Precision Measurement of the W Mass

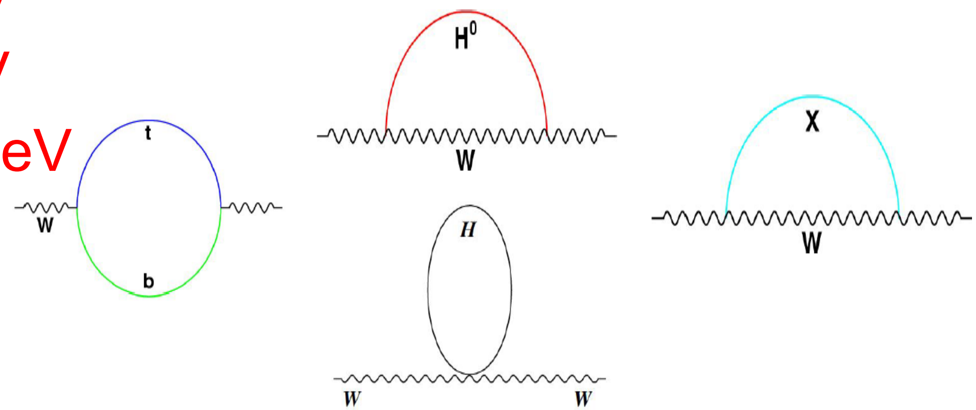
Giorgio Chiarelli
INFN Sezione di Pisa

FCCP 2022
Capri, 21/9/2022

Motivation for a precision measurement

Electroweak gauge sector constrained by known parameters:

- α_s =1/127.918(18)
- G_F =1.6637(1)x10-5GeV^{-2}
- M_Z =91.1876(21) GeV
- M_{top}= 172.89(59) GeV
- M_{Higgs} = 125.25(17) GeV



At tree level linked to M_W:

$M^2_W = \pi\alpha_{em}/\sqrt{2}\, G_F \sin\theta^2_W$

$\cos\theta_W = M_W / M_Z$

Can be affected by new particles

Starting point:

Previous CDF Result (2.2 fb^{-1})
Transverse Mass Fit Uncertainties (MeV)

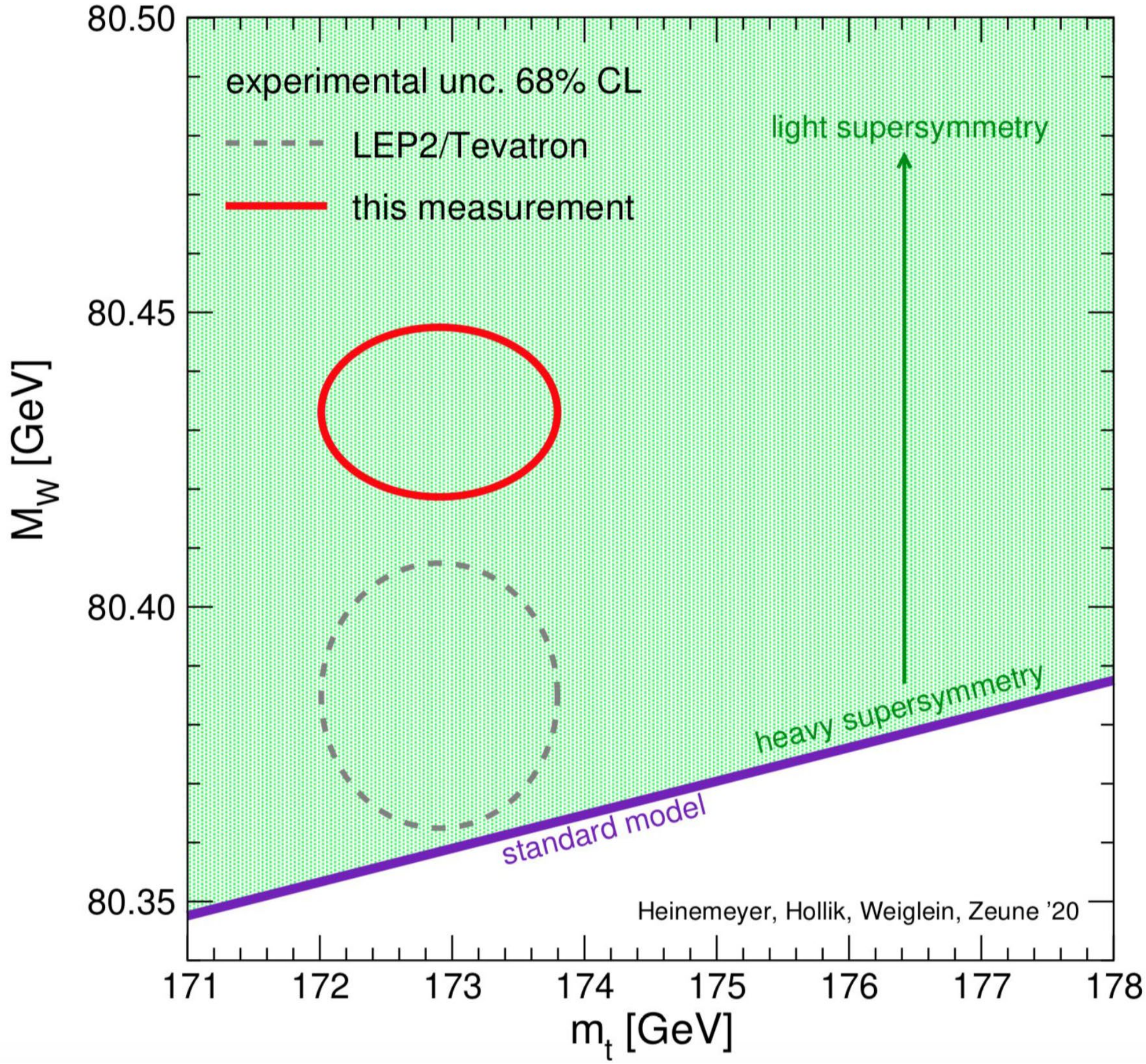
(CDF, PRL 108 (2012) 151803; Phys. Rev. D 89 (2014) 7, 072003)
Total uncertainty of 19 MeV on W boson mass

	electrons	muons	common
W statistics	19	16	0
Lepton energy scale	10	7	5
Lepton resolution	4	1	0
Recoil energy scale	5	5	5
Recoil energy resolution	7	7	7
Selection bias	0	0	0
Lepton removal	3	2	2
Backgrounds	4	3	0
pT(W) model	3	3	3
Parton dist. Functions	10	10	10
QED rad. Corrections	4	4	4
Total	23	26	15

Systematic uncertainties shown in green: statistics-limited by control data samples

If you are in a hurry

CDF M_W *vs* m_{top}



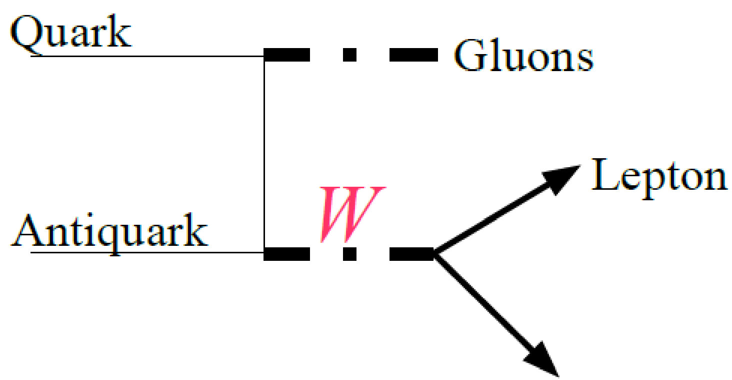
Updates wrt 2.2 fb-1

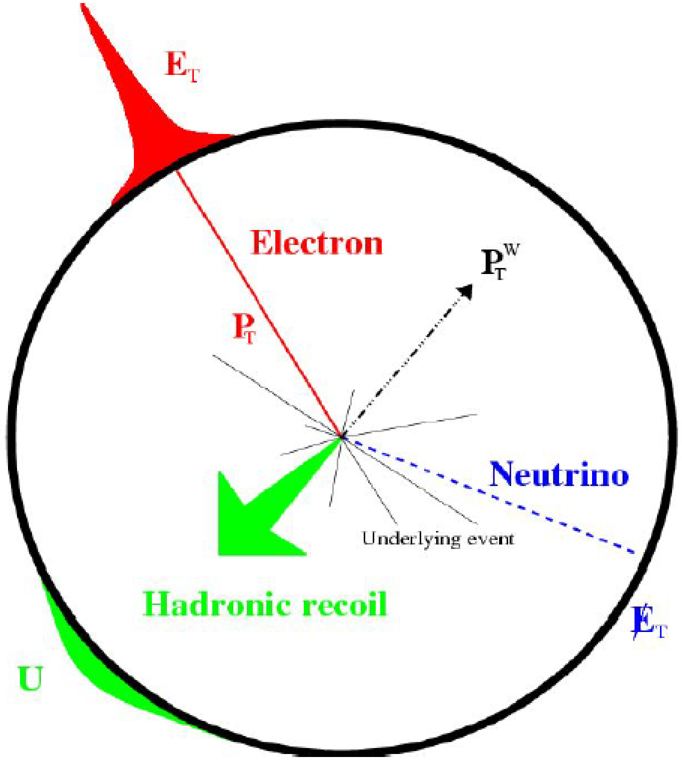
Method or technique	impact	section of paper
Detailed treatment of parton distribution functions	+3.5 MeV	IV A
Resolved beam-constraining bias in CDF reconstruction	+10 MeV	VI C
Improved COT alignment and drift model [65]	uniformity	VI
Improved modeling of calorimeter tower resolution	uniformity	III
Temporal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

Table S1

First two are additive to previous measurement

W Boson Production at the Tevatron





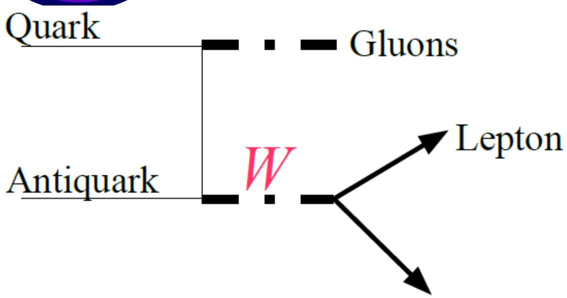
Quark-antiquark annihilation dominates (80%)

