High-Precision Measurement of the W Boson Mass with the CDF II Detector

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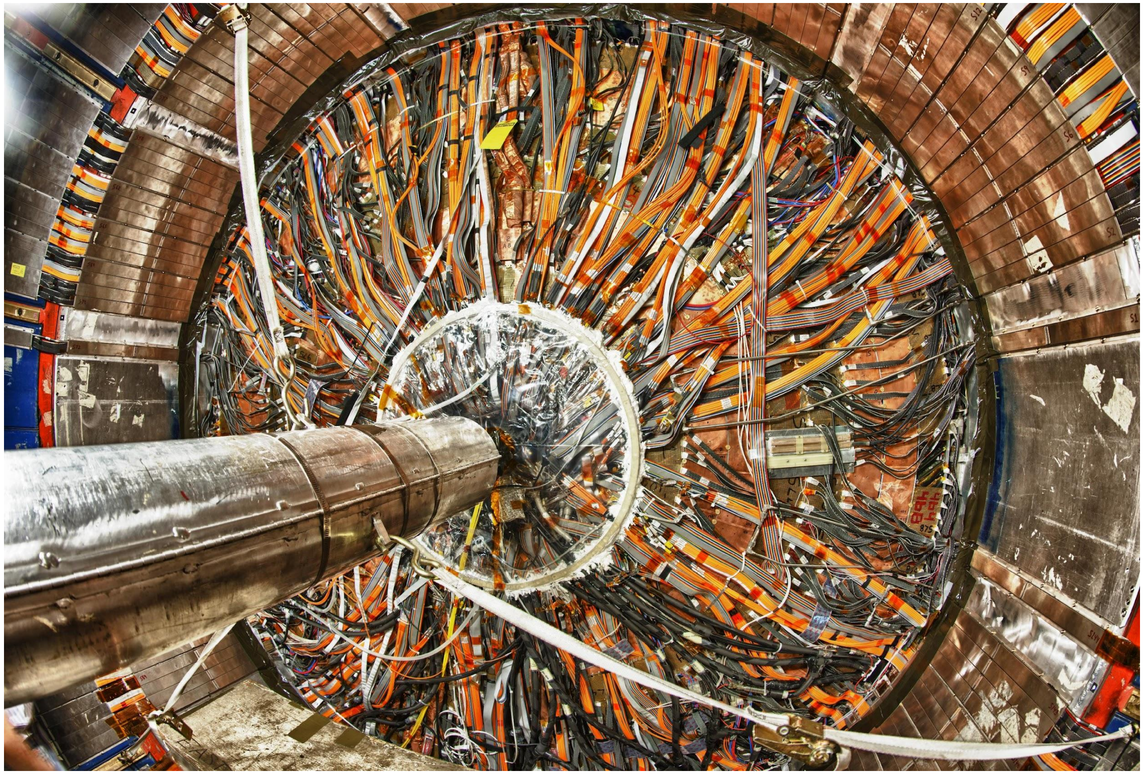
(much stolen from A. Kotwal's Wine & Cheese)
For the CDF Collaboration



The Mitchell Conference on Collider, Dark Matter, and Neutrino Physics 2022
May 25, 2022

Outline

- Motivation
- Some Details about Analysis Strategy, Experimental Apparatus and Data Samples
- Results and Systematic Uncertainties
- Conclusions

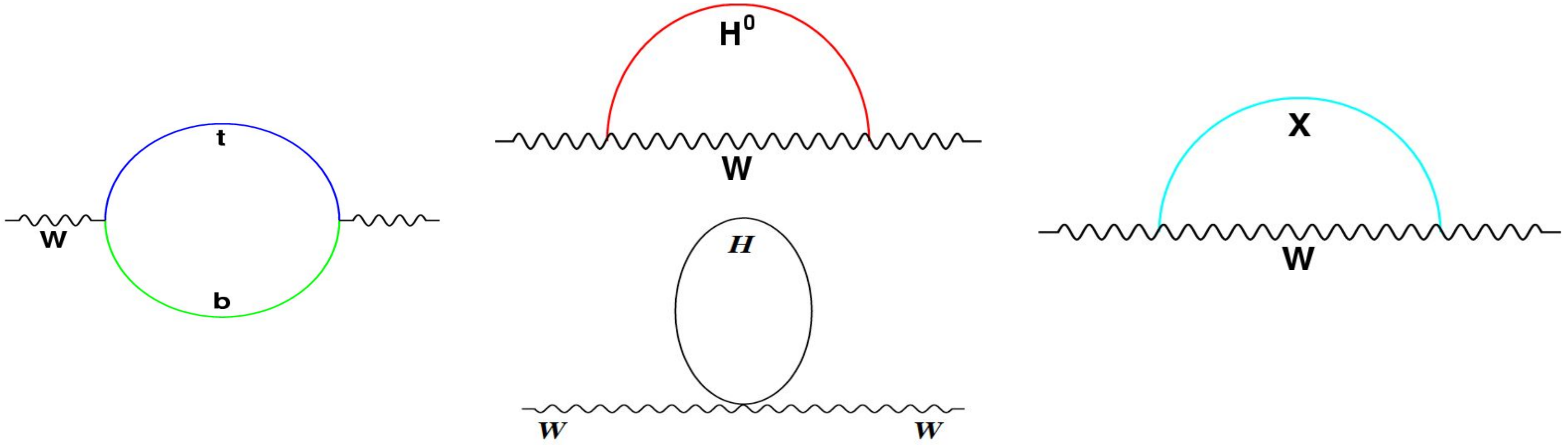
citation: *Science* **376**, 170 (April 7, 2022); DOI: 10.1126/science.abk1781

Motivation for Precision Measurements

- The electroweak gauge sector of the standard model is constrained by precisely known parameters
  - $\alpha_{EM}(M_Z) = 1 / 127.918(18)$
  - $G_F = 1.16637\ (1) \times 10^{-5}\ \mathrm{GeV}^{-2}$
  - $M_Z = 91.1876\ (21)$ GeV
  - $m_{top} = 172.89\ (59)$ GeV
  - $M_H = 125.25\ (17)$ GeV
- At tree-level, these parameters are related to M_W
  - $M_W^2 = \pi\alpha_{EM} / \sqrt{2}G_F \sin^2\vartheta_W$
    - Where ϑ_W is the Weinberg mixing angle, defined by
    - $\cos\vartheta_W = M_W/M_Z$

Motivation for Precision Measurements

- Radiative corrections due to heavy quark and Higgs loops and (potentially) undiscovered particles



Motivate the introduction of the ρ parameter: $M_W^2 = \rho\,[M_W(\text{tree})]^2$
with the predictions $\Delta\rho = (\rho - 1) \sim M_{top}^2$ and $\Delta\rho \sim \ln M_H$

Motivation for Precision Measurements

- The mass of the W boson is tightly constrained by the symmetries of the standard model, in conjunction with M_{top} and M_{Higgs}
  - The Higgs boson was the last missing component of the model
  - Following the observation of the Higgs boson, a measurement of the W-boson mass provides a stringent test of the model

- The W boson mass is presently constrained by SM global fits to a relative precision of 0.01%
  - provides a strong motivation to test the SM by measuring the mass to the same level of precision
  - SM expectation $M_W = 80{,}357 \pm 4_{inputs} \pm 4_{theory}$ MeV
  - Inputs include Z- and Higgs boson and top-quark masses, EM coupling and muon lifetime measurements

Beyond-SM Modifications to Expected M_W

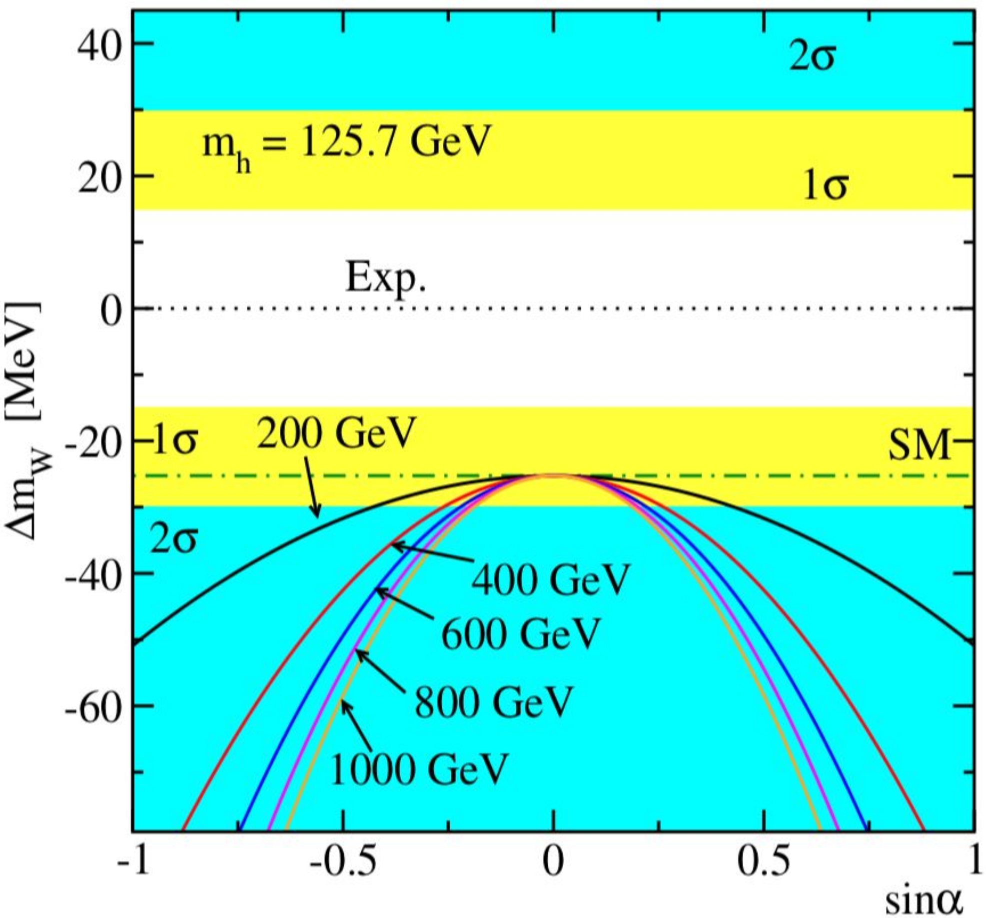
- Hypotheses to provide a deeper explanation of the Higgs field, its potential and the Higgs boson, include
  - Supersymmetry
  - Compositeness
  - New strong interactions
  - Extended Higgs sector

