Electroweak Physics at Tevatron

T. Yasuda, Fermilab

- Tevatron Collider Run II Goals
- D0 and CDF Detectors
- Constraining Higgs Mass
  - Electroweak Higher Order Corrections
- Top Quark Mass
- W Mass
- $\sin\theta_W$
- Γ_W
- Triple Gauge Boson Couplings
- σ_W as a luminosity monitor
- Concluding Remarks

Tevatron Collider Run II

- More bunches in Tevatron
- More pbars in a bunch
- Higher energy
- Main Injector
- Recycler Ring

	Run Ib	Run IIa	Run IIb
Bunches	6x6	36x36	140x105
Energy(GeV)	900x2	980x2	980x2
Protons/bunch	2.3×10^{11}	2.7×10^{11}	2.7×10^{11}
Antiprotons/bunch	5.5×10^{10}	3.0×10^{10}	1.0×10^{11}
Pbar production rate(hr^{-1})	6.0×10^{10}	1.0×10^{11}	5.2×10^{11}
Crossing angle(μrad)	0	0	136
Luminosity($cm^{-2}sec^{-1}$)	0.16×10^{32}	0.86×10^{32}	5.2×10^{32}
Int. Luminosity(pb^{-1}/week)	3.2	17.3	105
Bunch spacing(nsec)	~3500	396	132
Interactions/crossing	2.5	2.3	4.8

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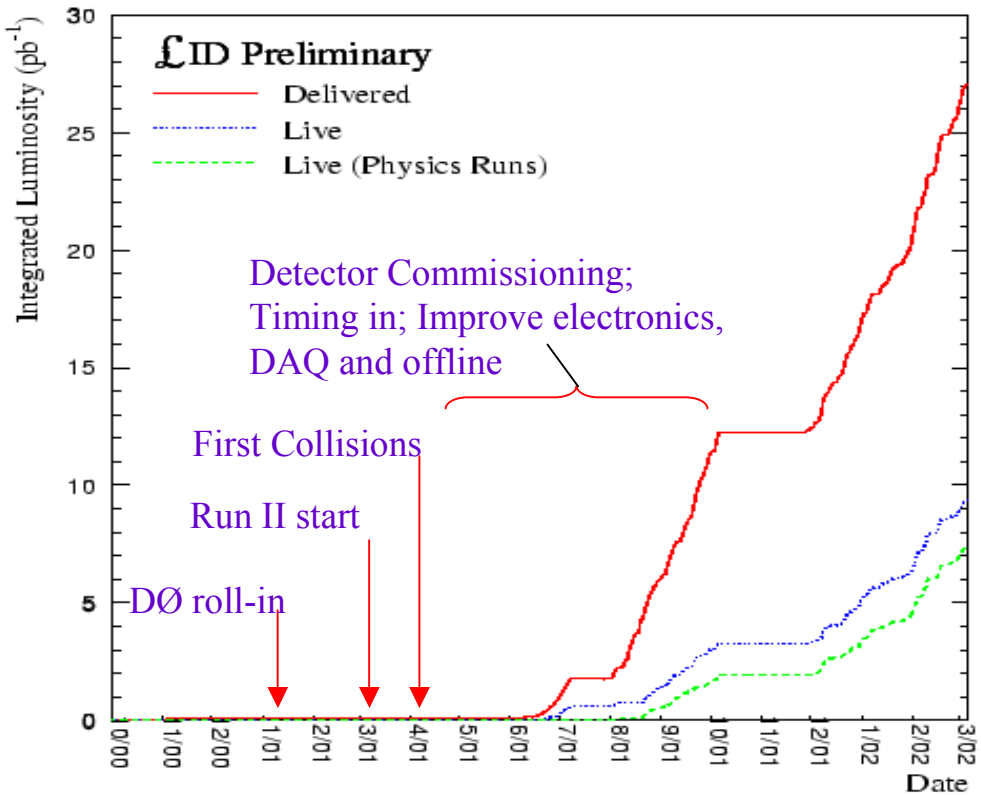
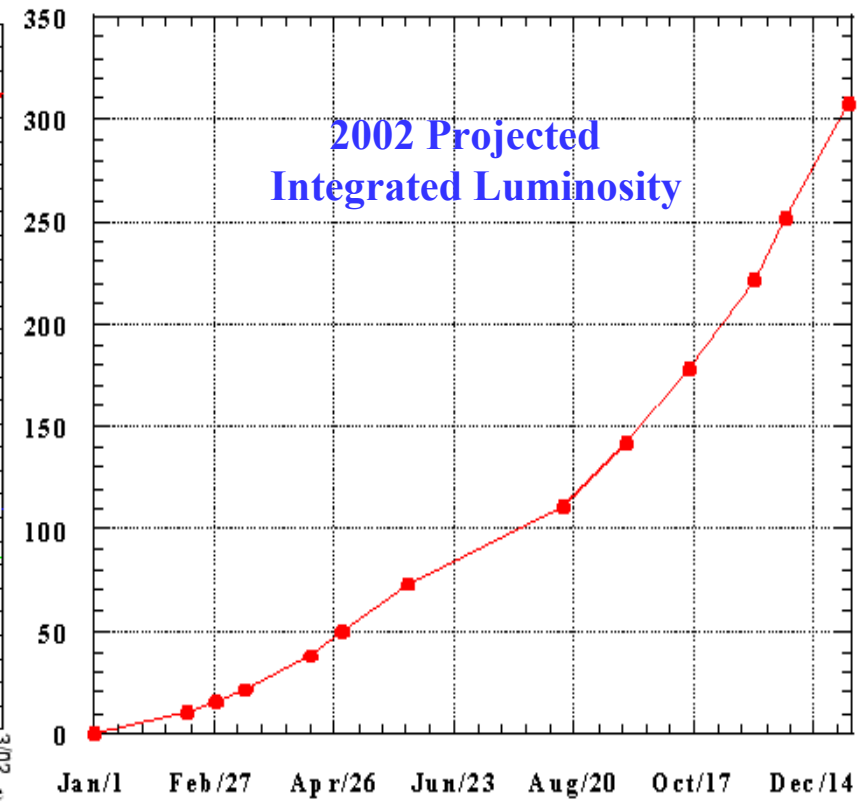
Integrated Luminosity





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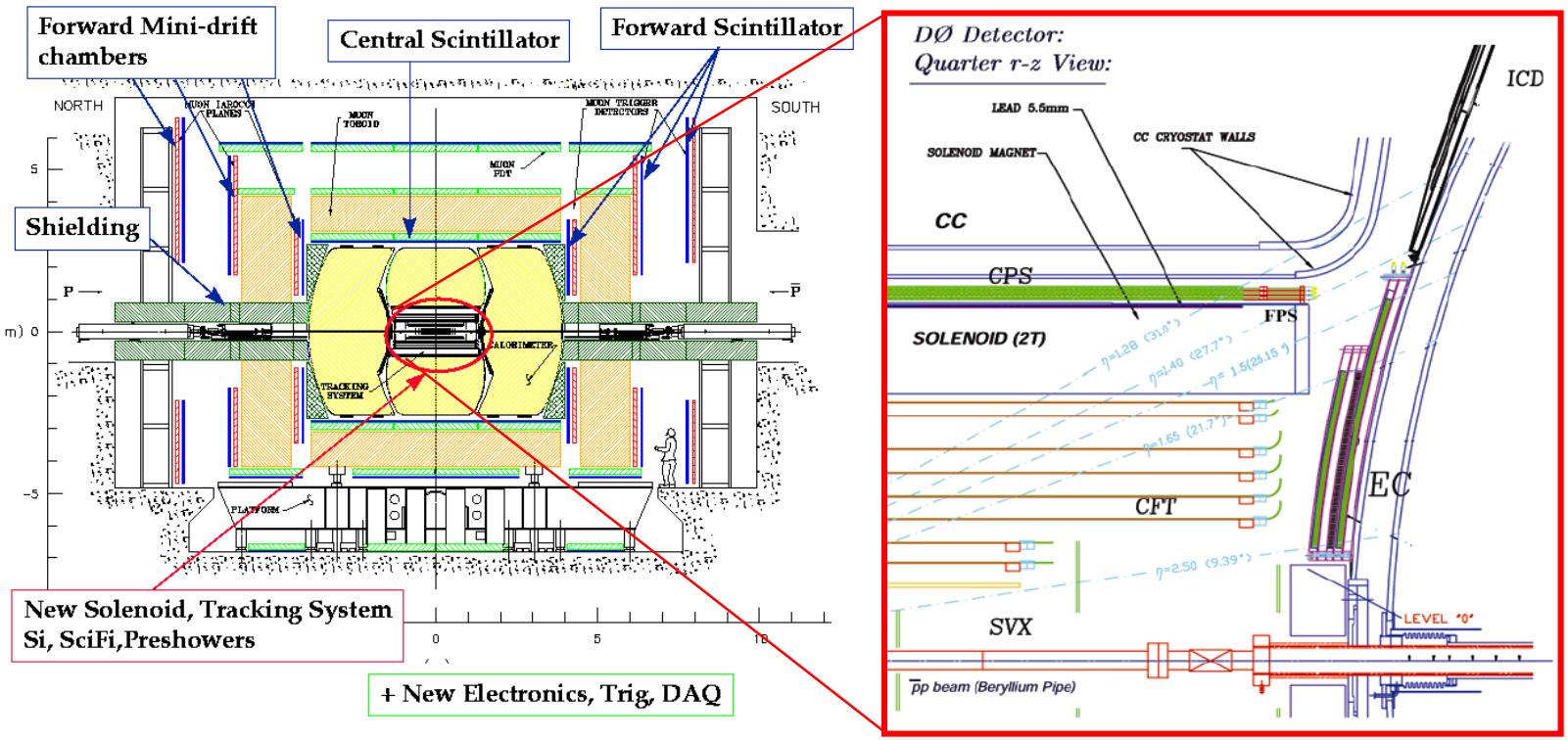
Run II D0 Detector



