Precision Measurement of the W Boson Mass at CDF

Bo Jayatilaka
Fermilab

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Fermilab

Outline

- Introduction: theoretical and experimental motivation
- Overall analysis strategy
- Theoretical inputs
- Track momentum scale determination
- Calorimeter energy scale determination
- Hadronic recoil calibration
- W mass fits
- Summary and outlook

T. Aaltonen et al, Science **376**, 170 (2022)
DOI: 10.1126/science.abk1781

The W boson mass in electroweak theory

- Electroweak sector of the standard model is constrained at tree level by

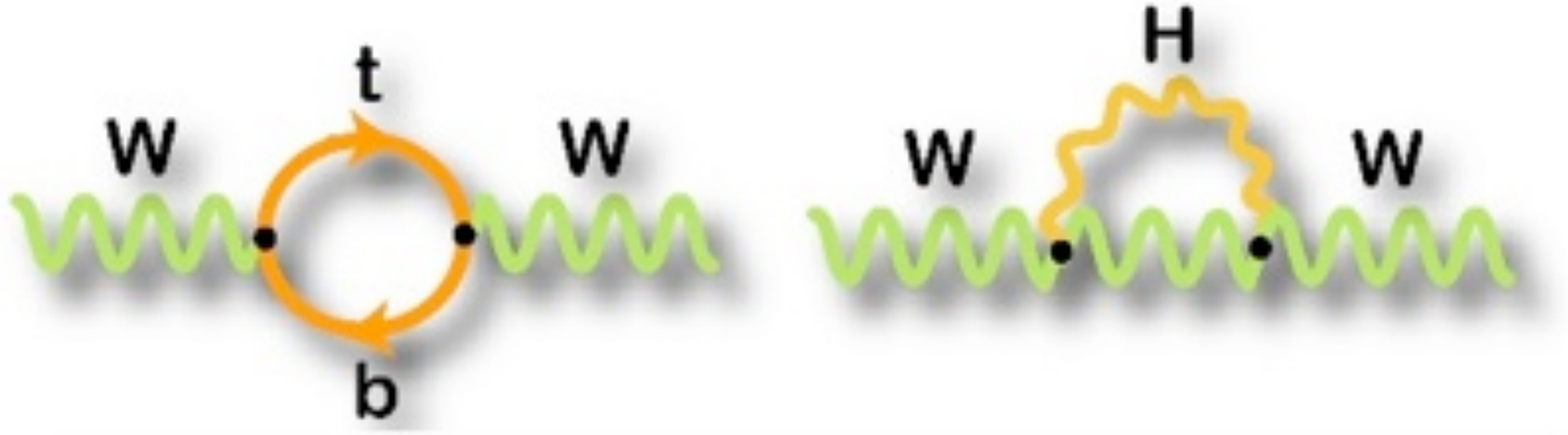
$$G_F = 1.16637(1) \times 10^{-5}\ \mathrm{GeV}^{-2} \qquad \alpha_{EM}(Q^2 = M_Z^2) = 1/127.918(18)$$

$$M_Z = 91.1876(21)\ \mathrm{GeV}/c^2$$

- Including radiative corrections, M_W is predicted by

$$M_W^2 = \frac{\pi \alpha_{EM}}{\sqrt{2} G_F \sin^2\theta_W (1 - \Delta r)} \text{ where } \sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2}$$

- Radiative corrections Δr are dominated by top and Higgs loops



$$m_t = 172.76(30)\ \mathrm{GeV}/c^2$$

$$M_H = 125.30(13)\ \mathrm{GeV}/c^2$$

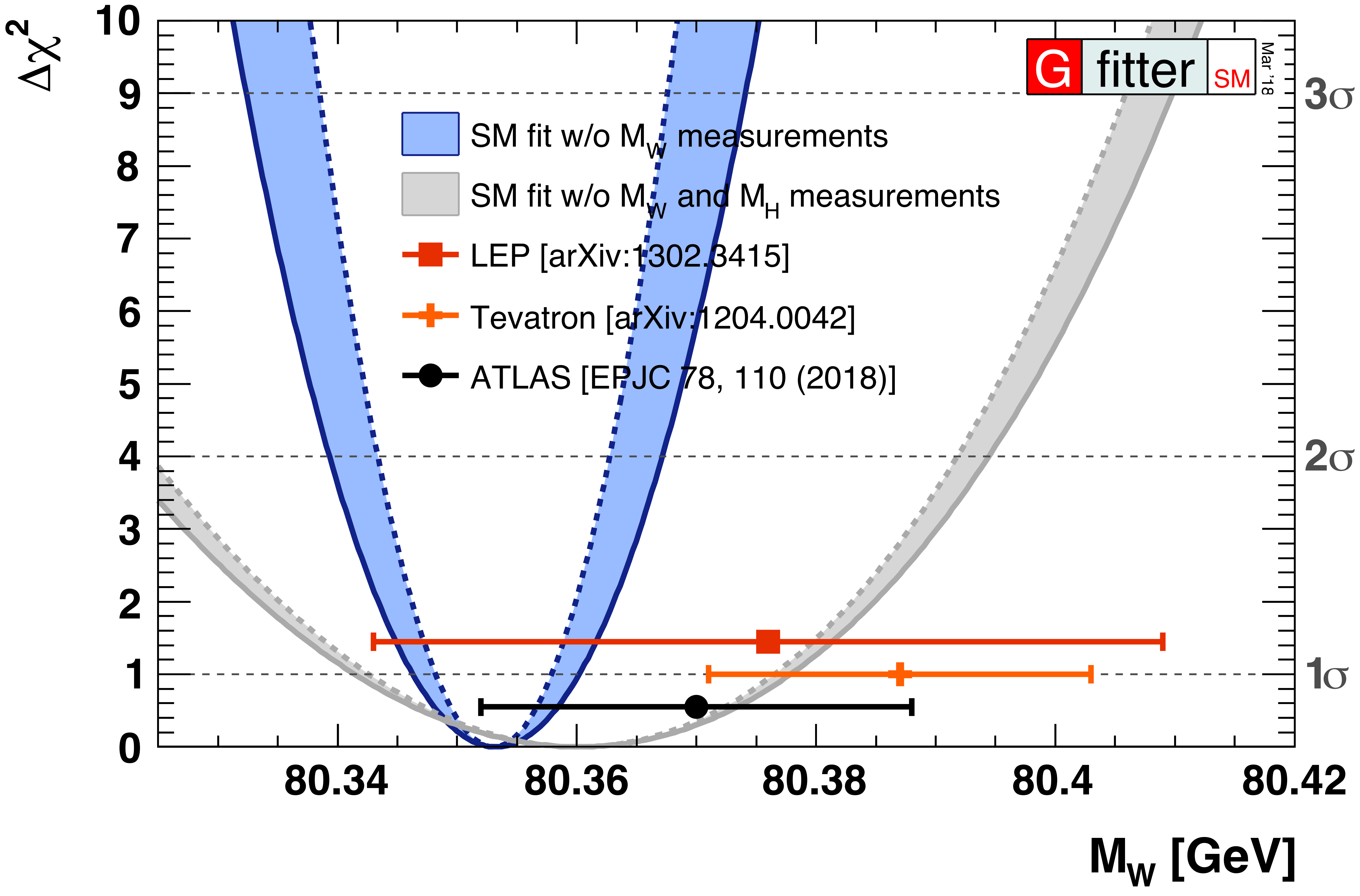
- Precision measurement of M_W provides a crucial test of the standard model

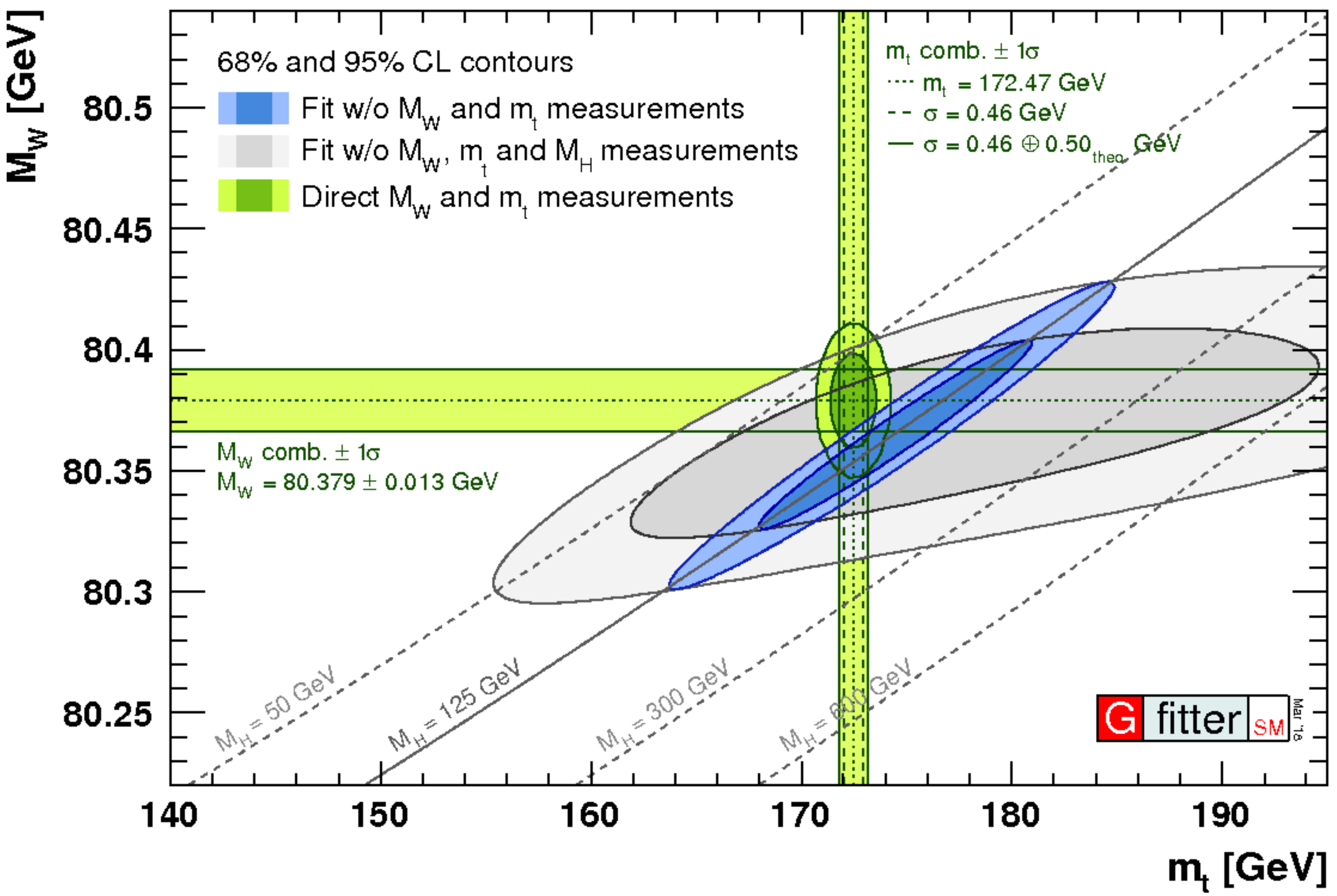
Standard model determination of M_W

- Following the discovery of the Higgs boson, M_W can be tightly constrained in the SM

M_W = 80357 ± 4 (inputs) ± 4 (theory) MeV

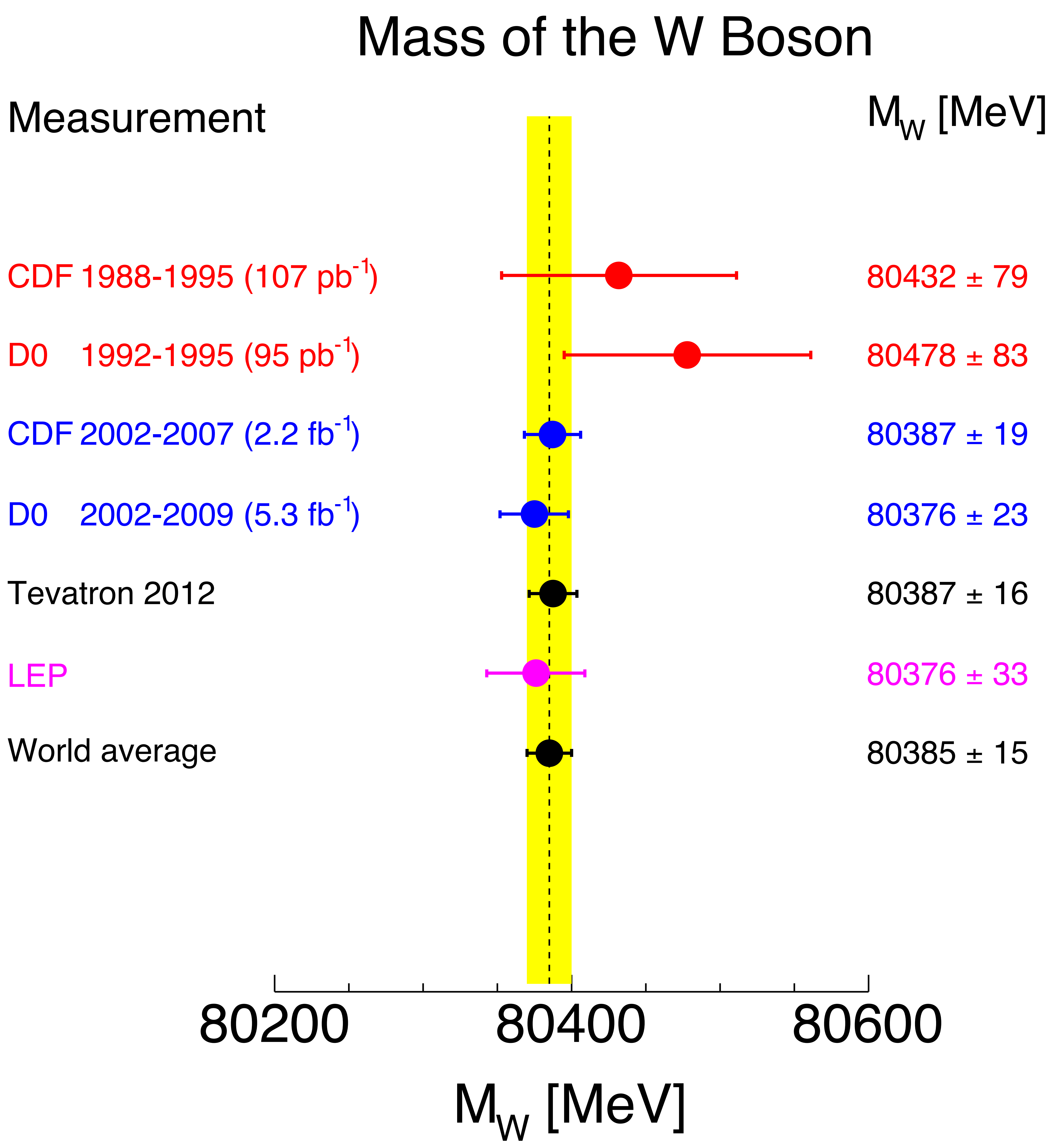
- Experimental measurement at this level of precision is crucial





Experimental determination(s) of M_W

- Summary shown as of last Tevatron combination
  - PRD 88, 052018 (2013)
- Since then, updated measurements from LHC experiments
  - ATLAS: M_W = 80370±19 MeV
    - EPJ C 78 (2018) 110
  - LHCb: M_W = 80354±32 MeV
    - JHEP 01 (2022) 036
- World Average (PDG 2020)
  - **M_W = 80379±12 MeV**
- 2012 CDF measurement made with ~25% available data
  - Goal: *match world average precision with full dataset*



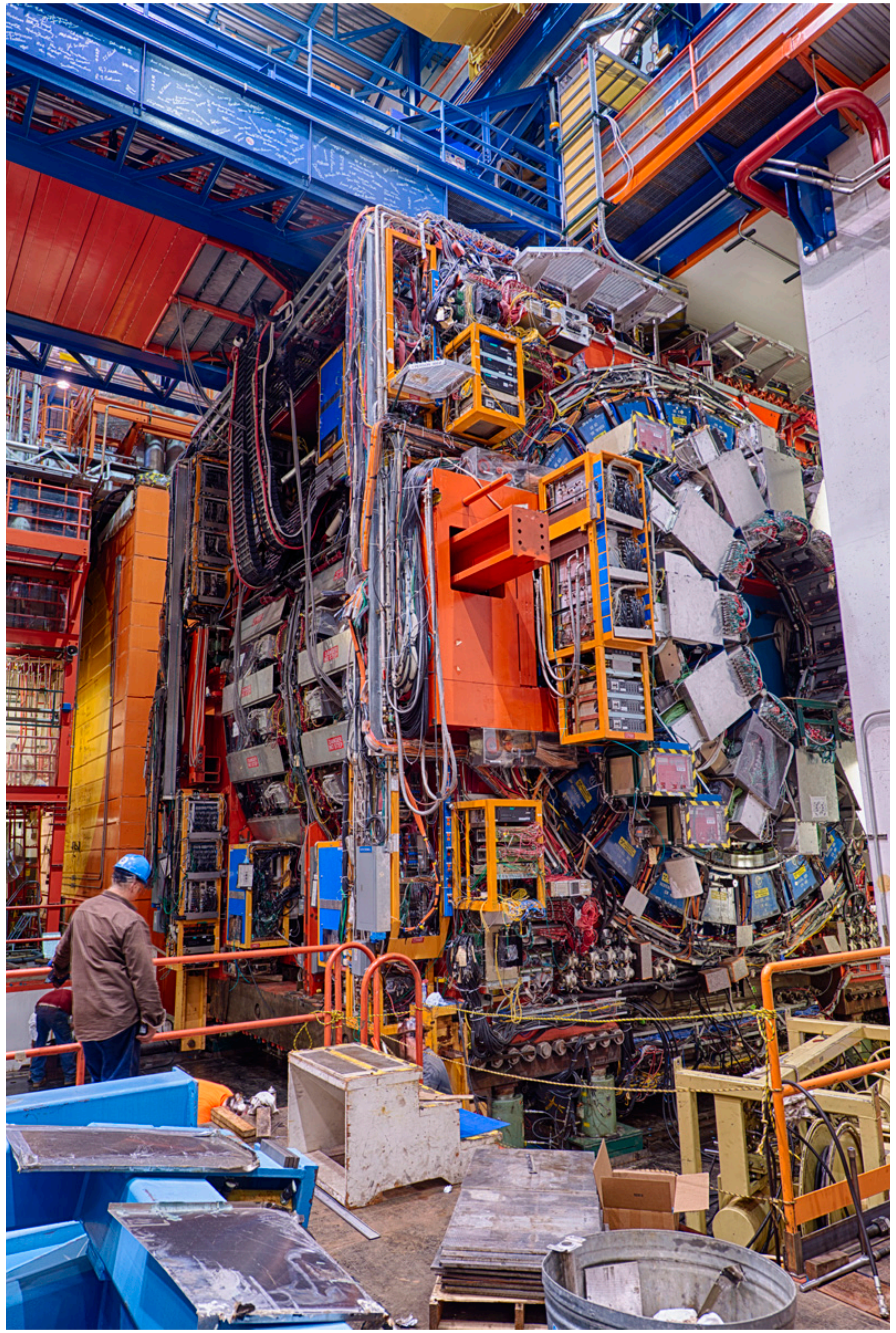
Analysis Strategy

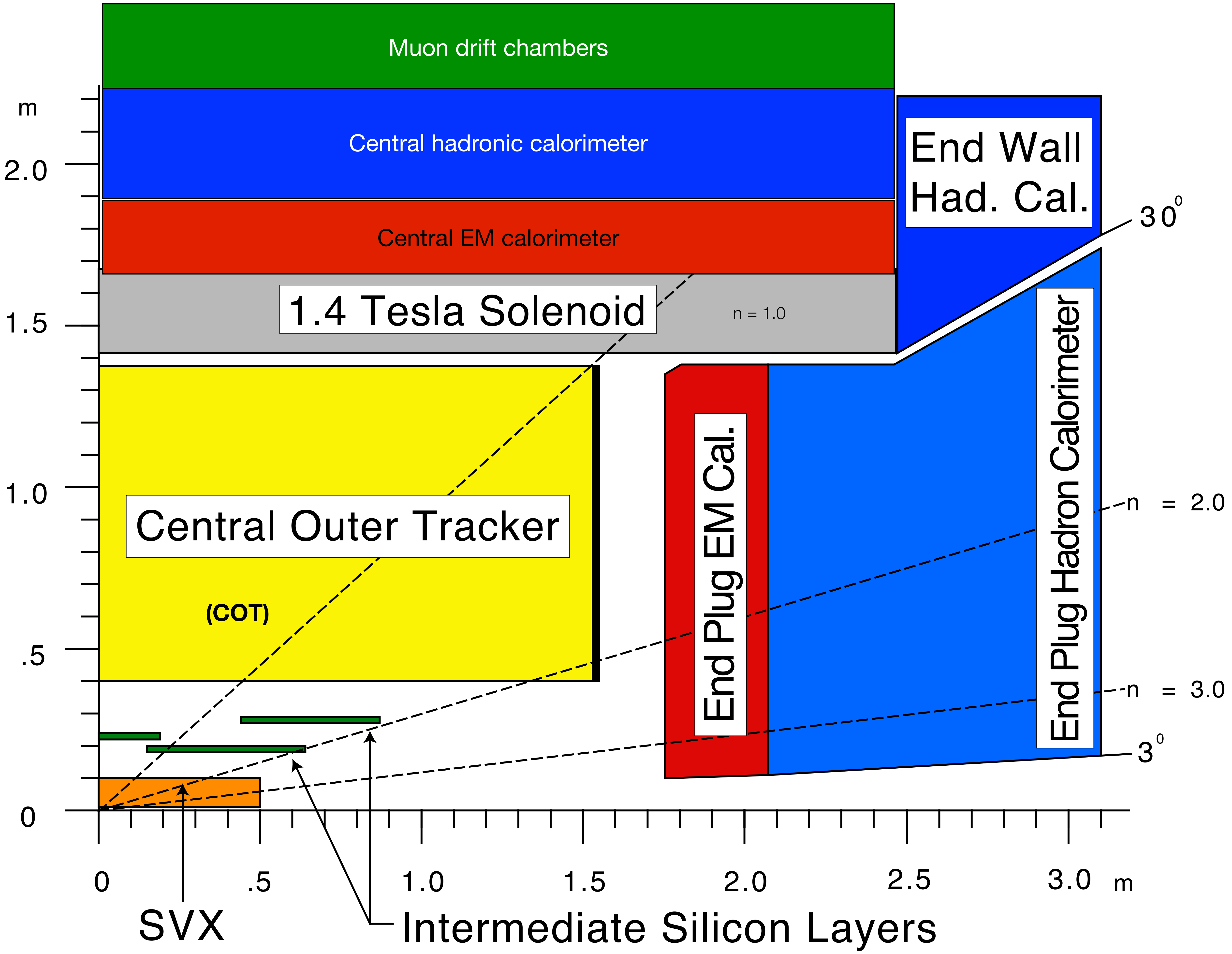
The Tevatron at Fermilab

- 1.96 TeV ppbar collider
  - Highest energy p-pbar collider in the world
  - First superconducting synchrotron ever built
  - Typical inst. lumi.: 3x10^{32} cm^{-2}s^{-1}
  - LHC (Run 2): ~2x10^{34} cm^{-2}s^{-1}
- Bunch spacing: 396 ns
  - LHC: 25 ns

- Ceased operations Sep 30, 2011
  - ~12 fb^{-1} delivered to CDF and DØ
  - W mass measurement utilizes 8.8 fb^{-1} after quality cuts

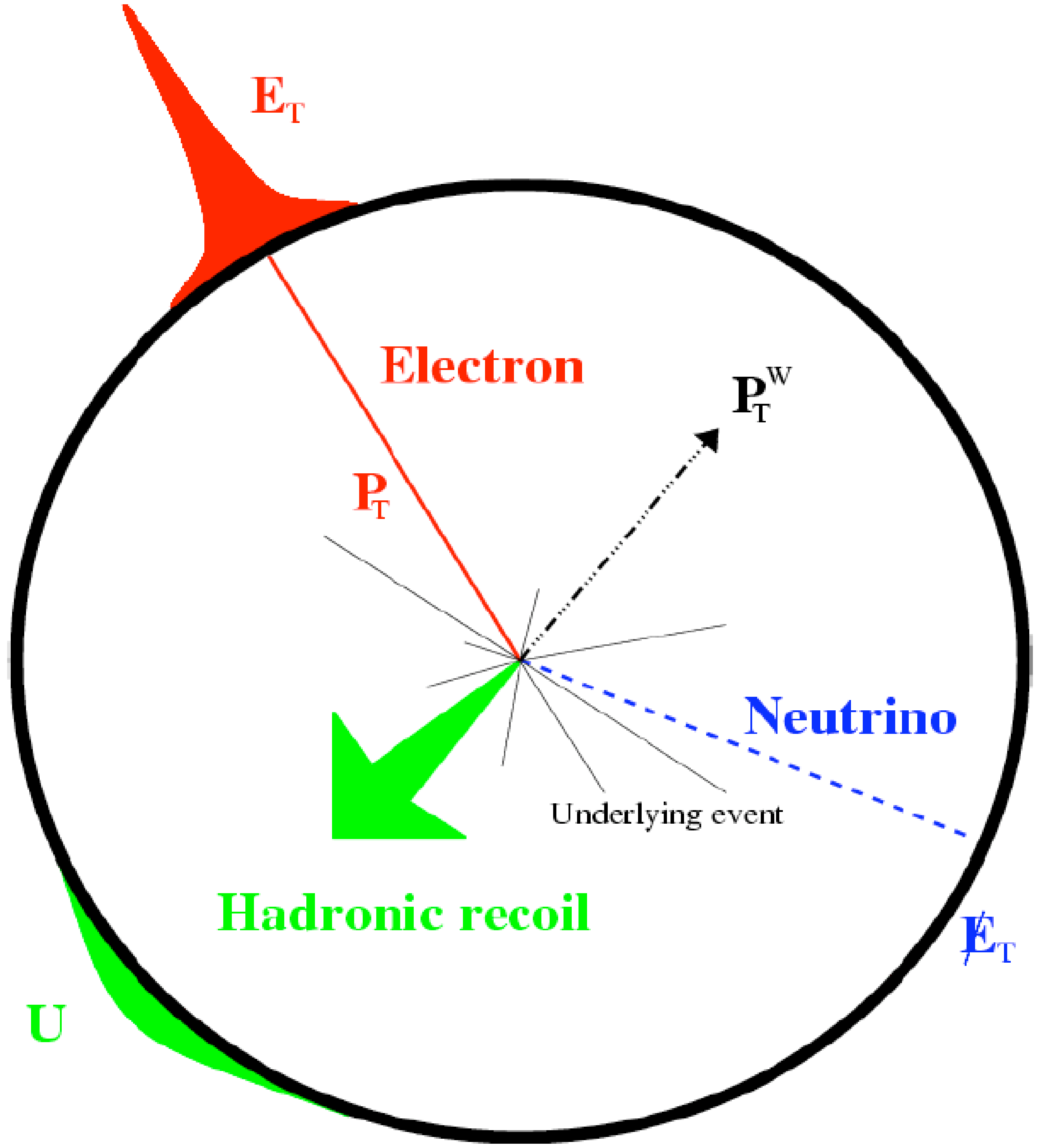
CDF II (2001-2011)





Obtaining precision

- Start with **clean, low-background** events
  - no taus, no hadronic decays
- Lepton p_T carries most information
  - Precision achieved: *0.004%*
- Hadronic recoil affects inference of neutrino energy
  - Calibrate to ~0.2%
  - Reduce impact by requiring $p_T(W) \ll M_W$
- Need:
  - Accurate **theoretical model**
    - Including boson p_T model and QED radiation
  - Tunable **fast simulation**
    - Parameterized detector description for study of systematic effects
  - Large data samples of well-measured states



Measurement strategy (broadly speaking)

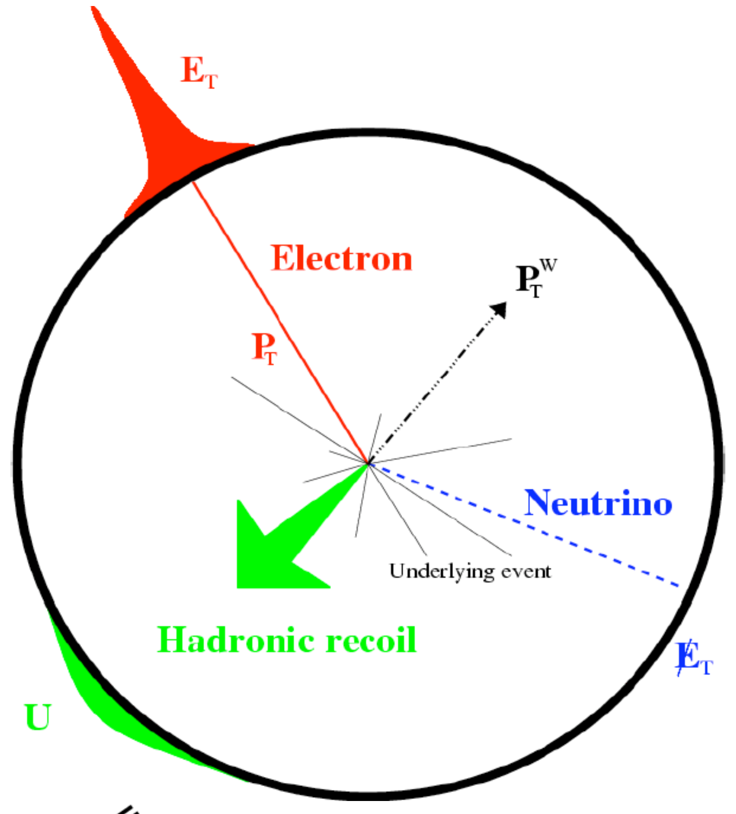
- Maximize internal constraints and cross-checks
- Why?
  - **Robustness**: Constrain the same parameter multiple ways
  - **Precision**: after demonstrating robustness, combine independent measurements

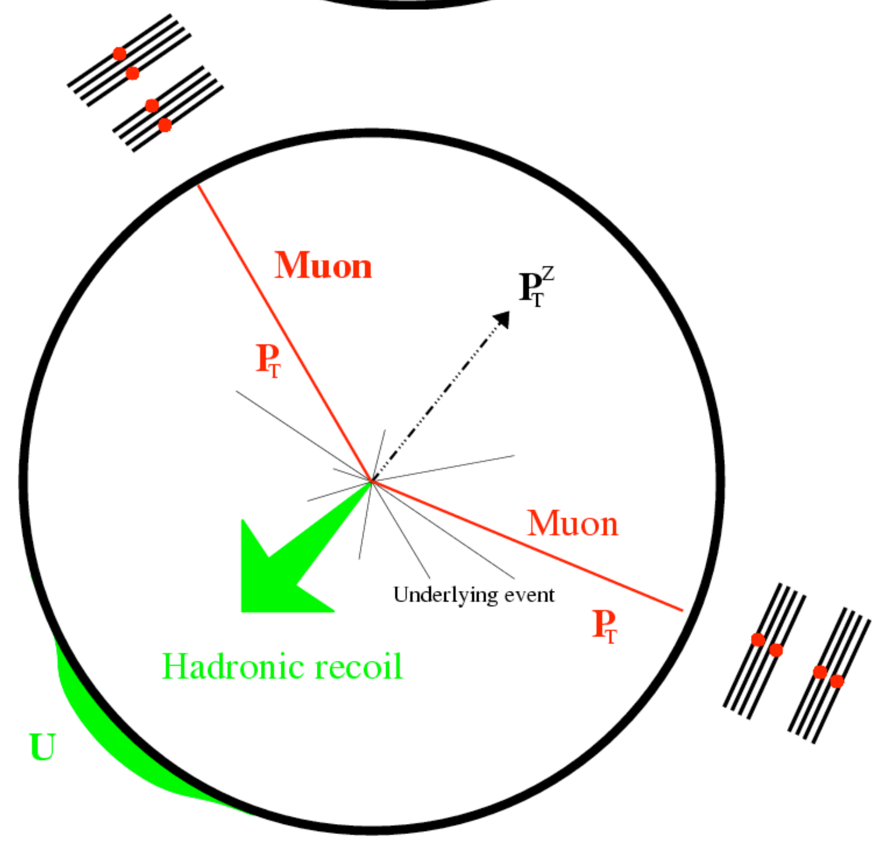
Measurement strategy (in practice)

