Precision measurement of the W boson mass using the full CDF Run II data set

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For the CDF Collaboration

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Outline

Tevatron

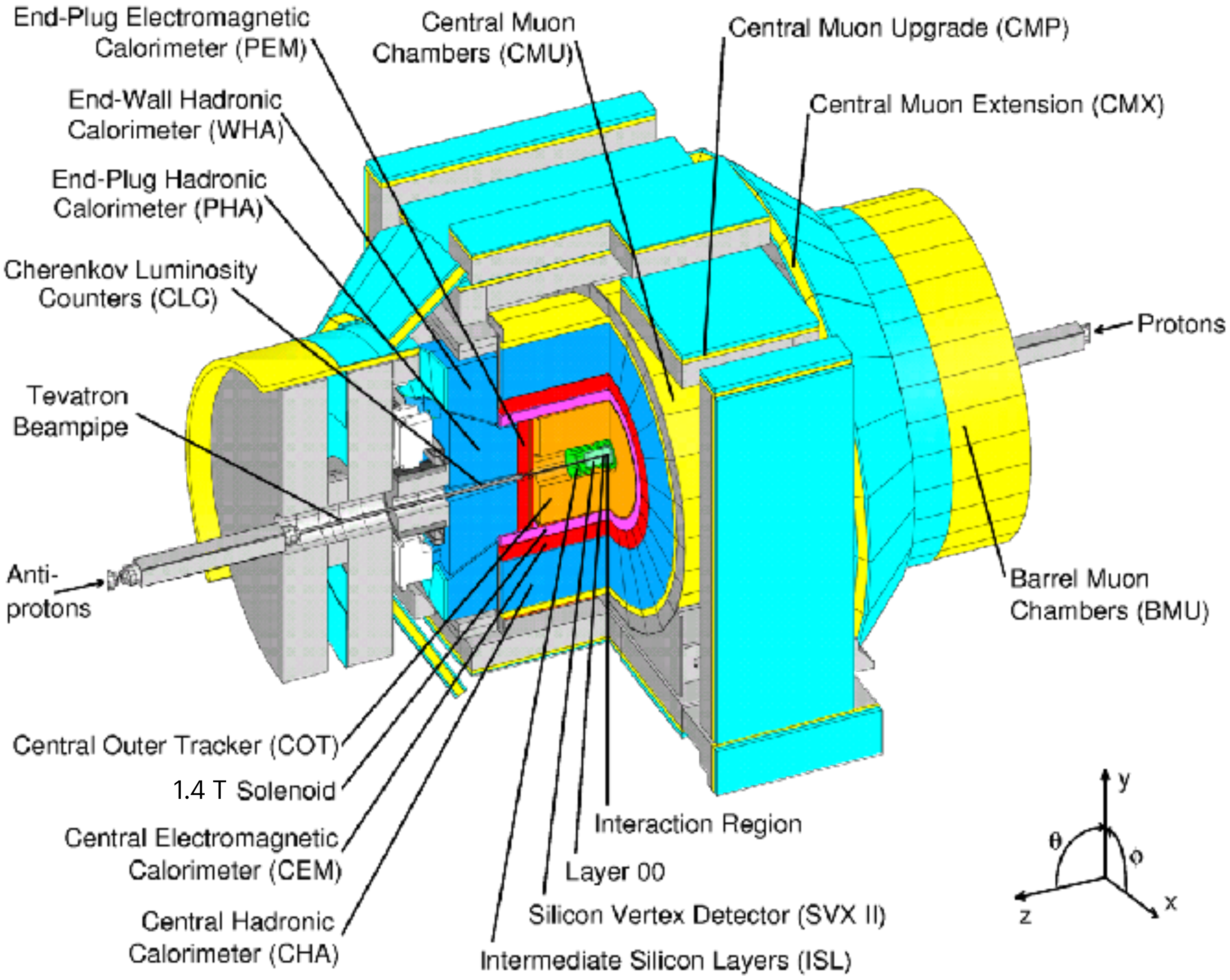
Proton-antiproton collider operating at a collision energy of 1.8 TeV in 1992–96 (Run I) and 1.96 TeV in 2001–11 (Run II)

Highest-energy collider until 2010

- Located at Fermilab near Chicago
- 1 km radius
- 1976: Construction started
- 1985: Commissioning
- 1987: CDF Run 0
- Continuous upgrades over 25 years of operations

CDF

First CDF $p\bar{p}$ event: 1985
End of operations: 2011



Lepton coverage:
$|\eta| < 1.5$ (muons)
$|\eta| < 2.0$ (electrons)

Jets up to $|\eta| < 2.8$

b-tagging with
$|\eta| \lesssim 1.4$

Dijet mass resolution: ~16%

$\eta = -\ln[\tan(\theta/2)]$ $p_T = p \sin\theta$

The W boson mass in the Standard Model

The electroweak gauge sector of the SM is described by 3 free parameters (g, g′, v), which are constrained by 3 precisely measured observables:

- ✓ $\alpha(M_Z) = 1 / 127.918(18)$
- ✓ $G_F = 1.16637(1) \times 10^{-5}\ \mathrm{GeV}^2$
- ✓ $M_Z = 91.1876(21)\ \mathrm{GeV}$

PDG 2020

Fine structure constant from EM measurements

$$\alpha = \frac{g^2 g'^2}{4\pi(g^2 + g'^2)}$$

Fermi constant from muon life time

$$G_F = \frac{1}{\sqrt{2}\, v^2}$$

Pole mass of Z boson from LEP energy scan

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

These parameters constrain other electroweak observables, e.g. $M_W = g\,v/2$:

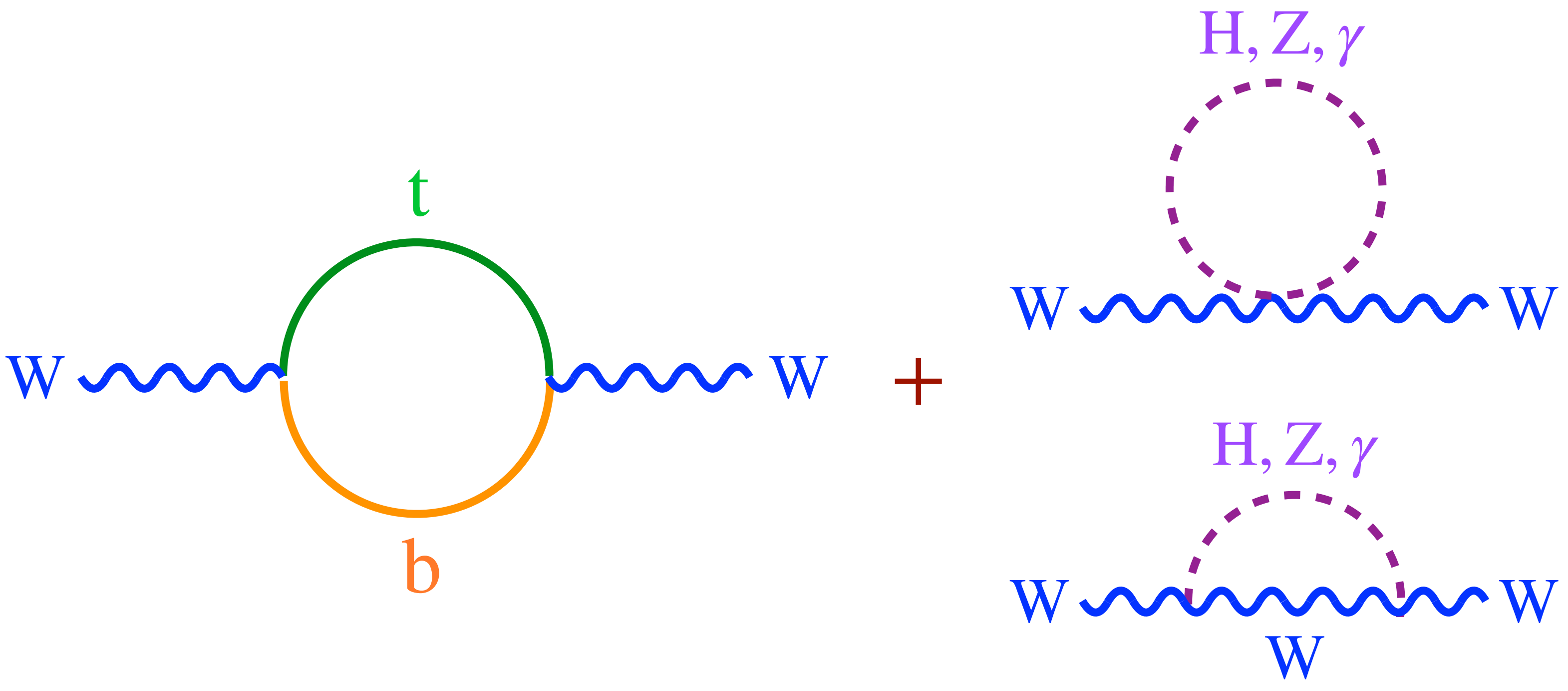
$$M_W = \frac{M_Z}{\sqrt{2}}\sqrt{1 + \sqrt{1 - \frac{\sqrt{8}\pi\alpha}{G_F M_Z^2}(1+\underset{\downarrow}{\Delta r})}}$$

arXiv:1902.05142

Loop corrections

⇒ M_W provides a very sensitive probe of internal consistency of the SM

Loop corrections to M_W



$$\Rightarrow \Delta r \sim m_t^2\,,\ \ln M_H\,,\ \Delta\alpha\,,\ \ldots$$

↓

Running EM coupling

↓

$$\Delta\alpha^{(5)}_{\mathrm{had}}(M_Z^2)$$

PDG 2020

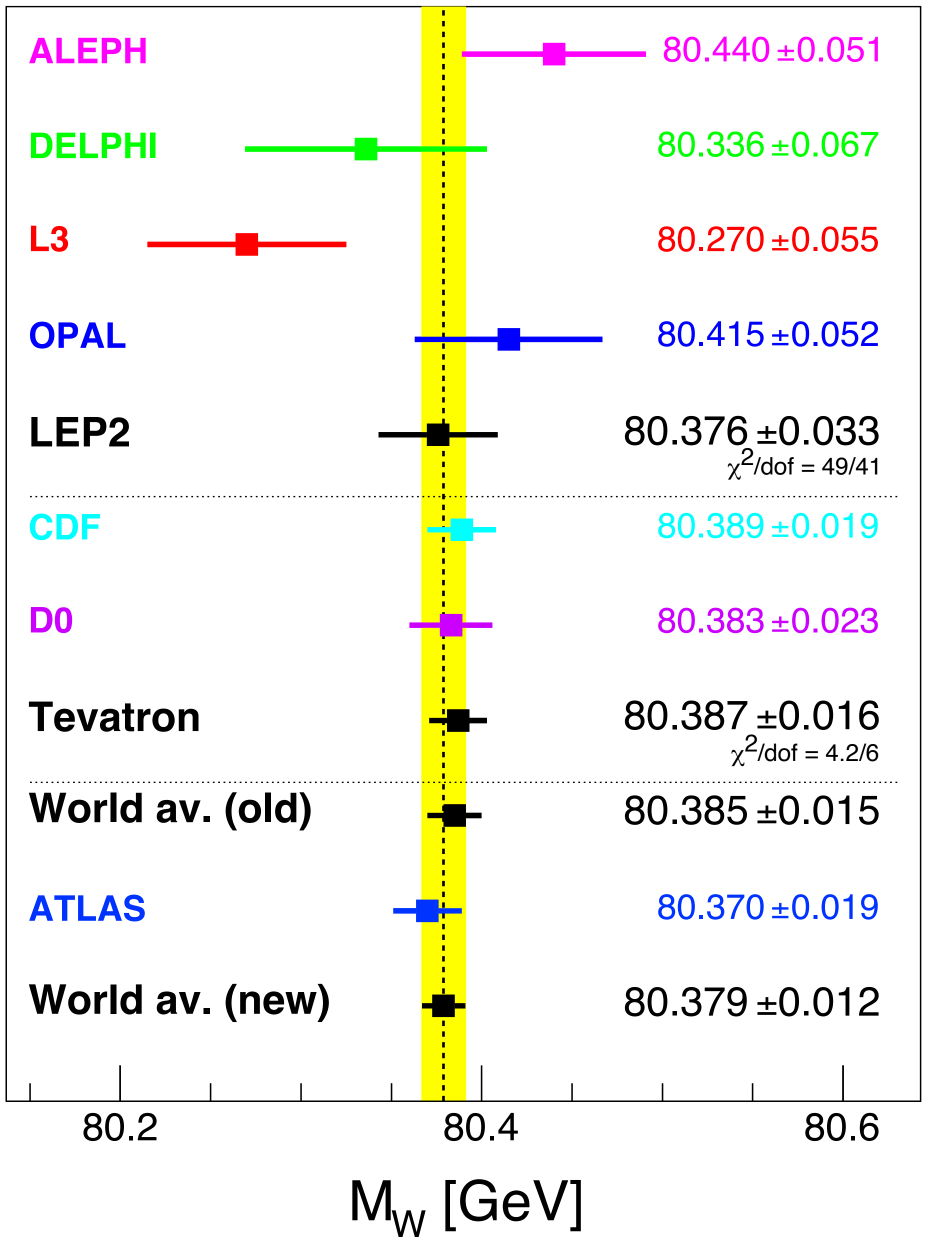
SM expectation for M_W:

$$M_W = 80357 \pm 4_{\mathrm{inputs}} \pm 4_{\mathrm{theory}}\ \mathrm{MeV} = 80357 \pm 6\ \mathrm{MeV}$$

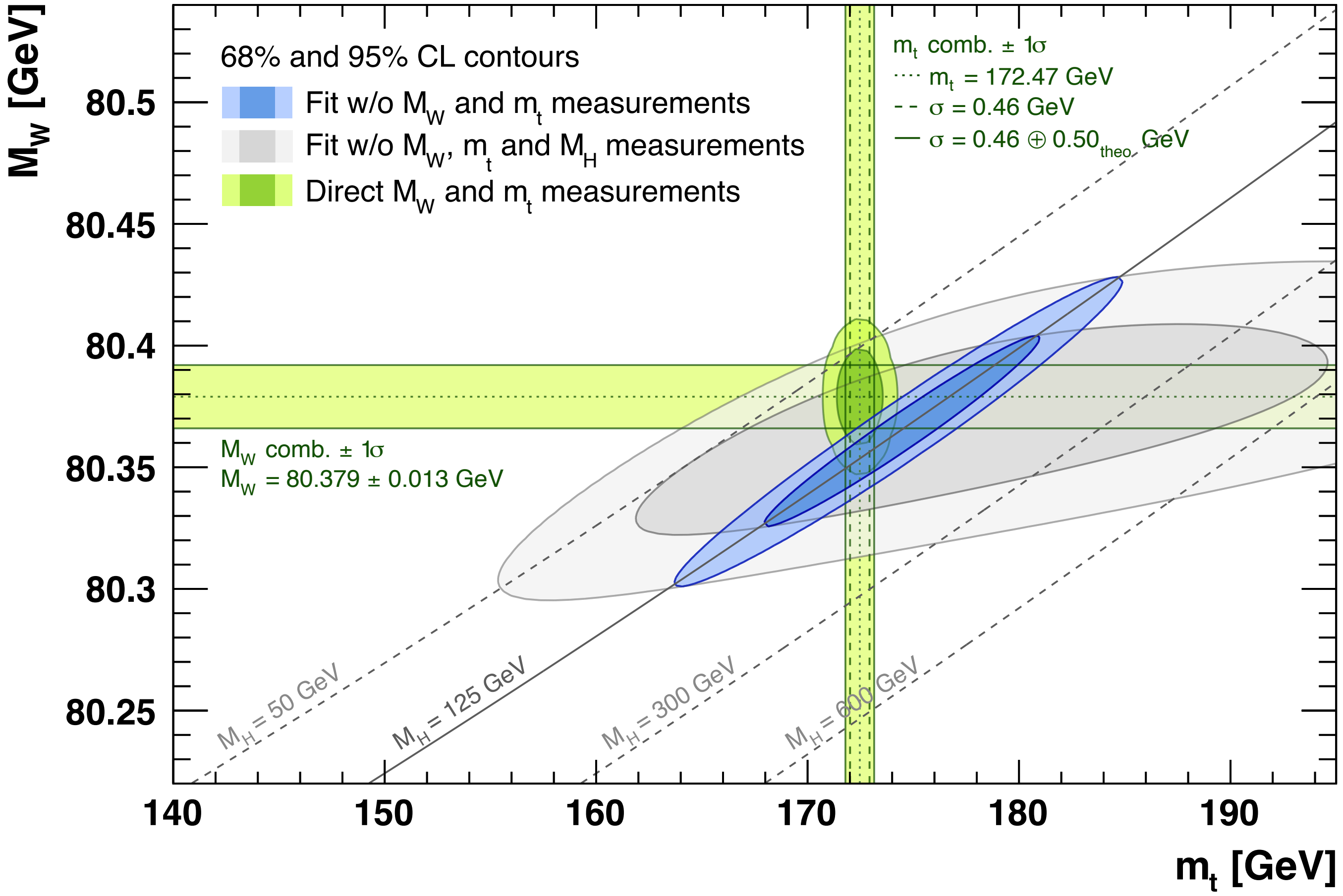
Global fits confirm the SM expectation down to the MeV level

Status of M_W measurements

PDG 2020 (results as of 2017)



Gfitter 2018: 1803.01853



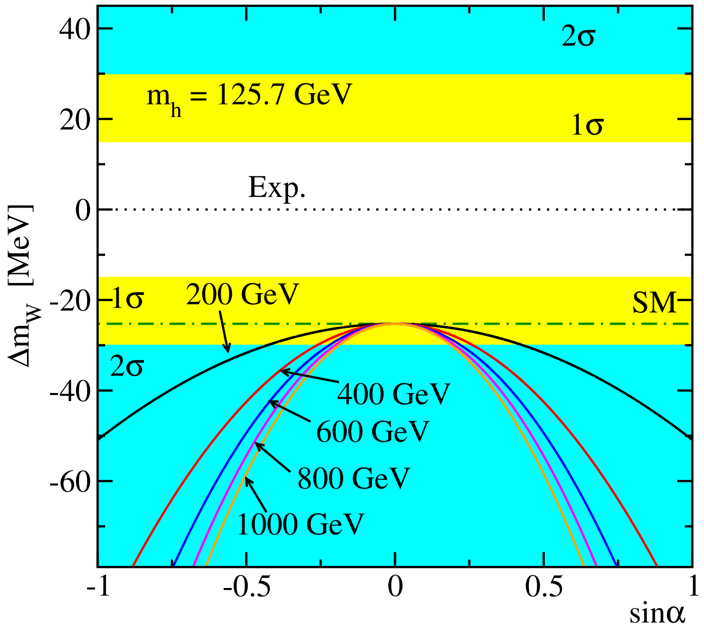
A mild (1-2σ) tension between global fit and direct measurements

Need more precise measurements of M_W and m_t in order to test efficiently the internal consistency of the SM and look for signs of new physics

M_W sensitivity to physics beyond SM

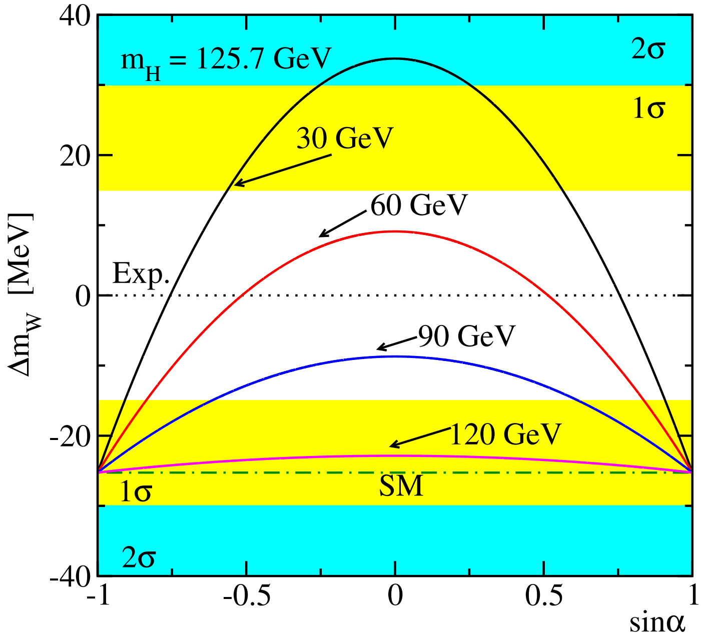
Similar to the SM case, M_W can be affected through loop corrections arising from particles proposed by various BSM theories

- Theories attempting to provide a deeper explanation of the Higgs sector:
  - Supersymmetry
  - Compositeness
  - New strong interactions
  - Extended Higgs sector
- Theories of Dark Matter particles
- Extended gauge sector



Scenario 1:
Light scalar is the SM Higgs, heavy scalar is the new particle

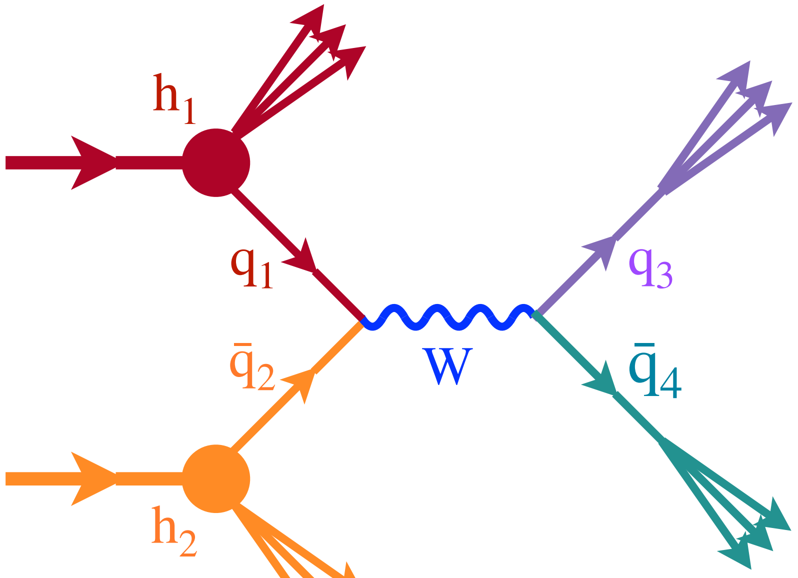
α = mixing angle



Scenario 2:
Heavy scalar is the SM Higgs, light scalar is the new particle

Illustrative example: Inclusion of an additional scalar particle with no SM charges, which mixes with the SM Higgs boson [PRD 90, 114018 (2014)]

