Measurement of the W Mass

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On behalf of the CDF, DØ, ATLAS, and CMS Collaborations

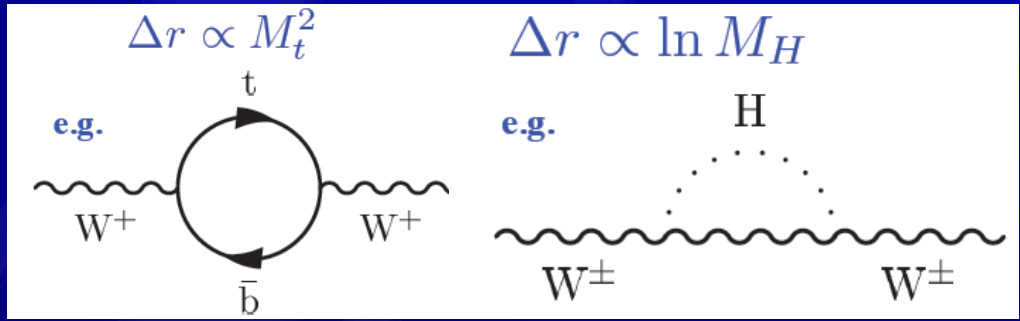
XXVI International Symposium On
Lepton Photon Interactions At High Energies
June 24, 2013

Motivation: Precision EW Tests

- In Standard Model Electroweak theory, the W mass can be calculated according to:

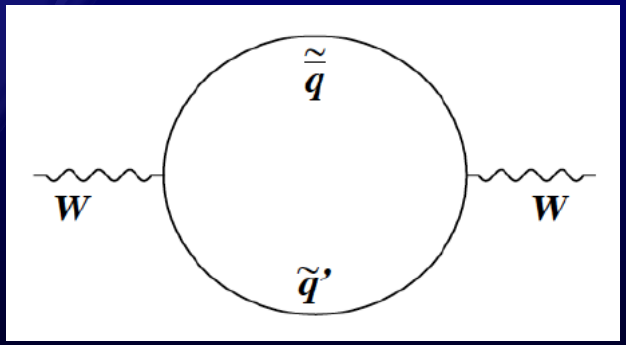
$$M_W = \sqrt{\frac{\pi\alpha}{\sqrt{2}G_F}}\frac{1}{\sin\theta_W\sqrt{1-\Delta r}}$$

- Where Δr are radiative loop corrections, calculated up to 3-loop order, with diagrams such as:



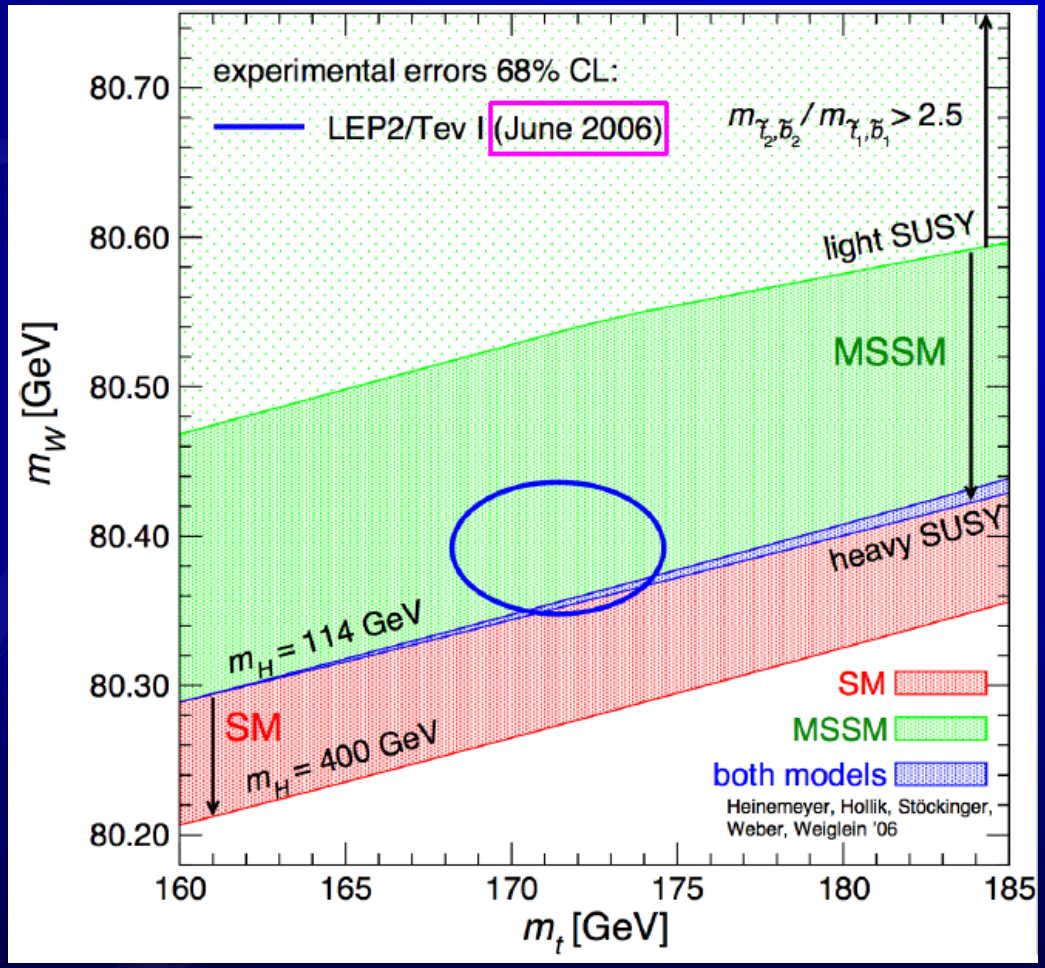
- So precise M_W and M_t measurements can constrain M_H (and vice-versa!)

- But additional loops can be generated from new physics, e.g. SUSY



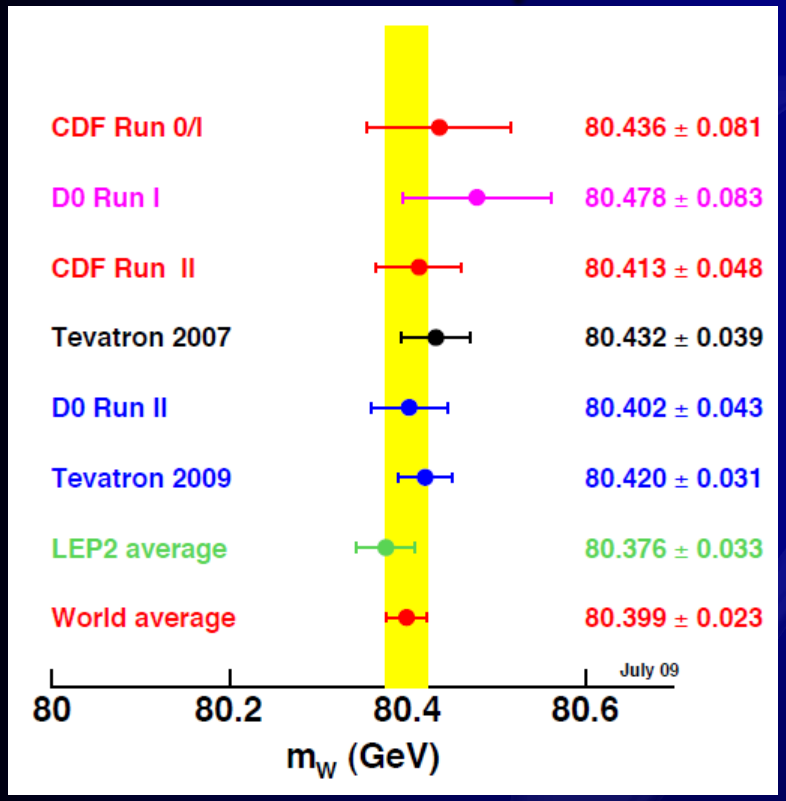
Motivation: Precision EW Tests

- The situation early in the Tevatron Run II era

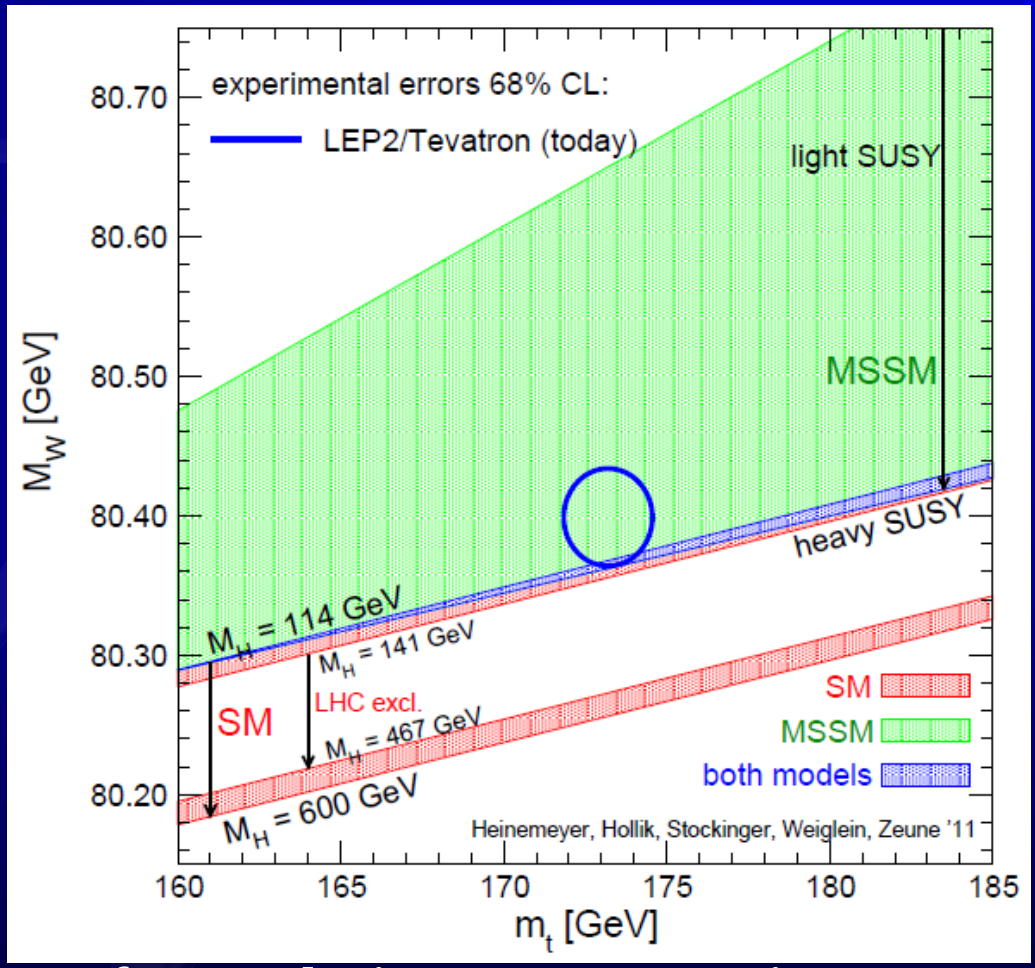


Motivation: Precision EW Tests

- Prior to February 2012…

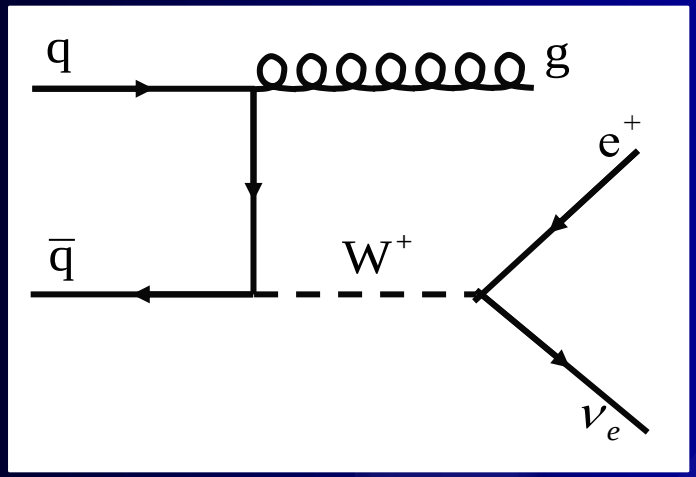


$m_t = 173.2 \pm 0.9$ GeV

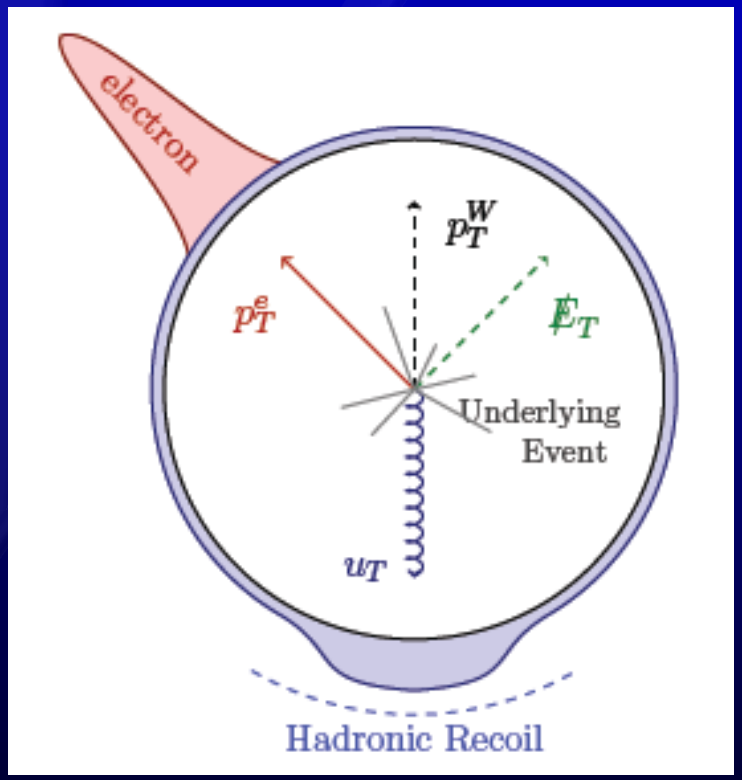


- Higgs is most sensitive to W mass - for equal Higgs mass constraint
  $\Delta m_W \sim 0.006 \Delta m_t$
- With $\Delta m_t = 0.9$ GeV, need $\Delta m_W = 5$ MeV for equivalent contribution!

