CDF W mass result experimental mini-review

J. Huston

Michigan State University

Josh Isaacson will follow with a mini-review of the theory important for the measurement (not the possible theory explanations of the result, which would take a full day)

Many of the figures are borrowed from Ashutosh Kotwal’s seminar at Fermilab.

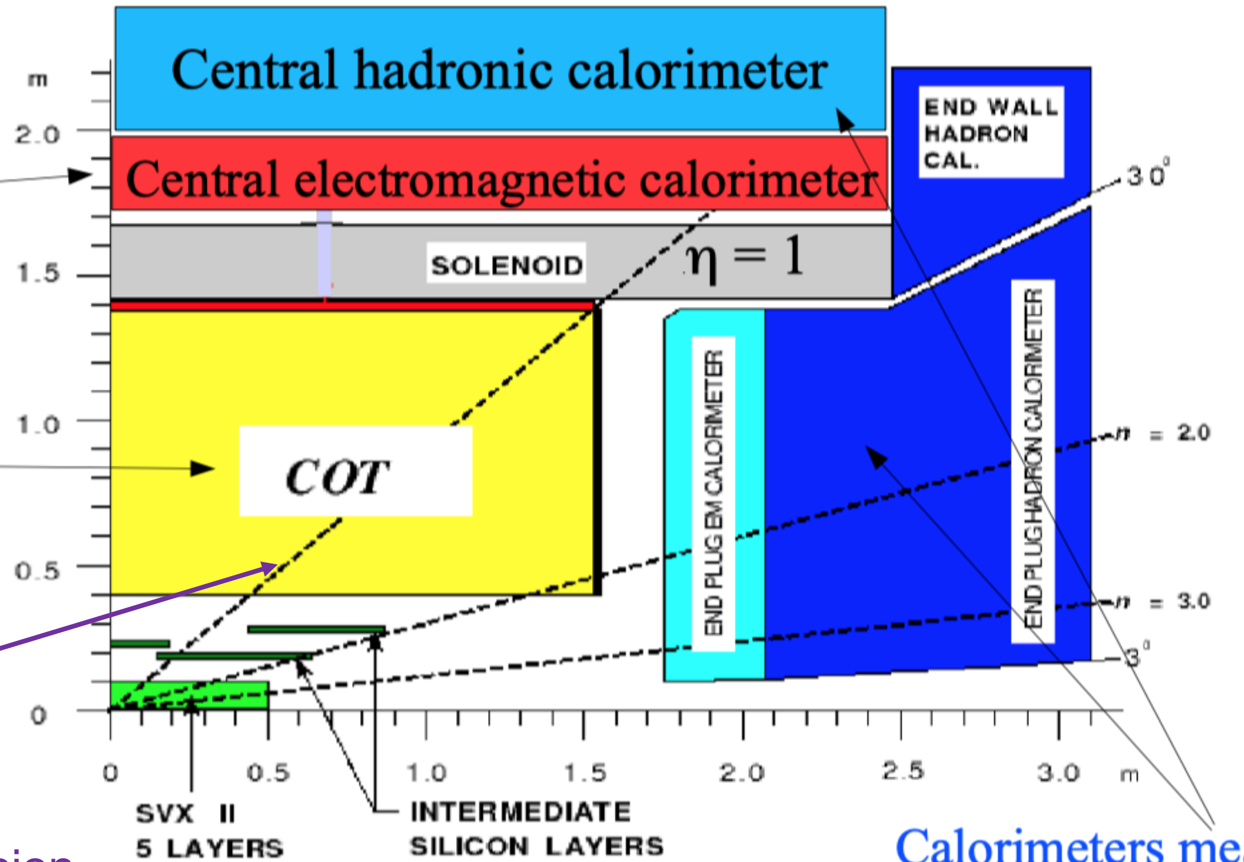
The ~~face~~ W mass that launched a thousand ~~ships~~ archive papers

No motivation needed for the importance of W mass measurements

The experiment (my home for almost 2 decades)

EM calorimeter provides precise electron energy measurement

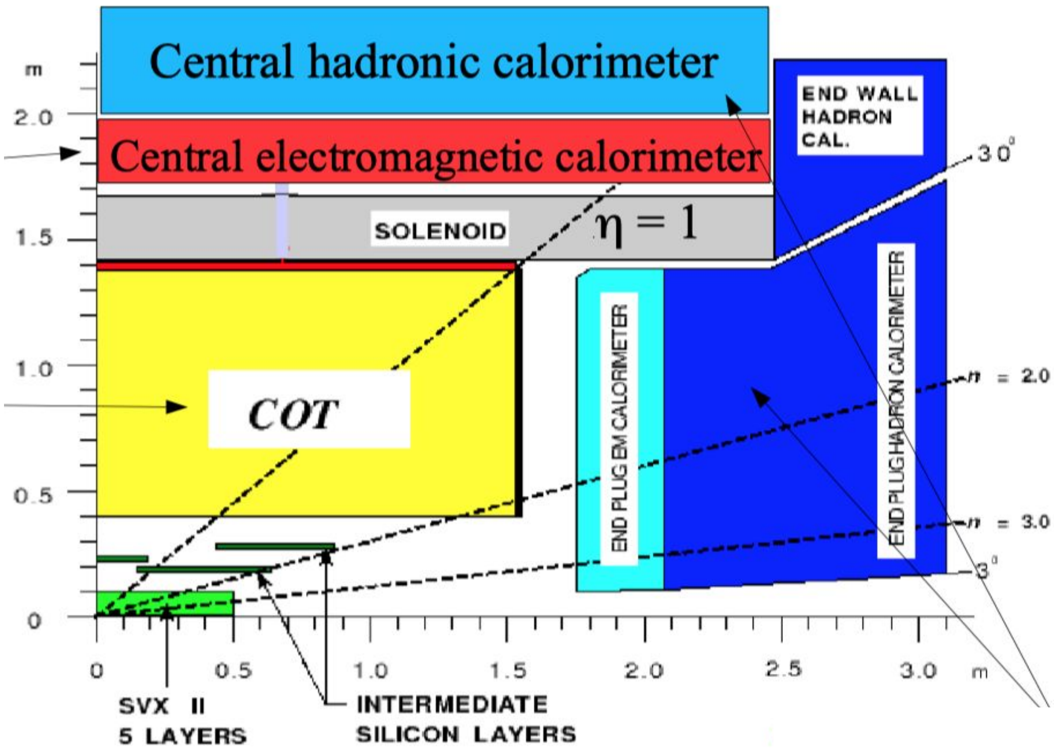
COT provides precise lepton track momentum measurement

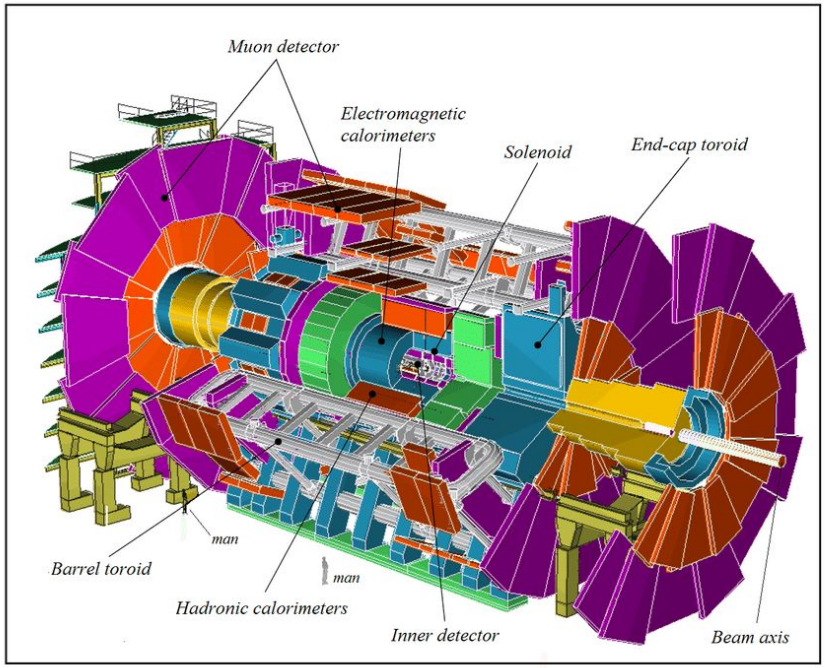


restrict lepton measurements to |η|<1, where measurement precision is greatest

Calorimeters measure hadronic recoil particles

Tevatron vs LHC experiments





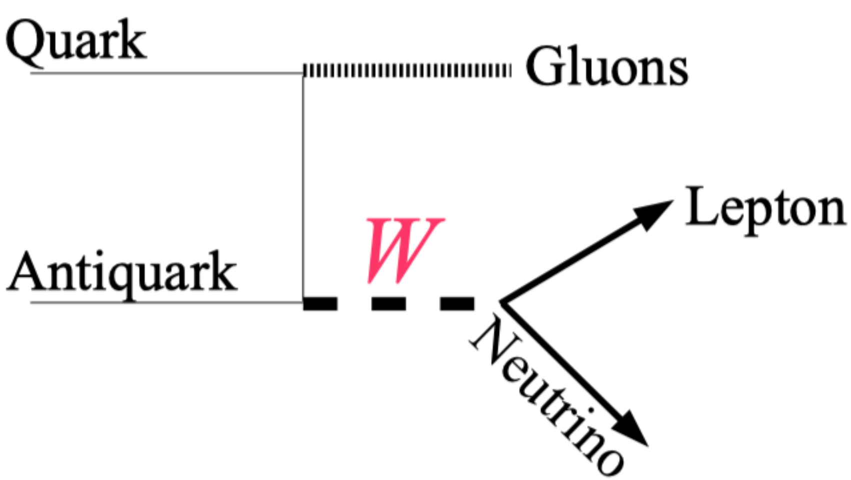
CDF has a smaller detector, smaller magnetic field, smaller precision tracking region, smaller collaboration than ATLAS.

