Oswaldo Guayasamín "Lágrimas de sangre" (1973)

High precision W mass measurement at the LHC

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On behalf of the CMS and ATLAS collaborations

QCD@LHC 2013
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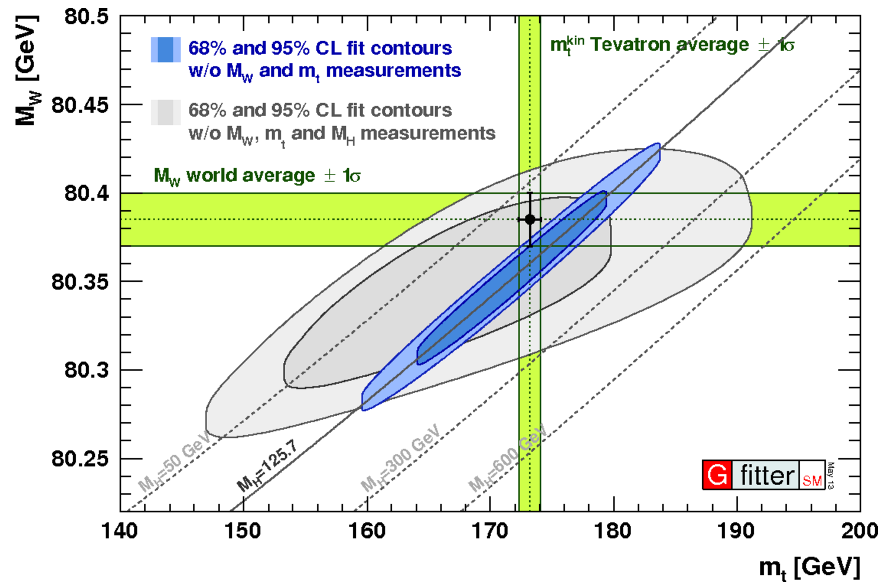
Outline

- W mass in the Standard Model (and beyond)
- Standing on the shoulders of giants: previous measurements
- Pinning down systematic uncertainties
- Conclusions

Motivations

- A precise measurement of M_W provides a crucial test of the SM
- The electroweak gauge sector of the standard model is constrained by three precisely known parameters
  - $\alpha_{EM}(M_Z) = 1 / 127.918(18)$
  - $G_F = 1.16637(1) \times 10^{-5}\ \mathrm{GeV}^{-2}$
  - $M_Z = 91.1876(21)$ GeV
- At tree-level, these parameters are related to M_W by
  - $M_W^2 = \pi\alpha_{EM} / \sqrt{2}G_F \sin 2\vartheta_W$
    Where ϑ_W is the weak mixing angle, defined by $\cos\vartheta_W = M_W/M_Z$

arxiv:1209.2716

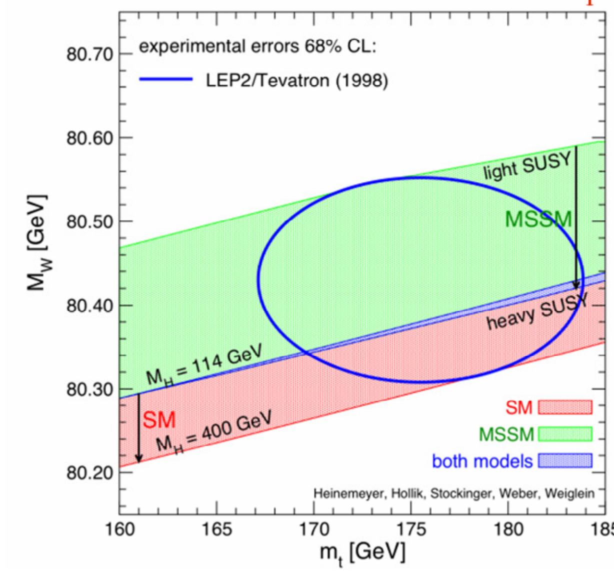


W mass beyond the Standard Model

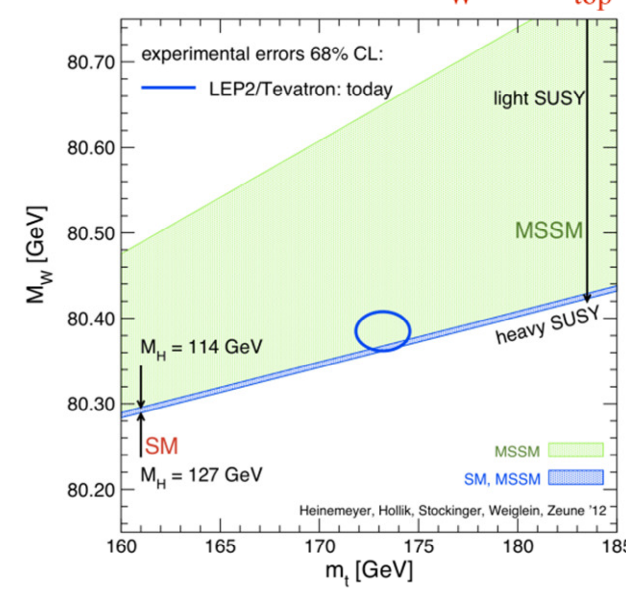
- Radiative corrections due to heavy quark and Higgs loops and exotica motivate the introduction of the ρ parameter:
  - $M_W^2 = \rho[M_W(\text{tree})]^2$
  - with the predictions $(\rho\text{-}1) \sim M^2_{top}$ and $(\rho\text{-}1) \sim \ln M_H$
  - In conjunction with M top , the W boson mass (over)constrains the mass of the Higgs boson, and possibly new particles beyond the standard model
  - After folding in limits on SUSY particles from direct searches, SUSY loops can contribute 100 MeV to M_W

