa_V^2 s^2}{s - m_h^2}\right)$$

$\kappa_V = 1$ perturbative unitarity in $WW \to WW$

- **Higgs couplings deviate from SM couplings** $\Rightarrow VV \to VV$ and $VV \to HH$ grow with E^2

Giudice,Grojean,Pomarol,Rattazzi; Contino eal '10,'13

Phenomenological Implications

▷ Modified Higgs couplings to SM gauge bosons and fermions

* Unitarity not restored any more in $V_L V_L$ — Giudice eal; Contino eal '10,'13
* Higgs production and decay rates changed — Espinosa,Grojean,MMM
* Influences compatibility with EWPT — Giudice eal; Barbieri eal; Contino; Agashe eal; Gillioz; Lavoura,Silva; Lodone; Anastasiou eal; Grojean eal; Gröber eal

▷ New couplings

* Compatibility with Flavour Constraints — Agashe,Perez,Soni; Csaki eal; Blanke eal; Bauer eal; Redi,Weiler; Keren-Zur eal; Barbieri eal; Redi; Vignaroli; Da Rold eal; Delaunay eal
* Influences Double Higgs Production — Gröber,MMM; Contino eal; Gillioz eal

▷ New Resonances

* Compatibility with LHC searches — Gillioz,Gröber,Kapuvari,MMM

▷ Partial Compositeness — Kaplan;Contino,Kramer,Son,Sundrum

* Compatibility with Flavour Constraints
* Modified Higgs Yukawa couplings
* New particles in Loop induced processes
* Compatibibilty with direct LHC Searches for new fermions, with EWPT

2 Benchmark Models MCHM4&5

- **SILH effective Lagrangian** (SILH = strongly interacting light Higgs) expansion for small

$$\xi \equiv v^2/f^2$$

Giudice, Grojean, Pomarol, Rattazzi

SM limit for $\xi \to 0$

- **Gauge couplings**

$$g_{HVV} = g_{HVV}^{SM} \sqrt{1-\xi}$$

- **Fermion couplings** depend on embedding into representations of the bulk symmetry

spinorial representations of $SO(5)$	fundamental representations of $SO(5)$
MCHM4	MCHM5
$g_{Hff} = g_{Hff}^{SM} \sqrt{1-\xi} \equiv g_{Hff}^{SM}\, c$	$g_{Hff} = g_{Hff}^{SM} \frac{1-2\xi}{\sqrt{1-\xi}} \equiv g_{Hff}^{SM}\, c$
universal shift of couplings no modifications of BRs	BRs depend on $\xi = v^2/f^2$

- **Higgs self-couplings** also model-dependent

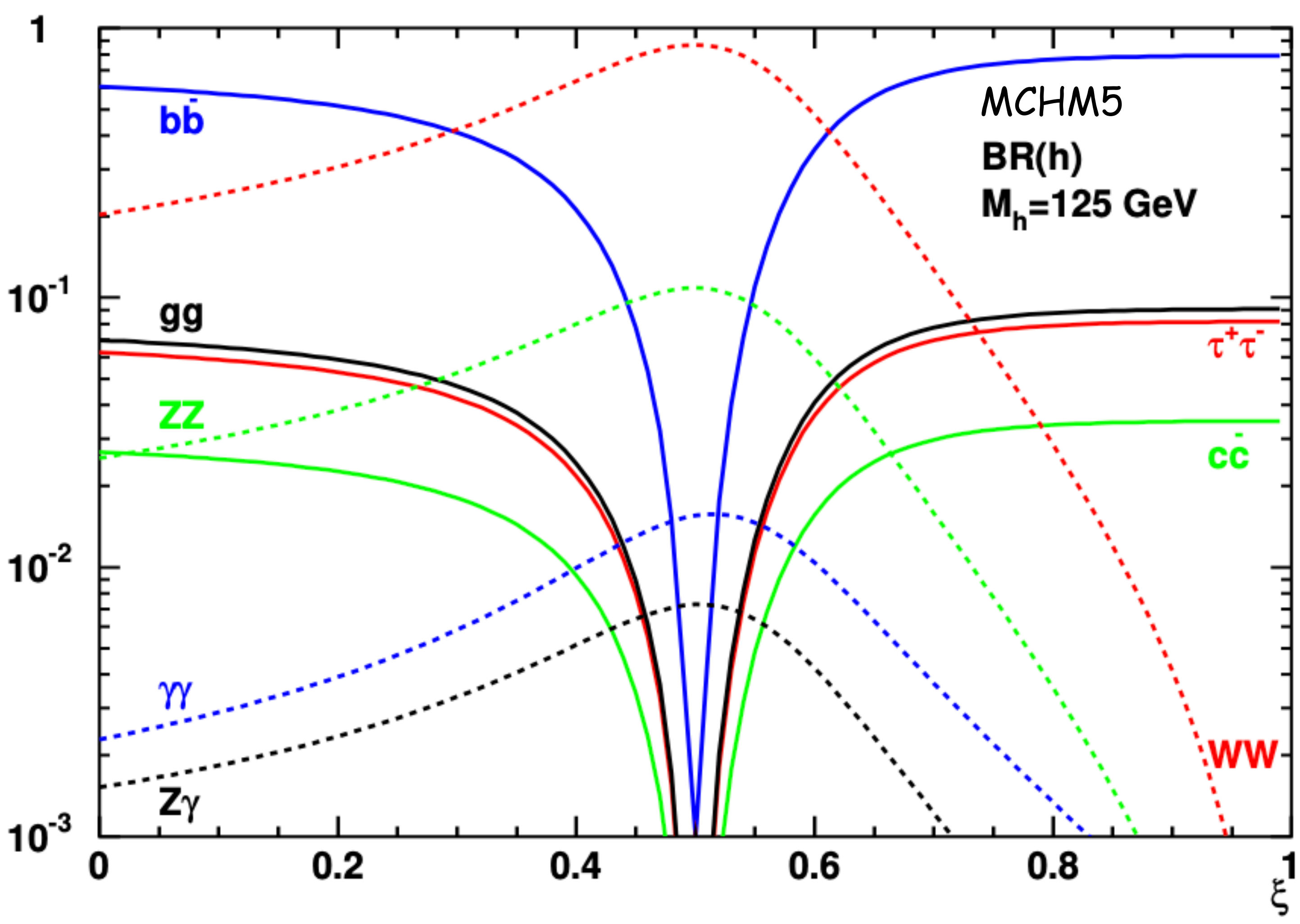
Contino eal; Gröber, MMM; Bock eal; Barger eal

Higgs Anomalous Couplings

- **Implementation for Higgs BRs:** eHDECAY Contino,Ghezzi,Grojean,MMM,Spira

  URL: http://www.itp.kit.edu/~maggie/eHDECAY/

[adapted from Grojean,Espinosa,MM,1003.3251]



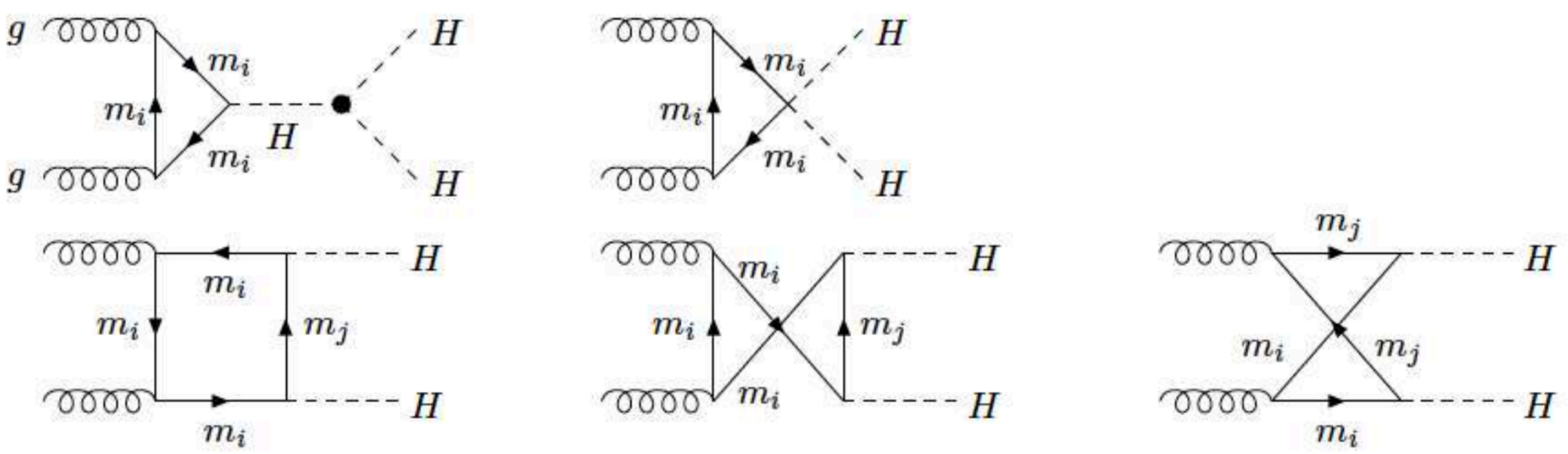
- **Double Higgs production through gluon fusion:**

  ∗ sensitive to trilinear Higgs self-coupling

  Baur,Glover; Spira eal; Djouadi,Kilian,MMM,Zerwas;Gröber,MMM

  ∗ access to anomalous $HHf\bar{f}$ coupling $(\sim \xi)$

  Contino eal '12



▷ Can be enhanced compared to the SM process

▷ Mediated by top and bottom loops and heavy quark loops; here heavy top partners

▷ Different fermions can contribute within one loop

New Physics in Higgs Pair Production

- **Questions:**
  - ∗ Taking into account LHC Higgs data: Can NP emerge in Higgs pair production despite the SM-like Higgs behaviour?
  - ∗ If yes: Can we see New Physics in Higgs pair production before any direct or indirect hints elsewhere?

- **Investigation**
  - ▷ in benchmark composite Higgs models ← large deviations from SM Higgs pair production due to novel 2-Higgs-2-fermion coupling [Gröber,MM; Dawson.,Furlan,Lewis]
  - ▷ including the NLO QCD corrections in large loop particle mass limit for models with vector-like fermions [Gröber,MM,Spira]

Applied Constraints

- **Assumption:** no new physics before Higgs pair production is accessible $\leadsto$ Higgs coupling deviations $<$ projected sensitivities for 300 fb^{-1} and 3000 fb^{-1}

- **Further constraints:** on parameter scan

  * direct search bounds for heavy fermions, projected to L_{300} and L_{3000}
  * exclude points for which $|V_{tb}| \leq 0.92$ [CMS, 2012]
  * check for EWPT [Gillioz,Gröber,Kapuvari,MM]

- **Sensitivity Criteria for NP in hh production:**

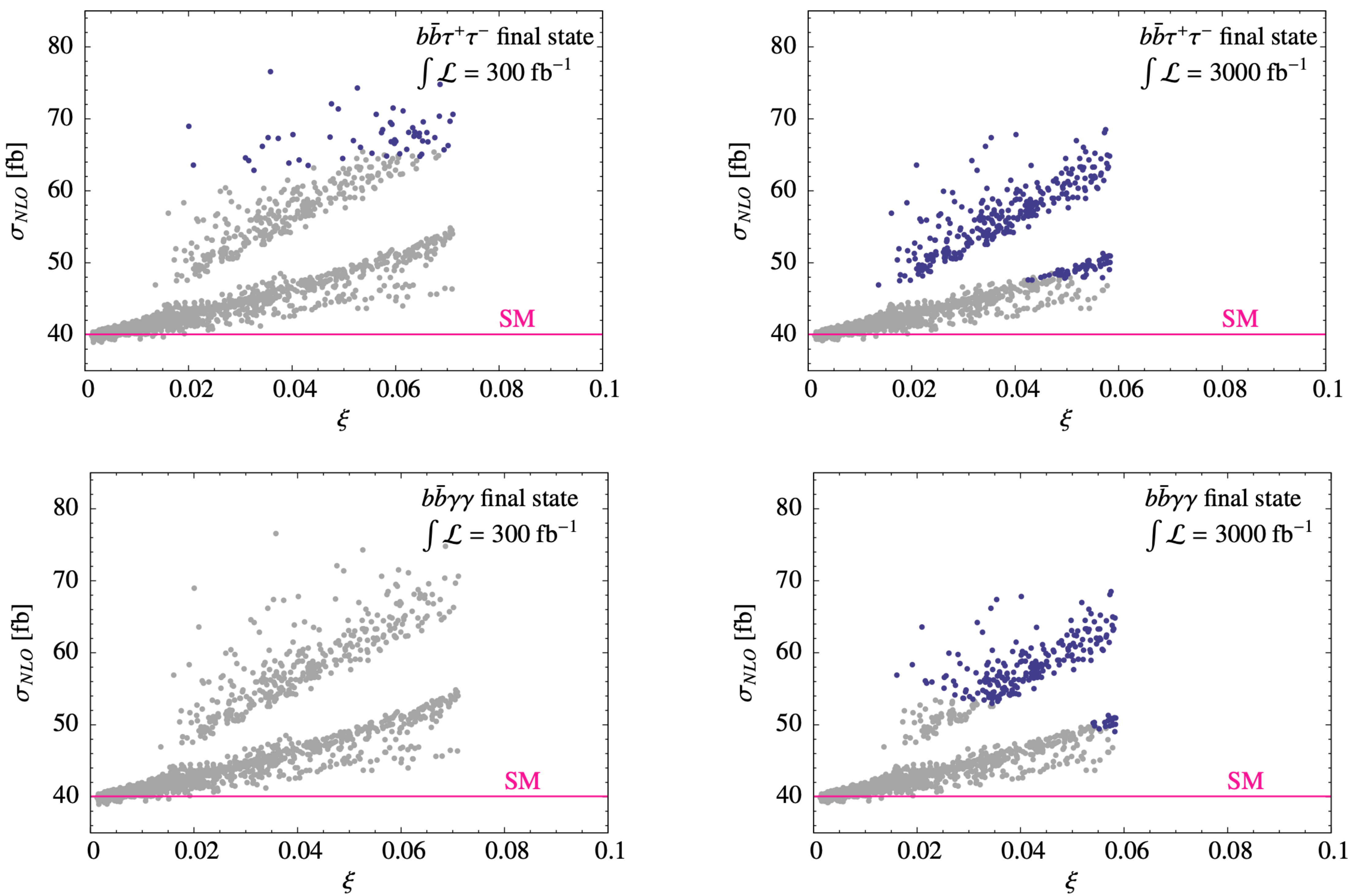
$$S_{\text{SM}} + 3\sqrt{S_{\text{SM}}} \leq S \quad \text{or} \qquad S_{\text{SM}} - 3\sqrt{S_{\text{SM}}} \geq S$$

S: number of signal events

Sensitivity to New Physics in Higgs Pair Production

MCHM10 w/ partial compositeness; blue points: HH distinguishable from SM HH at 3σ

[Gröber,MM,Spira,'16]

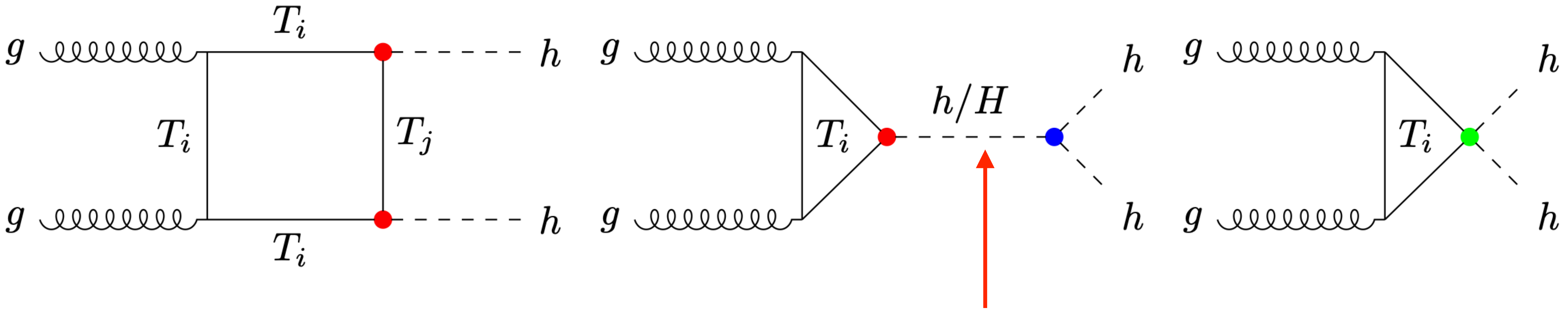


Higgs Pair Production in Composite 2HDM

- 2-Higgs Doublet Model (2HDM) w/ compositeness: [De Curtis,Delle Rose,Moretti,Yagyu,´18]

- Particle content: 2HDM:
  - 2 CP-even Higgs boson h, H with $m_h \leq m_H$, 1 CP-odd A, charged Higgs pair $H^\pm$
  - partial compositeness:
    - 4 top partners with $Q = 2/3$: $X_{2/3}$, $T_{2/3}$, $\tilde{T}_1, \tilde{T}_2$;
    - 1 bottom partner with $Q = -1/3$: $B_{-1/3}$;
    - 1 exotic fermion with $Q = 5/3$: $X_{5/3}$.

- Higgs Pair Production

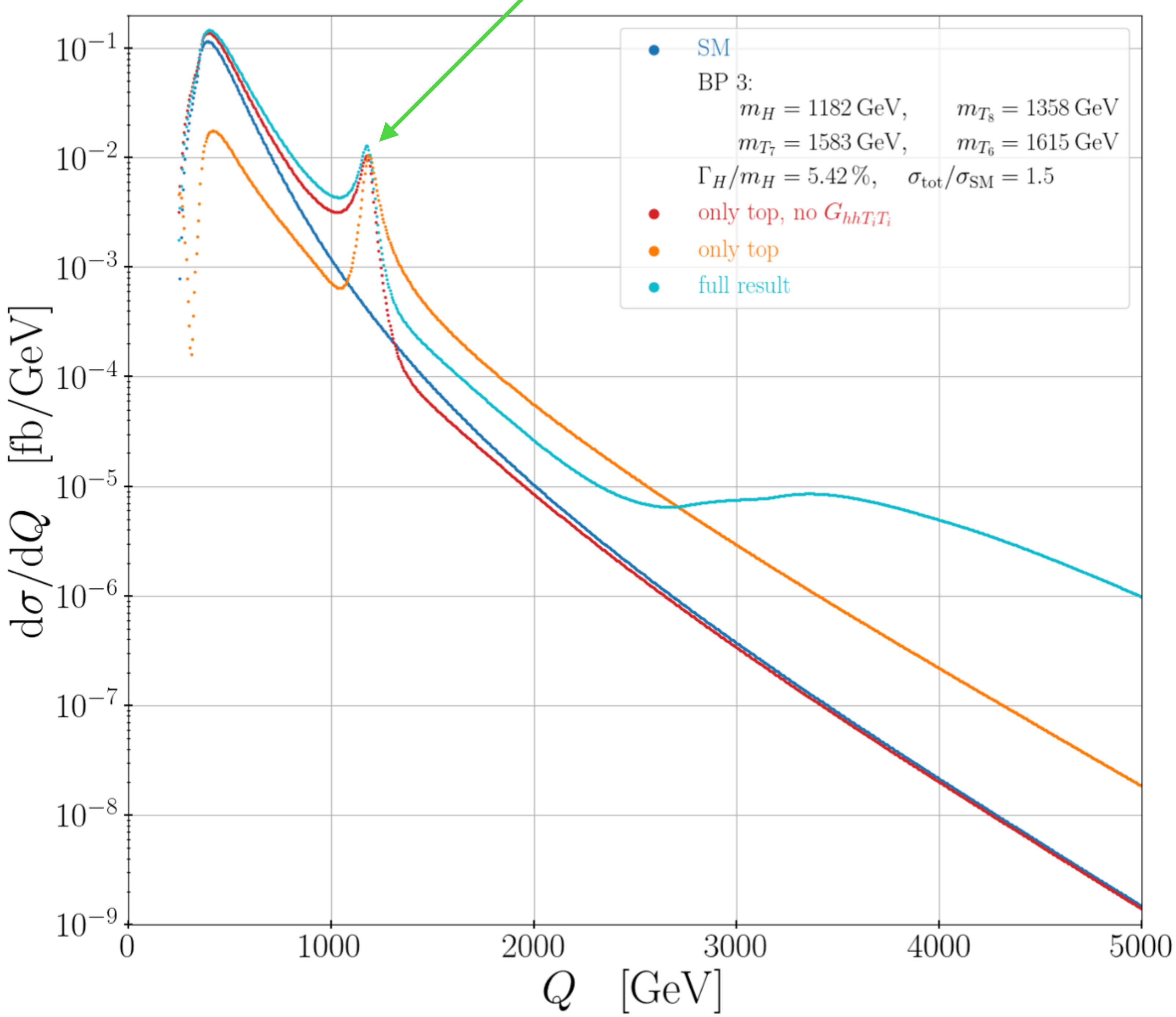


H exchange can resonantly enhance hh, if $m_H > 2m_h$

Invariant Mass Distribution

- Benchmark point BP3 w/ resonant enhancement

[De Curtis,Delle Rose,Egle,Moretti,MM,Sakurai,´23]



Red line: mimics elementary 2HDM; constructive(destructive) interference of triangle and box diagrams before(after) peak

Orange line: adding in 2-Higgs-2-fermion coupling contributions, interferes destructively ~> inversion of effect

Light blue line: all top partners added in enhancement before and after peak compared to SM

=> can in principle distinguish elementary from composite 2HDM

UV-Complete Models

The 2-Higgs Doublet Model (2HDM)

The 2-Higgs Doublet Model (2HDM)

- The 2-Higgs Doublet Model (2HDM) - Motivation:
  - one of the simplest SM extensions
  - provides DM candidate in its inert version
  - supersymmetry requires introduction of two Higgs doublets
  - provides strong-first-order phase transition (one of the three Sakharov conditions for the generation of the baryon asymmetry through EW symmetry breaking)

- Compatibility with constraints?

⁎ Rho parameter: fulfilled as it is a doublet extension

⁎ Flavour-changing neutral currents: will be discussed below

⁎ Unitarity constraints: amplitudes for longitudinal gauge boson scattering ($V_L V_L \to V_L V_L$) and fermion scattering ($f_+ \bar{f}_+ \to V_L V_L$, f_+=fermion w/ positive helicity) must not violate unitarity bounds. In SM, this is ensured by existence of light Higgs with couplings

$g_{HWW} = \frac{g m_W}{2}$ and $g_{Hff} = \frac{g m_f}{\sqrt{2} m_W}$

In 2HDM, there are two scalar Higgs bosons coupling to VV: h and H. For unitarity, they must fulfill the sum rules

$$\sum_i g^2_{h_i VV} = g^2_{hVV} + g^2_{HVV} = (g^{\rm SM}_{HVV})^2 \qquad \text{and} \qquad \sum_i g_{h_i VV} g_{h_i ff} = g_{hVV} g_{hff} + g_{HVV} g_{Hff} = g^{\rm SM}_{HVV} g^{\rm SM}_{Hff}$$

The 2HDM Higgs Potential

[T.D.Lee,Phys.Rev.D8(1973)1226; Branco eal.,1106.0034]

- 2HDM Higgs potential: $SU(2)_L \times U(1)_Y$ gauge-invariant, renormalizable, CP conservation, discrete $\mathbb{Z}_2$ symmetry under which $\Phi_1 \to -\Phi_1, \Phi_2 \to \Phi_2$ => potential w/ softly broken $\mathbb{Z}_2$

$$V = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 \left(\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1 \right) + \frac{\lambda_1}{2} \left(\Phi_1^\dagger \Phi_1 \right)^2 + \frac{\lambda_2}{2} \left(\Phi_2^\dagger \Phi_2 \right)^2$$
$$+ \lambda_3 \Phi_1^\dagger \Phi_1 \Phi_2^\dagger \Phi_2 + \lambda_4 \Phi_1^\dagger \Phi_2 \Phi_2^\dagger \Phi_1 + \frac{\lambda_5}{2} \left[\left(\Phi_1^\dagger \Phi_2 \right)^2 + \left(\Phi_2^\dagger \Phi_1 \right)^2 \right]$$

CP conservation: all parameters are real

- Minimum of the potential: $\langle \Phi_1 \rangle = \begin{pmatrix} 0 \\ \frac{v_1}{\sqrt{2}} \end{pmatrix}$ and $\langle \Phi_2 \rangle = \begin{pmatrix} 0 \\ \frac{v_2}{\sqrt{2}} \end{pmatrix}$

- Expansion of Higgs doublets around VEVs: $\Phi_a = \begin{pmatrix} \phi_a^+ \\ \frac{v_a + \rho_a + i\eta_a}{\sqrt{2}} \end{pmatrix}, \qquad a = 1, 2$

- Higgs spectrum and masses: Plug in expansion in V, collect all terms bilinear in the fields ~> mass matrices; diagonalize mass matrices w/ orthogonal matrices that are functions of the mixing angles α (neutral CP-even matrix) and β (neutral CP-odd and charged matrices) ~> physical states

The 2HDM Higgs Potential

- Higgs spectrum and masses:

2 neutral CP-even Higgs bosons: h and H, with $m_h \leq m_H$
1 neutral CP-odd Higgs boson: A
2 charged Higgs bosons: H^+, H^-

Mixing angle β : $\tan\beta = \dfrac{v_2}{v_1}$; to reproduce the W and Z masses, we must have $v_1^2 + v_2^2 = v^2$

Masses:

$$m_{H^\pm}^2 = \left(\frac{m_{12}^2}{v_1 v_2} - \frac{\lambda_4 + \lambda_5}{2}\right)(v_1^2 + v_2^2) = M^2 - \frac{1}{2}(\lambda_4 + \lambda_5)v^2 \qquad M^2 = \frac{m_{12}^2}{\sin\beta\cos\beta}$$

$$m_A^2 = \left(\frac{m_{12}^2}{v_1 v_2} - \lambda_5\right)(v_1^2 + v_2^2) = M^2 - \lambda_5 v^2$$

$$m_{H,h}^2 = \frac{1}{2}\left[\mathcal{M}_{11} + \mathcal{M}_{22} \pm \sqrt{(\mathcal{M}_{11} - \mathcal{M}_{22})^2 + 4\mathcal{M}_{12}^2}\right]$$

$\mathcal{M}_{ij}$ matrix elements of the mass matrix in the neutral CP-even sector

- 2HDM input parameters: $m_h, m_H, m_A, m_{H^\pm}, m_{12}^2, \cos(\beta - \alpha), v, \tan\beta$

Decoupling

- Alignment limit: one of the neutral Higgs bosons has to be approximately aligned with the direction of the Higgs VEV in field space ~> limit of a SM Higgs

- Alignment with decoupling: Alignment limit in extended Higgs sector realized if all additional Higgs states are very heavy: decoupling limit

- Alignment without decoupling: occurs generically in 2HDMs

✏ Masses of the heavy 2HDM Higgs bosons take the form: $\Phi \equiv H, H^\pm, A$

$$m_\Phi^2 = M^2 + \lambda_i v^2 (+\mathcal{O}(v^4/M^2))$$

λ_i linear combination of $\lambda_1, \ldots, \lambda_5$

✏ In case $M^2 \gg \lambda_i v^2$: heavy Higgs bosons decouple, h behaves SM-like ($\sin(\beta-\alpha) \to 1$)
alignment/decoupling limit

✏ alignment without decoupling: H can become SM-like particle ($\cos(\beta-\alpha) \to 1$) ~> light Higgs h with mass below 125 GeV in the spectrum

✏ Strong coupling regime: $M^2 \leq \lambda_i v^2$: large value of m_Φ for λ_i large (limited by perturbativity)

Flavour-Changing Neutral Currents

- Yukawa Lagrangian:

$$\mathcal{L}_Y = -\Big\{ \bar{Q}'_L(\Gamma_1\Phi_1 + \Gamma_2\Phi_2)D'_R - \bar{Q}'_L(\Delta_1\tilde{\Phi}_1 + \Delta_2\tilde{\Phi}_2)U'_R + \bar{L}'(\Pi_1\Phi_1 + \Pi_2\Phi_2)E'_R + h.c. \Big\} ,$$

where Q'_L, L'_L denote the left-handed quark and lepton doublets and $Q \equiv (U,D)^T$, $L \equiv (\nu, E)^T$, with $U \equiv (u,c,t)^T$, $D \equiv (d,s,b)^T$, $\nu \equiv (\nu_e,\nu_\mu,\nu_\tau)^T$ and $E \equiv (e,\mu,\tau)^T$. The indices L,R denote left- and right-handed fermions f given by

$$f_{L,R} = P_{L,R} f \equiv \frac{1}{2}(1 \mp \gamma_5) f \, .$$

We have defined $\tilde{\Phi}_a = (\Phi_a^T \epsilon)^\dagger$, with

$$\epsilon = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} .$$

The couplings Γ_a, Δ_a and Π_a $(a = 1,2)$ are 3×3 complex matrices in flavour space.

Problem w/ 2 Higgs doublets: Mass and coupling matrices cannot be diagonalized simultaneously
~> FCNC at tree-level!

- Solution: Extend discrete $\mathbb{Z}_2$ symmetry of Higgs sector to Yukawa sector such that only one Higgs doublet couples to a given right-handed fermions

Flavour-Changing Neutral Currents

- Four 2HDM types:

  - type I 2HDM: All quarks couple to just one of the Higgs doublets (conventionally chosen to be Φ_2).
  - type II 2HDM: The $Q = 2/3$ right-handed (RH) quarks couple to one Higgs doublet (conventionally chosen to be Φ_2) and the $Q = -1/3$ RH quarks couple to the other (Φ_1).
  - Lepton-specific model: The RH quarks all couple to Φ_2 and the RH leptons couple to Φ_1.
  - Flipped model: The RH up-type quarks couple to Φ_2, the RH down-type quarks couple to Φ_1, as in type II, but now the RH leptons couple to Φ_2.

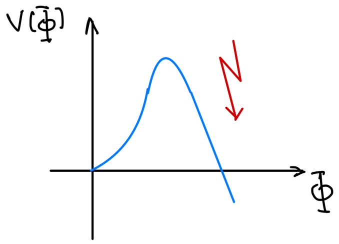
- Alternative solution: alignment in flavor space of the Yukawa couplings

$$\Gamma_2 = \xi_d e^{-i\theta}\Gamma_1 \,, \quad \Delta_2 = \xi_u^* e^{i\theta}\Delta_1 \,, \quad \Pi_2 = \xi_l e^{-i\theta}\Pi_1$$

masses and couplings are proportional to each other ~> can be diagonalized simultaneously
four Yukawa types appear as special cases of the aligned 2HDM (A2HDM)

Theory Constraints

- Potential Bounded-From-Below: quartic part of the potential positive for arbitrarily large field values ~> (tree-level analysis)



[Deshpande,Ma,'78;Klimenko,'85]

$$\lambda_1 \geq 0\,, \qquad \lambda_2 \geq 0$$
$$\lambda_3 \geq -\sqrt{\lambda_1\lambda_2}\,, \qquad \lambda_3 + \lambda_4 - |\lambda_5| \geq -\sqrt{\lambda_1\lambda_2}$$

Inclusion of higher-order effects: check the tree-level conditions for running λ_i at any scale Q up to which model is considered to be valid

$$\frac{d\lambda_i}{d\ln Q} = \beta_i(g_j)$$

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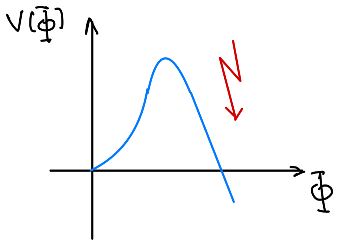

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$$\frac{d\lambda_i}{d \ln Q} = \beta_i(g_j)$$

• Electroweak vacuum w/ v=246 GeV is the global minimum:

possible 2HDM vacuum directions ω_i

$$\Phi_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} \rho_1 + i\,\eta_1 \\ \zeta_1 + \omega_1 + i\,\psi_1 \end{pmatrix}, \quad \Phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \rho_2 + \omega_{CB} + i\,\eta_2 \\ \zeta_2 + \omega_2 + i\,(\psi_2 + \omega_{CP}) \end{pmatrix}$$

neutral CP-conserving minima: ω_1, ω_2
neutral CP-violating minimum: ω_{CP}
charge-breaking minimum: ω_{CB}

Theory Constraints

- Electroweak vacuum w/ v=246 GeV is the global minimum:

[Ferreira eal,'04;Barroso eal,'05;Ivanov,'07;Ivanov'08]

- If the potential has a CP-conserving minimum ω_1, ω_2 , then any other stationary point (either ω_{CP} or ω_{CB}) is a saddle point w/ a higher value of the potential

[Ivanov'08;Barroso,'12,'13]

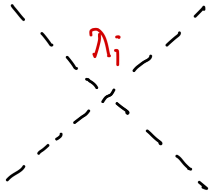
- Two CP-conserving minima could coexist, however! Panic Vacuum!

