Precision Electroweak Physics at Hadron Colliders

Matthias Schott on behalf of the ATLAS, CMS, LHCb, D0 + CDF Collaborations

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

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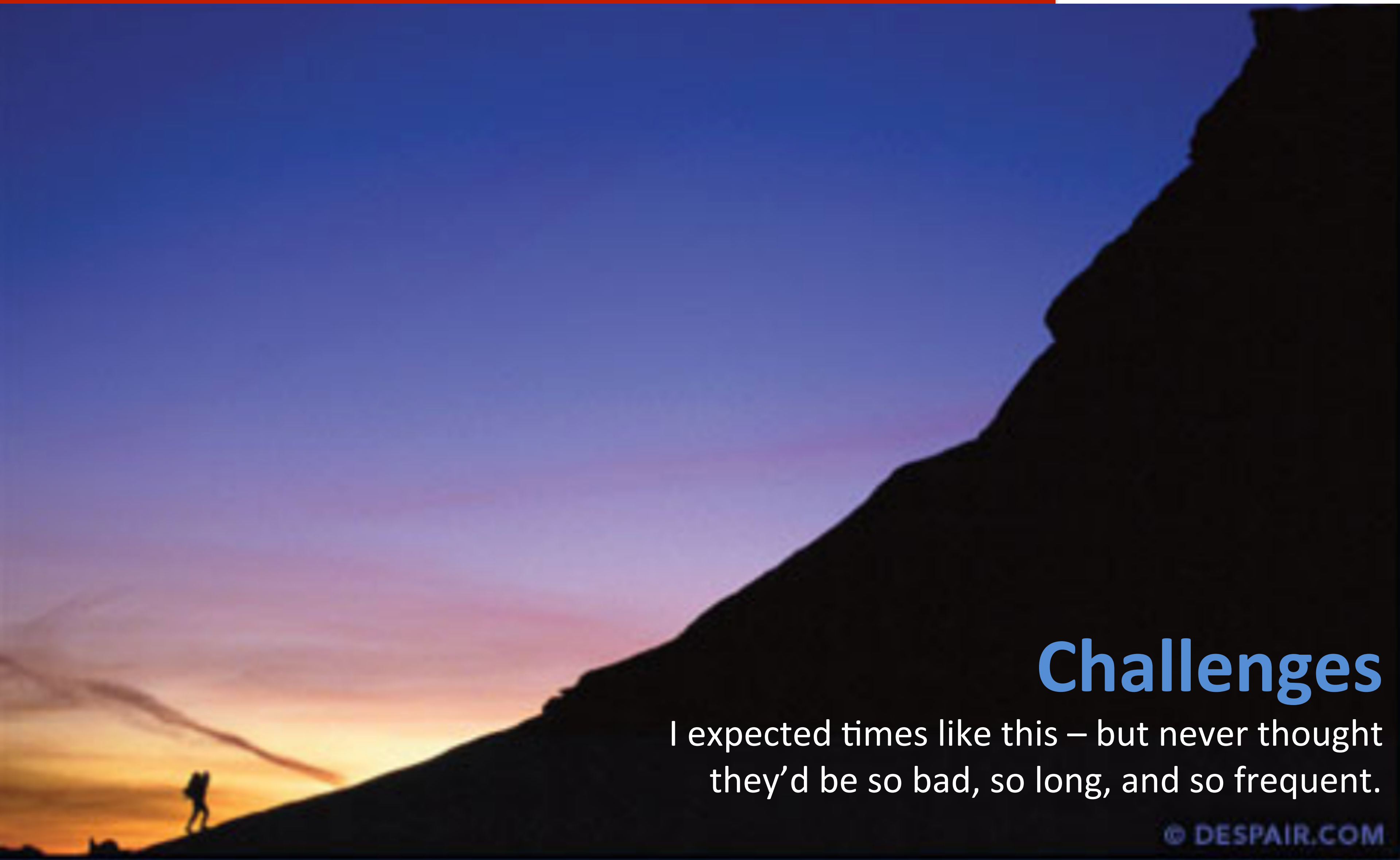
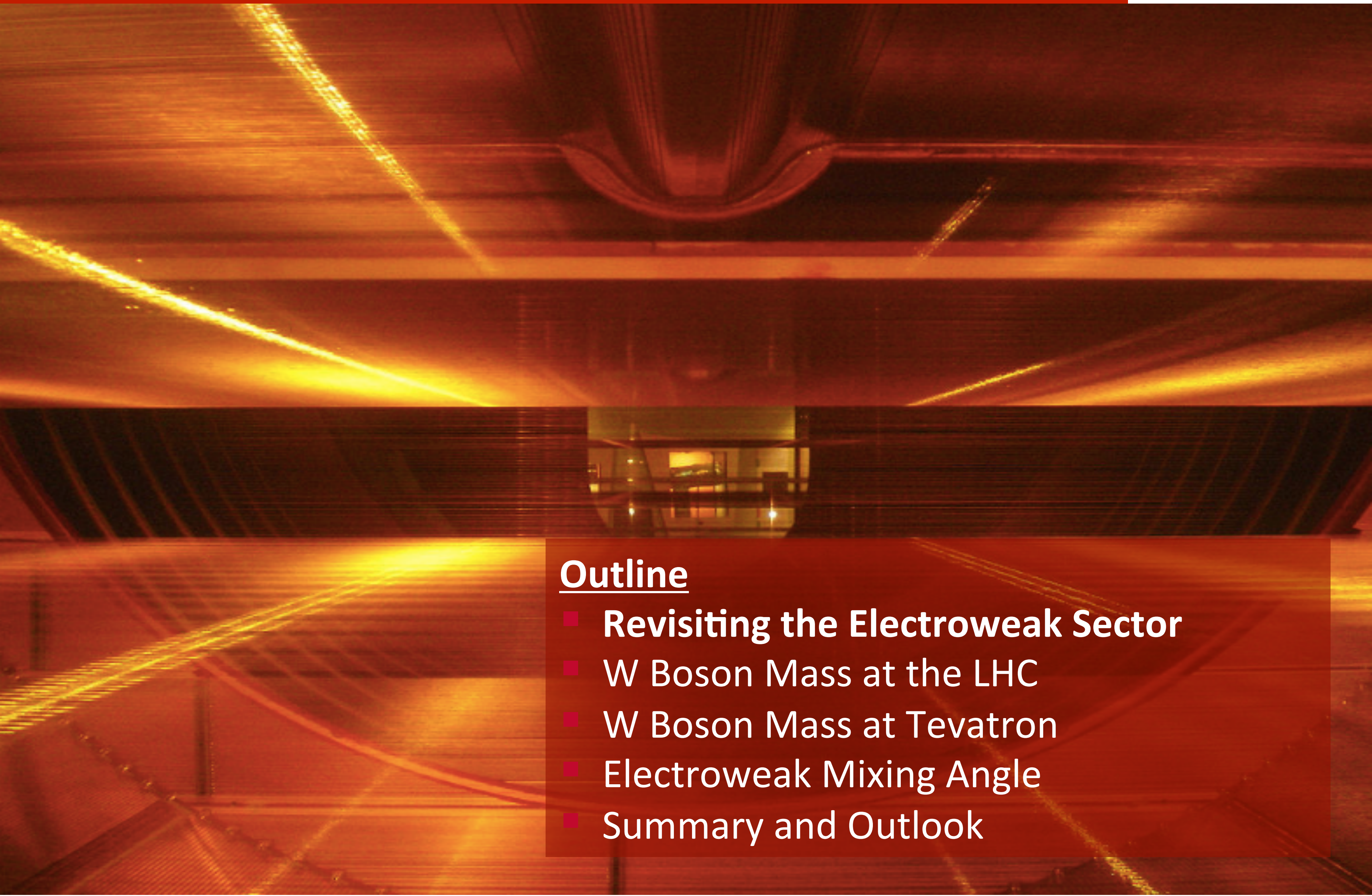


Revisiting the Electroweak Sector



Outline

- **Revisiting the Electroweak Sector**
- W Boson Mass at the LHC
- W Boson Mass at Tevatron
- Electroweak Mixing Angle
- Summary and Outlook

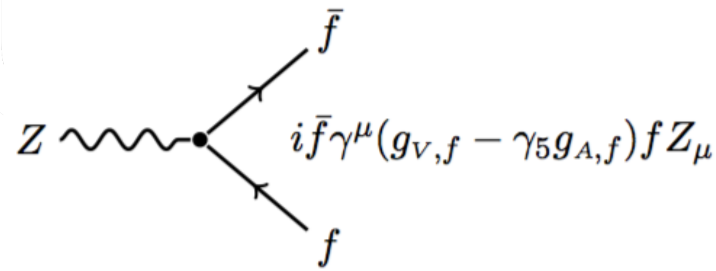
Summary of the Electroweak Sector

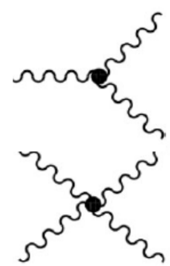
- The electroweak sector of the Standard Model has five parameters
  - α_{em}, G_F, m_W, m_Z, $\sin^2\theta_W$
  - (+ m_H for the scalar sector)

- However, they are not independent, but related by theory

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

- In this talk: Focus on EW observables
  - Tests of the **gauge structure** of the electroweak sector (e.g. dibosons, triboson, aTGC, qTGC, …) will be discussed in the talk of **Lara and Emily** later today

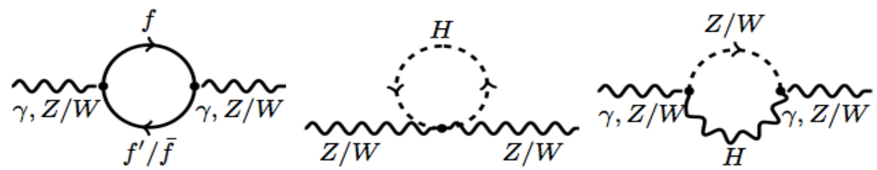




coupling	parameters	channel
$WW\gamma$	$\lambda_\gamma, \Delta k_\gamma$	$WW, W\gamma$
WWZ	$\lambda_Z, \Delta k_Z, \Delta g_1^Z$	WW, WZ
$ZZ\gamma$	h_3^Z, h_4^Z	$Z\gamma$
$Z\gamma\gamma$	h_3^γ, h_4^γ	$Z\gamma$
$Z\gamma Z$	$f_{40}^\gamma, f_{50}^\gamma$	ZZ
ZZZ	f_{40}^Z, f_{50}^Z	ZZ

Radiative Corrections

- Tree-level not sufficient
  - The impact of corrections stored in **EW form factors**



- The relation between SM parameters appear with **quadratic dependence on m_{top}, logarithmic dependence on M_H**

$$\sin^2\theta^f_{\text{eff}} = \kappa^f_Z \sin^2\theta_W$$

$$g_{V,f} = \sqrt{\rho^f_Z}(I^f_3 - 2Q^f \sin^2\theta^f_{\text{eff}})$$

$$g_{A,f} = \sqrt{\rho^f_Z} I^f_3$$

$$M^2_W = \frac{M^2_Z}{2}\left(1 + \sqrt{1 - \frac{\sqrt{8}\pi\alpha(1+\Delta r)}{G_F M^2_Z}}\right)$$