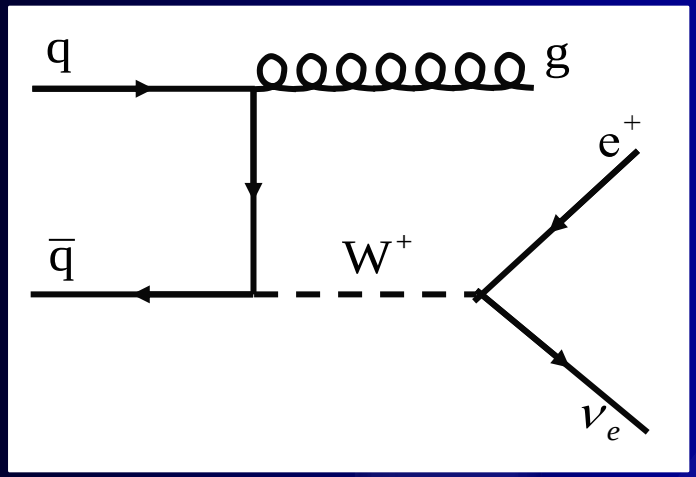
Measurement: Same Strategy



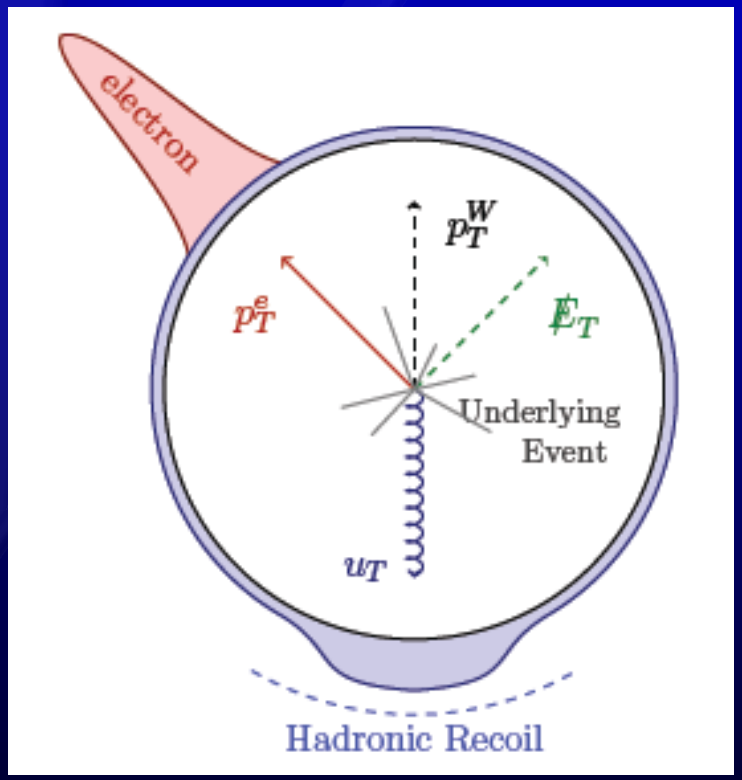
- **Simple task – just measure two objects:**
  - Charged lepton
  - Hadronic recoil



Measurement: Same Strategy

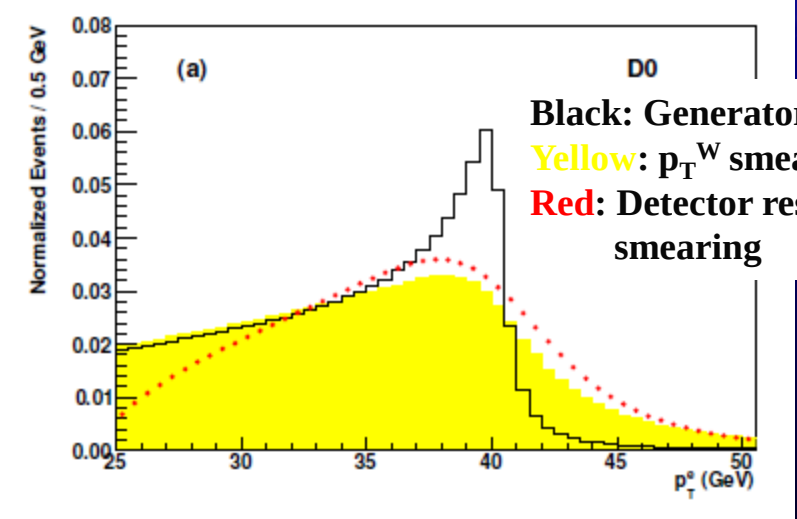


- **Not so simple task – just measure two objects:**
  - Charged lepton – 0.01% precision!
  - Hadronic recoil – < 1% precision!

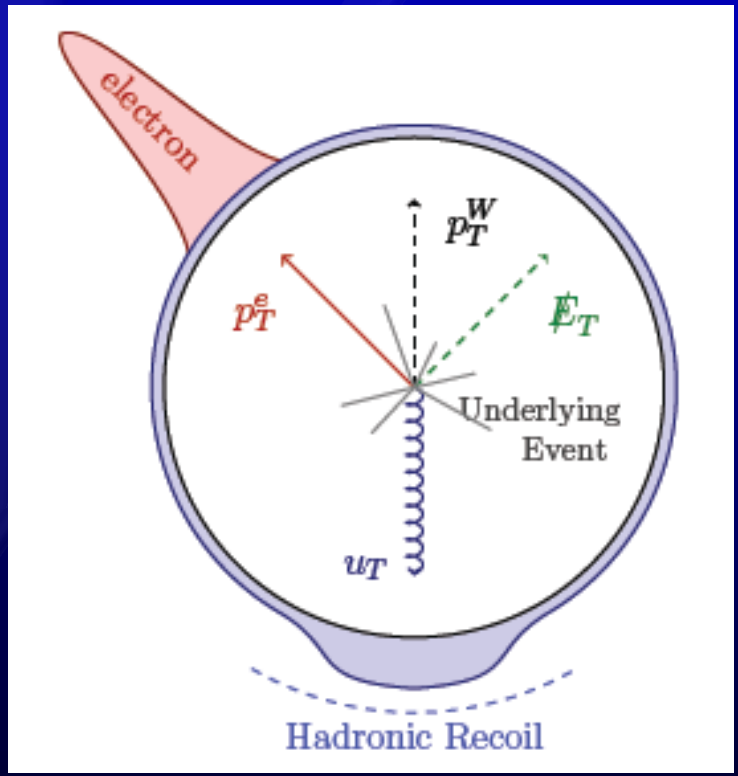


Measurement: Same Strategy

- **Transverse momentum carries mass information in $W \to l\upsilon$ events. Examine three kinematic distributions**
  - Transverse mass: $m_T = \sqrt{p_T^l \not{E}_T (1 - \cos \Delta\emptyset)}$
  - Lepton transverse momentum: p_T^l
  - Missing transverse energy: $\not{E}_T$
- **Use a parameterized fast MC detector simulation to generate templates to compare with data**



Black: Generator level
Yellow: $p_T{}^W$ smearing
Red: Detector resolution smearing



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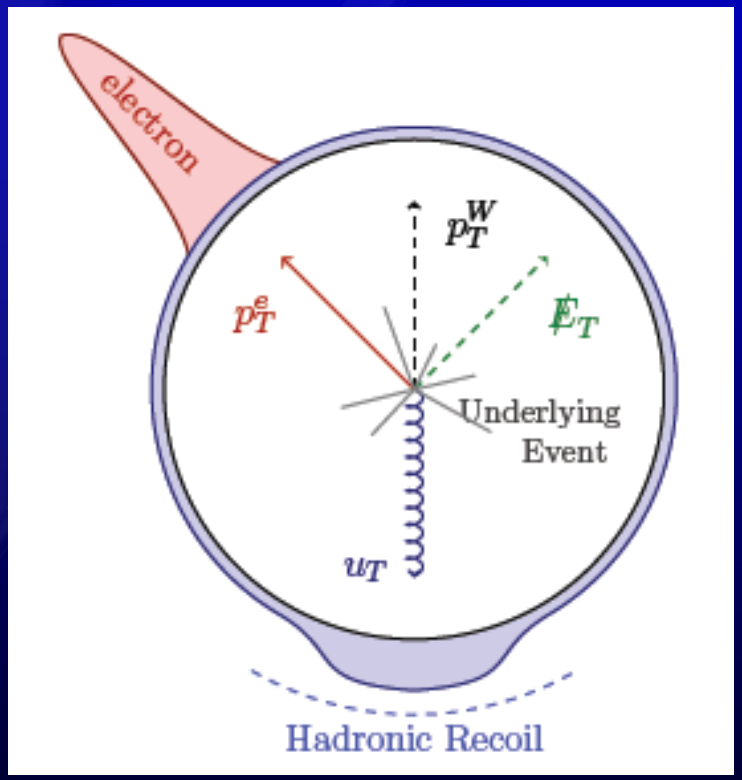
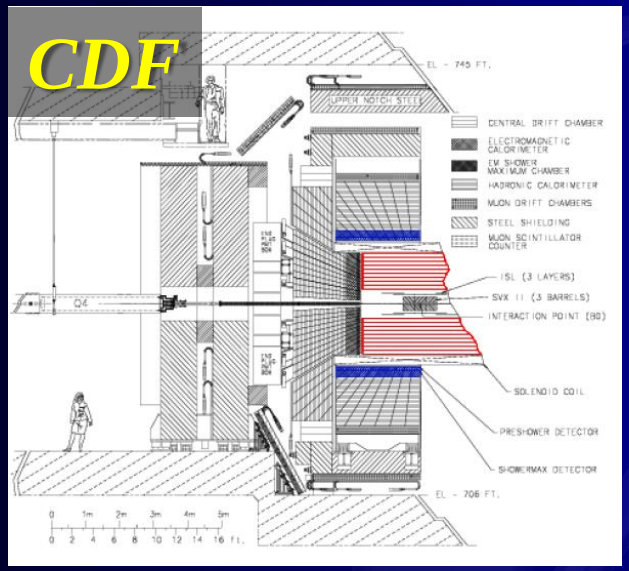
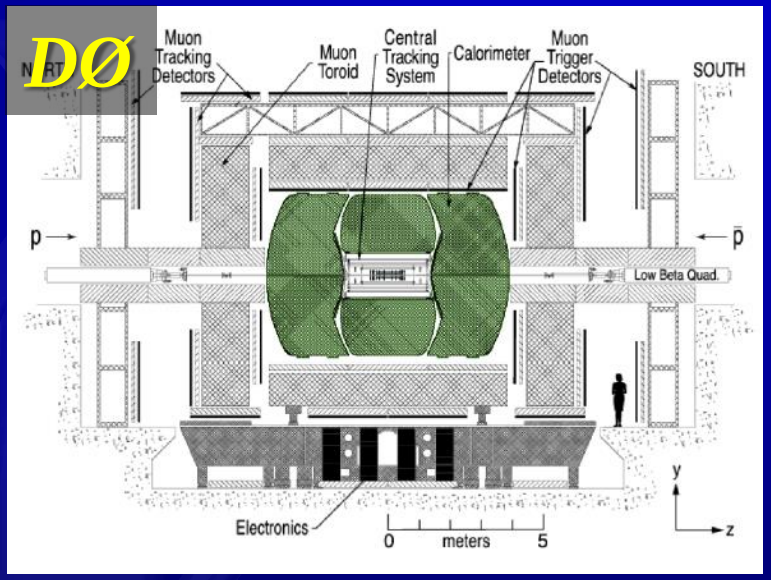
- **Use a parameterized fast MC detector simulation to generate templates to compare with data**
- **Calibrate fast MC with data**
  - Verify with the Z mass peak
- **Binned likelihood fit of data to templates to extract W mass**
- **Combine result from the different distributions since they are not completely correlated**



Measurement: Different Tactics

- CDF and D0 employ very different methods, esp. in fast MC simulation and calibration, to capitalize on strengths of their unique detectors

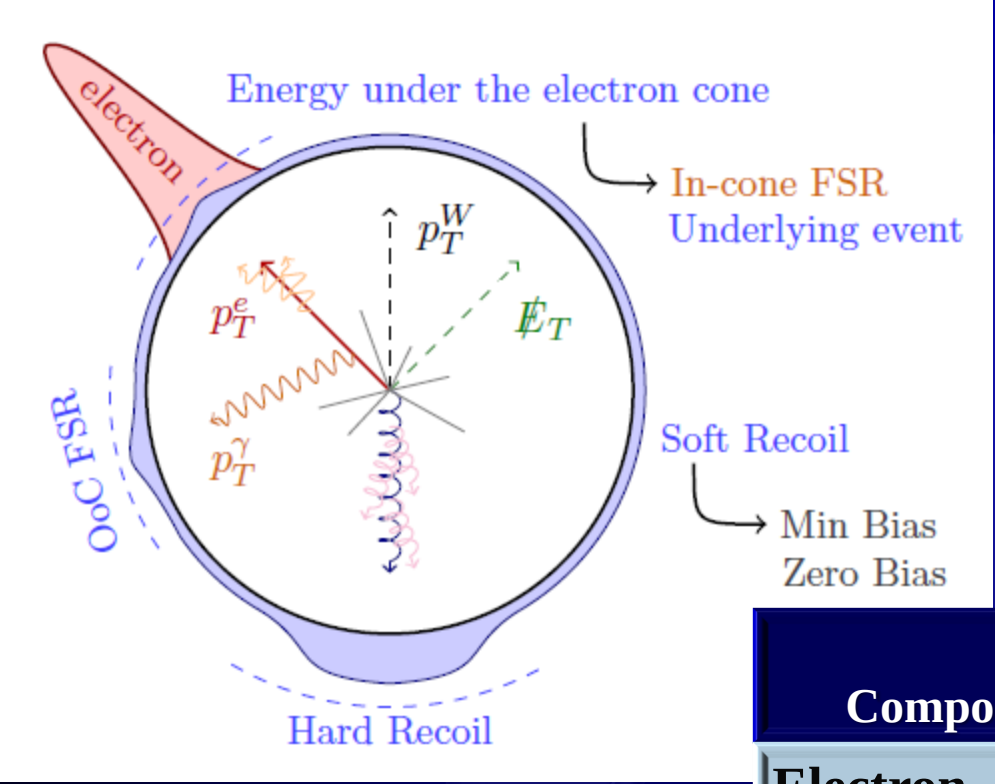




- Central tracking provides very good lepton momentum measurement
  - Muon resolution = 3.2% (at $p_T = 45$ GeV)
- Use $W \to e\upsilon$ and $W \to \mu\upsilon$ events
- Detailed tracker model
- Momentum scale calibration focus
  - Using $J/\psi \to \mu\mu$, $\Upsilon \to \mu\mu$, $Z \to \mu\mu$

- EM calorimeter provides very good electron energy measurement
  - Energy resolution = 3.3% (at $E = 45$ GeV)
- Use $W \to e\upsilon$ events
- Detailed calorimeter, E flow model
- Energy scale calibration focus
  - Using $Z \to ee$

Fast MC & Calibration



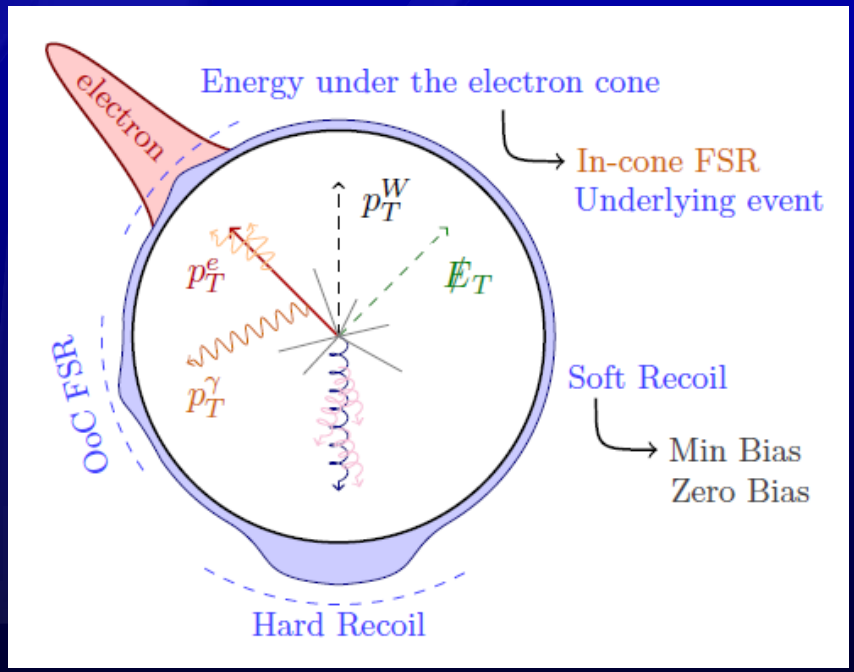
- What we're really dealing with…

ENERGY FLOW	
Component	$\sigma()$
Electron	50 GeV
Hadronic Recoil	5 GeV
Hadronic energy under cone	200 MeV
Final state radiation	100 MeV
Electron shower leakage	50 MeV

