Improving parton distribution uncertainties in a W mass measurement at the LHC

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In collaboration with Seth Quackenbush (FSU)
arXiv:1502.04671 (to appear in PRD August 2015)

Outline

1. Determining the W mass

2. PDF error in M_W at LHC

3. Conclusions

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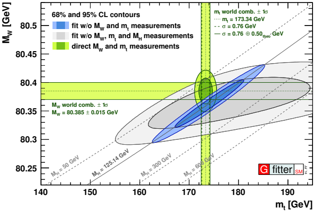
3. **Conclusions**

How well we (want to) know M_W

Current world average (dominated by Tevatron combined fit)

$$M_W = 80385 \pm 15 \text{ MeV}$$



SM: interested in consistency between M_W, M_t, $\sin^2\theta_{\rm eff}$ and the Higgs mass

Is the Universe only meta-stable?

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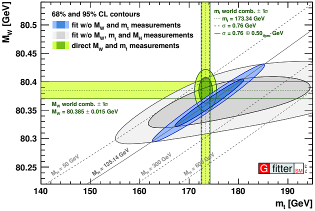

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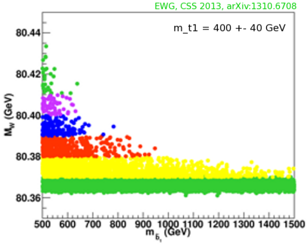


BSM: M_W very important

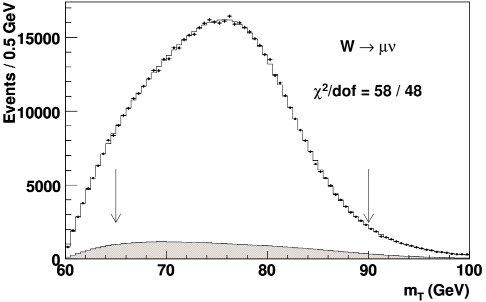
E.g., SUSY: predicts 2–20 MeV shifts

For BSM physics, we want to know M_W to 5 MeV or better.

Can we get there?

How the W mass is measured

- To measure the W mass to the sub-per-mille level requires fitting templates to observables in the final state $W \to e\nu(\mu\nu)$.
- Common choices are M_T^W, P_T^l, P_T^ν



W mass error is dominated by our capacity to predict the template shapes.

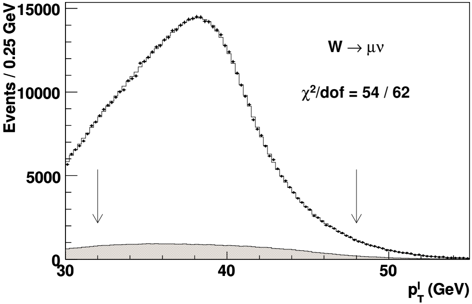
CDF, 1311.0894

- M_T is the most reliably predicted as it is the least sensitive to non-perturbative recoil energy (and PDFs as we'll see).

$$M_T = \sqrt{2P_T^l E_T^{\rm miss}[1 - \cos(\Delta\phi_{l,\rm miss})]}$$

Aside on using P_T^l

- An advantage of using P_T^l over M_T^W is the avoidance of poorly reconstructed missing energy E_T^{miss}.



Sharp peak experimentally easier to fit.

Large W mass error (9 MeV) due to P_T^W cut ($u_T < 15$ MeV).

CDF, 1311.0894

- Cut on W recoil forces theory calculation into non-perturbative region (est. w/ RESBOS). Trade good expt. error for larger theory error in p_T^l and loss of information on PDFs hidden in resummation.

We will see the PDF error for both M_T^W and P_T^l measurements, but P_T^l will not be competitive.

The dominant experimental error is theoretical. . .

Parton distribution functions (PDFs) dominate the current uncertainty.

m_T fit uncertainties

Source	$W \to \mu\nu$	$W \to e\nu$	Common
Lepton energy scale	7	10	5
Lepton energy resolution	1	4	0
Lepton efficiency	0	0	0
Lepton tower removal	2	3	2
Recoil scale	5	5	5
Recoil resolution	7	7	7
Backgrounds	3	4	0
PDFs	10	10	10
W boson p_T	3	3	3
Photon radiation	4	4	4
Statistical	16	19	0
Total	23	26	15

CDF, 1311.0894

Why? PDFs shift the rapidity distribution, and the fit is very sensitive to rapidity. That is the matrix-element level explanation.