- From LHC and Tevatron, $\Delta M_{top} \sim 1$ GeV $\rightarrow \Delta M_H/M_H \sim 8\%$
- Equivalent $\Delta M_W = 6$ MeV for the same Higgs mass constraint
  - Current world average $\Delta M_W = 15$ MeV
  - Progress on ΔM_W has the biggest impact in this context

1998 Status of M_W *vs* M_{top}

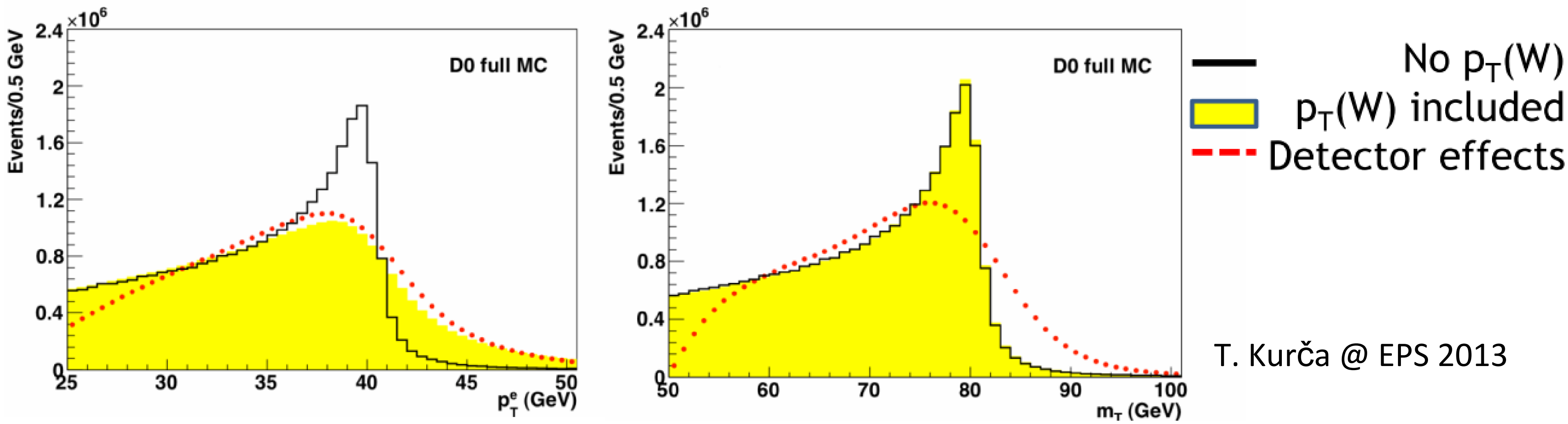


2012 Status of M_W *vs* M_{top}



Experimental observables

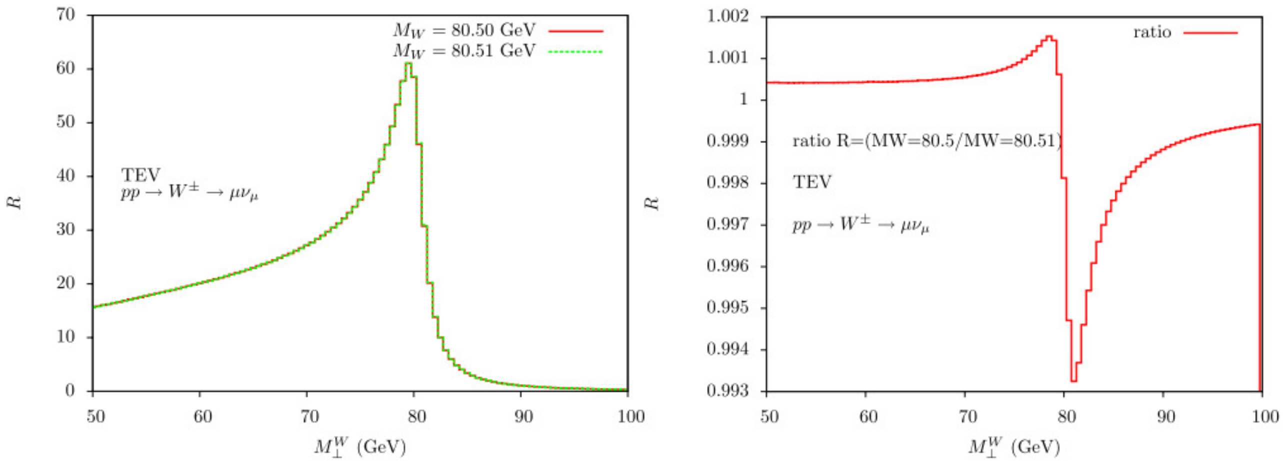
- Extract W mass from 3 observables transversal to the beam direction:
  - Lepton p_T $\rightarrow$ most affected by $p_T(W)$
  - W transverse mass M_T $\rightarrow$ sensitive to detector resolution effects
  - Missing E_T $\rightarrow$ dominated by detector resolution effects
- Complementary observables, not completely correlated



T. Kurča @ EPS 2013

Measurement strategy

- M_W is extracted with a template fit technique of various distributions of CC-DY
- In a template fit approach
  - the best theoretical prediction for a distribution is computed several times, with different values of M_W
  - each template is compared to the data
  - the measured M_W is the one of the template that maximizes the agreement with the data
- Which level of accuracy do we need?



