University of Glasgow

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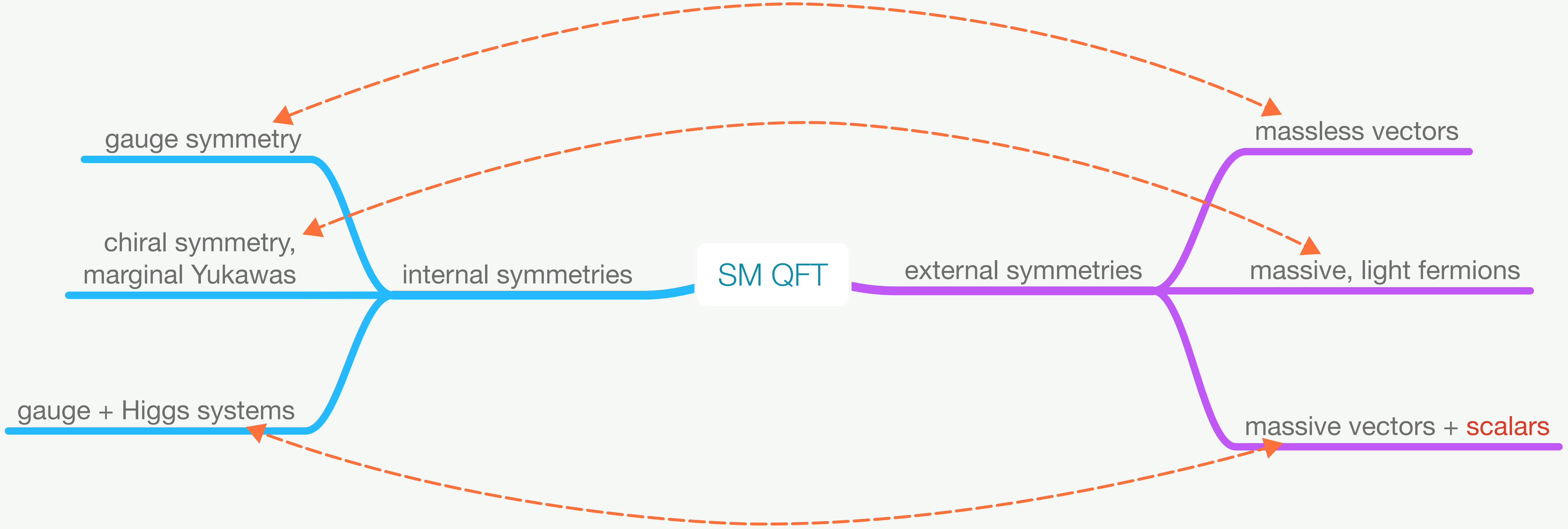
Compositeness, LHC and lattice

The Fate Of Naturalness

Brussels, 12.06.2016

based on
[CE, Harris,Spannowsky, Takeuchi ` 15]
[Del Debbio, CE, Zwicky ` 17]

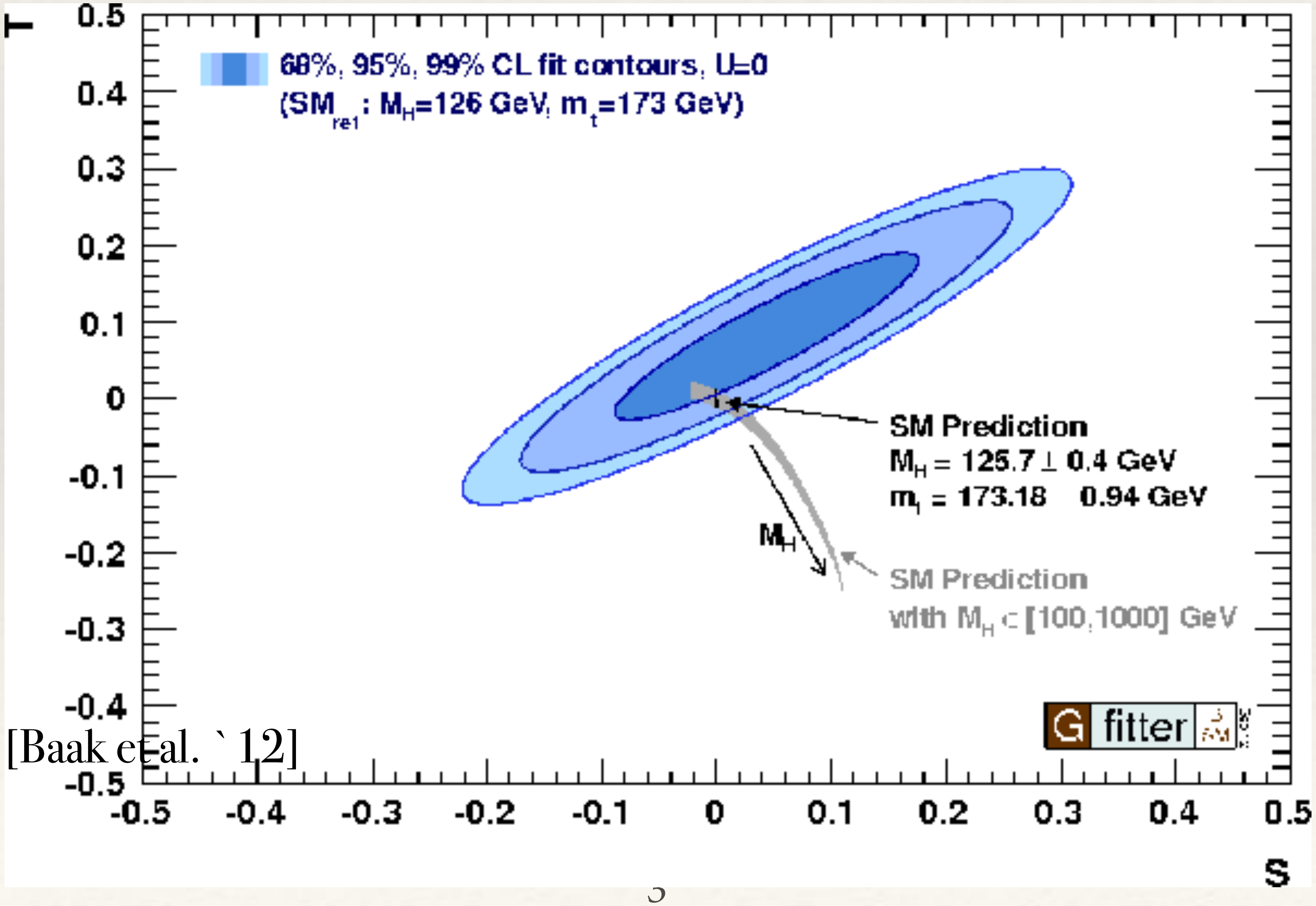
The perturbative Standard Model



"What's left at the LHC ?"

Compositeness = Naturalness?

- Higgs mass is the order parameter of the electroweak series convergence
- perturbativity (= unitarity, Higgs width, reliability of oblique corrections, etc) **tightly bound** to the Higgs mass parameter



[Baak et al. `12]

Compositeness = Naturalness?

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Compositeness = Naturalness?

- Higgs mass is the order parameter of the electroweak series convergence
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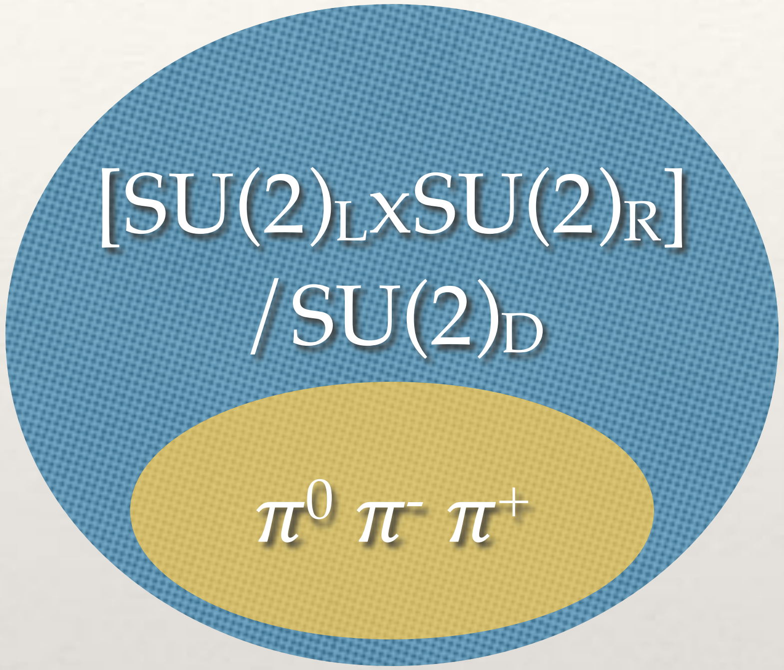
- Higgs discovery seems to fall into this perturbative QFT paradigm but nothing's guaranteed at this stage in the LHC programme
- **What do we know about the composite option?**
- **Is it enough to motivate complicated lattice investigations?**
- **Is the LHC fit for the future?**

A composite sketch

- interpret the electroweak scale as a radiative phenomenon, analogous to the pion mass splitting



$[SU(2)_L x SU(2)_R]$

$/SU(2)_D$

$\pi^0\ \pi^-\ \pi^+$

A composite sketch

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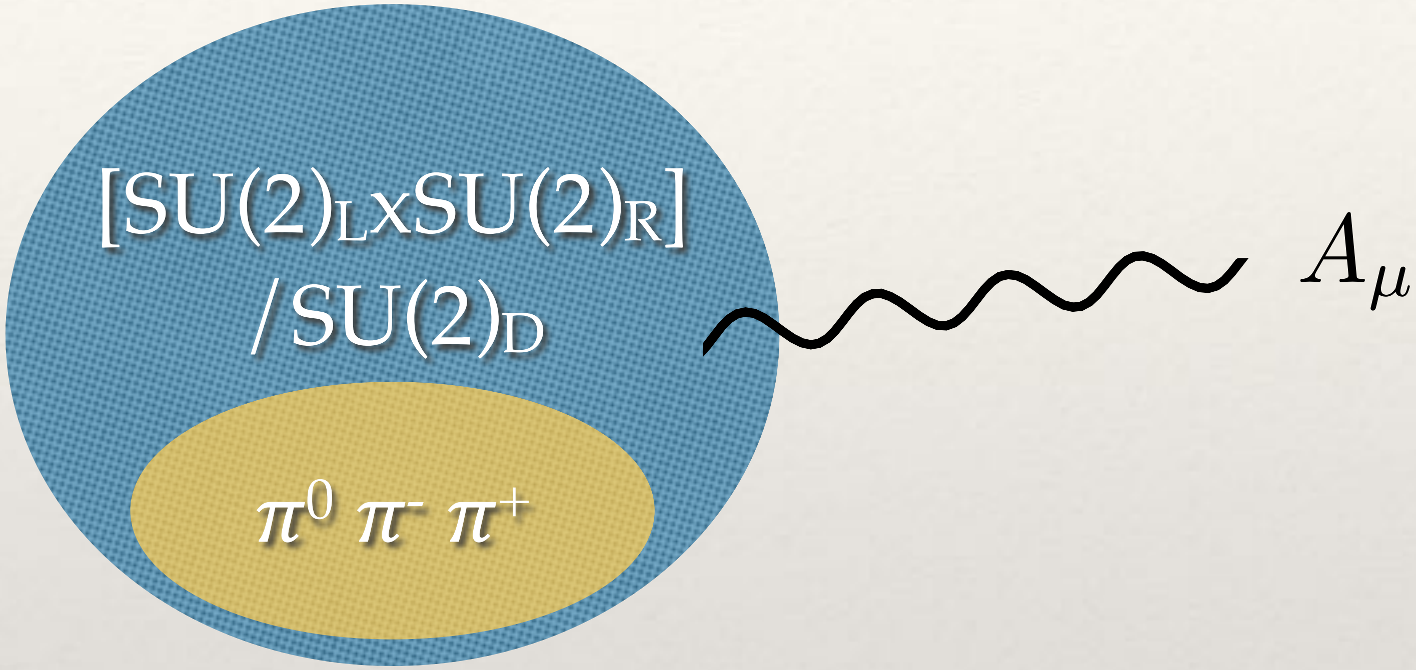

A composite sketch

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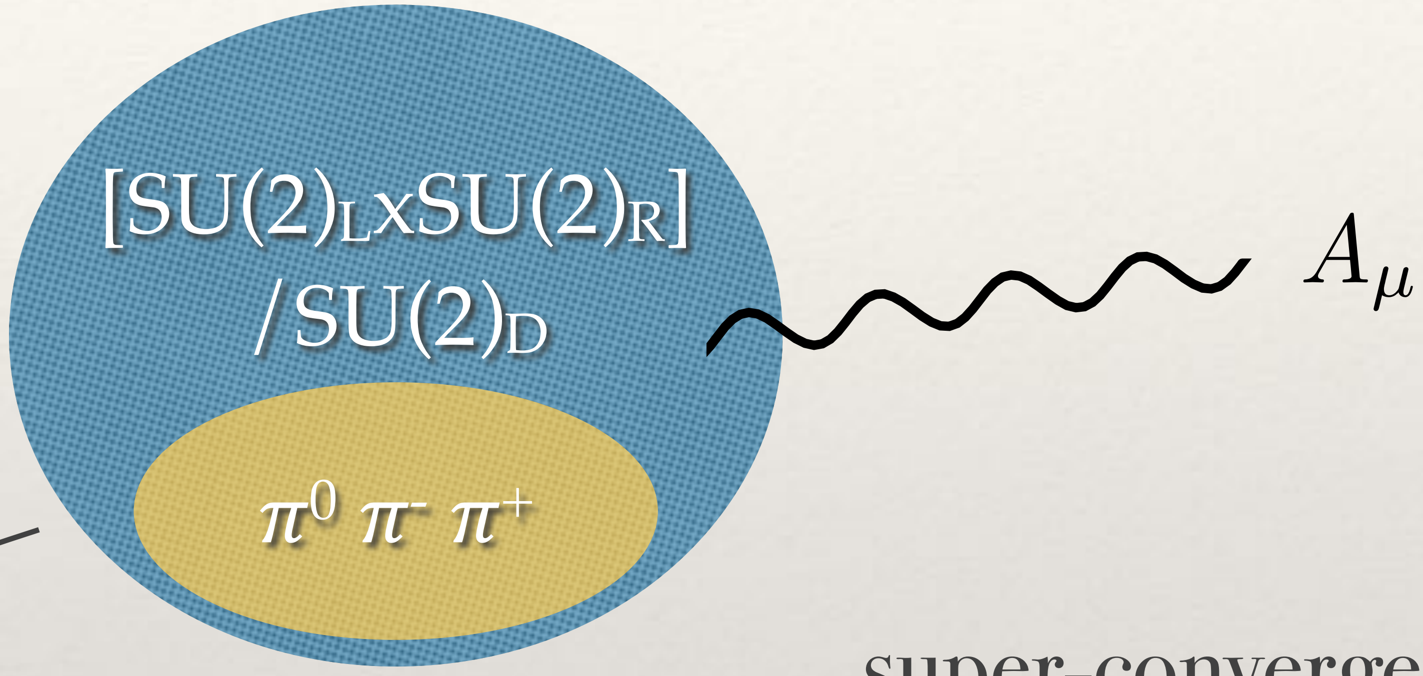
e.g. [Contino ` 10]



effective potential

[Coleman, Weinberg ` 73]...

super-convergent

[Weinberg ` 67]...

$$V(\pi) \simeq \frac{3}{8\pi^2}\alpha_{em}\frac{\sin^2(\pi/f_\pi)}{\pi^2}(\pi^+\pi^-)\int_0^\infty dQ^2\,\Pi_{LR}(Q^2)\,.$$

$$(m_{\pi^\pm} - m_{\pi_0})|_{\mathrm{TH}} \simeq 5.8\,\mathrm{MeV} \quad \text{vs} \quad (m_{\pi^\pm} - m_{\pi_0})|_{\mathrm{EXP}} \simeq 4.6\,\mathrm{MeV}$$

A composite sketch

- <u>not straightforward</u> to this adapt to the Higgs case

e.g. [Contino ` 10]

trigger
ELW symmetry
breaking not just
CW masses

respect global
symmetries in the
Higgs sector

LEP precision
measurements

…….

e.g. [Contino, da Rold, Pomarol ` 07]
[Agashe, Contino, Pomarol ` 06]

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- vacuum mis-alignement from $SU(2)_L \times U(1)_Y$ direction requires the presence of heavy fermions

gauge +
fermions

[Coleman, Weinberg ` 73]…

$$\hat{V}(\hat{h}) = \alpha \cos(2\hat{h}) - \beta \sin^2(2\hat{h})$$

fermions

A concrete model of compositeness

- gauge boson masses through symmetry choices [Agashe, Contino, Pomarol `06]
- fermion masses through mixing with baryonic matter (part. compositeness)

  [Kaplan `91]...... [Ferretti ` 16] [Sannino, Strumia, Vigiani ` 16]
- minimal pheno model $SO(5) \rightarrow SO(4) \simeq SU(2)_L \times SU(2)_R$
- fermions (and hypercolour baryons) in a 5 of SO(5)

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- but

$$\underbrace{SU(4)}_{G_{\rm HC}} \times \underbrace{SU(5) \times SU(3) \times SU(3)' \times U(1)_X \times U(1)'}_{G_F}$$

[Ferretti ` 14]

could work with

$$G_F/H_F = \frac{SU(5)}{SO(5)} \times \frac{SU(3) \times SU(3)'}{SU(3)} \times U(1)'$$

A concrete model of compositeness

- model predicts a number of exotics phenomenological implications

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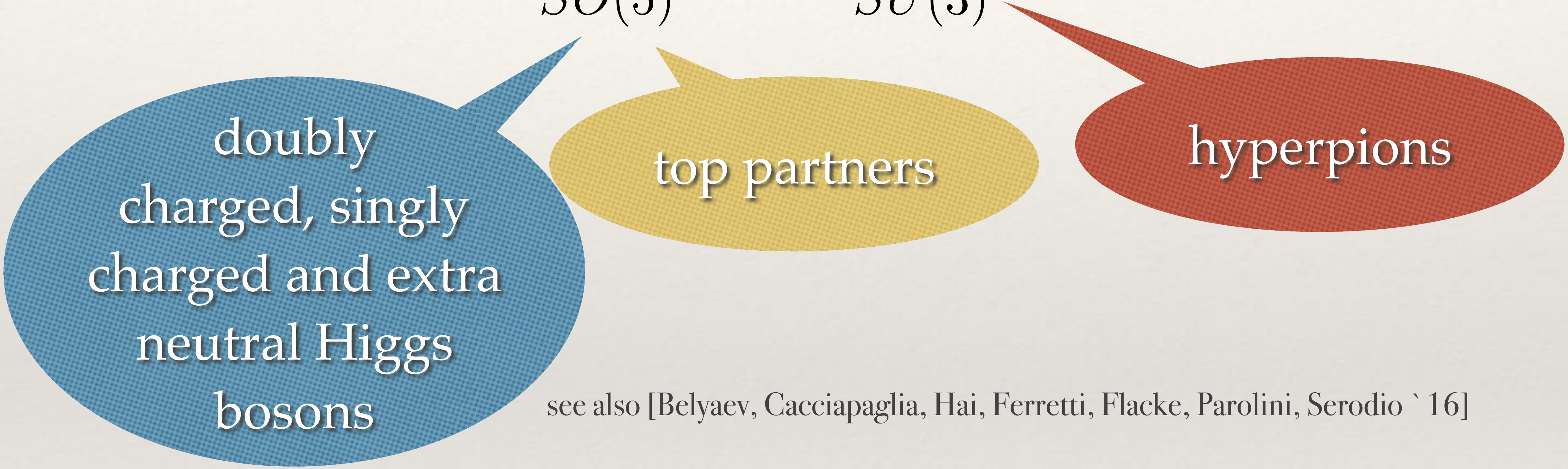

see also [Belyaev, Cacciapaglia, Hai, Ferretti, Flacke, Parolini, Serodio `16]

- *perform a scan over the parameter space inputting available ATLAS and CMS measurements to constrain and motivate LEC measurements from the lattice.*

[Del Debbio, CE, Zwicky `17]

Low Energy Constants

in units of *f*

$$\hat{V}(\hat{h}) = \alpha\cos(2\hat{h}) - \beta\sin^2(2\hat{h})$$

$$\alpha = -\hat{C}_{\rm LR}\frac{1}{2}\left(3g^2 + g'^2\right) < 0\,,$$

$$2\beta = -y^2\hat{C}_{\rm top} + \dots$$

T 4-point correlator

see also [Golterman, Shamir `15]

SU(2)xSU(2) correlator

$$C_{\rm LR} = \frac{3}{16\pi^2}\int_0^\infty {\rm d}q^2\, q^2\Pi^{33}_{LR}(q^2)$$

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SU(2)xSU(2) correlator

$$C_{\mathrm{LR}} = \frac{3}{16\pi^2}\int_0^\infty \mathrm{d}q^2\, q^2\Pi^{33}_{LR}(q^2)$$

$$\hat{V}(\hat{h}) = 4\beta(\sin^2(\hat{h}) - \xi)^2\,, \qquad \xi \equiv \frac{v^2}{f^2} = \sin^2(\langle\hat{h}\rangle) = \frac{\alpha + 2\beta}{4\beta}\,.$$

