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Effective Theory at the LHC

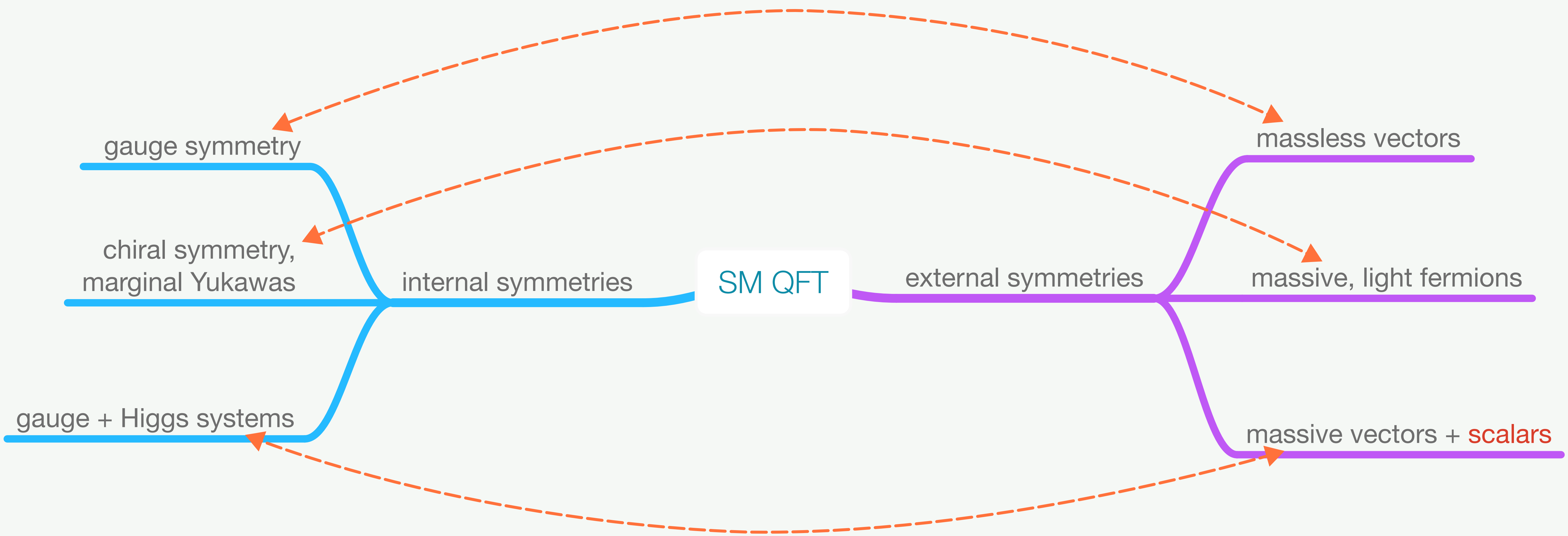
Genova, 04/04/2018

Outline

- EFT-inspired Higgs boson coupling measurements
- the role of high momentum transfers vs uncertainties
- adding degrees of freedom:

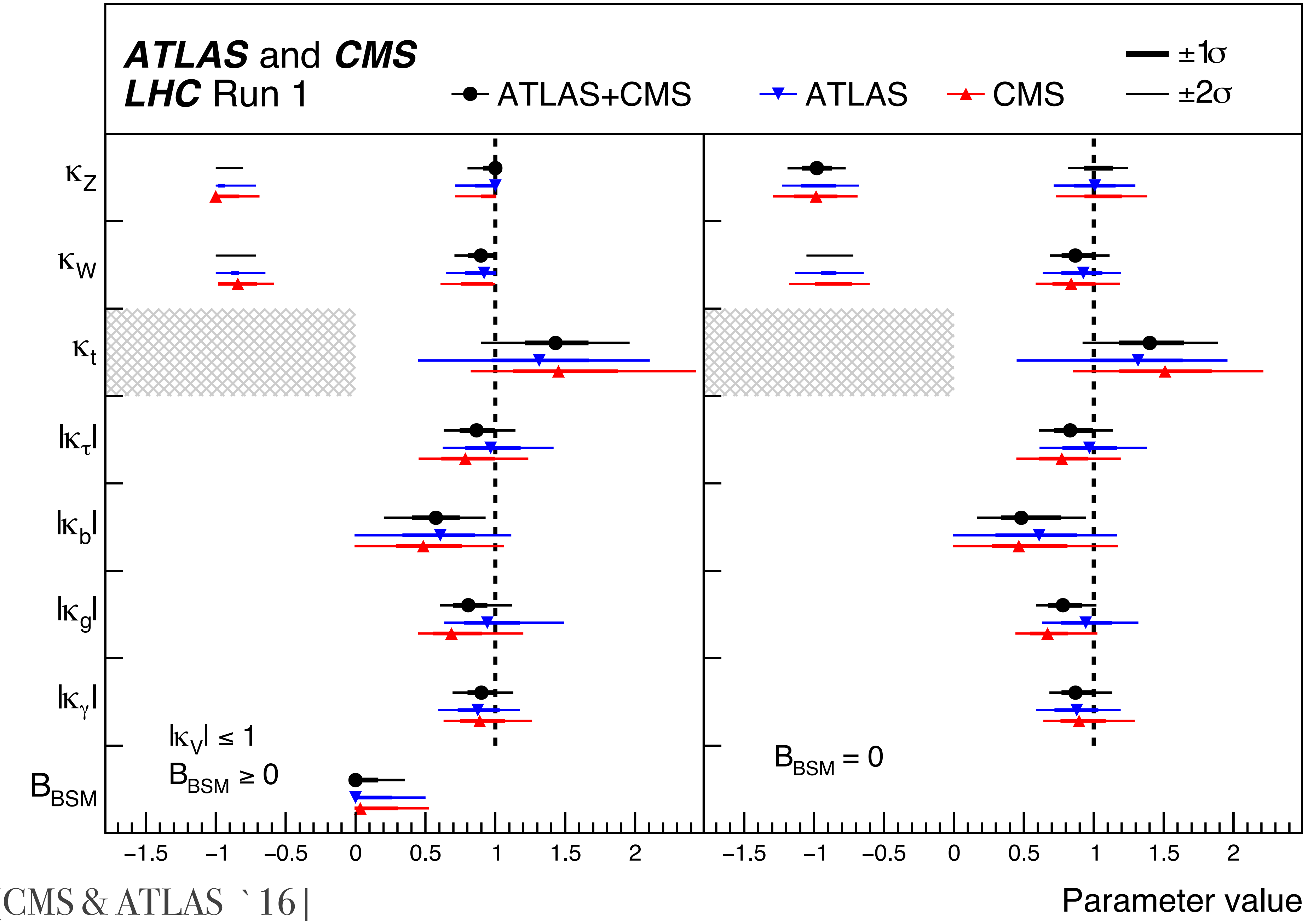
  unresolved/hidden Higgs decays and Composite Higgs physics

The Standard Model: taking stock



“What’s next at the LHC ?”

Status of LHC 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

no evidence for exotics

coupling/scale separated BSM physics

Effective Field Theory

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

[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

$$
\begin{aligned}
\mathcal{L}_{\rm SILH} =& \frac{\bar c_H}{2v^2}\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right) + \frac{\bar c_T}{2v^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) - \frac{\bar c_6 \lambda}{v^2}\left(H^\dagger H\right)^3 \\
&+ \left(\frac{\bar c_{u,i} y_{u,i}}{v^2} H^\dagger H \bar u_L^{(i)} H^c u_R^{(i)} + \text{h.c.}\right) + \left(\frac{\bar c_{d,i} y_{d,i}}{v^2} H^\dagger H \bar d_L^{(i)} H d_R^{(i)} + \text{h.c.}\right) \\
&+ \frac{i\bar c_W g}{2m_W^2}\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)\left(D^\nu W_{\mu\nu}\right)^i + \frac{i\bar c_B g'}{2m_W^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(\partial^\nu B_{\mu\nu}\right) \\
&+ \frac{i\bar c_{HW} g}{m_W^2}(D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu} + \frac{i\bar c_{HB} g'}{m_W^2}(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu} \\
&+ \frac{\bar c_\gamma {g'}^2}{m_W^2} H^\dagger H B_{\mu\nu} B^{\mu\nu} + \frac{\bar c_g g_S^2}{m_W^2} H^\dagger H G^a_{\mu\nu} G^{a\mu\nu} \,.
\end{aligned}
$$

+ [more - *not considered here*]

[Giudice, Grojean, Pomarol, Rattazzi `07]

Higgs decays

Higgs production

<u>consistent</u> differential distributions

[Ellis, Sanz, You `14, 17] [Falkowski et al. `15] [Butter et al. `16] ....

SILH Higgs phenomenology

$$\mathcal{L}_{\rm SILH} = \frac{\bar c_H}{2v^2}\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right) + \frac{\bar c_T}{2v^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) - \frac{\bar c_6\lambda}{v^2}\left(H^\dagger H\right)^3$$
$$+\left(\frac{\bar c_{u,i} y_{u,i}}{v^2} H^\dagger H \bar u_L^{(i)} H^c u_R^{(i)} + \text{h.c.}\right) + \left(\frac{\bar c_{d,i} y_{d,i}}{v^2} H^\dagger H \bar d_L^{(i)} H d_R^{(i)} + \text{h.c.}\right)$$
$$+\frac{i\bar c_W g}{2m_W^2}\left(H^\dagger\sigma^i \overleftrightarrow{D^\mu} H\right)\left(D^\nu W_{\mu\nu}\right)^i + \frac{i\bar c_B g'}{2m_W^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(\partial^\nu B_{\mu\nu}\right)$$
$$+\frac{i\bar c_{HW} g}{m_W^2}(D^\mu H)^\dagger\sigma^i(D^\nu H)W^i_{\mu\nu} + \frac{i\bar c_{HB} g'}{m_W^2}(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu}$$
$$+\frac{\bar c_\gamma {g'}^2}{m_W^2} H^\dagger H B_{\mu\nu}B^{\mu\nu} + \frac{\bar c_g g_S^2}{m_W^2} H^\dagger H G^a_{\mu\nu}G^{a\mu\nu}\,.$$

[Giudice, Grojean, Pomarol, Rattazzi `07]

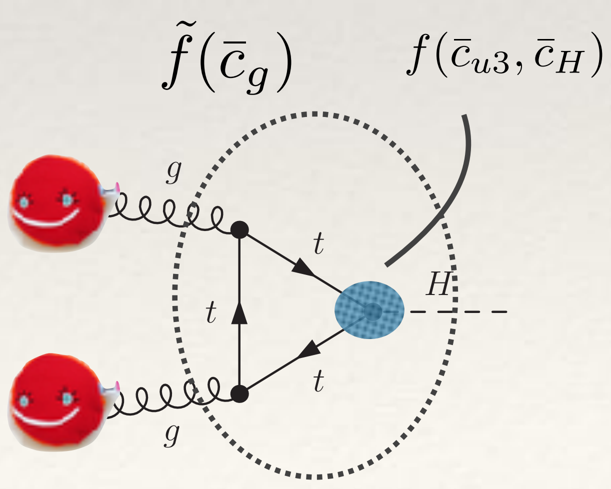
S,T=0 : $\bar c_T = 0, \quad \bar c_W = -\bar c_B$

more involved for full operator set [Berthier, Bjorn, Trott `16]

