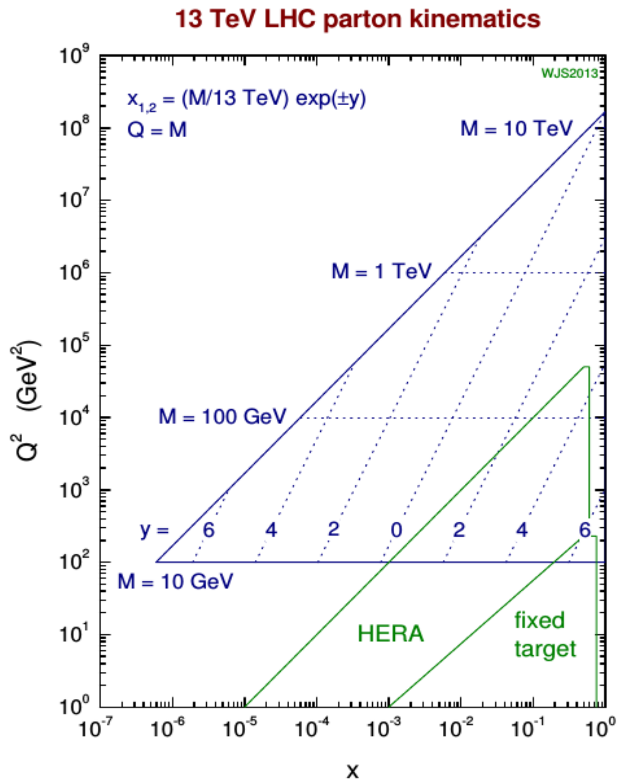
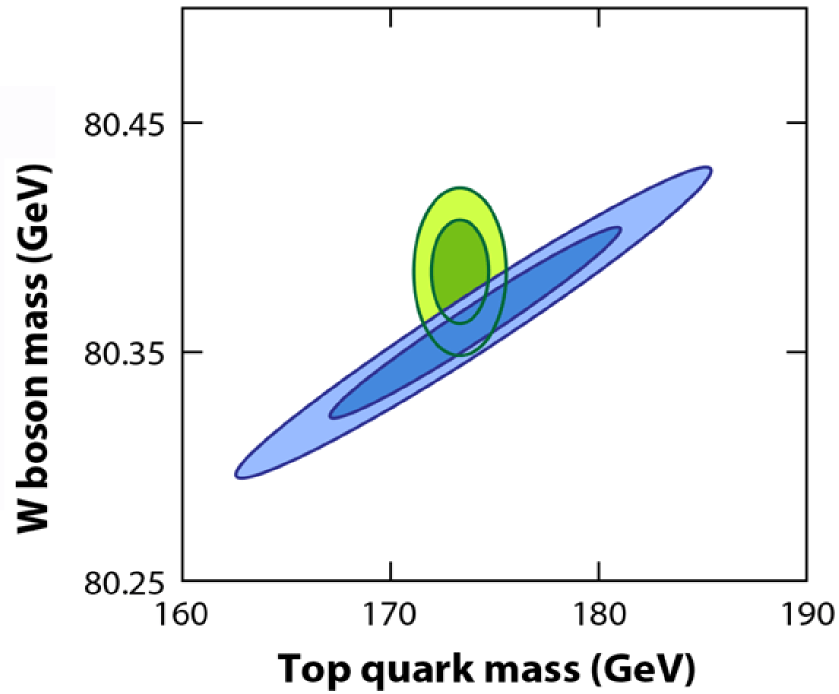
# Standard Model measurements




Chris Hays, Oxford University

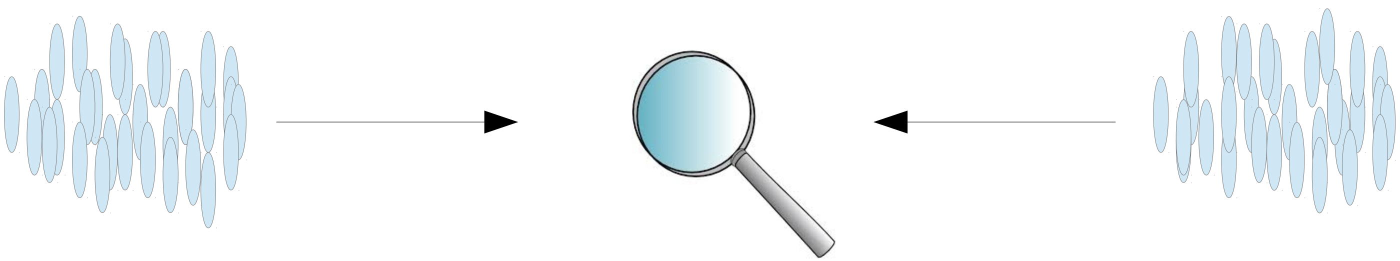
IOP Annual HEPP & APP conference
21 March 2016

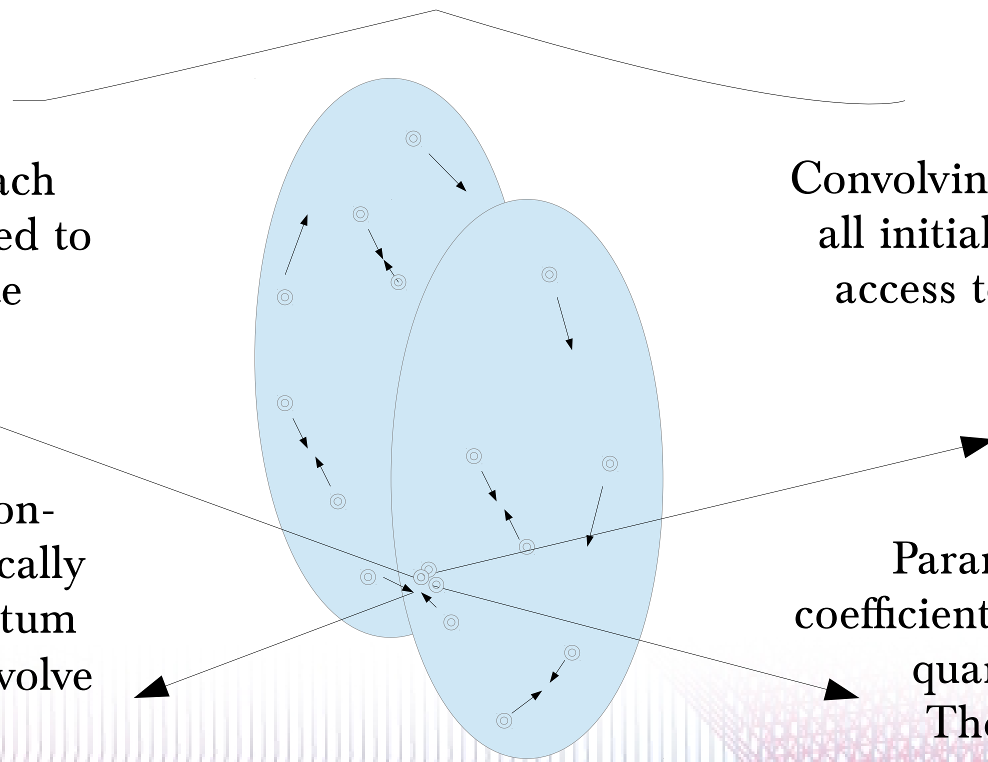
# Overview

- Hadron collider physics
- Parton distributions and underlying event
- Electroweak parameter measurements
- Electroweak boson self-coupling constraints

# Hadron collider physics

Highly relativistic (anti)proton bunches are collided inside a particle detector





Energy distribution of each parton in the proton needed to describe the initial state

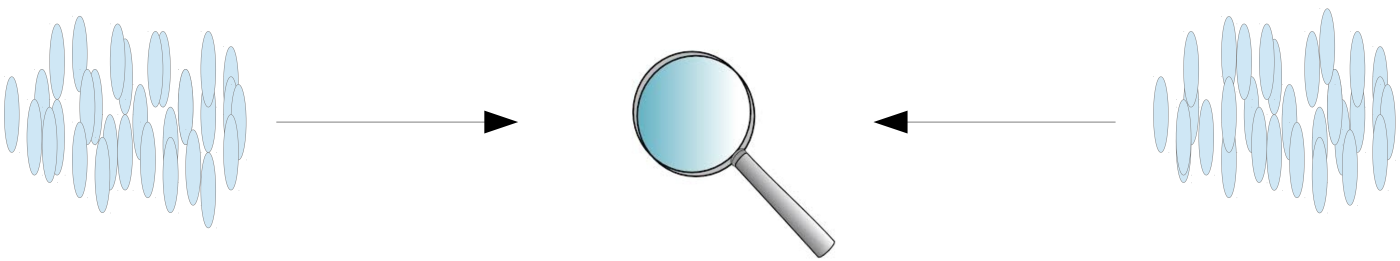
Distributions given by non-perturbative QCD: empirically determine parton momentum fraction x at low $Q^2$ and evolve to high $Q^2$

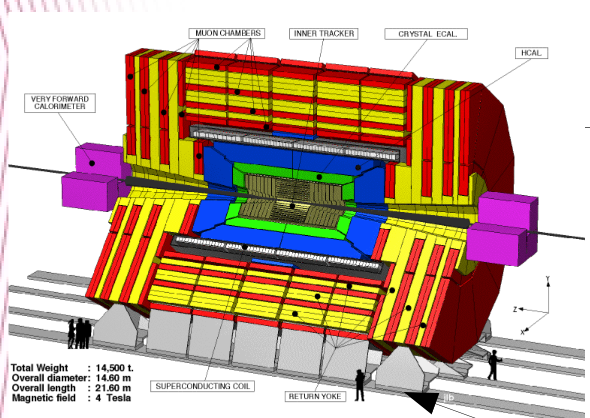
Convolving a given final state over all initial-state partons provides access to fundamental physics parameters

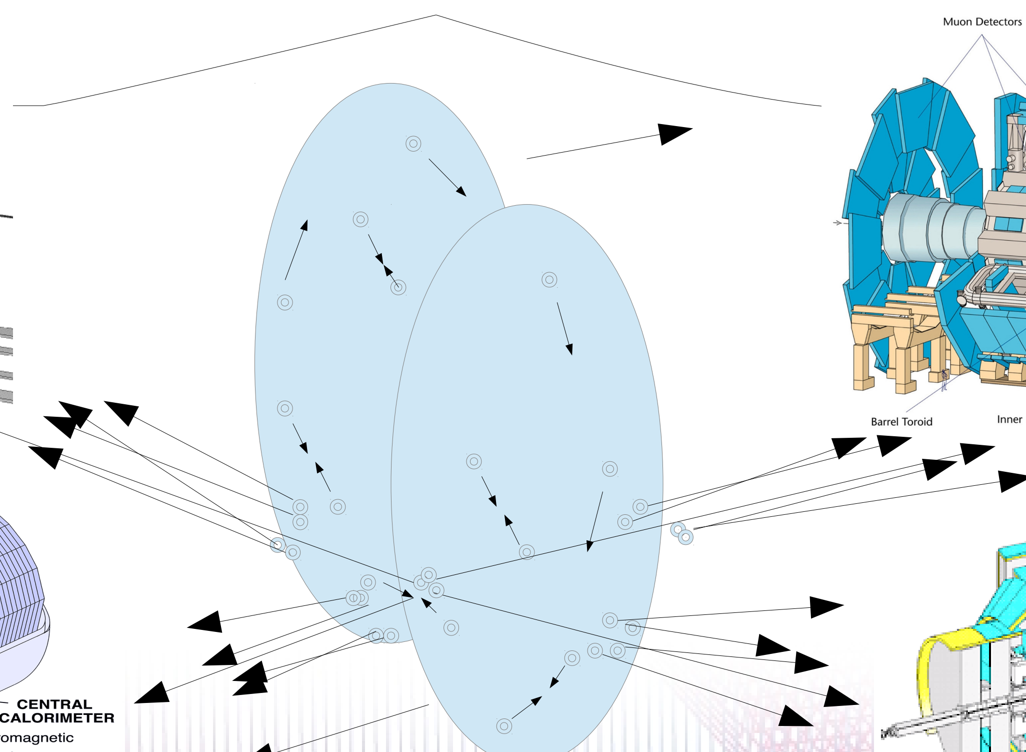
Parameters are operator coefficients in the Lagrangian of a quantum field theory:
The Standard Model

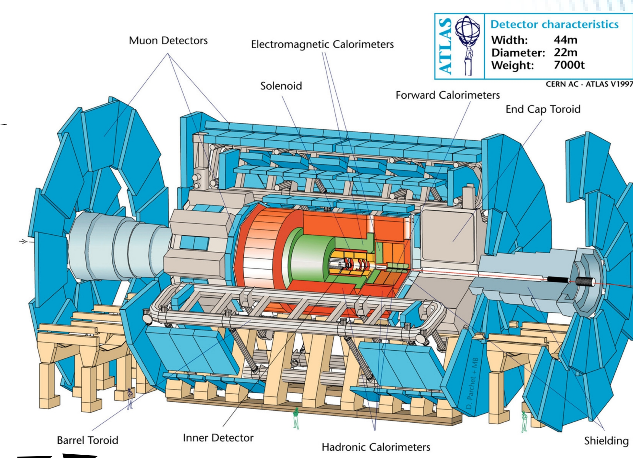
# Hadron collider physics

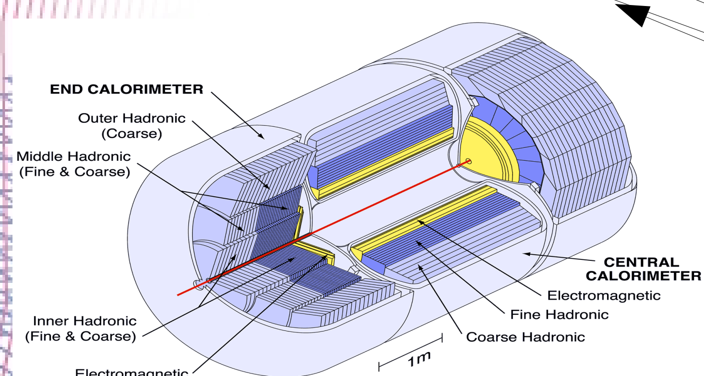
Highly relativistic (anti)proton bunches are collided inside a particle detector

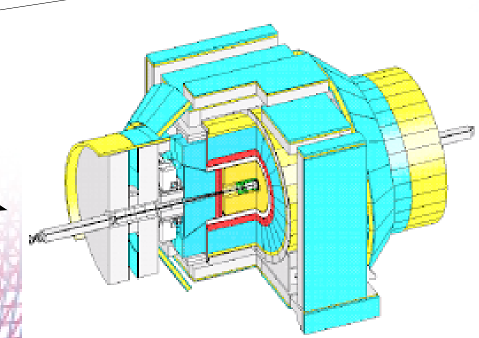




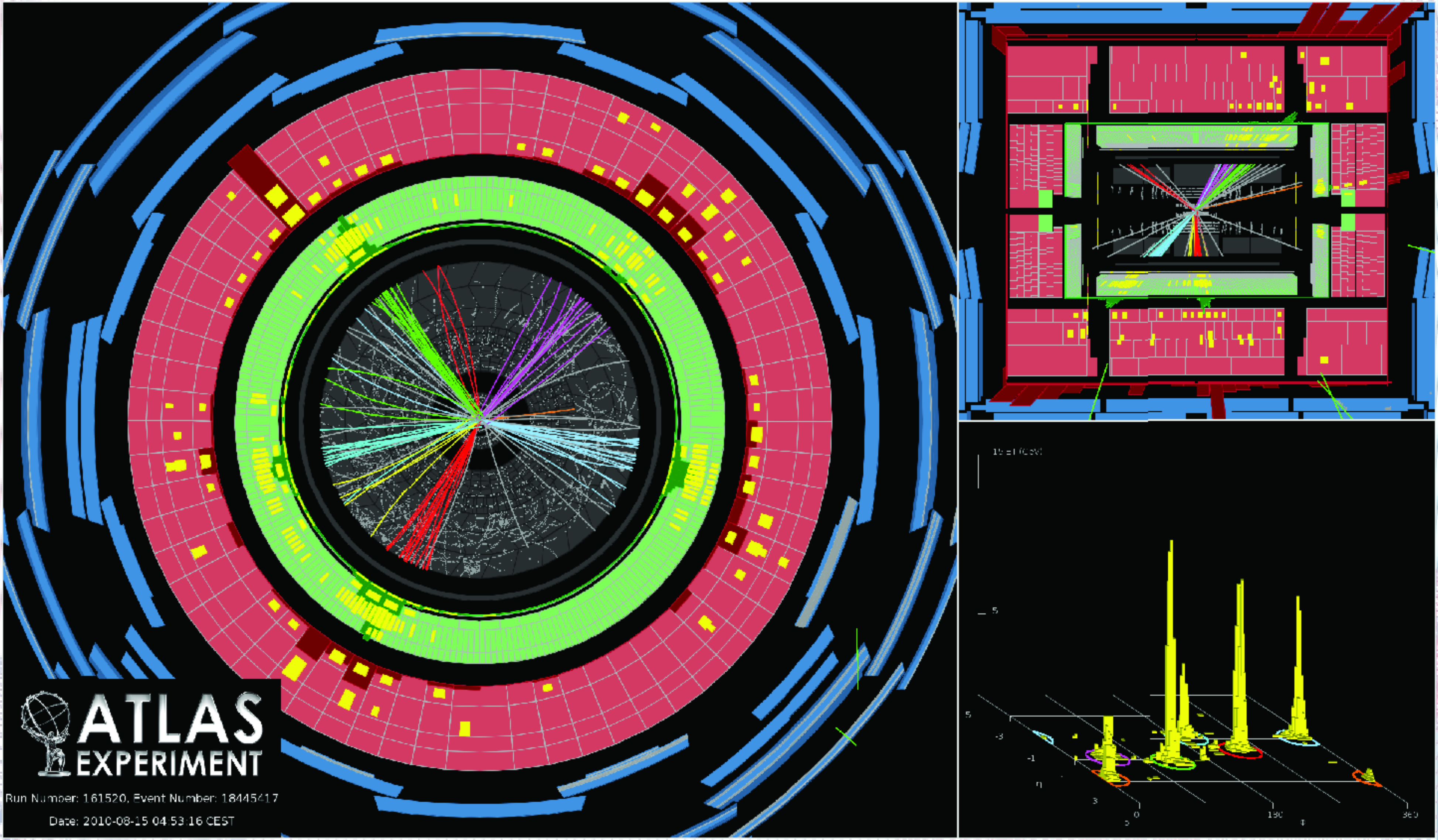


# Hadron collider physics

Final state of six hadronic jets

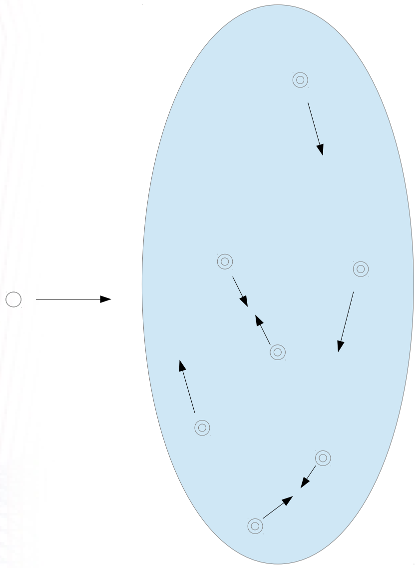


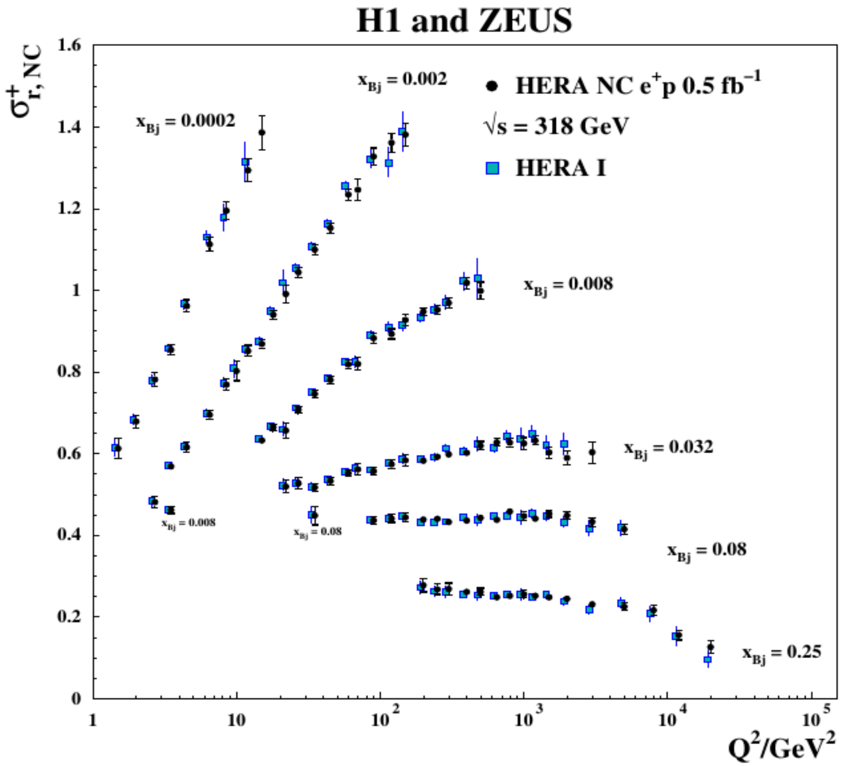

**LHC: 7 TeV → 8 TeV → 13 TeV**
**2011 → 2012 → 2015**

# Parton distribution functions

Empirical fit for distribution functions performed by multiple groups
MMHT, CTEQ, NNPDF, HERAPDF, and ABM