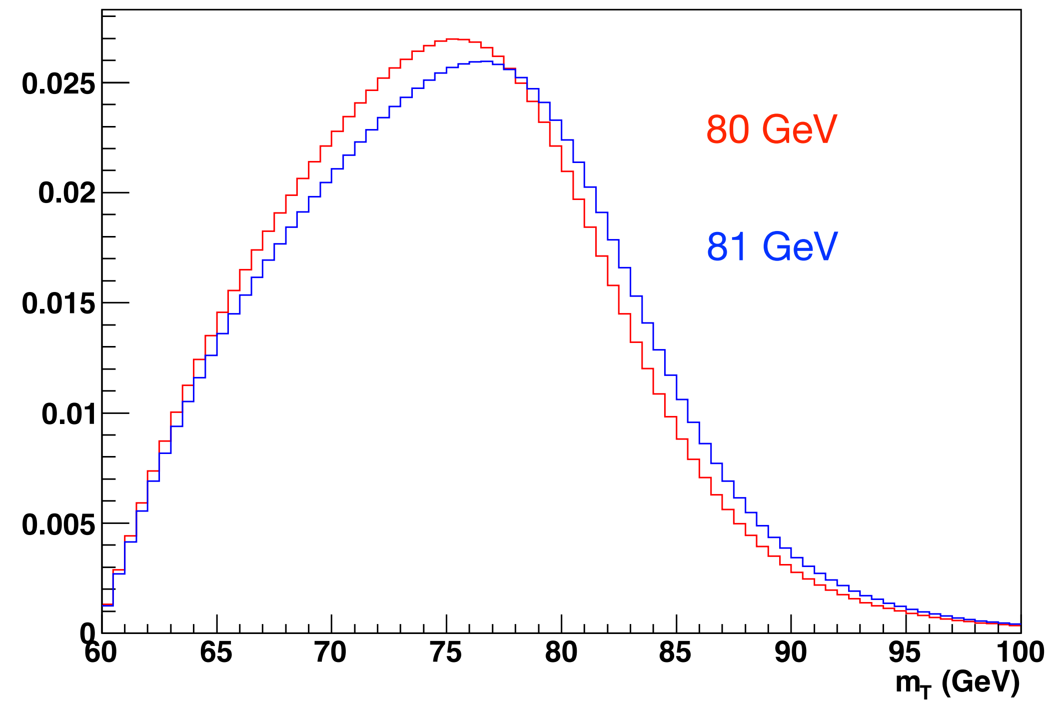
- Perform COT alignment with cosmic ray data
- Calibrate track momentum scale using dimuon resonances (J/ψ, Υ).
  - **Cross-check** with Z mass measurement and add as further calibration point
- Calibrate calorimeter energy using E/p of W and Z decays
  - **Cross-check** with Z mass measurement
- Calibrate hadronic recoil with Z decays to μ, e
  - **Cross-check** with W recoil distributions
- Perform fits to e/μ p_T, ν p_T, and **transverse mass**

$$m_T = \sqrt{2 p_T^{\ell} p_T^{\nu} (1 - \cos \Delta\theta_{\ell\nu})}$$

  - Binned maximum likelihood fit to templates from tuned simulation
- Combine all **six** fits to yield final answer

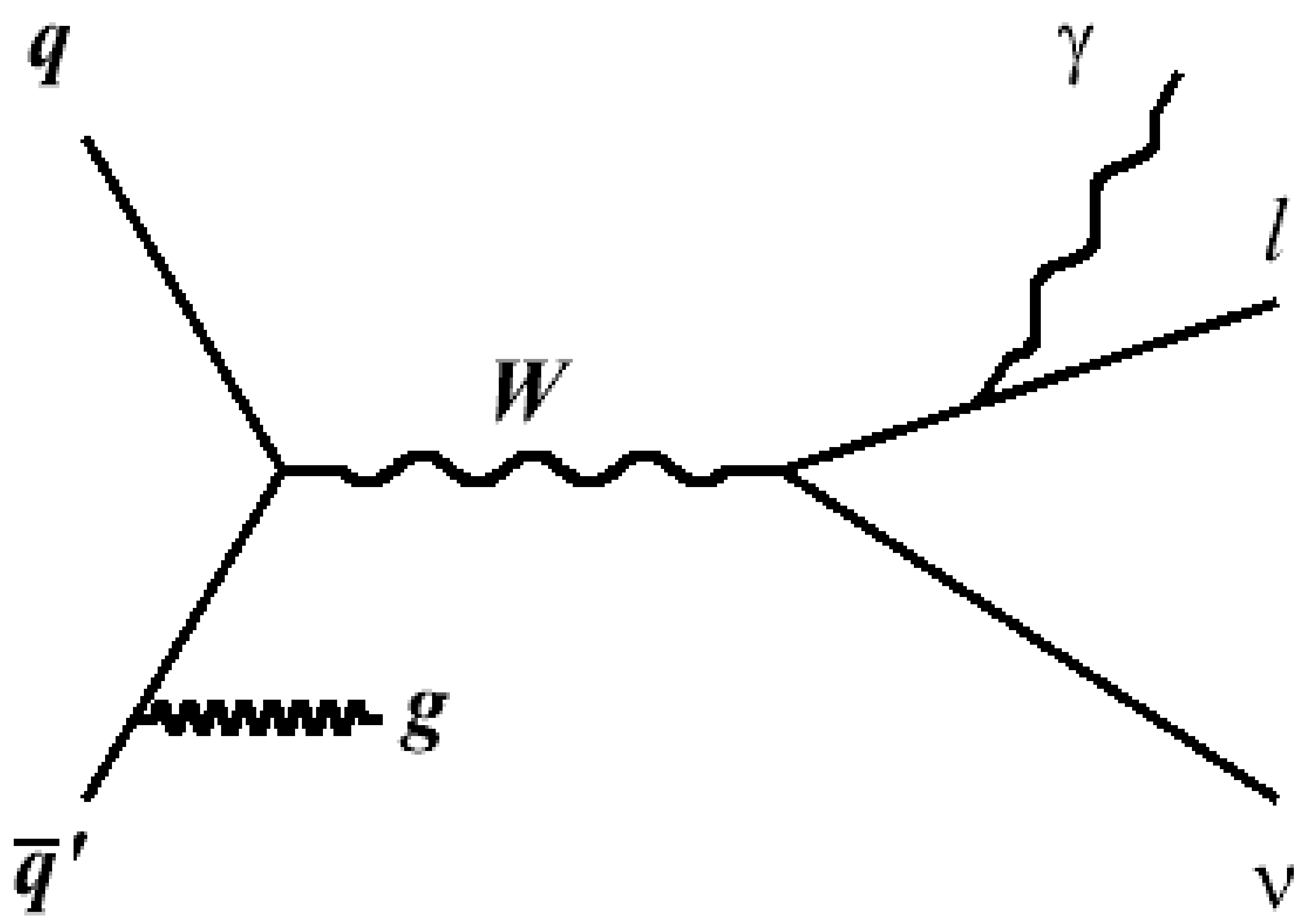






Selecting W (and Z) bosons at CDF

Production at the Tevatron dominated by $q\bar{q}$ (valence quarks)



Select $e\nu$ and $\mu\nu$ decays with high-p_T lepton trigger

Lepton candidates:
Electron E_T>30 GeV
(track p_T>18 GeV)
or Muon p_T>30 GeV

W boson candidates:
1 lepton passing cuts
$|\mathbf{u}| < 15$ GeV
$p_T^{\nu} > 30$ GeV
$60 < m_T < 100$ GeV

Z boson candidates:
2 lepton passing cuts
$66 < m_{ll} < 116$ GeV

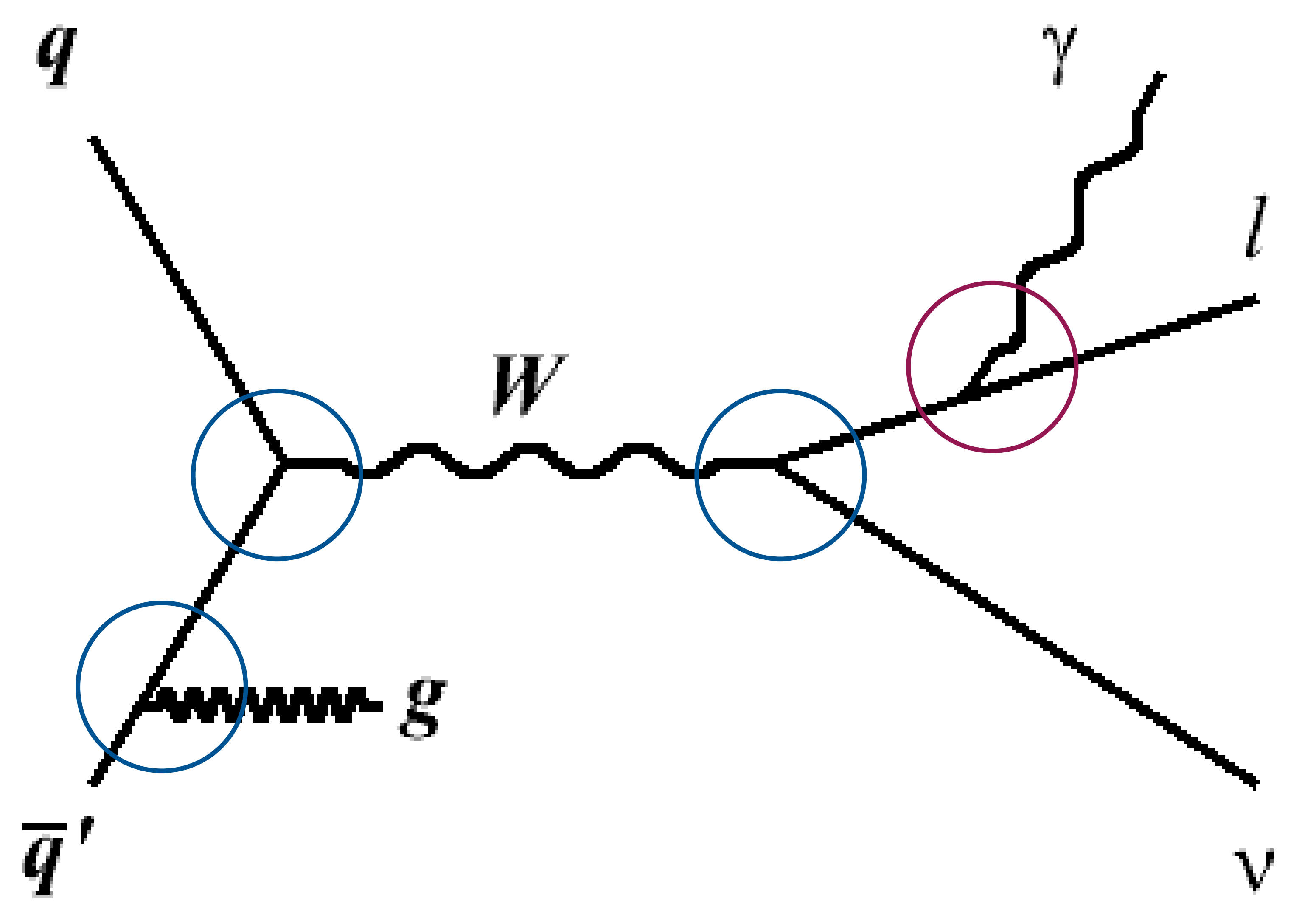
Analysis dataset: **8.8 fb^{-1}**

Candidate events:
W: 1811700 (*e*), 2424486 (μ)
Z: 66180 (*e*), 238534 (μ)

Theoretical Model

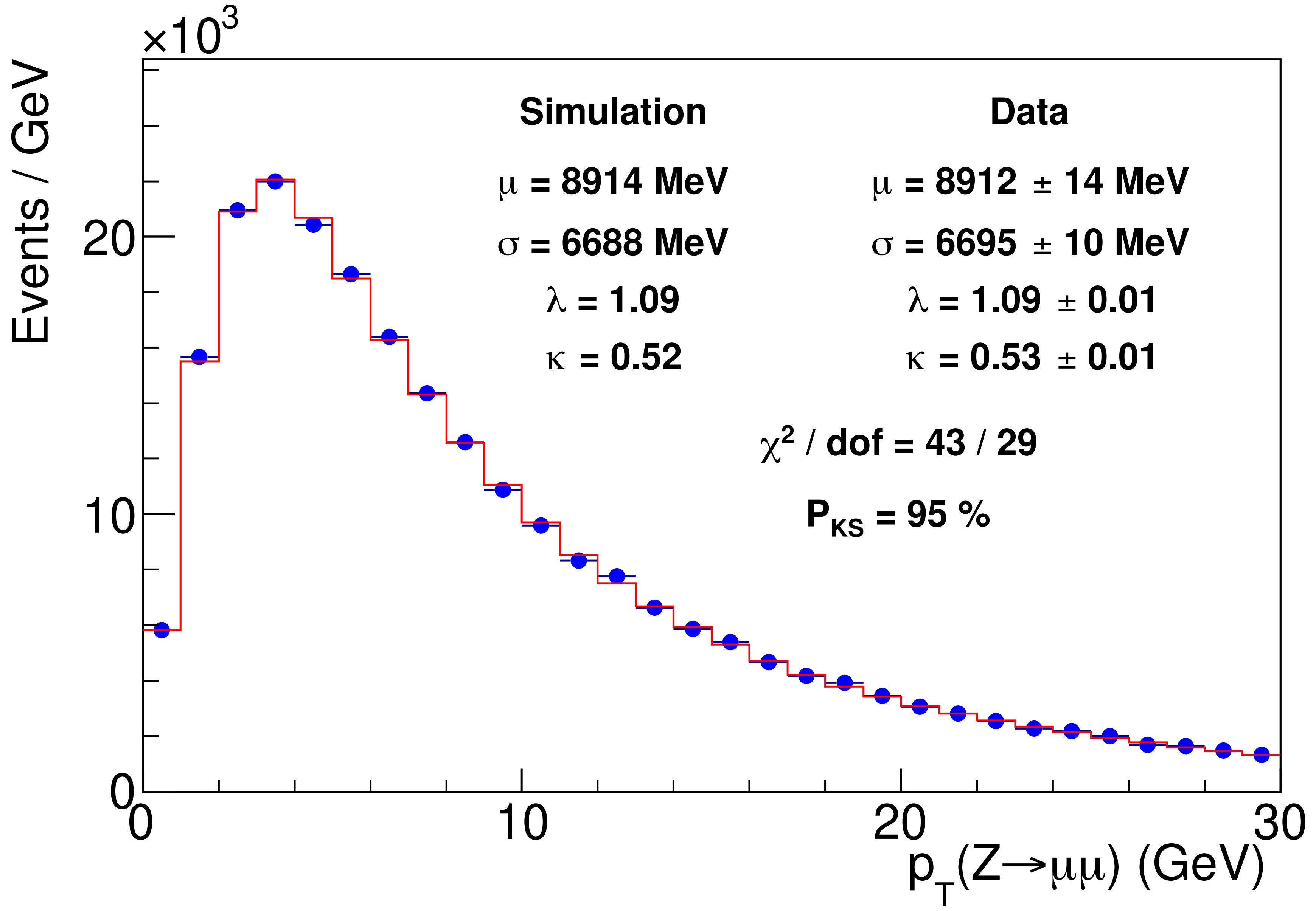
Event generation and boson p_T

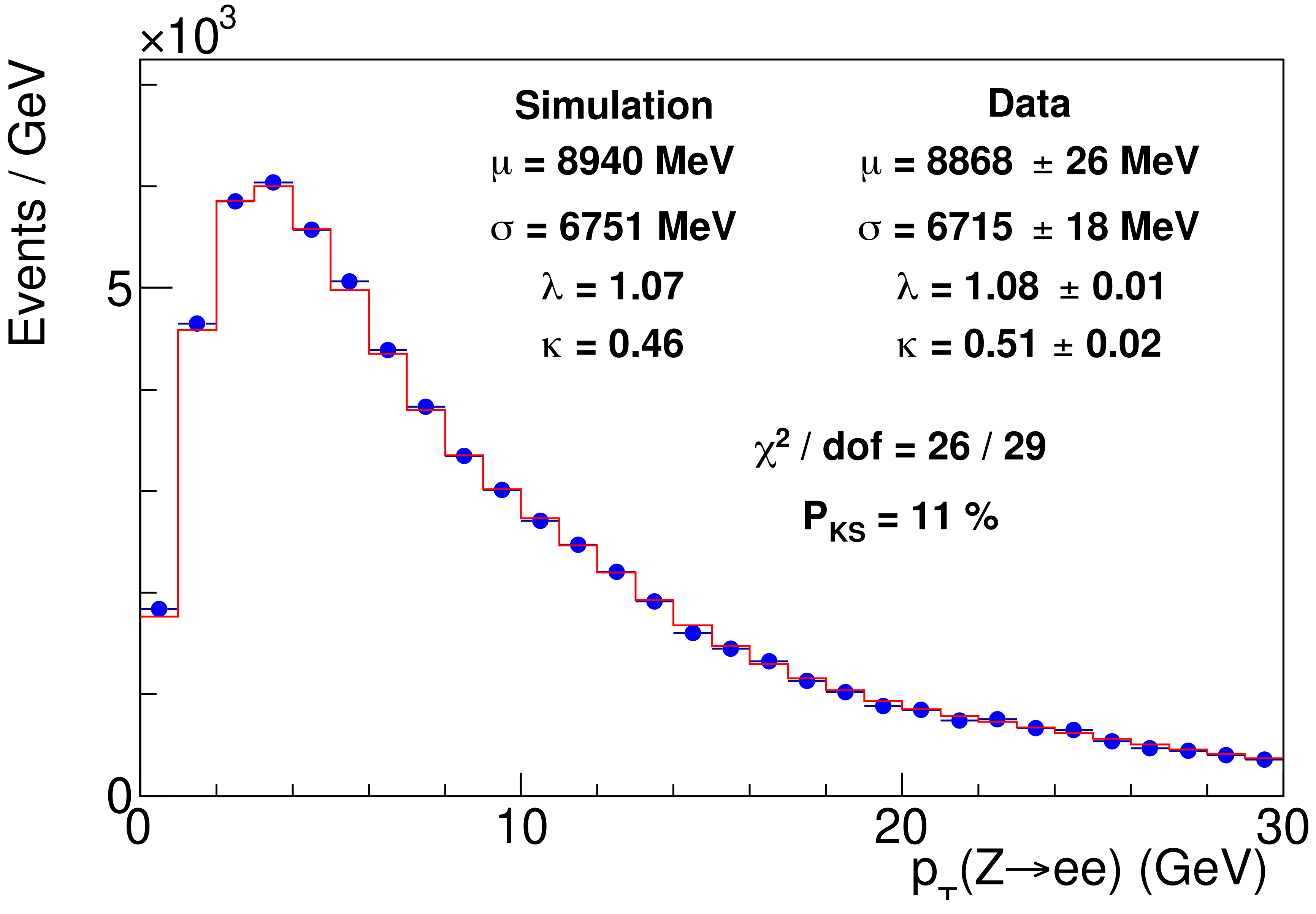
- Generator level simulation from **RESBOS**[1]
  - QCD effects, tunable parameters for non-perturbative regime (low-p_T)
- QED radiation simulated by **PHOTOS**[2]
  - FSR multiphoton simulation
- Fit parameters in boson p_T shape
  - Low p_T sensitive to g_2
  - Intermediate-high p_T sensitive to α_s
- Tuning with *Z* data applied to *W*s
- Uncertainty on perturbative calculation of p_T^W/p_T^Z estimated using **DYQT**[3]



[1]C Balazs and C-P Yuan, PRD **55**, 5558 (1997)
[2]P. Golonka and Z. Was, Eur. J. Phys. C **45**, 97 (2006)
[3]G. Bozzi et al, Nucl. Phys. B **815**, 174 (2009)

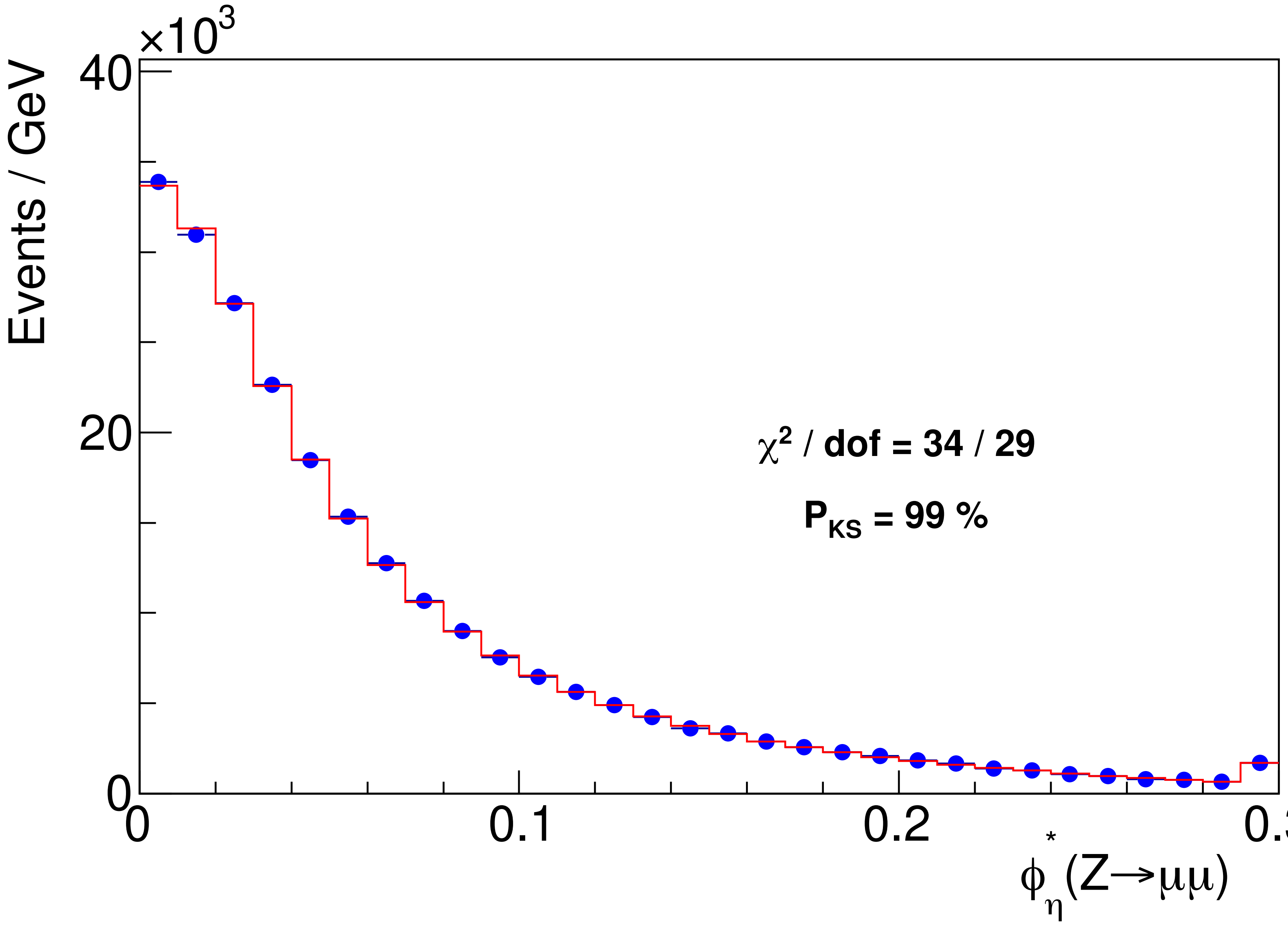
Boson p_T tuning and validation

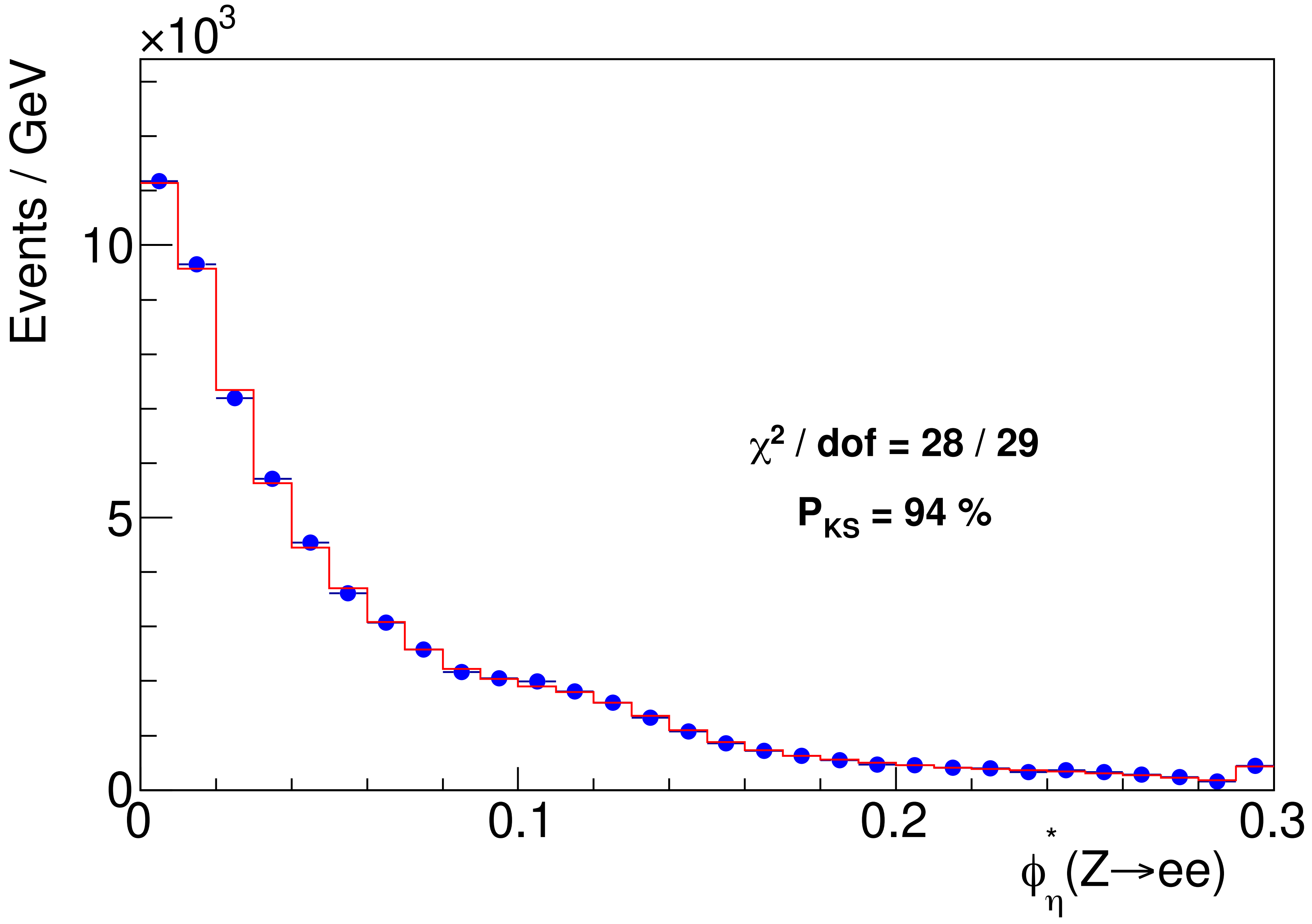




$\Delta M_W = 1.8$ MeV

$$\phi^*_\eta = \tan\left(\frac{\pi - \Delta\phi^{\ell\ell}}{2}\right) \operatorname{sech}\left(\frac{\eta^- - \eta^+}{2}\right)$$

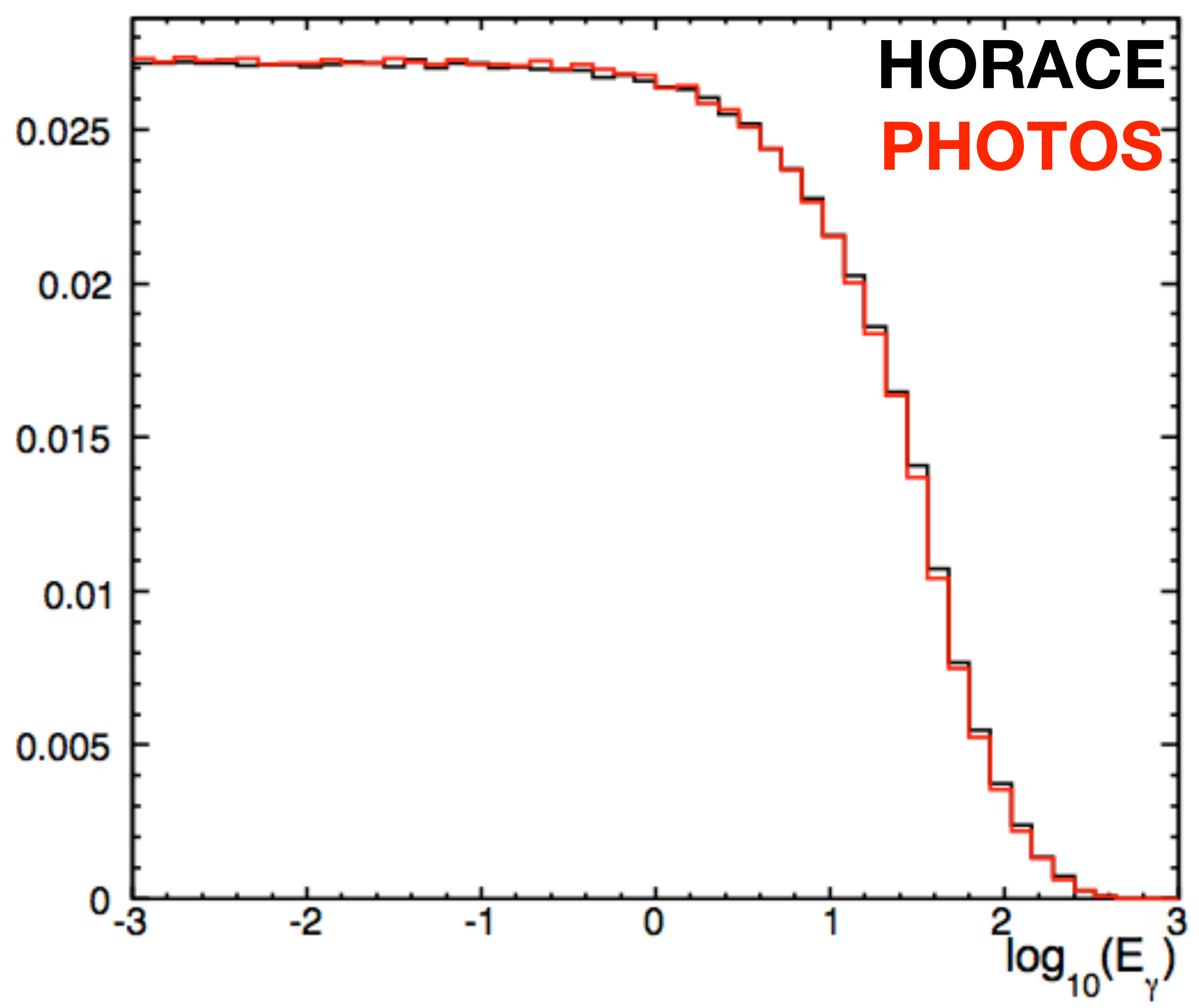


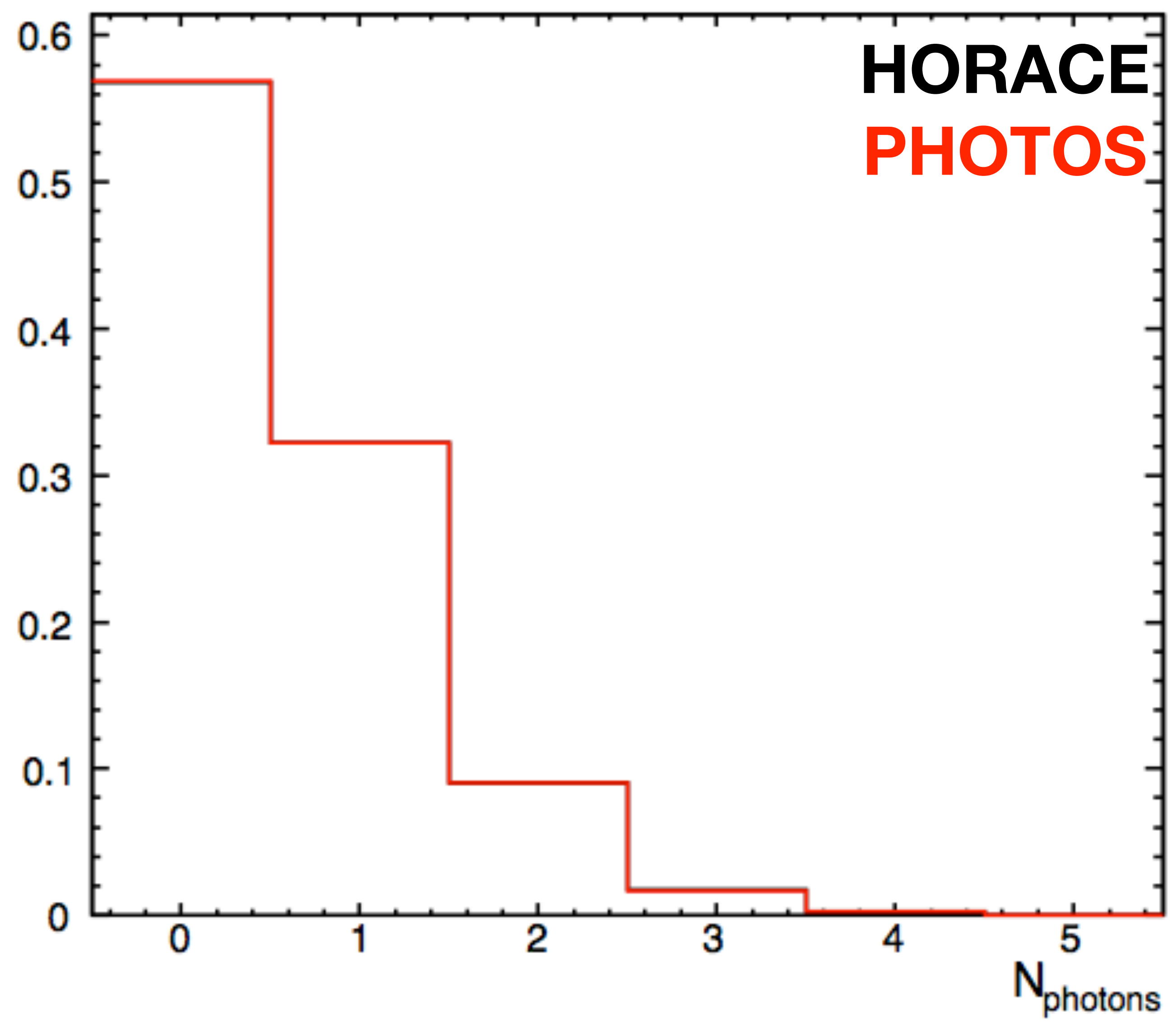


QED radiation

A. Kotwal and BJ, Adv. High Energy Phys. (2016) 1615081

- Extensive studies of QED effects using **HORACE**[1]
  - Leading log approximation vs. exact single photon calculation
  - Multi-photon calculations
  - Higher-order soft/virtual corrections
  - e^+e^- pair creation
  - ISR/FSR interference
  - Dependence on electroweak parameters/scheme
- Detailed comparison of HORACE and PHOTOS
  - Use PHOTOS in final model
- Total systematic uncertainty due to QED $\Delta M_W = 2.7$ MeV

