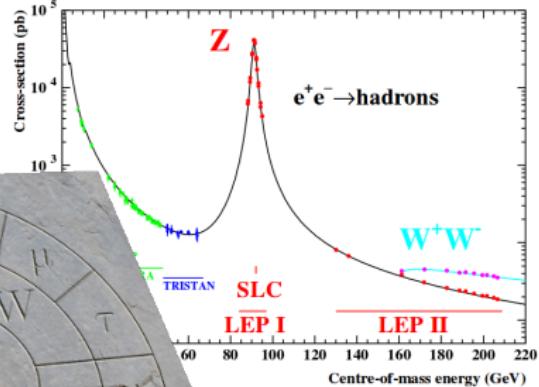
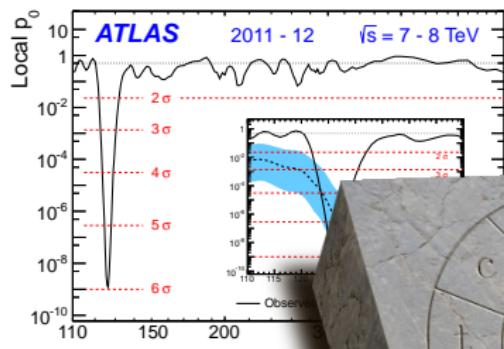


# Challenges in $M_W$ measurements with ATLAS and CMS

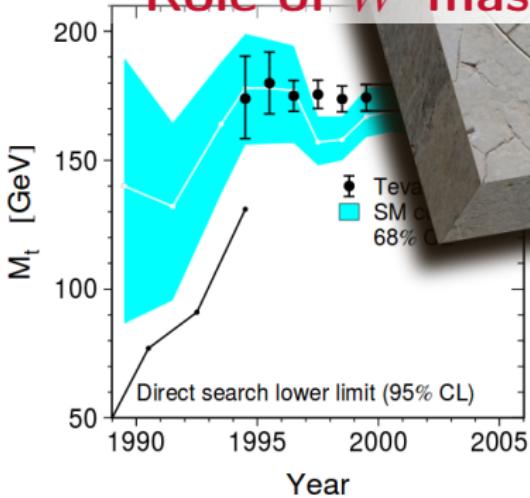
Jakub Cúth  
on behalf of ATLAS and CMS collaborations

Johannes Gutenberg Universität, Mainz

Monday 22<sup>nd</sup> August, 2016



## Role of $W$ mass in Standard Model



### Outline:

- ① Motivation and current measurements
- ②  $W$ -like measurement
- ③ Challenges in  $M_W$  measurement

# Predictive power of SM

## Radiative correction

- Tree level relations are not sufficient – radiative corrections are needed
- The impact of corrections stored in **EW form factors**, helps to define effective coupling at  $Z$ -pole

$$M_W^{\text{meas}} = (80.385 \pm 0.015) \text{ GeV}$$

$$M_W^2 = M_Z^2(1 - \sin^2 \theta_W)$$

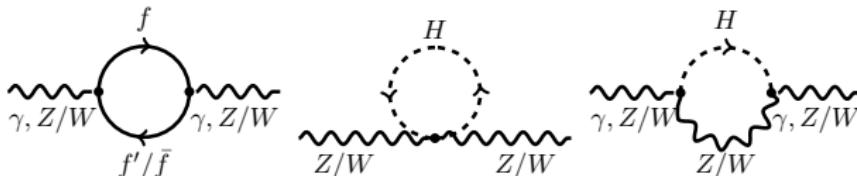
$$M_W^{\text{tree level}} = 79.891 \text{ GeV}$$

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

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

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

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



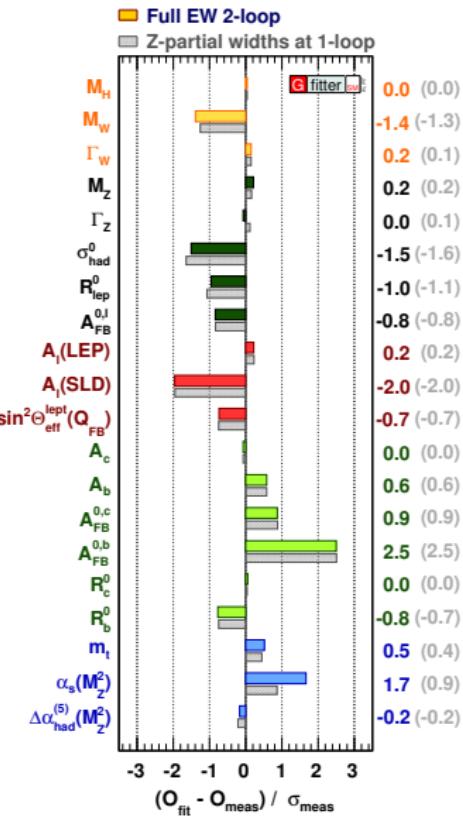
- Quadratic dependence on  $m_t$ , logarithmic dependence  $M_H$  appears

$$M_W \propto \left( \ln(M_H), m_t^2, M_Z, \Delta\alpha_{\text{had}}^{(5)}(M_Z^2), \alpha_S(M_Z^2) \right)$$