Hadronic Recoil Response Model

$\vec{u}_T = \vec{u}_T^{\,HARD}$ **(recoil against W/Z)**
$+ \vec{u}_T^{\,SOFT}$ **(spectator partons and pileup)**
$+ \vec{u}_T^{\,ELEC}$ **(hadronic leakage in cone, or electron leakage out of cone)**
$+ \vec{u}_T^{\,FSR}$ **(final state radiation photons)**

- **Modeled with data and and full MC, calibrated with Z events**
  - $\vec{u}_T^{\,HARD}$: $Z \to \nu\nu$ MC
  - $\vec{u}_T^{\,SOFT}$: min bias (spectators) and zero bias (pileup) events matched to $Z \to ee$ data



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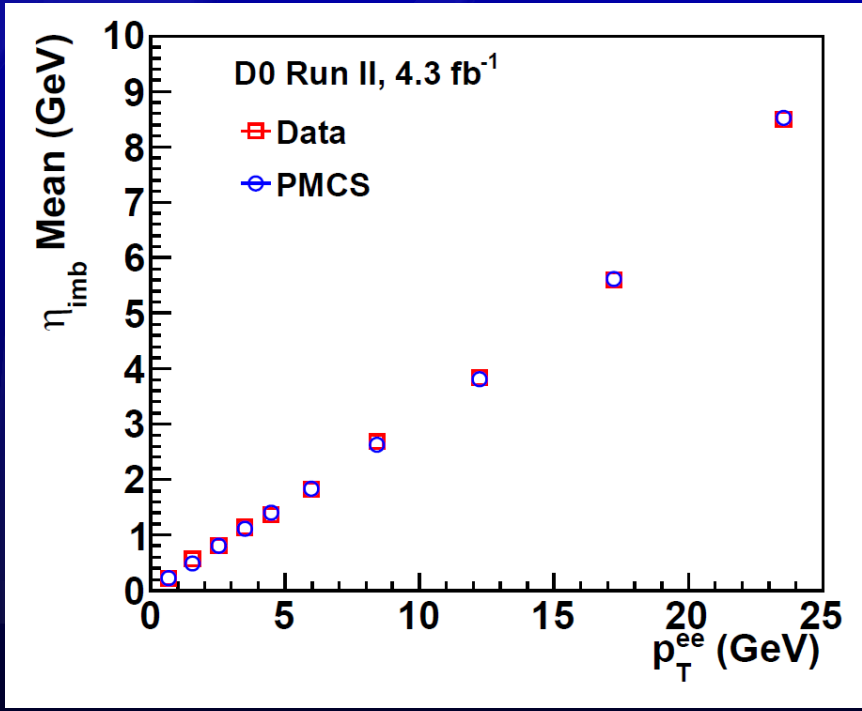
  - $\vec{u}_T^{\,HARD}$: $Z \to \nu\nu$ MC
  - $\vec{u}_T^{\,SOFT}$: min bias (spectators) and zero bias (pileup) events matched to $Z \to ee$ data
- **Tuned on the momentum imbalance in $Z \to ee$ data**



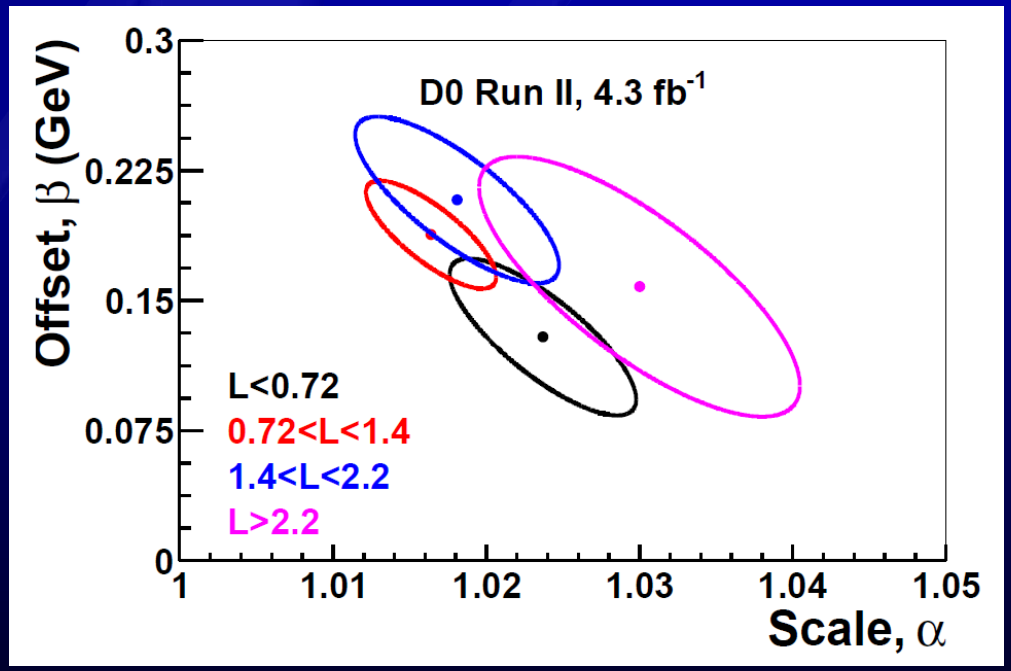
Electron Energy Response Model

- **Linear calorimeter response model**

$$R_{EM}(E_{true}) = \alpha \cdot (E_{true} - \overline{E}_{true}) + \beta + \overline{E}_{true}$$

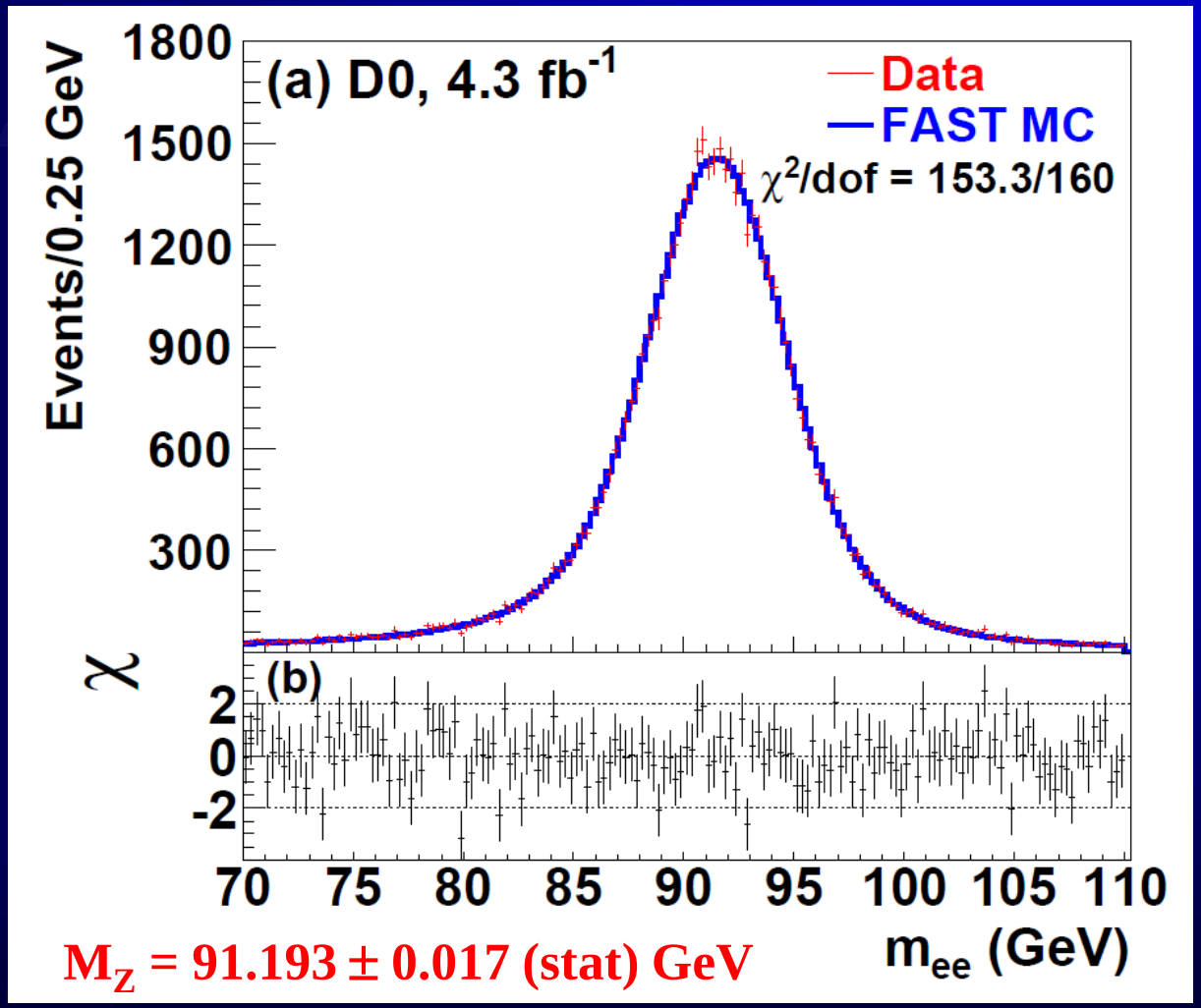
  - With corrections for dead material, underlying event, noise, etc.

- **Energy scale measured over broad range using boosted Z's**
- **Verify consistency at different luminosities**
- **Closure test with full MC**



Electron Energy Response Model

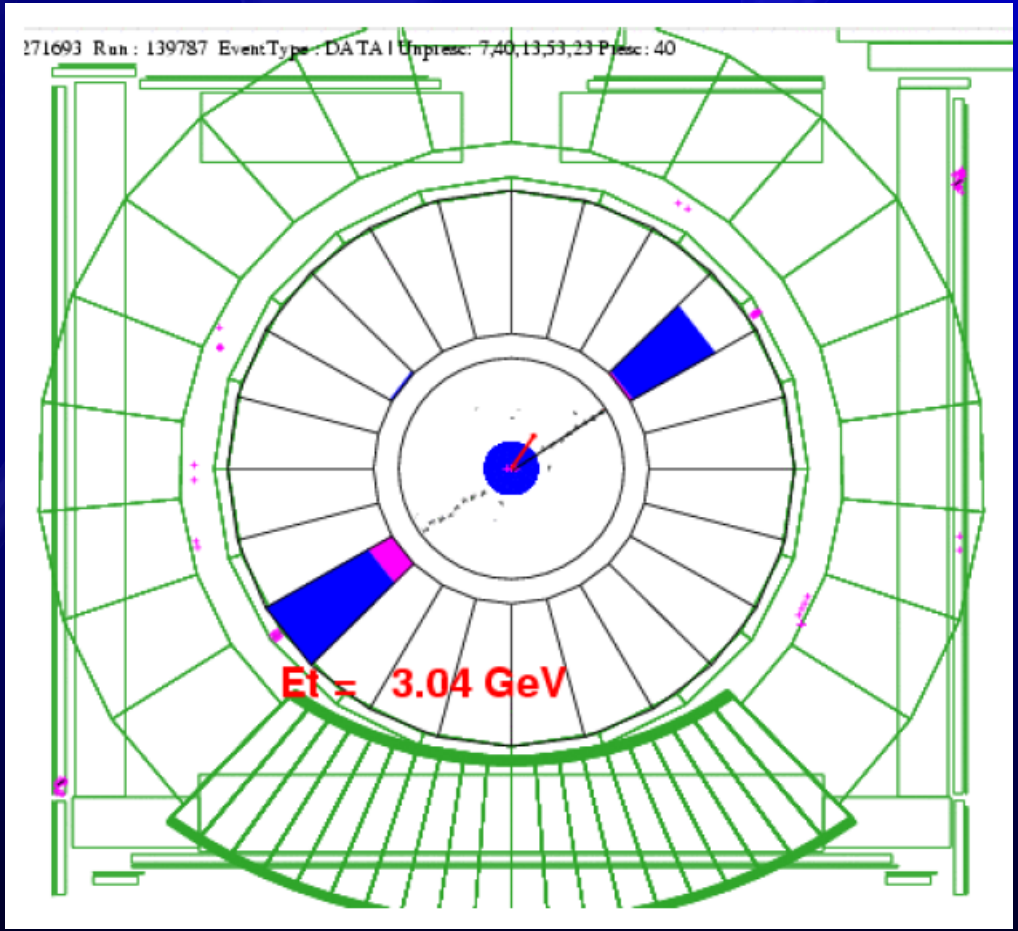
- Z Mass Fit



- Compare to PDG: M_Z = 91.188 ± 0.002 GeV

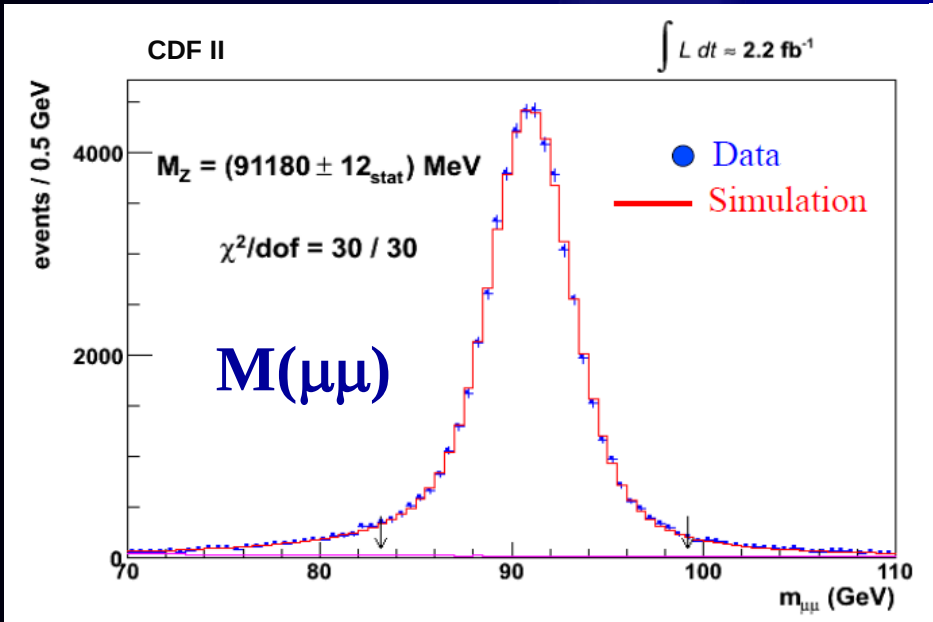
Tracking Model

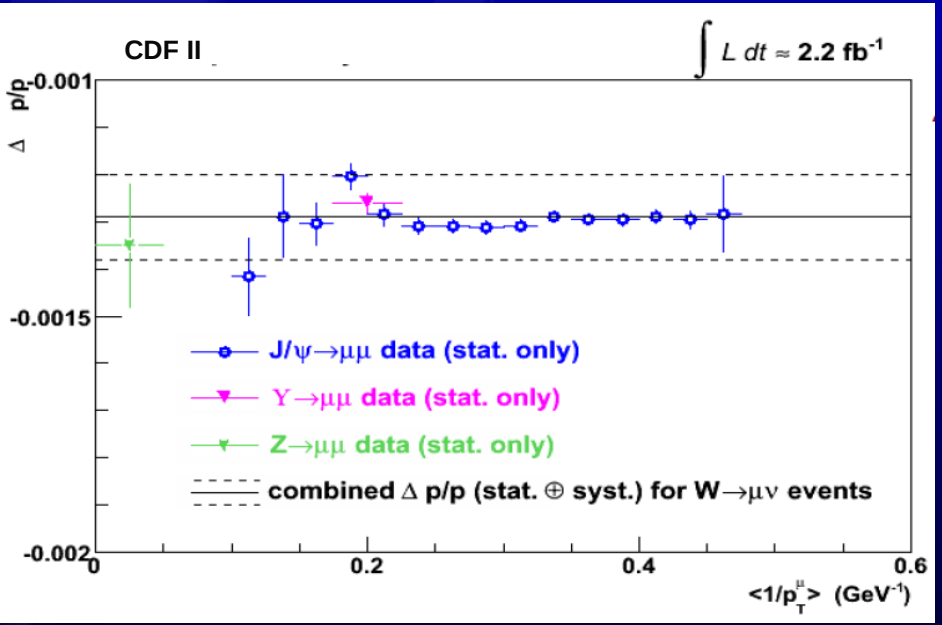
- First-principles simulation: e.g. detailed 3-D lookup table of tracker material for track and photon propagation
- Cell by cell internal alignment using 400k cosmic rays