Vacuum w/ the symmetry breaking pattern (v=246 GeV) is the global minimum if and only if

$$D = m_{12}^2(m_{11}^2 - \sqrt{\lambda_1/\lambda_2}\, m_{22}^2)(v_2/v_1 - (\lambda_1\lambda_2)^{1/4}) > 0$$

- Perturbative Unitarity:

make sure that the potential couplings do not become non-perturbatively large
analyze eigenvalues of the S matrix for scalar-scalar scattering amplitudes:



$$\begin{aligned}
a_\pm &= \frac{3}{2}(\lambda_1+\lambda_2) \pm \sqrt{\frac{9}{4}(\lambda_1-\lambda_2)^2 + (2\lambda_3+\lambda_4)^2}\,, \\
b_\pm &= \frac{1}{2}(\lambda_1+\lambda_2) \pm \frac{1}{2}\sqrt{(\lambda_1-\lambda_2)^2 + 4\lambda_4^2}\,, \\
c_\pm &= \frac{1}{2}(\lambda_1+\lambda_2) \pm \frac{1}{2}\sqrt{(\lambda_1-\lambda_2)^2 + 4\lambda_5^2}\,, \\
e_1 &= \lambda_3 + 2\lambda_4 - 3\lambda_5\,, \\
e_2 &= \lambda_3 - \lambda_5\,, \\
f_+ &= \lambda_3 + 2\lambda_4 + 3\lambda_5\,, \\
f_- &= \lambda_3 + \lambda_5\,, \\
f_1 &= \lambda_3 + \lambda_4\,, \\
p_1 &= \lambda_3 - \lambda_4\,.
\end{aligned}$$

=> Require (tree-level perturbative unitarity:

$$\begin{aligned}
|\lambda_3 - \lambda_4| &< 8\pi \\
|\lambda_3 + 2\lambda_4 \pm 3\lambda_5| &< 8\pi \\
\left|\frac{1}{2}\left(\lambda_1 + \lambda_2 + \sqrt{(\lambda_1-\lambda_2)^2 + 4\lambda_4^2}\right)\right| &< 8\pi \\
\left|\frac{1}{2}\left(\lambda_1 + \lambda_2 + \sqrt{(\lambda_1-\lambda_2)^2 + 4\lambda_5^2}\right)\right| &< 8\pi.
\end{aligned}$$

Theory Constraints

- Electroweak vacuum w/ v=246 GeV is the global minimum:

05;Ivanov,'07;Ivanov'08]

- If the potential has a CP-conserving minimum ω_1, ω_2 , … ry point (either ω_{CP} or ω_{CB}) is a saddle point w/ a higher valu…

Note: These rules are No longer valid when vacuum is investigated including higher-order corrections

vanov'08;Barroso,'12,'13]

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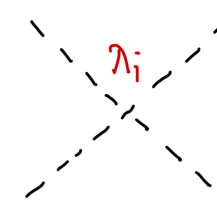

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f_+ &= \lambda_3 + 2\lambda_4 + 3\lambda_5\,,\\
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\left|\frac{1}{2}\left(\lambda_1+\lambda_2+\sqrt{(\lambda_1-\lambda_2)^2+4\lambda_5^2}\right)\right| &< 8\pi.
\end{aligned}$$

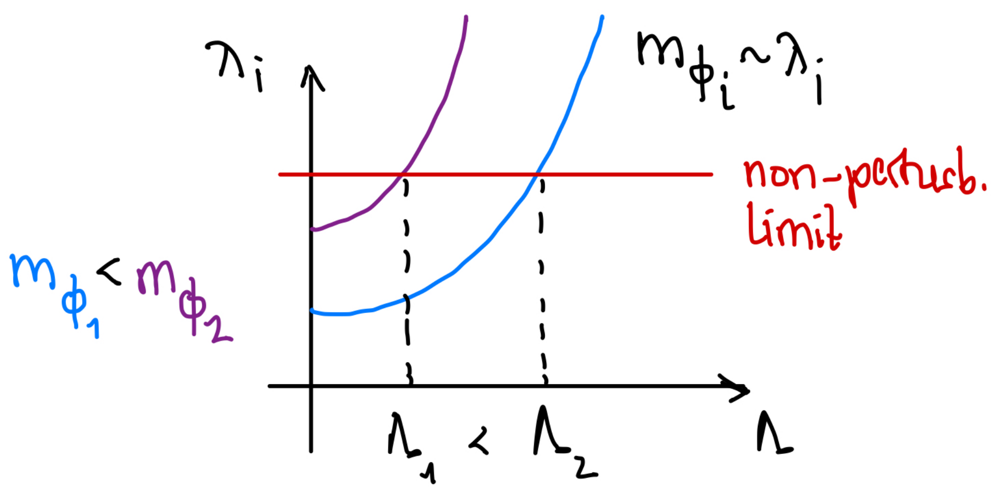
Theory Constraints

- Inclusion of renormalization group running of the parameters:
  (capture - „hopefully" - bulk of higher-order corrections)

[Basler,Ferreira,MM,Santos,'17]

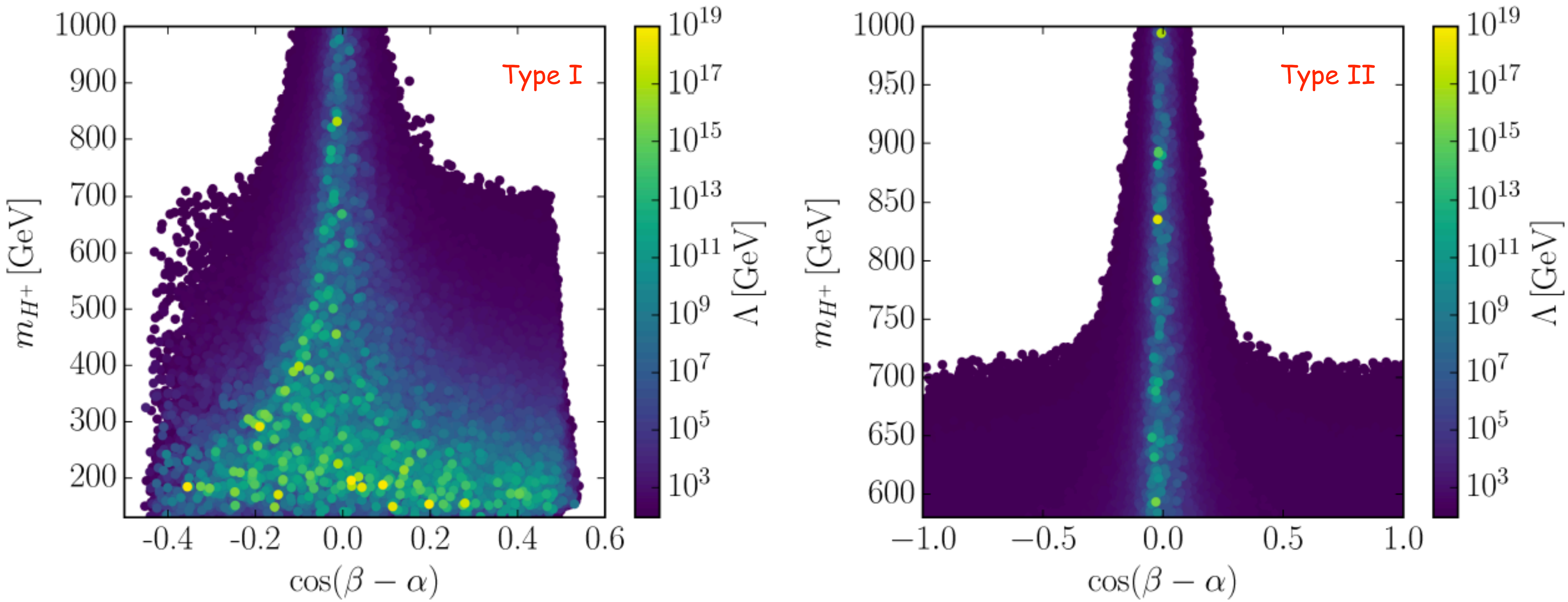
- Perform RGE running of all potential parameters and VEVs starting at m_Z
- At each scale between m_Z and the Planck scale verify whether the theoretical constraints are still verified
- If yes, proceed to a higher scale and repeat

Note: Higgs mass values and quartic couplings are closely related ~> if at scale m_Z we start with a heavy Higgs spectrum ~> start values of quartic couplings λ_i are large ~> scale up to which model remains perturbative, is lowered



Theory Constraints and High Scale Impact

Flavor constraints set stringent lower bound on $m_{H^\pm}$ in 2HDM Type II! [Basler,Ferreira,MM,Santos,'17]



$m_{H^\pm} \geq 500 GeV$ and requirement of validity up to the Planck scale ~> alignment (exp. & theor. constraints included)

See also [Chakrabarty eal; Bhupal Dev eal; Das,Saha; Chowdhury,Eberhardt; Ferreira eal; Cacchio eal; Cherchiglia,Nishi; Krauss eal; Goodsell,Staub; Braathen eal; ...]

EW Corrections to the 2HDM

- Precision predictions to Higgs observables indispensable: match experimental precision; be sensitive to subtle beyond-SM (BSM) effects; if detected, identify underlying model, distinction from possibly other models w/ similar features

- EW higher-order corrections in the 2HDM:
  - cautiously chose renormalization scheme in order not to introduce gauge parameter dependence in HO corrections from mixing angle renormalization;

    [Krause,Lorenz,MM,Santos,Ziesche,'16;Krause,MM,Santos,Ziesche,'16]
    [Denner,Jenniches,Lang,Sturm,'16;Altenkamp,Dittmaier,Rzehak,'17;Denner,Dittmaier,Lang,'18]

    solution: apply so-called tadpole scheme for the renormalization of the VEV
    project out gauge-parameter independent terms (pinching)

    See also N2HDM: [Krause,López-Val,MM,Santos,'17]; multi-Higgs: [Fox,Grimus,Löschner,'18;Grimus,Löschner,'18];
    singlet-extended SM: [Bojarski,Chalons,López-Val,Robens]; [Dittmaier,Rzehak,'22]

  - quartic couplings input parameters, only constrained by unitarity constraints =>

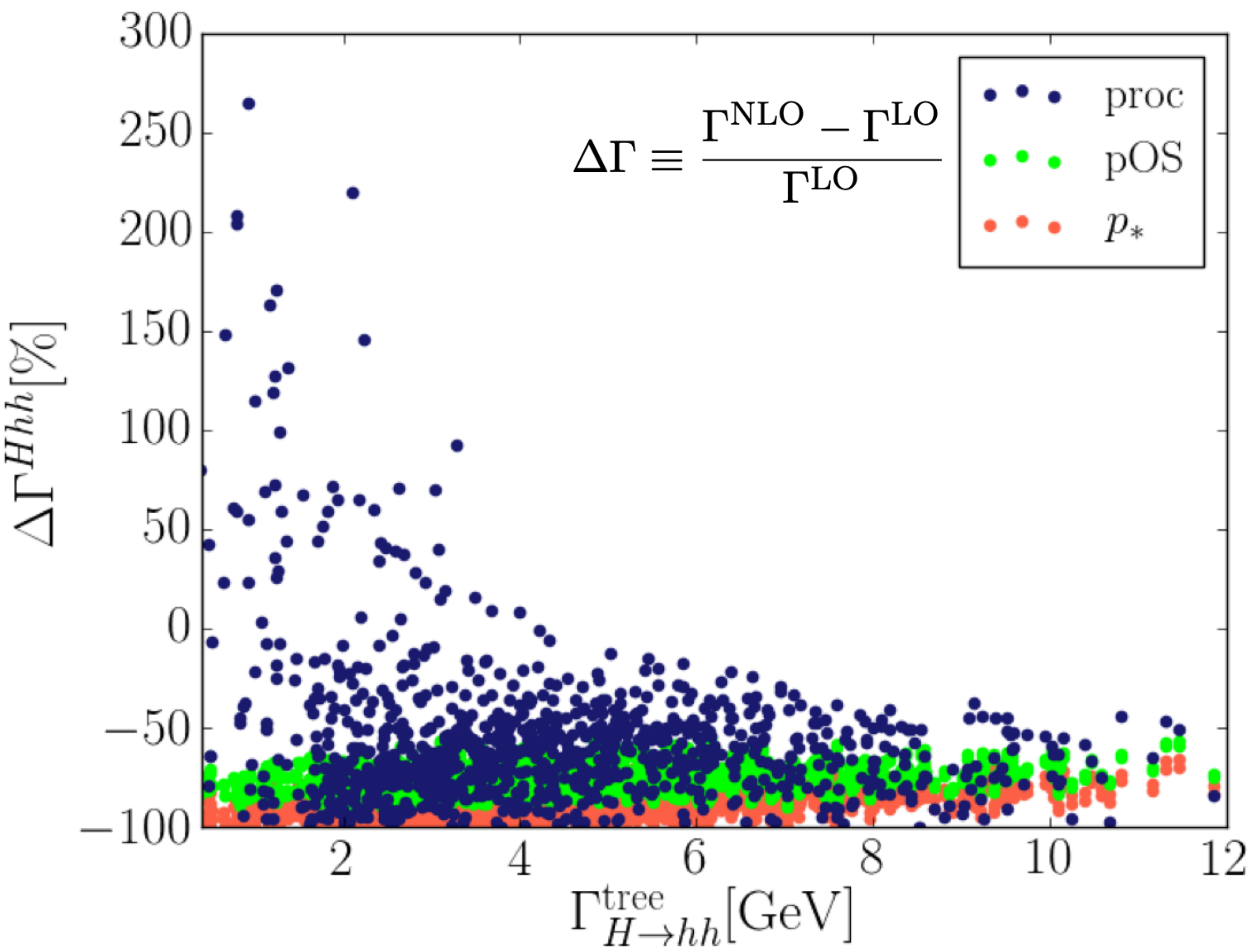
    [Kanemura,Kiyoura,Okada,Senaha,Yuan,'02;Braathen,Kanemura,'19,'20]; [Krause,MM,Santos,Ziesche,'16]; [Bahl,Braathen,Weiglein,'22]

    HO corrections involving trilinear Higgs self-coupling can be parametrically enhanced

EW Corrections to the 2HDM

[Krause,MM,Santos,Ziesche,'16]

Parameter scan in the 2HDM type II, exp. & theor. constraints applied



Parametrically enhanced NLO corrections in the non-decoupling limit

Program Codes for HO Corrections to the 2HDM

- Fortran code 2HDECAY: [Krause,MM,Spira,'18]

  partial decay widths and branching ratios at one-loop EW and including the state-of-the-art HO QCD corrections; includes tree-level off-shell decays and QCD corrections to the loop-induced decays; offers choice among renormalization schemes w/ automatic parameter conversion

[Krause,MM,'19]

SM

ΔBR	$b\bar{b}$	$\tau^+\tau^-$	$\mu^+\mu^-$	$s\bar{s}$	$c\bar{c}$	gg	$\gamma\gamma$	$Z\gamma$	W^+W^-	ZZ
	-1.76%	-1.59%	-3.52%	2.24%	-3.81%	4.34%	-2.29%	-0.71%	3.68%	1.61%

Table 6: Relative size of the EW corrections to the BRs of the SM Higgs boson $H_{\rm SM}$ with mass $m_{H_{\rm SM}} =$ 125.09 GeV.

- Based on Fortran code HDECAY: [Djouadi,Kalinowski,Spira,'97; Djouadi,Kalinowski,MM,Spira,'18]

  computation of LO decay widths, off-shell decays and loop-induced 2HDM decays including state-of-the-art QCD corrections

Program Codes for HO Corrections to the 2HDM

- Fortran code 2HDECAY: [Krause,MM,Spira,'18]

partial decay widths and branching ratios at one-loop EW and including the state-of-the-art HO QCD corrections; includes tree-level off-shell decays and QCD corrections to the loop-induced decays; offers choice among renormalization schemes w/ automatic parameter conversion [Krause,MM,'19]

SM

ΔBR	$b\bar{b}$	τ^+…	…	…$^+W^-$	ZZ
	-1.76%	-1.5…	…	…68%	1.61%

Table 6: Relative size of t… to… M… with mass $m_{H_{SM}}$ = 125.09 GeV.

2HDM

Type	$\Delta\text{BR}^{S_1}_{Hb\bar{b}}$
I	$\lesssim$ 15.0 % (48 %)
	$\lesssim$ 27.5 % (93 %)
II	$\lesssim$ 10.0 % (52 %)
	$\lesssim$ 25.0 % (92 %)
LS	$\lesssim$ 10.0 % (52 %)
	$\lesssim$ 25.0 % (92 %)
FL	$\lesssim$ 12.5 % (52 %)
	$\lesssim$ 32.5 % (88 %)

Type	$\Delta\text{BR}^{S_1}_{Ht\bar{t}}$
I	$\lesssim$ 5.0 % (48 %)
	$\lesssim$ 22.5 % (85 %)
II	$\lesssim$ 2.5 % (60 %)
	$\lesssim$ 10.0 % (86 %)
LS	$\lesssim$ 5.0 % (61 %)
	$\lesssim$ 15.0 % (88 %)
FL	$\lesssim$ 5.0 % (68 %)
	$\lesssim$ 12.5 % (87 %)

Type	$\Delta\text{BR}^{S_1}_{H\tau^+\tau^-}$
I	$\lesssim$ 15.0 % (49 %)
	$\lesssim$ 35.0 % (88 %)
II	$\lesssim$ 15.0 % (54 %)
	$\lesssim$ 25.0 % (91 %)
LS	$\lesssim$ 15.0 % (54 %)
	$\lesssim$ 27.5 % (90 %)
FL	$\lesssim$ 15.0 % (55 %)
	$\lesssim$ 27.5 % (90 %)

Type	$\Delta\text{BR}^{S_1}_{HZA}$
I	$\lesssim$ 5.0 % (51 %)
	$\lesssim$ 15.0 % (80 %)
II	$\lesssim$ 5.0 % (68 %)
	$\lesssim$ 10.0 % (91 %)
LS	$\lesssim$ 5.0 % (65 %)
	$\lesssim$ 10.0 % (86 %)
FL	$\lesssim$ 5.0 % (65 %)
	$\lesssim$ 10.0 % (88 %)

Type	$\Delta\text{BR}^{S_1}_{HW^\pm H^\mp}$
I	$\lesssim$ 5.0 % (56 %)
	$\lesssim$ 17.5 % (81 %)
II	$\lesssim$ 5.0 % (60 %)
	$\lesssim$ 10.0 % (87 %)
LS	$\lesssim$ 5.0 % (71 %)
	$\lesssim$ 7.5 % (84 %)
FL	$\lesssim$ 5.0 % (67 %)
	$\lesssim$ 7.5 % (85 %)

Type	$\Delta\text{BR}^{S_1}_{HZZ}$
I	$\lesssim$ 47.5 % (50 %)
	$\gtrsim$ 100.0 % (29 %)
II	$\lesssim$ 62.5 % (50 %)
	$\gtrsim$ 100.0 % (39 %)
LS	$\lesssim$ 67.5 % (50 %)
	$\gtrsim$ 100.0 % (38 %)
FL	$\lesssim$ 90.0 % (40 %)
	$\gtrsim$ 100.0 % (57 %)

Type	$\Delta\text{BR}^{S_1}_{Hhh}$
I	$\lesssim$ 90.0 % (28 %)
	$\gtrsim$ 100.0 % (70 %)
II	$\lesssim$ 90.0 % (10 %)
	$\gtrsim$ 100.0 % (89 %)
LS	$\lesssim$ 90.0 % (20 %)
	$\gtrsim$ 100.0 % (78 %)
FL	$\lesssim$ 90.0 % (14 %)
	$\gtrsim$ 100.0 % (84 %)

Program Codes for HO Corrections to the 2HDM

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  partial decay widths and branching ratios at one-loop EW and including the state-of-the-art HO QCD corrections; includes tree-level off-shell decays and QCD corrections to the loop-induced decays; offers choice among renormalization schemes w/ automatic parameter conversion

- Fortran code HCOUP: [Aiko,Kanemura,Kikuchi,Sakurai,Yagyu,'23]

  various Higgs effective vertices, decay rates, branching ratios at one-loop EW and HO QCD for 2HDM and Higgs singlet model

- Python code anyH3: [Bahl,Braathen,Gabelmann,Weiglein,'23]

  one-loop corrections to trilinear SM-like Higgs self-coupling λ_{hhh} for any renormalisable model for with arbitrary external momenta values; semi-automotic, flexible renormalisation procedure

The CP-Violating 2HDM (C2HDM)

The CP-Violating 2HDM (C2HDM)

- CP violation: one of the three Sakharov conditions for the generation of the baryon-anti baryon asymmetry through electroweak baryogenesis

- C2HDM Higgs potential: w/ softly broken $\mathbb{Z}_2$ symmetry [Ginzburg,Krawczyk,Osland,'02]

$$V = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left(m_{12}^2 \Phi_1^\dagger \Phi_2 + h.c. \right) + \frac{\lambda_1}{2} \left(\Phi_1^\dagger \Phi_1 \right)^2 + \frac{\lambda_2}{2} \left(\Phi_2^\dagger \Phi_2 \right)^2$$

$$+ \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \left[\frac{\lambda_5}{2} \left(\Phi_1^\dagger \Phi_2 \right)^2 + h.c. \right]$$

All parameters are real except for m_{12}^2 and λ_5: $m_{12}^2 = |m_{12}^2| e^{i\phi(m_{12}^2)}$, $\quad \lambda_5 = |\lambda_5| e^{i\phi(\lambda_5)}$

The two complex phases are not independent of each other

$$2\text{Re}(m_{12}^2) \tan\phi(m_{12}^2) = v_1 v_2 \, \text{Re}(\lambda_5) \tan\phi(\lambda_5)$$

Ensure CP violation (both phases cannot be removed simultaneously) by choosing:

$$\phi(\lambda_5) \neq 2\,\phi(m_{12}^2)$$

The CP-Violating 2HDM (C2HDM)

- Mass spectrum and mixing: CP violation ~> neutral formerly CP-even (h,H) and CP-odd (A) states mix to mass eigenstates H_i $(i = 1,2,3)$ with indefinite CP quantum number

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{v_1+\rho_1+i\eta_1}{\sqrt{2}} \end{pmatrix} \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{v_2+\rho_2+i\eta_2}{\sqrt{2}} \end{pmatrix} \quad \Rightarrow \quad \begin{pmatrix} H_1 \\ H_2 \\ H_3 \end{pmatrix} = R \begin{pmatrix} \rho_1 \\ \rho_2 \\ \rho_3 \end{pmatrix}$$

with $$R = \begin{pmatrix} c_1 c_2 & s_1 c_2 & s_2 \\ -(c_1 s_2 s_3 + s_1 c_3) & c_1 c_3 - s_1 s_2 s_3 & c_2 s_3 \\ -c_1 s_2 c_3 + s_1 s_3 & -(c_1 s_3 + s_1 s_2 c_3) & c_2 c_3 \end{pmatrix}$$ and $$m_{H_1} \le m_{H_2} \le m_{H_3}$$

$$-\pi/2 < \alpha_1 \le \pi/2, \qquad -\pi/2 < \alpha_2 \le \pi/2, \qquad -\pi/2 < \alpha_3 \le \pi/2$$

only two masses are independent:

$$m_{H_3}^2 = \frac{m_{H_1}^2 R_{13}(R_{12}\tan\beta - R_{11}) + m_{H_2}^2 R_{23}(R_{22}\tan\beta - R_{21})}{R_{33}(R_{31} - R_{32}\tan\beta)}$$

Charged Higgs sector is unchanged.

- C2HDM input parameters: $m_{H_i}, m_{H_j}, m_{H^\pm}, \mathrm{Re}(m_{12}^2), v, \tan\beta, R_{23}, c^2_{H_i VV}, c^2_{H_i tt}$, with $m_{H_i} \le m_{H_j}$ and sign of R_{13} to lift degeneracy from squared couplings

- Allowed amount of CP violation: stringently constrained by EDM measurements

The CP-Violating 2HDM (C2HDM)

- Mass spectrum and mixing: CP violation ~> neutral formerly CP-even (h,H) and CP-odd (A) states mix to mass eigenstates H_i $(i = 1,2,3)$ with indefinite CP quantum number

$$\Phi_1 = \begin{pmatrix} \phi \\ \frac{v_1+\rho}{\sqrt{}} \end{pmatrix} \quad \begin{pmatrix} H_1 \\ \\ \end{pmatrix} \quad \begin{pmatrix} \rho_1 \\ \rho_2 \\ \rho_3 \end{pmatrix}$$

3 neutral CP-mixed Higgs bosons: H_1, H_2, H_3,
with $m_{H_1} \leq m_{H_2} \leq m_{H_3}$
2 charged Higgs bosons: H^+, H^-

with $$R = \begin{pmatrix} \\ -(c_1 \ldots \\ -c_1 s_2 c_3 + s_1 s_3 & -(c_1 s_3 + s_1 s_2 c_3) & c_2 c_3 \end{pmatrix}$$ $\leq m_{H_2} \leq m_{H_3}$

$$-\pi/2 < \alpha_1 \leq \pi/2, \qquad -\pi/2 < \alpha_2 \leq \pi/2, \qquad -\pi/2 < \alpha_3 \leq \pi/2$$

only two masses are independent:

$$m_{H_3}^2 = \frac{m_{H_1}^2 R_{13}(R_{12}\tan\beta - R_{11}) + m_{H_2}^2 R_{23}(R_{22}\tan\beta - R_{21})}{R_{33}(R_{31} - R_{32}\tan\beta)}$$

Charged Higgs sector is unchanged.

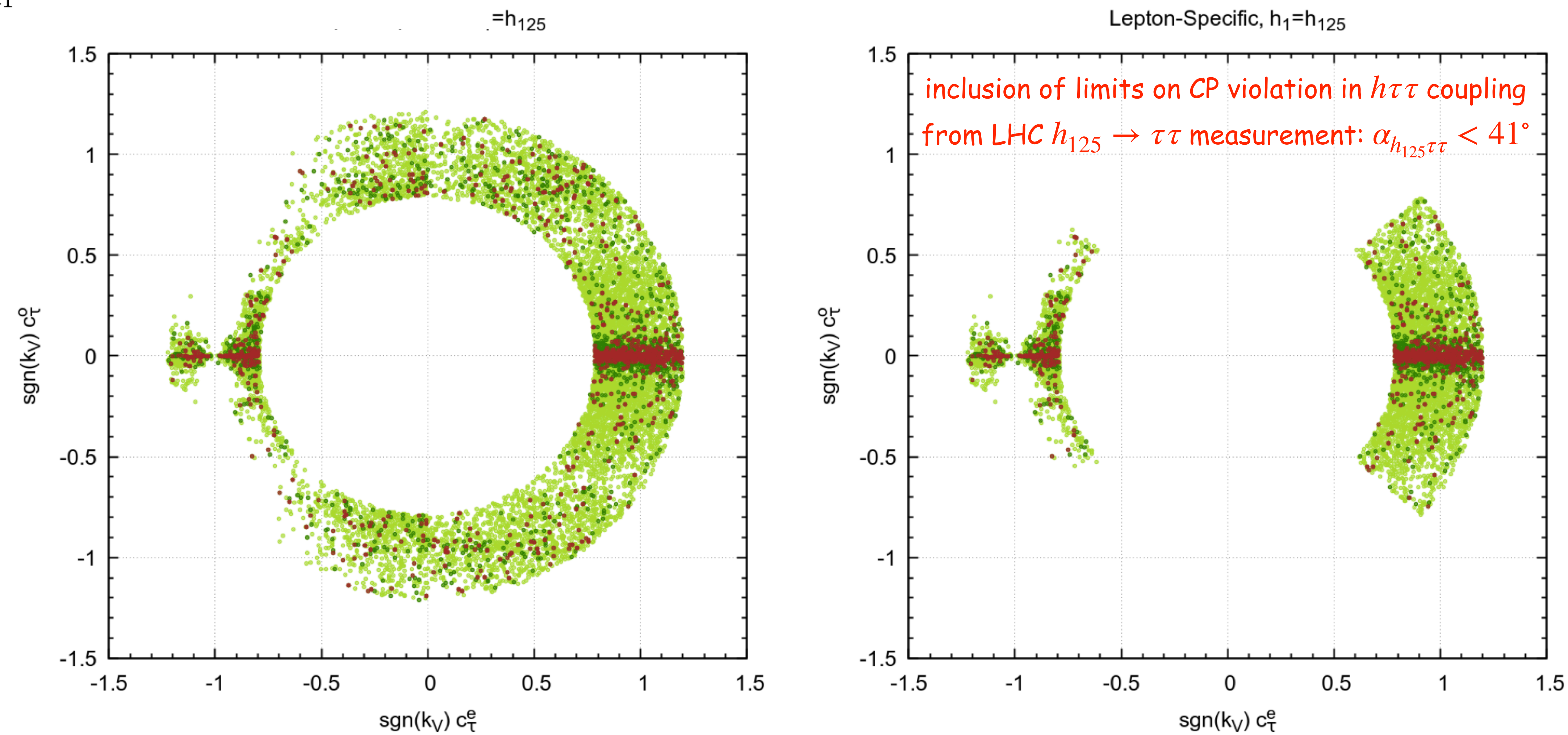
- C2HDM input parameters: $m_{H_i}, m_{H_j}, m_{H^\pm}, \text{Re}(m_{12}^2), v, \tan\beta, R_{23}, c^2_{H_iVV}, c^2_{H_itt}$, with $m_{H_i} \leq m_{H_j}$ and sign of R_{13} to lift degeneracy from squared couplings

- Allowed amount of CP violation: stringently constrained by EDM measurements

Interdependence between LHC Higgs Data and the Electron EDM

$$\mathcal{L}_Y = -\sum_{i=1}^{3} \frac{m_f}{v} \bar{f} \left[c^e(h_i f\bar{f}) + i c^o(h_i f \bar{f})\gamma_5 \right] f\, h_i$$

[Biekötter,Fontes,MM,Romão,Santos,Silva,'24]



Combined fits from LHC run2&3 on Higgs data&searches, new EDM results, data from direct CP-violation searches in angular correlations of the τ's in $h_{125} \to \tau\tau$, the bound on $m_{H^\pm}$ from $b \to s\gamma$ constrain possible amount of CP-violation: only in the LS case a sizable amount of CP-odd components, $|c^o| \approx |c^e|$, is still allowed, where CP violation occurs in the $h_{125}\tau\tau$ coupling. The amount is ultimately limited by the LHC measurements of $\alpha_{h_{125}\tau\tau}$

The dark red points obey the currently strongest limit on the eEDM 4.1 × 10–30 e.cm reported by JILA [60].

