$\mathcal{B}$SM $\mathcal{H}$iggs $\mathcal{P}$roperties

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LHCP14

Columbia University
June 2-7, 2014

BSM Higgs Properties - Not SUSY

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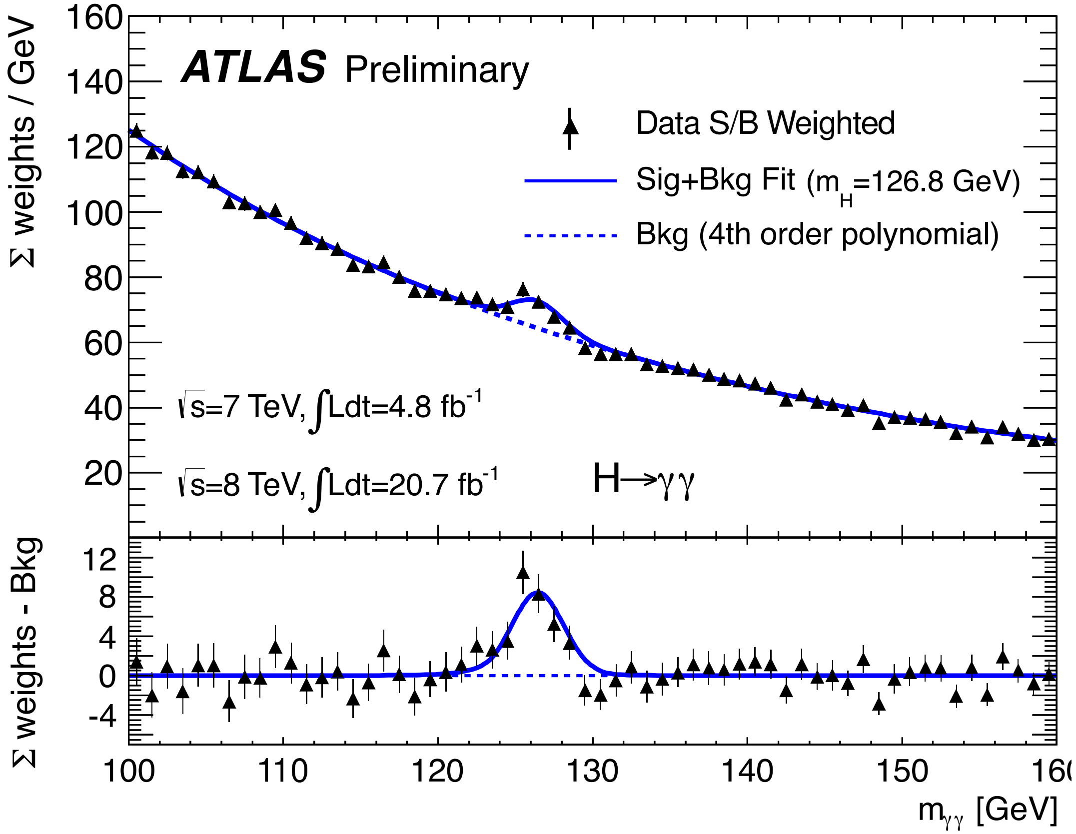
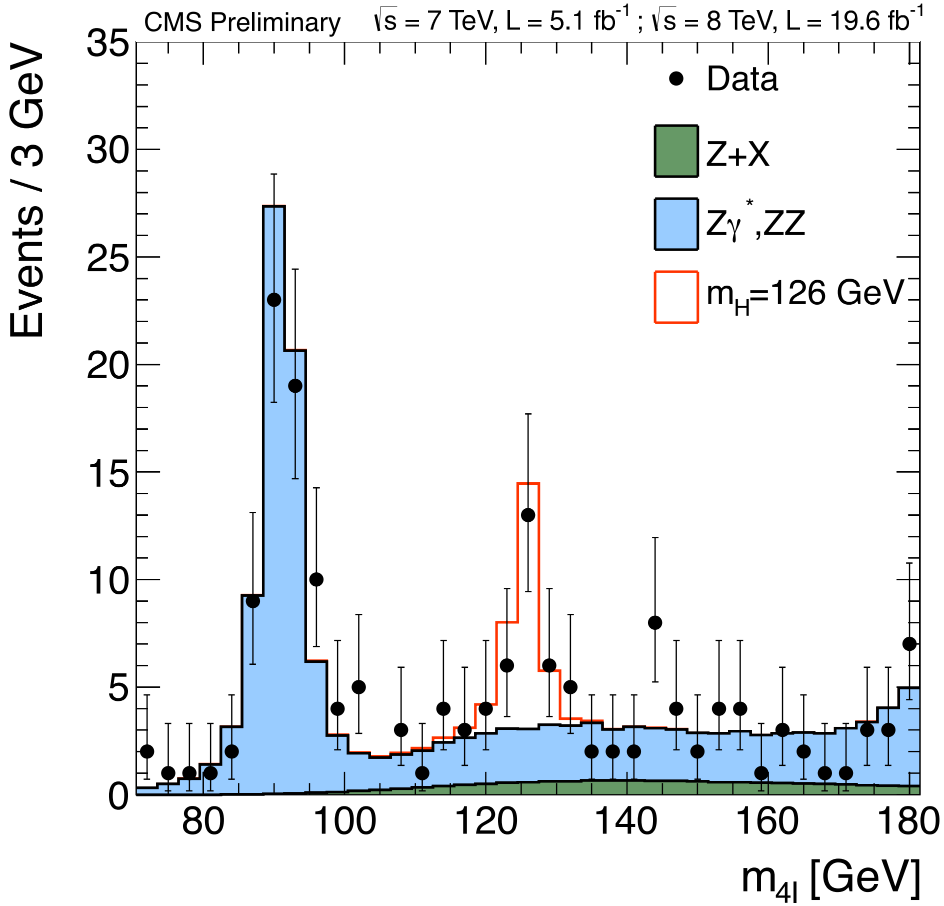
$\mathcal{LHC}$ $\mathcal{D}$iscovery of $\mathcal{N}$ew $\mathcal{S}$calar $\mathcal{P}$article

ATLAS-CONF-2013-12



CMS-PAS-HIG-13-002

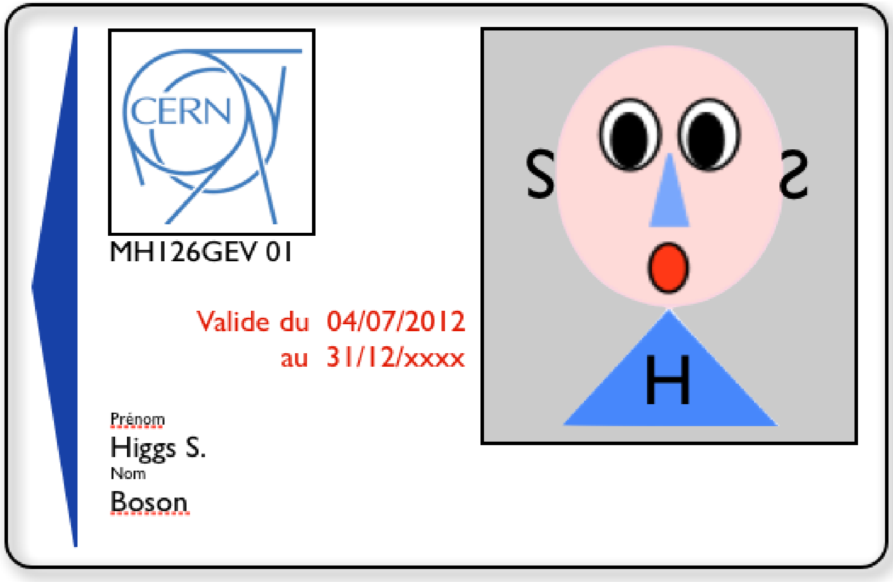


$\mathcal{I}$t is the $\mathcal{H}$iggs $\mathcal{B}$oson

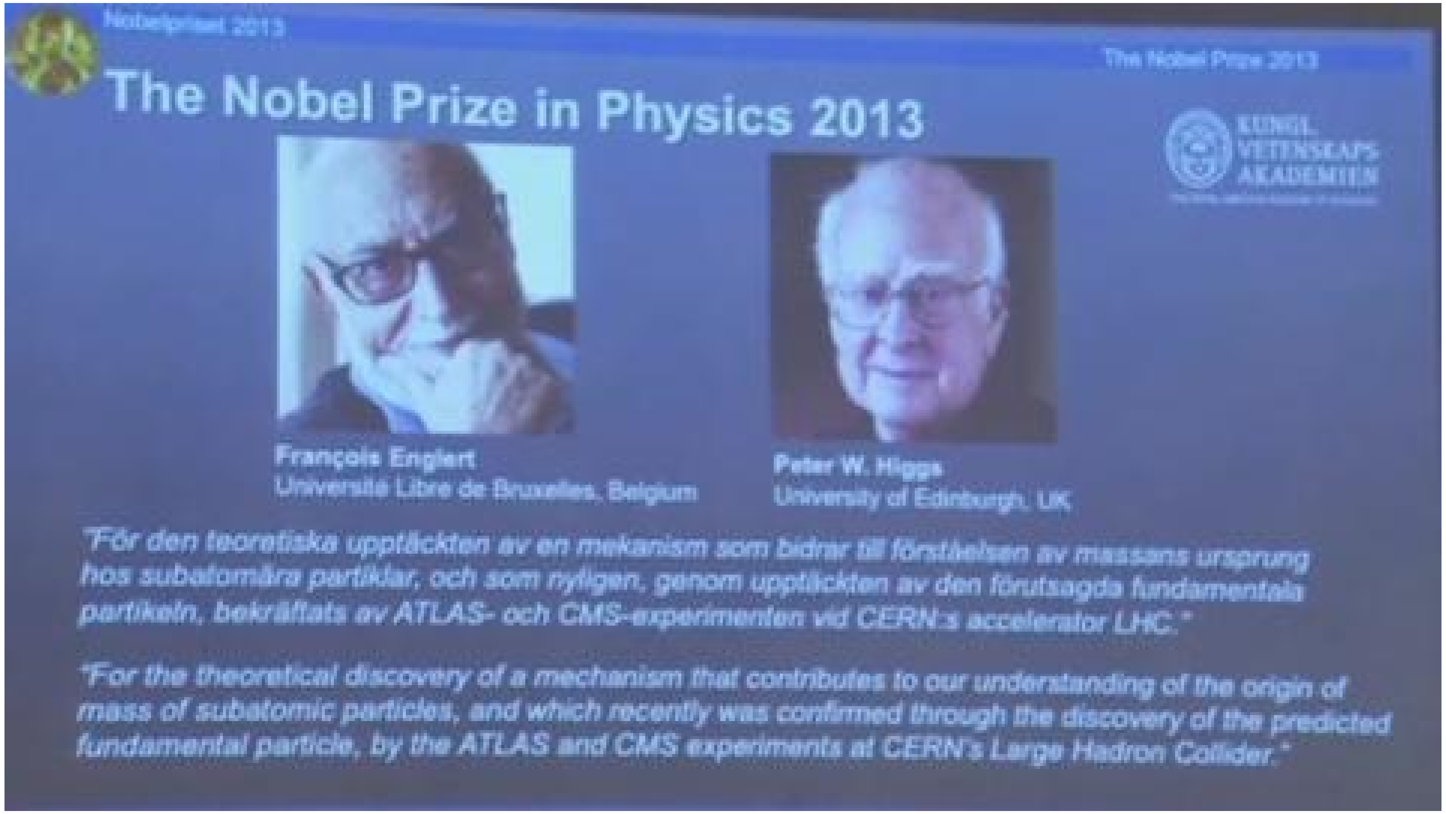
- **Investigation of properties of scalar particle:**

