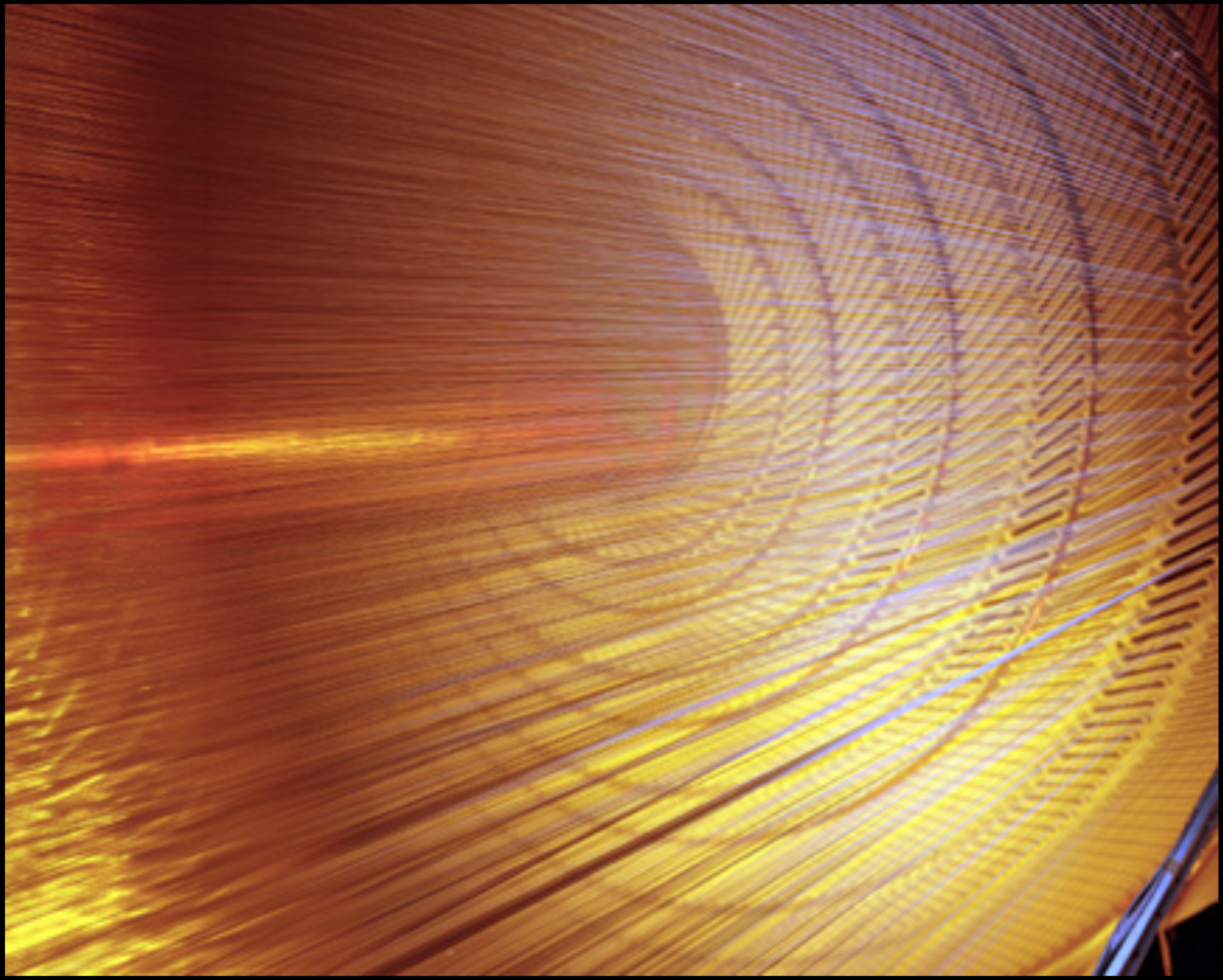
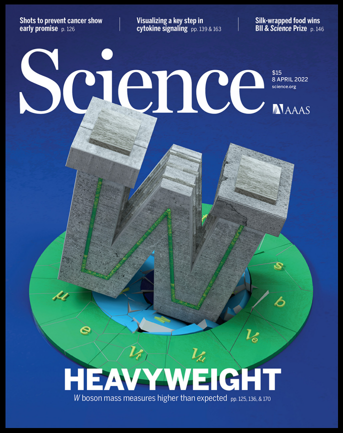
High-precision measurement of the W boson mass with the CDF II detector



Chris Hays, Oxford University

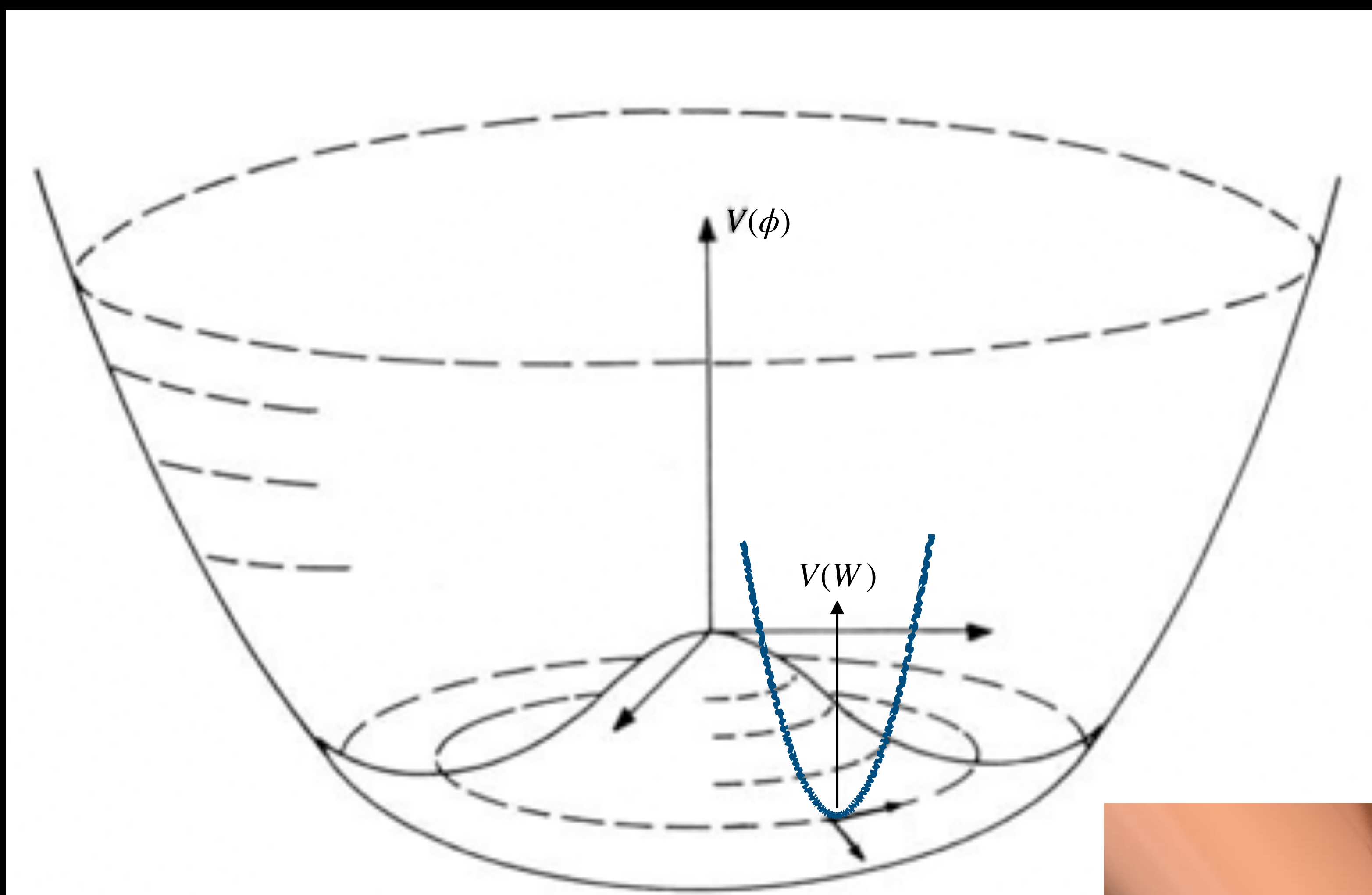
Imperial College seminar
31 May, 2023



Boson masses

Higgs field potential

Gauge field potential



$$V = -\frac{g^2v^2}{8}[(W_\mu^+)^2 + (W_\mu^-)^2] - \frac{v^2(g^2+g'^2)}{8}Z^\mu Z_\mu$$

$$m_W = \frac{v}{2}g$$

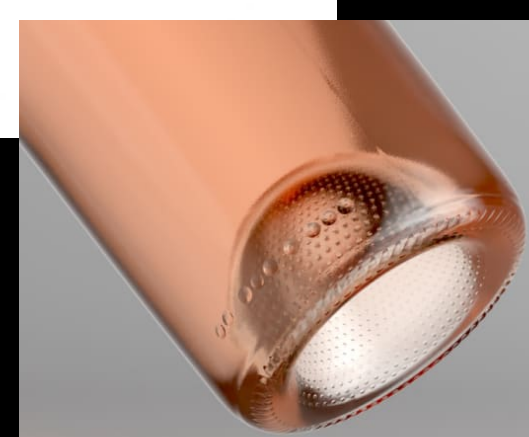
$$m_Z = \frac{v}{2}\sqrt{g^2+g'^2}$$

$v = 246$ GeV and $g = 0.64$:

$m_W = 78.7$ GeV

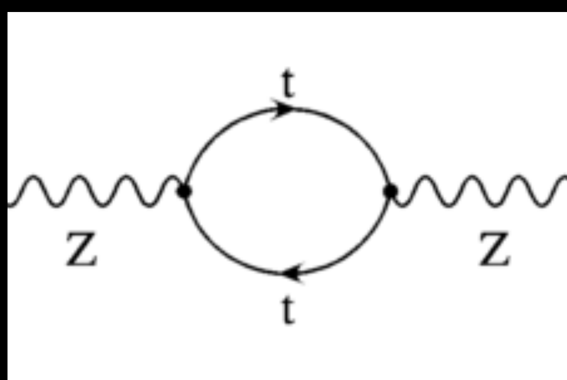
$m_H = v\sqrt{2\lambda} = 125$ GeV

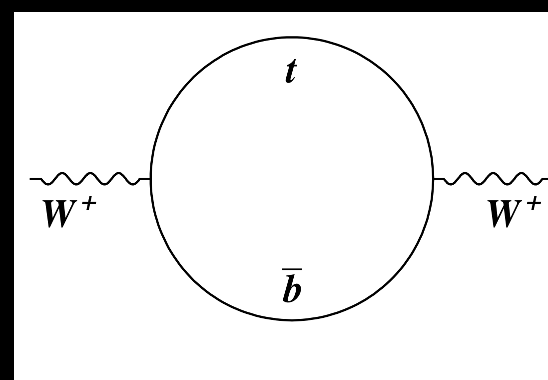
$\lambda \approx 0.1$



Quantum corrections

Gauge quantum corrections





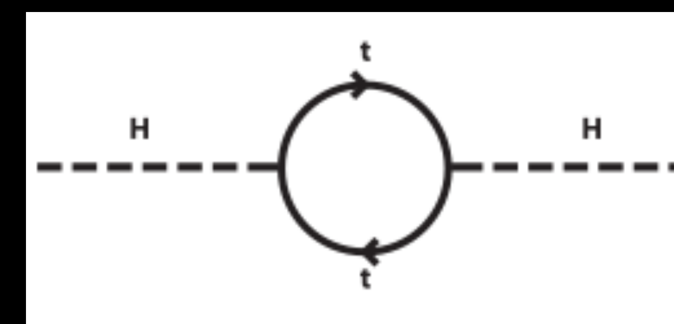
$$m_W^2 = \frac{\hbar^3}{c} \frac{\pi \alpha_{EM}}{\sqrt{2} G_F (1 - m_W^2/m_Z^2)(1 - \Delta r)}$$

$$\Delta r_{tb} = \frac{c}{\hbar^3} \frac{-3 G_F m_W^2}{8\sqrt{2}\pi^2 (m_Z^2 - m_W^2)} \times \left[m_t^2 + m_b^2 - \frac{2 m_t^2 m_b^2}{m_t^2 - m_b^2} \ln(m_t^2/m_b^2) \right]$$

SM calculation of W boson mass yields
80358 ± 4 MeV

Erler & Freitas
PDG (2022)

Higgs quantum corrections



Naively integrating to a cutoff scale Λ:

$$\Delta m_H^2 = \frac{3 g^2 m_t^2}{16 \pi^2 m_W^2} \Lambda^2$$

If there is no new physics up to scale Λ then we need 'fine-tuning' to cancel the quantum corrections

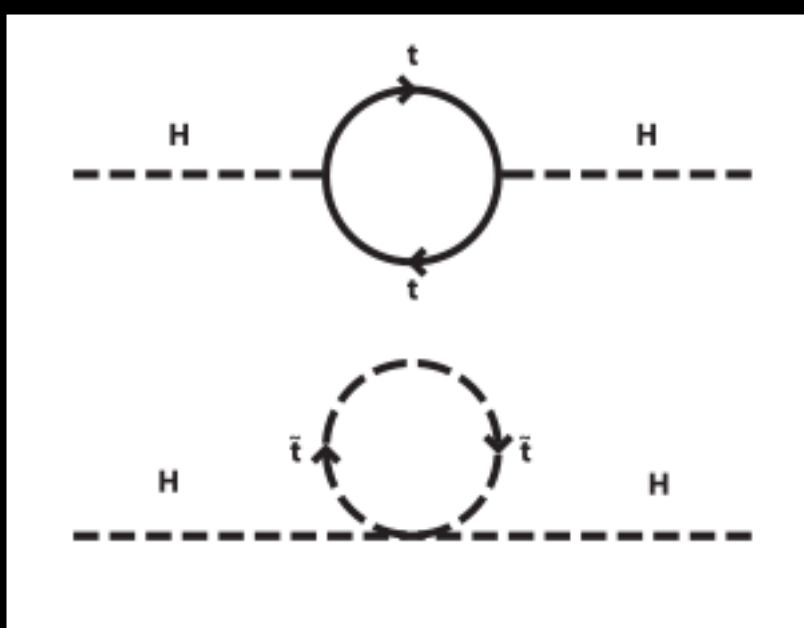
1% fine tuning: $\Lambda = 6.6$ TeV

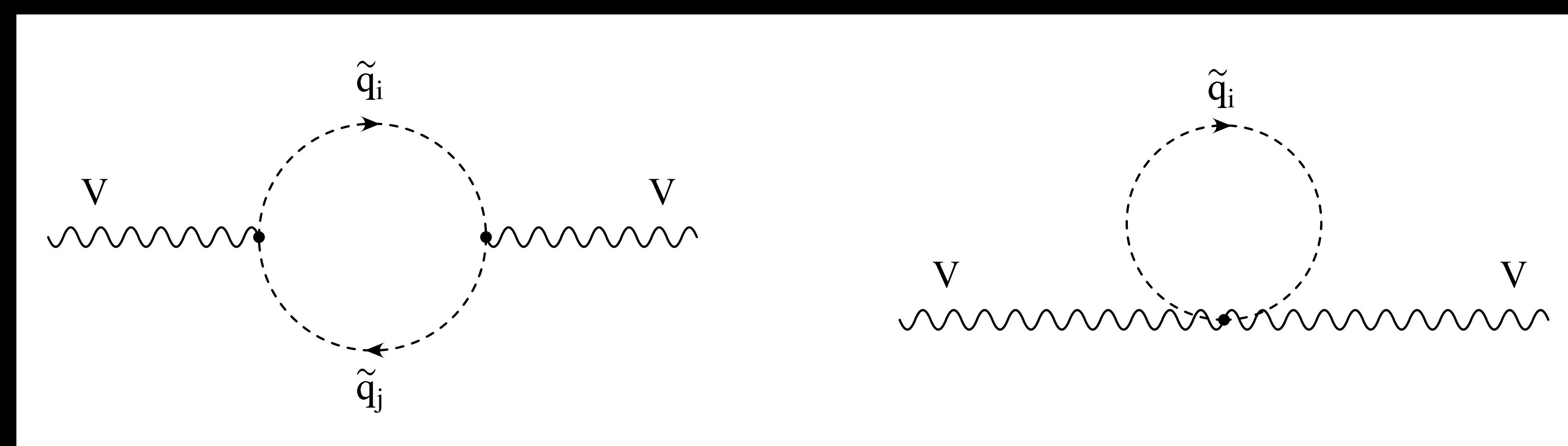
Motivates TeV-scale new physics

W boson mass

The W boson mass is the most sensitive observable to sources of ‘naturalness’

Classic example: **Supersymmetry**





Mass splittings in supersymmetric isospin doublets: different mass shifts for W & Z bosons

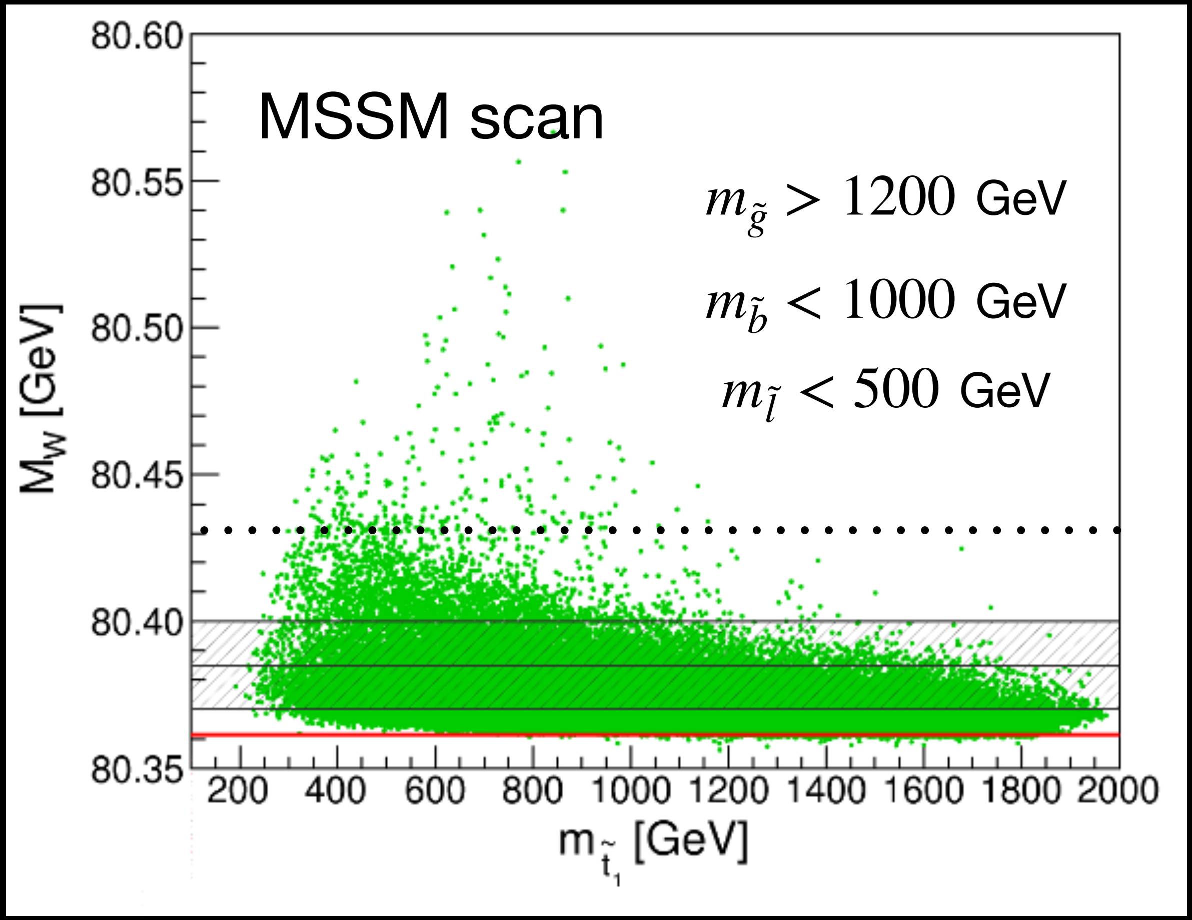
W boson mass

Difference in corrections to W and Z propagators encapsulated by ρ parameter

$$\Delta\rho = \frac{\Sigma^Z(0)}{M_Z^2} - \frac{\Sigma^W(0)}{M_W^2}$$

$$\Delta\rho_0^{\rm SUSY} = \frac{3\,G_\mu}{8\sqrt{2}\,\pi^2}\Big[-\sin^2\theta_{\tilde t}\cos^2\theta_{\tilde t}F_0(m_{\tilde t_1}^2, m_{\tilde t_2}^2) - \sin^2\theta_{\tilde b}\cos^2\theta_{\tilde b}F_0(m_{\tilde b_1}^2, m_{\tilde b_2}^2) + \cos^2\theta_{\tilde t}\cos^2\theta_{\tilde b}F_0(m_{\tilde t_1}^2, m_{\tilde b_1}^2) + \cos^2\theta_{\tilde t}\sin^2\theta_{\tilde b}F_0(m_{\tilde t_1}^2, m_{\tilde b_2}^2) + \sin^2\theta_{\tilde t}\cos^2\theta_{\tilde b}F_0(m_{\tilde t_2}^2, m_{\tilde b_1}^2) + \sin^2\theta_{\tilde t}\sin^2\theta_{\tilde b}F_0(m_{\tilde t_2}^2, m_{\tilde b_2}^2)\Big].$$

$$\delta M_W \approx \frac{M_W}{2}\frac{c_W^2}{c_W^2 - s_W^2}\Delta\rho$$



Heinemeyer, Hollik, Weiglein
Phys Rep 425, 265 (2006)

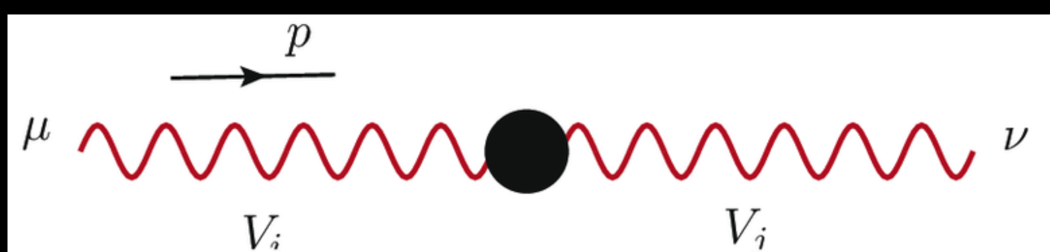
Heinemeyer, Hollik, Weiglein, Zeune
JHEP 12 (2013) 084

W boson mass

More generally the SM effective field theory parameterizes high-scale effects

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \mathcal{L}^{(5)} + \mathcal{L}^{(6)} + \mathcal{L}^{(7)} + \cdots, \qquad \mathcal{L}^{(d)} = \sum_{i=1}^{n_d} \frac{C_i^{(d)}}{\Lambda^{d-4}} Q_i^{(d)} \quad \text{for } d > 4.$$

I. Brivio and M. Trott, Phys. Rep. 793 (2019) 1



$$\frac{\delta m_W}{m_W} = \left(0.34 c_{HD} + 0.72 c_{HWB} + 0.37 c_{Hl3} - 0.19 c_{ll1}\right) \frac{v^2}{\Lambda^2}$$

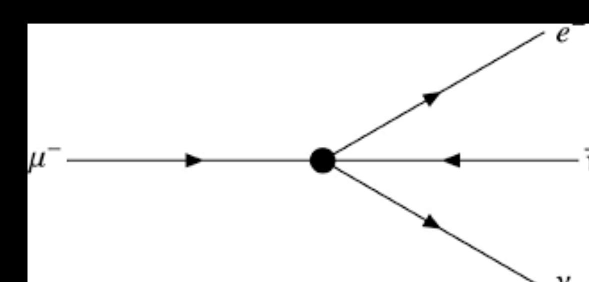
For $\delta m_W / m_W = 0.1\,\%$ and c_{HD}=1, $\Lambda = 4.5$ TeV

e.g. Z' boson

For $\delta m_W / m_W = 0.1\,\%$ and c_{HWB}=1, $\Lambda = 6.6$ TeV

e.g. compositeness

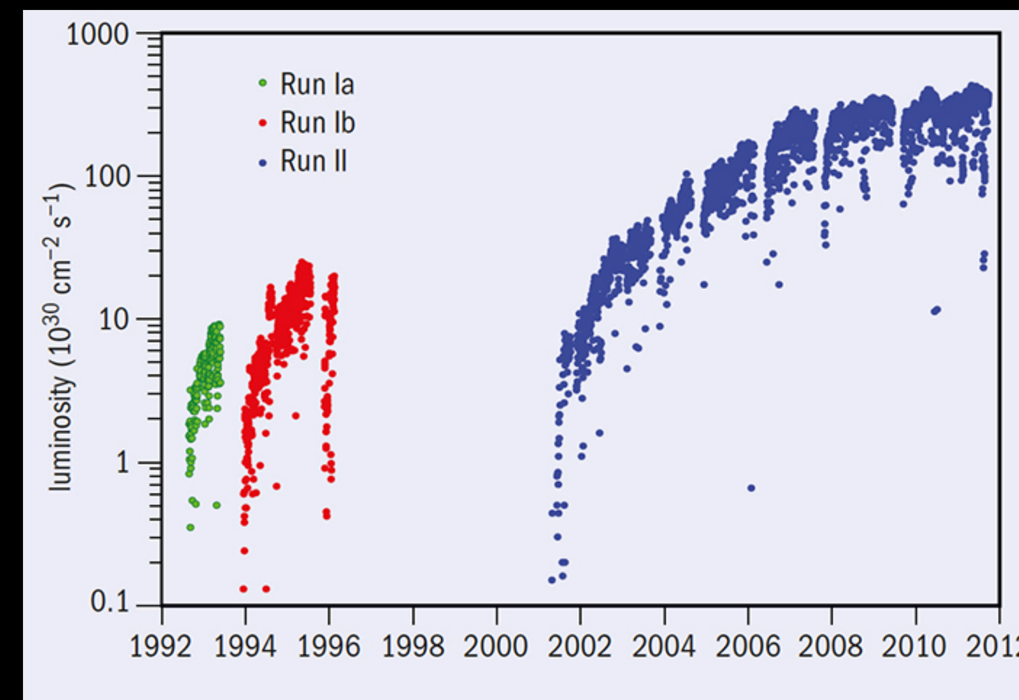
Smaller $c_i \rightarrow$ smaller Λ



Hadron-collider W boson mass measurements

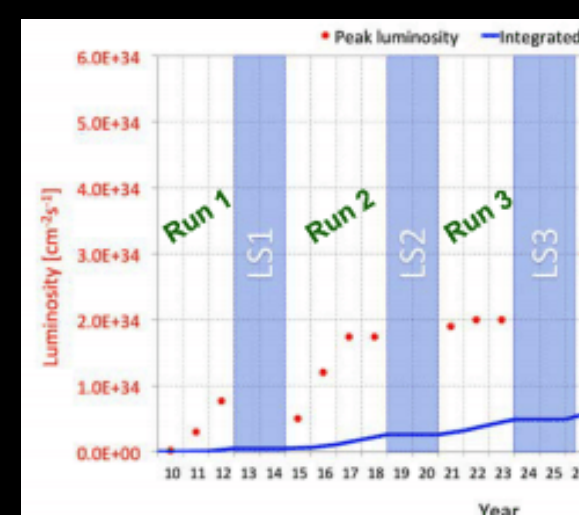
$\sqrt{s} = 1.96$ TeV proton-antiproton collisions from the Fermilab Tevatron

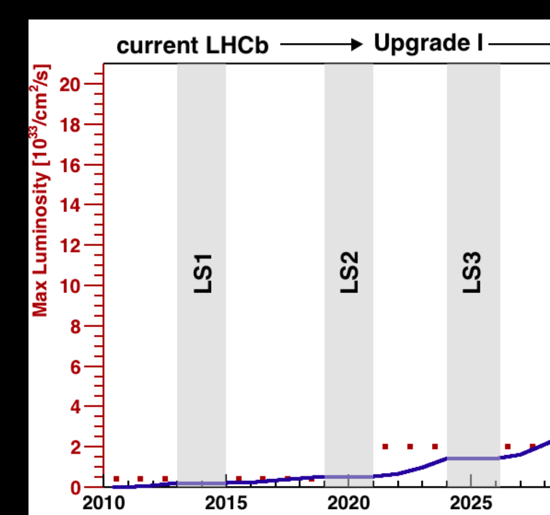
CDF: 8.8 fb^{-1} of integrated luminosity
D0: 5.3 fb^{-1} of integrated luminosity



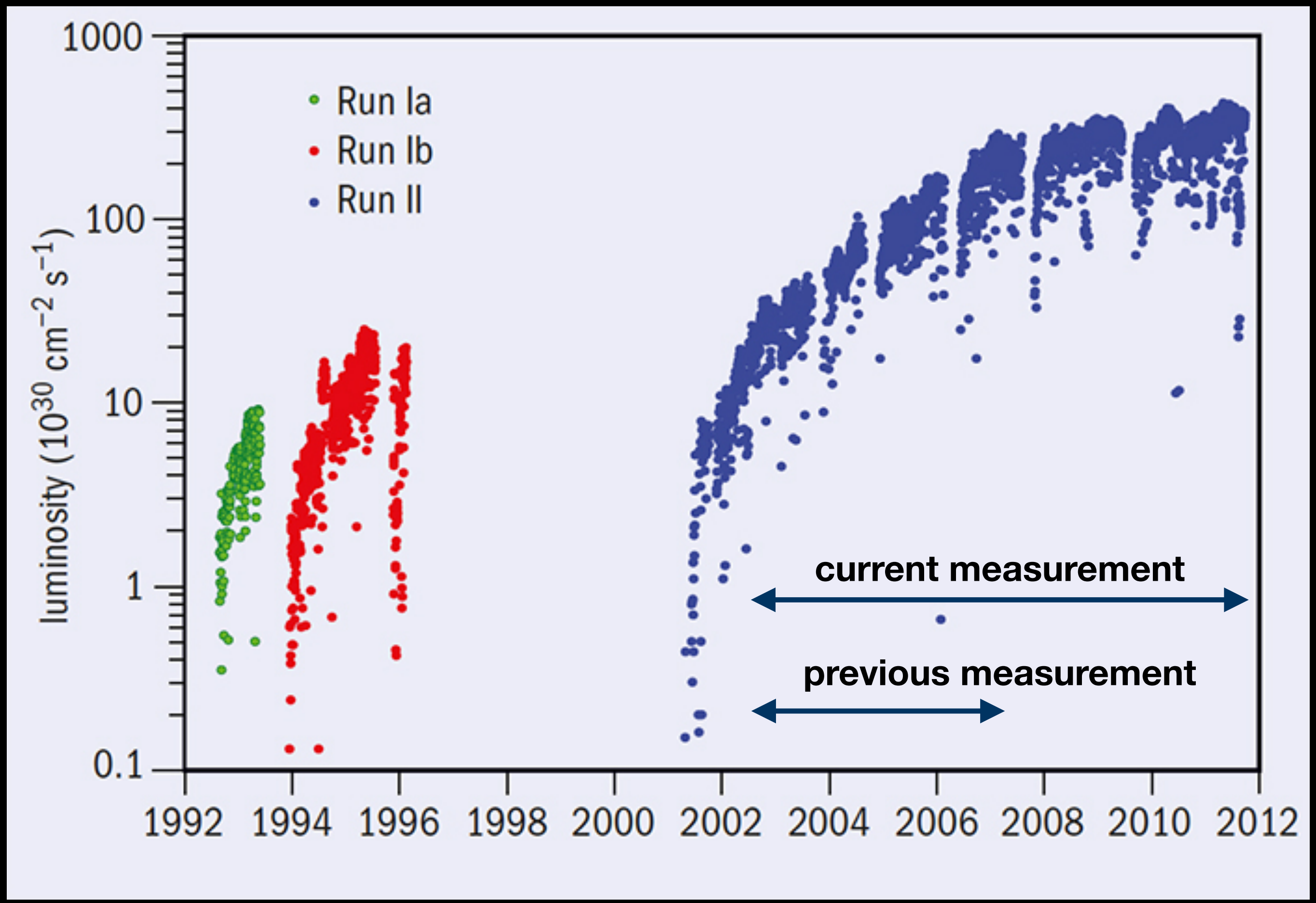
$\sqrt{s} = 7,\ 13$ TeV proton-proton collisions from the Large Hadron Collider

ATLAS: 4.1 fb^{-1} of integrated luminosity (7 TeV)
LHCb: 1.7 fb^{-1} of integrated luminosity (13 TeV)

