NORTHEASTERN UNIVERSITY
BOSTON, MASSACHUSETTS

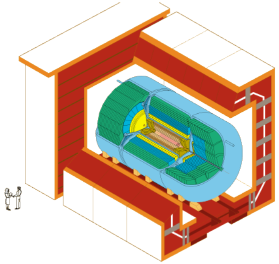
WZ Production and W Mass Measurement at DZero

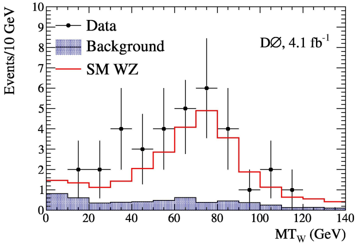
Joseph Haley
for the D0 Collaboration

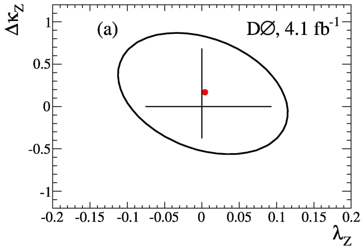
July 22, 2010

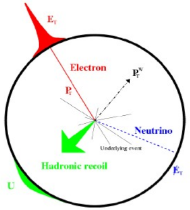
ICHEP
PARIS 2010

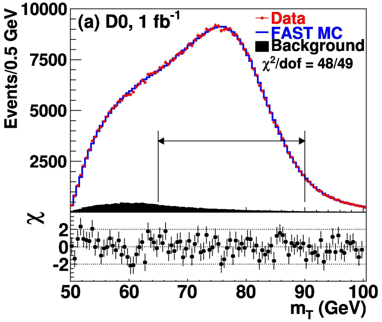
Outline









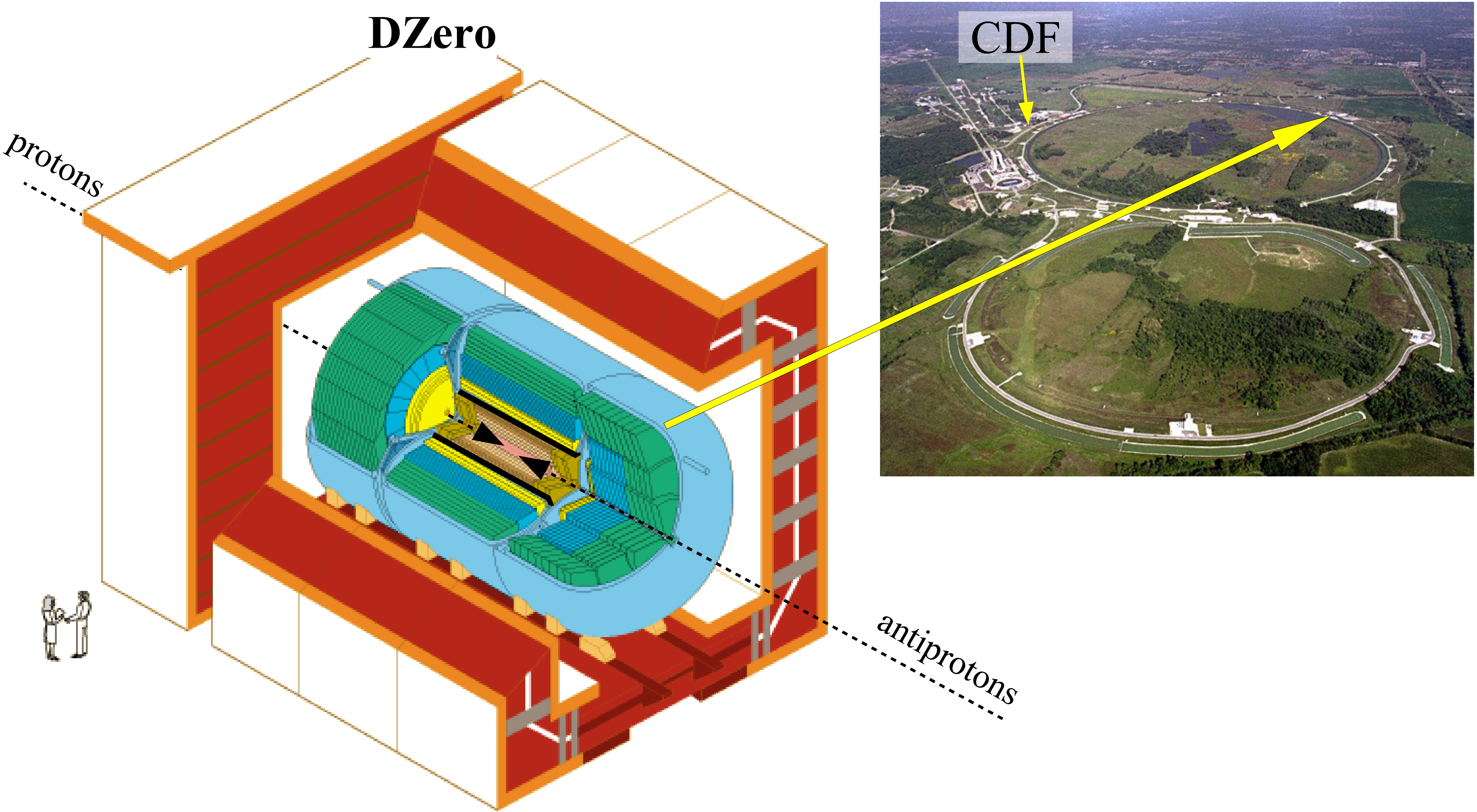


- The Tevatron and DZero Detector
- WZ→lνll
  - Motivation
  - Analysis Method
  - Cross Section and Anomalous Couplings
- W Mass
  - Motivation
  - Analysis Method
  - Results
- Conclusions

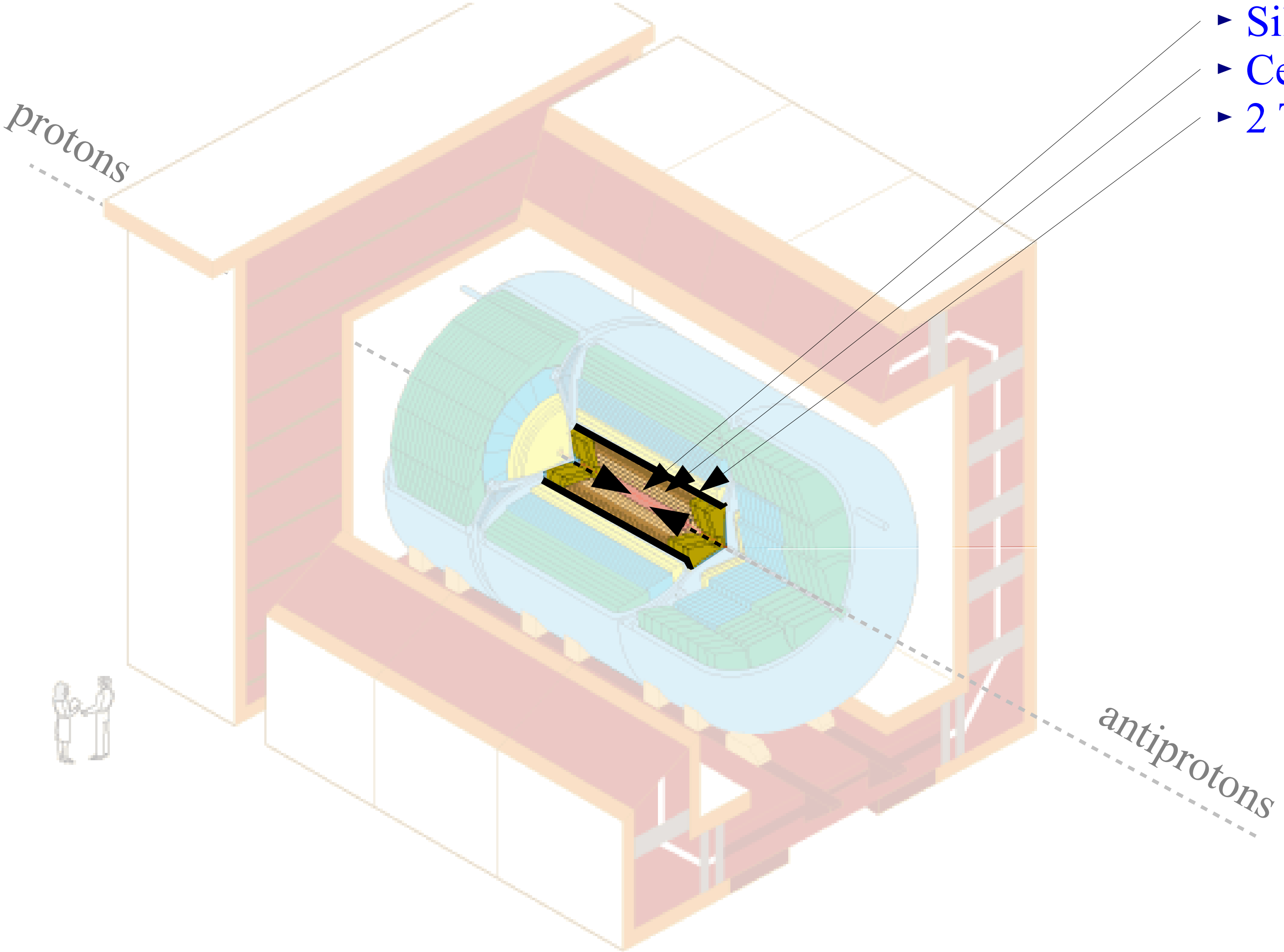
Tevatron

- The Tevatron is a vector boson factory
  - Able to deliver more than 50 pb^{-1}/week
    - ⇒ ~200 ***WZ*** events per week
    - ⇒ ~million ***W*** events per week
  - Proton-antiproton collisions are not as clean as e^+e^- collisions at LEP, but
    - Able to probe higher energies
    - Access to charged final states, which could not be produced at LEP
      ⇒$qq' \rightarrow W \rightarrow e\nu$ and $qq' \rightarrow WZ \rightarrow l\nu ll$

DZero Detector

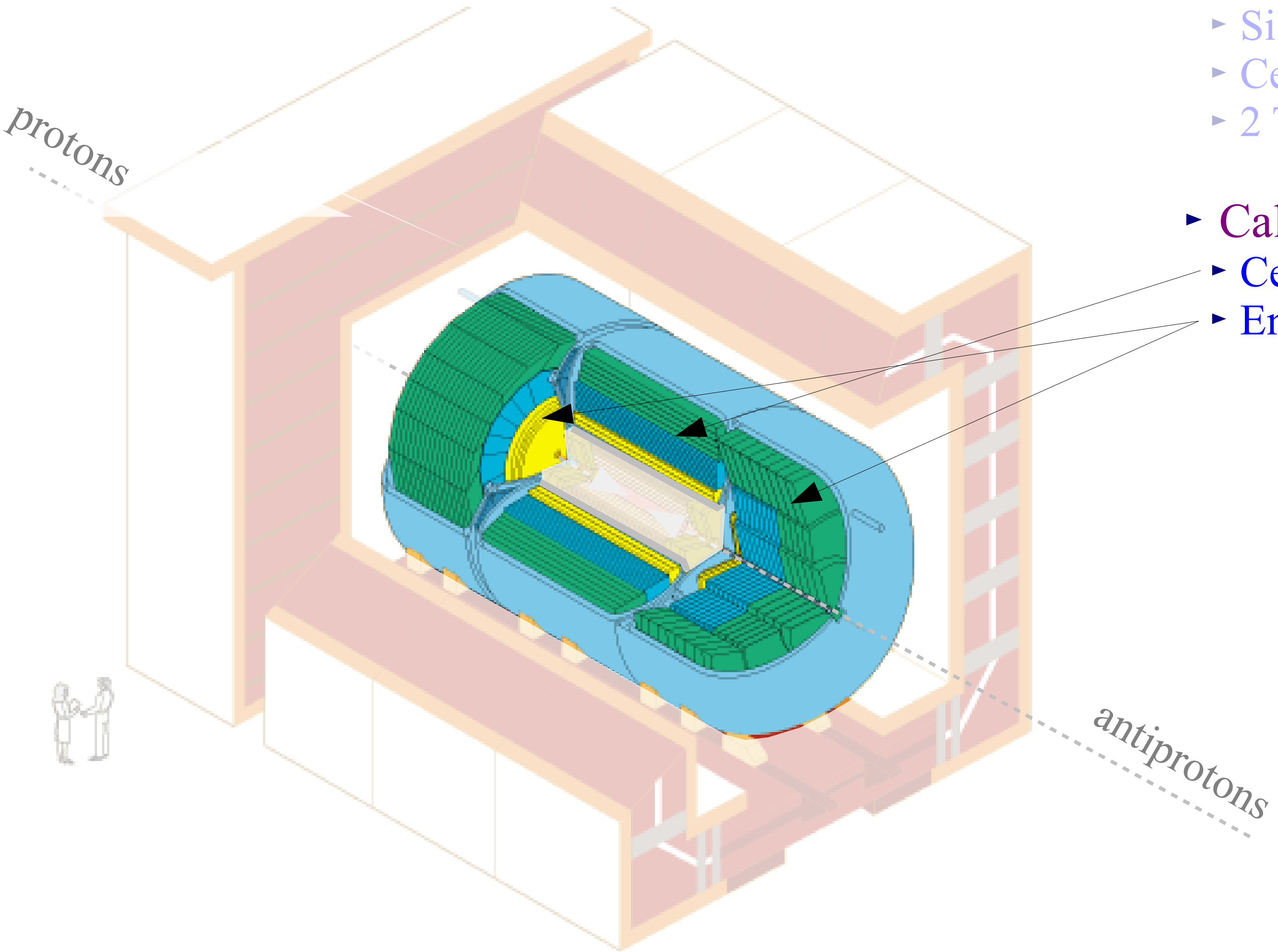


DZero Detector



- Central Tracking System
  - Silicon Micro-strip Tracker
  - Central Fiber Tracker
  - 2 T Solenoid Magnet