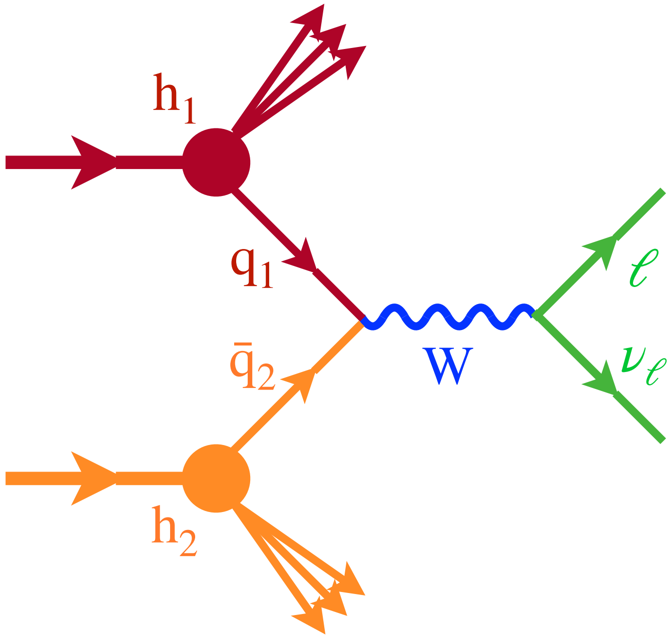
M_W measurement at hadron colliders



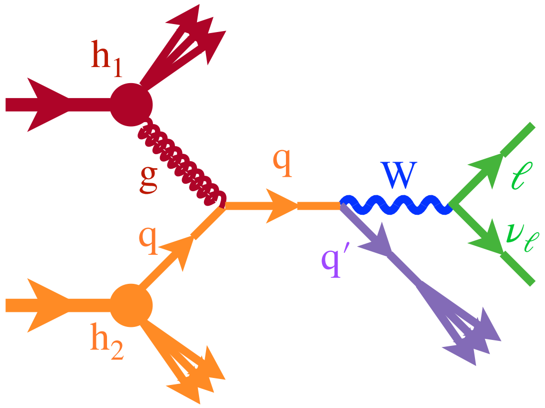
Fully reconstructable final state
but very poor resolution of jets

Tevatron: $h_1 = p, \ h_2 = \bar{p} \Rightarrow$ quark annihilation dominates (~80%)

LHC: $h_1 = p, \ h_2 = p \Rightarrow$ gluon-initiated processes dominate, e.g.:



Partially reconstructable final state
but very good resolution of lepton

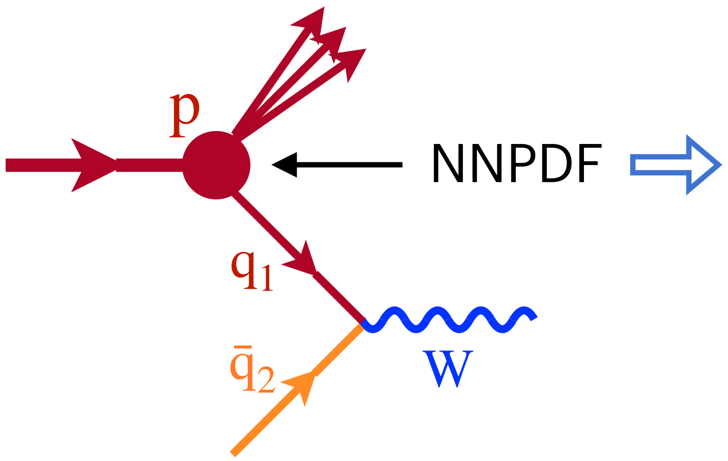


Can measure:

$$\left\{ \begin{array}{l} \vec{p}_T^{\,\ell} \\ \vec{p}_T^{\,\nu} = - \sum\limits_{\text{final state}} \vec{p}_T = \vec{\not{E}}_T \quad (\text{MET}) \\ m_T = \sqrt{2 p_T^\ell p_T^\nu \left[1 - \cos(\phi_\ell - \phi_\nu) \right]} \end{array} \right\} \Rightarrow$$

Fit M_W to p_T^ℓ, p_T^ν, and m_T spectra

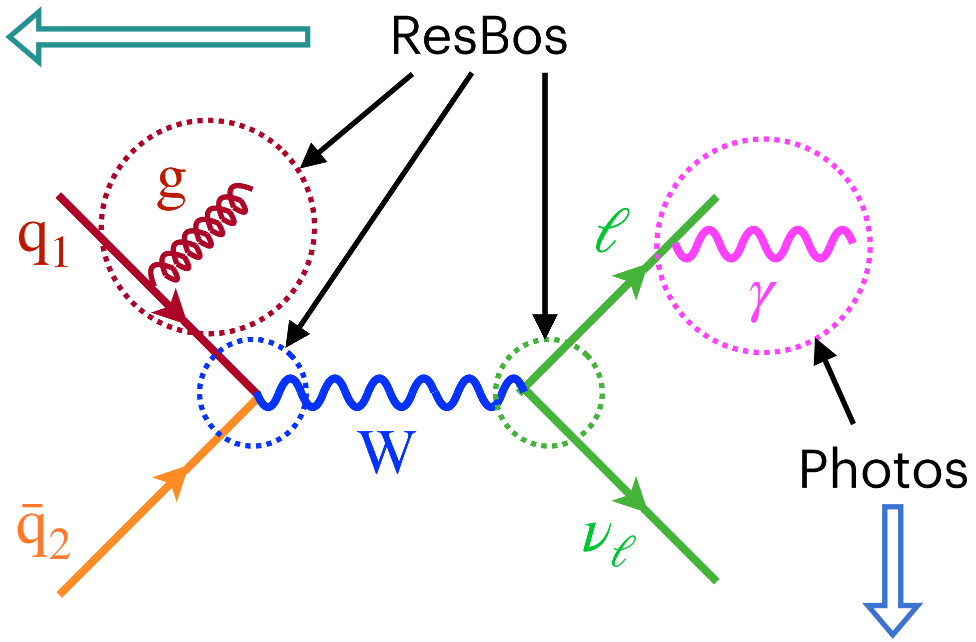
W/Z boson production and decay model



- The **NNPDF3.1** set at NNLO in α_s is used for parton densities in the proton [http://nnpdf.mi.infn.it]
- Built from gaussian-sampled “replicas” of data as inputs to ML algorithms
- Use 25 eigenvector PDF sets derived from 1000 replicas
  - ✓ Compute δM_W from each eigenvector PDF
  - ✓ Estimate the uncertainty of 3.9 MeV on M_W from the rms fit values obtained from the 25 eigenvectors

- ➡ Calculates $d\sigma/\left(dp_T^W dy_W\, dM_W\, d\cos\theta_\ell\, d\phi_\ell\right)$
- ➡ Calculation applies resummation of gluon ISR at NNLL, matched to NLO fixed-order matrix element

$$y = \frac{1}{2}\ln\frac{E + p_z}{E - p_z}$$

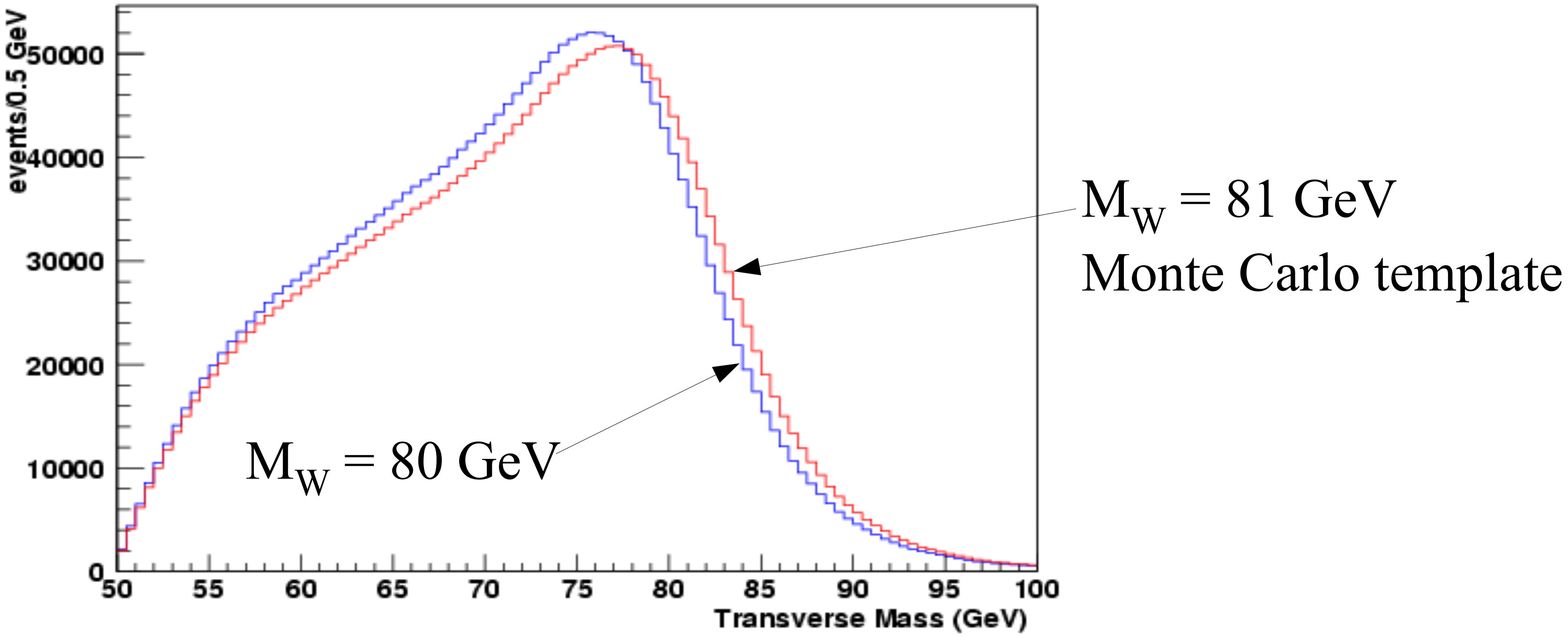


Validations confirm M_W systematic uncertainty of 3 MeV due to EM radiation

Signal simulation and template fitting

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

Example:



W and Z boson samples

Sample	Candidates
W → electron	1 811 700
Z → electrons	66 180
W → muon	2 424 486
Z → muons	238 534

- Integrated luminosity (collected between February 2002 — September 2011):
  - **$L = 8.8\ \mathrm{fb}^{-1}$** for both electron and muon channels
  - Identical running conditions for both channels guarantee cross-calibration
- Event selection gives fairly clean samples:
  - Mis-identification backgrounds ~0.5% of the signal

Analysis strategy

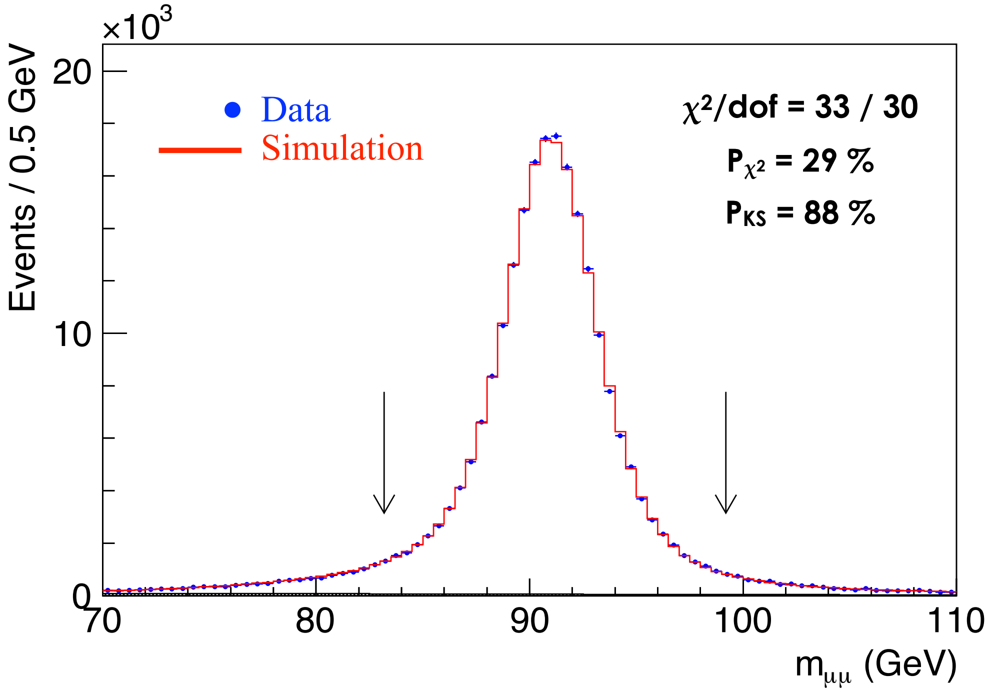
Energy scale measurements drive the W mass measurement

- ✳ Tracker calibration
  - ✓ Alignment of the Central Outer Tracker (COT) (2520 cells, 30240 sense wires) using cosmic rays
  - ✓ COT momentum scale and non-linearity constrained using $J/\psi \rightarrow \mu\mu$ and $\Upsilon \rightarrow \mu\mu$ mass fits
  - ✓ Calibration confirmed using $Z \rightarrow \mu\mu$ mass fit
- ✳ EM calorimeter calibration
  - ✓ COT momentum scale transferred to EM calorimeter using a fit to the peak of the E/p spectrum, around E/p ~ 1
  - ✓ Calorimeter energy scale confirmed using $Z \rightarrow ee$ mass fit
- ✳ Tracker and EM calorimeter resolutions
- ✳ Hadronic recoil modelling
- ✳ "Blinded" measurements of M_W in e and μ channels

Tracking momentum scale

Set by using J/ψ - Υ - Z → μμ resonances

- ➡ Fit the J/ψ mass in bins of $1/p_T(\mu)$ to measure the momentum scale at low $p_T(\mu)$ — J/ψ mass independent of $p_T(\mu)$ after 2.6% tuning of energy loss
- ➡ Fit the Υ mass to measure the momentum scale at higher $p_T(\mu)$ and validate beam-constraining procedure (Υ is prompt) by comparing the beam-constrained (**BC**) and non-beam-constrained (**NBC**) Υ mass fits



Using the momentum scale extracted from J/ψ / Υ → μμ data, perform "blind" measurement of M_Z from Z → μμ data

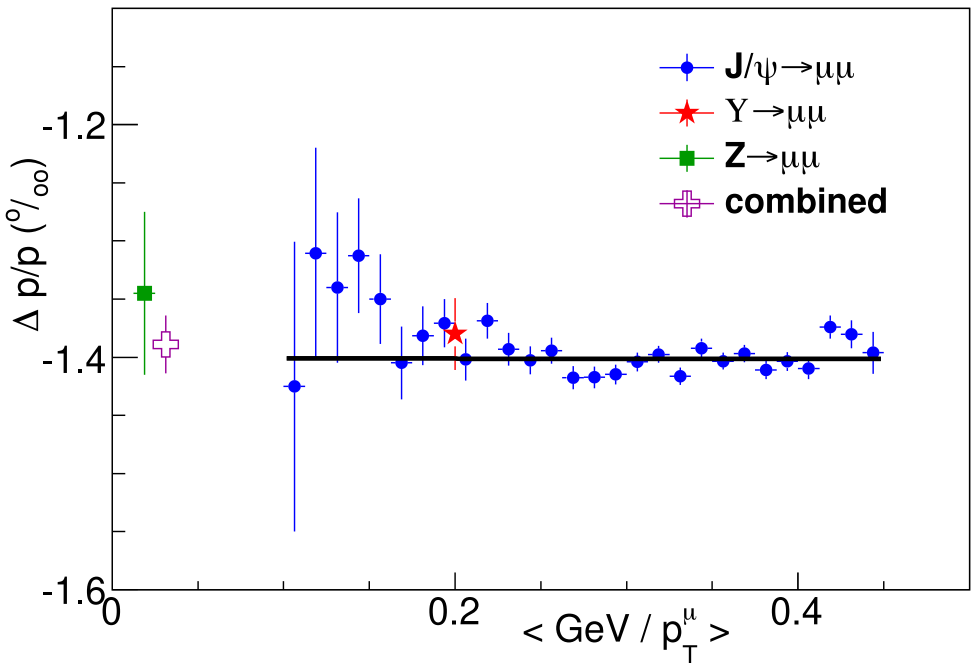
Measured M_Z consistent with PDG value of 91188 MeV

$$M_Z = 91192.0 \pm 6.4_{\text{stat}} \pm 2.3_{\text{mom. scale}} \pm 3.1_{\text{QED}} \pm 1.0_{\text{align.}}\ \text{MeV}$$

Final calibration using all J/ψ / Υ / Z → μμ fits yields an uncertainty of 2 MeV on M_W

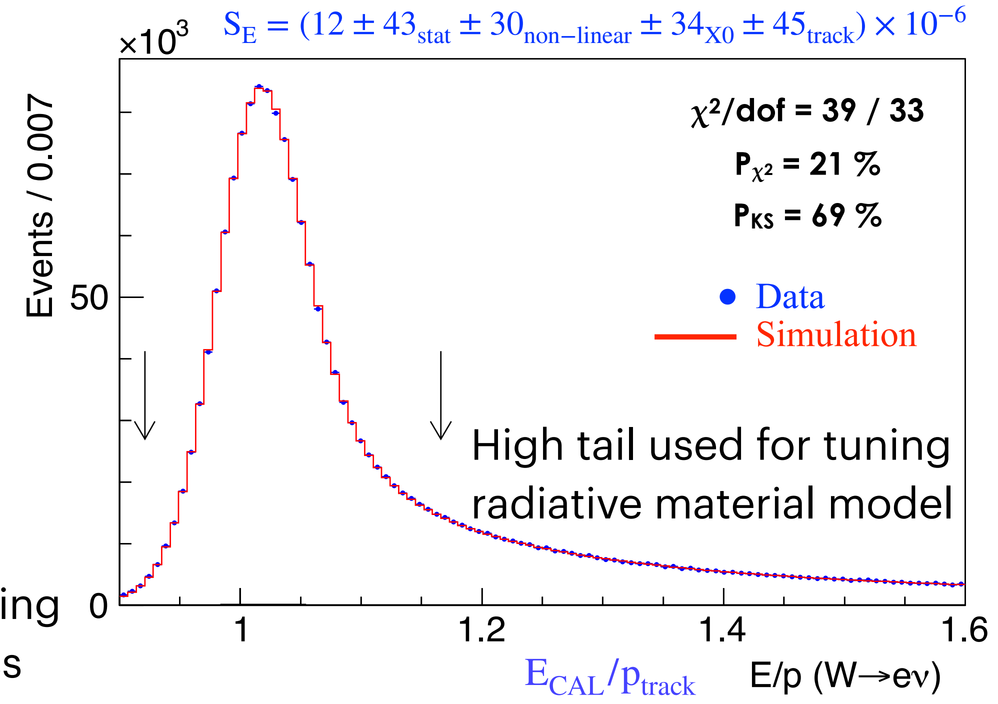
Combined momentum scale:

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



EM calorimeter response

- ➡ Energy loss distributions from GEANT4 calorimeter simulation tuned on data [NIMA 729 (2013) pp 25-35]
- ➡ Energy-dependent gain (non-linearity) determined from fits to W → eν and Z → ee E/p data in E_T bins
- ➡ Resolution model = sampling term plus constant
  - ▶ Coefficients fit to widths of E/p and Z → ee peaks



$S_E = (12 \pm 43_{stat} \pm 30_{non-linear} \pm 34_{X0} \pm 45_{track}) \times 10^{-6}$

High tail used for tuning radiative material model

Low tail used for tuning calorimeter thickness

✓ Perform "blind" measurement of M_Z from Z → ee data using E/p-based calibration

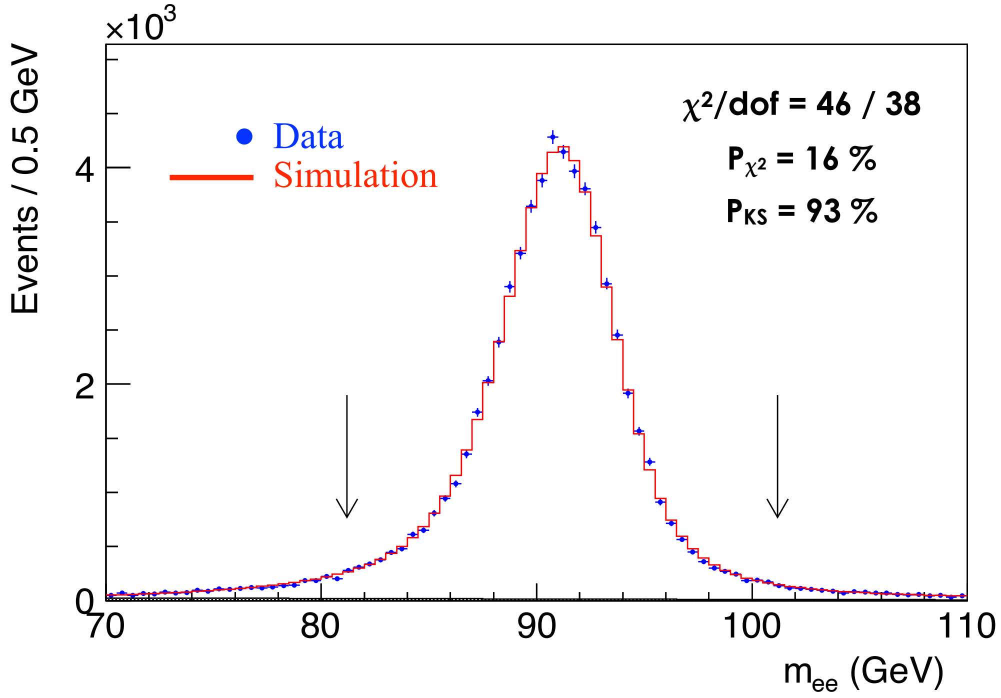
Measured M_Z consistent with PDG value of 91188 MeV

$$M_Z = 91194.3 \pm 13.8_{stat} \pm 6.5_{calor.} \pm 2.3_{mom.} \pm 3.1_{QED} \pm 0.8_{align.}\ \mathrm{MeV}$$

