The LHC's impact on the global electroweak fit

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The Gfitter group:
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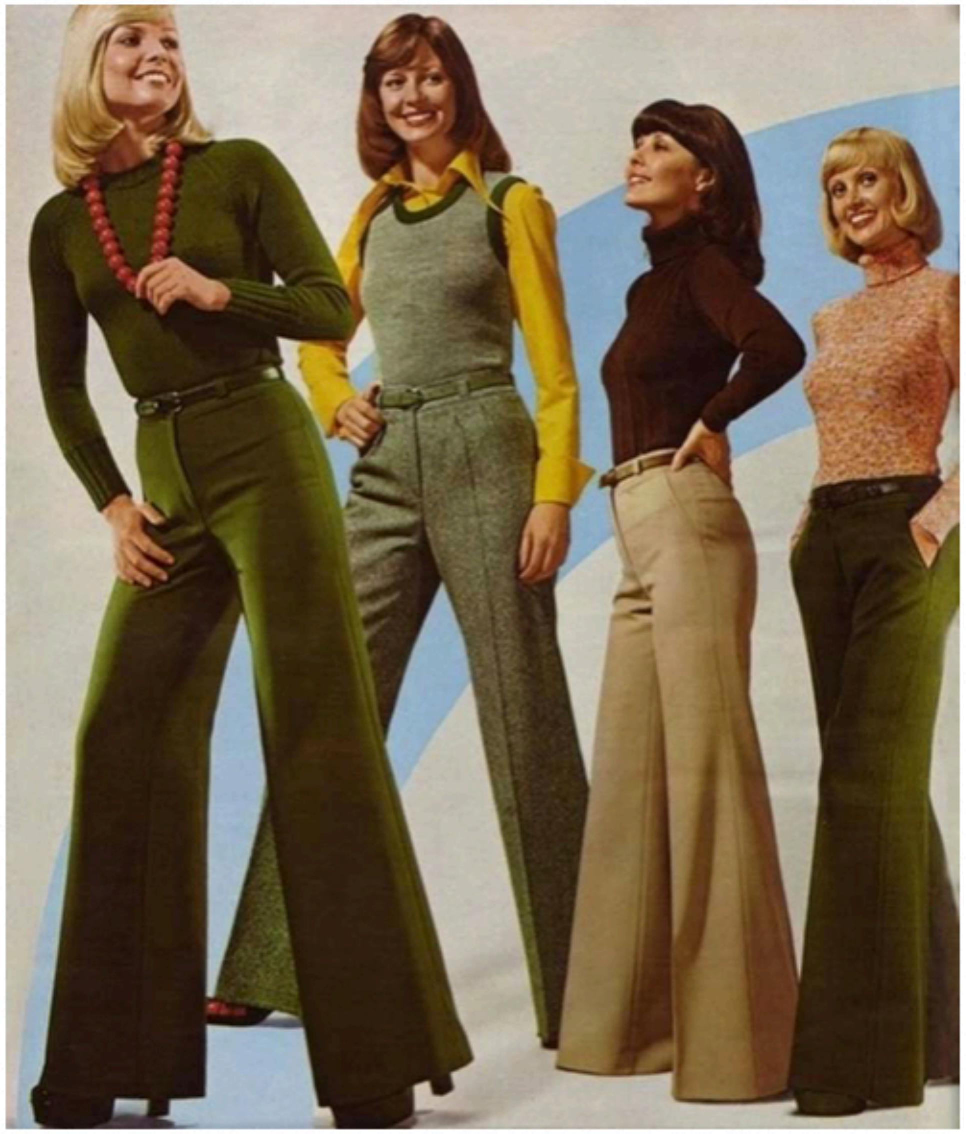
Based on 1509.00672, 1708.06355, 1803.01853

Let's assume we live in 



The Standard Model

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

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

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

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

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

Looks good so far...

But is it healthy?

EW Symmetry Breaking

Predicting M_W

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

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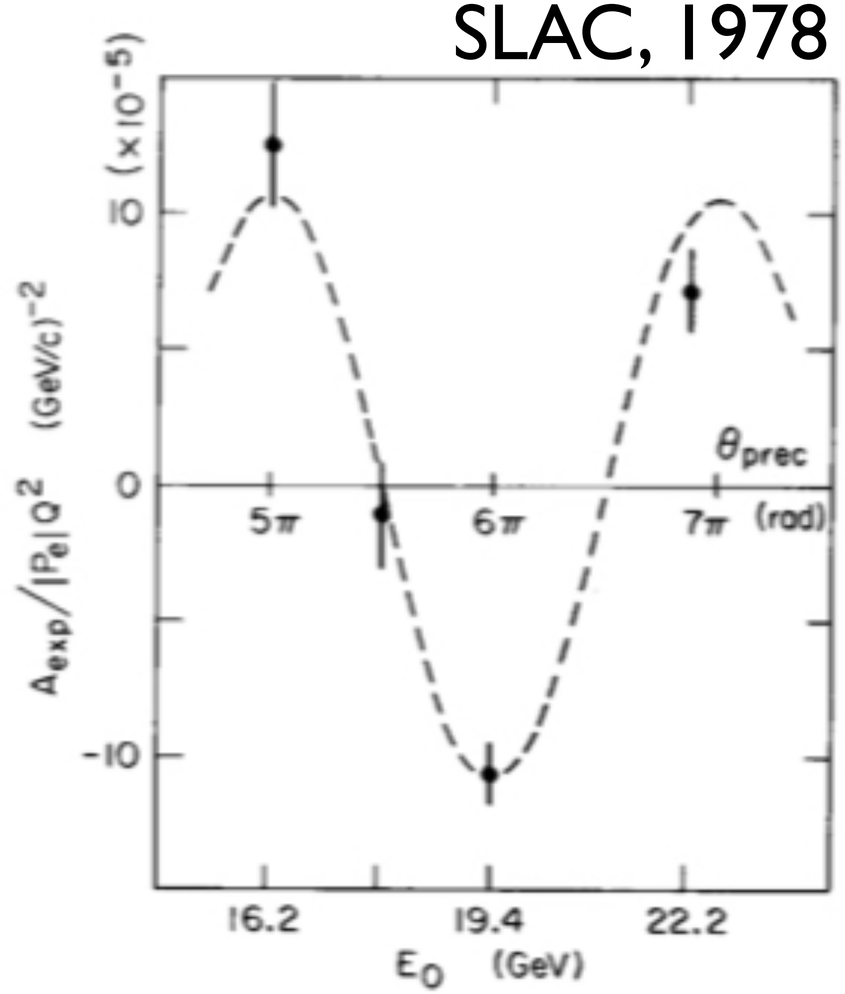
How large is $\sin\theta_W$?

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

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

SLAC, 1978



Here is our expectation:

$$\boxed{M_W = 82 \pm 6\,\mathrm{GeV}} \quad \text{and} \quad \boxed{M_Z = \frac{M_W}{\cos\theta_W} = 92 \pm 5\,\mathrm{GeV}}$$

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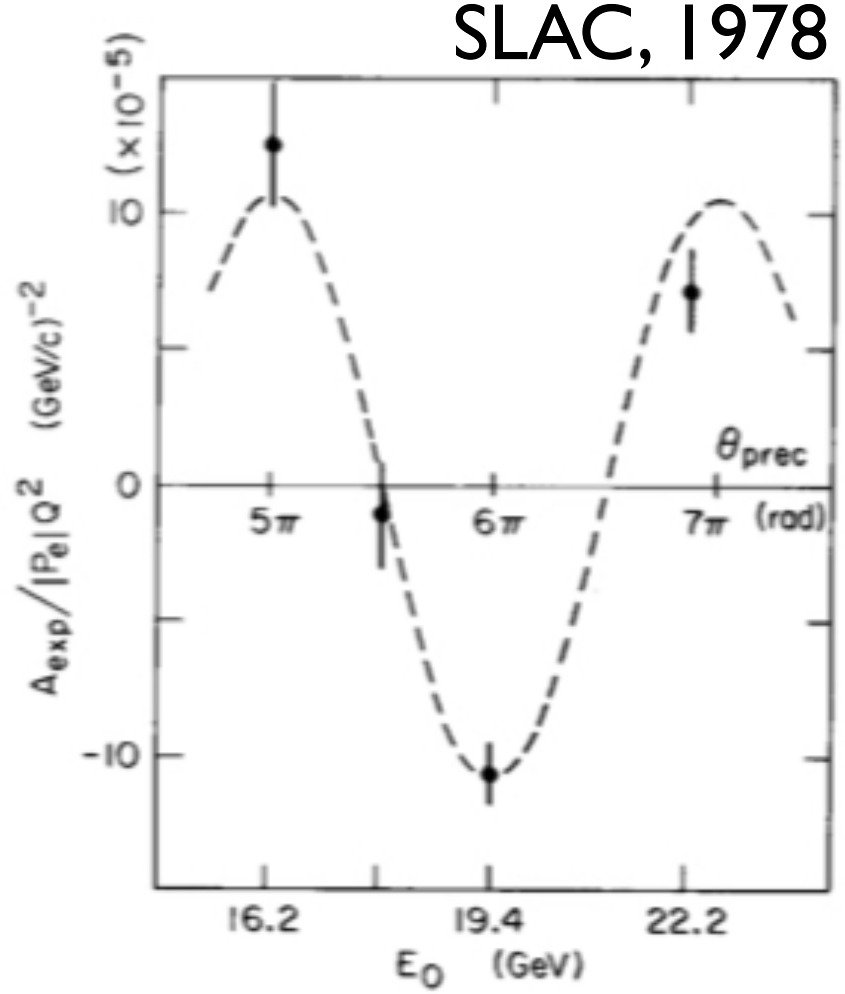
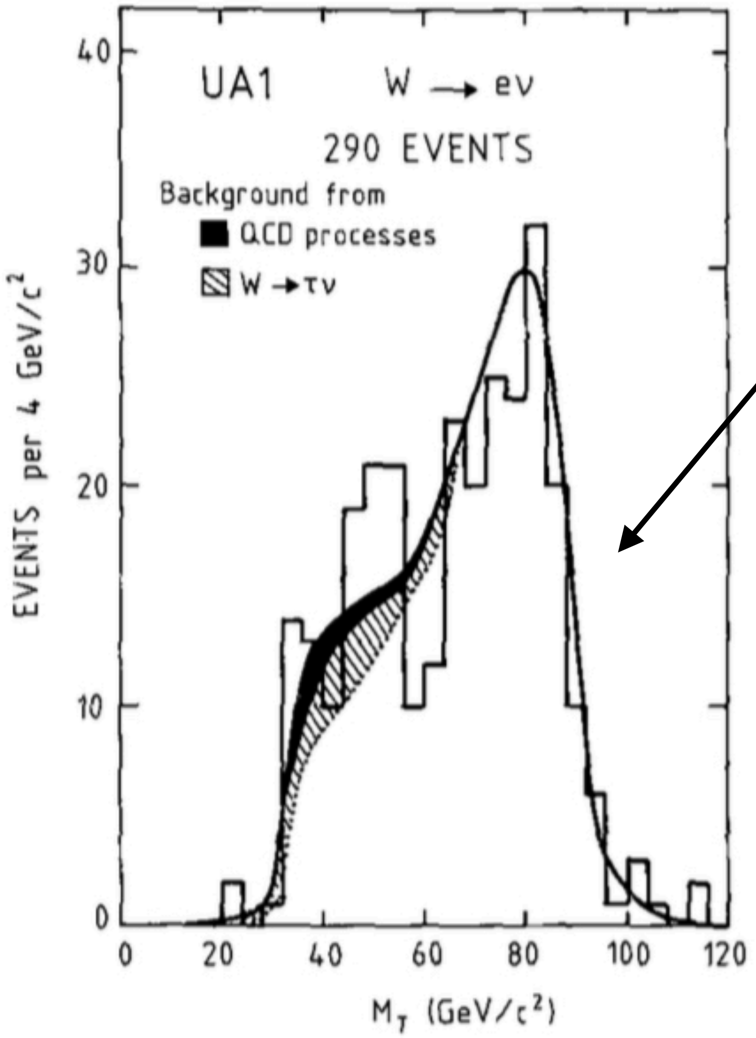


Here is our expectation:

$\boxed{M_W = 82 \pm 6\,\mathrm{GeV}}$ and $\boxed{M_Z = \frac{M_W}{\cos\theta_W} = 92 \pm 5\,\mathrm{GeV}}$

(we need a new collider)

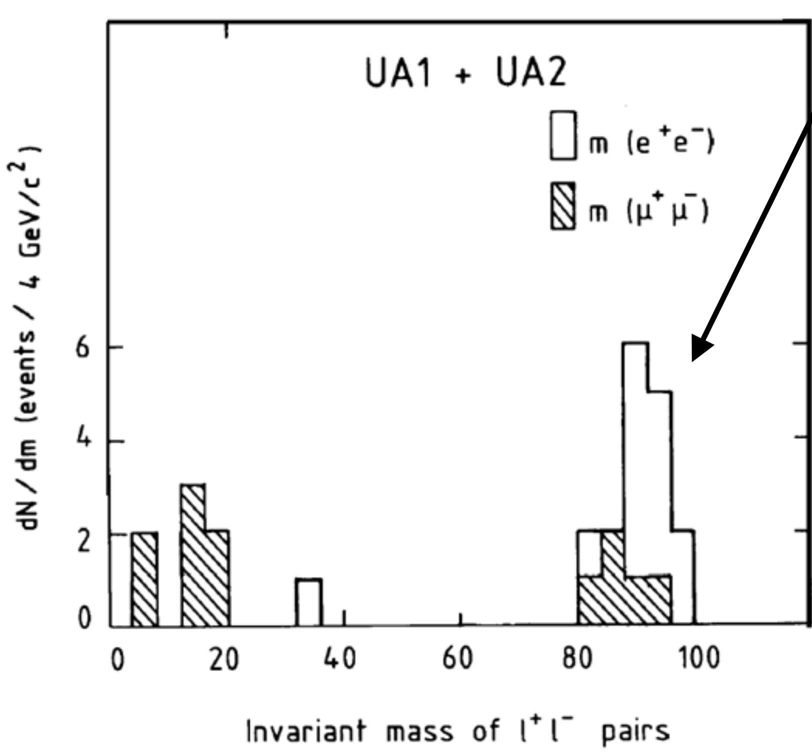
UA1 and UA2 (1983-1989)



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

Spot on!

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



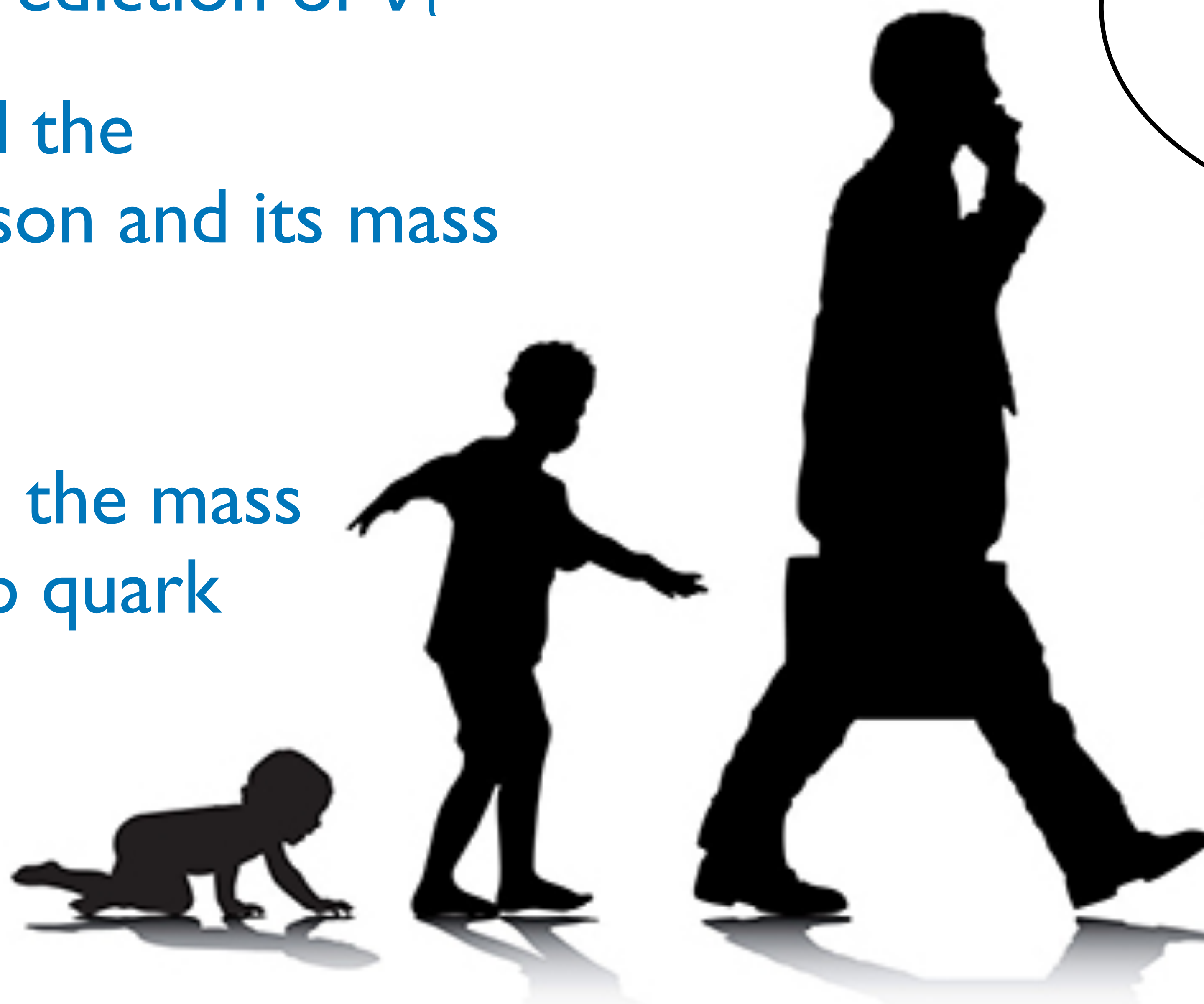
Healthy!

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…

Precise Predictions

Electroweak sector given by 3 parameters

- once v, g, g' are known, all other parameters are fixed

$$M_W = \frac{v|g|}{2}$$

$$M_Z = \frac{v\sqrt{g^2 + g'^2}}{2}$$

$$\cos\theta_W = \frac{M_W}{M_Z}$$

Use the three most precise parameters

- α : $\Delta\alpha/\alpha = 3\times10^{-10}$
- G_F : $\Delta G_F/G_F = 5\times10^{-7}$
- M_Z : $\Delta M_Z/M_Z = 2\times10^{-5}$

Make predictions using α, G_F and M_Z

- measure more than the minimal set of parameters to test the theory

$$M_W^2 = \frac{M_Z^2}{2}\left(1 + \sqrt{1 - \frac{\sqrt{8}\pi\alpha}{G_F M_Z^2}}\right)$$

Let's Try It Out!

Prediction of M_W

- M_W (theo) = 79.794 ± 0.004 GeV
  - includes $\alpha(M_Z)^{-1}$ = 127.944 ± 0.017
  - uncertainty from input parameter uncertainties (parametric)

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→ difference of 38 σ!

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Prediction of A_ℓ

$$A_\ell = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \frac{g_L^2 - g_R^2}{g_L^2 + g_R^2} = \frac{\left(\frac{1}{2} - s^2\right)^2 - s^4}{\left(\frac{1}{2} - s^2\right)^2 + s^4}$$

$$s^2 = \sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2}$$

- A_ℓ (theo) = 0.1252 ± 0.0004
  - M_W obtained from tree-level formula (above)
  - parametric uncertainties small

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→ difference of 13 σ!

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  - uncertainty from input parameter uncertainties (parametric)
- M_W (exp) = 80.385 ± 0.015 GeV → difference of 38 σ!

What went wrong?

How do m_t and M_H come into play?

Prediction of A

$$A_\ell = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \frac{g_L^2 - g_R^2}{g_L^2 + g_R^2} = \frac{\left(\frac{1}{2} - s^2\right)^2 - s^4}{\left(\frac{1}{2} - s^2\right)^2 + s^4} \qquad s^2 = \sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2}$$

- A_ℓ (theo) = 0.1252 ± 0.0004
  - M_W obtained from tree-level formula (above)
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- A_ℓ (exp) = 0.1499 ± 0.0018 → difference of 13 σ!