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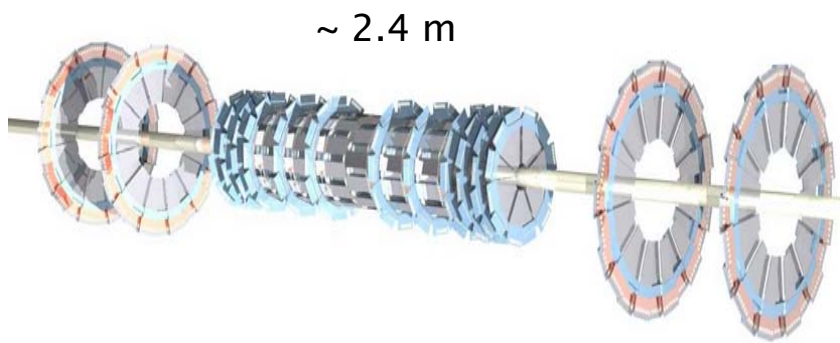
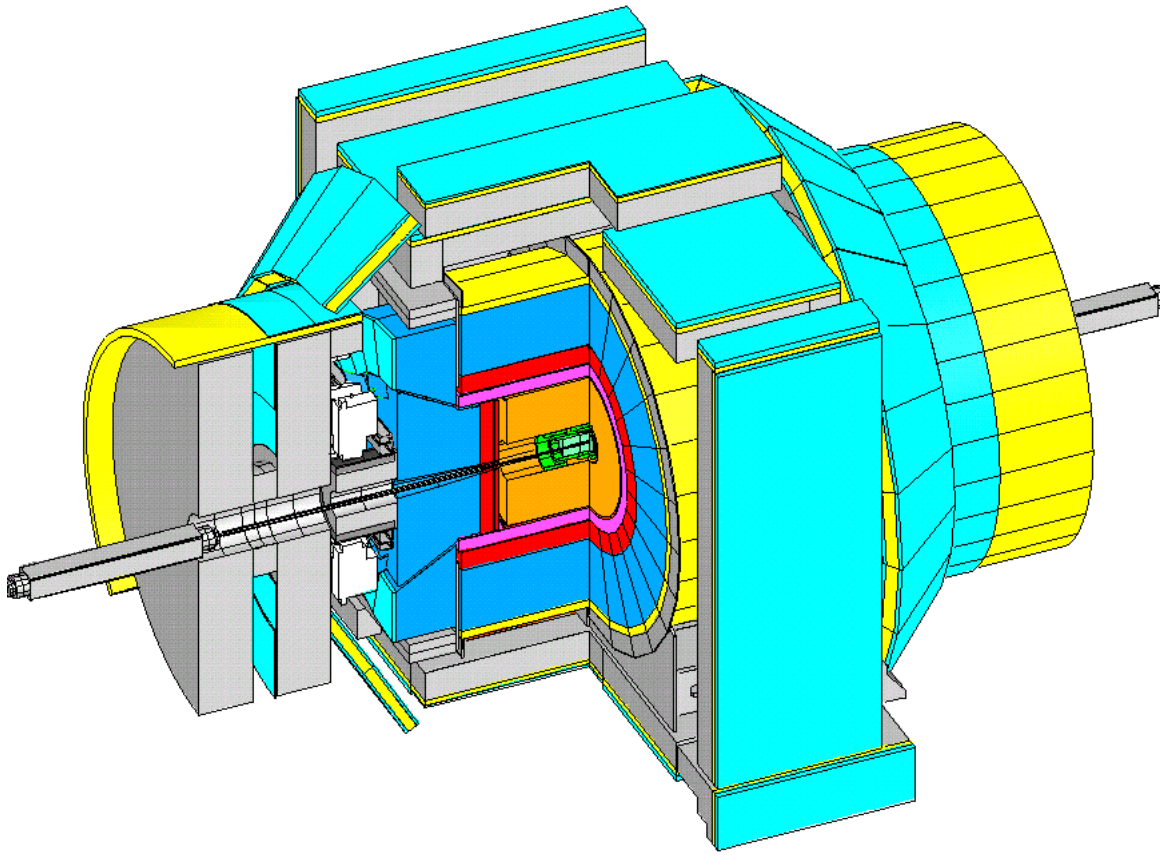
Run II D0 Detector

- New magnetic inner tracking system
  - 2T superconducting solenoid
  - 800k channel silicon strip detector
  - scintilating fiber tracker
  - preshower detectors
- Faster calorimeter readout electronics for shorter bunch spacings
- Upgraded muon system
  - new forward muon detectors
  - additional scintillation counters in central
  - Increased shielding
- Forward proton detector
- New trigger & DAQ system
  - Silicon Track Trigger
  - 10 kHz accept rate at L1
  - 1 kHz accept rate at L2
  - 50 Hz accept rate at L3



Run II CDF Detector



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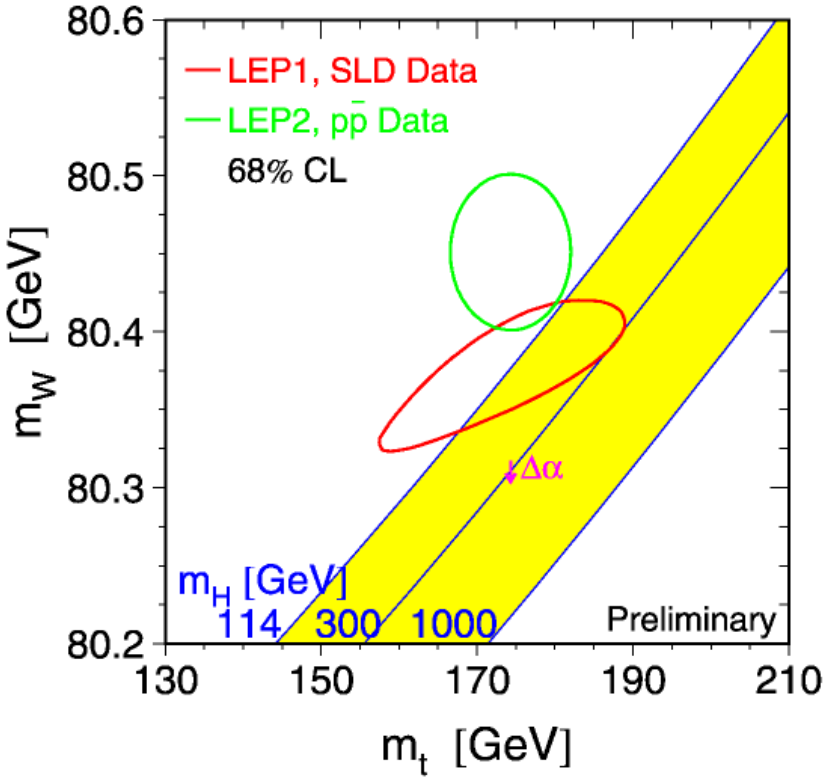
Run II CDF Detector

- New Silicon Microstrip Tracker
  - layer 00
  - SVXII detector
  - Intermediate Silicon Layers
- New Central Outer Tracker
  - 96 wire planes
  - 0.88 cm drift cells
  - 100 ns drift time
- New Time-of-Flight detector
  - TOF resolution ~100 ps
  - improve $\pi/k/p$ separation
- New Plug Calorimeters
  - scintillating tile calorimeter
- Silicon Vertex Trigger at L2
  - Triggering on impact parameters
- Cerenkov Luminosity Counter
- New trigger/DAQ system
  - $<$50 kHz accept rate at L1
  - 300 Hz accept rate at L2

Constraining Higgs Mass

- One of the most important goals of Tevatron Run II is to search Higgs boson.
- Precision Electroweak measurements can provide constraints on what Higgs mass should be.



