# Two Aspects of Higgs Pair Production: Precision and Electroweak Baryogenesis

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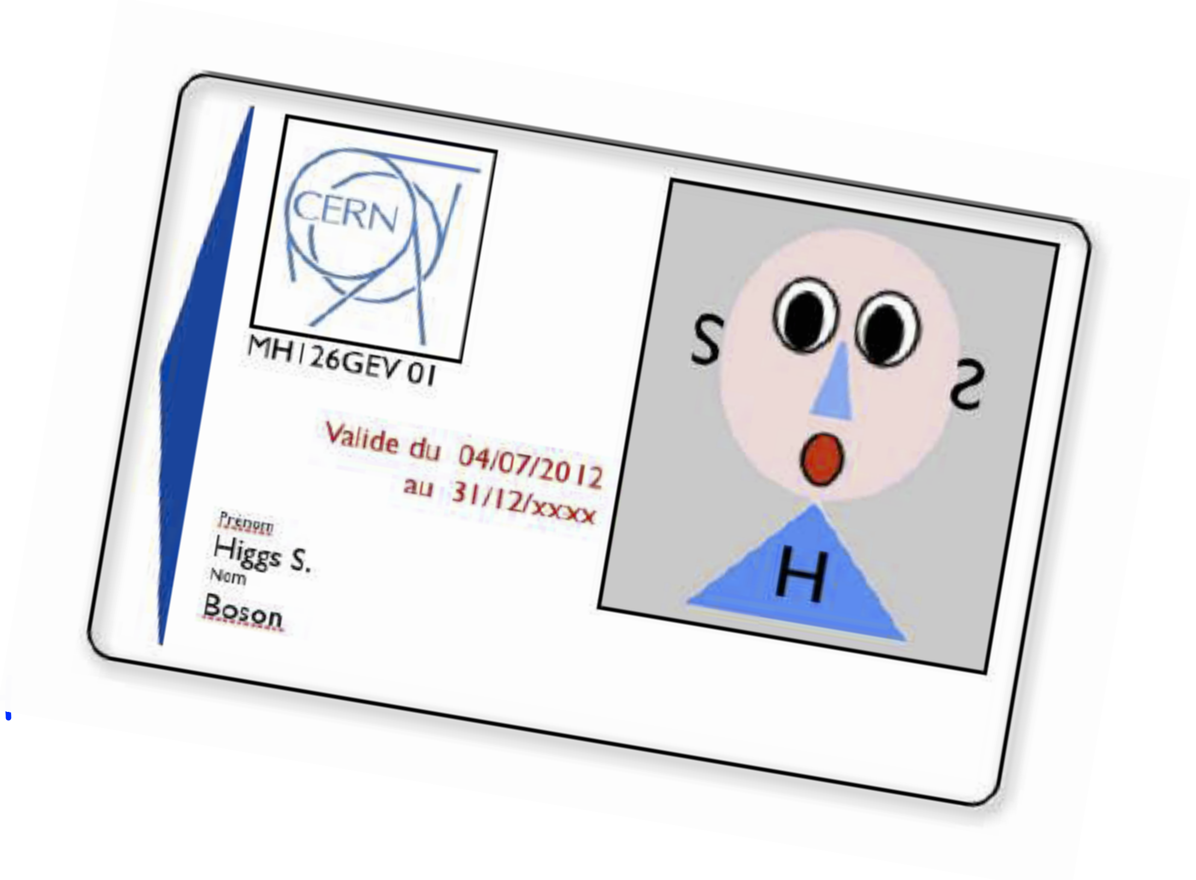
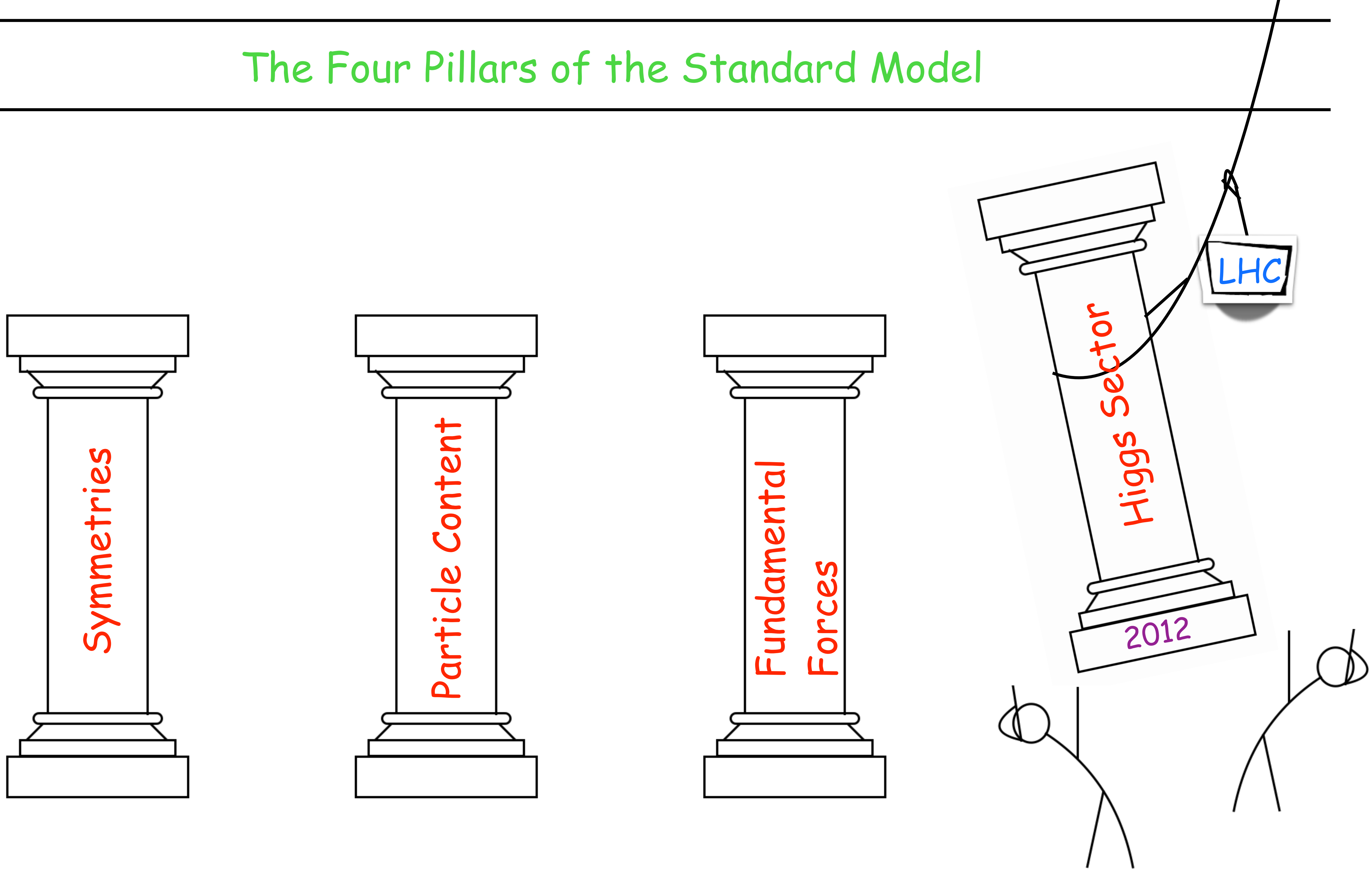
HPNP 2023
Osaka University, Japan
5-9 June 2023

# Outline

- Introduction
- Measuring Electroweak Symmetry Breaking
- Higher-Order Predictions for Higgs pair production
  - SM HH production, 2HDM hH, AA
  - uncertainties (ren./fact. scale, top mass)
- Top-Yukawa induced EW corrections to SM HH
- Higgs pair production and baryogenesis
  - 2HDM + dim-6 scalar operators
  - „CP in the Dark“



# The Four Pillars of the Standard Model



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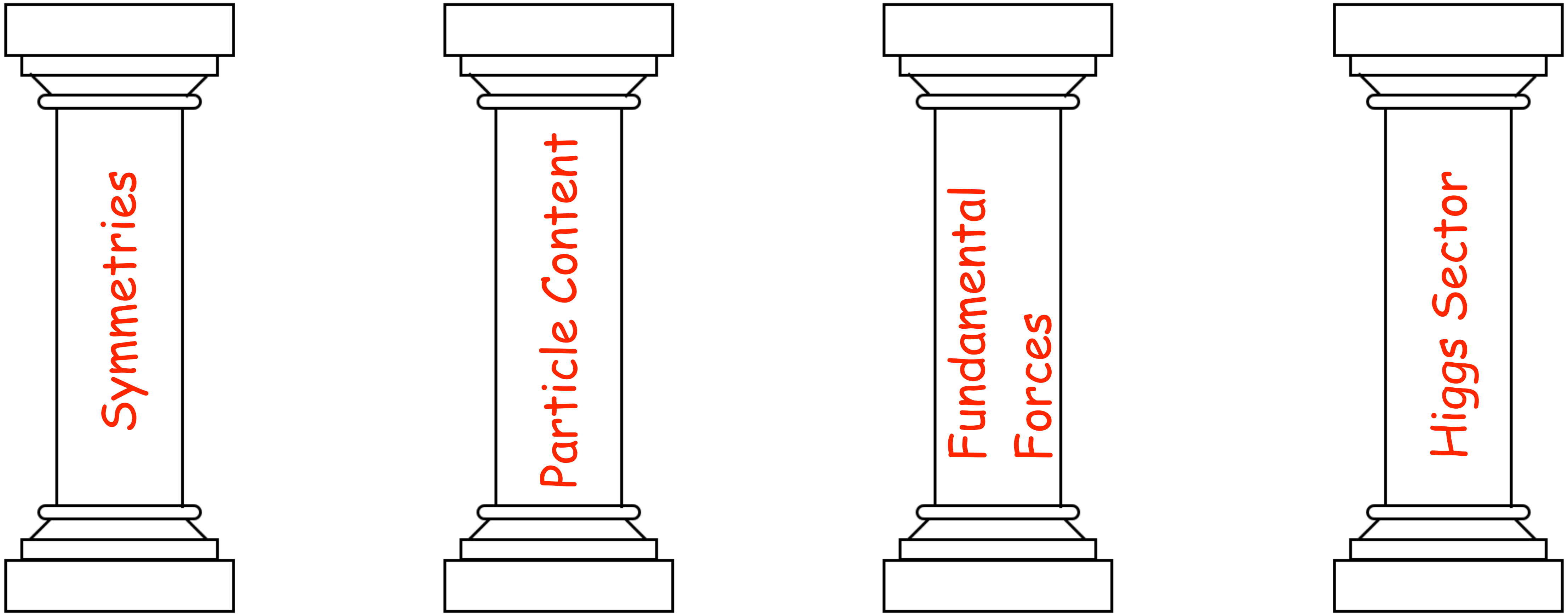
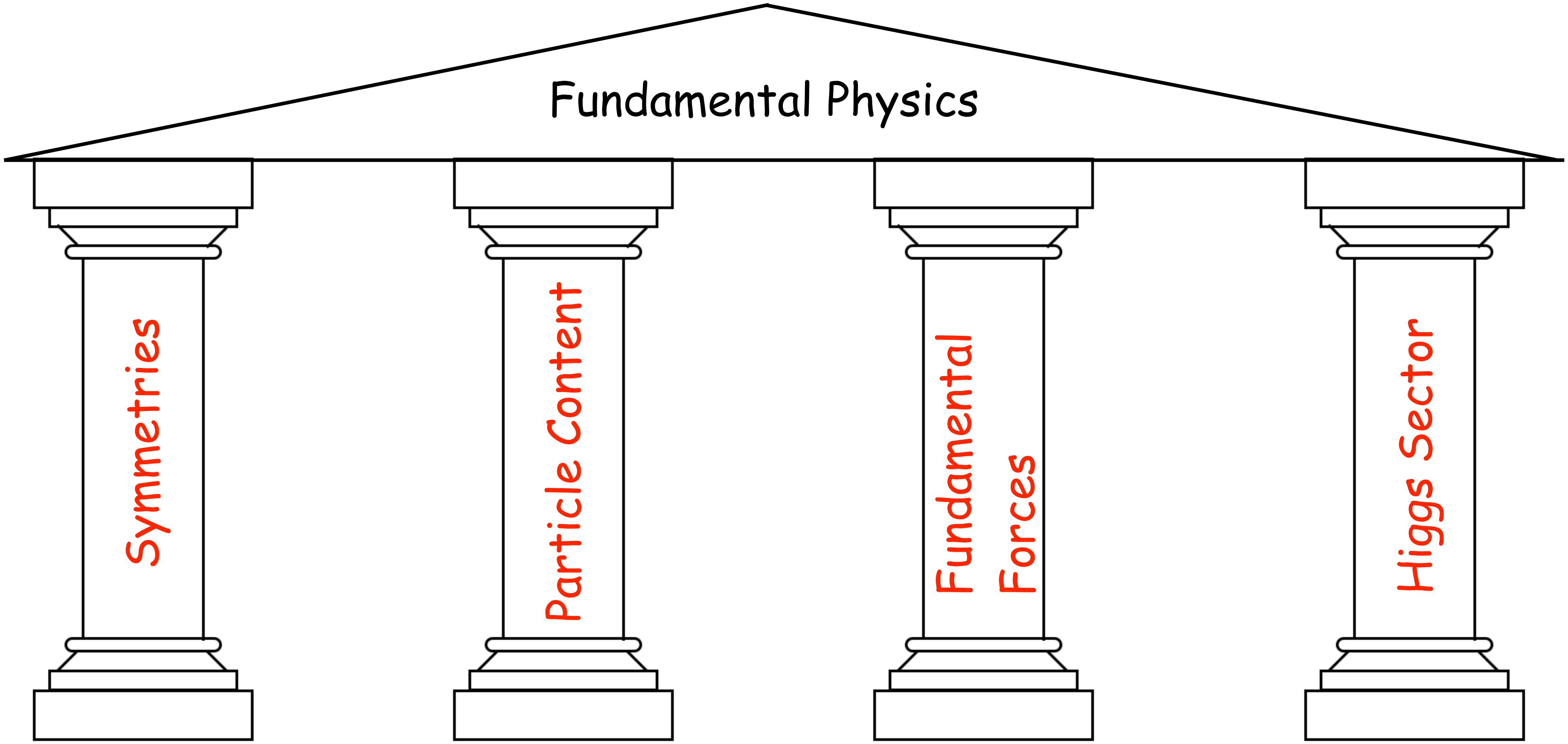
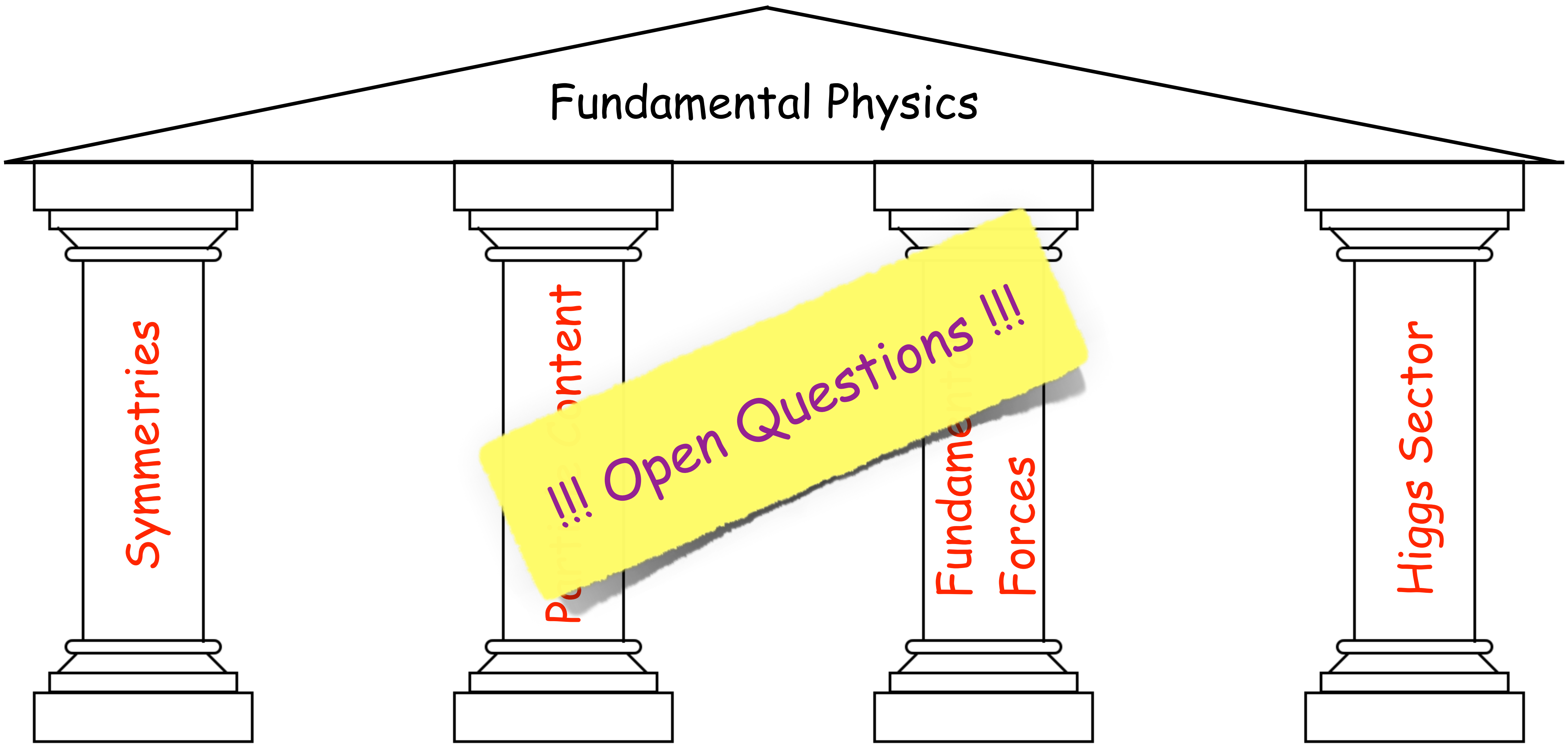
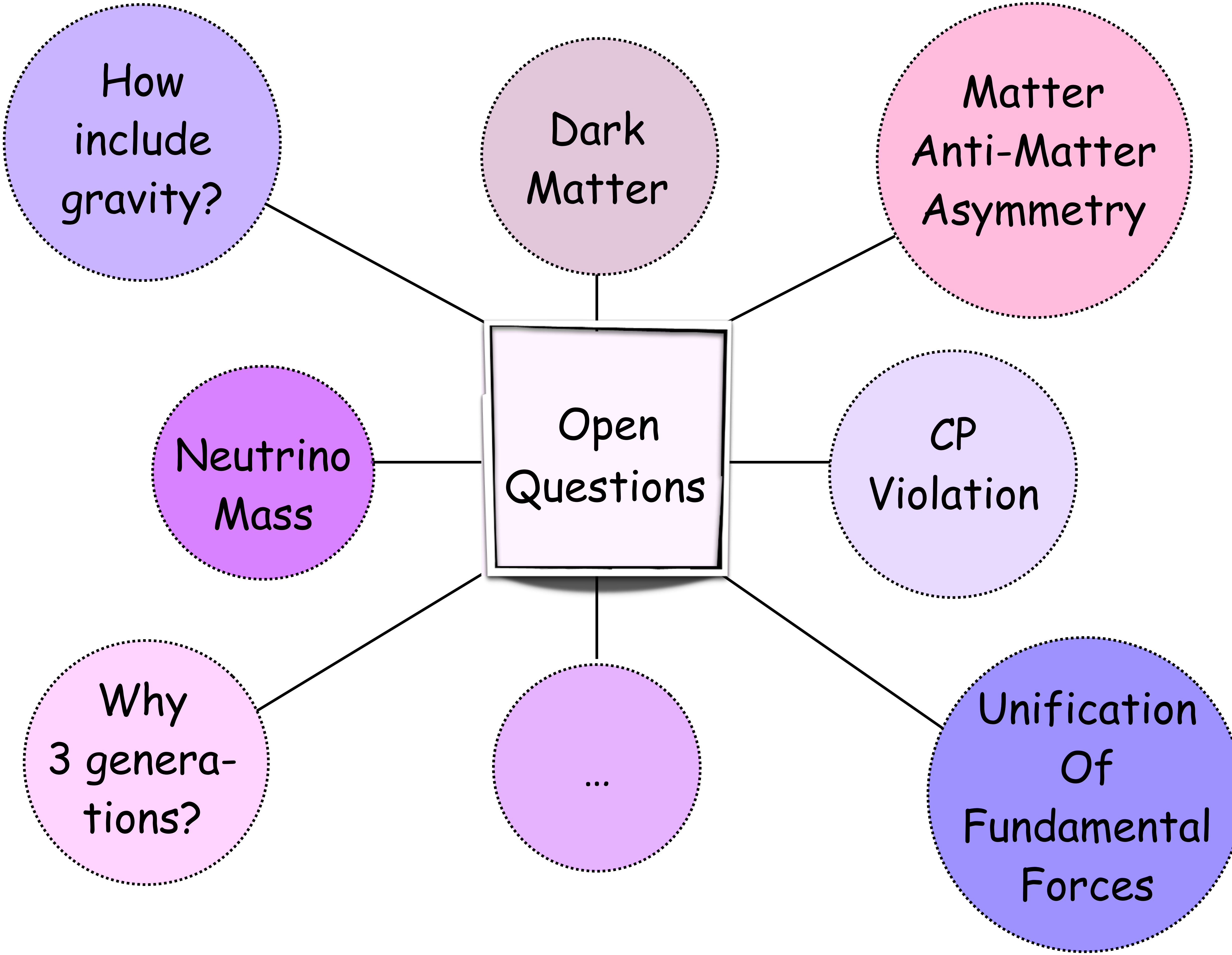


