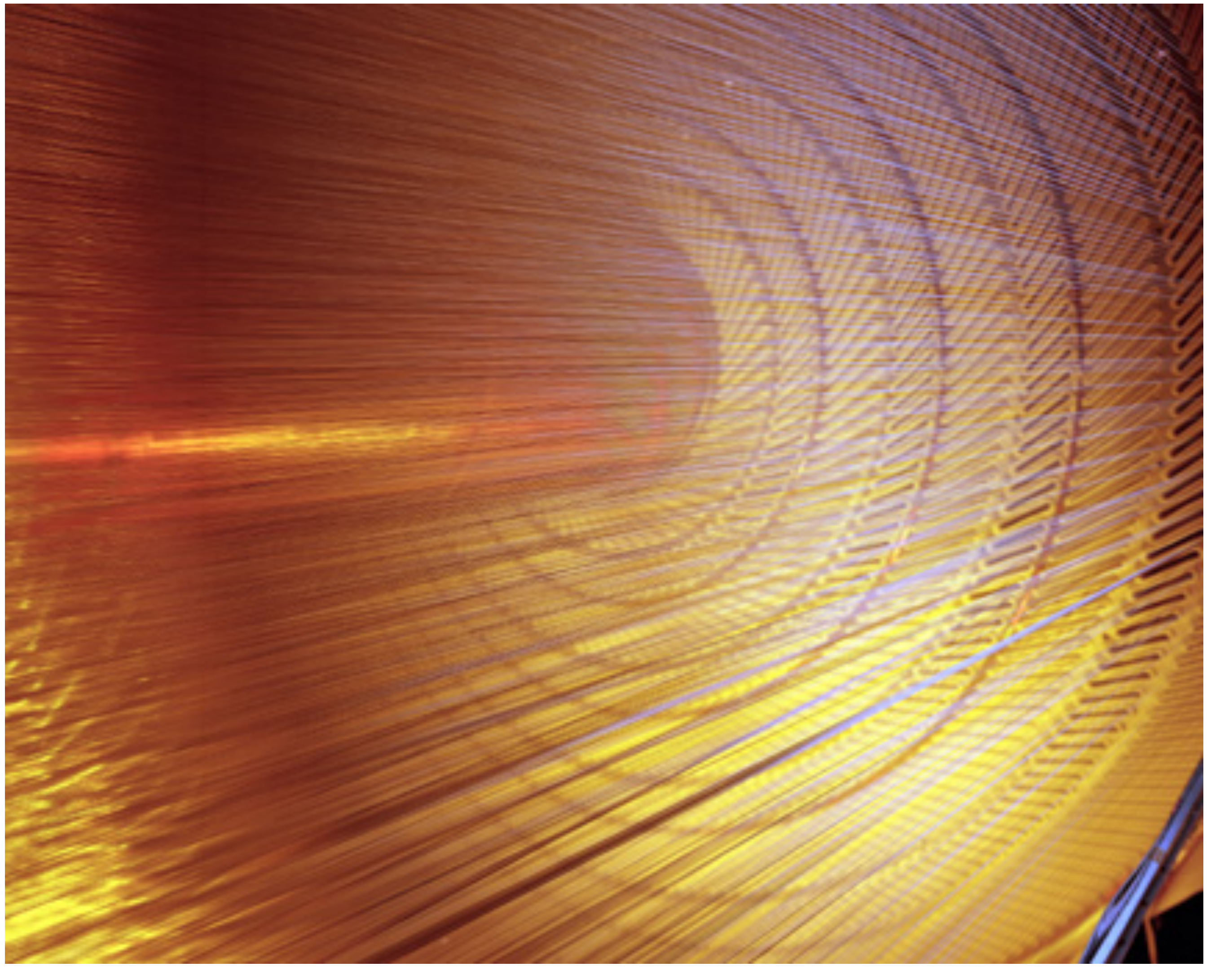
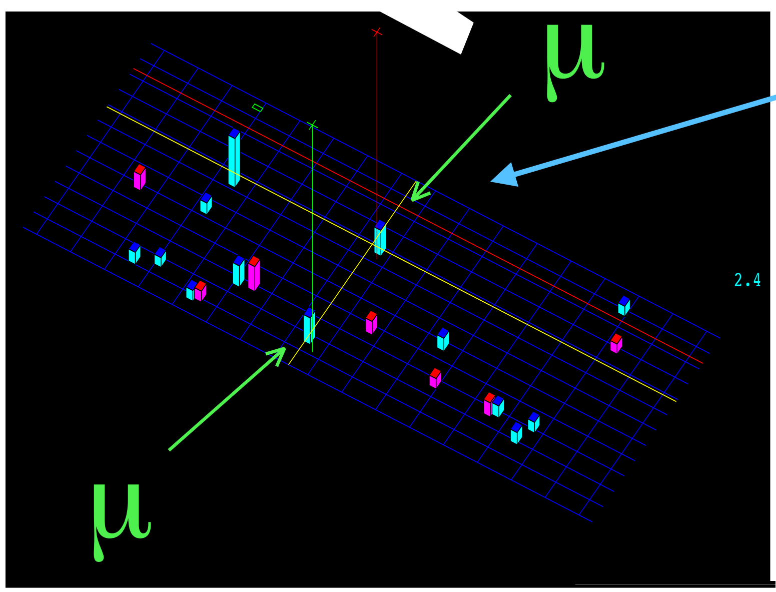
High precision measurement of the W boson mass with the CDF II detector