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

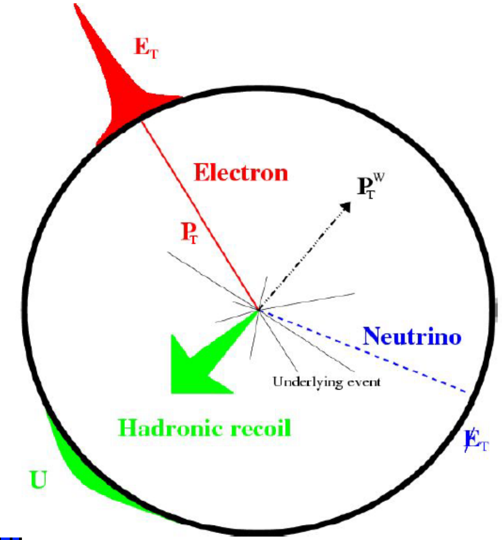
Initial state QCD radiation is O(10 GeV), measure as soft 'hadronic recoil' in calorimeter (calibrated to ~0.2%)

dilutes W mass information, fortunately $p_T(W) \ll M_W$

W boson, in CDF 2, Run-II

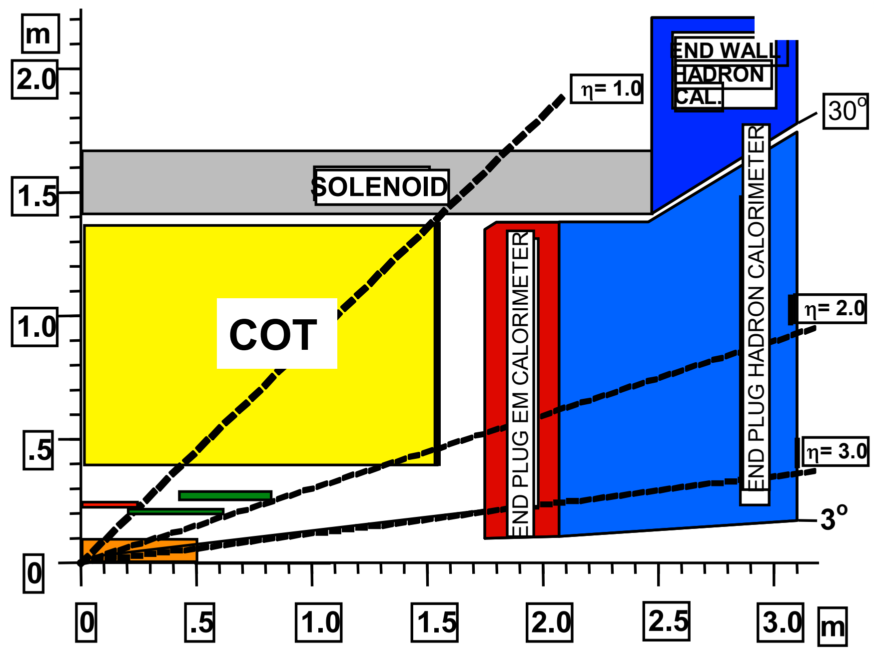


Lepton P_T
measured to 0.004%



EM calorimeters provide precise electon energy measurement

COT provides precise lepton momentum mesurement



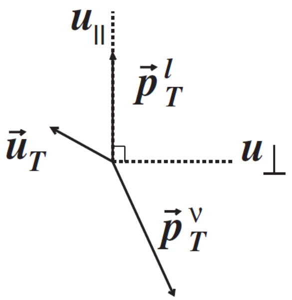
Calorimeters measure hadron recoil particles

Select W and Z bosons with central ($|\eta|<1$) leptons

W event selection

Select events with: high P_T leptons, small hadron recoil, maximize W mass info and reduce bck:

- Inclusive lepton triggers:
  - Loose lepton track and muon stub, calorimetr cluster Lepton P_T>18 GeV
- Offline selection:
  - Electron cluster, E_T>30 GeV, track P_T>18 GeV
  - Muon track P_T>30 GeV
  - Loose lepton ID to minimize bias
- W selection: P_{T_l}>30 GeV, $P_{T\nu}$>30 GeV, $|u_T|$<15 GeV
- $60<M_T<100$
- Reject events with 2nd charged lepton (Z candidates)



Data Samples & Strategy

Integrated luminosity (Feb-2002-Sept.2011)

- Electron and muons: 8.8 fb-1
- Identical running conditions in both channels

Event selection provides rather clean samples

- Mis-id bckg: ~0.5%

Analysis Strategy aims:

- Robustness:
  - constrain the same parameter in as many ways as possible
- Precision:
  - Combine independent, yet consistent, measurements
- Minimize bias:
  - Blinded analysis of Z and W samples

Sample	Candidates
W→electron	1811799
W→muons	2424486
Z→electrons	66180
Z→muons	238534

e/μ ratio scales with acceptance

Energy scale drives W mass

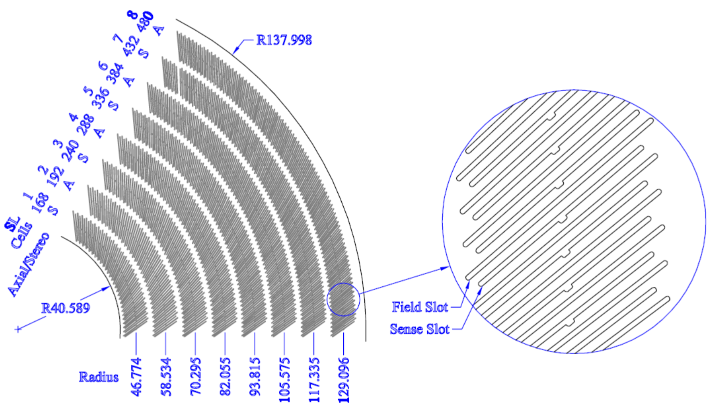
- Tracker Calibration
  - alignment of the COT (2,520 cells; 30,240 sense wires) using cosmic rays
  - COT momentum scale and tracker non-linearity constrained using $J/\psi \rightarrow \mu\mu$ and $\Upsilon \rightarrow \mu\mu$ mass fits
  - Confirmed using $Z \rightarrow \mu\mu$ mass fit
- EM Calorimeter Calibration
  - COT momentum scale transferred to EM calorimeter using a fit to the peak of the E/p spectrum, around $E/p \sim 1$
  - Calorimeter energy scale confirmed using $Z \rightarrow ee$ mass fit
- Tracker and EM Calorimeter resolutions
- Hadronic recoil modeling

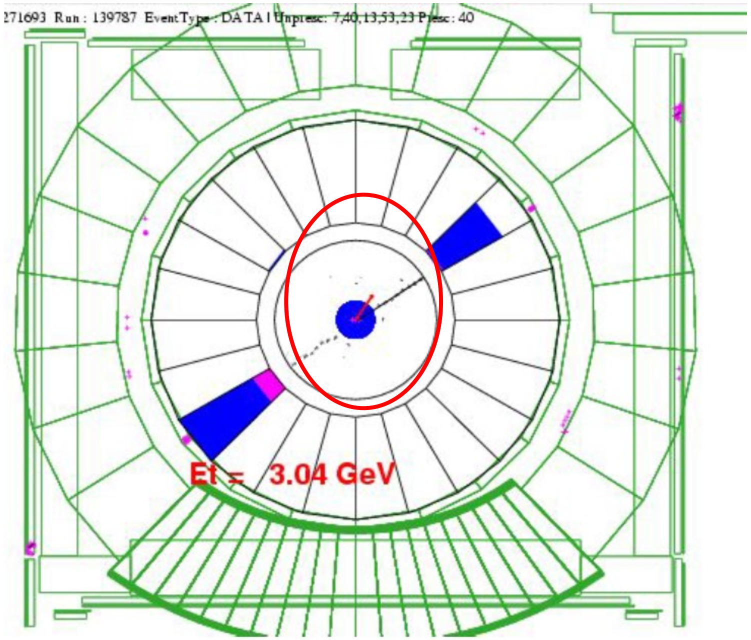
COT alignment

COT is made of 30K wires,

~2400 cells, individually aligned

480K cosmic muon events





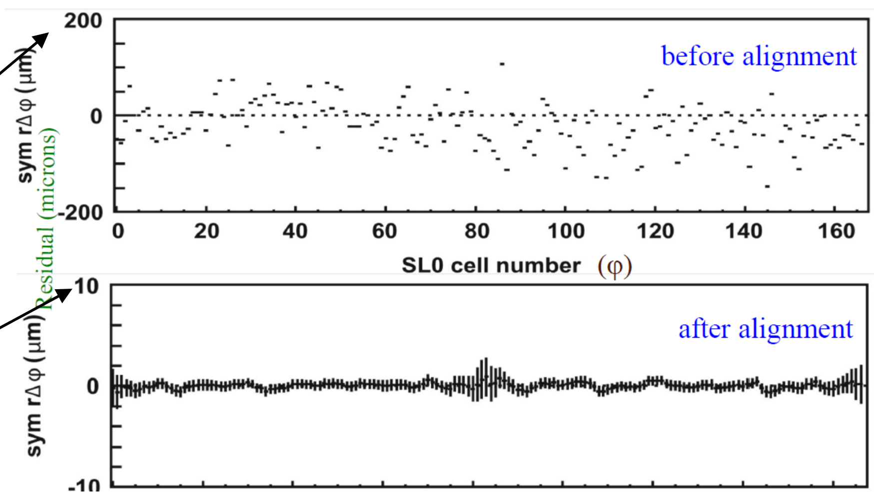
Fit COT hits on both sides, simultaneously to a single helix*: NIMA 506, 110 (2003)*

After the end of data taking, a lot of time to do that:

On the left residuals of COT cells before/after individual alignments

NIMA 762 (2014)