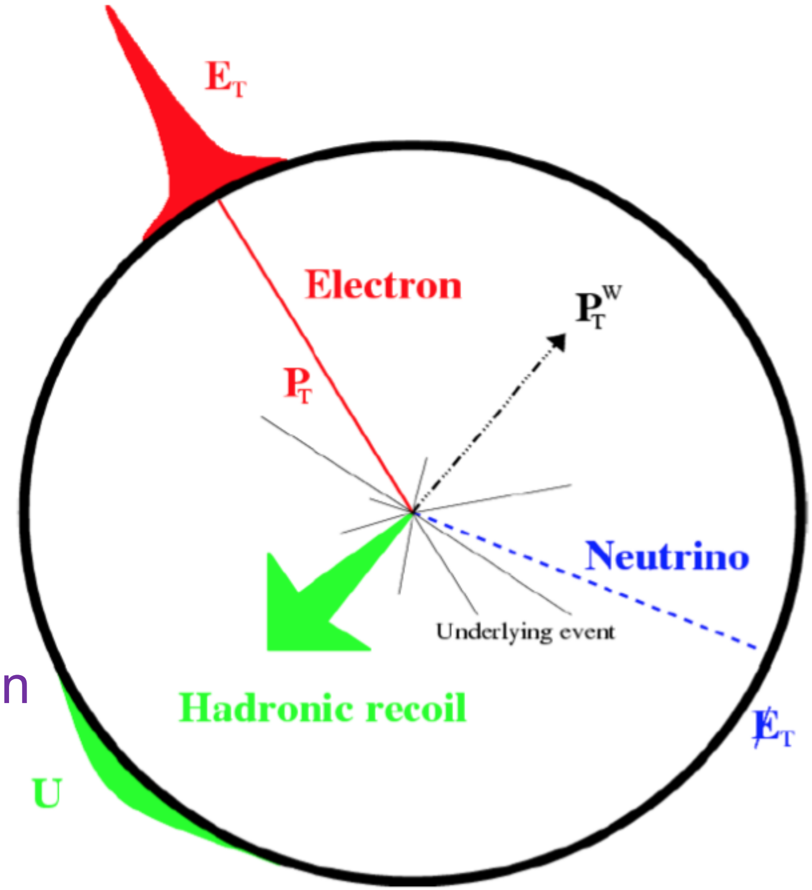
only 5% of overall W production involves 2nd generation quarks

But it also has smaller PDF uncertainties, smaller pileup and smaller “QCD” effects, as well as decades of experience. In addition, in comparison to the LHC experiments, it is a *noiseless* detector.

So expect very competitive measurements of m_W.

The measurement





Quark-antiquark annihilation dominates (80%) mostly in valence region

Lepton p_T carries most of *W* mass information, can be measured precisely (achieved 0.004%)

W mass can be determined through p_T of lepton, p_T of neutrino, and transverse mass, in both electron and muon channels, for both charge signs -> powerful cross-checks; more symmetry then at LHC because of pbar-p collider

Event selection for high purity W sample

- Electron
  - track: $30<p_T<55$ GeV
- Muon
  - track: $30<p_T<55$ GeV
- Missing transverse momentum
  - $30<p_T<55$ GeV
- Recoil u
  - $|\vec{u}|<15$ GeV
  - *similar to a cut on W p_T*
- W selection (for mass)
  - one (and only one) lepton, $|\eta_l|<1$, missing transverse momentum, $|\vec{u}|<15$ GeV
  - $60<m_T<100$ GeV
- Z selection
  - two leptons, opposite sign
  - $66<m_{ll}<116$ GeV

- Data set of 8.8 fb^{-1}, collected from Feb 2002-Sept 2011

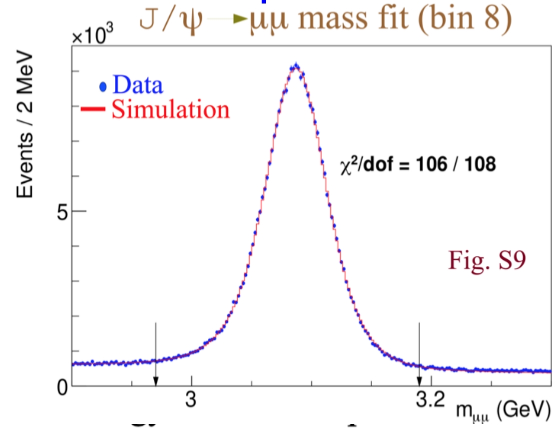
Sample	Candidates
$W \rightarrow$ electron	1 811 700
$Z \rightarrow$ electrons	66 180
$W \rightarrow$ muon	2 424 486
$Z \rightarrow$ muons	238 534

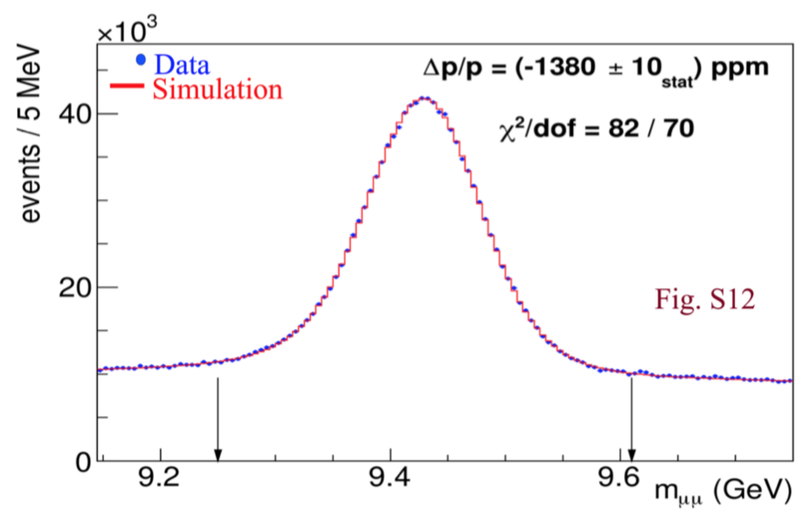
Very good background rejection; mis-identification backgrounds ~ 0.5%

Calibration

- Tracker
  - alignment of COT using cosmic rays
  - COT momentum scale constrained using $J/\psi \to \mu\mu$ and $\Upsilon \to \mu\mu$
    - confirmed using $Z \to \mu\mu$
- EM calorimeter
  - momentum scale transferred to EM calorimeter using E/p spectrum
    - confirmed using $Z \to ee$
- Hadronic recoil modeling
  - p_T-balance in $Z \to ll$ events

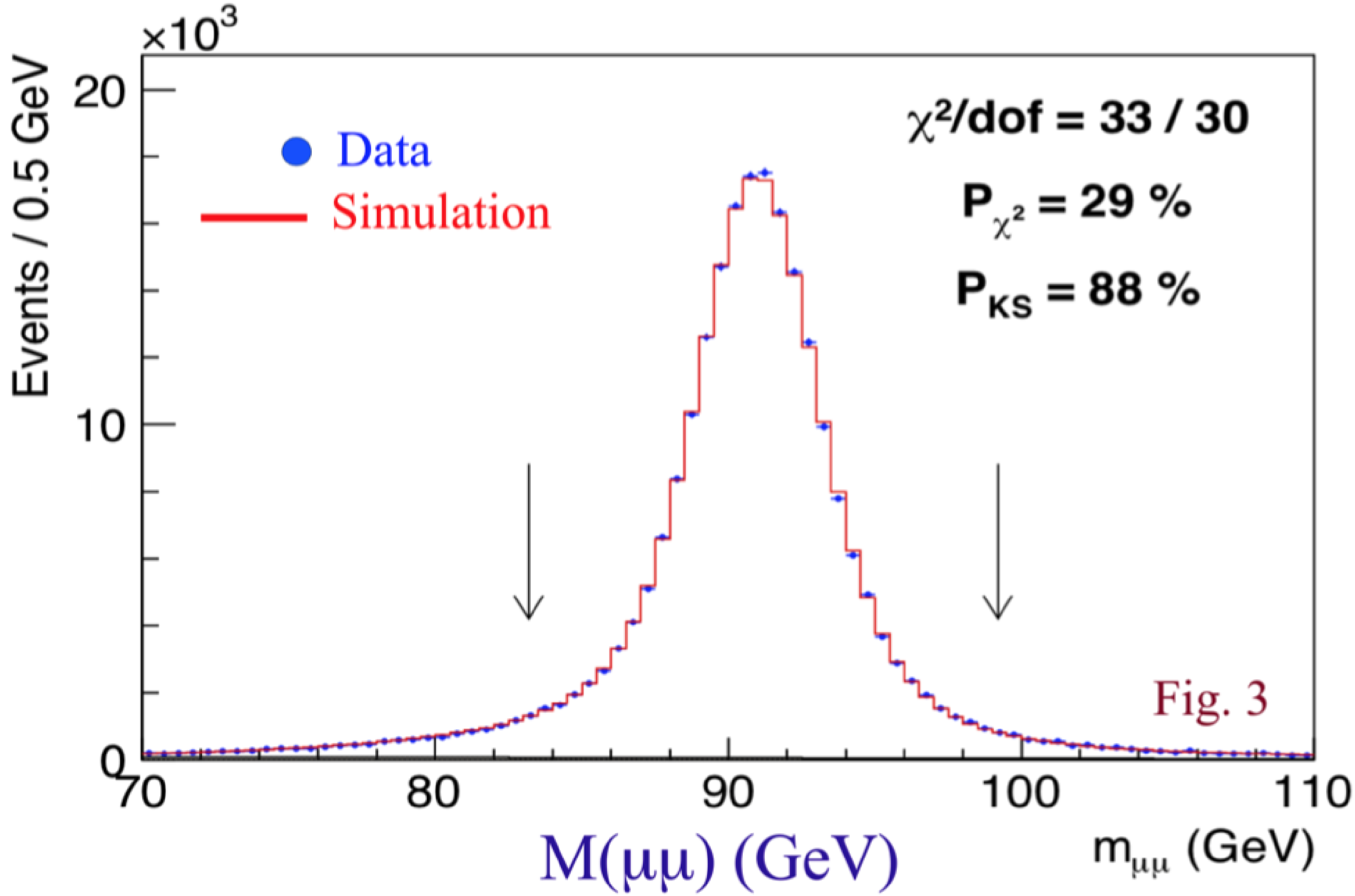
- Custom Monte Carlo detector simulation, with tracks and photons propagated through a high-resolution 3-D lookup table of material properties