C2HDM Higgs Decay Widths

[Fontes,MM,Romão,Santos,Silva,Wittbrodt,'17]

- Fortran code C2HDM_HDECAY: partial decay widths and branching ratios in the CP-violating 2HDM including off-shell decays, loop-induced decays and state-of-the-art higher-order QCD correction

The Next-to-2HDM (N2HDM)

The Next-to-2HDM (N2HDM)

[Chen,Freid,Sher,'14] [MM,Sampaio,Santos,Wittbrodt,'16]

- The N2HDM: based on the CP-conserving 2HDM w/ a softly broken $\mathbb{Z}_2$ symmetry, extended by a real singlet field Φ_S

- Motivation:
  - enlarged Higgs sector ~> rich phenomenology
  - study effect of singlet admixture
  - rich vacuum structure (possibility of strong first order phase transition)
  - possible Dark Matter candidate

The Next-to-2HDM (N2HDM)

[Chen,Freid,Sher,'14] [MM,Sampaio,Santos,Wittbrodt,'16]

- The N2HDM: based on the CP-conserving 2HDM w/ a softly broken $\mathbb{Z}_2$ symmetry, extended by a real singlet field Φ_S
- The tree-level potential:

$$
\begin{aligned}
V \;=\; & m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + h.c.) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 \\
& +\lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{\lambda_5}{2}[(\Phi_1^\dagger\Phi_2)^2 + h.c.] \\
& +\frac{1}{2}m_S^2\Phi_S^2 + \frac{\lambda_6}{8}\Phi_S^4 + \frac{\lambda_7}{2}(\Phi_1^\dagger\Phi_1)\Phi_S^2 + \frac{\lambda_8}{2}(\Phi_2^\dagger\Phi_2)\Phi_S^2 \,.
\end{aligned}
$$

} 2HDM structure

invariant under two discrete symmetries:

$$\mathbb{Z}_2:\quad \Phi_1 \to \Phi_1\,,\quad \Phi_2 \to -\Phi_2\,,\quad \Phi_S \to \Phi_S \quad \text{(softly broken)}$$

$$\mathbb{Z}_2':\quad \Phi_1 \to \Phi_1\,,\quad \Phi_2 \to \Phi_2\,,\quad \Phi_S \to -\Phi_S$$

- After EWSB:

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1+\rho_1+i\eta_1) \end{pmatrix}\,,\quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2+\rho_2+i\eta_2) \end{pmatrix}\,,\quad \Phi_S = v_S + \rho_S$$

The Next-to-2HDM (N2HDM)

- Higgs spectrum and mixing angles: charged ($H^\pm$) and pseudoscalar (A) sector unchanged, three neutral scalar field ρ_1, ρ_2, ρ_S mix to Higgs mass eigenstates $H_i\,(i = 1,2,3)$

$$\begin{pmatrix} H_1 \\ H_2 \\ H_3 \end{pmatrix} = R \begin{pmatrix} \rho_1 \\ \rho_2 \\ \rho_S \end{pmatrix} \quad \text{with} \quad R = \begin{pmatrix} c_{\alpha_1} c_{\alpha_2} & s_{\alpha_1} c_{\alpha_2} & s_{\alpha_2} \\ -(c_{\alpha_1} s_{\alpha_2} s_{\alpha_3} + s_{\alpha_1} c_{\alpha_3}) & c_{\alpha_1} c_{\alpha_3} - s_{\alpha_1} s_{\alpha_2} s_{\alpha_3} & c_{\alpha_2} s_{\alpha_3} \\ -c_{\alpha_1} s_{\alpha_2} c_{\alpha_3} + s_{\alpha_1} s_{\alpha_3} & -(c_{\alpha_1} s_{\alpha_3} + s_{\alpha_1} s_{\alpha_2} c_{\alpha_3}) & c_{\alpha_2} c_{\alpha_3} \end{pmatrix}$$

and $m_{H_1} < m_{H_2} < m_{H_3}$ $\qquad -\frac{\pi}{2} \le \alpha_{1,2,3} < \frac{\pi}{2}$

- N2HDM input parameters: $m_{H_{1,2,3}}, m_A, m_{H^\pm}, m_{12}^2, \alpha_1, \alpha_2, \alpha_3, v, \tan\beta$

- FCNCs at tree-level: avoided by extending $\mathbb{Z}_2$ symmetry to Yukawa sector ~> 4 N2HDM types analogously to the 2HDM

[MM,Sampaio,Santos,Wittbrodt,1612.01309]

e.g. Yukawa coupling modification factors of the N2HDM H_i Higgs bosons w.r.t. the corresponding SM coupling

	u-type	d-type	leptons
type I	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i2}}{s_\beta}$
type II	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i1}}{c_\beta}$	$\frac{R_{i1}}{c_\beta}$
lepton-specific	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i1}}{c_\beta}$
flipped	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i1}}{c_\beta}$	$\frac{R_{i2}}{s_\beta}$

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- Higgs spectrum and mixing angles: charged ($H^{\pm}$) and pseudoscalar (A) sector unchanged, three neutral scalar field ρ_1, ρ_2, ρ_S mix to Higgs mass eigenstates $H_i \, (i = 1{,}2{,}3)$

$$\begin{pmatrix} H_1 \\ H_2 \\ H_3 \end{pmatrix} = R \begin{pmatrix} \rho_1 \\ \rho_2 \\ \rho_S \end{pmatrix}$$

$$s_{\alpha_1} c_{\alpha_2} \quad s_{\alpha_2}$$
$$- s_{\alpha_1} s_{\alpha_2} s_{\alpha_3} \quad c_{\alpha_2} s_{\alpha_3}$$
$$+ s_{\alpha_1} s_{\alpha_2} c_{\alpha_3}) \quad c_{\alpha_2} c_{\alpha_3}$$

3 neutral CP-mixed Higgs bosons: H_1, H_2, H_3, with $m_{H_1} \le m_{H_2} \le m_{H_3}$
1 neutral CP-odd Higgs boson A
2 charged Higgs bosons: H^+, H^-

and $m_{H_1} < m_{H_2} <$ … $\qquad -\frac{\pi}{2} \le \alpha_{1,2,3} < \frac{\pi}{2}$

- N2HDM input parameters: $m_{H_{1,2,3}}, m_A, m_{H^{\pm}}, m_{12}^2, \alpha_1, \alpha_2, \alpha_3, v, \tan\beta$

- FCNCs at tree-level: avoided by extending $\mathbb{Z}_2$ symmetry to Yukawa sector ~> 4 N2HDM types analogously to the 2HDM

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lepton-specific	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i1}}{c_\beta}$
flipped	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i1}}{c_\beta}$	$\frac{R_{i2}}{s_\beta}$

Theory Constraints

- Theoretical constraints: tree-level perturbative unitarity, boundedness from below, global minimum; for details, cf. [MM,Sampaio,Santos,Wittbrodt,1612.01309]

- More on the N2HDM potential minimum structure: [Ferreira,MM,Santos,Weiglein,Wittbrodt,1905.1023]

  - First normal stationary point $\mathcal{N}$: both doublet w/ non-zero real VEV, singlet VEV=0 => $\mathbb{Z}_2'$ preserved; singlet does not mix w/ remaining scalars ~> DM phase

$$\langle\Phi_1\rangle_{\mathcal{N}} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_1 \end{pmatrix}, \quad \langle\Phi_2\rangle_{\mathcal{N}} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_2 \end{pmatrix}, \quad \langle\Phi_S\rangle_{\mathcal{N}} = 0$$

  - Second normal stationary point $\mathcal{N}s$: both doublet and singlet w/ non-zero real VEV => $\mathbb{Z}_2'$ broken; singlet mixes w/ the remaining scalars

$$\langle\Phi_1\rangle_{\mathcal{N}s} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_1' \end{pmatrix}, \quad \langle\Phi_2\rangle_{\mathcal{N}s} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_2' \end{pmatrix}, \quad \langle\Phi_S\rangle_{\mathcal{N}s} = v_S'$$

  - *Analogously first and second charge-breaking, resp. CP-breaking stationary points*

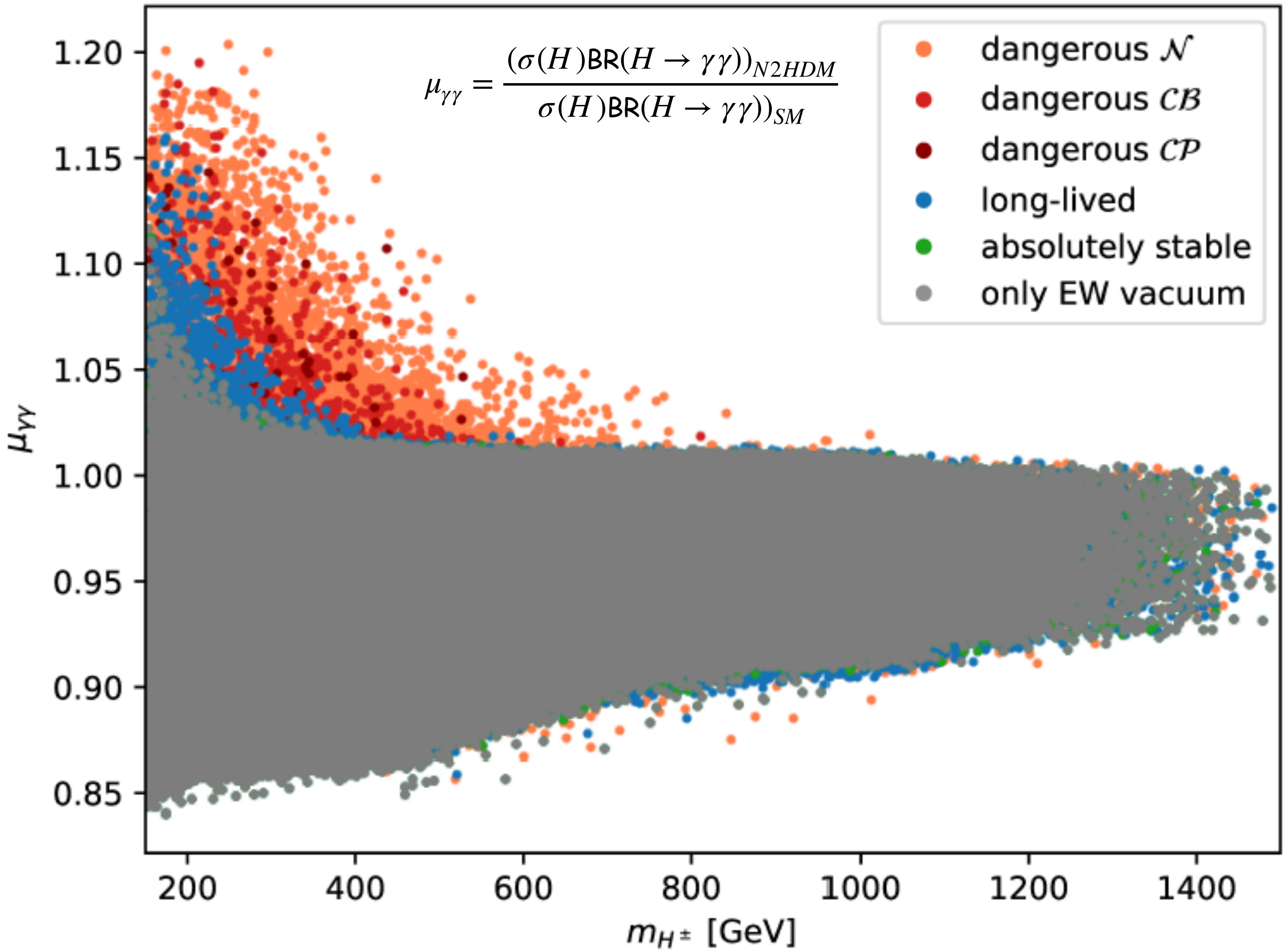
  - Stationary point S: doublets do not acquire VEV, only singlet has non-zero VEV ~> EW gauge bosons and fermions massless ~> unphysical

  - Further possibilities: existence of multiple minima of types $\mathcal{N}$, $\mathcal{N}$s or S, also panic vacuum!

Interplay Vacuum Stability and Collider Observables

Possible vacua in the Next-to-Minimal 2-Higgs-Doublet Model (N2HDM)

[Ferreira,MM,Santos,Weiglein,Wittbrodt,1905.1023]



Note: Vacuum structure will be changed through higher-order correction!

Interplay Vacuum Stability and Collider Observables

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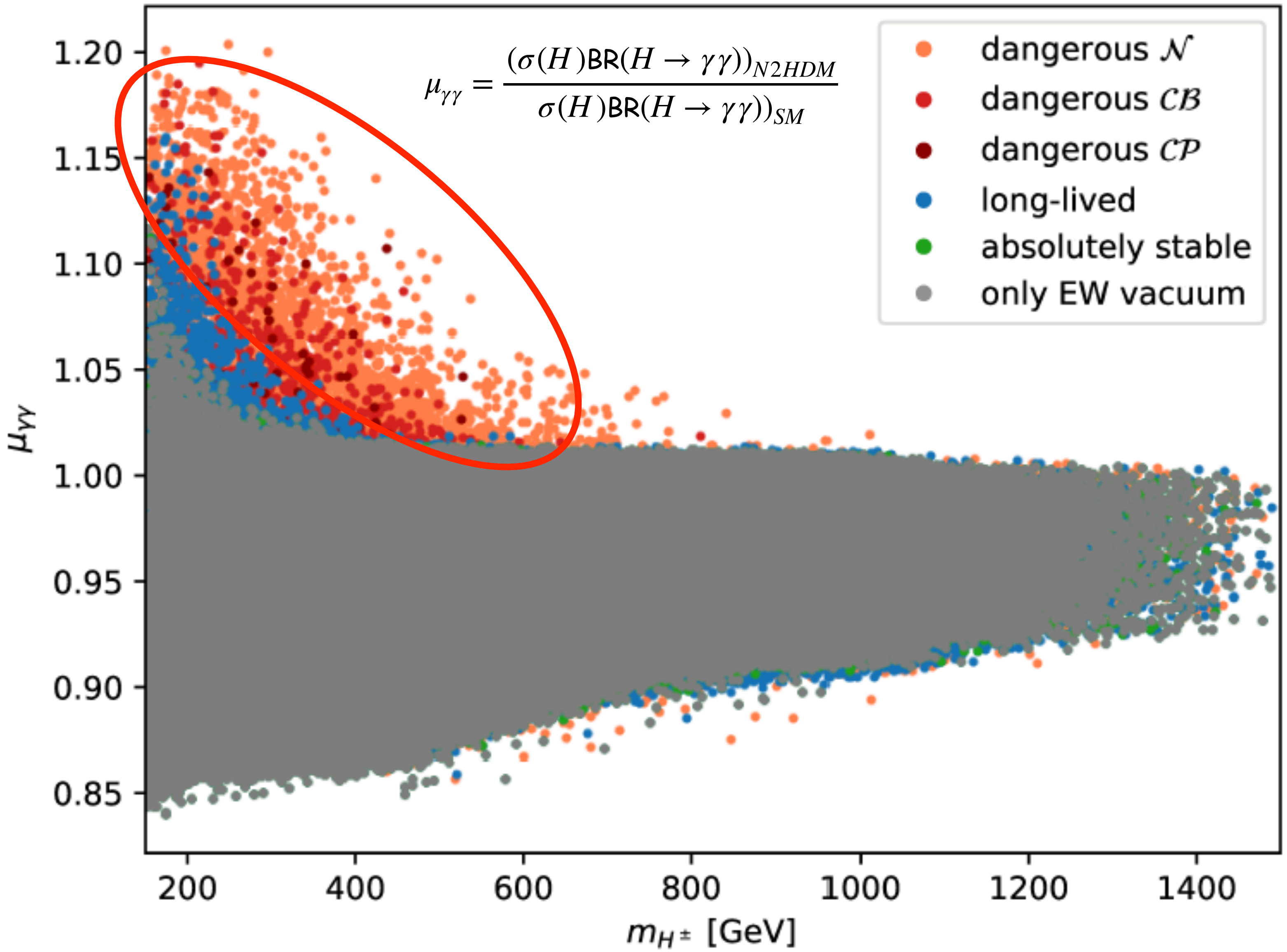


Note: Vacuum structure will be changed through higher-order correction!

The Dark Phases of the N2HDM

- Discrete symmetries: If both symmetries

$$\mathbb{Z}_2:\ \Phi_1 \to \Phi_1\ ,\quad \Phi_2 \to -\Phi_2\ ,\quad \Phi_S \to \Phi_S \qquad \mathbb{Z}_2':\ \Phi_1 \to \Phi_1\ ,\quad \Phi_2 \to \Phi_2\ ,\quad \Phi_S \to -\Phi_S$$

are exact ~> DM candidates; tree-level potential (no m_{12}^2):

$$\begin{aligned} V_{\text{Scalar}} = &\ m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 + \frac{\lambda_1}{2} \left(\Phi_1^\dagger \Phi_1\right)^2 + \frac{\lambda_2}{2} \left(\Phi_2^\dagger \Phi_2\right)^2 \\ &+ \lambda_3 \Phi_1^\dagger \Phi_1 \Phi_2^\dagger \Phi_2 + \lambda_4 \Phi_1^\dagger \Phi_2 \Phi_2^\dagger \Phi_1 + \frac{\lambda_5}{2} \left[\left(\Phi_1^\dagger \Phi_2\right)^2 + \text{h.c.}\right] \\ &+ \frac{1}{2} m_s^2 \Phi_S^2 + \frac{\lambda_6}{8} \Phi_S^4 + \frac{\lambda_7}{2} \Phi_1^\dagger \Phi_1 \Phi_S^2 + \frac{\lambda_8}{2} \Phi_2^\dagger \Phi_2 \Phi_S^2\,, \end{aligned}$$

Broken Phase (BP): doublets+singlet non-zero VeVs; $\mathbb{Z}_2$,$\mathbb{Z}_2'$ spont. broken ~> no DM candidates

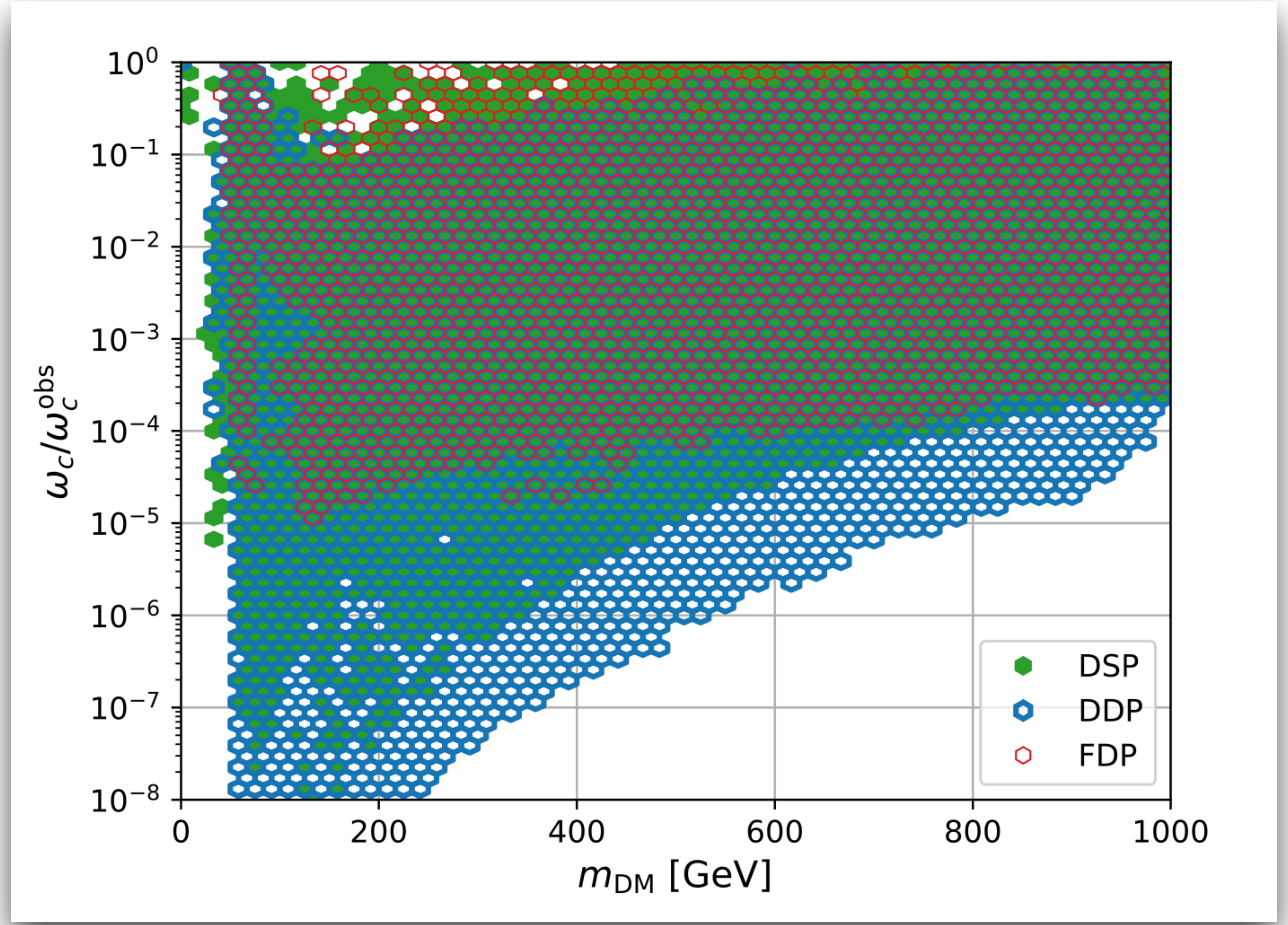
Dark Doublet Phase (DDP): one doublet+singlet non-zero VeVs; $\mathbb{Z}_2$ exact,$\mathbb{Z}_2'$ spont. broken ~> 4 dark sector particles ($A_D, H_D, H_D^\pm$), 2 visible particles (H_1, H_2)

Dark Singlet Phase (DSP): both doublets non-zero VeVs, singlet zero VEWV; $\mathbb{Z}_2'$ unbroken ~> 1 DM sector particle (H_D), 5 visible particles ($H_1, H_2, A, H^\pm$)

Fully Dark Phase (FDP): only one doublet non-zero VeV; $\mathbb{Z}_2$ and $\mathbb{Z}_2'$ exact ~> visible SM Higgs (H_{SM}), dark particles ($H_D^D, H_D^S, A_D, H_D^\pm$)

Impact on DM Observables - Relic Density

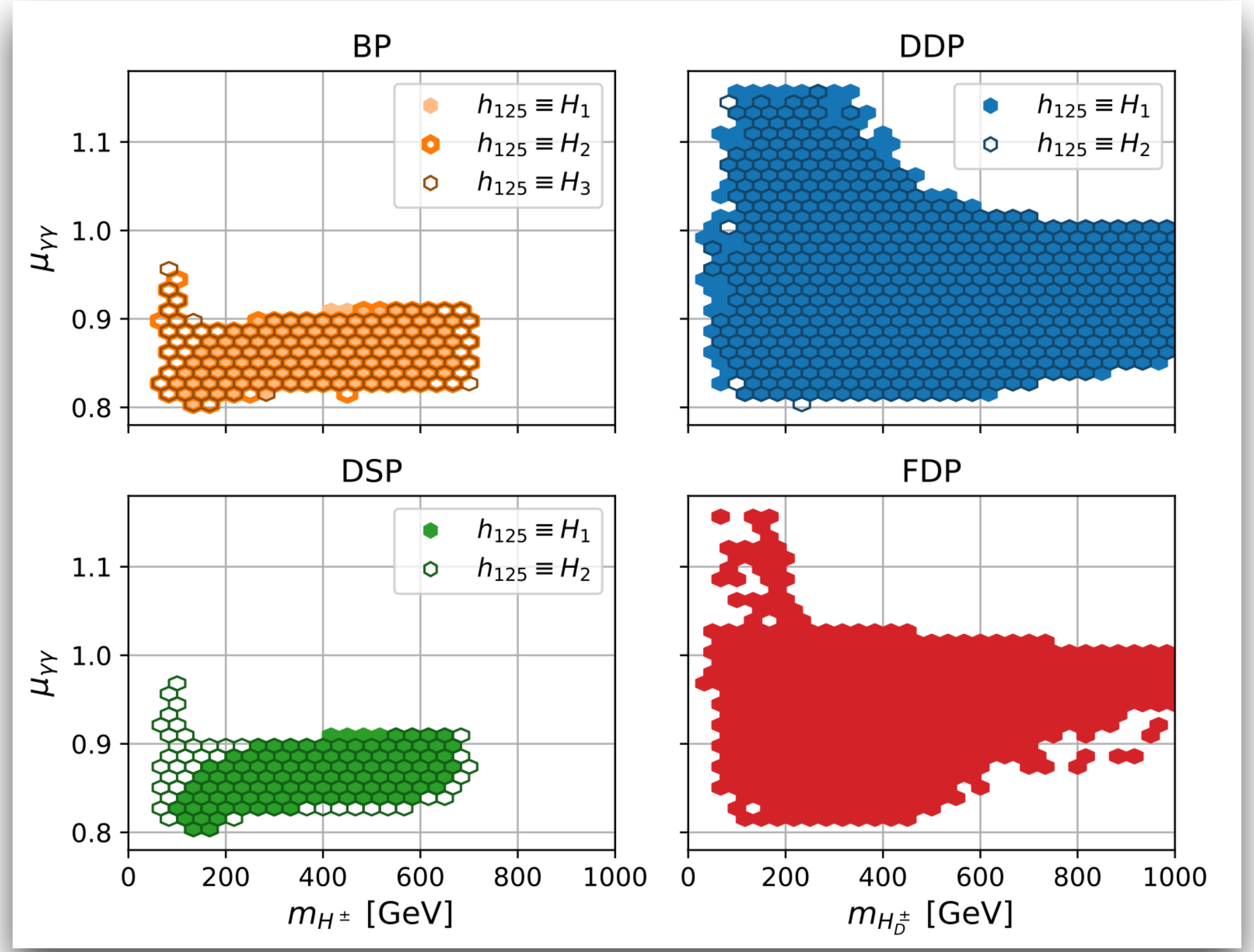
[Engeln,Ferreira,MM,Santos,Wittbrodt,2004.05382]



Interplay with Collider Observables

$$\mu_{\gamma\gamma} = \frac{(\sigma(H)\text{BR}(H \to \gamma\gamma))_{N2HDM}}{\sigma(H)\text{BR}(H \to \gamma\gamma))_{SM}}$$

[Engeln,Ferreira,MM,Santos,Wittbrodt,2004.05382]



Visible $H^\pm$ always suppress $\mu_{\gamma\gamma}$ compared to the SM; $H_D^\pm$ have more freedom in their couplings ~> enhance or suppress rate

=> $\mu_{\gamma\gamma}$ measurement could exclude BP, DSP

Program Codes for the N2HDM Decays

- Computation of the mu values: requires computation of the production cross sections (obtained from SM/MSSM results by multiplying w/ the appropriate coupling modification factors) and the decay widths:

[Engeln,MM,Wittbrodt,'18]

- Fortran code N2HDECAY: computation of the N2HDM branching ratios and decay widths including state-of-the-art QCD corrections and off-shell decays; also for the dark phases of the N2HDM

[Krause,MM,'19]

- Fortran code ewN2HDECAY: computation of the one-loop EW corrections to the N2HDM on-shell Higgs decays including the state-of-the-art HO QCD corrections (not for the dark phases)

Program Codes for the N2HDM Decays

[Krause,MM,'19]

- Fortran code ewN2HDECAY: computation of the one-loop EW corrections to the N2HDM on-shell Higgs decays including the state-of-the-art HO QCD corrections (not for the dark phases)

[Krause,MM,1912.03948]

Type	$\Delta\mathrm{BR}^{S_1}_{H_2 b\bar{b}}$
I	$\lesssim 7.5\,\%$ (48 %)
	$\lesssim 30.0\,\%$ (87 %)
II	$\lesssim 7.5\,\%$ (46 %)
	$\lesssim 25.0\,\%$ (90 %)
LS	$\lesssim 5.0\,\%$ (45 %)
	$\lesssim 22.5\,\%$ (90 %)
FL	$\lesssim 7.5\,\%$ (50 %)
	$\lesssim 30.0\,\%$ (90 %)

Type	$\Delta\mathrm{BR}^{S_1}_{H_2 \tau^+\tau^-}$
I	$\lesssim 10.0\,\%$ (51 %)
	$\lesssim 35.0\,\%$ (87 %)
II	$\lesssim 7.5\,\%$ (50 %)
	$\lesssim 25.0\,\%$ (90 %)
LS	$\lesssim 10.0\,\%$ (62 %)
	$\lesssim 22.5\,\%$ (90 %)
FL	$\lesssim 10.0\,\%$ (58 %)
	$\lesssim 30.0\,\%$ (86 %)

Type	$\Delta\mathrm{BR}^{S_1}_{H_2 W^\pm H^\mp}$
I	$\lesssim 12.5\,\%$ (41 %)
	$\gtrsim 100.0\,\%$ (33 %)
II	$\lesssim 7.5\,\%$ (59 %)
	$\gtrsim 100.0\,\%$ (19 %)
LS	$\lesssim 5.0\,\%$ (51 %)
	$\lesssim 20.0\,\%$ (83 %)
FL	$\lesssim 15.0\,\%$ (21 %)
	$\gtrsim 100.0\,\%$ (55 %)

Type	$\Delta\mathrm{BR}^{S_1}_{H_2 H_1 H_1}$
I	$\lesssim 50.0\,\%$ (50 %)
	$\gtrsim 100.0\,\%$ (37 %)
II	$\lesssim 40.0\,\%$ (50 %)
	$\gtrsim 100.0\,\%$ (31 %)
LS	$\lesssim 45.0\,\%$ (50 %)
	$\gtrsim 100.0\,\%$ (32 %)
FL	$\lesssim 37.5\,\%$ (50 %)
	$\gtrsim 100.0\,\%$ (29 %)

N2HDM Higgs Portal to DM

[Azevedo,Gabriel,MM,Sakurai,Santos,2104.03184]

