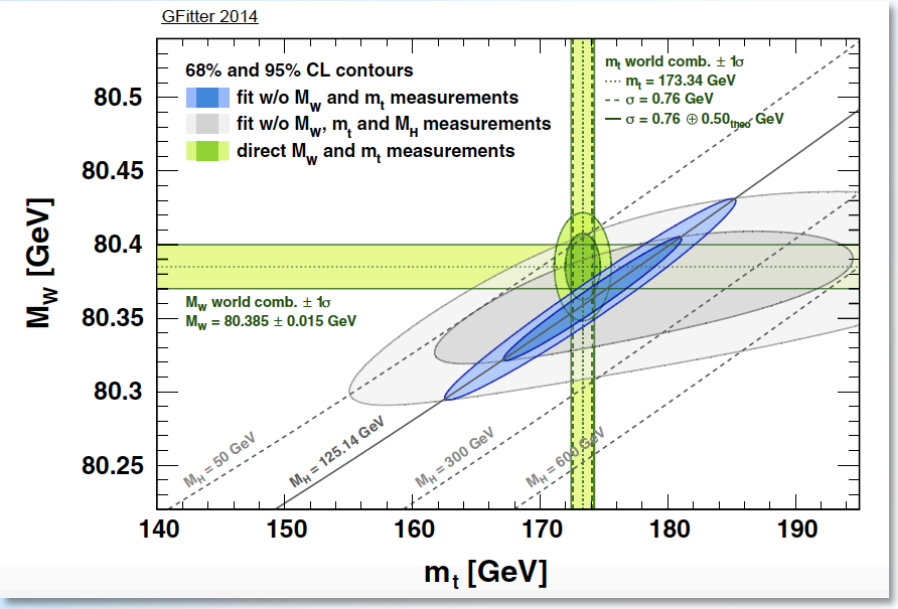
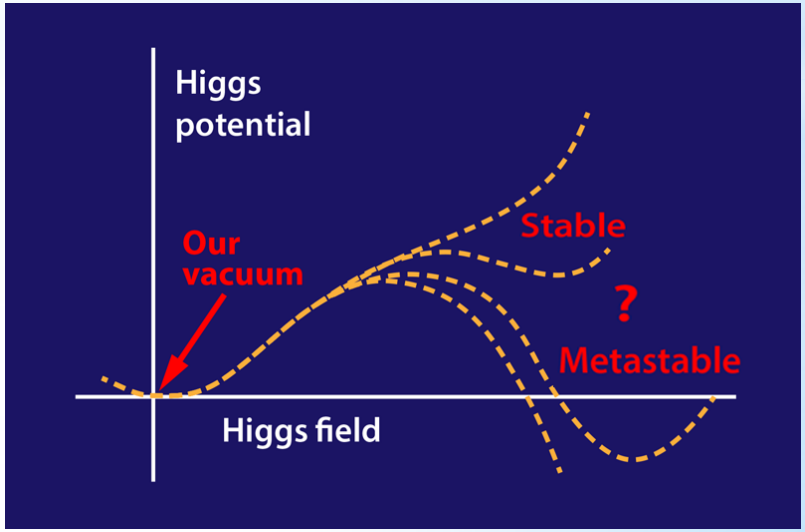
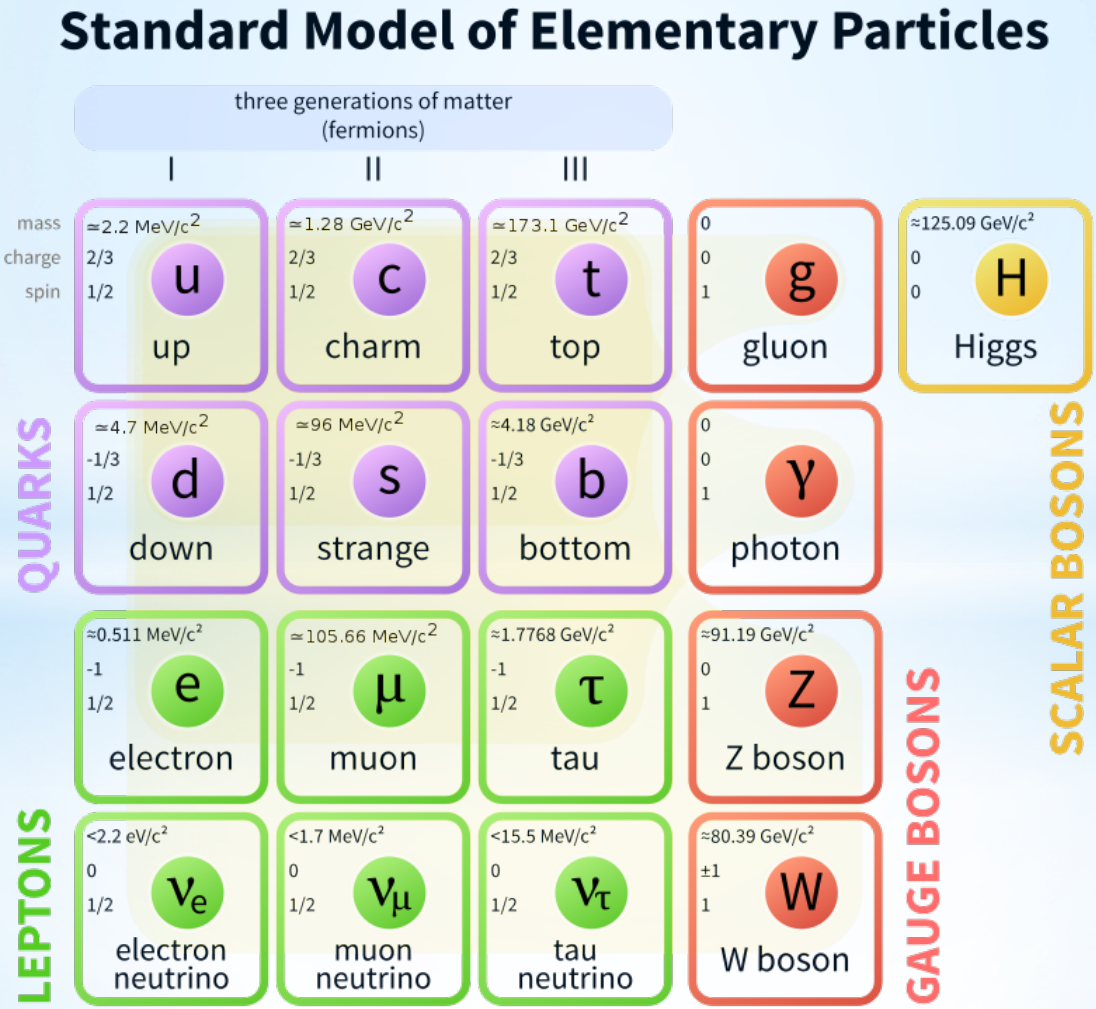
Electroweak precision measurements

Ulla Blumenschein, QMUL London





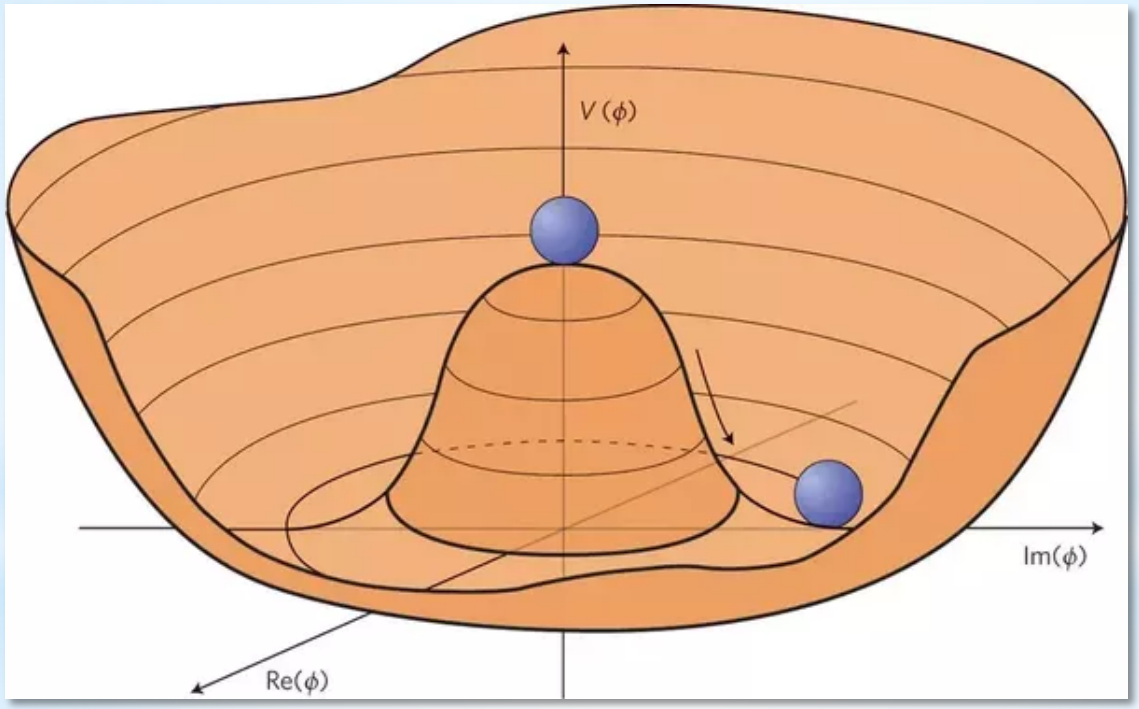
Measuring masses



Measuring masses

m(W)	= 80.385 ± 0.015 GeV	0.019 %
m(Z)	= 91.1876 ± 0.0021 GeV	0.0023 %
m(top)	= 172.44 ± 0.49 GeV	0.28 %
m(b)	= 4.18 ± 0.04 GeV	0.96 %
m(e)	= 0.5109989461 ± 0.0000000031 MeV	0.00000061 %
m(μ)	= 105.6583745 ± 0.0000024 MeV	0.0000023 %
m(tau	= 1776.86 ± 0.12 MeV	0.0067 %
m(pi+-)	= 139.57061 ± 0.00024 MeV	0.00017 %
m(pi0)	= 134.9770 ± 0.0005 MeV	0.00027 %
m(K+-)	= 493.677 ± 0.016 MeV	0.0032 %

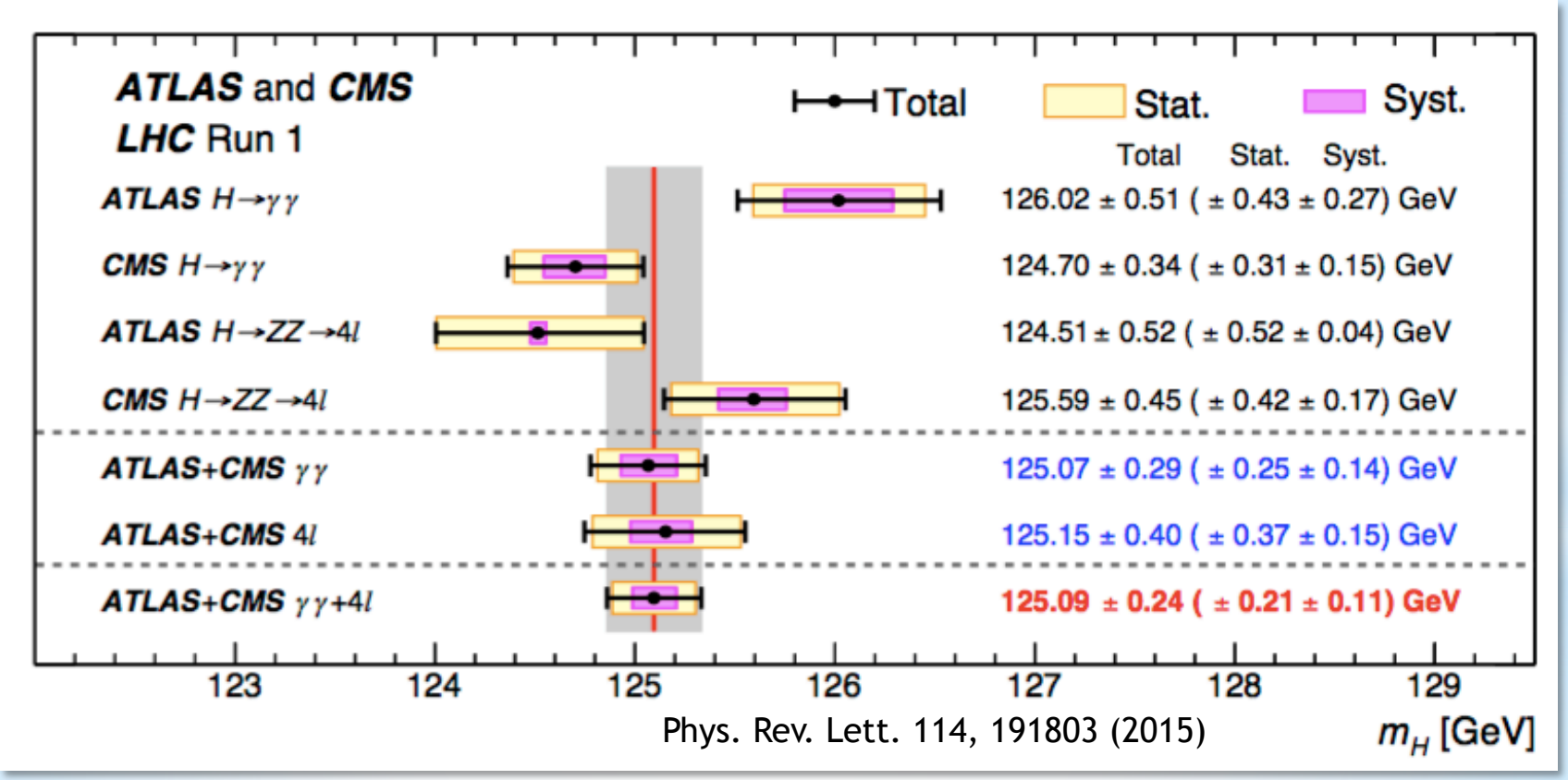
The Higgs potential



$$V_0 = -\frac{m_0^2}{2}|H_0|^2 + \lambda_0|H_0|^4$$

$$M_H^2 = 2\lambda v^2$$

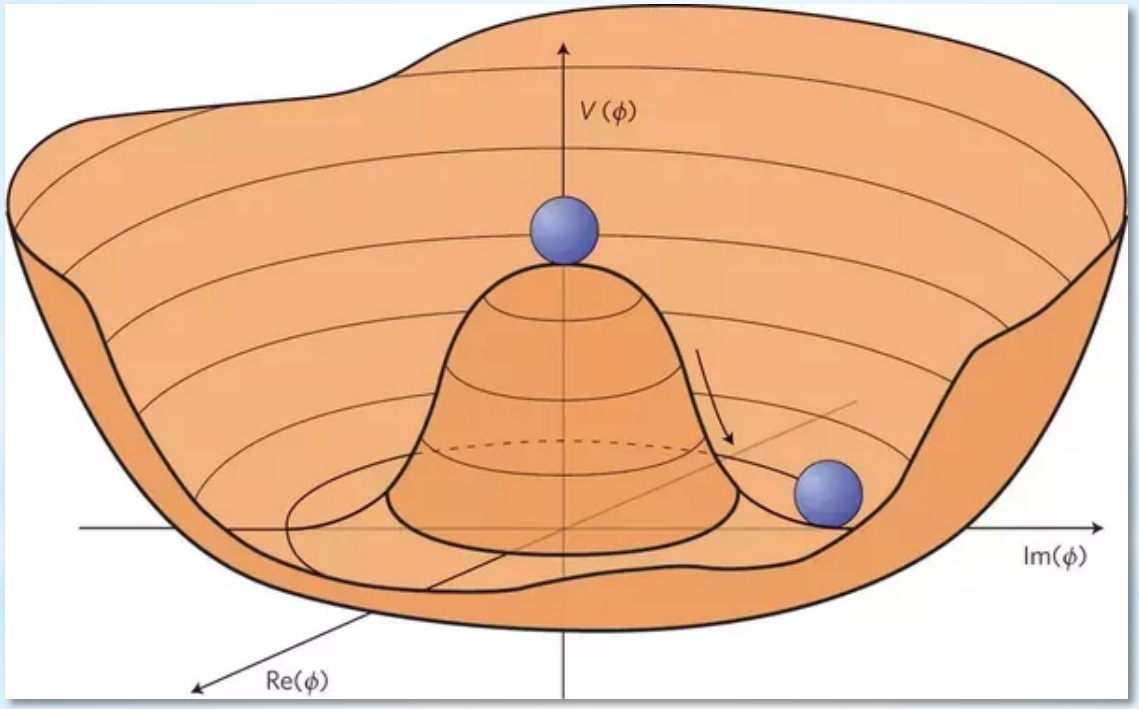
The Higgs mass



$$m_H = 125.09 \pm 0.24 \text{ GeV}$$
$$= 125.09 \pm 0.21\,(\text{stat.}) \pm 0.11\,(\text{syst.}) \text{ GeV}$$

Precision: 0.2%

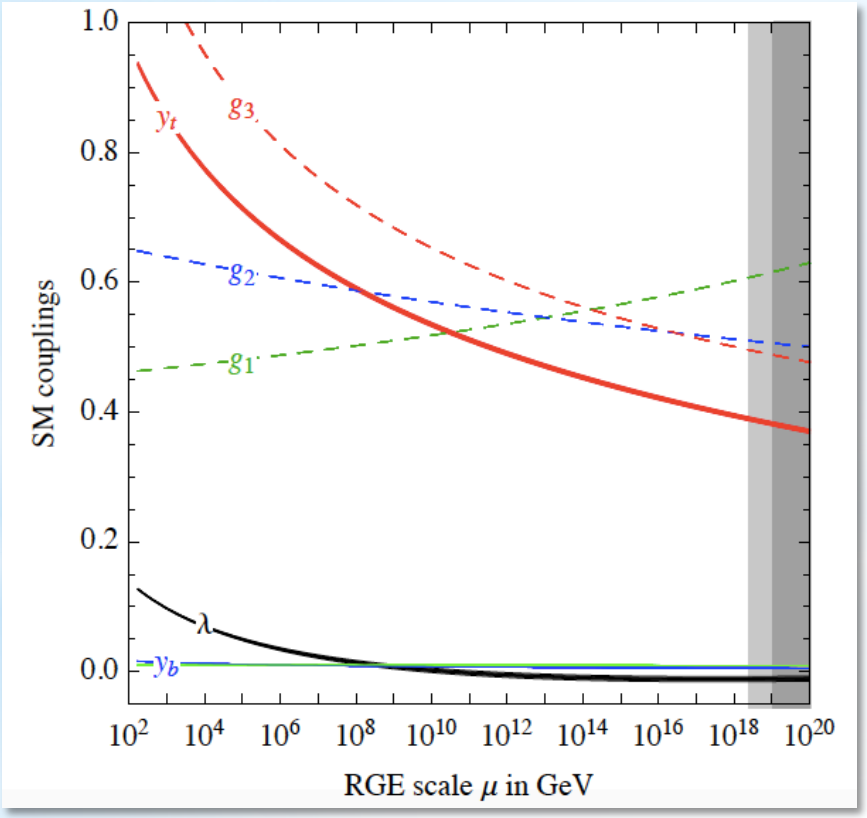
The Higgs potential

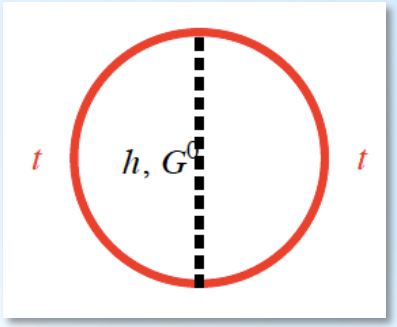


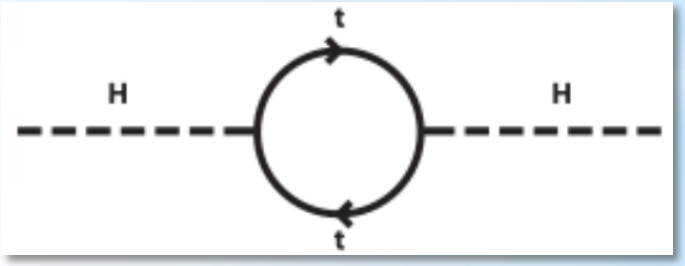
$$V_0 = -\frac{m_0^2}{2}|H_0|^2 + \lambda_0|H_0|^4$$

$$\lambda \doteq 0.13$$

RGE running of λ

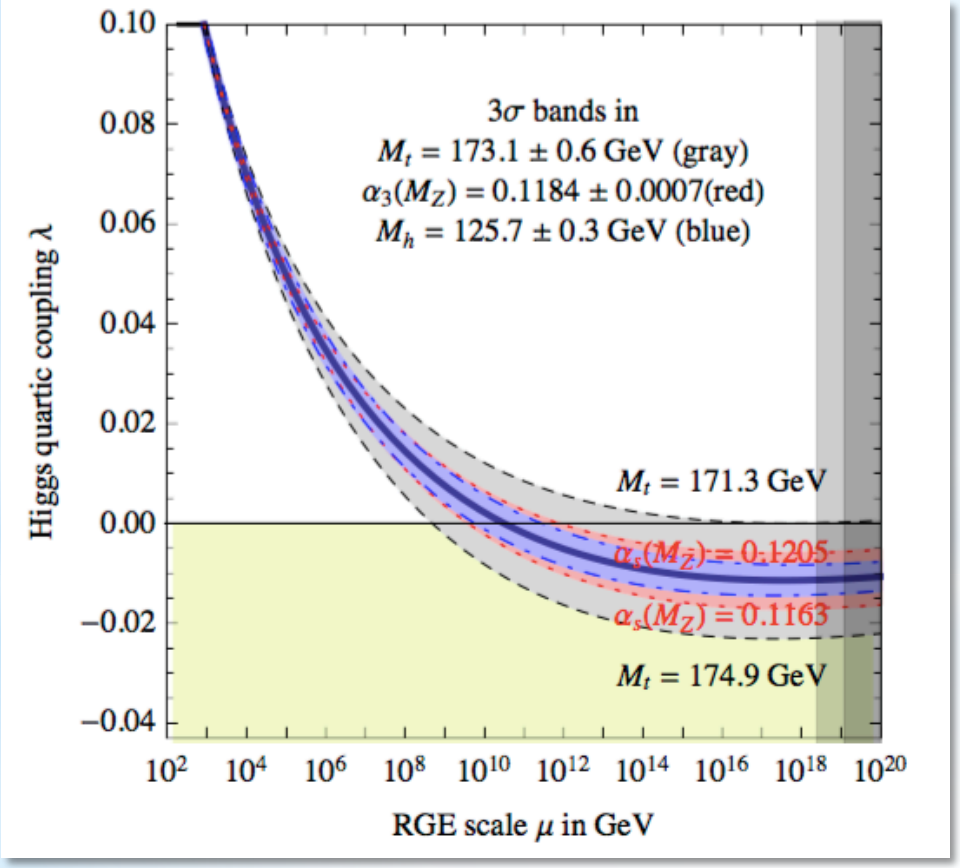


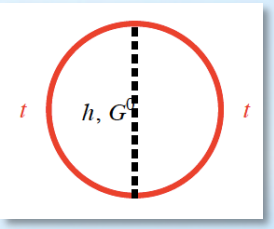


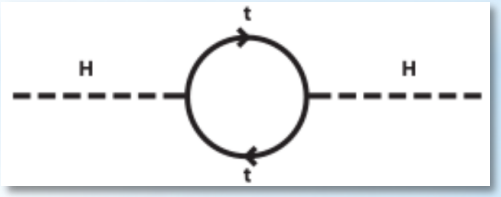


$$\lambda(H) = \lambda(M_H) + \frac{1}{4\pi^2}\left(-6\frac{m_t^4}{v^4} + 24\,\lambda(M_H)^2 + \ldots\right)\ln\left(\frac{H}{M_H}\right)$$

The Higgs potential

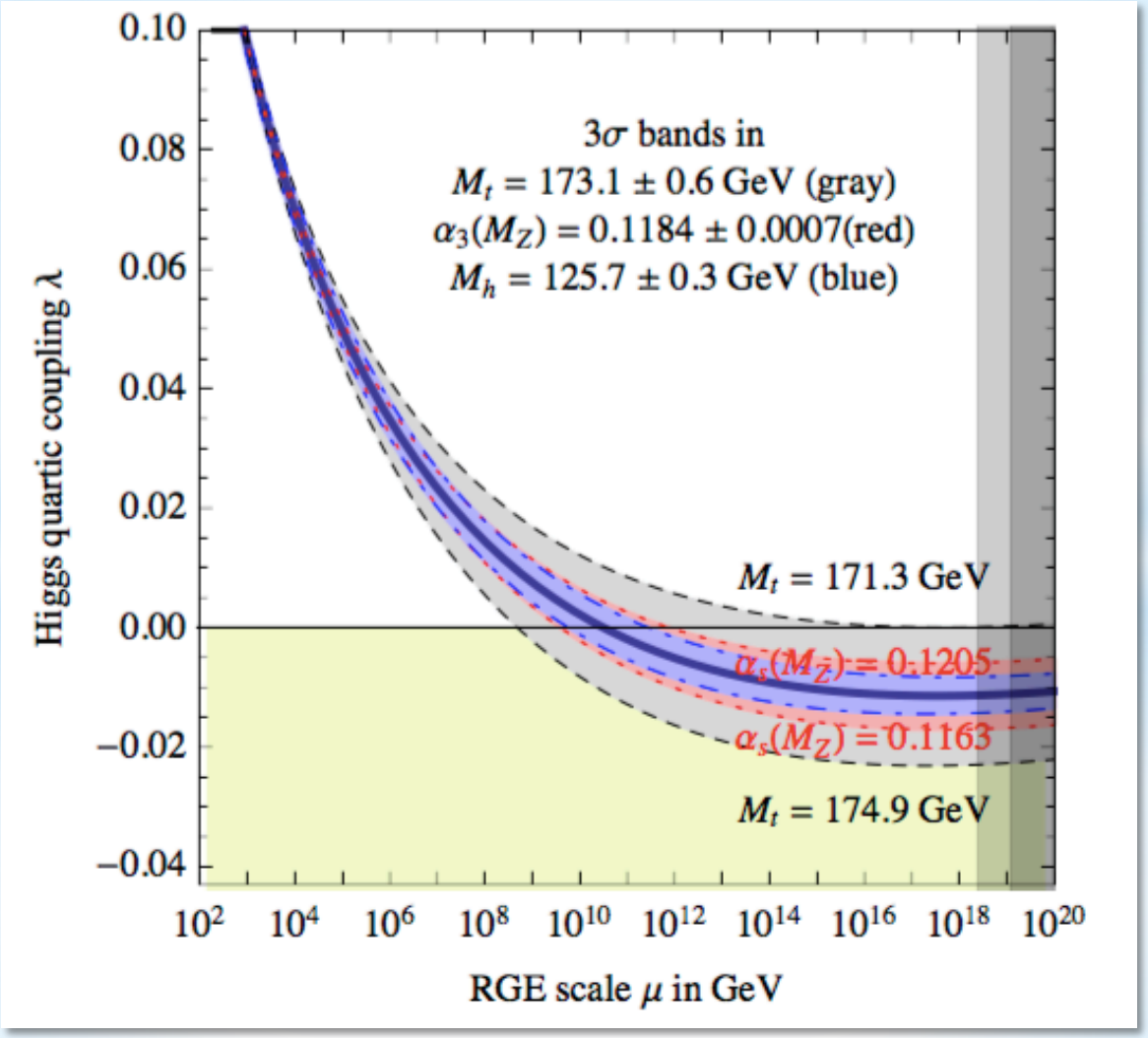






$$\lambda(H) \;=\; \lambda(M_H) + \frac{1}{4\pi^2}\left(-6\frac{m_t^4}{v^4} + 24\,\lambda(M_H)^2 + \ldots\right)\ln\left(\frac{H}{M_H}\right)$$

