ELECTROWEAK PHYSICS

Heidi Schellman – Northwestern University

What is not in this talk

- **Results from previous years – except for context**
- Top quark mass and single top production
  - Mousumi Datta
- The CKM matrix
  - Dave Hitlin and Tom Browder
- The MNS matrix
  - Bonnie Flemming
- The Higgs
  - Mark Kruse
- Weak boson production (QCD)
  - Don Lincoln
- These are arguably all electroweak measurements.

What's left

- Precision measurements of electroweak couplings and mass
  - The W mass
  - Measurements of the weak mixing angle.
- Very rare electroweak processes.
  - Diboson production

- And the future…

Predictions of GSW theory

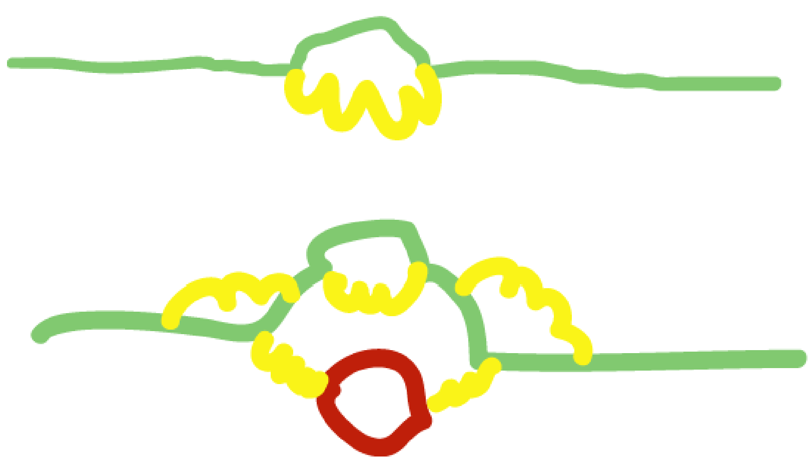
Couplings and Masses

- A neutral Z^0 boson
- W, Z^0 and γ couplings and masses have tightly constrained relations:
  - $M_W/M_Z = \cos\theta_w$
  - $e = g \sin\theta_w$

Higgs Field

- Symmetry breaking would like a Higgs Field
- There should be at least one physical scalar Higgs boson left over to observe

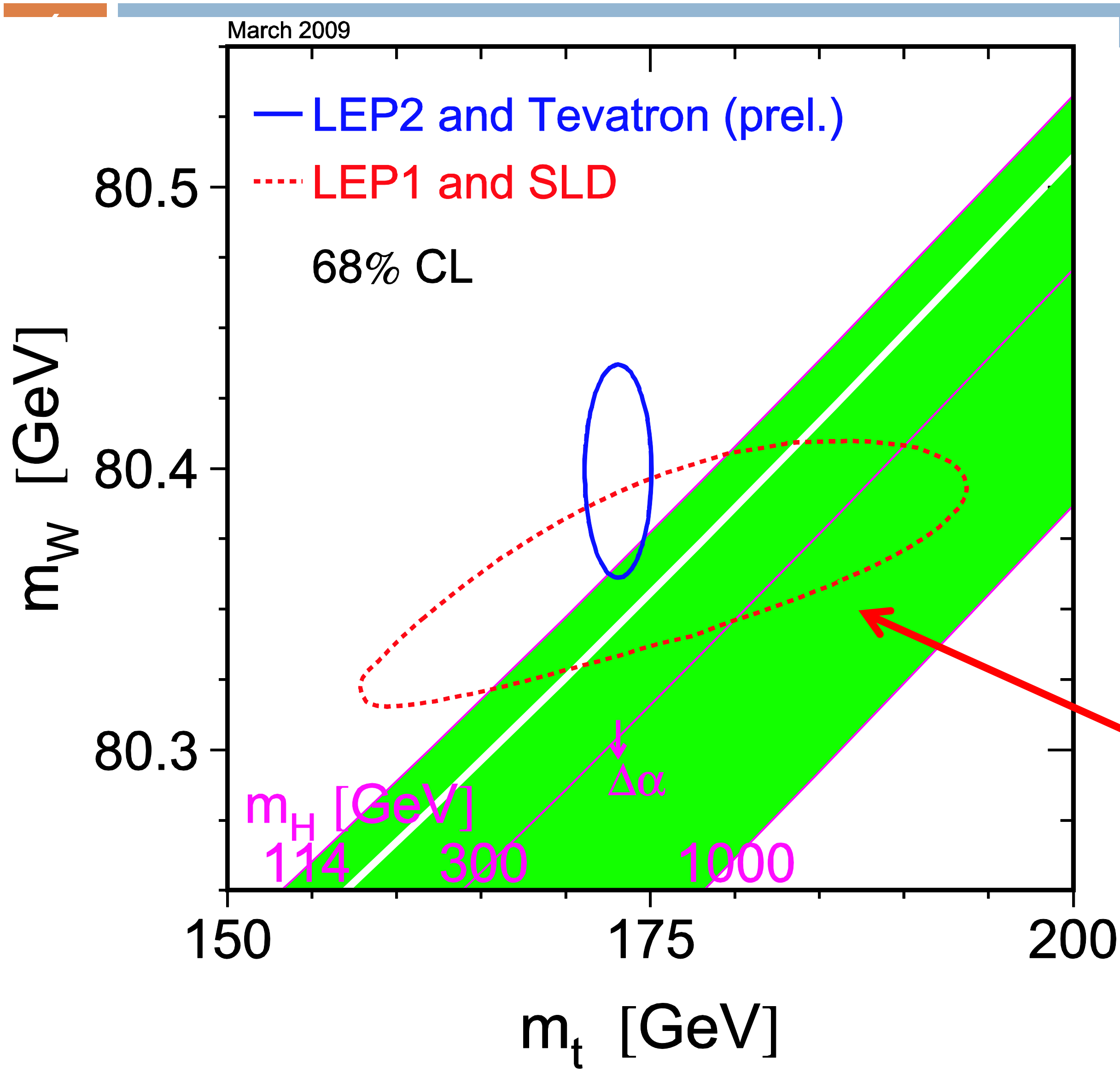
Why constants aren't constant



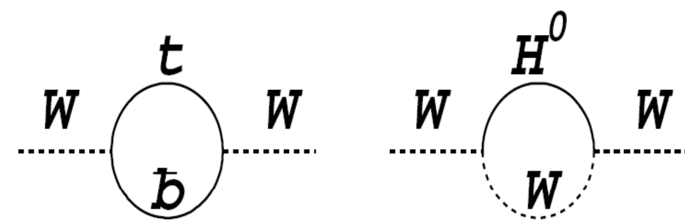
Renormalization

- This is an electron
- This is a closeup of an electron
- This is a real closeup of an electron.
- Properties depend on distance/energy scale and properties of all other particles which can couple

Relations of masses and angles



$$M_W = \sqrt{\frac{\pi\alpha}{\sqrt{2}G_F}}\,\frac{1}{\sin\theta_W\sqrt{1-\Delta r}}$$



$\Delta r \propto M_t^2$ $\Delta r \propto \log M_H$

Measure θ_W, predict M_W

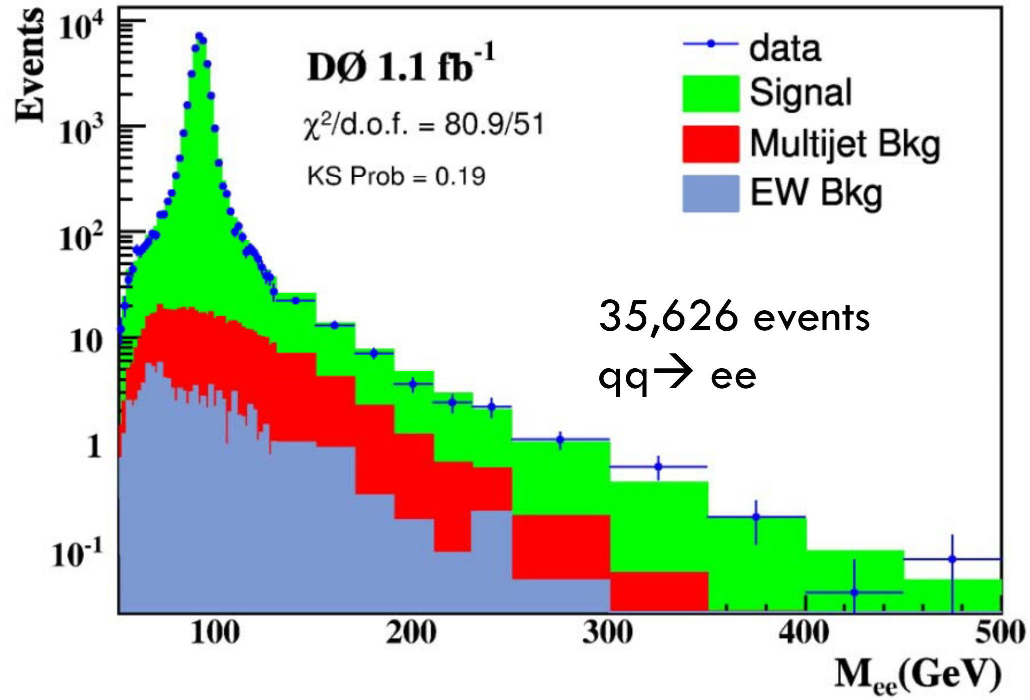
Consistency of indirect and direct measures?

LEP/SLD measurements of M_{Z}, M_W, $\sin^2\theta_w$

- LEP/SLD e^+e^-
  - Measure Z mass 91.1876+/- 0.0021 GeV
  - Measure Z weak couplings to all fermions by measuring γ^*/Z interference and the Z width.
  - Precise measurement of $\sin^2\theta_w$
  - Measure the W mass with 0.033 GeV resolution
- Tevatron - hadron-hadron scattering
  - Forward backward asymmetry A_{FB}
  - M_W

Z's at hadron colliders

- LEP recorded 17M Z events ee→ff of Which 1.7M were to Leptons (including tau's)



- Tevatron now has reconstructed

~ 0.2-0.6M events x 2 channels (ee+μμ) x 2 expts (D0/CDF)

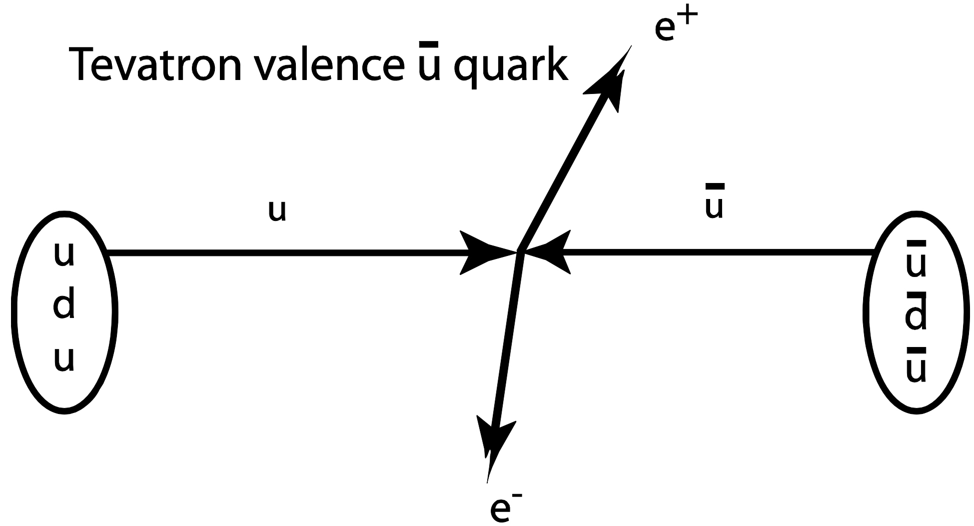
~ up to 1.6 M Z→ℓℓ already depending on cuts.

Close to LEP statistics!

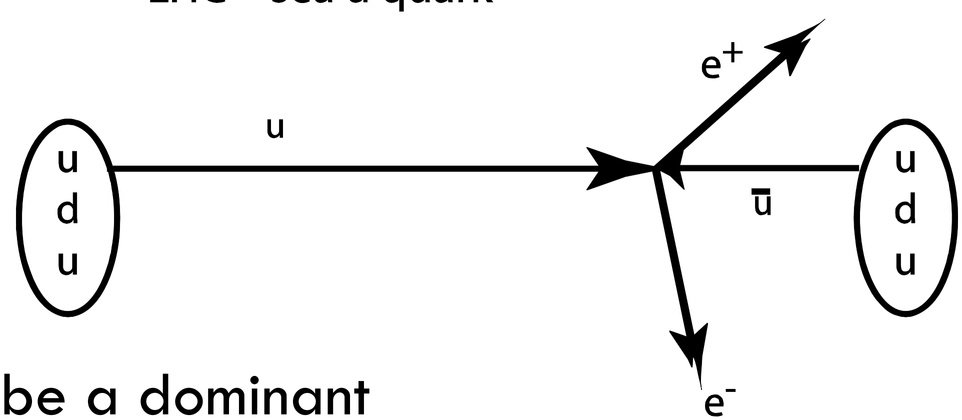
- LHC experiments expected to have much higher cross sections with ~2 M Z→ ℓℓ in the first fb^{-1} !

Signatures $u\bar{u} + d\bar{d} \rightarrow Z \rightarrow ll$

Tevatron is mainly valence-valence scattering.

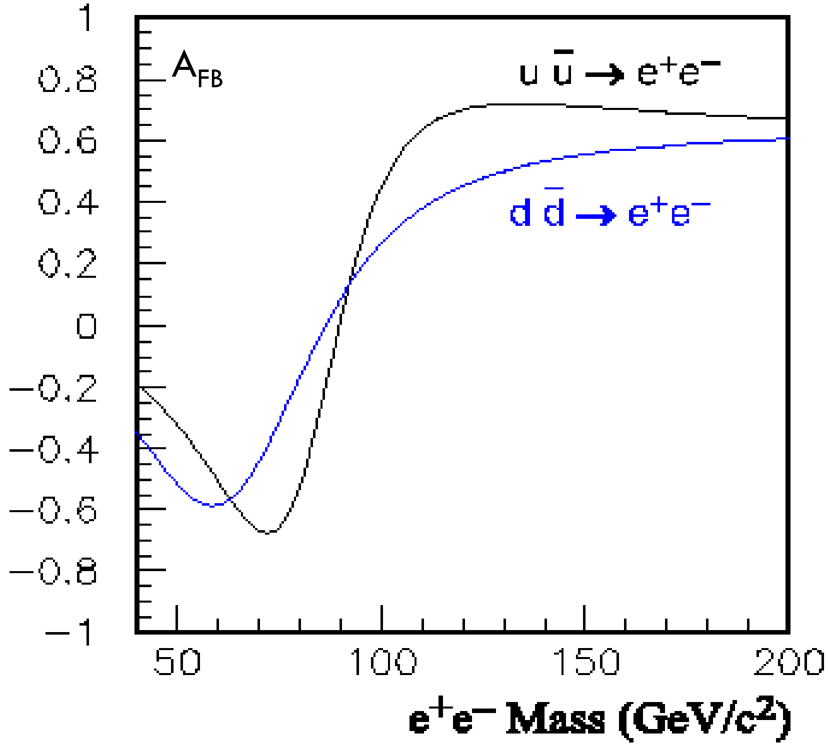


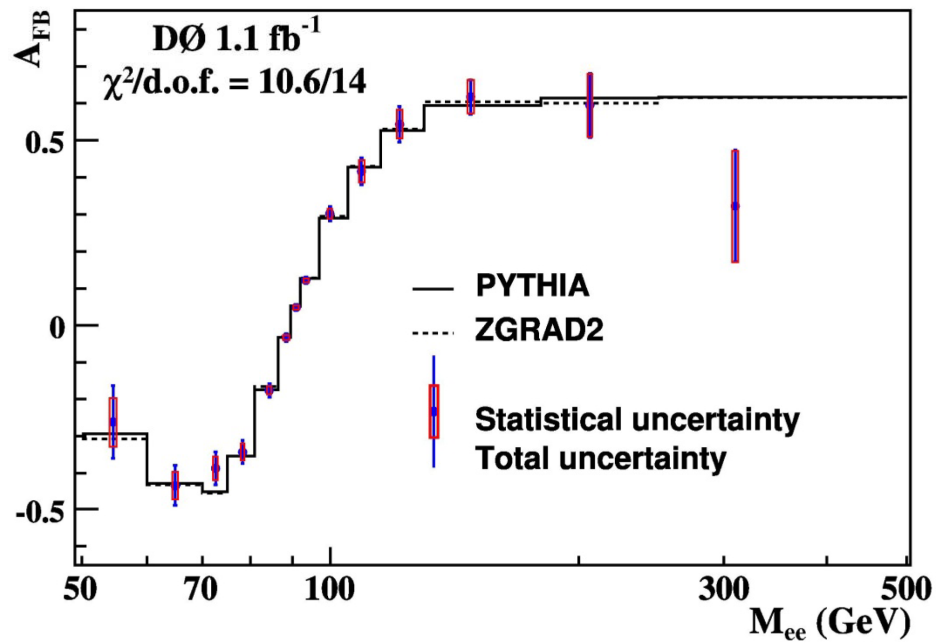
LHC is mainly valence-sea scattering and must choose boosted Z's to tell valence from sea.