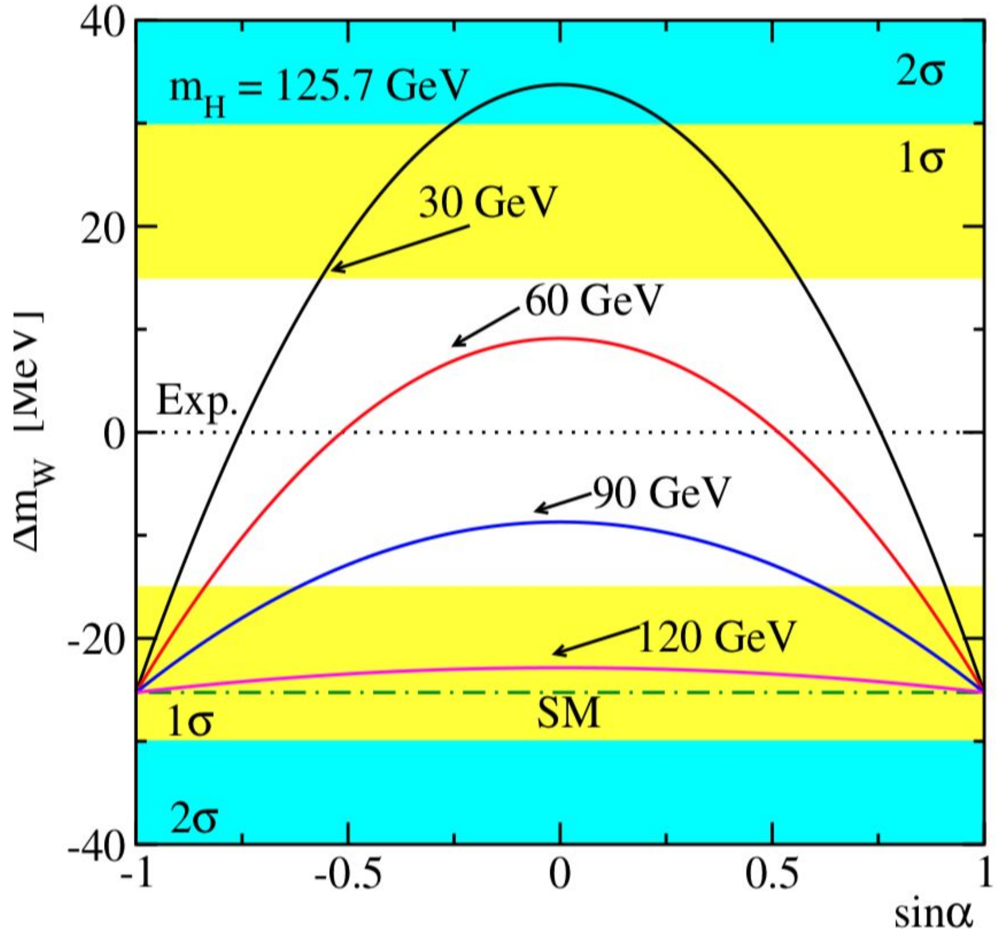
- Hypothetical sources of particulate dark matter

- Extended gauge sector

Single Scalar Extension of Higgs Sector

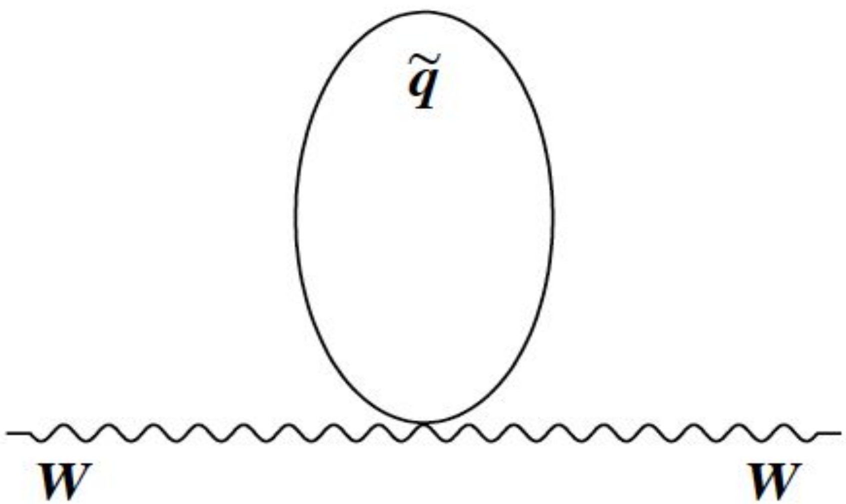
Inclusion of an additional scalar particle with no SM charges, which mixes with the Higgs boson

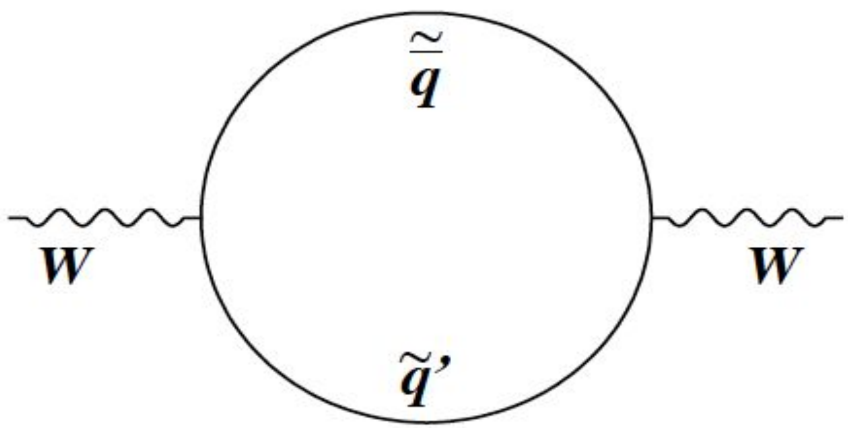




D. López-Val and T. Robens, Phys. Rev. D 90, 114018 (2014)

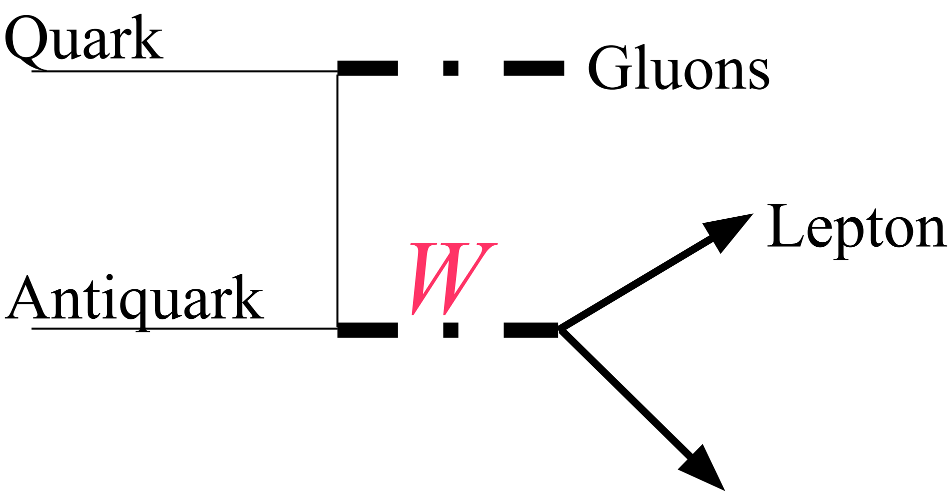
Contributions from Supersymmetric Particles



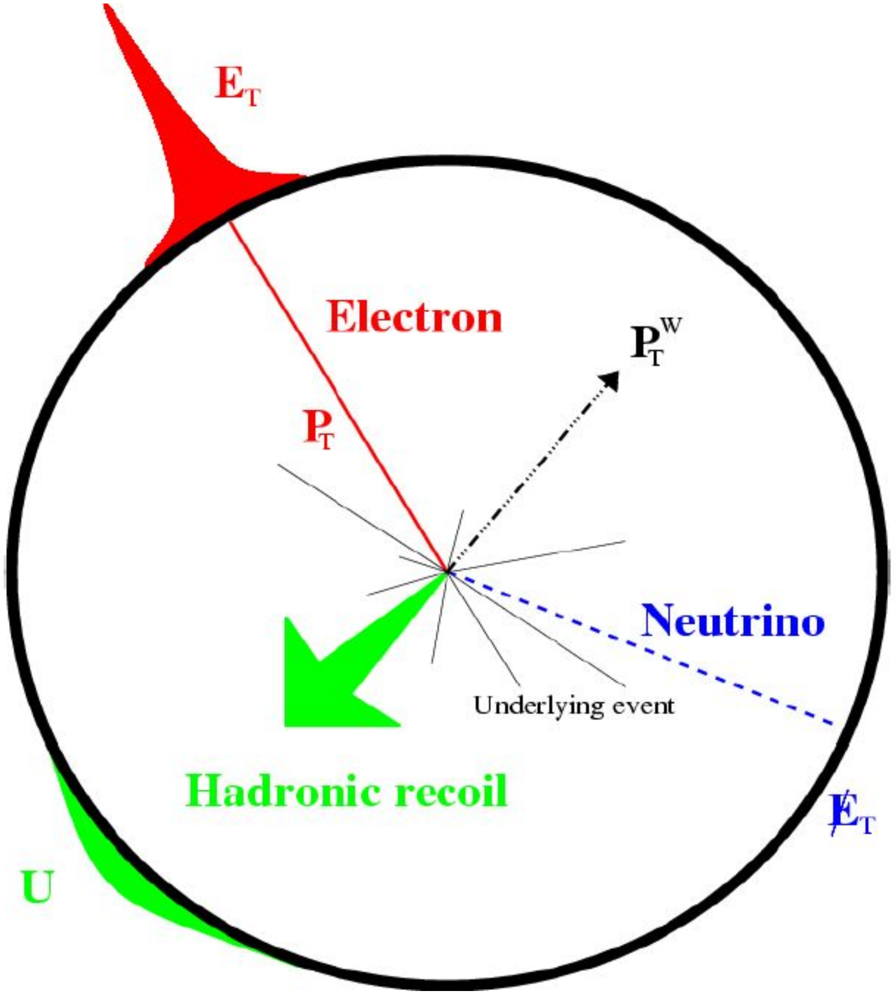


- Radiative correction depends on mass splitting (Δm^2) between squarks in SU(2) doublet
- SUSY loops can contribute tens of MeV to M_W
  - Multi-dimensional parameter space with significant exclusions from LHC

