EFT Fits to Higgs Data

(in a dimension-6 operator framework)

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in collaboration with

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Particles, Strings, and the Early Universe

Collaborative Research Center SFB 676

The Standard Model (5 years ago)

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

← kinetic terms of gauge fields

$$+ i \bar{\Psi} \not{D} \psi + h.c.$$

← kinetic and dynamic terms of matter fields (includes interactions)

The Standard Model (today)

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

kinetic terms
of gauge fields

$$+ i \bar{\Psi} \not{D} \psi + h.c.$$

kinetic and dynamic
terms of matter fields
(includes interactions)

$$+ \bar{\Psi}_i y_{ij} \psi_j \phi + h.c.$$

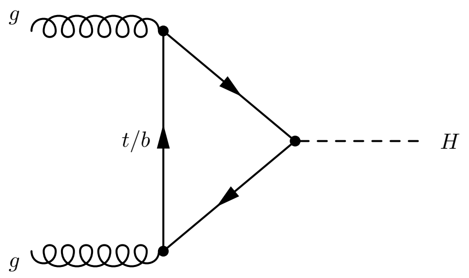
mass terms of
matter fields

$$+ |D_\mu \phi|^2 - V(\phi)$$

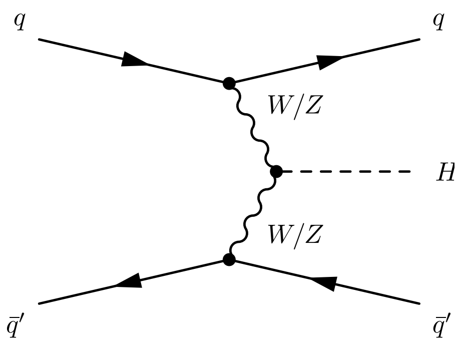
mass and dynamics
of the Higgs field

Testing the Higgs Sector

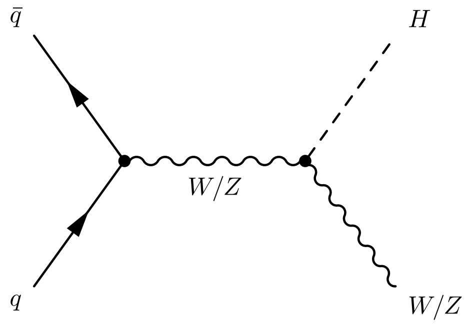
Measurements at the LHC: cover all bases



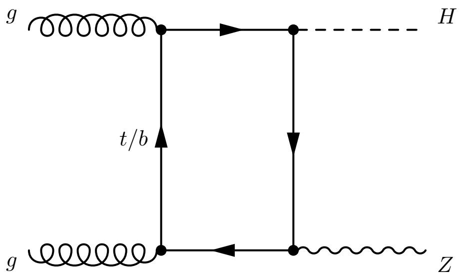
ggH



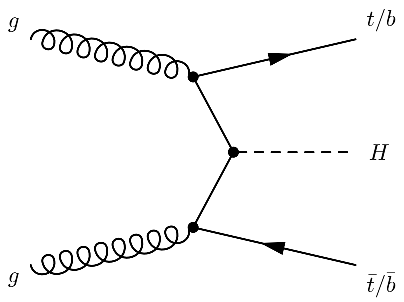
WBF



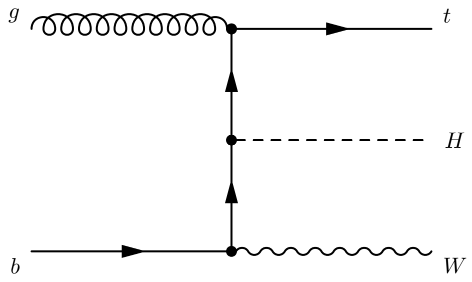
qq→VH



gg→ZH

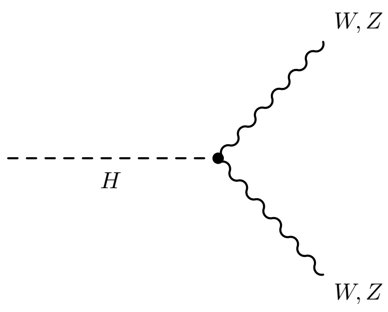


ttH, bbH

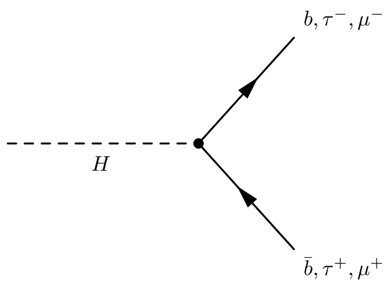


WtH

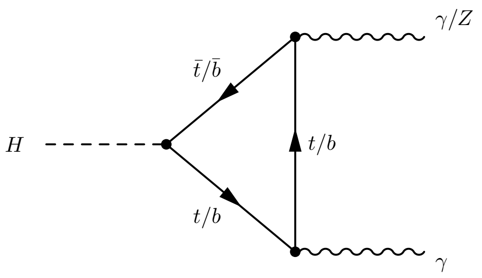
⊗



H→WW, H→ZZ



H→bb, H→ττ, H→μμ



H→γγ, H→Zγ

Kappa Framework

Assumption: single, narrow resonance at ~ 125 GeV

- signal strengths

$$\mu = \frac{\sigma \times \mathrm{BR}}{(\sigma \times \mathrm{BR})_{\mathrm{SM}}}$$

(this is what we "measure")

- decompose into production and decay:

$$\mu_i^f = \frac{\sigma_i \times \mathrm{BR}_f}{(\sigma_i \times \mathrm{BR}_f)_{\mathrm{SM}}} \equiv \mu_i \times \mu_f, \quad \text{with} \quad \mu_i = \frac{\sigma_i}{(\sigma_i)_{\mathrm{SM}}} \quad \text{and} \quad \mu_f = \frac{\mathrm{BR}_f}{(\mathrm{BR}_f)_{\mathrm{SM}}}$$

- in terms of unknown couplings (κ framework)

production cross section

partial decay width

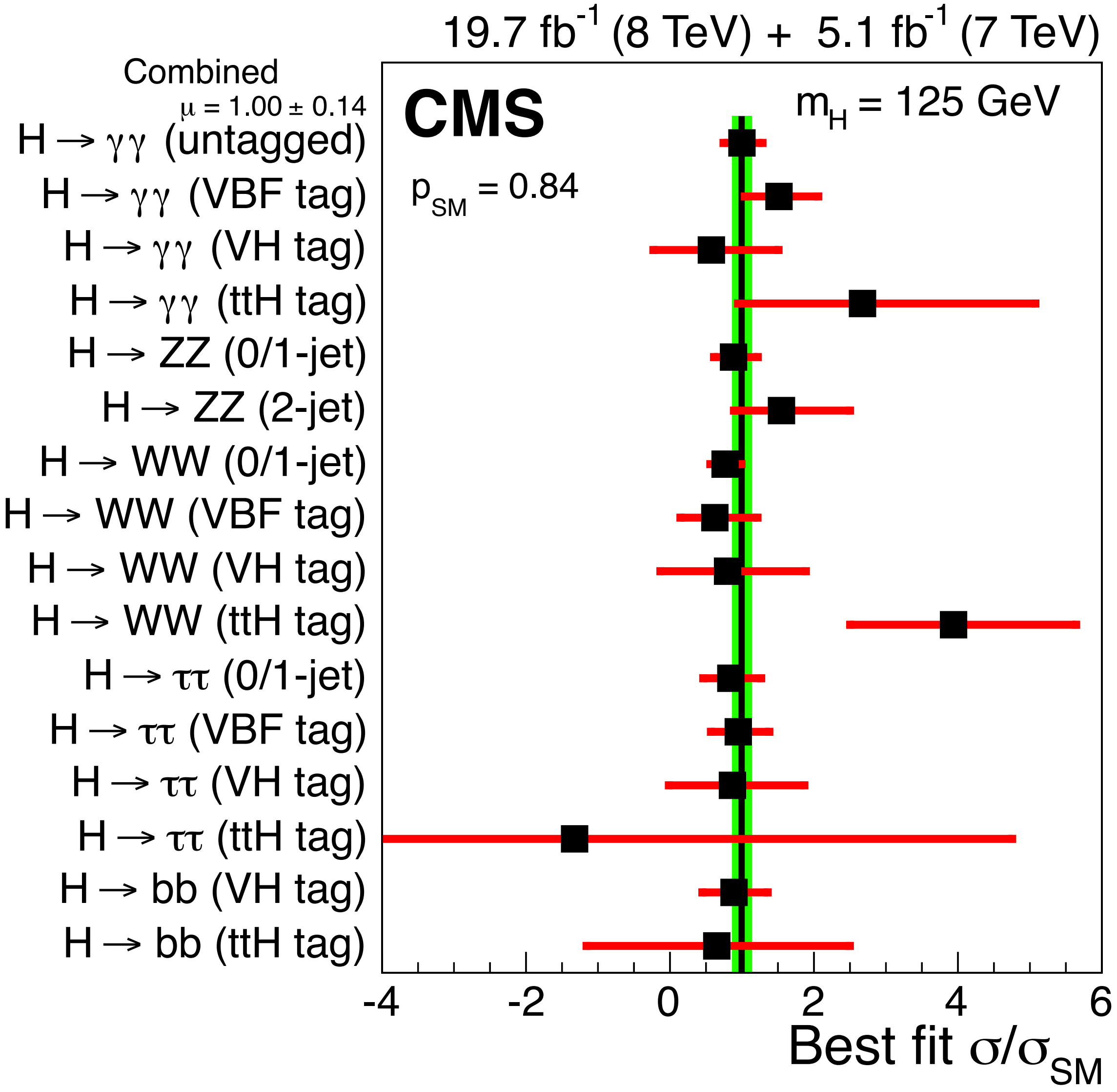
$$\sigma(i \to H \to f) = \frac{\sigma_i(\kappa_j) \cdot \Gamma_f(\kappa_j)}{\Gamma_H(\kappa_j)} \sim \frac{g_i^2\, g_f^2}{\Gamma_H}$$