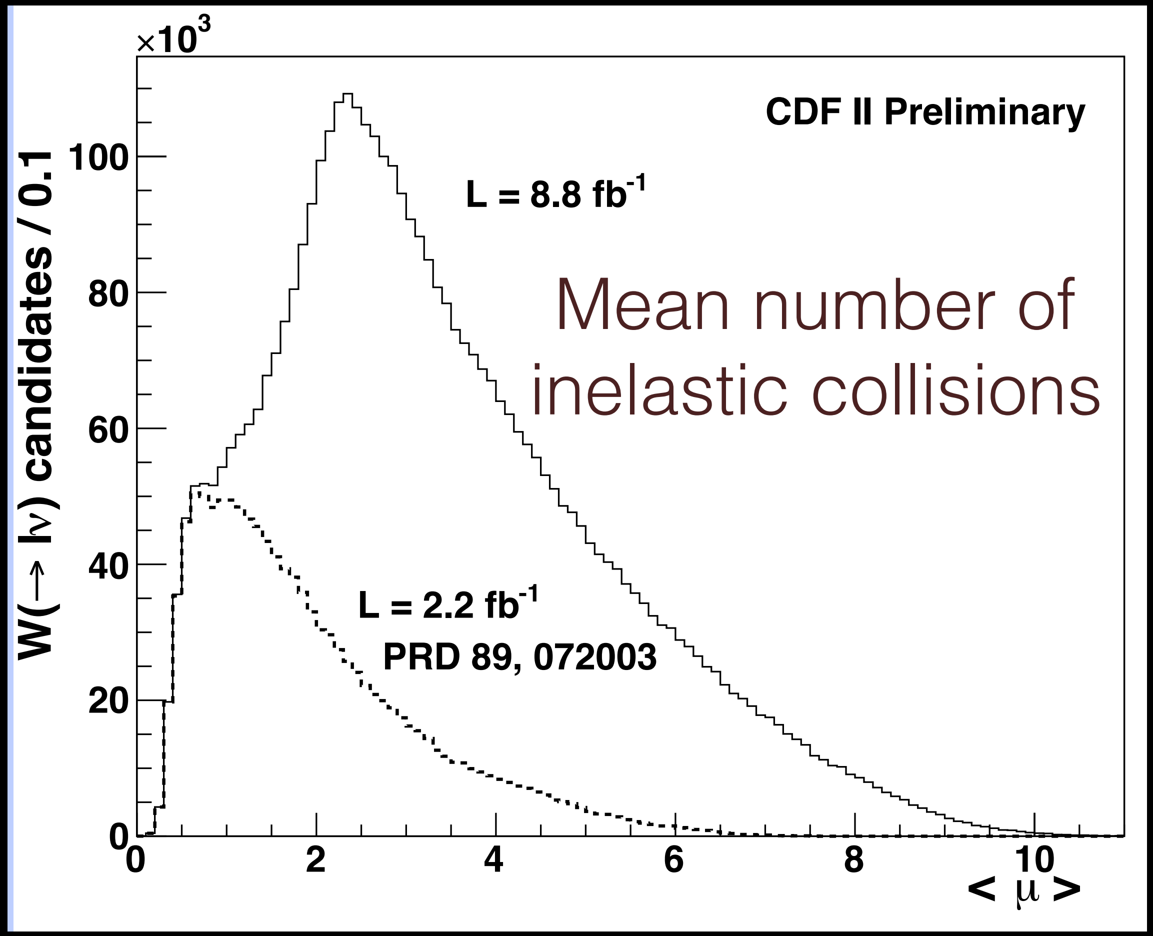




CDF II measurement of the W boson mass



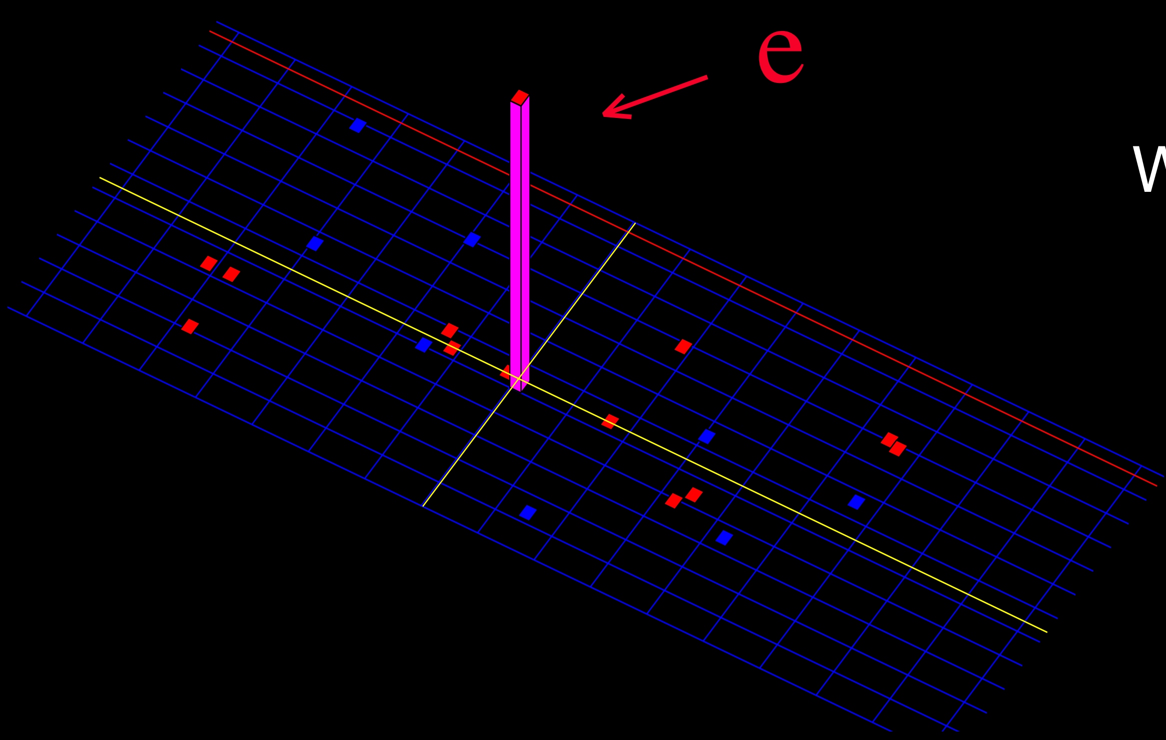
Measurement uses complete Tevatron Run II data set



4x the integrated luminosity of the previous measurement

Higher $\langle\mu\rangle$: peaks at 3

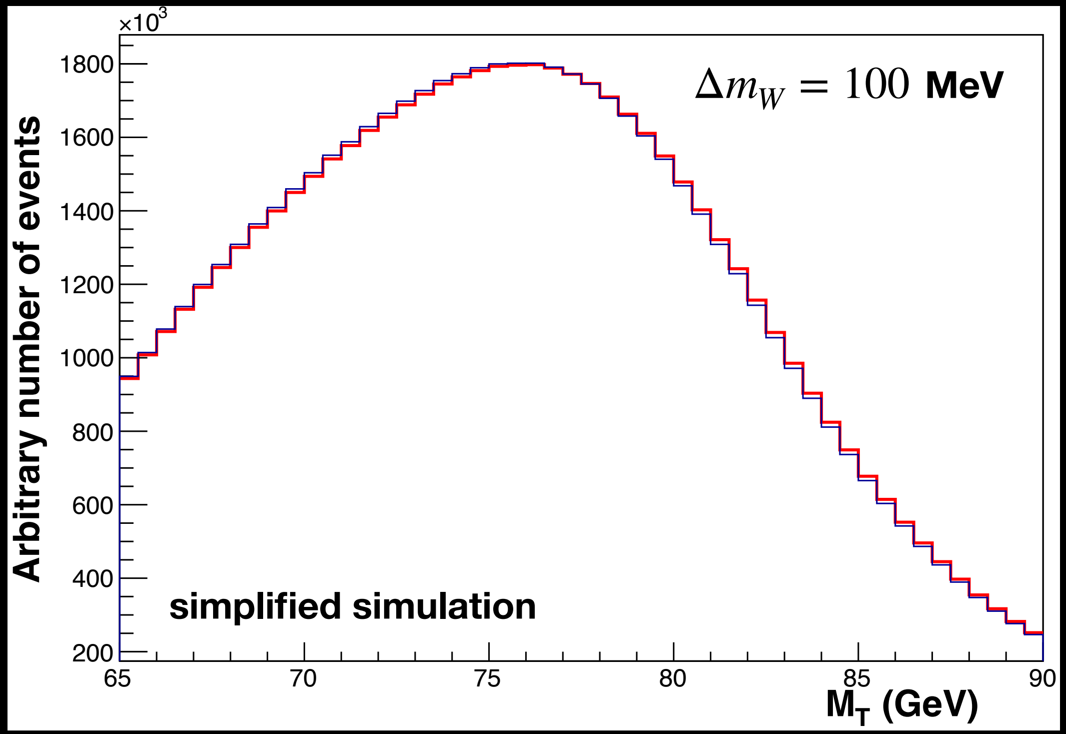
CDF II measurement of the W boson mass

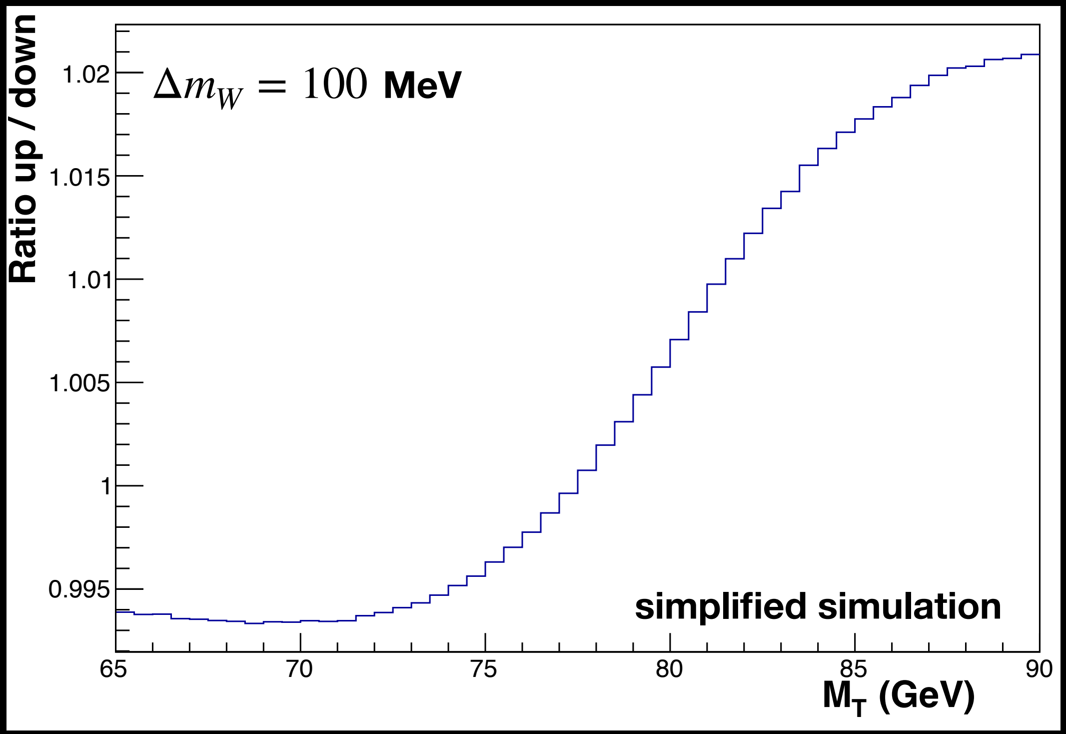


W bosons identified from their decays to $e\nu$ and $\mu\nu$

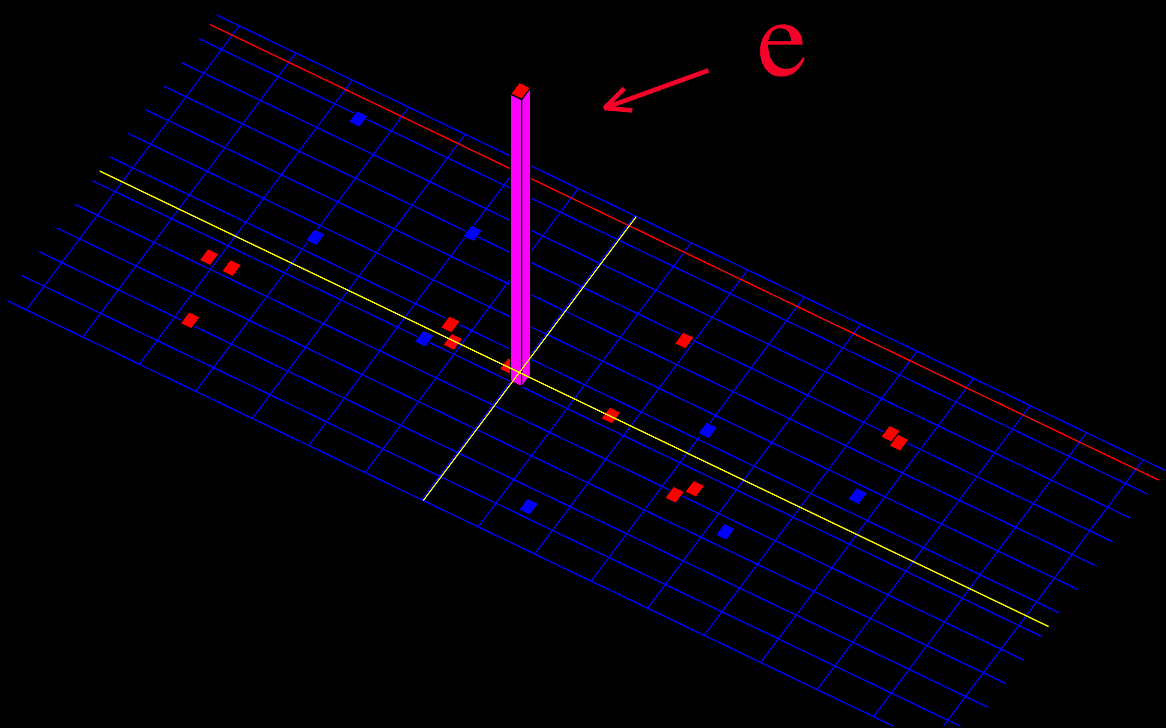
Mass measured by fitting template distributions of transverse momentum and mass

$$m_T = \sqrt{2 p_T^l \not{p}_T \left(1 - \cos\Delta\phi\right)}$$



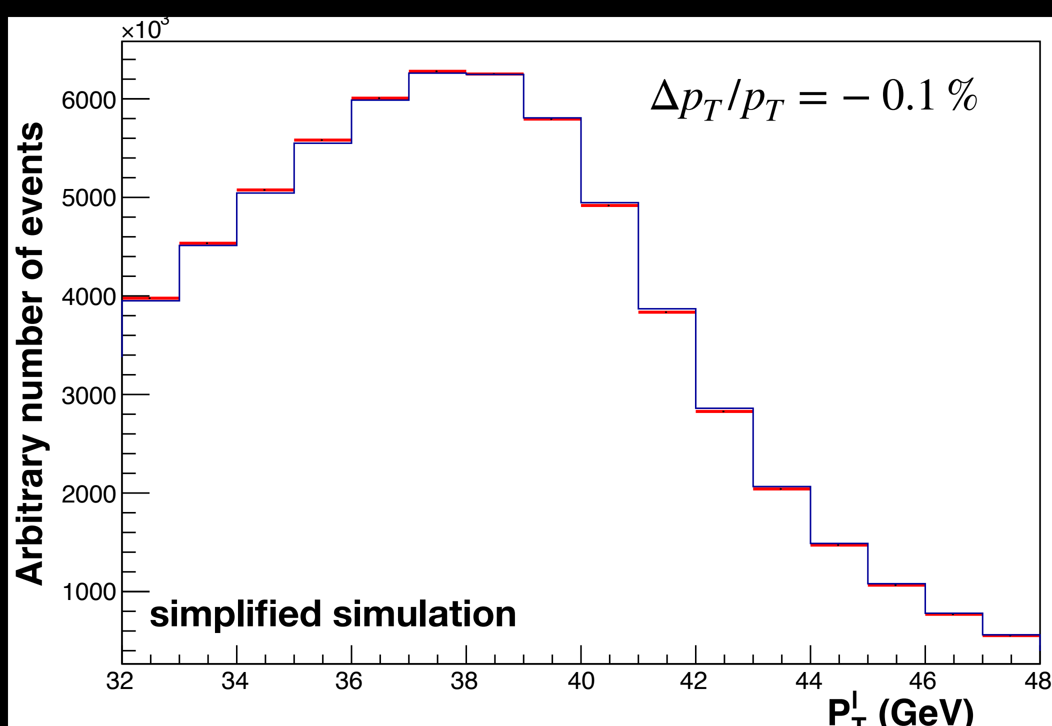


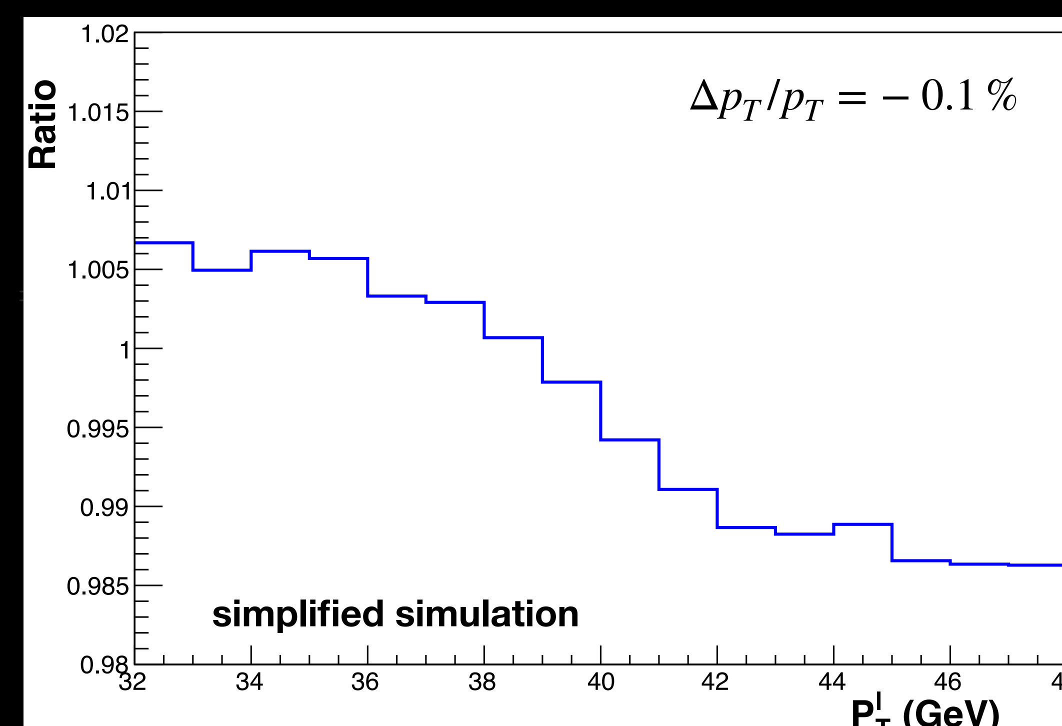
Calibrations



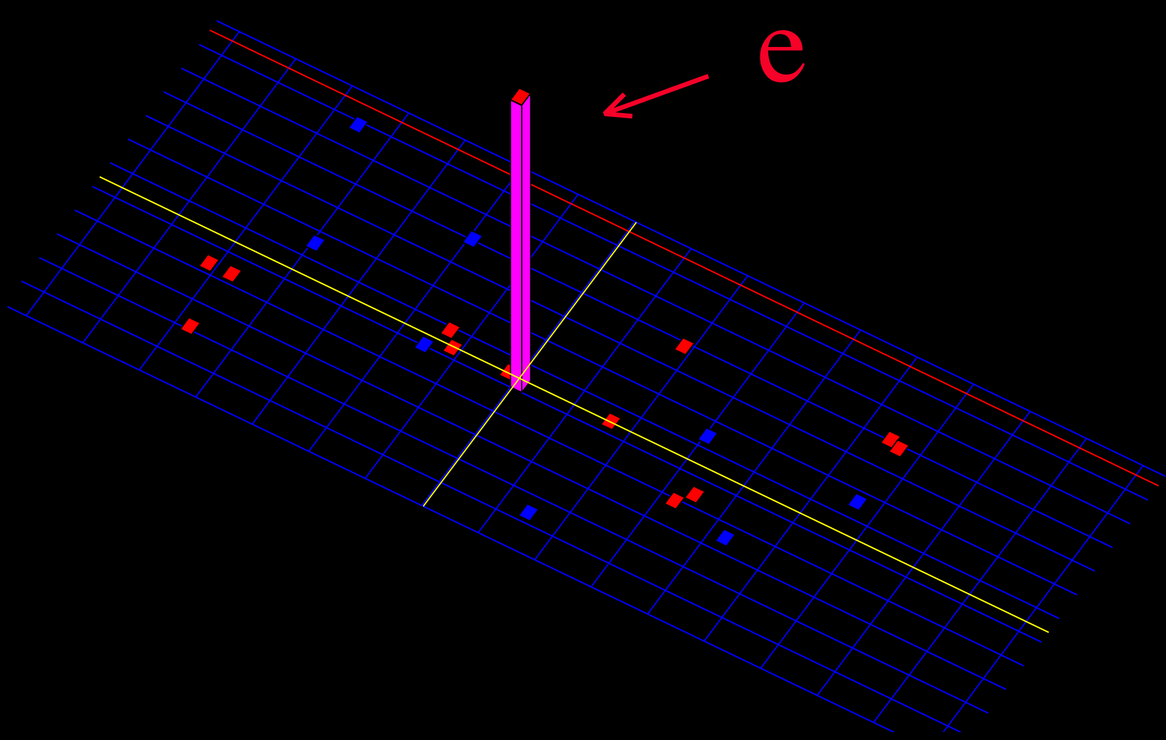
Measurement requires precise calibrations of momentum scale and resoution

Charged lepton scale



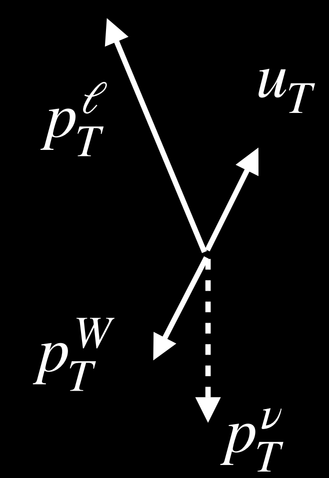


Calibrations

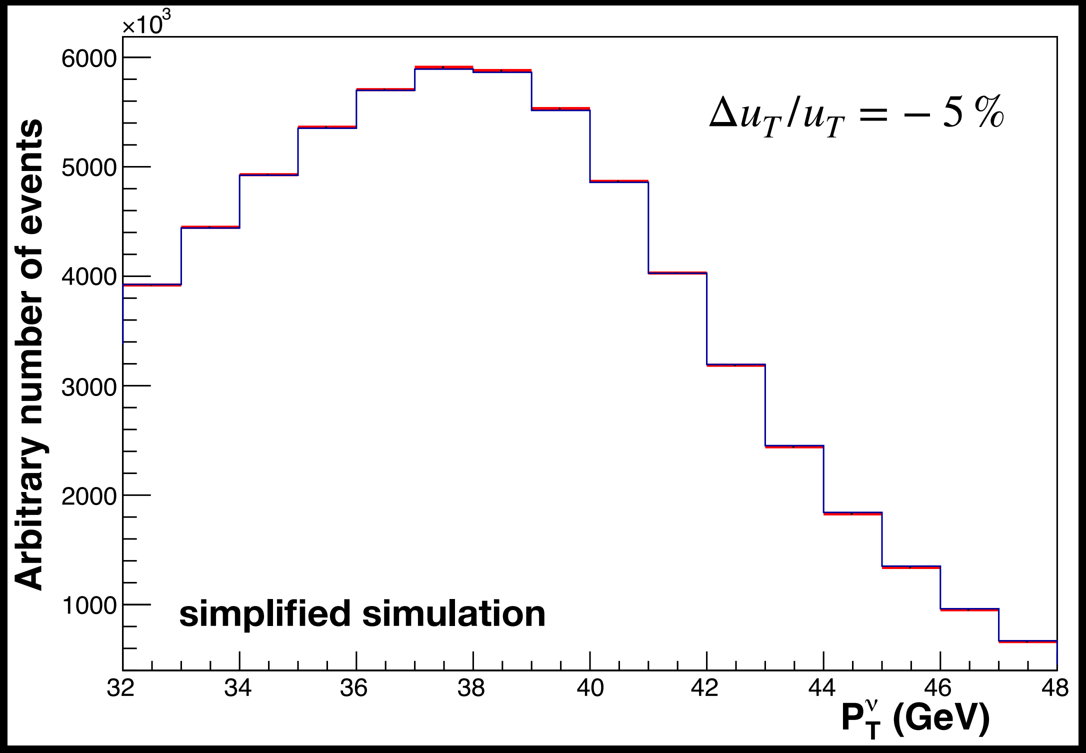


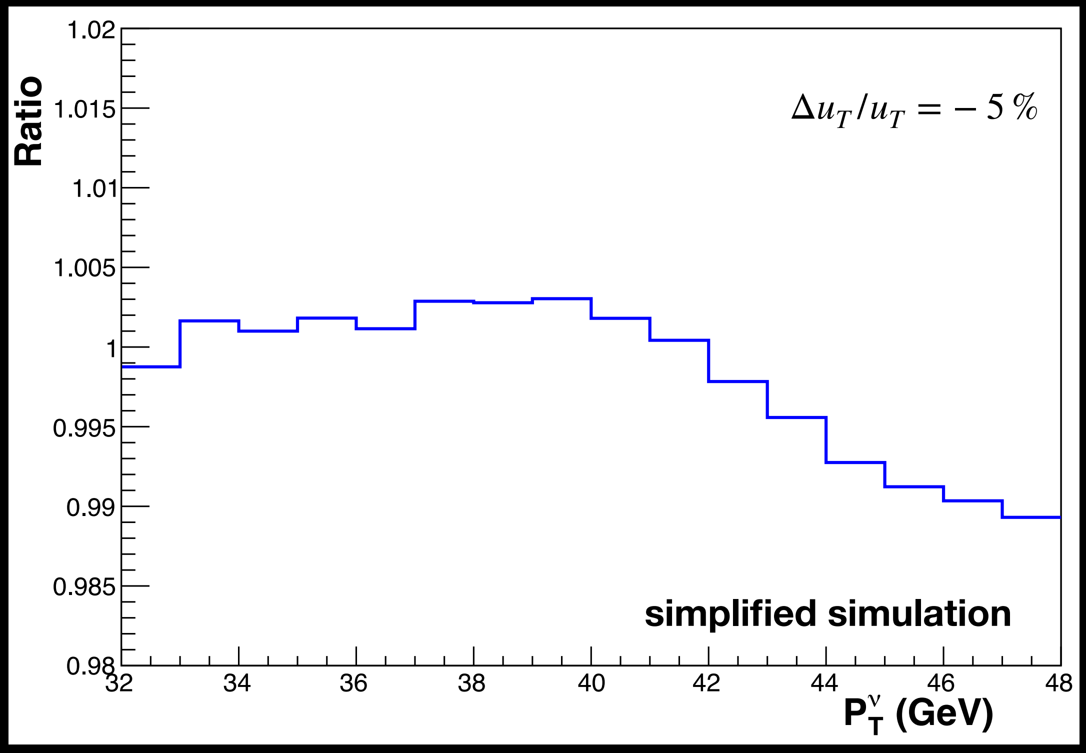
Measurement requires precise calibrations and momentum scale and resolution

$$\vec{\not{p}}_T = -(\vec{p}_T^{\,l} + \vec{u}_T)$$



Recoil scale





Detector simulation

Developed custom simulation for analysis

Models ionization energy loss, multiple scattering, bremsstrahlung, photon conversion, Compton scattering

Acceptance map for muon detectors

Parameterized GEANT4 model of electromagnetic calorimeter showers

Includes shower losses due to finite calorimeter thickness

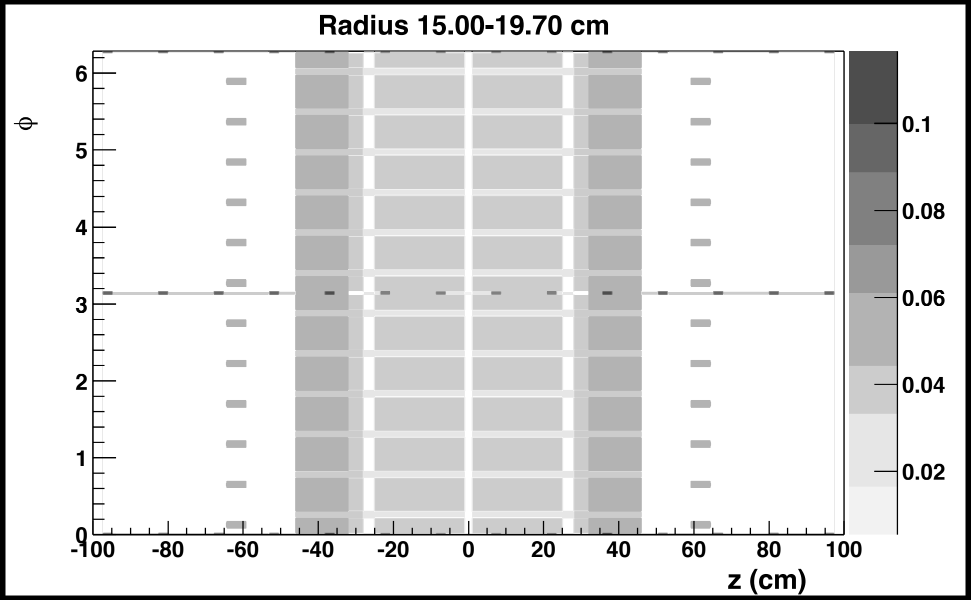
Kotwal & CH, NIMA 729, 25 (2013)

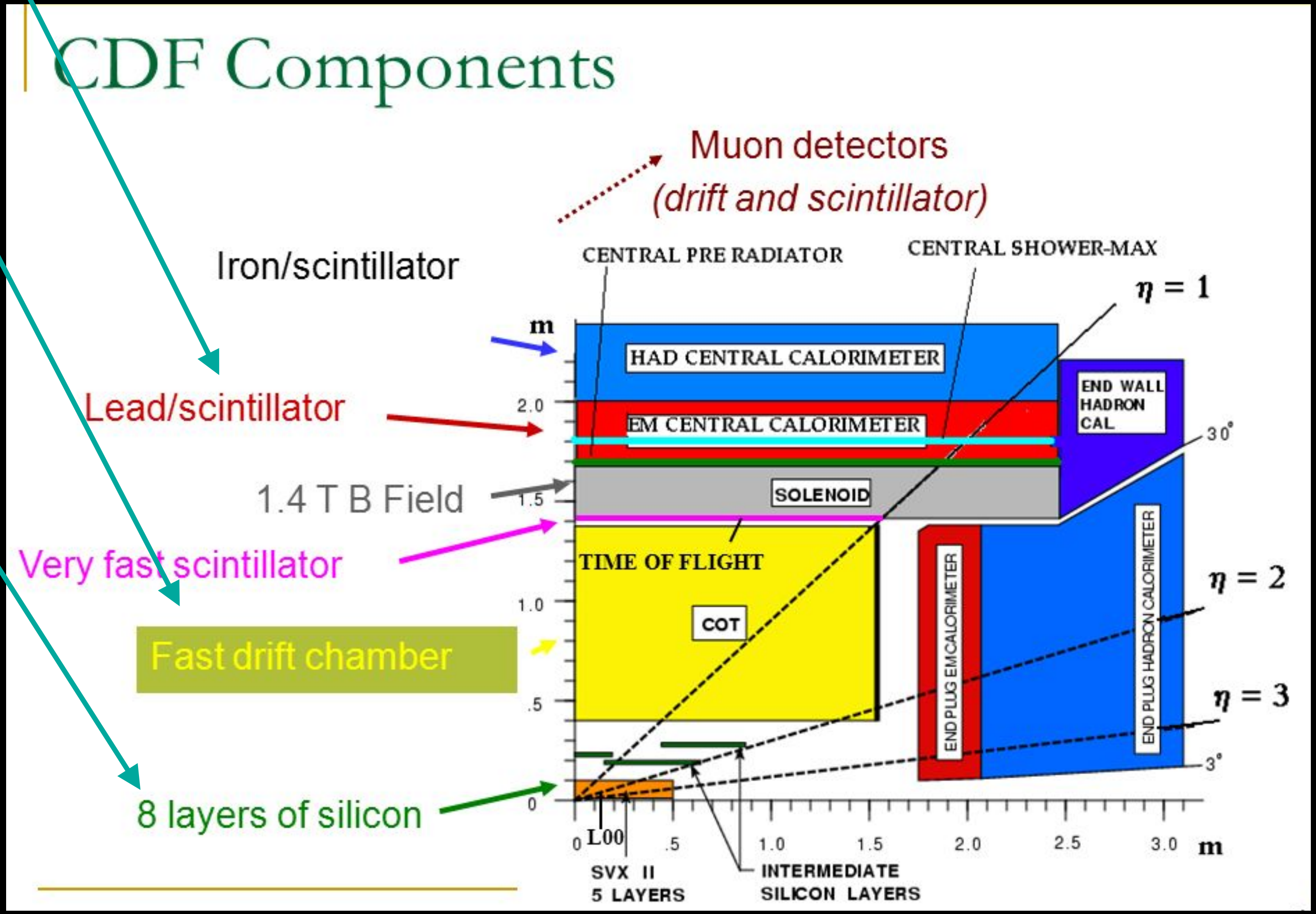
Hit-level model of central outer tracker

