University of Glasgow

Christoph Englert

Higgs Coupling Measurements and UV completions

Holography, conformal field theories, and lattice

28.06.2016

Does the EW scale result from confinement?

Does the EW scale result from confinement?

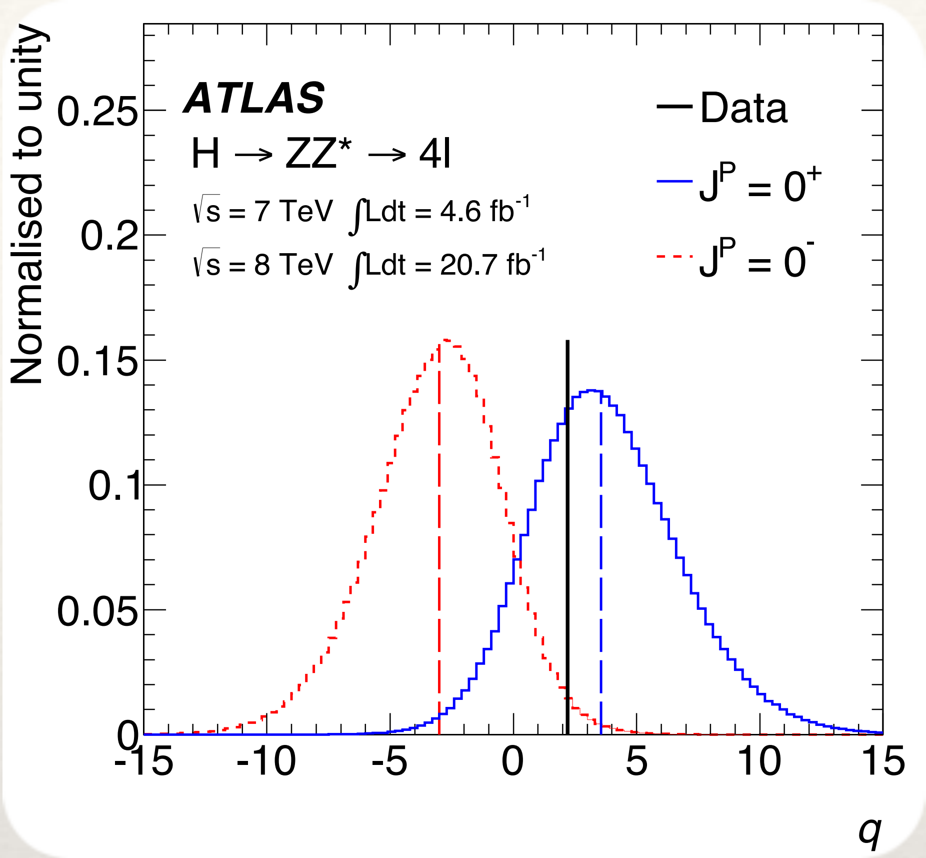
in this talk:

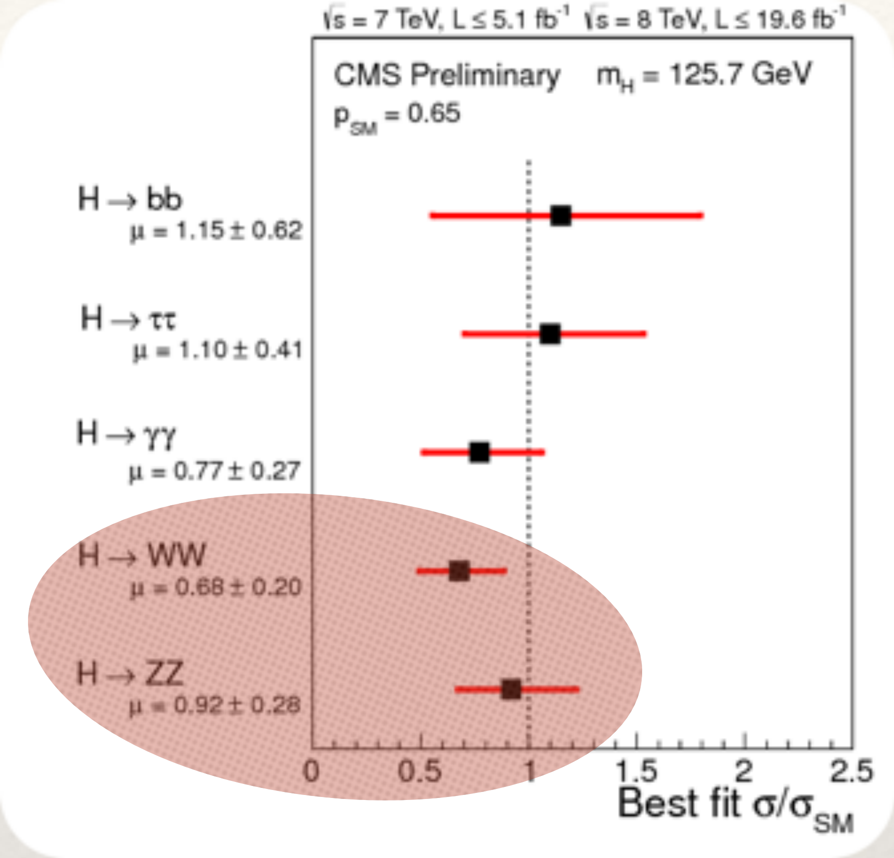
- ☛ Higgs boson coupling measurements
- ☛ LHC EFT fits of Higgs couplings
- ☛ some words about UV implications

inform model building and lattice investigations

LHC Phenomenology

Yang-Mills+Higgs is true





genuine Higgs properties:

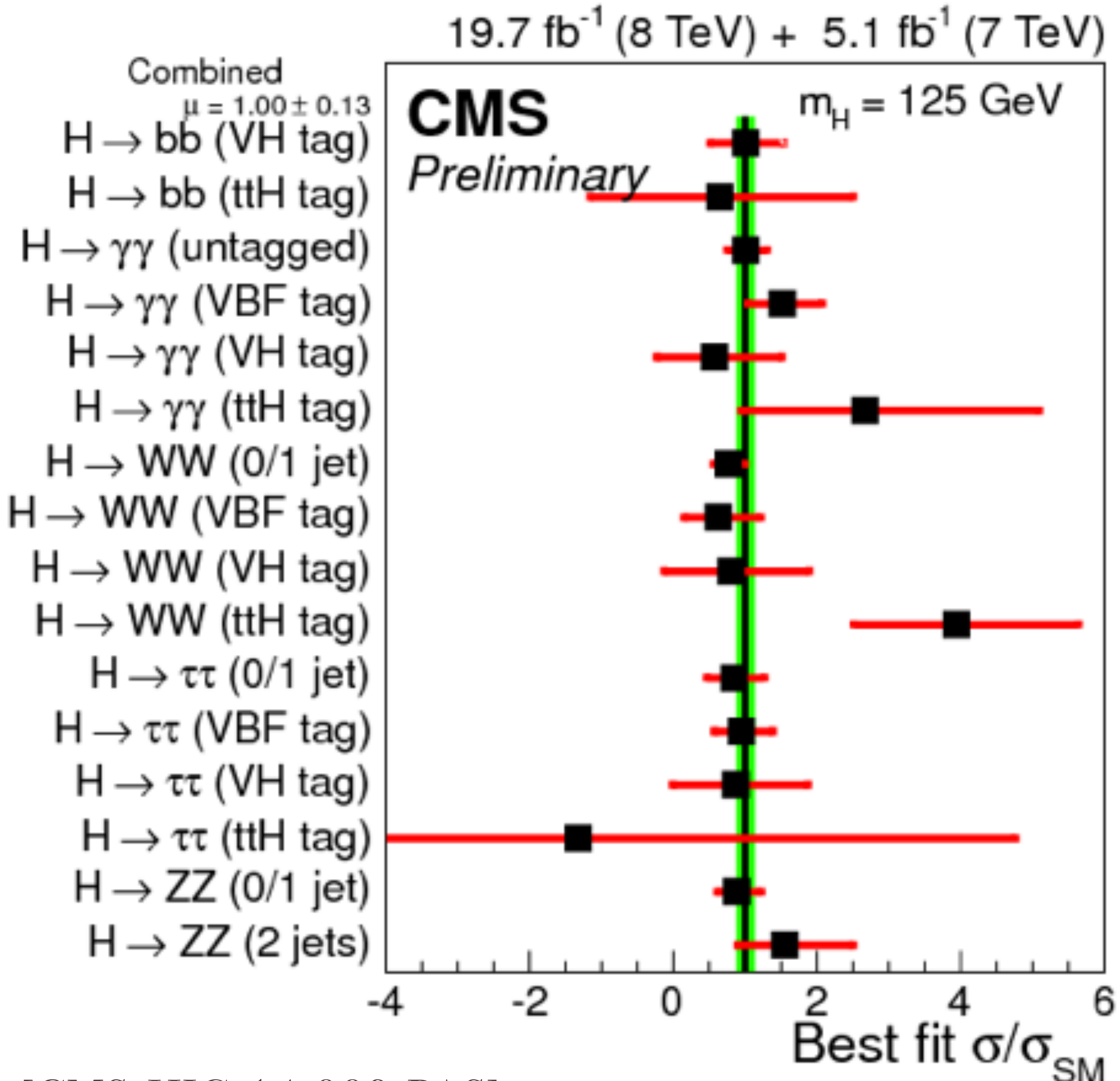
unitarity conservation and excitation of an isotropic and translationally invariant background field.