✓ Combine E/p calibration with Z → ee mass fit for maximum precision

Uncertainty on M_W from final calorimeter calibration 5.8 MeV

$$\Delta S_E = (-14 \pm 72)\ \text{parts per million}$$



Hadronic recoil model

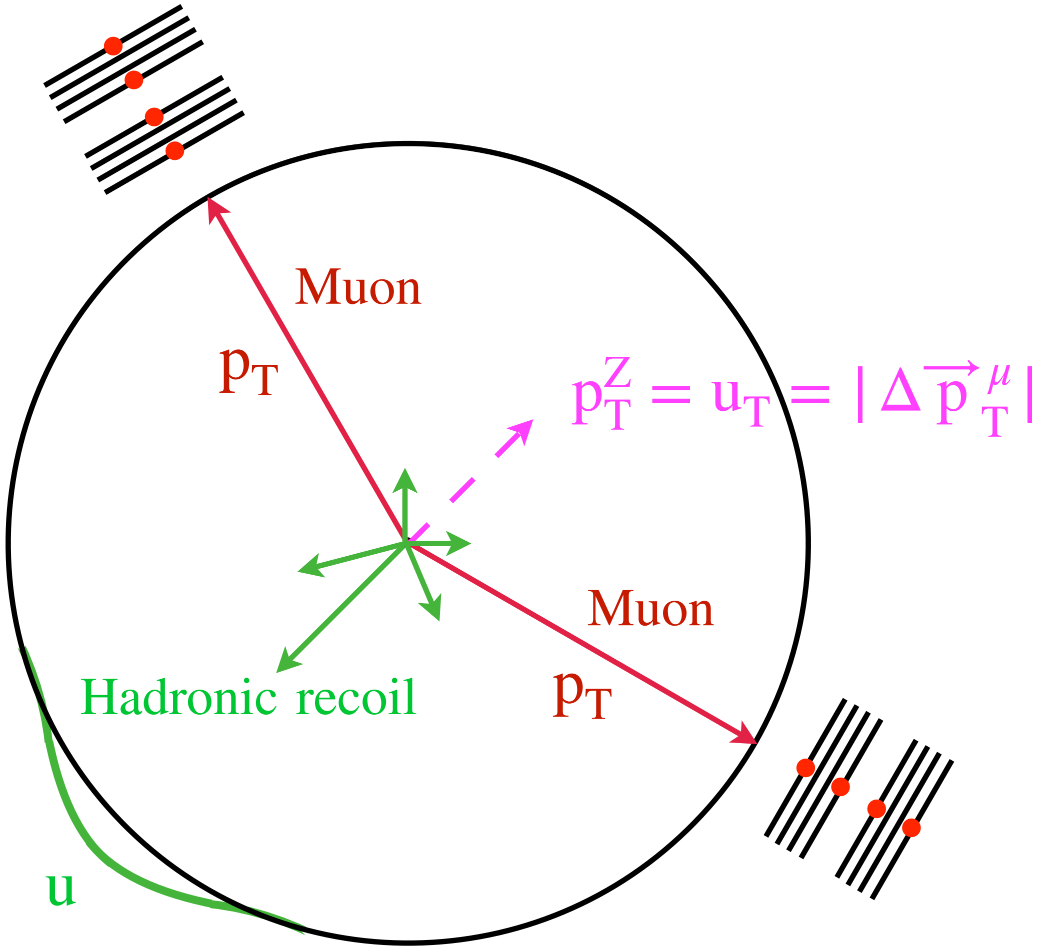
- Calorimeter towers containing lepton energy are removed from the hadronic recoil calculation

- Lost underlying event (UE) energy after lepton tower removal is recovered by rotating ϕ-windows in W boson data

- Exploit the similarity in the production and decay of W and Z bosons

- The detector response model for the hadronic recoil is tuned using the p_T balance in $Z \to \ell\ell$ events

- The transverse momentum of hadronic recoil **u** is calculated as 2D vector sum over calorimeter towers



Background fractions & associated M_W uncertainties

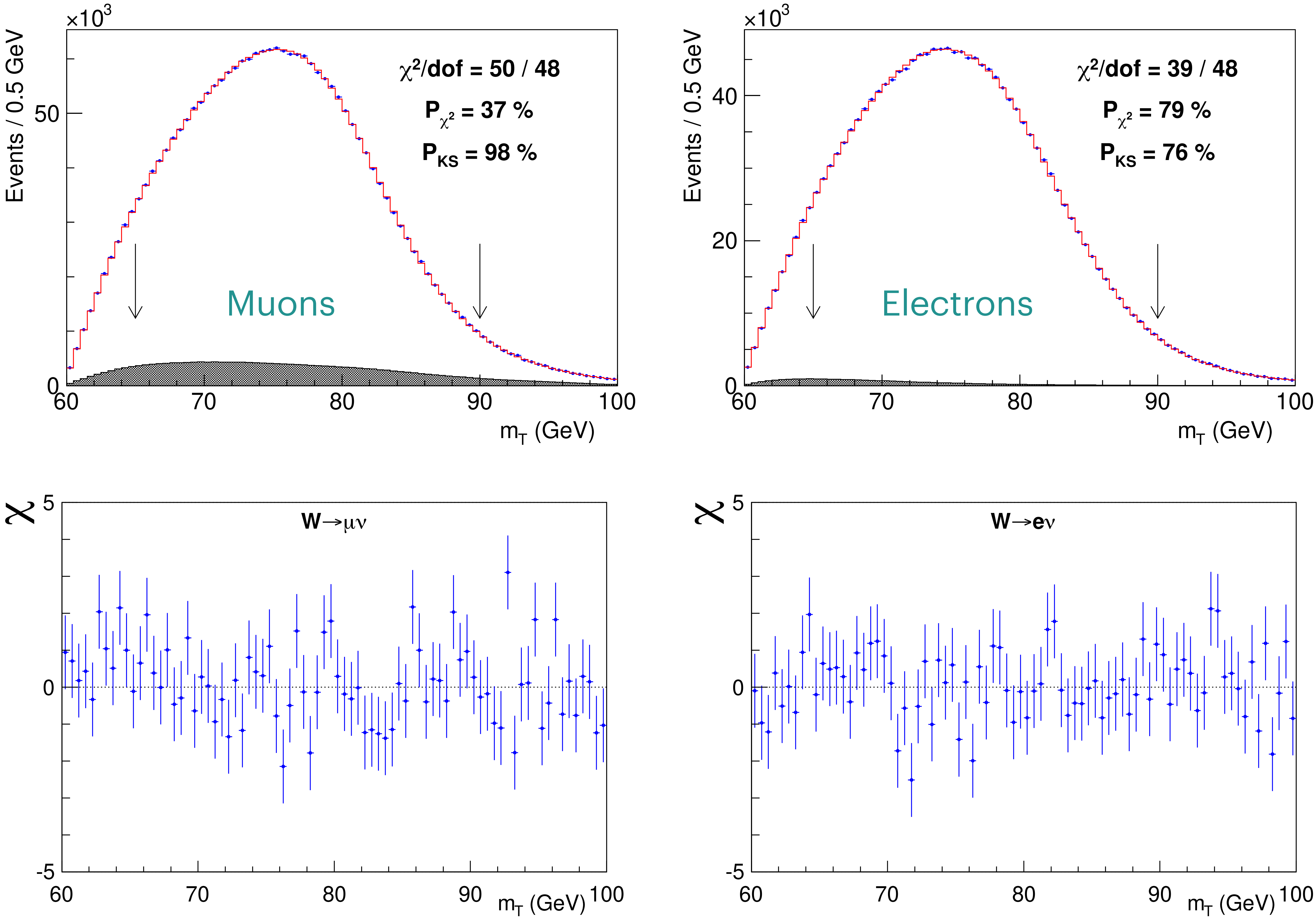
Muon channel

	Fraction	δM_W (MeV)		
Source	(%)	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)

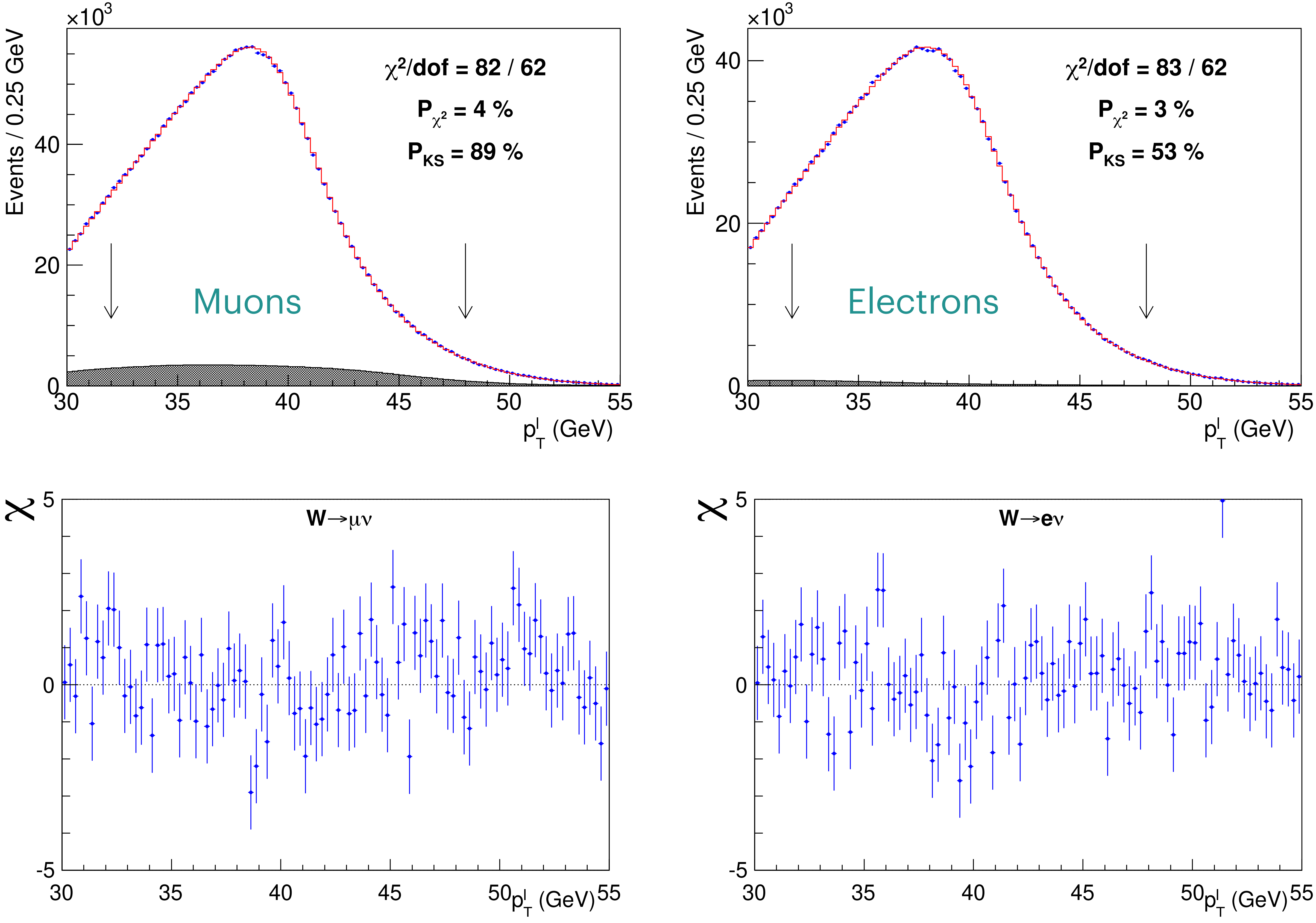
Electron channel

	Fraction	δM_W (MeV)		
Source	(%)	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)

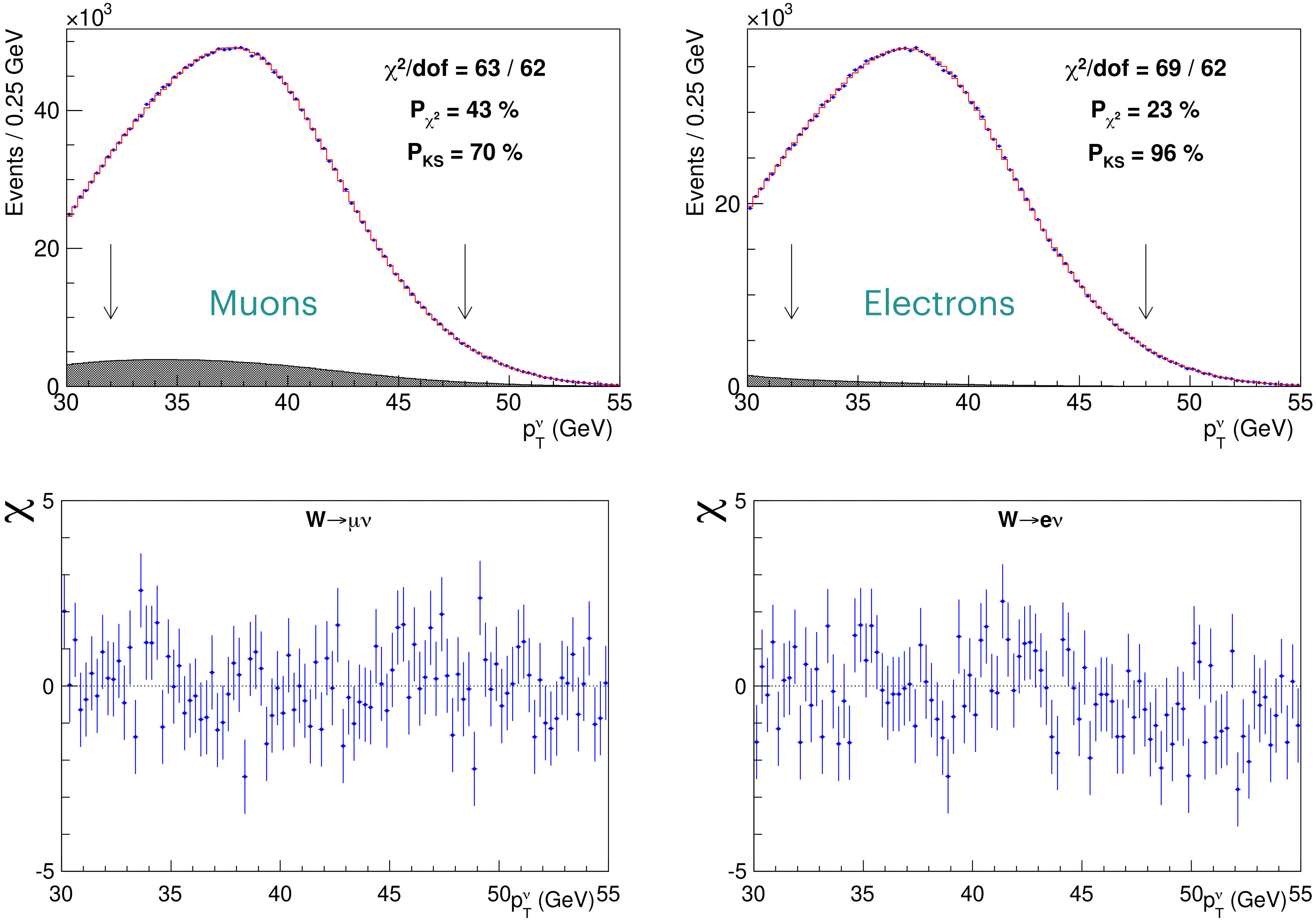
W transverse mass fits



Charged lepton p_T fits



Neutrino p_T fits



Summary of W mass fits

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

Combinations performed with the Best Linear Unbiased Estimator (BLUE) algorithm [NIMA 270, 110 (1988)], accounting for correlations determined with pseudoexperiments

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	$80\ 433.5 \pm 6.4_{\mathrm{stat}} \pm 6.9_{\mathrm{syst}}$	$7.4/5$

Consistency among all fits in both channels

Combined fit uncertainties

Source	Uncertainty (MeV)
⋆ Lepton energy scale and resolution	7
⋆ Recoil energy scale and resolution	6
Lepton removal	2
Backgrounds	3
⋆ $p_T(W)$ model	5
⋆ Parton distributions	10
QED radiation	4
W-boson statistics	12
Total	19

Uncertainties in the 2012 CDF result (2.2 fb^{-1})
[PRL 108, 151803 (2012); PRD 89, 072003 (2014)]

- ✓ Uncertainties from data-driven sources scale with integrated luminosity as expected
- ✓ Uncertainties from theory (W/Z p_T, PDF, QED) are improved by using updated theoretical inputs

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

Uncertainties in the 2022 CDF result (8.8 fb^{-1})

⋆ Dominant uncertainties

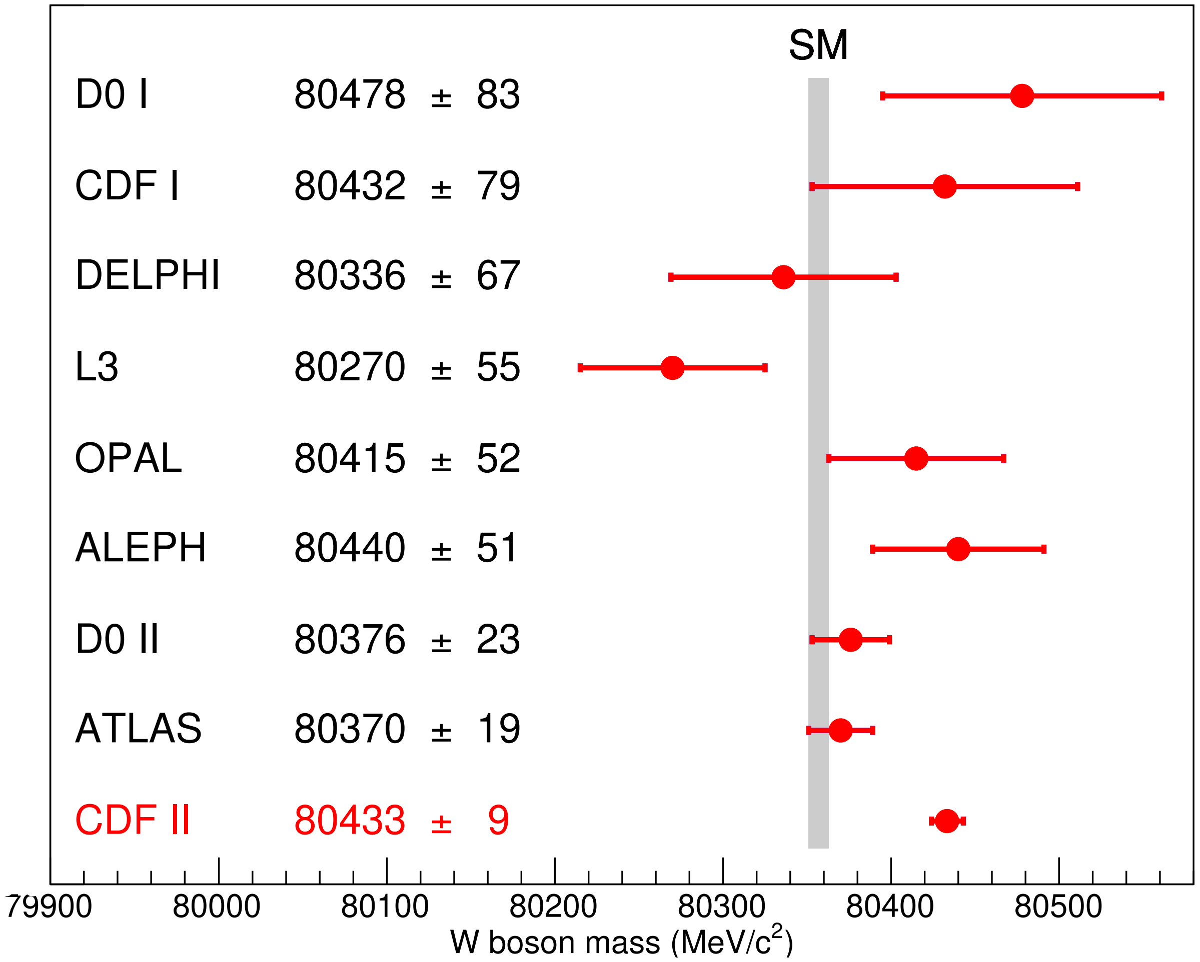
Improvements over the previous (2012) CDF measurement