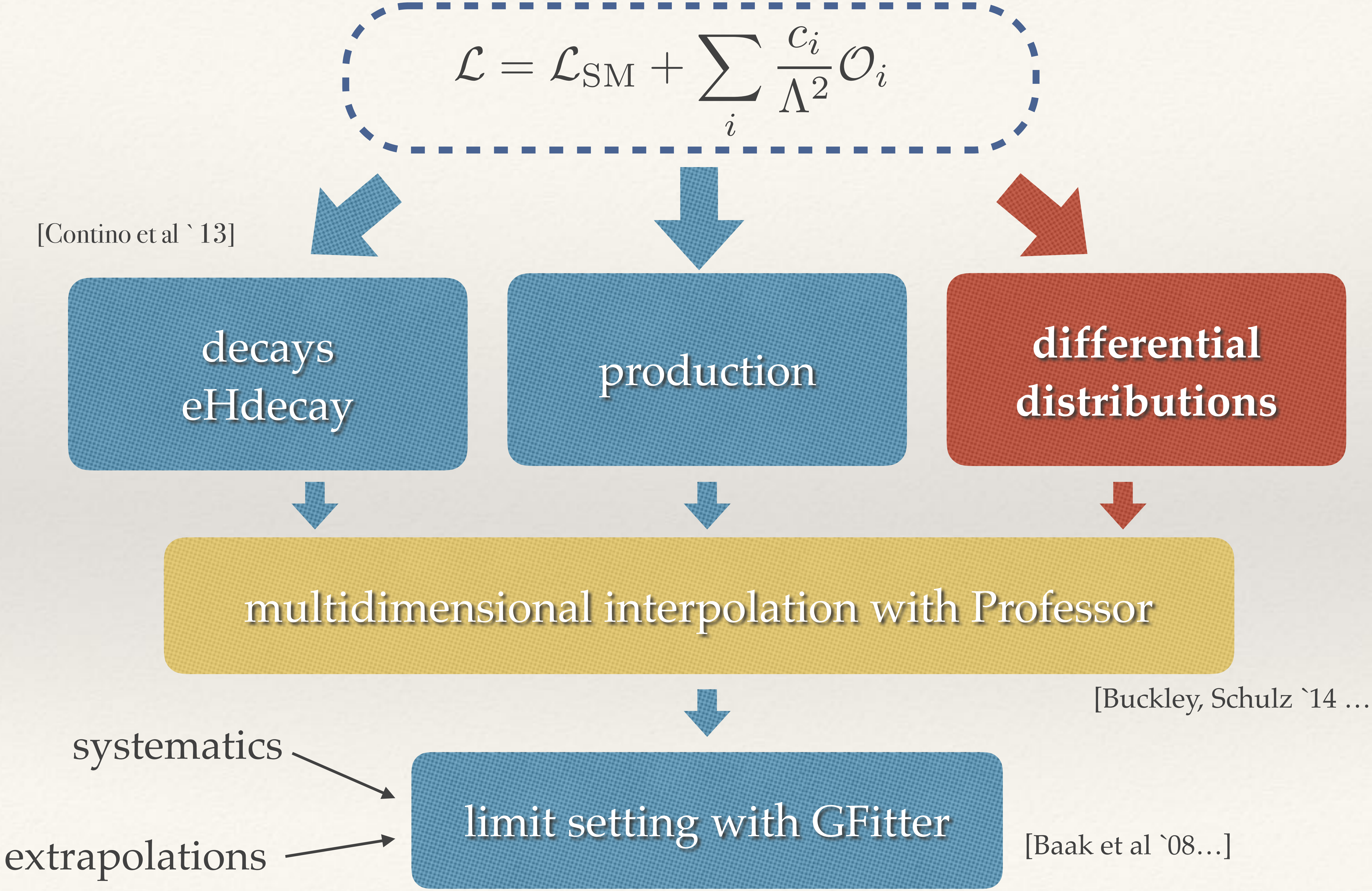
branching ratios
total width

[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)	$\bar c_W, \bar c_B, \bar c_{HW}, \bar c_{HB}, \bar c_\gamma, \bar c_H$



our fitting procedure in a nutshell



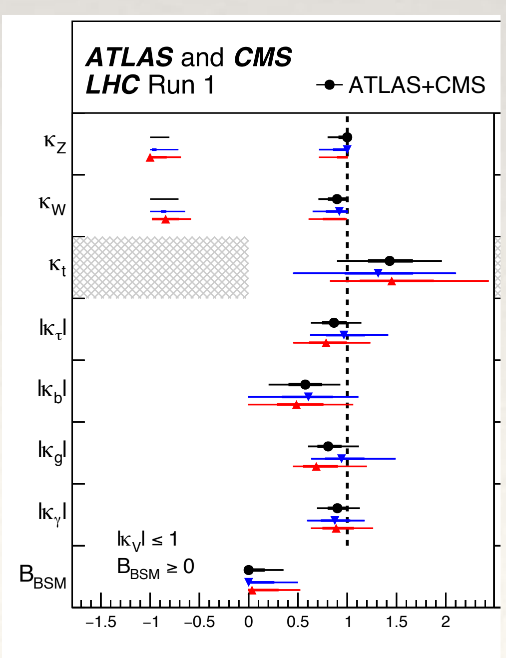
Fingerprinting the lack of new physics

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

decays
eHdecay

production

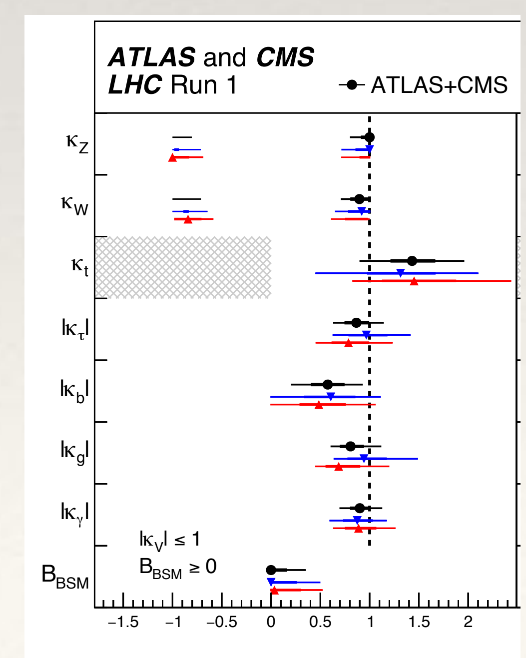
consistent
differential
distributions



low stats

[HXSWG YR 3]

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



A word of caution

consistent differential distributions

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

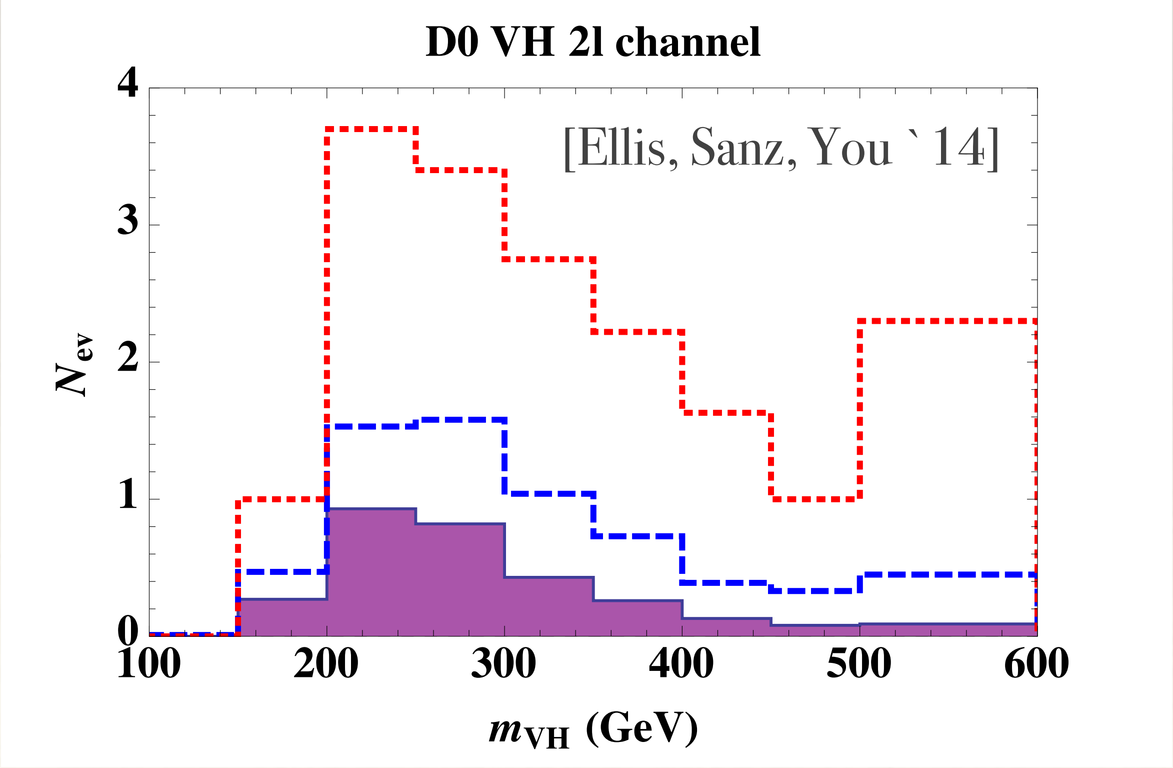
$$d\sigma = d\sigma^{\rm SM} + d\sigma^{\{O_i\}}/\Lambda^2$$

$$d\sigma^{\{O_i\}} \sim 2\,{\rm Re}\{\mathcal{M}_{\rm SM}\mathcal{M}^*_{d=6}\}$$

not necessarily positive definite
(cf. fixed order N^nLO)

conservative probe of validity of d=6 extension

☛ linearisation in every bin ⊕ positive definite integrated weights = **technical range of validity**