DZero Detector



- Central Tracking System
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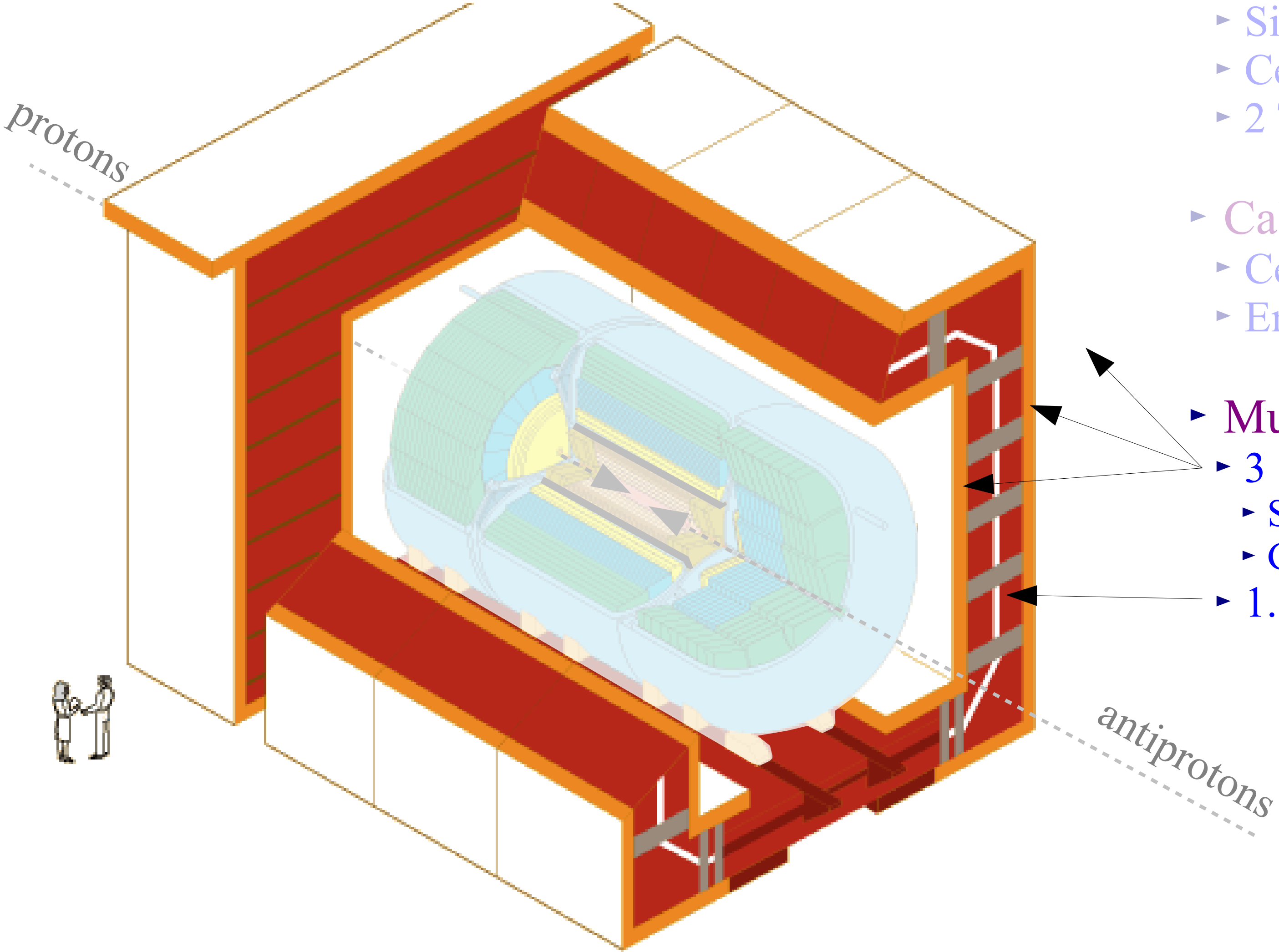
- Calorimeters
  - Central Calorimeter (CC)
  - End Calorimeters (EC)

DZero Detector

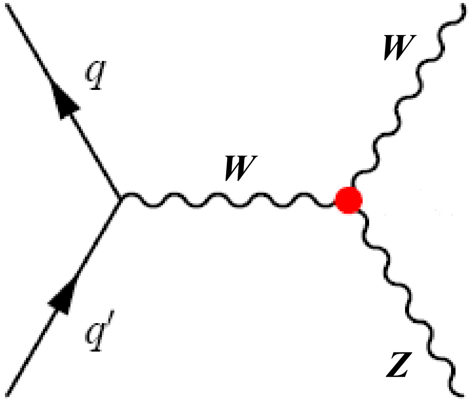


- Central Tracking System
  - Silicon Micro-strip Tracker
  - Central Fiber Tracker
  - 2 T Solenoid Magnet

- Calorimeters
  - Central Calorimeter (CC)
  - End Calorimeters (EC)

- Muon System
  - 3 sets of detectors
    - Scintillating tiles
    - Gas Drift Tubes
  - 1.8 T Toroid Magnets

$WZ \to l\nu ll$



- Provides a test of the (extremely successful) SM
  - WZ is the least studied vector diboson process
- Probe of possible new physics at a higher energy scale (Λ_{NP})
  - E.g., additional heavy gauge bosons predicted by many extension to the SM (SUSY, technicolor, ...)
- Improve understanding of a background to many Higgs and Beyond the SM searches

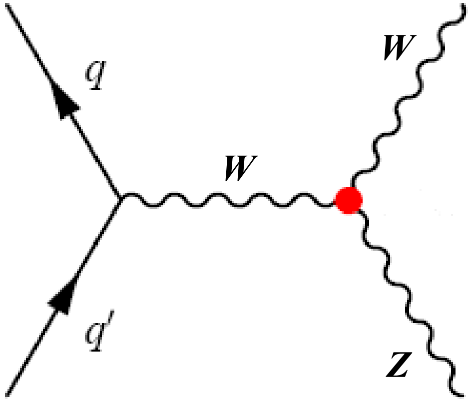
- SM is the low energy limit of a more general theory
  - The most general Lagrangian governing the ***WWZ*** triple gauge coupling (TGC) has 7 parameters
  - By assuming C and P conservation the number of parameters is reduced to 3

$$\Rightarrow g_1^Z, \kappa_Z, \lambda_Z \ ; \qquad \text{In the SM: } \lambda_Z = 0 \text{ and } g_1^Z = \kappa_Z = 1 \ \Rightarrow \begin{array}{l} \Delta\kappa_Z \equiv \kappa_Z - 1 \\ \Delta g_1^Z \equiv g_1^Z - 1 \end{array}$$

$\Delta\kappa$, Δg, or $\lambda \neq 0$ ⇒ anomalous TGCs

arXiv:1006.0761 [hep-ex]
(Submitted to Phys. Let. B)

$WZ \rightarrow l\nu ll$



- Provides a test of the (extremely successful) SM
  - WZ is the least studied vector diboson process
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  - E.g., additional heavy gauge bosons predicted by many extensions to the SM (SUSY, technicolor, ...)
- Improve understanding of a background to many Higgs and Beyond the SM searches

Any new physics that causes anomalous TGCs must respect unitarity. However, anomalous TGCs in the SM violate unitarity at high energies. Thus, a dipole form factor:

$$a(s) = \frac{a_0}{\left(1 - \frac{s}{\Lambda^2_{NP}}\right)^2}$$

is used to regulate this behavior. Λ_{NP} can be interpreted as the energy at which the new physics turns on. We used $\Lambda_{NP} = 2$ TeV when setting limits on anomalous TGCs.

- SM is the low energy limit of a more general theory
  - The most general Lagrangian governing the WWZ triple gauge coupling (TGC) has 7 parameters
  - By assuming C and P conservation the number of parameters is reduced to 3

$\Rightarrow g_1^Z, \kappa_Z, \lambda_Z$; In the SM: $\lambda_Z = 0$ and $g_1^Z = \kappa_Z = 1 \Rightarrow$ $\Delta\kappa_Z \equiv \kappa_Z - 1$, $\Delta g_1^Z \equiv g_1^Z - 1$

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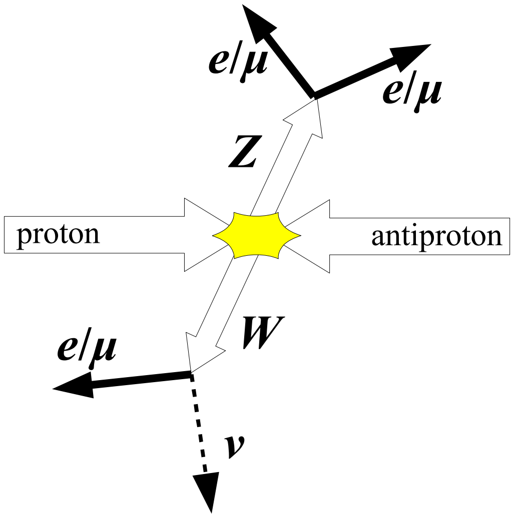
WZ→lνll: Signature

- Look for events with



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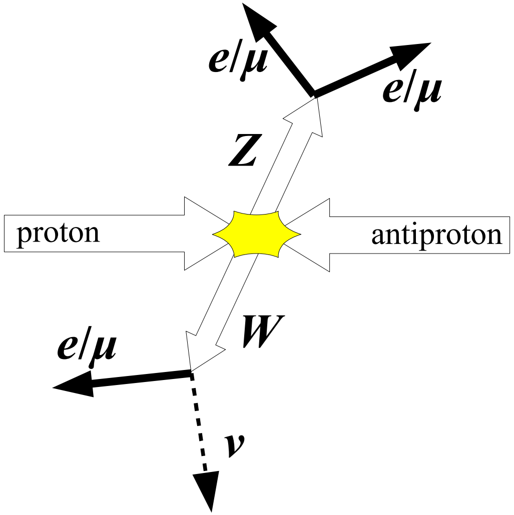
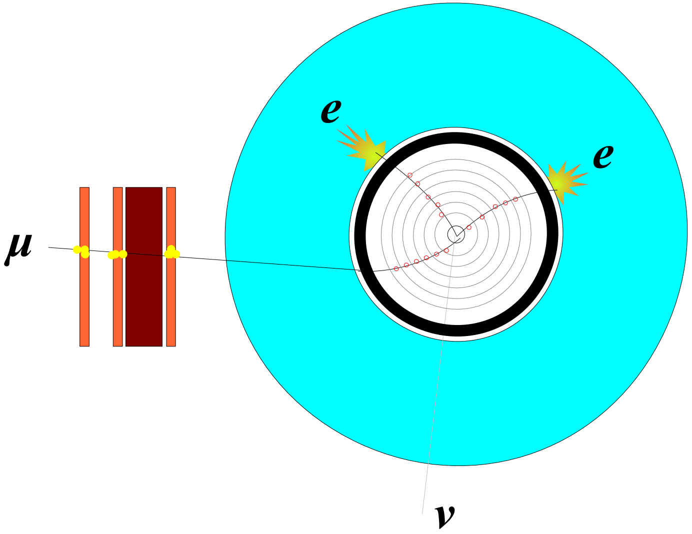
$WZ \rightarrow l\nu ll$: Signature

- Look for events with
  - Three isolated, high-energy leptons ⇒ eee, eeμ, eμμ, or μμμ
  - And evidence of a neutrino ⇒ large missing energy in the transverse plane ($\not{E}_T$)