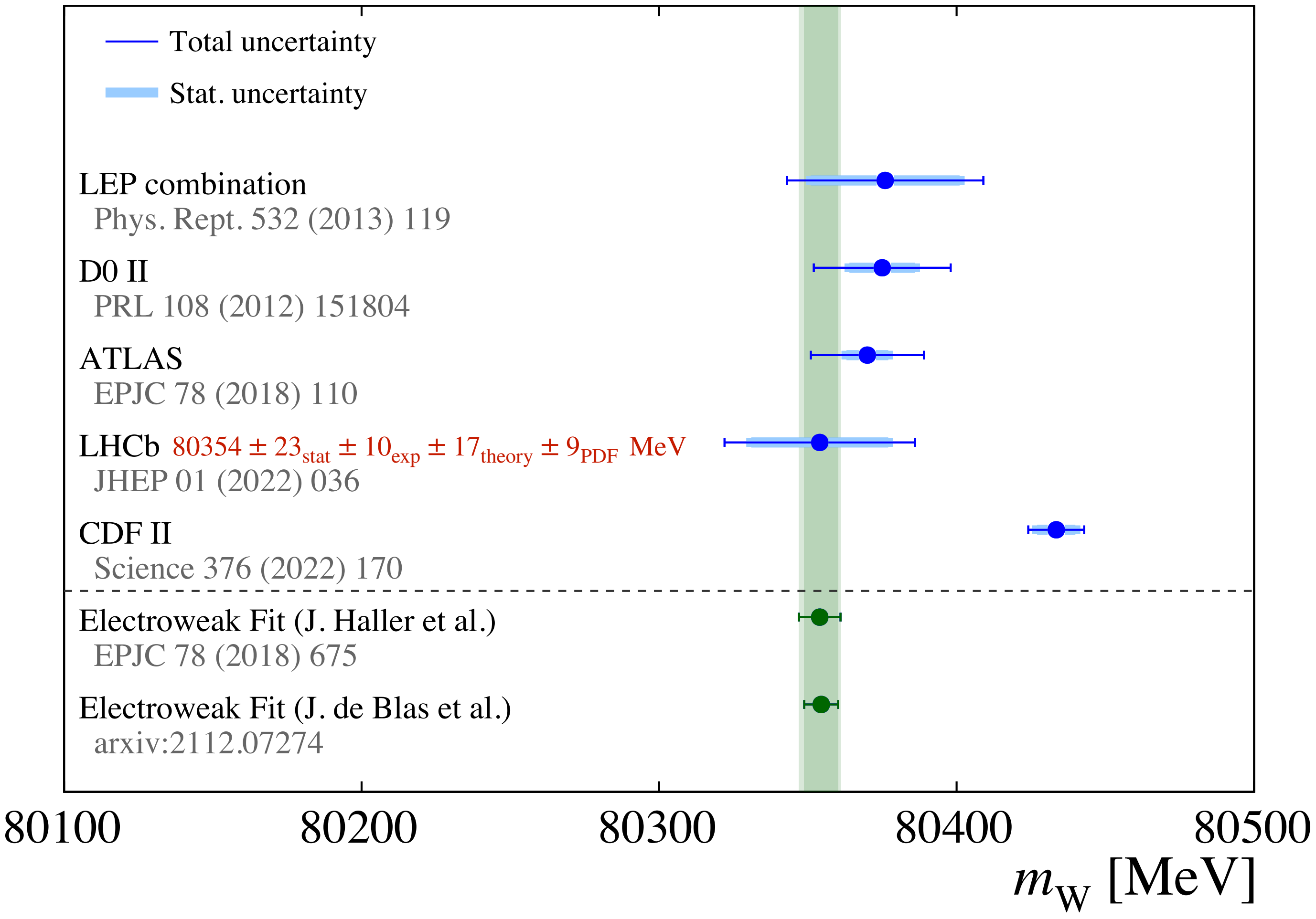
Method or technique	impact	section of paper
Detailed treatment of parton distribution functions	+3.5 MeV	IV A
Resolved beam-constraining bias in CDF reconstruction	+10 MeV	VI C
Improved COT alignment and drift model [65]	uniformity	VI
Improved modeling of calorimeter tower resolution	uniformity	III
Temporal 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

Applying the updates in PDF and track reconstruction, the 2012 result shifts to

$$\mathrm{M}_{\mathrm{W}}^{2012} = 80\,400.5 \pm 19\ \mathrm{MeV}$$

Updated status of M_W measurements





- Strong tension with SM expectation and global fit (7σ)
- Tension with recent LHC results (2-3σ)
- Still need higher precision from LHC to arrive at a firm conclusion

Summary

- ✳ The W boson mass measurement is a topic of great challenge, and thus of slow progress, but is reaching a really impressive precision at hadron colliders
- ✳ The achieved precision allows for tightly testing the internal consistency of the SM
- ✳ The new CDF measurement is twice as precise as previous measurements, with a total uncertainty of ~1 part in 10,000 [Science, 376:170-176, 04 (2022) & supp. material]:

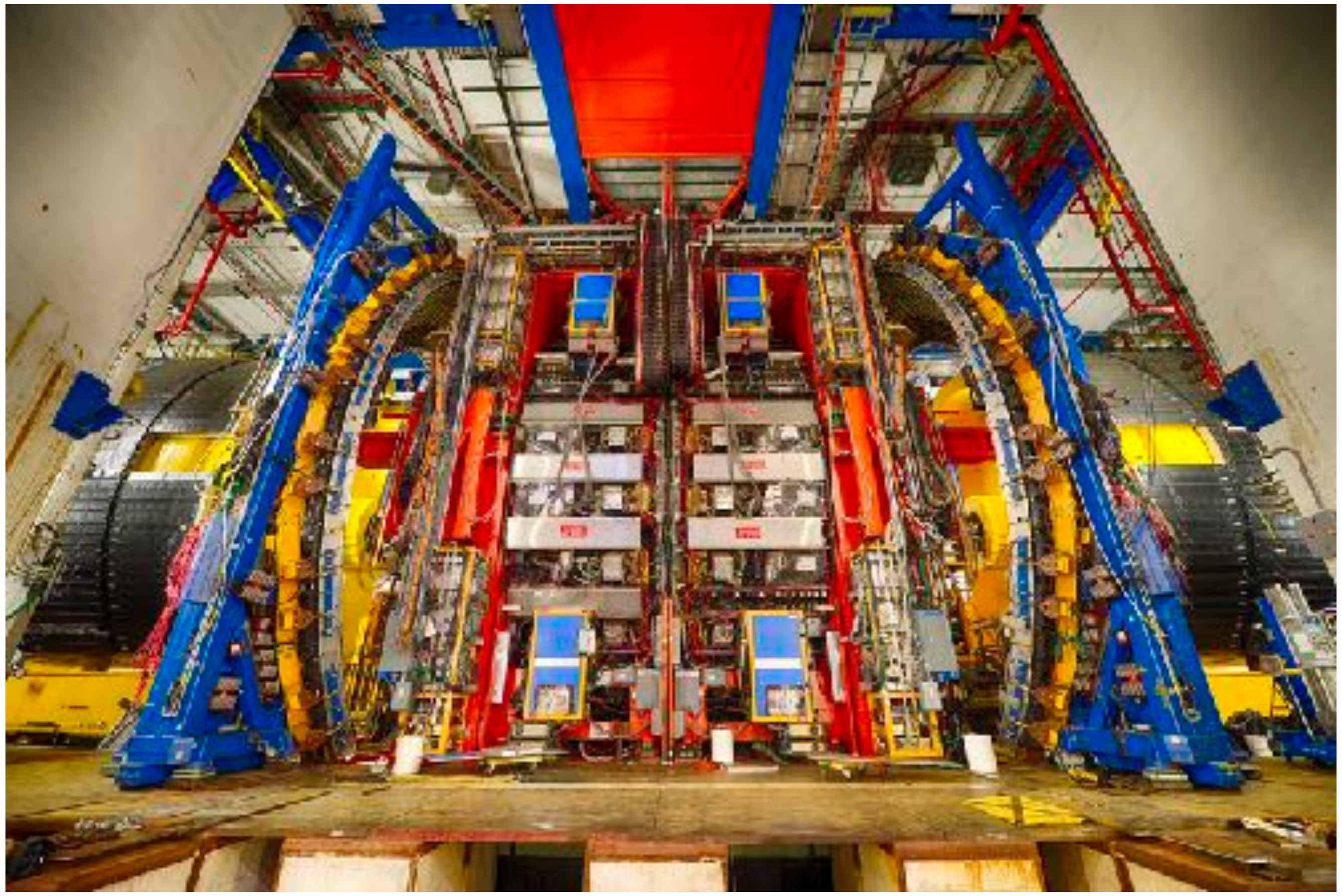
$$M_W = 80\,433.5 \pm 6.4_{stat} \pm 6.9_{syst}\ \text{MeV} \;=\; 80\,433.5 \pm 9.4\ \text{MeV}$$

- ✳ The new result differs from the SM expectation $M_W = 80\,357 \pm 6\ \text{MeV}$, with a significance of 7.0 σ
- ✳ The difference suggests the possibility of improvements to the SM calculation or of extensions to the SM

Backup

Tevatron and CDF

The Collider Detector at Fermilab (CDF)



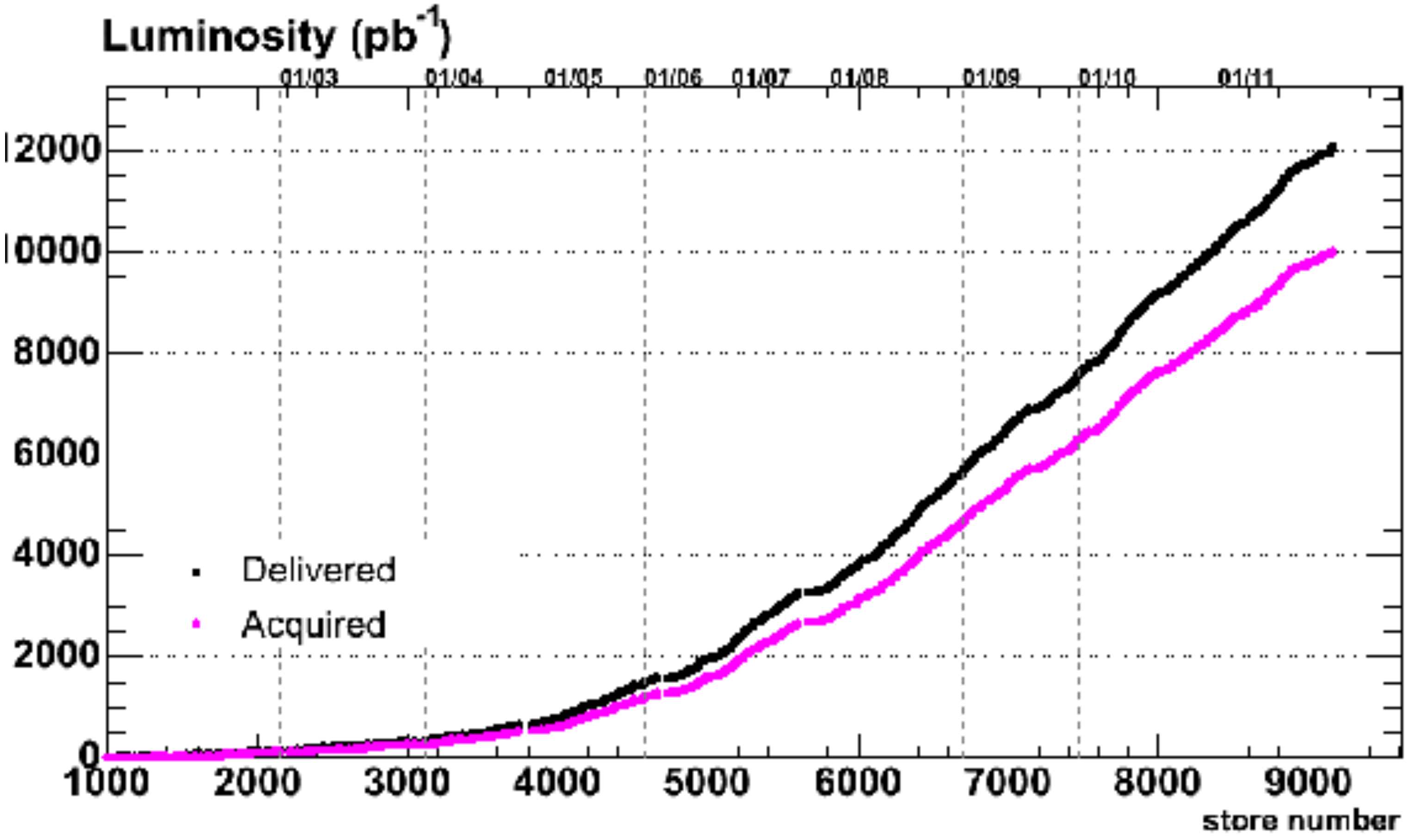
Side view

Front view

Size: 12×16 m
Weight: 4,500 tons

The void after the detector removal

CDF Run II data



Delivered 12 fb^{-1}
Acquired 10 fb^{-1}/experiment

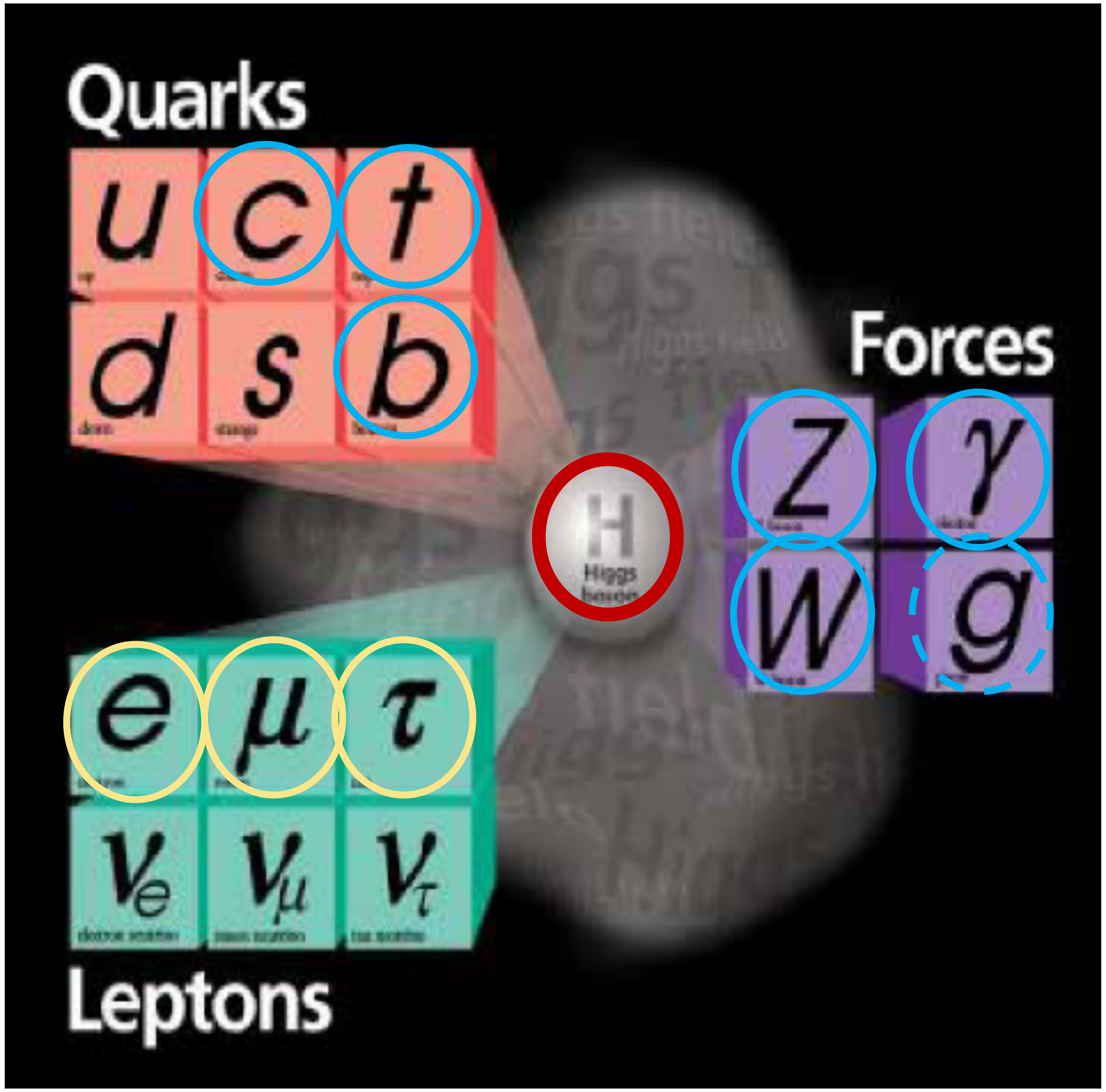
15B events total in Run II

Total dataset 10 + 9 PB
(including Monte Carlo)

- Special track & vertex triggers
- Coverage for “soft” physics
- Variety of collision energies (300, 900, 1960 GeV)
- **Unique p-pbar initial state** (complementary to LHC)

Physics potential

All about the Standard Model – and beyond:
https://cdf.fnal.gov/physintro.html



- ✦ Discoveries
  - ✓ New particles
  - ✓ Rare SM processes
  - ✓ Subtle behaviour
- ✦ Precision measurements
- ✦ Searches for new physics
- ✦ Hunting down the Higgs

➡ **600 PhDs**

➡ **700 papers**

➡ **50,000 citations**

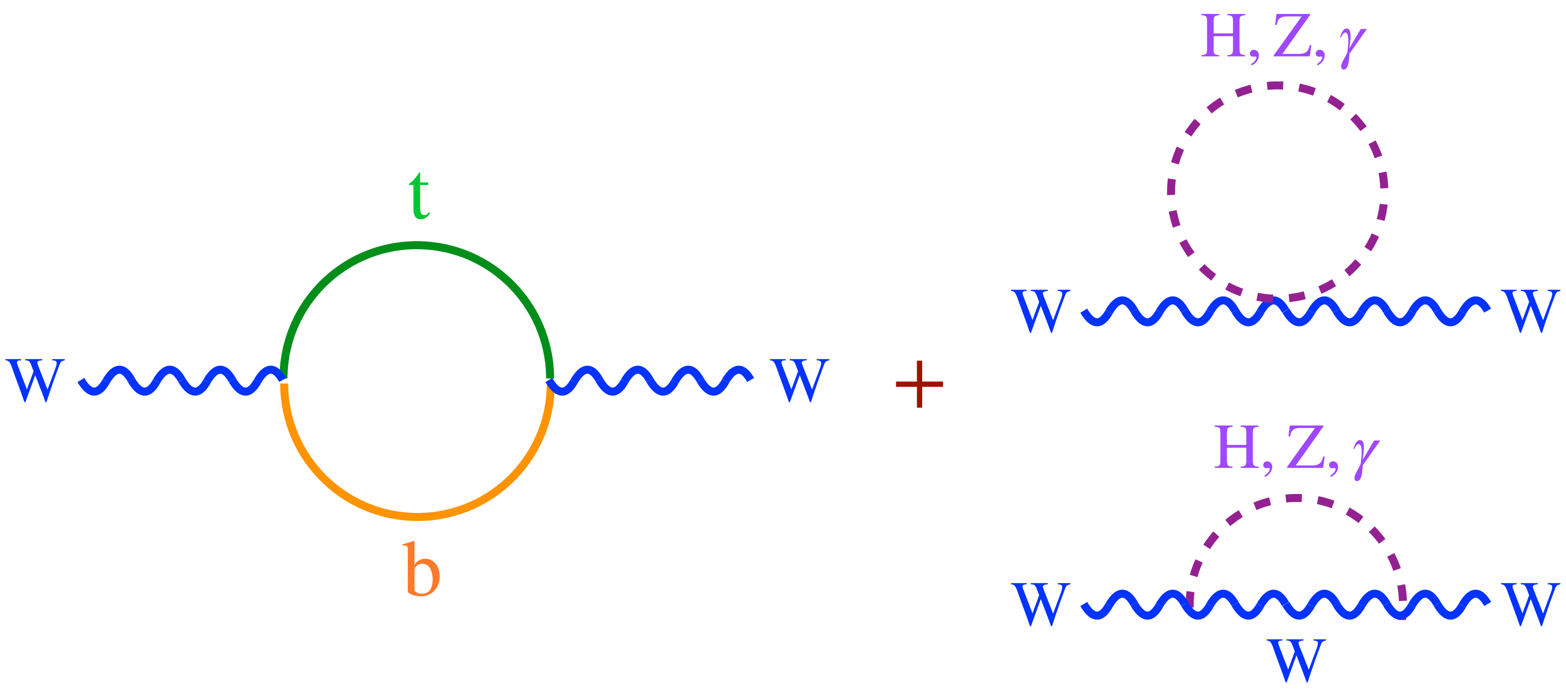
The CDF Collaboration

30 September 2011

Currently 400 members from 60 institutions around the World

Motivation

Loop corrections to M_W



$$\Rightarrow \Delta r \sim m_t^2\,,\ \ln M_H\,,\ \Delta\alpha\,,\ \ldots$$

↓ Running EM coupling

SM expectation for M_W:

PDG 2020

$$M_W = 80357 \pm 4_{\text{inputs}} \pm 4_{\text{theory}}\ \text{MeV} = 80357 \pm 6\ \text{MeV}$$

Global fits test the SM expectation down to the MeV level, e.g. for M_H = 125 GeV:

arXiv:1902.05142

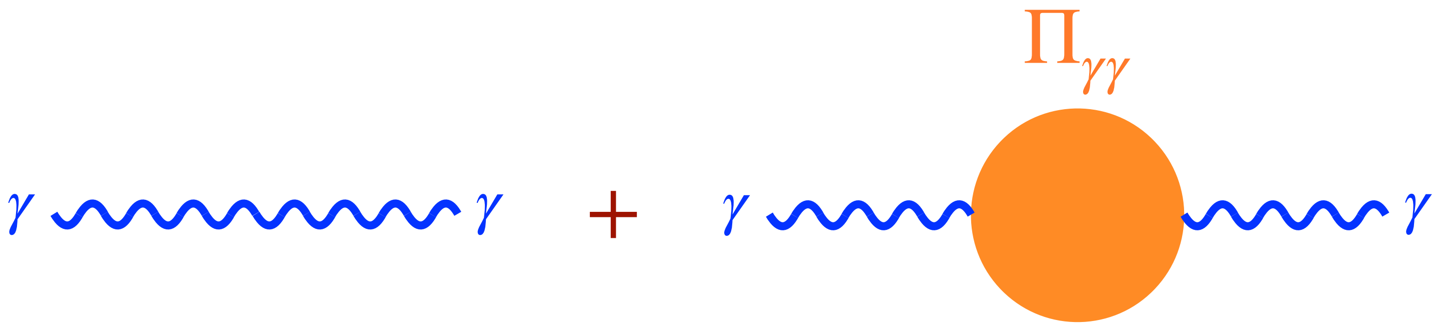
$$M_W = \left(M_W^{(0)} + c_t\Delta_t + c_t'\Delta_t^2 + c_Z\Delta_Z + c_\alpha\Delta_\alpha + c_{\alpha_s}\Delta_{\alpha_s}\right)\ \text{MeV}$$

$$\Delta_t = \left(\frac{m_t}{173\ \text{GeV}}\right)^2 - 1, \quad \Delta_Z = \frac{M_Z}{91.1876\ \text{GeV}} - 1, \quad \Delta_\alpha = \frac{\Delta\alpha_{\text{had}}^{(5)}(M_Z^2)}{0.0276} - 1, \quad \Delta_{\alpha_s} = \frac{\alpha_s(M_Z^2)}{0.119} - 1$$

$$M_W^{(0)} = 80359.5, \quad c_t = 520.5, \quad c_t' = -67.7, \quad c_Z = 115000, \quad c_\alpha = -503, \quad c_{\alpha_s} = -71.6$$