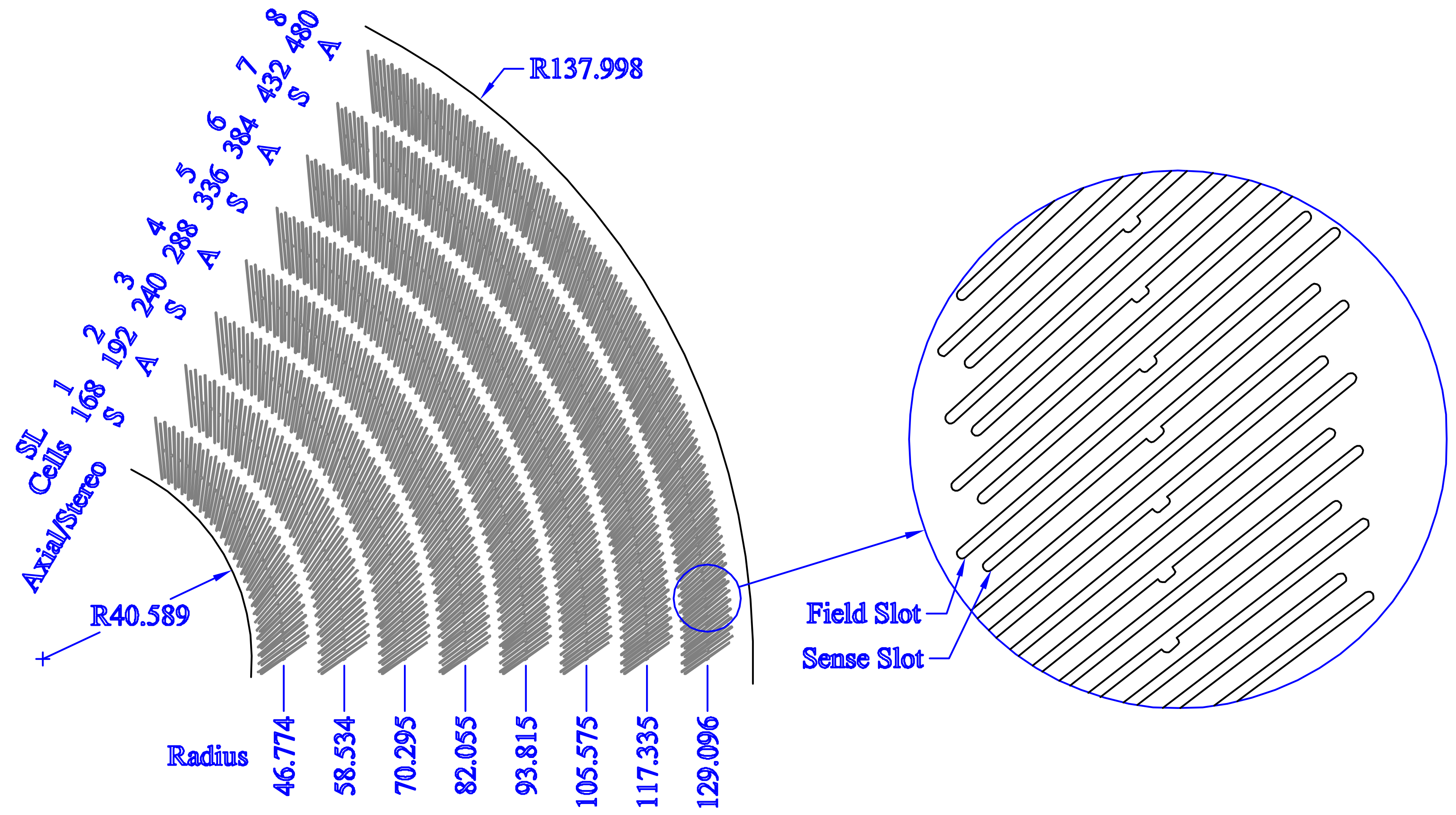




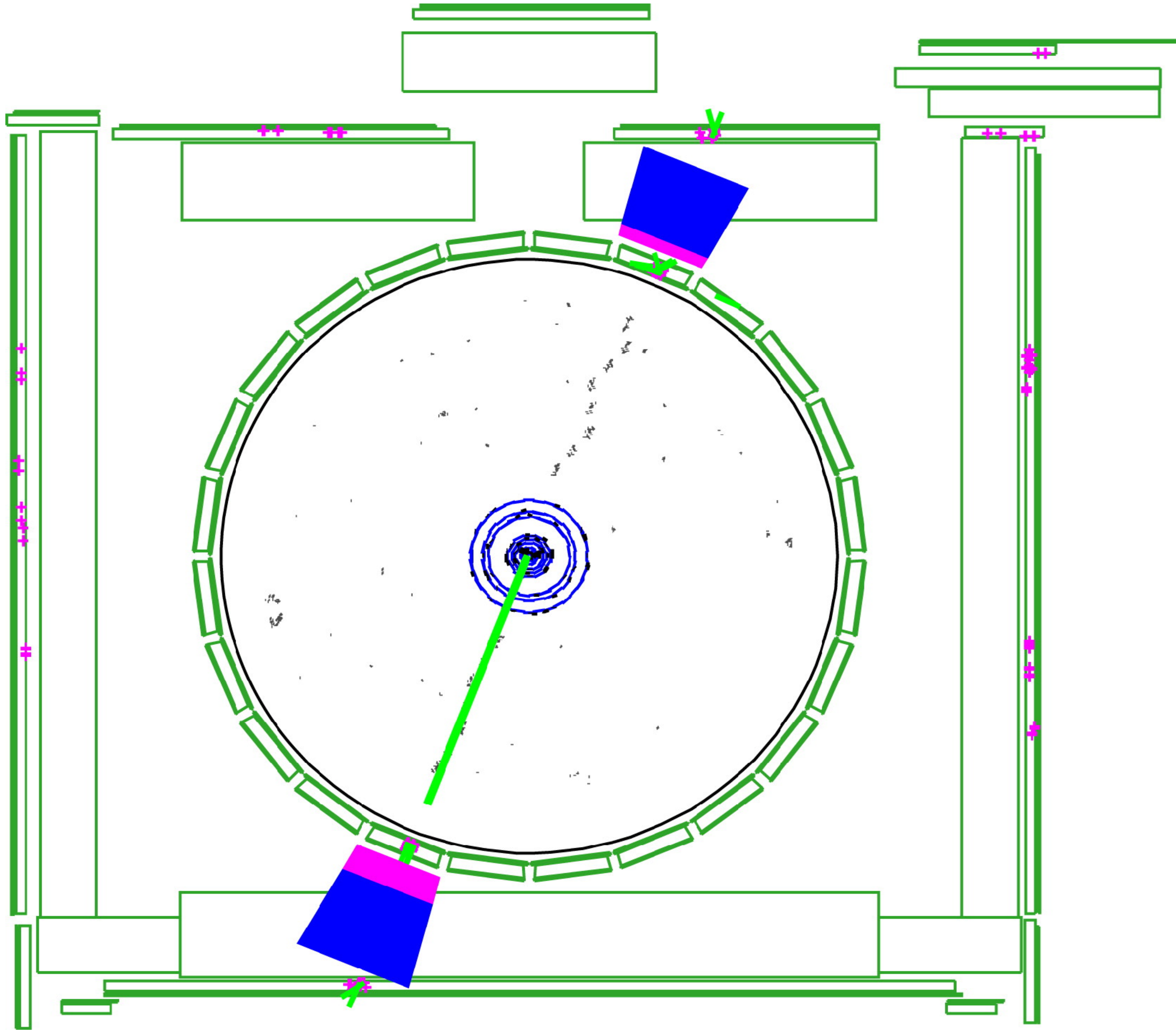
[1] *C.M. Carloni Calame, G. Montagna, O. Nicrosini and A. Vicini, JHEP **0710**:109 (2007)*

Tracker Alignment

COT alignment with cosmic rays



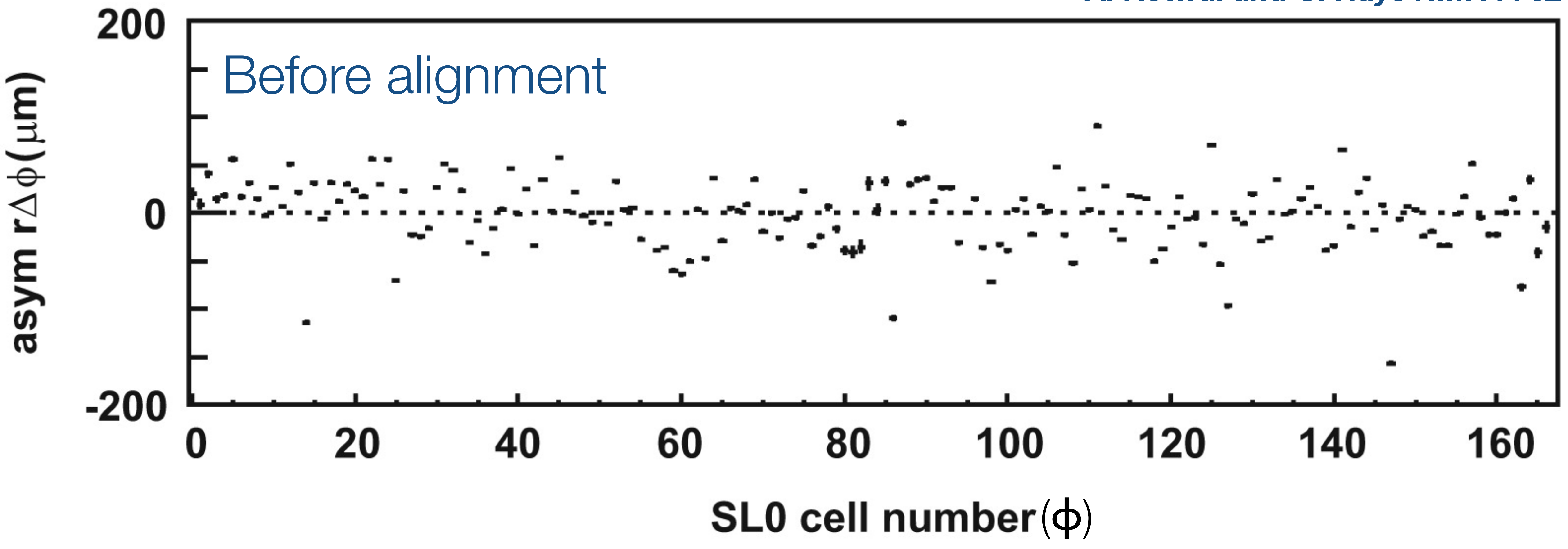
- COT consists of ~30k wires organized into ~2400 "cells"
- Accurate measure of wire positions crucial for precision track p_T
- Use *in-situ* cosmic ray data for alignment
  - Fit of COT hits on either side of vertex to single helix
  - A. Kotwal, H. Gerberich, C. Hays, NIM A **506**, 110 (2003)

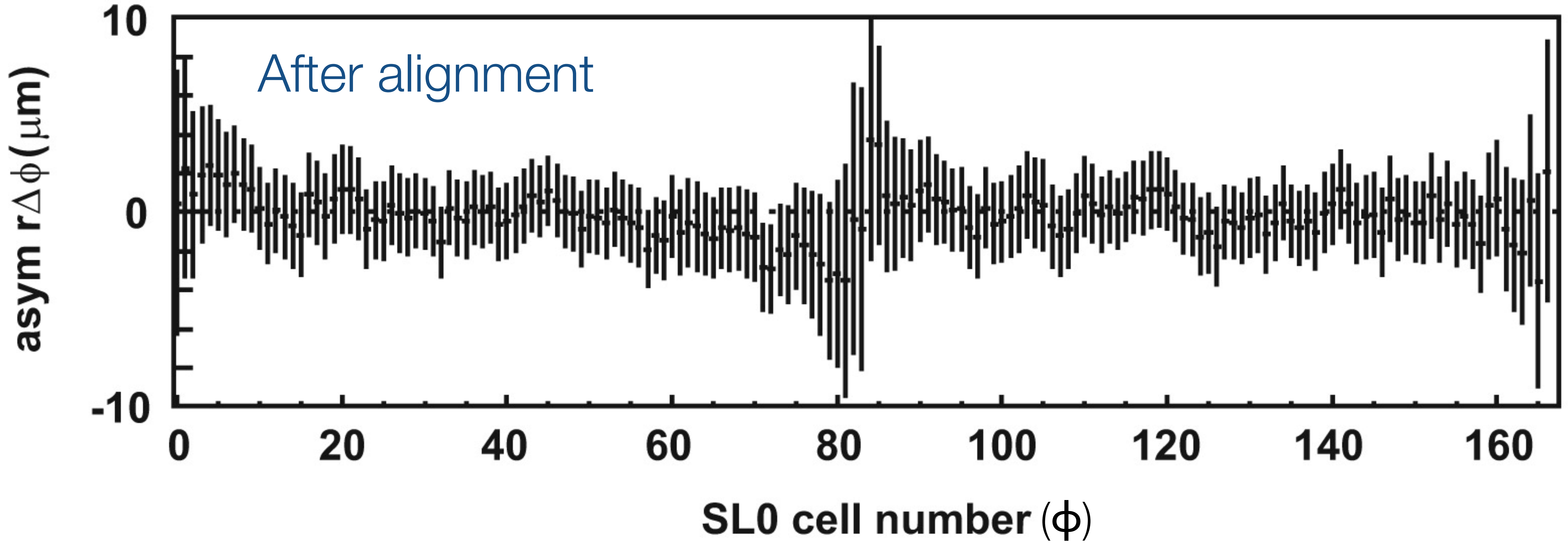


Tracker alignment

A. Kotwal and C. Hays NIM A 762 (2014) 85

Residuals: note the scales!

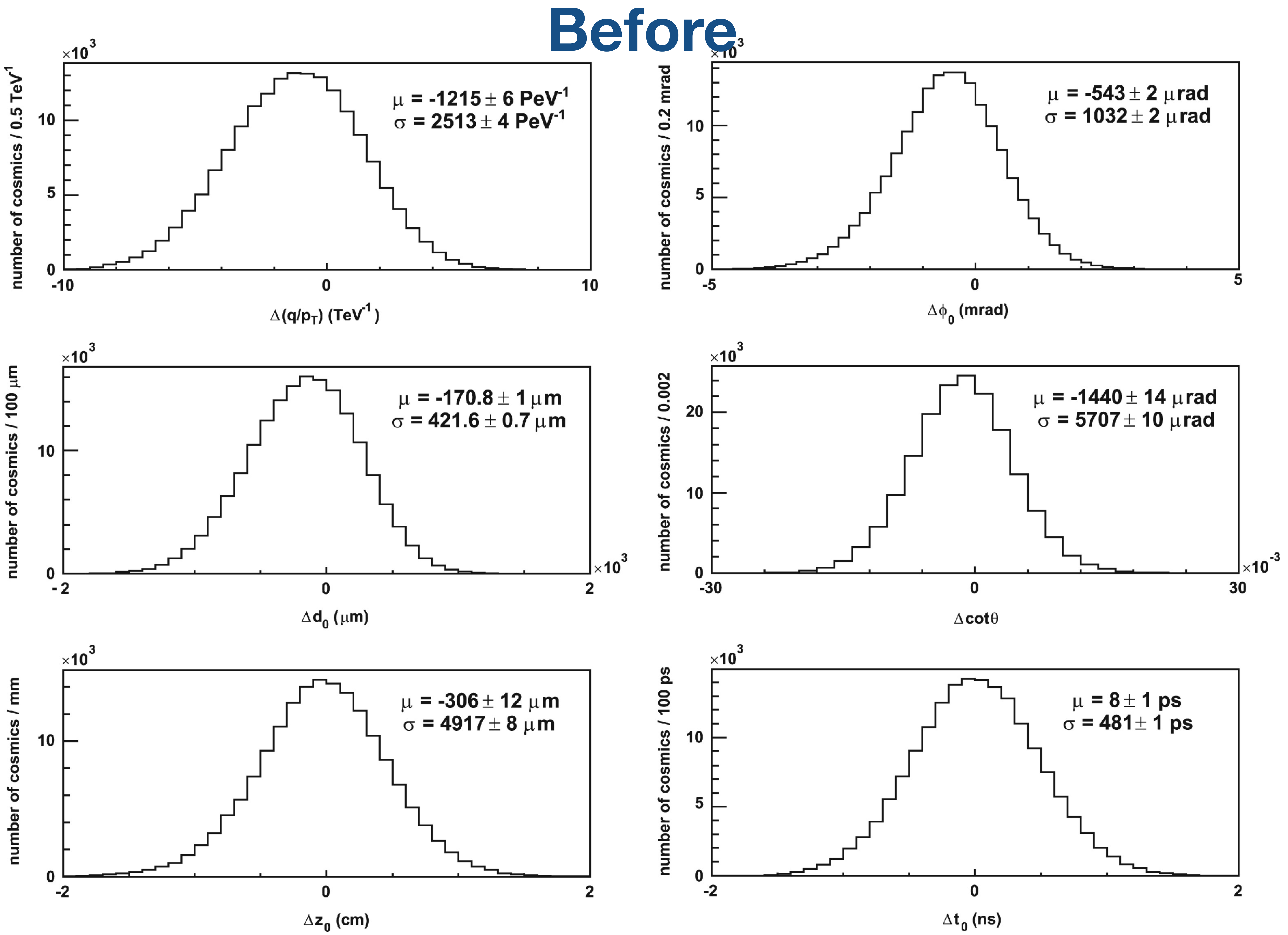




Relative alignment improves from ~50μm to ~1μm

Tracker alignment consistency

- Fit separate helices to cosmic ray tracks
- Compare track parameters between two tracks in each cosmic pair
    - Compare residuals with nominal CDF alignment (before cosmic ray alignment) and with cosmic ray alignment



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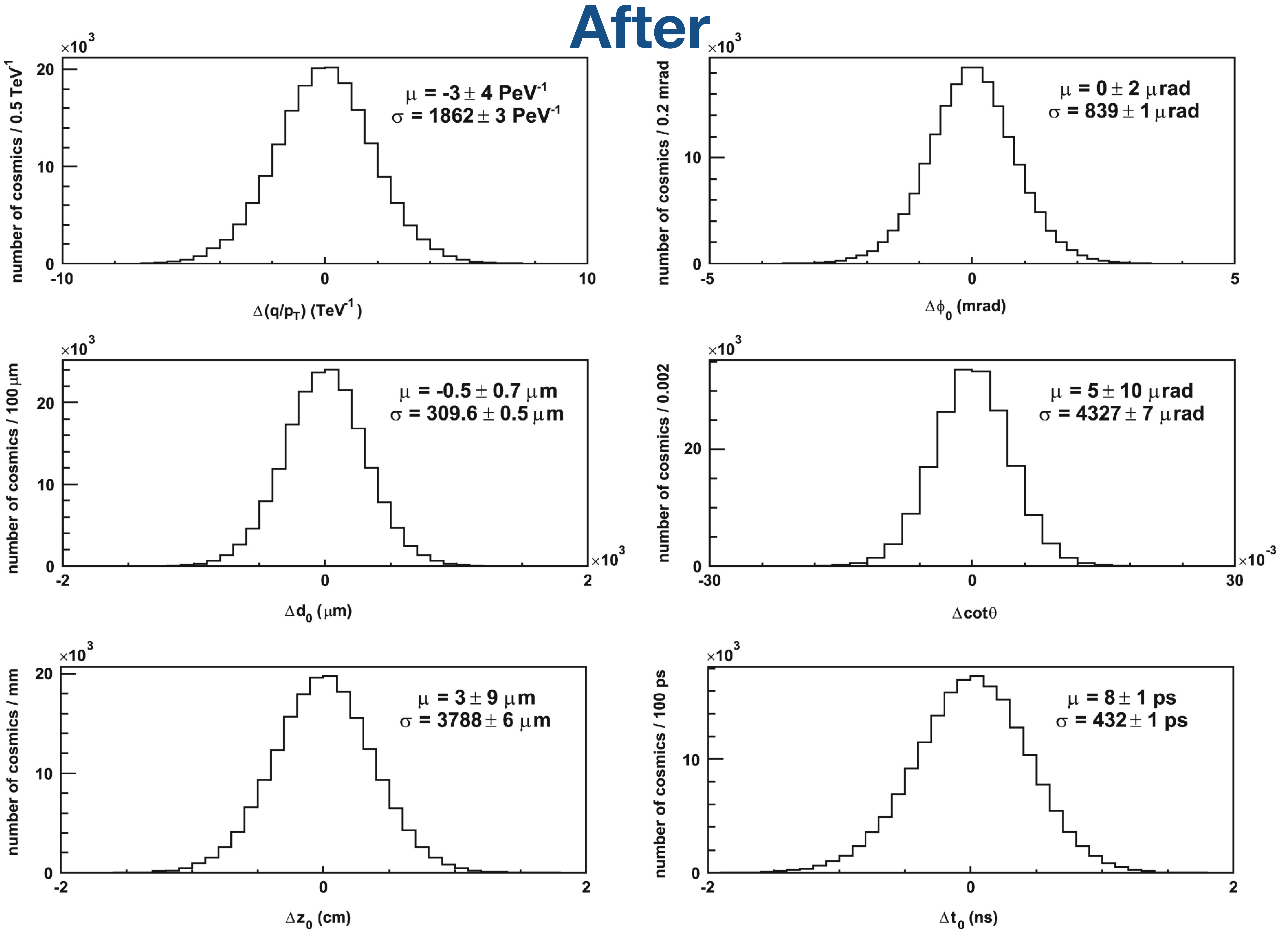
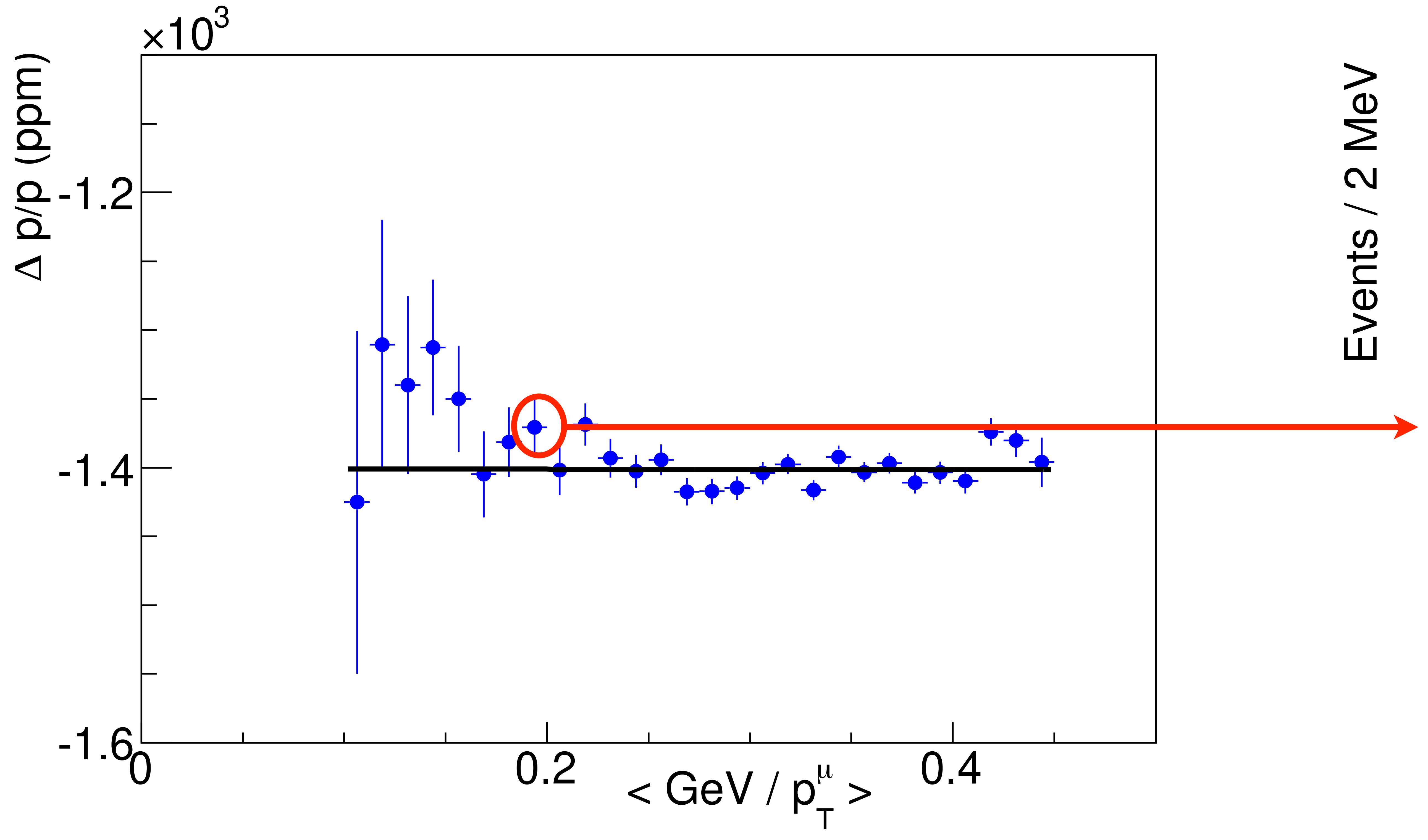
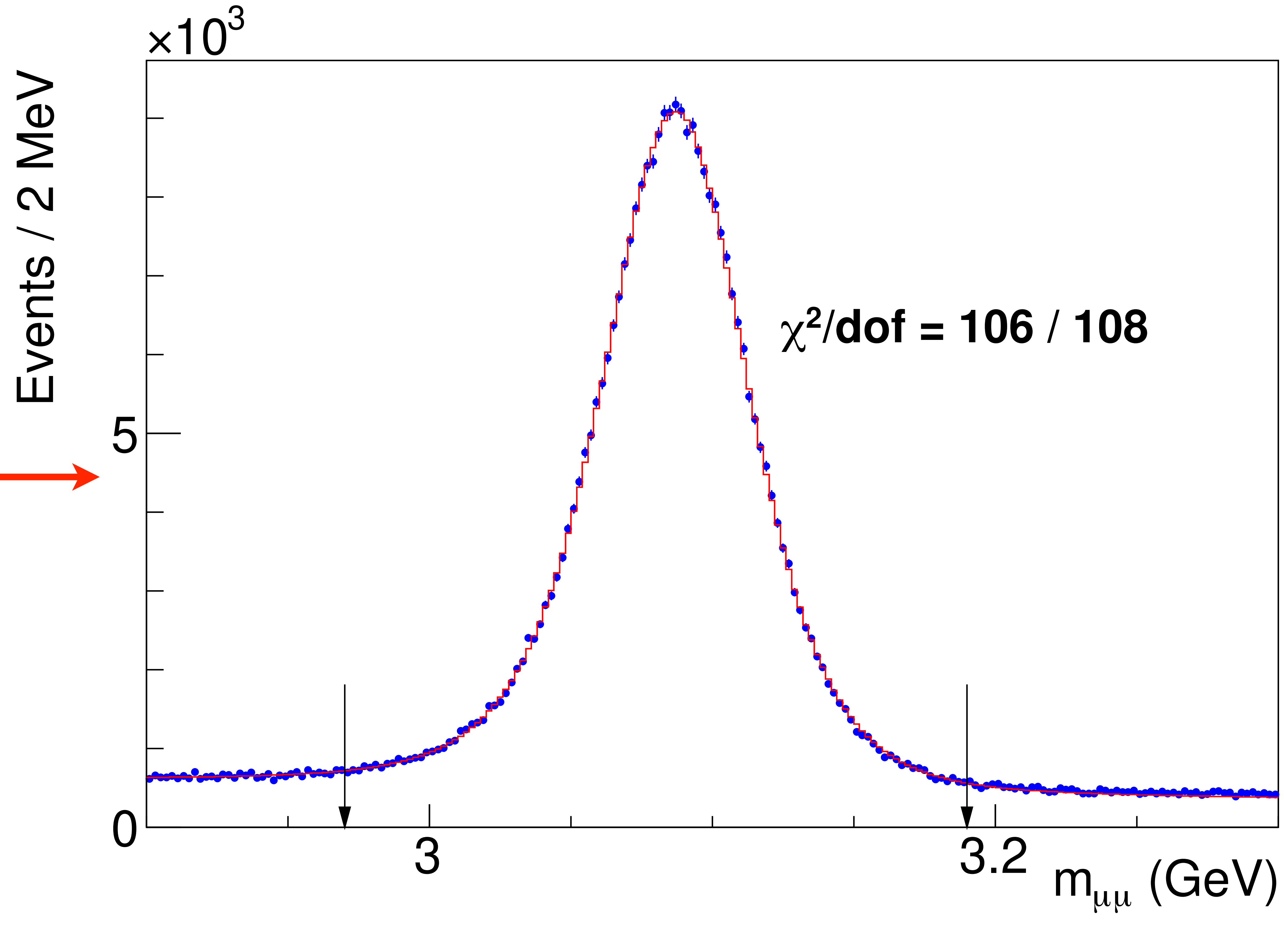


Track Momentum Scale

Track momentum scale: J/ψ

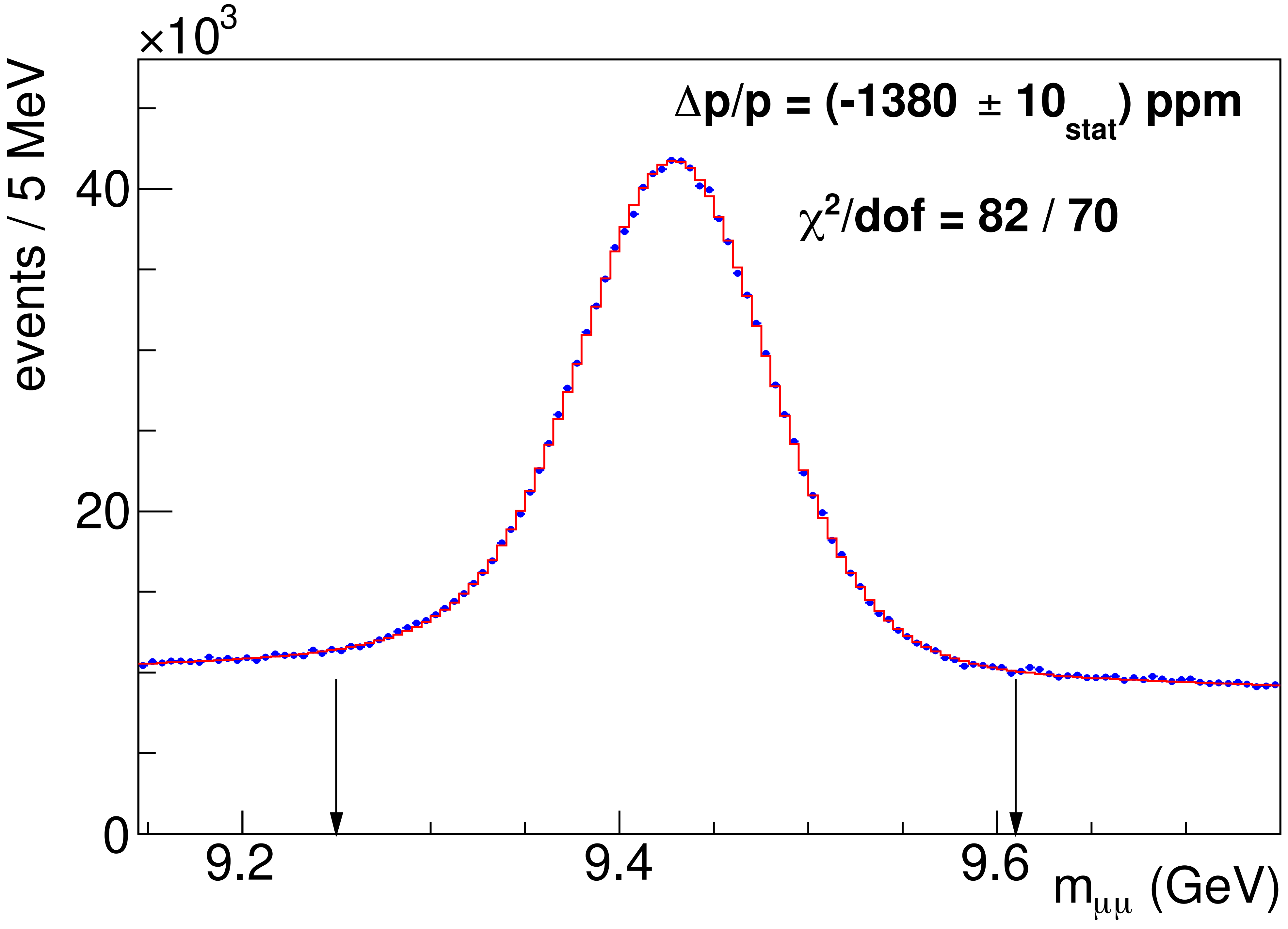
- Utilize large samples of **μμ resonances** (*J*/ψ, ϒ, *Z*) to set overall scale
- Size of *J*/ψ sample (~18M events) allows subsample fits
  - Fit *J*/ψ mass in bins of <$1/p_T(\mu)$> and apply material scale calibration (2.6%) to remove dependence
- Apply calibration from *J*/ψ to ϒ