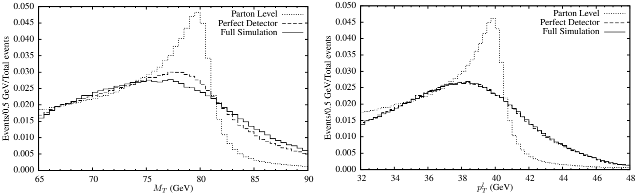
Actually, “PDF errors” are more subtle than prior results suggest. . .

“PDF errors” show up in multiple places

Seth Quackenbush, Z.S., arXiv:1502.04671

Many recent claims that PDF errors are under control have focused on the parton level. Bozzi, Rojo, Vicini 1104.2056, 1309.1311, 1310.6708, 1501.05587

1. Hard matrix-element PDF errors are only a small part of the story.



Tevatron	Parton level
M_T error	${}^{+8}_{-8}$ MeV
p_T^e error	${}^{+8}_{-8}$ MeV

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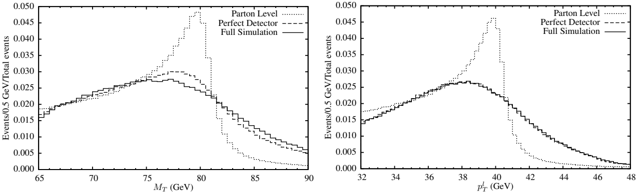

Tevatron	Parton level	+ shower
M_T error	$^{+8}_{-8}$ MeV	$^{+14}_{-13}$ MeV
p_T^e error	$^{+8}_{-8}$ MeV	$^{+22}_{-20}$ MeV

2. PDFs *also* appear in showering, and the sensitivity is larger because showers probe poorly constrained regions of PDFs. (High-x, low-Q^2)

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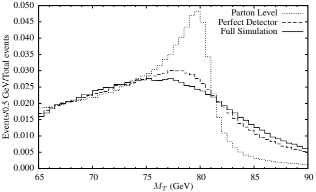

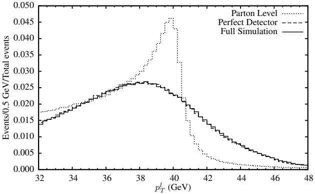

Tevatron	Parton level	+ shower	+ detector
M_T error	$^{+8}_{-8}$ MeV	$^{+14}_{-13}$ MeV	$^{+18}_{-16}$ MeV
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Using CTEQ 6.6

MSTW2008 NLO68% yield net 10/9 MeV

2. PDFs *also* appear in showering, and the sensitivity is larger because showers probe poorly constrained regions of PDFs. (High-x, low-Q^2)
3. Additionally, detector resolution dilutes M_T reconstruction in a way that increases sensitivity to PDF influence on shape.

The latter two effects are isolated for the first time here. ⇒ guidance

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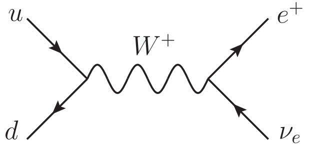
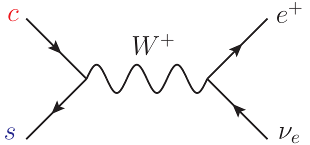
What are predictions at LHC? Can we reach 5 MeV?

- Theoretical (SM loop) errors ~ 4 MeV, but will go to ~ 1 MeV w/ 3-loop self-energies. CSS 2013, 1310.6708
- Experimental systematic errors should be 7 MeV or better. Statistical errors will be negligible.
- PDF errors previously estimated to be ± 25 MeV at LHC using CTEQ 6.1 PDFs. JPG 34, N193 (07)
- Claims have been made that correlations between W and Z can be used to reduce PDF uncertainties to $\sim 1 - 5$ MeV. These are based on old PDFs with spurious correlations.