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Electroweak Higher Order Corrections

- Standard model parameters:
  - $\alpha = 1/137.0359895(61)$
  - $G_F = 1.16637(1) \times 10^{-5} GeV^{-2}$
  - $M_Z = 91.1872 \pm 0.0021$ GeV
- With these, M_H can be constrained by M_t and M_W (or $\sin\theta_W$)
  - $\delta M_t = 2$GeV corresponds to $\delta M_W = 12$MeV
  - $\delta M_W = 30$MeV corresponds to $\delta M_H = 30$GeV

- Various schemes in use:
  - On-shell

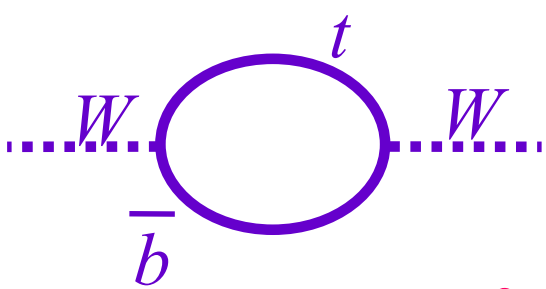
$$\sin^2\theta_W = 1 - M_W^2/M_Z^2$$

$$M_W = \frac{\pi\alpha}{\sqrt{2}G_F} \frac{1}{\sin\theta_W (1-\Delta r)^{1/2}}$$

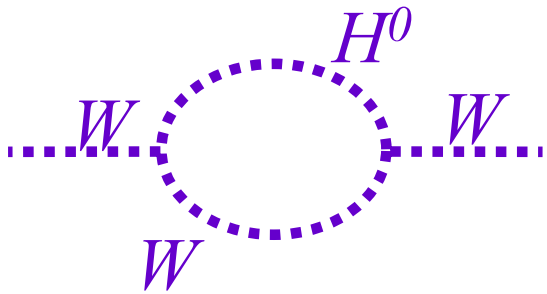
  - MS bar
  - Effective angle
    - used in LEP Asymmetry measurements

$$\sin^2\theta_W^{\text{effective}} = (1 + \Delta\kappa(M_t, M_H)) \sin^2\theta_W$$

Electroweak Higher Order Corrections



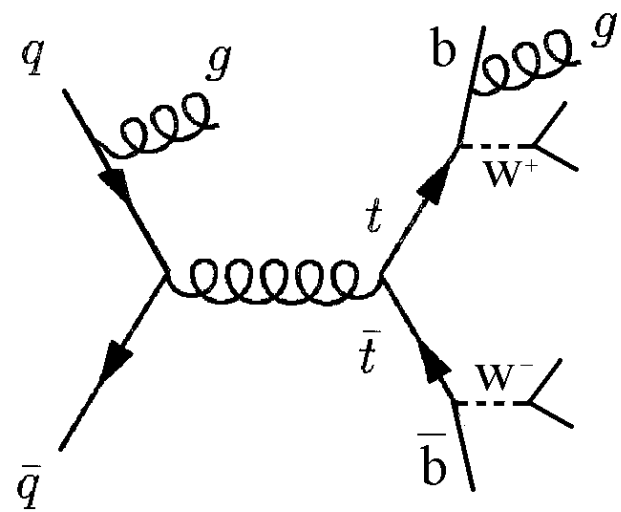
$\Delta m_W \propto m_t^2$



$\Delta m_W \propto \ln m_H$

Top Quark Mass Analyses from Run I

- Data
  - D0: 125 pb^{-1}, CDF: 109 pb^{-1}
- Dilepton channel
  - Clean signal
  - Small statistics
  - two undetected neutrinos
- Lepton+jets channel
  - Larger background
  - Larger statistics
  - one undetected neutrino
- All hadronic channel
  - Large background
  - Larger statistics
  - no undetected netrinos



	D0		CDF	
Channel	N_{obs}	N_{bg}	N_{obs}	N_{bg}
Dilepton	6	1.4±0.4	8	1.3±0.3
Lepton+jets	77	~50	76	~30
All hadronic	–	–	136	108±9

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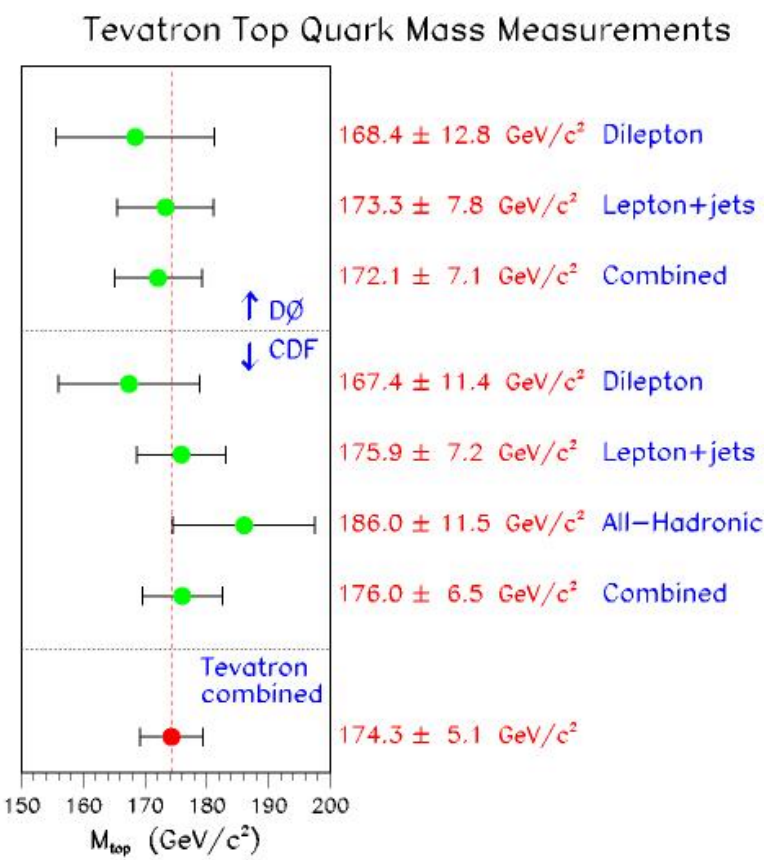
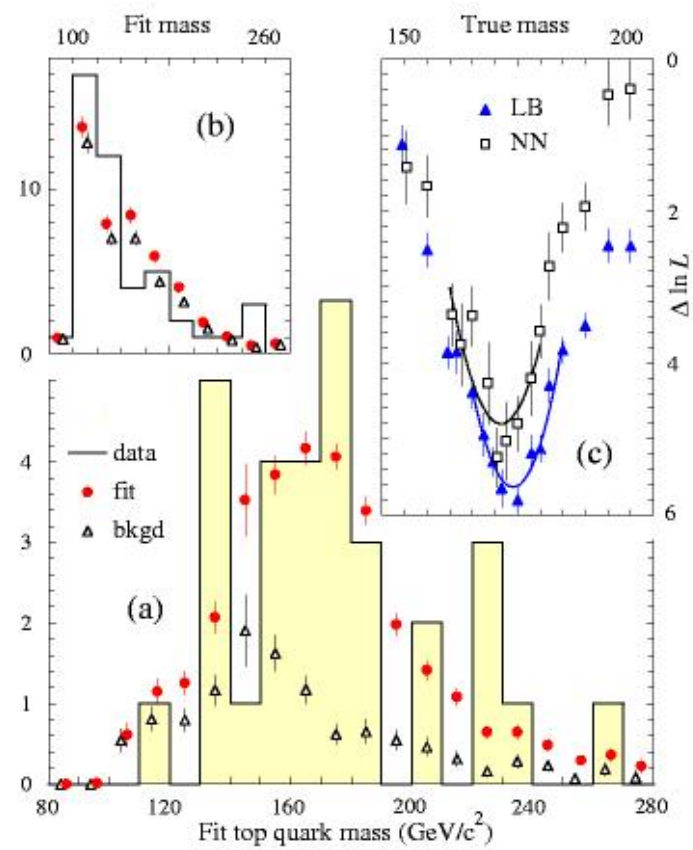
Top Quark Mass





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Run II Prospects for M_t measurements

- Lepton+jets channel

	Run I (D0)	Run IIa ($2fb^{-1}$)
statistics	5.6 GeV	1.3 GeV
Jet E scale	4.0 GeV	0.5 GeV
MC generator	3.1 GeV	0.7 GeV
MC model	1.6 GeV	0.4 GeV
Fit procedure	1.3 GeV	0.3 GeV
Total syst	5.5 GeV	1.0 GeV
Total	7.8 GeV	1.6 GeV

- dilepton channel (smaller syst, larger stat)

- Improvements
  - calibrate jet E scale using data
    - Z+jet, $W \to jj$, $Z \to bb$
  - Constrain gluon radiation effects in MC with data
  - double b-tag

Improved D0 W mass measurement

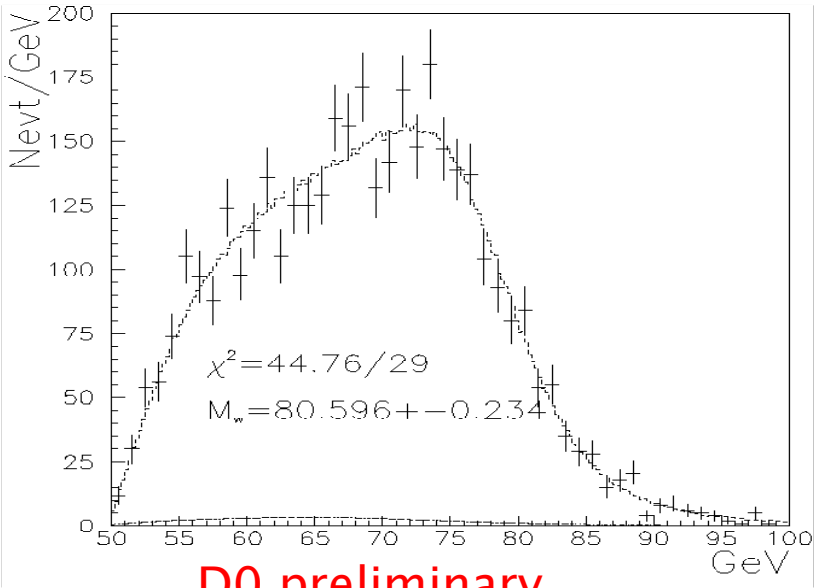
submitted to PRD, hep-ex/0204014, FERMILAB-Pub-02/055-E