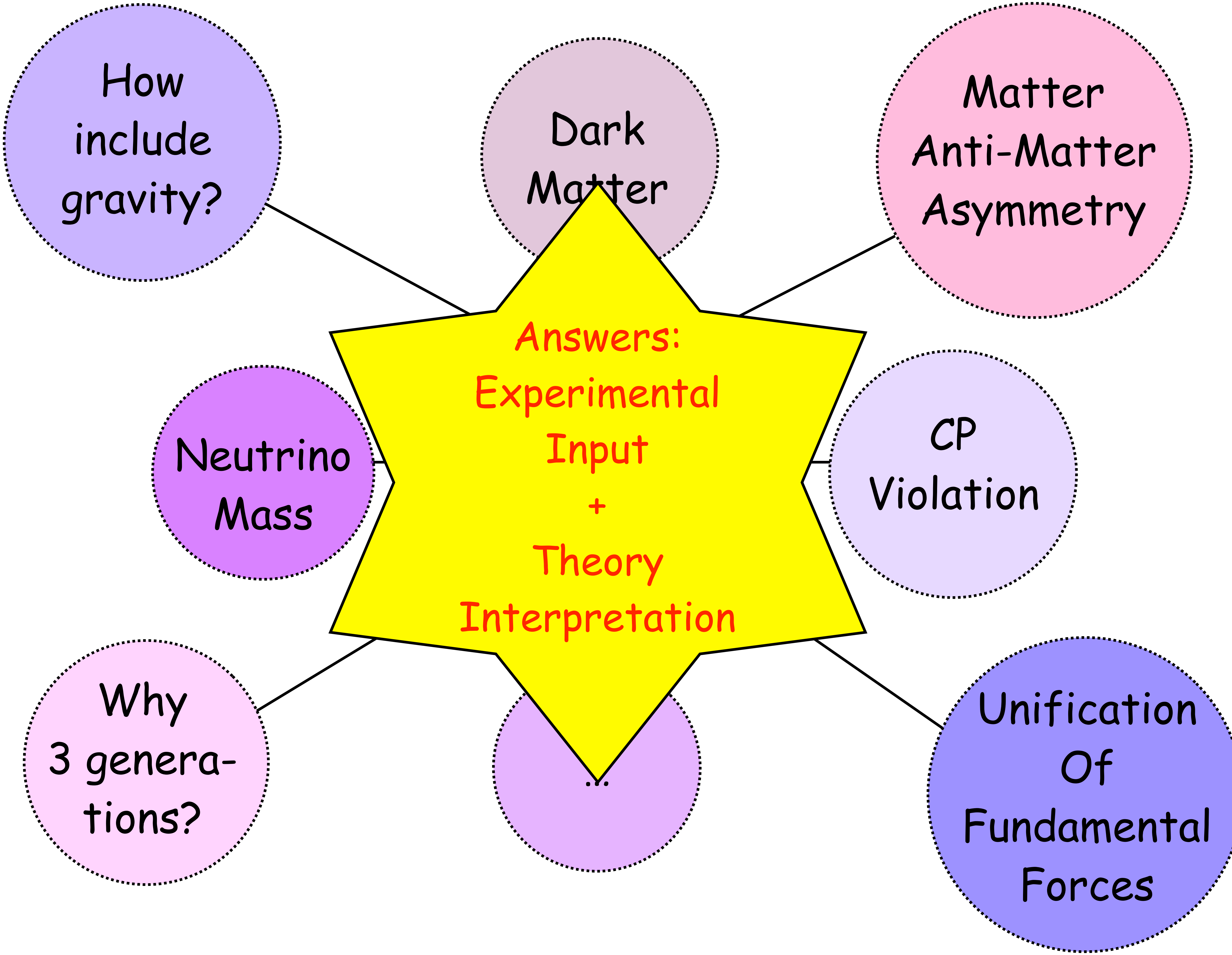
# The Standard Model is Structurally Complete



# The Standard Model is Structurally Complete - But




How include gravity?
Dark Matter
Matter Anti-Matter Asymmetry
Neutrino Mass
Open Questions
CP Violation
Why 3 genera-tions?
...
Unification Of Fundamental Forces


How include gravity?
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Answers: Experimental Input + Theory Interpretation
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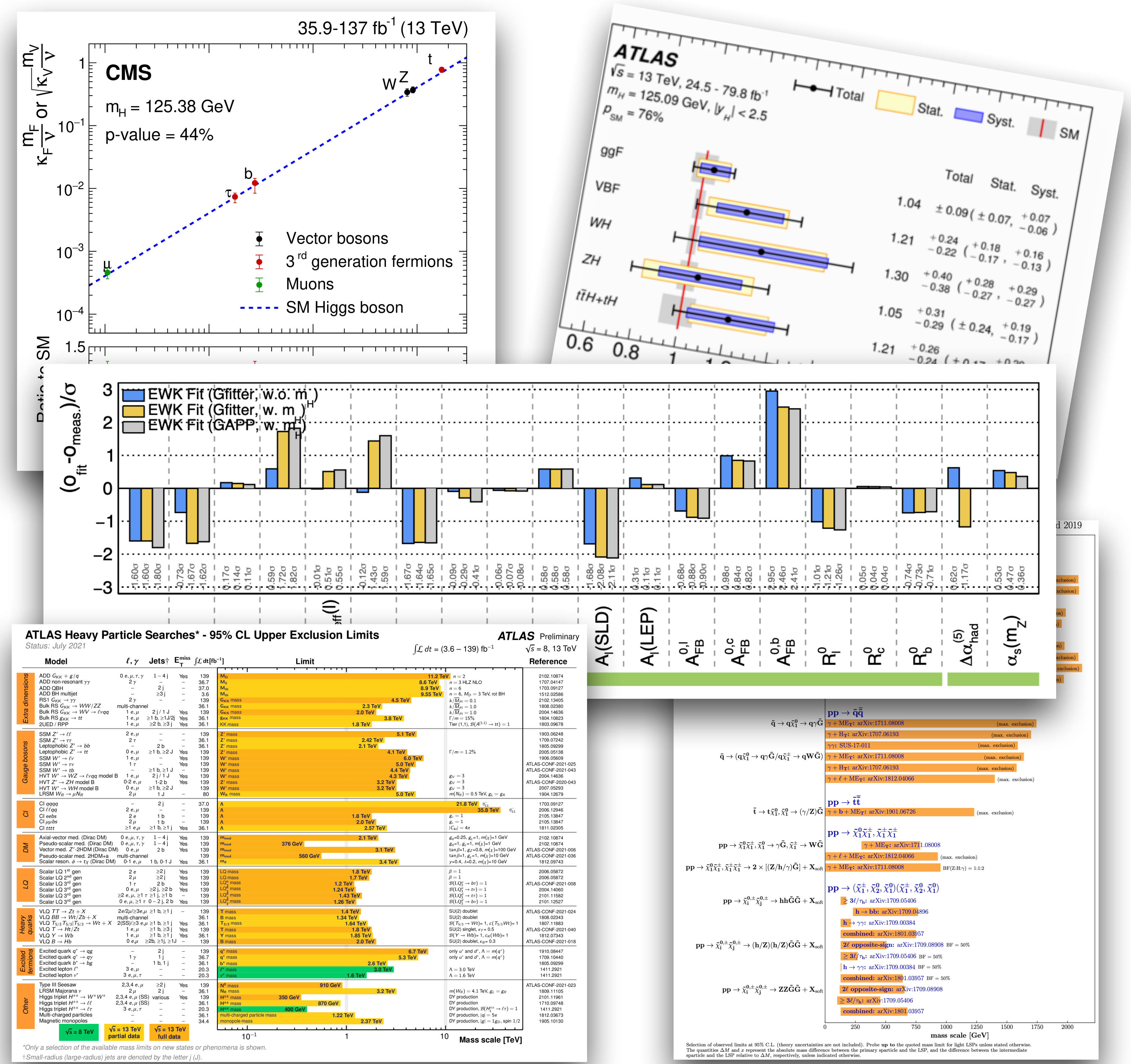
# Status

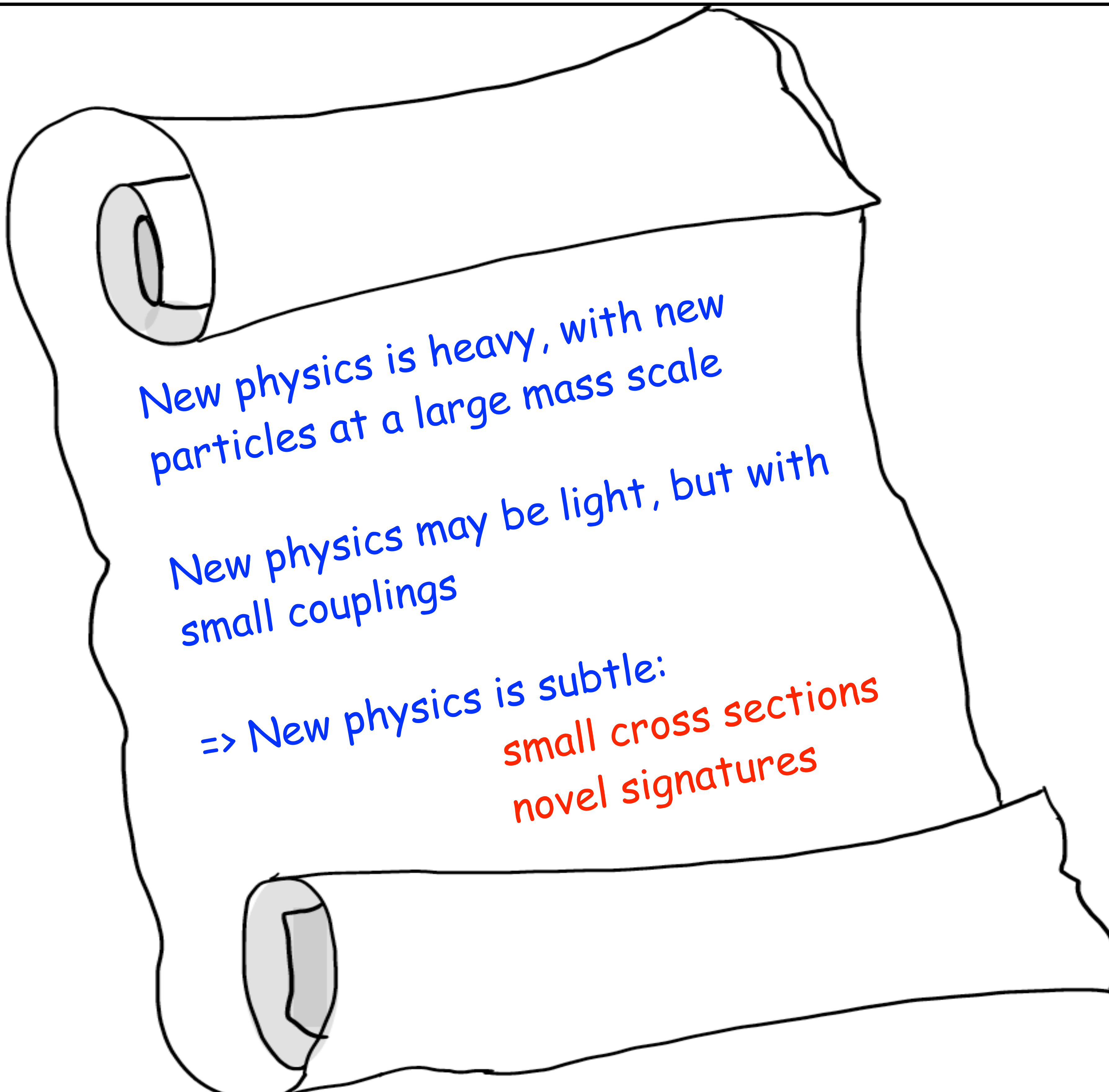



Discovered Higgs Boson behaves very SM-like

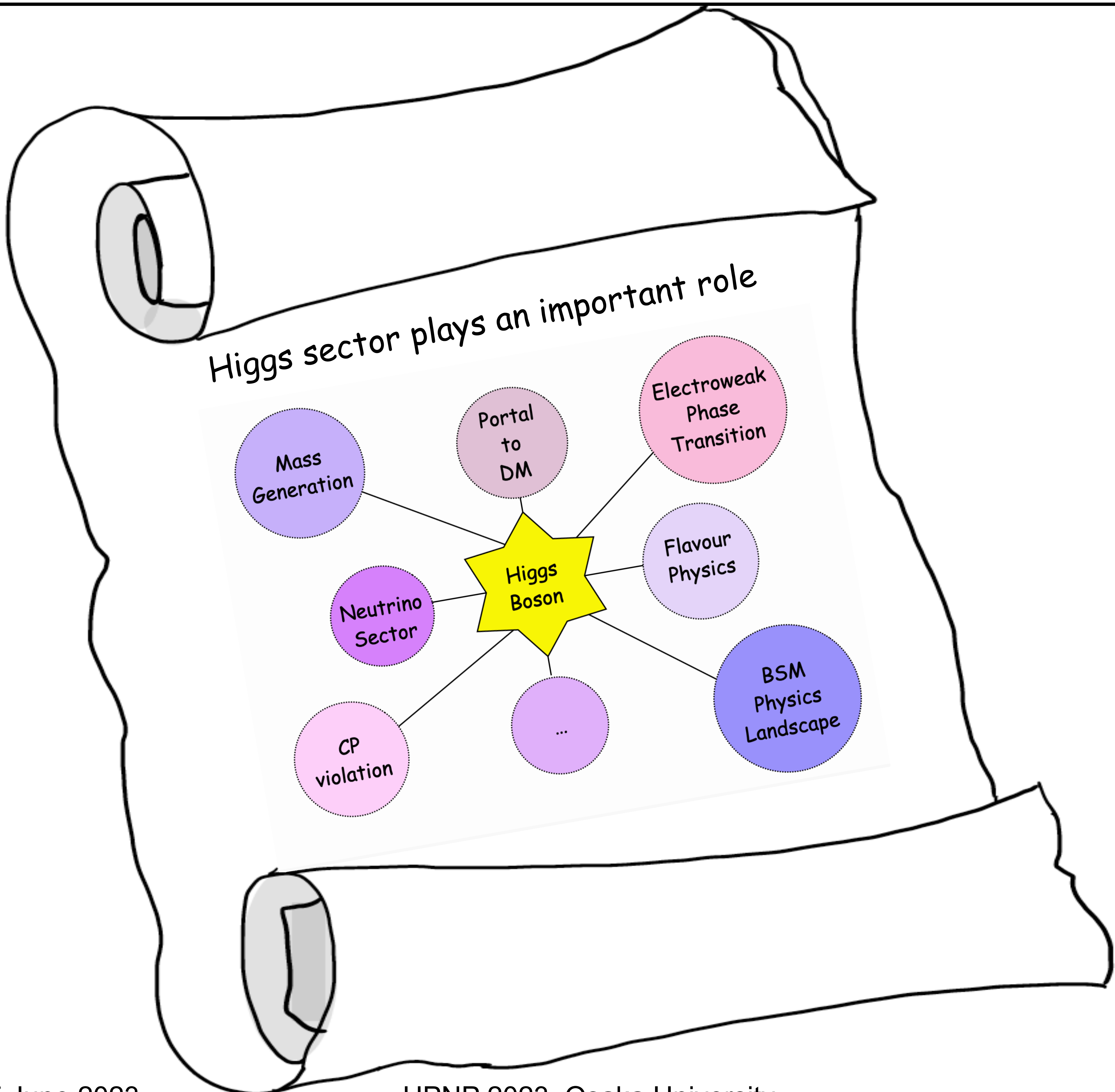
Consistency Test of the SM at the quantum level