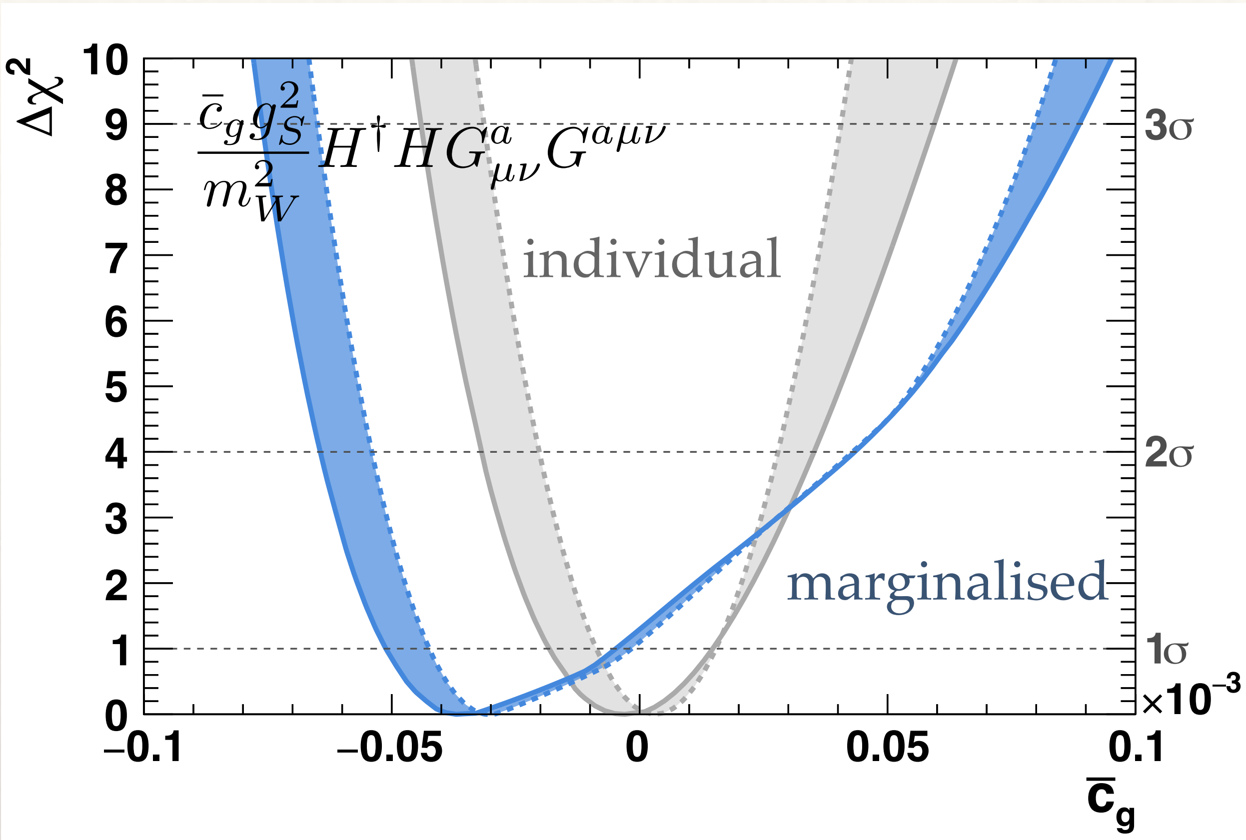
Higgs data: 7/8 TeV

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						

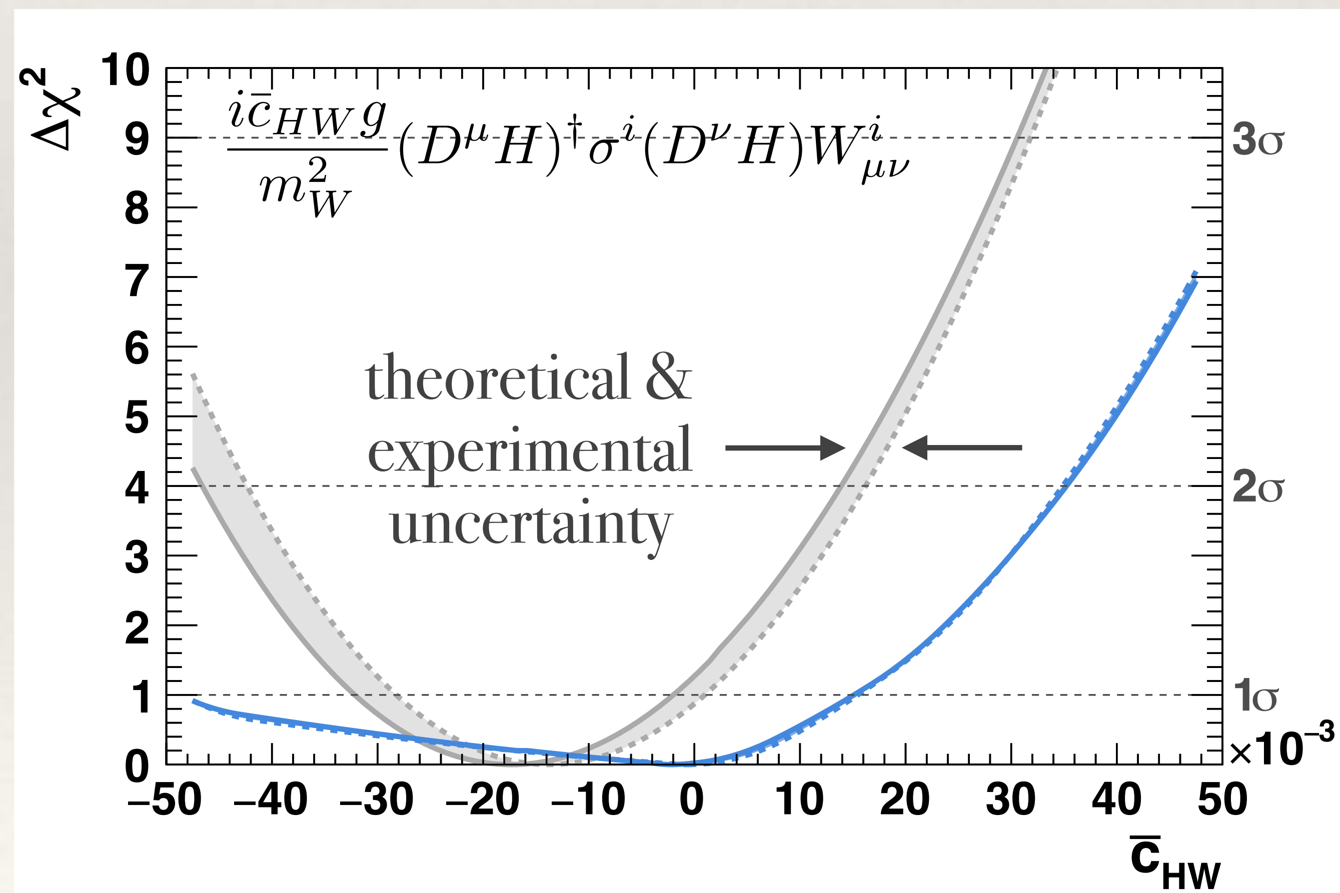
Search channel	energy $\sqrt{s}$	μ	SM signal composition [in %] ggH	VBF	WH	ZH	$t\bar{t}H$
ATLAS $pp \to H \to \gamma\gamma$ (central high p_T) [82]	8 TeV	$1.62^{+1.00}_{-0.83}$	7.1	25.4	20.1	21.0	26.4
ATLAS $pp \to H \to \gamma\gamma$ (central low p_T) [82]	8 TeV	$0.62^{+0.42}_{-0.40}$	31.8	22.2	18.5	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, $\tau_{had}\tau_{had}$) [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, $\tau_{had}\tau_{had}$) [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, $\tau_{lep}\tau_{had}$) [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, $\tau_{lep}\tau_{had}$) [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, $\tau_{lep}\tau_{lep}$) [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, $\tau_{lep}\tau_{lep}$) [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 ($1\ell 2\tau_{had}$) [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 ($2\ell 0\tau_{had}$) [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 ($2\ell 1\tau_{had}$) [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