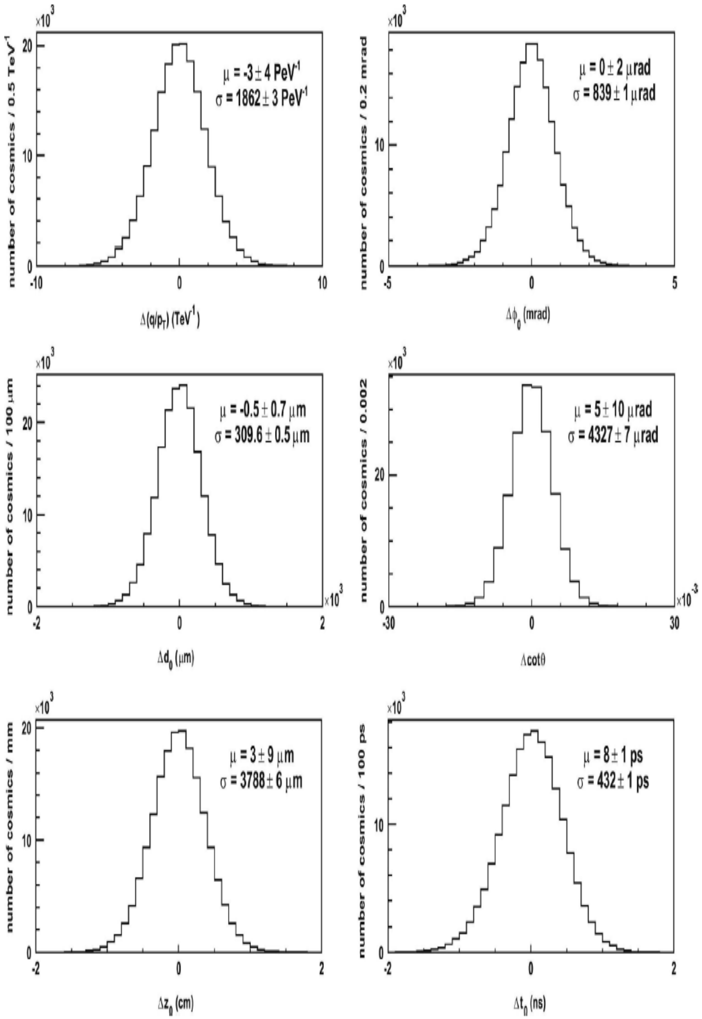
Vertical scale: from 200 μm to 10 μm



Checks of alignment

Fit separate helices to cosmic ray tracks

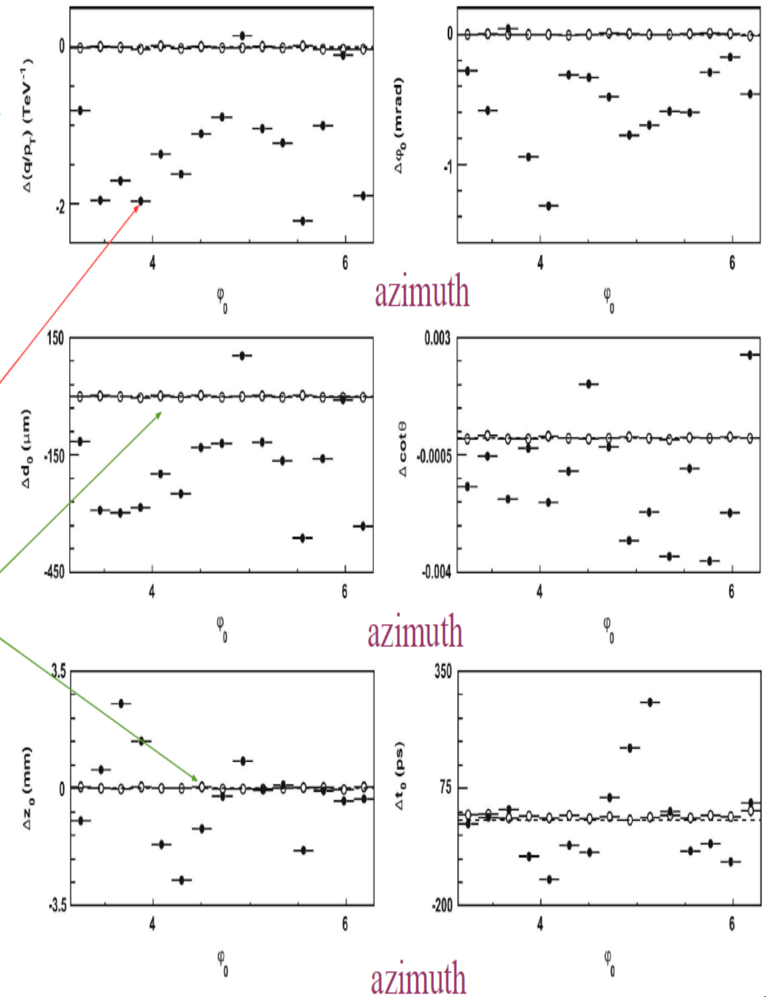
Compare track parameters of the two tracks: a measure of track parameter bias



track parameter bias versus azimuth

solid = before alignment

open = after alignment



Cross check of COT alignment

Alignment with cosmics remove most deformations degrees of freedom, but some remains

- Final cross-checks and correction using beam-constrained track curvature based on difference of <E/p> for electrons and positrons
- Final smooth correction to curvature as a function of polar and azimuthl angle:

$$q/\mathrm{p_T}\ (\text{measured}) = c_0 + c_1\, q/\mathrm{p_T} + c_2\, (q/\mathrm{p_T})^2 + \ldots$$

c_1: momentum scale

c_2 energy loss

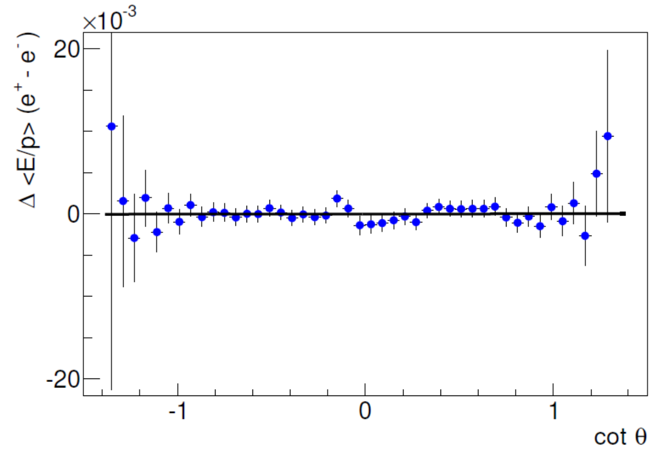


FIG. S6: Difference in $\langle E/p\rangle$ between positrons and electrons as a function of $\cot\theta$, and its linear fit. The curvature corrections given in Eq. (4) have been applied.

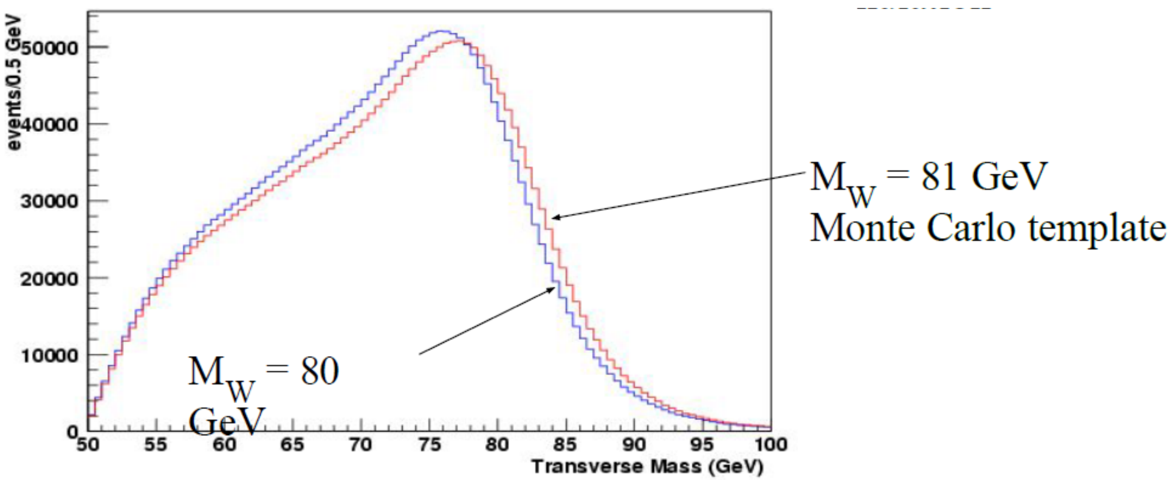
Signal generation and simulation

All signals generated using a custom Monte Carlo

- Generate fine-binned templates as a function of the fitting variable
- Perform binned maximum-likelihood fit to data

Custom Monte Carlo to make high-statistics template

- Full understanding of the detector, use of first principles

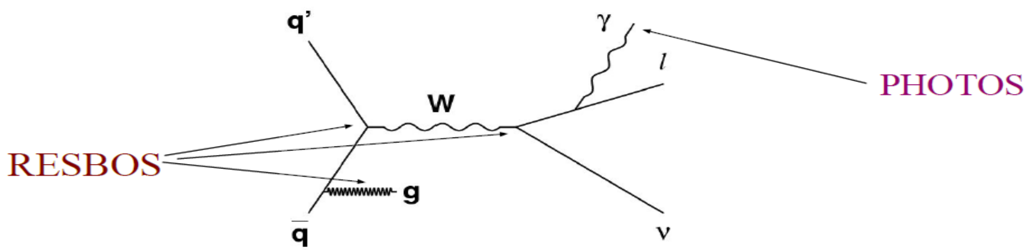


We fit 6 kinematic variables:

- Pt of the charged lepton, Pt of the neutrino, transverse mass using both electrons and muons

Generator Level

RESBOS provides generator level input for W and Z:



- Triple differential cross sections, and Pt dependent double-differential decay angular distribution
- Reliable Pt spectrum of the boson, and tunable spectrum in the low-PT part

QED effects:

Multiple radiative photons generated with PHOTOS

- Extensive comparison with HORACE (C.M. Carloni-Calame, G. Montagna, O. Nicrosini, A. Vicini)

Uncertainties in QED calculations

Extensive studies on uncertainties coming from:

- Leading log approximation
- Multi-photon calculation
- Higher order soft and virtual corrections
- Electron-positron pair creation
- QED/QCD interference
- Dependence on EWK parameters scheme

Overall systematic uncertainty due to QED radiation:

- 3 MeV on W mass

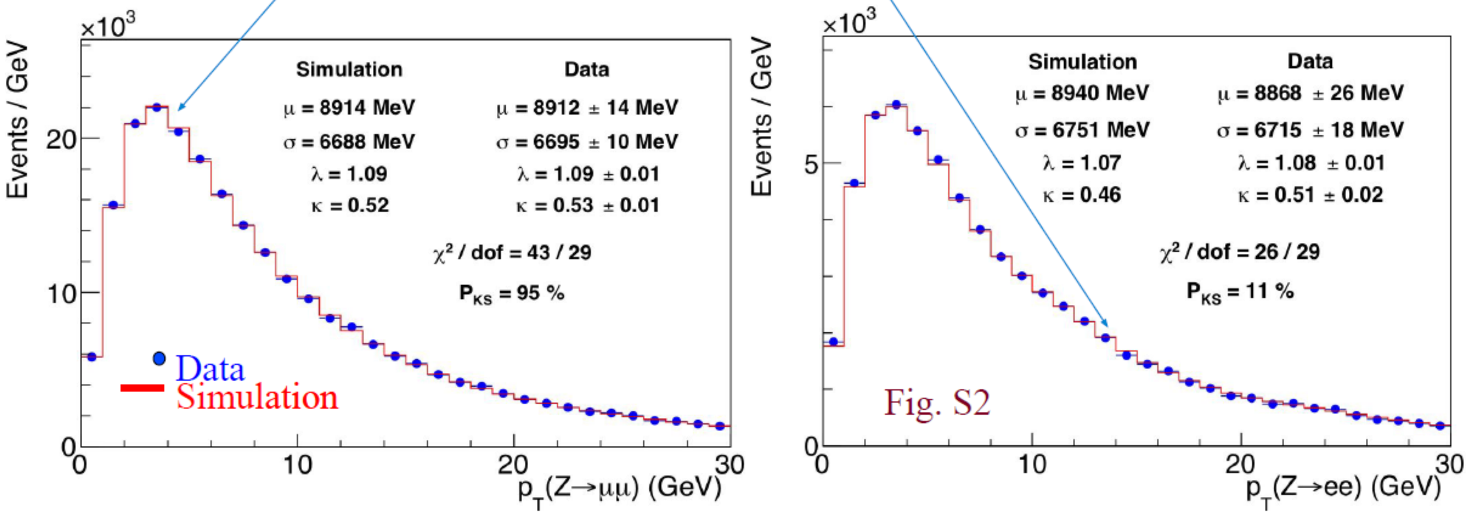
Constraining boson P_T

Fit non-perturbative parameter g_2 and α_s QCD coupling in Resbos to P_T(ll) spectra

- ΔM_W=1.8 MeV

Position of peak in boson p_T spectrum depends on g_2

Tail to peak ratio depends on α_s

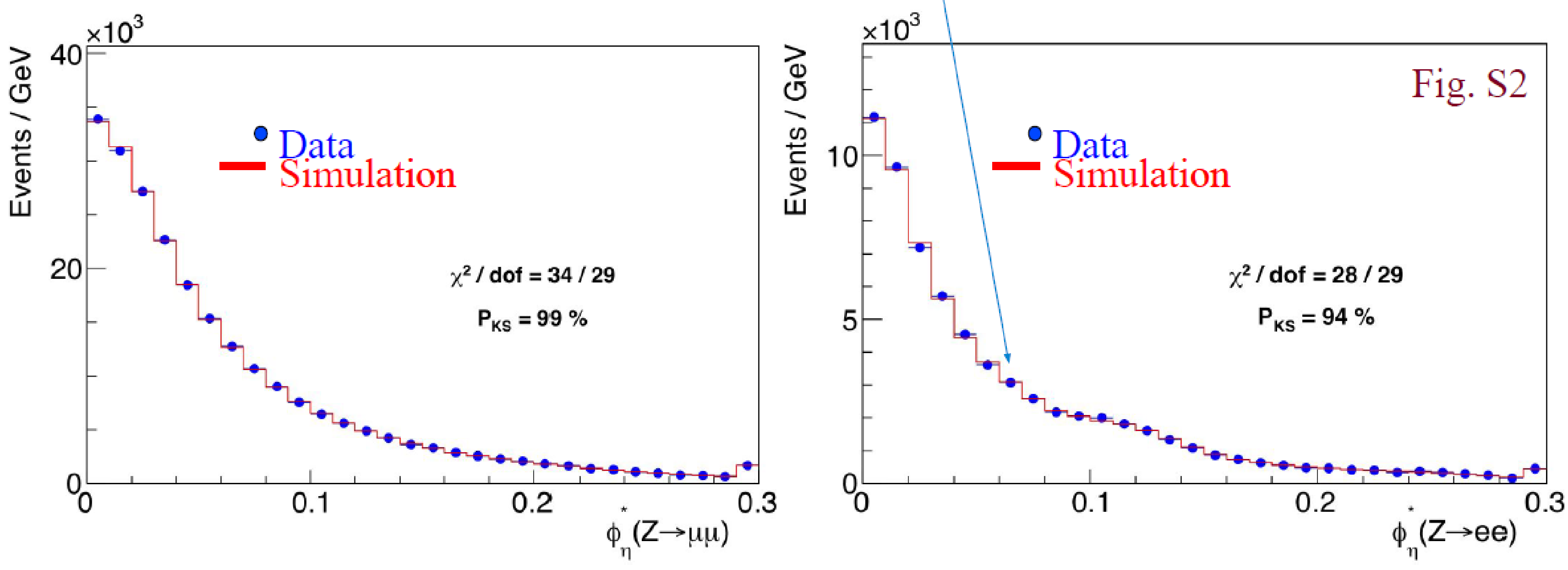


Check of P_T spectrum

New: use opening angle between leptons to check the P_T(ll) spectrum modeling, the variable is:

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

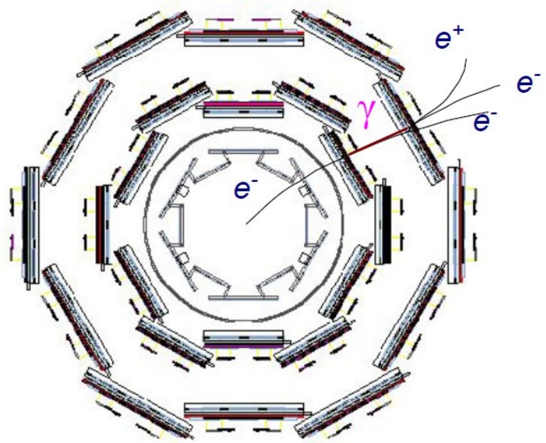
Acceptance effect modeled in simulation



Use of Custom MC simulation

We use a complete detector simulation of all quantities used in measurements:

- First principles simulation of tracking
  - Tracks and photons propagated through a detailed 3D lookup table of material in silicon detector and COT.
    At each material interactions calculate:
    - Ionization losses (including Landau fluctuations), bremstrahhlung photons down to 400 KeV
    - Simulate photon conversion and Compton scattering
      - Propagate
    - Multiple scattering, including non-gaussian tail



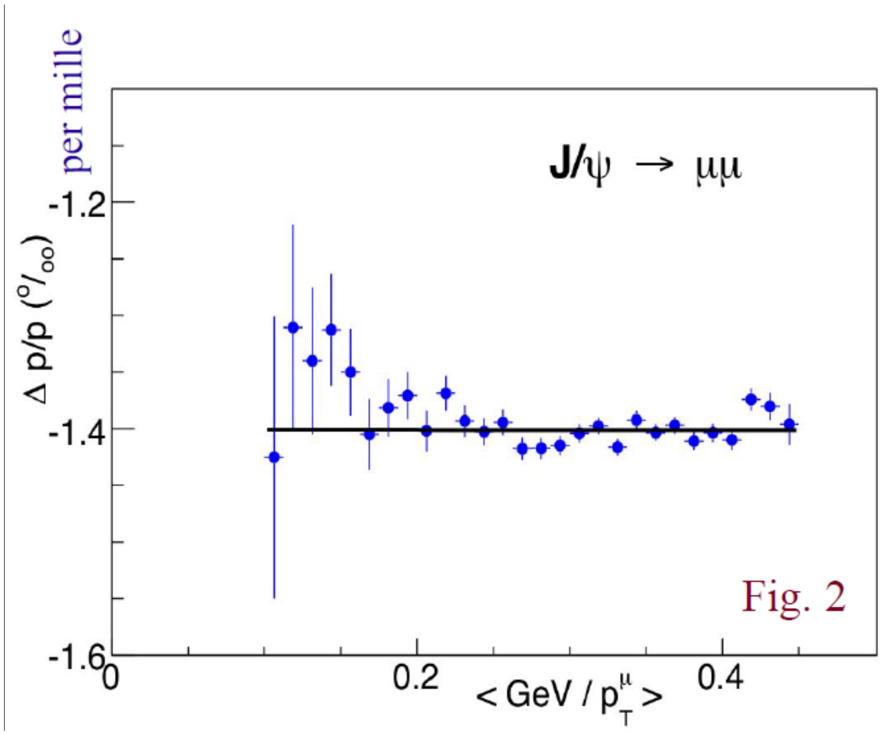
Material lookup table:

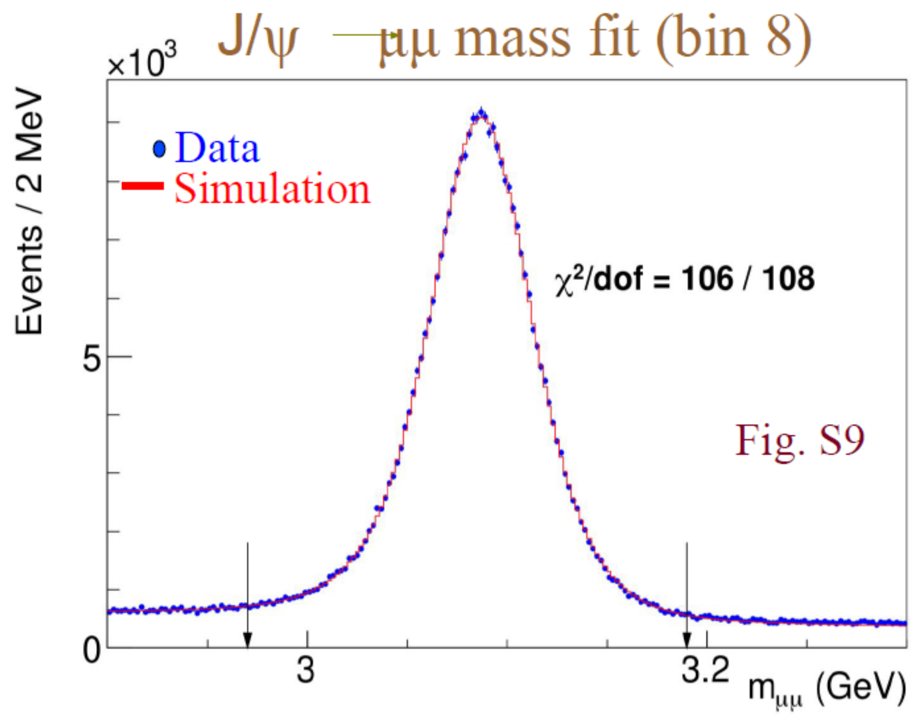
- Starting from detailed construction data
- Tuned with conversion electrons

Tracking momentum scale

Set using $J/\Psi \rightarrow \mu\mu$, $\Upsilon \rightarrow \mu\mu$ resonances, and $Z \rightarrow \mu\mu$

- Extracted by J/Ψ in bins of $1/P_T$ and extrapolated to 0 curvature

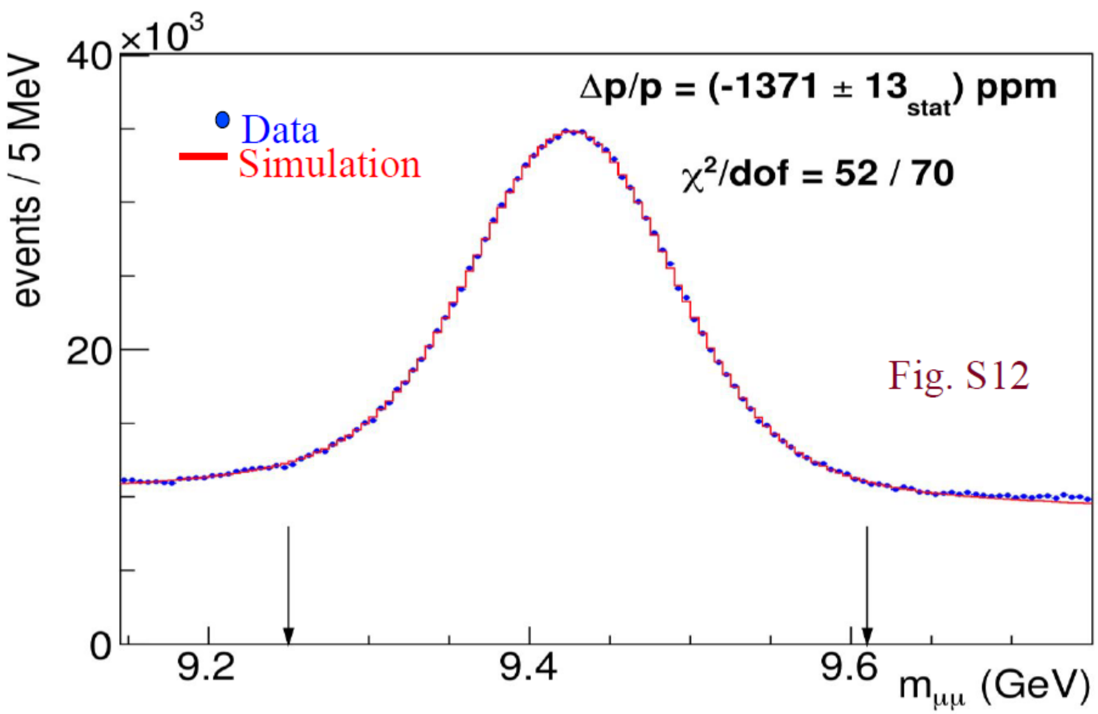




Using Upsilon

$\Upsilon \to \mu\mu$ provides

- Momentum scale at larger P_T
- Validation of beam-constrained (Υ produced prompt)
- Cross check of Beam-Constrained vs Non-BC
  - We resolved previous discrepancy of BC vs NBC result
    - And removed related systematics



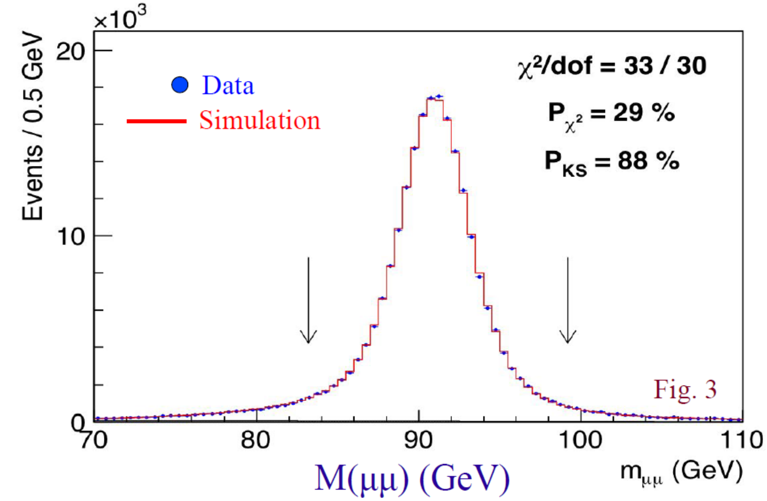
Non beam-constrained $\Upsilon \to \mu\mu$ mass fit

Final list of tracking systematics

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 pp
Statistical NBC (BC)	2	13(10)	0
Total	29	36	16 ppm

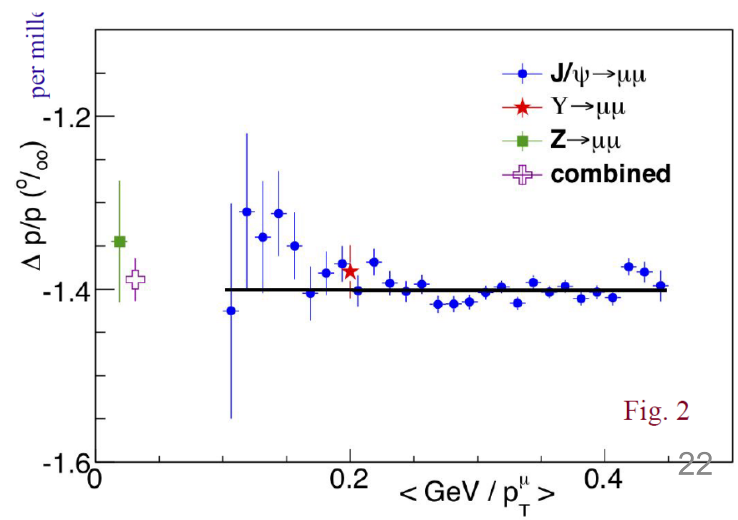
Z mass consistent with PDG value (91188 MeV) (0.7σ statistical)

$M_Z = 91192.0 \pm 6.4_{stat} \pm 2.3_{momentum} \pm 3.1_{QED} \pm 1_{alignment}$ MeV



Uncertainty on $M_{W,Z}$ = 2 MeV

Linearity plot for muon tracks



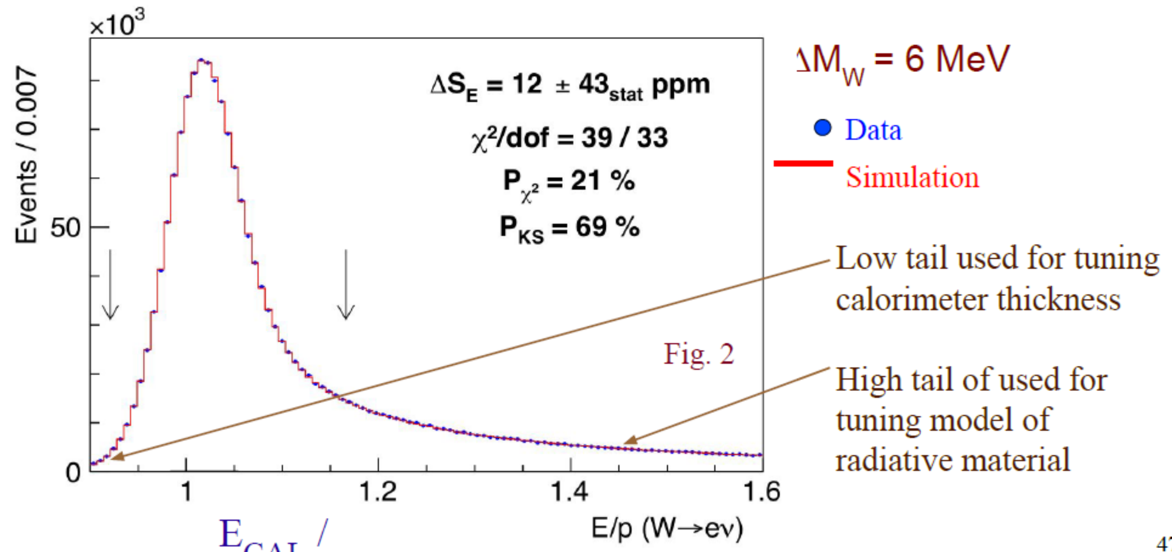
Calorimeter

Simulation for e/γ:
Distributions of energy response obtained by GEANT4 detailed simulation, tuned on data

- Leakage into hadronic calorimeter
- Absorption in magnet coil
- Dependence on incident angle and E_T
- Energy-dependent gain (non-linearity) parameterized and fit from data

EM energy scale:

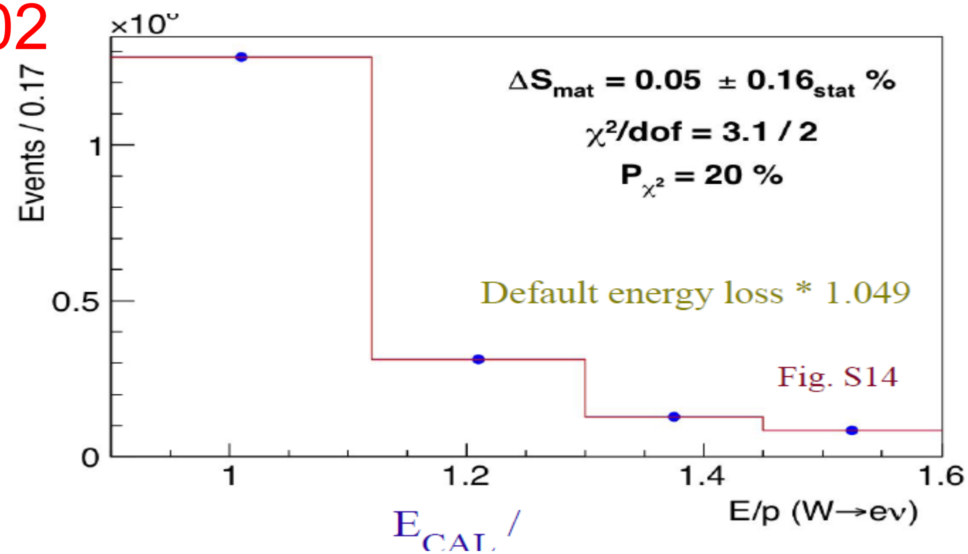
- E/p peak from $W \rightarrow e\nu$ provides measurement of EM scale



Checks

Material budget

- From E/p tail excellent match after scaling of X_0
  $S_{X_0} = 1.049 \pm 0.002$

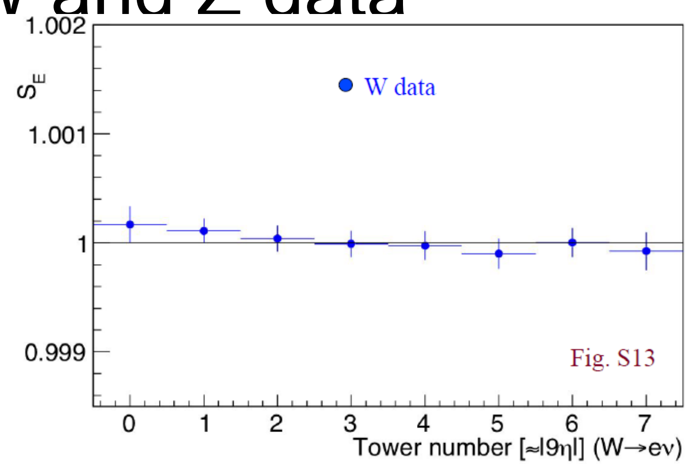


E_M non linearity, tuned with W and Z data

- Perform E/p fit in bins of E_T
- Correct with

$$S_E = 1 + \beta \log(E_T / 39\ \mathrm{GeV})$$

$$\beta = (7.2 \pm 0.4_{stat}) \times 10^{-3}$$



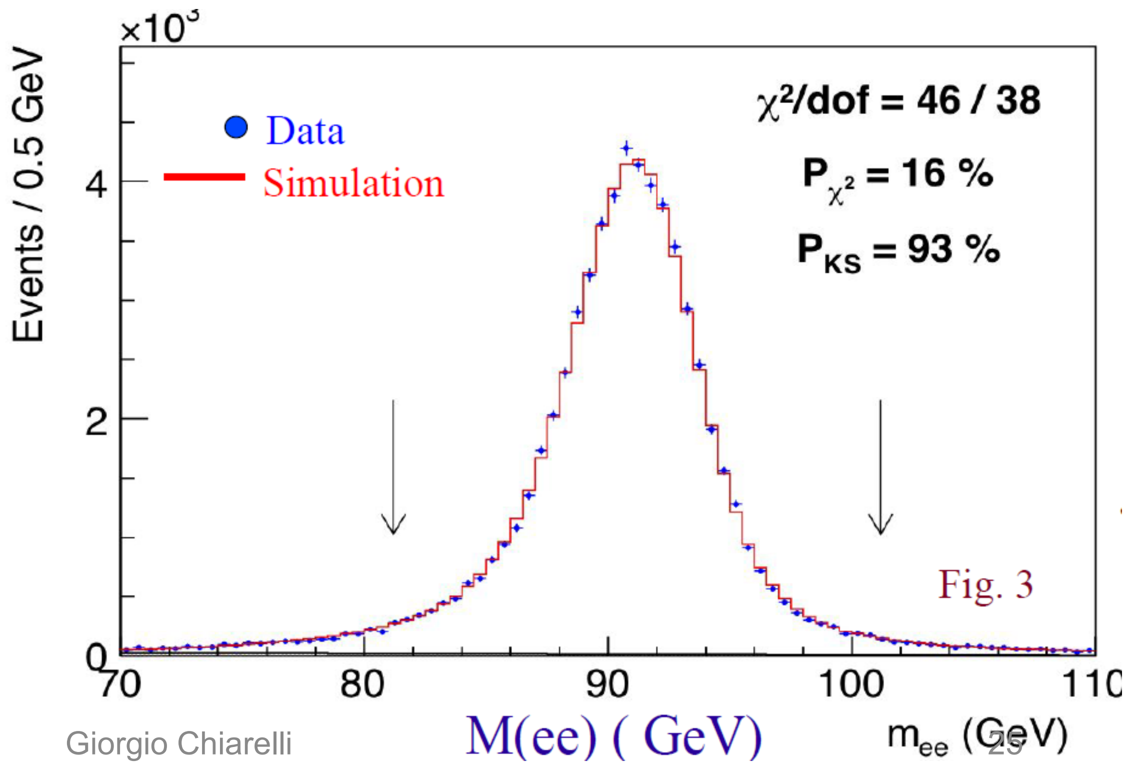
Z mass

Perform blind check of Z mass using E/p calibration

- Consistent with PDG (91188 MeV) within 0.5σ

$$M_Z = 91194.3 \pm 13.8_{stat} \pm 6.5_{calorimeter} \pm 2.3_{momentum} \pm 3.1_{QED} \pm 0.8_{alignment}\ \mathrm{MeV}$$

- Combine E/p calibration with Z→ee mass for best accuracy



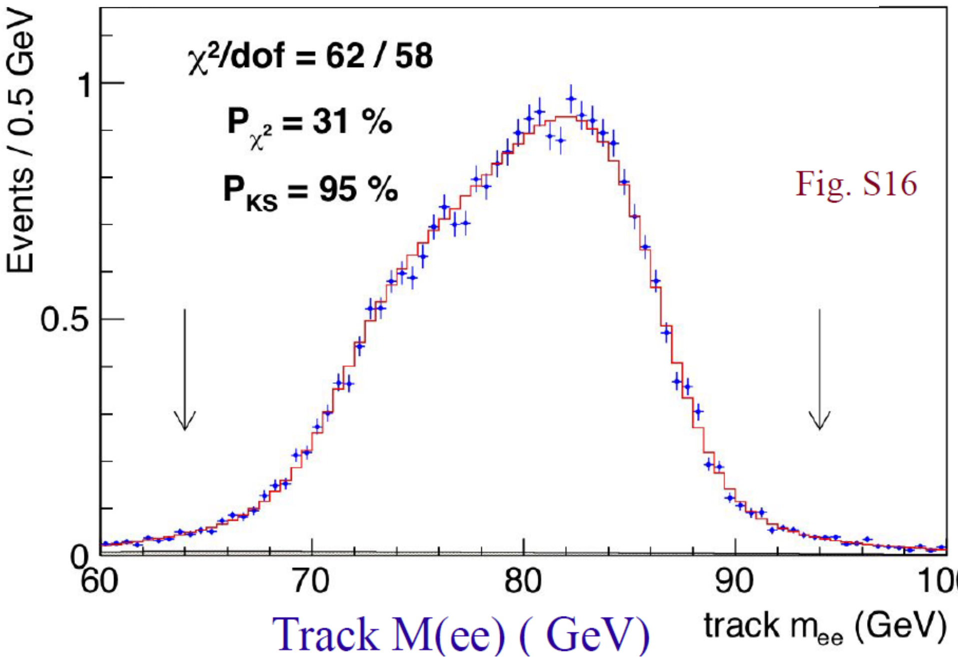
Checks using Z electrons

Track-based MZ

- ➢ $(E/p)_1<1.1$&$(E/p)_2>1.1$

Clusters and tracks

- ➢ Radiative and non-radiative regions
  - ➢ Check of correction
- ➢ Check of tracking for electrons and muons



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

Lepton resolutions

Tracking resolution parameterized in the custom simulation by

- Radius-dependent drift chamber hit resolution $\sigma_h \sim (150 \pm 1\ \text{stat})\ \mu m$
- Beamspot size $\sigma_b = (36.0 \pm 0.5\text{stat})\ \mu m$
- Tuned on the widths of the $Z \rightarrow \mu\mu$ (beam-constrained) and $\Upsilon \rightarrow \mu\mu$ (both beam constrained and non-beam constrained) mass peaks
- ΔM_W (muons): 0.3 MeV

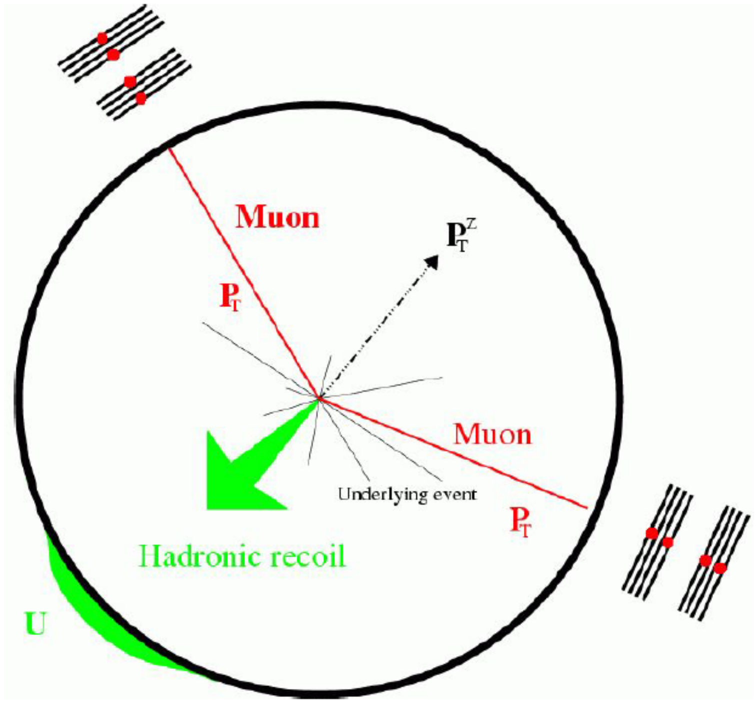
Electron cluster resolution parameterized in the custom simulation by