No direct discovery of New Physics so far

# Where is New Physics?



# Where is New Physics?




Measuring Electroweak
Symmetry breaking

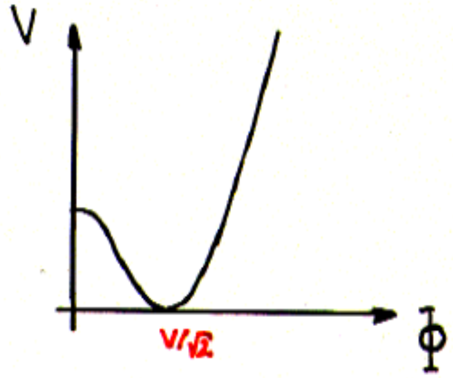
# Ultimate Test of the Higgs Mechanism

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

$$V(\Phi) = \lambda (\Phi^\dagger \Phi - \frac{v^2}{2})^2$$

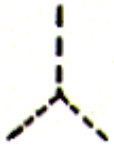
$v = 246$ GeV

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v+H \end{pmatrix} \rightsquigarrow$$




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

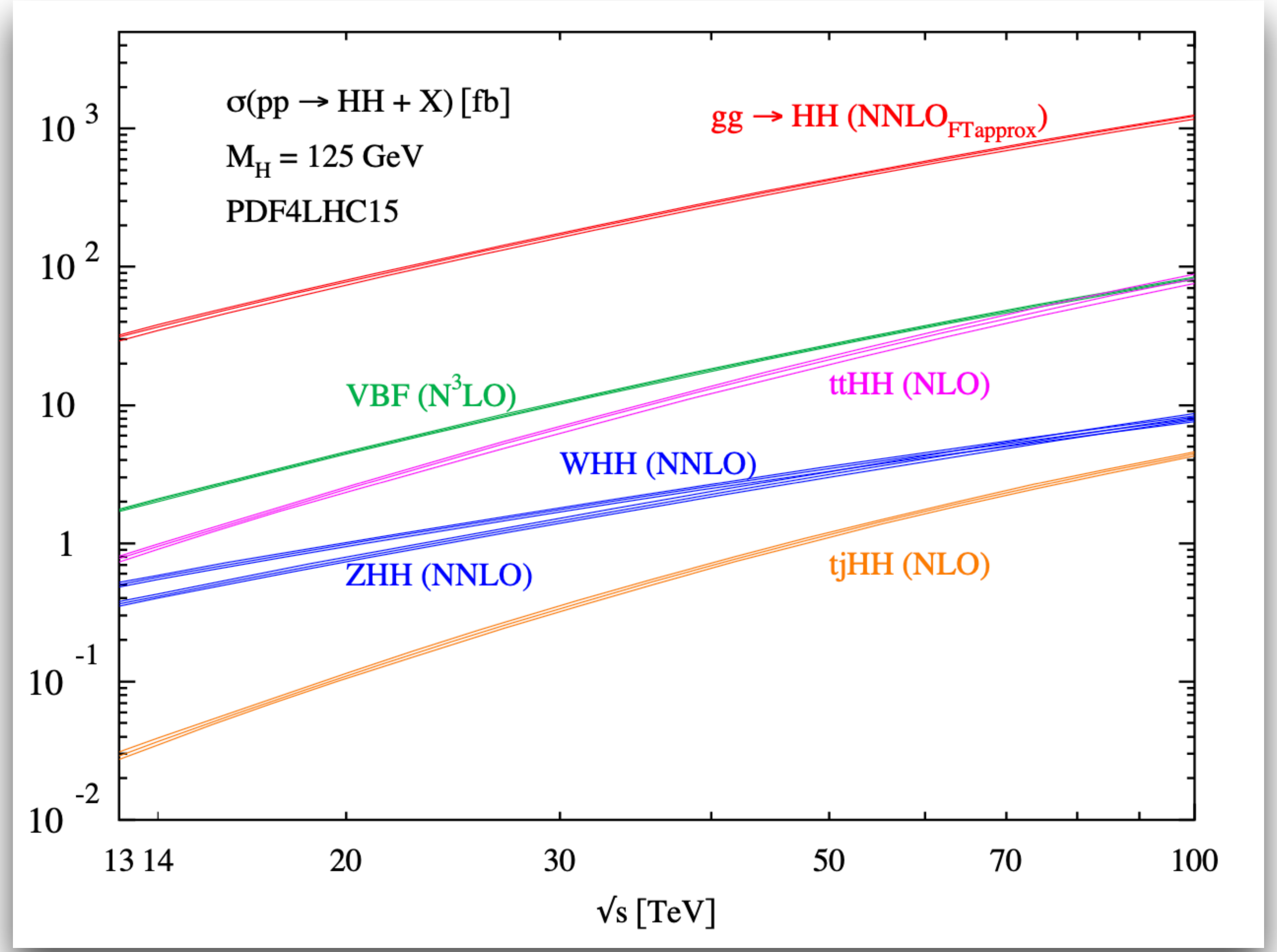
(a) trilinear coupling : via Higgs pair production

(b) quadrilinear coupling : via triple Higgs production

measurement of the Higgs self-couplings and reconstruction of the Higgs potential $\Rightarrow$ establish the scalar sector of the Higgs mechanism experimentally

# Double Higgs Production Processes

[HH, White paper]



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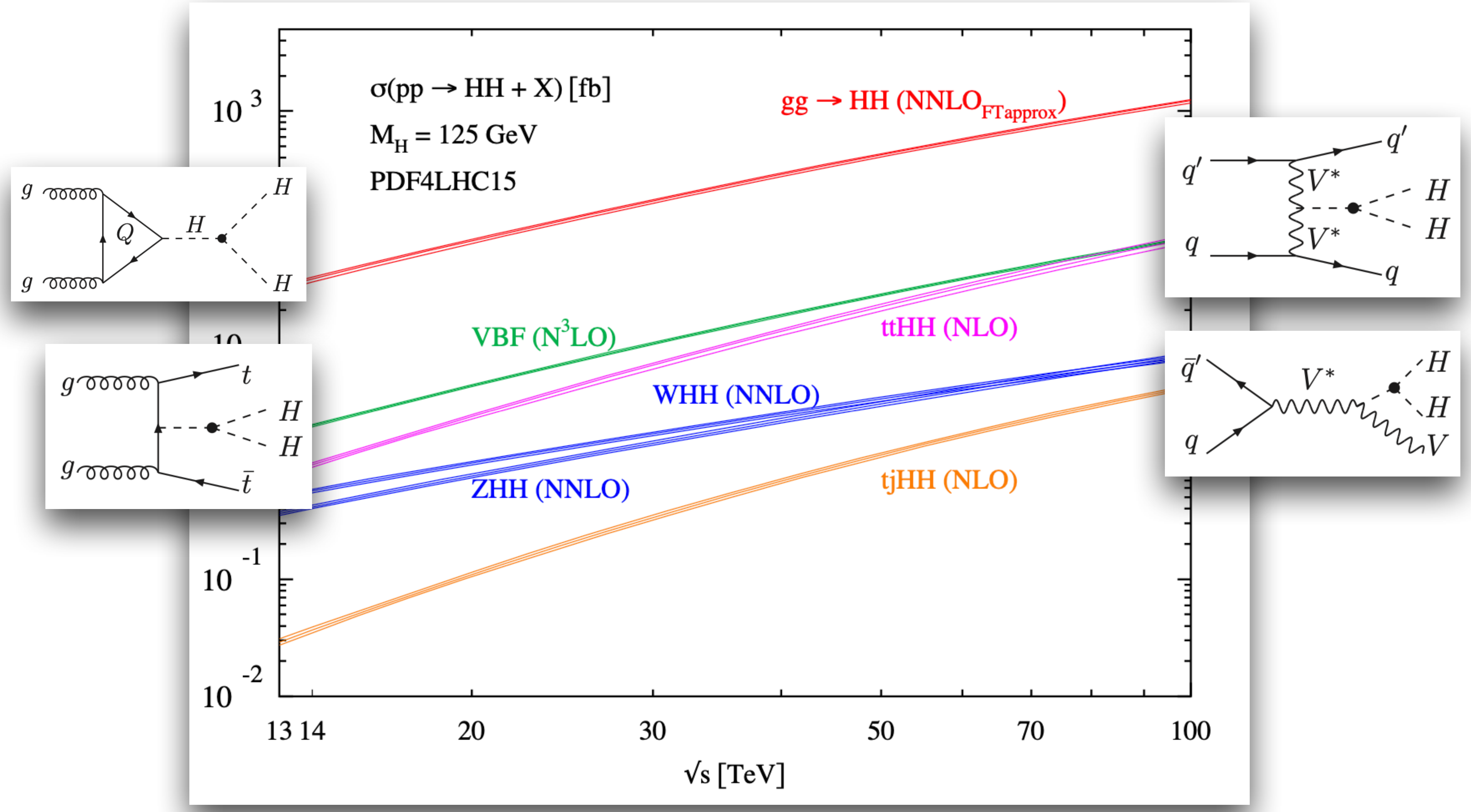
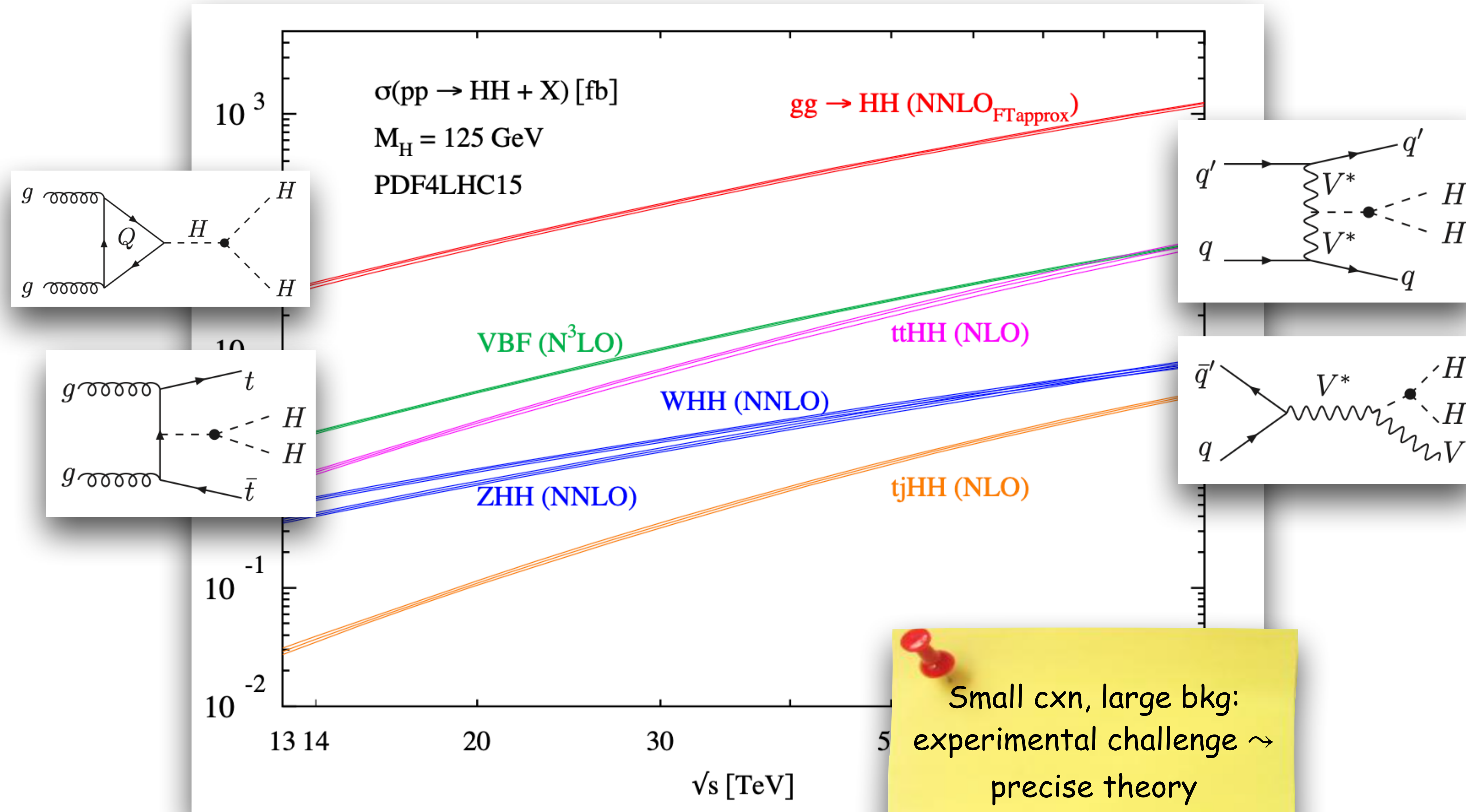


# Double Higgs Production Processes

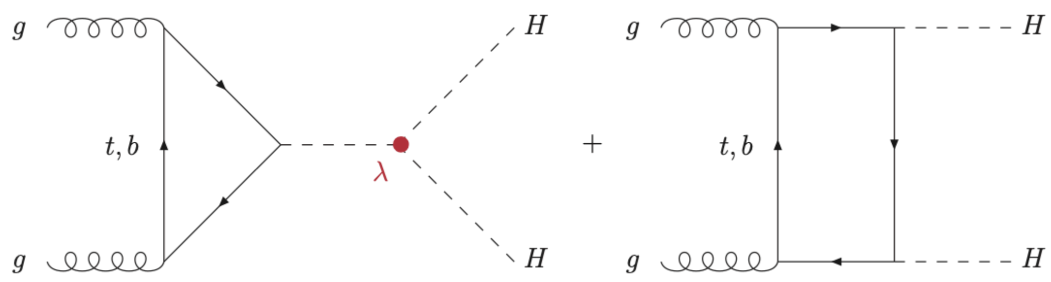
[HH, White paper]



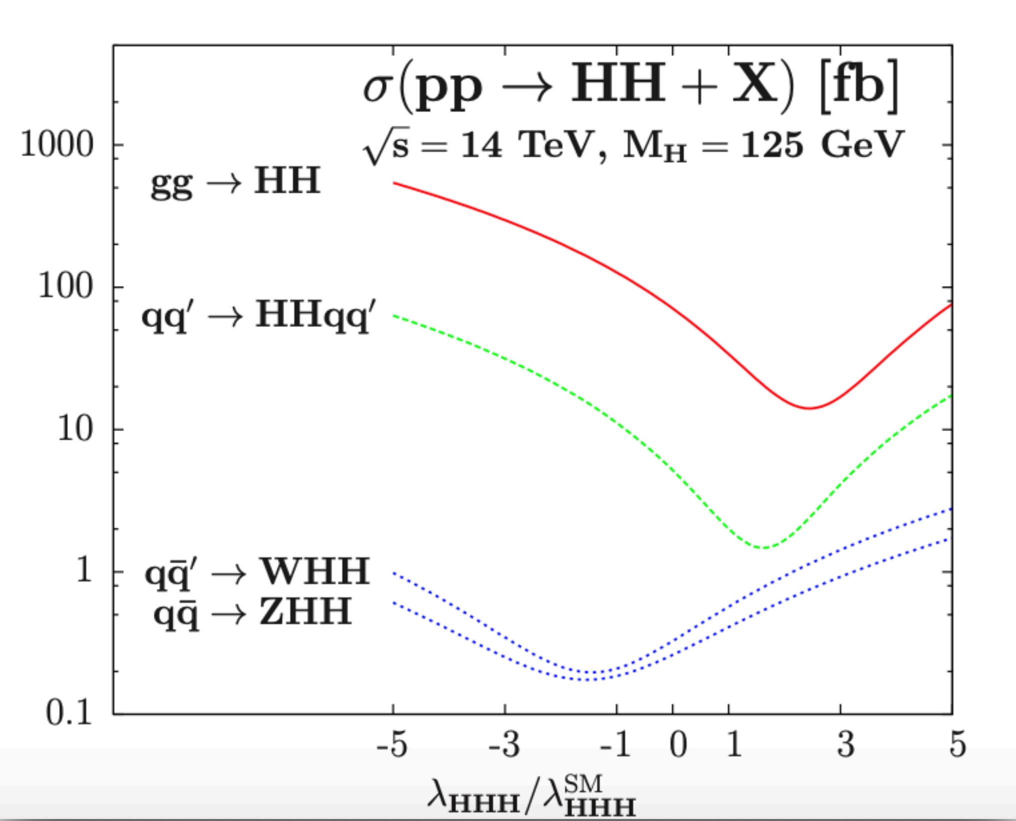

Small cxn, large bkg: experimental challenge ⇝ precise theory predictions required

