Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

The Electroweak Fit

Gfitter

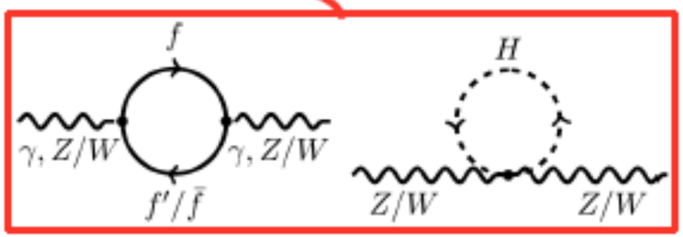
- Gauge & scalar sector is determined by 4 parameters (choose α, G_F, M_Z, M_H)
- Other parameters and observables related by theory

$$\sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2} \qquad M_W^2 \sin^2\theta_W = \frac{\pi\alpha}{\sqrt{2}\,G_F}$$

→ over-constrained theory

- Other SM parameters (quark masses, M_H, α_S) enter by radiative corrections

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



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

- G_F known with high precision → not varied in the fit

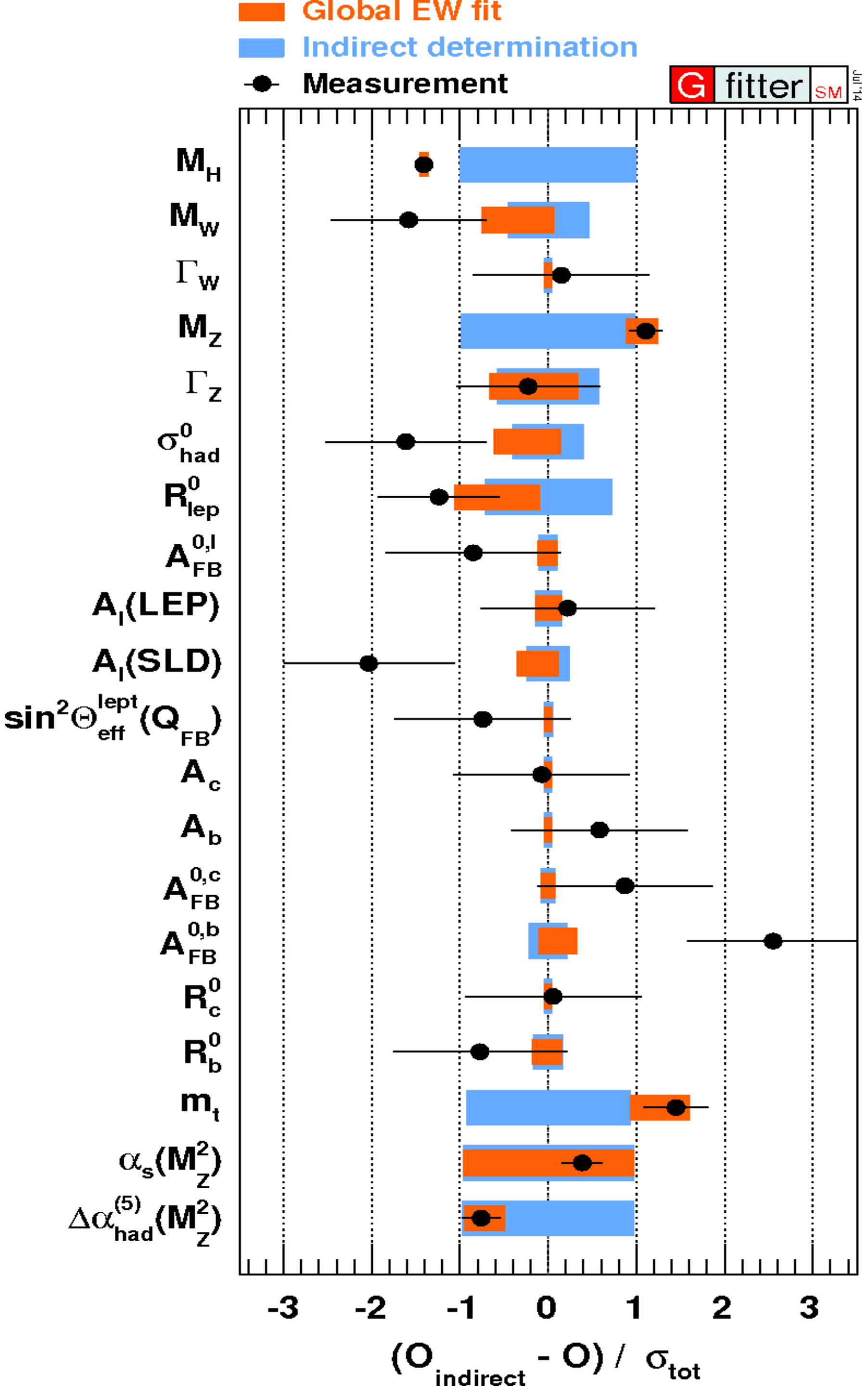
- Consistent set of full EW 2-loop calculations is available:
  - $\sin^2\Theta^f_{eff}$: effective weak mixing angle (from ratio g_V/g_A)
    (M. Awramik et al., PRL 93, 201805 (2004), JHEP 11, 048 (2006), Nucl. Phys. B813, 174 (2009))
  - M_W: mass of the W boson, includes QCD corrections at 4-loop level
    (M. Awramik et al., PRD 69, 053006 (2004), PRL 89, 241801 (2002))
  - Γ_f: partial widths of the Z boson (A. Freitas, JHEP 04, 070 (2014))
  - Radiator functions to Γ_f: QED and QCD corrections up to N^{3}LO
    (Baikov et al., PRL 108, 222003 (2012))
  - (Γ_W: width of the W boson, only 1-loop EW corrections included
    (Cho et al., JHEP 1111, 068 (2011))
- Estimate uncertainties due to unknown higher orders (using a geometric series):

$\delta_{\text{theo}} M_W$	4 MeV	$\delta_{\text{theo}} \Gamma_{u,c}$	0.12 MeV
$\delta_{\text{theo}} \sin^2\theta^f_{\text{eff}}$	$4.7 \cdot 10^{-5}$	$\delta_{\text{theo}} \Gamma_b$	0.21 MeV
$\delta_{\text{theo}} \Gamma_{e,\mu,\tau}$	0.012 MeV	$\delta_{\text{theo}} \sigma^0_{\text{had}}$	6 pb
$\delta_{\text{theo}} \Gamma_\nu$	0.014 MeV	$\delta_{\text{theo}} \mathcal{R}_{V,A}$	$\sim \mathcal{O}(\alpha_s^4)$
$\delta_{\text{theo}} \Gamma_{d,s}$	0.09 MeV	$\boxed{\delta_{\text{theo}} m_t}$	$\boxed{0.5\ \text{GeV}}$

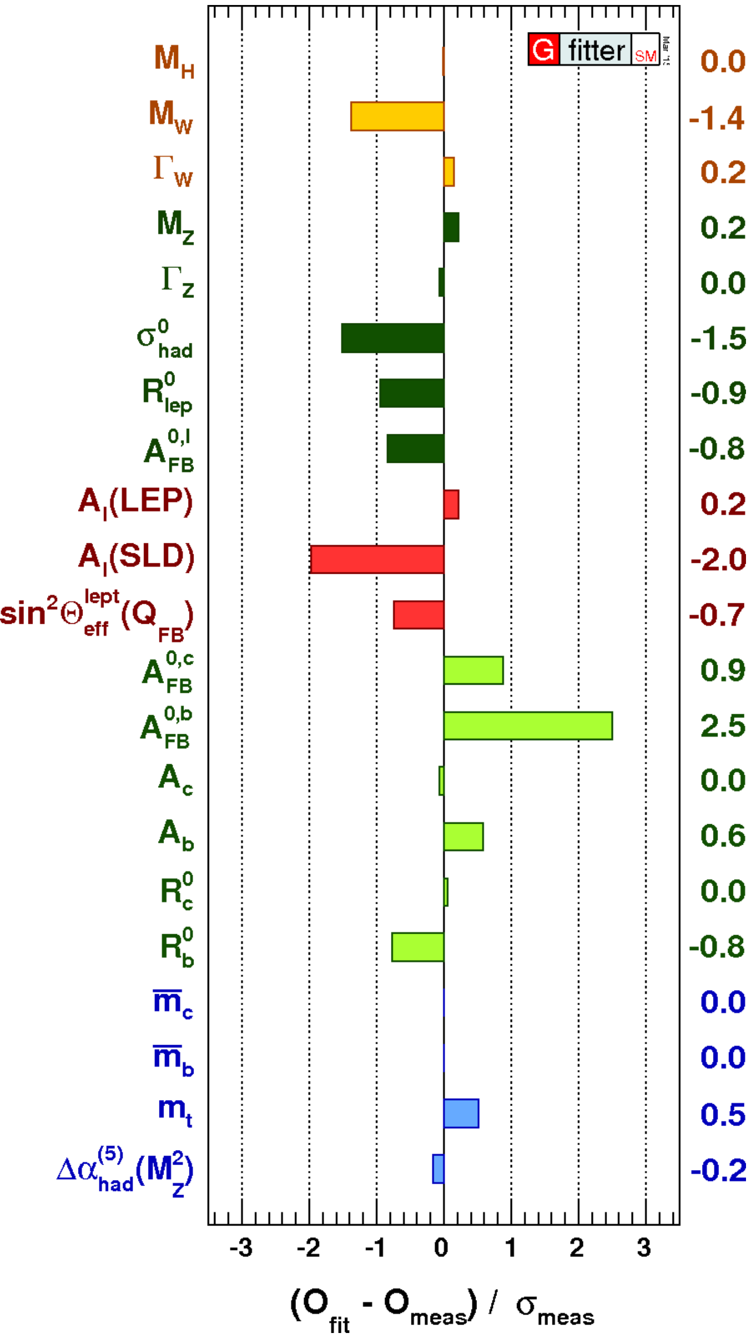
Uncertainty on m_t:
Relation between m_{pole}
and measured mass

- All SM parameters measured in experiments
- Input from e^+e^- colliders (LEP+SLC):
  - M_Z, M_W, Γ_W, Γ_Z
  - forward-backward asymmetries
  - partial-Z-width ratios R
- Input from hadron colliders (LHC+Tevatron):
  - M_W, Γ_W
  - M_H
  - m_t
- $\alpha_s(M_Z^2)$ enters the fit as free parameter
- Evolution of α parameterized with $\Delta\alpha^{(5)}_{had}$