Layer-by-layer resolution functions and efficiencies

Material map of inner silicon detector

Includes radiation lengths and Bethe-Bloch terms

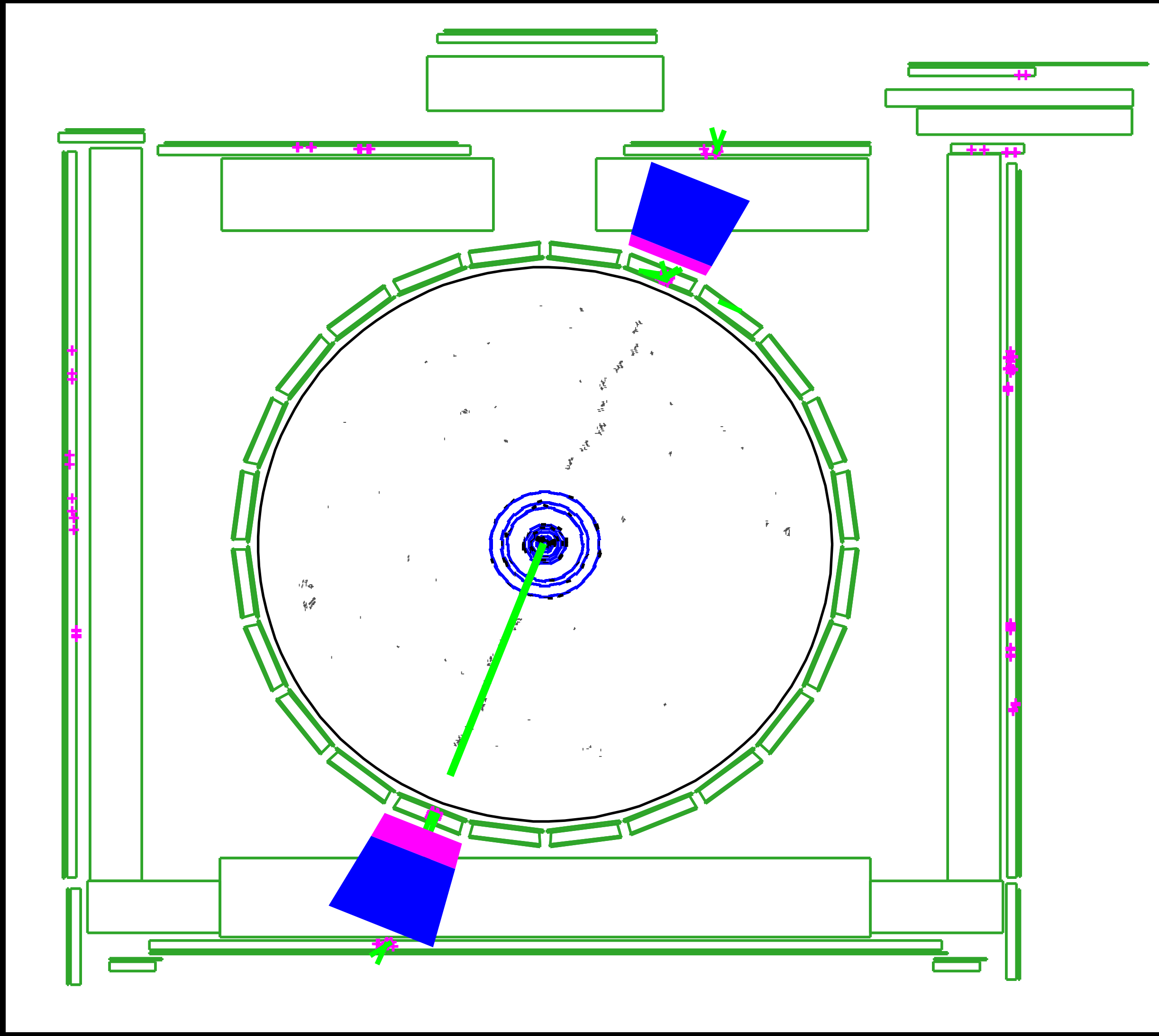


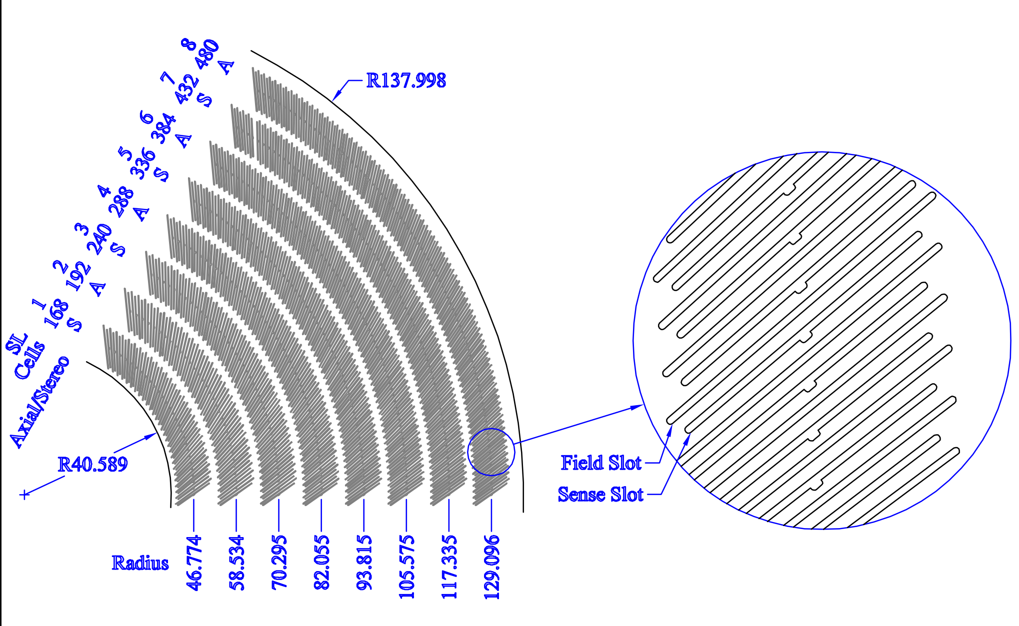


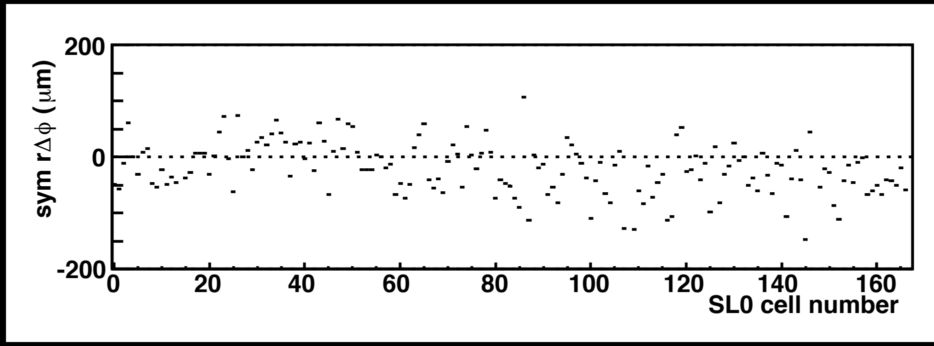
Muon momentum calibration

First step is to align the drift chamber (the "central outer tracker" or COT)

Two degrees of freedom (shift & rotation) for each of 2520 cells made up of twelve sense wires constrained using hit residuals from cosmic-ray tracks





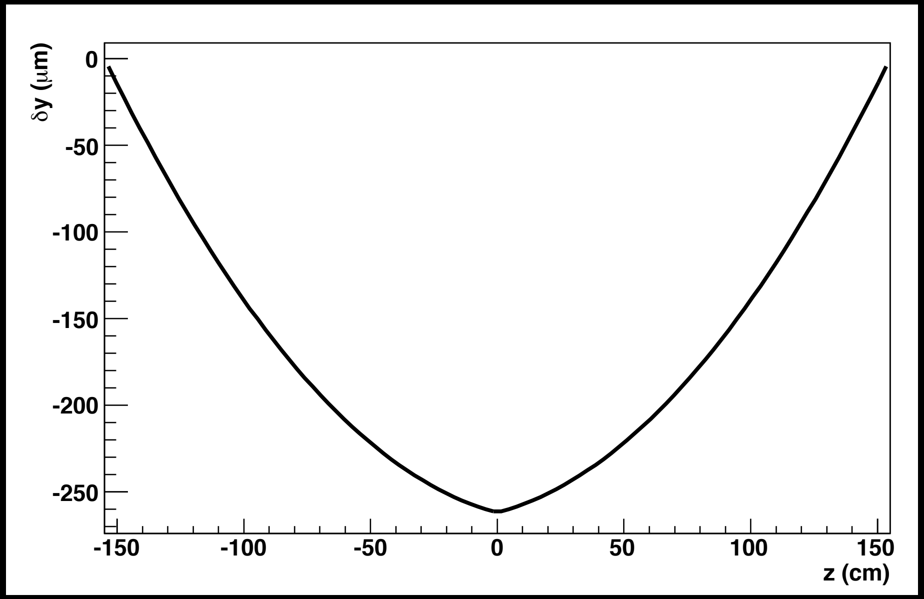


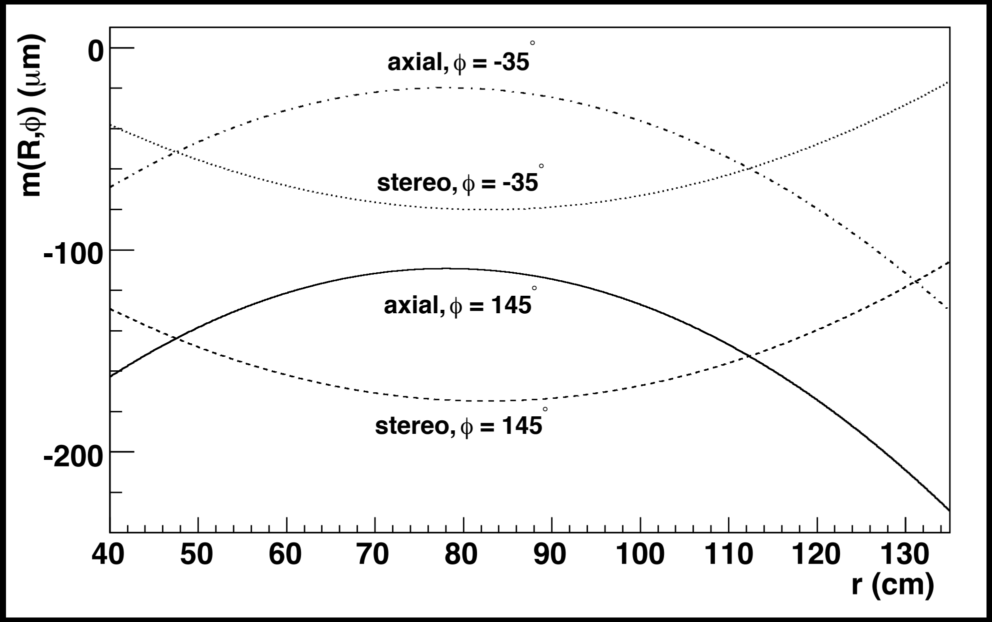
Kotwal & CH, NIMA 762, 85 (2014)

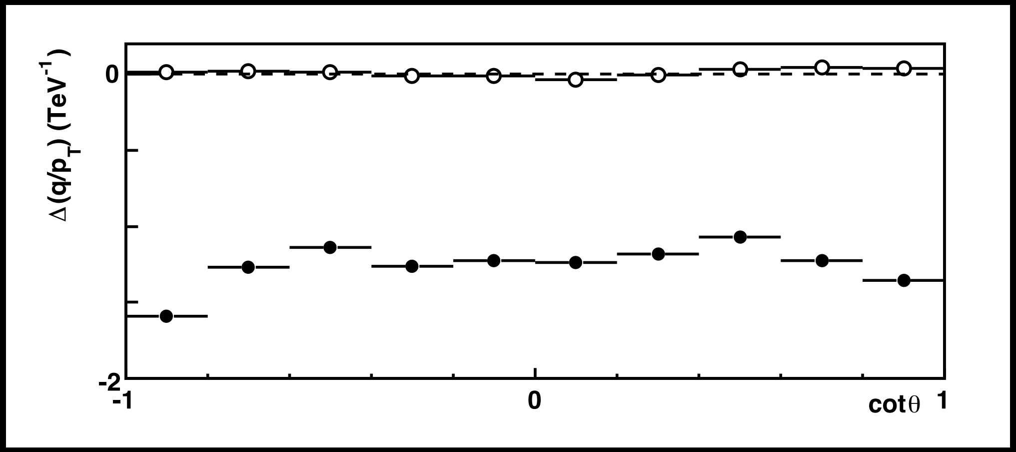
Muon momentum calibration

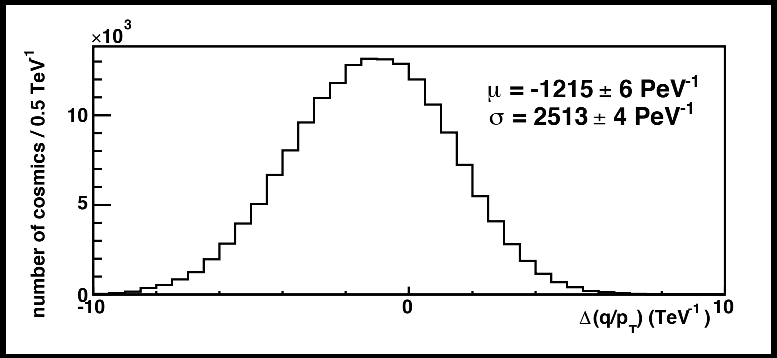
First step is to align the drift chamber (the “central outer tracker” or COT)

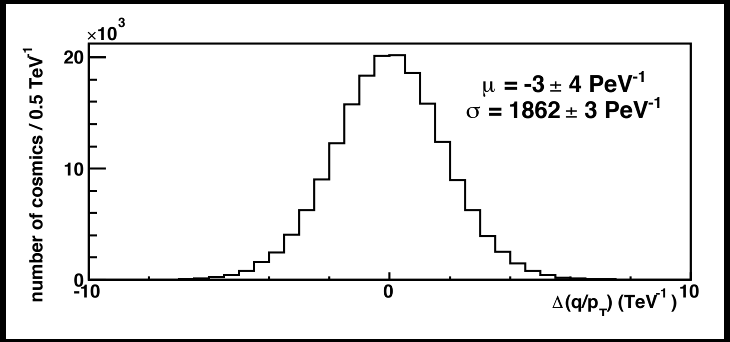
Two parameters for the electrostatic deflection of the wire within the chamber constrained using difference between fit parameters of incoming and outgoing cosmic-ray tracks











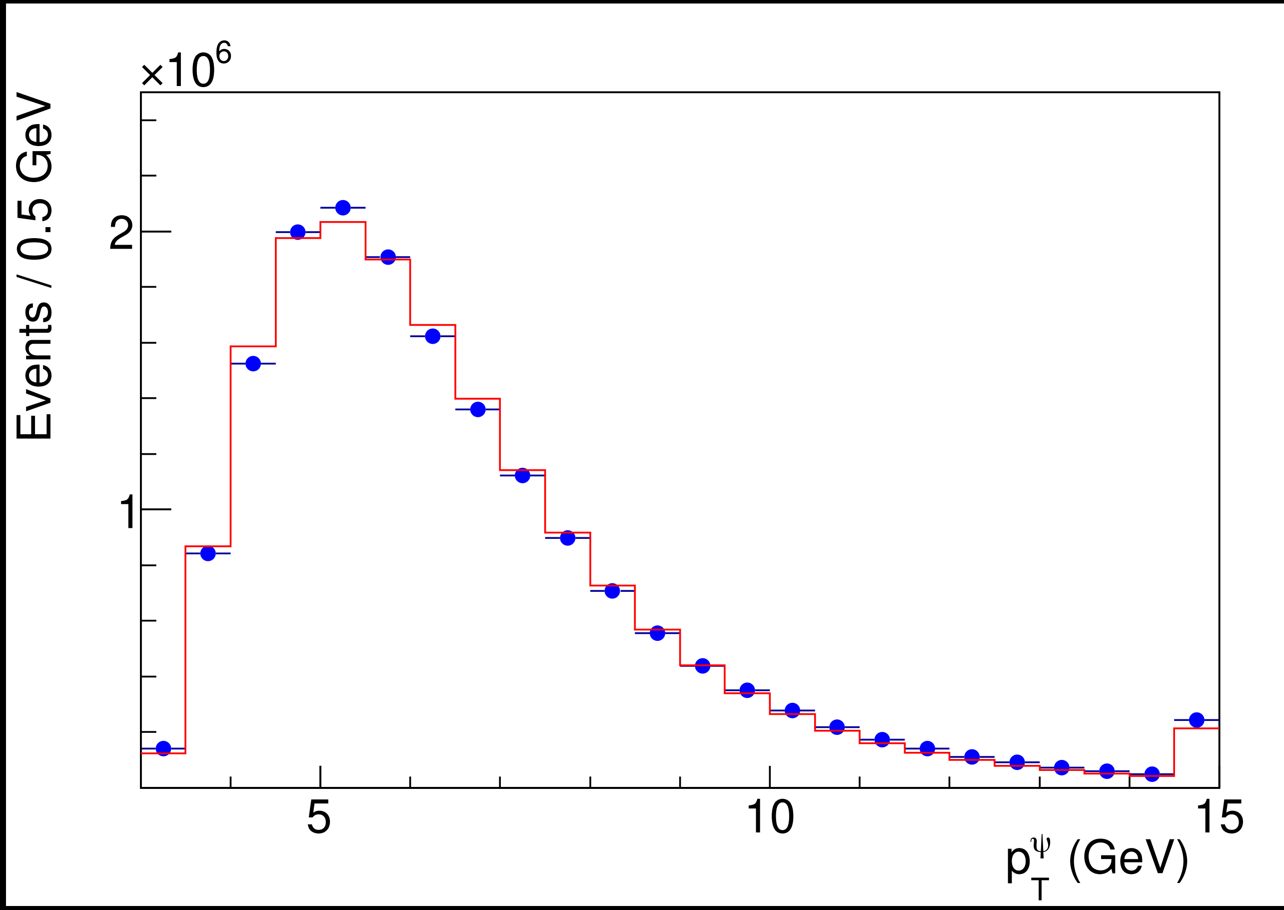
Muon momentum calibration

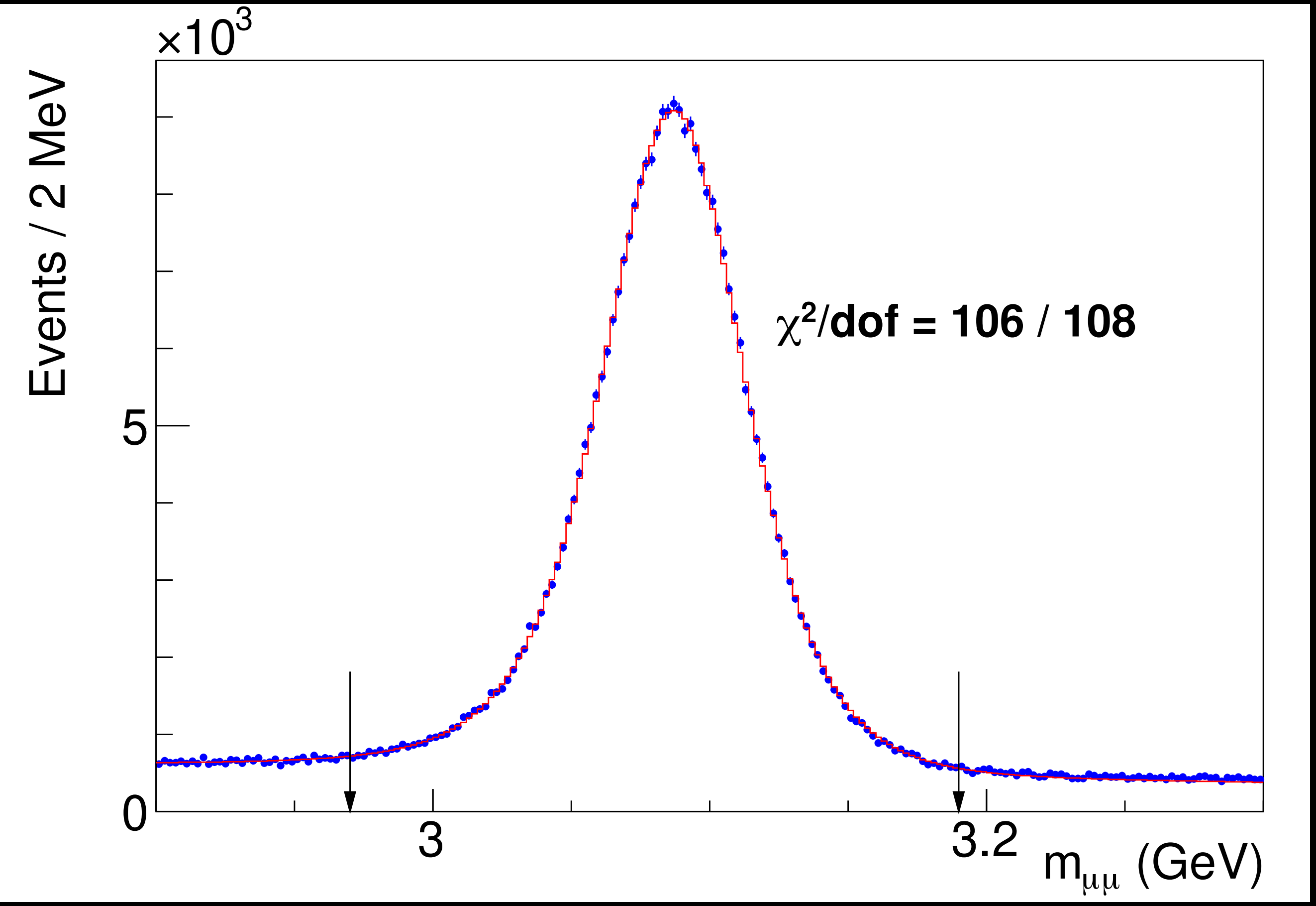
Second step is to calibrate the momentum scale using J/ψ decays to muons

Simulation:

Adjust kinematics to match the data

Model resonance shape using hit-level simulation and NLO form factor for QED radiation





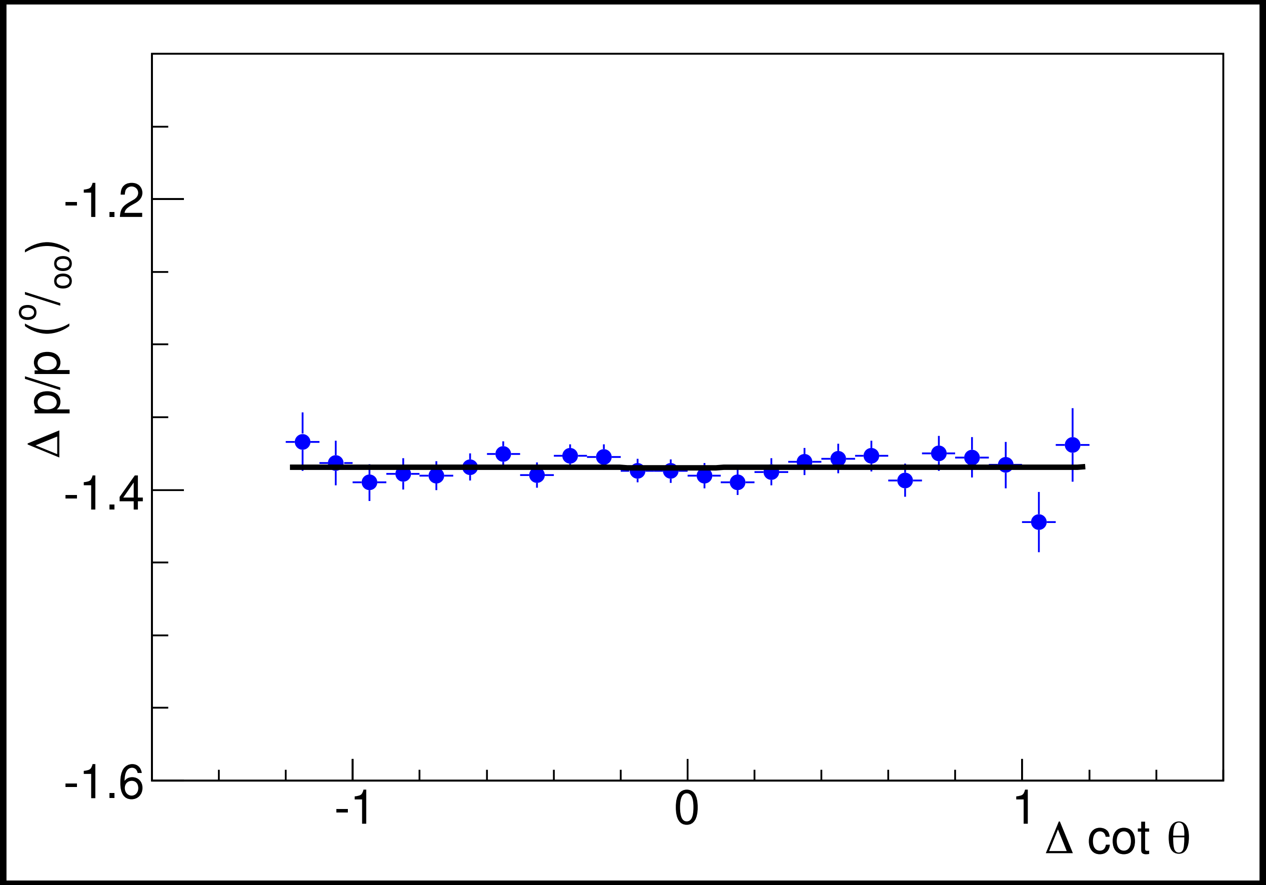
Muon momentum calibration

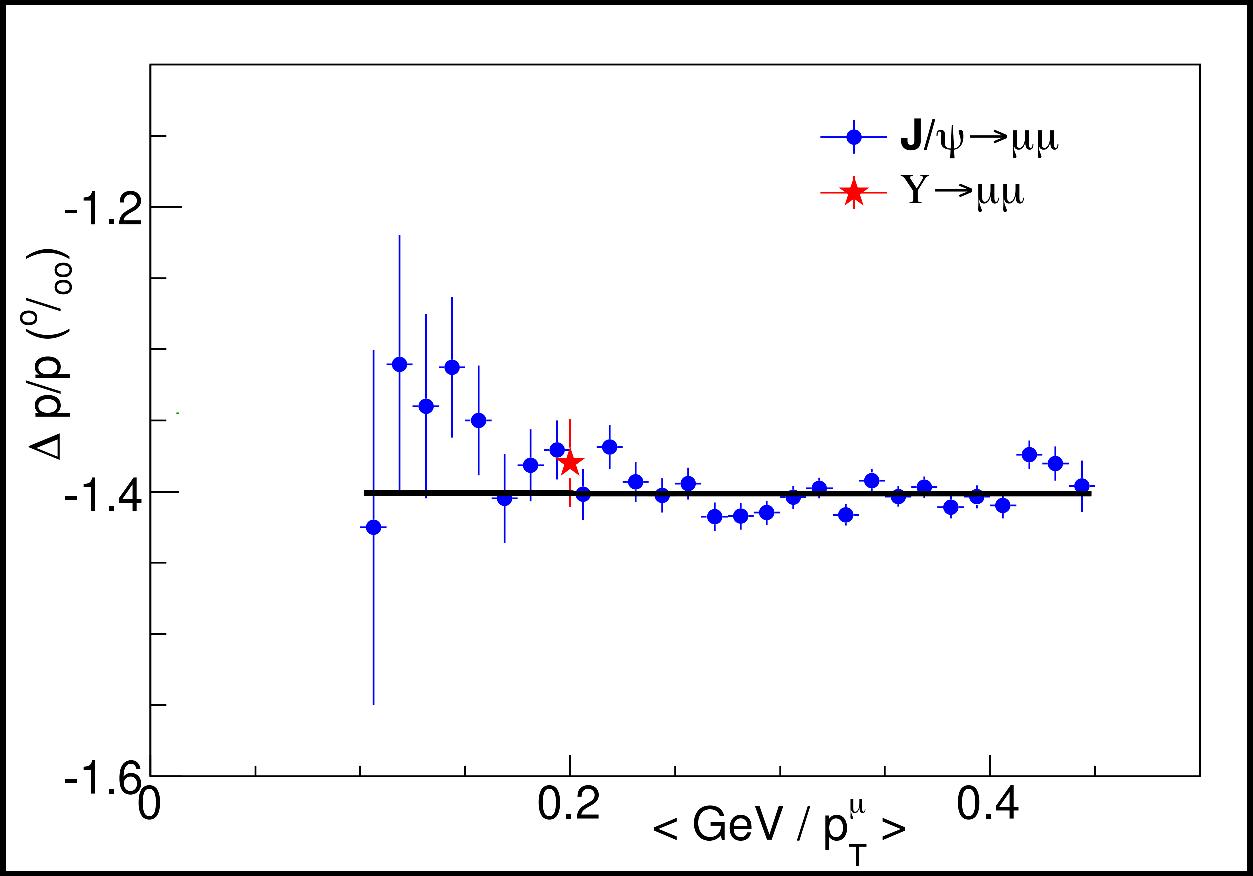
Second step is to calibrate the momentum scale using J/ψ decays to muons

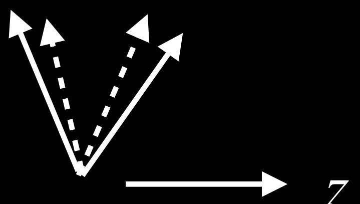
Simulation corrections:

Correct the length scale of the tracker with mass measurement as a function of $\Delta \cot \theta$

Correct the amount of upstream material with mass measurement as a function of p_T^{-1}



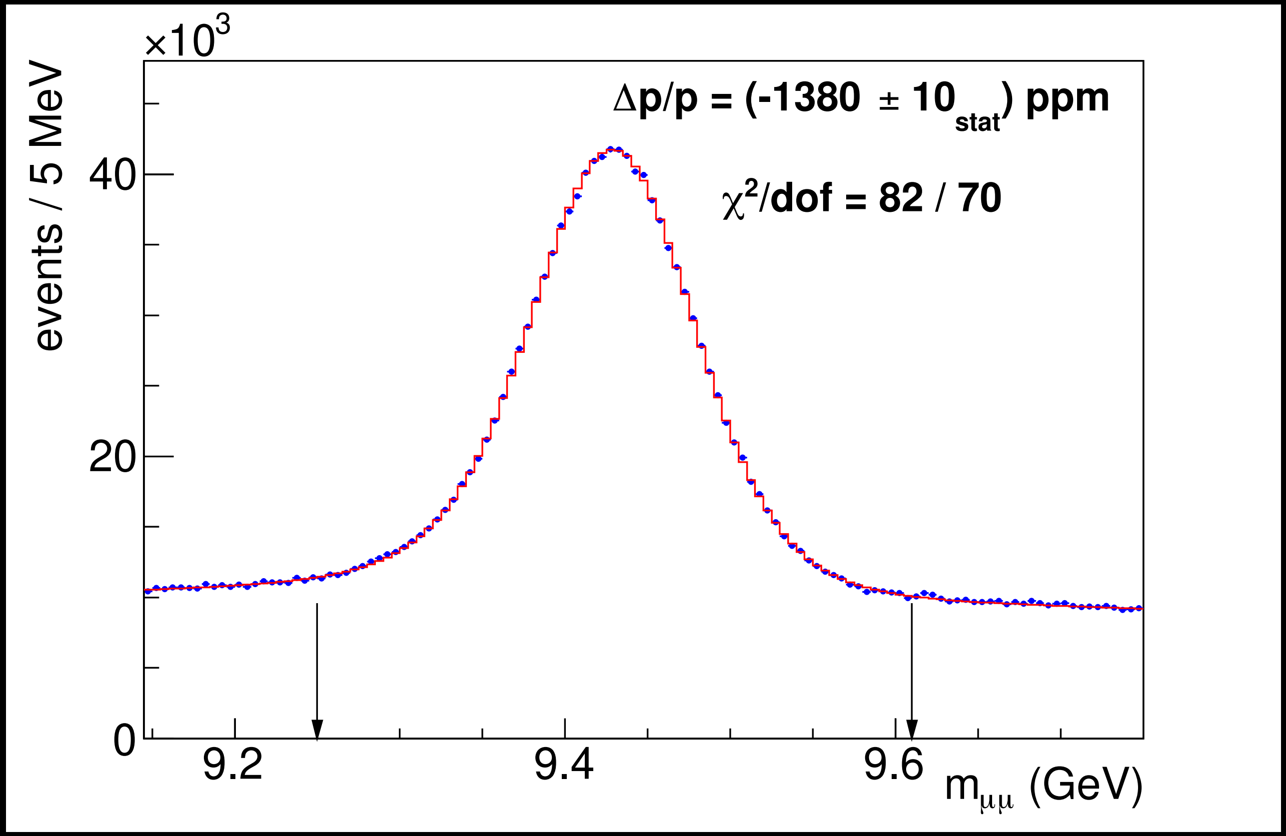




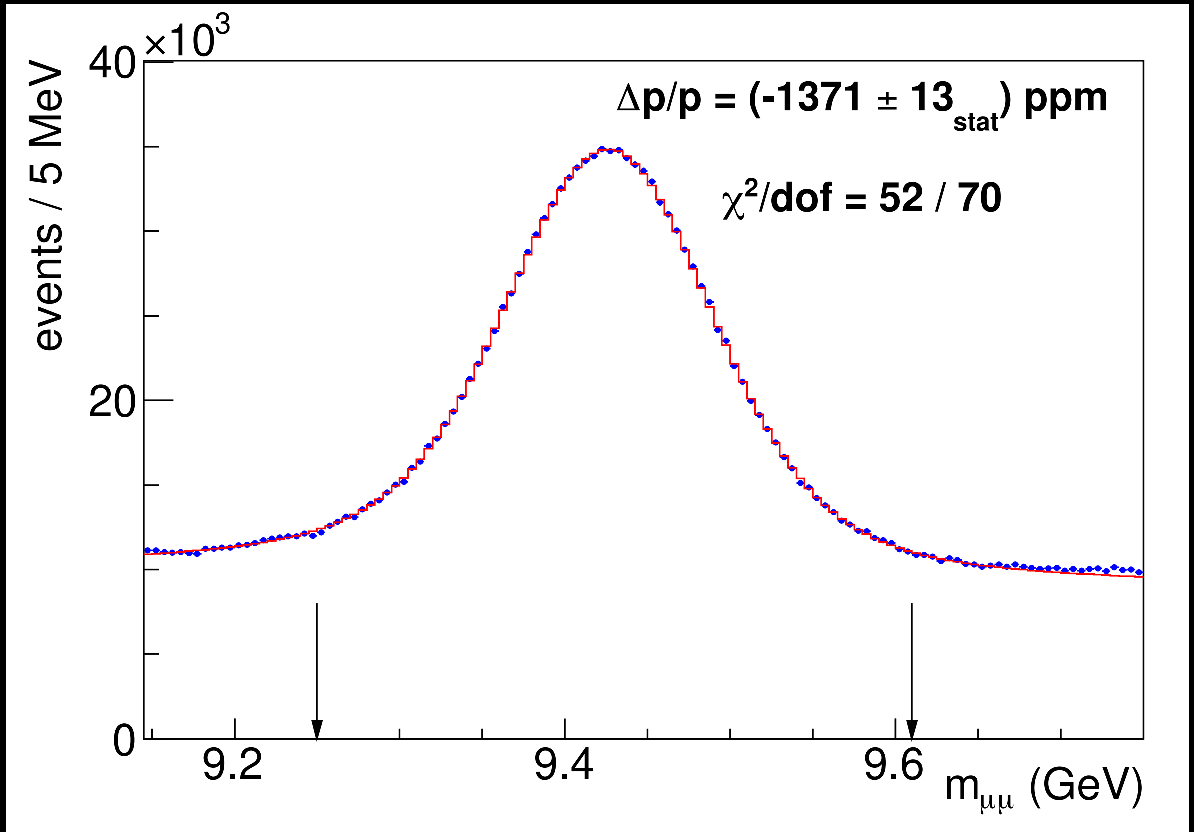
Muon momentum calibration

Third step is to calibrate the scale using Υ decays to muons

Compare fit results with and without constraining the track to the collision point



