High-Precision Measurement of the W Boson Mass with the CDF II Detector

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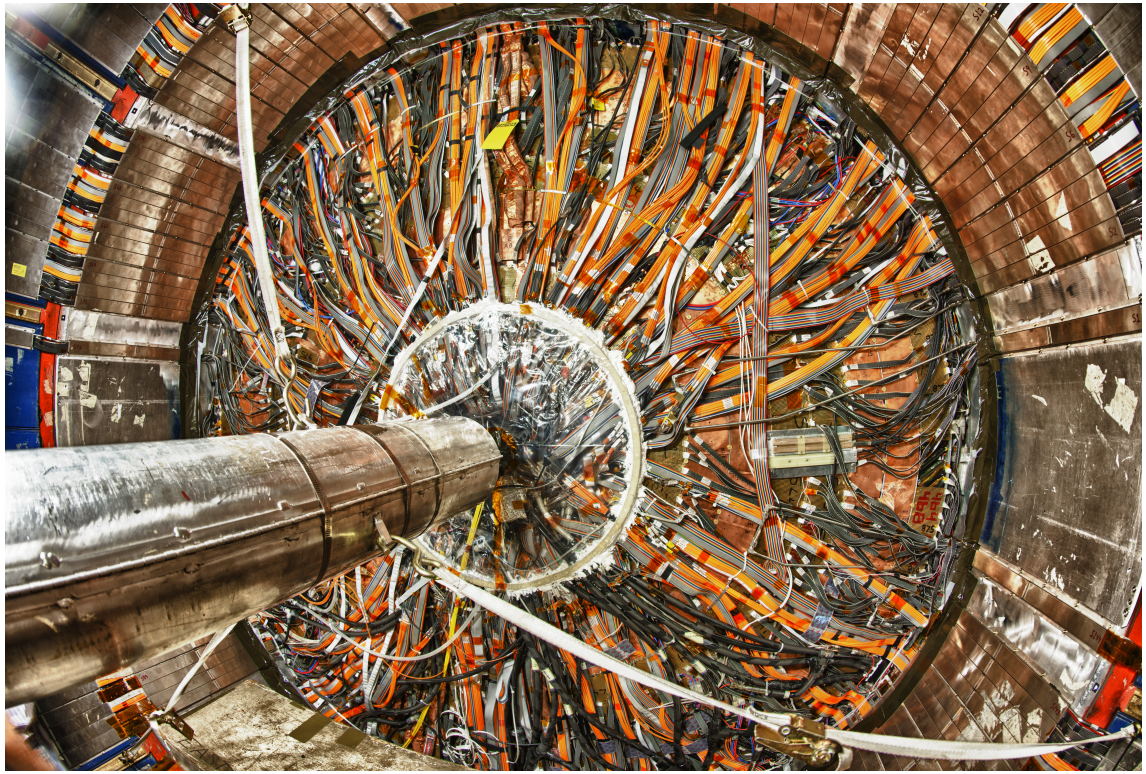
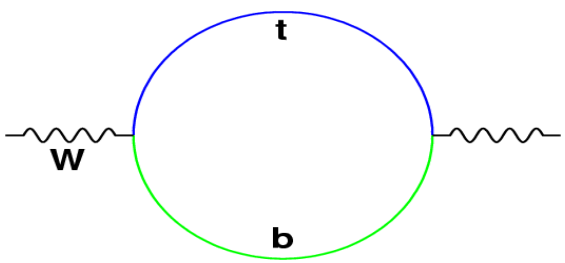
For the CDF Collaboration

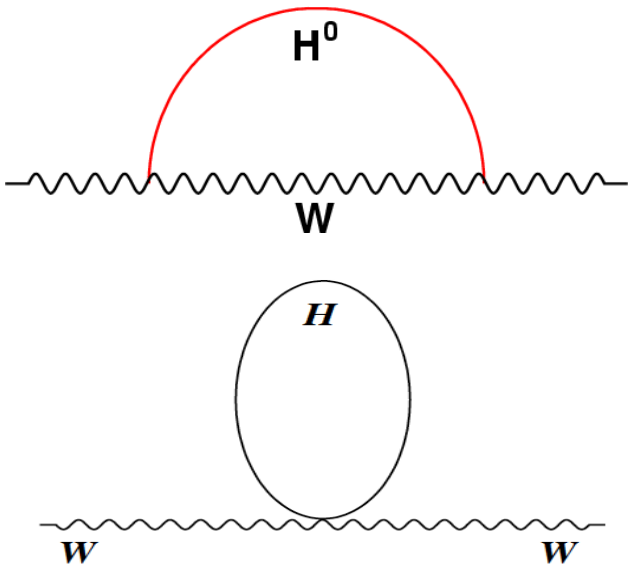


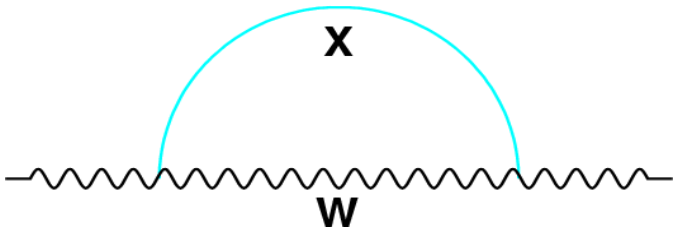
XVth Quark Confinement and Hadron Spectrum Conference
University of Stavanger
August 1, 2022

Motivation for Precision Measurements

- Radiative corrections due to heavy quark and Higgs loops and (potentially) undiscovered particles