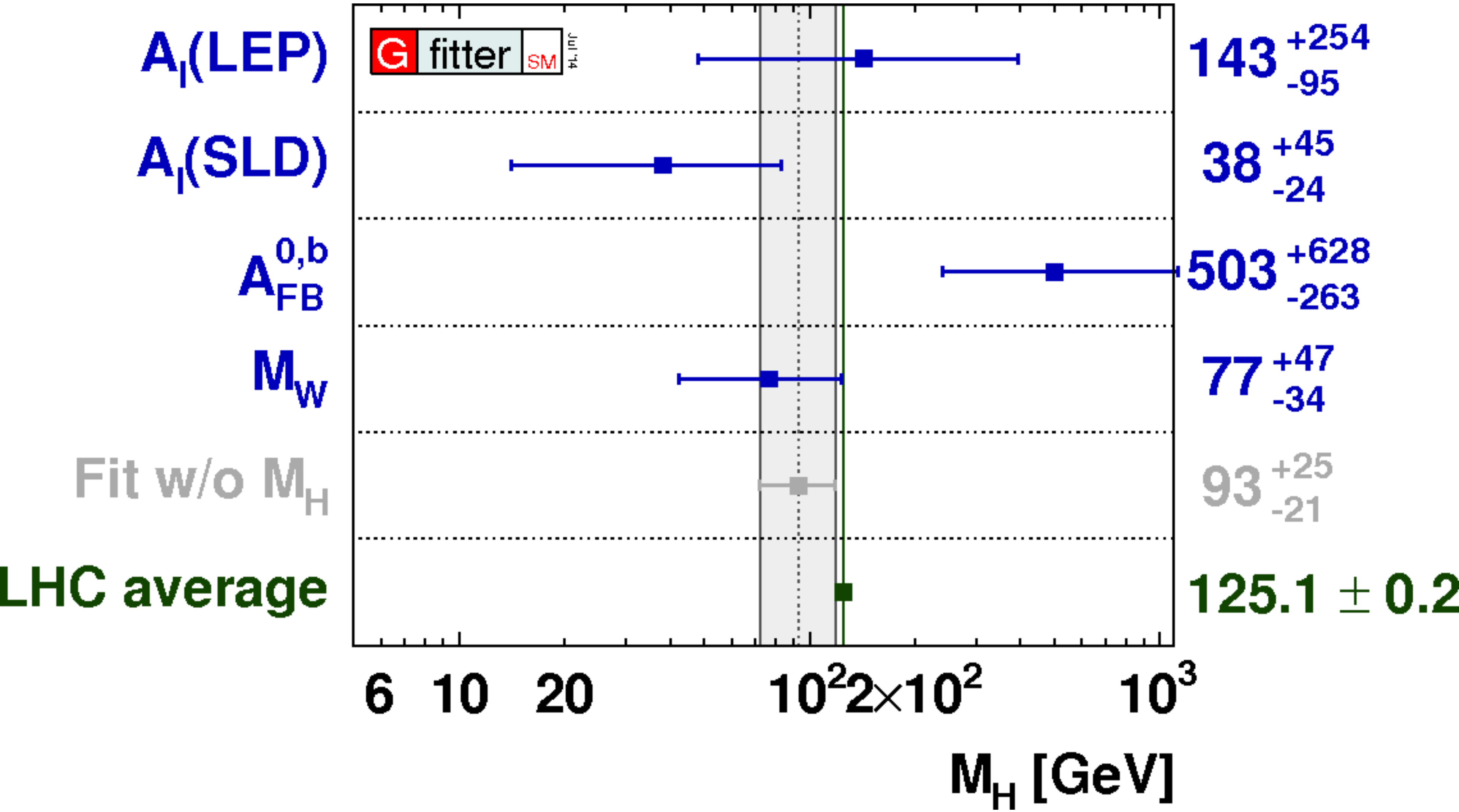
M_H [GeV]	125.14 ± 0.24
M_W [GeV]	80.385 ± 0.015
Γ_W [GeV]	2.085 ± 0.042
M_Z [GeV]	91.1875 ± 0.0021
Γ_Z [GeV]	2.4952 ± 0.0023
σ^0_{had} [nb]	41.540 ± 0.037
R^0_ℓ	20.767 ± 0.025
$A^{0,\ell}_{\text{FB}}$	0.0171 ± 0.0010
A_ℓ	0.1499 ± 0.0018
$\sin^2\theta^\ell_{\text{eff}}(Q_{\text{FB}})$	0.2324 ± 0.0012
A_c	0.670 ± 0.027
A_b	0.923 ± 0.020
$A^{0,c}_{\text{FB}}$	0.0707 ± 0.0035
$A^{0,b}_{\text{FB}}$	0.0992 ± 0.0016
R^0_c	0.1721 ± 0.0030
R^0_b	0.21629 ± 0.00066
$\overline{m}_c$ [GeV]	$1.27^{+0.07}_{-0.11}$
$\overline{m}_b$ [GeV]	$4.20^{+0.17}_{-0.07}$
m_t [GeV]	173.34 ± 0.76
$\Delta\alpha^{(5)}_{\text{had}}(M_Z^2)$	2757 ± 10



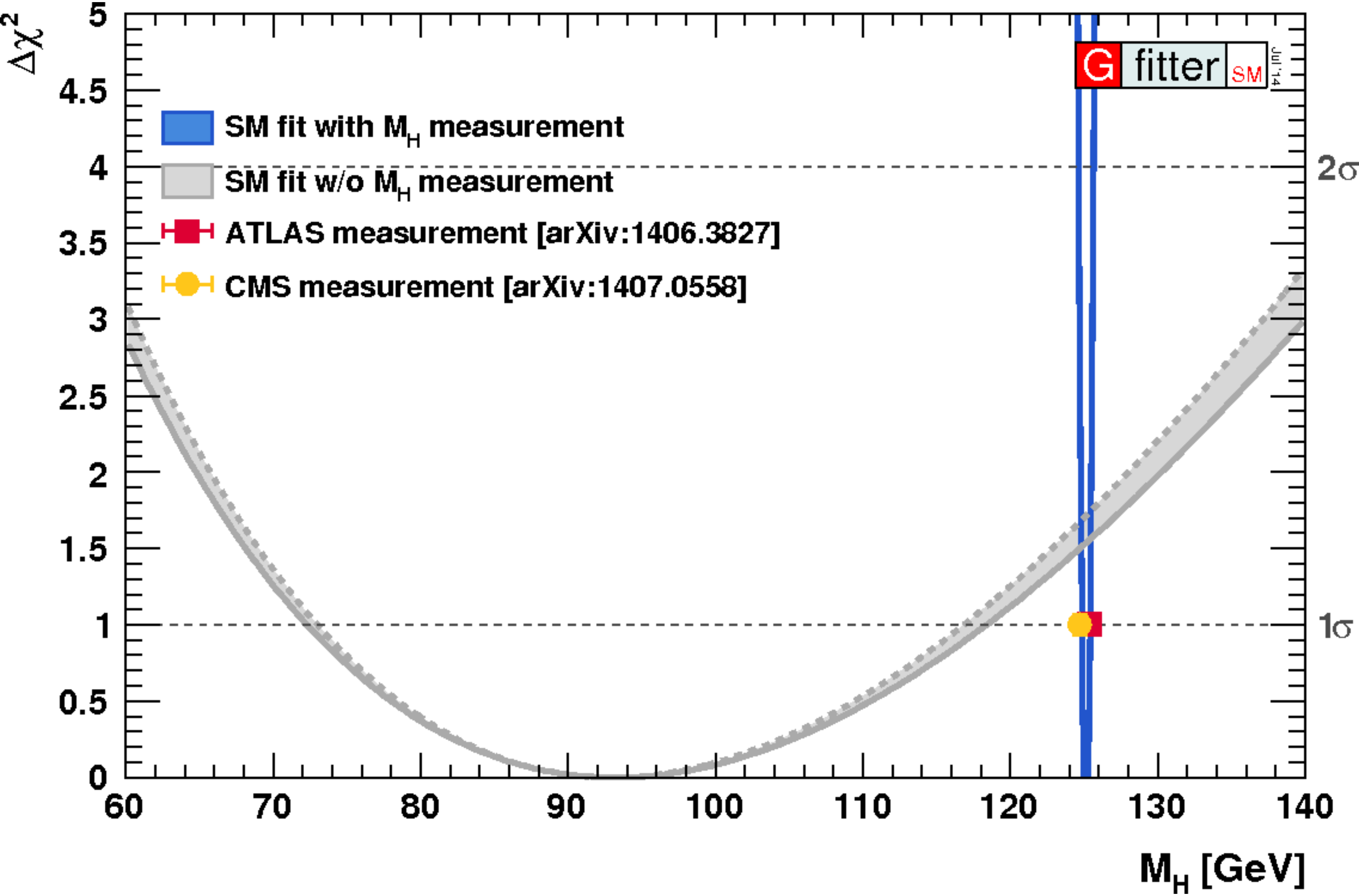
Global EW fit
Indirect determination
Measurement
G fitter SM
Jul '14
M_H
M_W
Γ_W
M_Z
Γ_Z
σ^0_{had}
R^0_{lep}
$A^{0,l}_{FB}$
A_l(LEP)
A_l(SLD)
$\sin^2\Theta^{lept}_{eff}(Q_{FB})$
A_c
A_b
$A^{0,c}_{FB}$
$A^{0,b}_{FB}$
R^0_c
R^0_b
m_t
$\alpha_s(M^2_Z)$
$\Delta\alpha^{(5)}_{had}(M^2_Z)$
-3
-2
-1
0
1
2
3
$(O_{indirect} - O) / \sigma_{tot}$



- Global χ^2=17.8 (for ndof = 14), p-value=0.21
- Predictions consistent with measurements
- Largest deviation for $A_{FB}^{0,b}$ ~ 2.5σ