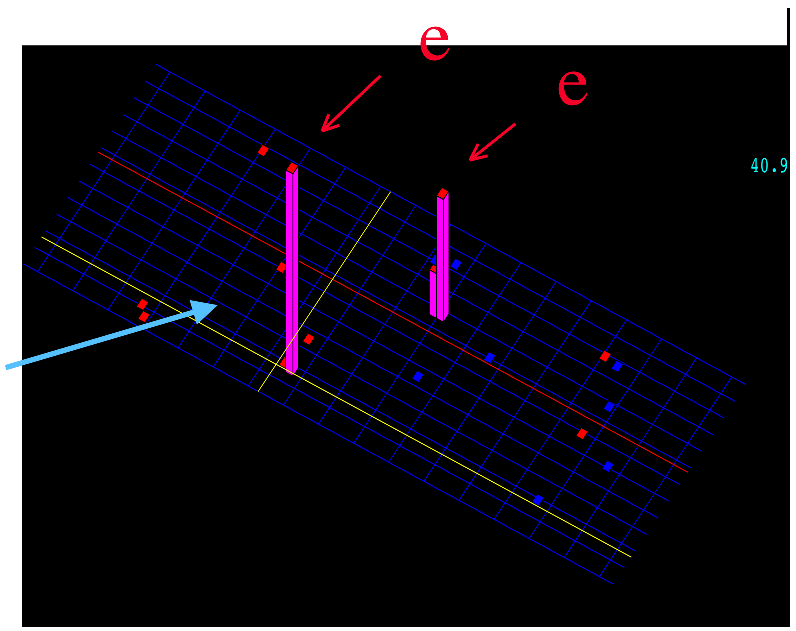
Chris Hays, Oxford University

SCET workshop
22 April 2022

Overview

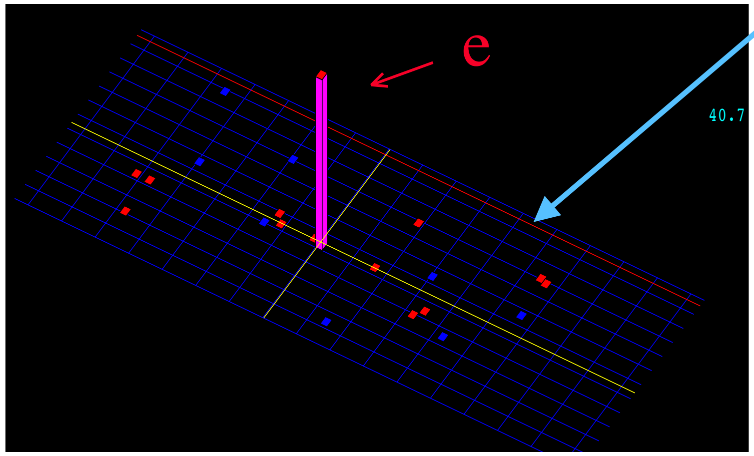


Muon momentum calibration



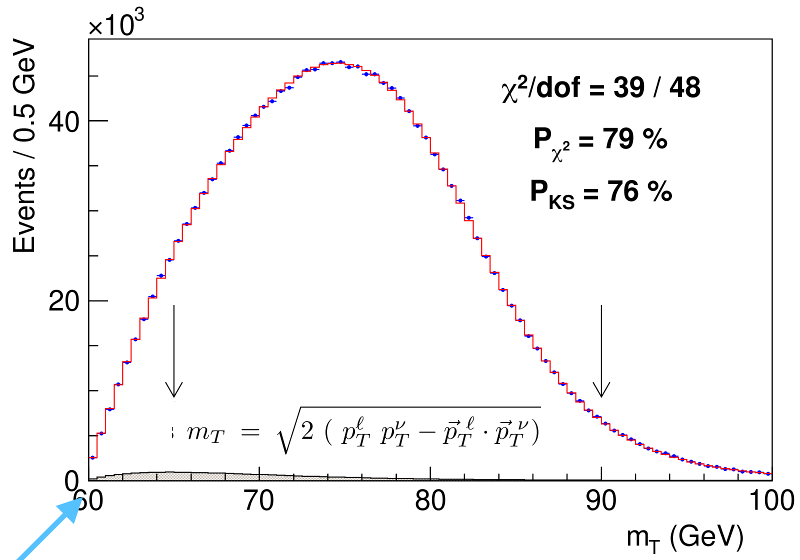
Electron momentum calibration

Recoil calibration



W selection & background

W & Z production & decay



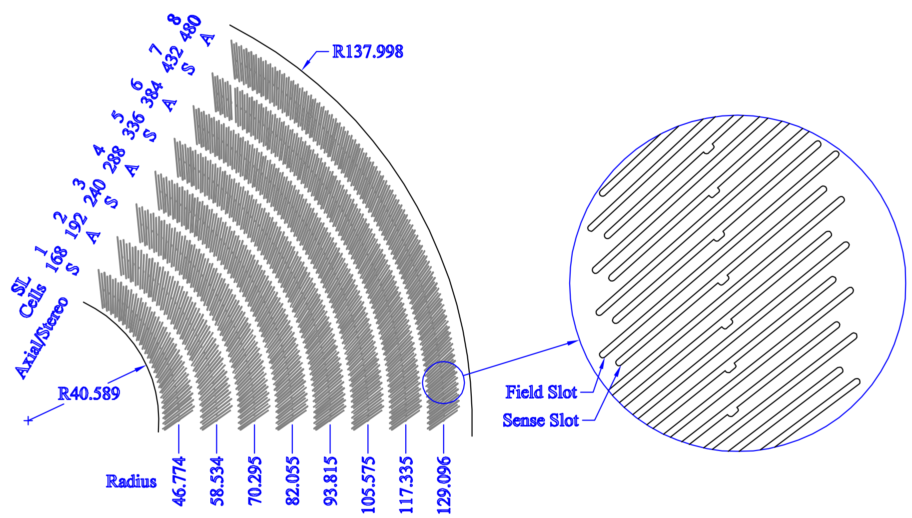
W boson mass measurement

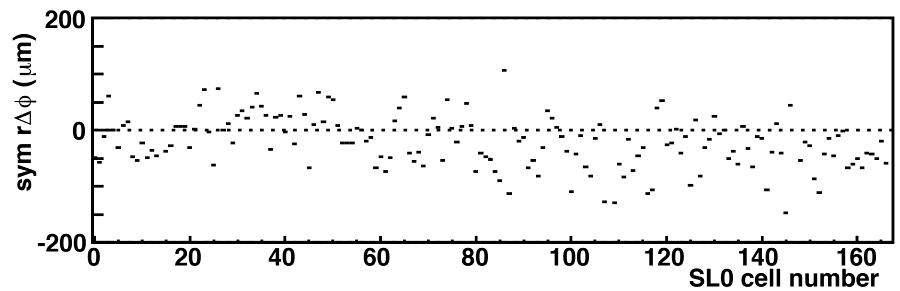
Muon momentum calibration

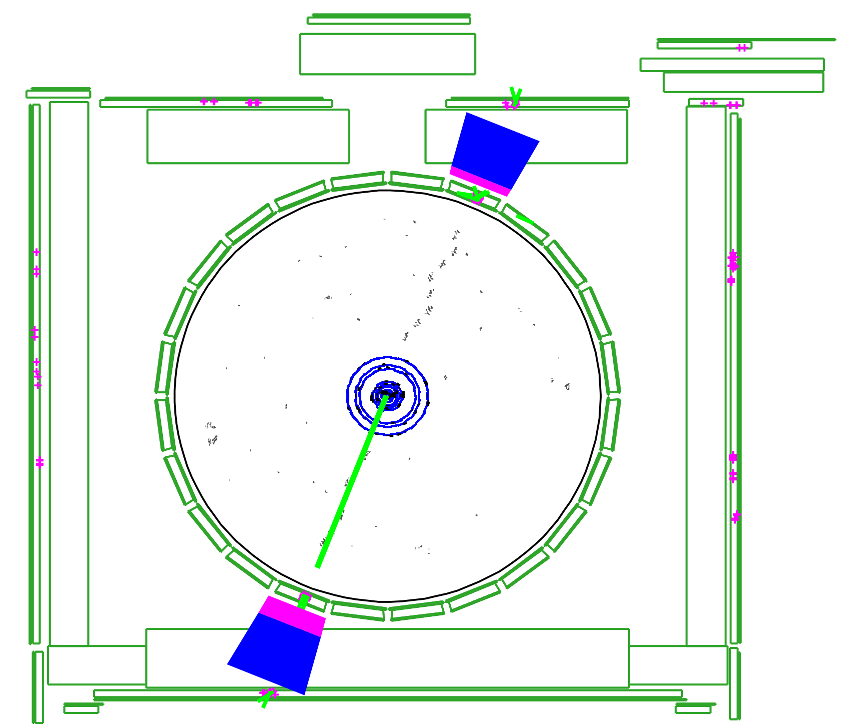
First step is the alignment of the drift chamber (the “central outer tracker” or COT)

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

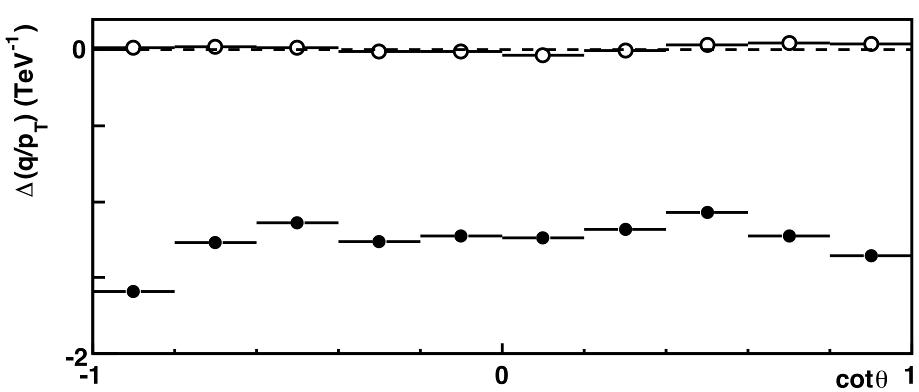


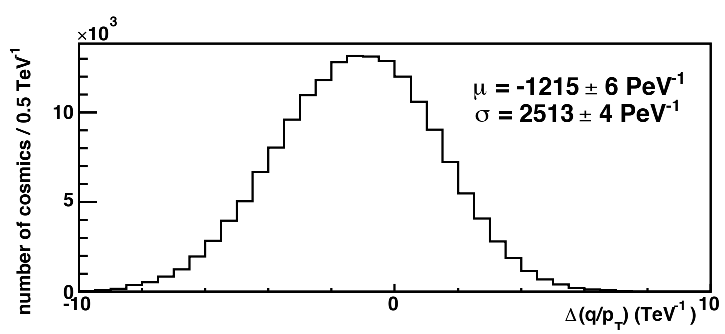




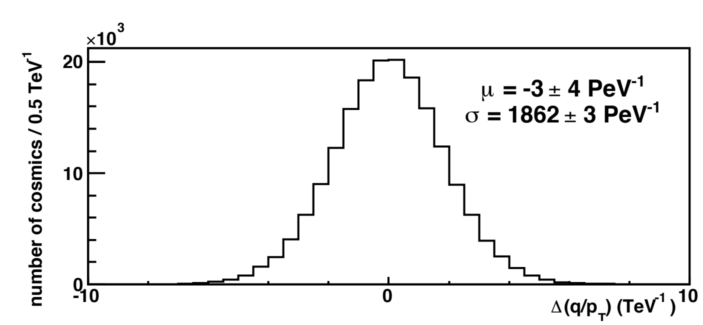
AVK & CH,1404.3457 & NIM A 762, 85 (2014)

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





Before



After

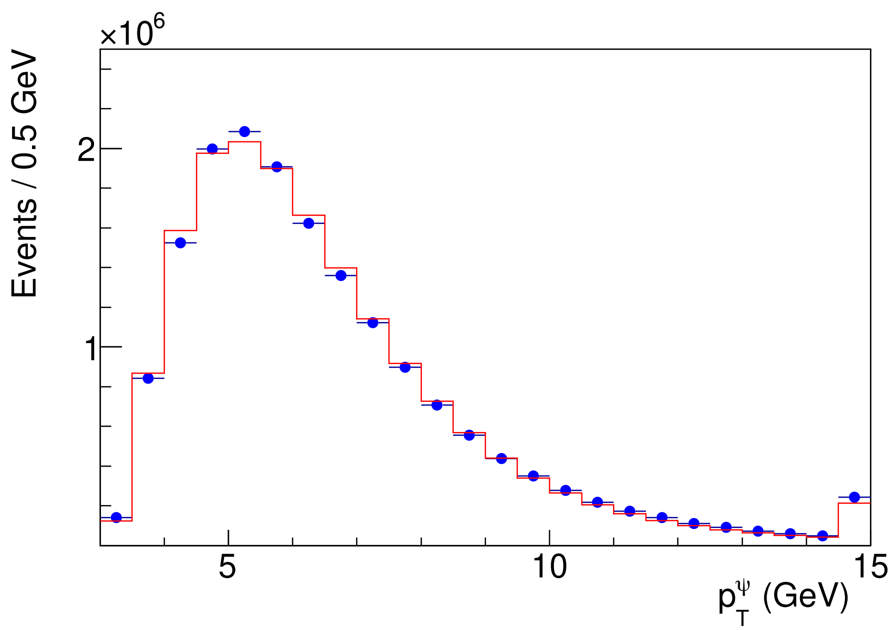
Muon momentum calibration

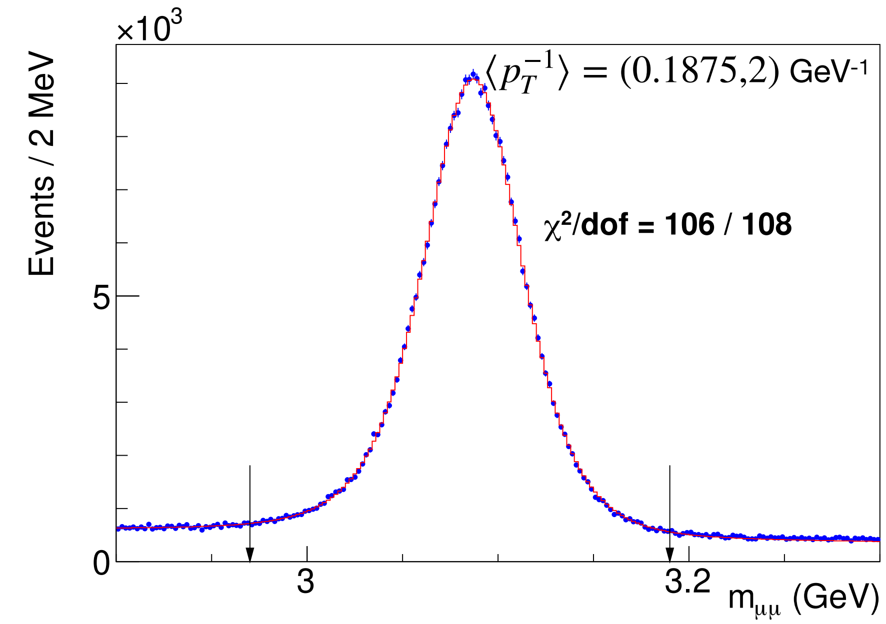
Second step is the scale calibration from J/ψ decays to muons

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

Tune relevant production distributions to match data

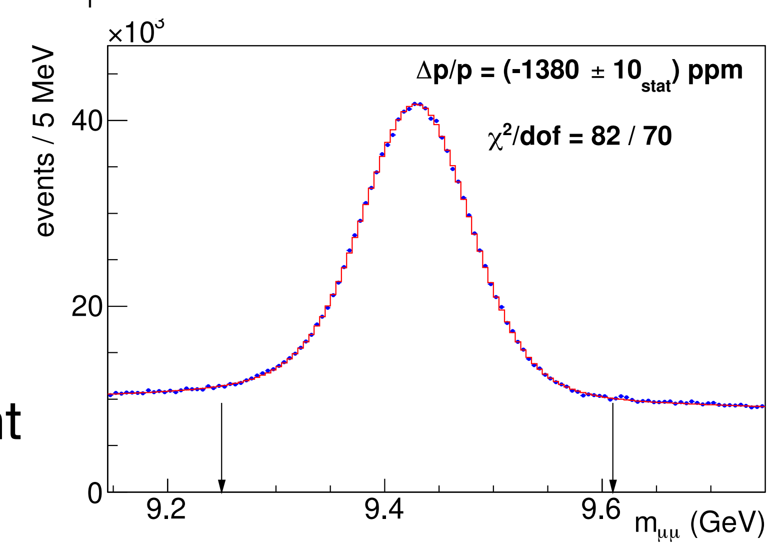
Use J/ψ data to improve precision on the length scale of the tracker and the amount of upstream material