Phys. Rev. D83, 113008 (2011)

- The measured M_W value does not depend on the normalization of the distributions but rather on their shape
- If we aim at measuring M_W with < 10 MeV of error, are we able to control the shape of the distributions and the theoretical uncertainties at the few per mille level?

The big picture

Theoretical uncertainties

Experimental uncertainties

W mass

W production and decay model
- Resbos
- DYRES

EWK corrections
- PHOTOS
- POWHEG NLO QCD+EWK

Parton Distribution Functions
- CTEQ
- NNPDF
- MSTW

Templates
- MC driven
- DATA driven (Z)

Detector simulation
- Fast sim
- GEANT

Fitting variables
- m_T
- Lepton pT
- MET

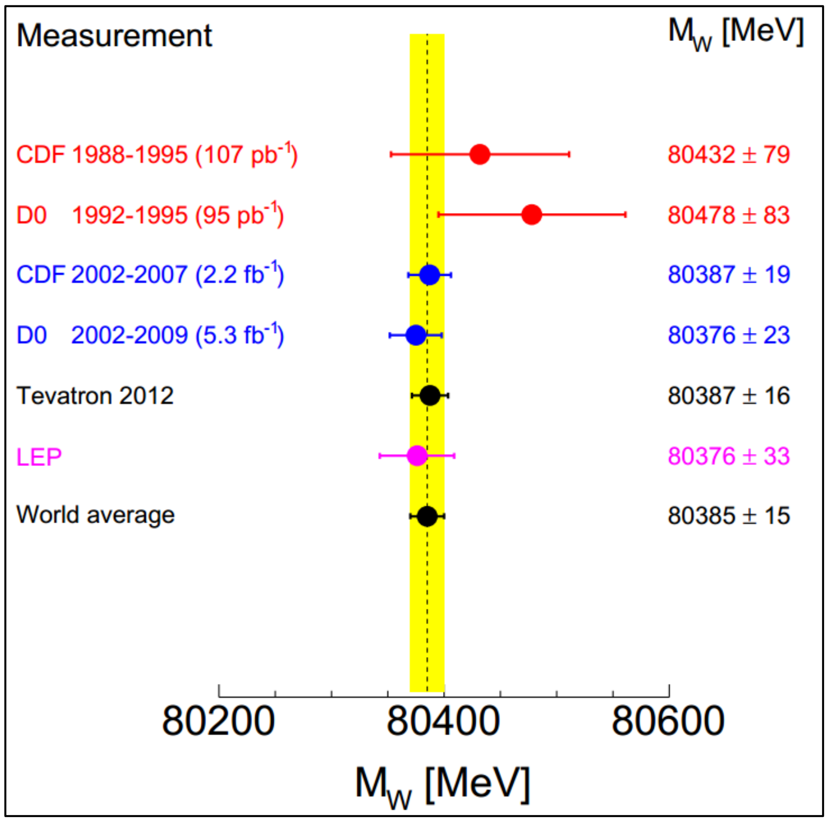
Lepton energy scale and resolution
- Z, J/ψ events

Hadronic recoil model
- Z events

Backgrounds
- TTbar, VV, QCD

Previous measurements

- Long series of W mass measurement starting from LEP
- Highest precision with single measurement is 19 MeV by CDF
- World average is 80385 ± 15 MeV



arxiv:1307.7627

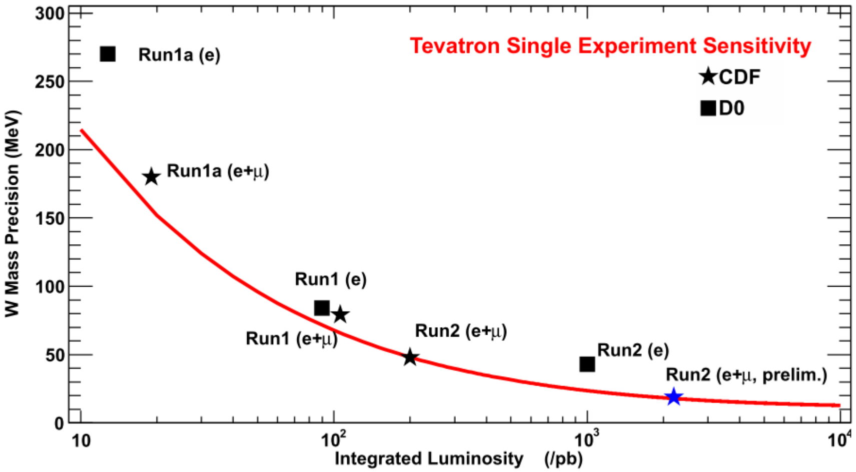
Detailed uncertainties as of last CDF measurement

Source	Uncertainty (MeV)
Lepton energy scale and resolution	7
Recoil energy scale and resolution	6
Lepton removal	2
Backgrounds	3
$p_T(W)$ model	5
Parton distributions	10
QED radiation	4
W-boson statistics	12
Total	19