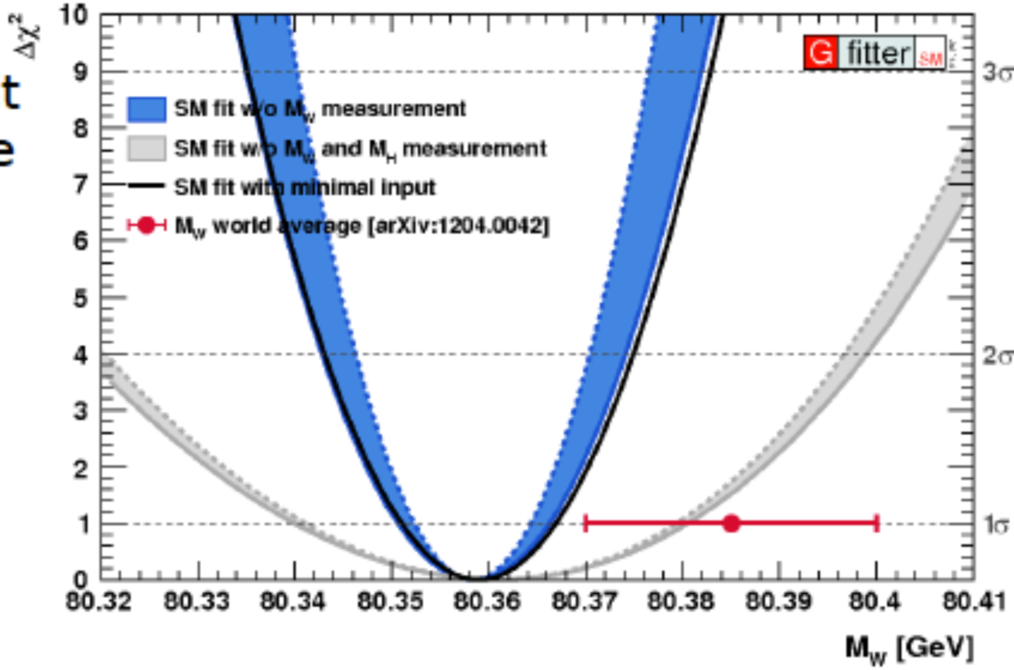


fitter
SM
Jul '14
A_l(LEP)
143^{+254}_{-95}
A_l(SLD)
38^{+45}_{-24}
$A_{FB}^{0,b}$
503^{+628}_{-263}
M_W
77^{+47}_{-34}
Fit w/o M_H
93^{+25}_{-21}
LHC average
125.1 ± 0.2
6
10
20
10^2
2×10^2
10^3
M_H [GeV]



$\Delta\chi^2$
SM fit with M_H measurement
SM fit w/o M_H measurement
ATLAS measurement [arXiv:1406.3827]
CMS measurement [arXiv:1407.0558]
G fitter SM
Jul '14
2σ
1σ
M_H [GeV]

- Perform fit without including direct measurement of observable in the fit
- Indirect determination of M_W more precise than direct measurement



$$
\begin{aligned}
M_W &= 80.3584 \pm 0.0046_{m_t} \pm 0.0030_{\delta_{\rm theo} m_t} \pm 0.0026_{M_Z} \pm 0.0018_{\Delta\alpha_{\rm had}} \\
&\qquad \pm 0.0020_{\alpha_S} \pm 0.0001_{M_H} \pm 0.0040_{\delta_{\rm theo} M_W}\ \mathrm{GeV}\,, \\
&= 80.358 \pm 0.008_{\rm tot}\ \mathrm{GeV}\,.
\end{aligned}
$$

compared to world average:
80.385 ± 0.015 GeV
(difference of 1.6 σ)

New ATLAS measurement (2017): M_W = 80.370 +- 0.019 GeV

Other indirect determinations:

$$M_H = 93^{+25}_{-21}\,\mathrm{GeV}$$

direct value: 125.09 ± 0.24 GeV

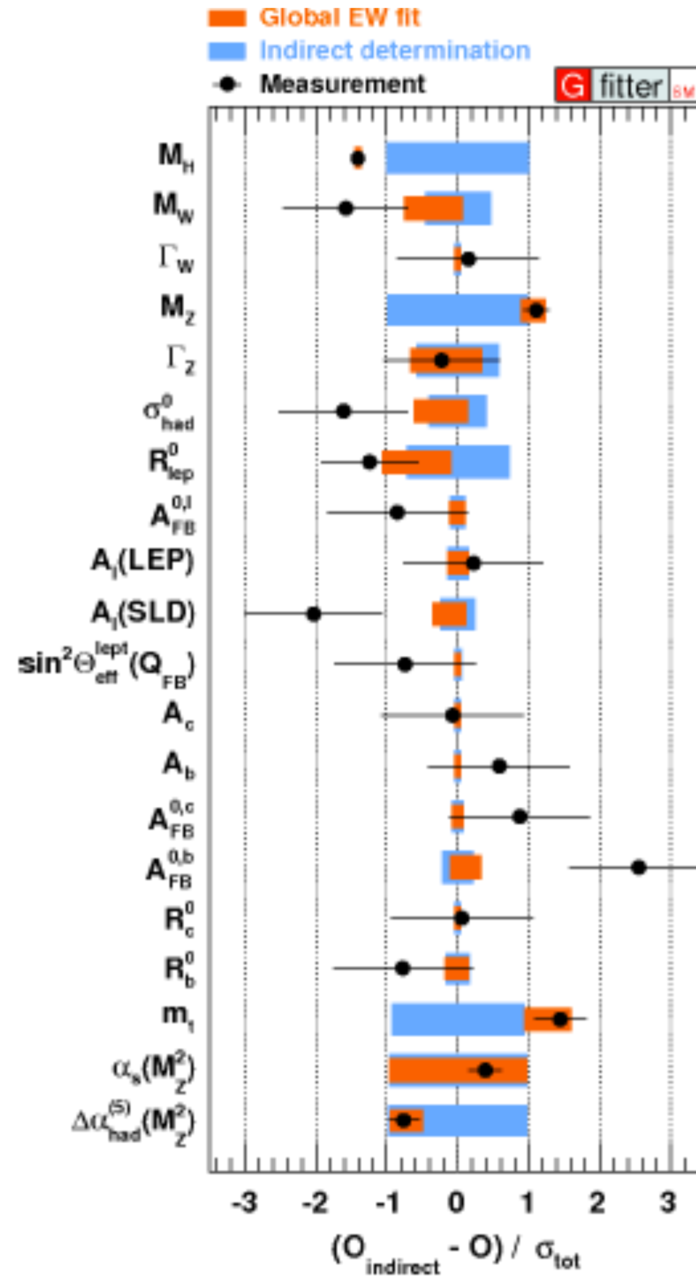
$$m_t = 177.0^{+2.3}_{-2.4}\,\mathrm{GeV}$$