$\mathcal{I}$t is the $\mathcal{H}$iggs $\mathcal{B}$oson

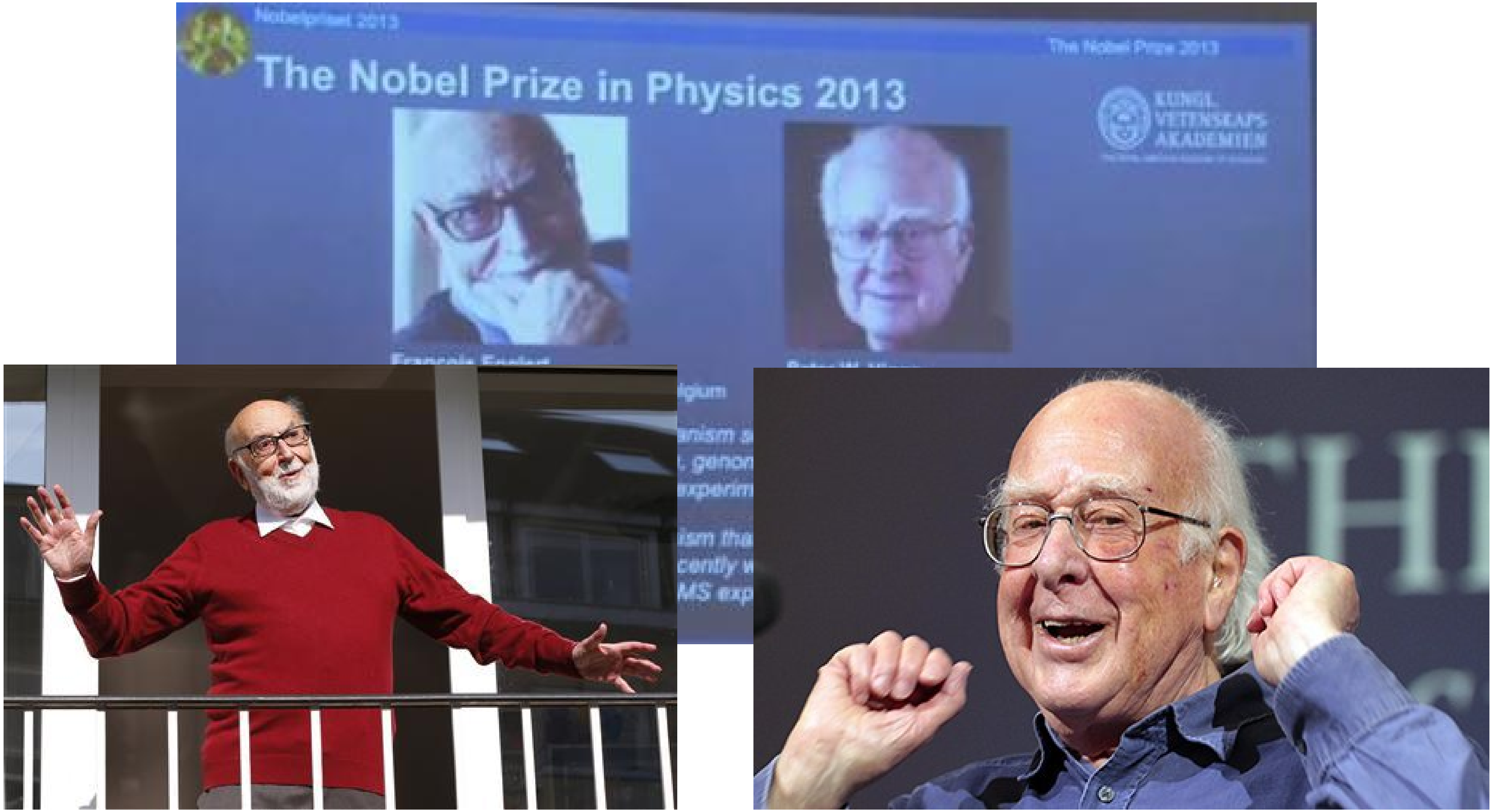
- **Investigation of properties of scalar particle:** $\rightsquigarrow$ Higgs Boson



$\mathcal{I}$t is the $\mathcal{H}$iggs $\mathcal{B}$oson



$\mathcal{I}$t is the $\mathcal{H}$iggs $\mathcal{B}$oson



$\mathcal{T}$he $\mathcal{M}$enu

◇ **Introduction**

◇ **Composite Higgs Boson**

  ∗ Phenomenological Implications

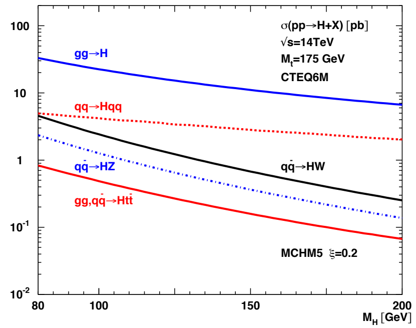
◇ **Effective Lagrangian Approach**

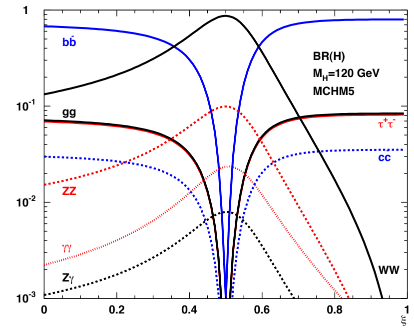
  ∗ Relevant Operators

◇ **Specific Models**

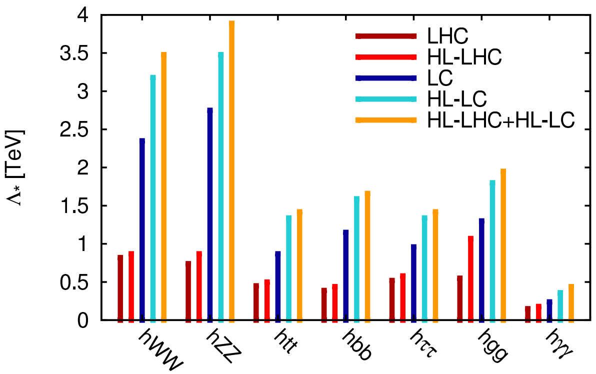
  ∗ Coupling Measurements

◇ **Summary**





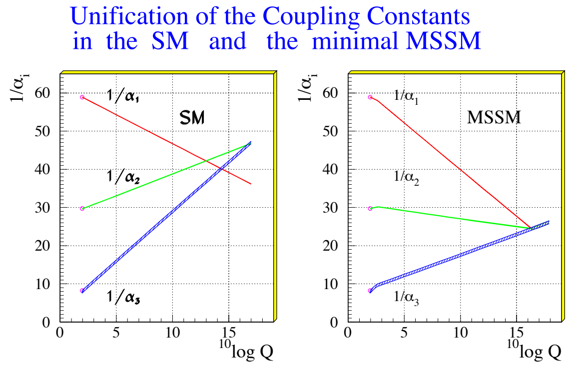
$$\mathcal{L}_{\text{eff}} = \sum_n \frac{f_n}{\Lambda^2} \mathcal{O}_n$$



Introduction

$\mathcal{O}$pen $\mathcal{P}$roblems

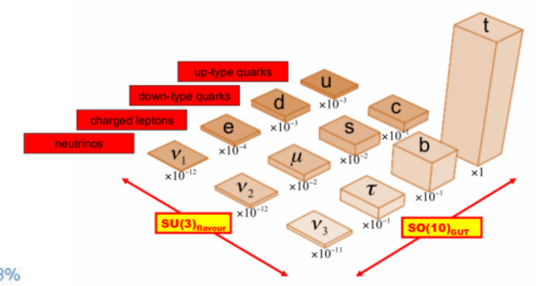
◇ What is the mechanism beyond EWSB? Weak or strong dynamics?



◇ Huge Higgs mass corrections - finetuning?

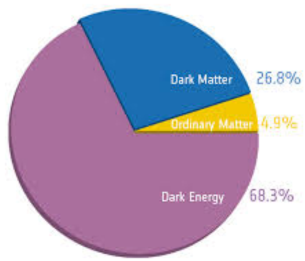
◇ Do the gauge couplings unify?

◇ Incorporation of gravity?



◇ Puzzling spectrum of fermion masses and mixings

◇ What is the nature of Dark Matter?



◇ Origin of matter-antimatter asymmetry?

◇ New sources of CP violation?

◇ ...

$\mathcal{B}$ig $\mathcal{Q}$uestions - $\mathcal{B}$ig $\mathcal{I}$deas

- ◇ What is the mechanism beyond EWSB? Weak or strong dynamics?
- ◇ Huge Higgs mass corrections - finetuning?
- ◇ Do the gauge couplings unify?
- ◇ Incorporation of gravity?
- ◇ Puzzling spectrum of fermion masses and mixings
- ◇ What is the nature of Dark Matter?
- ◇ Origin of matter-antimatter asymmetry?
- ◇ New sources of CP violation?
- ◇ ...

Supersymmetry

Compositeness

Extra Dimensions

Extended Higgs Sectors

Top Partner W'/Z'

Minimal Dark Matter

Hidden Sector ...

Big Questions - Big Ideas

- What is the mechanism beyond EWSB? Weak or strong dynamics?
- Huge Higgs mass corrections - finetuning?
- Do the gauge couplings unify?
- Incorporation of gravity?
- Puzzling spectrum of fermion masses and mixings
- What is the nature of Dark Matter?
- Origin of matter-antimatter asymmetry?
- New sources of CP violation?
- ...

No Observation of Physics Beyond the SM so Far!

Supersymmetry

Compositeness

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Big Questions - Big Ideas

- What is the mechanism beyond EWSB? Weak or strong dynamics?
- Huge Higgs mass corrections - finetuning?
- Do the gauge couplings unify?
- Incorporation of gravity?
- Puzzling spectrum of fermion masses and mixings
- What is the nature of Dark Matter?
- Origin of matter-antimatter asymmetry?
- New sources of CP violation?
- ...

Naturalness:

New Physics just around the corner

Supersymmetry

Compositeness

Extra Dimensions

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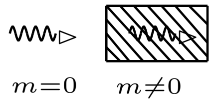
Hidden Sector ...

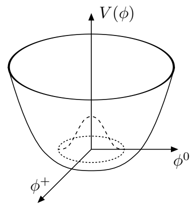
What Can We Learn From Higgs Physics?