☛ "spontaneous" symmetry breaking

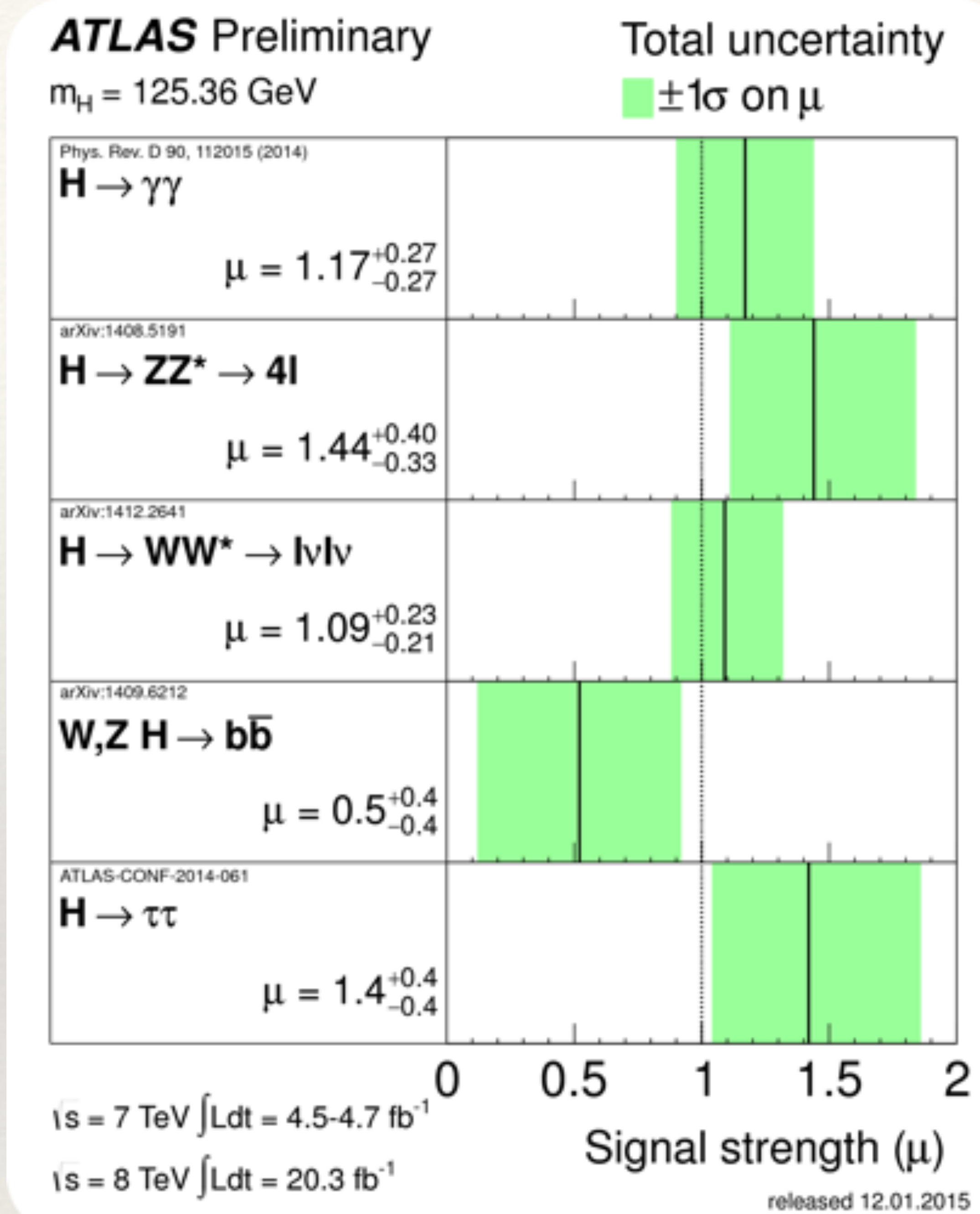
[Higgs `64] [Brout, Englert `64] [Guralnik, Hagen, Kibble `64]

☛ CP even bias

Status of LHC measurements



[CMS HIG-14-009-PAS]



☛ 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

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

[Buchmüller, Wyler `87]
[Hagiwara, Peccei, Zeppenfeld, Hikasa `87]
[Giudice, Grojean, Pomarol, Rattazzi `07]
[Grzadkowski, Iskrzynski, Misiak, Rosiek `10]
….

concrete models

- (N)MSSM
- Higgs portals
- 2HDMs
- …

Fingerprinting the lack of new physics

the SM is flawed

no evidence for exotics

coupling/scale separated BSM physics

Effective Field Theory

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

[Buchmüller, Wyler `87]
[Hagiwara, Peccei, Zeppenfeld, Hikasa `87]
[Giudice, Grojean, Pomarol, Rattazzi `07]
[Grzadkowski, Iskrzynski, Misiak, Rosiek `10]
....

compositeness

concrete models

- (N)MSSM
- Higgs portals
- 2HDMs
- …

Fingerprinting the lack of new physics

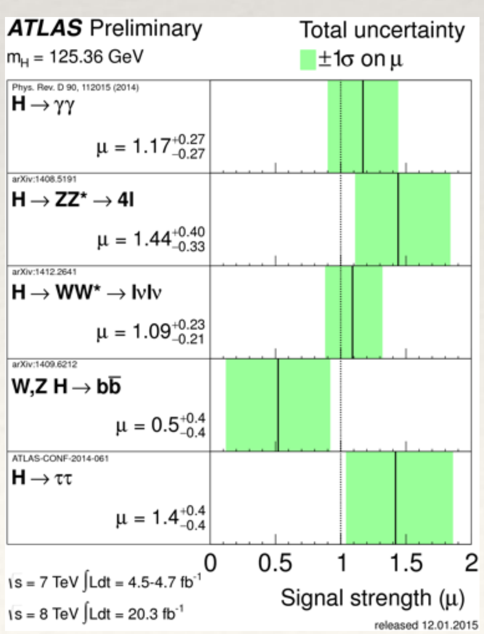
$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$$

decays

production

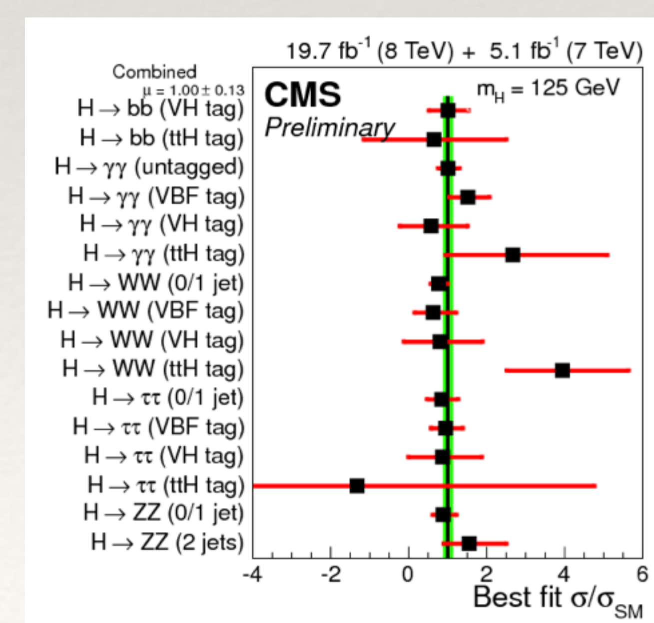
<u>consistent</u> differential distributions

low stats



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

[HXSWG YR 3]



linear Higgs effective field theory

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

[Giudice, Grojean, Pomarol, Rattazzi `07]

Higgs decays

Higgs production

<u>consistent</u>
differential
distributions

linear Higgs effective field theory

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

[Giudice, Grojean, Pomarol, Rattazzi `07]

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)	$\bar{c}_W, \bar{c}_B, \bar{c}_{HW}, \bar{c}_{HB}, \bar{c}_\gamma, \bar{c}_H$

linear Higgs effective field theory

ELW precision constraints

[Falkowski, Riva `15]

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

[Giudice, Grojean, Pomarol, Rattazzi `07]

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)	$\bar{c}_W, \bar{c}_B, \bar{c}_{HW}, \bar{c}_{HB}, \bar{c}_\gamma, \bar{c}_H$

A word of caution

consistent differential distributions

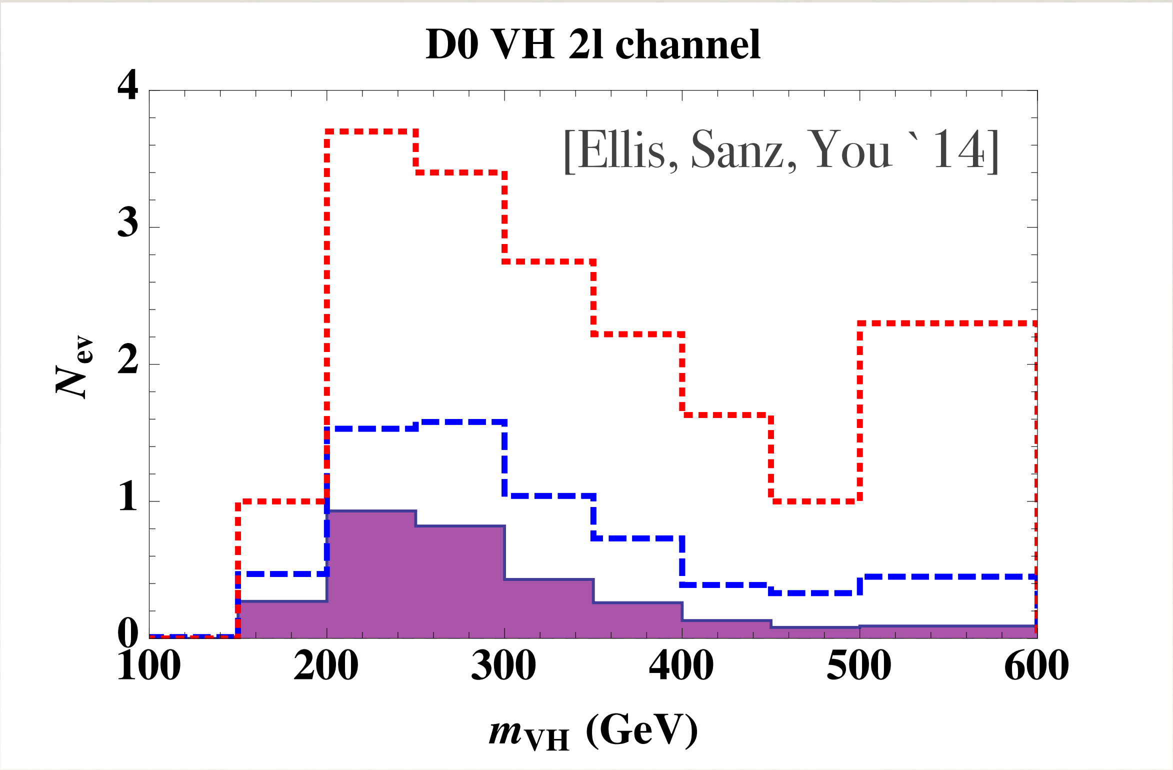
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$$