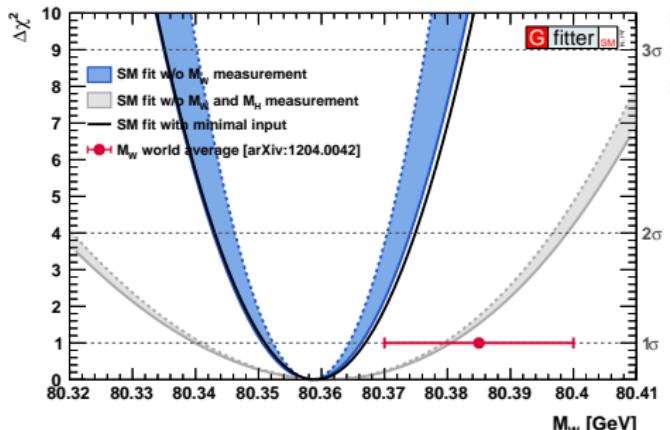
$$M_W^{\text{indirect}} = 80.358 \pm 0.008 \text{ GeV}$$

# Global electroweak fits

- Input for global electroweak fit mostly from
  - LEP+SLD:  $Z$  boson observables
  - Tevatron:  $W$  boson, top quark mass
  - LHC: Higgs boson, top quark mass
- Further improvements on  $M_H$  precision would leave the fit unchanged
- Improvements on  $m_t$  will be limited by theoretical uncertainty on pole-mass definition
- Largest discrepancy  $A_I(\text{SLD})$  and  $A_{\text{FB}}^{0,b}$ , both sensitive to  $s_W^2$
- Full two loop EW prediction increased pull on  $M_W$



# Indirect estimation of $W$ mass

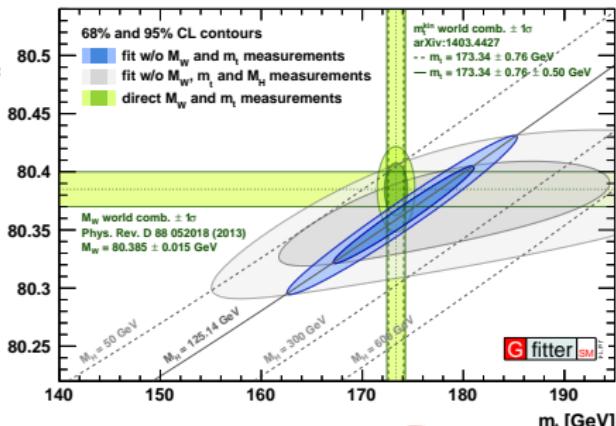


$$\delta^{\text{direct}} M_W = 15 \text{ MeV}$$

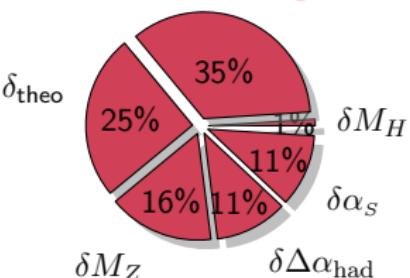
$$\delta^{\text{indirect}} M_W = 8 \text{ MeV}$$

$$\Delta M_W \sim 1.8\sigma$$

- $M_W^{\text{indirect}}$  would be improved by  $m_t$  measurement
- $M_W^{\text{direct}}$  will be improved by us!



$\delta m_t$



# Current status from Tevatron

- Proton/anti-proton 1.96 TeV collisions:
  - No difference in  $W^+/W^-$
  - Low pile-up environment
  - Reduce impact of heavy quarks

CDF (channels combined)	Unc. (MeV)
Lepton scale and resolution	7
Recoil scale and resolution	6
Lepton tower removal	2
Backgrounds	3
PDF	10
$p_T^W$ model	5
Photon radiation	4
Statistical	12
Total	19

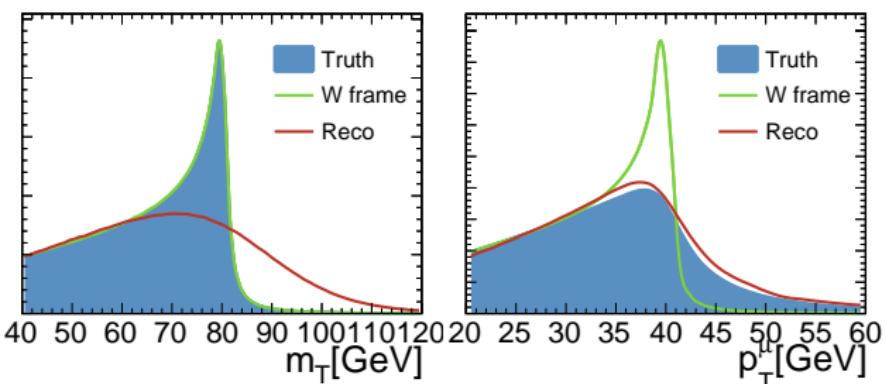
D0 (fits combined) $\sigma(m_W)$ MeV	Pub'09 1 fb <sup>-1</sup> (CC)	Pub'12 4.3 fb <sup>-1</sup> (CC)	Proj 10 fb <sup>-1</sup> (CC)	Proj 10 fb <sup>-1</sup> (CC+EC)
Electron Energy Scale	34	16	11	10
Electron Energy Resolution	2	2	2	2
Electron Energy Nonlinearity	4	4	2	2
$W$ and $Z$ Electron Eloss diff	4	4	2	2
Recoil Model	6	5	3	2
Electron Efficiencies	5	1	1	1
Backgrounds	2	2	2	2
PDF	9	11	11	5
QED	7	7	3	3
Boson $p_T$	2	2	2	2
Statistical	23	13	9	8
Total	44	26	19	15