total width

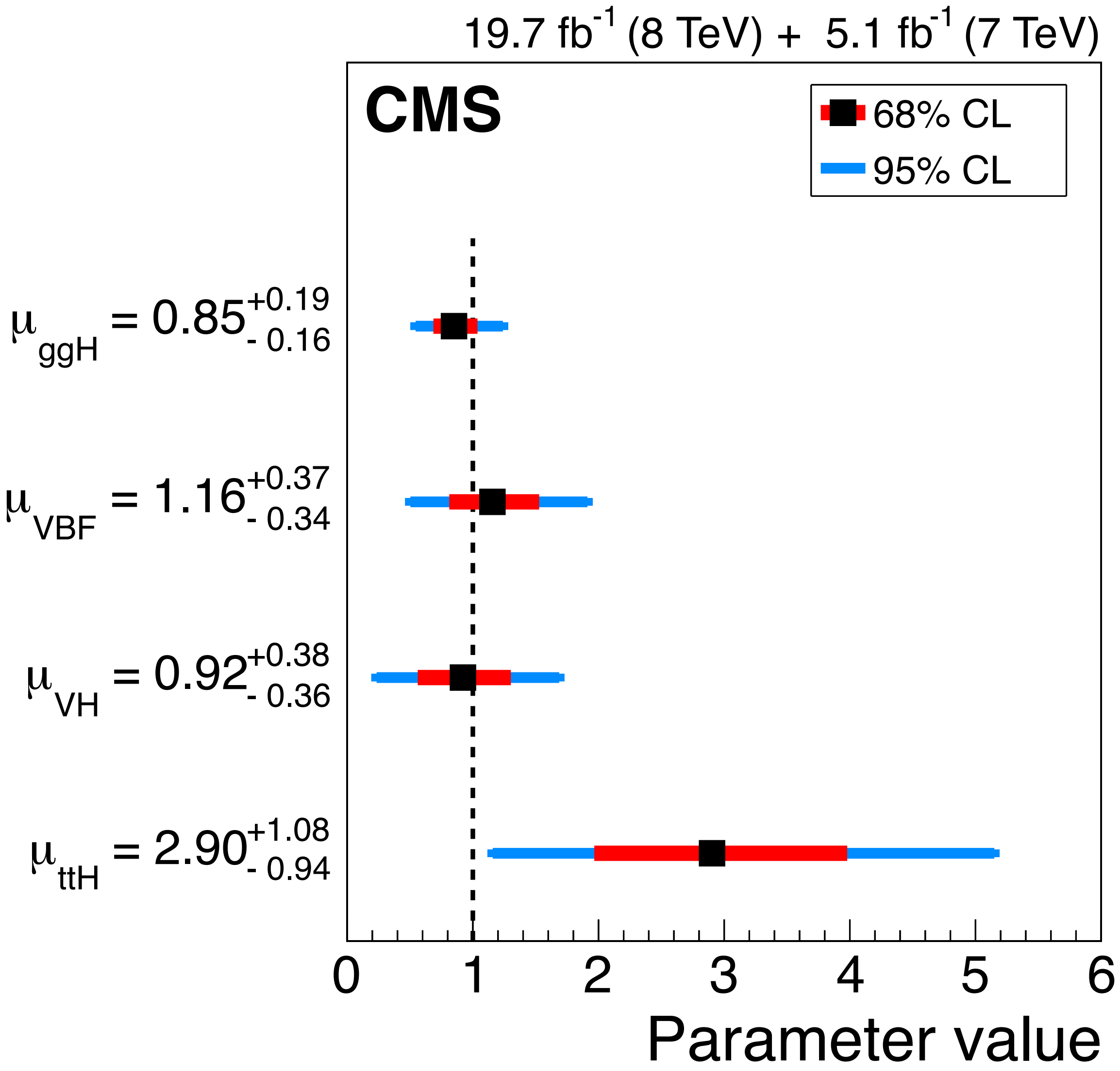
Testing the Higgs Sector

[CMS, 1412.8662]

Measurements



Interpretation



Fits based on total rates, no dynamics

Back to what we know

> A man should look for what is, and not for what he thinks should be.
>
> A. Einstein

Or: Based on what we know, what can we add to the SM?

Adding new terms to the SM Lagrangian:

Wilson coefficients

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{g_i^2}{\Lambda_{\mathrm{NP}}^2} \mathcal{O}_i$$

operators of dimension 6

- respect SM gauge symmetry (SU(2) x U(1))
- include only SM fields

mass scale of new physics (should be large)

Dim-6 SILH Basis

- Focus on operators with Higgs involvement
- Do not consider operators constrained by electroweak precision measurements (and $c_T = 0$, $c_W = -c_B$)

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

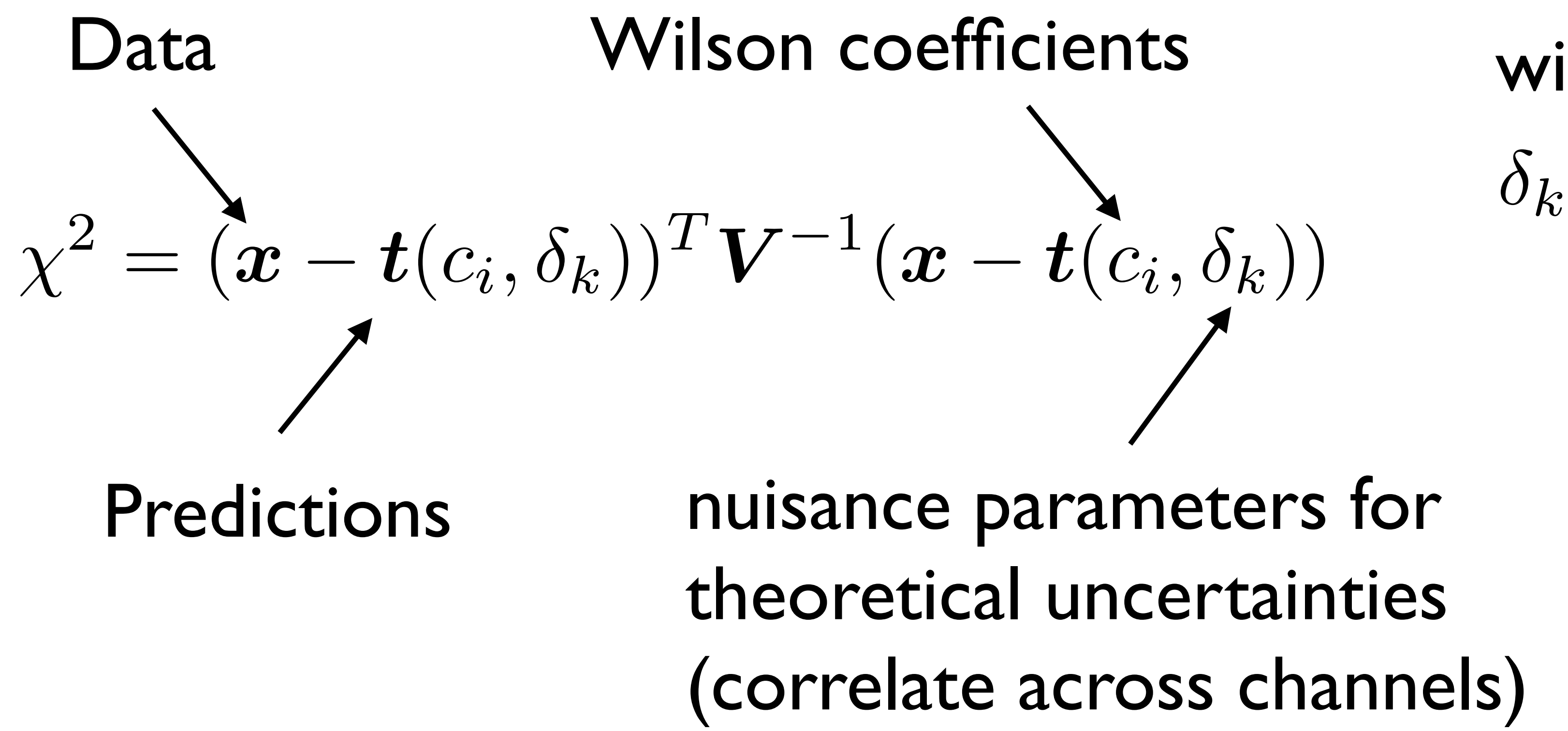
- **8** operators of interest left

Focus on linear contribution: $\mathcal{M} = \mathcal{M}_{\mathrm{SM}} + \mathcal{M}_{d=6}$

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

Fit Framework

- Fast parametrisation of calculations: Professor [Buckley et al., 0907.2973]
  - production: VBFNLO [Arnold et al., 1207.4975]
  - decay: eHDECAY [Contino et al., 1403.3381]
  - predictions normalised to results from HXSWG
- Run 1 Higgs data: HiggsSignals [Bechtle et al., 1305.1933]
- Statistical framework: Gfitter [Gfitter group, 0811.0009]



Data

Wilson coefficients

$$\chi^2 = (\boldsymbol{x} - \boldsymbol{t}(c_i, \delta_k))^T \boldsymbol{V}^{-1} (\boldsymbol{x} - \boldsymbol{t}(c_i, \delta_k))$$

Predictions

nuisance parameters for theoretical uncertainties (correlate across channels)

with $\boldsymbol{V} = \boldsymbol{V}_{\text{stat}} + \boldsymbol{V}_{\text{syst}}$

δ_k taken to be normal distributed

Theoretical Uncertainties

- assume uncertainties from SM h.o. calculations

production process		decay process	
$pp \to H$	14.7	$H \to b\bar{b}$	6.1
$pp \to H + \text{j}$	15	$H \to \gamma\gamma$	5.4
$pp \to H + 2\text{j}$	15	$H \to \tau^+\tau^-$	2.8
$pp \to HZ$	5.1	$H \to 4l$	4.8
$pp \to HW$	3.7	$H \to 2l2\nu$	4.8
$pp \to t\bar{t}H$	12	$H \to Z\gamma$	9.4
		$H \to \mu^+\mu^-$	2.8

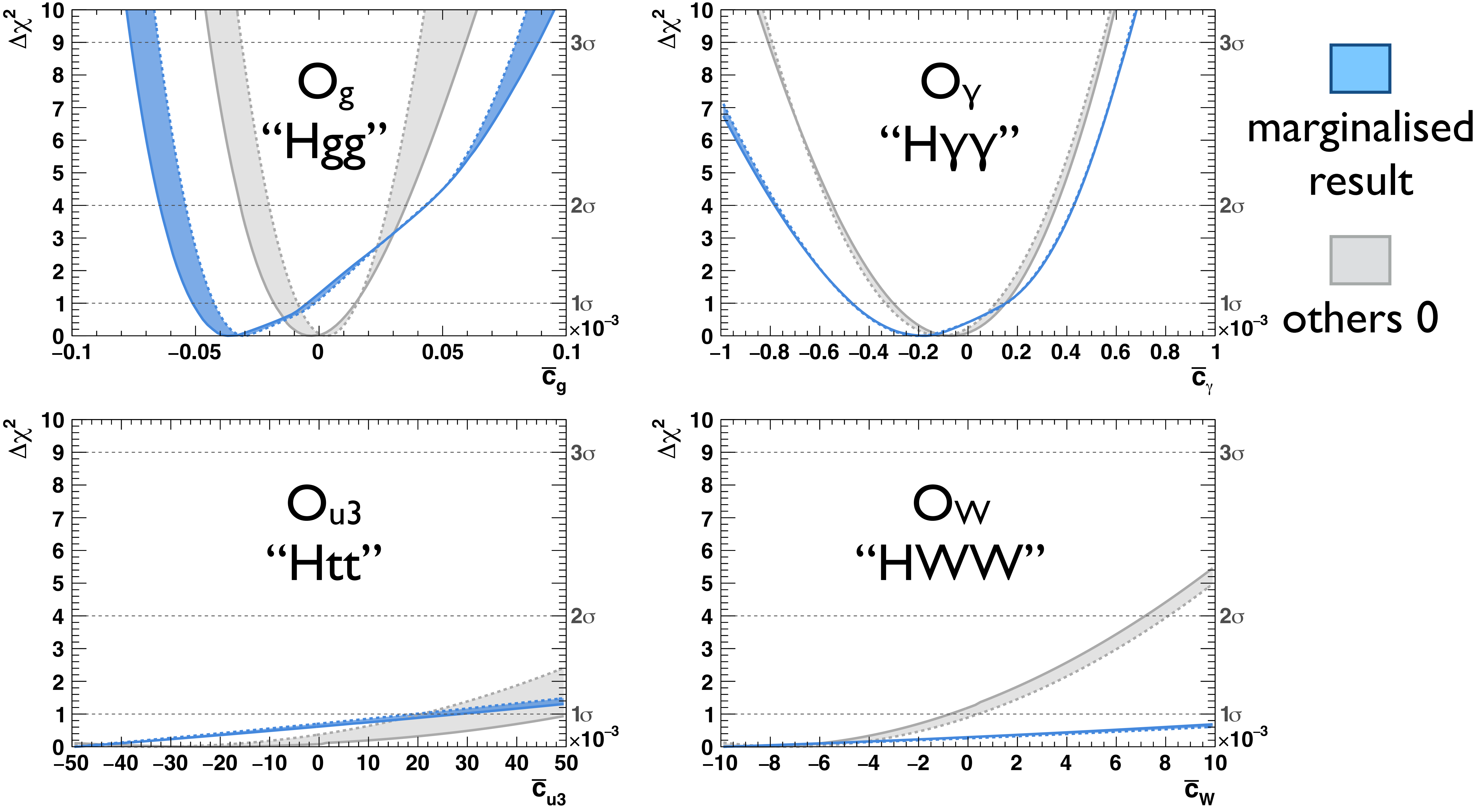
- two nuisance parameters (δ_{SM}, δ_{O6}) for each
  - production
  - decay