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

not necessarily positive definite (cf. fixed order N^{n}LO)

conservative probe of validity of d=6 extension

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

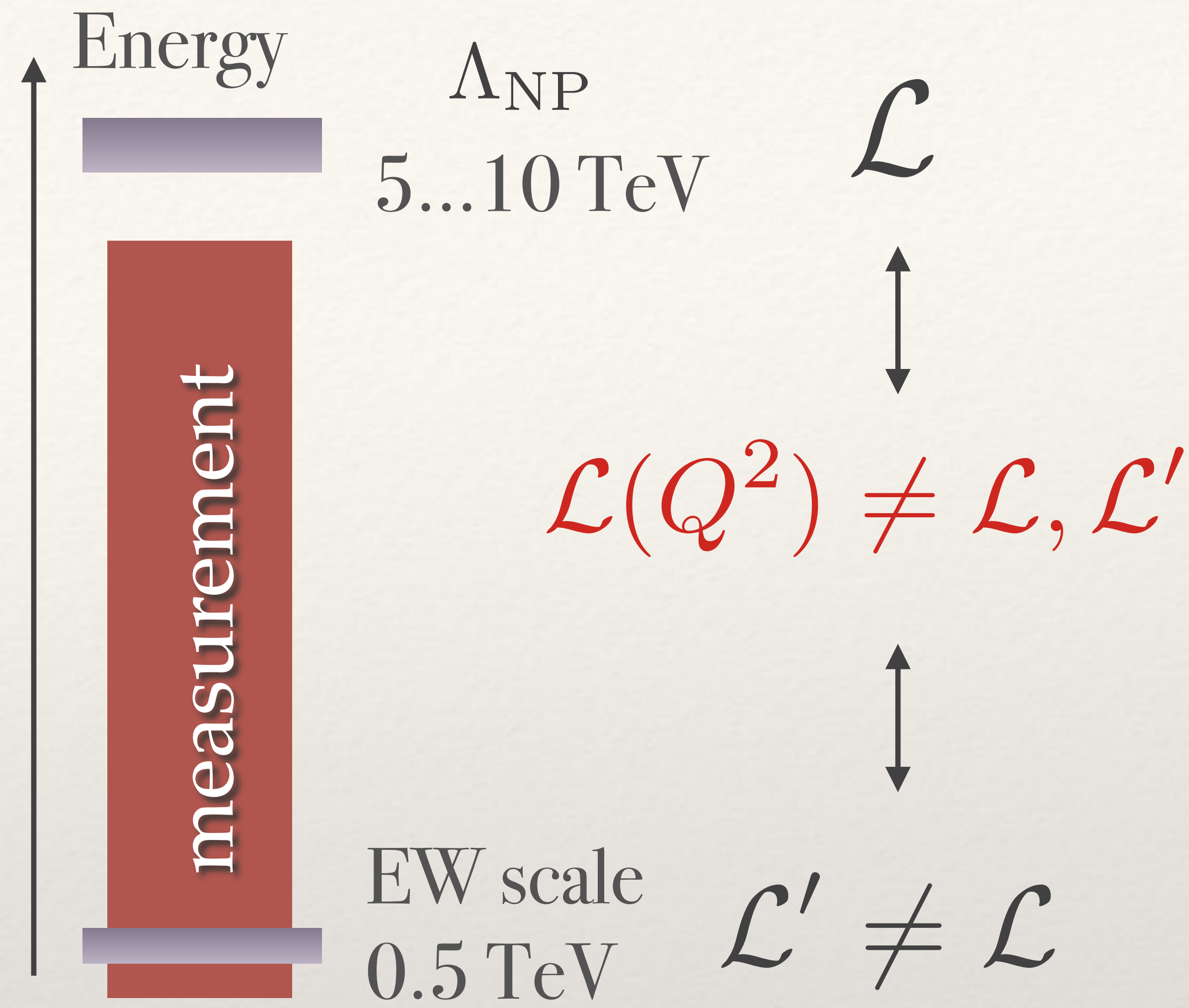


consistent differential distributions

A word of caution

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

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



- evolution from renormalization group equations, **choice of scales**
  [Grojean, Jenkins, Manohar, Trott `13] [Jenkins, Manohar, Trott `13] [Elias-Miro, Espinosa, Masso, Pomarol `13]
- consistent interpretation requires **communication of resolved scales**
  [Isidori, Trott `13] [CE, Spannowsky `14]

Higgs EFT current status

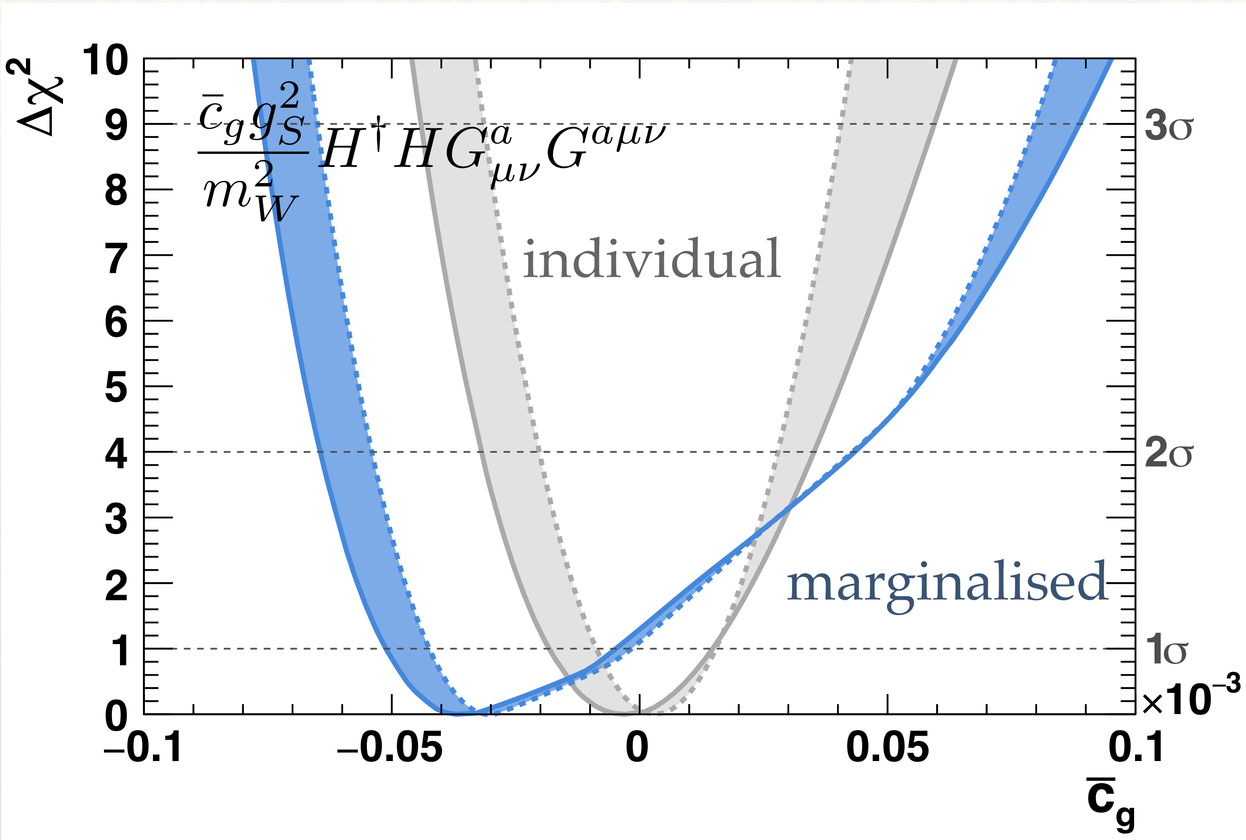
Search channel	energy $\sqrt{s}$	μ	SM ggH
ATLAS $pp \to H \to \gamma\gamma$ (central high p_T) [82]	8 TeV	$1.62^{+1.00}_{-0.83}$	7.1
ATLAS $pp \to H \to \gamma\gamma$ (central low p_T) [82]	8 TeV	$0.62^{+0.42}_{-0.40}$	31.8
ATLAS $pp \to H \to \gamma\gamma$ (forward high p_T) [82]	8 TeV	$1.73^{+1.34}_{-1.18}$	7.1
ATLAS $pp \to H \to \gamma\gamma$ (forward low p_T) [82]	8 TeV	$2.03^{+0.57}_{-0.53}$	29.0
ATLAS $pp \to H \to \gamma\gamma$ ($t\bar{t}$H hadronic) [82]	8 TeV	$-0.84^{+3.23}_{-1.25}$	0.1
ATLAS $pp \to H \to \gamma\gamma$ ($t\bar{t}$H leptonic) [82]	8 TeV	$2.42^{+3.21}_{-2.07}$	0.0
ATLAS $pp \to H \to \gamma\gamma$ (VBF loose) [82]	8 TeV	$1.33^{+0.92}_{-0.77}$	3.7
ATLAS $pp \to H \to \gamma\gamma$ (VBF tight) [82]	8 TeV	$0.68^{+0.67}_{-0.51}$	1.4
ATLAS $pp \to H \to \gamma\gamma$ (VH dijet) [82]	8 TeV	$0.23^{+1.67}_{-1.39}$	1.9
ATLAS $pp \to H \to \gamma\gamma$ (VH E_T^{miss}) [82]	8 TeV	$3.51^{+3.30}_{-2.42}$	0.2
ATLAS $pp \to H \to \gamma\gamma$ (VH 1ℓ) [82]	8 TeV	$0.41^{+1.43}_{-1.06}$	0.0
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
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
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
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
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
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
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
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
ATLAS $pp \to H \to ZZ \to 4\ell$ (ggH-like) [84]	7/8 TeV	$1.66^{+0.51}_{-0.44}$	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
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
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
ATLAS $pp \to t\bar{t}H \to$ leptons ($2\ell 1\tau_{\text{had}}$) [97]	8 TeV	$-0.90^{+3.10}_{-2.00}$	0.0
ATLAS $pp \to t\bar{t}H \to$ leptons (3ℓ) [97]	8 TeV	$2.80^{+2.20}_{-1.80}$	0.0
ATLAS $pp \to t\bar{t}H \to$ leptons (4ℓ) [97]	8 TeV	$1.80^{+6.90}_{-6.90}$	0.0
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
ATLAS $pp \to VH \to Vb\bar{b}$ (0ℓ) [92]	7/8 TeV	$-0.35^{+0.55}_{-0.52}$	0.0
ATLAS $pp \to VH \to Vb\bar{b}$ (1ℓ) [92]	7/8 TeV	$1.17^{+0.66}_{-0.60}$	0.0
ATLAS $pp \to VH \to Vb\bar{b}$ (2ℓ) [92]	7/8 TeV	$0.94^{+0.88}_{-0.79}$	0.0
ATLAS $pp \to VH \to VWW$ (2ℓ) [87]	7/8 TeV	$3.70^{+1.90}_{-1.80}$	0.0
ATLAS $pp \to VH \to VWW$ (3ℓ) [87]	7/8 TeV	$0.72^{+1.30}_{-1.10}$	0.0
ATLAS $pp \to VH \to VWW$ (4ℓ) [87]	7/8 TeV	$4.90^{+4.60}_{-3.10}$	0.0