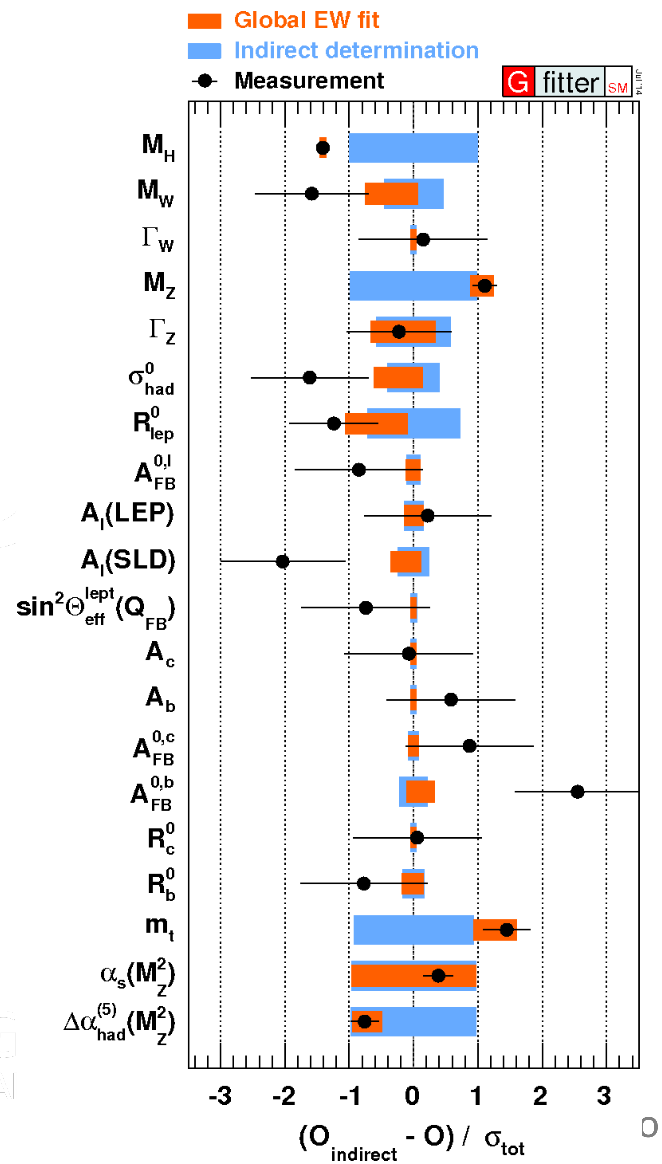
- Idea of electroweak fits
  - Measure many different observables in the experiment
  - Calculate the relations between all observables in SM
  - **Probe the consistency of the SM / Predict observables**

$$M_W\left(\ln(M_H), m^2_t, M_Z, \Delta\alpha^{(5)}_{\text{had}}(M^2_Z), \alpha_s(M^2_Z)\right)$$

$$\sin^2\theta^f_{\text{eff}}\left(\ln(M_H), M_H, m^2_t, M_Z, \Delta\alpha^{(5)}_{\text{had}}(M^2_Z), \alpha_s(M^2_Z)\right)$$

Input to the Global Electroweak Fit

- Input for the gobal electroweak fit mostly from
  - LEP: Z boson observables
  - Tevatron: W boson, top quark mass
  - LHC: **Higgs Boson, top quark mass (see dedicated top-session**)
- Note: improvement on **m_H precision** leaves fit unchanged
- Improvement on m_{top} will be **limited by theoretical uncertainty** on pole-mass definition (See talk by Sven-Olaf Moch)
- Largest discrepancy between A_l(SLD) and $A_{FB}^{0,b}$, both sensitive to $\sin^2\theta_W$



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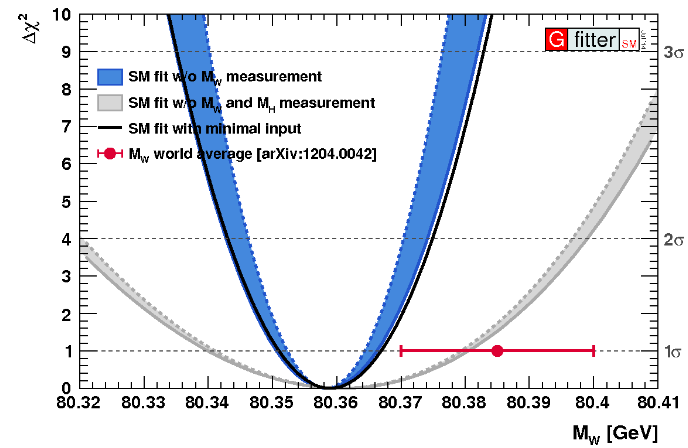
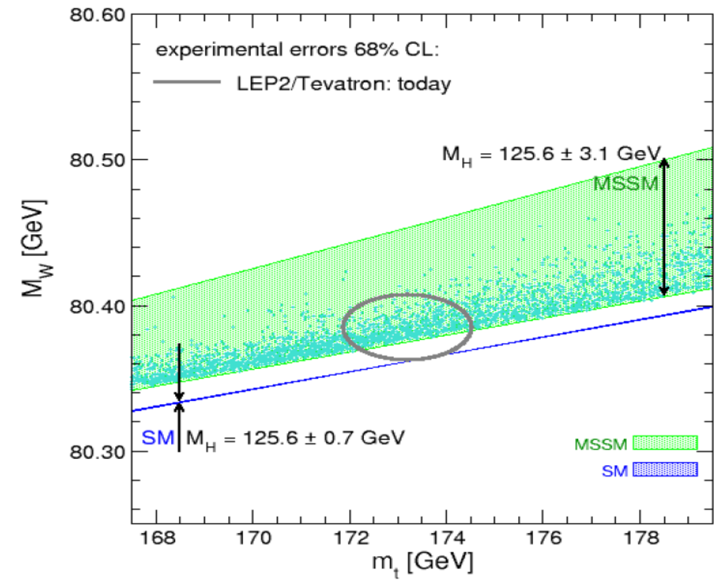
What we need: m_W, m_{top}, $\sin^2\theta_W$

- "Simple" thing: Test consistency of the Standard Model
  - Current **p-value = 0.22**
  - In order to match the m_{top} precision, we would need $\Delta m_W < 5$ MeV
    - Side-Note: also **no Γ_W measurement** at LHC yet

- Electroweak precision measurements are **sensitive to several new physics scenarios**, e.g. SUSY
  - Radiative correction depends on mass splitting (Δm^2) between squarks in SU(2) doublet
  - Precision on m_W could significantly limit the allowed MSSM space





[S. Heinemeyer et. al. arXiv:1311.1663]

The W Boson Mass at the LHC and Support Measurements

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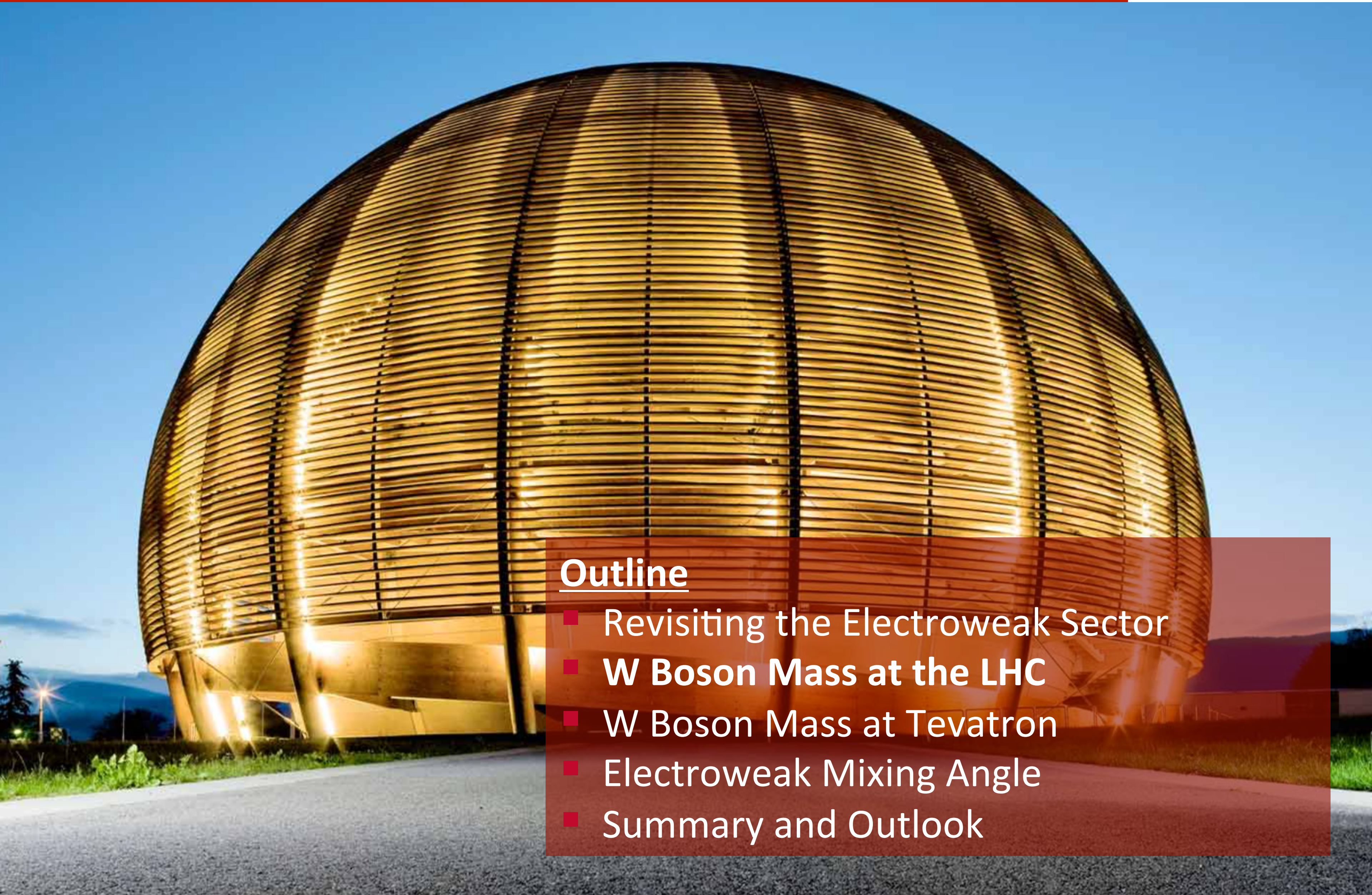

Outline

- Revisiting the Electroweak Sector
- **W Boson Mass at the LHC**
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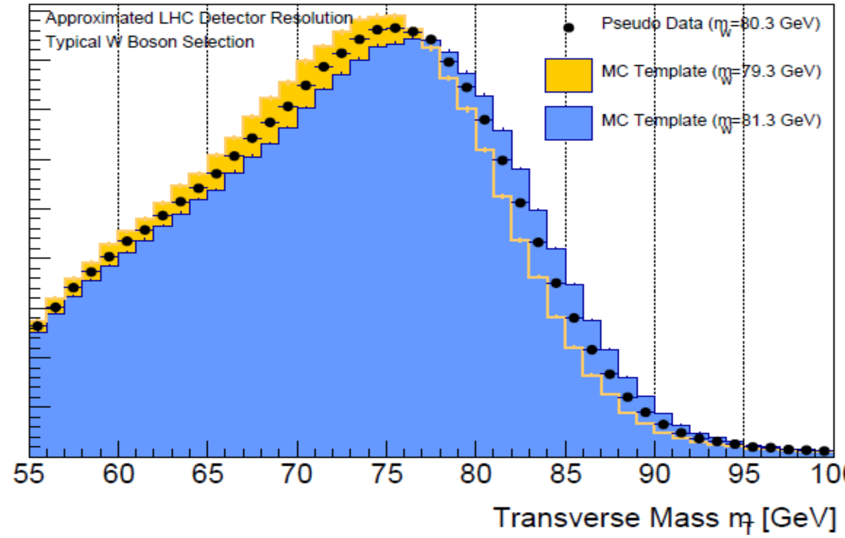
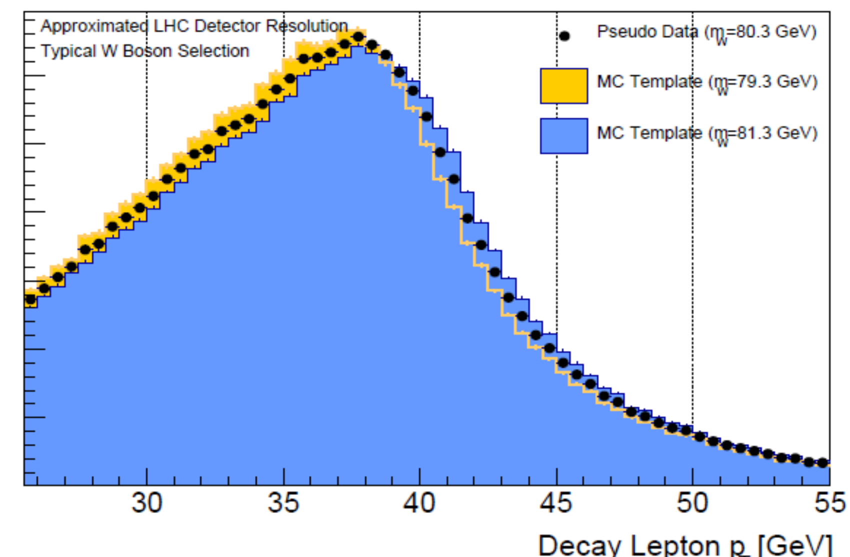
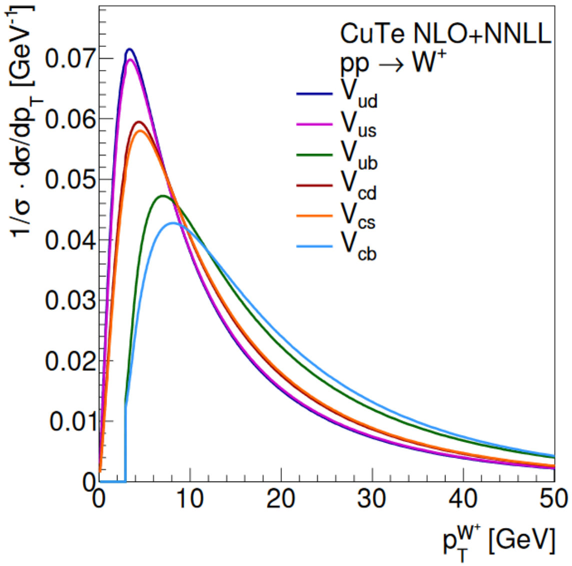
Measurement Principle