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 $p_T(W) << M_W$

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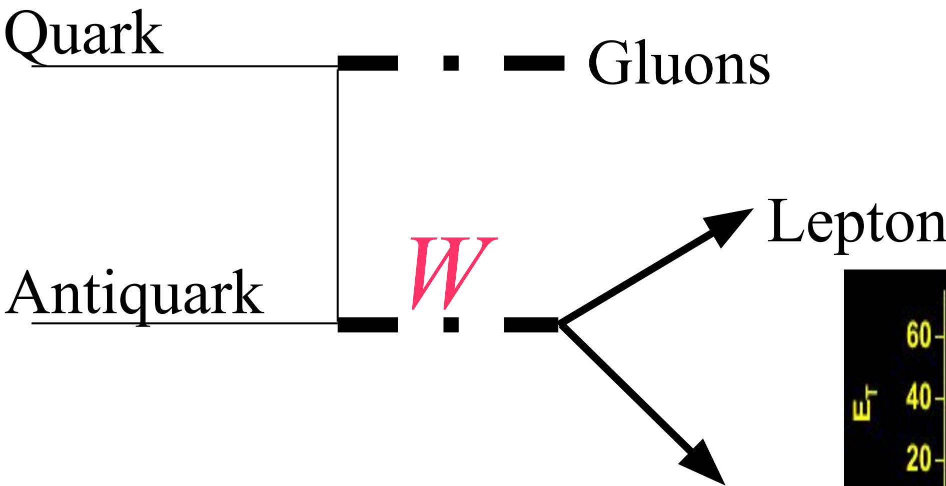

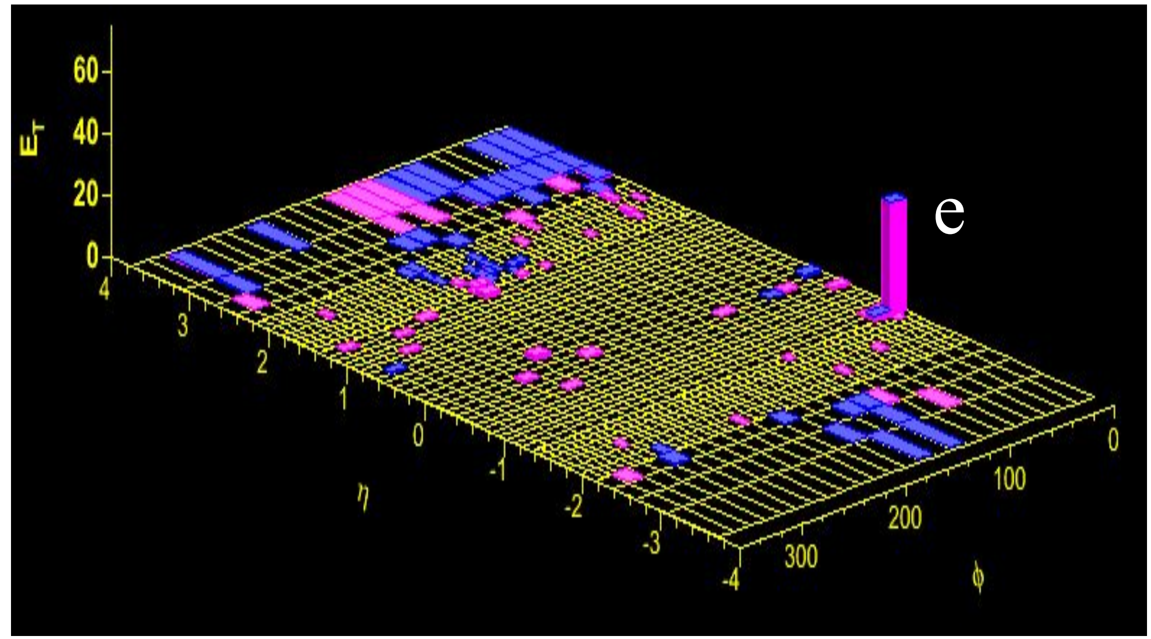

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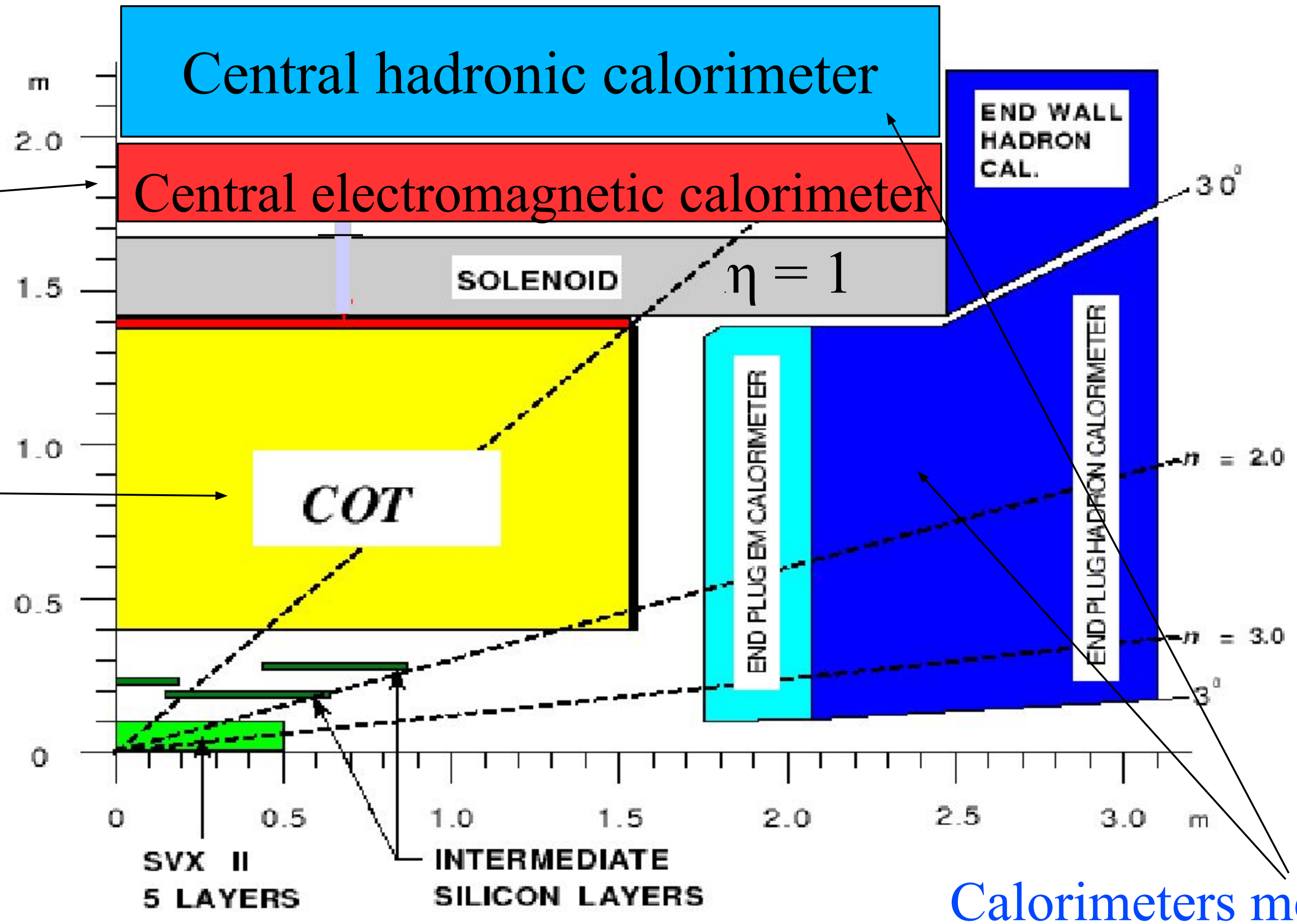
Quadrant of Collider Detector at Fermilab (CDF)