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	$1.24^{+4.23}_{-2.70}$	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	20.5	18.4	37.7
CMS $pp \to H \to \gamma\gamma$ (untagged 1) [83]	7 TeV	$1.23^{+0.98}_{-0.88}$	30.6	17.4	20.9	19.5	11.7
CMS $pp \to H \to \gamma\gamma$ (untagged 1) [83]	8 TeV	$0.92^{+0.57}_{-0.49}$	13.7	20.3	21.7	22.4	21.8
CMS $pp \to H \to \gamma\gamma$ (untagged 2) [83]	7 TeV	$1.60^{+1.25}_{-1.17}$	30.3	16.8	20.6	20.8	11.5
CMS $pp \to H \to \gamma\gamma$ (untagged 2) [83]	8 TeV	$1.10^{+0.48}_{-0.44}$	22.9	18.8	21.1	20.3	16.9
CMS $pp \to H \to \gamma\gamma$ (untagged 3) [83]	7 TeV	$2.61^{+1.74}_{-1.65}$	30.9	16.7	21.0	19.7	11.7
CMS $pp \to H \to \gamma\gamma$ (untagged 3) [83]	8 TeV	$0.65^{+0.65}_{-0.89}$	23.4	17.9	20.6	20.7	17.3
CMS $pp \to H \to \gamma\gamma$ (untagged 4) [83]	8 TeV	$1.46^{+1.29}_{-1.24}$	28.5	17.6	20.6	19.5	13.8
CMS $pp \to H \to \gamma\gamma$ (VBF dijet 0) [83]	7 TeV	$4.85^{+2.17}_{-1.76}$	1.8	94.9	0.7	0.9	1.7
CMS $pp \to H \to \gamma\gamma$ (VBF dijet 0) [83]	8 TeV	$0.82^{+0.75}_{-0.58}$	1.3	96.1	0.5	0.4	1.7
CMS $pp \to H \to \gamma\gamma$ (VBF dijet 1) [83]	7 TeV	$2.60^{+2.16}_{-1.76}$	4.2	81.2	3.4	3.5	7.7
CMS $pp \to H \to \gamma\gamma$ (VBF dijet 1) [83]	8 TeV	$-0.21^{+0.75}_{-0.69}$	2.3	91.4	1.6	0.9	3.7
CMS $pp \to H \to \gamma\gamma$ (VBF dijet 2) [83]	8 TeV	$2.60^{+1.33}_{-0.99}$	3.8	72.8	4.0	4.0	15.4
CMS $pp \to H \to \gamma\gamma$ (VH dijet) [83]	7 TeV	$7.86^{+8.86}_{-6.40}$	1.0	1.3	42.8	41.1	13.8
CMS $pp \to H \to \gamma\gamma$ (VH dijet) [83]	8 TeV	$0.39^{+2.16}_{-1.48}$	0.9	1.5	40.3	40.1	17.3
CMS $pp \to H \to \gamma\gamma$ (VH E_T^{miss}) [83]	7 TeV	$4.32^{+6.72}_{-4.15}$	0.1	0.3	23.8	44.2	31.6
CMS $pp \to H \to \gamma\gamma$ (VH E_T^{miss}) [83]	8 TeV	$0.08^{+1.86}_{-1.28}$	0.3	0.7	20.1	35.6	43.3
CMS $pp \to H \to \gamma\gamma$ (VH loose) [83]	7 TeV	$3.10^{+8.29}_{-5.34}$	0.1	0.5	70.2	23.3	5.9
CMS $pp \to H \to \gamma\gamma$ (VH loose) [83]	8 TeV	$1.24^{+3.69}_{-2.62}$	0.1	0.4	66.3	24.7	8.5
CMS $pp \to H \to \gamma\gamma$ (VH tight) [83]	8 TeV	$-0.34^{+1.30}_{-0.63}$	0.0	0.1	57.2	24.4	18.4
CMS $pp \to H \to \mu\mu$ [94]	7/8 TeV	$2.90^{+2.80}_{-2.70}$	20.0	20.0	20.0	20.0	20.0
CMS $pp \to H \to \tau\tau$ (0 jet) [91]	7/8 TeV	$0.40^{+0.73}_{-1.13}$	70.2	8.8	10.5	10.5	0.0
CMS $pp \to H \to \tau\tau$ (1 jet) [91]	7/8 TeV	$1.06^{+0.47}_{-0.47}$	12.8	31.0	28.1	28.1	0.0
CMS $pp \to H \to WW \to 2\ell 2\nu$ (0/1 jet) [88]	7/8 TeV	$0.74^{+0.22}_{-0.20}$	19.0	31.3	24.9	24.9	0.0
CMS $pp \to H \to WW \to 2\ell 2\nu$ (VBF) [88]	7/8 TeV	$0.60^{+0.57}_{-0.46}$	2.0	98.0	0.0	0.0	0.0
CMS $pp \to H \to ZZ \to 4\ell$ (0/1 jet) [85, 131]	7/8 TeV	$0.88^{+0.34}_{-0.27}$	41.7	58.3	0.0	0.0	0.0
CMS $pp \to H \to ZZ \to 4\ell$ (2 jet) [85, 131]	7/8 TeV	$1.55^{+0.95}_{-0.66}$	16.7	83.3	0.0	0.0	0.0
CMS $pp \to t\bar{t}H \to 2\ell$ (same sign) [96]	8 TeV	$5.30^{+2.10}_{-1.80}$	0.0	0.0	0.0	0.0	100.0
CMS $pp \to t\bar{t}H \to 3\ell$ [96]	8 TeV	$3.10^{+2.40}_{-2.00}$	0.0	0.0	0.0	0.0	100.0
CMS $pp \to t\bar{t}H \to 4\ell$ [96]	8 TeV	$-4.70^{+5.00}_{-1.30}$	0.0	0.0	0.0	0.0	100.0
CMS $pp \to t\bar{t}H \to t\bar{t}b\bar{b}$ [96]	7/8 TeV	$0.70^{+1.90}_{-1.90}$	0.0	0.0	0.0	0.0	100.0
CMS $pp \to t\bar{t}H \to t\bar{t}\gamma\gamma$ [96]	8 TeV	$2.70^{+2.60}_{-1.80}$	0.0	0.0	0.0	0.0	100.0
CMS $pp \to t\bar{t}H \to t\bar{t}\tau\tau$ [96]	7/8 TeV	$-1.30^{+6.30}_{-5.50}$	0.0	0.0	0.0	0.0	100.0
CMS $pp \to H \to \tau\tau$ (VBF) [91]	7/8 TeV	$0.93^{+0.41}_{-0.41}$	14.3	85.7	0.0	0.0	0.0
CMS $pp \to WH \to \ell\nu b\bar{b}$ [93]	7/8 TeV	$1.10^{+0.90}_{-0.90}$	0.0	0.0	100.0	0.0	0.0
CMS $pp \to ZH \to 2\ell b\bar{b}$ [93]	7/8 TeV	$0.80^{+1.00}_{-1.00}$	0.0	0.0	0.0	100.0	0.0
CMS $pp \to ZH \to \nu\nu b\bar{b}$ [93]	7/8 TeV	$1.00^{+0.80}_{-0.80}$	0.0	0.0	0.0	100.0	0.0
CMS $pp \to VH \to \tau\tau$ [91]	7/8 TeV	$0.98^{+1.68}_{-1.50}$	0.0	0.0	50.0	50.0	0.0
CMS $pp \to VH \to WW \to 2\ell 2\nu$ [88]	7/8 TeV	$0.39^{+1.97}_{-1.87}$	3.6	3.6	46.4	46.4	0.0
CMS $pp \to VH \to VWW$ (hadronic V) [89]	7/8 TeV	$1.00^{+2.00}_{-2.00}$	4.2	3.5	49.1	43.2	0.0
CMS $pp \to WH \to WW \to 3\ell 3\nu$ [88]	7/8 TeV	$0.56^{+1.27}_{-0.95}$	0.0	0.0	100.0	0.0	0.0

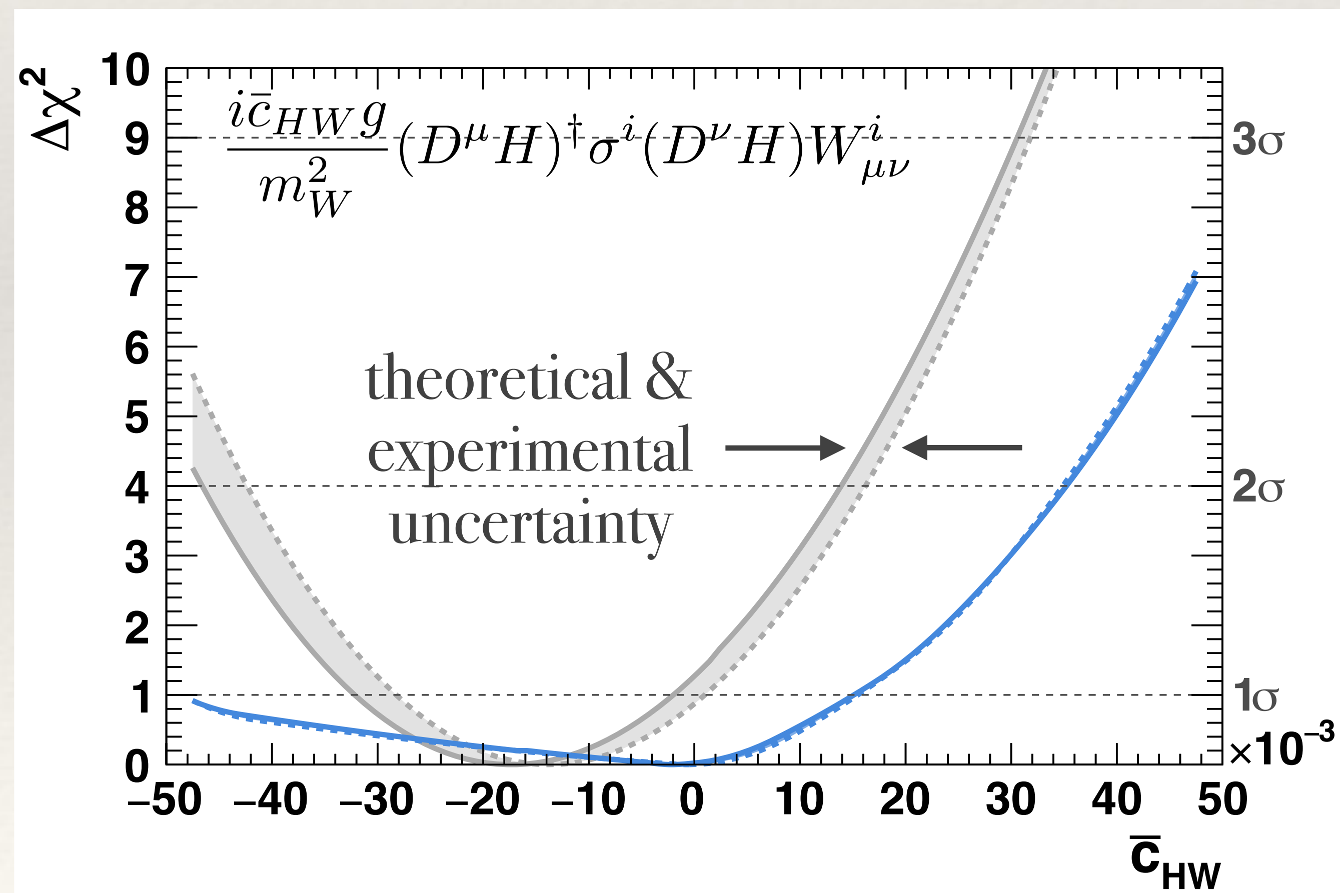
Higgs EFT current status

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

[Ellis, Sanz, You ` 14]
[Corbett, Eboli, Goncalves, Fraile, Plehn, Rauch ` 15]
[Falkowski, Gonzales, Greljo, Marzocca ` 15]
[CE, Kogler, Schulz, Spannowsky ` 15]