The Higgs potential



The Higgs potential

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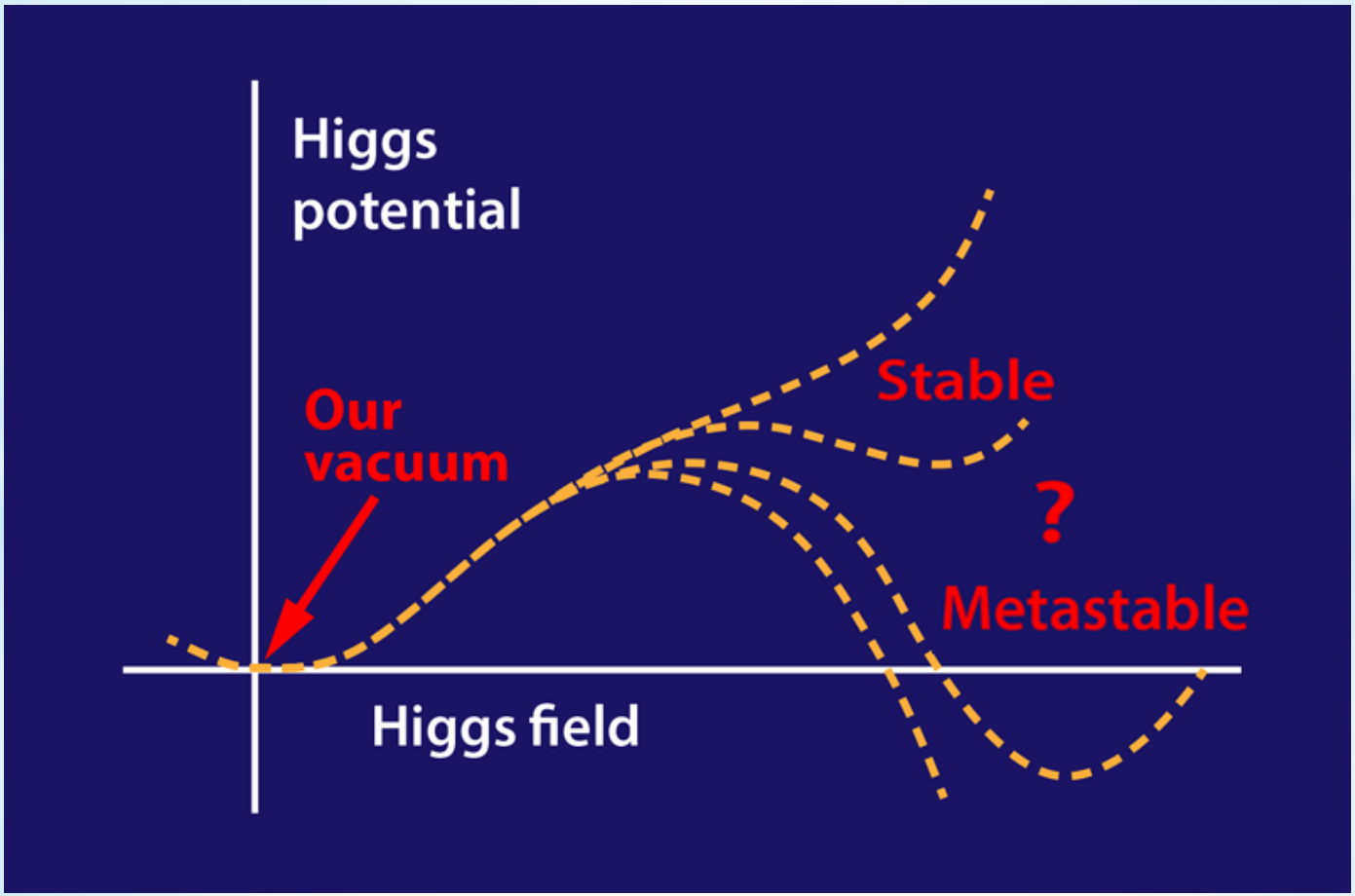

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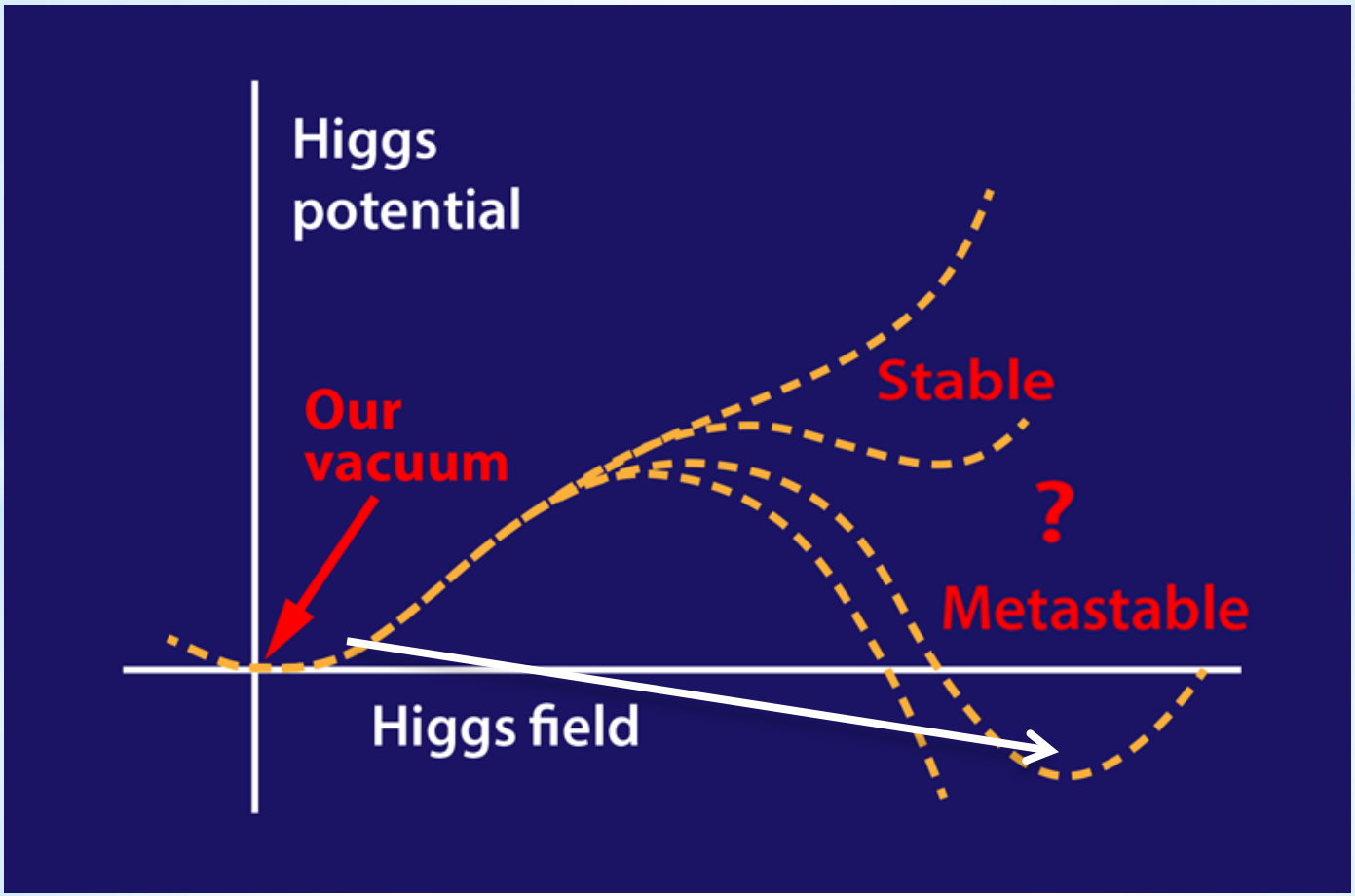

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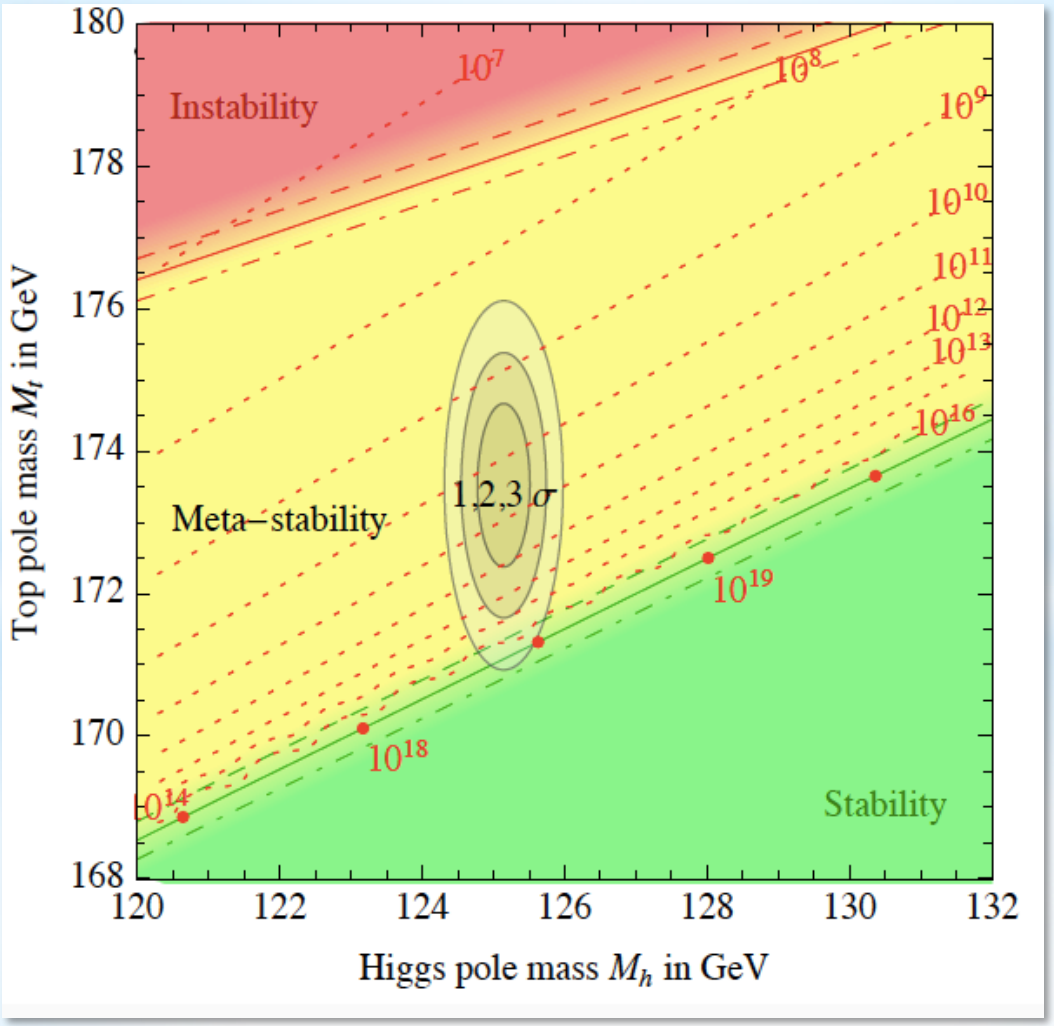
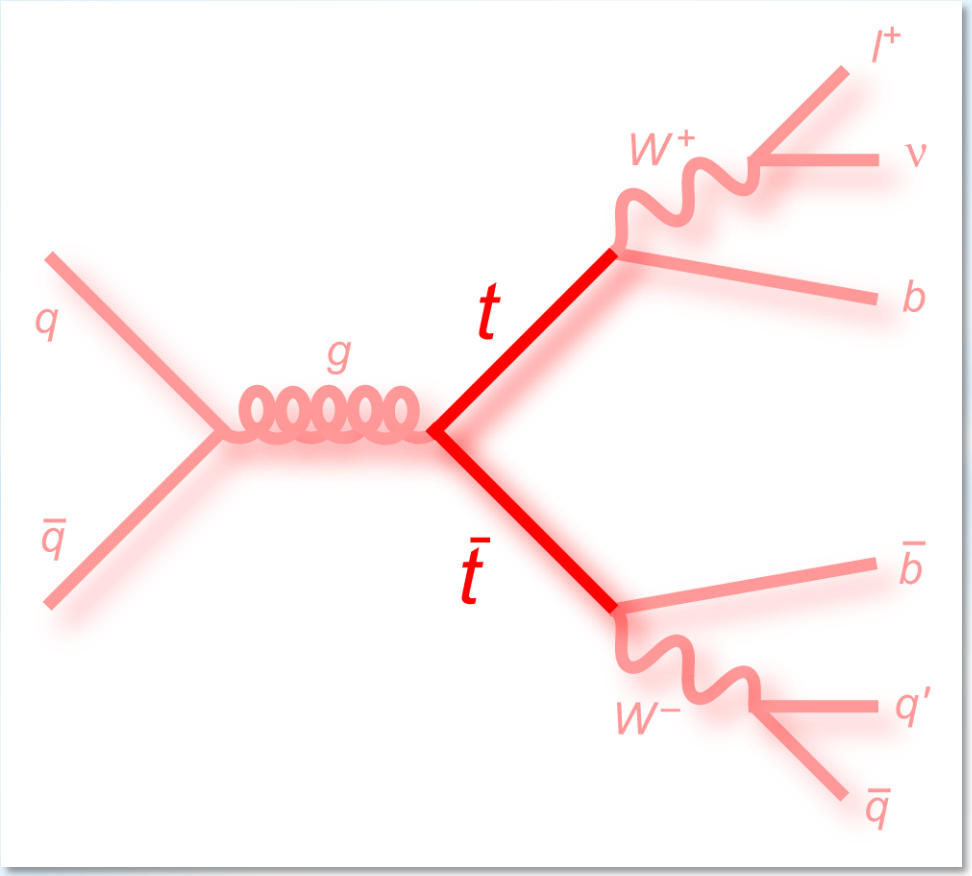


Top mass measurements

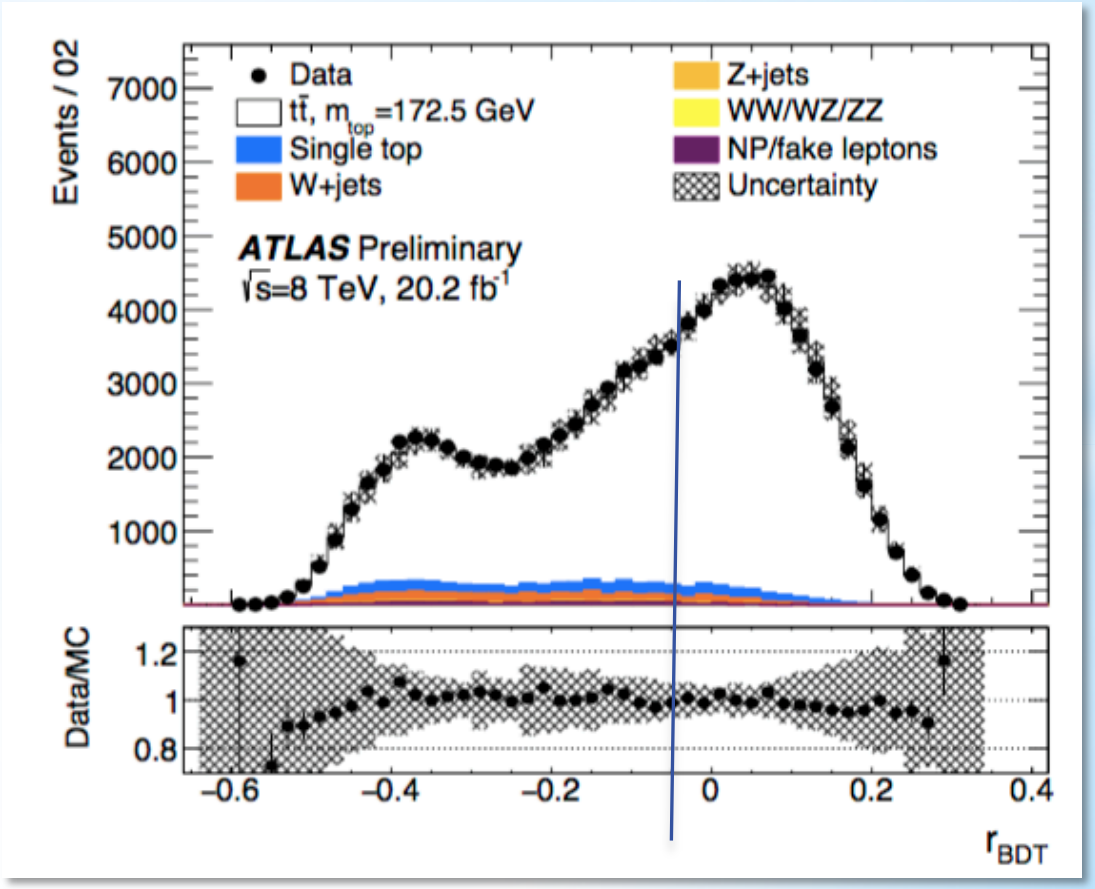
Example: ATLAS: lepton+jets channel, 8TeV data



Top mass measurements

Example: ATLAS: lepton+jets channel, 8TeV data

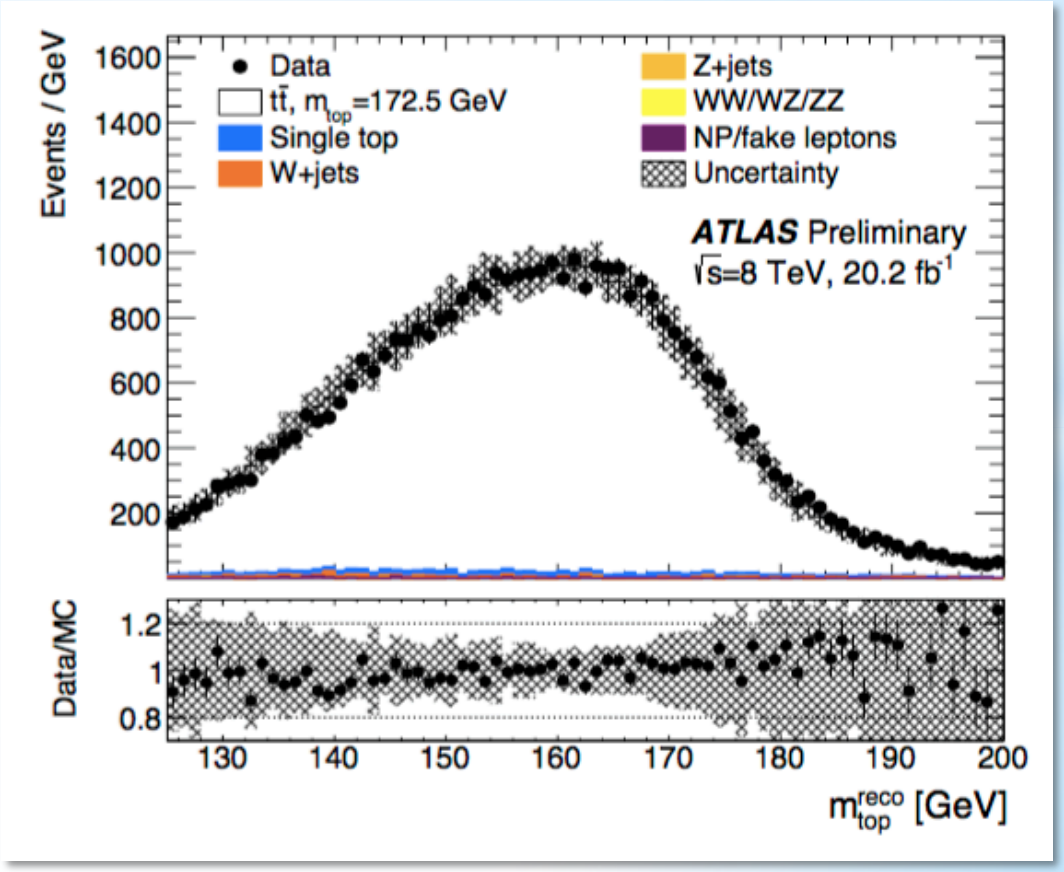
1) Preselection
2) Full reconstruction of the event
3) BDT to separate well-reconstructed events from wrongly matched events



Top mass measurements

Example: ATLAS: lepton+jets channel, 8TeV data

1) Preselection
2) Full reconstruction of the event
3) BDT to separate well-reconstructed events from wrongly matched events
4) Combined template fit of the top mass, the jet energy scale and the b-jet energy scale



Top mass measurements

Example: ATLAS: lepton+jets channel, 8TeV data

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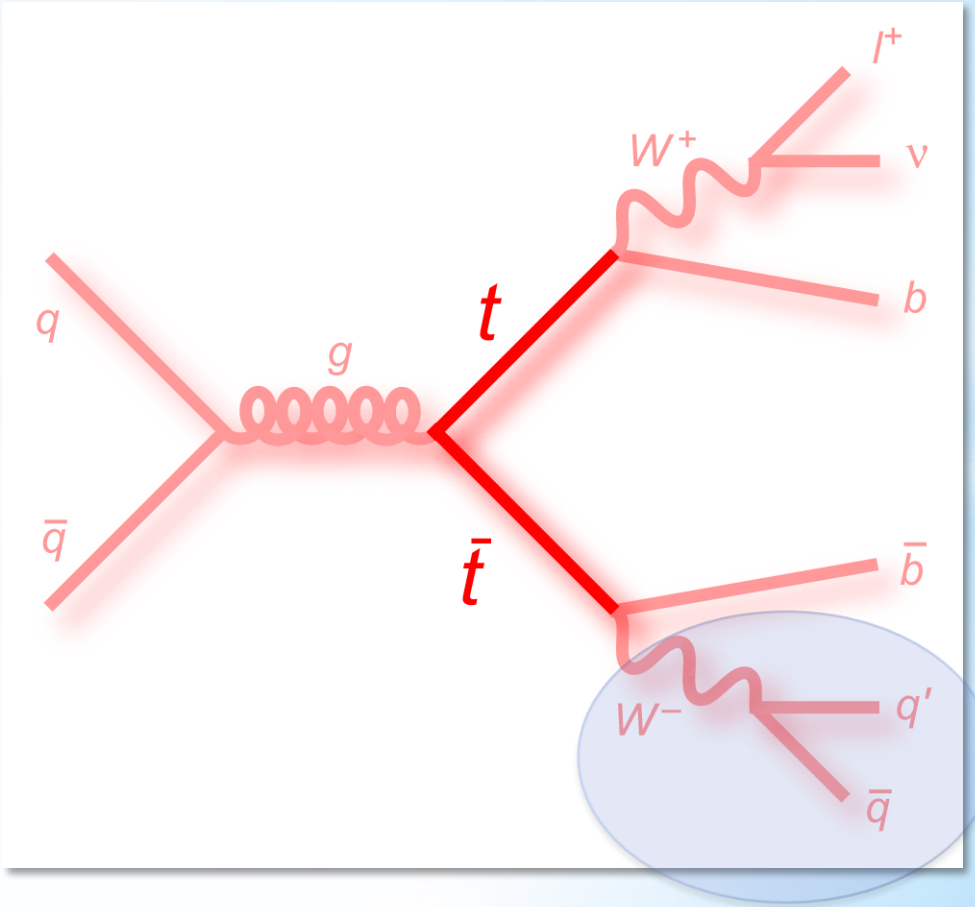
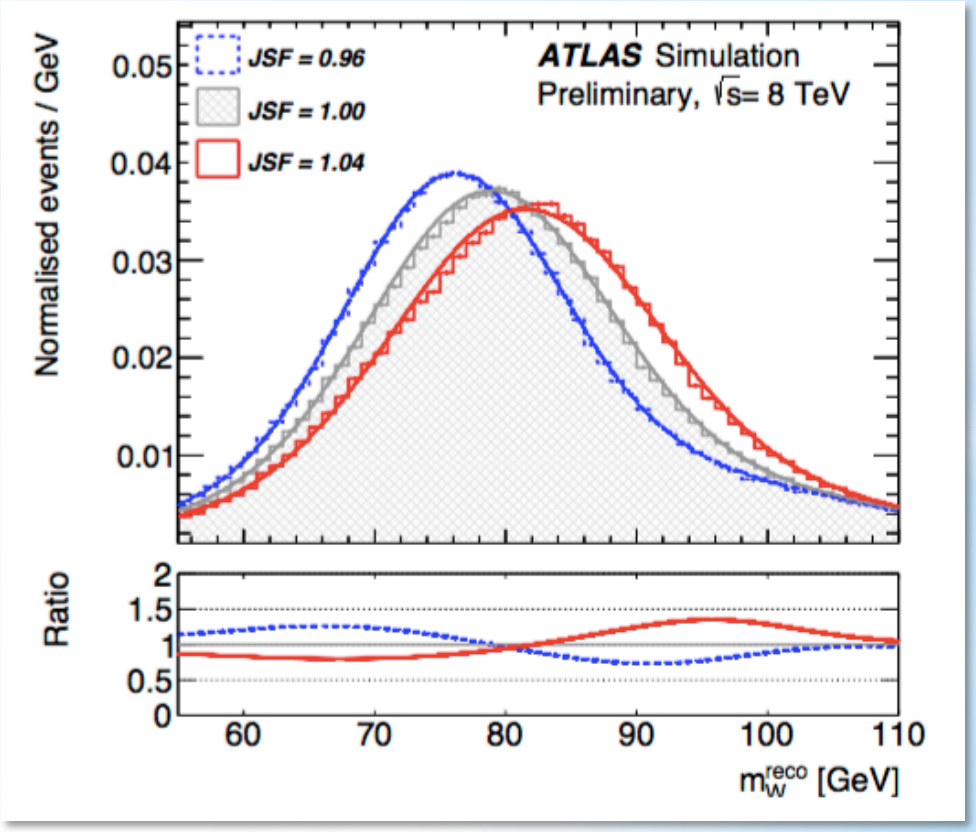