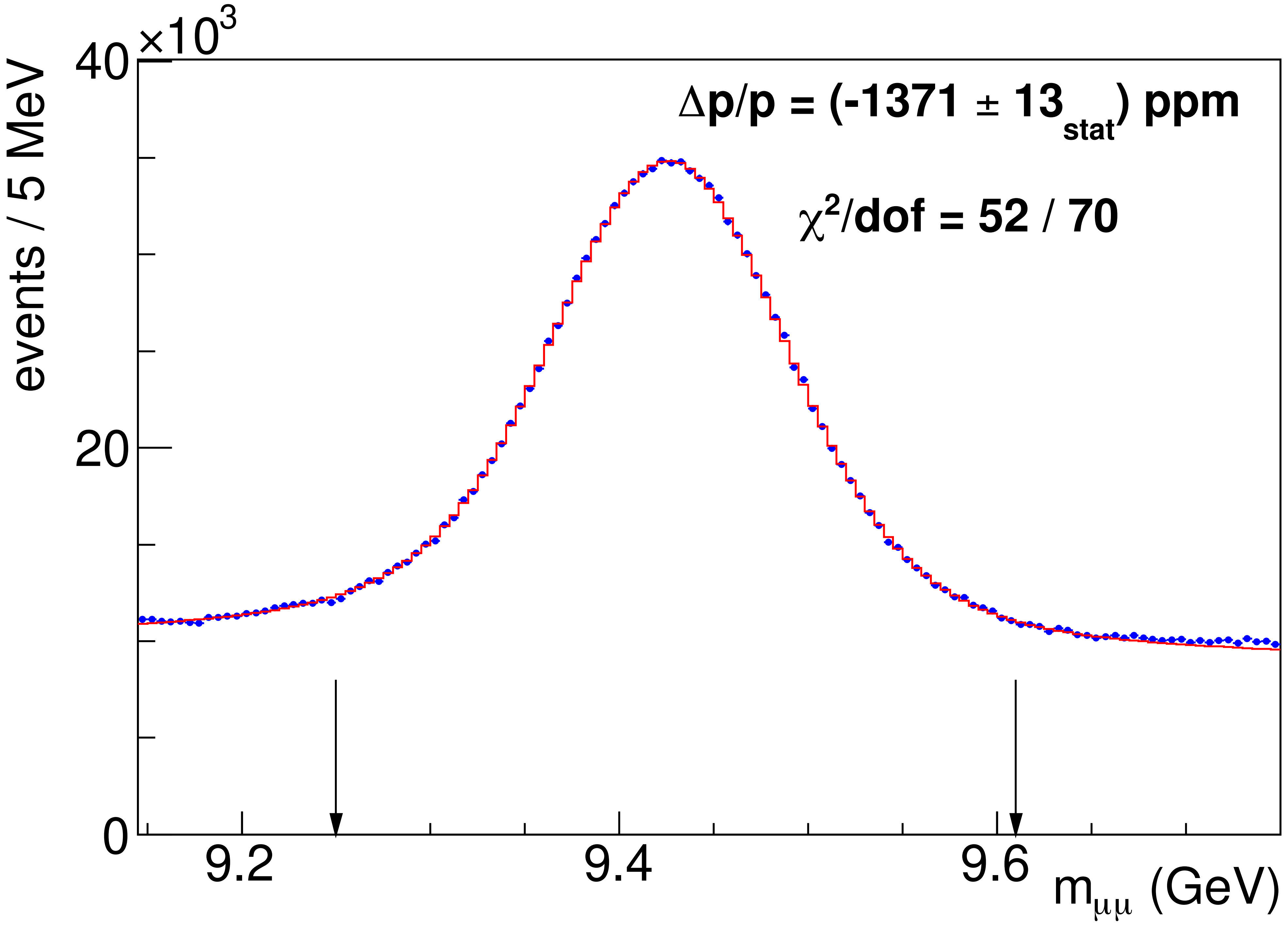


Track momentum scale: ϒ

- ϒ sample provides higher-p_T sample
- ϒs produced promptly: validation of beam-constraining (BC) procedure
  - Perform fit with BC and non-BC tracks for consistency
- Combine *J*/ψ and ϒ scales and apply to *Z*s



beam-constrained tracks



non-beam-constrained tracks

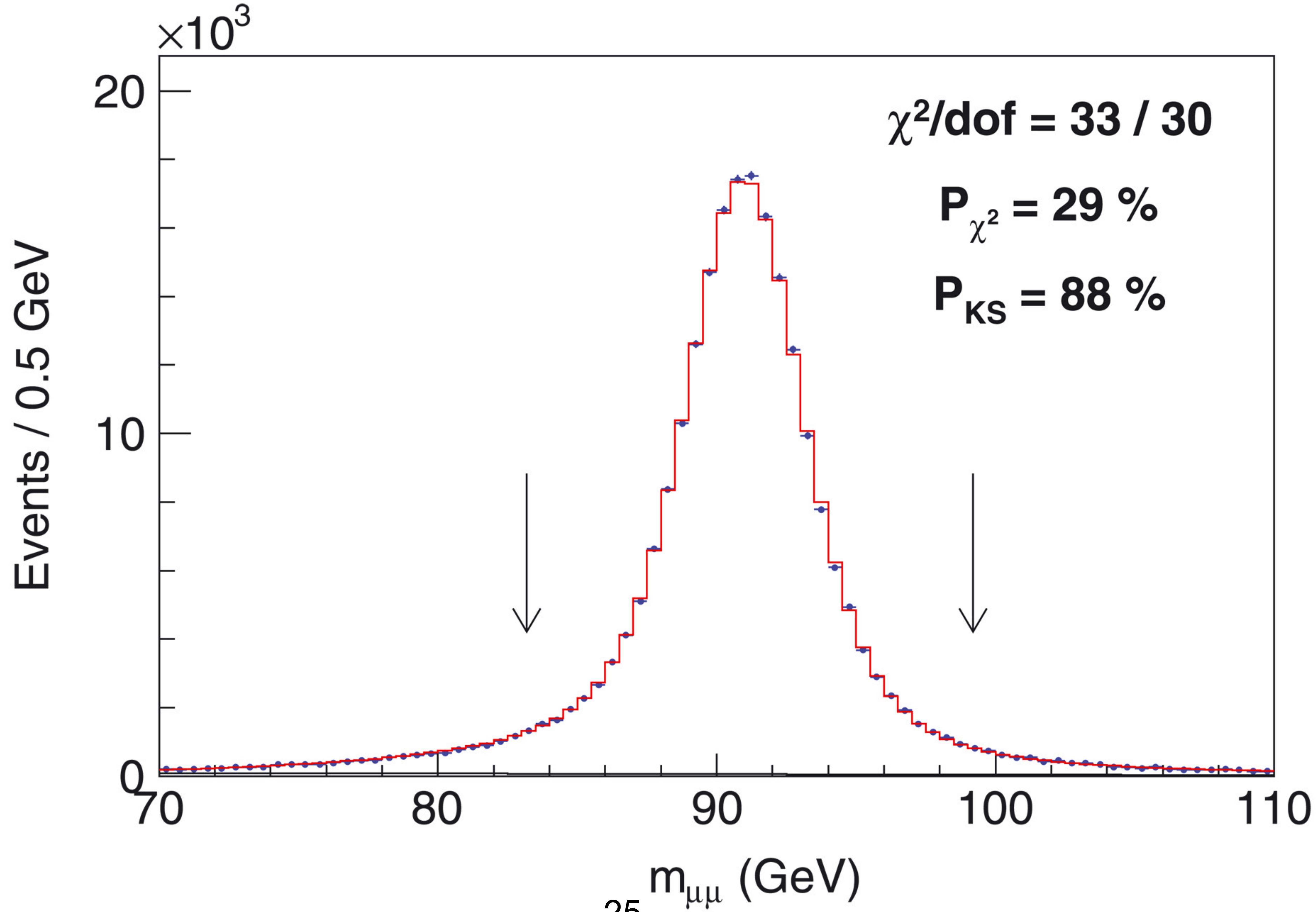
Track momentum scale: systematic uncertainties

- Systematics as fractional uncertainty on momentum scale
  - In parts per million (ppm)
- Uncertainty on ϒ scale maps to ~2 MeV uncertainty on W or Z mass
- Single largest source of uncertainty now ϒ mass world average!
  - Other dominant uncertainties are B-field non-uniformity, material energy loss, and trigger efficiency

Source	J/ψ (ppm)	Υ (ppm)	Correlation (%)
QED	1	1	100
Magnetic field non-uniformity	13	13	100
Ionizing material correction	11	8	100
Resolution model	10	1	100
Background model	7	6	0
COT alignment correction	4	8	0
Trigger efficiency	18	9	100
Fit range	2	1	100
$\Delta p/p$ step size	2	2	0
World-average mass value	4	27	0
Total systematic	29	34	16 ppm
Statistical NBC (BC)	2	13(10)	0
Total	29	36	16 ppm

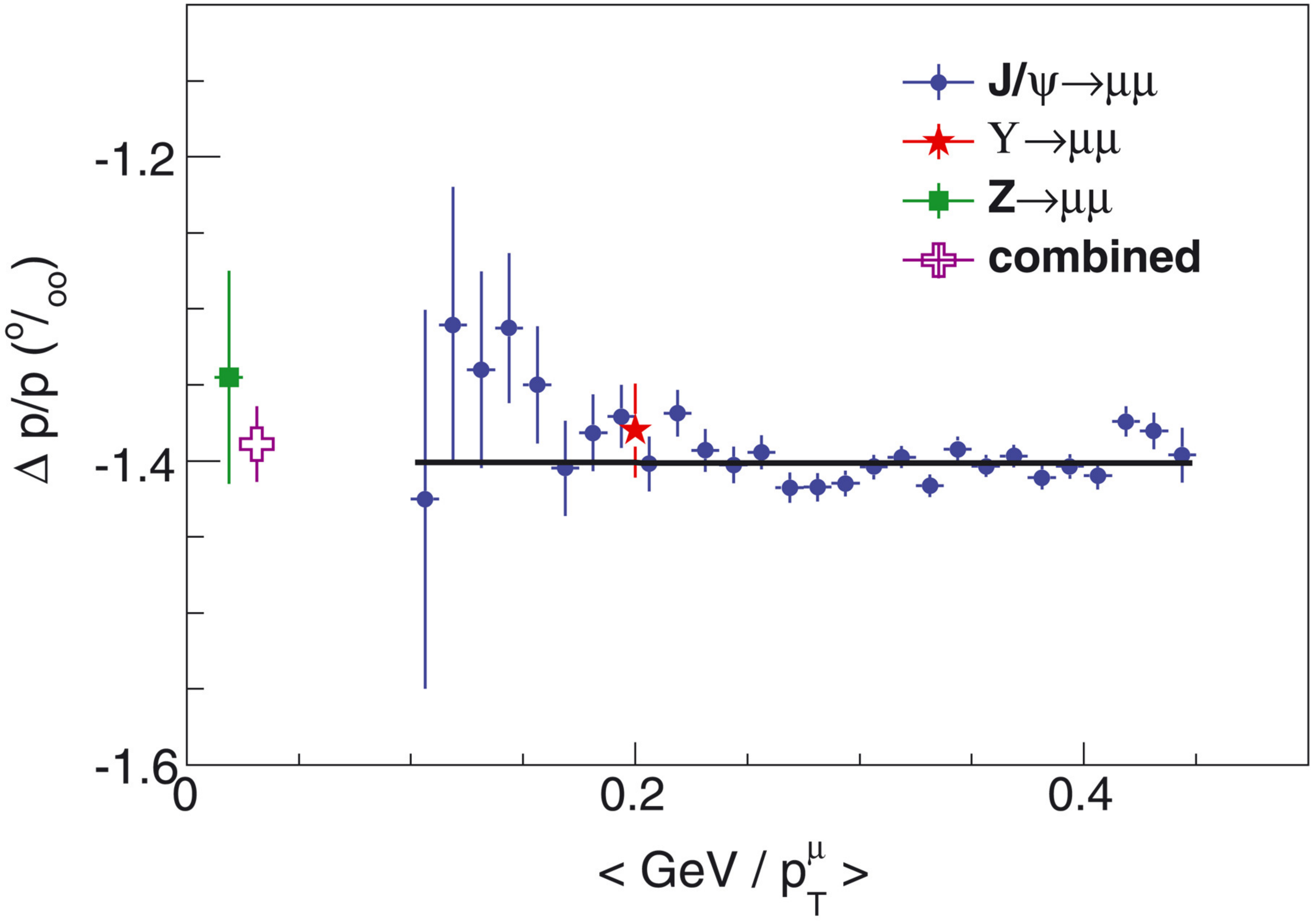
Muon Z mass measurement

- Perform **independent** measurement of *Z* mass using tuned momentum scale
  - Fit central value kept blind during scale calibration
  - $M_Z = 91192.0 \pm 6.4_{stat} \pm 2.3_{p\text{-}scale} \pm 3.1_{QED} \pm 1_{alignment}$ = **91192.0±7.5 MeV**
  - Excellent agreement with world average (91187.6±2.1 MeV)



Final momentum scale

- Add Z data as final calibration point for momentum scale
  - ***$\Delta p/p_{final}$* = (-1389 ± 25_{syst}) ppm**
  - Apply scale to *W* muons and *E/p* calibration
  - Results in ΔM_W = 2 MeV

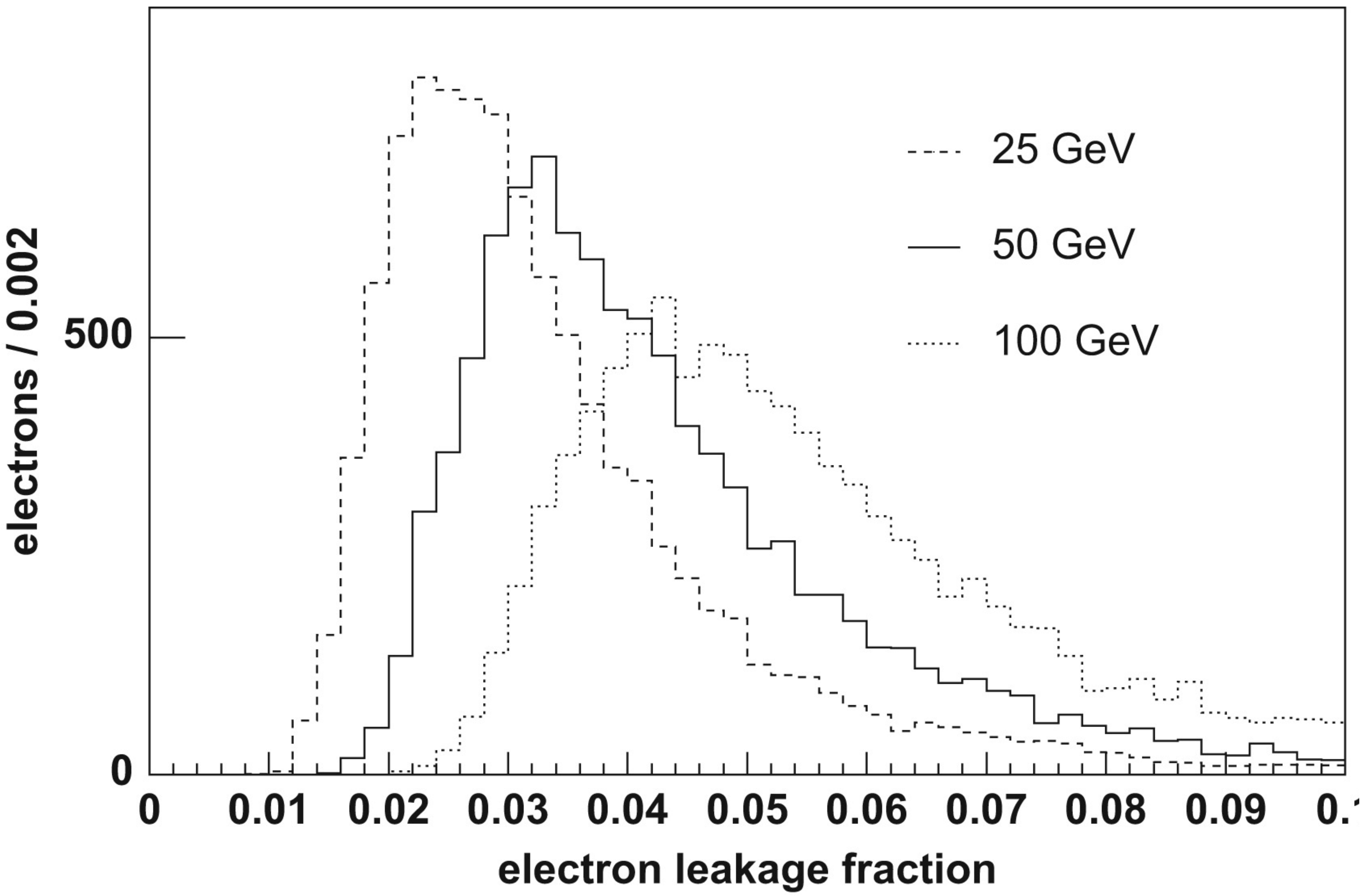


EM Calorimeter Scale

Simulation for electrons and photons

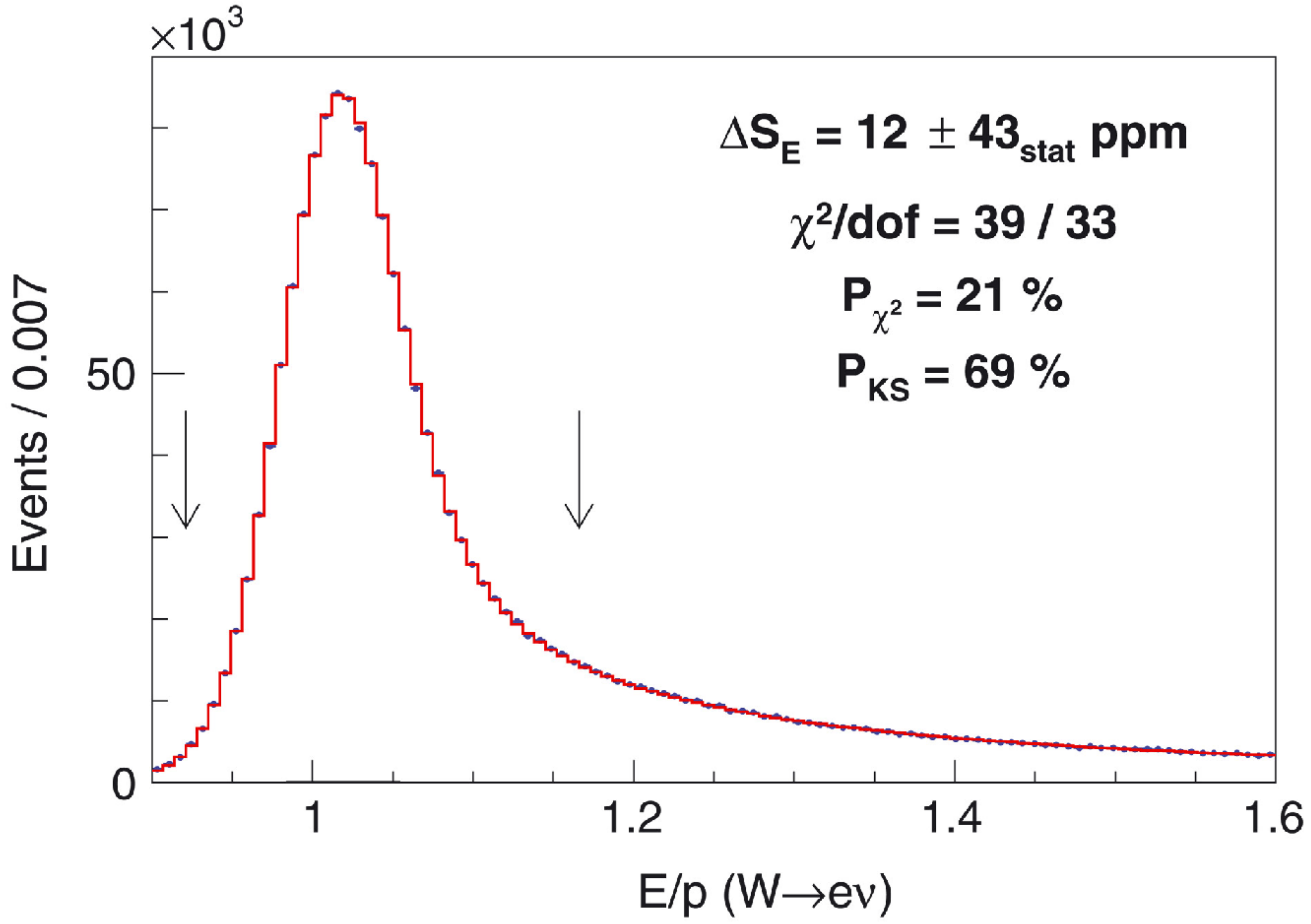
A. Kotwal and C. Hays NIM A 729 (2013) 25

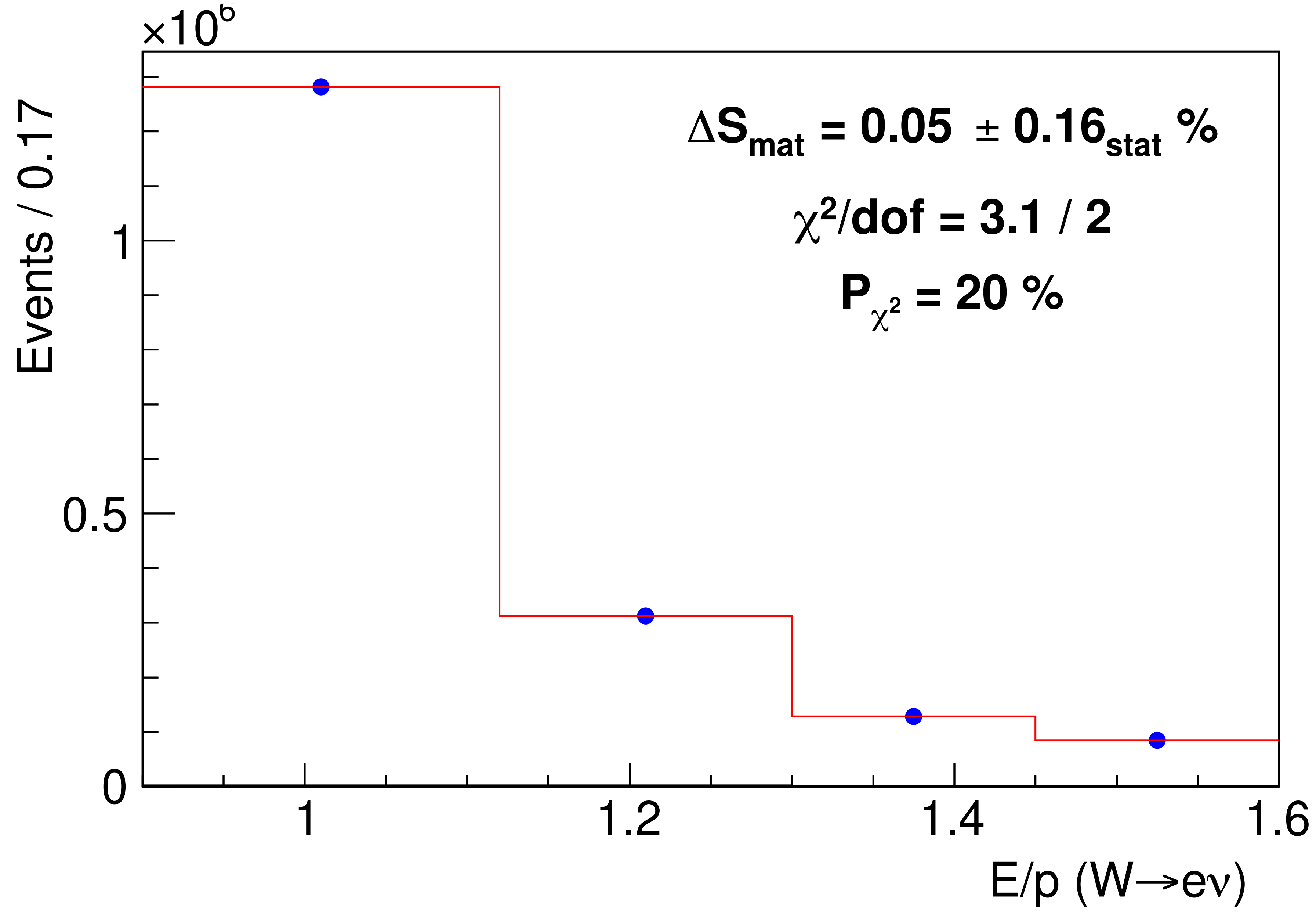
- EM energy loss studied using detailed GEANT4-based simulation
  - Leakage into hadronic calorimeter
  - Absorption into coil
  - Dependence on incident angle and E_T
  - Detailed bremsstrahlung modeling including Landau-Pomeranchuk-Migdal (LPM) suppression
  - Sophisticated material map for tracker region of detector



Energy scale calibration

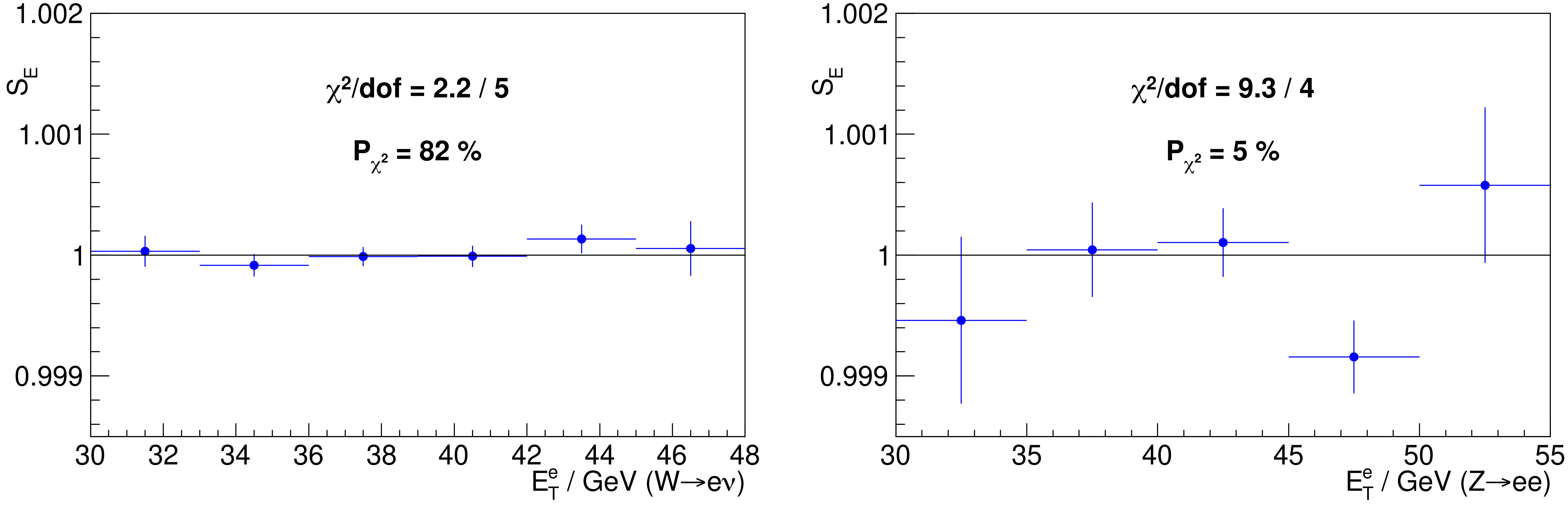
- Calibrate EM calorimeter response using *W* and *Z* *E*/*p* distributions
  - Fit to peak to obtain scale (central value of 1 by construction)
    - $\Delta S_E = (43_{stat} \pm 30_{non\text{-}linearity} \pm 34_{X0} \pm 45_{COT})$ ppm
  - Fit to tail to tune amount of radiative material
    - Apply scale factor to material model $S_{X0} = 1.049 \pm 0.002$
- Systematic uncertainty $\Delta M_W = 6$ MeV





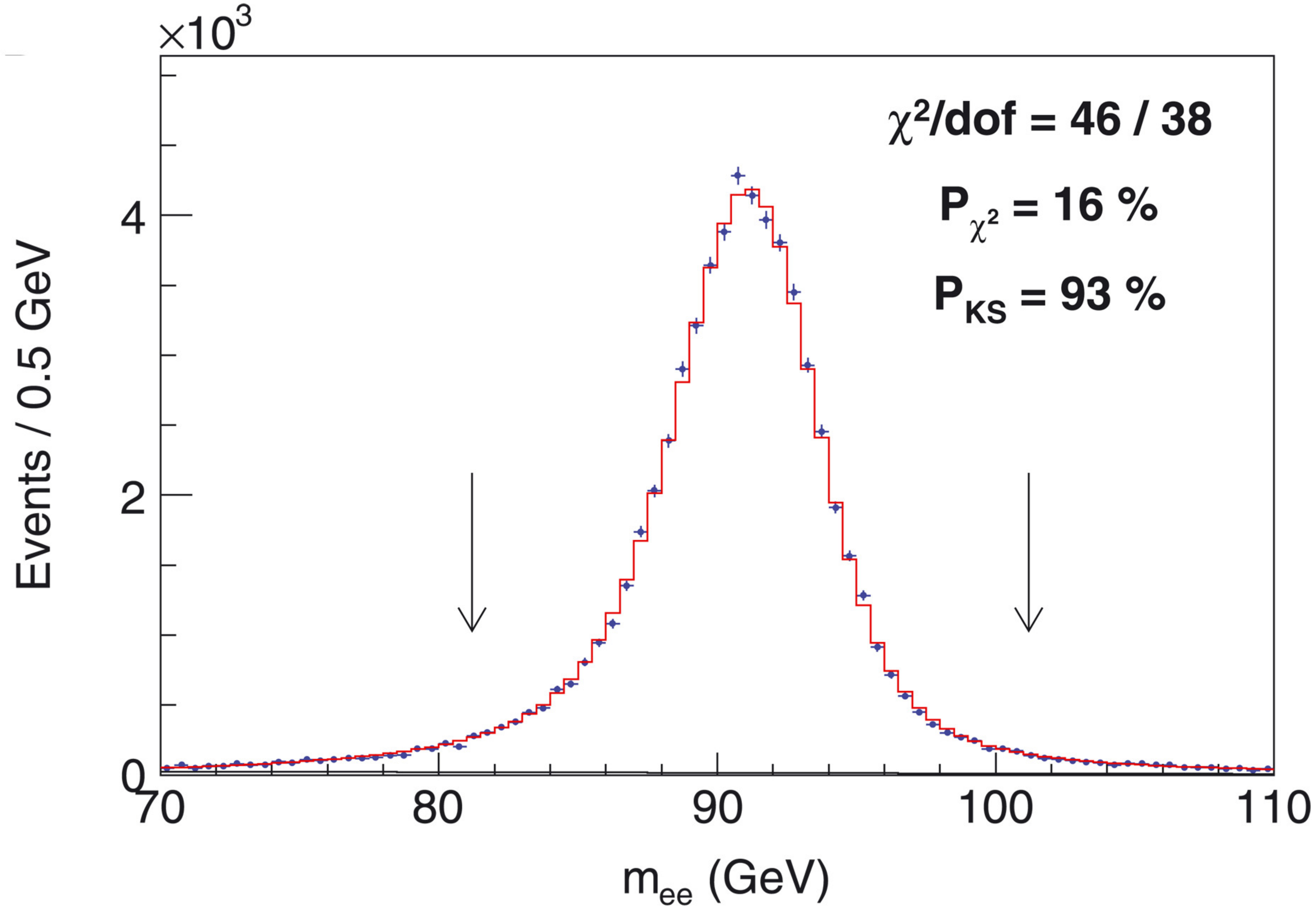
EM scale non-linearity

- Fit E/p in bins of electron E_T
  - Parameterize non-linearity as $S_E = 1 + \beta \log(E_T/39\ \text{GeV})$
- Tune using W and Z data and obtain $\beta = (7.2 \pm 0.4_{stat}) \times 10^{-3}$
  - ΔM_W = 2 MeV
- Obtain flat response in E_T after tuning