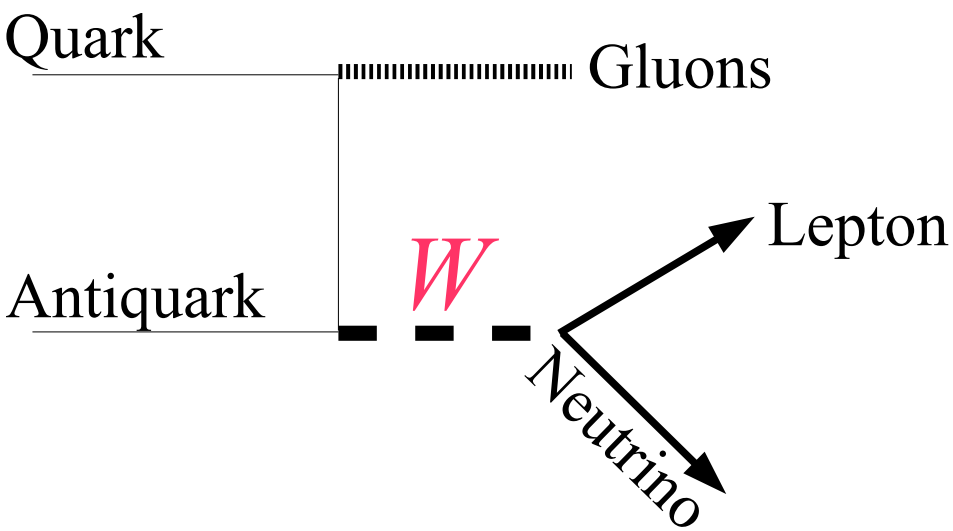


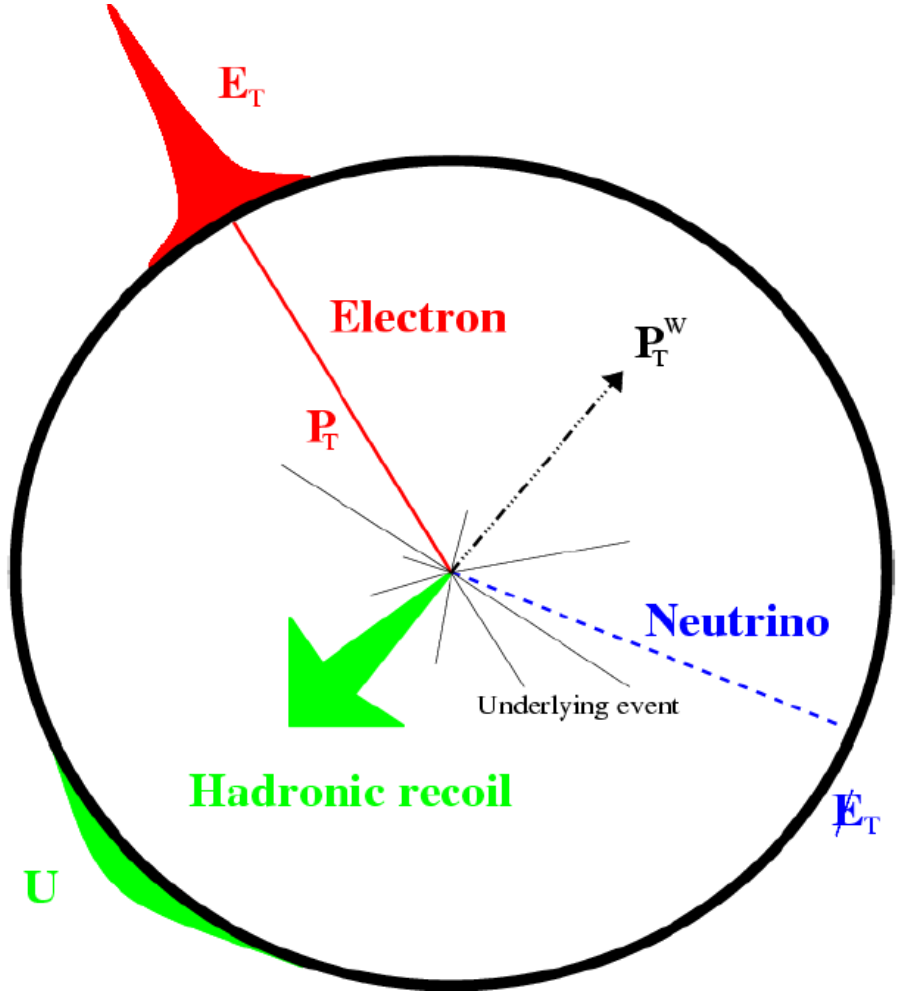
Motivate the introduction of the ρ parameter: $M_W^2 = \rho\,[M_W(\text{tree})]^2$
with the predictions $\Delta\rho = (\rho-1) \sim M_{top}^2$ and $\Delta\rho \sim \ln M_H$

Beyond-SM Modifications to Expected M_W

- Hypotheses to provide a deeper explanation of the Higgs field, its potential and the Higgs boson, include
  - Supersymmetry
  - Compositeness
  - New strong interactions
  - Extended Higgs sector
- Hypothetical sources of particulate dark matter
- Extended gauge sector

W Boson Production at the Tevatron



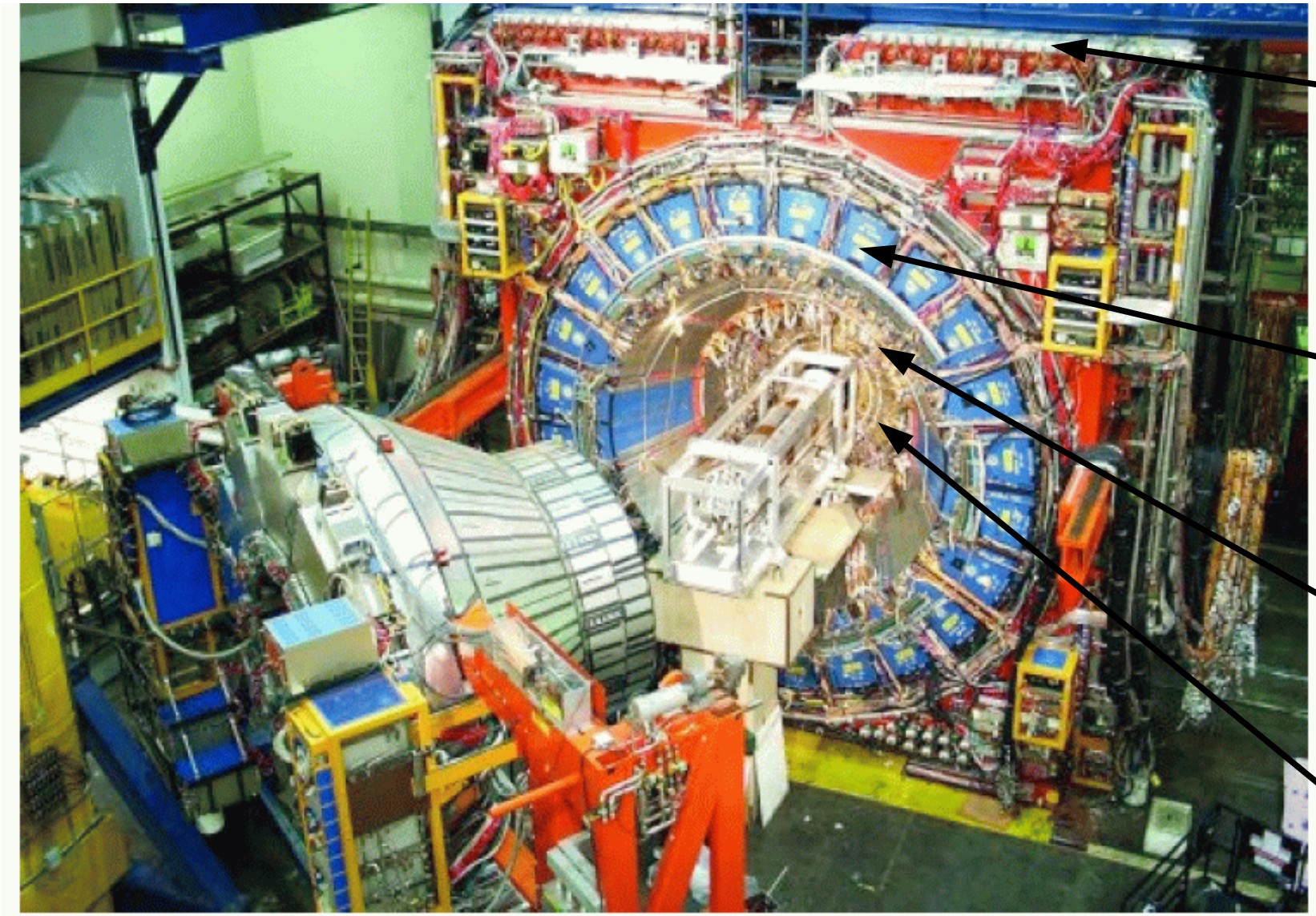


Quark-antiquark annihilation dominates (80%)

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

Initial state QCD radiation is O(10 GeV), measure as soft 'hadronic recoil' in calorimeter (calibrated to ~0.2%)
dilutes *W* mass information, fortunately $p_T(W) << M_W$

Collider Detector at Fermilab (CDF)



Strategy

Maximize the number of internal constraints and cross-checks

Driven by three goals:

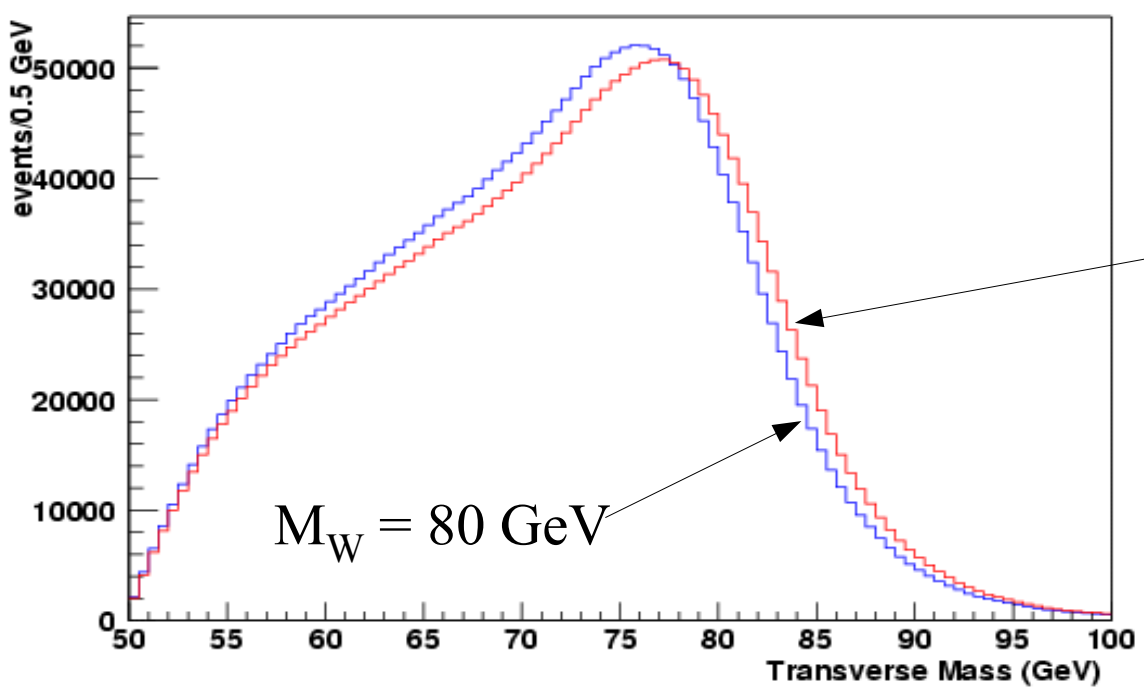
1) Robustness: constrain the same parameters in as many different ways as possible