# Higgs Pair Production through Gluon Fusion

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




- Threshold region sensitive to $\lambda$; 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 $M_{HH}$

# Higher-Order Predictions for Di-Higgs Production

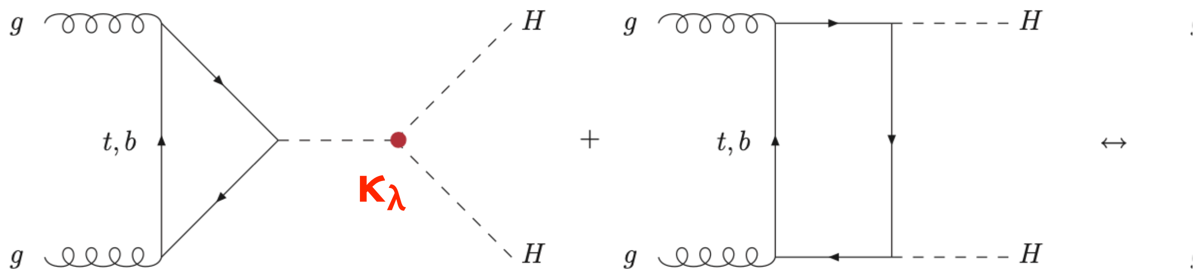
# Higher-Order Corrections to Higgs Pair Production

- 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]
- $N^3LO$ 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]

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 $\kappa_\lambda$

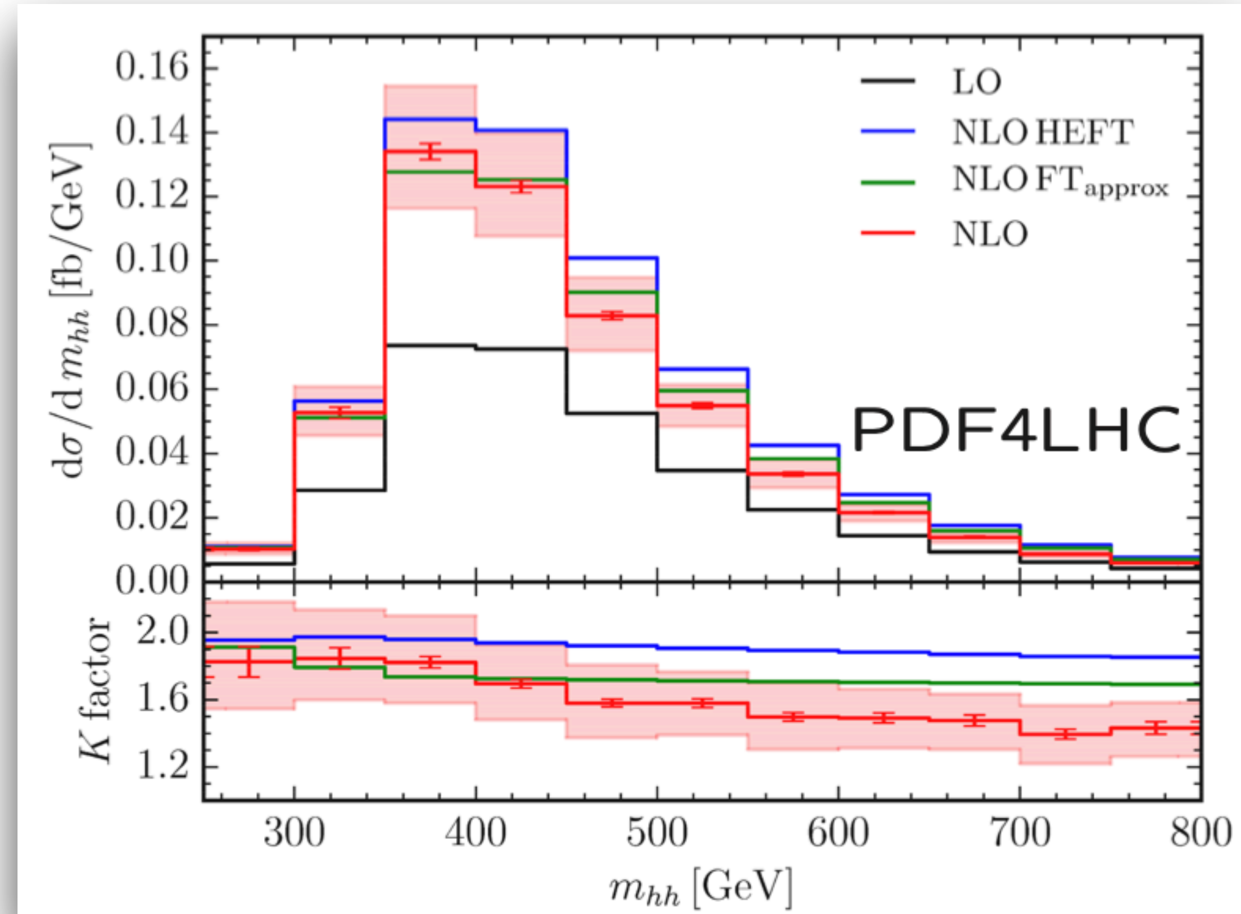
-> uncertainties on di-Higgs cross sections

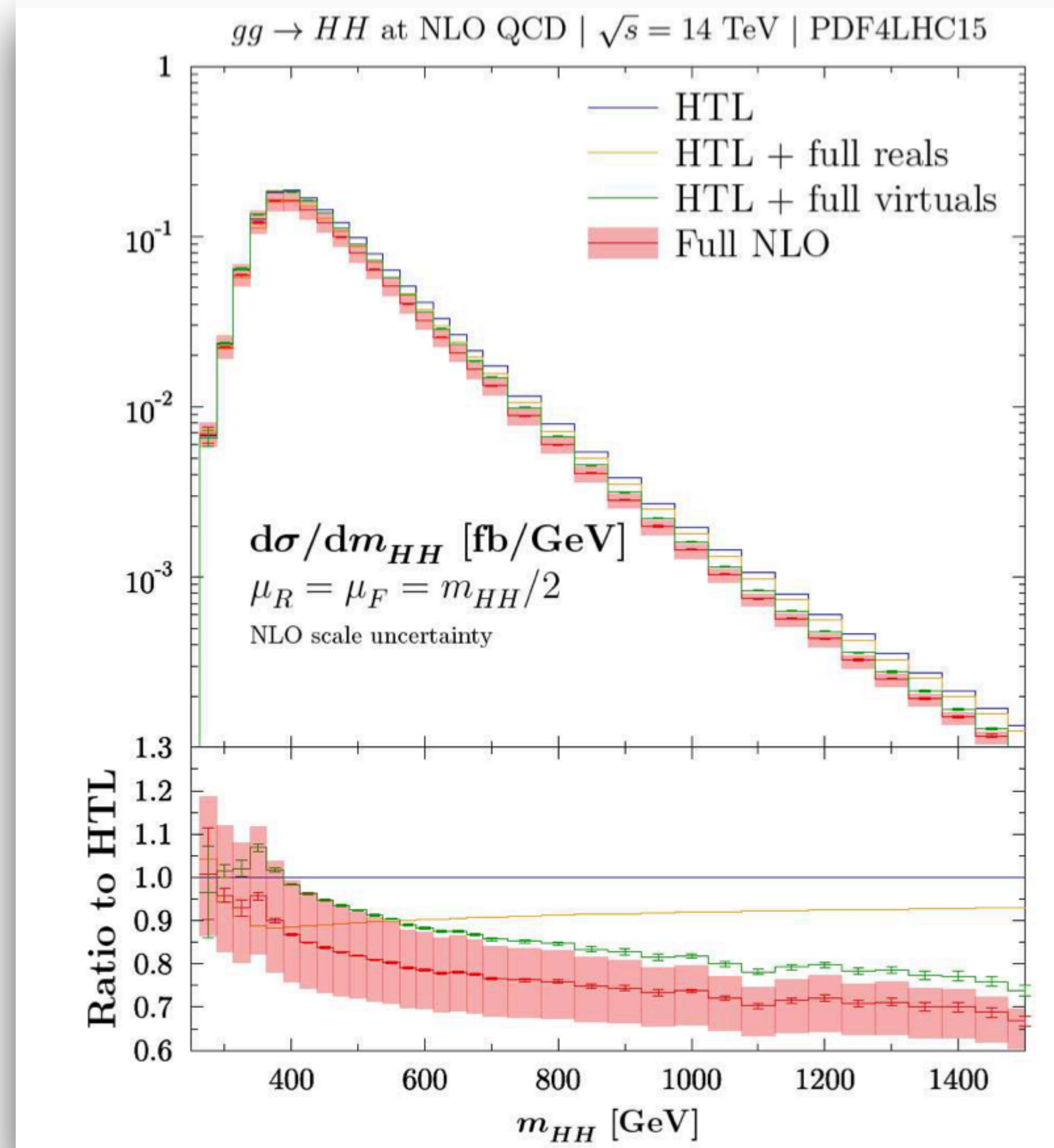


# Full NLO Calculation

[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 20-30% for distributions

# Uncertainties due to $m_t$

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

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

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

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

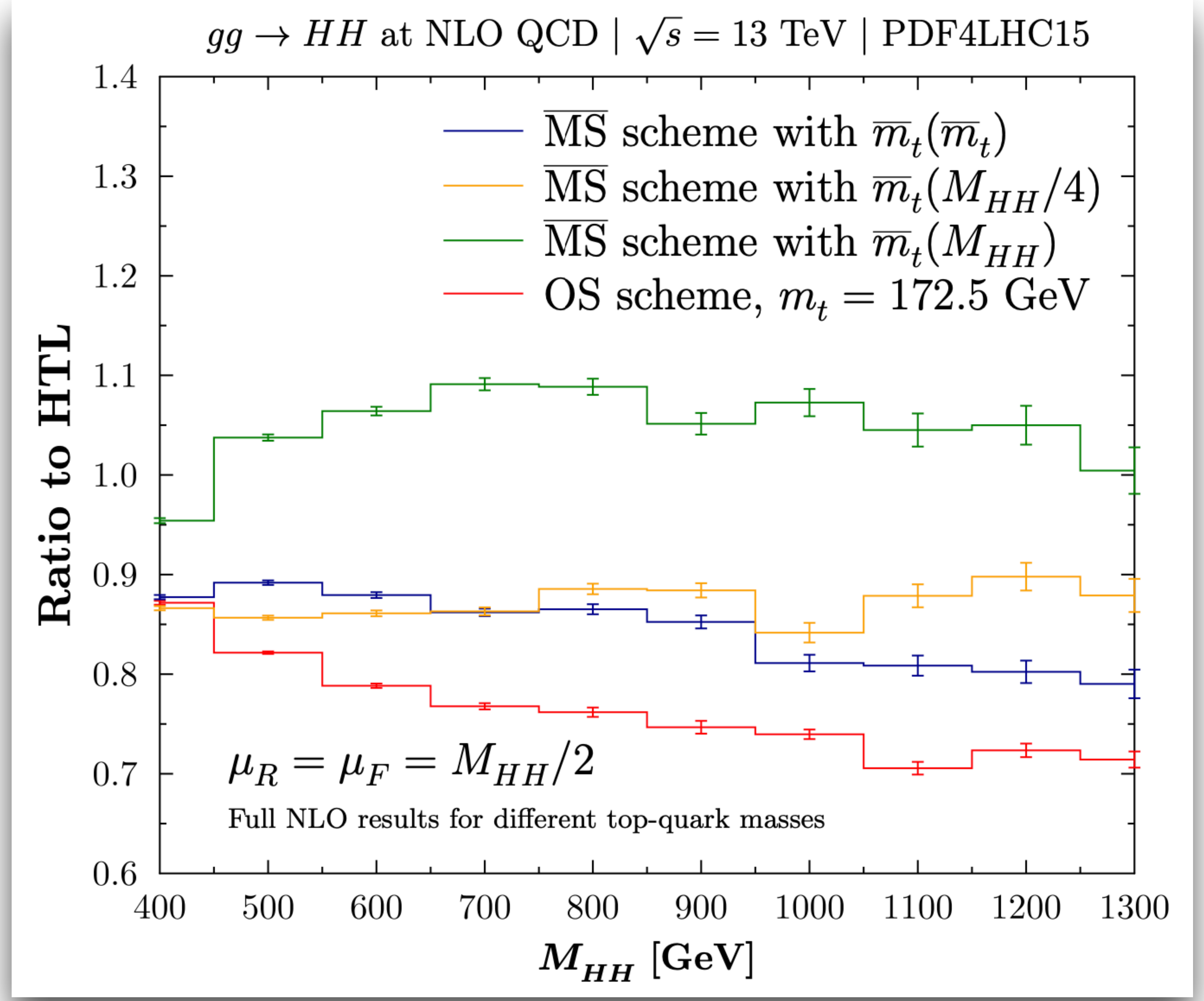
$$\Delta F_{1,mass} \rightarrow \frac{\alpha_s}{\pi}\left\{2F_{1,LO}\left[\log\frac{\mu_t^2}{\hat{s}} + \frac{4}{3}\right] + \frac{\overline{m}_t^2(\mu_t)}{\hat{s}}G_1(\hat{s},\hat{t})\right\},$$

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

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

# Scale Choice

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



# Uncertainties at NLO

- Renormalization and factorization scale uncertainties at NLO:

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

- $m_t$ scale/scheme uncertainties at NLO:

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

- Linear sum of uncertainties ~>

# Final Uncertainties at $FT_{approx}$

- 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 $\text{NNLO}_{\text{FTapprox}}$:

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

# NLO QCD Corrections to 2HDM Higgs Pairs

# CP-Conserving 2HDM

[Lee,'73], [Branco eal,'11]

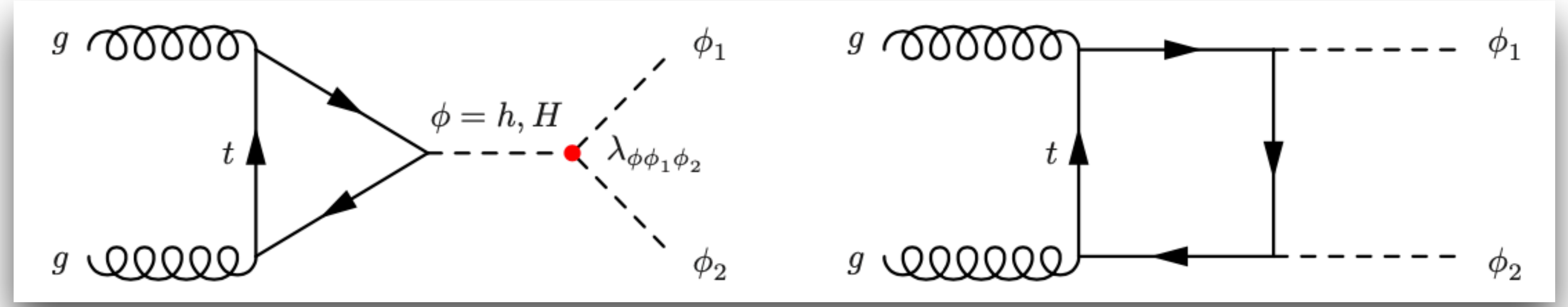
- 2HDM Higgs potential w/ softly broken $\mathbb{Z}_2$ symmetry:

$$V_{\rm tree} = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left[ m_{12}^2 \Phi_1^\dagger \Phi_2 + {\rm h.c.} \right] + \frac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \left[ \frac{1}{2}\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + {\rm h.c.} \right] .$$

- Higgs spectrum after EWSB: 2 CP-even h,H with $m_h < m_H$,
  1 CP-odd A,
  charged Higgs pair $H^\pm$

# Gluon Fusion into $\phi_1\phi_2$ with $\phi_1\phi_2$=hH, AA

✦ Contributing diagrams at leading order:



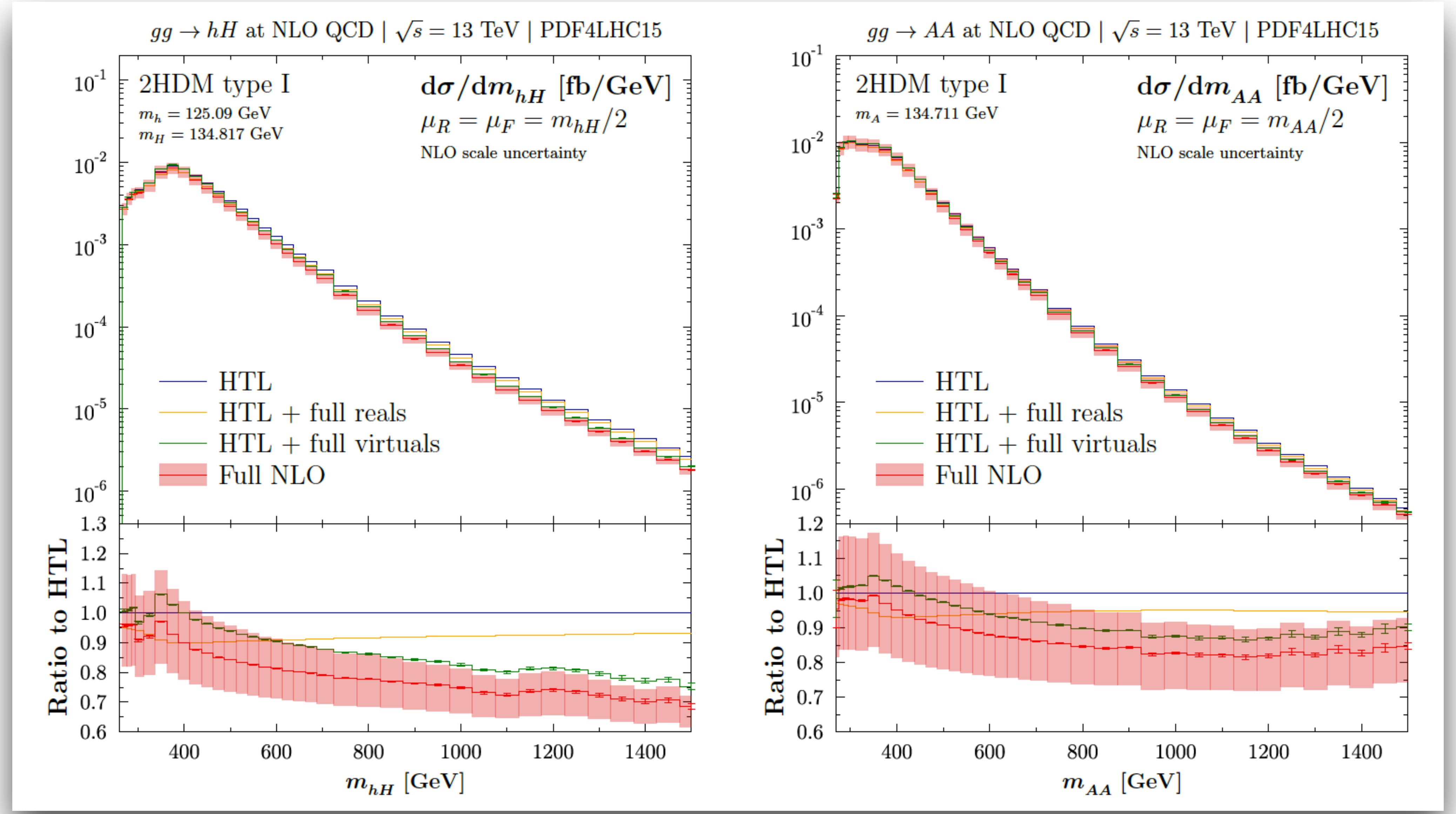

✦ 2HDM type 1 benchmark point (compatible w/ theor. & exp. constraints):

[taken from Abouabid et al.,'22]

$$
\begin{aligned}
m_h &= 125.09\,\text{GeV}, & m_H &= 134.817\,\text{GeV}, \\
m_A &= 134.711\,\text{GeV}, & m_{H^\pm} &= 161.5\,\text{GeV}, \\
m_{12}^2 &= 4305\,\text{GeV}^2, & \alpha &= -0.102, \\
\tan\beta &= 3.759, & v &= 246.22\,\text{GeV}\,.
\end{aligned}
$$

# NLO Top Mass Effects in Invariant Mass Distributions

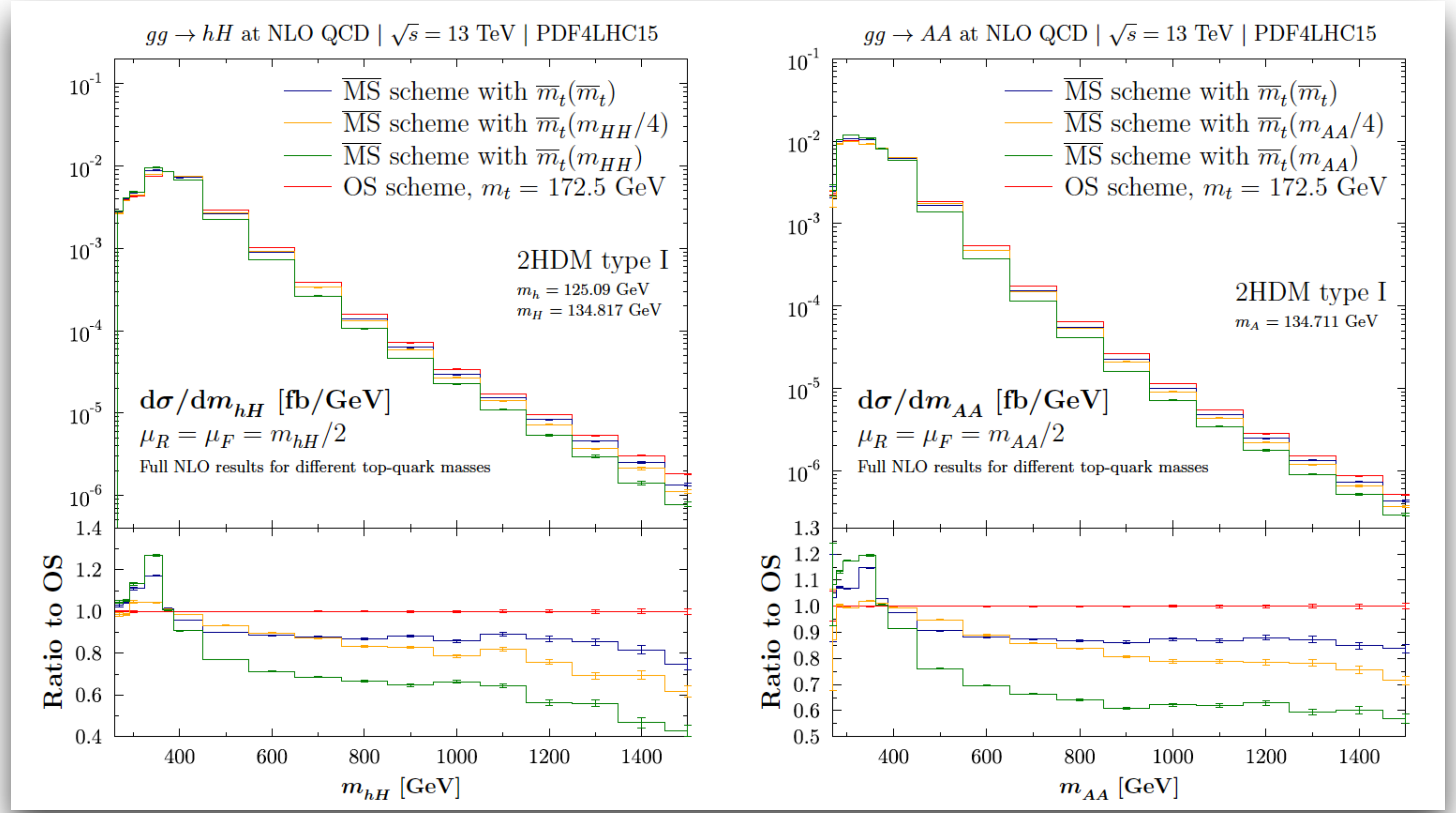
[Baglio,Campanario,Glaus,MM,Ronca,Spira,'23]




- Mass effects in distributions: -30% (-15%) at Q~1.5 TeV for hH (AA)
- increases w/ c.m. energy (results provided for 14, 27, 100 TeV)
- Mass effects on total cxn: -12% (-5%) at 13 TeV (increases w/ c.m. energy)

# Top Quark Scale and Scheme Uncertainties

[Baglio,Campanario,Glaus,MM,Ronca,Spira,'23]



# Top Quark Scale and Scheme Uncertainties in Total Cross Section

[Baglio,Campanario,Glaus,MM,Ronca,Spira,'23]

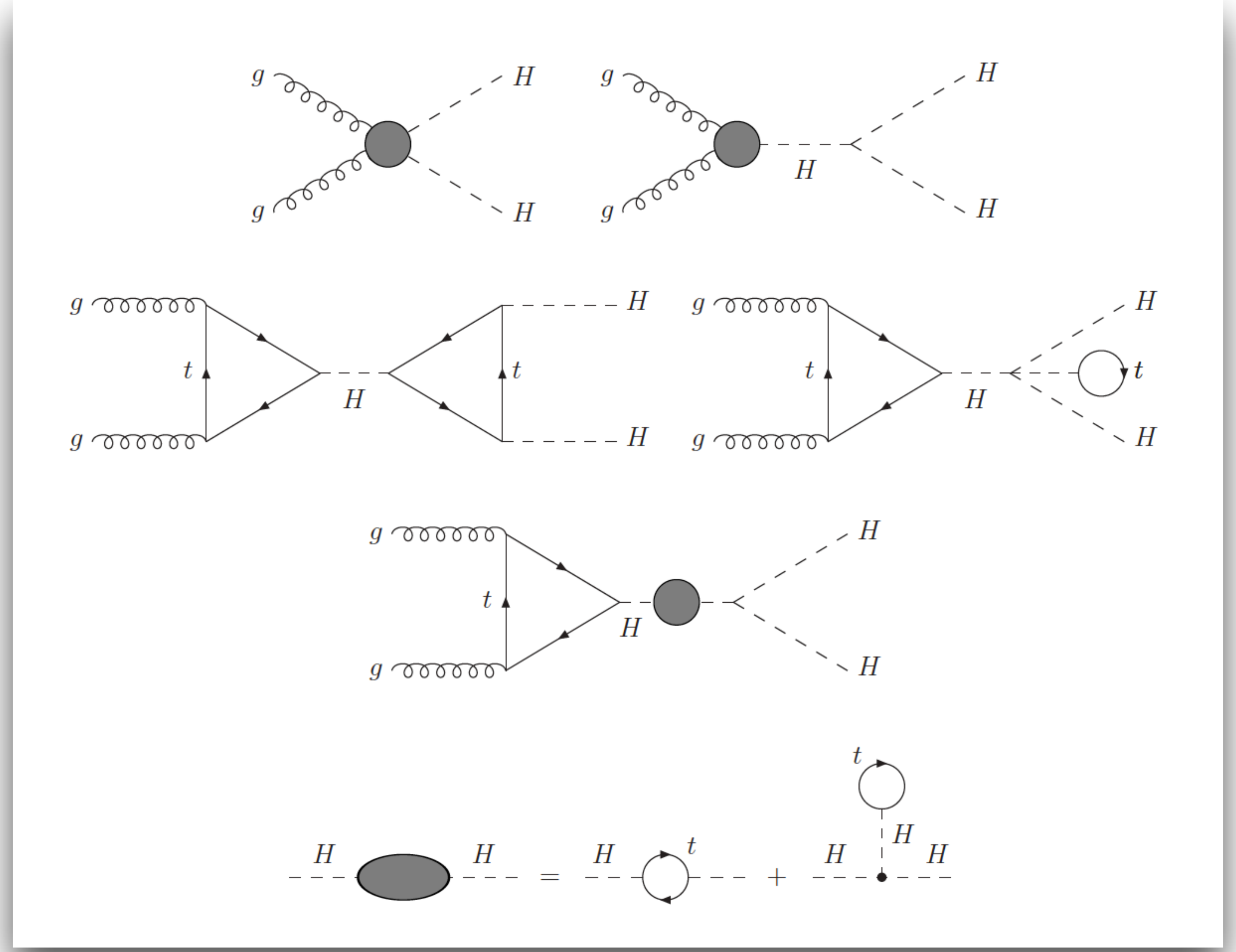
$$
\begin{aligned}
13\ \text{TeV}: &\quad \sigma_{gg\to hH} = 1.592(1)^{+6\%}_{-11\%}\ \text{fb},\\
14\ \text{TeV}: &\quad \sigma_{gg\to hH} = 1.876(1)^{+6\%}_{-11\%}\ \text{fb},\\
27\ \text{TeV}: &\quad \sigma_{gg\to hH} = 7.036(4)^{+5\%}_{-12\%}\ \text{fb},\\
100\ \text{TeV}: &\quad \sigma_{gg\to hH} = 60.49(4)^{+4\%}_{-14\%}\ \text{fb},
\end{aligned}
$$

$$
\begin{aligned}
13\ \text{TeV}: &\quad \sigma_{gg\to AA} = 1.643(1)^{+9\%}_{-7\%}\ \text{fb},\\
14\ \text{TeV}: &\quad \sigma_{gg\to AA} = 1.927(1)^{+9\%}_{-8\%}\ \text{fb},\\
27\ \text{TeV}: &\quad \sigma_{gg\to AA} = 7.012(4)^{+8\%}_{-8\%}\ \text{fb},\\
100\ \text{TeV}: &\quad \sigma_{gg\to AA} = 58.12(3)^{+7\%}_{-9\%}\ \text{fb}.
\end{aligned}
$$

# Top-Yukawa-Induced EW Corrections to Higgs Pair Production

# Top-Yukawa-Induced Corrections to Higgs Pair Production

- Part of the electroweak corrections to Higgs pair production
- Full top-mass dependence in the triple Higgs vertex and self-energy corrections
  HTL in radiative corrections to the effective ggH and ggHH vertices

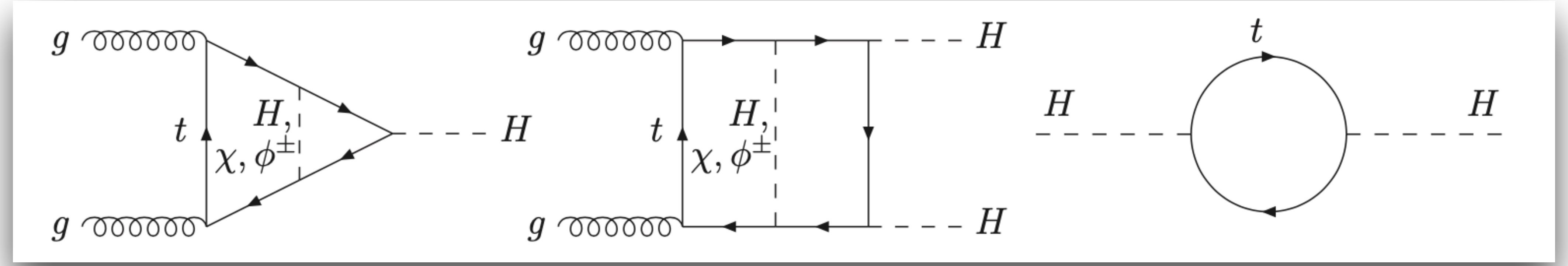


# Effective Lagrangians

- Effective ggH and ggHH vertices (top-Yukawa induced EW corrections in HTL):

$$\mathcal{L}_{eff} = \frac{\alpha_s}{12\pi} G^{a\mu\nu} G^a_{\mu\nu} \left\{ (1+\delta_1)\frac{H}{v} + (1+\eta_1)\frac{H^2}{2v^2} + \mathcal{O}(H^3) \right\}$$

$$\delta_1 = \frac{x_t}{2} + \mathcal{O}(x_t^2) \qquad \eta_1 = 4x_t + \mathcal{O}(x_t^2) \qquad x_t = \frac{m_t^2}{(4\pi)^2 v^2}$$