We want to update these estimates with newer PDFs (CT10, CT10W) and improve them since 25 MeV $\gg$ 5 MeV





We find the uncertainty in newer PDFs comes from both *ud and cs* initial states.

Modern PDF errors and known-unknowns

LHC	7 TeV	13 TeV
	CT10	CT10
m_T error	$^{+39}_{-39}$	$^{+30}_{-27}$
p_T^e error	$^{+59}_{-54}$	$^{+54}_{-52}$

- Errors have grown significantly, $\pm 25 \Rightarrow \pm\, 39$. Why?
  Going from CTEQ 6.1 (or MRS08) to CTEQ 6.6+, constraints on functional form of s PDF relaxed $\Rightarrow$ *doubled* s uncertainty

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- CT10W includes W asymmetry data incompatible with CT10.
  - Difference corresponds to an uncertainty in the u/d forward (large-$|\eta_e|$) contribution
  - *and* a hint of possible future improvement in PDFs with LHC data

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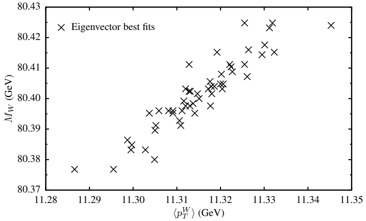
- WARNING: Constraints on c have *not* been relaxed. We estimate another ± 10 MeV using CTEQ6.6C2 intrinsic charm (IC) PDFs.

Regardless of which PDFs are used, the error is still too large.
We need to do more.

PDF effects on momentum distributions

or Why it will be hard for P_T^l to compete with M_T^W.

Resummed calculations (RESBOS, DYRES) give good shape predictions in the non-perturbative region of P_T^W probed. What if the PDF shifts?



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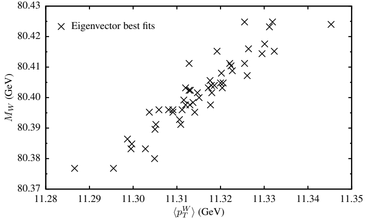

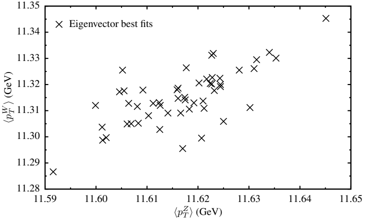

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While P_T^W and P_T^Z are loosely correlated (and we use this) it is not as strong as predicted by old PDFs.

Z and W initial states are different, and even less correlated in the experimental measurement than ME-level PDFs would suggest.

This is one of many places we find correlations are weaker than previously believed. We need something more robust.

Robust error improvement

Two general handles exist to improve PDF uncertainties:

1. Separate into 4 measurements: W^+ vs. W^- in central vs. forward regions ($|\eta_e| < 1.3$ vs. > 1.6)
   Careful accounting of correlations between regions $\Rightarrow \pm 20$ MeV
2. Normalize to Z boson measurements and mass Giele, Keller ph/9704419
   To summarize: Older PDFs had false correlations due to restrictions on PDF functional forms that led to significant overestimates of effectiveness.

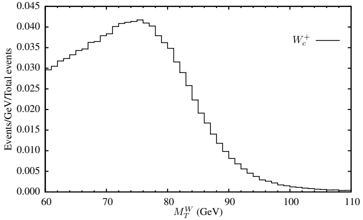
   W and Z have different initial states.

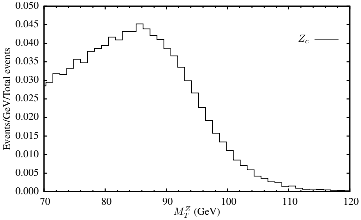
   We have created a more robust method to fit Z bosons accounting for correlations between initial states of $W : ud/cs$ and $Z : u\bar{u}/d\bar{d}/s\bar{s}/c\bar{c}$

Robust method to include Z

We propose to combine the 4 measurements of M_W above $W^{+/-}_{c/f}$ with 4 measurements of $M^i_W = \cos\theta_W M^i_Z$ split into central/forward, and $+/-$ defined by requiring *only* $e^\pm$ from Z to have same acceptance as the $e^\pm$ from the $W^\pm$.

$$M_W + \sum_{i\in Z} \alpha_i M^i_W = \sum_{i\in W,Z} \alpha_i M^i_W$$





We minimize the 8x8 covariance matrix formed from these measurements, and check stability for various PDFs in 1502.04671

Effectively, we are primarily reducing the dominant PDF error that came in through the showering component (w/ some reduction of detector effects and ME parts).