- aim towards a fully differential fit



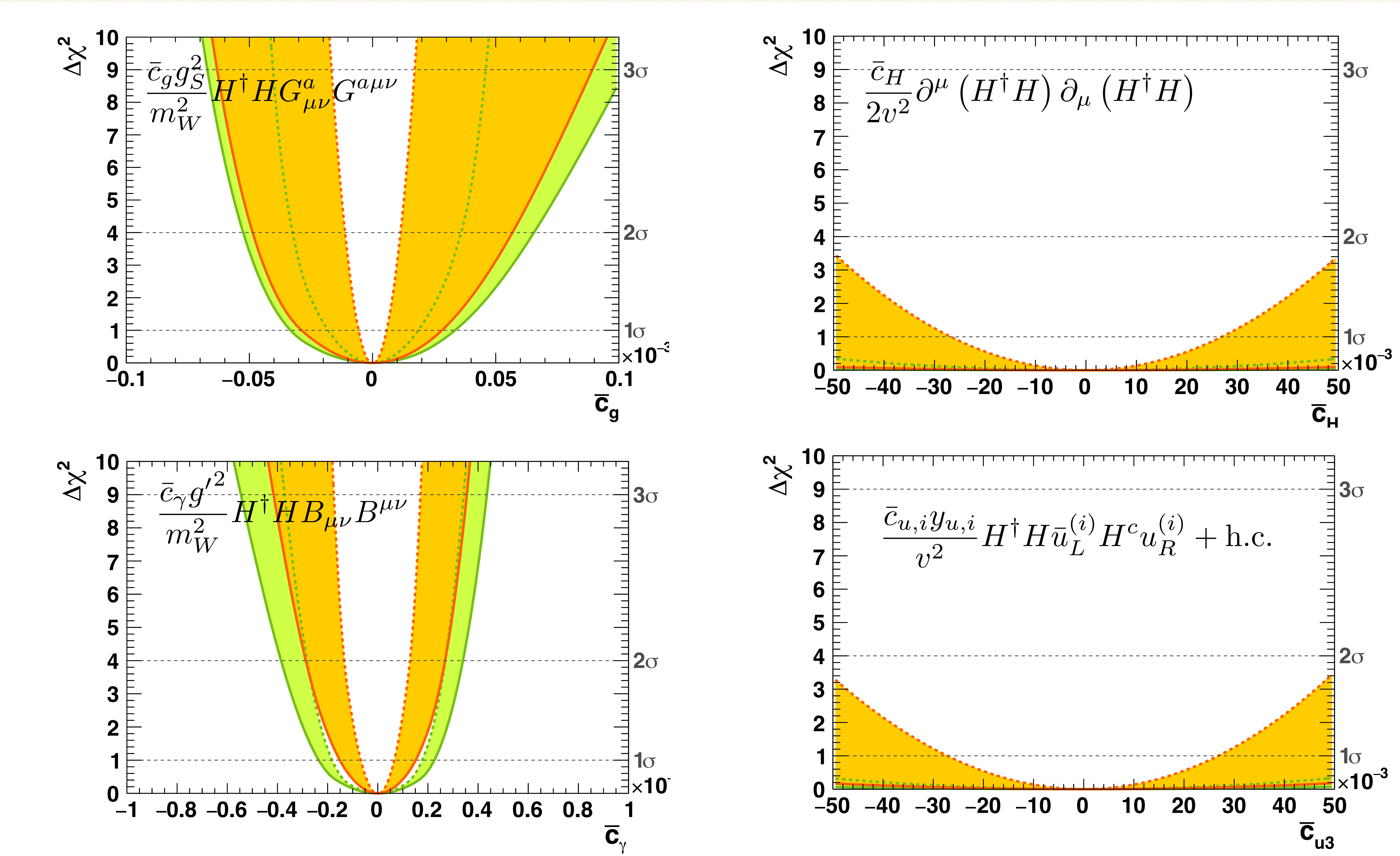
- not terribly sensitive at this stage, coupling deviations of order 10% SM allowed

- systematic uncertainties not too limiting anymore in some places

[CE, Kogler, Schulz, Spannowsky ` 15]

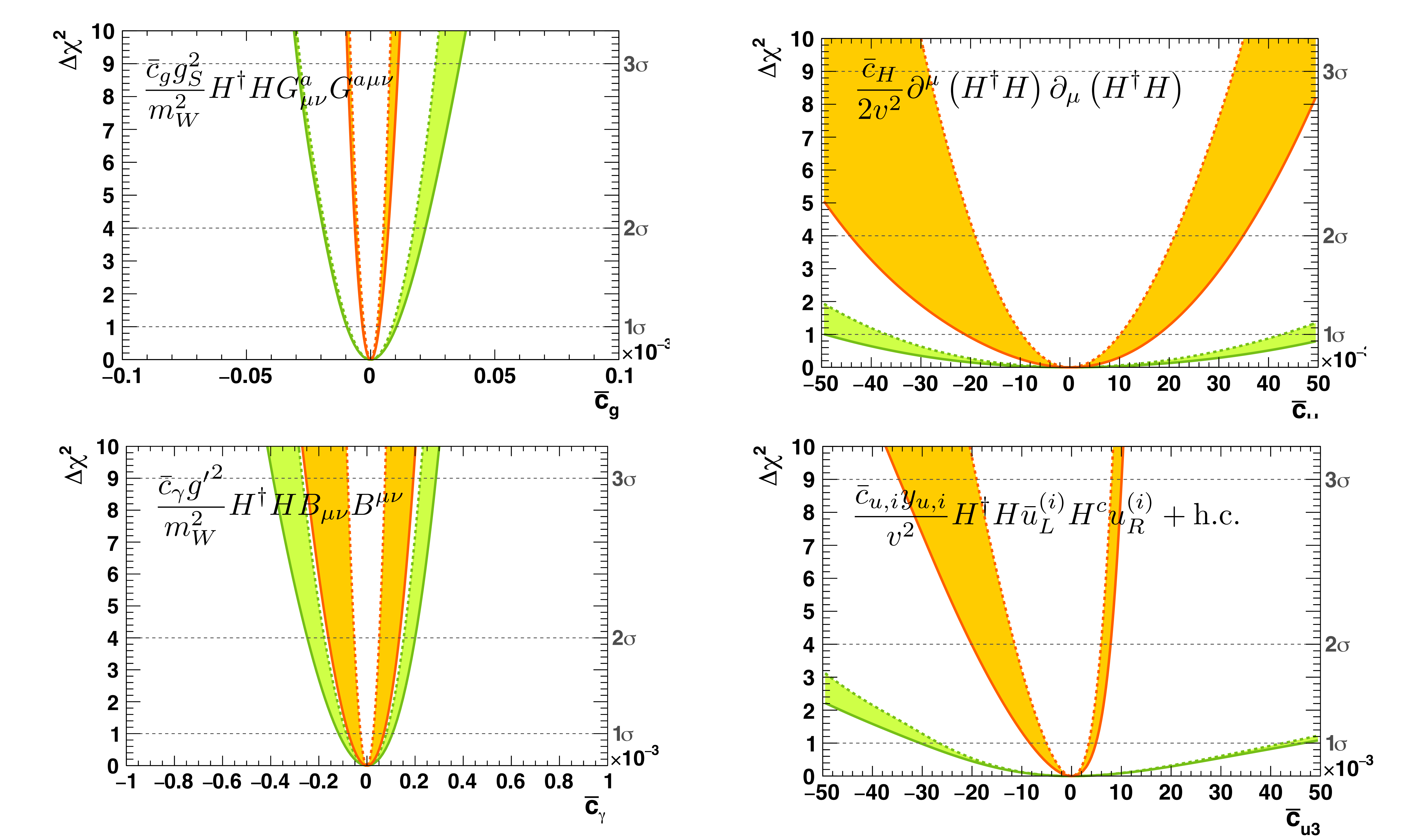
Higgs EFT current status

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



Higgs EFT current status

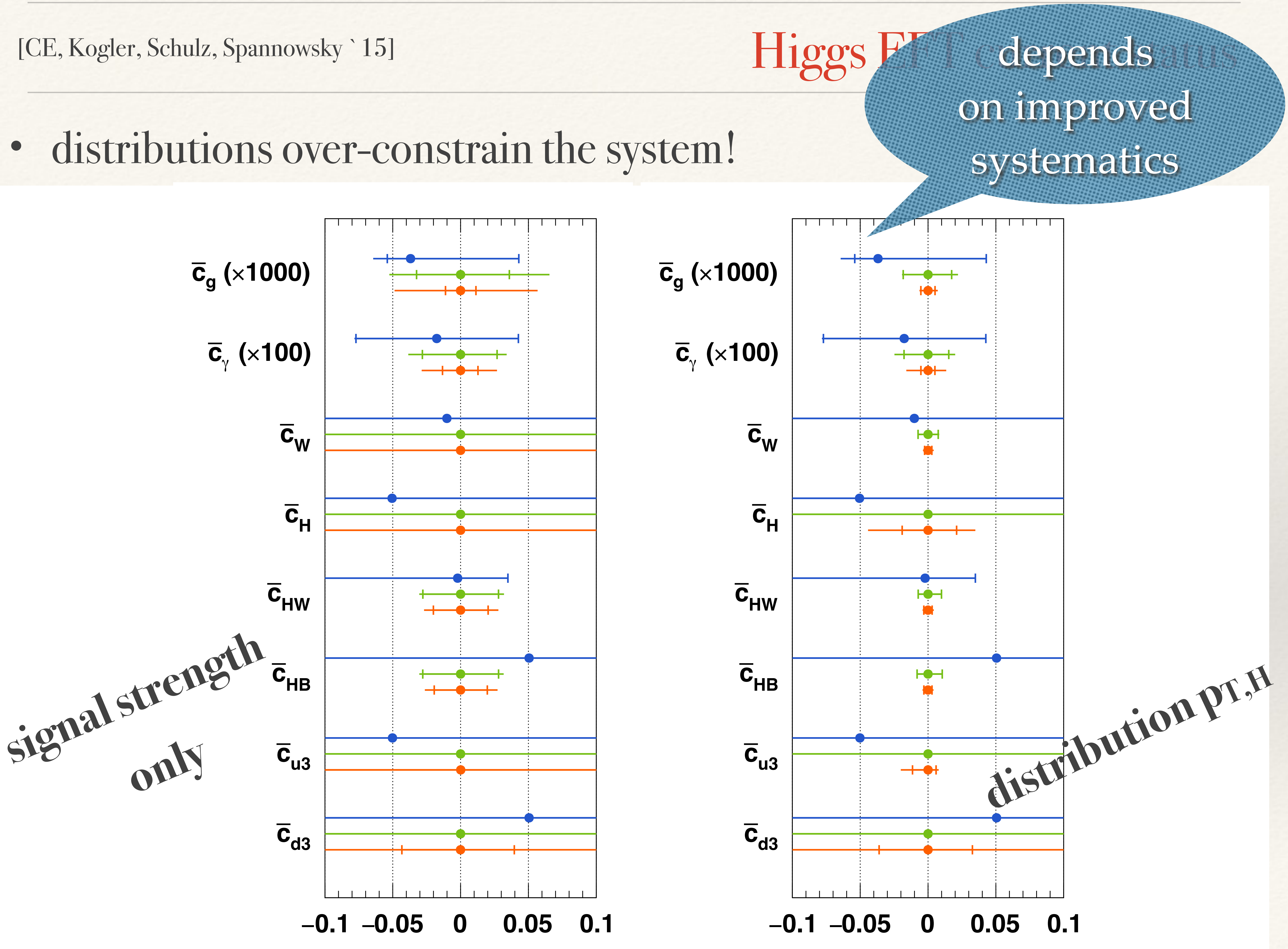
- …switch on differential distributions



[CE, Kogler, Schulz, Spannowsky ` 15]

