Update of the electroweak fit and BSM constraints in the scalar sector

Diagnosing the SM's Physical Condition with the Global EW Fit

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and
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Moriond EW
La Thuile, March 12, 2018

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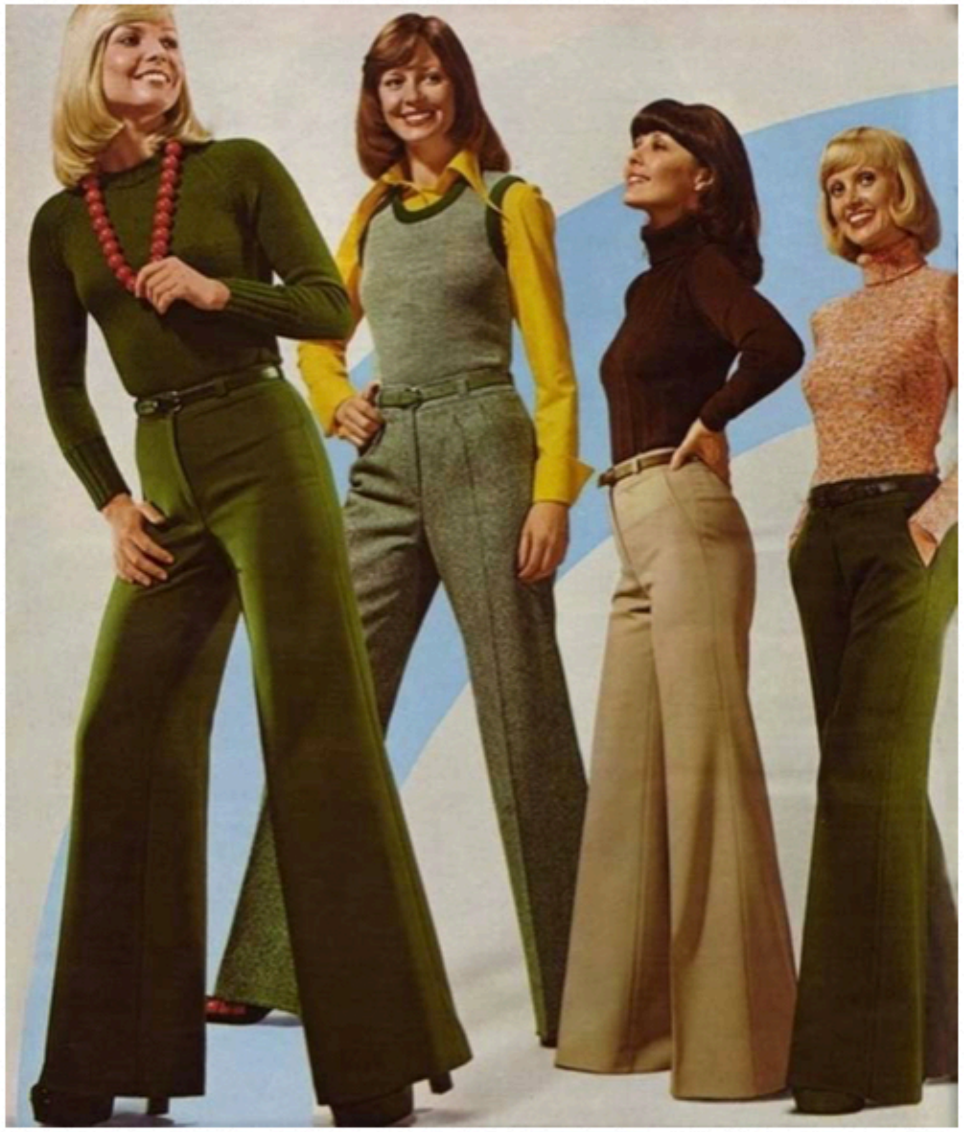
Based on 1509.00672, 1708.06355, 1803.01853

Let’s assume we live in



The Standard Model

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

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

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

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

The Standard Model

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + h.c. + \bar{\psi}_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

Looks good so far...

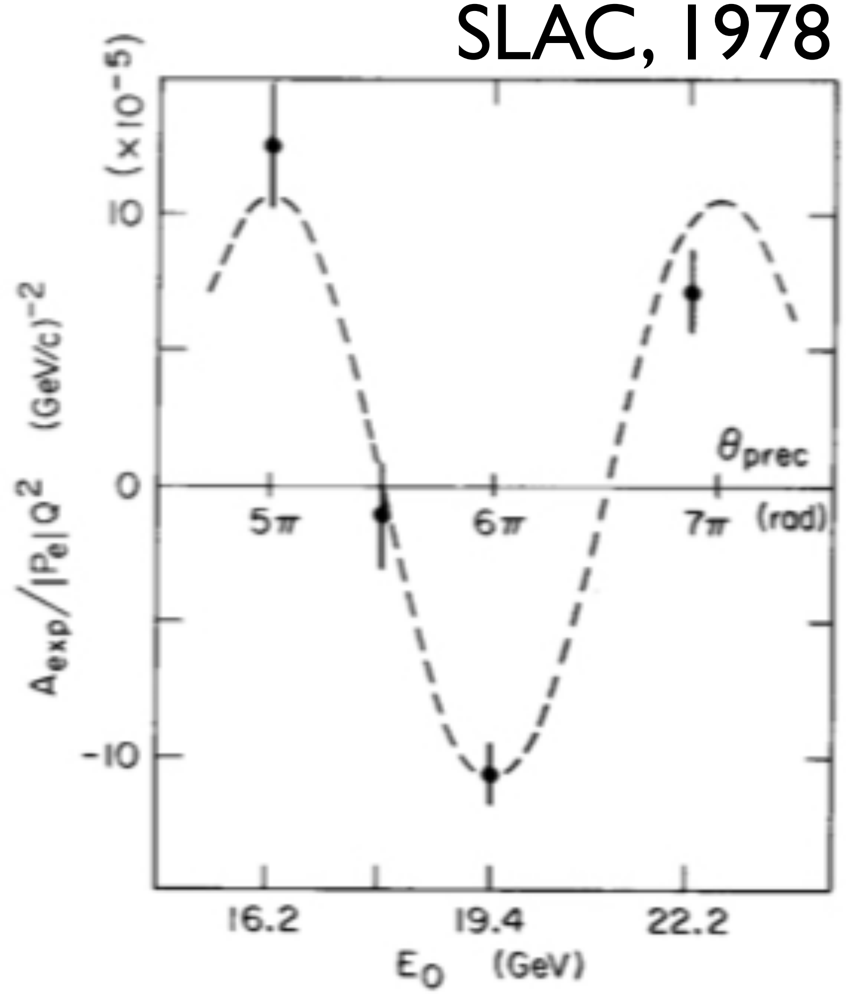
But is it healthy?

EW Symmetry Breaking

Predicting M_W

$$M_W = \frac{1}{2}\frac{\sqrt{4\pi\alpha}}{\sin\theta_W}246\,\mathrm{GeV} = \frac{37}{\sin\theta_W}\,\mathrm{GeV}$$

SLAC, 1978



How large is $\sin\theta_W$?

Polarised electrons on deuterium (asymmetry in cross section for different polarisations)

$$\sin^2\theta_W = 0.20 \pm 0.03$$

Here is our expectation:

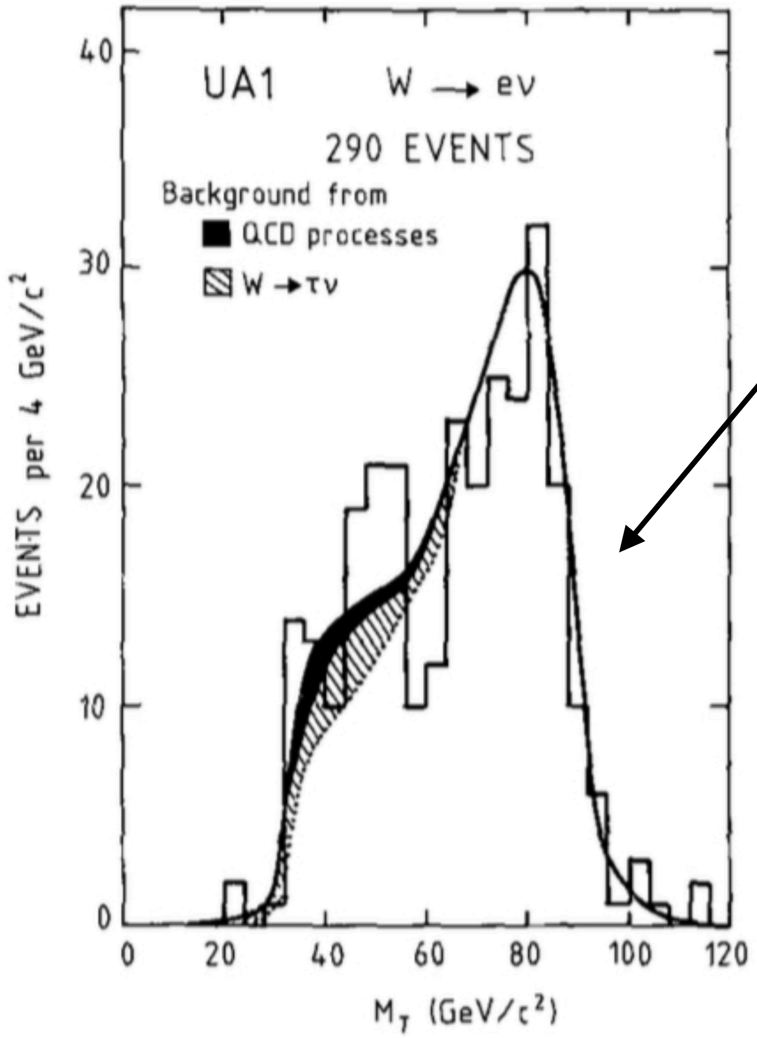
$$\boxed{M_W = 82 \pm 6\,\mathrm{GeV}}$$

and

$$\boxed{M_Z = \frac{M_W}{\cos\theta_W} = 92 \pm 5\,\mathrm{GeV}}$$

(we need a new collider)

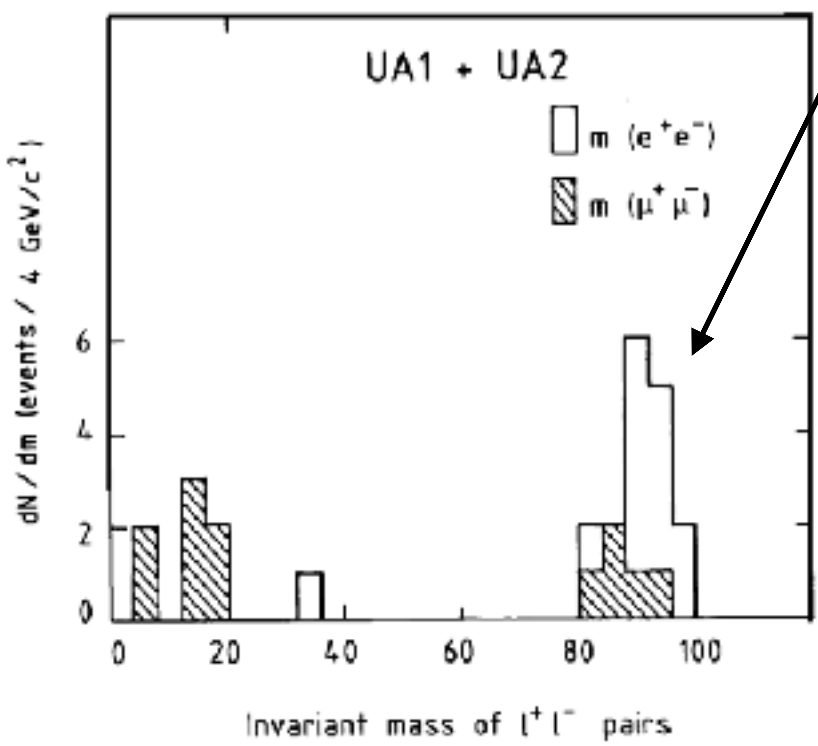
UA1 and UA2 (1983-1989)



$$M_W = 82.7 \pm 1.0_{\rm stat} \pm 2.7_{\rm syst}\ {\rm GeV}$$

Spot on!

$$M_Z = 93.1 \pm 1.0_{\rm stat} \pm 3.1_{\rm syst}\ {\rm GeV}$$



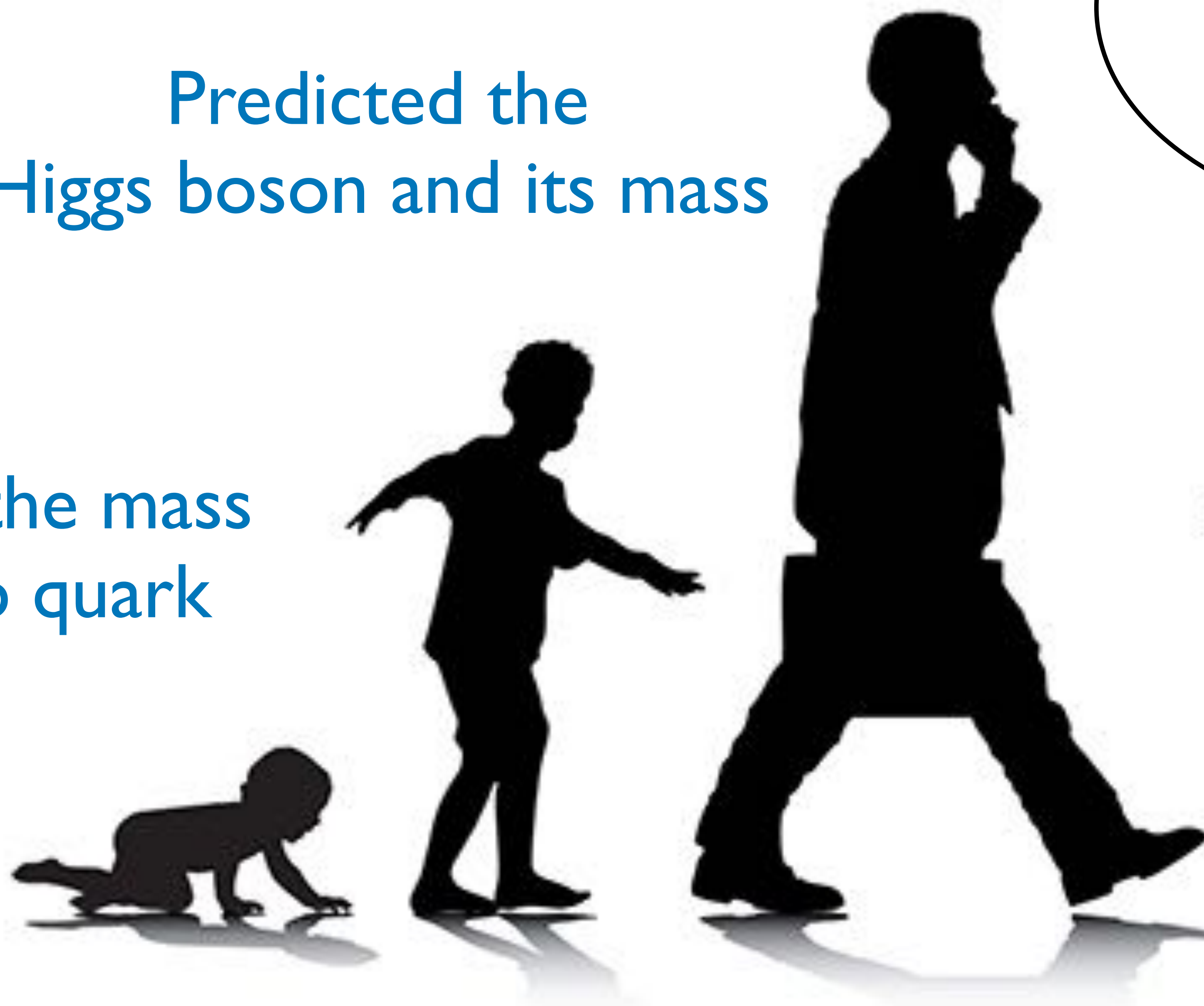
Healthy!

Prediction of b quark

Prediction of ν_τ

Predicted the
Higgs boson and its mass

Predicted the mass
of the top quark



Hello Mr. SM!
How are you
today?