$$\boxed{\mu_{i,f} = \frac{\sigma^{\text{O6}}_{i,f} + u^{\text{O6}}_{i,f}(1 - \delta^{\text{O6}}_{i,f})}{\sigma^{\text{SM}}_{i,f} + u^{\text{SM}}_{i,f}(1 - \delta^{\text{SM}}_{i,f})}}$$

process, in other words: rate uncertainties only (for now)

- 26 nuisances, 8 Wilson coefficients = 34 free parameters

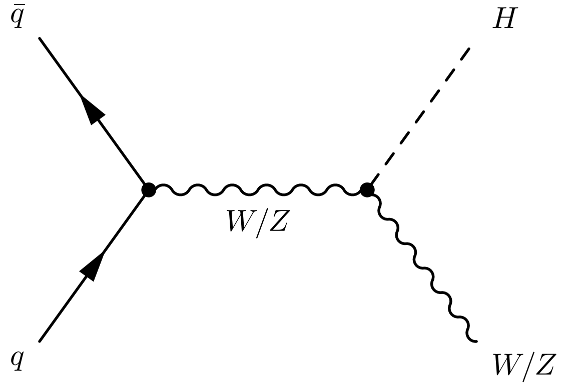
Constraints from Run 1



No noteworthy constraints on other 4 operators (within region of validity)

How well can the LHC do?

- Study LHC’s reach for 300 and 3000 fb^{-1} (per experiment)
- Extrapolate run 1 measurements
  - Consider measurements only for leptonic decays of W, Z



$\longrightarrow$ any final state

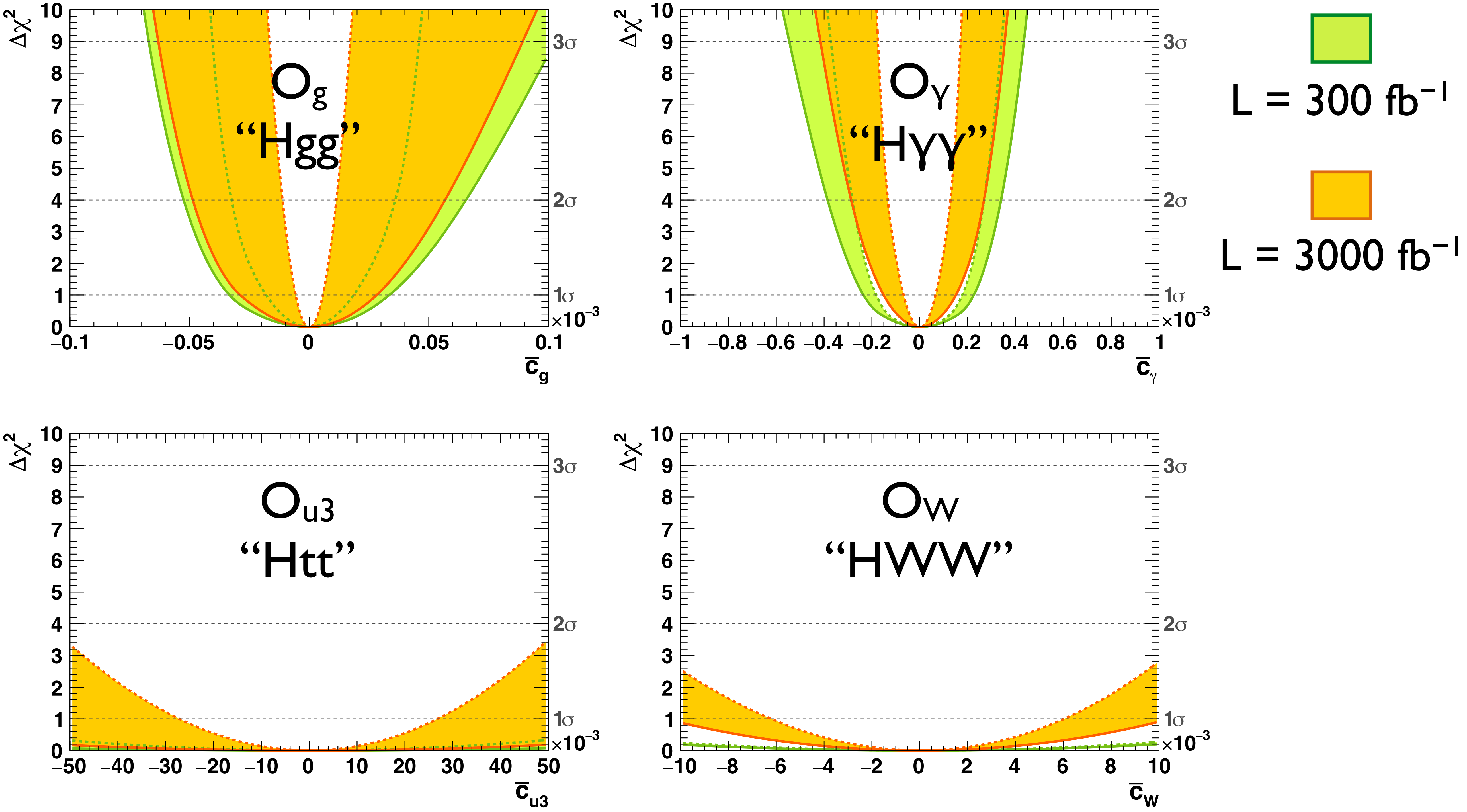
$\longrightarrow$ ℓν / ℓℓ

  - Estimate expected number of events

$$N = \epsilon_p \times \epsilon_d \times \sigma(H + X) \times \mathrm{BR}(H \to YY) \times \mathrm{BR}(X, Y \to \text{final state}) \times L$$

  - Additional uncertainties from systematics and backgrounds for each process
  - Scale systematic uncertainties with luminosity
- Cross check extrapolations with ATLAS/CMS results ✓

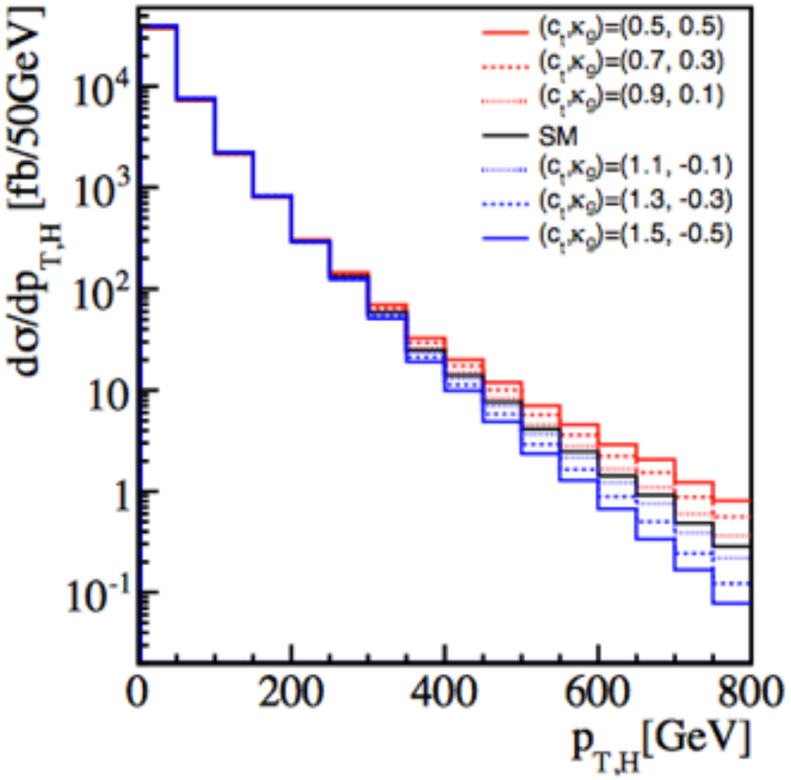
Constraints from Run 2



No constraints on O_{u3} and O_W with L = 300 to 3000 fb^{-1} !