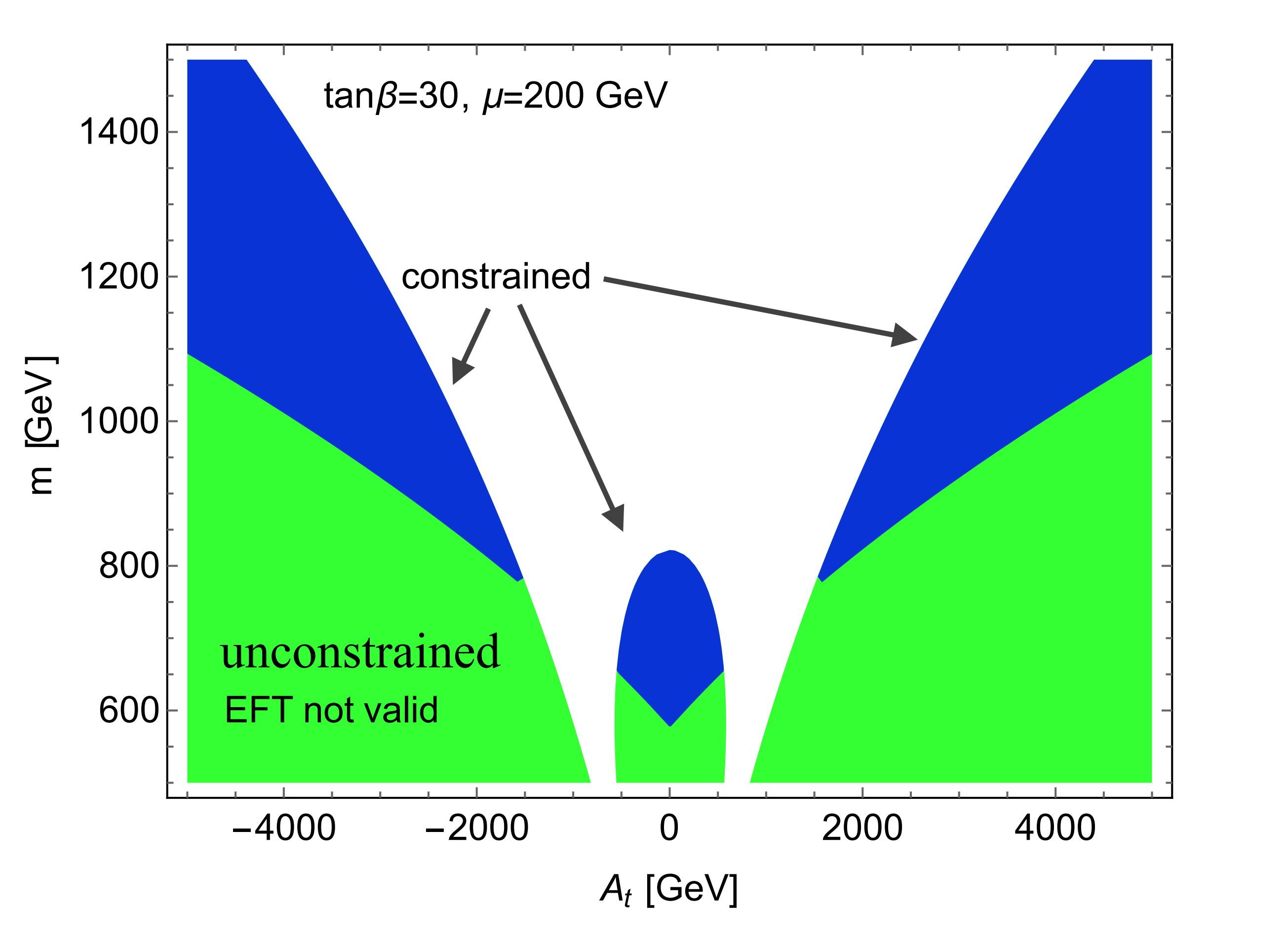
Higgs EFT

- distributions over-constrain the system!



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**

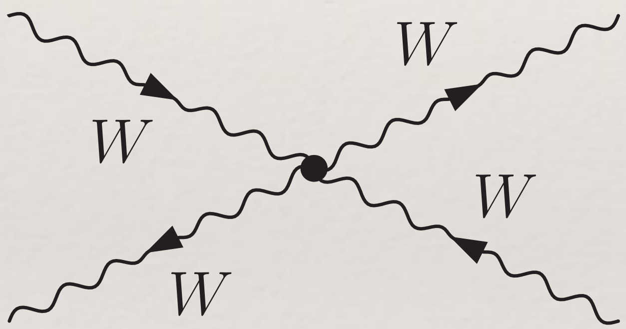
Implications for new physics: Compositeness

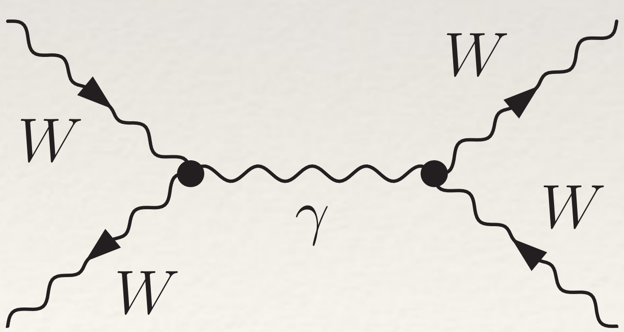
- deviations from the SM Higgs couplings pattern unavoidable in PC

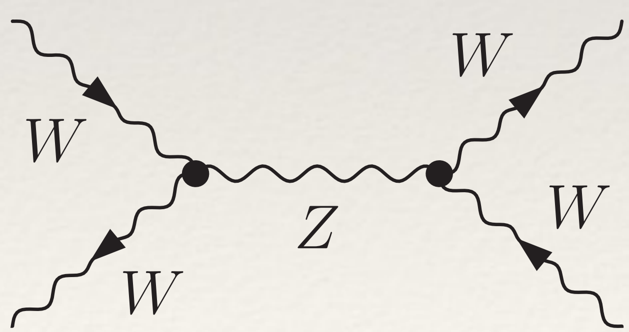
$$SO(5)/SO(4) + \text{extra states}$$

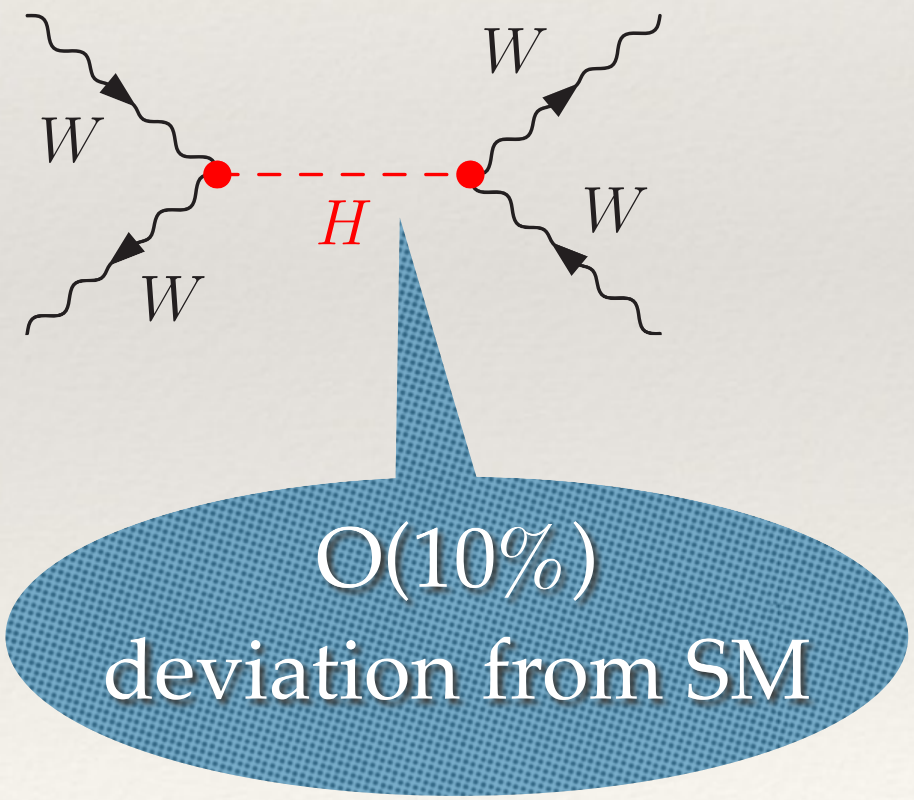
- UV complete picture should lend good UV properties off-resonance

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



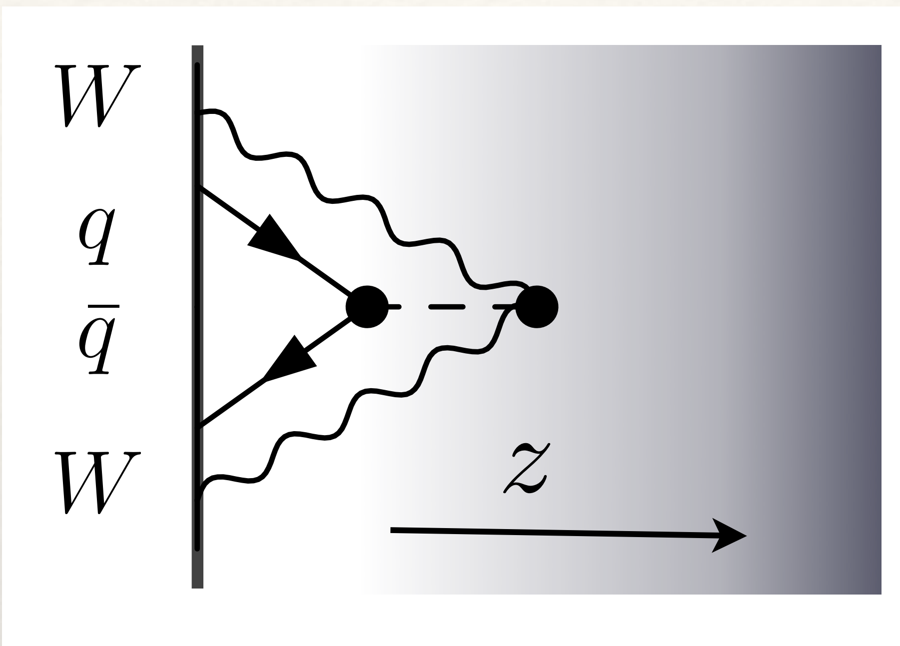






Implications for new physics: Compositeness

- Large N arguments (e.g. holography)



