



Higgs Phenomenology

– from data to interpretation –

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Recent results from Moriond '17: 'All quiet on the Higgs front'

Mass:

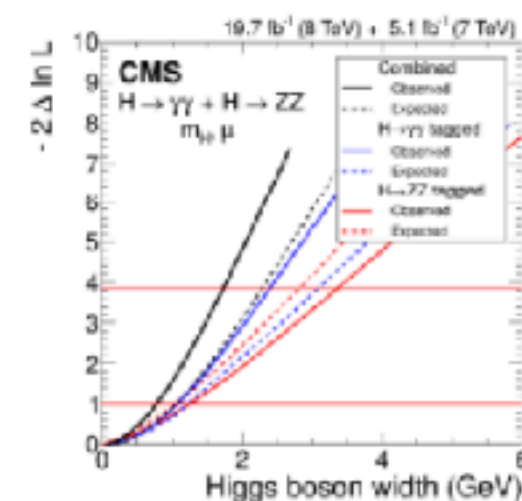
Use per event mass uncertainty + ME-based kinematic discriminant + Z_1 mass constraint:

$$125.26 \pm 0.20 \text{ (stat.)} \pm 0.08 \text{ (sys.) GeV}$$

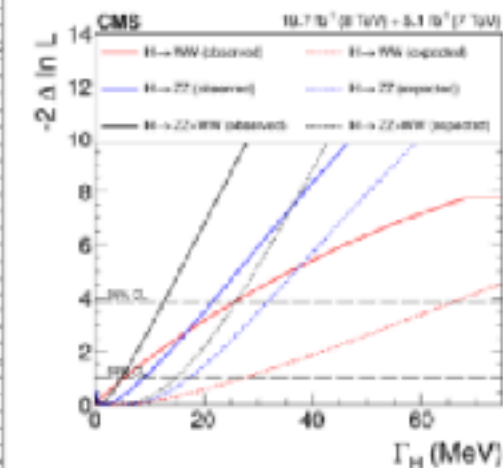
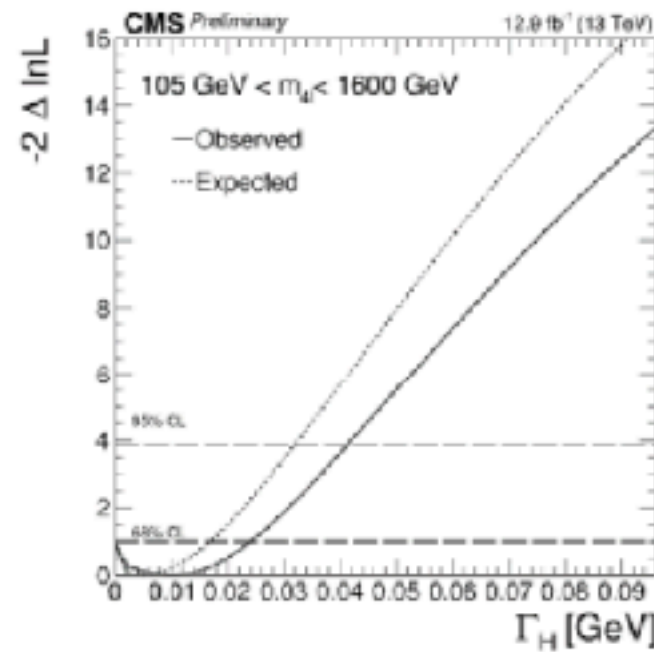
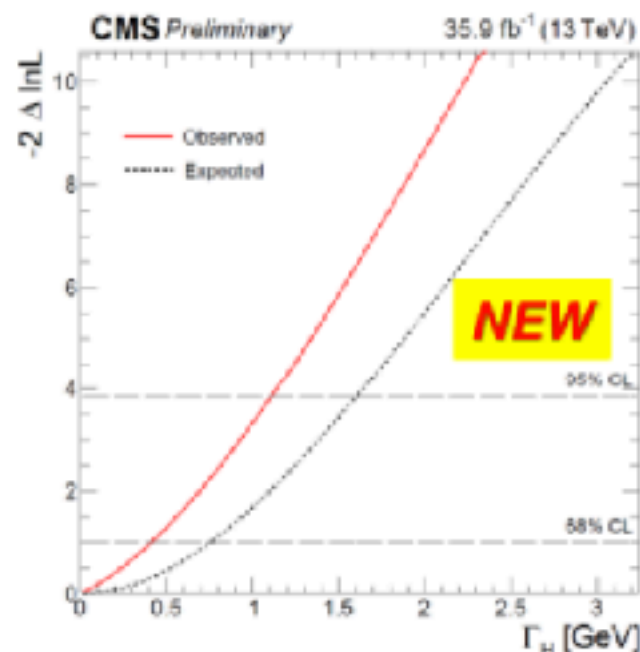
Run I ATLAS+CMS (4l, $\gamma\gamma$) combination: $125.09 \pm 0.21 \text{ (stat.)} \pm 0.11 \text{ (sys.) GeV}$

width:

- Mass width is measured with two very different methods.
- $\Gamma_H = 0.00^{+0.41}_{-0.00} \text{ GeV}$ with only on-shell
 - Tighter limit than Run 1
- $\Gamma_H = 10^{+14}_{-10} \text{ MeV}$ with both on-shell and off-shell
 - With strong theory assumptions
 - With only 12.9 fb^{-1}



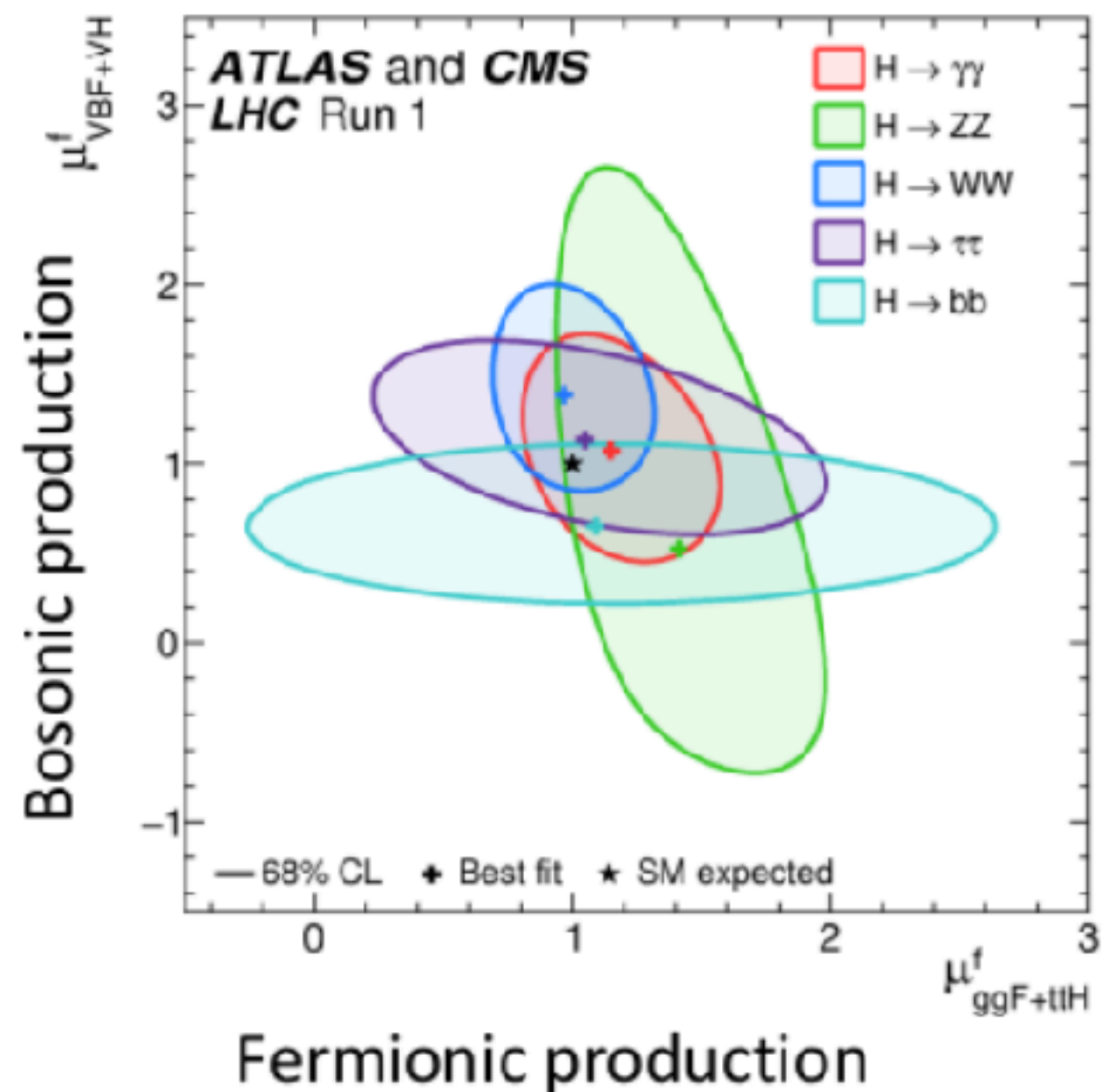
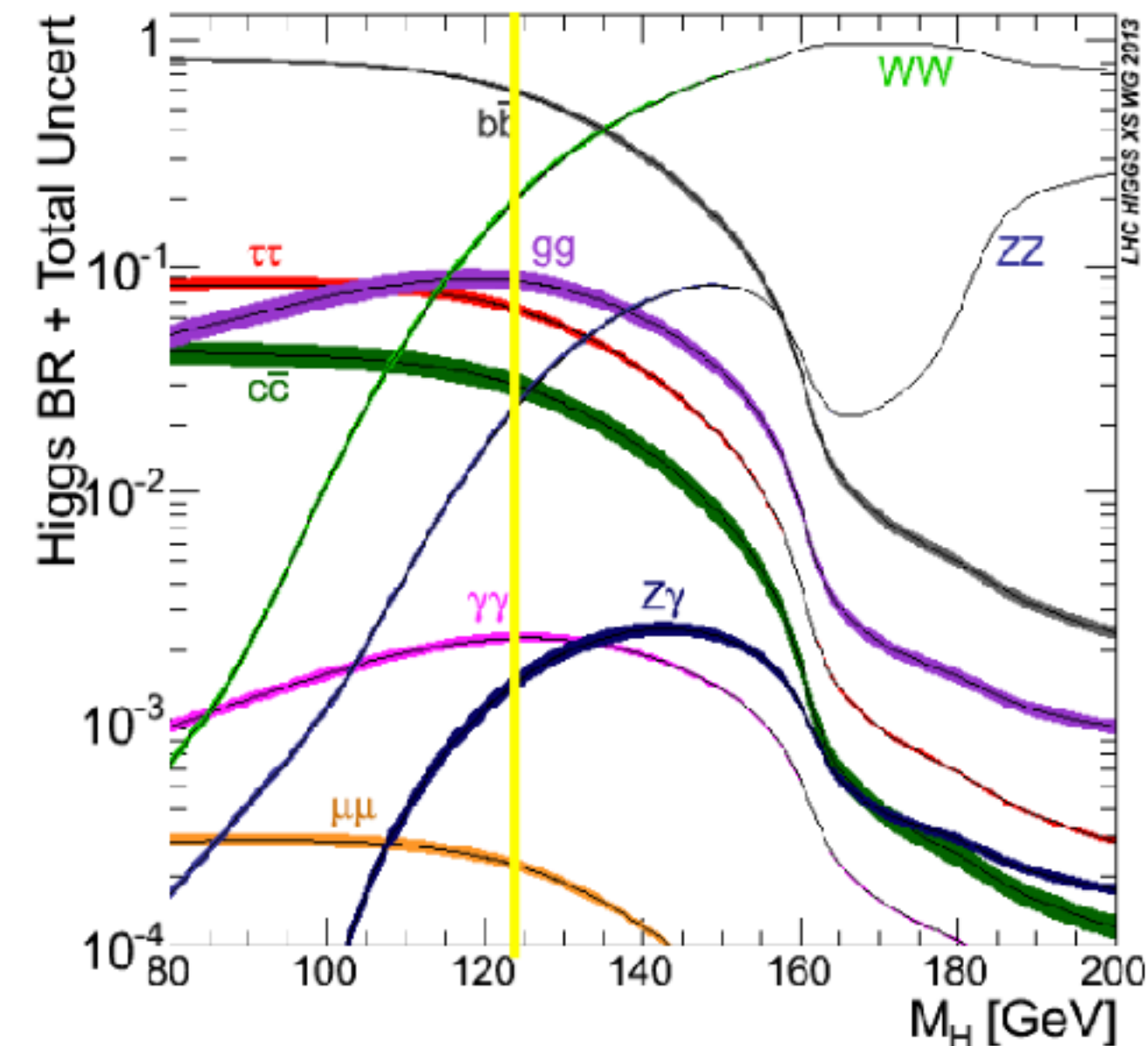
EPJC 75 (2015) 212



JHEP 09 (2016) 051

Recent results from Moriond '17: 'All quiet on the Higgs front'

Higgs couplings:

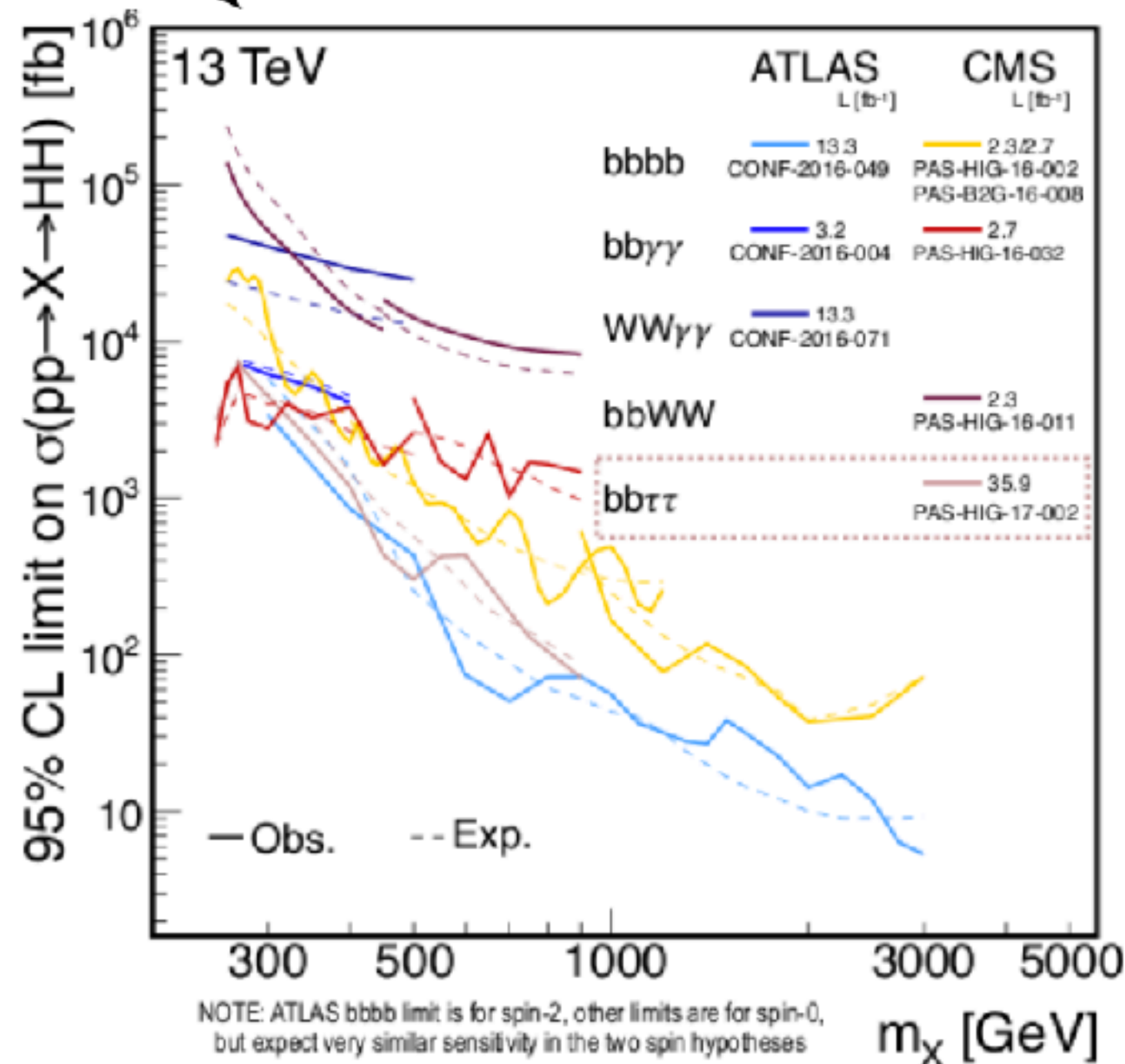


Recent results from Moriond '17: 'All quiet on the Higgs front'

BEH self-coupling

Resonant (BSM) search

Non-resonant (SM) search



Chan.	Obs. (exp.) 95% C.L. limit on σ/σ_{SM}	
		
bbbb	29 (38)	342 (308)
bbWW	-	410 (227)
bb $\tau\tau$	-	28 (25)
bb $\gamma\gamma$	117 (161)	91 (90)
WW $\gamma\gamma$	747 (386)	-

2.3-3.2 fb⁻¹ 13.3 fb⁻¹ 35.9 fb⁻¹

☐: Test of anomalous HH couplings

Observation will require
full HL-LHC statistics
& ATLAS+CMS combination

Due to absence of signs of new physics

HEP has 'Big Mac' blues,
i.e. why nature not like (as natural as) advertised?