EM calorimeter provides precise electron energy measurement

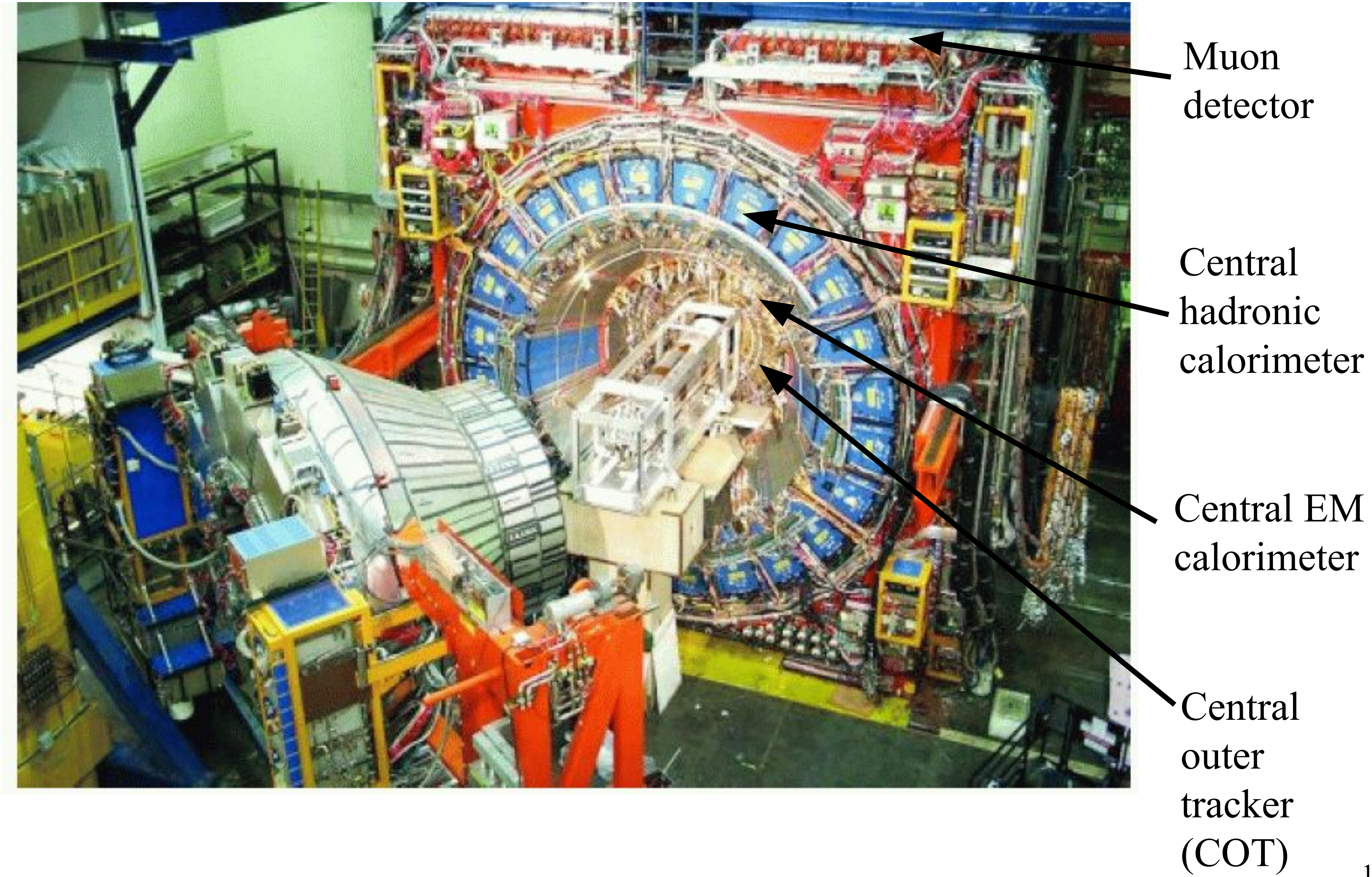
COT provides precise lepton track momentum measurement



Calorimeters measure hadronic recoil particles

Select W and Z bosons with central (| η | < 1) leptons

Collider Detector at Fermilab (CDF)



W & Z Data 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):
  - Electron and muon channels: $L = 8.8\ \text{fb}^{-1}$
  - Identical running conditions for both channels, guarantees cross-calibration
- Event selection gives fairly clean samples
  - Mis-identification backgrounds ~ 0.5%

Analysis Strategy

Strategy

Maximize the number of internal constraints and cross-checks

Driven by three goals:

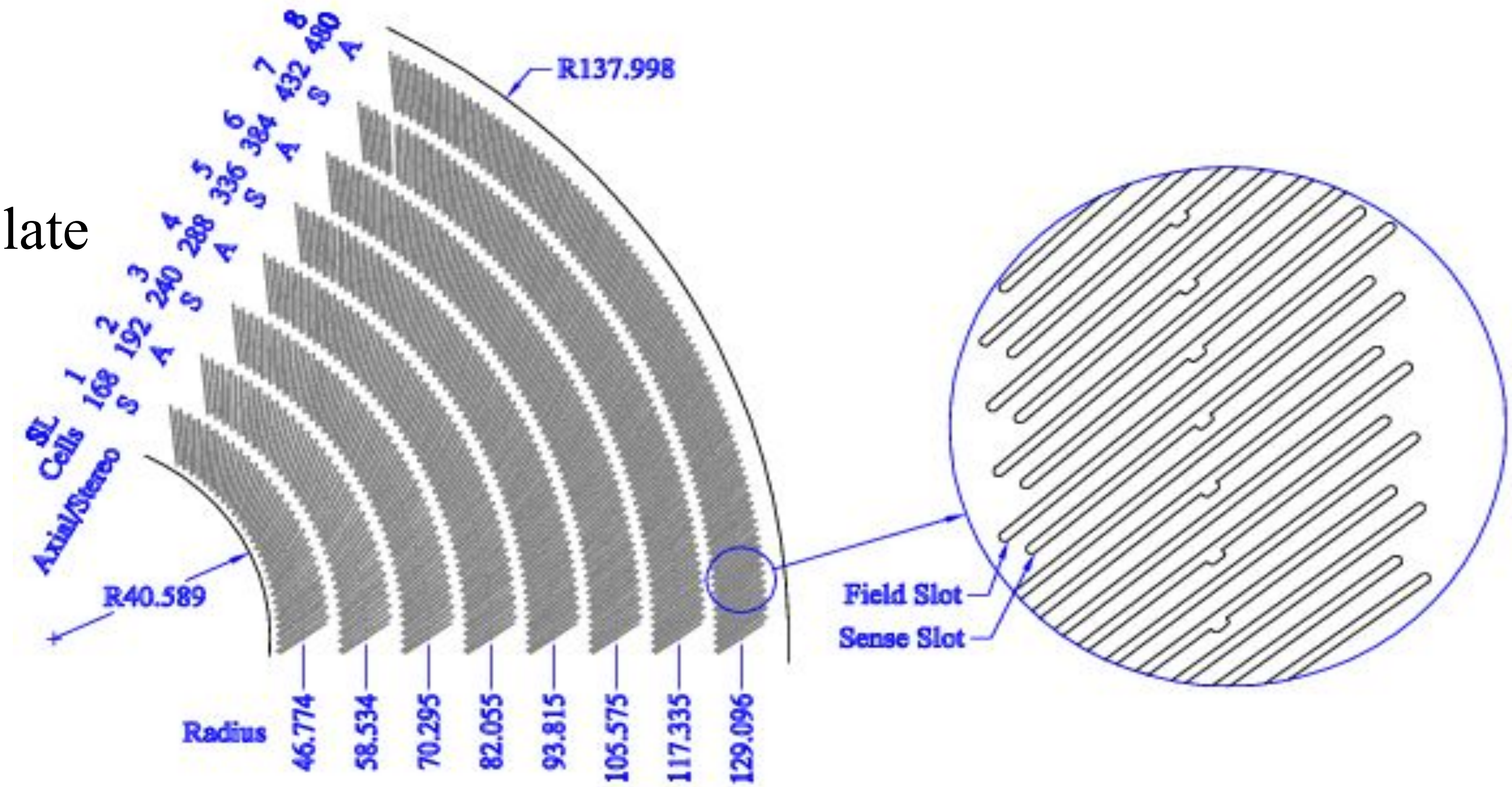
1) Robustness: constrain the same parameters in as many different ways as possible