Verified by countless measurements…

Comprehensive Medical Assessment

Fit is overconstrained

- all $\boxed{\text{free parameters}}$ measured ($\alpha_s(M_Z)$ unconstrained in fit)
  - most input from e^+e^- colliders
    - M_Z : $2\cdot 10^{-5}$
  - but crucial input from hadron colliders:
    - m_t : $4\cdot 10^{-3}$
    - M_H : $2\cdot 10^{-3}$
    - M_W : $2\cdot 10^{-4}$
  - remarkable precision (<1%)
- require precision calculations (NNLO corrections available)

M_H [GeV]	125.1 ± 0.2	LHC
M_W [GeV]	80.379 ± 0.013	Tev.+LHC
Γ_W [GeV]	2.085 ± 0.042	
M_Z [GeV]	91.1875 ± 0.0021	LEP
Γ_Z [GeV]	2.4952 ± 0.0023	
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	
R^0_ℓ	20.767 ± 0.025	
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	SLD
$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012	
$\sin^2\theta^\ell_{\rm eff}(\rm TEV)$	0.23148 ± 0.00033	Tev. (+LHC?)
A_c	0.670 ± 0.027	SLD
A_b	0.923 ± 0.020	
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	LEP
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	
R^0_c	0.1721 ± 0.0030	
R^0_b	0.21629 ± 0.00066	
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$	2760 ± 9	low E
$\overline{m}_c$ [GeV]	$1.27\,^{+0.07}_{-0.11}$	
$\overline{m}_b$ [GeV]	$4.20\,^{+0.17}_{-0.07}$	
m_t [GeV]$^{(\bigtriangledown)}$	172.47 ± 0.68	Tev.+LHC

Comprehensive Medical Assessment

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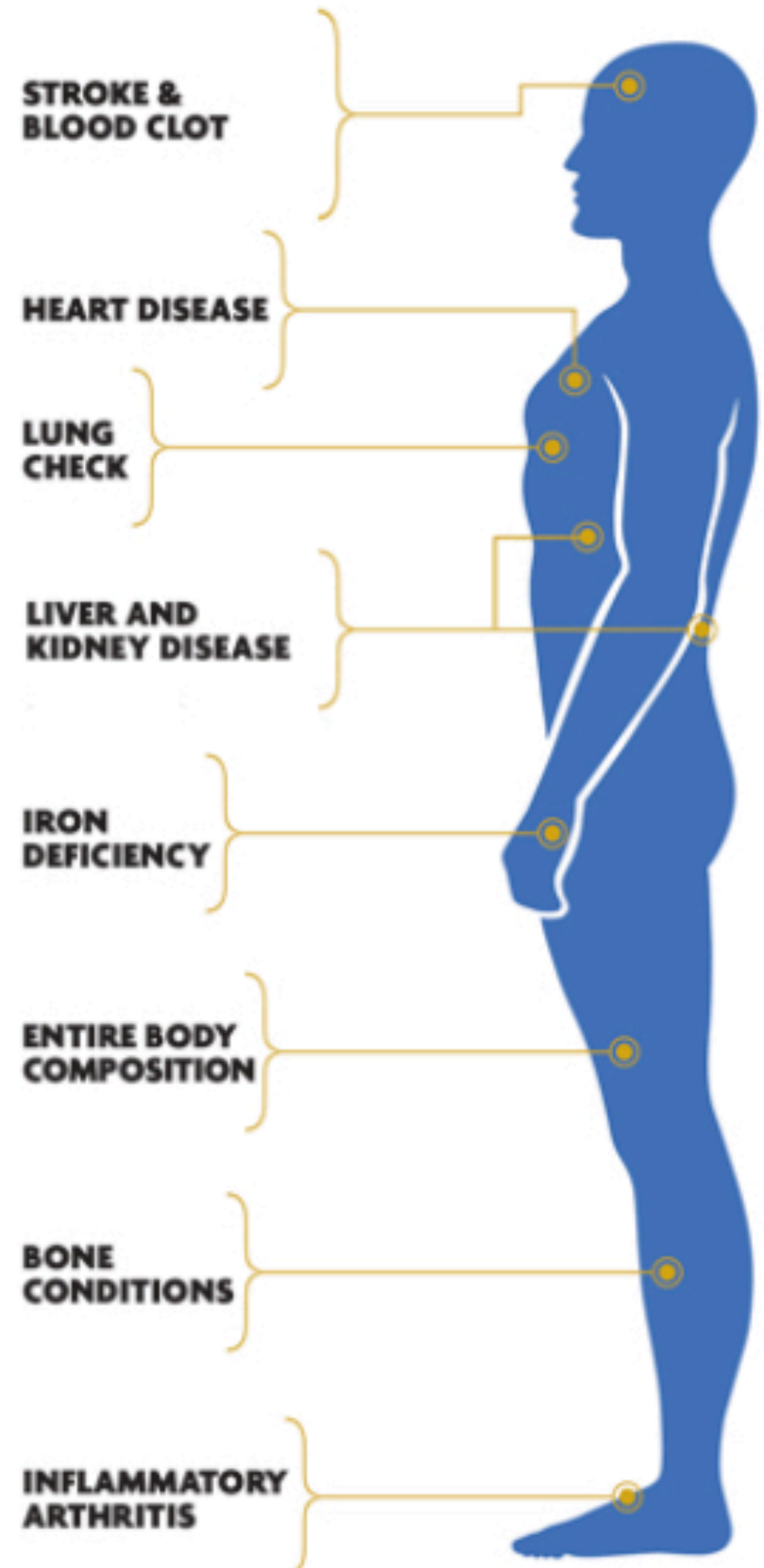
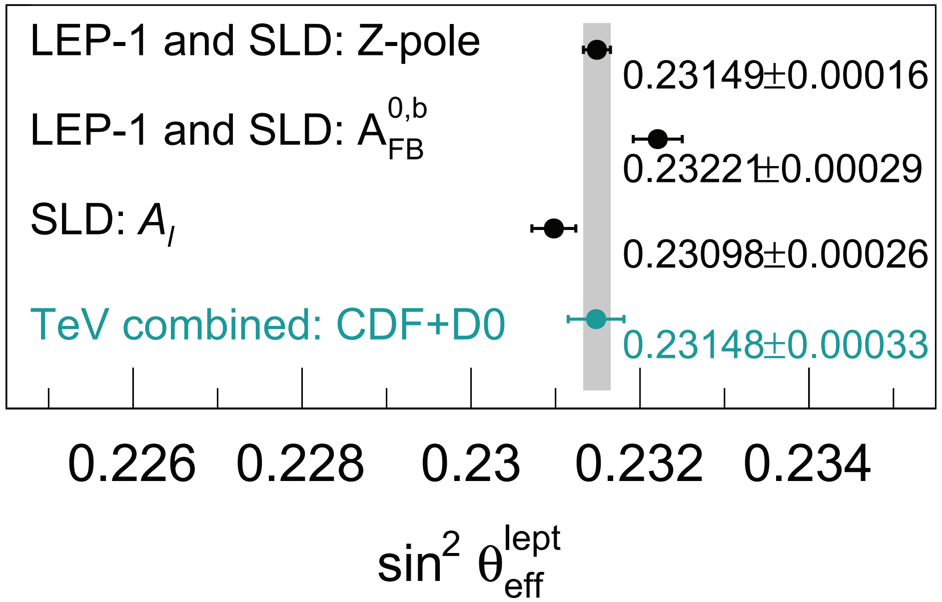


Global Fit: News

$\sin^2\theta^l_{eff}$ Tevatron Combination [CDF, D0, 1801.06283]



e and μ combined, full dataset

In EW fit: $\Delta\chi^2 = +0.02$

Hadronic vacuum polarisation [M. Davier et al., EPJC 77, 827 (2017)]

Newest $e^+e^-\rightarrow$hadrons data (e.g. Barbar and VEPP-2000)

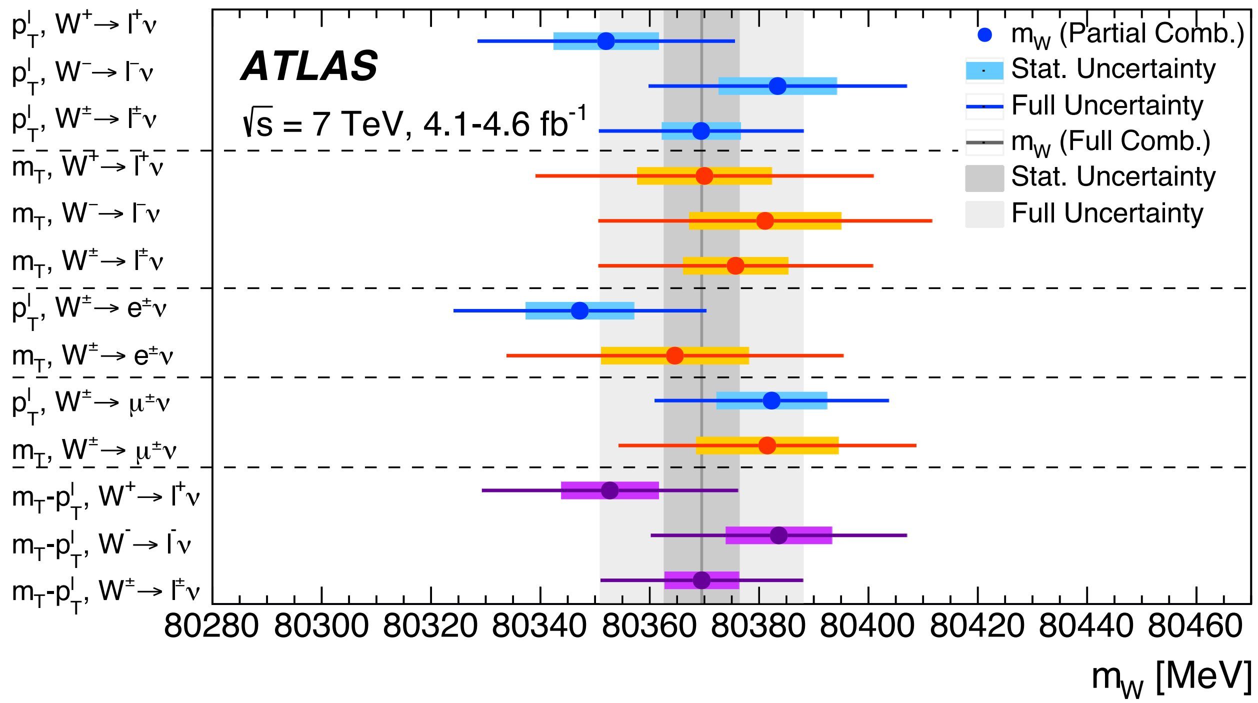
$\Delta\alpha^{(5)}_{had}(M_Z^2) = (2760 \pm 9) \cdot 10^{-5}$

previously: $(2757 \pm 10) \cdot 10^{-5}$

In EW fit: $\Delta\chi^2 = +0.17$

ATLAS M_W Measurement

[ATLAS, EPJC 78 (2018) 110]

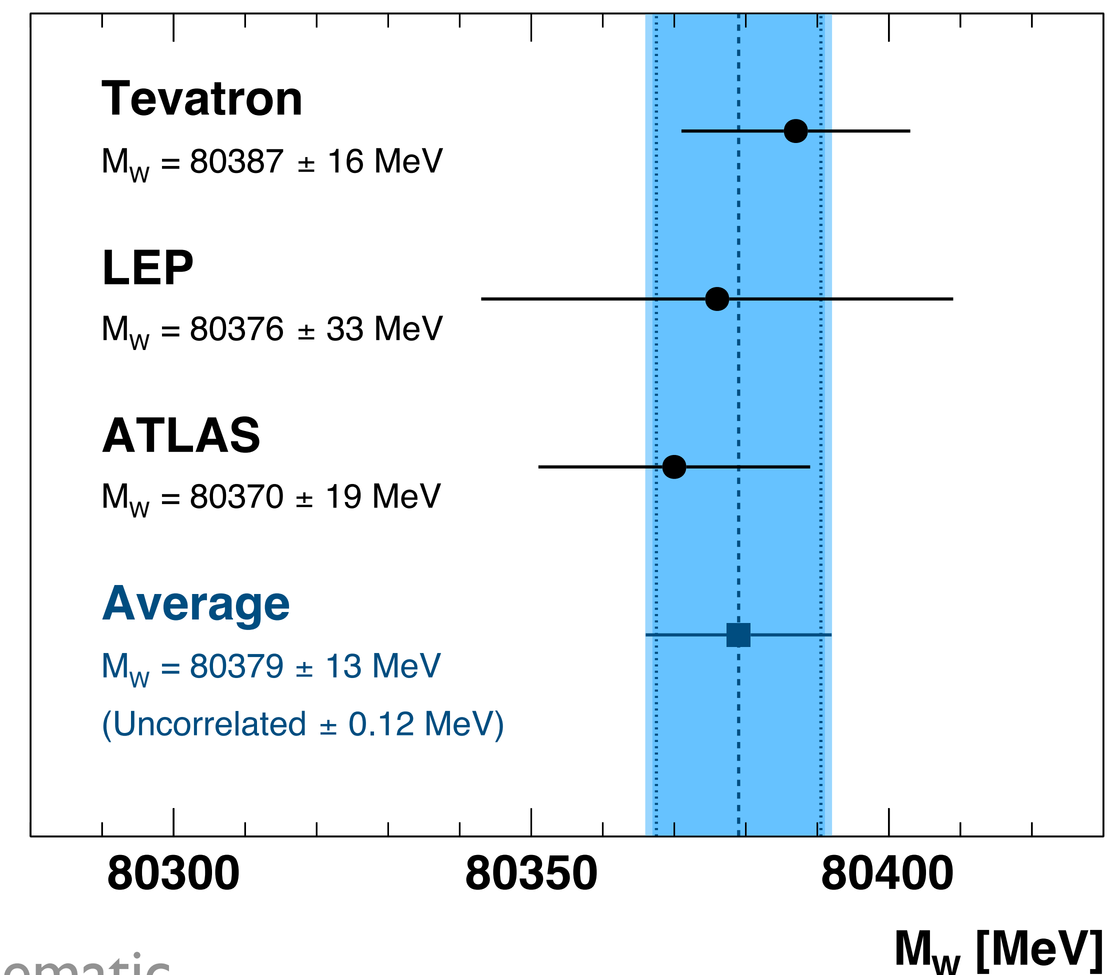


ATLAS

$M_W = 80370 \pm 7_{(stat)} \pm 11_{(exp.syst)} \pm 14_{(mod.syst)}$ MeV

Tevatron [CDF, D0, 1204.0042]

$M_W = 80387 \pm 8_{(stat)} \pm 8_{(exp.syst)} \pm 12_{(mod.syst)}$ MeV



New average

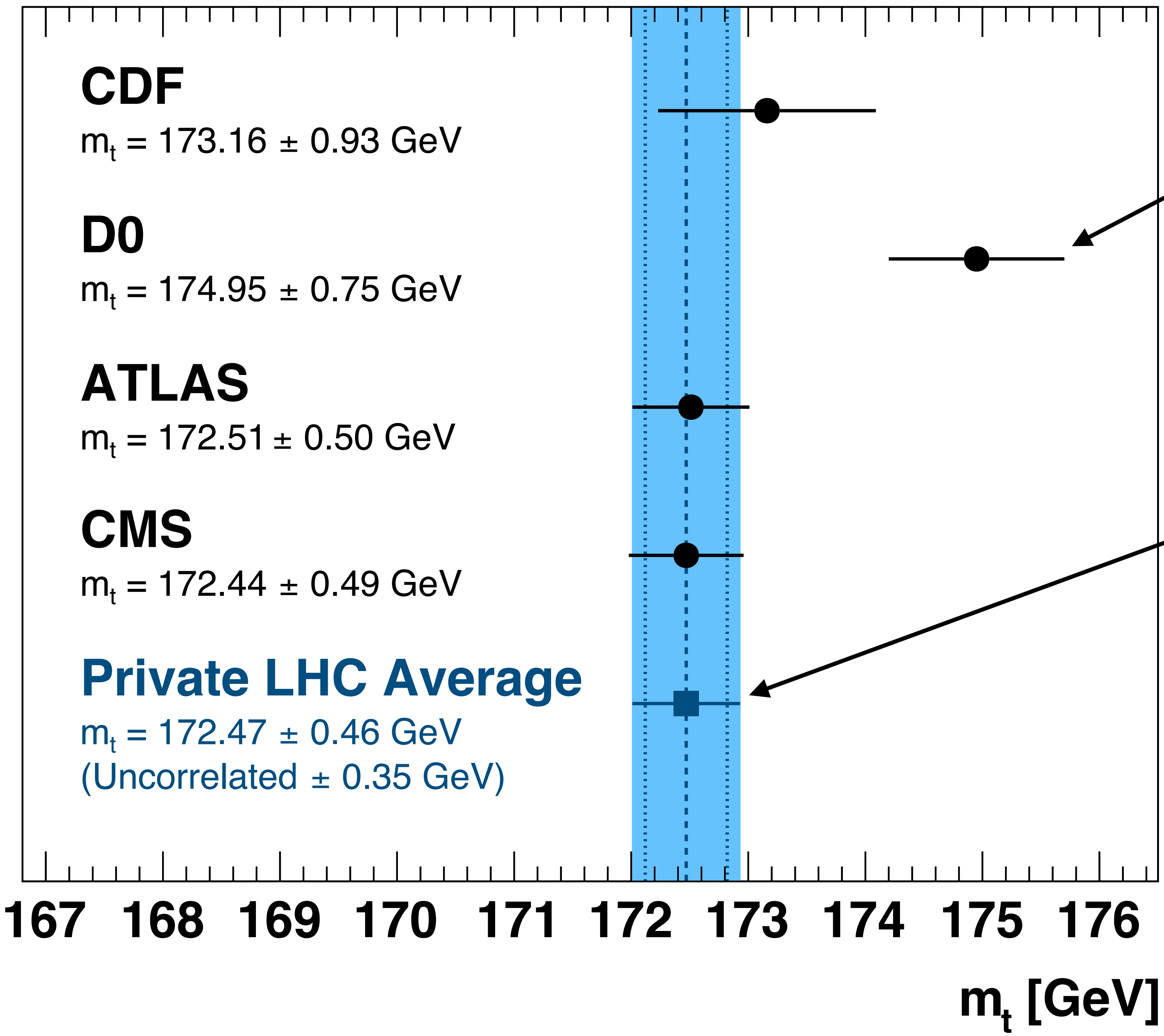
smaller by 6 MeV, uncertainty of 13 MeV

(15 MeV previously)