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

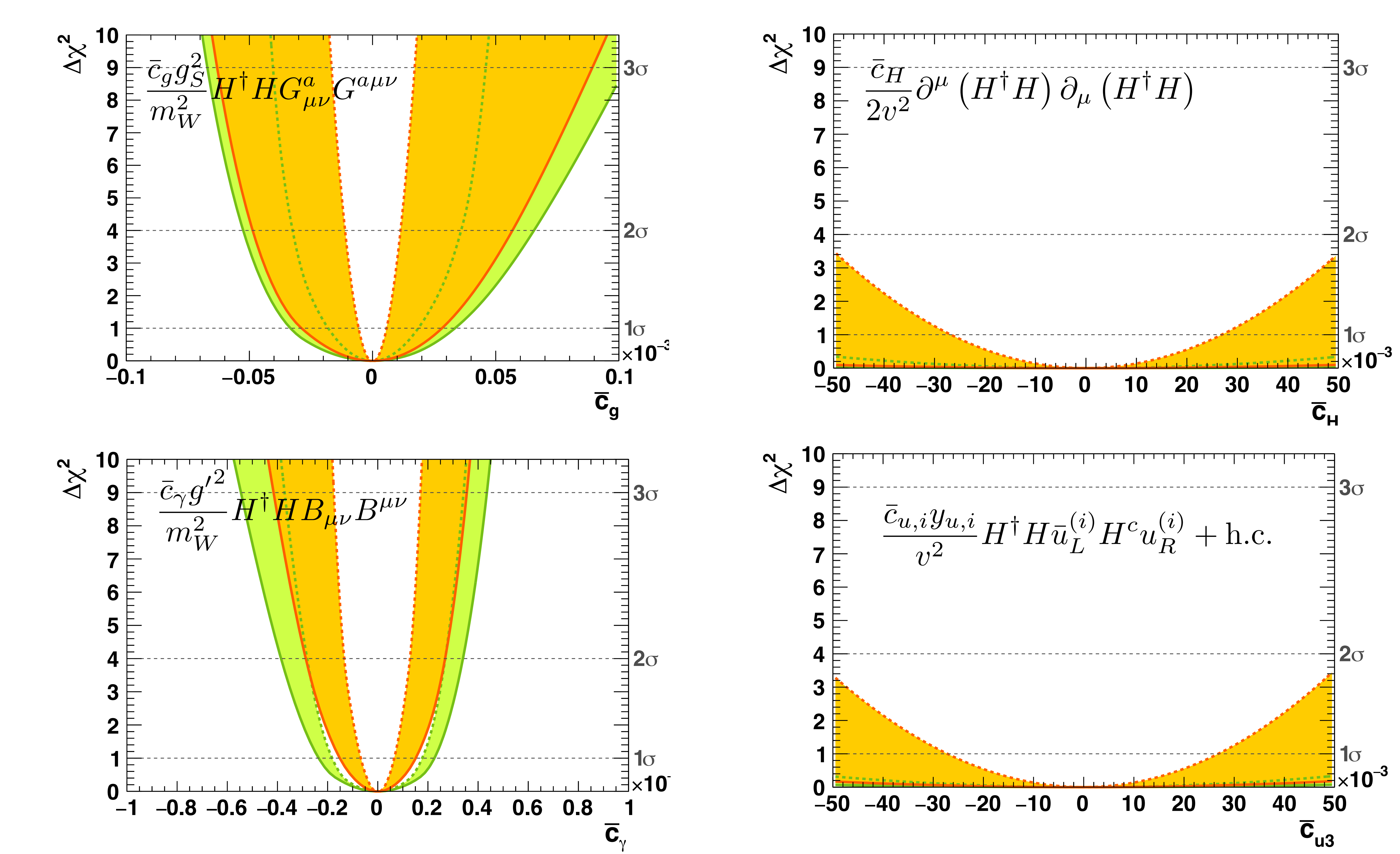


- not terribly sensitive at this stage, coupling deviations of order 10% allowed

- systematic uncertainties not too limiting anymore more on that later

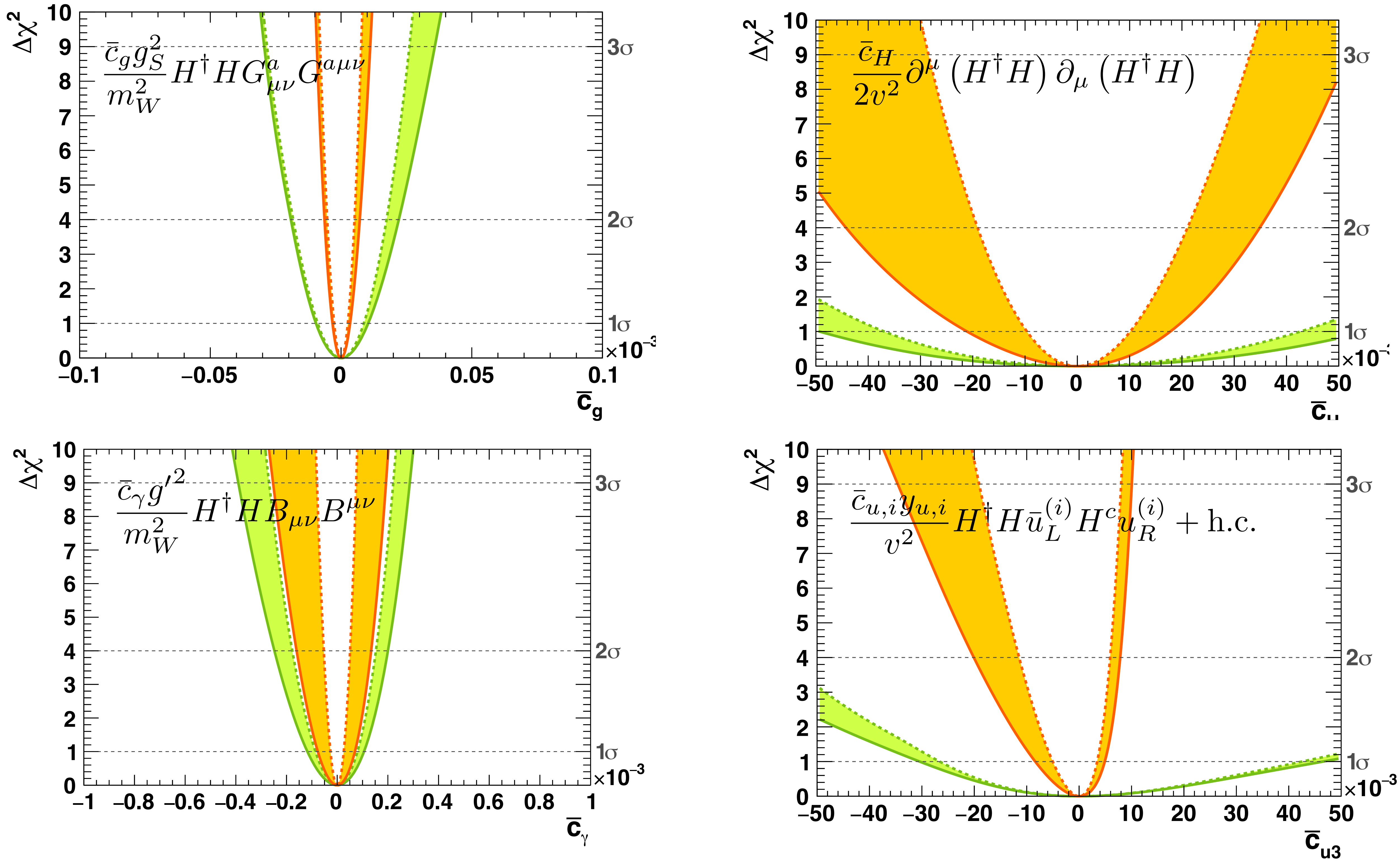
Higgs measurements: future

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



Higgs measurements: future

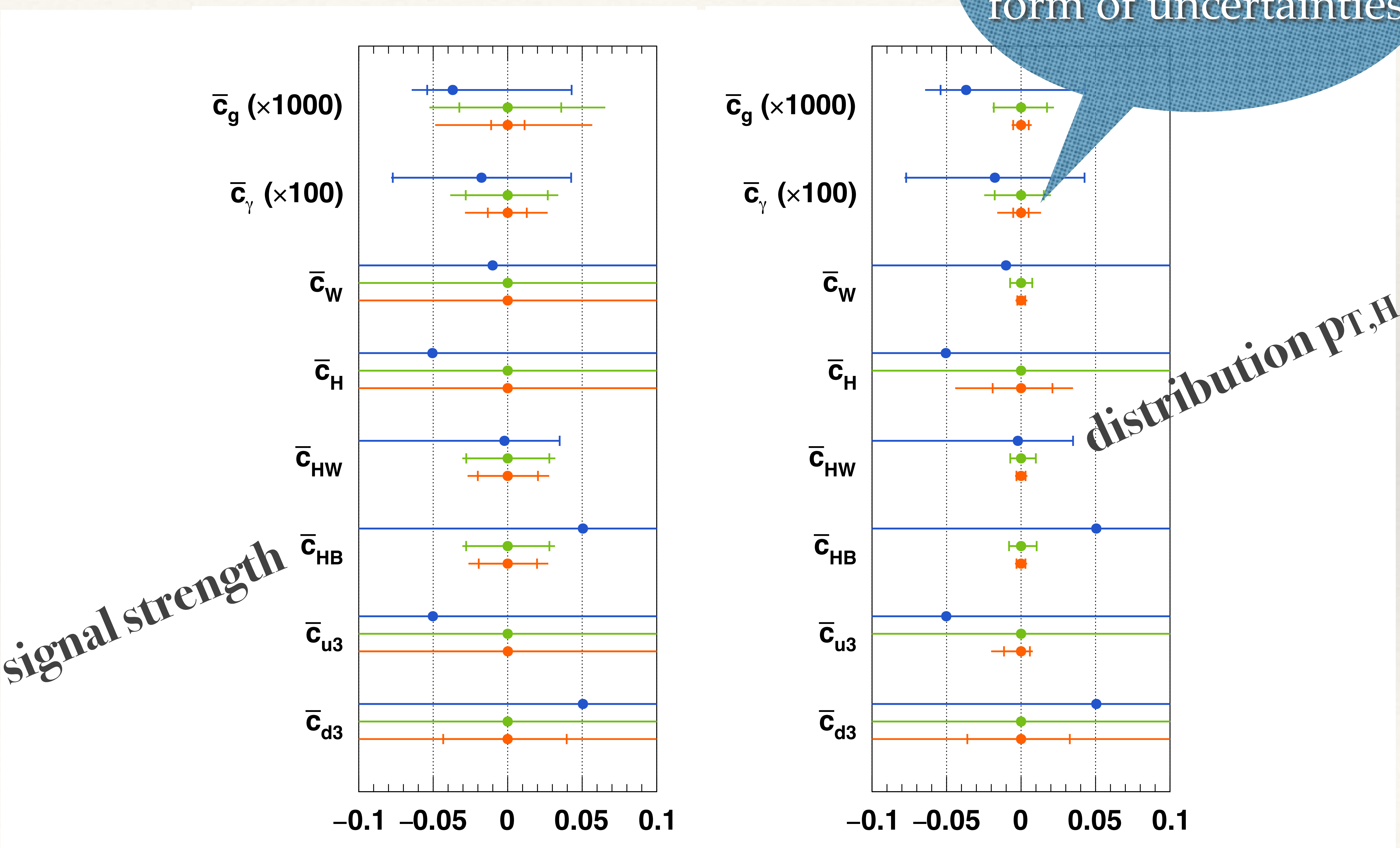
- …switch on differential distributions (*flat uncertainties*)



Higgs measurements: future

- distributions overconstrain the BSM couplings!

depends on improved functional form of uncertainties



Role of uncertainties

- so far theoretical uncertainties flat in Higgs transverse momentum

transparent but not realistic

importance of high p_T phase space region in light of bigger uncertainty?

Role of uncertainties

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transparent but not realistic

importance of high p_T phase space region in light of bigger uncertainty?

- theoretical uncertainties parametrised via

$$\delta(p_\mathrm{T}^H) = \delta_0[a + b f(p_\mathrm{T}^H)]$$

inclusive production uncertainty

p_T - dependent uncertainty

Role of uncertainties

- theoretical uncertainties parametrised via

$$\delta(p_{\mathrm{T}}^{H}) = \delta_0[a + b f(p_{\mathrm{T}}^{H})]$$

inclusive production uncertainty

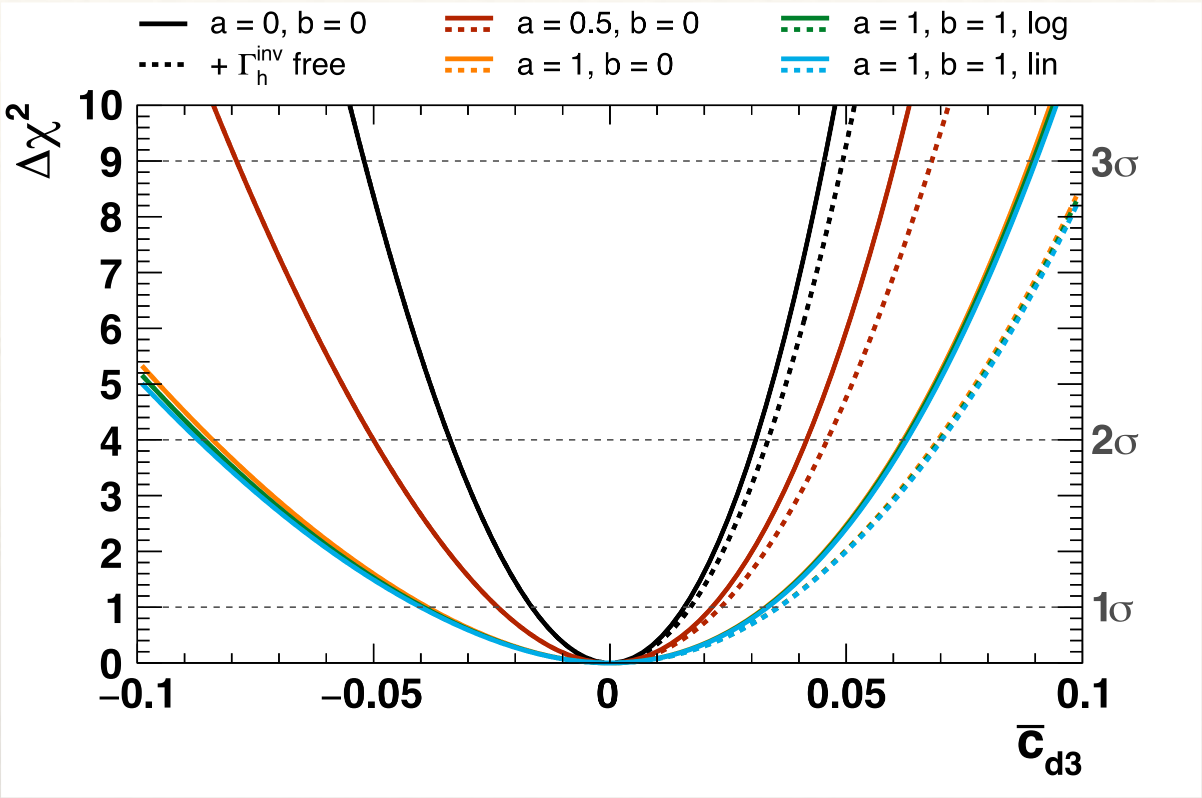
p_T - dependent uncertainty

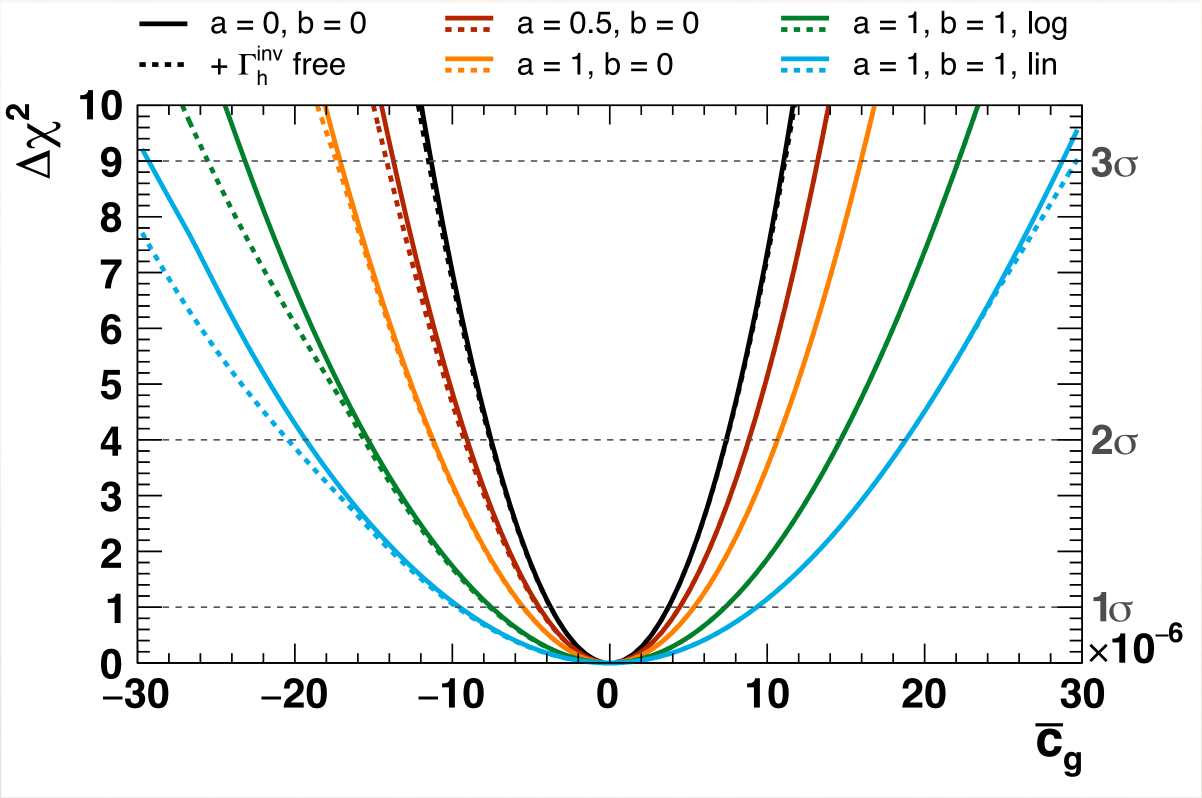
- here: choose two parameter dependence

$$\delta_{\mathrm{inc}} \sim a \quad \otimes \quad \begin{array}{l} \delta(p_T) \sim b\,\dfrac{p_T}{m_h} \\ \delta(p_T) \sim b\,\log\left(1 + \dfrac{p_T}{m_h}\right) \end{array}$$

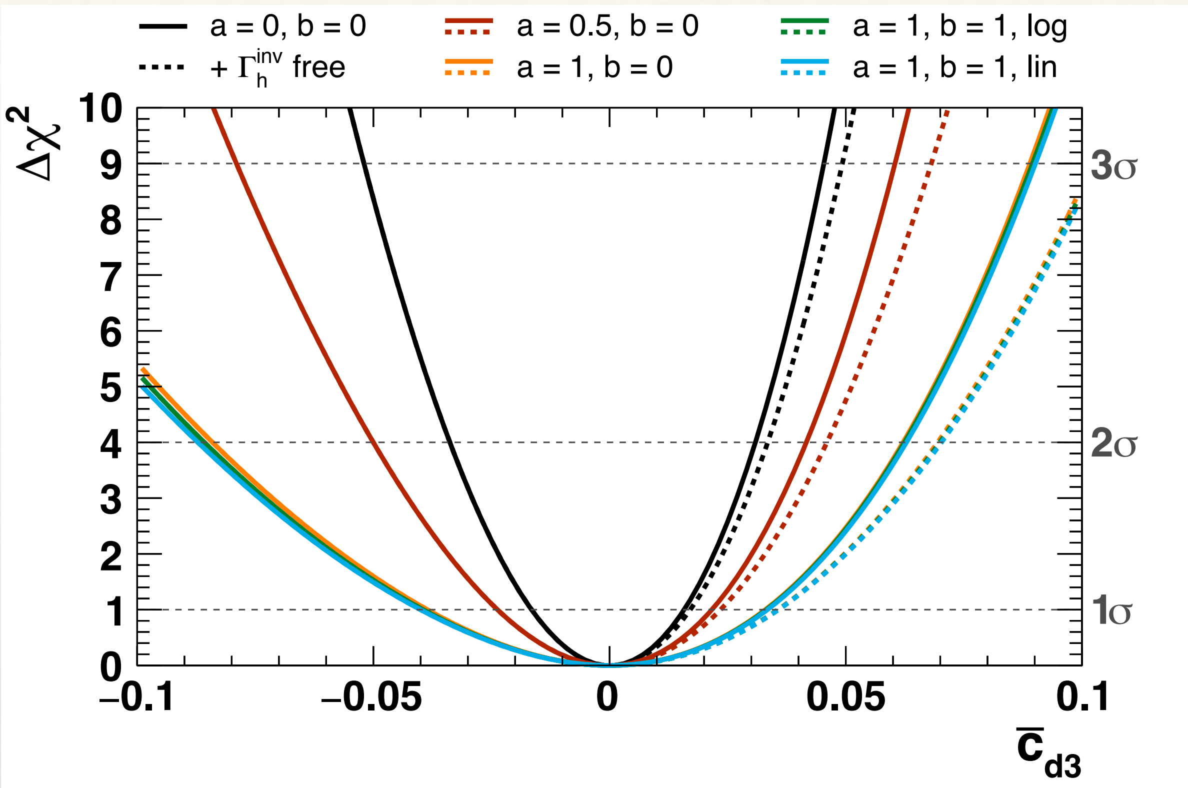
e.g. [Caola, Forte, Marzani, Muselli, Vita ` 16]