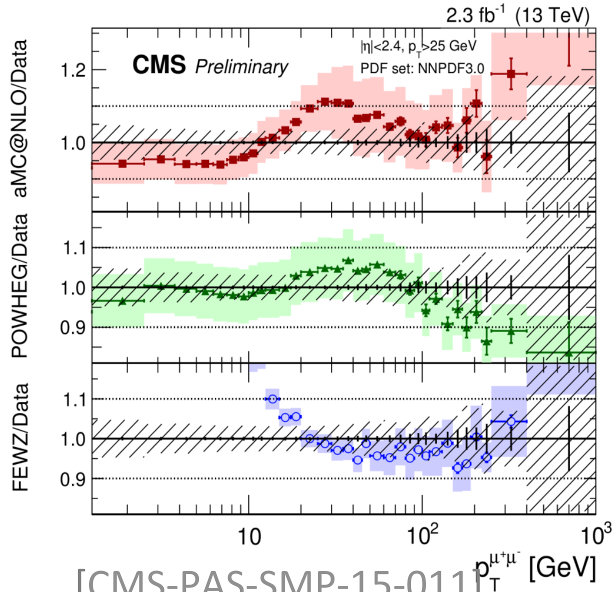
- Basic approach to measure W boson mass is a template fit
- Relevant observables
  - **Lepton transverse momentum**
  - **Transverse mass**
  - (missing transverse energy)
- Relies on perfect understanding of
  - Detector response (**See talk by Nenad this afternoon**)
  - Physics modelling
- Expect different physics modelling effects for W^+, W^- and different rapidities



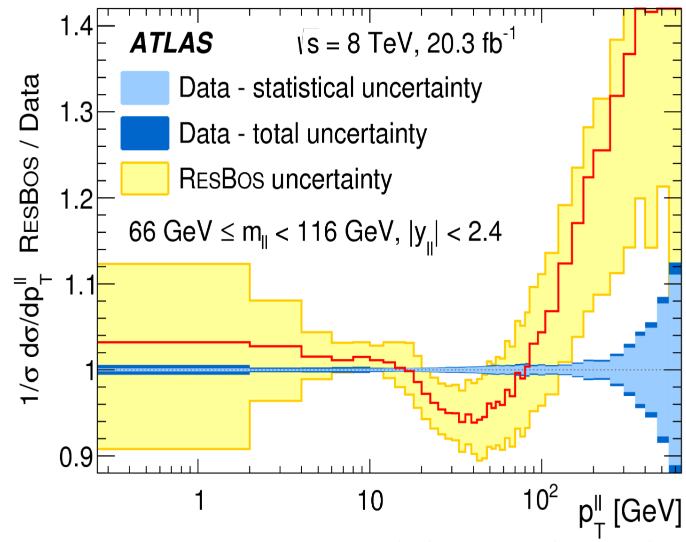


Modeling of Vector Boson p_T

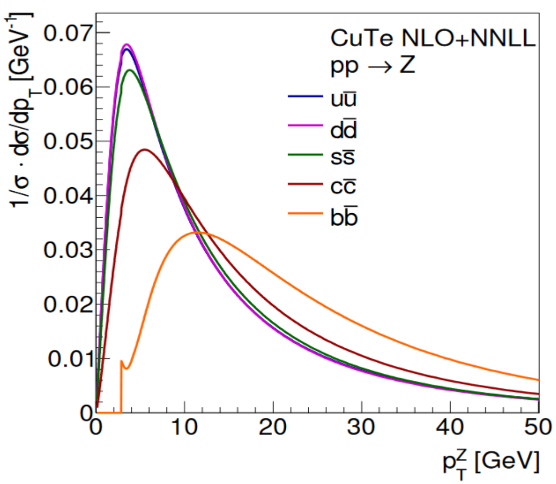




[CMS-PAS-SMP-15-011]



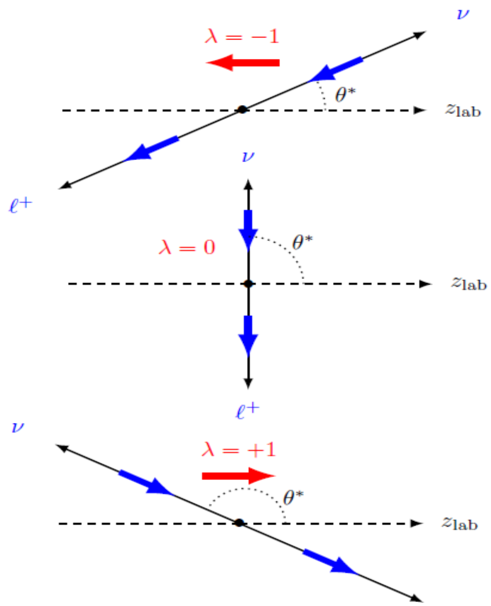
[Eur. Phys. J. C 76(5), 1-61 (2016)]

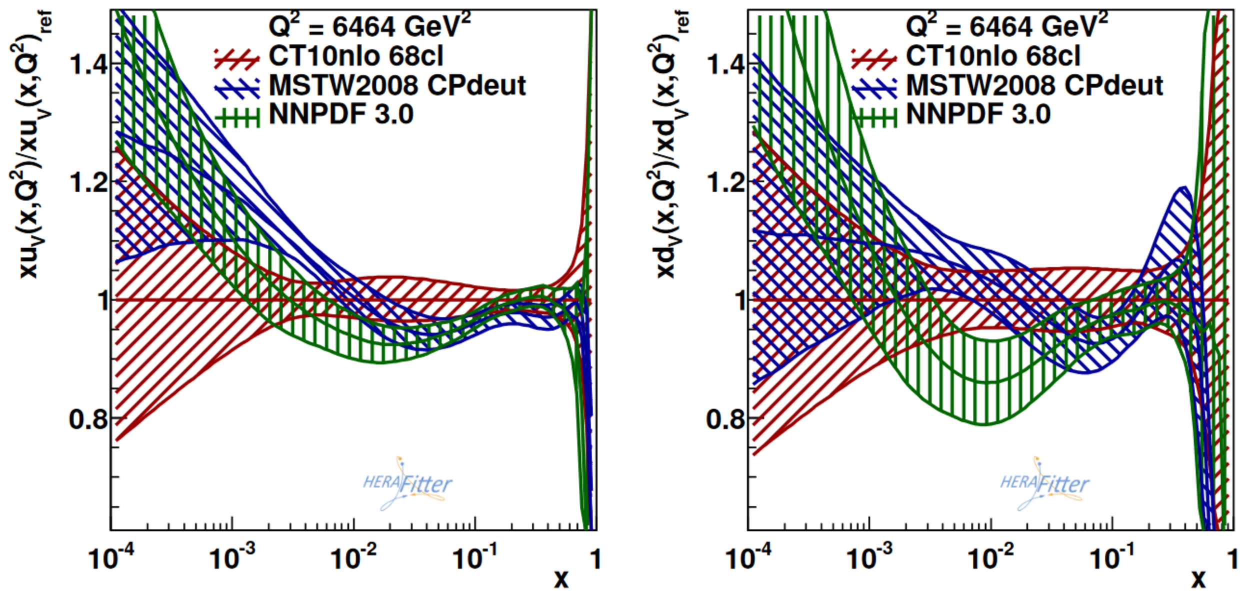


[ATL-PHYS-PUB-2014-015]

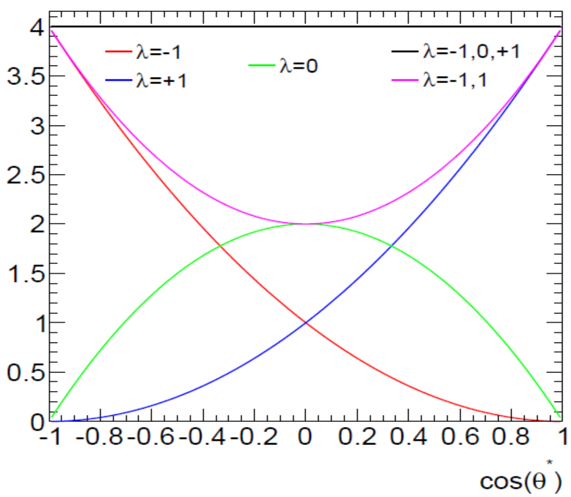
- Modelling of $p_T(W)$ impacts directly the p_T lepton distributions and relies on **NNLO and NNLL/resummed calculations**
  - Idea: Precision measurement of $p_T(Z)$ and tune model parameters
  - **Problem**: different generators predict different transfers from Z to W
- PDFs play a different role in W and Z production

PDF Effects



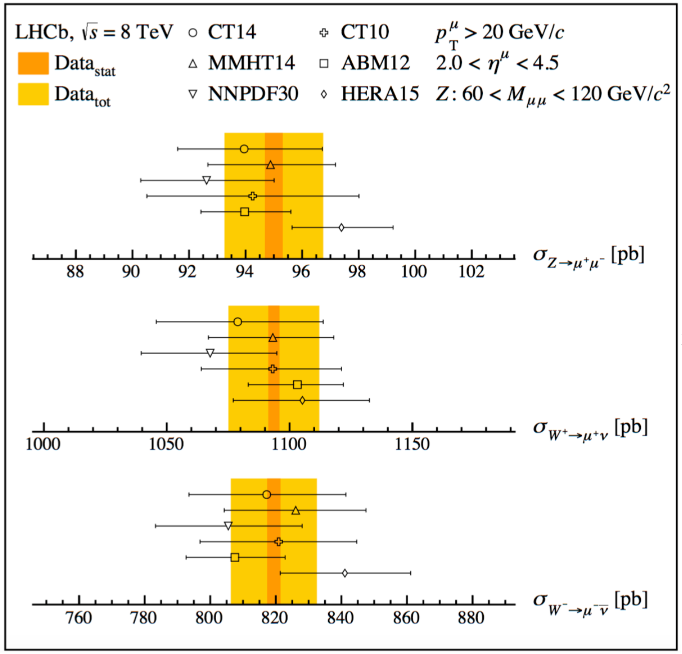


[ATL-PHYS-PUB-2014-015]

