Electroweak Physics

Darien Wood

(Дарий Робертович Вуд)

Northeastern University

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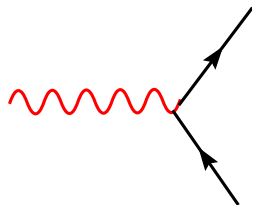
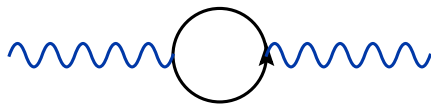
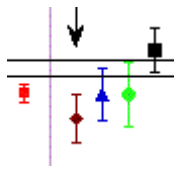
Thanks to:
EW session conveners (E. Boos, T. Wyatt), parallel session speakers (M. Lancaster, M. Wielers, U. D'Hondt, M. Malberti, S. Blessing, A. Tapper, E. Lipeles, P. Azzurri, M. Verzocchi, S. Yost, A. Straessner, V. Chekelian, B. Y. Tikhonov, A. Penin, F. Canelli, R. Chierici, D. Wicke, Y.D. Ri, C. Parkes, J. Kuehn, W. Wagner, A. Onofre, G. Eilam, V. Zykunov, A. Krutov, F. Piccinini, S. Eidelman), K. Nagano, E. Perez, D. Denisov, E. James, C. Hayes, M. Grunewald, LEP Electroweak Working Group

Testing the Standard Model of Electroweak Physics

- Precision measurements of electroweak parameters
  - Complement direct searches for new physics
  - Explore higher mass scales through virtual effects
  - Can reveal the more fundamental structure of the theory
- Outline
  - The players: experiments and theory
  - Couplings
  - Masses and widths
  - Global fits to the Standard Model
  - Prospects







LEP & SLC Experiments

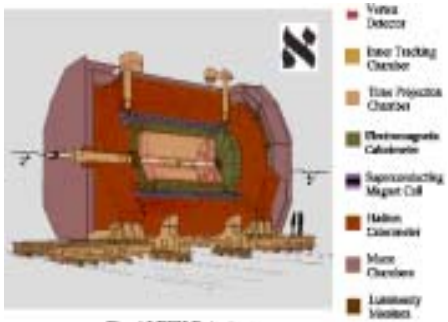
LEP 1: (Aleph, Delphi, L3, Opal) 1989-1995, e^+e^- collisions on Z pole (**17 million Z events recorded**)

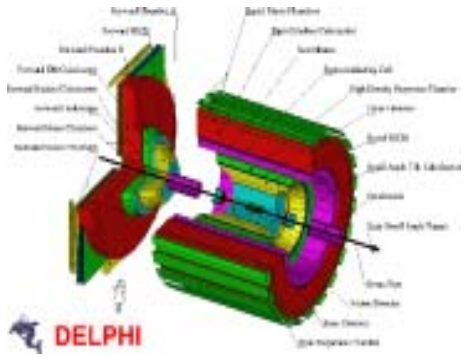
SLD at SLC: 1992-1998, e+e- collisions on Z pole with polarized beam (**600 thousand Z events recorded**)

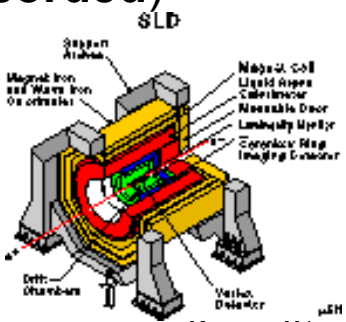
Final combined Z-pole results released in September 2005 (hep-ex/0509008)

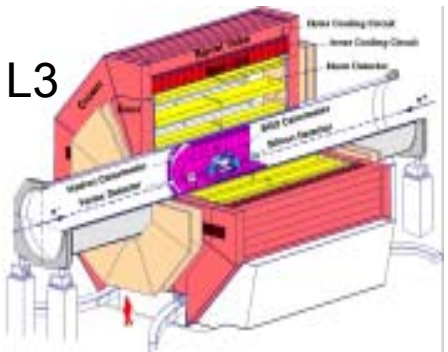
LEP 2: 1996-2000, e+e- collisions at E_{cm}=130 GeV-209 GeV

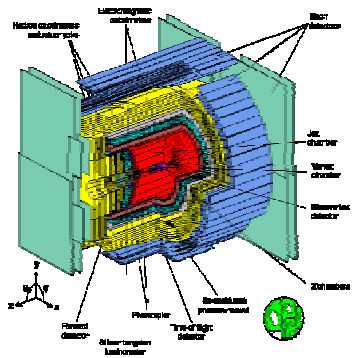
• emphasis on W pair producition (**40 thousand WW events recorded**)











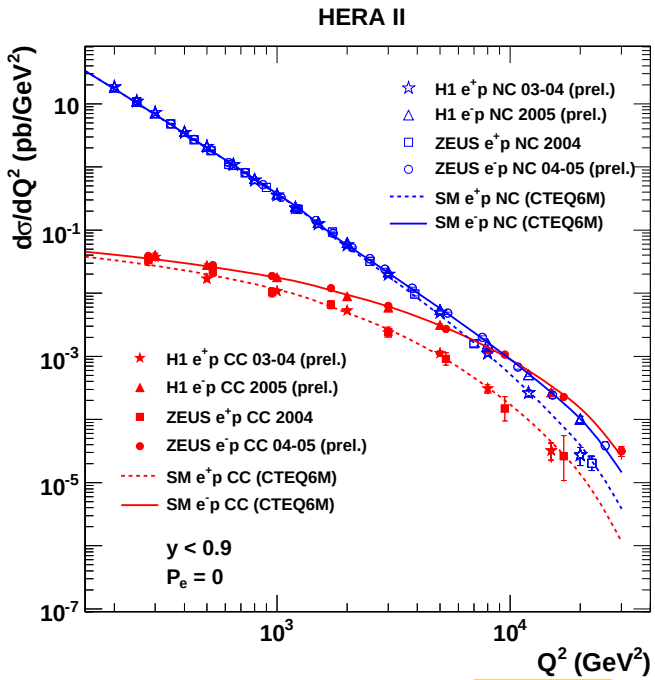
HERA Experiments

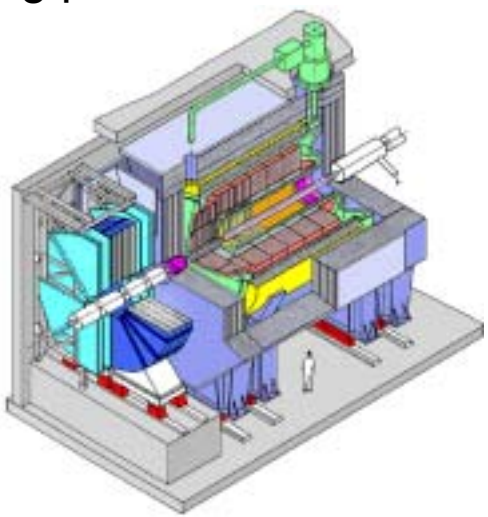
$e^{\pm}p$ collisions at E_{cm}=318 GeV

HERA-I 1994-2000 (~100 pb^{-1})