- 82 pb^{-1} of Run I data
- Using edge electrons in the central calorimeter
  - Previous analyses discarded two 10% azimuthal regions near an edge
- 14% increase in the W boson sample in CC
- Improved determination of the response parameters using edge and non-edge Z's

- W mass with edge electrons
  - M_W=80.574±0.405GeV
- CC W mass
  - M_W=80.446±0.108GeV (old)
  - M_W=80.438±0.107GeV (new)
- EC W mass
  - M_W=80.691±0.227GeV (old)
  - M_W=80.679±0.209GeV (new)
- CC + EC W mass
  - M_W=80.482±0.091GeV (old)
  - M_W=80.481±0.085GeV (new)
- All combined
  - M_W=80.483±0.084GeV

“Edge”

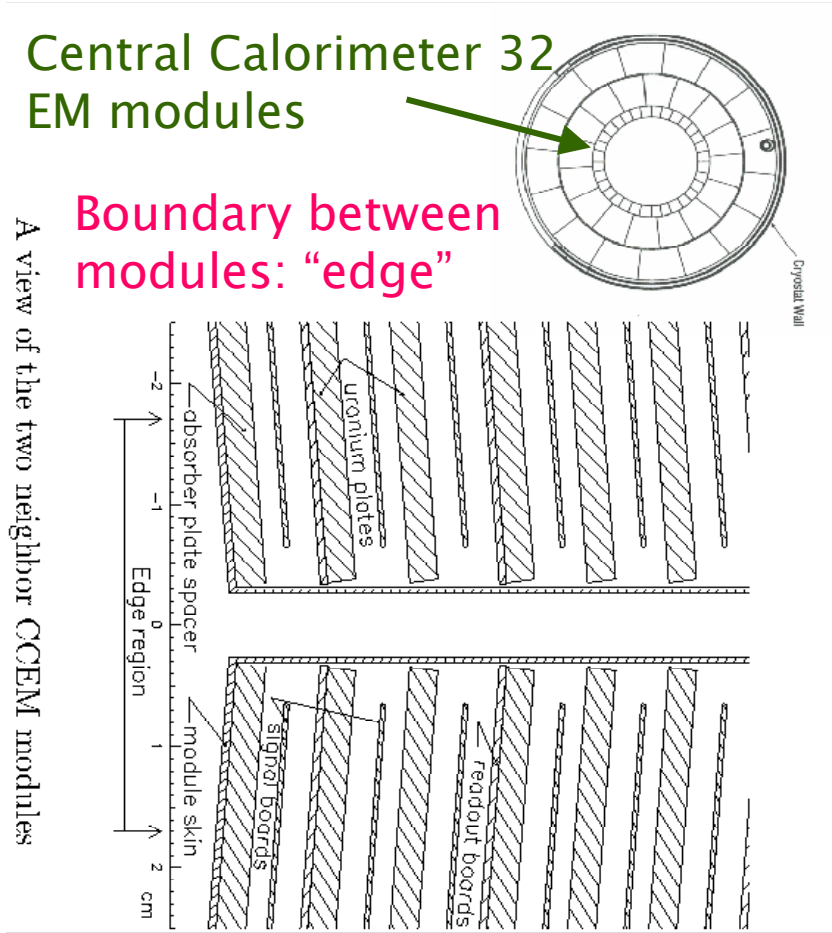
MT distribution with edge electrons



D0 preliminary

Central Calorimeter 32 EM modules

Boundary between modules: “edge”



A view of the two neighbor CCEM modules

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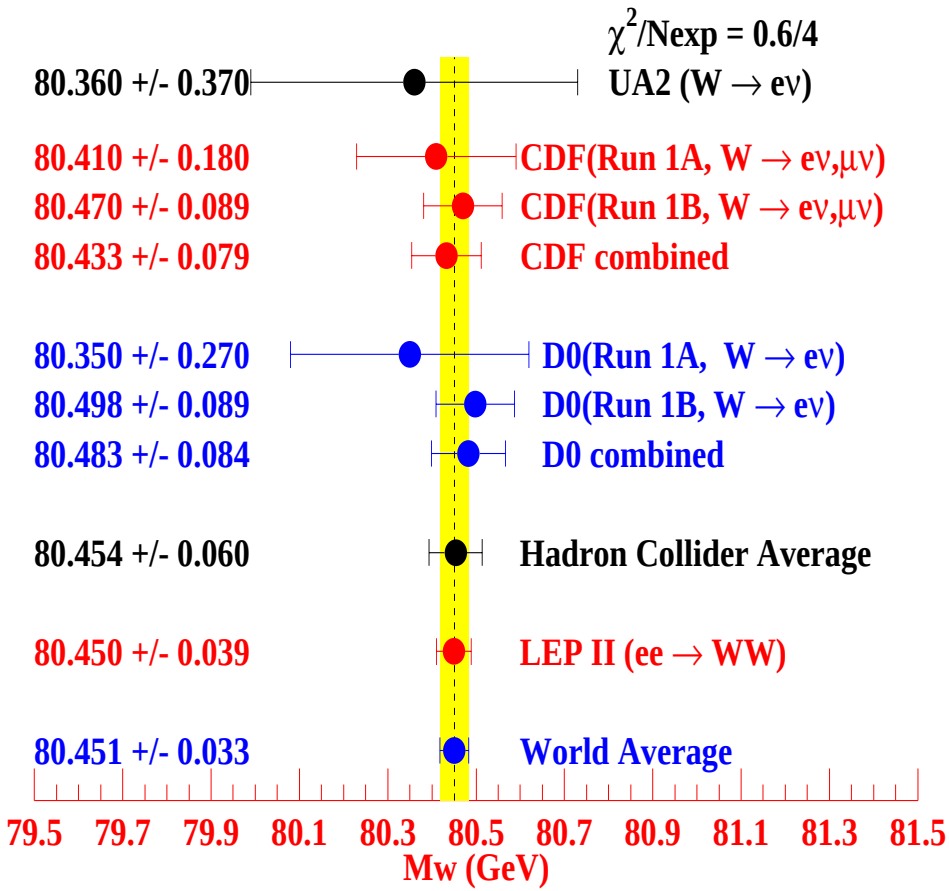
W Mass Measurements

- Updated D0 measurement with additionally constrained calibration and edge electron fits (8% improvement)



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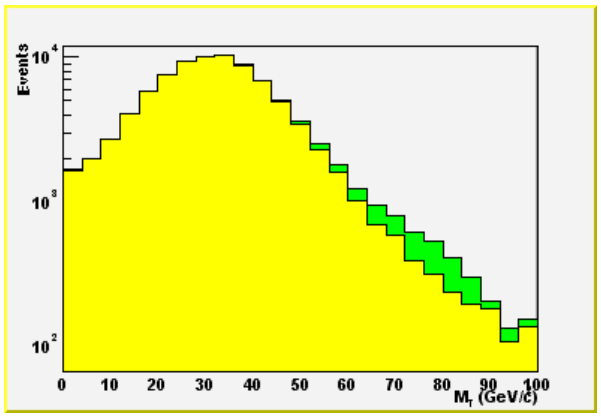
Prospects for W mass Measurements in Run II

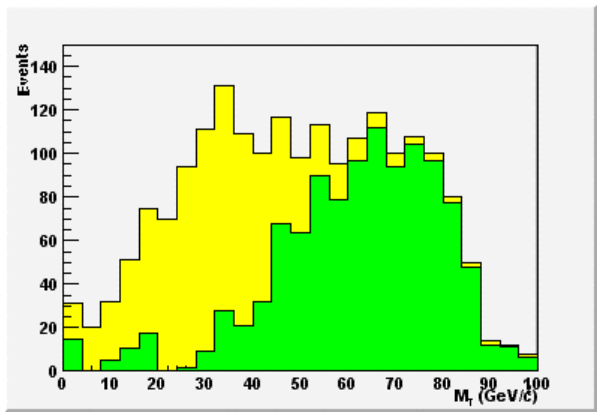
- Run IIa with $\int \mathcal{L}dt = 2fb^{-1}$
- Stat. uncertainty=13MeV/c^2 per channel, per experiment
- Detector-specific uncertainties scale as $1/\sqrt{N_Z}$
  - lepton energy and momentum scale
  - W recoil modeling
  - 15MeV/c^2
- Theoretical uncertainties
  - PDF
  - W p_T
  - QCD higher order effects
  - QED radiative effects
  - 20MeV/c^2
- Total uncertainty=30MeV/c^2 per channel, per experiment
- Run IIb with $\int \mathcal{L}dt = 15fb^{-1}$
- Stat. uncertainty=5MeV/c^2 per channel, per experiment
- Systematic uncertainties are hard to predict at this level
  - Hopefully improved as stat. Uncertainties
- 10 MeV/c^2 measurement possible