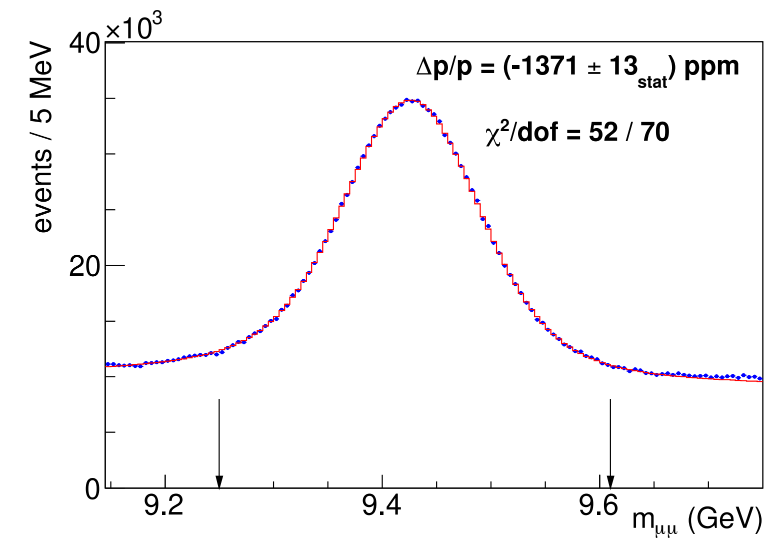


Third step is the scale calibration from Υ decays to muons

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



with constraint



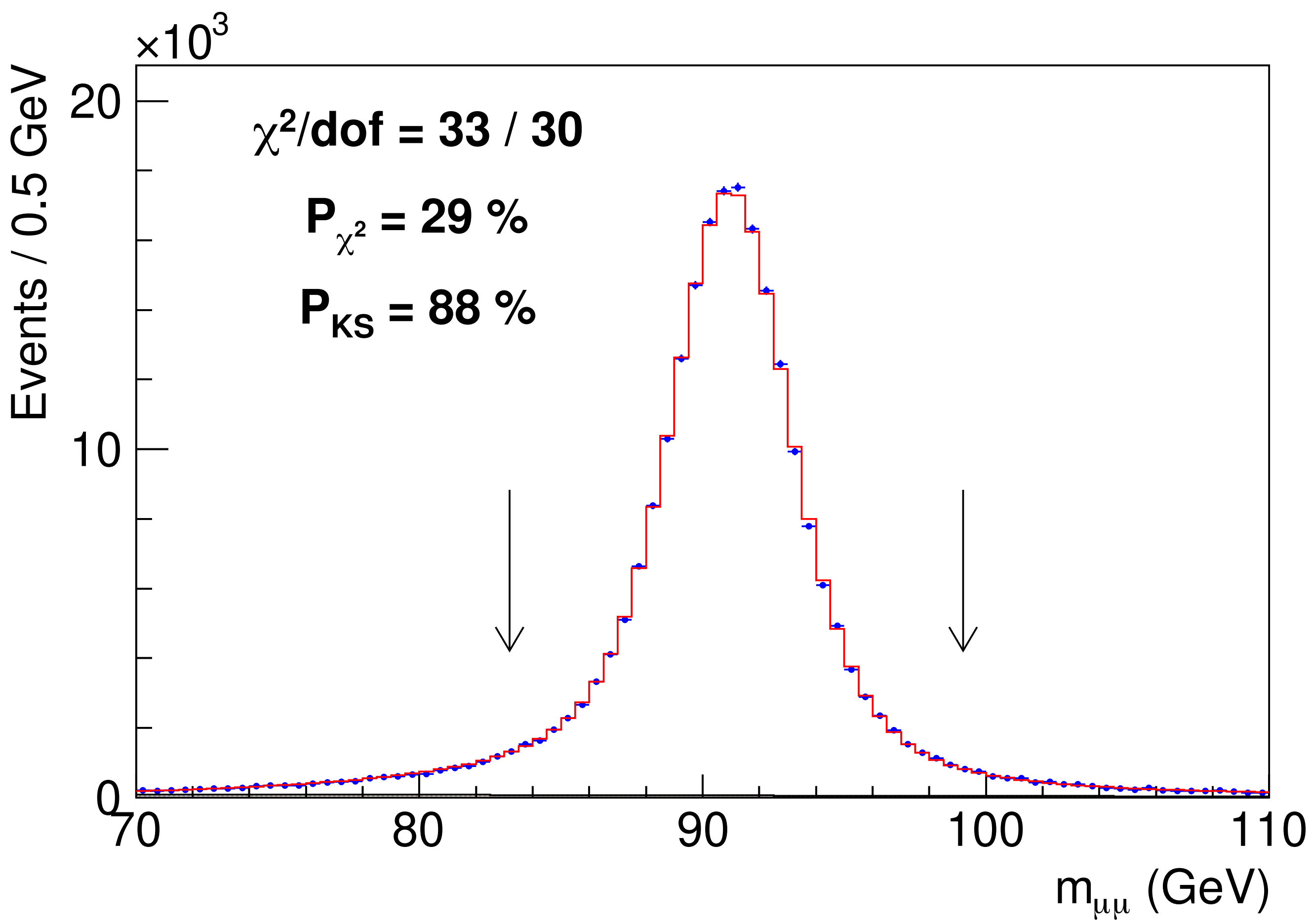
without constraint

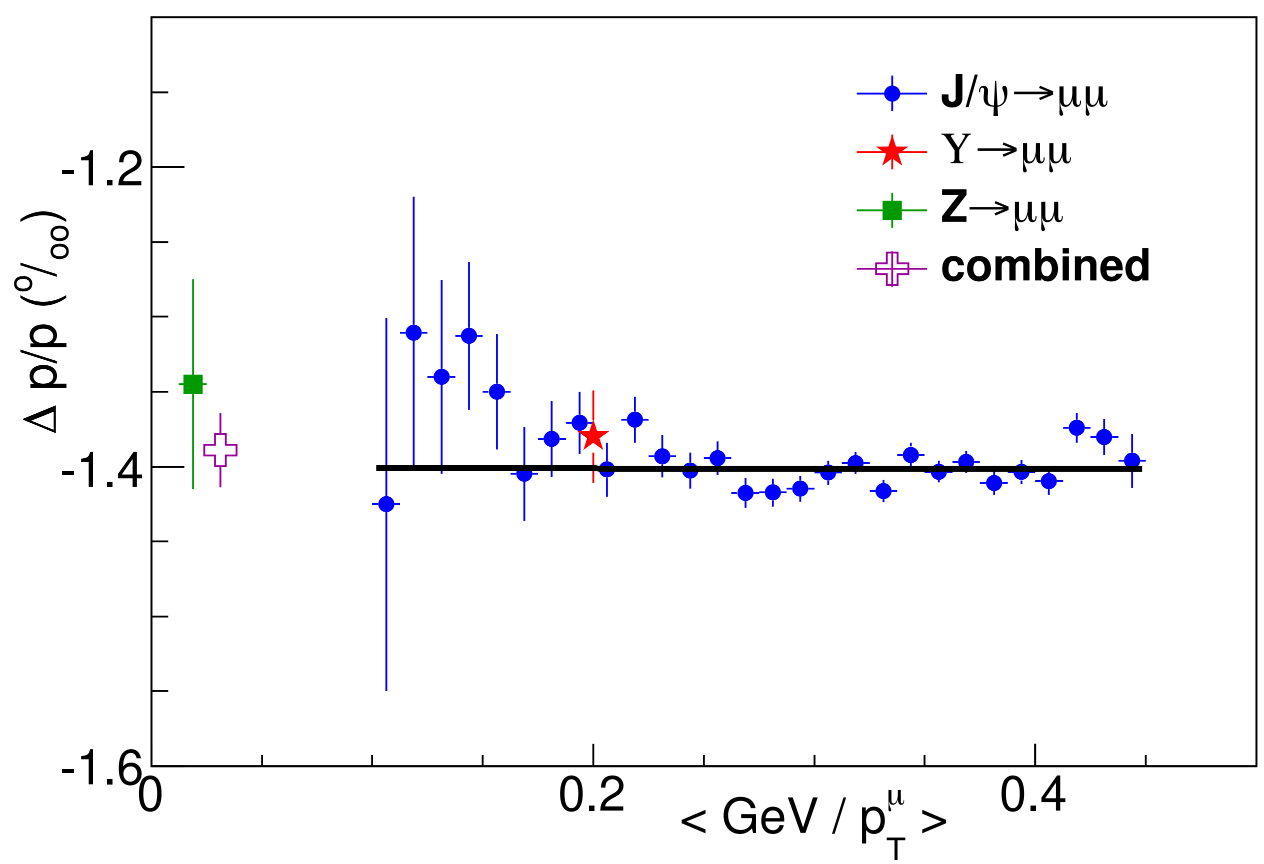
Muon momentum calibration

Final step is the measurement of the Z boson mass

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

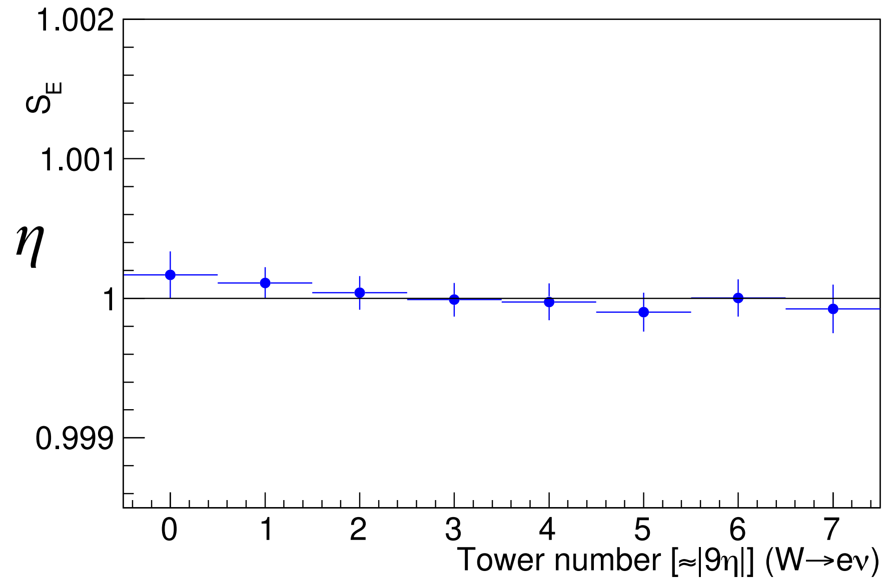
Result blinded with [-50,50] MeV offset until previous steps were complete
Then combine all measurements into a final charged-track momentum scale