Higgs coupling modifier

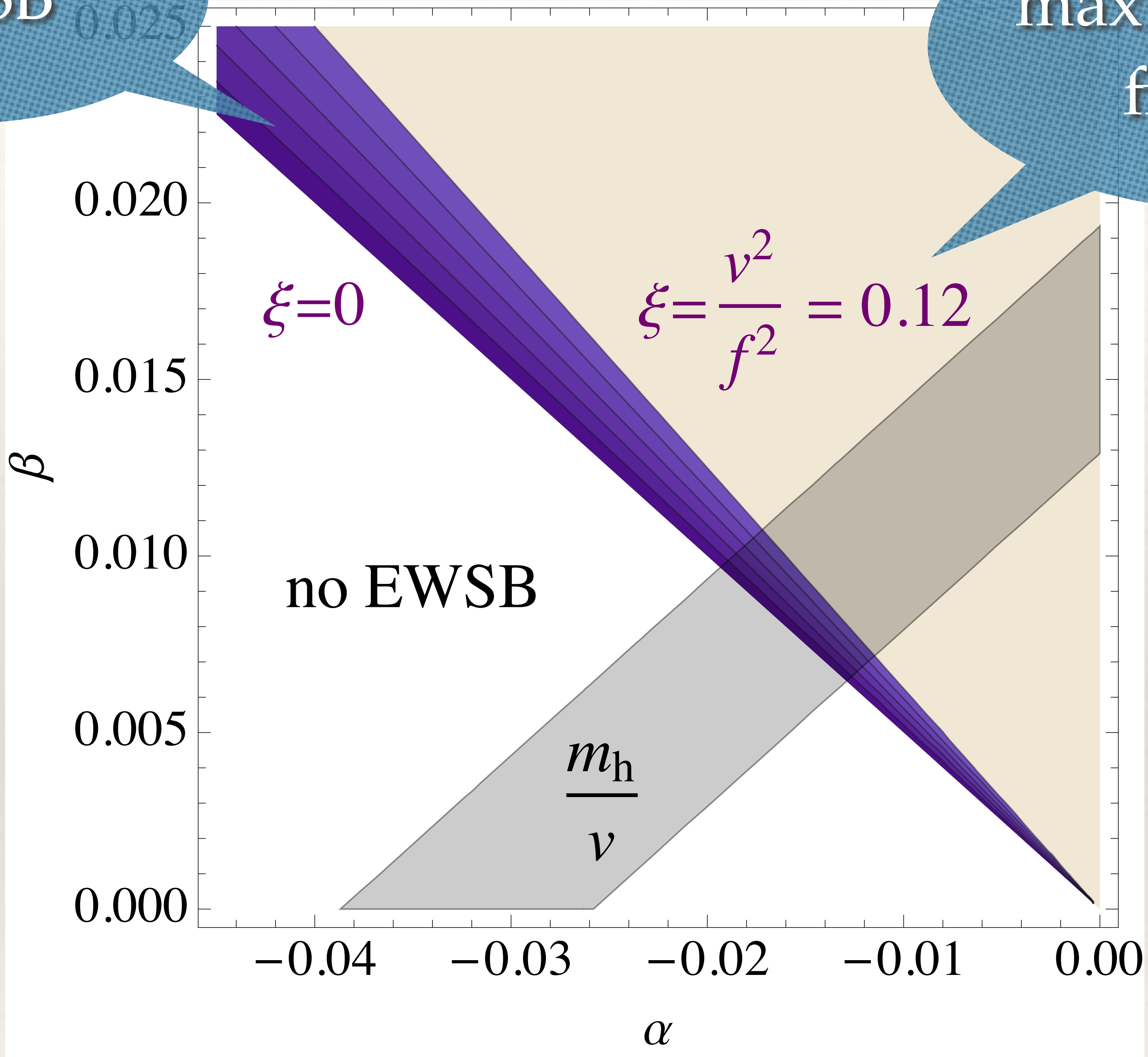
e.g.
$g_{VVh} = \sqrt{1-\xi}\, g^{\mathrm{SM}}_{VVh}$

- EWSB for $\alpha + 2\beta > 0$. Then

$$\hat{m}_h^2 = \hat{V}''(\langle\hat{h}\rangle) = 32\beta\xi(1-\xi) = 8\beta - 2\alpha^2/\beta$$

Low Energy Constants

EWSB



max range from fit [later]

tuning!?

$$\frac{m_h^2}{v^2} = 32\beta(1-\xi) = 8(2\beta-\alpha) \simeq 0.258$$ (ass. 20% radiative corrections)

Low Energy Constants

triplet Higgs masses

$$V = \hat{C}_{\rm LR}\left(3g^2 + g'^2)(2H^\dagger H + \frac{16}{3}\phi_+^\dagger\phi_+) + 8g^2\phi_0\phi_0\right) + 8\hat{F}_{\rm LL}\phi_+^\dagger\phi_+$$

$$m_{\phi_0}^2 = 16g^2\hat{C}_{\rm LR}\ ,$$

$$m_{\phi_+}^2 = 16(g^2 + \frac{g'^2}{3})\hat{C}_{\rm LR} + 8\hat{F}_{\rm LL}$$

$$\hat{m}_\Phi = \left(\frac{32|\alpha|}{3}\right)^{\frac{1}{2}} = 4\left(\hat{C}_{\rm LR}\left(g^2 + \frac{g'^2}{3}\right)\right)^{\frac{1}{2}} \simeq 0.36\ ,$$

$$\hat{m}_{\Phi_0} = \left(\frac{32|\alpha|}{3}r_g\right)^{\frac{1}{2}} = 4(\hat{C}_{\rm LR}g^2)^{\frac{1}{2}} \simeq 0.34\,,$$

can expect small EWPD corrections compared to standard MCHM5 scenario

e.g [Gilioz et al. ` 12]

A concrete model of compositeness

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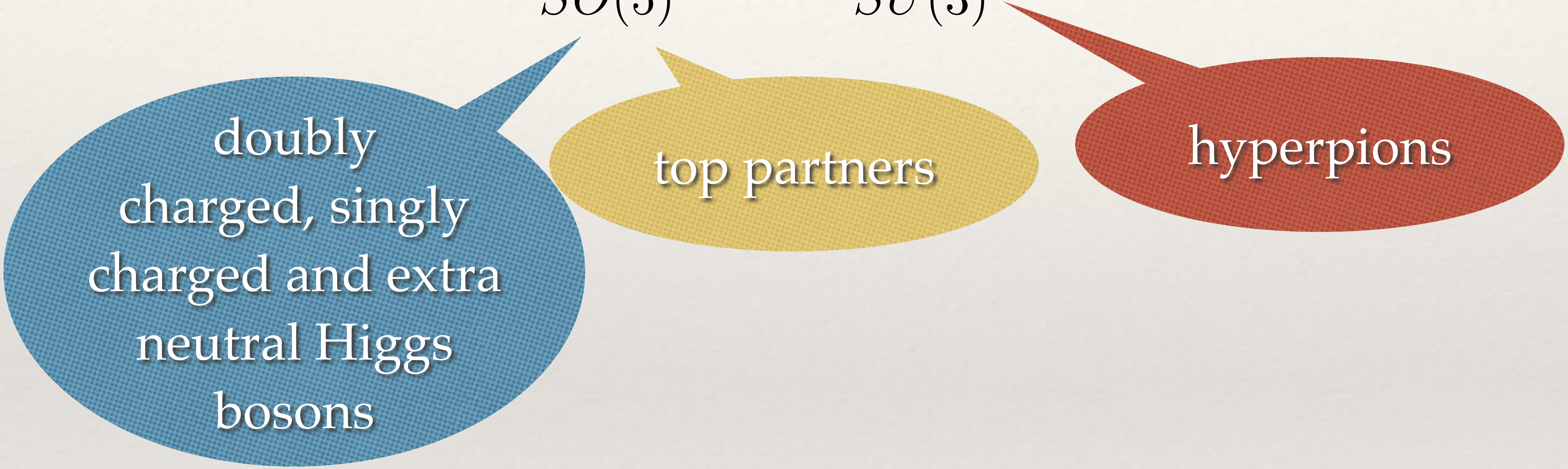
$$G_F/H_F = \frac{SU(5)}{SO(5)} \times \frac{SU(3) \times SU(3)'}{SU(3)} \times U(1)'$$



doubly charged, singly charged and extra neutral Higgs bosons

top partners

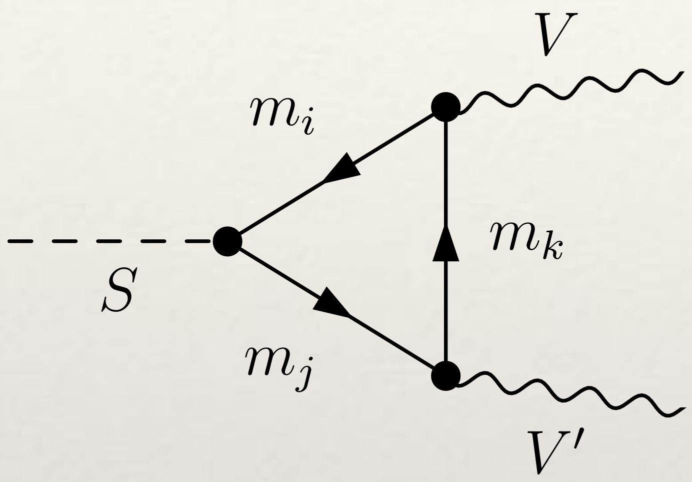
hyperpions

[Matsedonskyi, Panico, Wulzer ` 15]

- top partner constraints
- compatibility with exotics searches
- compatibility with Higgs signal strength measurements

Technicalities

- Higgs production becomes a multi-scale problem
- quantum dynamics does not respect "global" EFT bias



$$\hat{O}_1 = \hat{S}\hat{V}^{\mu}\hat{V}'_{\mu}\,,$$
$$\hat{O}_2 = \hat{S}\hat{V}^{\mu\nu}\hat{V}'_{\mu\nu}\,,$$
$$\hat{O}_3 = \hat{S}\hat{V}^{\mu\nu}\widetilde{\hat{V}'}_{\mu\nu}$$

EWSB

$$i\mathcal{A} = \sum_i C_i \langle \hat{O}_i \rangle \xrightarrow{\text{1-loop}} i\mathcal{A} = \underbrace{(C_1 + \delta Z_C)}_{=0} \langle \hat{O}_1 \rangle^R + \ldots$$

top mass
bottom masses

top + bottom
partner spectra

gauge & Higgs
couplings

constraints

[Del Debbio, CE, Zwicky in prep.]

results at a glance

- no constraints from charged Higgs searches
- doubly charged Higgs bosons produced via Drell Yan might be accessible at the LHC

[CE, Schichtel, Spannowsky `16]

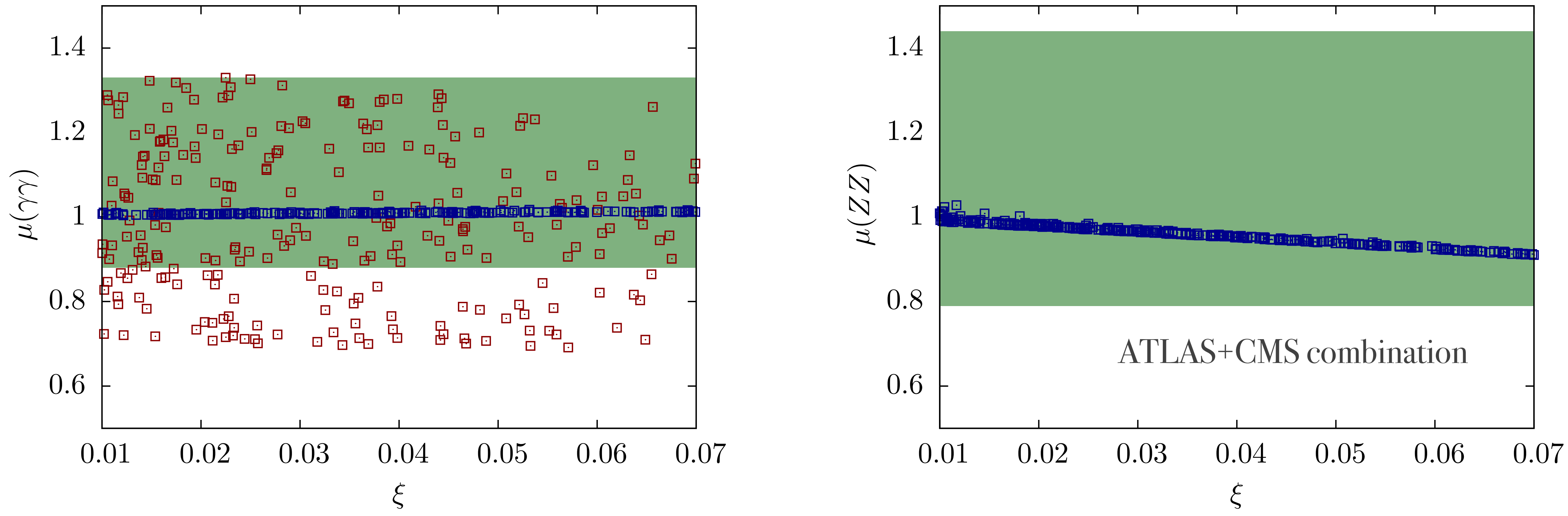
[Del Debbio, CE, Zwicky in prep.]

results at a glance

- no constraints from charge Higgs searches
- doubly charged Higgs bosons produced via Drell Yan might be accessible at the LHC in the future

[CE, Schichtel, Spannowsky ` 16]

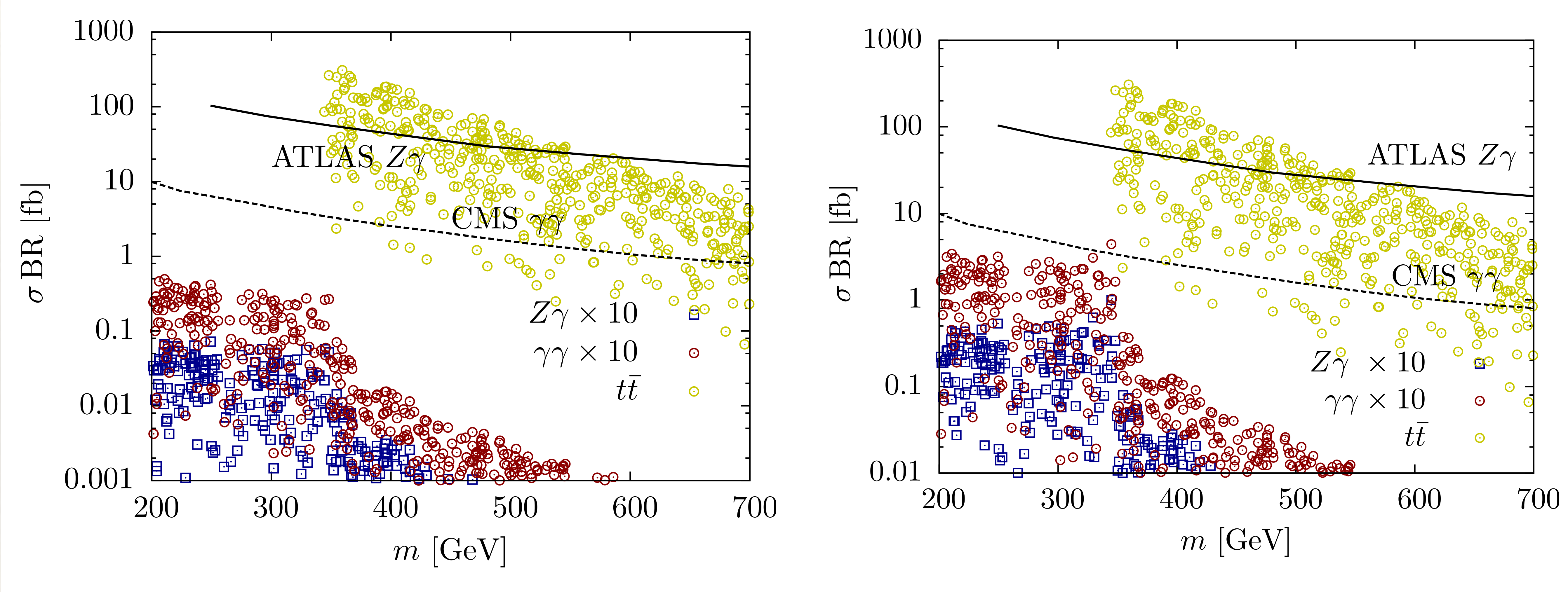
- Higgs signal strength - no news here either



[Del Debbio, CE, Zwicky in prep.]

results at a glance

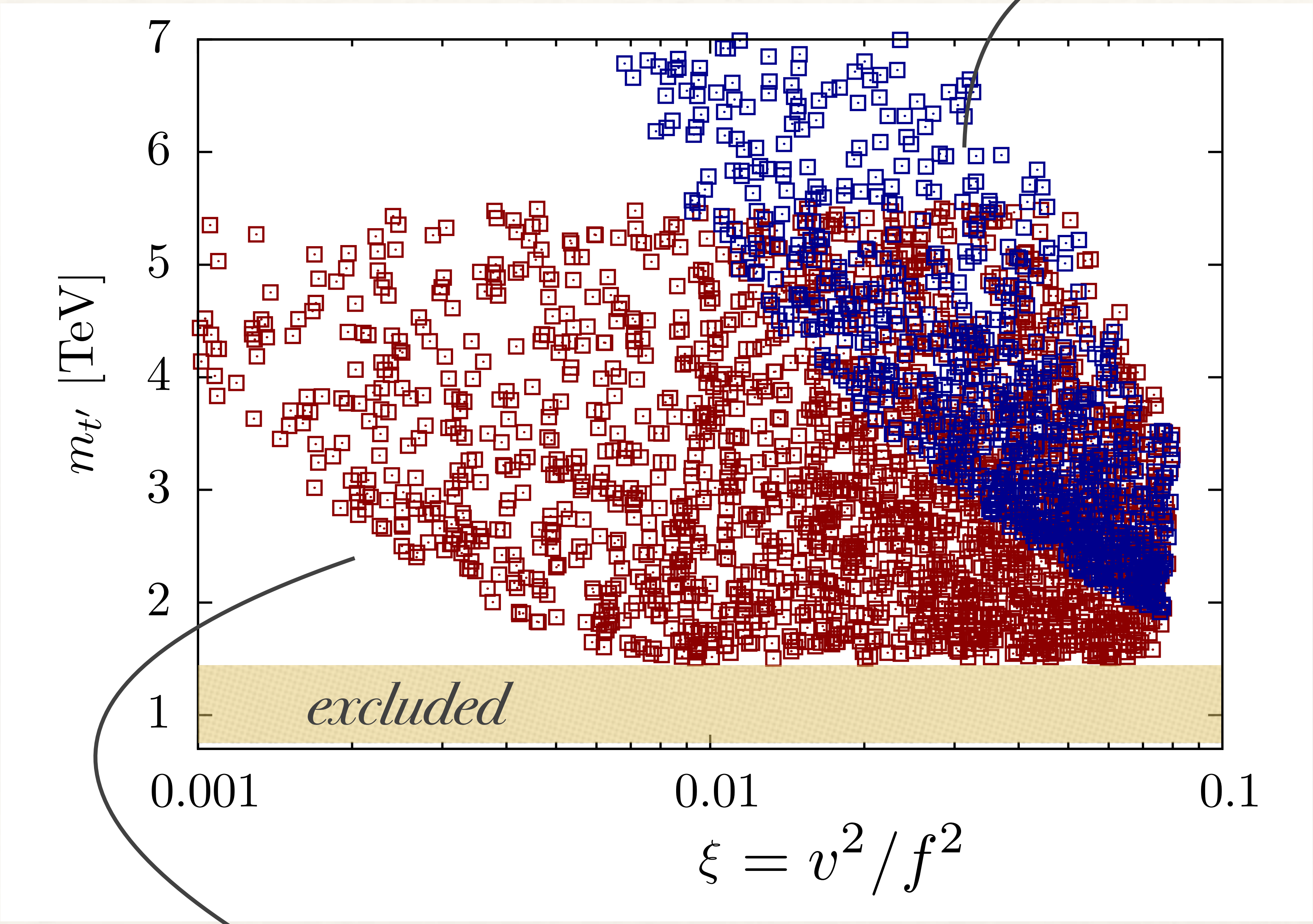
- searches for extra scalar / pseudoscalar Higgs bosons with couplings to top quarks



- extra scalars with net bottom coupling avoid experimental detection

lots of parameter space available = let lattice do their thing

Top partner predictions



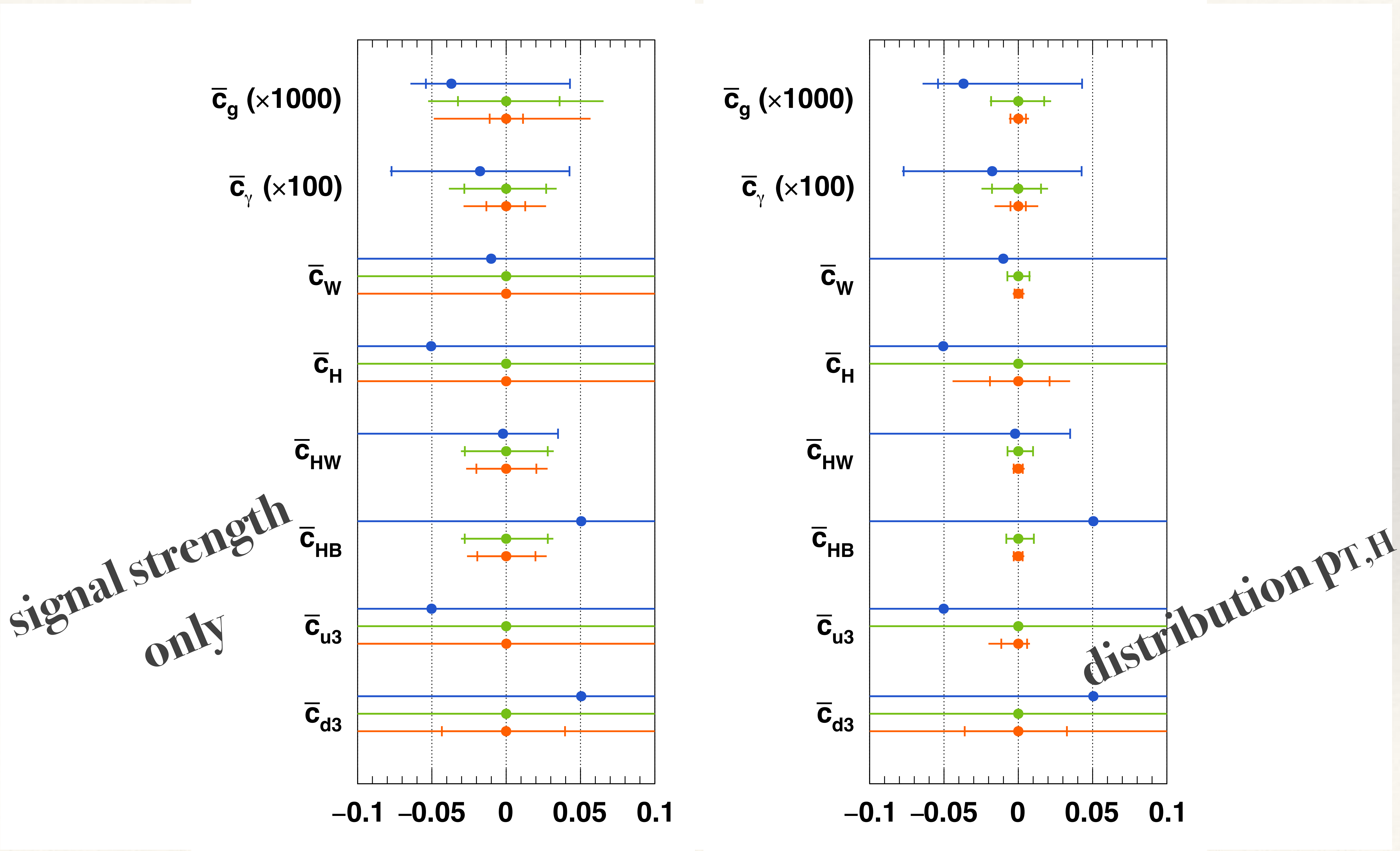
mock lattice measurement of $\frac{\text{baryon mass}}{\text{decay constant}}$

top partners democratic

[CE, Kogler, Schulz, Spannowsky ` 15]

Higgs couplings 3/ab

- distributions over-constrain the system!