Running EM coupling for M_W

$$\alpha = \frac{e^2}{4\pi}\left[1 + \lim_{q^2\to 0}\frac{\Pi_{\gamma\gamma}(q^2)}{q^2}\right]$$



The hadronic contribution to $\Pi_{\gamma\gamma}(0)$ cannot be computed perturbatively, but it can be traded for another experimental observable: $R_{had}(q^2) = \sigma_{had}(q^2)\,/\,\sigma_{\ell^+\ell^-}(q^2)$

arXiv:1902.05142

$$\alpha(M_Z^2) = \frac{e^2}{4\pi}\left[1 + \frac{\Pi_{\gamma\gamma}(M_Z^2)}{M_Z^2}\right] = \frac{\alpha}{1 - \Delta\alpha(M_Z^2)}$$

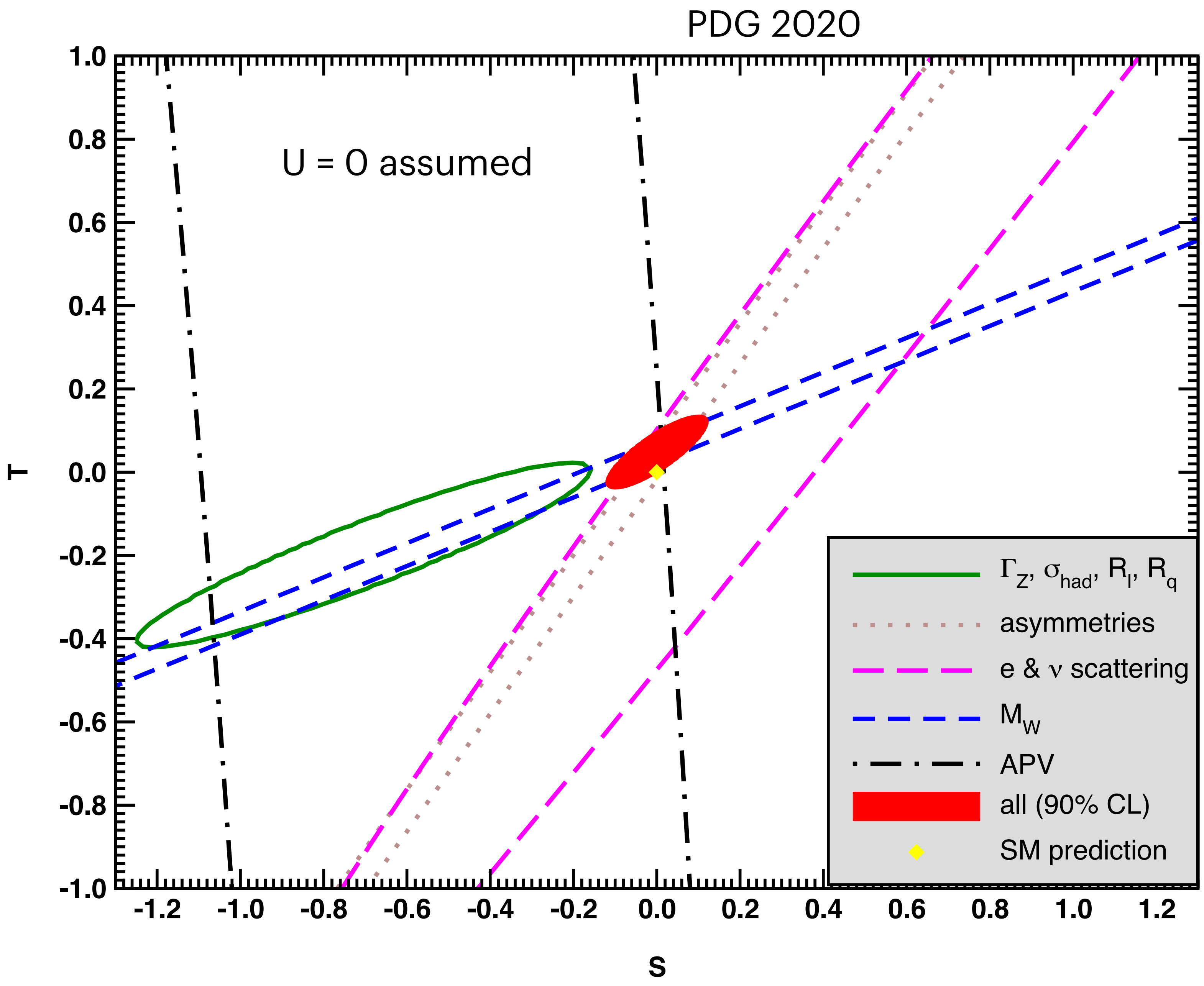
$$\Delta\alpha(M_Z^2) = \underbrace{\Delta\alpha_{\ell}(M_Z^2) + \Delta\alpha_{top}(M_Z^2)}_{\text{calculable}} + \Delta\alpha^{(5)}_{had}(M_Z^2)$$

$$\Delta\alpha^{(5)}_{had}(M_Z^2) = -\frac{M_Z^2}{3\pi}\int_{(2m_\pi)^2}^{\infty}\frac{R_{had}(q^2)dq^2}{q^2(q^2 - M_Z^2)} = 0.02758 \pm 0.00035$$

$\Delta\alpha^{(5)}_{had}(M_Z^2)$ is one of the biggest sources of uncertainty in electroweak studies

Constraints on new physics from M_W measurements

Generic parameterisation of new physics (except extended EWK sector) contributing to vacuum polarisation corrections on 4-fermion scattering processes: Peskin-Takeuchi “oblique” parameters S, T, U



Additionally, M_W is the only observable constraining U

M_W and asymmetries are the most powerful observables

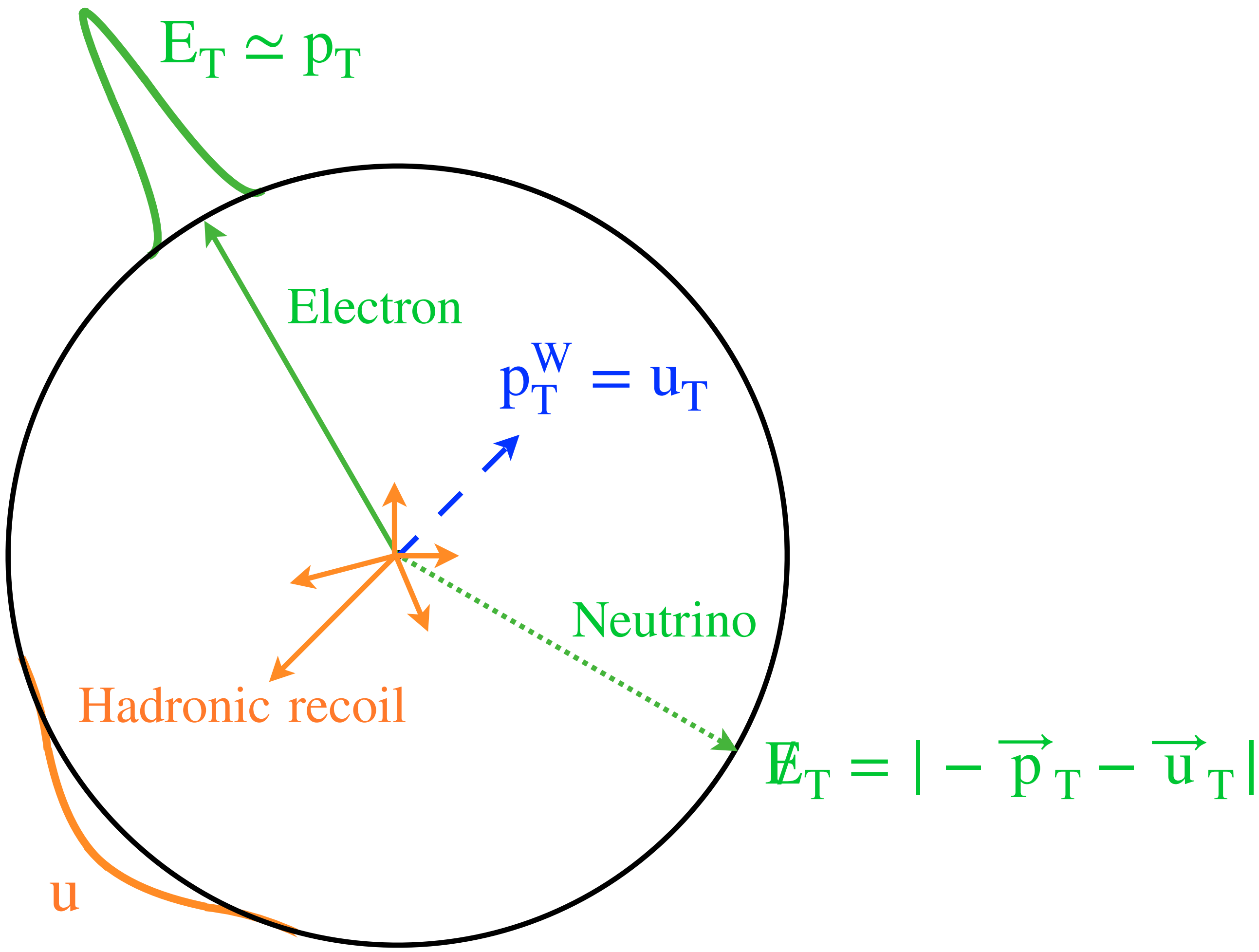
Analysis strategy

W boson production and decay

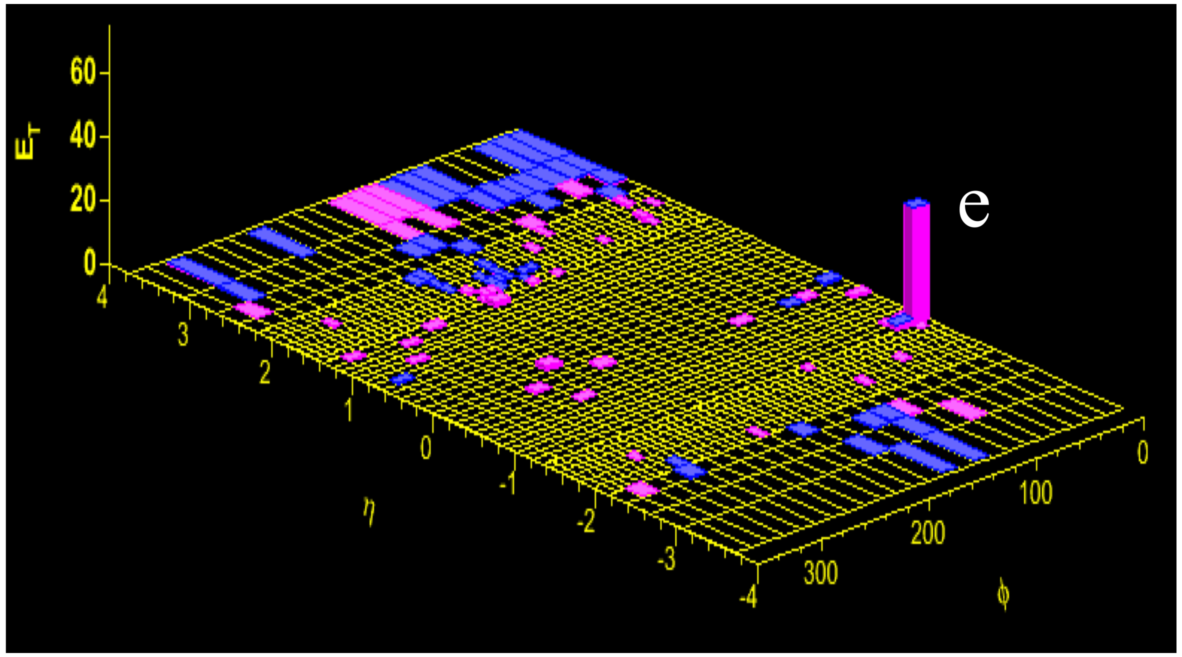
Lepton p_T carries most of the M_W information and can be measured precisely (achieved 0.004%)

Hadronic activity from initial state ("hadronic recoil"), of O(10 GeV), is measured in the calorimeter (calibrated to ~0.2%)

Non-W backgrounds are small and partly measured from data



CDF event display



p_T^ℓ, p_T^ν, and m_T templates are simulated as functions of M_W using accurate models of:

- Initial state (anti)proton
- W production mechanism
- W decay mechanism

Event selection

- Goal: Select events with high p_T central ($|\eta| < 1$) leptons and small hadronic recoil activity, to maximise M_W information content and minimise backgrounds

- Use inclusive lepton triggers: loose lepton track and muon stub / calorimeter cluster requirements, with lepton $p_T > 18$ GeV
  - Kinematic efficiency of trigger ~100% for offline event selection

- Offline selection requirements:
  - Electron cluster $E_T > 30$ GeV, track $p_T > 18$ GeV
  - Muon track $p_T > 30$ GeV
  - Loose lepton identification requirements to minimise bias

- W boson event selection: one selected lepton, $|u| < 15$ GeV and MET > 30 GeV

- Z boson event selection: two selected leptons

Analysis strategy

Maximise the number of internal constraints and cross-checks

Driven by three conditions:

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

2. *Precision: combine independent measurements after showing consistency*

3. *Bias minimisation: blinded measurements of M_Z and M_W*

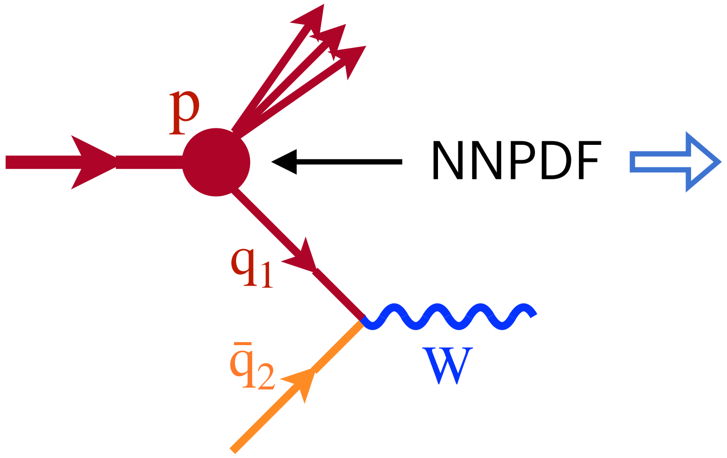
   - All W and Z mass fit results were blinded with a random offset in the range [–50,50] MeV

   - The blinding offset was removed after the analysis was declared frozen

   - The technique allows to study all aspects of the data while keeping the M_Z and M_W results unknown within ± 50 MeV

Simulation

Model of the colliding protons



- The **NNPDF3.1** set at NNLO in α_s is used for parton densities in the proton [http://nnpdf.mi.infn.it]
- Built from gaussian-sampled “replicas” of data as inputs to ML algorithms
- Use 25 eigenvector PDF sets derived from 1000 replicas
  - ✓ Compute δM_W from each eigenvector PDF
  - ✓ Estimate the uncertainty of 3.9 MeV on M_W from the rms fit values obtained from the 25 eigenvectors
- Central M_W values from NNPDF3.1 and from other NNLO sets (CT18, MMHT2014) agree within 2.1 MeV
- Central M_W values from NNPDF3.1 at NLO and from other NLO sets (ABMP16, CJ15, MMHT2014) agree within 3 MeV
- M_W uncertainty from missing higher-order QCD effects is estimated to be 0.4 MeV
  - ✓ varying the factorisation and renormalisation scales
  - ✓ comparing the results obtained with two event generators using different models of soft gluon radiation (ResBos and MadGraph aMC@NLO + Pythia)

W/Z boson production and decay model

- The production model must account for the hadronic activity in the initial state
- The perturbative expansion of $d\sigma/dp_T^W$ has terms proportional to $\alpha_s^n \ln^{2n}\left(p_T^2/M_W^2\right)$
- The series diverges as $p_T^W \to 0$
- Need to include corrections to all orders by resumming the series

Two resummation methods

Analytical

- Formal resummation matched to fixed-order matrix element
- Pros:
  - High accuracy
- Cons:
  - Inclusive final states only
  - Numerically expensive
- Used by CDF to fit M_W

Numerical

- Parton showers
- Pros:
  - Exclusive final states
  - Fast
- Cons:
  - Currently only LL with some subleading effects included
- Used by ATLAS to fit M_W

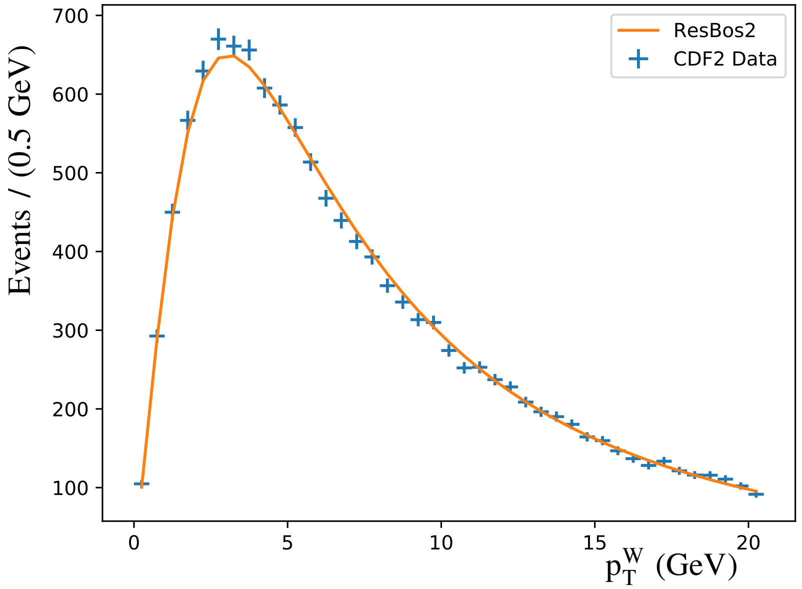
- The decay model must account for spin correlations among W/Z and the leptons, and for EM radiation from the charged particles

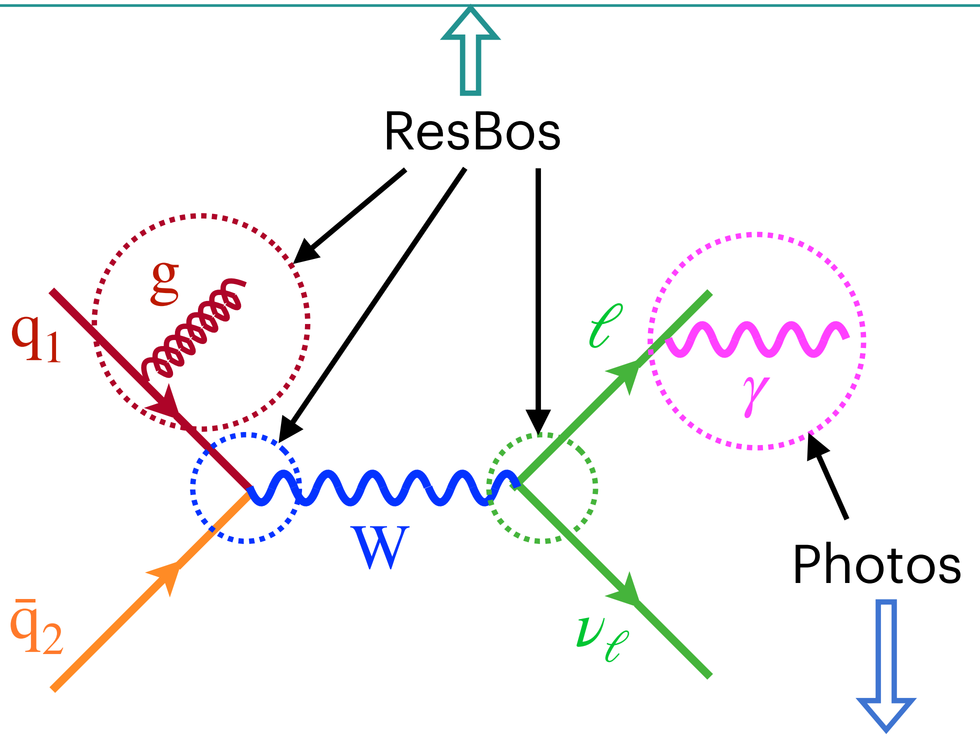
W/Z boson production and decay model

- ✳ The model used by CDF for W/Z boson production and decay is provided by **ResBos** [PRD 56, 5568 (1997) & refs. therein]
- ✳ The model used for multi-photon radiation is generated with **Photos** [EPJC 45, 97 (2006) & refs. therein] and validated comparing with **Horace** [JHEP 0710:109 (2007)]