$W \to e\nu$ from Run II data (D0)

w/o. track matching

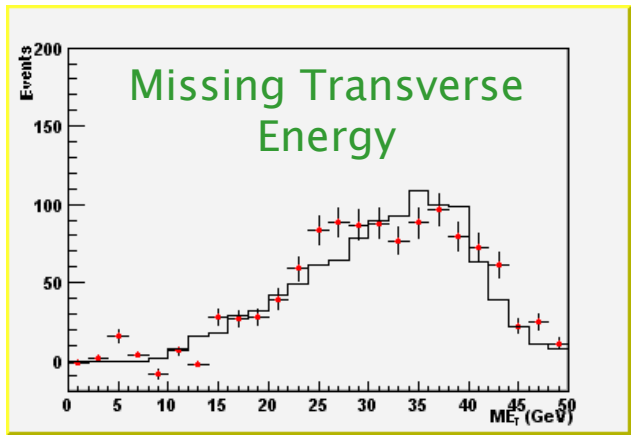


w. track matching

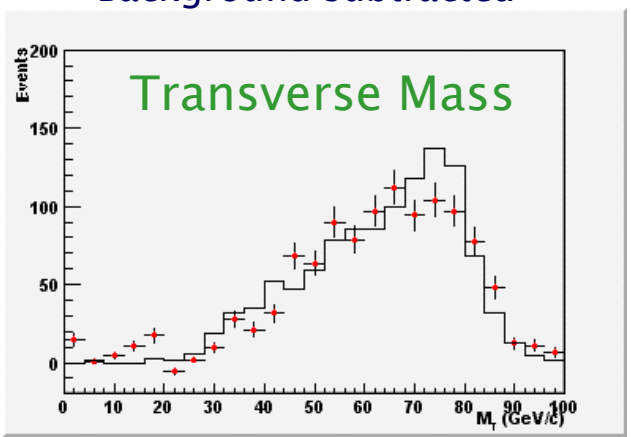


Track matching necessary to disentangle overwhelming QCD background

Background subtracted



Background subtracted



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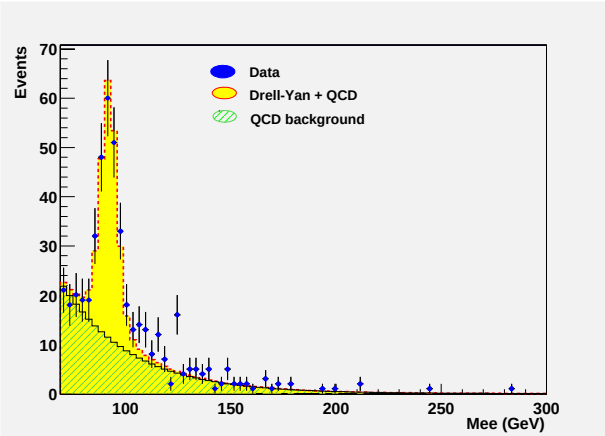
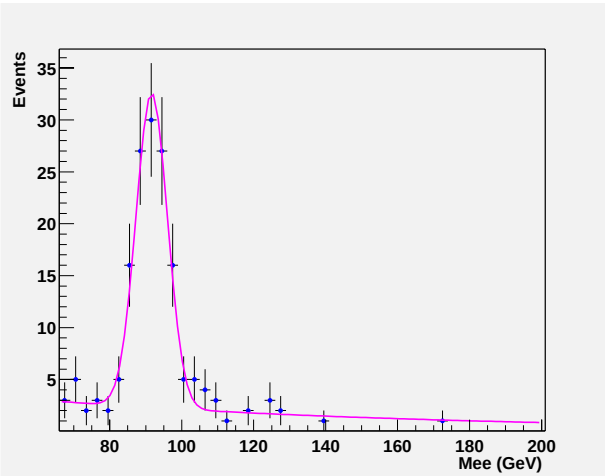
$Z \to ee$ from Run II data (D0)



DØ Run II
Preliminary

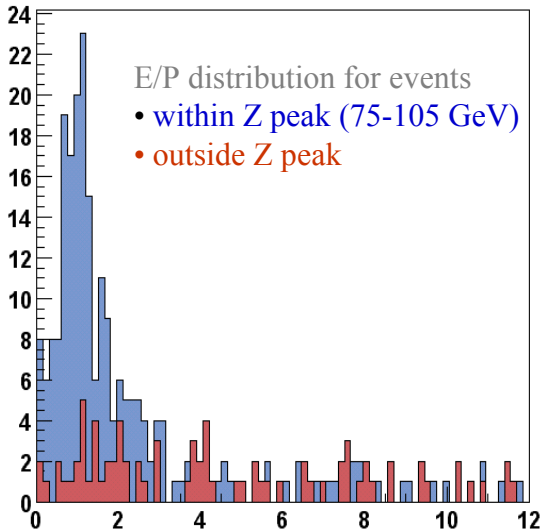
w/o track match



with track match

Matched track:

- $|\phi_{electron} - \phi_{track}| < 0.02$
- Close to vertex (< 1 mm)
- $|E/P|<2$



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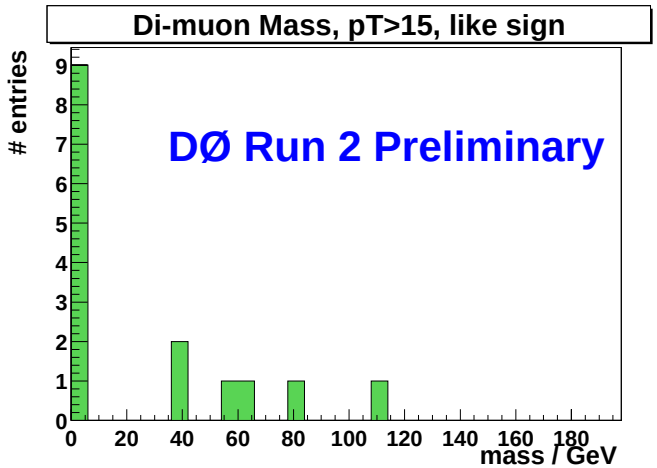
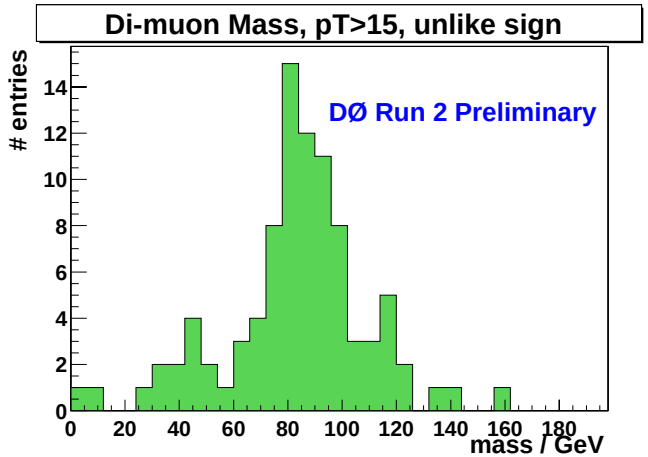
Di-muon Mass Plots from Run II (D0)

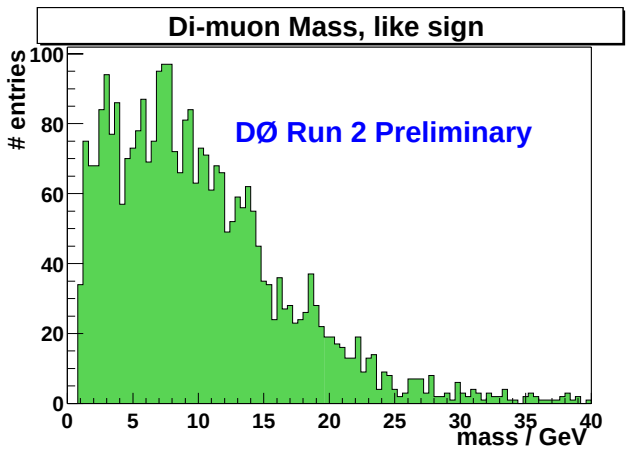
Taking the 'best' track for each muon, applying the correction to axial tracks

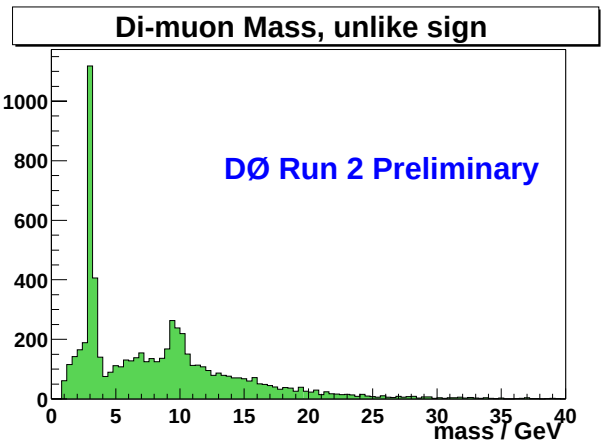
Top two plots require pT > 15 GeV gtracks