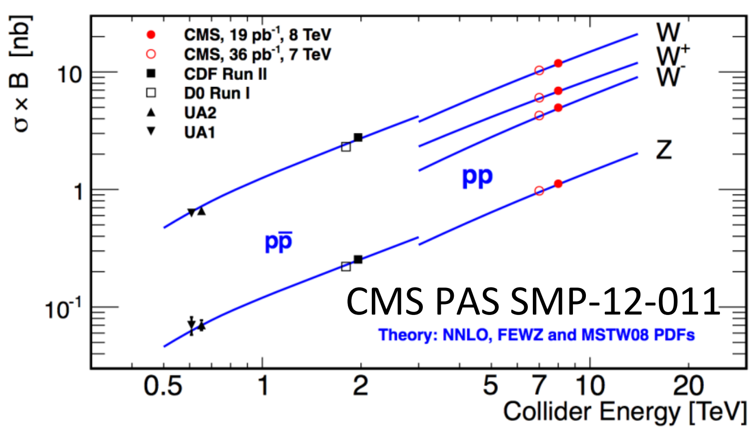
Phys. Rev. Lett. 108, 151803 (2012)

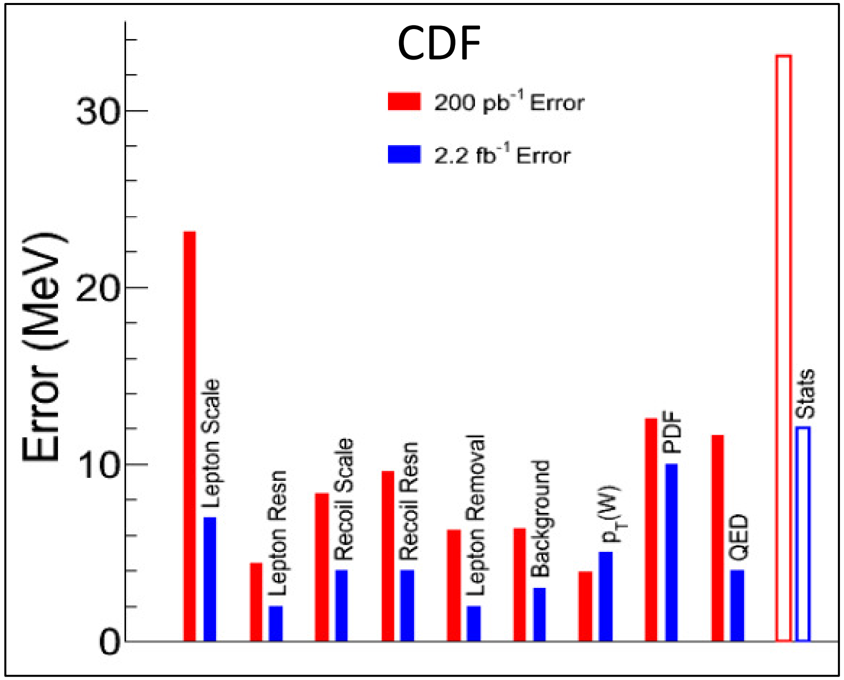
Systematics vs statistics

- For most of the sources of systematic uncertainties, Tevatron demonstrated that is possible to better control them with more statistics
- Exception is the PDF uncertainty, where a dedicated effort is required to improve sensitivity
- Factor of 2-5 statistics of W and Z bosons available at Tevatron wrt published results



- Huge samples at LHC:
  - 10 fb^{-1} at 8 TeV provide O(40M) W boson and O(2.5M) Z boson candidates per decay channel per experiment
    - Statistical uncertainty on W mass fit ~2 MeV
  - Much bigger pileup wrt Tevatron

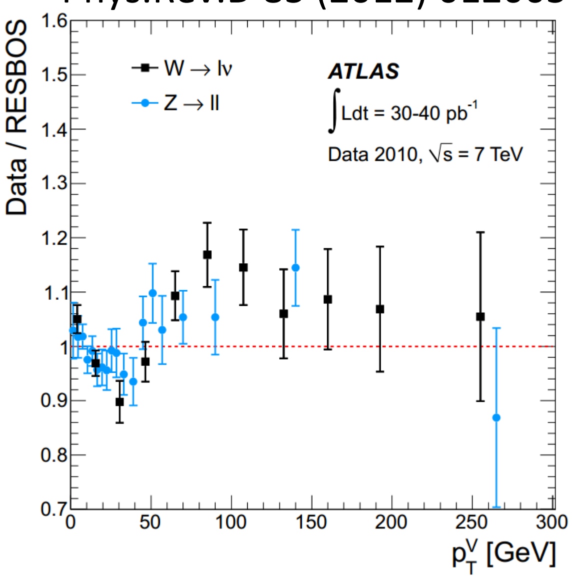




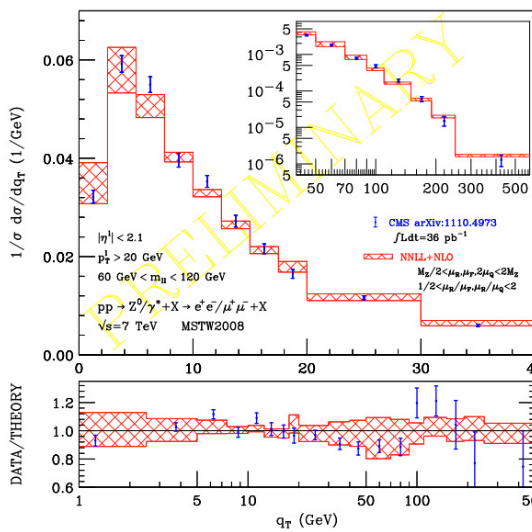
Theoretical uncertainties (I)