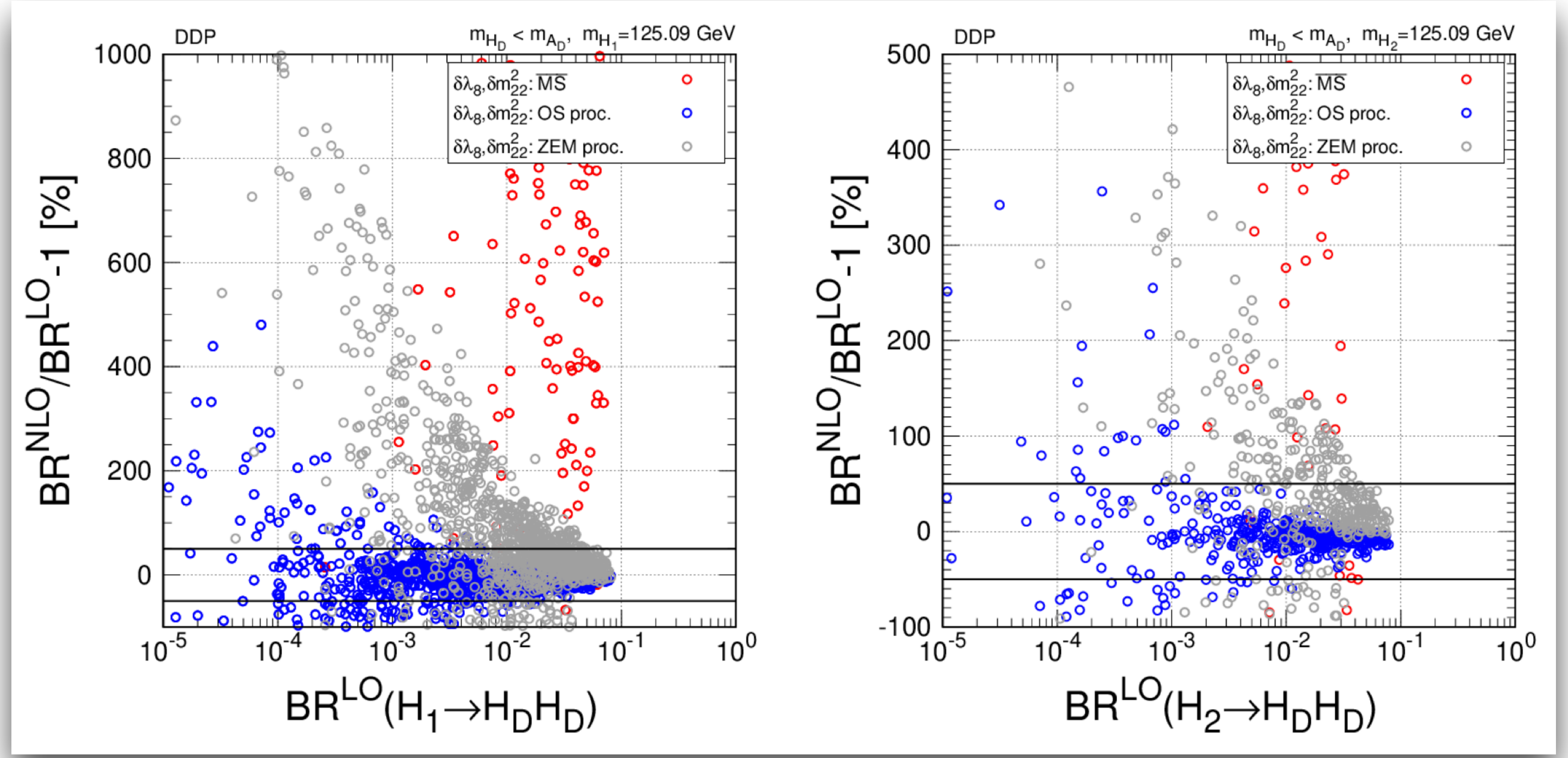
- Dark Doublet Phase of the N2HDM: one doublet (Φ_1) and singlet (Φ_S) acquire VEV ~> $\mathbb{Z}_2$ ($\mathbb{Z}_2'$) unbroken (broken) (≙ extension of the inert 2HDM) ~> spectrum; visible; H_1, H_2, dark sector: $H_D, A_D, H^\pm$: lighter of the H_D, A_D is the DM candidate

- LHC search for DM particles: Higgs decay into DM, $H_1/H_2 \to DM\,DM$

NLO EW Corrections to Higgs → DM DM

[Azevedo,Gabriel,MM,Sakurai,Santos,2104.03184]

$m_{H_1} = 125$ GeV $\qquad\qquad$ $m_{H_2} = 125$ GeV



Experimental bound on invisible branching ratio: $BR_{inv} = 0.11$
OS proc. scheme: most stable renormalization scheme; large corrections appear for very small LO BR below LHC sensitivity

NLO EW Corrections to Higgs → DM DM

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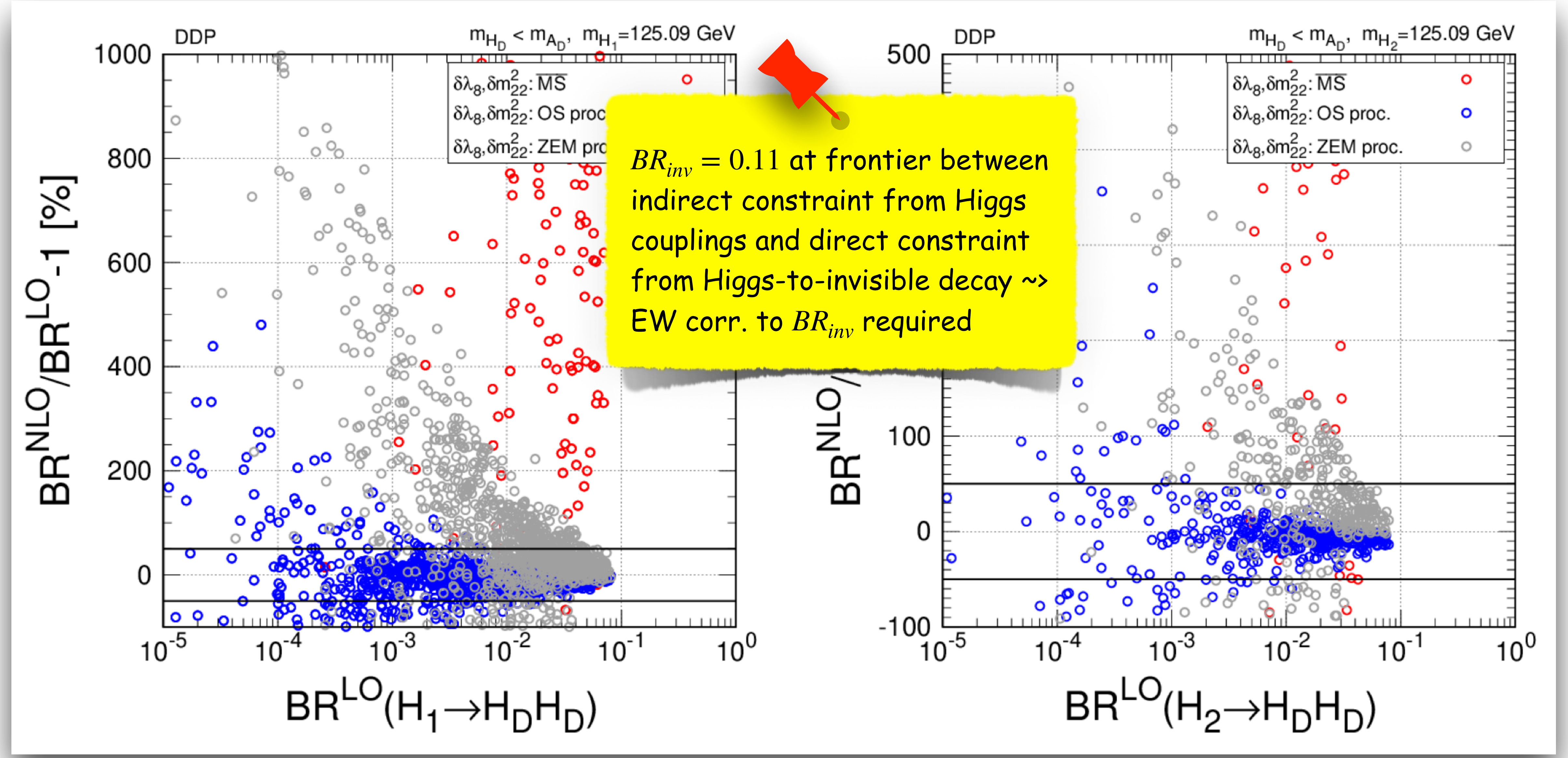


Experimental bound on invisible branching ratio: $BR_{inv} = 0.11$

OS proc. scheme: most stable renormalization scheme; large corrections appear for very small LO BR below LHC sensitivity

Supersymmetry

Supersymmetry Motivation

- Supersymmetry: relates bosons $\leftrightarrow$ fermions:

$$\left.\begin{array}{l} Q|F>=|B> \\ Q|B>=|F> \end{array}\right\} \text{1 multiplet}$$

- Motivation:

(i) maximal symmetry of the S matrix compatible with Poincaré group (space-time symmetry)

Coleman-Mandula theorem: Bosonic operators cannot extend the Poincaré algebra.

Fermionic operators: $Q \sim$ spin $\frac{1}{2} \Rightarrow$ graded Lie-algebra

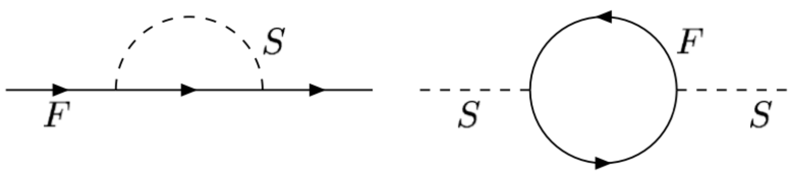
(ii) Hierarchy problem

Standard Model: ELW scale $v \sim 10^2$ GeV – GUT scale $M_{GUT} \sim 10^{16}$ GeV

Fermion masses stable against radiative corrections.

Boson masses unstable:

$$\mathcal{L}_1 = \bar{\psi}(i\partial\!\!\!/ - m_F)\psi + \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2}m_S^2 S^2 - \frac{\lambda_F}{2}\bar{\psi}\psi S$$



$$\delta m_F = -\frac{3\lambda_F^2 m_F}{64\pi^2}\log\frac{\Lambda^2}{m_F^2} + \ldots$$

$$\delta m_S^2 = -\frac{\lambda_F^2}{8\pi^2}\left[\Lambda^2 - m_F^2 \log\frac{\Lambda^2}{m_F^2}\right] + \ldots$$

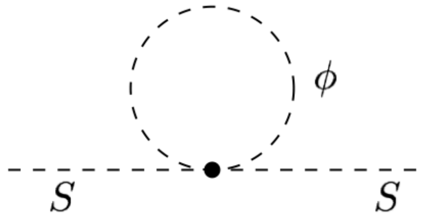
F : mild log. divergence $\sim m_F \log\Lambda \to 0$ for $m_F \to 0$ ($m_F \to 0 \to \gamma_5$-symmetry)

B : quadratic divergence $\sim \Lambda^2 \to$ cancelled only by fine-tuning of the bare mass term.
Bosonic masses cannot be kept small in a natural way within the presence of high-energy scales

SUPERSYMMETRY:
Bosonic masses can be kept small in a natural way if bosons are related to fermions.

Hierarchy Problem

$$\mathcal{L}_2 = |\partial_\mu \phi_1|^2 + |\partial_\mu \phi_2|^2 + \frac{\lambda_S}{2} S^2(|\phi_1|^2 + |\phi_2|^2) - m_\phi^2(|\phi_1|^2 + |\phi_2|^2) \quad [\psi \leftrightarrow \phi_1, \phi_2]$$



$$\delta m_S'^2 = +\frac{\lambda_S^2}{8\pi^2}\left[\Lambda^2 - m_\phi^2 \log\frac{\Lambda^2}{m_\phi^2}\right] + \ldots \qquad (\pm\text{Pauli principle})$$

$$\delta m_S^2 = -\frac{\lambda_F^2}{8\pi^2}\left[\Lambda^2 - m_F^2 \log\frac{\Lambda^2}{m_F^2}\right] + \ldots$$

SUSY: degree of freedoms : 2 fermionic $\leftrightarrow$ 2 bosonic; $\lambda_F = \lambda_S$ } $\delta m_S^2 \sim \frac{\lambda^2}{8\pi^2}(m_F^2 - m_\phi^2) \log \Lambda^2$

If SUSY is exact (unbroken), then $m_F = m_\phi$ ~> no log divergence left

Motivation

(iii) Higgs mechanism generated via radiative corrections (for $m_t \sim 100...200$ GeV) → T

(iv) Unification of elm + weak + strong couplings → T

$$\frac{1}{\alpha_i(Q^2)} = \frac{1}{\alpha_i} - \frac{b_i}{2\pi}\log Q^2 \quad \text{for} \quad i = U(1), SU(2), SU(3)$$

SM: No single crossing point: order of magnitude deficit.

SUSY: Unification of couplings $\delta\alpha/\alpha \approx 1.5\%$. Depends solely on quantum numbers, independent of mass spectrum beyond ~ 1 TeV.

(v) Cold Dark Matter (CDM): If SUSY particles assigned conserved multiplicative quantum number,

R-parity $= +1$ SM, $= -1$ SUSY, then

SUSY particles prod. pairwise in SM collisions lightest SUSY particle stable: CDM candidate

(vi) Local SUSY: enforces gravity

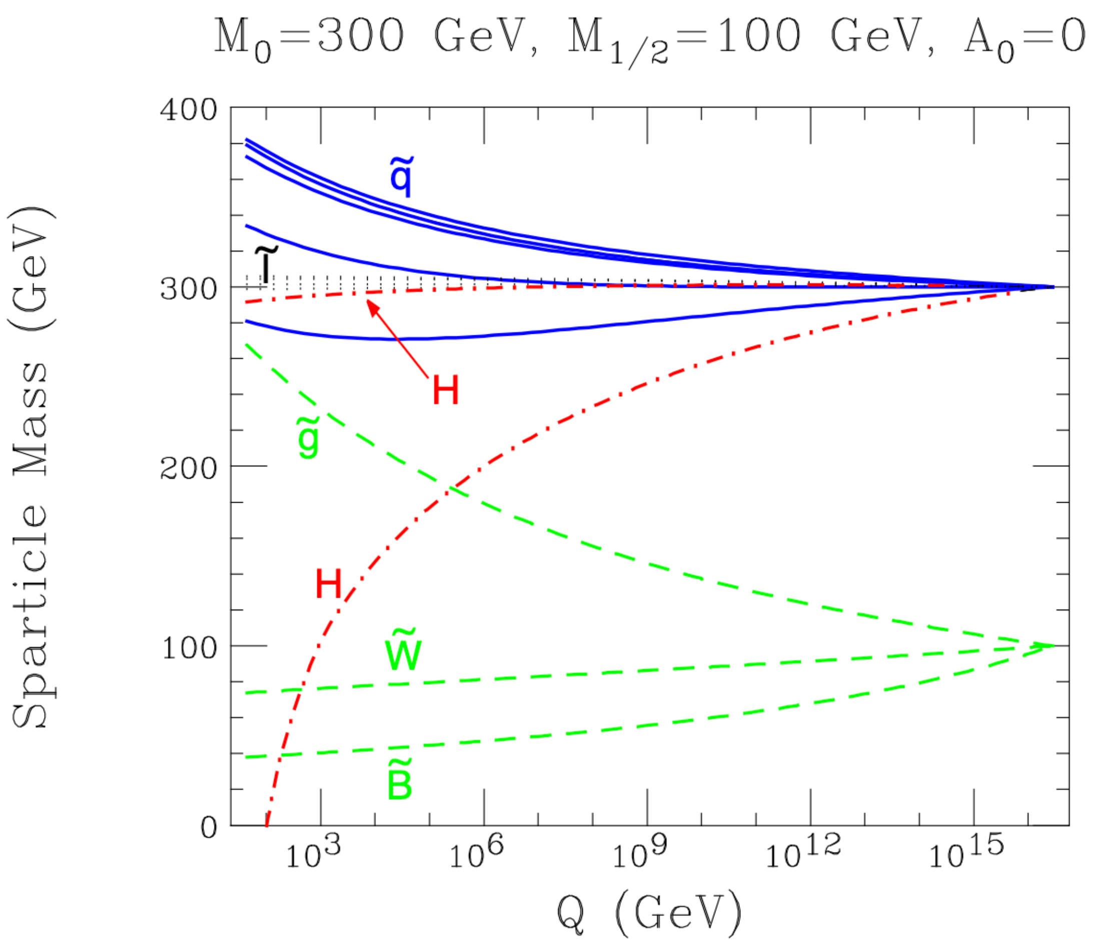
Evolution: $M_{H_2}^2(Q^2) \approx M_0^2 + \mu^2 - \frac{3g_t^2}{8\pi^2}(3M_0^2 + \mu^2)\log\frac{M_{GUT}}{Q}$

Bagger

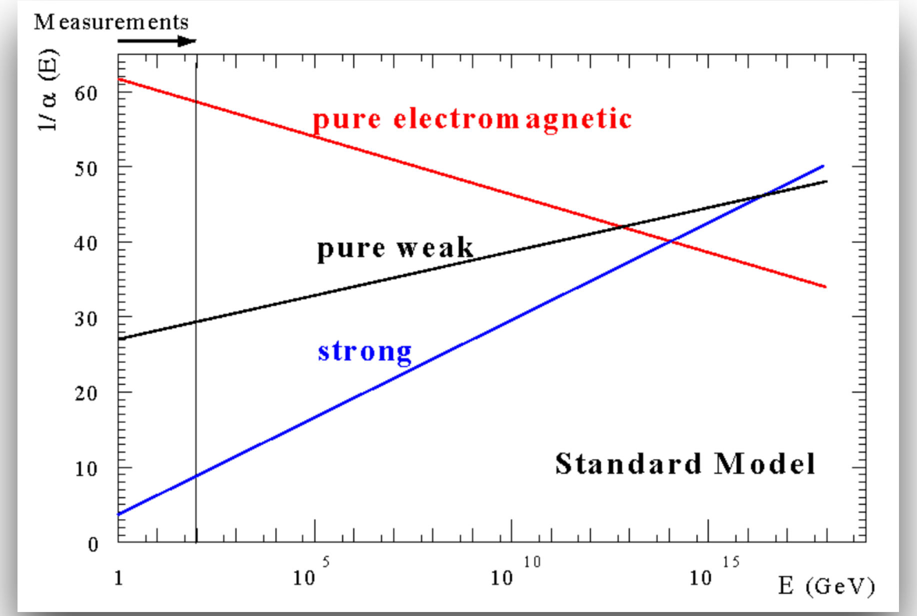
$M_{H_2}^2(M_Z^2) < 0$ possible for $m_t \sim 100 - 200$ GeV

$\rightarrow$ radiative symmetry breaking

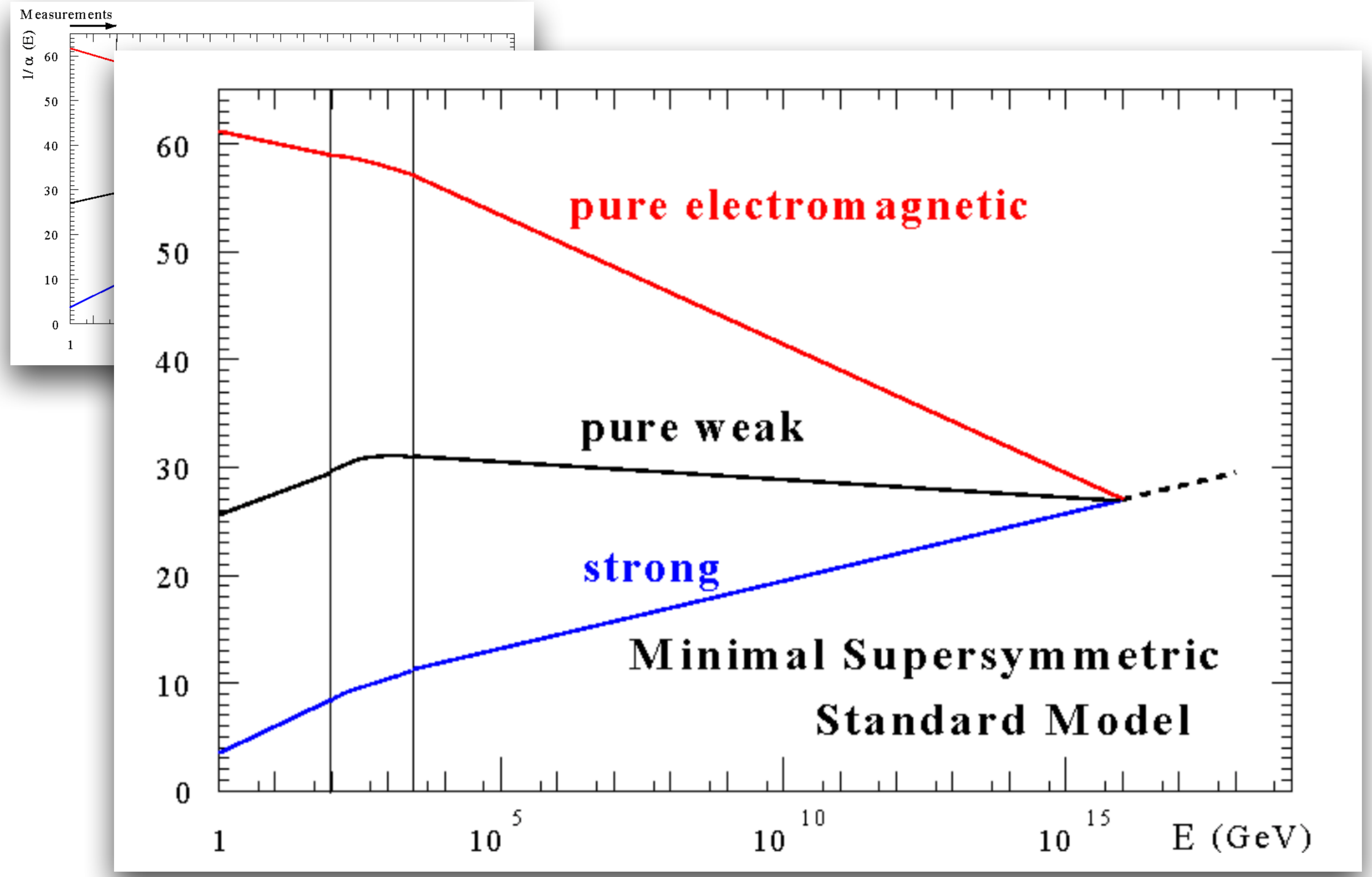
$SU_3 \times SU_2 \times U_1 \rightarrow SU_3 \times U_1^{em}$



Gauge Coupling Unification



Gauge Coupling Unification



Low-energy Supersymmetry:

1) Doubling of particle spectrum, enlarged Higgs sector
2) Equal coupling constants in the fermionic ~ bosonic couplings
3) $m_{SM} \sim \mathcal{O}(100$ GeV $\Rightarrow m_\phi \equiv \tilde{m} \leq \mathcal{O}(1$ TeV)

SM alone cannot be formulated as SUSY theory ⇒

SUSY-Standard Model $= SM \otimes SUSY(N=1)$

minimal particle content

→ Doubling of particle spectrum: SM+SUSY partner

✦ Minimal Supersymmetric Standard Model (MSSM):

Benchmark model, compatible with experiment, for exploiting phenomenology of SUSY models

✦ Interactions:

Gauge field and matter Lagrangians adapted to $SU(3) \times SU(2) \times U(1)$

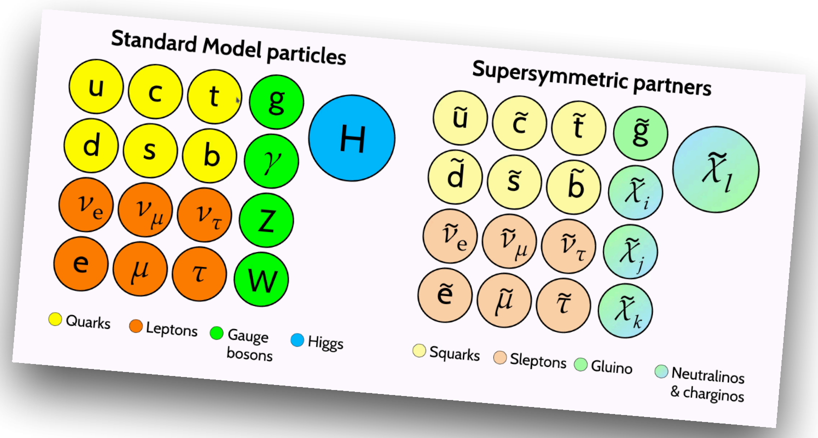
MSSM Particle Content

- Higgs sector: Give masses to up- and down-type quarks + anomaly-free theory ⇒ left-chiral superfield $\hat{H}_2$ with hypercharge $Y = +1$ and left-chiral superfield $\hat{H}_1$ with $Y = -1$

$$\hat{H}_2 = (\hat{h}_2^+, \hat{h}_2^0)^T , \quad \hat{H}_1 = (\hat{h}_1^{0*}, -\hat{h}_1^-)^T$$

- Matter- and Higgs-superfield and particle content of the MSSM:

Superfield	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	Particle content
$\hat{L} = \begin{pmatrix} \hat{\nu}_{eL} \\ \hat{e}_L \end{pmatrix}$	$\mathbf{1}$	$\mathbf{2}$	-1	$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}, \begin{pmatrix} \tilde{\nu}_L \\ \tilde{e}_L \end{pmatrix}$
$\hat{E}^c$	$\mathbf{1}$	$\mathbf{1}$	2	$\bar{e}_R, \tilde{e}_R^*$
$\hat{Q} = \begin{pmatrix} \hat{u}_L \\ \hat{d}_L \end{pmatrix}$	$\mathbf{3}$	$\mathbf{2}$	$\frac{1}{3}$	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} \tilde{u}_L \\ \tilde{d}_L \end{pmatrix}$
$\hat{U}^c$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$-\frac{4}{3}$	$\bar{u}_R, \tilde{u}_R^*$
$\hat{D}^c$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$\frac{2}{3}$	$\bar{d}_R, \tilde{d}_R^*$
$\hat{H}_2 = \begin{pmatrix} \hat{h}_2^+ \\ \hat{h}_2^0 \end{pmatrix}$	$\mathbf{1}$	$\mathbf{2}$	1	$\begin{pmatrix} H_2 \\ \tilde{h}_2 \end{pmatrix}$
$\hat{H}_1 = \begin{pmatrix} \hat{h}_1^{0*} \\ -\hat{h}_1^- \end{pmatrix}$	$\mathbf{1}$	$\mathbf{2^*}$	-1	$\begin{pmatrix} H_1 \\ \tilde{h}_1 \end{pmatrix}$



- Gauge-superfield and particle content of the MSSM:

Superfield	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	Particle content
$\hat{G}^a$	$\mathbf{8}$	$\mathbf{1}$	0	$G^\mu, \tilde{g}$
$\hat{W}^i$	$\mathbf{1}$	$\mathbf{3}$	0	$W_i^\mu, \tilde{w}_i$
$\hat{B}$	$\mathbf{1}$	$\mathbf{1}$	0	$B^\mu, \tilde{b}$

MSSM Higgs Sector

- MSSM Higgs potential: CP conservation

$$V_{Higgs} = (m_{H_1}^2 + |\mu|^2)|H_1|^2 + (m_{H_2}^2 + |\mu|^2)|H_2|^2 - B\mu\epsilon_{ij}(H_1^i H_2^j + h.c.)$$
$$+\frac{g^2+g'^2}{8}[|H_1|^2 - |H_2|^2]^2 + \frac{g^2}{2}|H_1^\dagger H_2|^2$$

2 complex Higgs doublets

$$H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} h_1^{0*} \\ -h_1^- \end{pmatrix} \quad \text{and} \quad H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} h_2^+ \\ h_2^0 \end{pmatrix}$$

g, g': SU(2) and U(1) couplings, μ higgsino parameter, $B\mu$ arises from the soft SUSY breaking Lagrangian

- EWSB: charged components do not acquire VEV ~> EM symmetry unbroken; require compatibility w/ the phenomenology of the EWSB $SU(2)_L \times U(1)_Y \to U(1)_{em}$

$$< H_1^0 > \equiv \frac{v_1}{\sqrt{2}} \quad \text{and} \quad < H_2^0 > \equiv \frac{v_2}{\sqrt{2}} \quad \text{with} \quad v_1^2 + v_2^2 = v^2 = 4\frac{m_Z^2}{g^2+g'^2} \approx 246 \text{ GeV}, \; \tan\beta = \frac{v_2}{v_1}$$

Insert expansion of Higgs doublets around EW minimum in Higgs potential, extract terms bilinear in the fields ~> mass matrices ~> diagonalization ~> Higgs mass eigenstates

MSSM Higgs Sector

- MSSM Higgs spectrum and masses: CP conservation

> 2 neutral CP-even Higgs bosons: h and H, with $m_h \leq m_H$
> 1 neutral CP-odd Higgs boson: A
> 2 charged Higgs bosons: H^+, H^-

Tree-level masses:

$$m_A^2 = B\mu(\cot\beta + \tan\beta) \; , \; m_{H^\pm}^2 = m_A^2 + m_W^2$$

$$m_{h,H}^2 = \frac{1}{2}[(m_A^2 + m_Z^2) \mp \sqrt{(m_A^2 + m_Z^2)^2 - 4m_A^2 m_Z^2 \cos^2 2\beta}]$$

~>

$$\begin{aligned} M_h &< m_Z, M_A \\ M_H &> m_Z, M_A \\ M_{H^\pm} &> M_A, m_W \end{aligned}$$

mixing angles: β diagonalizes CP-odd & charged sector, α diagonalizes neutral CP-even sector

- Remarks:

- light Higgs mass m_h given in terms of the gauge couplings ($B\mu \sim \mathcal{O}(m_Z)$) ~> no hierarchy problem (Higgs quartic couplings in potential are given in terms of the gauge couplings!)
- at tree-level: $M_h < m_Z$ ~> higher-order corrections to Higgs mass are crucial to shift Higgs mass to the measured 125 GeV
- tree-level MSSM Higgs sector can be parametrized by only 2 parameters, usually chosen to be: $m_A, \tan\beta$

MSSM Higgs Sector

• MSSM Higgs poten…

$V_{Higg…}$ … $+ h.c.)$

2 complex Higgs do…

$H_1 =$ … $\begin{pmatrix} h_2^+ \\ h_2^0 \end{pmatrix}$

g, g': SU(2) and U(1… … soft SUSY breaking Lagrangian…

A word on SUSY breaking:

We have not discovered any SUSY particles yet
~> SM and SUSY masses cannot be equal
~> SUSY is softly broken (as couplings are kept equal)

We do not know the exact SUSY breaking mechanism
~> parametrize our ignorance through soft-SUSY breaking Lagrangian

[Girardello,Grisaru]

$$\begin{array}{lll} \mathcal{L}_{soft} = & -\frac{1}{2} M_i \bar{\lambda}_i \lambda_i & \text{for the gauginos} \\ & - m_{\tilde{f}}^2 |\tilde{f}|^2 + \dots & \text{for sfermions, Higgs} \\ & - U_2(\varphi) - U_3(\varphi) + h.c. & \text{super potential} \end{array}$$

• EWSB: charged co… …en; require compatibility w/ the … $)_{em}$

$$< H_1^0 > \equiv \frac{v_1}{\sqrt{2}} \quad \text{and} \quad < H_2^0 > \equiv \frac{v_2}{\sqrt{2}} \quad \text{with} \quad v_1^2 + v_2^2 = v^2 = 4\frac{m_Z^2}{g^2 + g'^2} \approx 246\text{ GeV}, \quad \tan\beta = \frac{v_2}{v_1}$$

Insert expansion of Higgs doublets around EW minimum in Higgs potential, extract terms bilinear in the fields ~> mass matrices ~> diagonalization ~> Higgs mass eigenstates

MSSM Higgs Sector

MSSM Higgs sector – supersymmetry & anomaly free theory ⇒ 2 complex Higgs doublets

$\stackrel{\text{EWSB}}{\longrightarrow}$ neutral, CP-even h, H | neutral, CP-odd A | charged H^+, H^-

Higgs masses including HO corrections

$$M_h \lesssim 140 \text{ GeV}$$
$$M_{A,H,H^\pm} \sim \mathcal{O}(v)...1 \text{ TeV}$$

Ellis et al;Okada et al;Haber,Hempfling; Hoang et al;Carena et al;Heinemeyer et al; Zhang et al;Brignole et al;...