Bottom two plots require pT > 2 GeV gtracks









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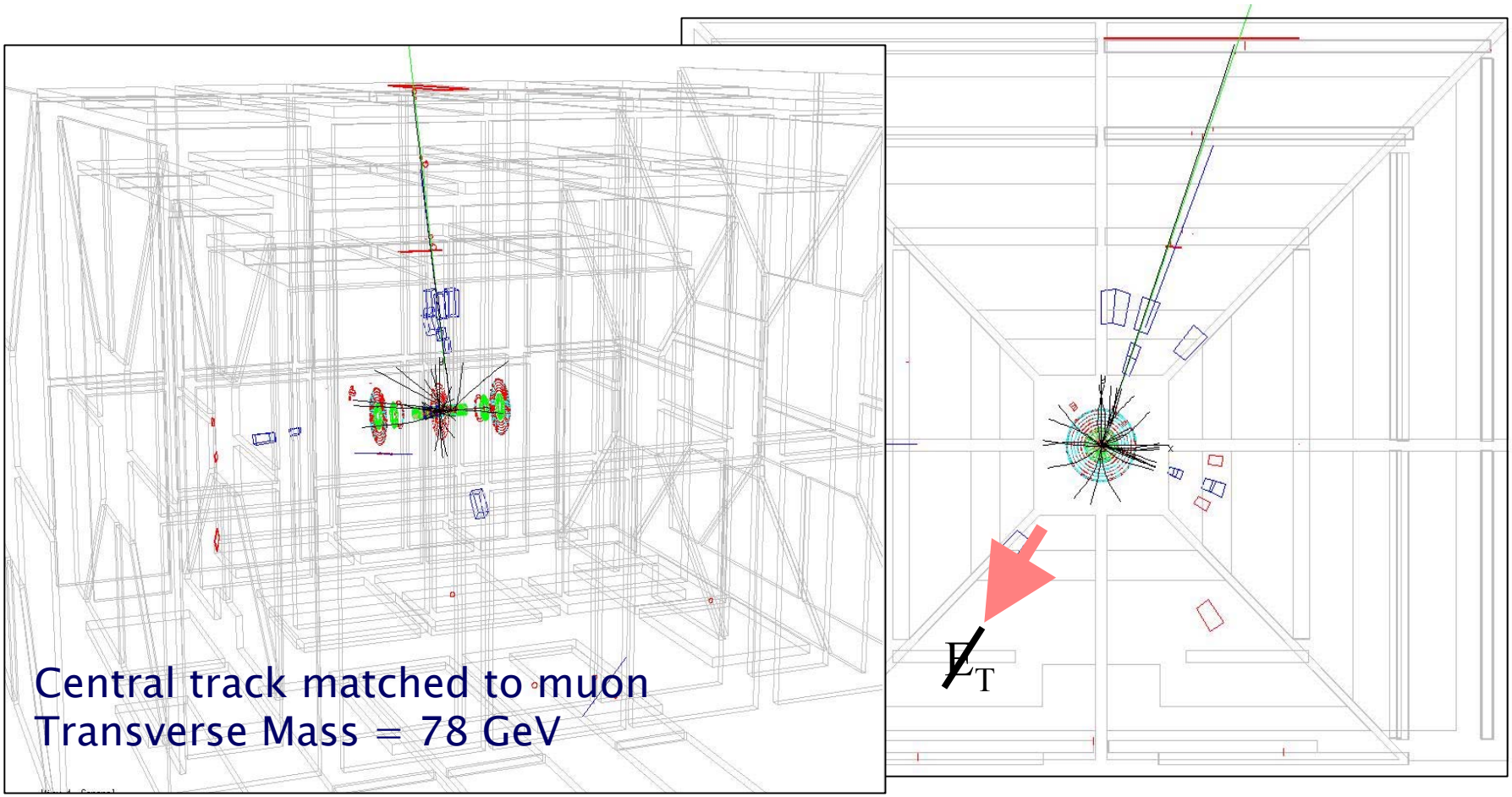
$W \to \mu\nu$ Candidate from Run II (D0)



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W Mass from ν Interactions

NuTev, PRD 88, 091802(2002)

- Measure $\sin^2\theta_W^{(\text{on-shell})}$ from the ratio of neutral and charged current interactions

$$R^- \equiv \frac{\sigma(\nu_\mu N \to \nu_\mu X) - \sigma(\bar{\nu}_\mu N \to \bar{\nu}_\mu X)}{\sigma(\nu_\mu N \to \mu^- X) - \sigma(\bar{\nu}_\mu N \to \mu^+ X)} = \frac{R^\nu - r R^{\bar{\nu}}}{1-r} = g_L^2 - g_R^2$$

where

$$g_L^2 = (\epsilon_L^u)^2 + (\epsilon_L^d)^2 = \frac{1}{2} - \sin^2\theta_W + \frac{5}{9}\sin^4\theta_W$$

$$g_R^2 = (\epsilon_R^u)^2 + (\epsilon_R^d)^2 = \frac{5}{9}\sin^4\theta_W$$

$$\sin^2\theta_W^{(\text{on-shell})} = 0.2277 \pm 0.0013(\text{stat.}) \pm 0.0009(\text{syst.}) - 0.00022 \times \left(\frac{M_t^2 - (175\text{GeV})^2}{(50\text{GeV})^2}\right) + 0.00032 \times \ln\left(\frac{M_H}{150\text{GeV}}\right)$$

$\rightarrow M_W = 80.14 \pm 0.08\text{GeV}$

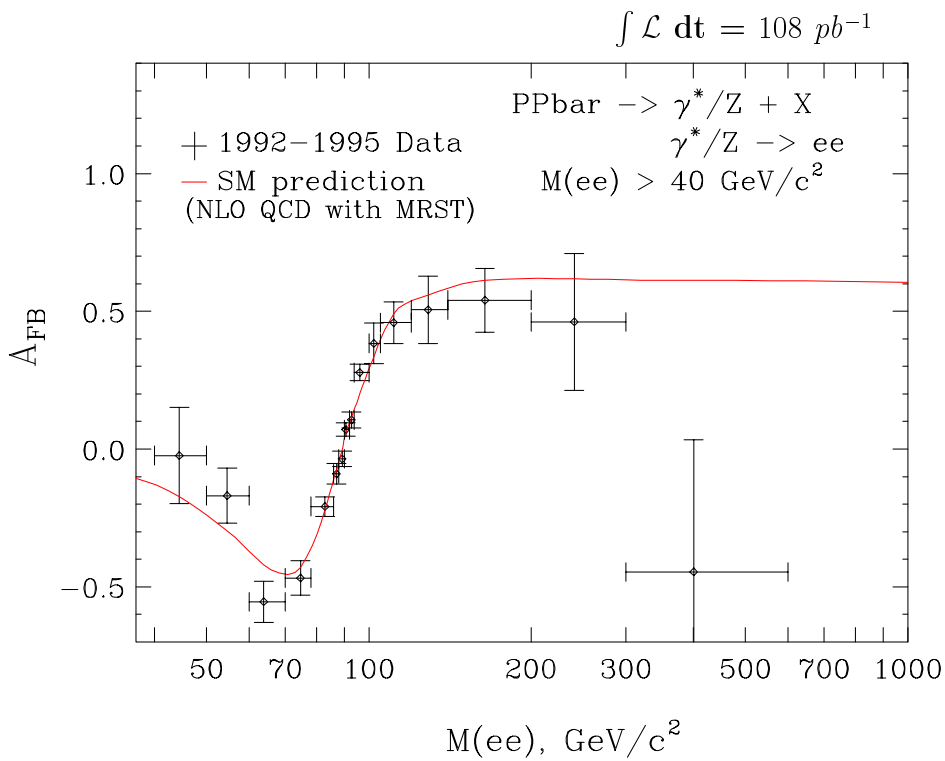
$\sin\theta_W$ from Forward-Backward Asymmetry

- $\sin^2\theta_{eff}=(1+\Delta\kappa)\sin\theta_W$
- LEP Experiments:
  - $A_{FB}^{0,l}=0.0171\pm0.0010$ from total of 1.7M events
    - $\sin^2\theta_{eff}=0.23099\pm0.00053$
  - $A_{FB}^{0,b}=0.0990\pm0.0017$
    - $\sin^2\theta_{eff}=0.23226\pm0.00031$
  - $A_{FB}^{0,c}=0.0685\pm0.0034$
    - $\sin^2\theta_{eff}=0.23272\pm0.00079$
- First measurement by CDF at Tevatron
- CDF: PRL 77, 2616(1996)
  - $A_{FB}=0.070\pm0.016$ for $75<M_{ee}<105\text{GeV}/c^2$ from 5463 e^+e^- events in 110pb^{-1}
  - $A_{FB}=0.43\pm0.10$ for $M_{ee}>105\text{GeV}/c^2$
- With 10fb^{-1}, D0 and CDF will each have 1M $e^+e^-+\mu^+\mu^-$ events.
  - Competitive to LEP measurements

$d\sigma/dM$ and A_{FB} from CDF Run I Analysis

PRL 87,131802 (2001)

Forward-Backward Charge Asymmetry, A_{FB}



Solid line is NLO QCD calculation with MRST (NLO) PDFs

$$A^i_{FB} = \frac{\left(\frac{d\sigma}{dM_i}\right)^+ - \left(\frac{d\sigma}{dM_i}\right)^-}{\left(\frac{d\sigma}{dM_i}\right)^+ + \left(\frac{d\sigma}{dM_i}\right)^-}$$

- Good agreement with SM
- The highest bin (4 events – $300<M_{ee}<600$GeV) is 2.2σ below the SM prediction (probability of 2.5%)
- Negative asymmetry in this region could result from new interactions