Electron momentum calibration

First step is the correction for response variations in space and time

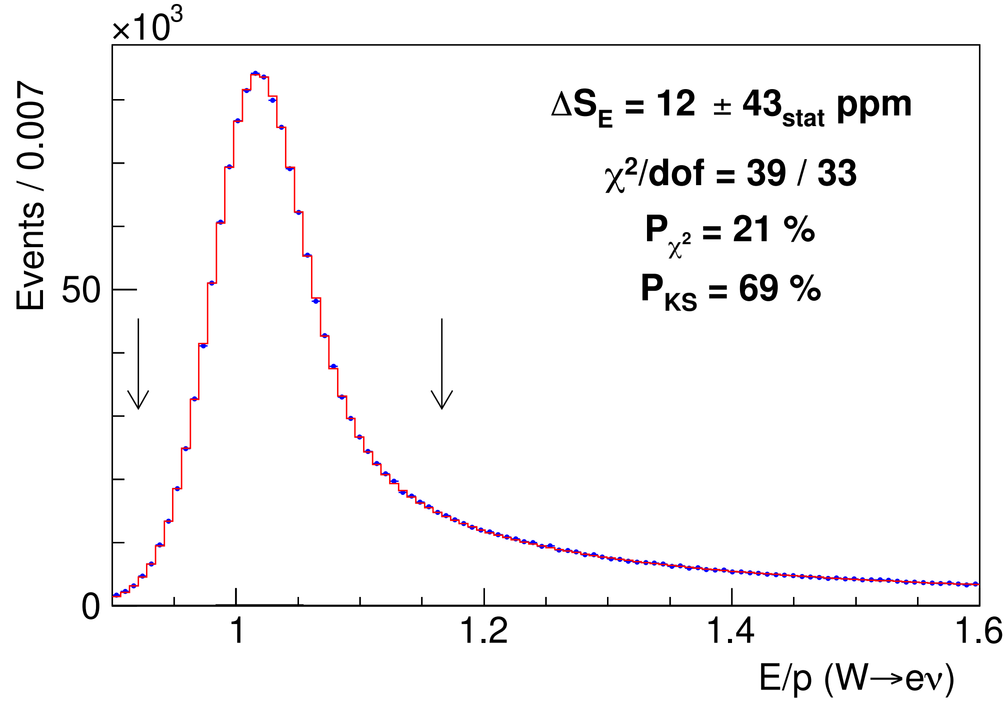


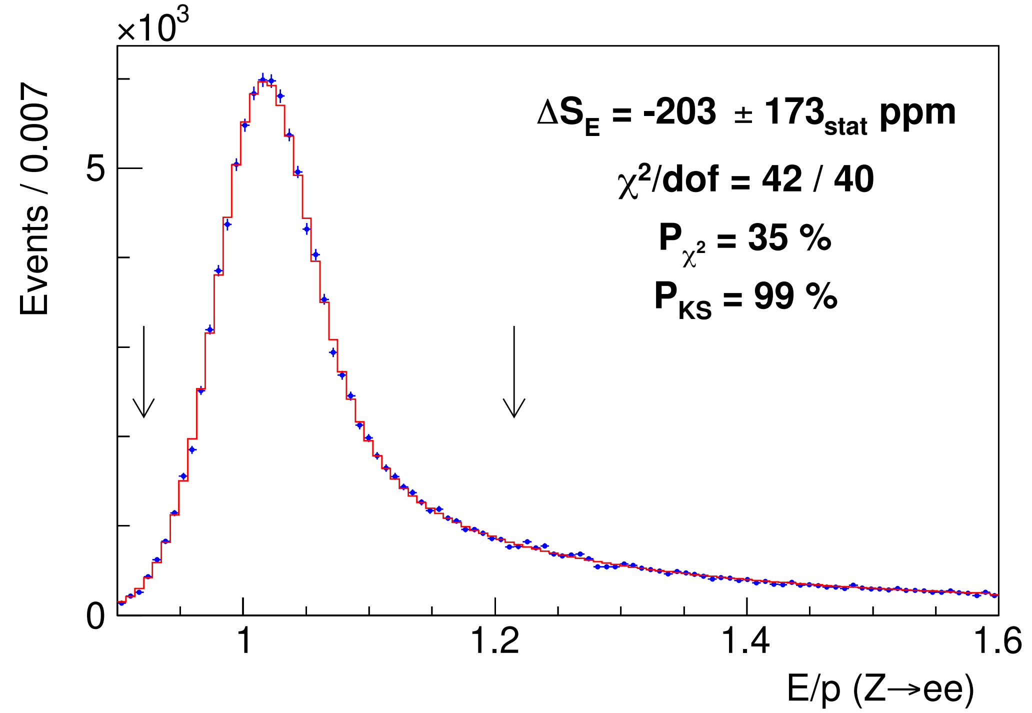
Fit ratio of calorimeter energy to track momentum to correct each tower in η
Use mean E/p to remove time dependence & response variations in tower

Second step is the calibration of the energy scale using E/p

AVK & CH, 1308.2025 & NIM A 729, 25 (2013)

Custom parameterized GEANT simulation of calorimeter
Use E/p lineshape to correct for small non-linear energy response and variations in calorimeter thickness





Electron momentum calibration

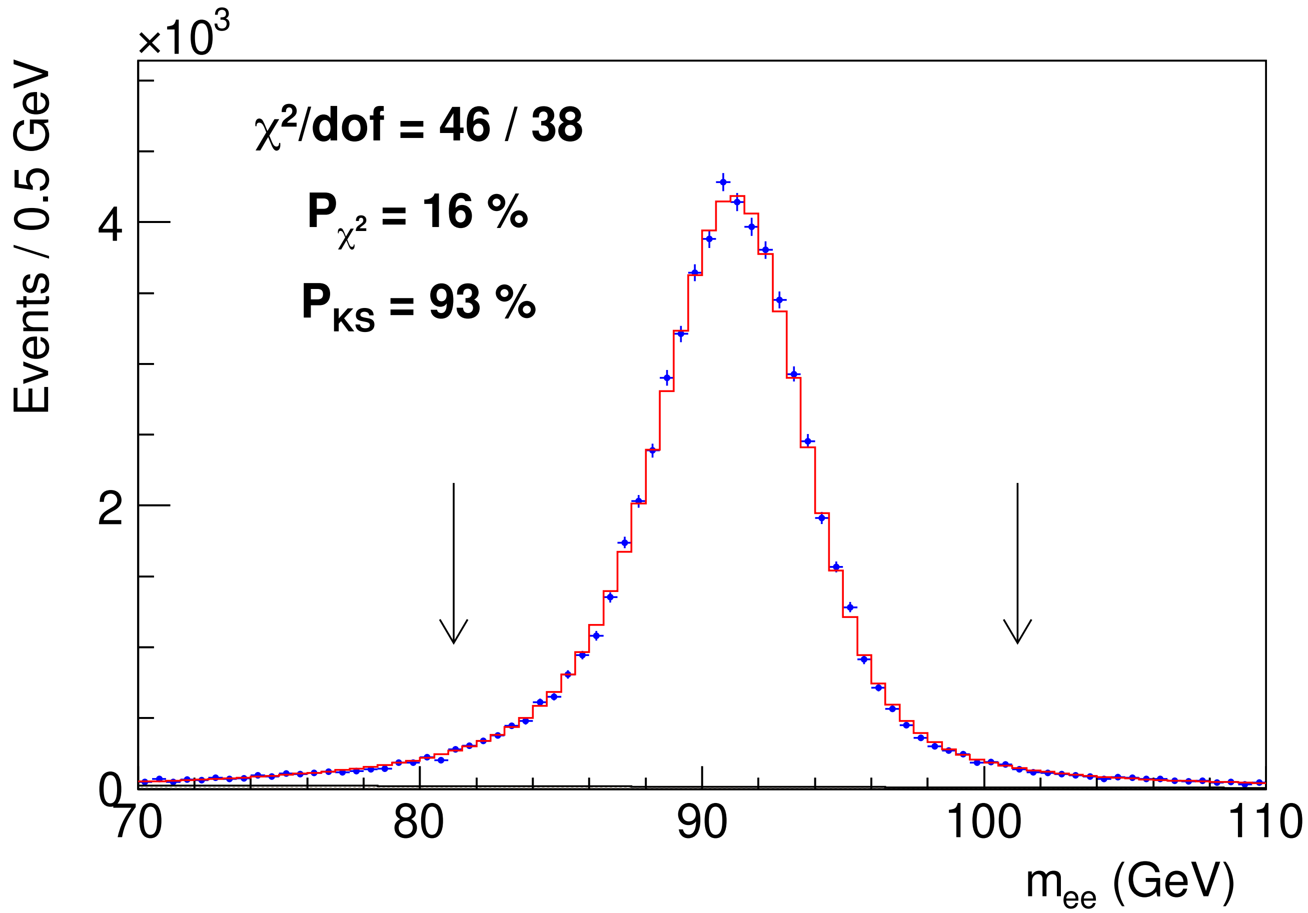
Final step is the measurement of the Z boson mass