- $\sigma = 12.6\% / \sqrt{ET}$ (sampling term)
- constant term $\kappa = (0.73 \pm 0.02\text{stat})\ \%$
- Tuned on the widths of the E/p peak and the $Z \rightarrow ee$ peak (selecting radiative electrons)
- ΔM_W (electrons): 0.9 MeV

Recoil model

Exploit similarity in production and decay of W and Z

Detector response for recoil tuned using P_T balance in $Z \to ll$ decays

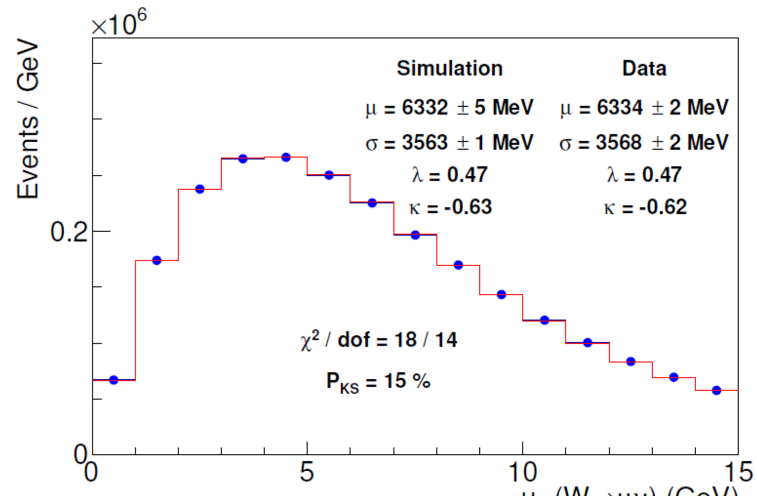


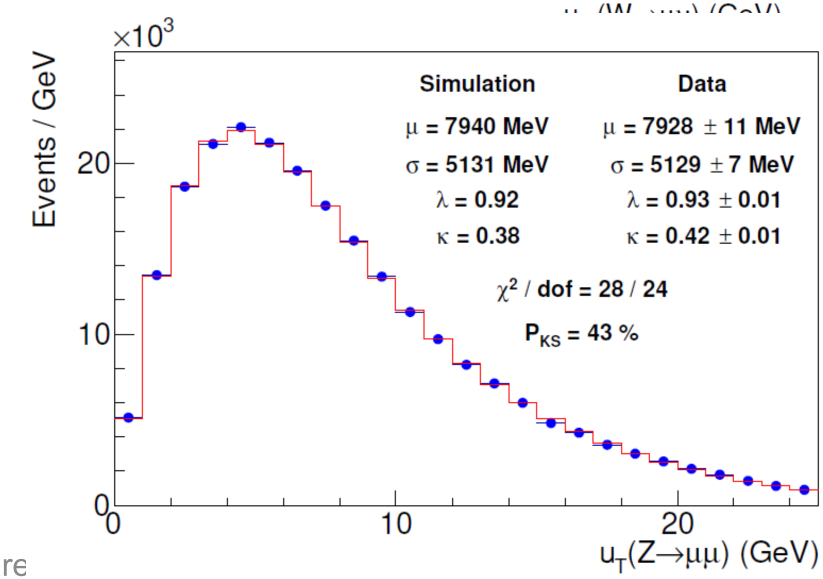
Transverse momentum of Hadronic recoil (***u***), calculated as 2-vector sum over calorimeter towers

Additional constraint from P_{T_W} in W boson events

NEW: In addition to the $P_T(Z)$ data constrain on the boson P_T spectrum,

- the ratio of $P_T(W)$ / $P_T(Z)$ spectra is also constrained from $P_T(W)$ data
- DYqT code: triple-differential cross section calculation at NNLO-QCD used to model scale variation of ratio
- $P_T(W)$ data is used as constraint on ratio model
- correlation with hadronic recoil model is taken into account





Parton distribution functions

- Affect W boson kinematic line-shapes through acceptance cuts
- We use **NNPDF3.1** as the default NNLO PDFs
- Use ensemble of 25 '*uncertainty*' PDFs $\Rightarrow$3.9 MeV
  - Represent variations of eigenvectors in the PDF parameter space
  - compute δM_W contribution from each error PDF
- Central values from NNLO PDF sets CT18, MMHT2014 and NNPDF3.1 agree within **2.1** MeV of their midpoint
- As an additional check, central values from NLO PDF sets ABMP16, CJ15, MMHT2014 and NNPDF3.1 agree within 3 MeV of their midpoint
- Missing higher-order QCD effects estimated to be 0.4 MeV
  - varying the factorization and renormalization scales
  - comparing two event generators with different resummation and non-perturbative schemes.

Early May, Resbos Authors (C.P. Yuan et al.) published

- https://arxiv.org/pdf/2205.02788.pdf

- In this paper they compare our procedure (Resbos1+constraint from data) with Resbos2 (higher order), and confirm our uncertainty estimate

Backgrounds

Muon channel

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)

Electron channel

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)

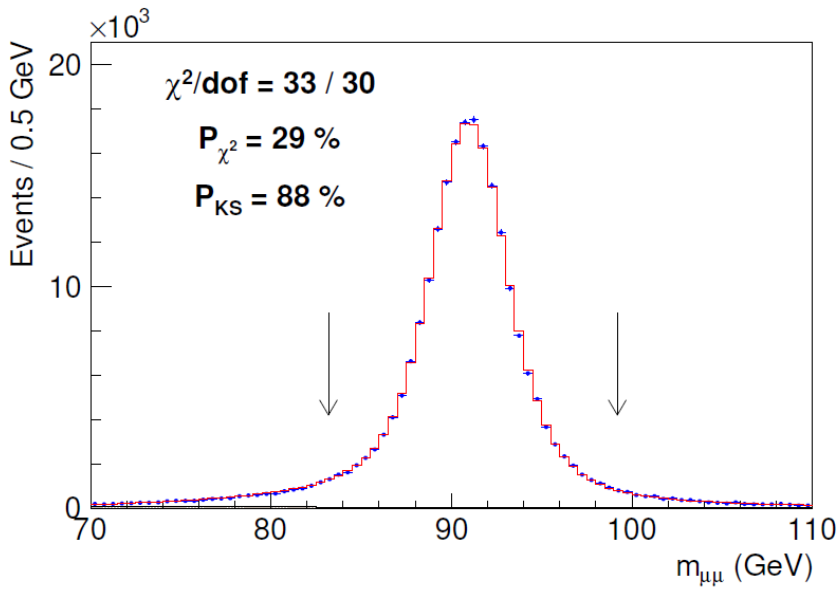
Backgrounds are small
(except $Z \to \mu\mu$ with a forward muon)

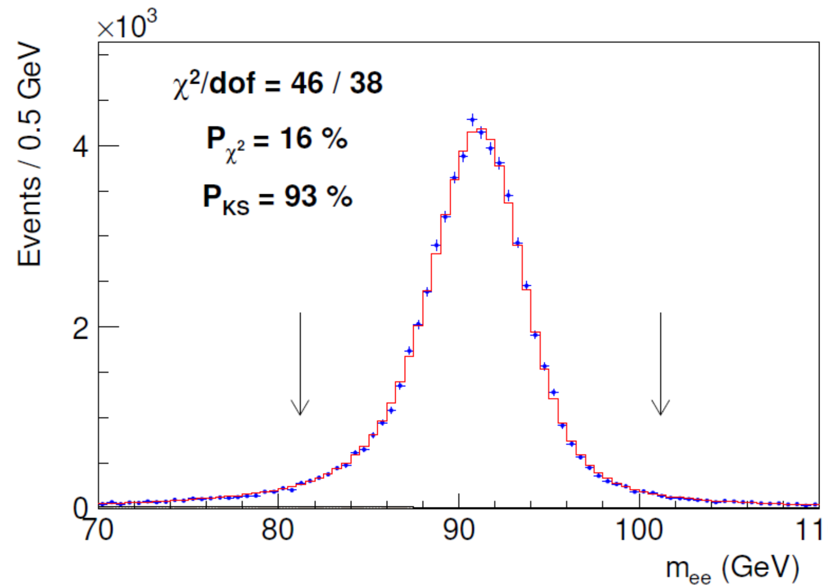
Fitting blind

All fits (Z, W) blinded with an unknown [-50,+50] MeV offset

- In this way we studied the techinque and the systematics close to the actual value keeping Z and W mass exact value, unknown by ±50 MeV

Offset **removed *after*** the analysis was declared "frozen" and "approved"