PDF's will be a dominant uncertainty.

Current measurement from D0





Phys. Rev. Lett. **101**, 191801 (2008), arXiv.org:0804.3220

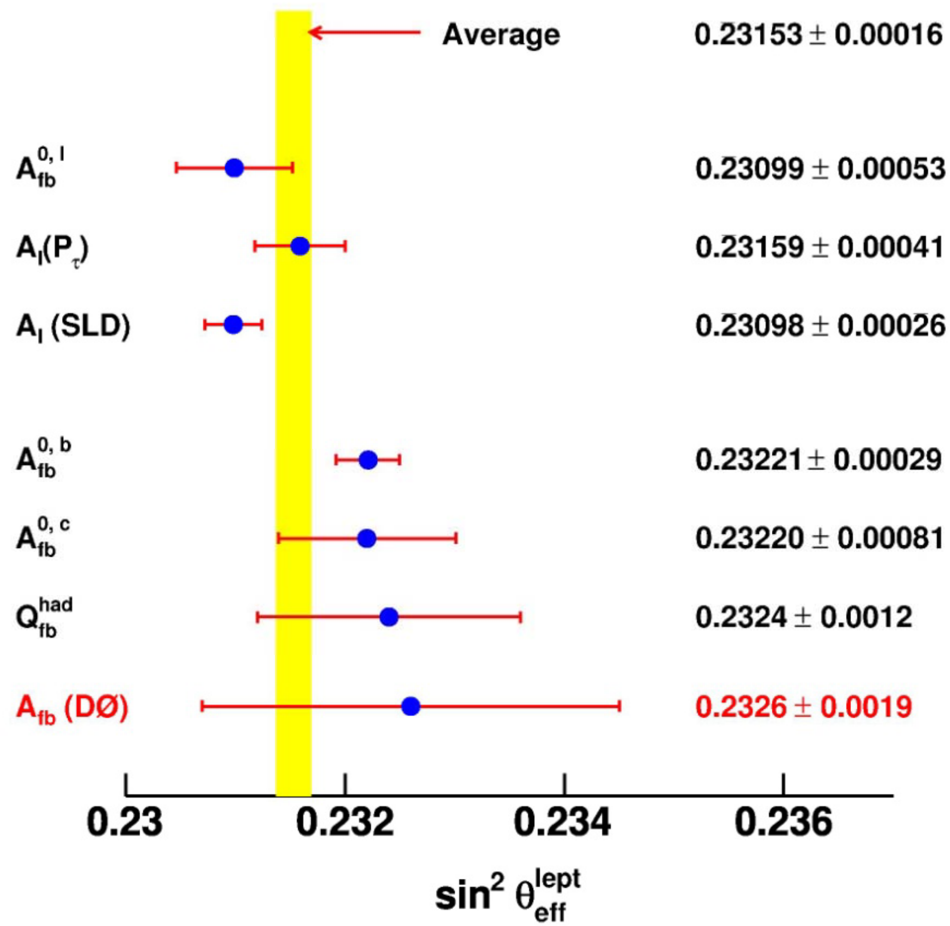
$q\bar{q} \rightarrow Z/\gamma^* \rightarrow ee$

$\sin^2\theta_w = 0.2326 \pm 0.0018(stat) \pm 0.006(syst)$

Trang Hoang
Friday EWK IIII

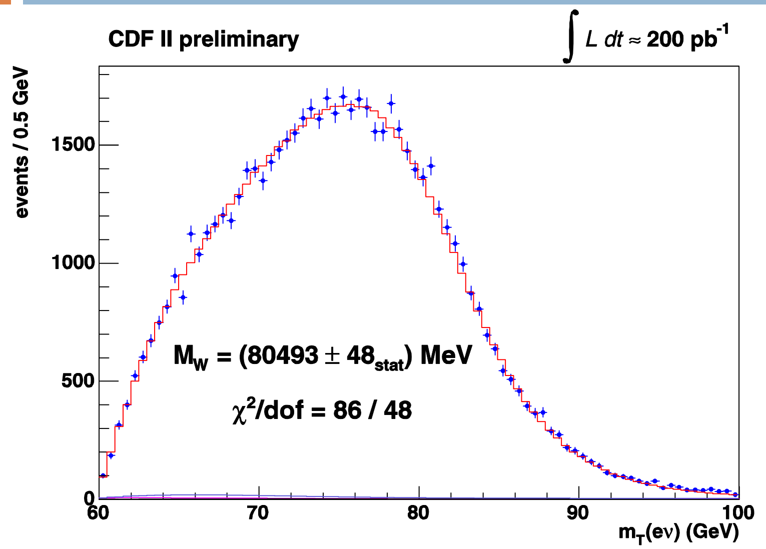
A_{FB} measurements

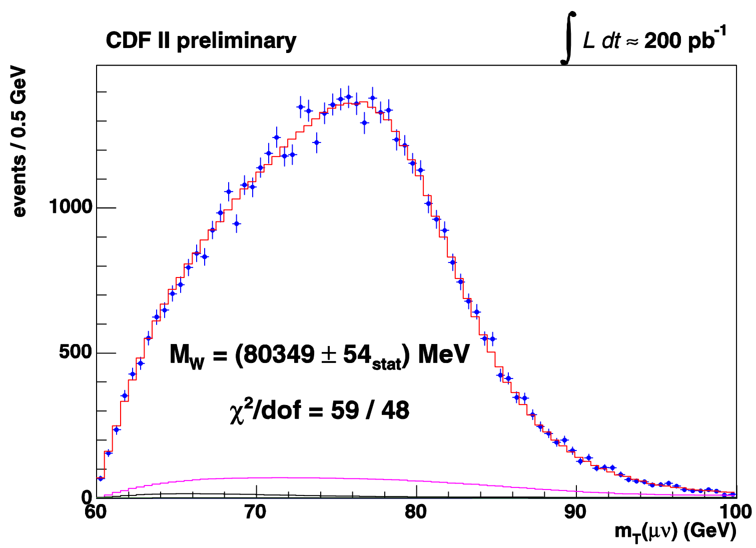
Future measurements from the Tevatron and the LHC are expected to reach 0.0005 or better accuracy. The limiting factor is probably PDF's.



W mass from CDF - 2007

Chris Hays
Tuesday
EWK I





CDF II $L = 200\ pb^{-1}$

m_T Uncertainty [MeV]	Electrons	Muons	Common
Lepton Scale	30	17	17
Lepton Resolution	9	3	0
Recoil Scale	9	9	9
Recoil Resolution	7	7	7
$u_{\parallel}$ Efficiency	3	1	0
Lepton Removal	8	5	5
Backgrounds	8	9	0
$p_T(W)$	3	3	3
PDF	11	11	11
QED	11	12	11
Total Systematic	39	27	26
Statistical	48	54	0
Total	62	60	26

Both muon and electron channels
Scale set by the CDF tracker
Absolute measurement of M_W

New W mass measurement

Jyotsna Osta
Tuesday
EWK I

- 1 fb^{-1} of data taken 2002-2006
- ~ 18,725 Z and 499,830 W candidates in the electron channel only.
- Use data to determine corrections wherever possible
- Blind analysis – central mass value hidden until everything has been reviewed.
- Because Z→ee is the main calibration, this is effectively a M_W/M_Z measurement – many physics effects cancel.
- NOT very correlated with the CDF measurement!

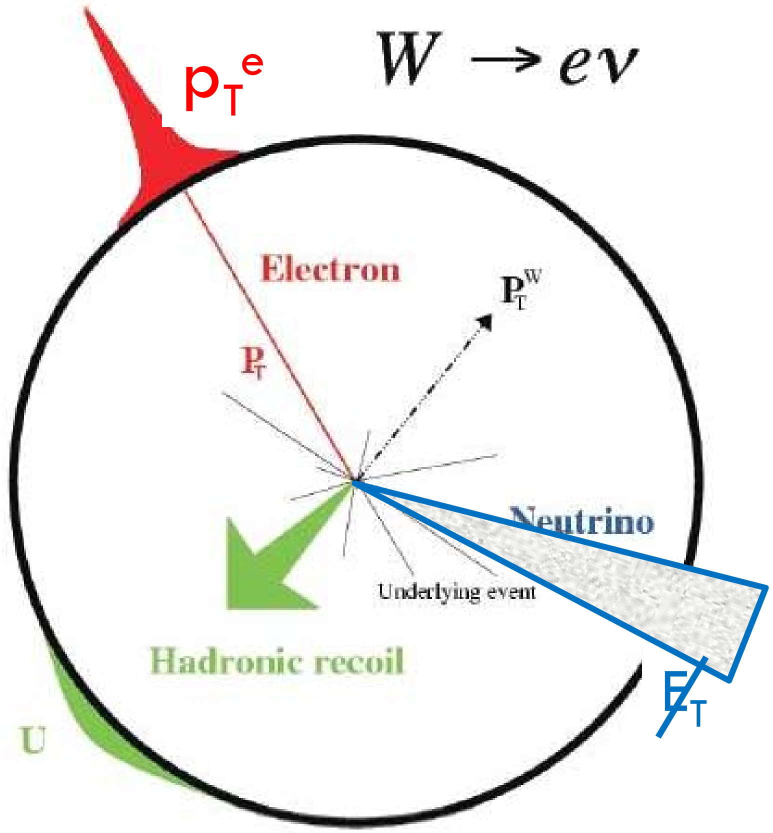
W boson mass - W -> eν mode

- Cannot measure ν or W momentum along beam
- Use variables defined in transverse plane