Test of the Higgs mechanism

- Mass, Total Width – m, Γ
- Interaction with a scalar Higgs with $v \approx 246$ GeV$\neq 0$ $\rightsquigarrow$ $g_{HXX} \sim m_X$



- Spin and parity quantum numbers – J^{PC}
- EWSB requires Higgs potential – $\lambda_{HHH}, \lambda_{HHHH}$



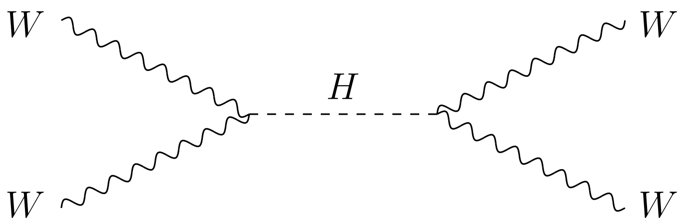
✐ Is it *the* Standard Model *Higgs* boson?

✐ Is it the harbinger of New Physics?

$\mathcal{W}$hat is the $\mathcal{D}$ynamical $\mathcal{O}$rigin of $\mathcal{EWSB}$?

$\mathcal{I}$s the Higgs boson $\mathcal{E}$lementary or $\mathcal{C}$omposite?

Weakly coupled models

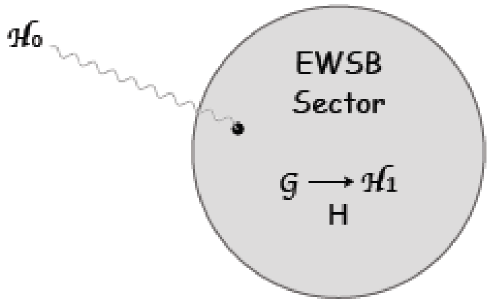


$\mathcal{S}$M, $\mathcal{S}$USY, ...

SUSY Partner ~ 1 TeV

New particles necessary to stabilise the Higgs boson mass

Strongly-interacting dynamics



$\mathcal{C}$omposite $\mathcal{H}$iggs

top partners $\gtrsim 700$ GeV

Resonances for unitarity

Higgs boson composite object

Cartoon from R.Contino [1005.4269]

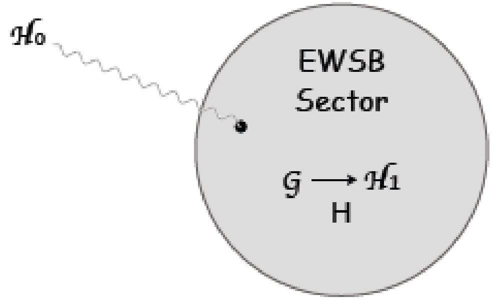
$\mathcal{C}$omposite $\mathcal{H}$iggs
$\mathcal{S}$trong EWSB

$\mathcal{C}$omposite $\mathcal{H}$iggs $\mathcal{B}$oson

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 $\mathcal{H}_0 = G_{\text{SM}} = SU(2)_L \times U(1)_Y$; $\mathcal{G} \to \mathcal{H}_1 \supset G_{\text{SM}}$
  - $\mathcal{H}_1$ contains 'custodial' $SO(4) \cong SU(2)_L \times SU(2)_R$ (protect T parameter)
  - SM fields are external to strong sector $\rightsquigarrow$ elementary

Composite Higgs Boson

- **Possible symmetry patterns**

  Examples:

  - $SO(5)/SO(4)$: 4 PGBs $= W_L^\pm, Z_L, h \rightarrow$ Minimal Comp. Higgs Model — Agashe,Contino,Pomarol
  - $SO(6)/SO(5)$: 5 PGBs $= W_L^\pm, Z_L, h, a \rightarrow$ Next MCHM — Gripaios,Pomarol,Riva,Serra
  - ... — 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

$\mathcal{P}$artial $\mathcal{C}$ompositeness

- **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 $\leadsto$ Higgs potential induced

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

  ◇ Light Higgs boson requires light top partners

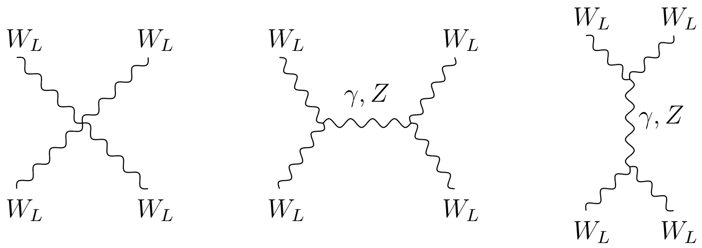
  Matsedonskyi,Panico,Wulzer; Redi,Tesi; Marzocca,Serone,Shu; Pomarol,Riva

$\mathcal{P}$henomenological $\mathcal{I}$mplications?

▷ Modified Higgs couplings to SM gauge bosons and fermions

  * Unitarity not restored any more in $V_L V_L$ scattering

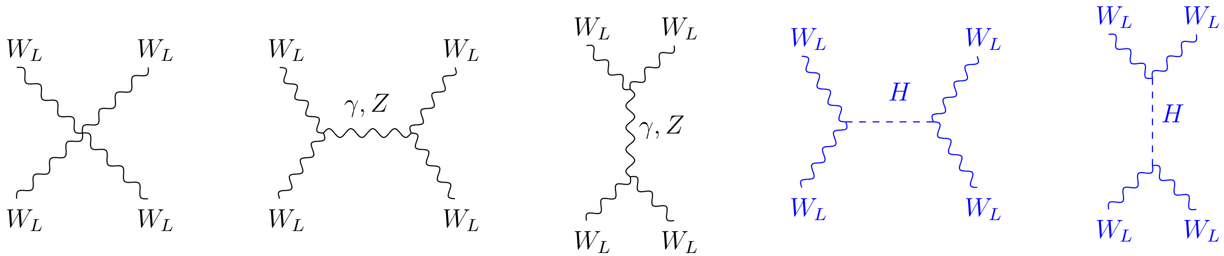
- **Longitudinal W boson scattering**



$$\mathcal{A} = \frac{s}{v^2}$$

$\mathcal{I}$mplications of $\mathcal{H}$iggs $\mathcal{C}$oupling $\mathcal{D}$eviations

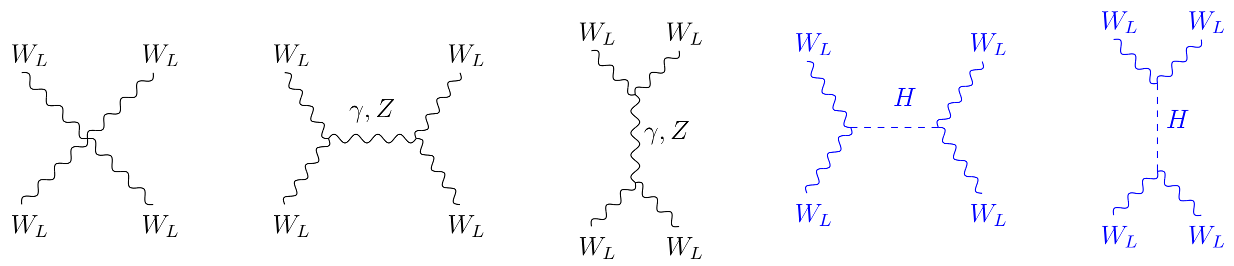
- **Longitudinal W boson scattering**



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

$\mathcal{I}$mplications of $\mathcal{H}$iggs $\mathcal{C}$oupling $\mathcal{D}$eviations

- **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

$\mathcal{P}$henomenological $\mathcal{I}$mplications?

▷ 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

$\mathcal{H}$iggs $\mathcal{A}$nomalous $\mathcal{C}$ouplings

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

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

Giudice,Grojean,Pomarol,Rattazzi

SM limit for $\xi \to 0$

$\mathcal{H}$iggs $\mathcal{A}$nomalous $\mathcal{C}$ouplings

- **Large ξ?** The 5D MCHM ($SO(5)/SO(4)$) provides completion for large ξ Contino eal; Agashe eal
- **Gauge couplings**

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

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

spinorial representations of $SO(5)$

MCHM4

$$g_{Hff} = g^{SM}_{Hff}\sqrt{1-\xi} \equiv g^{SM}_{Hff}\, c$$

universal shift of couplings

no modifications of BRs

fundamental representations of $SO(5)$

MCHM5

$$g_{Hff} = g^{SM}_{Hff}\frac{1-2\xi}{\sqrt{1-\xi}} \equiv g^{SM}_{Hff}\, c$$

BRs depend on $\xi = v^2/f^2$

- **Higgs self-couplings** also model-dependent Contino eal; Gröber,MMM; Bock eal; Barger eal