Obtained by assuming 50% correlation of model systematic, very robust against changes

New m_t Measurements

7 and 8 TeV combinations by ATLAS and CMS published



Deviation of 3 - 4σ w.r.t. LHC average

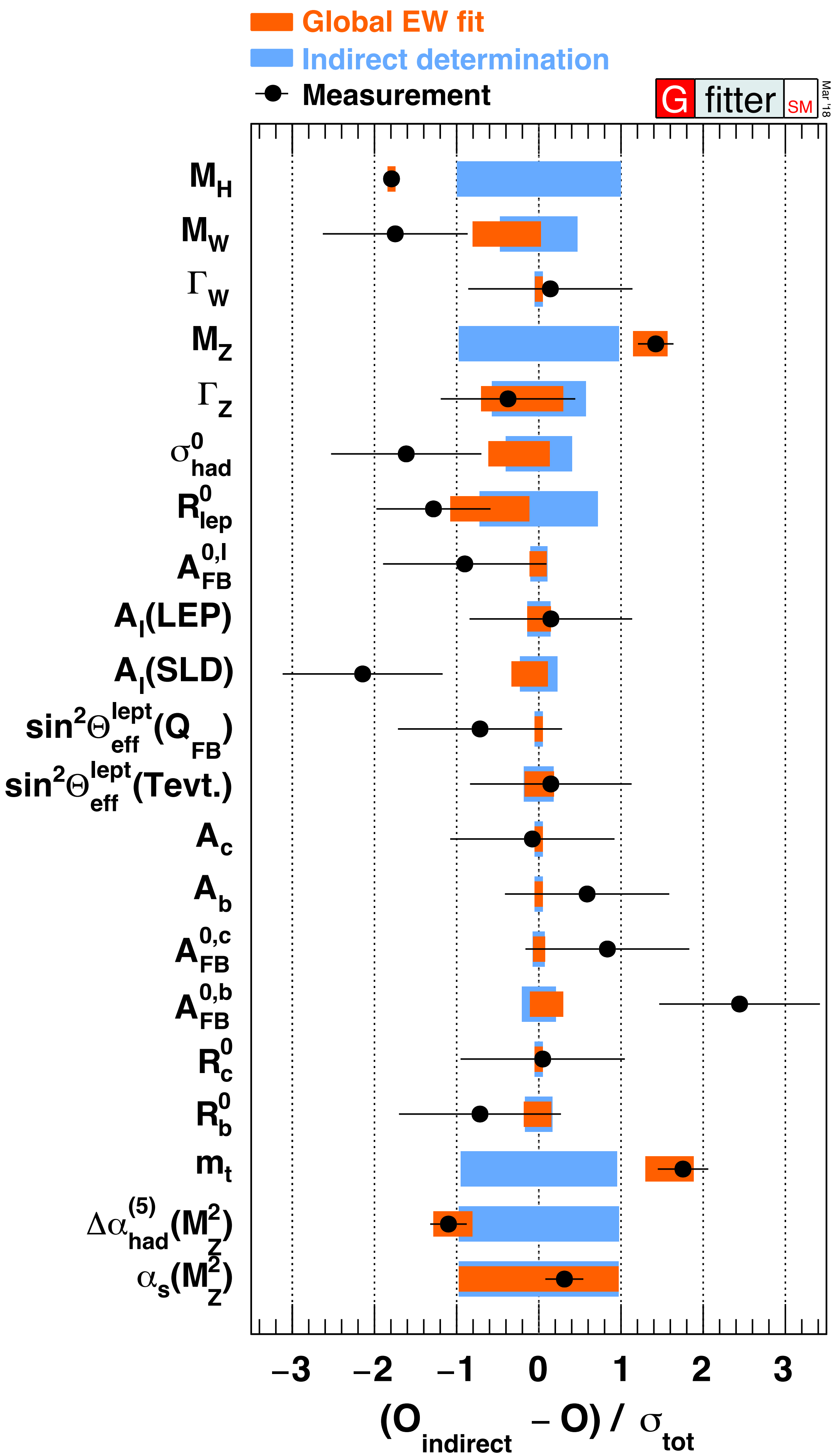
Depending on assumed correlation Tevatron combination: 2.3-3σ

Average

Smaller by 0.87 GeV uncertainty of 0.46 GeV (0.76 MeV previously)

Obtained by assuming 0.7 correlation

Additional theoretical uncertainty of 0.5 GeV

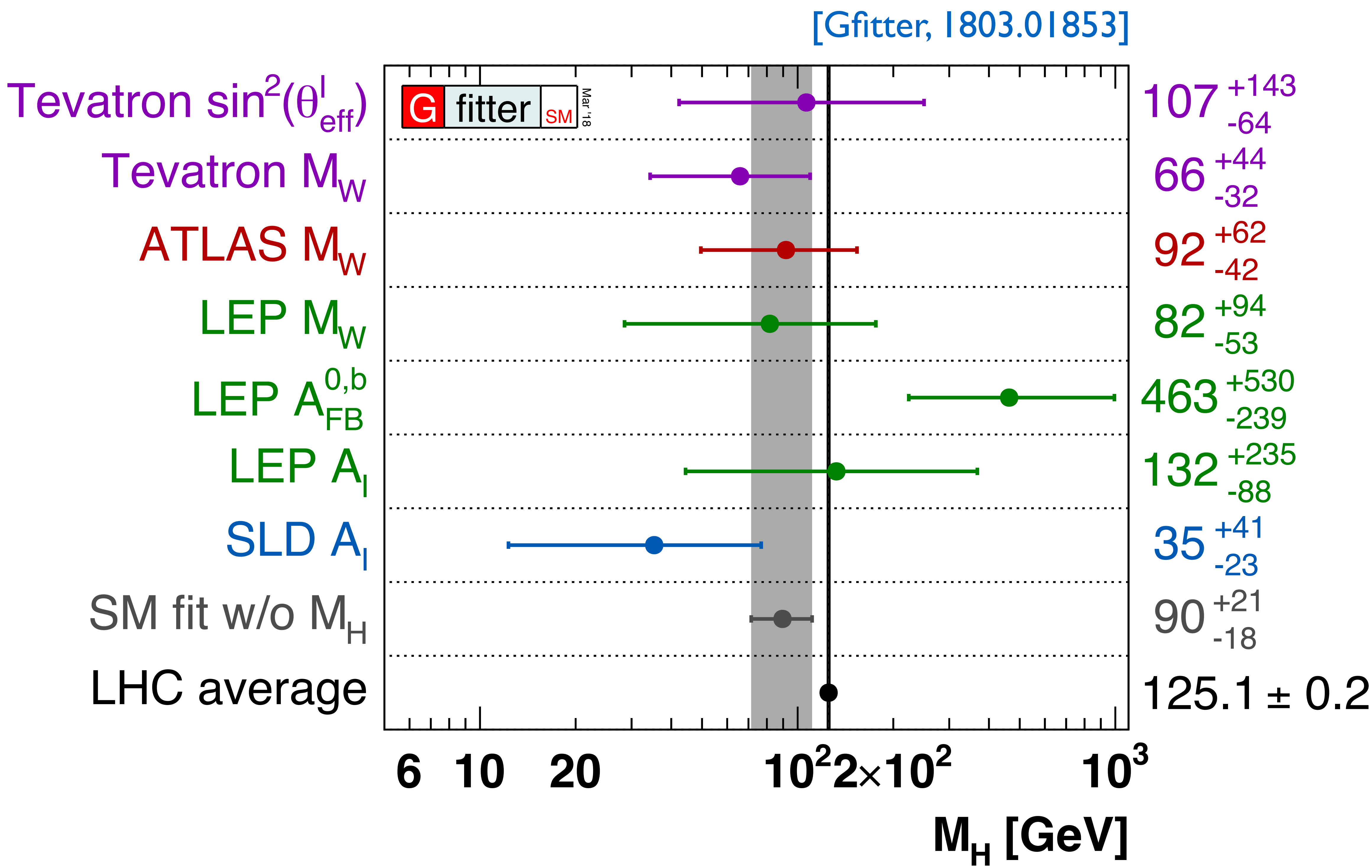


SM Fit Results

- χ^2_{min}= **18.6** Prob(χ^2_{min}, 15) = **23%**
  - χ^2_{min}(old m_t) = 17.3
  - χ^2_{min}(old M_W) = 19.3
- M_W: −1.5σ (−1.4σ previously)
  - central value smaller by 4 MeV
  - uncertainty reduced by 1 MeV
- m_t: 0.5σ (unchanged)
  - central value: 177 → 176.4 GeV
  - uncertainty reduced by 0.3 GeV
  - can reach ±0.9 GeV with perfect knowledge of M_W
- largest deviations in b-sector:
  - $A^{0,b}_{FB}$ with 2.5σ

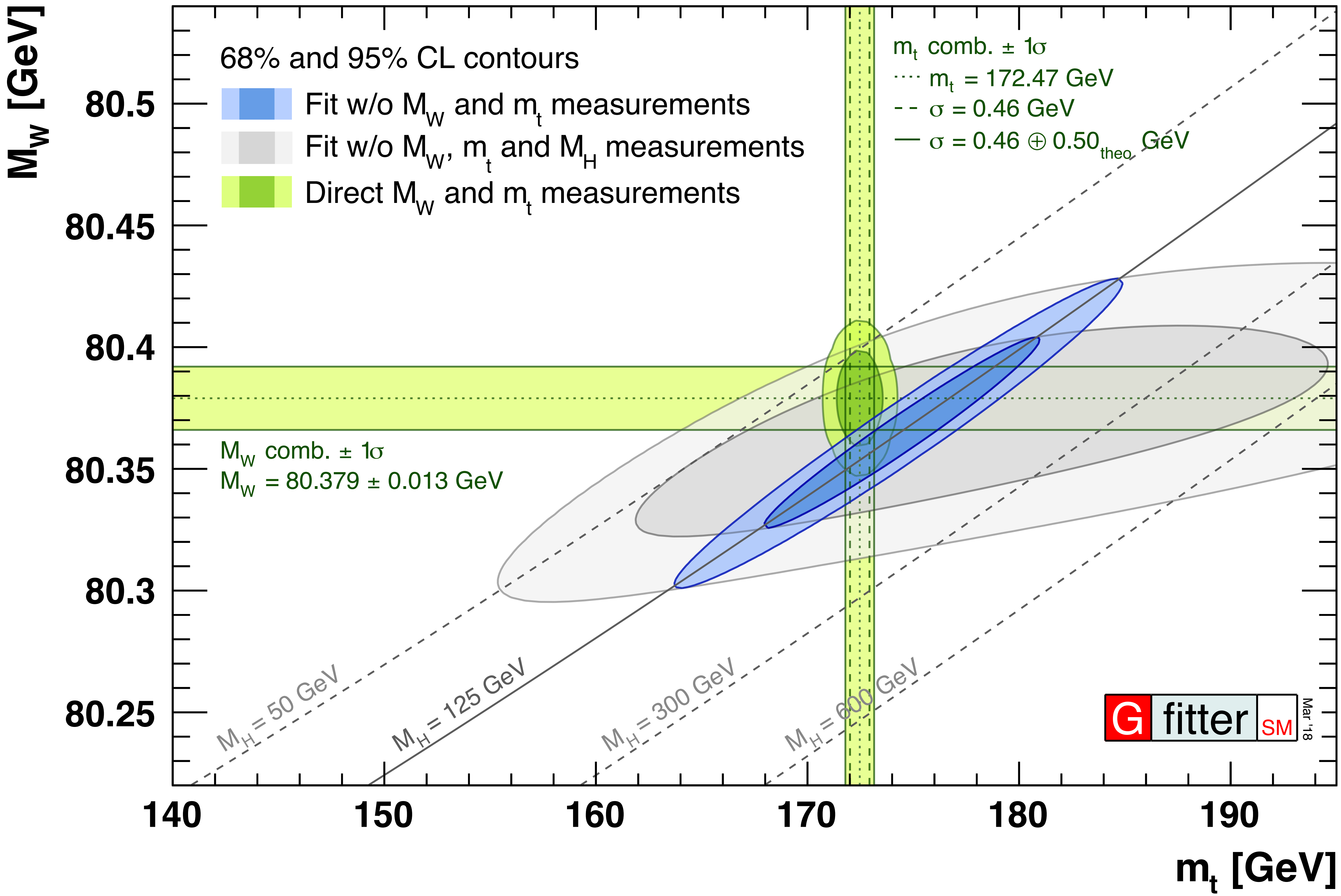
[Gfitter, 1803.01853]

Predicting M_H



SM: Incredibly Healthy!

[Gfitter, 1803.01853]




One
APPLE
a DAY
KEEPS the
DOCTOR
Away


One
APPLE
a DAY
KEEPS the
DOCTOR
Away


AN APPLE A DAY
YOU DIE ANYWAY

Extending the Scalar Sector

2HDM with Z_2 symmetry, no CP violation at tree level

- Five scalars: h, H, A, $H^\pm$
- Light h set to the observed scalar state at 125 GeV
- Free parameters: α, β, M_H, M_A, $M_{H\pm}$, breaking scale M_{12}^2

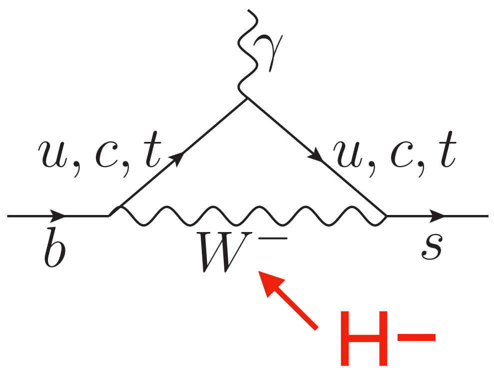
Coupling scale factor	Type I	Type II	Lepton-specific	Flipped
κ_V	$\sin(\beta-\alpha)$			
κ_u	$\cos(\alpha)/\sin(\beta)$			
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$
κ_ℓ	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$

Constraints on free parameters?