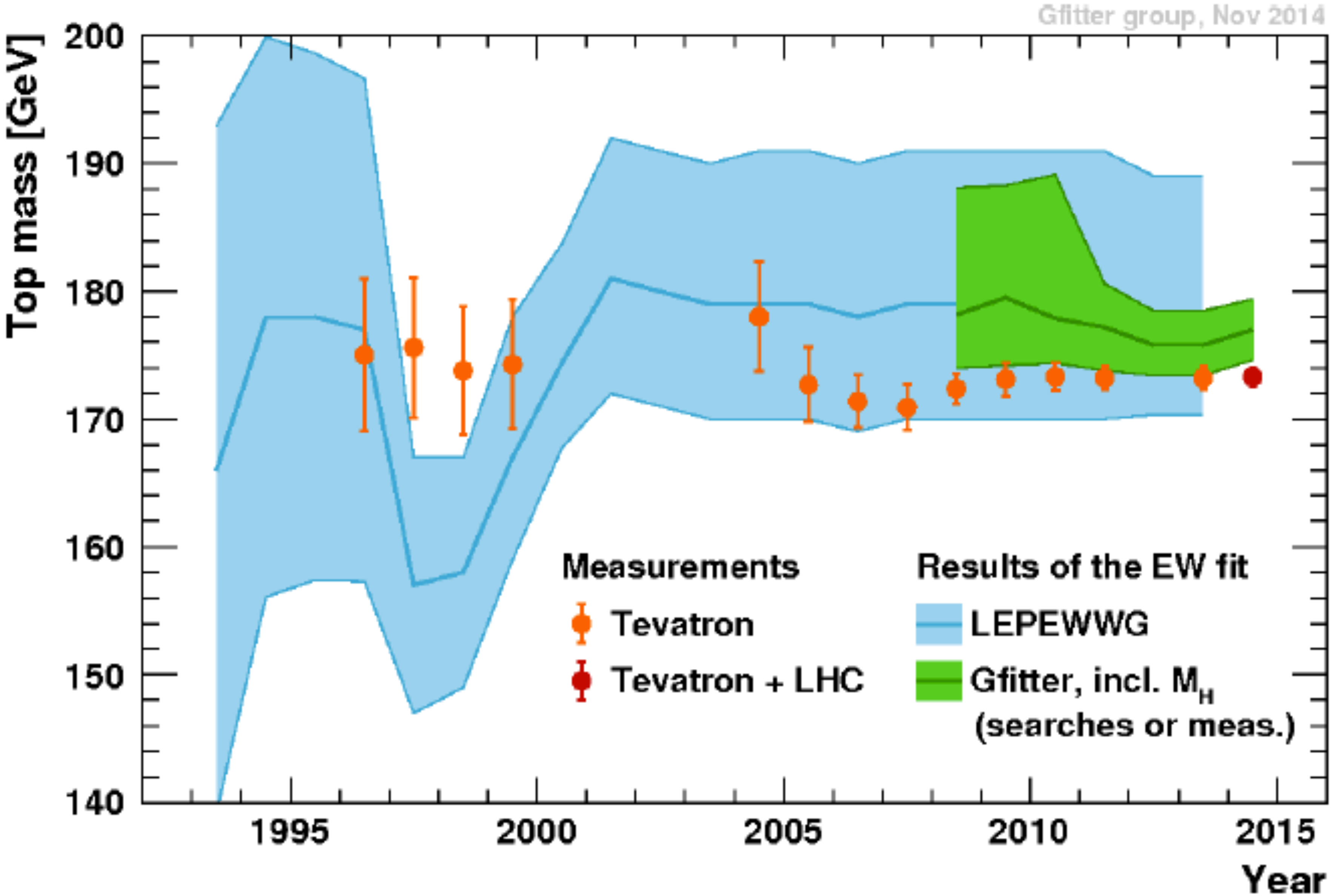
direct value: 173.34 ± 0.76 GeV

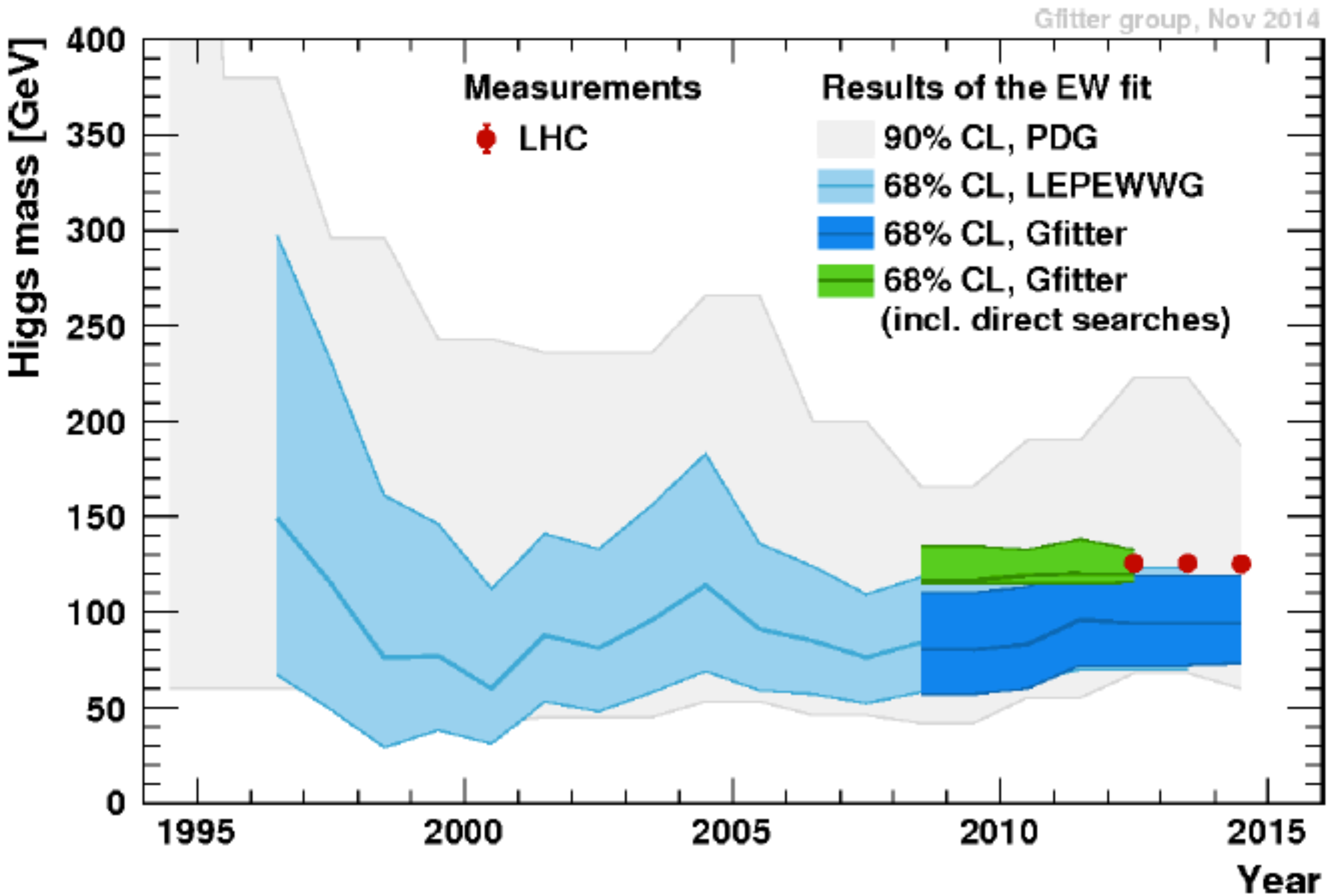
direct value from cross section:

173.68 ± 0.20 (stat) + 1.58 -0.97 (syst) GeV

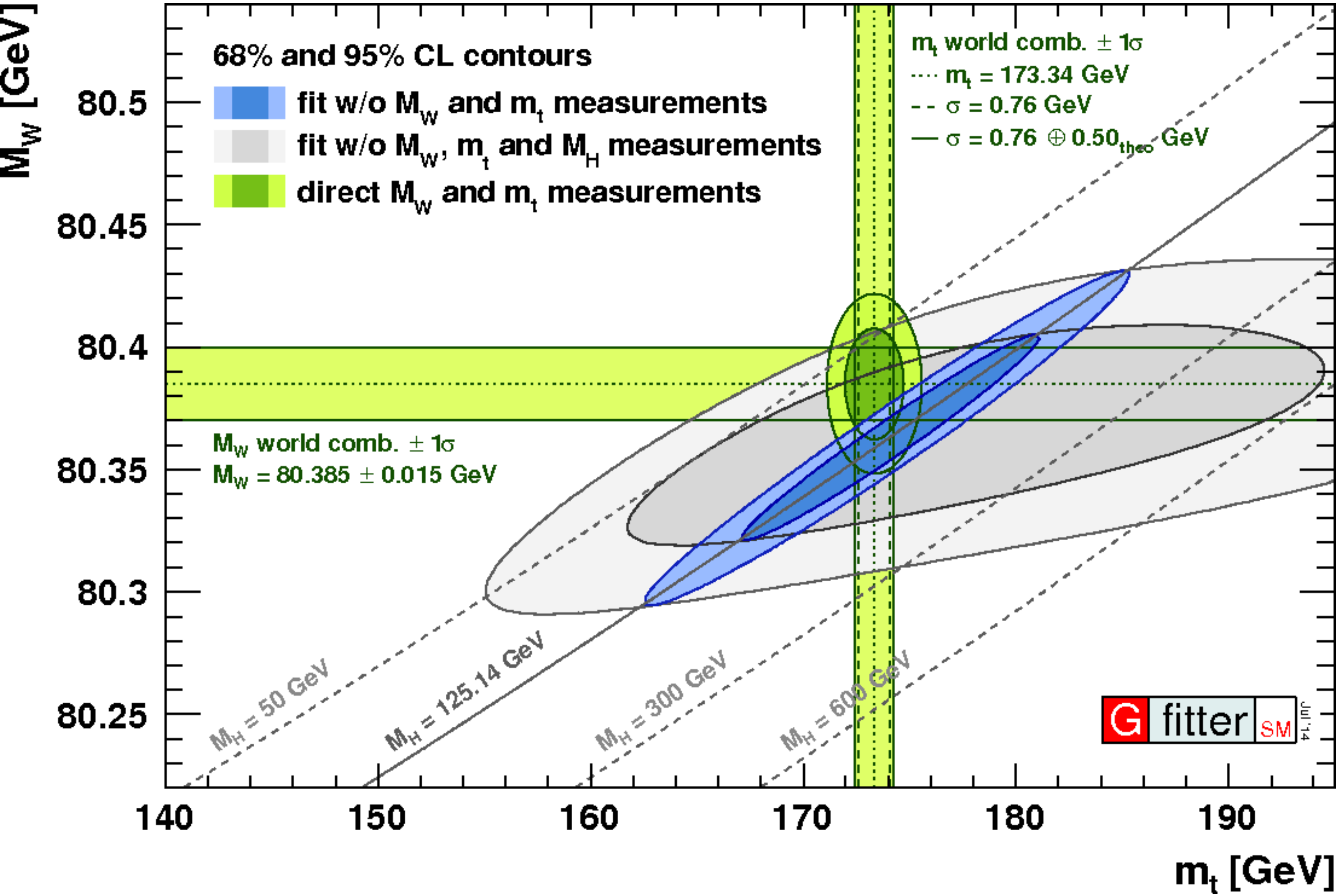
(arXiv:1603.06536)

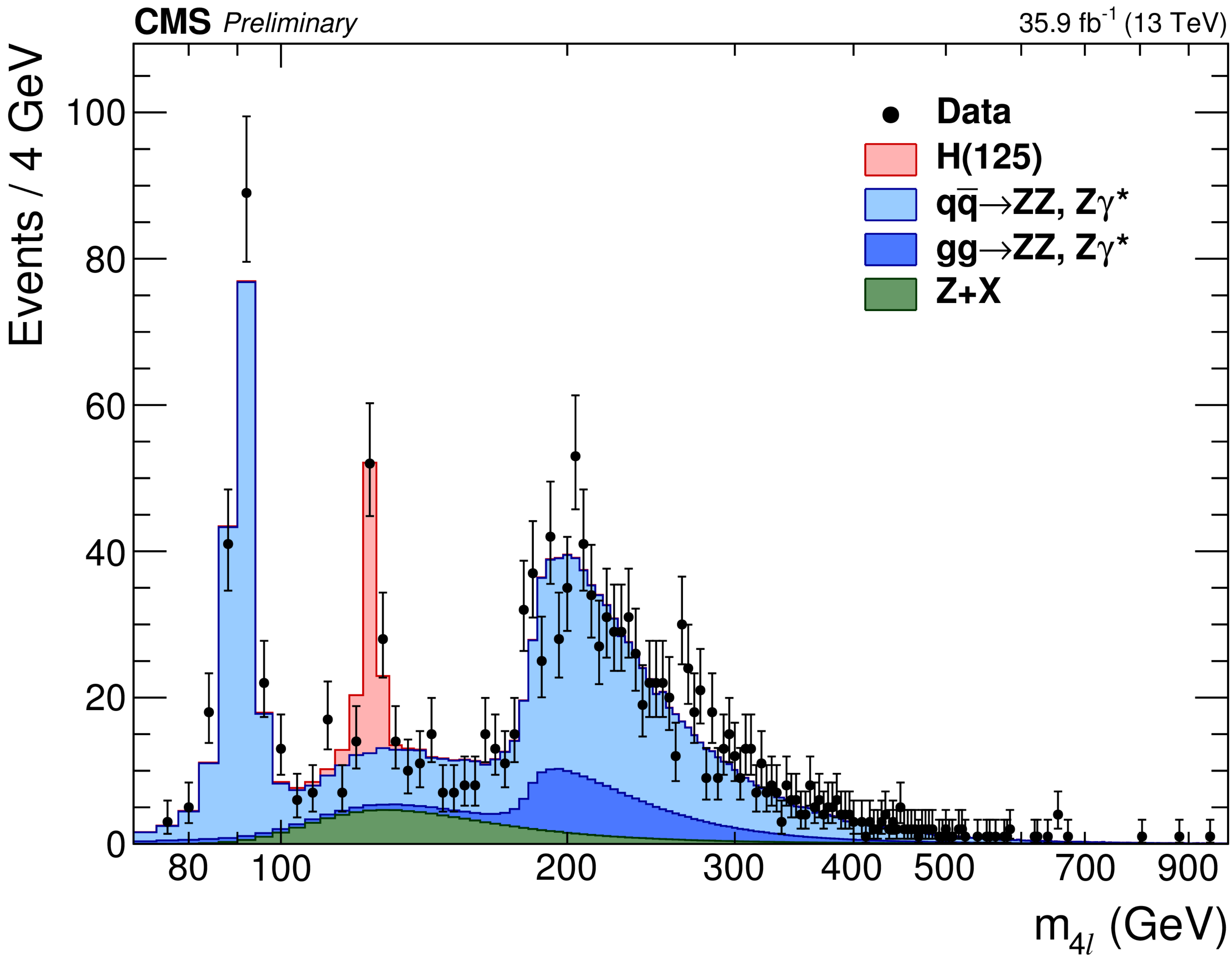



Gfitter group, Nov 2014
Top mass [GeV]
200
190
180
170
160
150
140
1995
2000
2005
2010
2015
Year
Measurements
Tevatron
Tevatron + LHC
Results of the EW fit
LEPEWWG
Gfitter, incl. M_H
(searches or meas.)