Momentum Scale Calibration

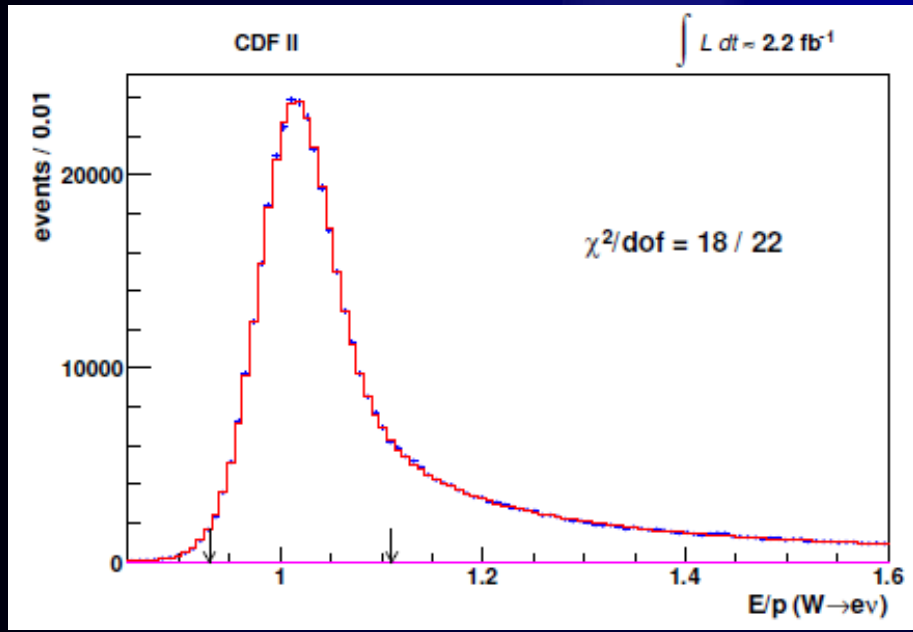
- Use $J/\psi \to \mu\mu$, $\Upsilon \to \mu\mu$ to set the momentum scale
- Verify on the $Z \to \mu\mu$ mass peak
- Combine all three for final calibration

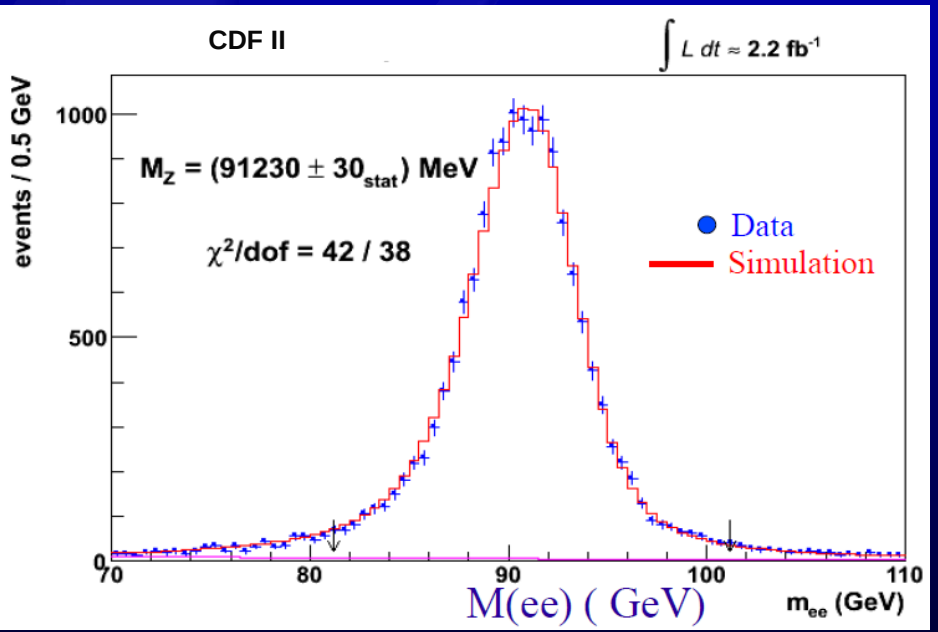




Momentum Scale →Energy Scale

- Use *E/p* peak from *W→ev* events to calibrate EM calorimeter
- Verify on the *Z → ee* mass peak
- Combine *E/p* with *Z* mass for final calibration



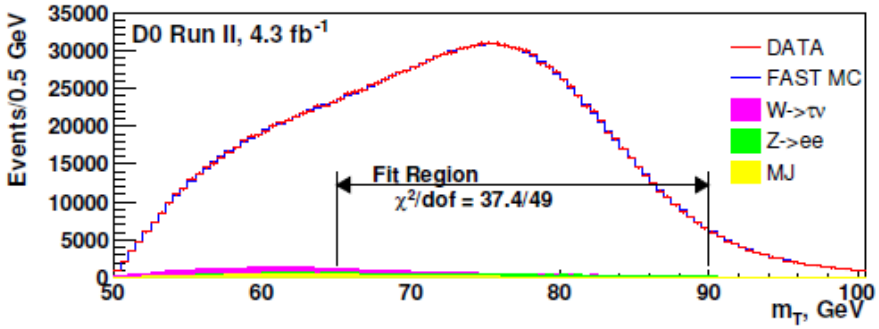


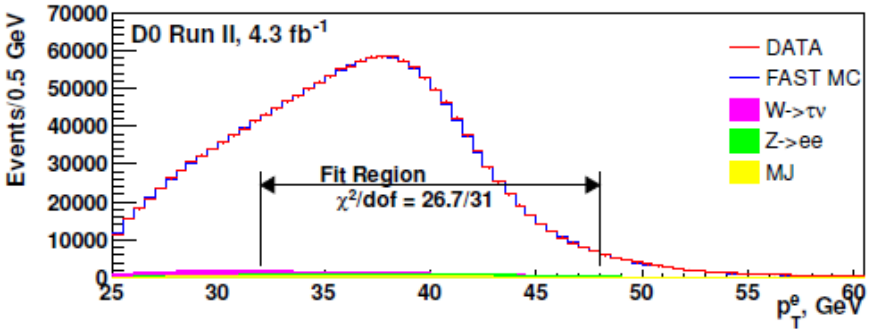
Systematic Uncertainty

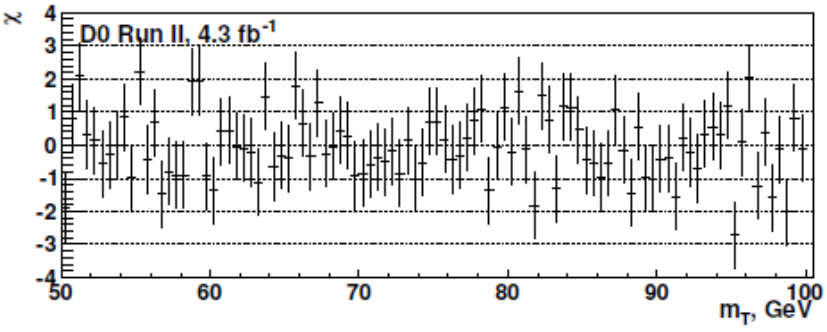
- **Systematic uncertainty breakdown in m_T measurement**

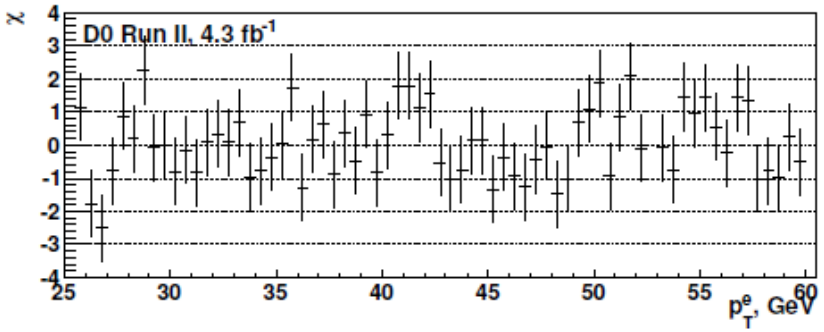
Source	CDF $m_T(\mu,\nu)$	CDF $m_T(e,\nu)$	DØ $m_T(e,\nu)$
Experimental – Statistical power of the calibration sample.			
Lepton Energy Scale	7	10	16
Lepton Energy Resolution	1	4	2
Lepton Energy Non-Linearity			4
Lepton Energy Loss			4
Recoil Energy Scale	5	5	
Recoil Energy Resolution	7	7	
Lepton Removal	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

D0 Results



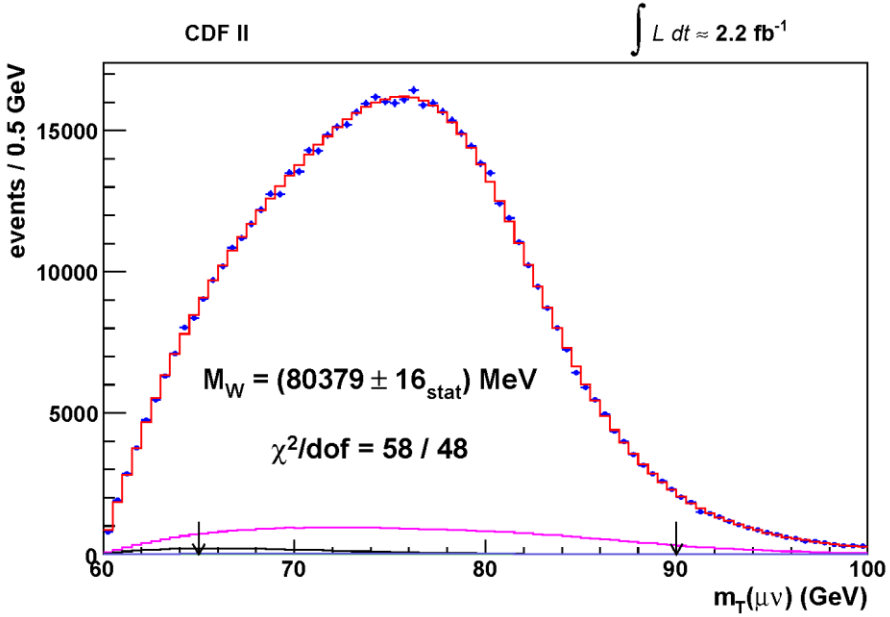


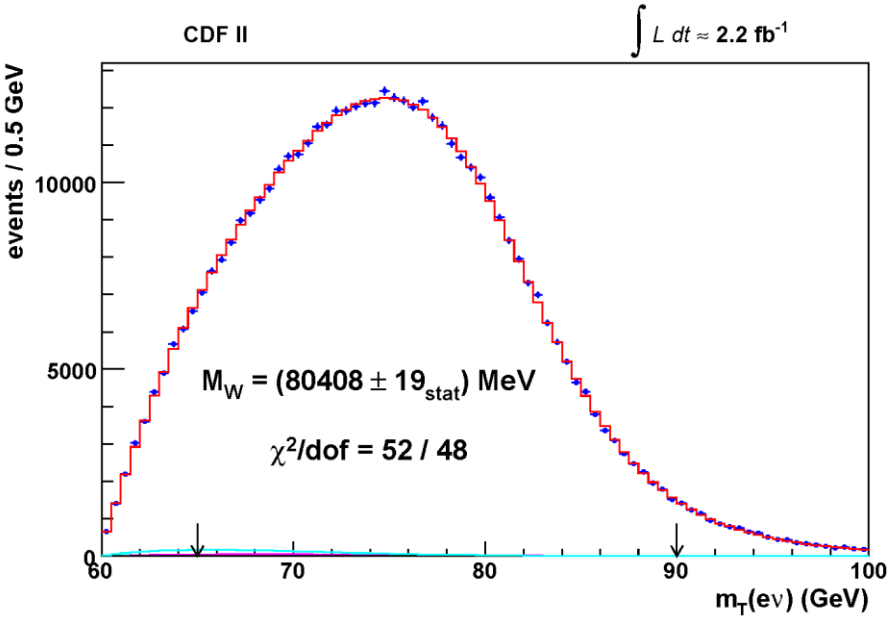




Method $(4.3\,fb^{-1})$	M_W (MeV)
$m_T(e,\nu)$	80371 ± 13(stat)
$p_T(e)$	80343 ± 14(stat)
$\not\!\!E_T(e,\nu)$	80355 ± 15(stat)
Combination $m_T \oplus p_T$ $(4.3\,fb^{-1})$	80367 ± 26(syst + stat)
Combination $(5.3\,fb^{-1})$	**80375 ± 23**(syst + stat)