Commercial

Reality

Sure, it (Higgs boson) does the job, but...

- Discovery of Higgs boson huge success
- However, Higgs boson remnant/
by-product of BEH mechanism

No detailed understanding so far

Not enough evidence to identify theory of nature



‘Do you have to yell ‘Eureka’ every time you see something new?’



New Physics has got to be out there:

- Matter/Anti-Matter asymmetry
- Dark Matter
- Hierarchy Problem
- Inflation



connect Higgs with high-scale physics

The Higgs as window to new physics: Connecting measurements with UV physics

Kappa Framework

- ▶ NP models simple rescaling of couplings
- ▶ No new Lorentz-structures or kinematics

EFT

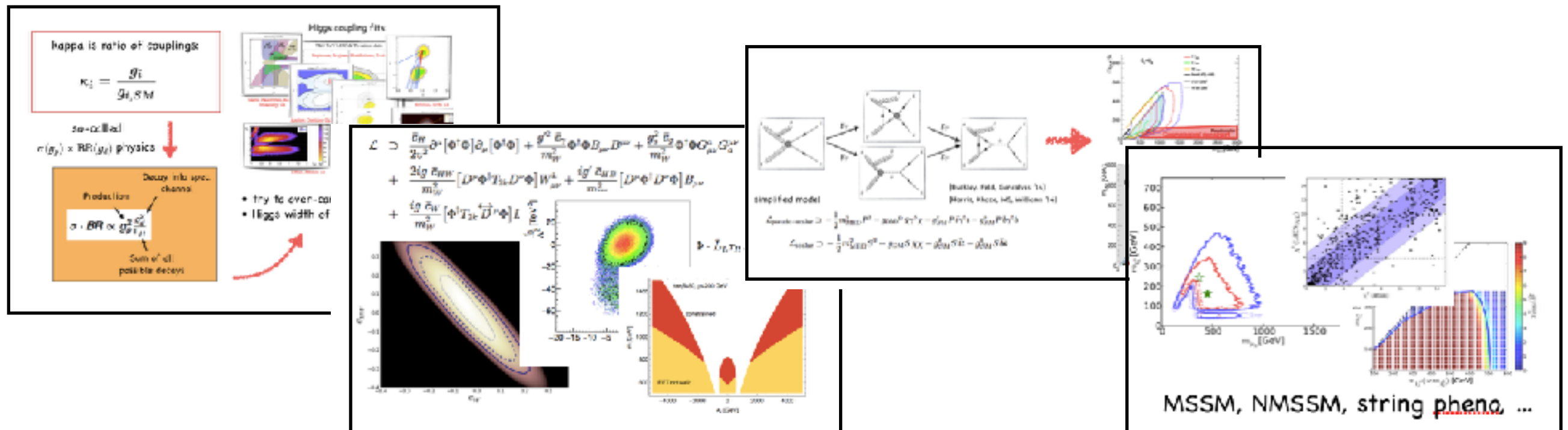
- ▶ SM degrees of freedom and symmetries
- ▶ New kinematics/ Lorentz structures

Simplified Models

- ▶ New low-energy degrees of freedom
- ▶ Subset of states of full models, reflective at scale of measurement

Full (UV) Model

- Very complex and often high-dimensional parameter space
- Allows to correlate high-scale and low-scale physics



Complexity/Flexibility

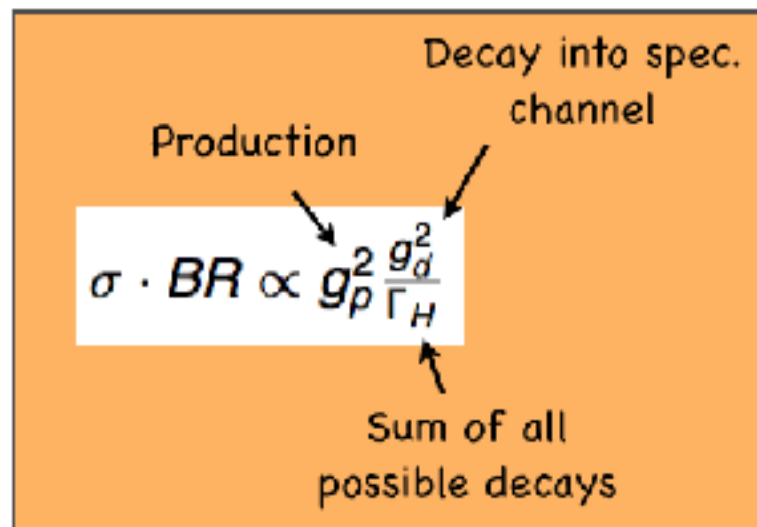
Coupling measurement during Run 1 using kappa-framework:

kappa is ratio of couplings:

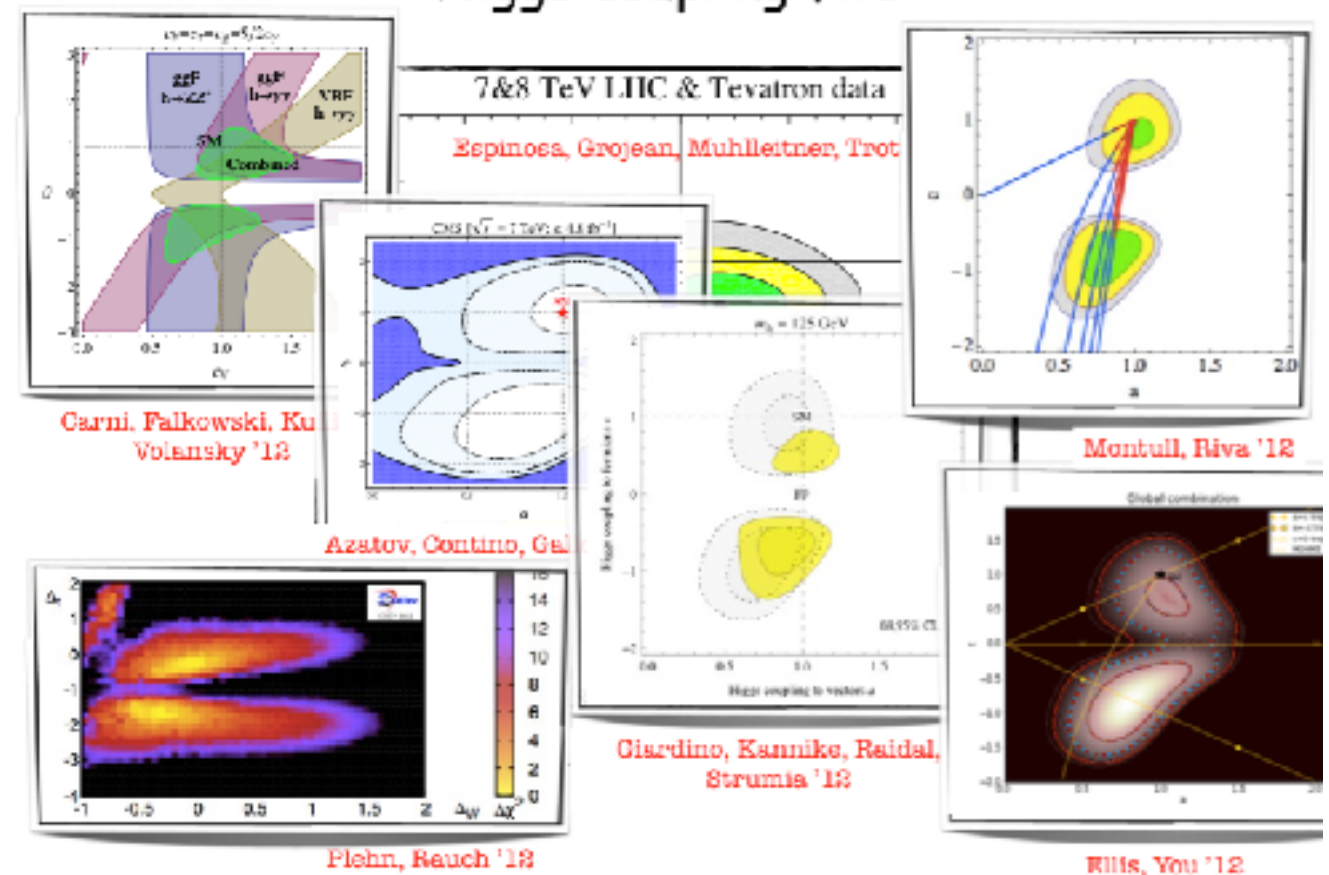
$$\kappa_i = \frac{g_i}{g_{i,SM}}$$

so-called

$\sigma(g_p) \times \text{BR}(g_d)$ physics



Higgs coupling fits



- try to over-constrain couplings basis
- Higgs width of particular importance

- ➔ Higgs coupling fits based on total rates... no dynamics
- ➔ No new Lorentz structures, limited applicability for new physics

Struggle for a unified language (basis) for Higgs EFT

Basis

- Complete
- Inspired by UV physics?

Several available:

Warsaw Basis	[1008.4884]
SILH Basis	[hep-ph/070164]
Primary/Higgs Basis	[1405.0181]

Practicality

- Manageable number of operators for fit

Validity

- Validity range of EFT set by kinematic of measurement

Precision

- Resummation of large log (RGE improved pert. theory)
- Full NLO



Basis and choice of operators to consider

Agnostic operator basis highly complex:

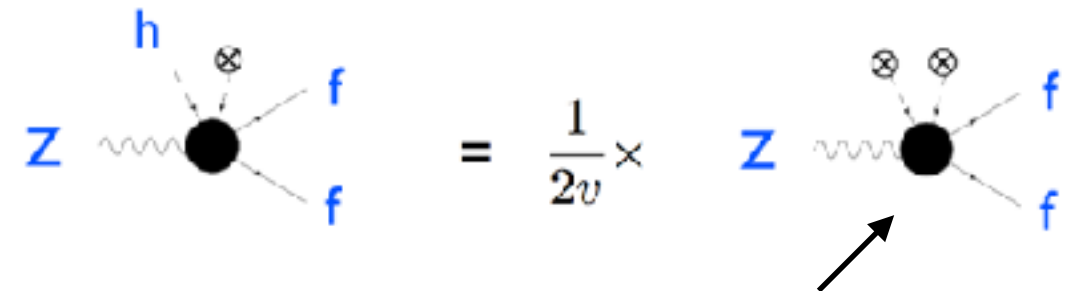
2499 non-redundant parameters at dim-6

Flavor diagonal still complex:

59 operators

- Focus on operators with Higgs involvement (new kid on the block)

$\mathcal{O}_H = \frac{1}{2}(\partial^\mu H^\dagger \partial_\mu H)^2$ $\mathcal{O}_T = \frac{1}{2}(H^\dagger \overleftrightarrow{D}_\mu H)^2$ $\mathcal{O}_6 = \lambda H ^6$	$\mathcal{O}_1 = \mu (H^\dagger H) \partial_\mu H$ $\mathcal{O}_2 = \mu (H^\dagger H) \partial_\mu H^\dagger$ $\mathcal{O}_3 = \mu (H^\dagger H) \partial_\mu H^\dagger \partial^\mu H$ $\mathcal{O}_4 = \mu (H^\dagger H) \partial_\mu H^\dagger \partial^\mu H^\dagger$ $\mathcal{O}_5 = \mu (H^\dagger H) \partial_\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H$ $\mathcal{O}_6 = \mu (H^\dagger H) \partial_\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger$ $\mathcal{O}_7 = \mu (H^\dagger H) \partial_\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H$ $\mathcal{O}_8 = \mu (H^\dagger H) \partial_\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger$ $\mathcal{O}_9 = \mu (H^\dagger H) \partial_\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H$ $\mathcal{O}_{10} = \mu (H^\dagger H) \partial_\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger$	$\mathcal{O}_{11} = \mu (H^\dagger H) \partial_\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H$ $\mathcal{O}_{12} = \mu (H^\dagger H) \partial_\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger$ $\mathcal{O}_{13} = \mu (H^\dagger H) \partial_\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H$ $\mathcal{O}_{14} = \mu (H^\dagger H) \partial_\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger$ $\mathcal{O}_{15} = \mu (H^\dagger H) \partial_\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H$ $\mathcal{O}_{16} = \mu (H^\dagger H) \partial_\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger$	$\mathcal{O}_{17} = \mu (H^\dagger H) \partial_\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H$ $\mathcal{O}_{18} = \mu (H^\dagger H) \partial_\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger$ $\mathcal{O}_{19} = \mu (H^\dagger H) \partial_\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H$ $\mathcal{O}_{20} = \mu (H^\dagger H) \partial_\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger \partial^\mu H^\dagger$
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constrained by LEP at permille level

- Focus on operators that are probed predominantly at LHC

Choose SILH basis:

here $c_T \sim T$ and $c_B + c_W \sim S$

[Peskin, Takeuchi '91]

$$\begin{aligned} \mathcal{L}_{\text{SILH}} = & \frac{\bar{c}_H}{2v^2} \partial^\mu (H^\dagger H) \partial_\mu (H^\dagger H) + \frac{\bar{c}_T}{2v^2} (H^\dagger \overleftrightarrow{D}^\mu H) (H^\dagger \overleftrightarrow{D}_\mu H) - \frac{\bar{c}_6 \lambda}{v^2} (H^\dagger H)^3 \\ & + \left(\frac{\bar{c}_{u,i} y_{u,i}}{v^2} H^\dagger H \bar{u}_L^{(i)} H^c u_R^{(i)} + \text{h.c.} \right) + \left(\frac{\bar{c}_{d,i} y_{d,i}}{v^2} H^\dagger H \bar{d}_L^{(i)} H d_R^{(i)} + \text{h.c.} \right) \\ & + \frac{i \bar{c}_W g}{2m_W^2} (H^\dagger \sigma^i \overleftrightarrow{D}^\mu H) (D^\nu W_{\mu\nu})^i + \frac{i \bar{c}_B g'}{2m_W^2} (H^\dagger \overleftrightarrow{D}^\mu H) (\partial^\nu B_{\mu\nu}) \\ & + \frac{i \bar{c}_H W g}{m_W^2} (D^\mu H)^\dagger \sigma^i (D^\nu H) W_{\mu\nu}^i + \frac{i \bar{c}_H B g'}{m_W^2} (D^\mu H)^\dagger (D^\nu H) B_{\mu\nu} \\ & + \frac{\bar{c}_1 g'^2}{m_W^2} H^\dagger H B_{\mu\nu} B^{\mu\nu} + \frac{\bar{c}_2 g_S^2}{m_W^2} H^\dagger H G_{\mu\nu}^a G^{a\mu\nu}. \end{aligned}$$

[Giudice, Grojean, Pomarol, Rattazzi '07]