2) Precision: combine independent measurements after showing consistency

3) minimize bias: blinded measurements of M_Z and M_W

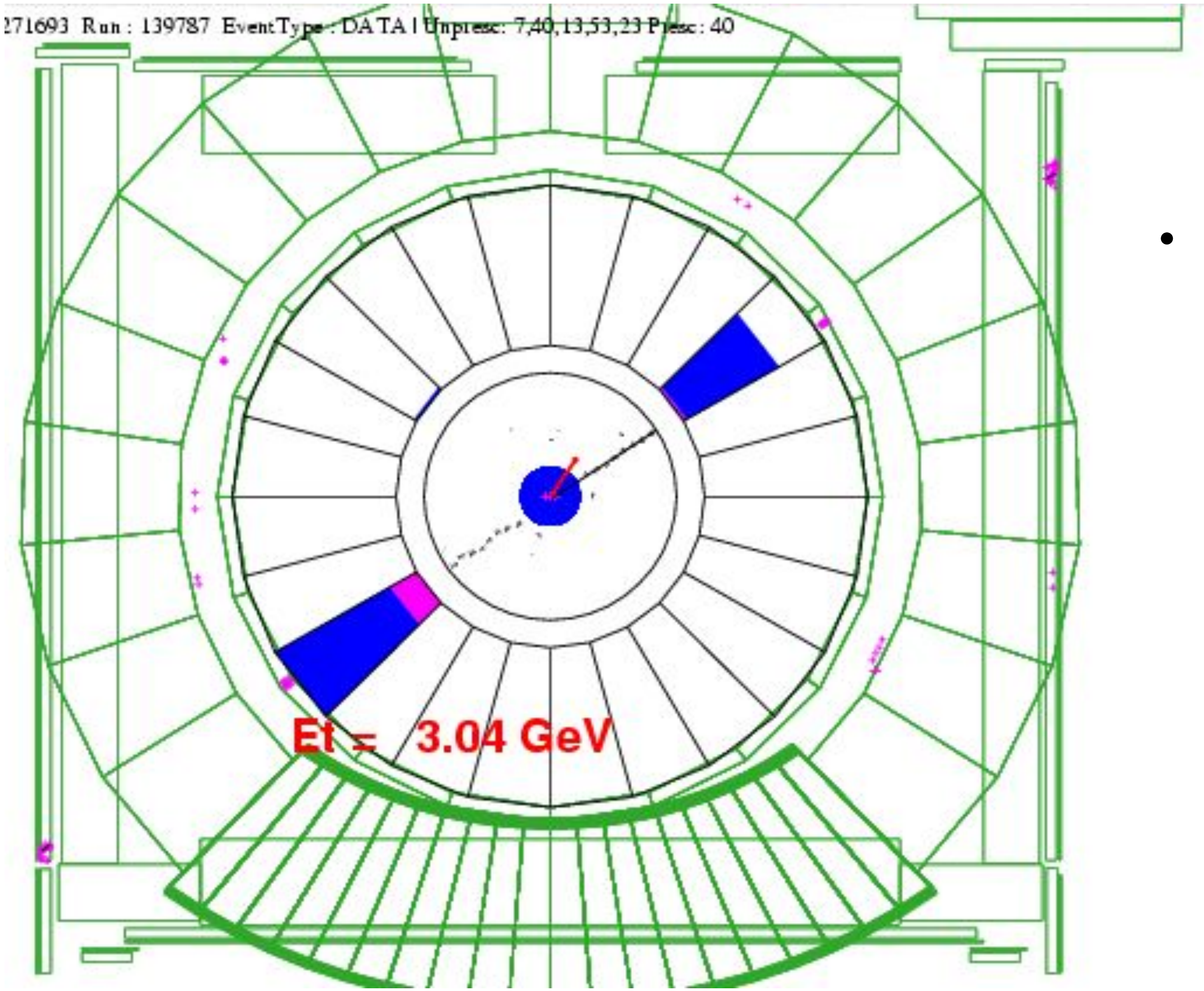
Drift Chamber (COT) Alignment

COT endplate geometry



Internal Alignment of COT

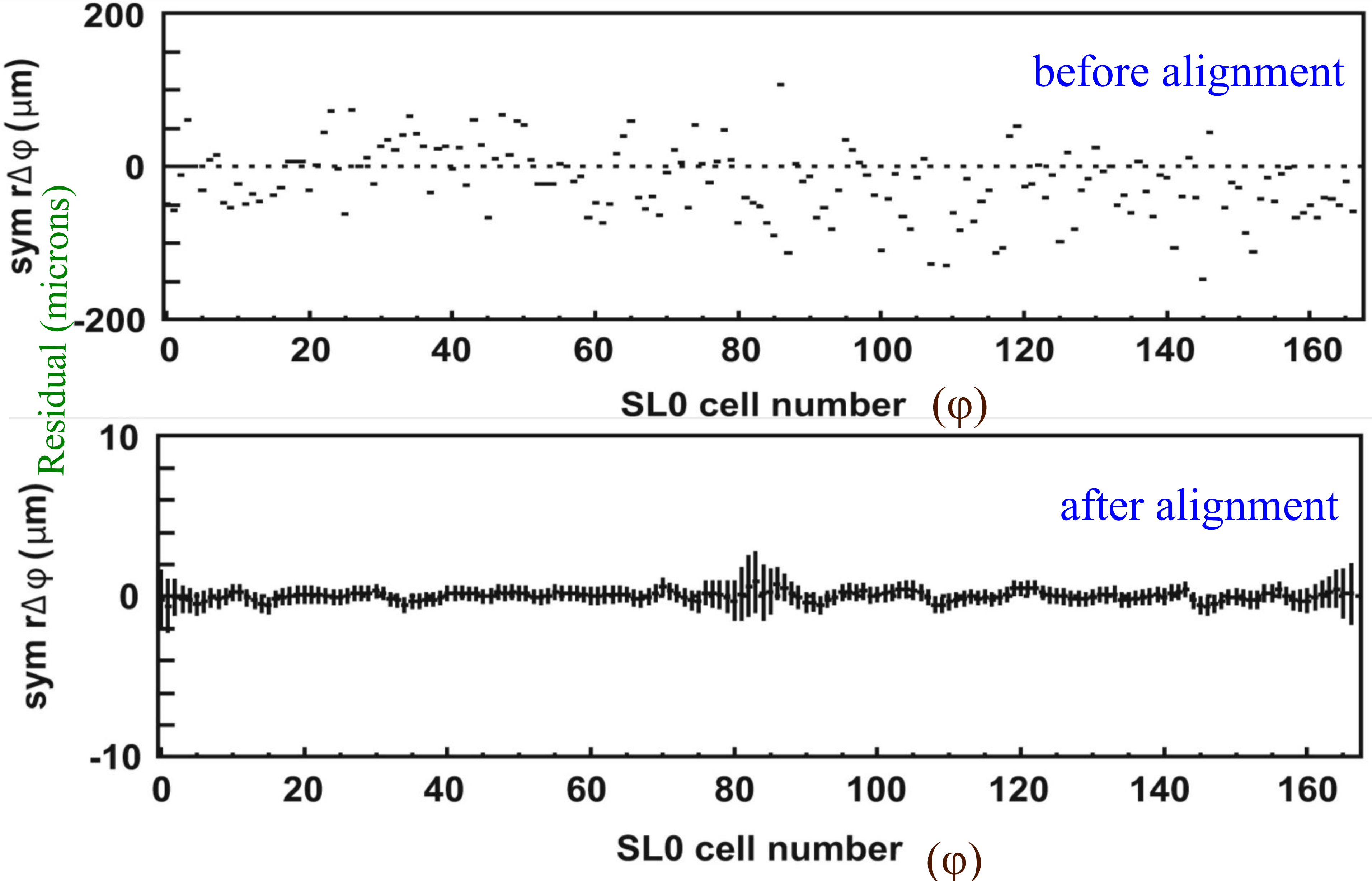
- Use a clean sample of ~480*k* cosmic rays for cell-by-cell internal alignment



- Fit COT hits on both sides simultaneously to a single helix (AVK, H. Gerberich and C. Hays, NIMA 506, 110 (2003))
  - Time of incidence is a floated parameter in this 'di-cosmic fit'

Residuals of COT cells after alignment

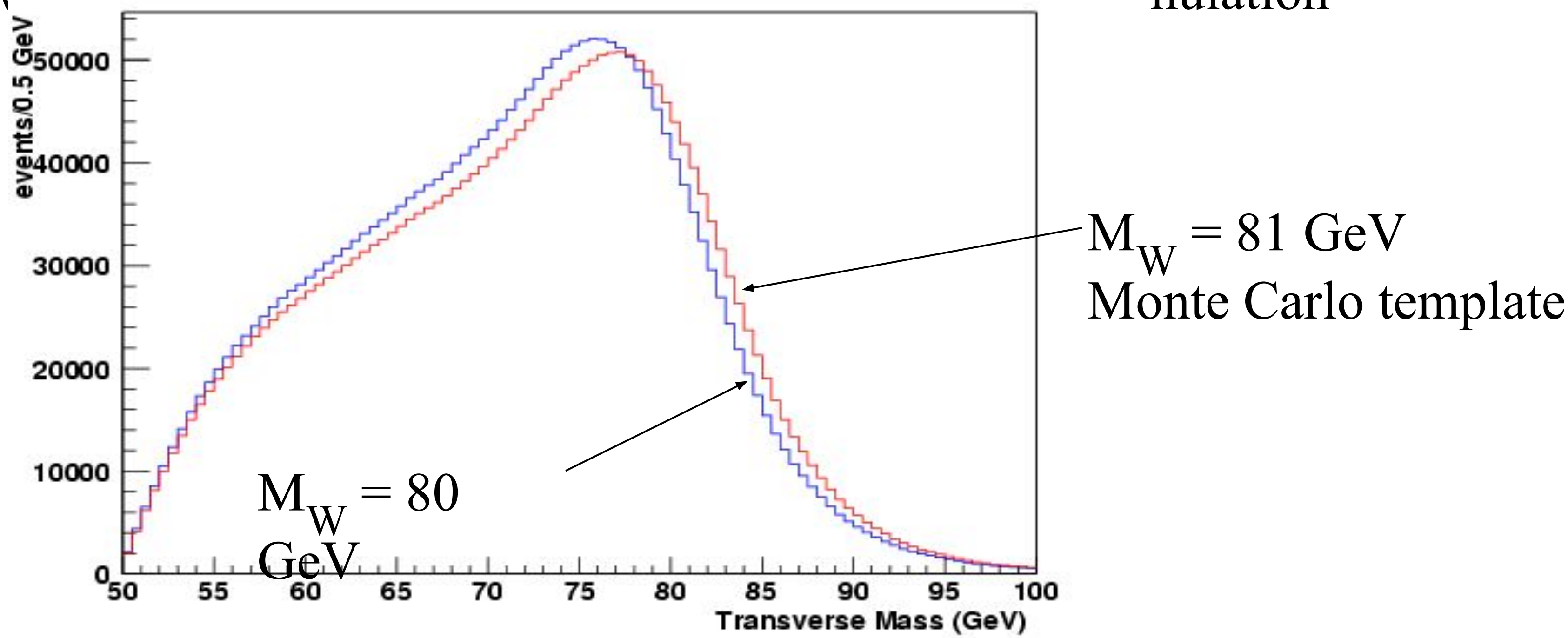
(AVK & CH, *NIM A* 762 (2014) pp 85-99)



Final relative alignment of cells ~1 μm (initial alignment ~50 μm)

Signal Simulation and Template Fitting

- All signals simulated using a Custom Monte Carlo
  - Generate finely-spaced templates as a function of the fit variable
  - perform binned maximum-likelihood fits to the data
- Custom fast Monte Carlo makes smooth, high statistics templates
  - And prov nulation



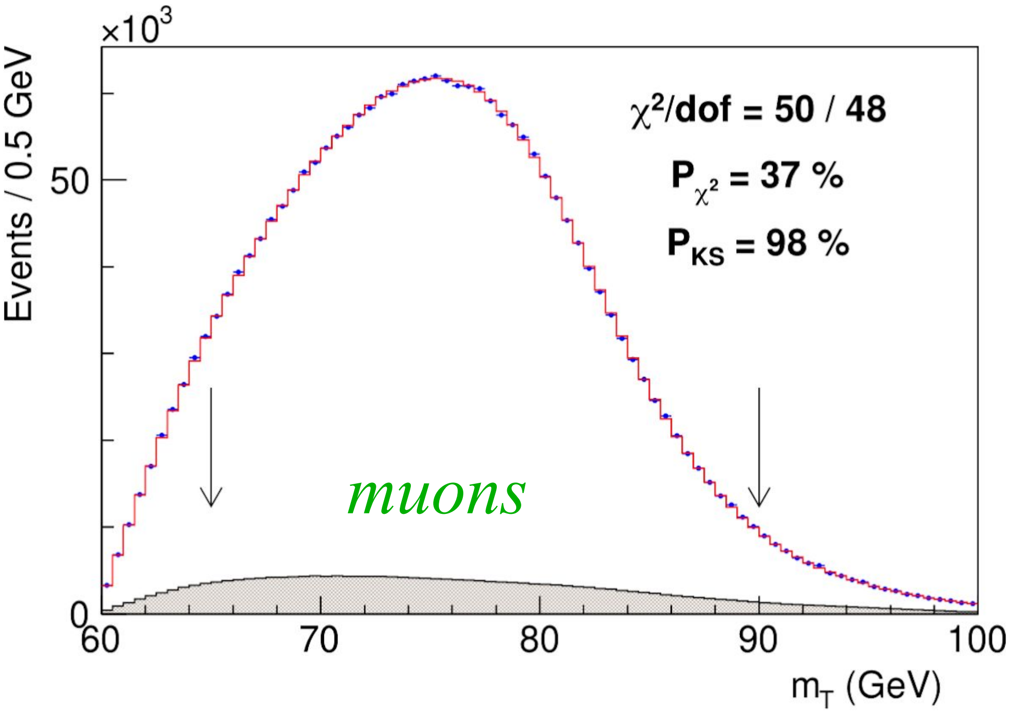
- We will extract the W mass from six kinematic distributions: Transverse mass, charged lepton p_T and missing E_T using both electron and muon channels