- Constraining Boson pT Spectrum – Open Questions
  - How many parameters needed to describe pT spectrum at the 1 MeV level of precision on W boson mass (3 times better than today)
  - Do these parameters have a well-defined meaning for pT(Z) vs pT(W) spectrum?
  - Are there any non-perturbative effects that differ for W bosons vs Z bosons ? At what level does $p_T(Z)$ measurement not constrain $p_T(W)$ spectrum?
    - Charm-induced production and charm quark mass is the canonical example of such an effect
  - RESBOS widely used. New competitor in the game: DYRES

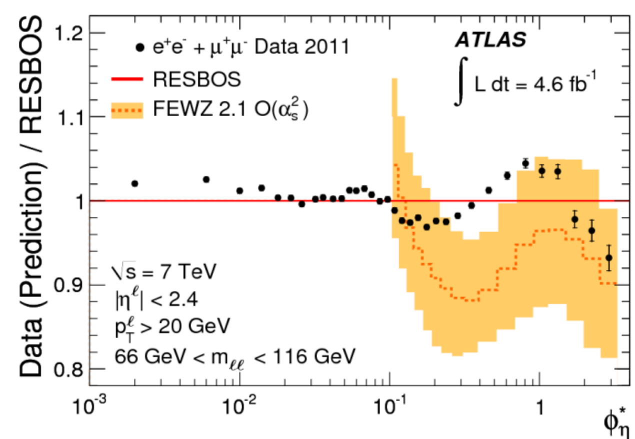
Phys.Rev.D 85 (2012) 012005



CMS (Phys. Rev. D 85, 032002)
compared to DYRES



ATLAS (Phys. Lett. B720, 32)



Theoretical uncertainties (II)

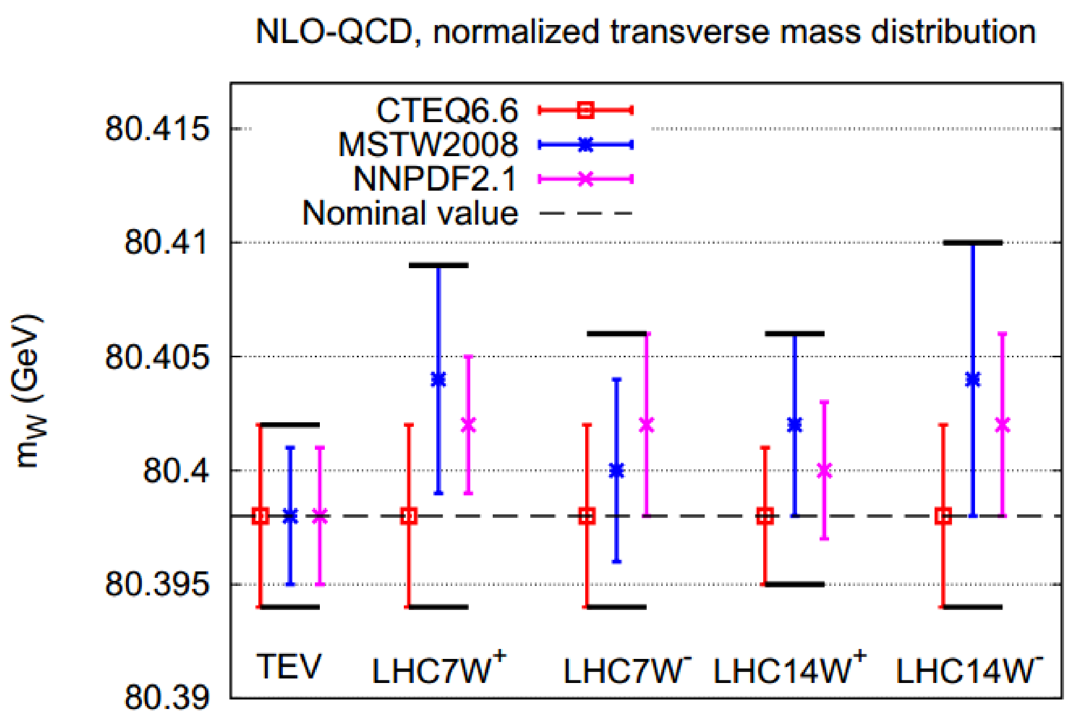
- W boson Decay Angular Distribution – Open Questions
  - Important to check theoretical calculations, which feed into other precision measurements (eg. M_W measurement in the case of W boson's decay angular coefficients)
  - W boson decay angular distribution (which affects lepton pT spectrum and hence mass measurement) deviates from Born-level V-A prediction due to QCD radiation
  - How accurately can we calculate these coefficients at low pT(W) ?