# Measurement principle

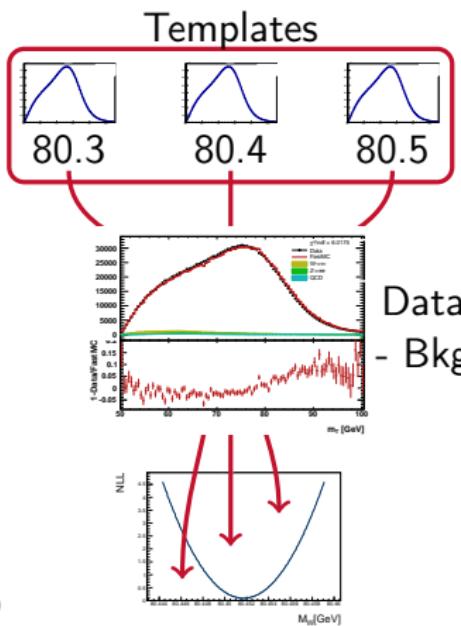
- transverse plane  $\Rightarrow$  boost invariant
- fitting separately in three distributions:

$$m_T \quad p_T^e \quad \cancel{E}_T$$

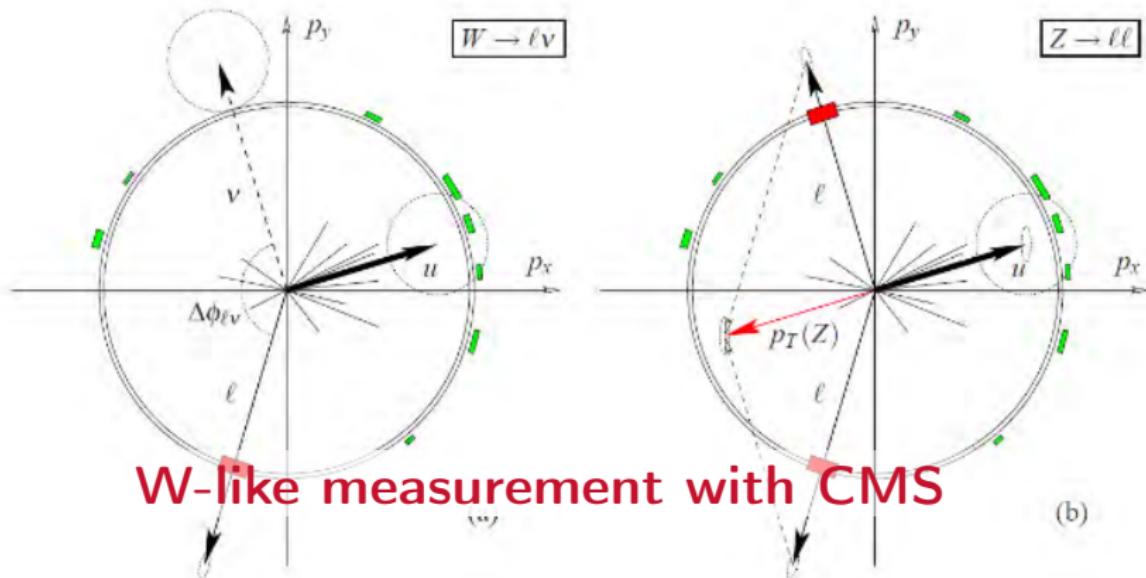
- $p_T^e$  affected by  $p_T(W)$
- $m_T$  affected by transverse recoil



$$m_T = \sqrt{2p_T^e \cancel{E}_T (1 - \cos \Delta\varphi)}$$



- LHC measurement based on analysis and experiences of Tevatron work
- Statistical precision:
  - 7 TeV data ( $\sim 4.5 \text{ fb}^{-1}$ ) : less than 10 MeV per  $e/\mu$  channel
  - extrapolated to 8 TeV data ( $\sim 20 \text{ fb}^{-1}$ ) : less than 5 MeV per channel
  - each experiment can go below 5 MeV with Run 1
- Challenges at the LHC
  - Higher pileup environment affects hadronic recoil resolution and calibration
  - Different energy regime  $1.96 \text{ TeV} \rightarrow 7, 8, 13 \text{ TeV}$ ,  $p\bar{p} \rightarrow pp$ : larger theoretical uncertainties
  - Non symmetric production of  $W^+$  and  $W^-$ : Charge depended analysis
- Advantages :
  - Large calibration samples:  $\sim 10^6 Z \rightarrow \mu\mu/ee$  events
  - Large pseudorapidity coverage
  - MC templates built with full detector simulation and with the newest theoretical tools



## Outline:

- ① Motivation and current measurements
- ② **W-like measurement**
- ③ Challenges in  $M_W$  measurement