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

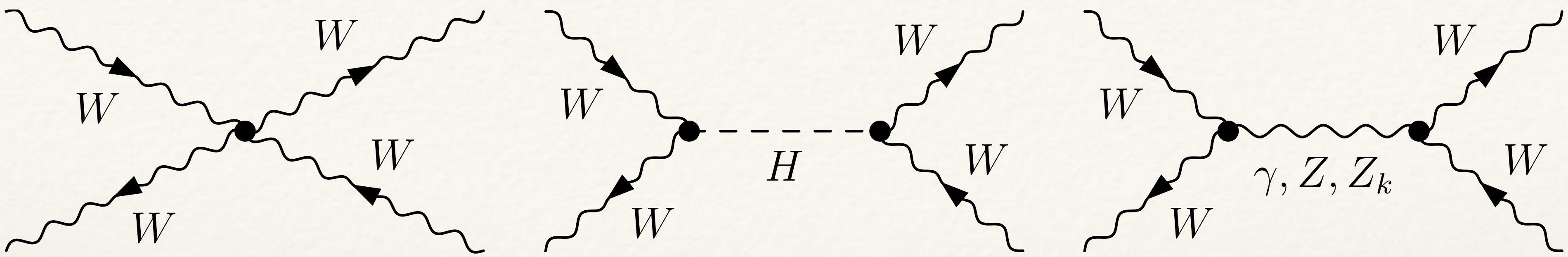
$$\widetilde{\Gamma}[J] = \sum_n \frac{i^n}{n!} \int \cdots \int \mathrm{d}^4 x_1 \cdots \mathrm{d}x_n\, \widetilde{\Gamma}_n(x_1, \ldots, x_n)$$
$$\times\, J(x_1) \cdots J(x_n)\,,$$

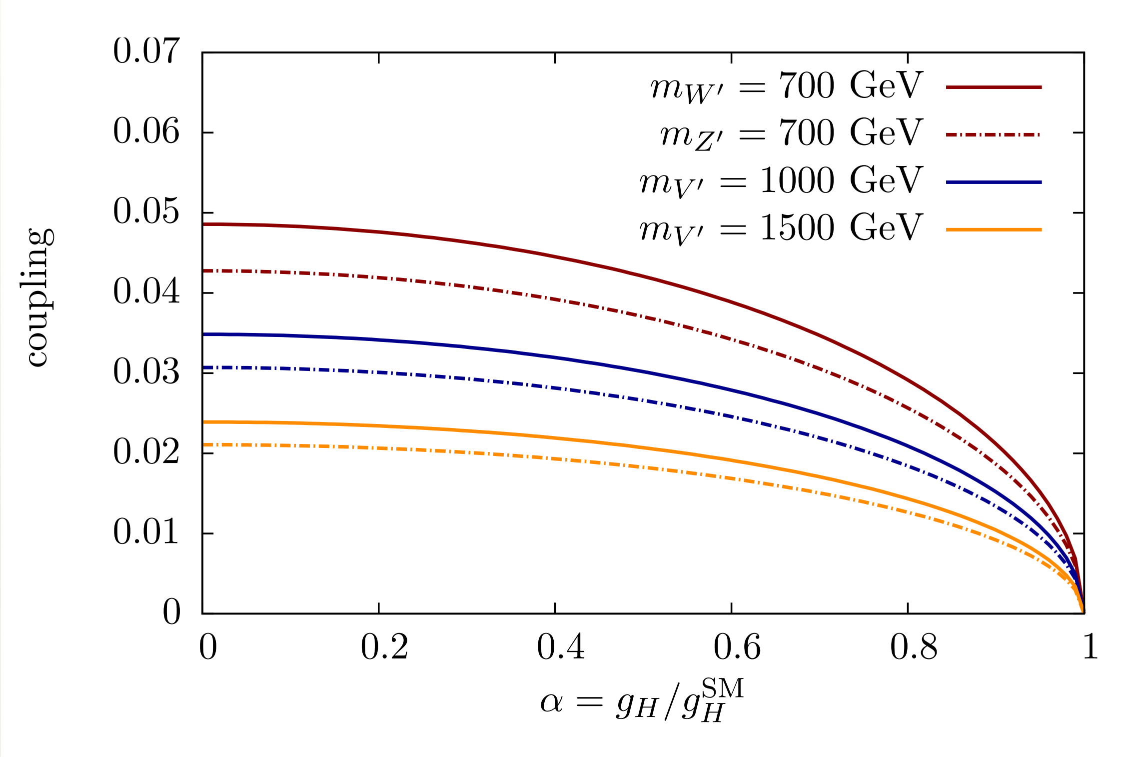
- unitarity restored in general background geometries

[Stancato, Terning ` 12]
[CE, Spannowsky, Stancato, Terning ` 13]

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

Implications for new physics: Compositeness





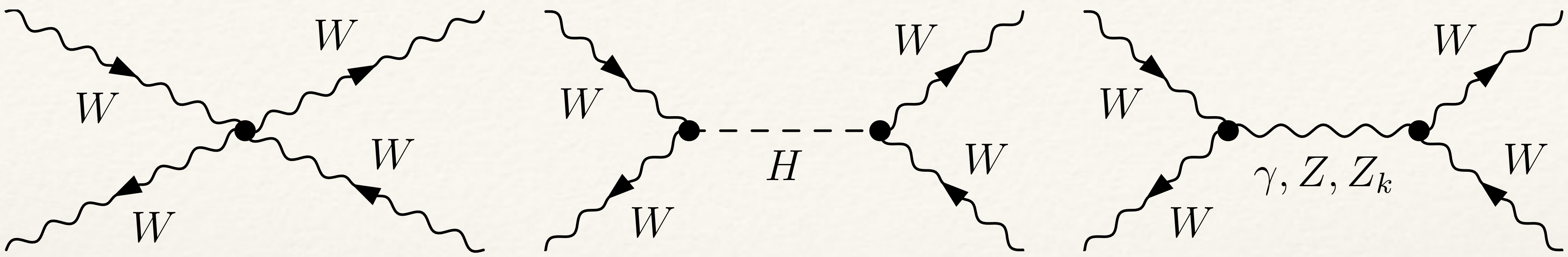
$$g_{WWWW} = g^2_{WW\gamma} + \sum_i g^2_{WWZ_i}$$

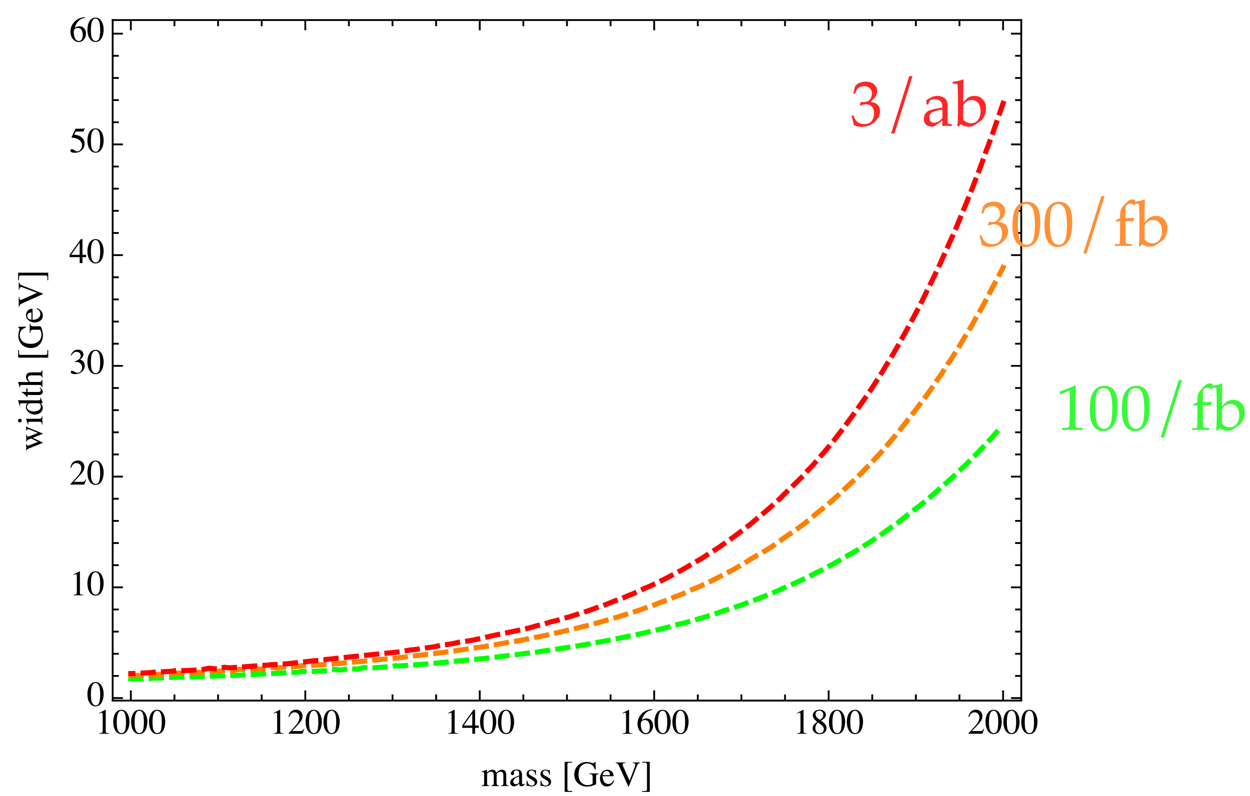
$$4m_W^2 g_{WWWW} = \sum_i 3m_i^2 g^2_{WWZ_i} + \sum_i g^2_{WWH_i}\,,$$

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

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

Implications for new physics: Compositeness





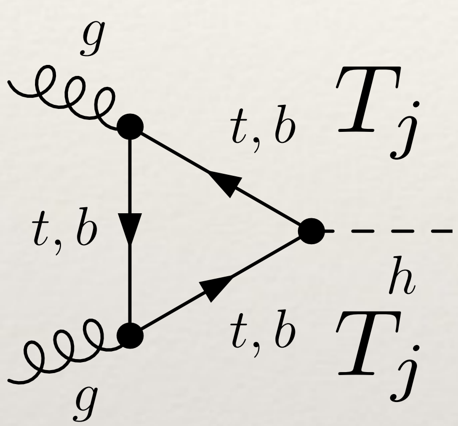
[CE, Harris, Spannowsky, Takeuchi ` 15]

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

Compositeness: Complementary channels

- if the Higgs is a PNGB: operators $\sim H^\dagger H$ are suppressed by explicit symmetry violation