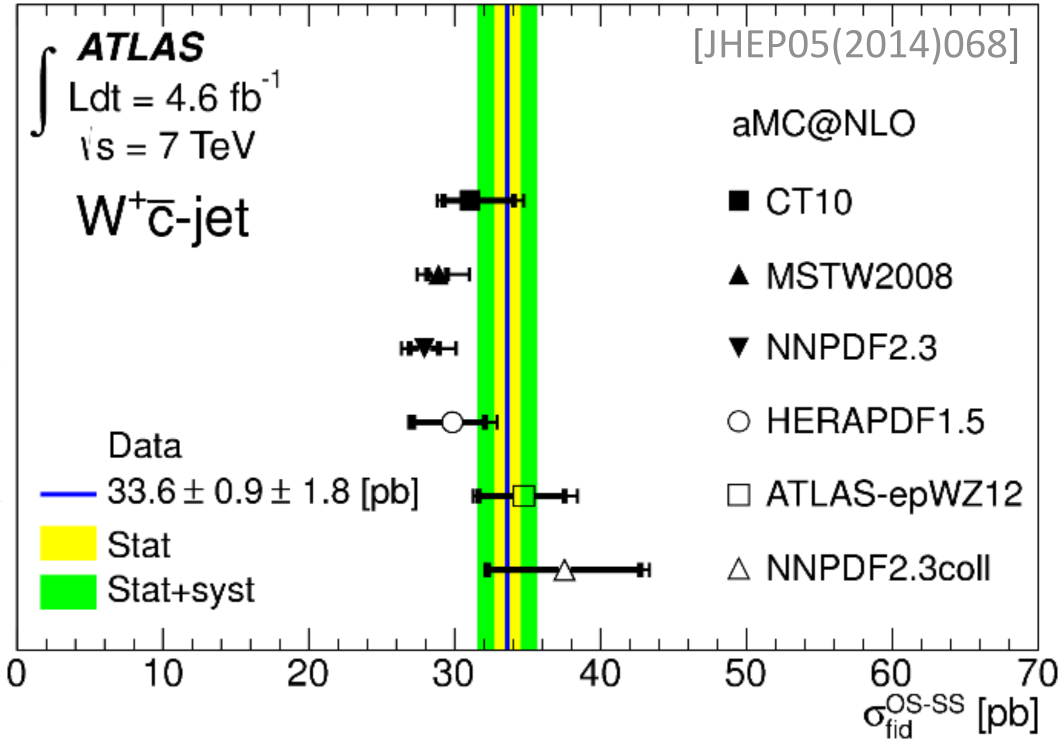


- Dominating PDF uncertainties due to **uncertainty on the W boson polarization**
  - caused by the relative contribution of u,d, anti-u, -d quarks and gluons
  - Polarisation impacts the p_T spectrum of the decay leptons
- Uncertainties on **heavy quark PDFs**

PDF Related Measurements



[JHEP 01 (2016) 155]



- All single boson production cross-sections restrict PDFs
  - Differential W and Z boson production (**also at high rapidities** LHCb)
  - Differential **precision more important** than center of mass energy
- Test heavy flavor PDFs, e.g. via VB+c-jet measurements
- Even **not all 7 TeV measurements are yet published**

Angular Coefficients

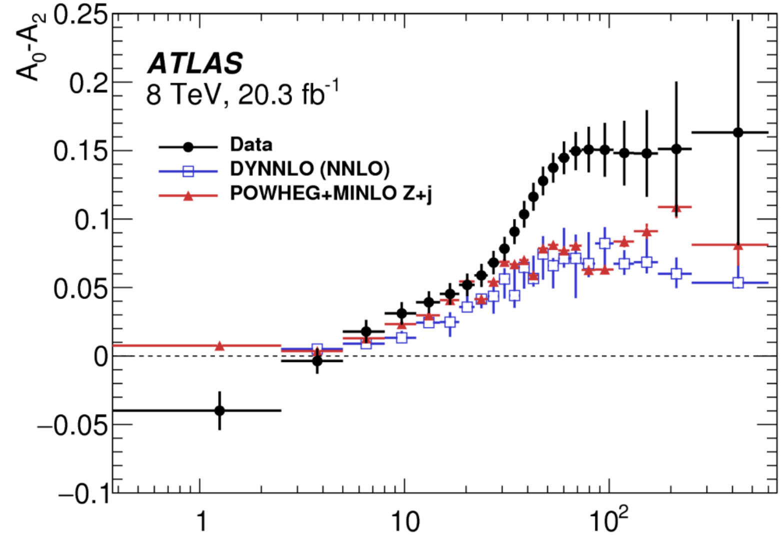
- The fully differential DY cross section can be reorganised by **factorising the dynamic of the boson** production, and the kinematic of the decay (CS-Frame)

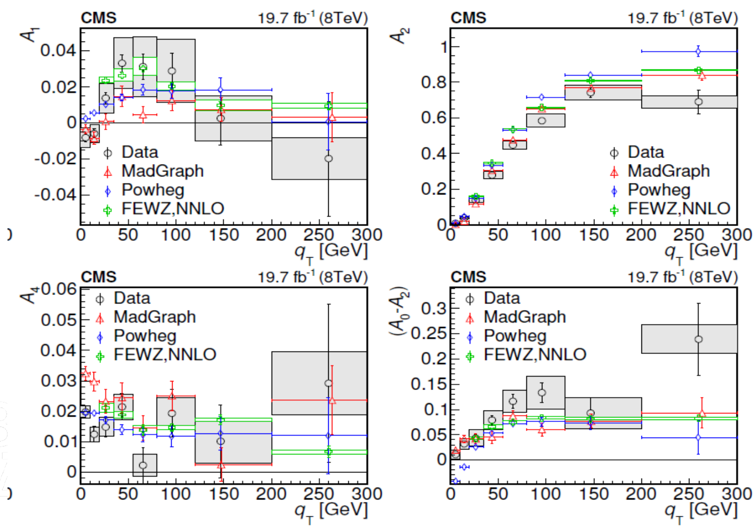
$$\frac{d\sigma}{dp_T^2 dy dM d\cos\theta d\phi} = \frac{3}{16\pi}\frac{d\sigma}{dp_T^2 dy dM} \times [(1+\cos^2\theta) + A_0 \frac{1}{2}(1-3\cos^2\theta) + A_1 \sin 2\theta \cos\phi + A_2 \frac{1}{2}\sin^2\theta\cos 2\phi + A_3 \sin\theta\cos\phi + A_4 \cos\theta + A_5 \sin^2\theta \sin 2\phi + A_6 \sin 2\theta \sin\phi + A_7 \sin\theta\sin\phi]$$

- Uncertainties in A_i will **affect decay kinematics** of leptons

- CMS and ATLAS Results:
  - Significant **differences** to predictions
  - A_2 shows sensitivity to parton shower implementation

[ATLAS-STDM-2014-10]



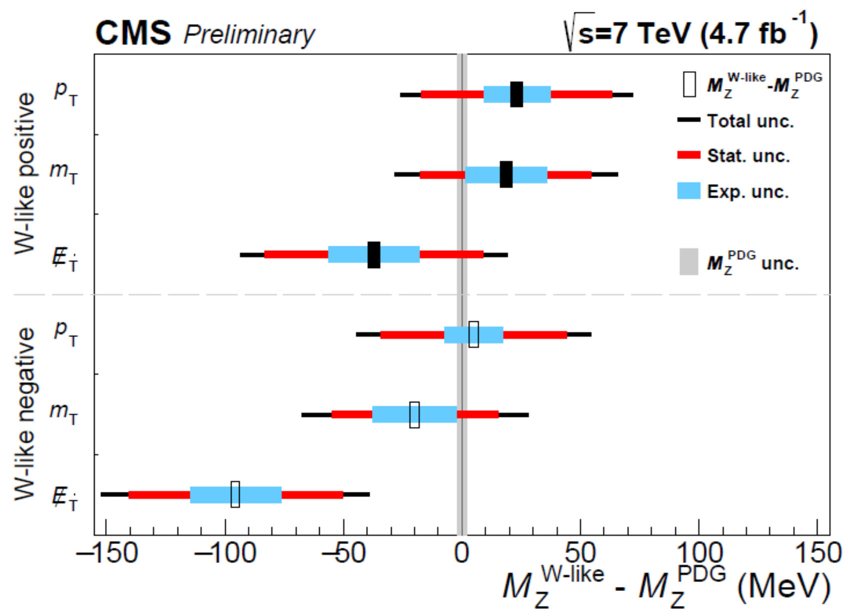


[PLB 750 (2015) 154]

Testing with Z Bosons

- The **full detector response calibration** of the m_W measurement can be tested to a large extend by „remeasureing“ the Z boson mass, mimicing the W
  - Turn one decay lepton in a pseudo neutrino
- CMS note using 7 TeV data
  - Validation of muon calibration
  - Statistically dominated (More in Nenad‘s talk)
- Model **uncertainties cannot** be easily transfered from Z to W
  - Also **some detector systematics** have to be treated carefully

	$M_Z^{\text{W like}+}$			$M_Z^{\text{W like}-}$		
Sources of uncertainty	p_T	m_T	$\not{E}_T$	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



[CMS PAS SMP-14-007]

The W Boson Mass at Tevatron

Outline

- Revisiting the Electroweak Sector
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Latest Results from CDF and D0

- **Proton / anti-proton** collisions reduce impact of heavy quarks
  - No differences between W^+/W^-
  - Simplier extrapolation from Z to W
  - Low pile-up

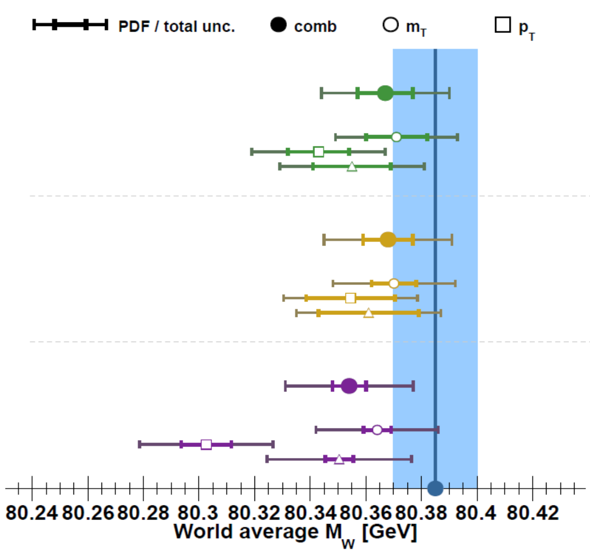
- CDF measurement in e/mu channel
  - Only 20% of data-set used
  - Calibration via J/Psi, Upsilon and Z

- D0 uses only electron channel
  - Acceptance up to η<1.0
  - Parameterized simulation

- D0 started a **first effort** to allow for an easy reavaluation of m_W with new PDF-sets

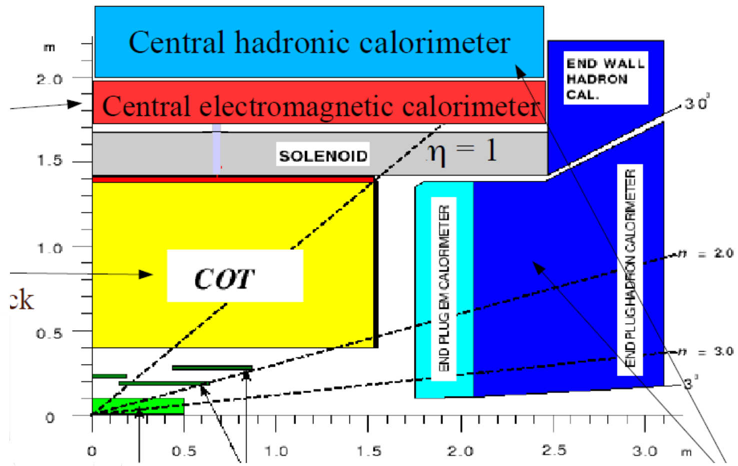
Source	CDF $m_T(\mu,\nu)$	CDF $m_T(e,\nu)$	DØ $m_T(e,\nu)$
Experimental – Statistical power of the calibration sample.			
Lepton Energy Scale	7	10	16
Lepton Energy Resolution	1	4	2
Lepton Energy Non-Linearity			4
Lepton Energy Loss			4
Recoil Energy Scale	5	5	
Recoil Energy Resolution	7	7	
Lepton Removal	2	3	
Recoil Model			5
Efficiency Model			1
Background	3	4	2
W production and decay model – Not statistically driven.			
PDF	10	10	11
QED	4	4	7
Boson p_T	3	3	2