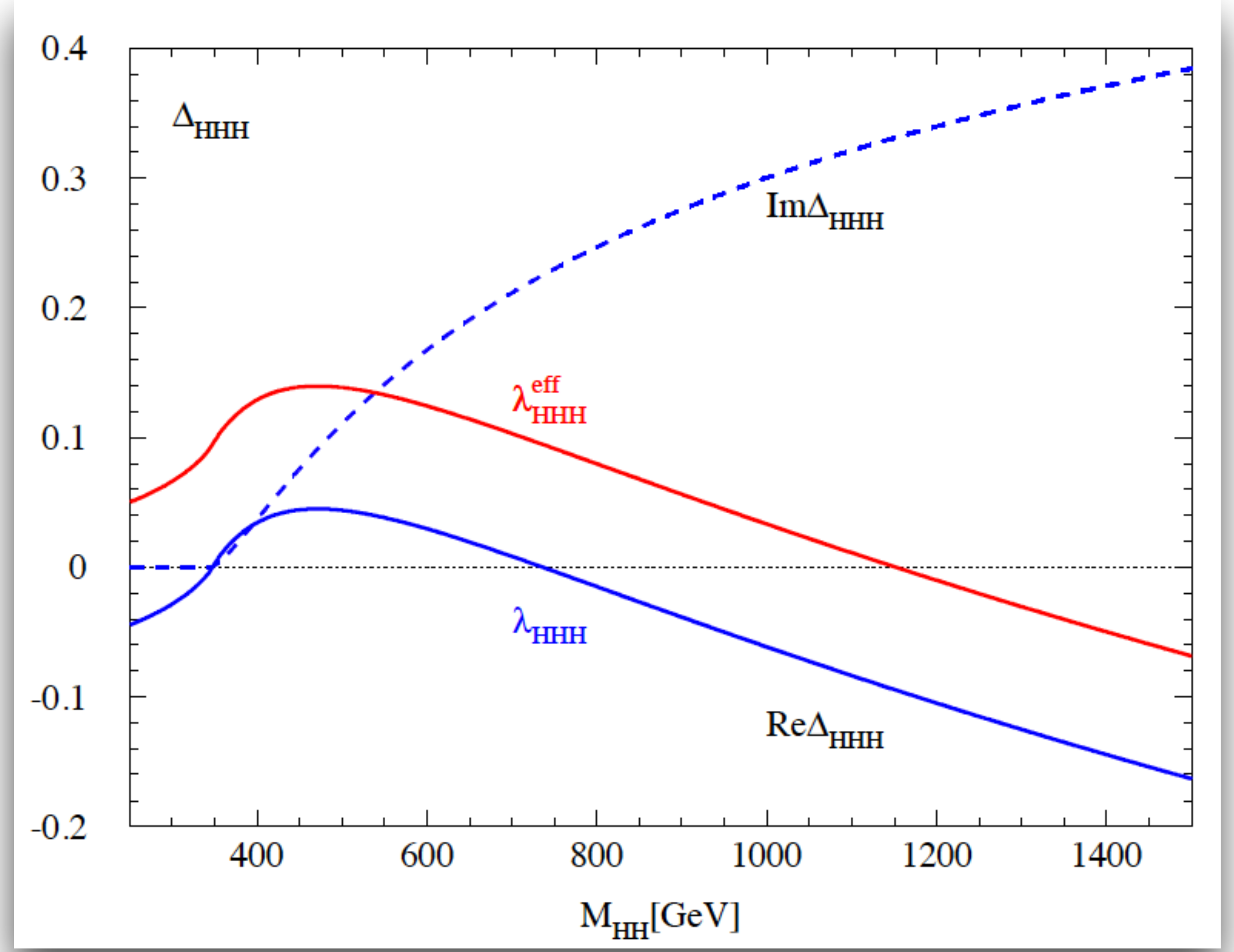

- Effective Higgs self-couplings: from effective Higgs potential

$$\lambda^{eff}_{HHH} = 3\frac{M_H^2}{v} - \frac{3m_t^4}{\pi^2 v^3} \approx 0.91 \times 3\frac{M_H^2}{v}$$

$$\lambda^{eff}_{HHHH} = 3\frac{M_H^2}{v^2} + \Delta\lambda_{HHHH} \qquad \Delta\lambda_{HHHH} = -\frac{12 m_t^4}{\pi^2 v^4}$$

# Relative Top-Yukawa-Induced EW Correction Factor $\Delta_{HHH}$

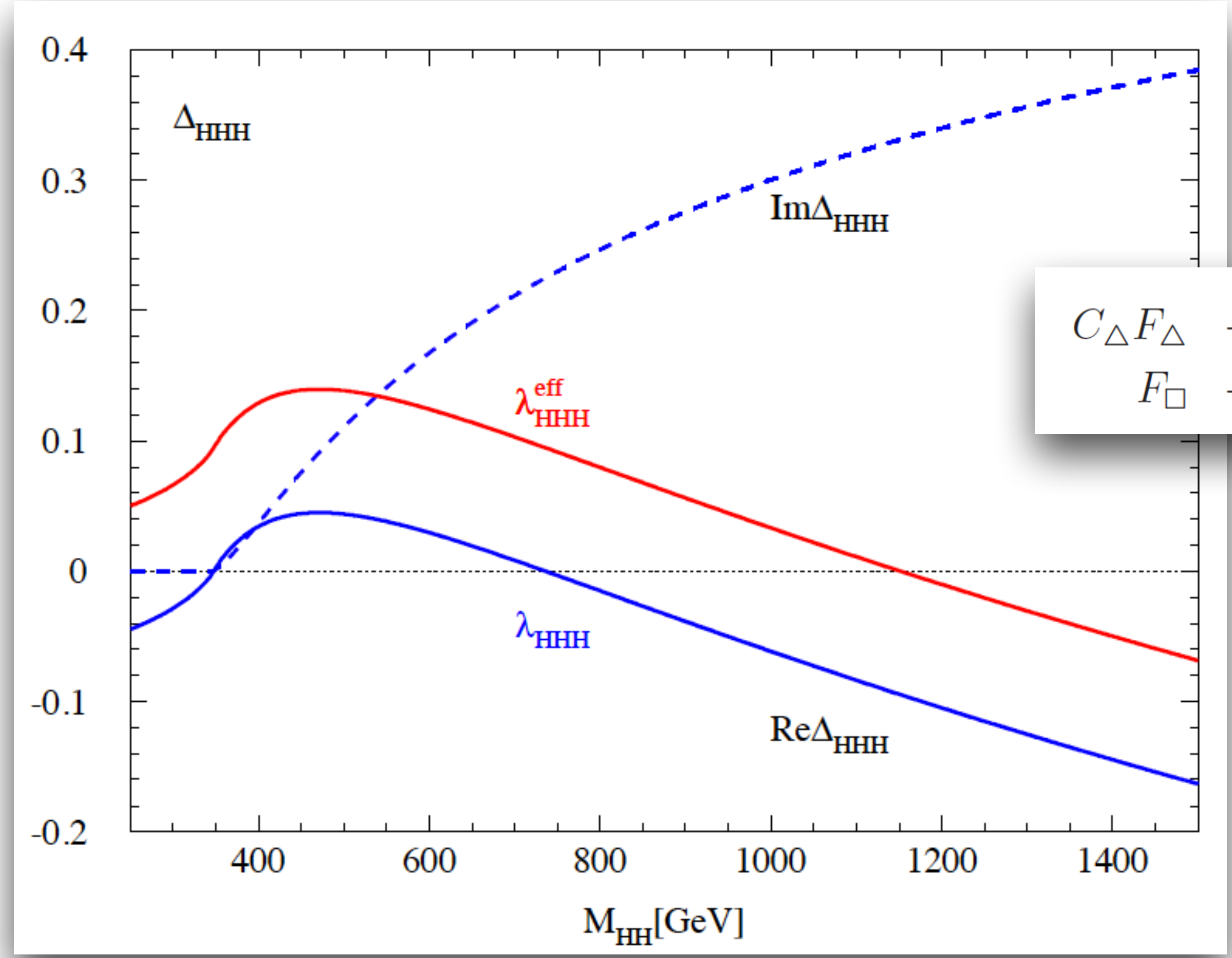
[MM,Schlenk,Spira,'22]




Effective trilinear coupling does not capture the bulk of the EW corrections

# Relative Top-Yukawa-Induced EW Correction Factor $\Delta_{HHH}$

[MM,Schlenk,Spira,'22]

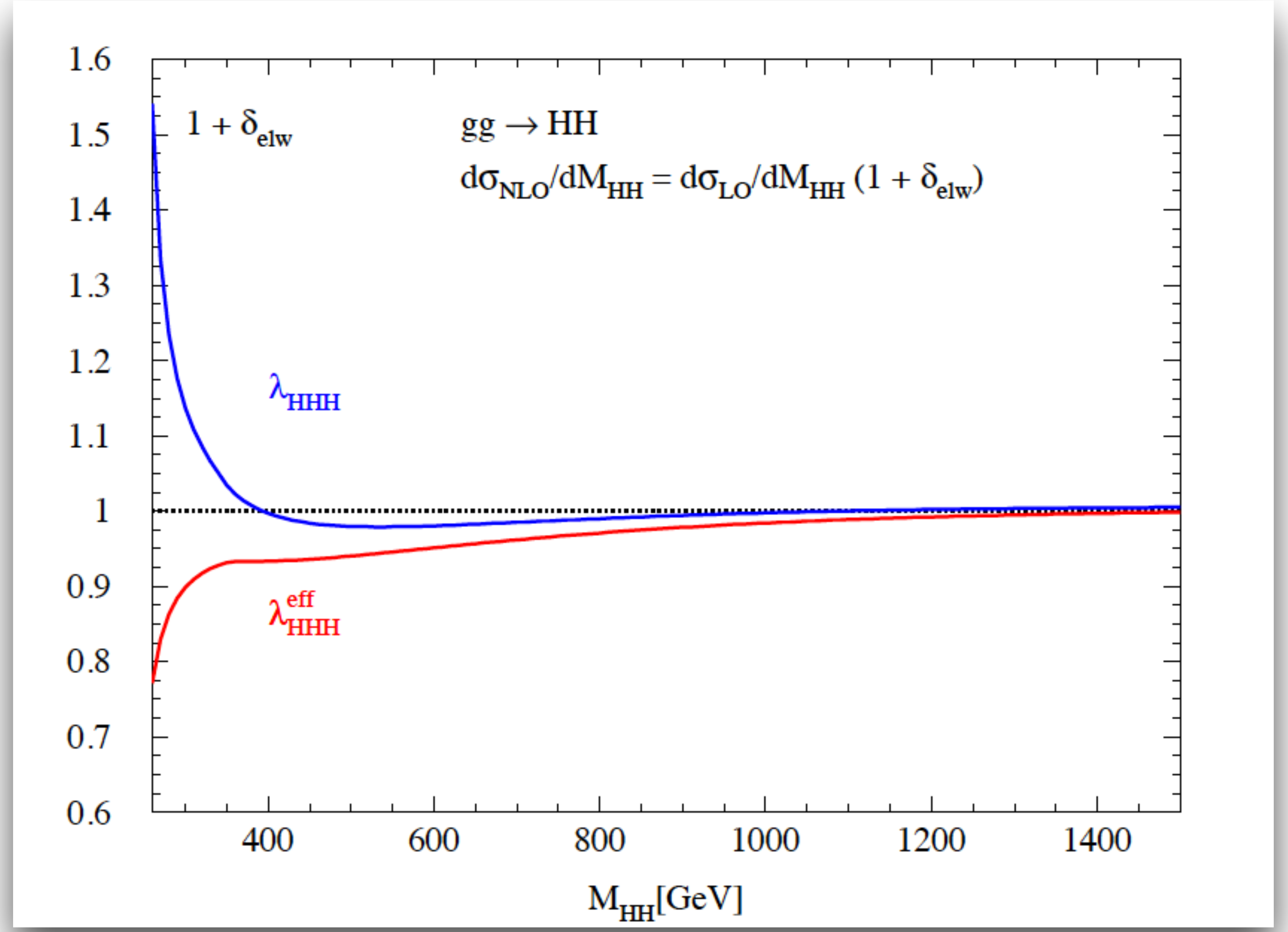



$$
\begin{aligned}
C_\triangle F_\triangle &\to C_\triangle F_\triangle (1+\Delta_\triangle) \\
F_\Box &\to F_\Box (1+\Delta_\Box)\,,
\end{aligned}
$$

Effective trilinear coupling does not capture the bulk of the EW corrections

# Relative Top-Yukawa-Induced EW Correction to differential HH prod

[MM,Schlenk,Spira,'22]




- Large enhancement near threshold because of vanishing LO matrix element
- Suppression is lifted by mismatch of EW corrections to triangle and box diagrams

# Effect of Top-Yukawa-Induced EW Corrections on Total Cxn

✦ Effect of top-Yukawa-induced EW correction on total integrated hadronic cross section:

$$
\begin{aligned}
\sigma &= K_{elw} \times \sigma_{LO} \\
K_{elw} &\approx 1.002 \qquad (\lambda_{HHH}) \\
K_{elw}^{eff} &\approx 0.938 \qquad (\lambda_{HHH}^{eff})
\end{aligned}
$$

- Corrections induce an effect of about 0.2%
- Bulk of corrections cannot be absorbed in the effective trilinear Higgs coupling (leads to an artificial increase of the relative EW corrections)
- ~> Inclusion of complete EW corrections is mandatory


HH and Baryogenesis
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学生証を提示頂いた方限定!!
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手指消毒

- **Electroweak Baryogenesis (EWBG):** generation of the observed baryon-antibaryon asymmetry in the electroweak phase transition (EWPT) [Riemer-Sorensen, Jenssen '17]

$$5.8 \cdot 10^{-10} < \frac{n_B - n_{\bar{B}}}{n_\gamma} < 6.6 \cdot 10^{-10}$$

- **Sakharov Conditions:** [Sakharov '67]
  - $(i)$ $B$ number violaton (sphaleron processes)
  - $(ii)$ $C$ and $CP$ violation
  - $(iii)$ Departure from thermal equilibrium

- **Additional constraint:** EW phase transition must be strong first order PT [Quiros '94; Moore '99]

$$\xi_c \equiv \frac{\langle \Phi_c \rangle}{T_c} \geq 1$$

$\langle \Phi_c \rangle$ and $T_c$ field configuration and temperature at phase transition

- 2HDM type II struggle to reach SFOEWPT (compared to type I)

[see e.g. Basler,Krause,MM,Wittbrodt,Wlotzka,'16]

- For 2HDM type II points with $\xi_c < 1$:

What extra dynamics is required to achieve SFOEWPT?

- Our model: CP-conserving 2HDM with softly broken discrete $Z_2$ symmetry

$$V_{\text{tree}}(\Phi_1,\Phi_2) = m_{11}^2(\Phi_1^\dagger\Phi_1) + m_{22}^2(\Phi_2^\dagger\Phi_2) - m_{12}^2(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1) + \lambda_1(\Phi_1^\dagger\Phi_1)^2 + \lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{1}{2}\lambda_5[(\Phi_1^\dagger\Phi_2)^2 + (\Phi_2^\dagger\Phi_1)^2]$$

- Extended by (purely scalar) dim-6 EFT contributions to the Higgs potential [Anisha eal,´19]

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{2HDM}} + \sum_i \frac{C_6^i}{\Lambda^2} O_6^i \quad \Rightarrow \quad V_{\text{dim-6}} = -\sum_i \frac{C_6^i}{\Lambda^2} O_6^i$$

- Higgs pair production: a tool for fingerprinting an SFOEWPT?

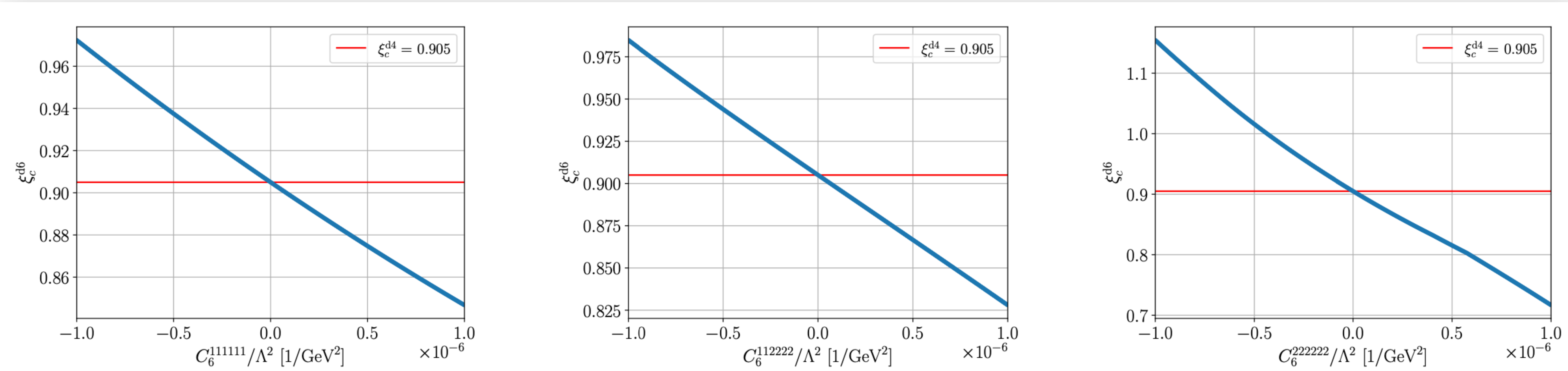
| | | | |
|---|---|---|---|
| $O_6^{111111}$ | $(\Phi_1^\dagger\Phi_1)^3$ | $O_6^{222222}$ | $(\Phi_2^\dagger\Phi_2)^3$ |
| $O_6^{111122}$ | $(\Phi_1^\dagger\Phi_1)^2(\Phi_2^\dagger\Phi_2)$ | $O_6^{112222}$ | $(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2)^2$ |
| $O_6^{122111}$ | $(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)(\Phi_1^\dagger\Phi_1)$ | $O_6^{122122}$ | $(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2)$ |
| $O_6^{121211}$ | $(\Phi_1^\dagger\Phi_2)^2(\Phi_1^\dagger\Phi_1)$ + h.c. | $O_6^{121222}$ | $(\Phi_1^\dagger\Phi_2)^2(\Phi_2^\dagger\Phi_2)$ + h.c. |

- absorb dim-6 contributions (to scalar masses) in shifts $\lambda_i \to \lambda_i + \delta\lambda_i$, $m_{12}^2 \to m_{12}^2 + \delta m_{12}^2$

$\Rightarrow$ scalar mass spectrum same as for dim-4 @ LO
$\Rightarrow$ shift EFT effects into **Higgs self-couplings** & **multi-Higgs final states**

# Effect of Dim-6 Operators

[Anisha,Biermann,Englert,MM,'22]