- Data from H coupling measurements, flavour decays, EWPO
- Full fit to all data, let 2HDM parameters vary freely
  - Identify preferred or excluded regions

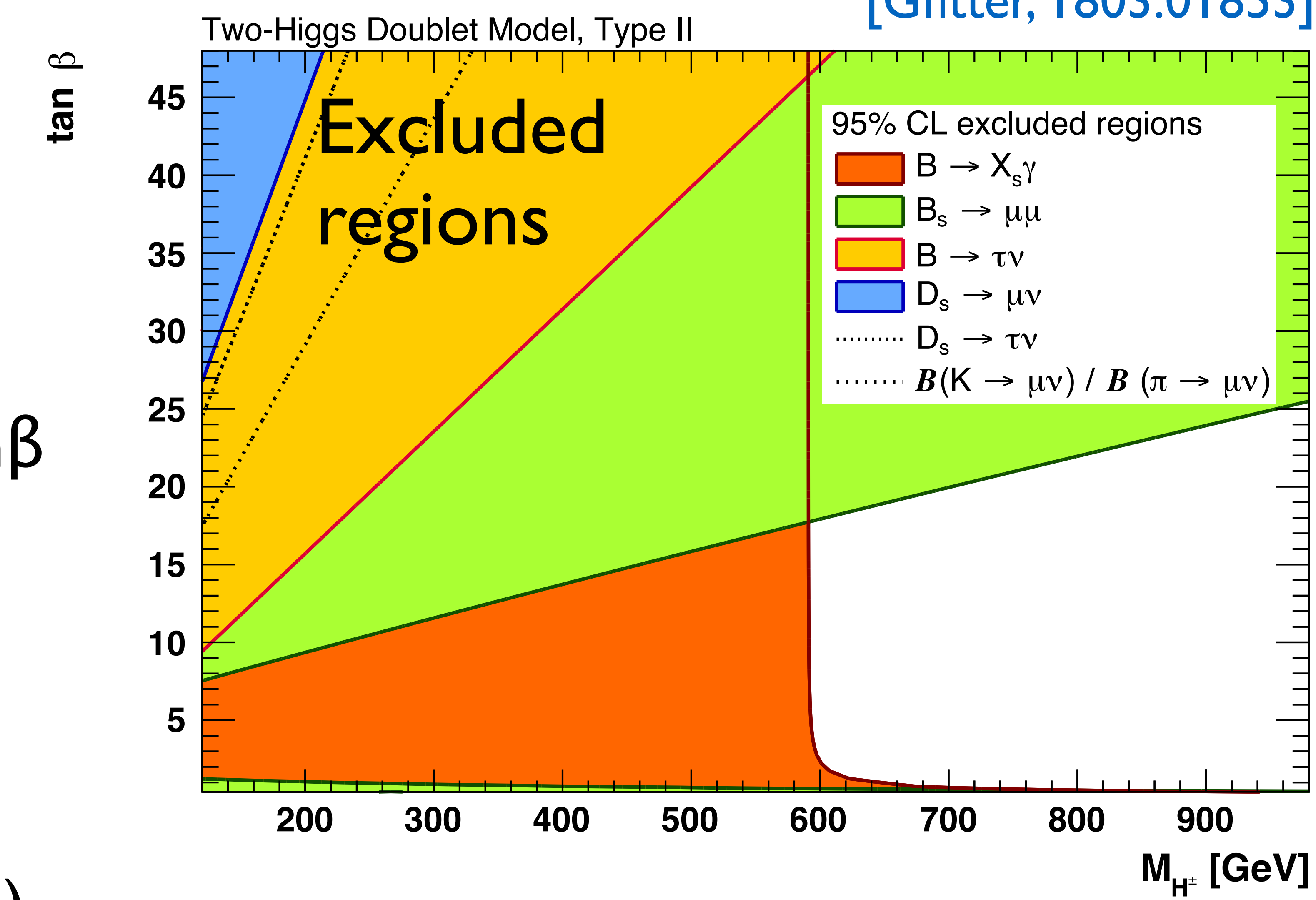
2HDM Flavour Constraints

- New scalars give important contributions to flavour observables
  - Example: $B \to X_s \gamma$



- Sensitivity to $M_{H\pm}$ and $\tan\beta$

[Gfitter, 1803.01853]



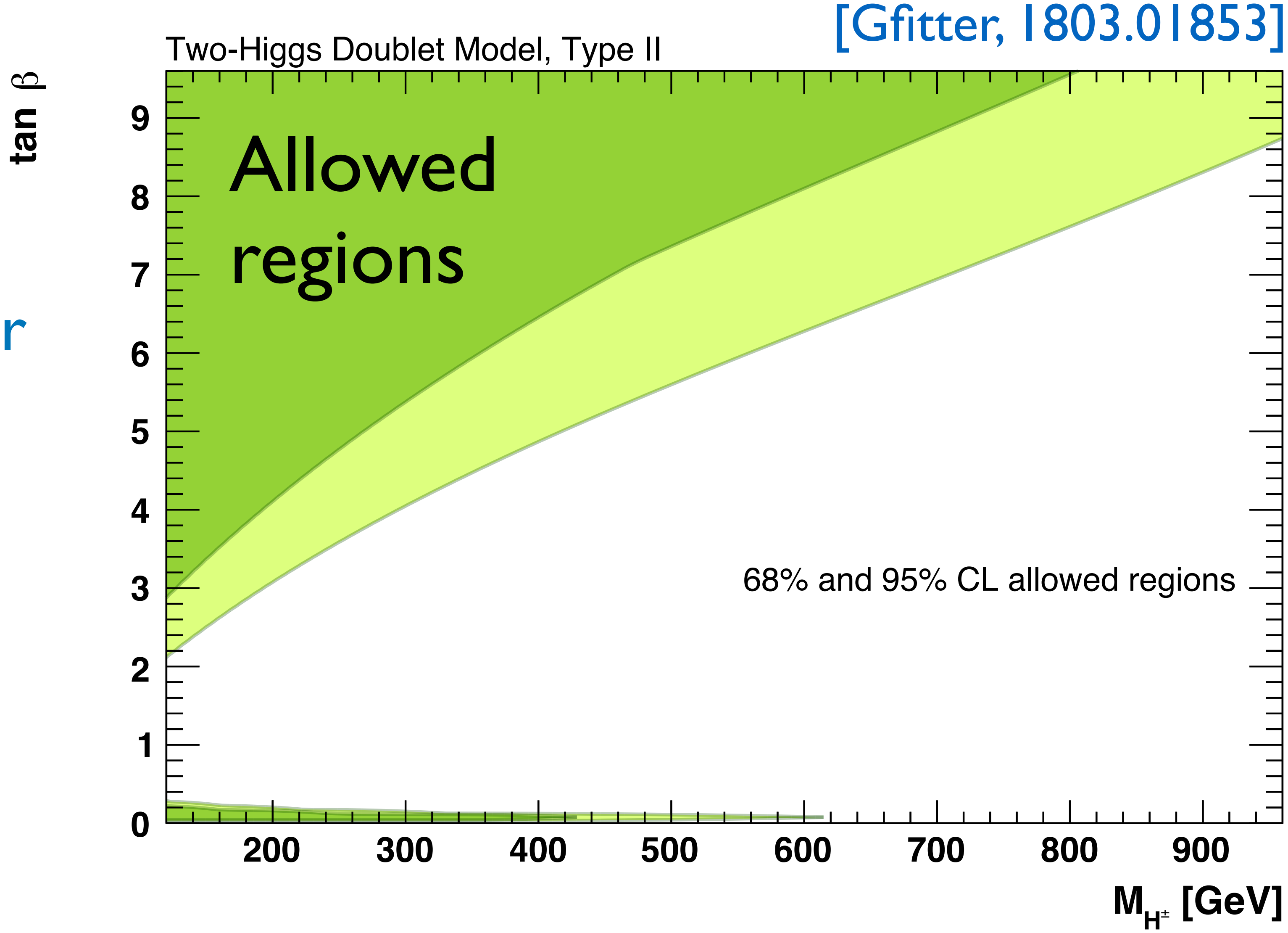
- R(D) and R(D*) can only be explained in *Type II* (large $\tan\beta$ and small M_{H+})
  → excluded by other flavour data
  - excluded from further fits

Muon g−2

Long-standing deviation in the SM: $\Delta a_\mu = (268 \pm 63 \pm 43) \cdot 10^{-11}$ (3.5σ)

[Gfitter, 1803.01853]

- Allowed regions in *Type II* and *flipped* scenarios
  - not compatible with other flavour data ($B_s \to \mu\mu$ and $B \to X_s\gamma$)
- Δa_μ can be accommodated in *Type I* and *lepton specific* scenarios



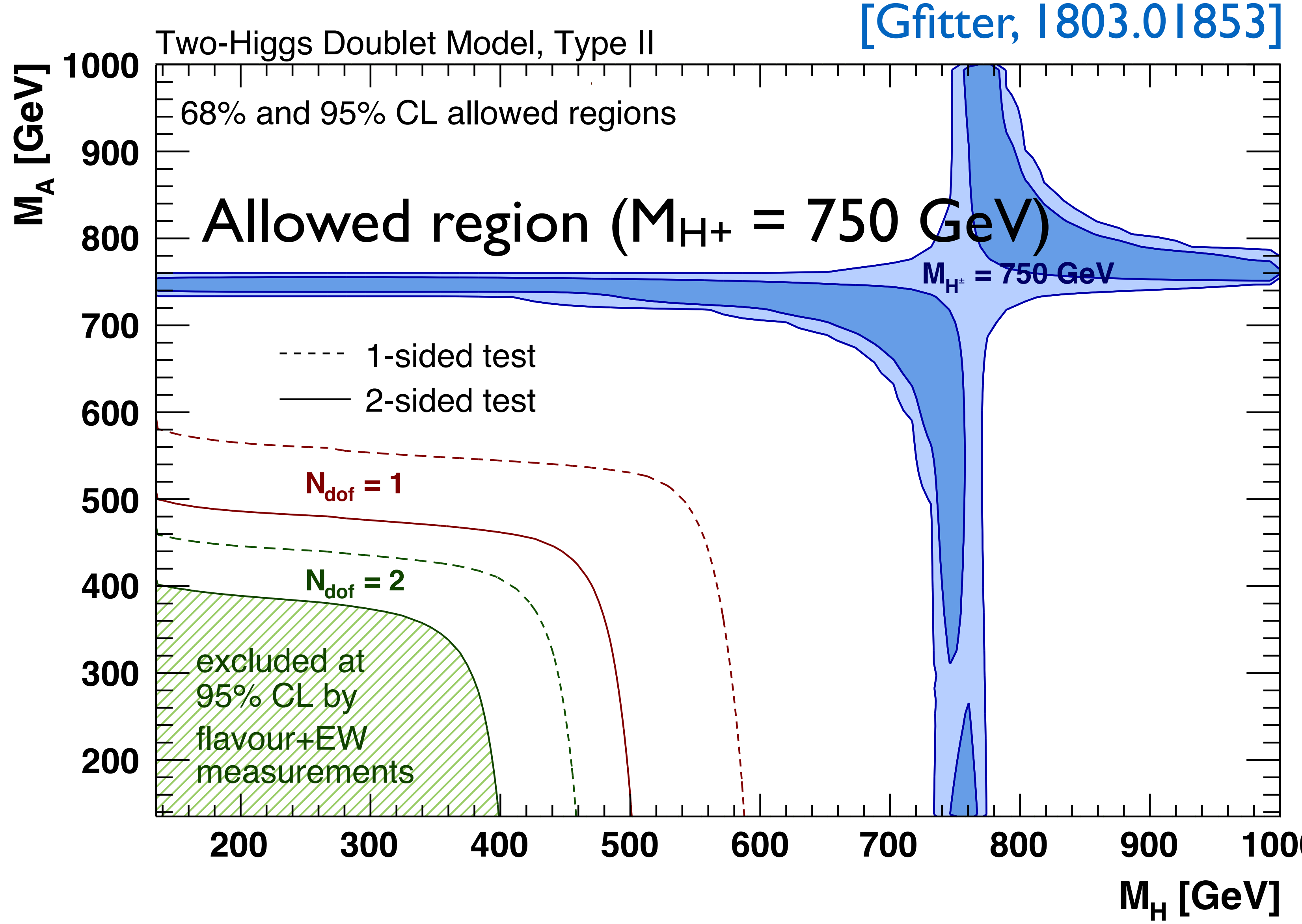
2HDM Global Fit

Combination of EWPO (through oblique parameters S,T,U), flavour data, $(g-2)_\mu$ and H coupling measurements

[Gfitter, 1803.01853]

- **Exclude**
  $M_A, M_H < 400$-500 GeV
  in *Type II* and *flipped*

- **No exclusions**
  of MA and MH
  in *Type I* and
  lepton specific



- **Direct searches**
  - No absolute limits on M_A, M_H, M_H: large freedom of parameter choices
  - Important constraints in specific parameter regions

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?

Adding new terms to the Lagrangian, SMEFT:

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

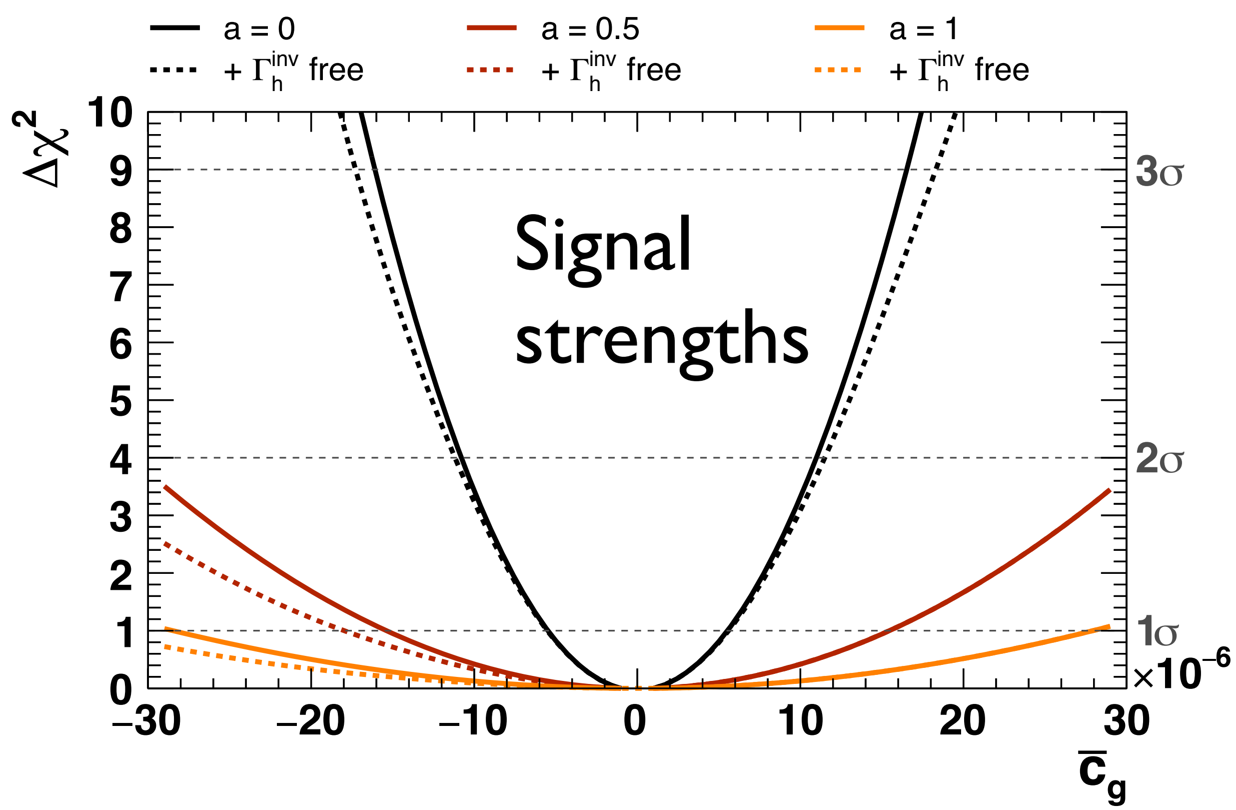
operators of dimension 6
- respect SM gauge symmetry (SU(2) x U(1))
- include only SM fields

- SILH basis, focus on operators with H involvement, EWPO: $c_T = 0$, $c_W = -c_B$
- **8** operators of interest

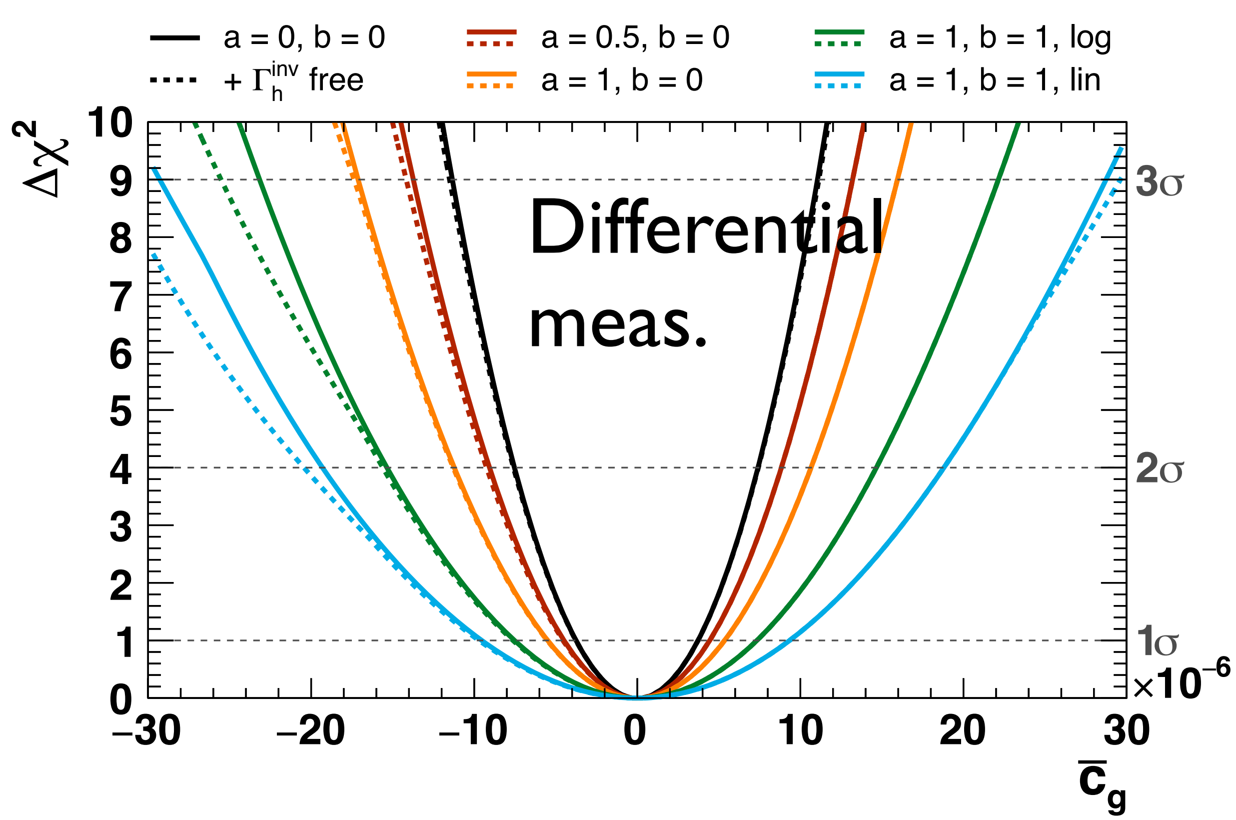
Focus on linear contribution: $|\mathcal{M}|^2 = |\mathcal{M}_{\rm SM}|^2 + 2\,{\rm Re}\{\mathcal{M}_{\rm SM}\mathcal{M}^*_{d=6}\} + \mathcal{O}(1/\Lambda^4)$