(Blinded) Z->μμ mass check (momentum scale)

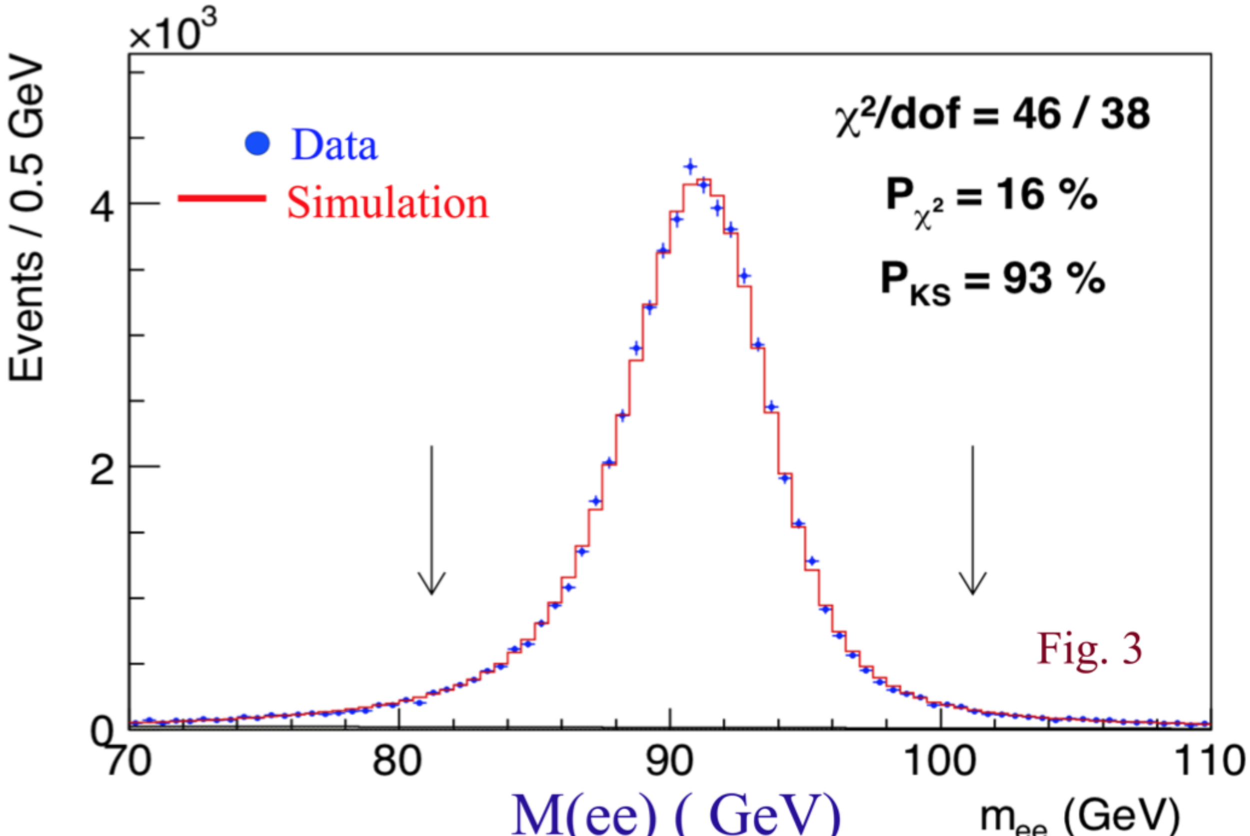
- Z mass consistent with PDG value (91188 MeV) (0.7σ statistical)
- $M_Z = 91192.0 \pm 6.4_{stat} \pm 2.3_{momentum} \pm 3.1_{QED} \pm 1_{alignment}$ MeV



(Blinded) Z->ee mass check (energy scale)

- Consistent with PDG value (91188 MeV) within 0.5σ (statistical)
- $M_Z = 91194.3 \pm 13.8_{stat} \pm 6.5_{calorimeter} \pm 2.3_{momentum} \pm 3.1_{QED} \pm 0.8_{alignment}$ MeV

- Combine E/p-based calibration with $Z \rightarrow ee$ mass for maximum precision

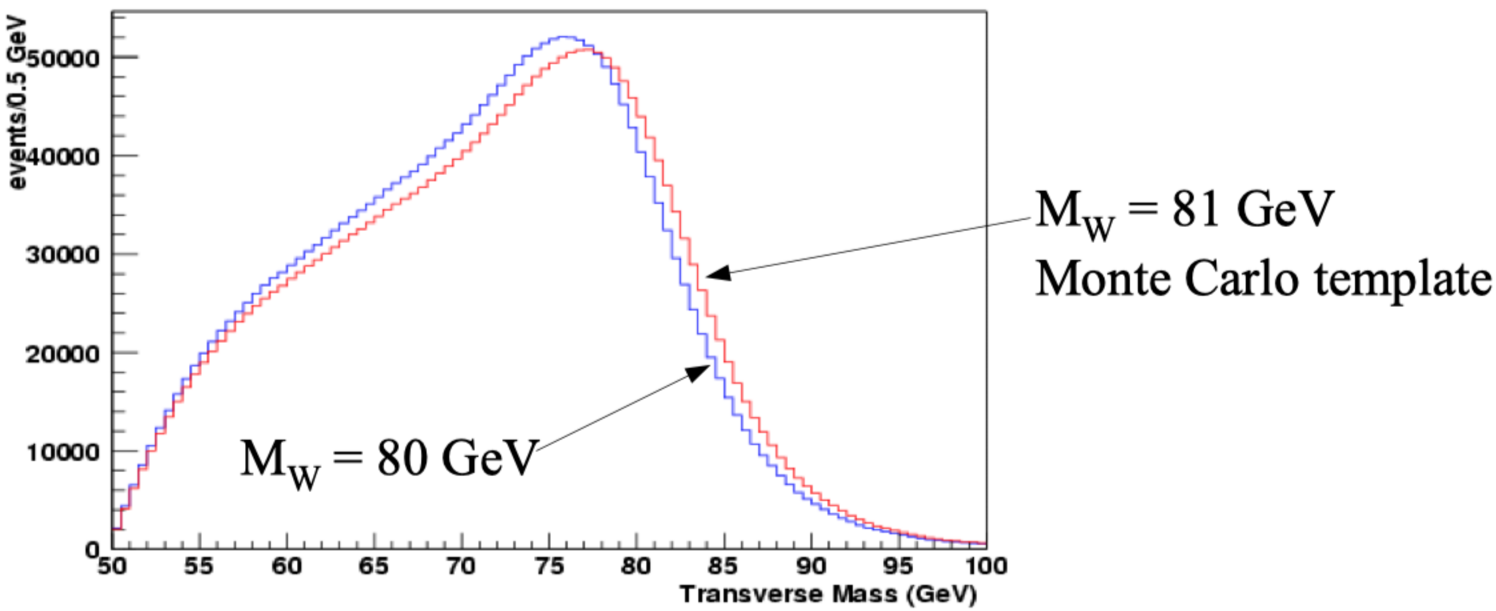


$\Delta S_E = -14 \pm 72$ ppm

Signal simulation and template fitting

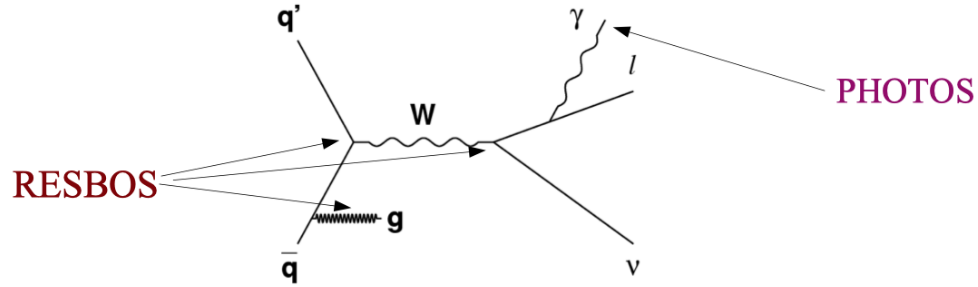
- Signals simulated using custom fast Monte Carlo
- W mass extracted from 6 kinematic distributions
  - transverse mass
  - charged lepton p_T
  - neutrino p_T (missing E_T)
  - both electron and muon channels

$$m_T = \sqrt{2\left(p_T^{\ell} p_T^{\nu} - \vec{p}_T^{\,\ell} \cdot \vec{p}_T^{\,\nu}\right)}$$