Flat Directions

[Englert, Spannowsky, 1408.5147]

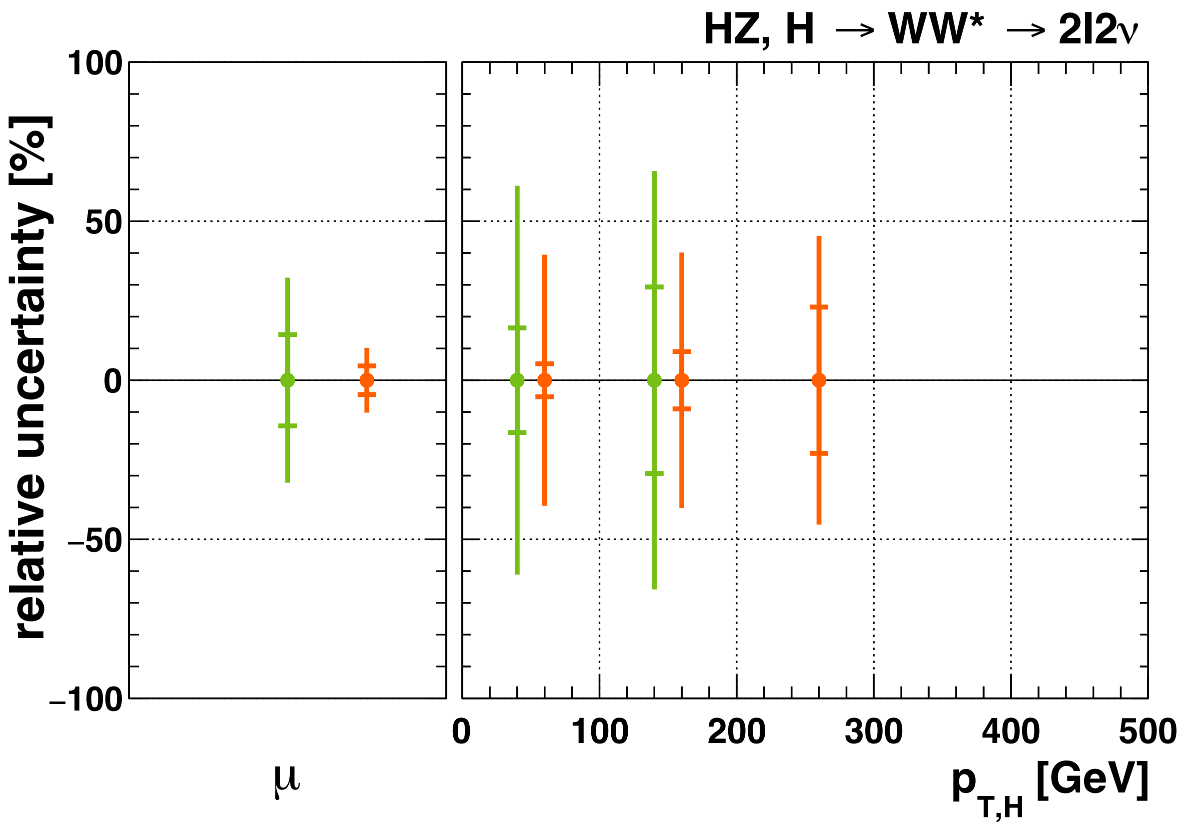


Multi-parameter fit

- Combinations of coefficients c_i can result in same signal strength
- No sensitivity without fixing some to 0

Solution

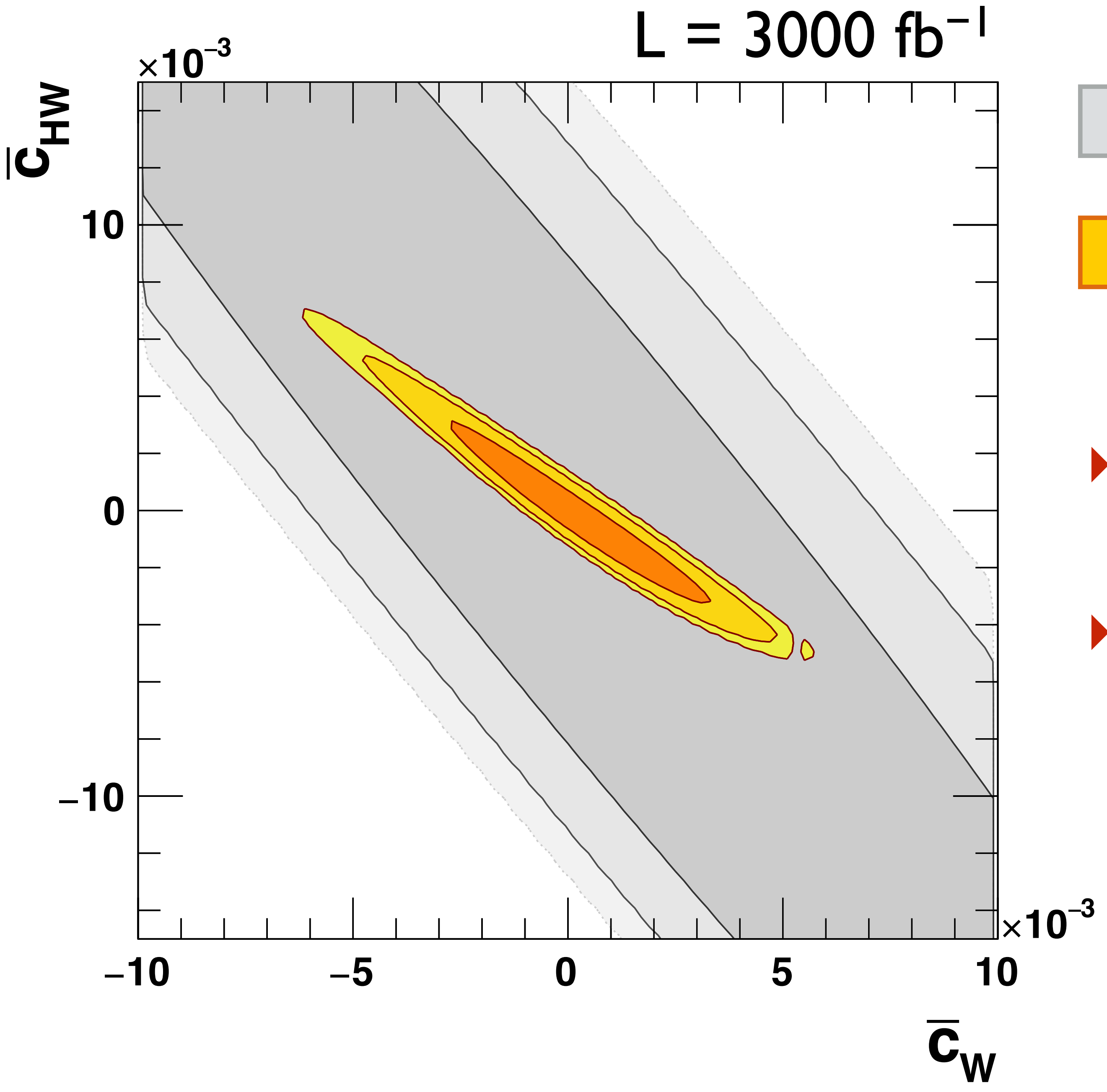
- different behaviour at high energies
- include differential measurements of $p_{T,H}$



Pseudo data

- extrapolate uncertainties from inclusive measurements
- correlated systematics across $p_{T,H}$
- assume perfect separation into production and decay channels

Lift flat directions



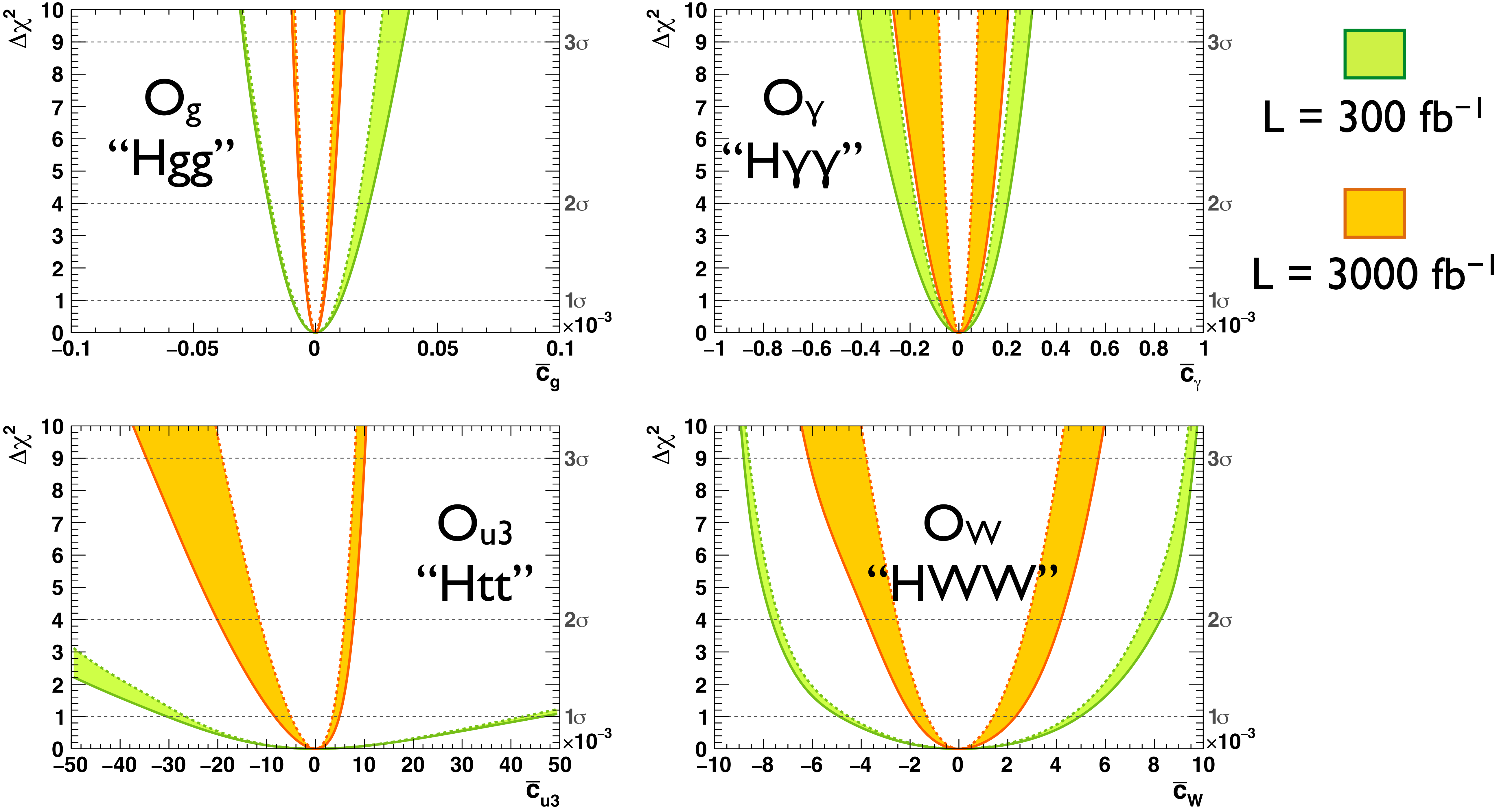
⬜ only signal strength

🟨 including $p_{T,H}$ measurements

- Strong correlations between coefficients are lifted
- Simultaneous constraints on all parameters possible

[Englert, RK, Schulz, Spannowsky, 1509.00672]

Constraints from Run 2



Much tighter constraints when using $p_{T,H}$ measurements!