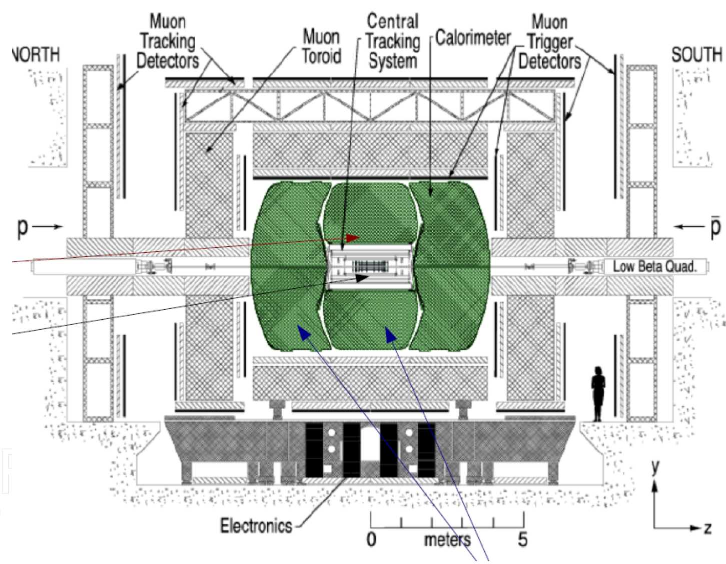
[Phys.Rev. D88 (2013)]



Possible Updates

- Factor 2-5 more statistics available
- Newer PDF sets, *e.g.* CT10W include more recent data
  - Dominant sources of W mass uncertainty are the *d*-valence and *d-u* degrees of freedom
  - Inclusion of all **LHC results on W$^+$, W$^-$ and Z will also help to improve Tevatron** measurements
- Improvement in theoretical predictions of $p_T(W/Z)$ needed in order to accommodate measured $p_T(W/Z)$ spectra at Tevatron/LHC





The Electroweak Mixing Angle

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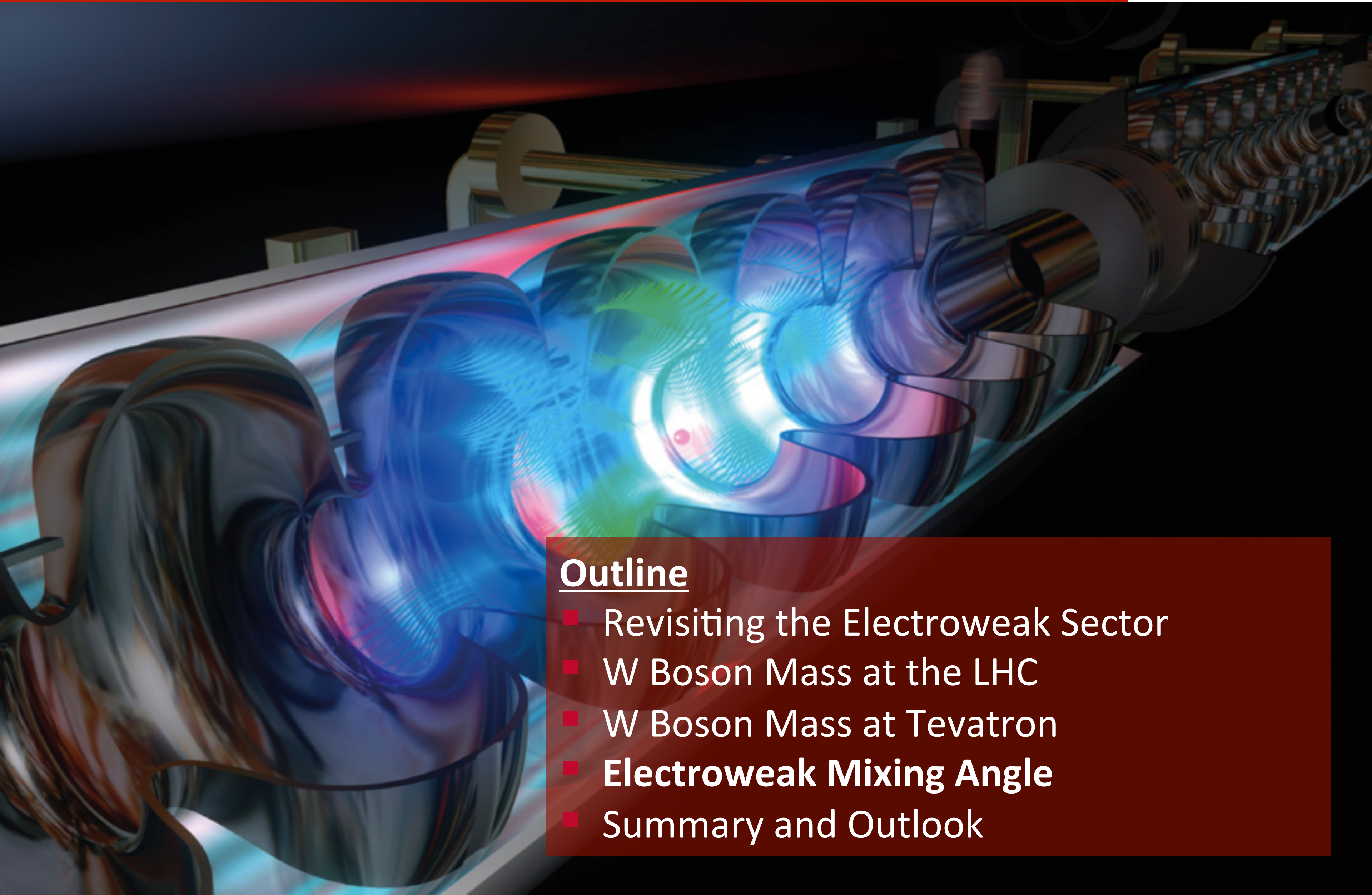

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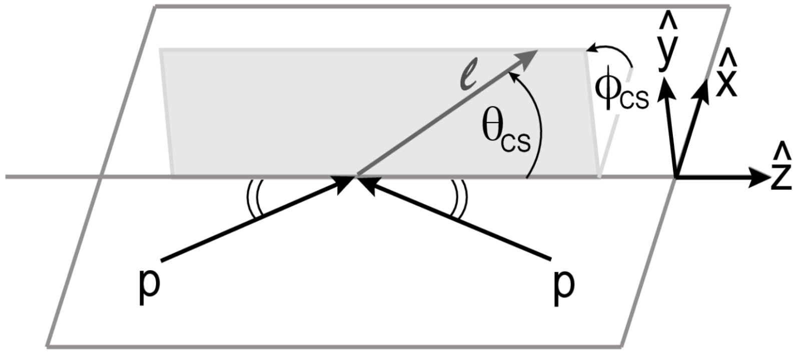
How to measure $\sin^2\theta_W^{eff}$?

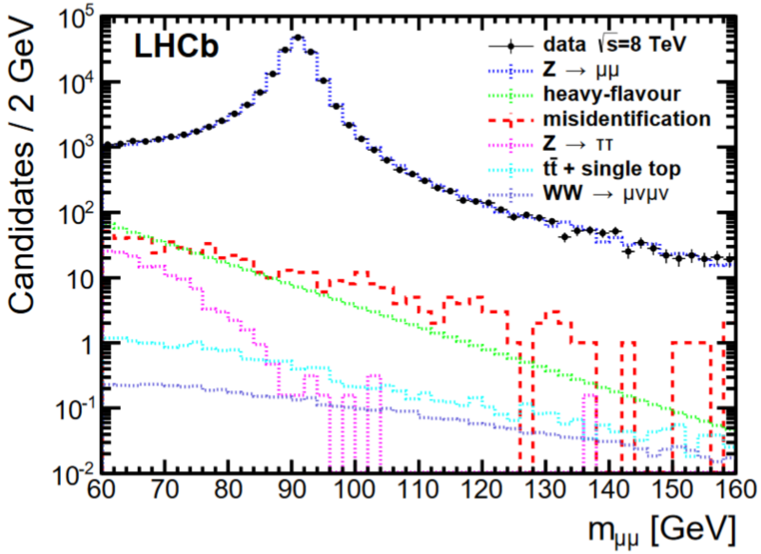
- **Forward-Backward Asymmetry**
  - Z couplings differ for left- and right-handed fermions
  - **Define A_{FB}** in Collin-Soper Frame
    - Defined w.r.t. to incoming quark and outgoing lepton

$$A_{\mathrm{FB}} = \frac{N_{\cos\theta^*_{CS}\geq 0} - N_{\cos\theta^*_{CS}<0}}{N_{\cos\theta^*_{CS}\geq 0} + N_{\cos\theta^*_{CS}<0}}$$

- A_{FB} linked to the weak mixing angle, via the relation

$$A_{FB} = \frac{16}{3} \cdot \frac{(1-4|Q_f|\sin^2\theta_W)}{1+(1-4|Q_f|\sin^2\theta_W)^2} \cdot \frac{(1-4|Q_{f'}|\sin^2\theta_W)}{1+(1-4|Q_{f'}|\sin^2\theta_W)^2}$$

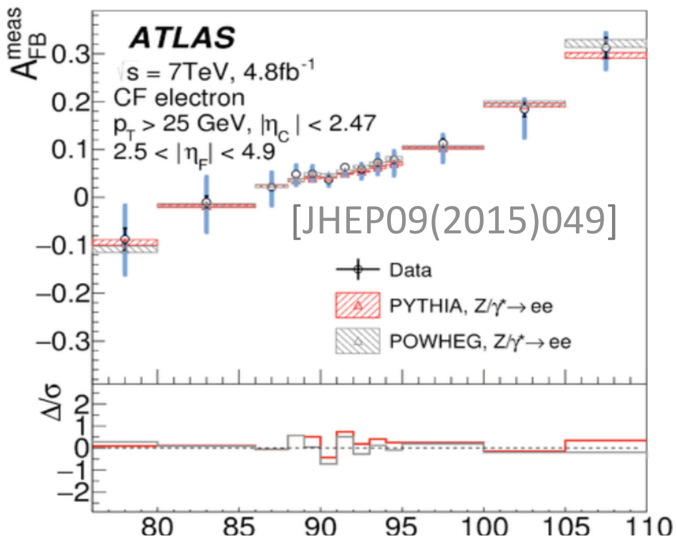




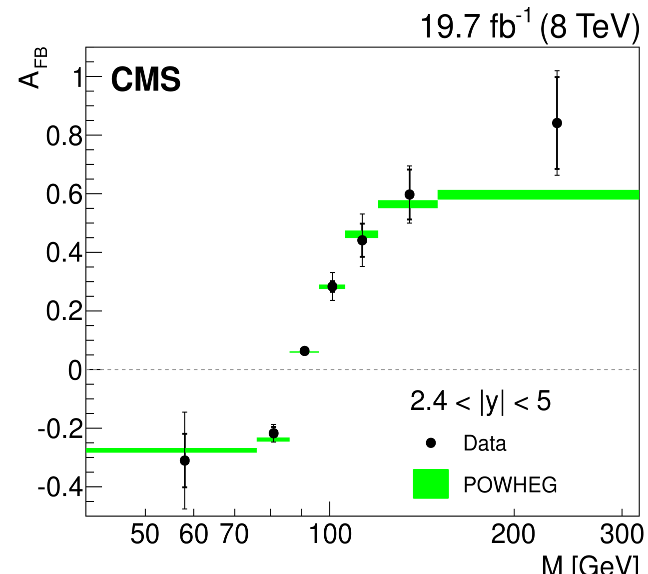
[LHCb arXiv1509.07645]