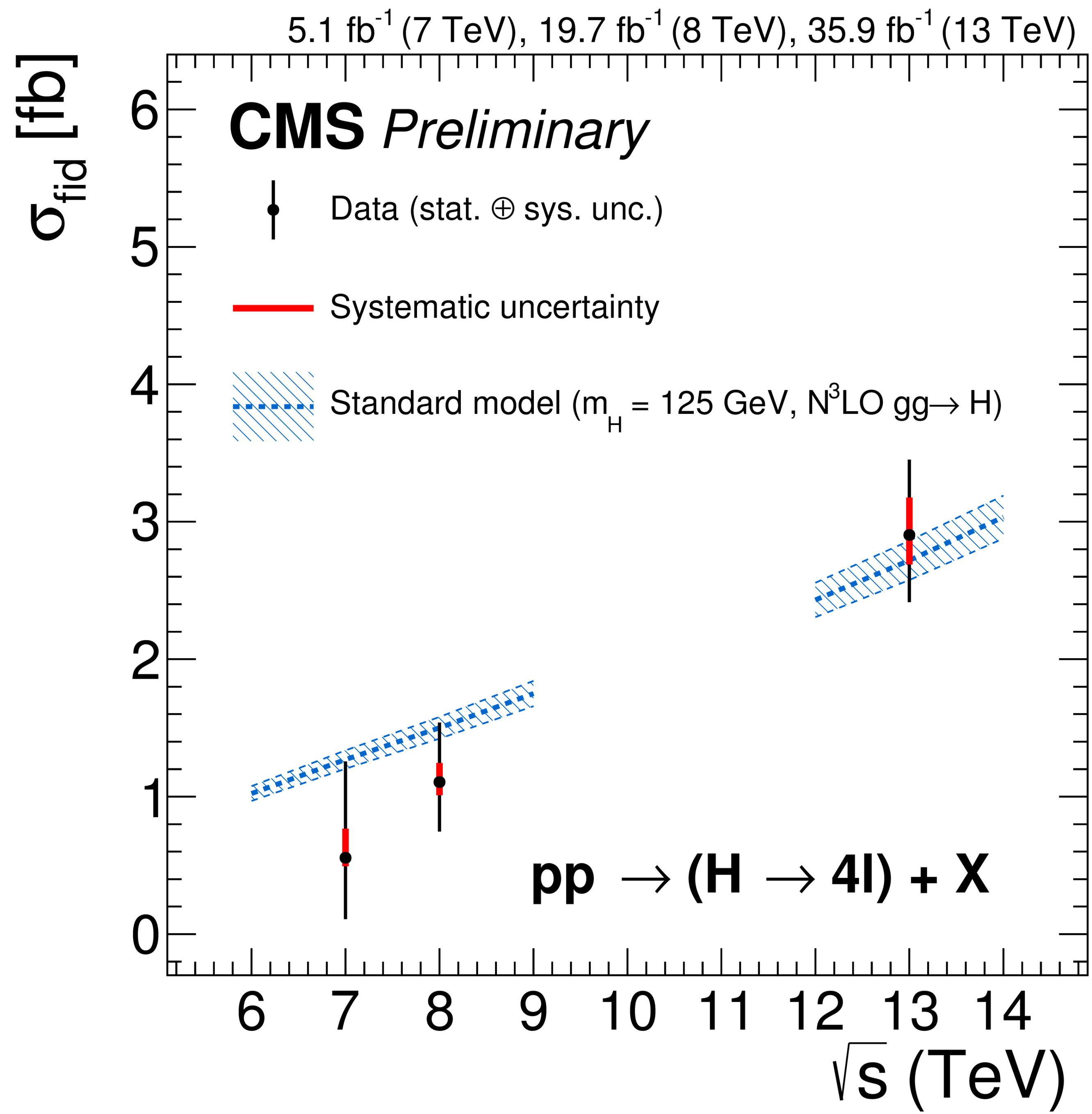


Gfitter group, Nov 2014
Higgs mass [GeV]
400
350
300
250
200
150
100
50
0
1995
2000
2005
2010
2015
Year
Measurements
LHC
Results of the EW fit
90% CL, PDG
68% CL, LEPEWWG
68% CL, Gfitter
68% CL, Gfitter
(incl. direct searches)

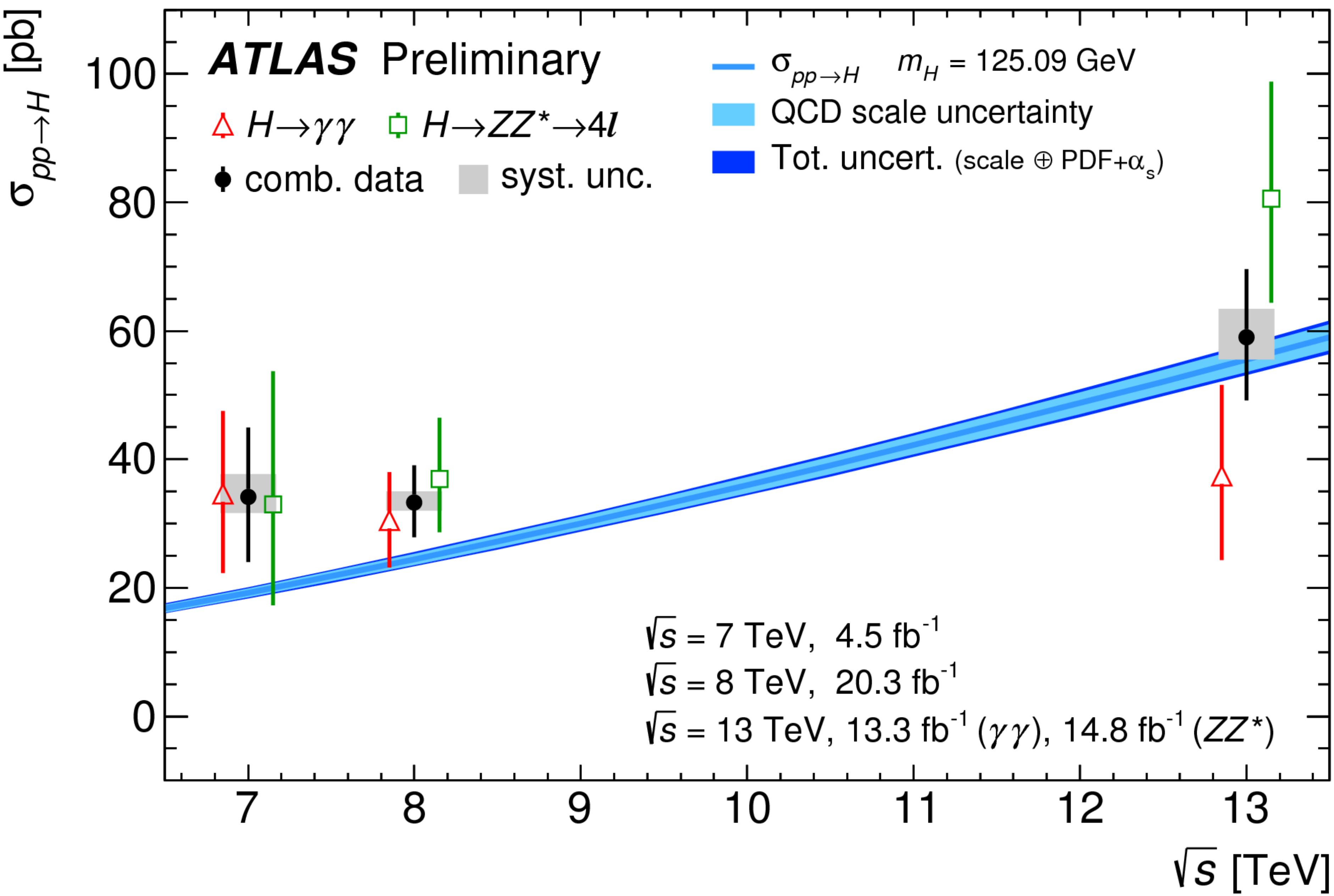

68% and 95% CL contours
fit w/o M_W and m_t measurements
fit w/o M_W, m_t and M_H measurements
direct M_W and m_t measurements
m_t world comb. ± 1σ
m_t = 173.34 GeV
σ = 0.76 GeV
σ = 0.76 ⊕ 0.50_{theo} GeV
M_W world comb. ± 1σ
M_W = 80.385 ± 0.015 GeV
M_H = 50 GeV
M_H = 125.14 GeV
M_H = 300 GeV
M_H = 600 GeV
G fitter SM
Jul '14
M_W [GeV]
m_t [GeV]
80.25
80.3
80.35
80.4
80.45
80.5
140
150
160
170
180
190