Decoupling limit:

$M_A \sim M_H \sim M_{H^\pm} \gtrsim v$

$M_h \to$ max. value, $\tan\beta$ fixed; h becomes SM-like

Modified couplings with respect to the SM: (decoupling limit Gunion,Haber)

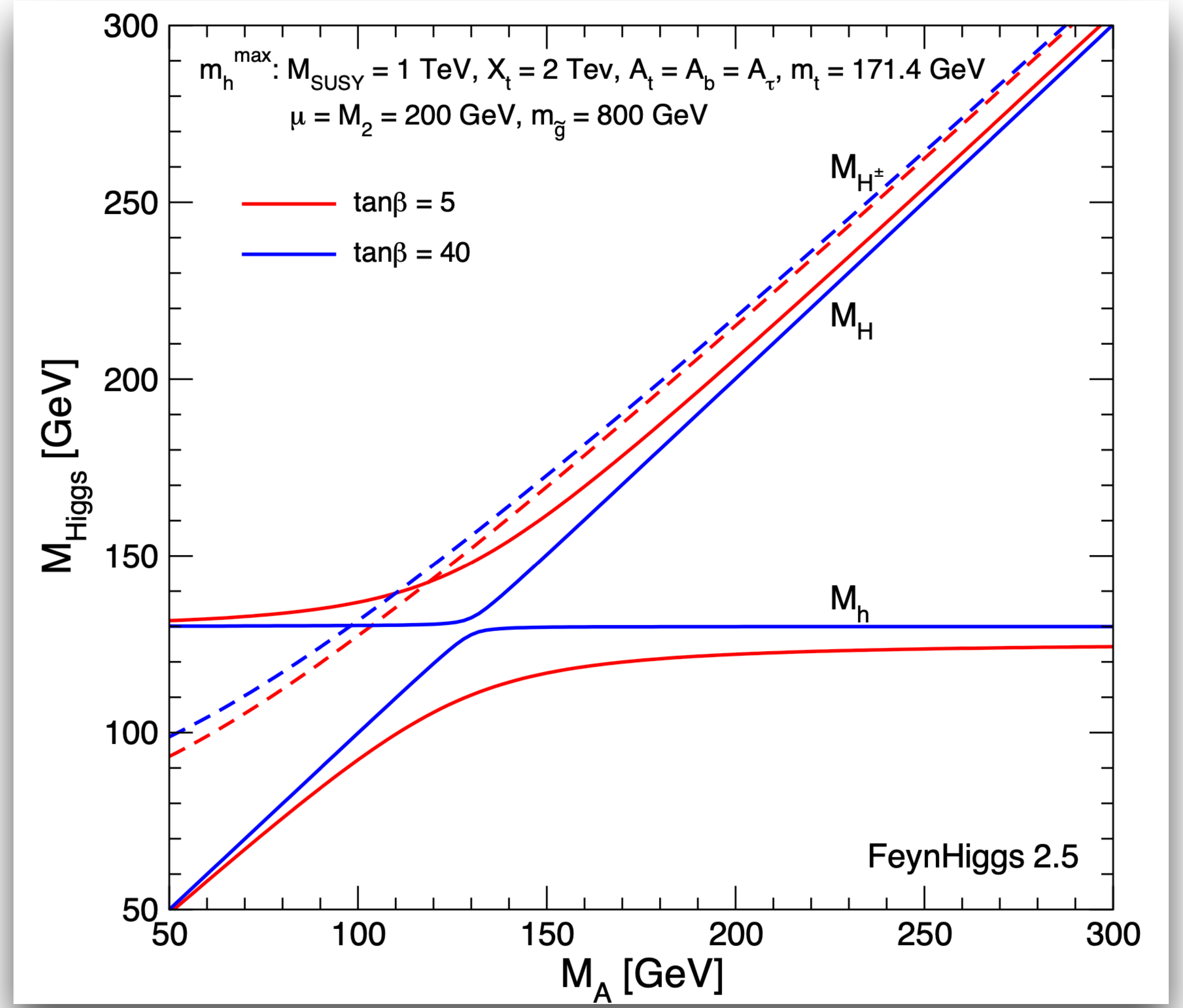
Φ	$g_{\Phi u\bar{u}}$	$g_{\phi d\bar{d}}$	$g_{\Phi VV}$
h	$c_\alpha/s_\beta \to 1$	$-s_\alpha/c_\beta \to 1$	$s_{\beta-\alpha} \to 1$
H	$s_\alpha/s_\beta \to 1/\text{tg}\beta$	$c_\alpha/c_\beta \to \text{tg}\beta$	$c_{\beta-\alpha} \to 0$
A	$1/\text{tg}\beta$	$\text{tg}\beta$	0

$\tan\beta \uparrow \Rightarrow g_{\Phi uu} \downarrow$

$g_{\Phi dd} \uparrow$

$g_{\Phi VV}^{MSSM} \lesssim g_{\Phi VV}^{SM}$

MSSM Higgs Boson Masses



Upper bound on M_h

for $M_A \gg M_Z$: decoupling limit w/ SM-like light Higgs and all other Higgs bosons heavy

Supersymmetry - The NMSSM

The Next-to Minimal Supersymmetric SM (NMSSM)

- The NMSSM: extension of MSSM Higgs sector by complex singlet field

- Motivation:
  - solution of the μ problem
  - less tension to shift the SM-like Higgs mass to 125 GeV (tree-level mass has additional contribution
  - enlarged Higgs sector ~> interesting phenomenology (e.g. Higgs-to-Higgs cascade decays (e.g. $H_i \to H_j H_j \to (H_k H_k)(H_k H_k)$, $m_{H_i} \geq 2m_{H_j} \geq 2m_{H_k}$)
  - CP-violation at tree-level possible in the Higgs sector
  - Cancellations in the various EDM contributions ~> more sizable CP violation still possible [King,MM,Nevzorov,Walz,'15]

- Review articles:
  - U. Ellwanger, A. Teixeira, Phys.Rept.496(2010)1, arXiv:0910.1785[hep-ph]
  - M. Maniatis, Int.J.Mod.Phys.A25(2010),3505, arXiv:0906.0777[hep-ph]

The NMSSM Higgs Sector

- **CP-Violating NMSSM:** scale-invariant, $\mathbb{Z}_3$-symmetric

- **Higgs Potential:** complex/CP-violating

$$\begin{aligned} V_H &= (|\lambda S|^2 + m_{H_d}^2) H_d^\dagger H_d + (|\lambda S|^2 + m_{H_u}^2) H_u^\dagger H_u + m_S^2 |S|^2 \\ &+ \frac{1}{8}(g_2^2 + g_1^2)(H_d^\dagger H_d - H_u^\dagger H_u)^2 + \frac{1}{2} g_2^2 |H_d^\dagger H_u|^2 \\ &+ | - \epsilon^{ij} \lambda H_{d,i} H_{u,j} + \kappa S^2|^2 + \left[- \epsilon^{ij} \lambda A_\lambda S H_{d,i} H_{u,j} + \frac{1}{3} \kappa A_\kappa S^3 + \text{h.c.} \right] \end{aligned}$$

- **Higgs Fields after EWSB:**

$$H_d = \begin{pmatrix} \frac{1}{\sqrt{2}}(v_d + h_d + i a_d) \\ h_d^- \end{pmatrix}, \; H_u = e^{i\varphi_u} \begin{pmatrix} h_u^+ \\ \frac{1}{\sqrt{2}}(v_u + h_u + i a_u) \end{pmatrix}, \; S = \frac{e^{i\varphi_s}}{\sqrt{2}}(v_s + h_s + i a_s)$$

- **MSSM Limit:** $\lambda, \kappa \to 0$ at $\kappa/\lambda =$ const., $A_\lambda, A_\kappa, \mu_{\text{eff}}$ fixed

- **Effective μ parameter:**

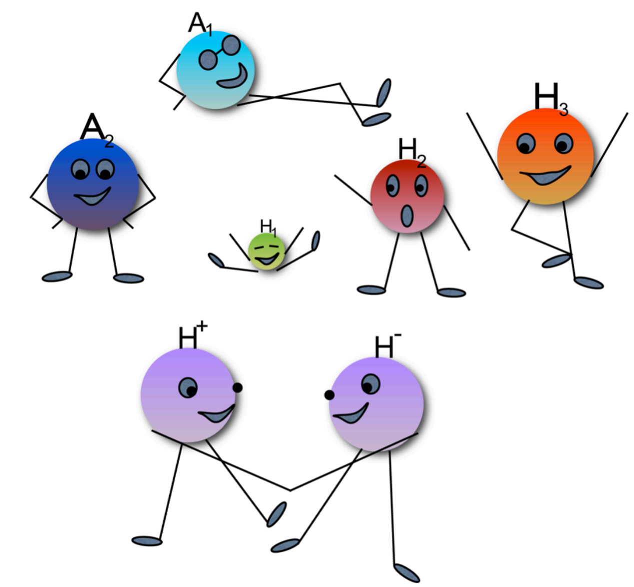
$$\mu_{\text{eff}} = \frac{\lambda v_s e^{i\varphi_s}}{\sqrt{2}}$$

The Higgs Spectrum

✦ Tree-level Higgs potential: (neglecting D-term contributions)

CP-conserving (CPC): 3 CP-even Higgs bosons H_i (i=1,2,3),
2 CP-odd Higgs boson A_j (j=1,2),
2 charged H^+,H^-

CP-violating (CPV): 5 CP-mixing Higgs bosons H_k (k=1,...,5),
2 charged Higgs bosons H^+, H^-



✦ Higgs boson mass:

* SM: fundamental parameter, not predicted by the theory

* Supersymmetry: calculable from input parameters;
quantum corrections Δm^2_H are important!

$$\text{MSSM:} \quad m_H^2 \approx M_Z^2 \cos^2 2\beta \qquad + \Delta m_H^2 \quad \leftarrow (85\text{ GeV})^2\,!$$

$$\text{NMSSM:} \quad m_H^2 \approx M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta \quad + \Delta m_H^2 \quad \leftarrow (55\text{ GeV})^2$$

✦ NMSSM: less important loop corrections needed compared to the MSSM

✦ Why precision predictions for Higgs masses?

compare calculated value w/ 125 GeV ⇒ indirect constraint of viable BSM parameter space!

Spectrum Calculations

❖ Methods for Higgs mass calculations: fixed-order (FO) - effective field theory (EFT) - hybrid

- FO → full (N)MSSM perturb. series truncated at fixed order reliable for not too heavy SUSY masses
- EFT → some very heavy SUSY masses: large logarithms require resummation
- hybrid → combines virtues of fixed order and EFT calculation

❖ Fixed-Order Calculations: exp. exclusion limits push SUSY masses to high scales

~> terms ~ $y_x \ln(M_{Sx}/M_x)$ with y_x Yukawa coupling, M_x (M_{Sx}) mass of (SUSY partner) particle

most important contribution from top/stop sector ~> large hierarchy~> large logs ~> resummation!

needed for reliable results

❖ EFT calculations: full theory matched to to effective low-energy theory at high-scale;
RGE running from high scale to EW scale resums large logs

Spectrum Calculations

❖ Methods for Higgs mass calculations: fixed-order (FO) - effective field theory (EFT) - hybrid

fixed-order (FO)	effective field theory (EFT)	hybrid
full (N)MSSM perturb. series truncated at fixed order reliable for not too heavy SUSY masses	some very heavy SUSY masses: large logarithms require resummation	combines virtues of fixed order and EFT calculation

❖ Status MSSM spectrum calculations:

FO: up to 2-loop in on-shell (OS) and DR scheme, partial 3-loop in DR scheme

EFT: up to N²LL (included in calculators), N³LL

Hybrid: FeynHiggs, FlexibleEFTHiggs, N³LO+N³LL QCD corrections

❖ Status NMSSM spectrum calculations:

FO: up to 2-loop in mixed OS-DR scheme and in DR-scheme

EFT: matching to quartic coupling in NMSSM w/ all BSM particles at TeV scale

e.g. [Gabelmann,MM,Staub,´18,´19][Bagnaschi eal,´22]

Hybrid: FlexibleEFTHiggs, SARAH+SPheno

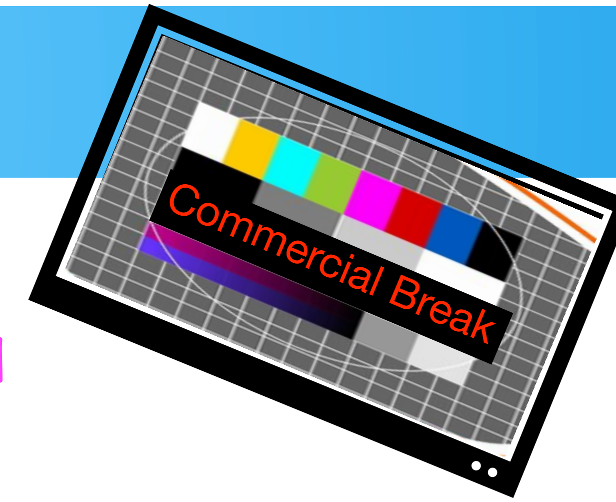
NMSSM Spectrum Calculators

- FlexibleSUSY [Athron,Bach,Harries,Kotlarski,Kwasnitza,Park,Stöckinger,Voigt,Ziebell]: DR, FO & hybrid, through FlexibleEFTHiggs
- NMSSMCALC:[Baglio,Borschensky,Dao,Gabelmann,Gröber,Krause,Le,MM,Rzehak,Spira,Streicher,Walz]: FO, real & complex NMSSM, DR and mixed OS-DR
- NMSSMTools [Ellwanger,Gunion,Hugonie]: FO, DR scheme
- SOFTSUSY [Allanach,Athron,Bednyakov,Tunstall,Voig,RuizdeAustri,Williams]: FO, DR scheme
- SPheno [Porod,Staub]: FO, DR scheme

Remarks:

- comparison of codes in DR scheme: [Staub,Athron,Ellwanger,Gröber,MM,Slavich,Voigt,'15] FlexibleSUSY,NMSSMCALC,NMSSMTools, SOFTSUSY,SPheno
- comparison of codes in mixed OS-DR scheme: [Drechsel,Gröber,Heinemeyer,MM,Rzehak,Weiglein,'16] FeynHiggs, NMSSMCALC
- solution of Goldstone boson catastrophe [Braathen,Goodsell,´16], [Braathen,Goodsell,Staub,'17]
- advances in FeynHiggs: [Drechsel,Galeta,Heinemeyer,Hollik,Liebler,Moortgat-Pick,Paßehr,Weiglein] real&complex NMSSM, GNMSSM: 1-loop in, 2-loop&resummation of HO log-effects only in MSSM limit, no public code yet
- OS masses CP-violating NMSSM, consistent description production/decay [Domingo,Drechsel,Paßehr]

The Code NMSSMCALC



Implementation of mass corrections in our code NMSSMCALC
[Baglio,Borschensky,Dao,Gabelmann,Gröber,Krause,MM,Le,Rzehak,Spira,Streicher,Walz]

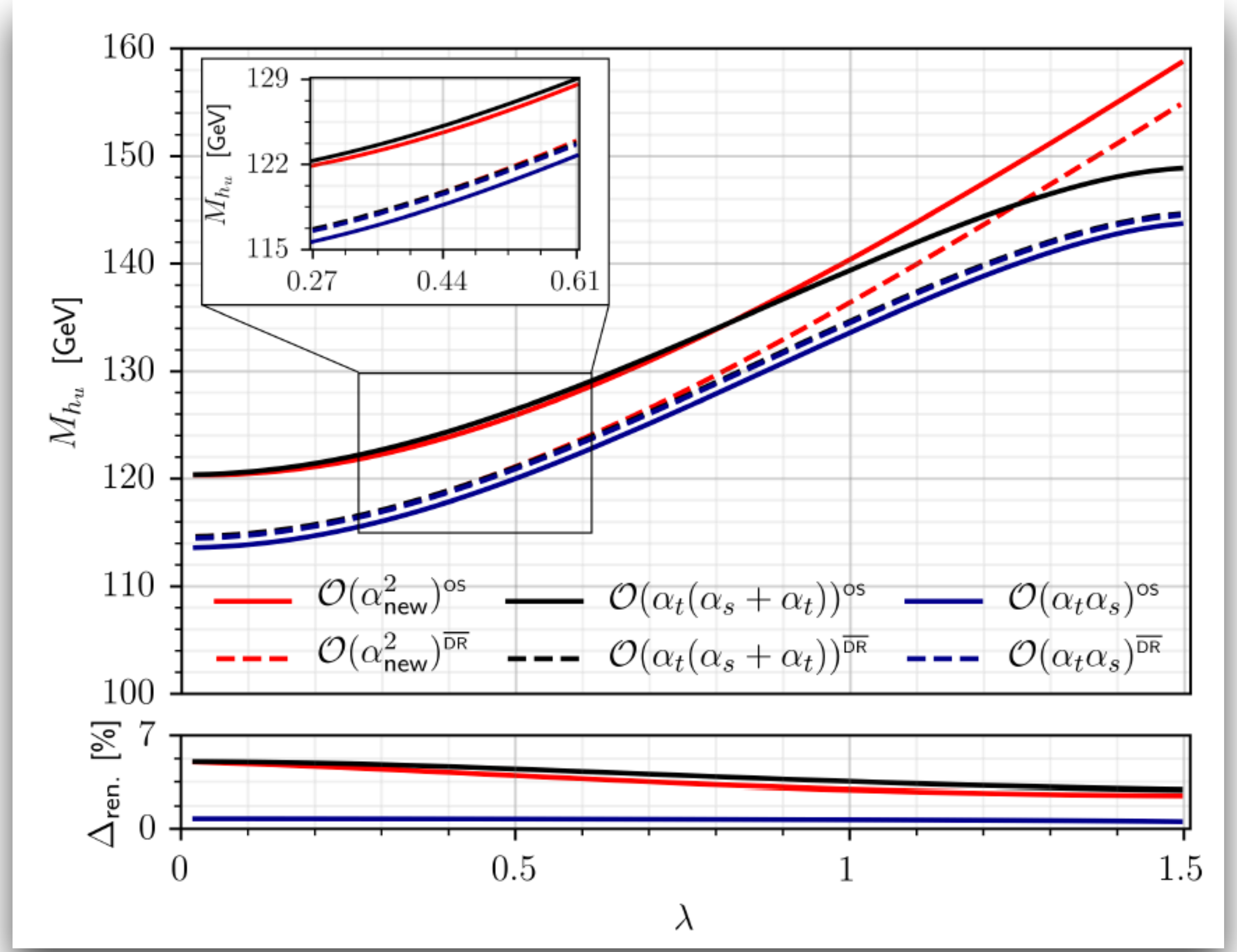
One-loop masses [Ender,Graf,MM,Rzehak,'12], [Graf,Gröber,MM.Rzehak,Walz,'12]
Two-Loop $\mathcal{O}(\alpha_t\alpha_s)$ [MM,Nhung,Rzehak,Walz,'15]
Two-Loop $\mathcal{O}(\alpha_t+\alpha_t\alpha_s)$ [Dao,Gröber,Krause,MM,Rzehak,'19]
Two-Loop $\mathcal{O}((\alpha_t+\alpha_\lambda+\alpha_\kappa)^2 + \alpha_t\alpha_s)$ [Dao,Gabelmann,MM,Rzehak,'21]

The Fortran Code NMSSMCALC:

- Calculator of one- and two-loop Higgs mass corrections and Higgs self-couplings as well as of Higgs decay widths in the CP-conserving and CP-violating NMSSM
- Computation of the muon magnetic and the electric dipole moment
- Computation of the rho parameter and the W mass prediction up to two-loop EW NMSSM

$\mathcal{O}(\alpha_{new}^2) \equiv \mathcal{O}((\alpha_\lambda+\alpha_\kappa+\alpha_t)^2+\alpha_t\alpha_s)$ Mass Corrections in the CP-Violating NMSSM

Corrections to h_u-like Higgs ($\triangleq$ SM-like Higgs) [Dao,Gabelmann,MM,Rzehak,'21]



$$\Delta_{\text{ren}} = \frac{\left|\lambda^{m_t(\overline{\text{DR}})} - \lambda^{m_t(\text{OS})}\right|}{\lambda^{m_t(\overline{\text{DR}})}}$$

: remaining theoretical error: $\mathcal{O}$(few%)

$\mathcal{O}(\alpha_{new}^2) \equiv \mathcal{O}((\alpha_\lambda+\alpha_\kappa+\alpha_t)^2+\alpha_t\alpha_s)$ Mass Corrections in the CP-Violating NMSSM

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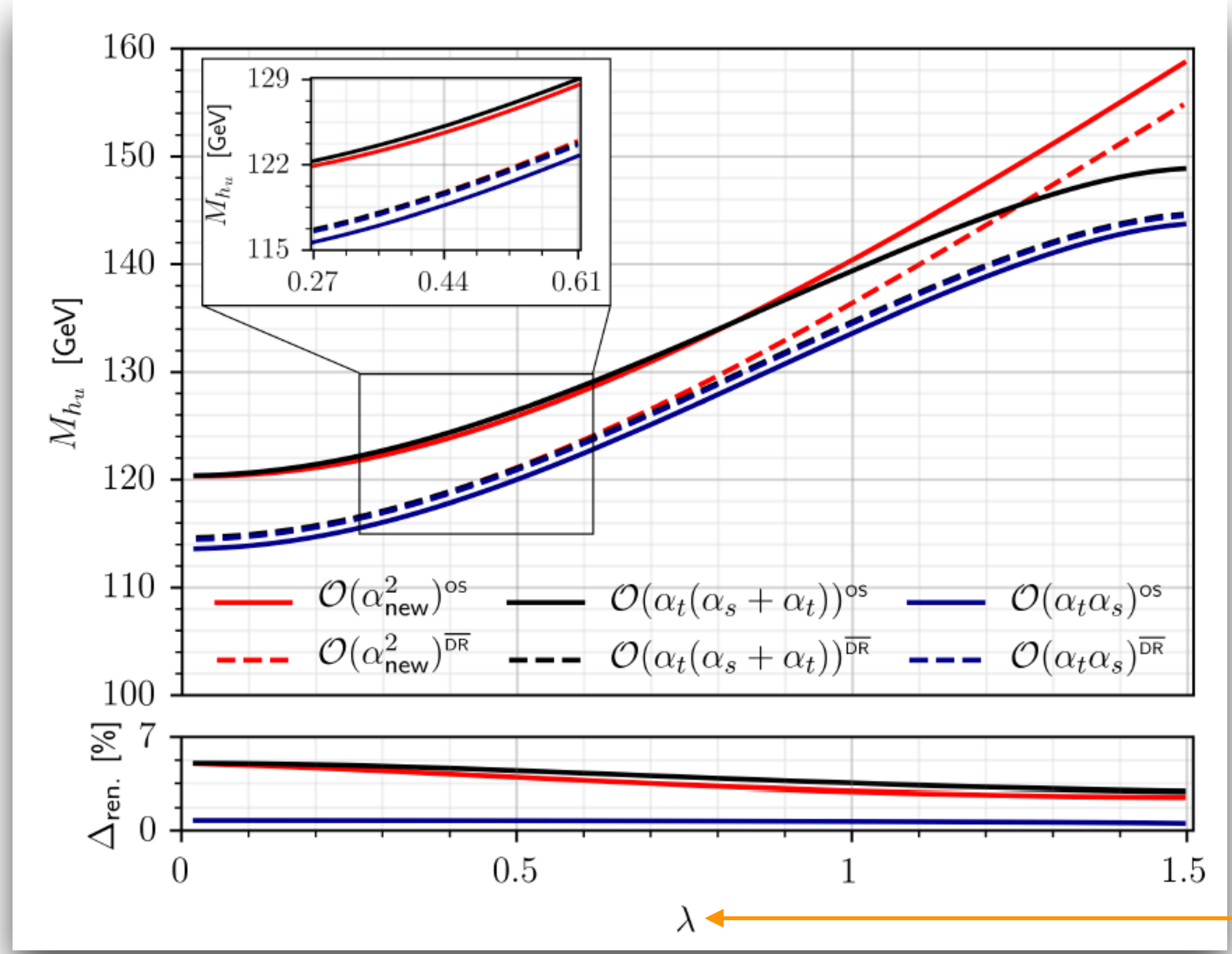


NMSSM specific couplings λ, κ related to new singlet field in superpotential

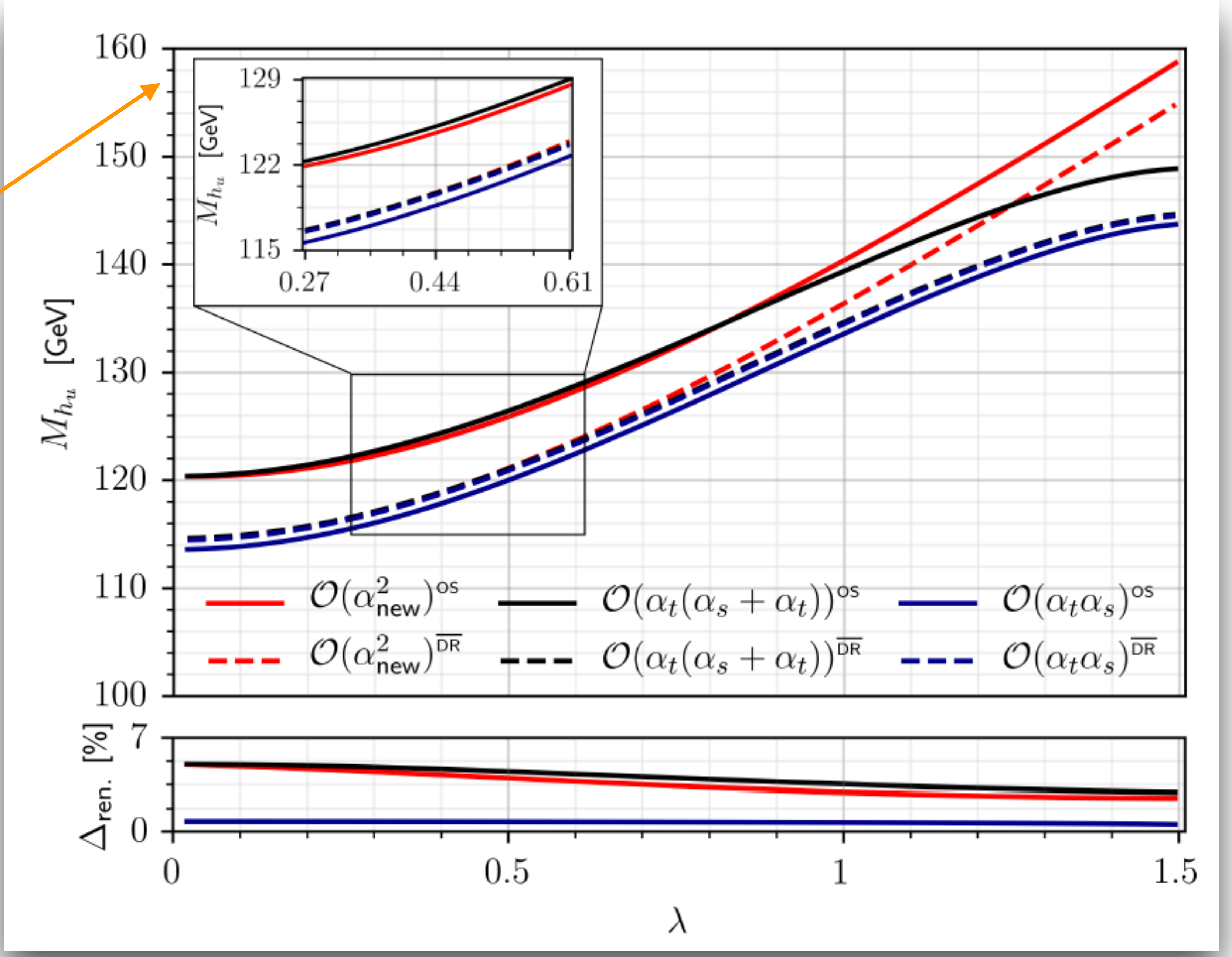
$$\Delta_{\text{ren}} = \frac{\left|\lambda^{m_t(\overline{\text{DR}})} - \lambda^{m_t(\text{OS})}\right|}{\lambda^{m_t(\overline{\text{DR}})}}$$

: remaining theoretical error: $\mathcal{O}$(few%)

Corrections to h_u-like Higgs ($\hat{=}$ SM-like Higgs)

[Dao,Gabelmann,MM,Rzehak,'21]

Zoomed: compatible w/ HiggsSignals after including the new correction



$$\Delta_{ren} = \frac{\left|\lambda^{m_t(\overline{DR})} - \lambda^{m_t(OS)}\right|}{\lambda^{m_t(\overline{DR})}}$$

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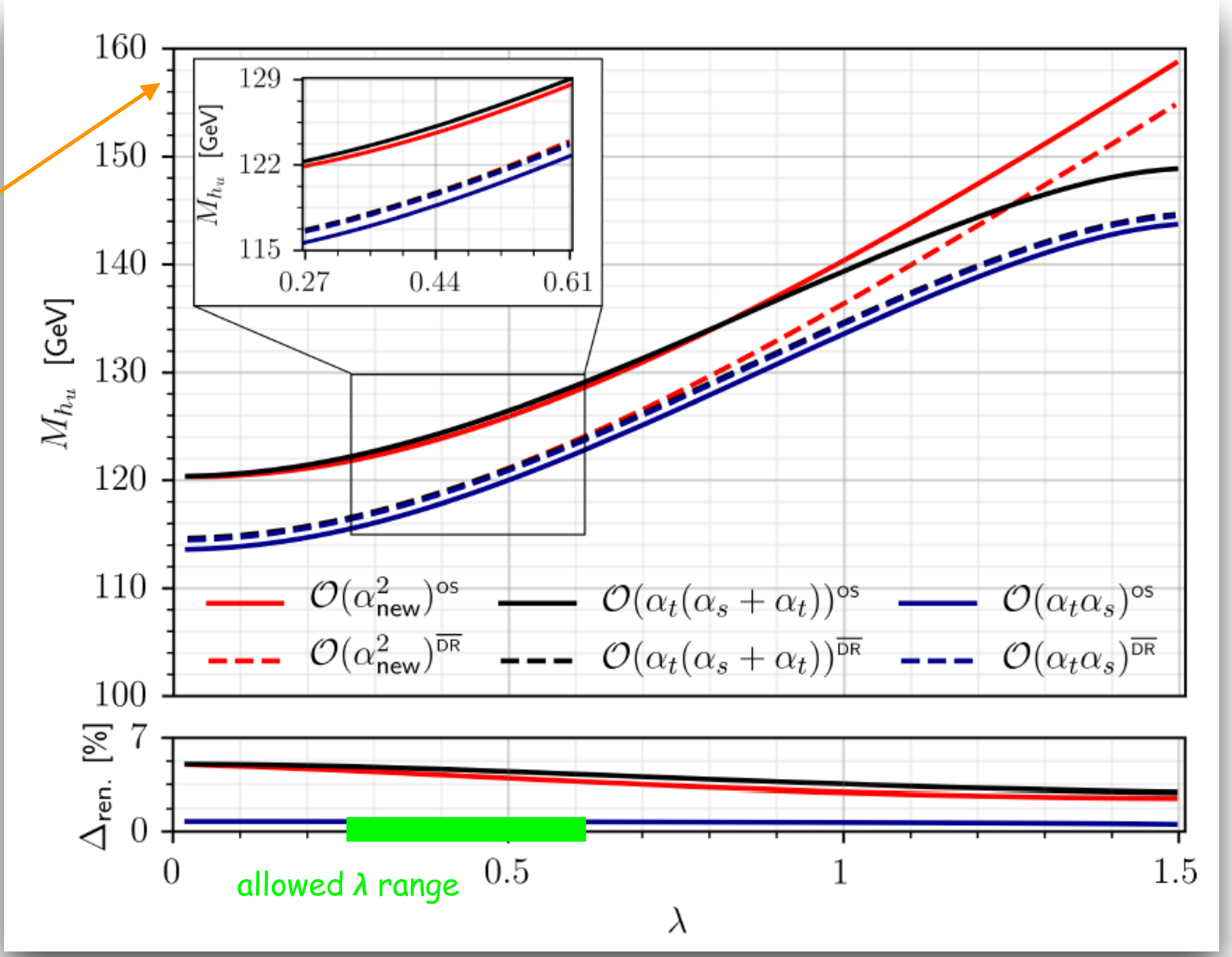

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: remaining theoretical error: $\mathcal{O}$(few%)

Spectrum Calculations - EFT Approach

❖ Methods for Higgs mass calculations: fixed-order (FO) - effective field theory (EFT) - hybrid

- full (N)MSSM perturb. series truncated at fixed order reliable for not too heavy SUSY masses
- some very heavy SUSY masses: large logarithms require resummation
- combines virtues of fixed order and EFT calculation

❖ EFT calculations, Matching:

- SUSY couplings matched to corresponding couplings in EFT theory such that physics at matching scale μ_R is the same
- In case we have only SM particles plus heavy SUSY particles:
  EFT is the SM => $\lambda_{SM}(\mu_R) = \lambda_{BSM}(\mu_R)$ [receives only BSM contributions]
- We have terms like $y_x \ln(M_{Sx}/M_x)$, respectively $y_x (\ln(M_{Sx}/\mu_R^2) + \ln(\mu_R^2/M_x^2))$, with μ_R=M_{Sx} =>
  $y_x \ln(\mu_R^2/M_x^2)$ <= resummed via RGEs for y_x

Quartic Coupling Matching

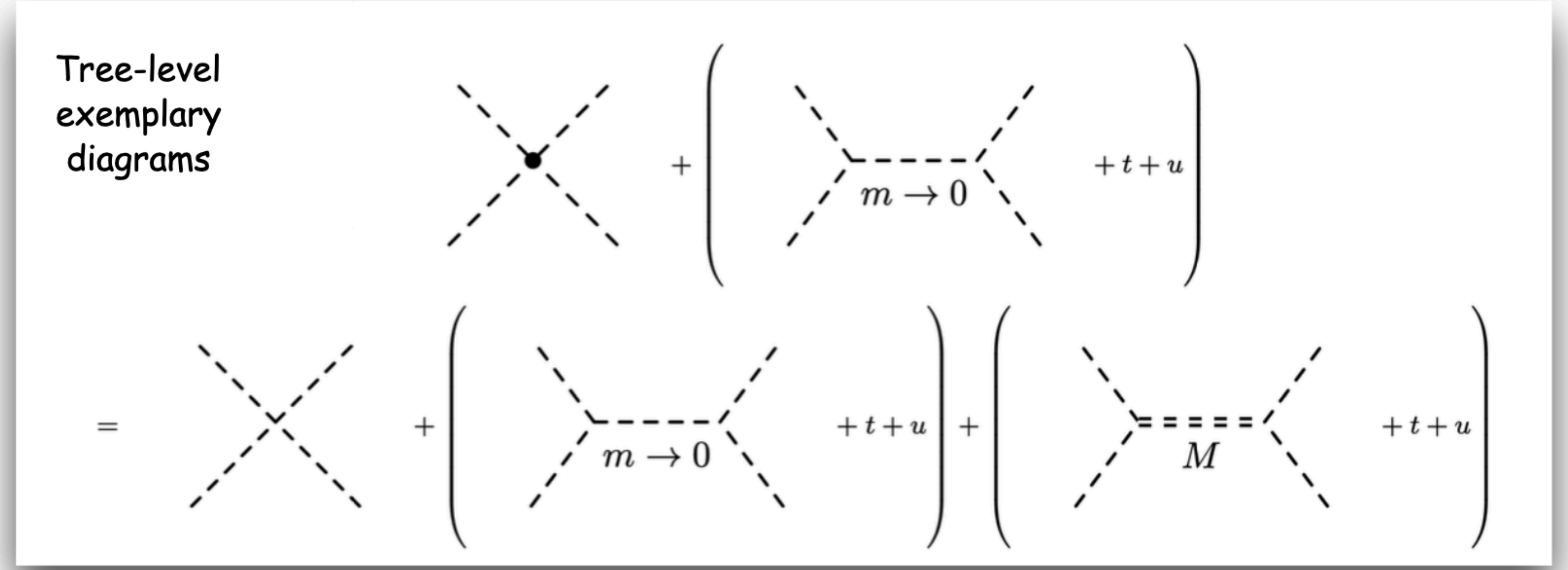
Quartic Coupling Matching (unbroken EW symmetry; $v_u,v_d \to 0$, $\tan\beta = v_u/v_d$=const., $v_S \neq 0$):

[Bagnaschi eal,´22] for real NMSSM
our work: complex NMSSM

$$\lambda_H^{\mathrm{SM},\overline{\mathrm{MS}}}(Q_{\mathrm{match}}) = \lambda_H^{\mathrm{NMSSM},\overline{\mathrm{MS}}}(Q_{\mathrm{match}})$$

effective quartic coupling after subtracting the SM contributions:

$$\lambda_{\mathrm{NMSSM}}^{\overline{\mathrm{DR}}}(Q_{\mathrm{match}}) = \lambda_{\mathrm{NMSSM}}^{\mathrm{tree}} + \Delta\lambda_{\mathrm{NMSSM}}^{1l} + \Delta\lambda_{\mathrm{MSSM}}^{2l}$$



m (M) light (heavy) mass scale

- - - - - light scalars = = = = = heavy scalars

Pole Mass Matching

Pole Mass Matching/„Hybrid" (broken EW symmetry, v≪M$_{SUSY}$): e.g. [Athron eal, ´16]

$$M^2_{h,\text{SM}} \stackrel{!}{=} M^2_{h,\text{NMSSM}}$$

$$M^2_{h,X} = m^2_{h,X} - \hat{\Sigma}_{h,X}(M^2_{h,X}) \qquad \text{with} \qquad X = \text{SM}, \text{NMSSM}$$

$m_{h,\text{SM}}$ and $m_{h,\text{NMSSM}}$ denote the running $\overline{\text{MS}}$ and $\overline{\text{DR}}$ masses of the SM(-like) Higgs states

Tree Level: $m^2_{h,\text{SM}} = 2\lambda^{\text{eff.}}_{\text{SM}} v^2_{\text{SM}} \stackrel{!}{=} m^2_{h,\text{NMSSM}}$ $\rightsquigarrow$ $\lambda^{\text{eff.}}_{\text{SM}} = \dfrac{m^2_{h,\text{NMSSM}}}{2v^2_{\text{NMSSM}}}$

One-Loop Level: $\lambda^{\text{eff.}}_{\text{SM}} = \dfrac{1}{2v^2_{\text{SM}}}\left[m^2_{h,\text{NMSSM}} - \hat{\Sigma}_{h,\text{NMSSM}}(m^2_{h,\text{NMSSM}}) + \hat{\Sigma}_{h,\text{SM}}(m^2_{h,\text{SM}})\right]$

Leading terms in expansion in v/M$_{SUSY}$

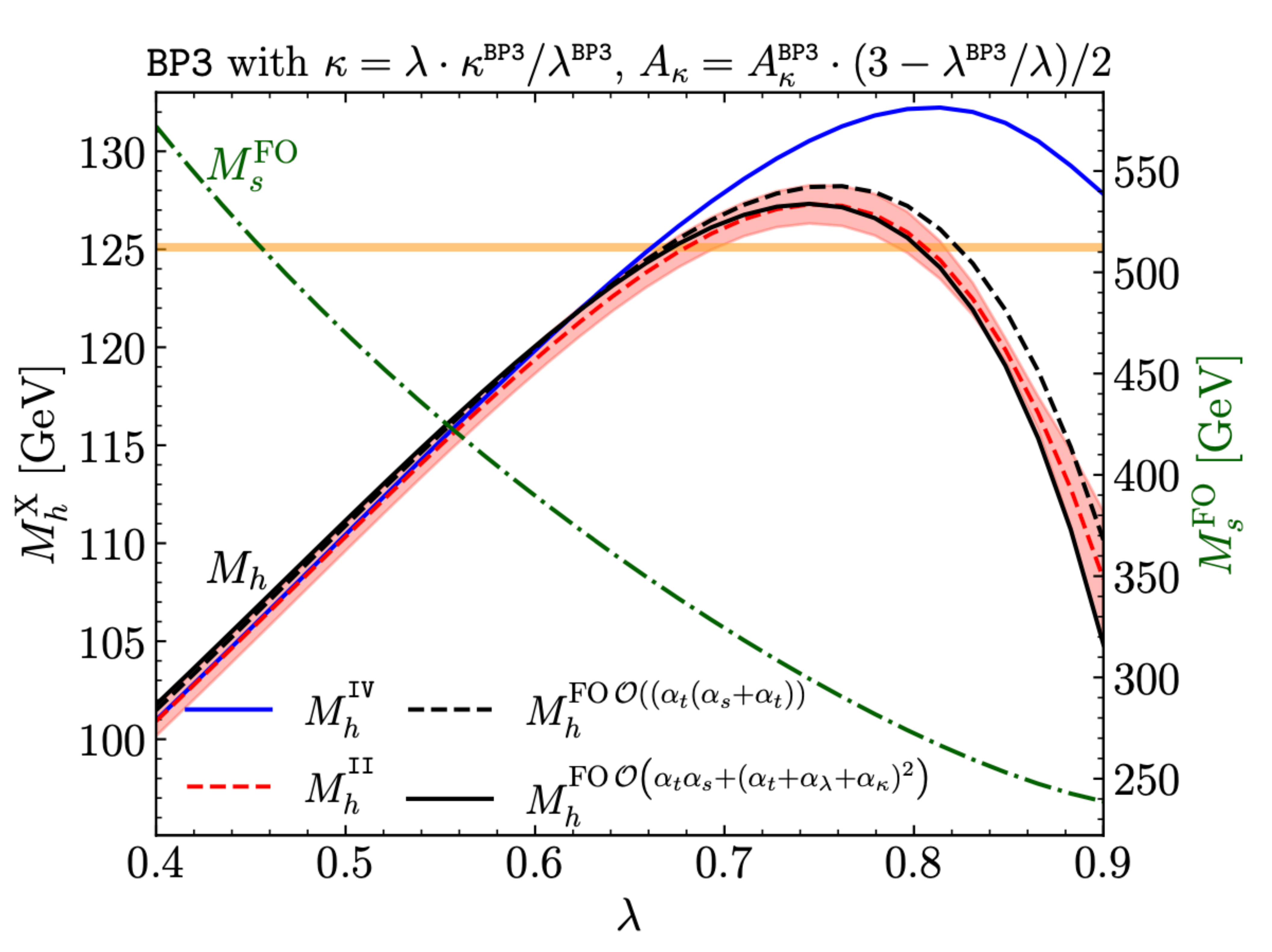
$$\lambda^{\text{eff.}}_{\text{SM}} = \frac{1}{2v^2_{\text{NMSSM}}}\left[m^2_{h,\text{NMSSM}} - \Delta\hat{\Sigma}_h - 2m^2_{h,\text{NMSSM}}\Delta\hat{\Sigma}'_h\right]$$

with $\Delta\hat{\Sigma}^{(\prime)}_h \equiv \hat{\Sigma}^{(\prime)}_{h,\text{NMSSM}}(0) - \hat{\Sigma}^{(\prime)}_{h,\text{SM}}(0)$

$\hat{\Sigma}_h$ renormalized self-energy

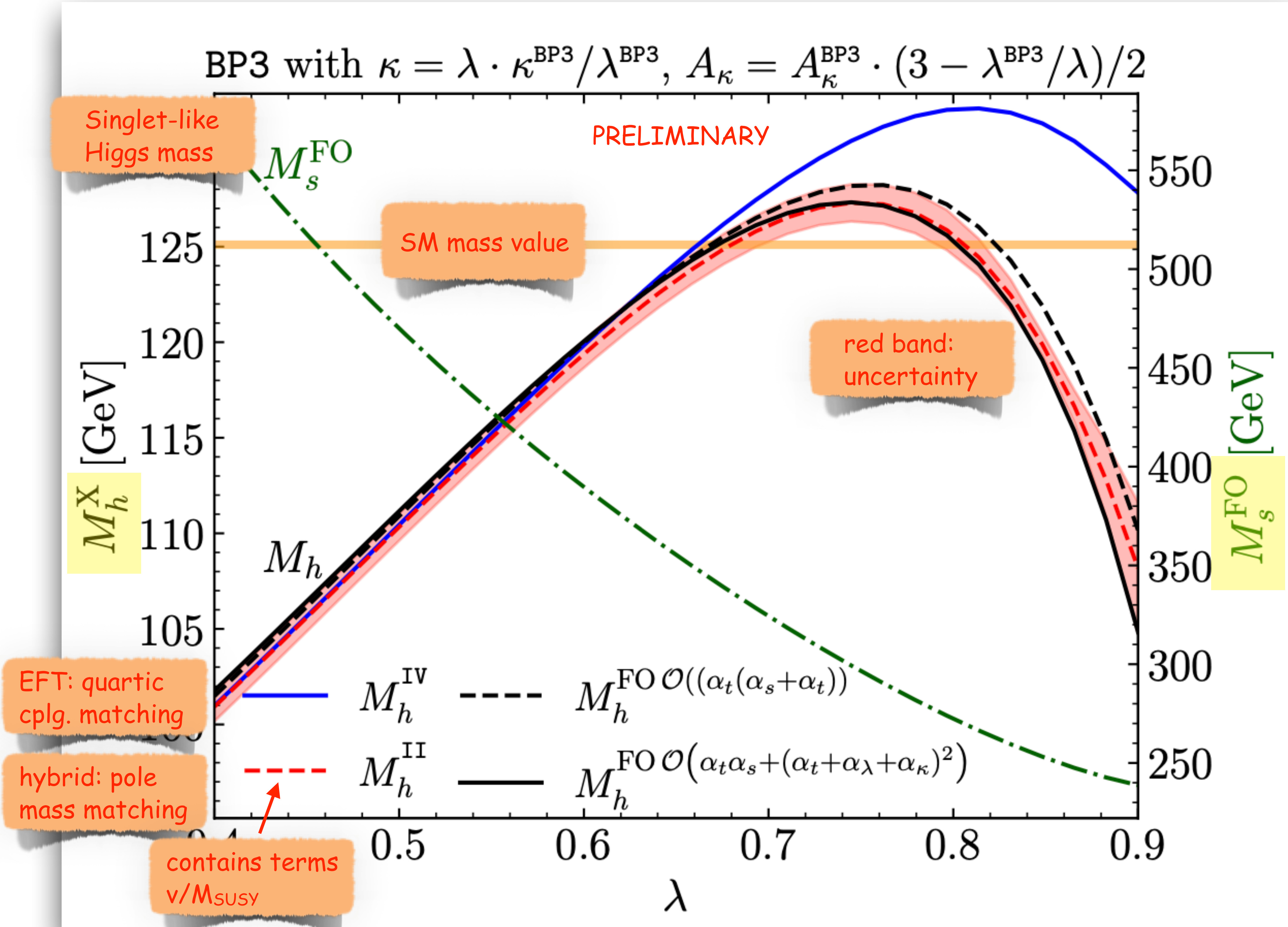
Results

[Borschensky,Dao,Gabelmann,MM,Rzehak]



Results

[Borschensky,Dao,Gabelmann,MM,Rzehak]



Trilinear Higgs Self-Coupling

- SM Higgs potential in physical gauge:

$$V(H) = \frac{1}{2} M_H^2 H^2 + \frac{M_H^2}{2v} H^3 + \frac{M_H^2}{8v^2} H^4$$

Higgs mass : $M_H = \sqrt{2\lambda}\, v$

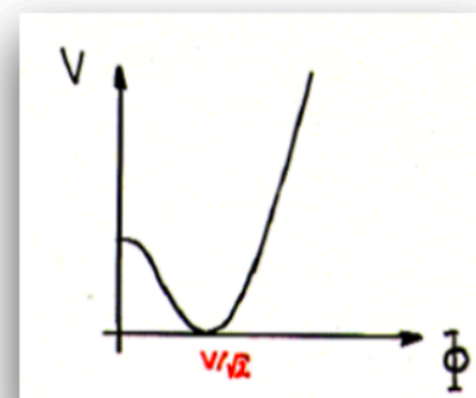
trilinear Higg self-coupling : $\lambda_{HHH} = 3 M_H^2 / M_Z^2$

quadrilinear Higgs self-coupling : $\lambda_{HHHH} = 3 M_H^2 / M_Z^4$

(units $\lambda_0 = 33.8\,\text{GeV}/\lambda_0^2$)

- Masses $M_{ij}=(\partial^2 V_H/\phi_i\,\phi_j)|_{\phi=0}$ and Higgs self-couplings $\lambda_{ijk}=(\partial^3 V_H/\phi_i\,\phi_j\,\phi_k)|_{\phi=0}$ related through Higgs potential V_H => catch up in precision w/ masses

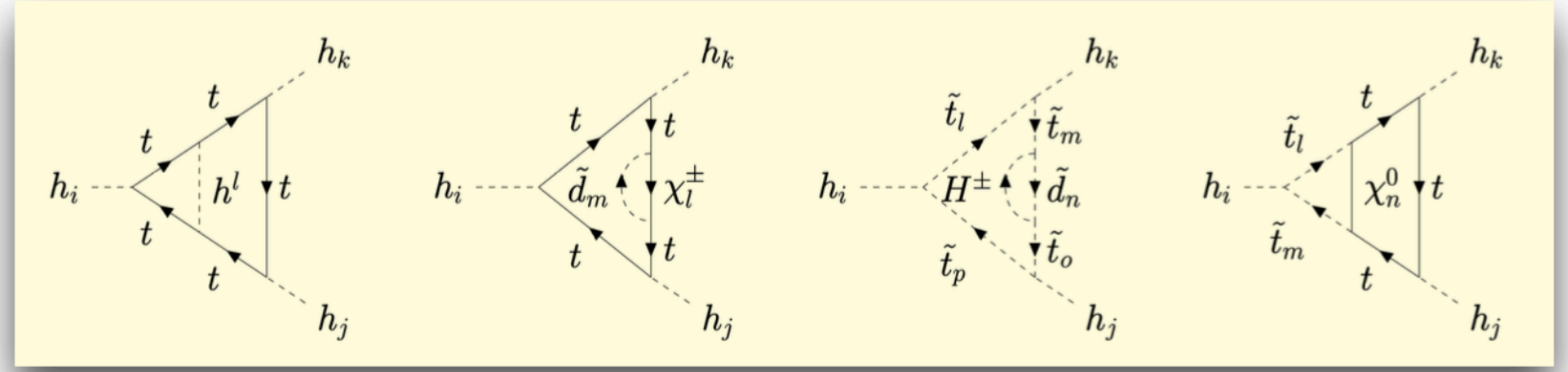
- Importance of the trilinear Higgs self-coupling:
  - determines shape of the Higgs potential
  - Sensitive to beyond-Standard-Model physics
  - Important input for Higgs pair production
  - Important input for Higgs-to-Higgs decays
  - Important input for electroweak phase transitions



- Previous work: full 1-loop [Dao,MM,Streicher,Walz,'13]
  2-loop at $\mathcal{O}(\alpha_t \alpha_s)$ [Dao,MM,Ziesche,'15]
  Present work: 2-loop $\mathcal{O}(\alpha_t(\alpha_s+\alpha_t))$ [Borschensky,Dao,Gabelmann,MM,Rzehak,'22]

Trilinear Higgs Self-Coupling at 2L $\mathcal{O}(\alpha_t(\alpha_s+\alpha_t))$

- New corrections at $\mathcal{O}(\alpha_t^2)$: all 2-loop diagrams with top/stops and at most one Higgs/Higgsino field, e.g.

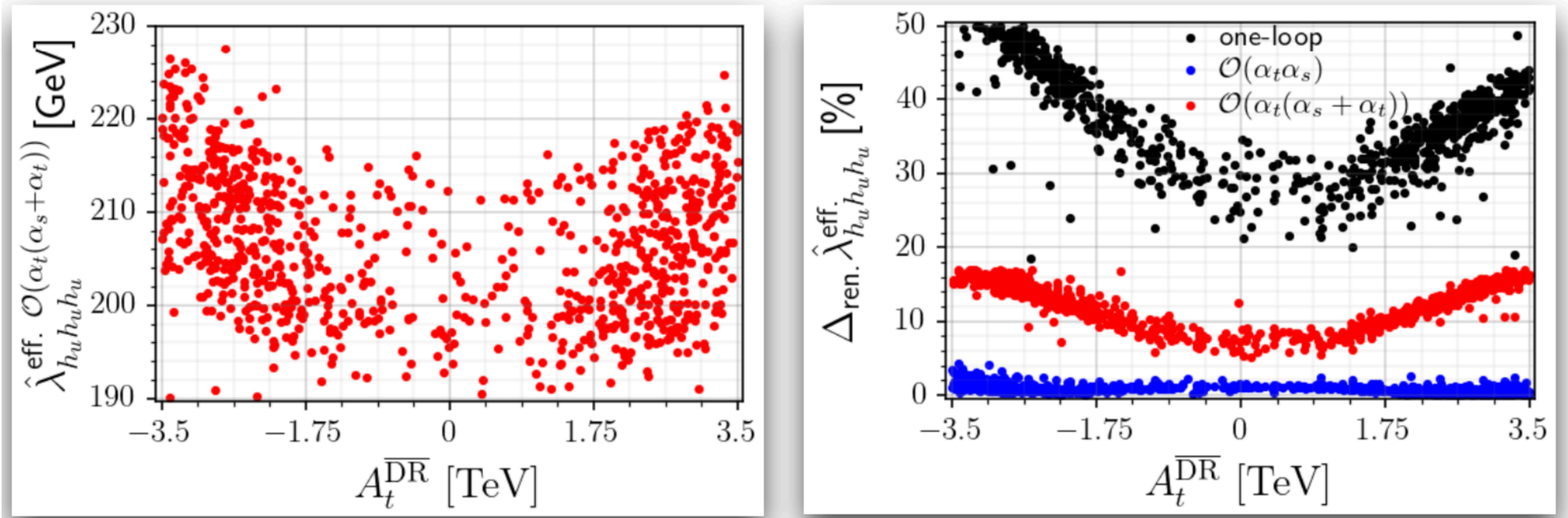


proportional to top mass m_t and soft SUSY-breaking trilinear stop mass parameter A_t

- Approximations:
  - gaugeless limit $g_1, g_2 \to 0$ (keeping $\tan\theta_W = g_2/g_1$ fixed)
  - vanishing external momenta → effective coupling

Trilinear Higgs Self-Coupling at 2L $\mathcal{O}(\alpha_t(\alpha_s + \alpha_t))$

Corrections to h_u-like Higgs ($\hat{=}$SM-like Higgs) [Borschensky,Dao,Gabelmann,MM,Rzehak,´22]



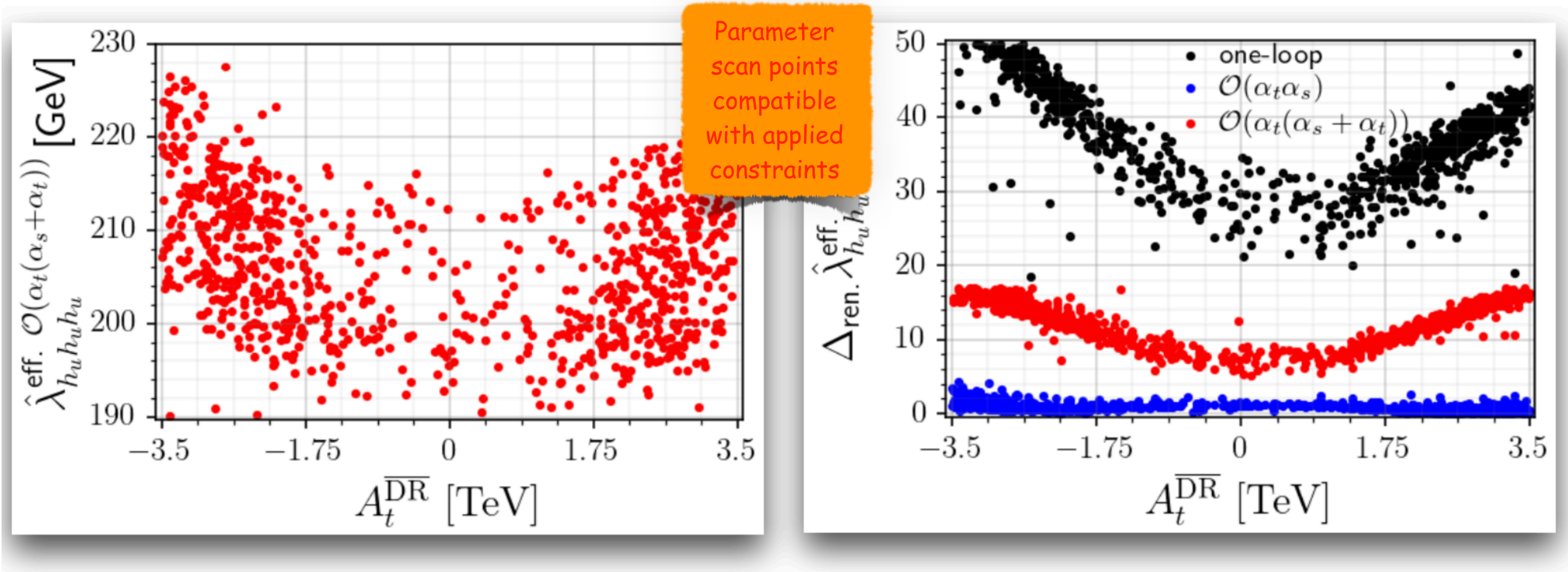
$\hat{\lambda}^{\text{eff}}_{abc}$: renormalized loop-corrected Higgs self-coupling at vanishing external momentum

Estimate of theor. uncertainty via renorm. scheme dependence: $\Delta_{\text{ren}} = \frac{\left|\lambda^{m_t(\overline{\text{DR}})} - \lambda^{m_t(\text{OS})}\right|}{\lambda^{m_t(\overline{\text{DR}})}}$

Results comply w/ SM value $\lambda^{\text{SM}}_{HHH} = \frac{3M_H^2}{v} = 191 \text{ GeV}$ within theoretical uncertainty

Trilinear Higgs Self-Coupling at 2L $\mathcal{O}(\alpha_t(\alpha_s+\alpha_t))$

Corrections to h_u-like Higgs ($\hat{=}$SM-like Higgs) [Borschensky,Dao,Gabelmann,MM,Rzehak,'22]



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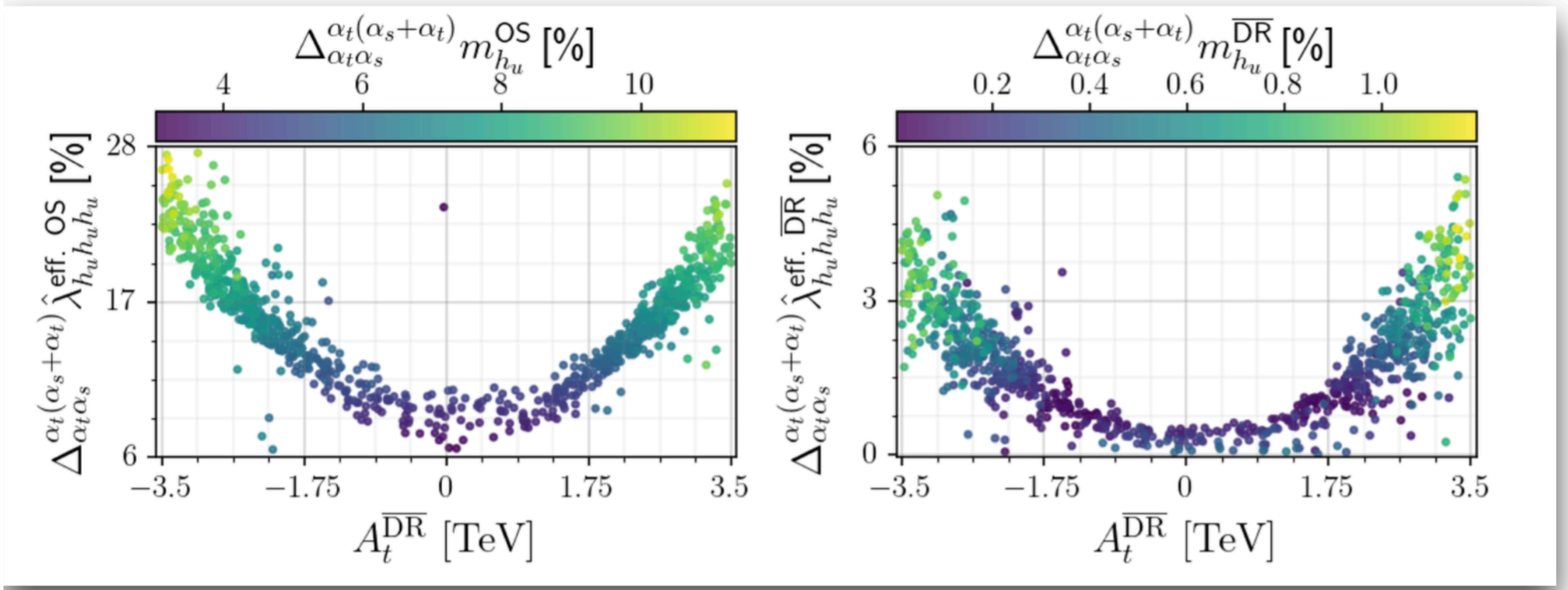
Size of Corrections at 2L $\mathcal{O}(\alpha_t(\alpha_s + \alpha_t))$

Corrections to h_u-like Higgs ($\triangleq$SM-like Higgs) [Borschensky,Dao,Gabelmann,MM,Rzehak,´22]



$$\Delta^{\alpha_{i+1}}_{\alpha_i} = \frac{|\lambda^{\alpha_{i+1}} - \lambda^{\alpha_i}|}{\lambda^{\alpha_i}}$$

- Correlation with size of mass corrections
- Smaller corrections in the DRbar than in the OS scheme due to partial resummation of of higher-order terms

Impact on Higgs Pair Production

Benchmark Point BP10: [Borschensky,Dao,Gabelmann,MM,Rzehak,´22]

Parameter Point BP10**:** All complex phases are set to zero and the remaining input parameters are given by

$$\begin{aligned}
|\lambda| &= 0.65\,,\ |\kappa| = 0.65\,,\ \mathrm{Re}(A_\kappa) = -432\ \mathrm{GeV}\,,\ |\mu_{\mathrm{eff}}| = 225\ \mathrm{GeV}\,,\ \tan\beta = 2.6\,,\\
M_{H^\pm} &= 611\ \mathrm{GeV}\,,\ m_{\tilde{Q}_3} = 1304\ \mathrm{GeV}\,,\ m_{\tilde{t}_R} = 1576\ \mathrm{GeV}\,,\ m_{\tilde{X}\neq\tilde{Q}_3,\tilde{t}_R} = 3\ \mathrm{TeV}\,,\\
A_t &= 46\ \mathrm{GeV}\,,\ A_b = -1790\ \mathrm{GeV}\,,\ A_\tau = -93\ \mathrm{GeV}\,,\ A_c = 267\ \mathrm{GeV}\,,\\
A_s &= -618\ \mathrm{GeV}\,,\ A_\mu = 1851\ \mathrm{GeV}\,,\ A_u = -59\ \mathrm{GeV}\,,\ A_d = -175\ \mathrm{GeV}\,,\\
A_e &= 1600\ \mathrm{GeV}\,,\ |M_1| = 810\ \mathrm{GeV}\,,\ |M_2| = 642\ \mathrm{GeV}\,,\ M_3 = 2\ \mathrm{TeV}\,. \qquad (38)
\end{aligned}$$

	$h_1\ [h_u]$	$h_2\ [h_s]$	$h_3\ [h_d]$	$a_1\ [a_s]$	$a_2\ [a_d]$
tree-level	97.21	307.80	626.13	556.71	617.22
one-loop	131.46 (114.81)	299.65 (299.28)	625.96 (625.52)	543.58 (543.69)	615.82 (616.01)
two-loop $\mathcal{O}(\alpha_t\alpha_s)$	118.90 (120.36)	299.40 (299.38)	625.78 (625.58)	543.73 (543.60)	615.90 (615.96)
two-loop $\mathcal{O}(\alpha_t(\alpha_s+\alpha_t))$	123.53 (120.14)	299.44 (299.38)	625.89 (625.57)	543.73 (543.60)	615.90 (615.96)
two-loop $\mathcal{O}(\alpha_{\lambda\kappa}^2)$	122.36 (119.97)	300.27 (299.90)	625.94 (625.65)	543.34 (543.47)	615.91 (616.01)

Impact on Higgs Pair Production

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di-Higgs can dominated by resonant h_2 production w/ $h_2 \to h_u h_u$

Impact on Higgs Pair Production

loop order
mass tril.cplg.