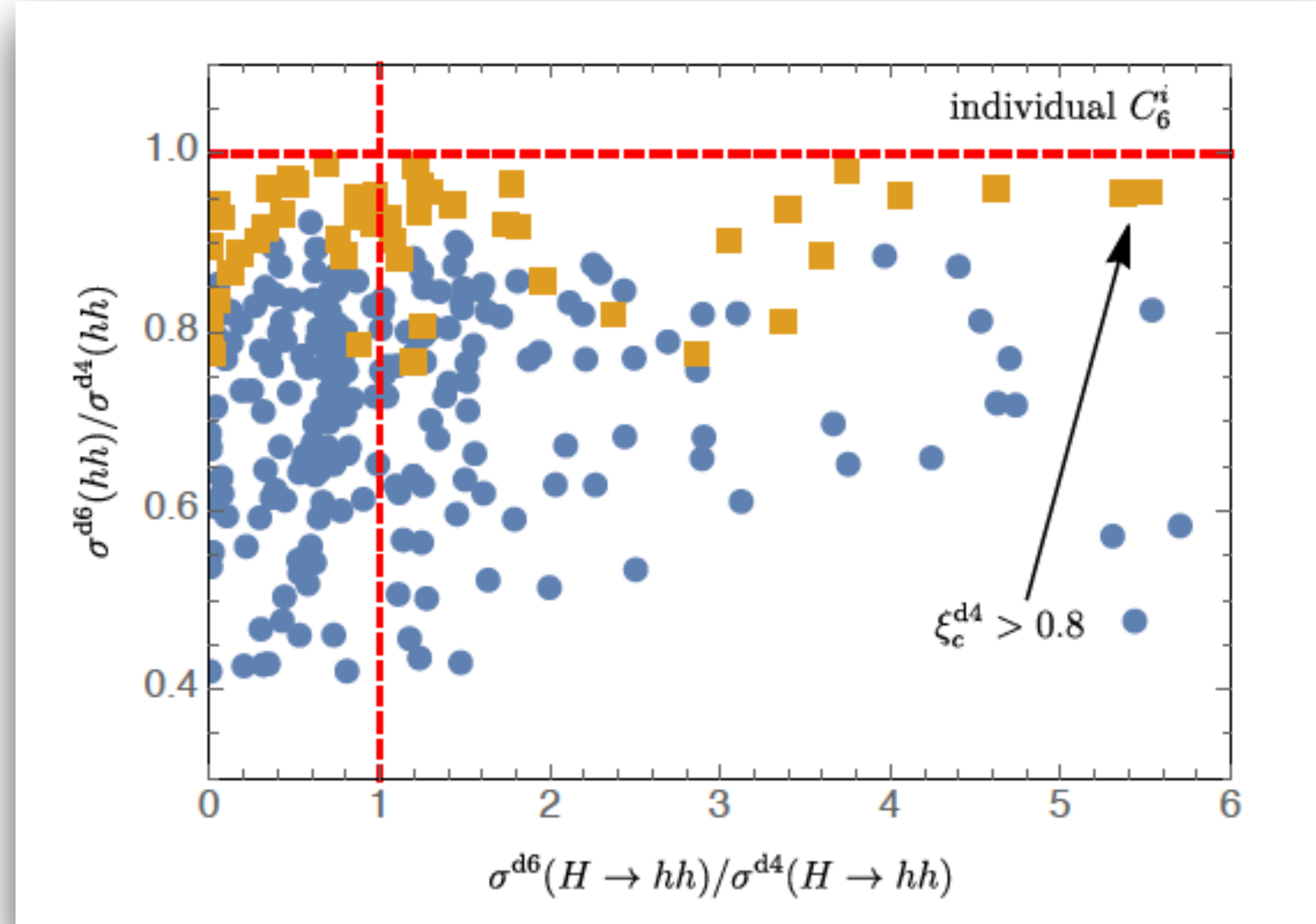

impact of individual Wilson coefficients on $\xi_c^{d6}$ for $\xi_c^{d4} \cong 0.9$:

- linear response ~ $C^i_6$ -> perturbativity ok
- SFOEWPT achievable in agreement with experimental constraints

interference effects in heavy Higgs production in tt final state are width dependent -> sensitive to EFT modifications: overall effect is small after taking the Higgs data constraints into account => hh production important tool for fingerprinting SFOEWPT

# Strength of EWPT and hh production

[Anisha,Biermann,Englert,MM,'22]

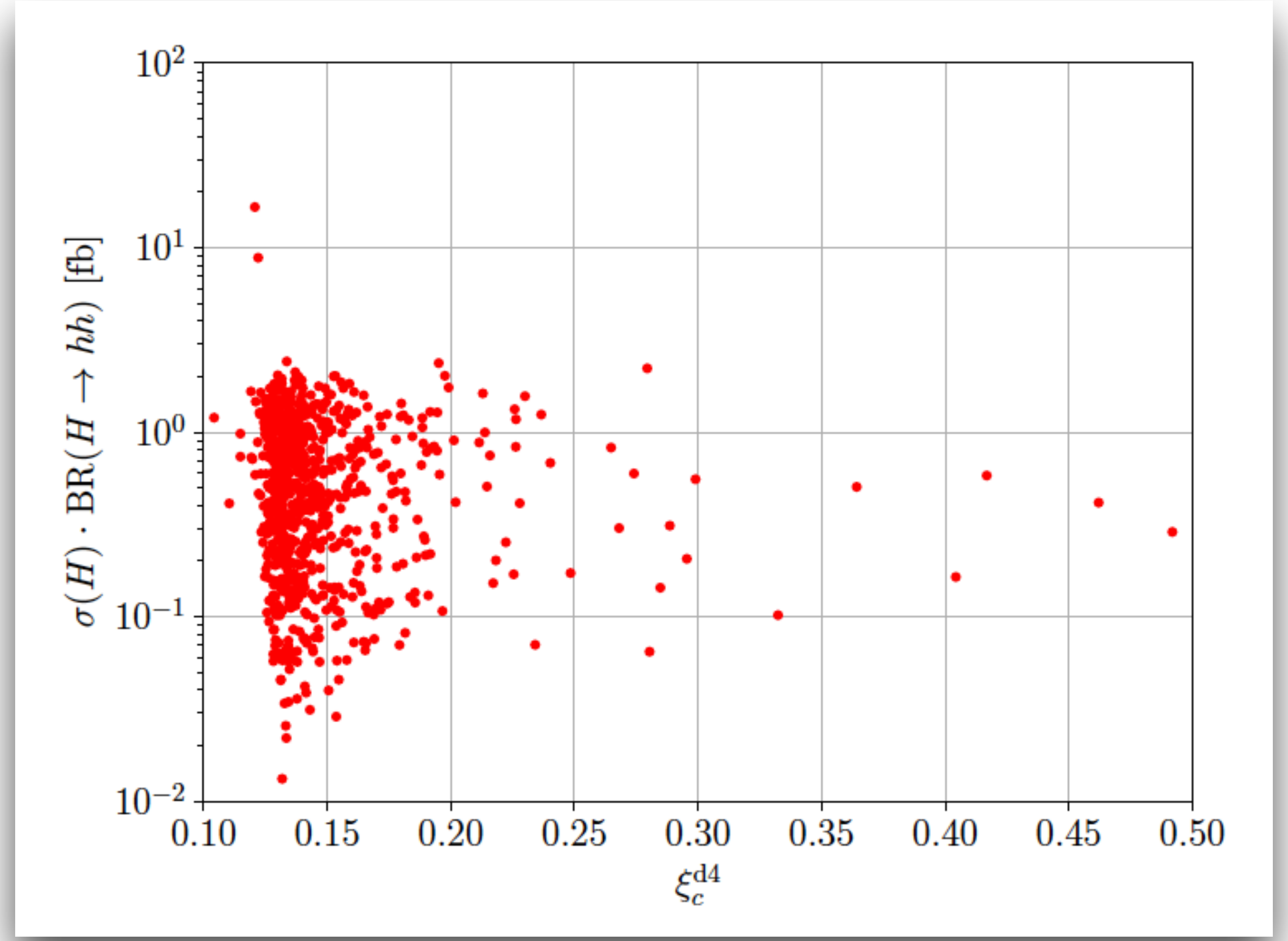



Points with $\xi_c^{d6} \cong 1$ for $\xi_c^{d4} \geqq 0.3$, orange points $\xi_c^{d4} > 0.8$

- suppression of overall hh: additional potential contributions enhance $\lambda_{hhh}$ by O(50%)
- analysis of the separated res. production H→hh compared to hh continuum production
  → indirect constraint on $\xi_c \sim 1$

# Correlation of $\xi_c^{d4}$ and resonant H→hh Production

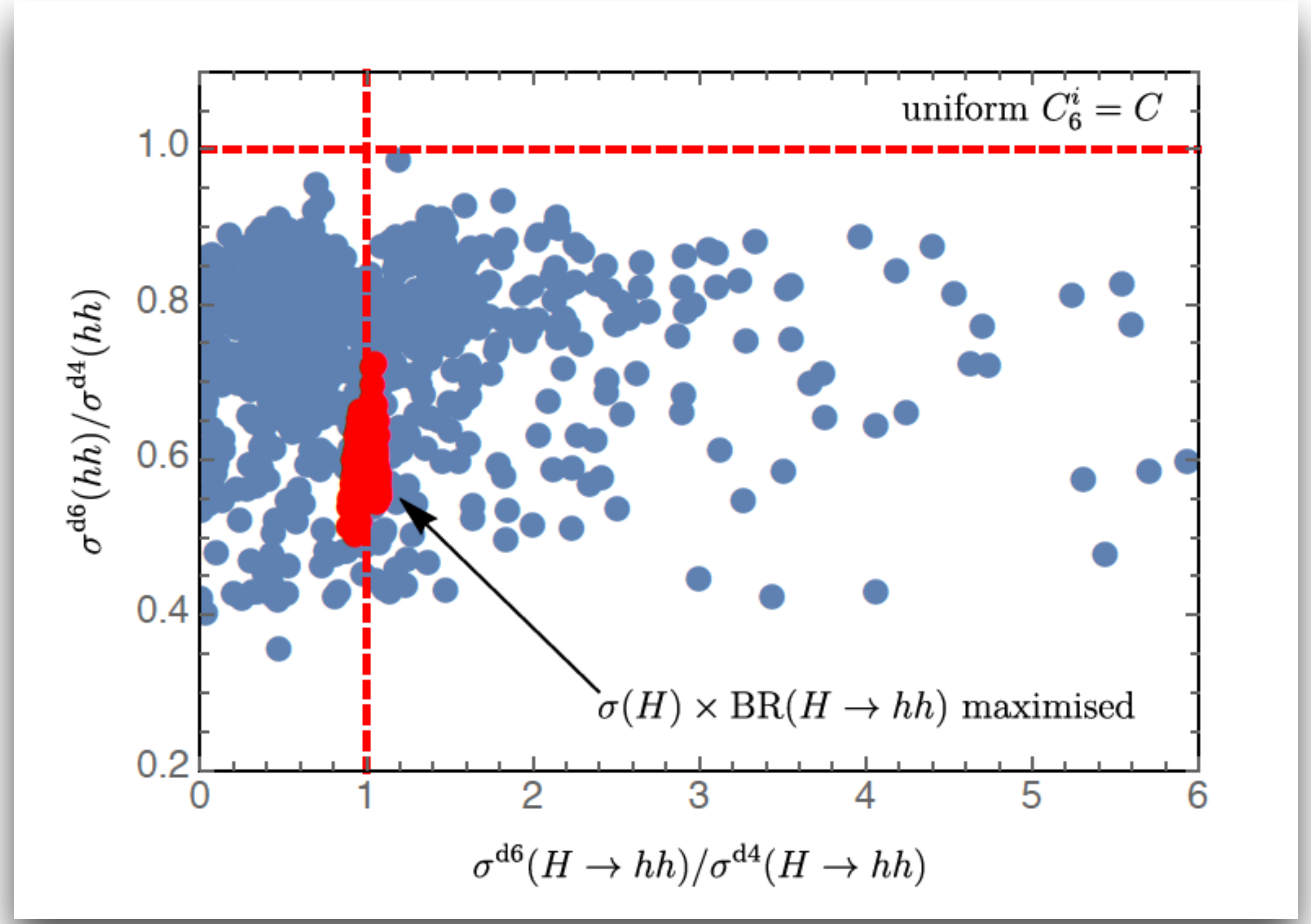
[Anisha,Biermann,Englert,MM,'22]




- Higgsphilic points characterized by larger distance $|1- \xi_c^{d4}|$

  ⇝ interplay of different dim-6 operators to achieve $\xi_c$~1 in a controlled way

[Anisha,Biermann,Englert,MM,'22]




- Resonant H→hh production enhancement factor of 2.5 possible for cxn in fb range
- Higgs-philic points: resonance contribution modified by ~5-10%, continuum production modified by ~50%

# More on Electroweak Phase Transition and Baryogenesis

# Model „CP in the Dark“

✦ Next-to-Minimal 2-Higgs Doublet Model: [Azevedo,Ferreira,MM,Patel,Santos,'18]

$$
\begin{aligned}
V^{(0)} = \; & m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 + \frac{m_S^2}{2}\Phi_S^2 + \left(A\Phi_1^\dagger\Phi_2\Phi_S + \text{ h.c.}\right) \\
& + \frac{\lambda_1}{2}|\Phi_1|^4 + \frac{\lambda_2}{2}|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \frac{\lambda_5}{2}[(\Phi_1^\dagger\Phi_2)^2 + (\Phi_2^\dagger\Phi_1)^2] \\
& + \frac{\lambda_6}{4}\Phi_S^4 + \frac{\lambda_7}{2}|\Phi_1|^2\Phi_S^2 + \frac{\lambda_8}{2}|\Phi_2|^2\Phi_S^2 \, .
\end{aligned}
$$

✦ with one discrete $\mathbb{Z}_2$ symmetry: $\Phi_1 \to \Phi_1 \, , \quad \Phi_2 \to -\Phi_2 \, , \quad \Phi_S \to -\Phi_S$

one SM-like Higgs plus dark sector: $h_1,h_2,h_3,H^\pm$

✦ trilinear coupling $A$ is complex: dark sector with CP violation <- not constrained by electric dipole moment

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$$+ \frac{\lambda_1}{2}|\Phi_1|^4 + \frac{\lambda_2}{2}|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \frac{\lambda_5}{2}[(\Phi_1^\dagger\Phi_2)^2 + (\Phi_2^\dagger\Phi_1)^2]$$
$$+ \frac{\lambda_6}{4}\Phi_S^4 + \frac{\lambda_7}{2}|\Phi_1|^2\Phi_S^2 + \frac{\lambda_8}{2}|\Phi_2|^2\Phi_S^2 .$$

✦ with one discrete $\mathbb{Z}_2$ symmetry: $\Phi_1 \to \Phi_1 , \quad \Phi_2 \to -\Phi_2 , \quad \Phi_S \to -\Phi_S$

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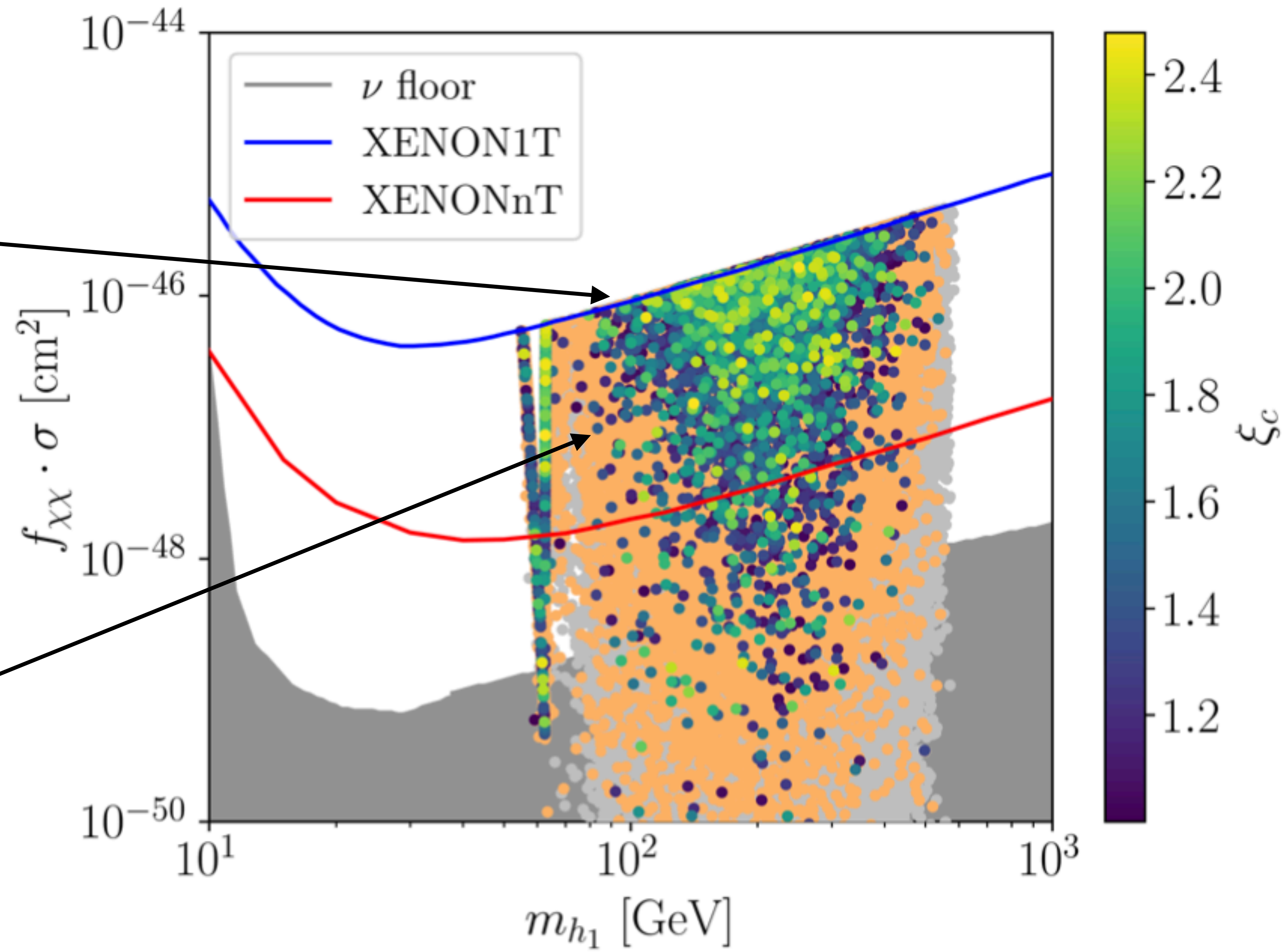
✦ trilinear coupling $A$ is complex: dark sector with CP violation <- not constrained by electric dipole moment