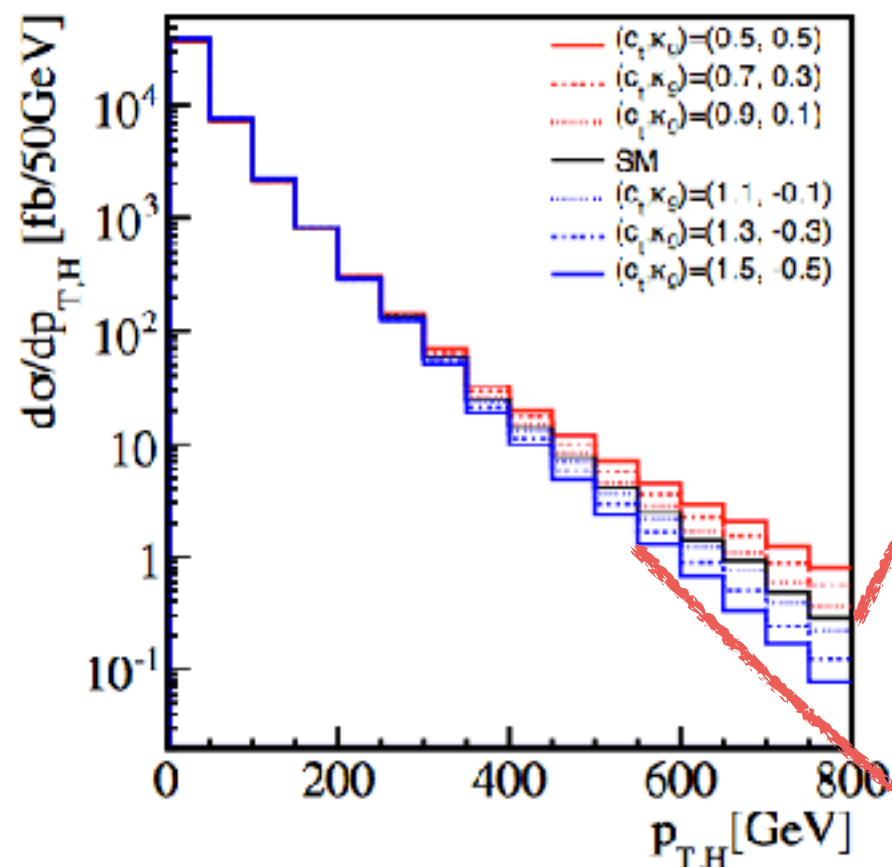
Validity and Relevance of EFT

EFT used to set limits on UV models from non-observation of new physics

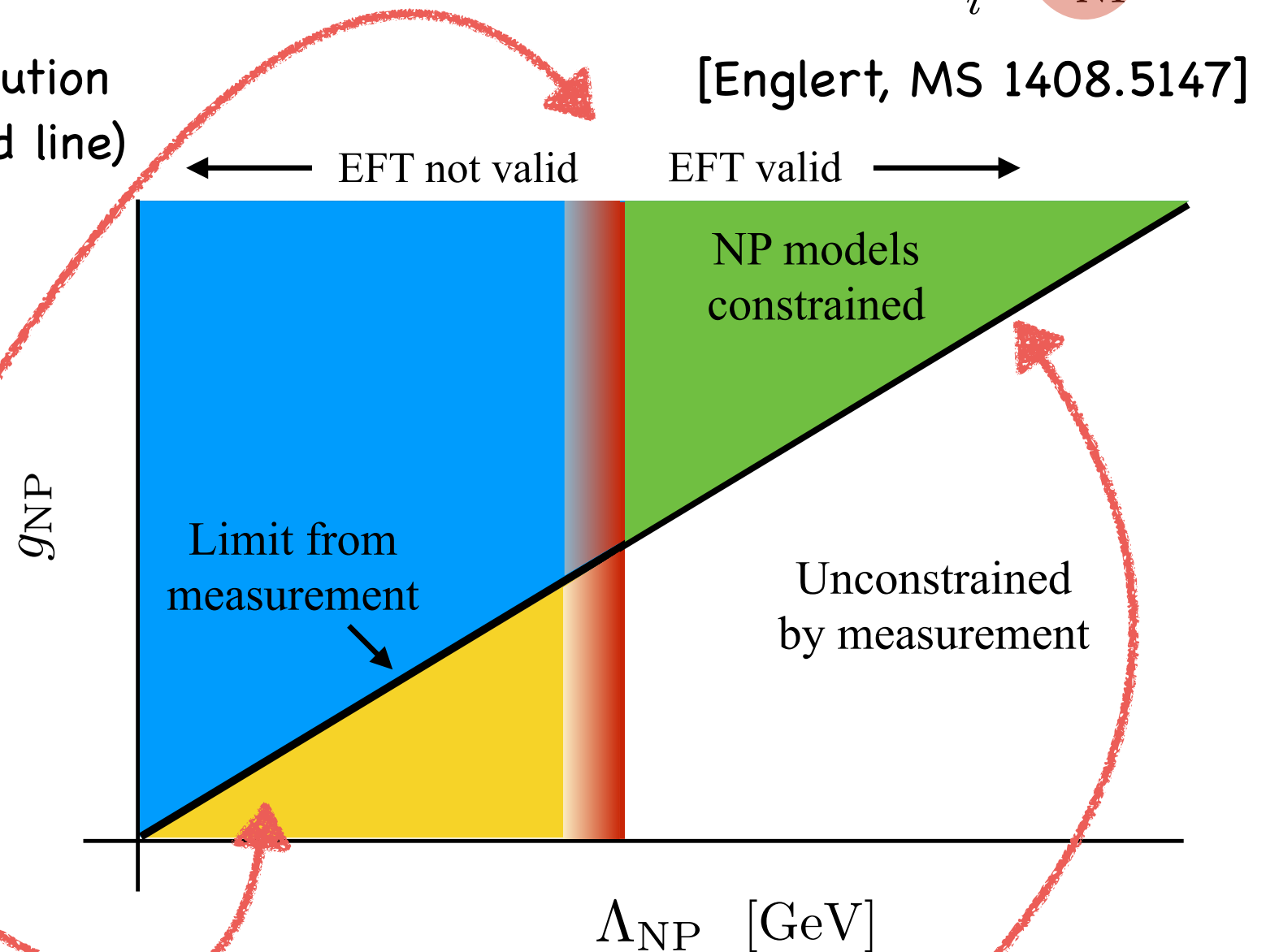
Lagrangian dim-6: $\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_i \frac{g_i^2}{\Lambda_{\text{NP}}^2} \mathcal{O}_i$

[Englert, MS 1408.5147]

Endpoint of kinematic distribution sets lower cut-off for NP (red line)

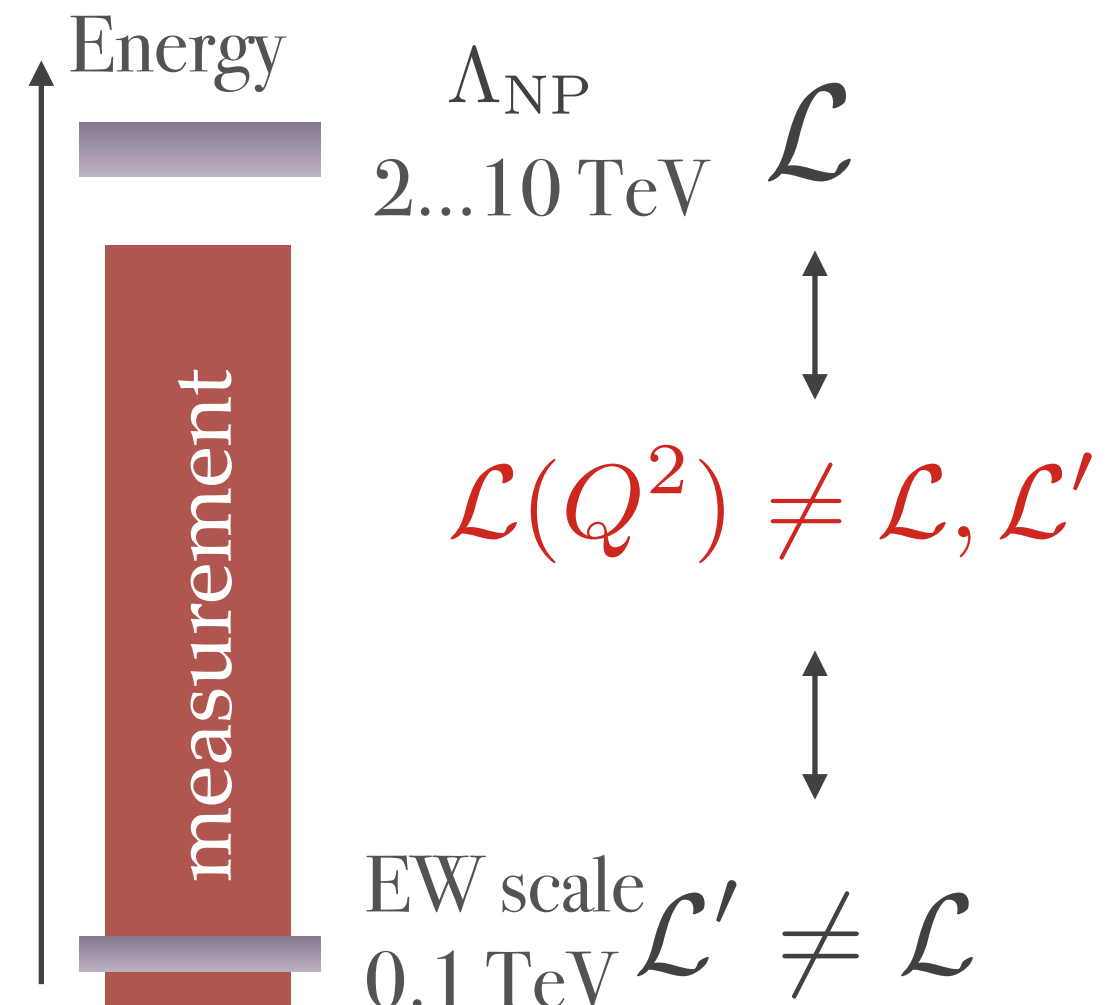
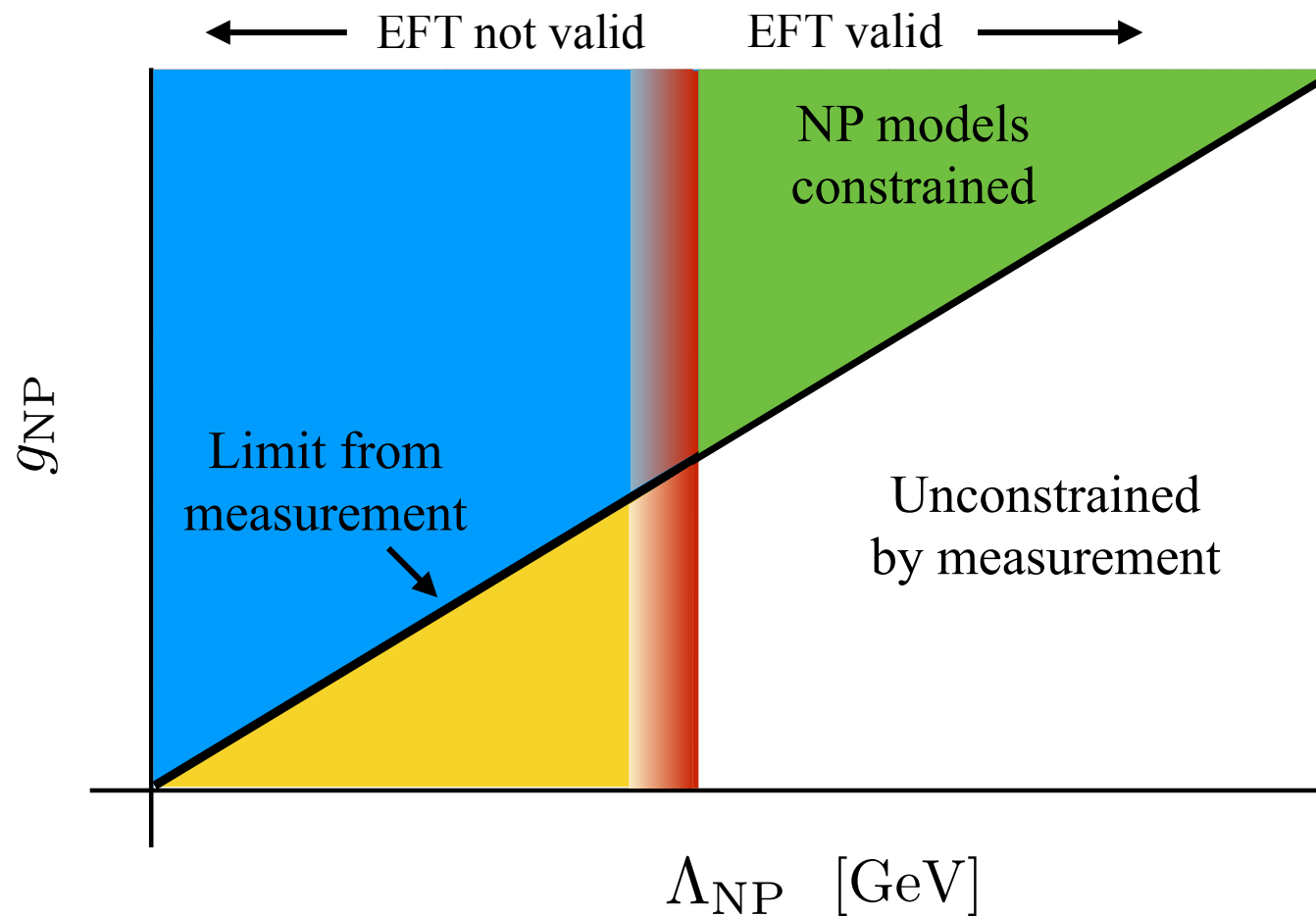


shape sets limit on Wilson coefficient (black line)



Any UV (weakly coupled) models left?

Validity and Relevance of EFT



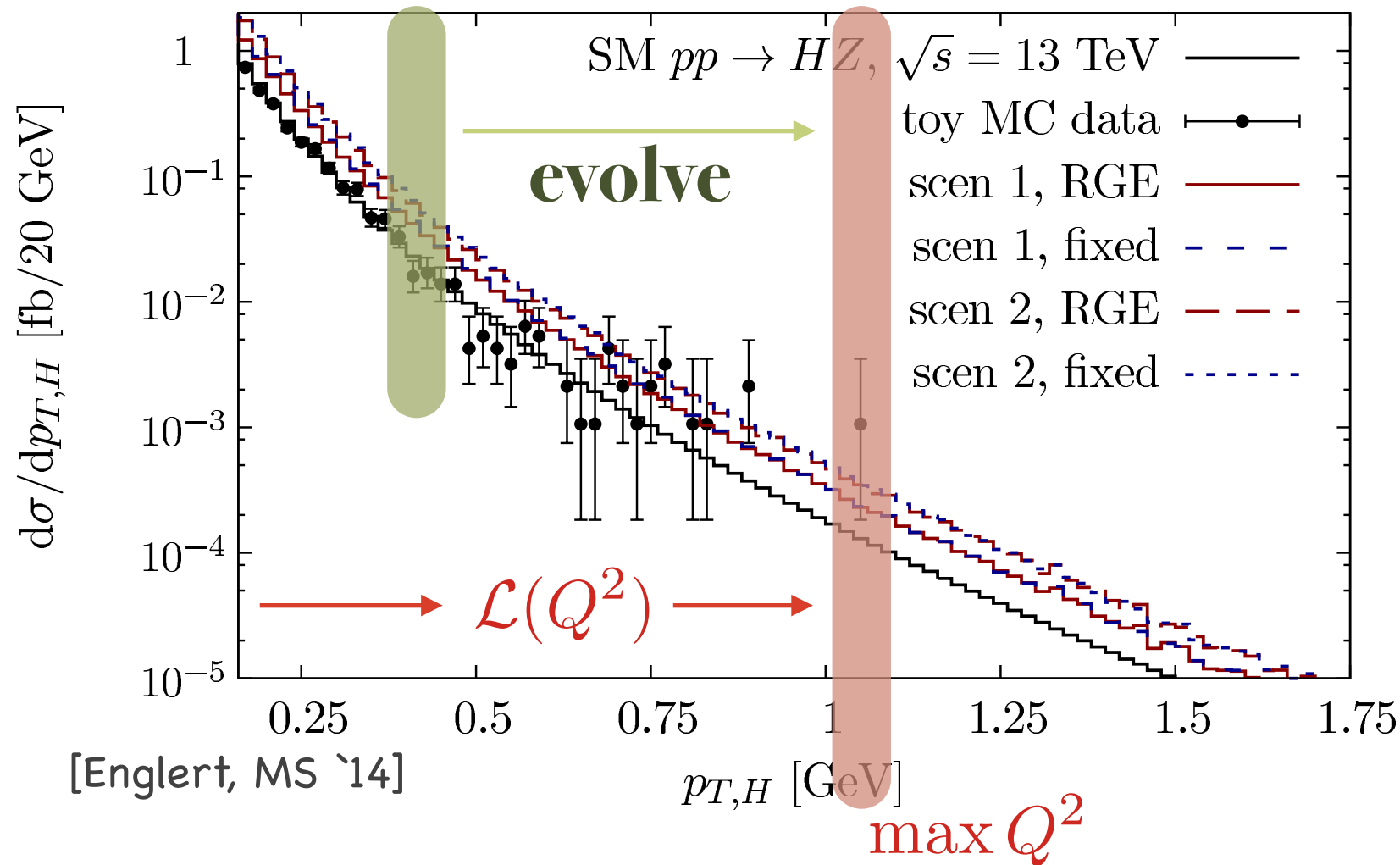
Lagrangian dim-6:
$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_i \frac{g_i^2}{\Lambda_{\text{NP}}^2} \mathcal{O}_i$$