HERA-II, 2003-present

- **polarized $e^{\pm}$ beams** (left and right)
- ~10pb^{-1} to ~80pb^{-1} in each of the four configurations
- taking polarized e^{+} until mid 2007



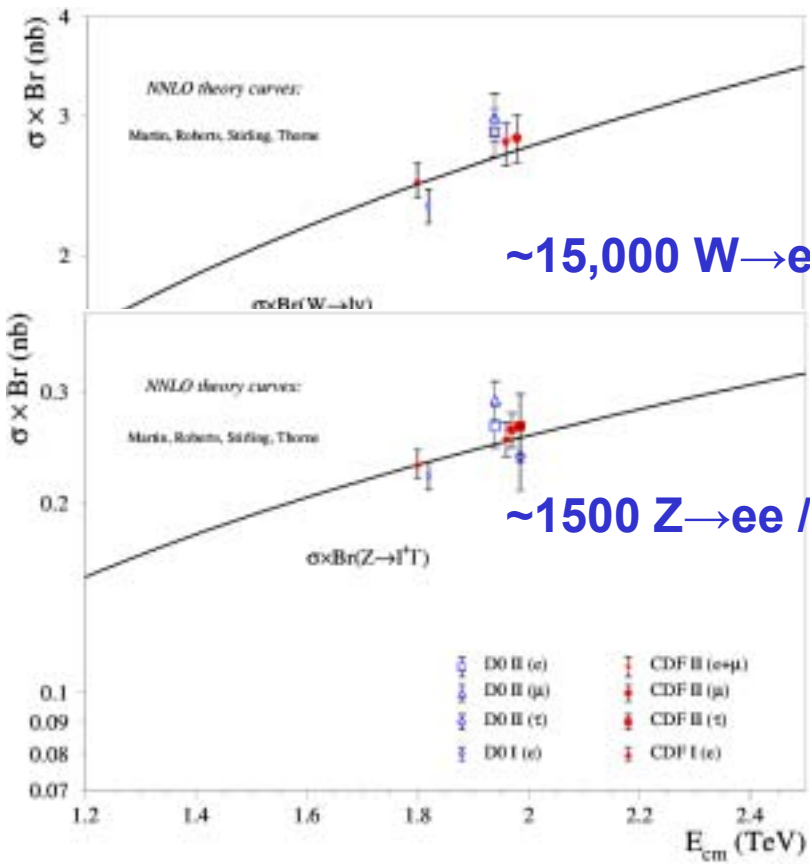


Tevatron Experiments

Proton-antiproton → W+X, Z+X, $t\bar{t}$+X, etc.

Run 1: 1992-1996, E_{cm}=1.8 TeV, ~100 pb^{-1}/experiment

Run II: 2001-present, E_{cm}=1.96 TeV, >1 fb^{-1}/experiment so far



~15,000 W→eν /exp/wk

~1500 Z→ee /exp/wk

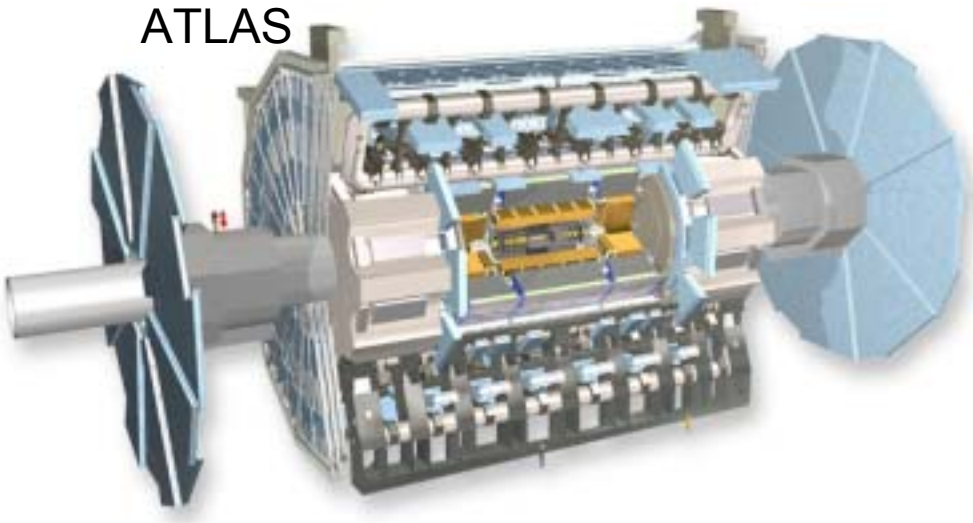
LHC Experiments

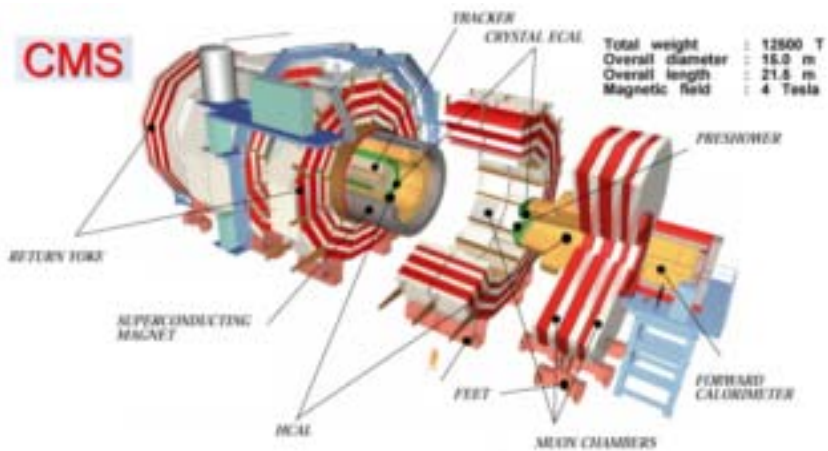
pp collisions at $\mathbf{E_{cm} = 14\ TeV}$