HERA ep data determines bulk of structure functions

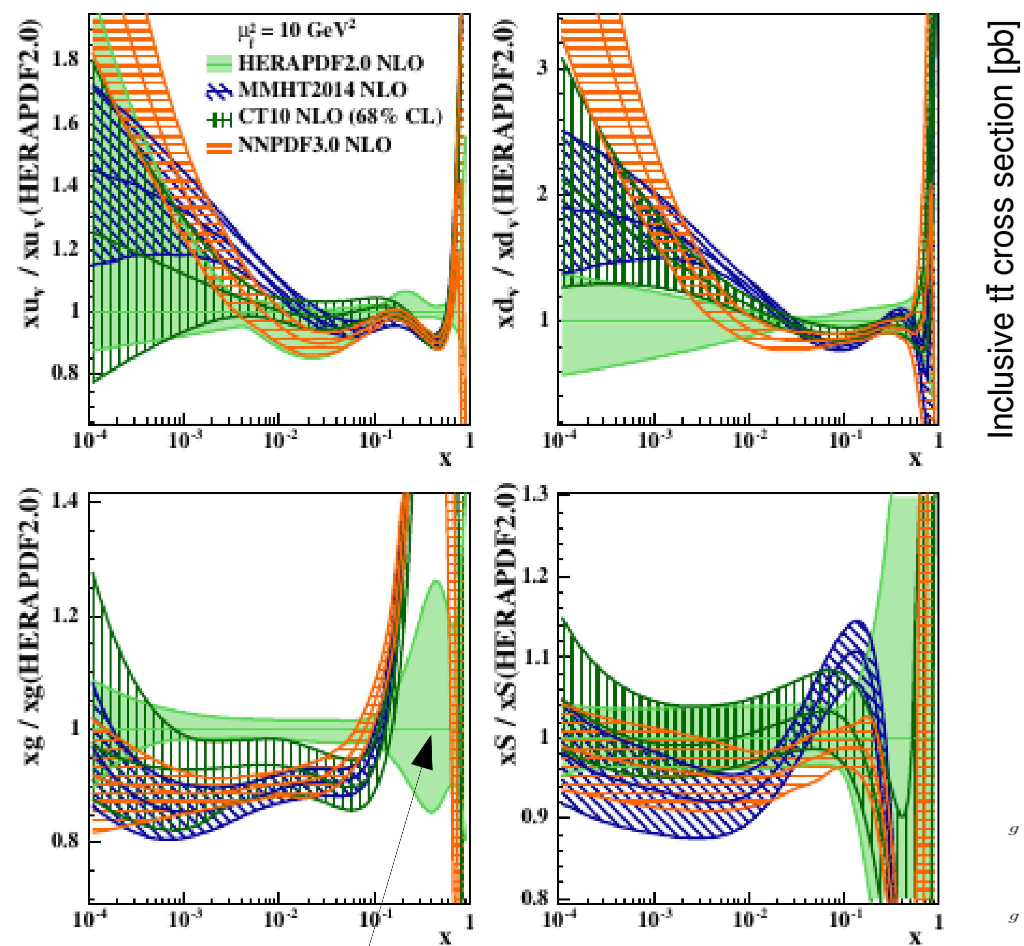


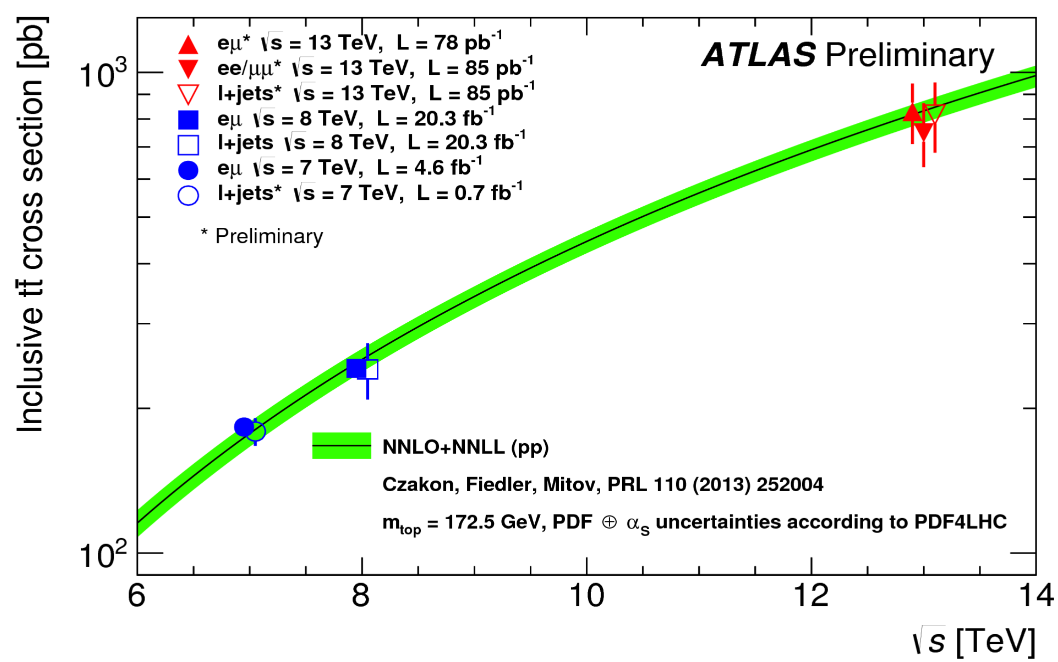


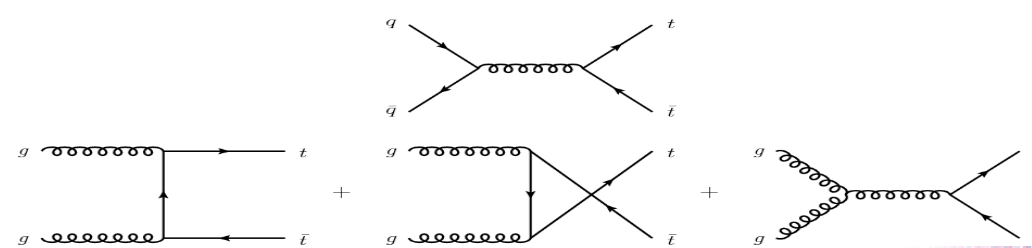

Final combination of ZEUS and H1 experimental results incorporated into HERAPDF2.0

**arxiv:1506.06042**

# Parton distribution functions



Gluon at high x not well determined by HERA

Best constrained by $p\overset{(-)}{p}$ collision data

Top quark pairs produced by high-x gluons

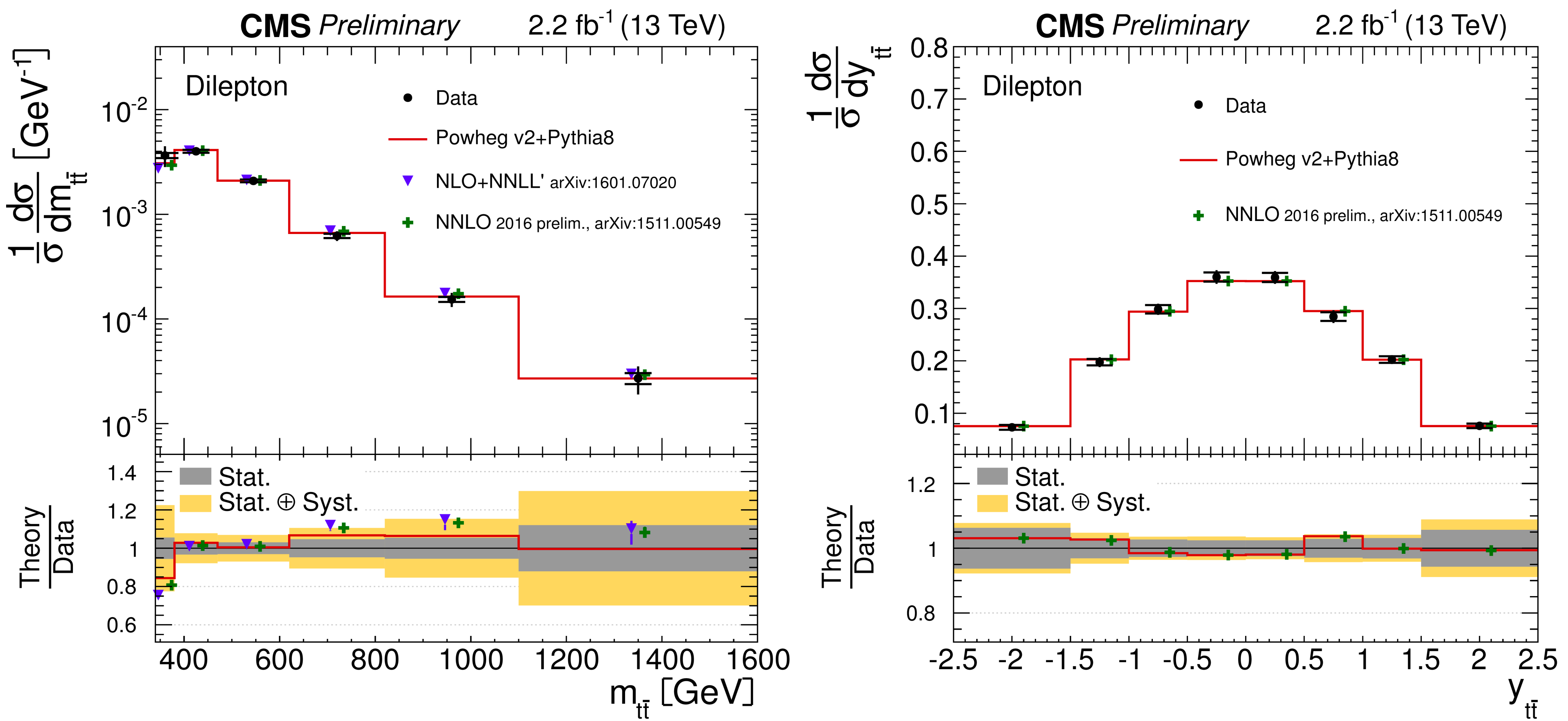
Now have cross section measurements at 3 LHC energies (+ 2 Tevatron energies)



**See talk by F Wilk (parallel 2B)**

# Differential top quark production

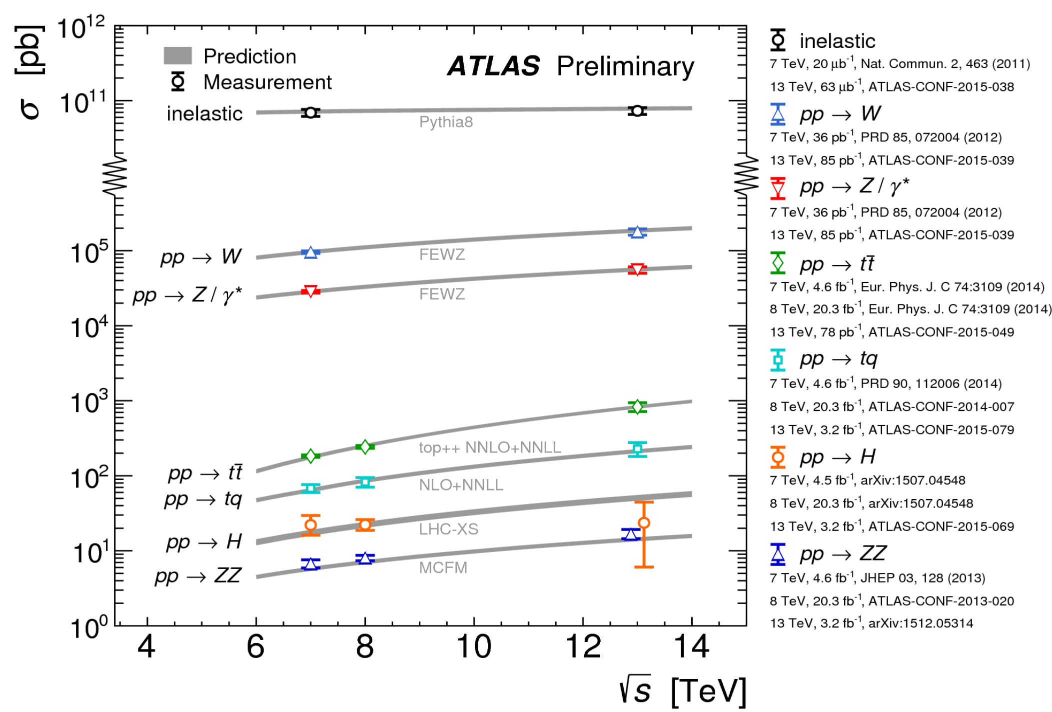
Further probe kinematics with measurements differential in mass and rapidity of the tt pair



# Parton distribution functions

Wide range of LHC data further constraining PDFs:
inclusive jet, W/Z cross sections, W+charm, W/Z+jets, bb, cc

| Reaction | Observable | PDFs | $x$ | $Q$ |
|---|---|---|---|---|
| $pp \to W^{\pm} + X$ | $d\sigma(W^{\pm})/dy_l$ | $q, \bar{q}$ | $10^{-3} \lesssim x \lesssim 0.7$ | $\sim M_W$ |
| $pp \to \gamma^*/Z + X$ | $d^2\sigma(\gamma^*/Z)/dy_{ll}dM_{ll}$ | $q, \bar{q}$ | $10^{-3} \lesssim x \lesssim 0.7$ | $5\text{ GeV} \lesssim Q \lesssim 2$ TeV |
| $pp \to \gamma^*/Z + \text{jet} + X$ | $d\sigma(\gamma^*/Z)/dp_T^{ll}$ | $q, g$ | $10^{-2} \lesssim x \lesssim 0.7$ | $200\text{ GeV} \lesssim Q \lesssim 1$ TeV |
| $pp \to \text{jet}+X$ | $d\sigma(\text{jet})/dp_T dy$ | $q, g$ | $10^{-2} \lesssim x \lesssim 0.8$ | $20\text{ GeV} \lesssim Q \lesssim 3$ TeV |
| $pp \to \text{jet} + \text{jet}+X$ | $d\sigma(\text{jet})/dM_{jj}dy_{jj}$ | $q, g$ | $10^{-2} \lesssim x \lesssim 0.8$ | $500\text{ GeV} \lesssim Q \lesssim 5$ TeV |
| $pp \to t\bar{t}+X$ | $\sigma(t\bar{t})$, $d\sigma(t\bar{t})/dM_{t\bar{t}}$, ... | $g$ | $0.1 \lesssim x \lesssim 0.7$ | $350\text{ GeV} \lesssim Q \lesssim 1$ TeV |
| $pp \to c\bar{c}+X$ | $d\sigma(c\bar{c})/dp_{T,c}dy_c$ | $g$ | $10^{-5} \lesssim x \lesssim 10^{-3}$ | $1\text{ GeV} \lesssim Q \lesssim 10$ GeV |
| $pp \to b\bar{b}+X$ | $d\sigma(b\bar{b})/dp_{T,c}dy_c$ | $g$ | $10^{-4} \lesssim x \lesssim 10^{-2}$ | $5\text{ GeV} \lesssim Q \lesssim 30$ GeV |
| $pp \to W+c$ | $d\sigma(W+c)/d\eta_l$ | $s, \bar{s}$ | $0.01 \lesssim x \lesssim 0.5$ | $\sim M_W$ |




13 TeV measurements probe new range of x, $Q^2$

**J Phys G 42 (2015), 103103**

**W/Z & ZZ cross section results:**
**R Owen, L Armitage & S Richter, J Rosten (parallel 2B)**

# Parton distribution functions

Developments from PDF4LHC

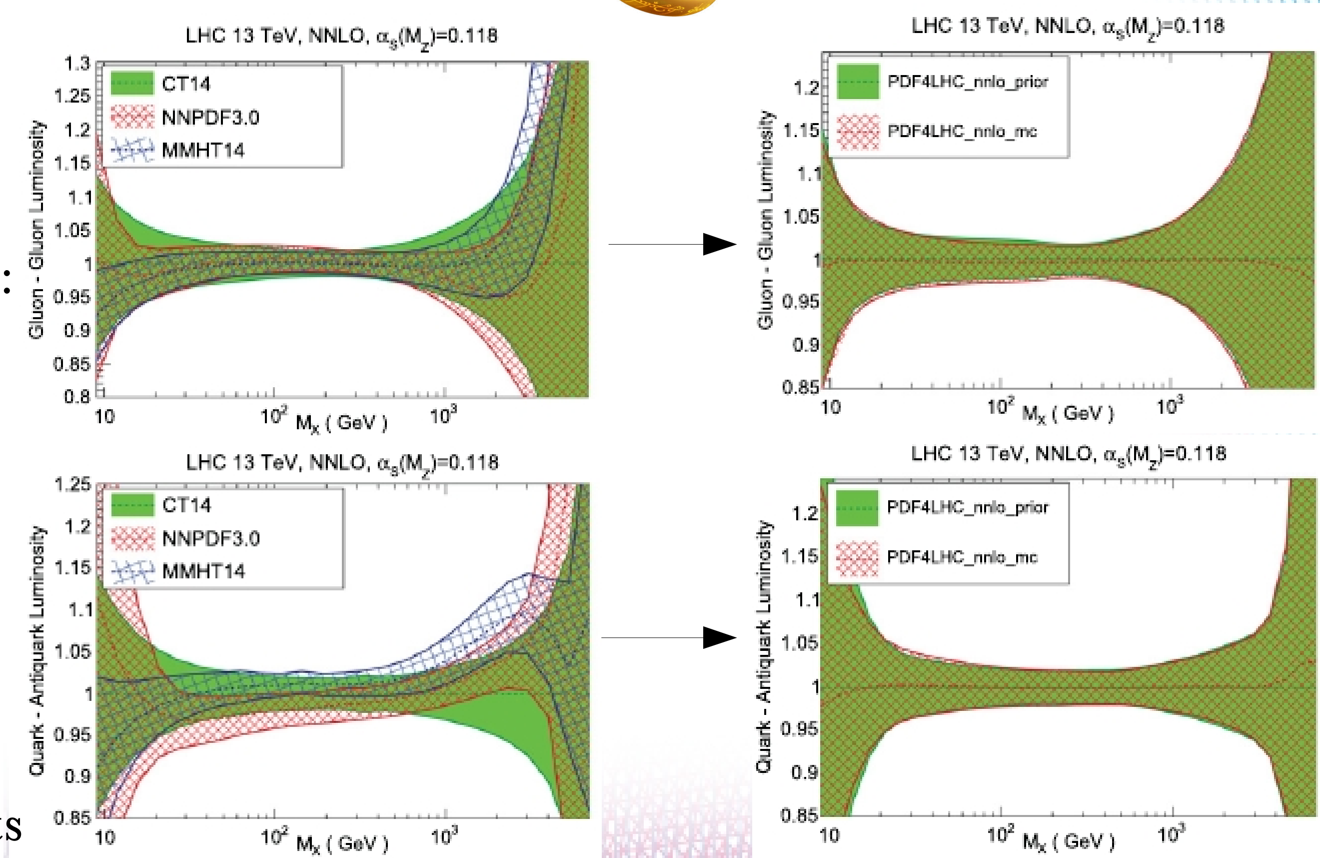
**2010**: First prescription for uncertainties @ LHC -- envelope of CTEQ, MSTW, NNPDF
**2012**: PDF updates including fits to data at NNLO; separate $\alpha_s$ uncertainty
**2016**: Combined PDF4LHC set -- *one set to rule them all* 

Incorporates many LHC 7/8 TeV measurements

Improved consistency in new sets: produce ensemble of sets

Uncertainty eigenvectors also available

Currently being integrated into Run 2 analyses: Expanding implementation of correlations and in situ constraints