Electron Z mass and final EM energy scale

- Perform **independent** measurement of *Z* mass using calibrated EM scale
  - M_Z = 91194.3±13.8$_{stat}$±6.5$_{E/p}$±2.3$_{p\text{-}scale}$±3.1$_{QED}$±0.8$_{alignment}$=**91194.3±15.8 MeV**
    - Excellent agreement with world average (91187.6±2.1 MeV)
- Combine *E/p* calibration with M_Z to obtain final EM calibration



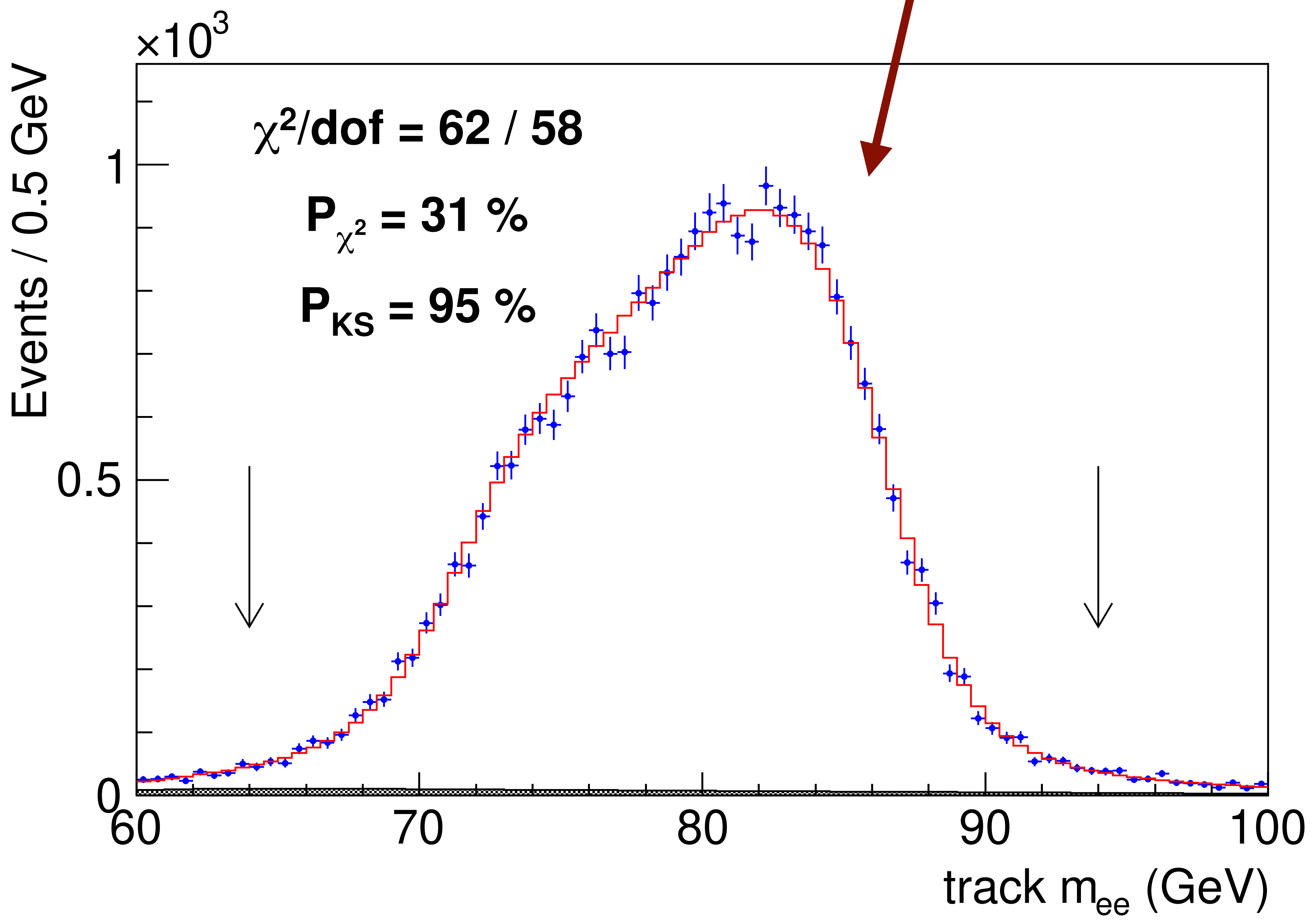
Final ΔS_E = -14±72 ppm

ΔM_W = 5.8 MeV

Z mass cross-checks using electrons

- Perform Z mass measurements (blinded) as cross checks
  - EM clusters vs track only
  - Radiative (E/p >1.1)/non-radiative (E/p<1.1)electron pairs
- Validates tracking model tuned with muons as applied to electrons
- Validates radiative energy loss model

Electrons	Calorimeter	Track
$E/p < 1.1$ only	$91\,190.9 \pm 19.7$	$91\,215.2 \pm 22.4$
$E/p > 1.1$ and $E/p < 1.1$	$91\,201.1 \pm 21.5$	$91\,259.9 \pm 39.0$
$E/p > 1.1$ only	$91\,184.5 \pm 46.4$	$91\,167.7 \pm 109.9$



Lepton resolution

- Muons
  - Track resolution determined by uncertainty on beamspot size (36±0.5 μm) and track hit resolution (150±1 μm)
  - Tuned using widths of Z and ϒ peaks
  - Systematic uncertainty (muons) $\Delta M_W = 0.3$ MeV

- Electrons
  - EM calorimeter resolution defined by sampling term and constant term

$$\sigma/E = 12.6\,\%\sqrt{E/\mathrm{GeV}} \oplus \kappa$$

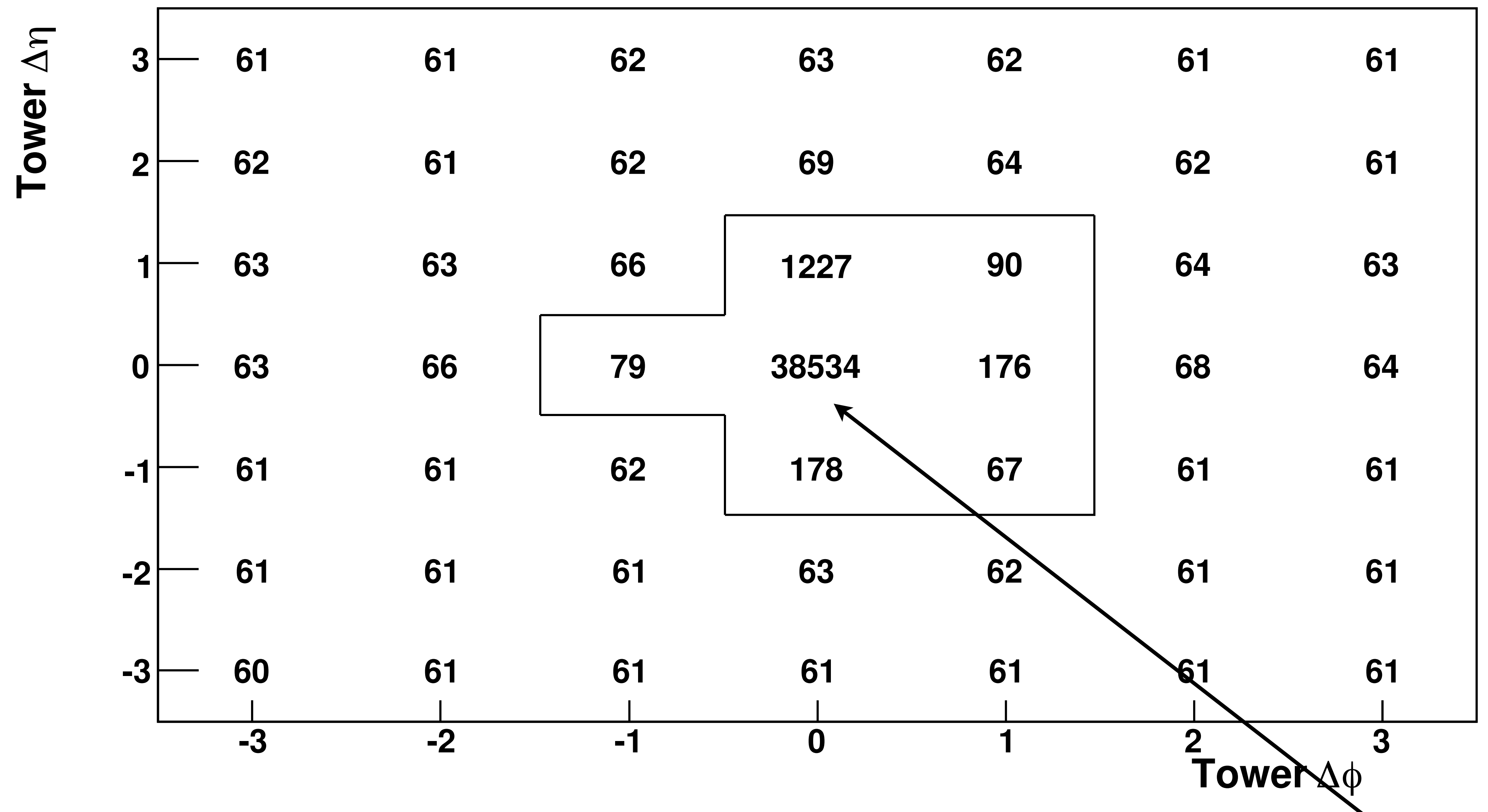
  - Constant term tuned using E/p distribution $\kappa = (0.73 \pm 0.02_{stat})\%$
  - Systematic uncertainty (electrons) $\Delta M_W = 0.9$ MeV

Hadronic Recoil

Hadronic recoil: lepton removal

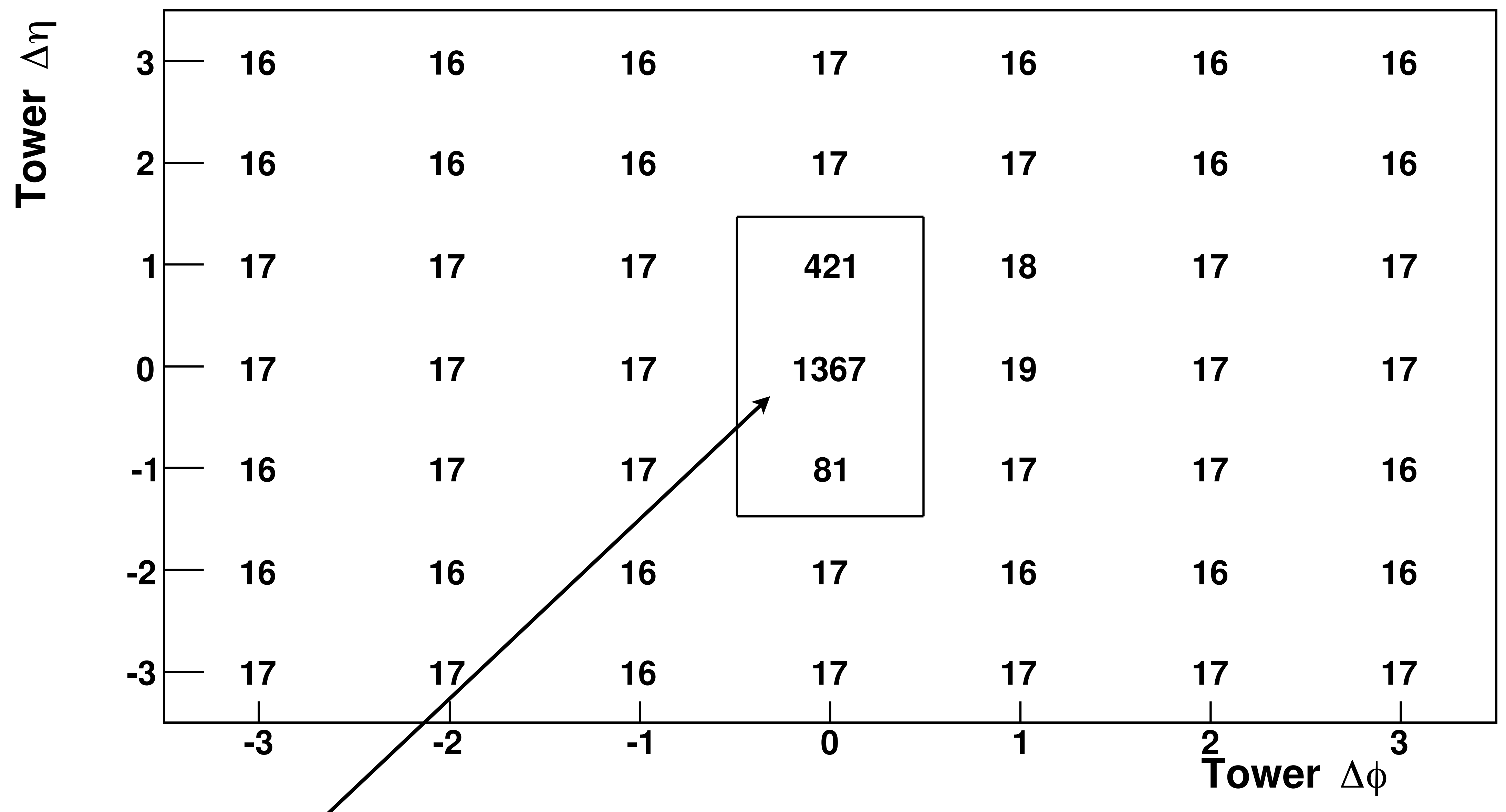
- Hadronic recoil ***u*** is vector sum of all calorimeter towers minus towers containing lepton energy
- Some underlying event energy removed with “lepton towers”
  - Estimate using rotated lepton removal windows
  - Systematic uncertainty $\Delta M_W = 1$ MeV

Electron channel W data:
Mean EM calorimeter deposition (MeV)



Default towers removed

Muon channel W data:
Mean hadronic calorimeter deposition (MeV)



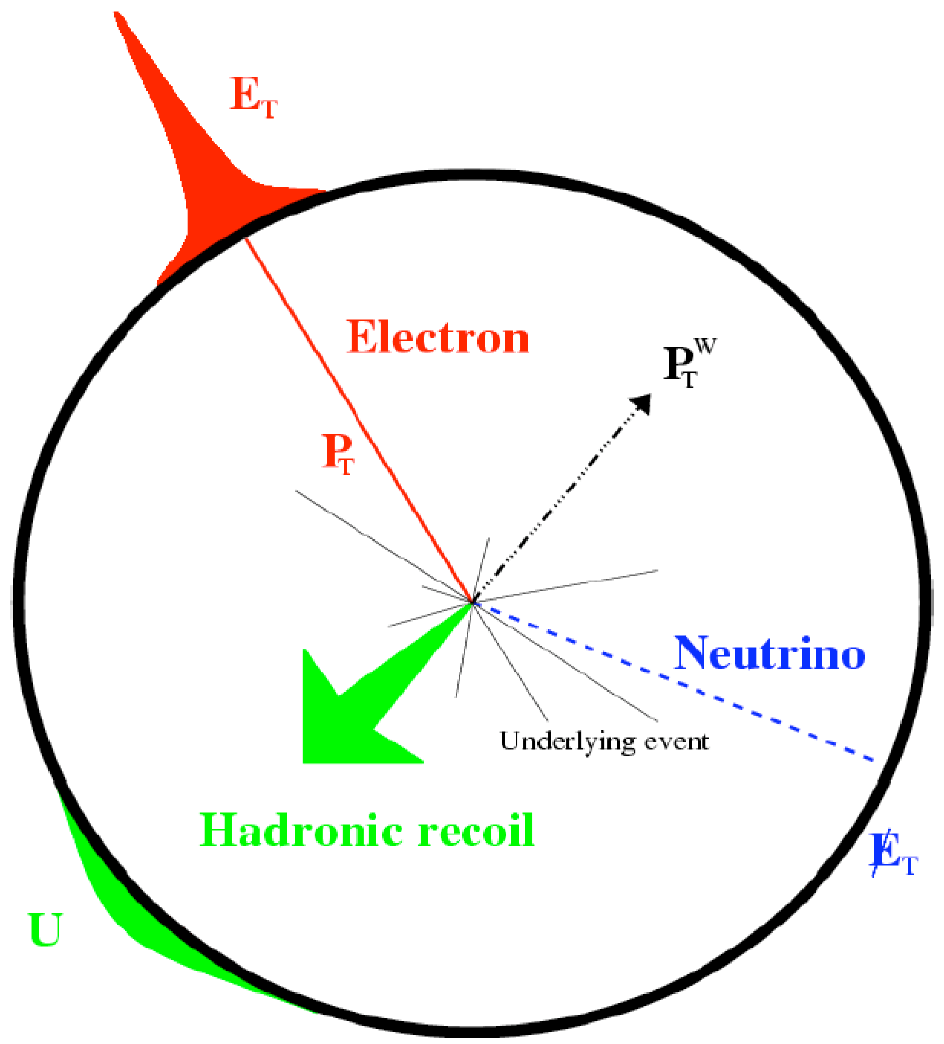
Central lepton tower

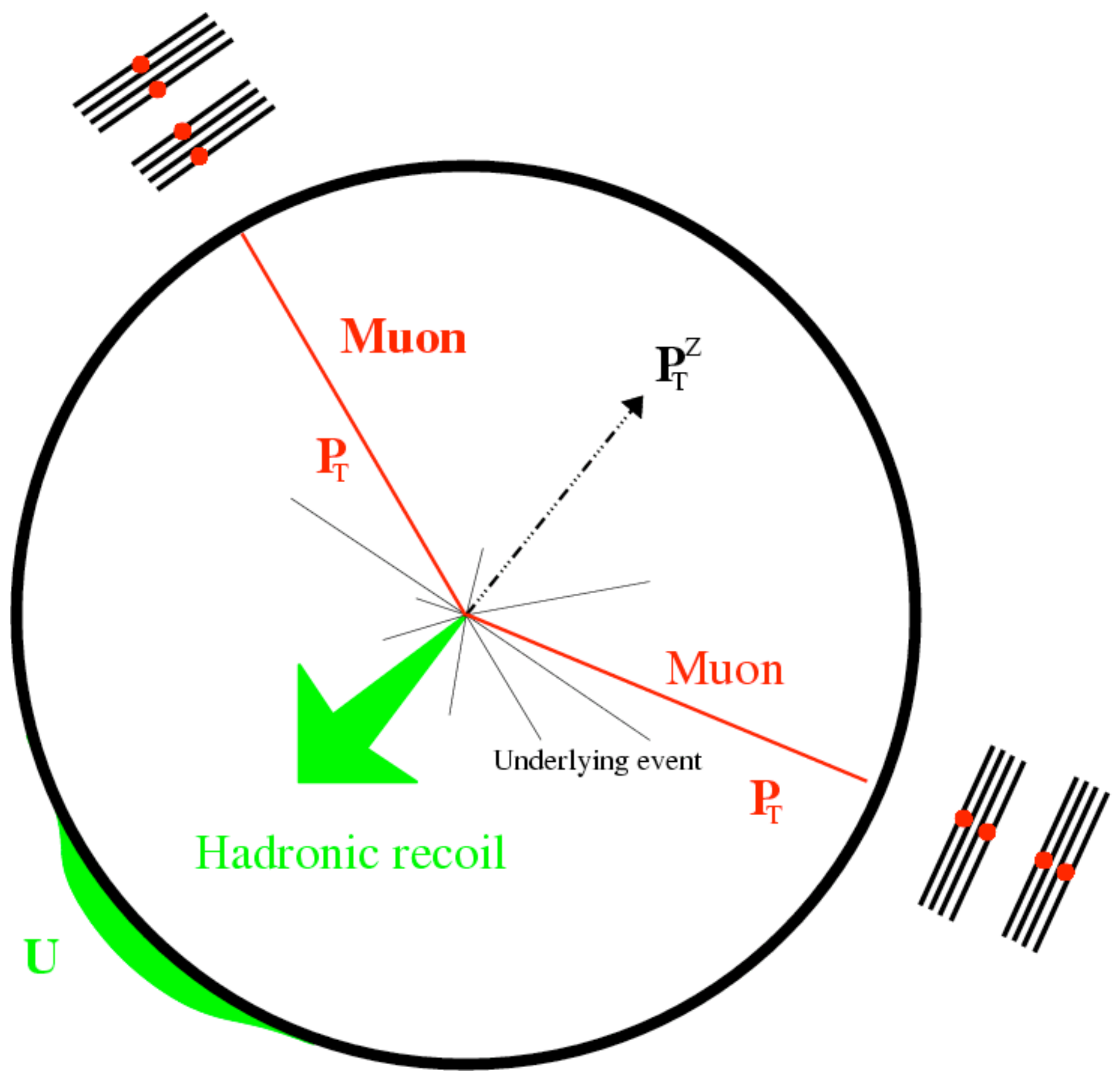
Recoil model

- Parametrize recoil model and tune using data

- Two components
  1. Soft “spectator interaction” component
     - Randomly oriented (~3 additional interactions per event)
     - Model using minimum-bias data

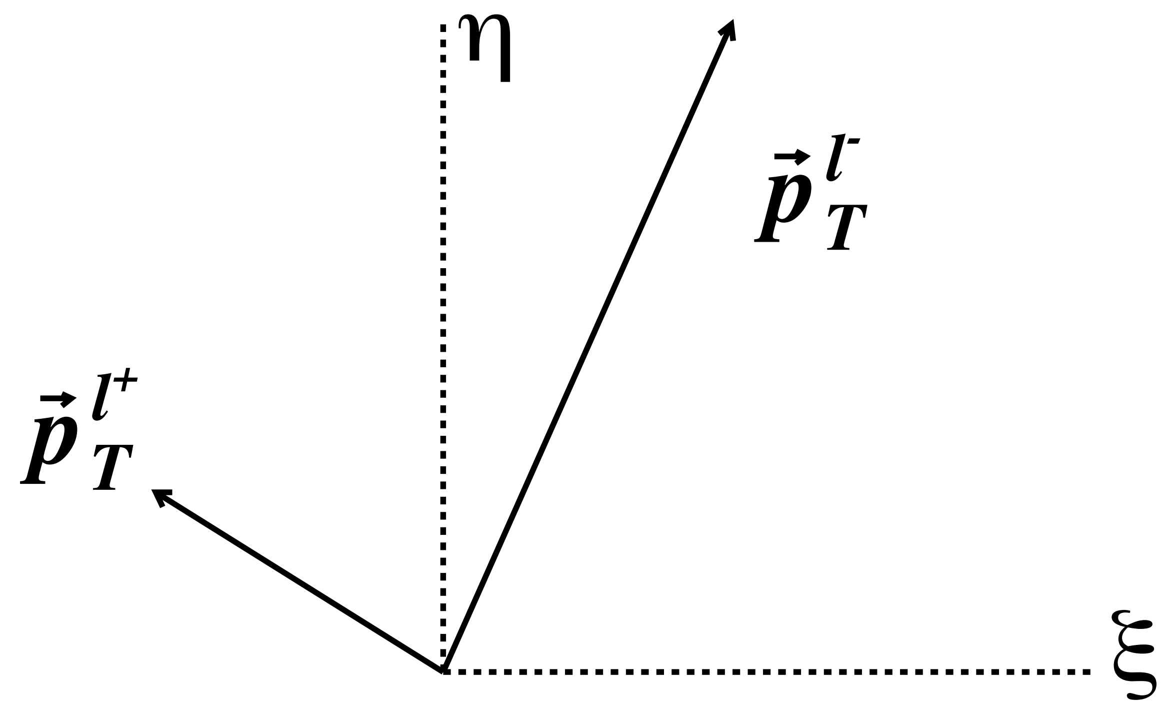
  2. Hard “jet” component
     - Boson p_T dependent response and resolution
     - Tune by balancing boson p_T and recoil in Z events

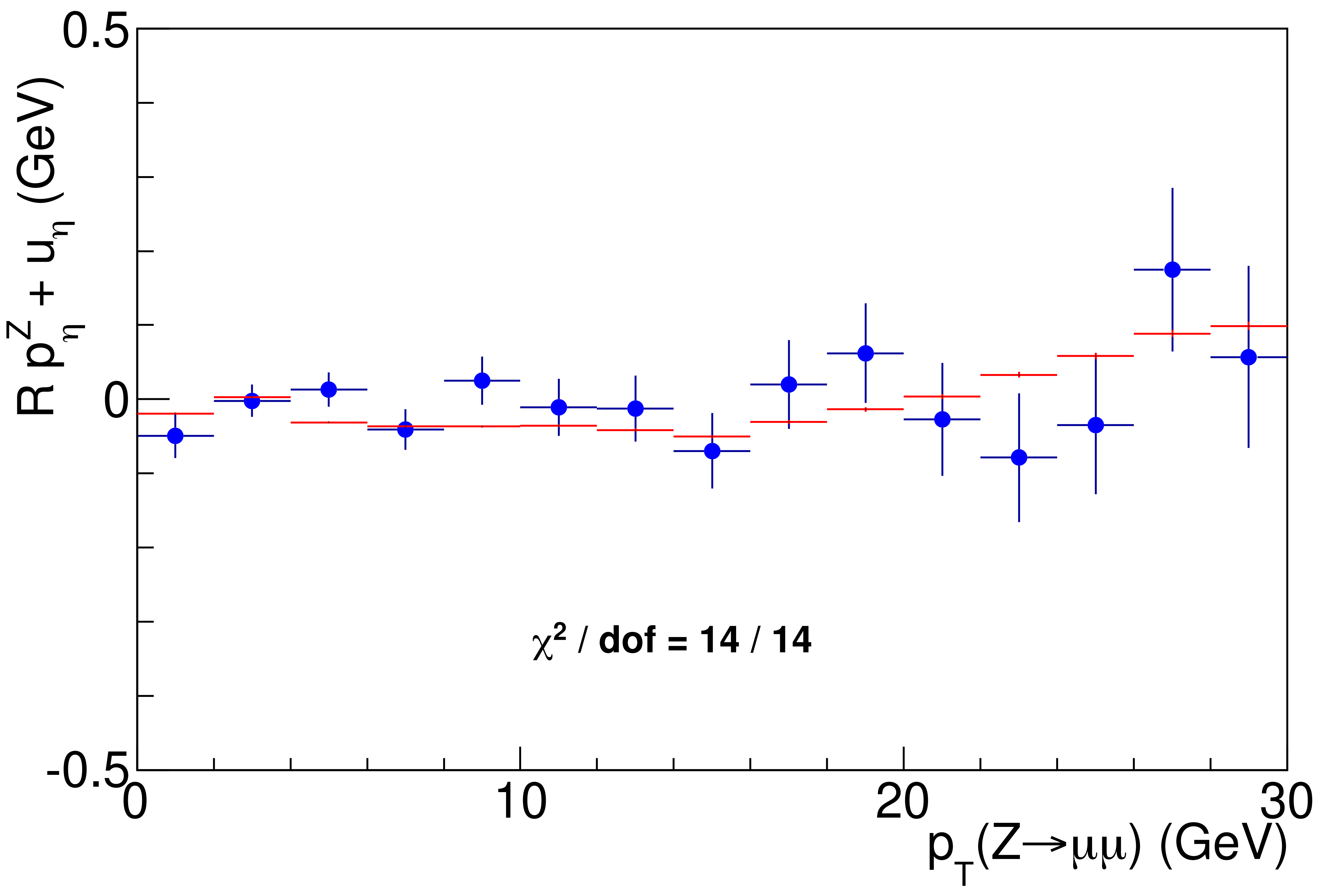


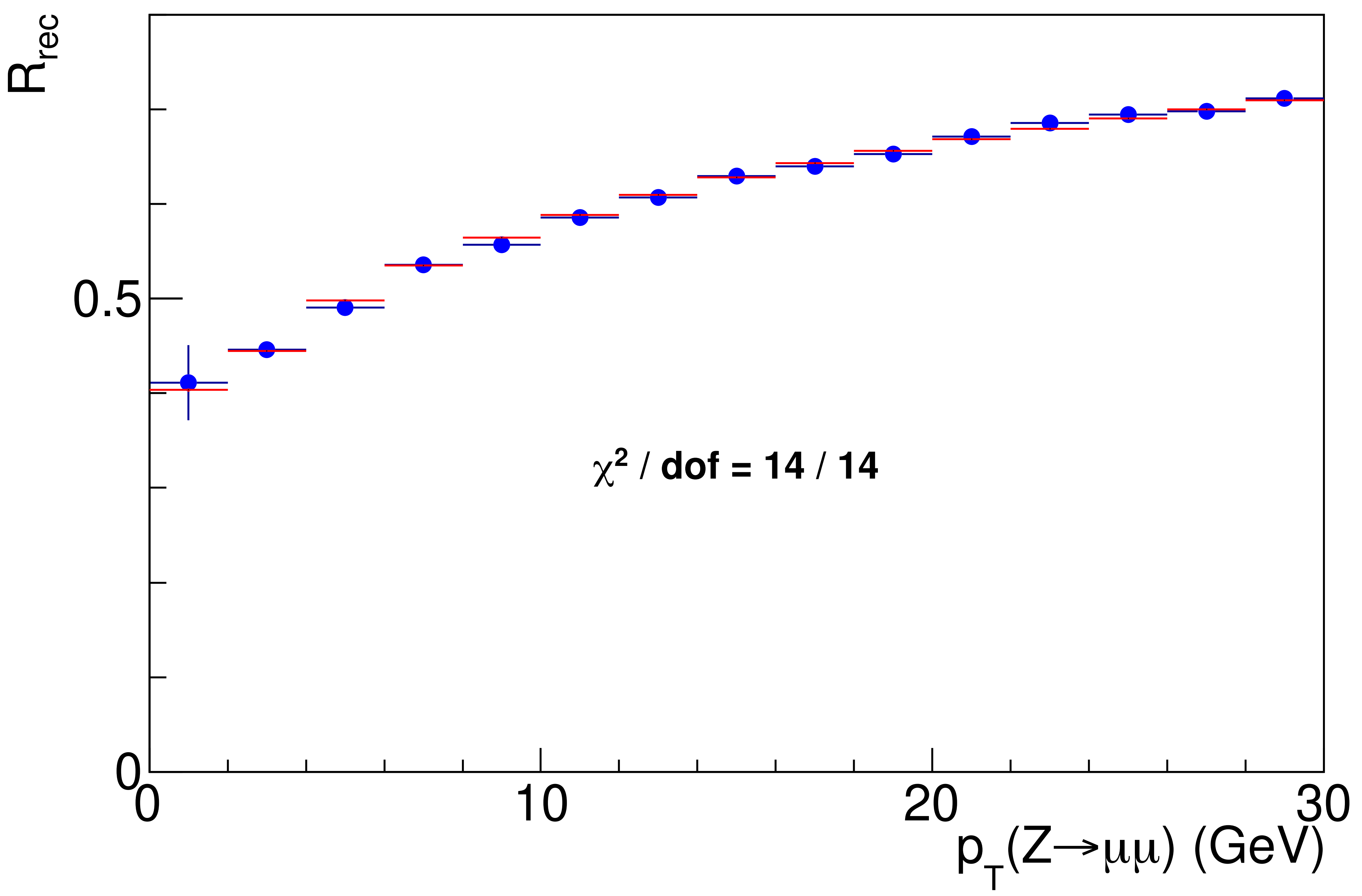


Calibrating recoil response

- Recoil scale $R = u_{meas}/u_{true}$
  - Calibrate by balancing Z p_T against $p_T + u$ along η axis
    ΔM_W = 2 MeV