with constraint



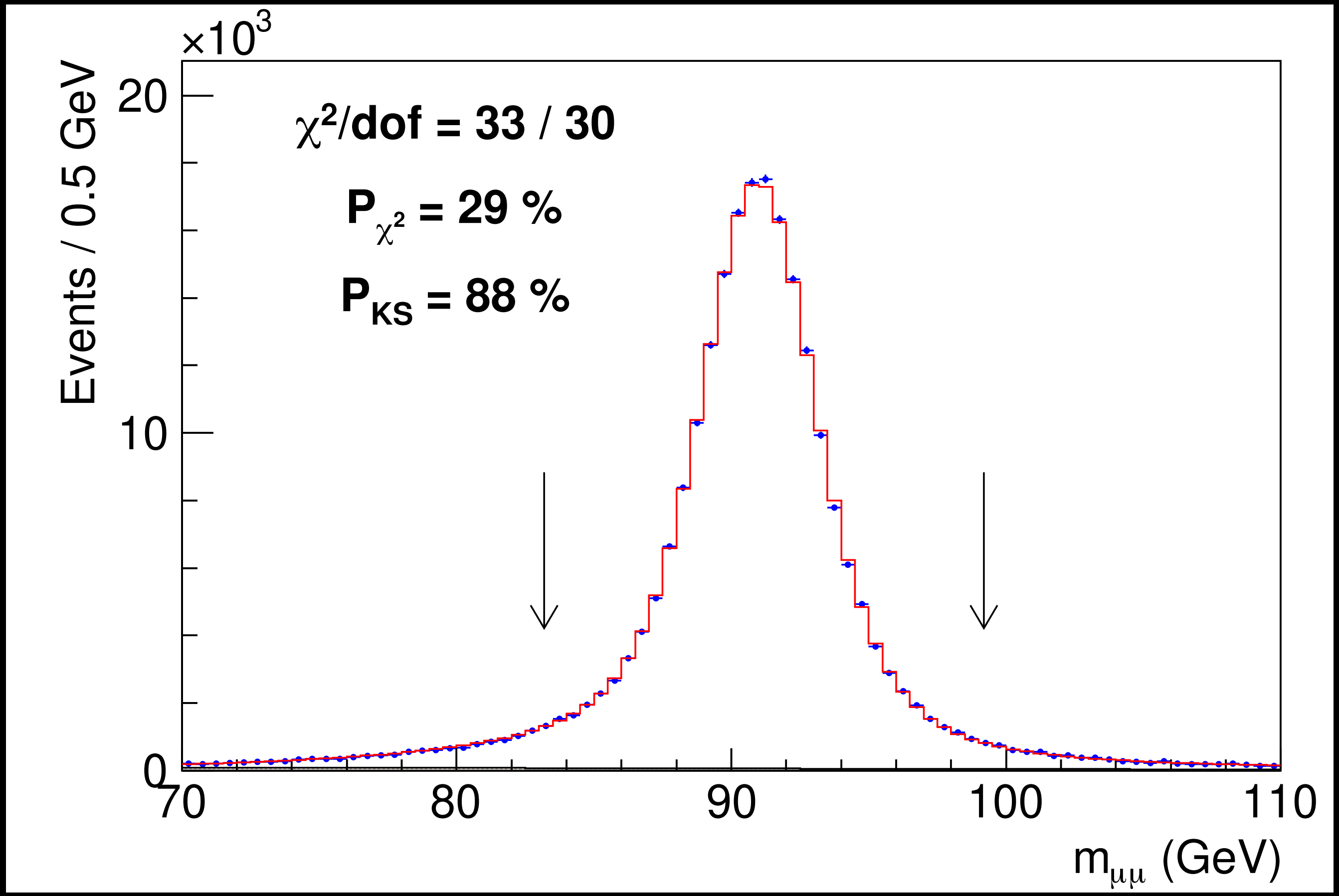
without constraint

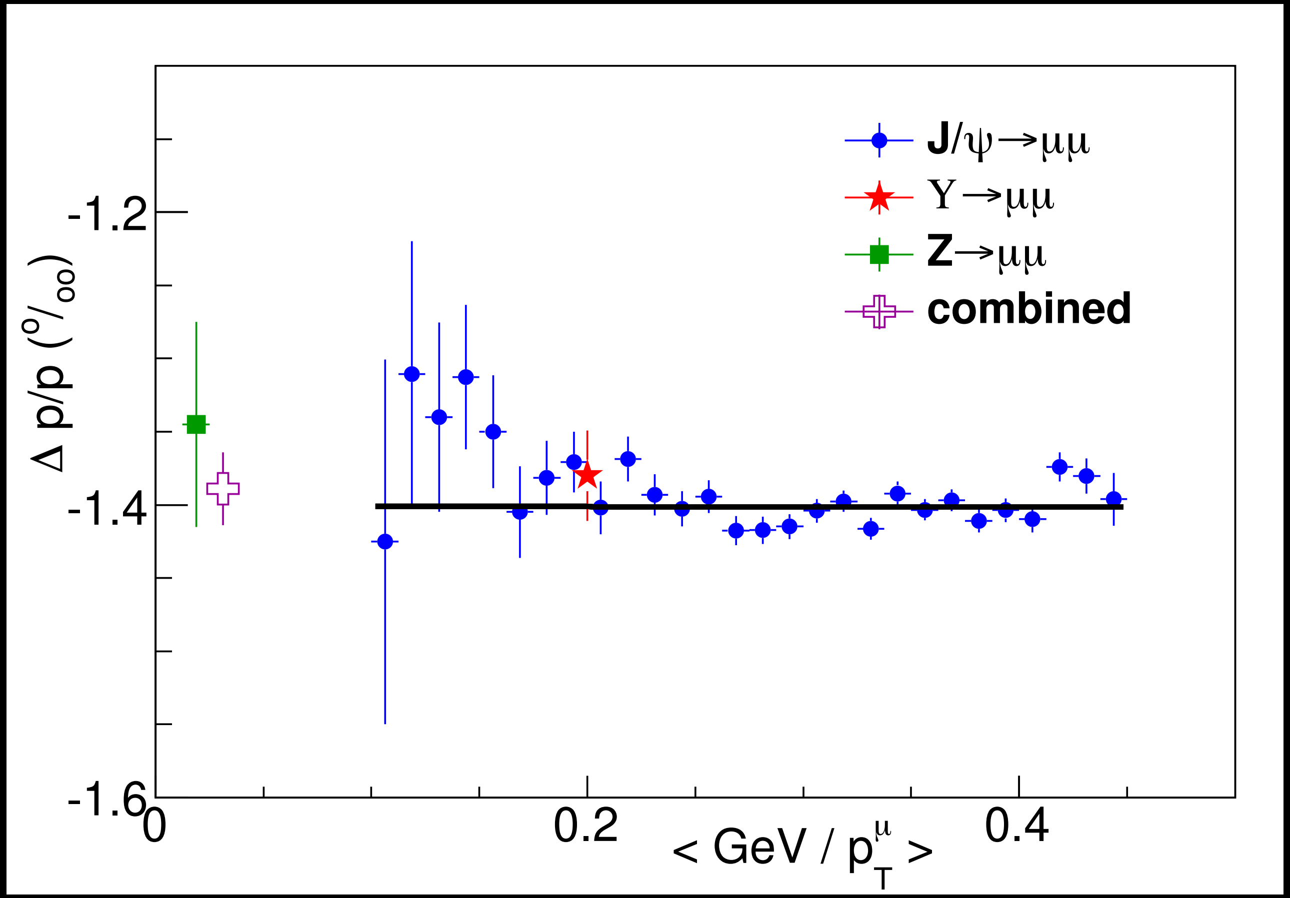
Muon momentum calibration

Final step is to measure the Z boson mass

$$M_Z = 91\ 192.0 \pm 6.4_{stat} \pm 4.0_{sys}\ \text{MeV}$$

Most precise determination of the Z boson mass at a hadron collider: uncertainty **3.6 × LEP**
Combine all measurements into a final charged-track momentum scale





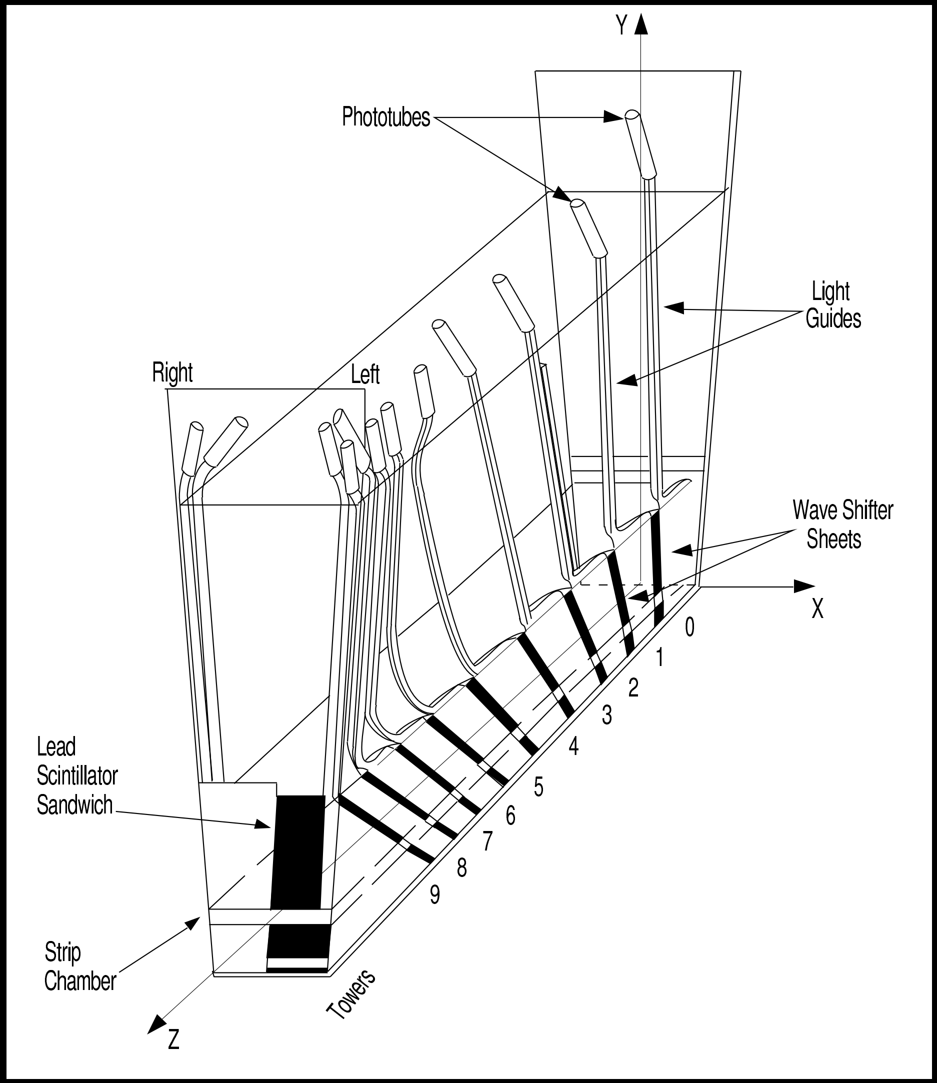
Electron momentum calibration

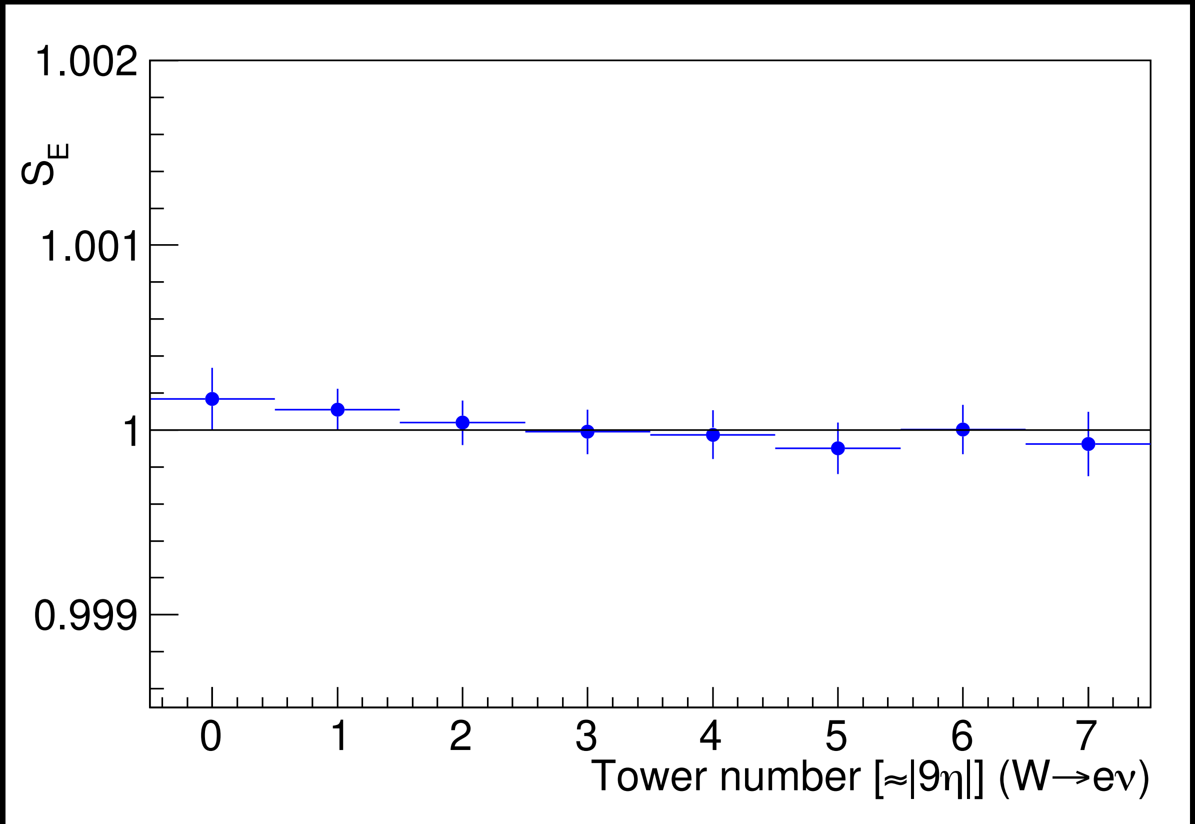
First step is to transfer the track calibration to the calorimeter (E/p) using W & Z decays

Data corrections:

Use mean E/p to remove time dependence & response variations in tower

Fit ratio of calorimeter energy to track momentum to correct each tower in η



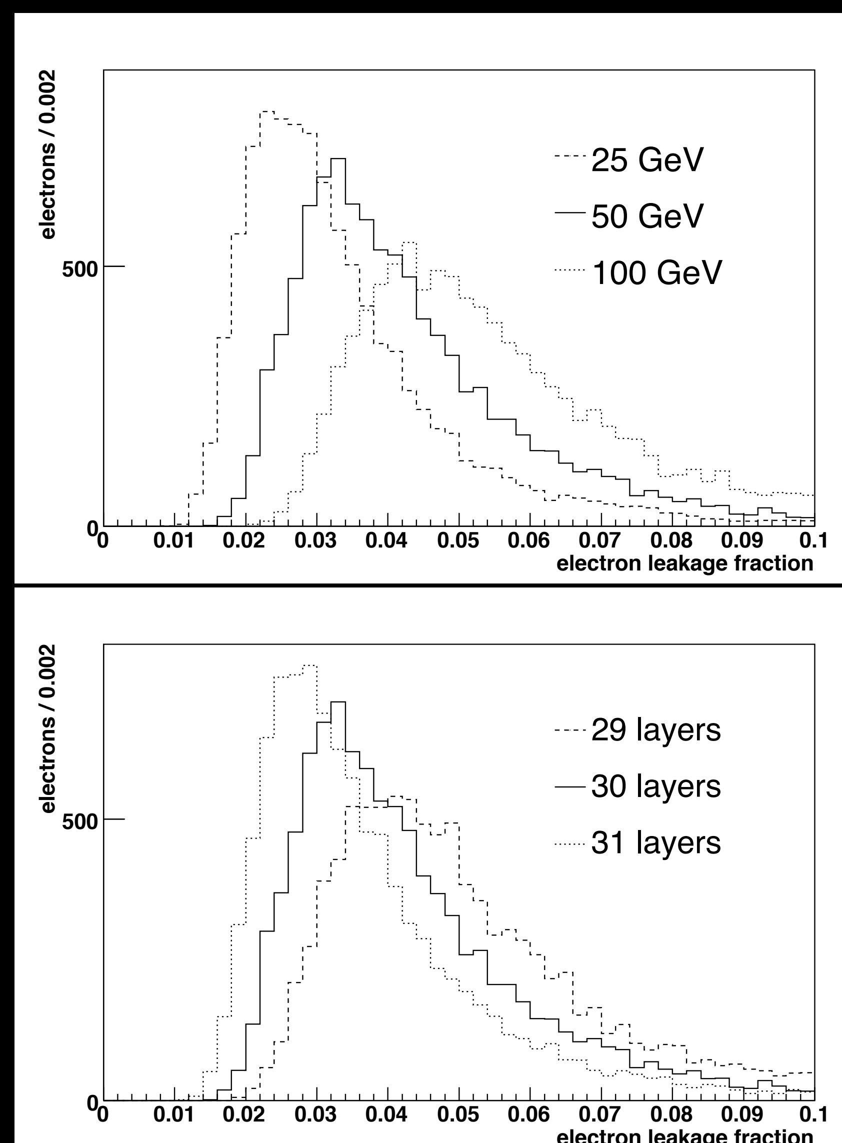


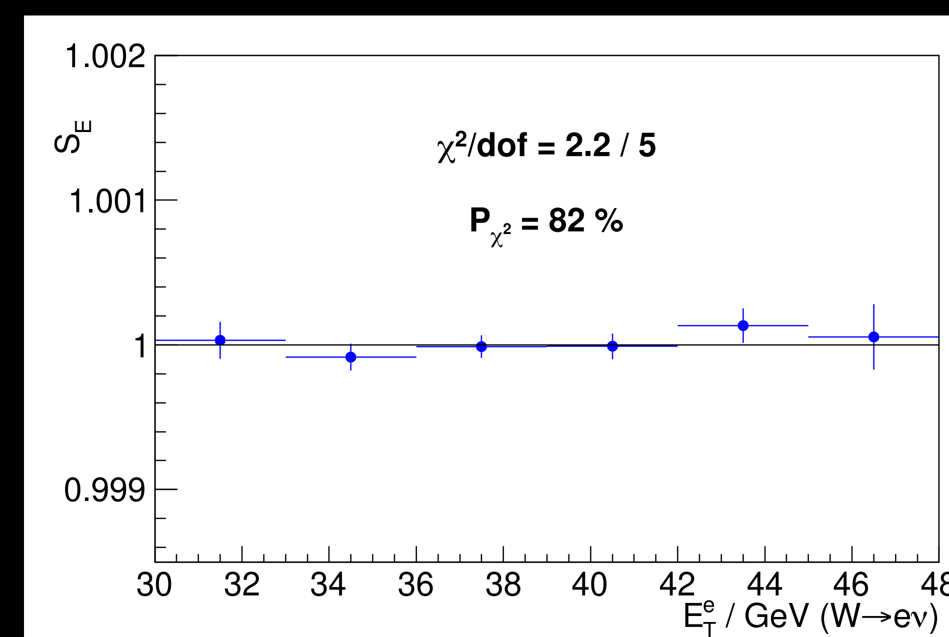
Electron momentum calibration

First step is to transfer the track calibration to the calorimeter (E/p) using W & Z decays

Parameterize calorimeter shower deposition and leakage based on GEANT4
Determine small calorimeter thickness corrections using region of low E/p in data
Fit calorimeter scale as a function of E_T to correct for any remaining energy dependence

Tower	Thickness (x_0)	Number of lead sheets
0	17.9	30
1	18.2	30
2	18.2	29
3	17.8	27
4	18.0	26
5	17.7	24
6	18.1	23
7	17.7	21
8	18.0	20





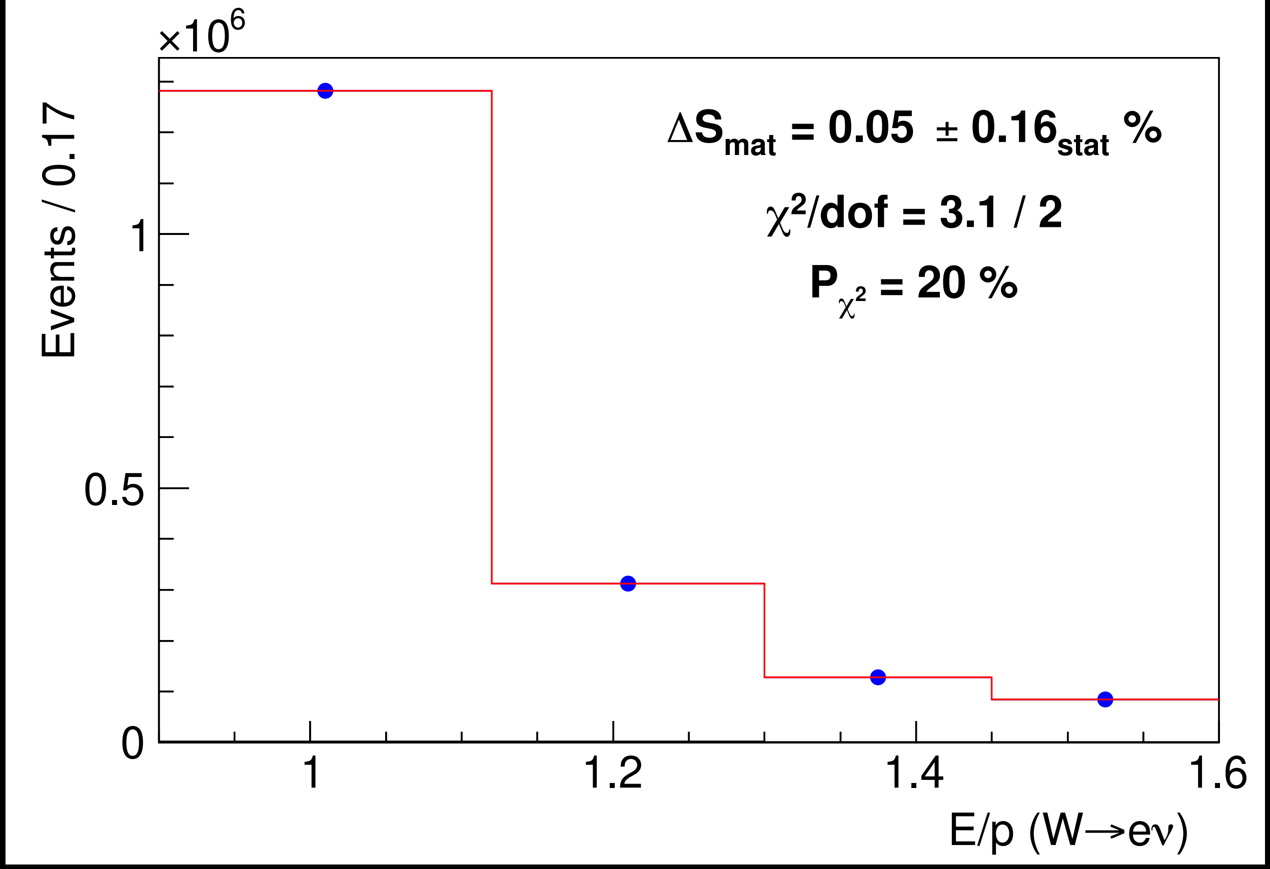
Kotwal & CH, NIMA 729, 25 (2013)

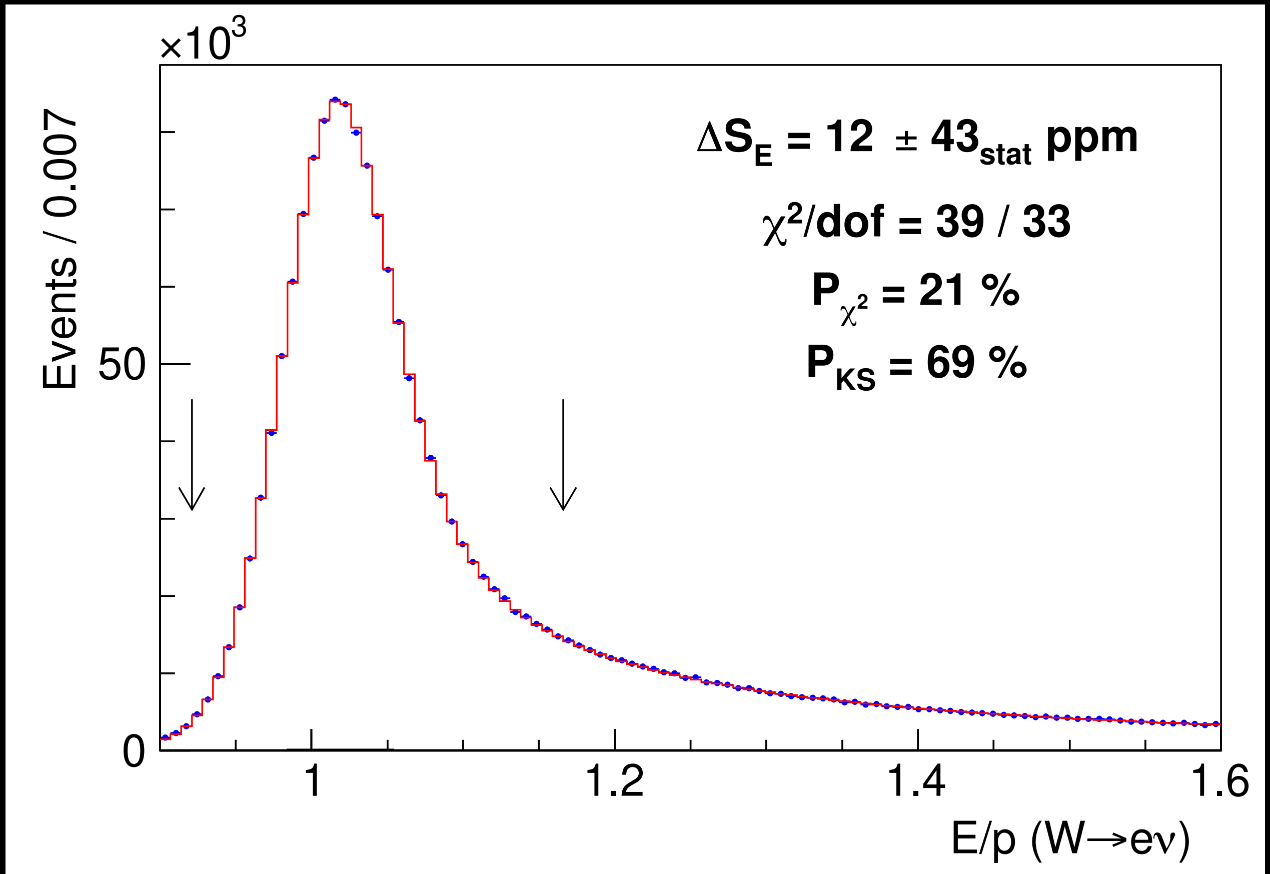
Electron momentum calibration

First step is to transfer the track calibration to the calorimeter (E/p) using W & Z decays

Model bremsstrahlung and pair production upstream of the drift chamber
Tune energy loss due to material upstream of the tracker (high E/p)

Sampling resolution given by $\sigma_E/E = \sqrt{\frac{12.6\,\%}{E_T} + \kappa^2}$ with $\kappa = 0.7 - 1.1\,\%$ increasing with tower η





Electron momentum calibration

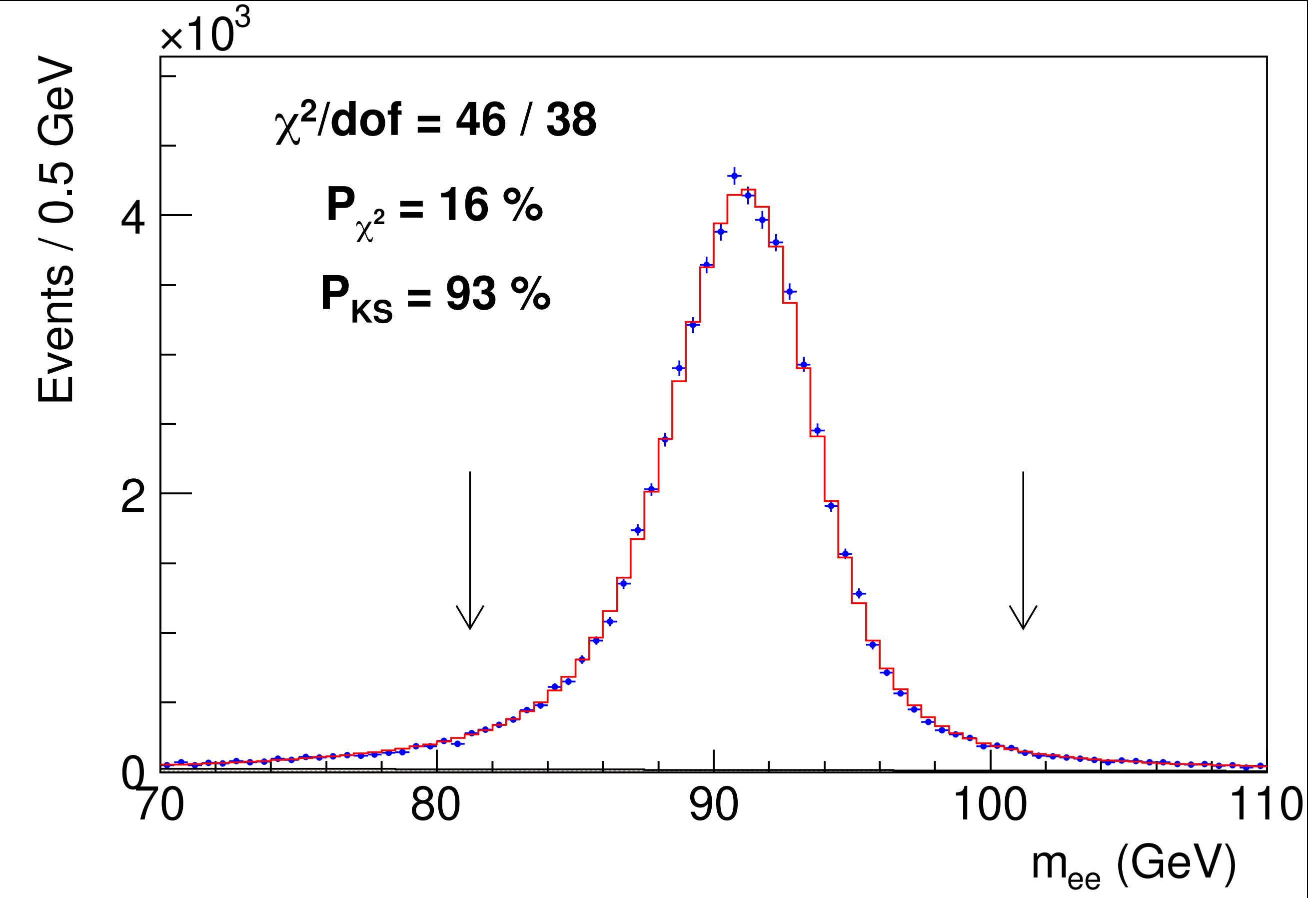
Second step is the measurement of the Z boson mass

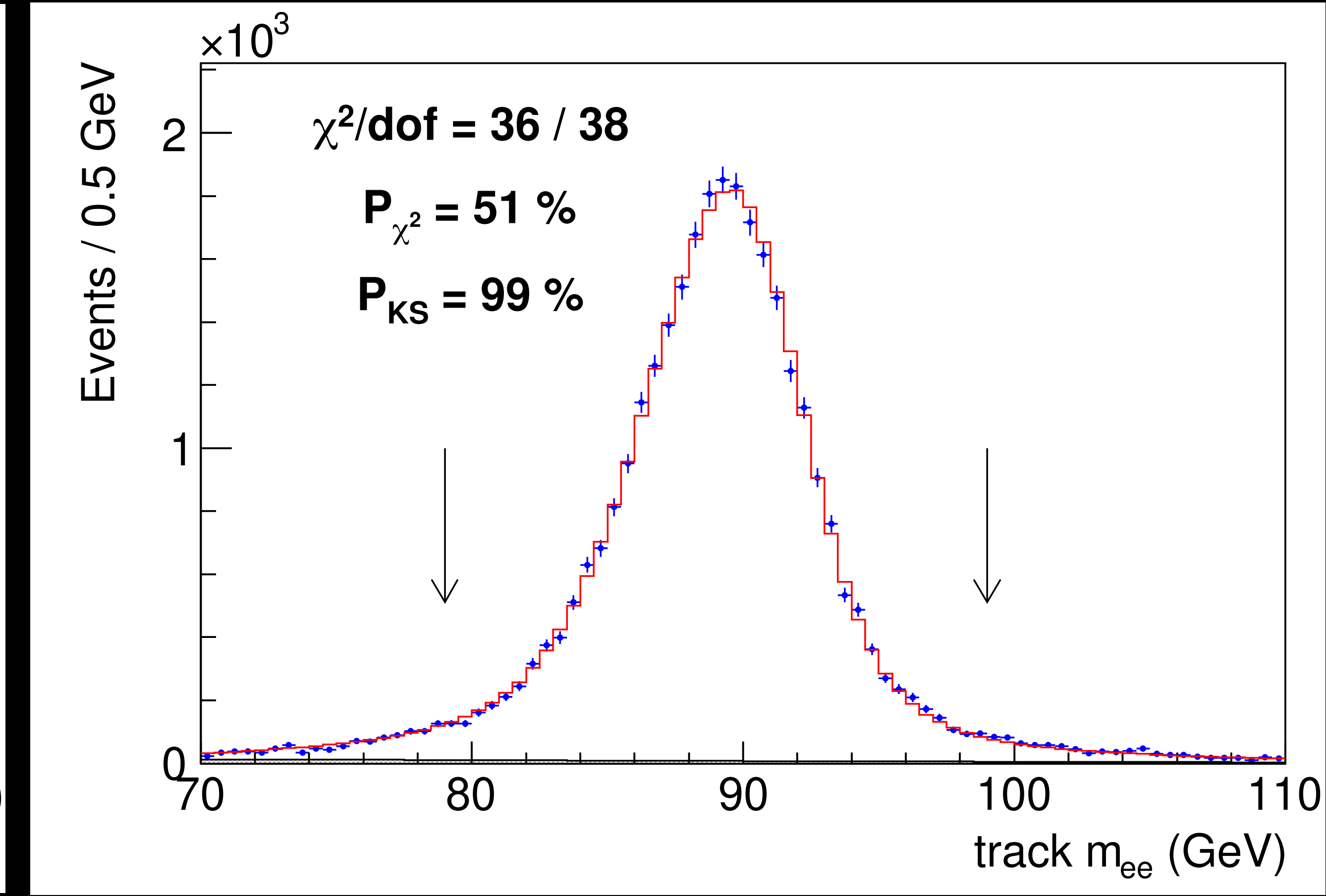
$$M_Z = 91\ 194.3 \pm 13.8_{stat} \pm 7.6_{sys}\ \text{MeV}$$

As a consistency check measure mass using only track information

e.g. $M_Z = 91\ 215.2 \pm 22.4$ MeV for non-radiative electrons (E/p<1.1)