[Englert, RK, Schulz, Spannowsky, 1509.00672]

Constraints from HL-LHC



- Signal strength only
  - Combinations of coefficients c_i can result in same signal strength
  - Weak constraints, even with 3000 fb^{-1}



- Different behaviour at high energies
  - go differential in $p_{T,H}$
    - generate pseudo-data
    - uncertainties extrapolated from μs
  - Lift flat directions
  - Much tighter constraints!
    - Improves LHC physics potential

[Englert, RK, Schulz, Spannowsky, 1708.06355]

Prospects of the EW Fit

Future developments for the SM EW fit

- $\Delta\alpha^{(5)}_{had}(M_Z^2)$ Low energy data (esp. $\pi+\pi-$), also pQCD/lattice
- M_W LHC Measurements! Theory uncertainty of 4 MeV!
- m_t Experimental progress and theoretical interpretations
- $\sin^2\theta^l_{eff}$ Can the LHC improve?
- A_{FB}^{0b} Z+b production at LHC, e.g. [M. Beccaria et al., PLB 730, 149 (2014)]

Extensions of the scalar sector

- $B \to X_s\gamma$, $B_s \to \mu\mu$, $(g-2)_\mu$…, precision H coupling measurements
- Direct searches: cover all possible final states

General extension with the SMEFT

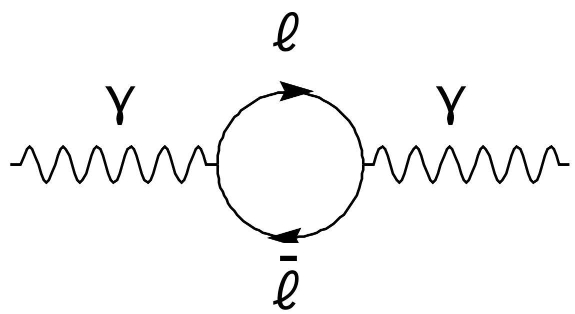
- EWPO, LEP 2 data, flavour data [J. Ellis et al., 1803.03252]
- Differential H measurements, also sensitivity to H self-coupling λ!

Additional Material

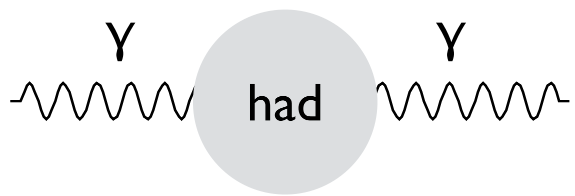
Precision Estimates: Corrections

Modifications of Propagators and Vertices

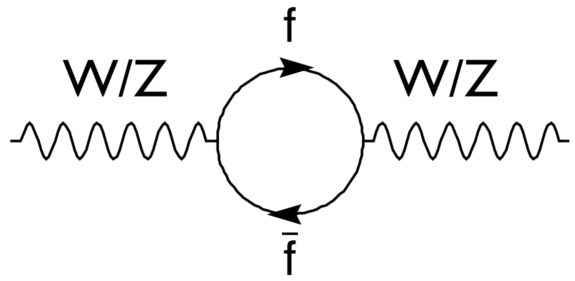
- QED corrections
  - leptonic loop insertions
    - calculable to high precision
  - quark loop insertions (hadronic)
    - partially not calculable in pure pQCD
- Weak corrections
  - Insertion of fermion loops
    - high sensitivity to m_f (if $m_f \gg m_W$)
  - Insertion of boson loops
    - logarithmic sensitivity to M_H
- QCD corrections
  - Sensitivity to strong coupling
    - numerically small contribution $(1 + \alpha_s/\pi)$



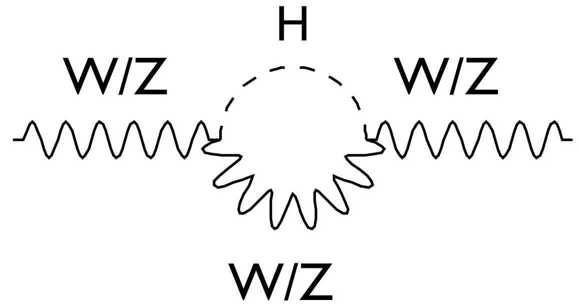
$\propto \alpha \ln \frac{s}{m_\ell^2}$



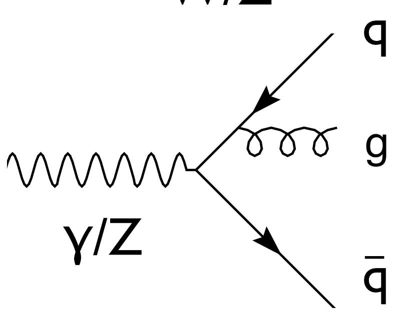
$\propto \Delta\alpha_{\mathrm{had}}(s)$



$\propto N_C m_f^2$

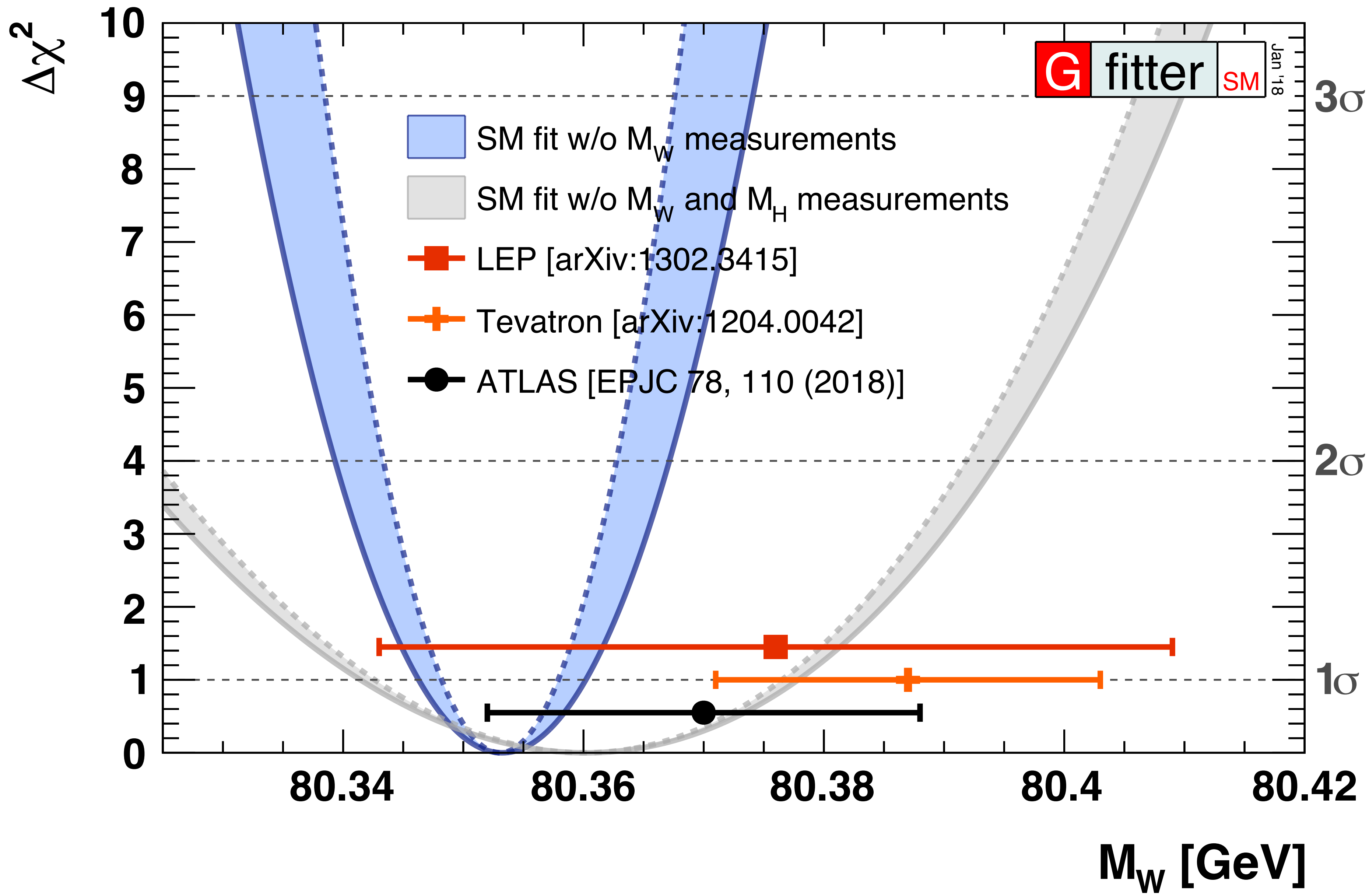


$\propto \ln \frac{M_H^2}{M_W^2}$



$\propto \alpha_s(s)$

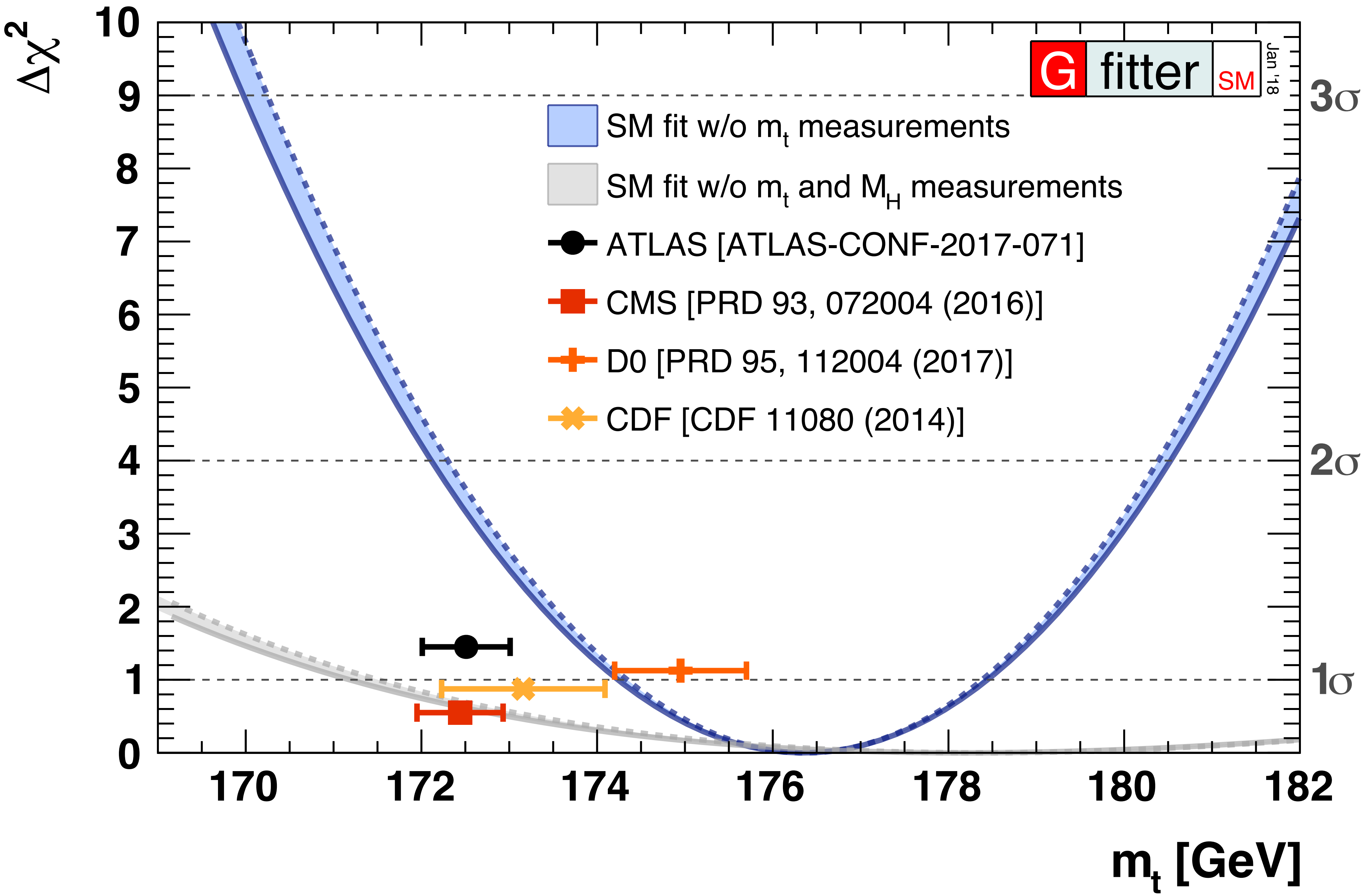
Predicting M_W



$$M_W = 80.3535 \pm 0.0027_{m_t} \pm 0.0030_{\delta_{\text{theo}} m_t} \pm 0.0026_{M_Z} \pm 0.0026_{\alpha_S} \pm 0.0024_{\Delta\alpha_{\text{had}}} \pm 0.0001_{M_H} \pm 0.0040_{\delta_{\text{theo}} M_W}\ \text{GeV}\,,$$

$$= 80.354 \pm 0.007_{\text{tot}}\ \text{GeV}$$ (exp: ± 0.013 GeV)

Predicting m_t

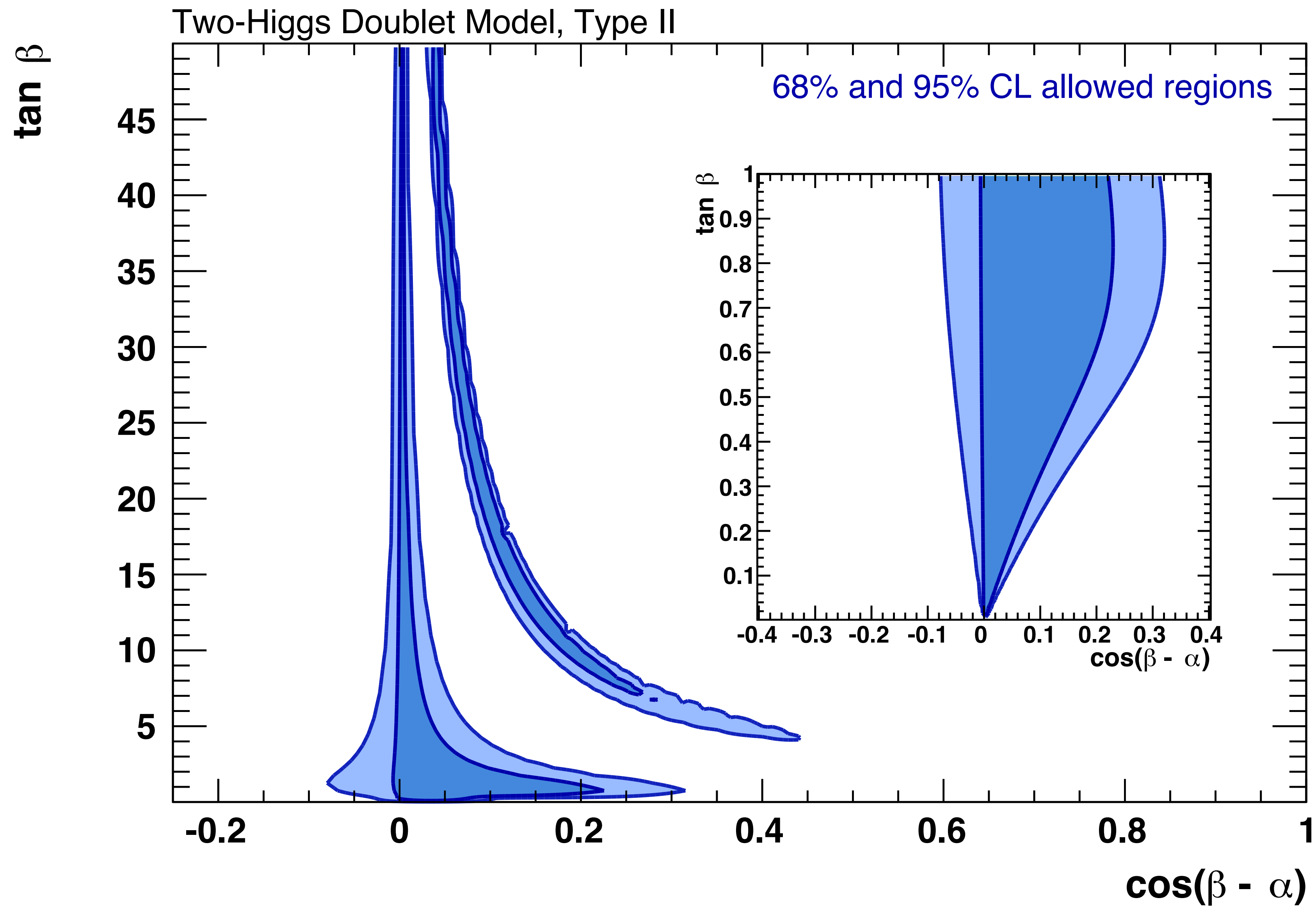


$m_t = 176.4 \pm 2.1\,\mathrm{GeV}$ (exp: ± 0.46 GeV)