# From Z to W-like

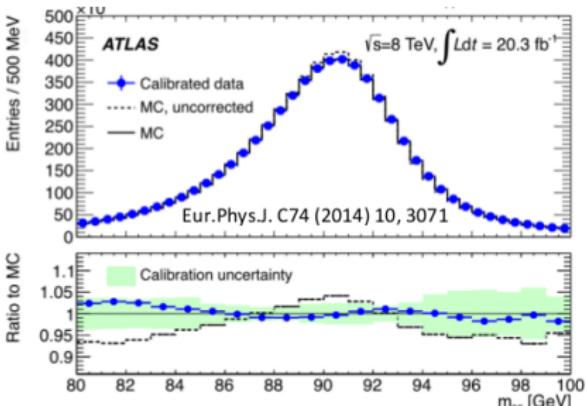
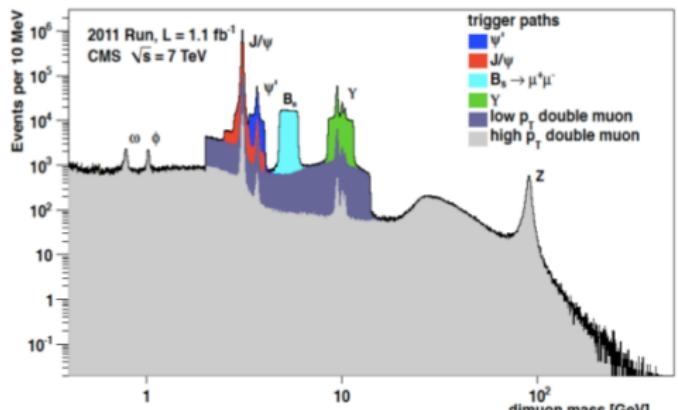
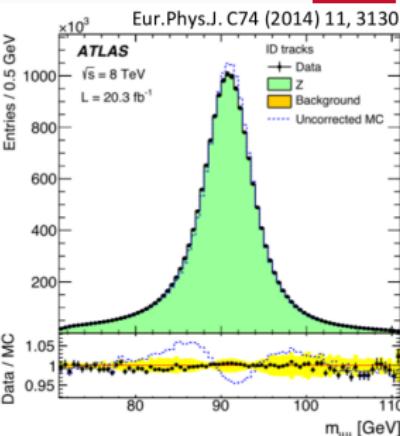
- $M_Z$  measurement in "W like"  $Z \rightarrow \mu\mu$  events
  - central "tag muon"  $|\eta| < 0.9$ , second muon removed,  $\cancel{E}_T$  and  $m_T$  recomputed
  - low background
  - use dilepton system to constrain the theory part
- Proof of principle intermediate step
  - Validate tools and techniques to be used in  $M_W$  measurement
  - Stimulate improvements in the modeling of  $W$  production
  - Statistical uncertainty  $\sim$  Tevatron level
- Split the sample: half for calibration, half for the measurement
- Caveat: additional systematics need to be accounted for the  $M_W$  measurements
  - PDFs in  $W$  production
  - $Z \rightarrow W$  extrapolation
  - Background

CMS PAS SMP-14-007

Systematic source	W-like	W
PDF	skip	✓ YES
Boson PT	skip	✓ YES
Boson PT W/Z extrapolation	NO	✓ YES
EWK correction	skip	✓ YES
Polarization	skip	✓ YES
$\mu$ momentum scale	✓ YES	✓ YES
$\mu$ tr-iso-id efficiency	✓ YES	✓ YES
Missing et scale/resolution DATA/MC agreement	✓ YES	✓ YES
MET W/Z extrapolation	NO	✓ YES
Background to 1 lepton	NO	✓ YES

# Lepton momentum calibration

- Bottom line: use resonances ( $J/\psi, Y, Z$ )
- For low boson  $p_T^W$ :  $m_t \sim 2p_T^\mu + p_T^W$ 
  - To get 10 MeV on  $M_W$ :  $10^{-4}$  precision required on  $p_T^\mu$  scale (40 GeV)
  - Resolution less crucial



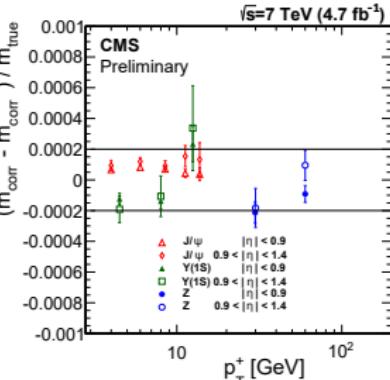
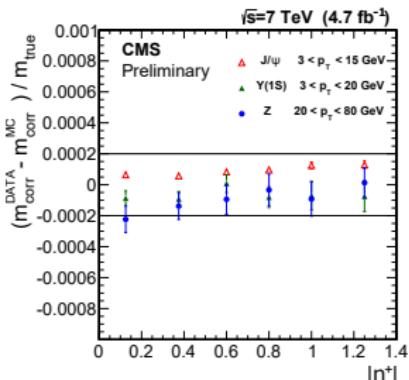
# Lepton momentum calibration

- Calibrate muon curvature ( $1/p_T$ ) using  $J/\psi$ ,  $Y$  at 7 TeV

$$k^c = (\boxed{A} - 1)k + \boxed{qM} + \boxed{\frac{k}{1 + k\epsilon \sin \theta}}$$

mag. field      misalign      material

- Use a physically motivated calibration model to cover the whole  $p_T$  spectrum
- Scale corrections are derived for both data and simulation
- Resolution corrections included, accounting for multiple scattering and single hit resolution