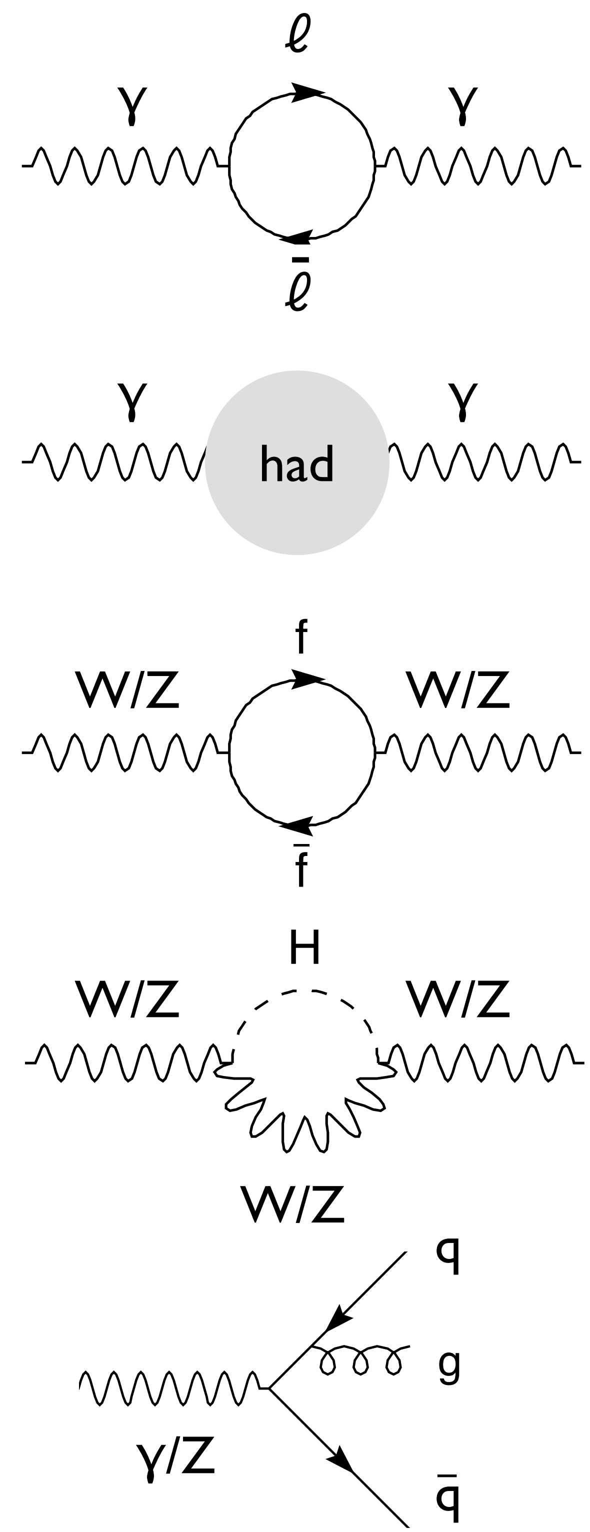
Radiative Corrections

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 $(1 + \alpha_s/\pi)$



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

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

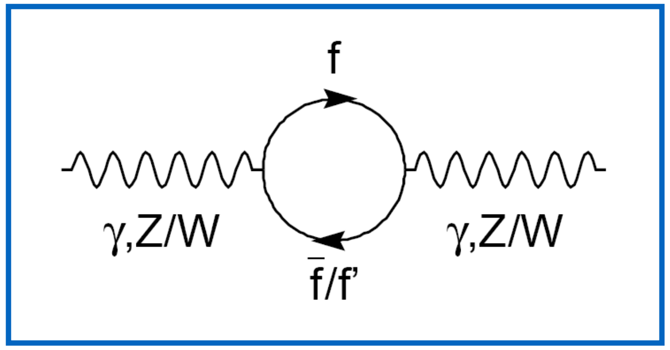
$\propto N_C m_f^2$

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

$\propto \alpha_s(s)$

Electroweak Form Factors

Parametrisation of radiative corrections

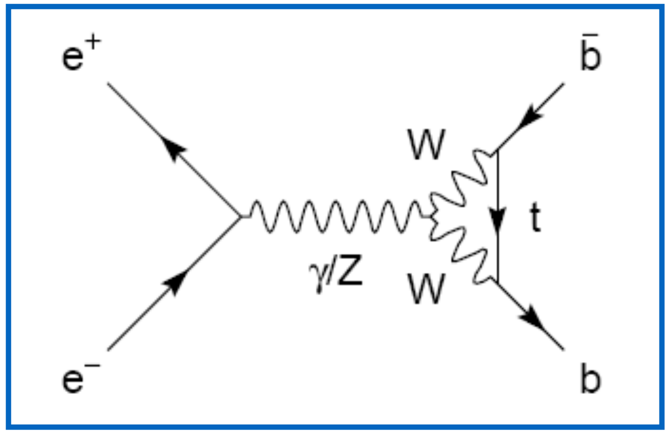


- Encode all corrections in form factors ρ, κ, Δr
- Effective couplings at the Z-pole:

$$g_{V,f} = \sqrt{\rho_Z^f}\left(I_3^f - 2Q^f \sin^2\theta_{\rm eff}^f\right)$$

$$g_{A,f} = \sqrt{\rho_Z^f} I_3^f$$

$$\sin^2\theta_{\rm eff}^f = \kappa_Z^f \sin^2\theta_W$$



  - flavour dependence of κ for b-quarks (Wtb vertex)

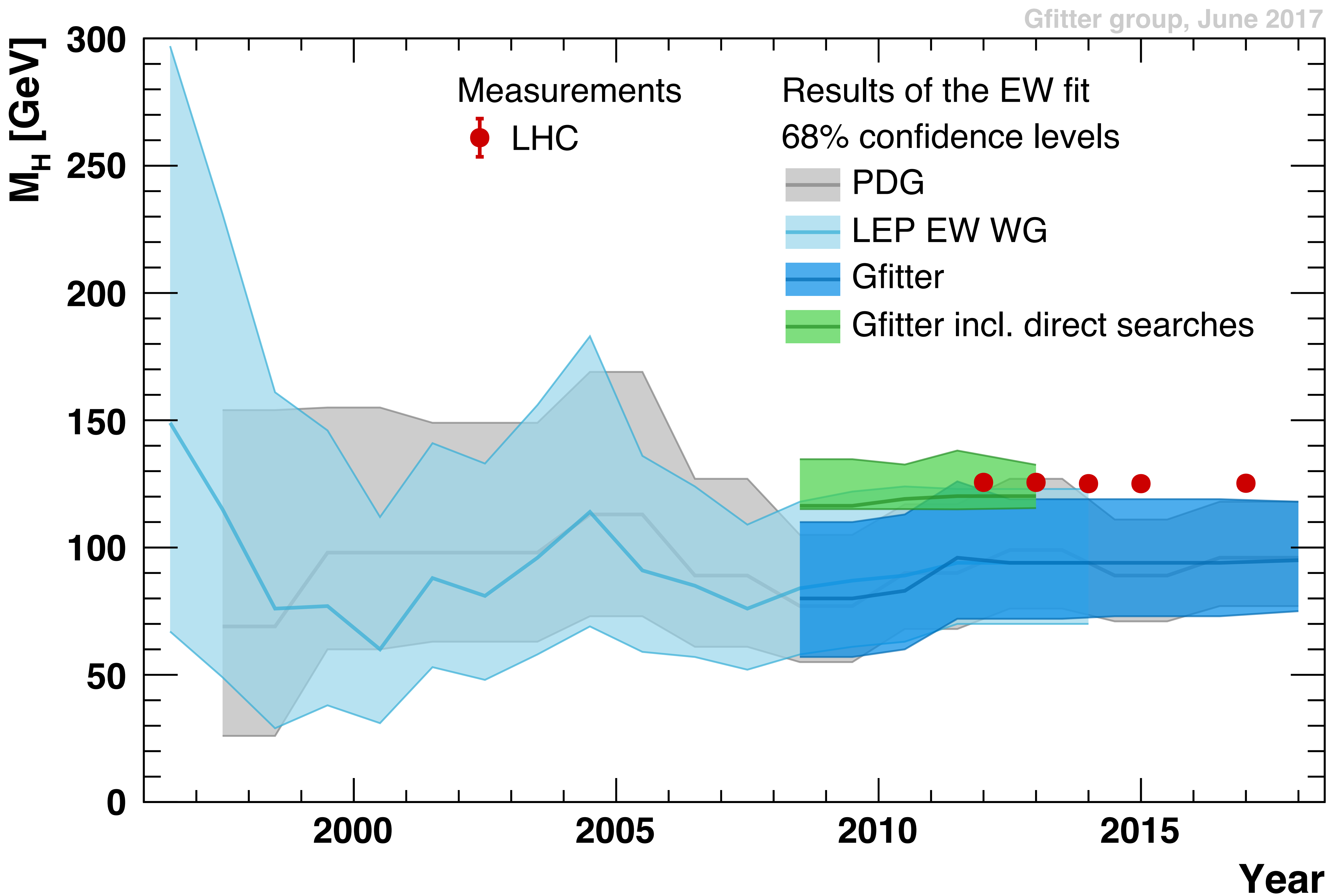
- Mass of the W boson: $M_W^2 = \frac{M_Z^2}{2}\left(1+\sqrt{1-\frac{\sqrt{8}\pi\alpha(1+\Delta r)}{G_F M_Z^2}}\right)$

- ρ, κ, Δr take dependence of free parameters (m_t, M_H, α_s...)

$$\Delta r = -\frac{3\alpha c_W^2}{16\pi s_W^4}\frac{m_t^2}{M_W^2} + \frac{11\alpha}{48\pi s_W^2}\ln\frac{M_H^2}{M_W^2} + \ldots$$

(need to solve iteratively)

Predicting M_H



Free Parameters

EW sector

- $\boxed{G_F}$: $\Delta G_F/G_F = 5\times10^{-7}$
- $\boxed{M_Z}$: $\Delta M_Z/M_Z = 2\times10^{-5}$
- evolution of fine structure constant ($\Delta\alpha/\alpha = 3\times10^{-10}$) to scale s

$$\begin{array}{rcccccc} \Delta\alpha(s) & = & \boxed{\Delta\alpha_{\rm lep}(s)} & + & \boxed{\Delta\alpha^{(5)}_{\rm had}(s)} & + & \boxed{\Delta\alpha_{\rm top}(s)} \\ \text{relative precision} & = & 1\times10^{-6} & & 2\times10^{-4} & & 1\times10^{-7} \end{array}$$

Fermion masses

- $\boxed{m_c, m_b}$: precision of about 7% and 1%, sufficient (see later)
- $\boxed{m_t}$ crucial parameter, experimental precision of 0.5% (more later)

Strong sector

- $\boxed{\alpha_s}$: can be constrained using Z-pole measurements

Higgs sector

- $\boxed{M_H}$: precision of LHC measurements is 0.3%

Measure more than minimal set to constrain the theory

Experimental Input

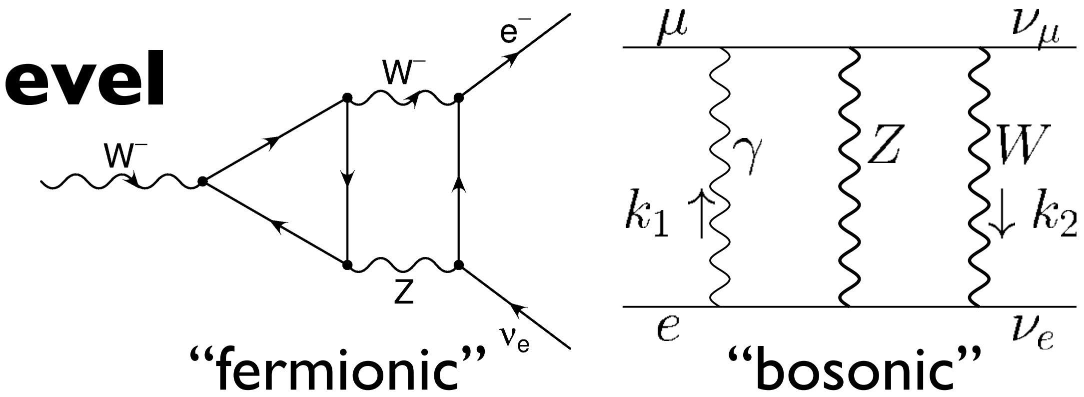
Fit is overconstrained

- All free parameters measured ($\alpha_s(M_Z)$ unconstrained in fit)
  - Most input from e^+e^- colliders
    - M_Z : $2\cdot 10^{-5}$
  - Crucial input from Tevatron and LHC:
    - m_t : $4\cdot 10^{-3}$
    - M_H : $2\cdot 10^{-3}$
    - M_W : $2\cdot 10^{-4}$
  - Remarkable precision, O(0.1%)
- 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]$^{(\triangledown)}$	172.47 ± 0.68	Tev.+LHC

Precision Calculations

All observables calculated at 2-loop level

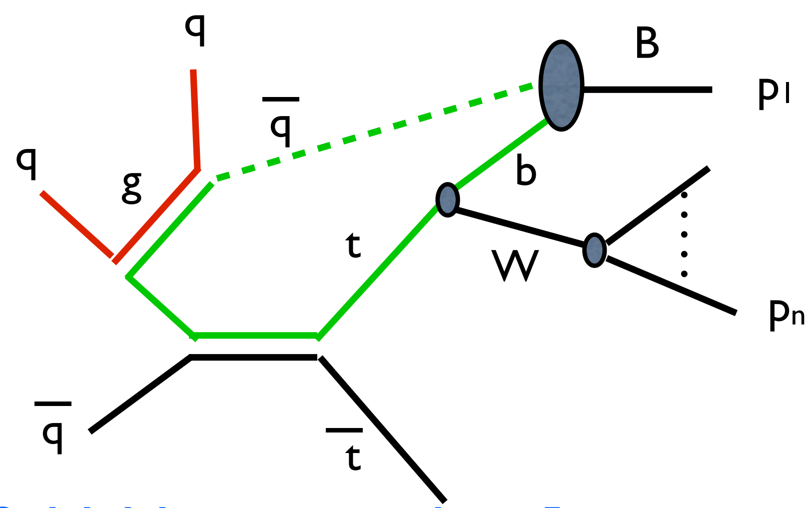


- **M_W** : full EW one- and two-loop calculation of fermionic and bosonic contributions
  [M Awramik et al., PRD 69, 053006 (2004), PRL 89, 241801 (2002)]
  + 4-loop QCD correction [Chetyrkin et al., PRL 97, 102003 (2006)]
- **$\sin^2\theta^f_{eff}$** : same order as M_W, calculations for leptons and all quark flavours
  [M Awramik et al, PRL 93, 201805 (2004), JHEP 11, 048 (2006), Nucl. Phys. B813, 174 (2009)]
- **partial widths Γ_f** : fermionic corrections in two-loop for all flavours (includes predictions for σ^0_{had}) [A. Freitas, JHEP04, 070 (2014)]
- **Radiator functions**: QCD corrections at N³LO
  [Baikov et al., PRL 108, 222003 (2012)]
- **Γ_W** : one-loop EW corrections available, negligible impact on fit
  [Cho et al, JHEP 1111, 068 (2011)]
- **all calculations**: one- and two-loop QCD corrections and leading terms of higher order corrections

Theoretical Uncertainties

- estimated using a geometric series ($a_n = a\, r^n$), example: $\mathcal{O}(\alpha^2\alpha_s) = \frac{\mathcal{O}(\alpha^2)}{\mathcal{O}(\alpha)}\mathcal{O}(\alpha\alpha_s)$
  - similar results from scale variations
- reasonable estimates for all observables
- exception: m_t !

$$M^2_{exp} = \left(\sum_{i=1,\ldots,n} p_i\right)^2$$



[A. Hoang 1412.3649, M. Mangano, others]

  - MC parameter, translation to m^{pole} unknown
  - uncertainties from colour structure, hadronisation and $m^{pole} \rightarrow m_t(m_t)$ smaller

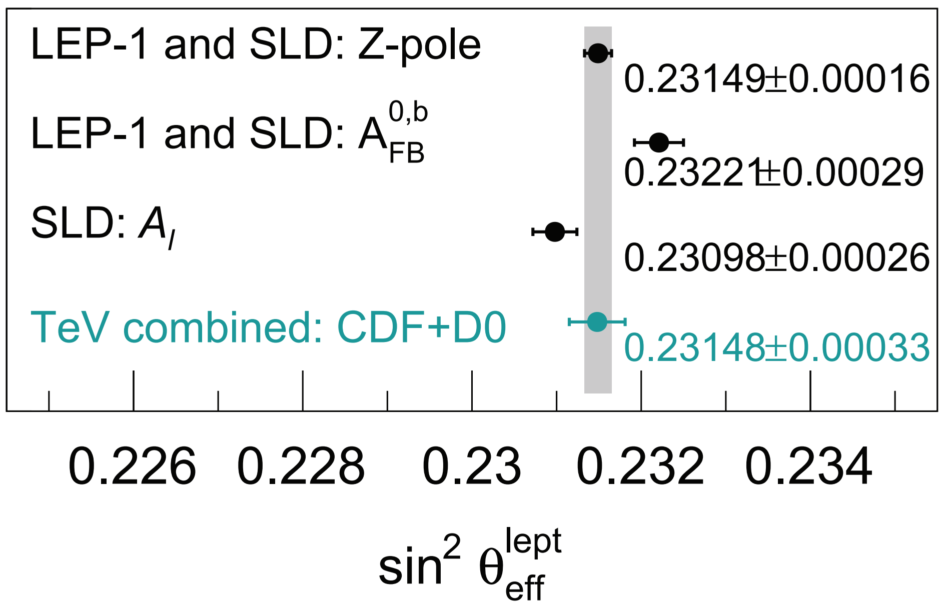
important

Observable	Exp. error	Theo. error
M_W	13 MeV	4 MeV
$\sin^2\theta^l_{\text{eff}}$	$1.6\cdot 10^{-4}$	$0.5\cdot 10^{-4}$
Γ_Z	2.3 MeV	0.5 MeV
σ^0_{had}	37 pb	6 pb
R^0_b	$6.6\cdot 10^{-4}$	$1.5\cdot 10^{-4}$
m_t	0.46 GeV	0.5 GeV

- 10 additional free parameters, Gaussian likelihood
- important missing higher order terms:
  - $O(\alpha^2\alpha_s)$, $O(\alpha\alpha_s^2)$, $O(\alpha^2_{bos})$ (in some cases), $O(\alpha^3)$, $O(\alpha_s^5)$ (rad. functions)

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)]

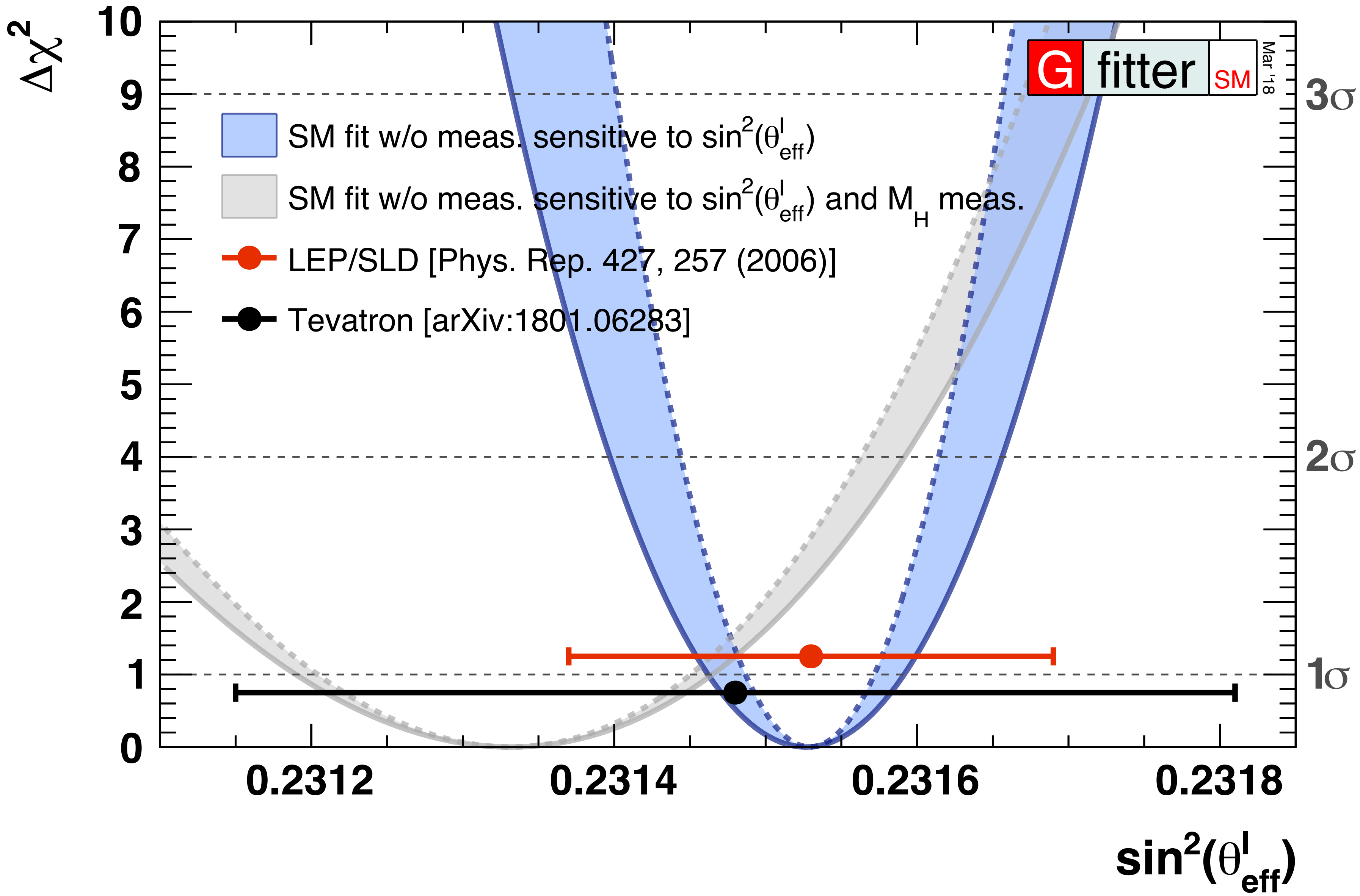
Newest $e^+e^-\to$hadrons data (e.g. Barbar and VEPP-2000)

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

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

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

Predicting $\sin^2\theta_{\rm eff}$

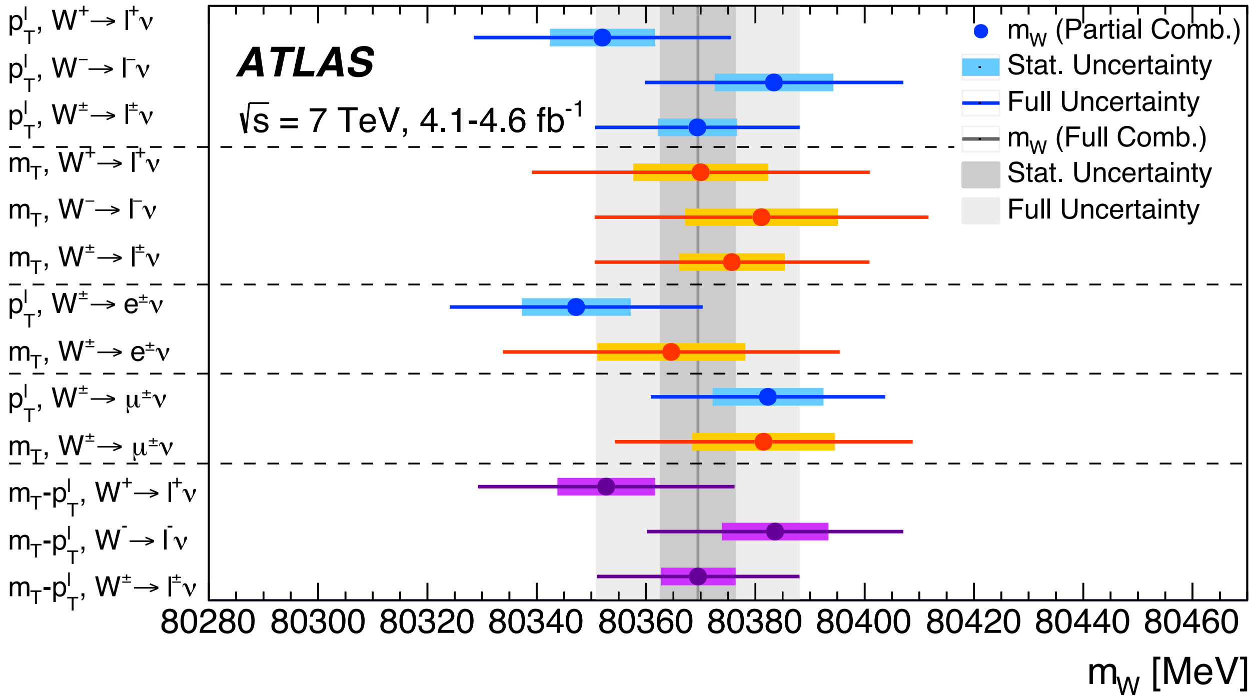


$$
\begin{aligned}
\sin^2\theta^\ell_{\rm eff} &= 0.231532 \pm 0.000011_{m_t} \pm 0.000016_{\delta_{\rm theo} m_t} \pm 0.000012_{M_Z} \pm 0.000021_{\alpha_S} \\
&\quad \pm 0.000035_{\Delta\alpha_{\rm had}} \pm 0.000001_{M_H} \pm 0.000040_{\delta_{\rm theo}\sin^2\theta^\ell_{\rm eff}}\,, \\
&= 0.23153 \pm 0.00006_{\rm tot}\,.
\end{aligned}
$$

(LEP: ±0.00016, Tevatron: ±0.00033)