Results from the LHC

- LHC-Challenge: **where is the quark?**
  - Misidentified quark-direction results in dilution of A_{FB}
  - Forward Z events have smallest dilution effects! LHCb!
- A_{FB} measured as a function of $m_{\mu\mu}$ (LHCb) and $m_{\mu\mu}/m_{ee}$ (ATLAS/CMS)
- **Measurement approach**
  - Use template fitting to extract $\sin^2\theta_W$
  - Alternative: Publish unfolded measurement of A_{FB} and decouple extraction of $\sin^2\theta_W$



[JHEP09(2015)049]



[CMS-SMP-14-004-pas]

Overview and Reachable Precision

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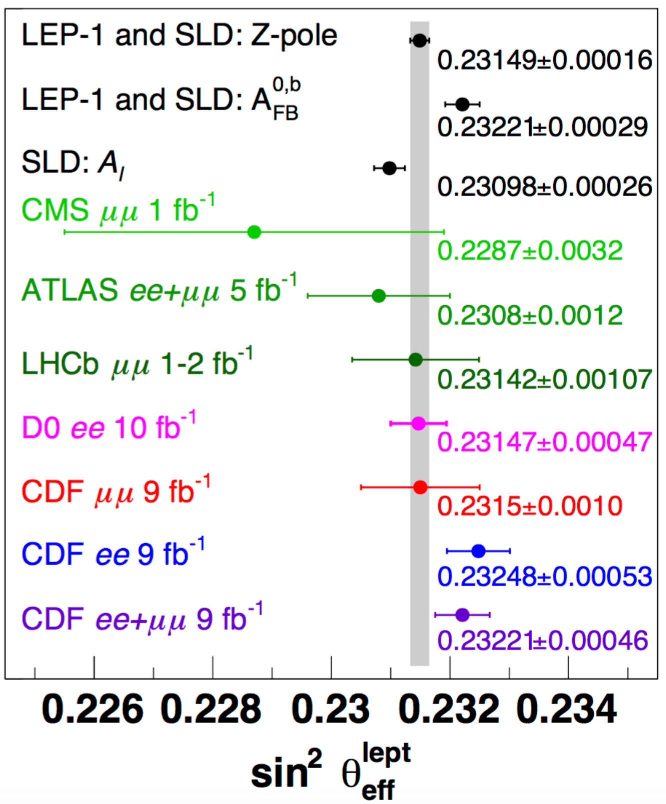
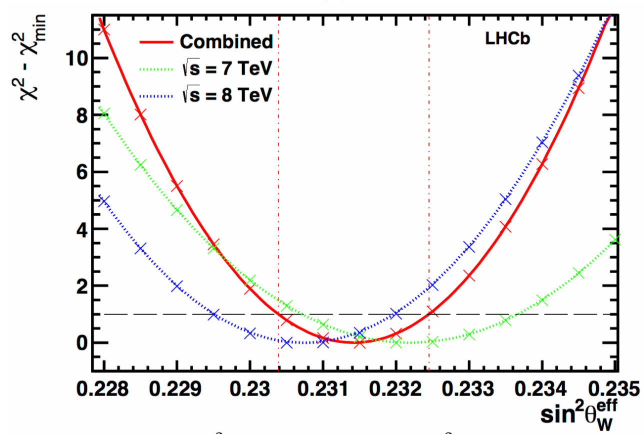
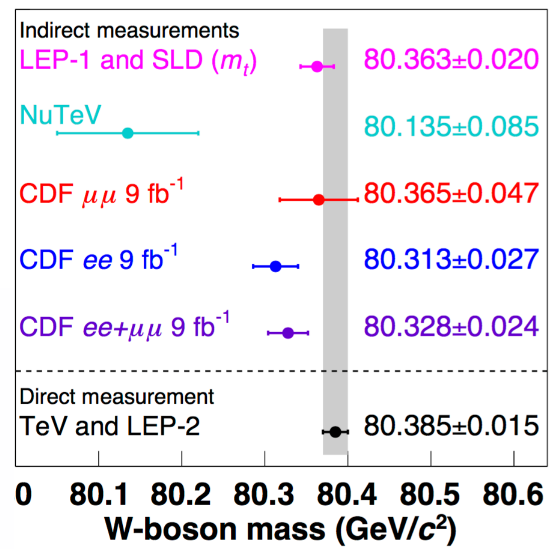
- Dominating uncertainties **due to PDFs**
- LEP and SLD measurement still most precise measurement
  - new CDF measurement gets close to solve discrepancy
  - **Profiling during $\sin^2\theta_W$ fit** might be able to improve PDF uncertainties



Uncertainty source	CC electrons $[10^{-4}]$	CF electrons $[10^{-4}]$	Muons $[10^{-4}]$	Combined $[10^{-4}]$
PDF	10	10	9	9
MC statistics	5	2	5	2
Electron energy scale	4	6	–	3
Electron energy resolution	4	5	–	2
Muon energy scale	–	–	5	2
Higher-order corrections	3	1	3	2
Other sources	1	1	2	2



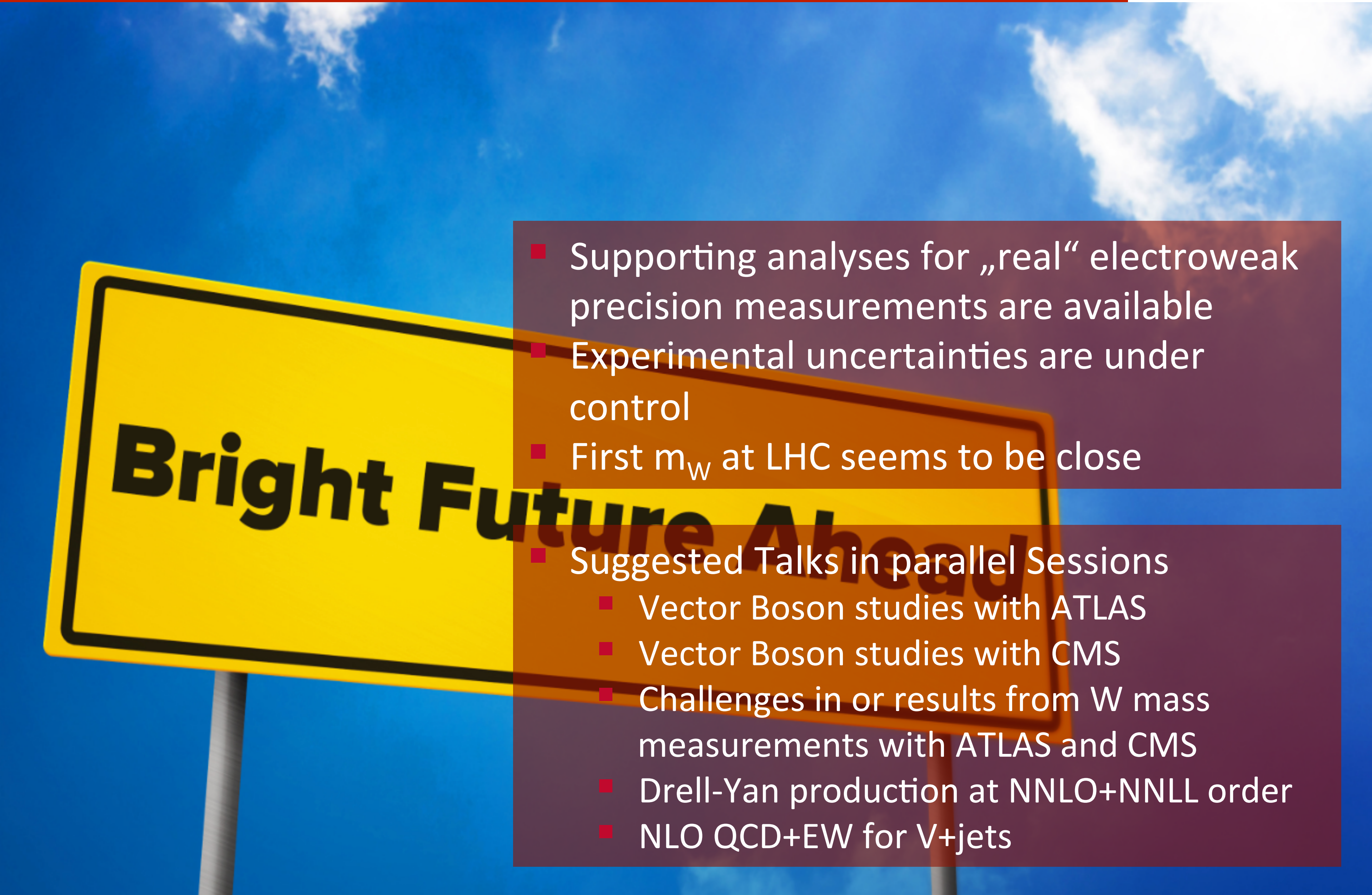
[LHCb arXiv1509.07645]



[CDF arXiv:1605.02719]

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

Summary And Outlook

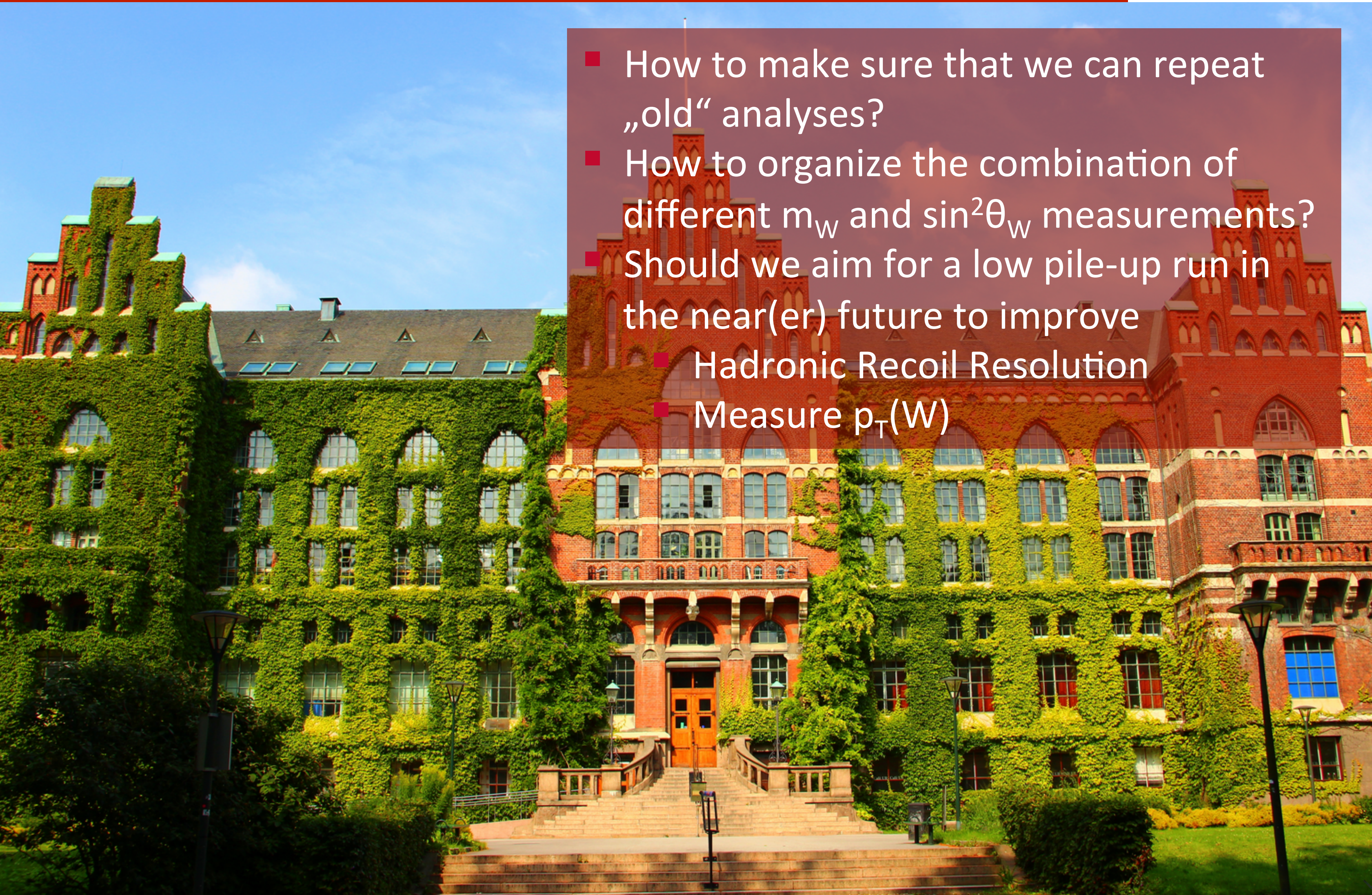


- Supporting analyses for „real“ electroweak precision measurements are available
- Experimental uncertainties are under control
- First m_W at LHC seems to be close