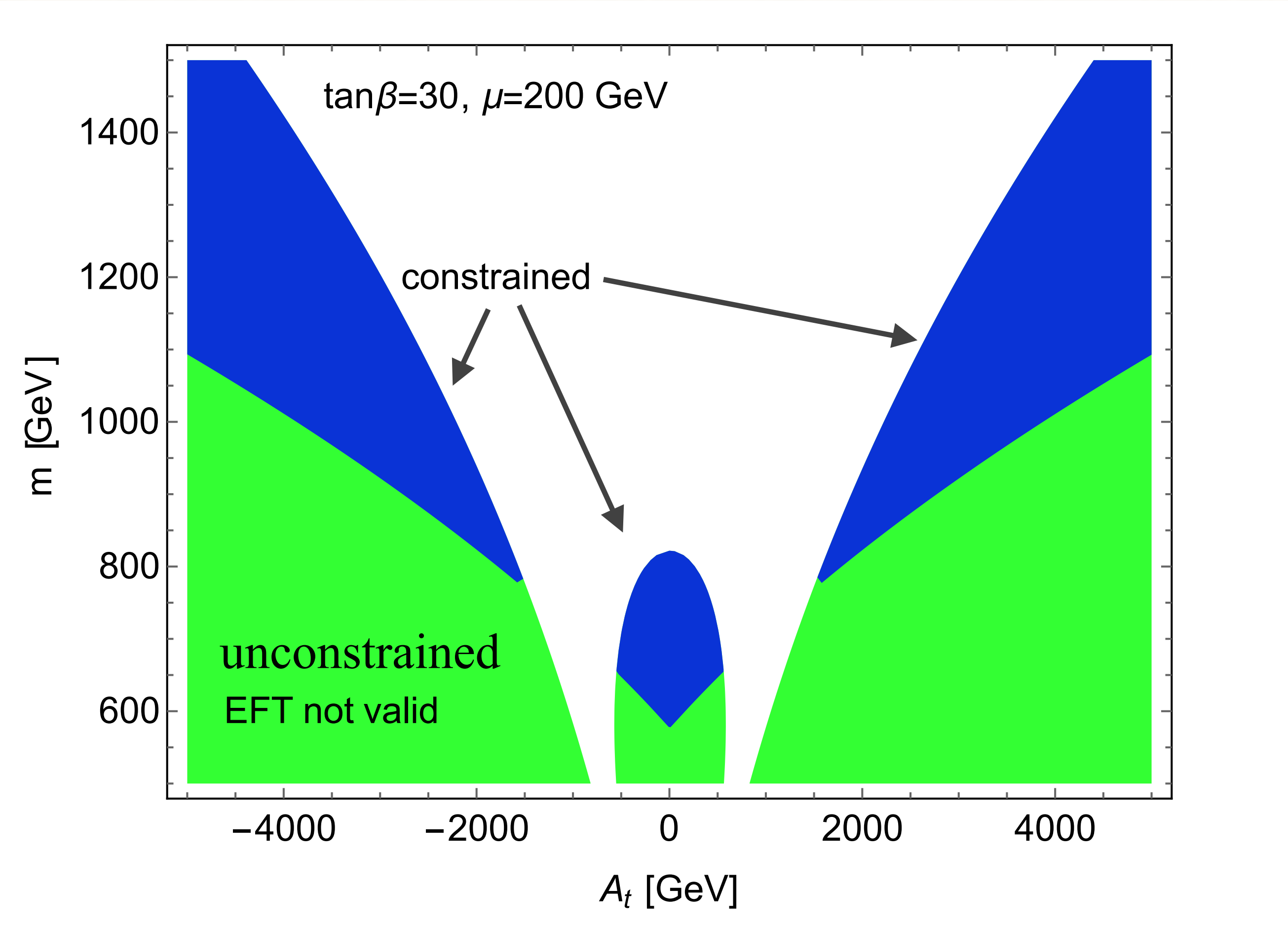


signal strength only

distribution $p_{T,H}$

Implications for new physics

MSSM



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

e.g. [Drozd, Ellis, Quevillon, You `15]

Composite Higgs

$$\bar{c}_g \sim \frac{m_W^2}{16\pi^2 f^2}\frac{y_t^2}{g_\rho^2}$$

$\Lambda > 2.8$ TeV

resonances outside
Higgs kinematic coverage,
can be trusted

Implications for new physics: Compositeness

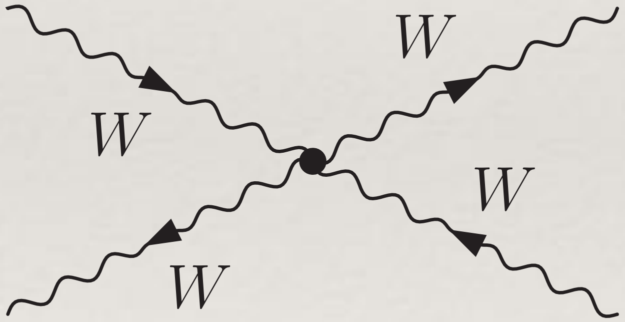
- deviations from the SM Higgs couplings pattern unavoidable in PC

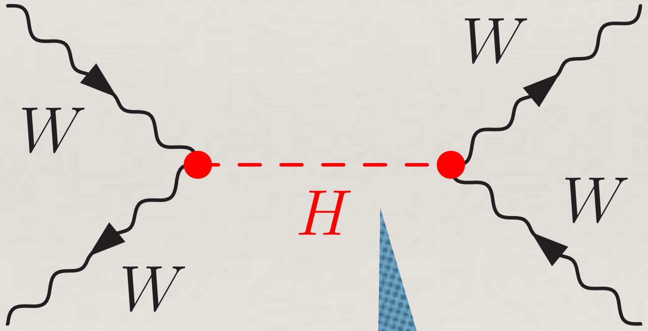
$$SO(5)/SO(4) \text{ + extra states}$$

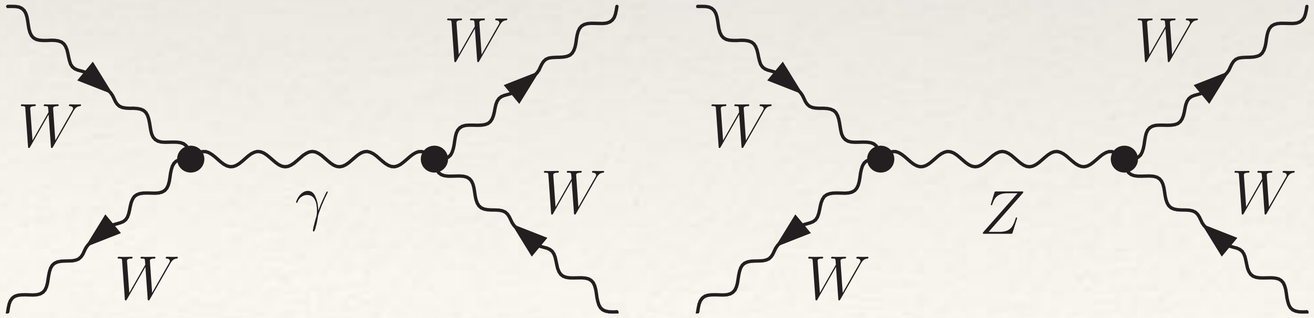
- UV complete picture should lend good UV properties off-resonance

$$\varepsilon_L^\mu = k^\mu/m_W + \mathcal{O}(m_W/E)$$

perturbativity?



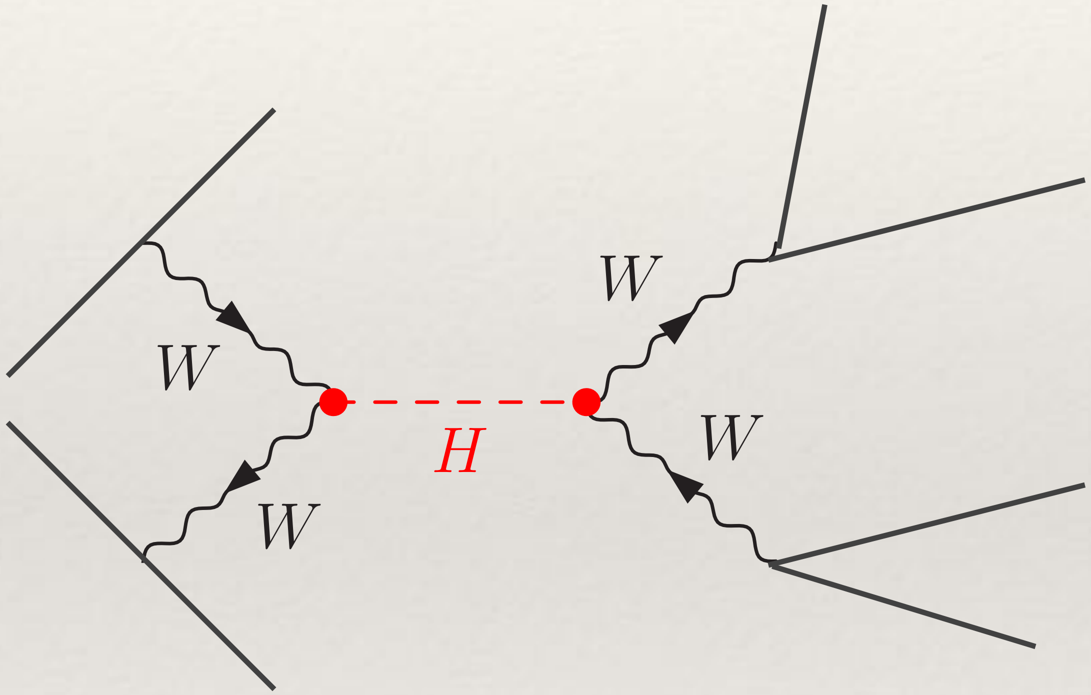




O(10%)
deviation from SM

Implications for new physics: Compositeness

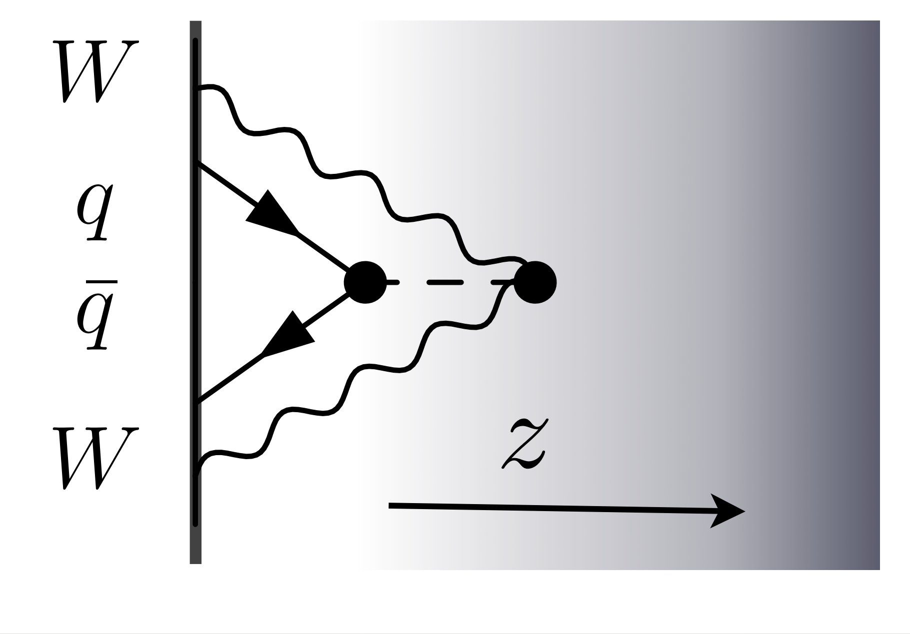
- BUT….
- longitudinal polarisations contribute mass suppressed in golden channels!



- VV amplitude growth highly suppressed, excess in cross section due to lack of absorptive contribution above the the Higgs mass

Implications for new physics: Compositeness

☛ Large N arguments (holography…)



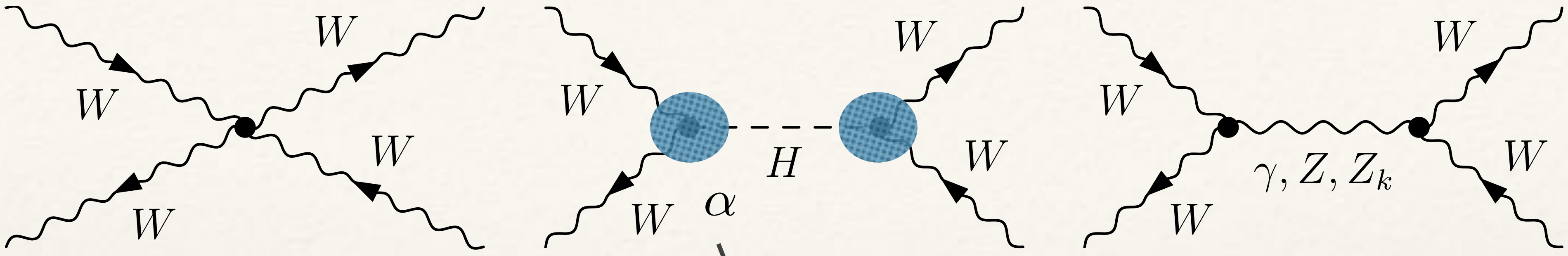
$$\Gamma_n(\xi_1,\ldots,\xi_n) = \frac{\delta^n \Gamma[J]}{i^n\,\delta J(\xi_1)\cdots J(\xi_n)}$$

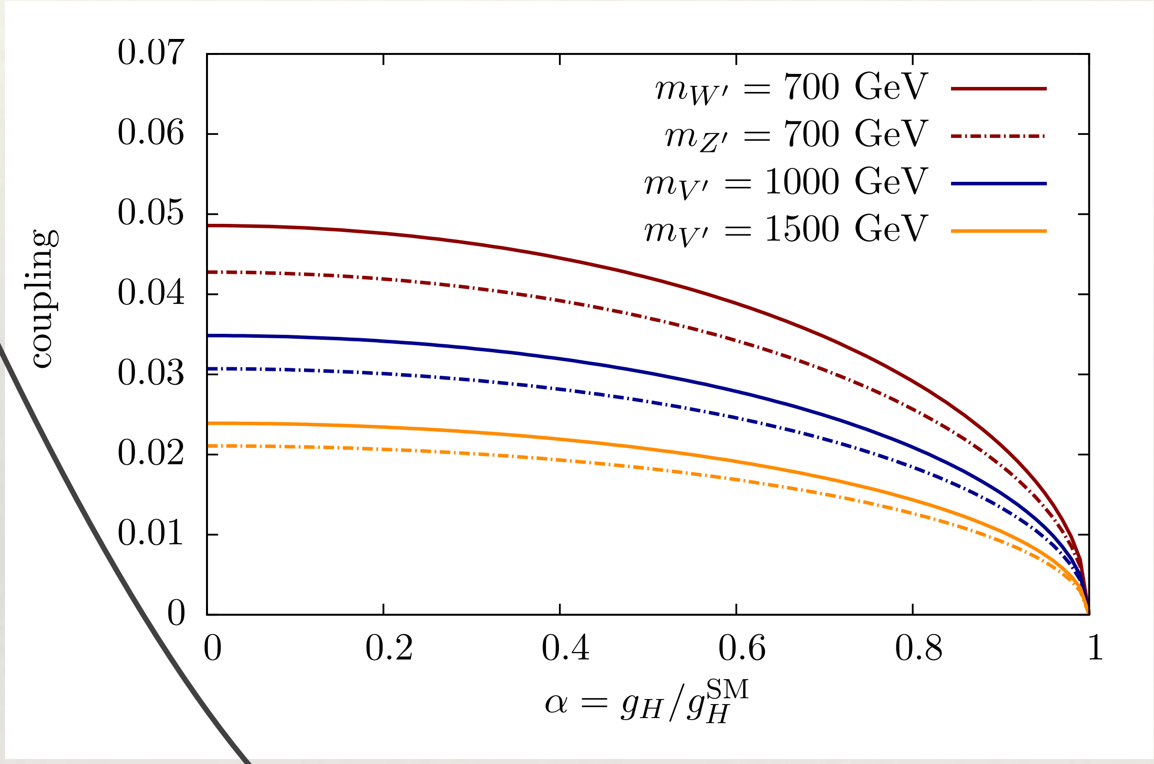
$$\widetilde{\Gamma}[J] = \sum_n \frac{i^n}{n!}\int\cdots\int \mathrm{d}^4 x_1 \cdots \mathrm{d}x_n\, \widetilde{\Gamma}_n(x_1,\ldots,x_n)$$
$$\times\, J(x_1)\cdots J(x_n)\,,$$

☛ unitarity restored in general background geometries

☛ resonances take over the job in scenarios admitting canonical particle interpretations as a limit

Implications for new physics: Compositeness





[CE, Harris,Spannowsky, Takeuchi ` 15]

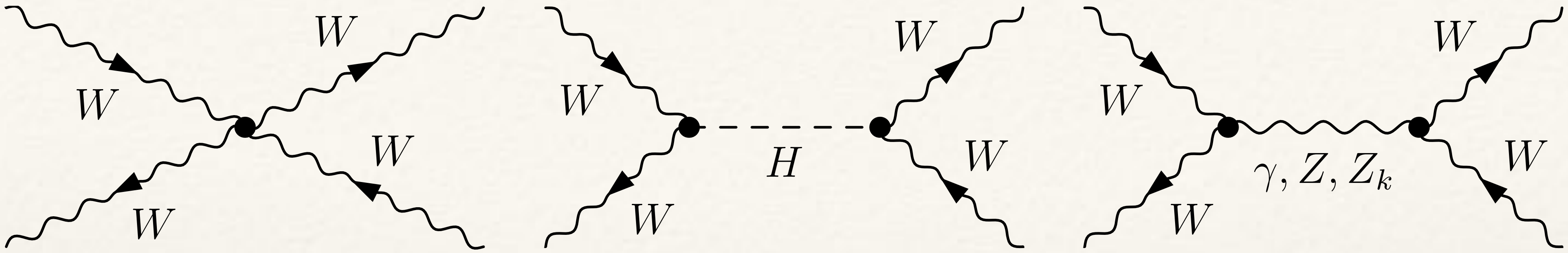
$$g_{WWWW} = g^2_{WW\gamma} + \sum_i g^2_{WWZ_i}$$

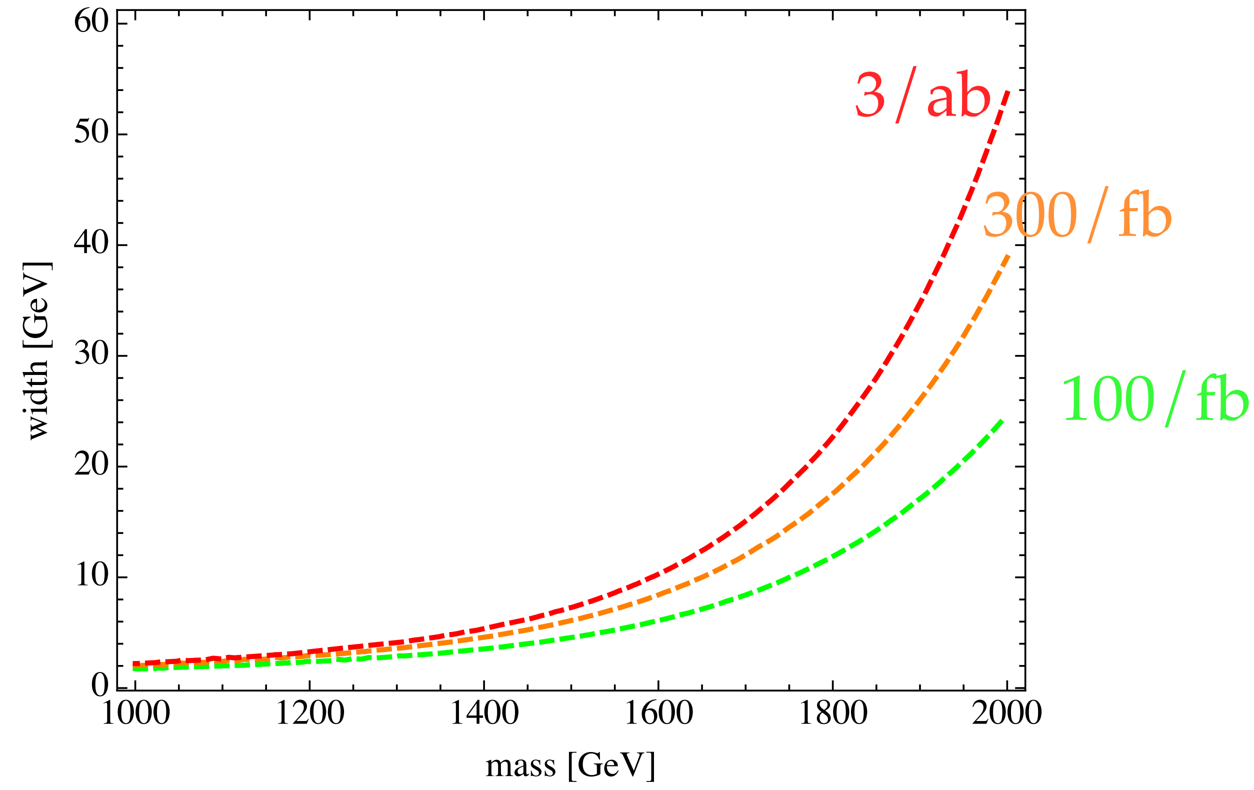
$$4m_W^2 g_{WWWW} = \sum_i 3m_i^2 g^2_{WWZ_i} + \sum_i g^2_{WWH_i} \,,$$

$$g_{WWZZ} = \sum_i g^2_{W_iWZ}$$

$$2(m_W^2 + m_Z^2) g_{WWZZ} = \sum_i \left(3m_i^2 - \frac{(m_Z^2 - m_W^2)^2}{m_i^2}\right) g^2_{W_iWZ} + \sum_i g_{WWH_i} g_{ZZH_i} \,.$$

Implications for new physics: Compositeness





[CE, Harris, Spannowsky, Takeuchi ` 15]

- fermiophobic = WBF

  [CE, Harris,Spannowsky, Takeuchi ` 15]
- fermiophilic = Drell-Yan

  [Pappadopulo, et al. ` 14]
- LHC run 2 will zero in on those states
- realistic spectra require lattice input

Summary

- **Is PNGBism still natural?**

  Maybe yes, maybe no – only a first principle calculation can tell (need to go beyond χPT).

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  Maybe yes, maybe no – only a first principle calculation can tell (need to go beyond χPT).

- **Can the LHC provide hints?**

  Yes, within the kinematic coverage of the machine.

- **Can the lattice provide hints?**

  Most definitely yes, but this will take time.