Theory-level predictions

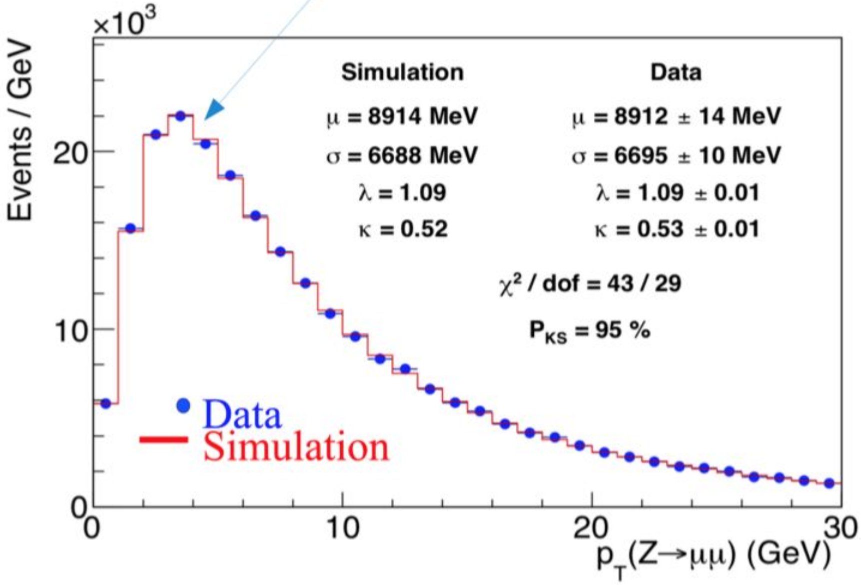
- Predictions for W/Z production and decay provided by ResBos
  - with multiple radiative photons generated by PHOTOS
- Characterize transverse momentum distributions; <u>at low p_T, have tunable non-perturbative parameters</u>

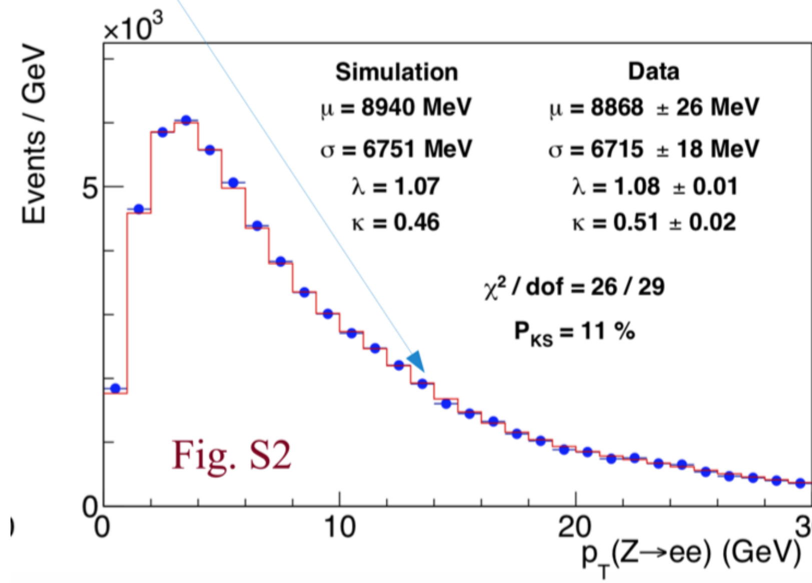


The version used is NNLL+NLO. See Josh's talk for impact of higher orders and of PDFs.

Position of peak in boson p_T spectrum depends on g_2 (non-perturbative Sudakov factor)

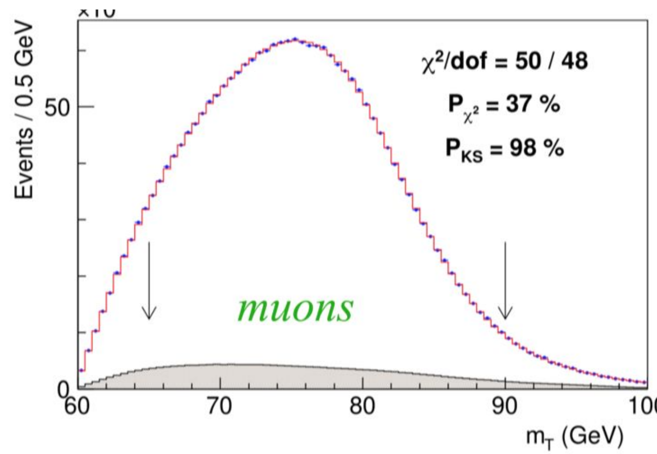
Tail to peak ratio depends on α_s





W Transverse Mass Fits

restrict W mass fit range to that shown by arrows; a bit more restrictive then purity cuts



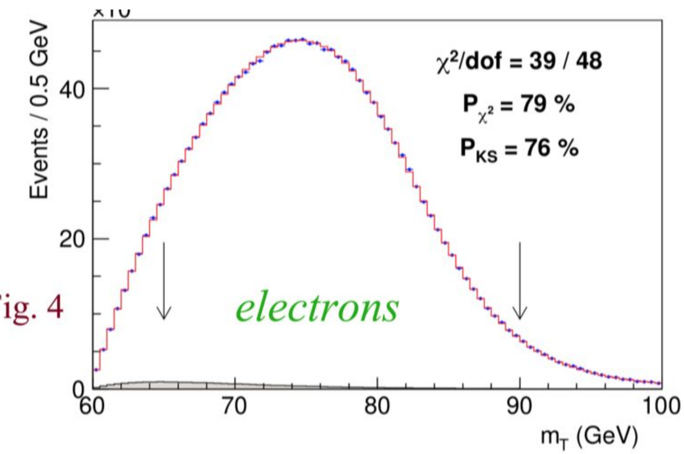
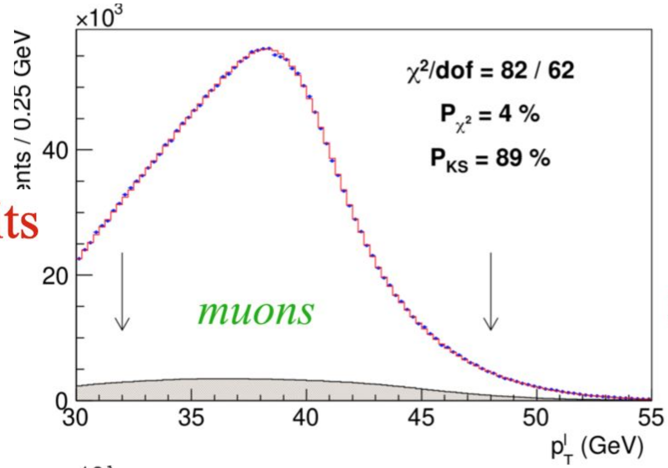


Fig. 4

W Charged Lepton p_T Fits



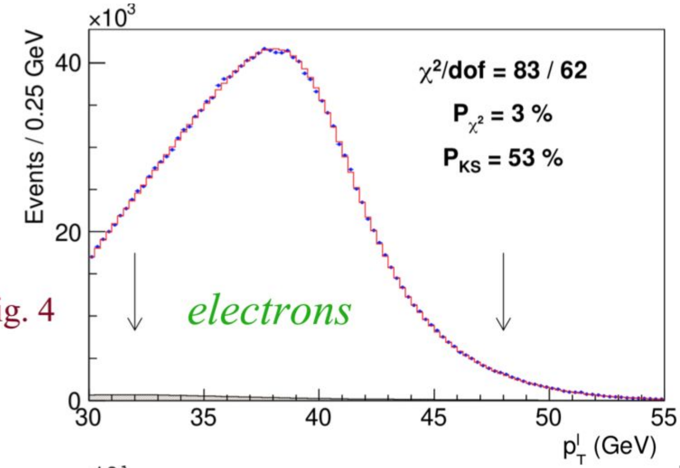
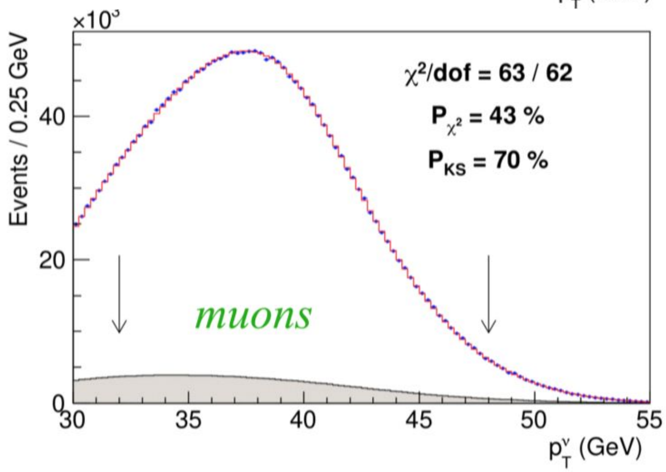


Fig. 4

W Neutrino p_T Fits



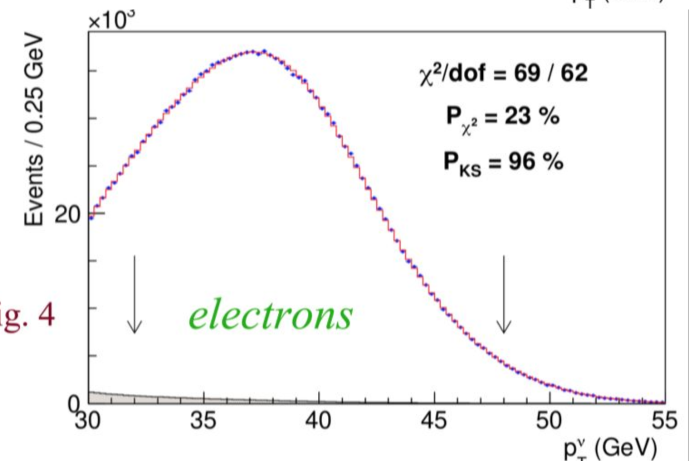


Fig. 4

Distribution	W-boson mass (MeV)	χ^2/dof
$m_T(e,\nu)$	$80\ 429.1 \pm 10.3_{\text{stat}} \pm 8.5_{\text{syst}}$	39/48
$p_T^\ell(e)$	$80\ 411.4 \pm 10.7_{\text{stat}} \pm 11.8_{\text{syst}}$	83/62
$p_T^\nu(e)$	$80\ 426.3 \pm 14.5_{\text{stat}} \pm 11.7_{\text{syst}}$	69/62
$m_T(\mu,\nu)$	$80\ 446.1 \pm 9.2_{\text{stat}} \pm 7.3_{\text{syst}}$	50/48
$p_T^\ell(\mu)$	$80\ 428.2 \pm 9.6_{\text{stat}} \pm 10.3_{\text{syst}}$	82/62
$p_T^\nu(\mu)$	$80\ 428.9 \pm 13.1_{\text{stat}} \pm 10.9_{\text{syst}}$	63/62
combination	$80\ 433.5 \pm 6.4_{\text{stat}} \pm 6.9_{\text{syst}}$	7.4/5