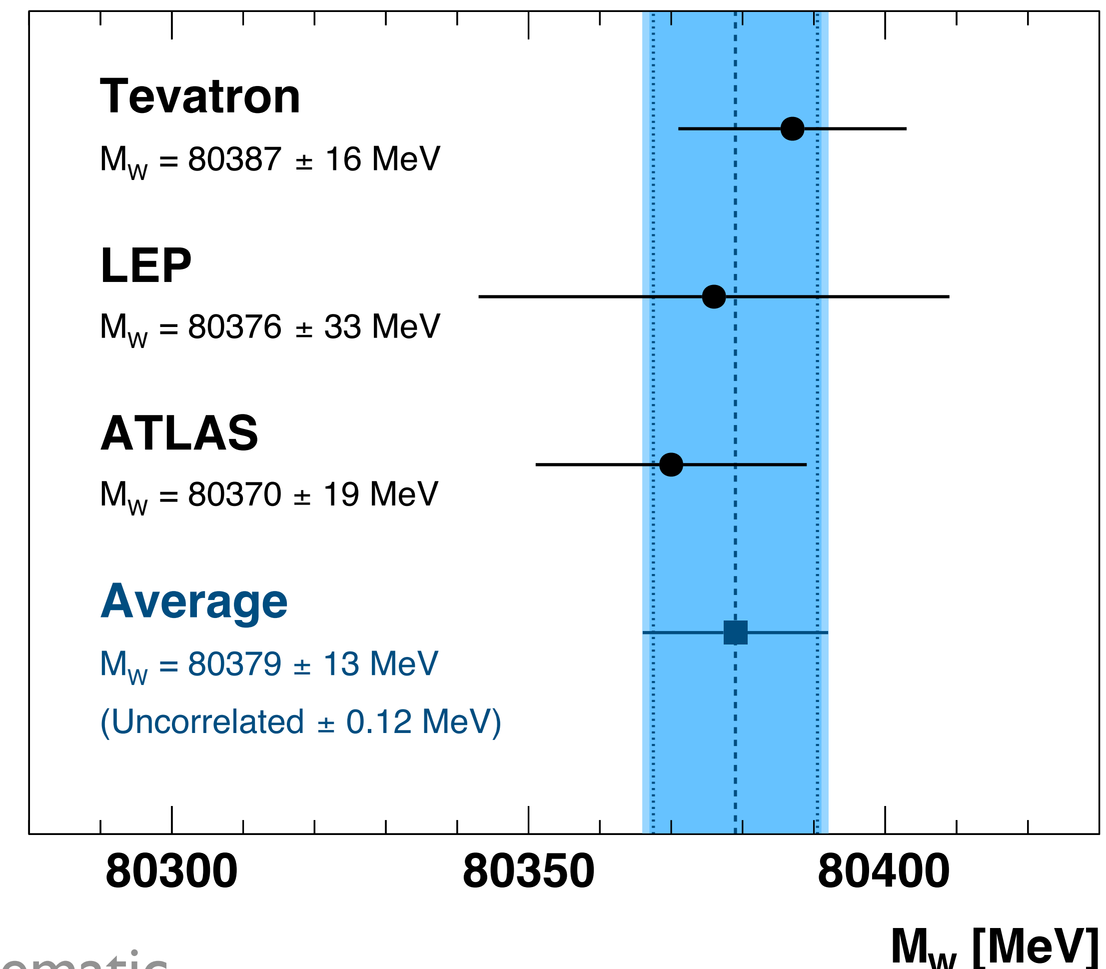
ATLAS M_W Measurement

[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]

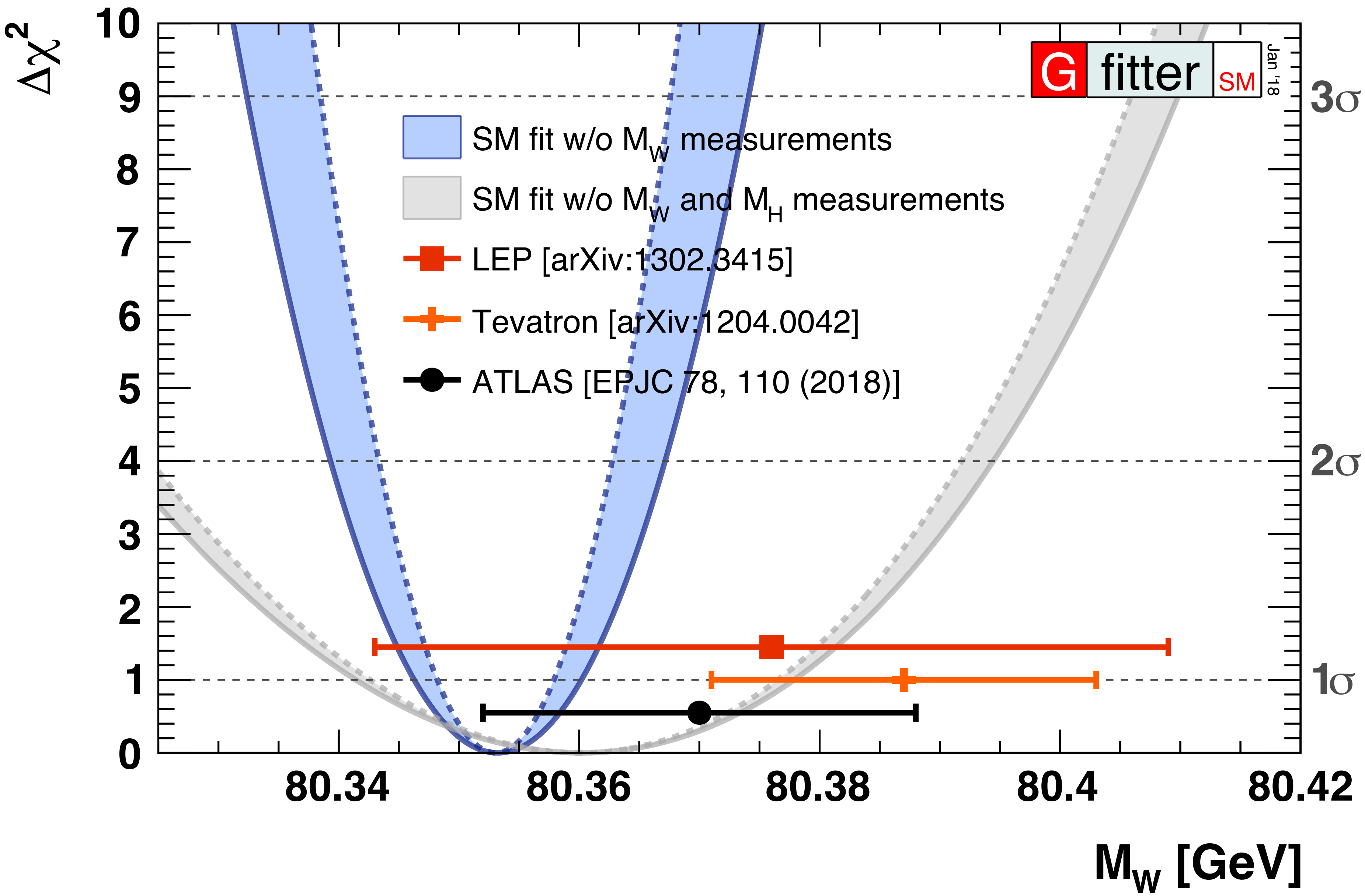
$M_W = 80387 \pm 8_{(stat)} \pm 8_{(exp.syst)}$
$\pm 12_{(mod.\,syst)}$ MeV

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

Predicting M_W

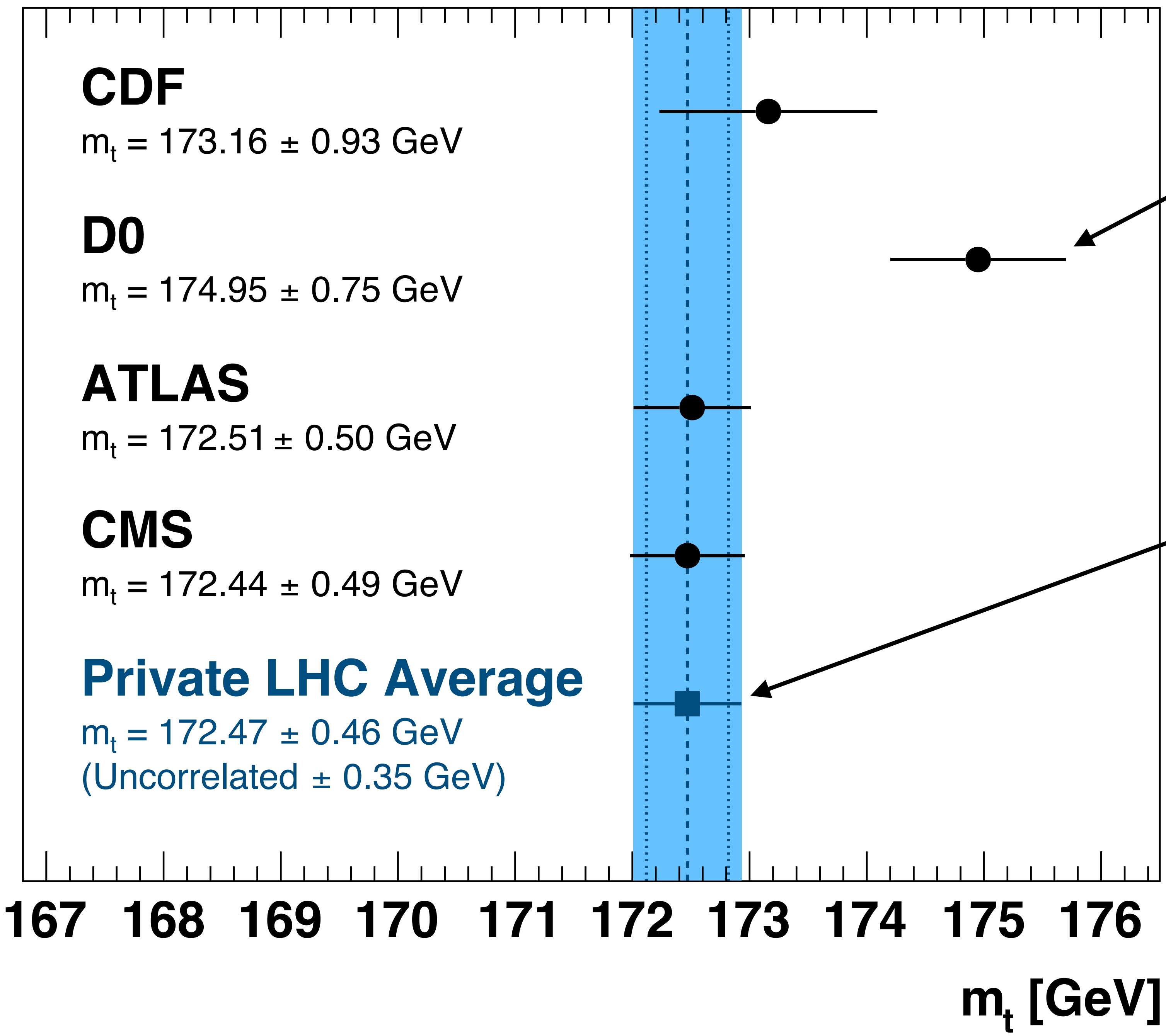


$$
\begin{aligned}
M_W &= 80.3535 \pm 0.0027_{m_t} \pm 0.0030_{\delta_{\rm theo} m_t} \pm 0.0026_{M_Z} \pm 0.0026_{\alpha_S} \\
&\quad \pm 0.0024_{\Delta\alpha_{\rm had}} \pm 0.0001_{M_H} \pm 0.0040_{\delta_{\rm theo} M_W}\ \text{GeV}\,, \\
&= 80.354 \pm 0.007_{\rm tot}\ \text{GeV}
\end{aligned}
$$

(exp: ± 0.013 GeV)

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

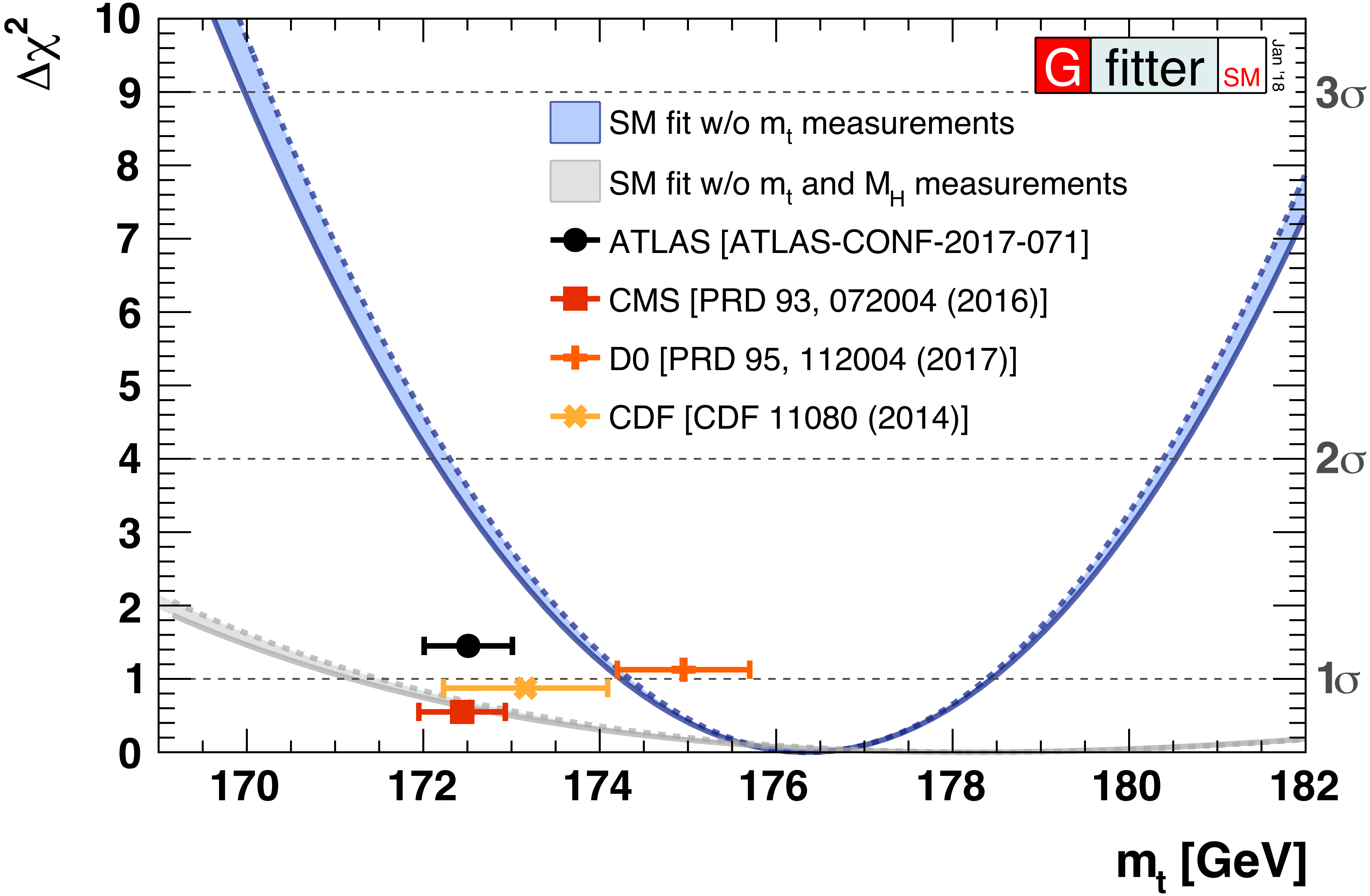
Average

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

Obtained by assuming 0.7 correlation

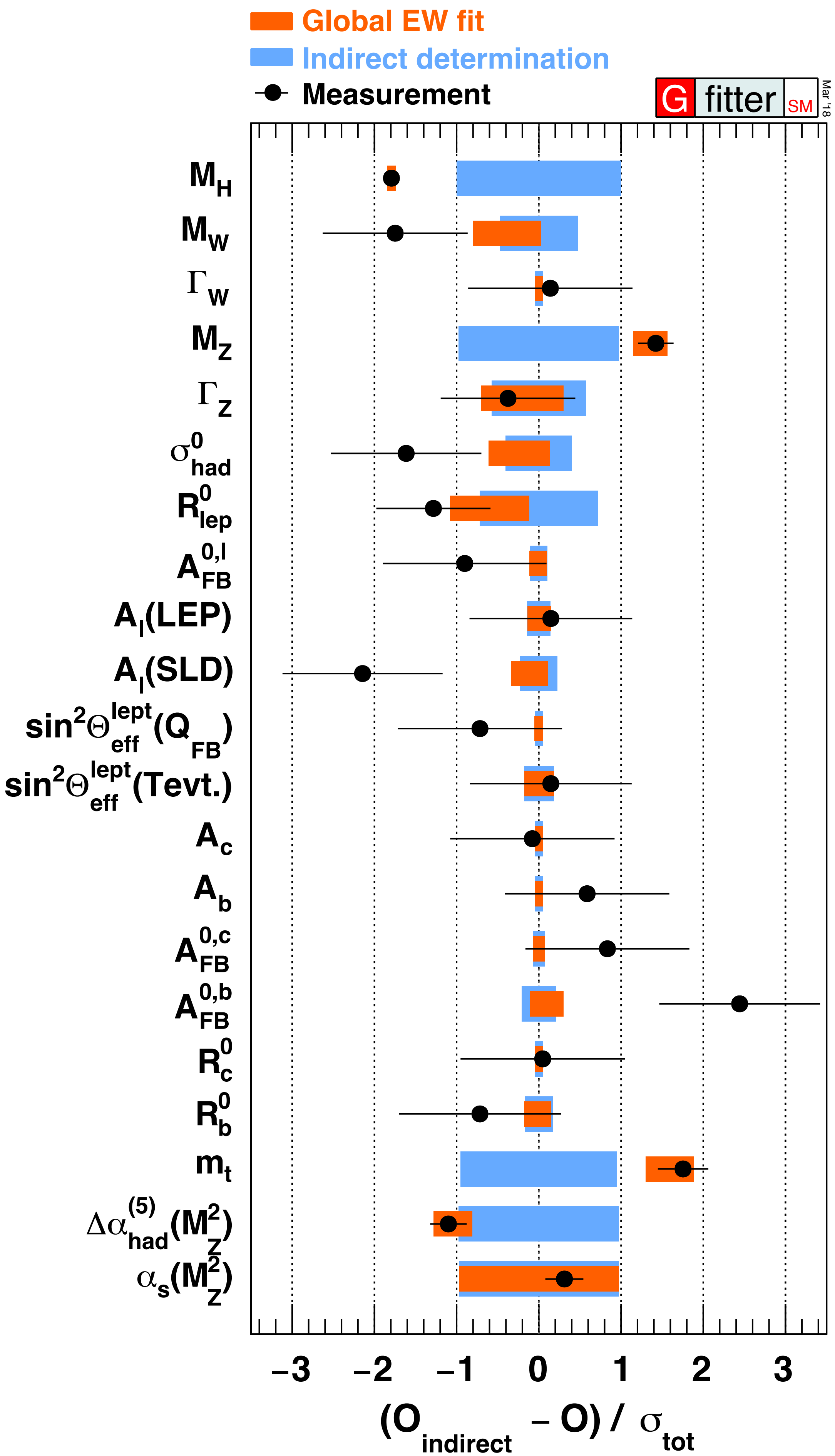
Additional theoretical uncertainty of 0.5 GeV

Predicting m_t



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

(perfect knowledge of M_W: ± 0.9 GeV)



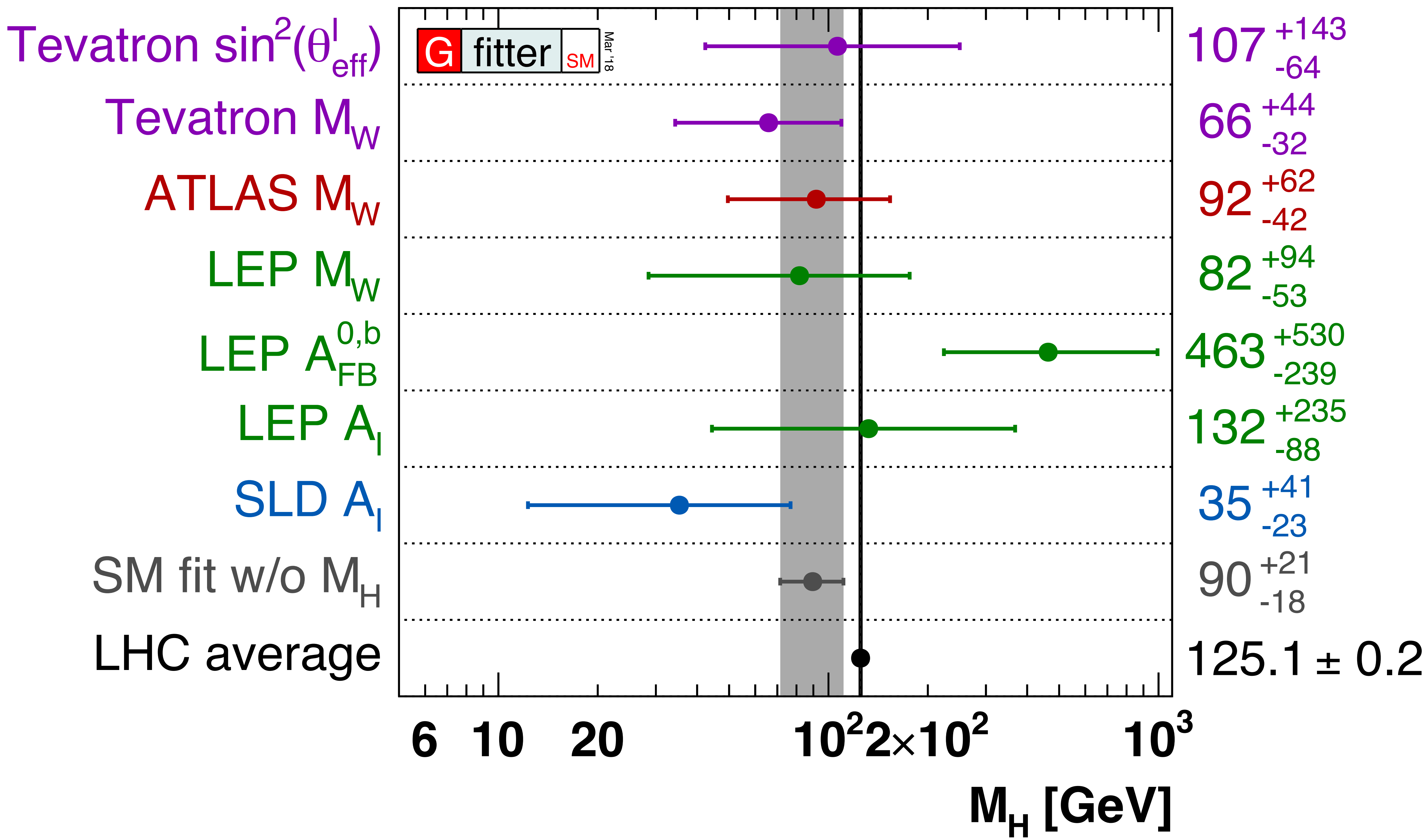
SM Fit Results

- 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]

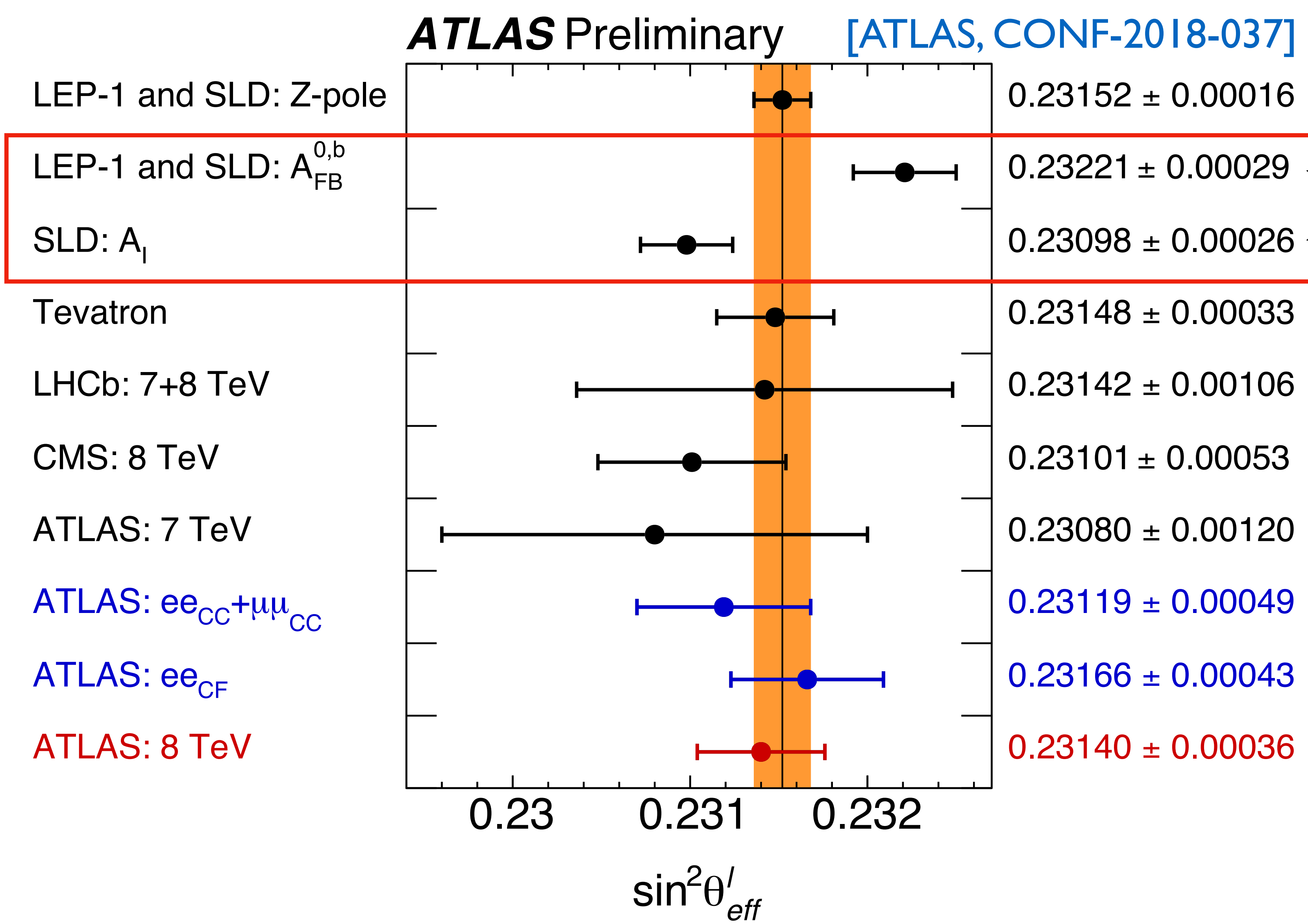
Predicting M_H

[Gfitter, 1803.01853]



What If...