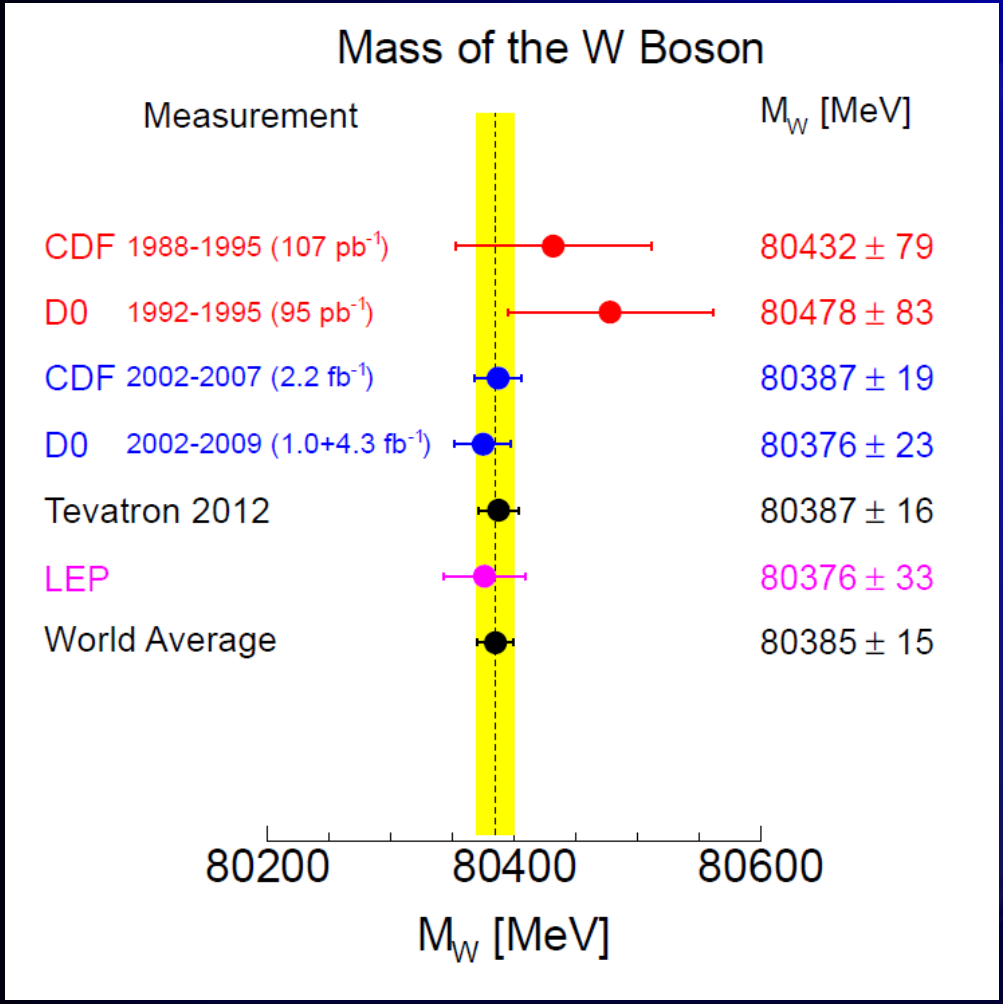
CDF Results





Method $(2.2\,fb^{-1})$	M_W (MeV)	Method $(2.2\,fb^{-1})$	M_W (MeV)
$m_T(\mu,\nu)$	$80379 \pm 16(\text{stat})$	$m_T(e,\nu)$	$80408 \pm 19(\text{stat})$
$p_T(\mu)$	$80348 \pm 18(\text{stat})$	$p_T(e)$	$80393 \pm 21(\text{stat})$
$\not\!\!E_T(\mu,\nu)$	$80406 \pm 22(\text{stat})$	$\not\!\!E_T(e,\nu)$	$80431 \pm 25(\text{stat})$
Combination $(2.2\,fb^{-1})$		$\mathbf{80387 \pm 19}\,MeV\,(\text{syst} + \text{stat})$	

New World Average



- **Both CDF and D0 results reach precision of previous world average**
- **CDF result is most precise W mass measurement**
- **Theory uncertainties are now the limitation**

CDF: PRL **108**, 151803 (2012)

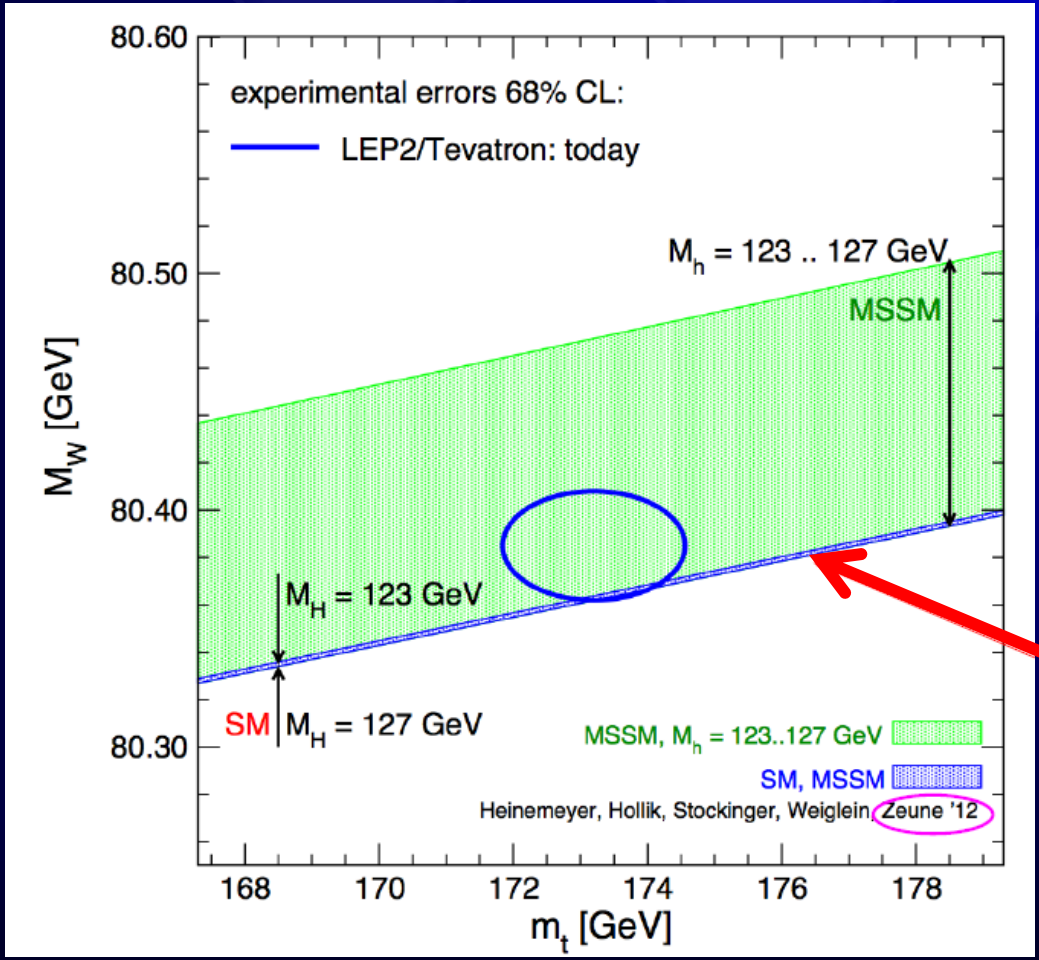
DØ: PRL **108**, 151804 (2012)

Tevatron Combination Note

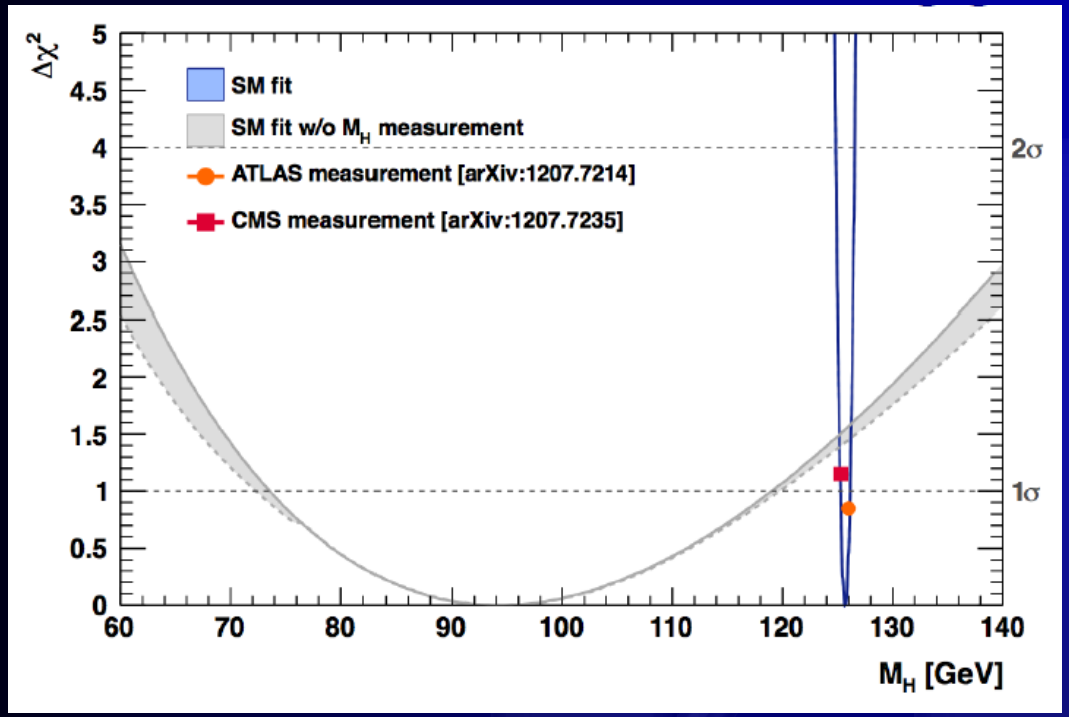
– publication arXiv number in this space soon!

New Higgs Constraint

- New indirect Higgs measurement is consistent with SM interpretation of Higgs boson discovered at the LHC



New W Constraint



Gfitter: arXiv: 1209.2716 [hep-ph]

- **Indirect constraint:**
  $M_H = 94^{+25}_{-22}$ GeV
- **Direct measurement:**
  $M_H = 125 \pm 2$ GeV
- **Consistent at 1.3σ**

- **Turn the electroweak fit around to use Higgs and top to constrain *W***
- **Indirect constraint:** $M_W = 80.359 \pm 0.011$ GeV
- **Direct measurement:** $M_W = 80.385 \pm 0.015$ GeV
- **EW fit now has higher precision than direct measurement**

What Next? - Tevatron

- **More data!**
  - Understand high inst. luminosity data (CDF)
- **Reduce PDF uncertainty**
  - *W* charge asymmetry measurement
  - Increased η coverage (D0)

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Experimental – Statistical power of the calibration sample.			
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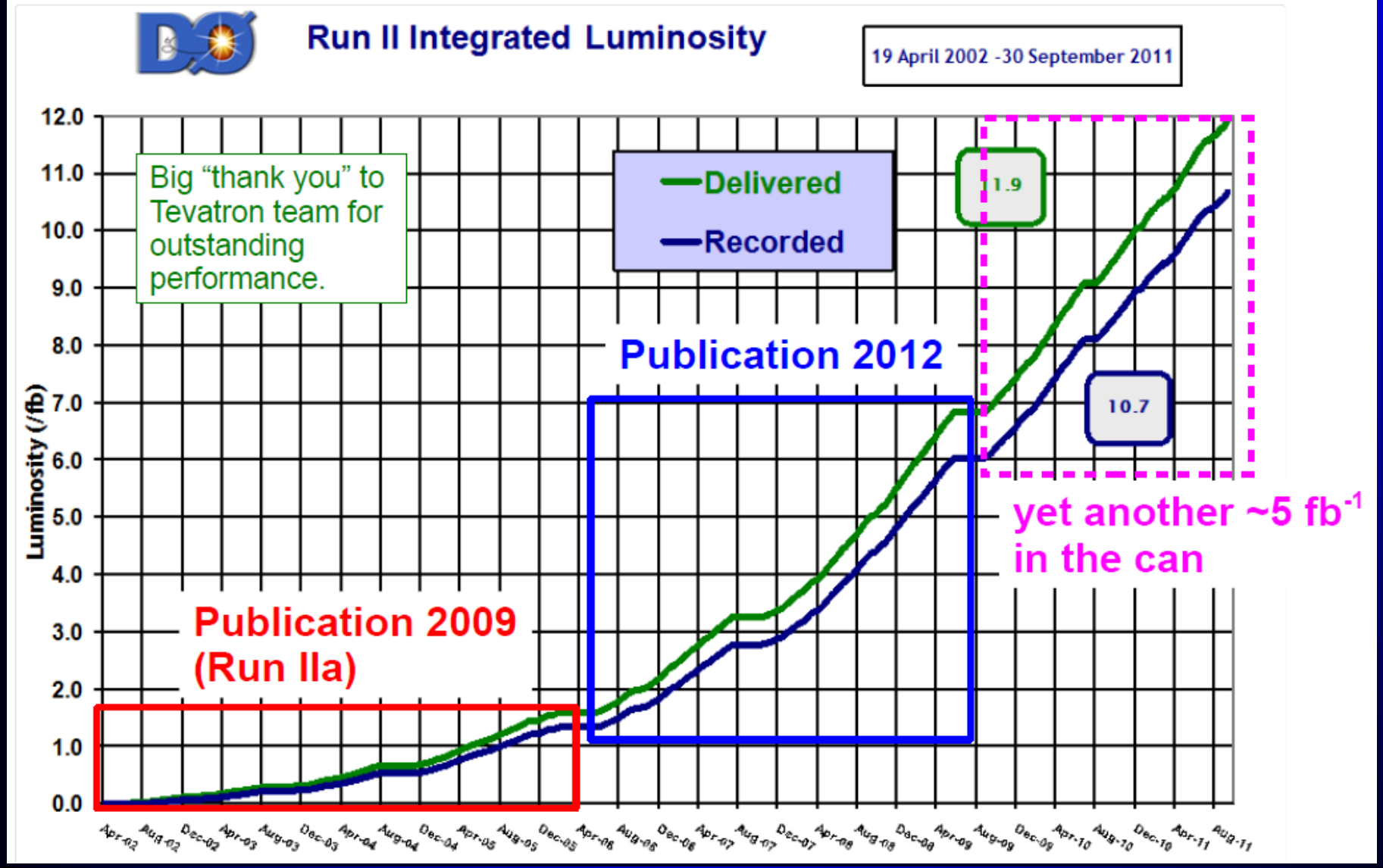
QED	4	4	7
Boson p_T	3	3	2
W statistics	12		13

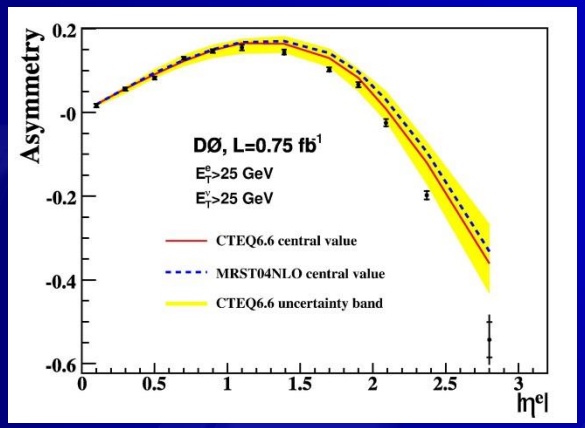
- **Improve QED understanding**
- **Improve DC alignment, calibration (CDF)**
- **Improve electron E loss and shower model (D0)**

More Tevatron Data



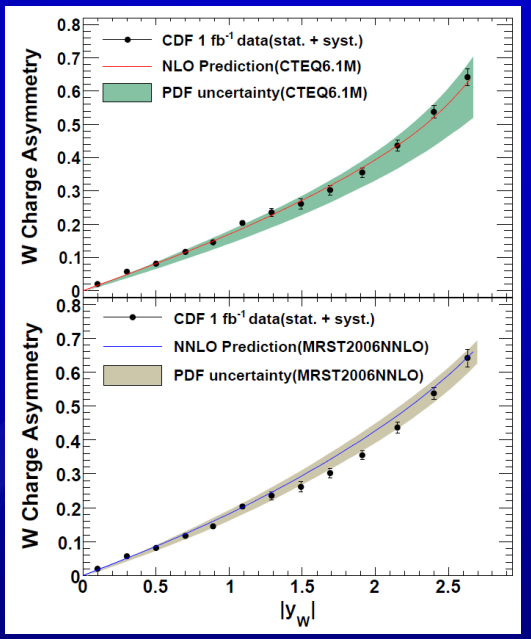
Reducing PDF Uncertainties

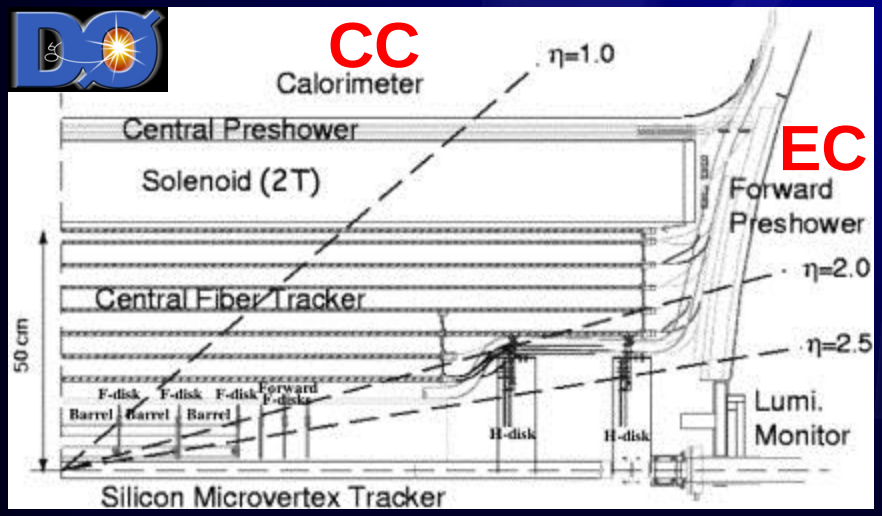
- **W Charge Asymmetry**
  - Constrain u/d with Tevatron rather than low energy experiment data
  - New full data set results coming soon!