$$m_T = \sqrt{2\, p_T^e\, \not{E}_T\, (1-\cos\Delta\phi)}$$

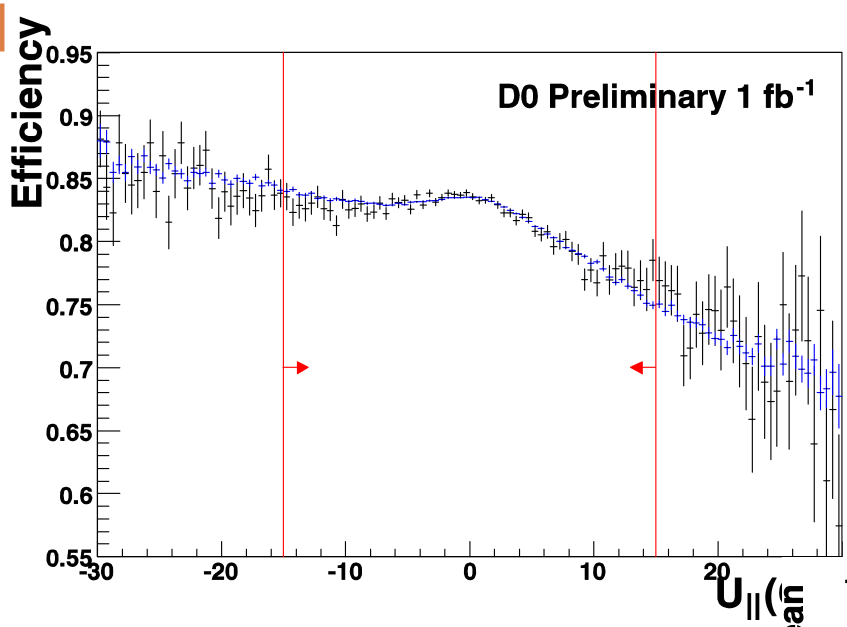
p_T^e

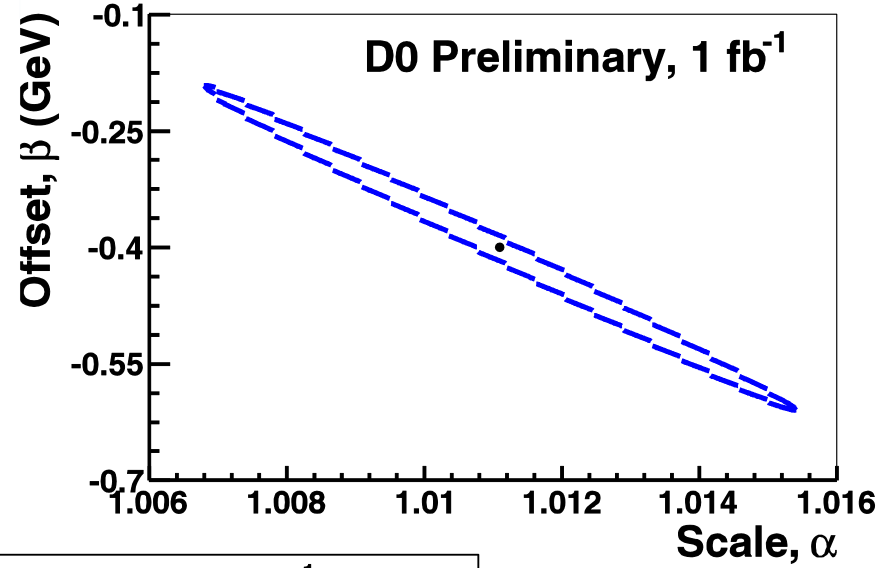
$\not{E}_T$ = inferred neutrino p_T^ν

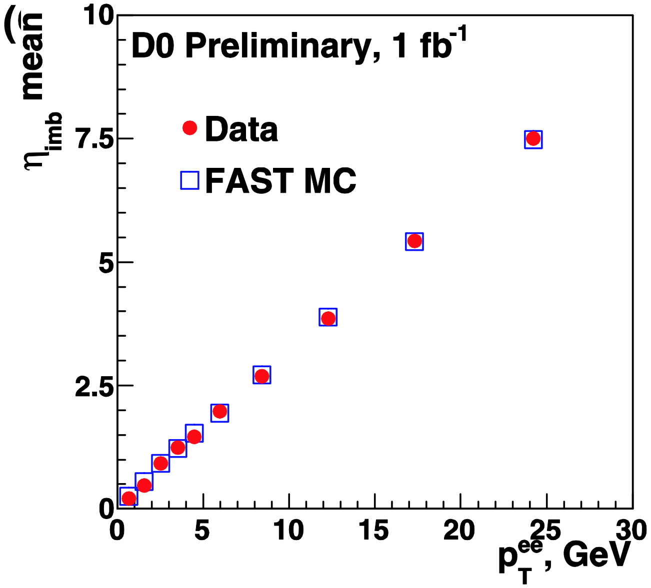


Only electrons with |η| < 1.1 used

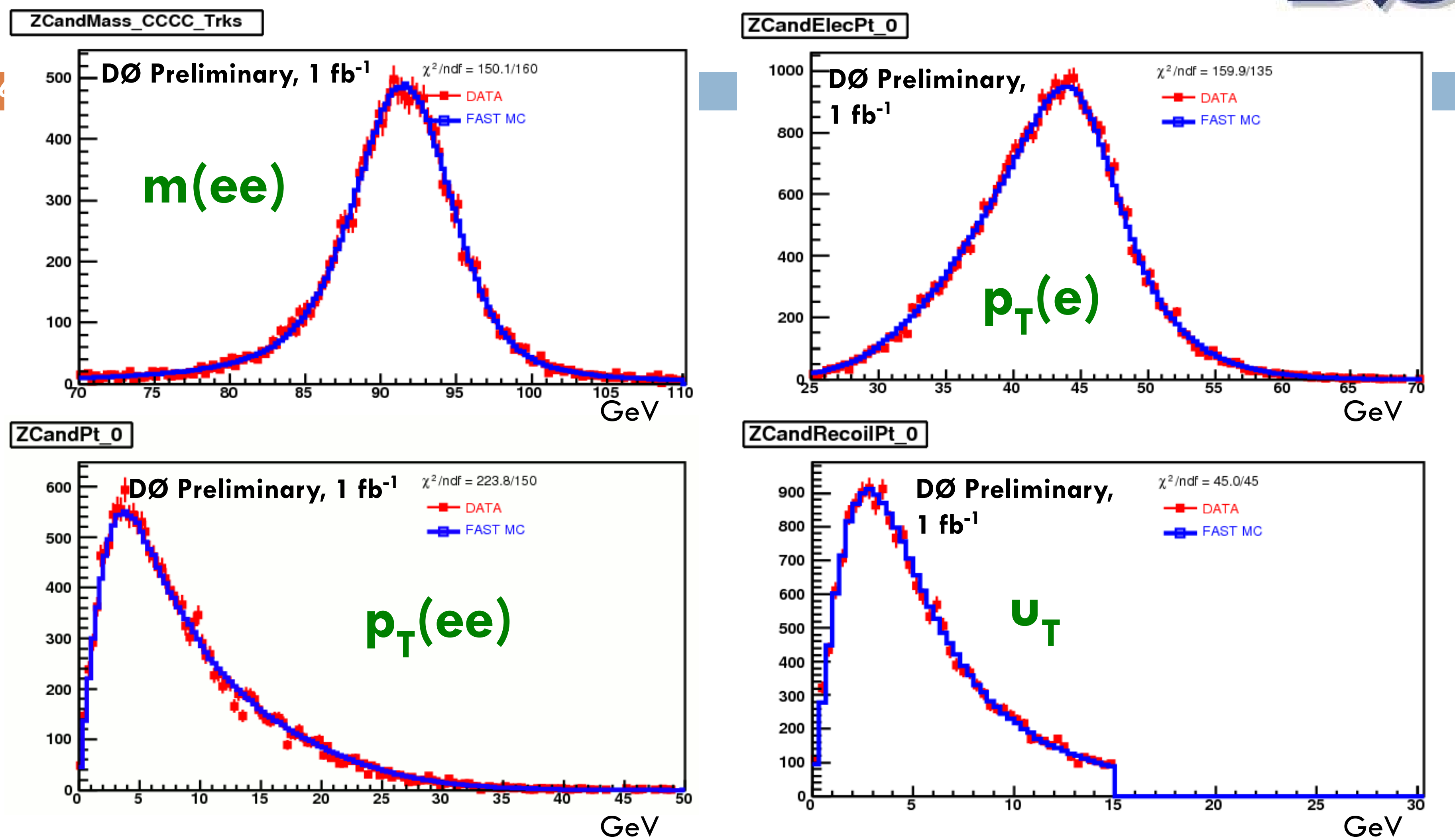
Crosschecks







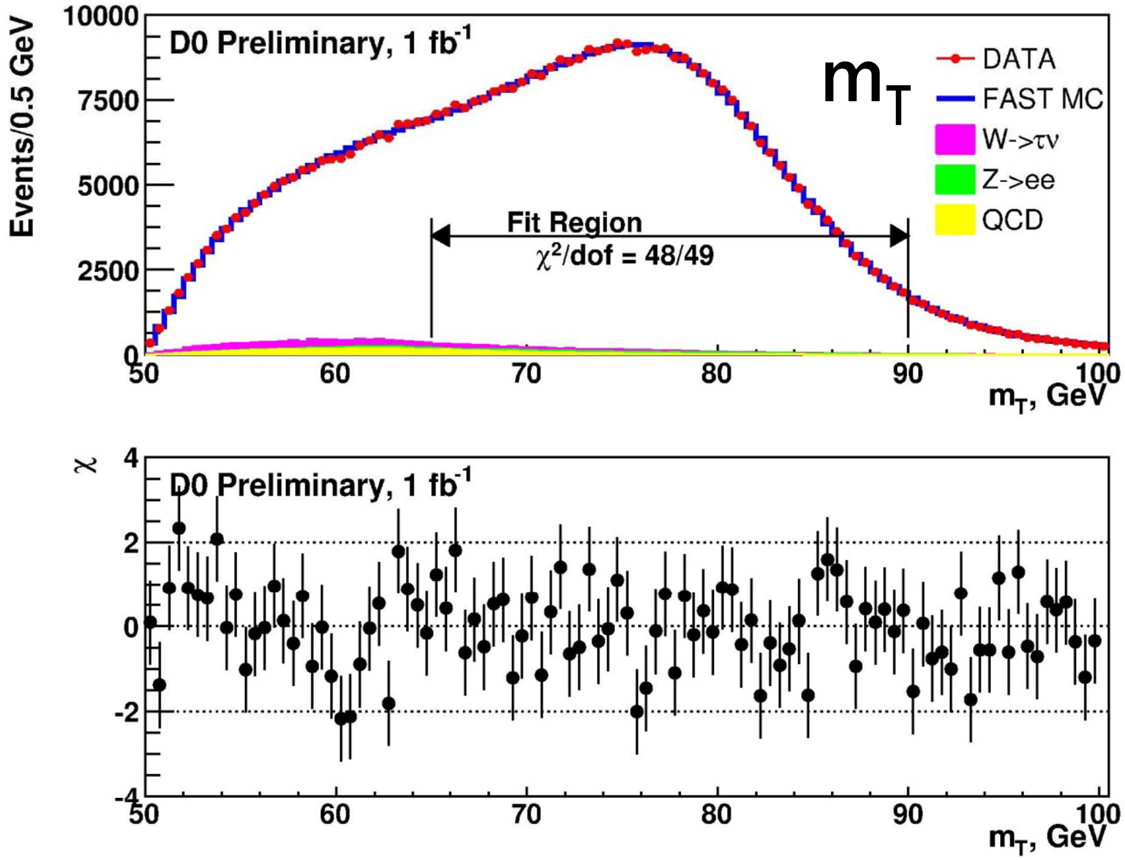
Check everything… Results: Z → e e data



Good agreement between parameterized MC and collider data.

W boson mass

- Fit data to simulated distributions by varying m_W

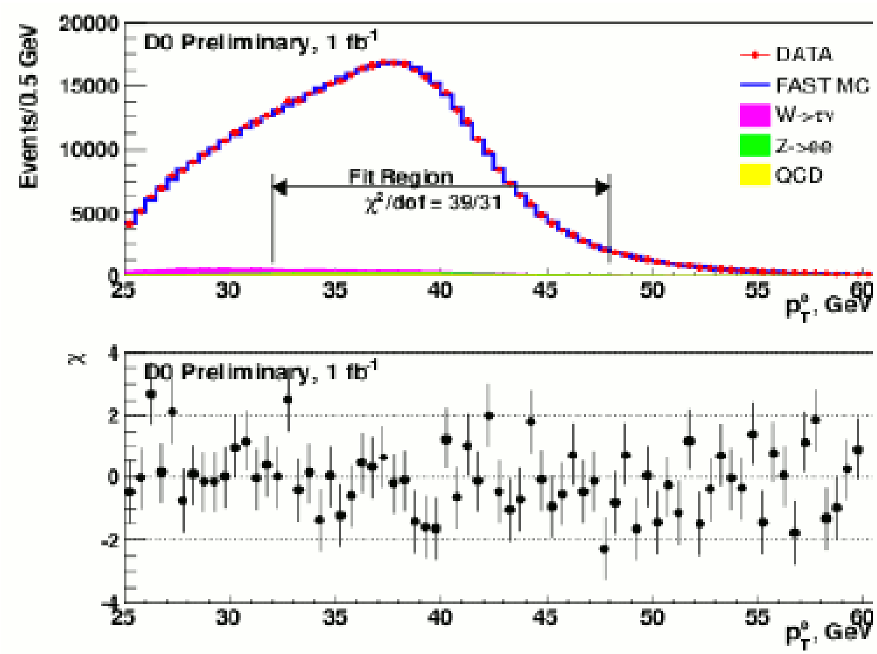


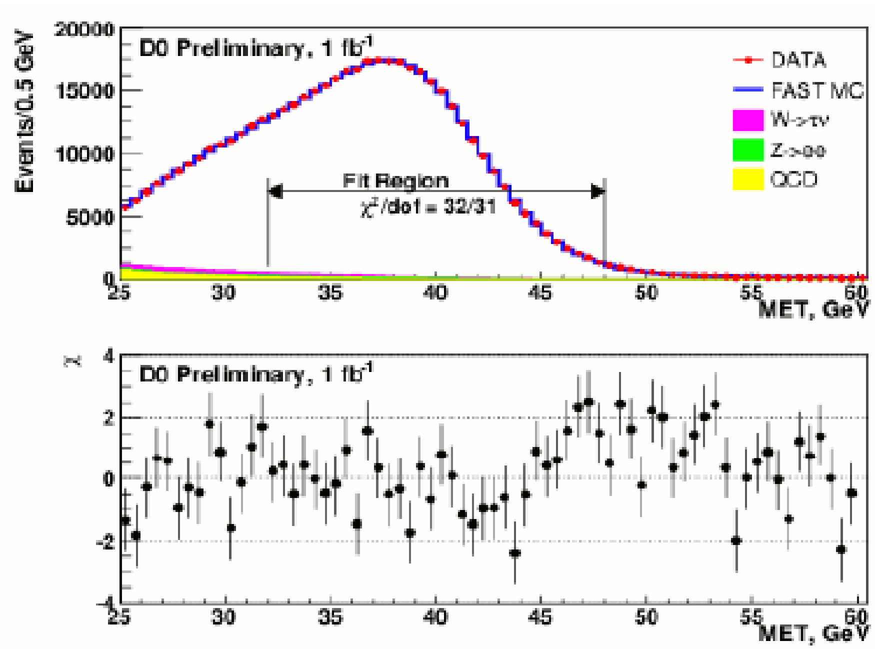
Hid the fitted W mass value until all control plots were OK

Also fit p_T^e, p_T^ν

$m_W = 80.401 \pm 0.023 \pm 0.037$ GeV

Also fit to $p_T(e)$ and $p_T(\nu)$





m(W) = 80.400 ± 0.027 GeV (stat)

m(W) = 80.402 ± 0.023 GeV (stat)

W boson mass

$m_W(m_T)$ = 80.401 ± 0.023 (stat) ± 0.037 (syst) GeV

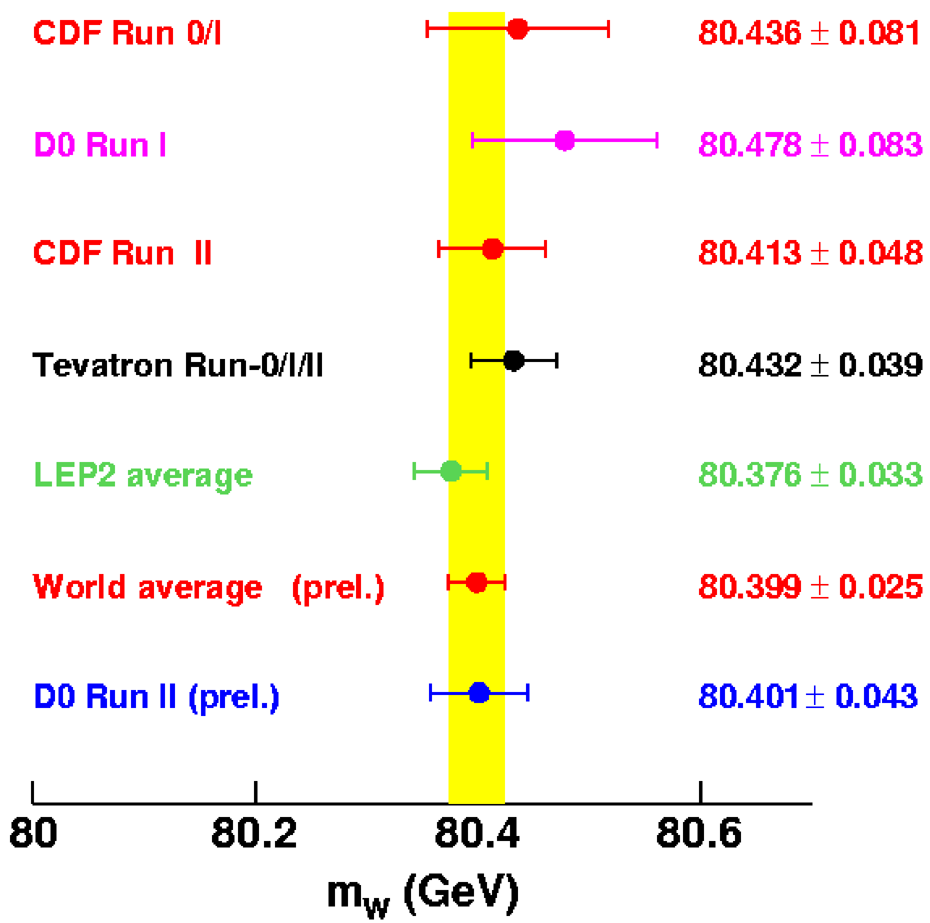
$m_W(p_{Te})$ = 80.400 ± 0.027 (stat) ± 0.040 (syst) GeV

$m_W(p_{T\nu})$ = 80.402 ± 0.023 (stat) ± 0.044 (syst) GeV

Source	$\sigma(m_W)$ MeV m_T	p_T^e	$\not{E}_T$
Electron energy calibration	34	34	34
Electron resolution model	2	2	3
Electron energy offset	4	6	7
Electron energy loss model	4	4	4
Recoil model	6	12	20
Electron efficiencies	5	6	5
Backgrounds	2	5	4
Experimental Subtotal	35	37	41
PDF	9	11	14
QED	7	7	9
Boson p_T	2	5	2
Theory Subtotal	12	14	17
Total	37	40	44

Limited by
Z->ee statistics,
will improve with
more data

Summary of direct measurements



Higgs Mass Constraints

Andreas Hoecker
(CERN)
EPS 2009

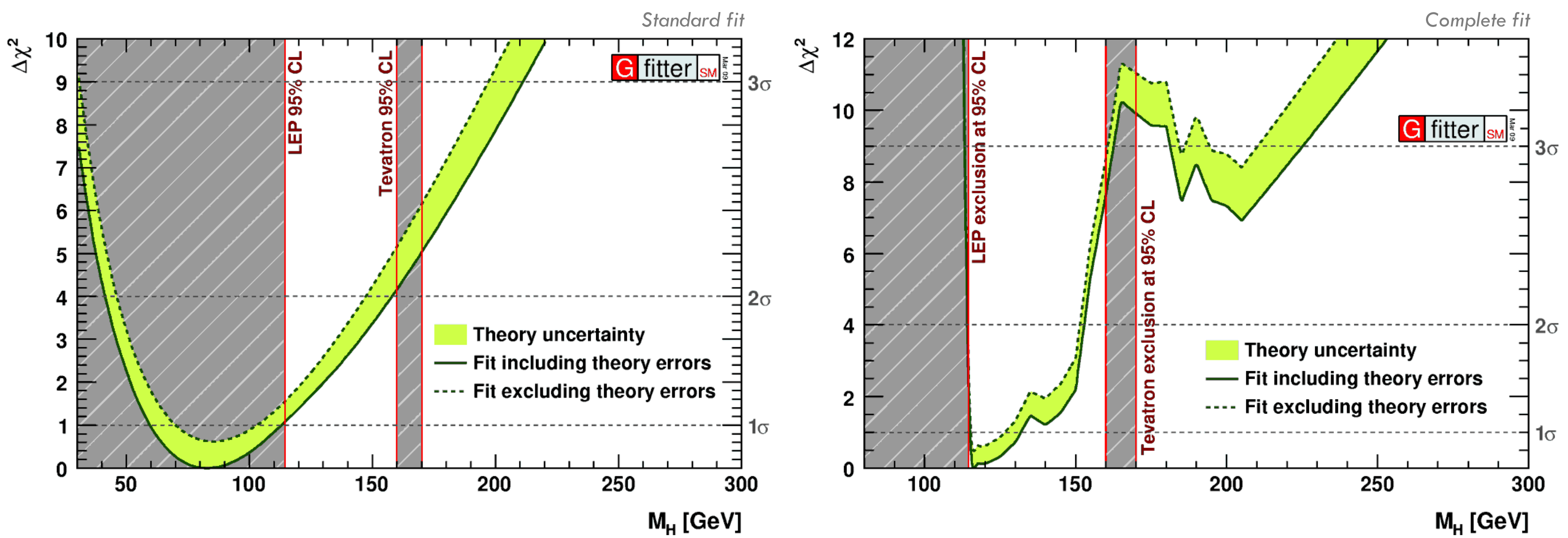
M_H from *Standard fit*:

- Central value $\pm 1\sigma$: $M_H = 80^{+30}_{-23}$ GeV
- 2σ interval: [42, 158] GeV

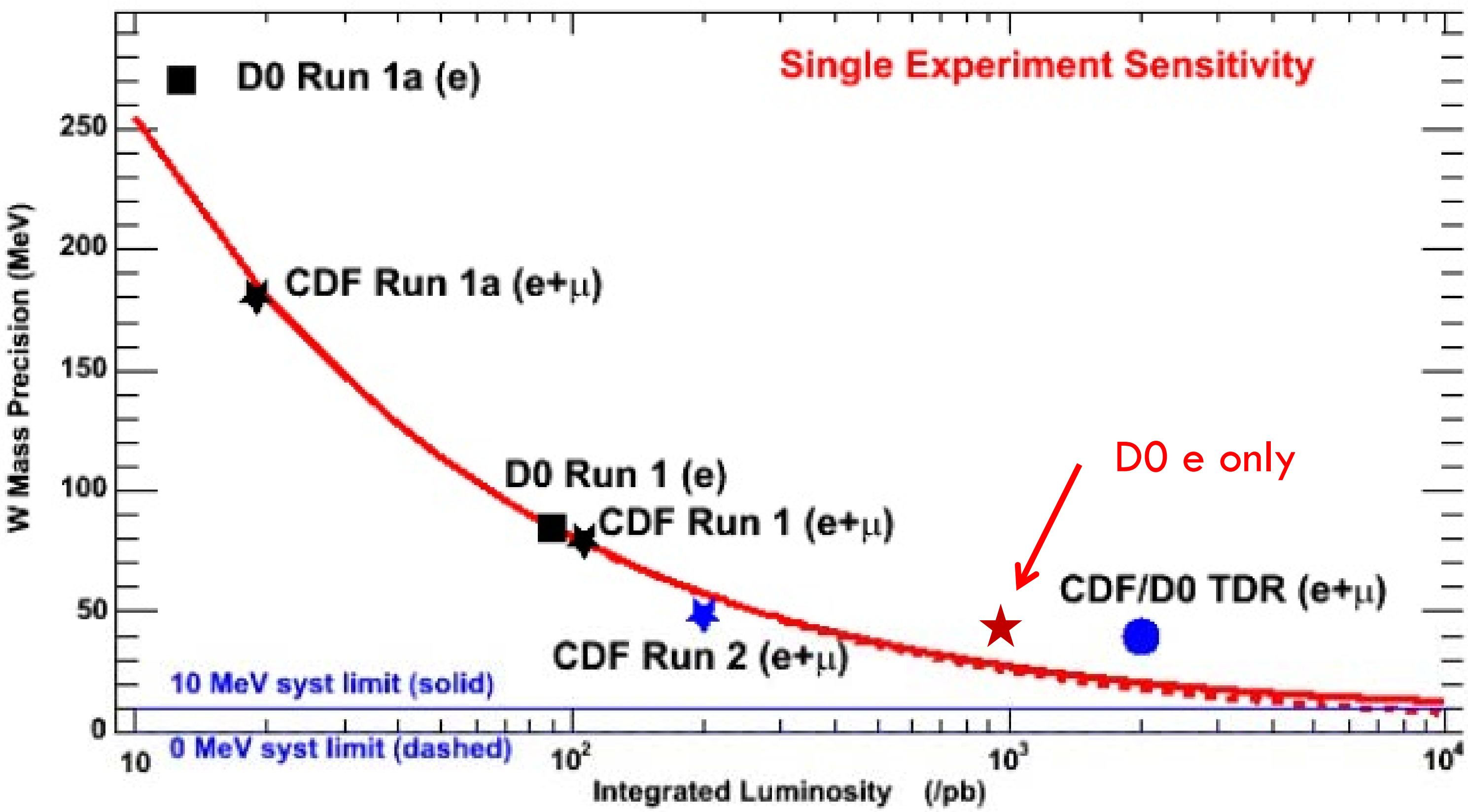
Green band due to *Rfit* treatment of theory errors, fixed errors lead to larger χ^2_{min}

M_H from *Complete fit*:

- Central value $\pm 1\sigma$: $M_H = 116^{+16}_{-1.3}$ GeV
- 2σ interval: [114, 153] GeV



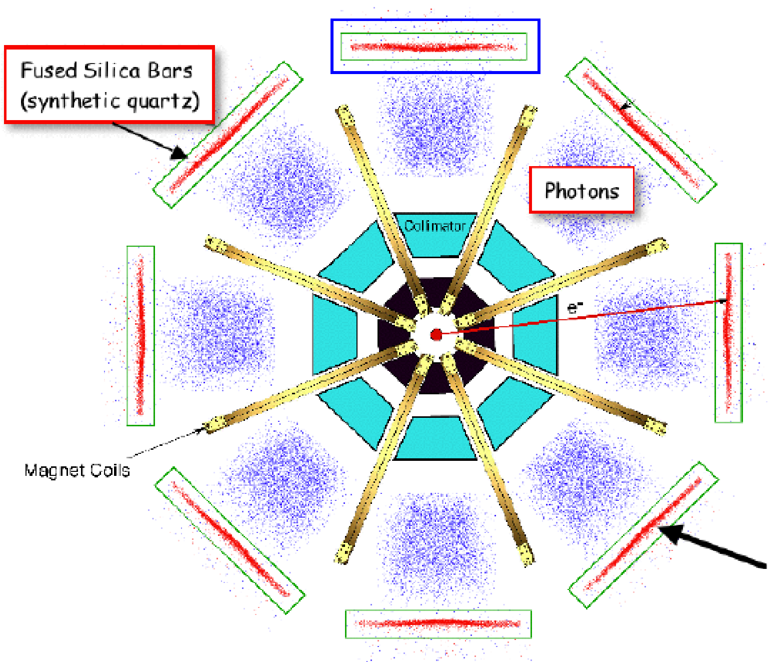
The future…



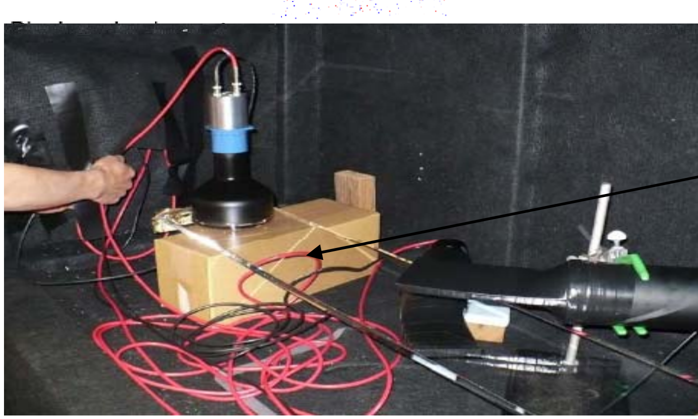
Single Experiment Sensitivity
D0 Run 1a (e)
CDF Run 1a (e+μ)
D0 Run 1 (e)
CDF Run 1 (e+μ)
CDF Run 2 (e+μ)
CDF/D0 TDR (e+μ)
D0 e only
10 MeV syst limit (solid)
0 MeV syst limit (dashed)
W Mass Precision (MeV)
Integrated Luminosity (/pb)
250
200
150
100
50
0
10
10²
10³
10⁴

QWeak Parity violation in e-p scattering at $Q^2 = 0.026$ $(GeV/c)^2$.

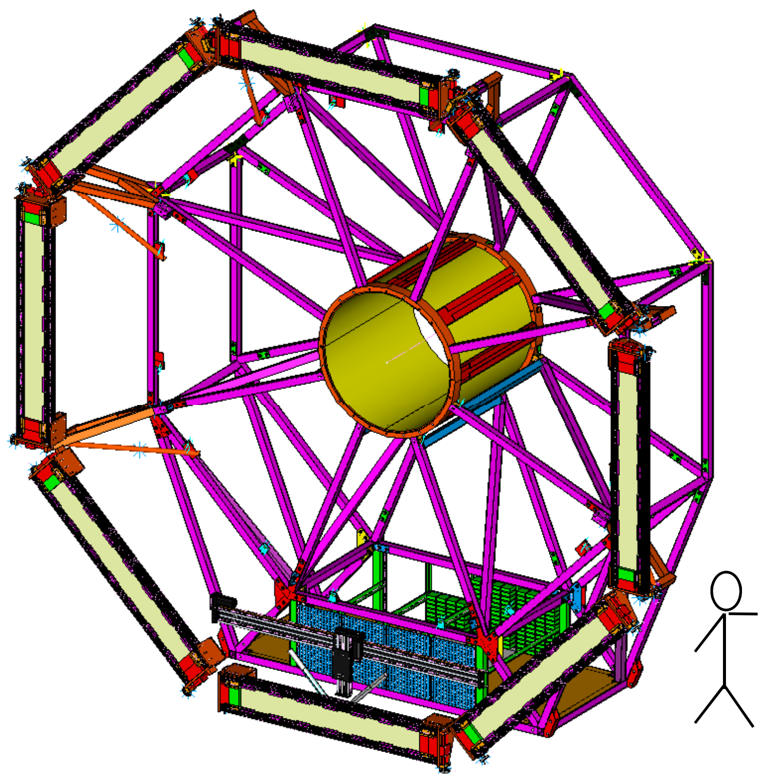
Scheduled for ~223 days at 1.165 GeV.
Start construction 2009
End data taking 2012



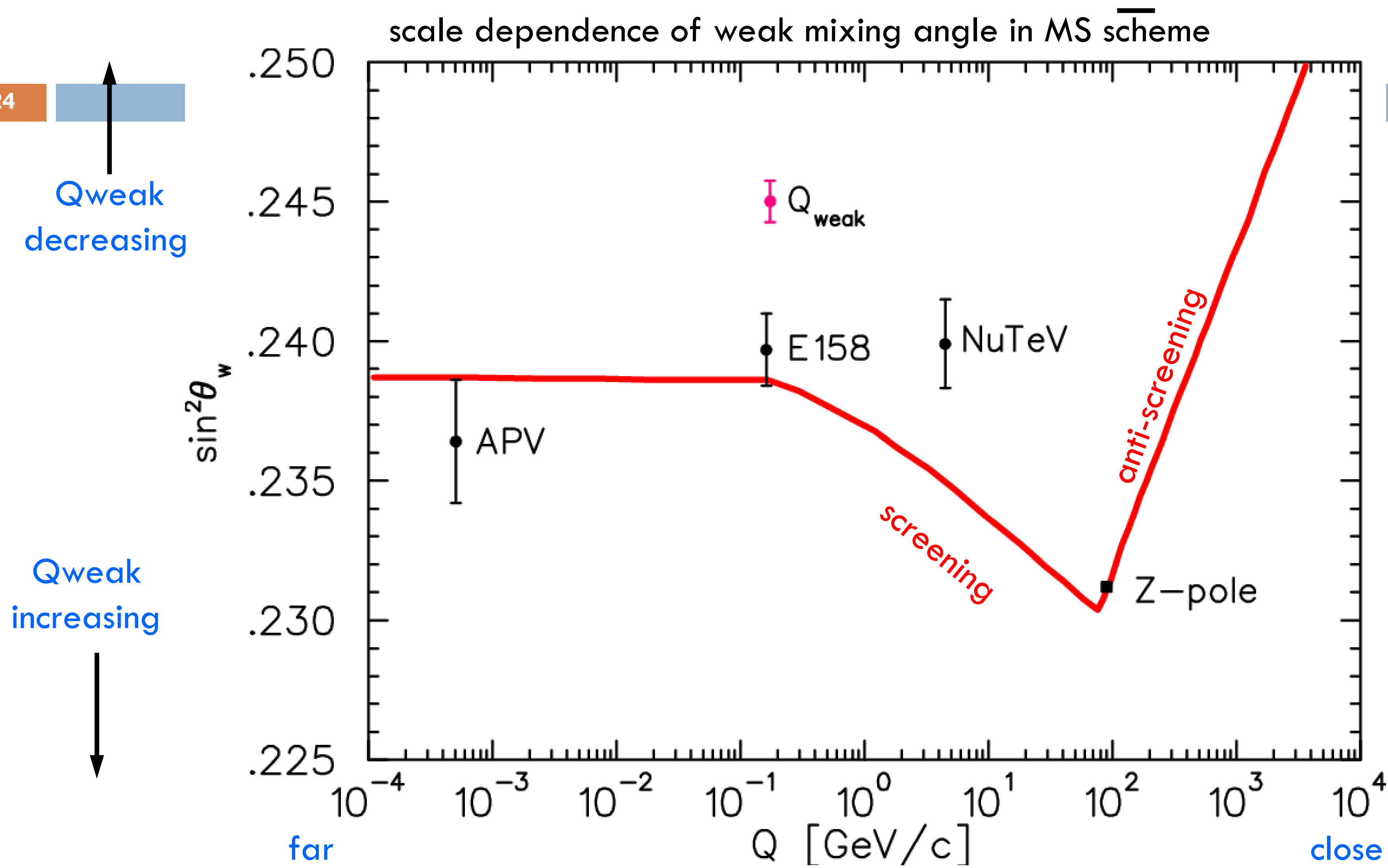
Elastically scattered electrons



Quartz bar cosmic tests



Running of $\sin^2\theta_w$

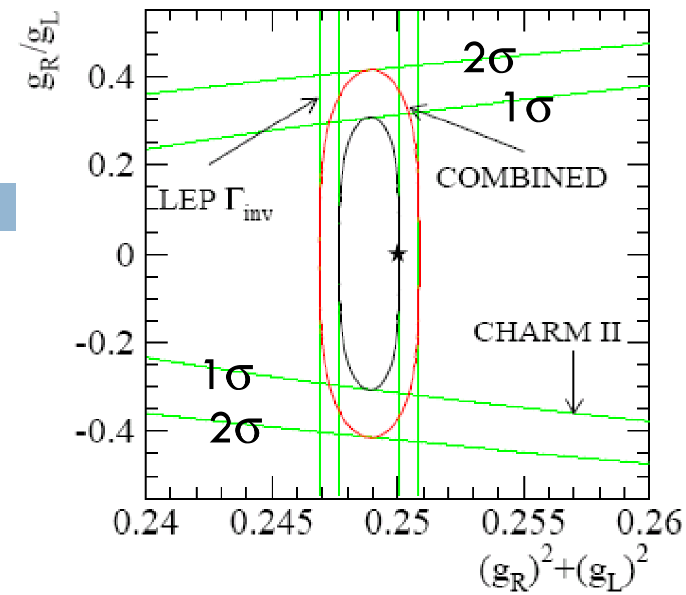


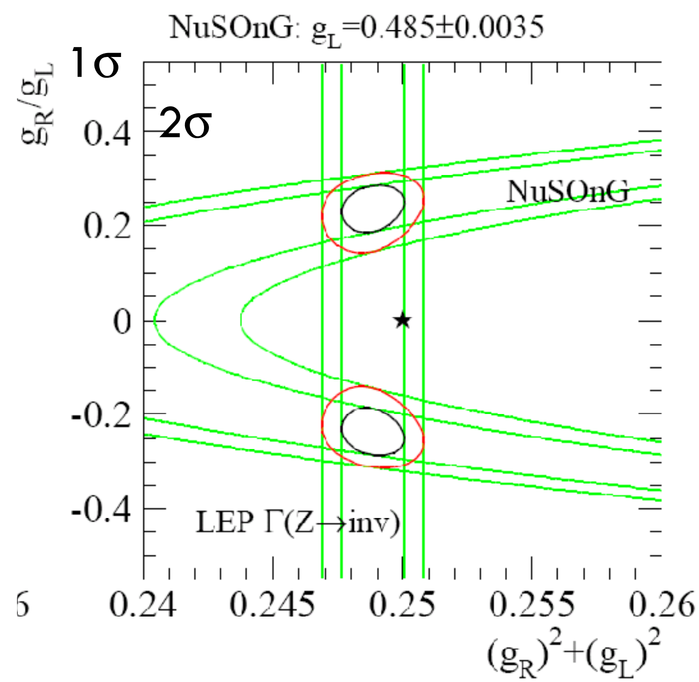
PDG 2008 Review: "Electroweak and constraints on New Physics Model" J. Erler & P. Langacker