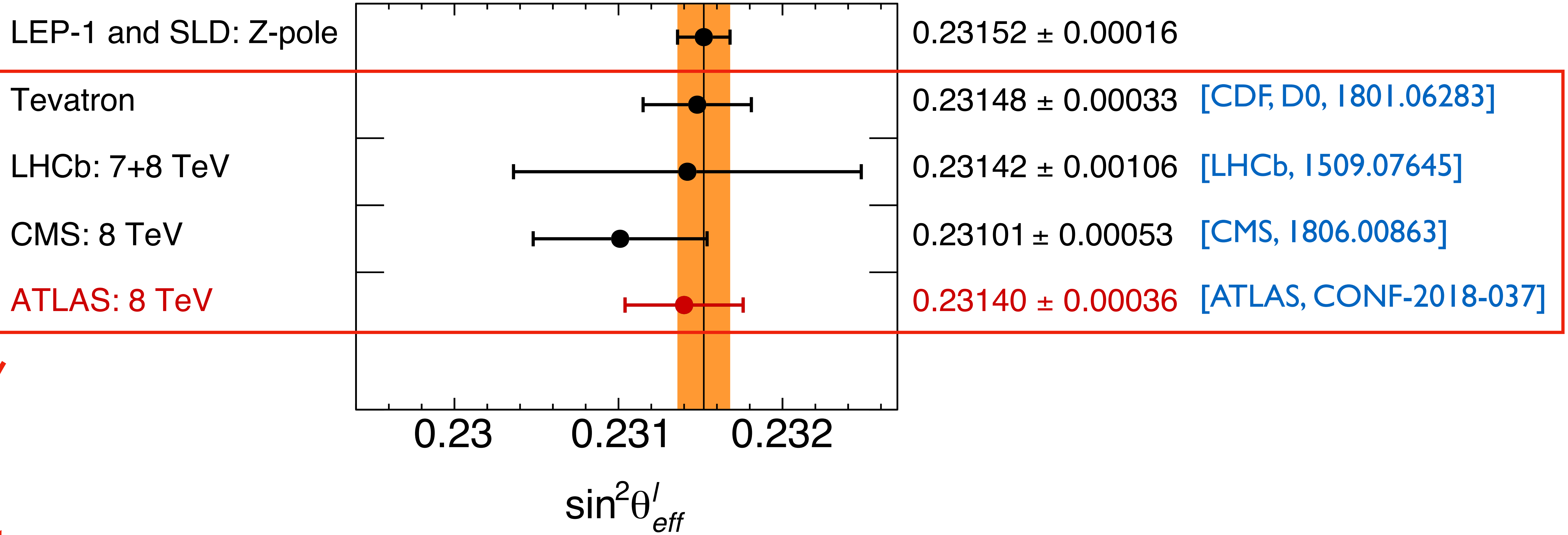
... we had not measured $\sin^2\theta^l_{eff}$ at e^+e^- colliders? [Sven H.]



> 3σ disagreement

measurements from hadron colliders are gaining in precision

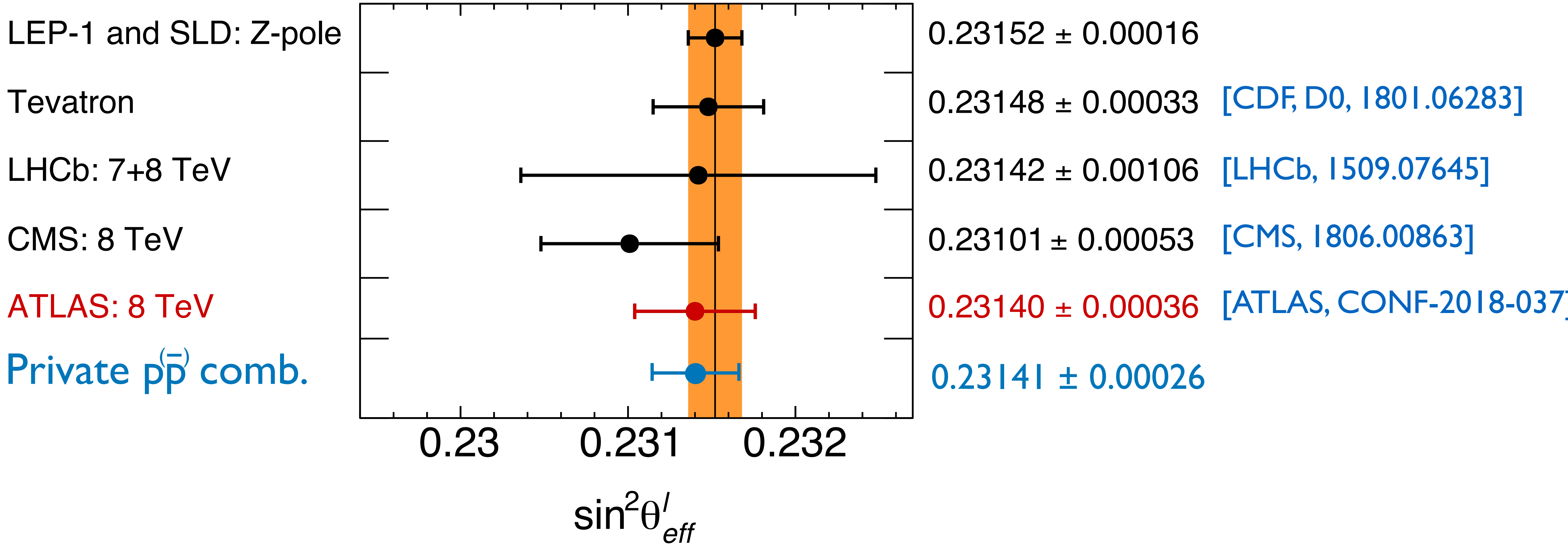
$\sin^2\theta_{eff}$ from Hadron Colliders



Combination of Tevatron and LHC results

- Assume PDF uncertainties correlated
  - 100% (ATLAS/CMS), 50% (ATLAS+CMS/Tevatron), 50% (ATLAS+CMS/LHCb), 30% (LHCb/Tevatron)
  - PDFs fully correlated: increase of uncertainty by 0.00002, same central value
- Other uncertainties uncorrelated

$\sin^2\theta_{eff}$ from Hadron Colliders



Combination with χ^2/ndf = 0.7/3 (p-value of 0.87)

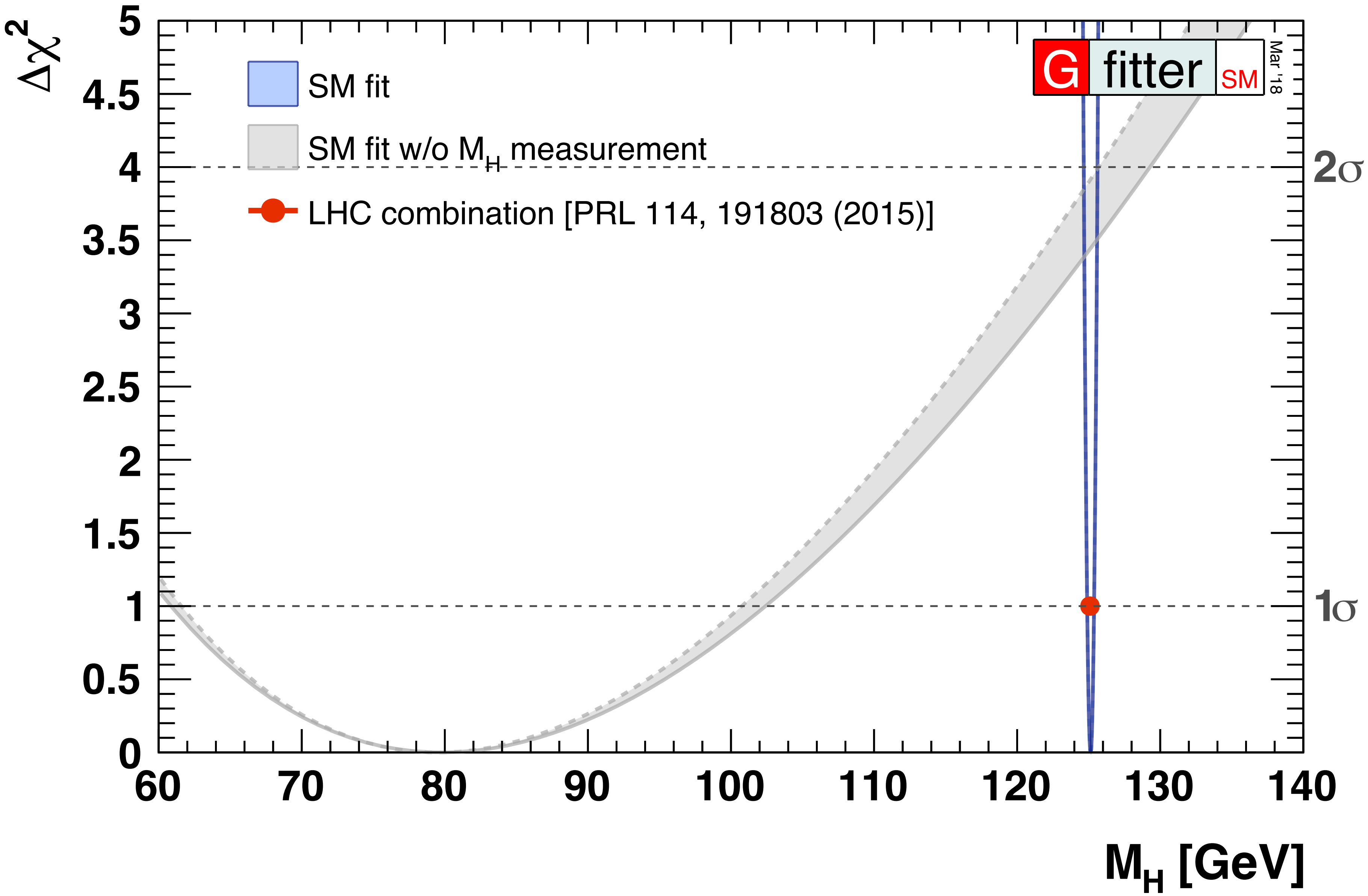
- $\sin^2\theta^l_{eff} = 0.23141 \pm 0.00026$
  - within 1.2σ of SLD A_ℓ and 2.1σ of A^{0b}_{FB}
- only a factor ~1.6 in sensitivity from e^+e^- combination (as precise as A_ℓ)

(need to wait for a better estimate from the experimental collaborations)

$\sin^2\theta_{eff}$ ($p\bar{p}$) in EW Fit

Remove all LEP and SLD asymmetries, include private $\sin^2\theta^l_{eff}$

- χ^2 / ndf = 7.1 / 7, p-value of 0.42
  - compare to 18.6 / 15, p-value of 0.23



$M_H = 80 ^{+23}_{-19}$ GeV

1.8σ from LHC value

χ^2 / ndf = 3.6 / 6

without M_W :

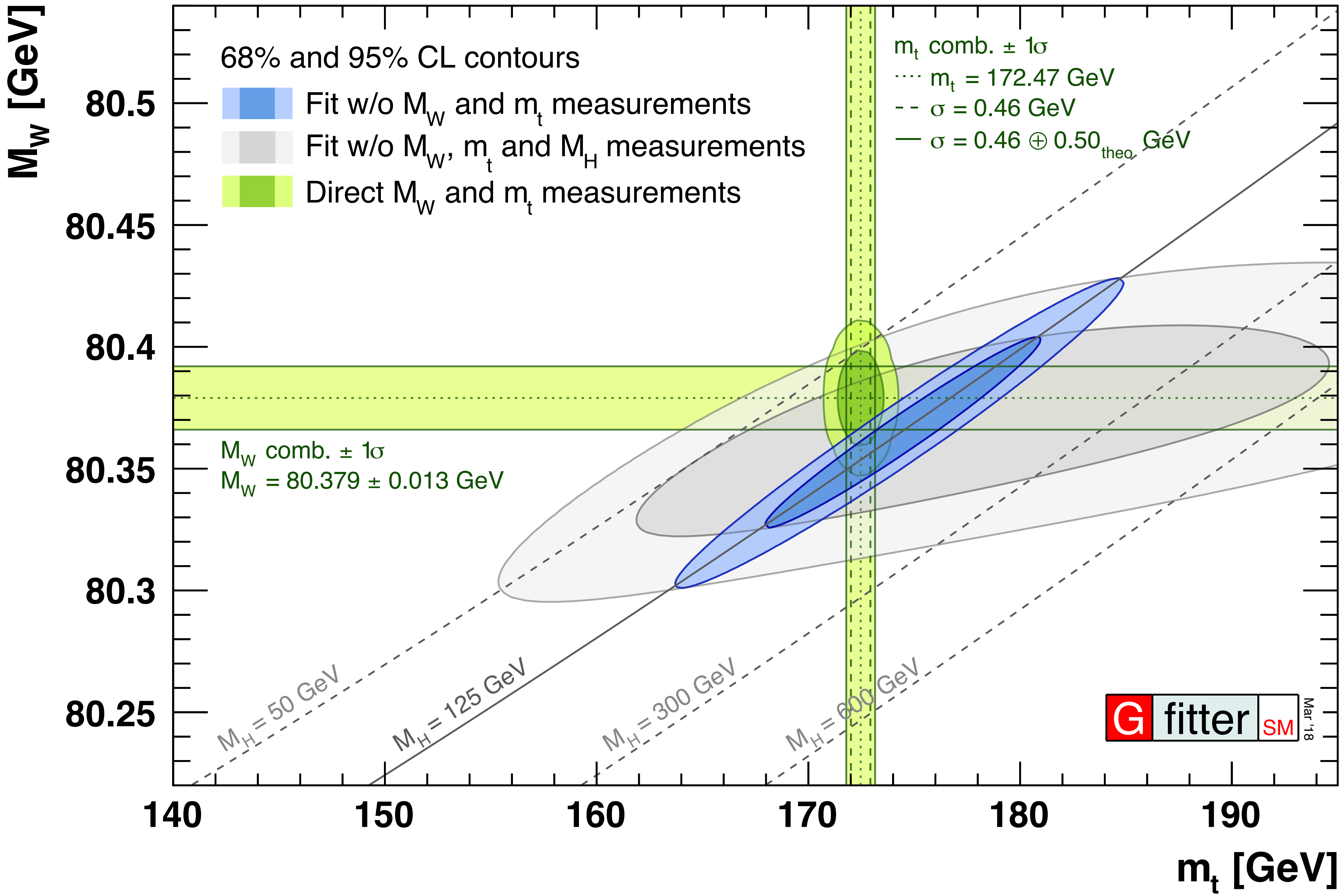
$M_H = 91 ^{+98}_{-49}$ GeV

ultimate HL-LHC with LHeC PDFs:

$M_H = 80 ^{+14}_{-12}$ GeV

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

Increasing Precision: M_W

warning:
personal guesses

Dominant uncertainties for indirect constraints

- **4.0 MeV: Calculations, theo**
  - three-loop EW and mixed two-loop EW/QCD — O(10) years
- **3.0 MeV: m_t theo**
  - connection between m_t(MC) and m_t(pole) — O(5) years
- **2.7 MeV: m_t exp**
  - first Run 2 measurements available — LHC Run 2/3, O(5) years
- **2.6 MeV: M_Z exp**
  - improvement with ILC/GigaZ — O(30) years
- **2.0 MeV: α_s exp / theo**
  - understanding measurements / lattice calculations — O(5) years
- **1.8 MeV: $\Delta\alpha_{had}$ exp / theo**
  - measurements at low energy e^+e^- machines (ρ, charm)
    higher order pQCD calculations — O(10) years

Increasing Precision: M_W

warning:
personal guesses

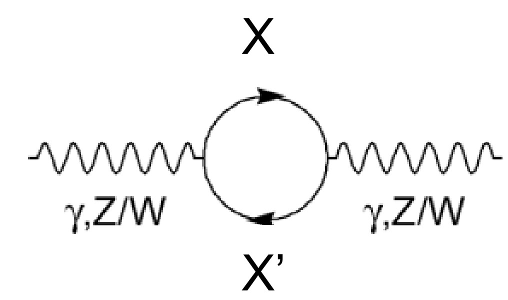
Dominant uncertainties for indirect constraints

- **4.0 MeV: Calculations, theo**
  - three-loop EW and mixed two-loop EW/QCD — O(10) years
- **3.0 MeV: m_t theo**
  - connection be… — O(5) years
- **2.7 MeV: m_t …**
  - first Run 2 me… …2/3, O(5) years
- **2.6 MeV: M_Z …**
  - improvement … — O(30) years
- **2.0 MeV: α_s exp / theo**
  - understanding measurements / lattice calculations — O(5) years
- **1.8 MeV: $\Delta\alpha_{had}$ exp / theo**
  - measurements at low energy e^+e^- machines (ρ, charm) higher order pQCD calculations — O(10) years

Expect significant improvements within next 5-10 years!
Note: about same time as experimental results for M_W measurements should reach ~ 10 MeV

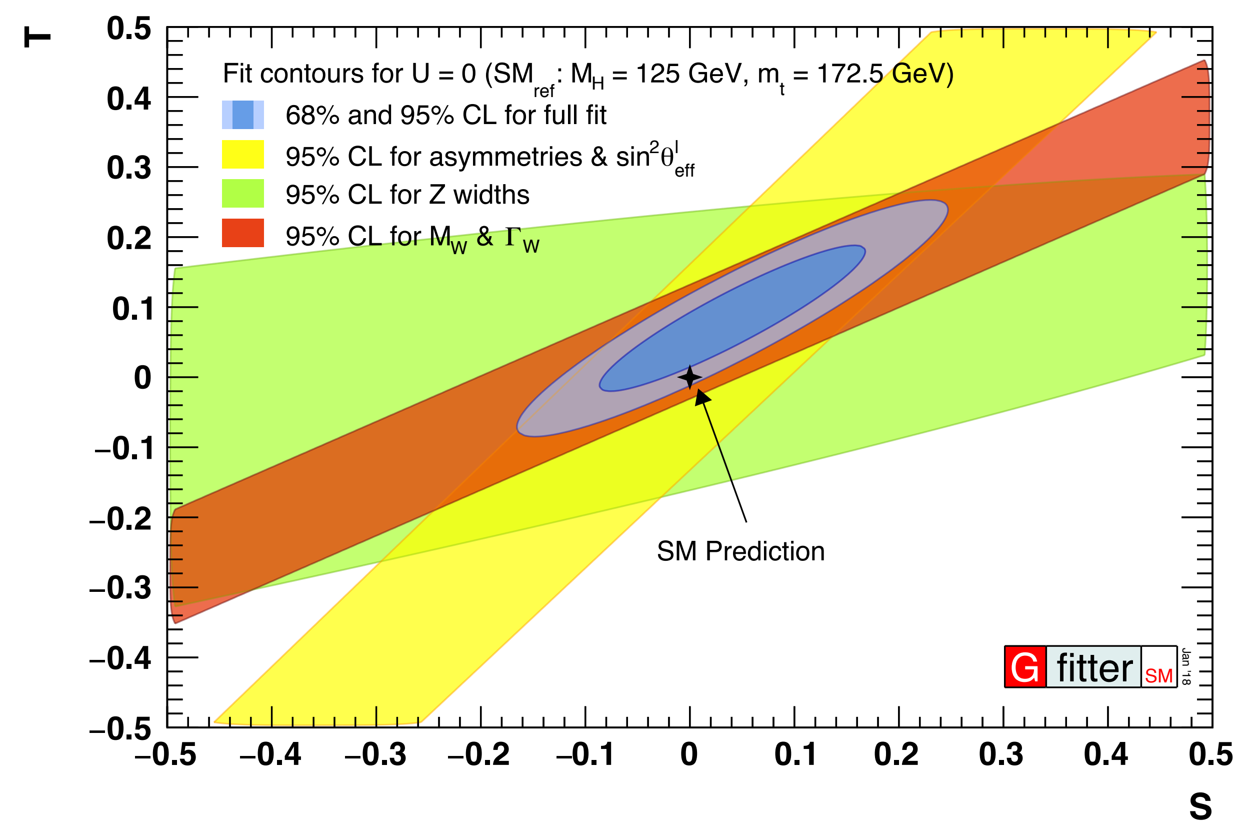
BSM: Oblique Corrections

- If energy scale of NP is high, BSM physics could appear dominantly through vacuum polarisation corrections



- Described by STU parameters
  [Peskin and Takeuchi, Phys. Rev. D46, 1 (1991)]

stronger constraints with U = 0:



- SM: M_H = 125 GeV, m_t = 173 GeV
  this defines (S,T,U) = (0,0,0)
- S, T depend logarithmically on M_H
- Fit result:
  S = 0.05 ± 0.11
  T = 0.09 ± 0.13
  U = 0.01 ± 0.11

	S	T	U
S	1	+0.90	-0,59
T		1	-0,83
U			1

- No indication for new physics
- Use this to constrain parameter space in BSM models