Correlation matrices and fits

We are minimizing $\sum_i \alpha_j Cov(M_W^i, M_W^j) = 0, j \in Z$ (here using CT10).

$$\begin{pmatrix} 1 & 0.474 & 0.476 & 0.074 & \mathbf{0.876} & 0.27 & \mathbf{0.412} & -0.153 \\ 0.474 & 1 & 0.062 & -0.018 & 0.552 & 0.521 & 0.107 & -0.069 \\ 0.476 & 0.062 & 1 & 0.33 & \mathbf{0.501} & -0.426 & \mathbf{0.730} & 0.458 \\ 0.074 & -0.018 & 0.33 & 1 & -0.073 & -0.034 & 0.108 & 0.292 \\ 0.876 & 0.552 & 0.501 & -0.073 & 1 & 0.229 & 0.41 & -0.027 \\ 0.27 & 0.521 & -0.426 & -0.034 & 0.229 & 1 & -0.345 & -0.394 \\ 0.412 & 0.107 & 0.730 & 0.108 & 0.41 & -0.345 & 1 & 0.368 \\ -0.153 & -0.069 & 0.458 & 0.292 & -0.027 & -0.394 & 0.368 & 1 \end{pmatrix}$$

$$\alpha = \begin{pmatrix} 0.401 \\ 0.117 \\ 0.560 \\ -0.078 \\ -0.648 \\ 0.014 \\ -0.503 \\ 0.018 \end{pmatrix} \text{ for } \begin{pmatrix} W_c^+ \\ W_f^+ \\ W_c^- \\ W_f^- \\ Z_c^+ \\ Z_f^+ \\ Z_c^- \\ Z_f^- \end{pmatrix}$$

Relevant correlations were 85% in CTEQ 6.1, drop to 40% with CT10.

The result — $\delta M_W \sim \pm 10$–12 MeV from PDFs

M_T^W	CT10	CT10W
7 TeV	$^{+11}_{-10}$	$^{+8}_{-8}$
13 TeV	$^{+10}_{-11}$	$^{+7}_{-11}$

- Older PDFs predict ± 6 MeV! Correlations are not *that* good.
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Interesting observation: The full correlated fits are dominated by the *difference* between the W and Z measurements in the central $|\eta_e| < 1.3$ region.

In this region there is a better kinematic balance between small-x u/d and sea quarks that stabilizes result. One might just measure here. . .

Optimized PDF uncertainty using P_T^l

Repeating the same robust correlation calculation for P_T^l induces a HUGE improvement in that measurement.

P_T^l	CT10	CT10W
7 TeV	$^{+17}_{-17}$	$^{+11}_{-14}$
13 TeV	$^{+18}_{-16}$	$^{+14}_{-15}$

The uncertainty drops from ±50–60 MeV down to ±17 MeV (w/ the caveat that *charm* effects are not considered here).

The upshot is the P_T^l measurement will be a good check on the technique, but will not have a large pull in the extracted W mass measurement.

Conclusions

Seth Quackenbush, Z.S., arXiv:1502.04671, PRD August

- The dominant uncertainty in M_W comes from PDFs. We've isolated effects from: matrix element vs. showering vs. detector resolution
- Spurious correlations in older PDFs or ME-level prior analyses led to some overoptimistic error estimates.
- Despite poorly determined uncertainties in c, we can use rapidity, lepton sign, and Z mass measurements to achieve $\pm$10–12 MeV.
- With small improvements to overall PDF uncertainties (particularly from forward u/d data at LHC) we are confident our method can reach the 5 MeV desired to test BSM physics.

THANK YOU