[Englert, RK, Schulz, Spannowsky, 1509.00672]

Study Impact of Theory Uncertainties

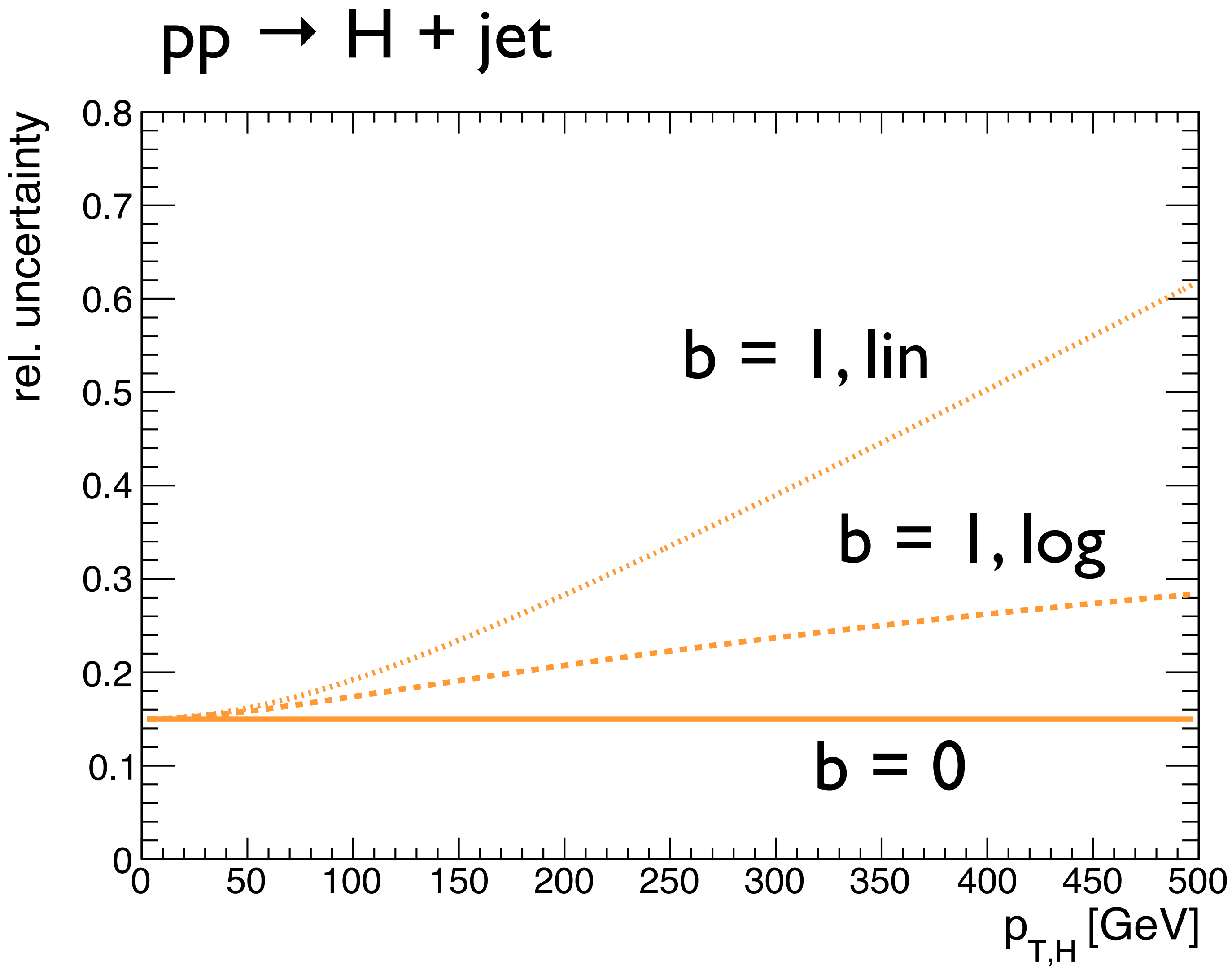
Uncertainties in tails of $p_{T,H}$

- One additional nuisance parameter for each production mode (+6)
  - vary inclusive rate and tails independently
  - logarithmic or linear dependence

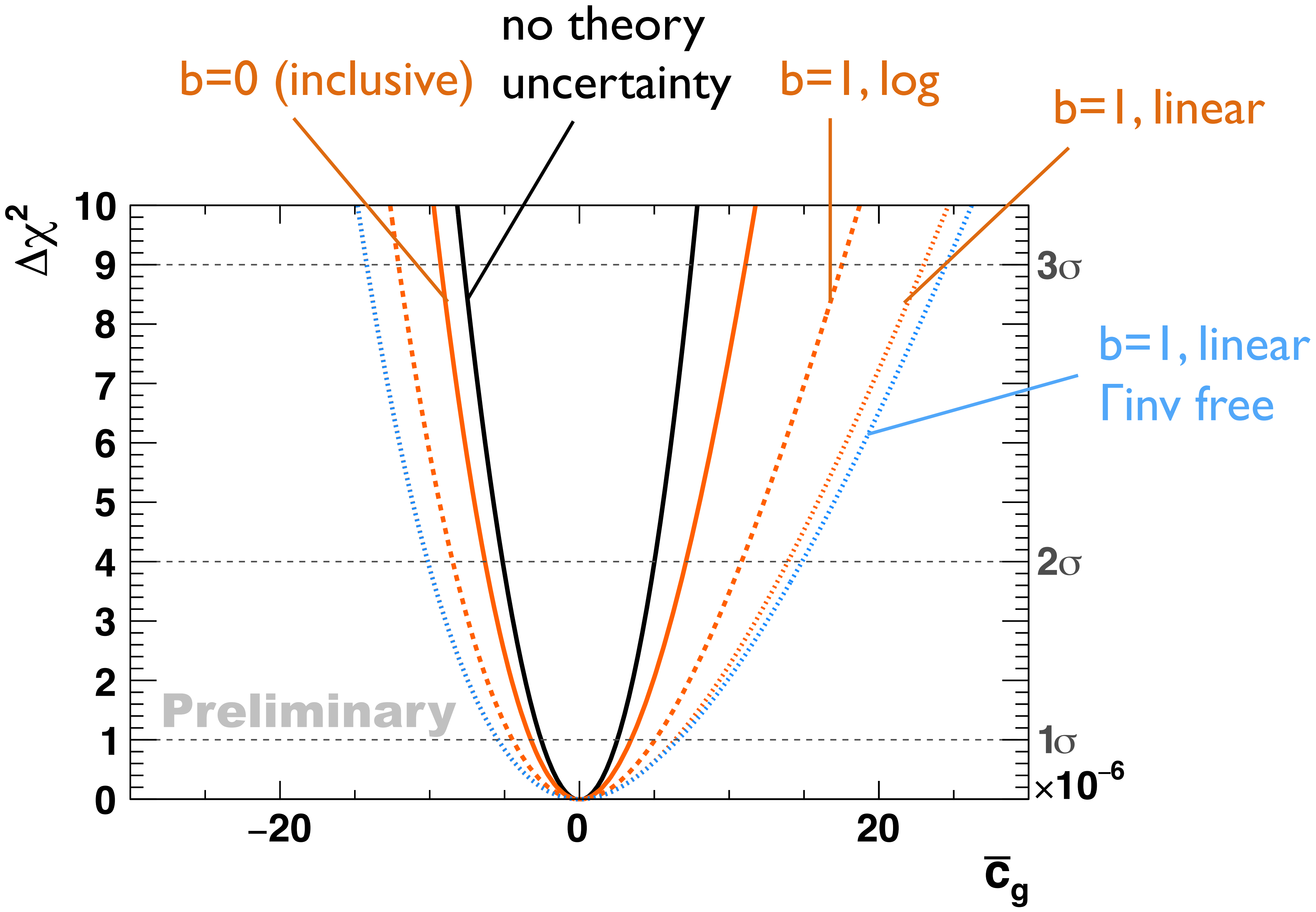
$$\Delta_i = u_i\big(\underbrace{a(1-\delta_i)}_{\text{inclusive}} \oplus \underbrace{b(1-\delta_{i,\text{tail}})f(p_{\text{T,H}})}_{\text{tail}}\big)$$

log: $$f(p_{\text{T,H}}) = \log\left(\frac{M_{\text{H}}+p_{\text{T,H}}}{M_{\text{H}}}\right)$$

lin: $$f(p_{\text{T,H}}) = \frac{p_{\text{T,H}}}{M_{\text{H}}}$$

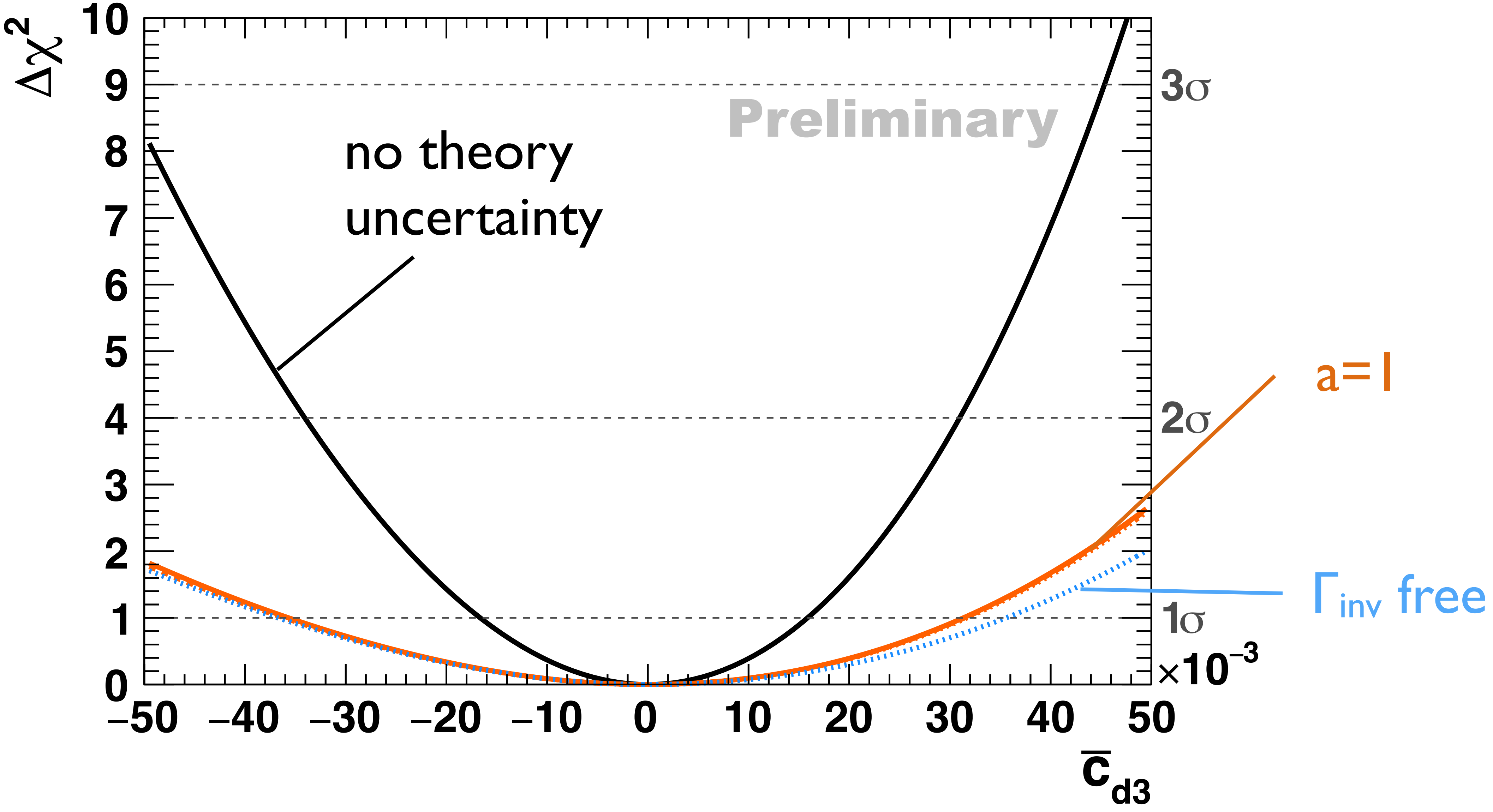


Impact of Theory Uncertainties



95% CL constraints on c_g weaker by a factor of **2 (log)** or **3 (linear)**

Impact of Theory Uncertainties



95% CL constraints on c_{d3} weaker by a factor of **2**, independent of tails

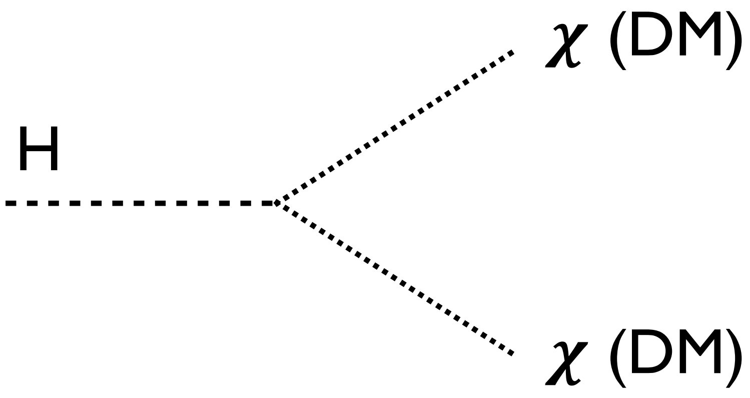
→ constraints from decay only, impact of theo. unc. still sizeable

Invisible Width

Invisible Width

Everything looks SM-like (so far)

- What if there are BSM contributions to the Higgs decay?