(perfect knowledge of M_W: ± 0.9 GeV)

2HDM and H measurements

- Alignment solution
  - $\cos(\beta-\alpha) = 0$ (light h is SM solution, $\kappa_V = 1$)
- Flipped solution
  - $\beta+\alpha = \pi/2$
    - inverted sign of down-type fermion couplings
    - new data on bb and ττ will constrain this region



Dim-6 SILH Basis

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

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

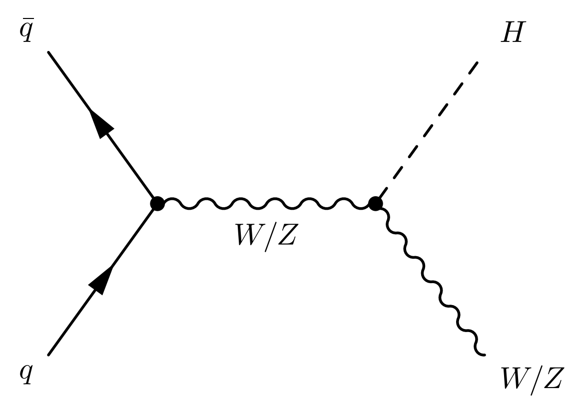
- **8** operators of interest left

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

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

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 ✓

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
$pp \to H + \mathrm{j}$	15	$H \to \gamma\gamma$	5.4
$pp \to H + 2\mathrm{j}$	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

$$\boxed{\mu_{i,f} = \frac{\sigma_{i,f}^{\mathrm{O6}} + u_{i,f}^{\mathrm{O6}}(1 - \delta_{i,f}^{\mathrm{O6}})}{\sigma_{i,f}^{\mathrm{SM}} + u_{i,f}^{\mathrm{SM}}(1 - \delta_{i,f}^{\mathrm{SM}})}}$$

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

- 26 nuisances, 8 Wilson coefficients = 34 free parameters

Impact of Theory Uncertainties

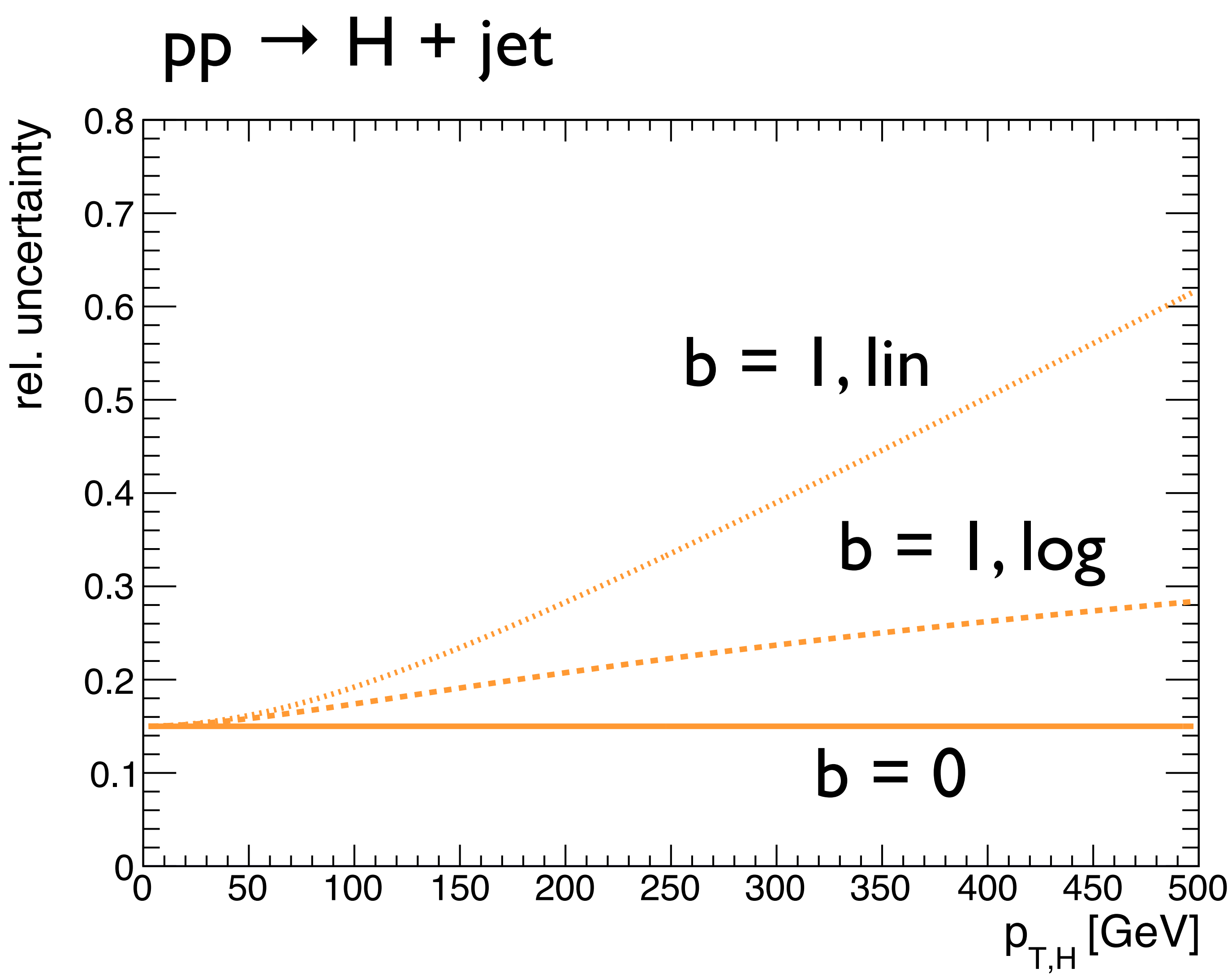
Uncertainties in tails of $p_{T,H}$

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

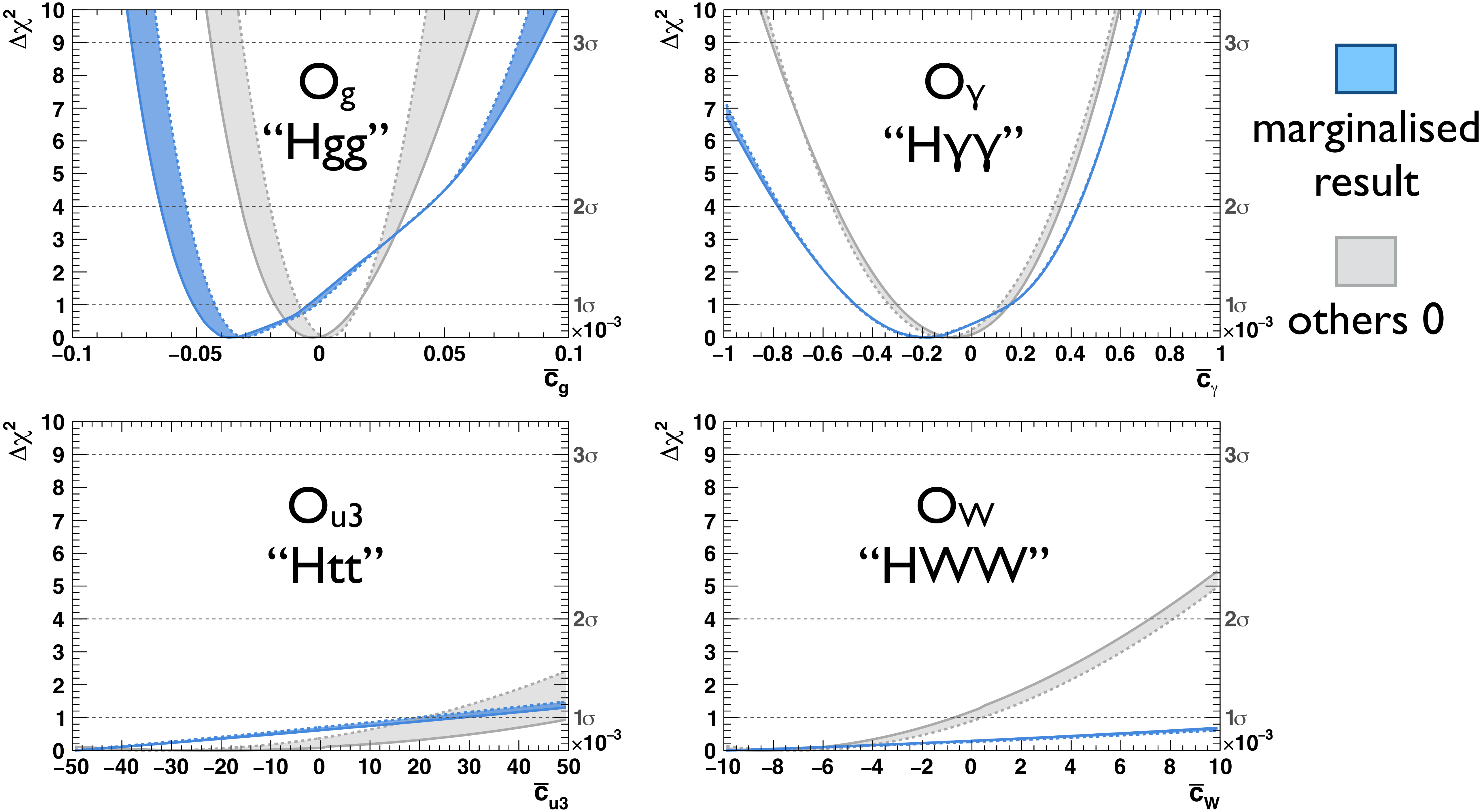
$$\Delta_i = u_i(\underbrace{a(1-\delta_i)}_{\text{inclusive}} \oplus \underbrace{b(1-\delta_{i,\text{tail}})f(p_{\text{T,H}})}_{\text{tail}})$$

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

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



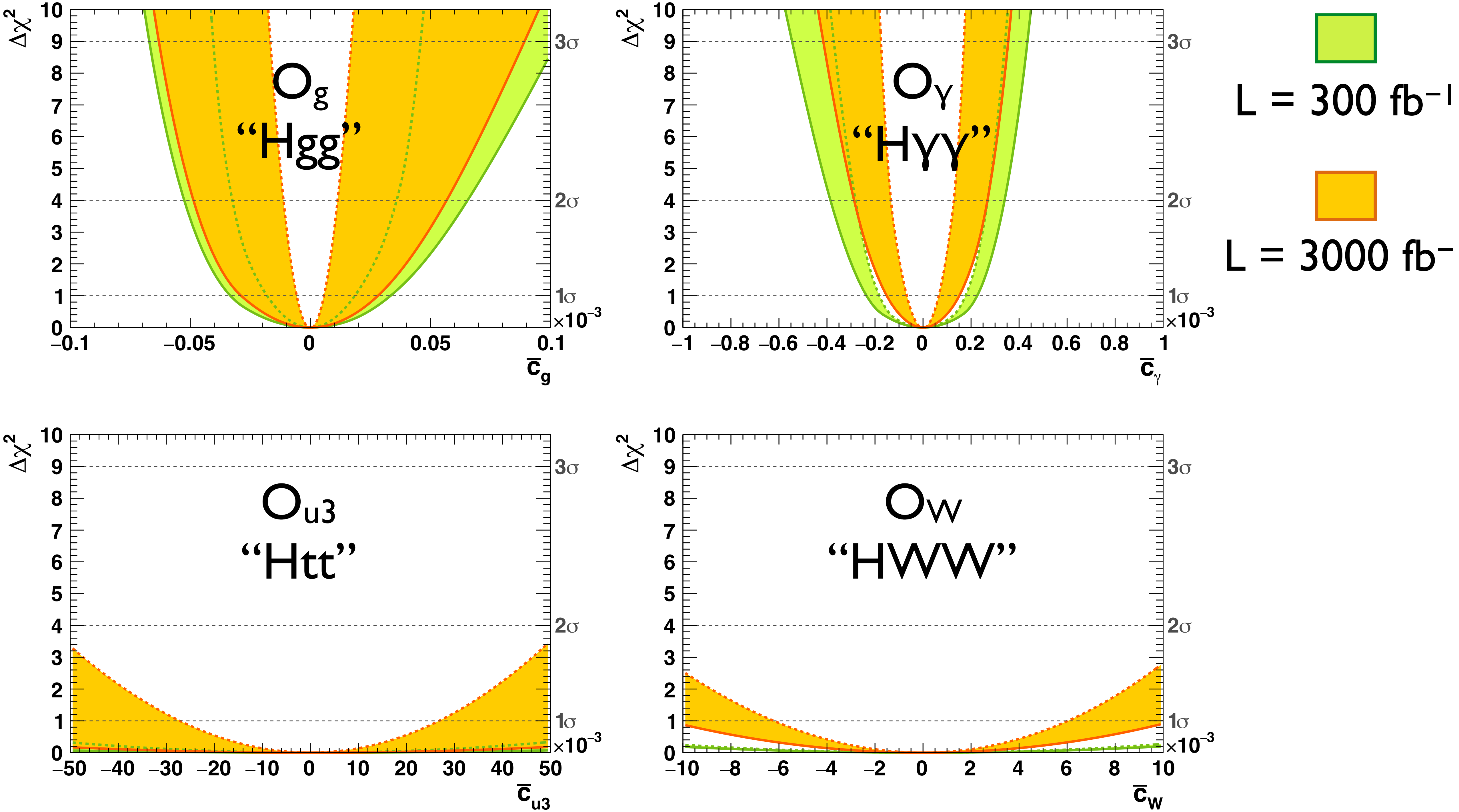
Constraints from Run 1



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

[Englert, RK, Schulz, Spannowsky, 1509.00672]

Constraints from HL-LHC



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

[Englert, RK, Schulz, Spannowsky, 1509.00672]

Flat Directions

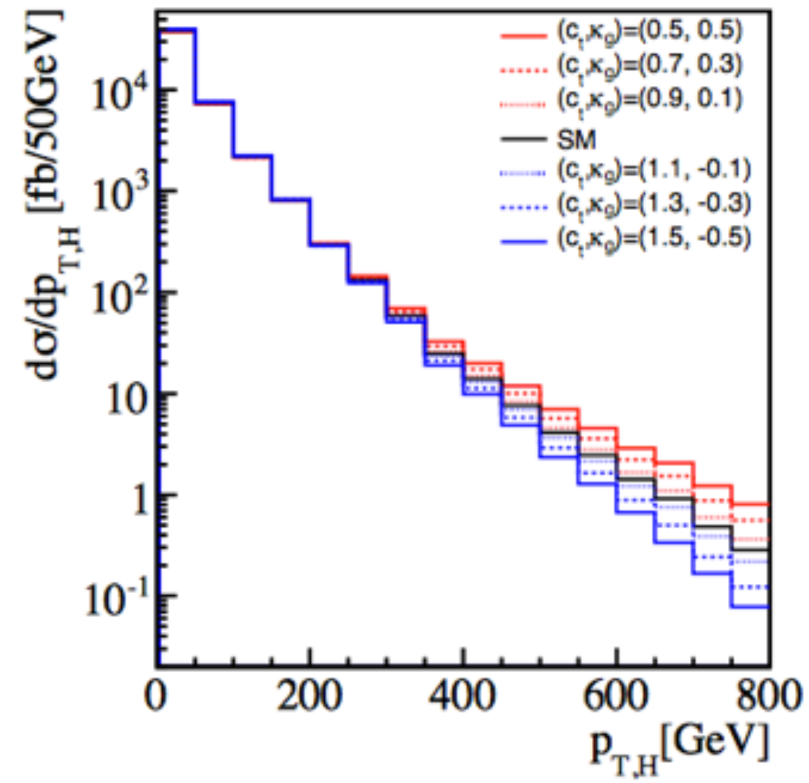
[Englert, Spannowsky, 1408.5147]