$\mathcal{H}$iggs $\mathcal{A}$nomalous $\mathcal{C}$ouplings

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

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

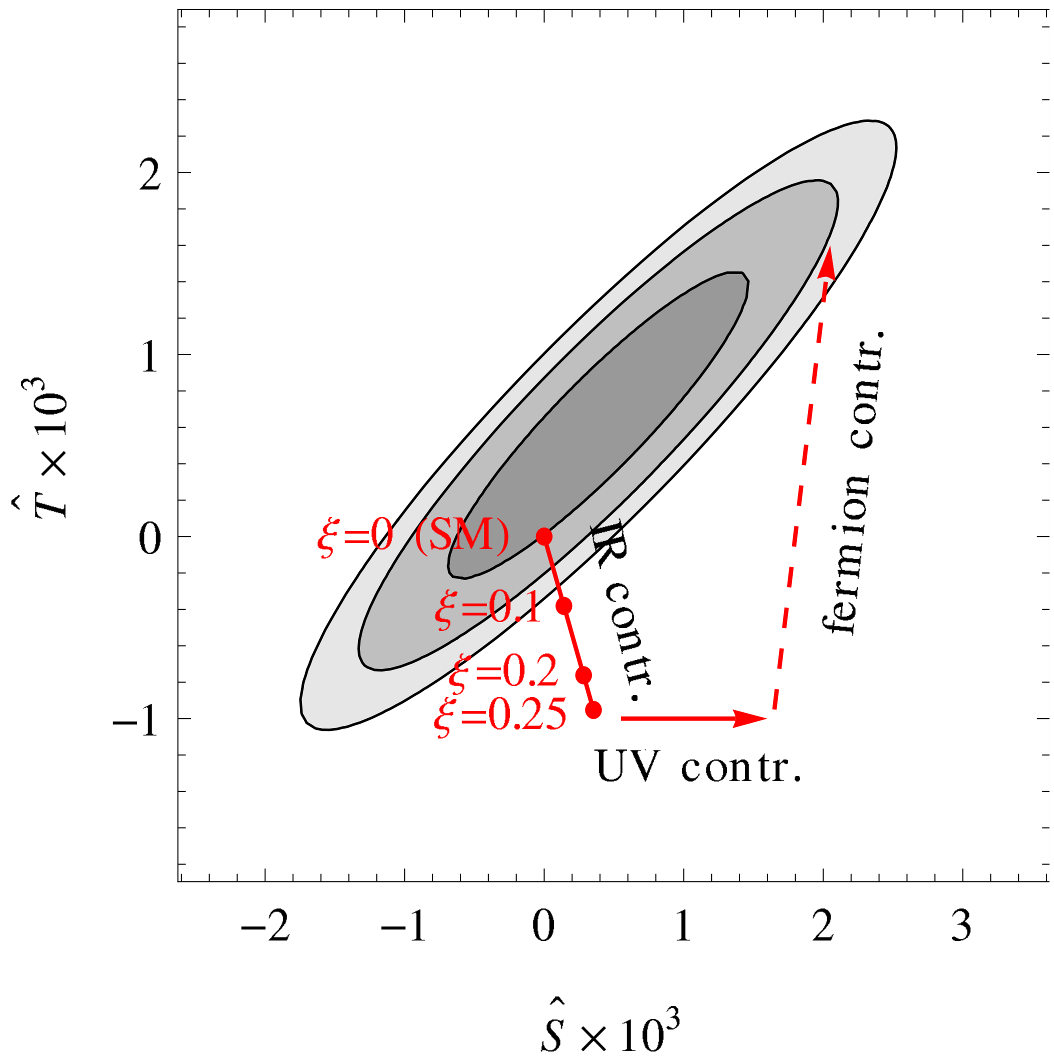
- **Gluon Fusion Production:**

  ▷ NNLO corrections '11 E.Furlan

  ▷ Two-loop Yukawa corrections in top partner singlet model '13 Dawson,Furlan

$\mathcal{C}$onstraints on the $\mathcal{O}$blique $\mathcal{P}$arameters

Grojean,Matsedonskyi,Panico



$\mathcal{H}$eavy $\mathcal{Q}$uark $\mathcal{P}$artners and $\mathcal{LHC}$ $\mathcal{S}$earches

- **Decay Channels:**

Top Partners:	$\mathcal{T} \to Wb,\ Zt,\ ht$
Bottom Partners:	$\mathcal{B} \to Wt,\ Zb,\ hb$
Charge-5/3 Fermions:	$\mathcal{X} \to Wt$

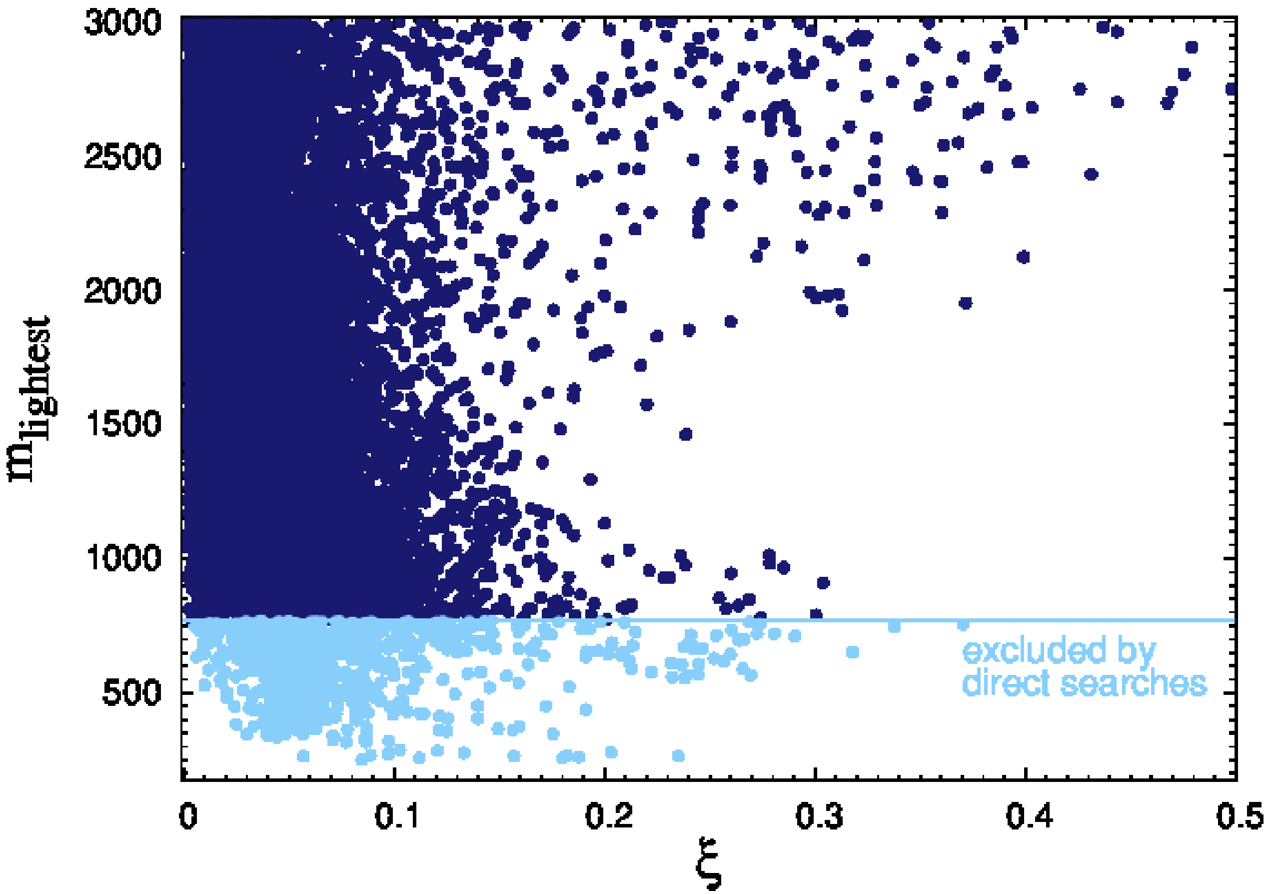
- **Limits from LHC Experiments:**

  The ATLAS Collaboration: ATLAS-CONF-2013-018, 051, 056, 060

  The CMS Collaboration: CMS PAS B2G-12-019, Phys. Lett. **B729** (2014) 149

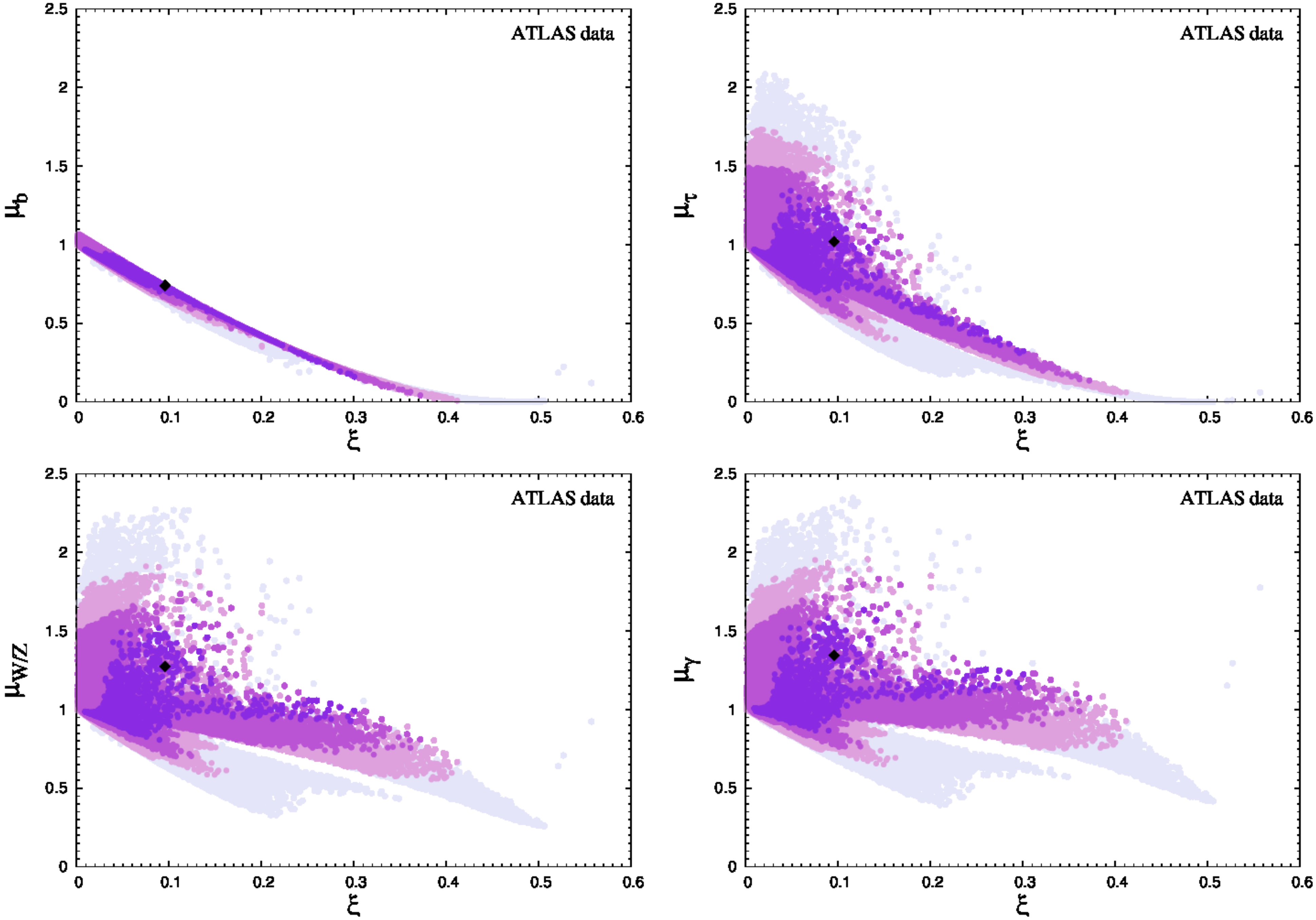
$\mathcal{H}$eavy $\mathcal{Q}$uark $\mathcal{P}$artners and $\mathcal{LHC}$ $\mathcal{S}$earches

Gillioz,Gröber,Kapuvari,MMM



- **Compatibility with ATLAS Moriond'13 data, EWPD, $|V_{tb}|$, direct searches, w/ top&bottom partners** ($\xi^{\text{best fit}} = v^2/f^2 = 0.096$)