(dark portal)

- Contribution to the total width: $\Gamma_{\text{tot}} = \Gamma_{\text{SM}} + \Gamma_{\text{inv}}$

note:
Γ_{SM} = 4 MeV

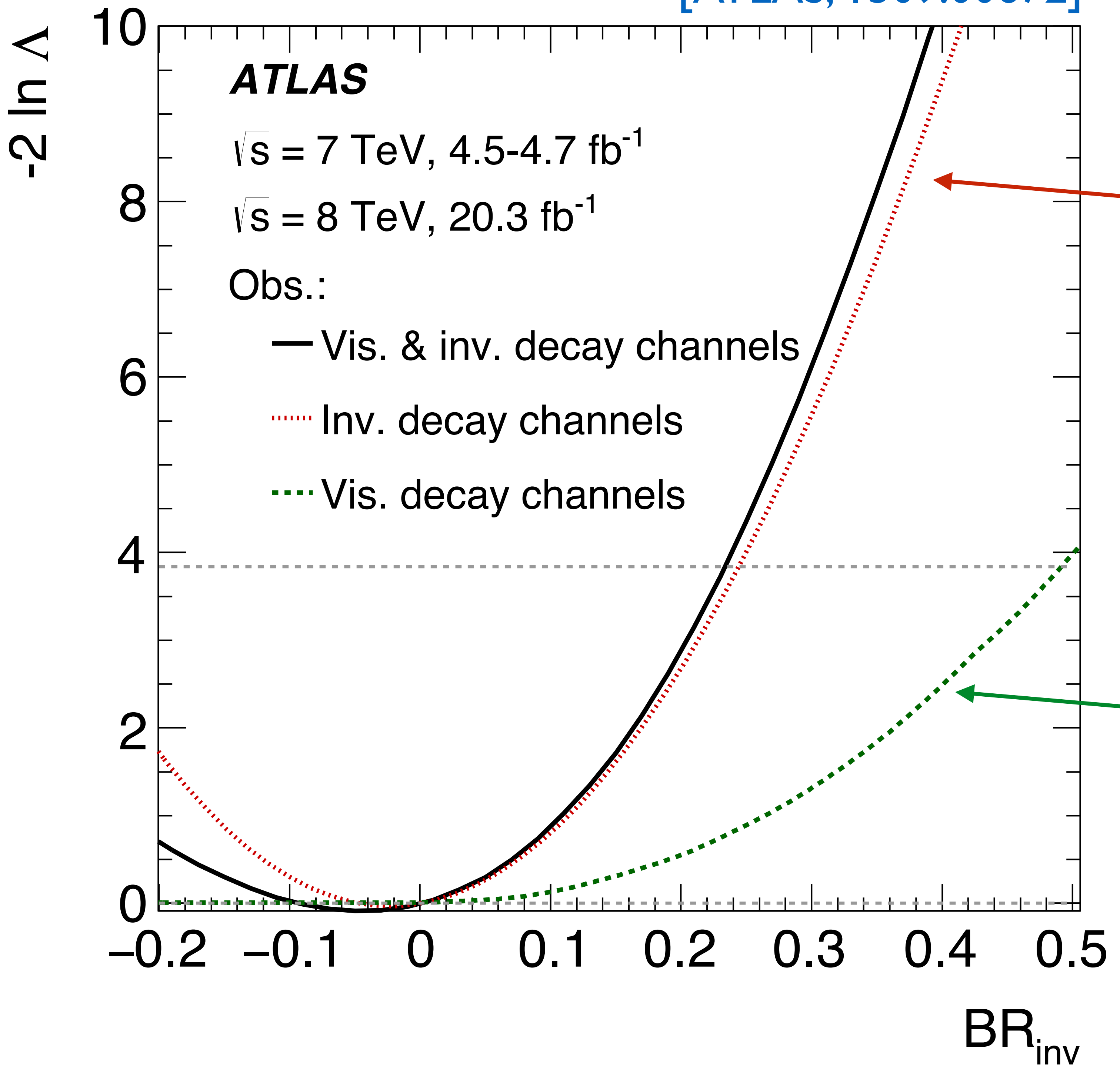
effect on signal strengths:

$$\mu_i^f = \frac{\sigma_i \times \text{BR}_f}{(\sigma_i \times \text{BR}_f)_{\text{SM}}} \quad \text{with} \quad \text{BR}_f = \frac{\Gamma_f}{\Gamma_{\text{tot}}}$$

→ if Γ_{tot} (and Γ_{inv}) increases, signal strengths decrease

Run 1 Constraints

[ATLAS, 1509.00672]



direct searches
(e.g. VBF → jj + MET,
assume SM production)

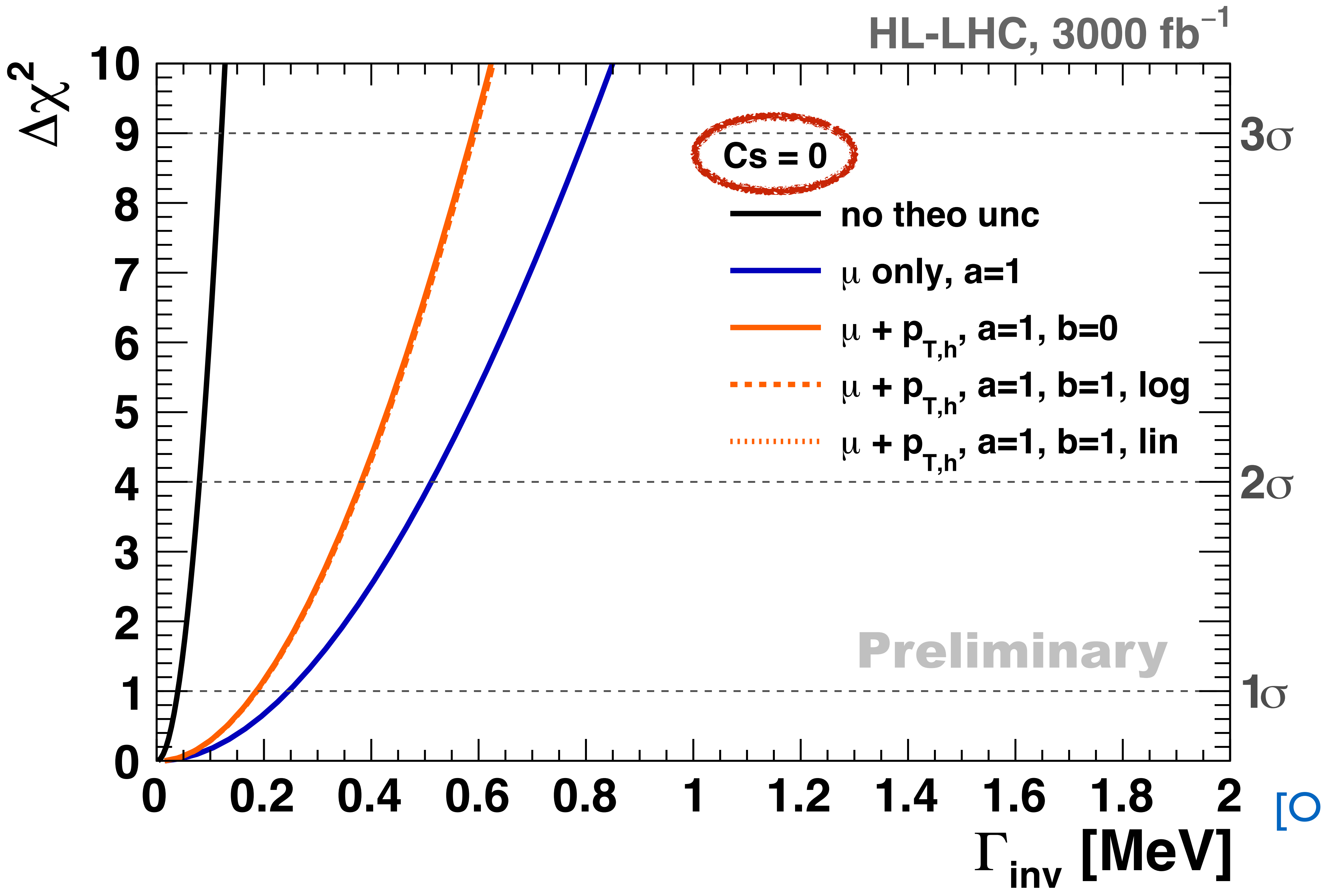
0.25 in BR$_{inv}$
= Γ_{inv} of 1.3 MeV

from signal strength
measurements (κ_V < 1)

0.5 in BR$_{inv}$
= Γ_{inv} of 4 MeV

(similar results from CMS)

Invisible Width with HL-LHC



No BSM contributions beyond BR_{inv} :