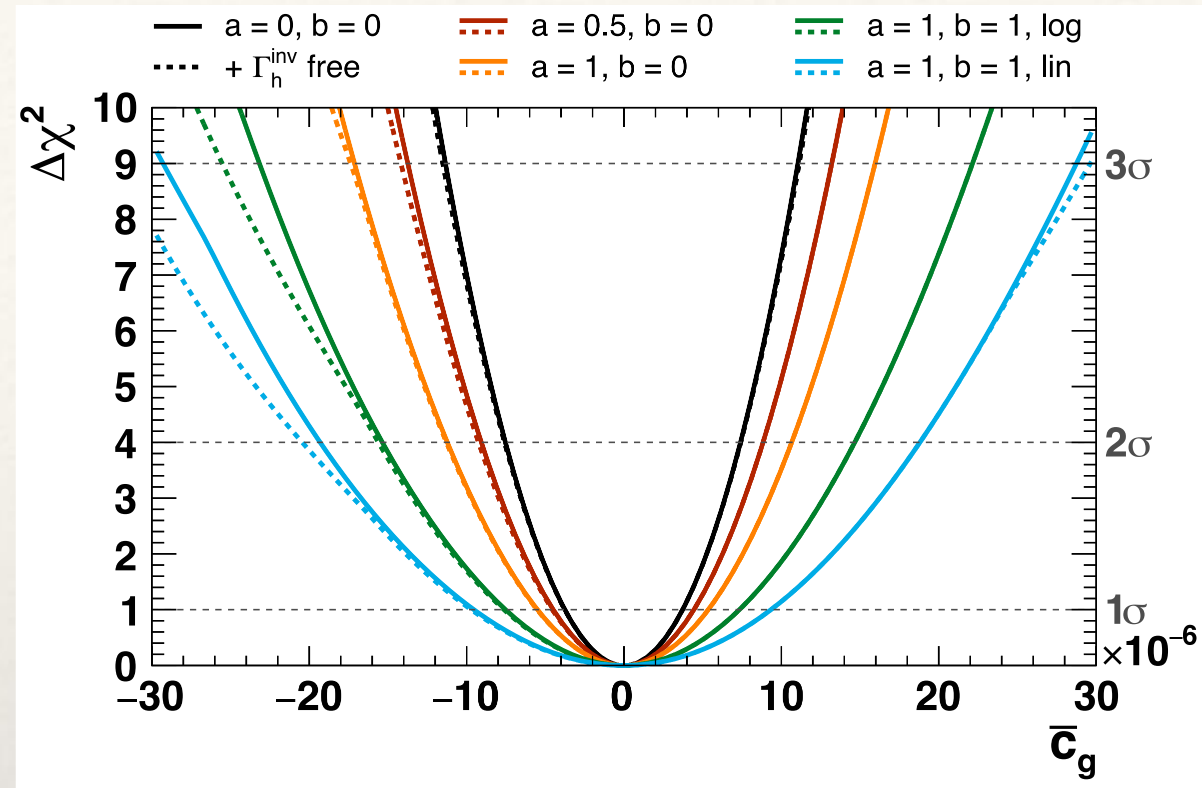
Role of uncertainties





Role of uncertainties





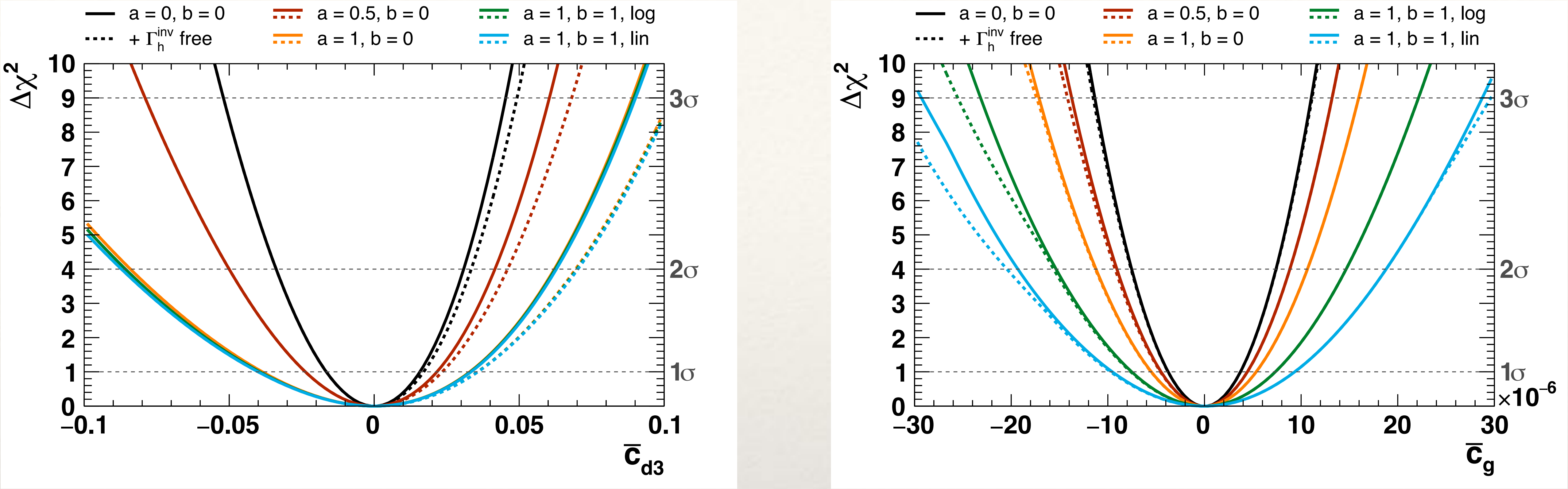
- decay-relevant operators with suppressed production contributions

re-scale distributions

degeneracy lifted by "tails"

- decay-relevant operators with dominant production contributions

Role of uncertainties



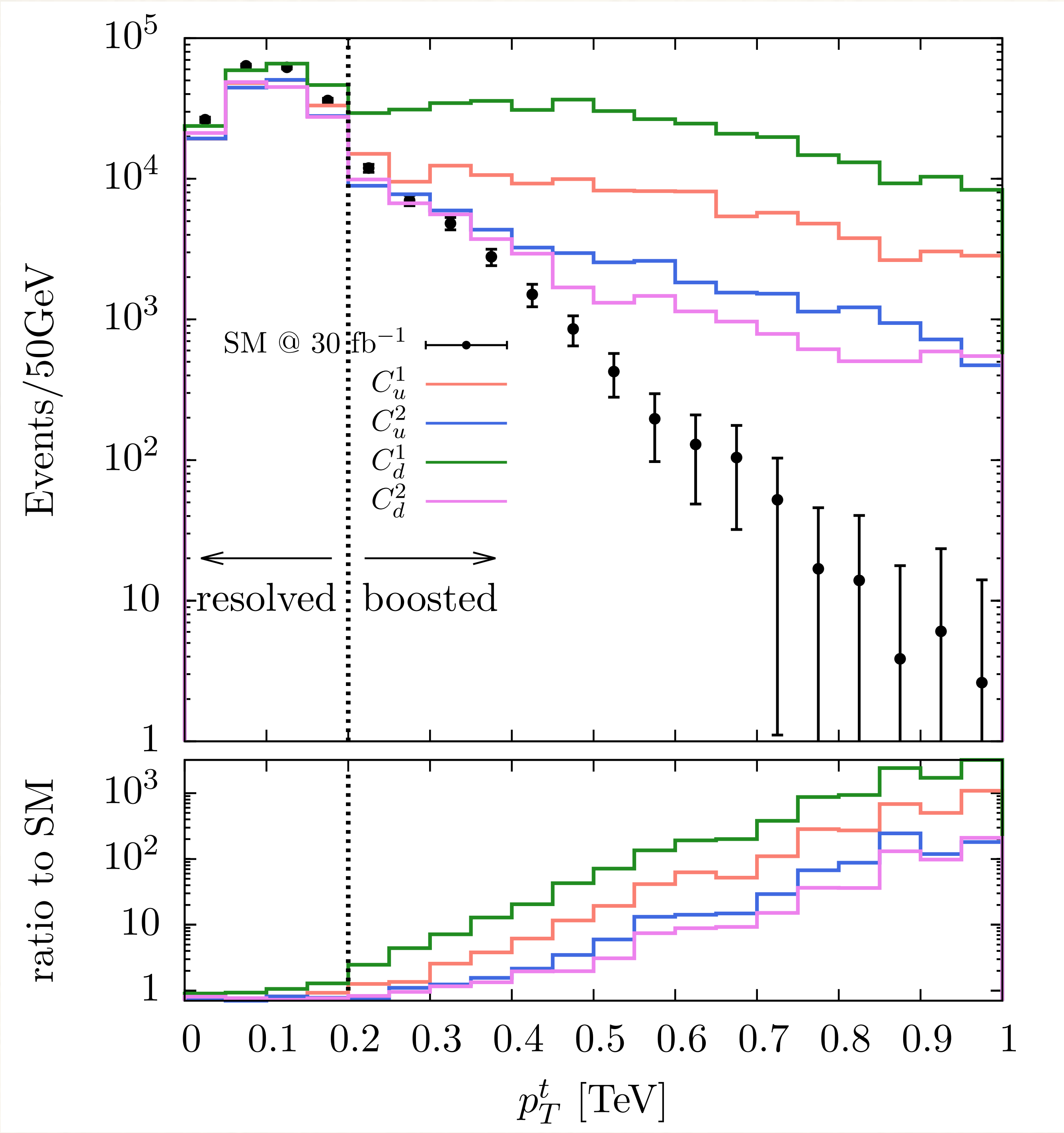
- comparably small impact of tail uncertainties (lin vs log ~ 35% different shape uncertainty at 150 GeV p_T
- **decoupled (non-resonant) new physics perturbatively constrained at low transverse momentum.**