Data at full energy expected in 2008

In each fb^{-1}, expect
- 10,000,000 $W \rightarrow \ell\nu$
- 1,000,000 $Z \rightarrow \ell^+\ell^-$
- 300,000 $t\bar{t} \rightarrow \ell\nu$+jets

ATLAS





See Fabiola Gianotti's talk (tomorrow) for status and physics prospects for early data

Theory

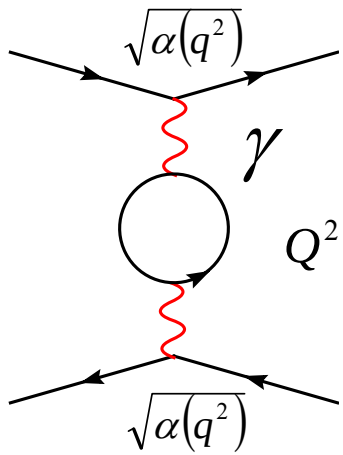
- Precision studies of electroweak observables makes strong demands on theory
  - At increased energy of future machines (LHC, ILC), new corrections become important
    - examples: EW corrections to production at LHC, Bremmstrahlung at ILC
  - Increasing experimental precision requires higher order calculation to match
    - example: Bhabha scattering at DAPHNE, EW corrections to muon g-2

Presented at this meeting
• Radiative corrections to Bremsstrahlung (S. Yost)
• two-loop calculation of Bhabha scattering (A. Penin)
• EW corrections to gauge boson and top production at hadron colliders (J. Kuehn)
• FCNC top production and decay (G. Eilam)
• weak radiative corrections to Drell Yan process (V. Zykunov)
• matching parton shower and matrix elements in QED (F. Piccinini)
• relativistic calculation of the neutron charge form factor (A. Krutov)
• status of muon g-2 (S. Eidelman)

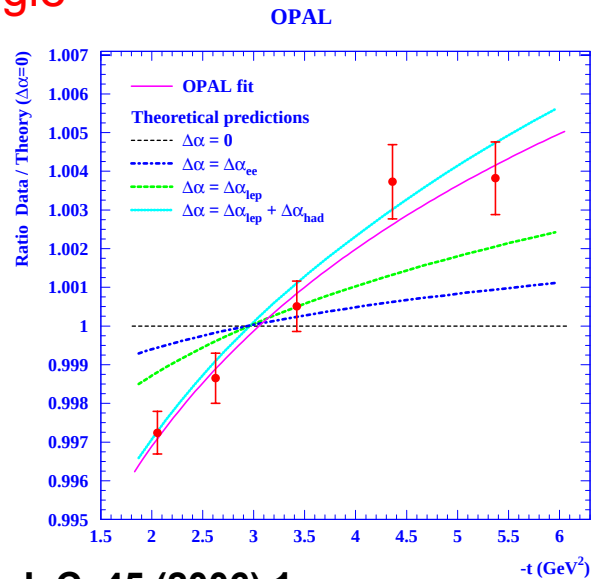
γee couplings: α_{EM} at LEP

- Running of α_{EM} measured at LEP
- Bhabha scattering at low angle dominated by t-channel
  - $q^2<0$
  - q^2 measured by scattering angle

$$\alpha(q^2) = \frac{\alpha_0}{1-\Delta\alpha(q^2)}$$



$$Q^2 = -q^2 = -t$$



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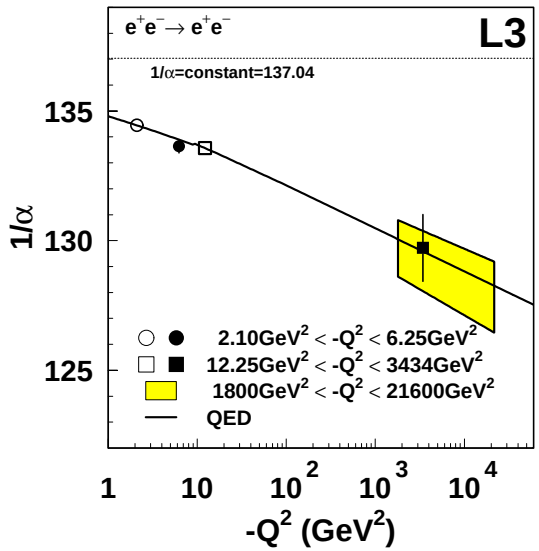
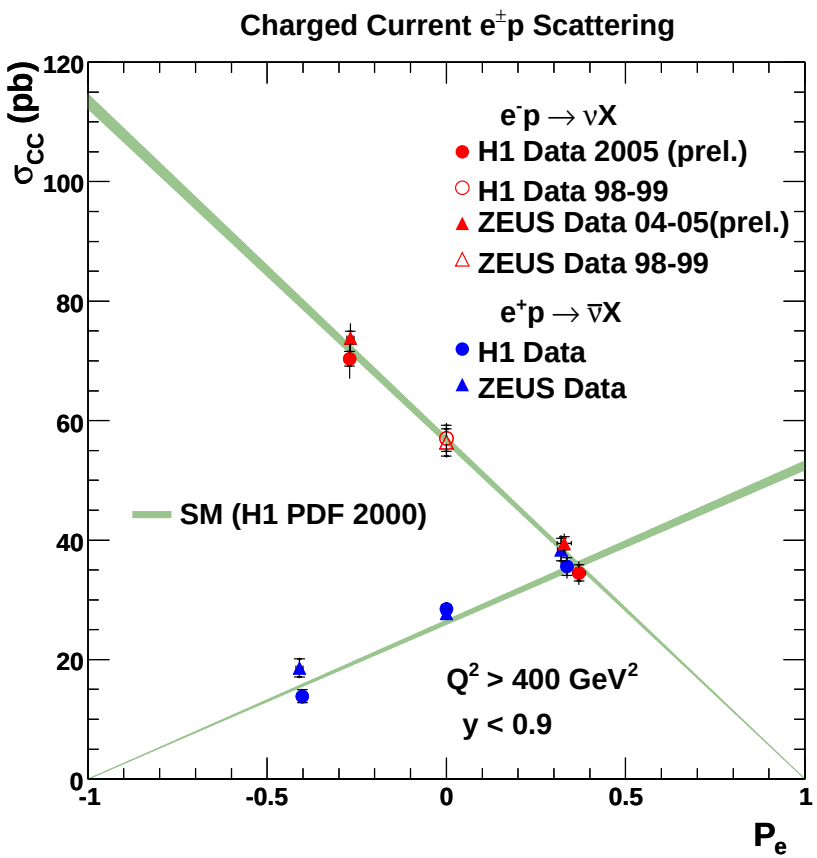
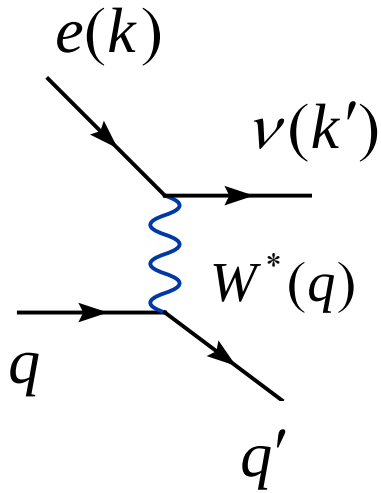