- scale hierarchies similar to flavor physics $m_W/\text{mb} \sim 20$
- evolution from renormalization group equations

[Grojean, Jenkins, Manohar, Trott '13] [Jenkins, Manohar, Trott '13] [Elias-Miro et al '13]

- consistent interpretation requires **communication of resolved scales**

[Isidori, Trott '13] [Englert, MS '14]



$$\hat{O}_W = \frac{g^2}{2\Lambda_{\text{NP}}^2} \hat{H}^\dagger \hat{H} \hat{W}_{\mu\nu}^a \hat{W}^{a\mu\nu},$$

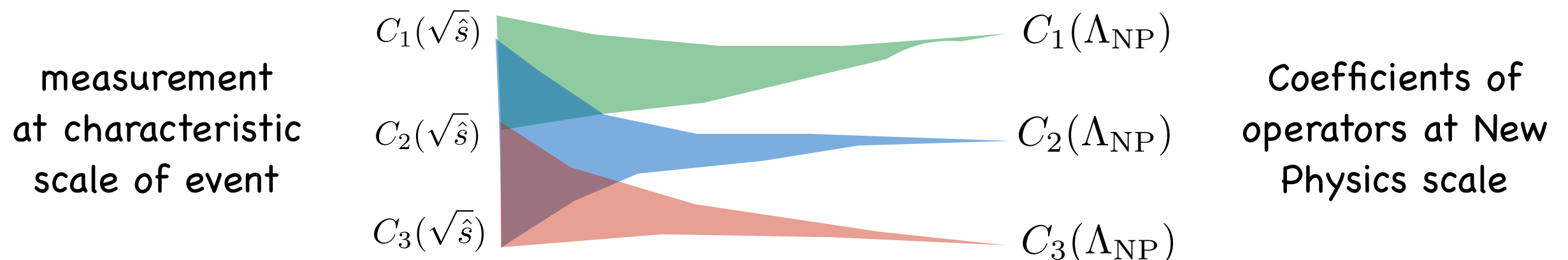
$$\hat{O}_B = \frac{g'^2}{2\Lambda_{\text{NP}}^2} \hat{H}^\dagger \hat{H} \hat{B}_{\mu\nu} \hat{B}^{\mu\nu},$$

$$\hat{O}_{WB} = \frac{gg'}{\Lambda_{\text{NP}}^2} \hat{H}^\dagger t^a \hat{H} \hat{W}_{\mu\nu}^a \hat{B}^{\mu\nu},$$

In general higher-order corrections induce scale dependence and mixing of operators

$$C_i(\sqrt{\hat{s}}) \simeq \left(\delta_{ij} + \gamma_{ij}(\sqrt{\hat{s}}) \log \frac{\sqrt{\hat{s}}}{\mu} \right) C_j(\mu)$$

As a result, each measured **event** probes a different combination of operators



Results for linearised LO EFT approach

[Englert, Kogler, Schulz, MS '15]

Focus on linear contribution
of EFT for theory prediction:

$$|\mathcal{M}|^2 = |\mathcal{M}_{\text{SM}}|^2 + 2 \text{Re}\{\mathcal{M}_{\text{SM}}\mathcal{M}_{d=6}^*\} + \mathcal{O}(1/\Lambda^4)$$

Number of predicted events:

$$N_{\text{th}} = \sigma(H + X) \times \text{BR}(H \rightarrow YY) \\ \times \mathcal{L} \times \text{BR}(X, Y \rightarrow \text{final state})$$

Each channel has own prod. and decay efficiencies:

$$N_{\text{ev}} = \epsilon_p \epsilon_d N_{\text{th}}$$

signal strength:

36 indep. meas. (300 fb)

46 indep. meas. (3000 fb)

differential:

88 indep. meas. (300 fb)

123 indep. meas. (3000 fb)



Decays: $H \rightarrow f\bar{f}$ $H \rightarrow \gamma\gamma$ $H \rightarrow \gamma Z$

$H \rightarrow ZZ^*$ $H \rightarrow WW^*$

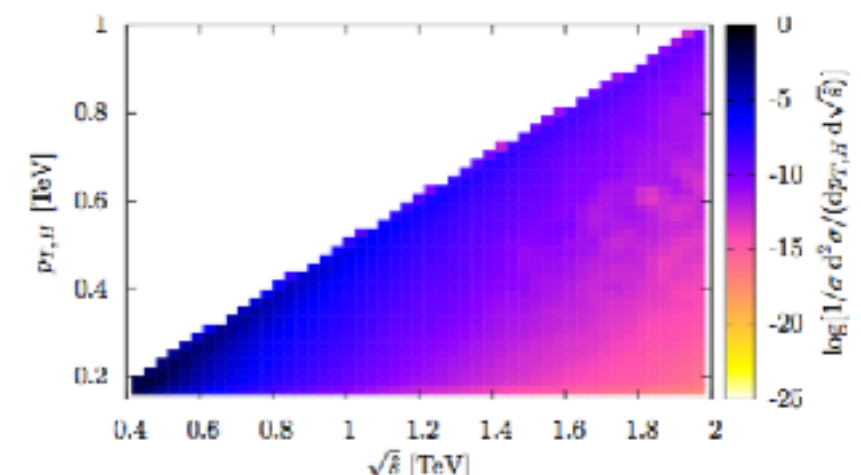
Production: $pp \rightarrow H$ $pp \rightarrow Hj$ $pp \rightarrow Hjj$

$pp \rightarrow HV$ $pp \rightarrow ttH$

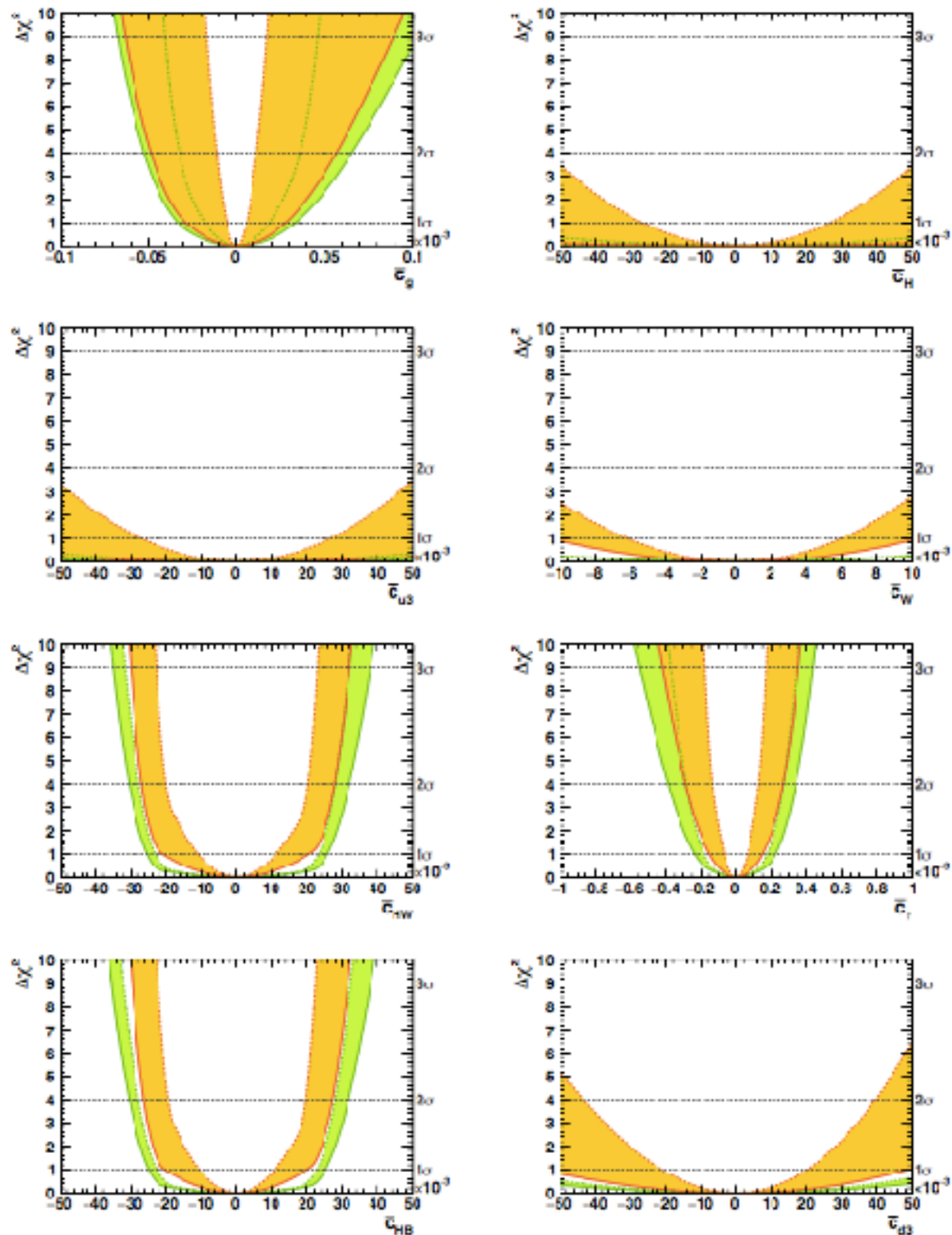
**Do we benefit from LHC's high energy
in Higgs physics?**