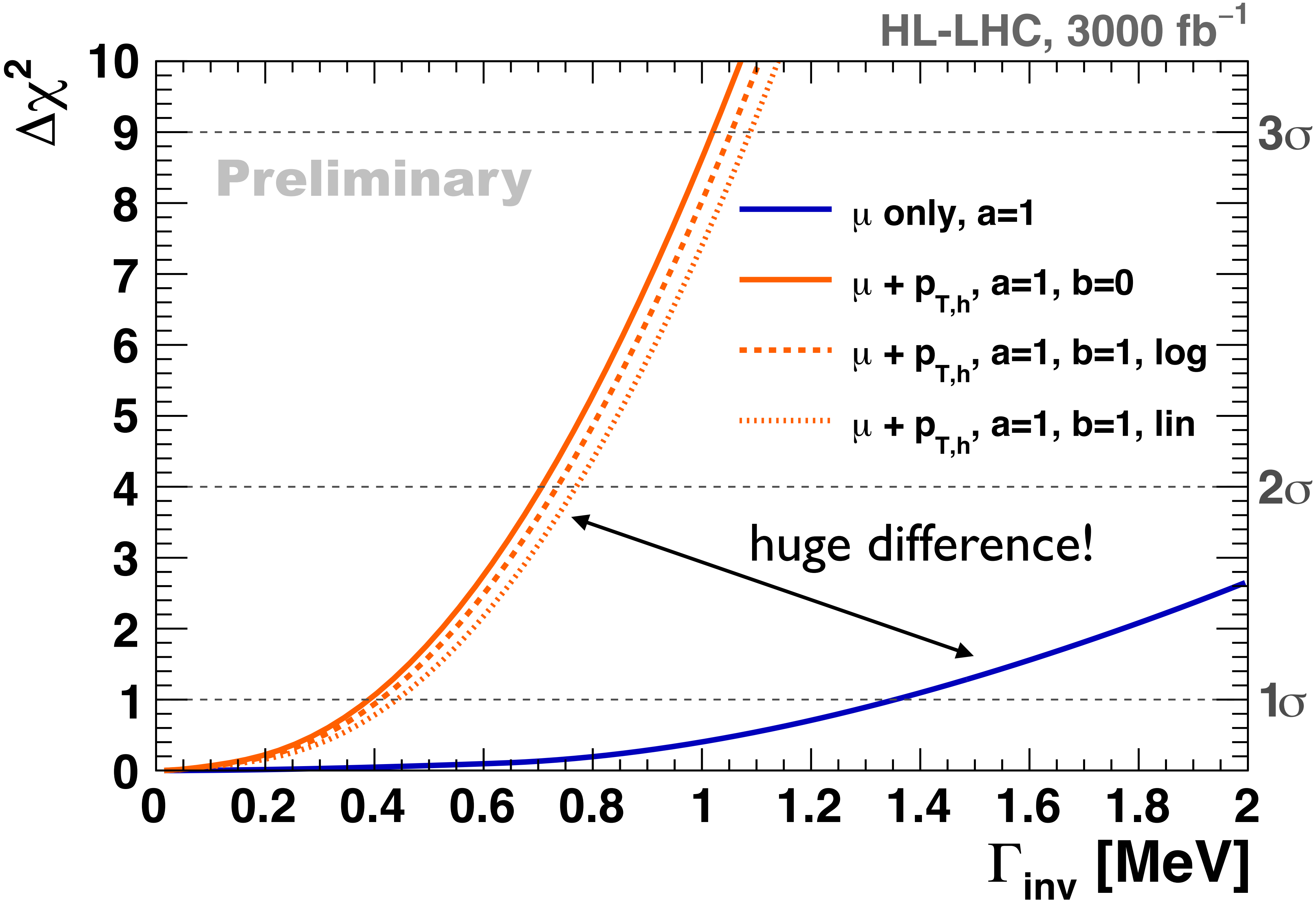
$BR_{inv} < 3\%$
(no theo unc)

$BR_{inv} < 9\text{-}11\%$
(with theo unc)

(very similar to expected direct measurements)
[Okawa et al., 1309.7925]

ATLAS study:
$BR_{inv} < 15\%$
[ATL-PHYS-PUB-2013-015]

Invisible Width with HL-LHC



huge difference!

Switch on dim-6 ops

BR_{inv} < 40% (μs only)

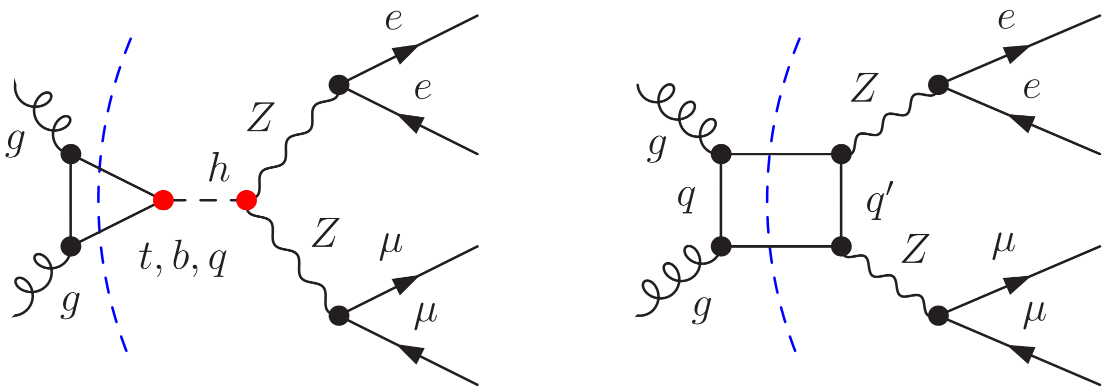
BR_{inv} ≲ 15% (with p_{TH} meas)

(not too far from constraints with SM+BR_{inv})

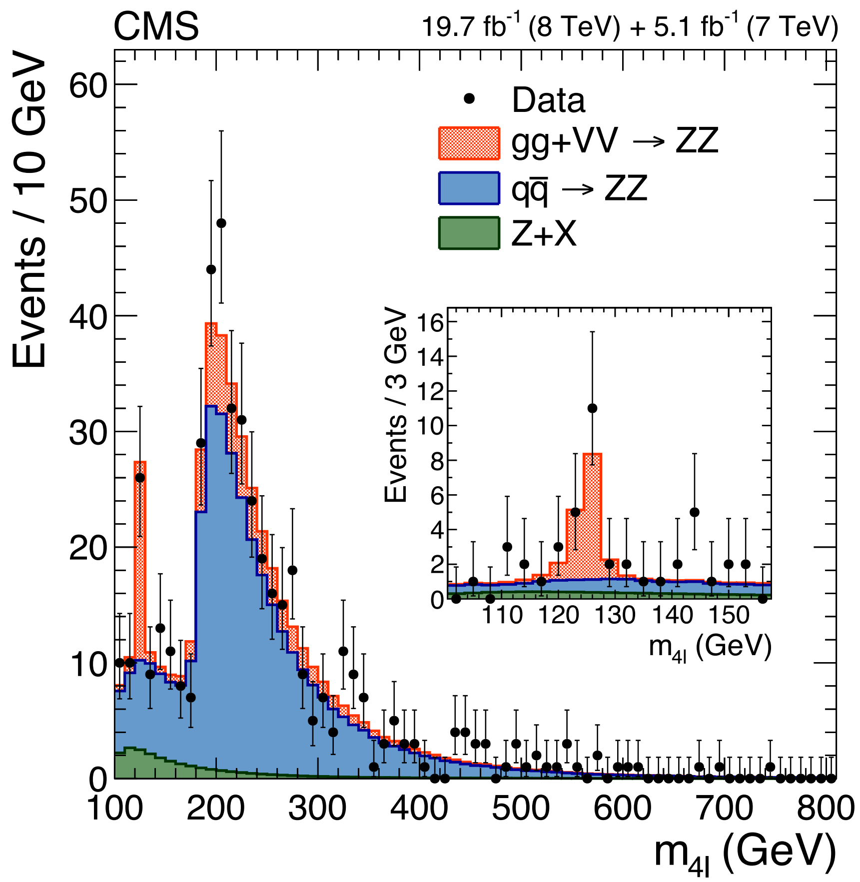
Off-shell Measurement

Can H→ZZ off-shell measurement help to constrain Γ_{inv}?

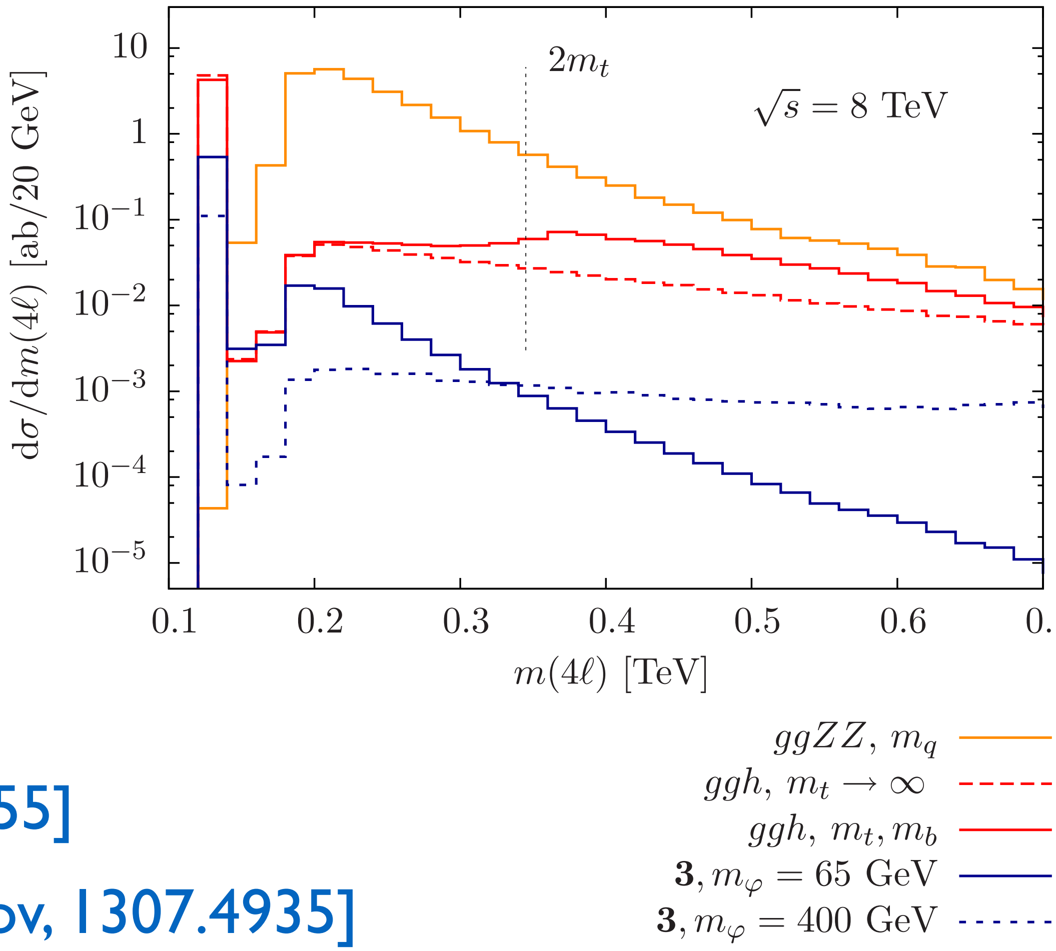
- Extrapolate run 1 measurement of $m_{4\ell}$, similar to $p_{T,H}$
  - off-shell: $m_{4\ell}$ > 330 GeV
  - dominated by statistics, ~ 15% uncertainty with HL-LHC



[Englert, Spannowsky,1405.0285]



[CMS, 1405.3455]