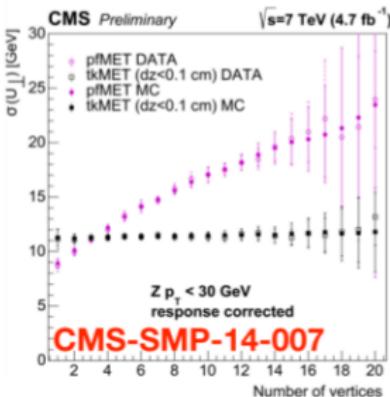
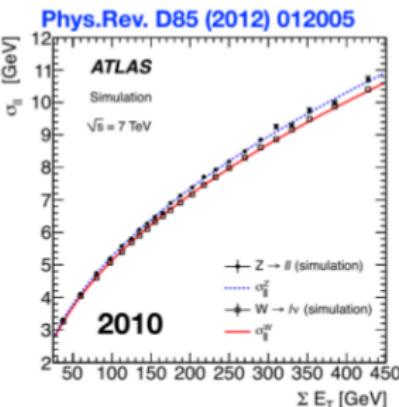
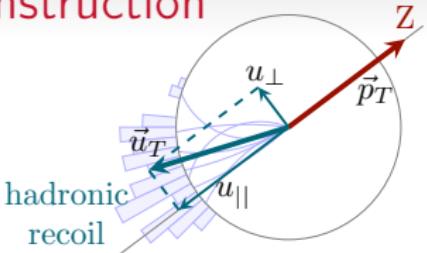


## Main Uncertainties:

- High mass extrapolation
- Statistics of calibration sample

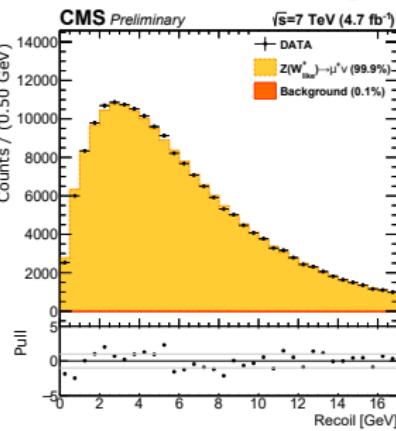
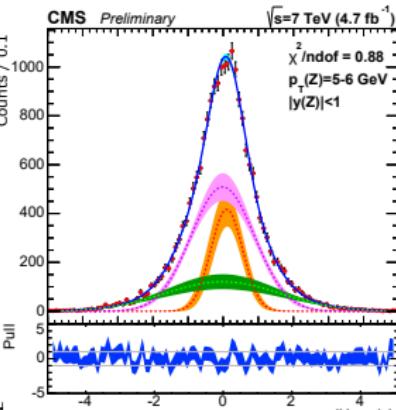
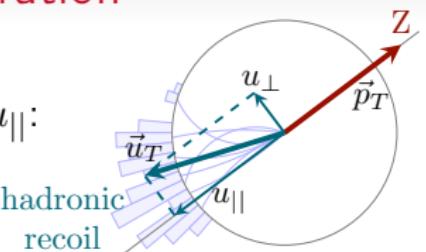
# Hadronic recoil – reconstruction

- Hadronic activity balancing boson  $p_T$  +UE, MPI, pileup
- ATLAS: dedicated recoil algorithm for  $W, Z$ 
  - Sum over calorimeter cells excluding the cells associated to the lepton.
- CMS: Particle flow algorithm (pfMET)
  - reconstruction and identification of each particle with an optimized combination of all subdetector information
- Similar resolution between ATLAS and CMS
- CMS improvement: tkMET
  - vectorial sum of the pf charged hadron with  $dz < 0.1$  cm
    - 80% efficiency for charged tracks  $p_T > 300$  MeV,  $|\eta| < 2.4$
  - Suppress in-time pileup at reconstruction level not considering pf hadrons/clusters associated to vertices other than the PV
  - Also for high pileup 8 TeV sample
- Better sensitivity (resolution) wrt pfMET in  $W$ (-like) events



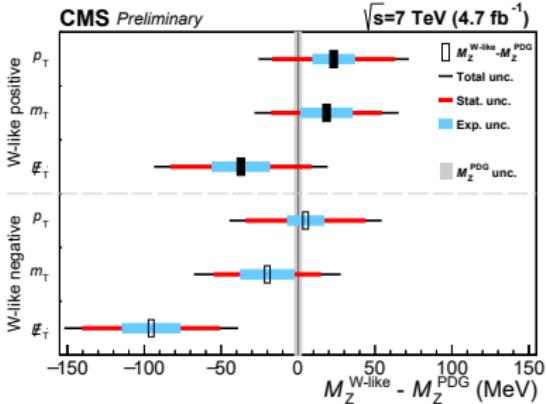
# Hadronic recoil – calibration

- Useful projections:  $u_{\perp}$ ,  $u_{||}$ :  
projections of  $u$  on axis  
perpendicular/parallel  
to boson  $p_T$
- Use to compare recoil  
resolution and response in data and MC
- CMS calibration example in the W-like measurement
  - 2D model with sum of 3 Gaussians vs boson  $p_T$
  - Derive corrections, apply them to simulation
  - Correction derived in boson rapidity bins to account  
for data/simulation discrepancies
- Main uncertainties:
  - Limited statistics of the calibration samples
  - Calibration model (alternative based on adaptive kernel)