Phys. Lett. B623 (2005) 25

Weν, Wqq' couplings: charge currents at HERA

- Polarized e^+ and e^- beams
  - Measure charged current cross sections as a function of polarization





$$Q^2 = -q^2 = -(k-k')^2$$

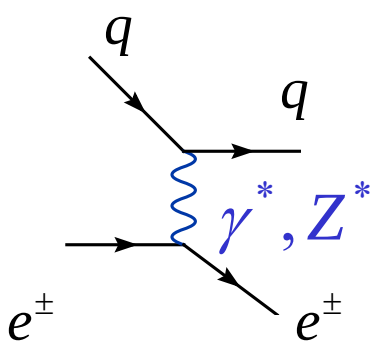
$$x = \frac{Q^2}{2p\cdot q} \qquad y = \frac{p\cdot q}{p\cdot k}$$

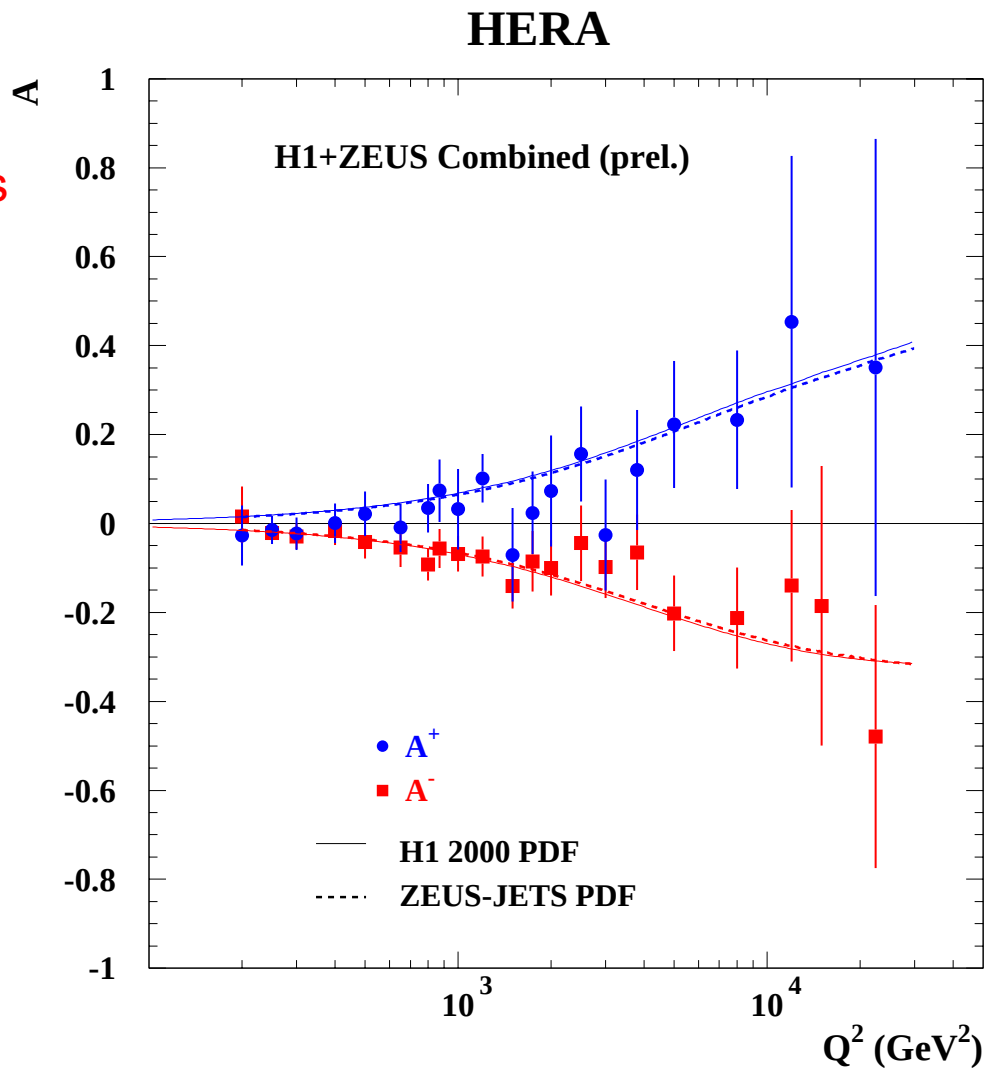
$$s = (p+k)^2 \qquad Q^2 = x\cdot y\cdot s$$

Zee, Zqq couplings: neutral currents at HERA

- Polarized e^+ and e^- beams
  - Measure ratio of neutral current cross sections for left and right polarizations as a function of Q^2.

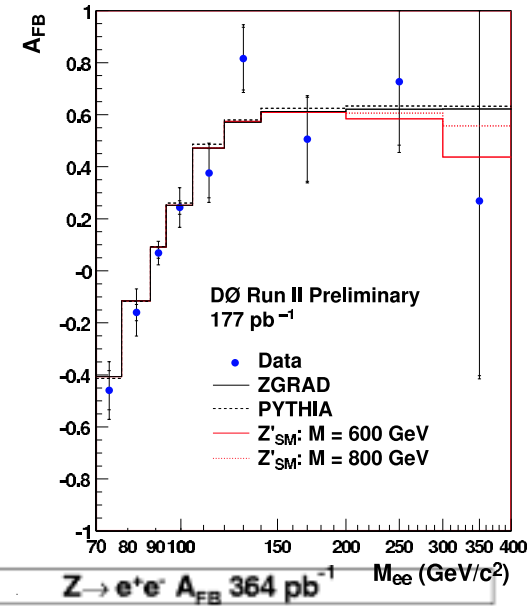
$$A^{\pm} = \frac{2}{P_R - P_L} \cdot \frac{\sigma^{\pm}(P_R) - \sigma^{\pm}(P_L)}{\sigma^{\pm}(P_R) + \sigma^{\pm}(P_L)}$$