CDF: PRL **102,** 181801 (2009)

DØ: PRL **101**, 211801 (2008)





- **Extend η coverage to forward EC calorimeters**
  - Transverse observables are insensitive to longitudinal PDF uncertainties
  - Related acceptance uncertainties introduced through η cuts

Projected D0 Uncertainty

Source	Public. 2009 (1.0 fb^{-1})	Public. 2012 (4.3 fb^{-1})	Proj. 10 fb^{-1}	Proj. 10 fb^{-1} improv.	Proj. 10 fb^{-1} improv. + EC
Statistical	23	13	9	9	8
Experimental syst.					
Electron energy scale	34	16	11	11	10
Electron energy resolution	2	2	2	2	2
EM shower model	4	4	4	2	2
Electron energy loss	4	4	4	2	2
Hadronic recoil	6	5	3	3	2
Electron ID efficiency	5	1	1	1	1
Backgrounds	2	2	2	2	2
Subtotal experimental syst.	35	18	13	12	11
***W* production and decay model**					
PDF	9	11	11	11	5
QED	7	7	7	3	3
boson p_T	2	2	2	2	2
Subtotal W model	12	13	13	12	6
Total systematic uncert.	37	22	19	17	13
Total	**44**	**26**	**21**	**19**	**15**

combination: 23

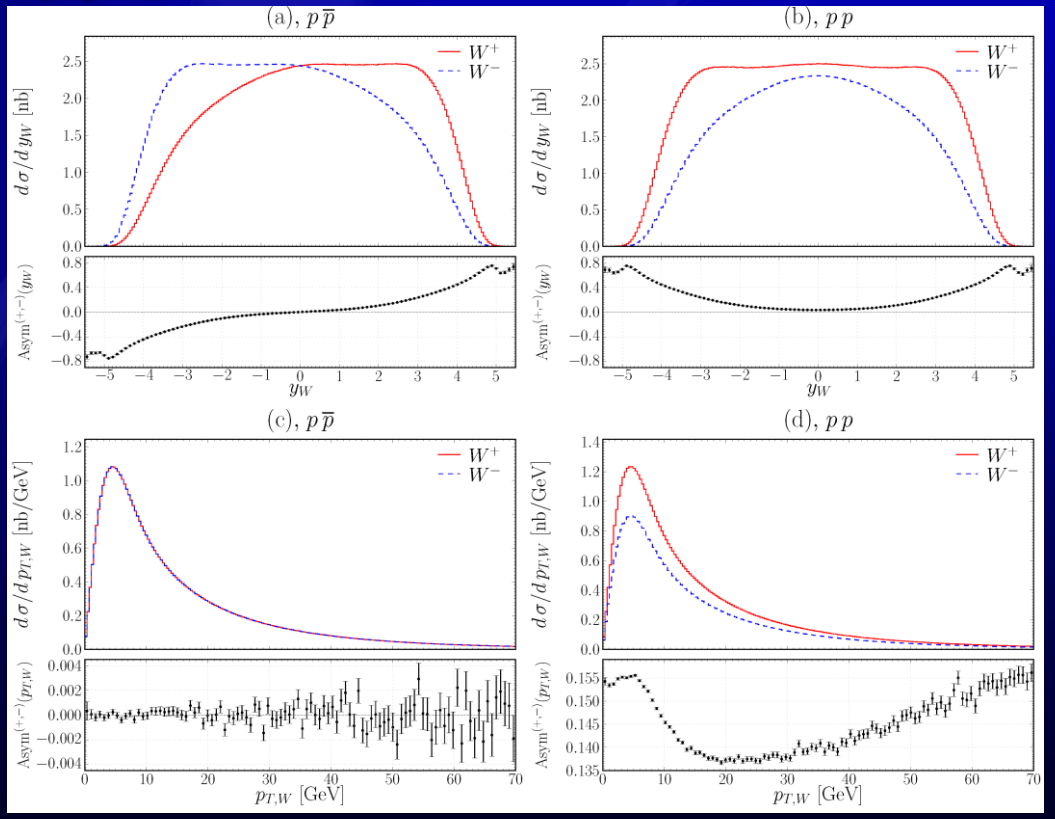
Projected CDF Uncertainty

Source	0.2/fb (MeV)	2.2/fb (MeV)	10/fb (MeV)
Lepton energy scale	23	7	3
Lepton energy resolution	4	2	1
Recoil energy scale	8	4	2
Lepton removal	6	2	1
Backgrounds	6	3	2
pT(W) model	4	5	2
PDFs	11	10	5
QED radiation	10	4	4
Total systematics	**34**	**15**	8
W statistics	34	12	6
Total	**48**	**19**	10

- **Combining CDF/D0, can achieve <10 MeV Tevatron precision!**
  - Addition of D0 EC eliminates full correlation of PDF uncertainty

What Next? - LHC

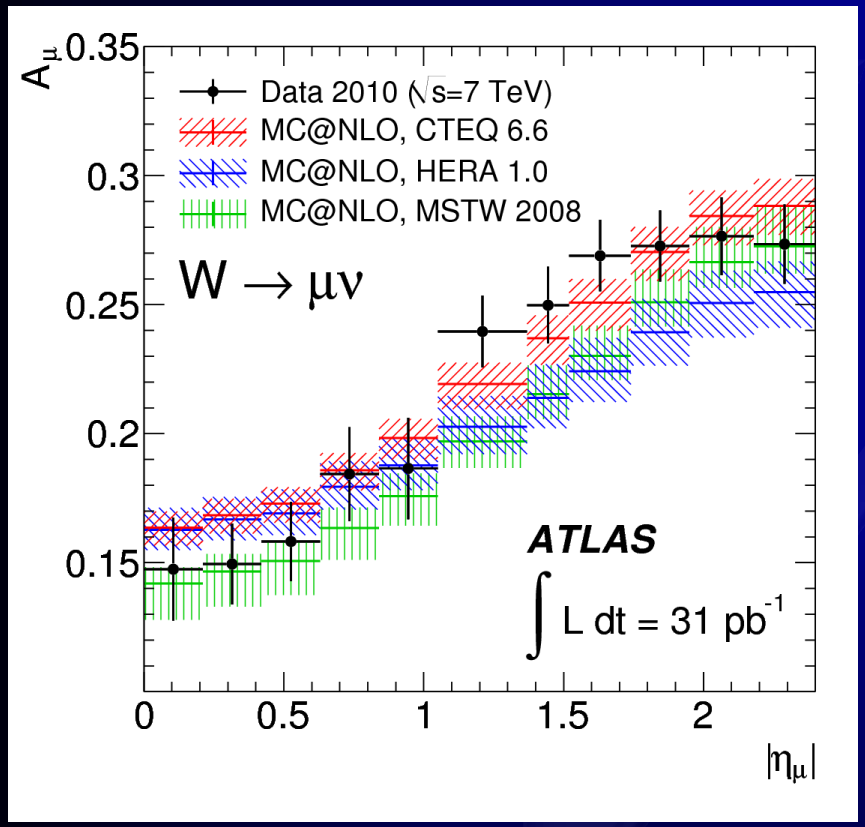
- **Advantage**: 'unlimited' W data - ~1 MeV statistical precision
- **Disadvantage**: $p\bar{p}$ collisions allow 'charge-blind' analysis that permits calibration of W's with Z's that is insensitive to differences in W^+, W^- and Z p_T spectra. This is not the case with pp collisions.
  - **PDFs for all 3 quark families must be known much better than at Tevatron**



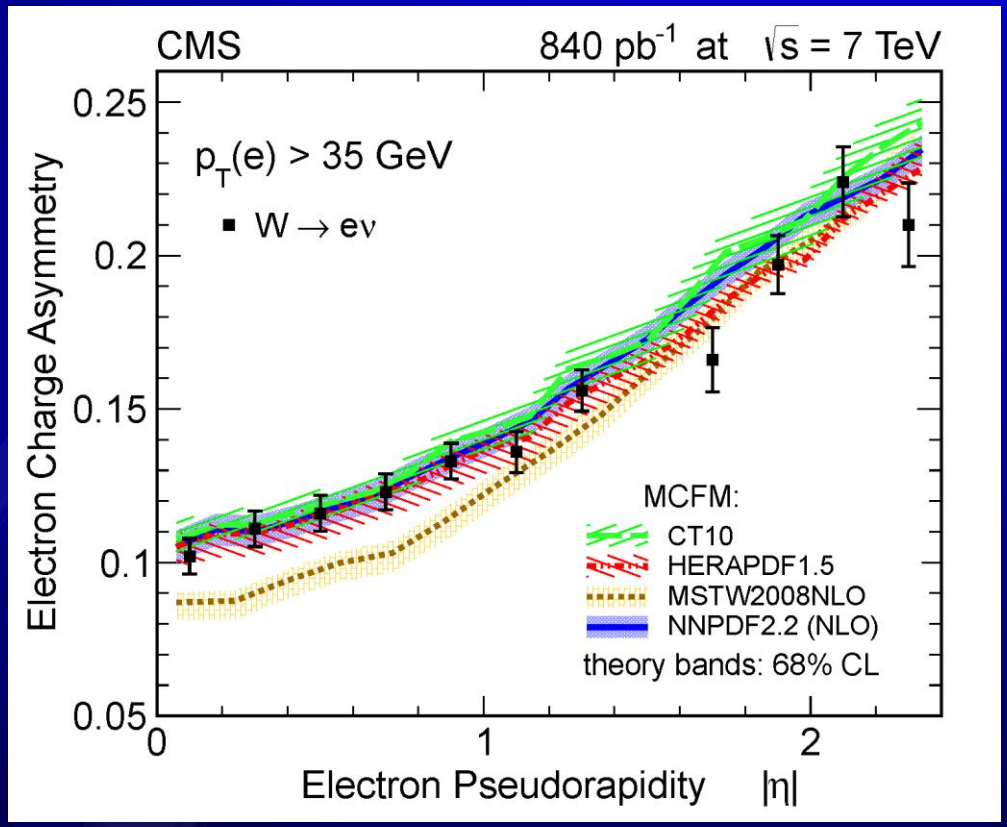
Krasny, et.al.: Eur.Phys.J. **C69**, 379 (2010)

Model-constraining Measurements

- **W Charge Asymmetry: Constrain *u*, *d* valence quark PDFs**



ATLAS: PLB **701,** 31 (2011)

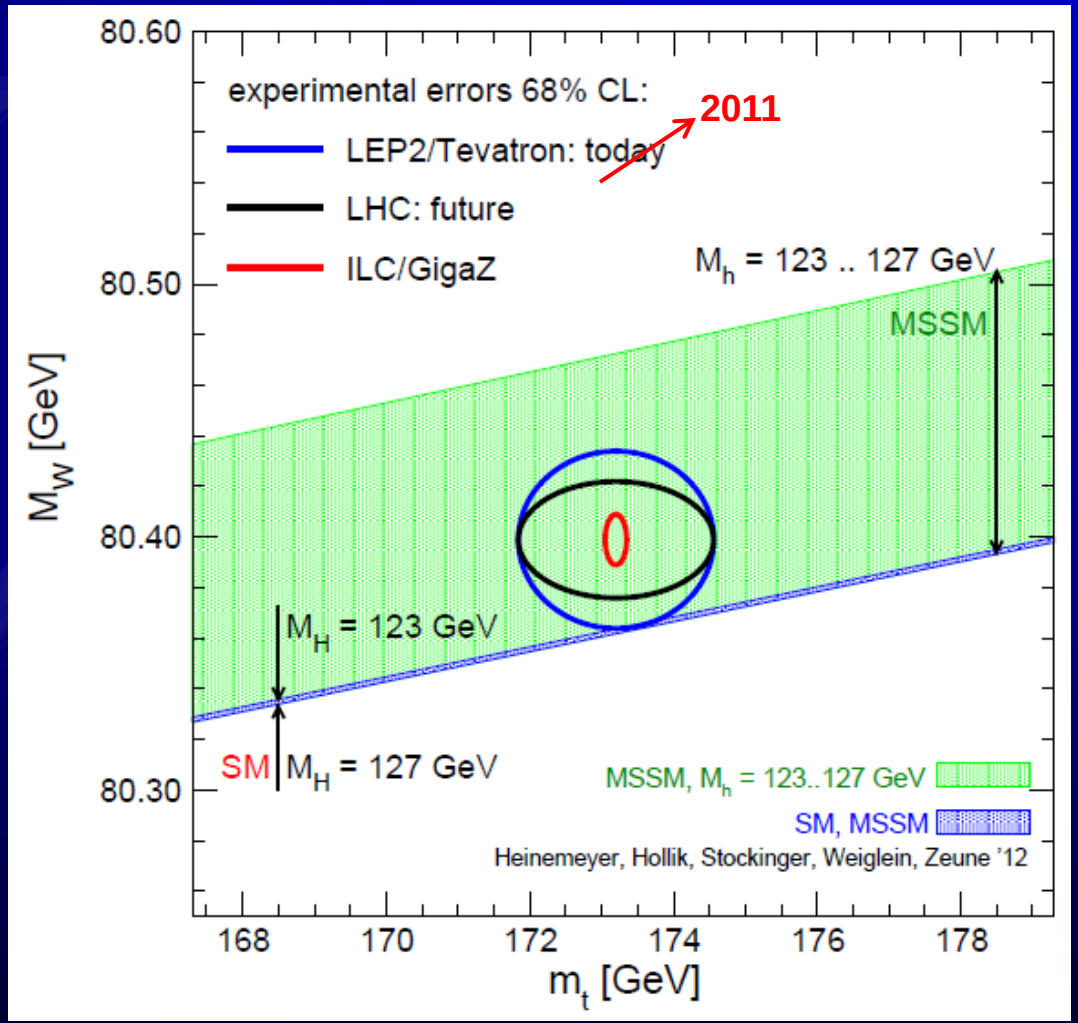


CMS: PRL **109**, 111806 (2012)