Top mass measurements

Example: ATLAS: lepton+jets channel, 8TeV data

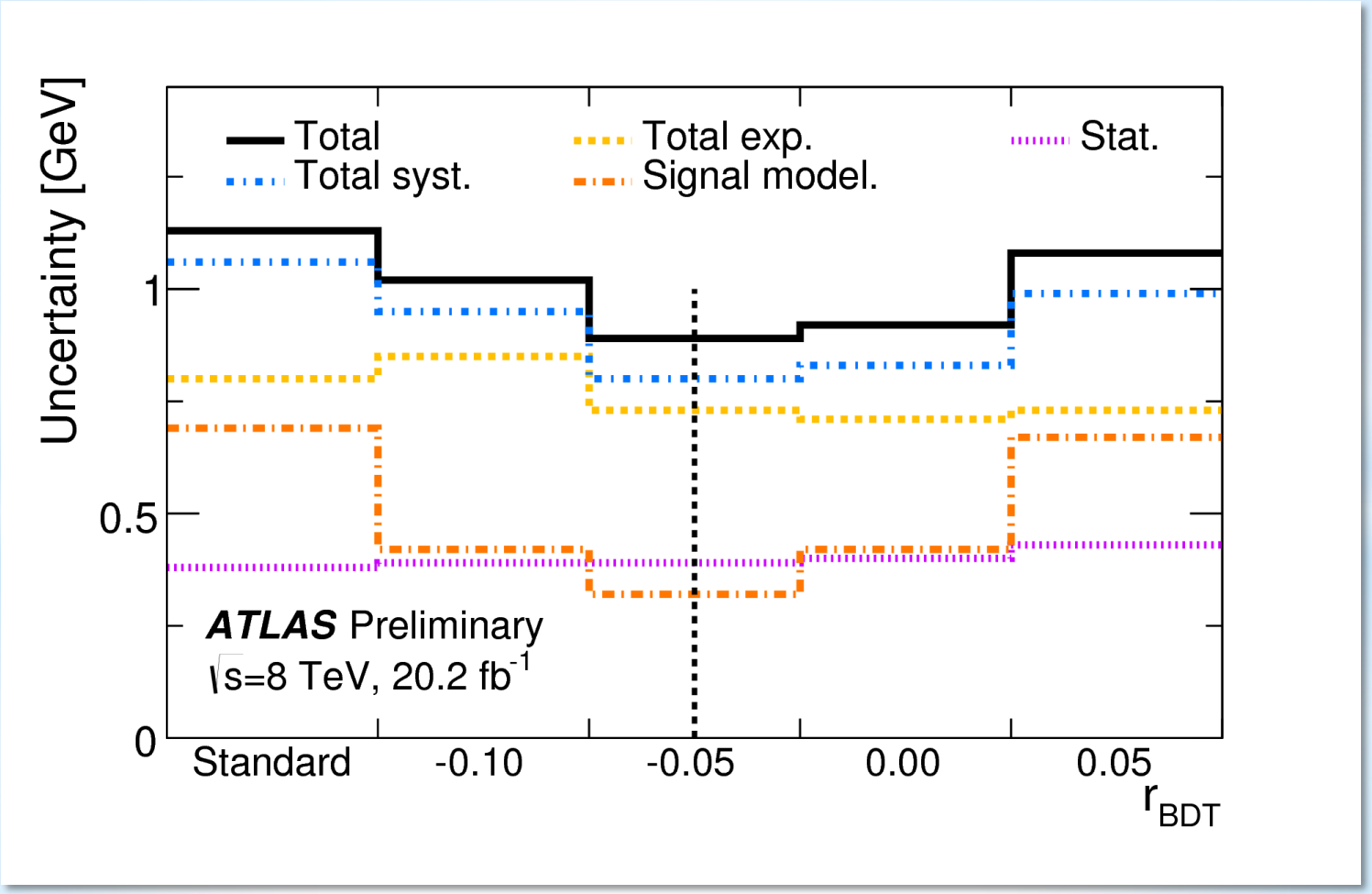
1) Preselection
2) Full reconstruction of the event
3) BDT to separate well-reconstructed events from wrongly matched events
4) Combined template fit of the top mass, the jet energy scale and the b-jet energy scale, using the reconstructed top mass, the reconstructed W mass and the b-jet/light jet transverse momentum ratio



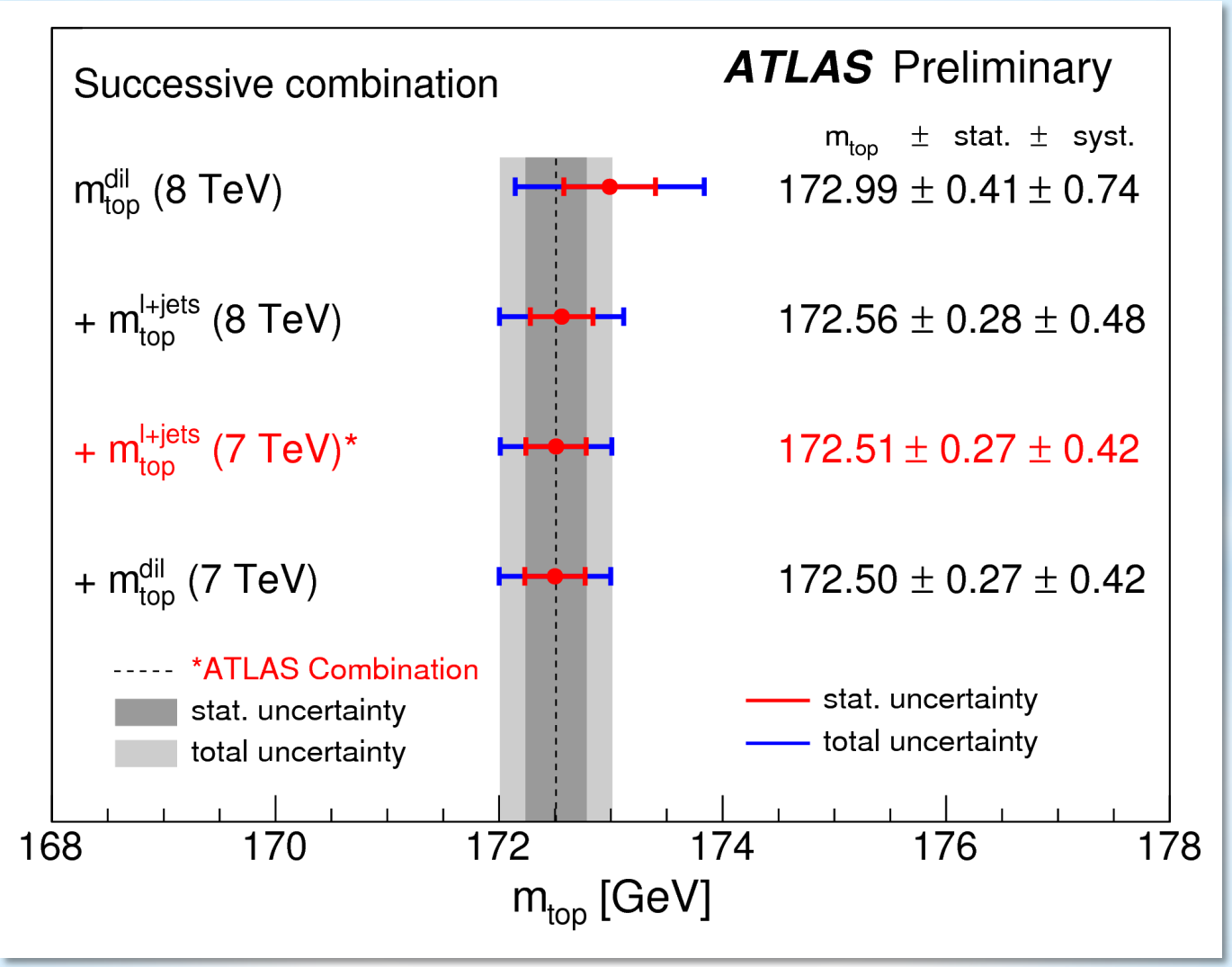
Top mass: uncertainties

	m_{top} [GeV]		
	$\sqrt{s}$ = 7 TeV	$\sqrt{s}$ = 8 TeV	
Event selection	Standard	Standard	BDT
Result	172.33	171.90	172.08
Statistics	0.75	0.38	0.39
– *Stat. comp.* (m_{top})	0.23	0.12	0.11
– *Stat. comp.* (JSF)	0.25	0.11	0.11
– *Stat. comp.* (bJSF)	0.67	0.34	0.35
Method	0.11 ± 0.10	0.04 ± 0.11	0.13 ± 0.11
Signal Monte Carlo generator	0.22 ± 0.21	0.50 ± 0.17	0.16 ± 0.17
Hadronisation	0.18 ± 0.12	0.05 ± 0.10	0.15 ± 0.10
Initial- and final-state QCD radiation	0.32 ± 0.06	0.28 ± 0.11	0.08 ± 0.11
Underlying event	0.15 ± 0.07	0.08 ± 0.15	0.08 ± 0.15
Colour reconnection	0.11 ± 0.07	0.37 ± 0.15	0.19 ± 0.15
Parton distribution function	0.25 ± 0.00	0.08 ± 0.00	0.09 ± 0.01
Background normalisation	0.10 ± 0.00	0.04 ± 0.00	0.08 ± 0.00
W+jets shape	0.29 ± 0.00	0.05 ± 0.00	0.11 ± 0.00
Fake leptons shape	0.05 ± 0.00	0	0
Jet energy scale	0.58 ± 0.11	0.63 ± 0.02	0.54 ± 0.02
Relative b-to-light-jet energy scale	0.06 ± 0.03	0.05 ± 0.01	0.03 ± 0.01
Jet energy resolution	0.22 ± 0.11	0.23 ± 0.03	0.20 ± 0.04
Jet reconstruction efficiency	0.12 ± 0.00	0.04 ± 0.01	0.02 ± 0.01
Jet vertex fraction	0.01 ± 0.00	0.13 ± 0.01	0.09 ± 0.01
b-tagging	0.50 ± 0.00	0.37 ± 0.00	0.38 ± 0.00
Leptons	0.04 ± 0.00	0.16 ± 0.01	0.16 ± 0.01
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.15 ± 0.04	0.08 ± 0.01	0.05 ± 0.01
Pile-up	0.02 ± 0.01	0.14 ± 0.01	0.15 ± 0.01
Total systematic uncertainty	1.03 ± 0.08	1.07 ± 0.10	0.82 ± 0.06
Total	1.27 ± 0.08	1.13 ± 0.10	0.91 ± 0.06