- top partners as predicted by PC conspire

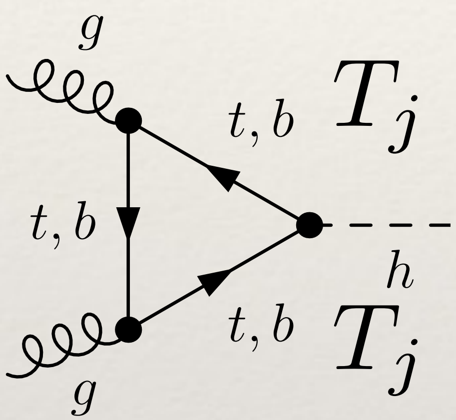


suppressed

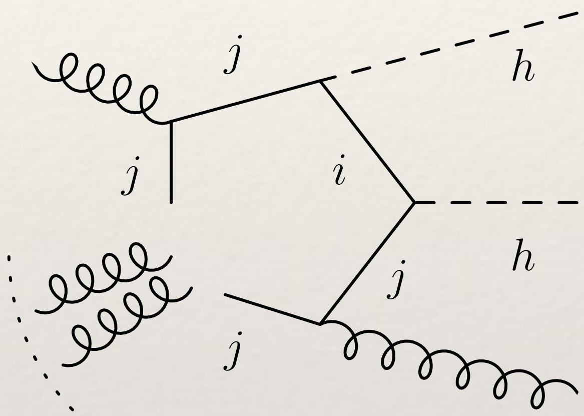
Compositeness: Complementary channels

- if the Higgs is a PNGB: operators $\sim H^\dagger H$ are suppressed by explicit symmetry violation

- top partners as predicted by PC conspire



suppressed, but



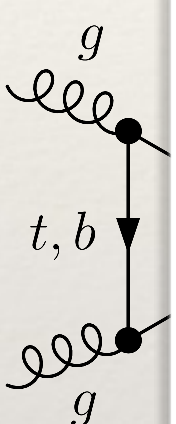
unsuppressed

similar $h \to Z\gamma$

[Contino et al. `13]

Compositeness: Complementary channels

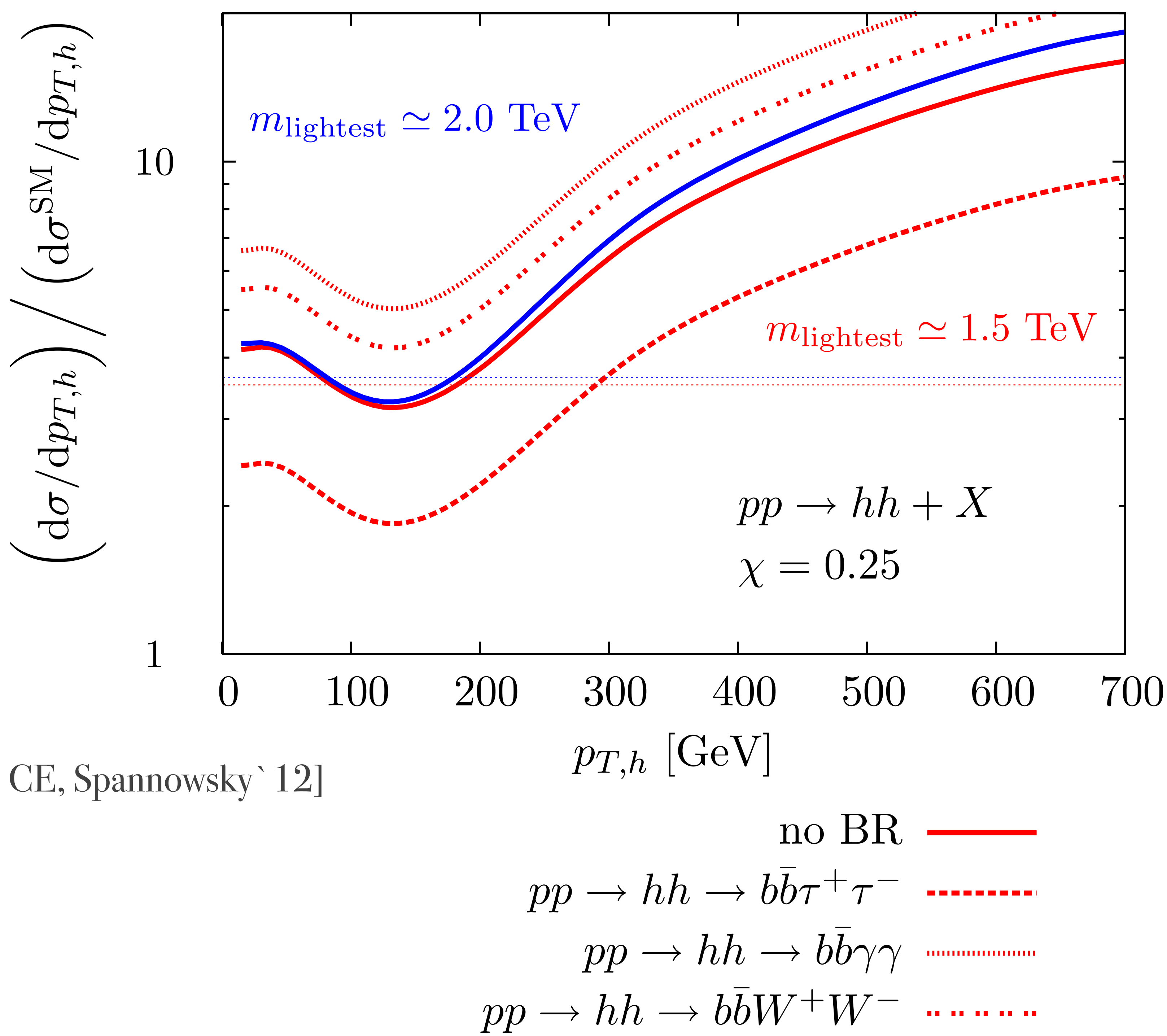
- if the
  expl
- top p



$\simeq 3$

ed

$Z\gamma$

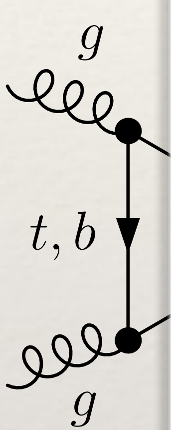


[Dolan, CE, Spannowsky` 12]

$$\sigma(hh+j)/\sigma(\mathrm{SM}) \simeq 4.6$$

Compositeness: Complementary channels

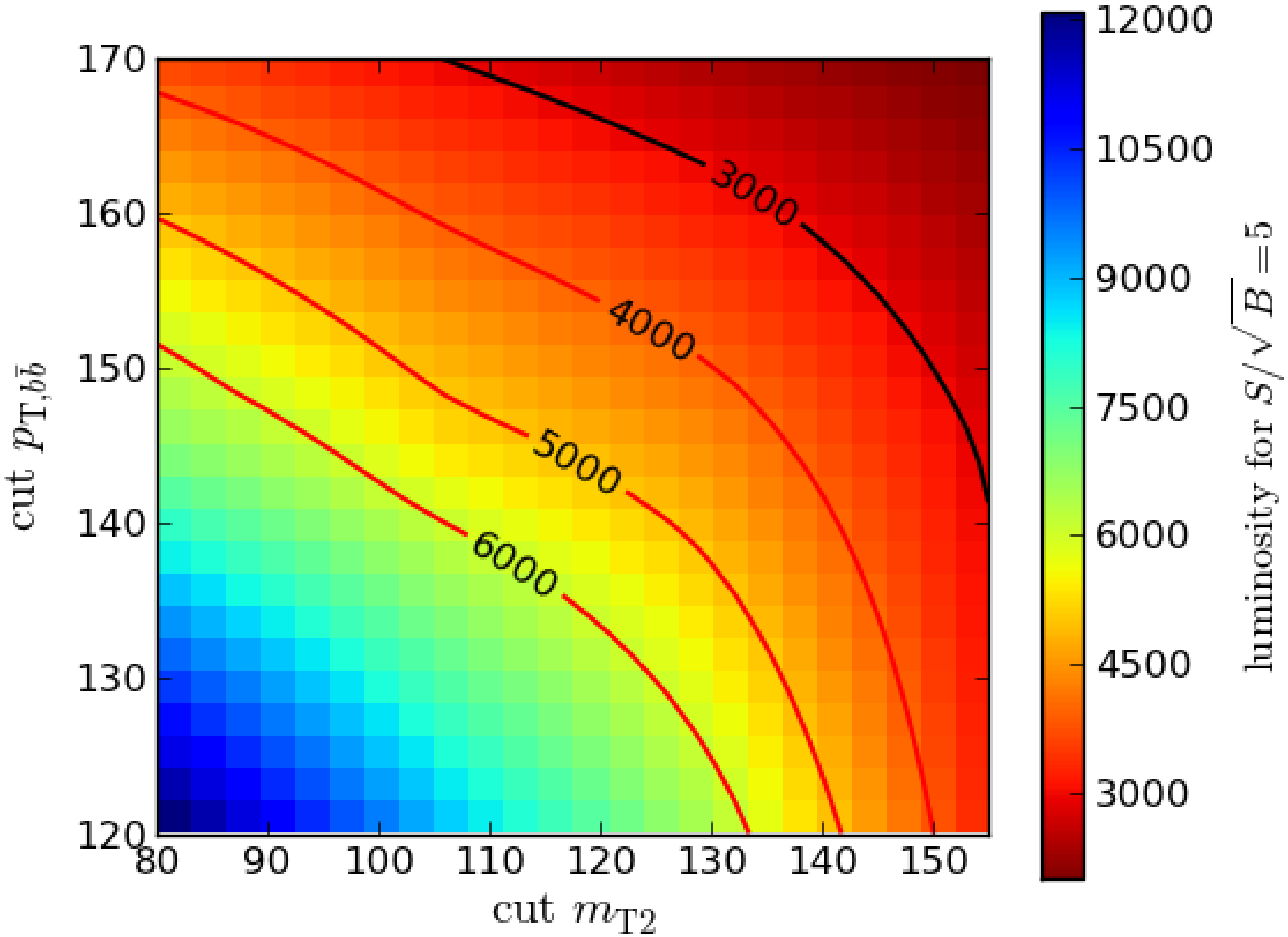
- if the … expl…
- top p…



… ed

… $Z\gamma$

$hh \to b\bar{b}\tau\tau$



[Barr, Dolan, CE, Spannowsky` 13]

Summary

higher statistics (= smaller systematics)!

differential cross sections !

high momentum transfer final states !

direct evidence for exotics ?!

Summary

higher statistics (= smaller systematics)!

differential cross sections !

high momentum transfer final states !

direct evidence for exotics ?!

- ☛ EFT analyses have seen tremendous progress recently
- ☛ developments for new fully differential fitting techniques
- ☛ pitfalls are known, not relevant at this stage of the LHC programme
- ☛ expect a tremendous improvement with more data
- ☛ …. but ultimately a losing game too, if new physics is decoupled
- ☛ LHC is zeroing in on exotics as predicted in composite Higgs models