Testing the Scalar Sector

Extending the Scalar Sector

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

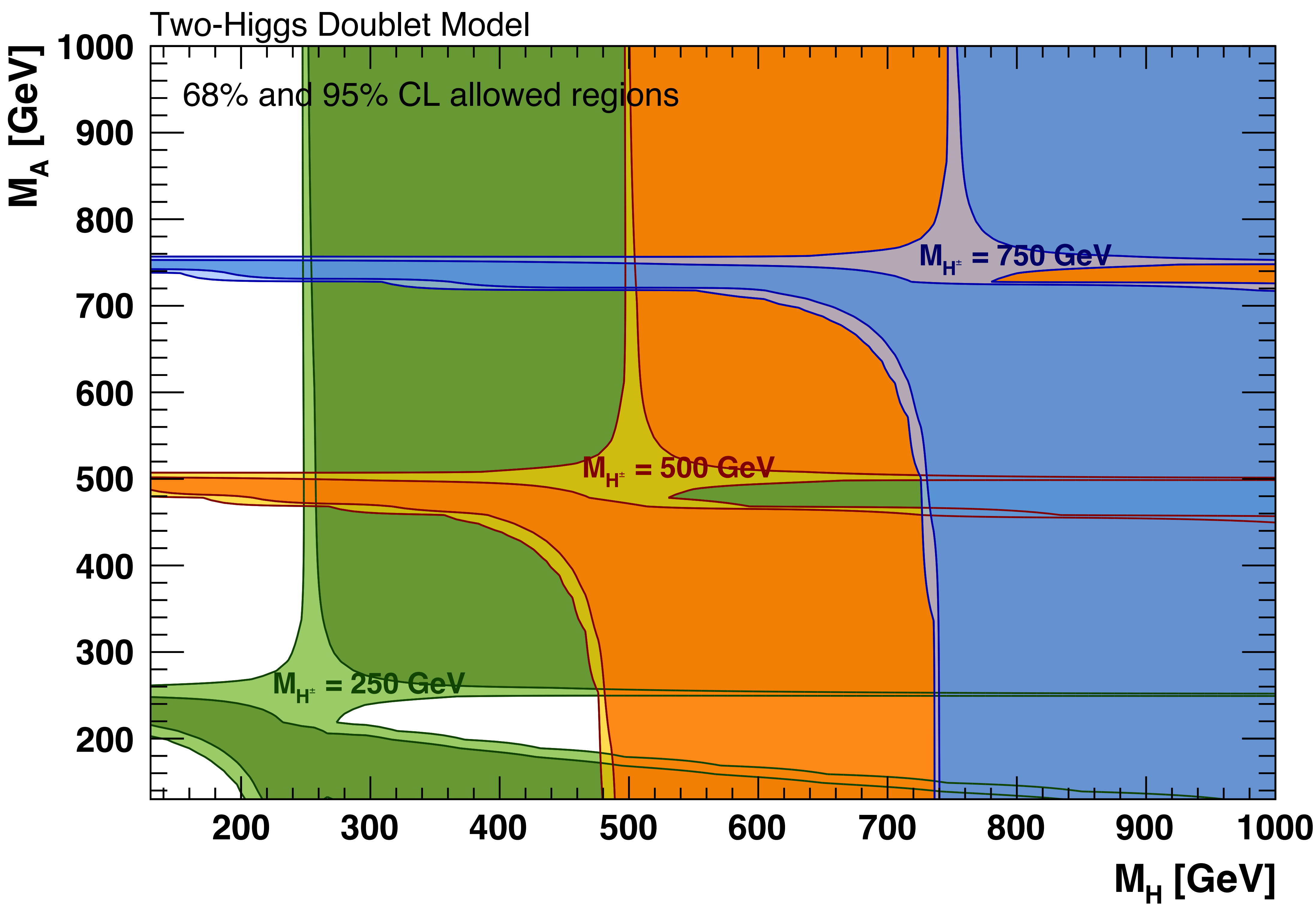
- Five scalars: h, H, A, $H^\pm$
- Light h set to the observed scalar state at 125 GeV
- Free parameters: α, β, M_H, M_A, $M_{H\pm}$, breaking scale M_{12}^2

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

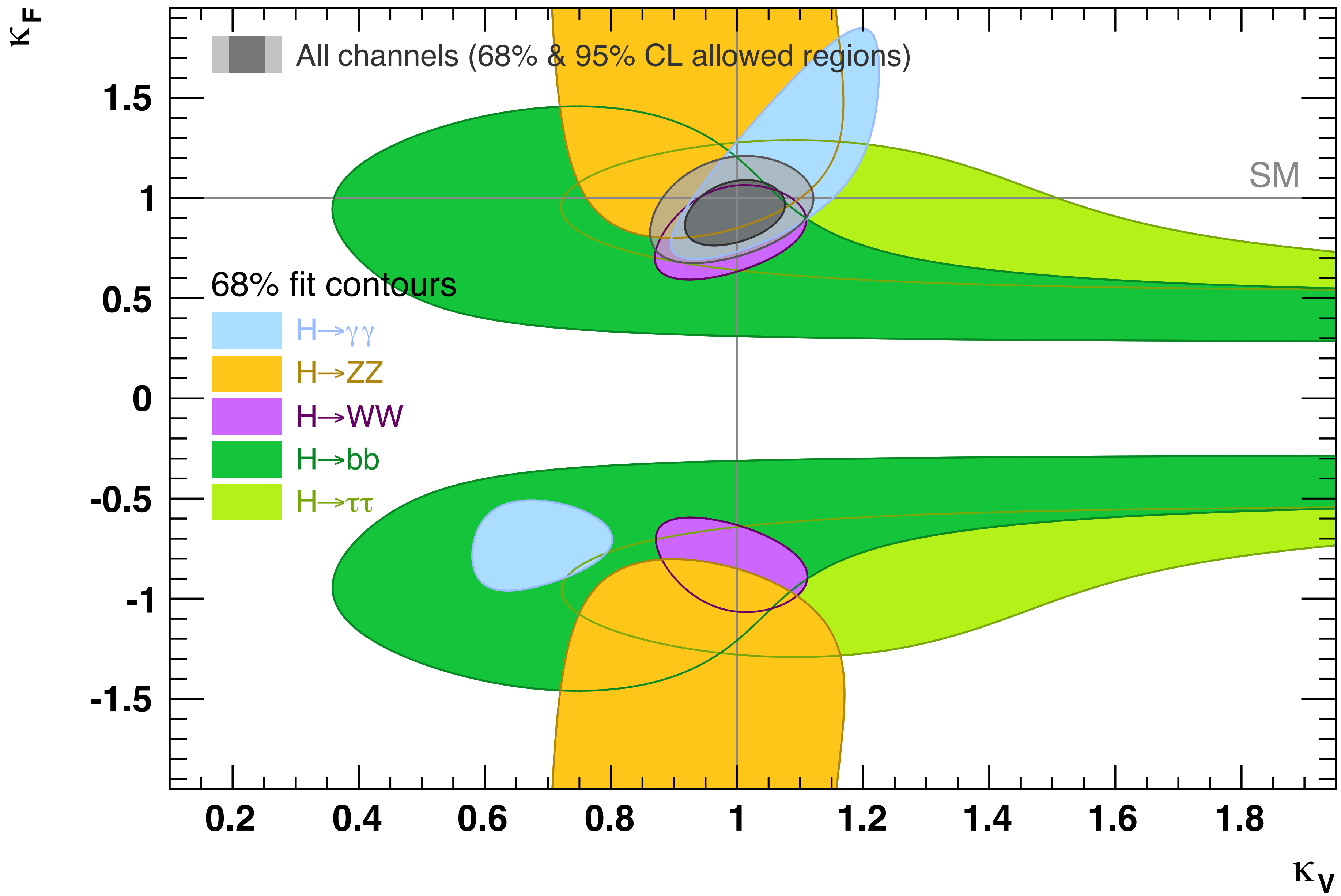
EWPD Constraints (STU)



- Weak constraints on masses, since tanβ and cos(β-α) are unconstrained

2HDM and H Measurements

- Coupling measurements place important constraints on 2HDMs
- ATLAS and CMS data from Run 1 combination

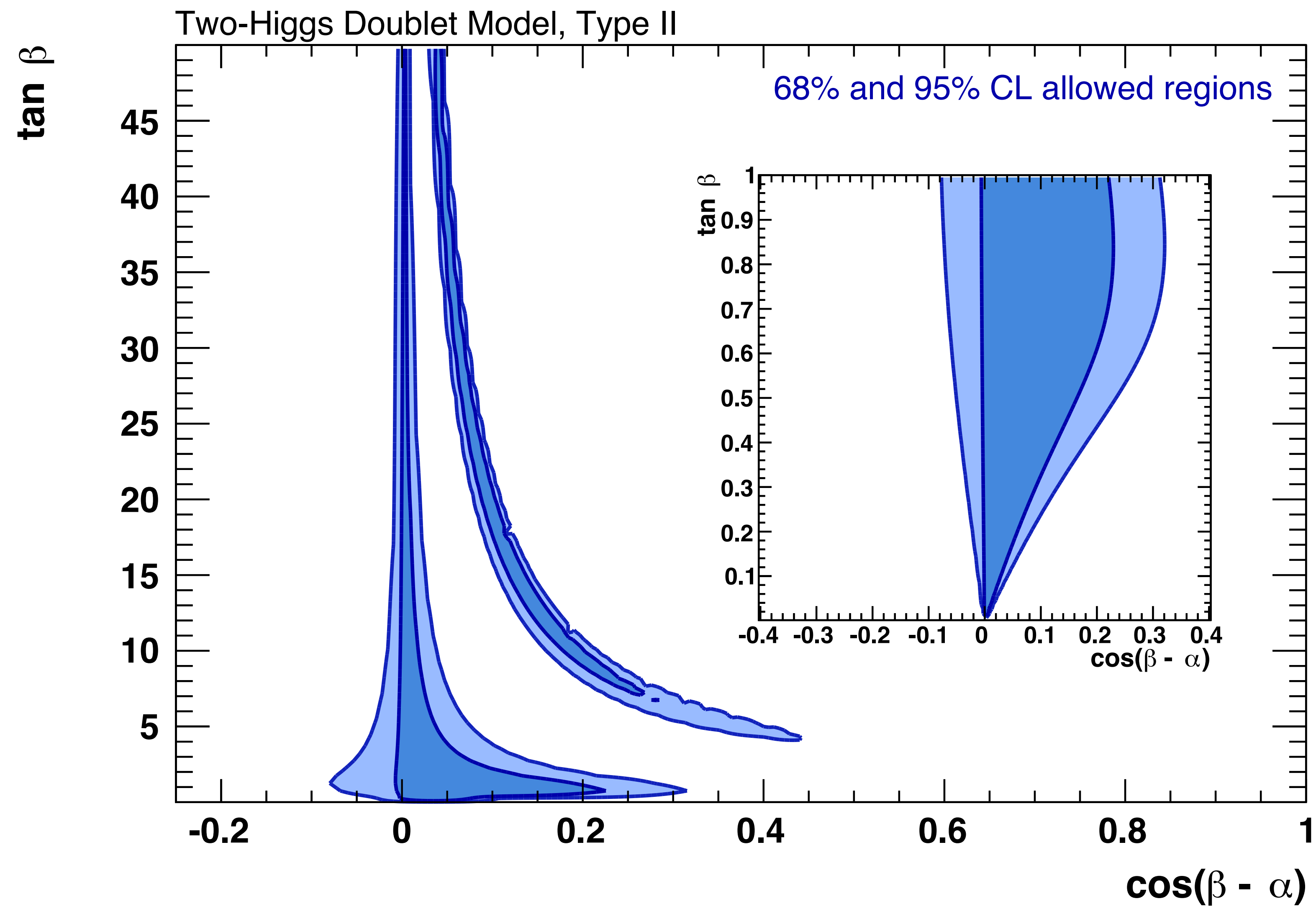


Reproduction of κ constraints using the public info available

2HDM and H Measurements

- Alignment solution
  - $\cos(\beta-\alpha) = 0$ (light h is SM solution, $\kappa_V = 1$)

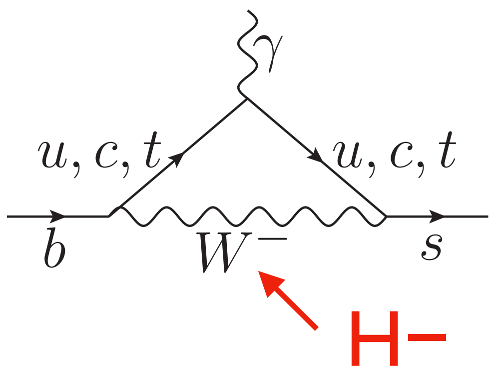
- Flipped solution
  - $\beta+\alpha = \pi/2$
    - inverted sign of down-type fermion couplings
    - new data on bb and $\tau\tau$ will constrain this region



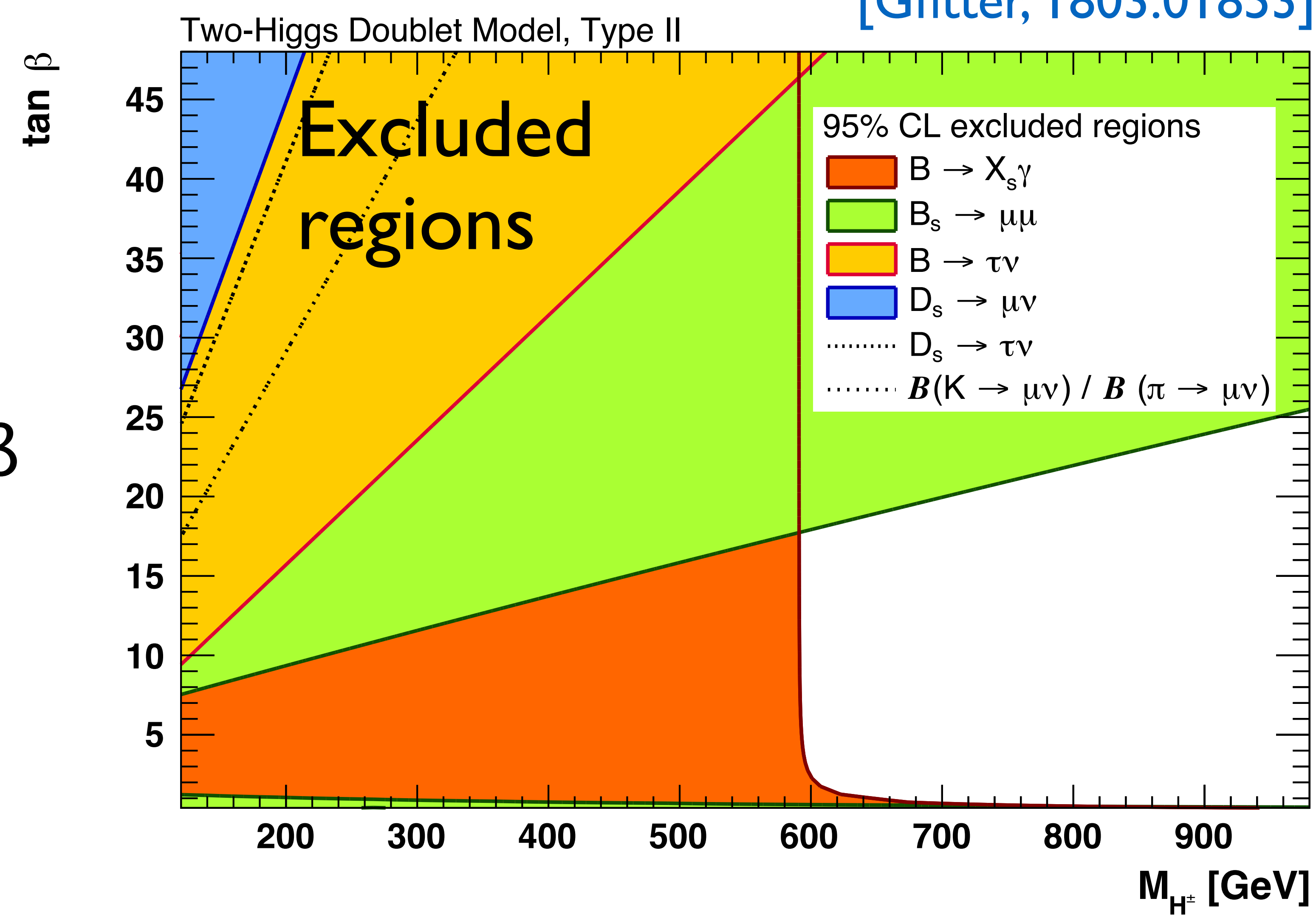
Predictions of BRs using 2HDMC [D. Eriksson et al., CPC 181, 189 (2010)]
7 additional, unconstraint parameters (4 masses, 2 angles, soft breaking scale): importance sampling with MultiNest [F. Feroz et al., arXiv:1306.2144]

2HDM Flavour Constraints

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



[Gfitter, 1803.01853]



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

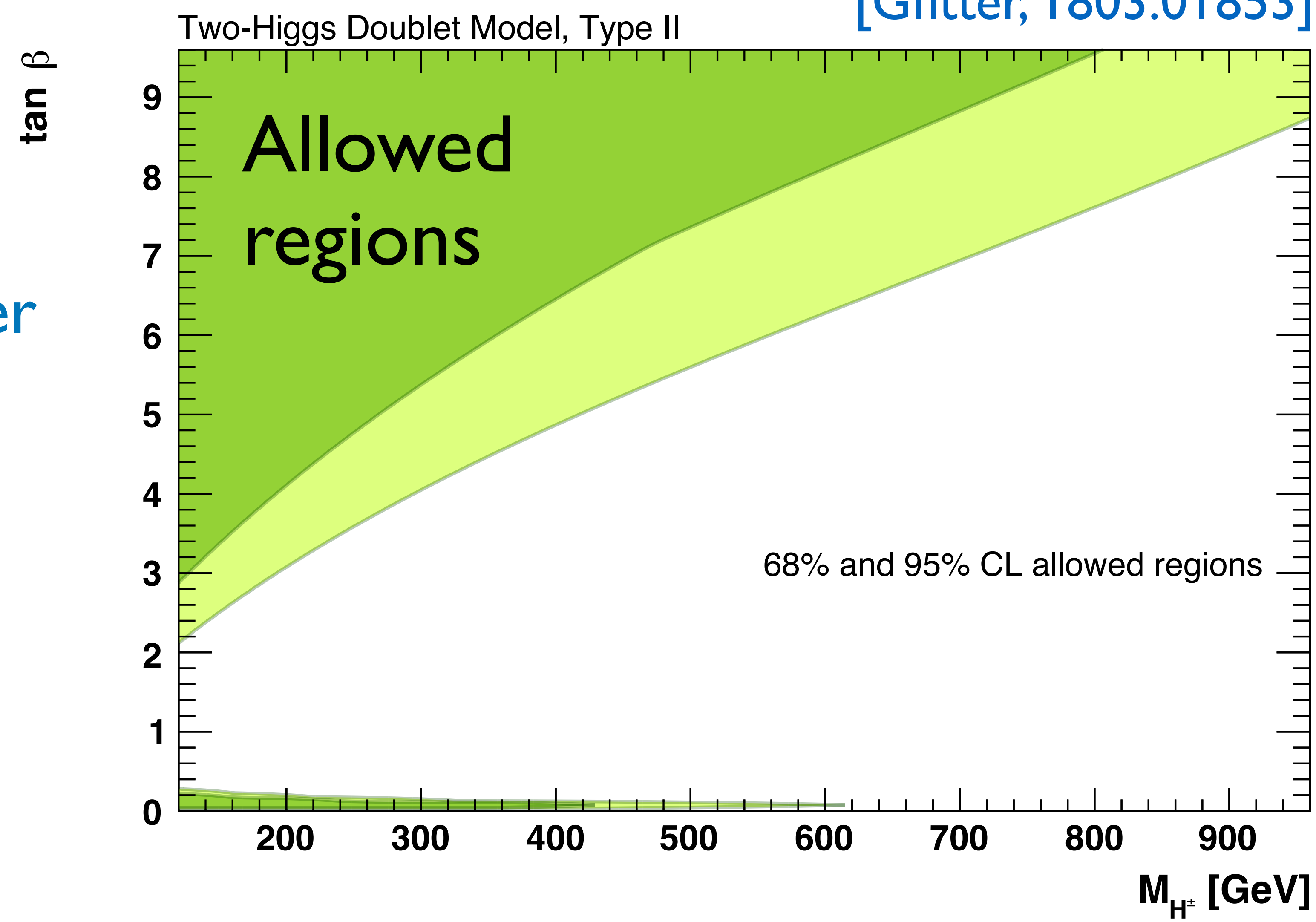
- R(D) and R(D*) can only be explained in *Type II* (large $\tan\beta$ and small M_{H+})
  → excluded by other flavour data
  - excluded from further fits

Muon g−2

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

- 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

[Gfitter, 1803.01853]



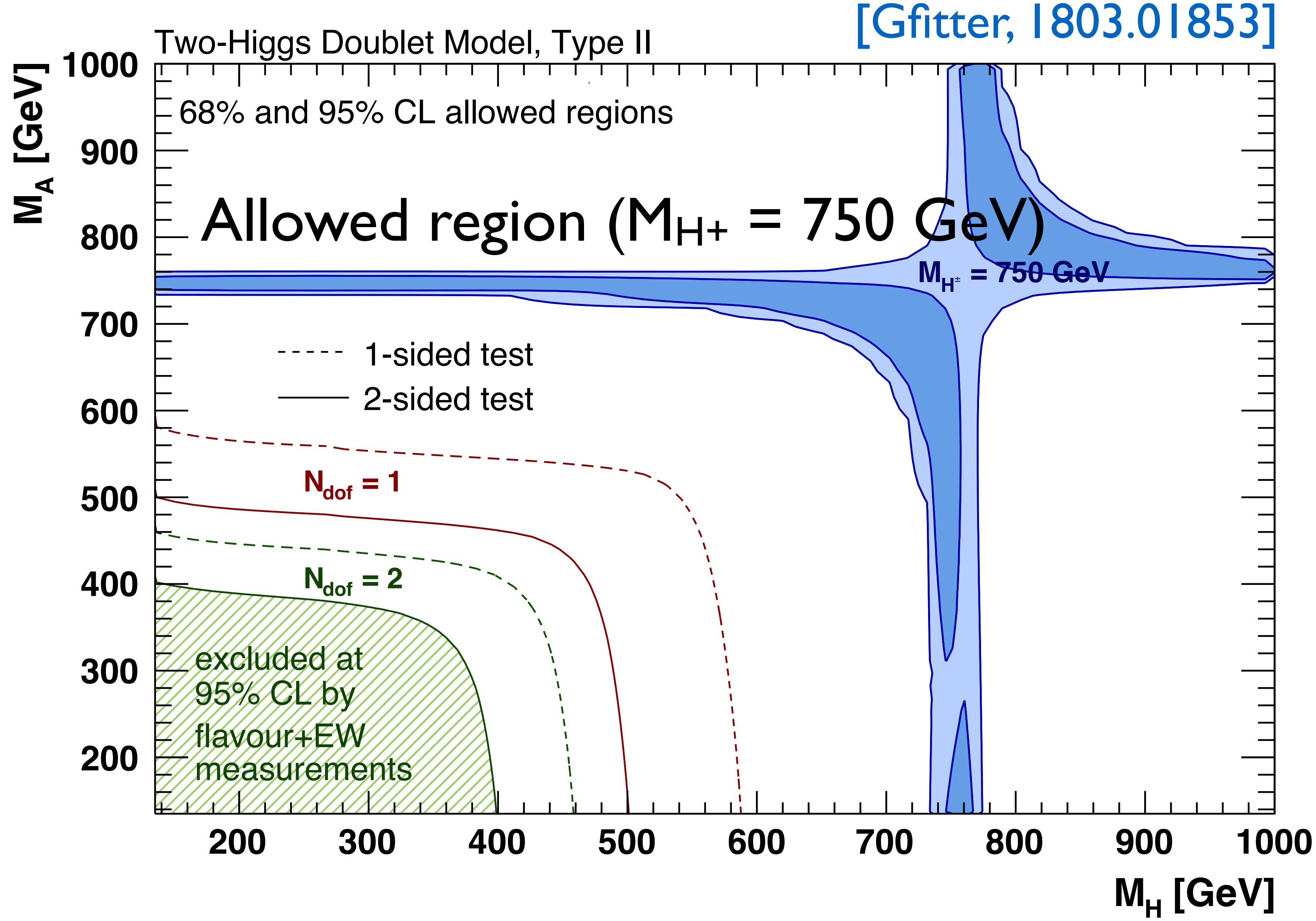
2HDM Global Fit

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

[Gfitter, 1803.01853]