2) Precision: combine independent measurements after showing consistency

3) minimize bias: blinded measurements of M_Z and M_W

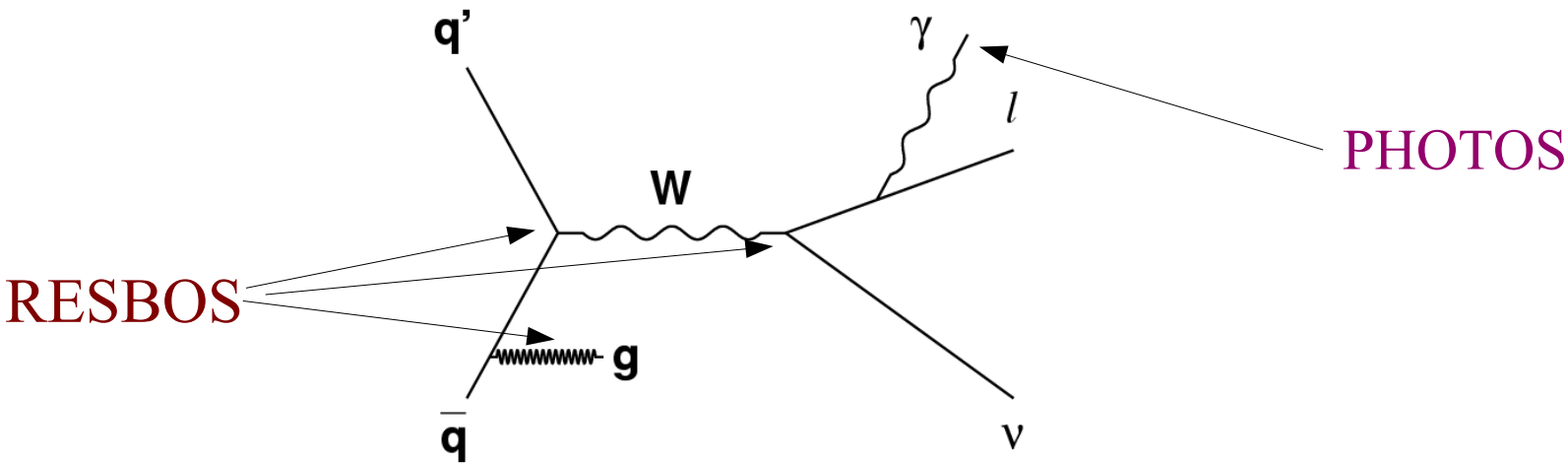
Signal Simulation and Template Fitting

- All signals simulated using a Custom Monte Carlo
  - Generate finely-spaced templates as a function of the fit variable
  - perform binned maximum-likelihood fits to the data
- Custom fast Monte Carlo makes smooth, high statistics templates
  - And provides analysis control over key components of the simulation



M_W = 81 GeV
Monte Carlo template

Generator-level Signal Simulation



- Generator-level input for W & Z simulation provided by RESBOS (C. Balazs & C.-P. Yuan, PRD56, 5558 (1997) and references therein), which
  - Fully differential production and decay distributions
  - Benchmarked to RESBOS2 (J. Isaacson, Y. Fu & C.-P. Yuan, arXiv:2205.02788)
- Multiple radiative photons generated according to PHOTOS (P. Golonka and Z. Was, Eur. J. Phys. C 45, 97 (2006) and references therein)
  - Calibrated to HORACE (C.M. Carloni Calame, G. Montagna, O. Nicrosini and A. Vicini, JHEP 0710:109,2007)

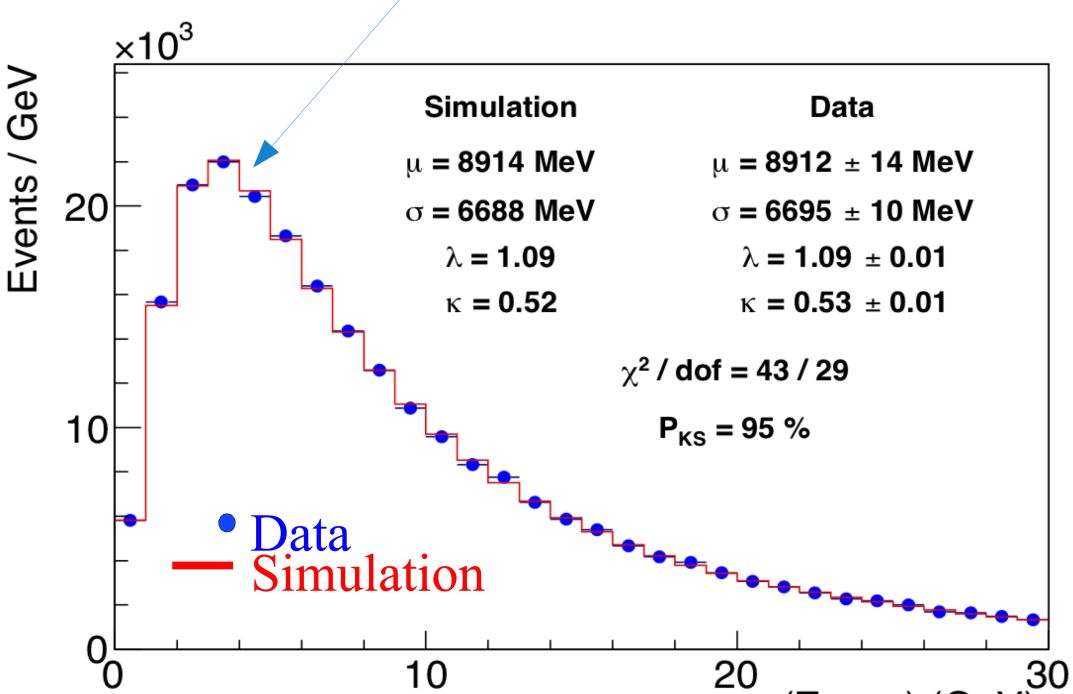
Constraining Boson p_T Spectrum

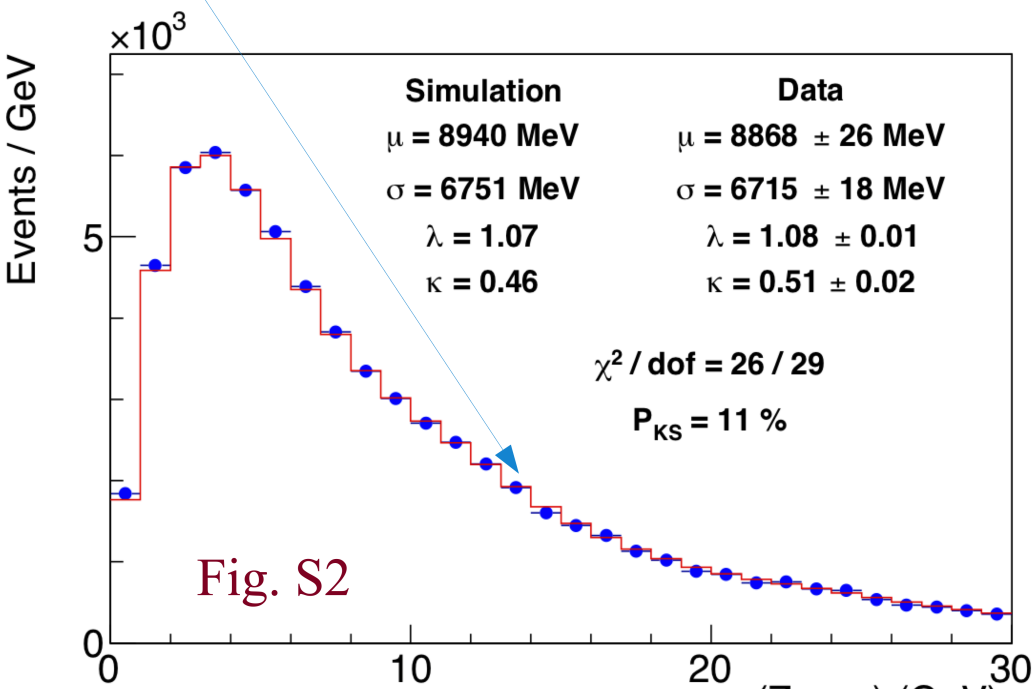
- Fit the non-perturbative parameter g_2 and QCD coupling α_s in RESBOS to $p_T(ll)$ spectra:

ΔM_W = 1.8 MeV

Position of peak in boson p_T spectrum depends on g_2

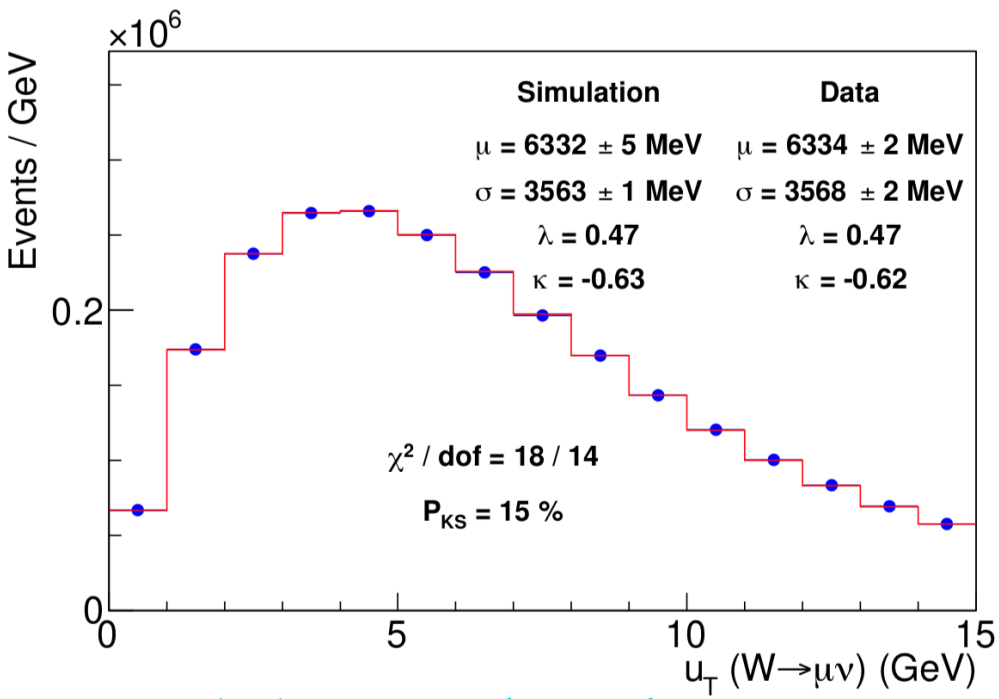
Tail to peak ratio depends on α_s





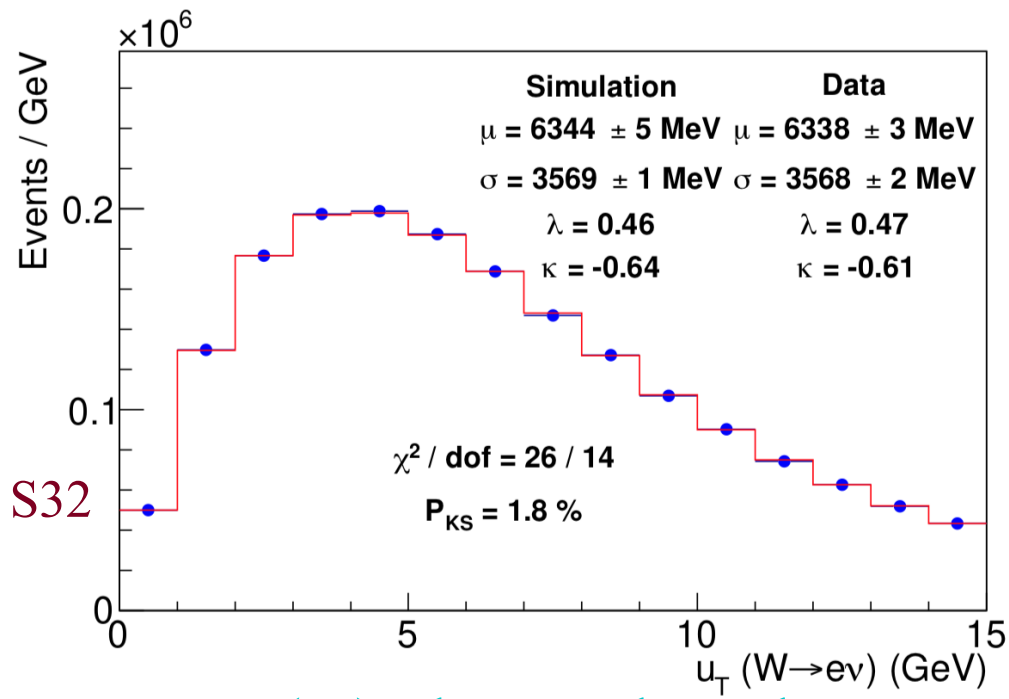
Additional Constraint on $p_T(W)$ Model with *W* boson events

- NEW: In addition to the $p_T(Z)$ data constrain on the boson p_T spectrum, the ratio of the $p_T(W)$ / $p_T(Z)$ spectra is also constrained from the $p_T(W)$ data
  - DyqT : triple-differential cross section calculation at NNLO-QCD used to model scale variation of ratio
  - $p_T(W)$ data is used as constraint on ratio model
  - correlation with hadronic recoil model is taken into account