Combination	m_T fit Electrons	m_T fit Muons	p_T^ℓ fit Electrons	p_T^ℓ fit Muons	p_T^ν fit Electrons	p_T^ν fit Muons	Value (MeV)	χ^2/dof	Probability (%)
m_T	✓	✓					$80\ 439.0 \pm 9.8$	1.2 / 1	28
p_T^ℓ			✓	✓			$80\ 421.2 \pm 11.9$	0.9 / 1	36
p_T^ν					✓	✓	$80\ 427.7 \pm 13.8$	0.0 / 1	91
m_T & p_T^ℓ	✓	✓	✓	✓			$80\ 435.4 \pm 9.5$	4.8 / 3	19
m_T & p_T^ν	✓	✓			✓	✓	$80\ 437.9 \pm 9.7$	2.2 / 3	53
p_T^ℓ & p_T^ν			✓	✓	✓	✓	$80\ 424.1 \pm 10.1$	1.1 / 3	78
Electrons	✓		✓		✓		$80\ 424.6 \pm 13.2$	3.3 / 2	19
Muons		✓		✓		✓	$80\ 437.9 \pm 11.0$	3.6 / 2	17
All	✓	✓	✓	✓	✓	✓	$80\ 433.5 \pm 9.4$	7.4 / 5	20

Table S9

- Combined electrons (3 fits): $M_W = 80424.6 \pm 13.2$ MeV, $P(\chi^2) = 19\%$
- Combined muons (3 fits): $M_W = 80437.9 \pm 11.0$ MeV, $P(\chi^2) = 17\%$

Distribution	W-boson mass (MeV)	χ^2/dof
$m_T(e,\nu)$	$80\ 429.1 \pm 10.3_{\rm stat} \pm 8.5_{\rm syst}$	39/48
$p_T^\ell(e)$	$80\ 411.4 \pm 10.7_{\rm stat} \pm 11.8_{\rm syst}$	83/62
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$p_T^\nu(\mu)$	$80\ 428.9 \pm 13.1_{\rm stat} \pm 10.9_{\rm syst}$	63/62
combination	$80\ 433.5 \pm 6.4_{\rm stat} \pm 6.9_{\rm syst}$	7.4/5

Weights in combination (%)

	m_T	p_T^l	p_T^ν
e	30	6.7	0.9
μ	34.2	18.7	9.5

m_T is the most important

Combination	m_T fit		p_T^ℓ fit		p_T^ν fit		Value (MeV)	χ^2/dof	Probability (%)
	Electrons	Muons	Electrons	Muons	Electrons	Muons			
m_T	✓	✓					$80\ 439.0 \pm 9.8$	1.2 / 1	28
p_T^ℓ			✓	✓			$80\ 421.2 \pm 11.9$	0.9 / 1	36
p_T^ν					✓	✓	$80\ 427.7 \pm 13.8$	0.0 / 1	91
m_T & p_T^ℓ	✓	✓	✓	✓			$80\ 435.4 \pm 9.5$	4.8 / 3	19
m_T & p_T^ν	✓	✓			✓	✓	$80\ 437.9 \pm 9.7$	2.2 / 3	53
p_T^ℓ & p_T^ν			✓	✓	✓	✓	$80\ 424.1 \pm 10.1$	1.1 / 3	78
Electrons	✓		✓		✓		$80\ 424.6 \pm 13.2$	3.3 / 2	19
Muons		✓		✓		✓	$80\ 437.9 \pm 11.0$	3.6 / 2	17
All	✓	✓	✓	✓	✓	✓	$80\ 433.5 \pm 9.4$	7.4 / 5	20

Table S9

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- Combined muons (3 fits): $M_W = 80437.9 \pm 11.0$ MeV, $P(\chi^2) = 17\%$

New CDF Result (8.8 fb^{-1})
All Fit Uncertainties (MeV)

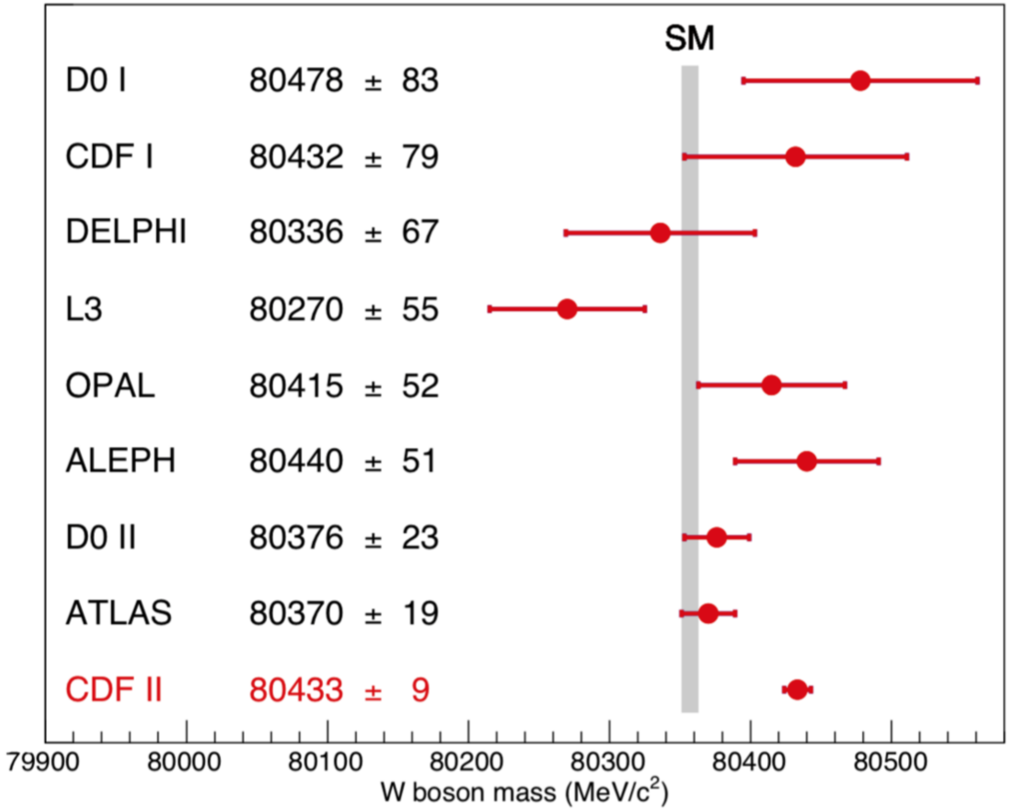
Source of systematic uncertainty	m_T fit Electrons	m_T fit Muons	m_T fit Common	p_T^ℓ fit Electrons	p_T^ℓ fit Muons	p_T^ℓ fit Common	p_T^ν fit Electrons	p_T^ν fit Muons	p_T^ν fit Common
Lepton energy scale	5.8	2.1	1.8	5.8	2.1	1.8	5.8	2.1	1.8
Lepton energy resolution	0.9	0.3	-0.3	0.9	0.3	-0.3	0.9	0.3	-0.3
Recoil energy scale	1.8	1.8	1.8	3.5	3.5	3.5	0.7	0.7	0.7
Recoil energy resolution	1.8	1.8	1.8	3.6	3.6	3.6	5.2	5.2	5.2
Lepton $u_{\|\|}$ efficiency	0.5	0.5	0	1.3	1.0	0	2.6	2.1	0
Lepton removal	1.0	1.7	0	0	0	0	2.0	3.4	0
Backgrounds	2.6	3.9	0	6.6	6.4	0	6.4	6.8	0
p_T^Z model	0.7	0.7	0.7	2.3	2.3	2.3	0.9	0.9	0.9
p_T^W/p_T^Z model	0.8	0.8	0.8	2.3	2.3	2.3	0.9	0.9	0.9
Parton distributions	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9
QED radiation	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7
Statistical	10.3	9.2	0	10.7	9.6	0	14.5	13.1	0
Total	13.5	11.8	5.8	16.0	14.1	7.9	18.8	17.1	7.4

Table S8

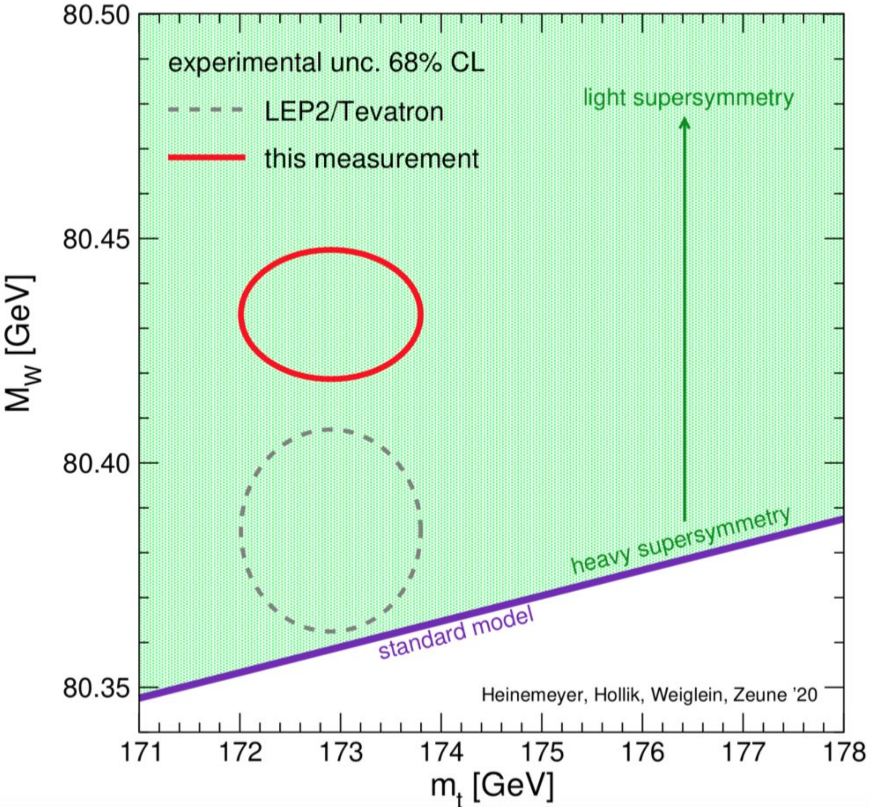
Comparison to result with 2 fb^{-1}

- Statistical precision of the measurement improves by almost a factor of 2
- Analysis improvements have reduced systematic errors
  - COT alignment and drift model and uniformity of the EM calorimeter response
  - accuracy and robustness of detector response and resolution model in the simulation
  - updates of theoretical inputs->see Josh's talk
- Improved understanding of PDFs and track reconstruction would have increased previous measurement by 13.5 MeV to 80,400.5 MeV (consistency with new measurement at the level of 1%)