W Mass Fits

Blind Analysis Technique

- All W and Z mass fit results were blinded with a random [-50,50] MeV offset hidden in the likelihood fitter
- Blinding offset removed after the analysis was declared frozen
- Technique allows to study all aspects of data while keeping Z boson mass and W boson mass result unknown within ±50 MeV

W Transverse Mass Fits



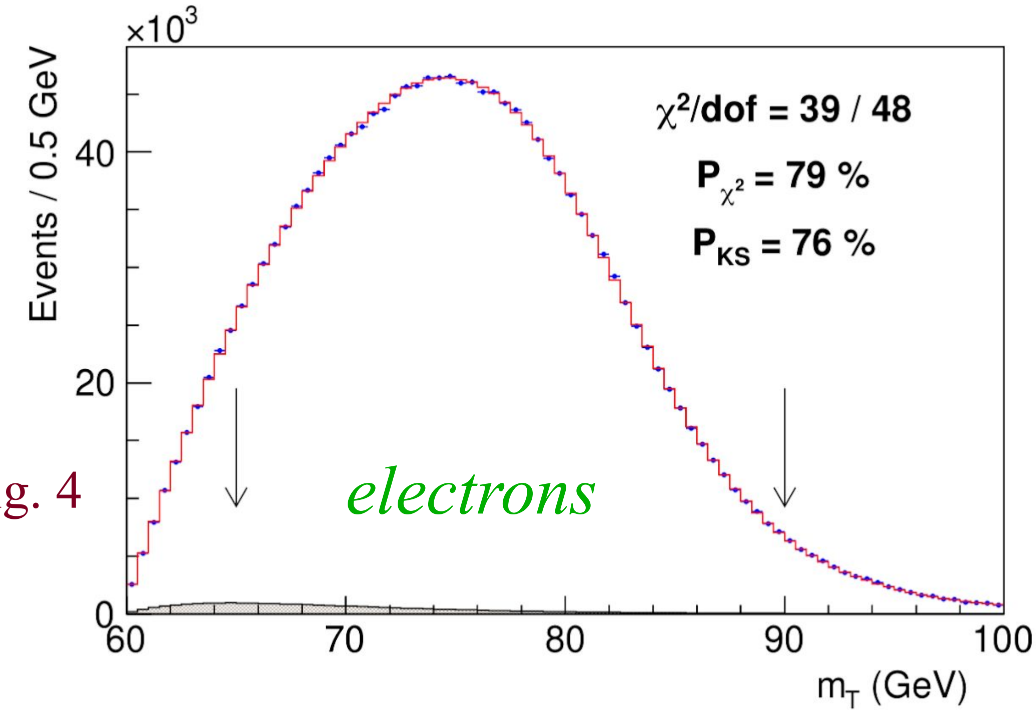
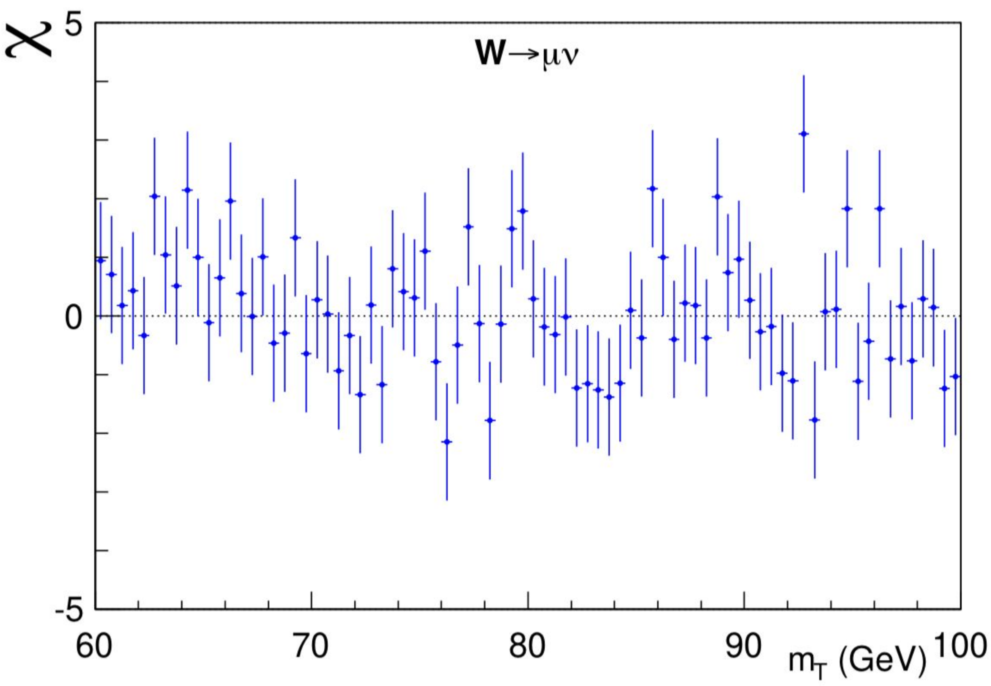


Fig. 4



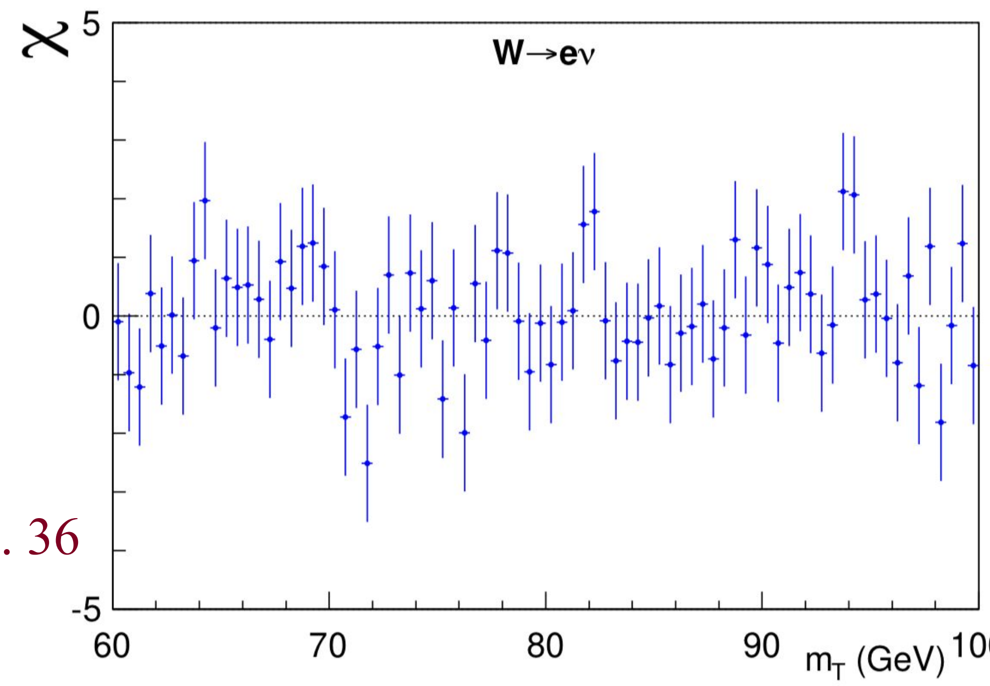
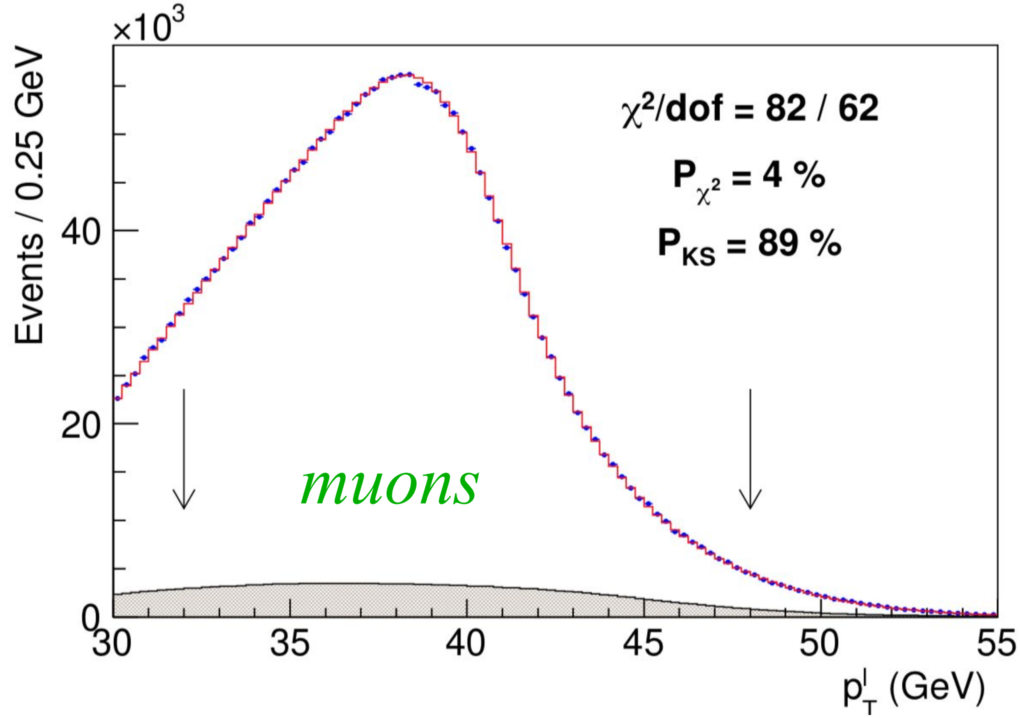