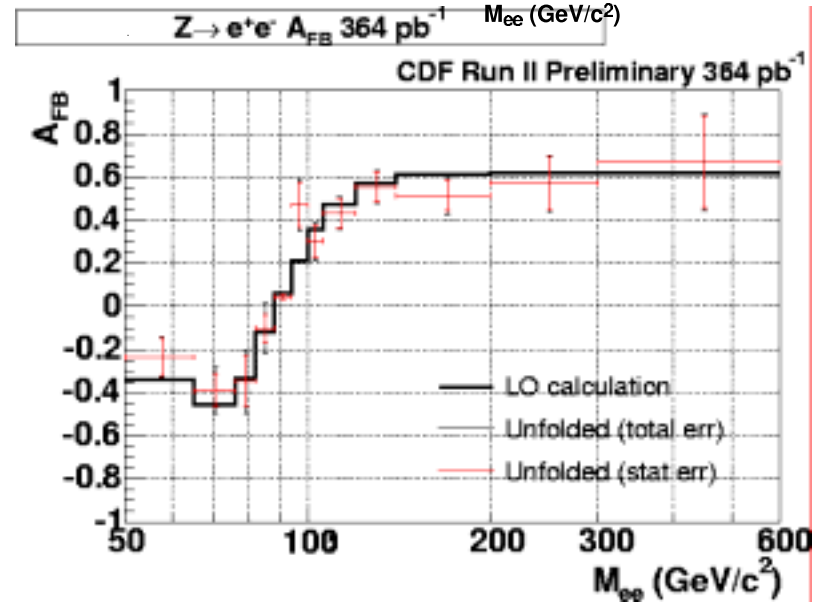


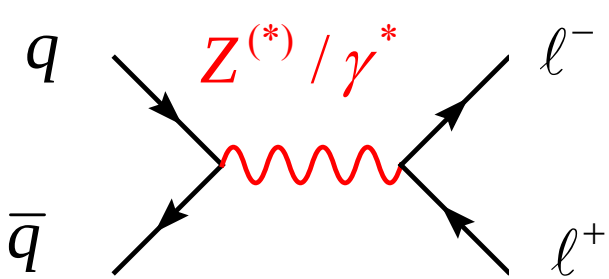


Zee, Zqq couplings: Z asymmetry at the Tevatron

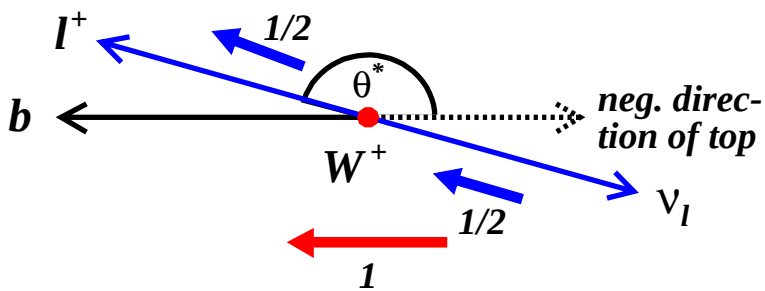
- **Measure forward/backward asymmetry of leptons from $Z^{(*)}/\gamma^*$ decays**
  - Sensitive to
    - Z-quark couplings a_u, v_u, a_d, v_d
    - Z-electron couplings a_e,v_e
    - $\sin^2\theta_W$
- **Explore timelike q^2 from (50 GeV)^2 to (600 GeV)^2**
- **Asymmetry changes sign around the Z pole**
- **Good agreement with SM**