Gillioz, Gröber, Kapuvari, MM



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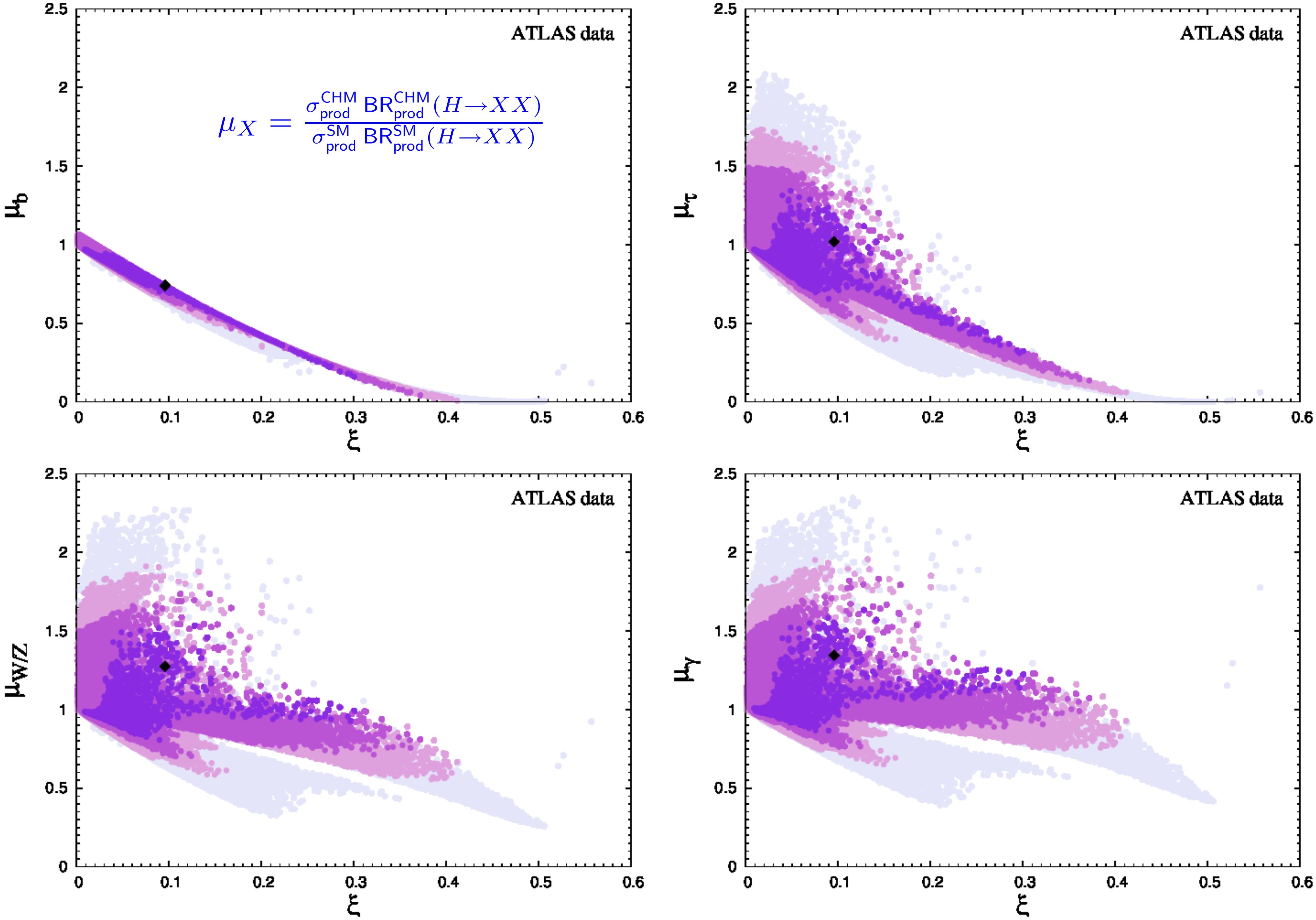
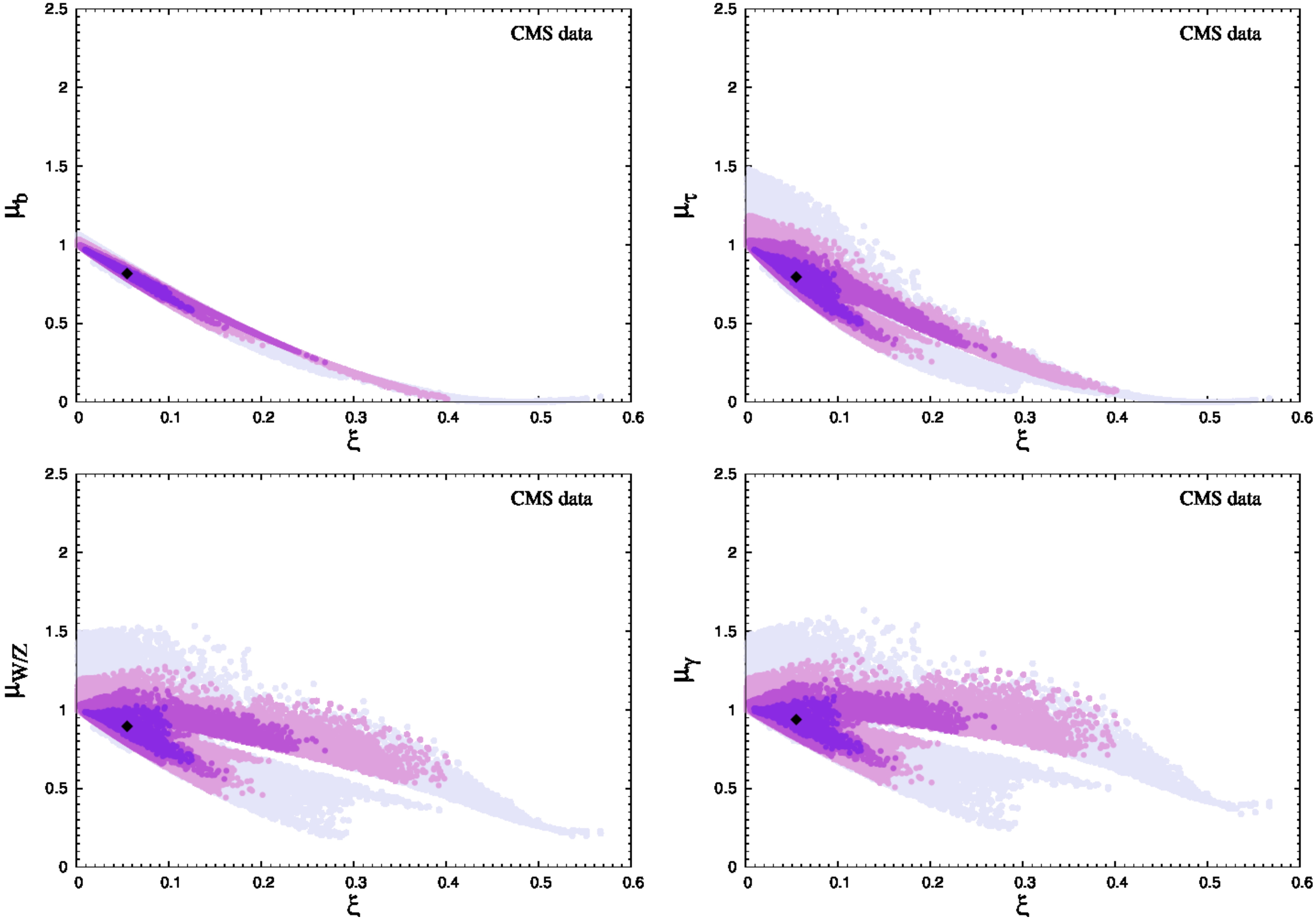


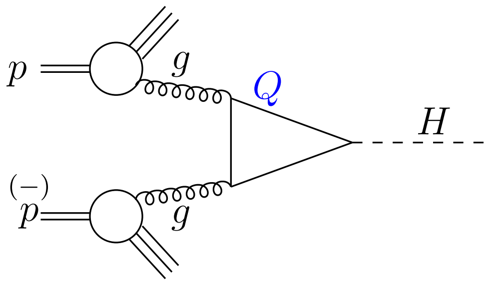
- **Compatibility with CMS Moriond'13 data, EWPD, $|V_{tb}|$, direct searches, w/ top&bottom partners** ($\xi^{\text{best fit}} = v^2/f^2 = 0.055$)

Gillioz, Gröber, Kapuvari, MM



$\mathcal{L}$oop $\mathcal{P}$rocesses: $\mathcal{S}$ensitivity to the $\mathcal{T}$op $\mathcal{P}$artners?

- **Single Higgs production through gluon fusion:** dominant production process at LHC

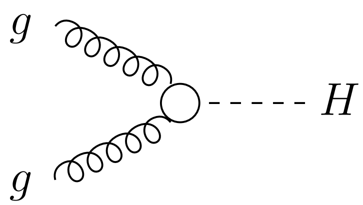


▷ Mediated by top and bottom loops and heavy quark loops; here heavy top partners

▷ Sensitivity to details of heavy composite sector?

$\mathcal{L}$oop $\mathcal{P}$rocesses: $\mathcal{S}$ensitivity to the $\mathcal{T}$op $\mathcal{P}$artners?

- **Single Higgs production through gluon fusion:** via Low-Energy Theorem (LET)



▷ Gluon fusion computed within LET is insensitive to details of the couplings and masses of strong sector — Falkowski;Low,Vichi;Azatov,Galloway;Furlan;Gillioz eal;Delaunay eal;Montull eal

▷ Reason: Cancellation between

∗ Correction of top Yukawa coupling due to mixing with heavy resonances and

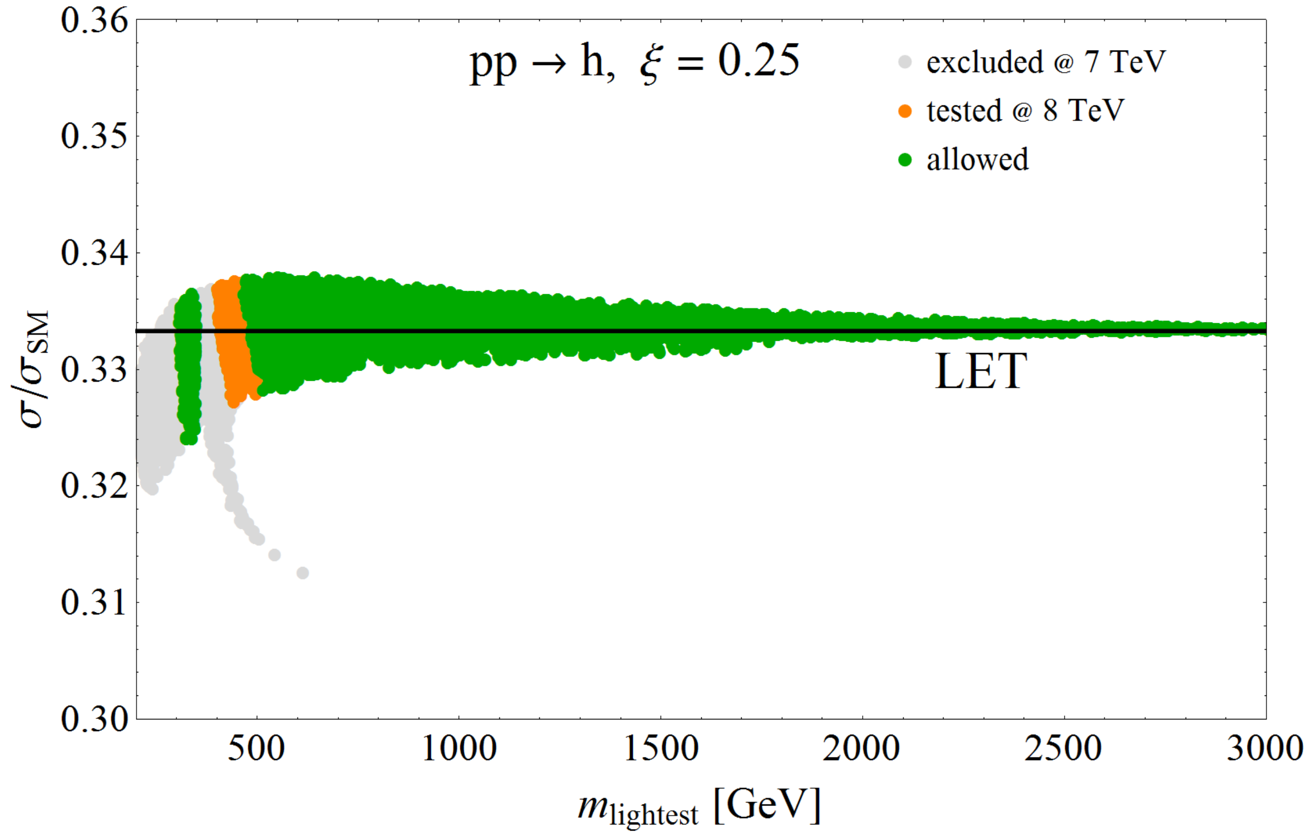
∗ Loops of extra fermions

▷ $\Rightarrow$ Cross section depends only on Higgs non-linearities $\sim \xi = v^2/f^2$, mixing effects drop out