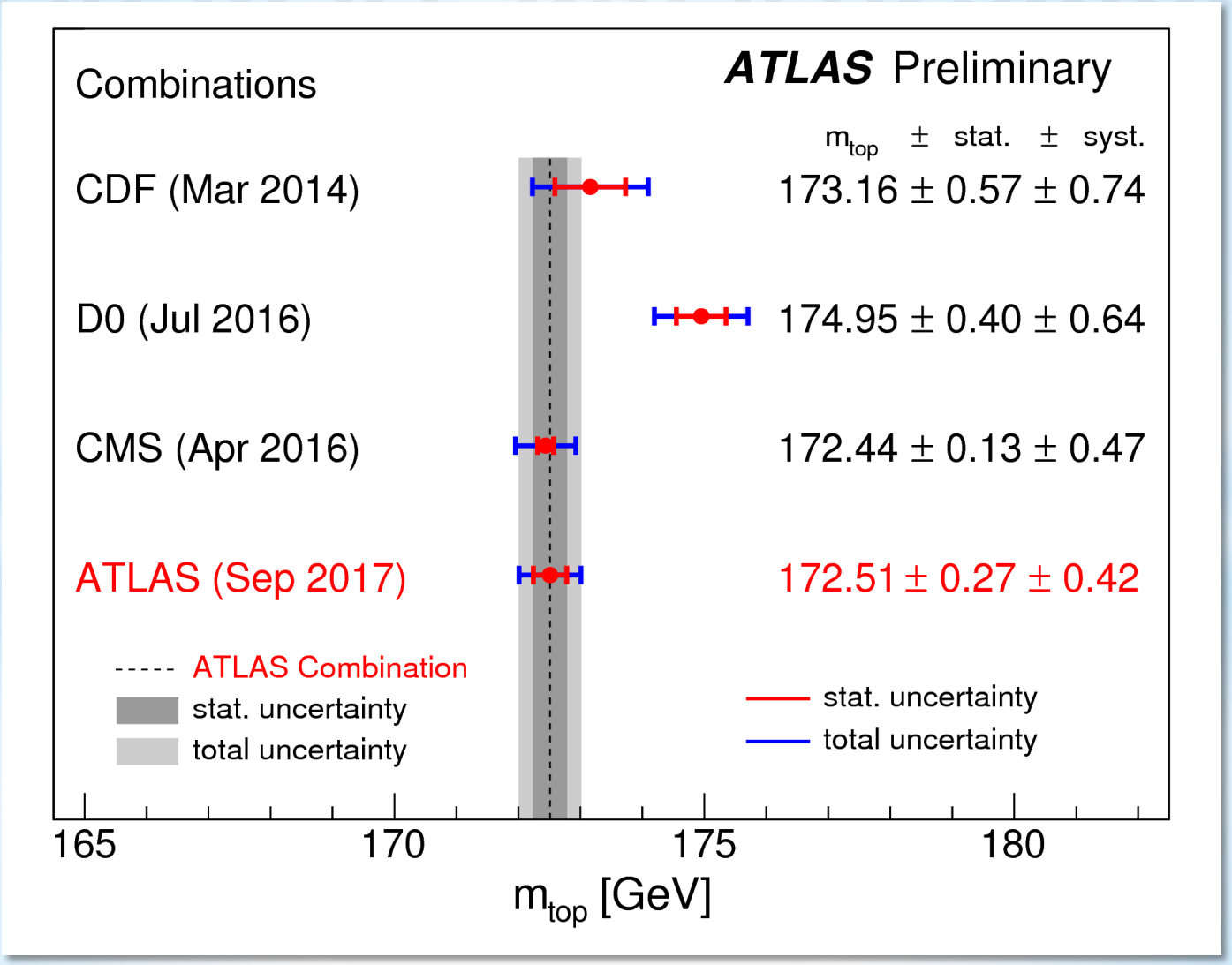
Top mass: uncertainties



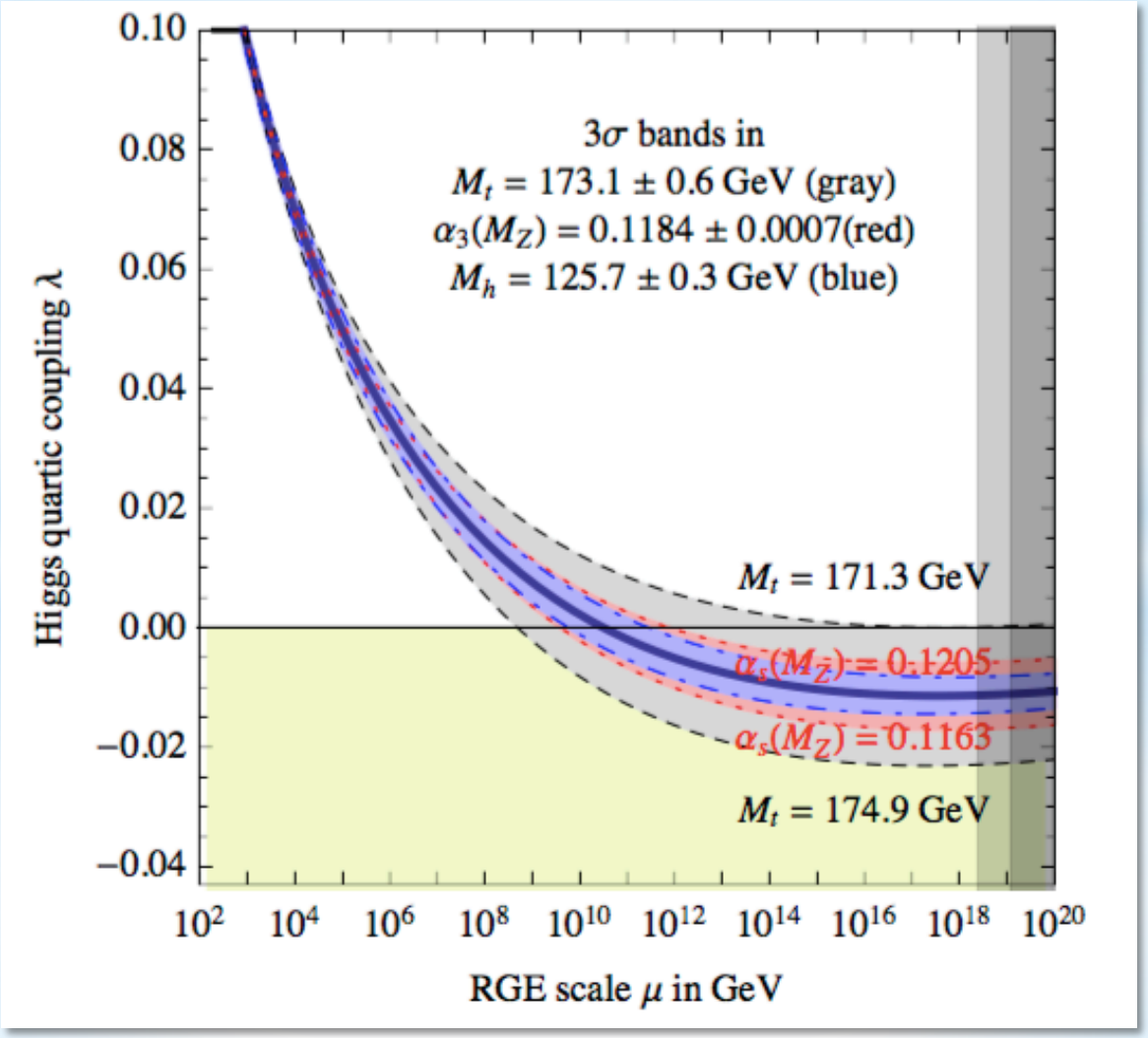
TOP mass measurements



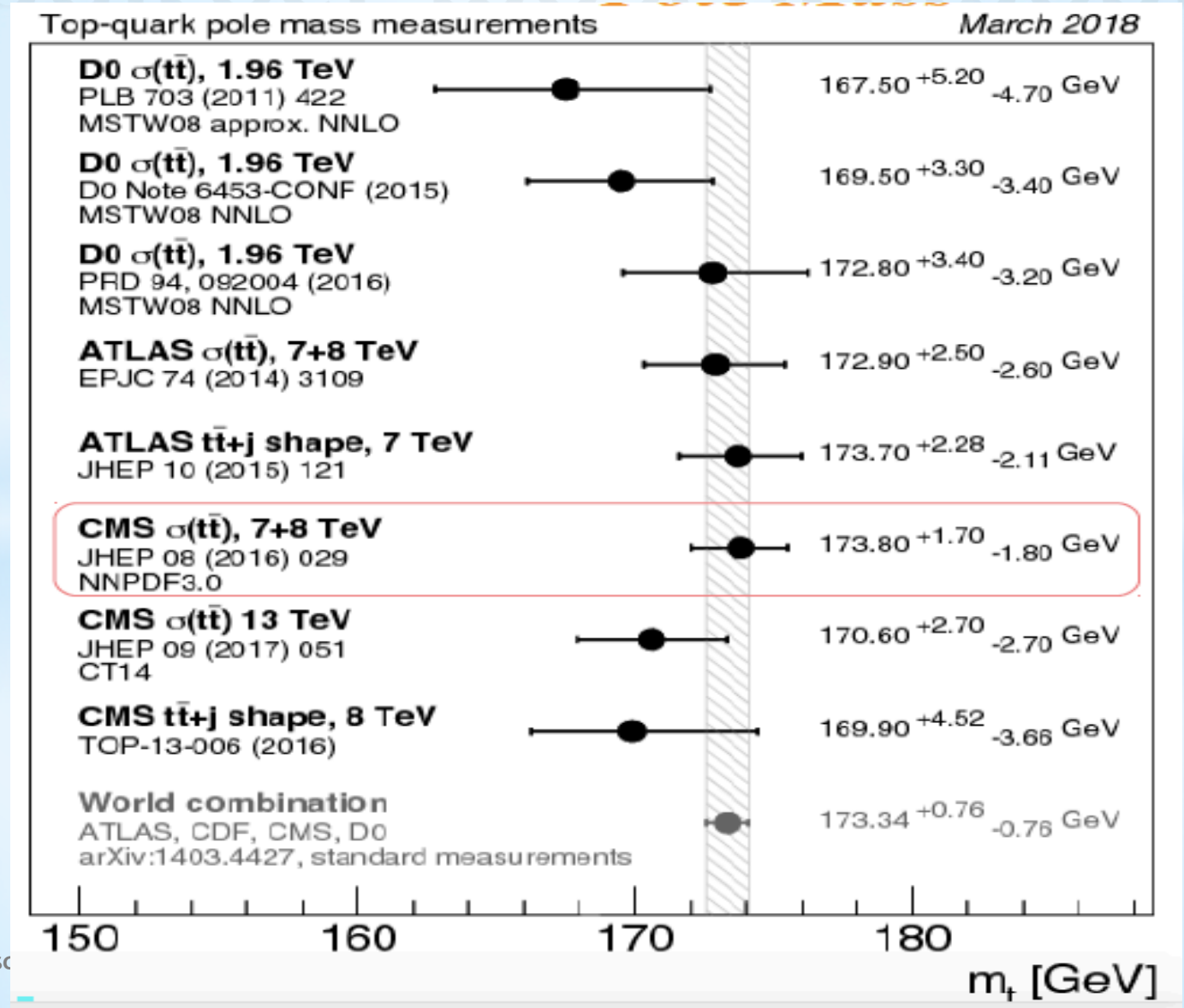
TOP mass measurements



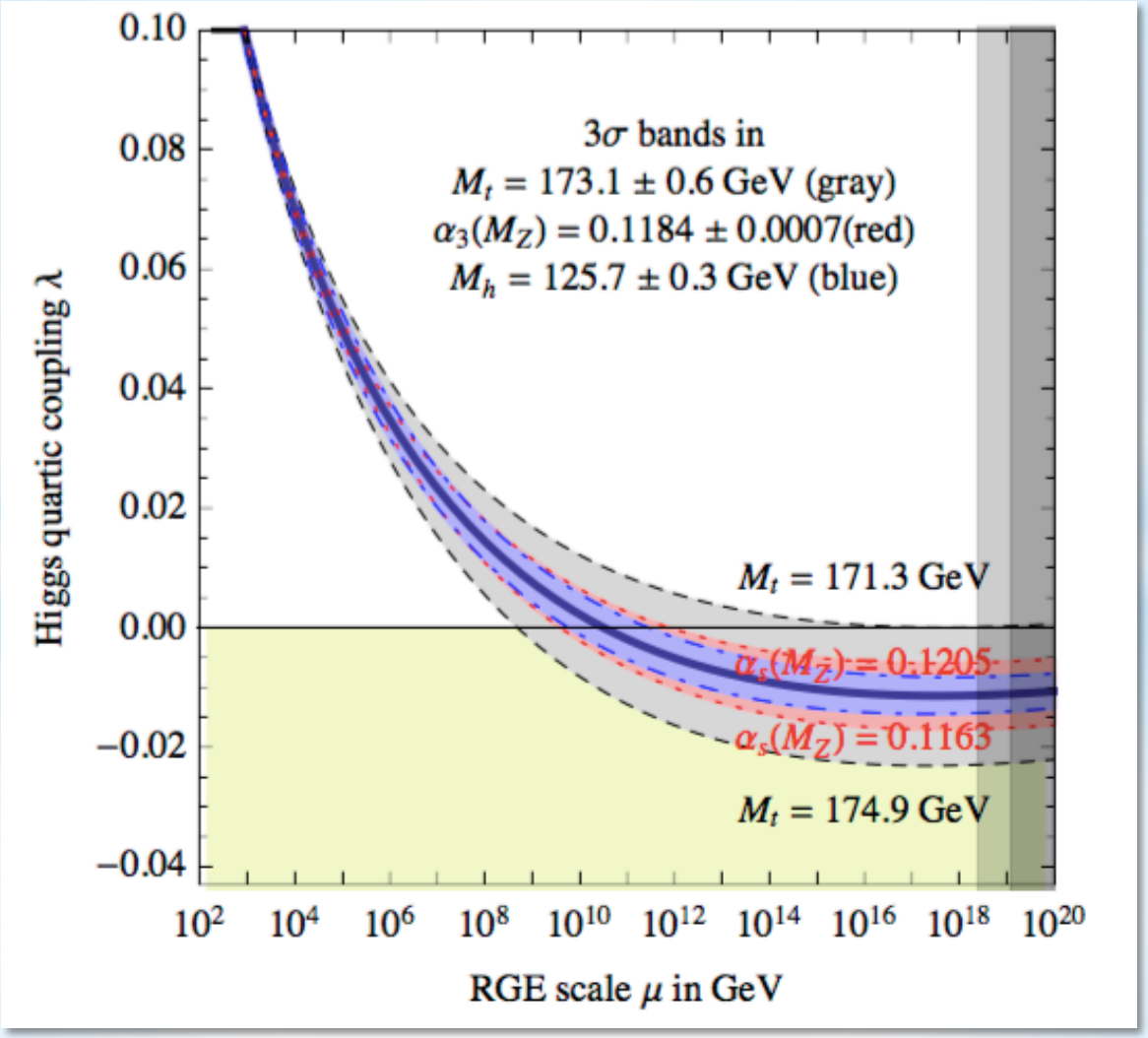
Higgs potential



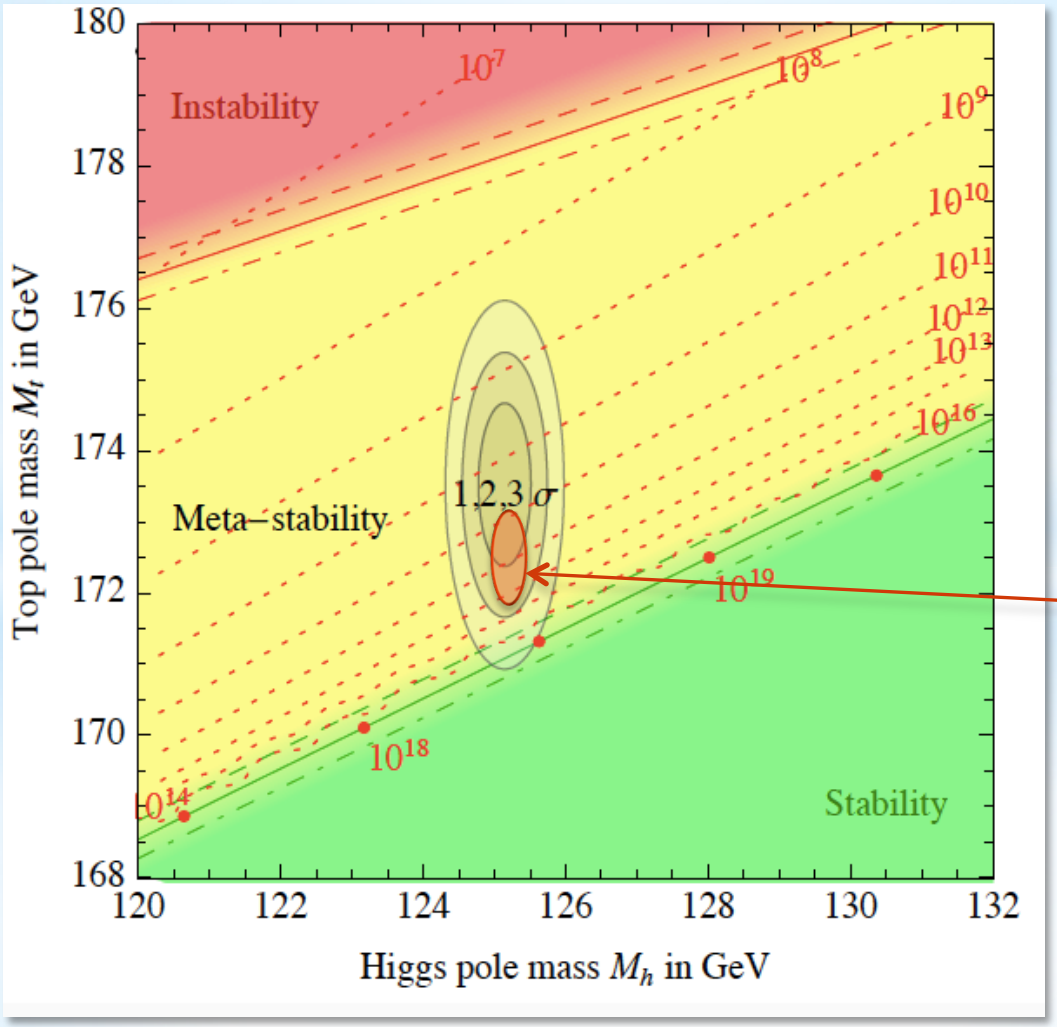
Indirect measurements



Higgs potential

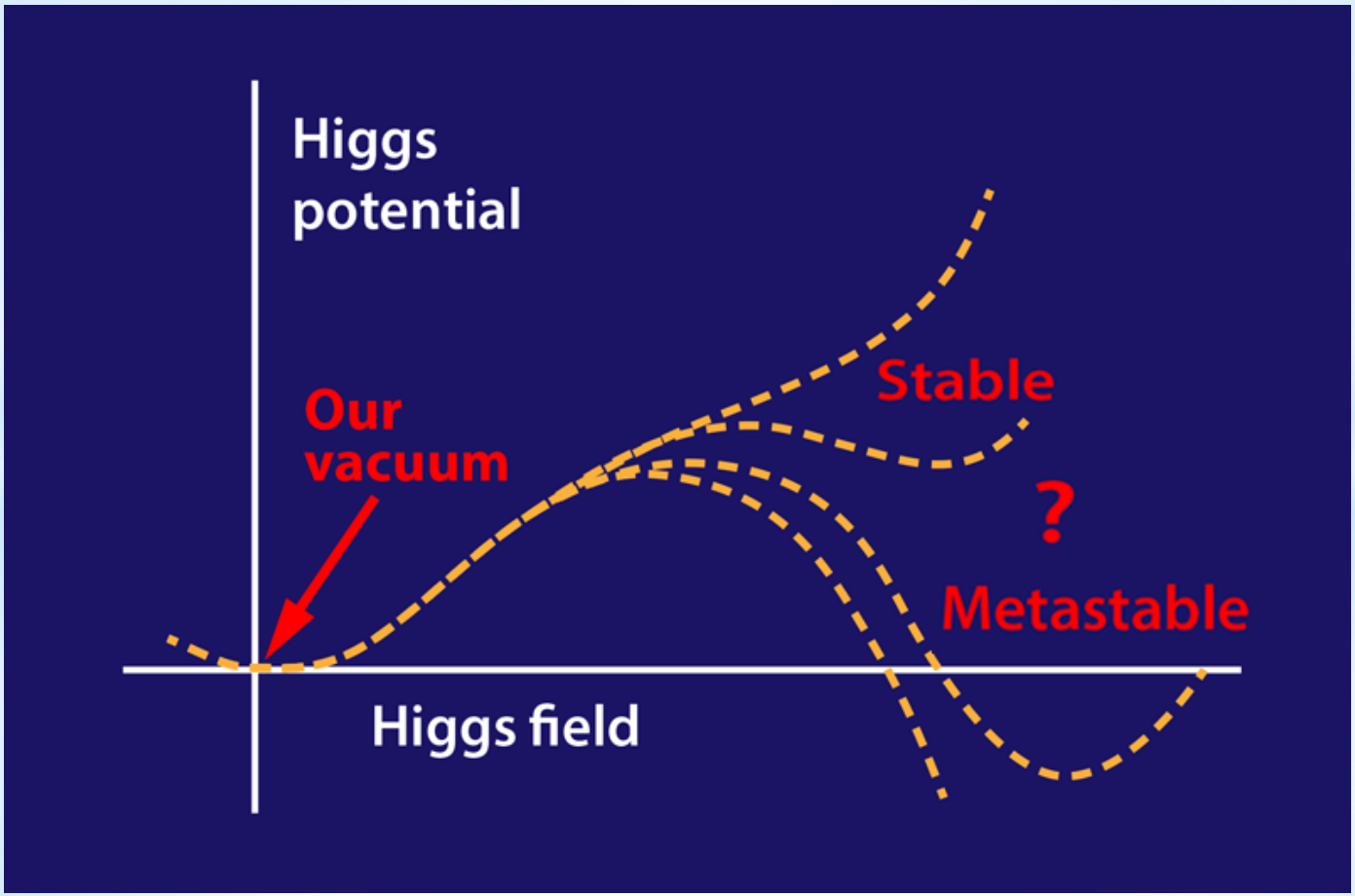


The Higgs potential



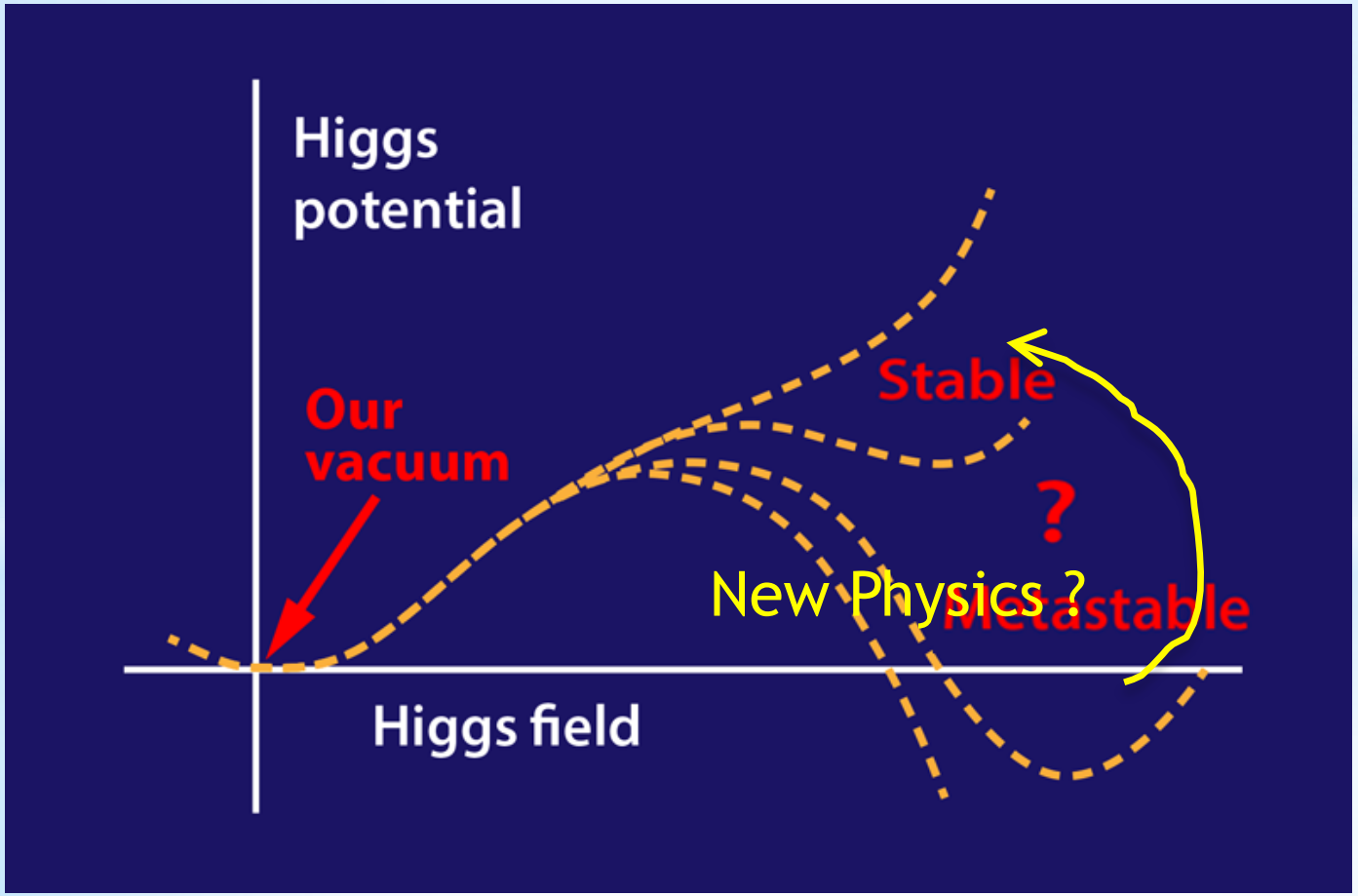
Run1 LHC

The Higgs potential

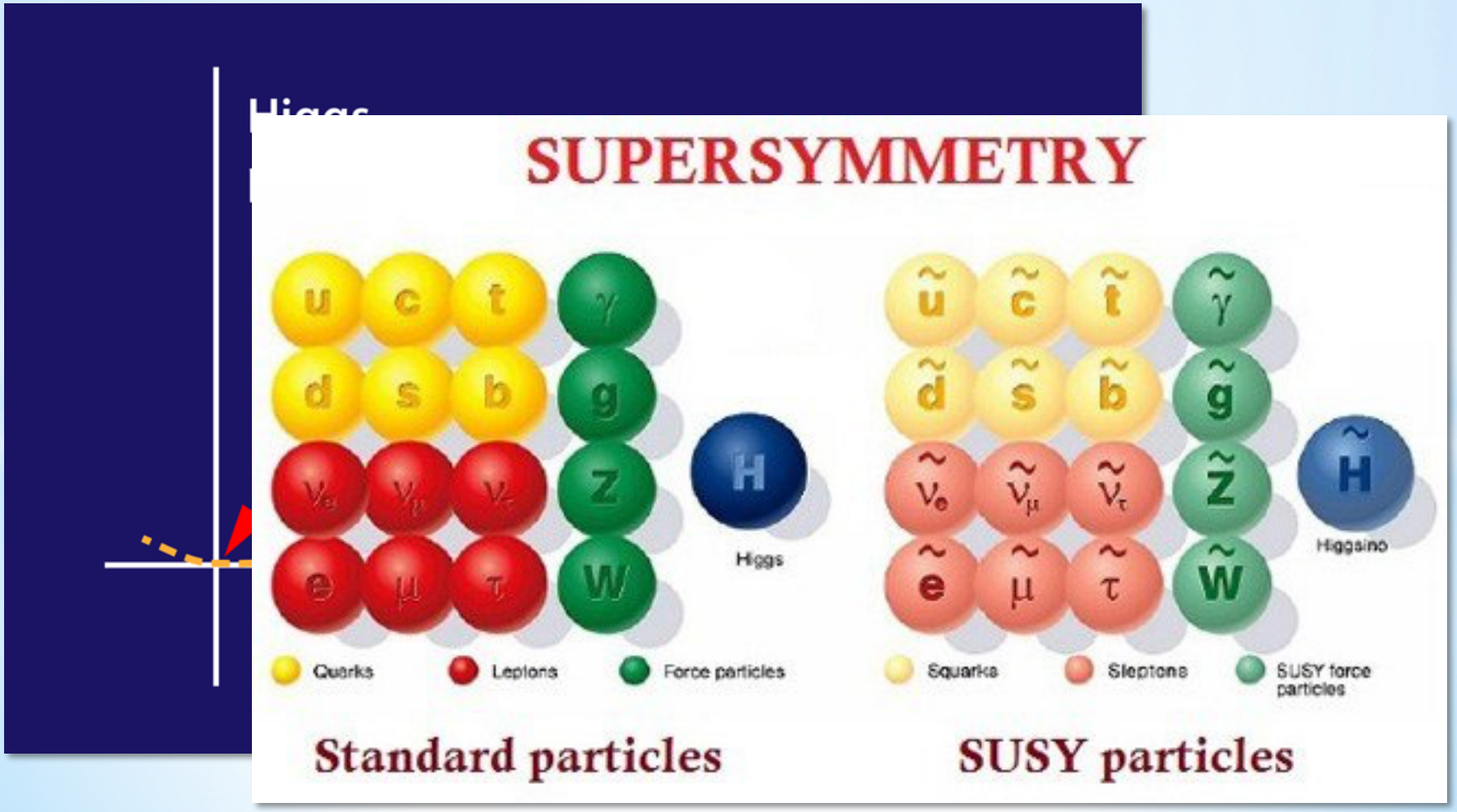


The Higgs potential

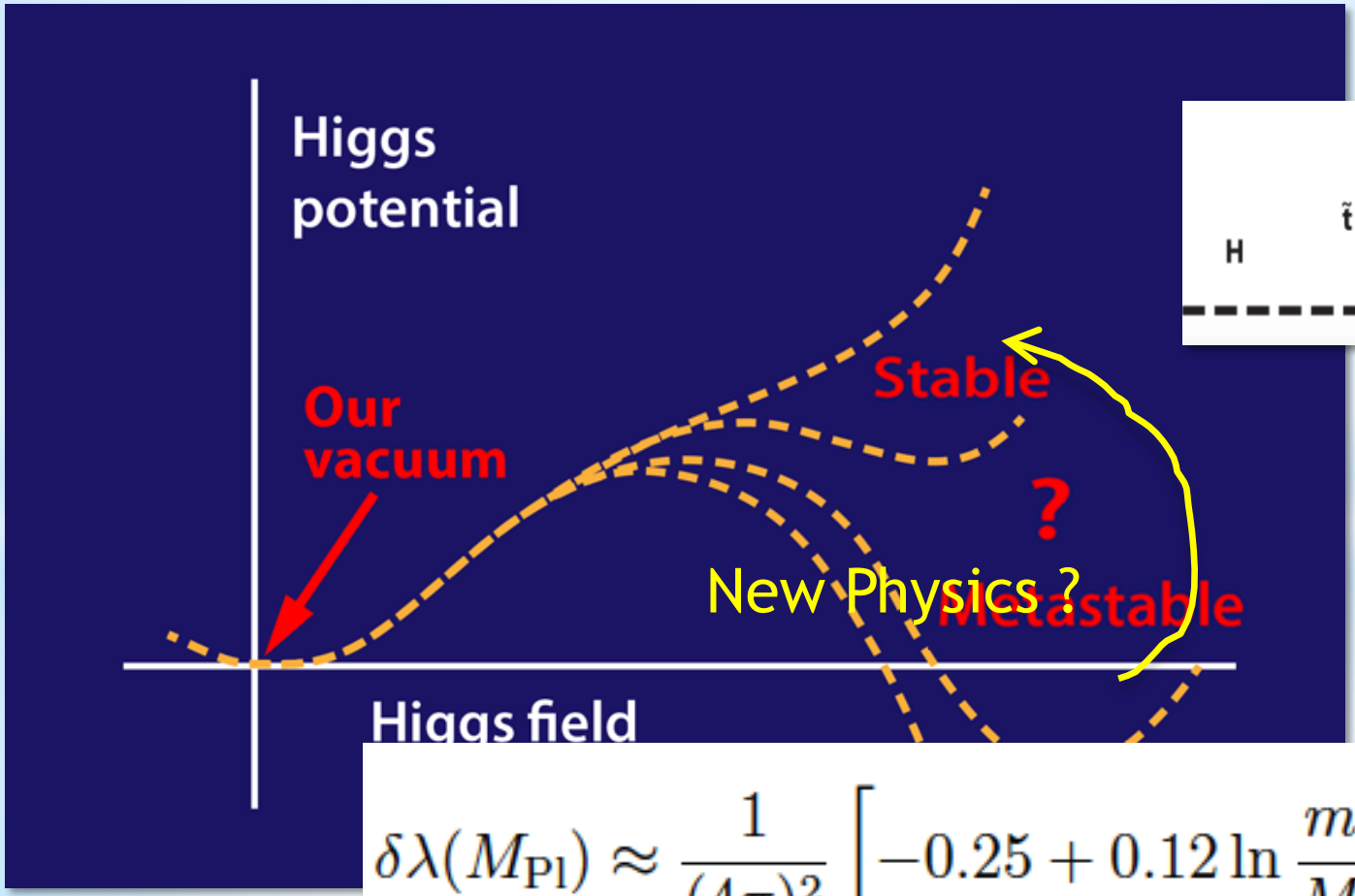
The Higgs potential

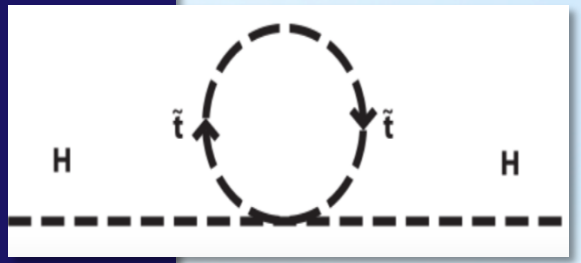


The Higgs potential



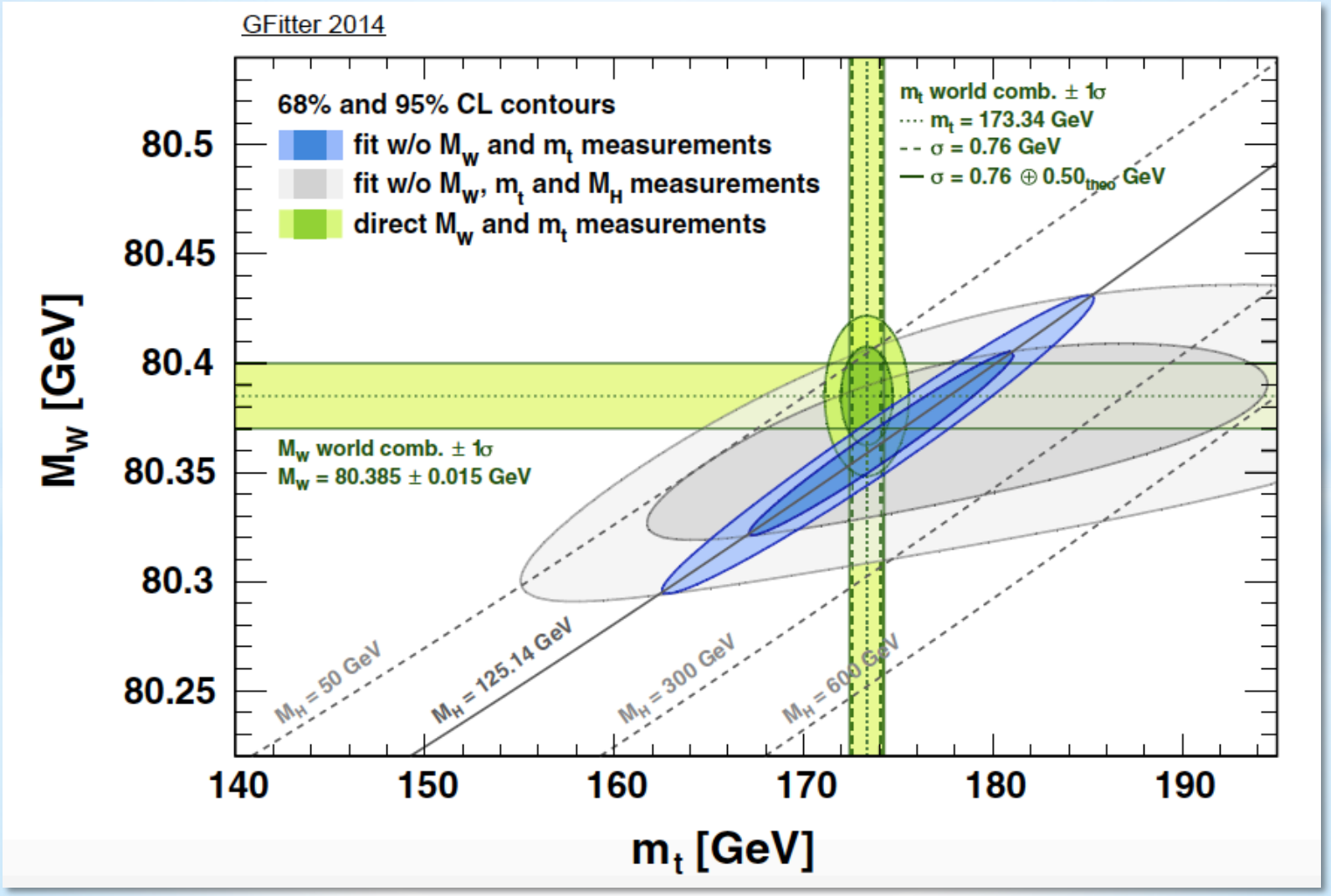
The Higgs potential





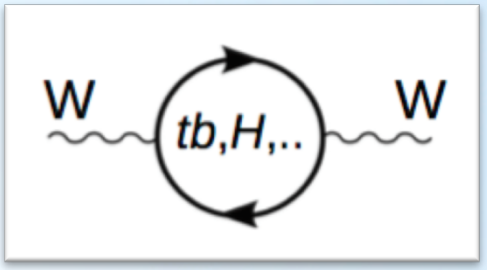
$$\delta\lambda(M_{\rm Pl}) \approx \frac{1}{(4\pi)^2}\left[-0.25 + 0.12\ln\frac{m_{\tilde{t}}}{M_2} + 0.05\ln\frac{m_A}{M_2}\right]$$

The SM is over-constrained

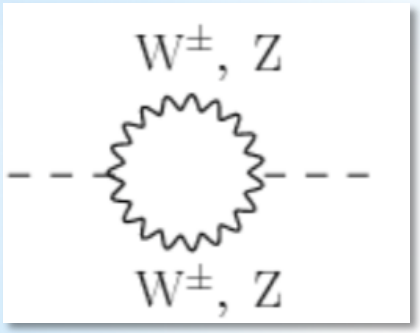


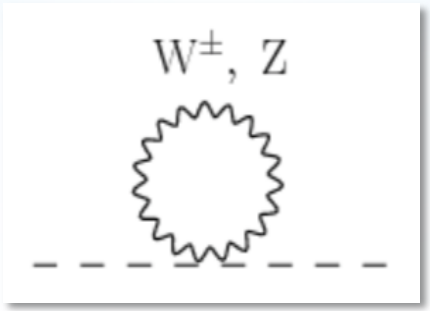
The SM is over-constrained

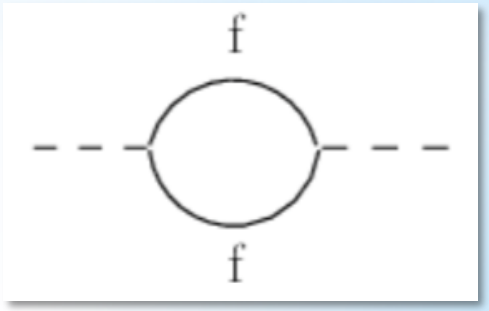
$$m_W^2 \sin^2\theta_W = \frac{\pi\alpha}{\sqrt{2}G_\mu}\frac{1}{1-\Delta r}$$



$$\Delta r = \Delta\alpha - \tan\theta_W \Delta\rho(m_{top}) + \Delta r^{SM}_{rem}(m_{top}, m_H) + \ldots$$







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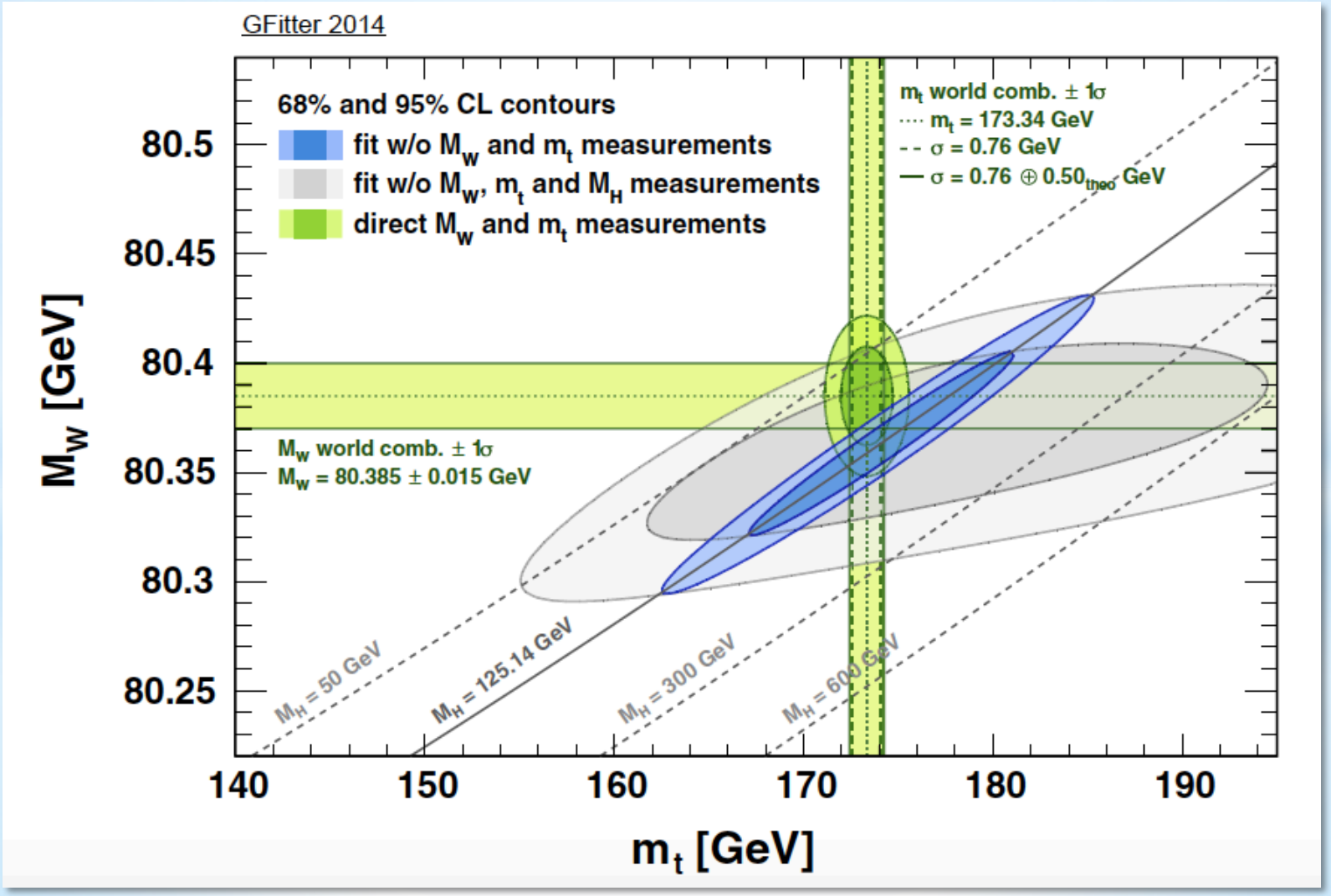