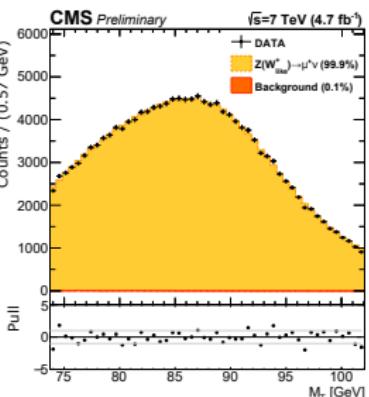


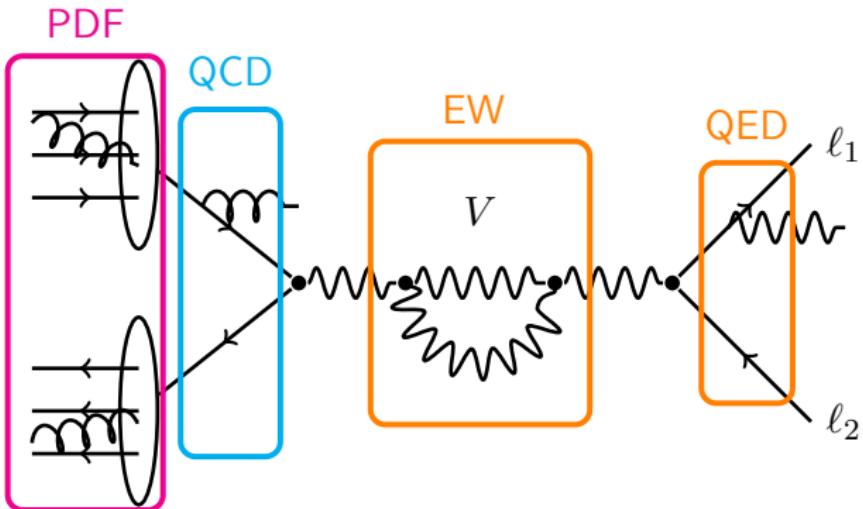
# W-like result

Sources of uncertainty	$M_Z^{W\text{-like}+}$			$M_Z^{W\text{-like}-}$		
	$p_T$	$m_T$	$\cancel{E}_T$	$p_T$	$m_T$	$\cancel{E}_T$
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



- Experimental uncertainty  $\sim 20 \text{ MeV } (\mu \text{ channel})$ 
  - Included statistical and systematic components of calibration
  - Competitive to Tevatron
- "Theoretical" uncertainty  $\sim 30 \text{ MeV}$ 
  - Don't translate directly to  $M_W$ , also  $Z \rightarrow W$  extrapolation (eg recoil calibration) not accounted for
  - PDF likely to be larger for  $W$  (for  $Z$  constrained by  $p_T$  and rapidity meas.)
  - QED systematics: on/off NLO EW correction in Powheg-EW (very conservative)
- Statistical uncertainty expected to decrease to few MeV level





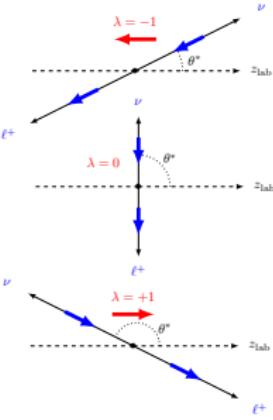
PYTHIA  
 DYNNLO, FEWZ,  
 POWHEG,  
 DYNNLOPS, SHERPA NNLO+PS,  
 RADY, SANC,  
 PHOTOS,  
 HORACE, WINHAC, WZGRAD,  
 POWHEG BMNNP, POWHEG BMNNPV, POWHEG BW  
 RESBOS, DYRES

## Challenges in $M_W$ measurement

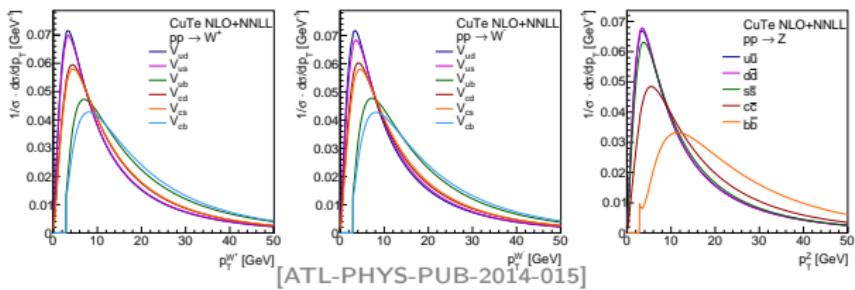
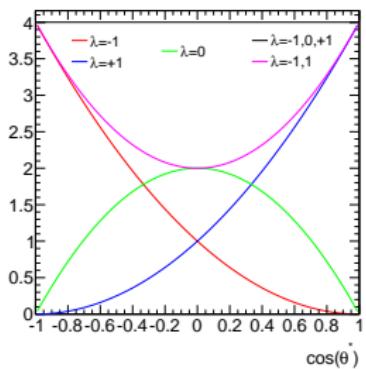
### Outline:

- ① Motivation and current measurements
- ② W-like measurement
- ③ Challenges in  $M_W$  measurement

# Challenges of $M_W$ measurement: PDF effects



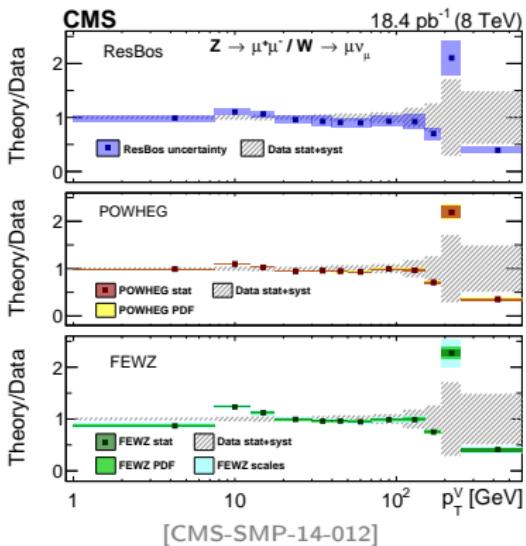
- PDF uncertainty coming from uncertainty of  $W$  polarization
- On  $M_W$  LHC PDF uncertainties are dominated by valence/sea ratio and **2<sup>nd</sup> generation partons**
- Dominant theoretical uncertainty for  $M_W$  Tevatron we put special effort into this
- PDF related measurements (e.g. differential x-section of  $Z, W$ ) from LHC experiments are ongoing and would constrain PDF.