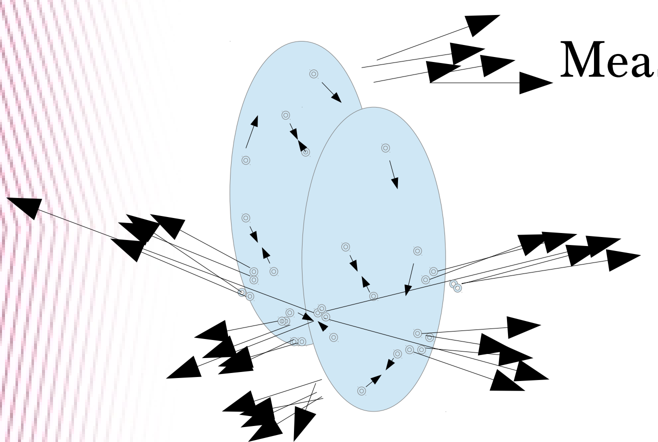



J Phys G 43 (2016), 123001

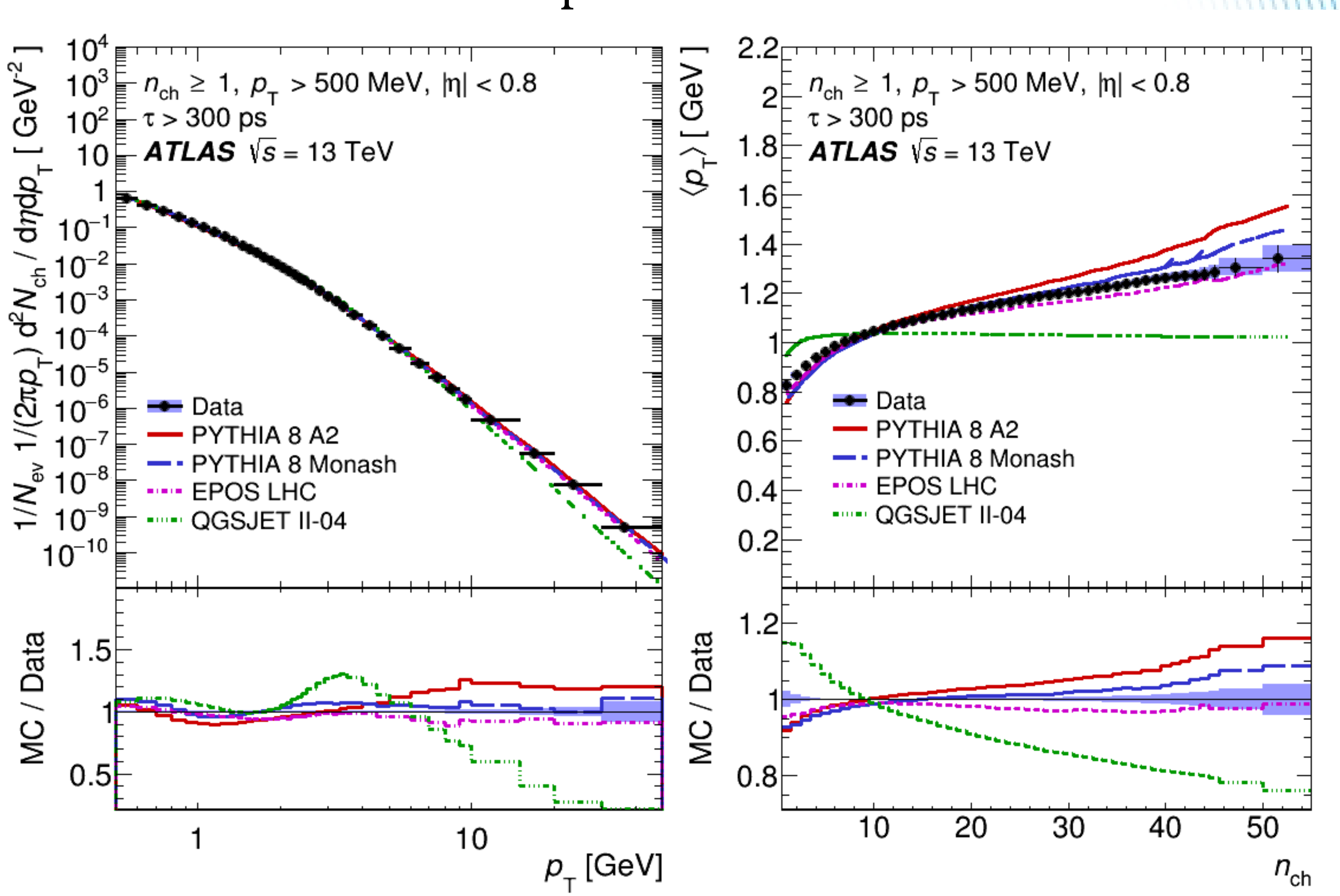
# Underlying event

Need to distinguish measurement final state from proton dissociation & secondary collisions

Non-perturbative effects: requires empirical models in Monte Carlo generators



Measurements constrain model parameters




Study charged tracks produced in inclusive collisions to focus on the breakup of the proton

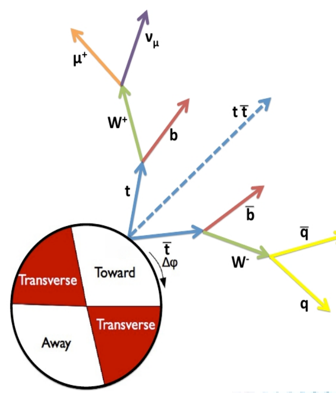
13 TeV results available for checking & improving tuning

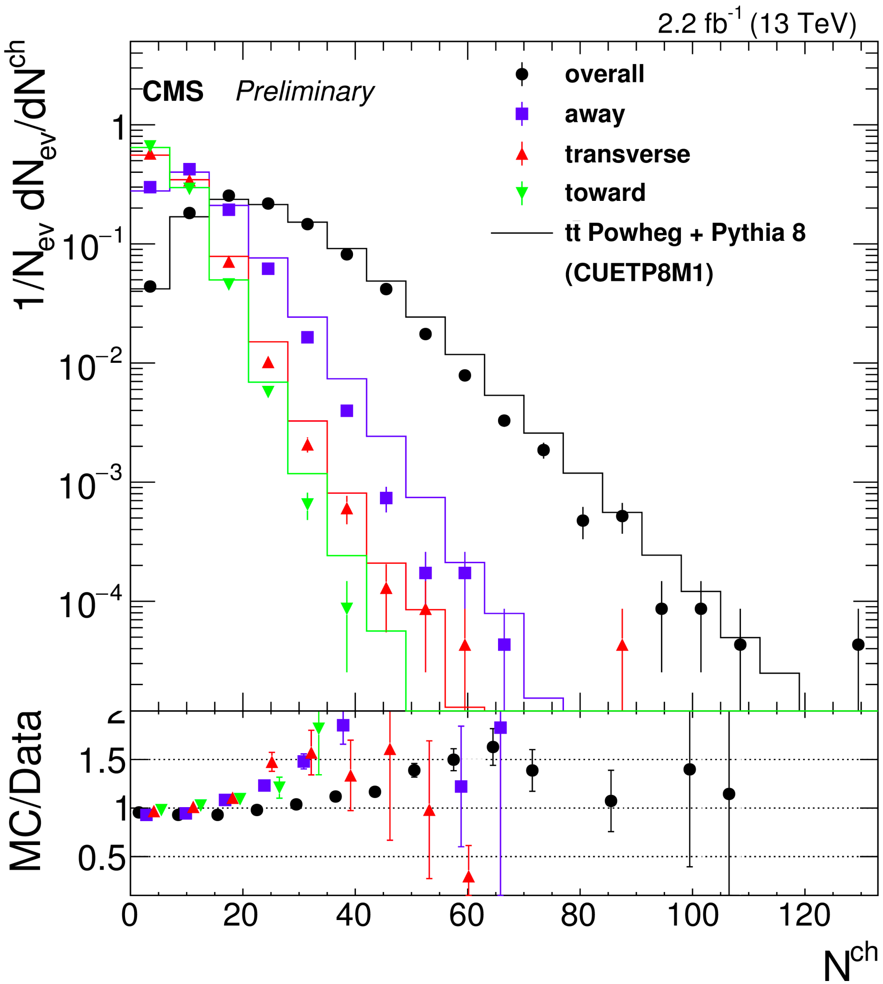
**arxiv:1506.06042**

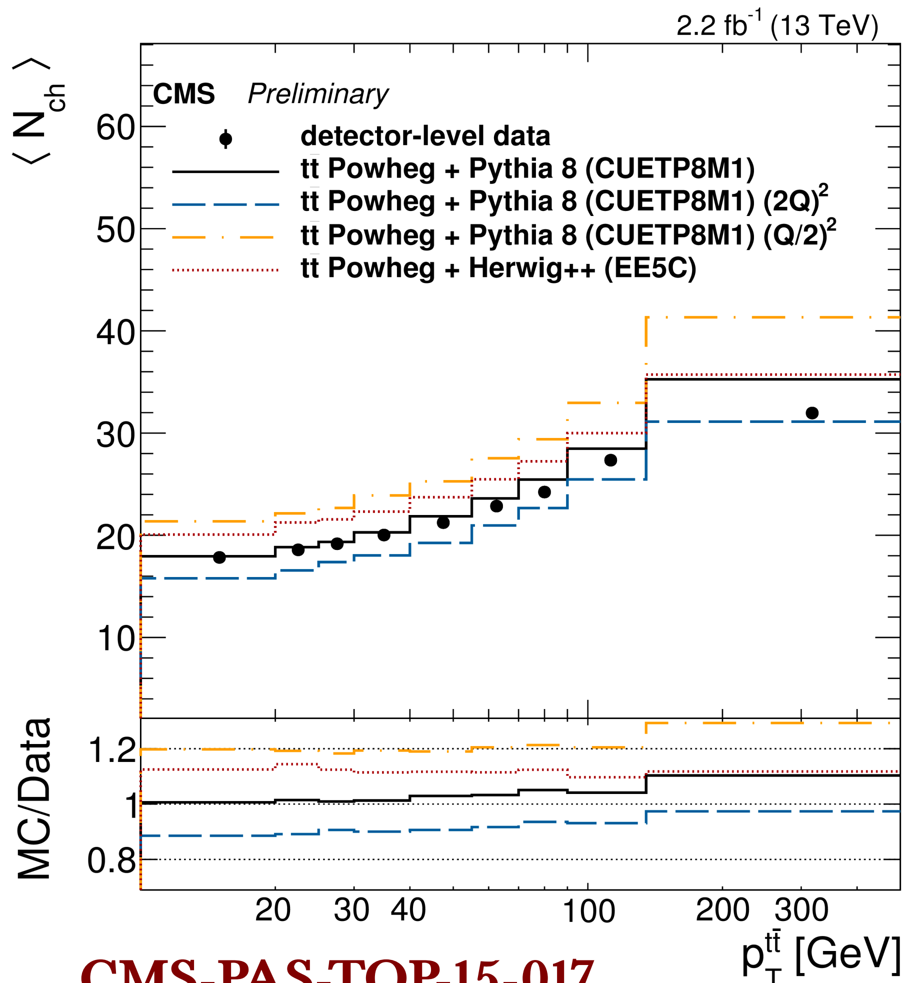
# Underlying event

Test modelling in high-$Q^2$ processes

E.g. tt production, with axis defined by $p_T$ of the tt system




**CMS-PAS-TOP-15-017**

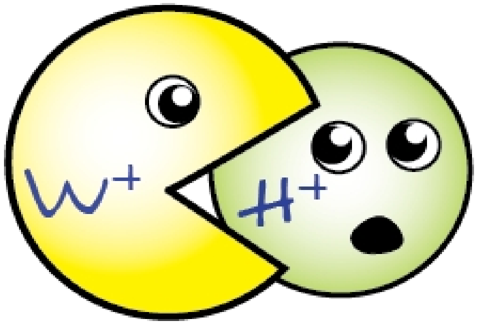
# Overview

- Hadron collider physics
- Parton distributions and underlying event
- Electroweak parameter measurements
- Electroweak boson self-coupling constraints

# W and Z boson measurements

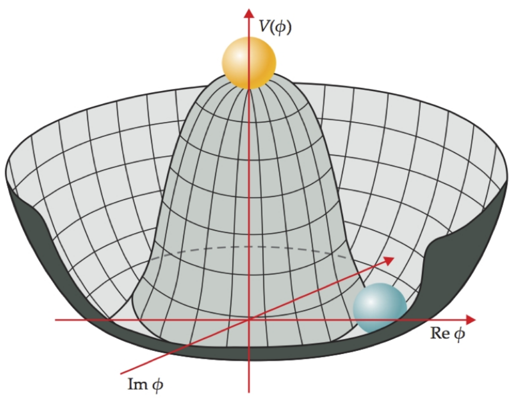
Physical W and Z bosons are a combination of:

- gauge bosons that transmit weak/hypercharge
- Goldstone bosons of the Higgs doublet
  - ◊ Higgs vacuum breaks charge conservation




*W/Z/Higgs physics fundamentally intertwined*

Evidenced by W and Z boson masses:




*Higgs vacuum expectation value*
*Extracted from Z boson mass*
*(v≡174 GeV)*

$$m_W = gv$$

$$m_Z = (g^2 + g'^2)^{1/2}\ v$$

Weak coupling
Extracted from muon lifetime

Hypercharge coupling
Extracted from electron anomalous magnetic moment

W boson gets mass from weak-charge coupling to vacuum energy
Z boson gets mass from weak-charge *and* hypercharge coupling to vacuum energy

$$\mathbf{m_W = \cos\theta_W\ m_Z}$$

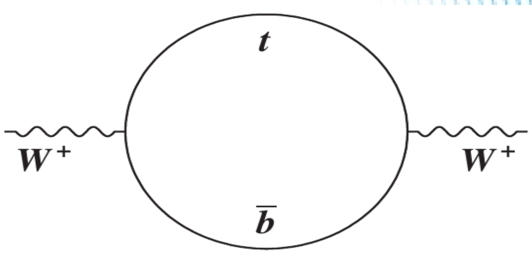
# W boson mass

Completely determined at tree level given three inputs:

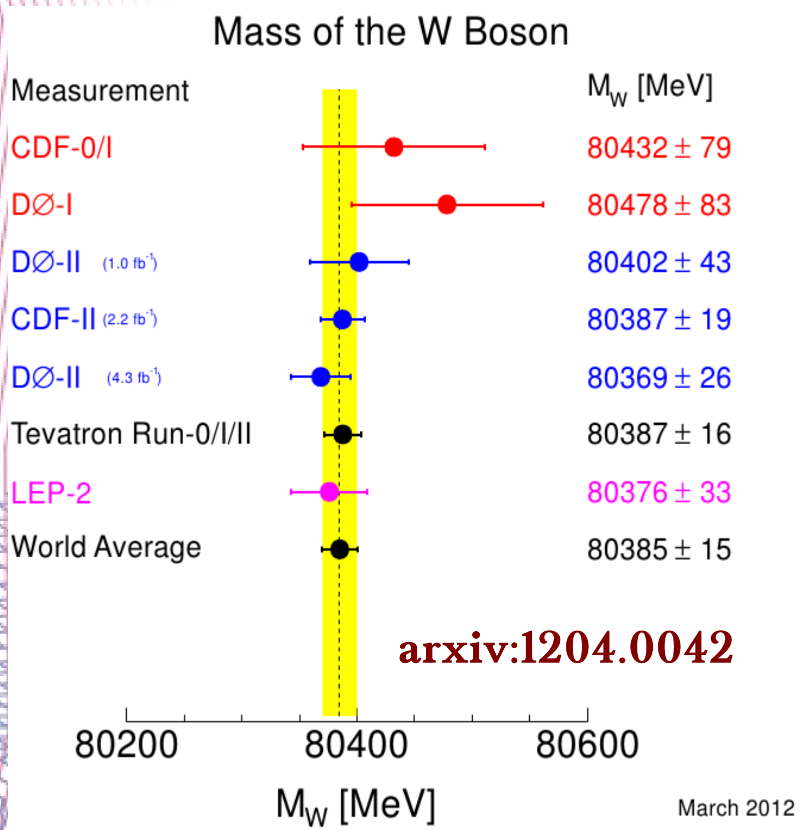
$$m_W = m_Z \left[ \tfrac{1}{2} + \tfrac{1}{4} \left(\pi\alpha_{EM} / G_F\, m_Z^2 \sqrt{2}\right) \right]^{1/2}$$
$$= 79\,964 \text{ MeV}$$

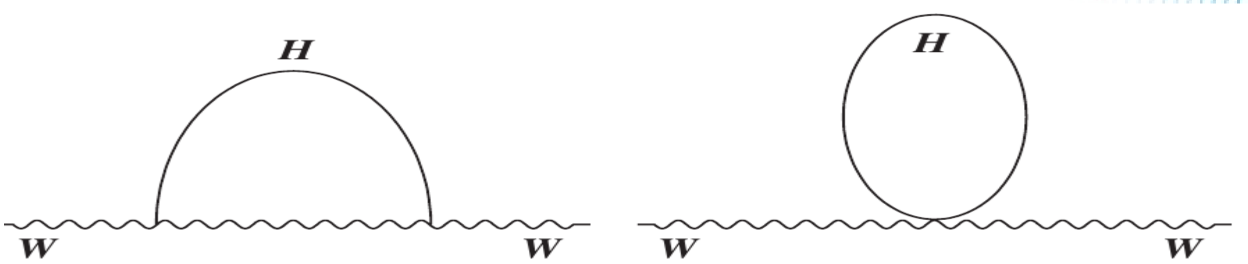
Radiative corrections important, dominantly the tb & Higgs loops

For $m_t$ = 173.34 ± 0.76 GeV and $m_H$ = 125.14 ± 0.24 GeV,




**$m_W^{SM}$ = 80 358 ± 8 MeV**




World average from direct measurements:

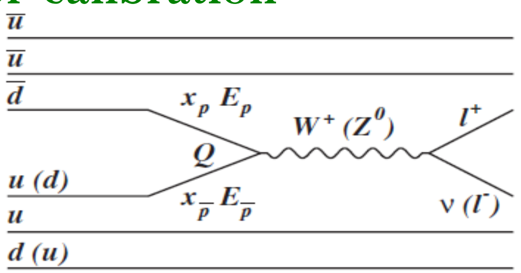
**$m_W^{direct}$ = 80 385 ± 15 MeV**

# W boson mass

Next round of direct measurements will reduce uncertainty by factor of ~2

- Final Tevatron data (increase yield by factors of 2 & 4 for D0 & CDF)
- First LHC data (7 TeV)

Early LHC studies investigating theoretical uncertainties & detector calibration




**Measurement strategy**:

Measure charged lepton momentum in transverse plane

Infer neutrino momentum using conservation of momentum ($p_x^i = p_y^i = 0$)

Fit for $m_W$ using transverse momenta and two-dimensional "transverse mass"

$$m_T = \sqrt{2 p_T^l \not{p}_T (1 - \cos\Delta\phi)}$$

**Experimental and theoretical requirements**:

Precise calibration of charged lepton momentum

Accurate model of hadronic radiation

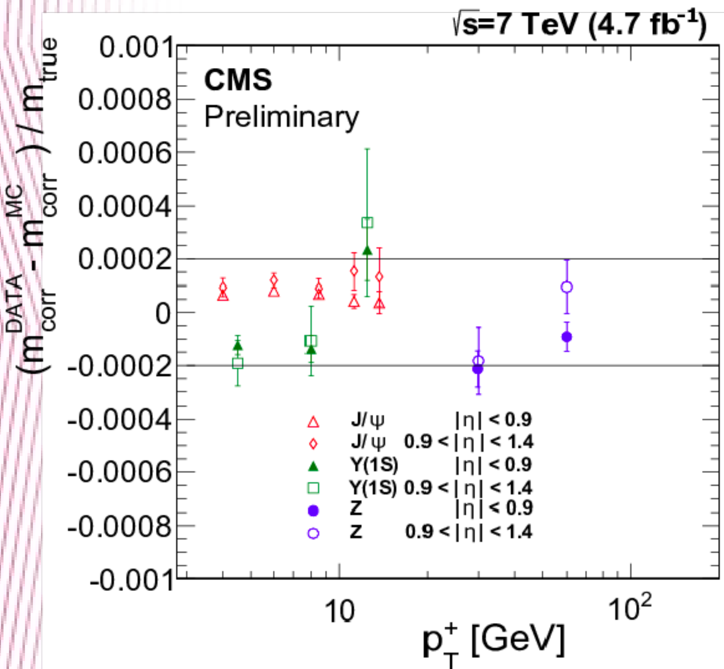
Accurate model of longitudinal and transverse momentum of W boson (PDFs & "soft" QCD)