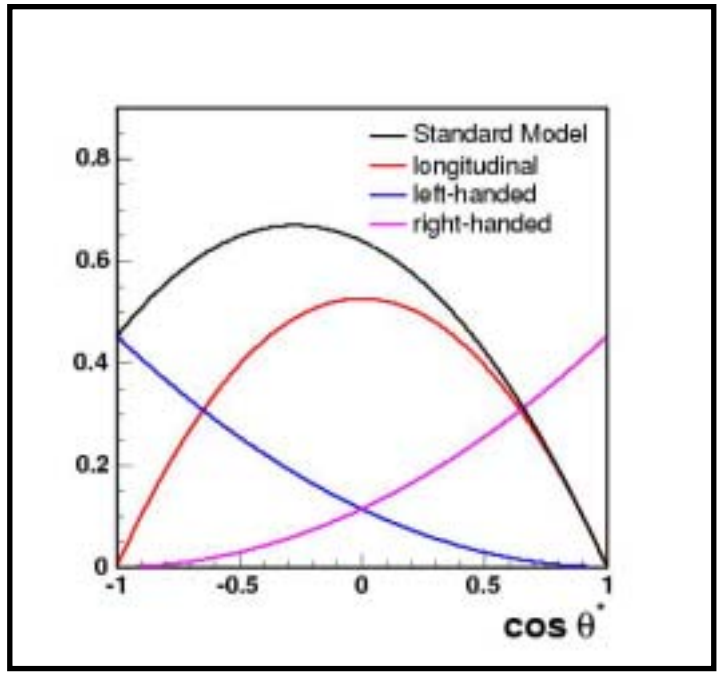






W helicity in top decays

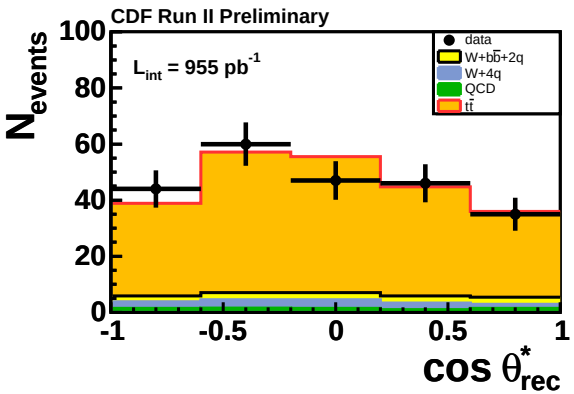


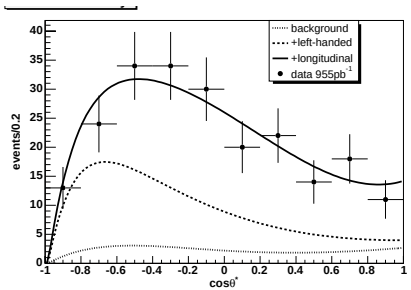


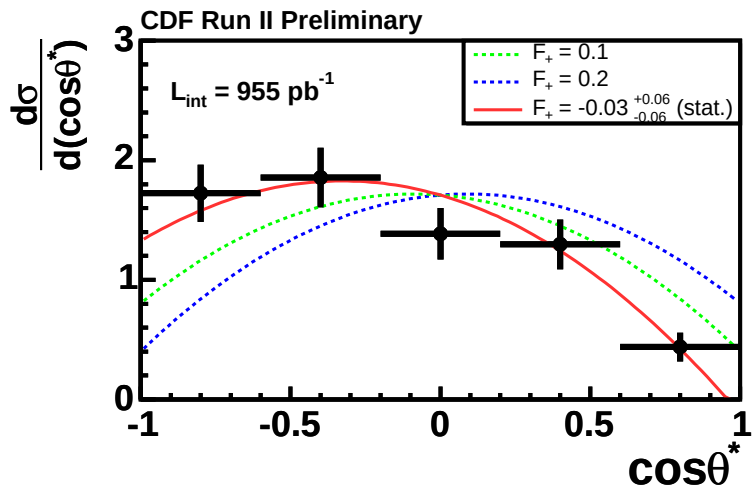
SM prediction of helicity fractions (assuming M_t=175GeV):

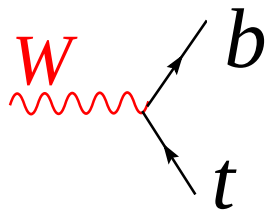
- longitudinal f_0 = 0.7
- left-handed f_- = 0.3
- right-handed f_+ = 0

W helicity in top decays







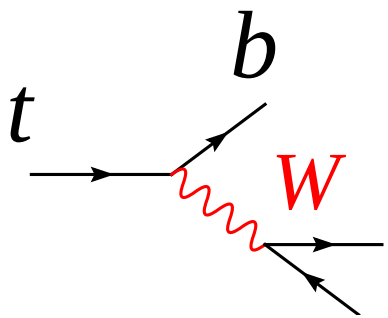


- f_0 is set to SM value in fitting f_+
- f_+ is set to zero in fitting f_0

	f_0	f_+
CDF (~700 pb^{-1}) [prelim]		-0.02 ± 0.07
CDF (955 pb^{-1}) [prelim]	$0.61 \pm 0.12(\text{stat}) \pm 0.04(\text{syst})$	$-0.06 \pm 0.06(\text{stat}) \pm 0.03(\text{syst})$
CDF (955 pb^{-1}) [prelim]	$0.59 \pm 0.12(\text{stat}) \pm^{0.07}_{0.06}(\text{syst})$	$-0.03 \pm 0.06(\text{stat}) \pm^{0.04}_{0.03}(\text{syst})$
DØ (370 pb^{-1}) [prelim]		$0.08 \pm 0.08(\text{stat}) \pm 0.05(\text{syst})$

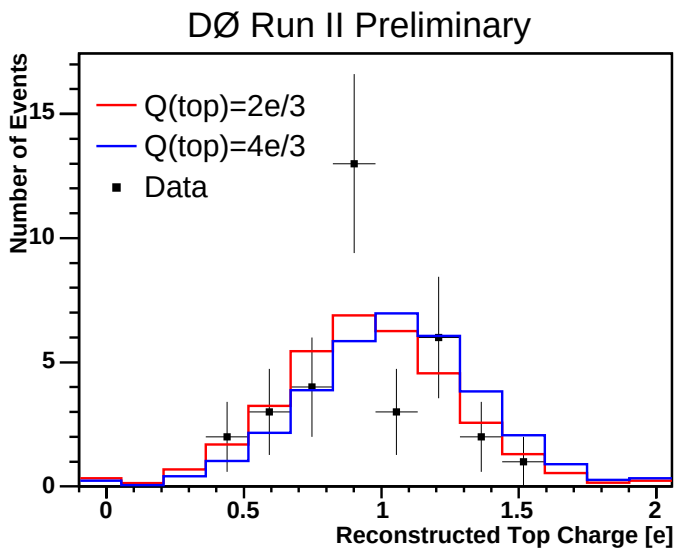
Top quark electric charge

- DØ (360 pb-1)
- Compare SM top charge hypothesis:
  - t(2/3)→W^++b(–1/3)
- To exotic hypthesis
  - t(-4/3)→W^-+b(–1/3)



$$t\bar{t} \rightarrow \ell \nu b \bar{b} j j$$

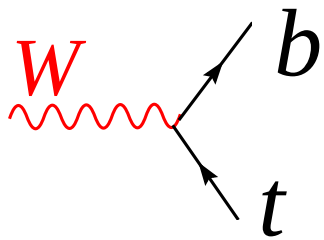
  - b-jets tagged with displaced vertices
  - Kinematic fitting to assign jets
  - Charge of b-jets measured from jet charge
- Q= –4/3 excluded at 94% CL (preliminary)



Wbt vertex: B(t→Wb)

- CDF and DØ measure

$$R = \frac{B(t \to Wb)}{B(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}$$



by counting the number of b-tagged jets in top events

$$\mathrm{R} = 1.03 \pm^{0.19}_{0.17}$$ DØ 230 pb^{-1}

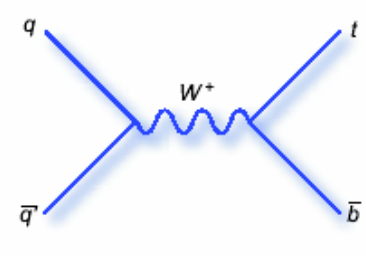
$$\mathrm{R} = 1.21 \pm^{0.21}_{0.19}$$ CDF 162 pb^{-1}

$$SM : |V_{tb}| \approx 0.999 \Rightarrow \mathrm{R} \approx 0.998$$

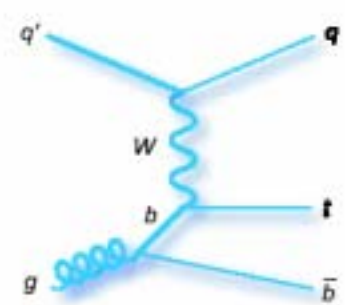
(R measurements can be turned into limits on $|V_{tb}|$ if you assume $|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2 = 1$)

Wtb vertex: search for single top

- rate measurement would give direct measurement of $|V_{tb}|$ CKM element **without** assuming $|V_{td}|^2 + |V_{ts}|^2 |V_{tb}|^2 = 1$
  - $\sigma \propto |V_{tb}|^2$
- cross sections a few times smaller than for tt
- signature
  - lepton
  - neutrino (missing E_T)
  - 2 b-jets (tagged)
  - characteristic kinematic and angular distributions
- **signals much harder to distinguish from backgrounds**
  - W+ ≥2 jets
  - tt
  - bb