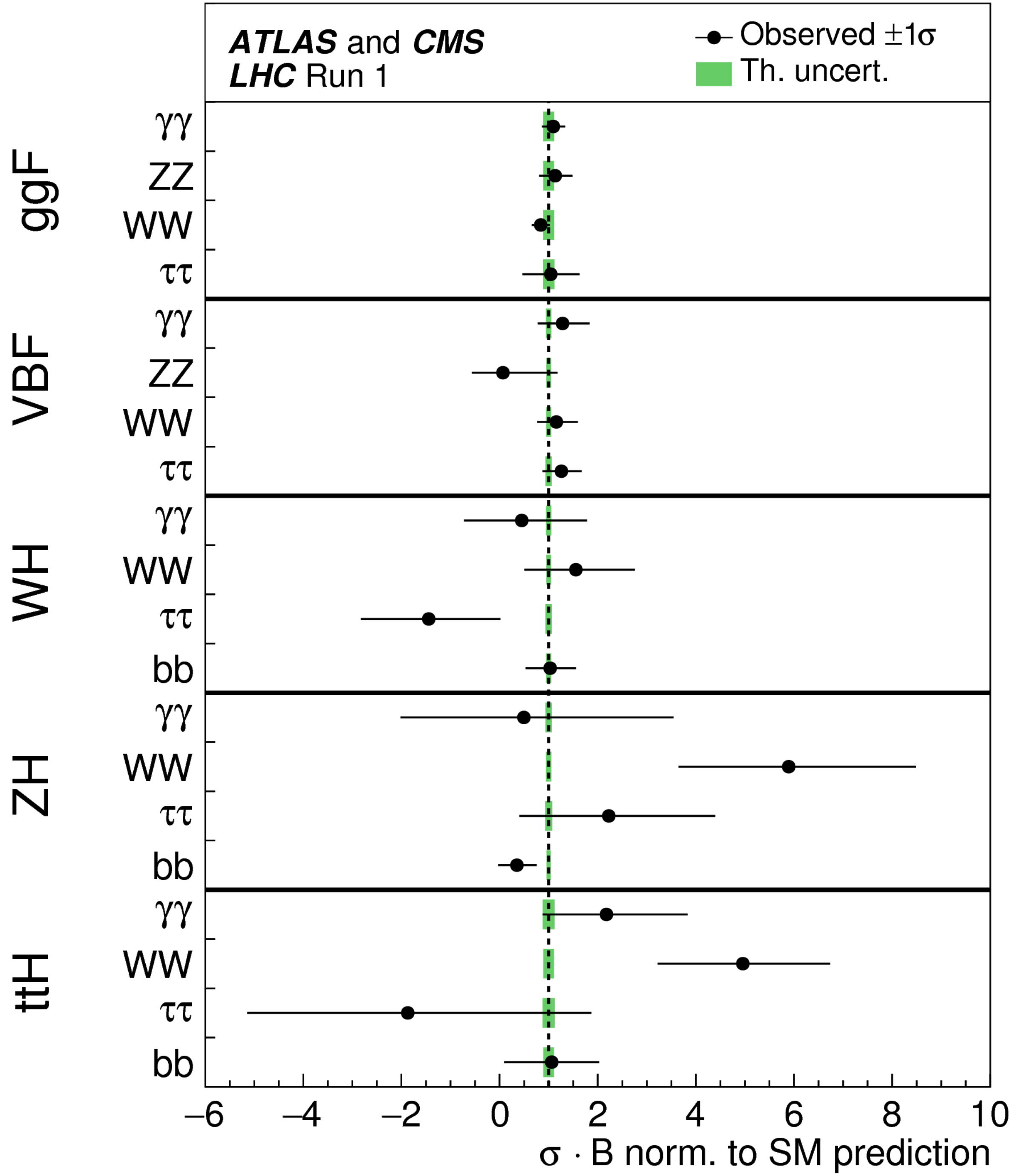
CMS Preliminary
35.9 fb-1 (13 TeV)
Events / 4 GeV
Data
H(125)
qq̄→ZZ, Zγ*
gg→ZZ, Zγ*
Z+X
m4l (GeV)
0
20
40
60
80
100
80
100
200
300
400
500
700
900



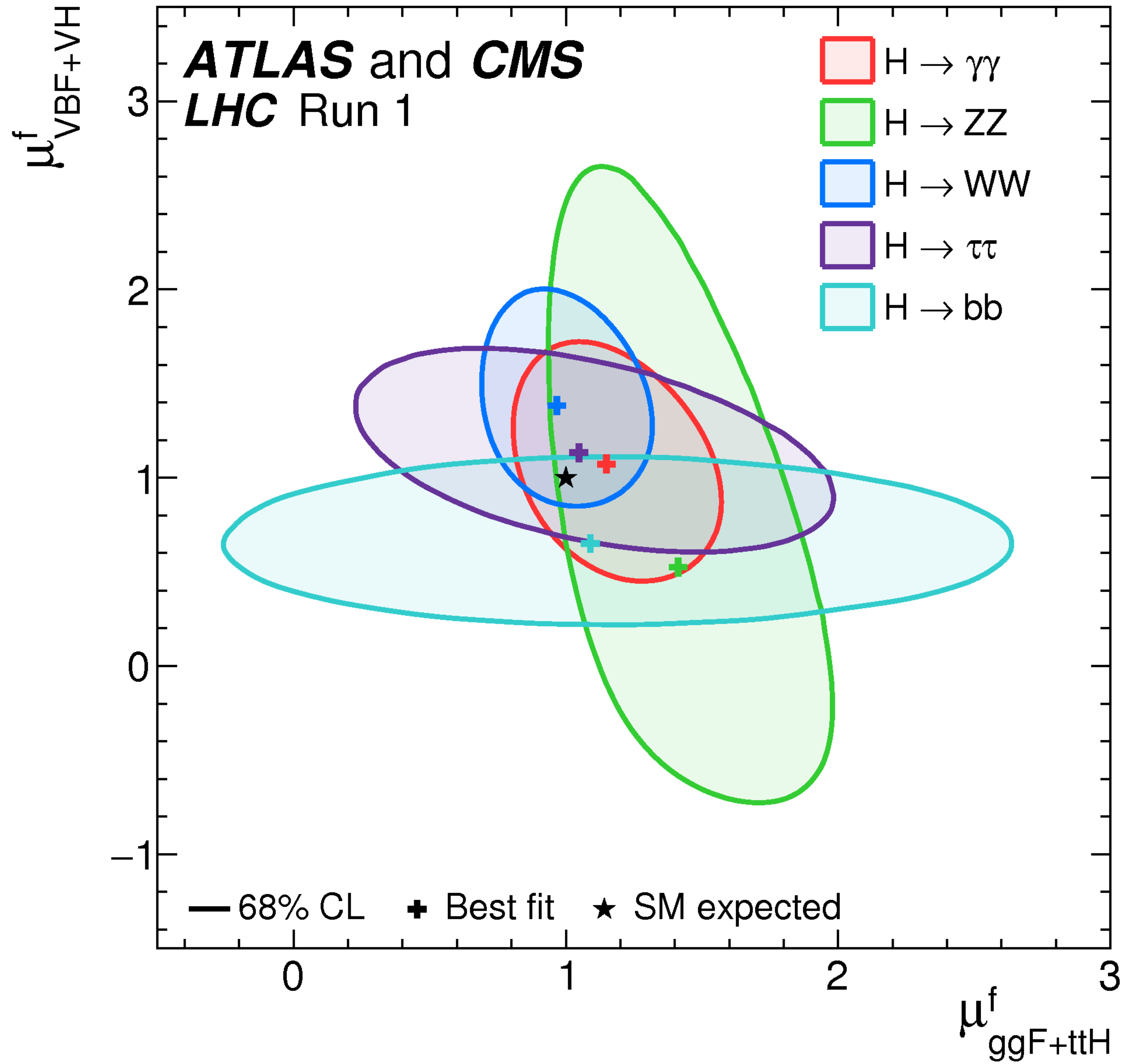
5.1 fb-1 (7 TeV), 19.7 fb-1 (8 TeV), 35.9 fb-1 (13 TeV)
CMS Preliminary
Data (stat. ⊕ sys. unc.)
Systematic uncertainty
Standard model (mH = 125 GeV, N3LO gg→ H)
pp → (H → 4l) + X
σfid [fb]
√s (TeV)
0
1
2
3
4
5
6
6
7
8
9
10
11
12
13
14



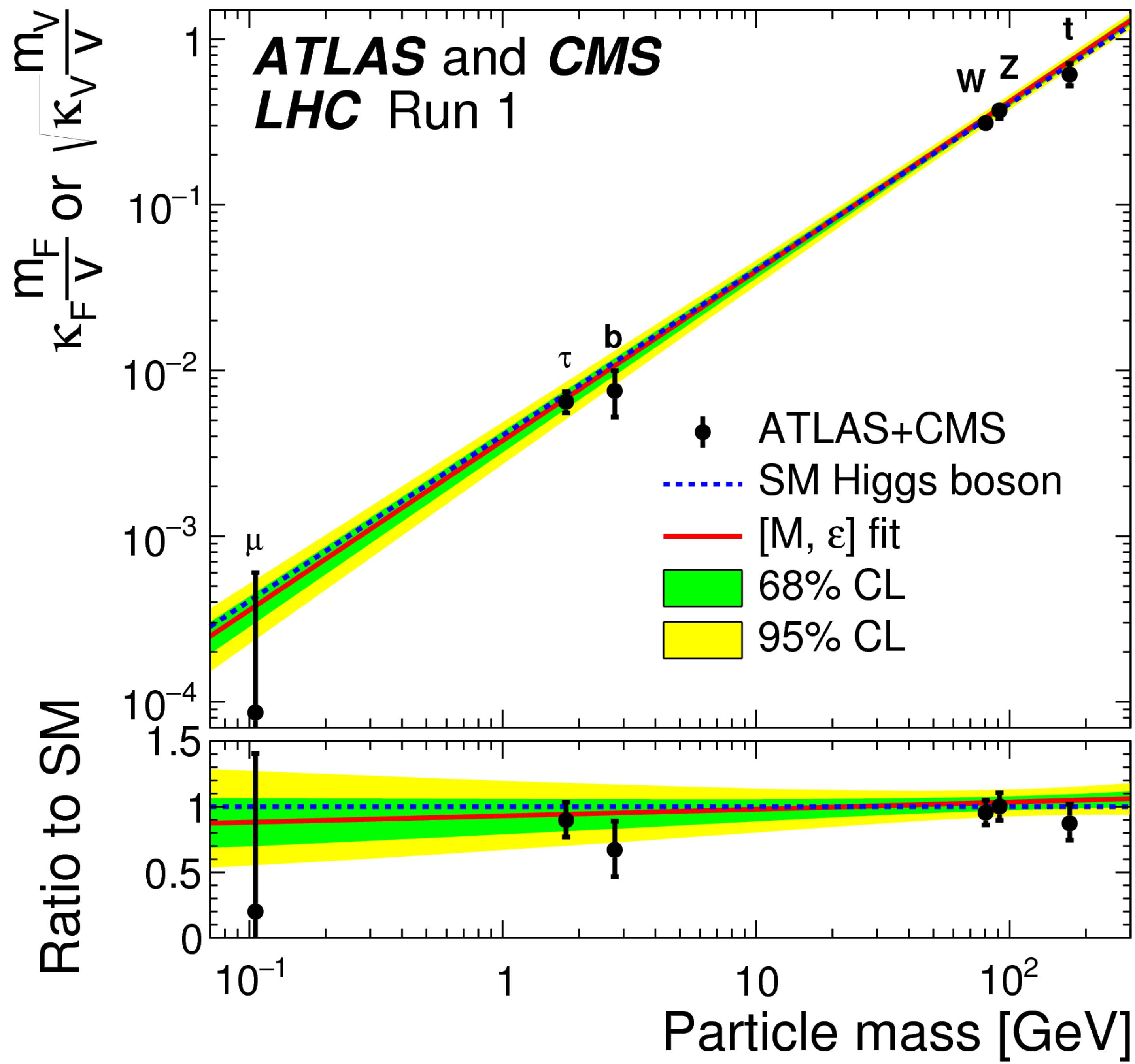
ATLAS Preliminary
$H\rightarrow\gamma\gamma$
$H\rightarrow ZZ^*\rightarrow 4l$
comb. data
syst. unc.
$\sigma_{pp\rightarrow H}$ m_H = 125.09 GeV
QCD scale uncertainty
Tot. uncert. (scale ⊕ PDF+α_s)
$\sqrt{s}$ = 7 TeV, 4.5 fb^{-1}
$\sqrt{s}$ = 8 TeV, 20.3 fb^{-1}
$\sqrt{s}$ = 13 TeV, 13.3 fb^{-1} ($\gamma\gamma$), 14.8 fb^{-1} (ZZ^*)
$\sigma_{pp\rightarrow H}$ [pb]
$\sqrt{s}$ [TeV]
0
20
40
60
80
100
7
8
9
10
11
12
13