# W boson mass

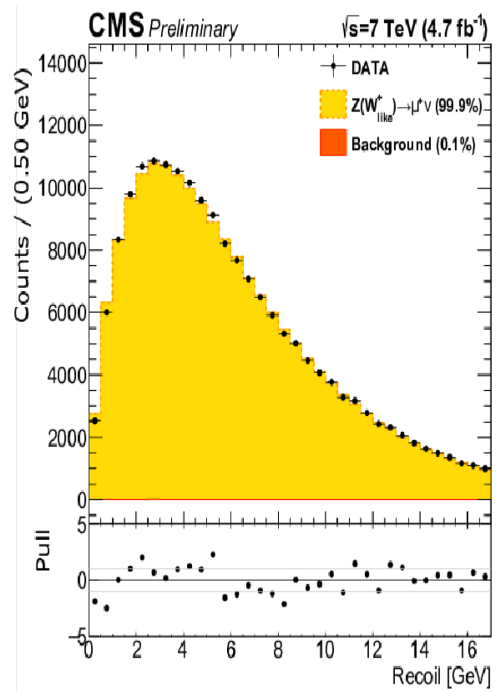
CMS-PAS-TOP-15-017

A first demonstration of muon and hadron calibrations performed by CMS

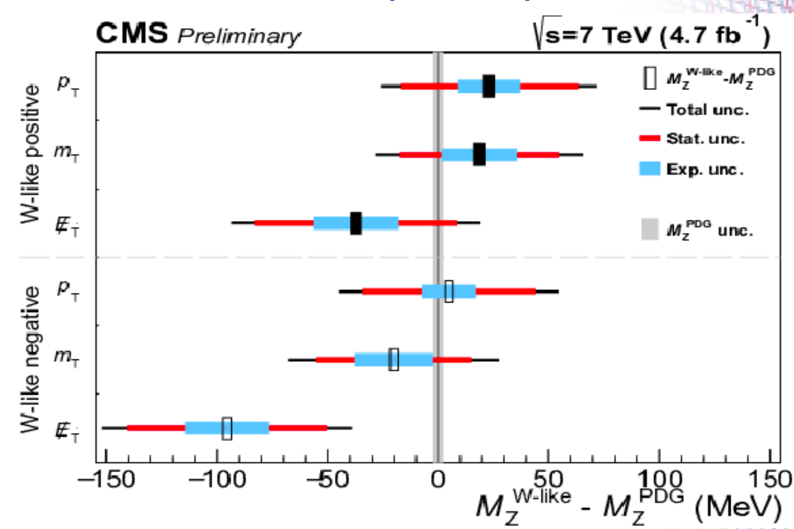
- Fit for $m_Z$ after removing one muon from $Z \to \mu\mu$ data candidates (7 TeV)




Muon momentum calibration: ~15 MeV uncertainty on $m_W$




Hadron calibration sufficient




Reasonable consistency considering ~50 MeV uncertainties

Roughly equal statistical and systematic uncertainties

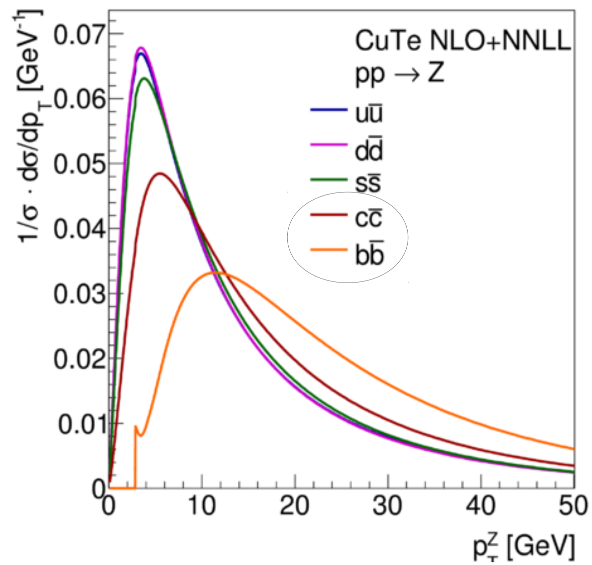
| Sources of uncertainty | $M_Z^{W\text{like}+}$ $p_T$ | $m_T$ | $\not{E}_T$ | $M_Z^{W\text{like}-}$ $p_T$ | $m_T$ | $\not{E}_T$ |
|---|---|---|---|---|---|---|
| Lepton efficiencies | 1 | 1 | 1 | 1 | 1 | 1 |
| Lepton calibration | 14 | 13 | 14 | 12 | 15 | 14 |
| Recoil calibration | 0 | 9 | 13 | 0 | 9 | 14 |
| Total experimental syst. uncertainties | 14 | 17 | 19 | 12 | 18 | 19 |
| Alternative data reweightings | 5 | 4 | 5 | 14 | 11 | 11 |
| PDF uncertainties | 6 | 5 | 5 | 6 | 5 | 5 |
| QED radiation | 22 | 23 | 24 | 23 | 23 | 24 |
| Simulated sample size | 7 | 6 | 8 | 7 | 6 | 8 |
| Total other syst. uncertainties | 24 | 25 | 27 | 28 | 27 | 28 |
| Total systematic uncertainties | 28 | 30 | 32 | 30 | 32 | 34 |
| Statistics of the data sample | 40 | 36 | 46 | 39 | 35 | 45 |
| Total stat.+syst. | 49 | 47 | 56 | 50 | 48 | 57 |

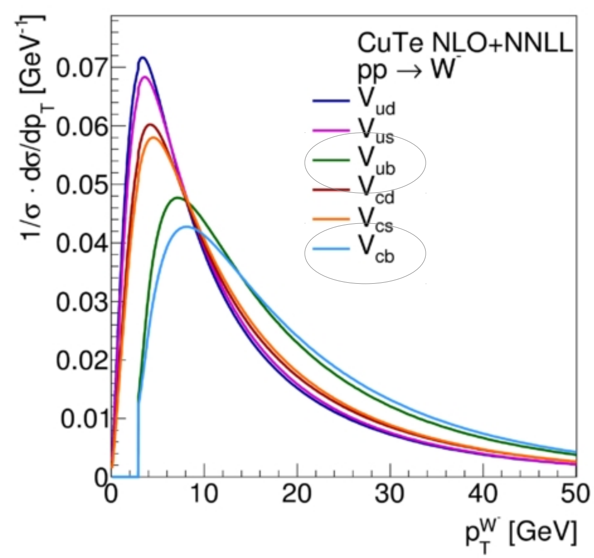
Larger W boson sample will cut statistical uncertainty by more than half

# W boson mass

Additional theoretical uncertainties in $m_W$ measurement from PDFs and W boson $p_T$

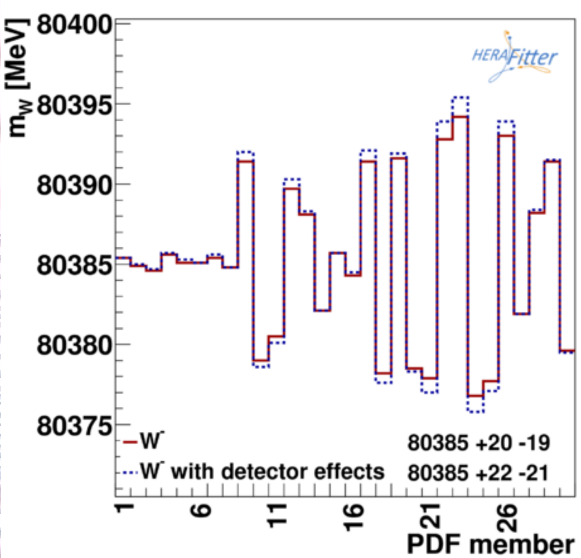
- Translation from measured $p_T^Z$ distribution to $p_T^W$ is sensitive to initial parton flavour

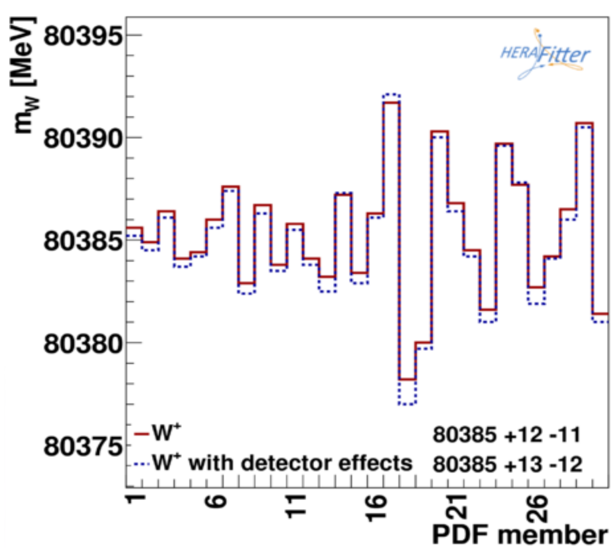



Heavy flavour quarks contribute more to Z boson production

Asymmetric PDF uncertainty between $W^+$ and $W^-$ production: $W^+$ has higher fraction of valence-quark production




**ATLAS-PHYS-PUB-2014-015**

c.f. CDF uncertainties:

| Source | Uncertainty |
|---|---|
| Lepton energy scale and resolution | 7 |
| Recoil energy scale and resolution | 6 |
| Lepton tower removal | 2 |
| Backgrounds | 3 |
| PDFs | 10 |
| $p_T(W)$ model | 5 |
| Photon radiation | 4 |
| Statistical | 12 |
| Total | 19 |

**Phys Rev D 89, 072003 (2014)**

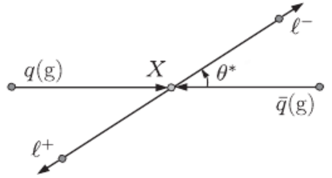
# Z forward-backward asymmetry

Measuring relative vector and axial couplings of Zff indirectly determines $m_W$

Fermions have V-A coupling to weak charge, V coupling to hypercharge

Relative V to A coupling → relative hypercharge to weak coupling → relative Z to W mass

Tevatron: Relative vector to axial couplings affect relative production of positive lepton along proton direction (forward) to production opposite to proton direction (backward)



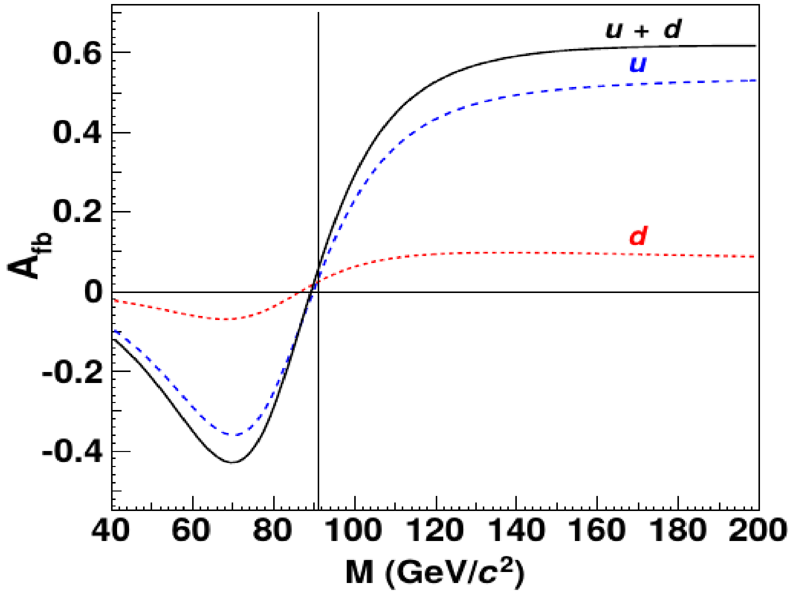

Procedurally: measure $A_{FB}$ → fit for $\sin^2\theta^{lep}$ → extract $\sin^2\theta_W$ → extract $m_W$

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

$$g_V^f = T_3^f - 2Q_f \sin^2\theta_W \text{ and}$$

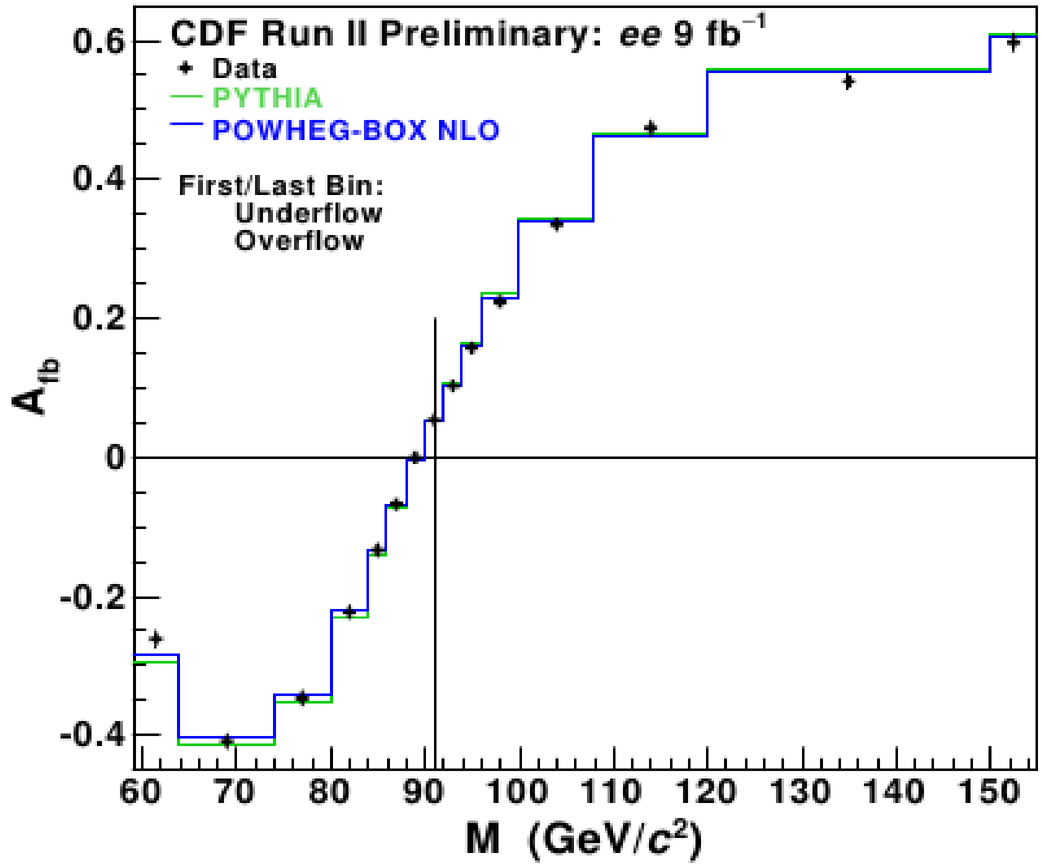
$$g_A^f = T_3^f,$$

Asymmetry depends on initial state partons: Important to have accurate PDFs

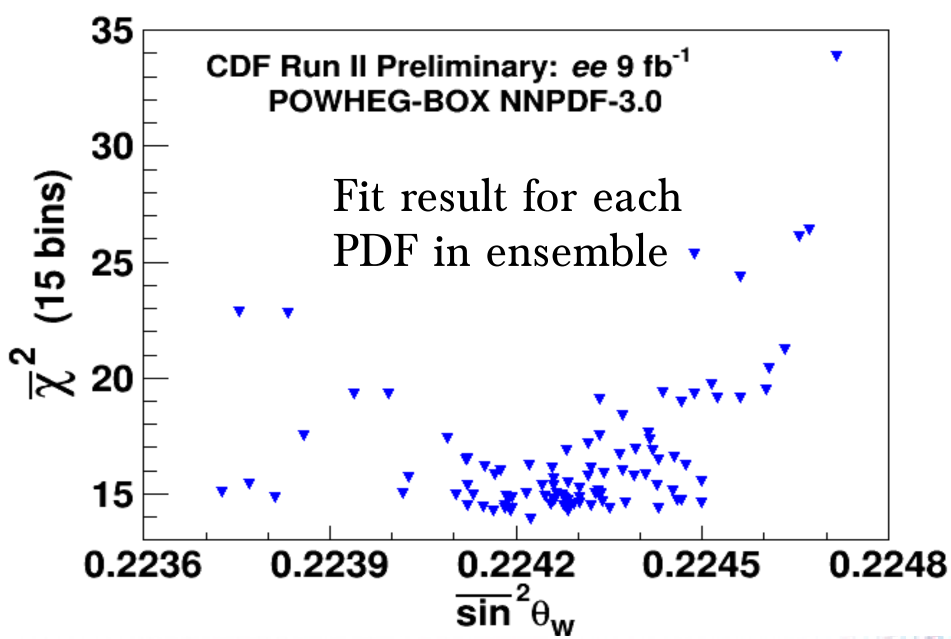


# Z forward-backward asymmetry

New CDF measurement maximizes statistical sensitivity by weighting each event according to the symmetrized angular distribution → an effective unbinned likelihood



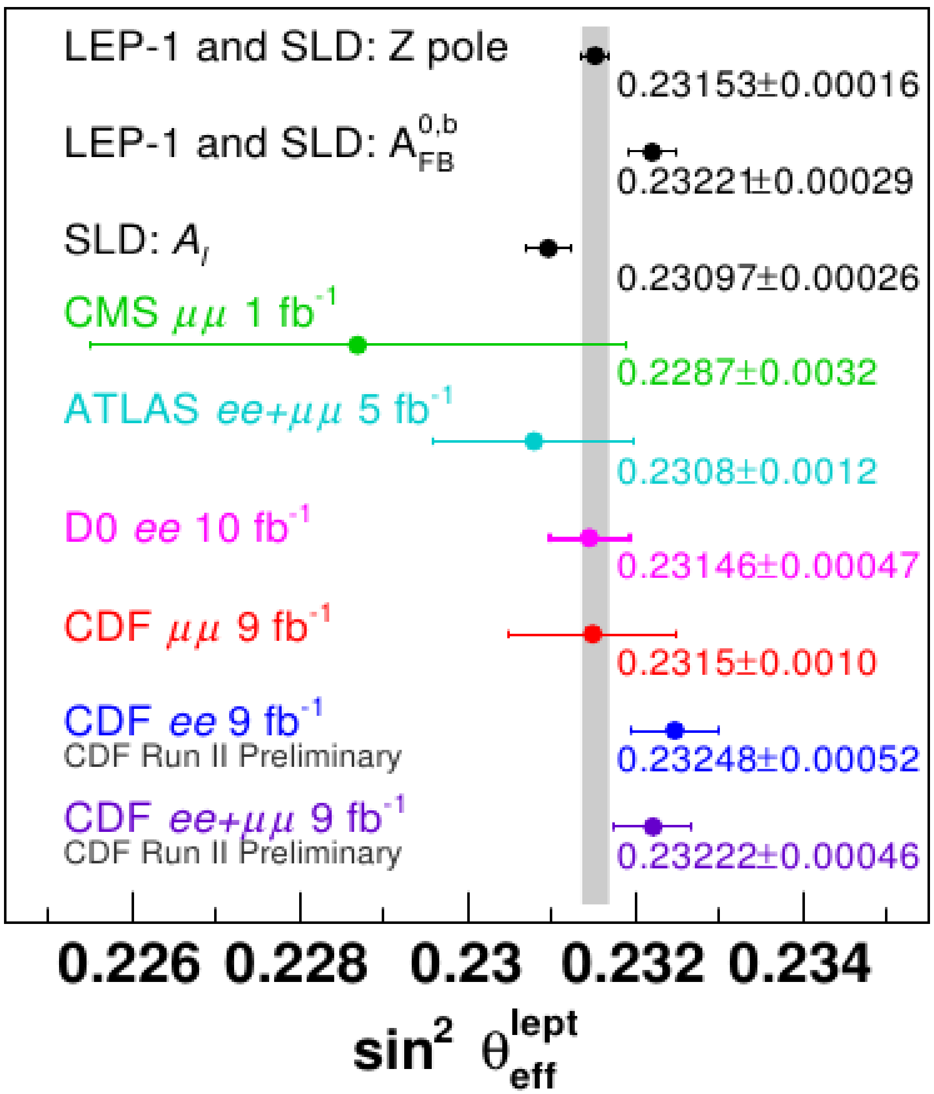

Measurement also reduces PDF uncertainty by weighting each PDF in NNPDF3.0 by a likelihood factor