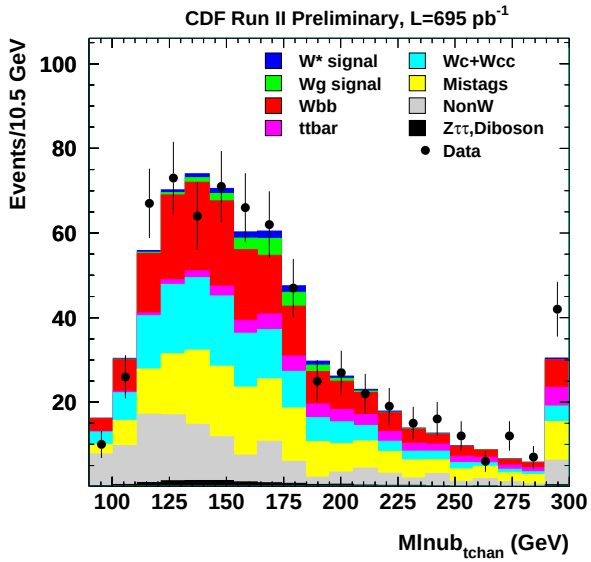


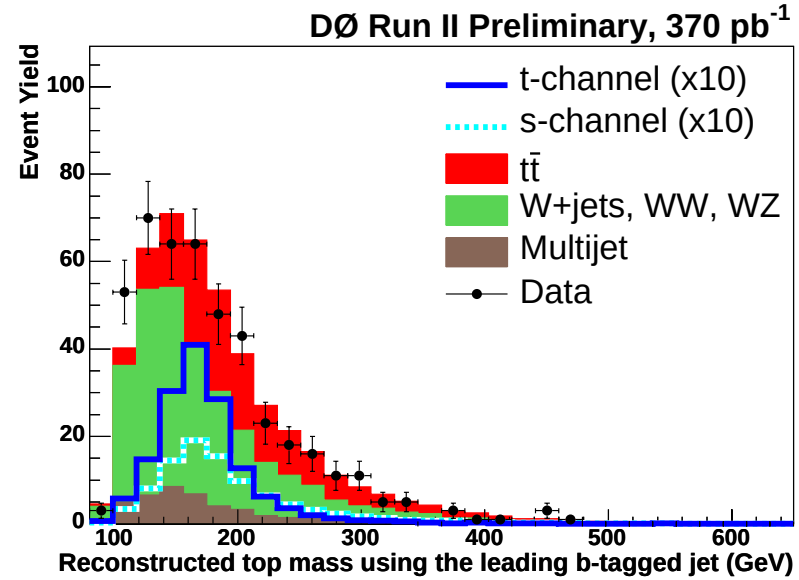
s-channel



t-channel

Single top limits





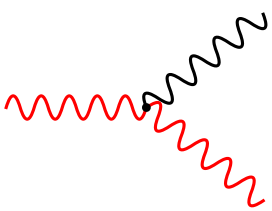
analysis / prediction	luminosity	s-channel xsec (pb)	t-channel xsec (pb)
DØ Likelihood	230 pb-1	<5.0*	<4.4*
CDF Neural Net	700 pb-1	<3.2*	<2.9*
Standard Model		0.88	1.98

B.W. Harris et al. PRD 66:054024 (2002)
compatible results: Campbell/Ellis/Tramontano, PRD 70:094012 (2004)

SM within reach in RunII

Trilinear Gauge Couplings

- Triple gauge boson vertices
  - WWγ, WWZ, ZZγ, Zγγ
- Can contribute to diboson production processes at LEP and the Tevatron
- New results from Tevatron on

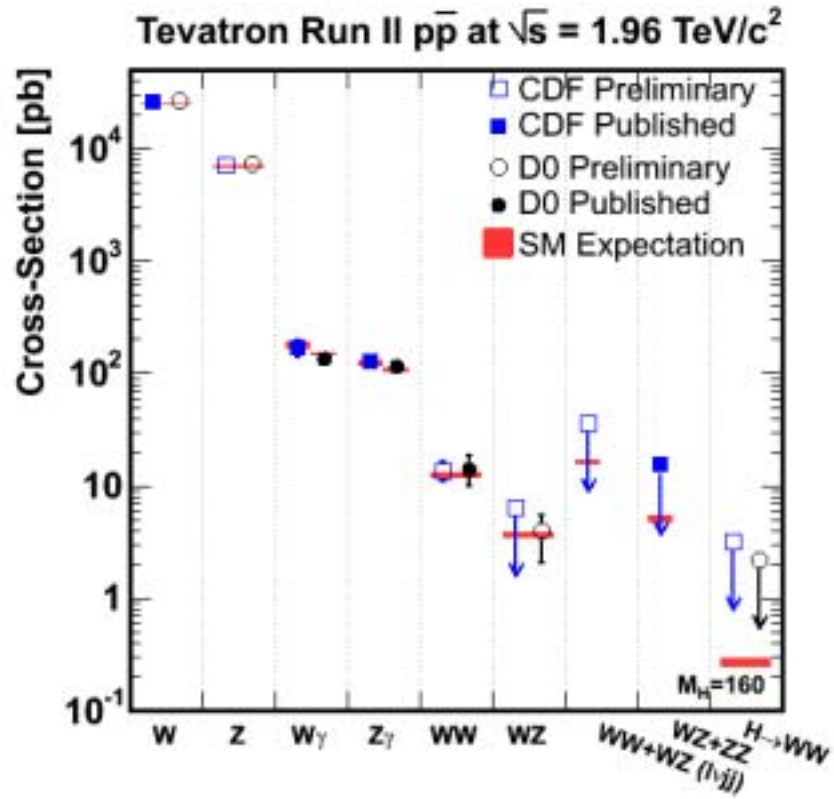


$$q\bar{q}' \to W\gamma$$

$$q\bar{q} \to Z\gamma$$

$$q\bar{q} \to WW$$

$$q\bar{q}' \to WZ$$



$$L_{WWV} = ig_1^{V}\left(W_{\mu\nu}W^{\mu}V^{\nu} - W_{\mu}V_{\nu}W^{\mu\nu}\right) + i\kappa_V W_{\mu}W_{\nu}V^{\mu\nu} + \frac{i\lambda_V}{M_W^2}W_{\lambda\mu}W_{\nu}^{\mu}V^{\nu\lambda}$$