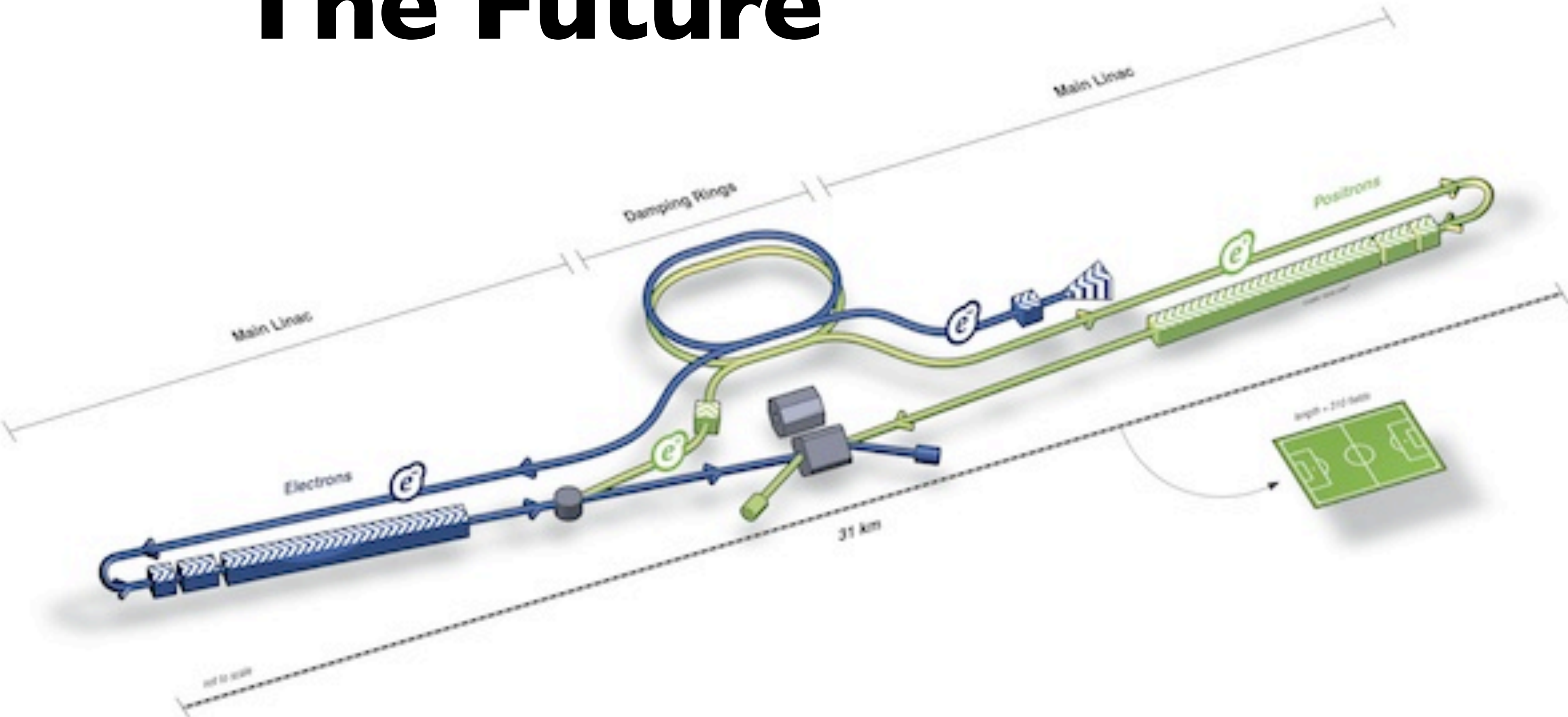
- **Exclude**
  M_A, M_H < 400-500 GeV
  in *Type II* and *flipped*

- **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

The Future

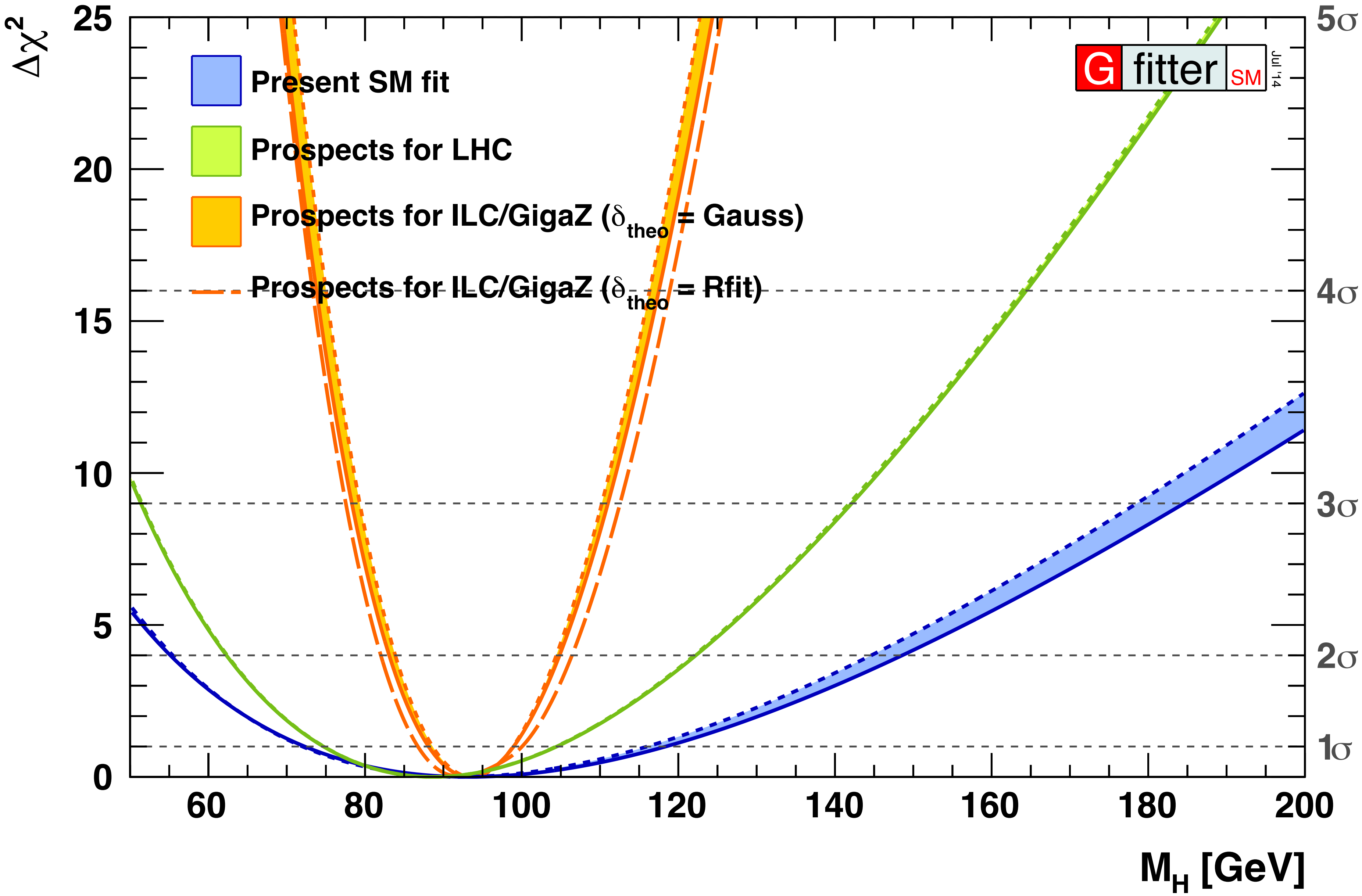

Main Linac
Damping Rings
Main Linac
Positrons
Electrons
31 km

Future Improvements

Parameter	Present	LHC	ILC/GigaZ	
M_H [GeV]	0.2	< 0.1	< 0.1	
M_W [MeV]	15	8	5	WW threshold
M_Z [MeV]	2.1	2.1	2.1	
m_t [GeV]	0.8	0.6	0.1	$t\bar{t}$ threshold scan
$\sin^2\theta^{\ell}_{\mathrm{eff}}$ $[10^{-5}]$	16	16	1.3	$\delta A^{0,f}_{LR}$: $10^{-3} \rightarrow 10^{-4}$
$\Delta\alpha^5_{\mathrm{had}}(M_Z^2)$ $[10^{-5}]$	10	5	5	low energy data, better α_s
R^0_l $[10^{-3}]$	25	25	4	high statistics on Z-pole
κ_V ($\lambda = 3\,\mathrm{TeV}$)	0.05	0.03	0.01	direct measurement of BRs

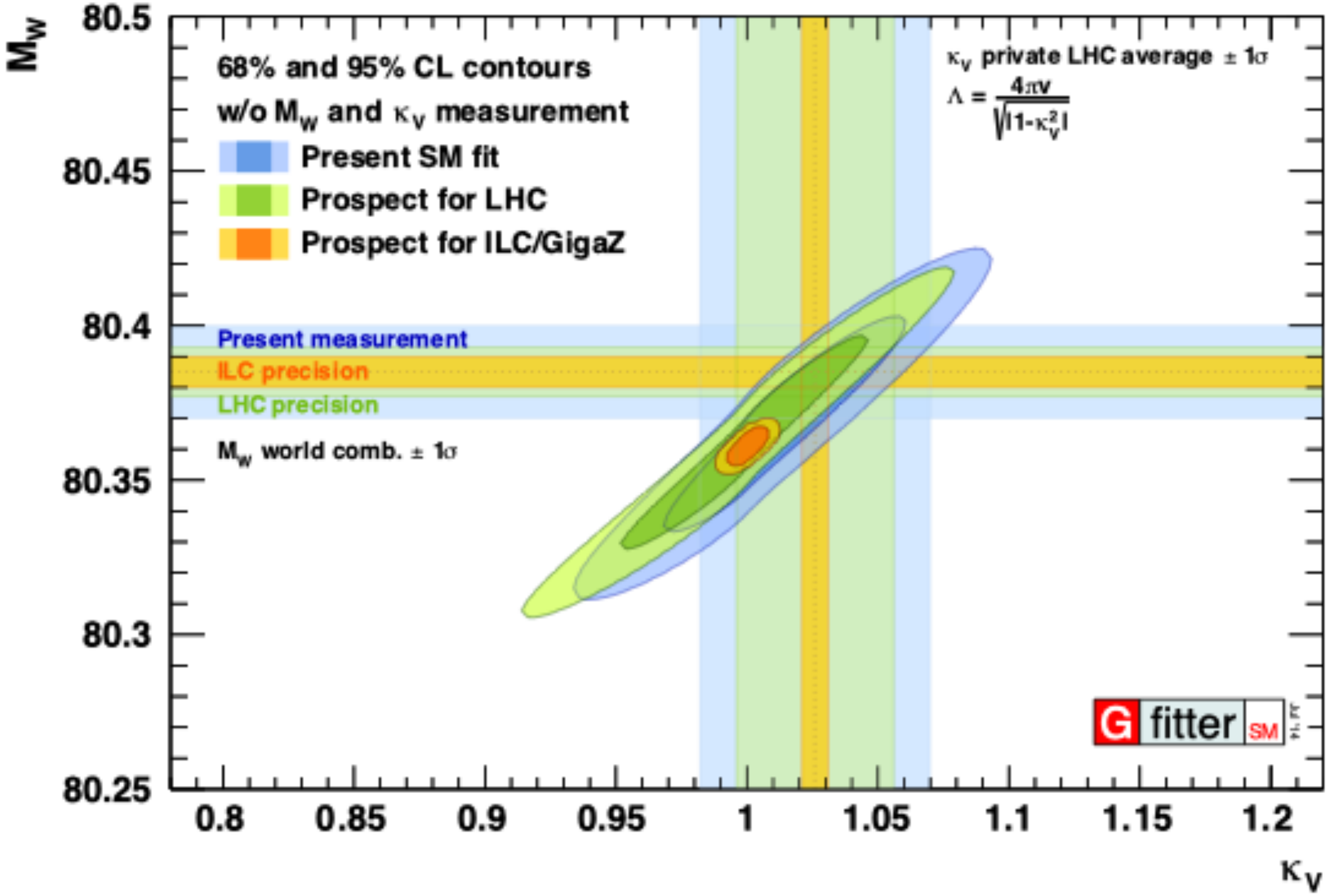
- theoretical uncertainties reduced by a factor of 4 (esp. M_W and $\sin^2\theta^l_{\mathrm{eff}}$)
  - implies three-loop EW calculations!
  - exception: $\delta_{\mathrm{theo}}\, m_t$ (LHC) = 0.25 GeV (factor 2)

Prospects Fits to M_H



- Uncertainty of ±5 to ±7 GeV possible in M_H with ILC/GigaZ
  - depending on central value and improvements in $\Delta\alpha_{had}$
  - precision on M_Z will become important again

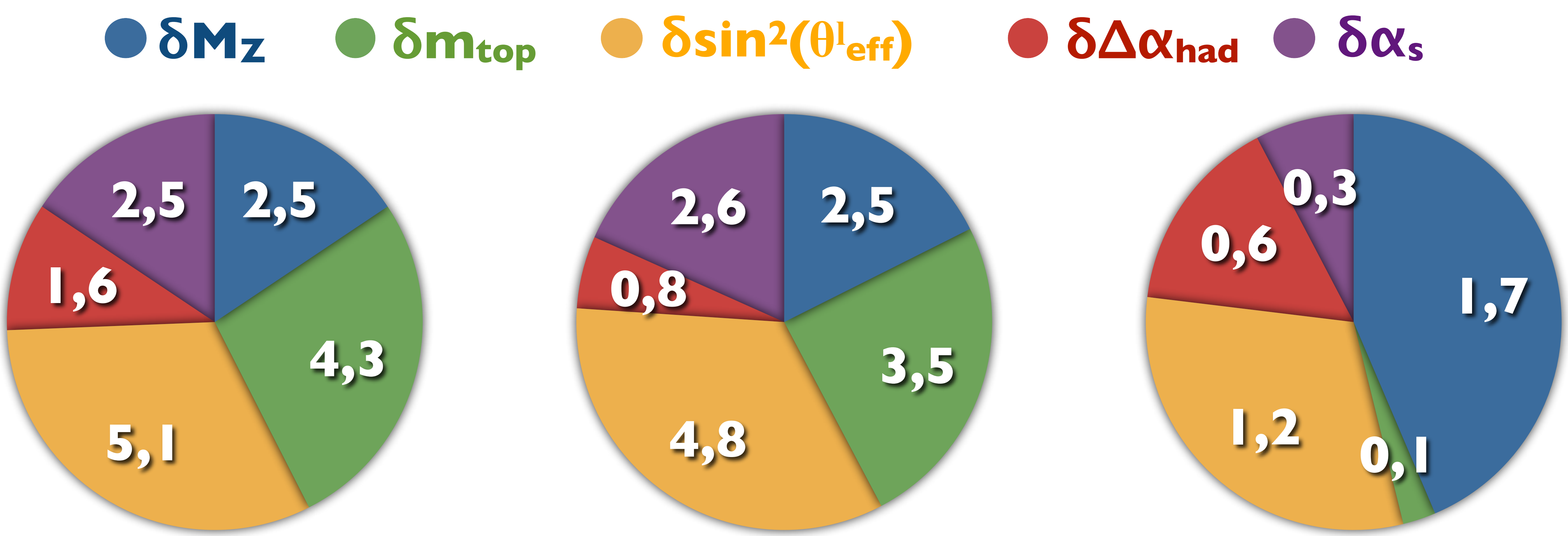
Prospects of EW Fit



- competitive results between EW fit and Higgs coupling measurements!
  - precision of about 1%
- ILC/GigaZ offers fantastic possibilities to test the SM and constrain NP

M_W : Impact of Uncertainties

Today	**LHC-300**	**ILC/GigaZ**
δ_{meas} = 15 MeV	δ_{meas} = 8 MeV	δ_{meas} = 5 MeV
δ_{fit} = 8 MeV	δ_{fit} = 6 MeV	δ_{fit} = 2 MeV



Impact of individual uncertainties on δM_W in fit (numbers in MeV)

- ILC/GigaZ: impact δM_Z of will become important again!

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

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

General extension with the SMEFT

- EWPO, LEP 2 data, flavour data
- Differential H measurements, also sensitivity to H self-coupling λ!

Additional Material

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:

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

operators of dimension 6

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

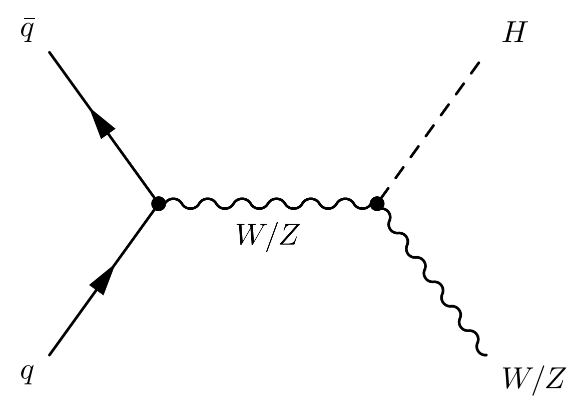
- SILH basis, focus on operators with H involvement, EWPO: $c_T = 0$, $c_W = -c_B$
- **8** operators of interest

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

[Englert, RK, Schulz, Spannowsky, 1509.00672]

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

$\longrightarrow$ $\ell\nu$ / $\ell\ell$

  - 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 ✓

Dim-6 SILH Basis

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

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

- **8** operators of interest left

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

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

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]

$$\chi^2 = (\underbrace{\boldsymbol{x}}_{\text{Data}} - \underbrace{\boldsymbol{t}}_{\text{Predictions}}(\underbrace{c_i}_{\text{Wilson coefficients}}, \underbrace{\delta_k}_{\text{nuisance parameters}}))^T \boldsymbol{V}^{-1} (\boldsymbol{x} - \boldsymbol{t}(c_i, \delta_k))$$

Data

Wilson coefficients

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

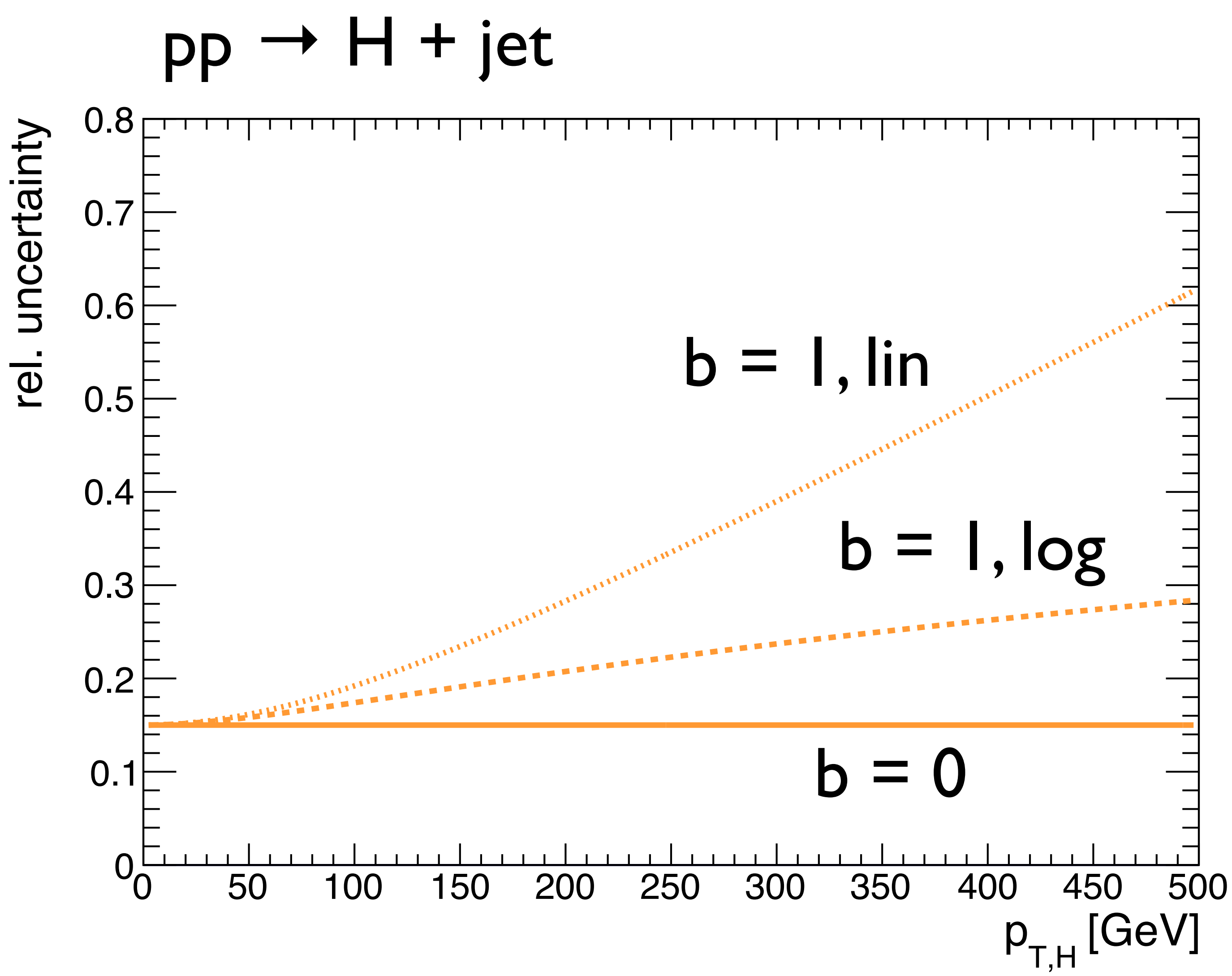
Uncertainties in tails of $p_{T,H}$

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

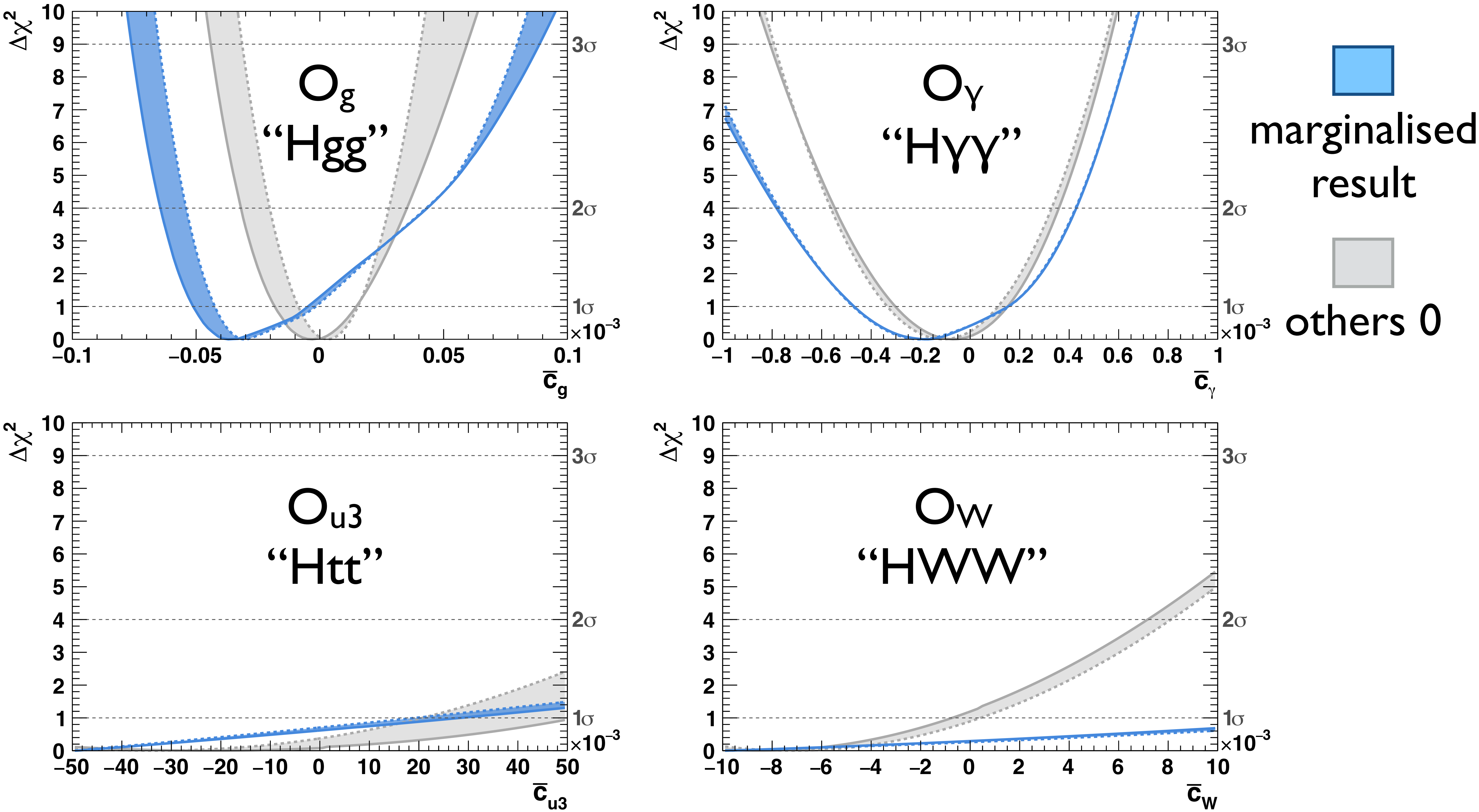
$$\Delta_i = u_i(\underbrace{a(1-\delta_i)}_{\text{inclusive}} \oplus \underbrace{b(1-\delta_{i,\mathrm{tail}})f(p_{\mathrm{T,H}})}_{\text{tail}})$$