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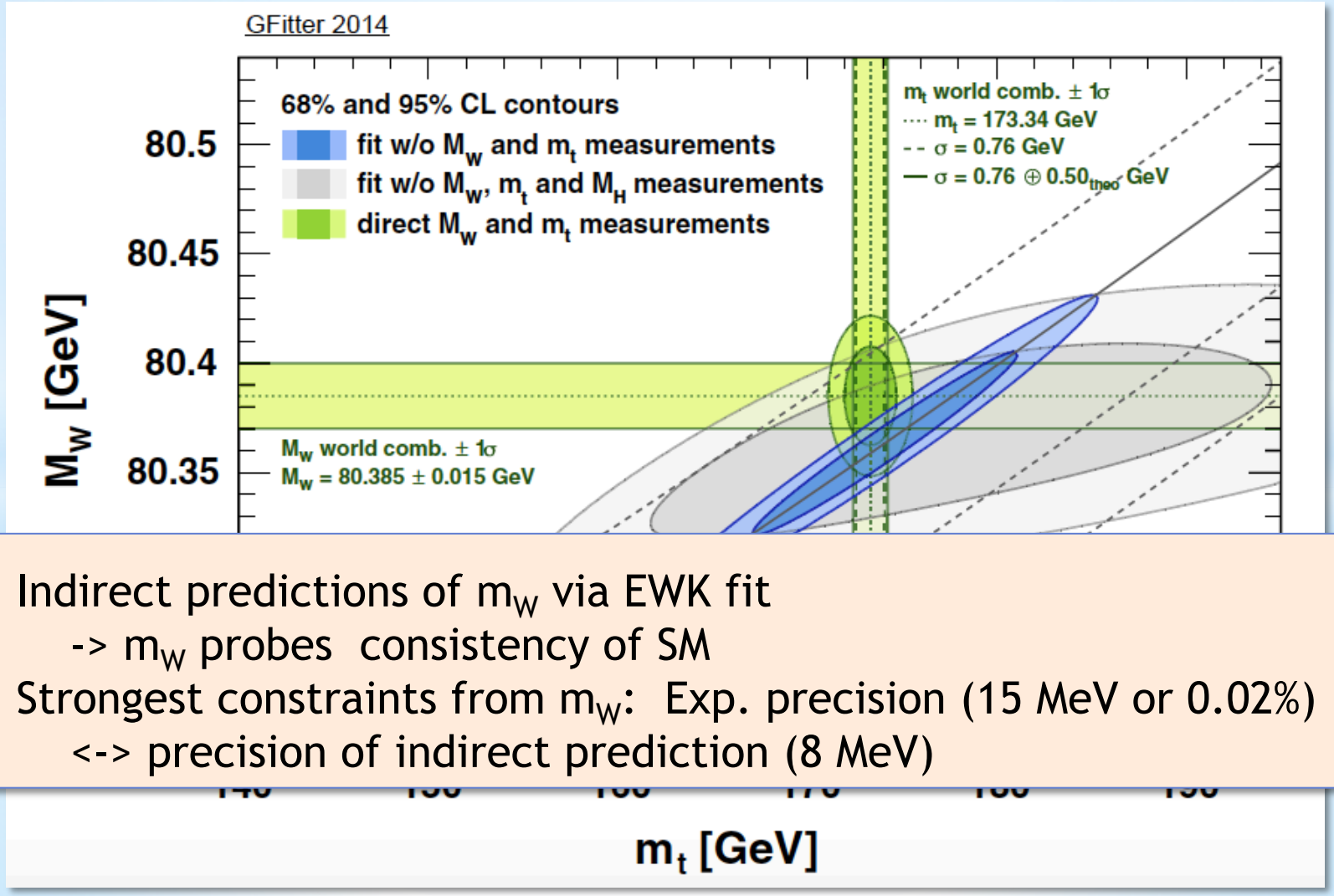
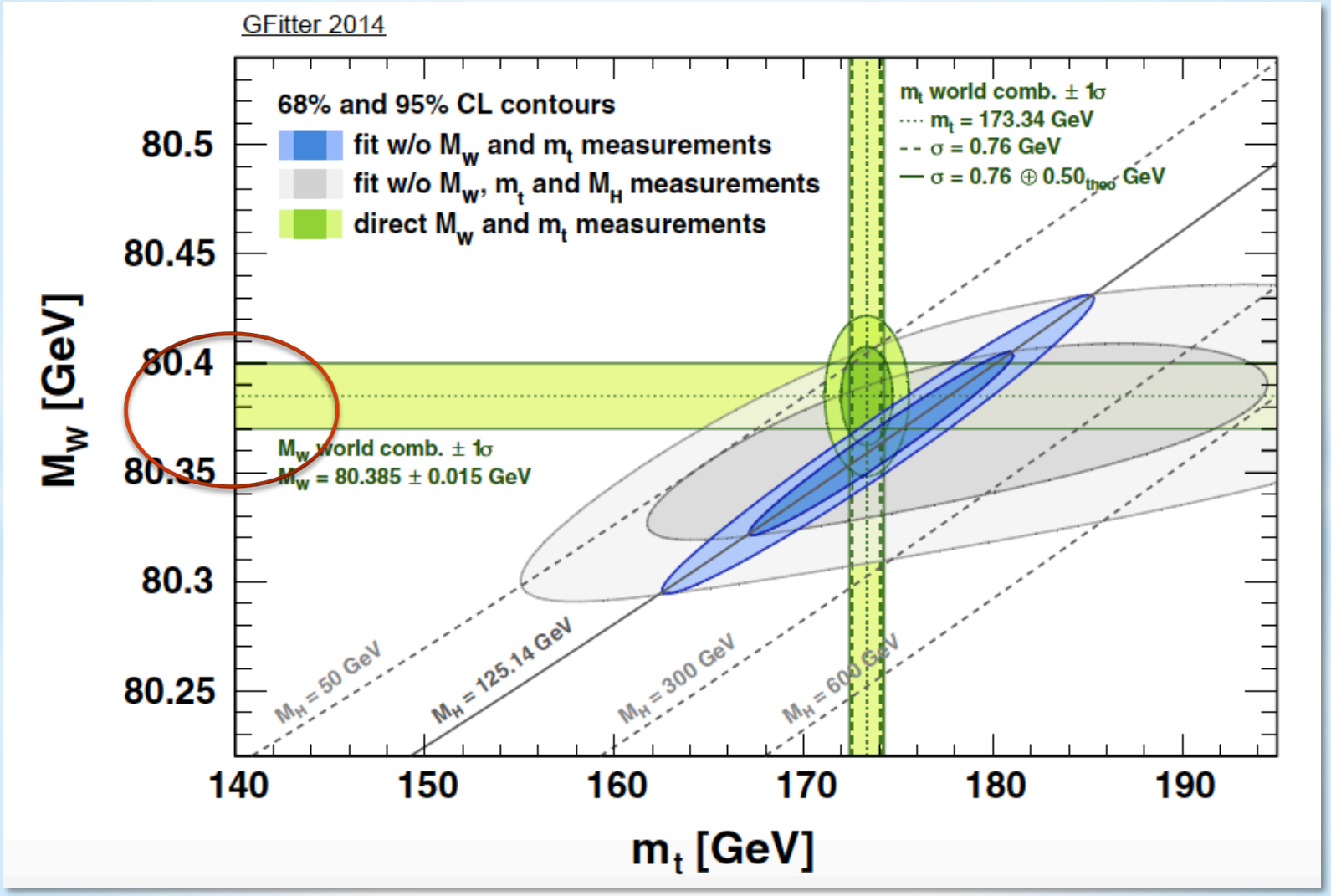
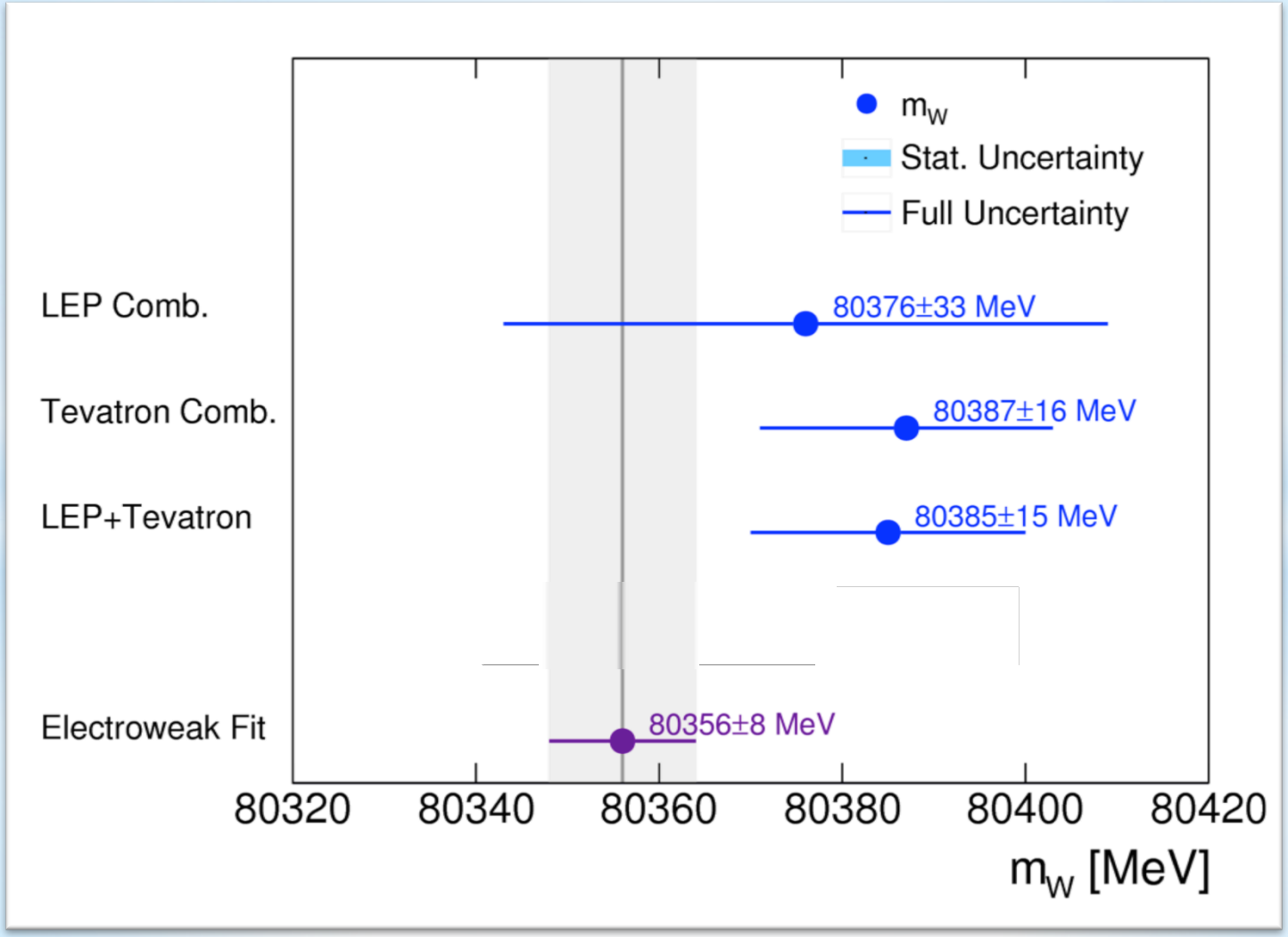


- Indirect predictions of m_W via EWK fit
- -> m_W probes consistency of SM
- Strongest constraints from m_W: Exp. precision (15 MeV or 0.02%)
- <-> precision of indirect prediction (8 MeV)

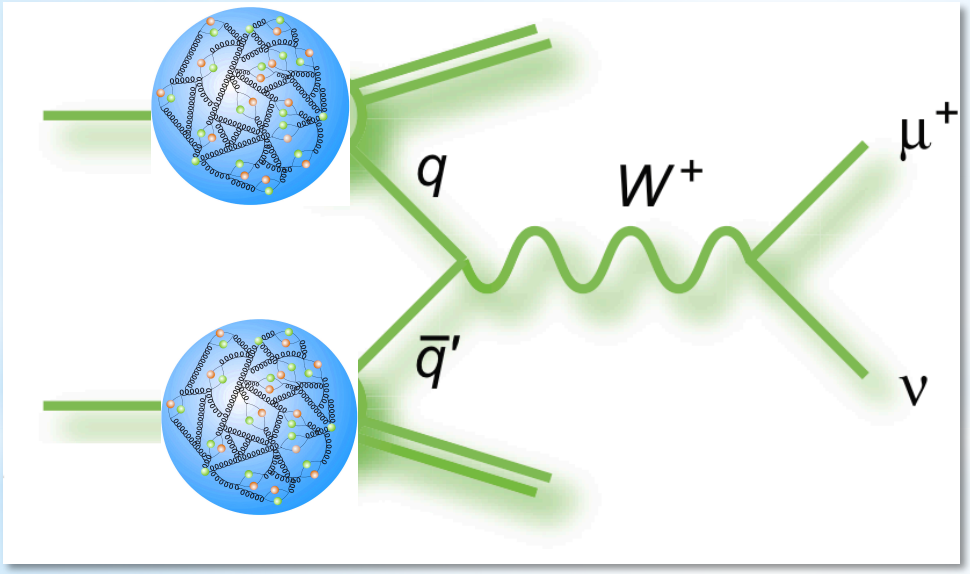
The SM is over-constrained



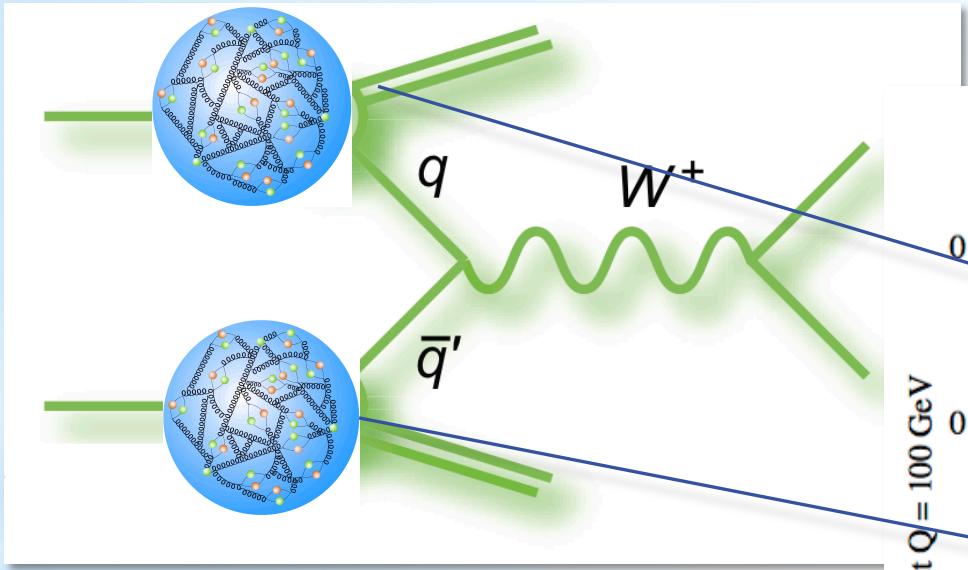
Previous mW measurements

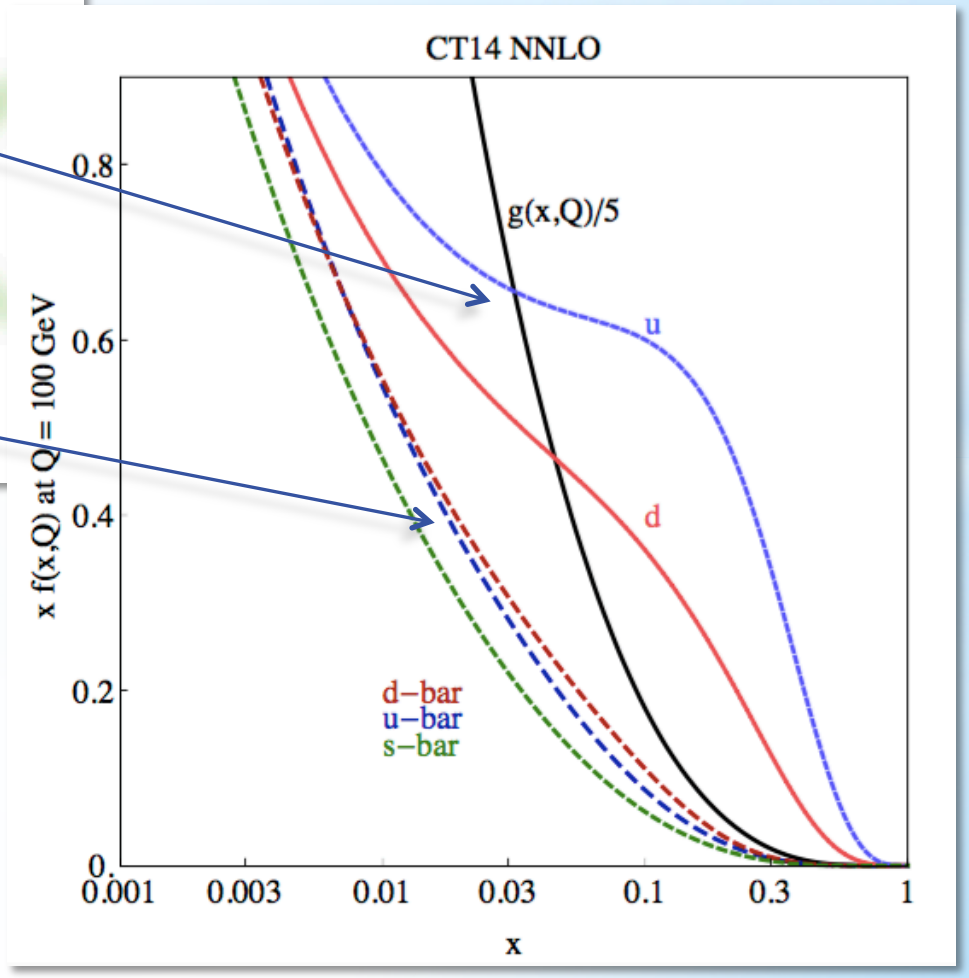


W production

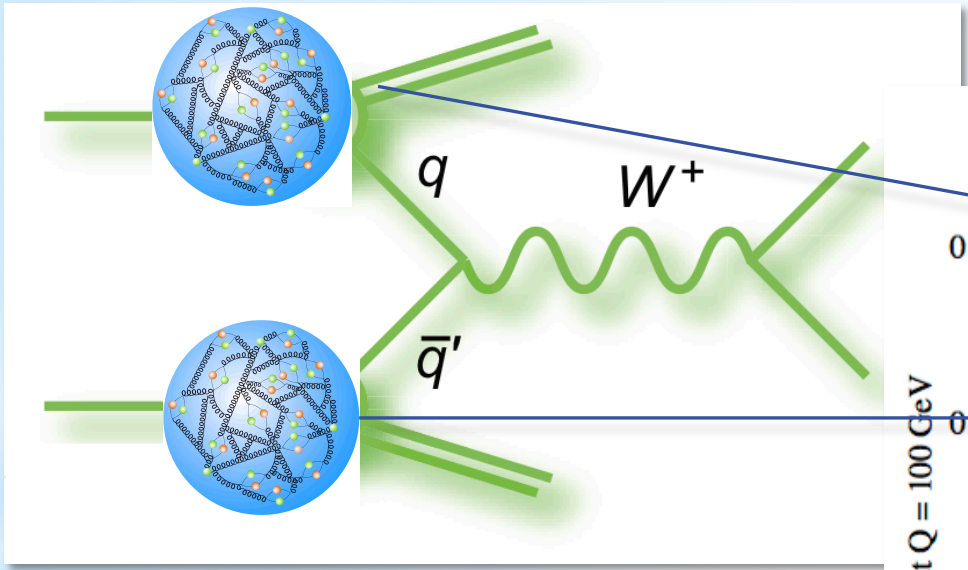


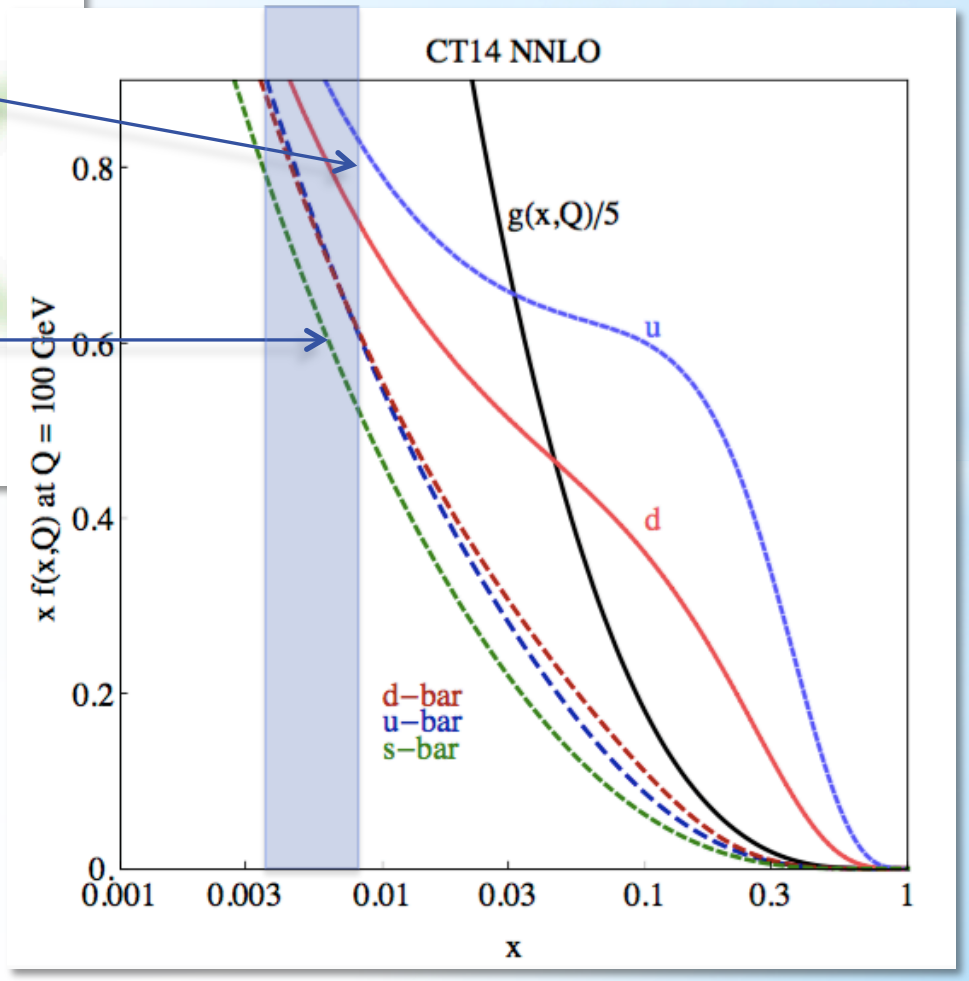
W production





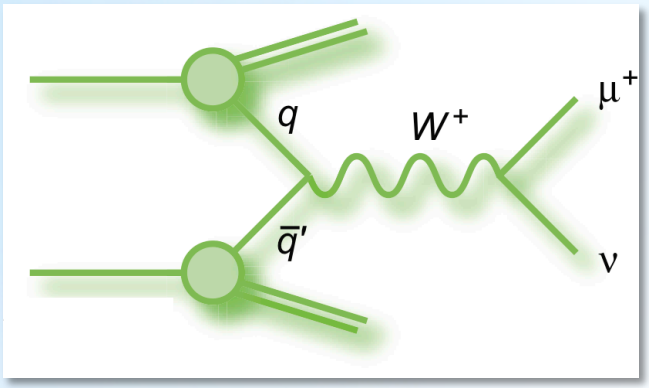
W reconstruction



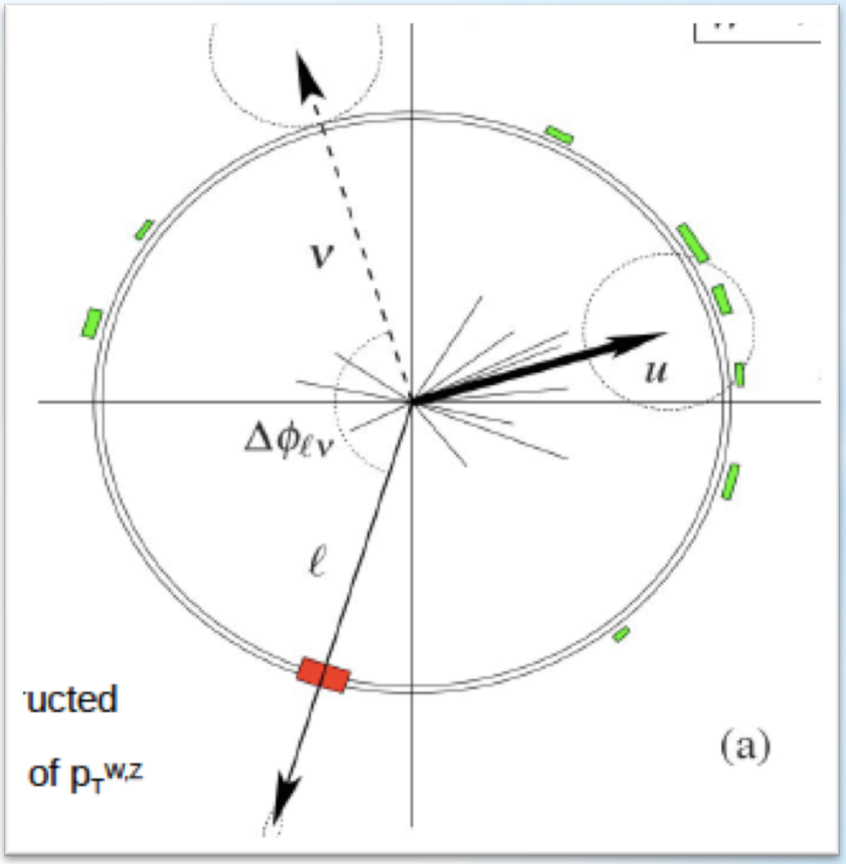


W hadronic recoil

arXiv:1701.07240

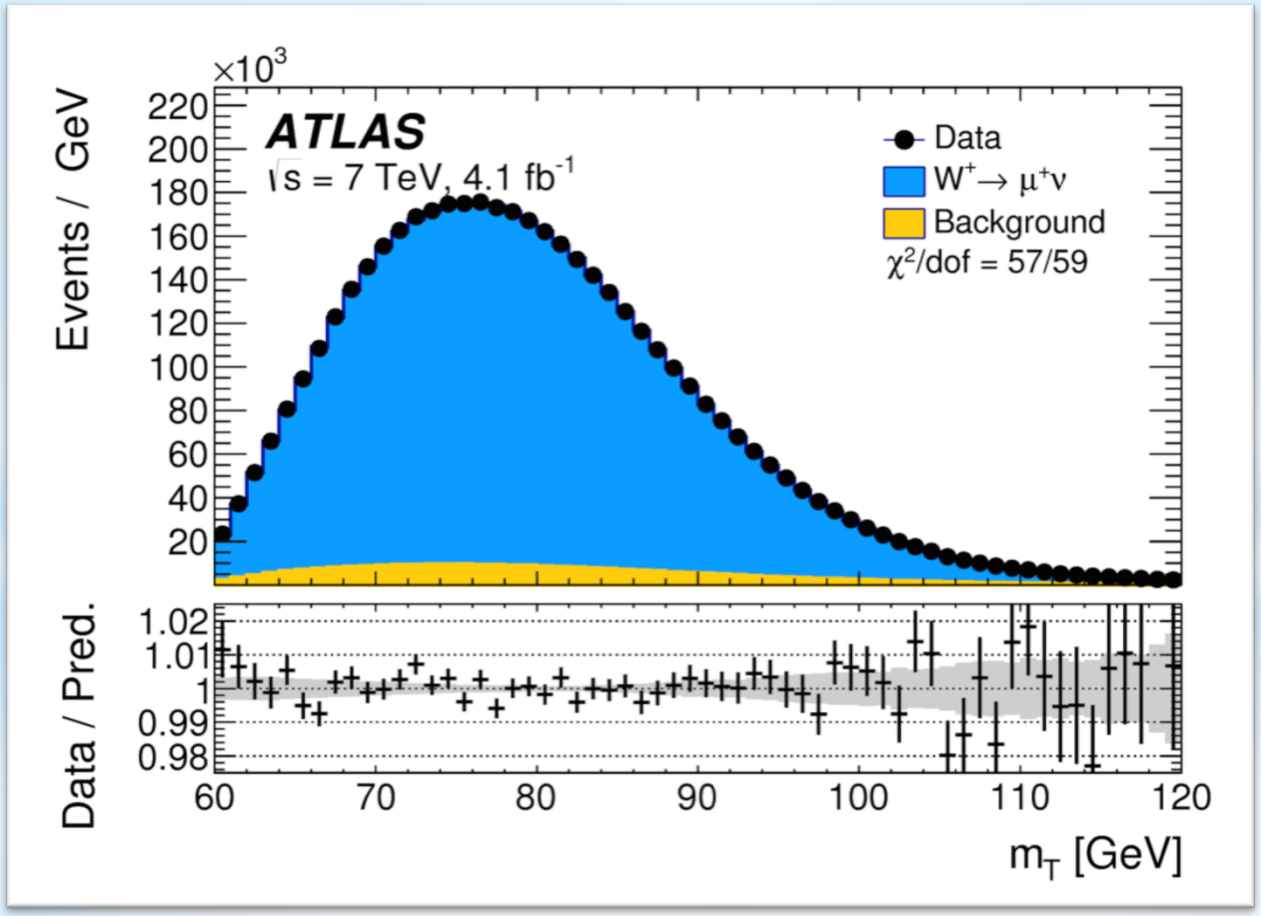


$$\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}} = -\left(\vec{p}_{\mathrm{T}}^{\,\ell} + \vec{u}_{\mathrm{T}}\right)$$