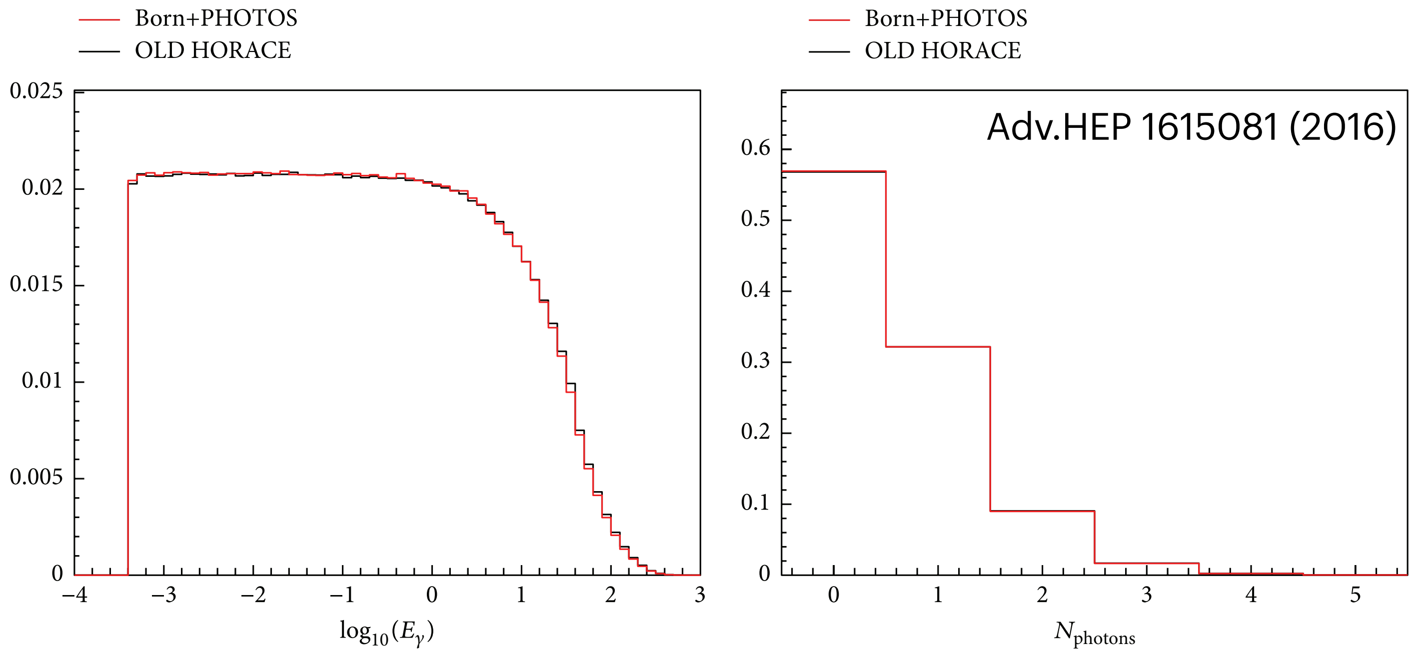
- ➡ Calculates $d\sigma/\left(dp_T^W dy_W\, dM_W\, d\cos\theta_\ell\, d\phi_\ell\right)$
- ➡ Calculation applies resummation of gluon ISR at NNLL, matched to NLO fixed-order matrix element

$$y = \frac{1}{2}\ln\frac{E+p_z}{E-p_z}$$




ResBos

Photos



Adv.HEP 1615081 (2016)

Validations confirm M_W systematic uncertainty of 3 MeV due to EM radiation

ResBos tuning

ResBos implements the Collins-Soper-Sterman formalism, which performs transverse momentum resummation in the impact parameter (b) space:

arXiv:2205.02788

LO squared matrix element

Fixed-order terms, finite in the limit $p_T \to 0$

$$\frac{d\sigma}{dQ^2 d^2\vec{p}_T dy d\cos\theta d\phi} = \sigma_0 \int \frac{d^2b}{(2\pi)^2} e^{i\vec{p}_T\cdot\vec{b}}\, W(b) + Y\left(Q, \vec{p}_T, x_1, x_2, \mu_R, \mu_F\right)$$

$$W(b) = e^{-S(b)}\, C\otimes f\left(x_1, C_3/b\right)\; C\otimes f\left(x_2, C_3/b\right) \longleftarrow$$

Collinear factors

Sudakov factor

$$S(b) = \int_{C_1^2/b}^{C_2^2Q^2} \frac{d\bar{\mu}^2}{\bar{\mu}^2}\left[\ln\left(\frac{C_2^2Q^2}{\bar{\mu}^2}\right) A\left(\bar{\mu}, C_1\right) + B\left(\bar{\mu}, C_1, C_2\right)\right]$$

$$x_{1,2} = \frac{Q}{\sqrt{s}} e^{\pm y}$$

Perturbative coefficients A, B, C

$$C\otimes f = \text{convolution of the hard collinear kernel with the PDF}$$

The lower limit C_1^2/b tends to 0 as $b \to \infty$, causing the integral S(b) to diverge, thus:

$$b^* = \frac{b}{\sqrt{1 + b^2/b_{max}^2}} \Rightarrow S(b) = S_{NP}(b) S_P(b^*),\; S_{NP}(b) = -b^2\left[g_1 + g_2\ln\left(\frac{Q}{2Q_0}\right) + g_1 g_3 \ln(100 x_1 x_2)\right]$$

g_1 (flavour-dependent) and g_3 constrained by the global fit, g_2 tuned to reproduce CDF $p_T(Z)$ data, with M_W — M_Z difference captured in Q dependence (Q_0 = 1.6 GeV)

ResBos angular coefficients

arXiv:2205.02788

$$\frac{d\sigma}{dQ^2 d^2\vec{p}_T dy d\cos\theta d\phi} = \frac{3}{16\pi}\frac{d\sigma}{dQ^2 d^2\vec{p}_T dy}$$

$$\otimes\Big[(1+\cos\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_1\sin 2\theta\cos\phi + \frac{1}{2}A_2\sin^2\theta\cos 2\phi$$

$$+ A_3\sin\theta\cos\phi + A_4\cos\theta + A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi\Big]$$

Only this survives at LO ($A_4^{LO} = 2$) due to the $V - A$ structure of the electroweak interaction

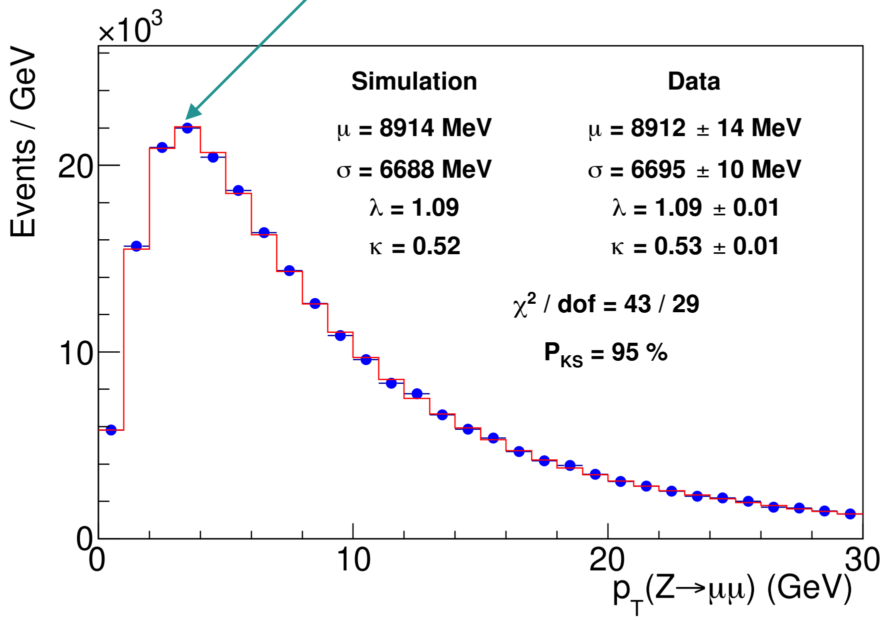
Non-zero at NNLO and beyond

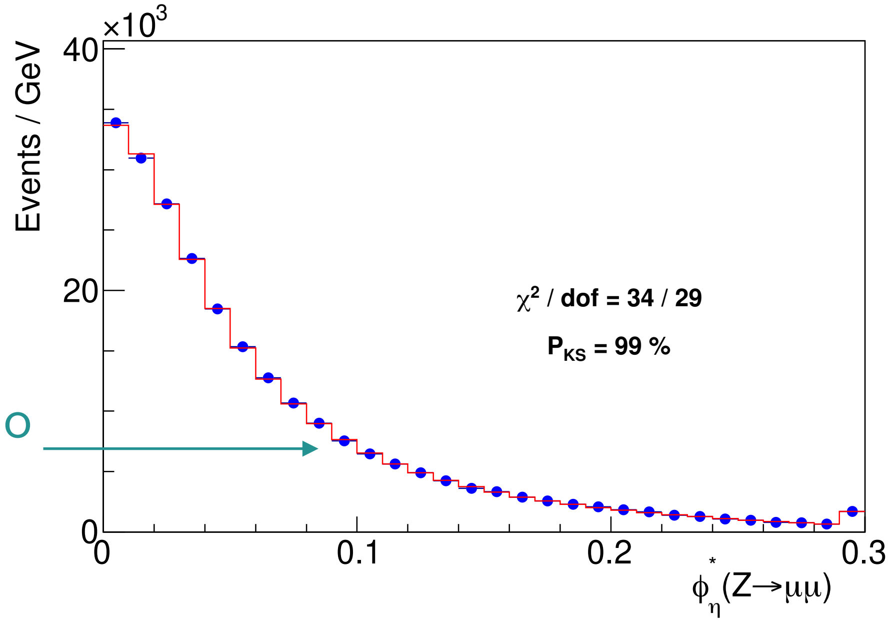
- A_i (i=0,...,7) determined perturbatively in the fixed-order calculation
- ResBos includes NNLO corrections only to the total rate, not to the A_i
- NNLO corrections affect only $p_T(W)$ > 30 GeV, but CDF has a cut of $p_T(W)$ < 15 GeV
- CDF used the NLO calculation, where the ResBos angular coefficients are exact

Constraining W/Z p_T spectrum from CDF data

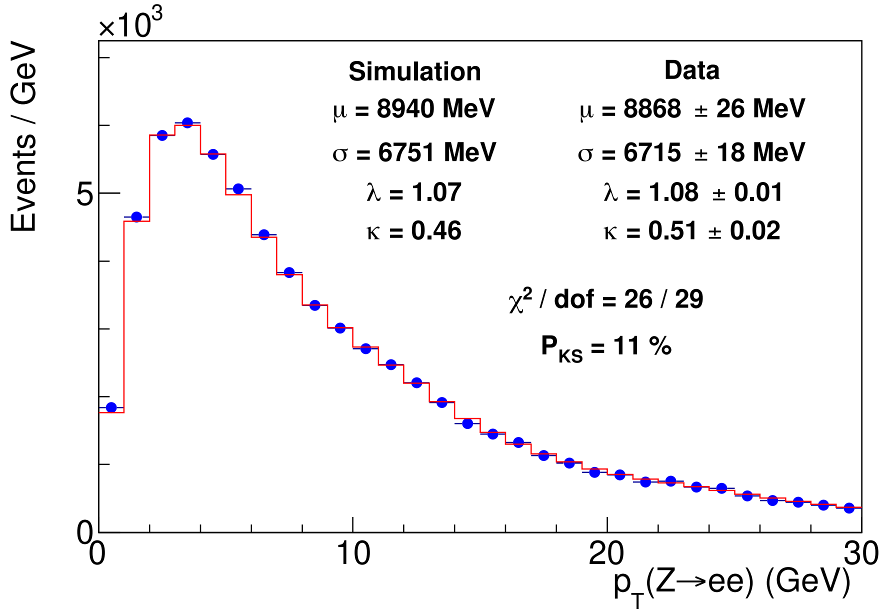
- Fitting ResBos non-perturbative parameter g_2 (used in resummation model) and α_s to $p_T(\ell\ell)$ spectra corrects the $p_T(W/Z)$ model, with an uncertainty of 1.8 MeV on M_W
- Check the $p_T(\ell\ell)$ model with the $\ell\ell$ opening angle $\phi^*_\eta = \cot(\Delta\phi_{\ell^-\ell^+}/2)\mathrm{sech}(\Delta\eta_{\ell^-\ell^+}/2)$

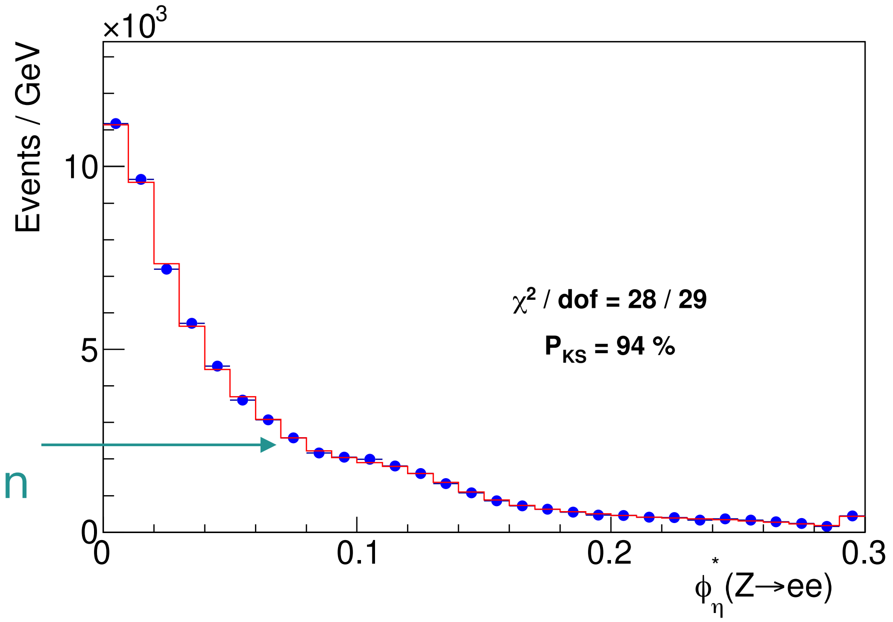
Peak position depends on g_2





Tail to peak ratio depends on α_s





Acceptance effect modelled in simulation

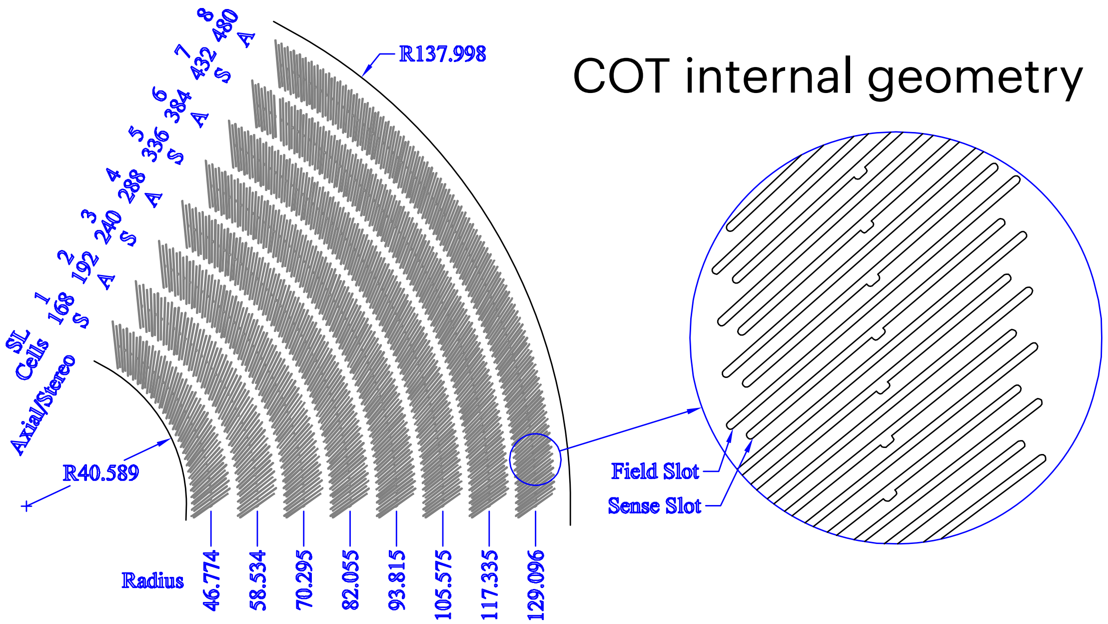
Custom Monte Carlo detector simulation

A complete detector model, based on first principles of particle tracking, to simulate all quantities measured in the data

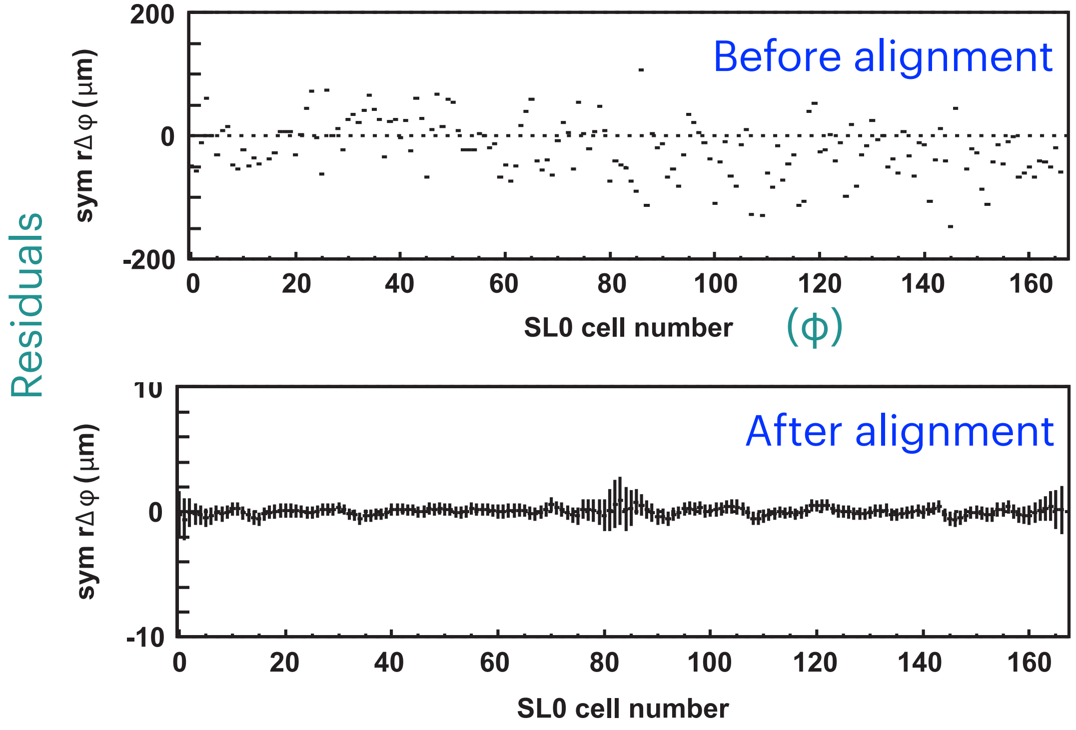
- Tracks and photons are propagated through a high-resolution 3D lookup table of material properties for the silicon detector and the COT, made from detailed construction-level knowledge
- At each material interaction:
  - ✓ Calculate ionisation energy loss according to detailed formulas and Landau distribution
  - ✓ Generate bremsstrahlung photons down to 0.4 MeV, using detailed cross section and spectrum calculations
  - ✓ Simulate photon conversion and Compton scattering
  - ✓ Propagate bremsstrahlung photons and conversion electrons
  - ✓ Simulate multiple Coulomb scattering, including non-Gaussian tail
- Deposit and smear hits on COT wires, and perform helix fit applying optional beam constraint

Detector studies

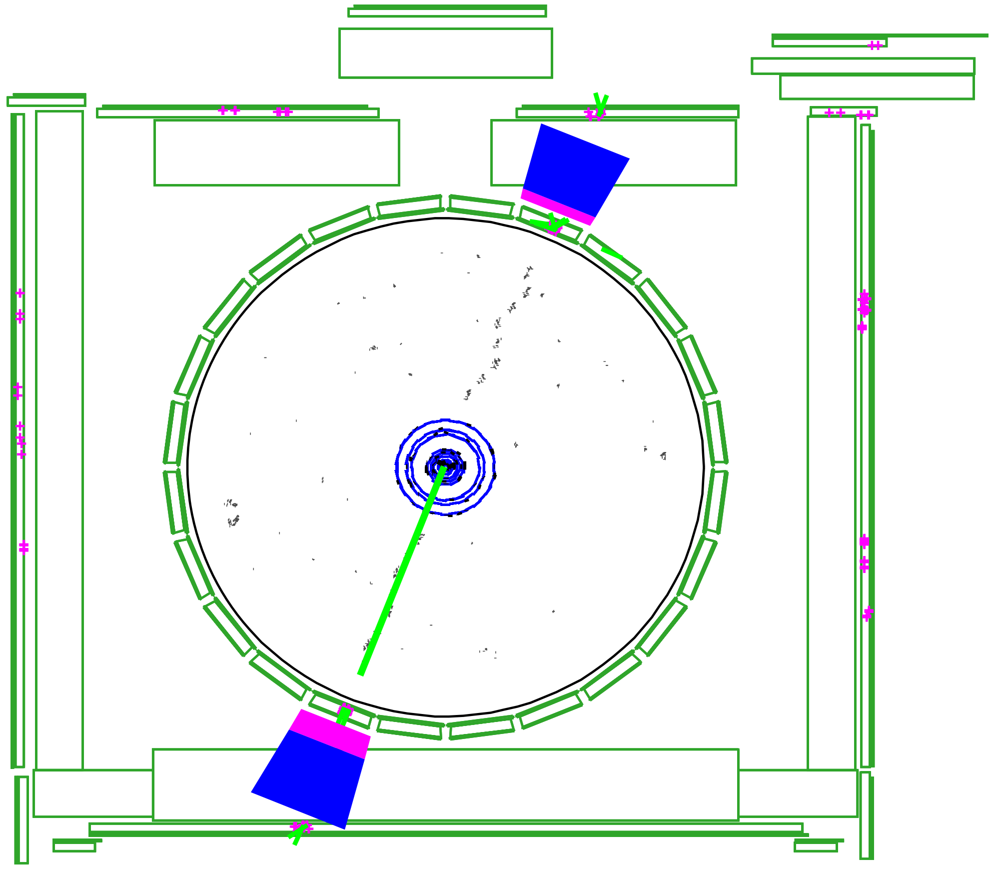
COT alignment using cosmic rays



COT internal geometry



Cosmic ray event display in coincidence with a beam crossing



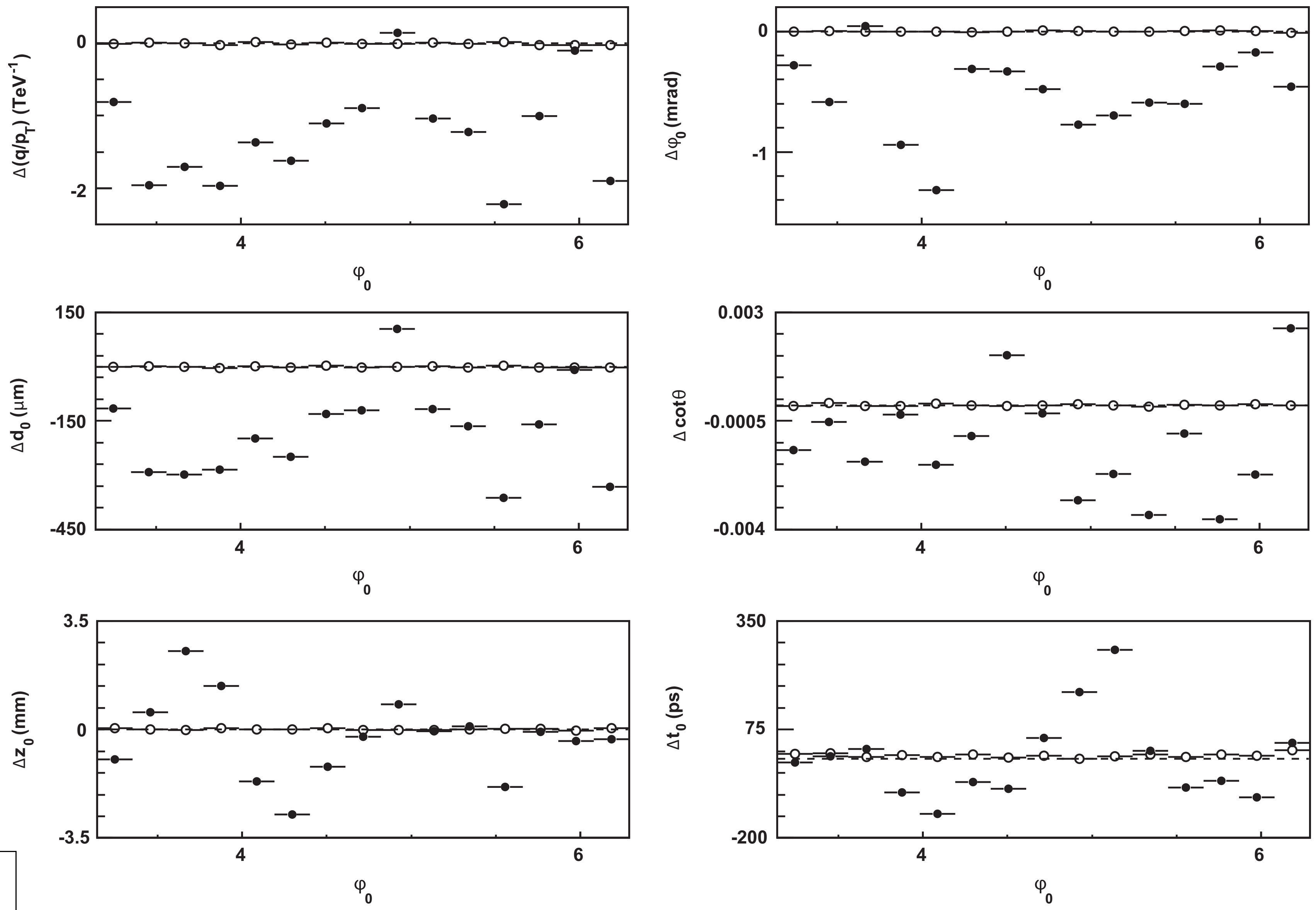
- Use a clean sample of ~480k cosmic rays for cell-by-cell internal alignment
- Initial (final) relative alignment of cells ~50 (~1) μm