Yang–Mills theories *had* to be right!

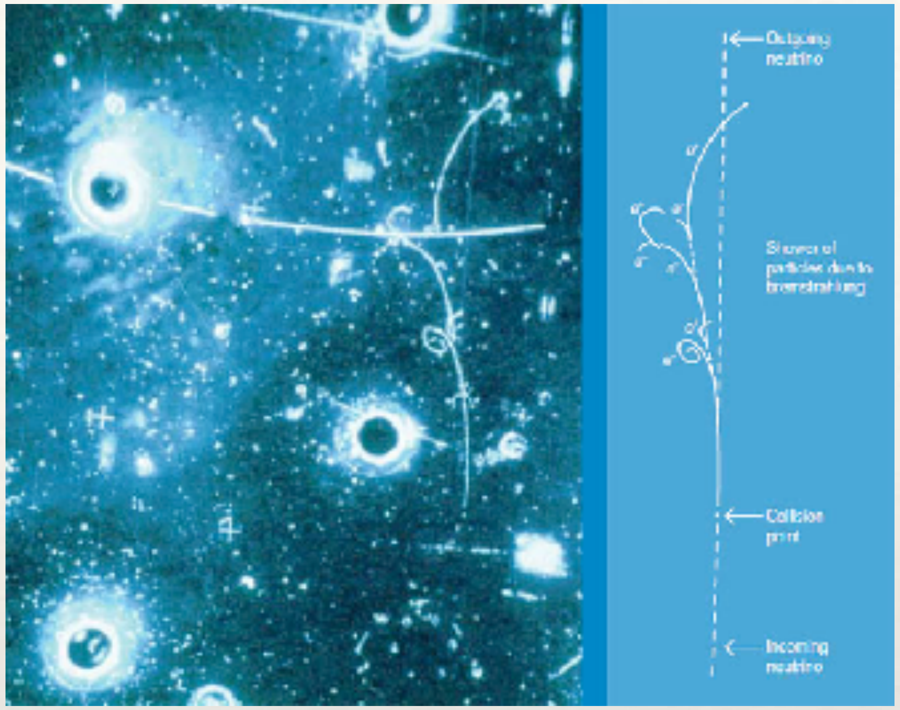
` t Hooft, “Under the Spell of the Gauge Principle”

Ws and Zs in 1983 at UA1/UA2

$$m_W \simeq 80.42 \text{ GeV}$$

$$m_Z \simeq 91.19 \text{ GeV}$$

How is this possible in perturbative Yang-Mills?



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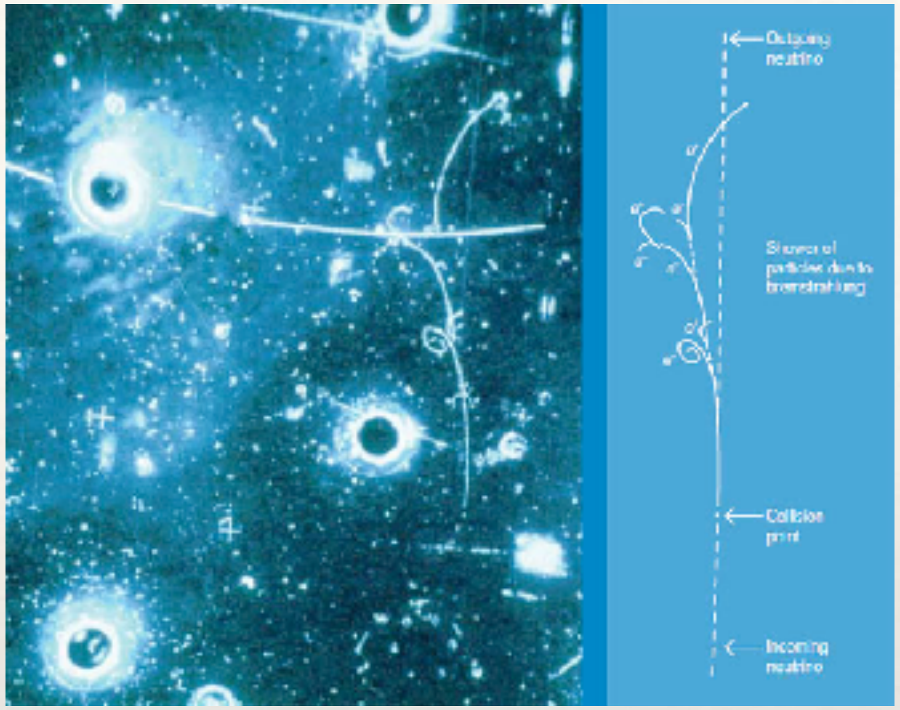


How is this possible in perturbative Yang-Mills?

☛ unique answer to this in 1964

[Higgs `64] [Brout, Englert `64]
[Guralnik, Hagen, Kibble `64]

- non-linear realisation of gauge symmetry in a Yang Mills+scalar sector is compatible with $\langle H \rangle \neq 0$

☛ "spontaneous" symmetry breaking

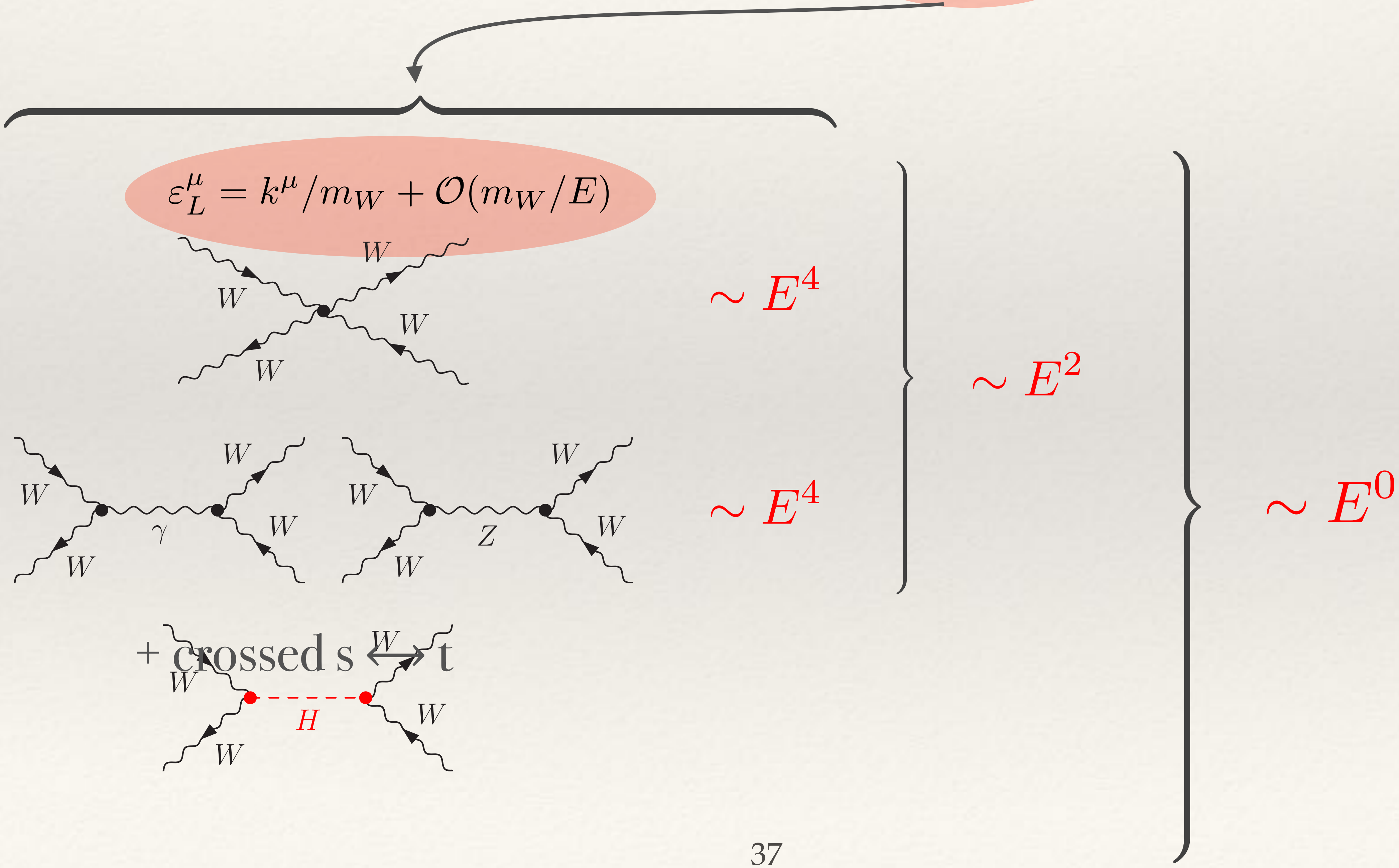
- massive gauge bosons, but no ghost problems at small distances

☛ order-by-order renormalizability and probability conservation

Yang–Mills theories *had* to be right!

- perturbative probability conservation in scattering processes potentially problematic for large momenta:

$$S^\dagger S = \mathbb{1} \implies a_\ell = \frac{1}{32\pi}\int_{-1}^{1} \mathrm{d}\cos\theta\, \mathcal{M}(\cos\theta) P_\ell(\cos\theta)\,, \qquad |a_\ell| \leq 1$$



$$\varepsilon_L^\mu = k^\mu/m_W + \mathcal{O}(m_W/E)$$

$\sim E^4$

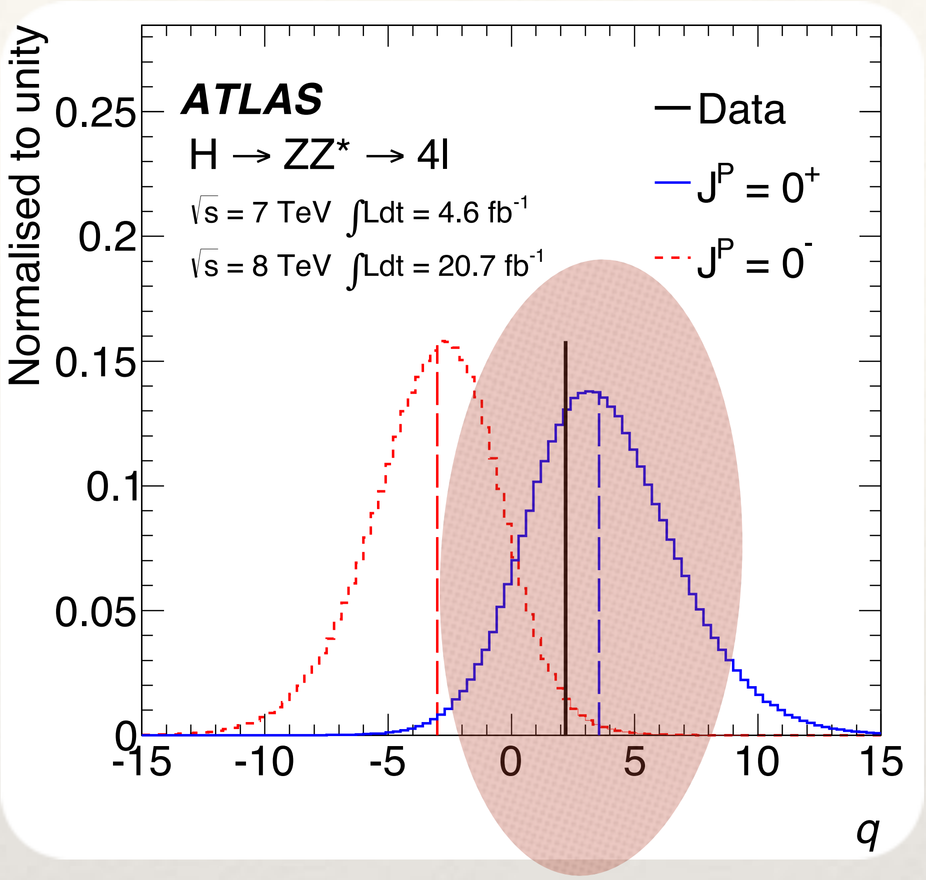
$\sim E^4$

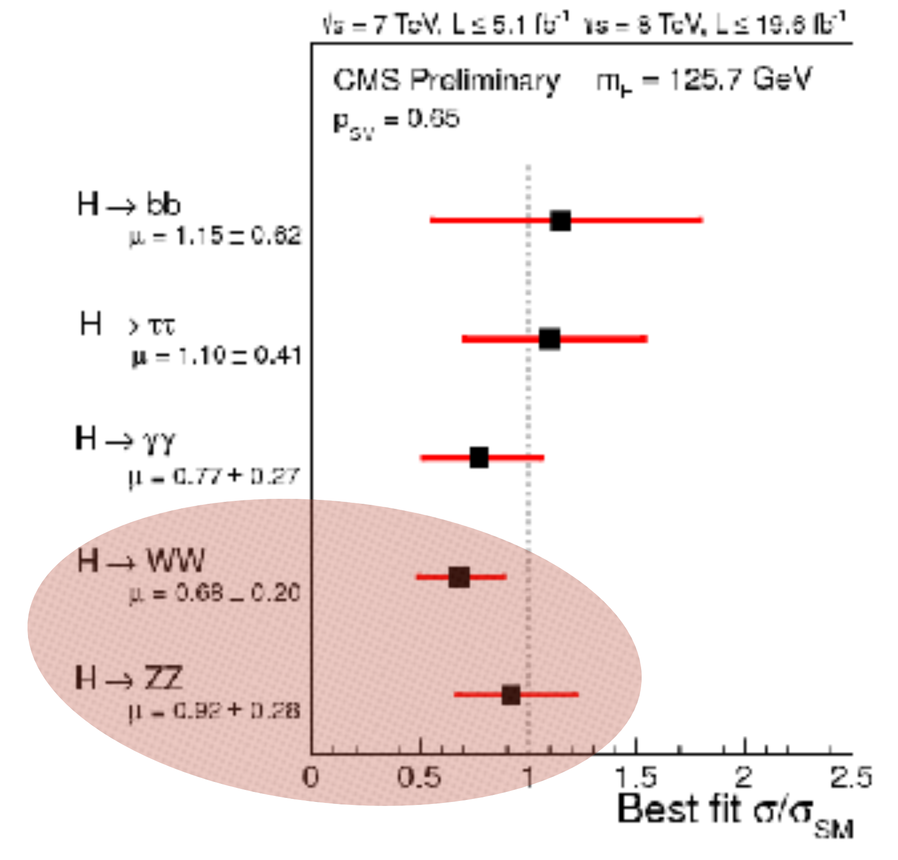
$\sim E^2$

$\sim E^0$

+ crossed s ⟷ t

after July 4th 2012





SM seemingly complete after July 4th 2012 and evidence for $J^{CP} = 0^+$ and couplings to (longitudinal) massive gauge bosons

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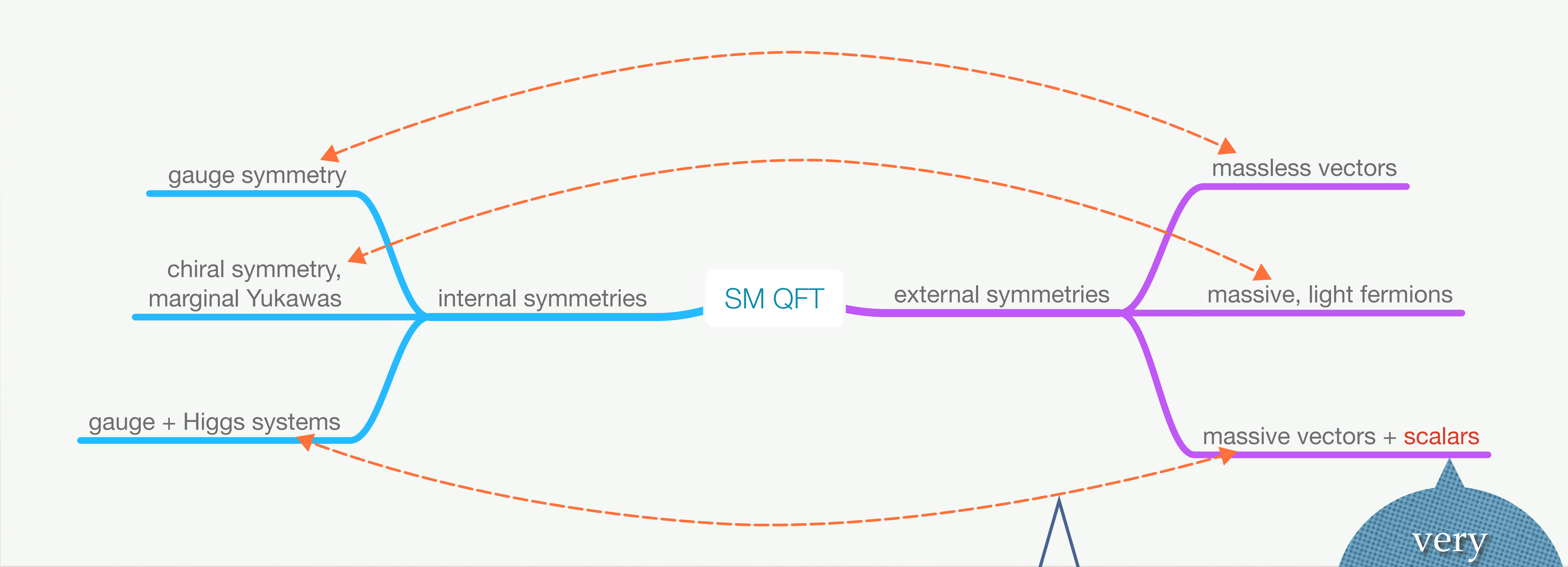
Higgs properties *sui generis*:

particle relates to unitarity conservation and seems to be an excitation of an isotropic and translationally invariant background field

The Standard Model: taking stock



SM QFT

internal symmetries

gauge symmetry

chiral symmetry,
marginal Yukawas

gauge + Higgs systems

external symmetries

massless vectors

massive, light fermions

massive vectors + scalars

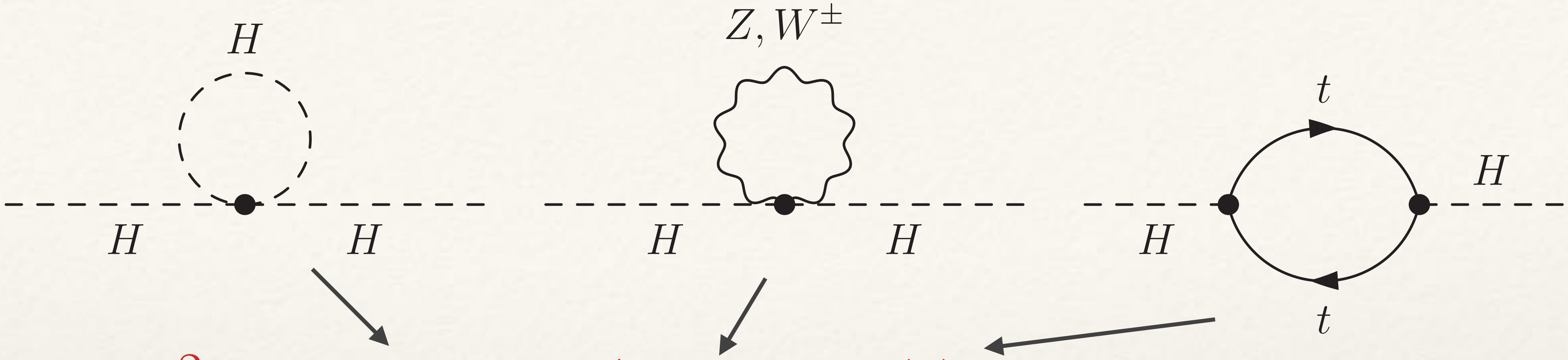
very
relevant
operators!

all SM symmetries have been "used up" to guarantee renormalizability and a priori unitarity, we have no protection fundamental mass scales

☛ ultraviolet catastrophe of the 21st century

The Standard Model: hierarchies

$$\delta m_H^2 \sim$$



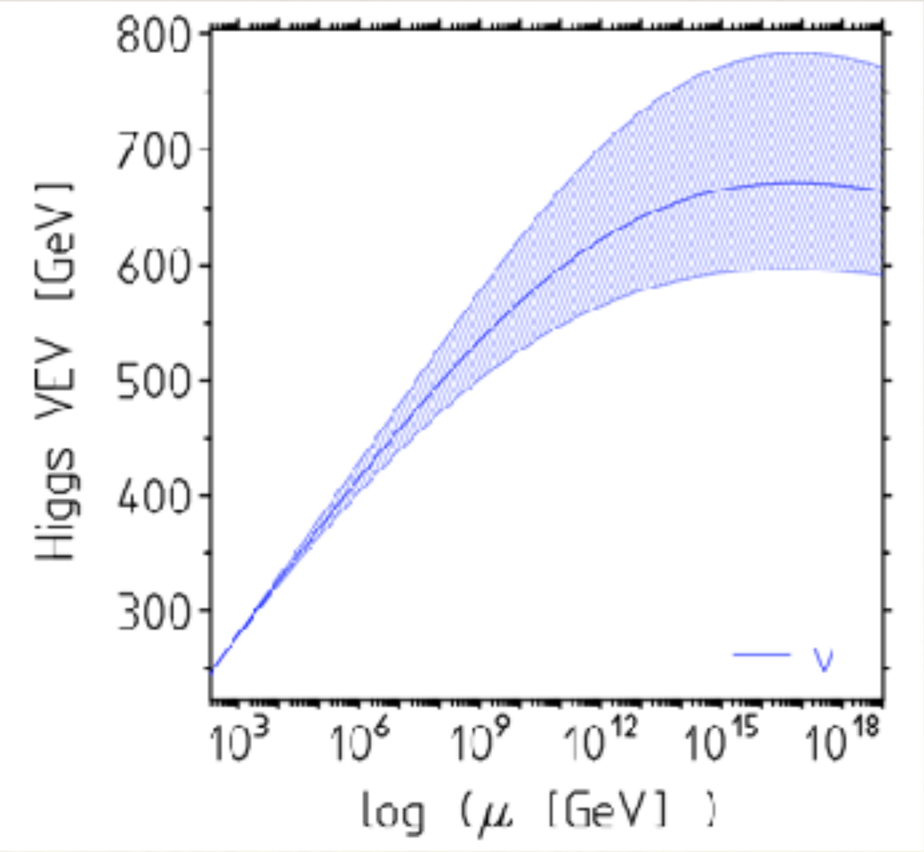
$$\delta m_H^2 \sim \text{UV cutoff/threshold(s)}$$

[Veltman `81]

$$\sim \underbrace{(m_H^2 + 2m_W^2 + m_Z^2 - 4m_t^2)}_{=\,0\ ?} \times \frac{\Lambda^2}{\langle H\rangle^2}$$

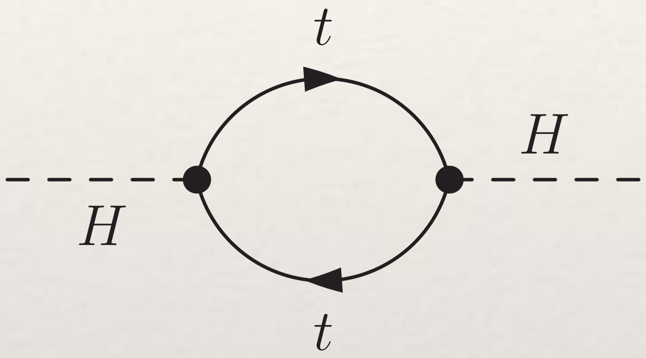
- this is regularisation scheme dependent
- hence, no straightforward interpretation
- however, no argument why we should have

$$v(M_{\text{Planck}}) \ll M_{\text{Planck}}$$



In this talk

- ☛ Higgs boson coupling measurements
- ☛ generic approaches to Higgs couplings and interpretation



based on **direct** measurements

- ☛ status of the top quark sector after the first LHC measurements

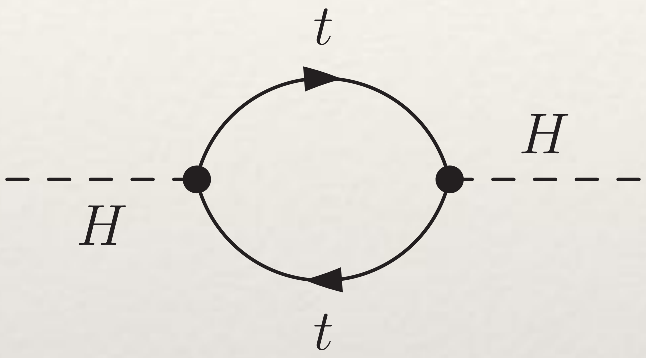
- ☛ Example of new physics: a UV-complete composite Higgs model

In this talk

- ☛ Higgs boson coupling measurements

differential distributions!