▷ LET approximates full cross section within a few percent

Single Higgs Production in MCHM5 w/ Top Partners

Gillioz,Gröber,Grojean,MMM,Salvioni



⋆ LET very accurate cross section for any heavy fermion spectrum: $\frac{\sigma}{\sigma_{SM}} = \frac{(1-2\xi)^2}{1-\xi}$

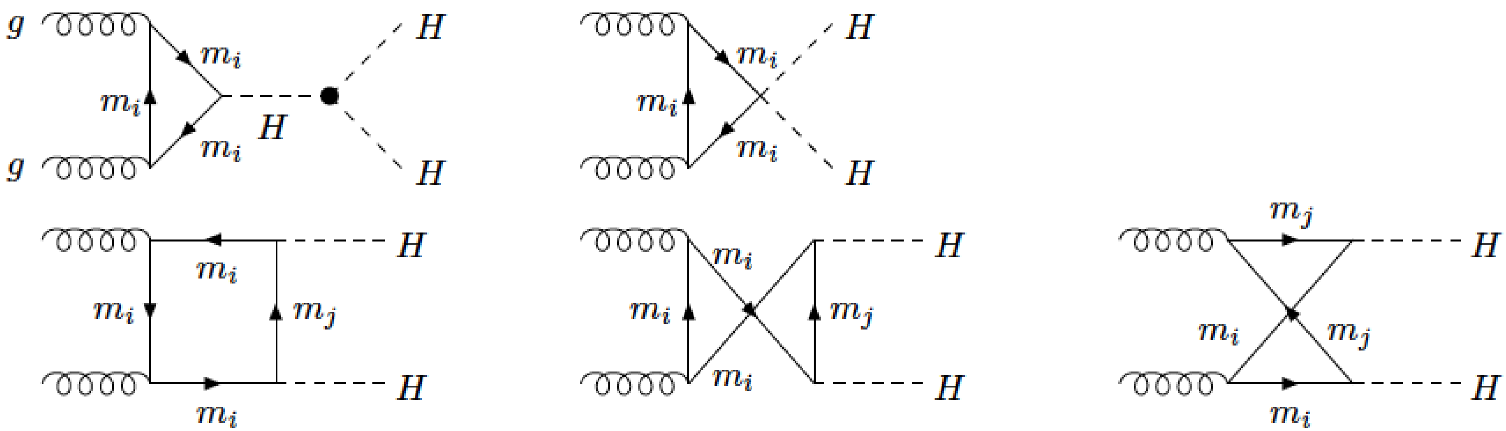
- Green points: allowed by EWPD and collider constraints
- Grey points: excluded by current collider constraints
- Orange: Projected exclusion by LHC8

What about Composite Double Higgs Production?

- **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 — Contino eal '12



▷ Can be enhanced compared to the SM process

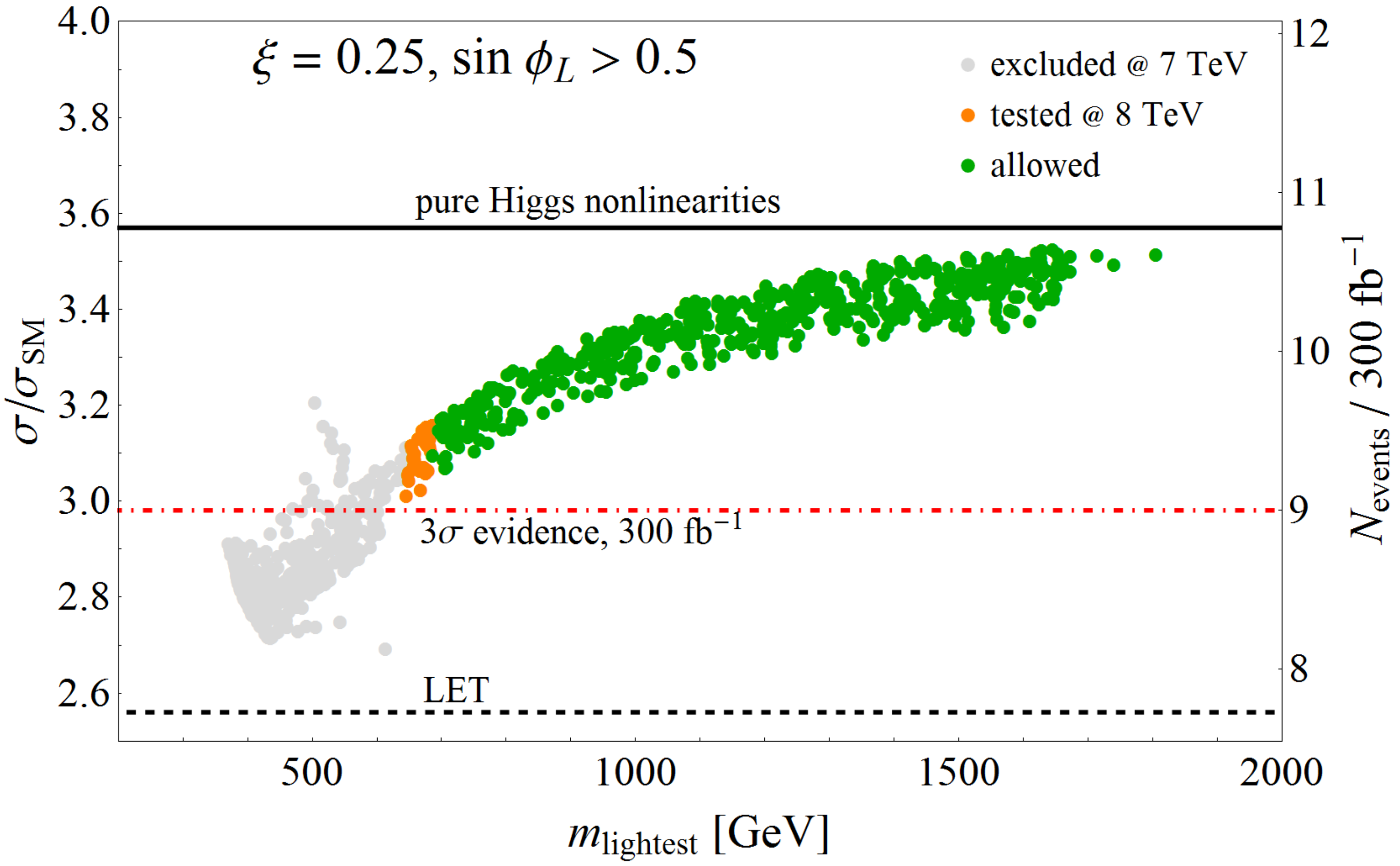
▷ Mediated by top and bottom loops and heavy quark loops; here heavy top partners

▷ Different fermions can contribute within one loop

▷ Sensitivity to details of heavy composite sector?

Double Higgs Production in MCHM5 w/ Top Partners

Gillioz,Gröber,Grojean,MMM,Salvioni



only top; partners

$\longleftarrow$ integrated out

top and partners

$\longleftarrow$ integrated out

$\mathcal{H}$ow to resolve the $\mathcal{T}$op $\mathcal{L}$oops?

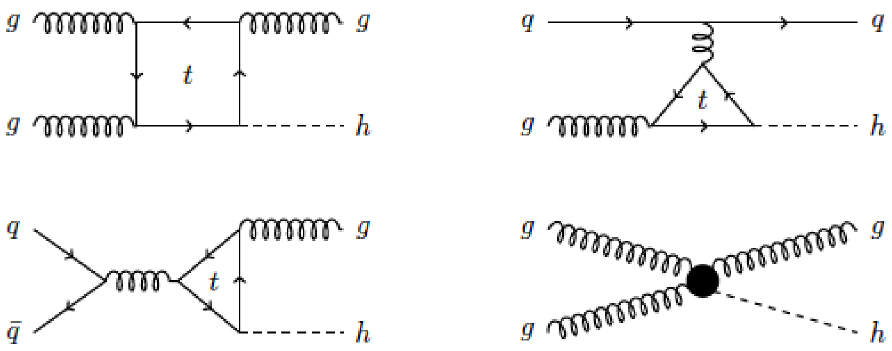
- **Inclusive gluon fusion Higgs production** cannot disentangle
  - long distance physics (modified top coupling)
  - short distance physics (new particles running in the loop)

- **Determination of top Yukawa coupling in $t\bar{t}H$ production: difficult**

  14%-4% LHC$^{14}_{300}$-LHC$^{14}_{3000}$ vs 10%-4% ILC$^{500}_{500}$-ILC$^{1000}_{1000}$

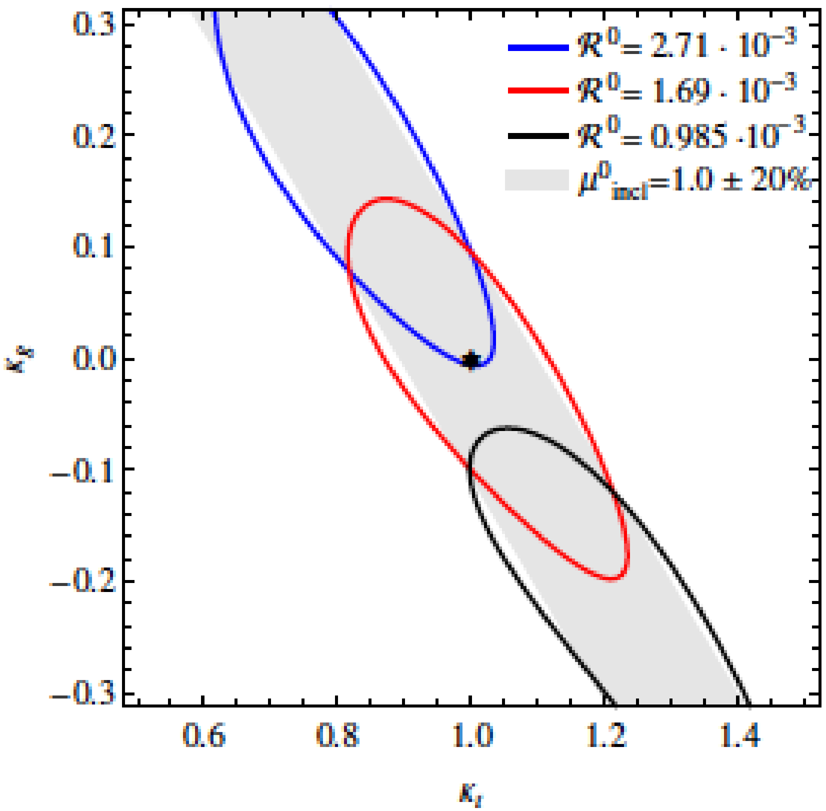
- **Alternative: Boosted Higgs production in association with a high p_T jet**

  Banfi,Martin,Sanz;Azatov,Paul;Grojean,Salvioni,Schlaffer,Weiler;Englert,McCullough,Spannowsky



$\mathcal{H}$ow to resolve the $\mathcal{T}$op $\mathcal{L}$oops?