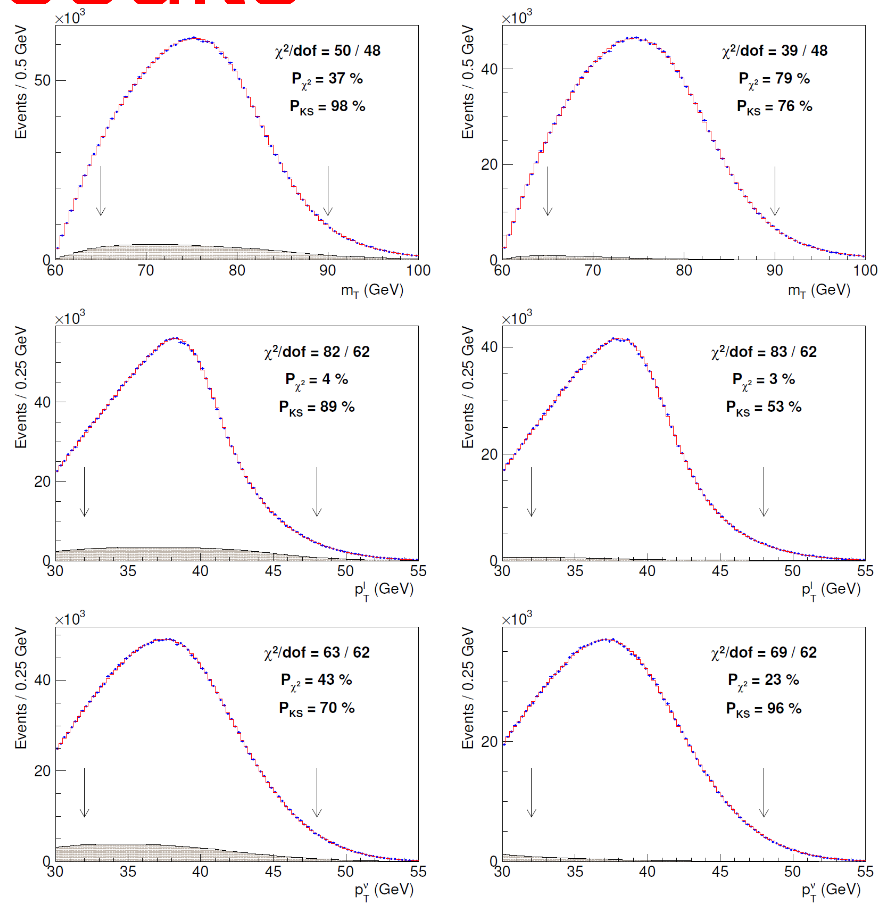




Fit Results

We fit 6 variables:

- Two channels (e, μ)
  - P_T charged lepton
  - P_T neutrino
  - M_T



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

Combined electrons (3 fits): M_W=80424.6±13.2 MeV, $P(\chi^2)$ =19%

Combined muons (3 fits) : M_W=80437.9±11.0 MeV, $P(\chi^2)$ =17%

Uncertainties: New & Old

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

Source	Uncertainty
Lepton Energy Scale	7
Lepton Energy Resolution	2
Recoil Energy Scale	4
Recoil Energy Resolution	4
$u_{\|\|}$ efficiency	0
Lepton Removal	2
Backgrounds	3
$p_T(W)$ model	5
Parton Distributions	10
QED radiation	4
W boson statistics	12
Total	19

Updates wrt 2.2 fb-1

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

Table S1

Several improvements thanks to theoretical work

W Boson Mass Measurements from Different Experiments

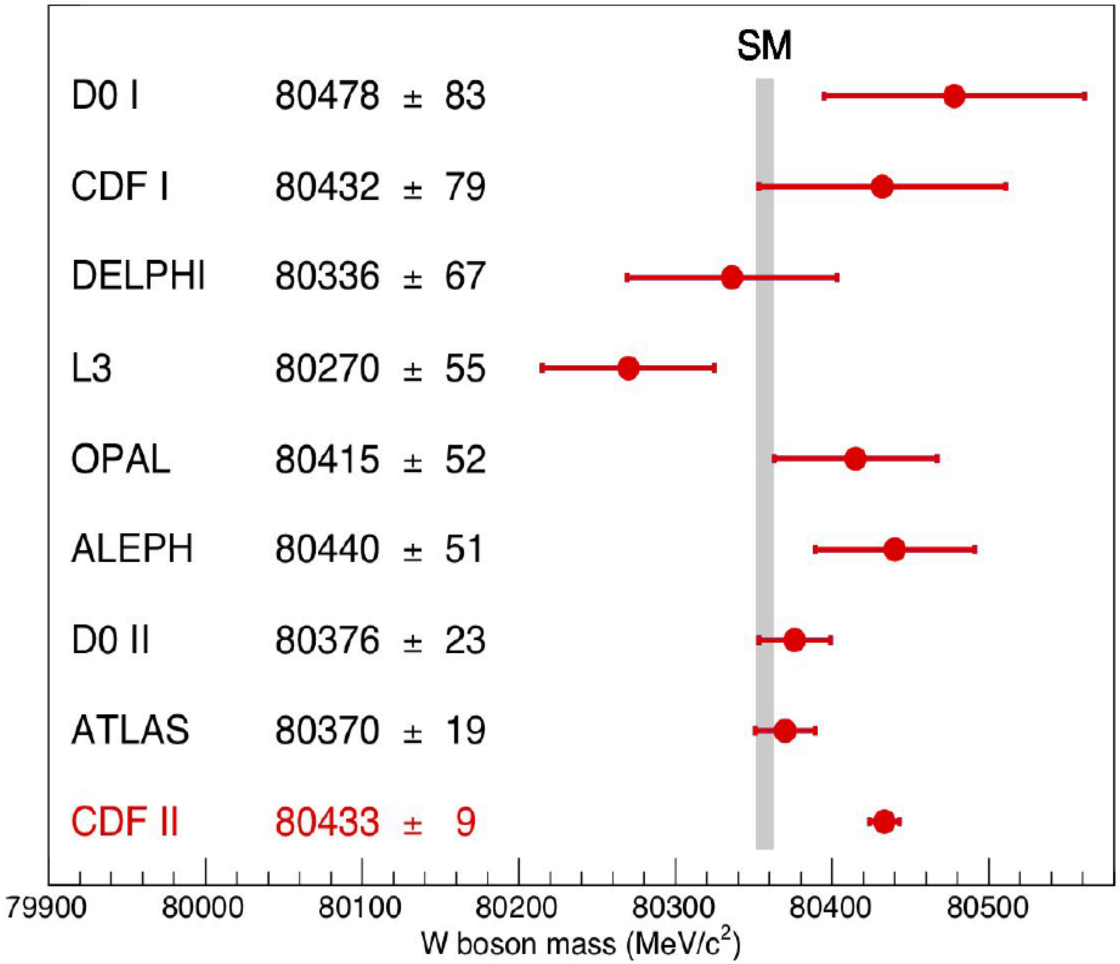


Fig. 5

SM expectation: $M_W = 80{,}357 \pm 4_{\text{inputs}} \pm 4_{\text{theory}}$ (PDG 2020)

LHCb measurement : $M_W = 80{,}354 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}}$ [*JHEP* **2022,** 36 (2022)]

Improvements over previous result

The statistical precision of the measurement from the four times larger sample is improved by almost a factor of 2

- To achieve a commensurate reduction in systematic uncertainties, a number of analysis improvements have been incorporated:
- These improvements are based on using cosmic-ray and collider data in ways not employed previously to improve:
  - the COT alignment and drift model and the uniformity of the EM calorimeter response
  - the accuracy and robustness of the detector response and resolution model in the simulationTtheoretical inputs to the analysis have been updated
- Upon incorporating the improved understanding of PDFs and track reconstruction, our *previous measurement* is increased by 13.5 MeV to 80400.5 MeV
  - consistency of the latter with the new measurement is at the percent probability level

Summary

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

- 39 years after its discovery...

New result is twice better than old one

- M_W=80433.5±6.4stat±6.9 syst MeV
  M_W=80433.5±9.4 (stat.+syst) MeV

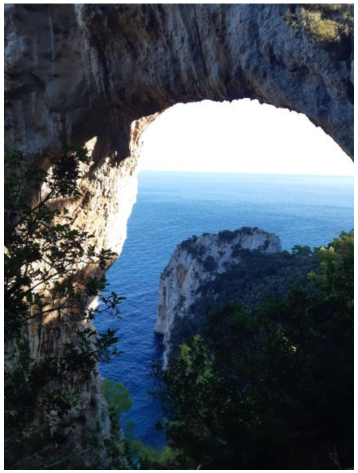
Difference from SM expectation, M=80357±6 MeV

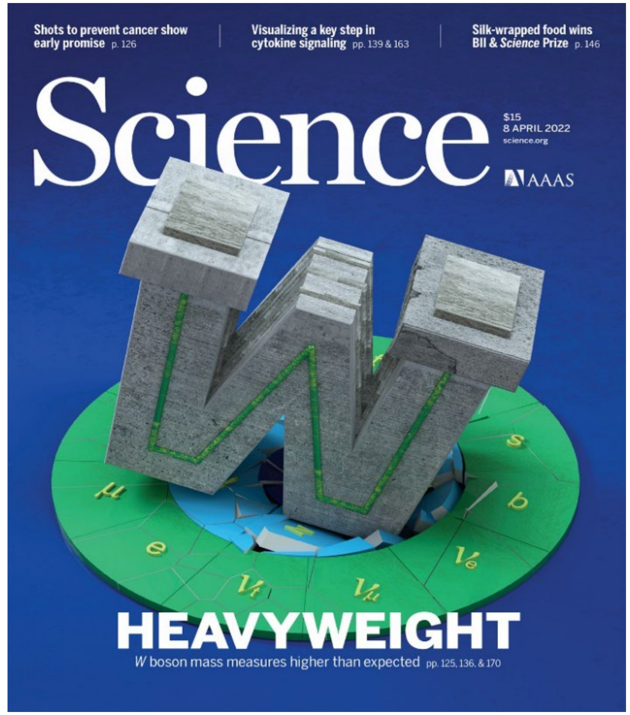
- significance of 7.0σ
- suggests the possibility of improvements to the SM calculation or of extensions to the SM

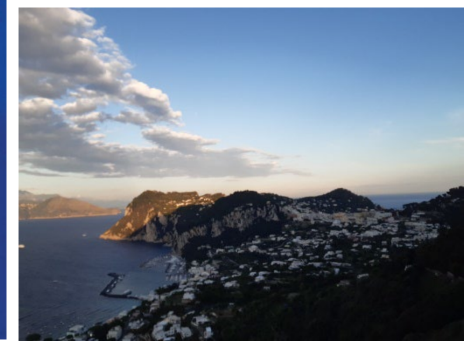
Ringraziamenti (non di prammatica)

Colgo l'occasione per ringraziare, a nome di tutto CDF, l'INFN per il suo supporto, continuo e convinto dai primi anni '80 del secolo scorso

- Generazioni di studenti si sono succeduti ed hanno contribuito al successo di questo esperimento
- Negli ultimi anni il supporto è continuato
  - Per questa analisi il CNAF ci ha dato la sicurezza che, a fronte di un supporto calante da parte di Fermilab, le nostre capacità di analisi erano garantite
- Un grazie sentito da parte degli spokespersons (Dave Toback & G.C.)







CDF M_W *vs* m_{top}

MW vs MHiggs