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

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



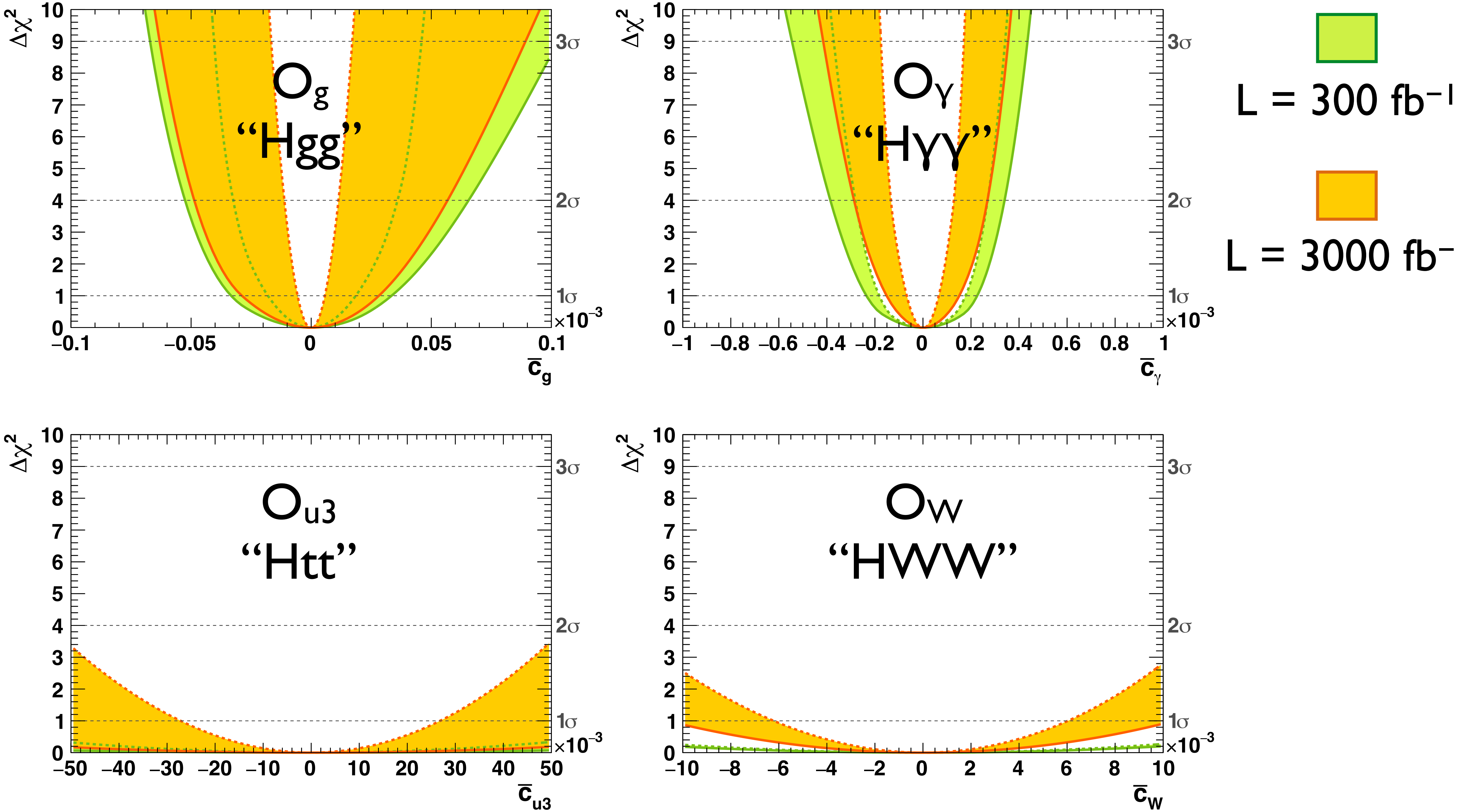
Constraints from Run I



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

[Englert, RK, Schulz, Spannowsky, 1509.00672]

Constraints from HL-LHC

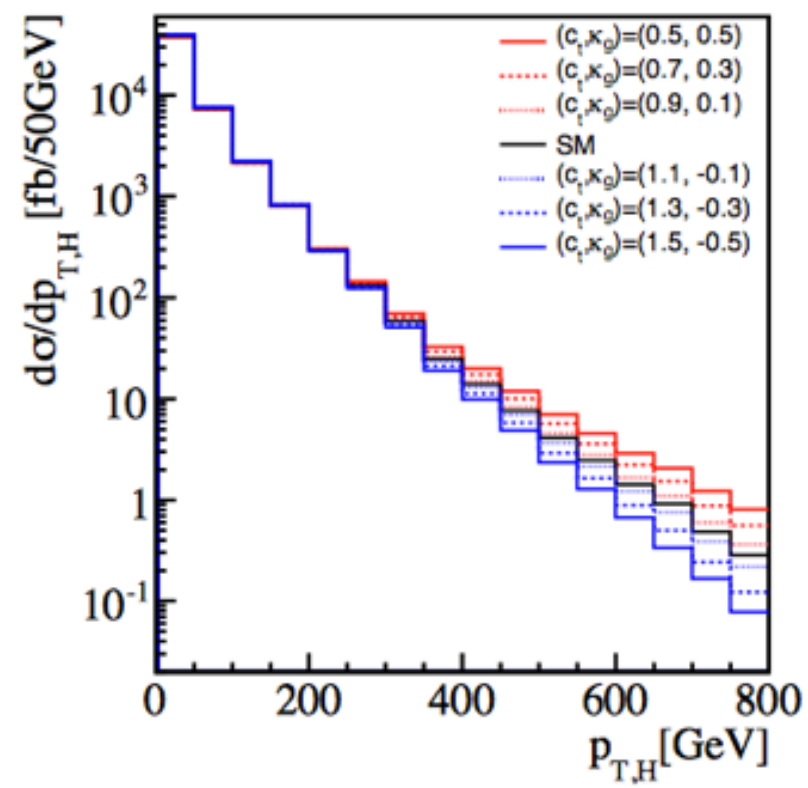


No constraints on O_{u3} and O_W
with L = 300 to 3000 fb^{-1} !

[Englert, RK, Schulz, Spannowsky, 1509.00672]

Flat Directions

[Englert, Spannowsky, 1408.5147]

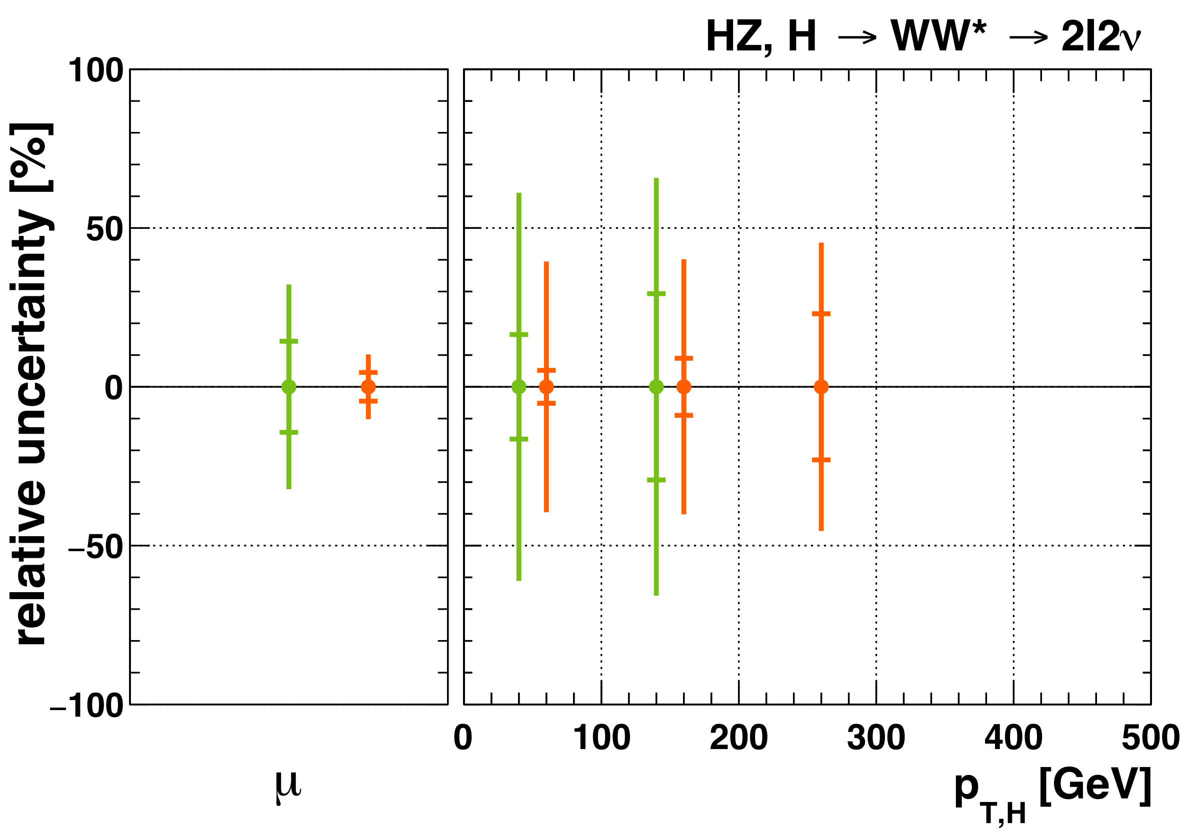


Multi-parameter fit

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

Solution

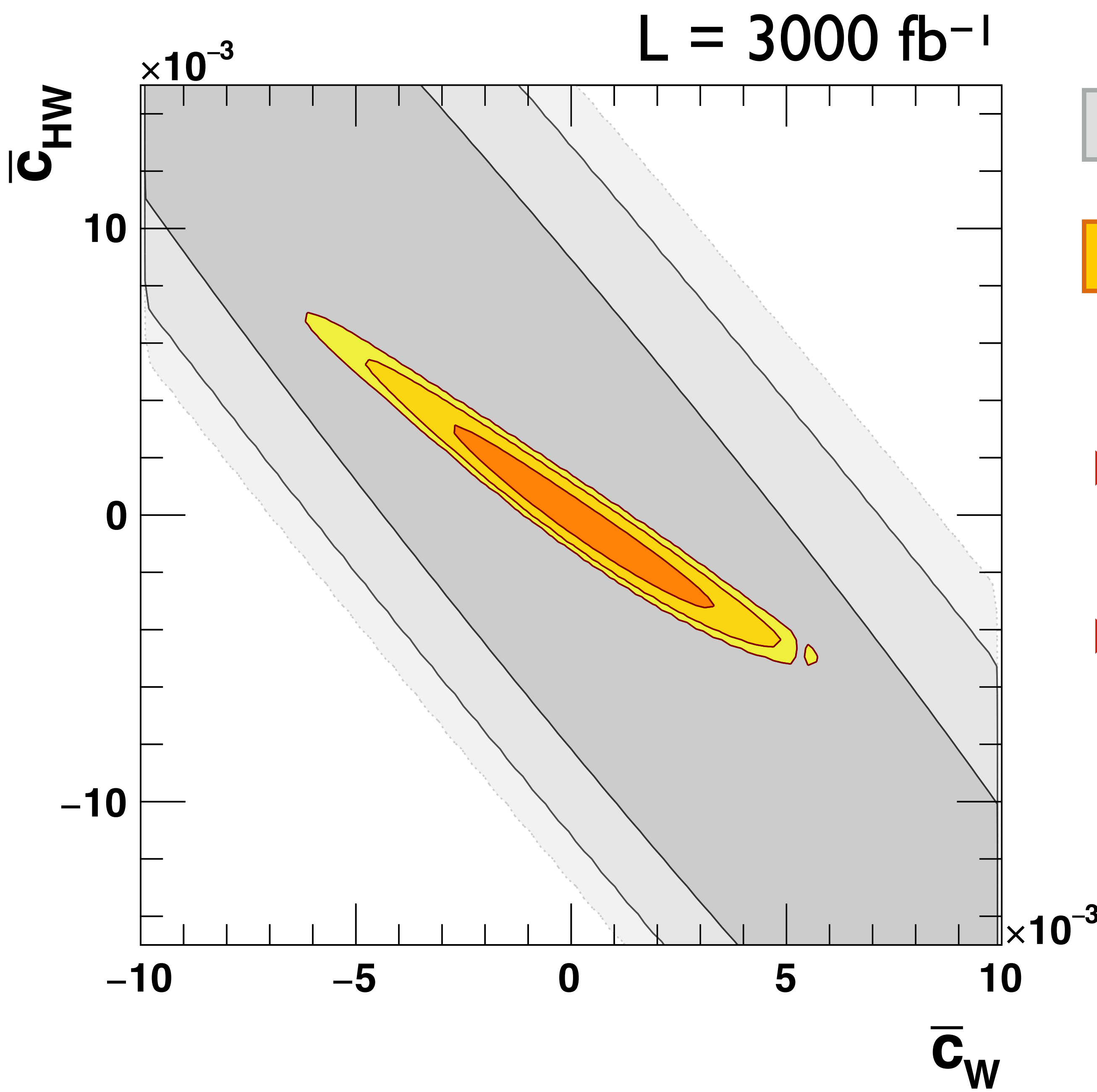
- different behaviour at high energies
- include differential measurements of $p_{T,H}$



Pseudo data

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

Lifting flat directions



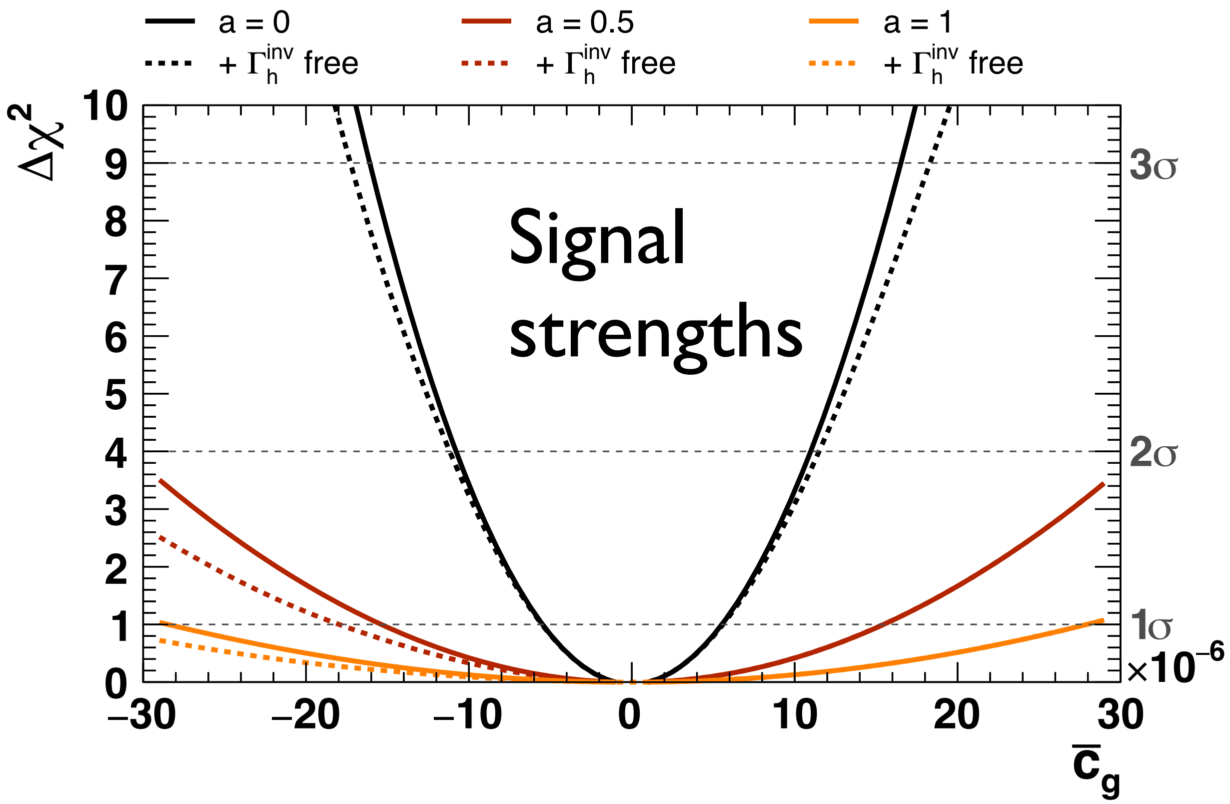
only signal strengths

including $p_{T,H}$ measurements

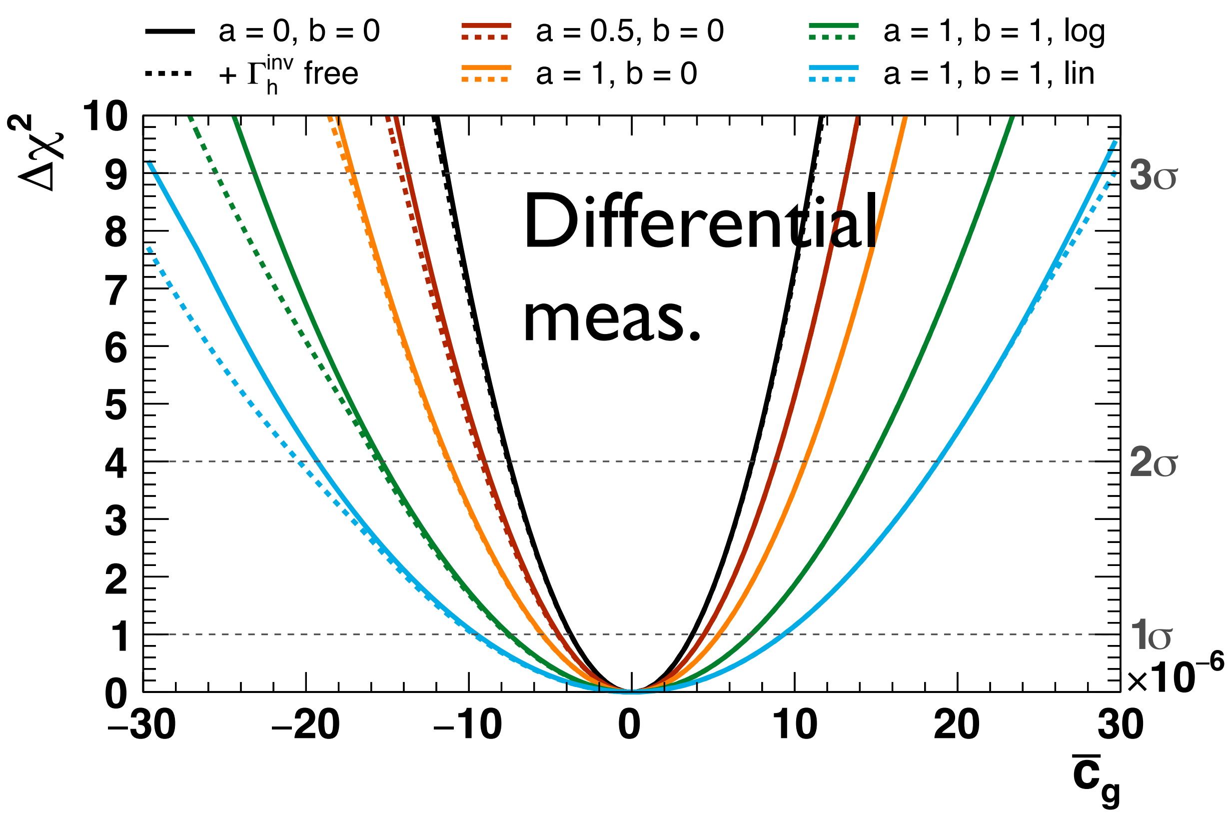
- Strong correlations between coefficients are lifted
- Simultaneous constraints on all parameters possible

[Englert, RK, Schulz, Spannowsky, 1509.00672]

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}



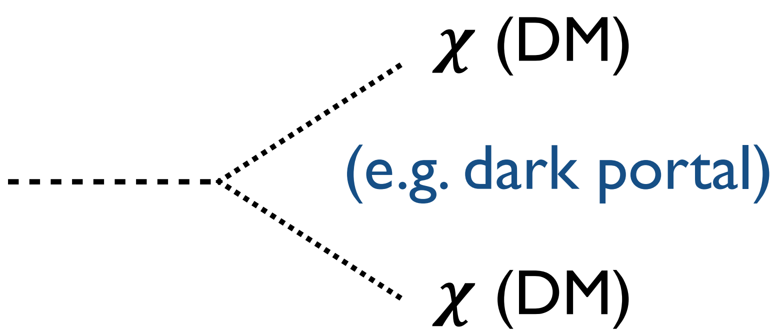
- Different behaviour at high energies
  - go differential in $p_{T,H}$
    - generate pseudo-data
    - uncertainties extrapolated from μs
  - Lift flat directions
  - Much tighter constraints!
    - Improves LHC physics potential