- Suggested Talks in parallel Sessions
  - Vector Boson studies with ATLAS
  - Vector Boson studies with CMS
  - Challenges in or results from W mass measurements with ATLAS and CMS
  - Drell-Yan production at NNLO+NNLL order
  - NLO QCD+EW for V+jets

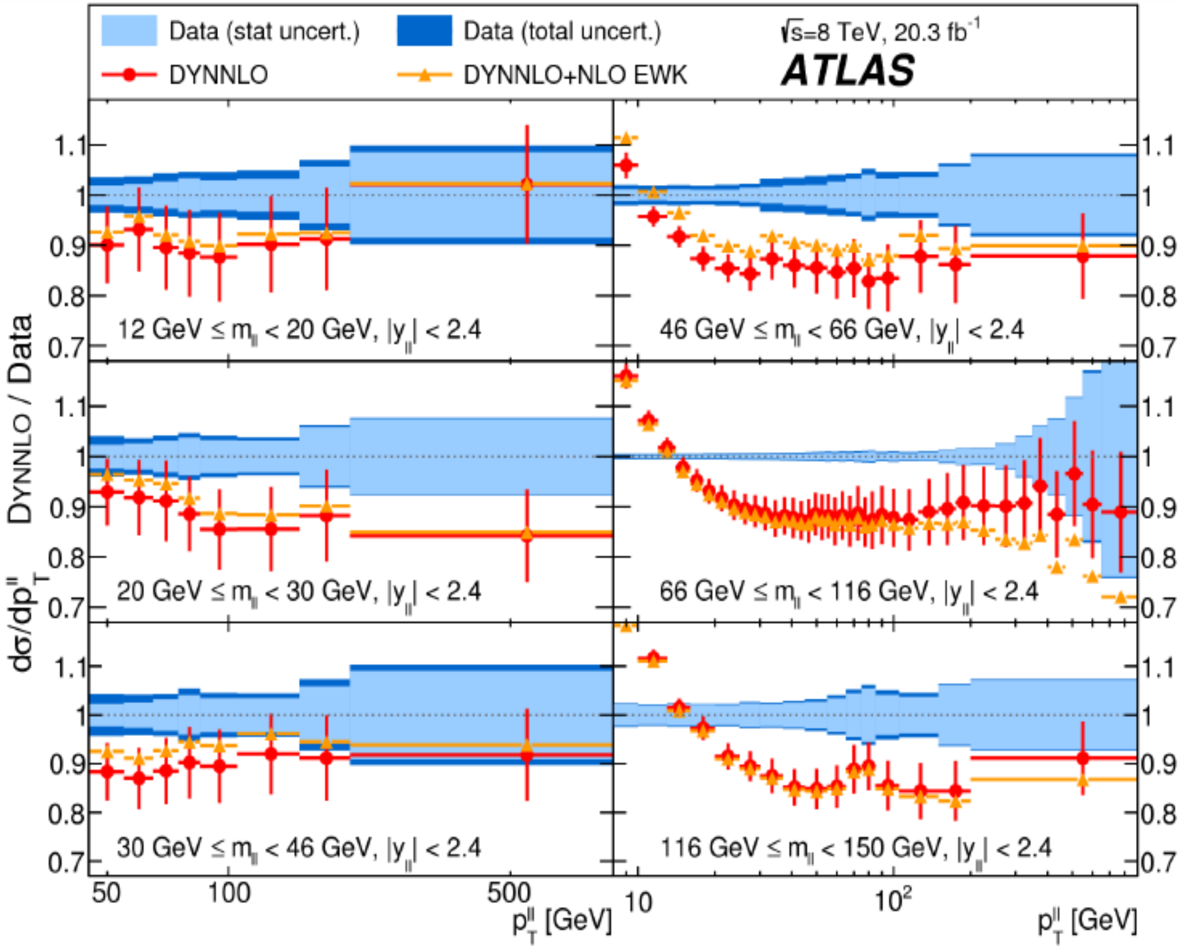
For Discussion

- How to make sure that we can repeat „old“ analyses?
- How to organize the combination of different m_W and $\sin^2\theta_W$ measurements?
- Should we aim for a low pile-up run in the near(er) future to improve
  - Hadronic Recoil Resolution
  - Measure $p_T(W)$



Modeling of Vector Boson p_T

- Do not expect that NNLO prediction describes low p_T spectrum
  - Parton Shower is missing
- Expect effect of NLO electroweak corrections for high $p_T(Z)$
  - Sensitivity is not yet high enough to resolve EWK contributions



[Eur. Phys. J. C 76(5), 1-61 (2016)]

Some words on the W boson width

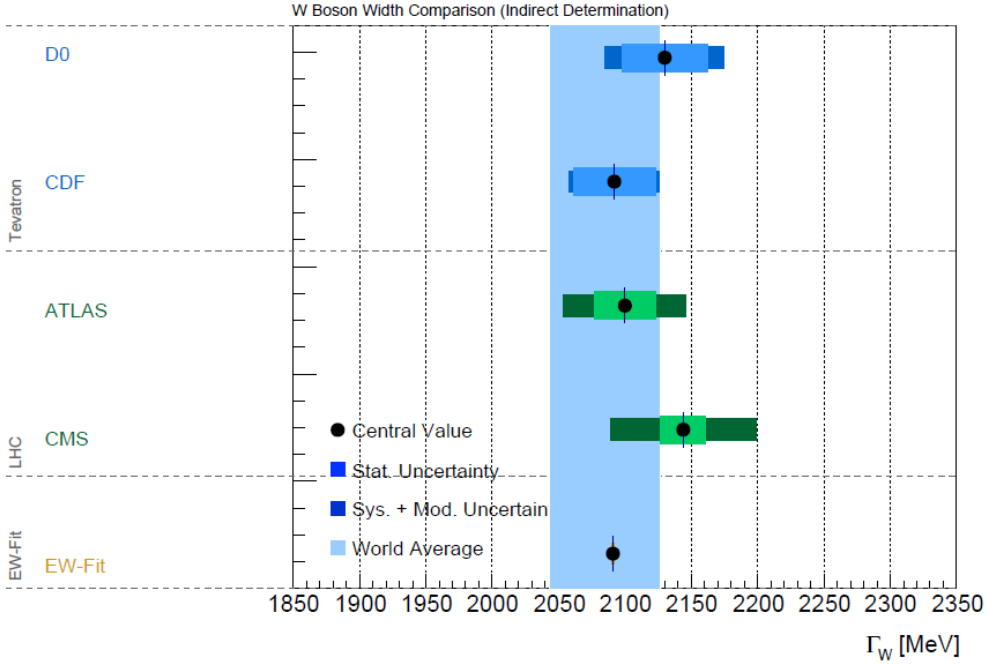
- Direct measurement of Γ_W from LEP and Tevatron experiments

- Indirect measurement possible via inclusive σ_W and σ_Z measurements via

$$R_{lep} = \frac{\sigma(pp \to W^{\pm} + X) \cdot BR(W^{\pm} \to l^{\pm}\nu)}{\sigma(pp \to Z^0 + X) \cdot BR(Z \to l^+l^-)}$$

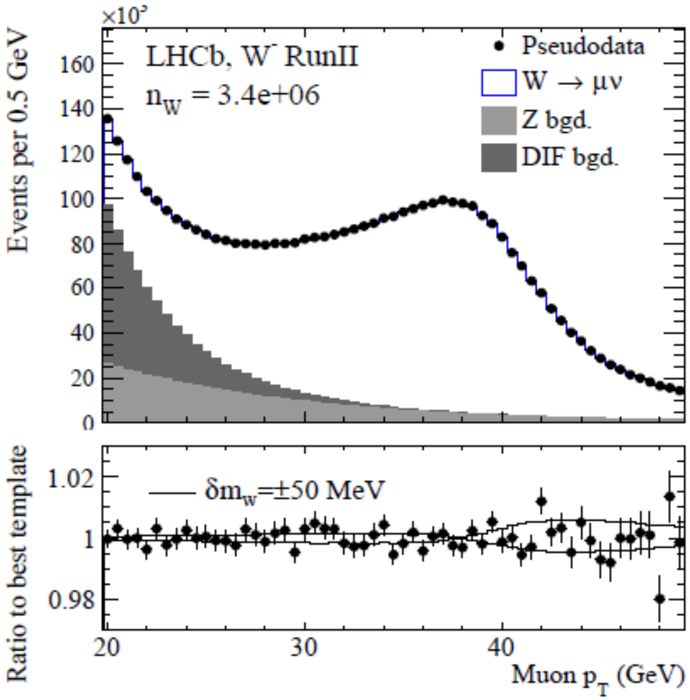
$$R_{lep} = \frac{\sigma_W}{\sigma_Z} \cdot \frac{\Gamma_{W^{\pm} \to l^{\pm}\nu}}{\Gamma_W} \cdot \frac{\Gamma_Z}{\Gamma_{Z \to l^+l^-}}.$$

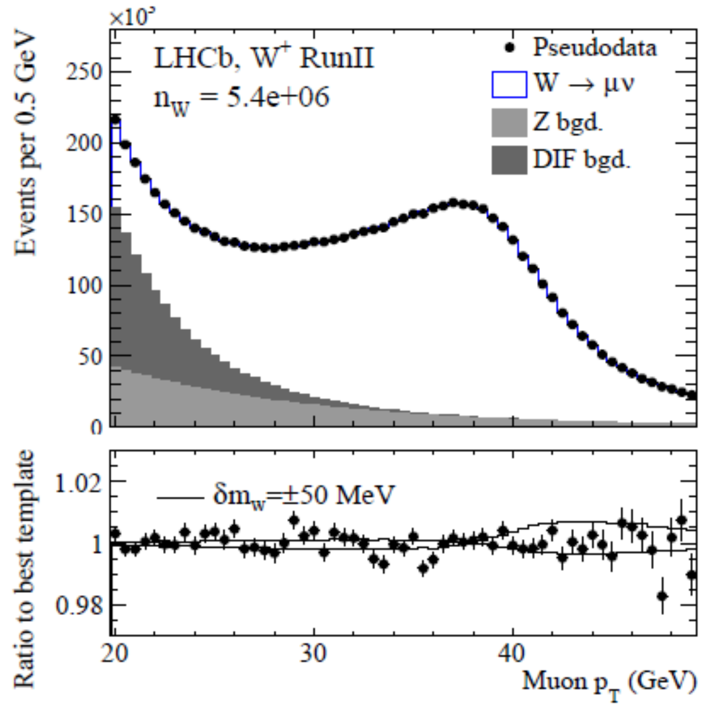
- However, this assumes a SM partial decay width
  - Cannot be used for the global electroweak fit



[PoS(LeptonPhoton2015)071]

What about forward muons?