Comparison



CDF M_W *vs* m_{top}

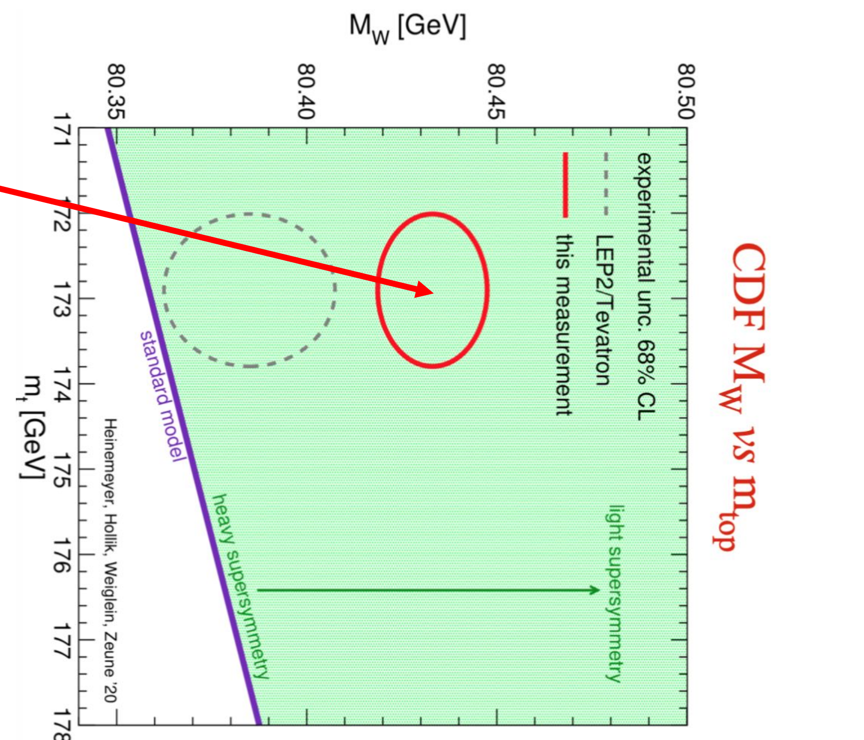


Some concluding throughts

- Fits with three different observables, with two lepton flavors, are all consistent, but inconsistent with SM prediction, and with many other measurements of W mass
- Could there be some common systematic(s) among all six of the CDF analyses?
- Would it be worthwhile to do a W-mass analysis of Z->ee/μμ?
  - it will be statistics limited, but confirmation of the central value would add an extra degree of robustness.

The ~~face~~ W mass that launched a thousand ~~ships~~ archive papers

We know the direction that all of these ships are sailing. The question is whether it will be worth the trip. (And whether it will take 20 years to get back.)



How to measure the W Mass: A Theory Perspective

Joshua Isaacson

Based on: arxiv:2205.02788

In Collaboration with: Yao Fu and C.-P. Yuan

Pheno 2022

10 May 2022

Standard Model: W Mass

Standard Model EW Fit

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

$$\Delta r=\Delta\alpha-\frac{c_W^2}{s_W^2}\Delta\rho+\Delta r_{\text{rem}}\left(M_H\right)\,,$$

where s_W^2 is the Weinberg angle, $\Delta\alpha$ is the correction to α from the light fermions, $\Delta\rho$ is the correction to the ρ parameter, and Δr_{rem} contains all corrections containing the Higgs mass.

Parameter	Fit Result
G_μ [GeV^{-2}]	1.1663787 $\times 10^{-5}$
$\alpha(0)^{-1}$	137.035999139
$\Delta\alpha_{\text{had}}^{(5)}(M_Z^2)$	0.027627 $\pm$ 0.000096
M_Z [GeV]	91.1883 $\pm$ 0.0021
M_H [GeV]	125.21 $\pm$ 0.12
m_t [GeV]	172.75 $\pm$ 0.44
M_W [GeV]	80.3591 $\pm$ 0.0052

Table reproduced from: HEPFit Group (2112.07274).

Experimental Measurements

- CDF Run II results most precise
- 7σ tension with SM
- 3σ tension between CDF-II and ATLAS result
- Missing LHCb result: 80,354 $\pm$ 32 MeV
- For more details see Joey Huston's talk

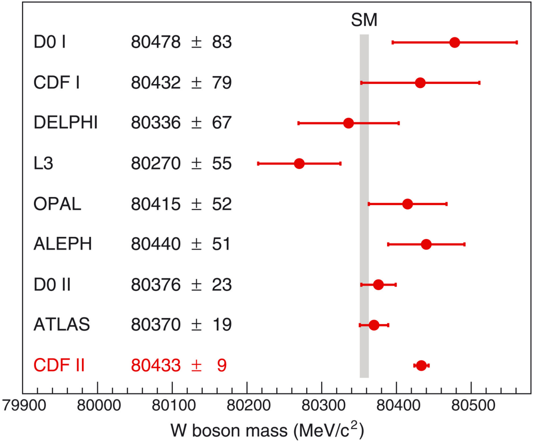
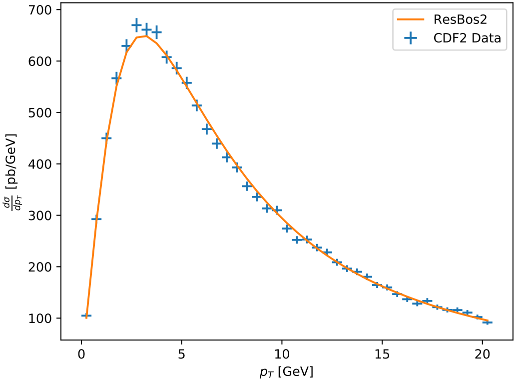


Figure reproduced from CDF-II measurement (Science 376, 170).

Theory Calculation

Breakdown of Fixed Order

- Perturbative series has terms proportional to $\alpha_s^n \log^m\left(\frac{p_T^2}{M_W^2}\right)$, $m \leq 2n$
- As $p_T^W \to 0$ the series no longer converges
- Need to include corrections to all orders by resumming the series



Analytic vs. Numeric Resummation

Analytic:

- Formal resummation (focus here on b-space CSS resummation)
- Pros:
  - High precision and accuracy
- Cons:
  - Inclusive only
  - Numerically expensive
- Used by CDF to obtain M_W

Numerical

- Parton Showers (Pythia, Sherpa, Herwig, Dire, Vincia)
- Pros:
  - Exclusive final states
  - Quick
- Cons:
  - Currently only LL with some subleading effects included
- Used by ATLAS to obtain M_W

Collins-Soper-Sterman Formalism

Resummation

$$\frac{d\sigma_{\text{res}}}{dQ^2 d^2\vec{q_T} dy d\Omega} = \sigma \int \frac{d^2b}{(2\pi)^2} e^{i\vec{q}_T\cdot\vec{b}} \tilde{W},$$

$$\tilde{W} = e^{-S(b)} \; C \otimes f(x_A, C_3/b) C \otimes f(x_B, C_3/b)$$

$$S(b) = \int_{\frac{C_1^2}{b^2}}^{C_2^2 Q^2} \frac{d\bar{\mu}^2}{\bar{\mu}^2} \left[\ln\left(\frac{C_2^2 Q^2}{\bar{\mu}^2}\right) A(\bar{\mu}) + B(\bar{\mu}) \right]$$

[Collins, Soper, Sterman, '85] [...]

Collins-Soper-Sterman Formalism

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- Electroweak cross section

[Collins, Soper, Sterman, '85] [...]

Collins-Soper-Sterman Formalism

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- Electroweak cross section
- Sudakov factor

[Collins, Soper, Sterman, '85] [...]

Collins-Soper-Sterman Formalism

Resummation

$$\frac{d\sigma_{\text{res}}}{dQ^2 d^2\vec{q_T} dy d\Omega} = \sigma \int \frac{d^2 b}{(2\pi)^2} e^{i\vec{q}_T \cdot \vec{b}} \tilde{W},$$

$$\tilde{W} = e^{-S(b)} C \otimes f(x_A, C_3/b) C \otimes f(x_B, C_3/b)$$

$$S(b) = \int_{\frac{C_1^2}{b^2}}^{C_2^2 Q^2} \frac{d\bar{\mu}^2}{\bar{\mu}^2} \left[\ln\left(\frac{C_2^2 Q^2}{\bar{\mu}^2}\right) A(\bar{\mu}) + B(\bar{\mu}) \right]$$

- Electroweak cross section
- Sudakov factor
- Collinear factors

[Collins, Soper, Sterman, '85] [...]