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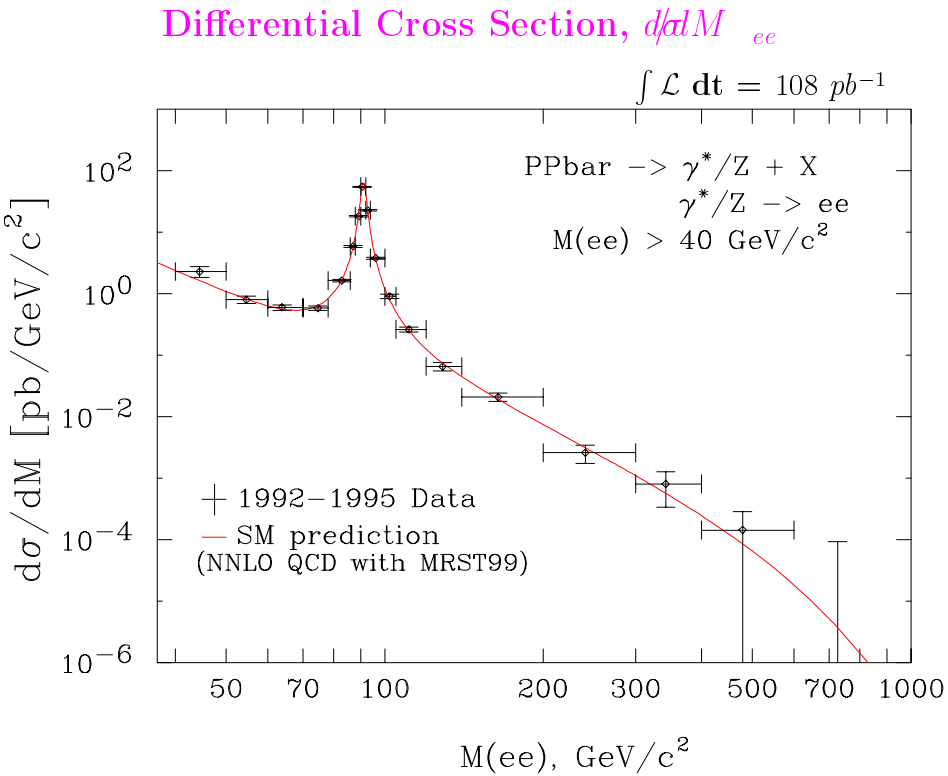
$d\sigma/dM$ and A_{FB} from CDF Run I Analysis

PRL 87,131802 (2001)



Solid line is NNLO QCD calculation with MRST99 (NLO) PDFs, scaled up by a factor 1.11.

- Compare to Standard Model Drell-Yan predictions and search for evidence of new interactions
  - additional gauge bosons
  - quark-lepton compositeness
  - exchange of R-parity violating SUSY particles
  - leptoquarks
  - extra dimensions
- Good agreement with SM

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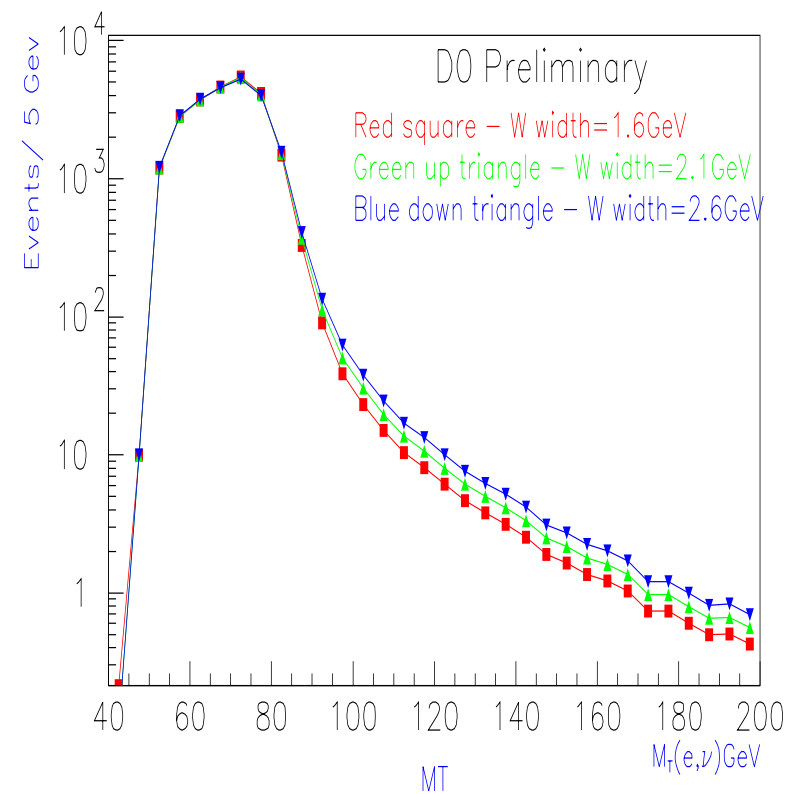
Direct Measurement of W Width

- Indirect measurement uses cross section measurements and theoretical inputs.

$$\mathcal{R} = \frac{\sigma(p\bar{p} \to W + X) \times B(W \to e\nu)}{\sigma(p\bar{p} \to Z + X) B(Z \to ee)}$$

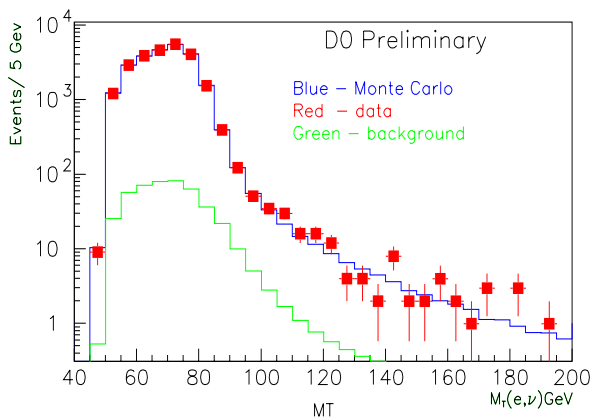
$$\mathcal{R} = \frac{\sigma_W}{\sigma_Z} \frac{\Gamma_Z}{\Gamma_{Z \to ll}} \frac{\Gamma_{W \to l\nu}}{\Gamma_W}$$

- Direct Measurement avoids using theoretical inputs.
- The tail region of $M_T(W)$ is sensitive to $\Gamma(W)$ and can be used to extract $\Gamma(W)$.

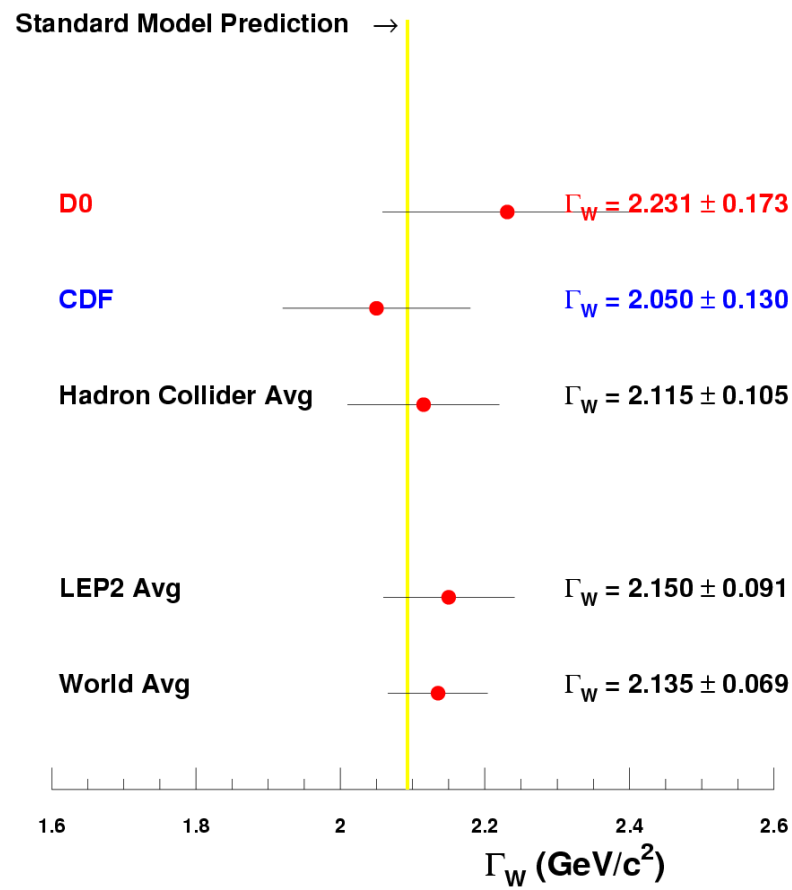


Direct Measurement of W Width

- D0 direct $\Gamma(W) = 2.231\ ^{+0.145}_{-0.138}$ (stat) $\pm$ 0.092 (syst) GeV



- Run IIa with 2fb^{-1}, each experiment can make a ~40MeV width measurement.