Same blinding as for muon channel

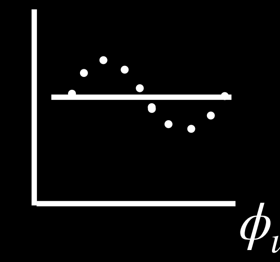




Recoil momentum calibration

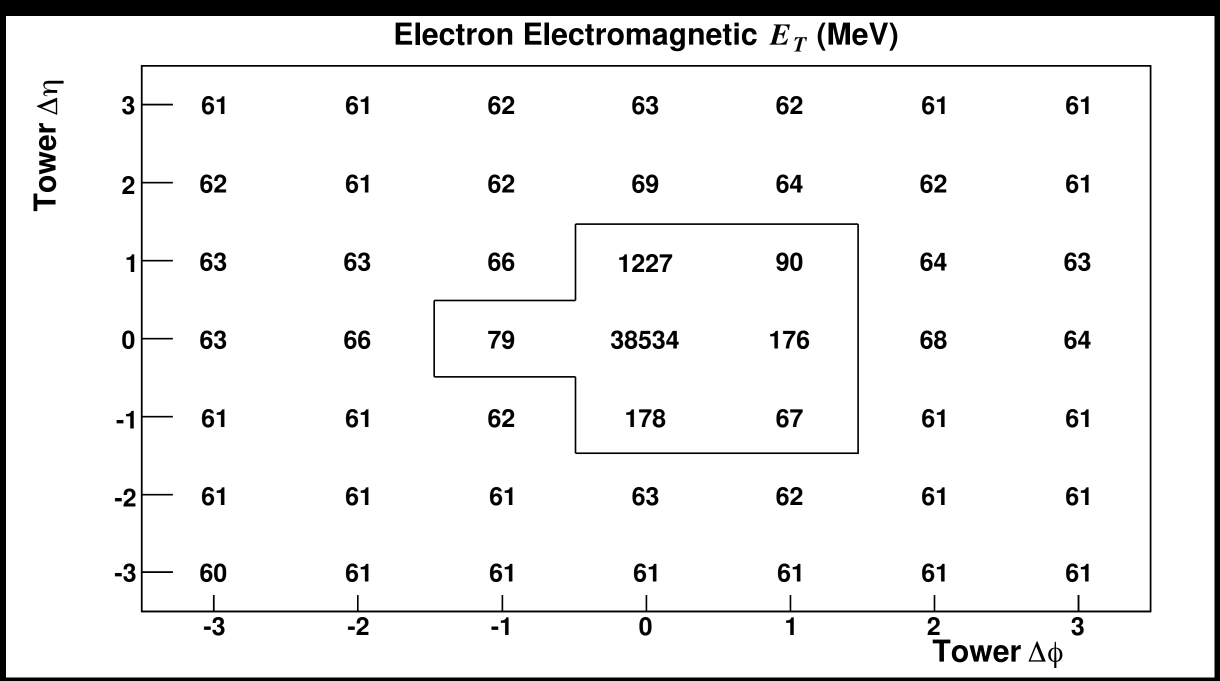
First step is the alignment of the calorimeters

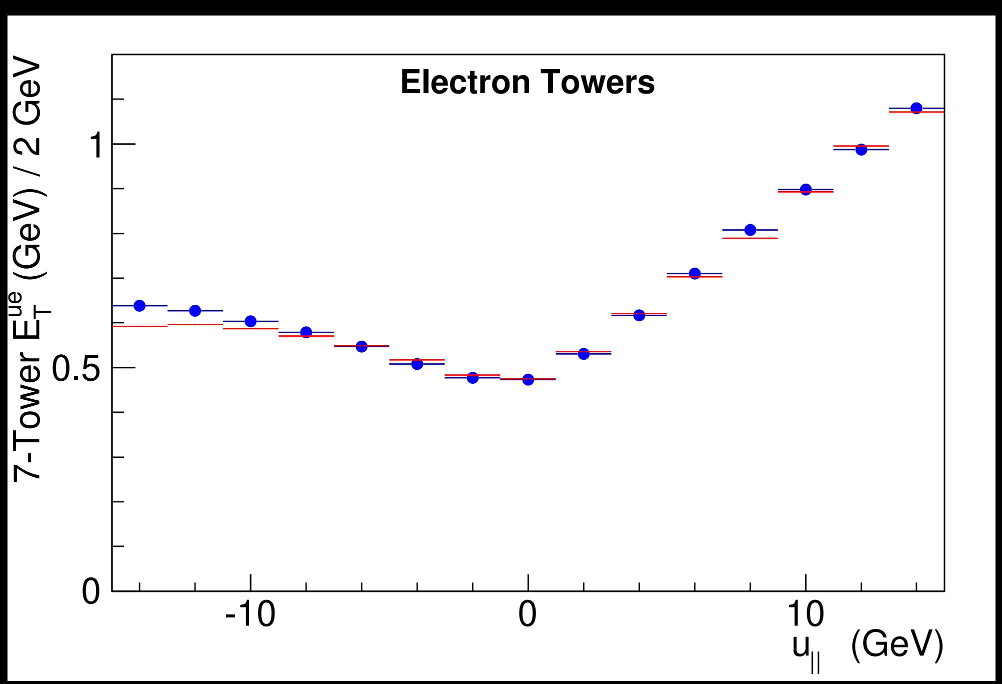
- Misalignments relative to the beam axis cause a modulation in the recoil direction
- Alignment performed separately for each run period using minimum-bias data



Second step is the reconstruction of the recoil

- Remove towers traversed by identified leptons
- Remove corresponding recoil energy in simulation using towers rotated by 90^o
  - *validate using towers rotated by 180^o*



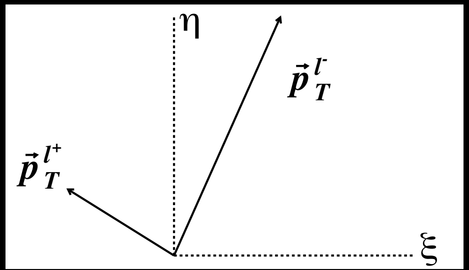


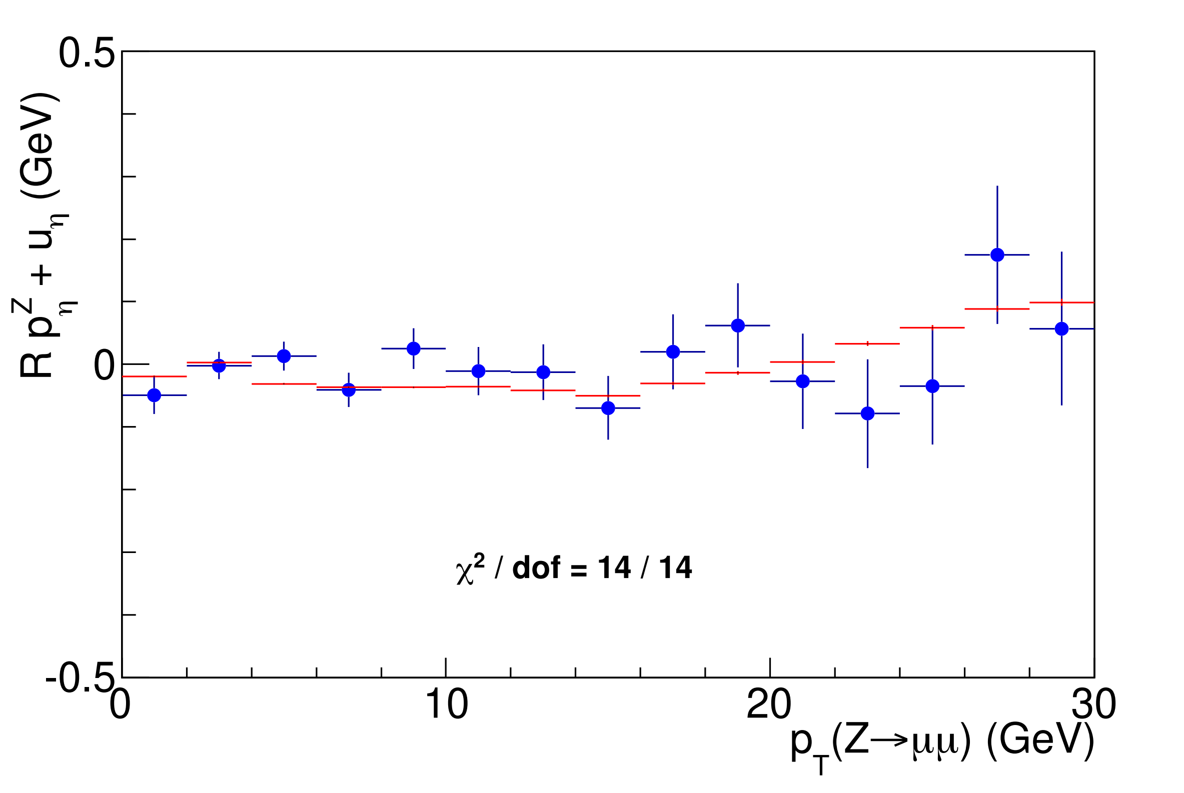
Recoil momentum calibration

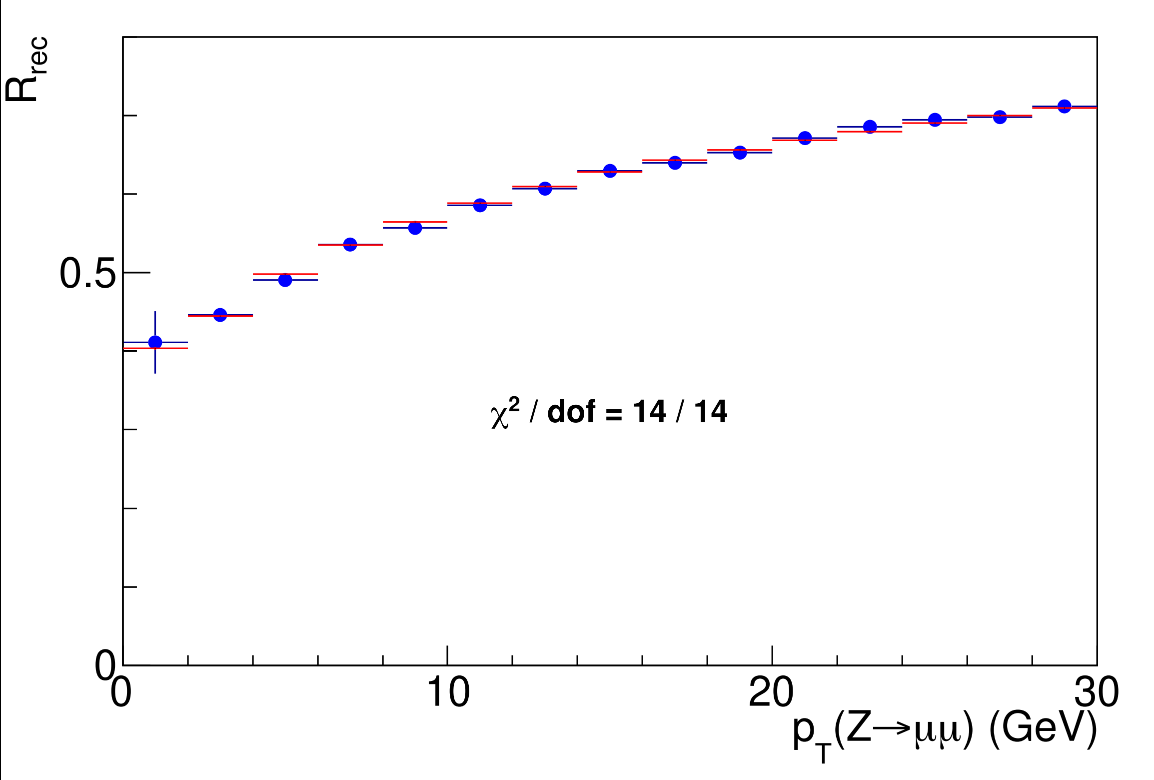
Third step is the calibration of the recoil response

Balance recoil against direction of p_T^Z

Check calibration using ratio of recoil magnitude to p_T^Z along direction of p_T^Z (R_{rec})



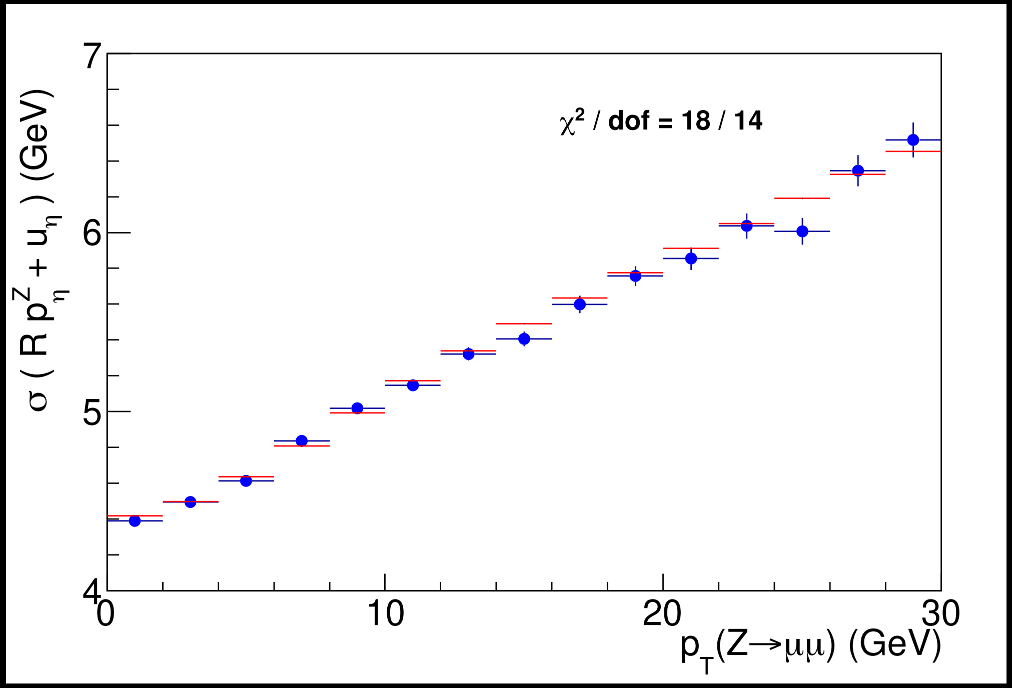


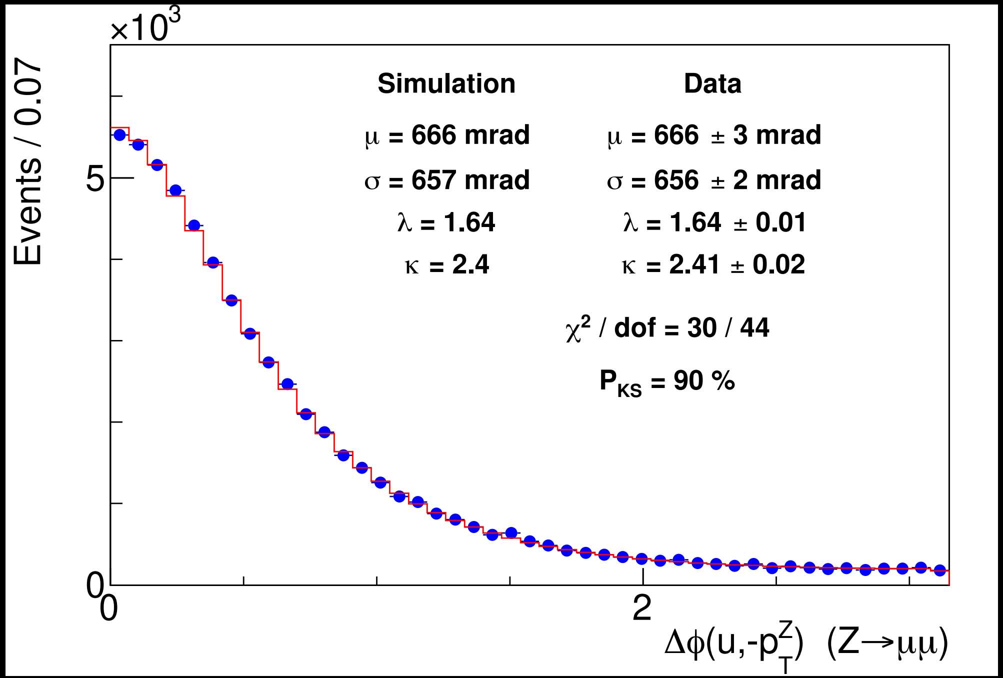


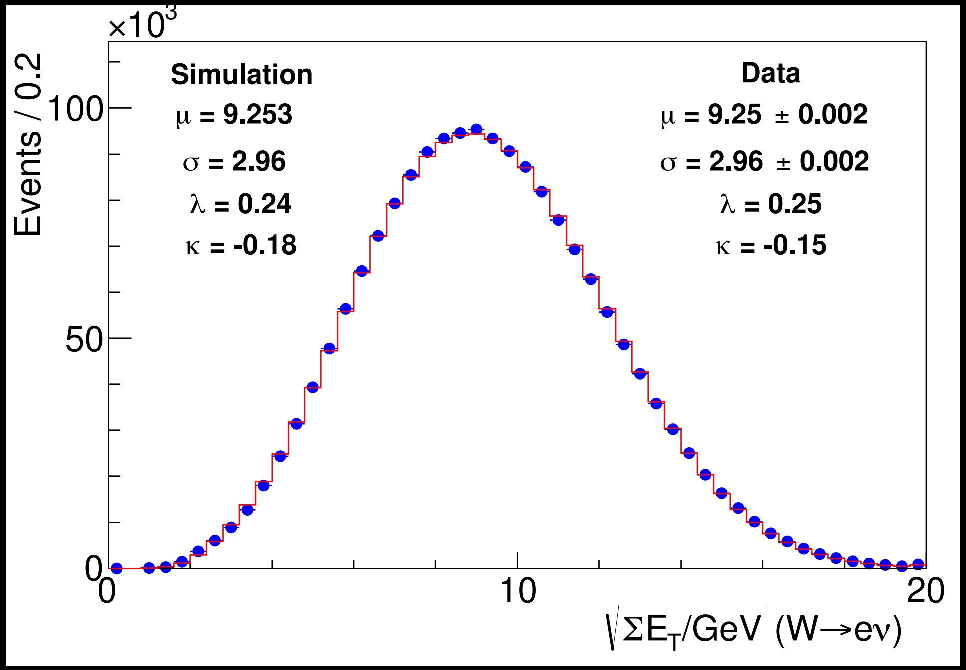
Recoil momentum calibration

Fourth step is the calibration of the recoil resolution

Includes jet-like energy and angular resolution, additional dijet fraction term, and pileup



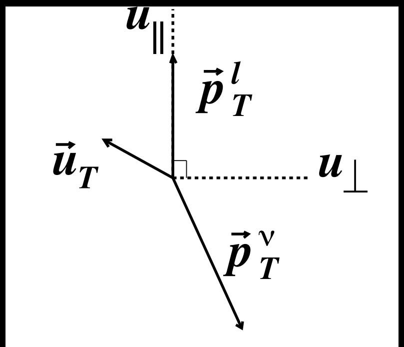




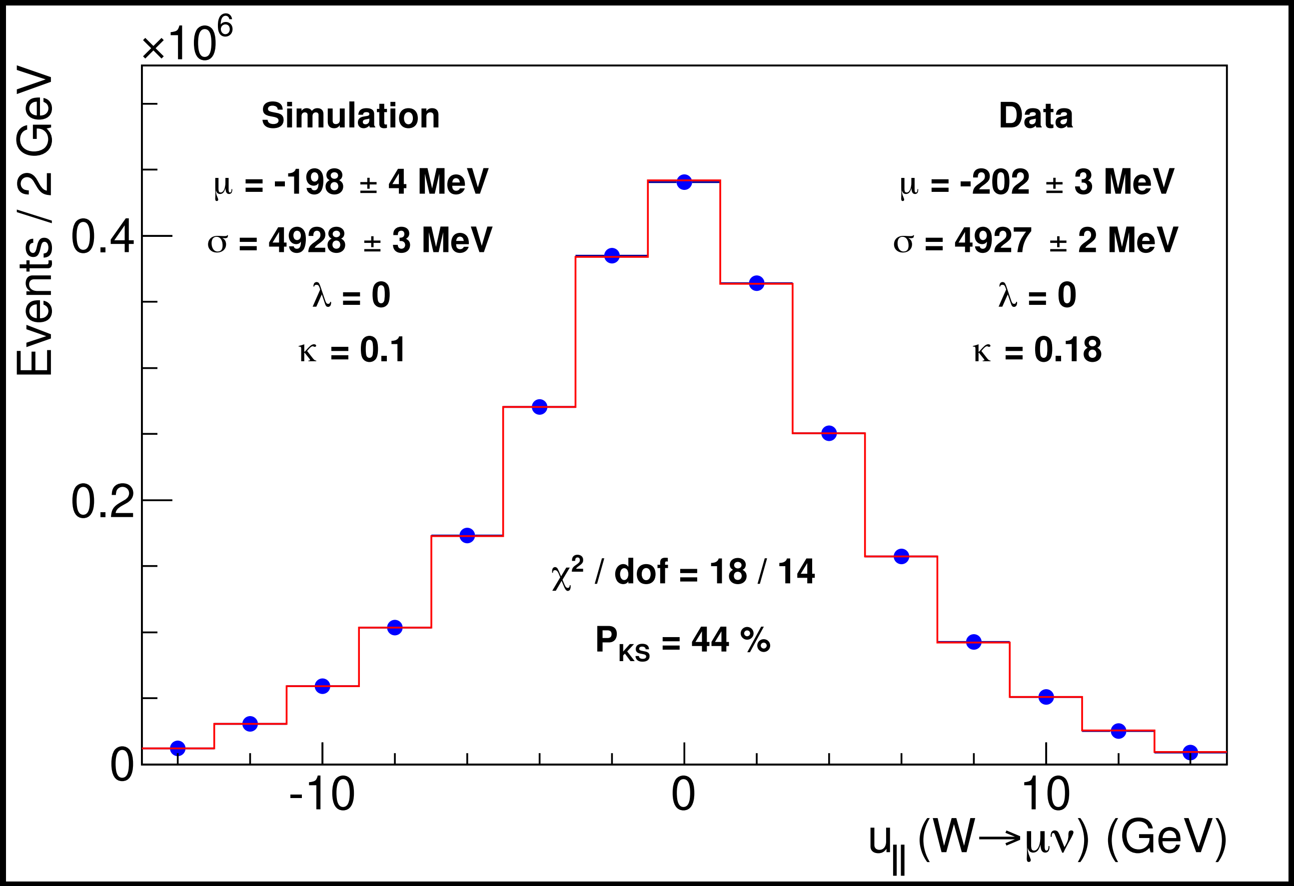
Recoil momentum validation

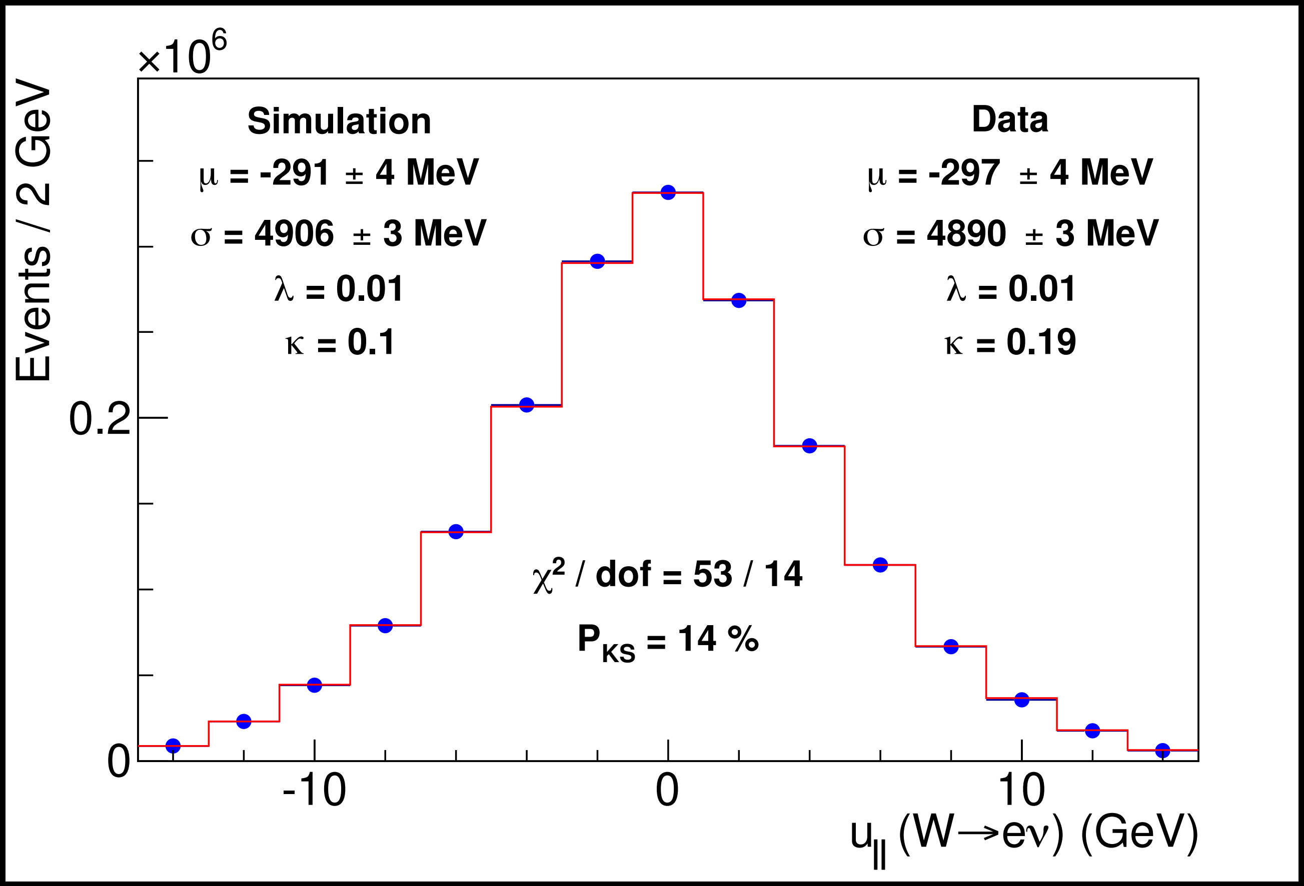
W boson recoil distributions validate the model

Most important is the recoil projected along the charged-lepton's momentum ($u_{||}$)



$$m_T \approx 2p_T\sqrt{1 + u_{||}/p_T} \approx 2p_T + u_{||}$$





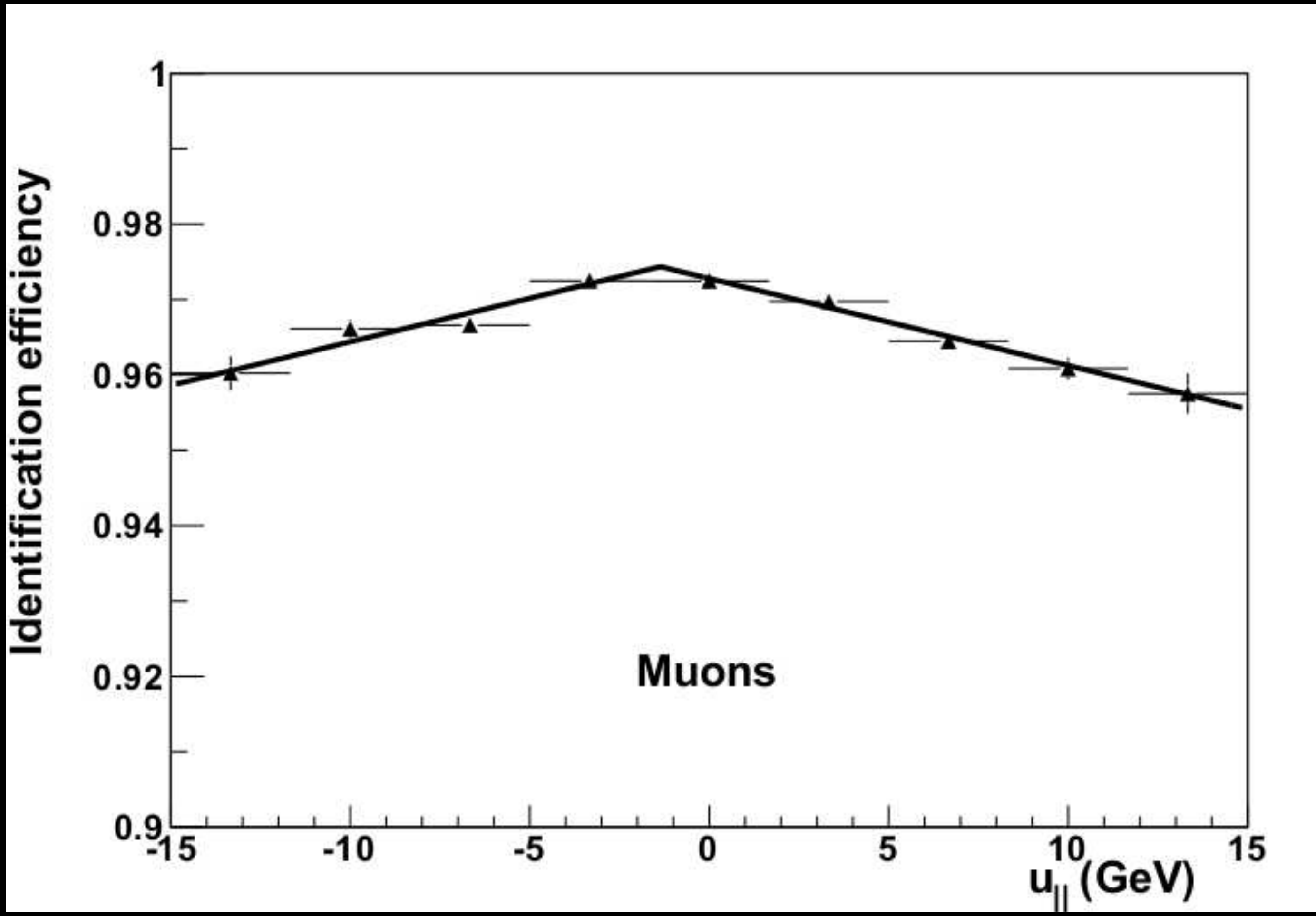
W boson candidates

W boson event selection

Triggers with low momentum thresholds (18 GeV) and very loose lepton id

Offline id also loose, efficiencies vary by 2% as hadronic recoil direction changes

No lepton isolation requirement in trigger or offline selection



Background suppressed by stringent hadronic recoil requirement

$u_T < 15$ GeV

Other kinematic requirements

Lepton and missing p_T in the range 30-55 GeV

Transverse mass in the range 60-100 GeV

2.4 M $W \to \mu\nu$ candidates

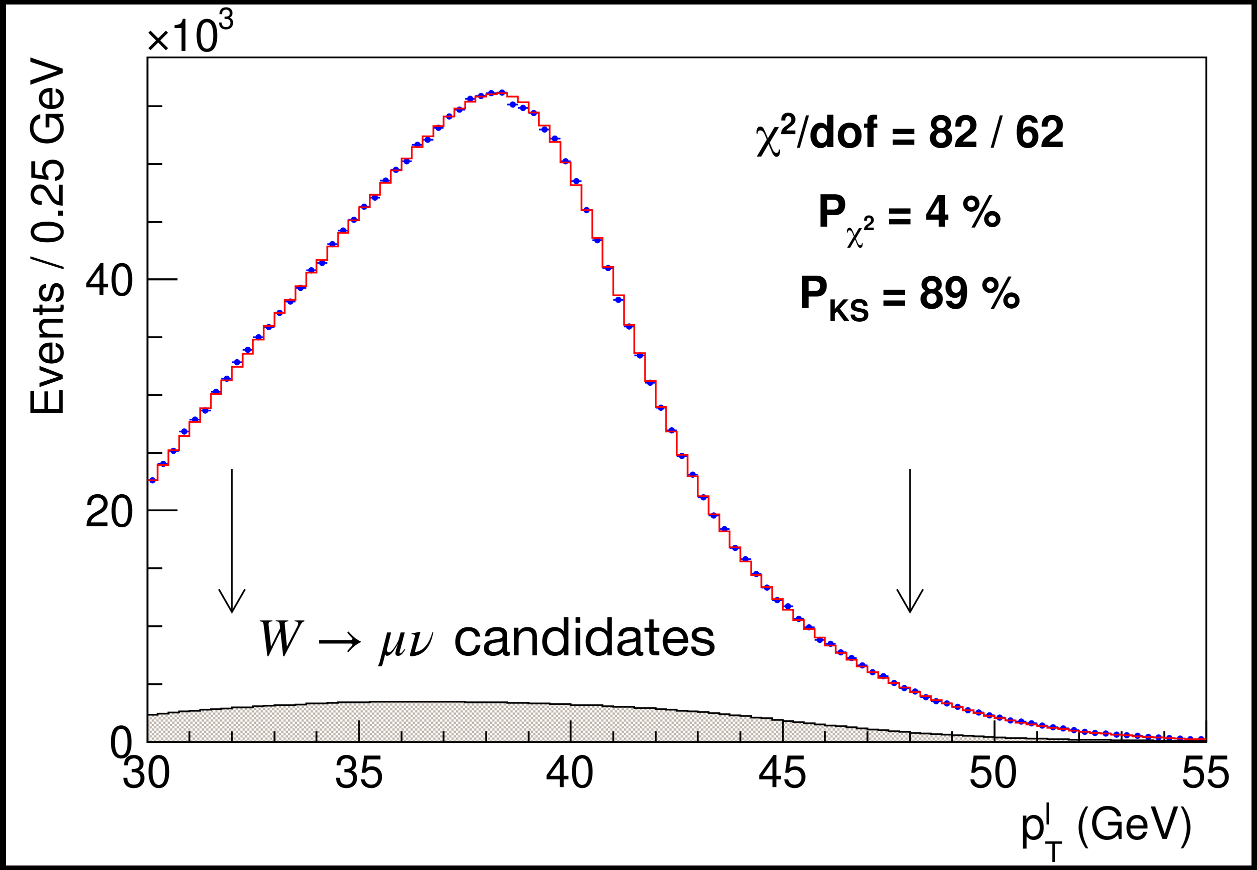
1.8 M $W \to e\nu$ candidates

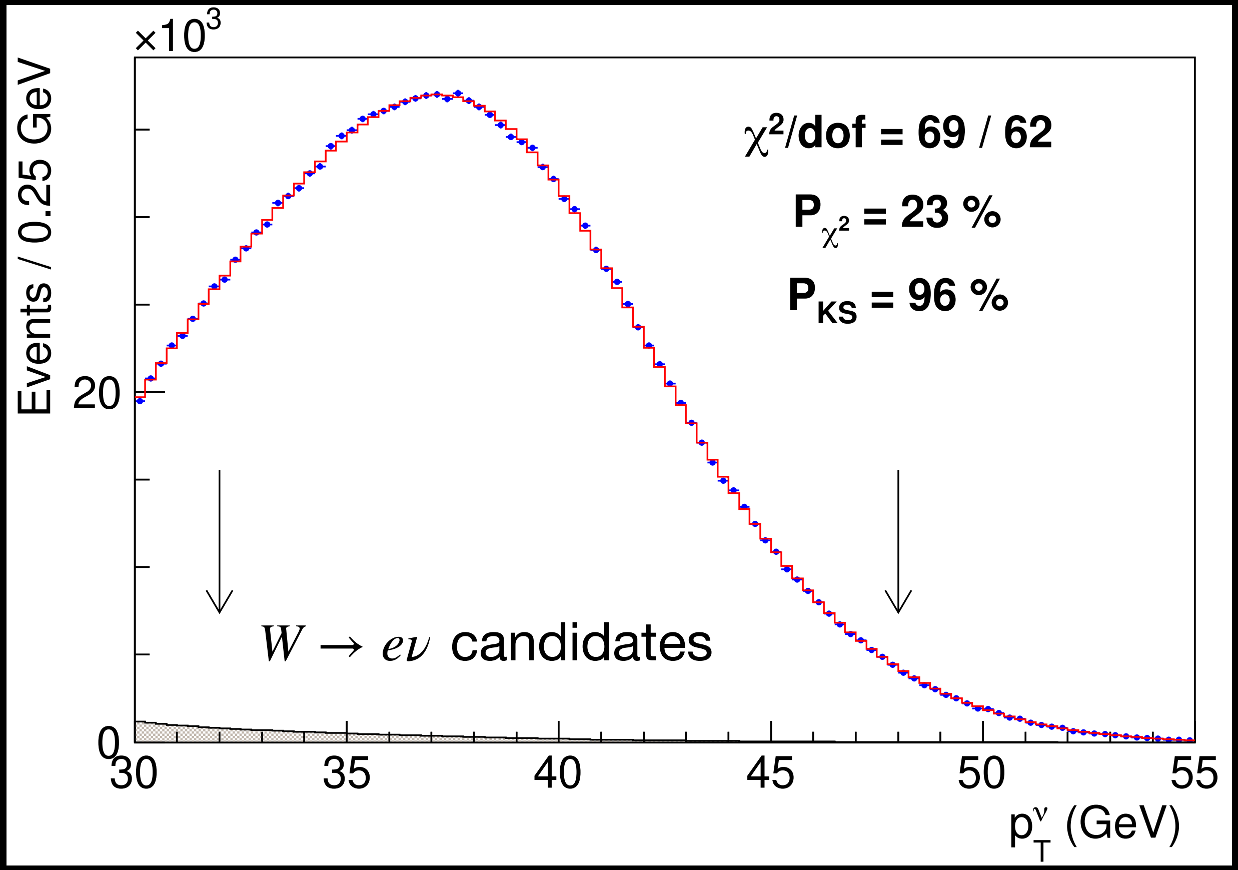
Backgrounds

Electroweak backgrounds modelled with fast simulation tuned with data and full simulation
Cross-checked with full simulation tuned to data