- ***W*+*c* Production: Constrain *s* quark PDF (see backup slides)**
- ***Z* p_T and *W* p_T: Constrain *W* recoil model (see backup slides)**

The Big Picture

- **LEP2/Tevatron**
  - Pre-2012 23 MeV precision
- **LHC**
  - 15 MeV *projection*
  - Equivalent to *current* world average precision with 2012 Tevatron results
- **ILC/GigaZ**
  - 7 MeV *projection*
  - ~ LHC *goal* for ΔM_W



The Big Picture

- **LEP2/Tevatron**
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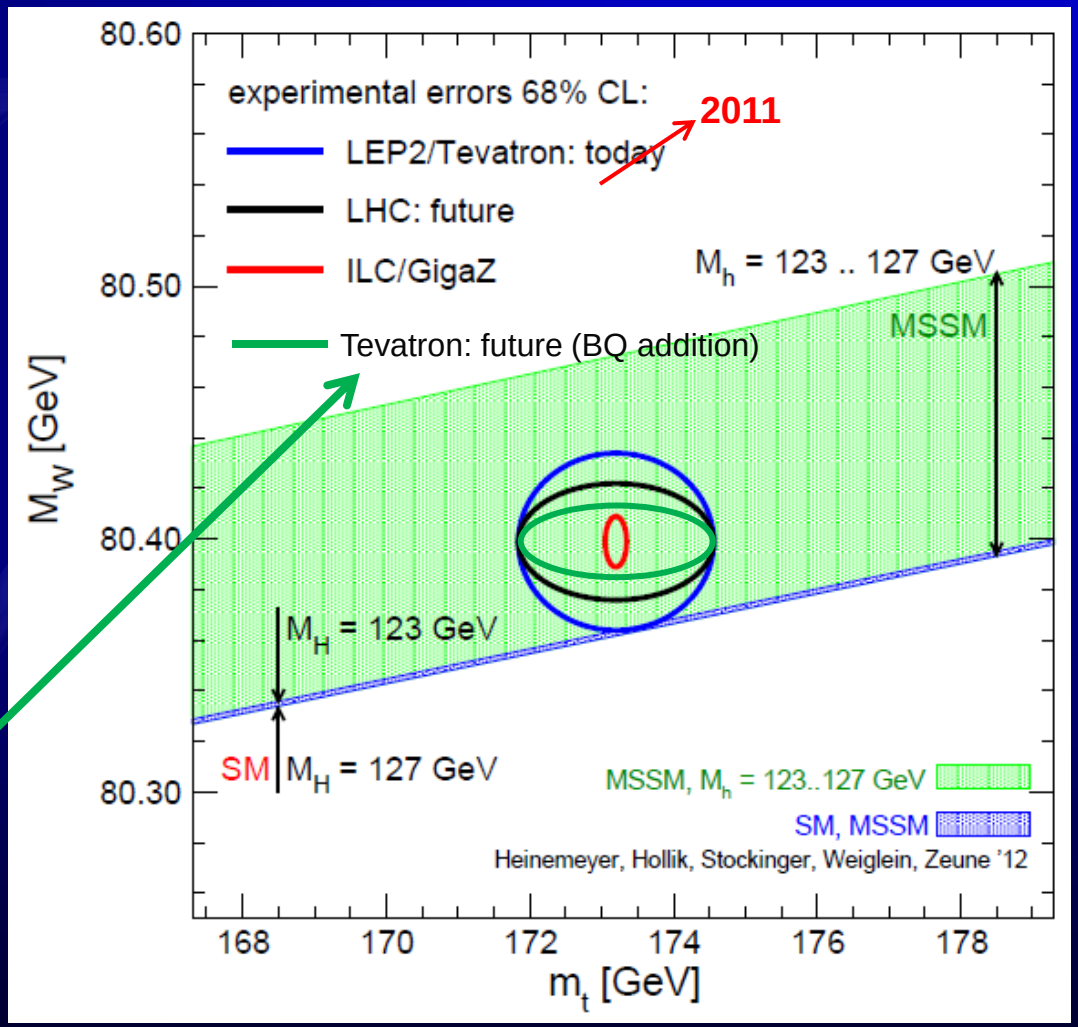
  - 7 MeV *projection*
  - ~ LHC *goal* for ΔM_W
- **Tevatron 10 fb^{-1}**
  - 10 MeV *goal*



Summary

- **The importance of W mass measurements for precision tests of the SM will only increase going forward.**
- **Both CDF and D0 have exceeded previous world average precision**
  - CDF has single most precise M_W measurement
  - $\boldsymbol{M_W(measured) = 80.385 \pm 0.015\ \text{GeV}}$
  - $\boldsymbol{M_W(EW\ fit) = 80.359 \pm 0.011\ \text{GeV}}$
  - Theory and model uncertainties must be improved!
- **The Tevatron (sooner) and the LHC (later) can exceed the precision of theory M_W prediction, enabling powerful tests of SM consistency and/or new physics!**

Thanks!

- **To the Tevatron and LHC accelerator folks!**
- **To the ATLAS, CDF, CMS, and D0 collaborations**
  - In particular to the W Mass / Electroweak analysis groups
  - Especially to
    - Jeffrey Berryhill, Maarten Boonekamp, Sasha Glazov, Joao Guimaraes da Costa, Bo Jayatilaka, Ashutosh Kotwal, Rafael Lopes de Sa, and Jan Stark

  for their very helpful contributions to the content of this talk!

Backup Slides

Event Selections

CDF analysis

- Analyzed $2.2\,fb^{-1}$.
- Uses $W \to e\nu$ and $W \to \mu\nu$ decay channels.
- Central leptons $|\eta| < 1$ with $30 < p_T < 55\,GeV$
- Missing transverse energy $30 < \not\!\!E_T < 55\,GeV$
- Transverse mass $60 < m_T < 100\,GeV$
- Hadronic recoil momentum $u_T < 15\,GeV$

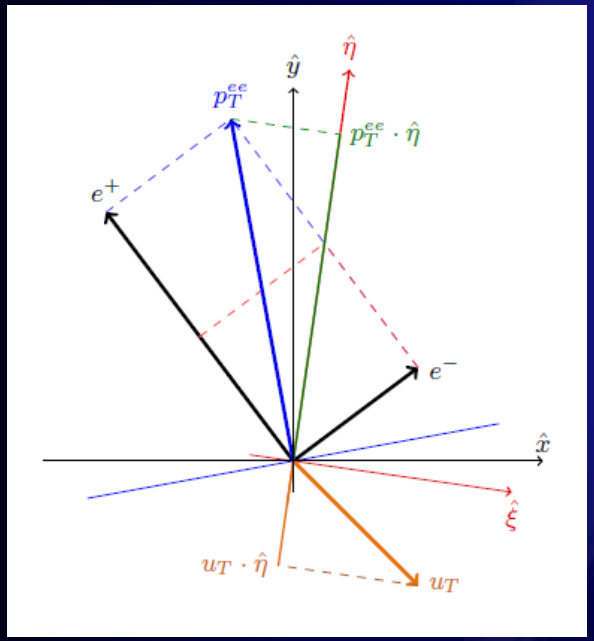
DØ analysis

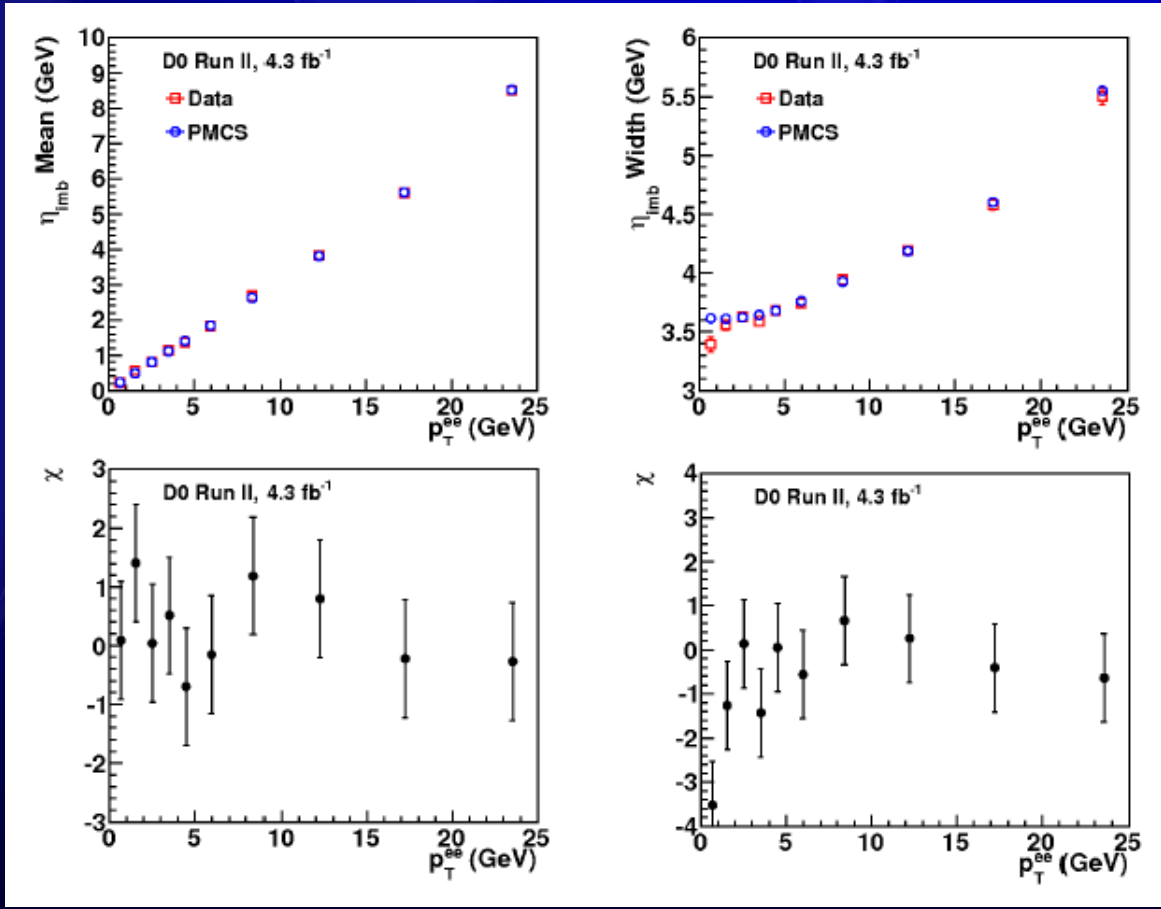
- Analyzed $4.3\,fb^{-1}$ ($1\,fb^{-1}$ analyzed before)
- Uses $W \to e\nu$ decay channel.
- Central electrons $|\eta| < 1.05$ with $p_T > 25\,GeV$
- Missing transverse energy $\not\!\!E_T > 25\,GeV$
- Transverse mass $50 < m_T < 200\,GeV$
- Hadronic recoil momentum $u_T < 15\,GeV$

	$W \to e\nu$ candidates	$W \to \mu\nu$ candidates	Total
CDF $2.2\,fb^{-1}$	$470,126$	$624,708$	$1,094,834$
DØ $4.3\,fb^{-1}$	$1,677,394$	–	$1,677,394$
$(+1\,fb^{-1})$			$2,177,224$