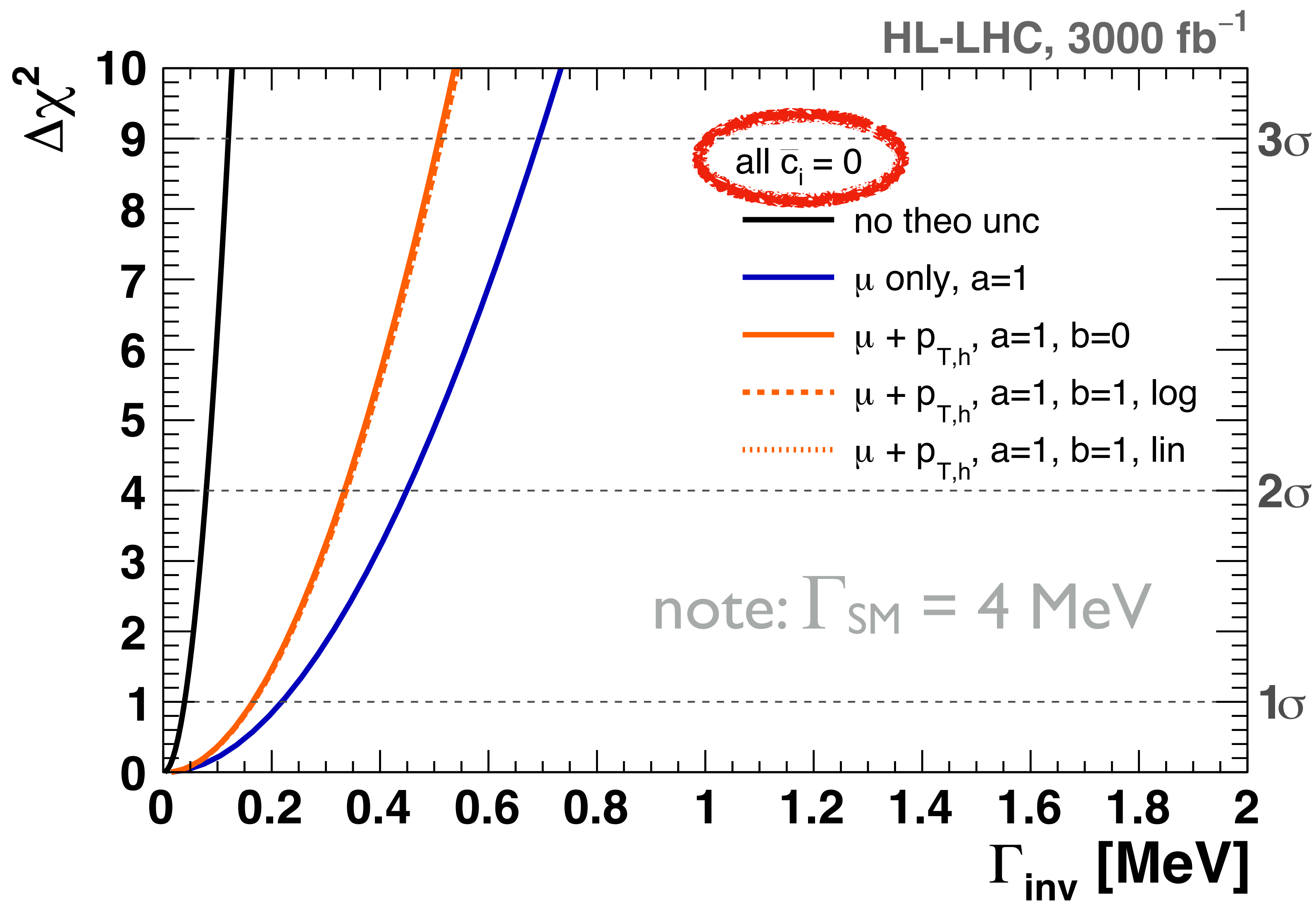
[Englert, RK, Schulz, Spannowsky, 1708.06355]

Invisible Width with HL-LHC

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]

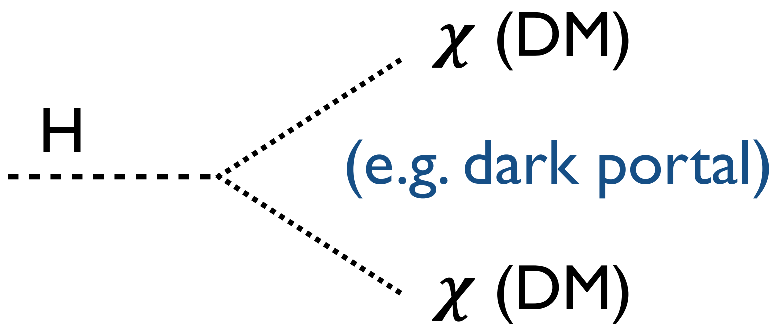
ATLAS study: BR_{inv} < 15%

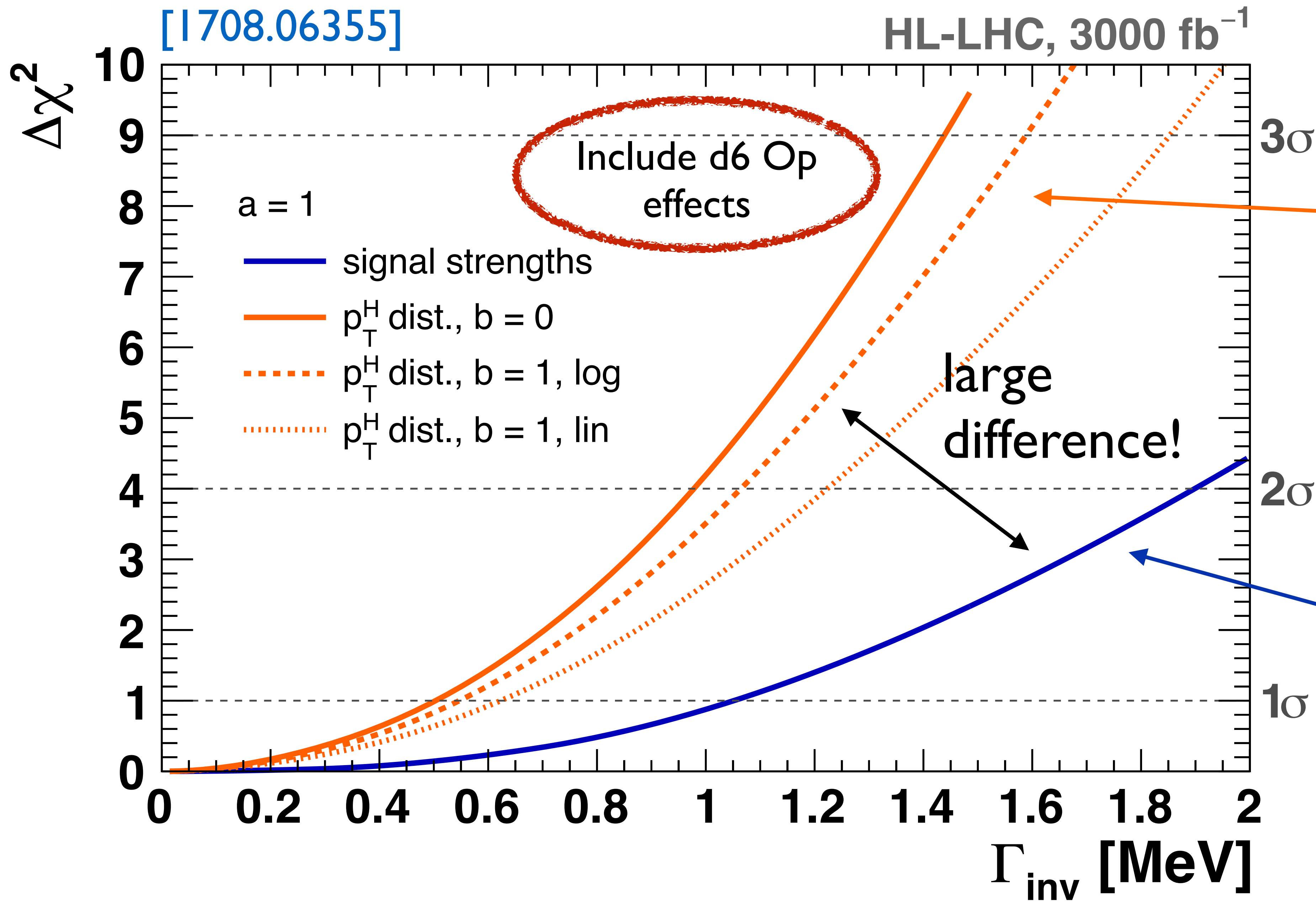
[ATL-PHYS-PUB-2013-015]

Invisible Width with HL-LHC

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

Include BSM effects through d6 Operators!





$BR_{inv} \lesssim$ 20-25%

(with p_{TH} meas)

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

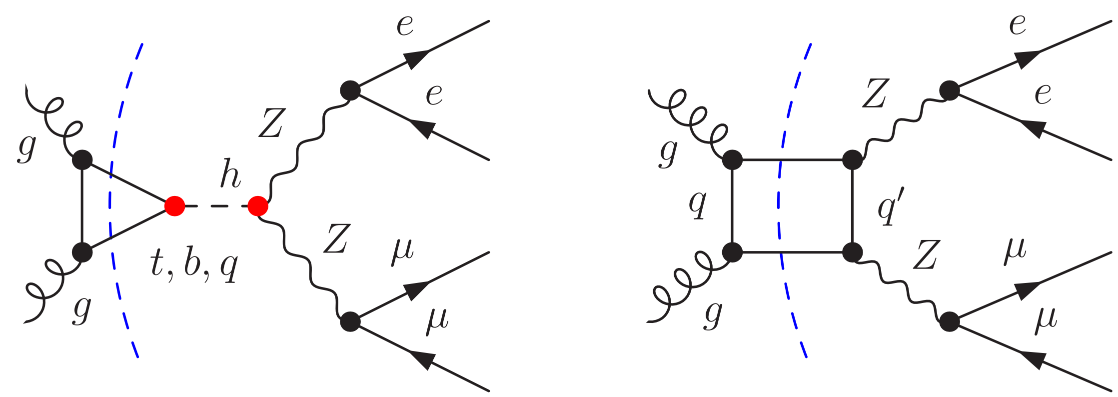
BR_{inv} < 30-35%

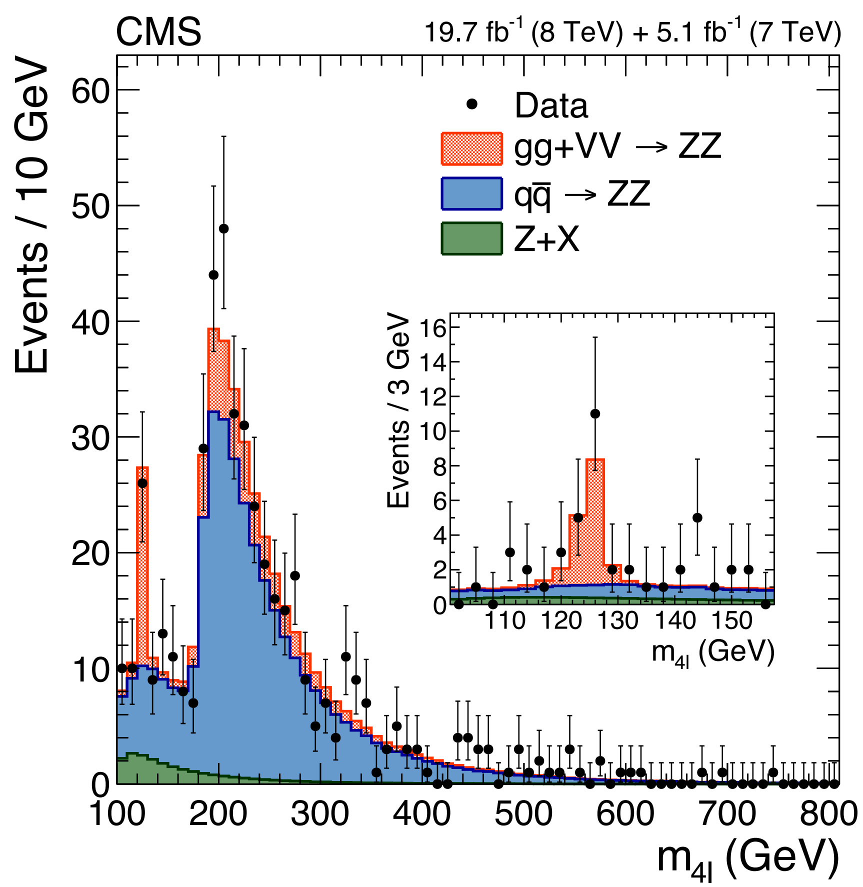
(μs only)

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

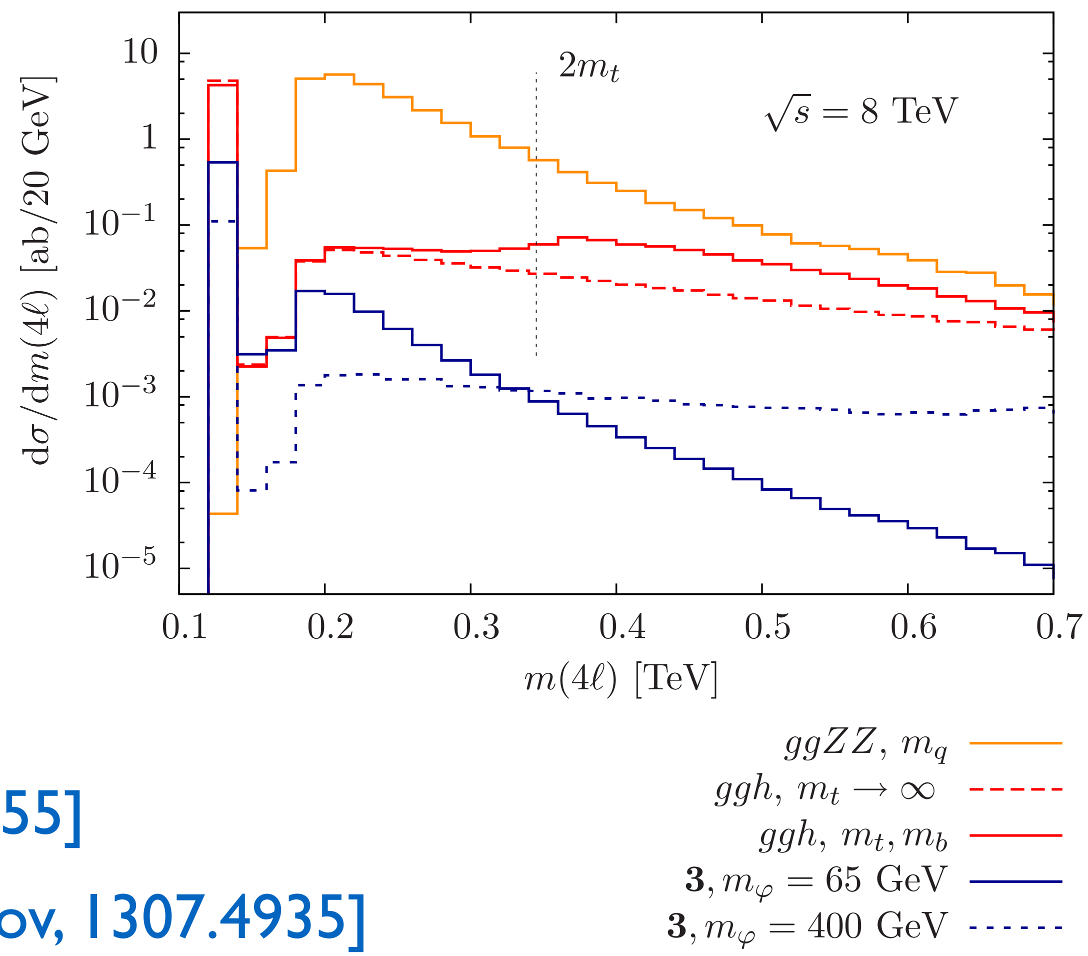




[CMS, 1405.3455]

[Caola, Melnikov, 1307.4935]

[Englert, Spannowsky, 1405.0285]

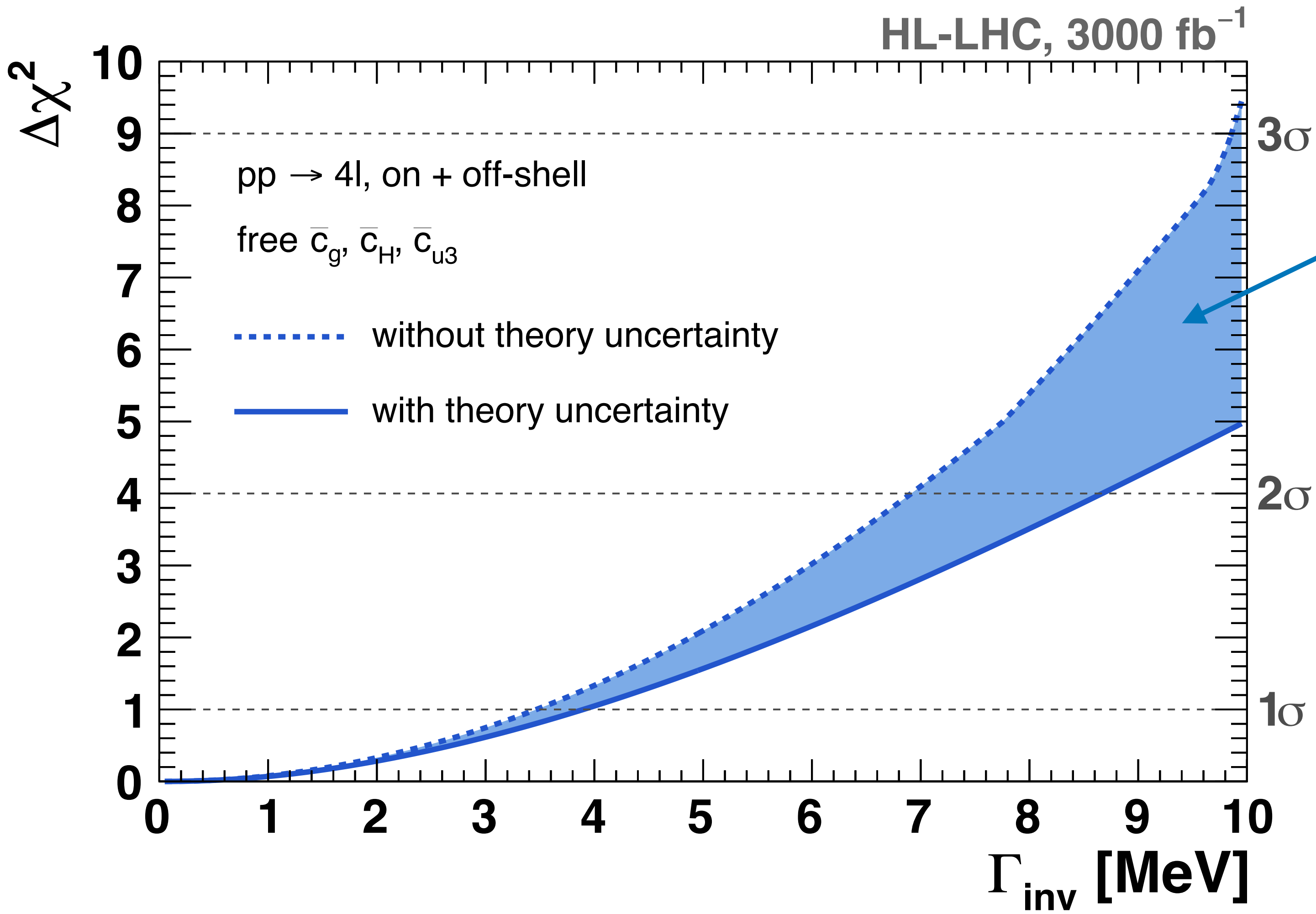


On-shell and off-shell

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

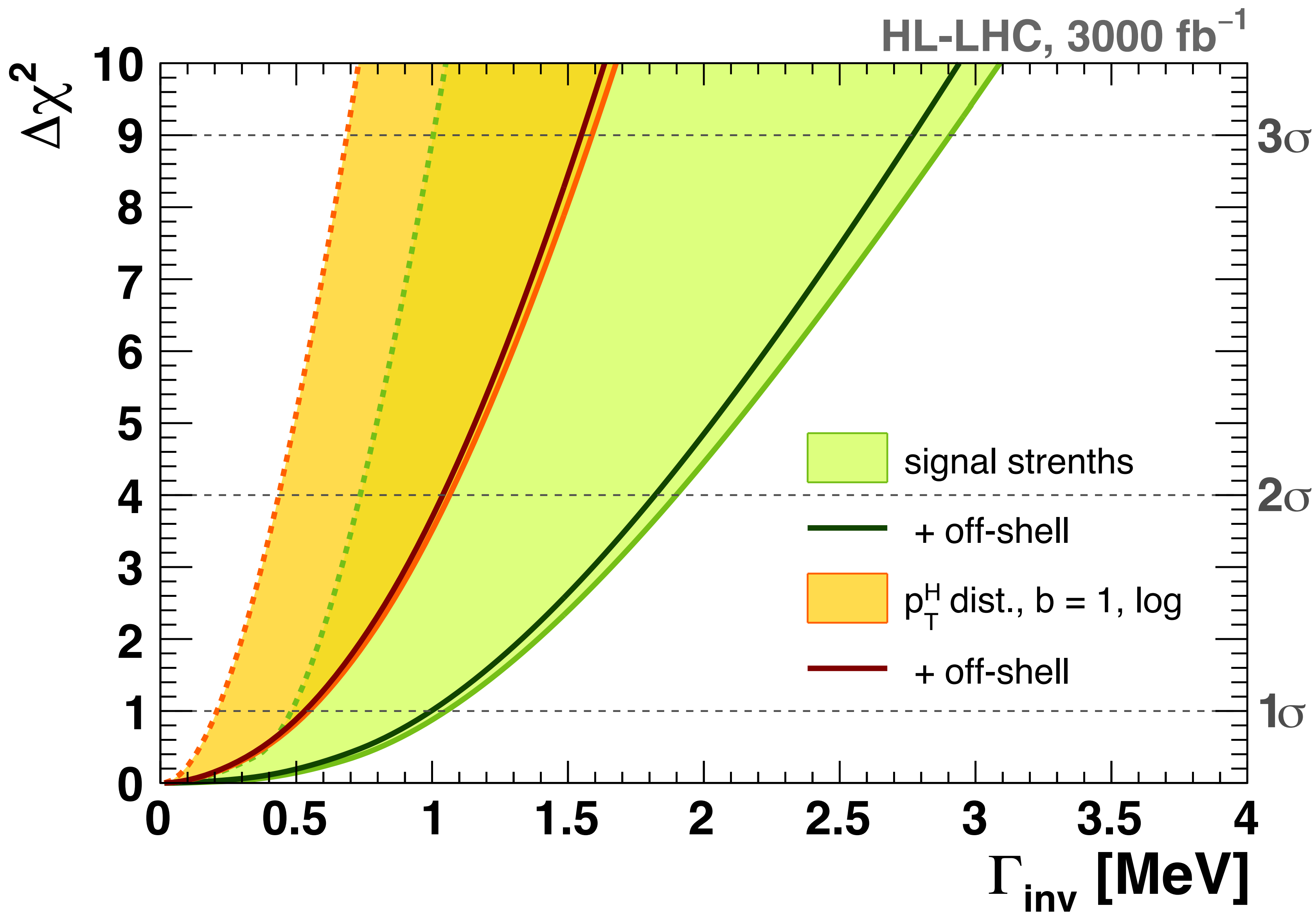
marginalise over c_g, c_{u3}, c_H
(others fixed to 0)



$\Gamma_{inv} \lesssim$ 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)