most likely and practical **p_T,H** unfolded

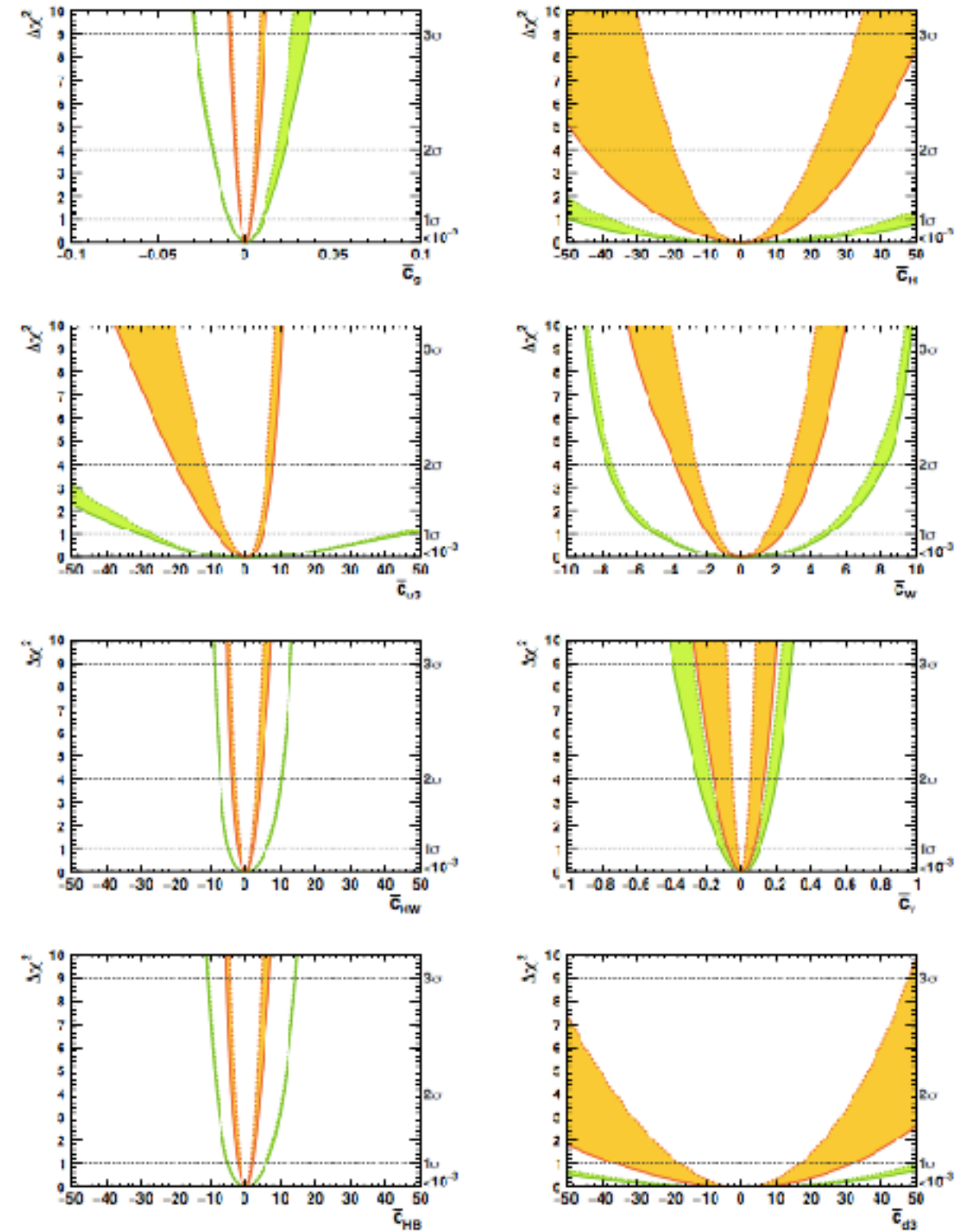


signal strength measurement

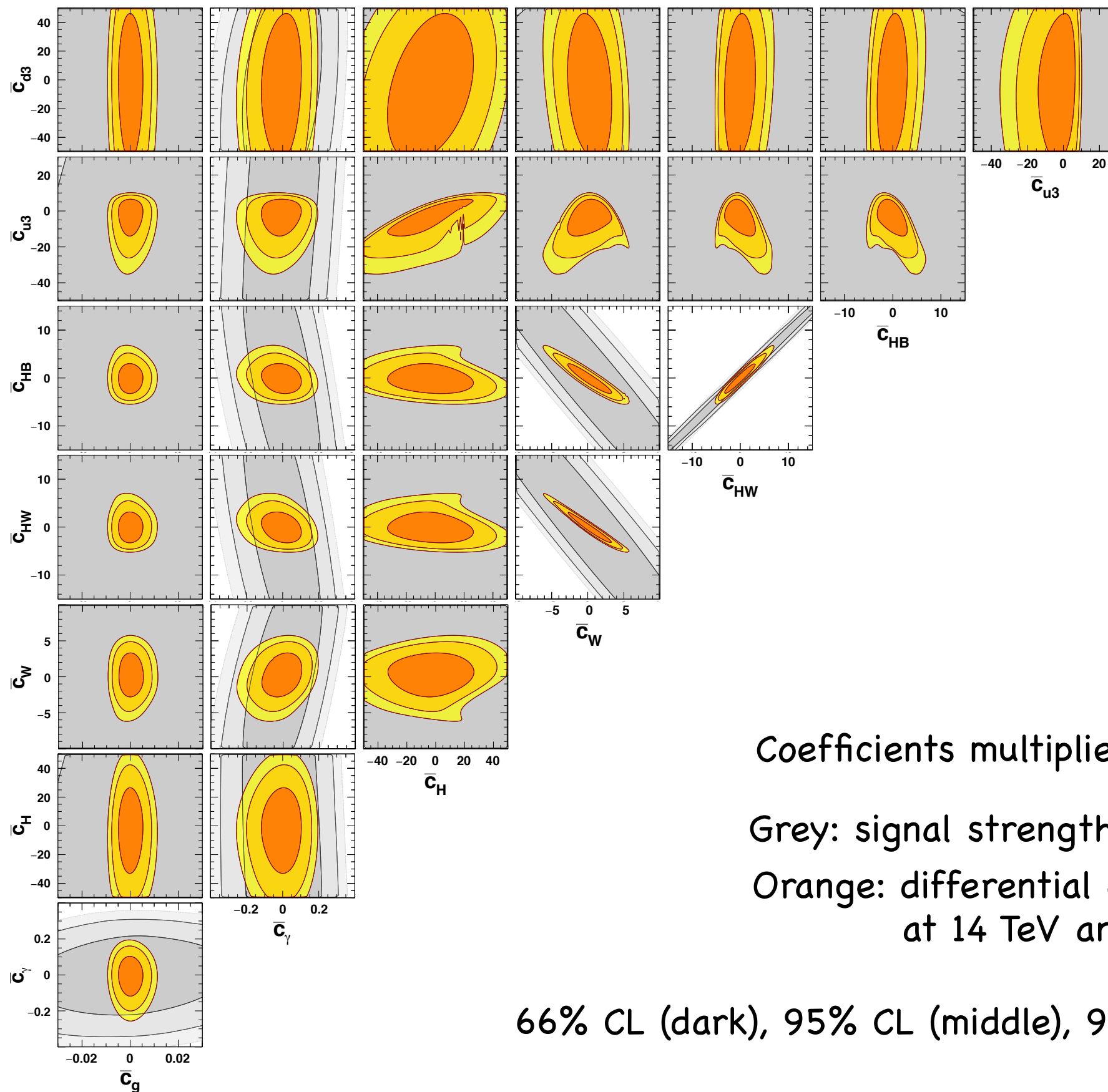


green = 300 ifb

differential measurement

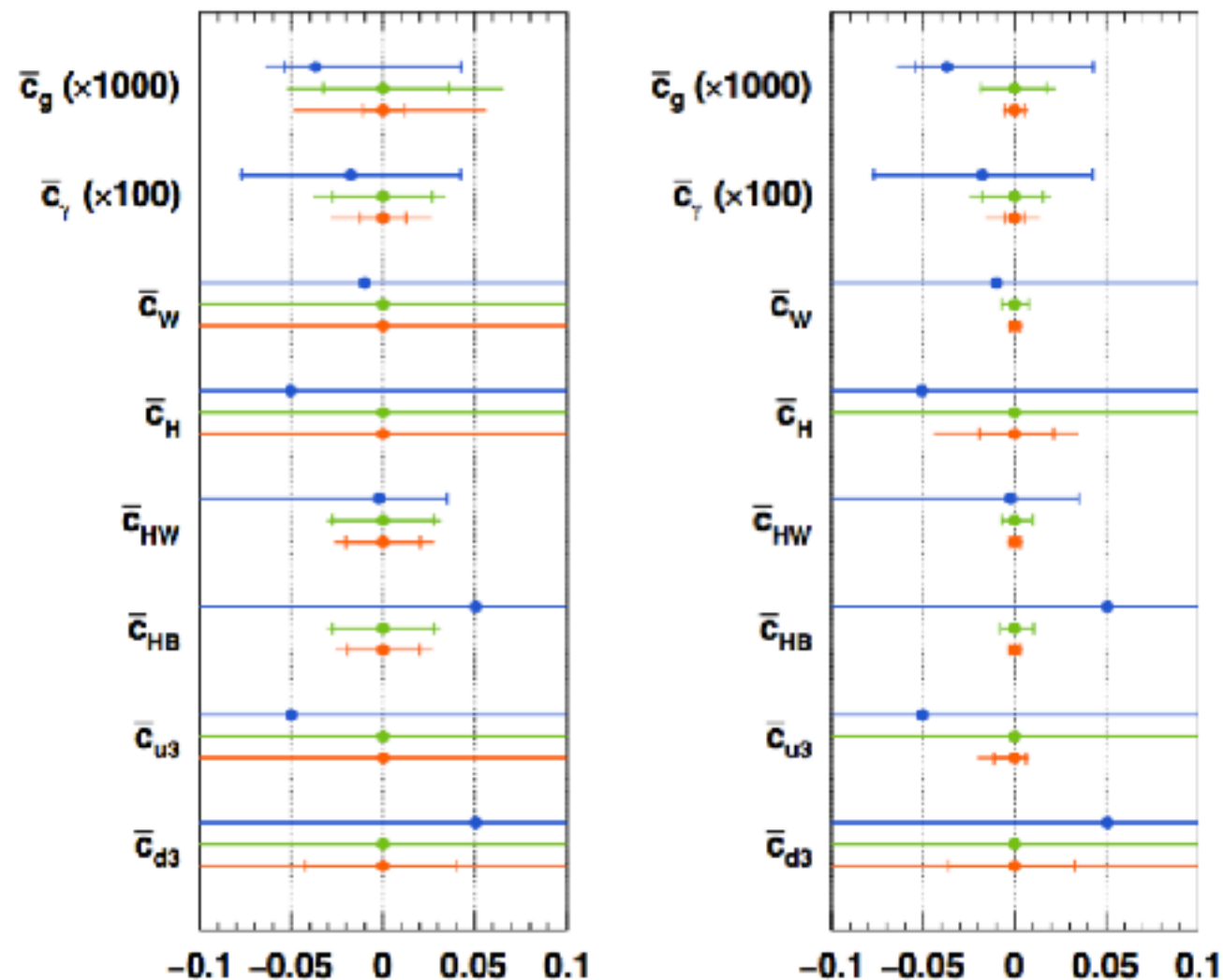


orange = 3000 ifb



Signal strength only

differential distributions



7/8 TeV (blue)

14 TeV, 300 ifb (green)

14 TeV, 3000 ifb (orange)

Setup allows to address most fundamental question for high-energy physics:

- Which theory calculations most important?
- Which systematic uncertainties most limiting?
- Where can we improve knowledge most?

Interpretation of results

Composite (SILH) Higgs:

One expects $\bar{c}_g \sim \frac{m_W^2}{16\pi^2} \frac{y_t^2}{\Lambda^2}$ with comp. scale $\Lambda \sim g_\rho f$

→ with $|\bar{c}_g| \lesssim 5 \times 10^{-6}$ we get $\Lambda \gtrsim 2.8 \text{ TeV}$

→ new fundamental physics with higher scale cannot be probed using our Higgs observables

MSSM:

$$\bar{c}_g = \frac{m_W^2}{(4\pi)^2} \frac{1}{24} \left(\frac{h_t^2 - g_1^2 c_{2\beta}/6}{m_{\tilde{Q}}^2} + \frac{h_t^2 + g_1^2 c_{2\beta}/3}{m_{\tilde{t}_R}^2} - \frac{h_t^2 X_t^2}{m_{\tilde{Q}}^2 m_{\tilde{t}_R}^2} \right)$$

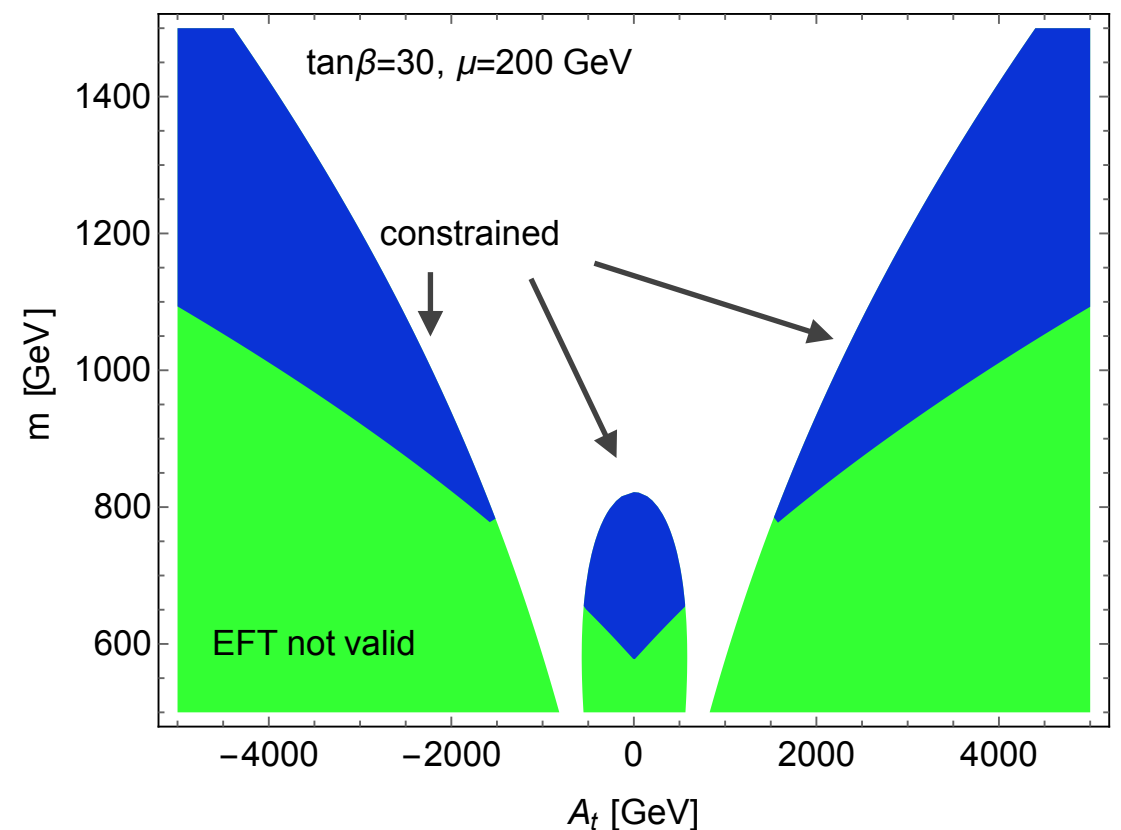
$$m_{\tilde{Q}} = m_{\tilde{t}} = m$$

$$\tan \beta = 30$$

$$\mu = 200 \text{ GeV}$$

$$h_t \equiv y_t s_\beta$$

→ large A_t can be constrained



Constraining the Higgs width at the LHC?

- alternative method using interference effects directly see [Dixon, Li '13]

Constraining the Higgs boson width with ZZ production at the LHC

Fabrizio Caola^{1,*} and Kirill Melnikov^{1,†}

¹*Department of Physics and Astronomy, Johns Hopkins University, Baltimore, USA*

We point out that existing measurements of $pp \rightarrow ZZ$ cross-section at the LHC in a broad range of ZZ invariant masses allow one to derive a model-independent upper bound on the Higgs boson width, thanks to strongly enhanced off-shell Higgs contribution. Using CMS data and considering events in the interval of ZZ invariant masses from 100 to 800 GeV, we find $\Gamma_H \leq 38.8 \Gamma_H^{\text{SM}} \approx 163$ MeV, at the 95% confidence level. Restricting ZZ invariant masses to $M_{ZZ} \geq 300$ GeV range, we estimate that this bound can be improved to $\Gamma_H \leq 21 \Gamma_H^{\text{SM}} \approx 88$ MeV.



[Caola, Melnikov PRD 88]

Measurement done in CMS-PAS-HIG-14-002 and presented at Moriond '14

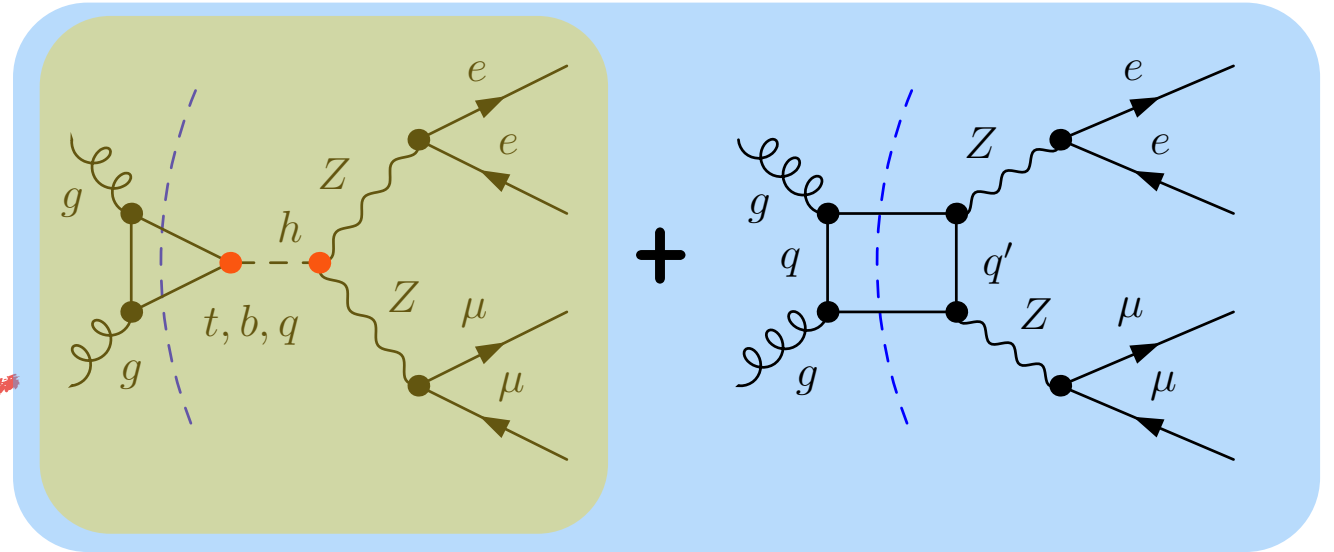
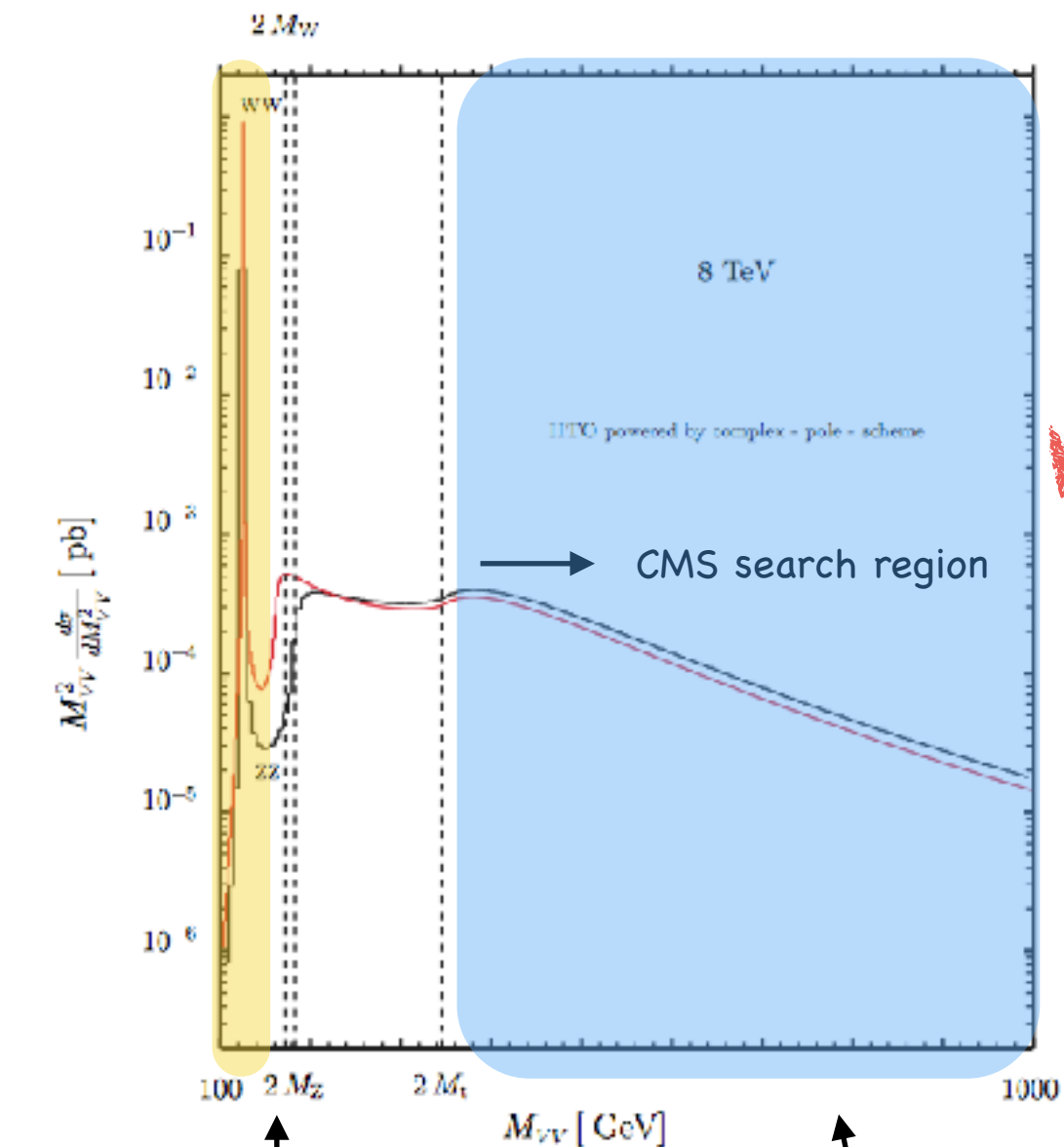
By now ATLAS has performed same measurement



How wide is a Higgs?