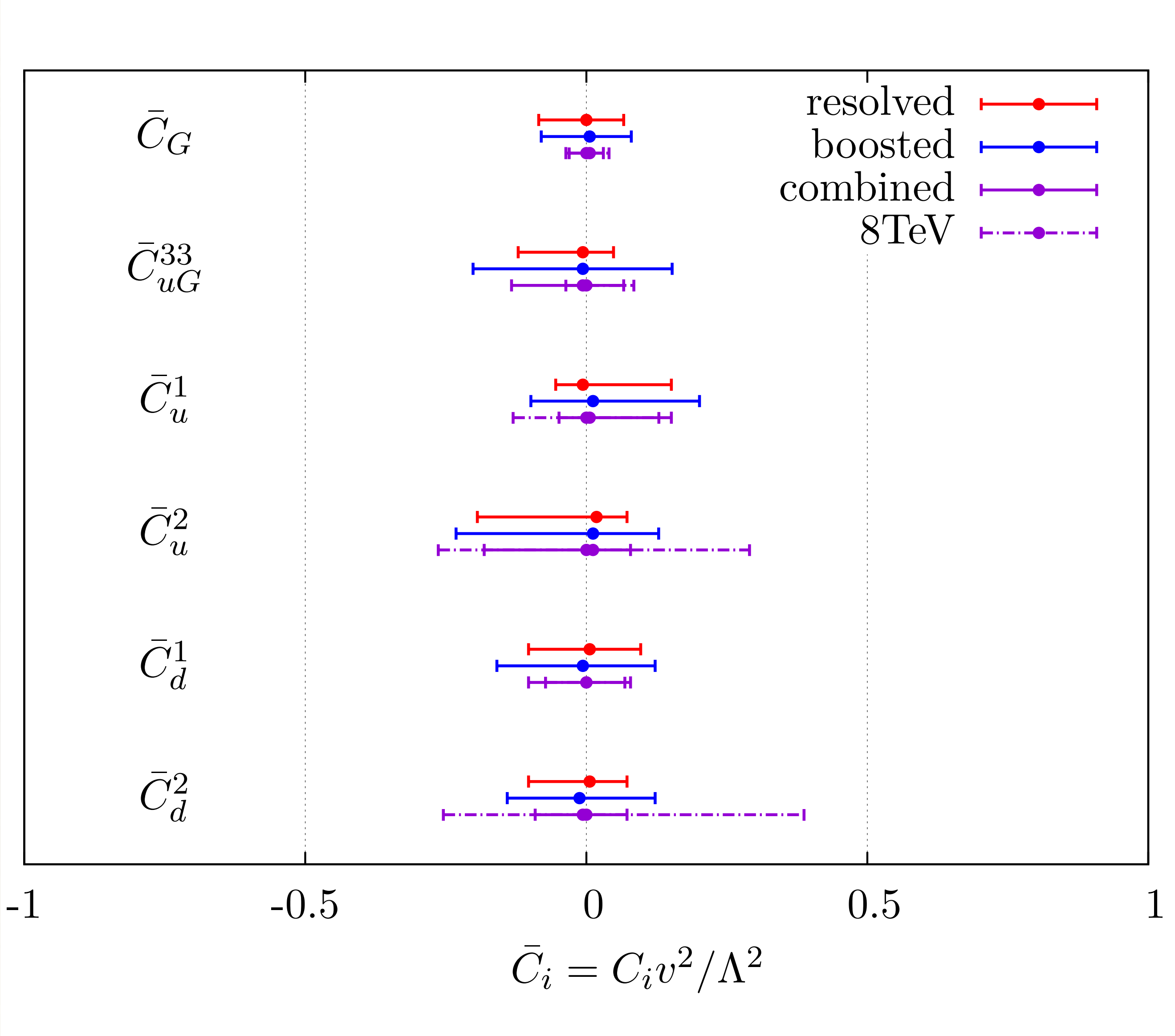
"fit will always pick region where null hypothesis is under good control"

[CE, Moore, Nordstrom, Russell ` 16]

Role of uncertainties

- Is this due to small production cross sections?
  No - similar conclusions hold for top sector fits





Fingerprinting the lack of new physics

the SM is flawed

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)

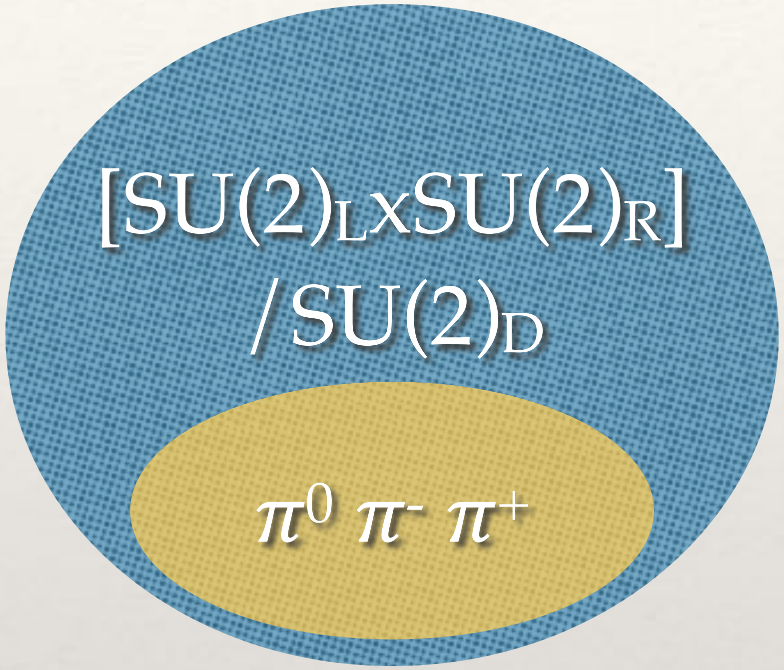
informs

+ additional dofs

concrete models

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

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



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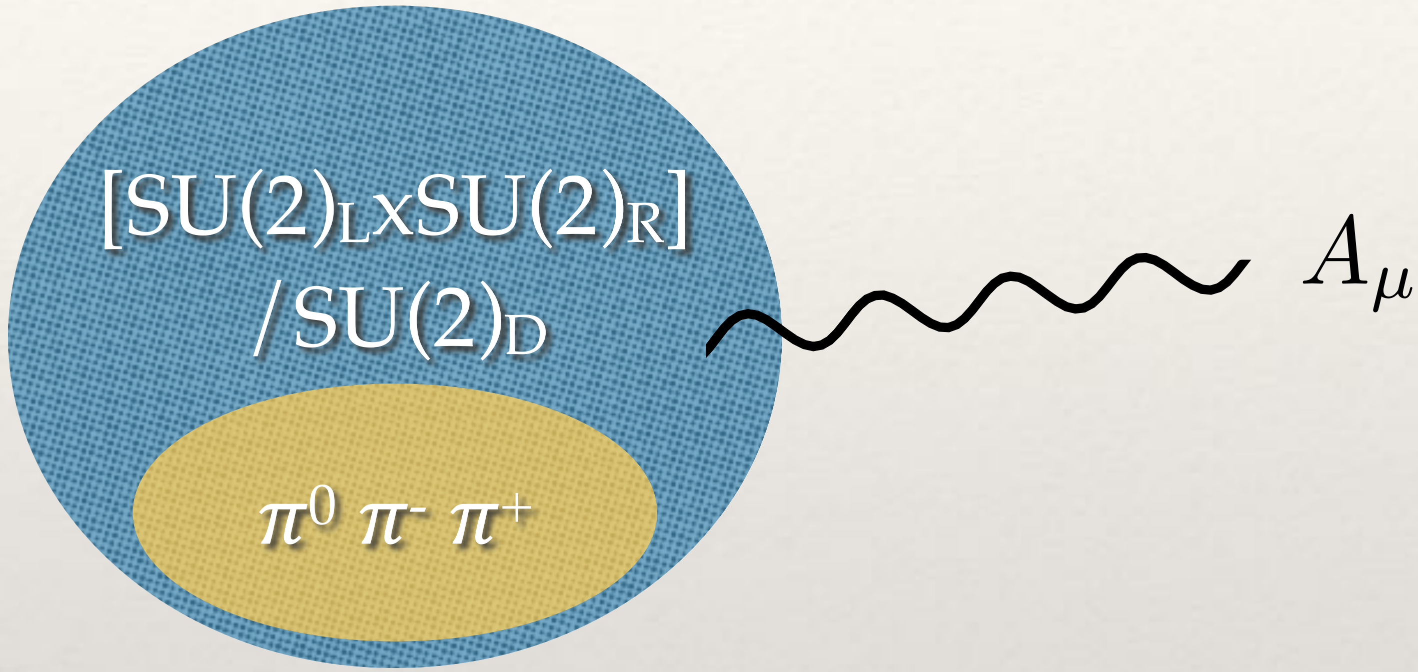

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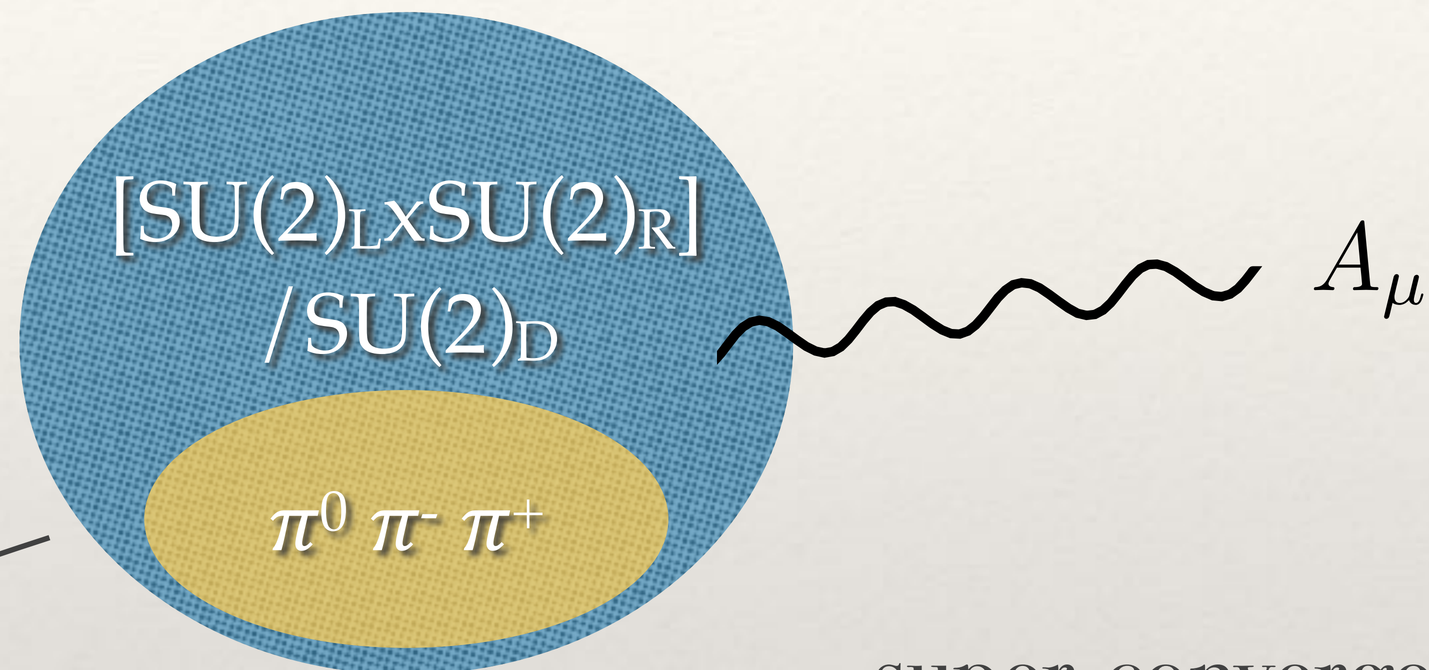

effective potential
[Coleman, Weinberg `73]...

super-convergent
[Weinberg `67]...

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

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

Generic hints of compositeness

- <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

…….

Generic hints of compositeness

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e.g. [Contino ` 10]

trigger ELW symmetry breaking not just CW masses

respect global symmetries in the Higgs sector

LEP precision measurements

....