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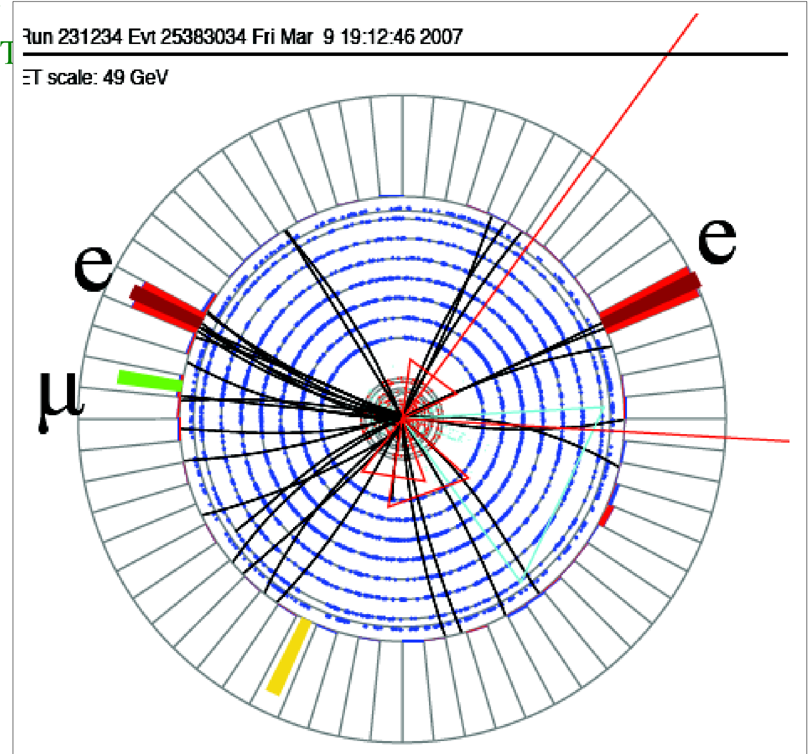
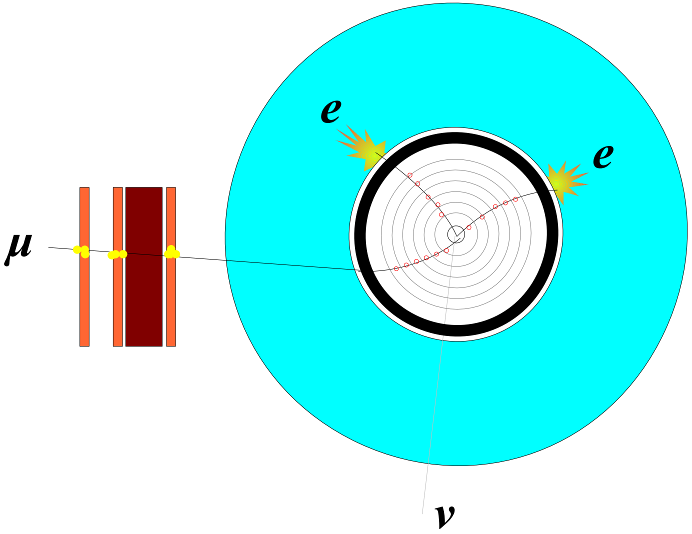


Actual eeμ candidate event



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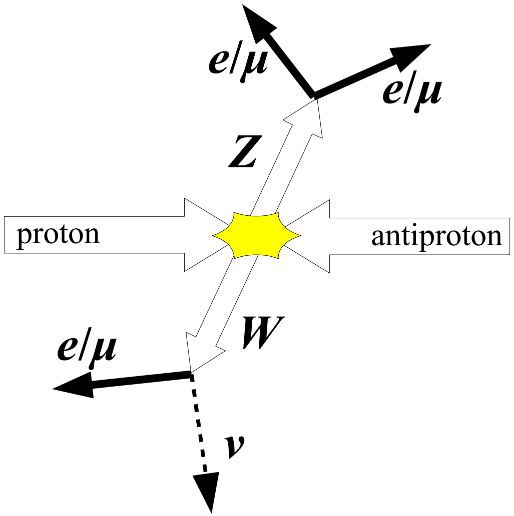

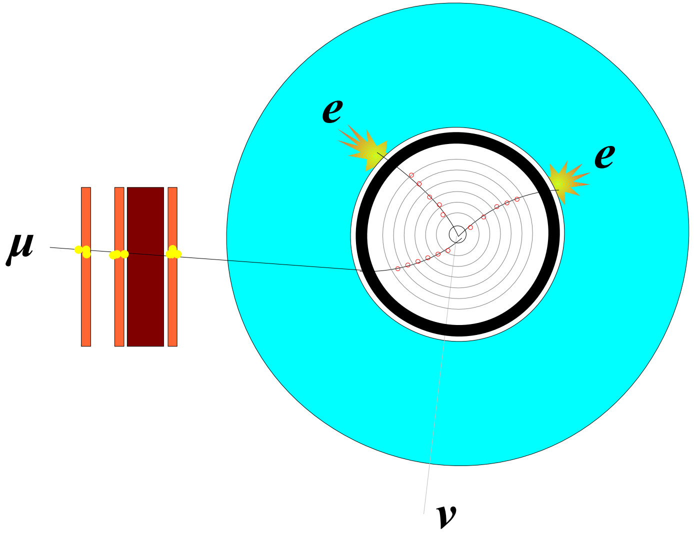

- Then,
  - Identify two of the leptons as coming from a Z decay
    - eeμ and eμμ events ⇒ require like-flavor leptons to have opposite charge
    - eee and μμμ events ⇒ the opposite-charge pair with a mass closest to the Z mass
  - The remaining lepton and the $\not\!\!E_T$ are assumed to come from a W decay

arXiv:1006.0761 [hep-ex]
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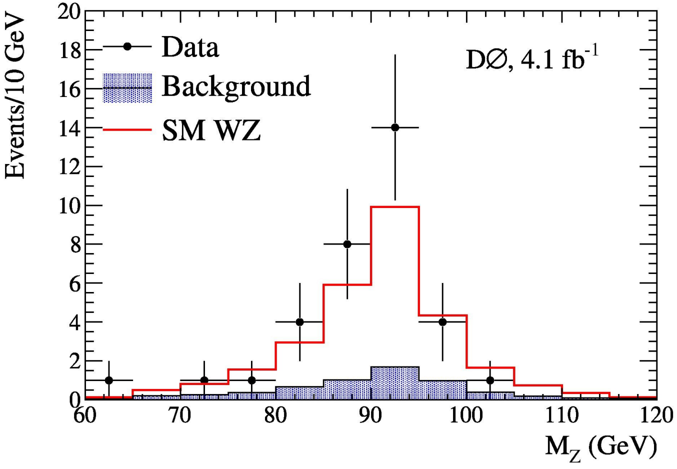
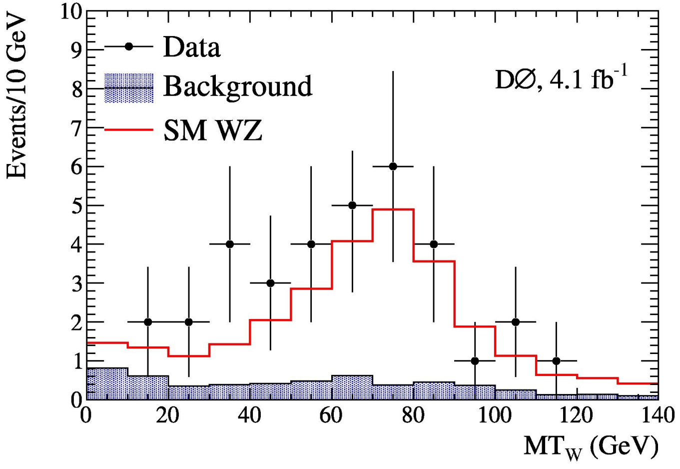
$WZ \rightarrow l\nu ll$: Cross Section

- Very clean signature: No SM background with three high p_T leptons + $\not{E}_T$
  - ***ZZ→llll*** background
    - One of the leptons is not identified and $\not{E}_T$ is mis-measured
  - ***Z/W***+jets and ***tt→WbWb→lνblνb*** backgrounds
    - A jet is misidentified as a lepton
- This analysis used 4.1 fb^{-1} of data
  - Predicted background: 6.03 ± 0.57
  - Predicted signal: 23.3 ± 1.5
  - Observed events: 34

$$\Rightarrow \sigma(\boldsymbol{WZ}) = 3.90^{+1.09}_{-0.90}\ \text{pb}$$

SM: $\sigma_{NLO}(\boldsymbol{WZ}) = 3.25 \pm 0.19$ pb





arXiv:1006.0761 [hep-ex]
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WZ→lνll: Cross Section

- Very clean signature: No SM background with three high p_T leptons + $\not{E}_T$
  - ***ZZ→llll*** background
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  - ***Z/W***+jets and ***tt→WbWb→lνblνb*** backgrounds
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Most precise measurement

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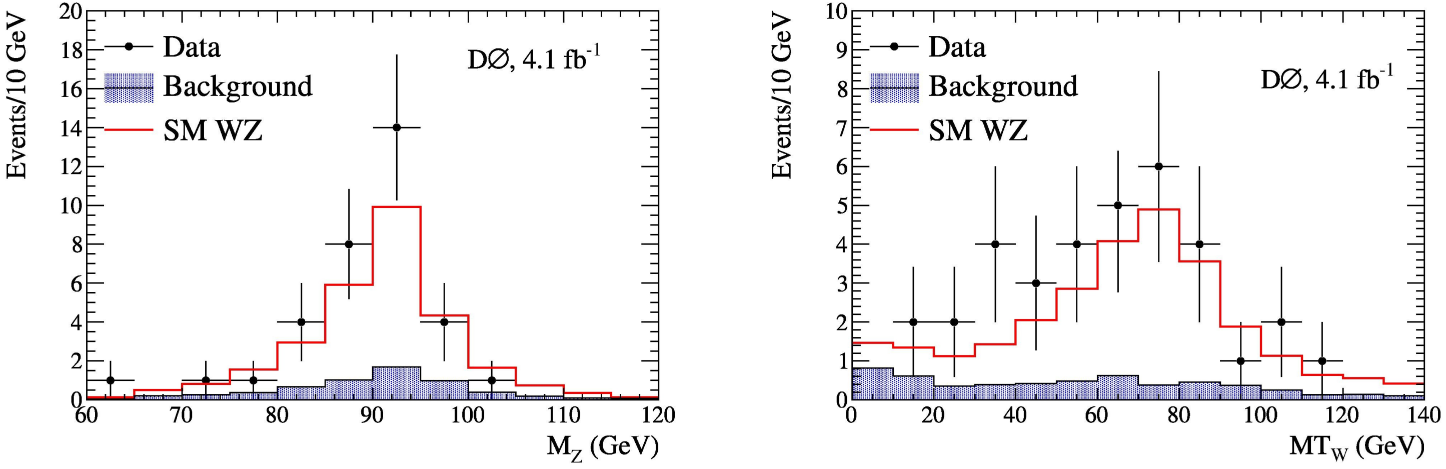

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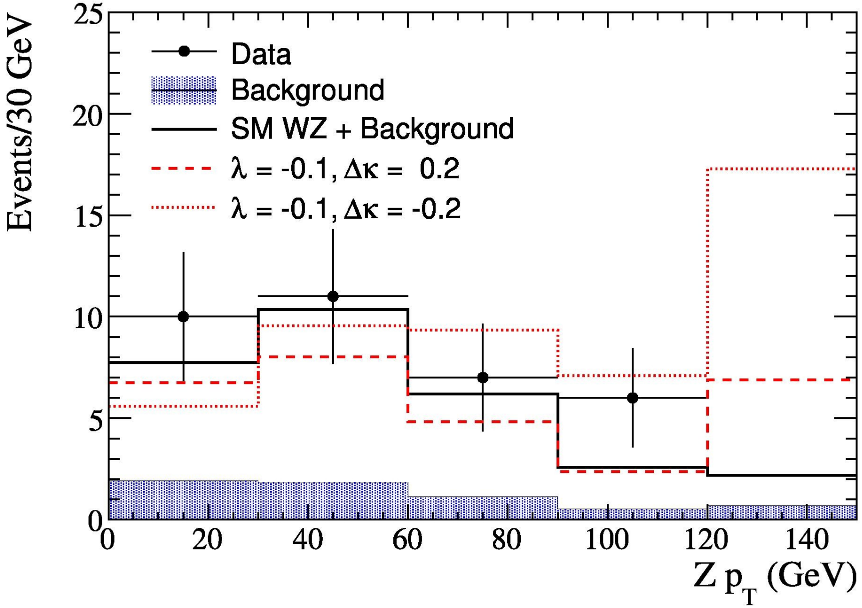
$WZ \rightarrow l\nu ll$: Anomalous Couplings

- Anomalous TGC change the event kinematics
  - High boson p_T is particularly sensitive to anomalous TGCs
- Setting limits on anomalous TGCs
  - Use MCFM to determine $p_T(\boldsymbol{Z})$ distribution predicted for different values of g_1^Z, κ_Z, and λ_Z
  - Calculate the likelihood of each prediction given the observed $p_T(\boldsymbol{Z})$ distribution