Largest background is $Z \rightarrow \mu\mu$ with one unreconstructed muon: **7.4% of data sample**
$W \rightarrow \tau\nu$ background is ~1% in each channel: largest background in electron sample

Background from hadrons misreconstructed as leptons estimated using data: 0.2-0.3%





W boson transverse momentum

Boson p_T impacts the p_T distributions of the decay leptons

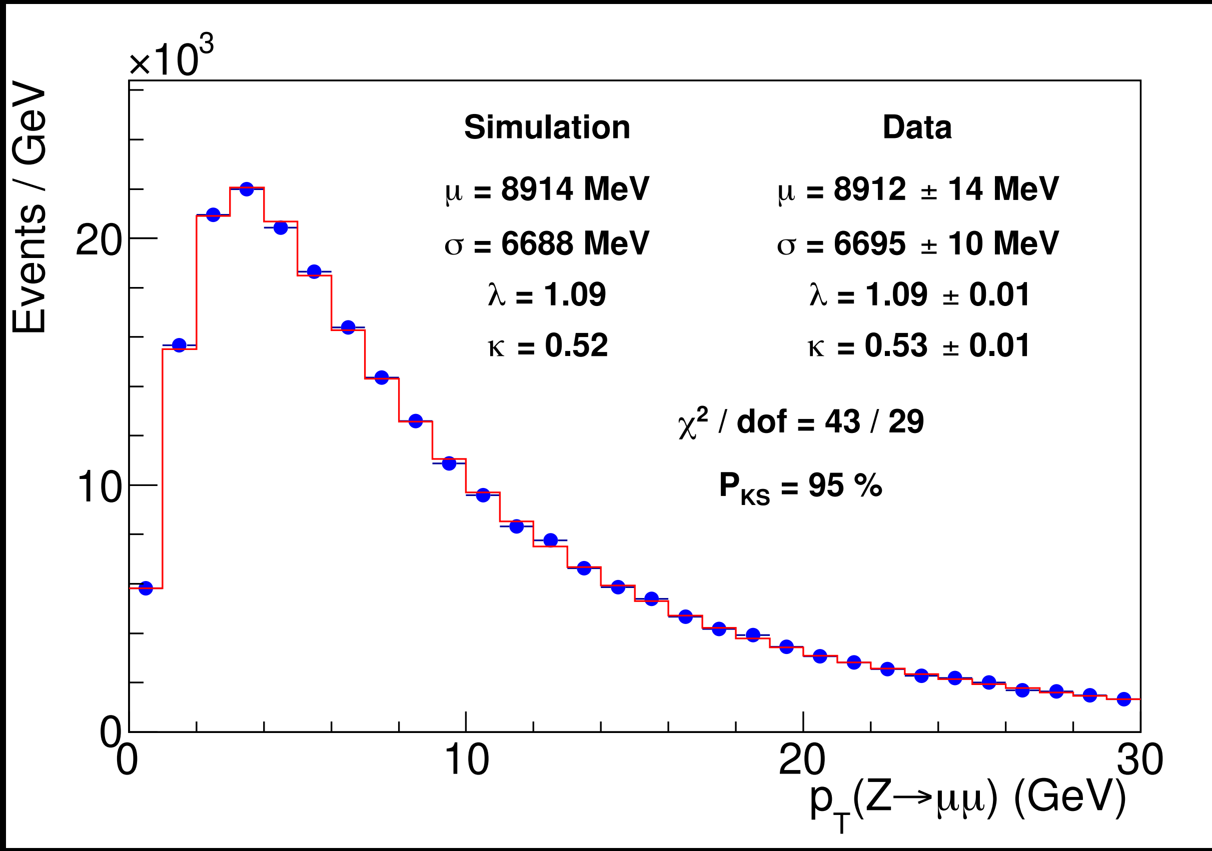
Transverse mass insensitive to p_T^W to first order

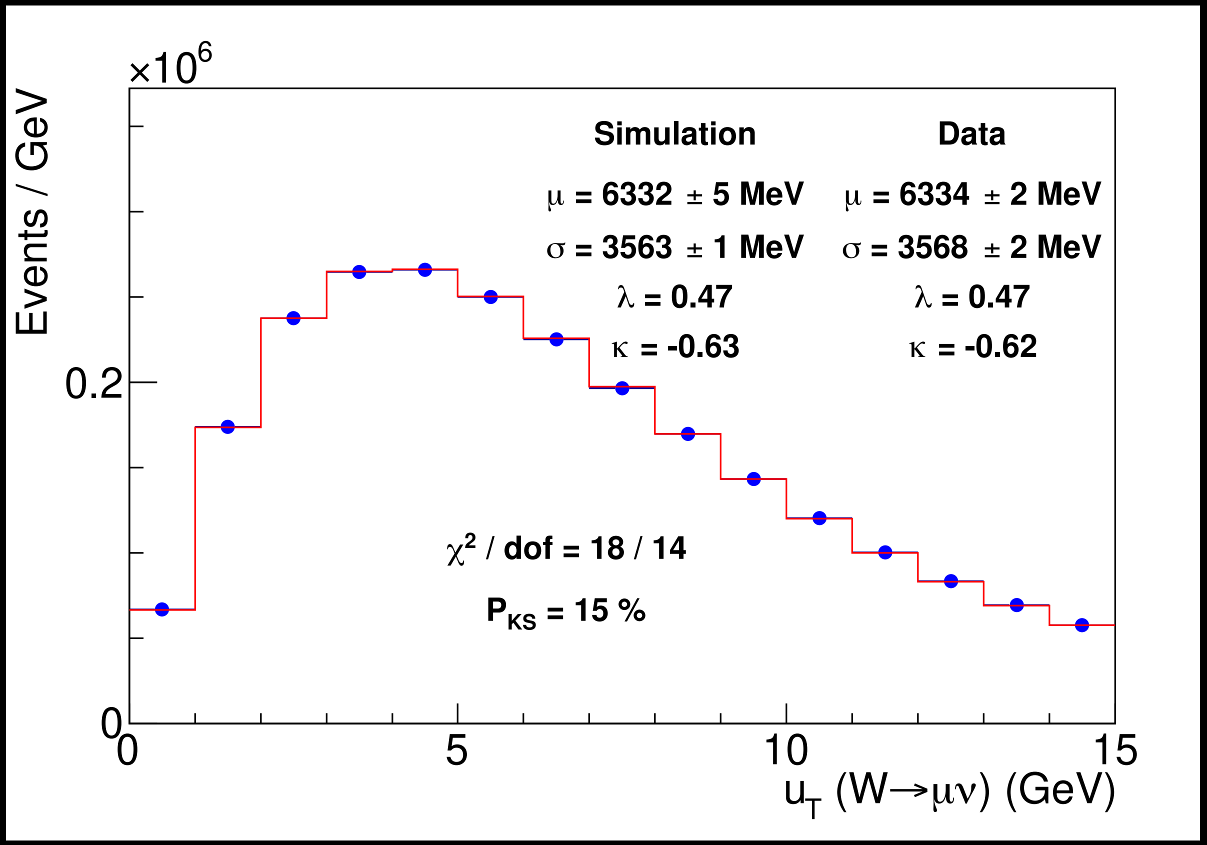
Resbos used to generate events with non-perturbative parameters and NNLL resummation to model the region of low boson p_T

Z boson p_T used to constrain the non-perturbative parameter g_2 and the perturbative coupling α_s

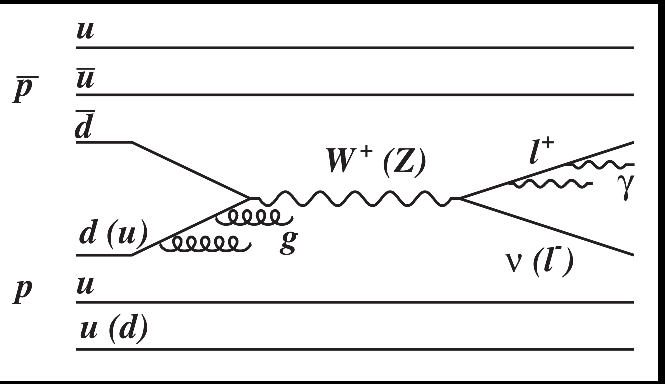
Resbos models W boson p_T well

uncertainty estimated using DYQT renormalization and resummation variations & constrained with data





W boson production and decay



Parton distributions impact the measurement through lepton acceptance

Restriction in η reduces the fraction of low-p_T leptons

Small correction applied to update to NNPDF3.1 NNLO PDF

The set with the most W charge asymmetry measurements at the time

Uncertainty determined using a principal component analysis on the replica set

Measurement sensitive to ~15 eigenvectors

Leading 25 eigenvectors used to estimate uncertainty (3.9 MeV)

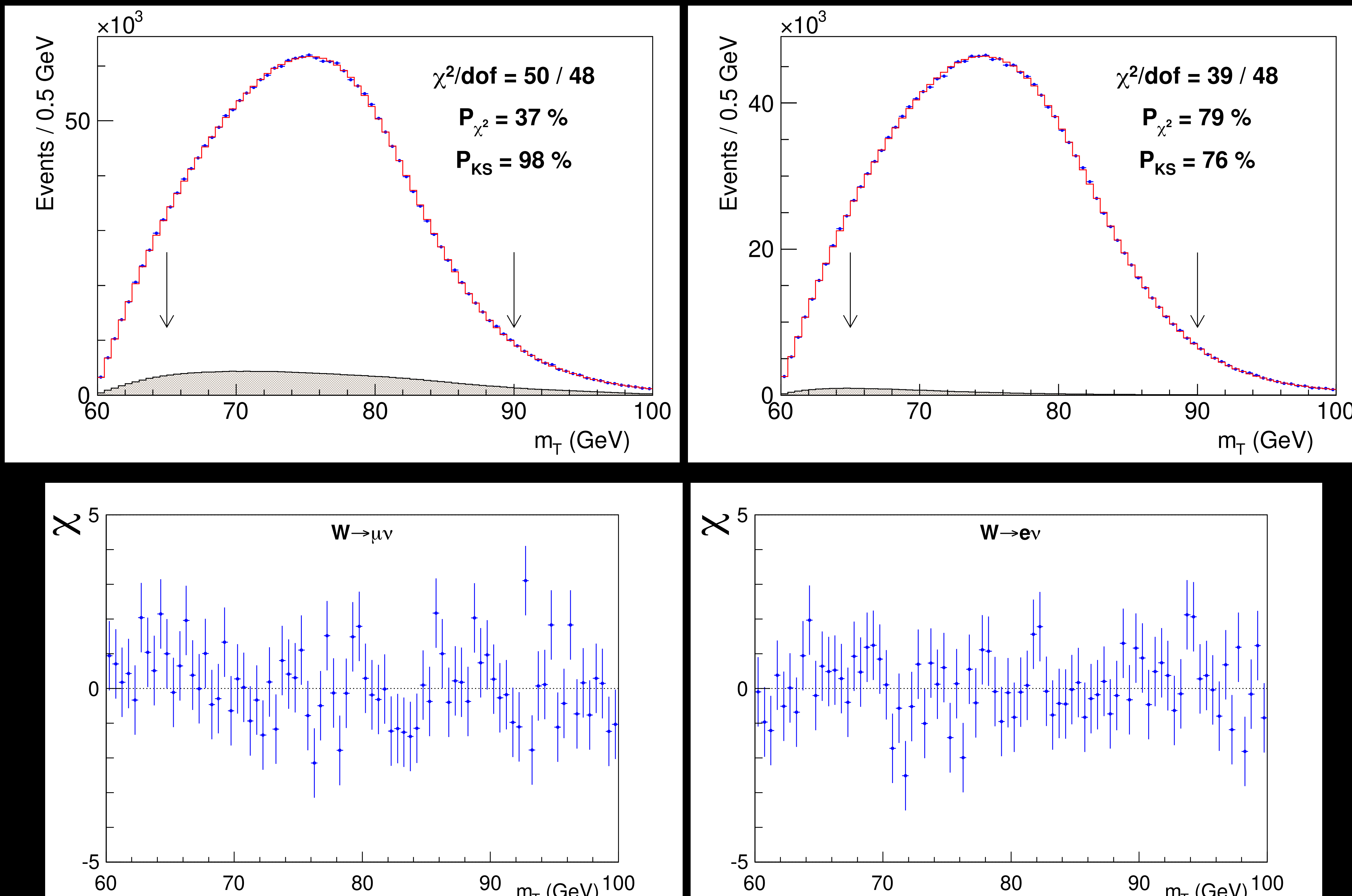
Three general NNLO PDF sets (NNPDF3.1, CT18, and MMHT14) have a range of ± 2.1 MeV from mean

Photos resummation with ME corrections used to model final-state photon radiation

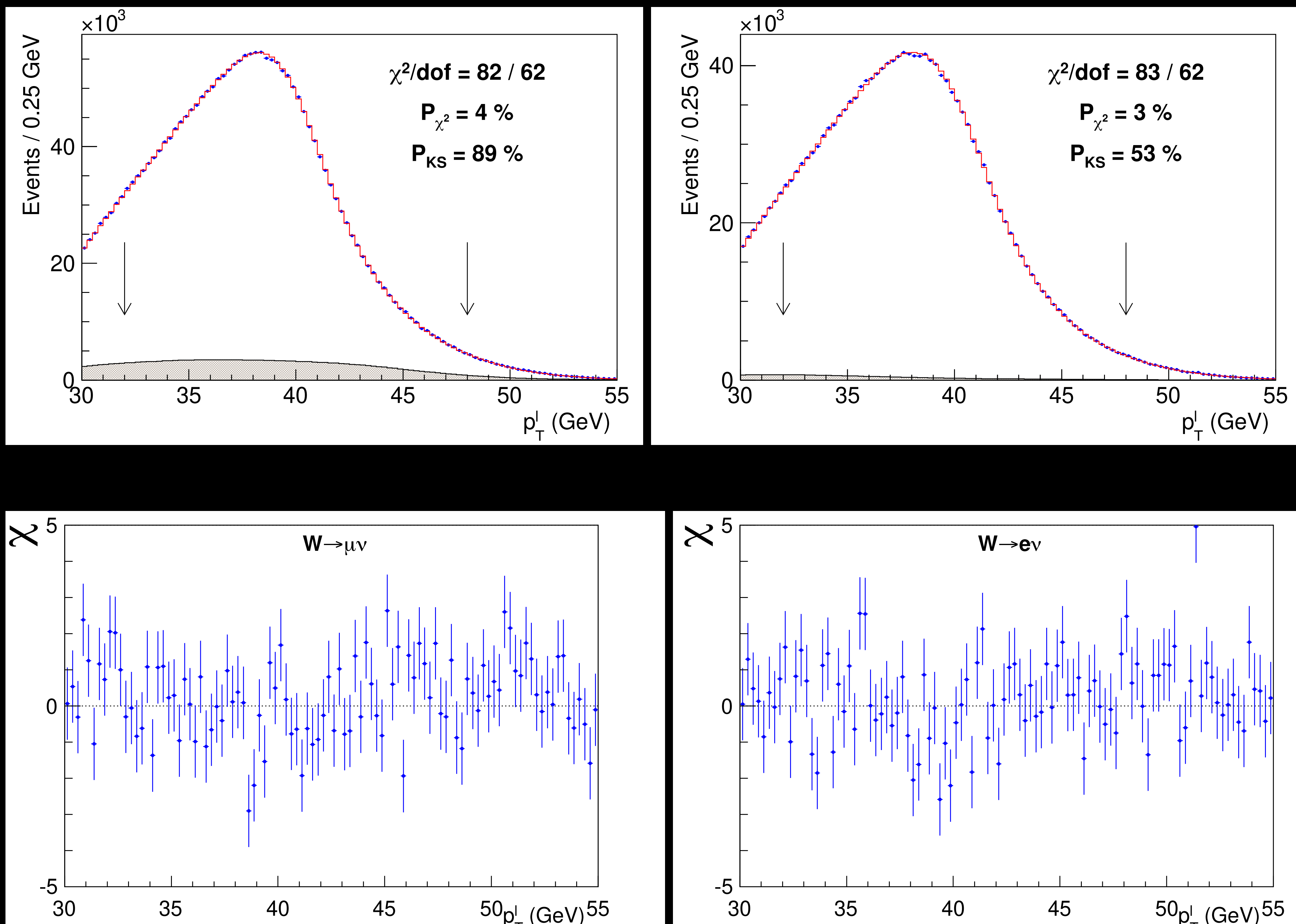
validated by studying the average radiation in EM towers around the charged lepton, and with the Z mass measurement

W boson mass measurement

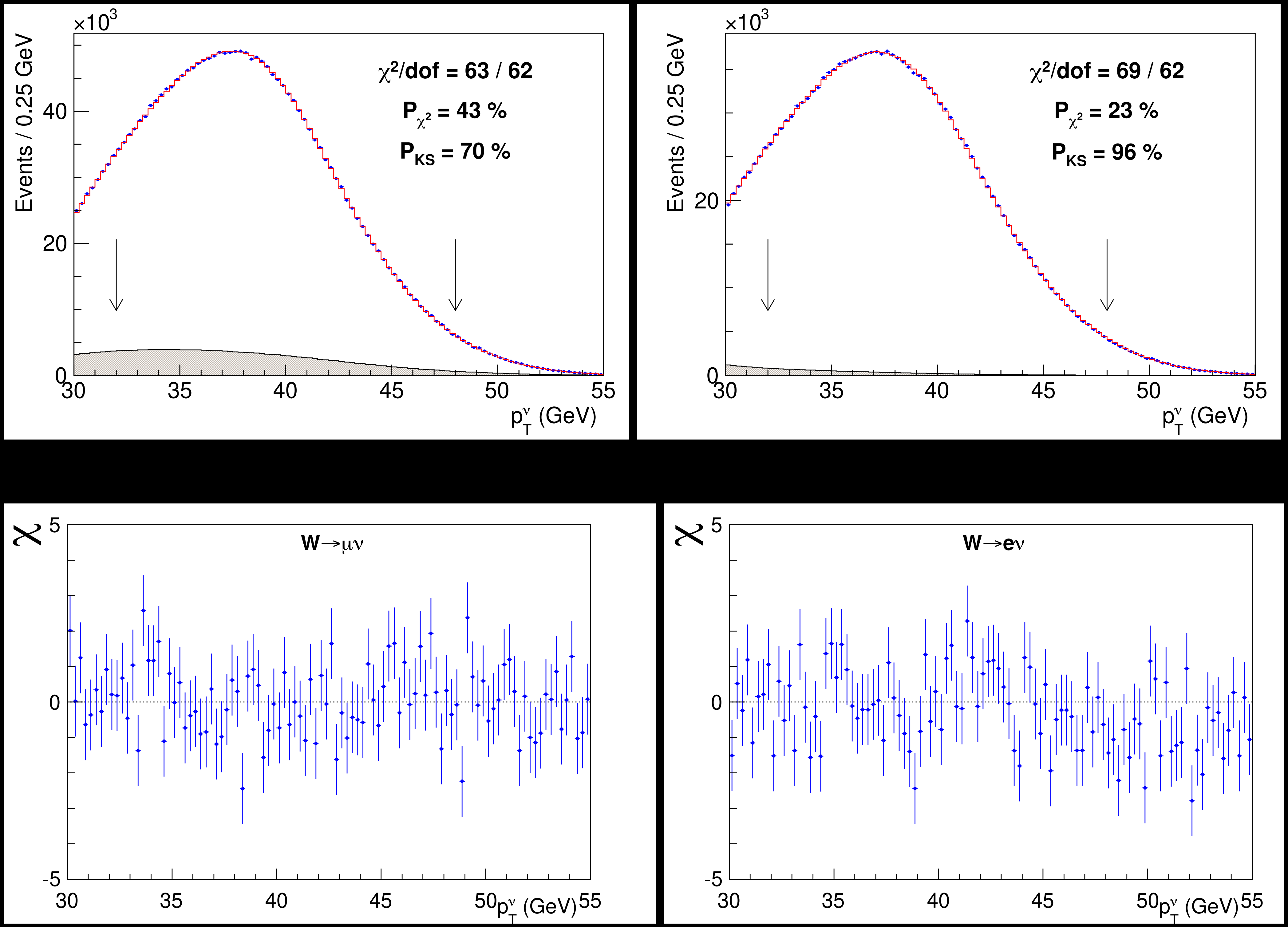
Result blinded by [-50,50] MeV offset until all previous steps complete



Mass measurement with p_T^ℓ distribution

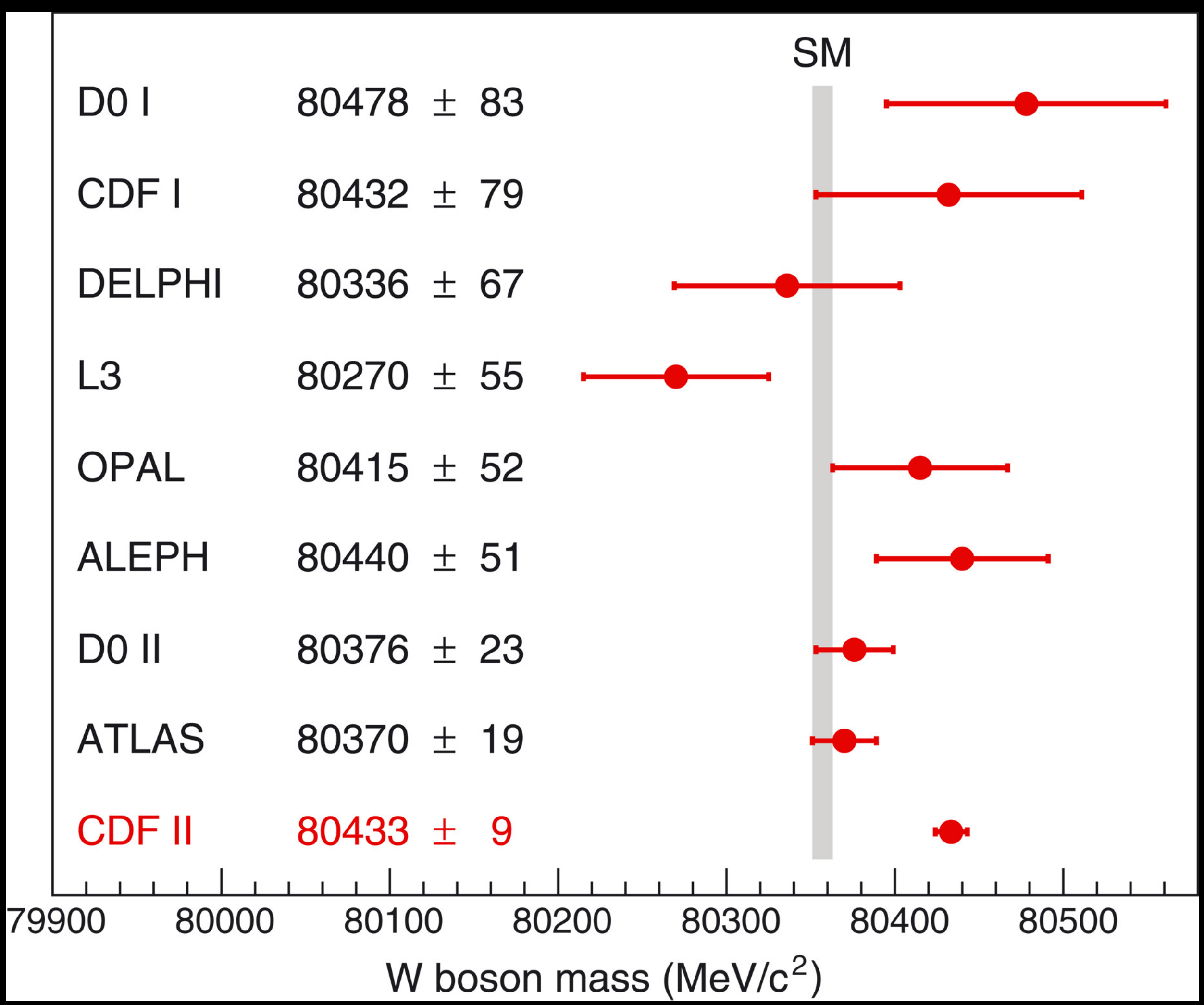


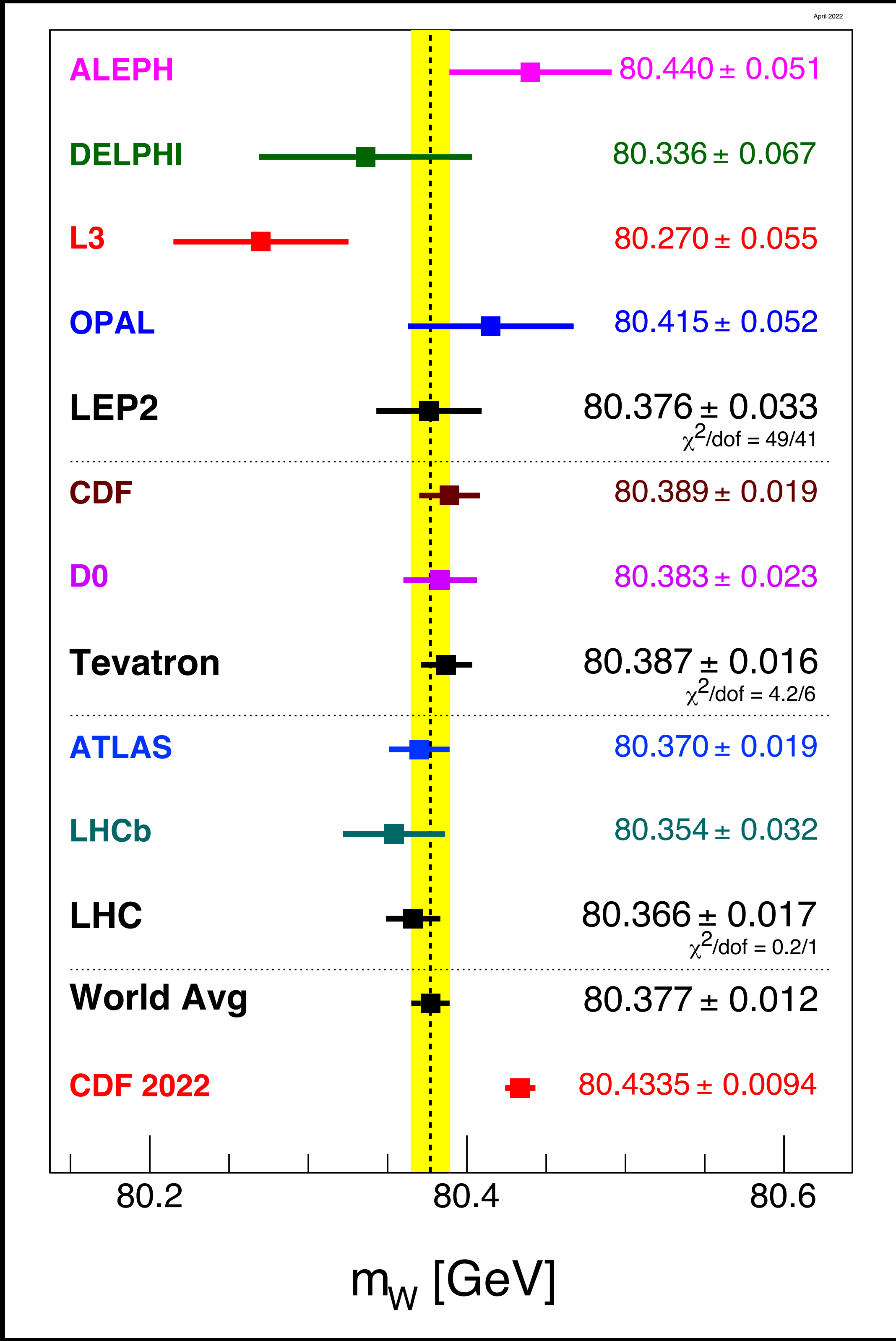
Mass measurement with p_T^ν distribution



W boson mass measurements

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





W boson mass measurements

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
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

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

Summary

The W boson mass is an important parameter in particle physics

Measurement of W boson mass with <10 MeV precision achieved with complete CDF data set

Result of >20 years of experience with the CDF II detector

0.01% precision required flexibility: all experimental aspects controlled by the analysis team
Reconstruction, alignment, calibration, simulation, analysis

Analysis procedures approved pre-unblinding and frozen

Surprising 0.1% deviation from SM motivates expanded study of m_W measurements and procedures

Future possibilities

Recoil tuning

Fine-tune calorimeter response corrections in data
Calibrate a shower Monte Carlo

Recoil validation

Compare W & Z & Υ response in events with a single lepton (remove any additional lepton)
Compare W & Z energy flows
Compare W & Z lepton removal energy distributions
Check electron removal towers for e^+ vs e^-, validate muons with nearby towers

Event generation

Generate events using a higher-order calculation
Validate p_T^W using high/low p_T^l asymmetry
Validate PDF using low p_T^l region and rapidity-dependent mass fits

Event selection

Vary lepton id (add isolation)

Analysis updates

Identify the effect of each analysis change in the muon channel

Luminosity & time dependence

Fit mass in subsets in time or luminosity
Perform pseudo-experiments to check KS probabilities

Muon resolution

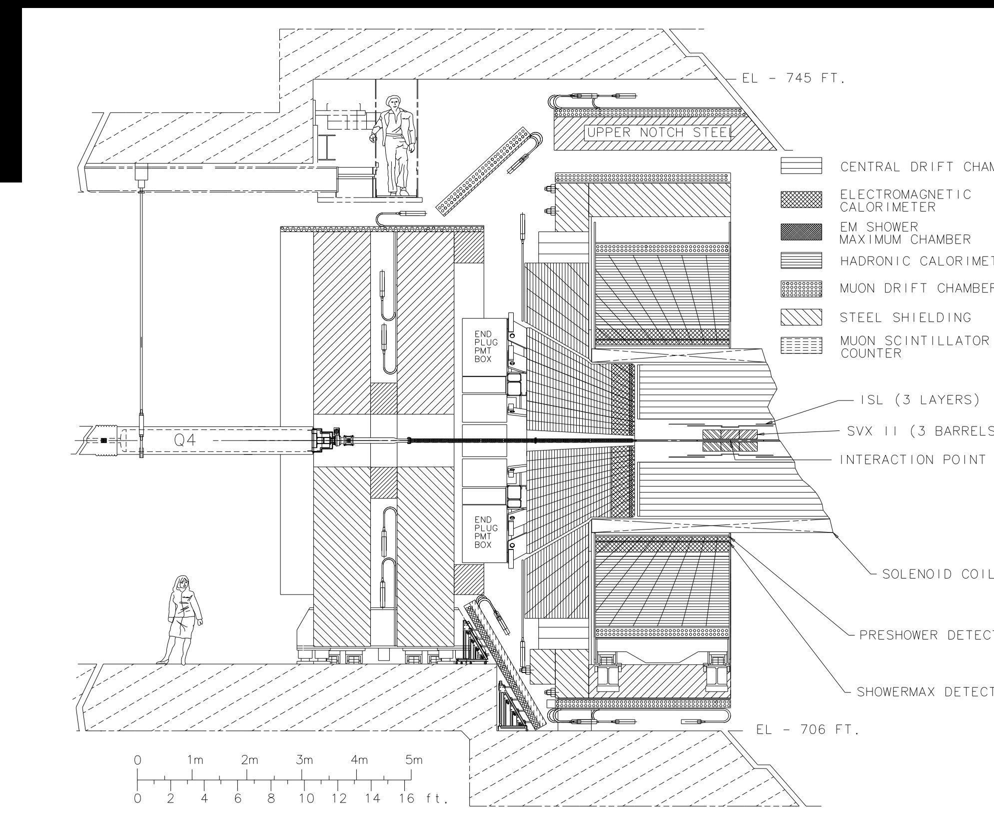
Implement beam spot size vs z and W vs Z z vertex distribution