NuSonG $\nu_e e \rightarrow \nu_e e$

Proposed 5 kT fine grained neutrino detector using a revived Tevatron neutrino beam

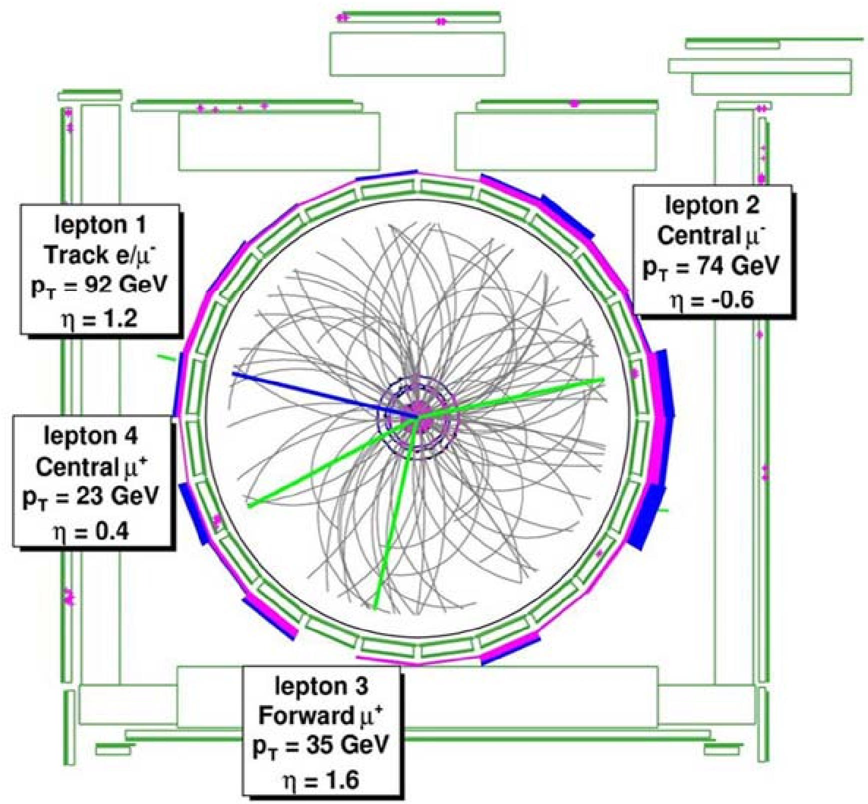
- ~1G DIS events
  - measure ρ and $\sin^2\theta_w$
  - Structure Functions
- 70K $\nu_e e \rightarrow \nu_e e$
- 7K anti-$\nu_e e \rightarrow$ anti-$\nu_e e$
  - measure ρ and $\sin^2\theta_w$
- 700K $\nu_\mu e \rightarrow \nu_e \mu$ for clean flux measurements





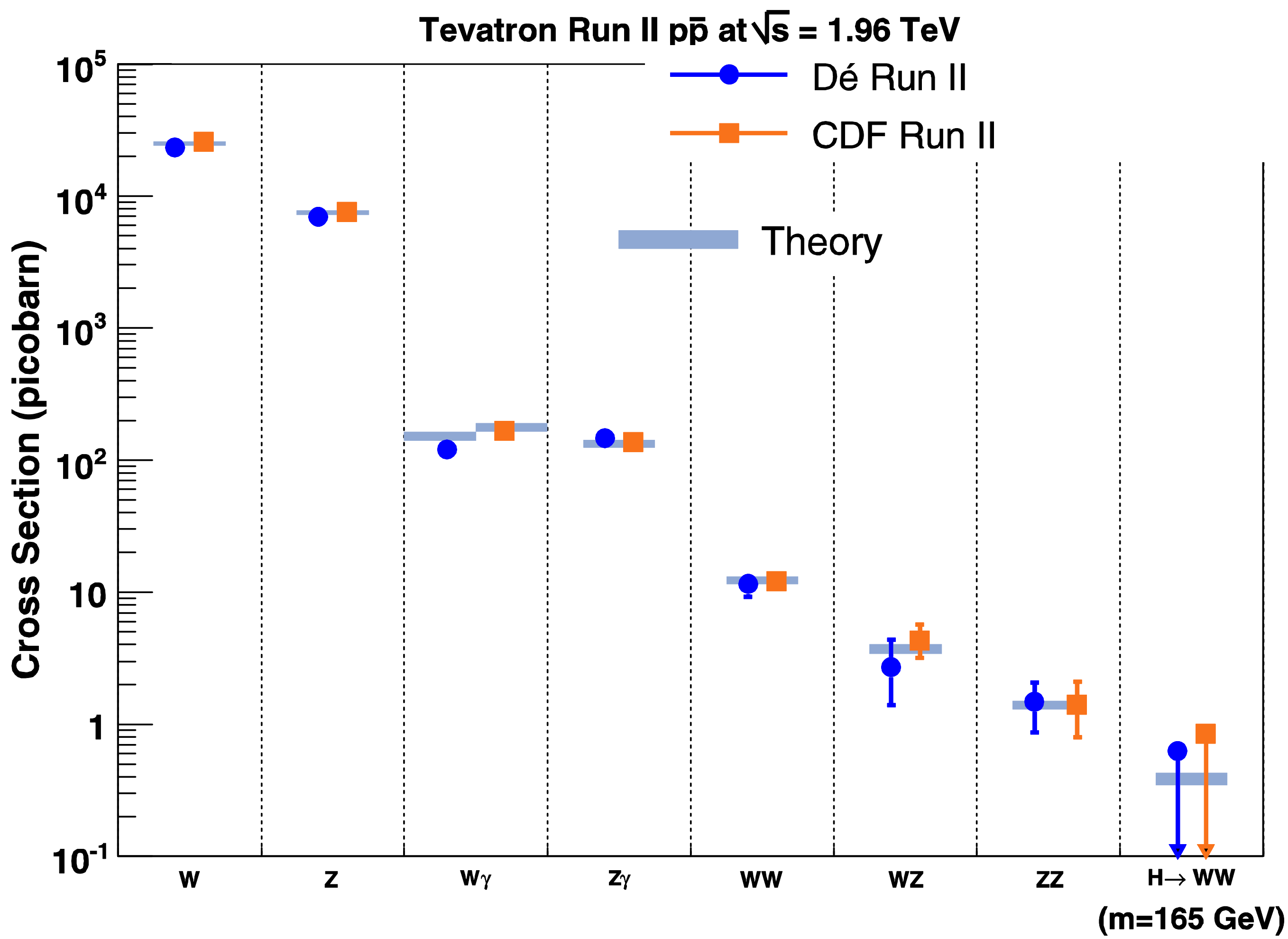
Dibosons and Anomalous Couplings

- Last year, CDF and D0 finished off the dibosons (except for HW)
- 6 ZZ → llll events between the two experiments with minimal background



CDF 3μ+t event

Summary of Bosons at the Tevatron



What to do for an encore?

- Highlights this year are
  - Use of much larger data samples
  - the difficult channels with Z→ νν and W/Z→ jj.
  - Improved limits on anomalous couplings

General Effective Lagrangian for charged (WWγ/WWZ):

$$\frac{L_{WWV}}{g_{WWV}} = ig_1^V (W_{\mu\nu}^* W^\mu V^\nu - W_\mu^* V_\nu W^{\mu\nu}) + i\kappa_V W_\mu^* W_\nu V^{\mu\nu} + i\frac{\lambda_V}{M_W^2} W_{\lambda\mu}^* W_\nu^\mu V^{\nu\lambda}$$
$$- g_4^V W_\mu^* W_\nu (\partial^\mu V^\nu + \partial^\nu V^\mu) + g_5^V \varepsilon^{\mu\nu\lambda\rho}(W_\mu^* \partial_\lambda W_\nu - \partial_\lambda W_\mu^* W_\nu) V_\rho + i\tilde{\kappa}_V W_\mu^* W_\nu \tilde{V}^{\mu\nu} + i\frac{\tilde{\lambda}_V}{M_W^2} W_{\lambda\mu}^* W_\nu^\mu \tilde{V}^{\nu\lambda}$$

EM gauge inv. ($g_1^\gamma = 1$), C and P conserving   5 couplings: κ_V, λ_V, g_1^Z

General Effective Lagrangian for neutral (ZZγ/Zγγ):

$$L_{\gamma ZV} = -ie\left[\left(h_1^V F^{\mu\nu} + h_3^V \tilde{F}^{\mu\nu}\right) Z_\mu \frac{(\Box + m_V^2)}{M_Z^2} V_\nu + \left(h_2^V F^{\mu\nu} + h_4^V \tilde{F}^{\mu\nu}\right) Z^\alpha \frac{(\Box + m_V^2)}{M_Z^4} \partial_\alpha \partial_\mu V_\nu\right]$$

CP conserving → $h_{3,4}^V$ couplings (V = γ, Z)

SM : $g_1^Z = \kappa_V = 1,\ \lambda_V = h_{3,4}^V = 0$ **SM Deviations :** $\Delta g_1^Z = g_1^Z - 1,\ \Delta\kappa_V = \kappa_V - 1$; $\Delta\lambda_V = \lambda_V - 0,\ \Delta h_{3,4}^V = h_{3,4}^V - 0$

$\Delta \neq 0$
ANOMALOUS COUPLINGS

Charged Triple Gauge Couplings

Probed by ***WW, WZ, and Wγ production***

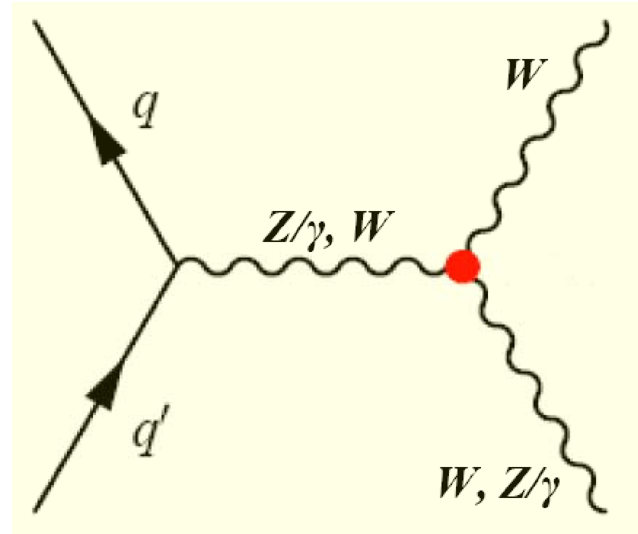
General Lagrangian has **14** parameters

Assume EM gauge invariance and C and P conservation

⇒ 5 TGC parameters:

$g^1_Z, \kappa_\gamma, \kappa_Z, \lambda_\gamma, \lambda_Z$

g^1 and κ are 1 in the SM, the rest are zero



Neutral Triple Gauge Couplings

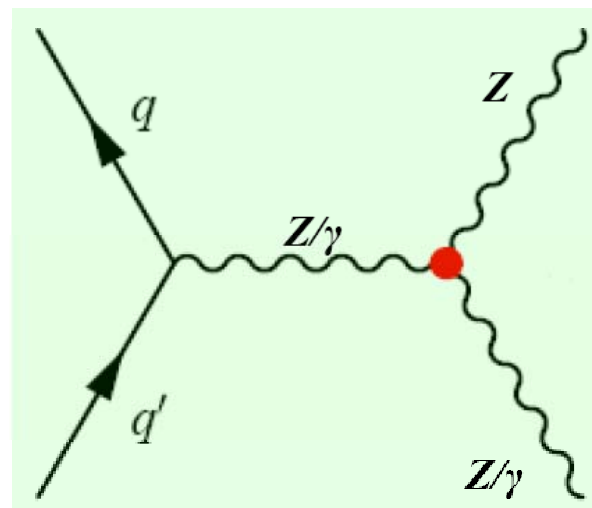
Probed by ***ZZ and Zγ production***

General Lagrangian has **8** TGC parameters

Assume CP conservation

⇒ 4 non-SM TGC parameters:

$h^3_\gamma, h^3_Z, h^4_\gamma, h^4_Z$ **all 0 in SM**



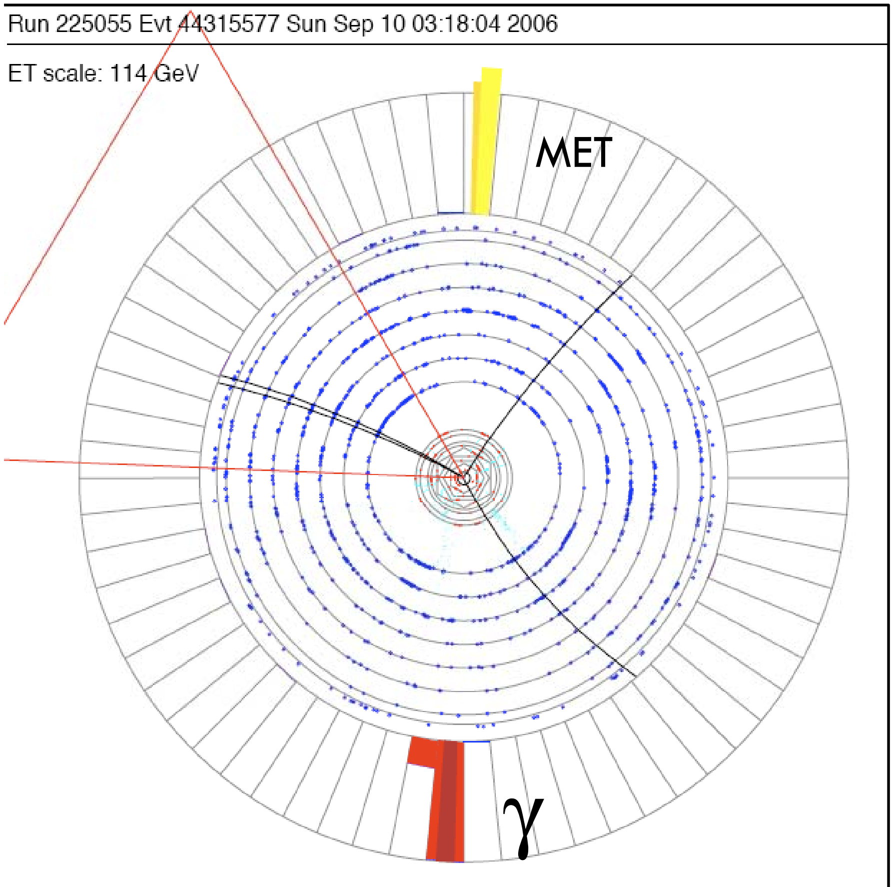
Strategies

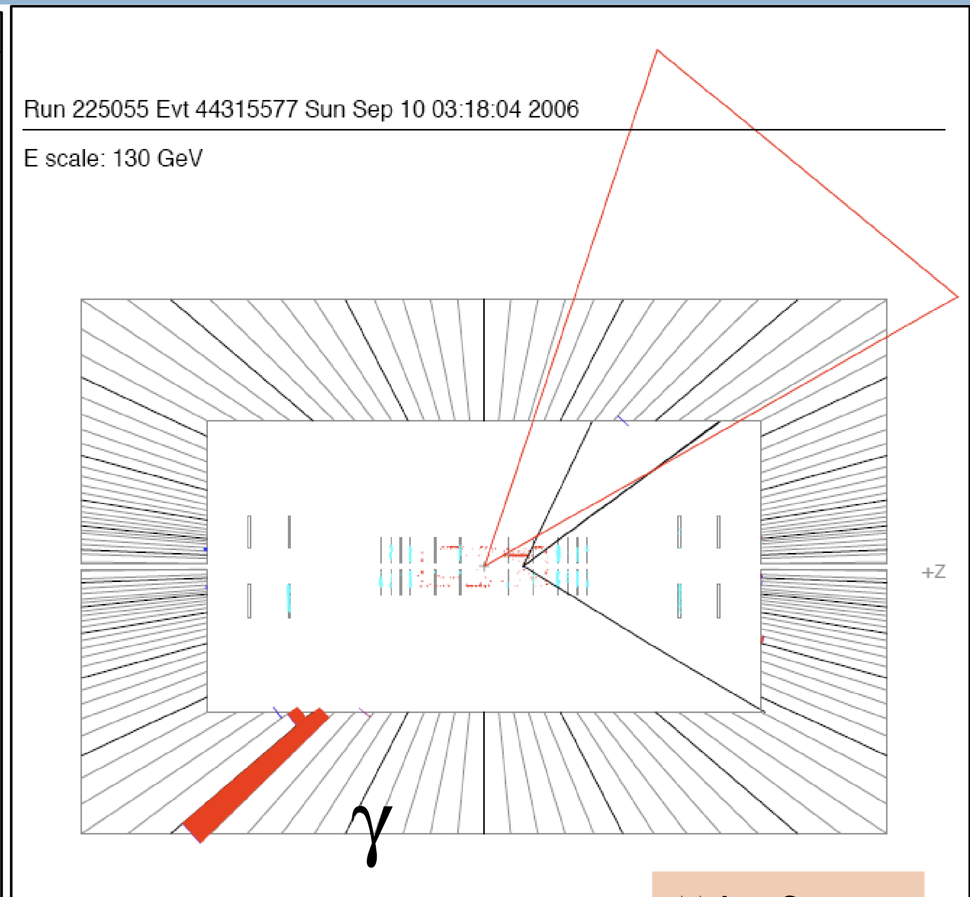
- These are very rare processes
- First do pure leptonic final states
  - Very small statistics
  - Very low background

☑Wγ → lνγ
☑Zγ → ll γ
☑WW → lνlν
☑WZ → lνll
☑ZZ → llll observation by D0 and CDF in 2008

- New! 3-5 times more data analyzed
- New! Can use more difficult signatures to get more statistics
  - Z+γ → vvγ is harder
  - W+W/Z →lvjj is really hard
  - Z + W/Z →vvjj is really really hard

ννγ candidate event

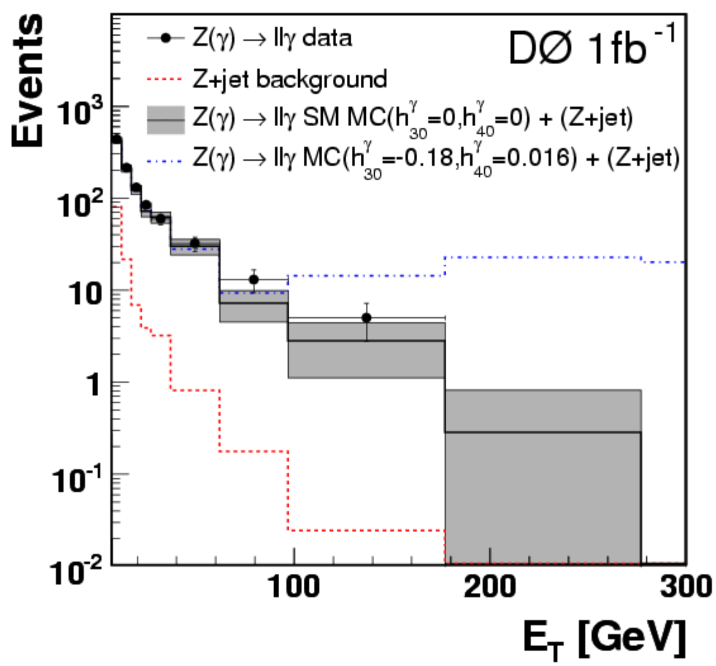




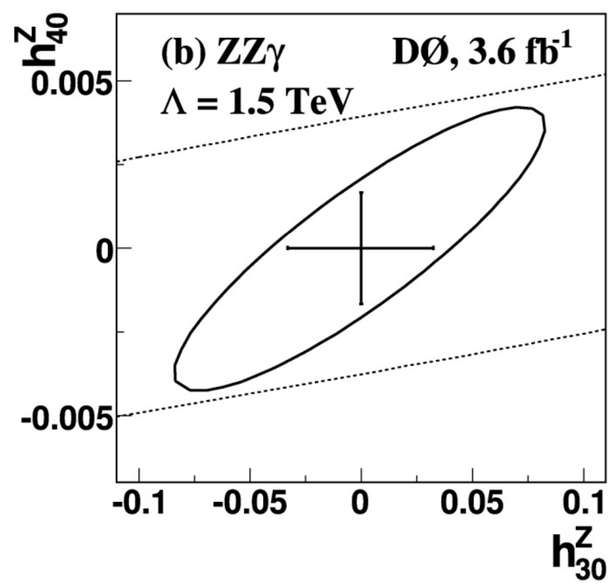
Mike Strang
Thursday
EWK II

$Z\gamma \rightarrow \nu\nu\gamma$

Select interactions with large, significant Missing transverse momentum



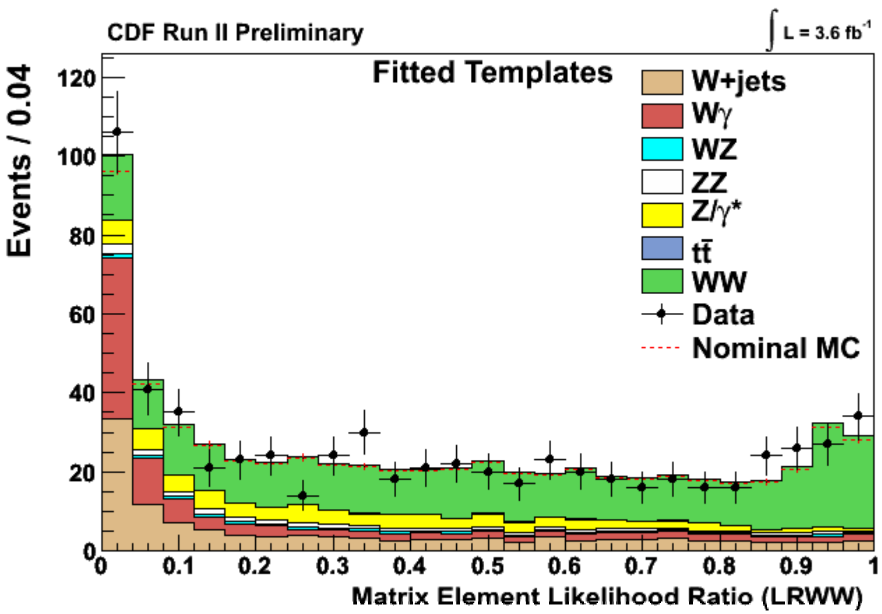
$Z\gamma \rightarrow \nu\nu\gamma$ avoids radiation off of the Z!

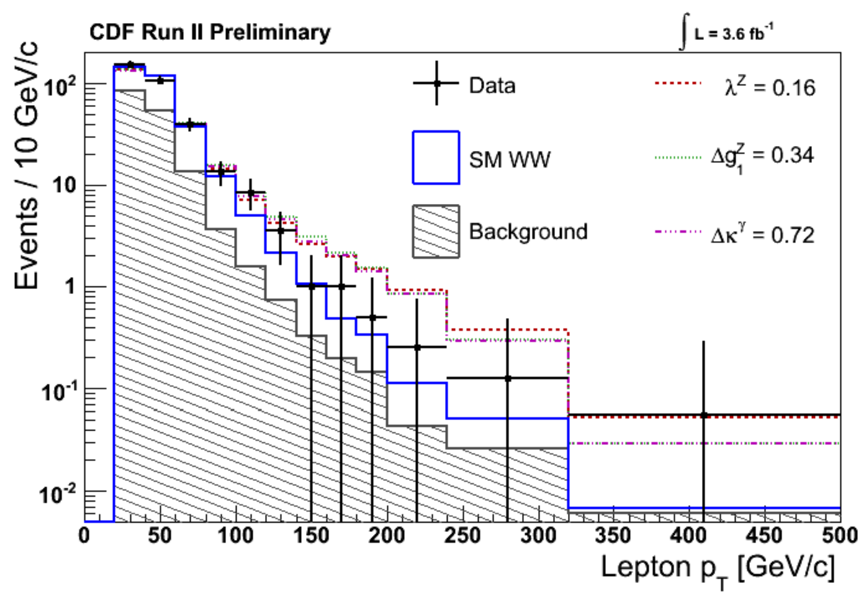


Limits on the anomalous couplings of Z's to photons. The standard model wants 0

CDF WW→ lνlν with 3.6 fb^{-1}

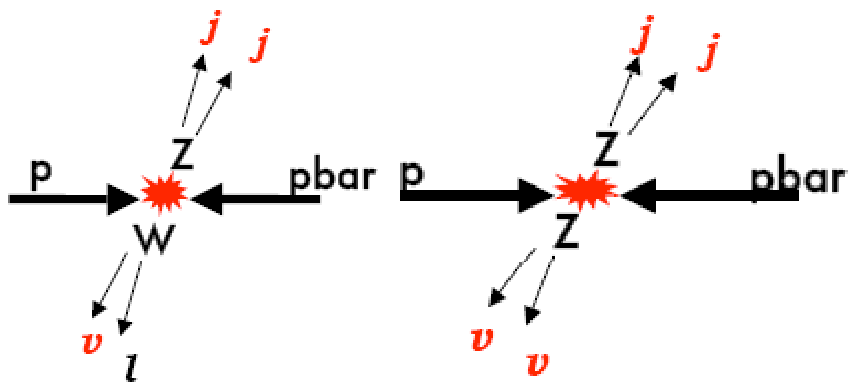
- Use matrix method likelihood method to assign probability to signal/background based on event kinematics





$$\sigma(p\bar{p} \rightarrow WW) = 12.1 \pm 0.9(\text{stat}) \ ^{+1.6}_{-1.4}(\text{syst}) \ \ [\text{pb}]$$

CDF Observation of VV→ MET+jj

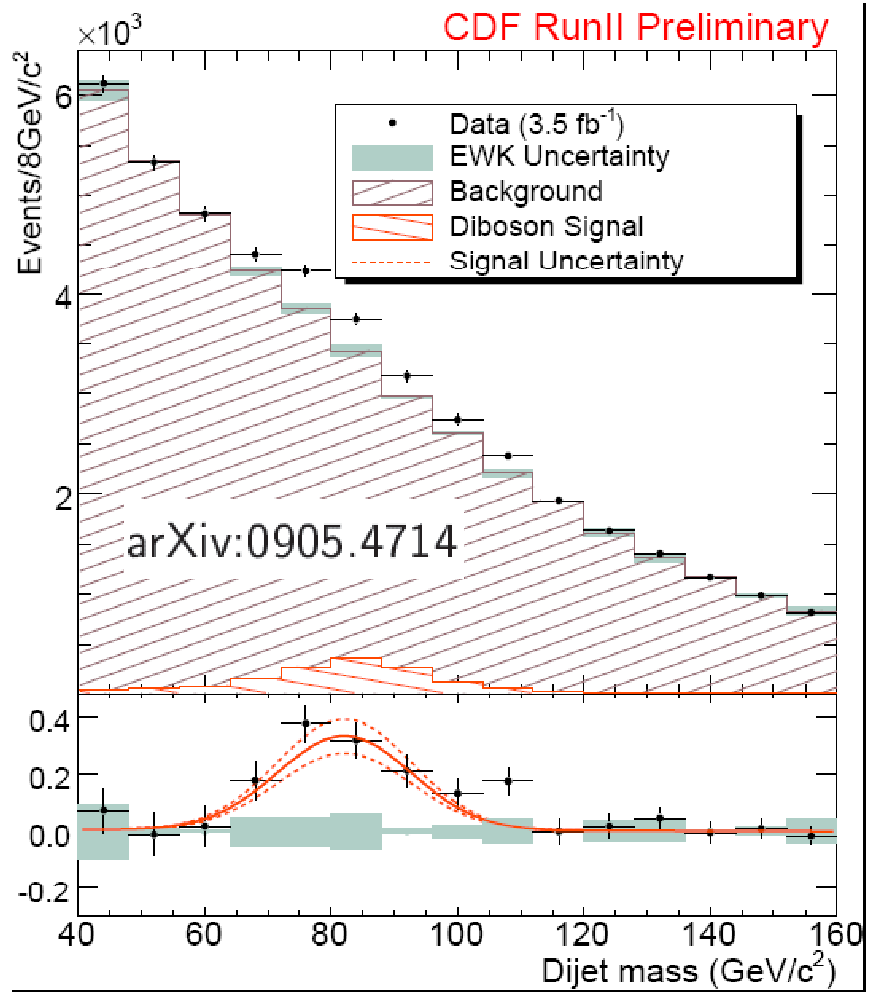


Events with 2 jets and MET > 60 GeV and high MET significance

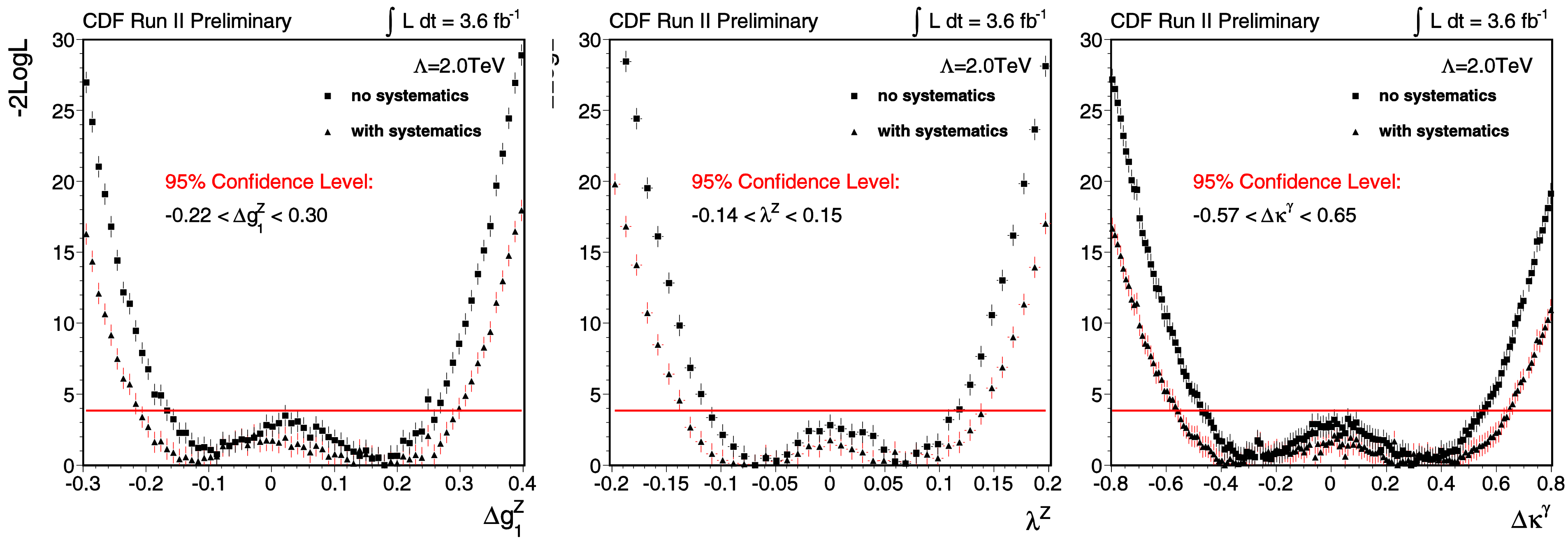
18±2.8(stat)±2.4(syst)±1.1(lumi) pb
16.8±0.5 pb (SM)