- Including EWK corrections – Recent improvements
  - At Tevatron W & Z simulation is provided by RESBOS, which contains only QCD corrections
  - Multiple radiative photons generated according to PHOTOS
  - Recently, NLO QCD+EWK corrections have been implemented in POWHEG for W & Z
    - How to combine the two approaches?
  - Recently NNPDF released a set containing EWK corrections, required to incorporate consistently EWK effects

$$
\begin{aligned}
\sigma_{tot} = \sigma_0 &+ \boxed{\alpha_s \sigma_{\alpha_s} + \alpha_s^2 \sigma_{\alpha_s^2}} + \ldots && \text{MCFM,FEWZ,DYNNLO} \\
&+ \boxed{\alpha \sigma_\alpha} + \alpha^2 \sigma_{\alpha^2} + \ldots && \text{WGRAD, RADY, HORACE, SANC} \\
&+ \alpha\alpha_s \, \sigma_{\alpha\alpha_s} + \alpha\alpha_s^2 \, \sigma_{\alpha\alpha_s^2} + \ldots
\end{aligned}
$$

Theoretical uncertainties (III)

- PDF Uncertainties – scope for improvement
  - At Tevatron dominant sources of W mass uncertainty are the d valence and d-u degrees of freedom
    - Is this still true at LHC?
  - Some authors claim (arXiv:1004.2597) that PDF will severely limit MW precision at LHC
  - Other authors show (Phys. Rev. D83, 113008) that even before adding LHC data, PDF should count O(20) MeV for M_W at LHC using transverse mass
    - In principle errors with lepton p_T can be larger because of the gluon dominance

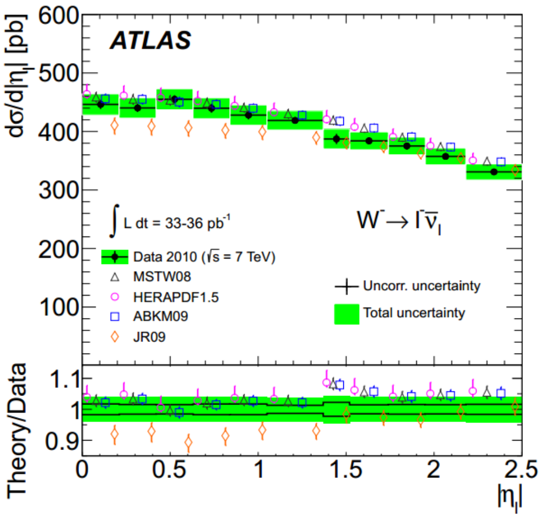


Phys. Rev. D83, 113008 (2011)

Theoretical uncertainties (IV)

- PDF Uncertainties – scope for improvement
  - Newer PDF sets include more recent Tevatron and LHC data
  - Tevatron and LHC measurements that can further constrain PDFs:
    - Z boson rapidity distribution, W $\rightarrow$ lν lepton rapidity distribution, W+charm
      - have impact on the strange quark
    - W boson charge asymmetry
      - New CMS muon W asymmetry data has relative uncertanties below 1%
      - According PRD 83, 113008, 2011 it should allow to constrain significantly the PDF uncertainties on the W mass measurement

Phys. Rev. D85, 072004 (2012)



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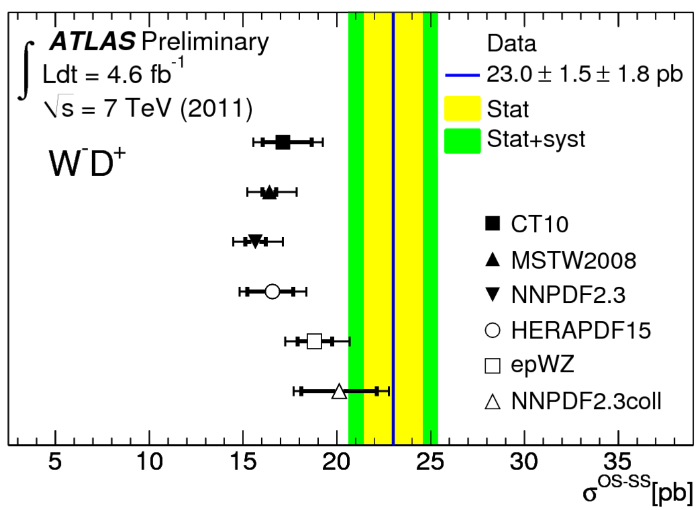

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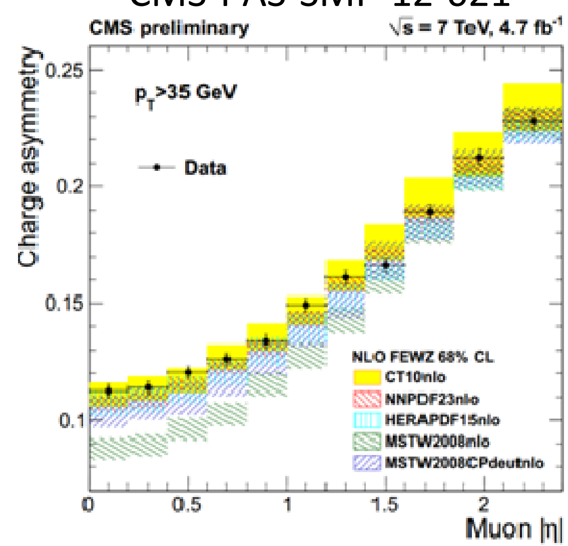
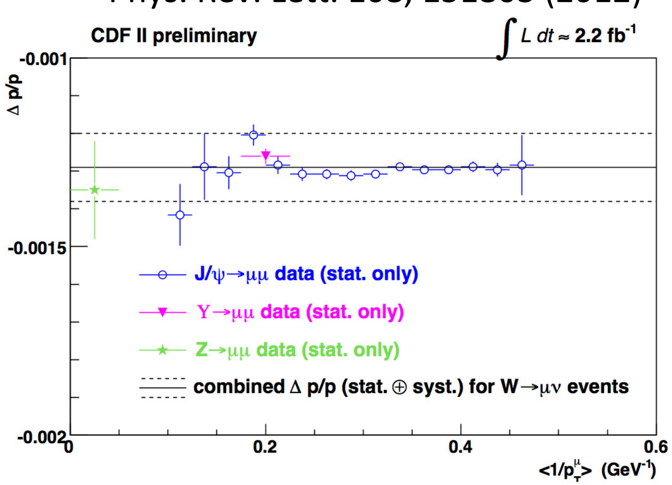