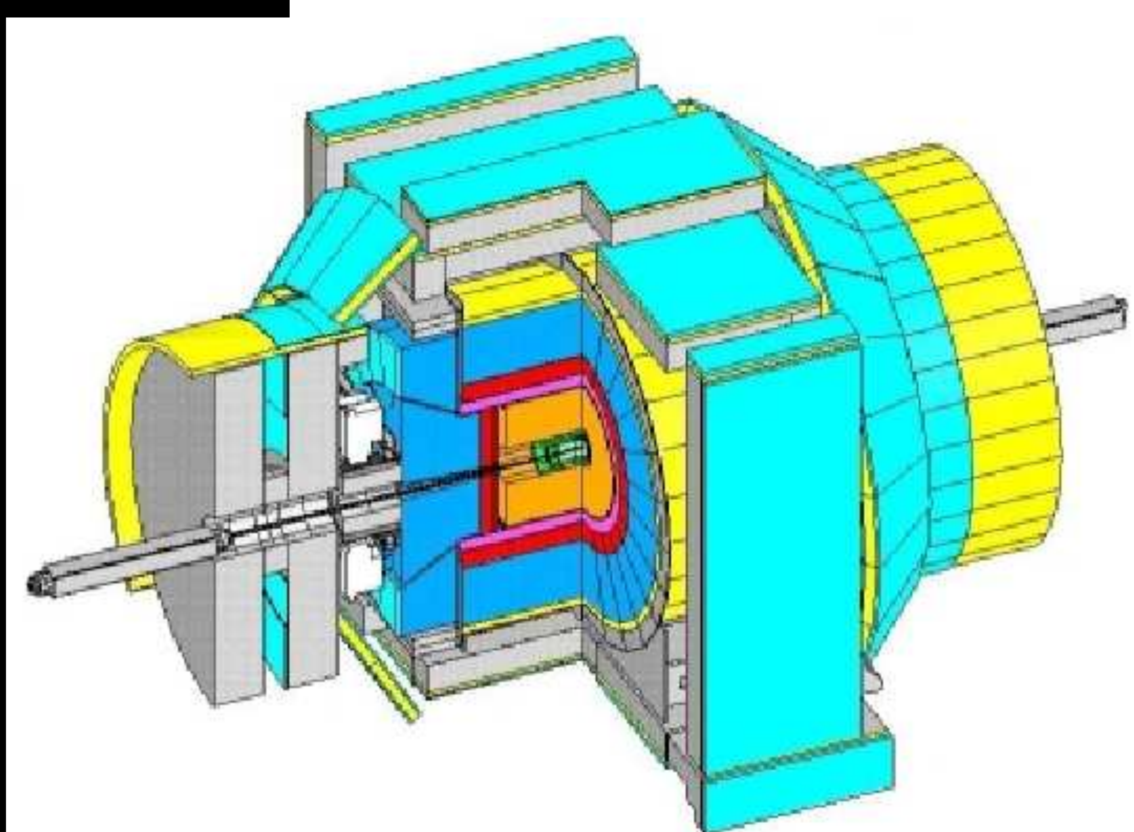
Uncertainties

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

Background fractions

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)



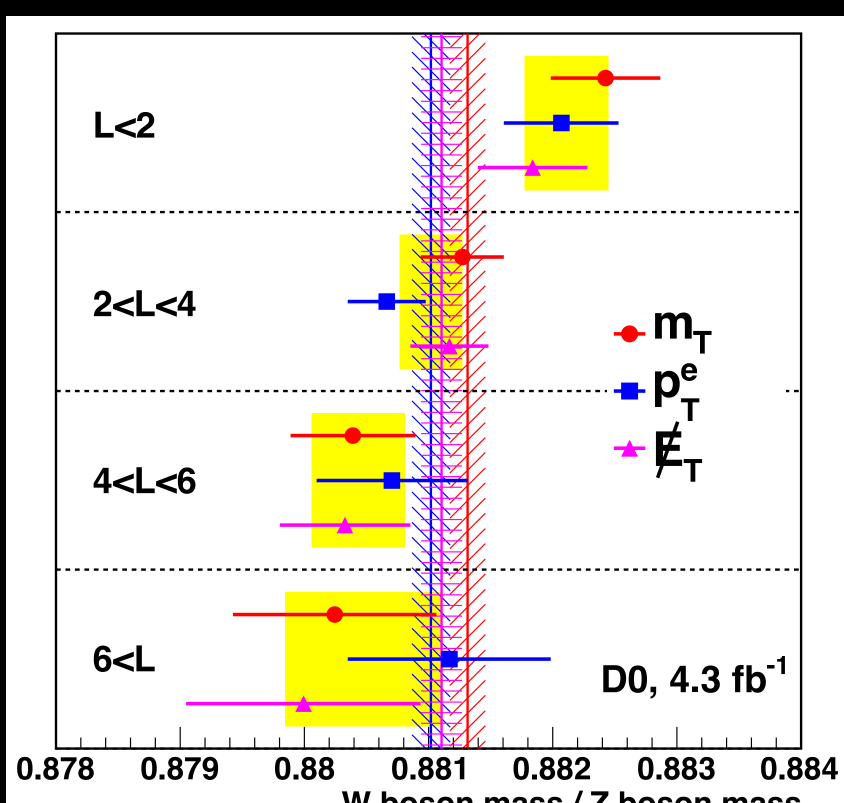


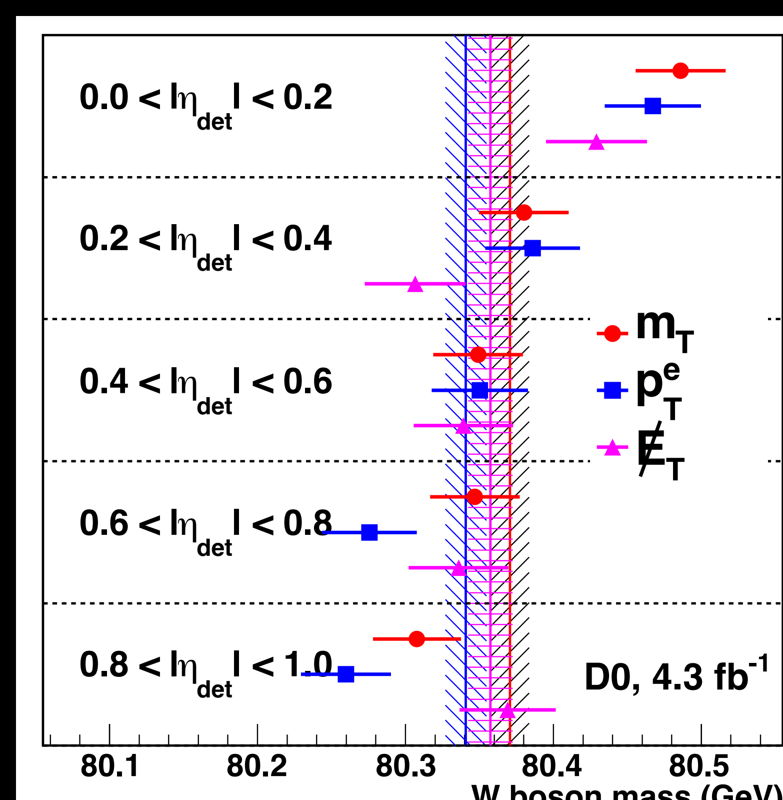
Source	Fraction (%)	δM_W (MeV) m_T fit	p_T^e fit	p_T^ν fit
$Z/\gamma^* \to ee$	0.134 ± 0.003	0.2 (0.3)	0.3 (0.0)	0.0 (0.6)
$W \to \tau\nu$	0.94 ± 0.01	0.6 (0.0)	0.6 (0.0)	0.6 (0.0)
Hadronic jets	0.34 ± 0.08	2.2 (1.2)	0.9 (6.5)	6.2 (-1.1)
Total	1.41 ± 0.08	2.3 (1.2)	1.1 (6.5)	6.2 (1.3)

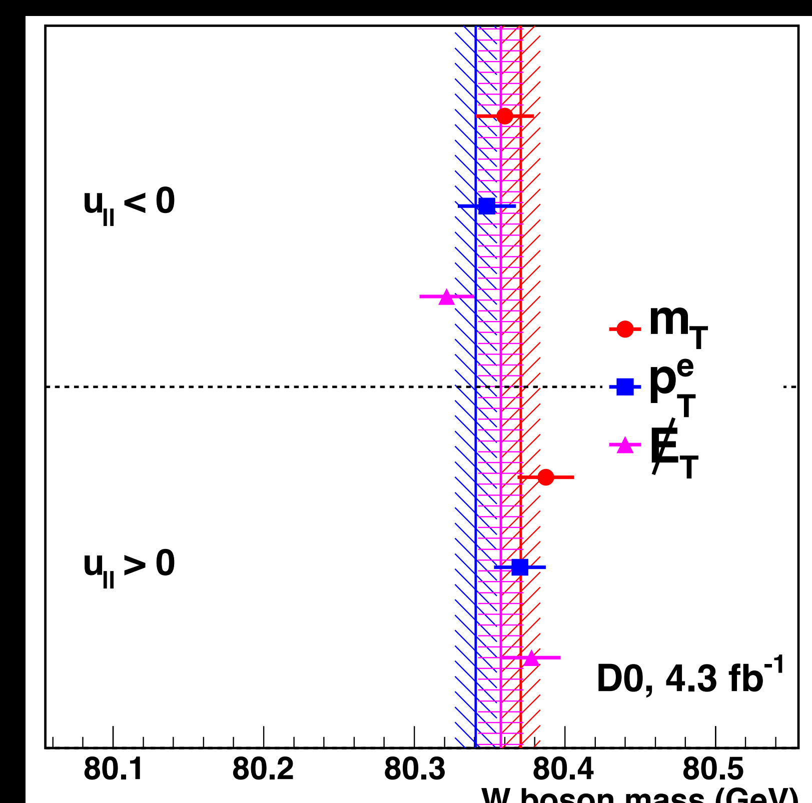
W boson mass measurements

Subset	$\chi^2_{\rm tot}/{\rm ndf}$	δm_W [MeV]
Polarity $= -1$	92.5/102	–
Polarity $= +1$	97.3/102	-57.5 ± 45.4
$\eta > 3.3$	115.4/102	–
$\eta < 3.3$	85.9/102	$+56.9 \pm 45.5$
Polarity $\times\, q = +1$	95.9/102	–
Polarity $\times\, q = -1$	98.2/102	$+16.1 \pm 45.4$
$\lvert\phi\rvert > \pi/2$	98.8/102	–
$\lvert\phi\rvert < \pi/2$	115.0/102	$+66.7 \pm 45.5$
$\phi < 0$	91.8/102	–
$\phi > 0$	103.0/102	-100.5 ± 45.3

LHCb



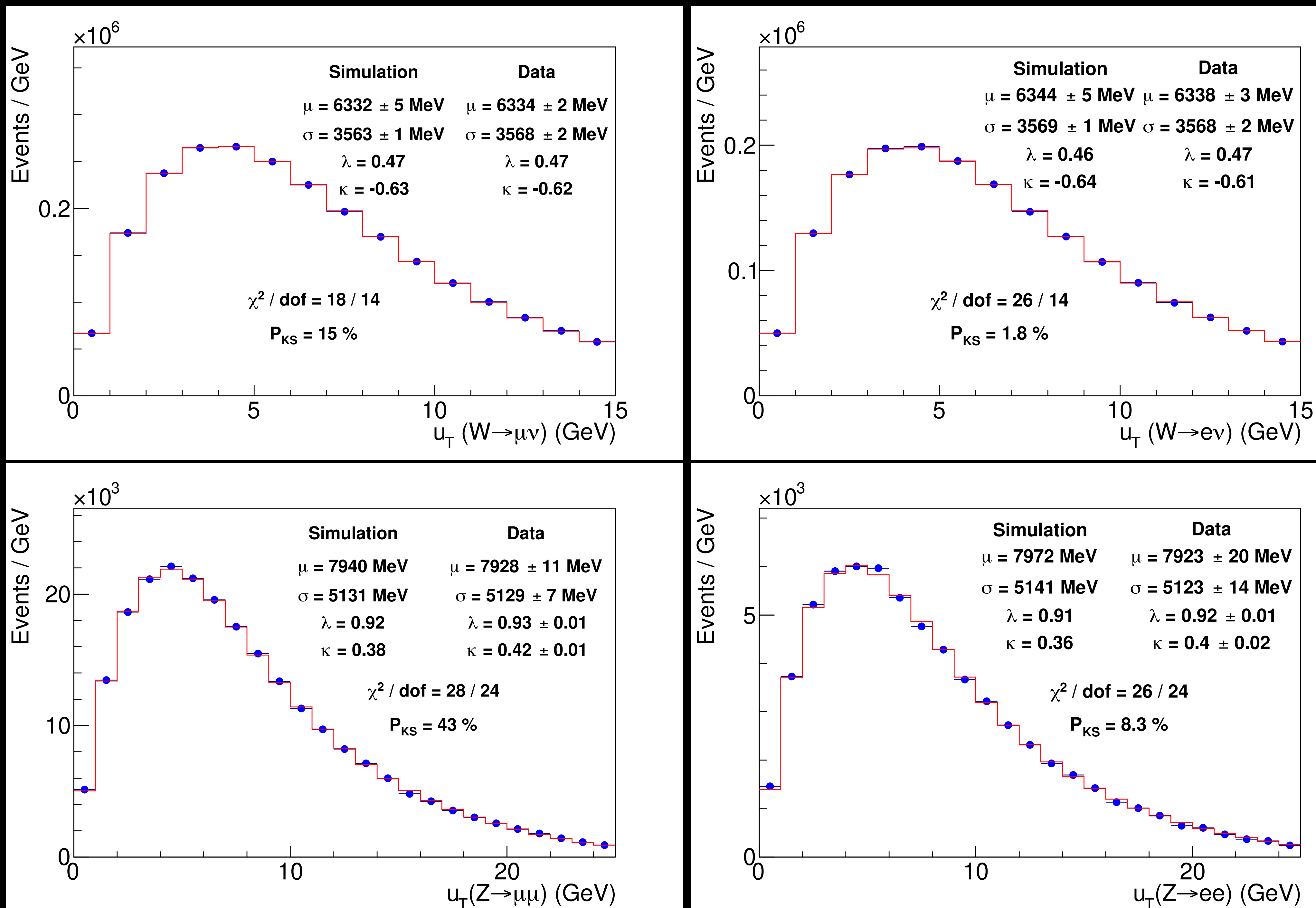




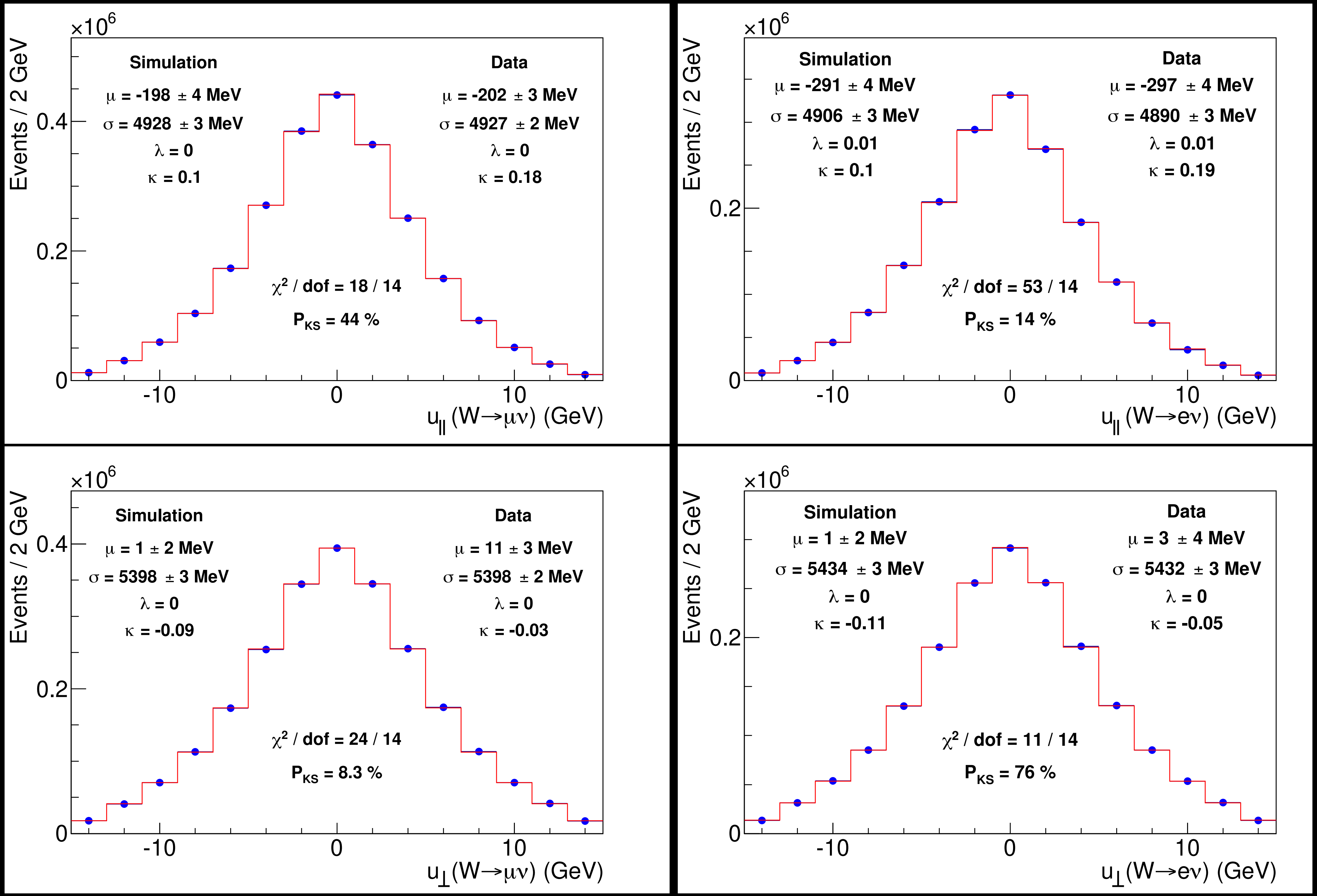
Initial state LO & NLO

W^+ initial	Type	Pythia LO	Madgraph LO	Madgraph NLO
u dbar	v-v	81.7%	82.0%	82.7%
dbar u	s-s	8.9%	9.0%	8.8%
u sbar	v-s	1.6%	1.9%	1.8%
sbar u	s-s	0.3%	0.3%	0.3%
c sbar	s-s	2.9%	2.9%	-
sbar c	s-s	2.9%	2.9%	-
c dbar	s-v	0.7%	0.7%	-
dbar c	s-s	0.2%	0.2%	-
u g	v-g		-	3.7%
g dbar	g-v		-	1.8%
g u	g-s		-	0.4%
dbar g	s-g		-	0.5%
g sbar	g-s		-	0.02%
sbar g	s-g		-	0.02%

Recoil in W & Z events

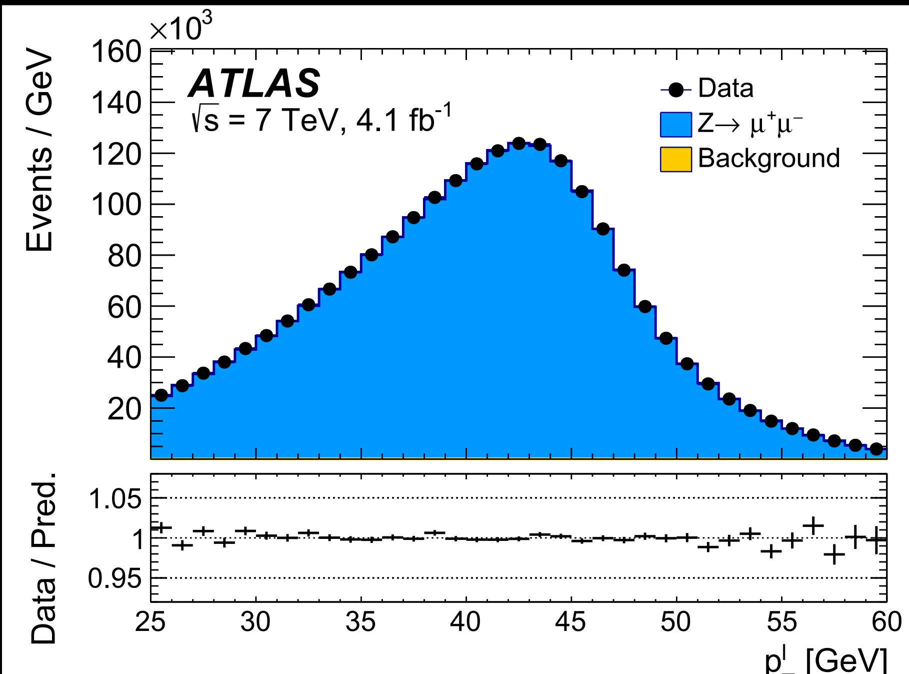


Recoil projections in W events

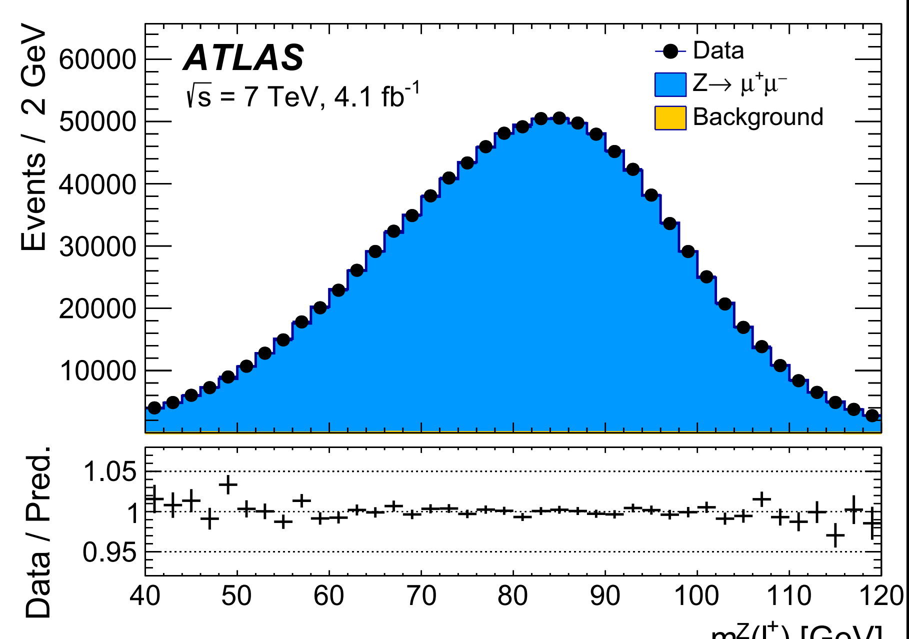


Recoil momentum validation

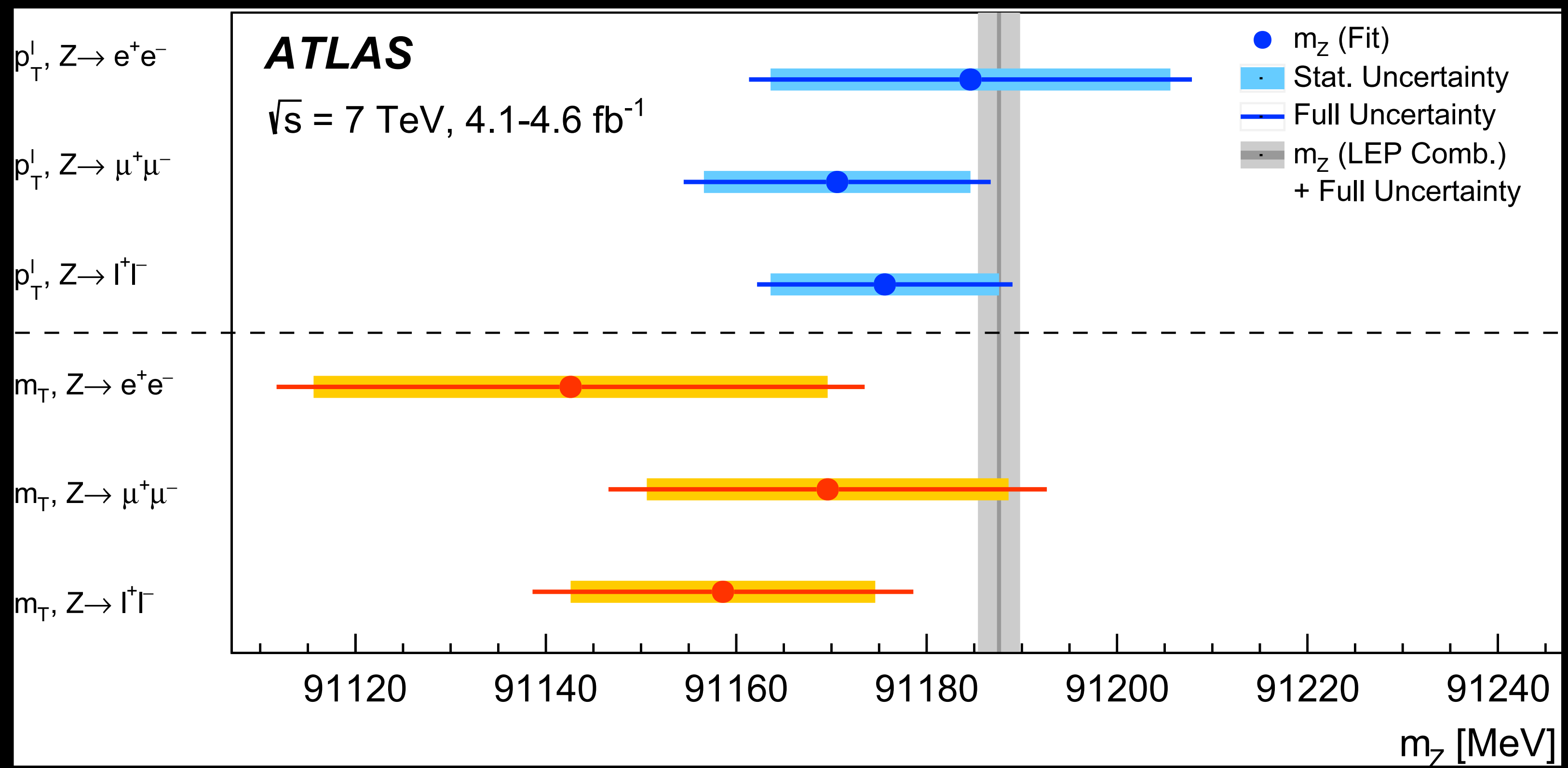
ATLAS validates the recoil model with single-lepton Z boson mass measurements



(b)



(d)

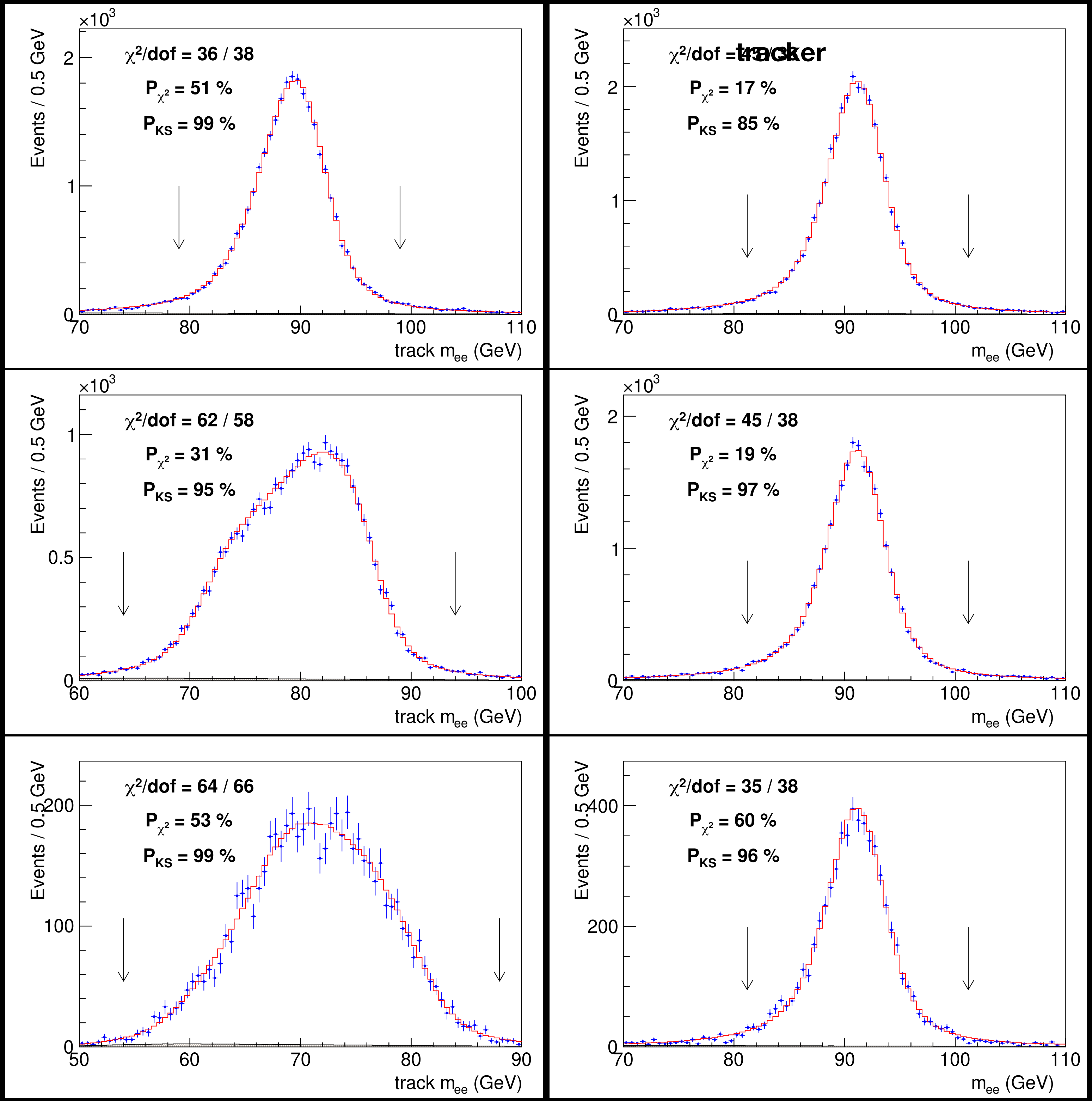


Lepton charge	ℓ^+		ℓ^-		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
Δm_Z [MeV]						
$Z \to ee$	$13 \pm 31 \pm 10$	$-93 \pm 38 \pm 15$	$-20 \pm 31 \pm 10$	$4 \pm 38 \pm 15$	$-3 \pm 21 \pm 10$	$-45 \pm 27 \pm 15$
$Z \to \mu\mu$	$1 \pm 22 \pm 8$	$-35 \pm 28 \pm 13$	$-36 \pm 22 \pm 8$	$-1 \pm 27 \pm 13$	$-17 \pm 14 \pm 8$	$-18 \pm 19 \pm 13$
Combined	$5 \pm 18 \pm 6$	$-58 \pm 23 \pm 12$	$-31 \pm 18 \pm 6$	$1 \pm 22 \pm 12$	$-12 \pm 12 \pm 6$	$-29 \pm 16 \pm 12$

Recoil model parameters

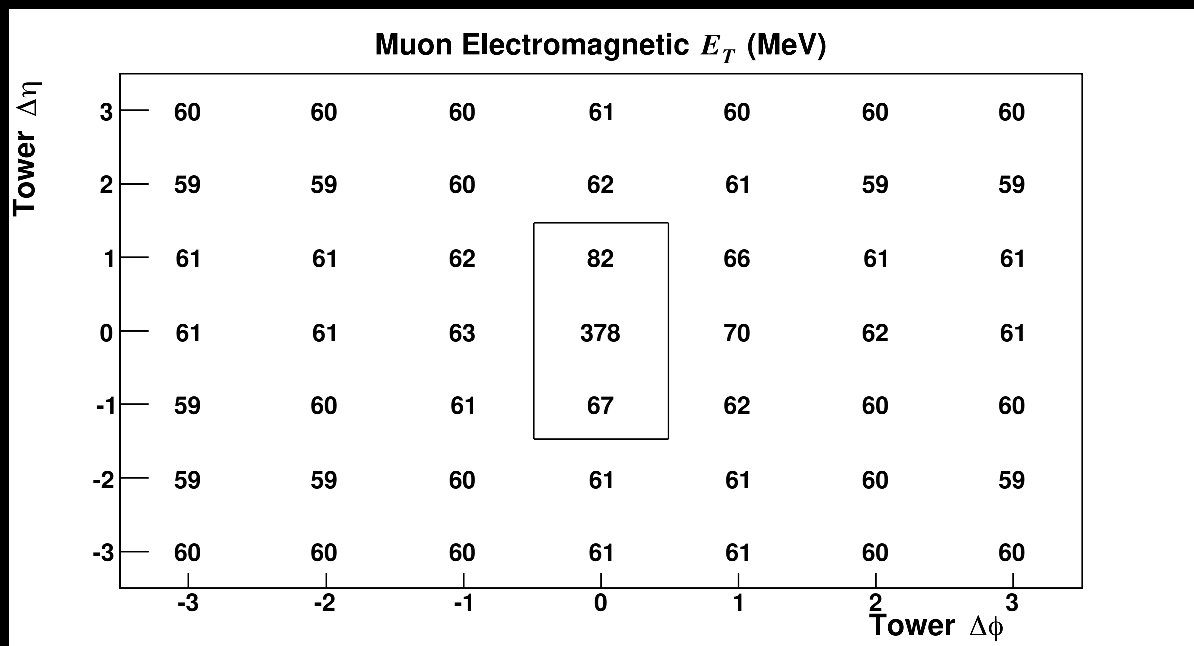
Parameter	Description	Source	m_T	p_T^ℓ	p_T^ν
a	average response	Fig. S23	−1.6	−2.9	−0.2
b	response non-linearity	Fig. S23	−0.8	−2.0	0.7
Response			1.8	3.5	0.7
N_V	spectator interactions	Fig. S24	0.5	−3.2	3.6
$s_{\rm had}$	sampling resolution	Fig. S24	0.3	0.3	0.8
$f_{\pi^0}^4$	EM fluctuations at low u_T	Fig. S25	−0.3	−0.2	−1.0
$f_{\pi^0}^{15}$	EM fluctuations at high u_T	Fig. S25	−0.3	−0.3	−0.2
α	angular resolution at low u_T	Fig. S26	1.4	0.1	2.5
β	angular resolution at intermediate u_T	Fig. S26	0.2	0.1	0.7
γ	angular resolution at high u_T	Fig. S26	0.3	0.3	0.7
f_2^a	average dijet component	Fig. S27	0.1	−1.1	0.8
f_2^s	variation of dijet component with u_T	Fig. S27	−0.1	−0.2	−0.1
k_ξ	average dijet resolution	Fig. S28	−0.1	0.1	−0.3
δ_ξ	fluctuations in dijet resolution	Fig. S28	−0.2	0.2	−1.1
A_ξ	higher-order term in dijet resolution	Fig. S28	0.1	−1.0	0.7
μ_ξ	—"—	Fig. S28	−0.5	−0.4	−0.9
ϵ_ξ	—"—	Fig. S28	0.1	−0.2	0.4
S_ξ^+	—"—	Fig. S28	0.5	−0.4	1.4
S_ξ^-	—"—	Fig. S28	−0.3	−0.2	−0.5
q_ξ	—"—	Fig. S28	−0.2	0.0	0.2
Resolution			1.8	3.6	5.2