**CDF note 11178**

# Z forward-backward asymmetry

Total uncertainty statistics-dominated
Systematic uncertainty PDF-dominated

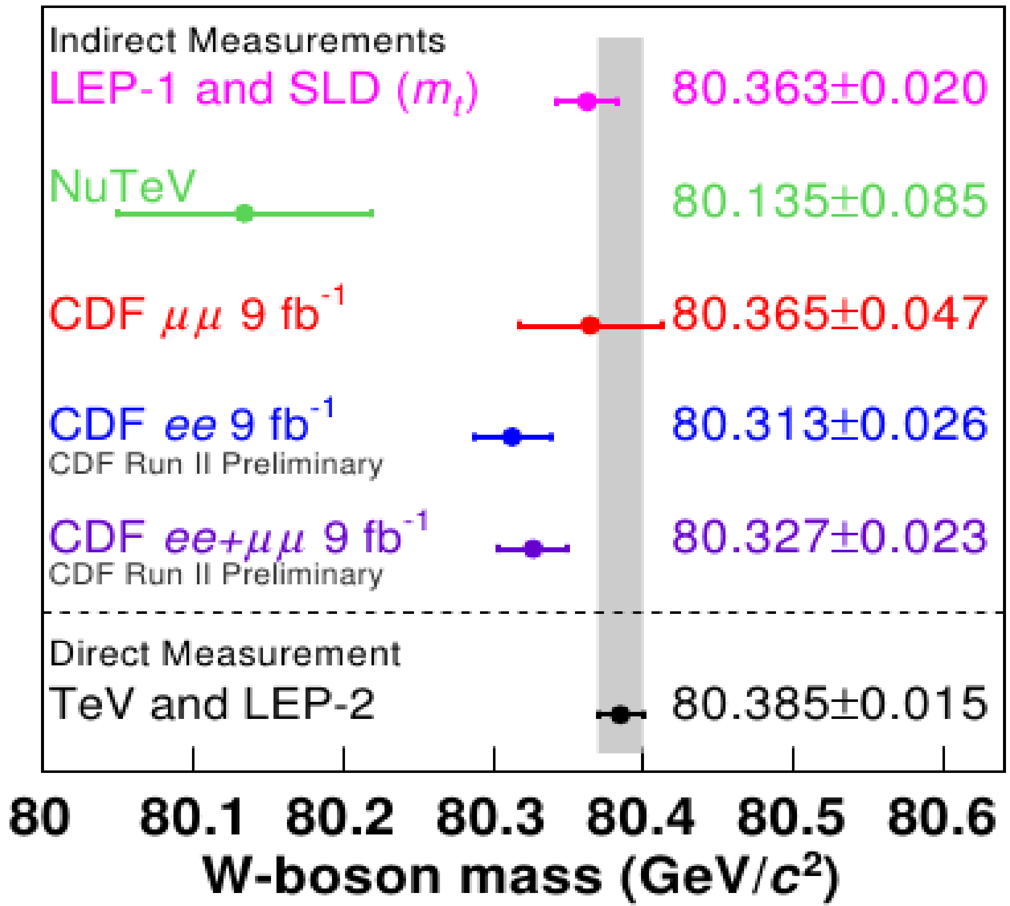



Final combined ee+μμ:

$$\sin^2\theta^{\rm lept}_{\rm eff} = 0.23221 \pm 0.00043 \pm 0.00018$$

$$\sin^2\theta_W = 0.22400 \pm 0.00041 \pm 0.00019$$

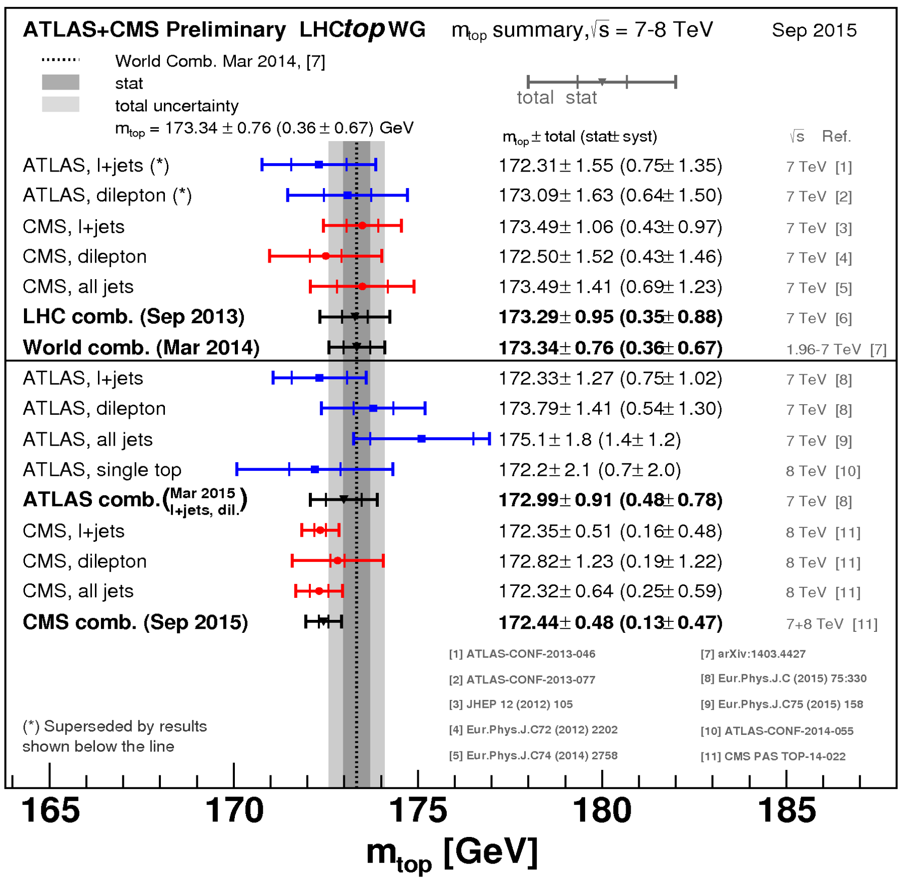
$$M_W\ ({\rm indirect}) = 80.328 \pm 0.021 \pm 0.010\ {\rm GeV}/c^2$$

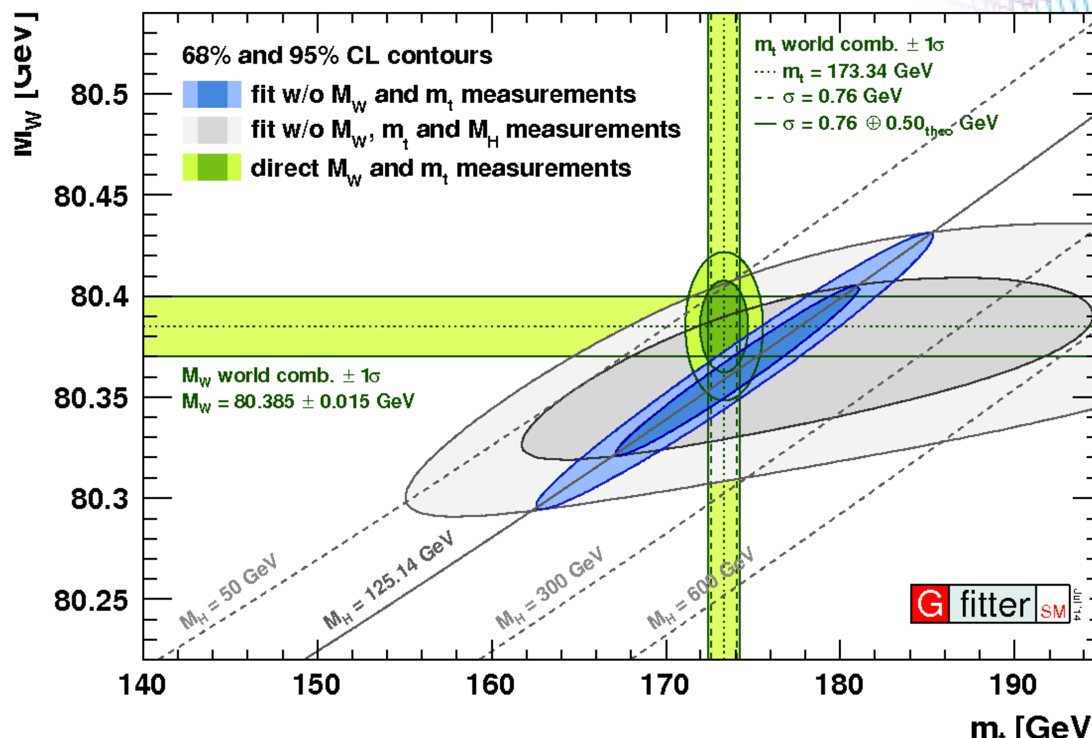


# Top quark mass

Top quark mass a key parameter in $m_W$ corrections: 1 GeV change in $m_t$ affects $m_W$ by 6 MeV

Leading uncertainty in SM prediction of $m_W$



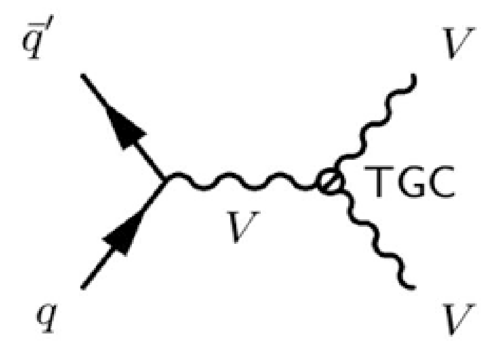

CMS combined 7 & 8 TeV $m_t$ is 0.9 GeV below the world average, with 30% lower uncertainty

CMS $m_t$ would reduce $m_W^{SM}$ by ~5 MeV, leading to ~2σ discrepancy with direct measurement

# Overview

- Hadron collider physics
- Parton distributions and underlying event
- Electroweak parameter measurements
- Electroweak boson self-coupling constraints

# Electroweak boson self-couplings




No free parameters in gauge boson self-couplings

Constrain possible non-SM "anomalous" couplings
- Non-renormalizable terms, can violate unitarity

Historically suppress anomalous couplings via a form factor
- Implies some new high-scale strong dynamics

$$\lambda(\hat{s}) = \frac{\lambda}{(1+\hat{s}/\Lambda^2)^2}$$

Recently also study constraints with no form factor
- Valid for new high-scale weak dynamics
- In line with proposed Higgs coupling constraints, historical LEP constraints

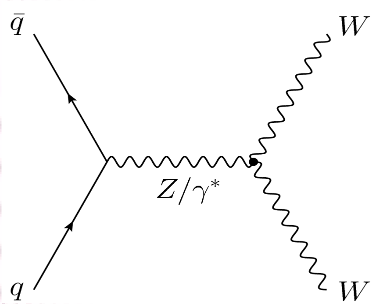
Apply to effective field theory: Lagrangian with all possible 6-dimensional terms

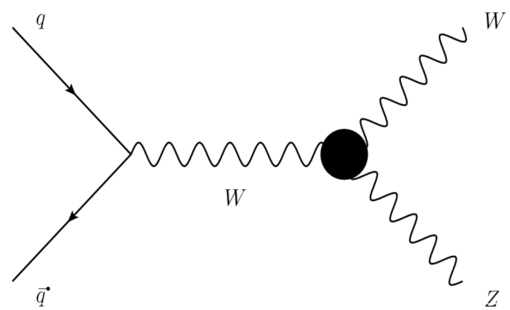
$$\begin{aligned}
\Delta\mathcal{L}_{\rm tgc} &= ie\left[\delta\kappa_\gamma A_{\mu\nu}\, W^+_\mu W^-_\nu + \tilde{\kappa}_\gamma \tilde{A}_{\mu\nu}\, W^+_\mu W^-_\nu\right] \\
&+ igc_\theta\left[\delta g_{1,z}\left(W^+_{\mu\nu}W^-_\mu - W^-_{\mu\nu}W^+_\mu\right) Z_\nu + \delta\kappa_z\, Z_{\mu\nu}\, W^+_\mu W^-_\nu + \tilde{\kappa}_z\, \tilde{Z}_{\mu\nu}\, W^+_\mu W^-_\nu\right] \\
&+ i\frac{e}{m_W^2}\left[\lambda_\gamma W^+_{\mu\nu}W^-_{\nu\rho}A_{\rho\mu} + \tilde{\lambda}_\gamma W^+_{\mu\nu}W^-_{\nu\rho}\tilde{A}_{\rho\mu}\right] + i\frac{gc_\theta}{m_W^2}\left[\lambda_z W^+_{\mu\nu}W^-_{\nu\rho}Z_{\rho\mu} + \tilde{\lambda}_z W^+_{\mu\nu}W^-_{\nu\rho}\tilde{Z}_{\rho\mu}\right] \\
&+ \frac{c_{3G}}{v^2} g_s^3 f^{abc} G^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu} + \frac{\tilde{c}_{3G}}{v^2} g_s^3 f^{abc} \widetilde{G}^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}, \qquad (3.6)
\end{aligned}$$