[G.Bozzi et. al, arXiv508.06954]

- Idea: Use forward muons at LHCb ($2<\eta<5$) to anti-correlate PDF uncertainties
  - Drawback: No E_T^{Miss}, i.e. Only p_T as sensitive observable
- Prediction: Improve PDF uncertainties on a combined CMS, ATLAS + LHCb measurement by 30%

Input to the Global Electroweak Fit

- Input for the gobal electroweak fit mostly from
  - LEP: Z boson observables
  - Tevatron: W boson, top quark mass
  - LHC: **Higgs Boson, top quark mass (see dedicated top-session)**
- Note: improvement on **m_H precision** leaves fit unchanged

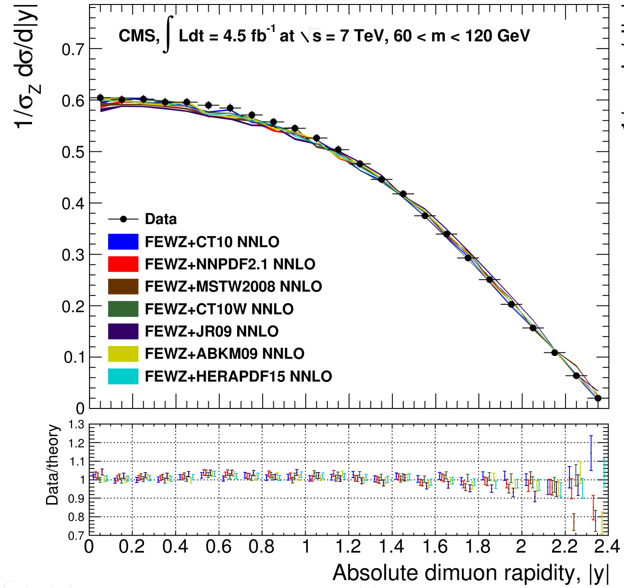
Parameter	Input value	Free in fit	Fit Result	w/o exp. input in line	w/o exp. input in line, no theo. unc
M_H [GeV]$^{(\circ)}$	125.14 ± 0.24	yes	125.14 ± 0.24	93^{+25}_{-21}	93^{+24}_{-20}
M_W [GeV]	80.385 ± 0.015	–	80.364 ± 0.007	80.358 ± 0.008	80.358 ± 0.006
Γ_W [GeV]	2.085 ± 0.042	–	2.091 ± 0.001	2.091 ± 0.001	2.091 ± 0.001
M_Z [GeV]	91.1875 ± 0.0021	yes	91.1880 ± 0.0021	91.200 ± 0.011	91.2000 ± 0.010
Γ_Z [GeV]	2.4952 ± 0.0023	–	2.4950 ± 0.0014	2.4946 ± 0.0016	2.4945 ± 0.0016
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	–	41.484 ± 0.015	41.475 ± 0.016	41.474 ± 0.015
R^0_ℓ	20.767 ± 0.025	–	20.743 ± 0.017	20.722 ± 0.026	20.721 ± 0.026
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	–	0.01626 ± 0.0001	0.01625 ± 0.0001	0.01625 ± 0.0001
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	–	0.1472 ± 0.0005	0.1472 ± 0.0005	0.1472 ± 0.0004
$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012	–	0.23150 ± 0.00006	0.23149 ± 0.00007	0.23150 ± 0.00005
A_c	0.670 ± 0.027	–	0.6680 ± 0.00022	0.6680 ± 0.00022	0.6680 ± 0.00016
A_b	0.923 ± 0.020	–	0.93463 ± 0.00004	0.93463 ± 0.00004	0.93463 ± 0.00003
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	–	0.0738 ± 0.0003	0.0738 ± 0.0003	0.0738 ± 0.0002
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	–	0.1032 ± 0.0004	0.1034 ± 0.0004	0.1033 ± 0.0003
R^0_c	0.1721 ± 0.0030	–	$0.17226^{+0.00009}_{-0.00008}$	0.17226 ± 0.00008	0.17226 ± 0.00006
R^0_b	0.21629 ± 0.00066	–	0.21578 ± 0.00011	0.21577 ± 0.00011	0.21577 ± 0.00004
$\overline{m}_c$ [GeV]	$1.27^{+0.07}_{-0.11}$	yes	$1.27^{+0.07}_{-0.11}$	–	–
$\overline{m}_b$ [GeV]	$4.20^{+0.17}_{-0.07}$	yes	$4.20^{+0.17}_{-0.07}$	–	–
m_t [GeV]	173.34 ± 0.76	yes	$173.81 \pm 0.85^{(\triangledown)}$	$177.0^{+2.3}_{-2.4}{}^{(\triangledown)}$	177.0 ± 2.3
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)^{(\dagger\triangle)}$	2757 ± 10	yes	2756 ± 10	2723 ± 44	2722 ± 42
$\alpha_s(M_Z^2)$	–	yes	0.1196 ± 0.0030	0.1196 ± 0.0030	0.1196 ± 0.0028

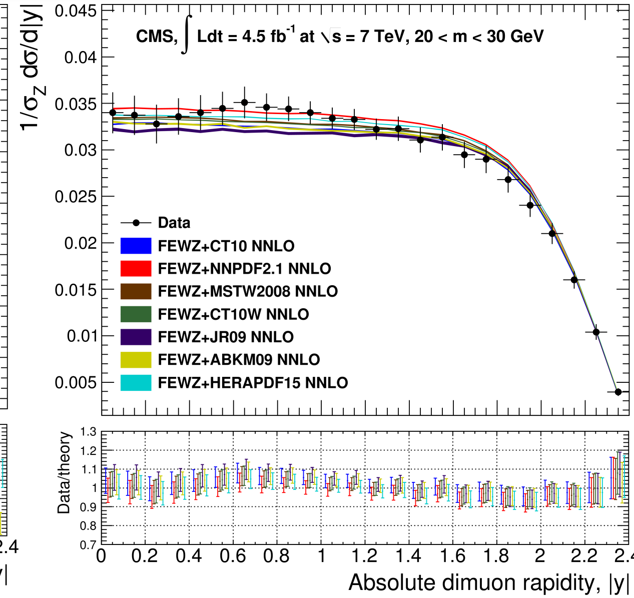
$^{(\circ)}$Average of the ATLAS and CMS measurements assuming no correlation of the systematic uncertainties.
$^{(\star)}$Average of the LEP and SLD A_ℓ measurements, used as two measurements in the fit.
$^{(\triangledown)}$The theoretical top mass uncertainty of 0.5 GeV is excluded.
$^{(\dagger)}$In units of 10^{-5}.
$^{(\triangle)}$Rescaled due to α_s dependence.

[Gfitter Collaboration]

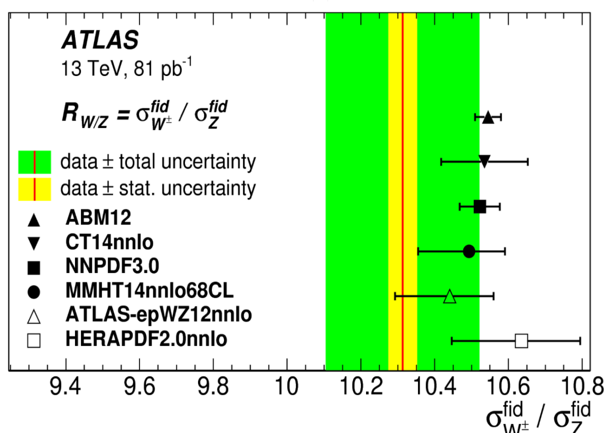
PDF Related Measurements (1/2)

- All single boson production cross-sections restrict PDFs
  - Differential W and Z boson production (also at high rapidities LHCb)
- Precision more important than center of mass energy

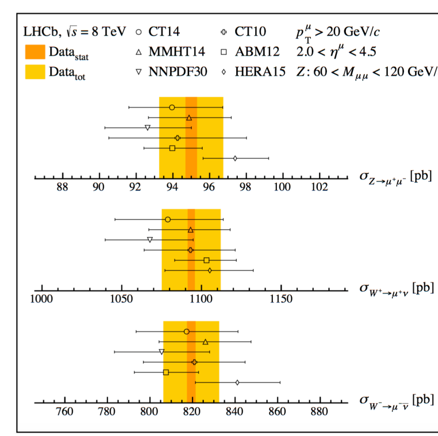




[JHEP 12 (2013) 030]



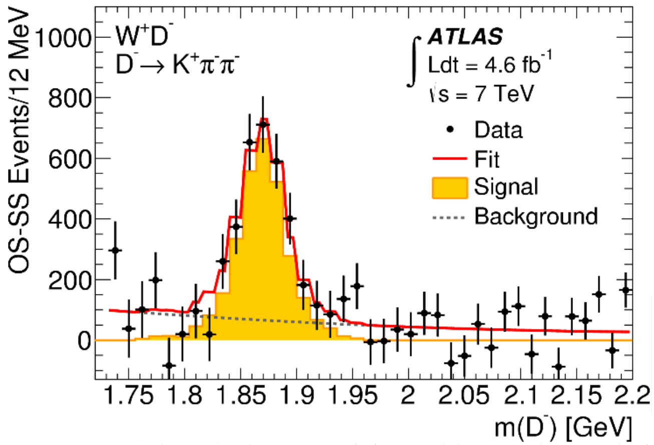
[arXiv:1603.09222]

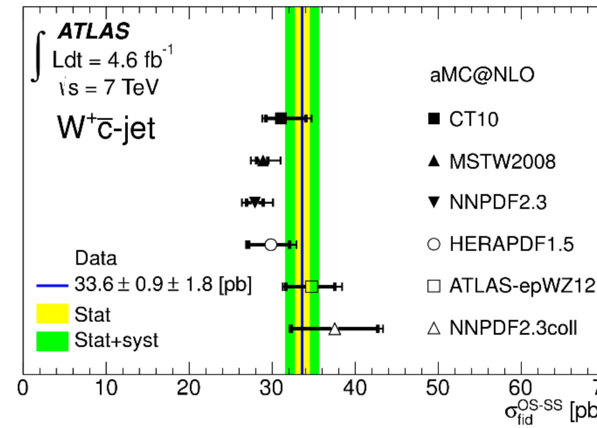


[JHEP 01 (2016) 155]

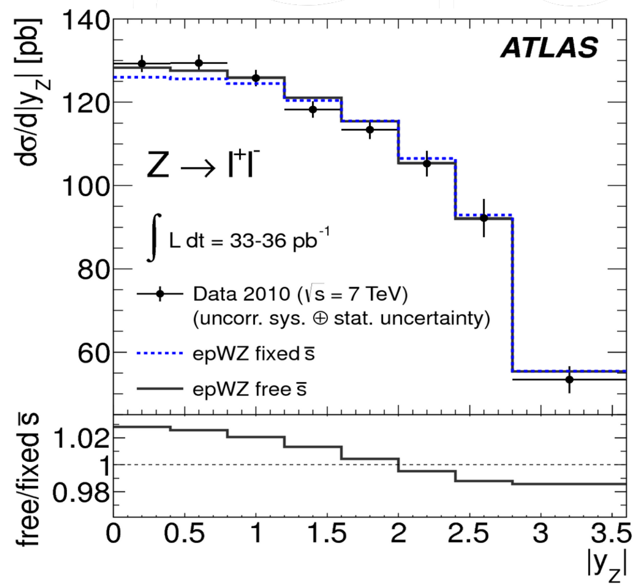
PDF Related Measurements (2/2)

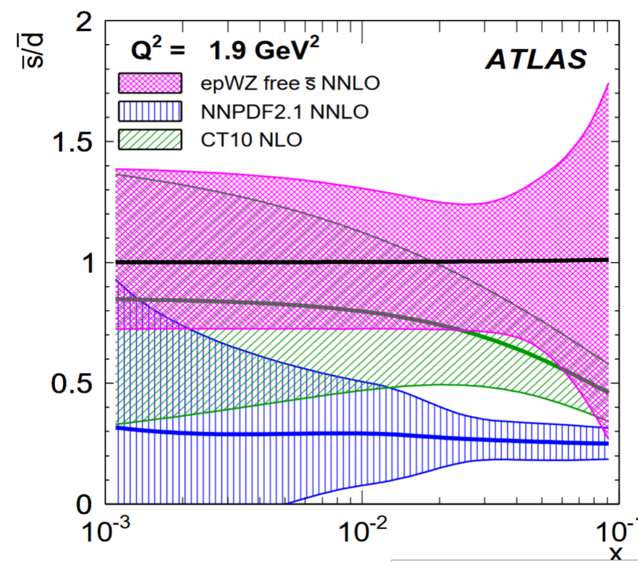
- Heavy flavor in the final state of W/Z bosons allows to test heavy flavor PDFs
- Even not all 7 TeV measurements are yet published
  - 35pb^{-1} Analysis from ATLAS predicts enhanced strangeness





[JHEP05(2014)068]





[Phys.Rev.Lett. 109 (2012) 012001]