arXiv:0905.4714

Eric James
Thursday
EWK III

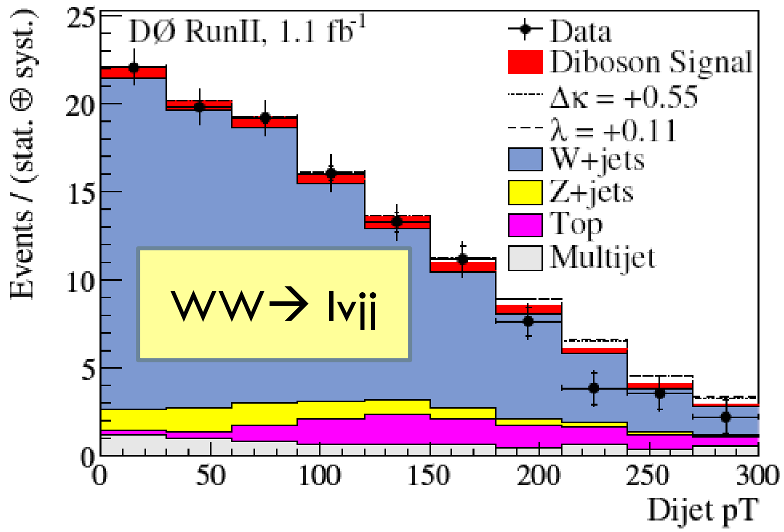


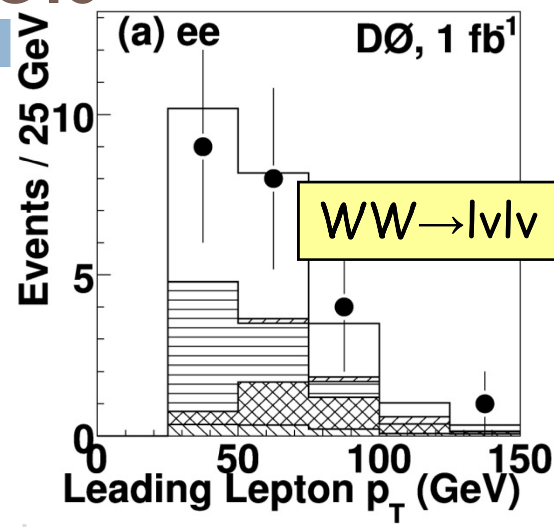
Charged Anomalous Couplings



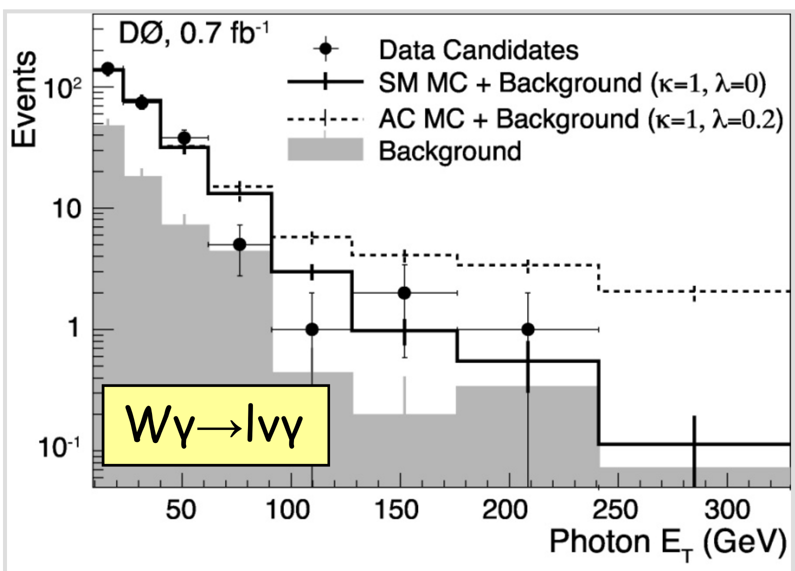
Set limits on charged Anomalous couplings

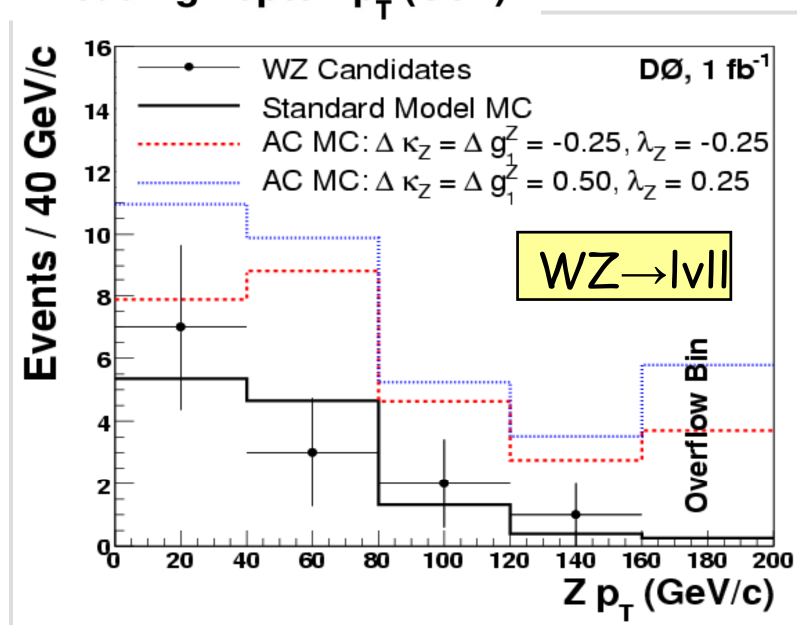
D0 – set charged TGC limits using pt in 4 channels



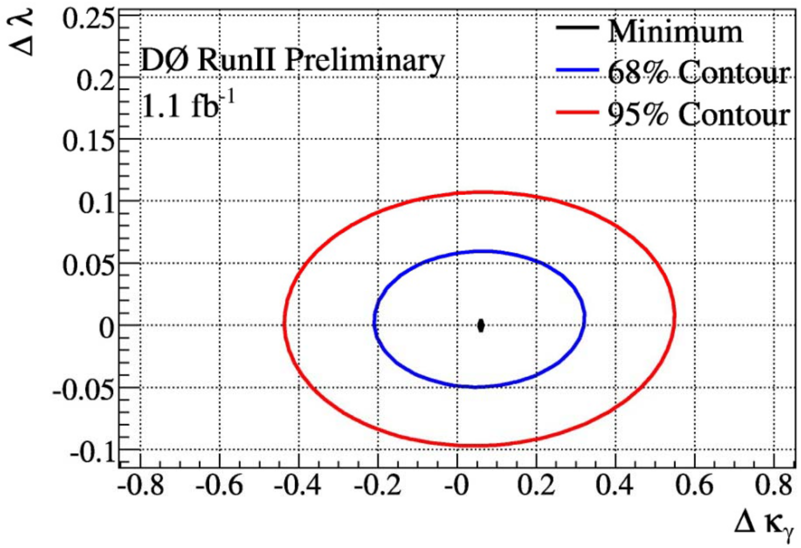


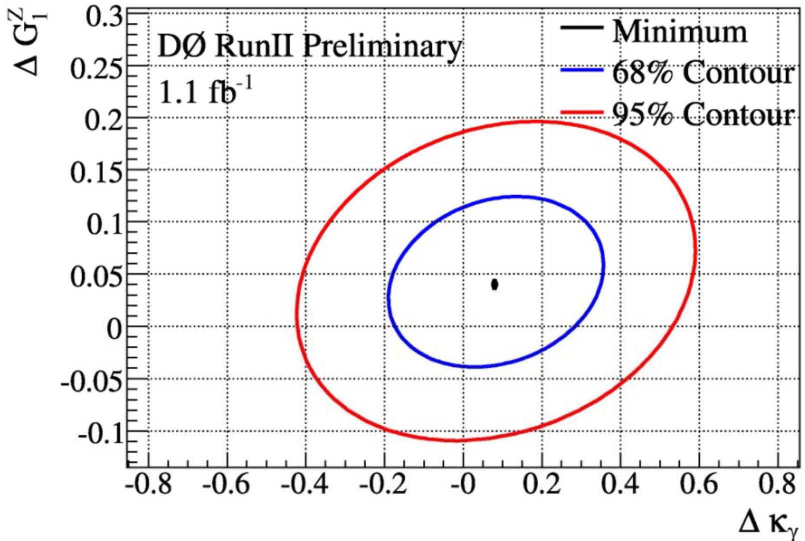
Jadranka Sekaric
Thursday
EWK III

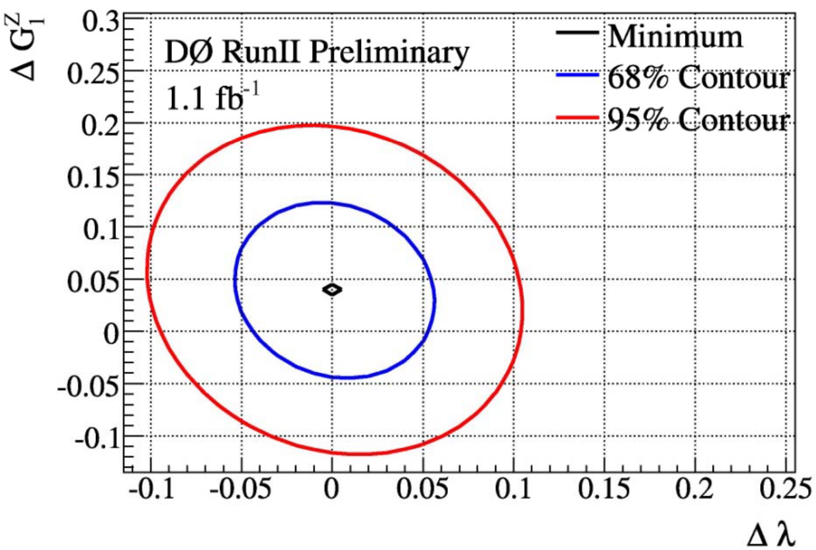




D0 limits on anomalous couplings from Wγ, WW, WZ





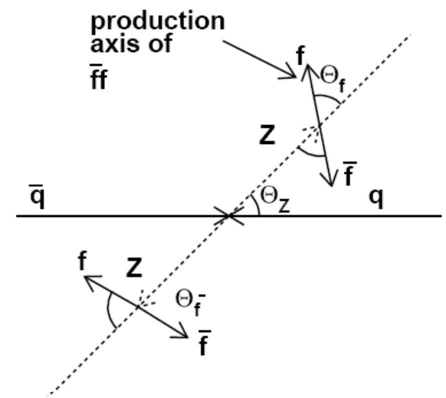


Can be interpreted as measurements of the magnetic dipole and quadrupole moments.

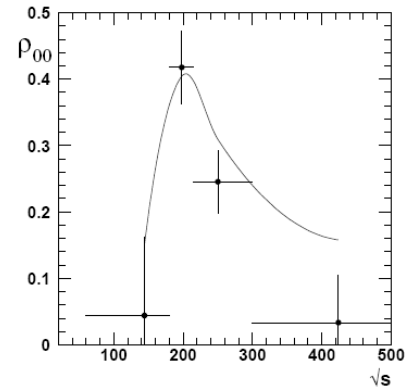
$$\mu_W = (1+\kappa+\lambda)\frac{e}{2M_W} = 2.02^{+0.08}_{-0.09}\ \frac{e}{2M_W}$$

$$q_W = -(\kappa-\lambda)\frac{e}{M_W^2} = 1.00 \pm 0.09\ \frac{e}{M_W^2}$$

Prospects for the future



- D0 and CDF can anticipate 3-10 times more data per channel
- Combining channels and experiments will increase the TGC sensitivity by a factor of 3-5.

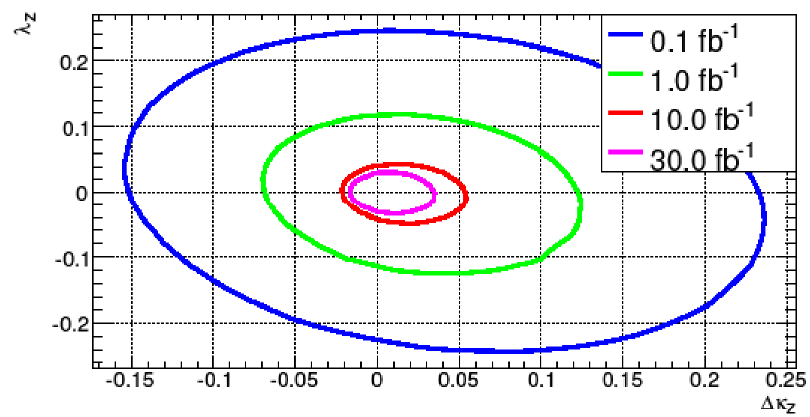


ZZ polarization

100 fb^{-1}

(Eyal Brodet ATLAS)

- LHC experiments have 10 times the cross section → 10 fb^{-1} of data → factor of 100 in statistics and 10 in sensitivity relative to current Tevatron.
- 200 fully reconstructed ZZ events in first 10 fb^{-1} !!

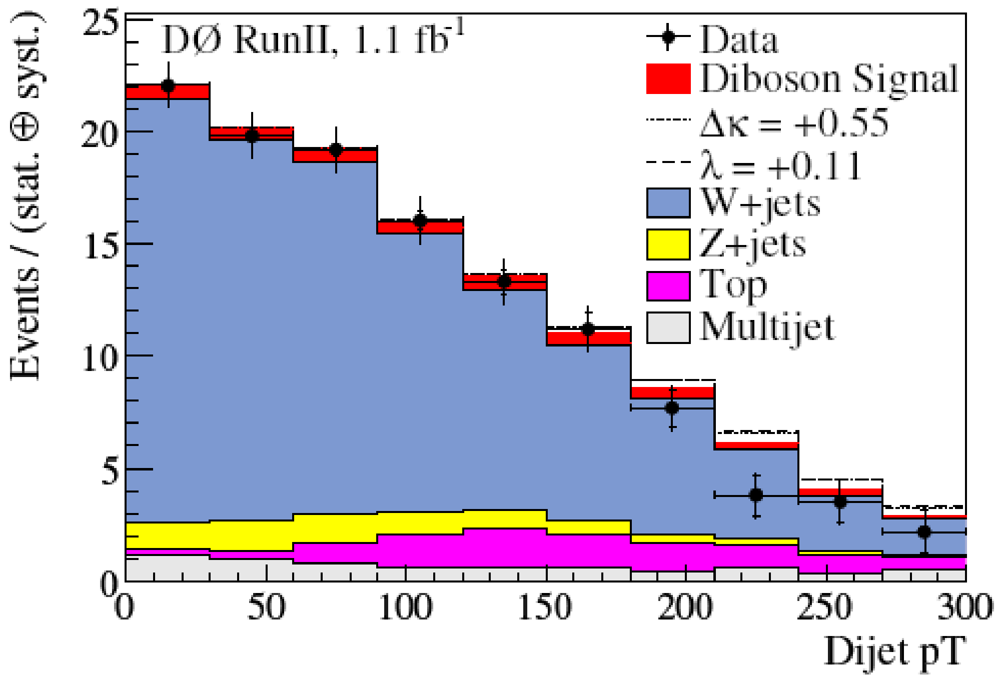


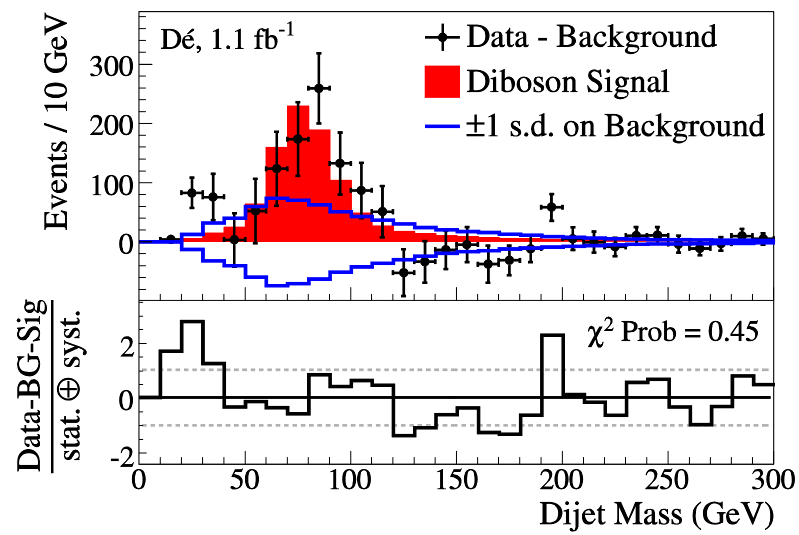
ATLAS PROJECTIONS from M_T^{WW}

Electroweak summary

- Major progress
- Precision EWK
  - W mass precision on track for 25 MeV/expt at Tevatron – maybe 10 MeV at LHC!
  - We are at the beginning of a new generation of measurements of $\sin^2\theta_W$ at colliders and fixed target
- DiBosons
  - All diboson channels seen even in hadronic final states
  - LHC will have enough statistics to do precision measurements of couplings and event kinematics very soon!