$p_T(W)$, muon channel

Fig. S32

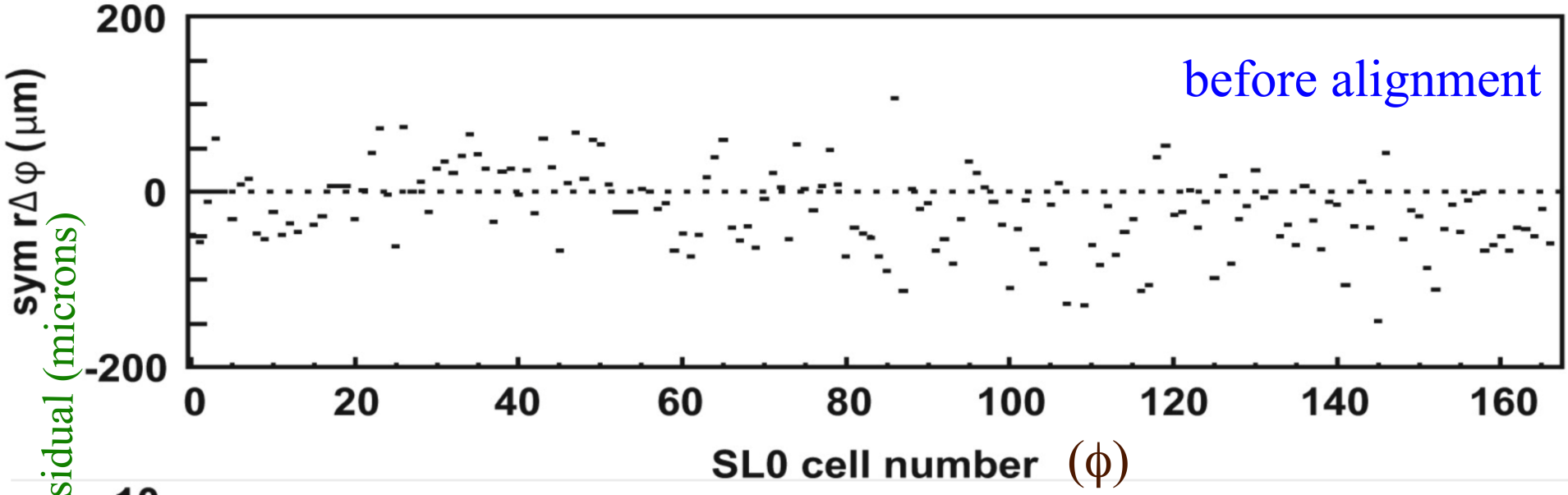


$p_T(W)$, electron channel

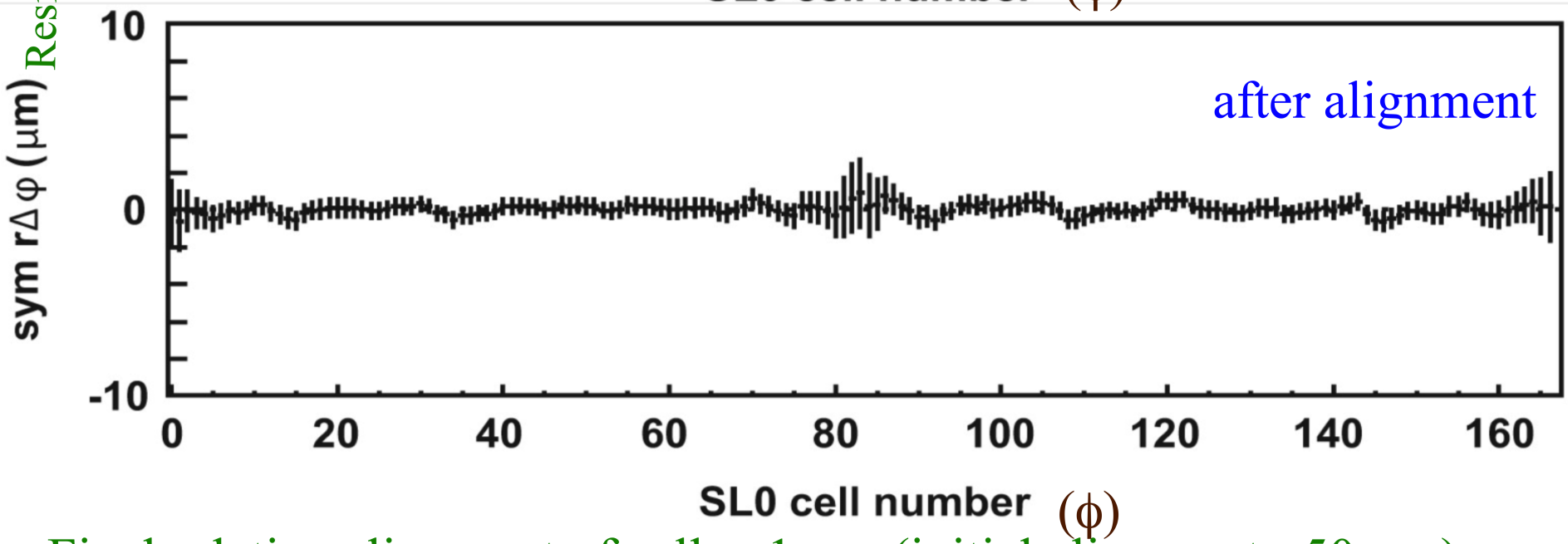
• Data
— Simulation

Residuals of drift chamber measurements after alignment

(AVK & CH, *NIM A* 762 (2014) pp 85-99)



Residual (microns)

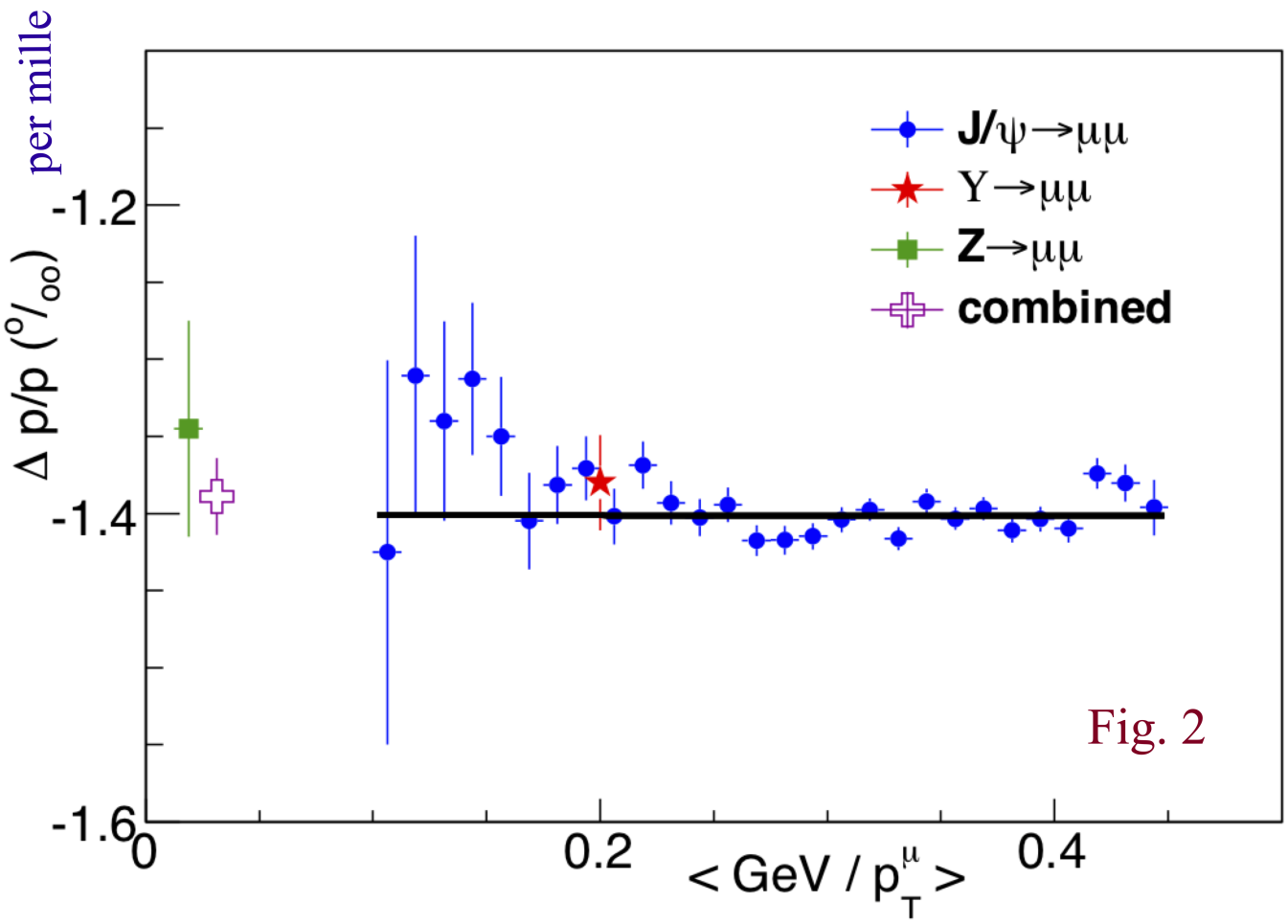


Final relative alignment of cells ~1 μm (initial alignment ~50 μm)

Tracker Linearity Cross-check & Combination

- Final calibration using the J/ψ, ϒ and Z bosons for calibration
- Combined momentum scale correction :

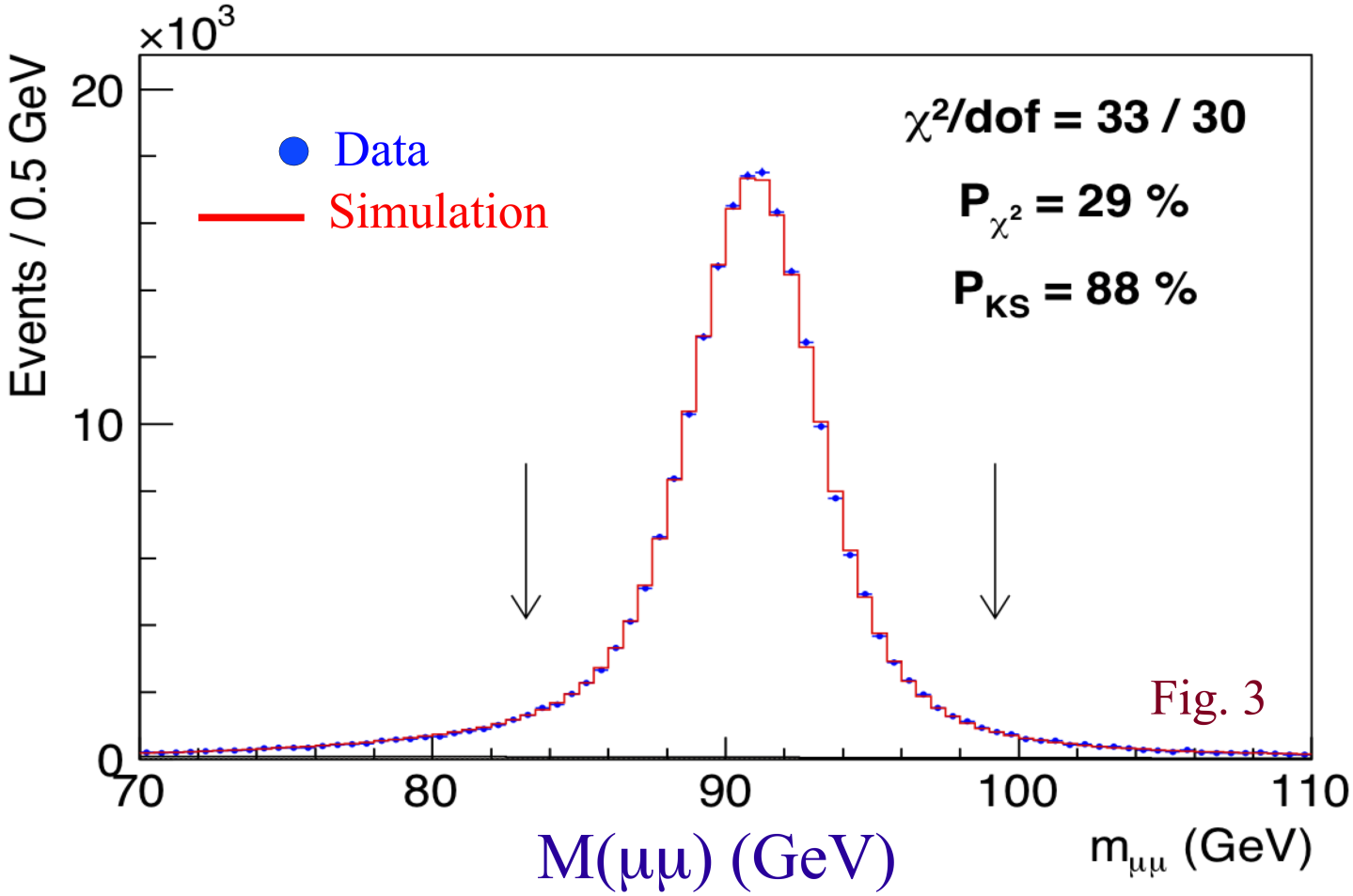
$$\Delta p/p = (-1389 \pm 25_{syst}) \text{ parts per million}$$