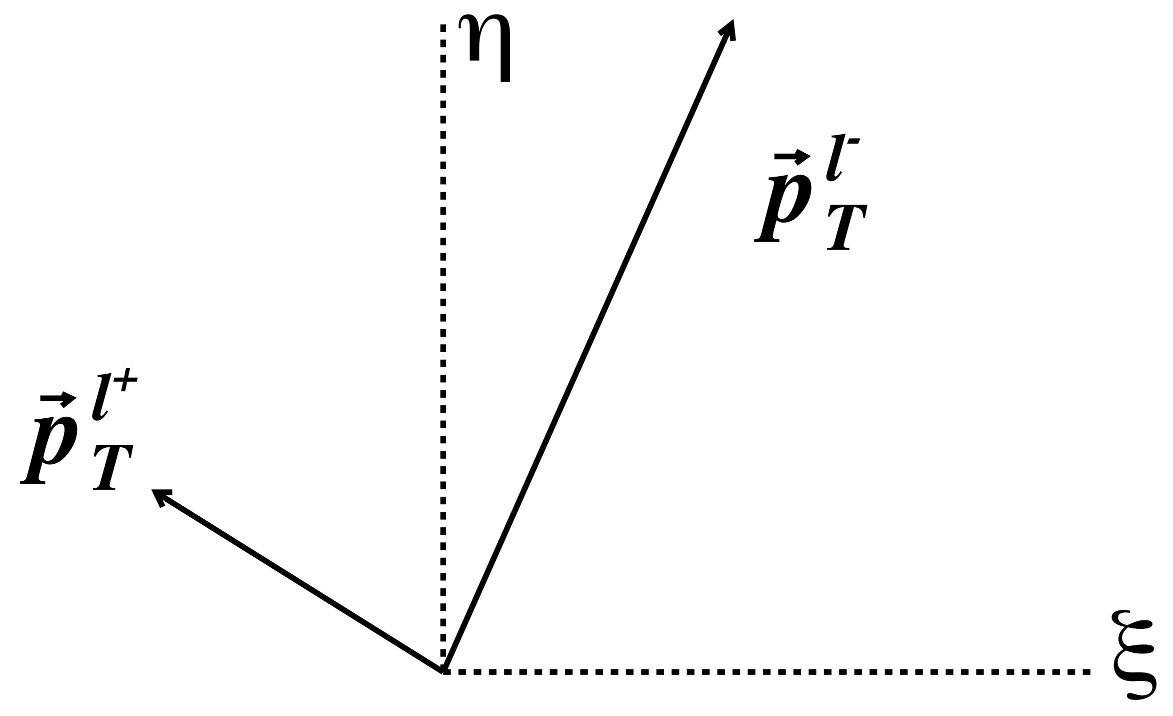


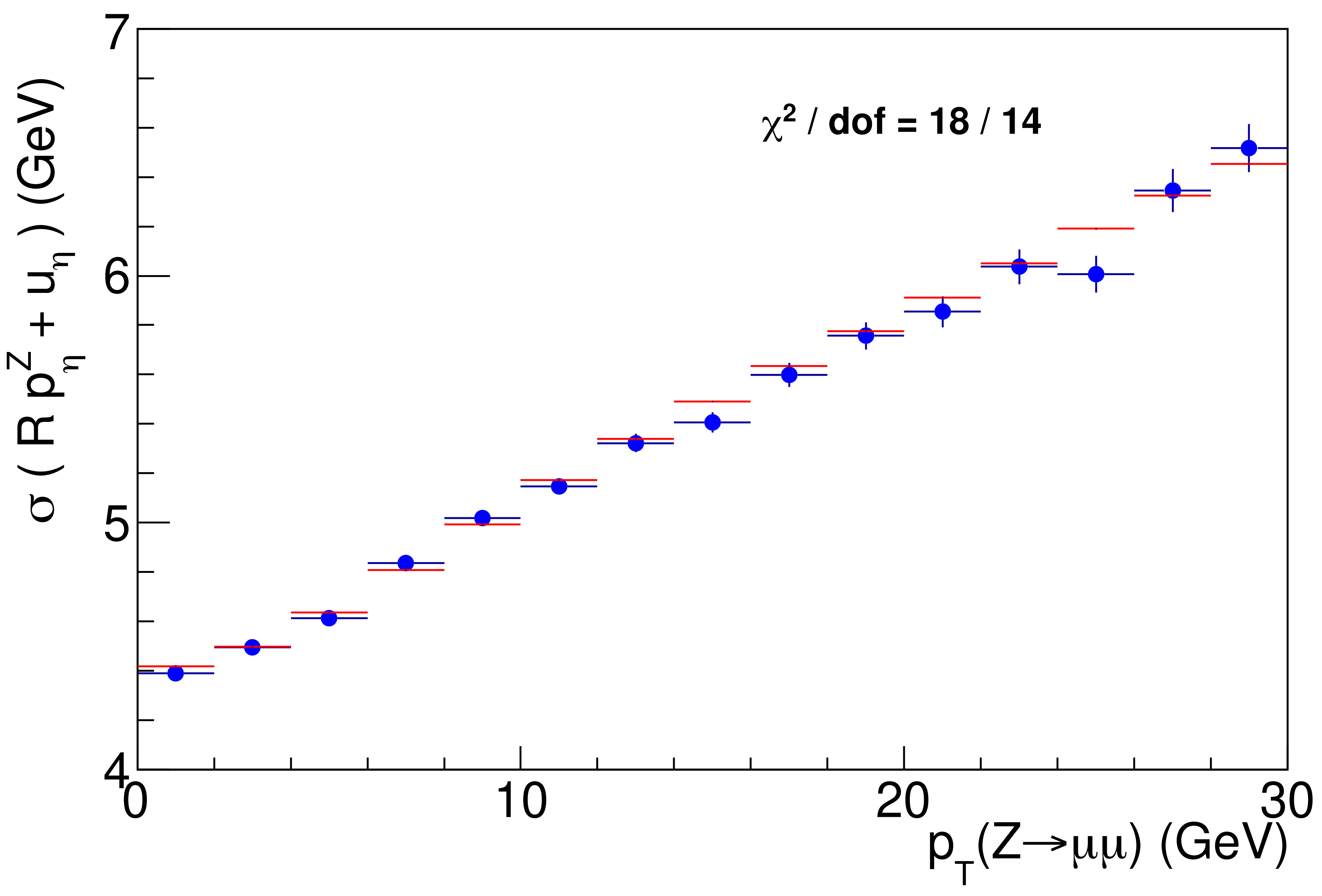


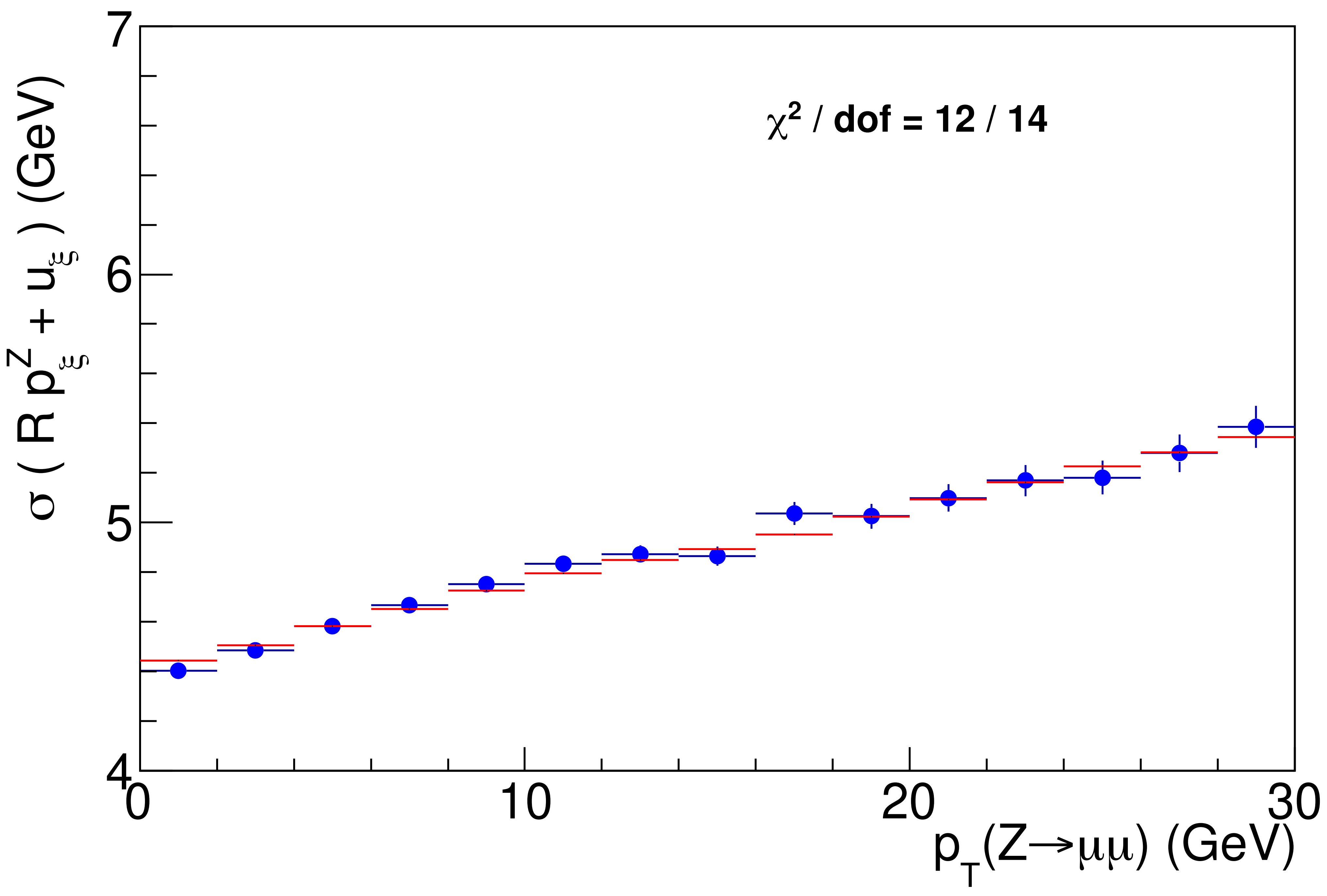


Calibrating recoil resolution

- Recoil **energy** resolution
  - Calibrate balancing $Z\ p_T$ against rms(p_T+u)
  - Dijet events contribute resolution term in ξ direction
  - ΔM_W = 1.8 MeV

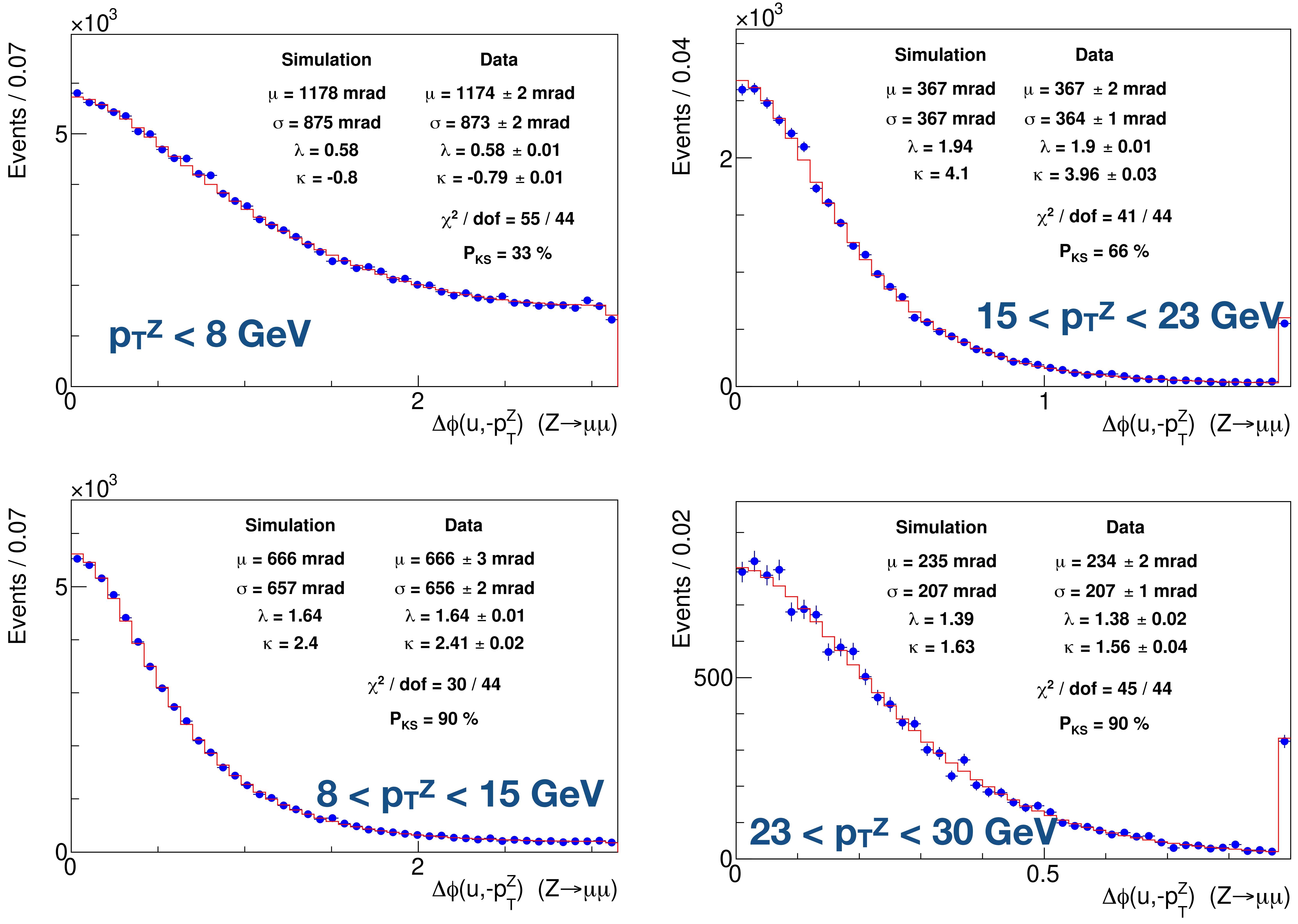






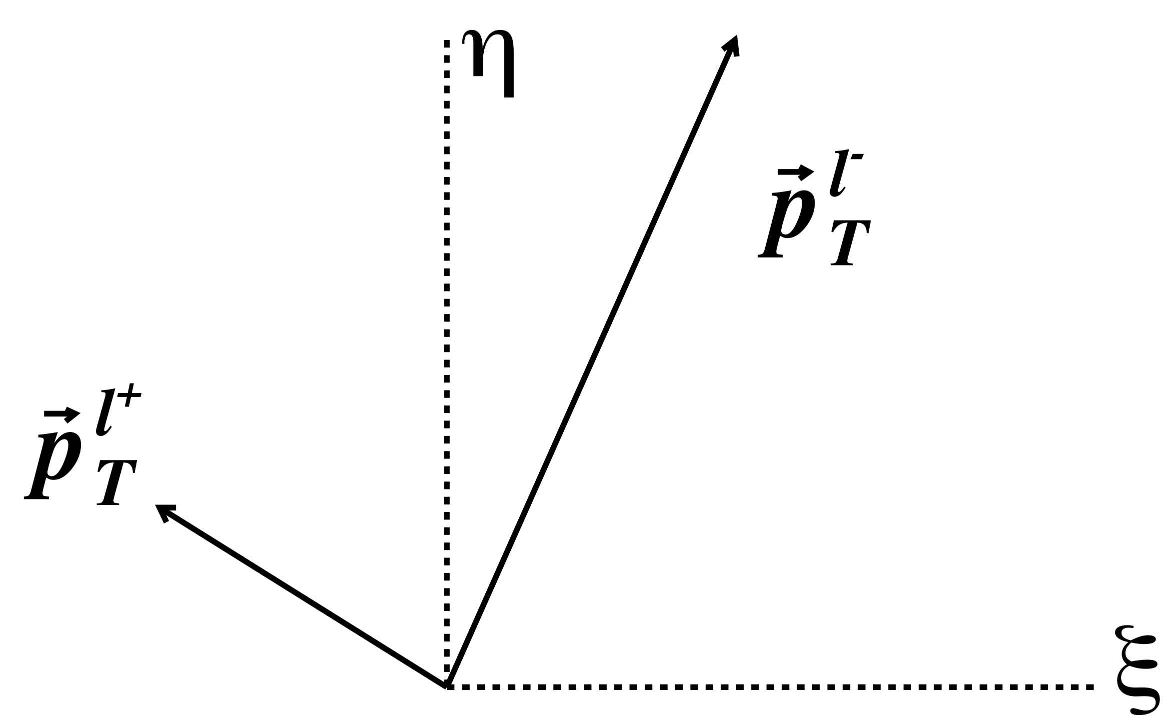
Calibrating recoil resolution

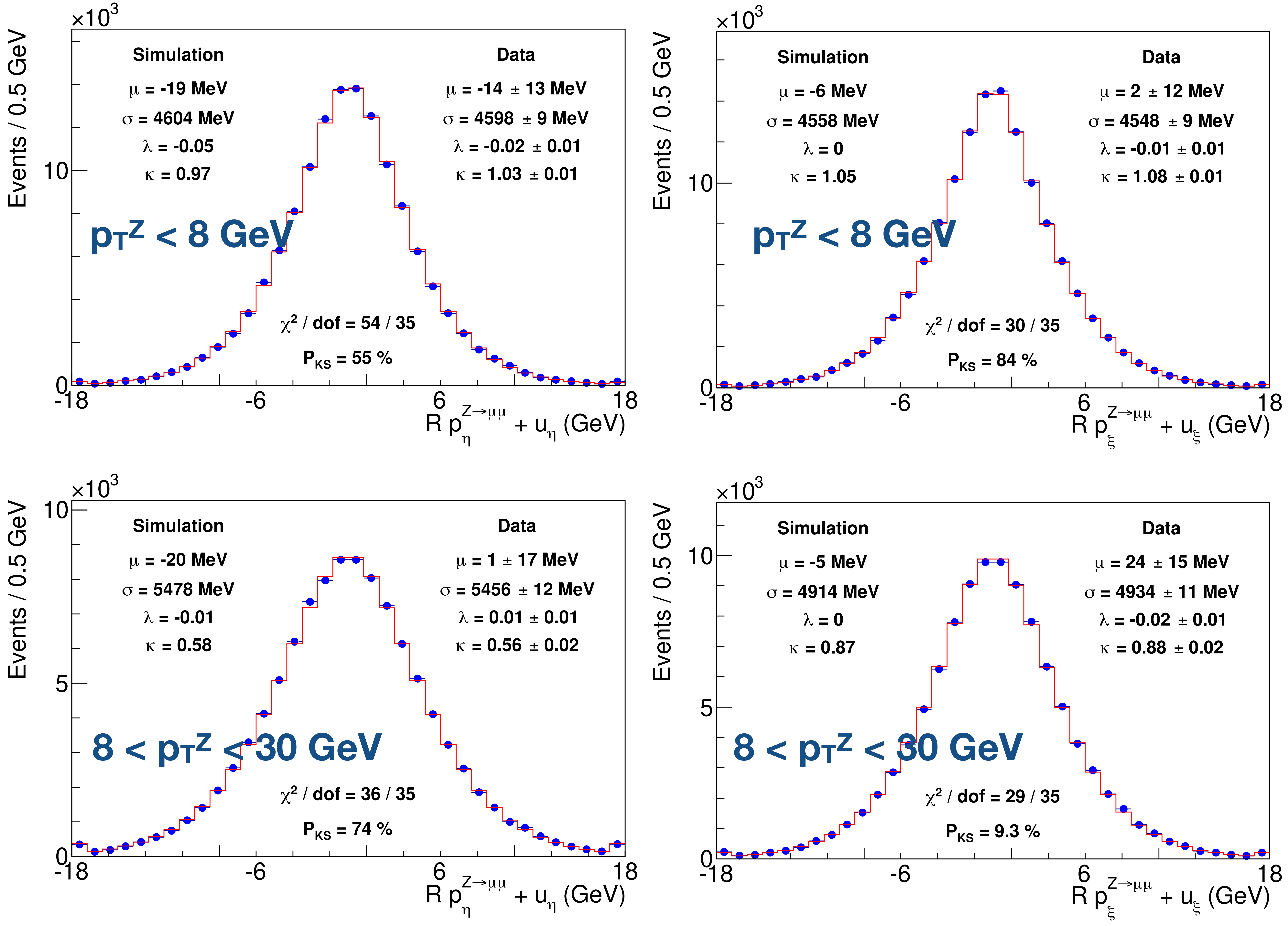
- Recoil **angular** resolution
  - Resolution of $\phi_{||}$ better determined than ϕ_u
  - Tune difference as function of p_T^Z
    - Four bins of p_T^Z shown



Additional recoil tuning

- Constrain additional recoil fluctuations
  - Recoil projected along and orthogonal to p_T^Z



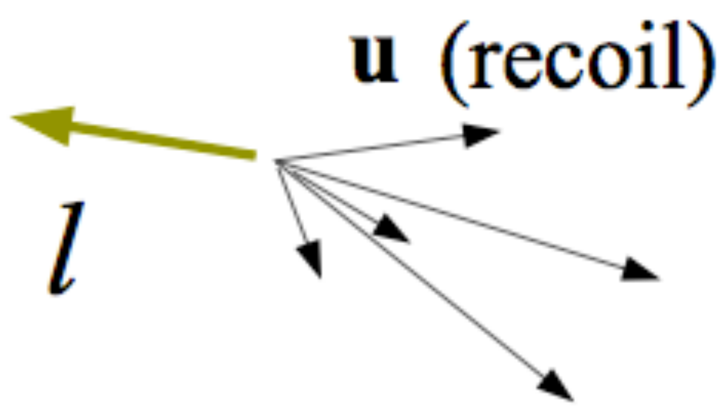


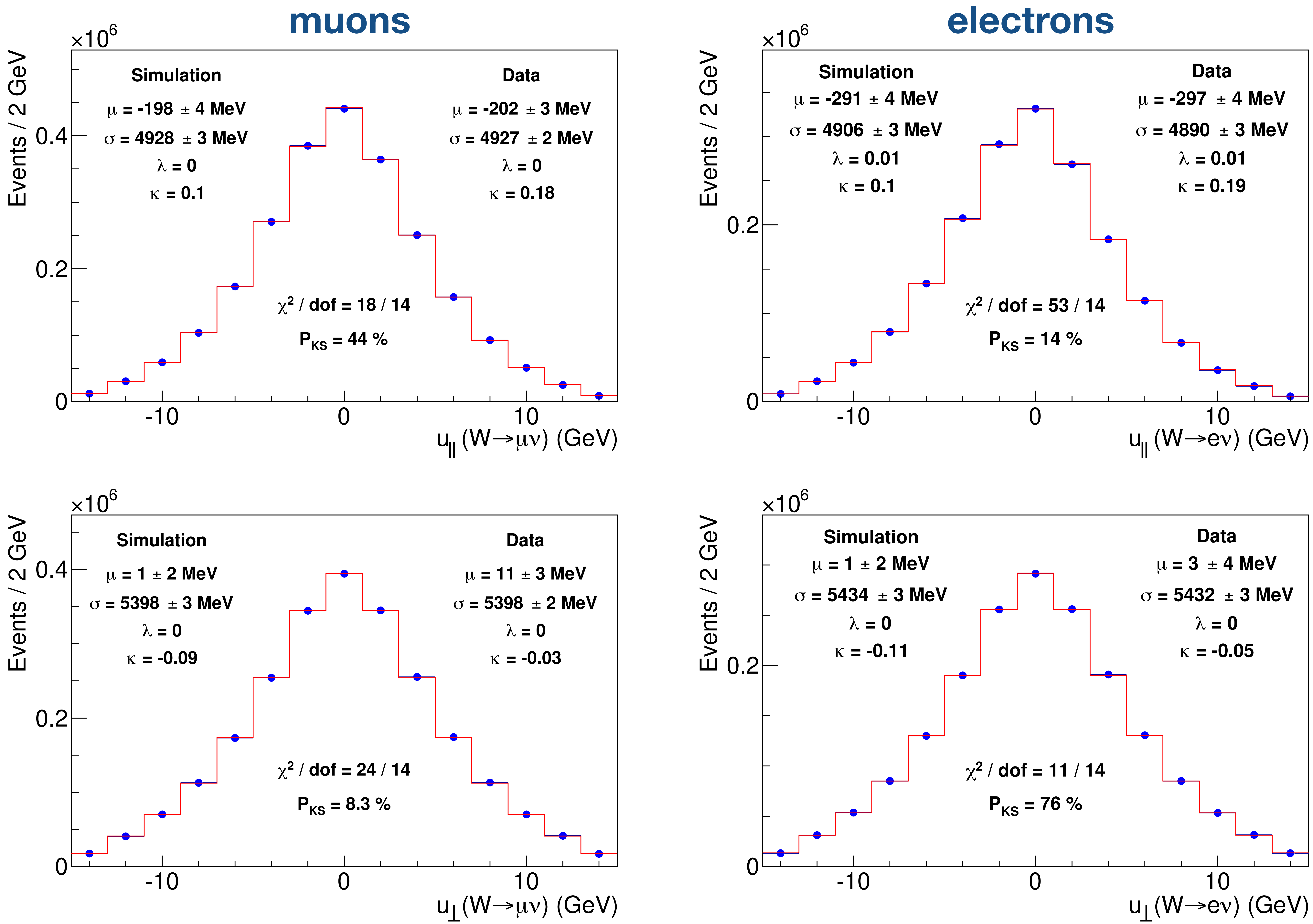
Recoil model validation

- Test recoil model with Ws
  - W events not used as input to recoil model
  - Much higher statistics than Z events
- Project recoil along and orthogonal to lepton direction

for $u \ll p_T^l$:

$m_T \approx 2p_T^l + u_{||}$, $p_T^\nu \approx 2p_T^l + 2u_{||}$





PDFs and Backgrounds

Parton Distribution Functions

- PDFs affect acceptance of events (and thus W/Z line-shapes)
- **NNPDF3.1**[1] used as default NNLO PDFs
  - Utilize 25 symmetric eigenvectors of NNPDF3.1 to determine systematic uncertainty
  - **ΔM_W=3.9 MeV**
- Compare central values to other NNLO PDF sets: CT18 and MMHT2014
  - Agree to within 2.1 MeV
- Compare central values to NLO PDF sets: ABMP16, CJ15, MMHT2014
  - Agree to within 3 MeV

[1]*R.D.Ball et al, Eur. Phys. J. C* ***77****, 663 (2017)*

Backgrounds

- Electroweak backgrounds ($Z \to ll$, $W \to \tau\nu$)
  - Modeled using custom simulation; validated with full GEANT-based CDF simulation
  - Tune recoil model and lepton response
- QCD backgrounds (hadronic jets, meson decay-in-flight)
  - Model using control regions in data
  - Estimate rates by anti-selecting on lepton quality cuts
- Cosmic rays
  - Estimated using custom tracking algorithm (reduced with >99% efficiency)
- Except $Z \to \mu\mu$ (lost forward muon), backgrounds are small
- Include all estimated background shapes in final templates

Background estimates and impact

muons

Source	Fraction (%)	δM_W (MeV) m_T fit	p_T^μ fit	p_T^ν fit
$Z/\gamma^* \to \mu\mu$	7.37 ± 0.10	1.6 (0.7)	3.6 (0.3)	0.1 (1.5)
$W \to \tau\nu$	0.880 ± 0.004	0.1 (0.0)	0.1 (0.0)	0.1 (0.0)
Hadronic jets	0.01 ± 0.04	0.1 (0.8)	-0.6 (0.8)	2.4 (0.5)
Decays in flight	0.20 ± 0.14	1.3 (3.1)	1.3 (5.0)	-5.2 (3.2)
Cosmic rays	0.01 ± 0.01	0.3 (0.0)	0.5 (0.0)	0.3 (0.3)
Total	8.47 ± 0.18	2.1 (3.3)	3.9 (5.1)	5.7 (3.6)

normalization (shape)

electrons

Source	Fraction (%)	δM_W (MeV) m_T fit	p_T^e fit	p_T^ν fit
$Z/\gamma^* \to ee$	0.134 ± 0.003	0.2 (0.3)	0.3 (0.0)	0.0 (0.6)
$W \to \tau\nu$	0.94 ± 0.01	0.6 (0.0)	0.6 (0.0)	0.6 (0.0)
Hadronic jets	0.34 ± 0.08	2.2 (1.2)	0.9 (6.5)	6.2 (-1.1)
Total	1.41 ± 0.08	2.3 (1.2)	1.1 (6.5)	6.2 (1.3)

normalization (shape)

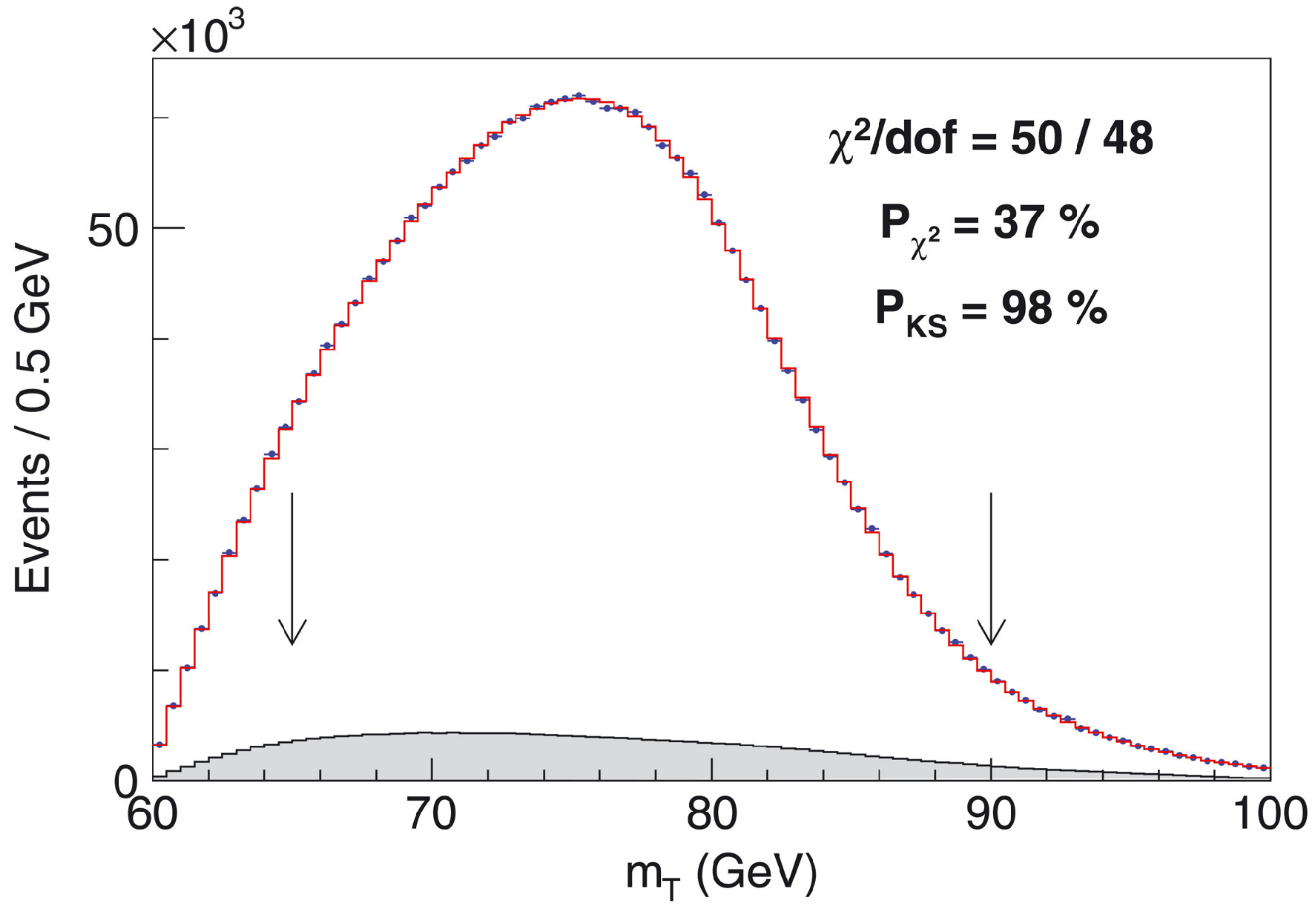
Results

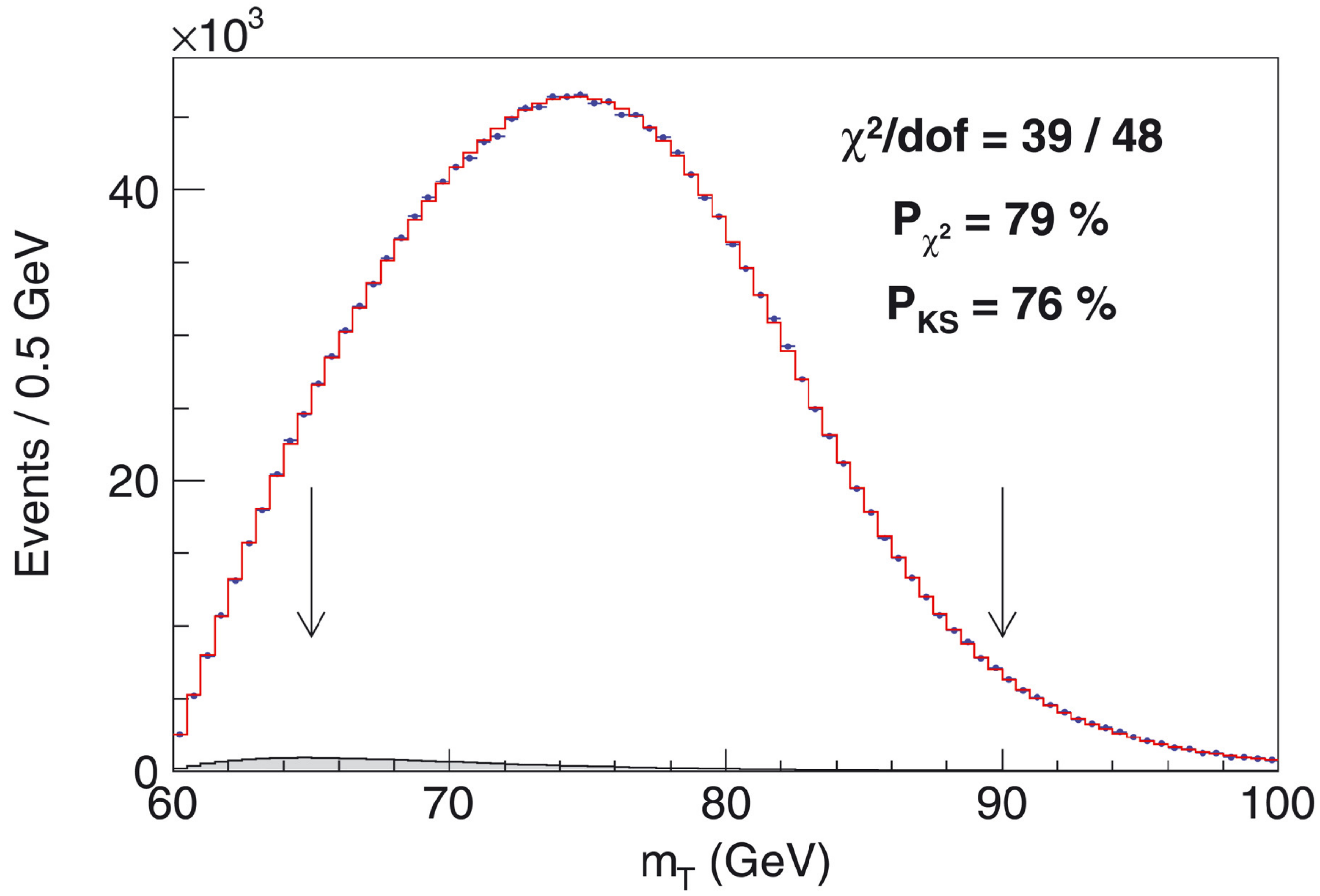
A word on blinding

- During development of analysis, all fits **blinded** with random offset from [-50,50] MeV
  - Common offset applied to all six mass fits
    - Allows for comparison and cross-check
  - During calibration of energy scales, separate offset applied to Z mass fits
    - Common to all Z mass fits
  - Blinding offsets kept in encrypted file during analysis