D0 WW+WZ→ lvjj





$$\sigma^{Meas}_{WW+WZ} = 20.2 \pm 4.4(stat + syst) \pm 1.2(lumi) \quad pb$$

86% W+jets

3% WW+WZ signal

Phys. Rev. Lett. 102 161801 (2009)

BACKUP slide

Improved Lepton Selection

- Lepton acceptance is a key in final states with 3 or more leptons!
- Try to use all tracks and electromagnetic objects found
- Use as much information as possible for each candidate

Electrons:

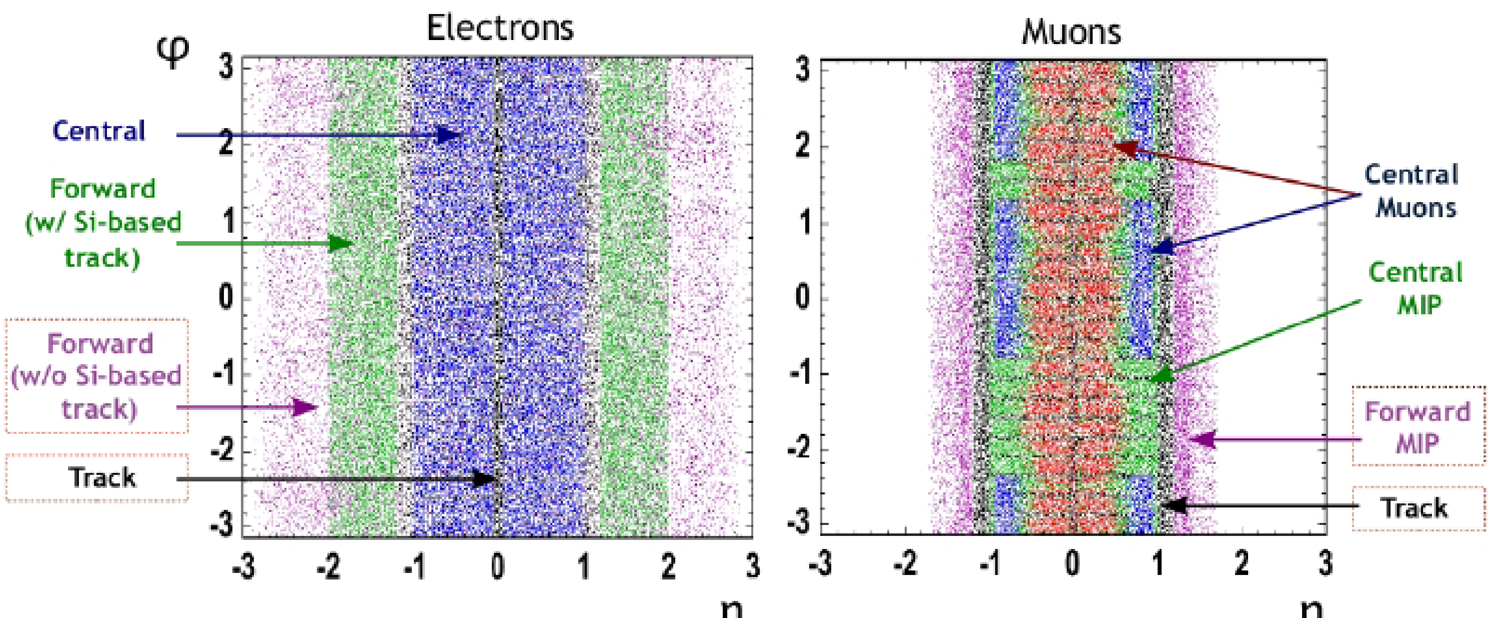
- Central calorimeter
- Forward calorimeter
- w/ or w/o Si-based track

Muons:

- Central muons with matched muon chamber hits
- (MIP): central and forward region

Tracks:

- Fill in regions not fiducial to calorimeters
- No distinction between e and μ.



In a perfect world, the

SU(2) fields are W_1, W_2 and W_3 with coupling g

U(1) field is B with coupling g'

But our world there is a Higgs field that gives particles mass - in doing so it mixes the SU(2) and U(1) to form a massless photon field A with coupling e and 3 heavy weakly interacting fields W^+, W^- and Z^0

The parameter θ_W represents the degree of mixing.

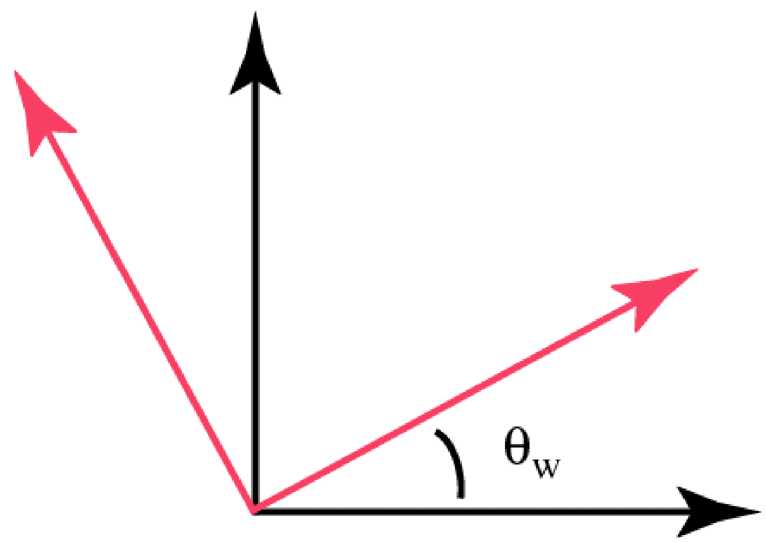
$$\theta_W \equiv \tan^{-1}(g'/g)$$

$$W^{\pm} \equiv (W^1 \mp iW^2)/\sqrt{2}$$

$$A \equiv B\cos\theta_W + W^3 \sin\theta_W$$

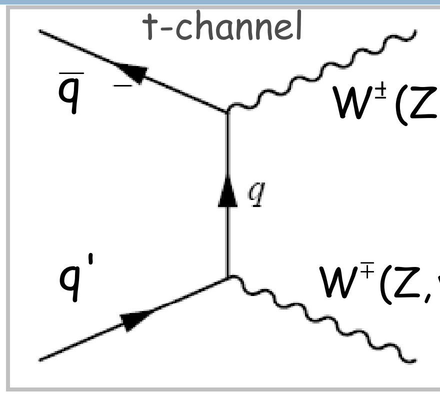
$$Z \equiv -B\sin\theta_W + W^3\cos\theta_W$$

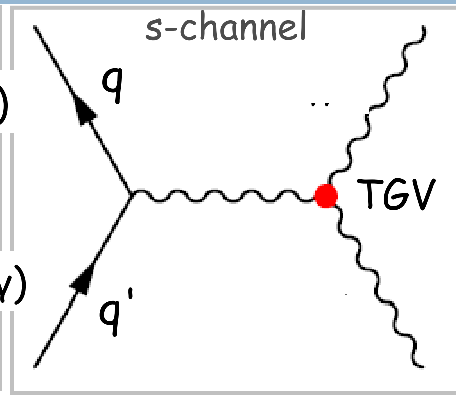
$$e = g\sin\theta_W \qquad \cos\theta_W = \frac{M_W}{M_Z}$$



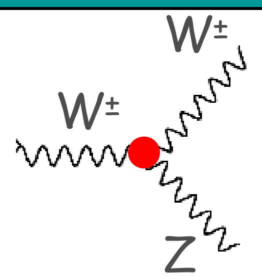
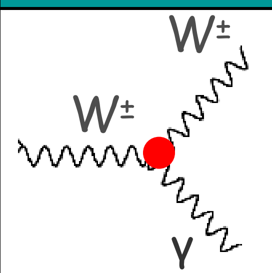
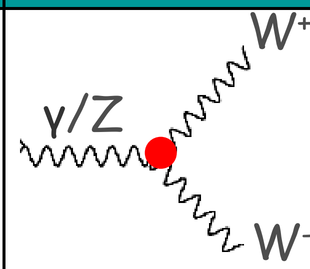
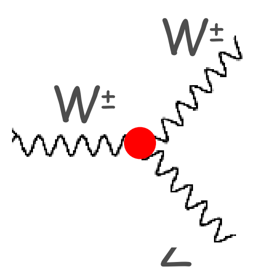
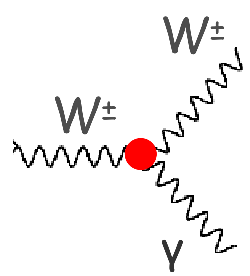
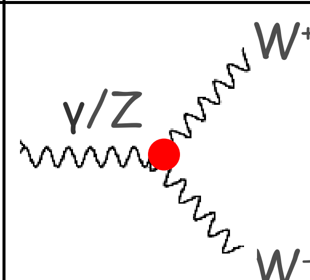
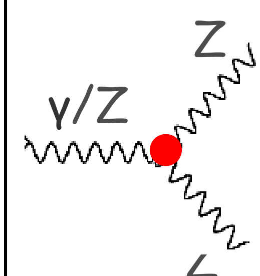
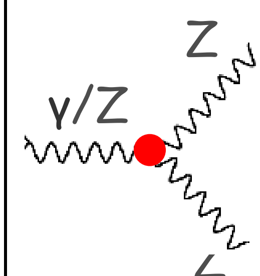
Anomalous couplings

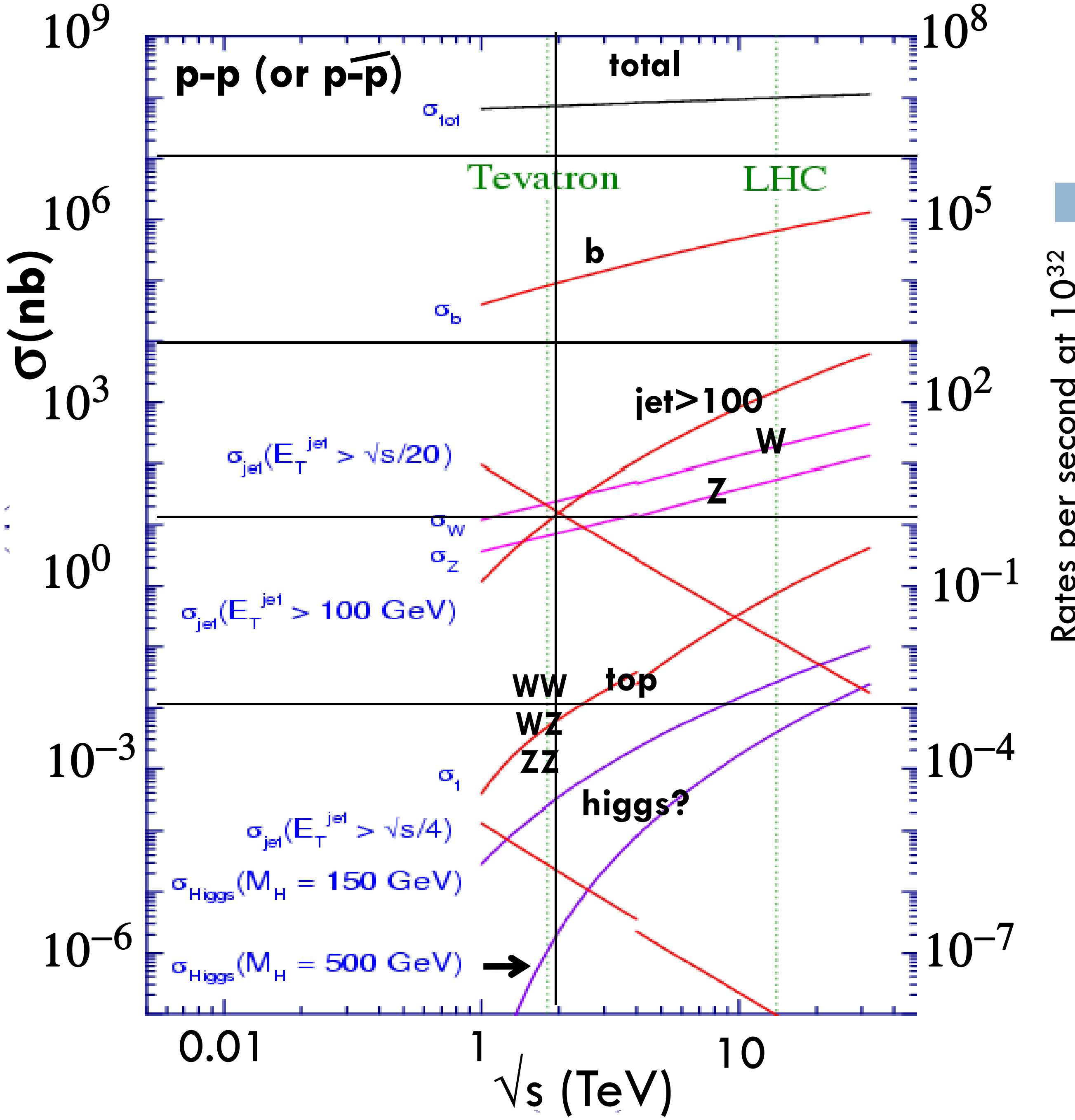
t – channel dominates total cross section





s – channel sensitive to TGCs due to the existence of TG vertex

Final State	WZ	Wγ	WW	ZZ	Zγ
SM				Highly suppressed in the SM	
Non-SM					


p-p (or p-p̄)
total
σ_{tot}
Tevatron
LHC
b
σ_b
jet>100
W
Z
$\sigma_{jet}(E_T^{jet} > \sqrt{s}/20)$
σ_W
σ_Z
$\sigma_{jet}(E_T^{jet} > 100$ GeV)
WW
WZ
ZZ
top
σ_t
higgs?
$\sigma_{jet}(E_T^{jet} > \sqrt{s}/4)$
$\sigma_{Higgs}(M_H = 150$ GeV)
$\sigma_{Higgs}(M_H = 500$ GeV)
σ(nb)
10^9
10^6
10^3
10^0
10^{-3}
10^{-6}
10^8
10^5
10^2
10^{-1}
10^{-4}
10^{-7}
Rates per second at 10^{32}
0.01
1
10
√s (TeV)