Fig. 36

W Charged Lepton p_T Fits



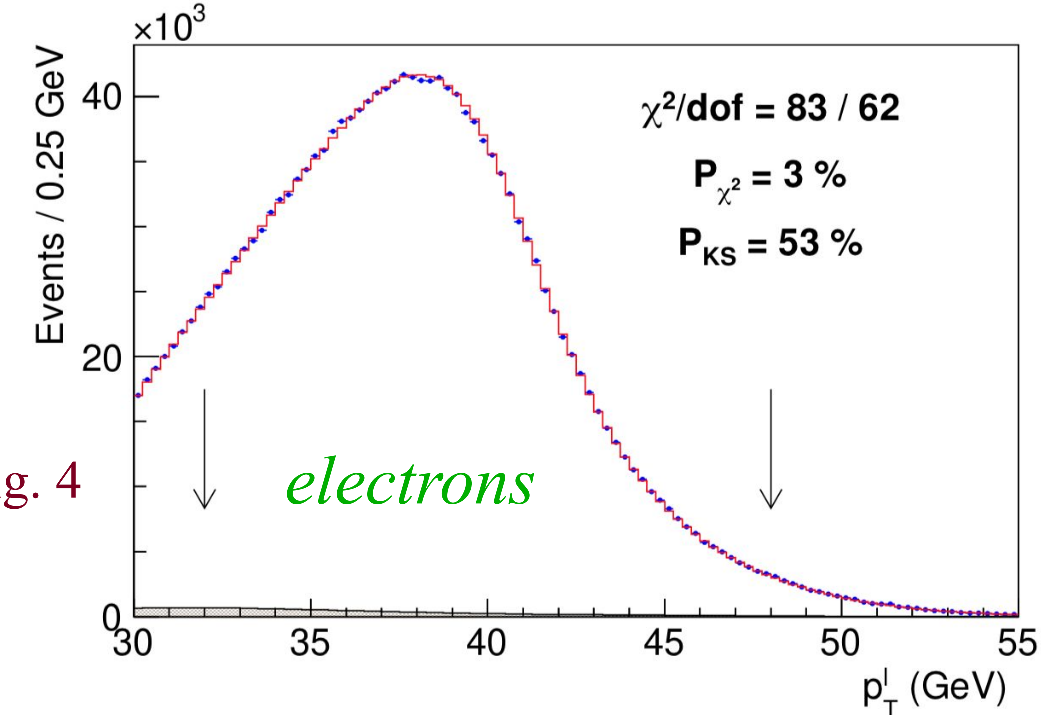
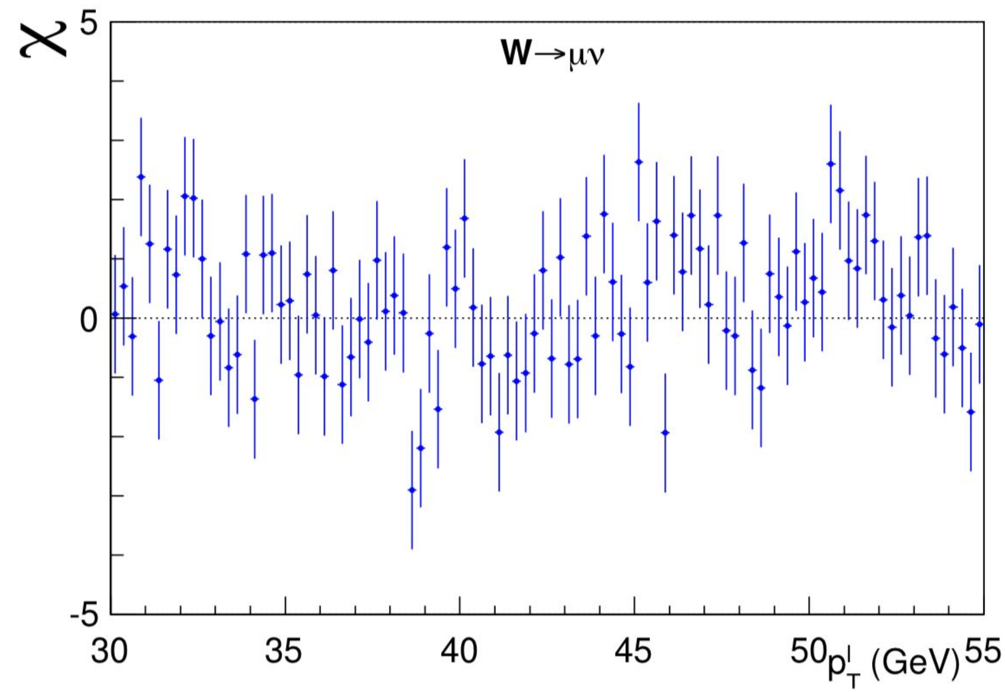


Fig. 4



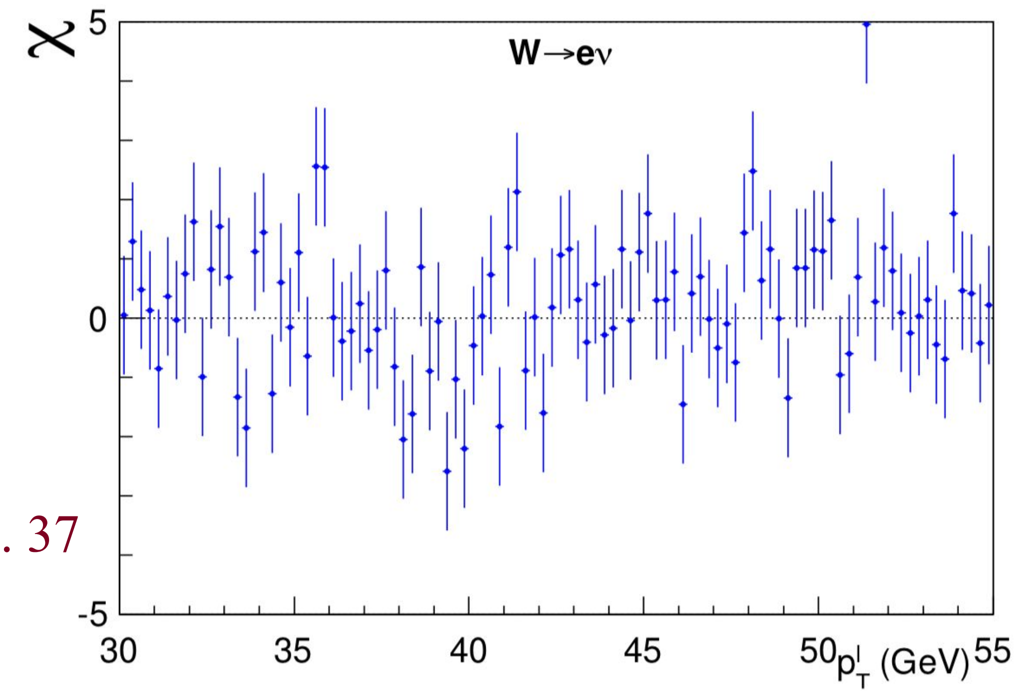
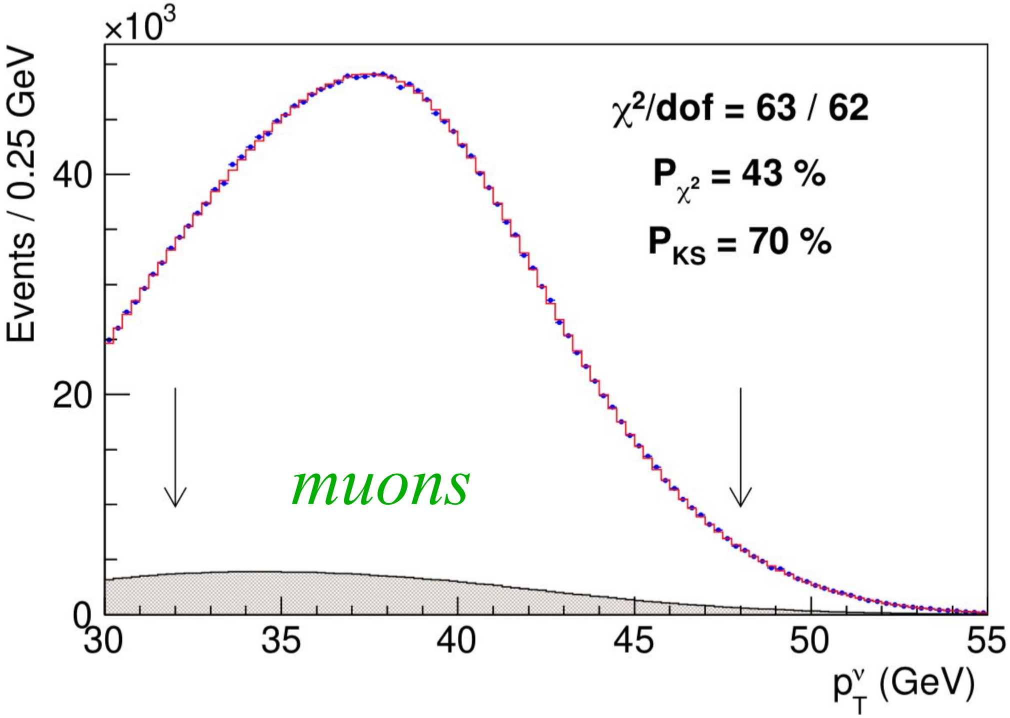
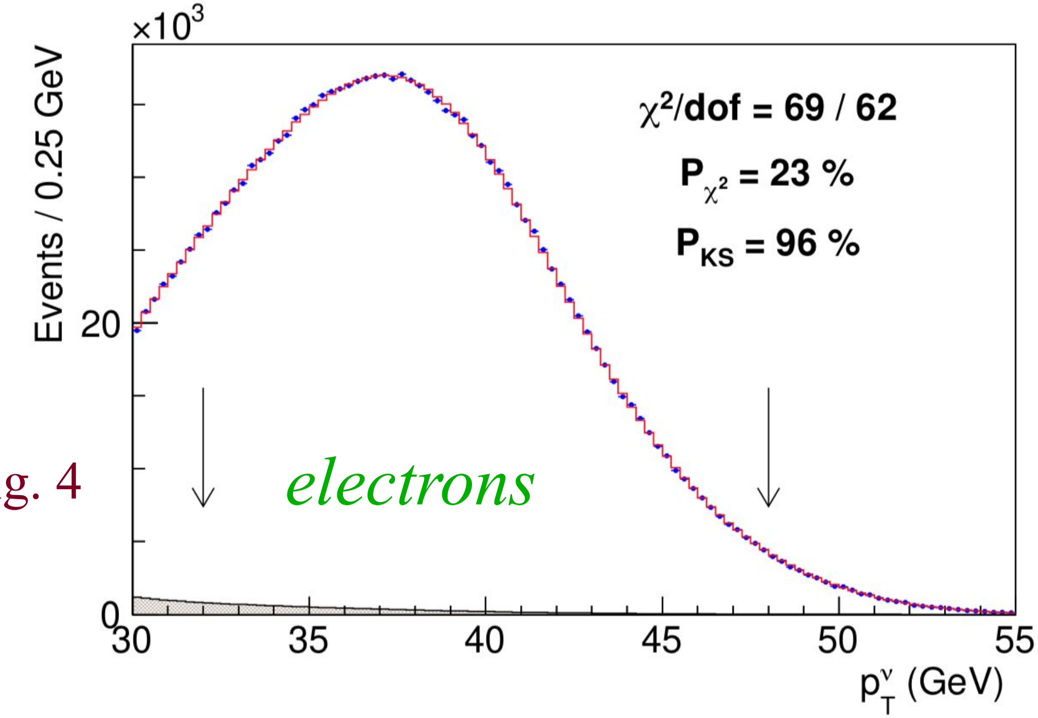