In accord with Heisenberg's uncertainty principle, short-lived particles have uncertain mass. So the Higgs boson, which gives mass to other particles, is uncertain about its own mass. New results from the CMS experiment at the CERN LHC have started to tell us how uncertain

Chosen language affects answer: CMS 'width' Measurement



I. Count events in on-shell region

→ fix signal strength $\mu_{i,j} = \sigma_{H,i} \times BR_j \sim \frac{g_{ggH} g_{HZZ}}{\Gamma_H}$

II. measure $g_{ggH}^2 g_{HZZ}^2$ in off-shell region using angular correlations of 4l decay products

III. insert off-shell coupling measurement in on-shell signal strength to bound width

$$\sigma_{gg \rightarrow H \rightarrow ZZ}^{\text{on-peak}} \sim \frac{g_{ggH}^2 g_{HZZ}^2}{\Gamma_H}$$

$$\sigma_{gg \rightarrow H \rightarrow ZZ}^{\text{off-peak}} \sim g_{ggH}^2 g_{HZZ}^2$$

Obs.(exp.) @95% C.L:

$$\Gamma_H < 4.2 (8.5) \Gamma_H^{\text{SM}}$$

$$\Gamma_H < 17.4 (35.3) \text{ MeV}$$



[Kauer, Passarino 2011]

[Caola, Melnikov 2013] [Campbell, Ellis, Williams 2013]

Example 'width-measurement'

Measure coupling off-shell $\rightarrow$ limit denominator on-shell

$$\sigma_{gg \rightarrow H \rightarrow ZZ}^{\text{on-peak}} \sim \frac{g_{ggH}^2 g_{HZZ}^2}{\Gamma_H} \longleftrightarrow \sigma_{gg \rightarrow H \rightarrow ZZ}^{\text{off-peak}} \sim g_{ggH}^2 g_{HZZ}^2$$

Kappa
Framework



- Assuming global coupling rescaling

EFT



- Assuming valid and no flat directions



Coupling assumptions strong
LEP limits stronger than LHC

$$0.73 \Gamma_{SM} \lesssim \Gamma_h \lesssim 1.87 \Gamma_{SM}$$

[Englert, McCullough, MS '15]

Simplified
Models



- Eg. **Higgs portal**, NP can contribute on-shell but not off-shell [Englert, MS '14]
- Eg. **Higgs triplet**, new scalar below measurement range cancels on-shell enhancement [Logan '15]

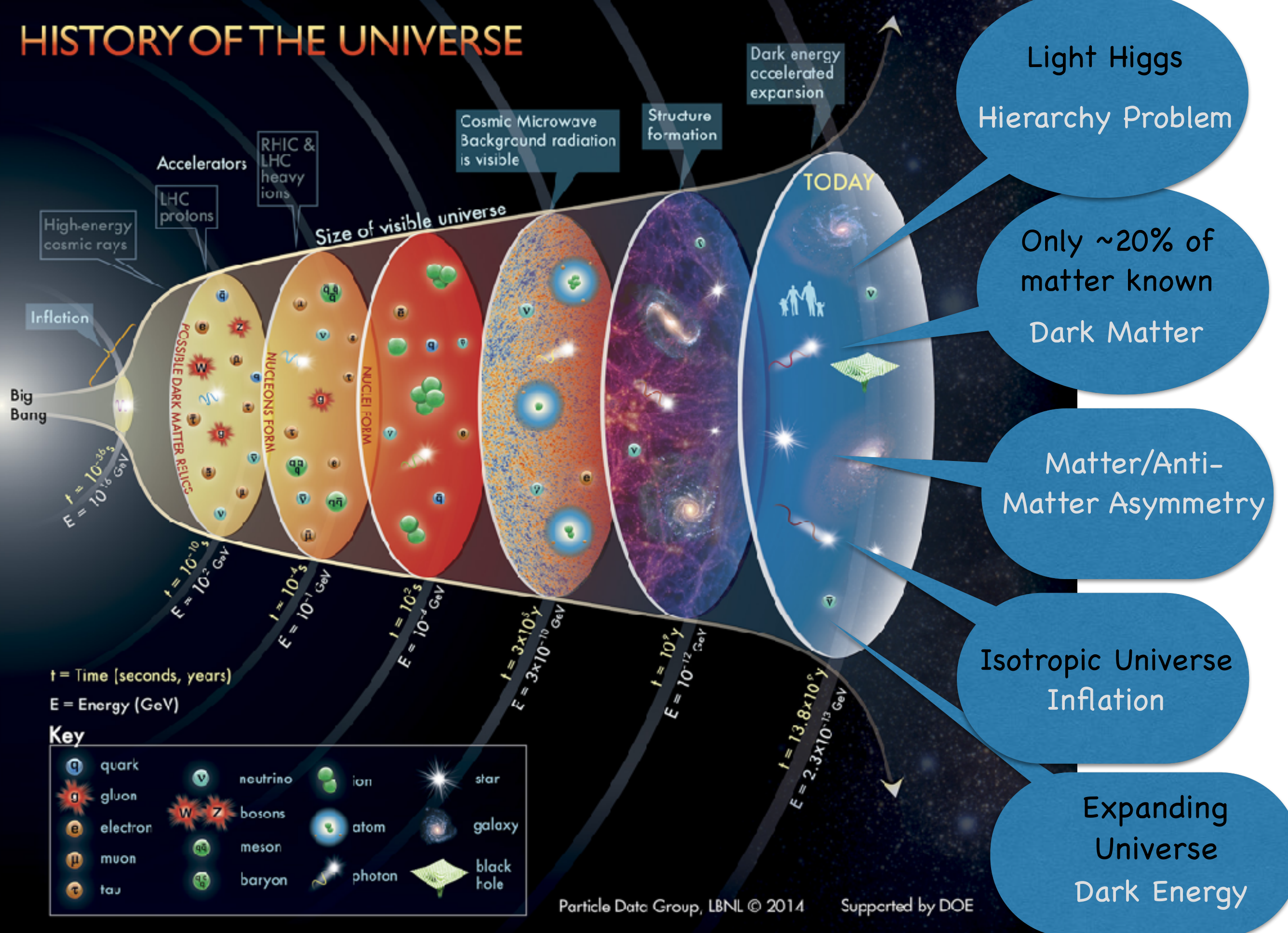
Full (UV)
Model



- Uninteresting width not a free parameter of the theory

width derived and fully determined

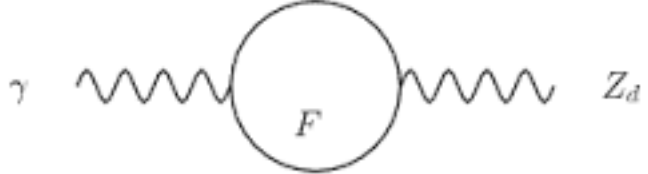
HISTORY OF THE UNIVERSE



Portals to Hidden Sectors

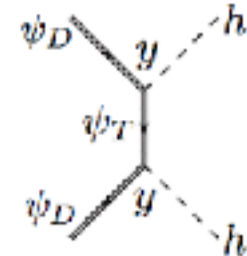
Possible portals at lowest order:

If extended scalar sector exists,
difficult to avoid



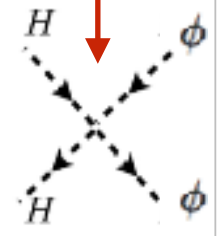
$$L_{\text{mix}} = -\frac{\chi_{\text{elec}}}{2} F_{\mu\nu} F'^{\mu\nu} - \frac{\chi_{\text{mag}}}{2} F_{\mu\nu} \tilde{F}'^{\mu\nu}$$

kinetic mixing



$$\frac{\alpha}{\Lambda} \bar{\chi} \chi (H^\dagger H)$$

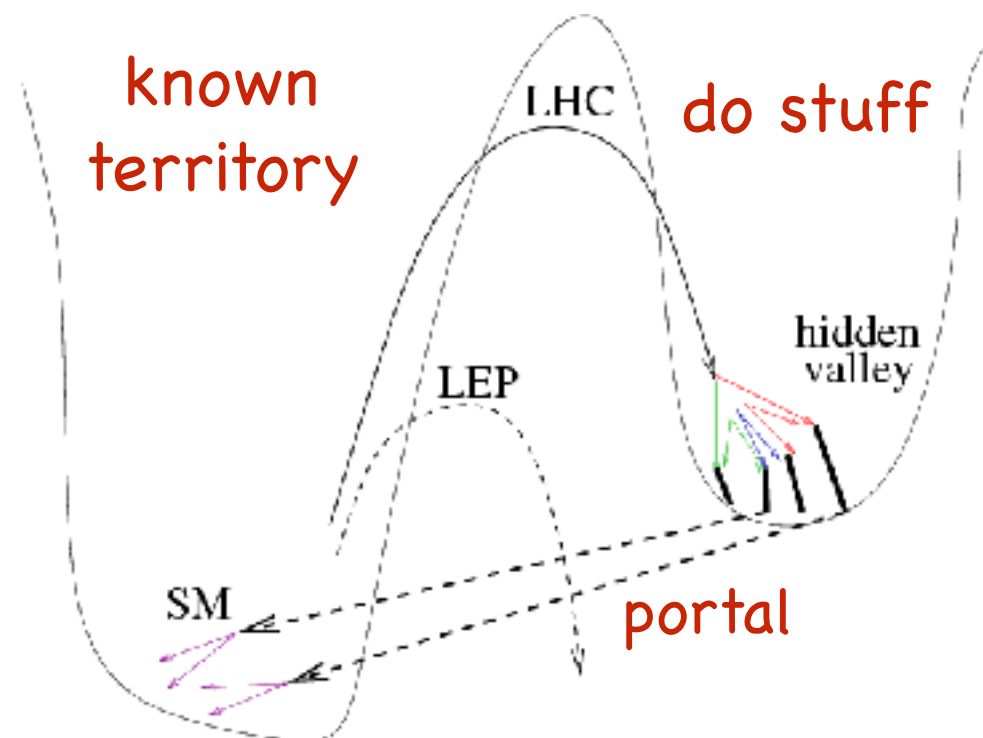
fermion-Higgs portal



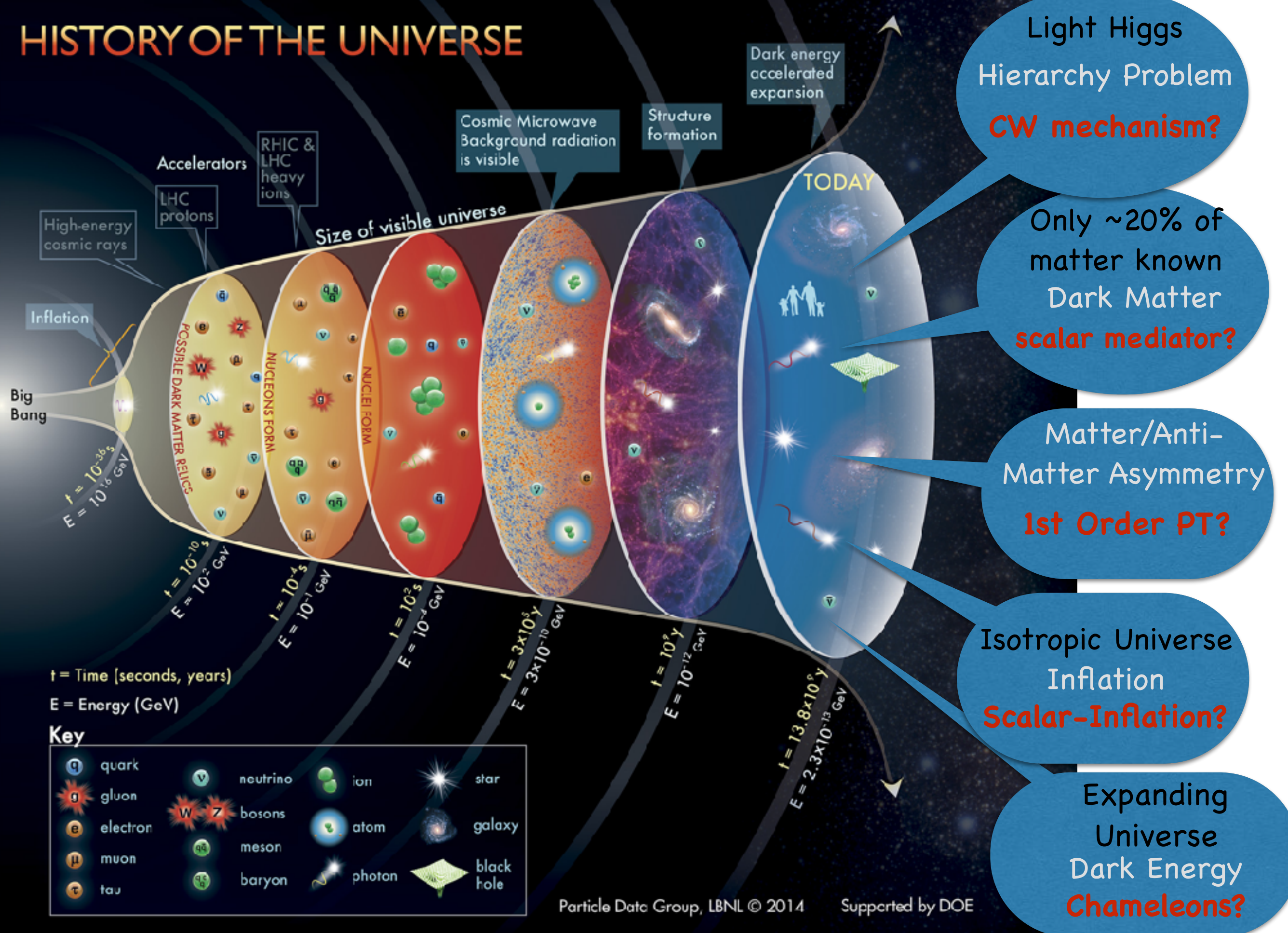
$$\mathcal{L}_{\text{int}} \ni \lambda_P |H(x)|^2 \phi(x)^2$$

Higgs portal

Augment Lagrangian by
term(s) that allow to access
new/hidden sector



HISTORY OF THE UNIVERSE



The minimal Higgs portal

$$\mathcal{V} = \mu_s^2 |\phi_s|^2 + \lambda_s |\phi_s|^4 + \mu_h^2 |\phi_h|^2 + \lambda_h |\phi_h|^4 + \eta_\chi |\phi_s|^2 |\phi_h|^2$$

$$\phi_j \rightarrow (v_j + H_j)/\sqrt{2} \quad v_j^2 = (-\mu_j^2 - \eta_\chi v_i^2/2)/\lambda_j \text{ for } i \neq j = s, h$$

The hidden Higgs fields do not contribute to electroweak symmetry breaking

Mass eigenstates

$$\begin{aligned} H_1 &= \cos \chi H_s + \sin \chi H_h \\ H_2 &= -\sin \chi H_s + \cos \chi H_h \end{aligned}$$

Mass matrix

$$\mathcal{M}^2 = \begin{pmatrix} 2\lambda_s v_s^2 & \eta_\chi v_s v_h \\ \eta_\chi v_s v_h & 2\lambda_h v_h^2 \end{pmatrix}$$

→ Seesaw mechanism for physical Higgs boson masses

→ All couplings globally weighted by $\cos \chi$ and $-\sin \chi$

→ Direct production and decay: $\sigma_1 = \cos^2 \chi \sigma_1^{\text{SM}} \quad \Gamma_1^{\text{vis}} = \cos^2 \chi \Gamma_1^{\text{SM}}$
 $\sigma_2 = \sin^2 \chi \sigma_2^{\text{SM}} \quad \Gamma_2^{\text{vis}} = \sin^2 \chi \Gamma_2^{\text{SM}}$

Baryogenesis

How to modify the Higgs potential to get SEWBP?

$$V_{\text{eff}}(h, T) = V_0(h) + V_0^{\text{loop}}(h) + V_T(h, T)$$

tree-level
potential

loop
corrections

thermal
corrections

thermal: add new bosons to the plasma to generate a thermal barrier

loop: add new particles whose loops reduce vac. energy difference,
so that W/Z loops create a barrier

tree-level: new scalars to modify tree-level potential
(Higgs portal)

non-ren operators, e.g. H^6 (SM with low cut-off)

[Grojean, Servant, Wells '05]

Baryogenesis

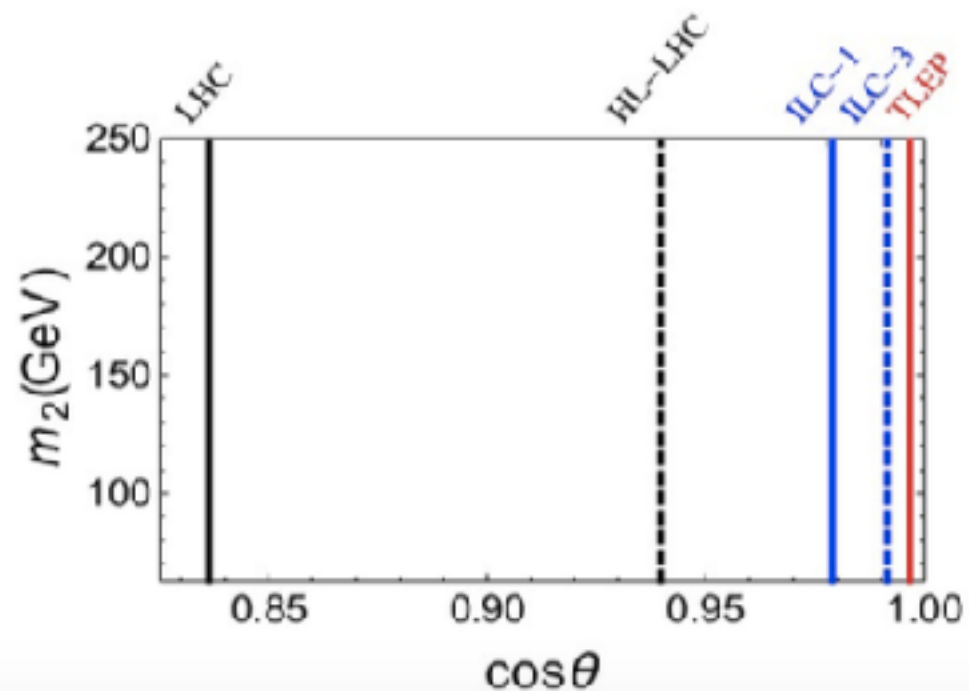
Simplest implementation of tree-level enhancement via singlet Higgs portal (xSM Model)

$$V(H, S) = -\mu^2 |H|^2 + \lambda |H|^4 + \underbrace{\frac{a_1}{2} S |H|^2 + \frac{a_2}{2} S^2 |H|^2}_{\text{Higgs Portal}} + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4$$