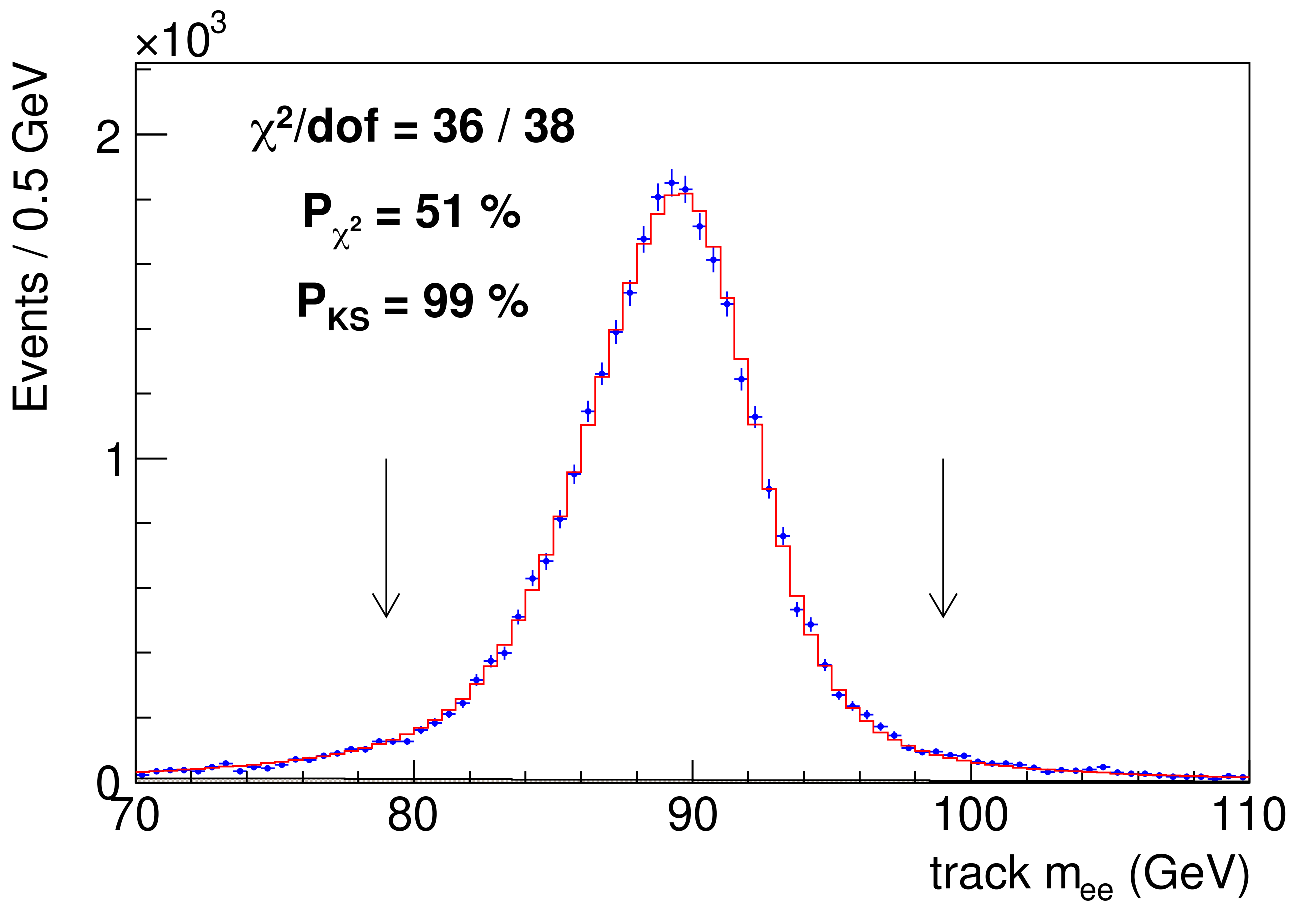
$$M_Z = 91\ 194.3 \pm 13.8_{stat} \pm 7.6_{sys}\ \text{MeV}$$

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 used as for muon channel



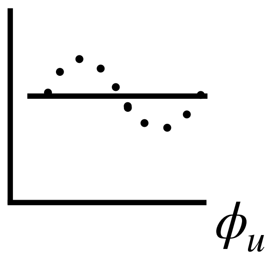


Recoil calibration

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 min bias data

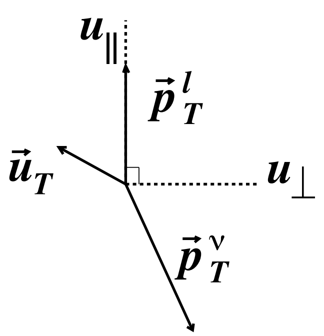


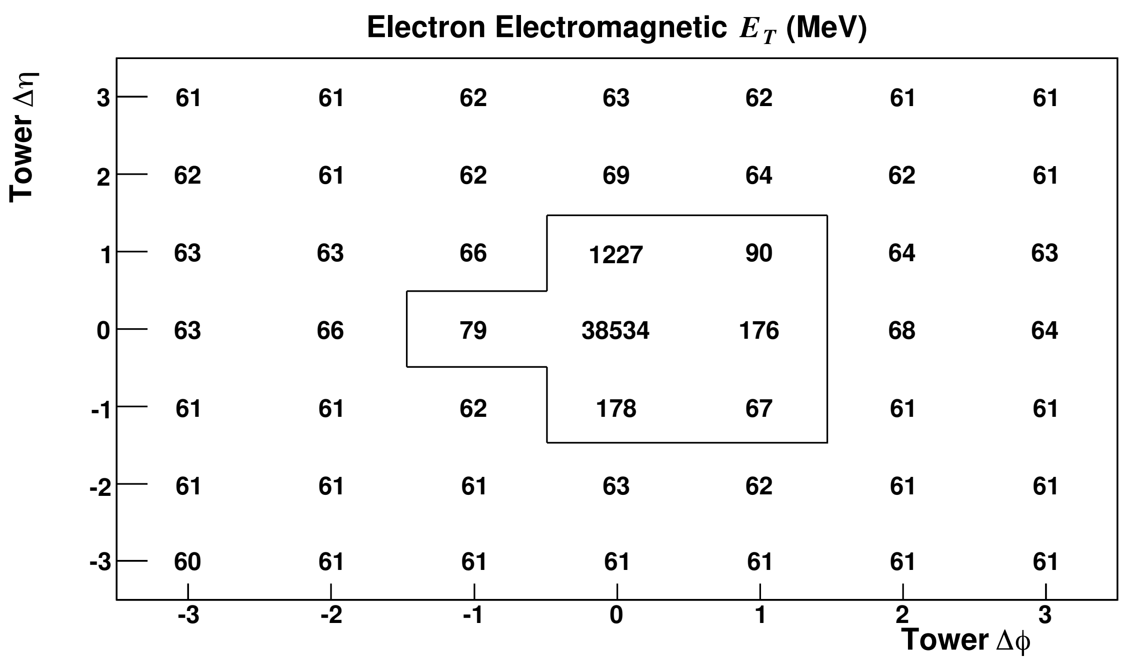
Second step is the reconstruction of the recoil

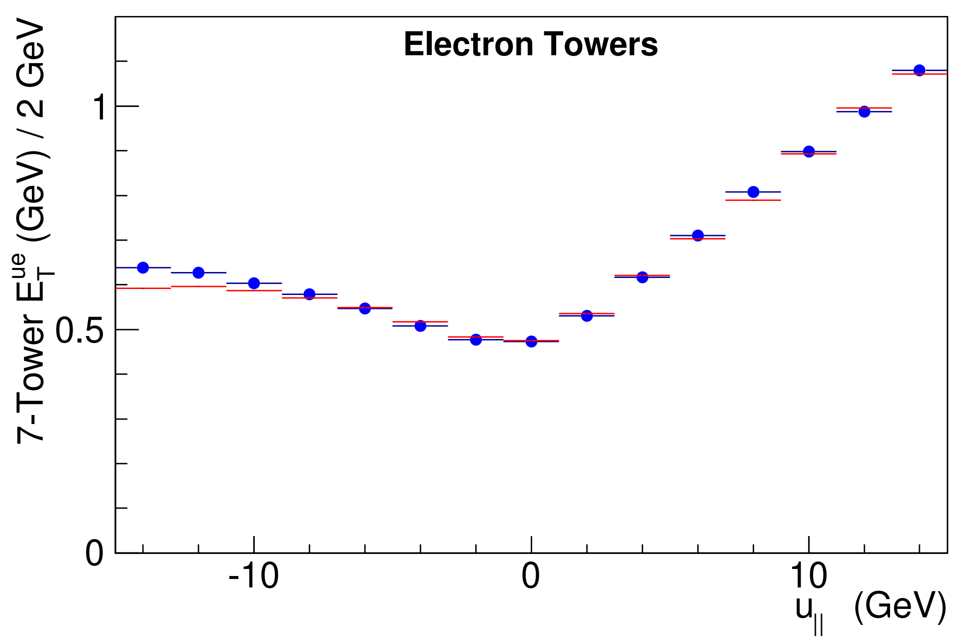
Remove towers traversed by identified leptons

Remove corresponding recoil energy in simulation using towers rotated by 90°

validate using towers rotated by 180°



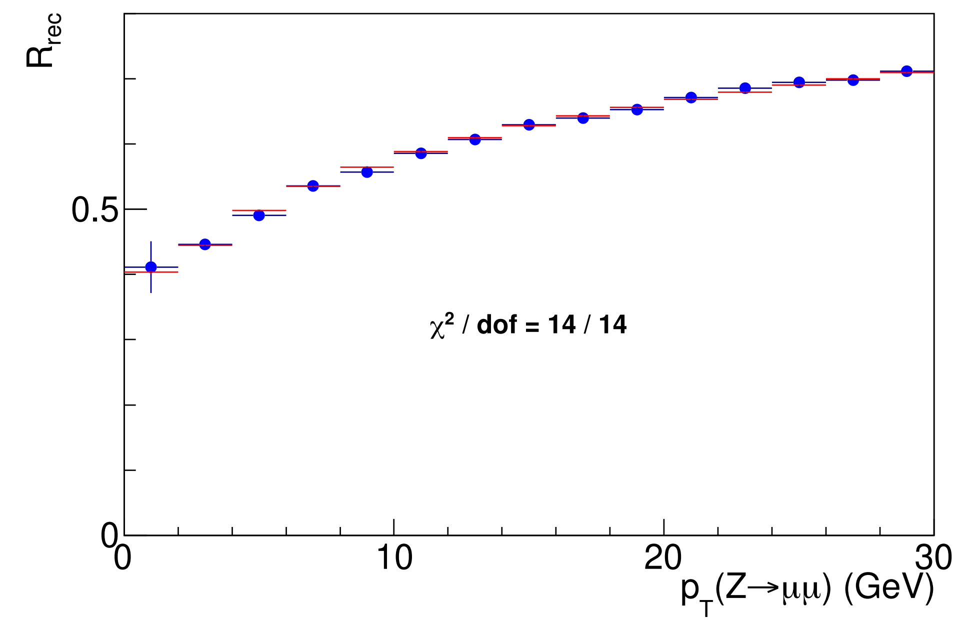




Recoil calibration

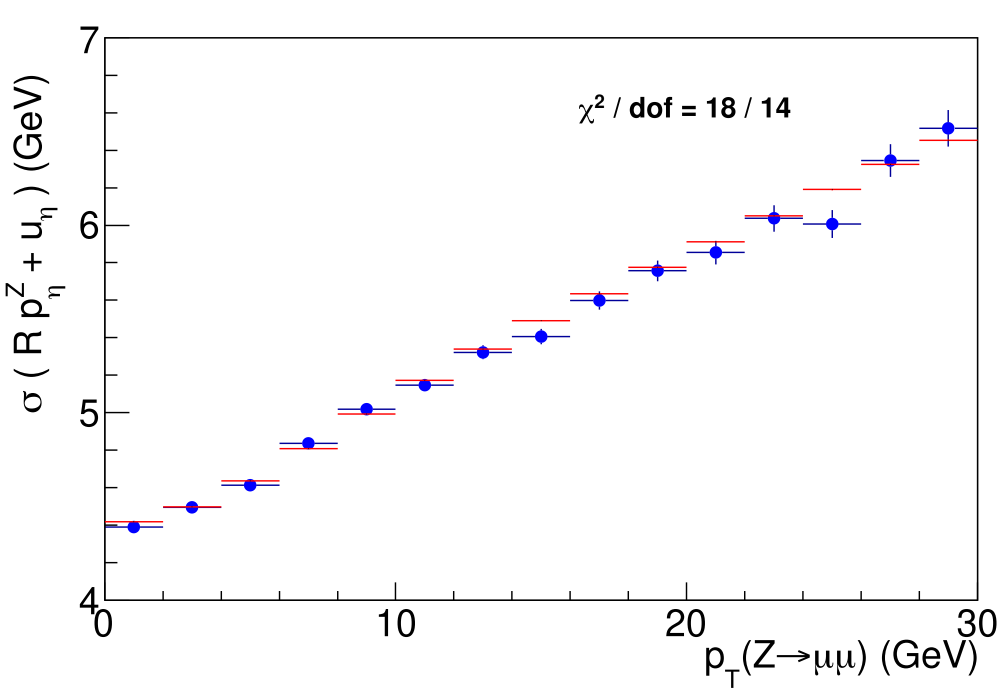
Third step is the calibration of the recoil response