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

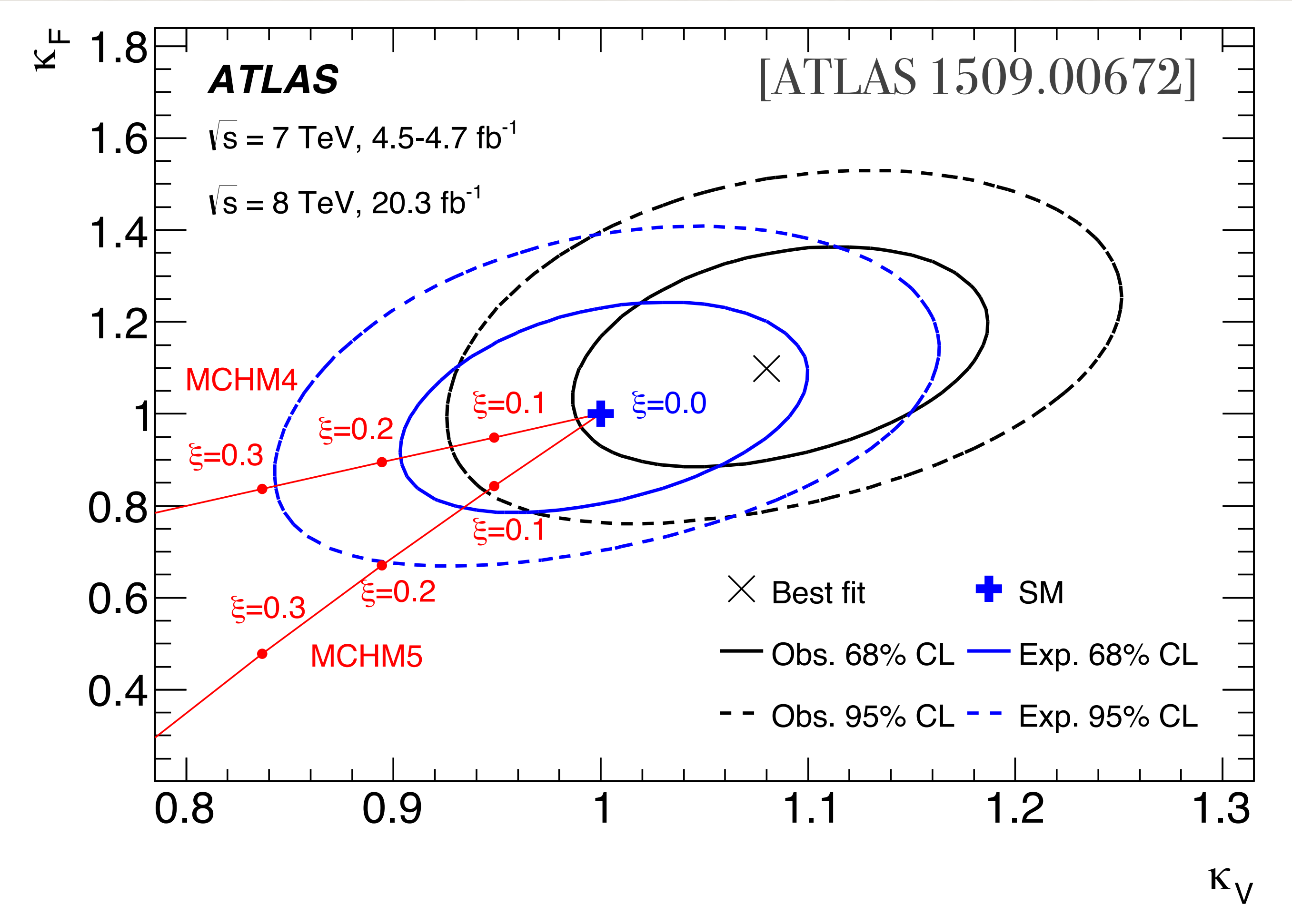
$$V(h) \simeq \alpha \cos\frac{h}{f} - \beta \sin^2\frac{h}{f}$$

fermions

gauge + fermions

Generic hints of compositeness

- gauge boson masses through symmetry choices
- fermion masses through mixing with baryonic matter (part. compositeness)
- minimal pheno model SO(5)→ SO(4) ≃ $SU(2)_L$ x $SU(2)_R$
- fermions (and hypercolour baryons) in a 4/5 of SO(5)



coupling modifiers

Model	hVV	$hhVV$	$hf\bar{f}$
MCHM4	$\sqrt{1-\xi}$	$1-2\xi$	$\sqrt{1-\xi}$
MCHM5	$\sqrt{1-\xi}$	$1-2\xi$	$\frac{1-2\xi}{\sqrt{1-\xi}}$

Generic hints of compositeness

- gauge boson masses through symmetry choices
- fermion masses through mixing with baryonic matter (part. compositeness)
- minimal pheno model $SO(5) \to SO(4) \simeq SU(2)_L \times SU(2)_R$
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so far no UV completion known for this!

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- but

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

[Ferretti `14]

could work with

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

[Rabi, Dimopoulos, Susskind `80]
[Preskill, Weinberg `81]

A concrete model of compositeness ?

- model predicts a number of exotics phenomenological implications

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

[CE, Schichtel, Spannowsky ` 17]

doubly charged, singly charged and extra neutral Higgs bosons

top partners

hyperpions

[Belyaev et al. ` 17]

[Matsedonskyi, Panico, Wulzer ` 15]

[CE, Ferretti, Spannowsky. ` 17]

$\mathbf{1}_0 + \mathbf{2}_{\pm 1/2} + \mathbf{3}_0 + \mathbf{3}_{\pm 1}$

similarities with [Georgi, Machacek ` 85]

- this could be a benchmark for lattice studies - but is it worth it ?

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- this could be a benchmark for lattice studies - but is it worth it ?

- **i.e. can or will the LHC limit the parameter space?**

[Del Debbio, CE, Zwicky ` 17]

Low Energy Constants

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

$$\alpha = \frac{1}{2}\hat{F}_{\rm LL} - \hat{c}_{\rm LR}$$

$$\beta = \frac{1}{2}\hat{F}_{\rm EW} - \frac{1}{4}\hat{F}_{\rm LL}\ .$$

SU(2)xSU(2) correlator

see also [Golterman, Shamir ` 15, 17]

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SU(2)xSU(2) correlator

Hyperbaryon 4-point correlator

see also [Golterman, Shamir ` 15, 17]

$$F_{\rm LR} = -(\lambda_1\lambda_2)^2\int_{x_{1,2,3}}\langle J_{\bar{L}Ri}(x_1,x_2)J^\dagger_{\bar{L}Rk}(x_3,x_4)\rangle_{i\neq k}\,,$$

$$F_{\rm RR} = -\lambda_2^4\times\int_{x_{1,2,3}}\langle J_{RRi}(x_1,x_2)J^\dagger_{RRk}(x_3,x_4)\rangle_{i\neq k}\,,$$

$$F_{\rm LL} = -\lambda_1^4\times\int_{x_{1,2,3}}\langle J_{LLi}(x_1,x_2)J^\dagger_{LLk}(x_3,x_4)\rangle_{i\neq k}\,,$$

$$C_{\rm LR} = \frac{3}{16\pi^2}\int_0^\infty {\rm d}q^2\, q^2\Pi^{33}_{LR}(q^2)\,,\quad \hat{F}_{\rm EW}\equiv\hat{F}_{\rm LR}-2\hat{F}_{\rm RR}$$

$$J_{\bar{L}Ri}(x_1,x_2) = \bar{t}_L\mathcal{B}_i(x_1)\bar{\mathcal{B}}_i t_R(x_2)\,,$$

$$J_{RRi}(x_1,x_2) = \bar{\mathcal{B}}_i(x_1)t_R\bar{\mathcal{B}}_i t_R(x_2)\,,$$

$$J_{LLi}(x_1,x_2) = \bar{\mathcal{B}}_i(x_1)t_L\bar{\mathcal{B}}_i t_L(x_2)\,.$$

$$\mathcal{B}_{Ria} = -\frac{1}{2}\epsilon^{ABCD}\epsilon_{abc}P_R\psi_{ABi}\chi^T_{Cb}CP_R\chi_{Dc}\,,$$

- first principle lattice calculation not possible with current techniques

but progress is being made e.g. [Ayar, DeGrand ` 17 & ` 18]

[Ferretti ` 14]

	$G_{\rm HC}$	$G_{\rm F}$				
	$SU(4)$	$SU(5)$	$SU(3)$	$SU(3)'$	$U(1)_X$	$U(1)'$
ψ	**6**	**5**	**1**	**1**	0	-1
χ	**4**	**1**	**3**	**1**	$-1/3$	$5/3$
$\tilde{\chi}$	$\bar{\mathbf{4}}$	**1**	**1**	$\bar{\mathbf{3}}$	$1/3$	$5/3$

Low Energy Constants: simplified

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

$$\alpha = \frac{1}{2}\hat{F}_{\rm LL} - \hat{c}_{\rm LR}$$

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Hyperbaryon 4-point correlator

see also [Golterman, Shamir ` 15, 17]

$$\alpha + 2\beta = \hat{F}_{\rm EW} - \hat{c}_{\rm LR} > 0\,.$$

for EWSB

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

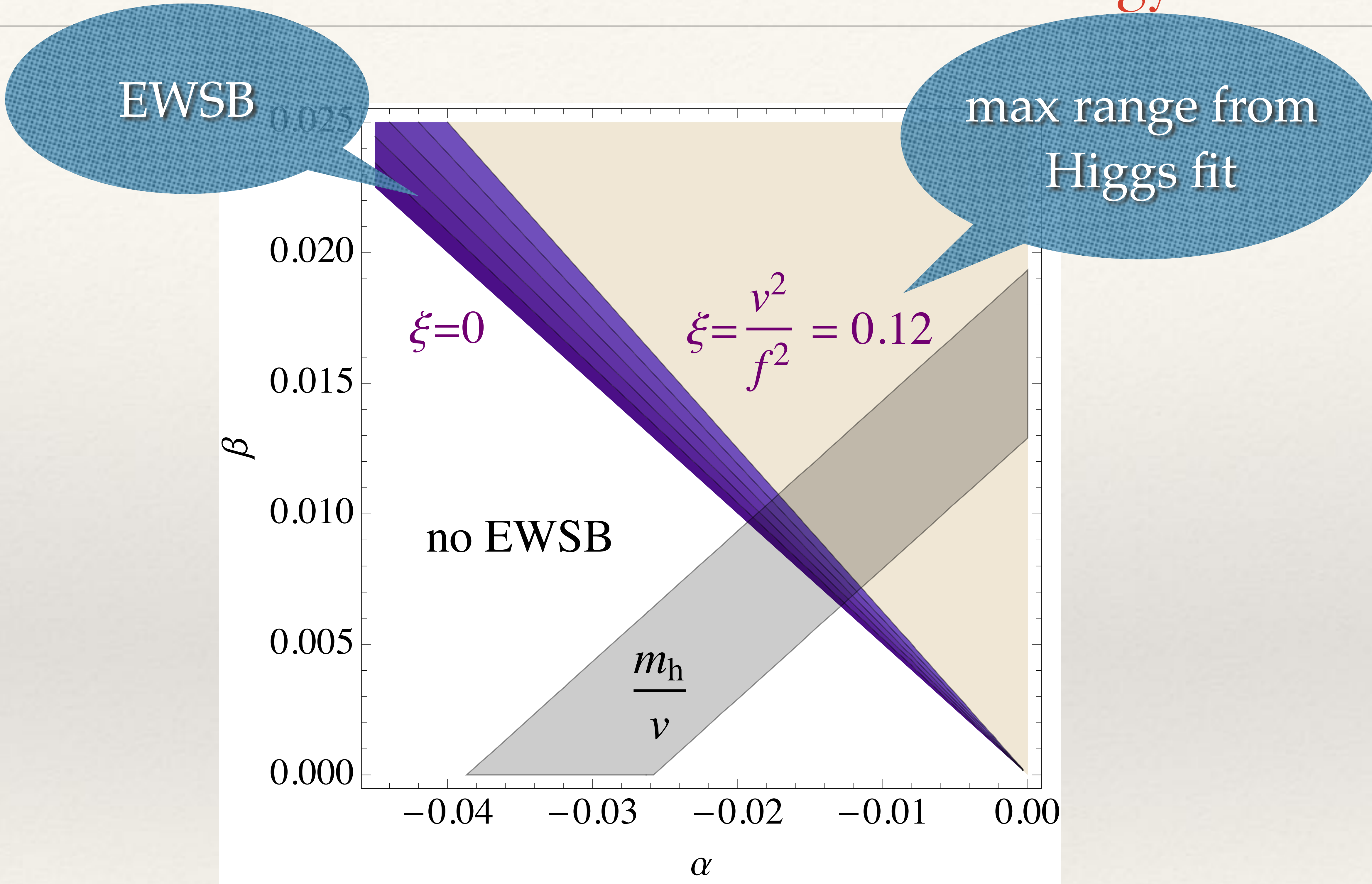
Higgs coupling modifier

e.g.