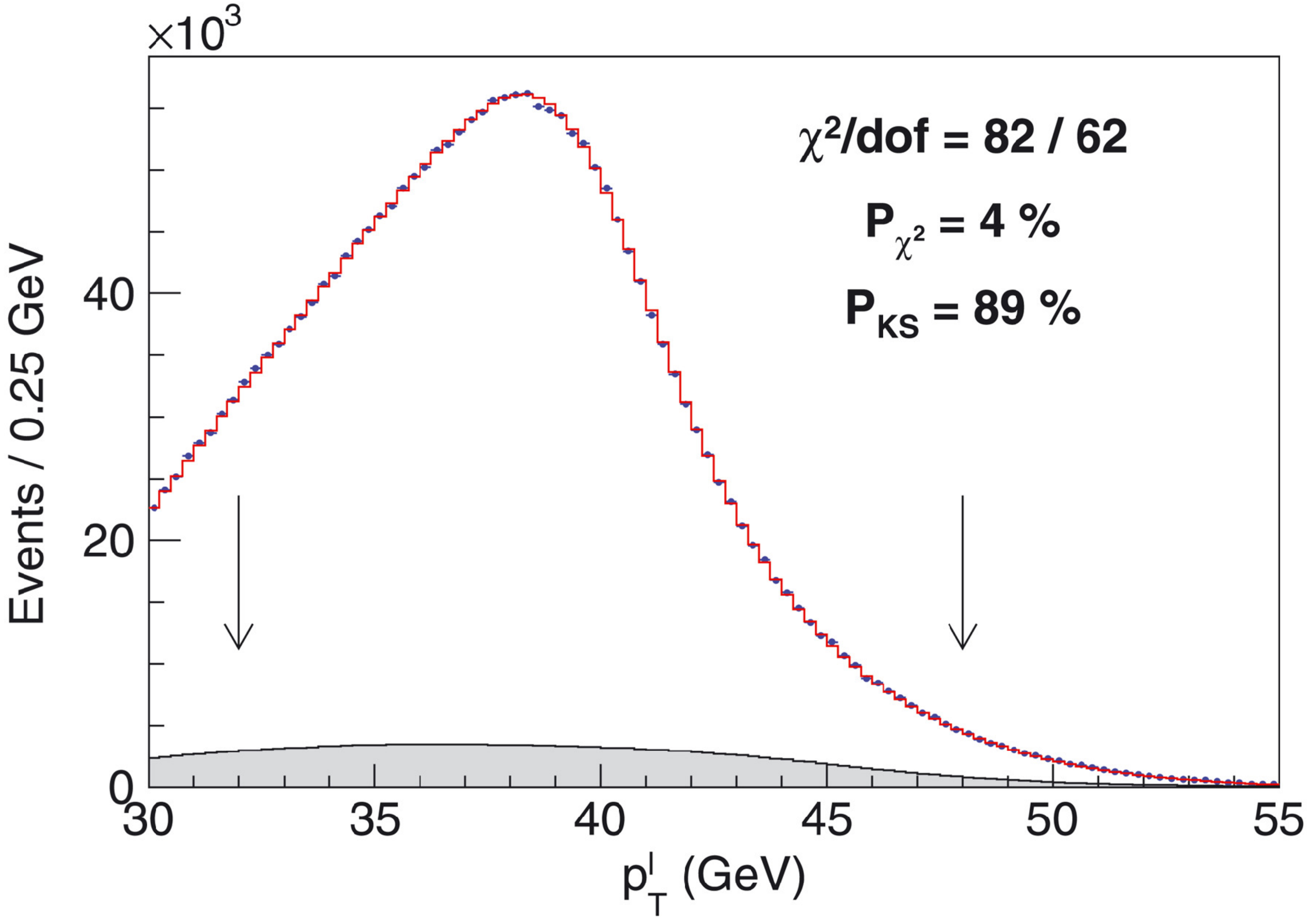
- **Blinding offset removed only after analysis frozen**

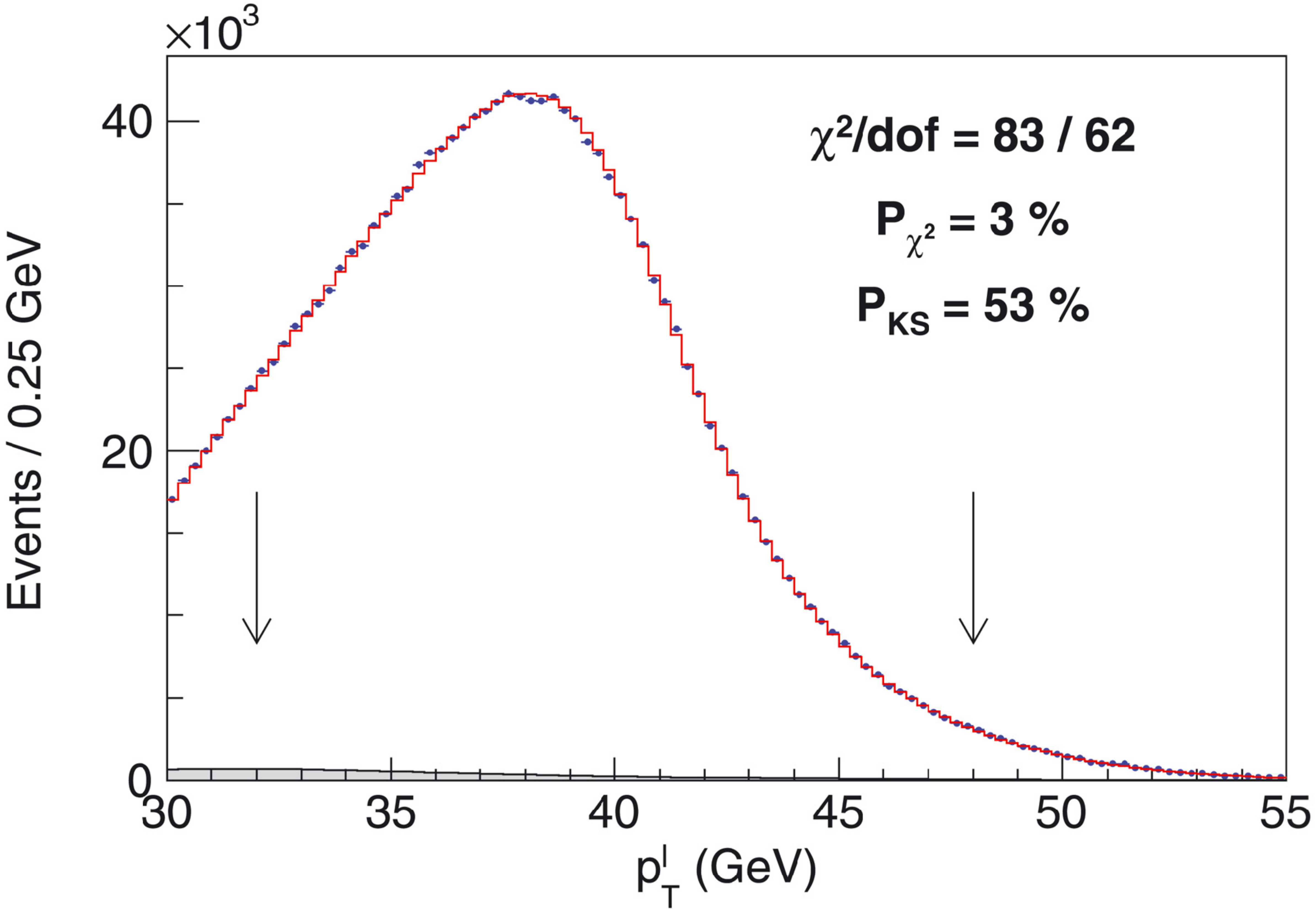
Transverse mass fits



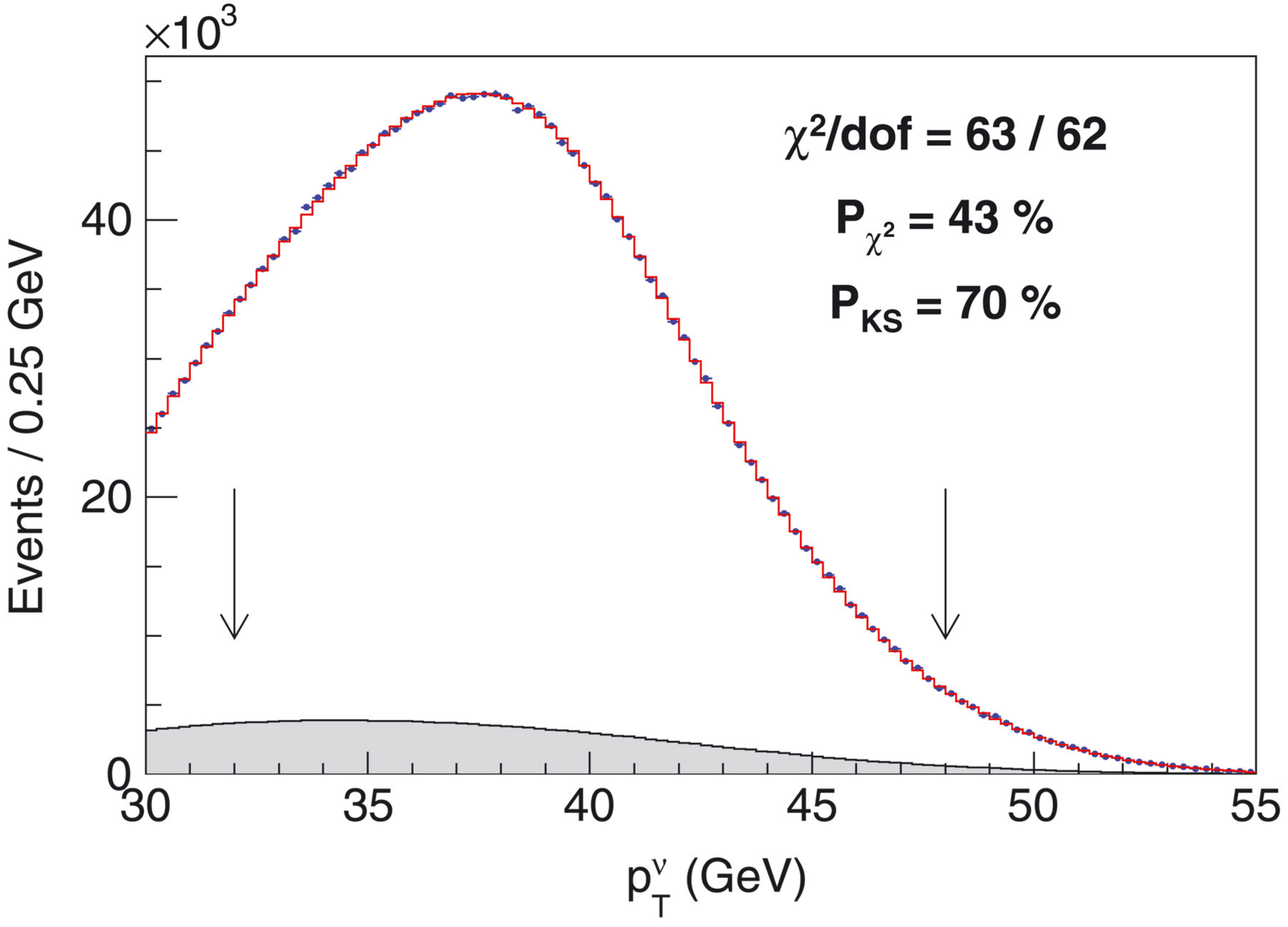


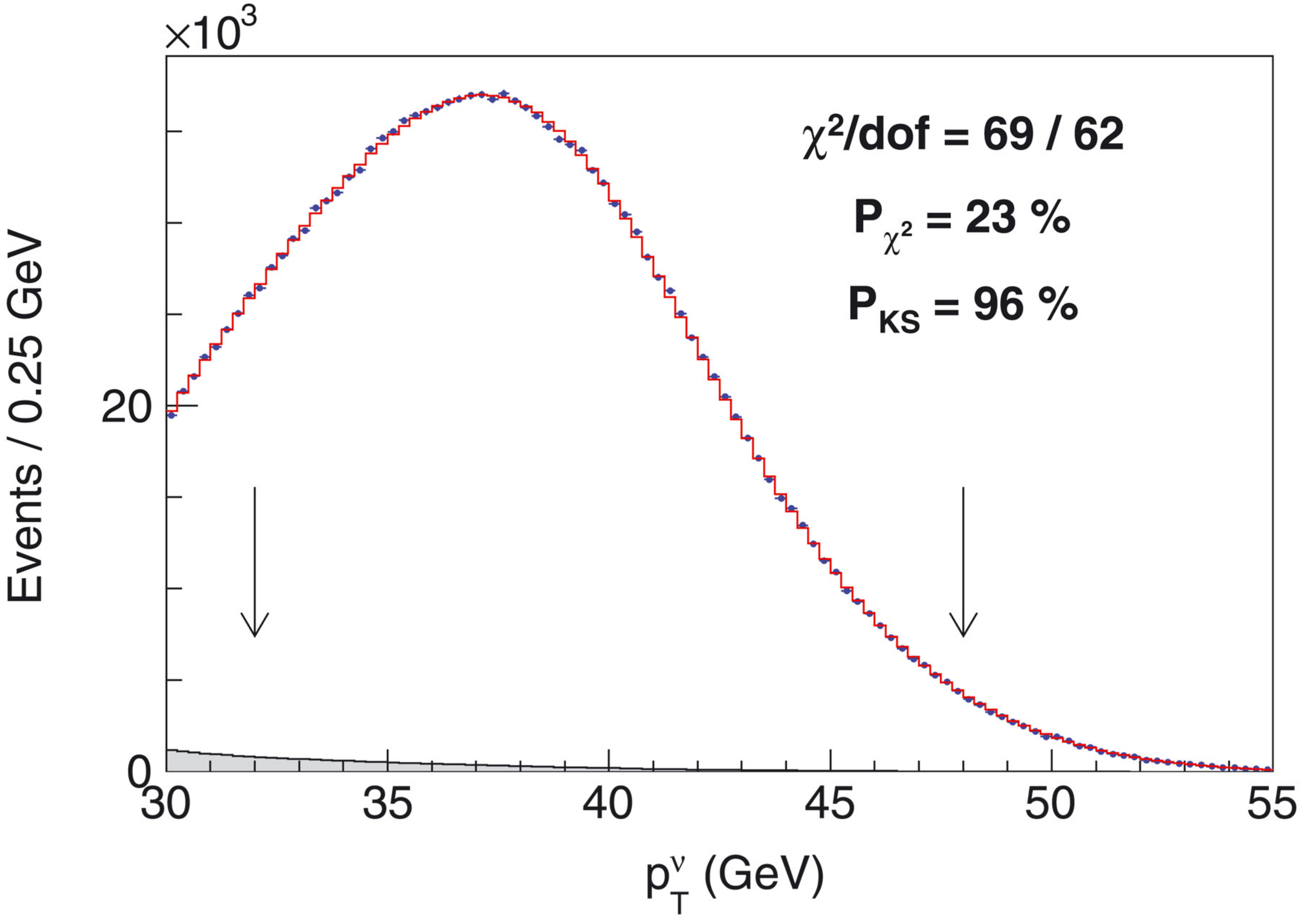
Charged lepton p_T fits





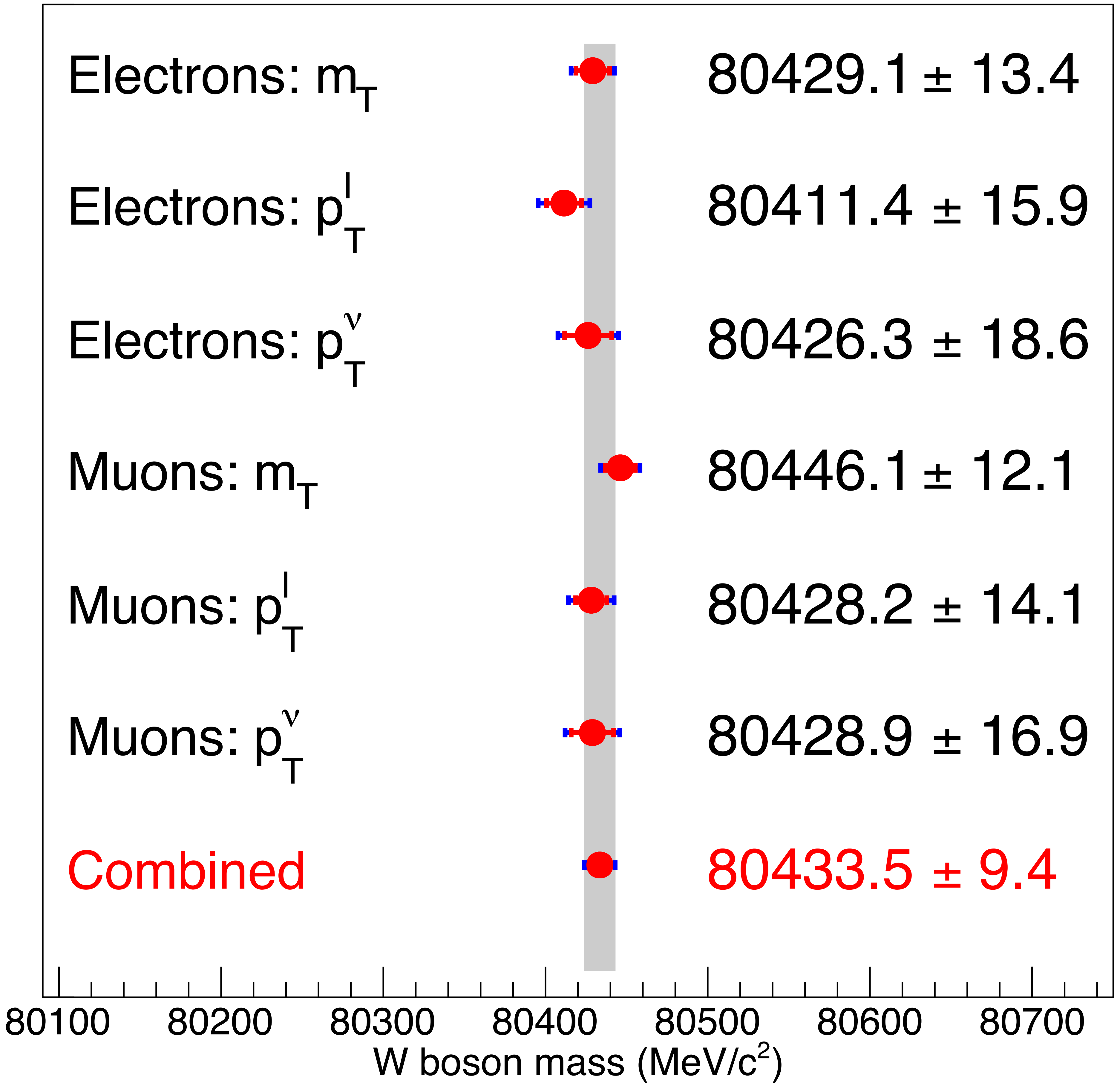
Neutrino p_T fits





All W mass fits

Fit	Fit result (MeV)	χ^2/dof
$W\to e\nu$ (m_T)	$80429.1 \pm 10.3_{stat} \pm 8.5_{syst}$	39/48
$W\to e\nu$ (p_T^l)	$80411.4 \pm 10.7_{stat} \pm 11.8_{syst}$	83/62
$W\to e\nu$ (p_T^ν)	$80426.3 \pm 14.5_{stat} \pm 11.7_{syst}$	69/62
$W\to \mu\nu$ (m_T)	$80446.1 \pm 9.2_{stat} \pm 7.9_{syst}$	50/48
$W\to \mu\nu$ (p_T^l)	$80428.2 \pm 9.6_{stat} \pm 10.3_{syst}$	54/62
$W\to \mu\nu$ (p_T^ν)	$80428.9 \pm 13.1_{stat} \pm 10.6_{syst}$	79/62
Combined	**$80433.5 \pm 6.4_{stat} \pm 6.9_{syst}$**	7.4/5



Combining fit results and cross-checks

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

All systematic uncertainties

Source of systematic uncertainty	m_T fit			p_T^ℓ fit			p_T^ν fit		
	Electrons	Muons	Common	Electrons	Muons	Common	Electrons	Muons	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

Combined uncertainties

Source	Uncertainty 8.8 fb^{-1} (MeV)
Lepton energy scale	3.0
Lepton energy resolution	1.2
Recoil energy scale	1.2
Recoil energy resolution	1.8
Lepton removal	1.2
Backgrounds	3.3
p_T model	2.2
PDFs	3.9
QED radiation	2.7
Total systematics	*6.9*
W statistics	9.4
Total	***9.4***

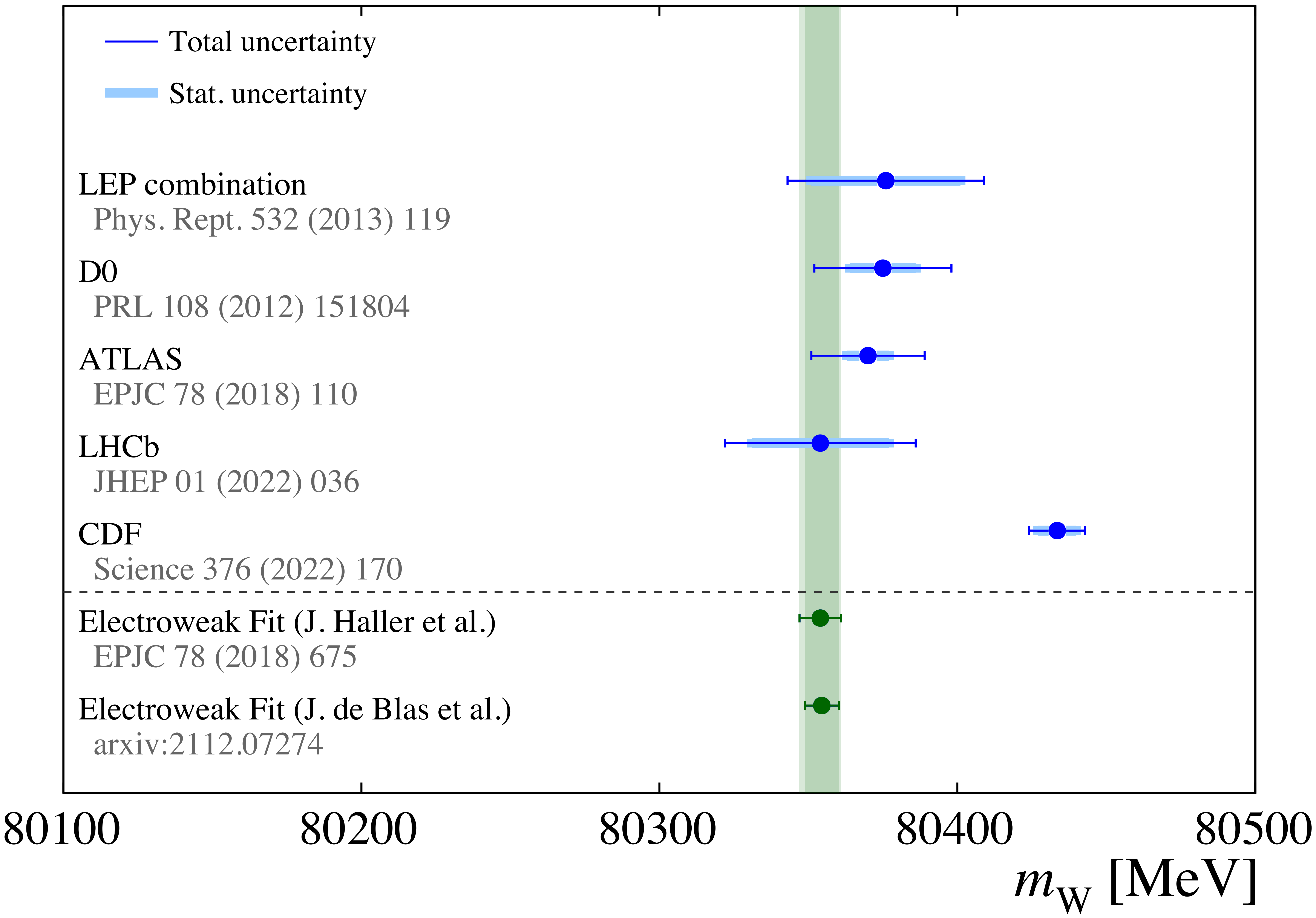
Combined uncertainties

Statistics limited by control data

Theory based (external inputs)

Source	Uncertainty 8.8 fb^{-1} (MeV)	Uncertainty 2.2 fb^{-1} (MeV)
Lepton energy scale	3.0	7
Lepton energy resolution	1.2	2
Recoil energy scale	1.2	4
Recoil energy resolution	1.8	4
Lepton removal	1.2	2
Backgrounds	3.3	3
p_T model	2.2	5
PDFs	3.9	10
QED radiation	2.7	4
Total systematics	*6.9*	*15*
W statistics	9.4	12
Total	***9.4***	***19***

New experimental landscape



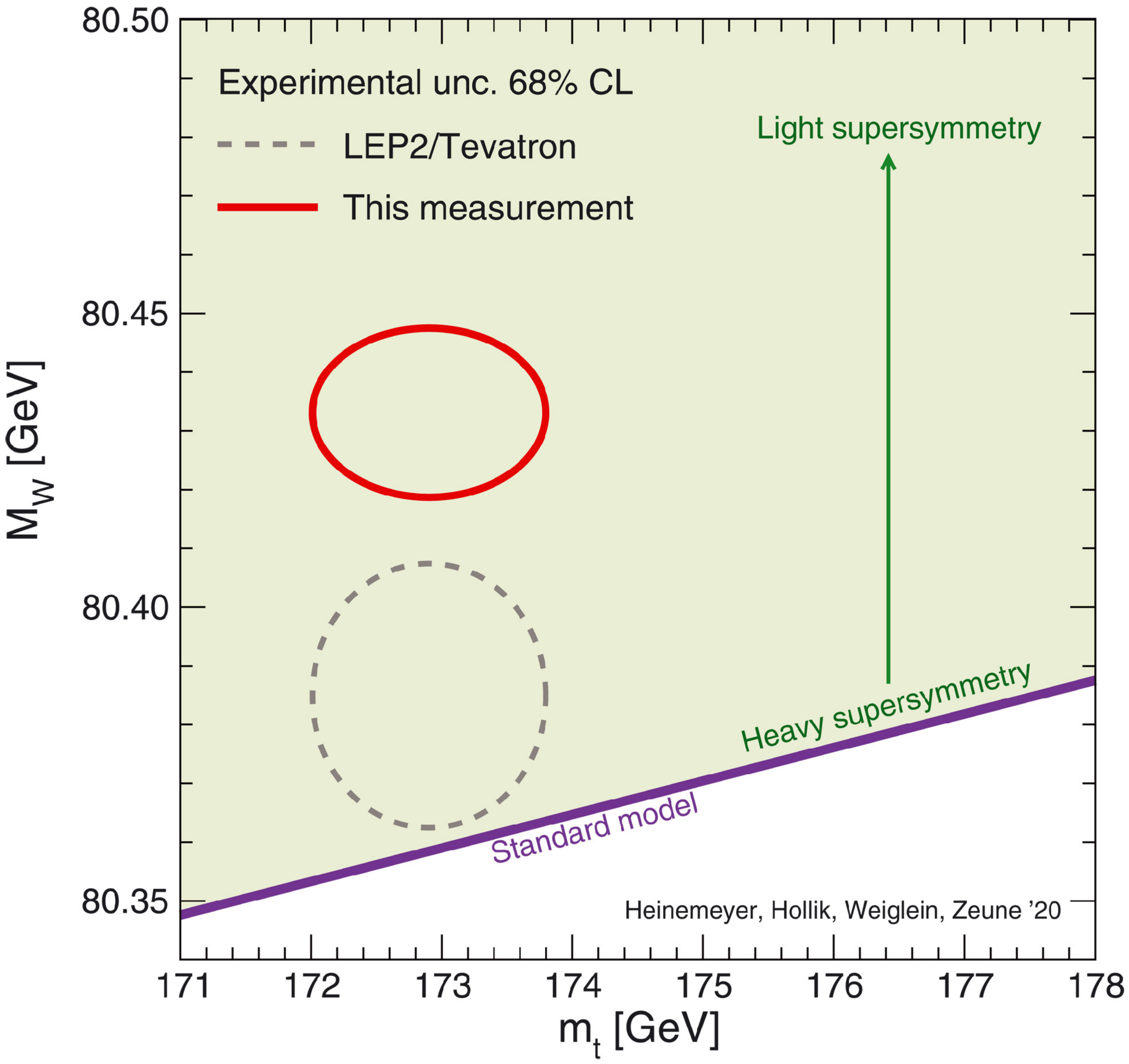
SM Expectation (PDG):

M_W=80357±4$_{inputs}$±4$_{theory}$ MeV

CDF Measurement:

M_W=80433.5±6.4$_{stat}$±6.9$_{syst}$ MeV

Updated m_{top} vs M_W



Analysis improvements vs. 2012

Method or technique	impact	section of paper
Detailed treatment of parton distribution functions	+3.5 MeV	IV A
Resolved beam-constraining bias in CDF reconstruction	+10 MeV	VI C
Improved COT alignment and drift model [65]	uniformity	VI
Improved modeling of calorimeter tower resolution	uniformity	III
Temporal uniformity calibration of CEM towers	uniformity	VII A
Lepton removal procedure corrected for luminosity	uniformity	VIII A
Higher-order calculation of QED radiation in J/ψ and Υ decays	accuracy	VI A & B
Modeling kurtosis of hadronic recoil energy resolution	accuracy	VIII B 2
Improved modeling of hadronic recoil angular resolution	accuracy	VIII B 3
Modeling dijet contribution to recoil resolution	accuracy	VIII B 4
Explicit luminosity matching of pileup	accuracy	VIII B 5
Modeling kurtosis of pileup resolution	accuracy	VIII B 5
Theory model of p_T^W/p_T^Z spectrum ratio	accuracy	IV B
Constraint from p_T^W data spectrum	robustness	VIII B 6
Cross-check of p_T^Z tuning	robustness	IV B

- Updated PDFs and track reconstruction would shift 2012 result by +13.5 MeV
  - 80387 MeV→80400.5 MeV
  - Consistent with new result at ~1% level

Conclusion

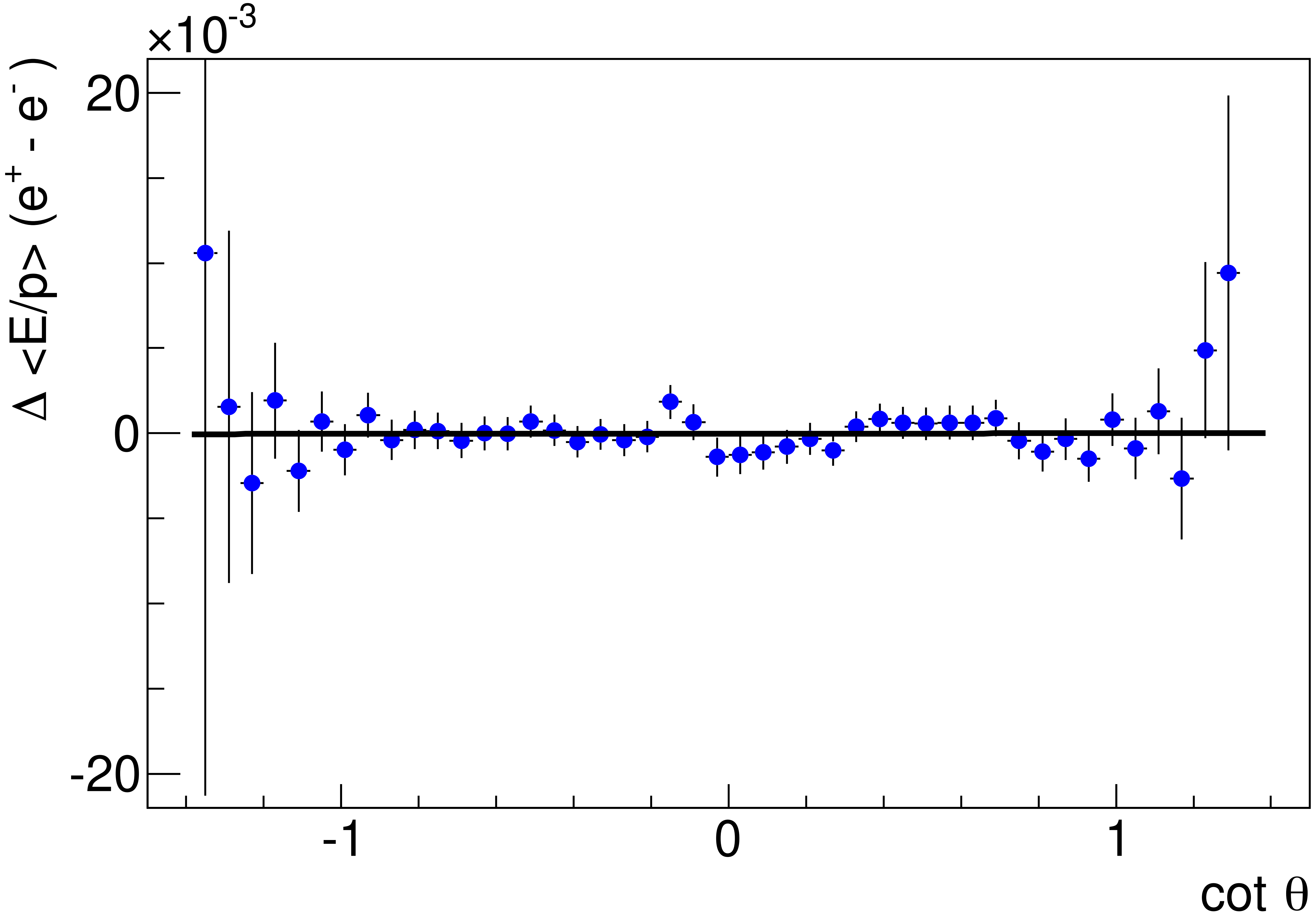
- CDF has performed the most precise single measurement of the W boson mass
  - **M_W = 80433.5±9.4 MeV** *[Science **376**, 170 (2022)]*
  - Utilizes the full Run II dataset collected by CDF
  - More precise than all previous measurements combined