# Strong First Order Phase Transition and DM Constraints

[Biermann,MM,Müller'22]

points compatible with direct detection

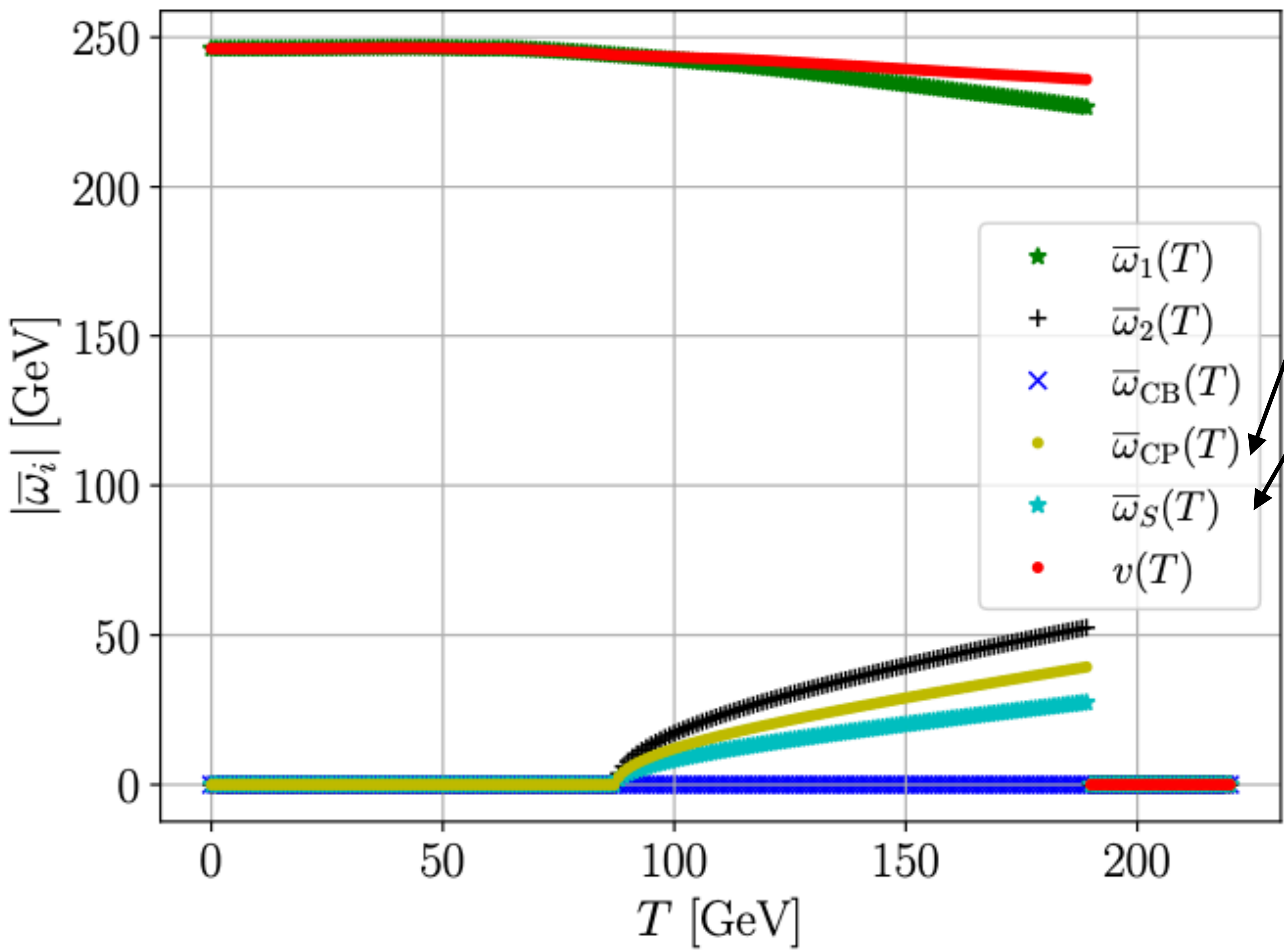



points with strong first order electro-weak phase Transition

points also compatible with DM relic density

# Spontaneous CP Violation

[Biermann,MM,Müller'22]




CP-violating VEV in dark sector plus singlet VEV generated spontaneously => CP violation transferred to visible sector

Strong first order electroweak phase transition

# Conclusions

- ✦ Precision predictions for Higgs pair production -> required for accurate extraction of Higgs self-coupling
  - NLO QCD corrections: mass effects 15% on top of LO; 20-30% for distributions
  - Uncertainty estimate: renormalization and factorization scale uncertainty, top mass scale and scheme uncertainty

- ✦ Top Yukawa-induced EW corrections to Higgs pair production:
  - effect of about 0.2%
  - bulk of corrections cannot be absorbed in the effective trilinear Higgs coupling

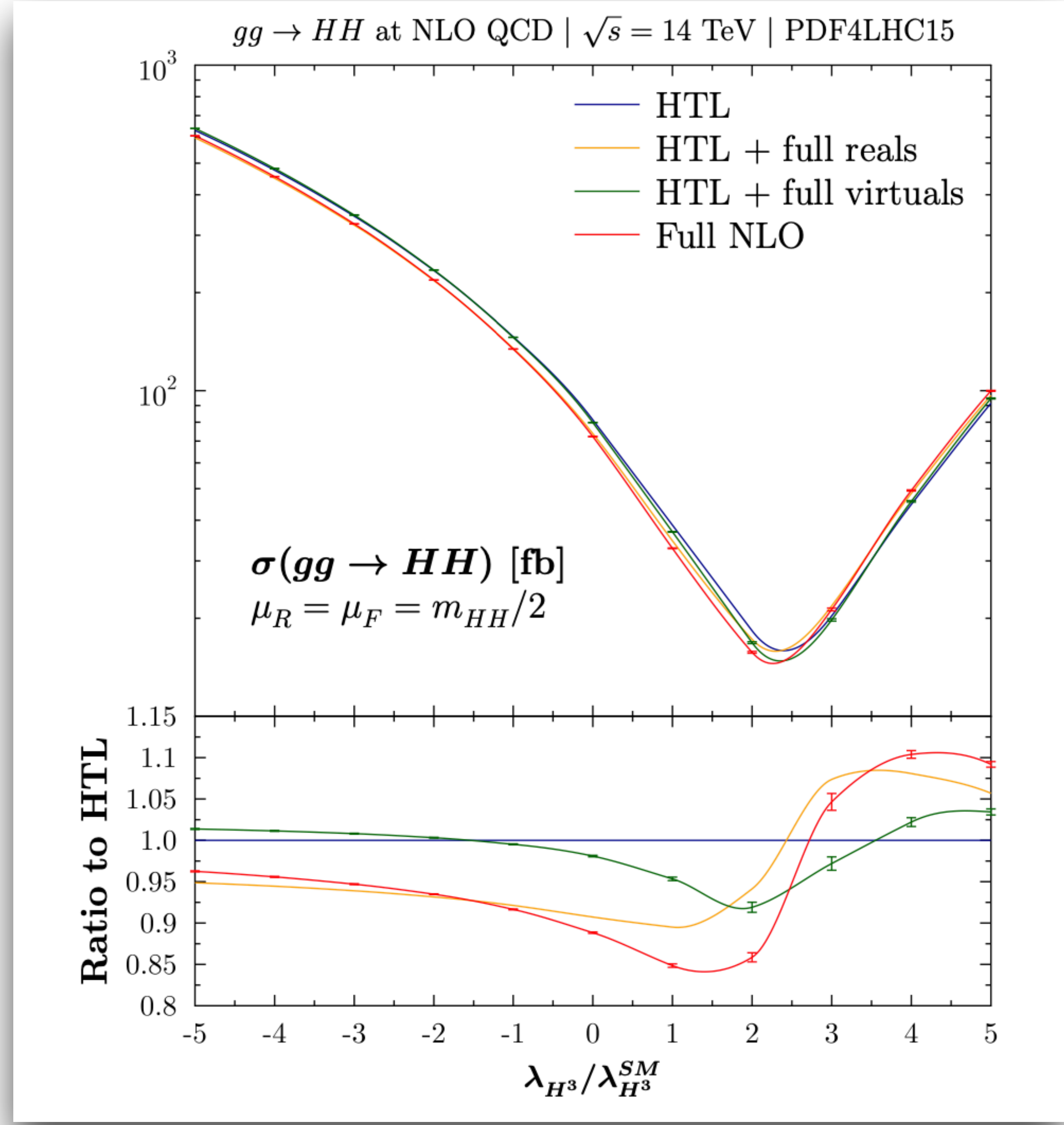
- ✦ 2HDM plus dim-6 operators (-> additional dynamics)
  - get an SFOEWPT in type II more easily
  - Higgsphilic scenario: dim-6 ops necessary for SFOEWPT => reduction of gg-> hh and modification of gg->H->hh; can be probed by LHC to some extent

- ✦ Model „CP in the Dark“ w/ CP violation in the dark sector
  - SFOEWPT & compatibility w/ DM constraints possible
  - spontaneous violation of CP and $\mathbb{Z}_2$ at EWPT ~> interesting for baryogenesis


Thank you for your attention!

# HH Cross Section Dependence on Higgs Self-Coupling

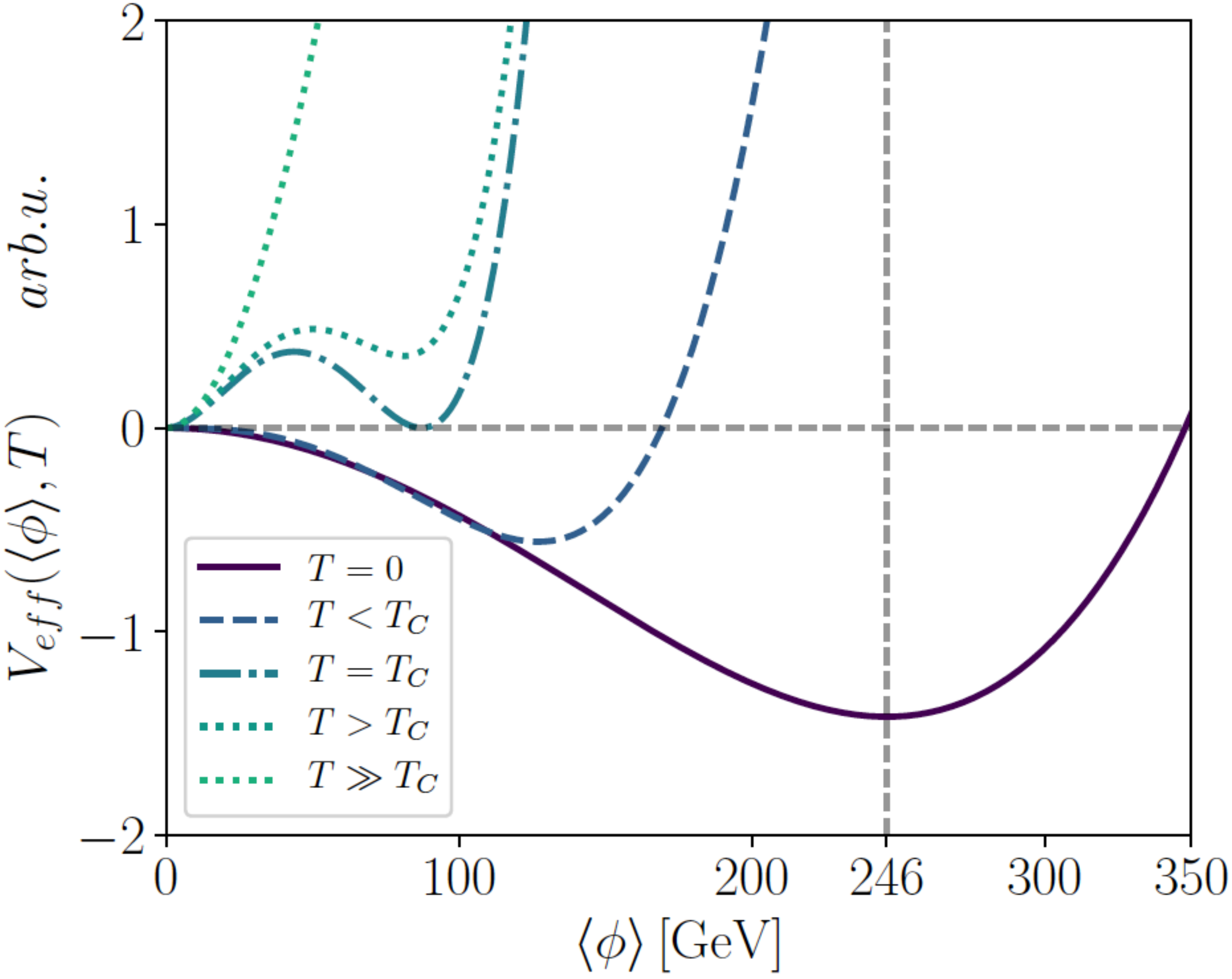
[Baglio,Campanario,Glaus,MM,Ronca,Spira]




$$gg \to HH:$$

$$\frac{\Delta\sigma}{\sigma} \sim -\frac{\Delta\lambda}{\lambda}$$

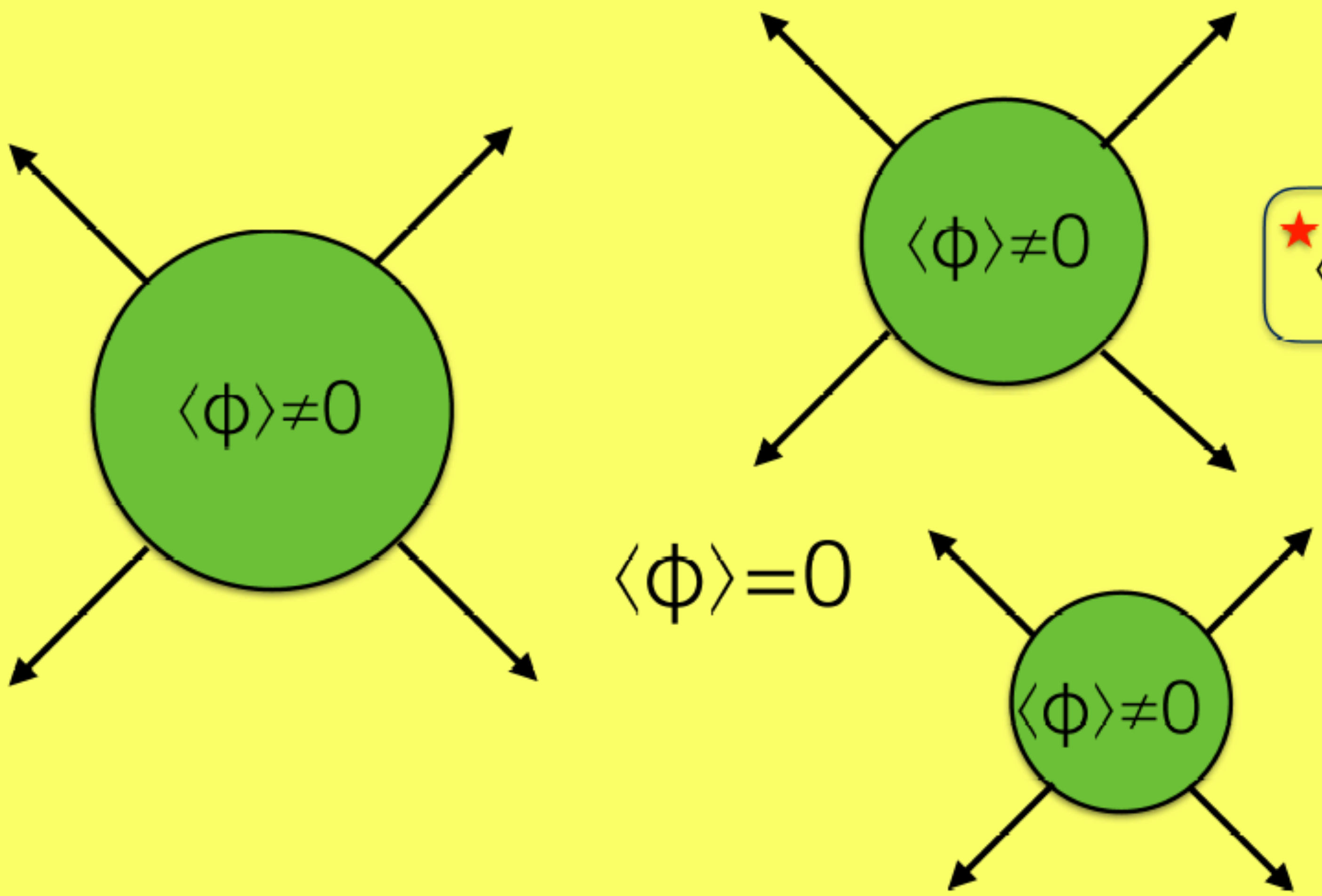
# Strong First Order Electroweak Phase Transition



# 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




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

$\phi_c, T_c$

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 ★