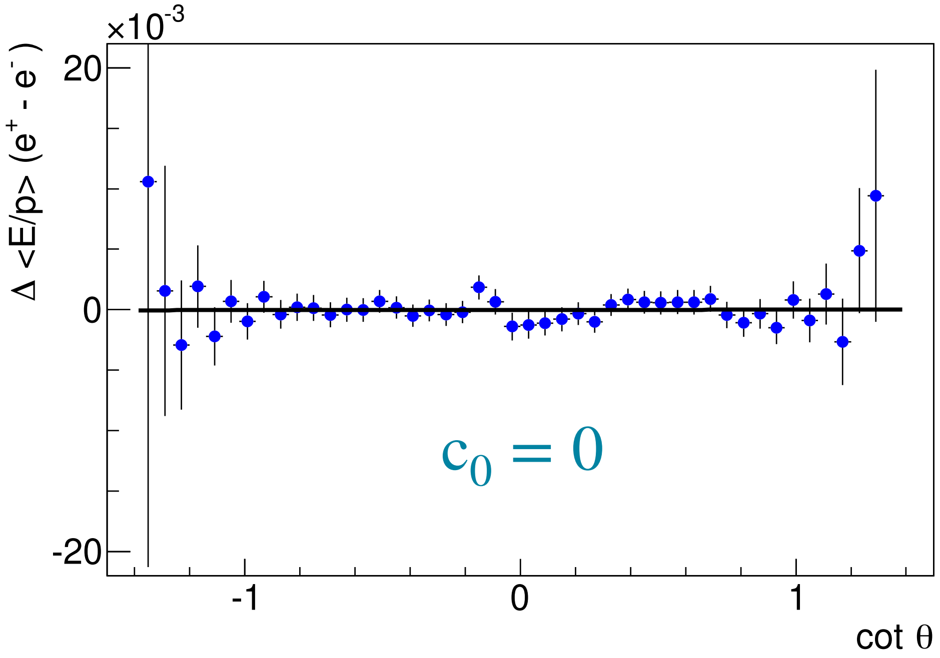
NIMA 762 (2014) pp 85-99

Check of the alignment procedure

Track parameter bias vs. azimuth

- Solid circles: before alignment
- Open circles: after alignment





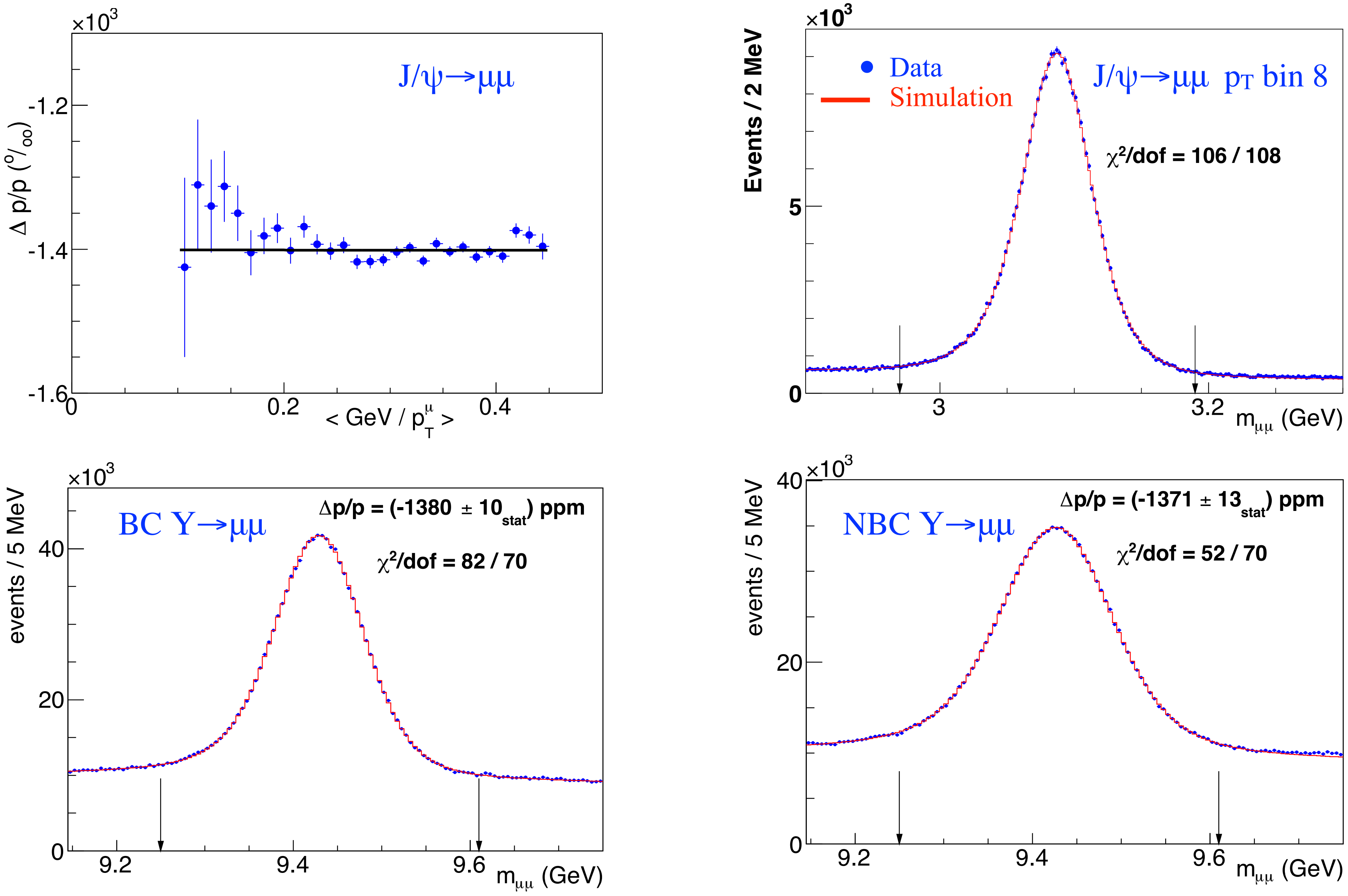
Smooth ad-hoc curvature corrections as a function of polar and azimuthal angles with statistical errors inducing an uncertainty of 1 MeV on M_W

$$(q/p_T)_{meas} = c_0 + \underbrace{c_1}_{\substack{\downarrow \\ \text{Momentum scale}}}(q/p_T)_{true} + \underbrace{c_2}_{\substack{\downarrow \\ \text{Energy loss}}}(q/p_T)^2_{true} + \dots$$

Tracking momentum scale

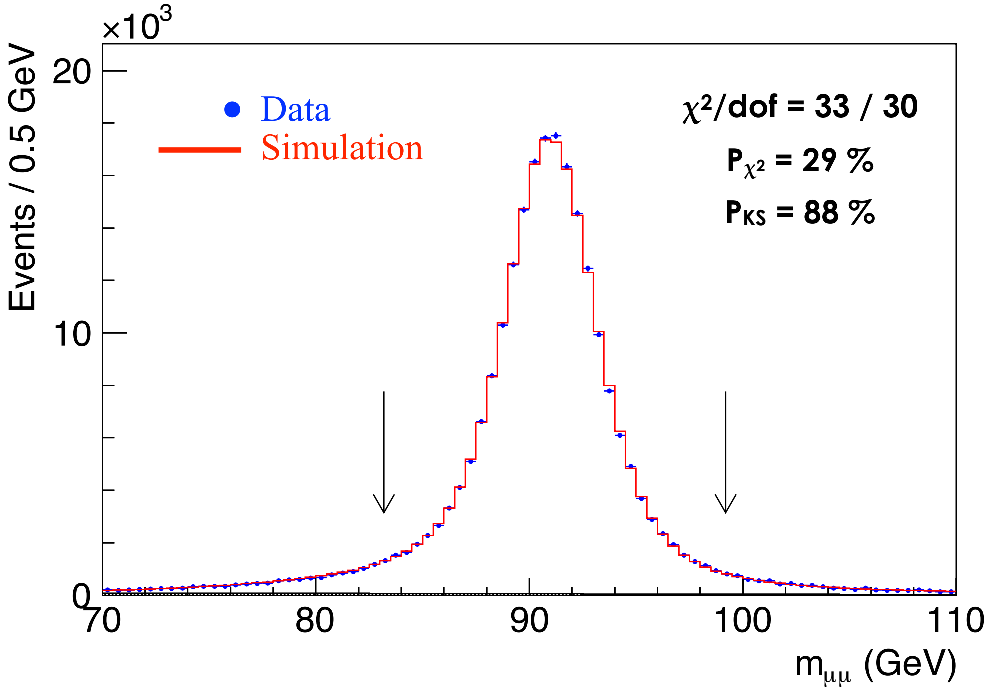
Set by using J/ψ / Υ / $Z \to \mu\mu$ resonances

- ➡ Fit the J/ψ mass in bins of $1/p_T(\mu)$ to measure the momentum scale at low $p_T(\mu)$ — J/ψ mass independent of $p_T(\mu)$ after 2.6% tuning of energy loss
- ➡ Fit the Υ mass to measure the momentum scale at higher $p_T(\mu)$ and validate beam-constraining procedure (Υ is prompt) by comparing the beam-constrained (**BC**) and non-beam-constrained (**NBC**) Υ mass fits



Cross-check and combination with Z → μμ

Using the momentum scale extracted from J/ψ / Υ → μμ data, perform "blind" measurement of M_Z from Z → μμ data



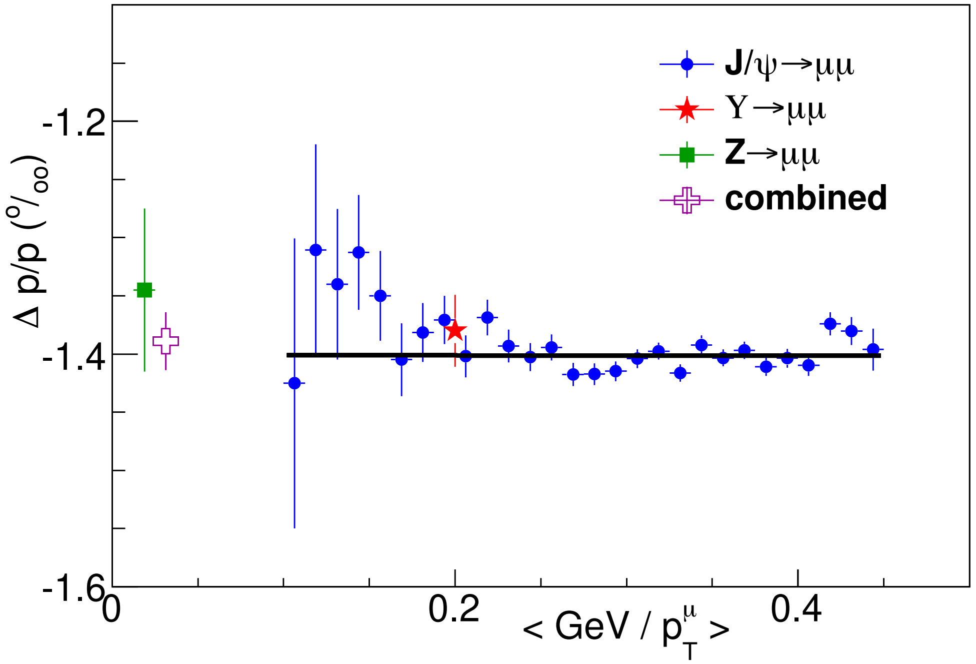
Measured M_Z consistent with PDG value of 91188 MeV

$$M_Z = 91192.0 \pm 6.4_{\text{stat}} \pm 2.3_{\text{mom. scale}} \pm 3.1_{\text{QED}} \pm 1.0_{\text{align.}}\ \text{MeV}$$

Final calibration using all J/ψ / Υ / Z → μμ fits yields an uncertainty of 2 MeV on M_W

Combined momentum scale:

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



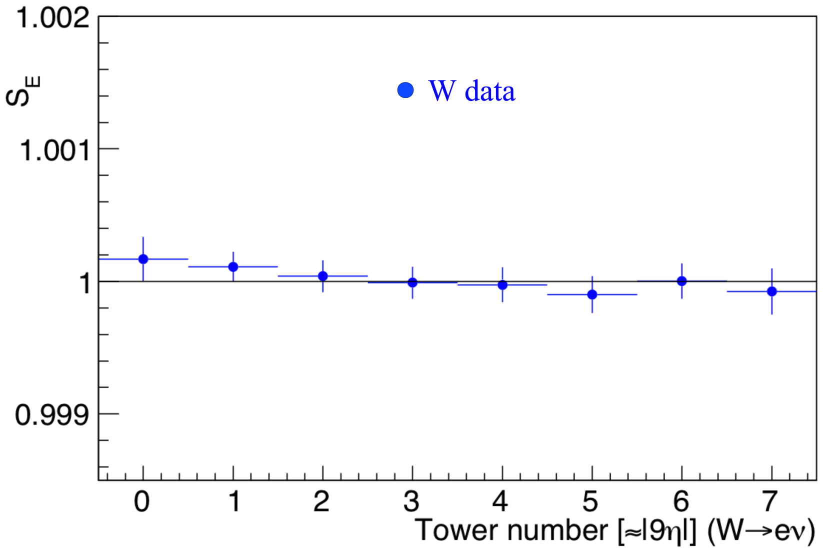
EM calorimeter response

- Energy loss distributions calculated using detailed GEANT4 calorimeter simulation tuned on CDF data [NIMA 729 (2013) pp 25-35], including:
  - Leakage into the hadronic calorimeter
  - Absorption in the coil
  - Dependence on the incident angle and E_T
- Energy-dependent gain (non-linearity) parametrised as $1 + \beta \ln(E_T/39\ \mathrm{GeV})$ with $\beta = (7.2 \pm 0.4_{\mathrm{stat}}) \times 10^{-3}$ from fits to $W \to e\nu$ and $Z \to ee$ E/p data in E_T bins
- Energy resolution parametrised as a fixed sampling term plus a tuneable constant
  - Constant terms are fit to the widths of the E/p and $Z \to ee$ peaks

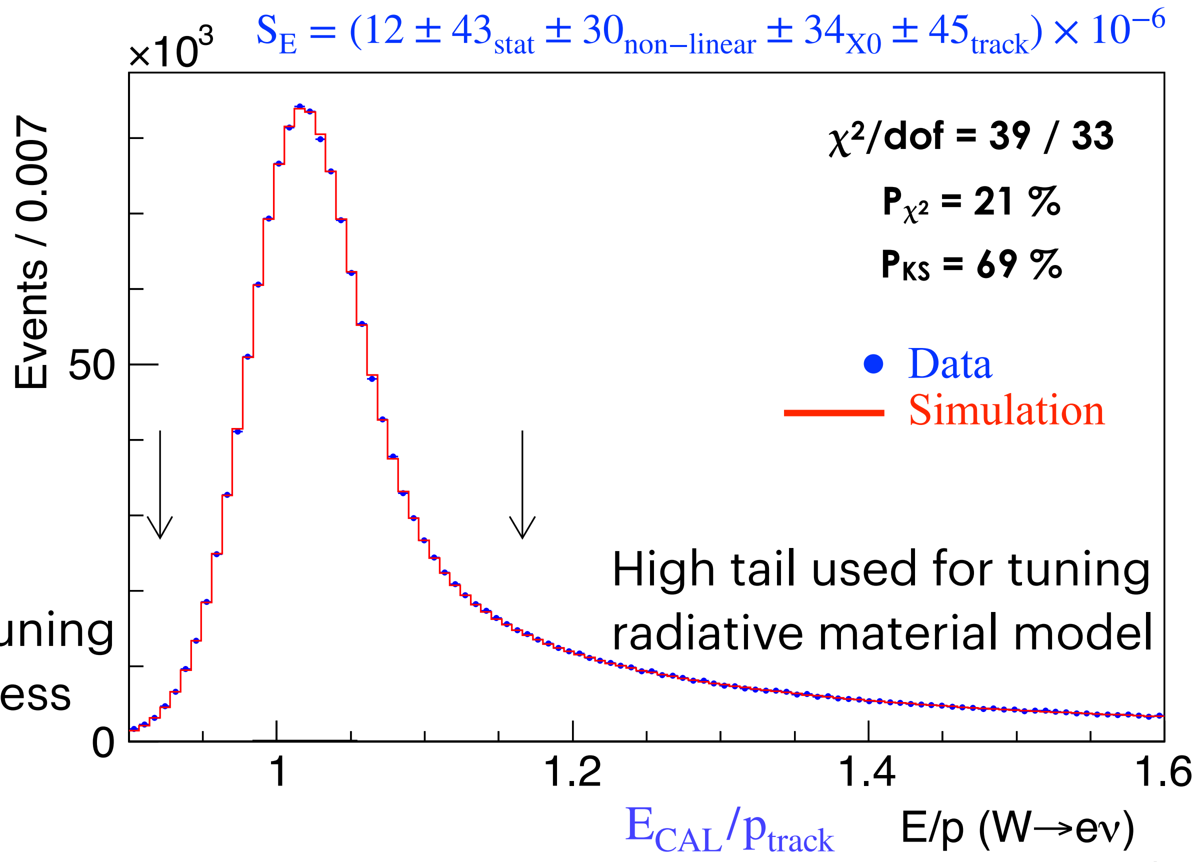
✓ Energy scale (S_E) uncertainty on M_W: 6 MeV

✓ Non-linearity (β) uncertainty on M_W: 2 MeV

✓ Performed uniformity check in bins of η



Low tail used for tuning calorimeter thickness


$S_E = (12 \pm 43_{\mathrm{stat}} \pm 30_{\mathrm{non-linear}} \pm 34_{X0} \pm 45_{\mathrm{track}}) \times 10^{-6}$

High tail used for tuning radiative material model

Z → ee mass cross-check and combination

✓ Perform "blind" measurement of M_Z from Z → ee data using E/p-based calibration