$\Delta M_W = 2$ MeV

$Z \rightarrow \mu\mu$ Mass Cross-check & Combination

- Using the J/ψ and ϒ momentum scale, performed "blinded" measurement of *Z* boson mass
  - 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



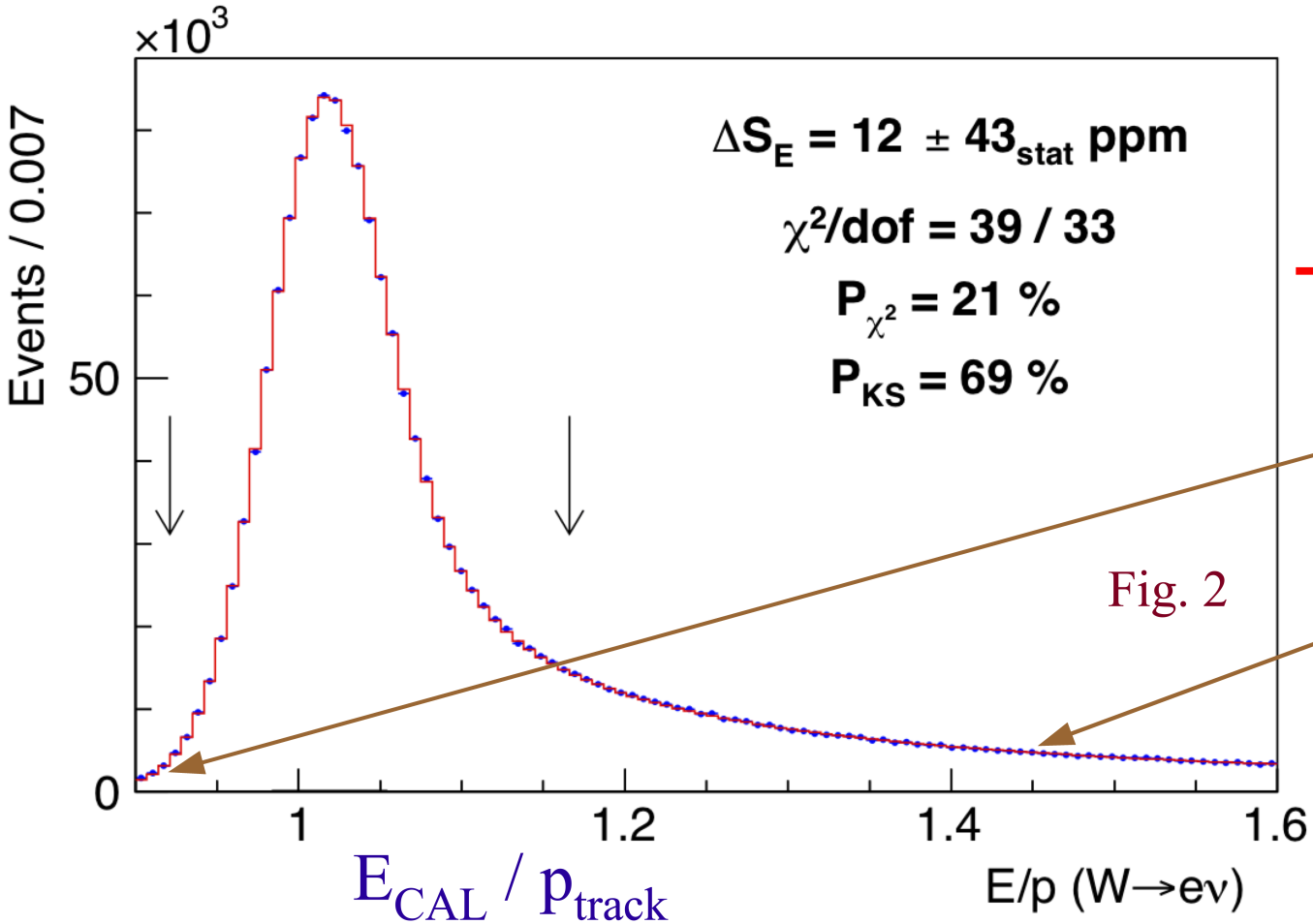
EM Calorimeter Scale

- E/p peak from $W \rightarrow e\upsilon$ decays provides measurements of EM calorimeter scale and its (E_T-dependent) non-linearity

$$\Delta S_E = (43_{stat} \pm 30_{non\text{-}linearity} \pm 34_{X0} \pm 45_{Tracker}) \text{ parts per million}$$

Setting S_E to 1 using E/p calibration from combined $W \rightarrow e\upsilon$ and $Z \rightarrow ee$ samples