ATLAS and CMS
LHC Run 1
Observed ±1σ
Th. uncert.
ggF
VBF
WH
ZH
ttH
γγ
ZZ
WW
ττ
bb
−6
−4
−2
0
2
4
6
8
10
σ · B norm. to SM prediction



ATLAS and CMS
LHC Run 1
H → γγ
H → ZZ
H → WW
H → ττ
H → bb
68% CL
Best fit
SM expected
$\mu^f_{\mathrm{VBF+VH}}$
$\mu^f_{\mathrm{ggF+ttH}}$
3
2
1
0
−1
0
1
2
3

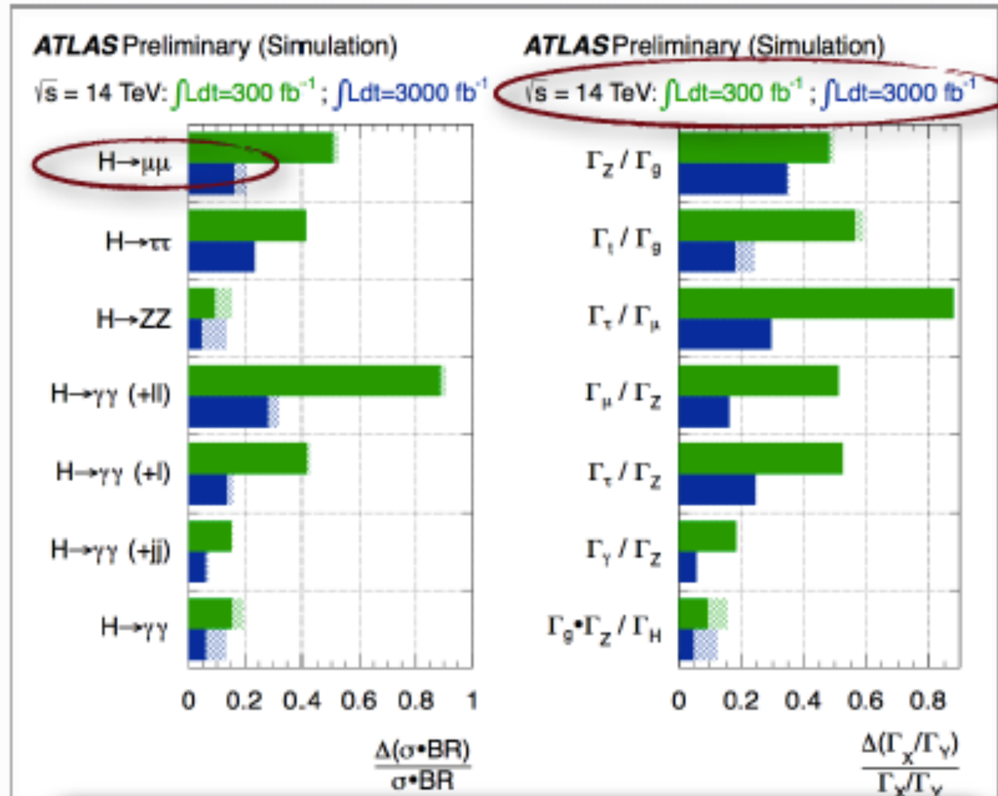


ATLAS and CMS
LHC Run 1
$\kappa_F \frac{m_F}{v}$ or $\sqrt{\kappa_V}\frac{m_V}{v}$
Ratio to SM
Particle mass [GeV]
ATLAS+CMS
SM Higgs boson
[M, ε] fit
68% CL
95% CL
μ
τ
b
W
Z
t

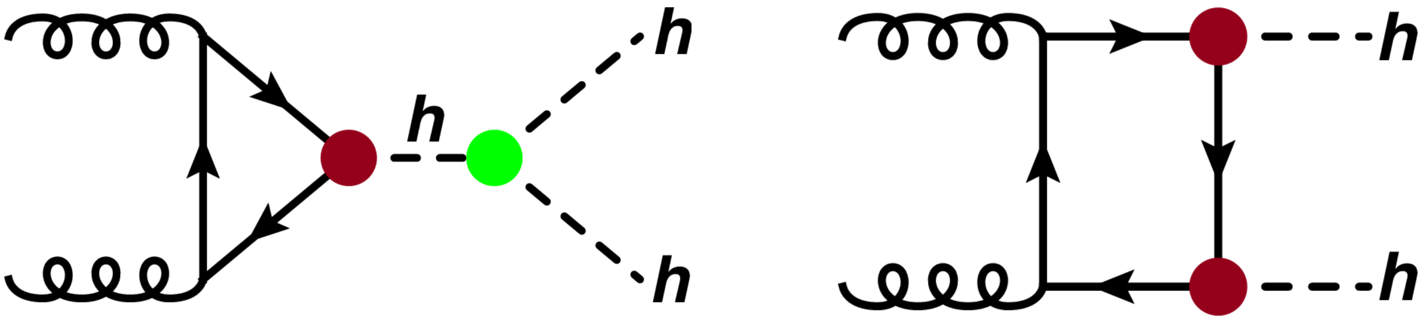
the shopping list

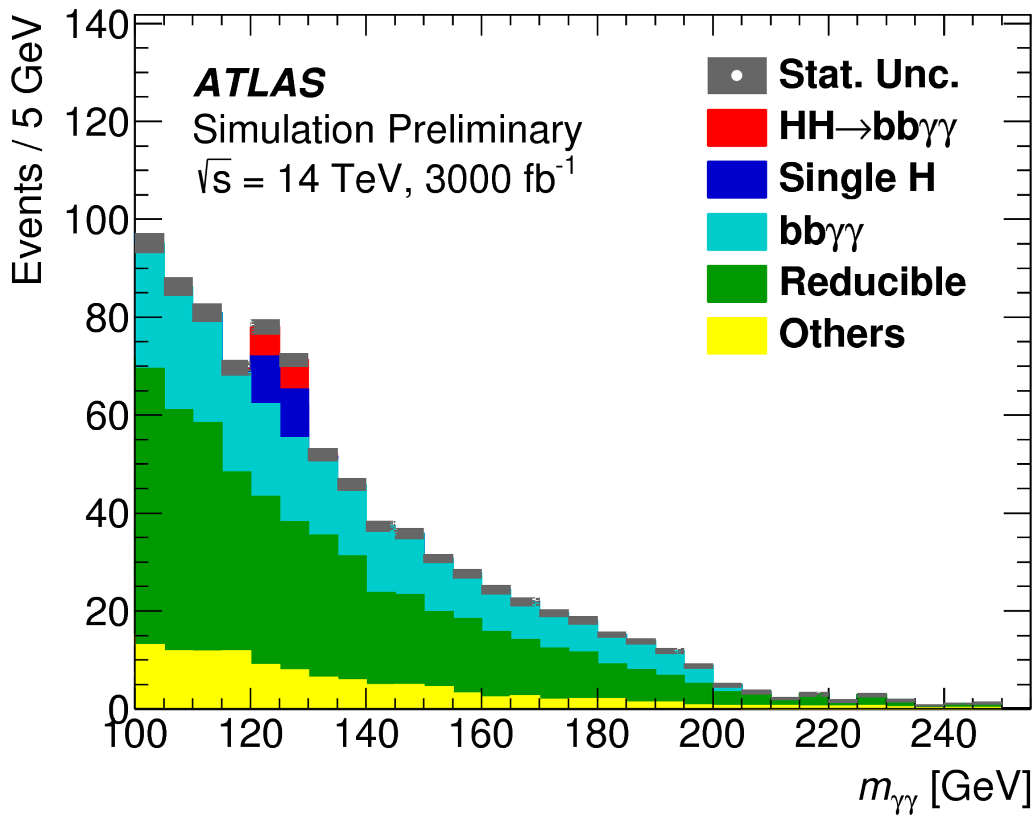
- mass
- spin and parity (J^P)
- CP (even, odd, or admixture?)
- couplings to vector bosons: is this boson related to EWSB, and how much does it contribute to restoring unitarity in $W_L W_L$ scattering
- couplings to fermions
  - is Yukawa interaction at work?
  - contribution to restoring unitarity?
- couplings proportional to mass ?
- is there only one such state, or more?
- elementary or composite?
- self-interaction

Scrutinizing the Higgs



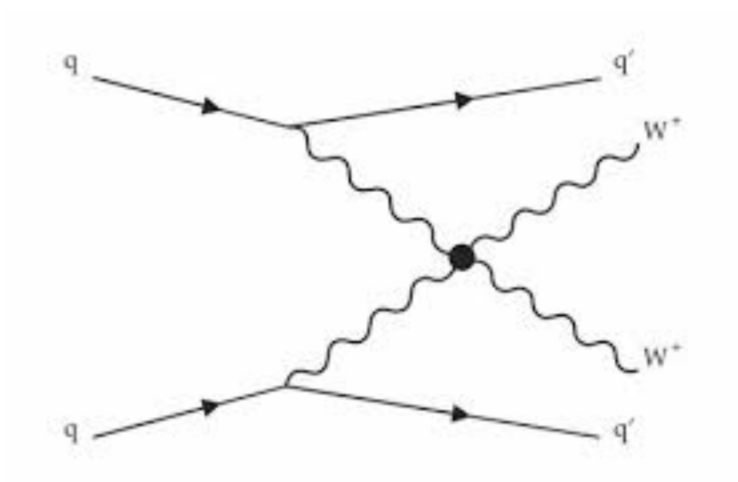
Higgs self-interaction: double Higgs production