Higgs - Singlet Mixing

Higgs Portal

Case 1: $m_{H_2} < 250$ GeV



No BSM decays of H_2

→ Searches for heavy scalars

Dilution of H_1 couplings

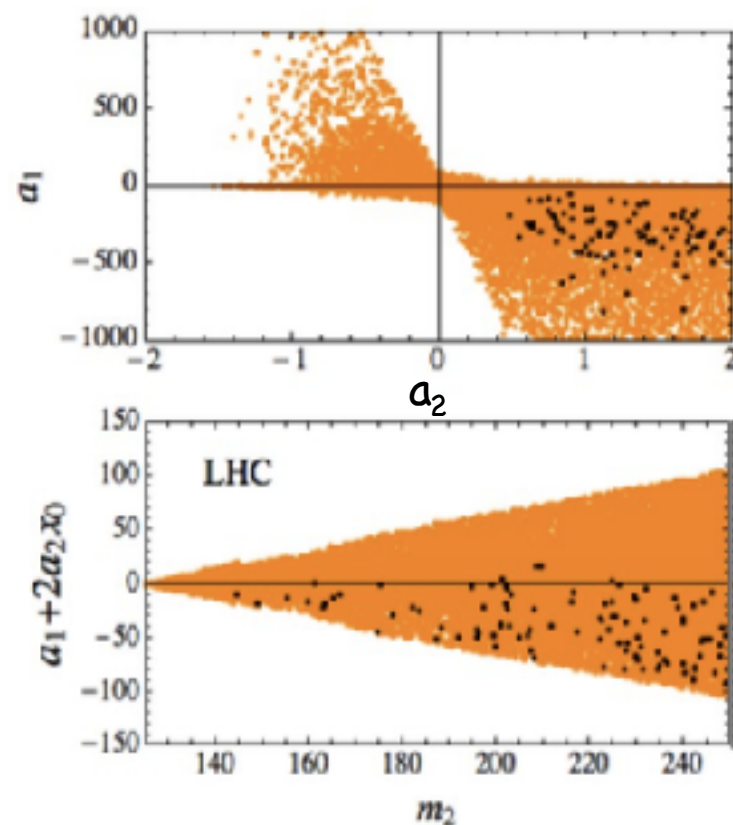
→ Higgs coupling measurements

[Profumo, Ramsey-Musolf, Wainwright, Winslow '14]

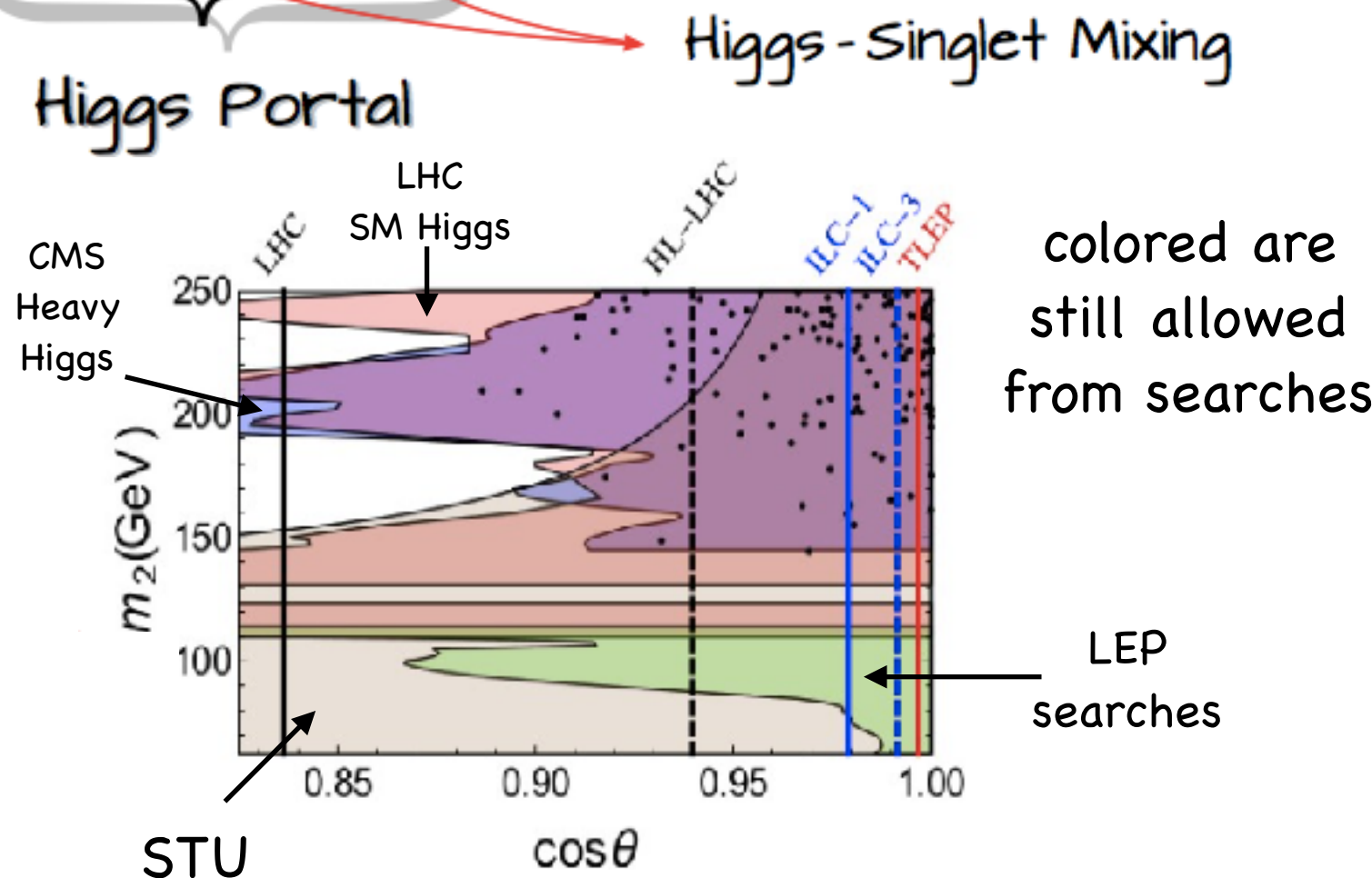
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- **Orange** points pass current limits from curr. LHC Higgs measurements
- **Black** points satisfy further req. of SFOEWPT



[Profumo, Ramsey-Musolf, Wainwright, Winslow '14]

Baryogenesis

Simplest implementation of tree-level enhancement via singlet Higgs portal

$$V(H, S) = -\mu^2 |H|^2 + \lambda |H|^4 + \underbrace{\frac{a_1}{2} S |H|^2 + \frac{a_2}{2} S^2 |H|^2}_{\text{Higgs Portal}} + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4$$

Higgs-Singlet Mixing

Case 2: $m_{H_2} > 250 \text{ GeV}$

Decay $H_2 \rightarrow H_1 H_1$ open

Resonant Higgs Pair Production

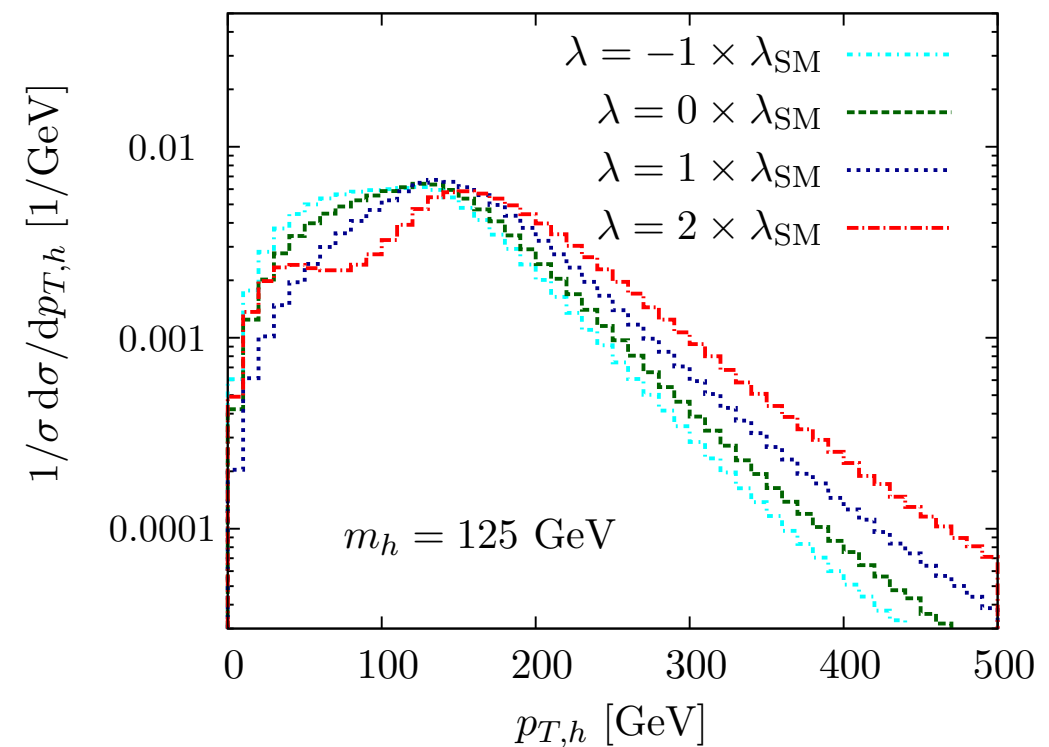
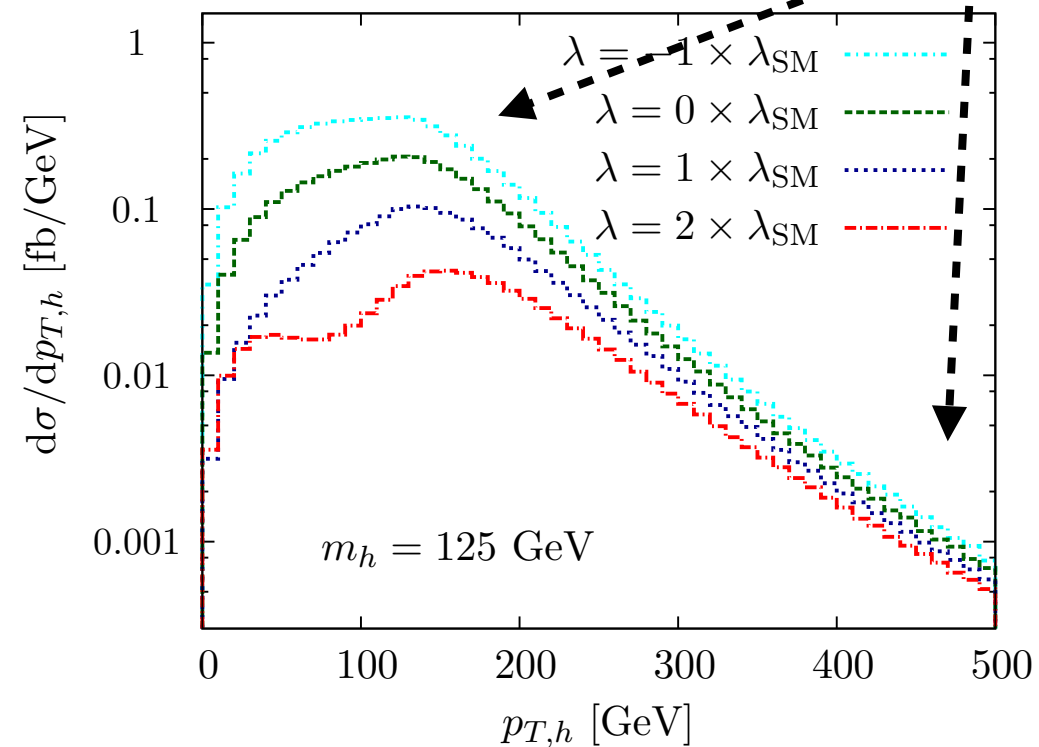
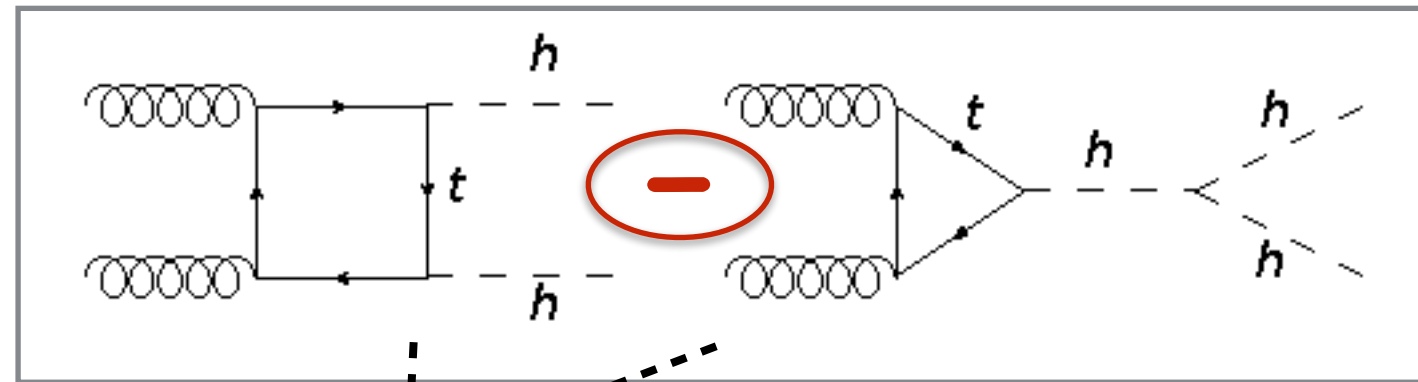
[Dolan, Englert, MS '13] [No, Ramsey-Musolf '14]