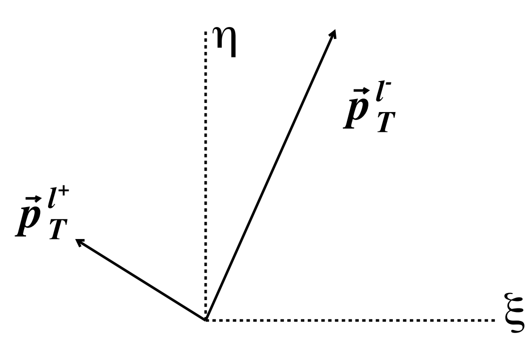
Model ratio of recoil magnitude to p_T^Z along direction of p_T^Z

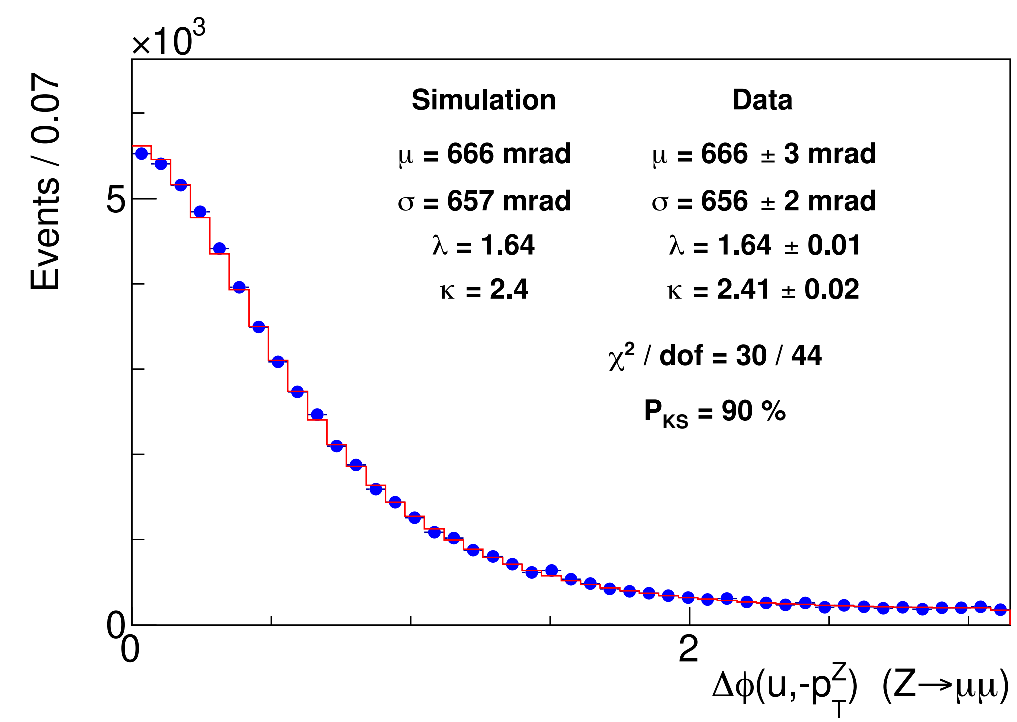


Fourth step is the calibration of the recoil resolution

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





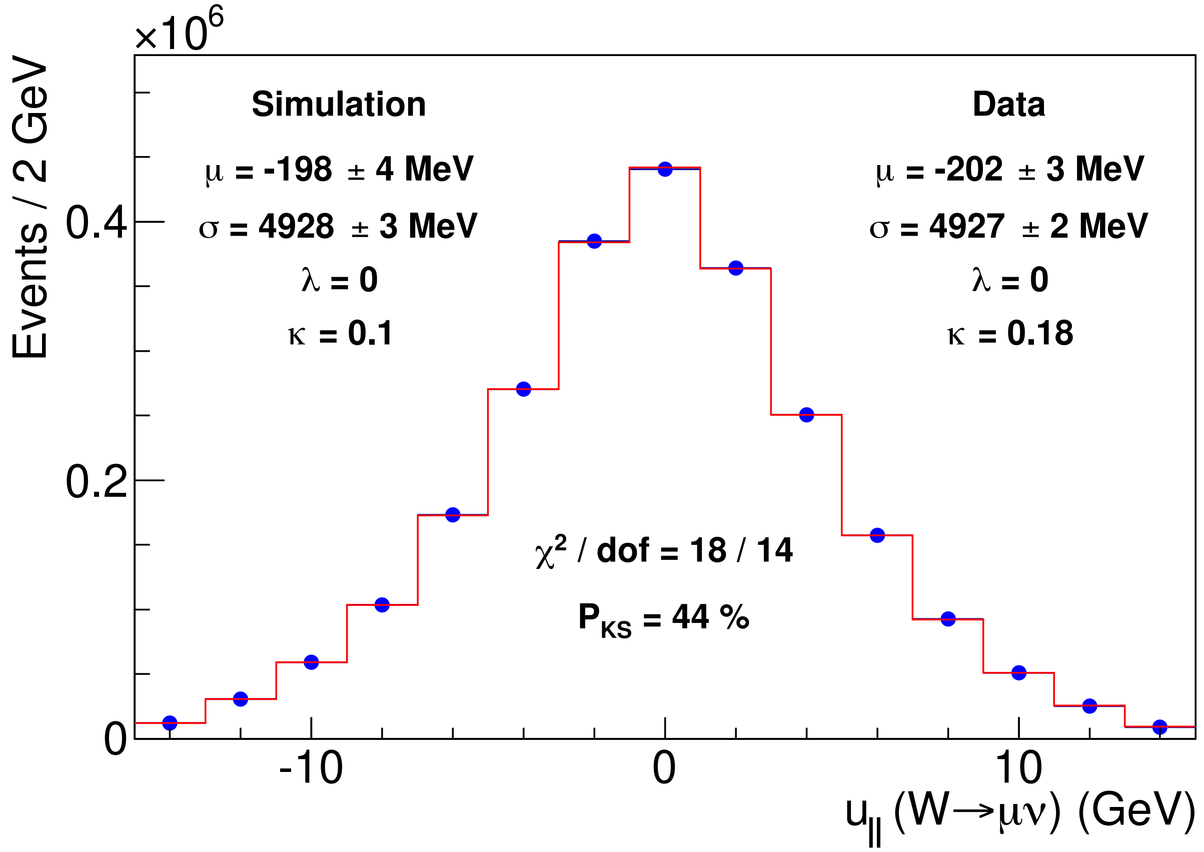


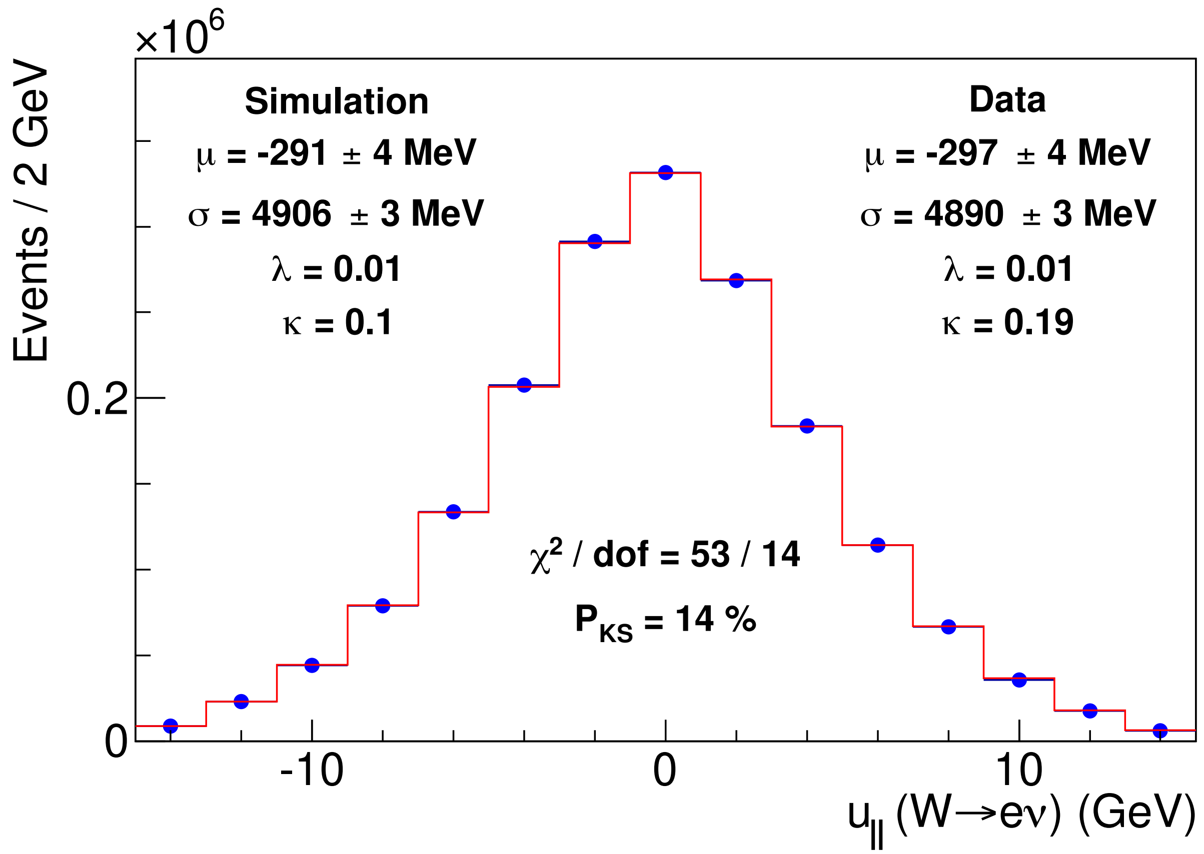
Recoil validation

W boson recoil distributions validate the model