- **High p_T** $\rightsquigarrow$ sensitivity to detail of loop particles — Baur,Glover; Langenegger eal
- **Remarks** $\diamond$ p_T distribution only known at LO
  - $\diamond$ in NLO in the heavy m_t approximation
    Schmidt; deFlorian eal; Ravindran eal; Glosser,Schmidt; Anastasiou eal; Boughezal eal; Harlander eal
  - $\diamond$ b-quark in resummed p_T Grazzini,Sargsyan; Alwall eal; Bagnaschi eal; Mantler,Wiesemann; Banfi eal



Grojean,Salvioni,Schlaffer,Weiler

Effective Lagrangian Approach

$\mathcal{G}$eneral $\mathcal{F}$ramework for $\mathcal{BSM}$ $\mathcal{S}$tudies

Aim: Study large class of BSM models through Higgs physics

$*$ Higgs couplings to SM particles, g_{hff}, g_{hVV}, Spin and CP quantum numbers, $\mathcal{J}^{\mathrm{CP}}$,
Higgs self-interactions, g_{hhh}, g_{hhhh}

Indirect impact of BSM on Higgs Physics

$*$ general coupling modifications: absolute value and tensor structure $\Rightarrow$

$*$ determination of couplings and CP properties cannot be treated separately in general

$*$ coupling modifications from new particles in loop induced couplings (e.g. g_{hgg}, $g_{h\gamma\gamma}$), mixing with other scalar states (e.g. extended Higgs sector, portal Higgs)

Direct impact of BSM Physics

$\diamond$ Higgs decays into new lighter particles, e.g. Higgs-to-Higgs decays, invisible Higgs decays; SM-like Higgs from cascade decays; detection of new particles; ...

$\mathcal{H}$ow access BSM physics in a general, model-independent way?

$\mathcal{E}$ffective $\mathcal{L}$agrangian $\mathcal{A}$pproach

- **Natural Mechanisms for EWSB**
  - ◇ New physics at some scale $\lambda \sim \mathcal{O}(\text{TeV})$
  - ◇ New physics generates deviations in SM Higgs physics

- **Convenient framework for model-independent analysis:** Effective Lagrangian Approach

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

  - $*$ assume few basic principles (e.g. field content, SM gauge symmetries)
  - $*$ parametrize SM deviations by higher-dimensional operators built of SM fields
  - $*$ Operators = low-energy remnants of heavy NP integrated out at $\Lambda \Rightarrow$
  - $*$ Operators suppressed by scale Λ

- **Example:** $SU(3) \times SU(2) \times U(1)$ invariance $\rightsquigarrow$ leading NP effects described by $D = 6$ operators

$$\mathcal{L}_{\text{eff}} = \sum_n \frac{f_n}{\Lambda^2} \mathcal{O}_n$$

$\mathcal{C}$hoice of $\mathcal{B}$asis

- **Number of Independent Dim-6 Operators** 59 assuming 1 generation of fermions
- **Different operator bases used in the literature**
- **What defines a good basis?**
  - ◇ captures in few operators impact of different NP scenarios
  - ◇ exploit correlations to eliminate redundant operators (EOM/field redefinitions)
  - ◇ separate operators with different sizes in their coefficients $\rightsquigarrow$
  - ◇ determine most relevant operators when investigating BSM scenarios
- **Operators relevant for Higgs physics:** e.g. Elias-Miró,Espinosa,Masso,Pomarol; Elias-Miró,Grojean,Gupta,Marzocca,Pomarol,Riva;Gupta,Pomarol,Riva
  - $*$ Operators only affecting Higgs physics (CP-conserving): **8**
  - $*$ Operators related to EWPT (LEP1, LEP2, Tevatron): **7**
  - $*$ Operators related to TGC measurements (LEP2, LHC): **3**

$\mathcal{H}$iggs $\mathcal{P}$rimaries

- **Higgs Primaries** Gupta,Pomarol,Riva

  set of physical quantities best suited to constrain NP

  ∗ Higgs/**8:** $h\gamma\gamma$, $hZ\gamma$, hgg, hff, hVV and h^3 couplings

  ∗ EWPT/**7**, TGC/**3**

- **Where to expect BSM effects?**

  ◇ $h \to Vff$ already constrained from e.g. TGC

  ◇ $BR(h \to Z\gamma)$ can still hide large deviations

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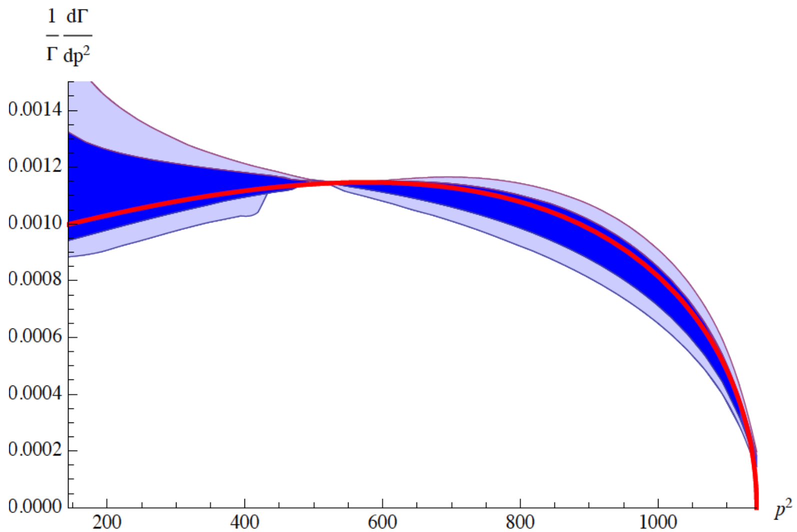
$h \to Z\gamma$ versus TGC



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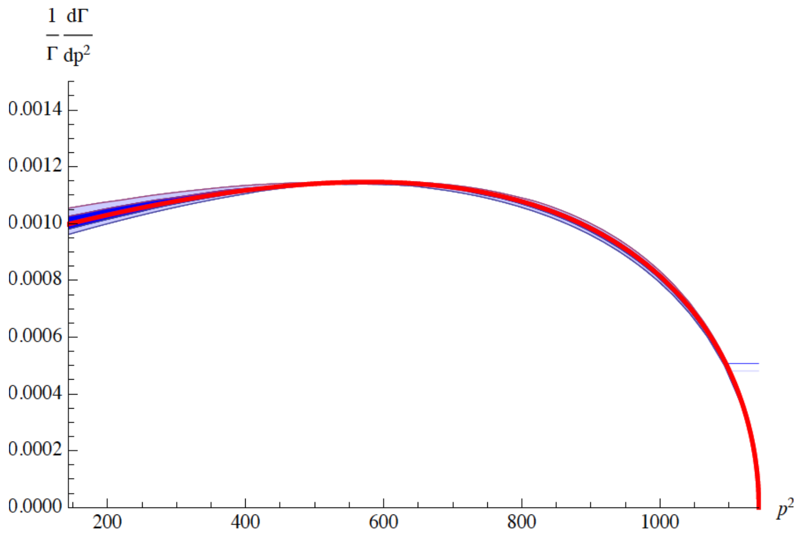


$\mathcal{E}$ffective $\mathcal{T}$heory $\mathcal{A}$pproach $\mathcal{V}$ersus $\mathcal{S}$pecific $\mathcal{M}$odels

- **Effective Field Theory Approach**
  - ∗ assume few basic principles (e.g. field content, SM gauge symmetries)
  - ∗ parametrize SM deviations by higher-dimensional operators

Advantage:	study large class of models
Disadvantage:	cannot account for effects from light particles in the loops, Higgs decays into non-SM particles
Solution:	study specific BSM models capturing these features

Going Beyond the SM

UnHiggs

Private Higgs

Little Higgs

Gaugephobic Higgs

Intermediate Higgs

Littlest Higgs

Slim Higgs

Composite Higgs

Fat Higgs

Higgsless

Portal Higgs

Gauge Higgs

Twin Higgs

Lone Higgs

Simplest Higgs

Phantom Higgs


Higgs Boson
Couplings

What Can We Learn From Coupling Measurements?

- ***The Standard Model Higgs Boson***
  - ◇ Test relation $g_{hXX} \sim m_X$ predicted by Higgs mechanism

- **Deviations from SM couplings ← New Physics**
  - ◇ modified Higgs properties through mixing effects with other scalars or mixture between elementary and composite state in case of a composite particle (partial compositeness)
  - ◇ modified Higgs properties through loop effects or effective low-energy operators (strong interaction)