Different channels possible

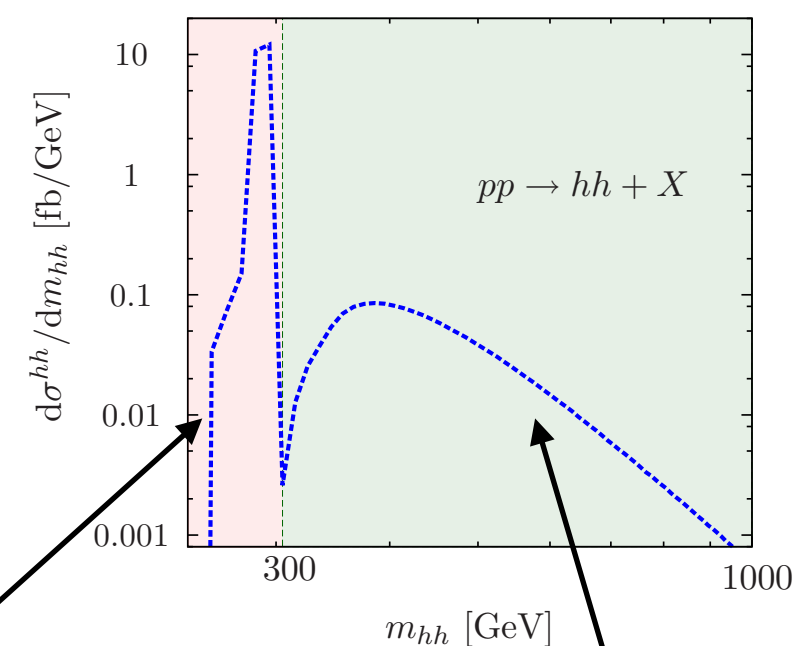
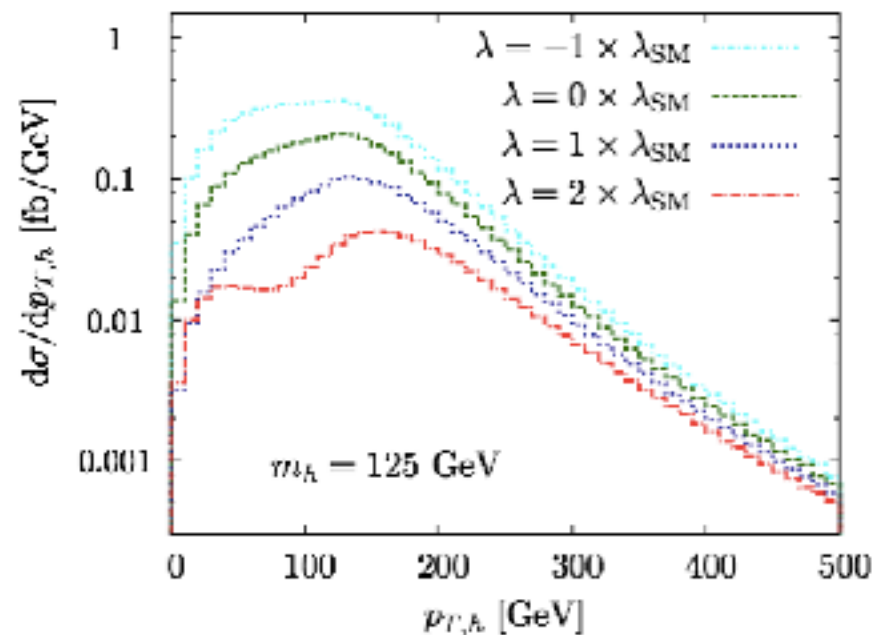
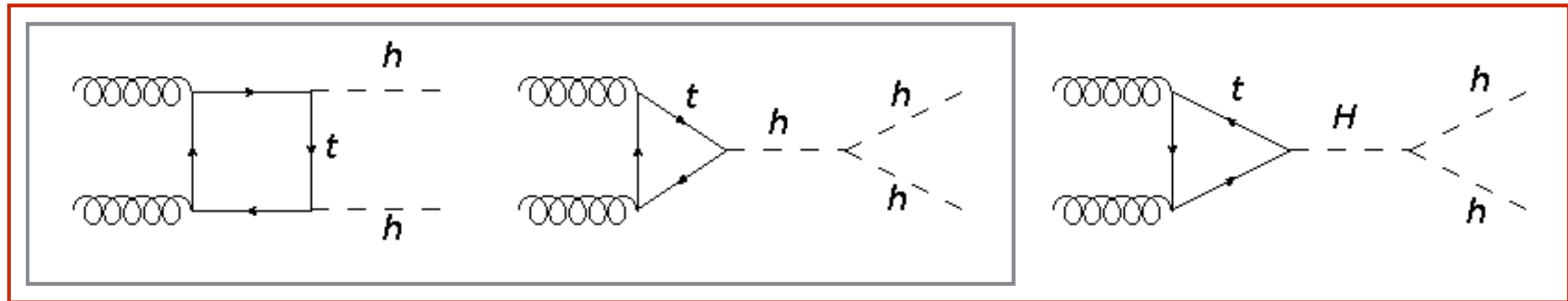
$b\bar{b}b\bar{b}$ $b\bar{b}WW$ $b\bar{b}\tau\tau$ $b\bar{b}\gamma\gamma$

Di-Higgs production in the SM:

destructive interference between y_{top} and λ contributions in SM



Resonant di-Higgs searches



resonance region

off-shell region

Eg. MSSM: $\lambda_{hhh} = 3 \cos 2\alpha \sin(\beta + \alpha)$

$$\lambda_{Hhh} = 2 \sin 2\alpha \sin(\beta + \alpha) - \cos 2\alpha \cos(\beta + \alpha)$$

$$\lambda_{HHh} = -2 \sin 2\alpha \cos(\beta + \alpha) - \cos 2\alpha \sin(\beta + \alpha)$$

Can measurement
alpha and beta angles

Maxi-sizing the trilinear Higgs self-coupling: how large could it be?

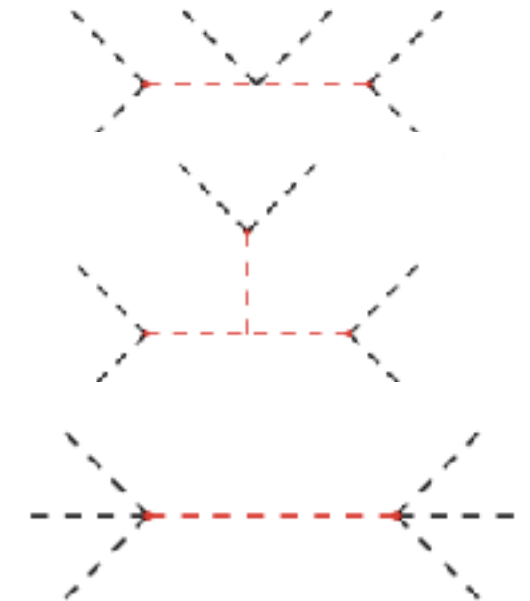
[Di Luzio,
Groeber, MS;
to appear]

Constraints from

- Higgs signal strength
- Perturbativity
- Vacuum stability
- Electroweak precision

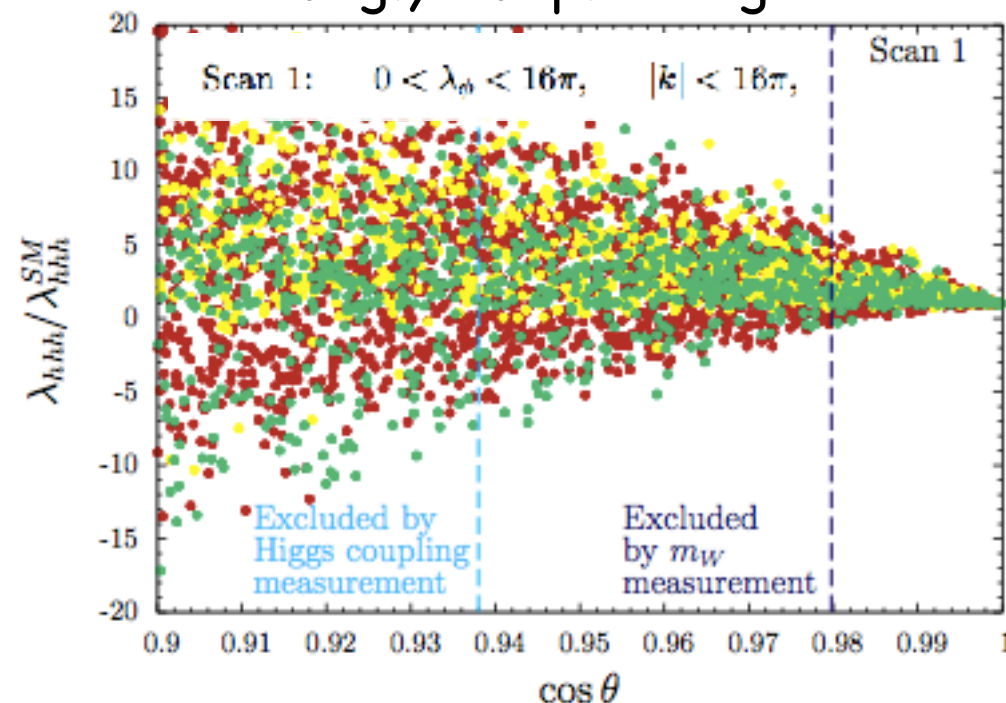
Tree-level enhanced models

Φ	$\mathcal{O}_\Phi$
$(1, 1, 0)$	$\Phi H H^\dagger$
$(1, 2, \frac{1}{2})$	$\Phi H H^\dagger H^\dagger$
$(1, 3, 0)$	$\Phi H H^\dagger$
$(1, 3, 1)$	$\Phi H^\dagger H^\dagger$
$(1, 4, \frac{1}{2})$	$\Phi H H^\dagger H^\dagger$
$(1, 4, \frac{3}{2})$	$\Phi H^\dagger H^\dagger H^\dagger$

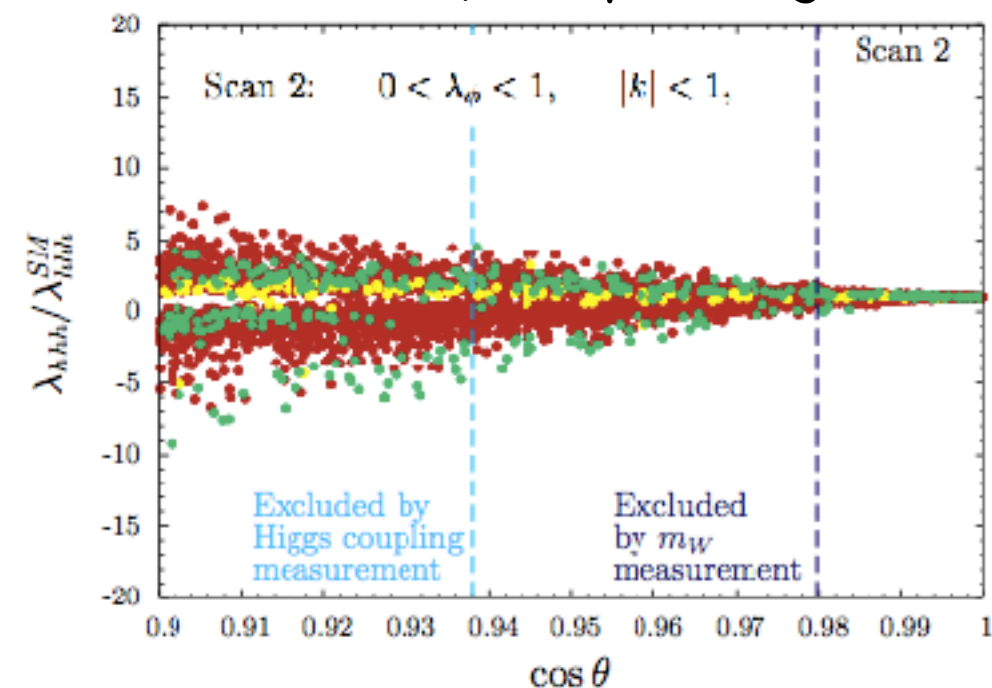


$$V(H, \phi) = -\mu_H^2 |H|^2 + \lambda_H |H|^4 + \frac{1}{2} m^2 \phi^2 + A |H|^2 \phi + \frac{1}{2} k |H|^2 \phi^2 + \frac{1}{3!} \mu \phi^3 + \frac{1}{4!} \lambda_\phi \phi^4$$

strongly-coupled regime



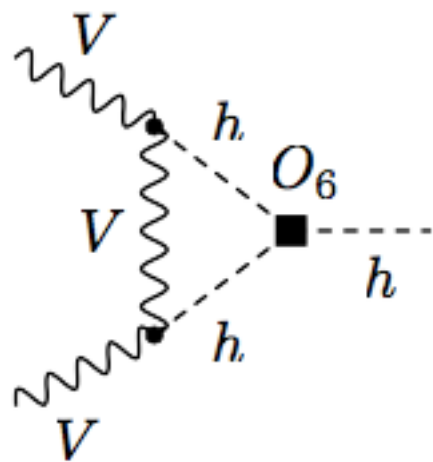
weakly-coupled regime



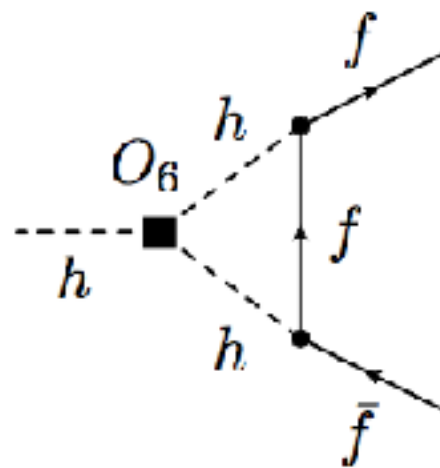
Indirect limits from single Higgs and ELW measurements

We assume only O_6 to be present (no other operator)

production



decay



LHC after run 1

$$\bar{c}_6 \in [-13.7, 16.7]$$

$$\bar{c}_6 \in [-15.5, 18.1] \text{ from } pp \rightarrow hh$$

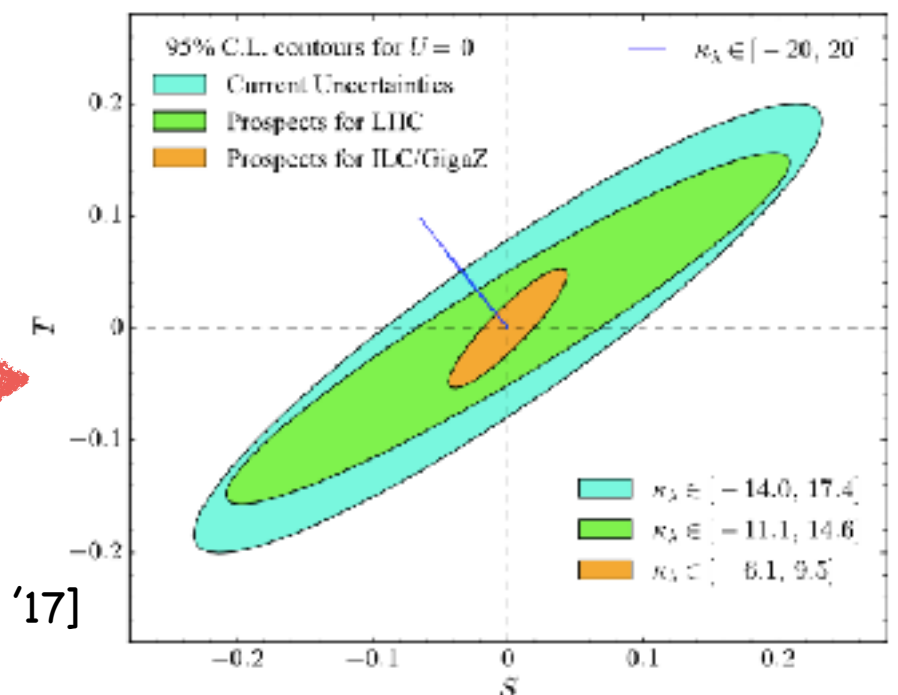
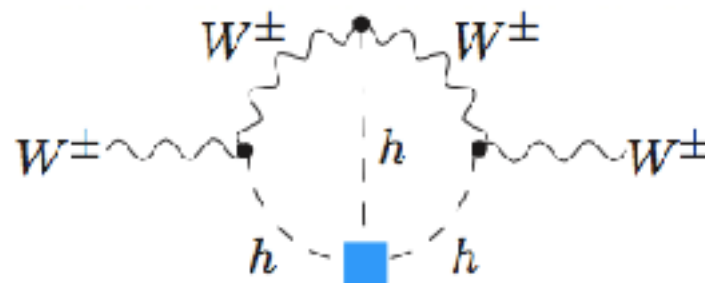
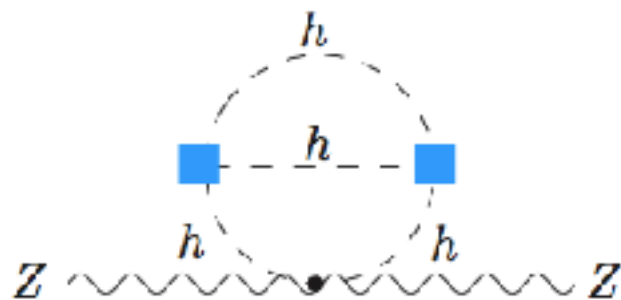
HL-LHC

$$\bar{c}_6 \in [-7.0, 10.4]$$

$$\bar{c}_6 \in [-1.8, 6.7] \text{ from } pp \rightarrow hh$$

[Gorbahn, Haisch '16] [Bizon, Gorbahn, Haisch, Zanderighi '16]

Electroweak precision observables



[Degrassi, Fedele, Giardino '17]

[Kribs, Maier, Rzehak, MS, Waite '17]

Summary of Higgs (portal) phenomenology

- **The Higgs gave it and the Higgs might take it away...**
the Big Mac Blues that is ;-)
- This Higgs portal model is one of the simplest ways to **address** many of the most fundamental problems in nature
- Can be understood as 'simplified model' for residual low energy states of UV models
- Would be shame if no connection was realised...

It encourages exp. searches and measurements for

- ➡ Higgs precision measurements (couplings, width, mass)
- ➡ Heavy Higgs searches in $H \rightarrow VV$, $H \rightarrow ff$
- ➡ Di-Higgs final states searches
- ➡ Heavy gauge bosons e.g. Z' , W'
- ➡ Gravitational waves

Plenty of work left to
perform at current and
future experiments