[Borschensky,Dao,Gabelmann,MM,Rzehak,'22]

1-loop

'1L1L'	σ^{OS} [fb]	$\sigma^{\overline{DR}}$ [fb]	$\kappa^{OS}_{H_1H_1H_1}$	$\kappa^{\overline{DR}}_{H_1H_1H_1}$	$\kappa^{OS}_{H_2H_1H_1}$	$\kappa^{\overline{DR}}_{H_2H_1H_1}$	$\Delta_{ren}\sigma$
'inp'	63.72	62.14	0.54	0.71	-0.25	-0.30	2.5%
'proc'	76.83	61.48	1.01	1.04	-0.30	-0.31	25%

2-loop $O(\alpha_t^2 + \alpha_s\alpha_t)$

'at2at2'	σ^{OS} [fb]	$\sigma^{\overline{DR}}$ [fb]	$\kappa^{OS}_{H_1H_1H_1}$	$\kappa^{\overline{DR}}_{H_1H_1H_1}$	$\kappa^{OS}_{H_2H_1H_1}$	$\kappa^{\overline{DR}}_{H_2H_1H_1}$	$\Delta_{ren}\sigma$
'inp'	68.98	61.25	0.61	0.65	-0.27	-0.28	12.6%
'proc'	71.69	62.57	1.03	1.02	-0.30	-0.31	14.6%

- 'inp': loop-corrected masses and mixing angles (-> Yukawa & trilinear couplings) in tree-level-like formulae: HO corrections to input parameters
- 'proc': additionally including loop-corrected trilinear Higgs self-coupling -> HO corrections to observable included (though **only partially**)

- 'inp': scheme dependence of input parameters uncanceled by scheme dependence of process-dependent corrections (at the same order)
- 'proc': remaining large uncertainty (14.6%): remaining missing EW corrections might be important

Measuring EWSB

Trilinear Higgs Self-Coupling

❖ SM Higgs potential: in physical gauge

$$V(H) = \frac{1}{2} M_H^2 H^2 + \frac{M_H^2}{2v} H^3 + \frac{M_H^2}{8v^2} H^4$$

Higgs mass : $M_H = \sqrt{2\lambda}\, v$

trilinear Higgs self-coupling : $\lambda_{HHH} = 3 M_H^2 / M_Z^2$

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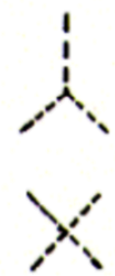
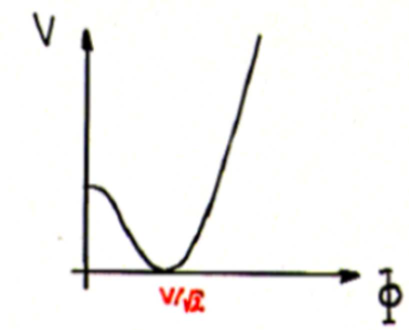
(units $\lambda_0 = 33.8\,\mathrm{GeV}/\lambda_0^2$)

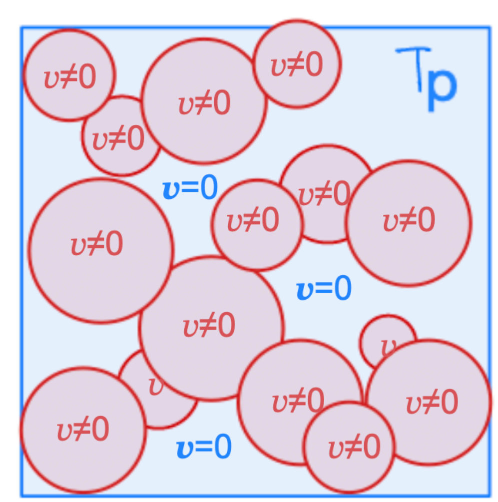




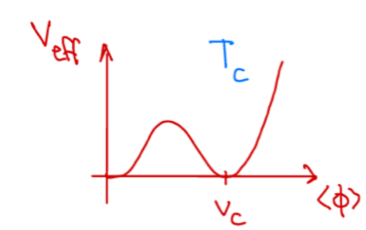
Measurement of the scalar boson self-couplings and Reconstruction of the EWSB potential	Experimental verification Of the scalar sector of the EWSB mechanism

❖ Importance of the trilinear Higgs self-coupling:

- Determines shape of the Higgs potential
- Sensitive to beyond-SM physics
- Important input for electroweak phase transition*



*matter-asymmetry through electroweak baryogenesis



Trilinear Higgs Self-Coupling

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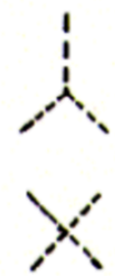
$$V(H) = \frac{1}{2} \ldots H^2 + \frac{M_H^2}{2v} H^3 + \frac{M_H^2}{8v^2} H^4$$

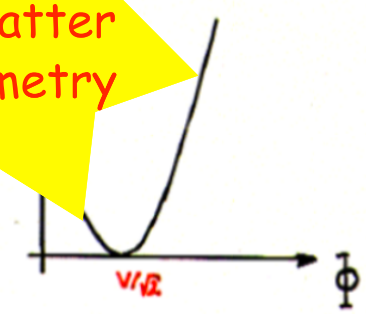
Higgs mass : $M_H = \sqrt{2\lambda}\, v$

tri… coupling : $\lambda_{HHH} = 3M_H^2/M_Z^2$

… coupling : $\lambda_{HHHH} = 3M_H^2/M_Z^4$

(unit … $= 33.8\,\mathrm{GeV}/\lambda_0^2$)





Ultimate test Higgs Mechanism

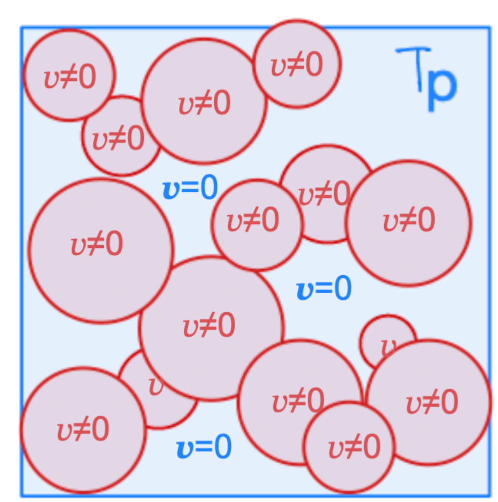
Matter-Antimatter Asymmetry

New Physics

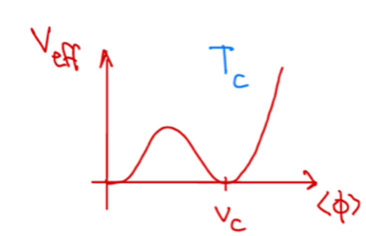
Evolution of Cosmos

Measurem… …alar boson self-couplings and Reconstruct… of … EWSB potential } Experimental verification Of the scalar sector of the EWSB mechanism

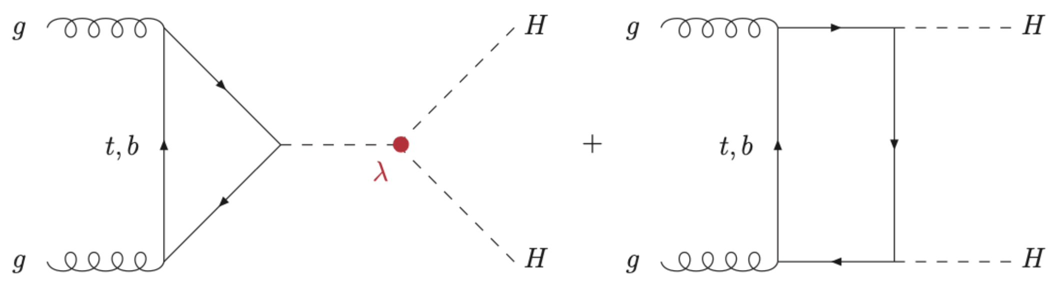
- Importance of the trilinear Higgs self-coupling:
  - Determines shape of the Higgs potential
  - Sensitive to beyond-SM physics
  - Important input for electroweak phase transition*



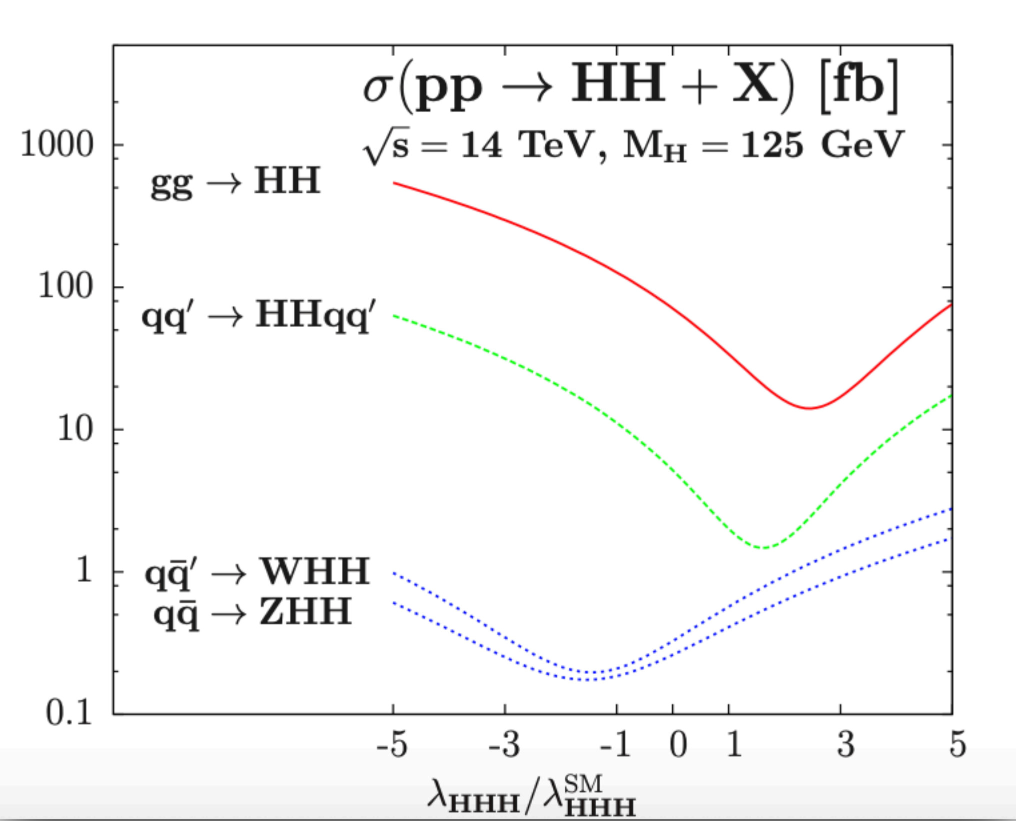
*matter-asymmetry through electroweak baryogenesis



- Loop mediated at leading order - SM: third generation dominant



- Threshold region sensitive to λ; large M_{HH}: sensitive to c_{tt}/c_{bb} [e.g. boosted Higgs pairs]



[Baglio,Djouadi,Gröber,MM,Quévillon,Spira]

$$gg \to HH : \frac{\Delta\sigma}{\sigma} \sim -\frac{\Delta\lambda}{\lambda}$$

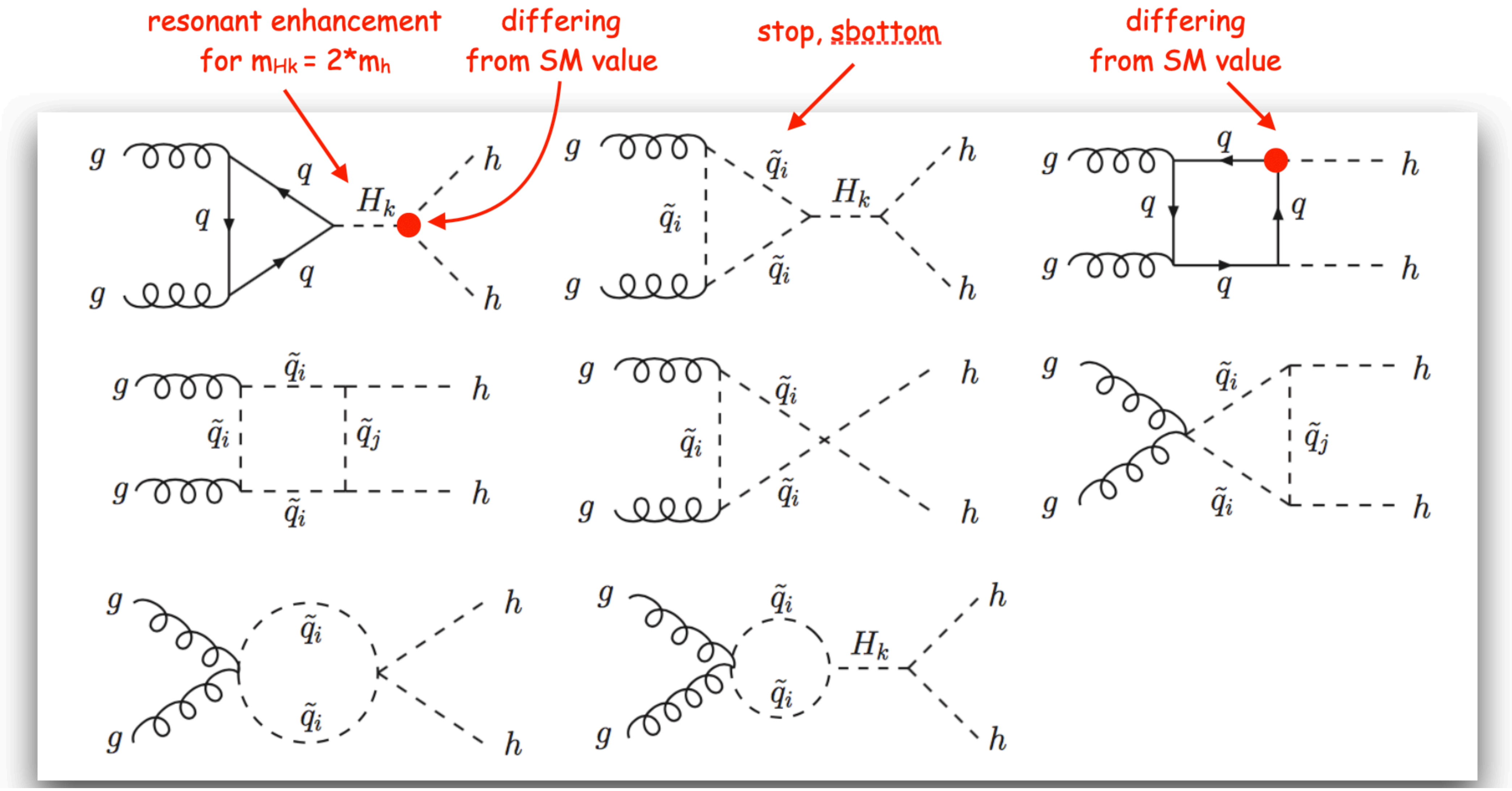
decreasing with M_{HH}

New Physics Effects in Higgs Pair Production

- **Cross section:** - different trilinear couplings - different Yukawa couplings - novel particles in the loops - resonant enhancement - novel couplings

- **Example NMSSM:**

[taken from Dao,MM,Streicher,Walz,´13]

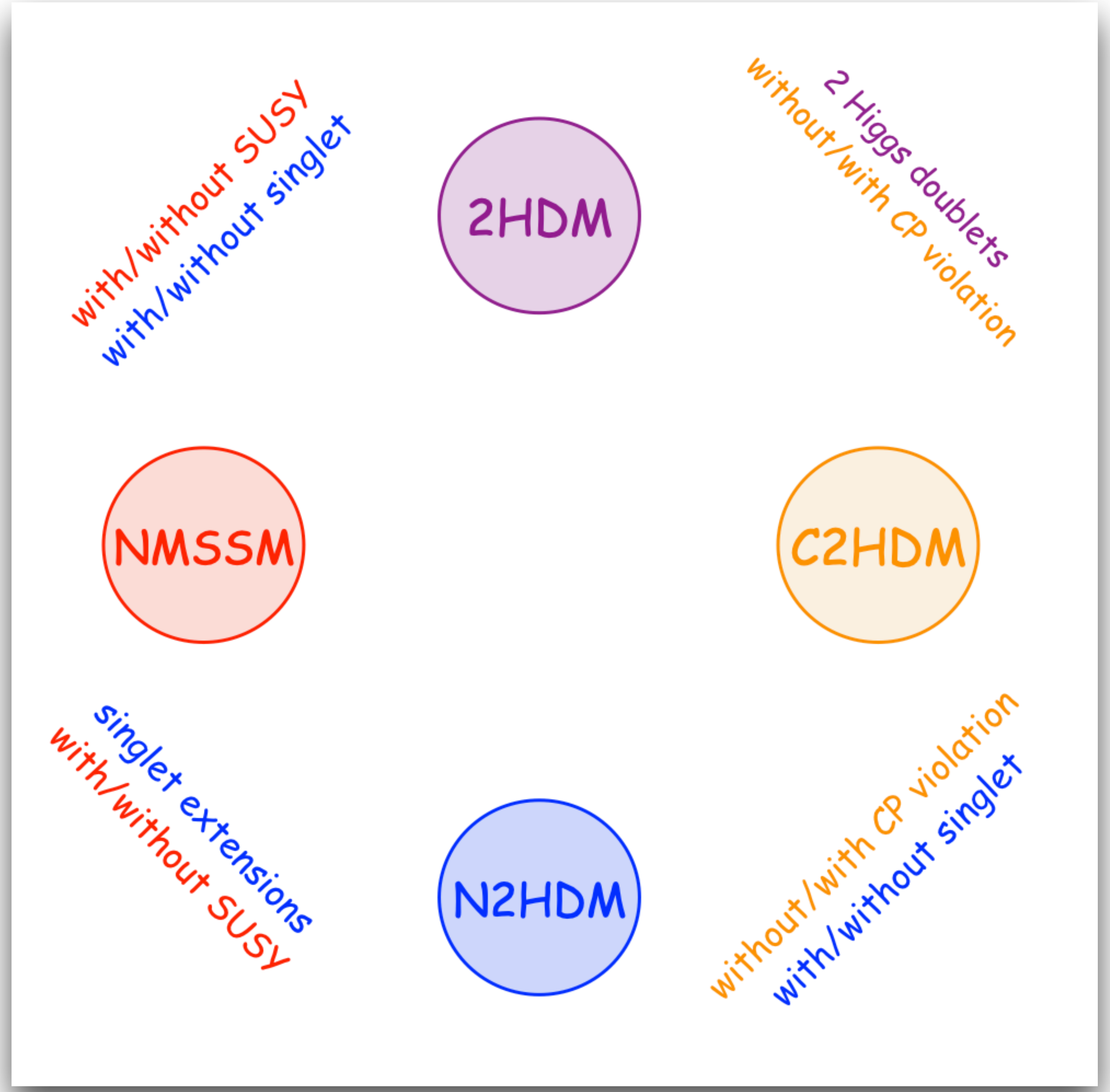


Overview on BSM Higgs Pair Production

Overview of Higgs Pair production possibilities
including theoretical and experimental constraints
in archetypical BSM Higgs sectors
including different symmetries

provide benchmark points / lines / planes
for experiment

Investigated Models



Investigated Models

2HDM	C2HDM	N2HDM	NMSSM
2 Higgs doublets	CP-violating	Singlet extension	Supersymmetry
h, H, A, H^+, H^-	H_1, H_2, H_3, H^+, H^-	H_1, H_2, H_3, H^+, H^-	$H_1, H_2, H_3, A, H^+, H^-$
SFOEWPT, DM, plus charged Higgs	plus CP violation baryogenesis	rich pheno, DM SFOEWPT	a lot (DM, CPviol, Hierarychy, ...)

Resonant Enhancement

Higgs-to-Higgs Cascade decays

- Following results based on:
  Abouabid, Arhrib, Azevedo, El Falaki, Ferreira, MMM, Santos, „Benchmarking Di-Higgs Production in Extended Higgs Sectors", JHEP 09 (2022) 011

How Define Resonant Di-Higgs Production?

Additional Higgs bosons H_k: possible resonant enhancement of the di-Higgs cross section

* If $m_{Hk} < m_{Hi} + m_{Hj}$ then clear case of „non-resonant" production
* If $m_{Hk} > m_{Hi} + m_{Hj}$: resonance contribution may be suppressed due to small couplings, large masses, large widths or destructive interference effects

* Distinction resonant/non-resonant: if cross section** more than 10% of total di-Higgs result ~> resonant limits

From an experimental point of view the cross section would not be distinguishable from „non-resonant" production then. => Our recipe:

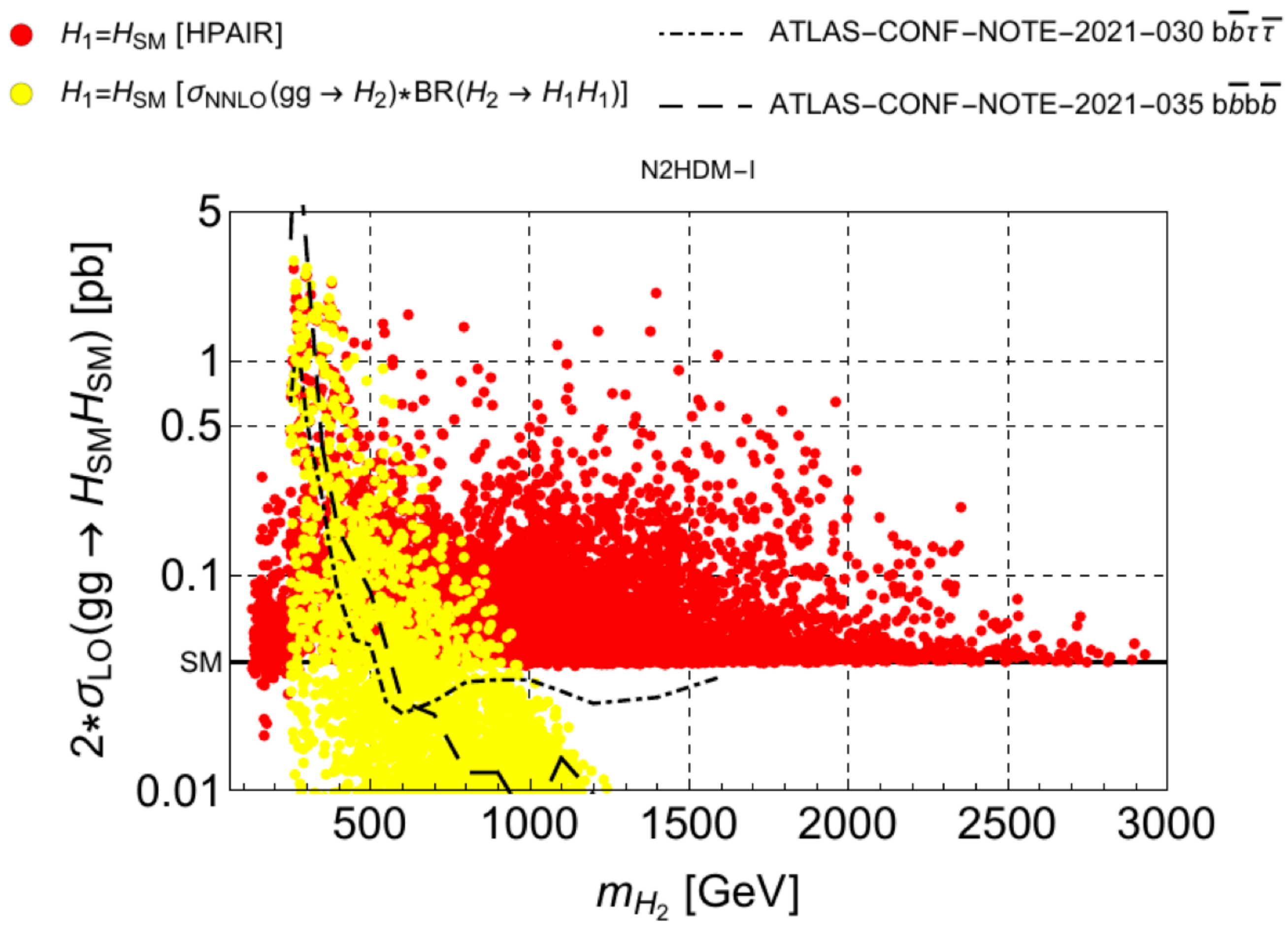
* HiggsBounds turned off for di-Higgs
* Use SusHi to calculate $\sigma(H_k)$ for all possible intermediate resonances H_k at NNLO QCD
* Calculate $\sigma(H_k) \times BR(H_k \to H_{SM} H_{SM})$** and compare it with experiment
* Exception: exp. limits assume narrow resonance -> we keep points if $(\Gamma_{tot}(H_k)/m_{Hk})_{limit} > 5\%$

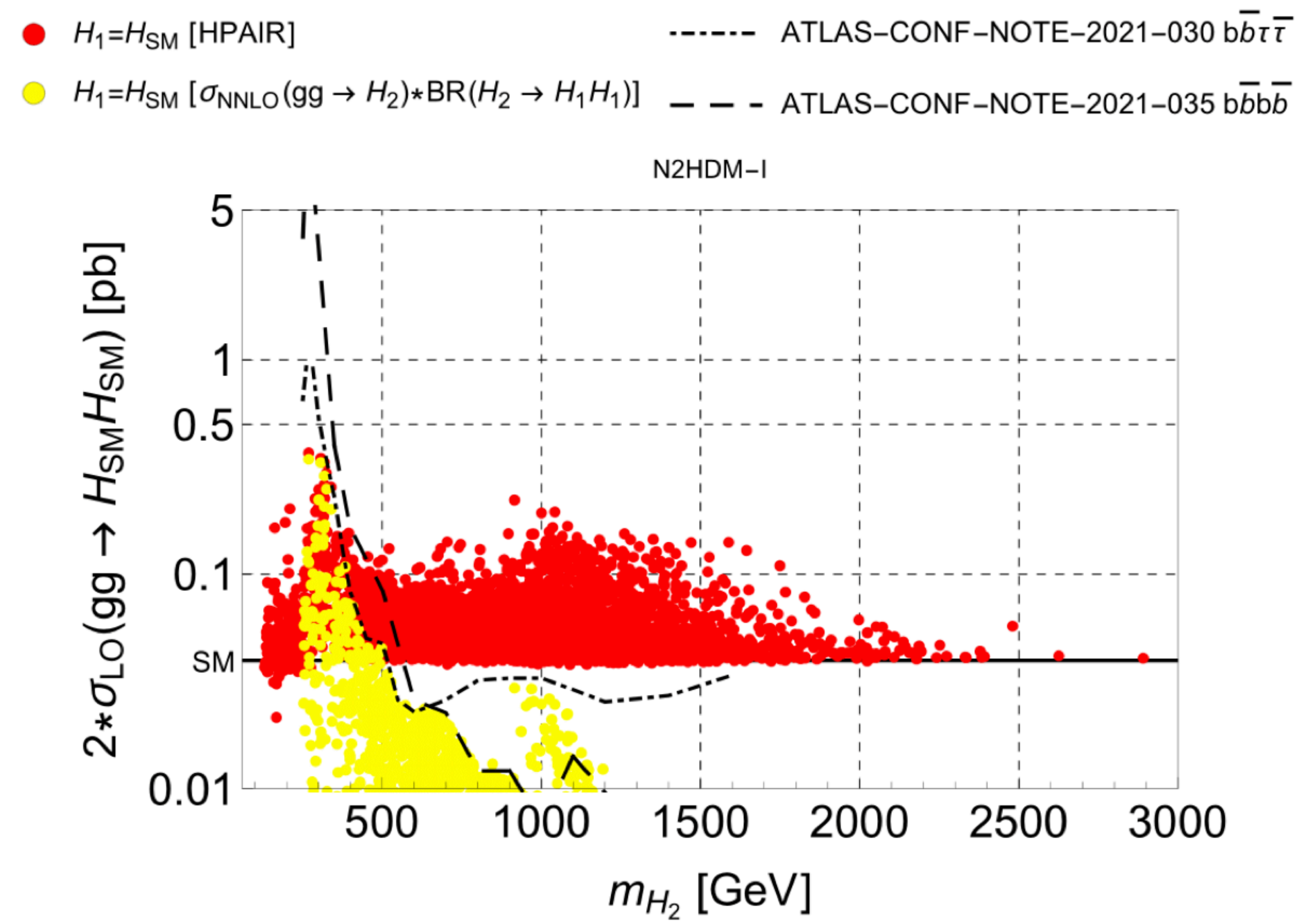
Provided final states on request: 4b, (2b)(2tau), (2b)(2gamma), (2b)(2W), (2b)(2Z), (2W)(2gamma), 4W

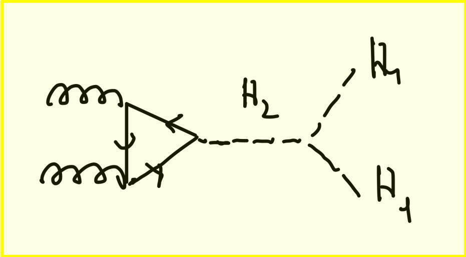
Suppress interfering Higgs signals by excluding scenarios with neighboring Higgs masses below 5 GeV.