- ☛ generic approaches to Higgs couplings and interpretation

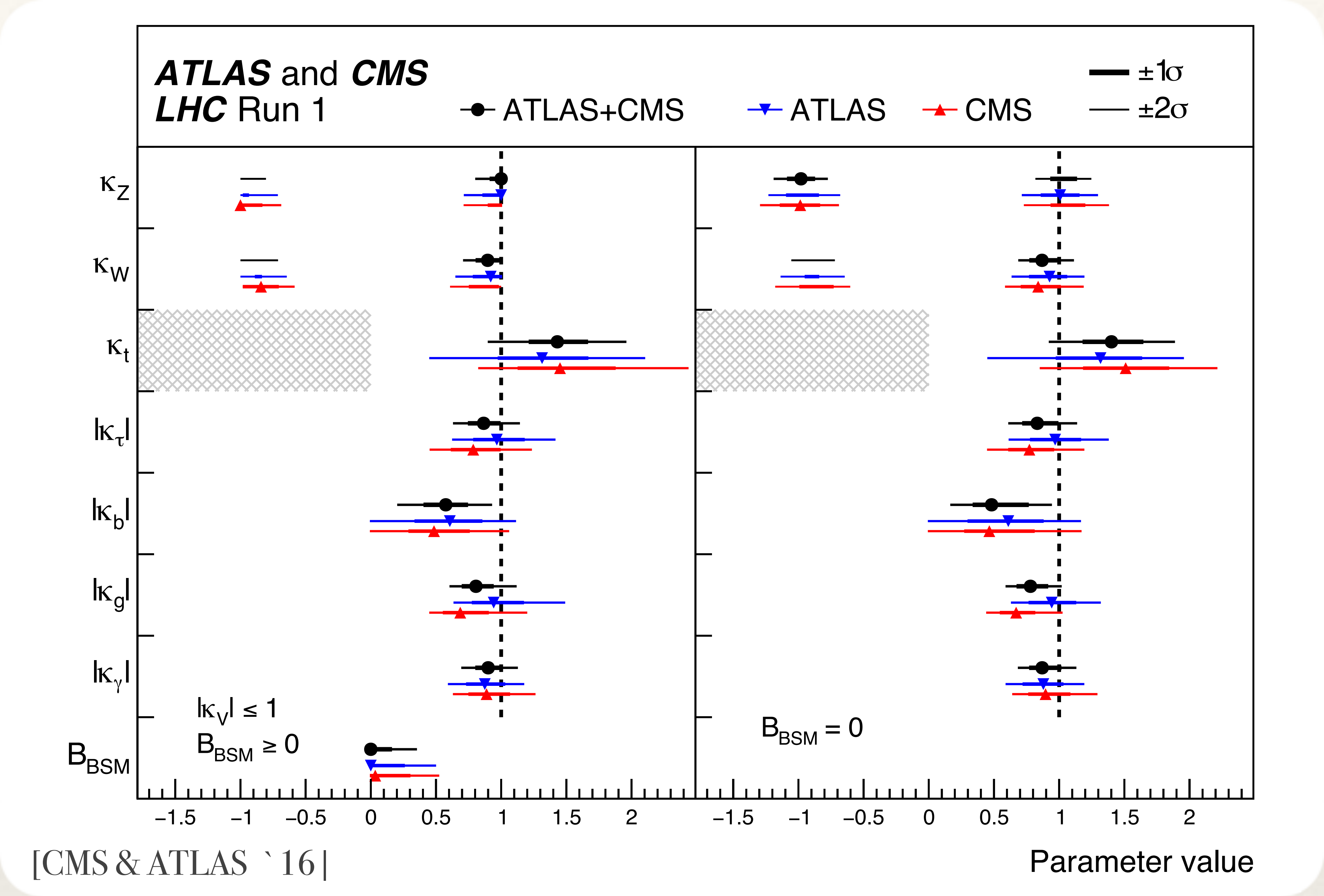


based on **direct** measurements

- ☛ status of the top quark sector after the first LHC measurements

- ☛ Example of new physics: a UV-complete composite Higgs model

Status of LHC Higgs measurements



[CMS & ATLAS `16]

- ☛ everything is consistent with the SM Higgs hypothesis (so far) but what are the implications for new physics?

Fingerprinting the lack of new physics

the SM is flawed!

but no evidence
for exotics!

**coupling/scale
separated BSM physics**

Effective Field Theory

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$$

[Buchmüller, Wyler `87]

[Hagiwara, Peccei, Zeppenfeld, Hikasa `87]

[Giudice, Grojean, Pomarol, Rattazzi `07]

[Grzadkowski, Iskrzynski, Misiak, Rosiek `10]

59 B-conserving operators ⊗ flavor ⊗ h.c., d=6
2499 parameters (reduces to 76 with N_f=1)

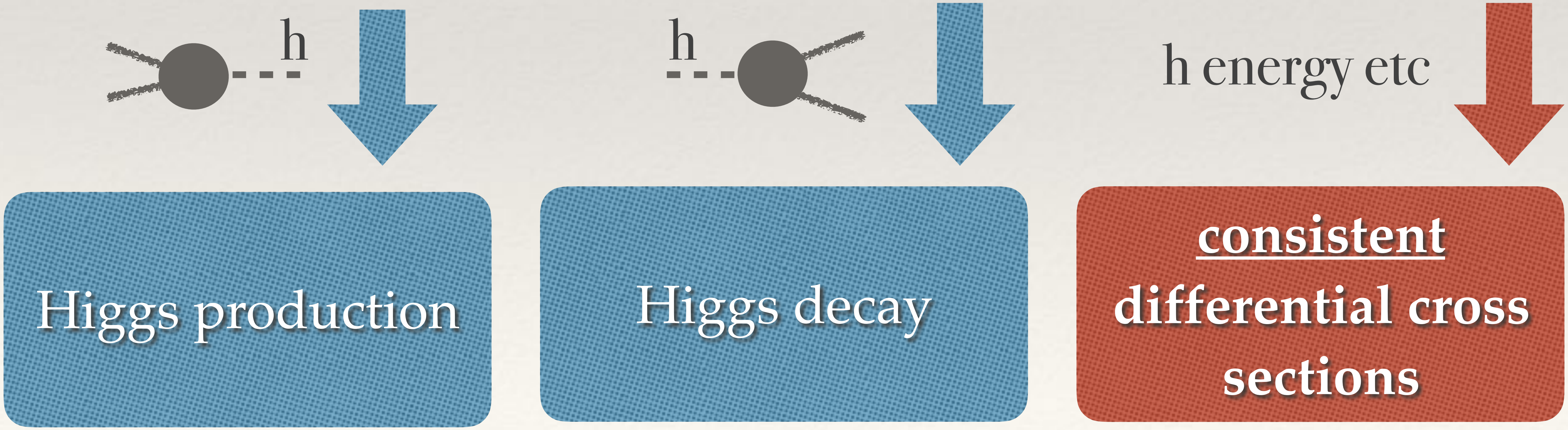
concrete models

- (N)MSSM
- Higgs portals
- compositeness
- …

SILH Higgs phenomenology

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

[Giudice, Grojean, Pomarol, Rattazzi `07]



h energy etc

Higgs production

Higgs decay

<u>consistent</u>
differential cross sections

Strongly Interacting Light Higgs phenomenology

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

S,T≈0 from LEP: $\bar{c}_T = 0, \quad \bar{c}_W = -\bar{c}_B$

[Giudice, Grojean, Pomarol, Rattazzi `07]

branching ratios
total width

[Contino et al `13]

production process	included sensitivity
$pp \to H$ $pp \to H + \mathrm{j}$ $pp \to H + 2\mathrm{j}$ (gluon fusion) $pp \to t\bar{t}H$	$\bar{c}_g, \bar{c}_{u3}, \bar{c}_H$
$pp \to VH$ $pp \to H + 2\mathrm{j}$ (weak boson fusion)	$\bar{c}_W, \bar{c}_B, \bar{c}_{HW}, \bar{c}_{HB}, \bar{c}_\gamma, \bar{c}_H$

Fingerprinting the lack of new physics

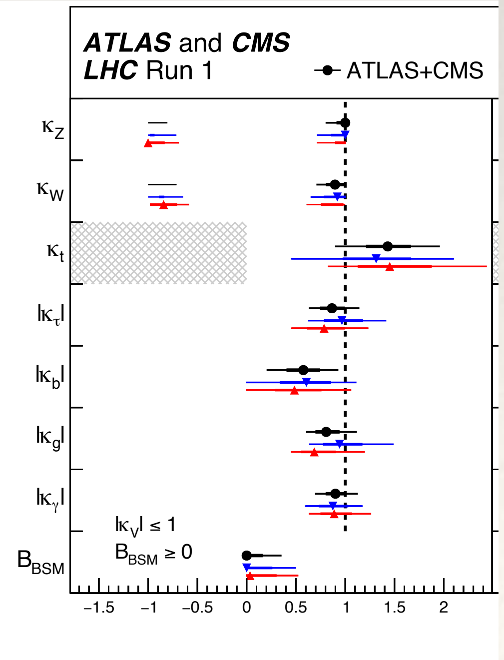
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$$

[Contino et al ` 13]

decays
eHdecay

production

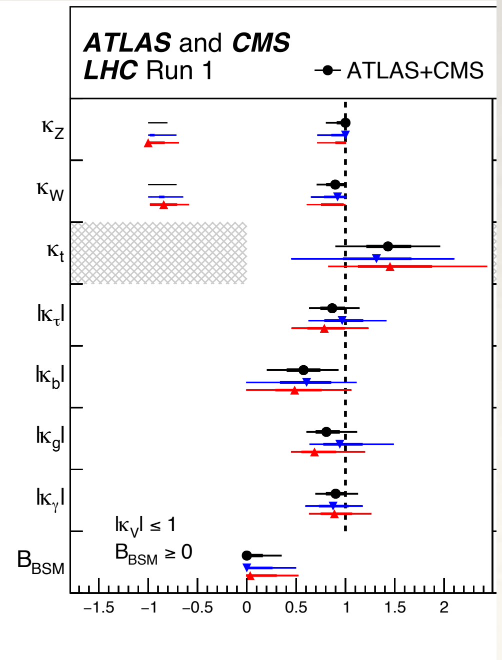
<u>consistent</u>
differential
distributions



low stats

[HXSWG YR 3]

$$\kappa_g = \frac{g^{SM} + \Delta g}{g^{SM}}$$



A word of caution

<u>consistent</u>
differential
distributions

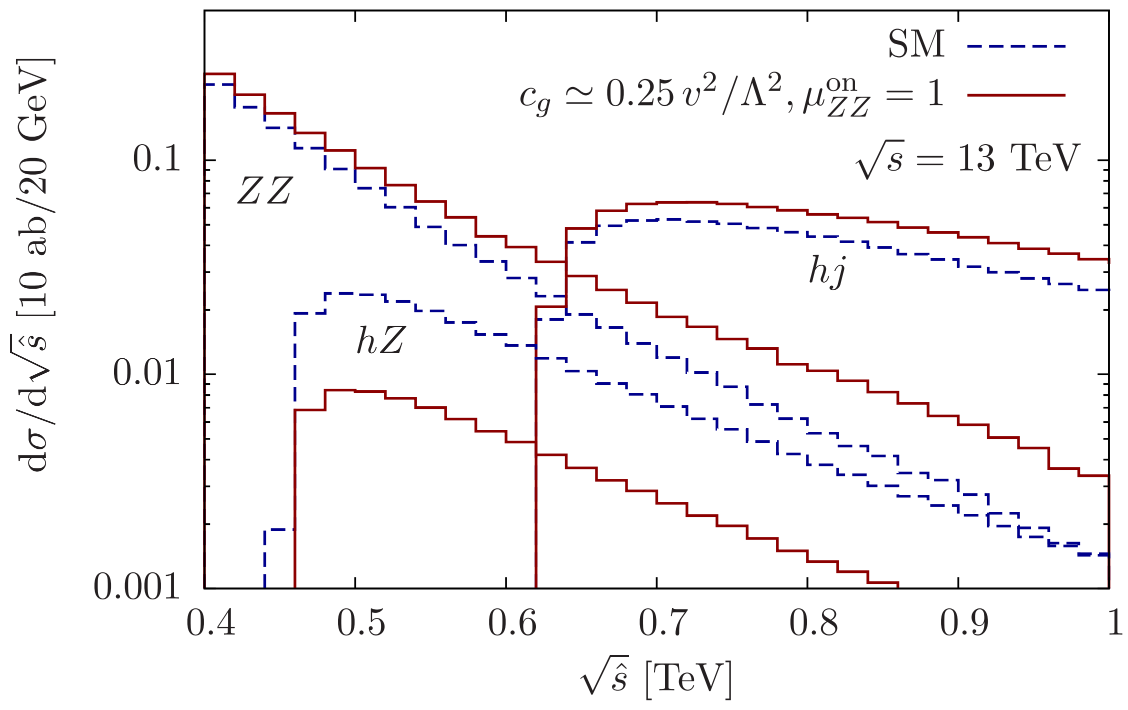
$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$$

$$\mathrm{d}\sigma = \mathrm{d}\sigma^{\mathrm{SM}} + \underset{\underset{2\,\mathrm{Re}\{\mathcal{M}_{\mathrm{SM}}\mathcal{M}^{*}_{d=6}\}}{\wr}}{\mathrm{d}\sigma^{\{O_i\}}}/\Lambda^2$$

not necessarily positive definite
(cf. fixed order NⁿLO)

conservative probe of validity of d=6 extension

similar analyses
[Isidori, Trott ` 13]
[Biekötter, Knochel, Krämer, Liu, Riva ` 14]



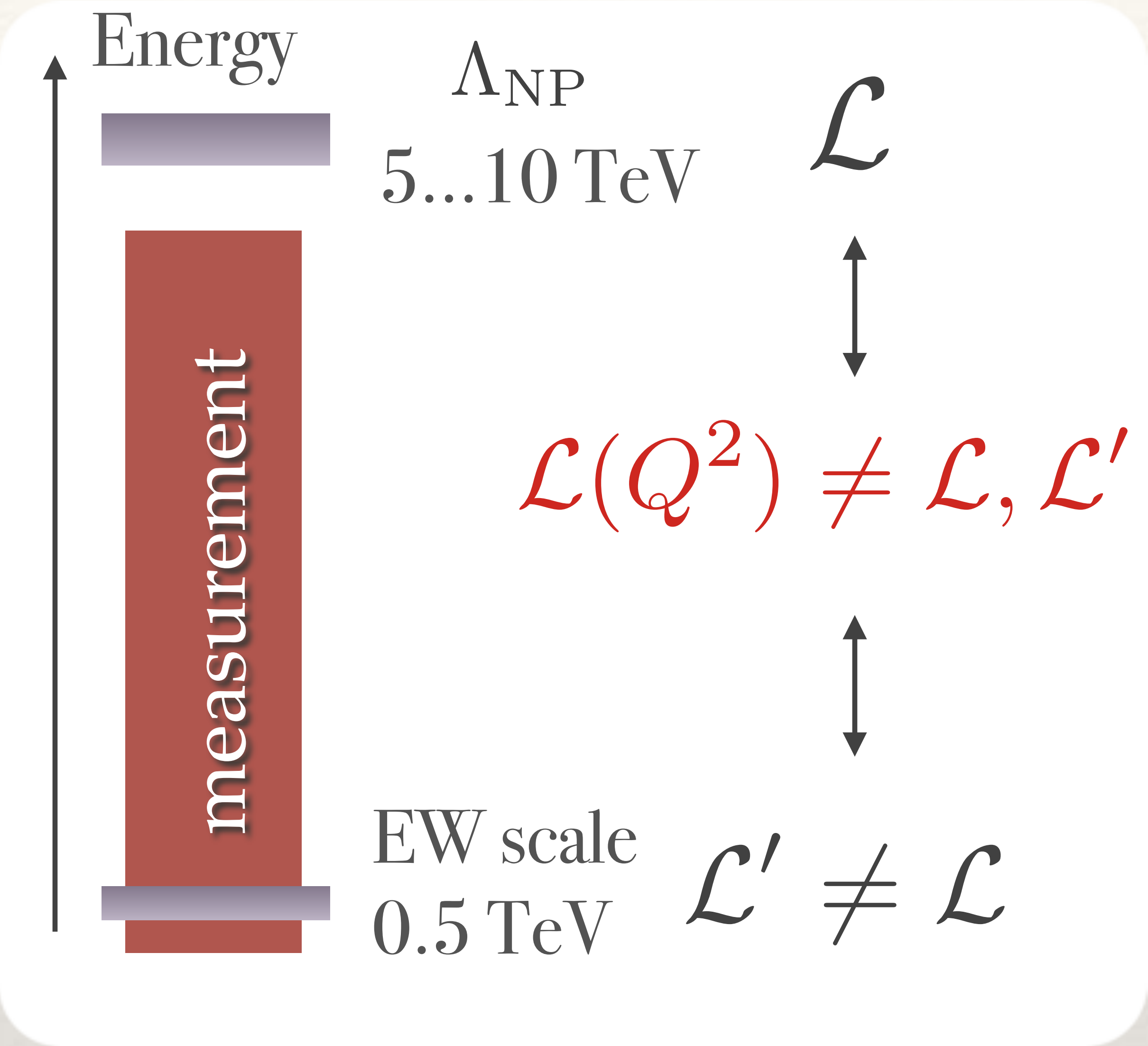
[CE, Soreq, Spannowsky ` 15]

A word of caution

consistent differential distributions

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$$

$$d\sigma \;=\; d\sigma^{\rm SM} + \underset{\substack{\wr \\ 2\,\mathrm{Re}\{\mathcal{M}_{\rm SM}\mathcal{M}^*_{d=6}\}}}{d\sigma^{\{O_i\}}}/\Lambda^2$$



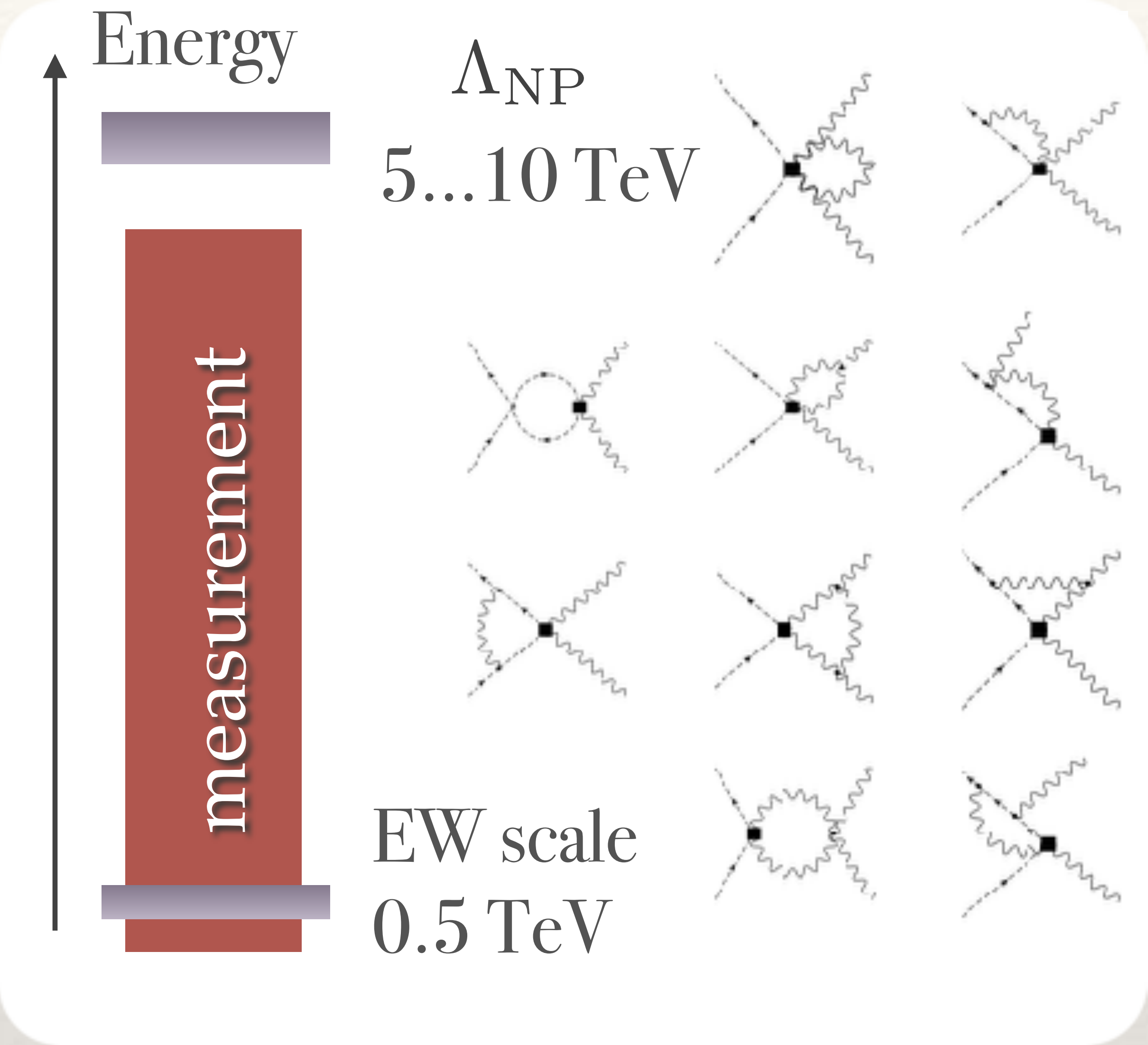
- evolution from renormalization group equations, **choice of scales**
  [Alam, Dawson, Szalapski ‘97] … [Grojean, Jenkins, Manohar, Trott ‘13] [Jenkins, Manohar, Trott ‘13] [Alonso et al. ‘13]
- consistent interpretation requires **communication of resolved scales**
  [Isidori, Trott ‘13] [CE, Spannowsky ‘14]