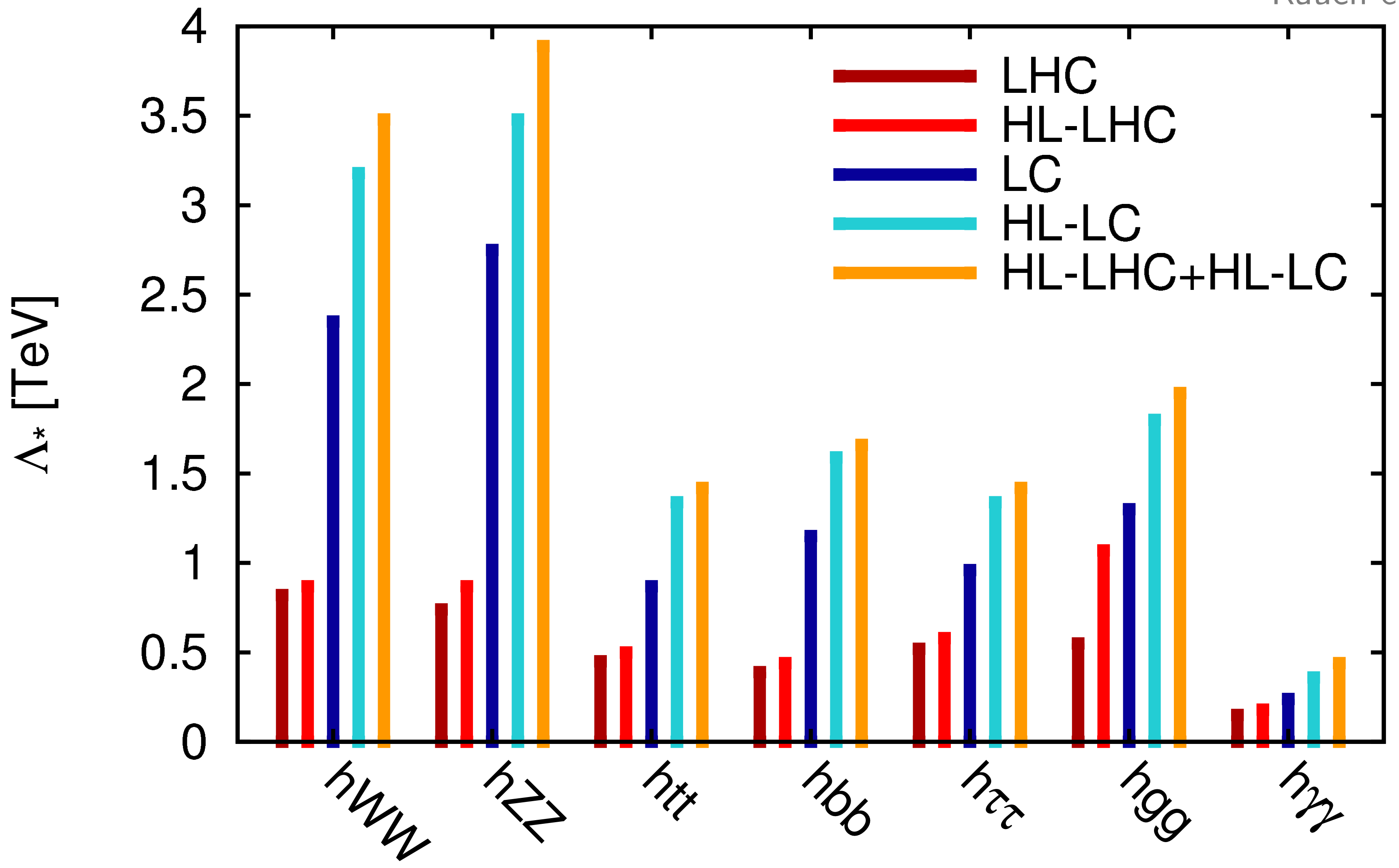
What is the Scale of New Physics that can be Probed?

- **Expansion in higher dimensional operators** to describe coupling deviation $\rightsquigarrow$

$$g_{hXX} = g_{hXX}^{\text{SM}}[1 + \Delta] \ : \ \Delta = \mathcal{O}(v^2/\Lambda_*^2)$$

$\mathcal{E}$ffective $\mathcal{N}$ew $\mathcal{P}$hysics $\mathcal{S}$cales

Rauch et al.



$\mathcal{E}$ffective $\mathcal{N}$ew $\mathcal{P}$hysics $\mathcal{S}$cales

- **Effective New Physics scales Λ_*** extracted from coupling measurements

Λ_* [TeV]	LHC	HL-LHC	LC	HL-LC	HL-LHC + HL-LC
hWW	0.82	0.87	2.35	3.18	3.48
hZZ	0.74	0.87	2.75	3.48	3.89
htt	0.45	0.50	0.87	1.34	1.42
hbb	0.39	0.44	1.15	1.59	1.66
$h\tau\tau$	0.52	0.58	0.96	1.34	1.42
hgg	0.55	1.07	1.30	1.80	1.95
$h\gamma\gamma$	0.15	0.18	0.24	0.36	0.44

Loop-induced couplings to gluons and photons contain only the contribution of the contact terms

$\mathcal{S}$trongly $\mathcal{I}$nteracting $\mathcal{L}$ight $\mathcal{H}$iggs ($\mathcal{SILH}$)

- **SILH Lagrangian:** first term of an expansion in $\xi = v^2/f^2$ [f: typical scale of strong sector]

Giudice,Grojean,Pomarol,Rattazzi

Englert,Freitas,MMM,Plehn,Rauch,Spira,Walz

ξ	LHC	HL-LHC	LC	HL-LC	HL-LHC+HL-LC
universal	0.076	0.051	0.008	0.0052	0.0052
non-universal	0.068	0.015	0.0023	0.0019	0.0019
f [TeV]					
universal	0.89	1.09	2.82	3.41	3.41
non-universal	0.94	1.98	5.13	5.65	5.65

universal: fermions in spinorial representation — Agashe,Contino,Pomarol

non-universal: fermions in fundamental representation — Contino,Da Rold,Pomarol

$\mathcal{M}$ixing $\mathcal{E}$ffects – 2HDM

- **ρ–parameter exp close to 1** $\leadsto$ extensions of Higgs sector by $SU(2)$ singlet or doublet
- **2HDM potential** assuming CP-conservation and global $\mathbb{Z}_2$ discrete symmetry $[\phi_1 \to -\phi_1]$

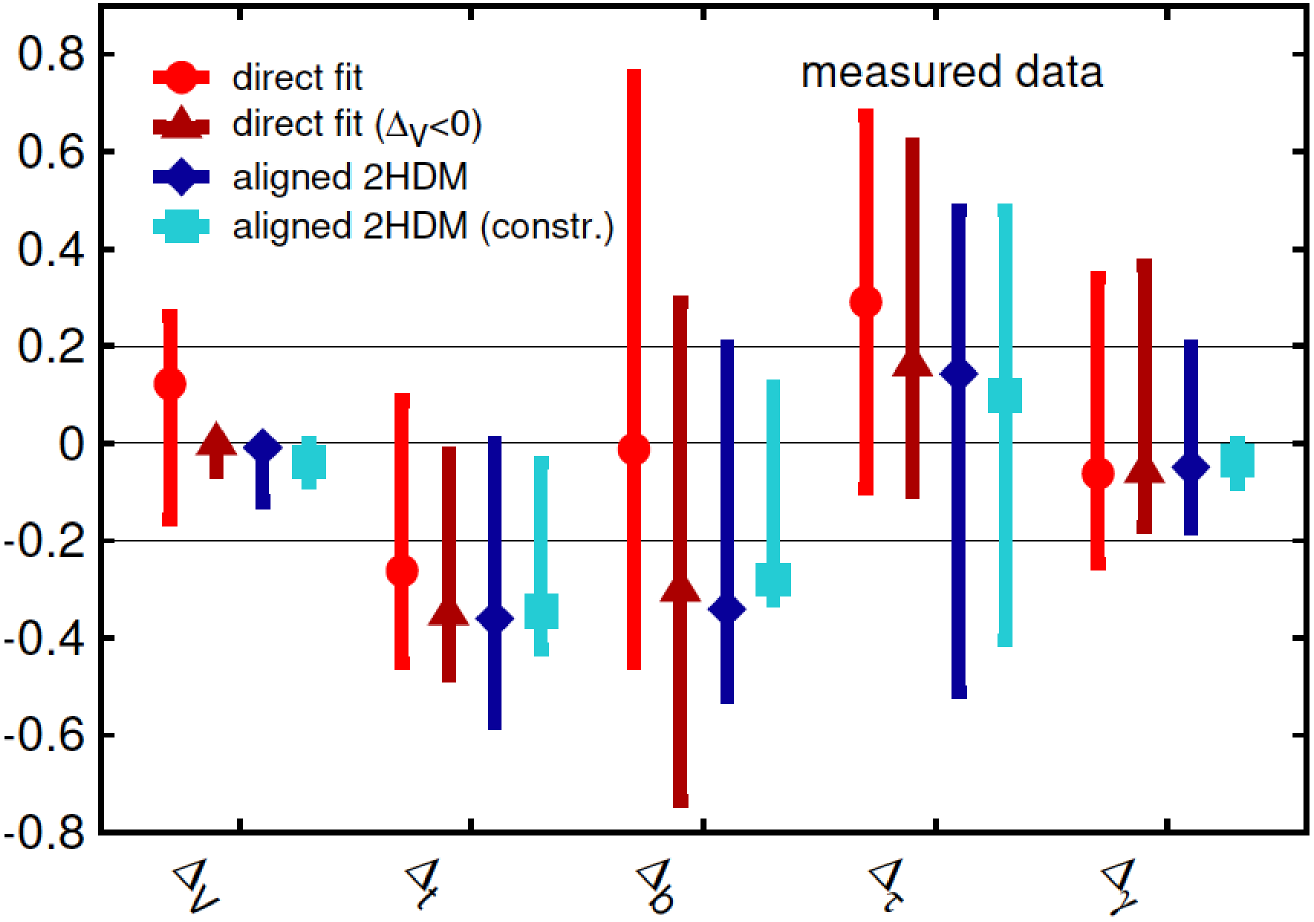
Flores,Sher; Gunion et al; Lee; Branco et al; Gunion,Haber

$$V = m_{11}|\phi_1|^2 + m_{22}^2|\phi_2|^2 - m_{12}^2(\phi_1^\dagger\phi_2 + \text{h.c}) + \lambda_1|\phi_1|^4 + \lambda_2|\phi_2|^4 + \lambda_3|\phi_1|^2|\phi_2|^2 + \lambda_4|\phi_1^\dagger\phi_2|^2 + \frac{1}{2}\lambda_5[(\phi_1^\dagger\phi_2)^2 + \text{h.c}]\,.$$

- **Couplings to fermions**
  - ◇ type I: all fermions couple only to ϕ_2;
  - ◇ type II: up-/down-type fermions couple to ϕ_2/ϕ_1, respectively; $\rightarrow$ MSSM
  - ◇ lepton-specific: quarks couple to ϕ_2 and charged leptons couple to ϕ_1;
  - ◇ flipped: up-type quarks and leptons couple to ϕ_2 and down-type quarks couple to ϕ_1.
- **Higgs sector after EWSB** CP-even neutral: h^0, H^0, CP-odd neutral; A^0, charged $H^\pm$

$\mathcal{F}$it to $\mathcal{C}$ouplings of $\mathcal{A}$ligned 2HDM

$g_X = g_X^{\mathrm{SM}}(1 + \Delta_X)$ Rauch et al.



Summary

- **Higgs Discovery**
  - ∗ Higgs Signal compatible with SM-like Higgs Boson
  - ∗ Interpretation within numerous BSM physics models possible
- **Composite Higgs Models**
  - ∗ Example for strong EWSB dynamics
  - ∗ Compatible with LHC Data
- **Effective Lagrangian Approach**
  - ∗ Covers a large class of models
  - ∗ Identify operators relevant for Higgs physics
  - ∗ Complement by investigations in specific models
- **Coupling Measurements**
  - ∗ 2HDM compatible with data
  - ∗ LHC accuracy allows to probe scales of $\mathcal{O}(1$ TeV$)$

Summary

Exciting times and discoveries are ahead of us.
With the LHC and HL-LHC we will have the excellent machine at hand
to investigate Higgs and New Physics and
gain insights in the true nature of the underlying theory

Work has only started!

Thank You For Your Attention!