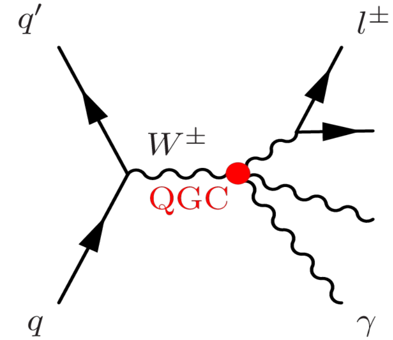
LHCHXSWG-INT-2015-001

# Gauge-boson self-coupling processes

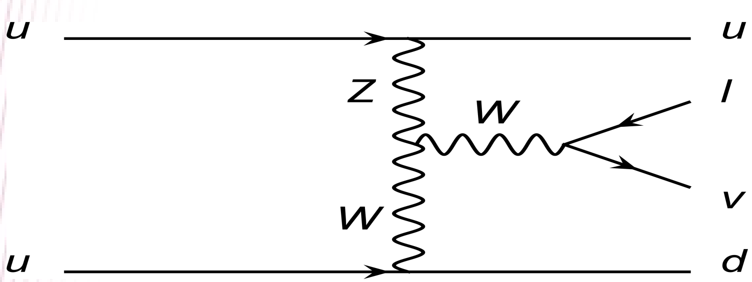
s-channel multiboson production

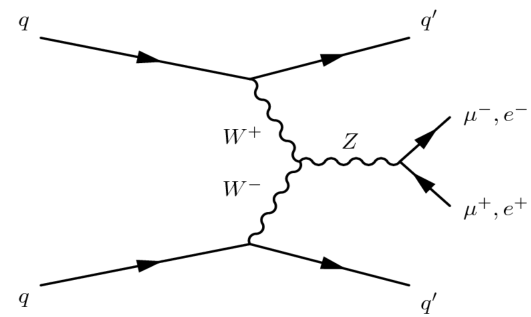


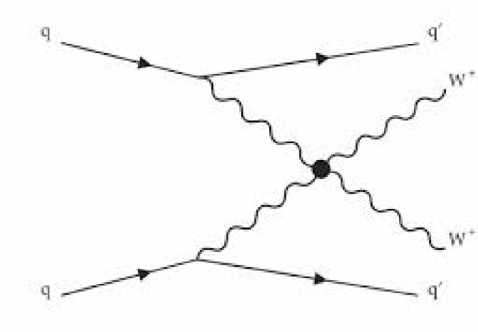



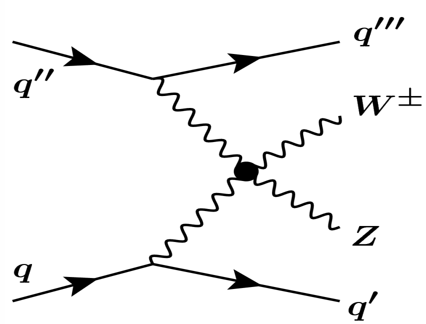

t-channel vector boson fusion

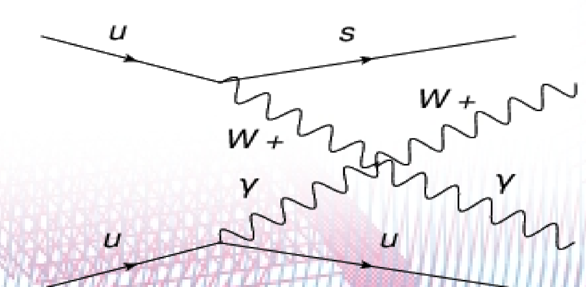



Vector boson scattering



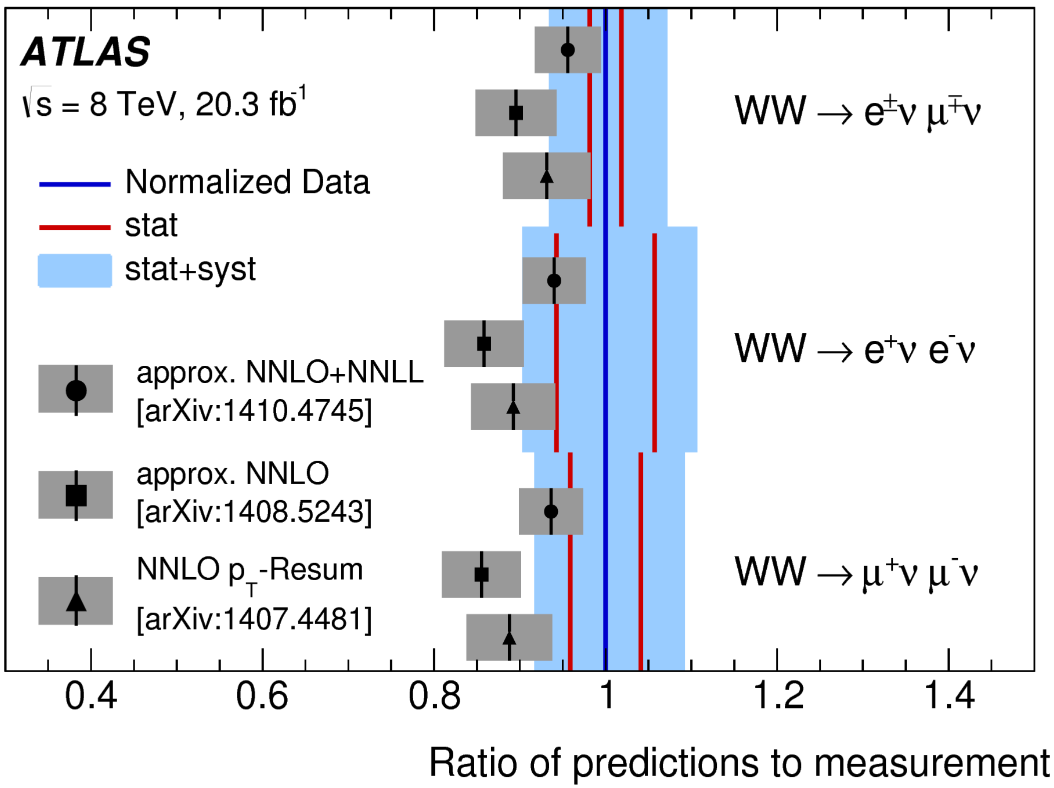



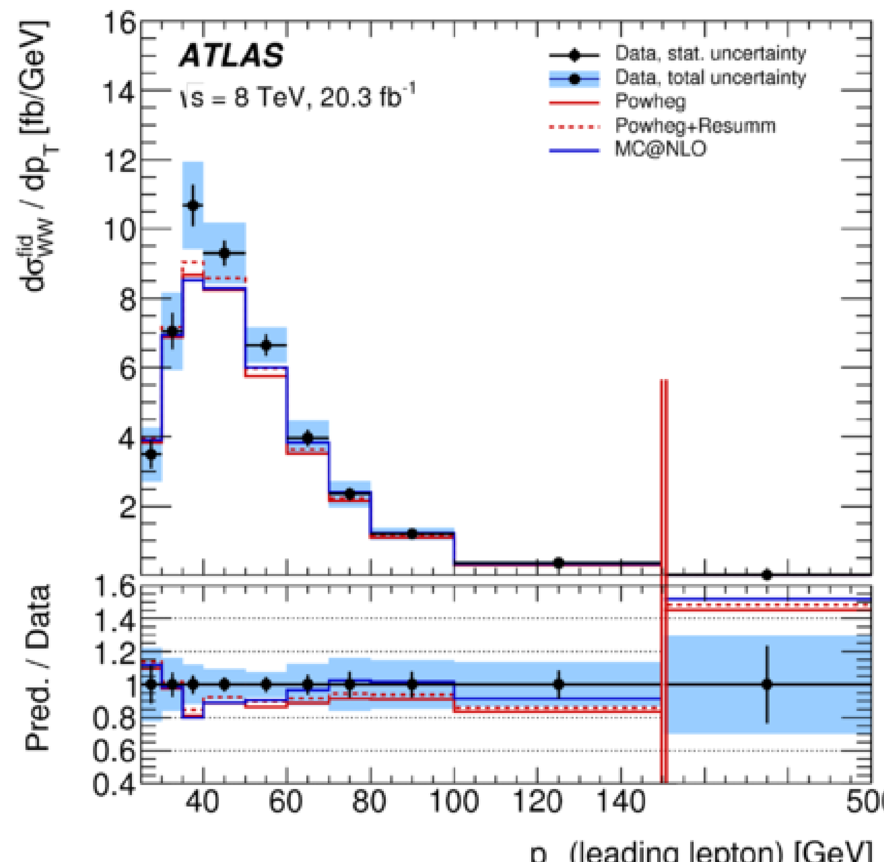
# WW production

Previous cross sections measured to be ~2σ higher than NLO SM prediction

Discrepancy reduced with NNLO+NNLL calculation

Top quark contributions important



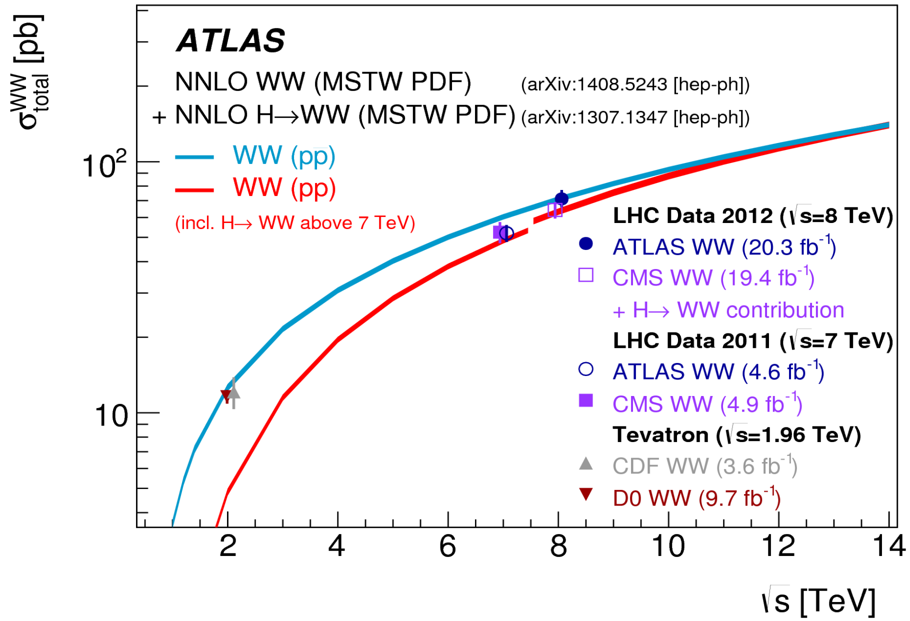




**arxiv:1603.01702**

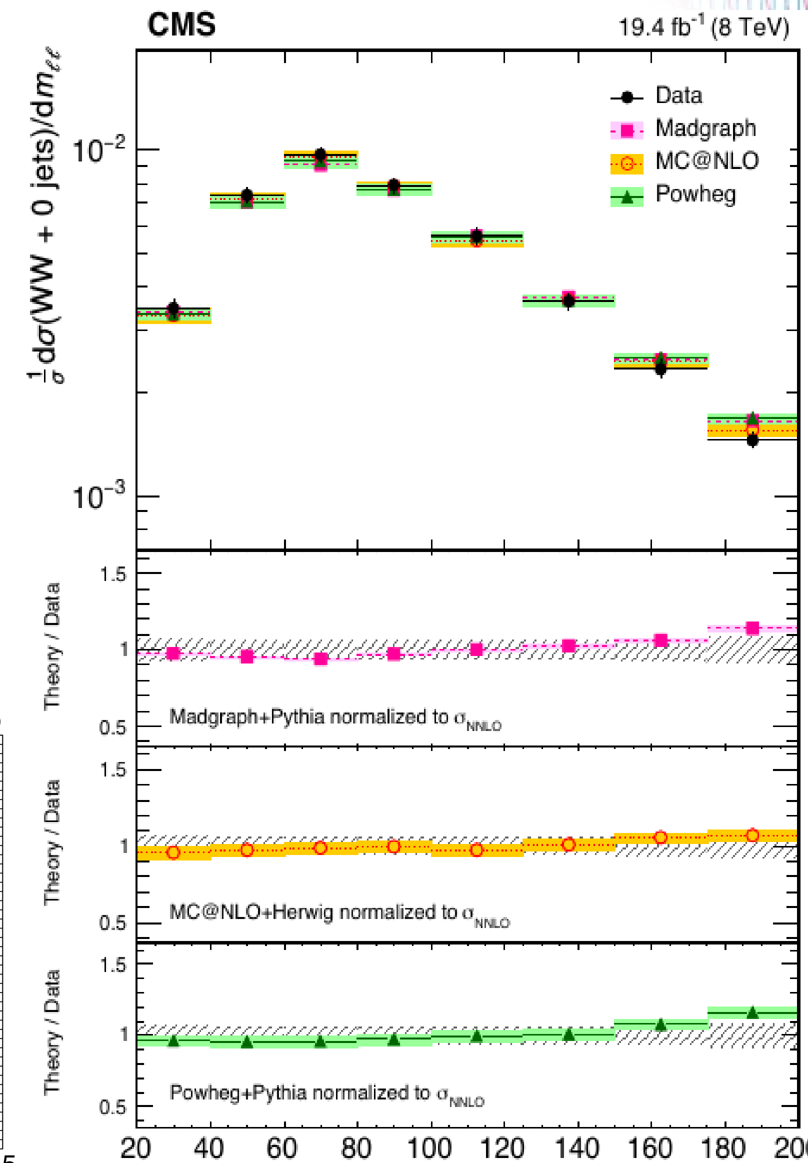
Discrepancy historically isolated at low $p_T$

Generator model dependent

# WW production

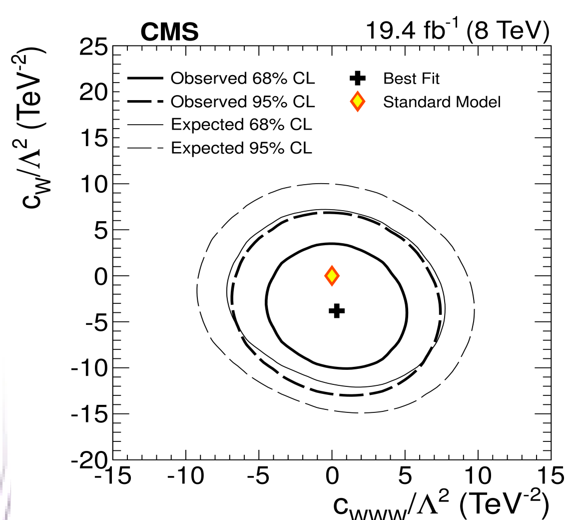



Measure key distribution used in H→WW measurement




Good agreement between measurements and NNLO predictions

First measurements of effective field theory operator coefficients in diboson production



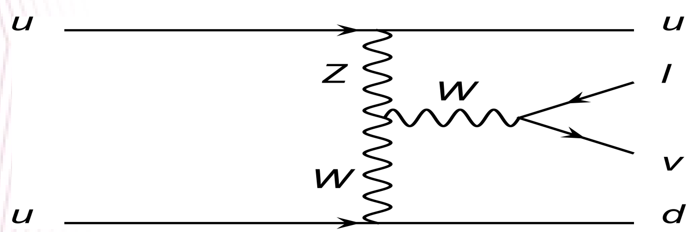

arxiv:1507.03268

# Vector-boson fusion

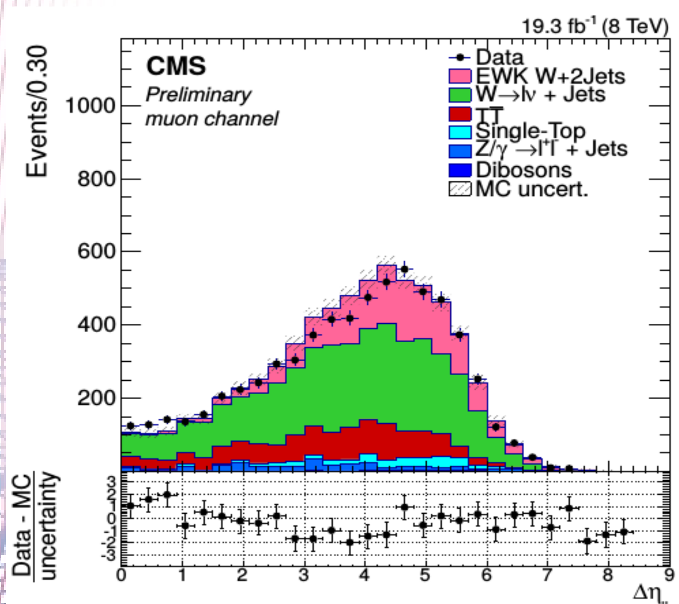
Single-boson production probes triple-gauge coupling through vector-boson fusion
An important channel for measuring Higgs boson couplings

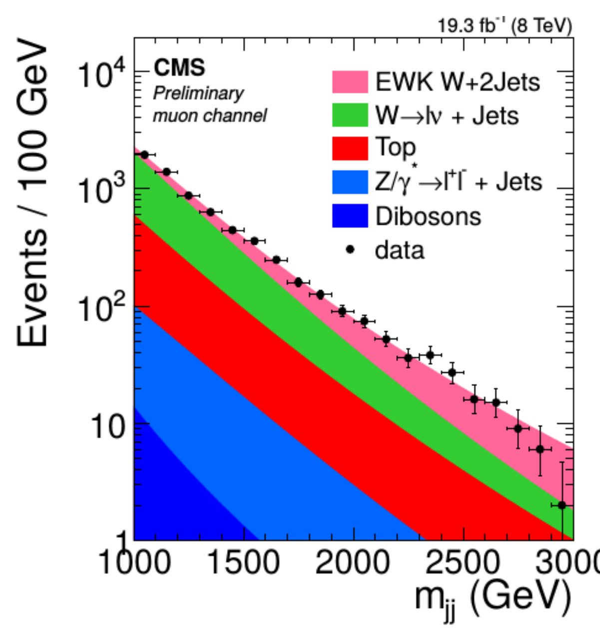
Vector boson fusion of a Z boson measured by ATLAS and CMS
VBF W production offers higher statistics, more precise test of signal and backgrounds

First measurement of VBF W at the LHC performed by CMS




Key characteristic of vector-boson fusion:
Forward and backward hadronic jets (t-channel exchange)
Large invariant mass of jets, large rapidity separation




$\sigma^{fid}_{meas} = 0.42 \pm 0.04 \pm 0.09$ pb

$\sigma^{fid}_{SM} = 0.50 \pm 0.03$ pb

Fiducial region:
$p_T^{j1}$>60 GeV, $p_T^{j2}$>50 GeV,
$m_{jj}$>1000 GeV, $|\eta_j|$<4.7

**CMS-PAS-SMP-13-012**

# Summary

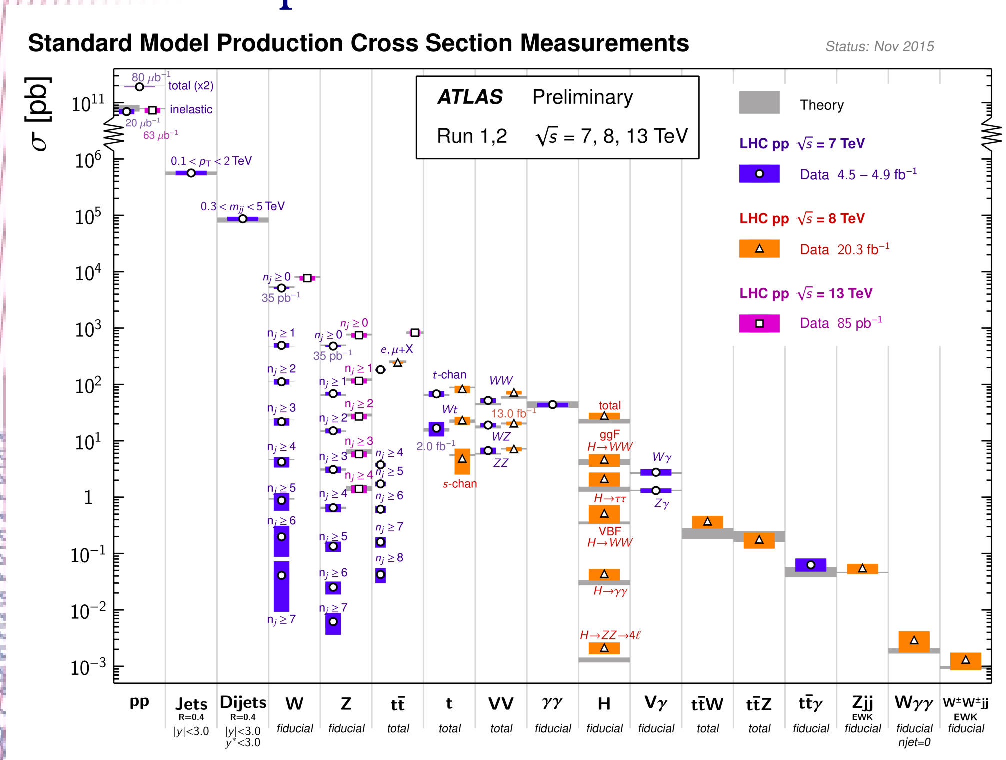
LHC has led to a step change in SM measurements

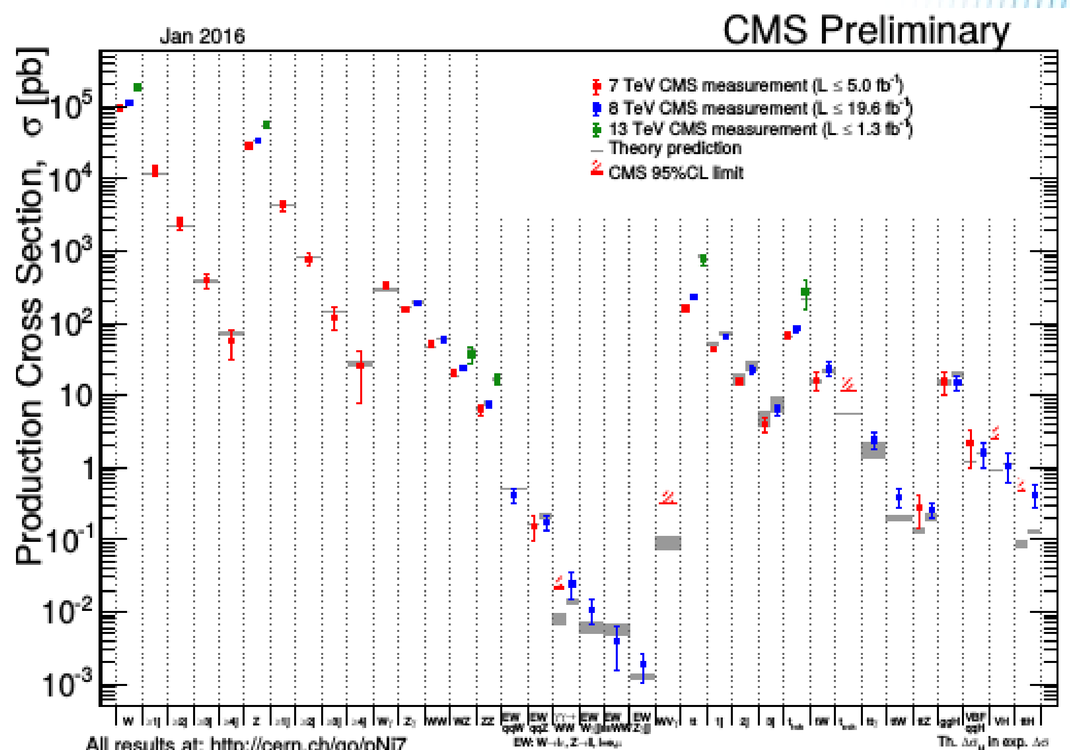
Theory:

- A uniform ensemble of parton distributions at NNLO
- Event generators at NNLO, merging of parton emissions at NLO

Experiment:

- Fiducial and differential cross section measurements
- Rare processes never before studied



# Higgs boson production

- Run 1 results use "kappa" ~model-independent framework
  - Multiplicative factors for Higgs terms in the Lagrangian

For a given production process or decay channel:

$$\kappa_j^2 = \sigma_j / \sigma_j^{SM} \qquad \kappa_j^2 = \Gamma^j / \Gamma^j_{SM}$$

Connect to measurements via "μ" factors (notation: i→H→f)

$$\mu_i = \frac{\sigma_i}{(\sigma_i)_{SM}} \quad \text{and} \quad \mu^f = \frac{BR^f}{(BR^f)_{SM}}.$$

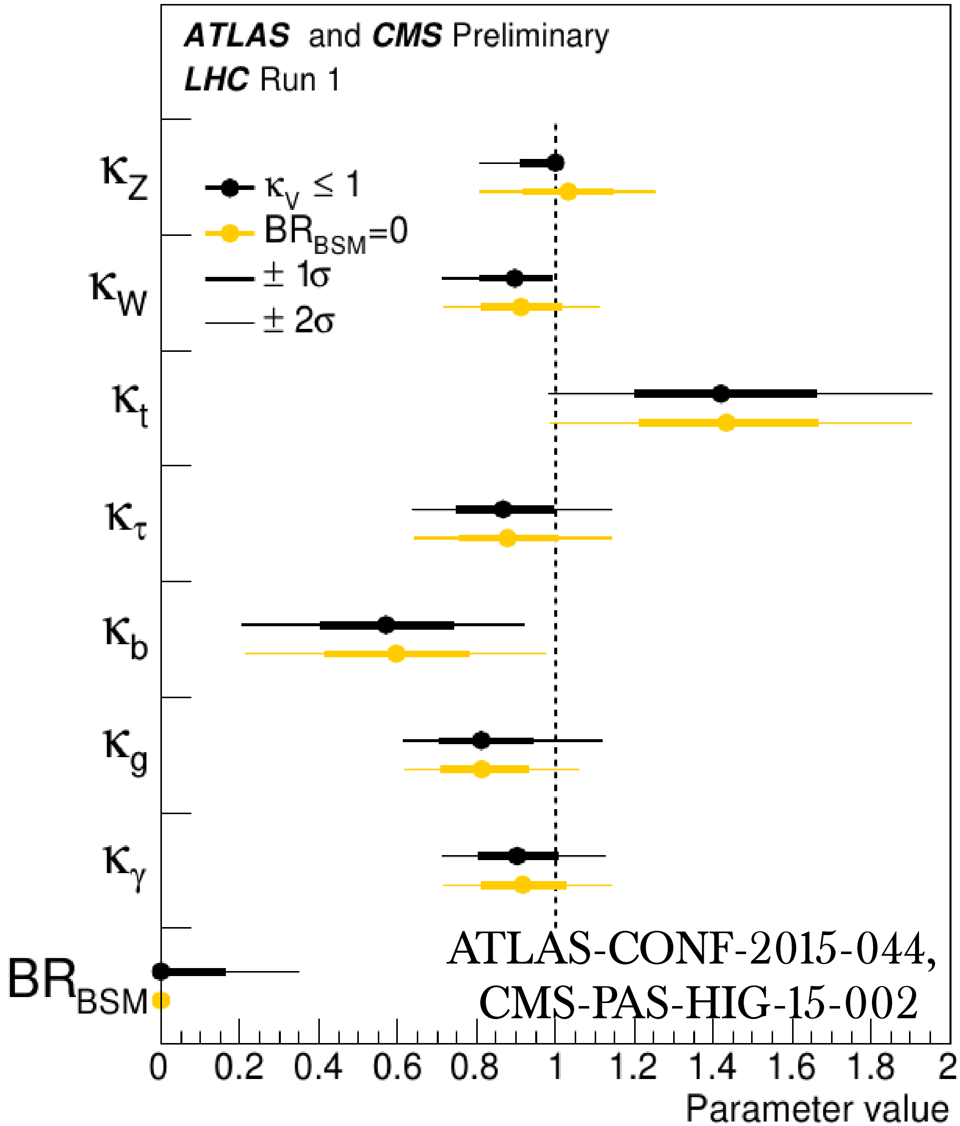
$$\mu_i^f = \frac{\sigma_i \cdot BR^f}{(\sigma_i)_{SM} \cdot (BR^f)_{SM}} = \mu_i \times \mu^f$$

| Production | Loops | Interference | Multiplicative factor |
|---|---|---|---|
| $\sigma(ggF)$ | ✓ | $b-t$ | $\kappa_g^2 \sim 1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$ |
| $\sigma(VBF)$ | – | – | $\sim 0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$ |
| $\sigma(WH)$ | – | – | $\sim \kappa_W^2$ |
| $\sigma(qq/qg \to ZH)$ | – | – | $\sim \kappa_Z^2$ |
| $\sigma(gg \to ZH)$ | ✓ | $Z-t$ | $\sim 2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$ |
| $\sigma(ttH)$ | – | – | $\sim \kappa_t^2$ |
| $\sigma(gb \to WtH)$ | – | $W-t$ | $\sim 1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t \kappa_W$ |
| $\sigma(qb \to tHq)$ | – | $W-t$ | $\sim 3.4 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$ |
| $\sigma(bbH)$ | – | – | $\sim \kappa_b^2$ |
| Partial decay width | | | |
| $\Gamma^{ZZ}$ | – | – | $\sim \kappa_Z^2$ |
| $\Gamma^{WW}$ | – | – | $\sim \kappa_W^2$ |
| $\Gamma^{\gamma\gamma}$ | ✓ | $W-t$ | $\kappa_\gamma^2 \sim 1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$ |
| $\Gamma^{\tau\tau}$ | – | – | $\sim \kappa_\tau^2$ |
| $\Gamma^{bb}$ | – | – | $\sim \kappa_b^2$ |
| $\Gamma^{\mu\mu}$ | – | – | $\sim \kappa_\mu^2$ |
| Total width for $BR_{BSM} = 0$ | | | |
| $\Gamma_H$ | ✓ | – | $\kappa_H^2 \sim 0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 + 0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{Z\gamma}^2 + 0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_\mu^2$ |