Hadronic Recoil Response Model

- Tuned on the momentum imbalance in $Z \rightarrow ee$ data

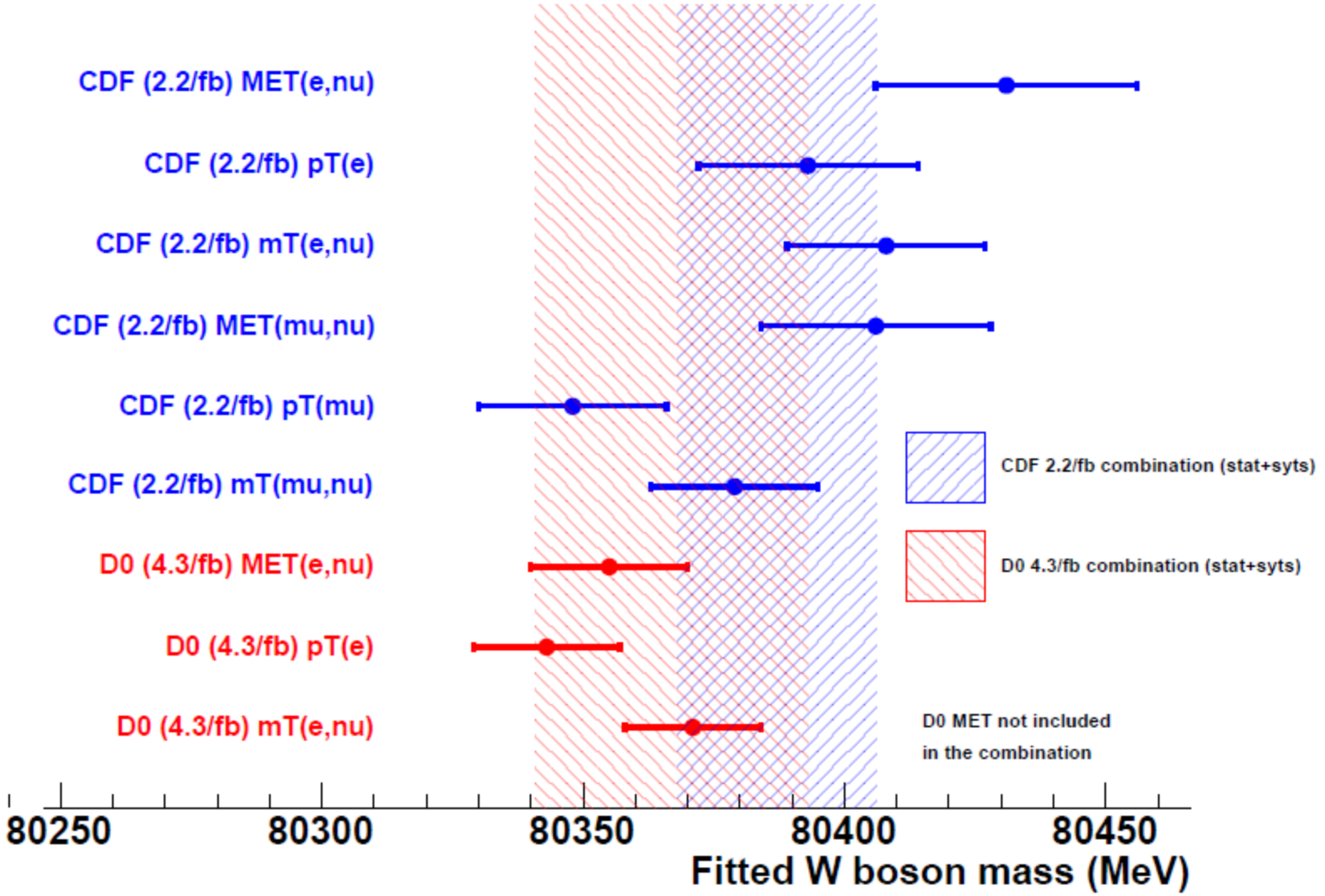




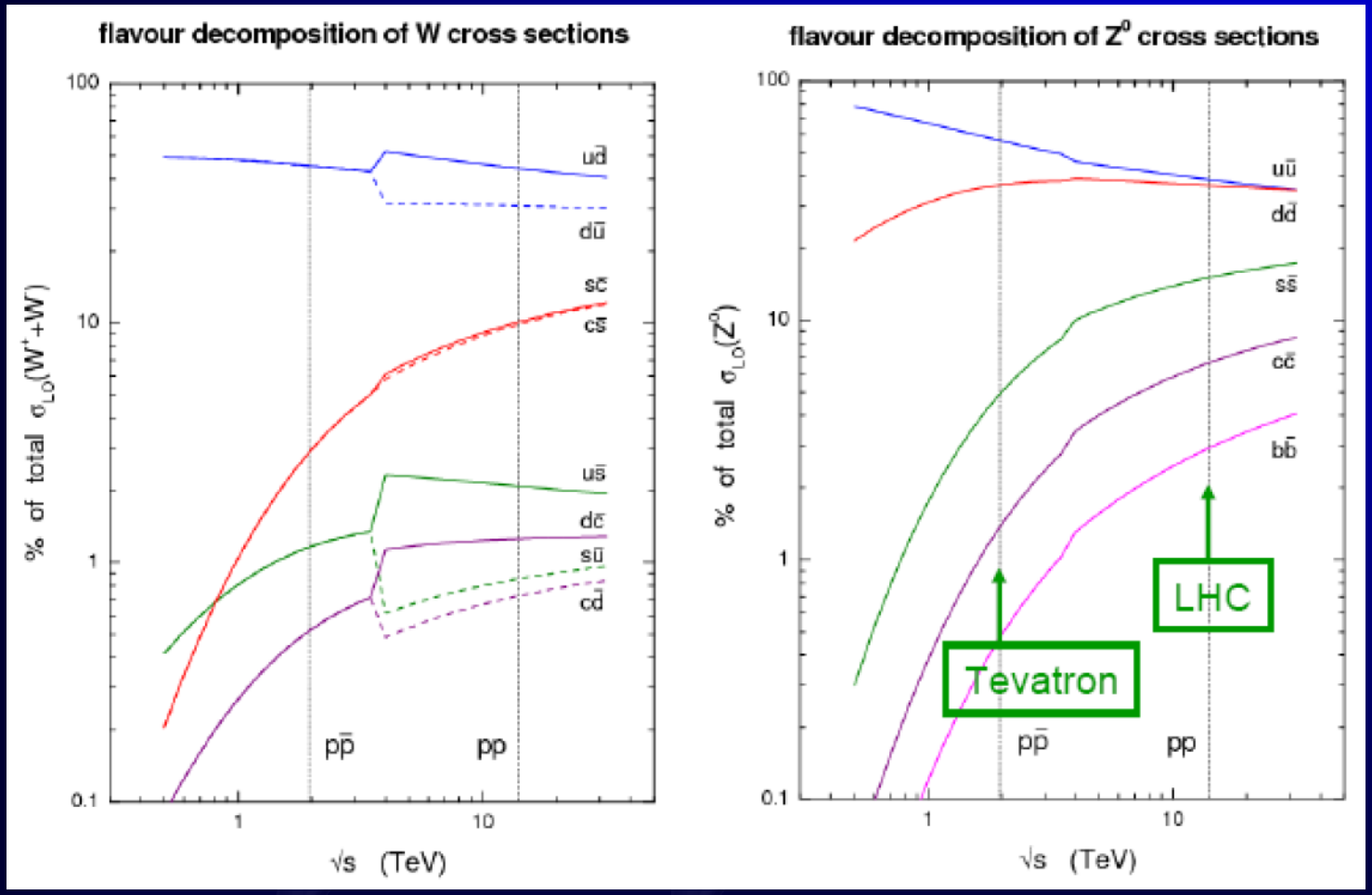
DØ Uncertainty Breakdown

Source	m_T MeV	p_T^e MeV	$\not\!\!E_T$ MeV
Experimental – Z statistics driven!			
Electron Energy Scale	16	17	16
Electron Energy Resolution	2	2	3
Electron Energy Nonlinearity	4	6	7
W and Z Electron energy loss differences	4	4	4
Recoil Model	5	6	14
Electron Efficiencies	1	3	5
Backgrounds	2	2	2
Experimental Total	18	20	24
W production and decay model – Not dependent on Z statistics!			
PDF	11	11	14
QED	7	7	9
Boson p_T	2	5	2
W model Total	13	14	17
Total Systematic Uncertainty	22	24	29
W Statistics	13	14	15
Total Uncertainty	26	28	33

Tevatron M_W Comparison



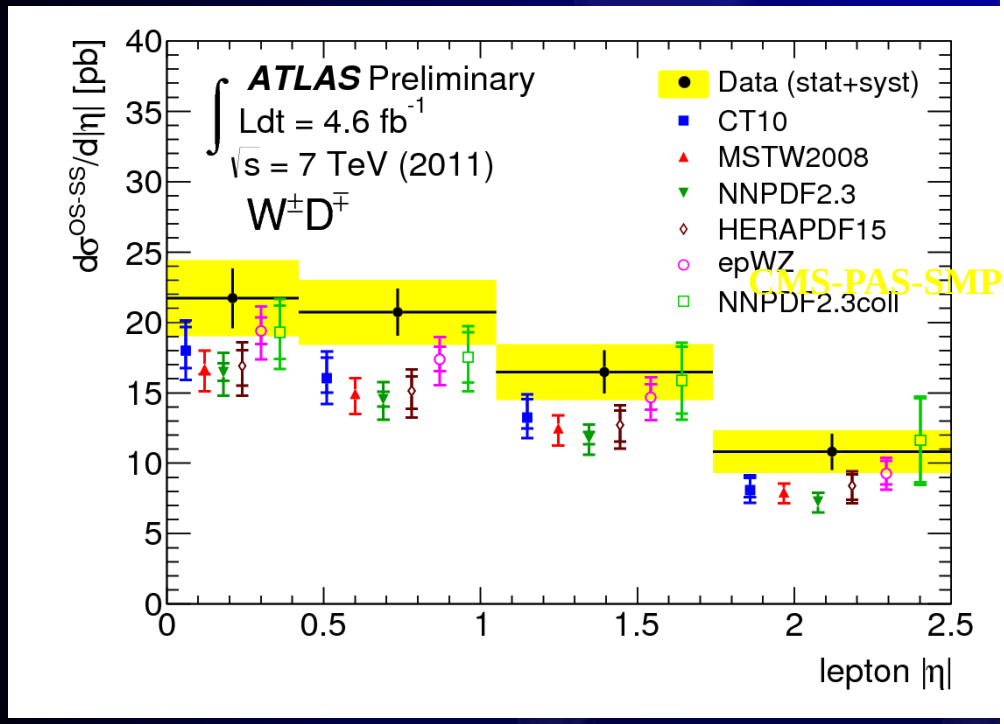
W/Z Cross Section Flavor Content

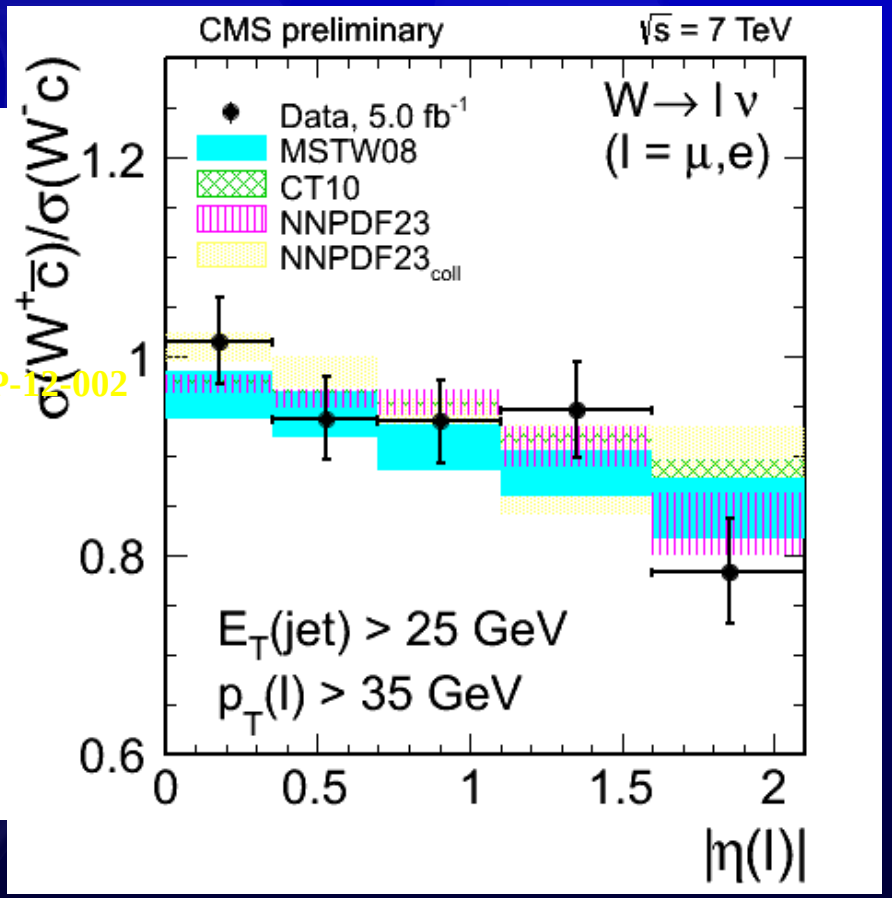


Krasny, et.al.: Eur.Phys.J. **C69**, 379 (2010)

W+c Production

- Constrain *s* quark PDF ($c\bar{s} \rightarrow W$ significant at LHC)





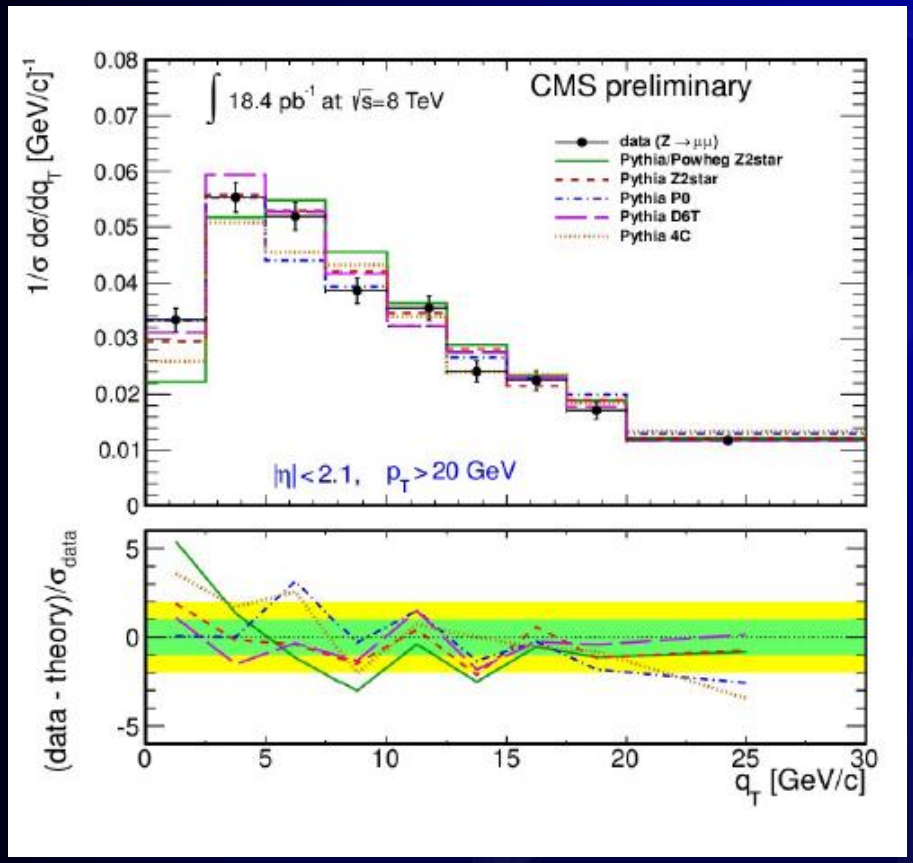
CMS-PAS-SMP-12-002

ATLAS: ATLAS-CONF-2013-045

CMS: CMS-PAS-SMP-12-002

$Z\ p_T\ /\ \phi^*$

- Constrain *W* recoil model



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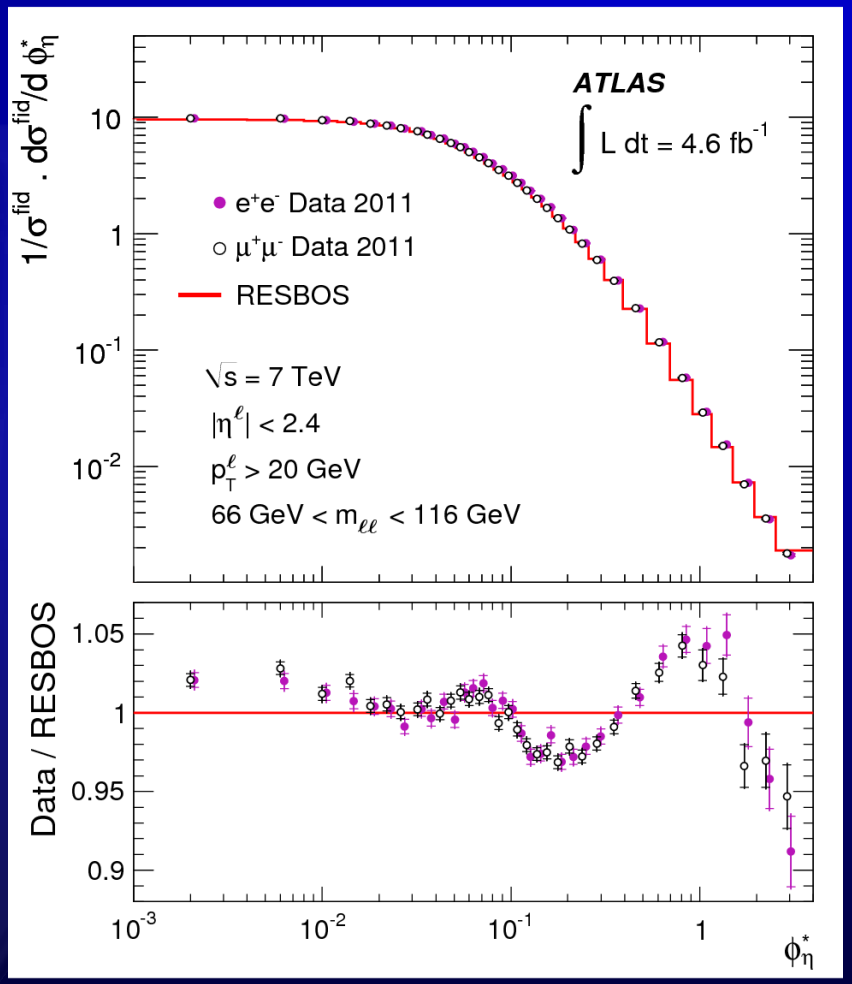

ATLAS: PLB **720,** 32 (2013)