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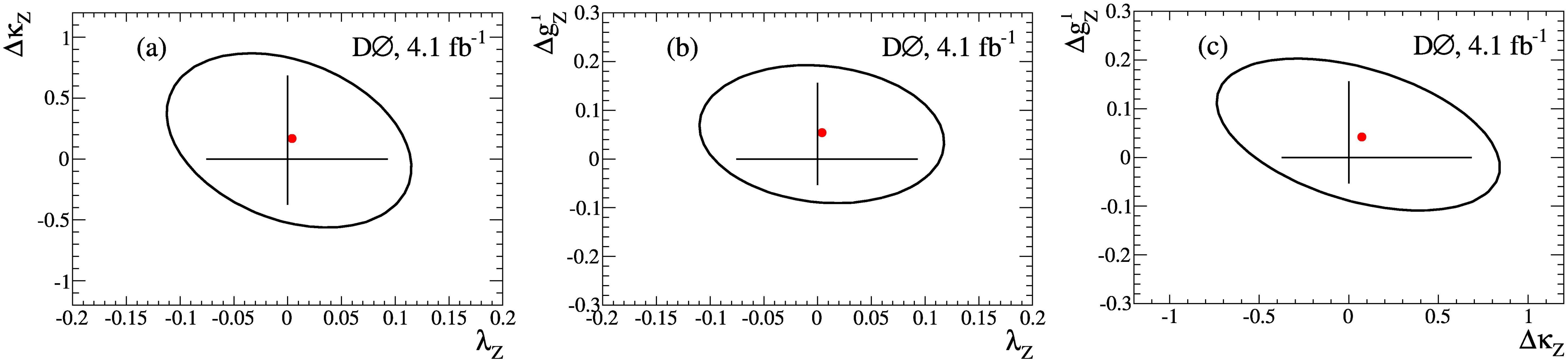
WZ→lνll: Anomalous Couplings

- Results

$\Lambda_{NP} = 2$ TeV



- 2-D 95% confidence contours (ellipses)
  - Two couplings are varies while the third fixed at the SM value
- 1-D 95% confidence intervals (lines)
  - One coupling is varied while the other two fixed at the SM values

$$-0.075 < \lambda_Z < 0.093$$
$$-0.053 < \Delta g_1^Z < 0.156$$
$$-0.376 < \Delta\kappa_Z < 0.686$$

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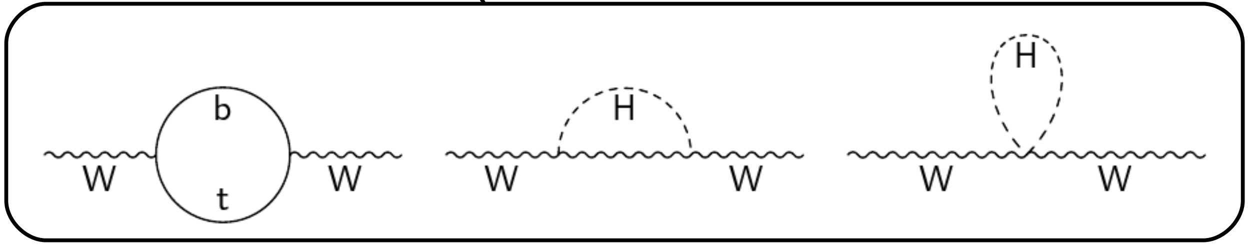
W Mass

- A precise measurement of the W mass probes physics at higher energy scales
  - Due to radiative corrections, the precise value of the W mass depends on the Higgs and top masses

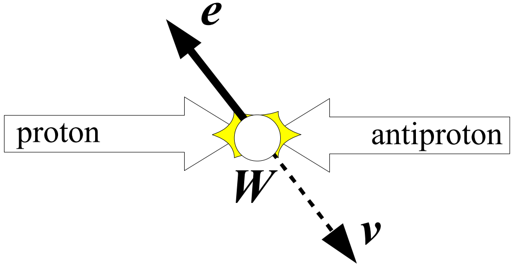
$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}\left(\frac{1}{1-\Delta r}\right); \quad \Delta r = \Delta\alpha + \Delta\rho(m_{top}^2) + \Delta\chi(\ln(m_H))$$



Phys.Rev.Lett.103:141801,2009

$W \rightarrow e\nu$: Signature

- Look for events with



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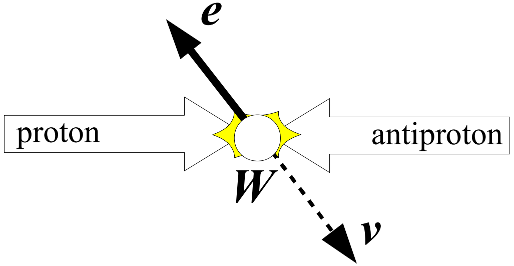
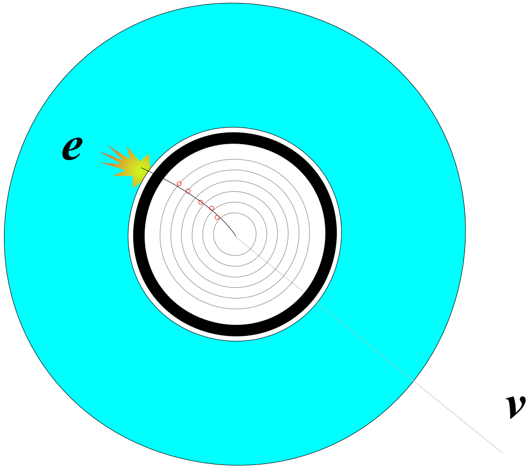
$W \rightarrow e\nu$: Signature

- Look for events with
  - One isolated, high-energy electron ($p^e_T > 25$ GeV)
  - And a neutrino ⇒ large missing energy transverse to the beam ($\not{E}_T > 25$ GeV)





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W→eν: Signature

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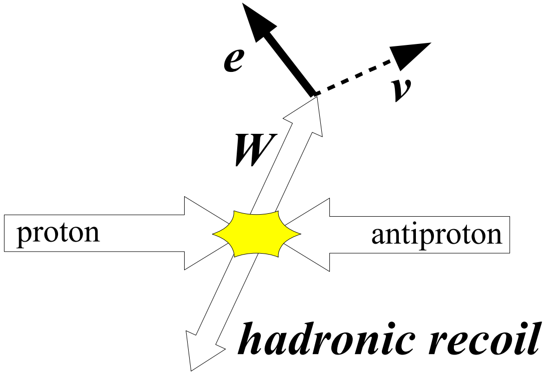
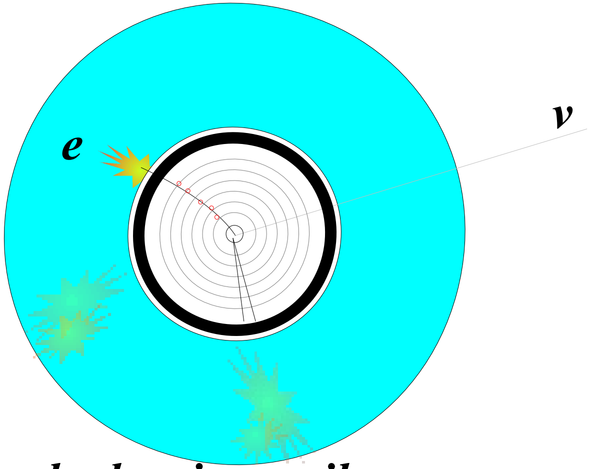




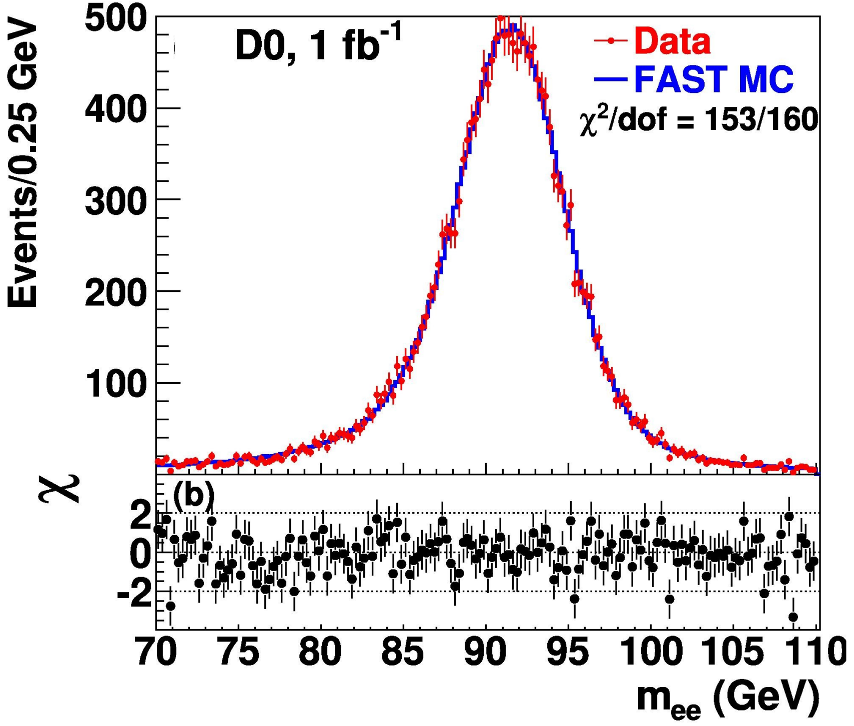
hadronic recoil, u_T

- There may be other energy (u_T) in the event from which the ***W*** is recoiling
  - We need to know u_T in order to calculate $\not{E}_{T} = -(\mathbf{p}^{e}_{T} + \boldsymbol{u}_{T})$
  - Difficult to model large u_T ⇒ Require recoil energy to be small ($u_T < 15$ GeV)
- 1 fb^{-1} of data ⇒ ~500,000 selected events

Phys.Rev.Lett.103:141801,2009

W Mass: Calibration

- The precision of the measurement is dominated by the electron energy scale calibration
  - Detector simulation
    - GEANT-based material simulation
    - Data driven electron shower shape corrections for uninstrumented material
      - Dead material modeled with 0.01 X_0 precision
  - Final calibration
    - Using ***Z*→*ee*** events, calibrate to the very precise measurement of M(***Z***) from LEP (ΔM(Z) ≈ 2 MeV)
      - This is effectively a measurement of M(***W***)/M(***Z***)
    - The precision of the calibration is limited by the statistics of ***Z*→*ee*** events

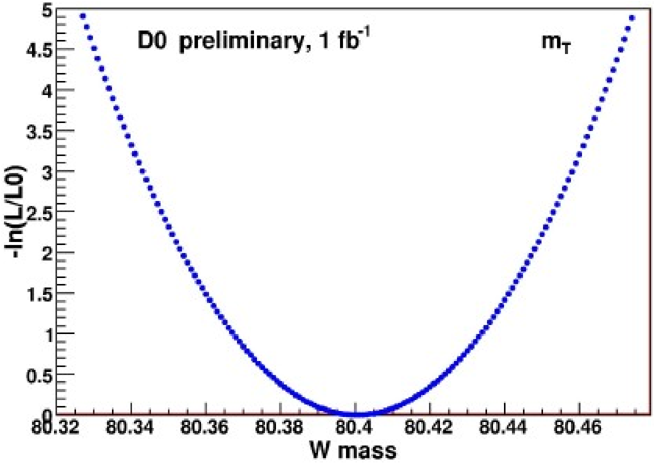


Phys.Rev.Lett.103:141801,2009

W Mass: Analysis Method

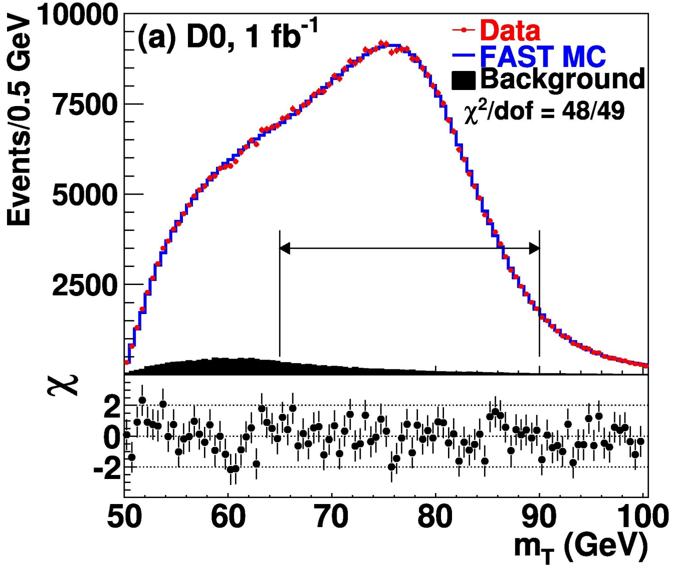
- Three different distributions were used to perform the measurement
  - Electron p_T (p^e_T)
  - Missing transverse energy ($\not{E}_T$)
  - Transverse W mass ($m_T(W) = \sqrt{2 p^e_T \not{E}_T (1 - \cos(\Delta\varphi(e,\not{E}_T)))}$)

- For each variable, generate template distributions for a range of test M(*W*) values
  - Simulate event with RESBOS + PHOTOS
  - Simulate detector efficiency/response via a fast parametric Monte Carlo simulation tune on ***Z→ee*** events
- Calculate the likelihood for each template to match the observed distribution