W transverse mass

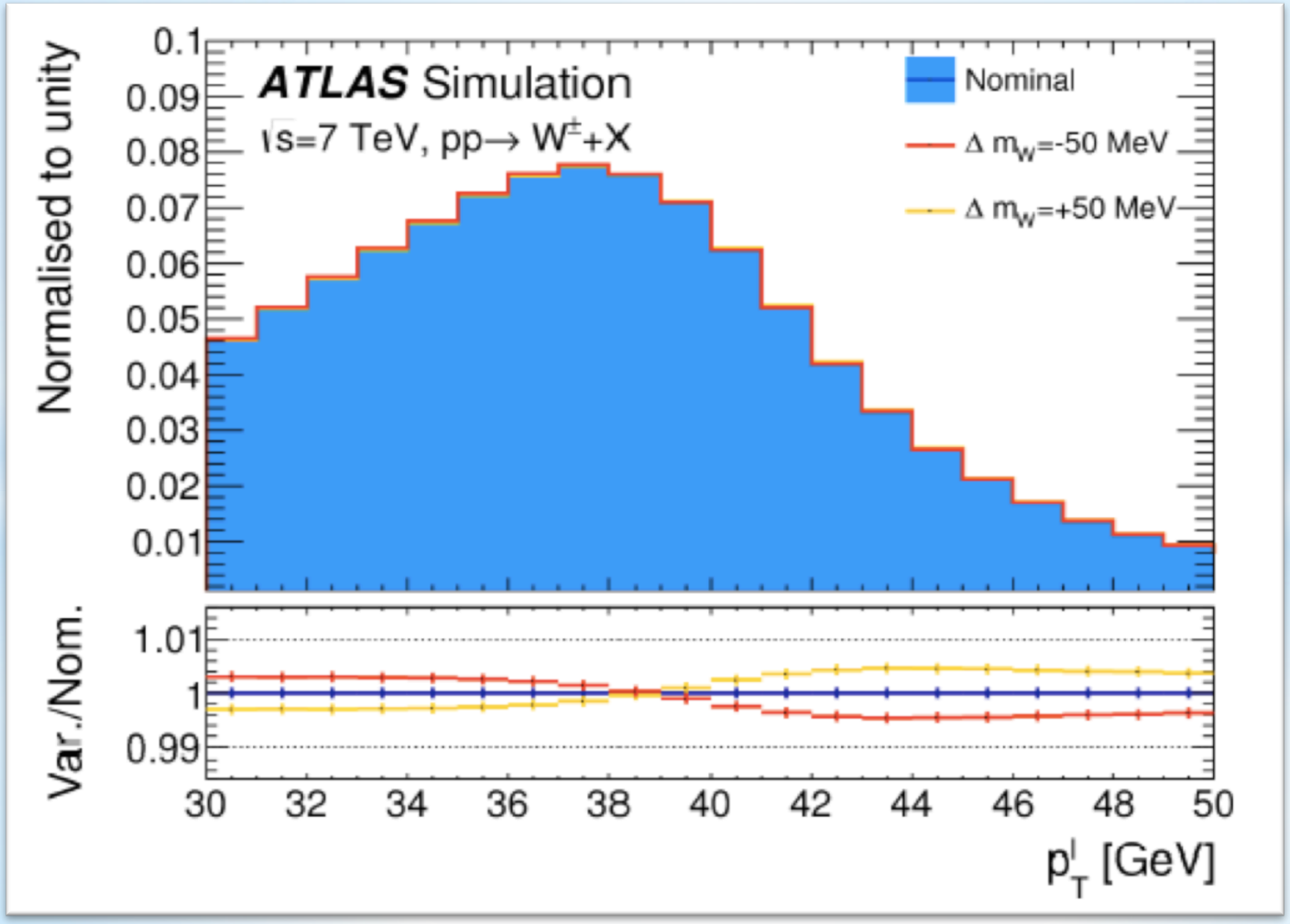
arXiv:1701.07240



$$m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\ell} p_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos \Delta\phi)},$$

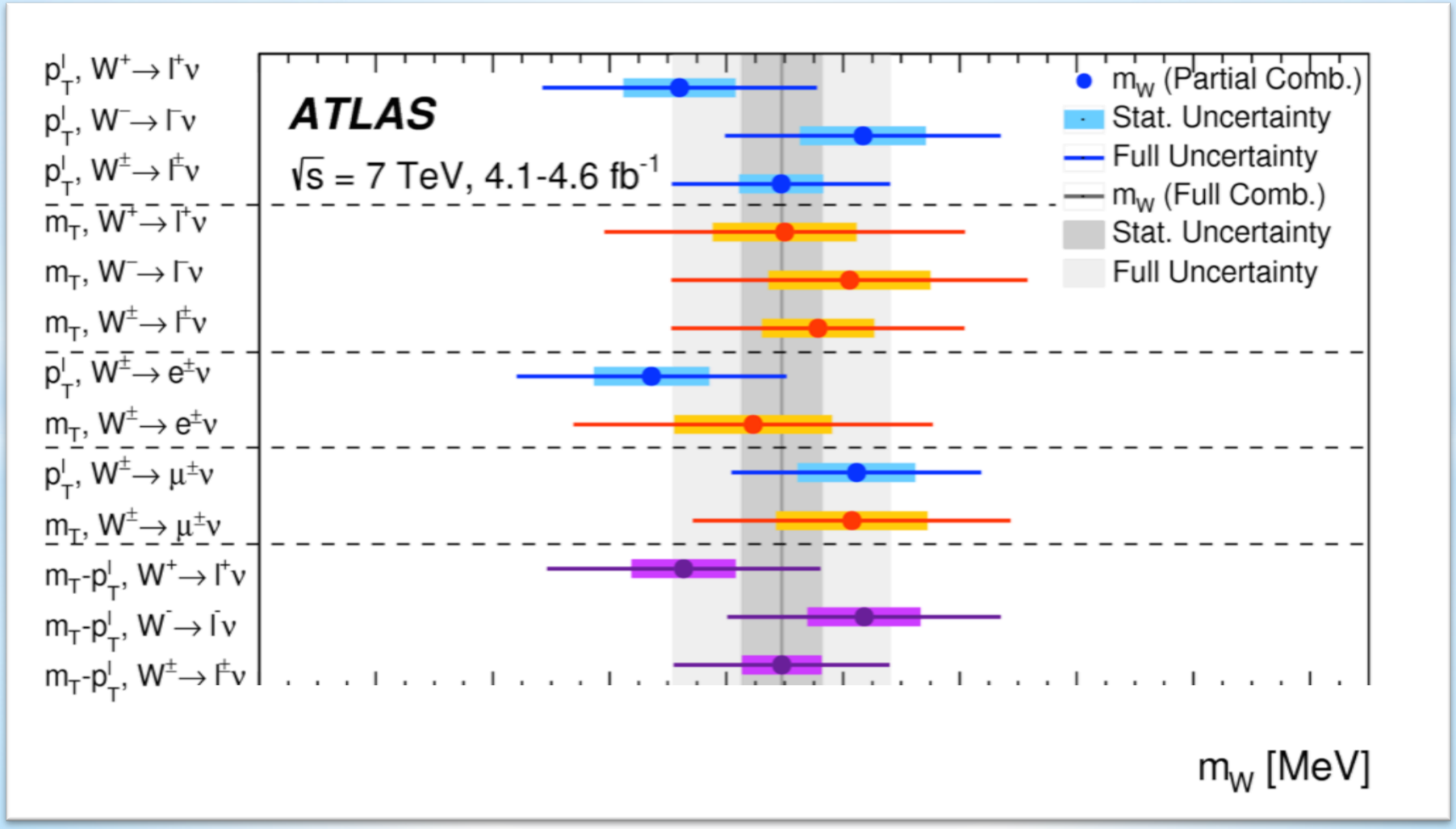
W transverse mass

arXiv:1701.07240



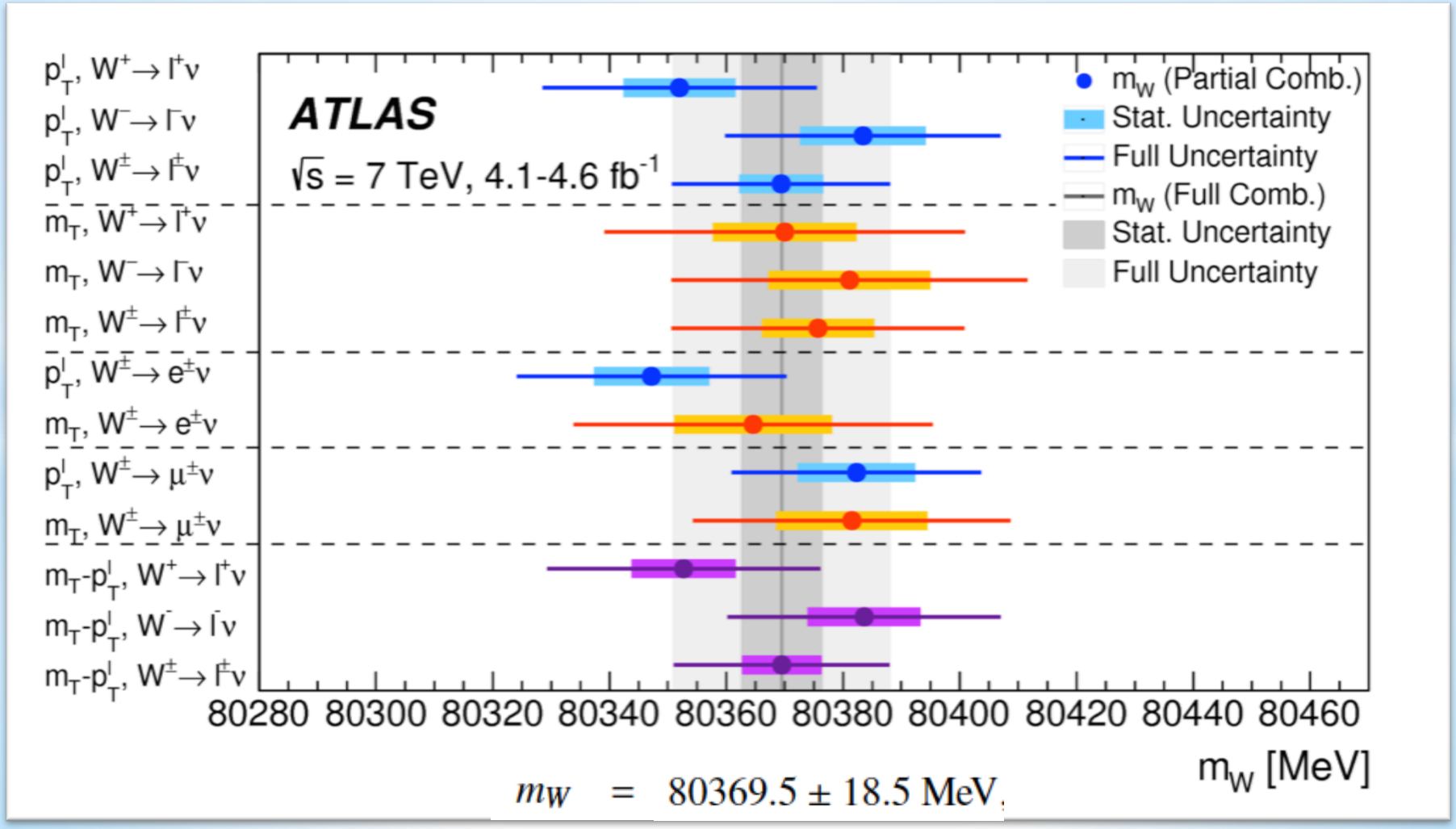
W mass: blinded

arXiv:1701.07240



W mass: unblinded

arXiv:1701.07240

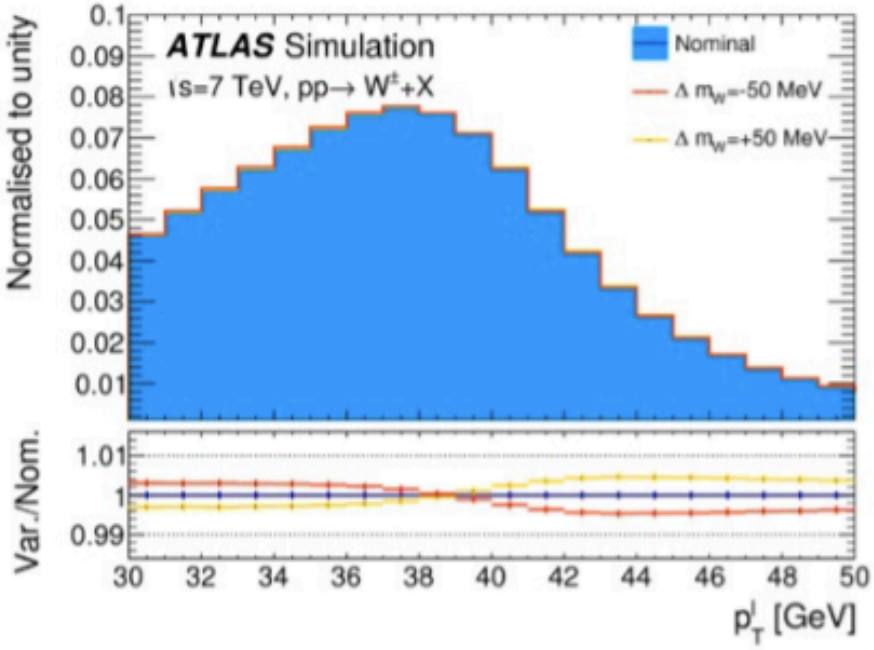


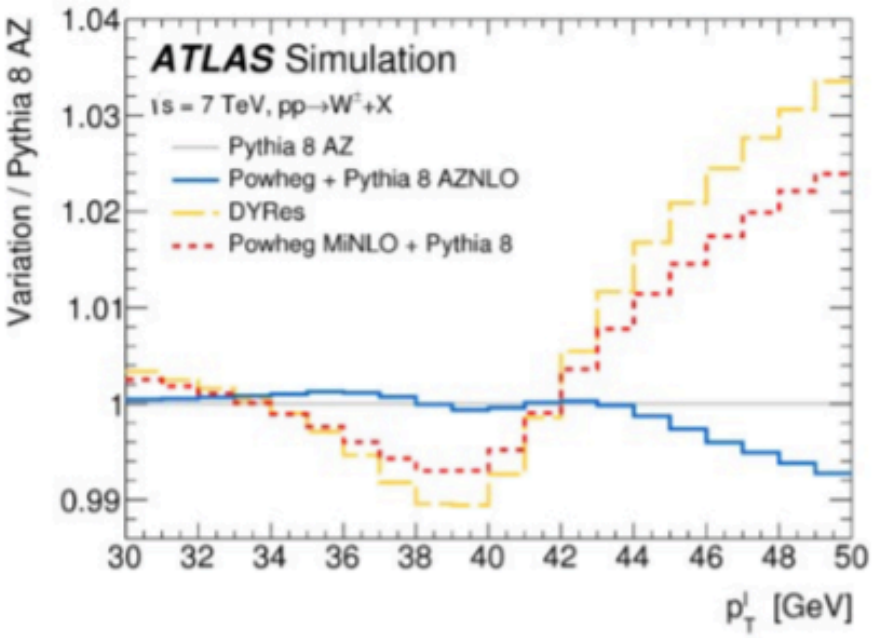
W mass: uncertainties

Dominating uncertainty from theory: pT(W) modeling, PDF

Combined categories	Value [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.	χ^2/dof of Comb.
m_T-p_T^ℓ, $W^\pm$, e-μ	80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5	29/27

Theory uncertainties





Theory uncertainties

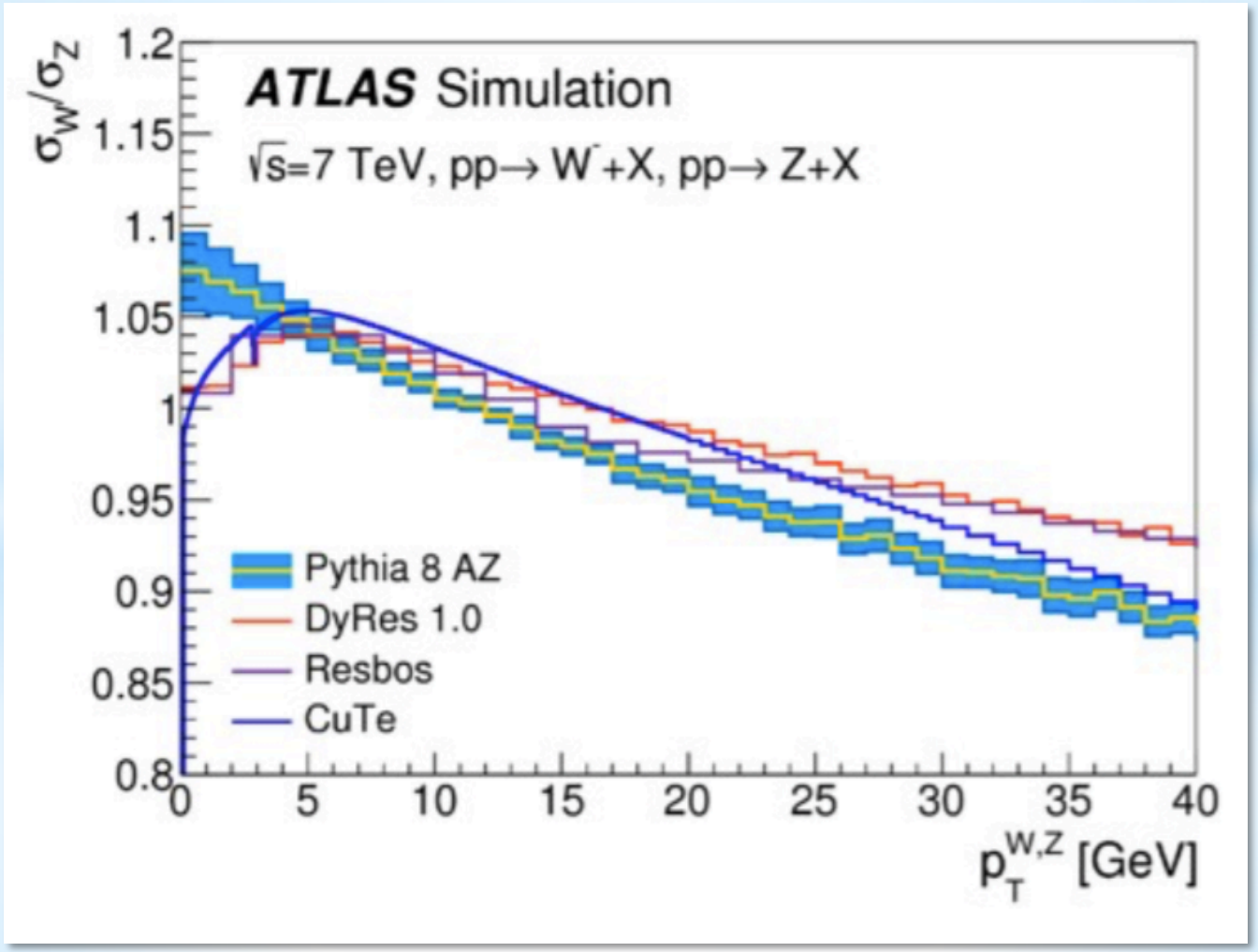
precisely measured pT(Z) -> prediction -> pT(W)

$$\frac{\partial \sigma_W^{\mathrm{True}}}{\partial p_{\mathrm{T}}} \sim \frac{\partial \sigma_W^{\mathrm{TH}}}{\partial p_{\mathrm{T}}}$$ 2-5% (NNLO+NNLL)

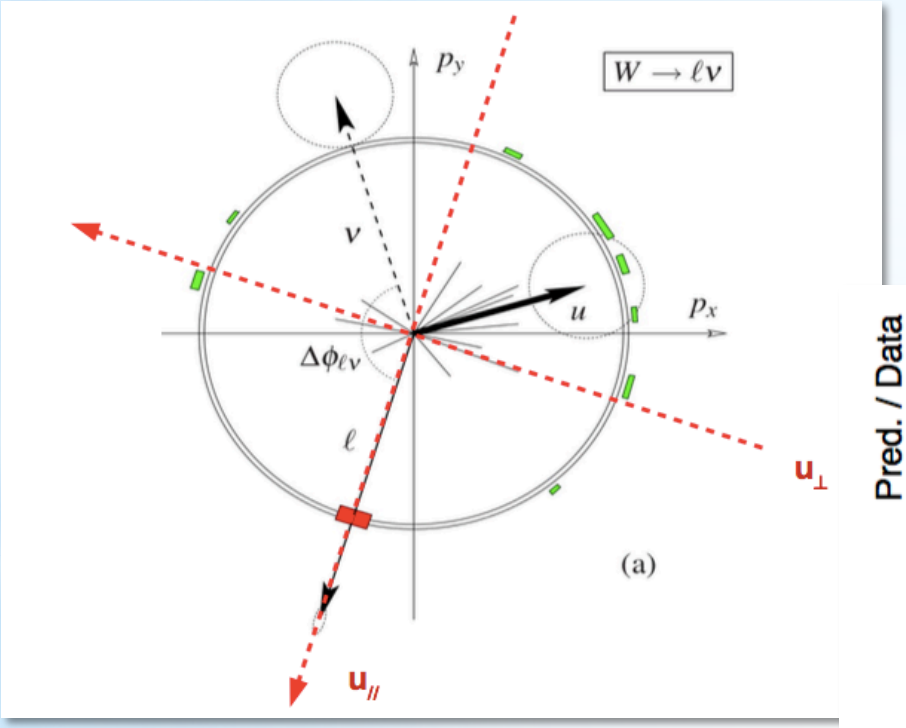
$$\sim \frac{\partial \sigma_Z^{\mathrm{Exp}}}{\partial p_{\mathrm{T}}} \times \frac{\partial \sigma_W^{\mathrm{TH}}/\partial p_{\mathrm{T}}}{\partial \sigma_Z^{\mathrm{TH}}/\partial p_{\mathrm{T}}}$$ 0.5% ⊕ 1-2% ? (NLL!)