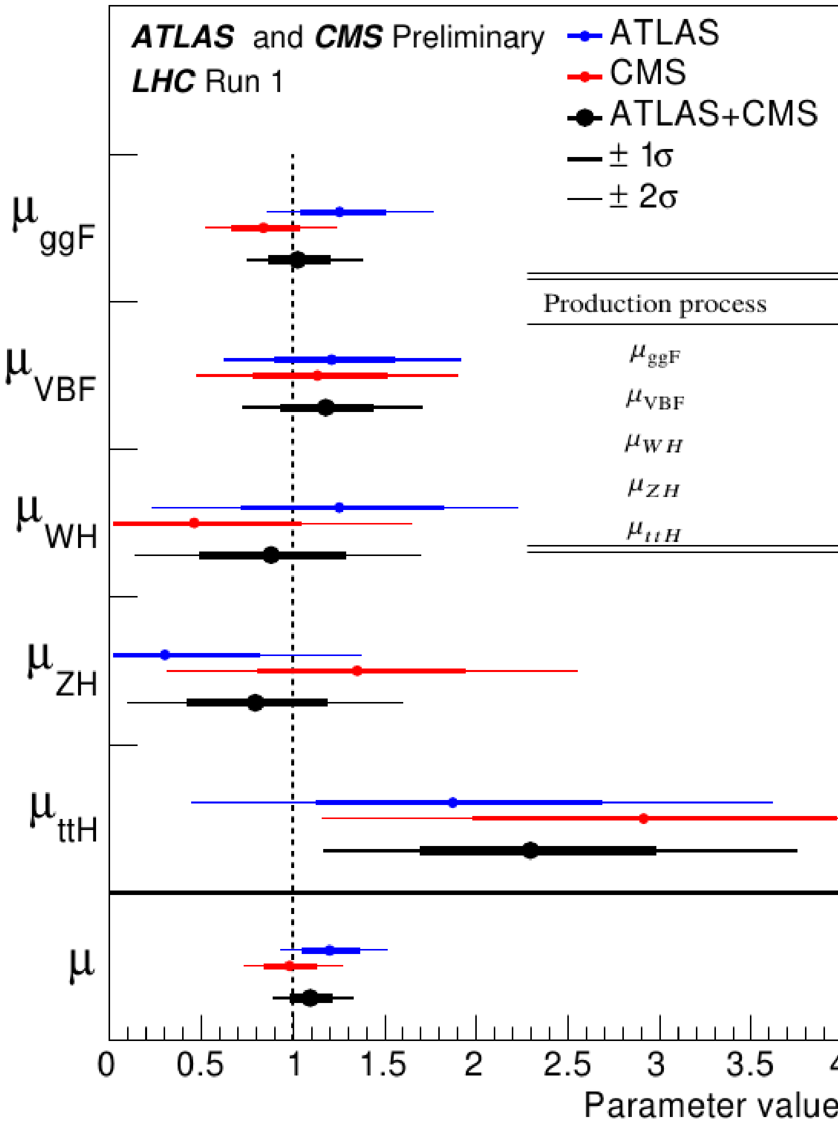
ATLAS-CONF-2015-044, CMS-PAS-HIG-15-002

# Higgs boson production

- Combined ATLAS+CMS κ and μ constraints




ATLAS-CONF-2015-044,
CMS-PAS-HIG-15-002



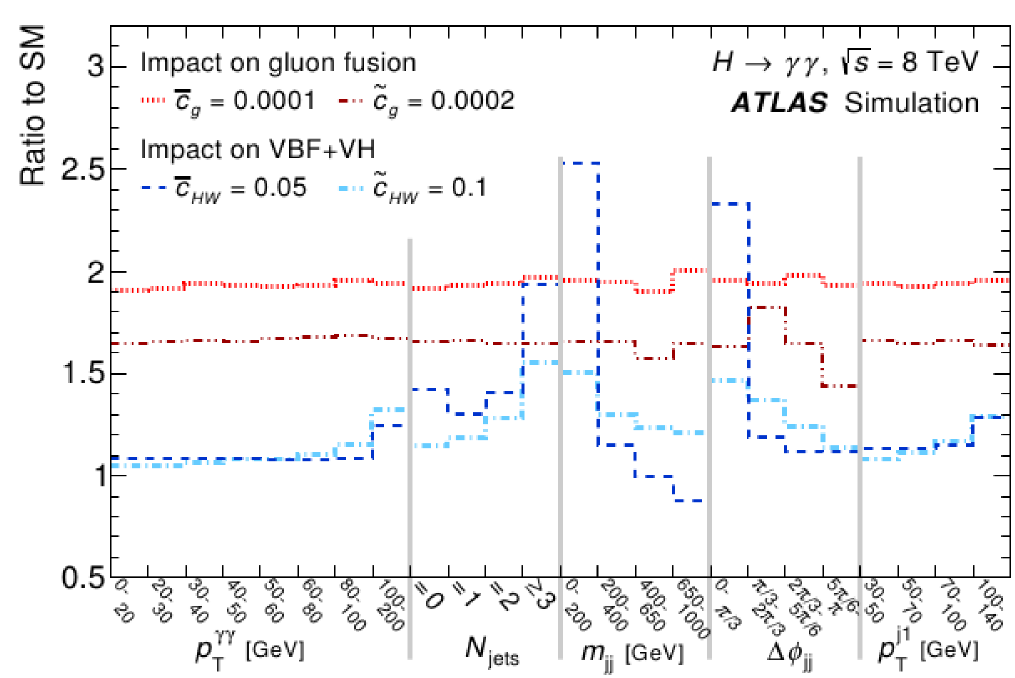

| Production process | ATLAS+CMS |
|---|---|
| $\mu_{ggF}$ | $1.03^{+0.17}_{-0.15}$ |
| $\mu_{VBF}$ | $1.18^{+0.25}_{-0.23}$ |
| $\mu_{WH}$ | $0.88^{+0.40}_{-0.38}$ |
| $\mu_{ZH}$ | $0.80^{+0.39}_{-0.36}$ |
| $\mu_{ttH}$ | $2.3^{+0.7}_{-0.6}$ |

# Higgs boson production

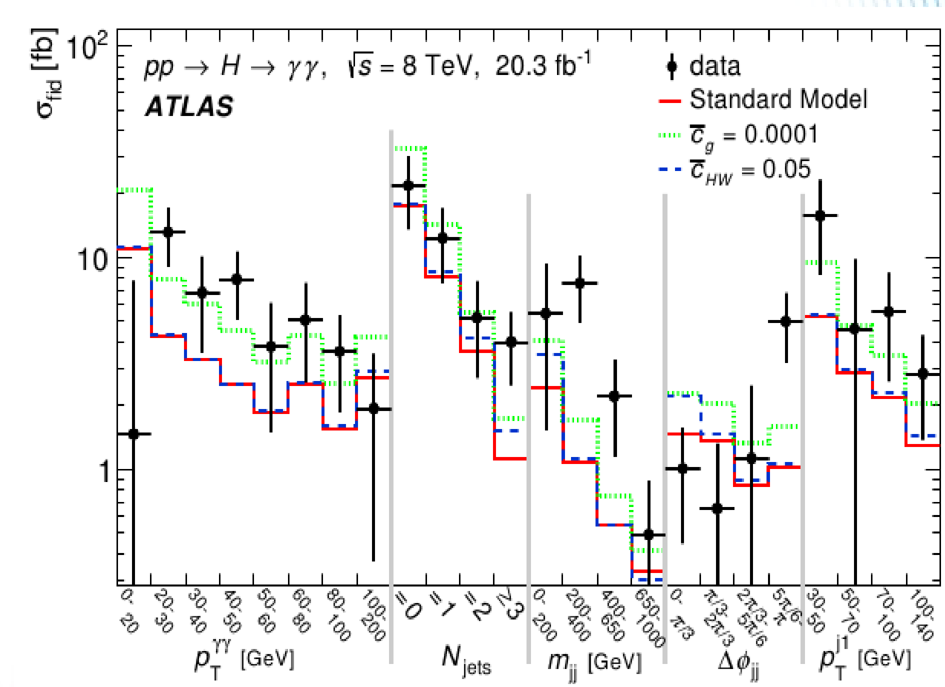
- First results with effective Lagrangian from ATLAS H→γγ
  - Consider only terms relevant for ggF and VBF production

$$\mathcal{L} = \bar{c}_\gamma O_\gamma + \bar{c}_g O_g + \bar{c}_{HW} O_{HW} + \bar{c}_{HB} O_{HB} + \tilde{c}_\gamma \tilde{O}_\gamma + \tilde{c}_g \tilde{O}_g + \tilde{c}_{HW} \tilde{O}_{HW} + \tilde{c}_{HB} \tilde{O}_{HB},$$

arxiv:1508.02507



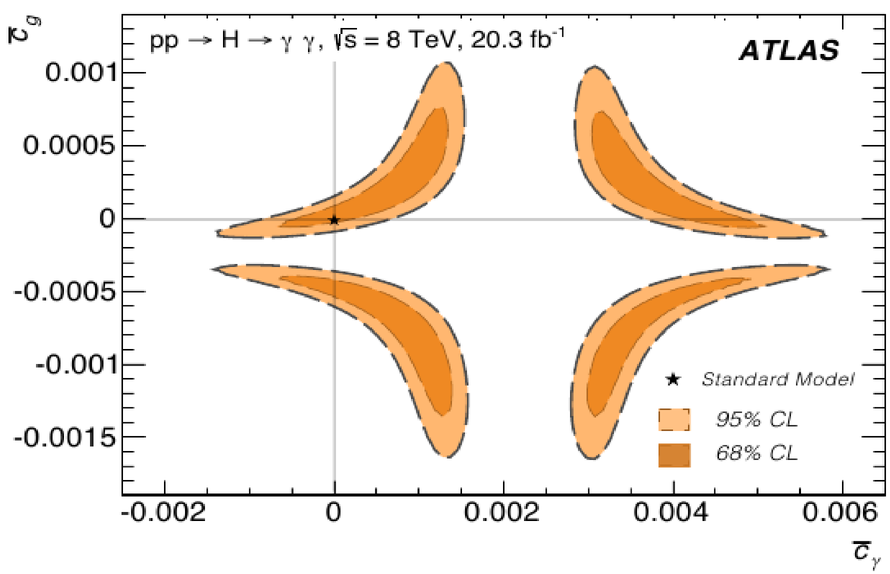

Impact of effective couplings



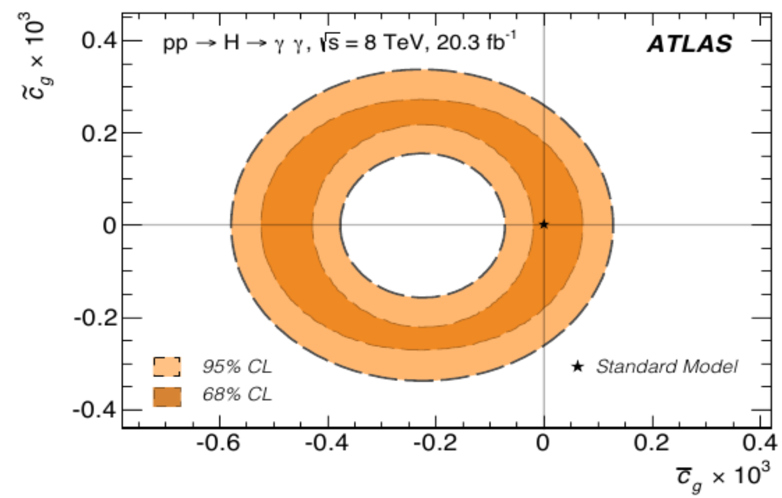

Measured results

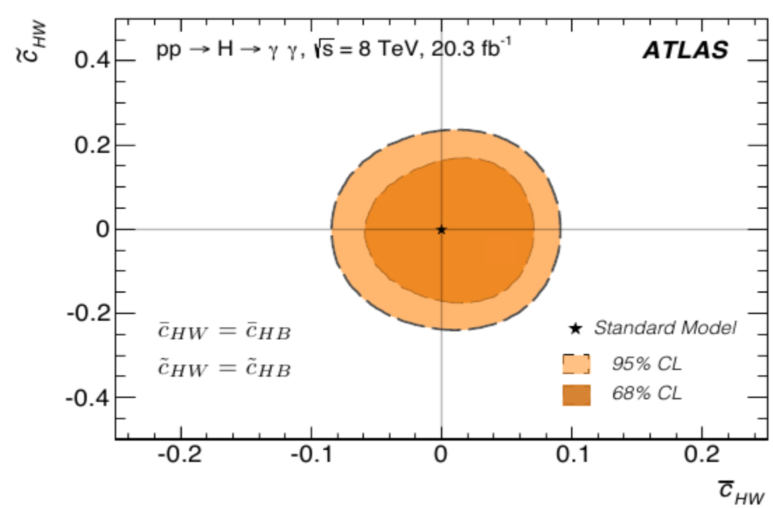
# Higgs boson production

- First results with effective Lagrangian from ATLAS $H \rightarrow \gamma\gamma$
  - Obtain constraints in 1- & 2-dimensional coupling planes




| Coefficient | 95% $1-CL$ limit |
|---|---|
| $\bar{c}_\gamma$ | $[-7.4, 5.7]\times10^{-4} \cup [3.8, 5.1]\times10^{-3}$ |
| $\tilde{c}_\gamma$ | $[-1.8, 1.8]\times10^{-3}$ |
| $\bar{c}_g$ | $[-0.7, 1.3]\times10^{-4} \cup [-5.8, -3.8]\times10^{-4}$ |
| $\tilde{c}_g$ | $[-2.4, 2.4]\times10^{-4}$ |
| $\bar{c}_{HW}$ | $[-8.6, 9.2]\times10^{-2}$ |
| $\tilde{c}_{HW}$ | $[-0.23, 0.23]$ |



# Higgs boson production

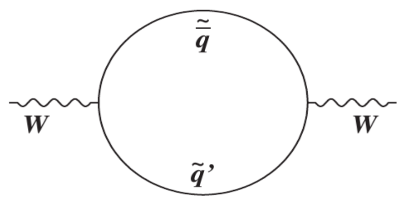
- Leading-order effective Lagrangian has limitations
  - Parameters have no sensitivity to e.g. pTH

- Ongoing work to extend to NLO and to add dimension-8 operators
  - already 59 operators at dimension-6

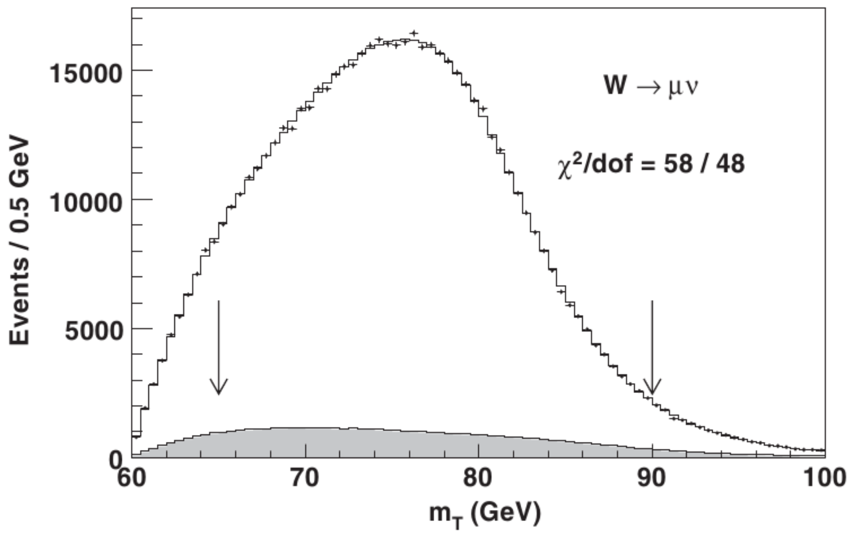
- Yellow report will also have prescription for connecting experimental constraints on EFT parameters to specific models
  - Also plan to investigate connections between exclusive cross sections to specific models

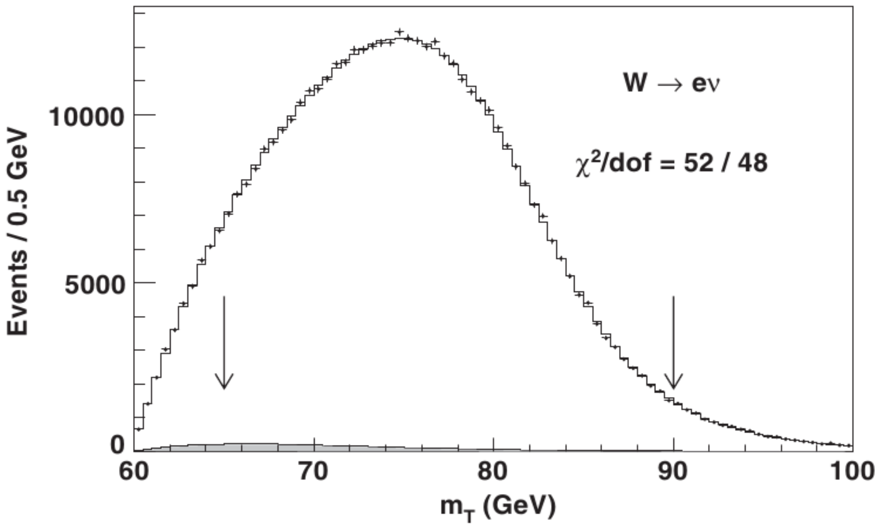
# W and Z boson masses

- W and Z bosons contain three fields of the Higgs doublet
  - Loop mass corrections common to those of the Higgs boson
  - W boson mass is predicted given the precise knowledge of the Z boson mass, electroweak couplings, and top mass



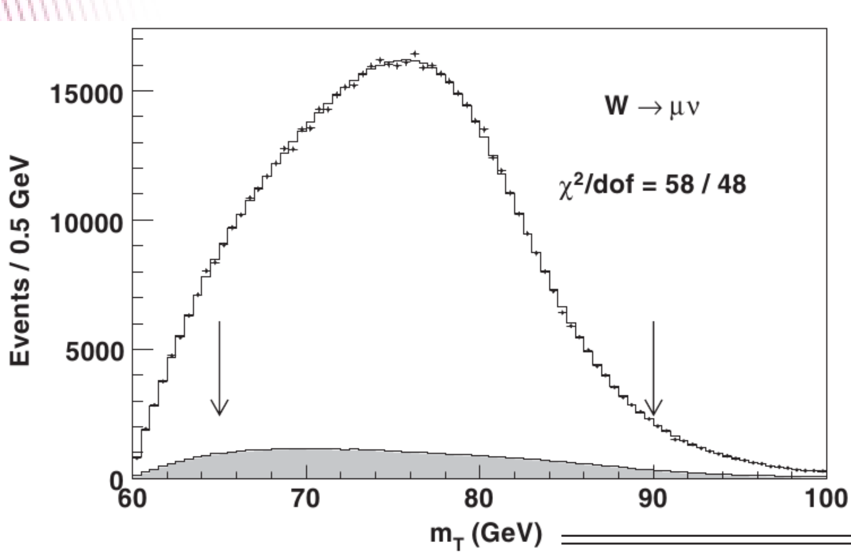

- Compare to direct measurement to probe corrections
- Sensitive to low-mass supersymmetry

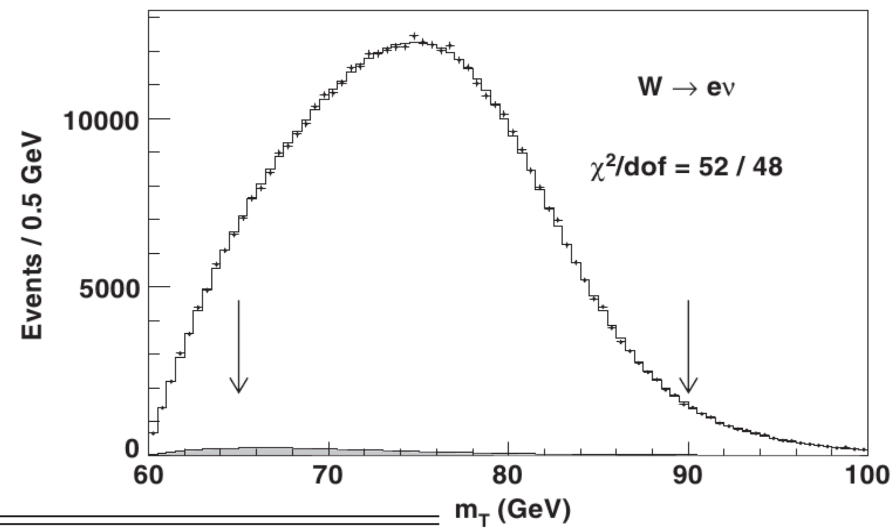


# W boson mass measurement

- Tevatron experiments analyzing final data set (~9 fb$^{-1}$)
  - Factors of 2-4 increase in events
  - CDF expects final uncertainty of ~10 MeV