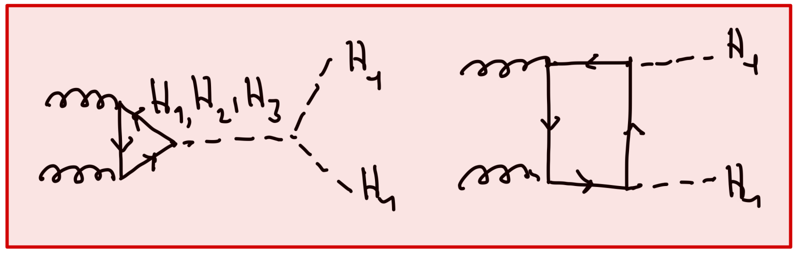
Impact of Resonant Searches

[Abouabid, Arhrib,Azevedo,El Falaki, Ferreira, MM,Santos,´21]





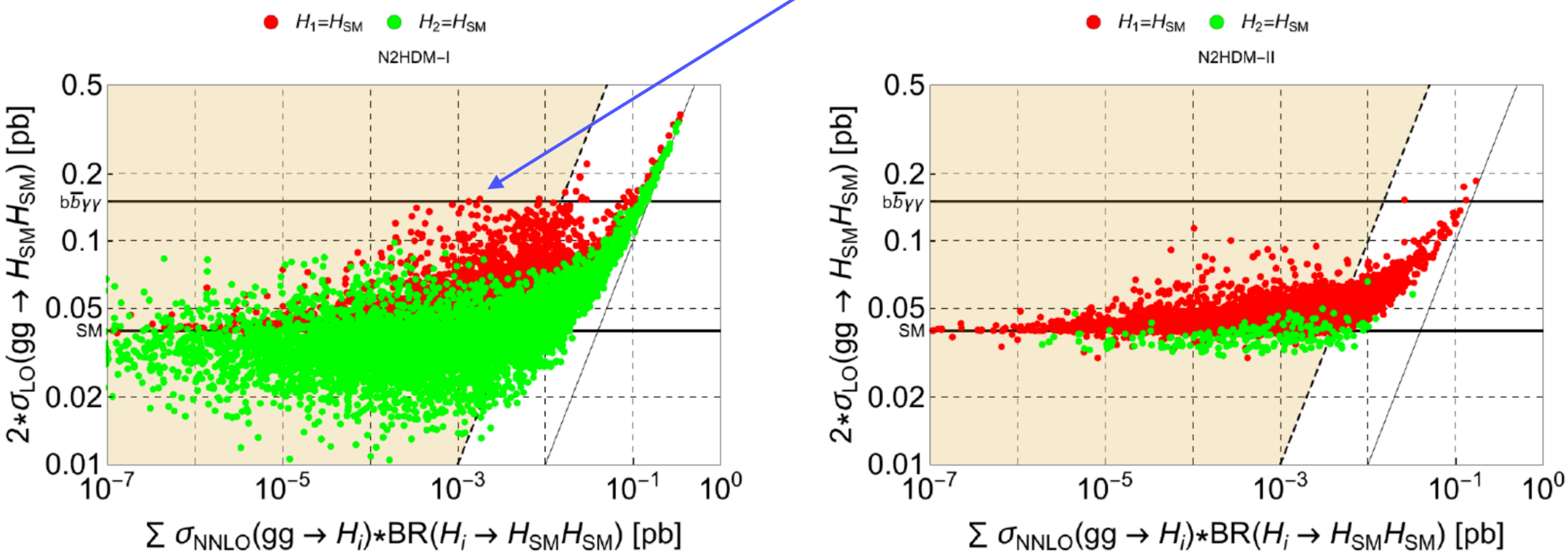




Impact of Non-Resonant Searches

Non-resonant experimental searches start cutting in N2HDM parameter space

[Abouabid, Arhrib,Azevedo,El Falaki, Ferreira, MM,Santos,´21]



Cross section resonantly dominated if $\sigma(H_k) \times BR(H_k \to H_{SM}\, H_{SM}) > 0.1\, \sigma(H_kH_k)$

Non-resonant experimental search limits applied

Maximum Cross Section Values-Resonant Production

[Abouabid, Arhrib,Azevedo,El Falaki, Ferreira, MM,Santos,´21]

Model \ SM-like	H1	H2
R2HDM T1	444 fb	
R2HDM T2	81 fb	
C2HDM T1	387 fb	47 fb
C2HDM T2	130 fb	no point
N2HDM T1	376 fb	344 fb
N2HDM T2	188 fb	63 fb
NMSSM	183 fb	65 fb

NLO SM HH production (in the heavy top limit): 38 fb

Ranges of Trilinear Higgs Couplings

[Abouabid, Arhrib,Azevedo,El Falaki, Ferreira, MM,Santos,´21]

	R2HDM		C2HDM	
	$y^{\rm R2HDM}_{t,H_{\rm SM}}/y_{t,H}$	$\lambda^{\rm R2HDM}_{3H_{\rm SM}}/\lambda_{3H}$	$y^{\rm C2HDM}_{t,H_{\rm SM}}/y_{t,H}$	$\lambda^{\rm C2HDM}_{3H_{\rm SM}}/\lambda_{3H}$
light I	0.893...1.069	-0.096...1.076	0.898...1.035	-0.035...1.227
medium I	n.a.	n.a.	0.889...1.028	0.251...1.172
heavy I	0.946...1.054	0.481...1.026	0.893...1.019	0.671...1.229
light II	0.951...1.040	0.692...0.999	0.956...1.040	0.096...0.999
medium II	n.a.	n.a.	–	–
heavy II	–	–	–	–

	N2HDM		NMSSM	
	$y^{\rm N2HDM}_{t,H_{\rm SM}}/y_{t,H}$	$\lambda^{\rm N2HDM}_{3H_{\rm SM}}/\lambda_{3H}$	$y^{\rm NMSSM}_{t,H_{\rm SM}}/y_{t,H}$	$\lambda^{\rm NMSSM}_{3H_{\rm SM}}/\lambda_{3H}$
light I	0.895...1.079	-1.160...1.004	n.a.	n.a.
medium I	0.874...1.049	-1.247...1.168	n.a.	n.a.
heavy I	0.893...1.030	0.770...1.112	n.a.	n.a.
light II	0.942...1.038	-0.608...0.999	0.826...1.003	0.024...0.747
medium II	0.942...1.029	0.613...0.994	0.916...1.000	-0.502...0.666
heavy II	–	–	–	–

(boxed) still compatible with zero

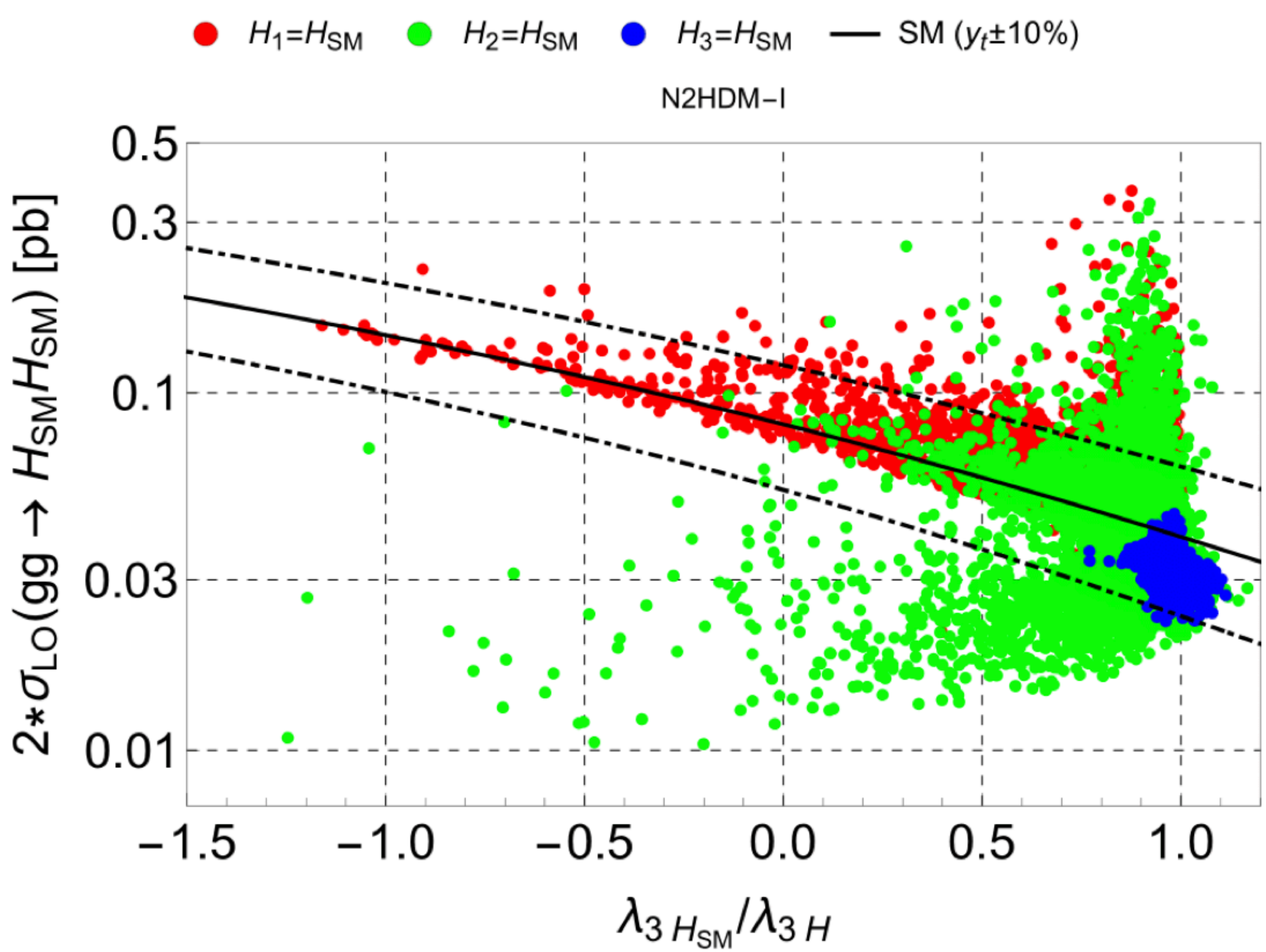
Large values of $\lambda_{3H_{SM}}$ required for SFOEWPT!

Interplay Top-Yukawa — Higgs Self-Coupling

Experiments provide limits on λ_{HHH} assuming SM top Yukawa coupling! But $y_t \pm 10\,\%$ still possible!

[Abouabid, Arhrib,Azevedo,El Falaki, Ferreira, MM,Santos,´21]

Full line:
SM HH production
as function of
λ variation
Dashed lines:
$y_t \pm 10\,\%$ variation



factor 2: roughly account
for NLO QCD corrections
HPAIR version with
NLO QCD corrections in
heavy top limit available
[Dao,MM,Streicher,Walz,'13]

Di-Higgs Beats Single Higgs

[Abouabid,Arhrib,Azevedo,El Falaki,Ferreira,MM,Santos,'21]

Possible for models w/ singlet-dominated and/or h_d-like (small gluon fusion production cxn!) non-SM-like Higgs boson => **NMSSM benchmark:**

λ	κ	A_λ [GeV]	A_κ [GeV]	$\mu_{\rm eff}$ [GeV]	$\tan\beta$
0.545	0.598	168	-739	258	2.255
$m_{H^\pm}$ [GeV]	M_1 [GeV]	M_2 [GeV]	M_3 [TeV]	A_t [GeV]	A_b [GeV]
548	437.872	498.548	2	-1028	1083
$m_{\tilde{Q}_3}$ [GeV]	$m_{\tilde{t}_R}$ [GeV]	$m_{\tilde{b}_R}$ [GeV]	A_τ [GeV]	$m_{\tilde{L}_3}$ [GeV]	$m_{\tilde{\tau}_R}$ [GeV]
1729	1886	3000	-1679.21	3000	3000

m_{H_1} [GeV]	m_{H_2} [GeV]	m_{H_3} [GeV]	m_{A_1} [GeV]	m_{A_2} [GeV]
123.20	319	560	545	783
$\Gamma^{tot}_{H_1}$ [GeV]	$\Gamma^{tot}_{H_2}$ [GeV]	$\Gamma^{tot}_{H_3}$ [GeV]	$\Gamma^{tot}_{A_1}$ [GeV]	$\Gamma^{tot}_{A_2}$ [GeV]
3.985×10^{-3}	0.010	4.207	6.399	6.913
h_{11}	h_{12}	h_{13}	h_{21}	h_{22}
0.419	0.909	0.015	0.187	-0.102
h_{23}	h_{31}	h_{32}	h_{33}	a_{11}
0.977	0.889	-0.407	-0.212	0.908
a_{21}	a_{13}	a_{23}		
-0.104	0.114	0.994		

singlet-like H_2

Di-Higgs Beats Single Higgs

[Abouabid,Arhrib,Azevedo,El Falaki,Ferreira,MM,Santos,'21]

Possible for models w/ singlet-dominated (suppressed couplings to SM particles) and/or h_d-like (suppressed direct production) non-SM-like Higgs boson => **NMSSM benchmark:**

H_2 is singlet-like: dominant decay channel into A_1 A_1

Single Higgs Production (4b final state)

$$\sigma^{\rm NNLO}(H_2)_{4b} = \sigma^{\rm NNLO}(H_2) \times {\rm BR}(H_2 \to A_1 A_1) \times {\rm BR}(A_1 \to b\bar{b})^2$$
$$= 13.54 \times 0.887 \times 0.704^2 \text{ fb} = 5.95 \text{ fb} \,.$$

Di-Higgs Production (6b final state)

$$\sigma^{\rm NLO}(H_1 H_2) = 111 \text{ fb} \qquad {\rm BR}(H_1 \to b\bar{b}) = 0.539$$

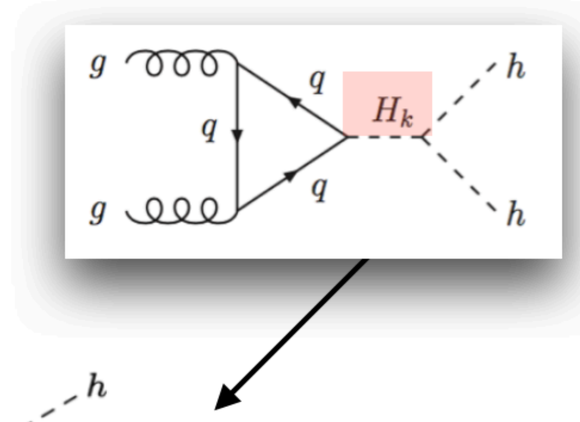
$$\sigma^{\rm NLO}(H_1 H_2) \times {\rm BR}(H_1 \to b\bar{b}) \times {\rm BR}(H_2 \to A_1 A_1) = 53 \text{ fb}$$

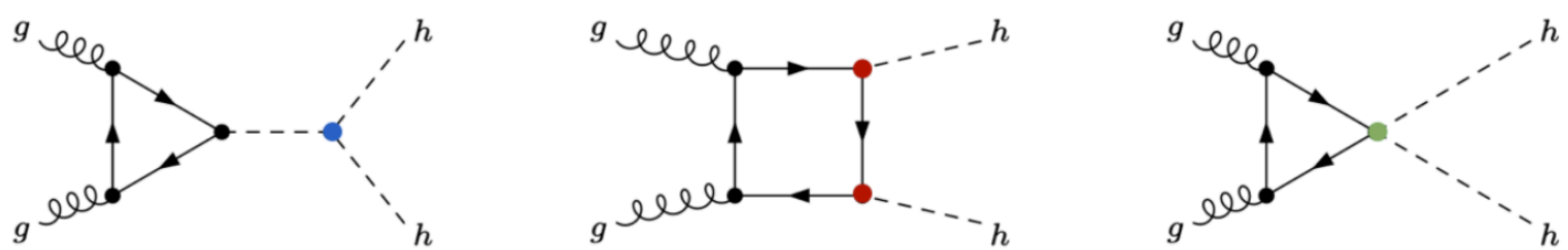
$$\sigma^{\rm NLO}(H_1 H_2)_{6b} = 53 \times 0.704^2 \text{ fb} = 26 \text{ fb}$$

Comparison with EFT

✦ Effective Lagrangian: $\Delta\mathcal{L}_{\text{non-lin}} \supset -m_t t\bar{t}\left(c_t \frac{h}{v} + c_{tt}\frac{h^2}{2v^2}\right) - c_3 \frac{1}{6}\left(\frac{3M_h^2}{v}\right) h^3$

c_3: trilinear coupling modification; c_t: top-Yukawa coupling modification;
c_{tt}: effective two-Higgs-two-fermion coupling
no c_g, c_{gg}: no new heavy colored BSM particles assumed





✦ Matching relations of our specific BSM models:

Higgs-top Yukawa coupling	:	$g_t^{H_{SM}}(\alpha_i,\beta)$	$\rightarrow$	c_t
trilinear Higgs coupling	:	$\frac{g_3^{H_{SM}H_{SM}H_{SM}}(p_i)}{3M^2_{H_{SM}}/v}$	$\rightarrow$	c_3
two-Higgs-two-top quark coupling	:	$\sum_{k=1}^{k_{max}}\left(\frac{-v}{m^2_{H_k}}\right) g_3^{H_k H_{SM} H_{SM}}(p_i)\, g_t^{H_k}(\alpha_i,\beta)$	$\rightarrow$	c_{tt}

2HDM versus EFT

[Abouabid, Arhrib,Azevedo,El Falaki, Ferreira, MM,Santos,´21]

✦ R2HDM T2 sample parameter point:

m_{H_1} [GeV]	m_{H_2} [GeV]	m_A [GeV]	$m_{H^\pm}$ [GeV]	α	$\tan\beta$	m_{12}^2 [GeV^2]
125.09	1131	1082	1067	-0.924	0.820	552749

✦ corresponding EFT values:

$$g_t^{H_2} = -1.126$$

$$c_3 = 0.782\,,\ c_t = 0.951\,,\ c_{tt} = -0.122$$

✦ goodness of approximation?:

m_{H_2} [GeV]	Γ_{H_2} [GeV]	c_{tt}	$g_3^{H_2H_1H_1}$ [GeV]	$\sigma_{\text{R2HDM}}^{\text{w/ res}}$ [fb]	$\sigma_{\text{SMEFT}}^{c_{tt}\neq 0}$ [fb]	ratio
1131	78.80	-0.1222	-504.52	30.5	26.1	86%
1200	89.74	-0.1031	-479.29	27.7	24.8	90%
1500	470.2	$-4.853\,10^{-2}$	-352.42	21.8	21.4	98%

✦ Remark:

$$\sigma_{\text{R2HDM}}^{\text{w/o res}} = 18.6\text{ fb} \quad \text{and} \quad \sigma_{\text{SMEFT}}^{c_{tt}=0} = 18.6\text{ fb}$$

N2HDM versus EFT

[Abouabid, Arhrib, Azevedo, El Falaki, Ferreira, MM, Santos, '21]

- **N2HDM T1 sample parameter point:**

m_{H_1} [GeV]	m_{H_2} [GeV]	m_{H_3} [GeV]	m_A [GeV]	$m_{H^\pm}$ [GeV]	$\tan\beta$
125.09	269	582	390	380	4.190
α_1	α_2	α_3	v_s [GeV]	$\text{Re}(m_{12}^2)$ [GeV^2]	
1.432	-0.109	0.535	1250	28112	

$$g_t^{H_2} = 0.179 \quad \text{and} \quad g_t^{H_3} = 2.337 \times 10^{-2}$$

- **corresponding EFT values:**

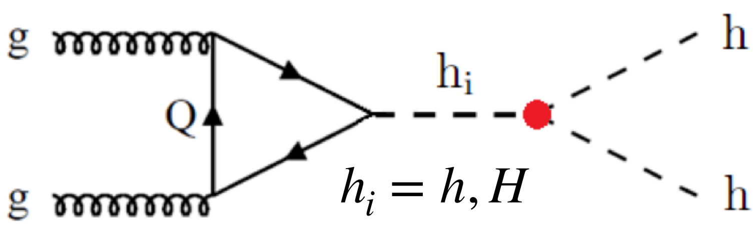
$$c_3 = 0.877\,, \; c_t = 1.012\,, \; c_{tt} = 4.127 \times 10^{-2}$$

- **goodness of approximation?: (m_{H3} kept fixed)**

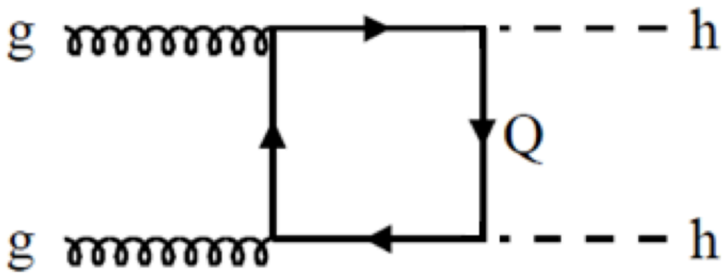
m_{H_2}	Γ_{H_2}	$c_{tt}^{H_2}$	c_{tt}	$g_3^{H_2H_1H_1}$	$\sigma_{\text{N2HDM}}^{\text{w/ res}}$ [fb]	$\sigma_{\text{SMEFT}}^{c_{tt}\neq 0}$ [fb]	ratio
269	0.075	4.410×10^{-2}	4.127×10^{-2}	-72.42	183.70	20.56	11%
300	0.083	3.170×10^{-2}	2.877×10^{-2}	-64.80	162.80	21.28	13%
400	0.177	9.544×10^{-3}	6.721×10^{-3}	-34.68	43.33	22.60	52%
420	0.229	6.895×10^{-3}	4.063×10^{-3}	-27.62	31.70	22.76	72%
440	0.284	4.600×10^{-3}	1.767×10^{-3}	-20.22	26.26	22.90	87%
450	0.315	3.564×10^{-3}	7.323×10^{-4}	-16.39	24.84	22.96	92%
500	2.567	-7.132×10^{-4}	-3.545×10^{-3}	4.05	23.56	23.22	99%

[Arco,Heinemeyer,MM,Radchenko,'23]

- Differential distribution required to disentangle the various NP effects in hh production



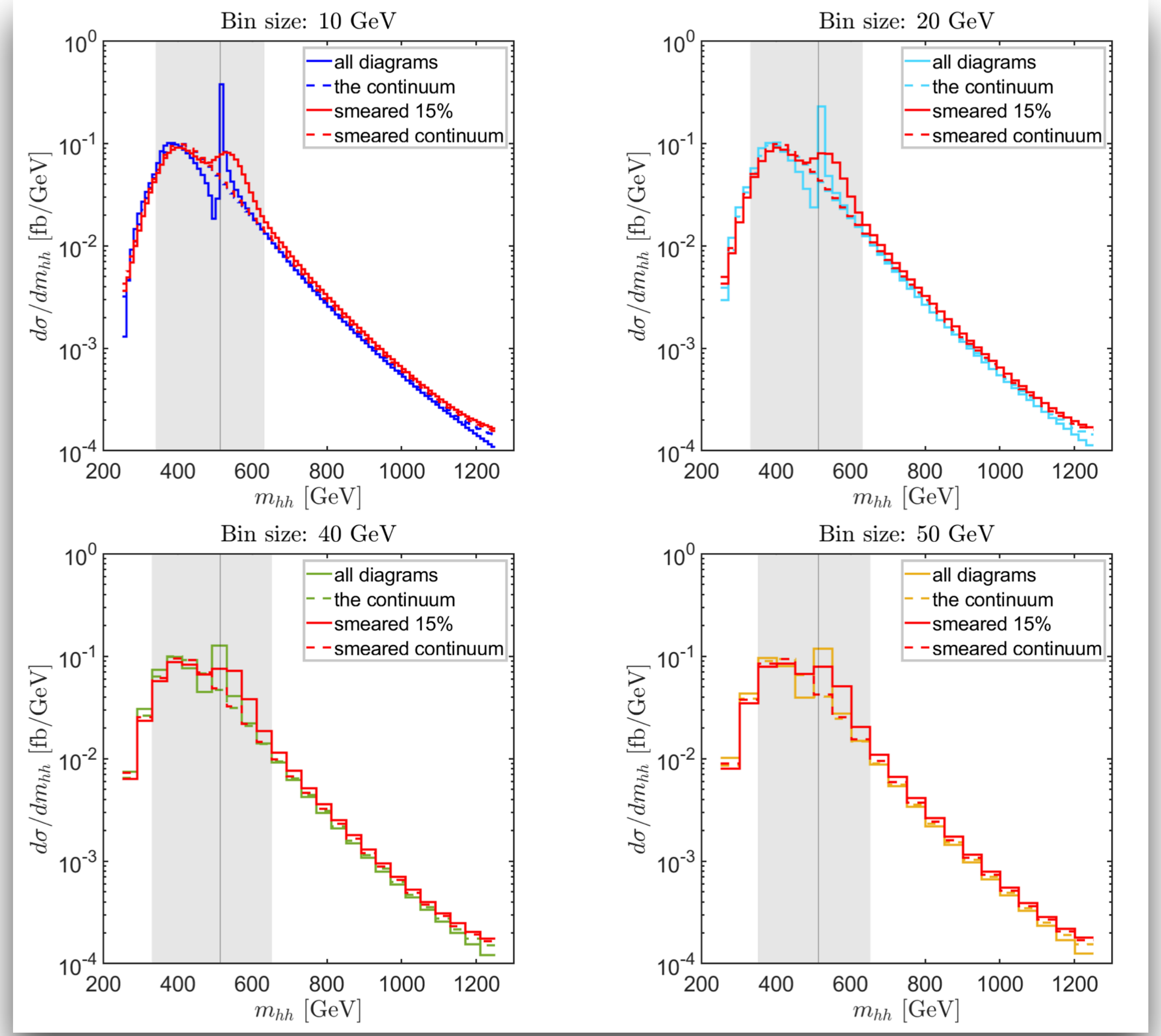
(a) Triangle diagram.



(b) Box diagram.

HL-LHC Sensititivty to BSM λ_{hhH}

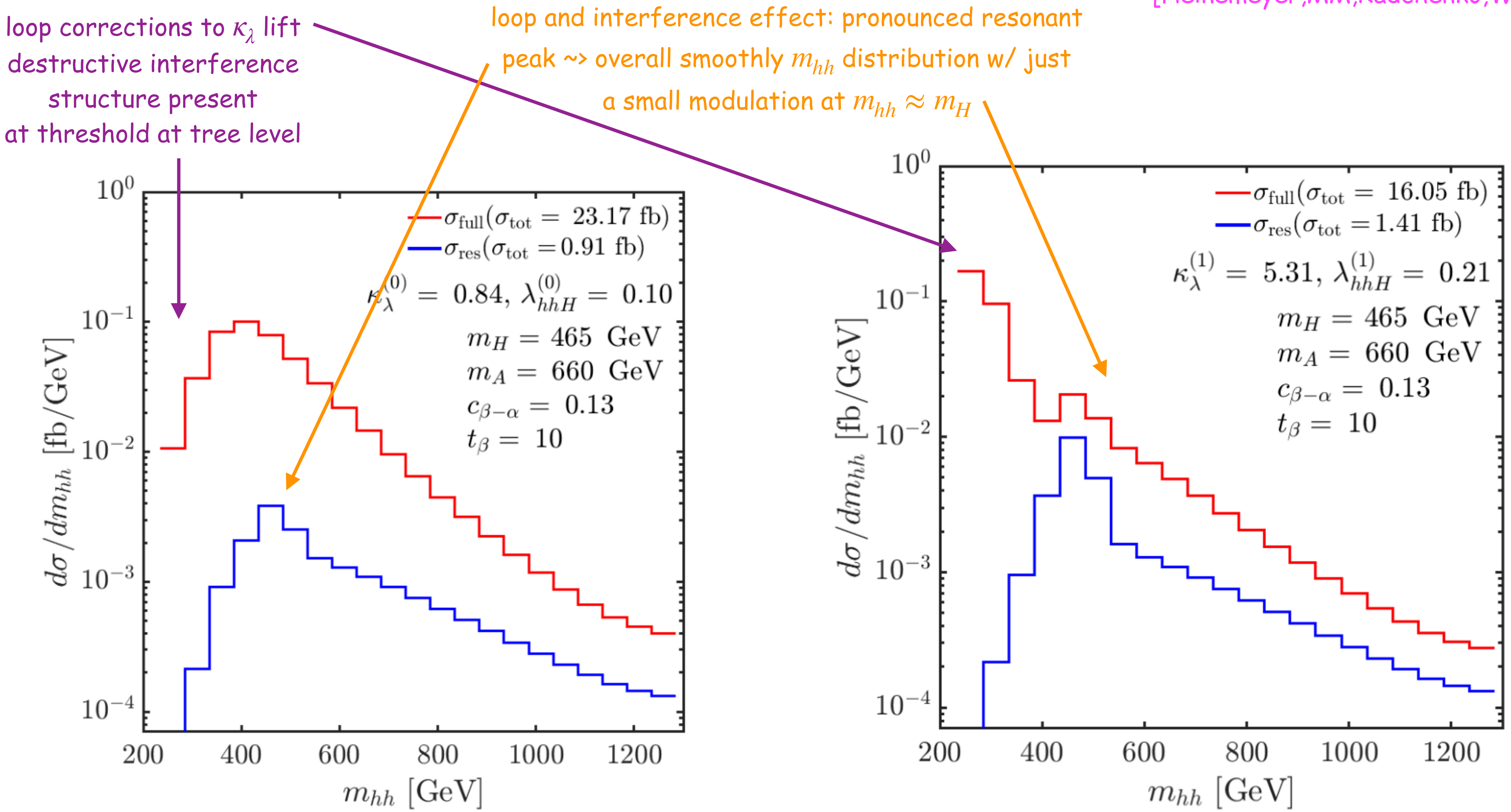
[Arco,Heinemeyer,MM,Radchenko,'22]



Depending on the scenario, a resonant H contribution to di-Higgs production can leave possibly visible effects in the m_{hh} distribution

Loop Corrections, Interference Effects and Experimental Limits

[Heinemeyer,MM,Radchenko,Weiglein,'23]



Exclusion limits obtained for the resonant di-Higgs searches by ATLAS and CMS may be too optimistic in view of the possible modifications in the invariant mass distribution in realistic scenarios, when all relevant contributions are taken into account.

Link To Slides

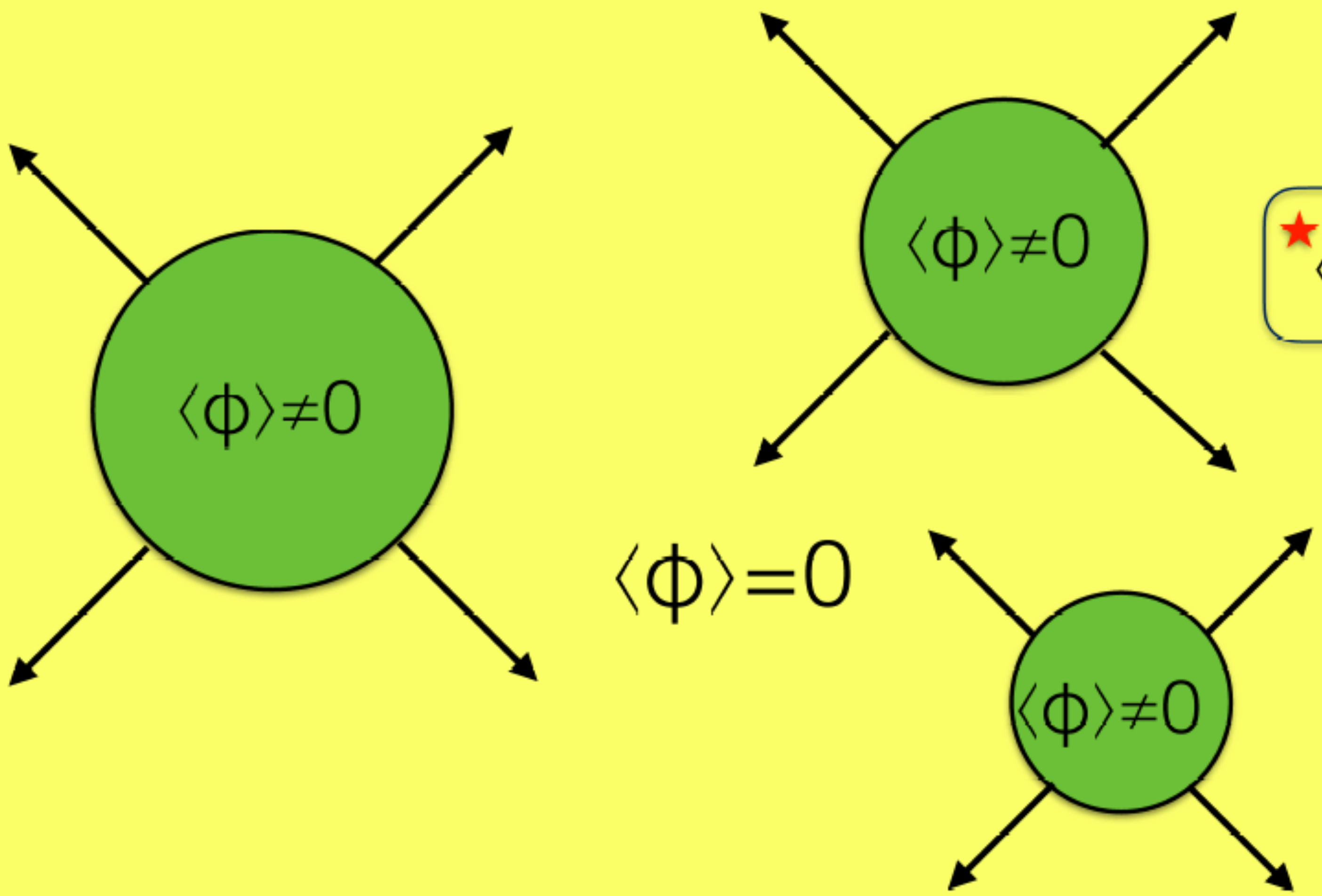
https://www.itp.kit.edu/~maggie/pre-susy24


Thank you for
your attention!

Baryogenesis in a Nutshell

Bubbles of the non-zero Higgs field VEV nucleate from the symmetric vacuum

They expand & particles in plasma interact with the phase interface in a CP-violating way



★ $\langle\phi_c(T_c)\rangle/T_c \geq 1$

ϕ_c, T_c
VEV and T at EW phase transition

CP-asymmetry is converted into a baryon asymmetry by sphalerons in the symmetric phase in front of bubble wall

Produced baryons muss not be washed out by sphaleron processes in symmetric phase in front of bubble wall ★