A word of caution

consistent differential distributions

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$$

$$d\sigma \;=\; d\sigma^{\mathrm{SM}} + \underset{\substack{\wr \\ 2\,\mathrm{Re}\{\mathcal{M}_{\mathrm{SM}}\mathcal{M}^*_{d=6}\}}}{d\sigma^{\{O_i\}}}/\Lambda^2$$



- evolution from renormalization group equations, **choice of scales**

  [Alam, Dawson, Szalapski `97] ... [Grojean, Jenkins, Manohar, Trott `13] [Jenkins, Manohar, Trott `13] [Alonso et al. `13]

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

  [Isidori, Trott `13] [CE, Spannowsky `14]

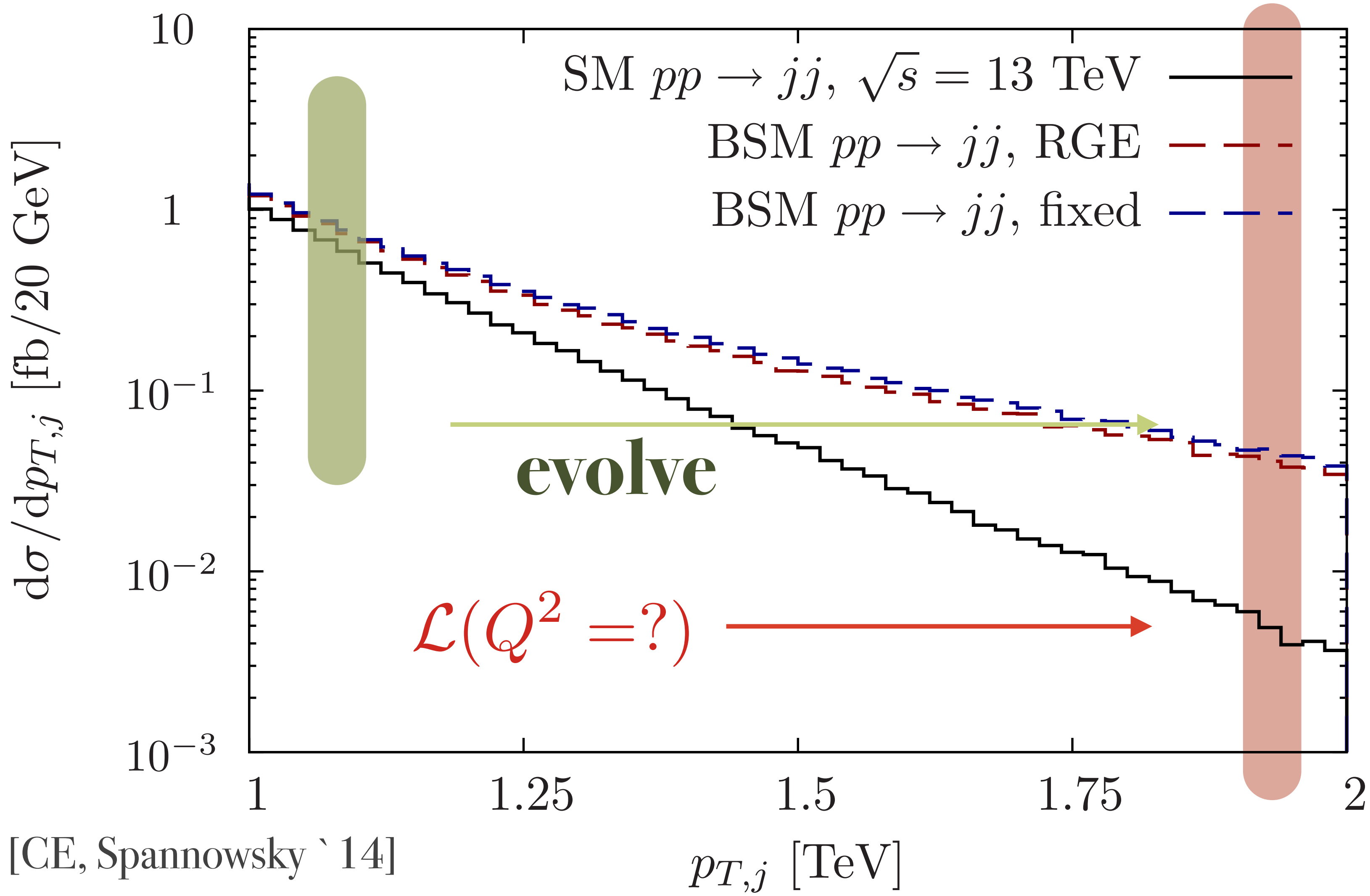
How can we interpret EFT measurements?

- evolution from renormalization group equations

[Alam, Dawson, Szalapski `97] … [Grojean, Jenkins, Manohar, Trott `13] [Jenkins, Manohar, Trott `13] [Alonso et al. `13]

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

[Isidori, Trott `13] [CE, Spannowsky `14]



[CE, Spannowsky `14]

$\max Q^2 = ?$

$$S_1 = (\bar{s}_a c_b)_{V-A}(\bar{u}_b d_a)_{V-A}\,,$$

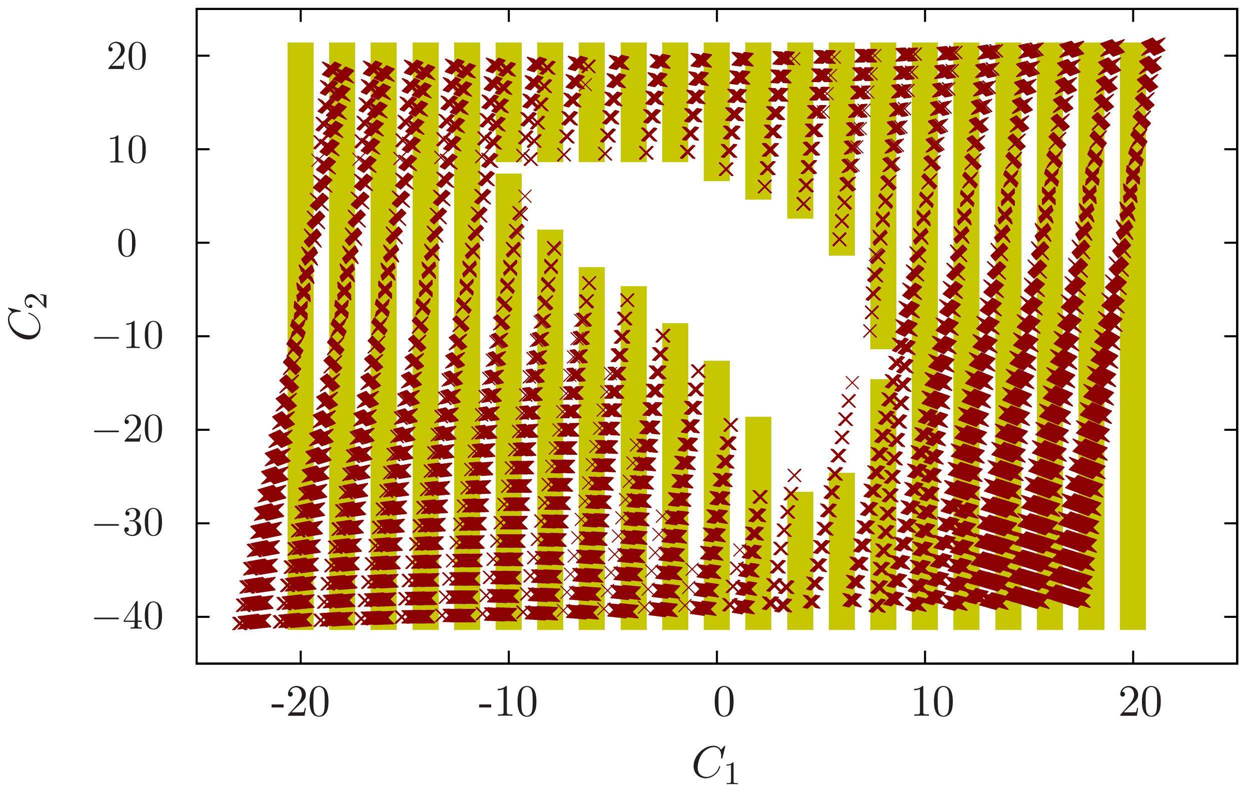
$$S_2 = (\bar{s}_a c_a)_{V-A}(\bar{u}_b d_b)_{V-A}\,,$$

A word of caution

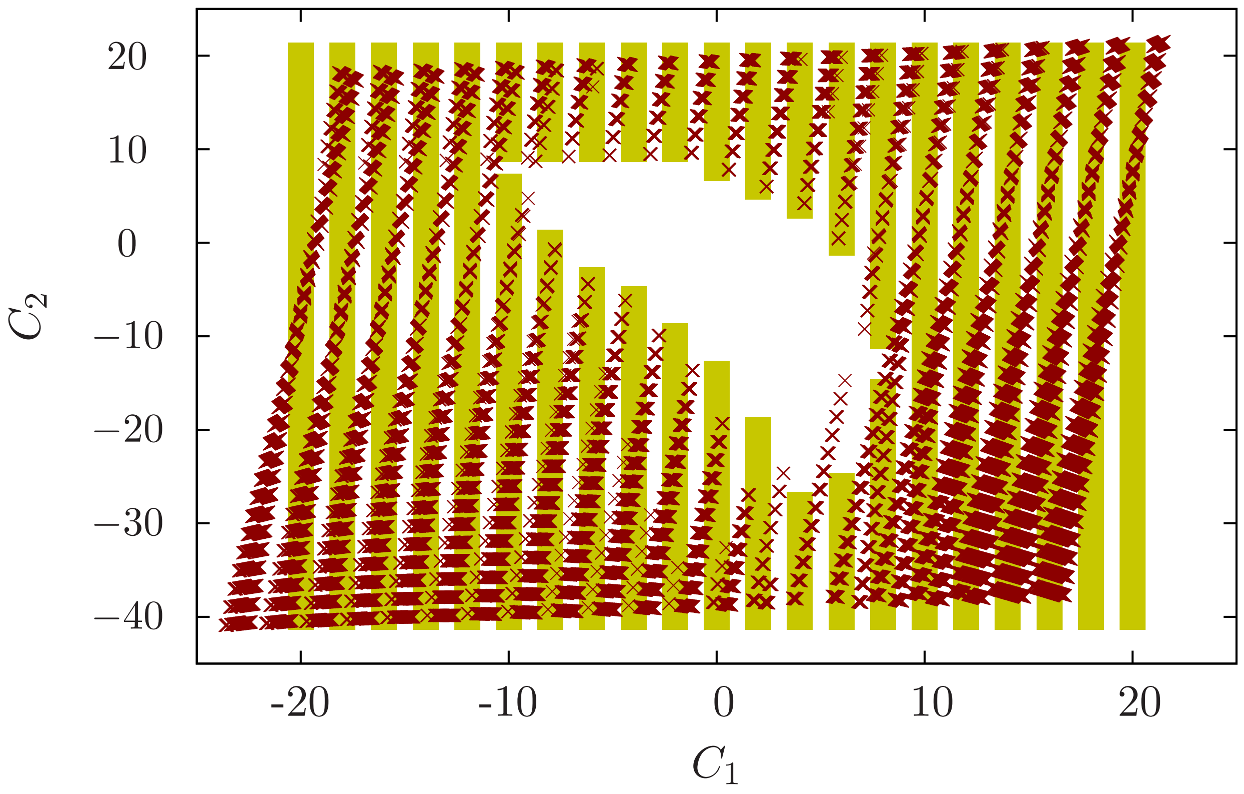
- evolution from renormalization group equations

  [Alam, Dawson, Szalapski `97] … [Grojean, Jenkins, Manohar, Trott `13] [Jenkins, Manohar, Trott `13] [Alonso et al. `13]
- consistent interpretation requires **communication of resolved scales**

  [Isidori, Trott `13] [CE, Spannowsky `14]
- effects can be in the $\sim 10\%$ range, not relevant at this stage

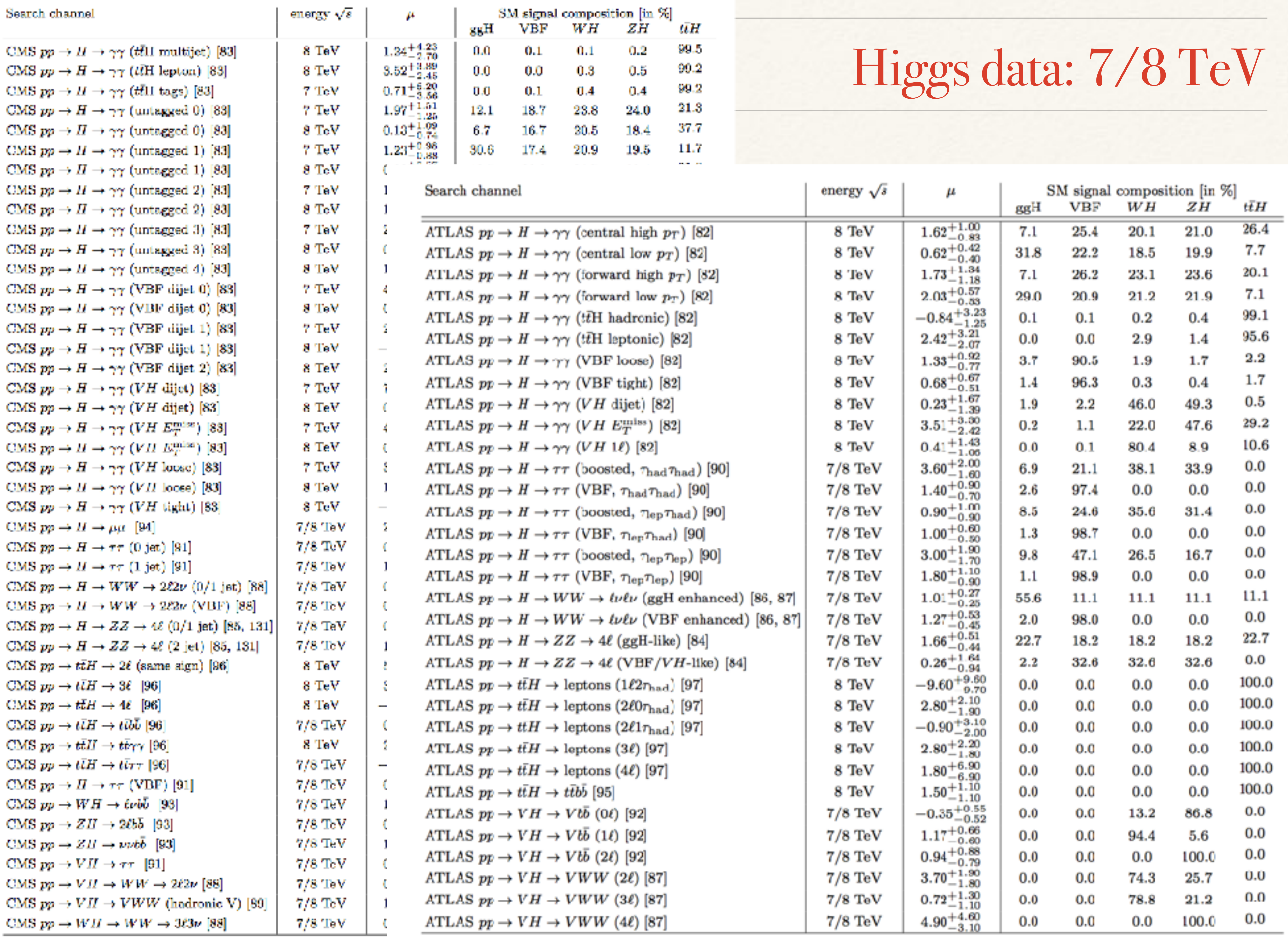


kinematic endpoint



outside run II coverage

Higgs data: 7/8 TeV



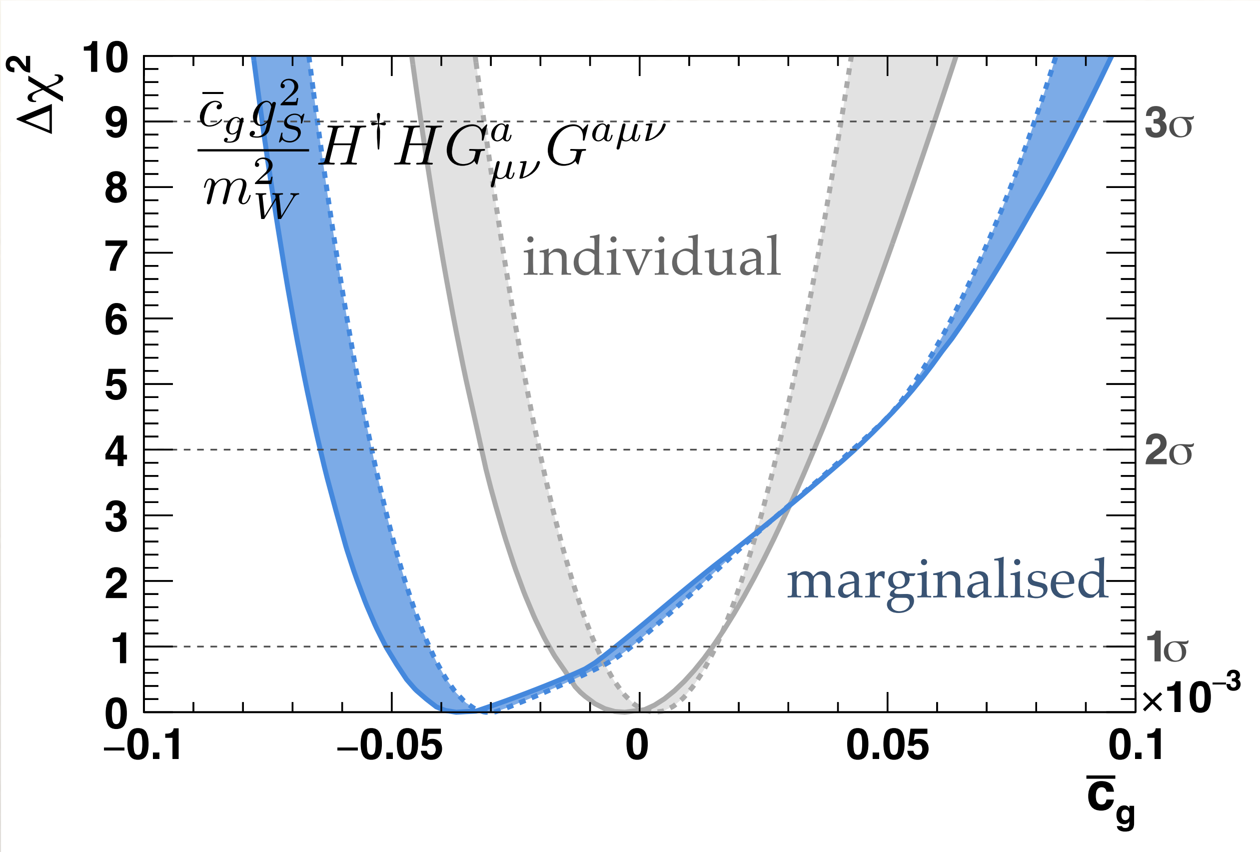
Search channel	energy $\sqrt{s}$	μ	SM signal composition [in %] ggH	VBF	WH	ZH	$t\bar{t}H$
CMS $pp \to H \to \gamma\gamma$ ($t\bar{t}$H multijet) [83]	8 TeV	$1.34^{+4.23}_{-2.70}$	0.0	0.1	0.1	0.2	99.5
CMS $pp \to H \to \gamma\gamma$ ($t\bar{t}$H lepton) [83]	8 TeV	$3.52^{+3.89}_{-2.45}$	0.0	0.0	0.3	0.5	99.2
CMS $pp \to H \to \gamma\gamma$ ($t\bar{t}$H tags) [83]	7 TeV	$0.71^{+6.20}_{-3.56}$	0.0	0.1	0.4	0.4	99.2
CMS $pp \to H \to \gamma\gamma$ (untagged 0) [83]	7 TeV	$1.97^{+1.51}_{-1.25}$	12.1	18.7	23.8	24.0	21.3
CMS $pp \to H \to \gamma\gamma$ (untagged 0) [83]	8 TeV	$0.13^{+1.09}_{-0.74}$	6.7	16.7	30.5	18.4	37.7
CMS $pp \to H \to \gamma\gamma$ (untagged 1) [83]	7 TeV	$1.23^{+0.96}_{-0.88}$	30.6	17.4	20.9	19.5	11.7
CMS $pp \to H \to \gamma\gamma$ (untagged 1) [83]	8 TeV						
CMS $pp \to H \to \gamma\gamma$ (untagged 2) [83]	7 TeV						
CMS $pp \to H \to \gamma\gamma$ (untagged 2) [83]	8 TeV						
CMS $pp \to H \to \gamma\gamma$ (untagged 3) [83]	7 TeV						
CMS $pp \to H \to \gamma\gamma$ (untagged 3) [83]	8 TeV						
CMS $pp \to H \to \gamma\gamma$ (untagged 4) [83]	8 TeV						
CMS $pp \to H \to \gamma\gamma$ (VBF dijet 0) [83]	7 TeV						
CMS $pp \to H \to \gamma\gamma$ (VBF dijet 0) [83]	8 TeV						
CMS $pp \to H \to \gamma\gamma$ (VBF dijet 1) [83]	7 TeV						
CMS $pp \to H \to \gamma\gamma$ (VBF dijet 1) [83]	8 TeV						
CMS $pp \to H \to \gamma\gamma$ (VBF dijet 2) [83]	8 TeV						
CMS $pp \to H \to \gamma\gamma$ (VH dijet) [83]	7 TeV						
CMS $pp \to H \to \gamma\gamma$ (VH dijet) [83]	8 TeV						
CMS $pp \to H \to \gamma\gamma$ (VH E_T^{miss}) [83]	7 TeV						
CMS $pp \to H \to \gamma\gamma$ (VH E_T^{miss}) [83]	8 TeV						
CMS $pp \to H \to \gamma\gamma$ (VH loose) [83]	7 TeV						
CMS $pp \to H \to \gamma\gamma$ (VH loose) [83]	8 TeV						
CMS $pp \to H \to \gamma\gamma$ (VH tight) [83]	8 TeV						
CMS $pp \to H \to \mu\mu$ [94]	7/8 TeV						
CMS $pp \to H \to \tau\tau$ (0 jet) [91]	7/8 TeV						
CMS $pp \to H \to \tau\tau$ (1 jet) [91]	7/8 TeV						
CMS $pp \to H \to WW \to 2\ell 2\nu$ (0/1 jet) [88]	7/8 TeV						
CMS $pp \to H \to WW \to 2\ell 2\nu$ (VBF) [88]	7/8 TeV						
CMS $pp \to H \to ZZ \to 4\ell$ (0/1 jet) [85, 131]	7/8 TeV						
CMS $pp \to H \to ZZ \to 4\ell$ (2 jet) [85, 131]	7/8 TeV						
CMS $pp \to t\bar{t}H \to 2\ell$ (same sign) [96]	8 TeV						
CMS $pp \to t\bar{t}H \to 3\ell$ [96]	8 TeV						
CMS $pp \to t\bar{t}H \to 4\ell$ [96]	8 TeV						
CMS $pp \to t\bar{t}H \to t\bar{t}b\bar{b}$ [96]	7/8 TeV						
CMS $pp \to t\bar{t}H \to t\bar{t}\gamma\gamma$ [96]	8 TeV						
CMS $pp \to t\bar{t}H \to t\bar{t}\tau\tau$ [96]	7/8 TeV						
CMS $pp \to H \to \tau\tau$ (VBF) [91]	7/8 TeV						
CMS $pp \to WH \to \ell\nu b\bar{b}$ [93]	7/8 TeV						
CMS $pp \to ZH \to 2\ell b\bar{b}$ [93]	7/8 TeV						
CMS $pp \to ZH \to \nu\nu b\bar{b}$ [93]	7/8 TeV						
CMS $pp \to VH \to \tau\tau$ [91]	7/8 TeV						
CMS $pp \to VH \to WW \to 2\ell 2\nu$ [88]	7/8 TeV						
CMS $pp \to VH \to VWW$ (hadronic V) [89]	7/8 TeV						
CMS $pp \to WH \to WW \to 3\ell 3\nu$ [88]	7/8 TeV						