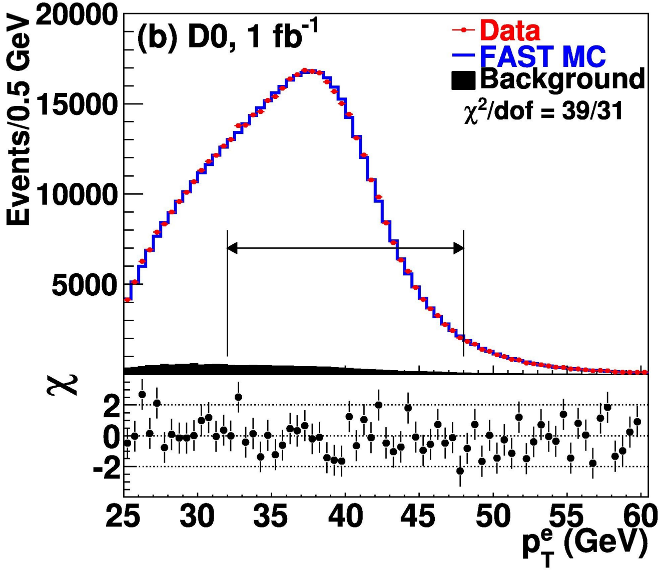


Phys.Rev.Lett.103:141801,2009

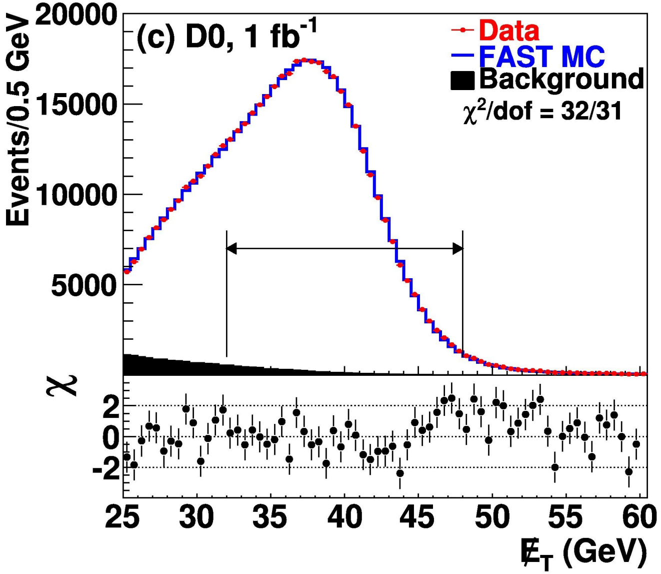
W Mass: Results



80.401 ±0.023(stat) ±0.037(syst) GeV



80.400 ±0.027(stat) ±0.040(syst) GeV

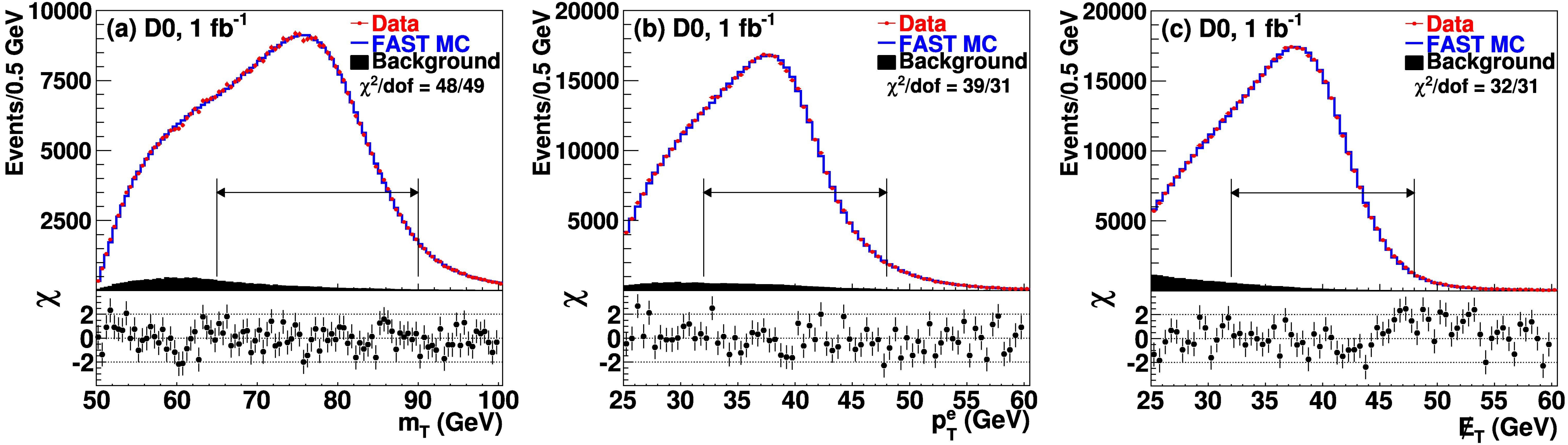


80.402 ±0.023(stat) ±0.043(syst) GeV

$$\Rightarrow \; M(\boldsymbol{W}) = 80.401 \pm 0.021\ (\text{stat}) \pm 0.038\ (\text{syst})\ \text{GeV}$$

Phys.Rev.Lett.103:141801,2009

W Mass: Results



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$$\Rightarrow \ \mathrm{M}(\boldsymbol{W}) \ = \ 80.401 \pm 0.021 \ (\mathrm{stat}) \pm 0.038 \ (\mathrm{syst}) \ \mathrm{GeV}$$

Most precise single measurement

Phys.Rev.Lett.103:141801,2009

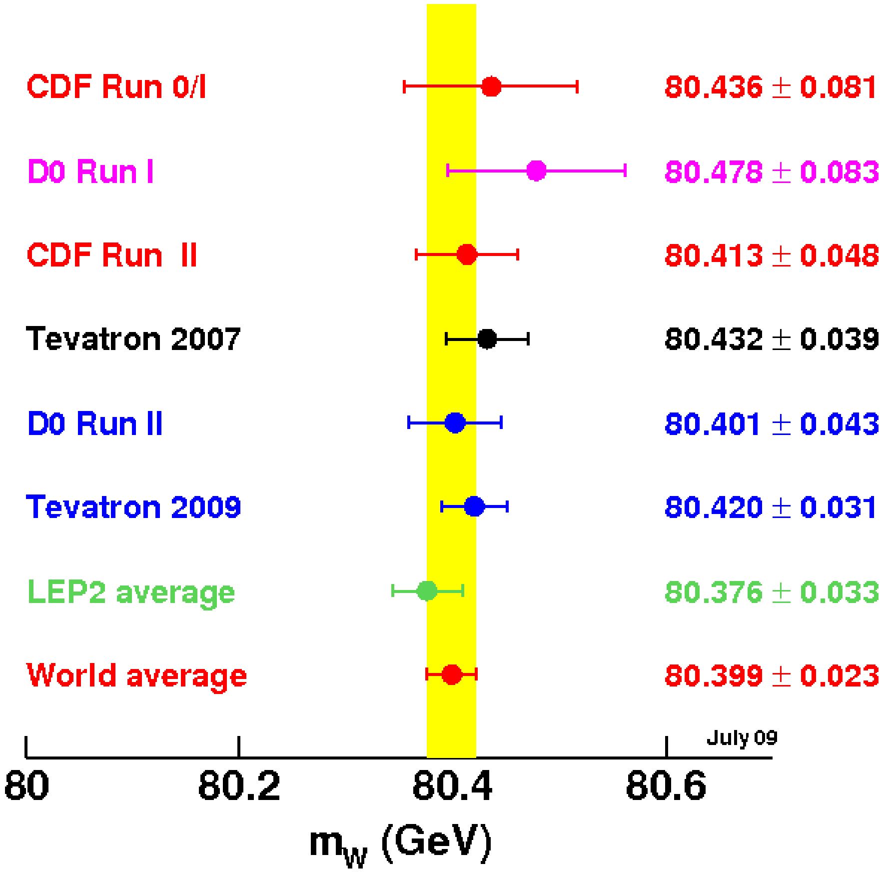
W Mass: Uncertainties

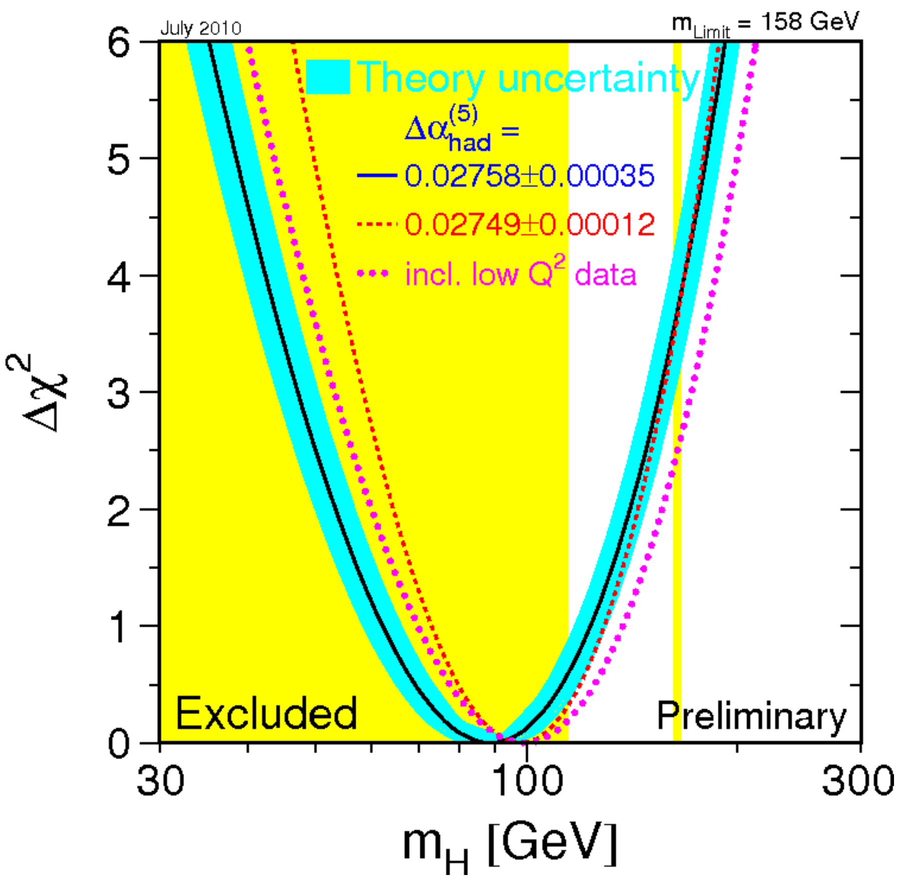
Source	m_T	p_T^e	$\not{E}_T$
Statistical	**23**	**27**	**23**
Systematic - Experimental			
Electron energy response	34	34	34
Electron energy resolution	2	2	3
Electron energy non-linearity	4	6	7
Electron energy loss differences	4	4	4
Recoil model	6	12	20
Efficiencies	5	6	5
Backgrounds	2	5	4
Experimental Subtotal	**35**	**37**	**41**
Systematic - W production and decay model			
PDF	10	11	11
QED	7	7	9
Boson pT	2	5	2
W model Subtotal	**12**	**14**	**17**
Systematic – Total	**37**	**40**	**44**

Phys.Rev.Lett.103:141801,2009

W Mass: Results

- World average ⇒ M(***W***) = 80.399 ± 0.023 GeV
  - EW fit (M(top)=173.1±1.3 GeV) ⇒ M(***H***) < 158 GeV





Conclusions

- Most precise measurement of ***WZ*** cross section
  - $\sigma(WZ) = 3.90^{+1.09}_{-0.90}$ GeV
- Some of the tightest limits on WWZ anomalous TGC

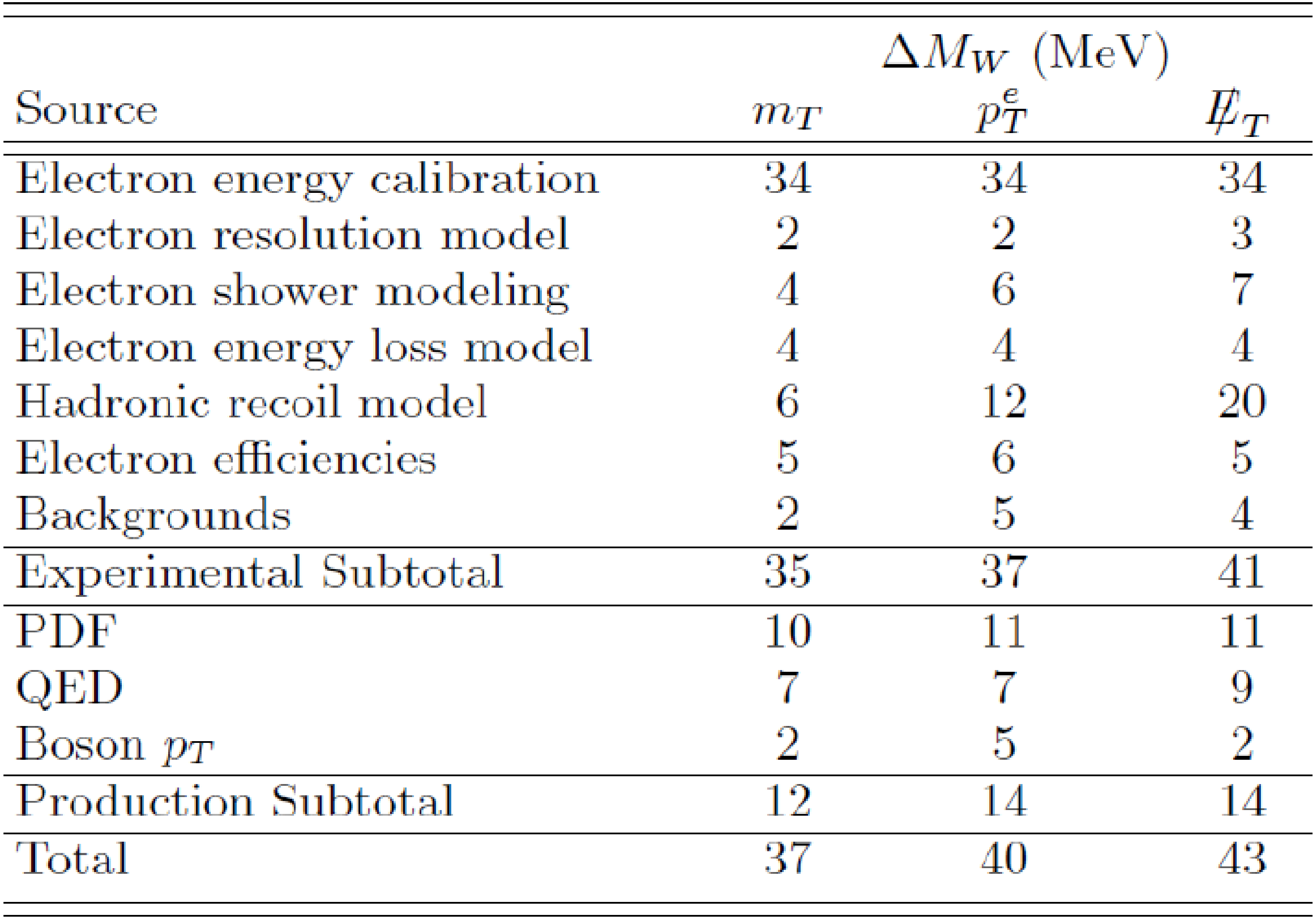
$$-0.075 < \lambda_Z < 0.093$$
$$-0.053 < \Delta g_1^Z < 0.156$$
$$-0.376 < \Delta\kappa_Z < 0.686$$