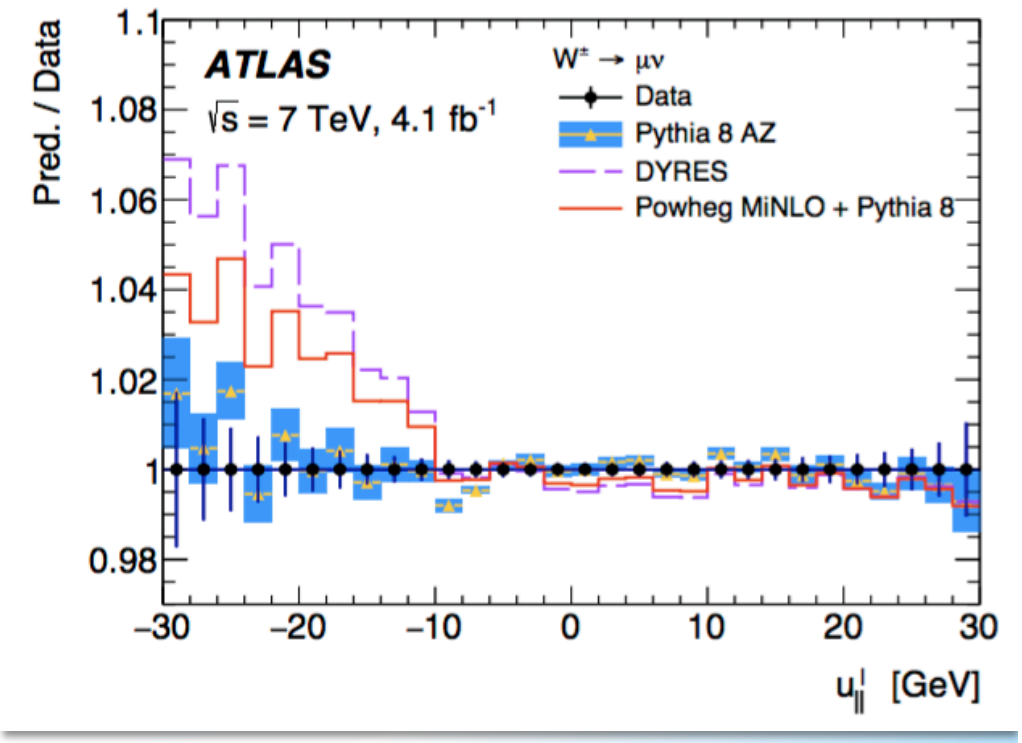
$$\sim \frac{\partial \sigma_W^{\mathrm{Exp}}}{\partial p_{\mathrm{T}}}$$ ~1% ? (experimental)

Theory uncertainties

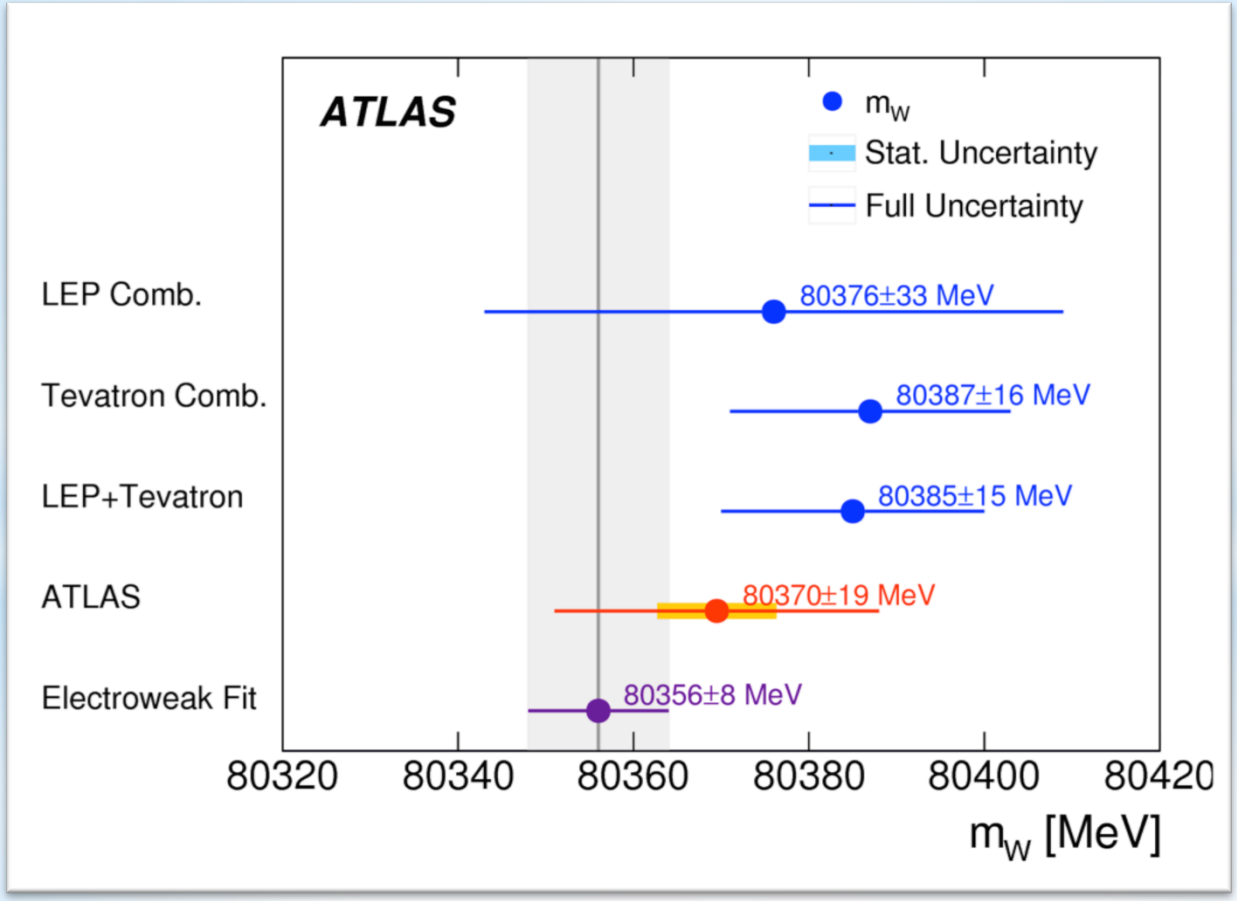


Theory uncertainties

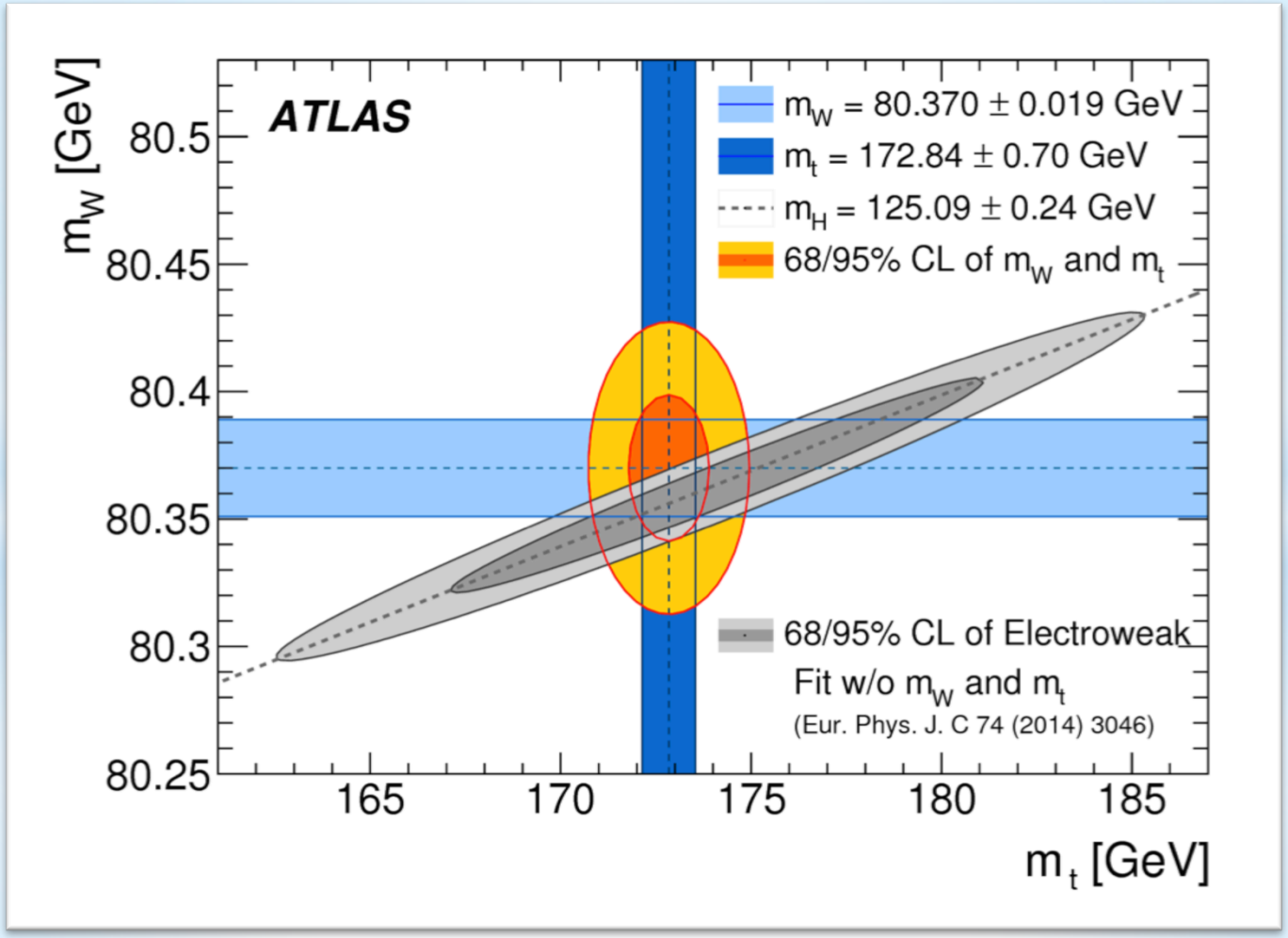




W mass measurement

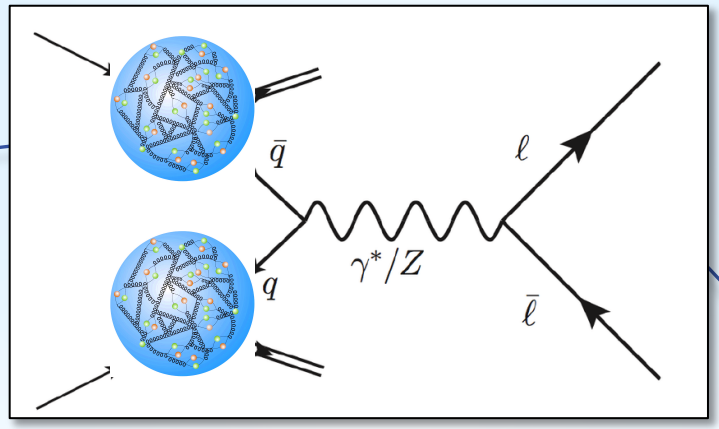


W mass measurement



Neutral Drell-Yan production

valence & sea PDF sensitivity through dσ/dη



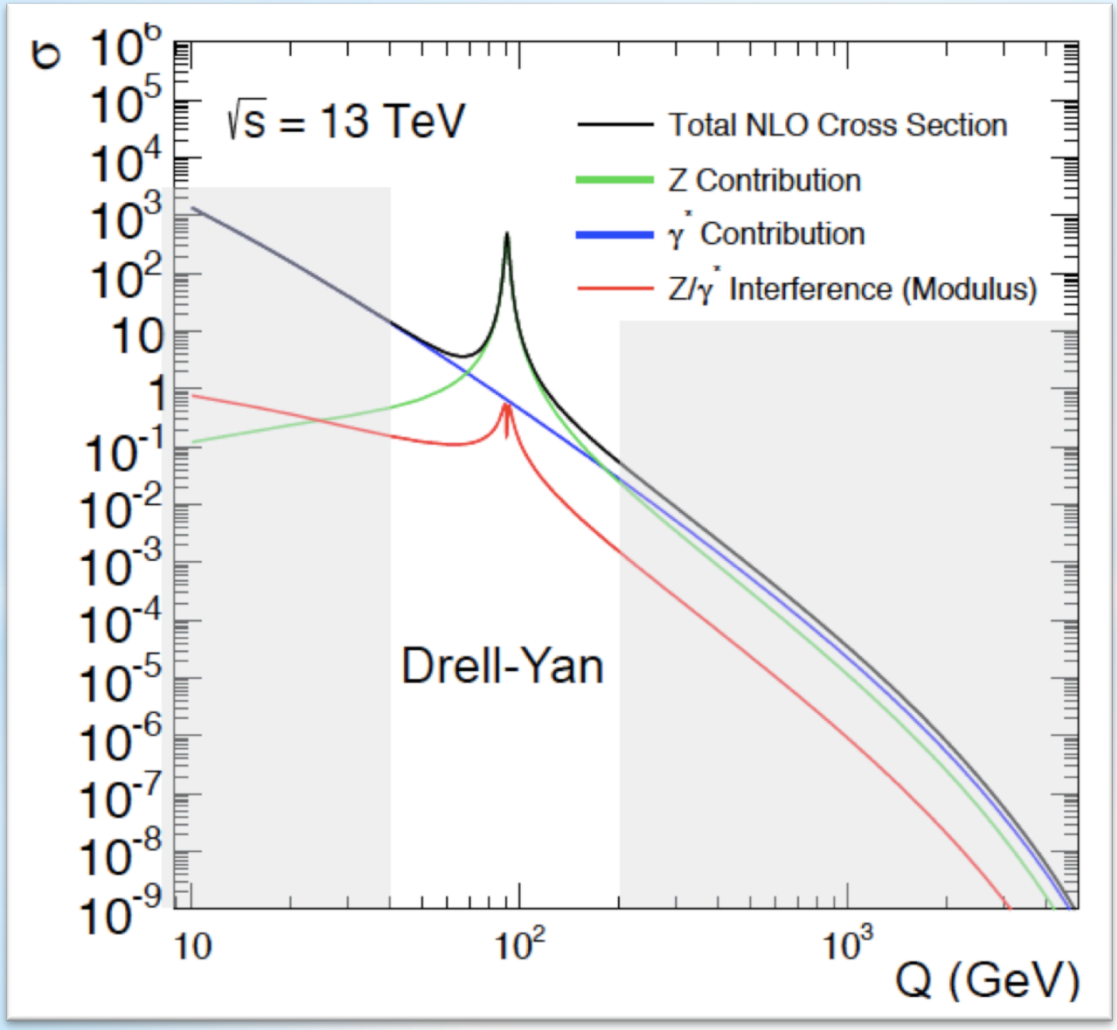
$$Z_\mu(x) = \cos\theta \times W^3_\mu(x) - \sin\theta \times B_\mu(x)$$
$$A_\mu(x) = \sin\theta \times W^3_\mu(x) + \cos\theta \times B_\mu(x)$$

$$\frac{g}{\cos\theta_W}(J^3 - \sin^2\theta_W J^{EM})Z^0 + eJ^{EM}A^0$$

Z boson:

$$g_L = \mathrm{I}_3 - \mathrm{Q}\sin^2\theta_W \qquad g_R = -\mathrm{Q}\sin^2\theta_W$$

Neutral Drell-Yan production



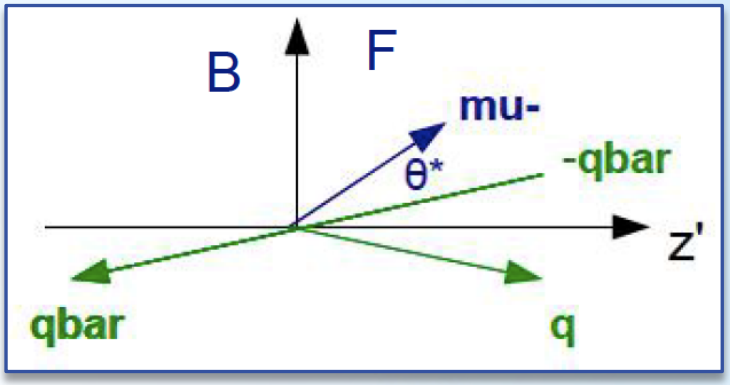
Z Boson:

$$g_L = \mathrm{I}_3 - \mathrm{Q}\sin^2\theta_W$$

$$g_R = -\mathrm{Q}\sin^2\theta_W$$

Forward-Backward Asymmetry

$$A_{\mathrm{FB}} = \frac{\sigma_{\mathrm{F}} - \sigma_{\mathrm{B}}}{\sigma_{\mathrm{F}} + \sigma_{\mathrm{B}}}$$



$$\frac{\mathrm{d}^3\sigma}{\mathrm{d}m_{\ell\ell}\mathrm{d}y_{\ell\ell}\mathrm{d}\cos\theta^*} = \frac{\pi\alpha^2}{3m_{\ell\ell}s}\sum_q P_q\left[f_q(x_1,Q^2)f_{\bar{q}}(x_2,Q^2) + (q \leftrightarrow \bar{q})\right]$$

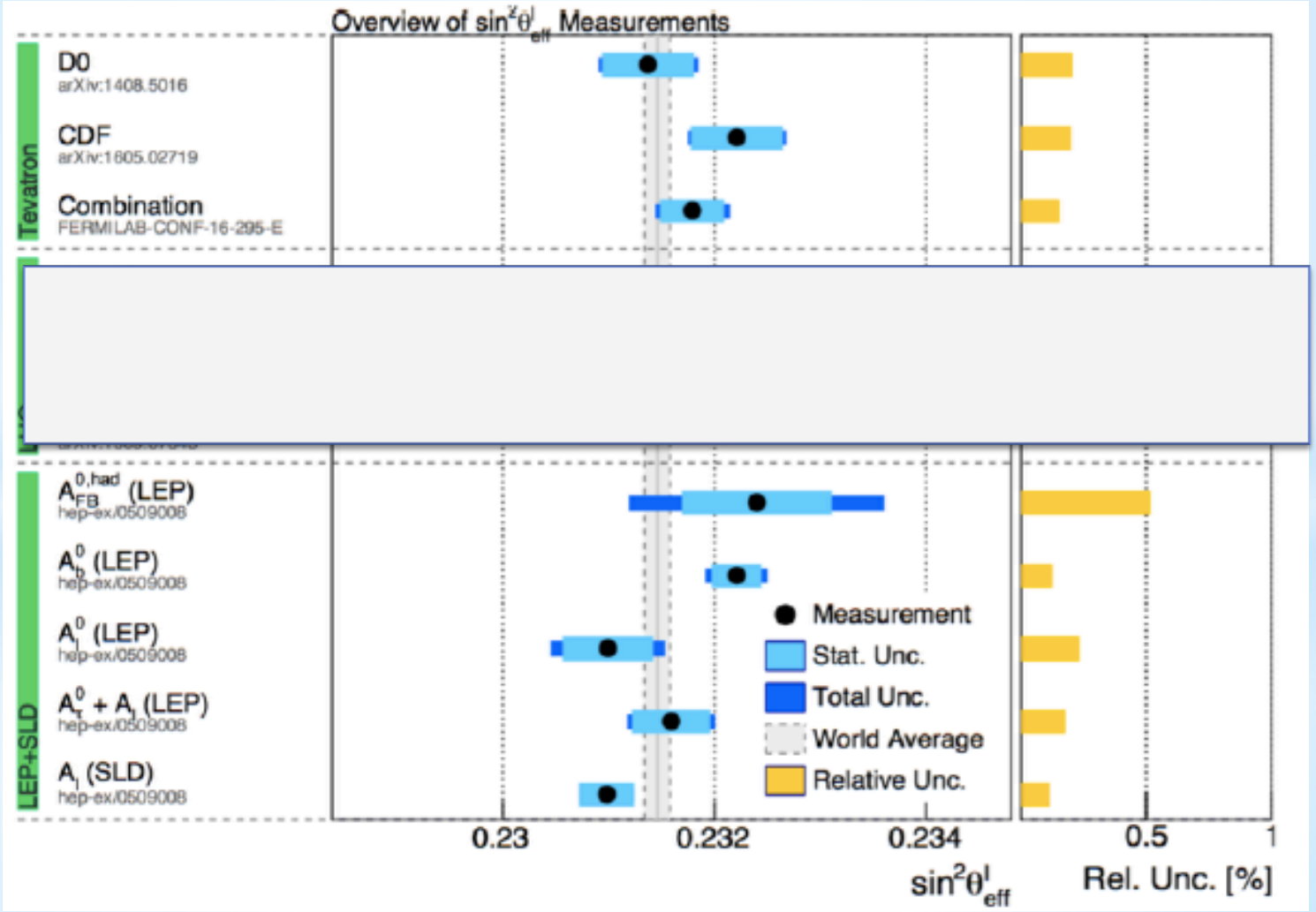
$$P_q = e_\ell^2 e_q^2(1+\cos^2\theta^*) \quad \gamma$$

$$+ e_\ell e_q \frac{2m_{\ell\ell}^2(m_{\ell\ell}^2 - m_{\mathrm{Z}}^2)}{\sin^2\theta_{\mathrm{W}}\cos^2\theta_{\mathrm{W}}[(m_{\ell\ell}^2 - m_{\mathrm{Z}}^2)^2 + \Gamma_{\mathrm{Z}}^2 m_{\mathrm{Z}}^2]}[v_\ell v_q(1+\cos^2\theta^*) + 2a_\ell a_q\cos\theta^*] \quad \gamma/\mathrm{Z}$$

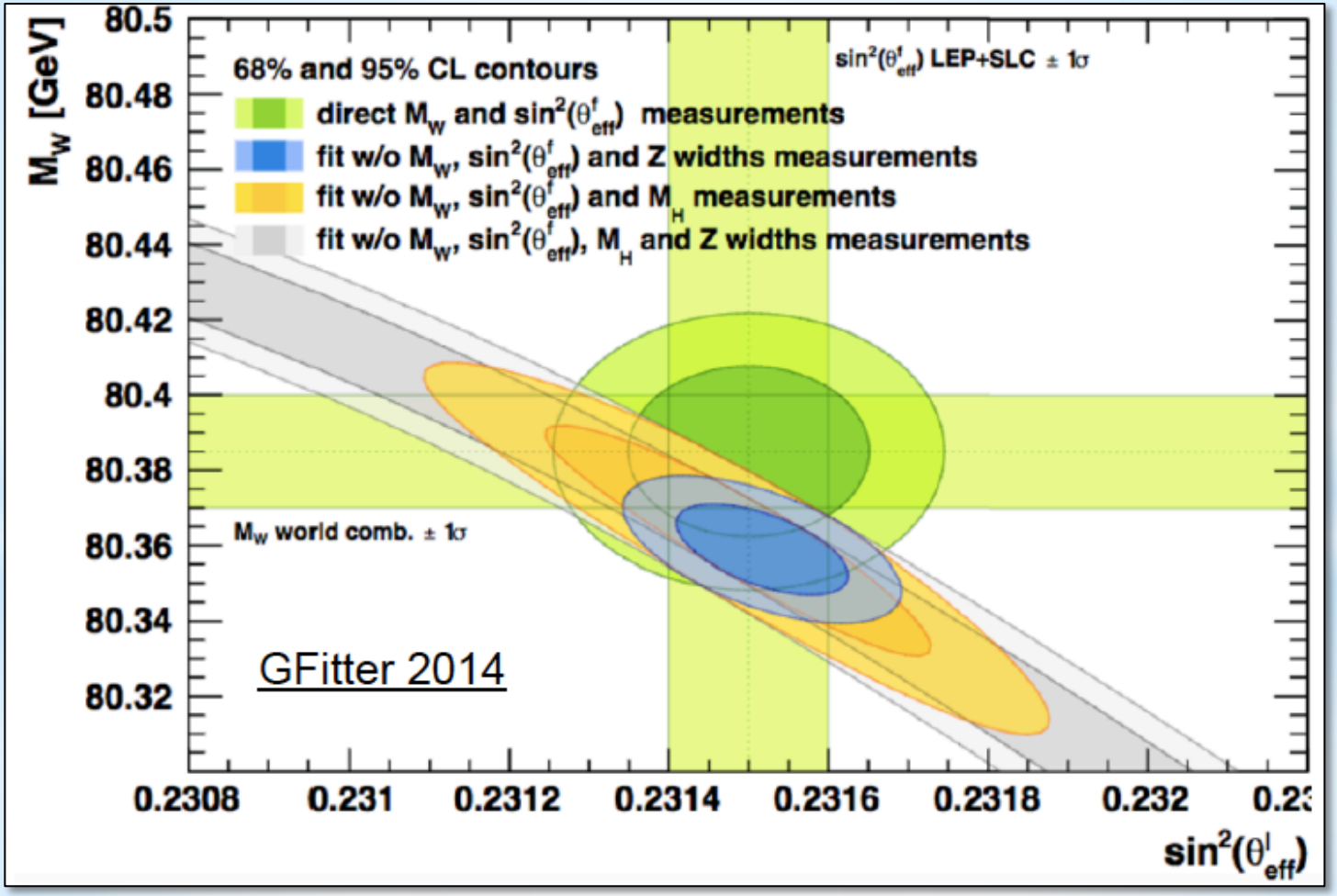
$$+ \frac{m_{\ell\ell}^4}{\sin^4\theta_{\mathrm{W}}\cos^4\theta_{\mathrm{W}}[(m_{\ell\ell}^2 - m_{\mathrm{Z}}^2)^2 + \Gamma_{\mathrm{Z}}^2 m_{\mathrm{Z}}^2]}[(a_\ell^2+v_\ell^2)(a_q^2+v_q^2)(1+\cos^2\theta^*) + 8a_\ell v_\ell a_q v_q\cos\theta^*].$$

Z

The Weinberg angle

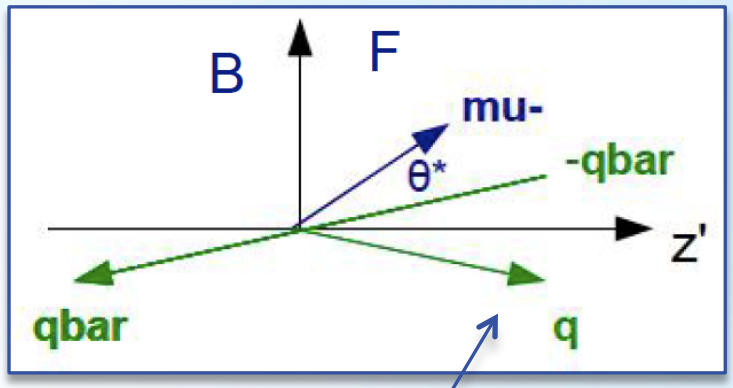


Neutral Drell-Yan production

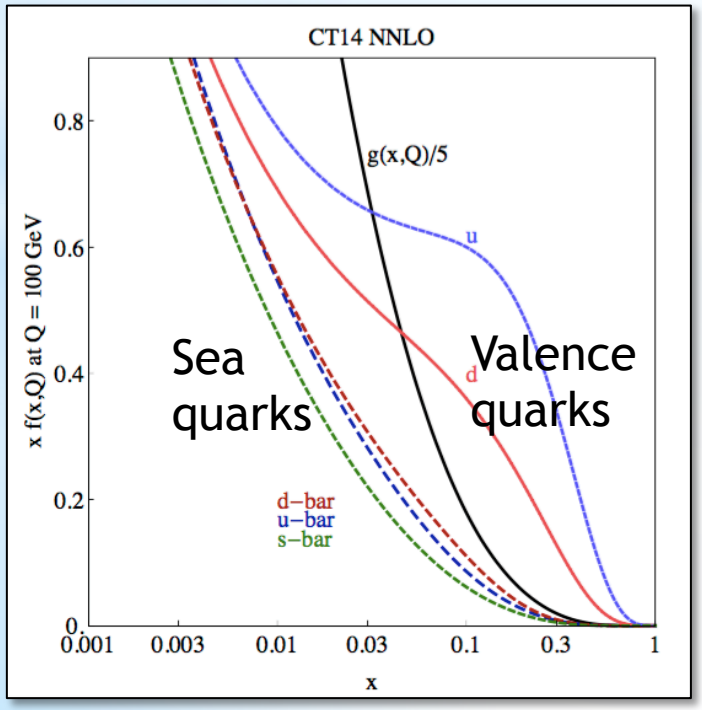


A_{FB}: dilution in pp colliders

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$



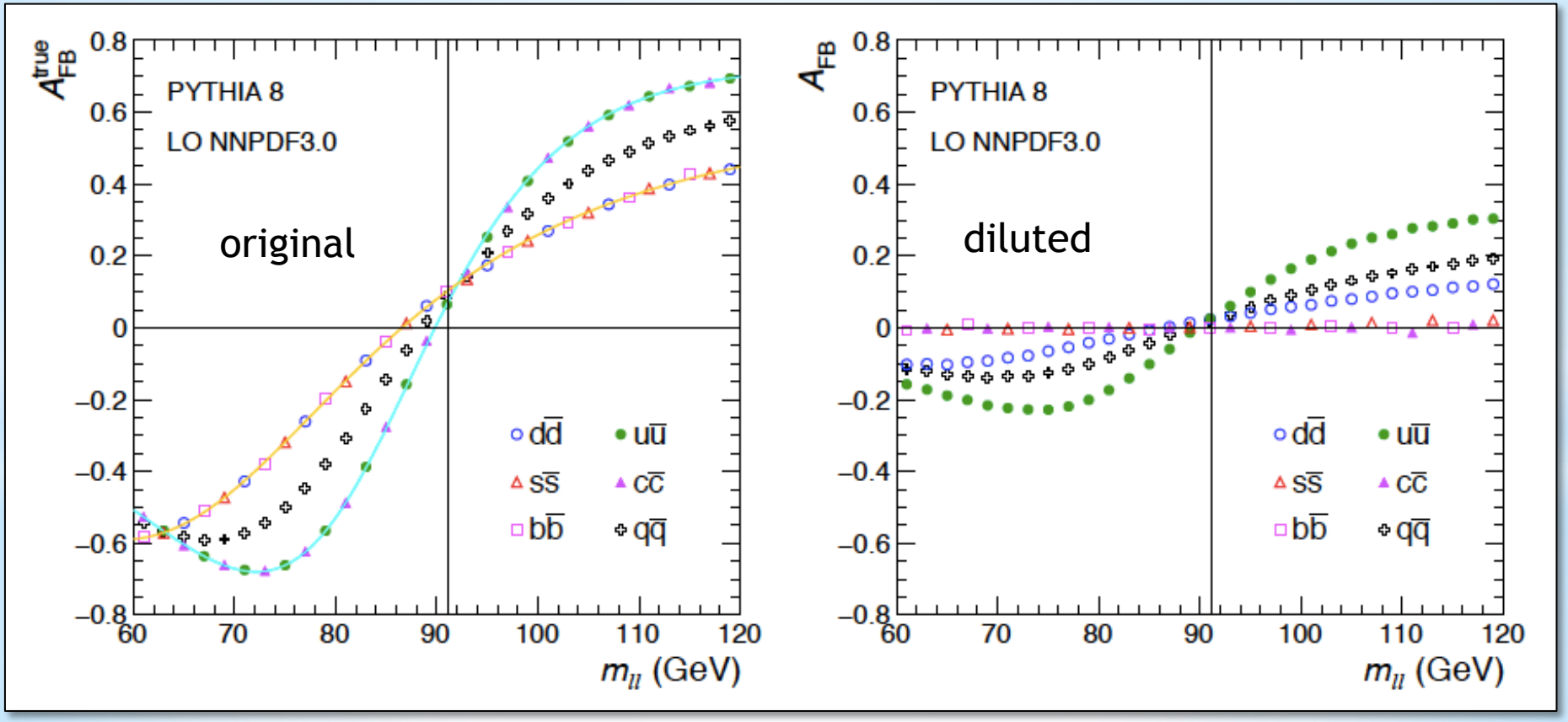
quark direction ??