$$g_{VVh} = \sqrt{1-\xi}\, g_{VVh}^{\rm SM}$$

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

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



$$\frac{m_h^2}{v^2} = 32\beta(1-\xi) = 8(2\beta-\alpha)$$

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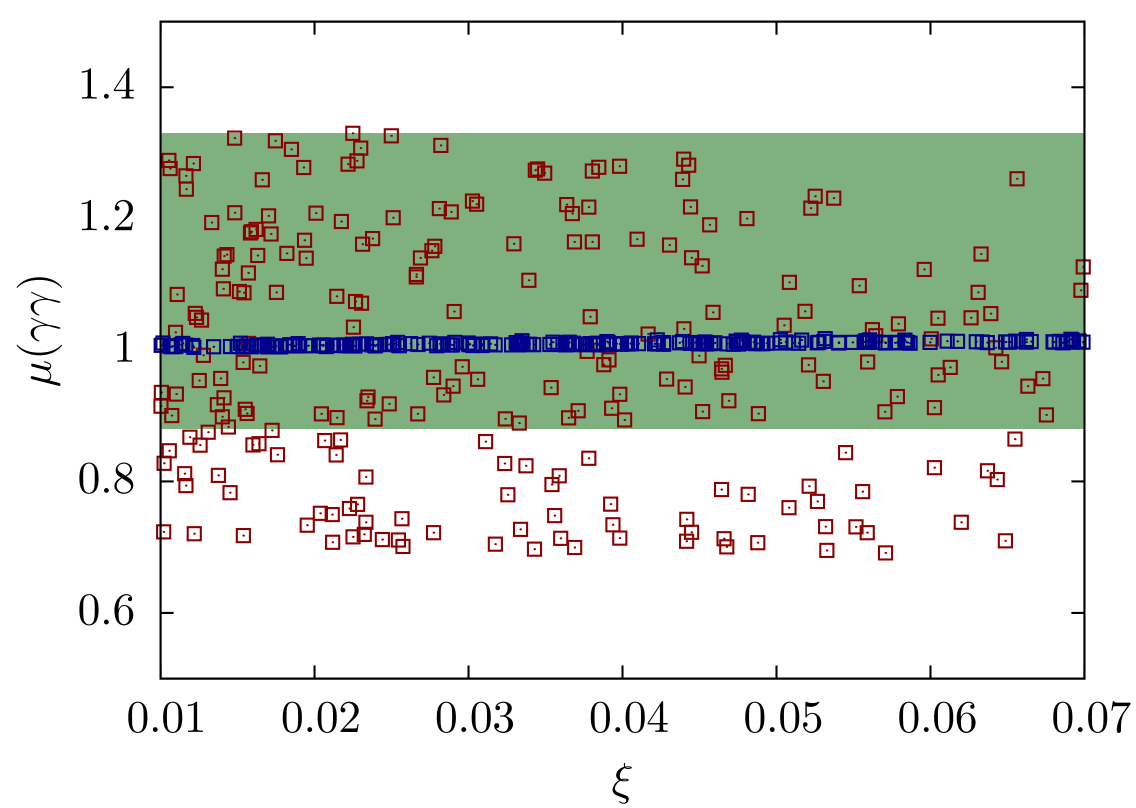
similarities with [Georgi, Machacek ` 85]

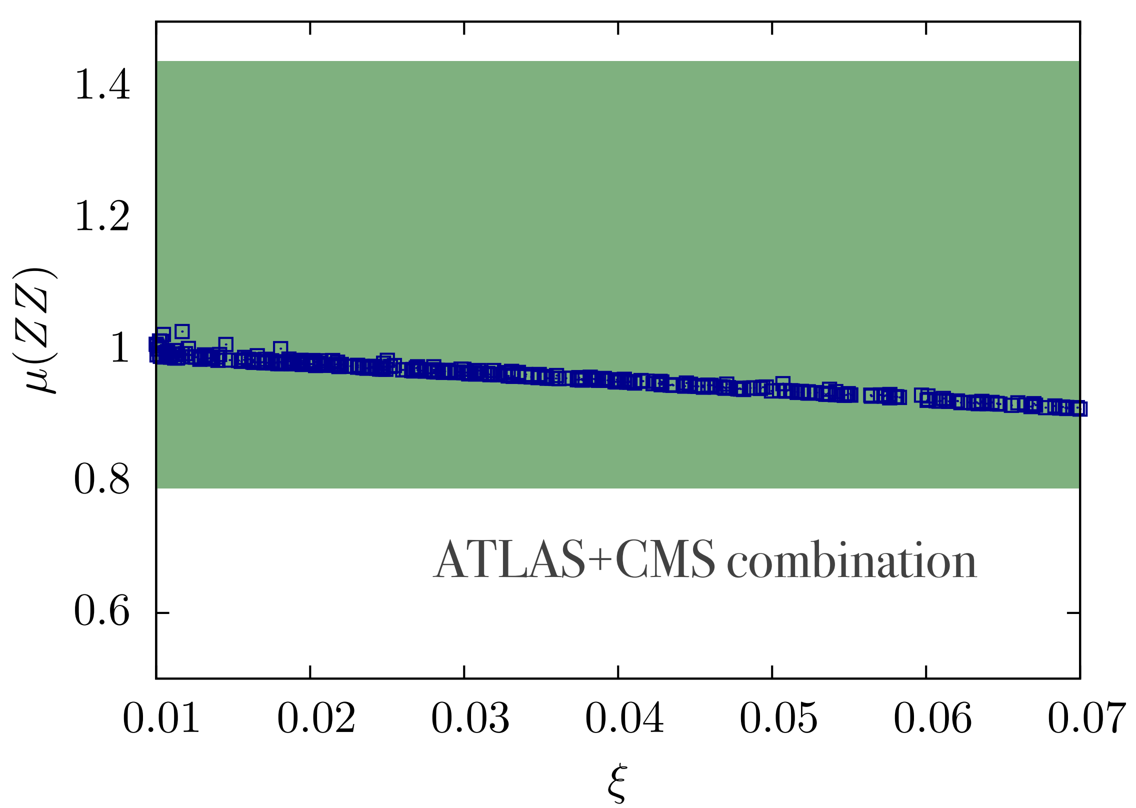
- top partner constraints
- compatibility with exotics searches
- compatibility with Higgs signal strength measurements

- no constraints from charged Higgs searches
- doubly charged Higgs bosons produced via Drell Yan might be accessible at the LHC in the future [CE, Schichtel, Spannowsky `16]

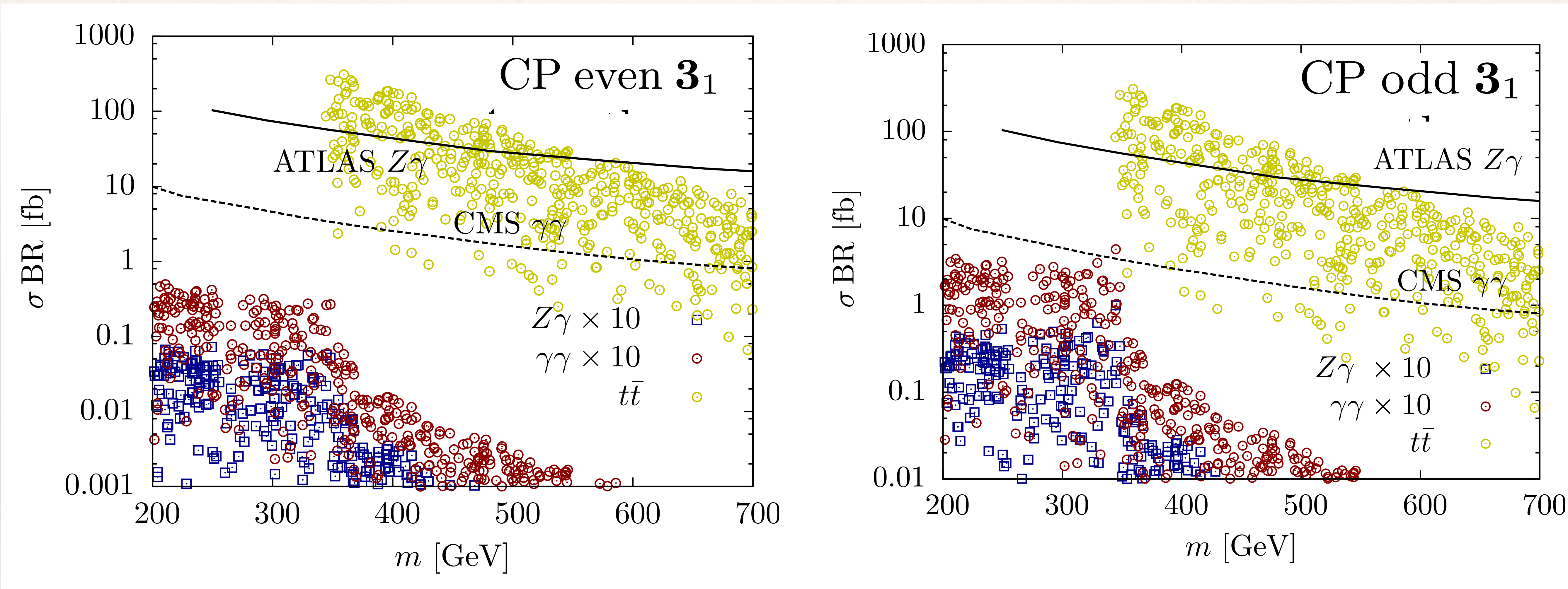
results at a glance

- no constraints from charged Higgs searches
- doubly charged Higgs bosons produced via Drell Yan might be accessible at the LHC in the future
- Higgs signal strength - no news here either



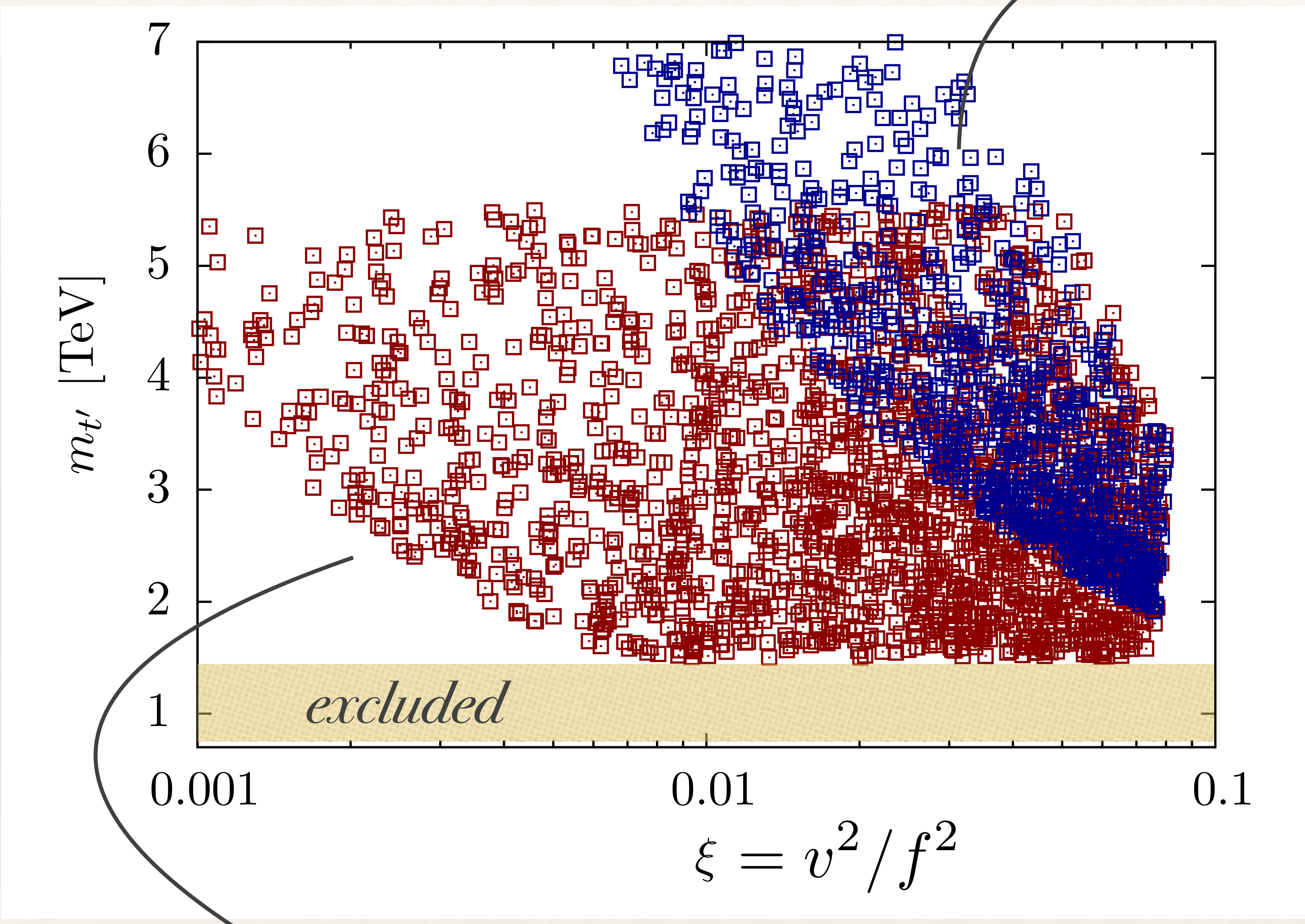


- searches for extra scalar / pseudoscalar Higgs bosons with couplings to top quarks



- extra scalars with net bottom coupling avoid experimental detection

Top partner predictions



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

top partners democratic

Lattice input crucial to pin down the very character of a concrete scenario!

- EFT is a promising avenue to interface LHC measurements and (some) UV interpretations
  - get low energy correlations right
  - hone sensitivity through differential techniques consistently
- however, current analyses not sensitive enough to provide a clear picture, but…

higher statistics (= smaller systematics)!

differential cross sections !

high momentum transfer final states !

direct evidence for exotics ?!