$\Delta M_W = 6$ MeV



E_{CAL} / p_{track}

● Data

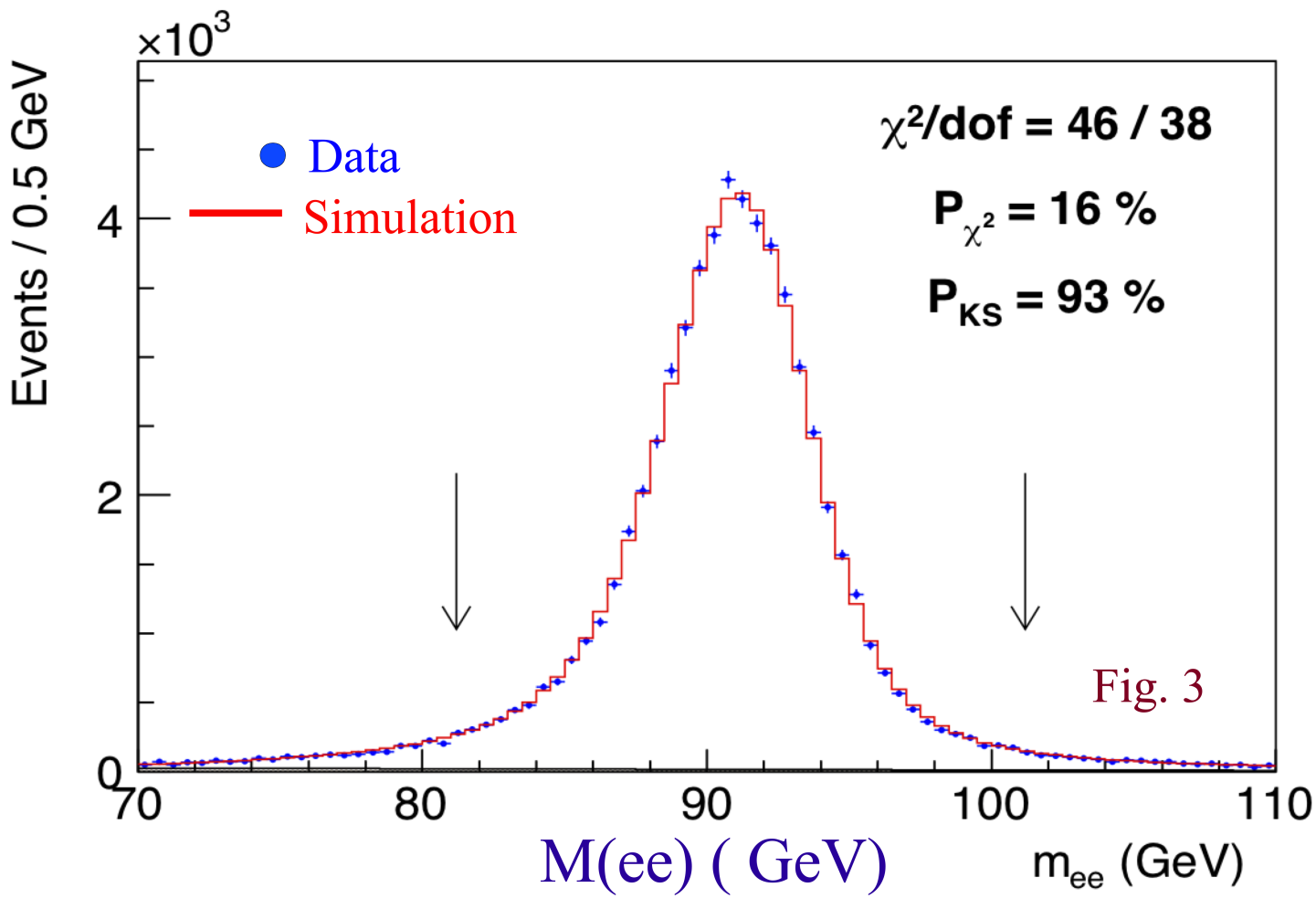
Simulation

Low tail used for tuning calorimeter thickness

High tail of used for tuning model of radiative material

$Z \rightarrow ee$ Mass Cross-check and Combination

- Performed "blind" measurement of Z mass using E/p-based calibration
  - 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



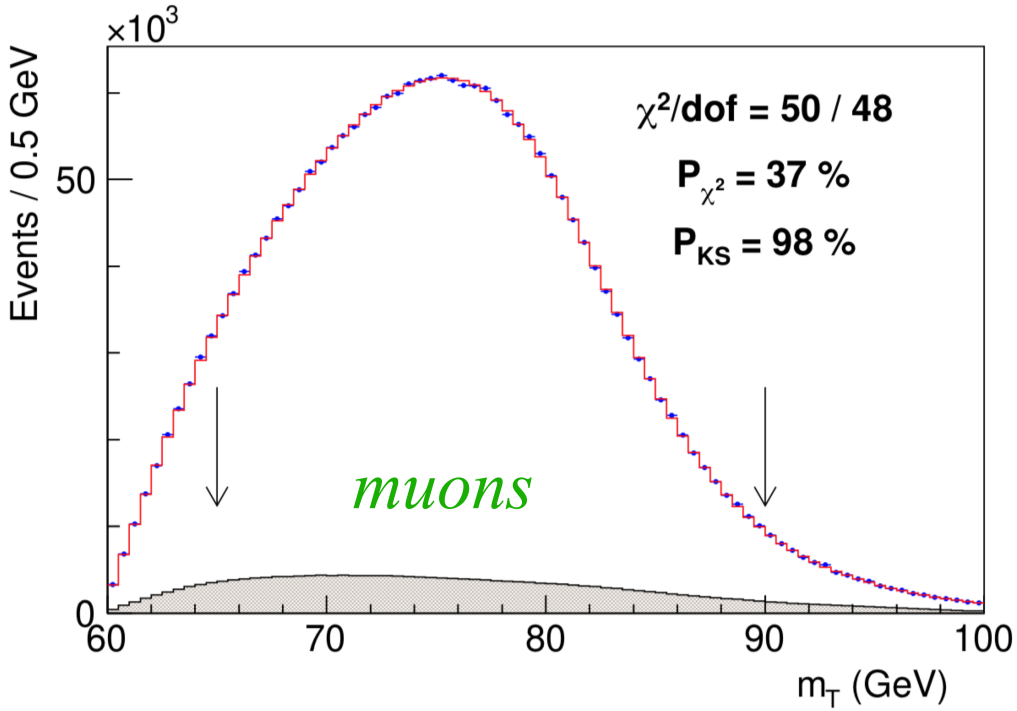
$\Delta M_W = 5.8$ MeV

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

New CDF Result (8.8 fb^{-1})
Combined Fit Systematic Uncertainties

Source	Uncertainty (MeV)
Lepton energy scale	3.0
Lepton energy resolution	1.2
Recoil energy scale	1.2
Recoil energy resolution	1.8
Lepton efficiency	0.4
Lepton removal	1.2
Backgrounds	3.3
p_T^Z model	1.8
p_T^W/p_T^Z model	1.3
Parton distributions	3.9
QED radiation	2.7
W boson statistics	6.4
Total	9.4

W Transverse Mass Fits



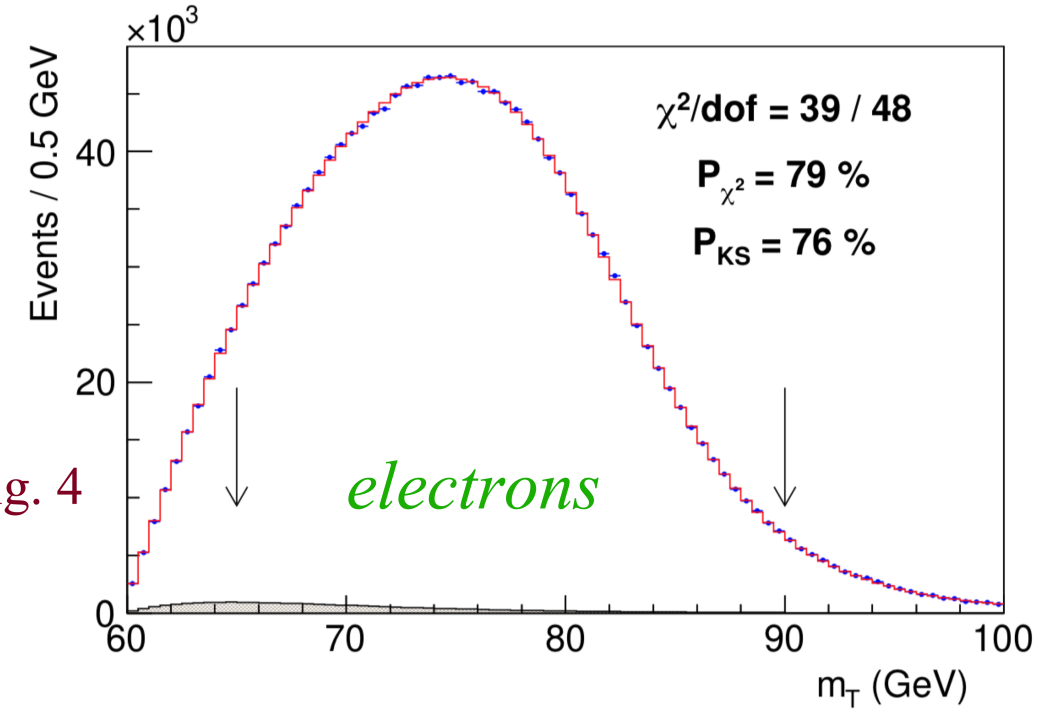
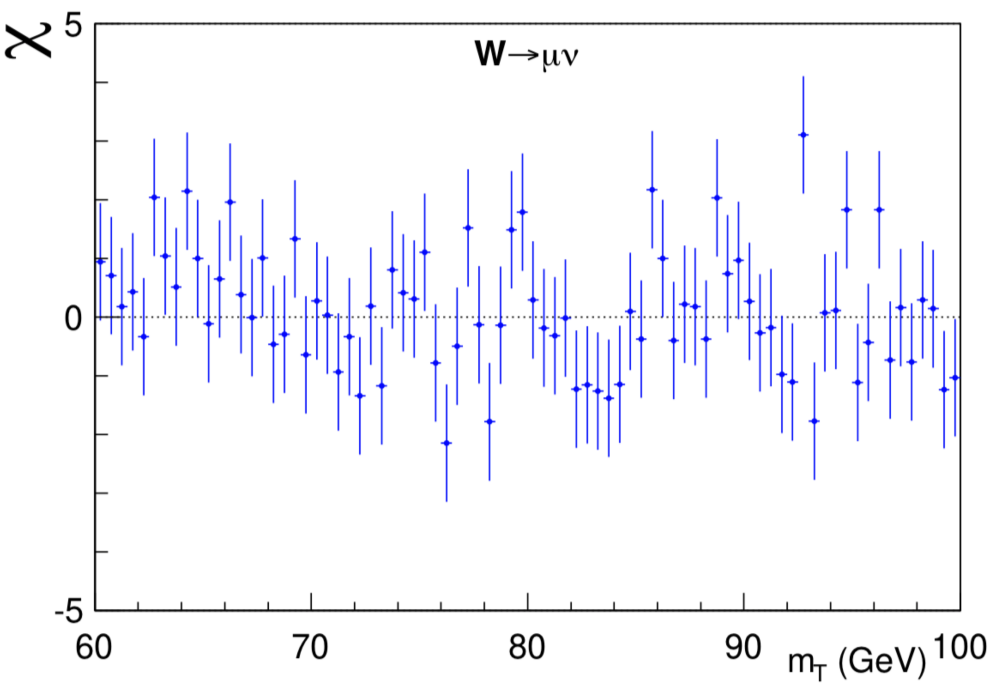