@ 95% CL
$\Lambda_{NP} = 2$ TeV

- Most precise single measurement of ***W*** boson mass
  - $M(W) = 80.401 \pm 0.021\ (\text{stat}) \pm 0.038\ (\text{syst})$ GeV
- Expect significant improvements with more data

thank you

W Mass: Systematic Uncertainties

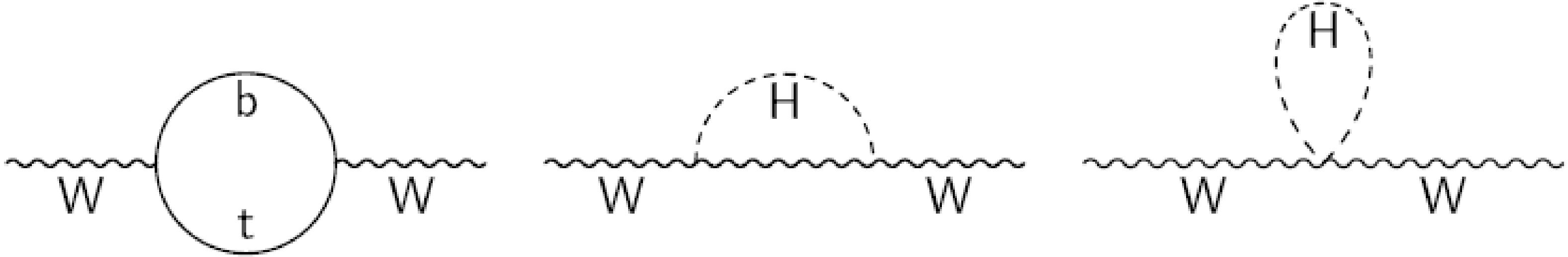


	ΔM_W (MeV)		
Source	m_T	p_T^e	$\not\!\!E_T$
Electron energy calibration	34	34	34
Electron resolution model	2	2	3
Electron shower modeling	4	6	7
Electron energy loss model	4	4	4
Hadronic recoil model	6	12	20
Electron efficiencies	5	6	5
Backgrounds	2	5	4
Experimental Subtotal	35	37	41
PDF	10	11	11
QED	7	7	9
Boson p_T	2	5	2
Production Subtotal	12	14	14
Total	37	40	43

W Mass

$$m_{\mathsf{W}}^2\left(1-\frac{m_{\mathsf{W}}^2}{m_{\mathsf{Z}}^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_{\mathsf{F}}}\left(\frac{1}{1-\Delta r}\right)$$

$$\Delta r=\Delta\alpha+\Delta\rho(m_{\mathsf{top}}^2)+\Delta\chi(\ln(m_{\mathsf{H}}))$$



To have equal uncertainty on m_{H}, $\Delta m_{\mathsf{W}} \approx 0.006 \cdot m_{\mathsf{top}}$

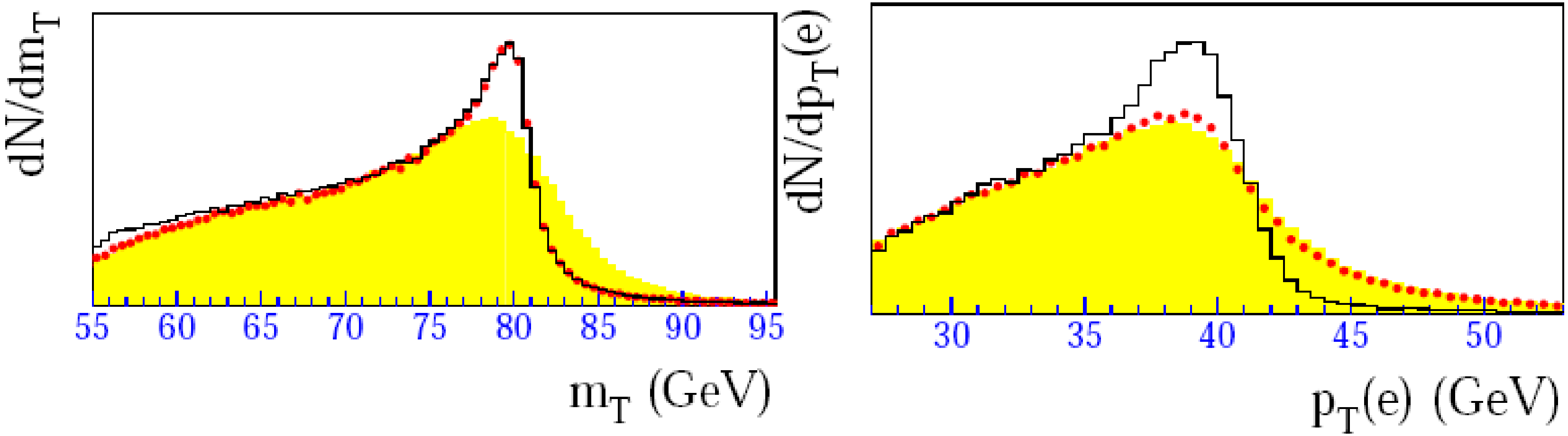
Current $\Delta m_{\mathsf{top}} = 1.3$ GeV $\Rightarrow$ $\Delta m_{\mathsf{W}} = 8$ MeV

W Mass

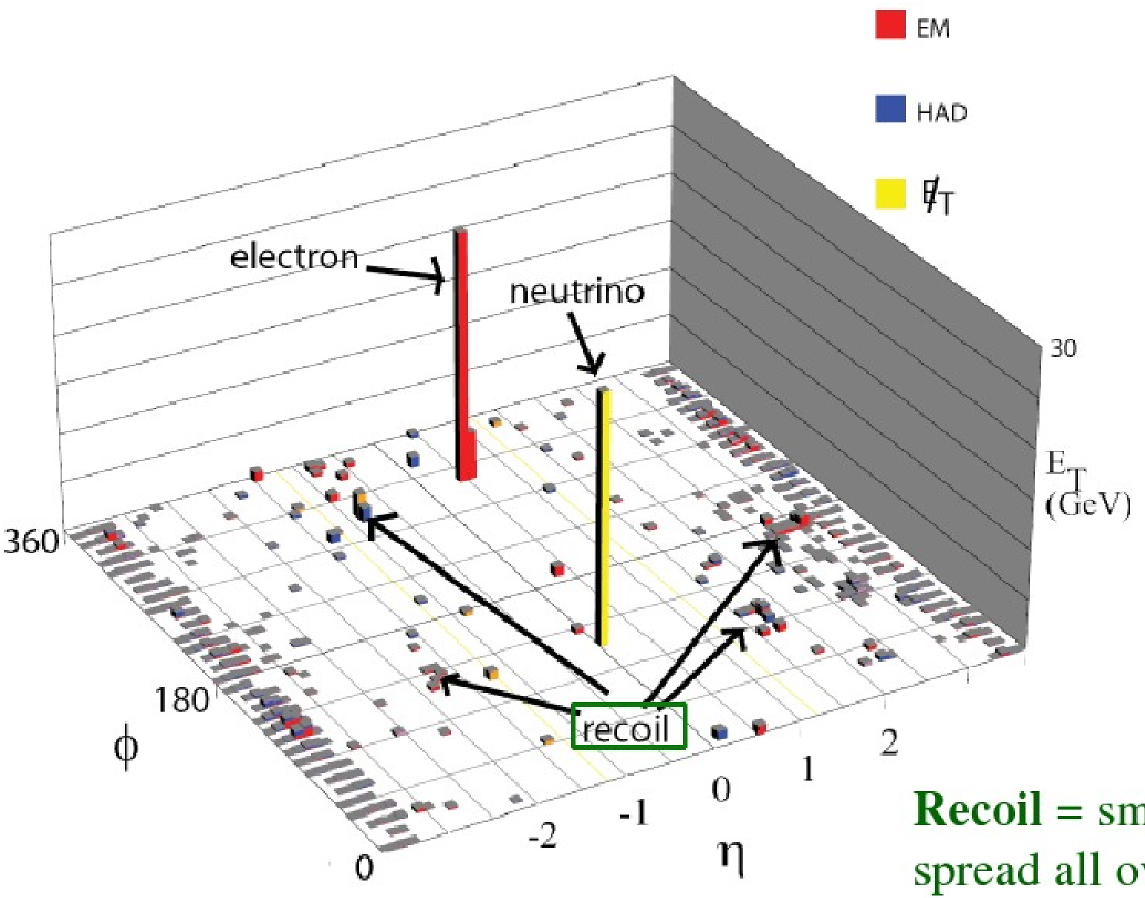
—— No detector effects, pT(W) ≡ 0

● No detector effects, typical pT(W) distribution

🟨 With detector effects, typical pT(W) distribution



W Mass Event Display



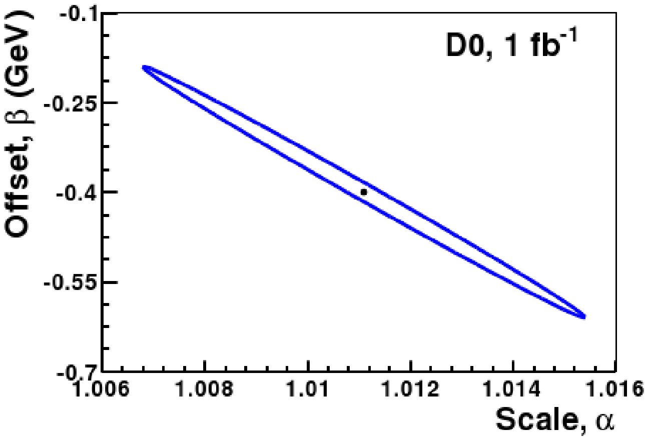
Recoil = small energy deposits spread all over the detector

⇒ sensitivity to small effects, challenges for modeling

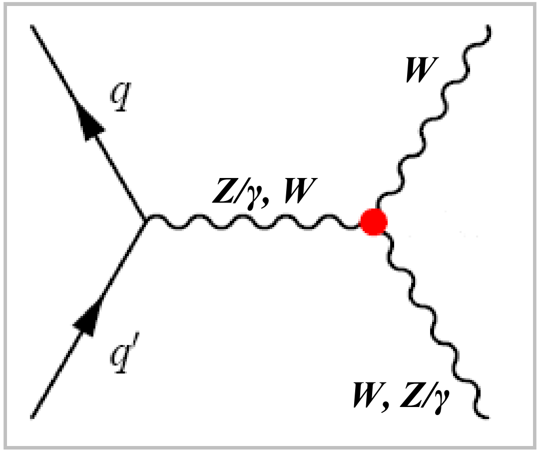
W Mass

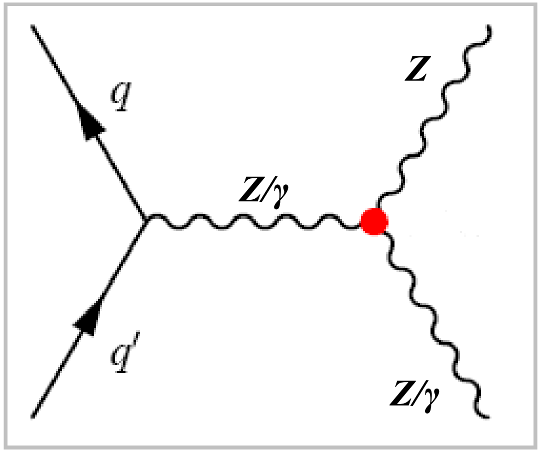
- Because we are looking at hadrons collision
  - We do not know the longitudinal momentum of the initial quarks
    - We cannot determine the longitudinal momentum of the neutrino
      - We cannot reconstruct the full W mass