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

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



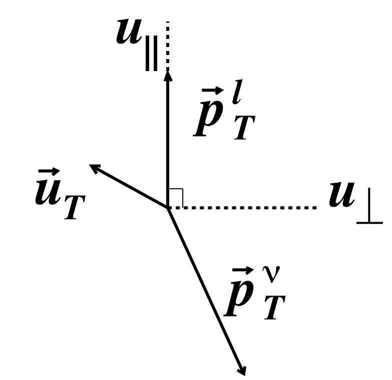


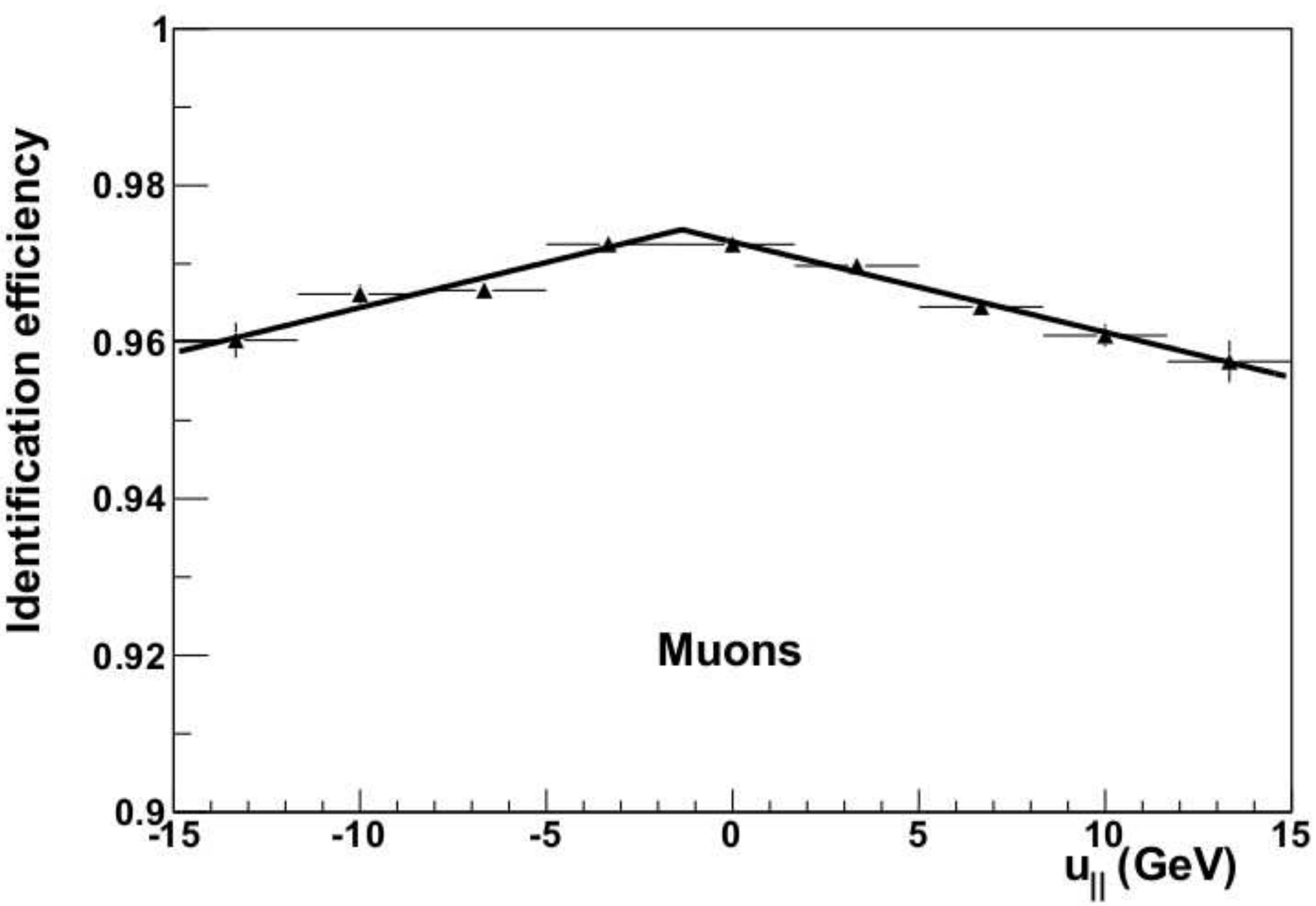
W boson selection

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

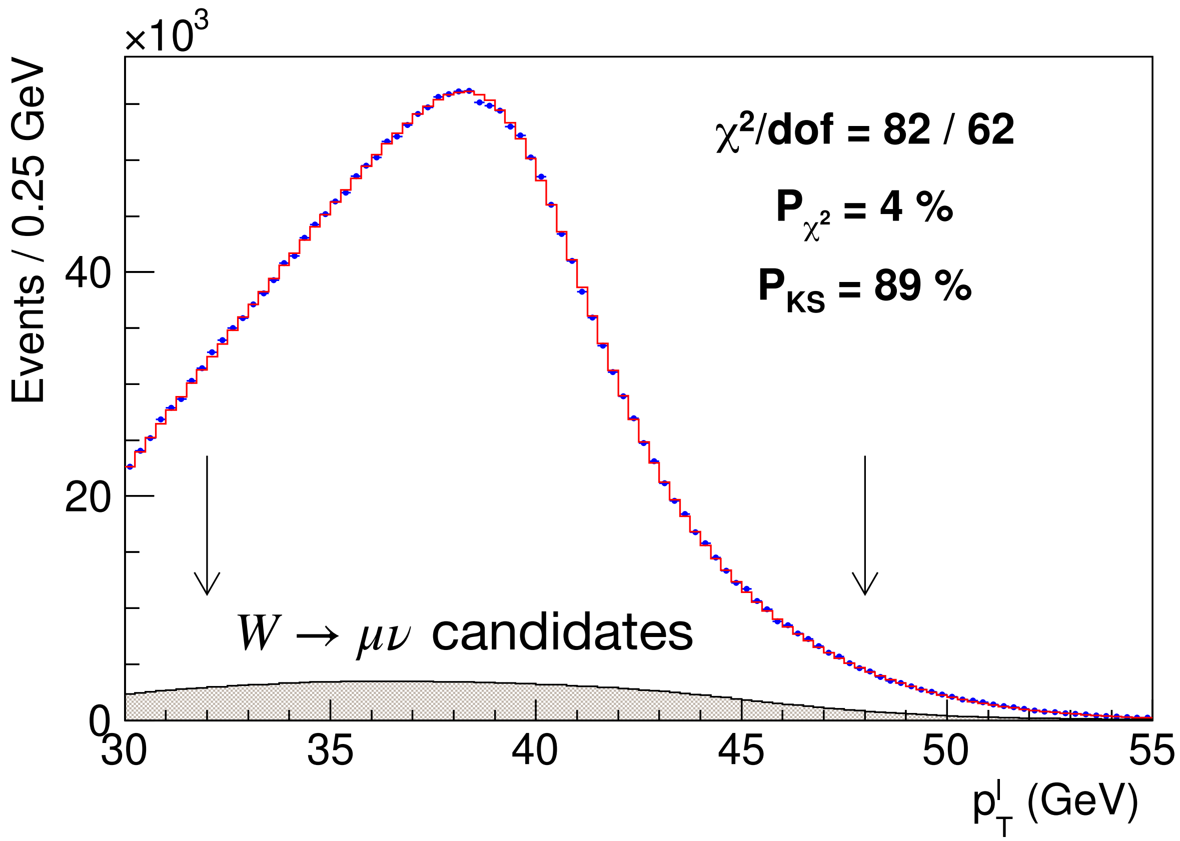
2.4 M $W \to \mu\nu$ candidates
1.8 M $W \to e\nu$ candidates