Experimental uncertainties (I)

- Lepton momentum scale:
  - lepton carries most of W mass information, can (must) be measured precisely
    - Tevatron achieved 0.03%
    - LHC in the H→ZZ →4μ mass context achieved 0.1%
      - Different phase space, interested in high efficiency more than purity
  - Using Z events, calibration ultimately limited by statistics → best-case scenario of statistical limit ~ 5 MeV precision
    - CDF used J/Psi and Y to reach better accuracy: is this the way to go?
    - Is the higher detector material budget a limiting factor at LHC?

Phys. Rev. Lett. 108, 151803 (2012)



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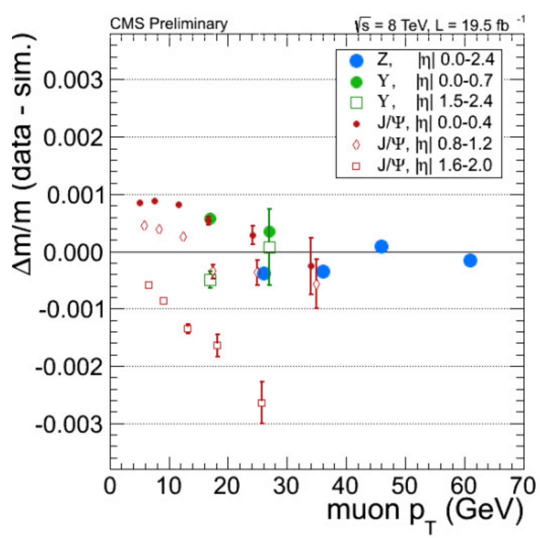

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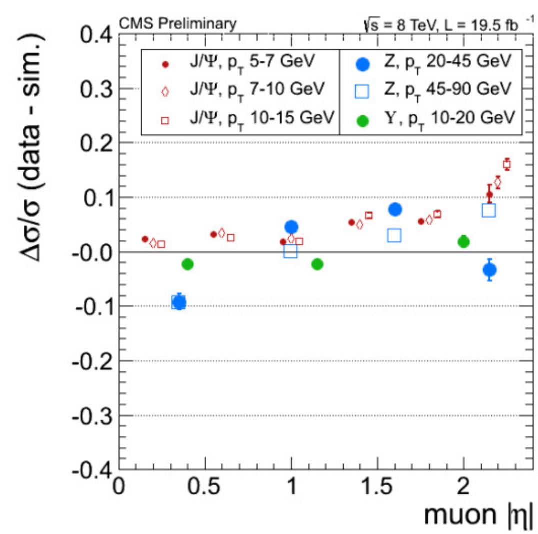
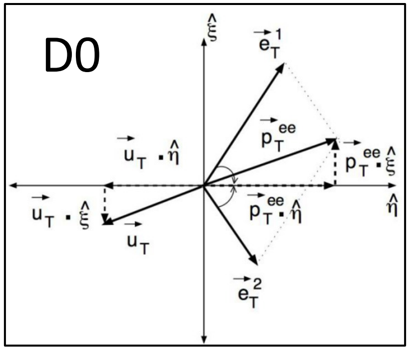
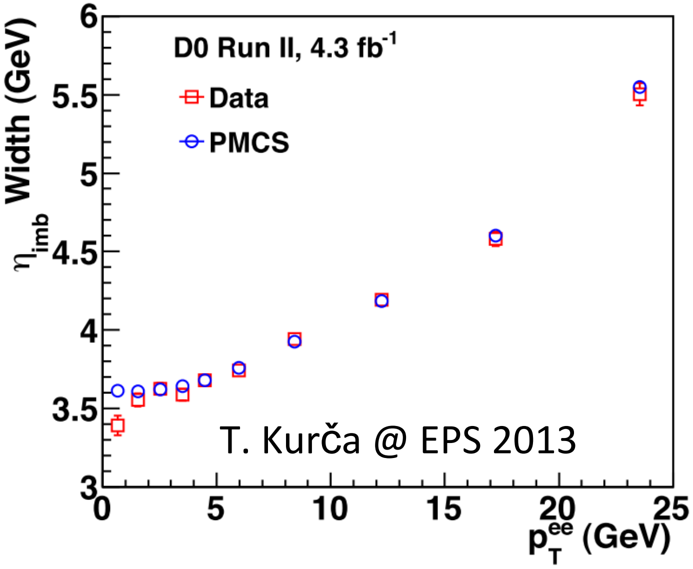