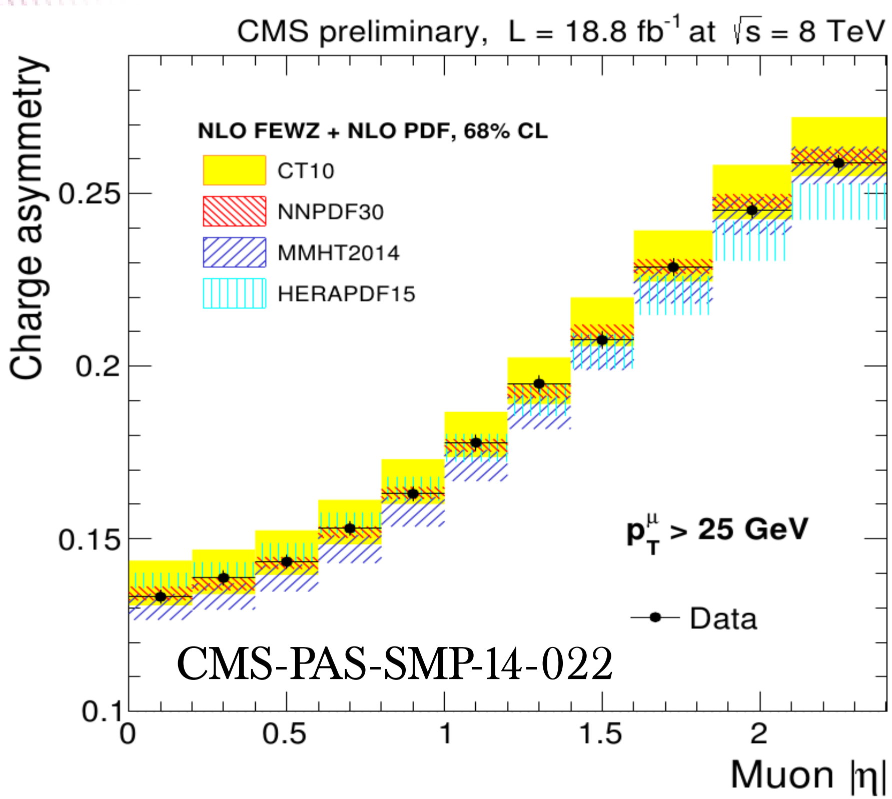



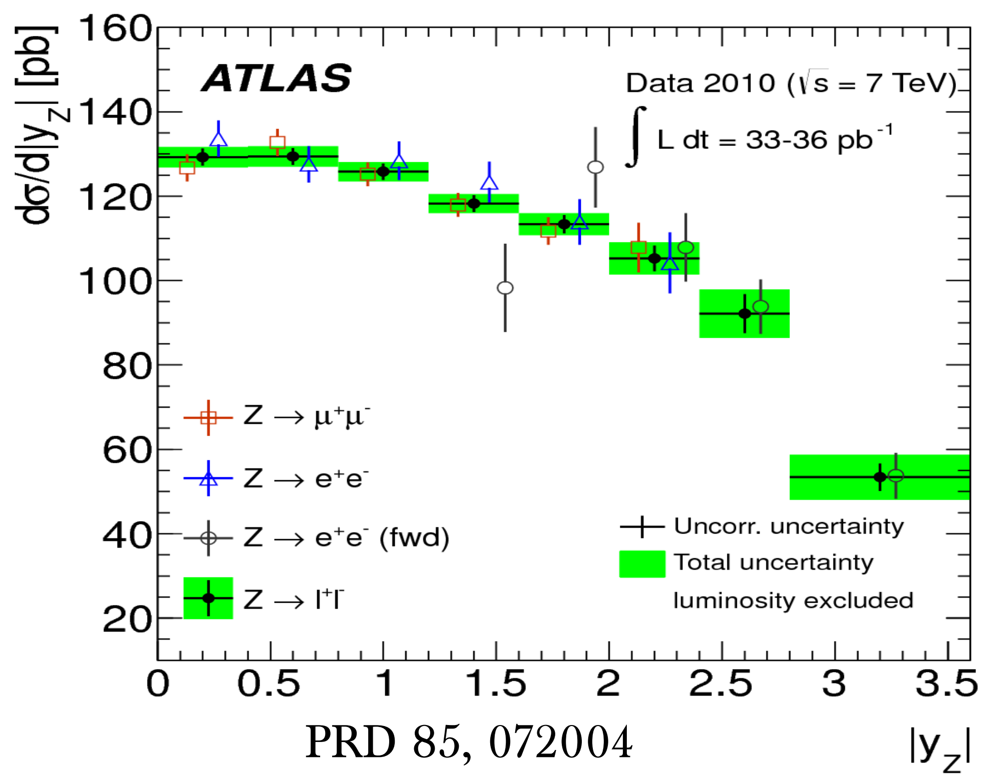

| Source | Uncertainty |
|---|---|
| Lepton energy scale and resolution | 7 |
| Recoil energy scale and resolution | 6 |
| Lepton tower removal | 2 |
| Backgrounds | 3 |
| PDFs | 10 |
| $p_T(W)$ model | 5 |
| Photon radiation | 4 |
| Statistical | 12 |
| Total | 19 |

PRD 89, 072003

# W boson mass measurement

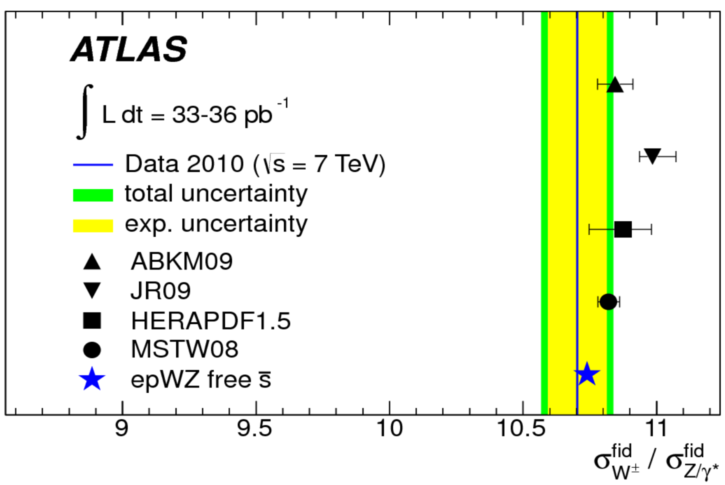
- LHC experiments laying groundwork for measurement
  - Many details of W & Z production need to be understood
    - Parton distribution function uncertainties dominate
    - Constrain with W+/W- asymmetry, Z rapidity

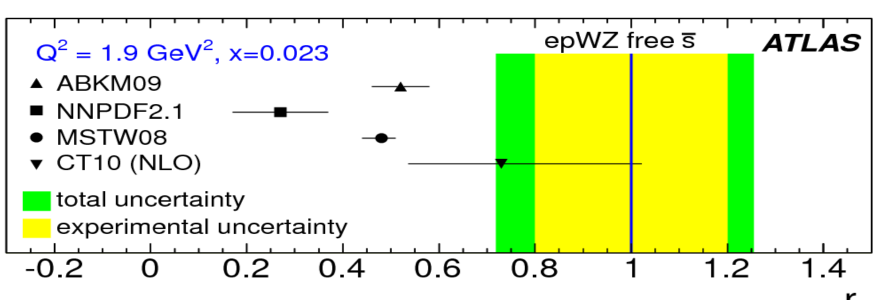


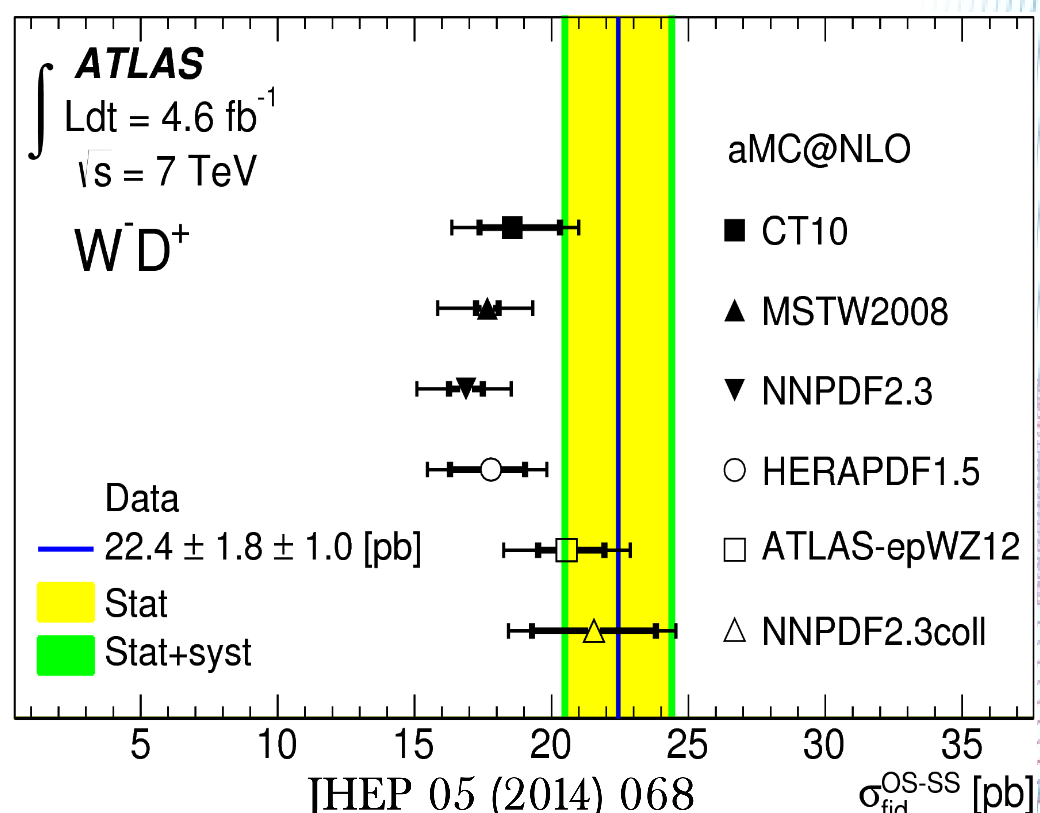
# W boson mass measurement

- LHC experiments laying groundwork for measurement
  - Many details of W & Z production need to be understood
    - Parton distribution function uncertainties dominate
    - Constrain with W/Z ratio, W+charm



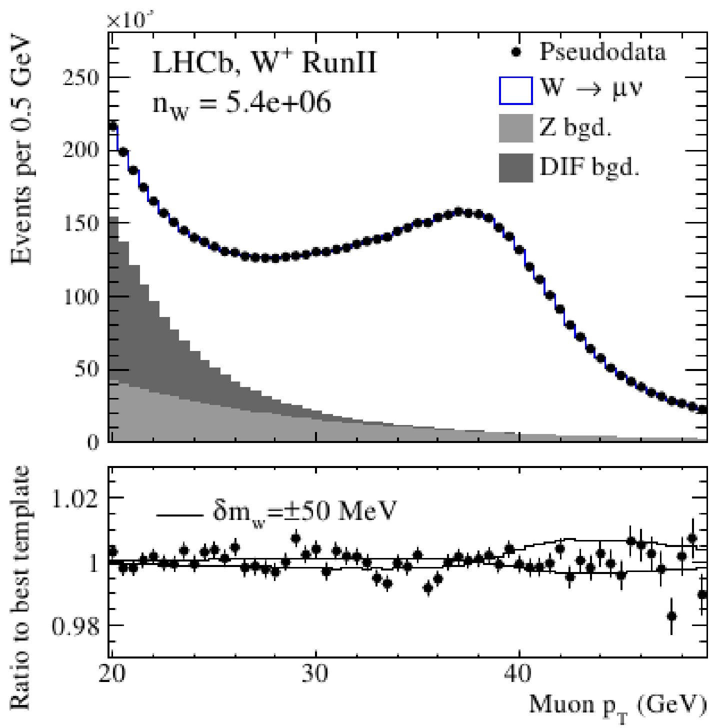

PRL 109, 012001




JHEP 05 (2014) 068

# W boson mass measurement

- LHC experiments laying groundwork for measurement
  - Many details of W & Z production need to be understood
    - Parton distribution function uncertainties dominate
    - Constrain with LHCb?



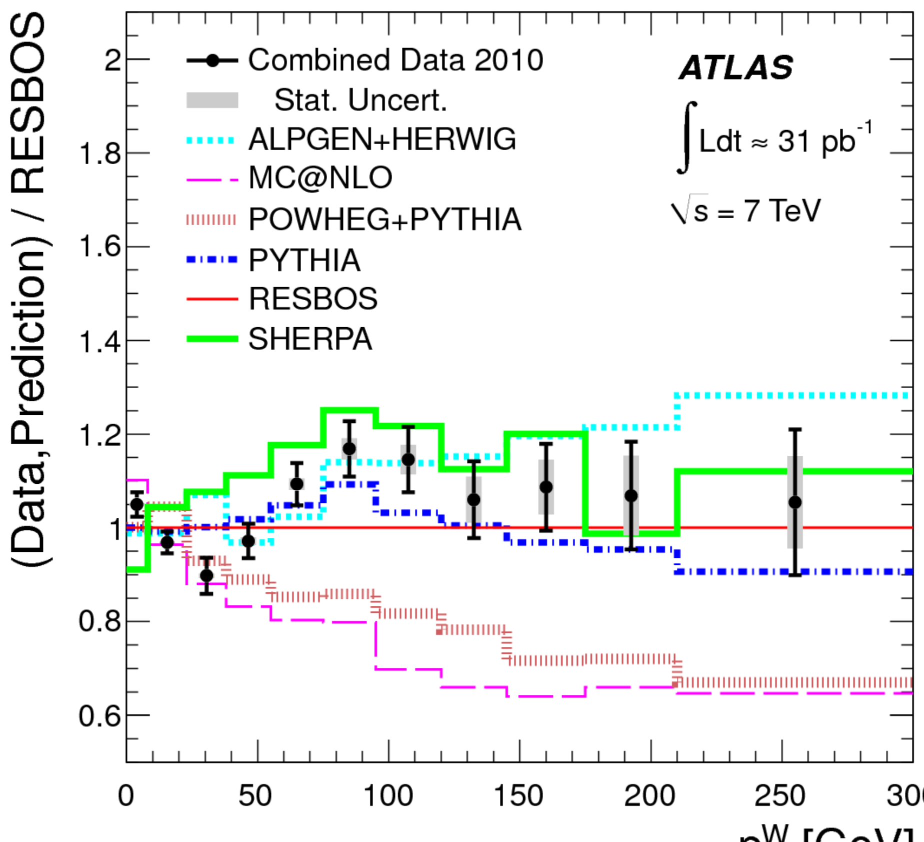

| | Run-I 3 fb$^{-1}$ | | Run-II 7 fb$^{-1}$ | |
|---|---|---|---|---|
| | $W^+$ | $W^-$ | $W^+$ | $W^-$ |
| Signal yields, $\times 10^6$ | 1.2 | 0.7 | 5.4 | 3.4 |
| $Z/\gamma^*$ background, $(B/S)$ | 0.15 | 0.15 | 0.15 | 0.15 |
| QCD background, $(B/S)$ | 0.15 | 0.15 | 0.15 | 0.15 |
| $\delta m_W$ (MeV) | | | | |
| Statistical | 19 | 29 | 9 | 12 |
| Momentum scale | 7 | 7 | 4 | 4 |
| Quadrature sum | 20 | 30 | 10 | 13 |

Could lead to ~25% reduction in combined PDF uncertainty

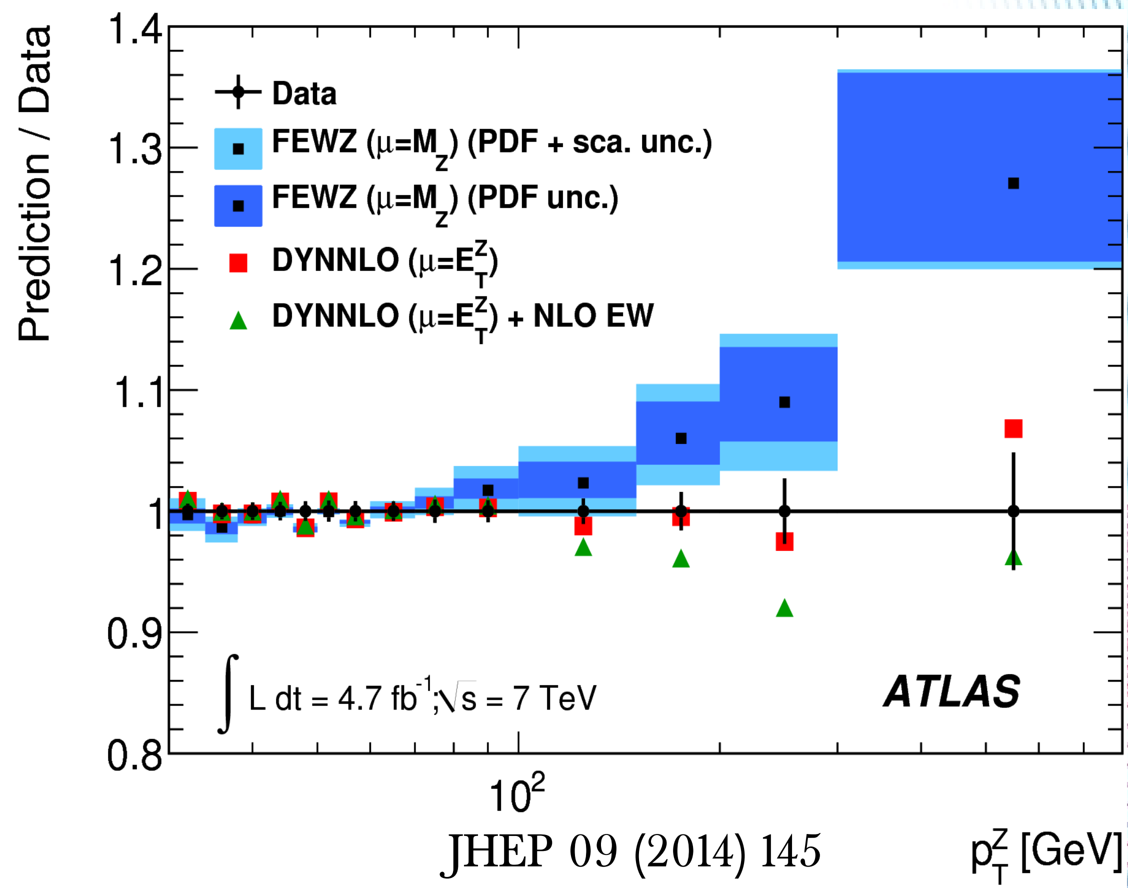
arxiv:1508.06954

# W boson mass measurement

- LHC experiments laying groundwork for measurement
  - Many details of W & Z production need to be understood
    - Transverse momentum distributions also important



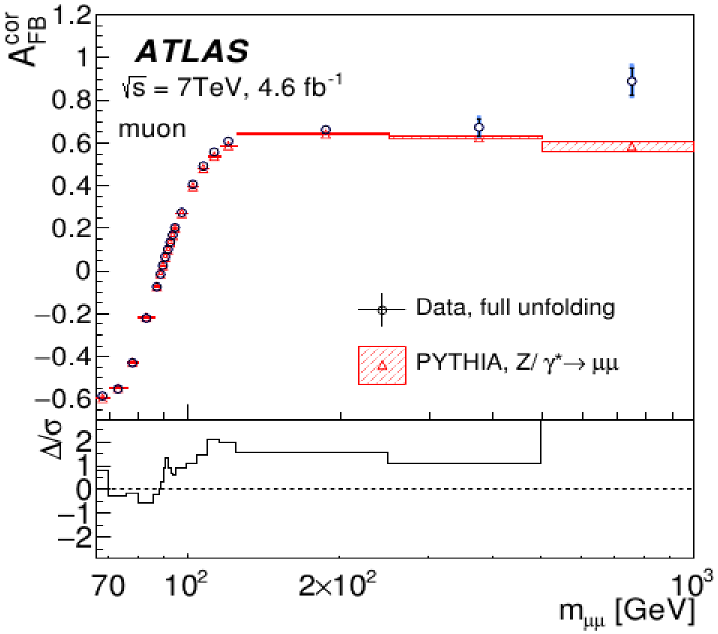

PRD 85, 012005




JHEP 09 (2014) 145

# Z boson asymmetry

- LHC measurements have significant PDF uncertainties
  - PDF improvements needed for both direct and indirect $m_W$




CMS

| source | correction | uncertainty |
|---|---|---|
| PDF | - | ±0.0013 |
| FSR | - | ±0.0011 |
| LO model (EWK) | - | ±0.0002 |
| LO model (QCD) | +0.0012 | ±0.0012 |
| resolution and alignment | +0.0007 | ±0.0013 |
| efficiency and acceptance | - | ±0.0003 |
| background | - | ±0.0001 |
| total | +0.0019 | ±0.0025 |

PRD 84, 112002

ATLAS

| | $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$ |
|---|---|
| CC electron | $0.2302 \pm 0.0009(\mathrm{stat.}) \pm 0.0008(\mathrm{syst.}) \pm 0.0010(\mathrm{PDF}) = 0.2302 \pm 0.0016$ |
| CF electron | $0.2312 \pm 0.0007(\mathrm{stat.}) \pm 0.0008(\mathrm{syst.}) \pm 0.0010(\mathrm{PDF}) = 0.2312 \pm 0.0014$ |
| Muon | $0.2307 \pm 0.0009(\mathrm{stat.}) \pm 0.0008(\mathrm{syst.}) \pm 0.0009(\mathrm{PDF}) = 0.2307 \pm 0.0015$ |
| El. combined | $0.2308 \pm 0.0006(\mathrm{stat.}) \pm 0.0007(\mathrm{syst.}) \pm 0.0010(\mathrm{PDF}) = 0.2308 \pm 0.0013$ |
| Combined | $0.2308 \pm 0.0005(\mathrm{stat.}) \pm 0.0006(\mathrm{syst.}) \pm 0.0009(\mathrm{PDF}) = 0.2308 \pm 0.0012$ |

JHEP 09 (2015) 049