- Final electron energy calibration



Anomalous Couplings





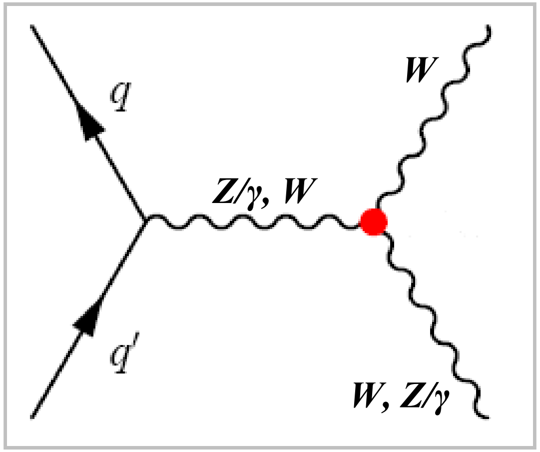
SM: $g_1^{\gamma}=g_1^{Z}=\kappa_{\gamma}=\kappa_Z=1$
and all others are zero

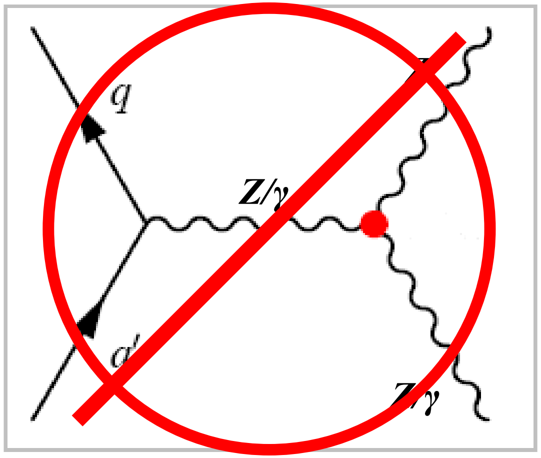
- ***ZWW*** and ***γWW*** couplings
  - General Lorentz invariant Lagrangian has 14 couplings

$$\frac{L_{WWV}}{g_{WWV}} = i\boxed{g_1^V}(W^*_{\mu\nu}W^{\mu}V^{\nu} - W^*_{\mu}V_{\nu}W^{\mu\nu}) + i\boxed{\kappa_V}W^*_{\mu}W_{\nu}V^{\mu\nu} + i\frac{\boxed{\lambda_V}}{M_W^2}W^*_{\lambda\mu}W^{\mu}_{\nu}V^{\nu\lambda}$$
$$- \boxed{g_4^V}W^*_{\mu}W_{\nu}\left(\partial^{\mu}V^{\nu} + \partial^{\nu}V^{\mu}\right) + \boxed{g_5^V}\varepsilon^{\mu\nu\lambda\rho}\left(W^*_{\mu}\partial_{\lambda}W_{\nu} - \partial_{\lambda}W^*_{\mu}W_{\nu}\right)V_{\rho}$$
$$+ \boxed{i\tilde{k}_V}W^*_{\mu}W_{\nu}\tilde{V}^{\mu\nu} + i\frac{\boxed{\tilde{\lambda}_V}}{M_W^2}W^*_{\lambda\mu}W^{\mu}_{\nu}\tilde{V}^{\nu\lambda}$$

- C and P conserving: $g_1^{\gamma}, g_1^{Z}, \kappa_{\gamma}, \kappa_Z, \lambda_{\gamma}, \lambda_Z$
- C and P violating, but CP conserving: g_5^{Z}
- CP violating: $g_4^{Z}, g_4^{Z}, k_{\gamma}, k_Z, \lambda_{\gamma}, \lambda_Z$

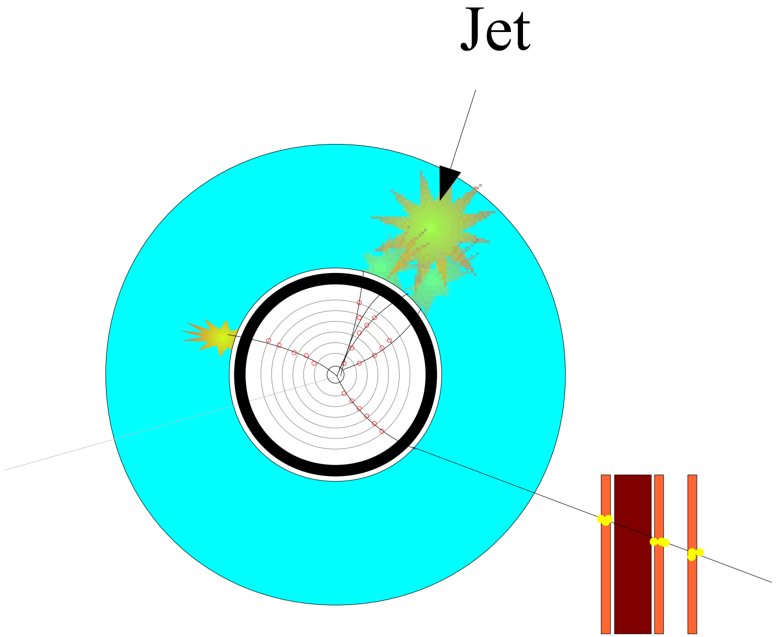
Anomalous Couplings



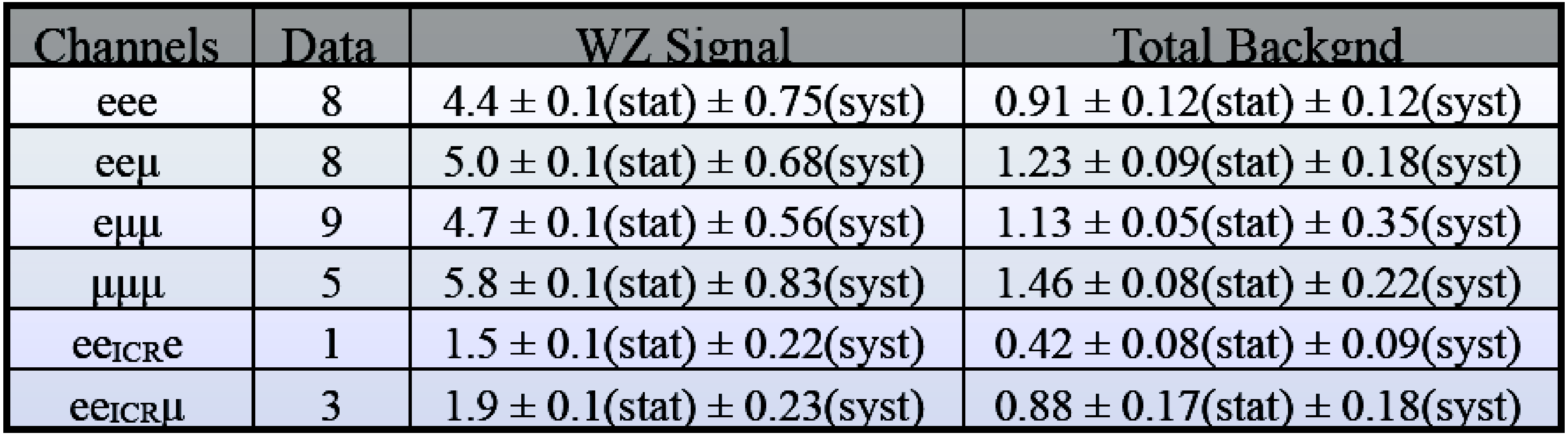


- ***ZWW*** and ***γWW*** couplings
  - In the SM:
    - ***γWW*** and ***ZWW*** TGCs
      - $g_1^Z = \kappa_\gamma = \kappa_Z = 1$ and $\lambda_\gamma = \lambda_Z = 0$
    - No ***γZZ*** and ***γγZ*** TGCs
      - $h_3^\gamma = h_3^Z = h_4^\gamma = h_4^Z = 0$
  - Measure deviations from SM
    - $\Delta\kappa_V \equiv \kappa_V - 1, \quad \Delta g_1^V \equiv g_1^V - 1$
    - $\Delta\lambda_V = \lambda_V, \quad \Delta h_3^V = h_3^V, \quad \Delta h_4^V = h_4^V$
    - $\Delta x \neq 0 \Rightarrow$ anomalous TGC

WZ→lνll: Signature



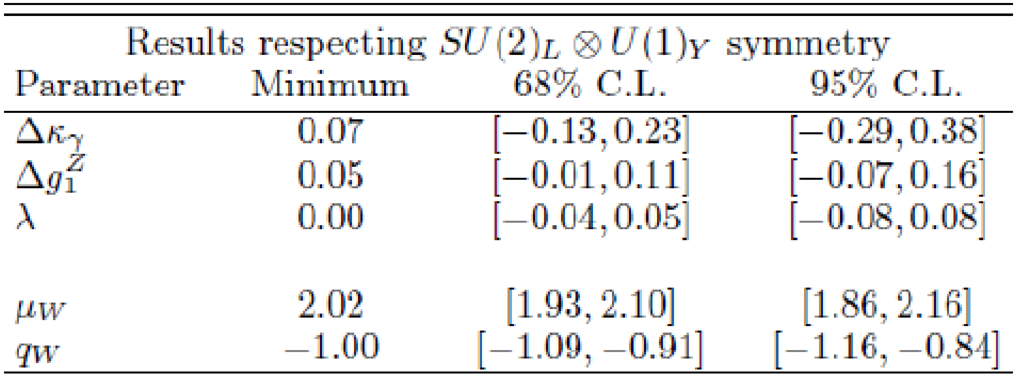
WZ Event Yields



Channels	Data	WZ Signal	Total Backgnd
eee	8	4.4 ± 0.1(stat) ± 0.75(syst)	0.91 ± 0.12(stat) ± 0.12(syst)
eeμ	8	5.0 ± 0.1(stat) ± 0.68(syst)	1.23 ± 0.09(stat) ± 0.18(syst)
eμμ	9	4.7 ± 0.1(stat) ± 0.56(syst)	1.13 ± 0.05(stat) ± 0.35(syst)
μμμ	5	5.8 ± 0.1(stat) ± 0.83(syst)	1.46 ± 0.08(stat) ± 0.22(syst)
$ee_{\mathrm{ICR}}e$	1	1.5 ± 0.1(stat) ± 0.22(syst)	0.42 ± 0.08(stat) ± 0.09(syst)
$ee_{\mathrm{ICR}}\mu$	3	1.9 ± 0.1(stat) ± 0.23(syst)	0.88 ± 0.17(stat) ± 0.18(syst)