Z/γ boosted -> work in specific lepton rest frame (Collin Sopers frame)

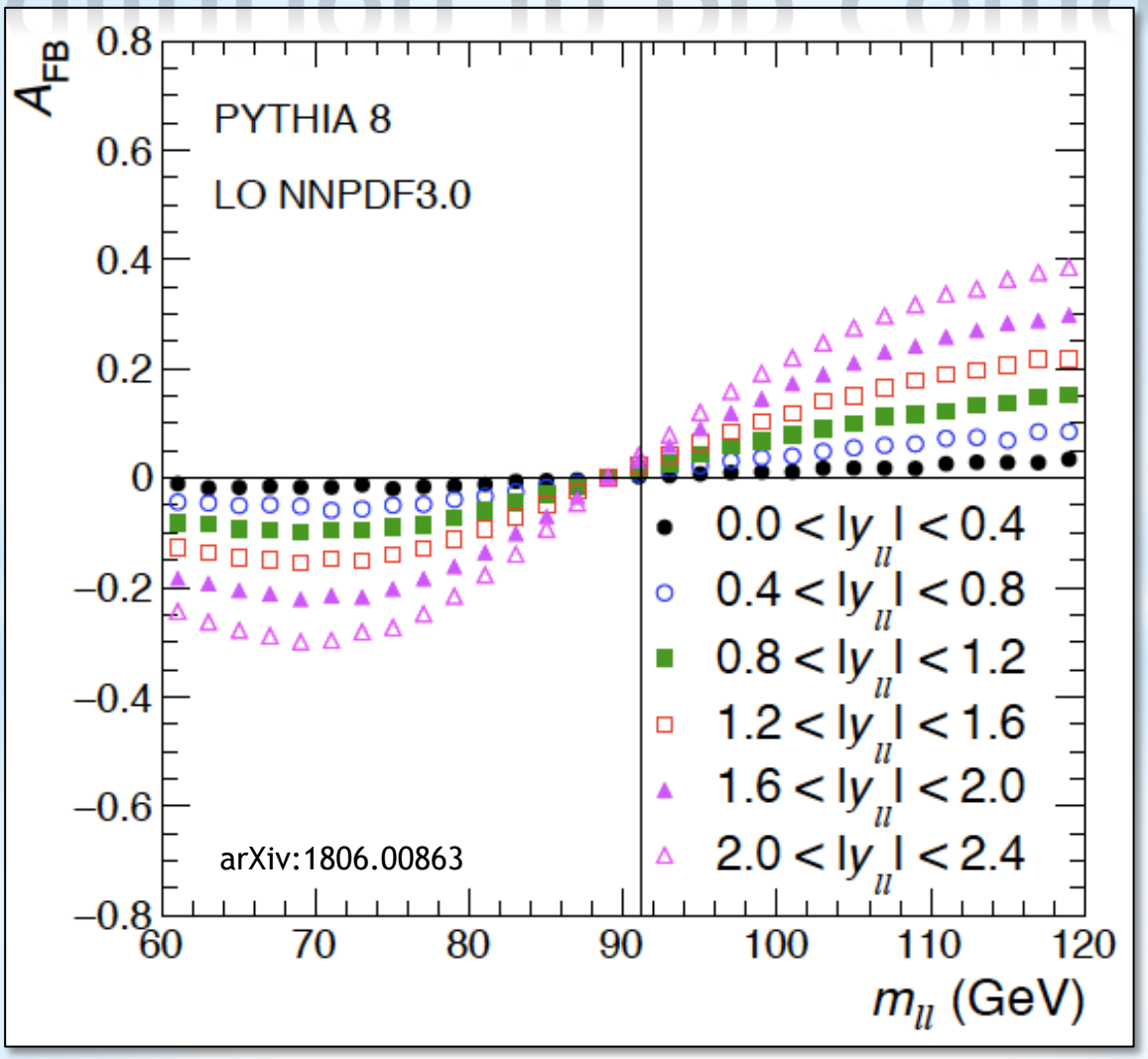
Polar angle θ* (lepton – quark)
-> from Z/γ direction -> dilution

A_{FB}: dilution in pp colliders

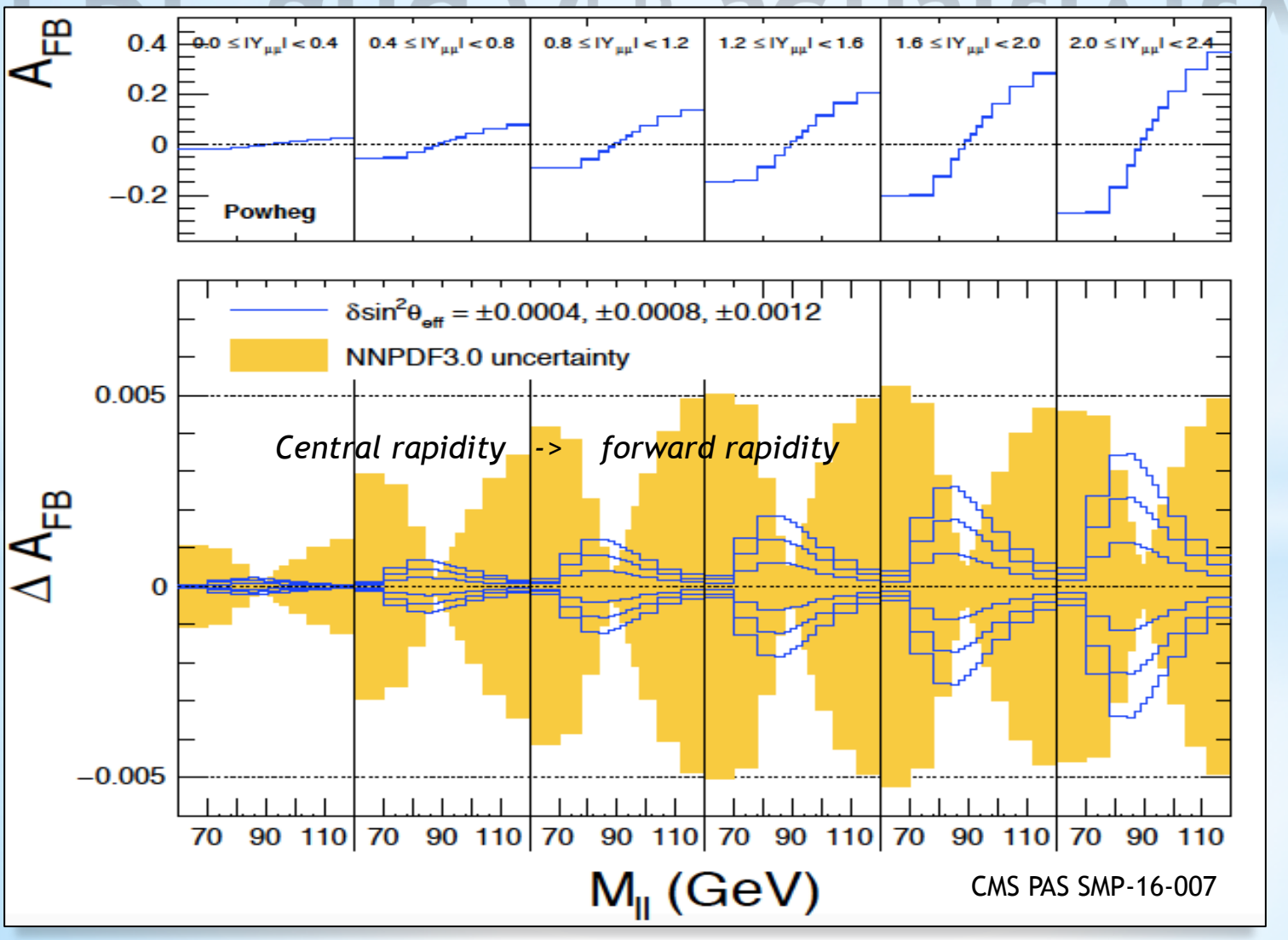


arXiv:1806.00863

A_{FB}: dilution in pp colliders



PDF and A_{FB} sensitivity



PDFs
Sensitivity off-peak

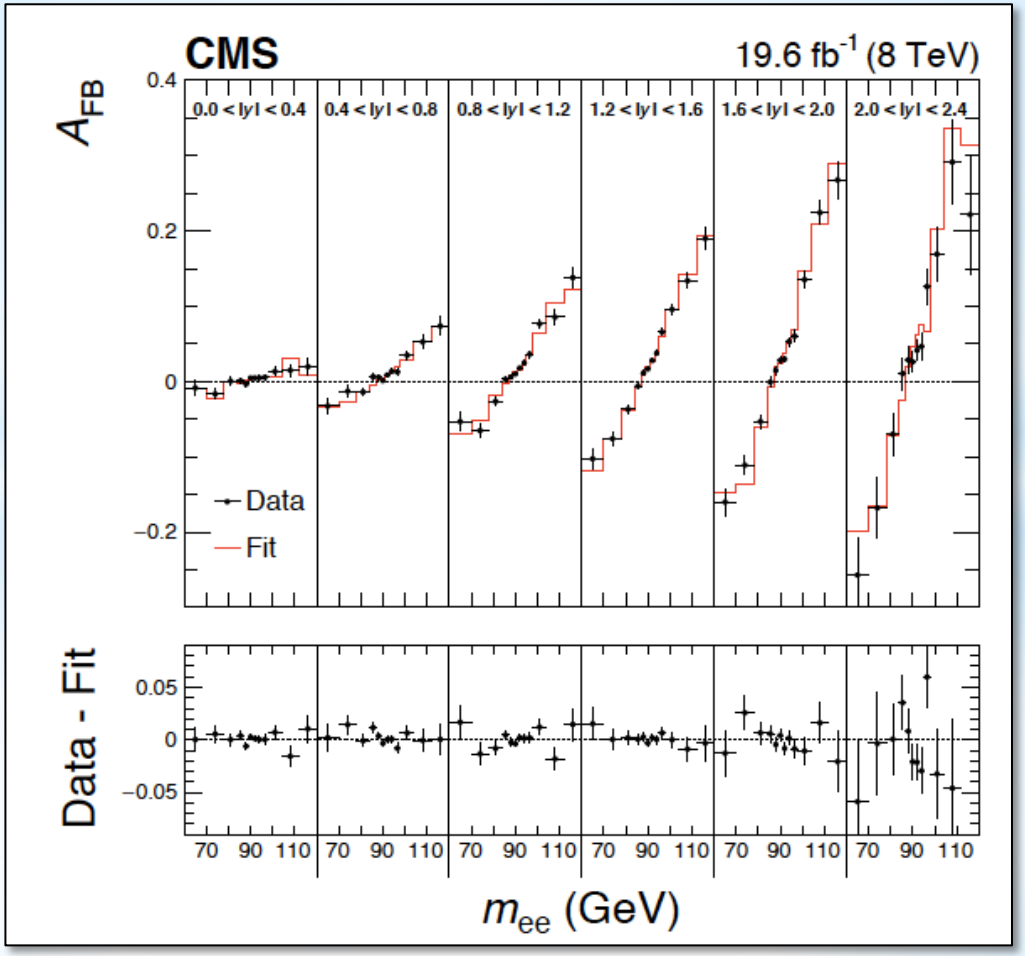
$\sin^2\theta_W$
Sensitivity at the peak and at large η

arXiv:1806.00863

Template fit

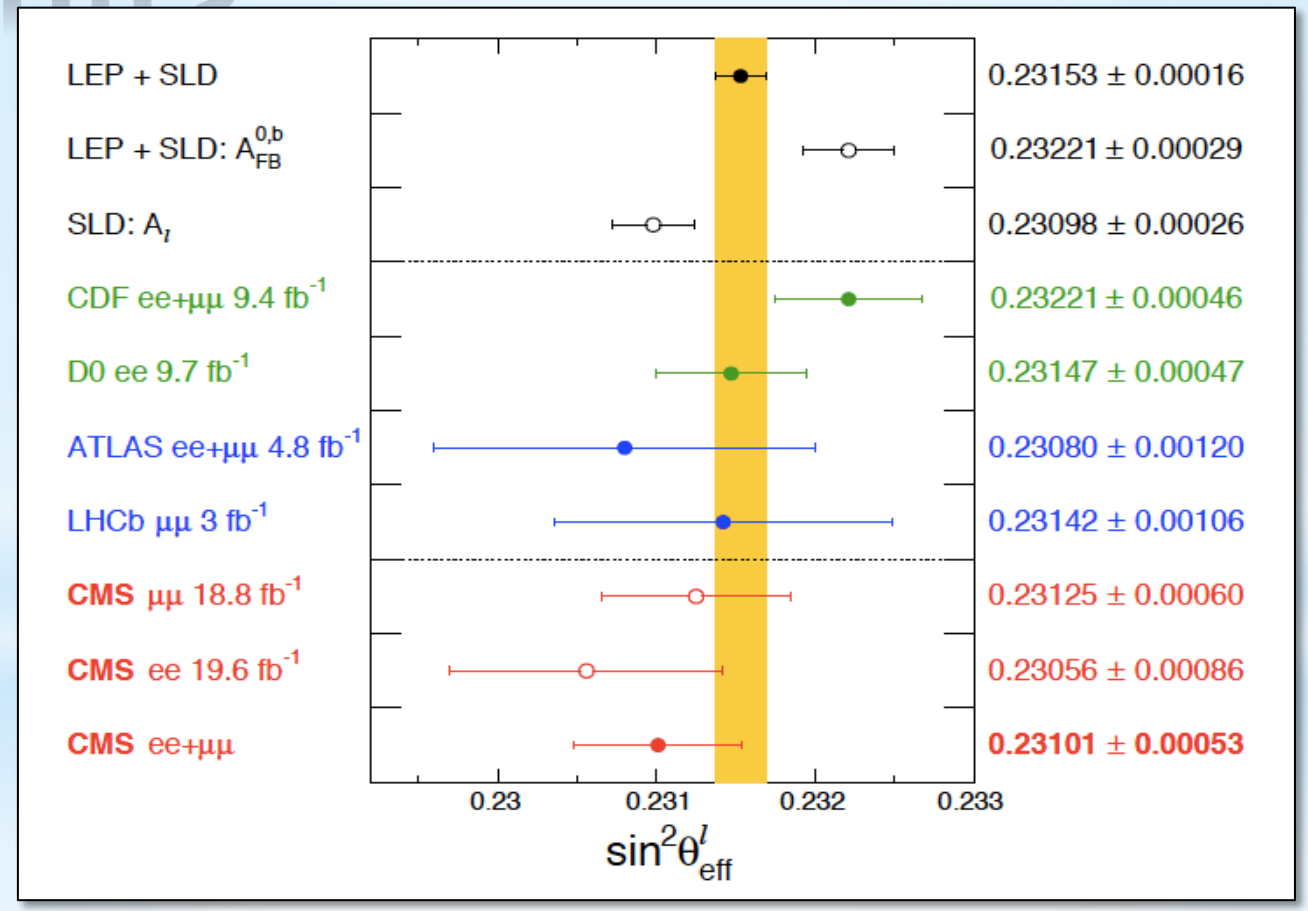
Template-fit (Powheg+Pythia8 templates) -> PDF & $\sin^2\theta_W$

arXiv:1806.00863



Results

arXiv:1806.00863

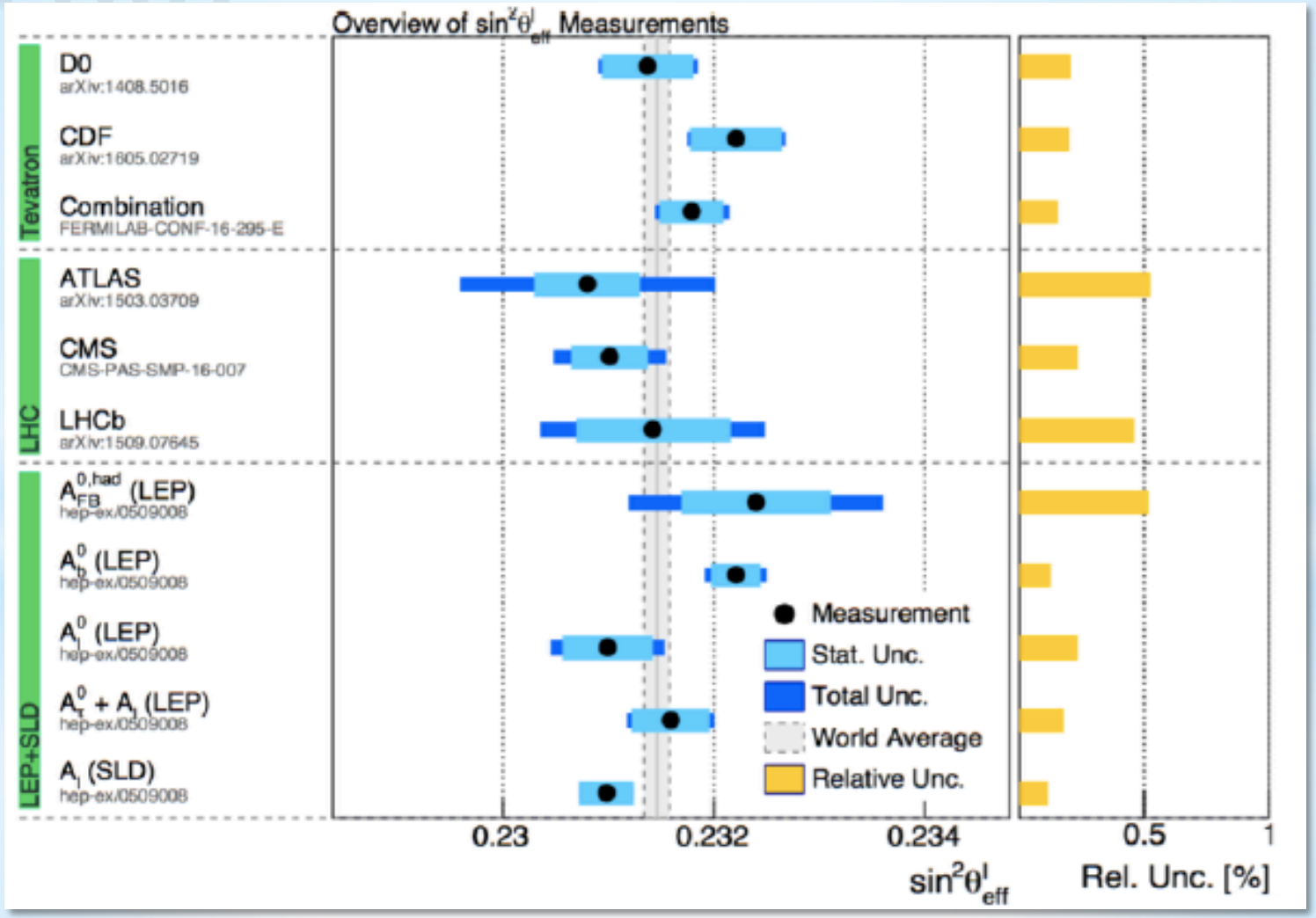


Uncertainties comparable with Tevatron experiments
Statistical uncertainties dominating component

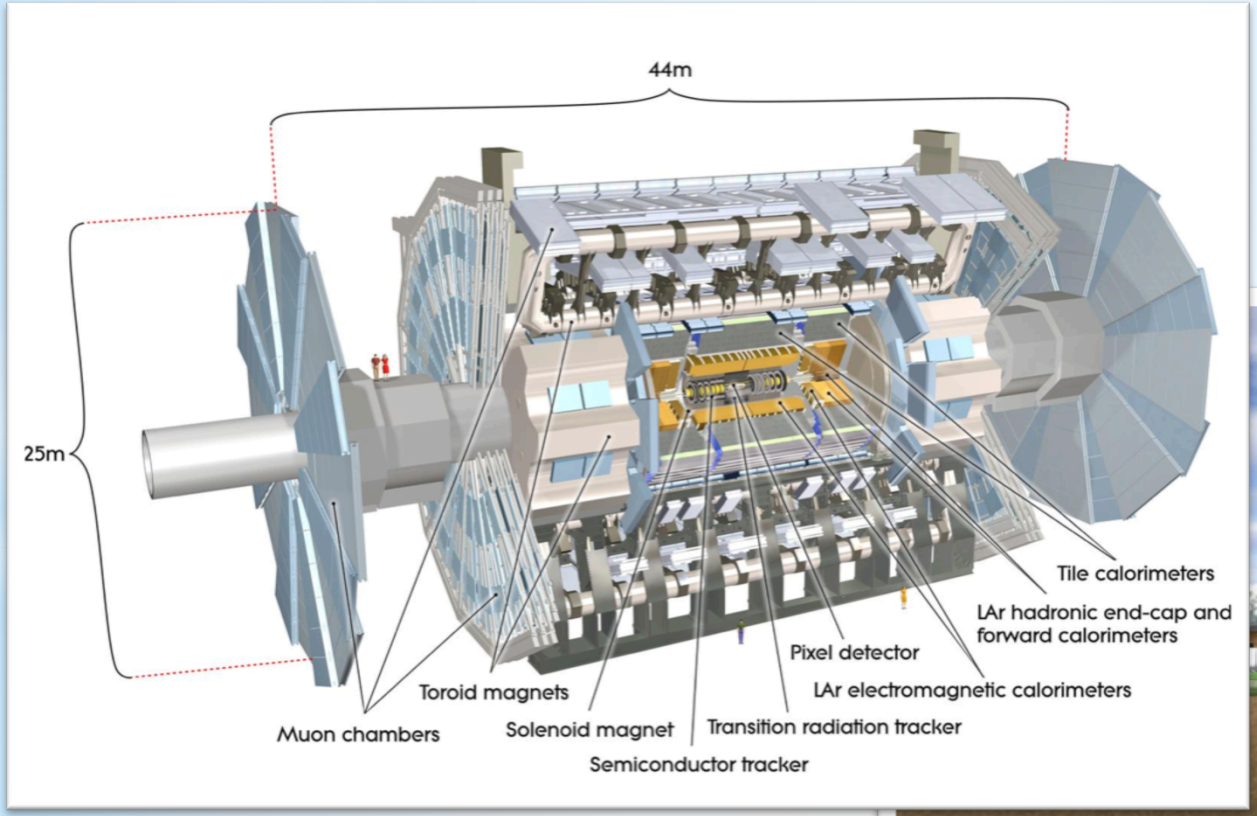
$$\sin^2\theta^{\ell}_{\text{eff}} = 0.23101 \pm 0.00036\,(\text{stat}) \pm 0.00018\,(\text{syst}) \pm 0.00016\,(\text{theo}) \pm 0.00031\,(\text{PDF})$$

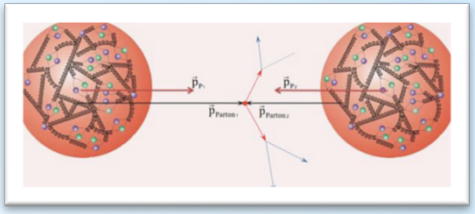
Results

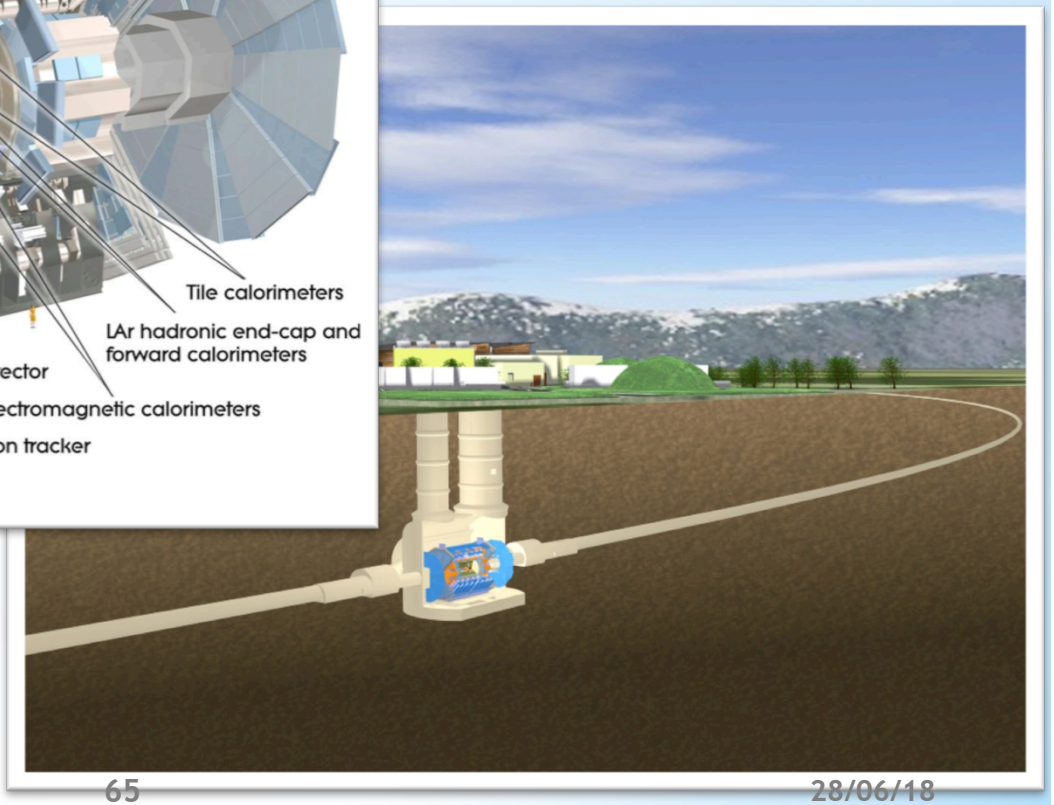
arXiv:1806.00863



The ATLAS experiment







LHC: proton synchrotron
Circumference: 27km
Center-of-mass energy: 13 TeV
40 MHz collisions (1 kHz recorded)

Appendix

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}p_{\mathrm{T}}\,\mathrm{d}y} = \left[\frac{\mathrm{d}\sigma(y)}{\mathrm{d}y}\right]\left[\frac{1}{\sigma_y}\frac{\mathrm{d}\sigma_y(p_{\mathrm{T}})}{\mathrm{d}p_{\mathrm{T}}}\right]$$

- Rapidity distribution and angular coefficients:
  - NNLO fixed-order QCD
  - PDF : CT10nnlo
- p_T distribution at given rapidity
  - Pythia AZ. Tuned parameters : α_S^{ISR} ; intrinsic k_T ; ISR cut-off
  - PDF used in the parton shower : CTEQ6L1

Appendix

$$\cos\theta^* = \frac{2(P_1^+ P_2^- - P_1^- P_2^+)}{\sqrt{m_{\ell\ell}^2(m_{\ell\ell}^2 + p_{\mathrm{T},\ell\ell}^2)}} \times \frac{p_{z,\ell\ell}}{|p_{z,\ell\ell}|}$$

$$v_f / a_f = 1 - 4|Q_f| \sin^2 \theta^f_{\mathrm{eff}}$$

Appendix

- The uncertainty in the W p_T distribution, for given Z p_T distribution (cont'd)