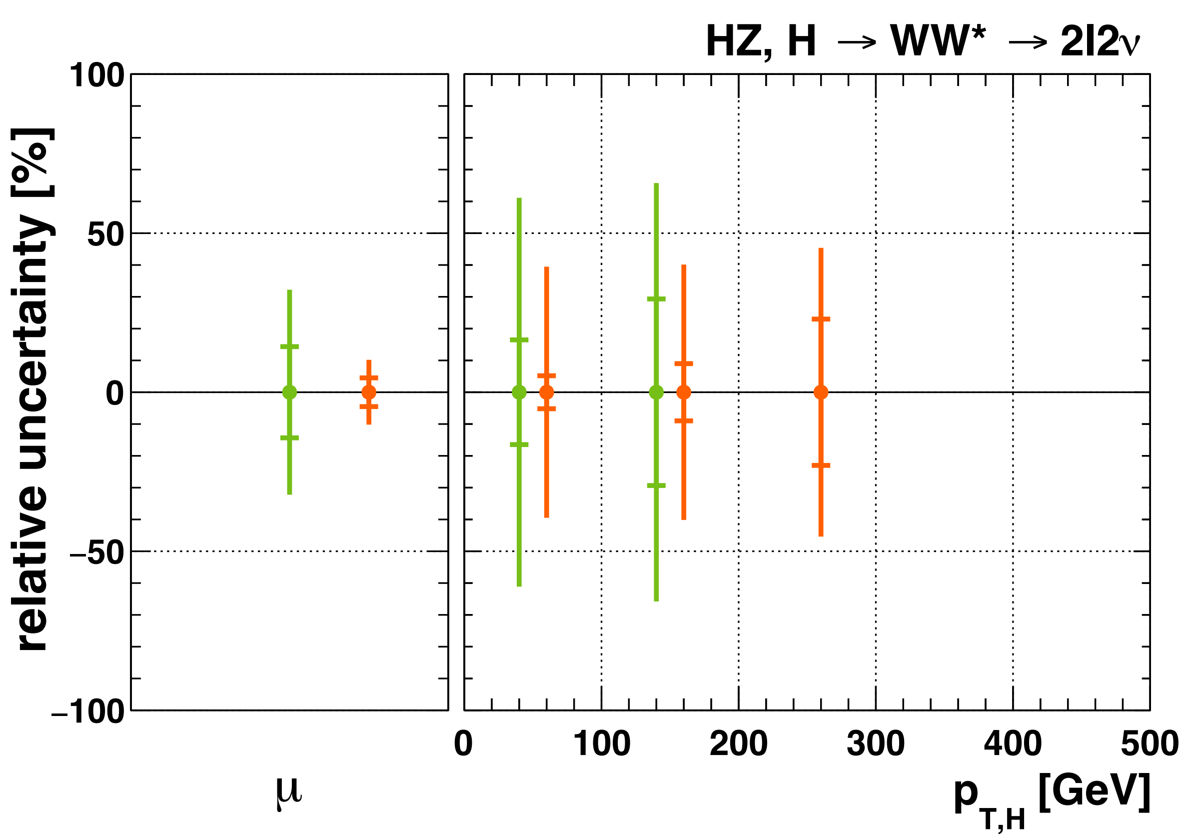
Multi-parameter fit

- 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 $p_{T,H}$

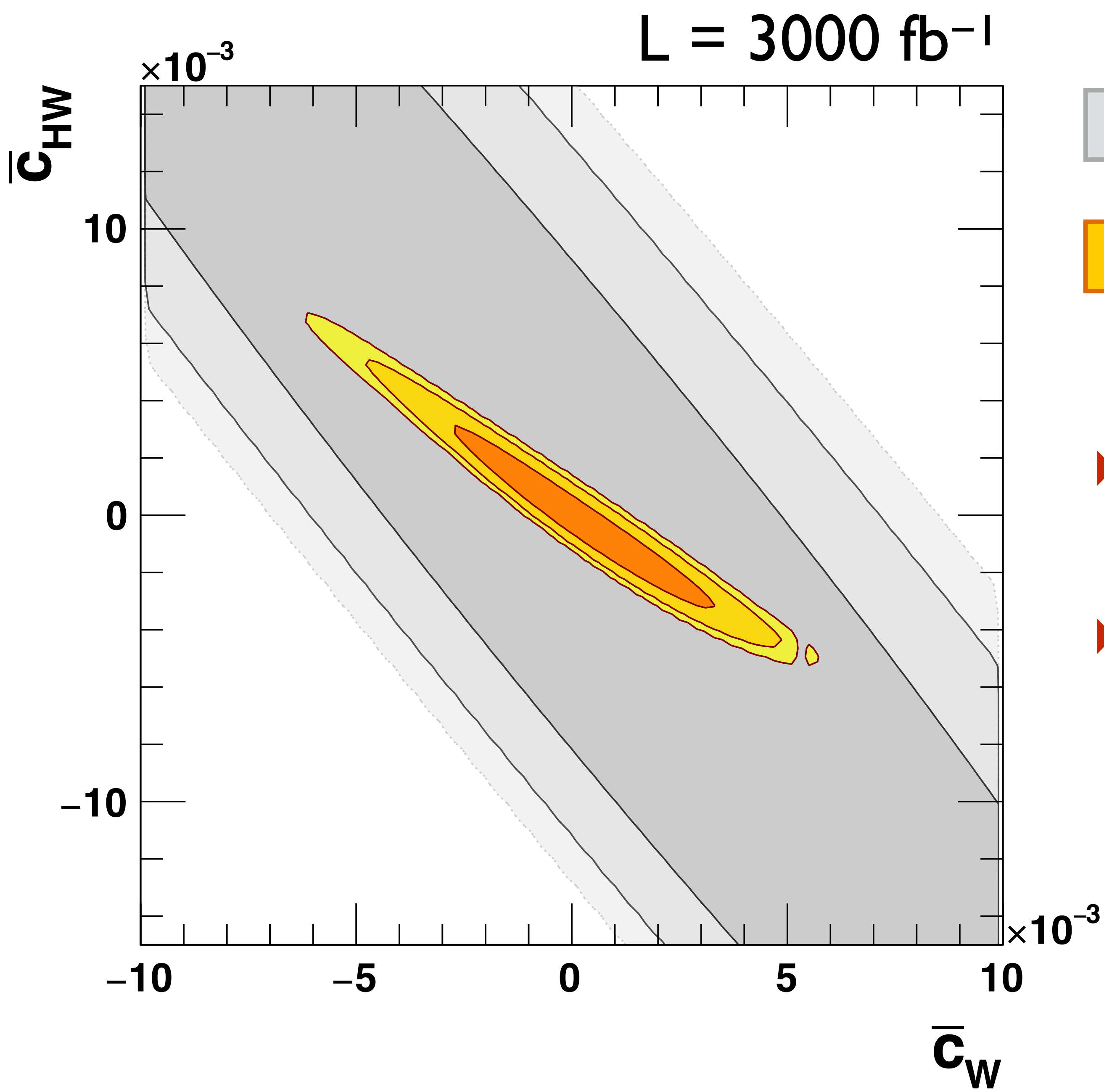




Pseudo data

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

Lifting flat directions



only signal strengths

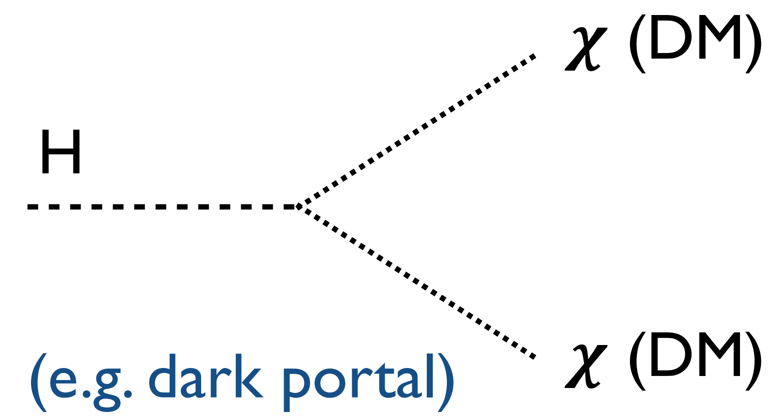
including $p_{T,H}$ measurements

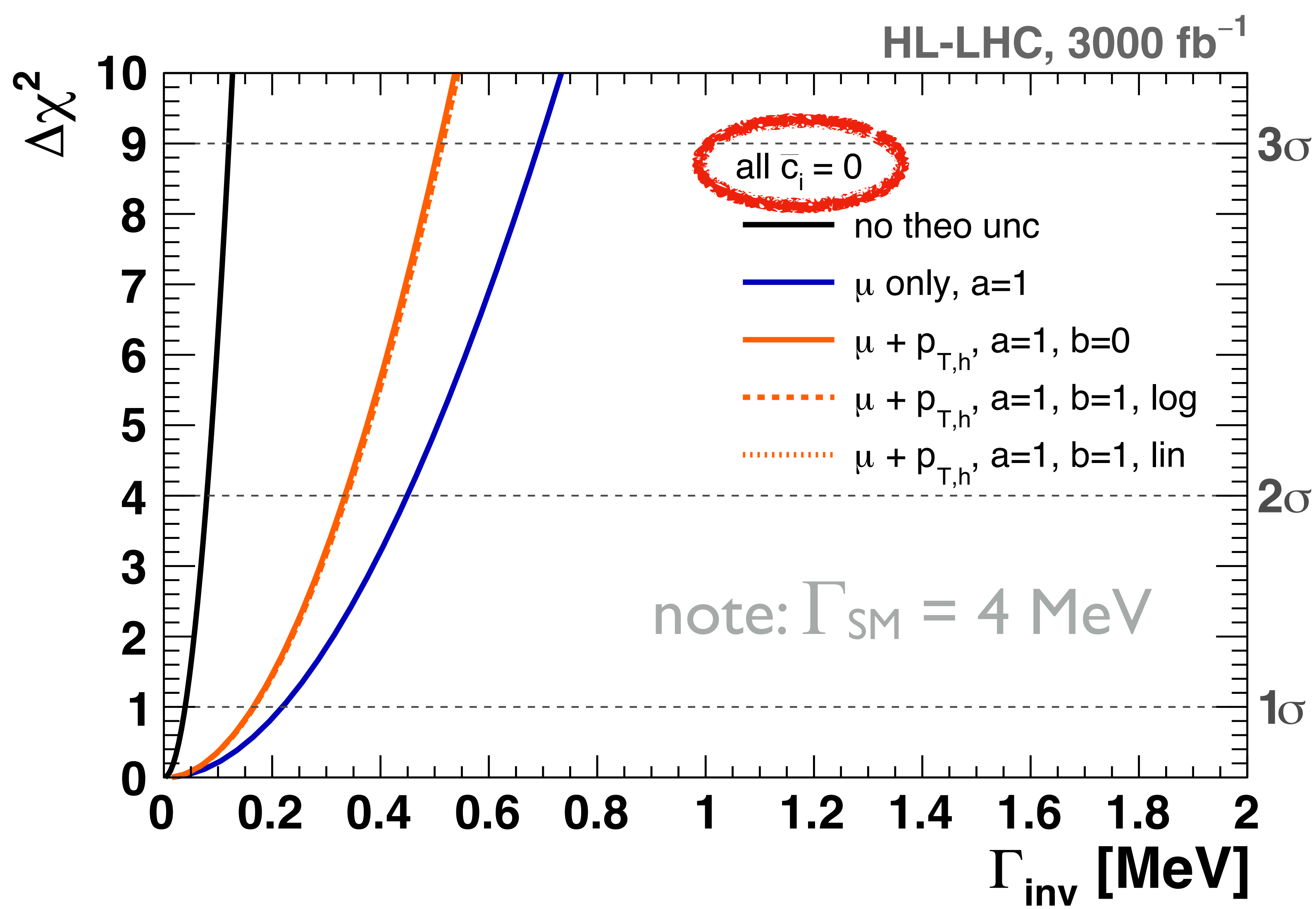
- Strong correlations between coefficients are lifted
- Simultaneous constraints on all parameters possible

[Englert, RK, Schulz, Spannowsky, 1509.00672]

Invisible Width

- Consider additional light degree of freedom
  - if Γ_{tot} (and Γ_{inv}) increases, signal strengths decrease





No BSM contributions beyond BR_{inv} :

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

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

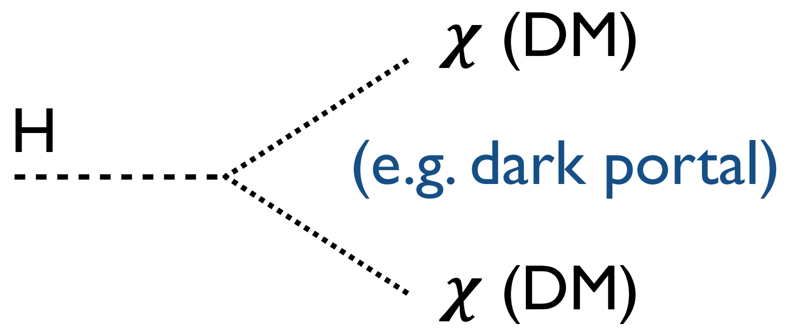
Very similar to expected direct measurements

[Okawa et al., 1309.7925]

ATLAS study: BR_{inv} < 15%

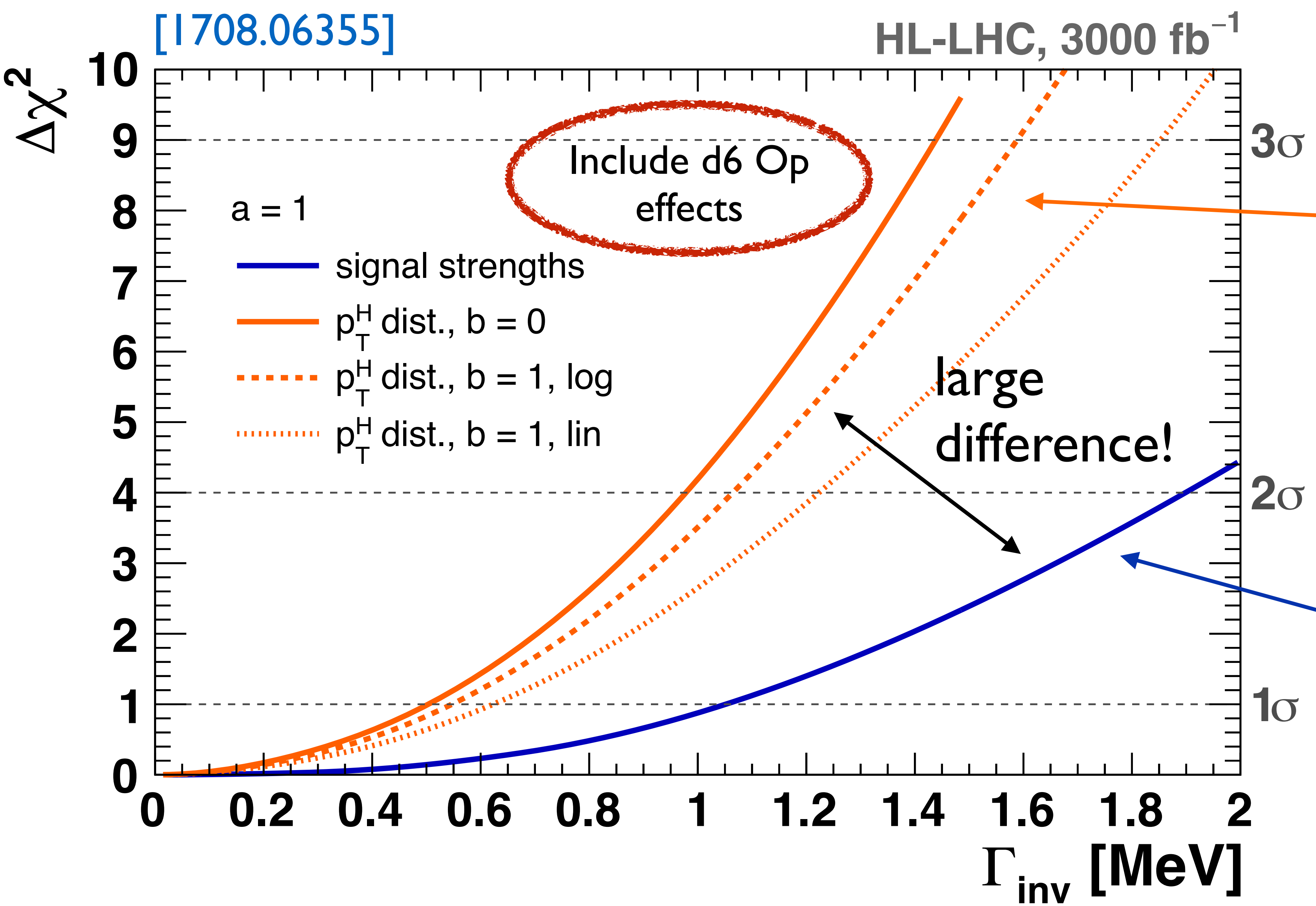
[ATL-PHYS-PUB-2013-015]