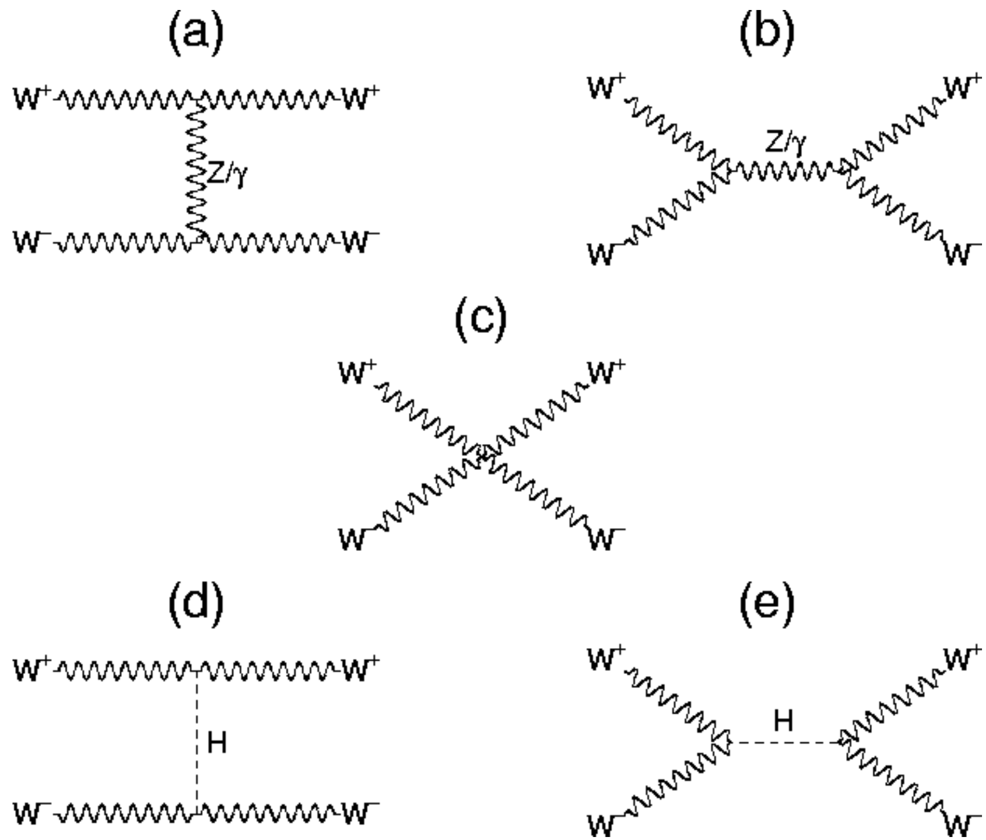




Note:
3000 fb^{-1}

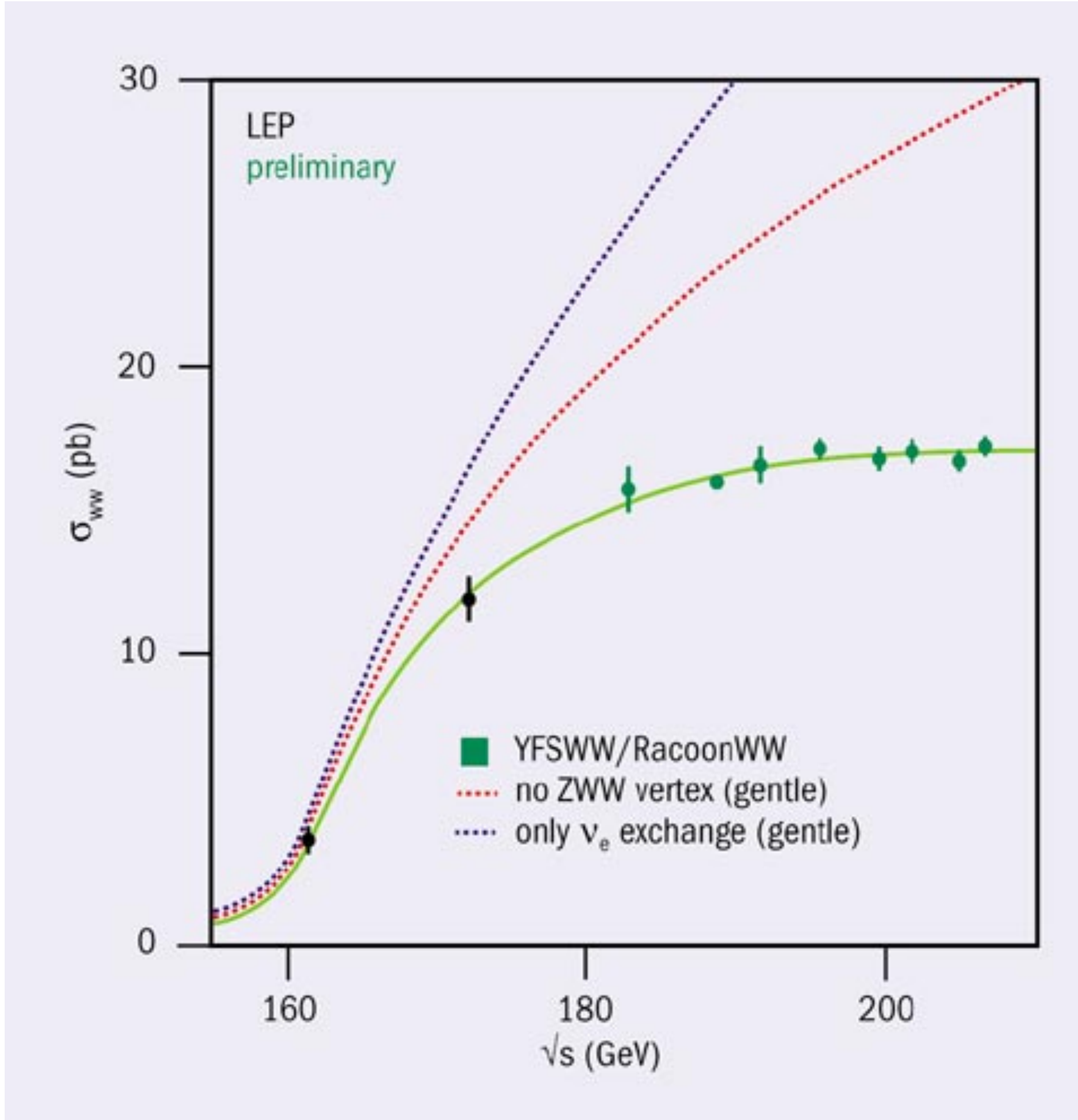
Higgs to keep WW scattering cross section finite

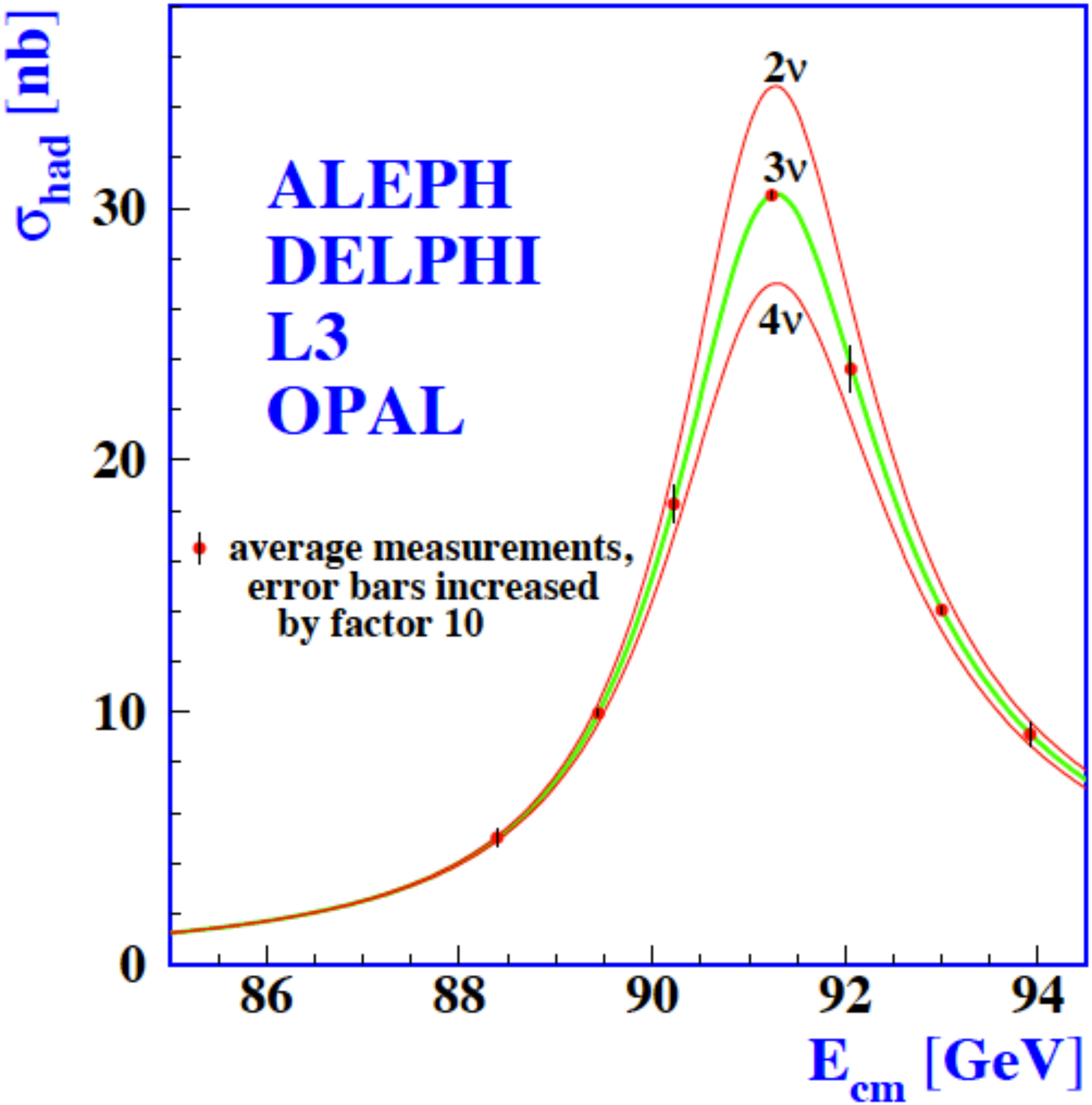




Also needs a very large data set: high-luminosity LHC

$e^+e^- \rightarrow W^+W^-$





σ_{had} [nb]
ALEPH
DELPHI
L3
OPAL
2ν
3ν
4ν
average measurements,
error bars increased
by factor 10
0
10
20
30
86
88
90
92
94
E_{cm} [GeV]