Collins-Soper-Sterman Formalism

Resummation

$$\frac{d\sigma_{\text{res}}}{dQ^2 d^2\vec{q_T} dy d\Omega} = \sigma \int \frac{d^2 b}{(2\pi)^2} e^{i\vec{q}_T\cdot\vec{b}} \tilde{W},$$

$$\tilde{W} = e^{-S(b)} C \otimes f(x_A, C_3/b) C \otimes f(x_B, C_3/b)$$

$$S(b) = \int_{\frac{C_1^2}{b^2}}^{C_2^2 Q^2} \frac{d\bar{\mu}^2}{\bar{\mu}^2} \left[\ln\left(\frac{C_2^2 Q^2}{\bar{\mu}^2}\right) A(\bar{\mu}) + B(\bar{\mu})\right]$$

- Electroweak cross section
- Sudakov factor
- Collinear factors
- Perturbative Coefficients (A, B, C)

[Collins, Soper, Sterman, '85] [...]

Order Definitions

Order	Boundary Condition	Anomalous Dimension γ_i (non-cusp)	Γ_{cusp}, β	Fixed Order Matching
LL	1	-	1-loop	-
NLL	1	1-loop	2-loop	-
NLL' (+ NLO)	α_s	1-loop	2-loop	α_s
NNLL (+ NLO)	α_s	2-loop	3-loop	α_s
NNLL' (+ NNLO)	α_s^2	2-loop	3-loop	α_s^2
N^3LL (+ NNLO)	α_s^2	3-loop	4-loop	α_s^2
N^3LL' (+ N^3LO)	α_s^3	3-loop	4-loop	α_s^3
N^4LL (+ N^3LO)	α_s^3	4-loop	5-loop	α_s^3

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N^{4}LL (+ N^{3}LO)	α_s^3	4-loop	5-loop	α_s^3

- ■ Accuracy used by CDF

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N^4LL (+ N^3LO)	α_s^3	4-loop	5-loop	α_s^3

- ■ (red) Accuracy used by CDF
- ■ (blue) Current accuracy available in ResBos code

Order Definitions

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- ■ Accuracy used by CDF
- ■ Current accuracy available in ResBos code
- ■ All terms known to this accuracy

Non-Perturbative Fit

$$S(b) = \int_{\frac{C_1^2}{b^2}}^{C_2^2 Q^2} \frac{d\bar{\mu}^2}{\bar{\mu}^2} \left[\ln\left(\frac{C_2^2 Q^2}{\bar{\mu}^2}\right) A(\bar{\mu}) + B(\bar{\mu}) \right]$$

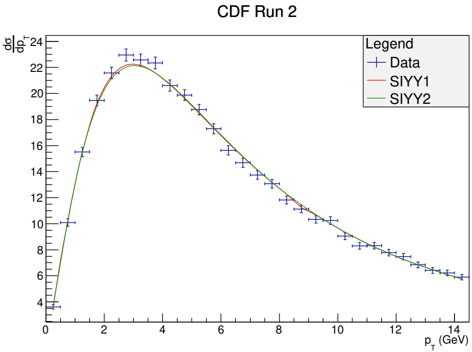
- Lower limit goes to zero as b goes to infinity
- Requires evaluation of $\alpha_s(C_1/b)$ which is non-perturbative
- Need to introduce a non-perturbative cutoff (b^*-prescription):

$$b^* = \frac{b}{\sqrt{1 + \frac{b^2}{b^2_{\text{max}}}}}$$

BLNY Form

$$S_{NP}(b) = -b^2 \left(g_1 + g_2 \log\left(\frac{Q}{2Q_0}\right) + g_1 g_3 \log(100 x_1 x_2) \right)$$

- g_1 and g_3 extracted from global fit
- g_2 tuned to reproduce CDF-II p_T^Z
- M_W vs. M_Z captured in Q dependence
- No flavor dependence included
- No consideration of uncertainty from changing form, but expected to be small



NOTE: SIYY2 is the same functional form as BLNY, but with $b_{\text{max}} = 1.5$ GeV^{-1}

Flavor Dependence

- Study on flavor dependence for $\sqrt{s} = 7$ TeV LHC
- $S_{NP}(b) = -b^2(g_a + g_{evo}\log(Q^2/Q_0^2)$, where g_a is the flavor dependent piece
- Found shift could be up to 10 MeV
- Additional studies are required to validate
- Unclear what the global shift would be

Set	u_v	d_v	u_s	d_s	others
1	0.34	0.26	0.46	0.59	0.32
2	0.34	0.46	0.56	0.32	0.51
3	0.55	0.34	0.33	0.55	0.30
4	0.53	0.49	0.37	0.22	0.52
5	0.42	0.38	0.29	0.57	0.27

Set	ΔM_W^+		ΔM_W^-	
	M_T	p_T^ℓ	M_T	p_T^ℓ
1	0	-1	-2	3
2	0	-6	-2	0
3	-1	9	-2	-4
4	0	0	-2	-4
5	0	4	-1	-3

Table reproduced from: Phys. Letters B 788 (2019) 542-545

Results

Methodology

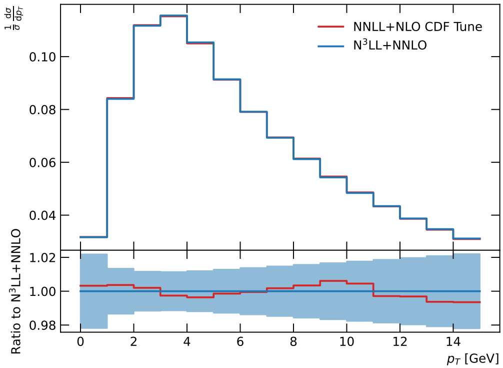
Our Procedure:

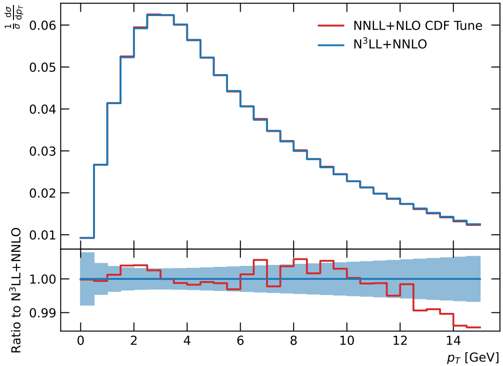
- Generate pseudodata using $N^3LL+NNLO$ prediction
- Tune NNLL+NLO prediction to reproduce $p_T(Z)$ data
- Validate tuned result against $p_T(W)$ data
- Use tuned result to generate mass templates
- Extract W mass from template fit for each observable
- Calculate the mass shift from the input value for pseudodata

Details:

- Pseudodata $M_W = 80,358$ MeV
- Cuts:
  - $p_T(Z) < 15$ GeV, $p_T(W) < 15$ GeV
  - $30 < p_T(\ell) < 55GeV$, $30 < p_T(\nu) < 55$ GeV
  - $|\eta(\ell)| < 1$
  - $66 < M_{\ell\ell} < 116$ GeV (Z events), $60 < m_T < 100$ GeV (W events)
- Number of Events:
  - 1,811,700 $W \to e\nu$
  - 66,180 $Z \to ee$
  - 2,424,486 $W \to \mu\nu$
  - 238,534 $Z \to \mu\mu$

Tuning to Pseudodata

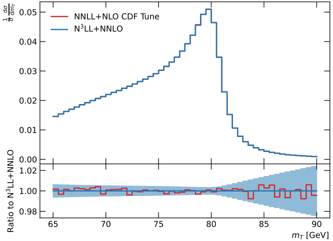




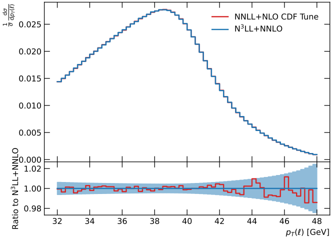
Tuned result:

- Fit to $p_T(Z) < 15$ GeV
- $g_2 = 0.662$ GeV^2
- $\alpha_S(M_Z) = 0.120$
- Tuned PDF set: `CT18NNLO_as_120`

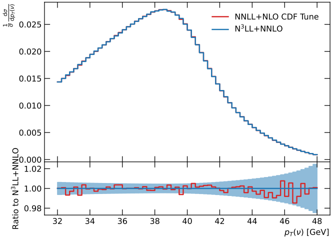
Results



Best Fit: $M_W = 80,386$ MeV



Best Fit: $M_W = 80,388$ MeV



Best Fit: $M_W = 80,389$ MeV

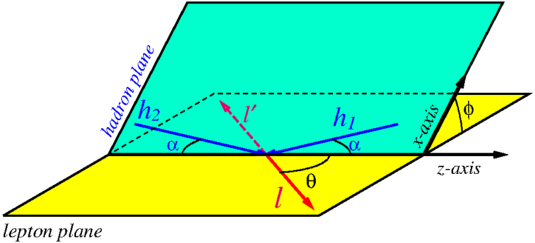
	Mass Shift [MeV]	
Observable	ResBos2	+Detector Effect+FSR
m_T	1.5 ± 0.5	0.2 ± 1.8 ± 1.0
$p_T(\ell)$	3.1 ± 2.1	4.3 ± 2.7 ± 1.3
$p_T(\nu)$	4.5 ± 2.1	3.0 ± 3.4 ± 2.2

Conclusions

- CDF used ResBos code at NNLL+NLO accuracy
- ResBos v2 is able to go to N^3LL+NNLO accuracy
- ResBos2 corrected major criticism of incorrect angular functions in the ResBos code
- Mimic CDF analysis using pseudoexperiments at N^3LL+NNLO accuracy
- Find shift to be consistent with 0 MeV and up to 10 MeV in worse case