Search channel	energy $\sqrt{s}$	μ	SM signal composition [in %] ggH	VBF	WH	ZH	$t\bar{t}H$
ATLAS $pp \to H \to \gamma\gamma$ (central high p_T) [82]	8 TeV	$1.62^{+1.00}_{-0.83}$	7.1	25.4	20.1	21.0	26.4
ATLAS $pp \to H \to \gamma\gamma$ (central low p_T) [82]	8 TeV	$0.62^{+0.42}_{-0.40}$	31.8	22.2	18.5	19.9	7.7
ATLAS $pp \to H \to \gamma\gamma$ (forward high p_T) [82]	8 TeV	$1.73^{+1.34}_{-1.18}$	7.1	26.2	23.1	23.6	20.1
ATLAS $pp \to H \to \gamma\gamma$ (forward low p_T) [82]	8 TeV	$2.03^{+0.57}_{-0.53}$	29.0	20.9	21.2	21.9	7.1
ATLAS $pp \to H \to \gamma\gamma$ ($t\bar{t}$H hadronic) [82]	8 TeV	$-0.84^{+3.23}_{-1.25}$	0.1	0.1	0.2	0.4	99.1
ATLAS $pp \to H \to \gamma\gamma$ ($t\bar{t}$H leptonic) [82]	8 TeV	$2.42^{+3.21}_{-2.07}$	0.0	0.0	2.9	1.4	95.6
ATLAS $pp \to H \to \gamma\gamma$ (VBF loose) [82]	8 TeV	$1.33^{+0.92}_{-0.77}$	3.7	90.5	1.9	1.7	2.2
ATLAS $pp \to H \to \gamma\gamma$ (VBF tight) [82]	8 TeV	$0.68^{+0.67}_{-0.51}$	1.4	96.3	0.3	0.4	1.7
ATLAS $pp \to H \to \gamma\gamma$ (VH dijet) [82]	8 TeV	$0.23^{+1.67}_{-1.39}$	1.9	2.2	46.0	49.3	0.5
ATLAS $pp \to H \to \gamma\gamma$ (VH E_T^{miss}) [82]	8 TeV	$3.51^{+3.30}_{-2.42}$	0.2	1.1	22.0	47.6	29.2
ATLAS $pp \to H \to \gamma\gamma$ (VH 1ℓ) [82]	8 TeV	$0.41^{+1.43}_{-1.06}$	0.0	0.1	80.4	8.9	10.6
ATLAS $pp \to H \to \tau\tau$ (boosted, $\tau_{\text{had}}\tau_{\text{had}}$) [90]	7/8 TeV	$3.60^{+2.00}_{-1.60}$	6.9	21.1	38.1	33.9	0.0
ATLAS $pp \to H \to \tau\tau$ (VBF, $\tau_{\text{had}}\tau_{\text{had}}$) [90]	7/8 TeV	$1.40^{+0.90}_{-0.70}$	2.6	97.4	0.0	0.0	0.0
ATLAS $pp \to H \to \tau\tau$ (boosted, $\tau_{\text{lep}}\tau_{\text{had}}$) [90]	7/8 TeV	$0.90^{+1.00}_{-0.90}$	8.5	24.6	35.6	31.4	0.0
ATLAS $pp \to H \to \tau\tau$ (VBF, $\tau_{\text{lep}}\tau_{\text{had}}$) [90]	7/8 TeV	$1.00^{+0.60}_{-0.50}$	1.3	98.7	0.0	0.0	0.0
ATLAS $pp \to H \to \tau\tau$ (boosted, $\tau_{\text{lep}}\tau_{\text{lep}}$) [90]	7/8 TeV	$3.00^{+1.90}_{-1.70}$	9.8	47.1	26.5	16.7	0.0
ATLAS $pp \to H \to \tau\tau$ (VBF, $\tau_{\text{lep}}\tau_{\text{lep}}$) [90]	7/8 TeV	$1.80^{+1.10}_{-0.90}$	1.1	98.9	0.0	0.0	0.0
ATLAS $pp \to H \to WW \to \ell\nu\ell\nu$ (ggH enhanced) [86, 87]	7/8 TeV	$1.01^{+0.27}_{-0.25}$	55.6	11.1	11.1	11.1	11.1
ATLAS $pp \to H \to WW \to \ell\nu\ell\nu$ (VBF enhanced) [86, 87]	7/8 TeV	$1.27^{+0.53}_{-0.45}$	2.0	98.0	0.0	0.0	0.0
ATLAS $pp \to H \to ZZ \to 4\ell$ (ggH-like) [84]	7/8 TeV	$1.66^{+0.51}_{-0.44}$	22.7	18.2	18.2	18.2	22.7
ATLAS $pp \to H \to ZZ \to 4\ell$ (VBF/VH-like) [84]	7/8 TeV	$0.26^{+1.64}_{-0.94}$	2.2	32.6	32.6	32.6	0.0
ATLAS $pp \to t\bar{t}H \to$ leptons ($1\ell 2\tau_{\text{had}}$) [97]	8 TeV	$-9.60^{+9.60}_{-9.70}$	0.0	0.0	0.0	0.0	100.0
ATLAS $pp \to t\bar{t}H \to$ leptons ($2\ell 0\tau_{\text{had}}$) [97]	8 TeV	$2.80^{+2.10}_{-1.90}$	0.0	0.0	0.0	0.0	100.0
ATLAS $pp \to ttH \to$ leptons ($2\ell 1\tau_{\text{had}}$) [97]	8 TeV	$-0.90^{+3.10}_{-2.00}$	0.0	0.0	0.0	0.0	100.0
ATLAS $pp \to t\bar{t}H \to$ leptons (3ℓ) [97]	8 TeV	$2.80^{+2.20}_{-1.80}$	0.0	0.0	0.0	0.0	100.0
ATLAS $pp \to t\bar{t}H \to$ leptons (4ℓ) [97]	8 TeV	$1.80^{+6.90}_{-6.90}$	0.0	0.0	0.0	0.0	100.0
ATLAS $pp \to t\bar{t}H \to t\bar{t}b\bar{b}$ [95]	8 TeV	$1.50^{+1.10}_{-1.10}$	0.0	0.0	0.0	0.0	100.0
ATLAS $pp \to VH \to Vb\bar{b}$ (0ℓ) [92]	7/8 TeV	$-0.35^{+0.55}_{-0.52}$	0.0	0.0	13.2	86.8	0.0
ATLAS $pp \to VH \to Vb\bar{b}$ (1ℓ) [92]	7/8 TeV	$1.17^{+0.66}_{-0.60}$	0.0	0.0	94.4	5.6	0.0
ATLAS $pp \to VH \to Vb\bar{b}$ (2ℓ) [92]	7/8 TeV	$0.94^{+0.88}_{-0.79}$	0.0	0.0	0.0	100.0	0.0
ATLAS $pp \to VH \to VWW$ (2ℓ) [87]	7/8 TeV	$3.70^{+1.90}_{-1.80}$	0.0	0.0	74.3	25.7	0.0
ATLAS $pp \to VH \to VWW$ (3ℓ) [87]	7/8 TeV	$0.72^{+1.30}_{-1.10}$	0.0	0.0	78.8	21.2	0.0
ATLAS $pp \to VH \to VWW$ (4ℓ) [87]	7/8 TeV	$4.90^{+4.60}_{-3.10}$	0.0	0.0	0.0	100.0	0.0

[CE, Kogler, Schulz, Spannowsky ` 15]

Higgs data: towards a differential Higgs fit

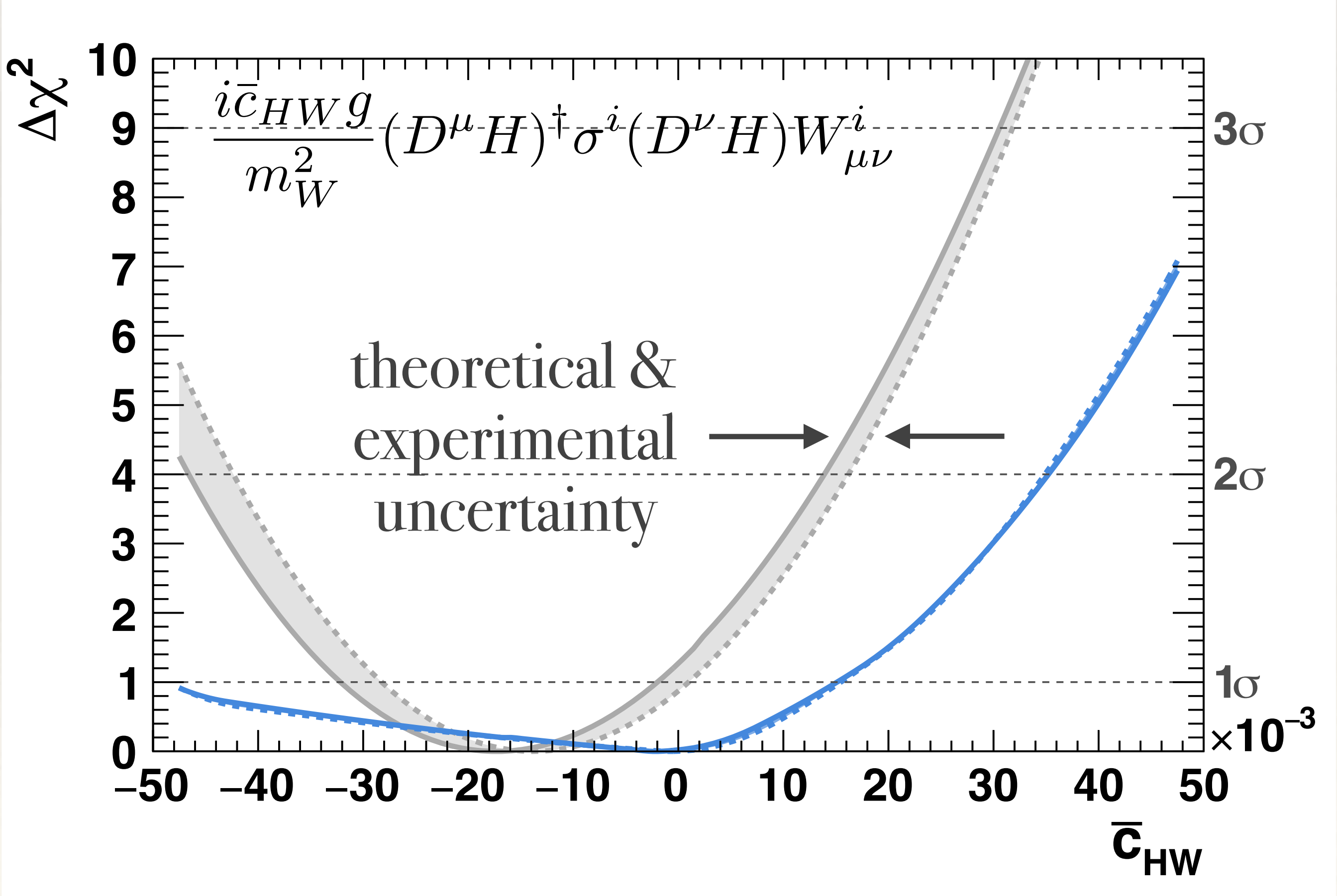
- current status (plethora of run 1 analyses included, narrow width)



- good agreement with fits by ATLAS and other theory groups

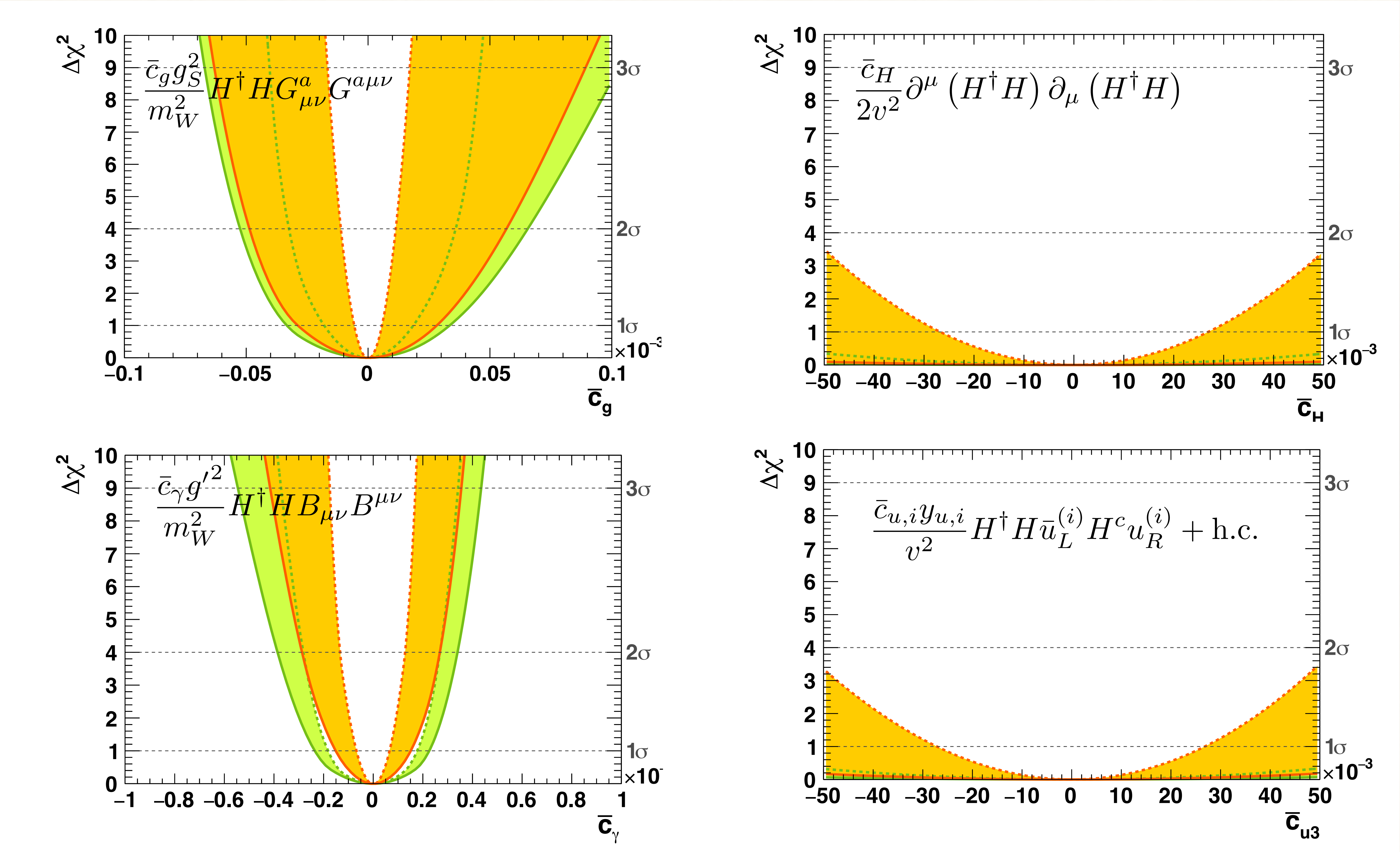
- not terribly sensitive at this stage, coupling deviations of order 10% allowed

- systematic uncertainties not too limiting anymore more on that later



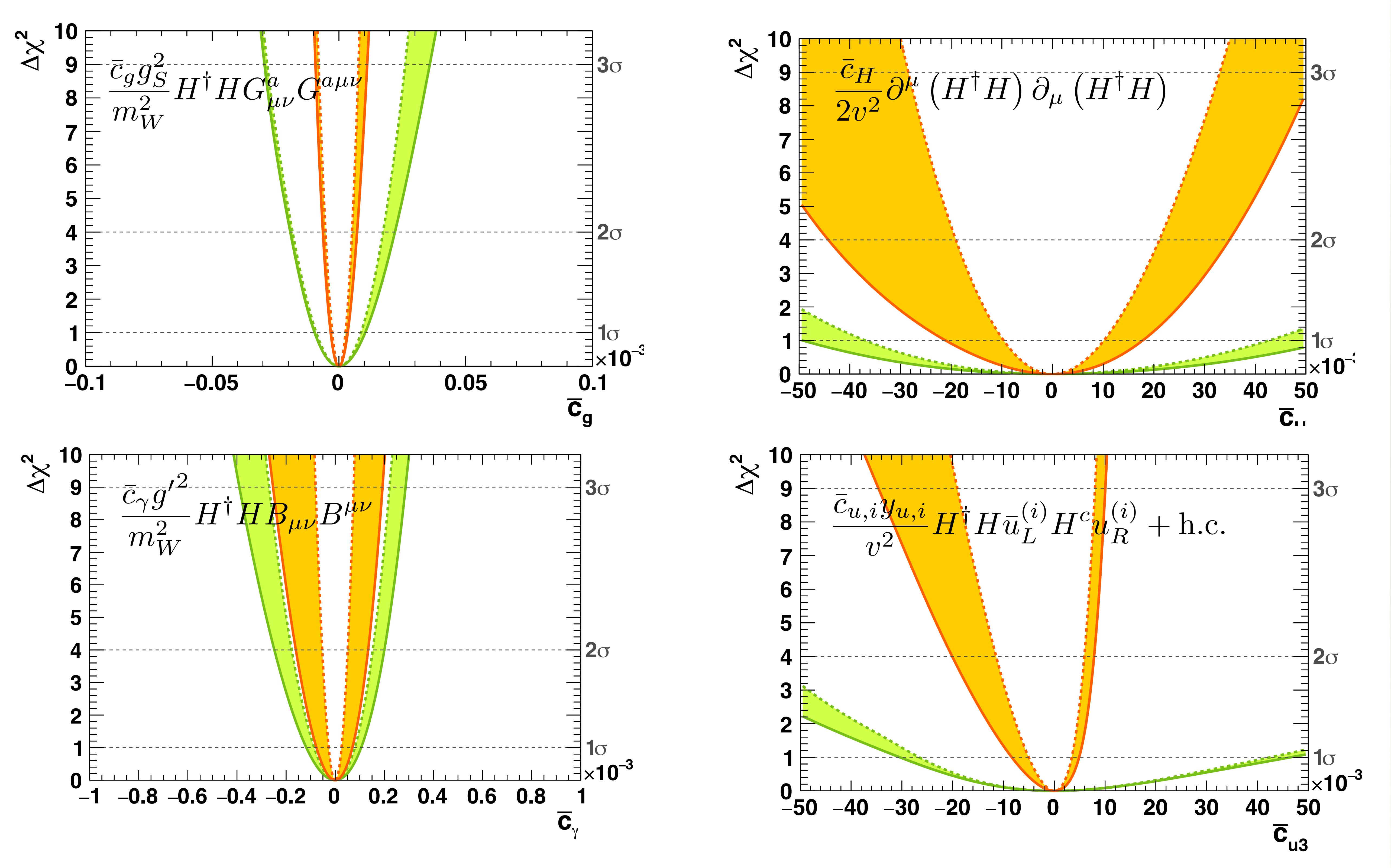
Higgs measurements: future

- extrapolation to 300/fb, 3/ab based on signal strength measurements



Higgs measurements: future

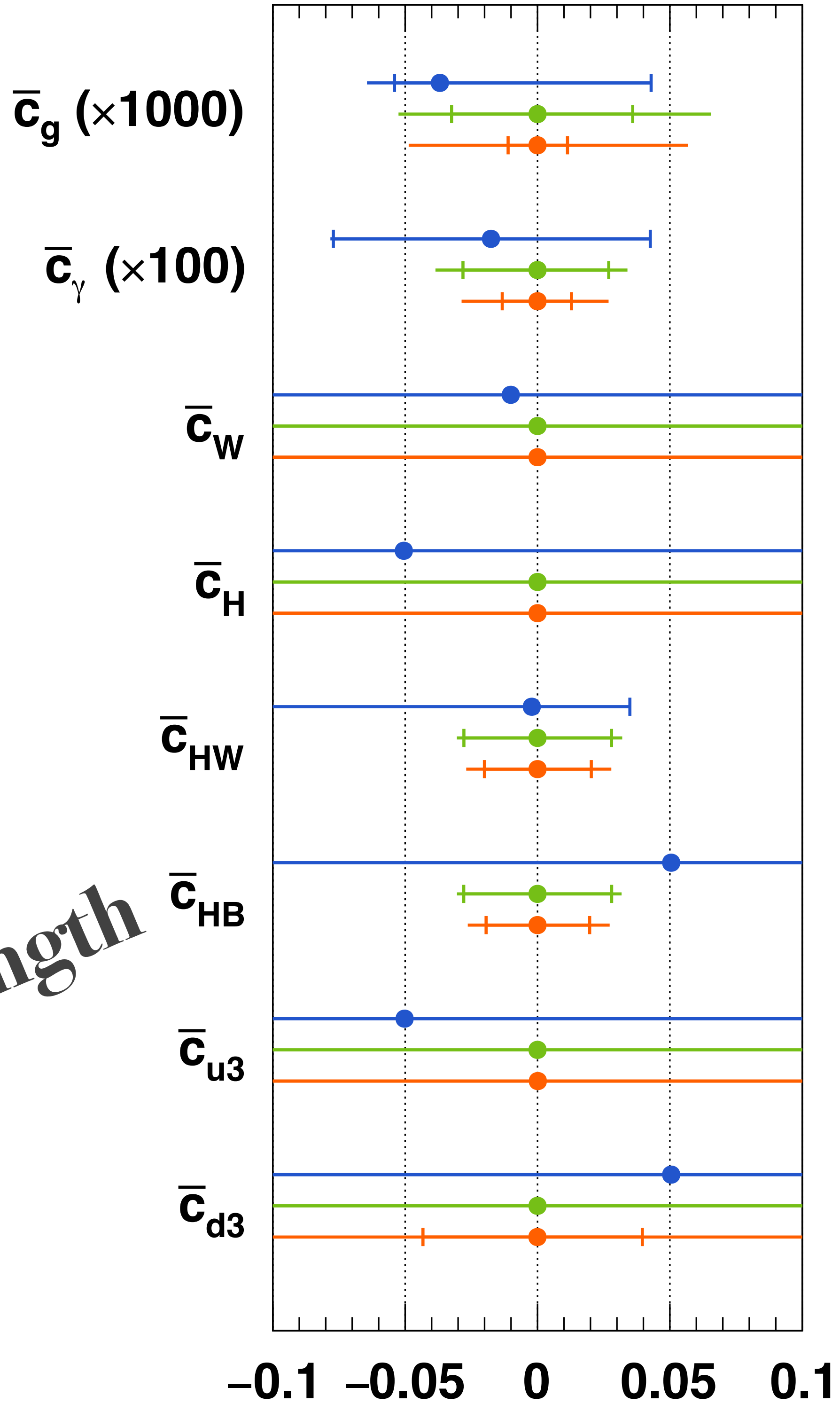
- …switch on differential distributions: unfolded Higgs p_T