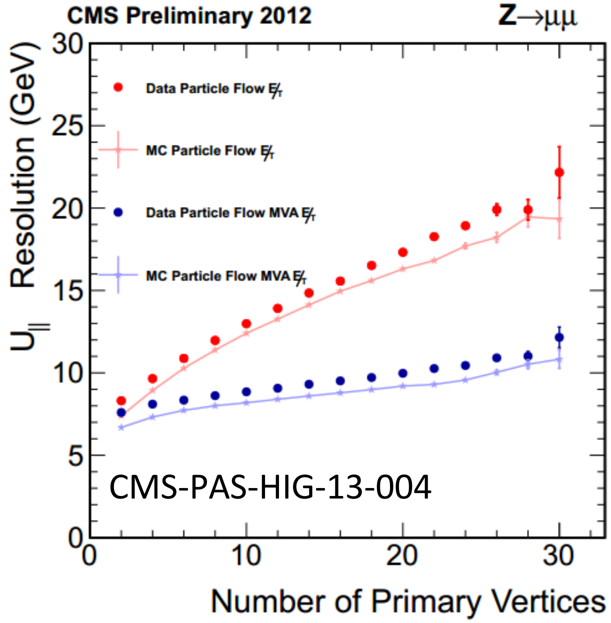
Experimental uncertainties (II)

- Hadronic recoil
  - Initial state QCD radiation is O(10 GeV), measured as soft 'hadronic recoil' in calorimeter
    - Pollutes W mass information, fortunately $p_T(W) << M_W$
  - Recoil calibrated to ~1% at Tevatron
  - CMS in the $H\rightarrow\tau\tau$ context achieved 5%
    - Different phase space, interested in high efficiency more than purity



NB: different projection axis between D0 and CMS





Experimental uncertainties (III)

- Open questions: can the Z $\rightarrow$ ll data constrain all the relevant W boson systematics?
  - Production and decay dynamics are slightly different
    - Different quark parton distribution functions
    - Non-perturbative (e.g. charm mass effects in cs $\rightarrow$ W) effects
    - QCD effects on polarization of W vs Z affects decay kinematics
  - Lepton energies different by ~10% in W vs Z events
  - Presence of second lepton influences the Z boson event relative to W
  - Reconstructed kinematic quantity different (invariant vs transverse mass)
  - Subtle differences in QED radiative corrections

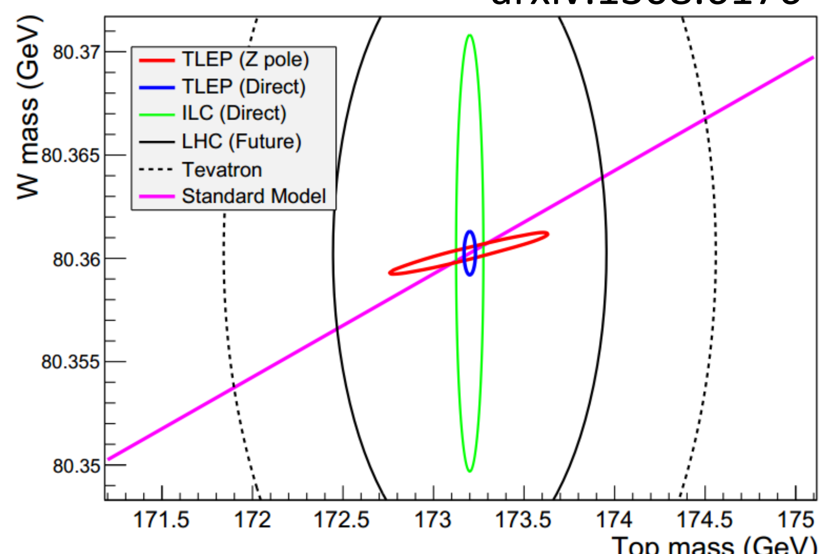
- Can we add other constraints from other mass resonances or better exploit the detector informations?
  - Tevatron showed that with every increase in statistics of the data samples, a new learning curve on the systematic effects is climbed

Conclusions

- The W boson mass is a very interesting parameter to measure with increasing precision
  - It requires a coordinate effort between experimental and theoretical communities

- D0 prediction for full data set
  - Significantly extend eta coverage
  - 15 MeV uncertainty (not including improvements in PDFs)
- CDF prediction for full dataset
  - 10 MeV uncertainty (including improvements in PDFs; hich are expected from measurements of W charge asymmetry)
- LHC is going to enter in the game: 10 MeV to 5 MeV, ultimate precision
  - Current measurements are critical steps towars this goal:
    - boson pT, rapidity spectra
    - W charge asymmetry
    - W+c jet

arxiv:1308.6176



- The next “quantum leap” in precision could come from a TLEP-like machine (0.5 MeV uncertainty)
  - We hope to see surprises already at LHC: stay tuned!

Backup slides

Improving PDFs with LHC data

- From the experimental data point of view, all the current and future needs of the LHC in terms of PDFs, including the measurement of MW can be addressed by a specific PDF program at the LHC
- There is a long list of measurements to be pursued, that will provide all required information on PDFs:
  - Inclusive jets and dijets, central and forward: large-x quarks and gluons
  - Isolated photons: medium-x gluons
  - Inclusive W and Z production and asymmetries: quark flavor separation, strangeness
  - W production with charm quarks: direct handle on strangeness
  - W production with jets: medium small-x gluon
  - Off resonance DY and W production at small and high mass: quarks at very small and very large-x
  - Top quark distributions: large-x gluon
  - Z+charm: intrinsic charm PDF
  - Single top production: gluon and bottom PDFs
  - Charmonium production: small-x gluon
- To maximize the LHC data impact on PDFs, it is crucial to coordinate a detailed PDF program between the LHC experiments and the Theory community