[ATL-PHYS-PUB-2014-015]

# Constraints on $p_T^W$ from $p_T^Z$ measurement

- Modeling of  $p_T^W$  impacts the lepton distribution and so  $M_W$  fit
- Strategy is to use  $p_T^Z$ ,  $\phi_\eta^*$  measurement to constrain  $p_T^W$  prediction.
- Fit  $p_T^Z$  and model  $p_T^W$  can be used for all models
- But models can predict differently transfer from  $Z \rightarrow W$
- Example: different treatment of heavy parton distributions among fixed and resummed calculations.

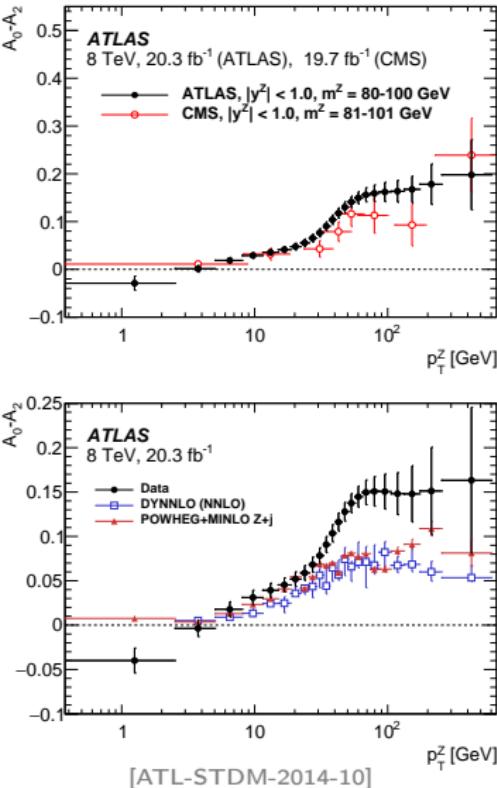


# Challenges of $M_W$ measurement: Angular effects

- Final state described by two angles  $\theta, \phi$  in Collins-Soper frame
- Angular dependence of Drell-Yan can be described by second order spherical polynomials.

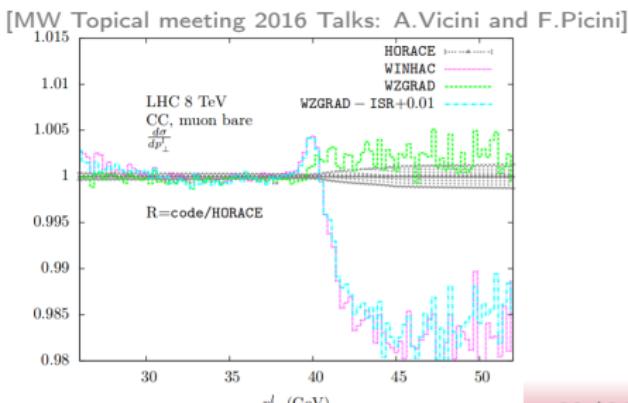
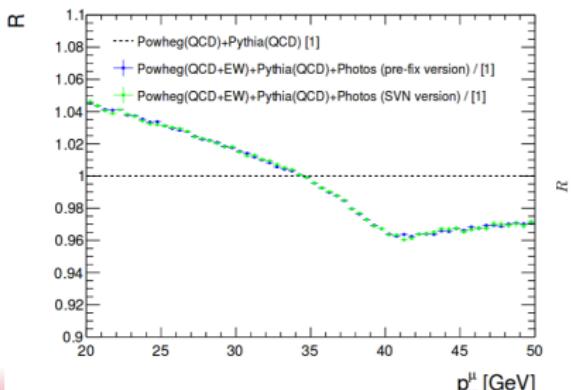
$$\frac{d\sigma}{dp_T^2 dy d\cos\theta d\varphi} = \frac{3}{16\pi} \frac{d\sigma^u}{dp_T^2 dy} [(1 + \cos^2\theta) \\ + \frac{1}{2} A_0(1 - 3\cos^2\theta) + A_1 \sin 2\theta \cos \varphi \\ + \frac{1}{2} A_2 \sin^2\theta \cos 2\varphi + A_3 \sin \theta \cos \varphi \\ + A_4 \cos \theta + A_5 \sin^2\theta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

- Measurements from ATLAS and CMS agree to each other but don't follow predictions