- Measurement in significant tension with SM prediction of the W boson mass
  - M_W = 80357±6 MeV
  - Deviation of approximately 7σ
  - Further measurement and/or theoretical calculation will be needed

Backup

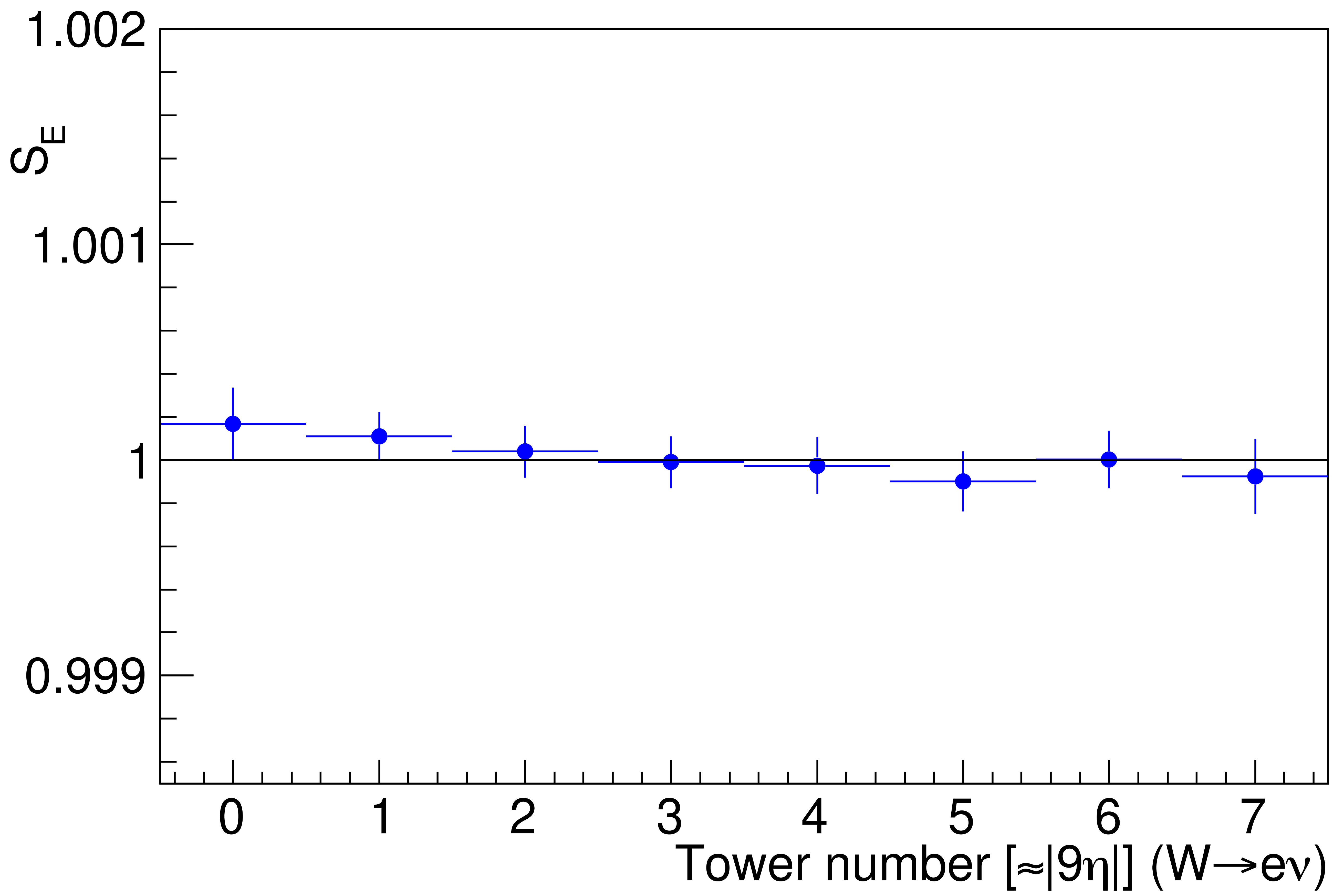
Residual alignment corrections

- Some "weakly constrained modes" not corrected by cosmic alignment
  - Study these using difference in <E/p> between e^+ and e^- events
  - Apply correction to alignment based on this difference

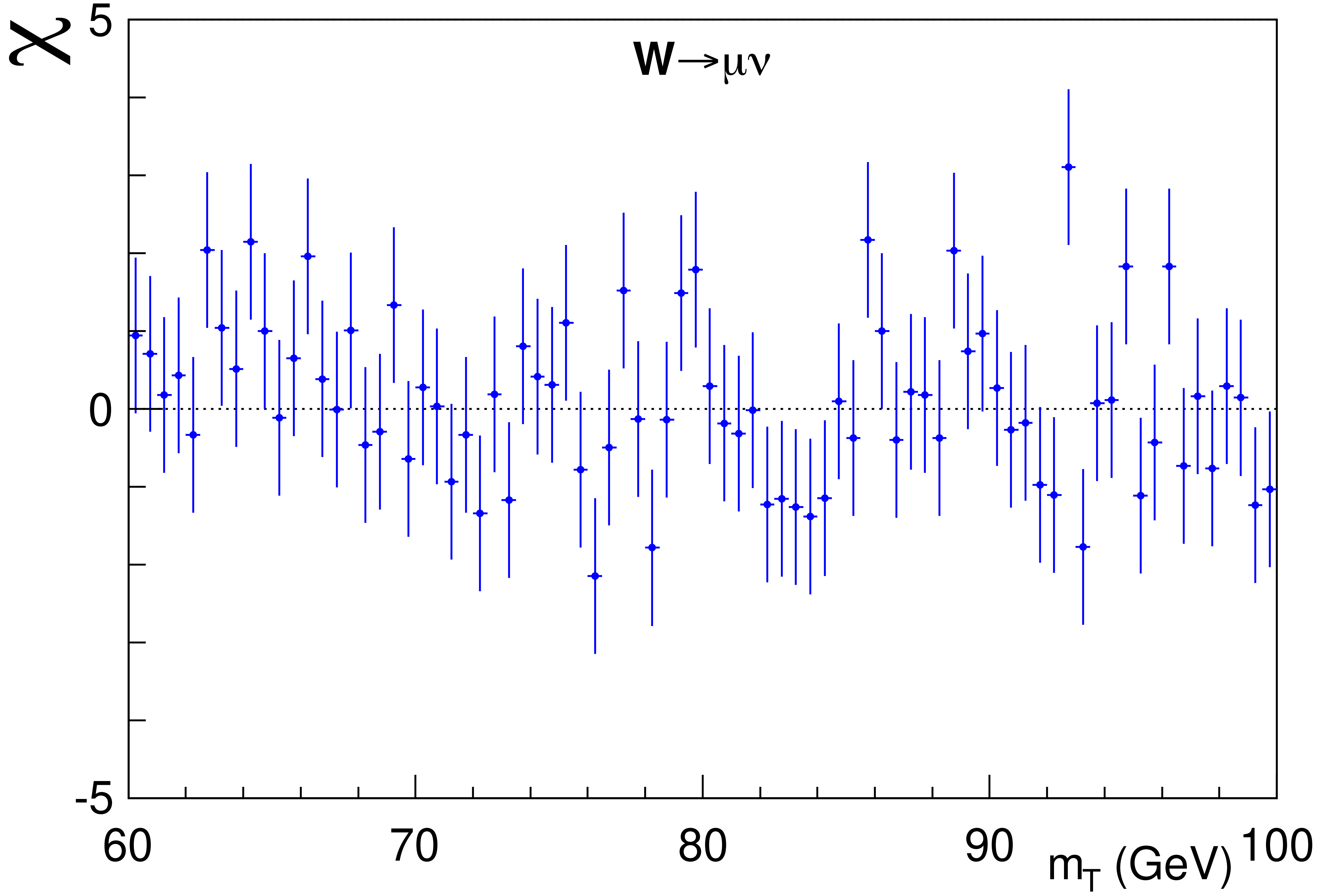


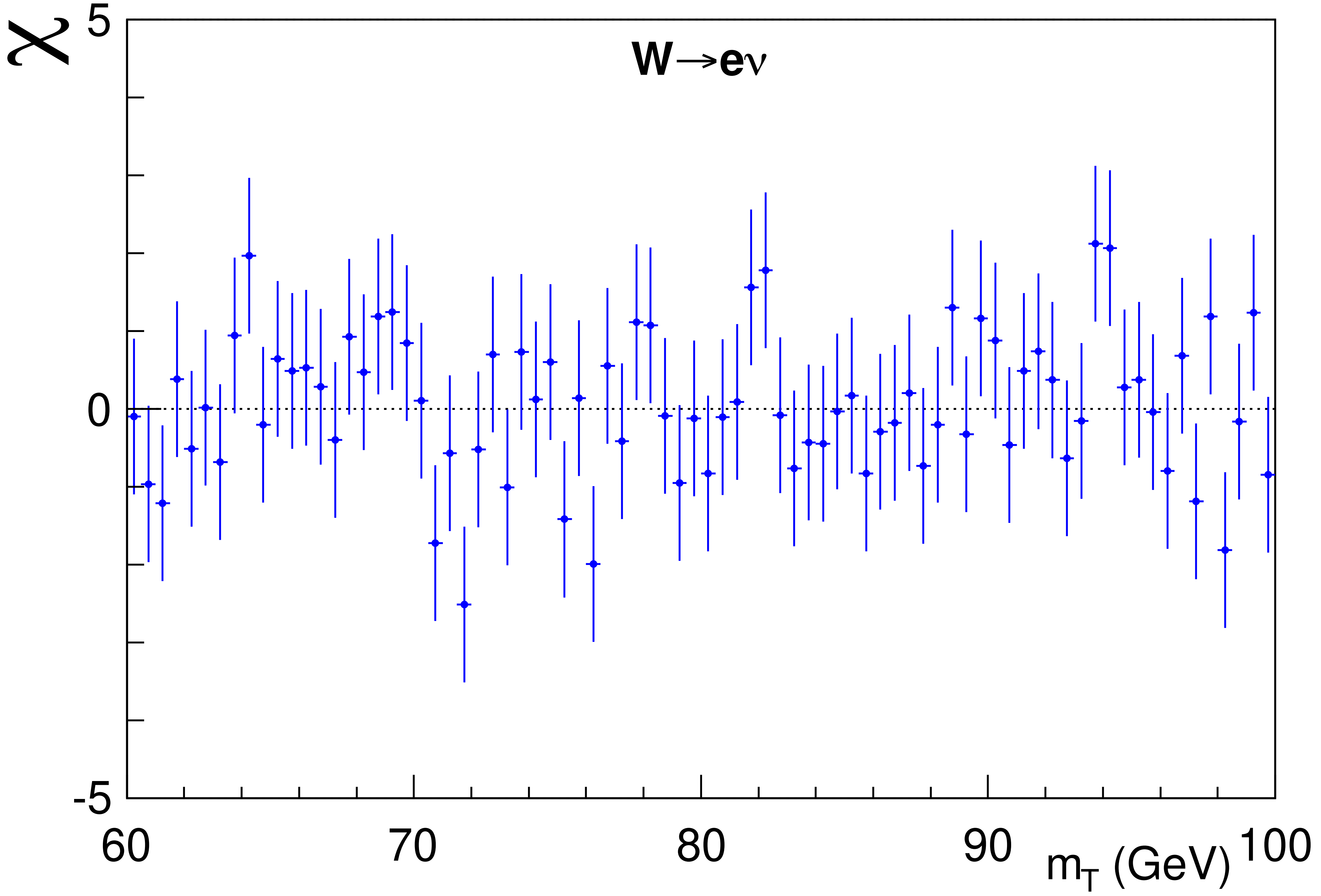
EM calorimeter spatial uniformity

- Apply tower-by-tower correction to flatten response in eta
  - Response after tuning flat

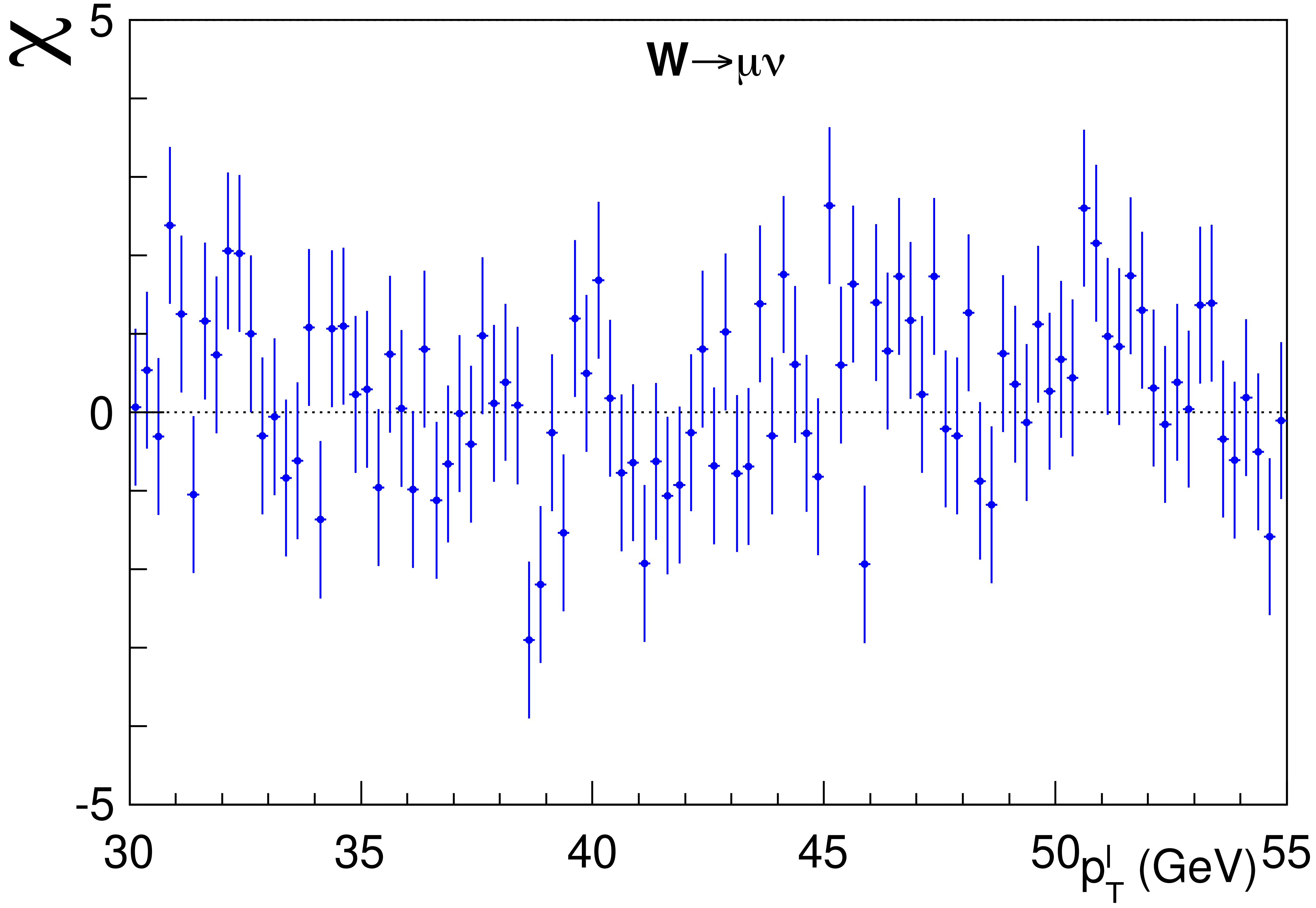


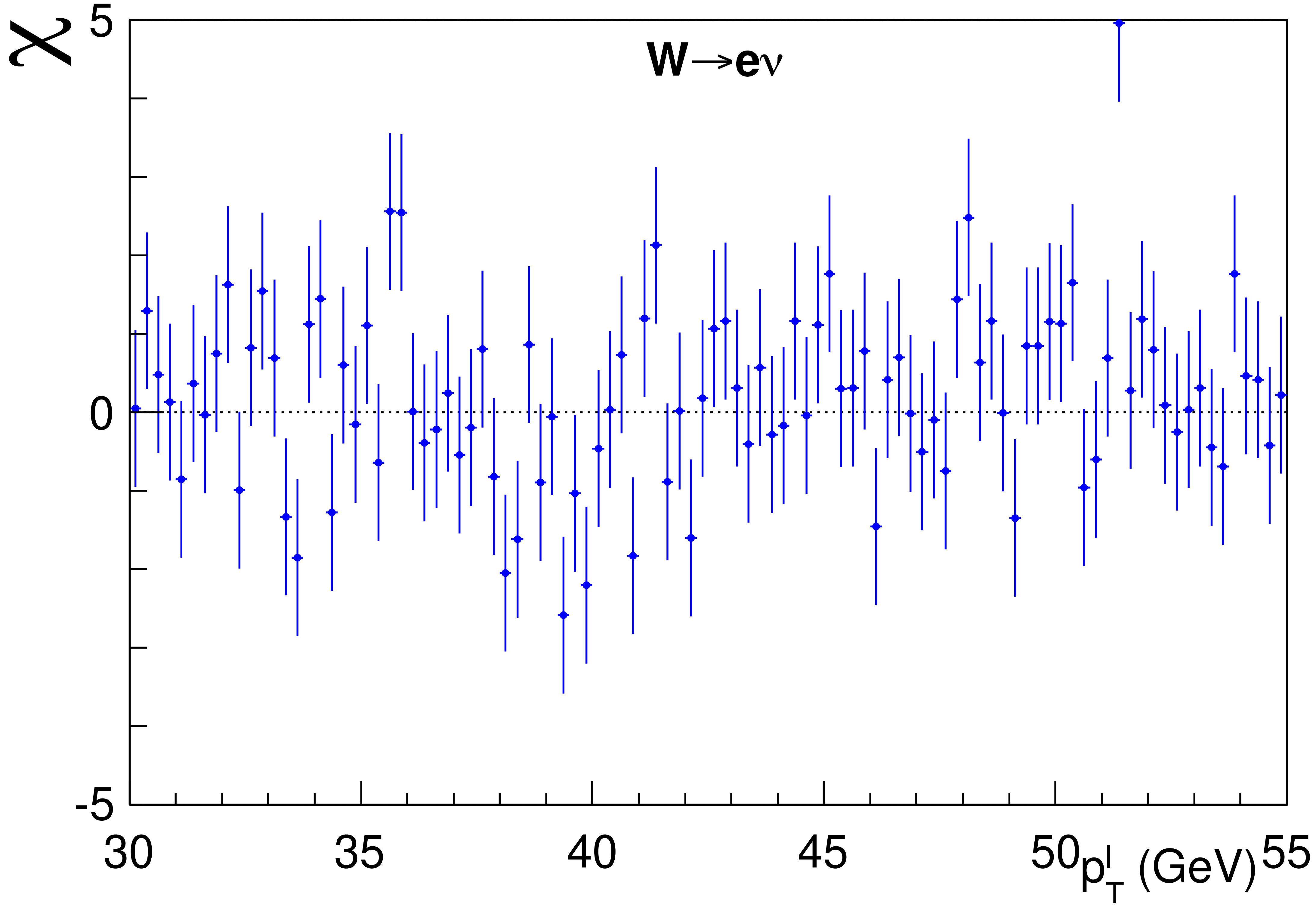
Fit residuals: m_T



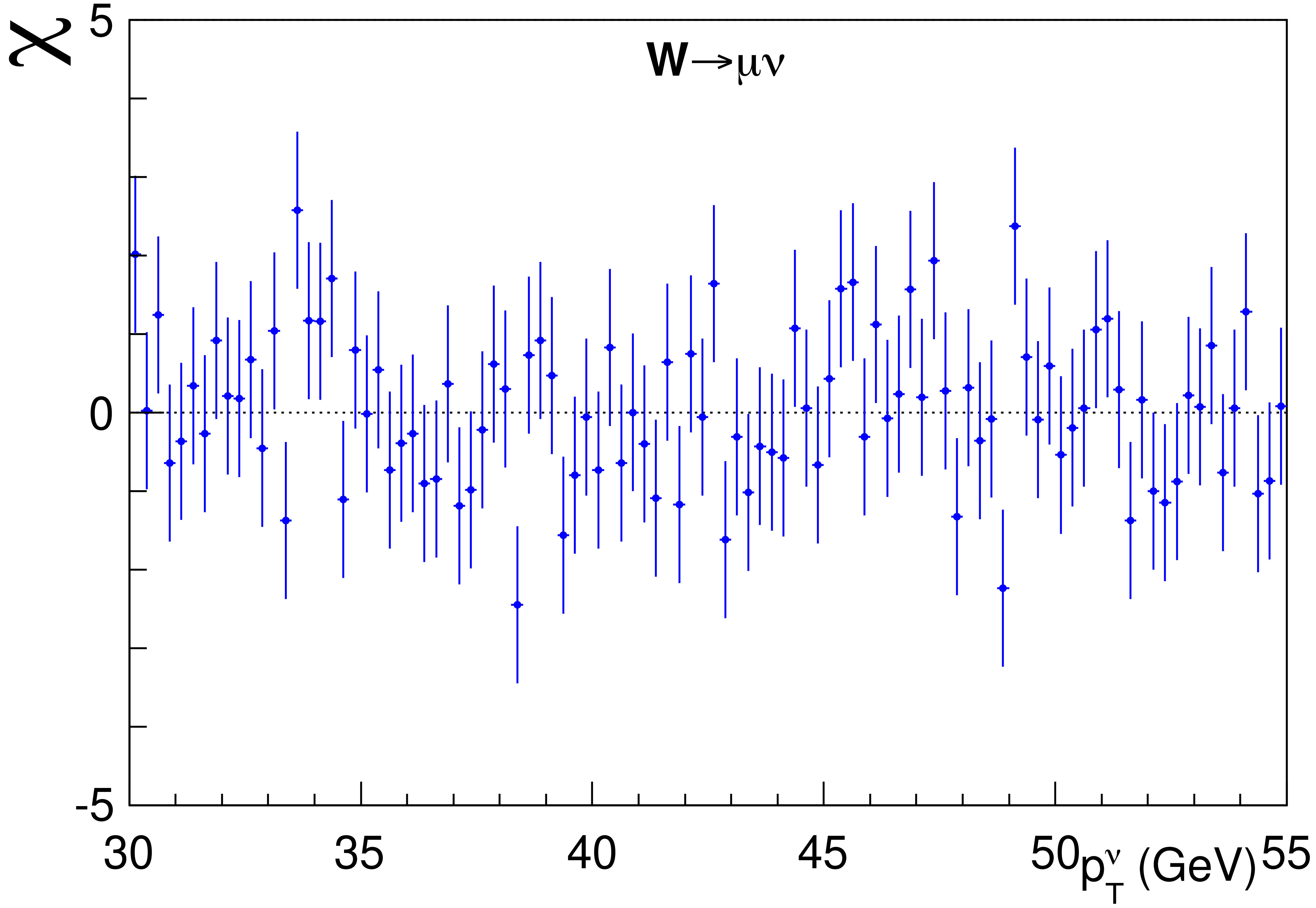


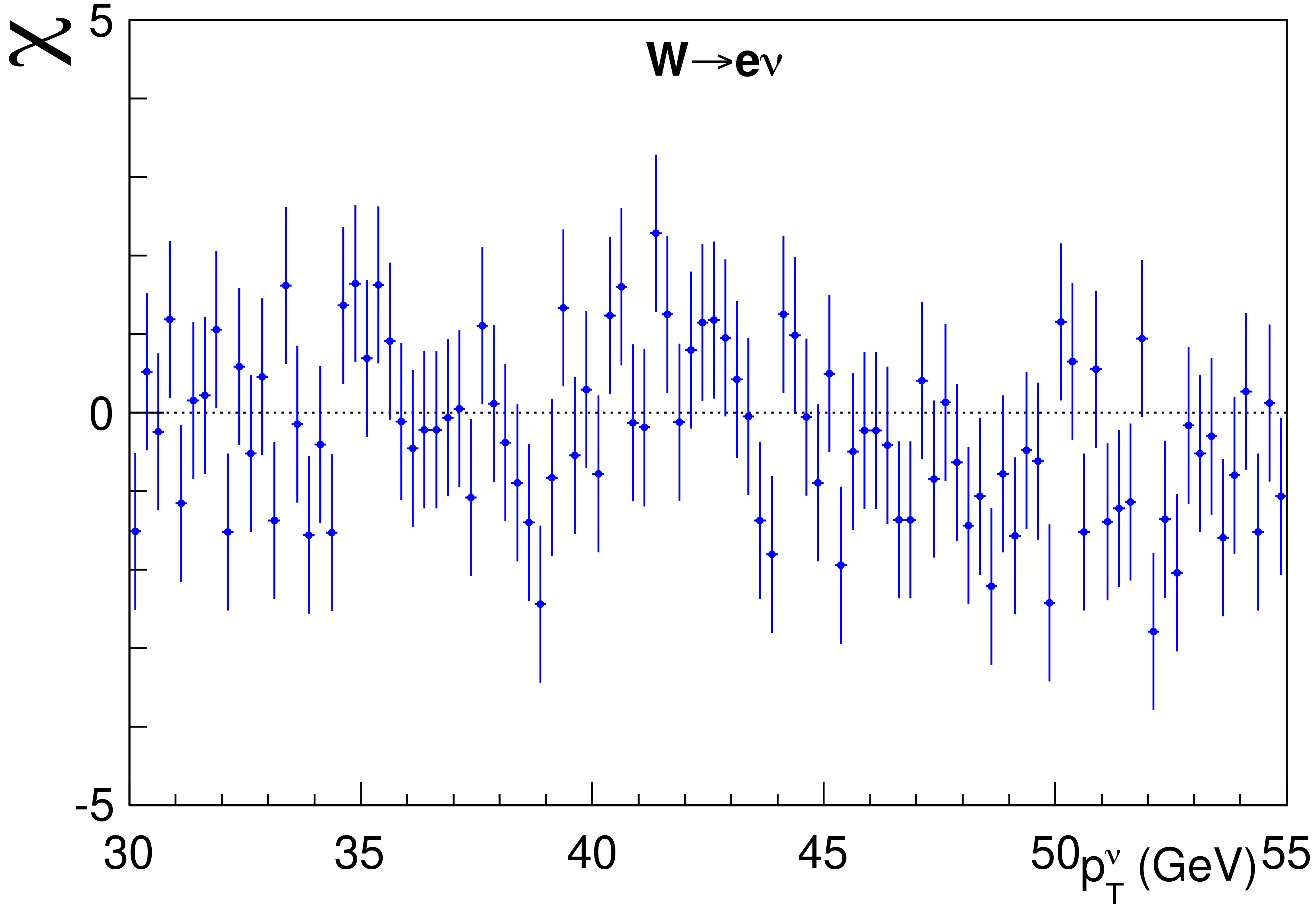
Fit residuals: charged lepton p_T



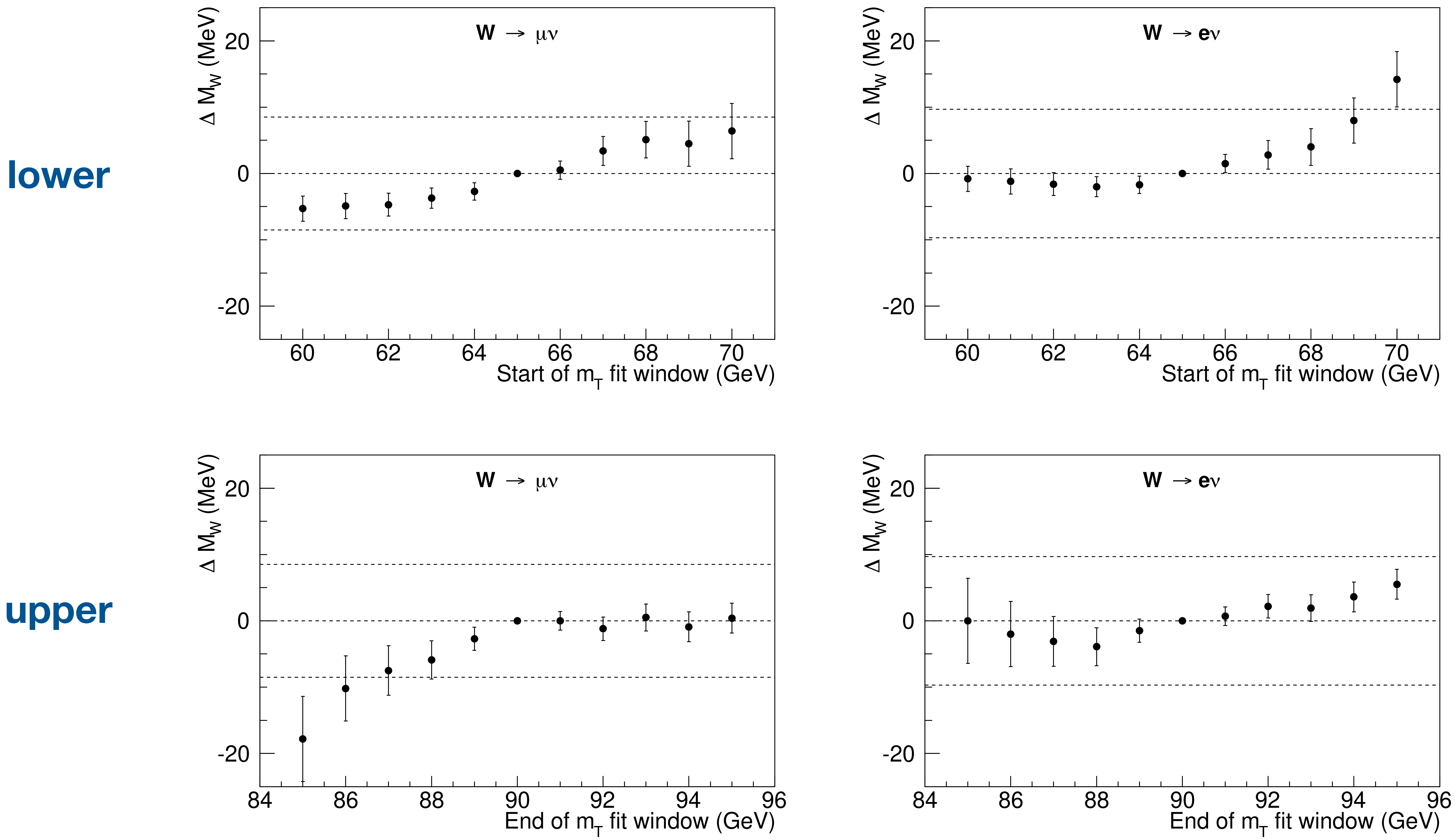


Fit residuals: neutrino p_T





Fit window variation: m_T fits



Additional fit subsamples

Fit difference	Muon channel	Electron channel
$M_W(\ell^+) - M_W(\ell^-)$	$-7.8 \pm 18.5_{\mathrm{stat}} \pm 12.7_{\mathrm{COT}}$	$14.7 \pm 21.3_{\mathrm{stat}} \pm 7.7^{\mathrm{E/p}}_{\mathrm{stat}}$ $(0.4 \pm 21.3_{\mathrm{stat}})$
$M_W(\phi_\ell > 0) - M_W(\phi_\ell < 0)$	$24.4 \pm 18.5_{\mathrm{stat}}$	$9.9 \pm 21.3_{\mathrm{stat}} \pm 7.5^{\mathrm{E/p}}_{\mathrm{stat}}$ $(-0.8 \pm 21.3_{\mathrm{stat}})$
$M_Z(\mathrm{run} > 271100) - M_Z(\mathrm{run} < 271100)$	$5.2 \pm 12.2_{\mathrm{stat}}$	$63.2 \pm 29.9_{\mathrm{stat}} \pm 8.2^{\mathrm{E/p}}_{\mathrm{stat}}$ $(-16.0 \pm 29.9_{\mathrm{stat}})$