Fig. 4



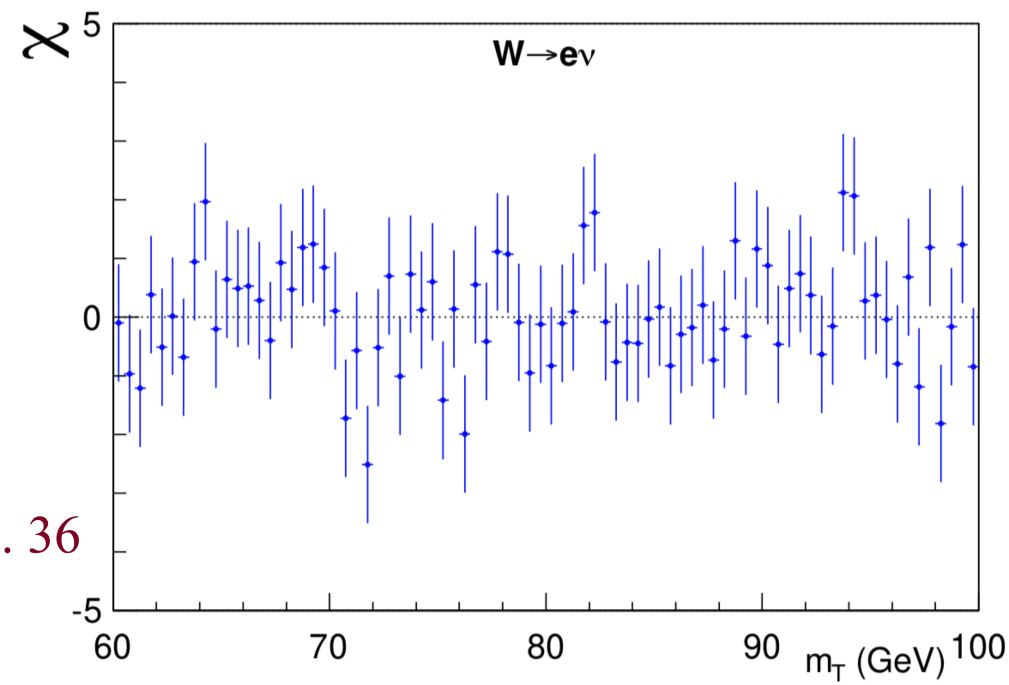


Fig. 36

Summary of W Mass Fits

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

Table 1

Consistency between two channels and three kinematic fits

citation: *Science* **376**, 170 (April 7, 2022); DOI: 10.1126/science.abk1781

Combinations of Fit Results

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

- 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, $P(\chi^2) = 17\%$
- All combined (6 fits): $M_W = 80433.5 \pm 9.4$ MeV, $P(\chi^2) = 20\%$

CDF M_W *vs* m_{top}

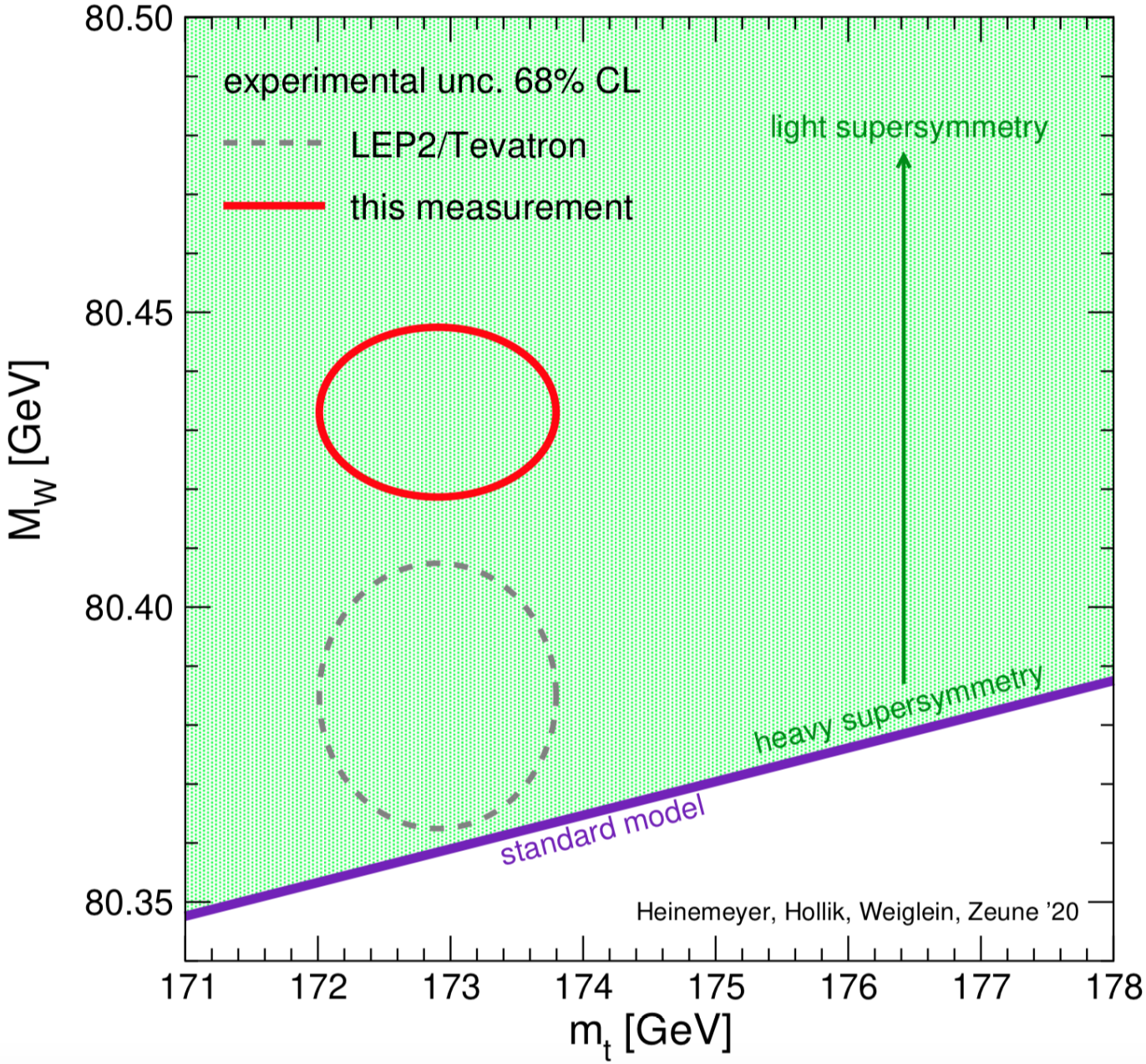


Fig. 1

Understanding Tevatron-LHC correlations and combination with ATLAS in progress

Summary

- The *W* boson mass is a very interesting parameter to measure with increasing precision

- New CDF result is twice as precise as previous measurements:

  - $M_W = 80433.5 \pm 6.4_{stat} \pm 6.9_{syst}$ MeV
    $= 80433.5 \pm 9.4$ MeV

- Difference from SM expectation of $M_W = 80{,}357 \pm 6$ MeV

  - significance of 7.0σ
  - suggests the possibility of improvements to the SM calculation or of extensions to the SM

Thank you for your attention !

Question to the Community

- The *W* boson mass deviation has triggered the investigation of a number of hypotheses of new physics.

- These hypotheses may predict new particles or phenomena that are observable at the HL-LHC and small experiments.

- Question: In the next few years, can the community converge on a list of concrete predictions that can serve as targets for searches or measurements for current and future experiments?

- The pursuit of some of these predictions may require the development of new technologies. The answers to the previous question provide the science case for the R&D effort and funding needed to pursue these technologies proactively.