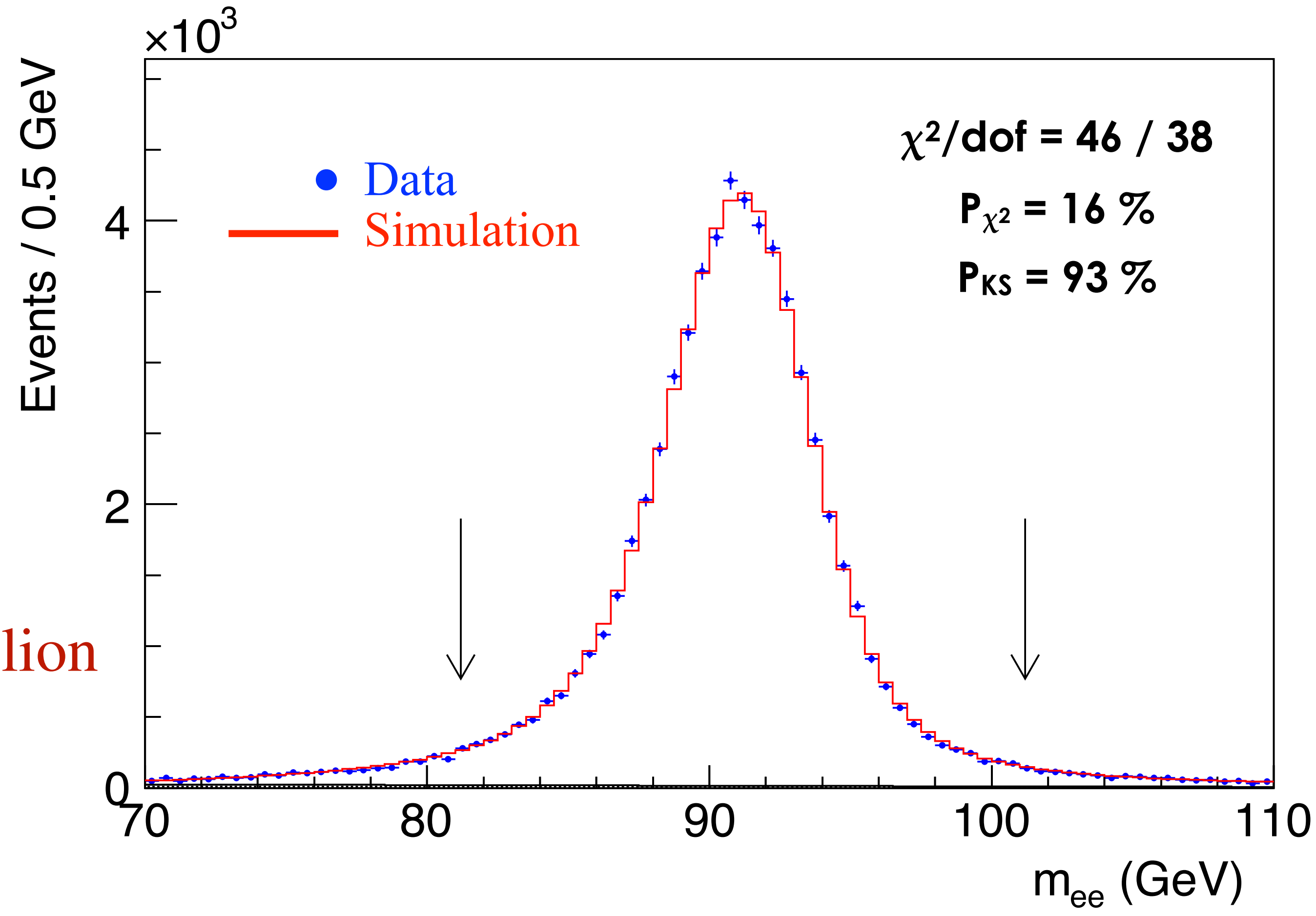
Measured M_Z consistent with PDG value of 91188 MeV

$$M_Z = 91194.3 \pm 13.8_{\text{stat}} \pm 6.5_{\text{calor.}} \pm 2.3_{\text{mom.}} \pm 3.1_{\text{QED}} \pm 0.8_{\text{align.}}\ \text{MeV}$$

✓ Combine E/p calibration with Z → ee mass fit for maximum precision

Uncertainty on M_W from final calorimeter calibration 5.8 MeV

$$\Delta S_E = (-14 \pm 72)\ \text{parts per million}$$



Lepton resolutions

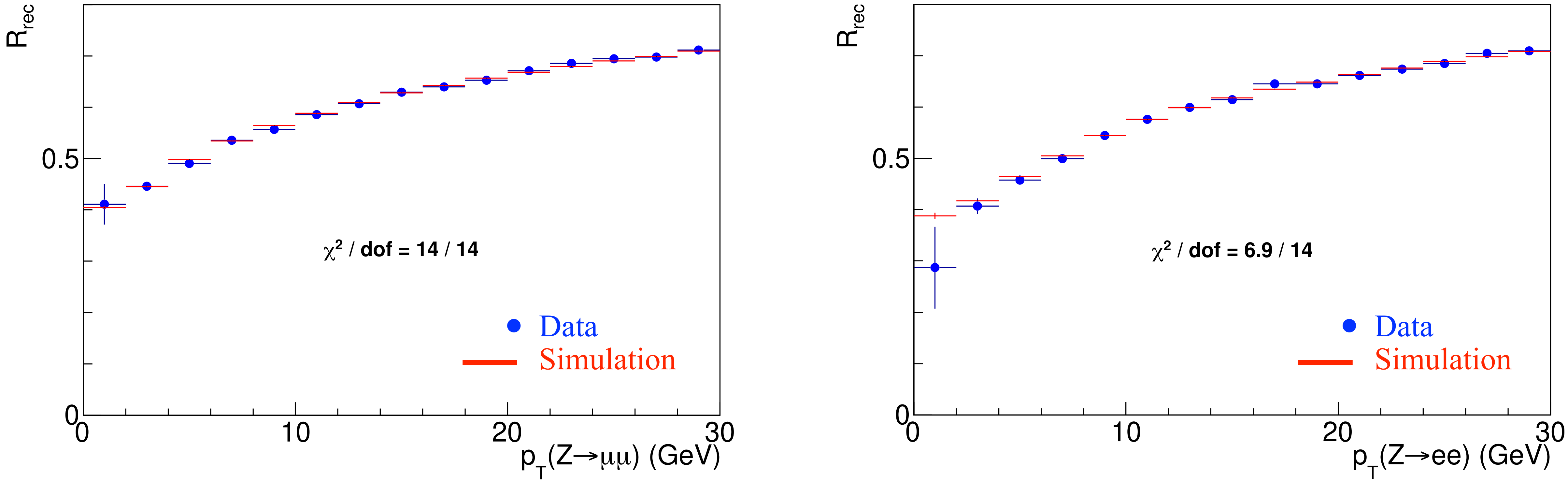
- Tracking resolution parametrised in custom simulation by:
  - Radius-dependent COT hit resolution $\sigma_h = (150 \pm 1_{\text{stat}})\ \mu\text{m}$
  - Beam spot size $\sigma_b = (36.0 \pm 0.5_{\text{stat}})\ \mu\text{m}$
  - Tuned on the widths of the $Z \rightarrow \mu\mu$ (beam-constrained) and $\Upsilon \rightarrow \mu\mu$ (both BC and NBC) mass peaks
  - Uncertainty on M_W from muon p_T resolution: 0.3 MeV
- Electron cluster resolution parametrised in custom simulation by:
  - $12.6\% / \sqrt{E_T}$ (sampling term)
  - Constant term $\kappa = (0.73 \pm 0.02_{\text{stat}})\%$
  - Tuned on the widths of the E/p and $Z \rightarrow ee$ peaks (selecting radiative electrons)
  - Uncertainty on M_W from electron E_T resolution: 0.9 MeV

Recoil model

Building the model

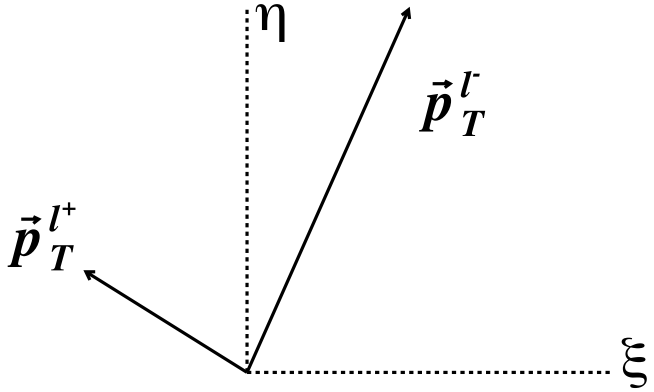
The hadronic recoil momentum vector **u** has:

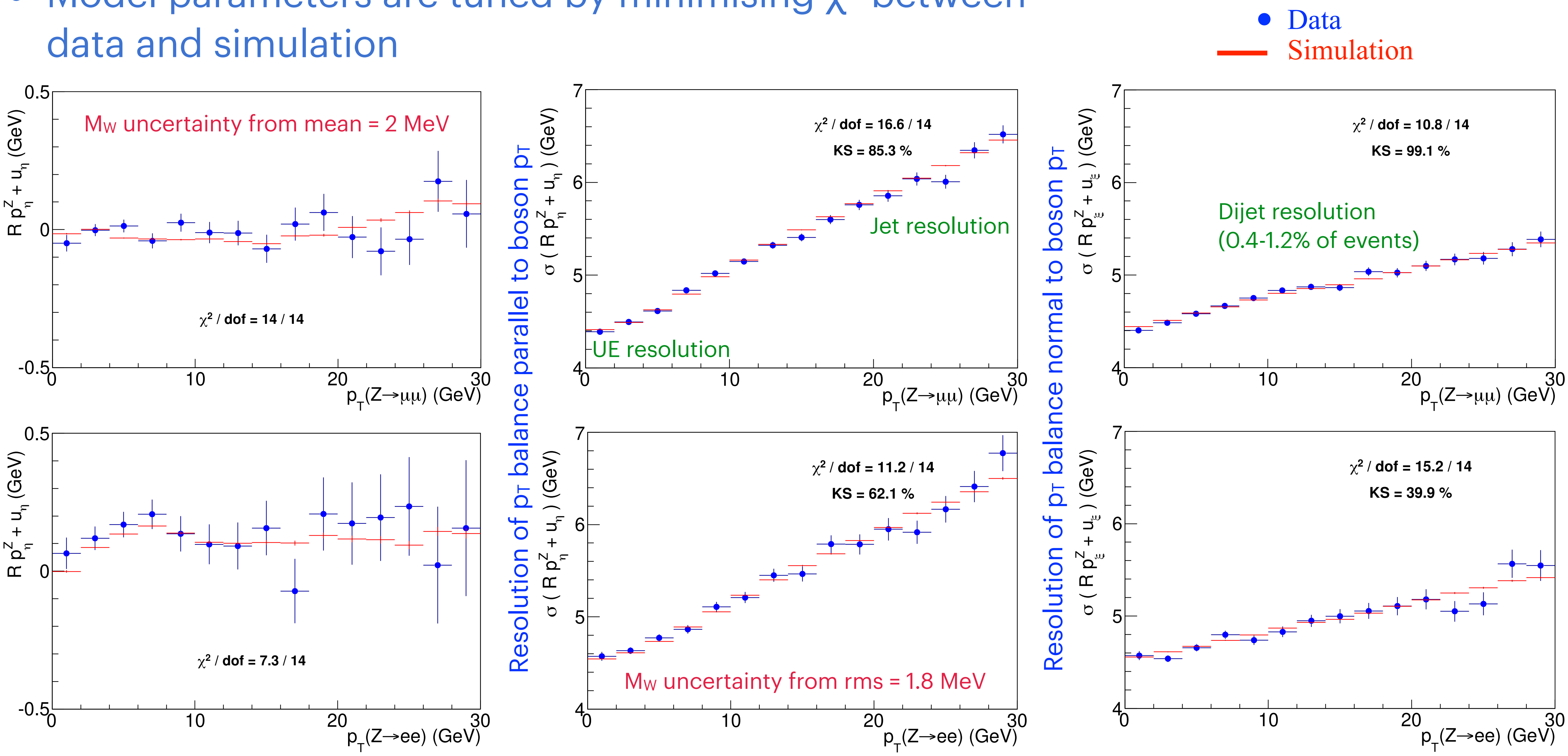
- A soft, randomly oriented "spectator interaction" component
  - ✓ Modelled using minimum-bias data with tuneable magnitude
- A hard "jet" component, directed opposite to the boson p_T
  - ✓ Use p_T-dependent response and resolution parameterisations
  - ✓ The hadronic response $R_{rec} = u_{reconstr.} / u_{true}$ is parametrised as a logarithmically increasing function of boson p_T motivated by Z boson data



Tuning the model with Z events

- Project the vector sum of $p_T(\ell\ell)$ and u on an axis η parallel to $p_T(\ell\ell)$ and an axis ξ normal to $p_T(\ell\ell)$
- Mean and rms values of projections as functions of $p_T(\ell\ell)$ provide information on hadronic model parameters
- Model parameters are tuned by minimising χ^2 between data and simulation





Mean p_T balance

Resolution of p_T balance parallel to boson p_T

Resolution of p_T balance normal to boson p_T

M_W uncertainty from mean = 2 MeV

Jet resolution

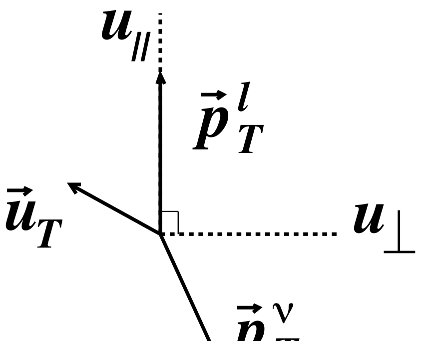
UE resolution

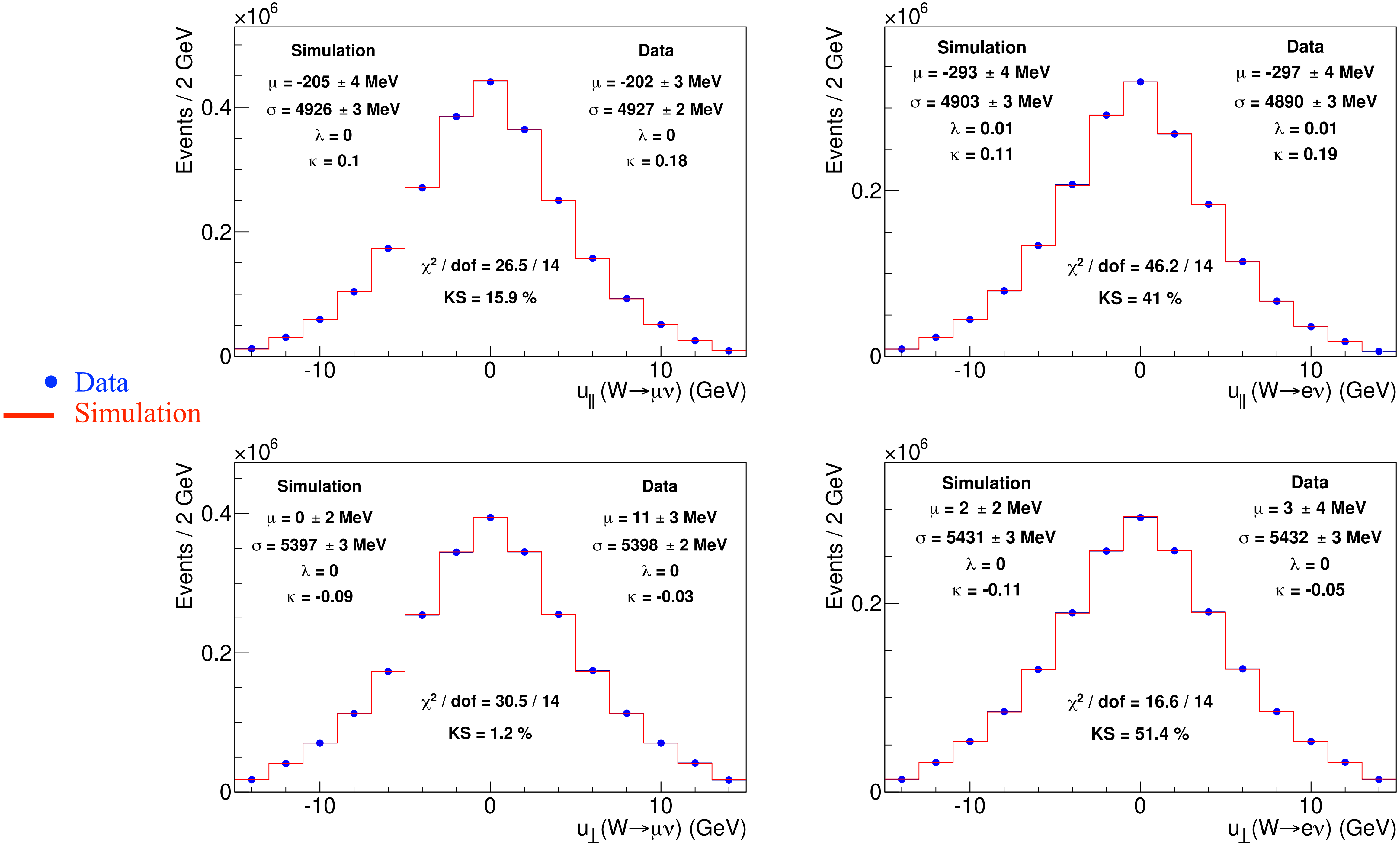
Dijet resolution
(0.4-1.2% of events)

M_W uncertainty from rms = 1.8 MeV

Testing the model with W events

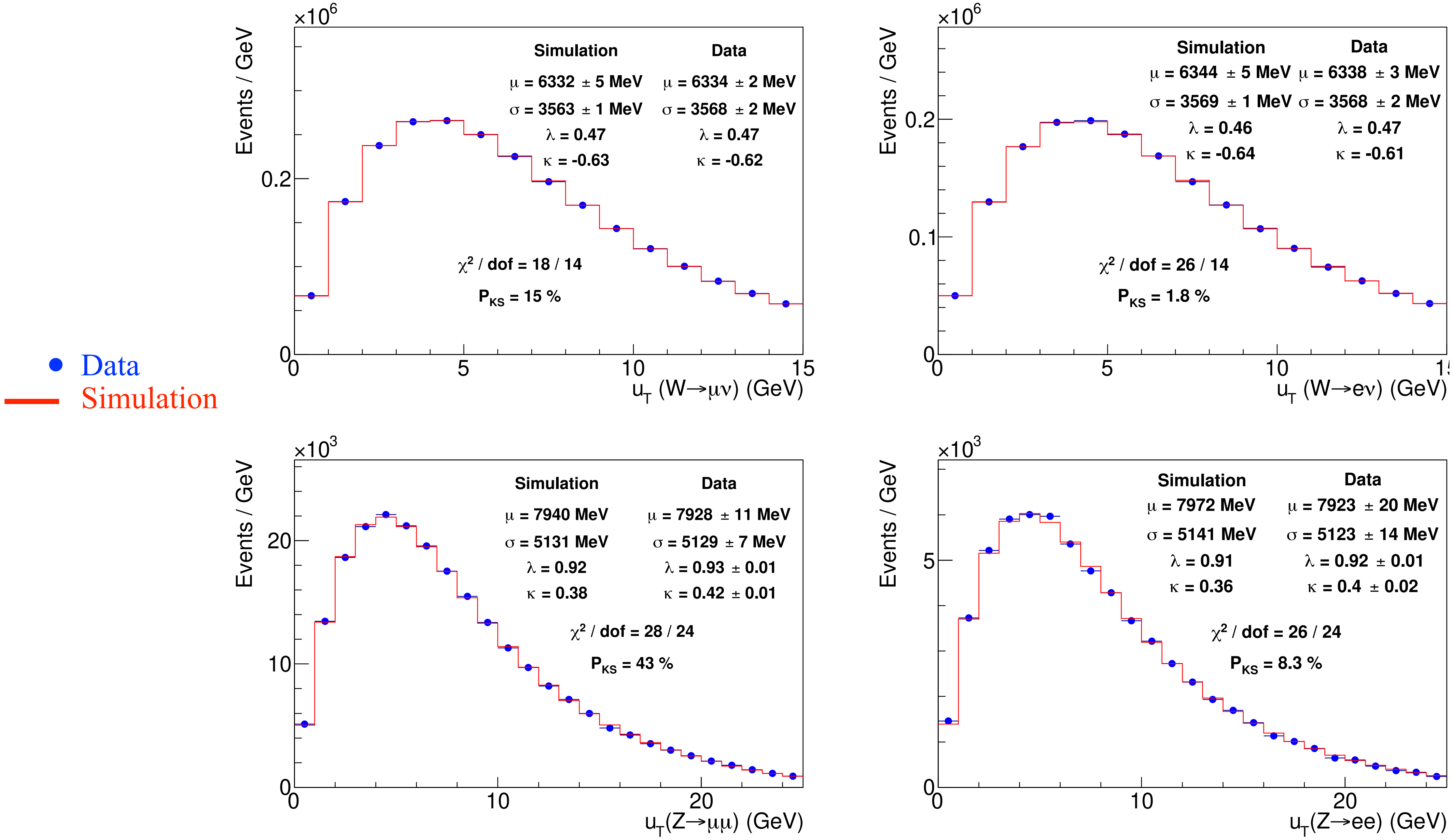
Test the recoil components parallel ($u_{\parallel}$) and normal ($u_{\perp}$) to the lepton momentum





Additional constraint on the recoil model with W events

- Use $\mathrm{d}\sigma/\left(\mathrm{d}p_T^V \mathrm{d}y_V\, \mathrm{d}M_V\right)$ $(V = W, Z)$ at NNLL + NNLO from **DYqT** [NPB 815, 174 (2009)] to model the scale variation of the ratio
- Use $p_T(W)$ data to reduce the scale uncertainty of the model, taking into account correlation with the hadronic recoil model



Backgrounds

Sources of background in the W sample

W → μν backgrounds:

- ✓ $Z/\gamma^* \to \mu\mu$ with one muon escaping detection, estimated from custom simulation
- ✓ $W \to \tau\nu \to \mu\nu\nu\nu$, estimated from custom simulation
- ✓ Multijet events where one jet mimics a muon, estimated using a NN discriminant for the misidentified and signal muons in the data
- ✓ Muons from decays-in-flight of low momentum long-lived mesons in the COT, resulting in reconstructed high p_T tracks, are estimated by fitting track χ^2/dof data templates of $Z \to \mu\mu$ (signal) and $W \to \mu\nu$ with large d_0 (background) to $W \to \mu\nu$ candidates (taking into account contamination from true $W \to \mu\nu$ events)
- ✓ Cosmic rays, removed with efficiency > 99% using a dedicated tracking algorithm, are estimated from a previous data sample scaled by the run-time to integrated luminosity ratio

W → eν backgrounds:

- ✓ $Z/\gamma^* \to ee$ with one muon escaping detection, estimated from custom simulation
- ✓ $W \to \tau\nu \to e\nu\nu\nu$, estimated from custom simulation
- ✓ Multijet events where one jet mimics an electron, estimated by fitting signal and background templates of track isolation, NN discriminant, and MET to $W \to e\nu$ data

Results

All fit uncertainties (MeV)

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

⋆ Dominant uncertainties

Cross checks

- Mass differences from subsamples with equal statistics
- In the electron channel, results are shown with calorimeter calibration using the E/p fit from the corresponding subsample (in parentheses) and from the full sample

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