# Challenges $M_W$ measurement: Electroweak effects

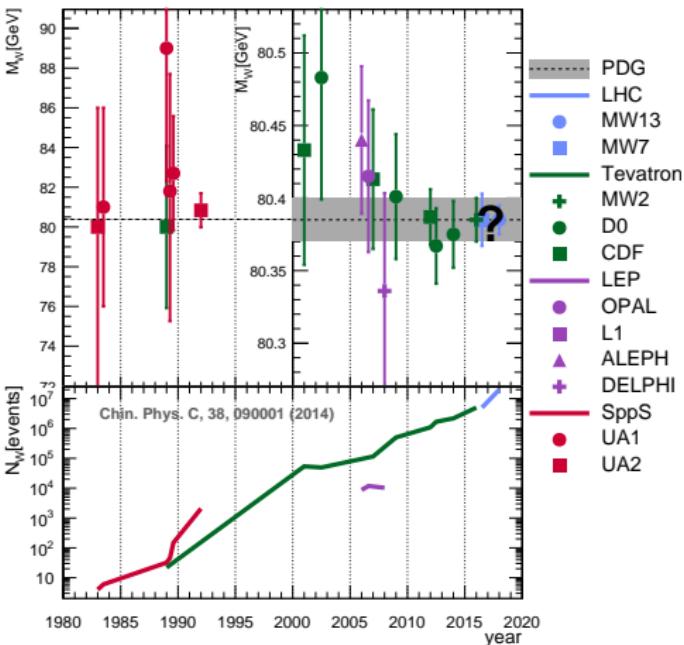
- Most of tools are focused on QCD higher order correction and photon radiation is treated by PHOTOS on top of generator
- However there is non-negligible contribution from NLO EW and cross terms with QED/QCD
- There tools on market:
  - POWHEG-BMNNP: adding EW term on QCD matrix element, but effects are overestimated
  - WINHAC: Matches final state YFS resummation with final-state NLO-EW, ISR is subtracted (need to add back with PS)
- Effort to have tool which covers all terms and interference from start



# Summary

- Long term effort to  $M_W$  measurement from many teams and experiments.
- Theoretical predictions more precise than measurement.
- With CMS we showed proof of concept for detector performance and fit methodology.
- Very close cooperation between theoretical and experimental groups

Thank you for your attention  
and brace yourself,  
 $M_W$  is coming.

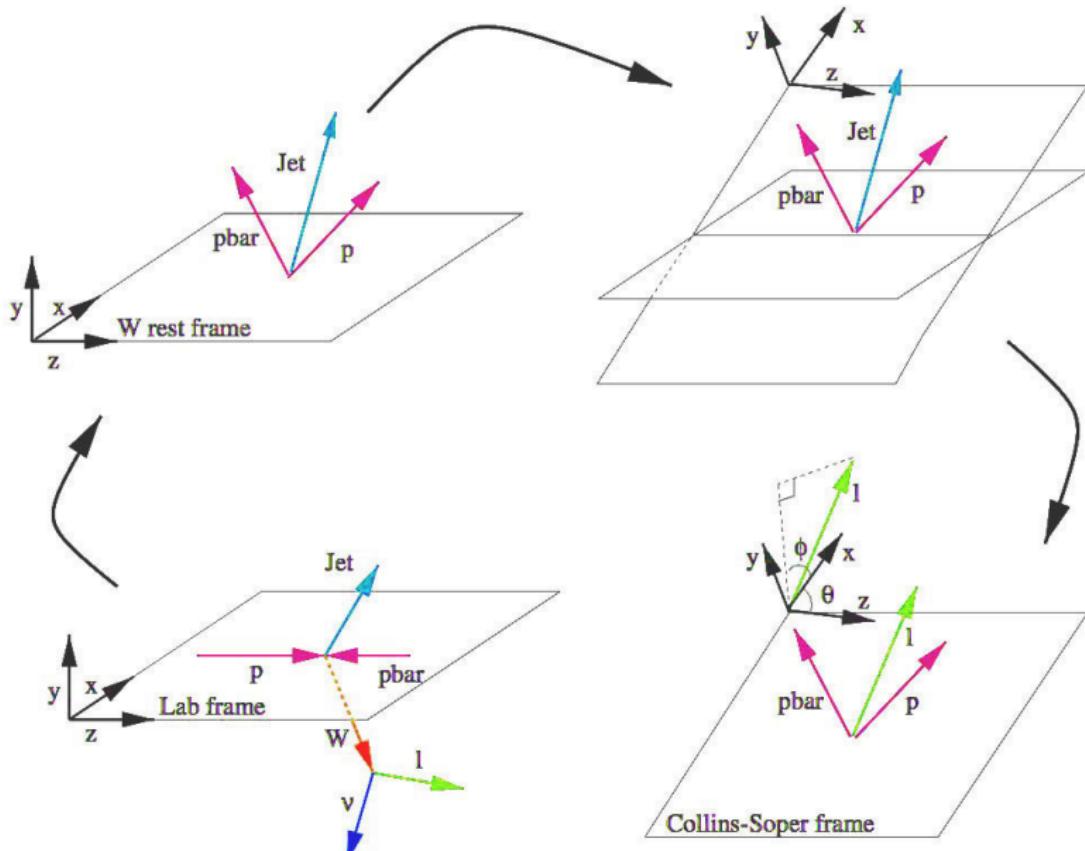


$M_W$  stands for My Wish!



Backup slides

# Collins-Soper frame



# $M_W$ topical meetings

- Novemer 2014 at Firenze: [<https://indico.cern.ch/event/340393/>]
- February 2015 at CERN: [<https://indico.cern.ch/event/367442/>]
- June 2016 at CERN: [<https://indico.cern.ch/event/533804/>]
- Next meeting: November 2016 Mainz