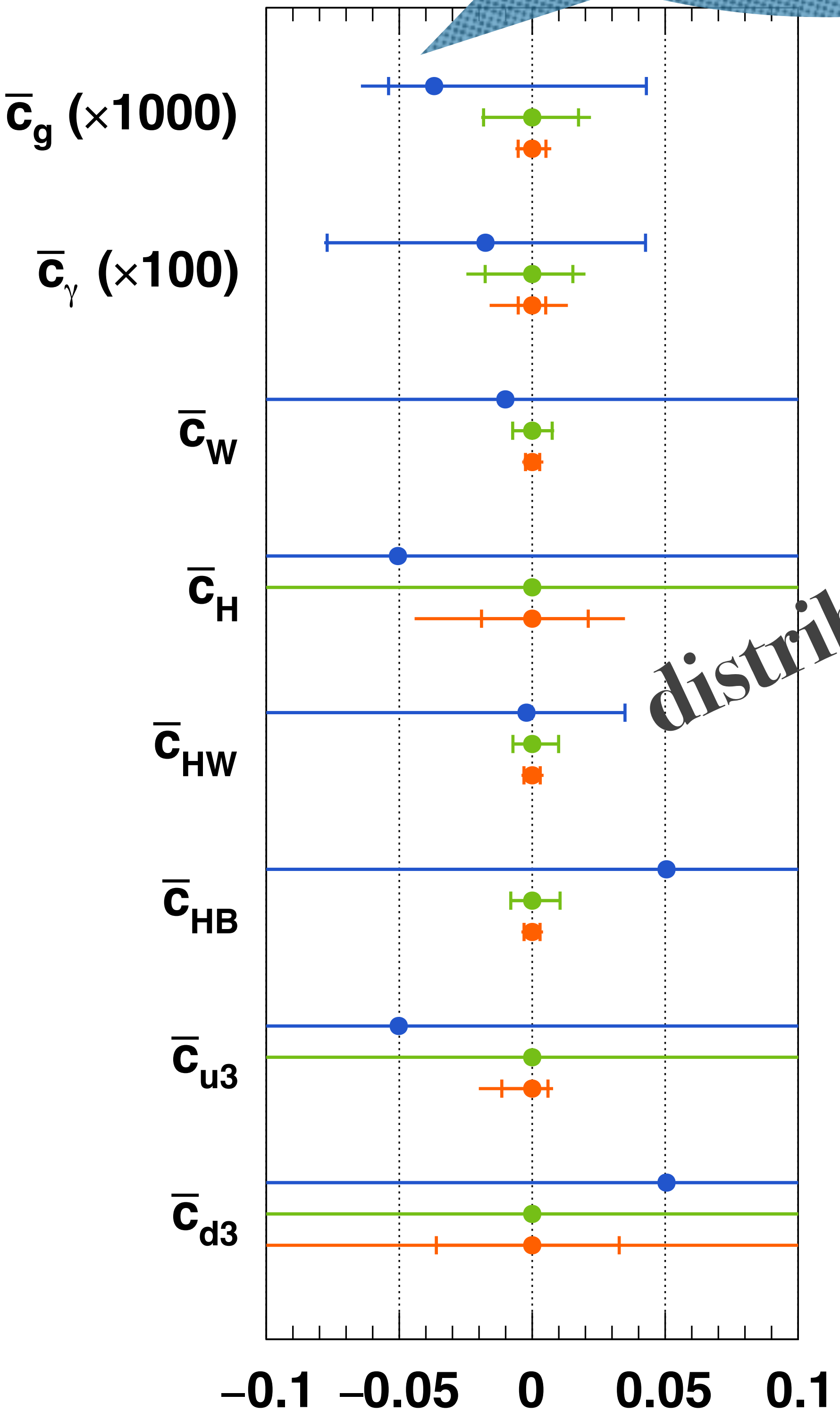
Higgs measurements future

- distributions over-constrain the system!

depends on improved systematics!



signal strength



distribution $p_{T,H}$

[Buckley , CE, Ferrando, Miller, Moore, Russell, White ` 15]

Top EFT status

- operators

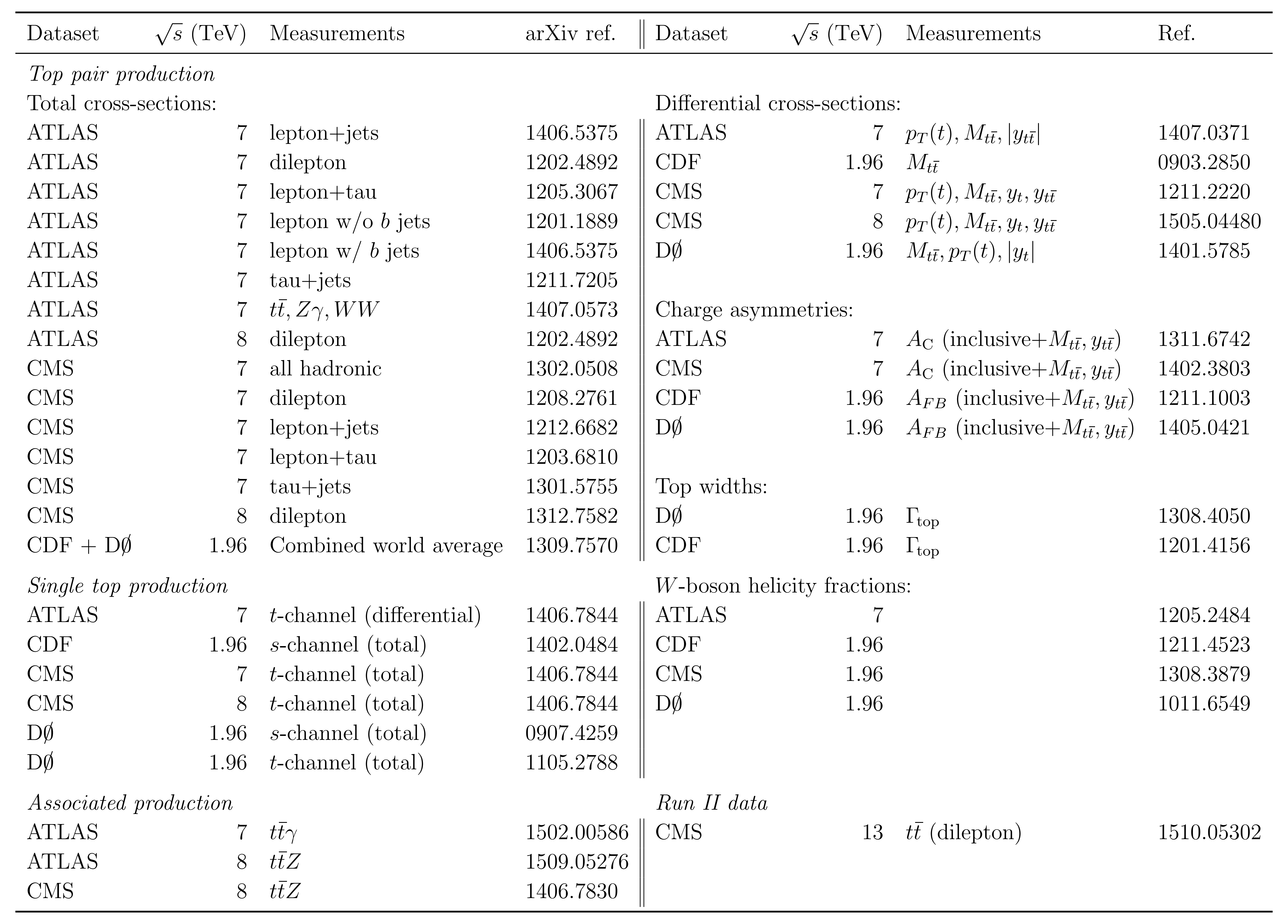
$$\begin{aligned} O_{qq}^{(1)} &= (\bar q \gamma_\mu q)(\bar q \gamma^\mu q) \\ O_{qq}^{(3)} &= (\bar q \gamma_\mu \tau^I q)(\bar q \gamma^\mu \tau^I q) \\ O_{uu} &= (\bar u \gamma_\mu u)(\bar u \gamma^\mu u) \\ O_{qu}^{(8)} &= (\bar q \gamma_\mu T^A q)(\bar u \gamma^\mu T^A u) \\ O_{qd}^{(8)} &= (\bar q \gamma_\mu T^A q)(\bar d \gamma^\mu T^A d) \\ O_{ud}^{(8)} &= (\bar u \gamma_\mu T^A u)(\bar d \gamma^\mu T^A d)\,. \end{aligned}$$

$$\begin{aligned} O_{uW} &= (\bar q \sigma^{\mu\nu} \tau^I u)\tilde\phi W_{\mu\nu}^I \\ O_{uG} &= (\bar q \sigma^{\mu\nu} T^A u)\tilde\phi G_{\mu\nu}^A \\ O_G &= f_{ABC} G_\mu^{A\nu} G_\nu^{B\lambda} G_\lambda^{C\mu} \\ O_{\tilde G} &= f_{ABC} \tilde G_\mu^{A\nu} G_\nu^{B\lambda} G_\lambda^{C\mu} \\ O_{\phi G} &= (\phi^\dagger \phi) G_{\mu\nu}^A G^{A\mu\nu} \end{aligned}$$

$$\begin{aligned} O_{\phi q}^{(3)} &= i(\phi^\dagger \overleftrightarrow{D}_\mu^I \phi)(\bar q \gamma^\mu \tau^I q) \\ O_{\phi q}^{(1)} &= i(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar q \gamma^\mu q) \\ O_{uB} &= (\bar q \sigma^{\mu\nu} u)\tilde\phi B_{\mu\nu} \\ O_{\phi u} &= (\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar u \gamma^\mu u) \\ O_{\phi \tilde G} &= (\phi^\dagger \phi) \tilde G_{\mu\nu}^A G^{A\mu\nu} \end{aligned}$$

- consider CP even operators
- neglect operators with chiral suppression for the interference with SM
- top pair production, single top production, top pair + Z production decay observables
- include differential distributions where reported

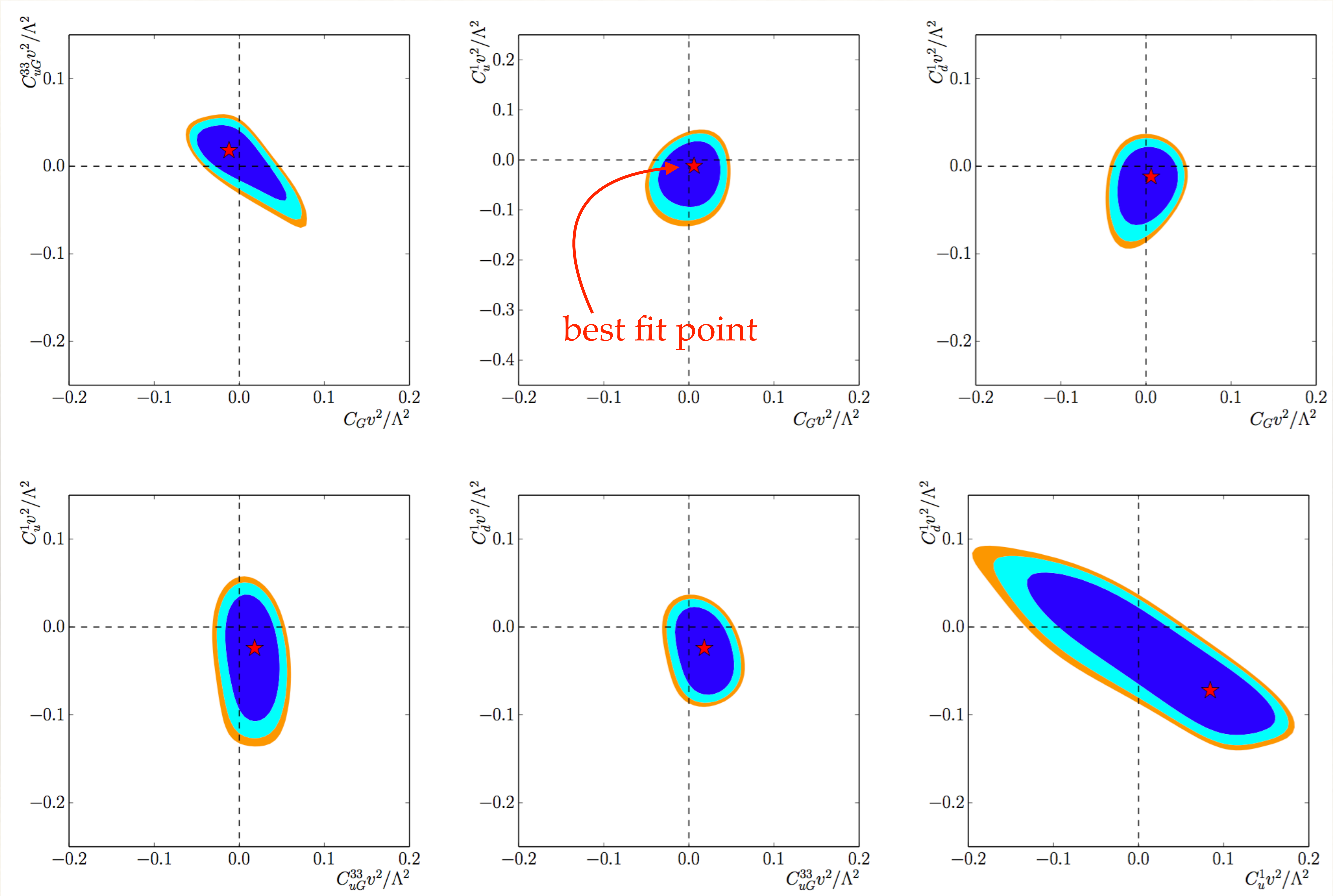
Top EFT status



Dataset	$\sqrt{s}$ (TeV)	Measurements	arXiv ref.
Top pair production			
Total cross-sections:			
ATLAS	7	lepton+jets	1406.5375
ATLAS	7	dilepton	1202.4892
ATLAS	7	lepton+tau	1205.3067
ATLAS	7	lepton w/o b jets	1201.1889
ATLAS	7	lepton w/ b jets	1406.5375
ATLAS	7	tau+jets	1211.7205
ATLAS	7	$t\bar{t}, Z\gamma, WW$	1407.0573
ATLAS	8	dilepton	1202.4892
CMS	7	all hadronic	1302.0508
CMS	7	dilepton	1208.2761
CMS	7	lepton+jets	1212.6682
CMS	7	lepton+tau	1203.6810
CMS	7	tau+jets	1301.5755
CMS	8	dilepton	1312.7582
CDF + DØ	1.96	Combined world average	1309.7570
Single top production			
ATLAS	7	t-channel (differential)	1406.7844
CDF	1.96	s-channel (total)	1402.0484
CMS	7	t-channel (total)	1406.7844
CMS	8	t-channel (total)	1406.7844
DØ	1.96	s-channel (total)	0907.4259
DØ	1.96	t-channel (total)	1105.2788
Associated production			
ATLAS	7	$t\bar{t}\gamma$	1502.00586
ATLAS	8	$t\bar{t}Z$	1509.05276
CMS	8	$t\bar{t}Z$	1406.7830

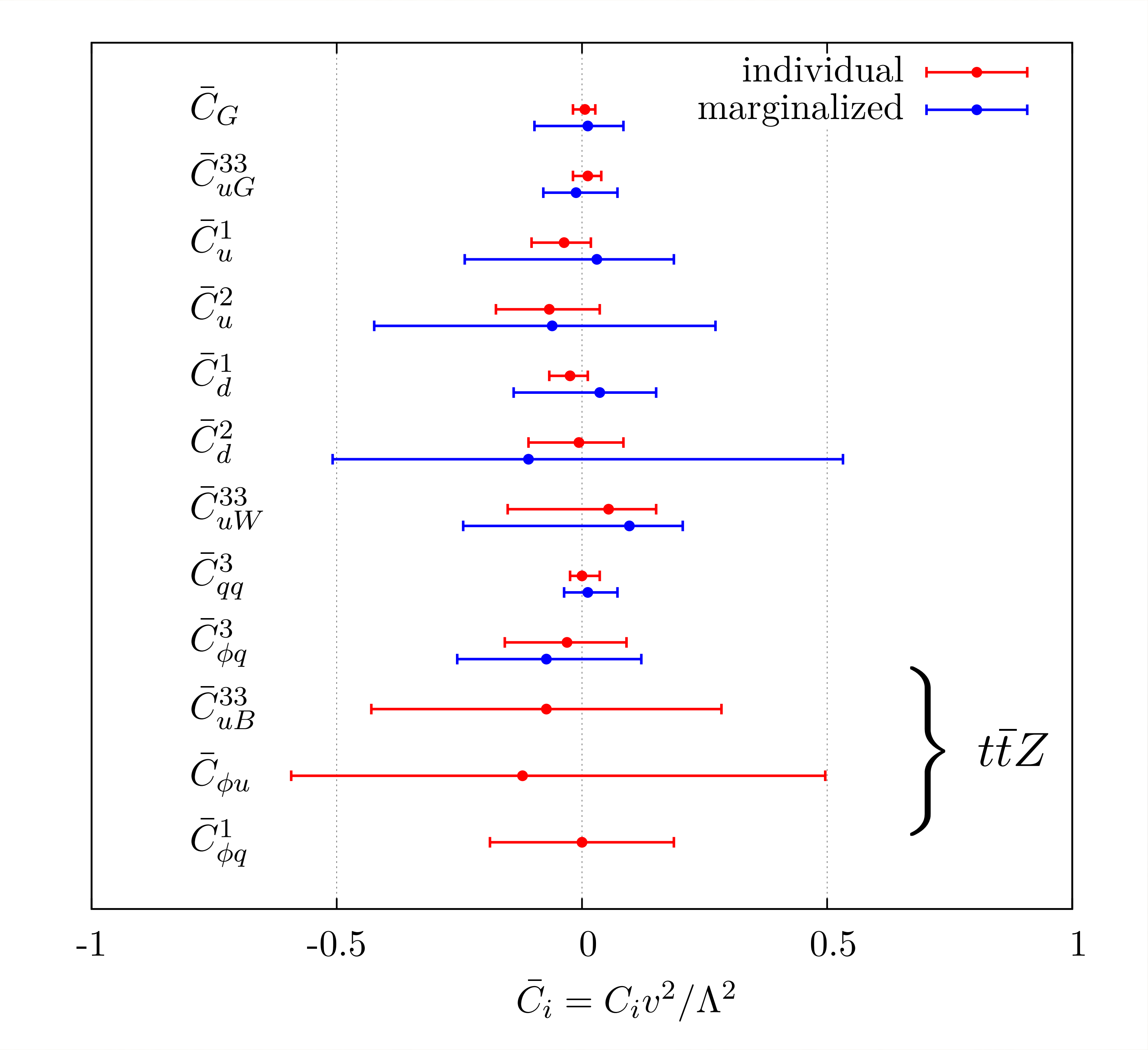
Dataset	$\sqrt{s}$ (TeV)	Measurements	Ref.
Differential cross-sections:			
ATLAS	7	$p_T(t), M_{t\bar{t}}, \|y_{t\bar{t}}\|$	1407.0371
CDF	1.96	$M_{t\bar{t}}$	0903.2850
CMS	7	$p_T(t), M_{t\bar{t}}, y_t, y_{t\bar{t}}$	1211.2220
CMS	8	$p_T(t), M_{t\bar{t}}, y_t, y_{t\bar{t}}$	1505.04480
DØ	1.96	$M_{t\bar{t}}, p_T(t), \|y_t\|$	1401.5785
Charge asymmetries:			
ATLAS	7	A_C (inclusive+$M_{t\bar{t}}, y_{t\bar{t}}$)	1311.6742
CMS	7	A_C (inclusive+$M_{t\bar{t}}, y_{t\bar{t}}$)	1402.3803
CDF	1.96	A_{FB} (inclusive+$M_{t\bar{t}}, y_{t\bar{t}}$)	1211.1003
DØ	1.96	A_{FB} (inclusive+$M_{t\bar{t}}, y_{t\bar{t}}$)	1405.0421
Top widths:			
DØ	1.96	Γ_{top}	1308.4050
CDF	1.96	Γ_{top}	1201.4156
W-boson helicity fractions:			
ATLAS	7		1205.2484
CDF	1.96		1211.4523
CMS	1.96		1308.3879
DØ	1.96		1011.6549
Run II data			
CMS	13	$t\bar{t}$ (dilepton)	1510.05302

Top quark pair production


best fit point

[Buckley , CE, Ferrando, Miller, Moore, Russell, White ` 15]

Summary of the top sector



axigluons

$$M \gtrsim 1.6 \text{ TeV}$$

W’

$$M \gtrsim 1.5 \text{ TeV}$$

top EFT still has a long way to go