Fig. 37

W Neutrino p_T Fits





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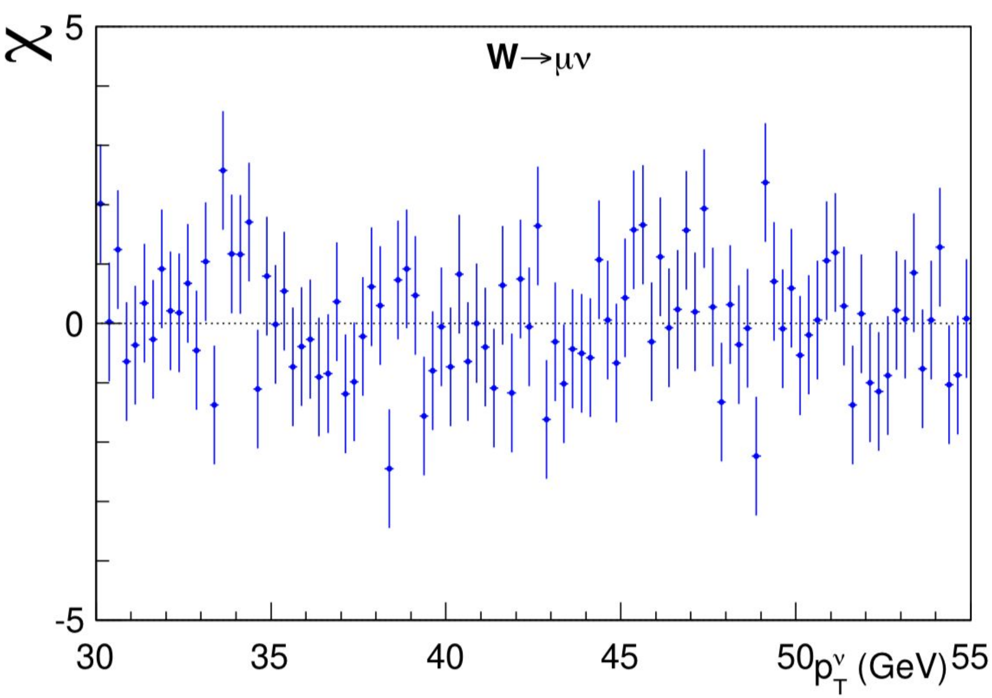

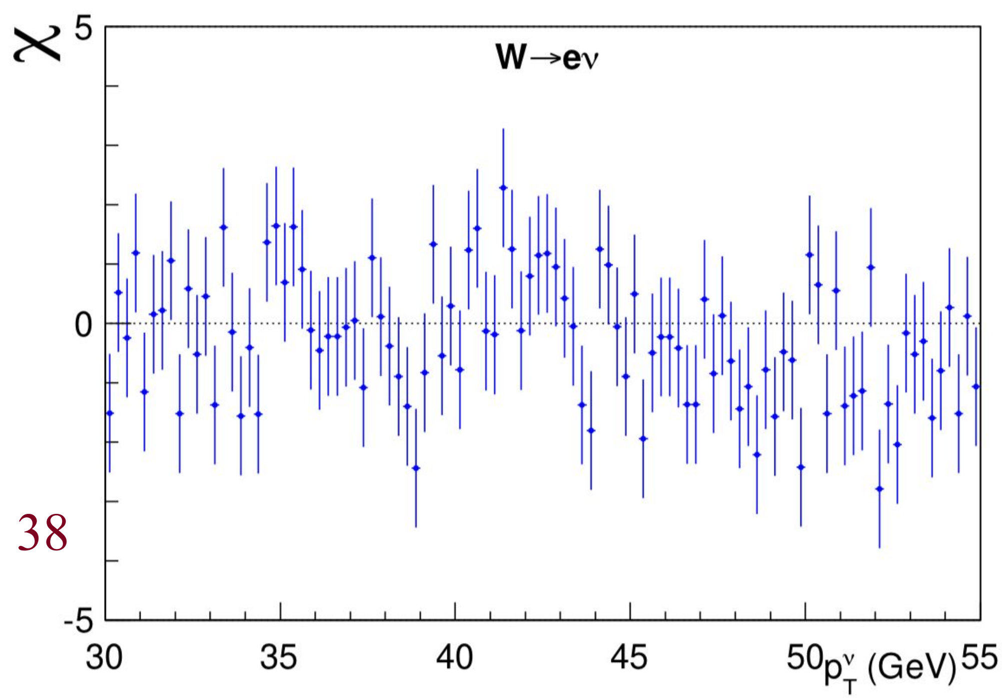

Fig. 38

Summary of *W* Mass Fits

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

Table 1

Consistency between two channels and three kinematic fits

New CDF Result (8.8 fb^{-1})
Combined Fit Systematic Uncertainties

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

Table 2

W Boson Mass Measurements from Different Experiments

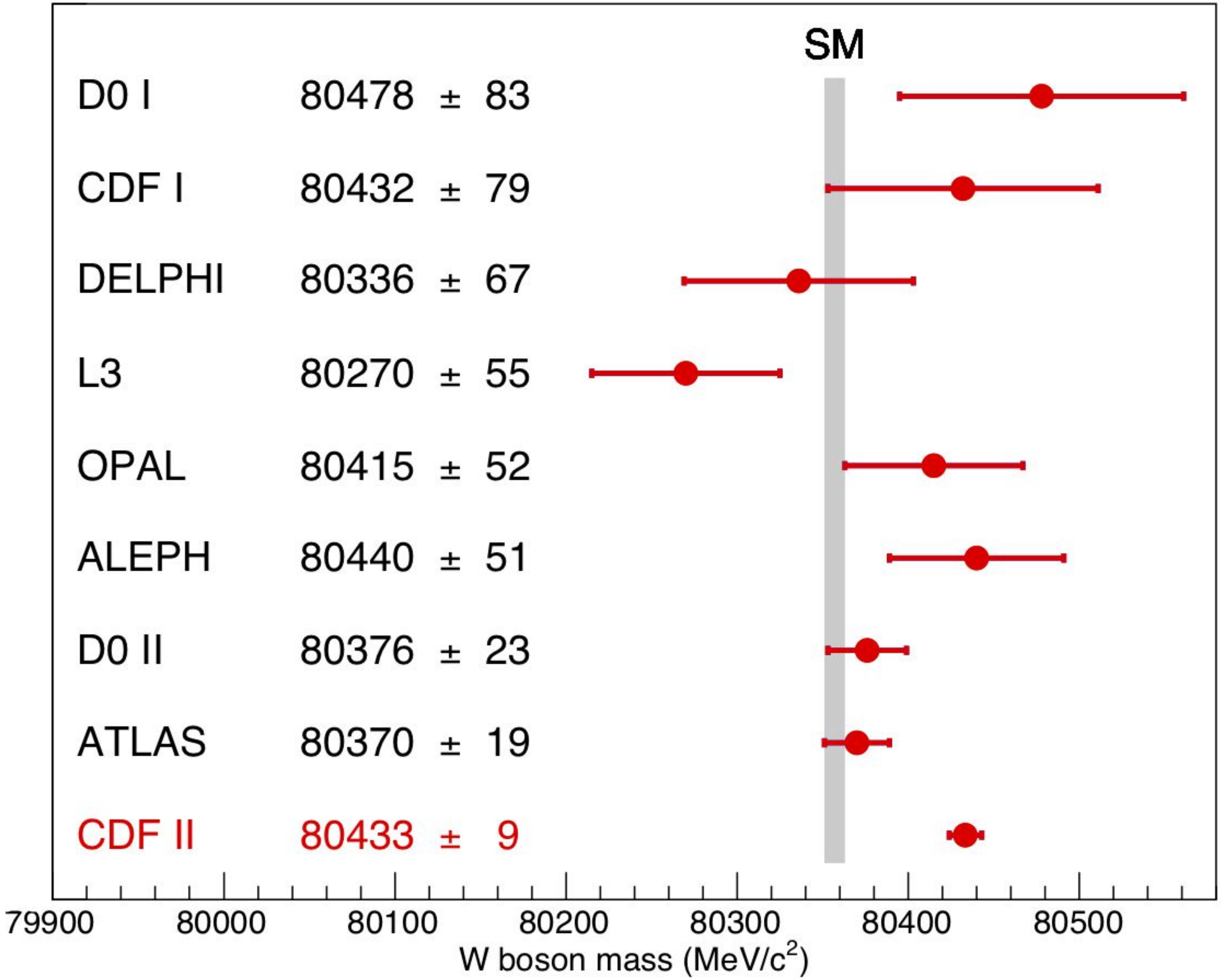

Fig. 5

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

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

Summary

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

- New CDF result is twice as precise as previous measurements:
  - $M_W = 80433.5 \pm 6.4_{stat} \pm 6.9_{syst}$ MeV
    80433.5 ± 9.4 MeV

- Difference from SM expectation of $M_W = 80{,}357 \pm 6$ MeV
  - significance of 7.0σ
  - suggests the possibility of improvements to the SM calculation or of extensions to the SM