Backup

Angular Coefficients



$$\frac{d\sigma}{dp_T^Z\, dy^Z\, dm^Z\, d\cos\theta\, d\phi} = \frac{3}{16\pi}\frac{d\sigma^{U+L}}{dp_T^Z\, dy^Z\, dm^Z}$$
$$\Big\{(1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_1 \sin 2\theta \cos\phi$$
$$+\frac{1}{2}A_2 \sin^2\theta \cos 2\phi + A_3 \sin\theta \cos\phi + A_4 \cos\theta$$
$$+A_5 \sin^2\theta \sin 2\phi + A_6 \sin 2\theta \sin\phi + A_7 \sin\theta \sin\phi\Big\}.$$

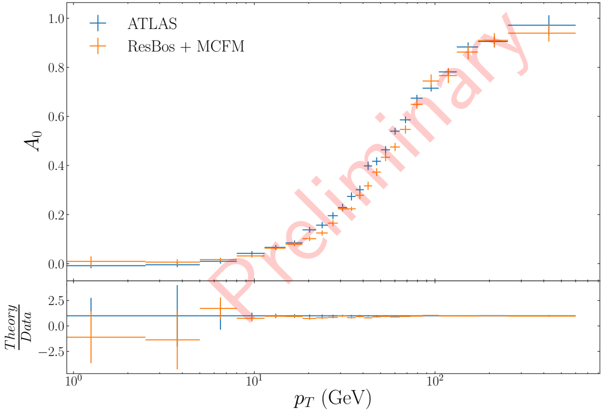
$$\langle P(\cos\theta,\phi)\rangle = \frac{\int P(\cos\theta,\phi) d\sigma(\cos\theta,\phi) d\cos\theta d\phi}{\int d\sigma(\cos\theta,\phi) d\cos\theta d\phi}.$$

$$\langle\frac{1}{2}(1-3\cos^2\theta)\rangle = \frac{3}{20}(A_0-\frac{2}{3});\quad \langle\sin 2\theta\cos\phi\rangle = \frac{1}{5}A_1;\quad \langle\sin^2\theta\cos 2\phi\rangle = \frac{1}{10}A_2;$$
$$\langle\sin\theta\cos\phi\rangle = \frac{1}{4}A_3;\quad \langle\cos\theta\rangle = \frac{1}{4}A_4;\quad \langle\sin^2\theta\sin 2\phi\rangle = \frac{1}{5}A_5;$$
$$\langle\sin 2\theta\sin\phi\rangle = \frac{1}{5}A_6;\quad \langle\sin\theta\sin\phi\rangle = \frac{1}{4}A_7.$$

NNLO Angular Coefficients

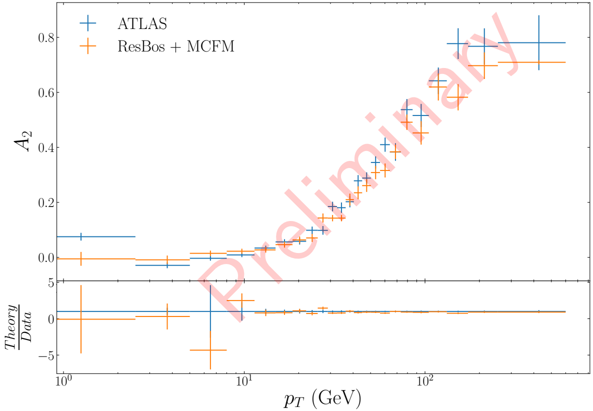
- Well known issue with angular coefficients in the ResBos code at NNLO (No issue with matching to NLO)
- CDF-II only used the NLO so the angular functions are exact to that order
- ResBos only included NNLO corrections to the total rate, but not to the angular functions
- This is an issue with matching to an incomplete NNLO calculation, and not an issue with the resummation or the matching to fixed order
- Only effects larger p_T ($p_T > 30$ GeV, CDF has a cut of $p_T < 15$ GeV)
- Has been resolved via matching to MCFM (preliminary results next slides)

NNLO Angular Coefficients



NOTE: Uncertainties are purely statistical for ResBos + MCFM

NNLO Angular Coefficients



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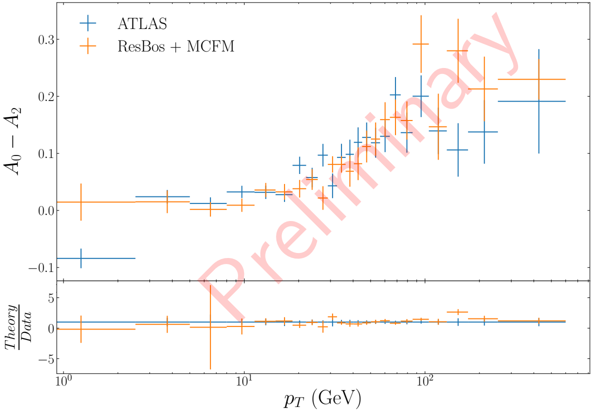
NNLO Angular Coefficients



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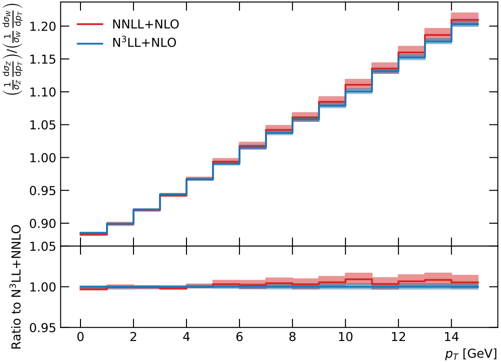
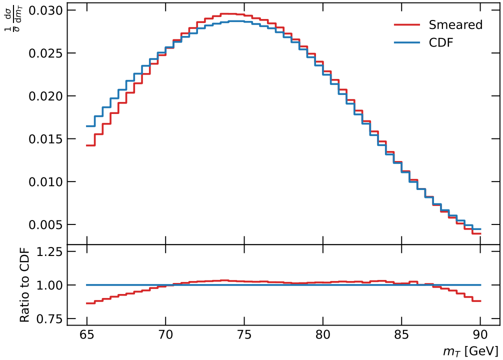
$P_T(Z)/P_T(W)$



- Ratio is stable to higher order corrections at small p_T
- Scale uncertainty only using correlated prediction
- Need to investigate the CDF estimated uncertainty from this ratio

Detector Smearing



Detector Smearing:

- Fit functional form (Smearing 1):
  $$\frac{\sigma}{E} = a \oplus \frac{b}{\sqrt{E}} \oplus \frac{c}{E}$$
- Use gaussian with 5%(11%) width for $\ell(\nu)$ (Smearing 2)
- Note results not sensitive to smearing effect if data and theory smeared identically

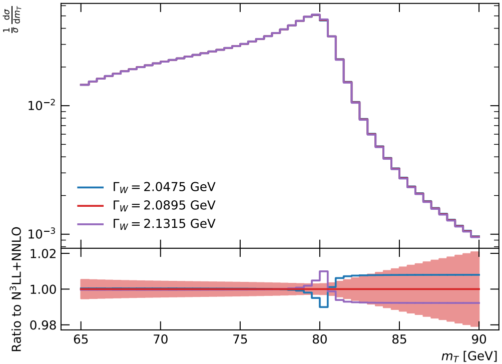
	Mass Shift [MeV]	
Observable	Smearing 1	Smearing 2
m_T	0.2 $\pm$ 1.8 $\pm$ 1.0	1.0 $\pm$ 2.1 $\pm$ 1.3
$p_T(\ell)$	4.3 $\pm$ 2.7 $\pm$ 1.3	4.5 $\pm$ 2.6 $\pm$ 1.4
$p_T(\nu)$	3.0 $\pm$ 3.4 $\pm$ 2.2	3.8 $\pm$ 4 $\pm$ 2.7

Width Effect

Width Effect:

- Central width: $\Gamma_W = 2.0895$ GeV
- NLO width proportional to M_W^3
- Negligible shift

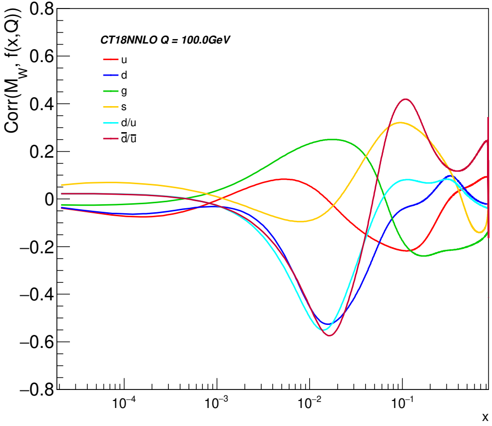
Width	Mass Shift [MeV]
2.0475 GeV	2.0 ± 0.5
2.1315 GeV	0.3 ± 0.5
NLO	1.2 ± 0.5



PDF Uncertainties

	m_T		$p_T(\ell)$		$p_T(\nu)$	
PDF Set	NNLO	NLO	NNLO	NLO	NNLO	NLO
CT18	0.0 ± 1.3	1.8 ± 1.2	0.0 ± 15.9	2.0 ± 14.3	0.0 ± 15.5	2.9 ± 14.2
MMHT2014	1.0 ± 0.6	2.6 ± 0.6	6.2 ± 7.8	36.7 ± 7.0	3.9 ± 7.5	36.0 ± 6.7
NNPDF3.1	1.1 ± 0.3	2.1 ± 0.4	2.1 ± 3.8	13.5 ± 4.9	5.4 ± 3.7	10.0 ± 4.9
CTEQ6M	N/A	2.8 ± 0.9	N/A	19.0 ± 10.4	N/A	20.9 ± 10.2

- Central value is shift from 80,385 MeV
- Uncertainty is the PDF uncertainty for the given set
- Need to combine to compare to 3.9 MeV from CDF
- Rough estimates say it is consistent with CDF



- PDF-induced correlation of M_W and CT18 NNLO error set vs. x at $Q = 100$ GeV
- Region around $x = \frac{M_W}{\sqrt{s}}$ dominated by $\bar{d}/\bar{u}$, d/u and d PDFs