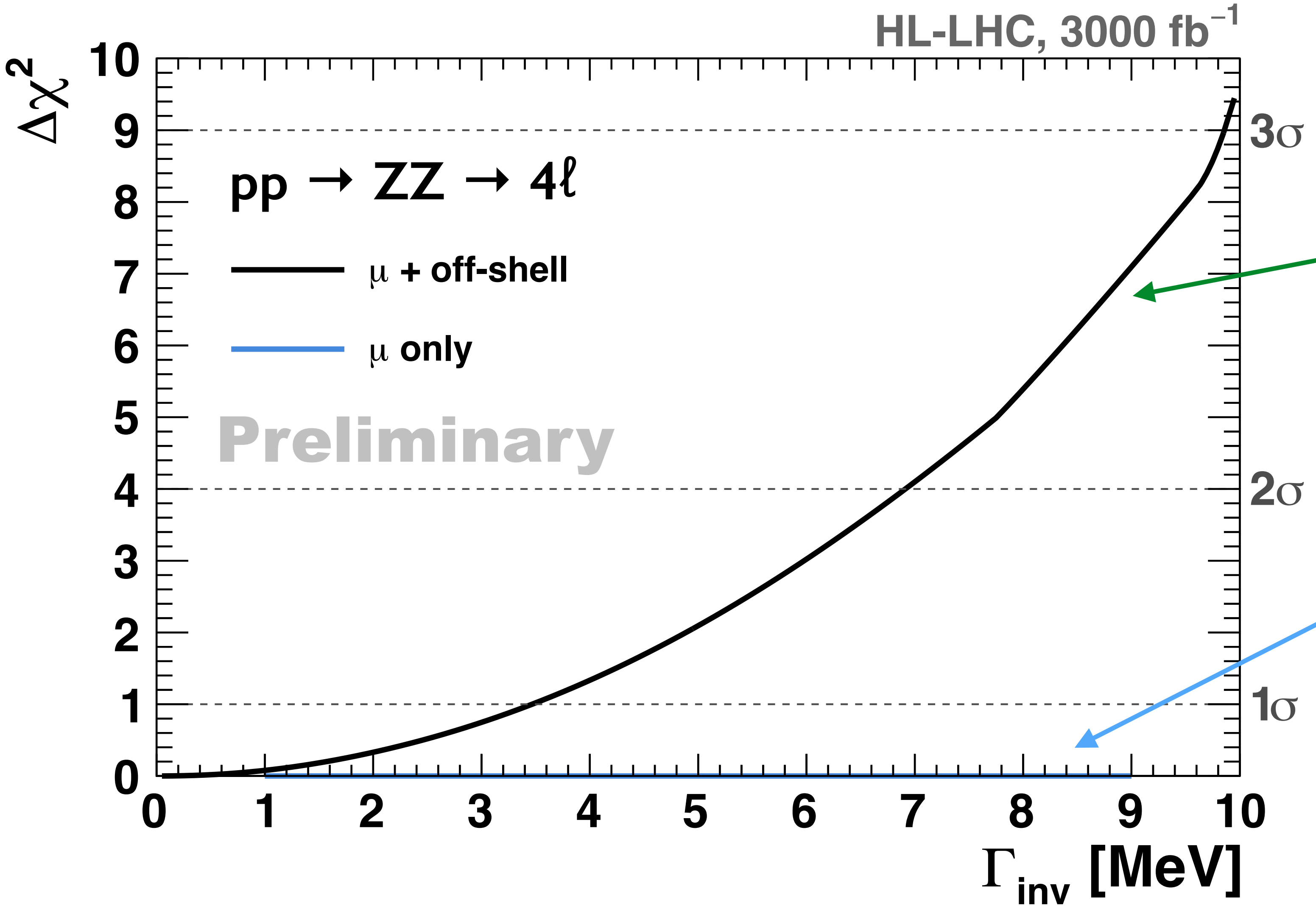
[Caola, Melnikov, 1307.4935]

On-shell and off-shell

Consider only pp→ZZ→4ℓ measurements

- on-shell: precision of 3% $\sim \frac{g_i^2\, g_f^2}{\Gamma_H}$
- off-shell: precision of 15% $\sim g_i^2\, g_f^2$

marginalise over c_g, c_{u3}, c_H (others fixed to 0)

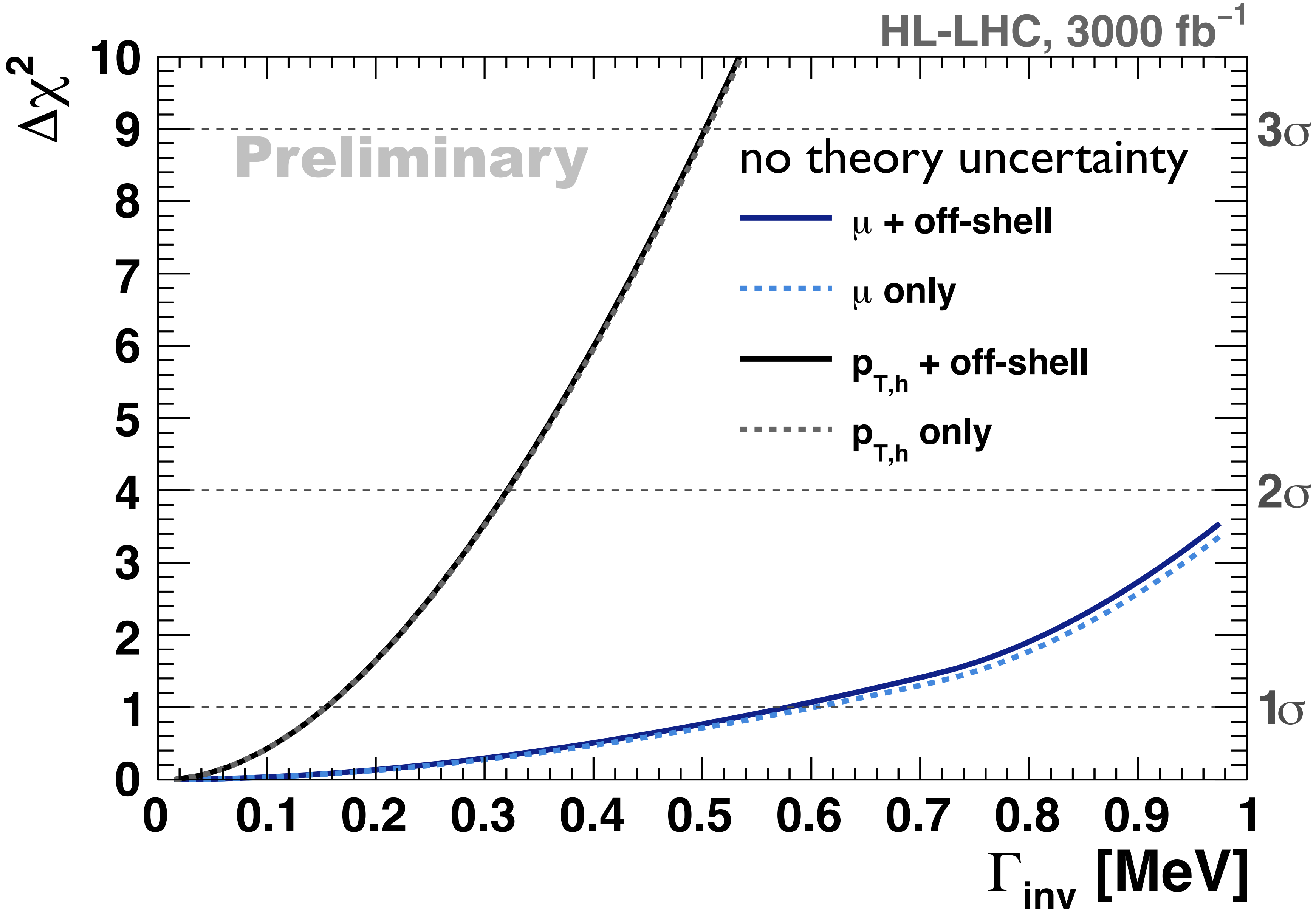


Γ_{inv} < 7 MeV at 95% CL with single measurement in the context of an EFT

can not constrain Γ_{inv} with only on-shell measurement

Off-shell measurement in the full fit

Study impact of off-shell measurement in full fit



marginalise over all c_i

Correlating on-shell and off-shell region a la Caola-Melnikov does not improve width constraint within EFT framework

(less sensitivity of off-shell compared to over-constrained measurement system)

Summary

H → inv one of the most promising avenues for new physics

- Current constraints

  $\mathrm{BR}_{\mathrm{inv}} < 25\text{-}50\%$ depending on assumptions

- Outlook for HL-LHC

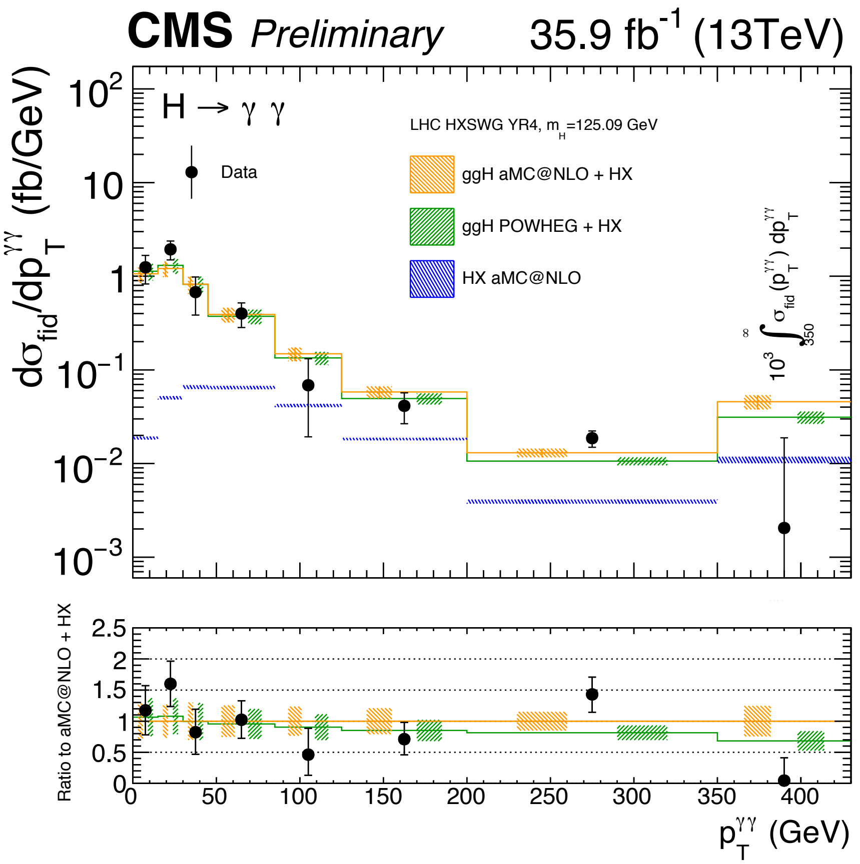
  $\mathrm{BR}_{\mathrm{inv}} < 10\%$ κ framework

- More general EFT, new dynamics

  $\mathrm{BR}_{\mathrm{inv}} < 40\%$ signal strengths only

  $\mathrm{BR}_{\mathrm{inv}} < 15\%$ differential measurements

[CMS, HIG-17-015]



Global EFT fit ideal tool to study impact of measurements and calculations