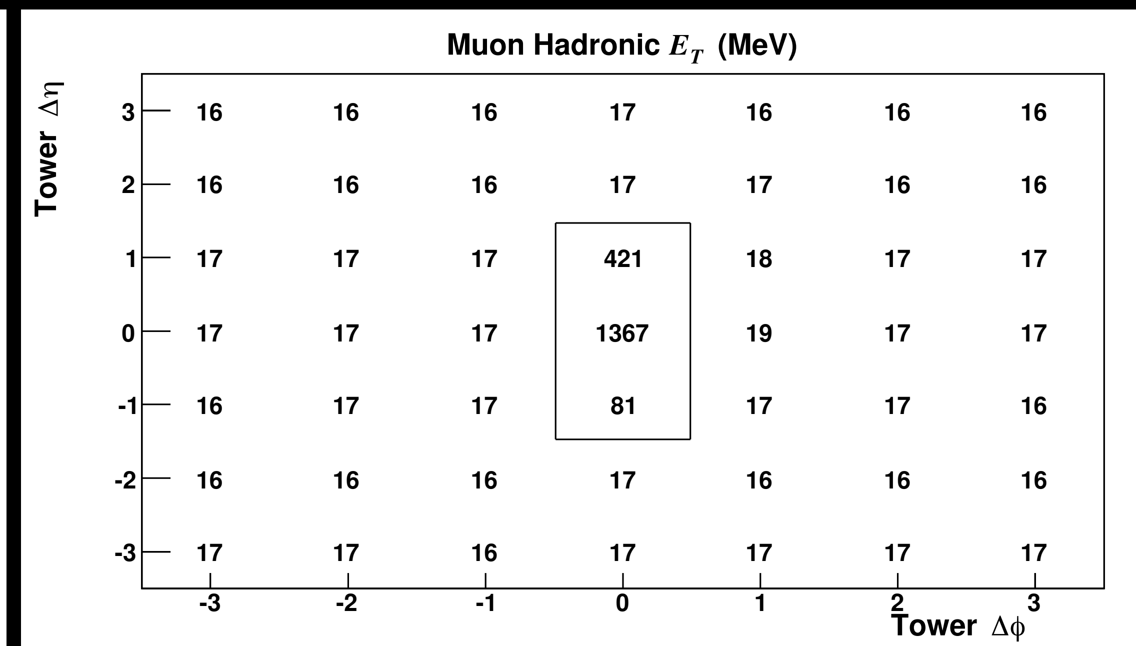
Z mass fits using tracker or calorimeter

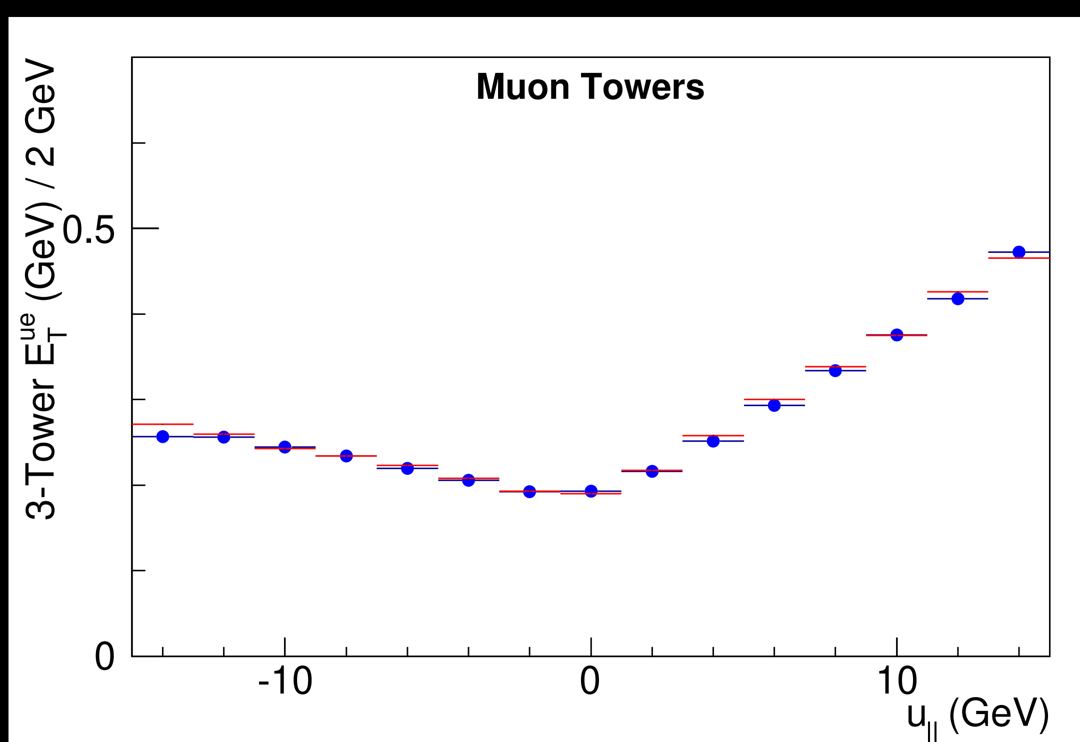


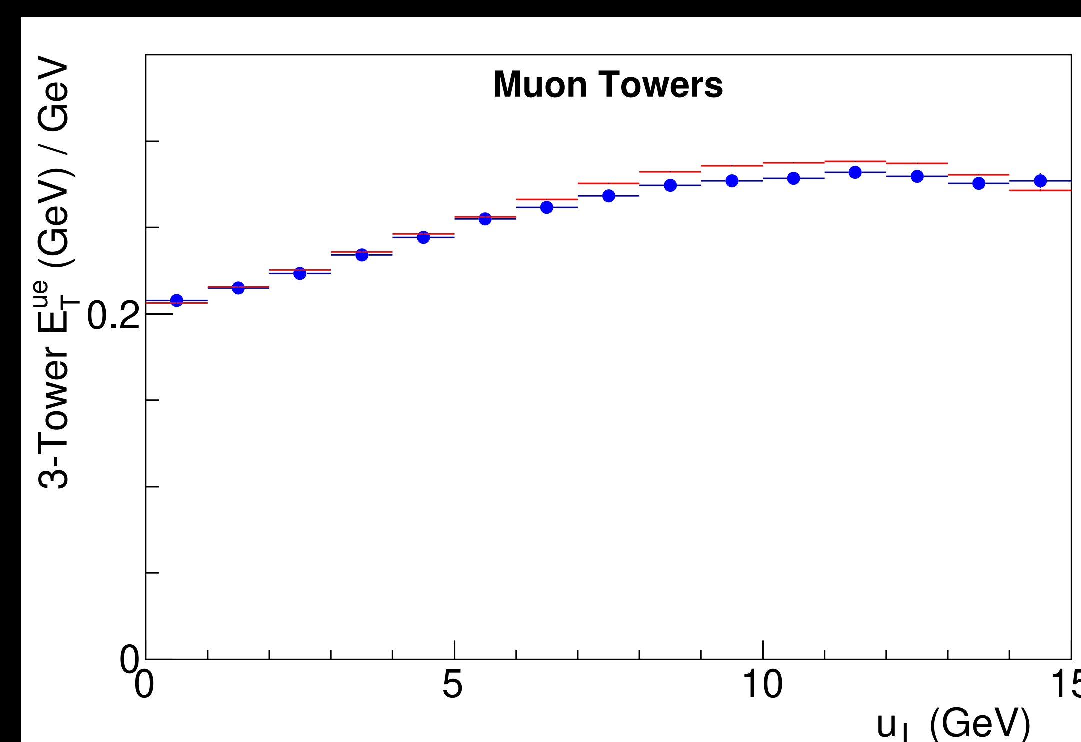
Electrons	Calorimeter	Track
$E/p < 1.1$ only	$91\,190.9 \pm 19.7$	$91\,215.2 \pm 22.4$
$E/p > 1.1$ and $E/p < 1.1$	$91\,201.1 \pm 21.5$	$91\,259.9 \pm 39.0$
$E/p > 1.1$ only	$91\,184.5 \pm 46.4$	$91\,167.7 \pm 109.9$

Recoil reconstruction in muon channel







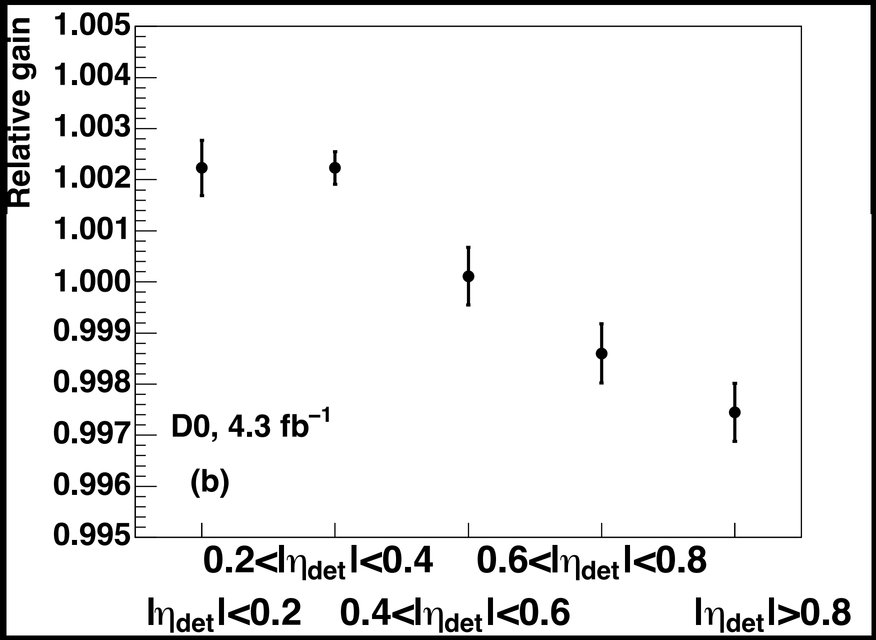


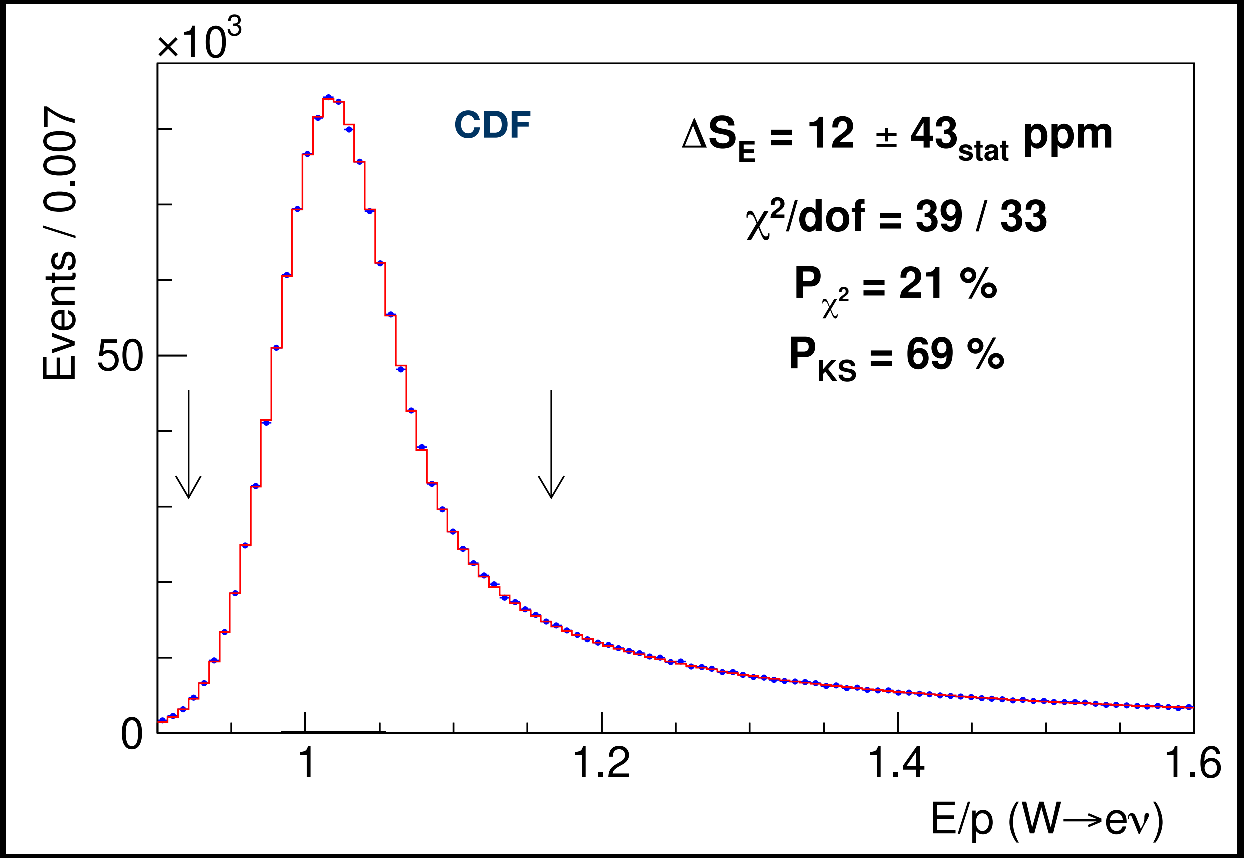
Electron momentum calibration

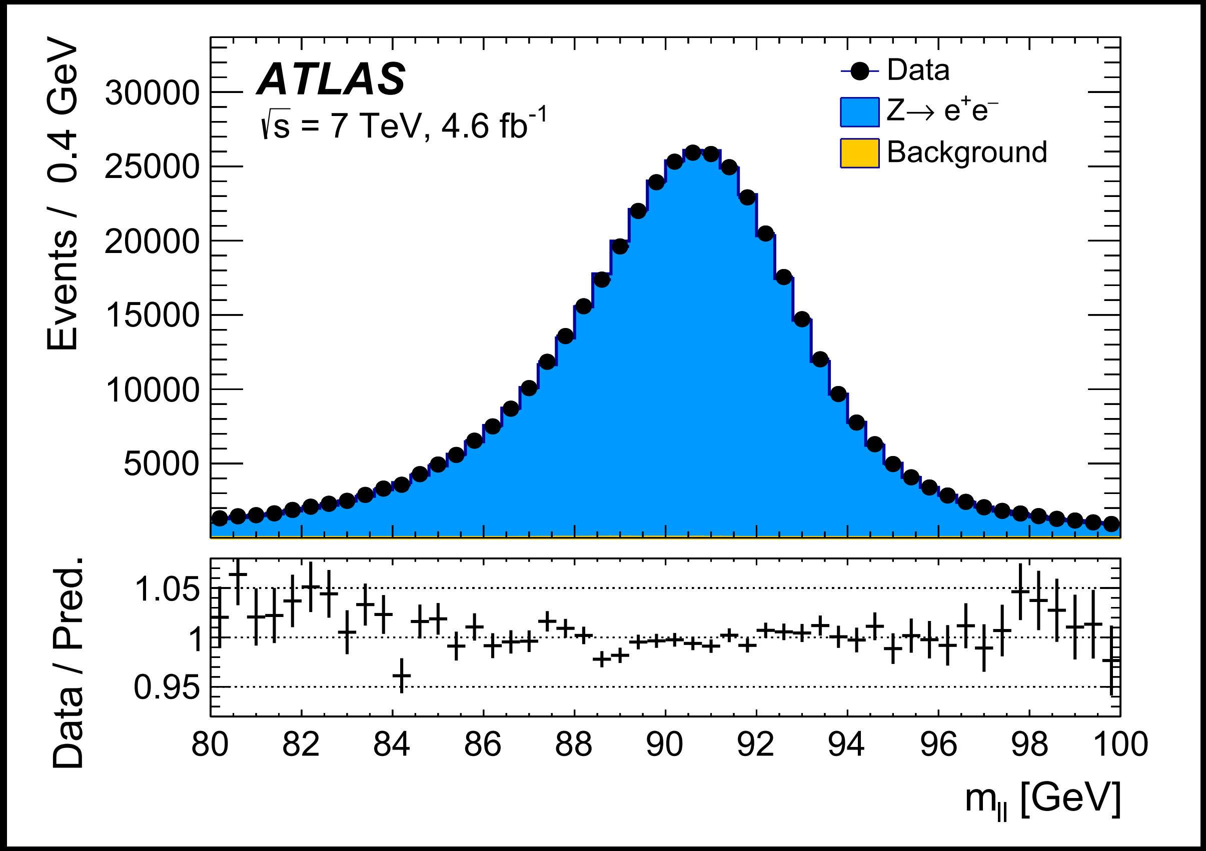
Third step is to calibrate the response

CDF: Transfer track momentum calibration to calorimeter using (E/p) distribution, combine with calibration from $Z \to ee$ decays

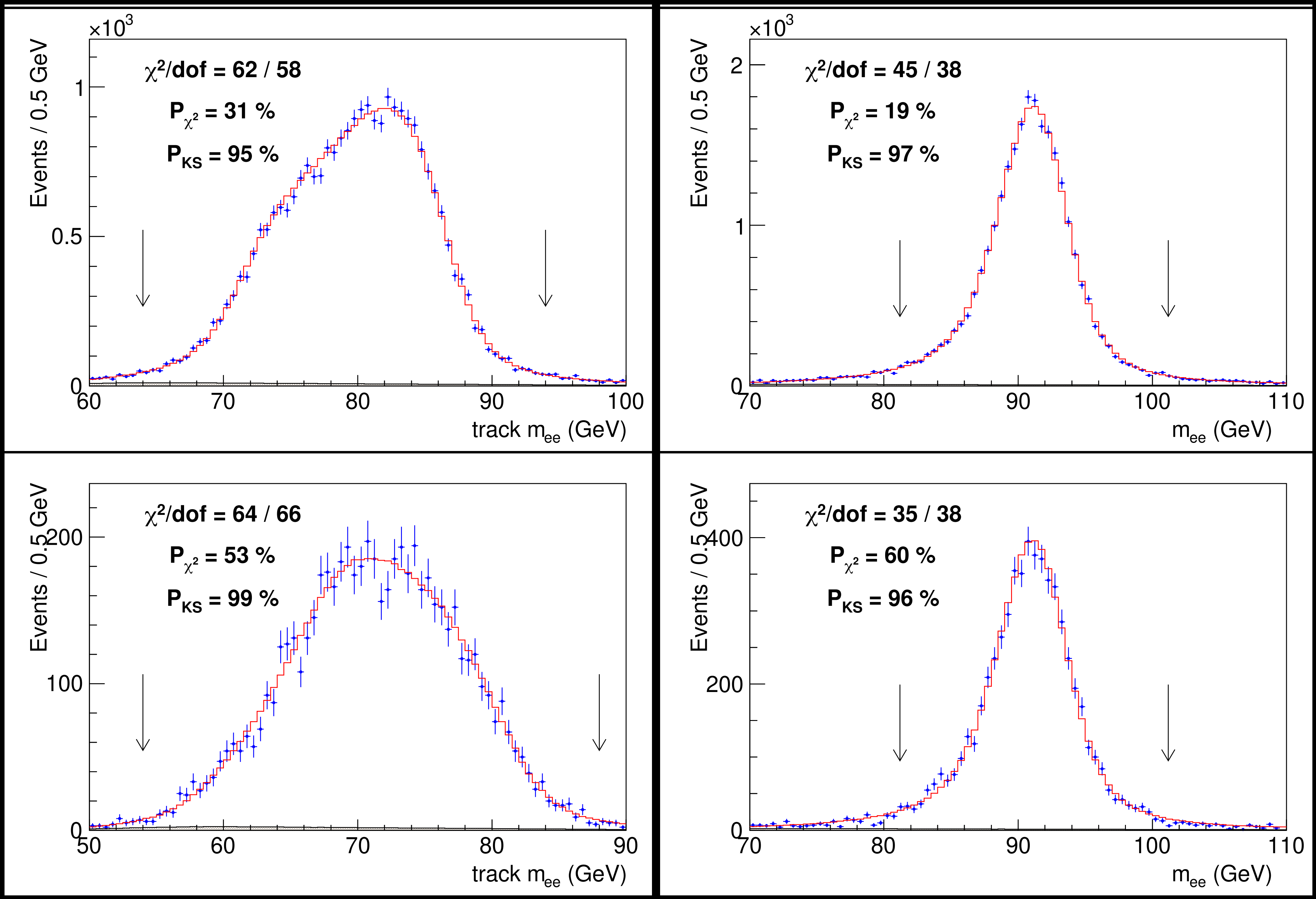
ATLAS & D0: Calibrate energy as a function of pseudorapidity using $Z \to ee$ decays







Electron momentum calibration



Muon momentum calibration

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

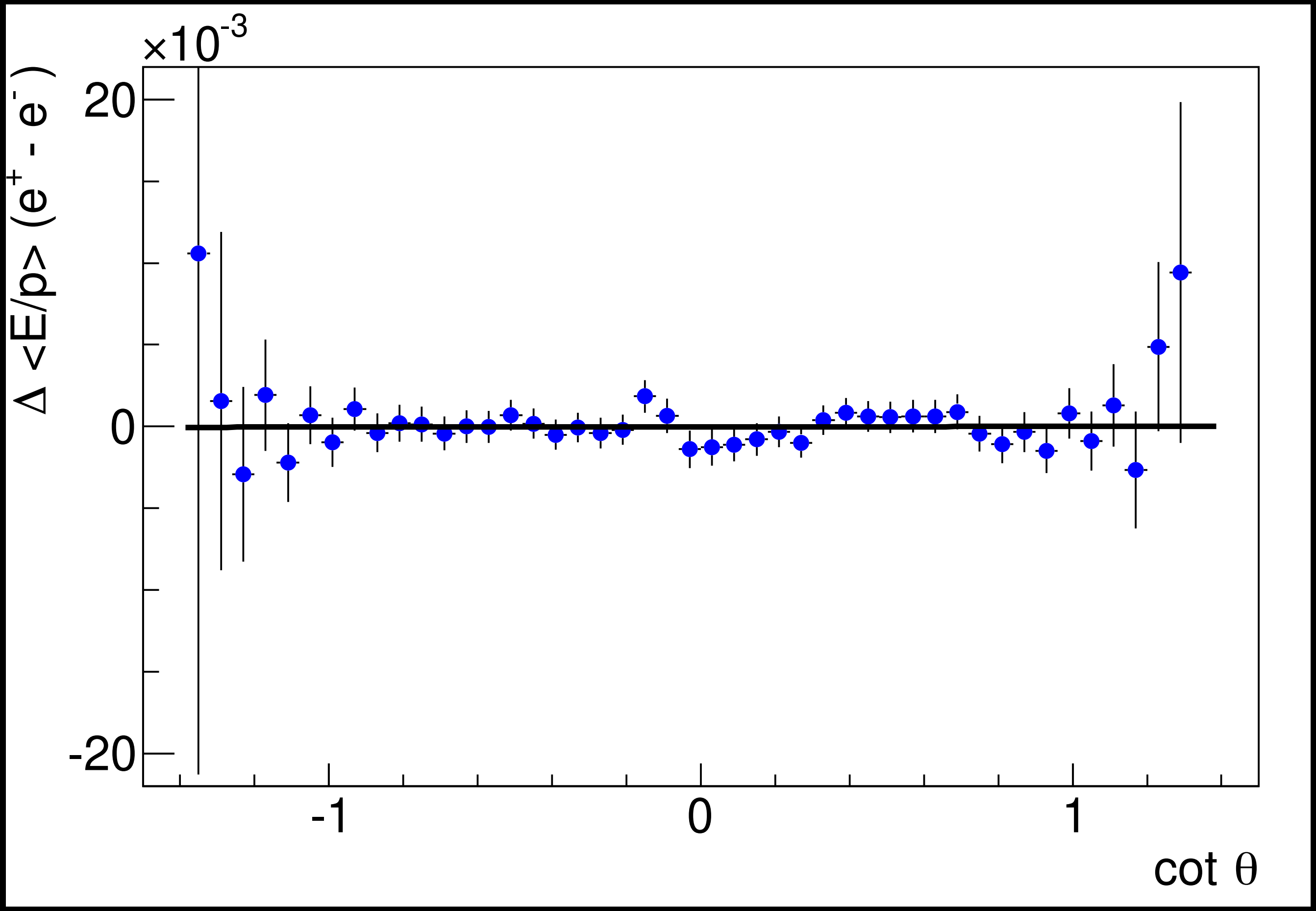
Track momentum calibration

Residual tracker misalignments studied using difference in E/p between electrons and positrons

Correction as a function of polar angle applied to measured tracks from W and Z decays

Linear dependence on cot theta would cause a bias in the m_W mass fit

No linear correction required, statistical precision from E/p constrains the bias to <0.8 MeV



Measurement updates

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

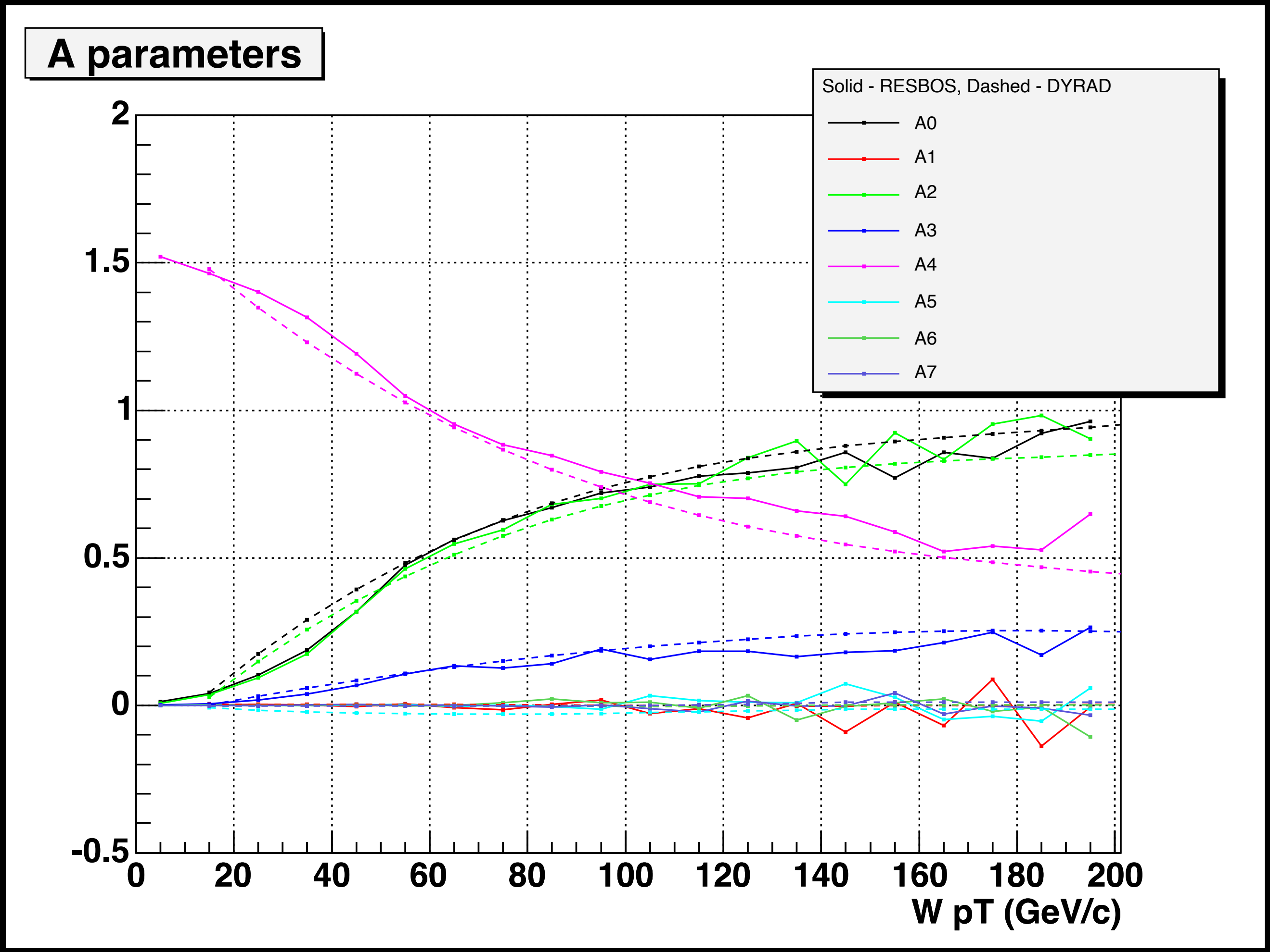
W boson mass fit results

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

Distribution	M_W (MeV)	χ^2/d.o.f.
$W \to e\nu$		
m_T	80408 ± 19	52/48
p_T^ℓ	80393 ± 21	60/62
p_T^ν	80431 ± 25	71/62
$W \to \mu\nu$		
m_T	80379 ± 16	57/48
p_T^ℓ	80348 ± 18	58/62
p_T^ν	80406 ± 22	82/62

Angular coefficients in decay

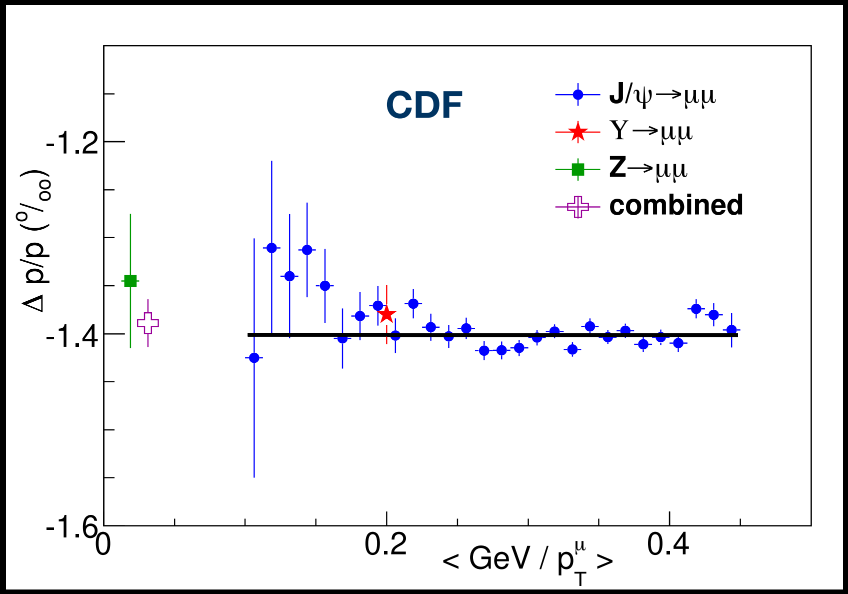
$$\frac{d^4\sigma}{dQ_T^2\,dy\,d\phi\,d(\cos\theta)} = \frac{3}{16\pi}\frac{d^2\sigma}{dQ_T^2\,dy}\times\Big[(1+\cos^2\theta)+ \frac{A_0}{2}(1-3\cos^2\theta) - A_1 Q\sin 2\theta\cos\phi + \frac{A_2}{2}\sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi - A_4 Q\cos\theta + A_5\sin^2\theta\sin 2\phi - A_6 Q\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi\Big]$$



I Vollrath thesis (2006)

Muon momentum calibration

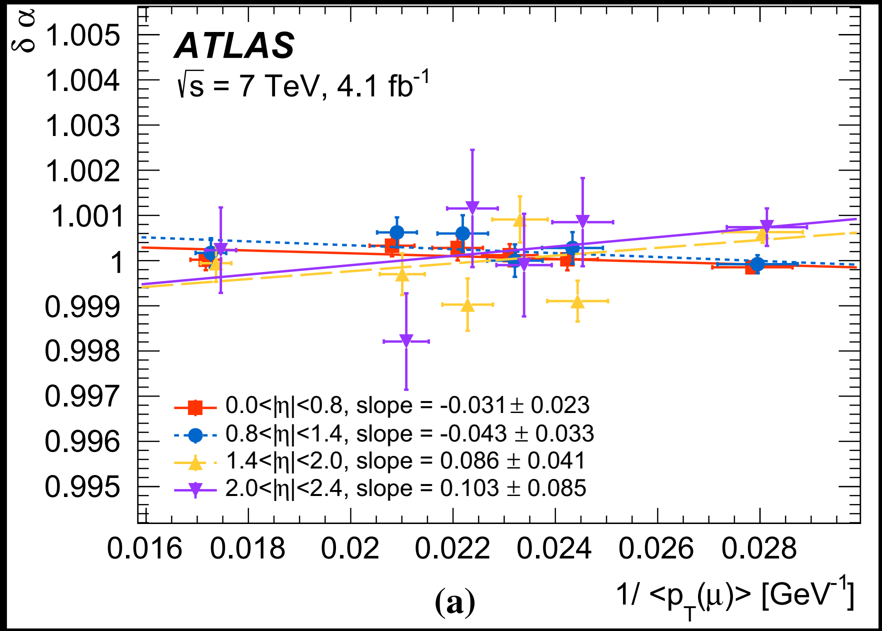
Third step is to calibrate the momentum scale using J/ψ, Υ, and Z decays to muons



CDF: Calibration uses all three resonances and includes a measurement of the Z mass prior to combining

ATLAS: Calibration uses the Z resonance in bins of pseudorapidity and azimuthal angle

$$p_{\mathrm{T}}^{\mathrm{MC,corr}} = p_{\mathrm{T}}^{\mathrm{MC}} \times [1 + \alpha(\eta, \phi)] \times \left[1 + \beta_{\mathrm{curv}}(\eta) \cdot G(0,1) \cdot p_{\mathrm{T}}^{\mathrm{MC}}\right]$$



LHCb: Calibration uses all three resonances