Previous TGC Limits

2009 D0 combination of ***WZ→lνll*** (previous)**,** ***Wγ→lνγ*****,** ***WW→lνlν*****,** ***WW+WZ→lνqq***

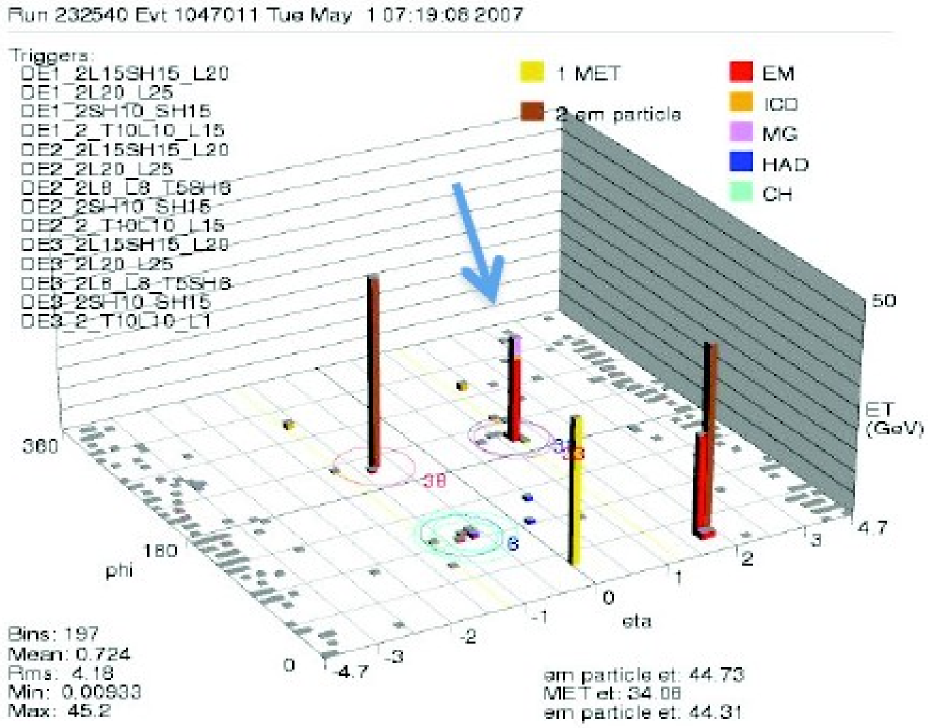


Results respecting $SU(2)_L \otimes U(1)_Y$ symmetry

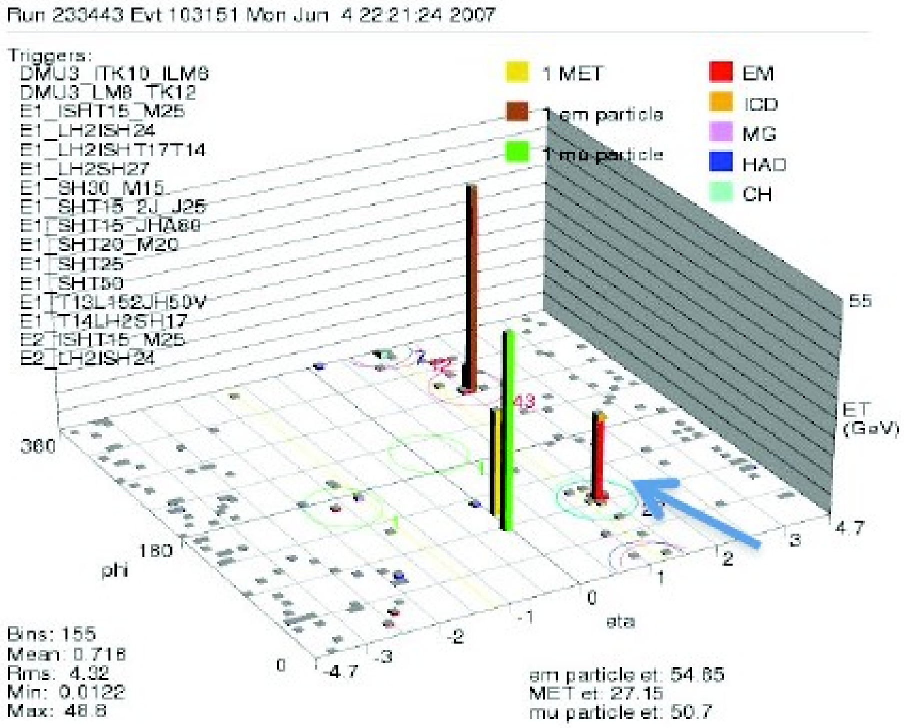
Parameter	Minimum	68% C.L.	95% C.L.
$\Delta\kappa_\gamma$	0.07	$[-0.13, 0.23]$	$[-0.29, 0.38]$
Δg_1^Z	0.05	$[-0.01, 0.11]$	$[-0.07, 0.16]$
λ	0.00	$[-0.04, 0.05]$	$[-0.08, 0.08]$
μ_W	2.02	$[1.93, 2.10]$	$[1.86, 2.16]$
q_W	-1.00	$[-1.09, -0.91]$	$[-1.16, -0.84]$

arXiv.org:0907.4952

WZ Event Displays



```
Run 232540 Evt 1047011 Tue May  1 07:19:08 2007

Triggers:
  DE1_2L15SH15_L20
  DE1_2L20_L25
  DE1_2SH10_SH15
  DE1_2_T10L10_L15
  DE2_2L15SH15_L20
  DE2_2L20_L25
  DE2_2L8_L8_T5SH8
  DE2_2SH10_SH15
  DE2_2_T10L10_L15
  DE3_2L15SH15_L20
  DE3_2L20_L25
  DE3_2L8_L8_T5SH8
  DE3_2SH10_SH15
  DE3_2_T10L10_L1

Bins: 197
Mean: 0.724
Rms:  4.18
Min:  0.00933
Max:  45.2

em particle et: 44.73
MET et: 34.08
em particle et: 44.31
```

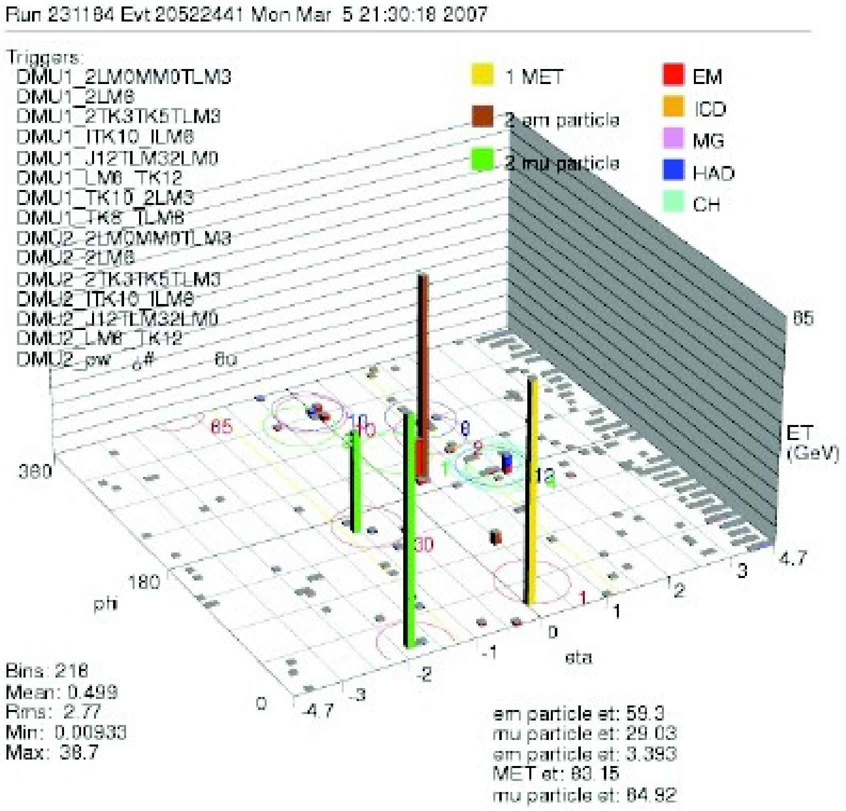


```
Run 233443 Evt 103151 Mon Jun  4 22:21:24 2007

Triggers:
  DMU3_ITK10_ILM8
  DMU3_LM8_TK12
  E1_ISHT15_M25
  E1_LH2ISH24
  E1_LH2ISHT17T14
  E1_LH2SH27
  E1_SH30_M15
  E1_SHT15_2J_J25
  E1_SHT15_JHA80
  E1_SHT20_M20
  E1_SHT25
  E1_SHT50
  E1_T13L152JH50V
  E1_T14LH2SH17
  E2_ISHT15_M25
  E2_LH2ISH24

Bins: 155
Mean: 0.718
Rms:  4.32
Min:  0.0122
Max:  48.8

em particle et: 54.85
MET et: 27.15
mu particle et: 50.7
```

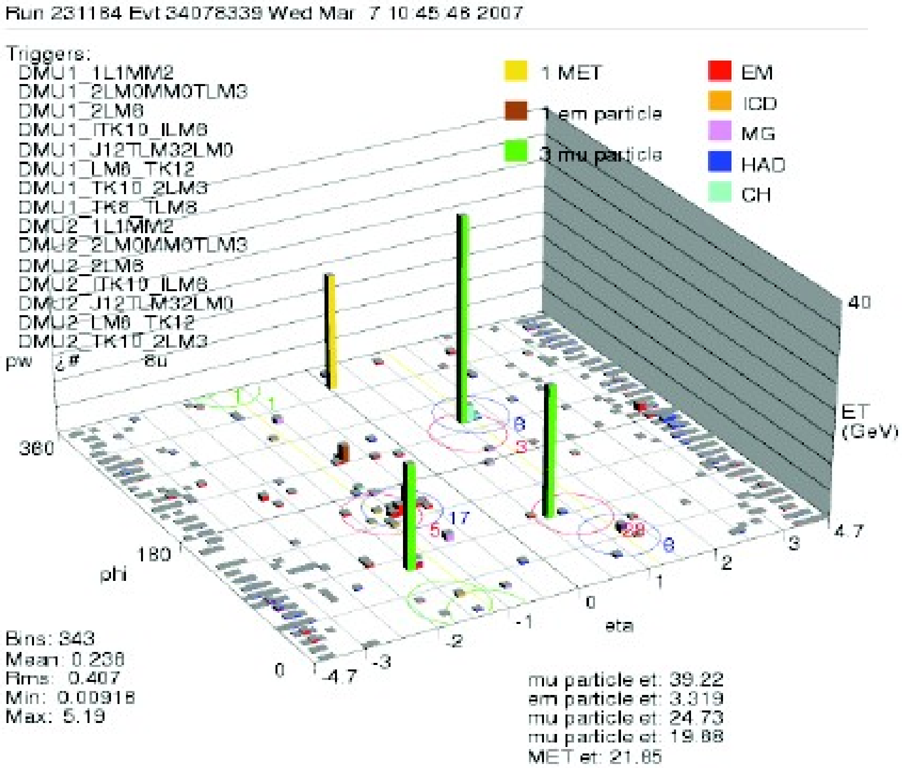
eee, in ICR

eeμ, in ICR

WZ Event Displays

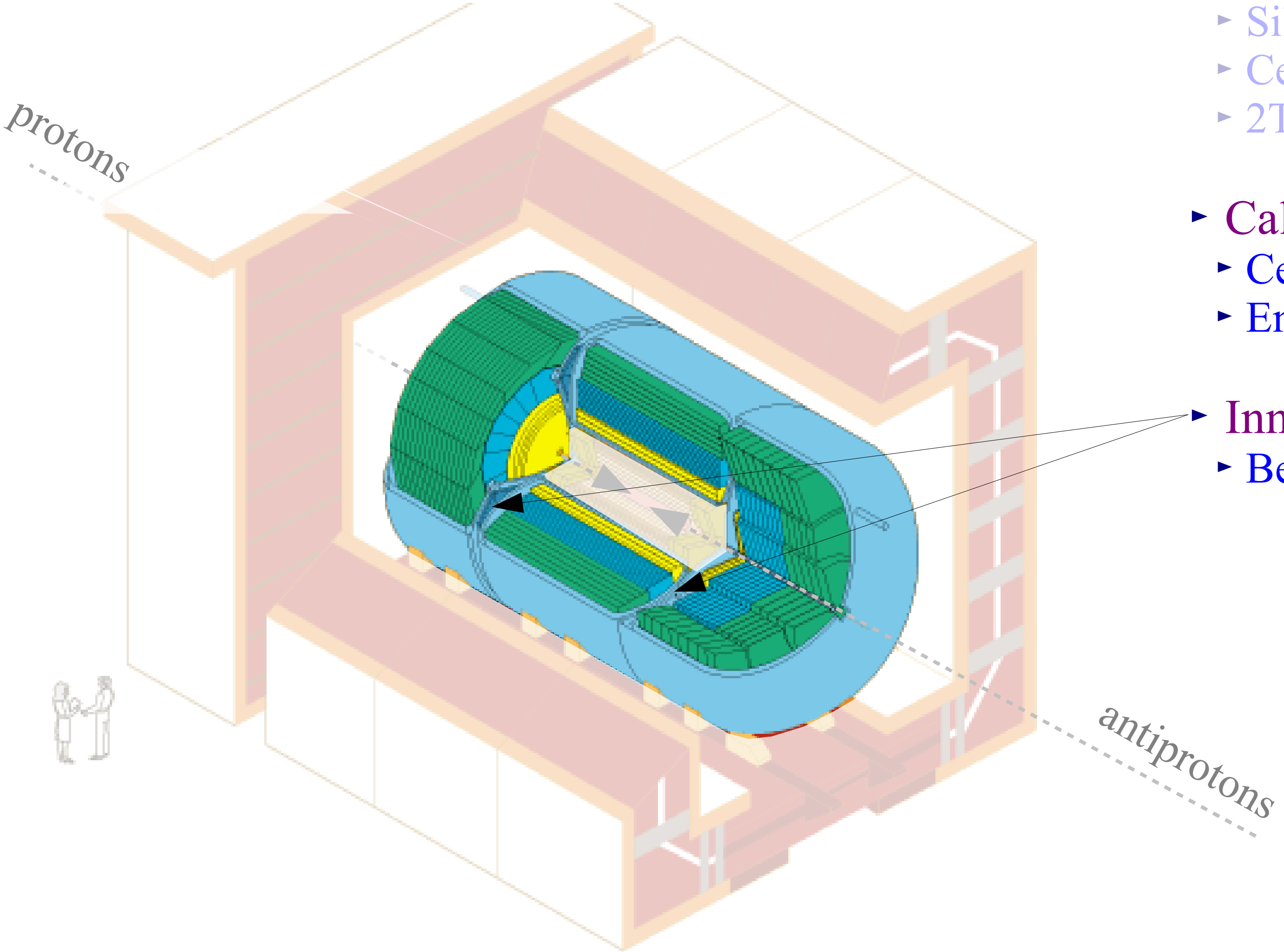


eμμ



μμμ

DZero Detector



- Central Tracking System
  - Silicon Micro-strip Tracker
  - Central Fiber Tracker
  - 2T Solenoid Magnet
- Calorimeters
  - Central Calorimeter (CC)
  - End Calorimeters (EC)
- Inner Cryostat Region
  - Between CC and EC