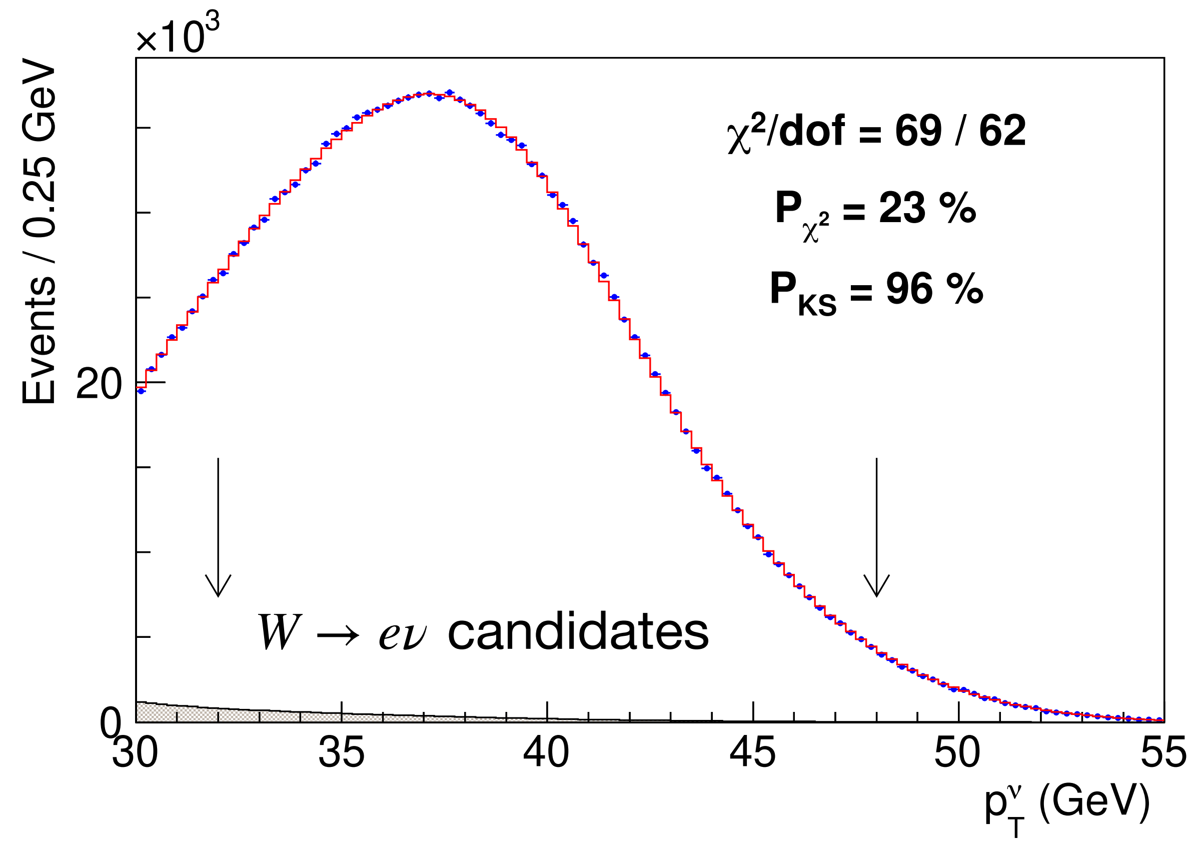
W boson backgrounds

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

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

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





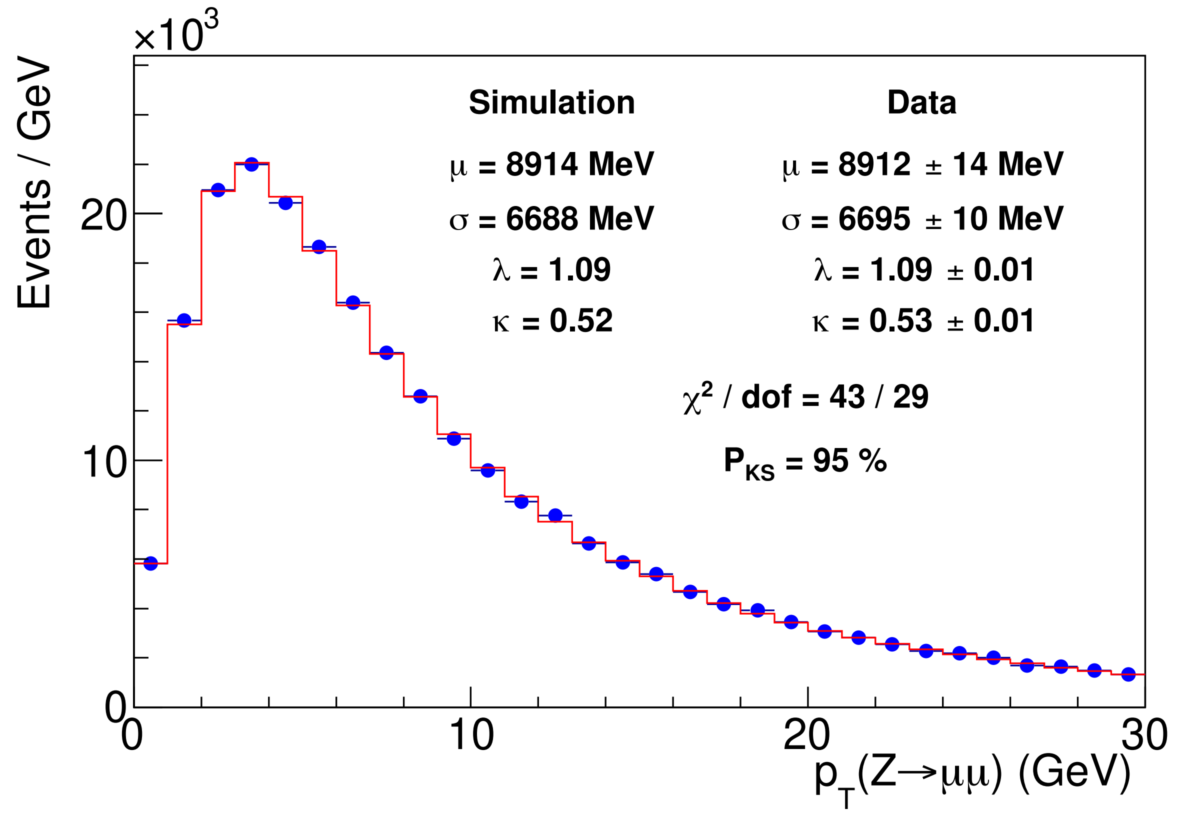
W boson production

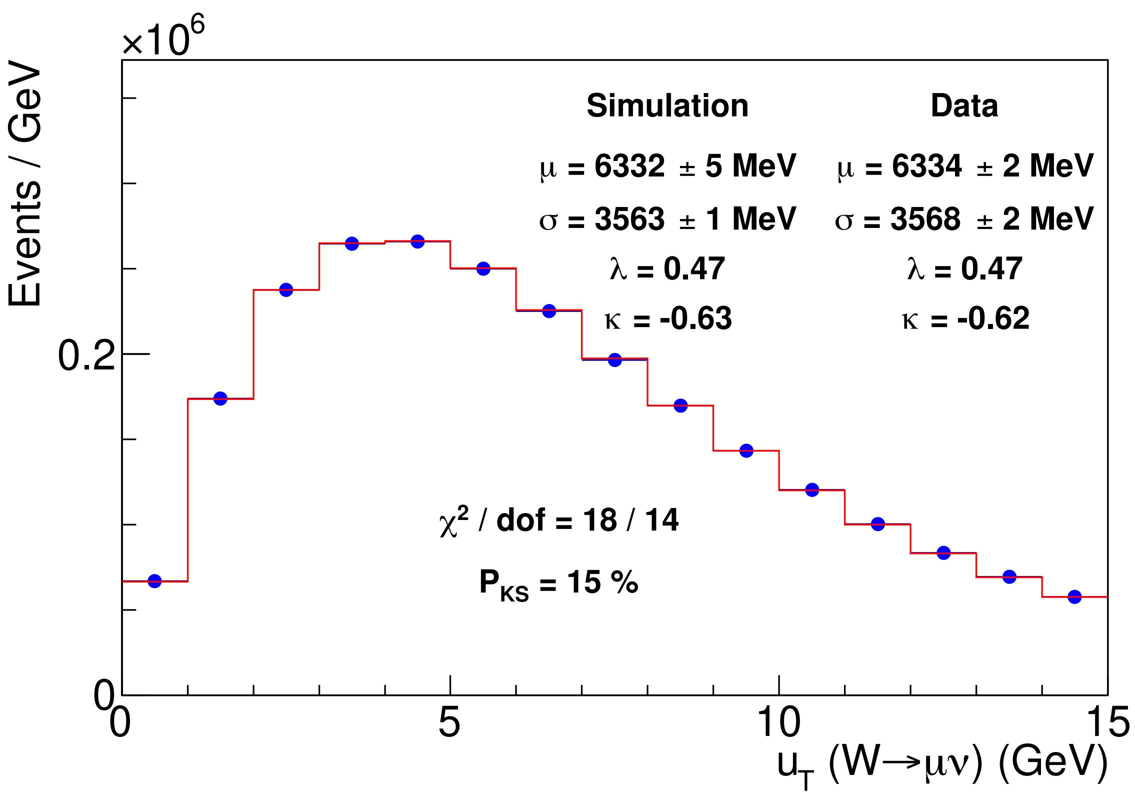
Boson p_T impacts the p_T distributions of the decay leptons

Use Resbos to generate events: two non-perturbative parameters and NNLL resummation to model the region of low boson p_T

Z boson p_T constrains the non-perturbative parameter g_2 and the perturbative coupling α_s

Resbos models W & Z boson p_T distributions well
uncertainty estimated using DYQT and constrained with data

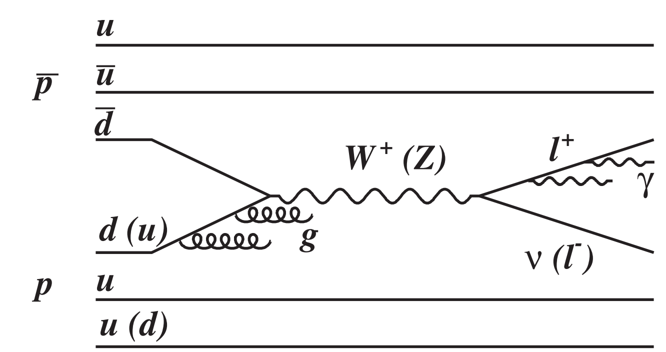




W boson production and decay

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)

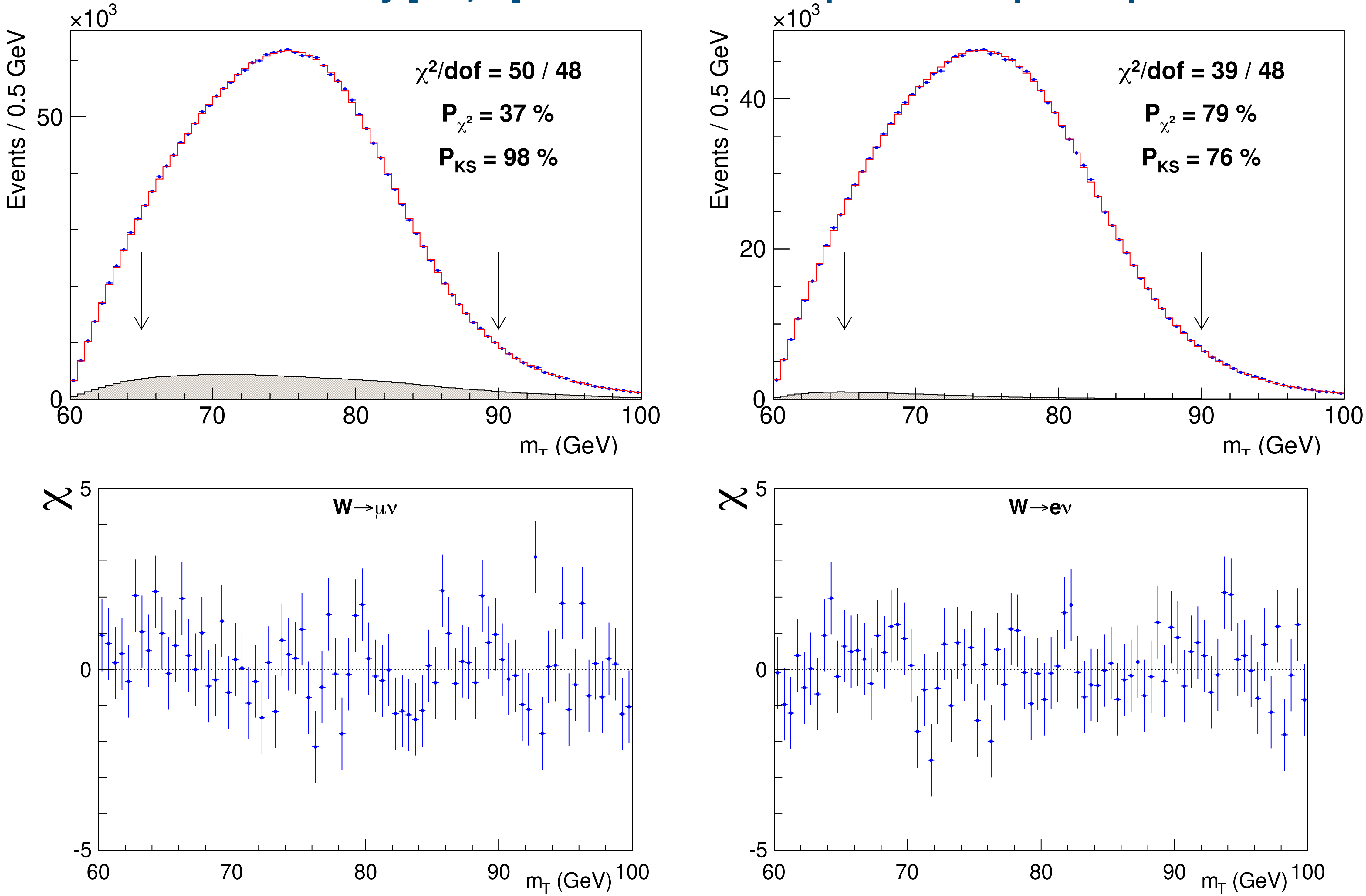
Three general NNLO PDF sets (NNPDF3.1, CT18, and MMHT14) have a range of ± 2.1 MeV from mean

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



W boson mass measurement

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

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

Summary

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

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

Analysis procedures approved pre-blinding and frozen

Surprising result motivates further study of m_W measurements and procedures

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

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%