Invisible Width with HL-LHC



Consider additional light degree of freedom

No BSM contributions beyond BR_{inv}: BR_{inv} < 10-15%



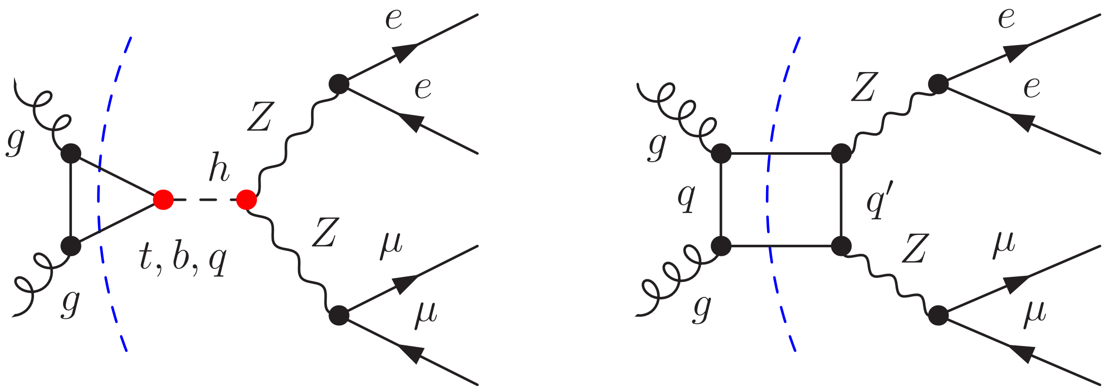
$BR_{inv} \lesssim$ 20-25%
(with p_{TH} meas)
(not too far from constraints with SM+BR_{inv})

BR_{inv} < 30-35%
(μs only)

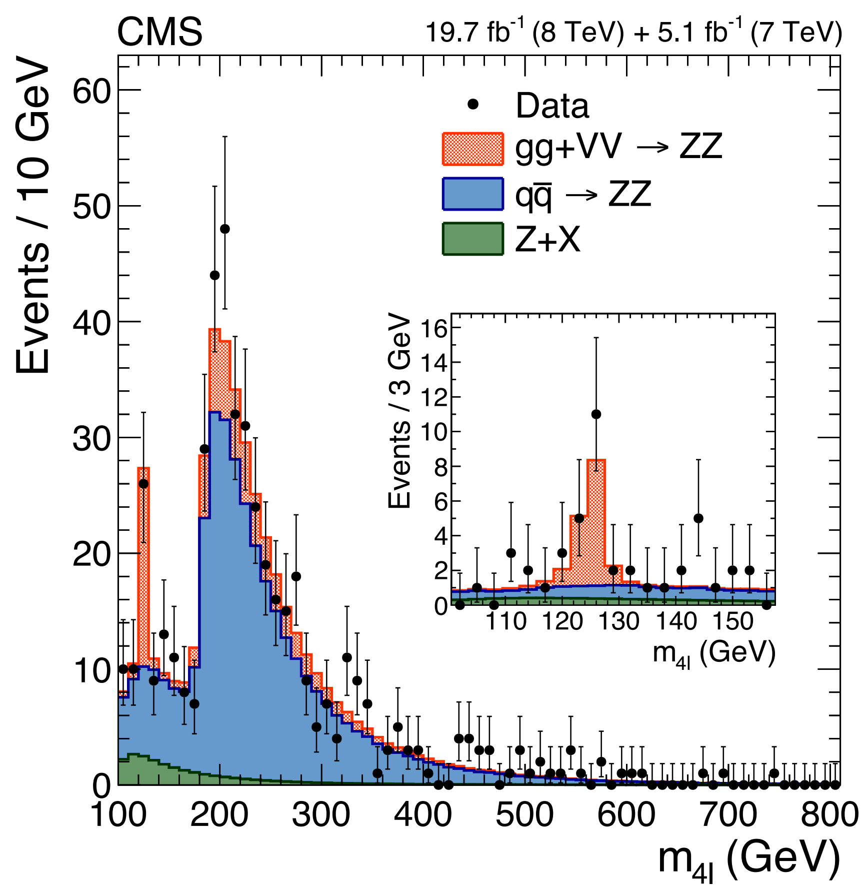
Off-shell Measurement

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

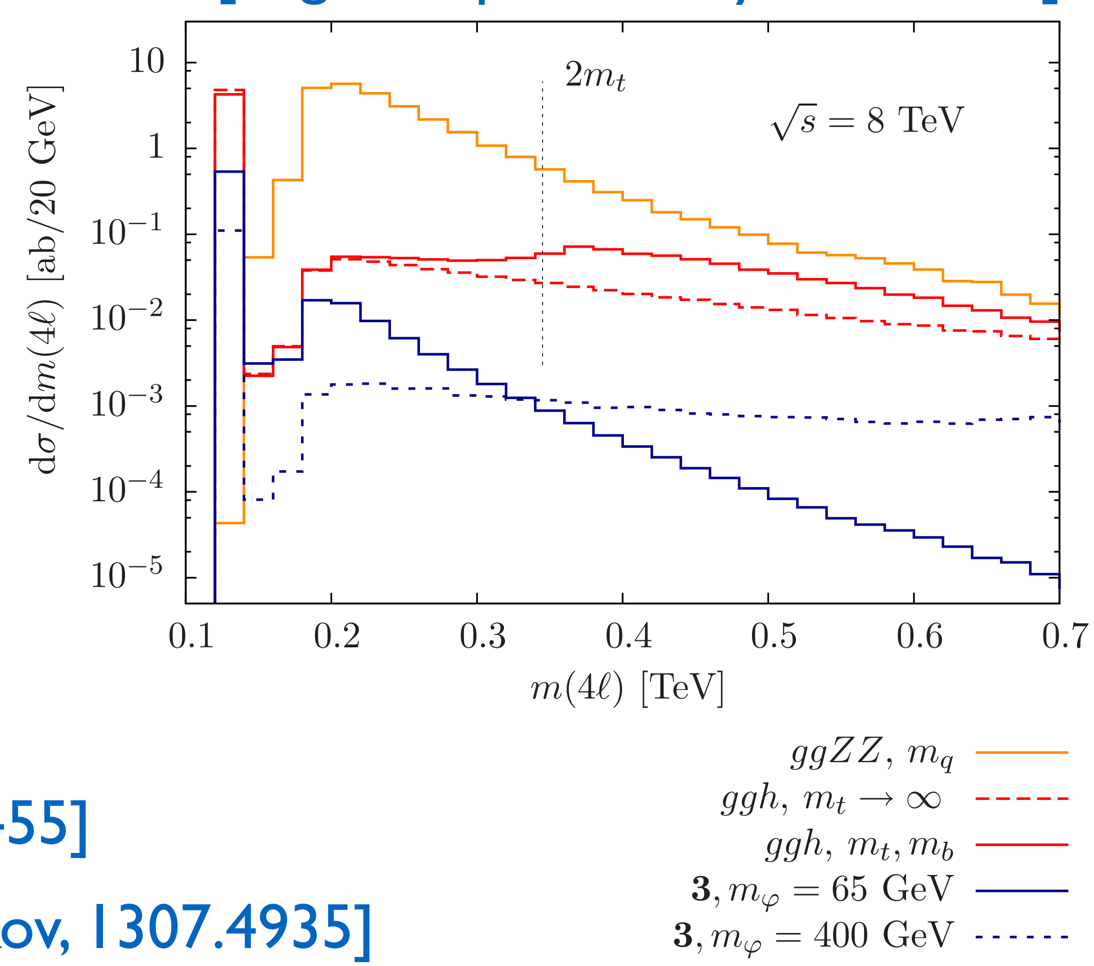
- Extrapolate run 1 measurement of $m_{4\ell}$, similar to $p_{T,H}$
  - off-shell: $m_{4\ell}$ > 330 GeV
  - dominated by statistics, ~ 15% uncertainty with HL-LHC



[Englert, Spannowsky, 1405.0285]



[CMS, 1405.3455]



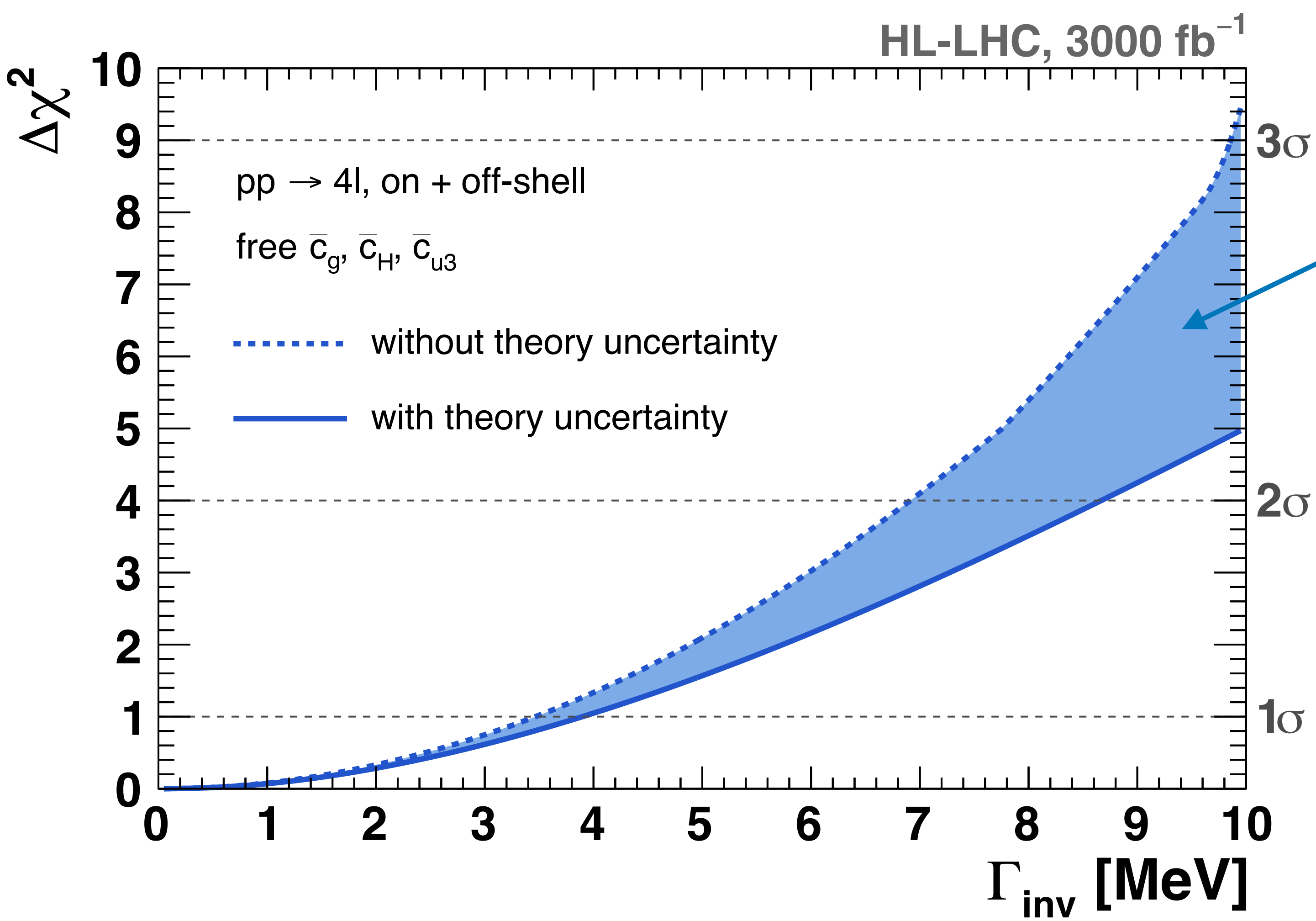
[Caola, Melnikov, 1307.4935]

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% $\sim g_i^2\, g_f^2$

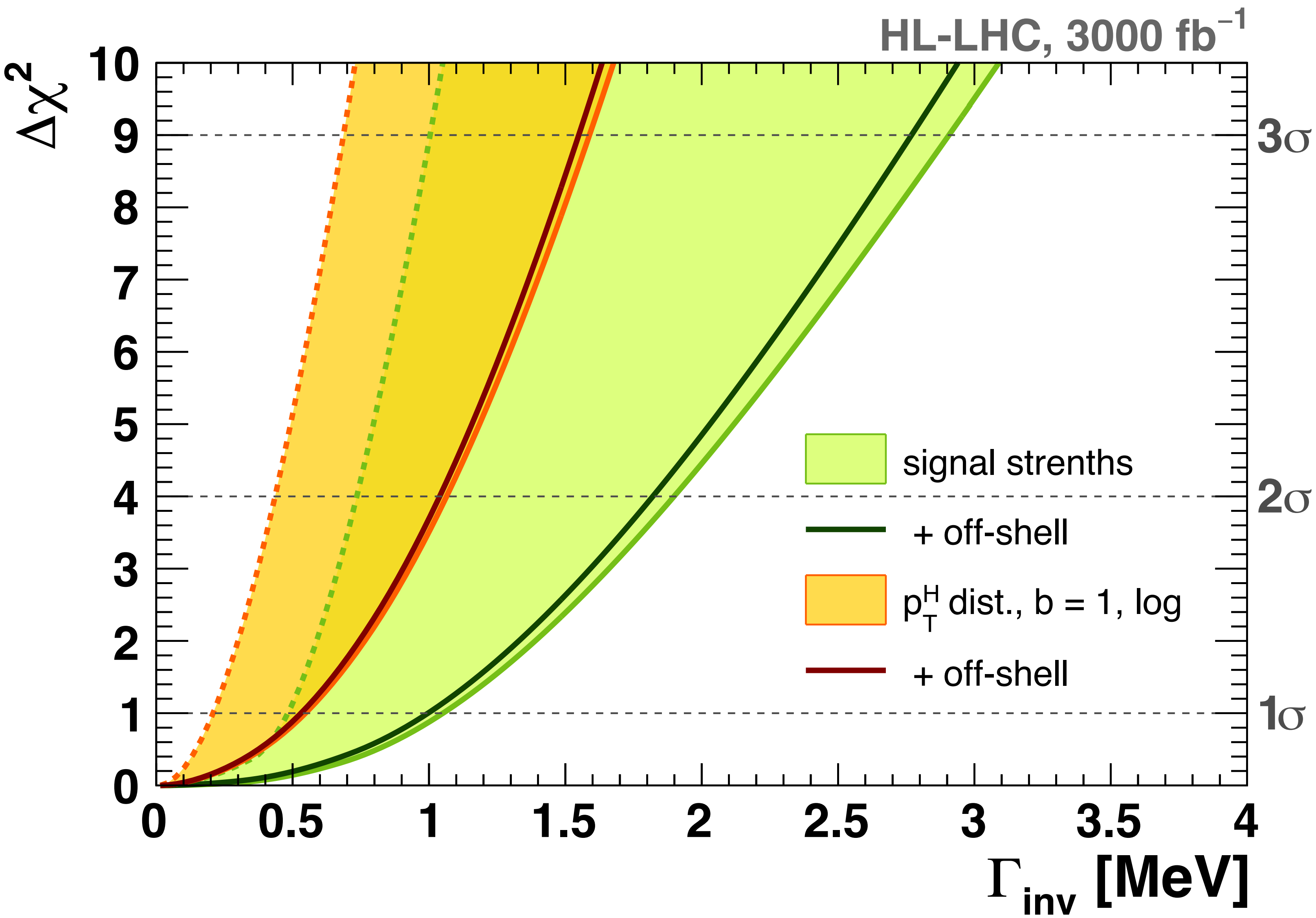
marginalise over c_g, c_{u3}, c_H (others fixed to 0)



$\Gamma_{inv} \lesssim 7$ MeV at 95% CL with single measurement in the context of an EFT

Off-shell measurement and Γ_{inv}

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)