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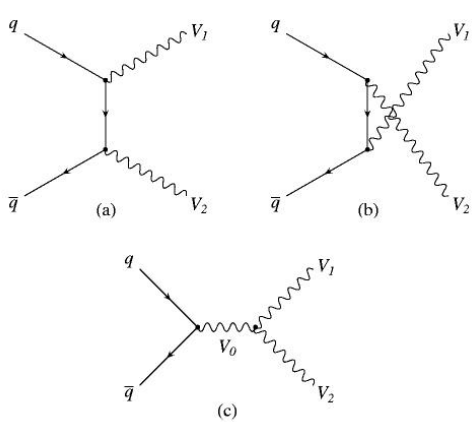
Triple Gauge Boson Couplings

- Direct consequence of the non-Abelian SU(2)xU(1)
- Measurements of the couplings – crucial direct test of SM
- Deviations from SM – Signal for new physics



- In Run I, $W\gamma$, $WW \rightarrow$ dileptons, $WW/WZ \rightarrow$ lepton+jets, and $WZ \rightarrow$ trileptons were studied.
- Combined fit of all available results provides the strictest limits on couplings from Tevatron.
- Expected improvements on limits from Run II will be proportional to $(\int L dt)^{1/4}$ without improvements in analysis technique.
  - With $15 fb^{-1}$, a factor of 3.5 improvement expected.

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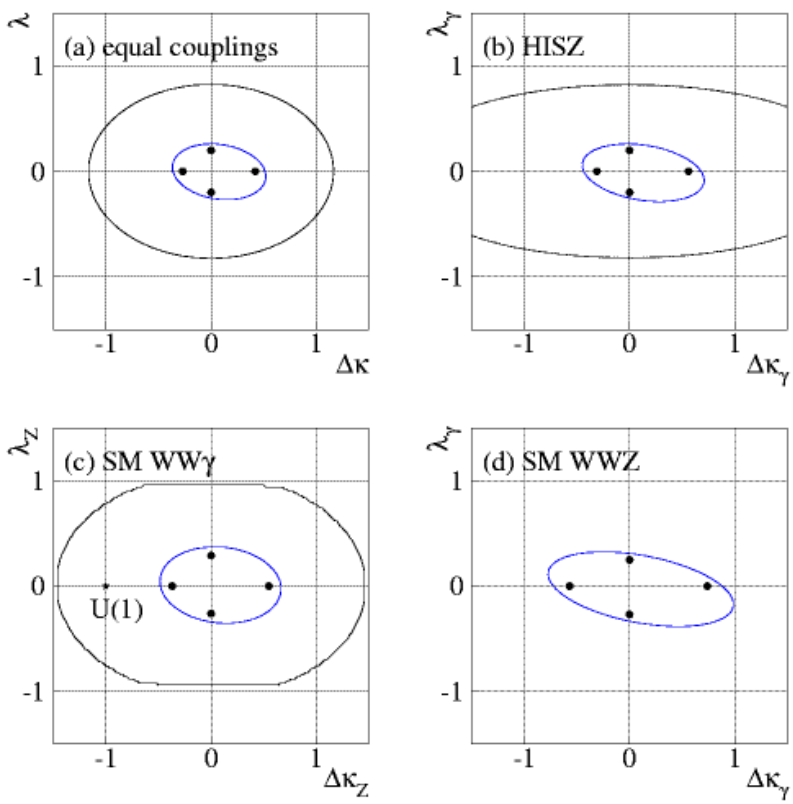
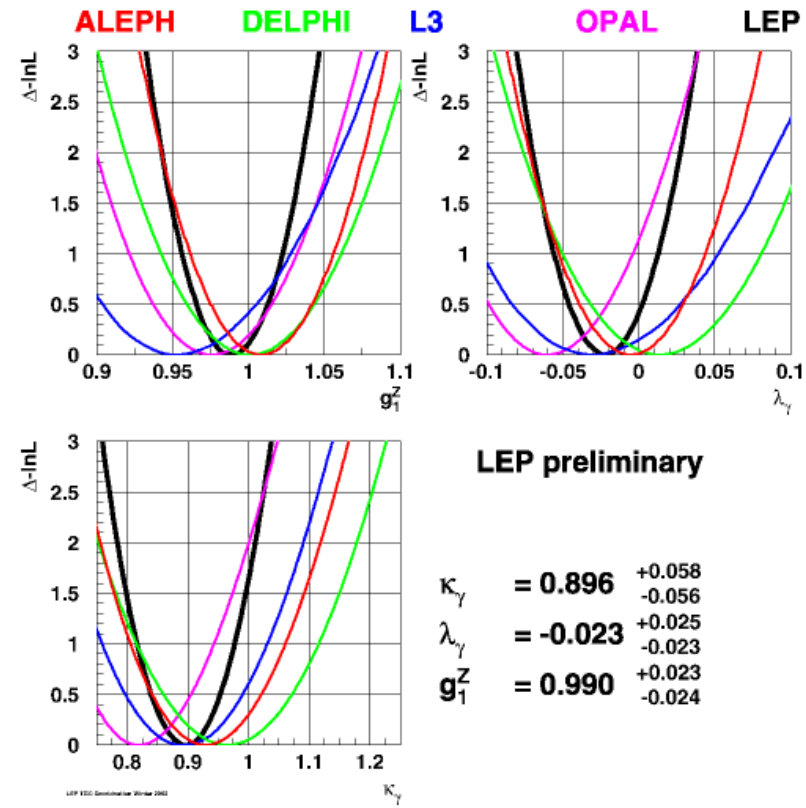
Limits on Triple Gauge Couplings





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Limits on Triple Gauge Couplings

D0 Run I Limits with ~100pb^{-1}:

$\lambda_\gamma = 0.00 \pm 0.10$

$\Delta\kappa_\gamma = -0.08 \pm 0.34$

LEP Limits:

$\lambda_\gamma = -0.023^{+0.025}_{-0.023}$

$\kappa_\gamma = 0.896^{+0.058}_{-0.056}$

LEP limits are 4 to 6 times tighter than D0 Run I limits.

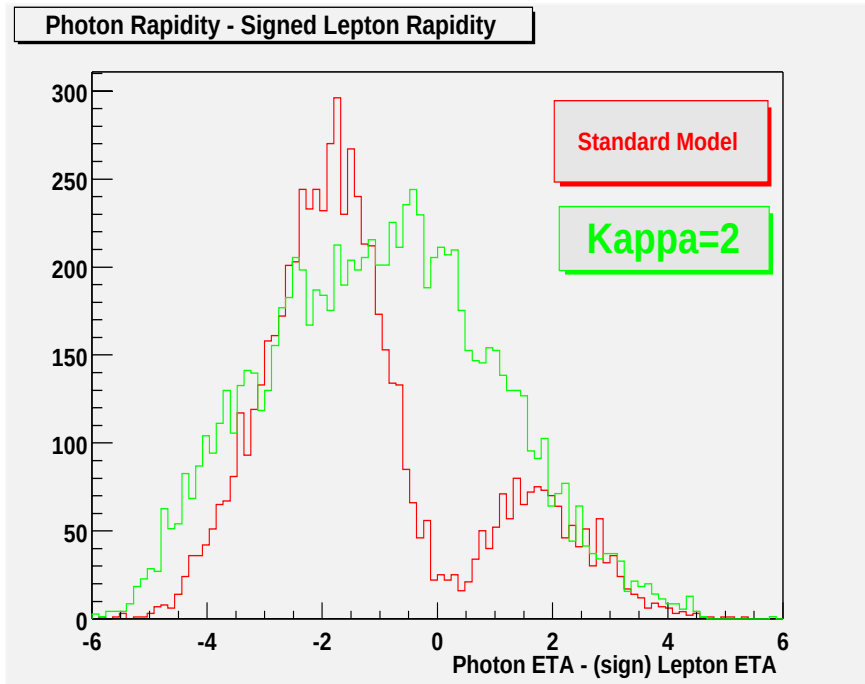
With 15fb^{-1}, D0 limits should improve by a factor of 3.5. Combining with CDF should make Tevatron limits competitive with LEP.

This assumes there will be no improvements in technique. But ...

Wγ Radiation Zero

- Destructive interference between S- and t-channel production diagrams casues amplitude zero in γ-lepton angular distribution (SM)
- If WWγ couplings are different from SM values, the gap is filled.
- With 2fb^{-1}, 1500 events in each of eνγ and μνγ channel
- with 15fb^{-1}, 11000 events each.

Generator level MC for the Radiation Amplitude Zero



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σ_W as a luminosity monitor

- The uncertainty on the integrated luminosity in Run I was 4.5% for both D0 and CDF.
- Normalized to the total inelastic cross section.
  - D0: world average
  - CDF: own measurement
- With1M $W \to e\nu$ in Run IIa with 2 fb^{-1}, σ_W can be used for normalization of integrated luminosity.
- 5 interactions/crossing in Run II b

- Estimated uncertainties on luminosity in Run II:

Component	Uncertainty
f_{QCD}	1.5 %
ε	0.9 %
A	0.5 %
N_{cand}	0.08 %
N_Z	0.0 %
A_τ/A	0.0 %
σ_W	4 %

- With improvements in σ_W, 3~4 % uncertainty possible.

Concluding Remarks

- Tevatron Run II has started, with ~30pb^{-1} delivered to each experiment so far.
- Shake down of the upgraded detectors in full swing.
- 300pb^{-1} will be delivered in 2002.
- With 2fb^{-1} from Run IIa, $\delta M_W = 30 MeV/c^2$ and $\delta M_t = 2 GeV/c^2$ are possible.
- Many interesting measurements are in horizon.
- Stay tuned.