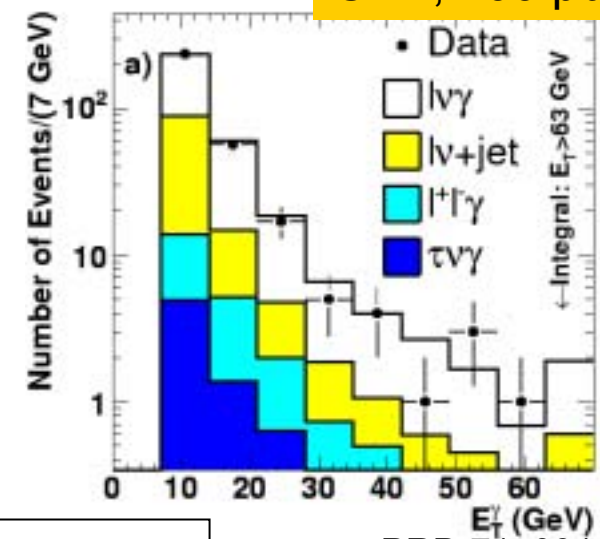
W+γ at the Tevatron

- Examines WWγ vertex
  - > 100 each in electron, muon channels for each experiment
- Cross section in good agreement with SM calculations
  - CDF, ETγ>7 GeV
    - 18.1±3.1 pb (obs) vs 19.3±1.4 pb (theory)
  - DØ, ETγ>8 GeV
    - 14.8±2.1 pb (obs) vs 16.0±0.4 pb (theory)
- Limits on WWγ TGC (DØ, 95% CL):

$$0.12 < \kappa_\gamma < 1.96$$
$$-0.20 < \lambda_\gamma < 0.20$$

PRL 94, 041803 (2005)

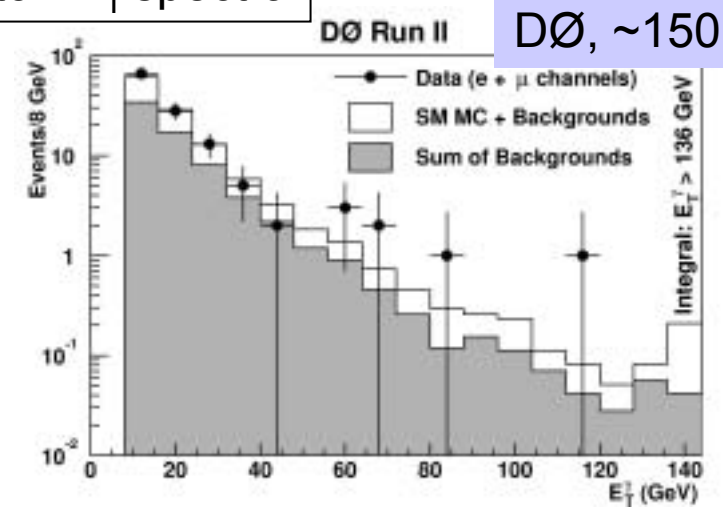
CDF, 200 pb^{-1}



Photon E_T spectra

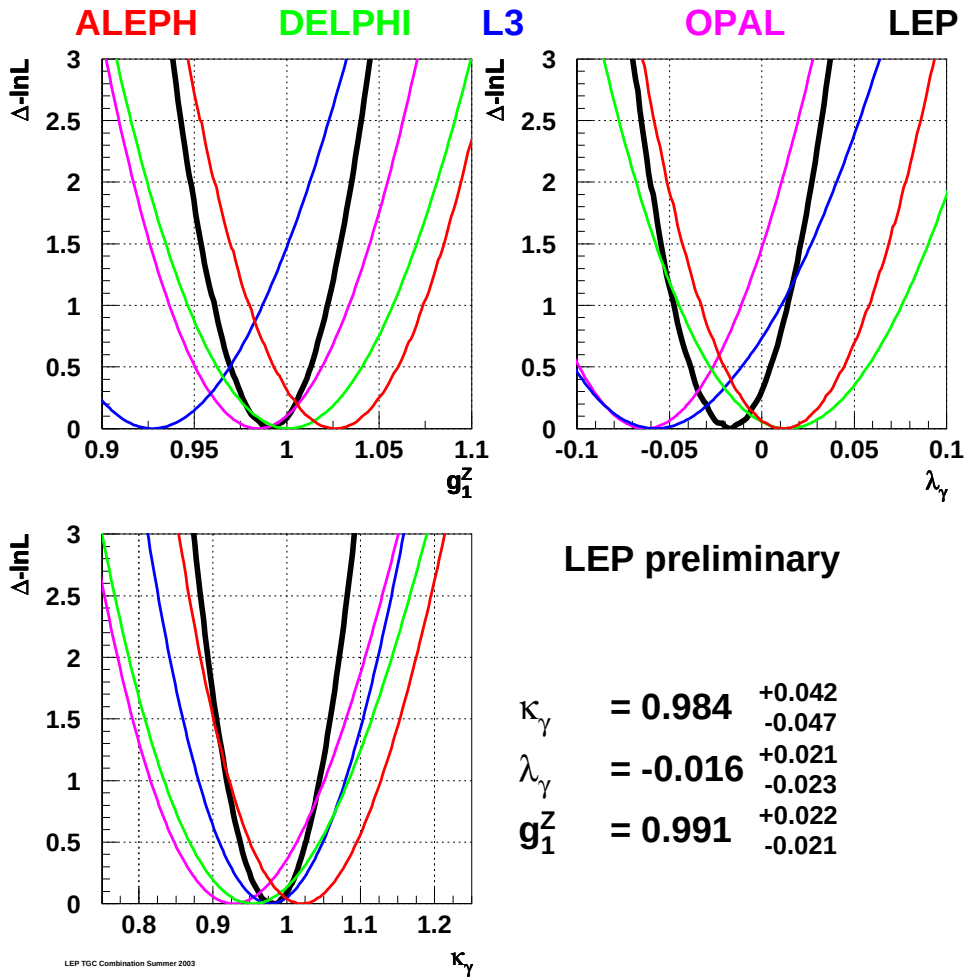
PRD 71, 091108 (2005)

DØ, ~150 pb^{-1}



WW and Wγ at LEP

- 2005 measurements from LEP of κ and λ still world's best



LEP preliminary

$\kappa_\gamma = 0.984^{+0.042}_{-0.047}$

$\lambda_\gamma = -0.016^{+0.021}_{-0.023}$

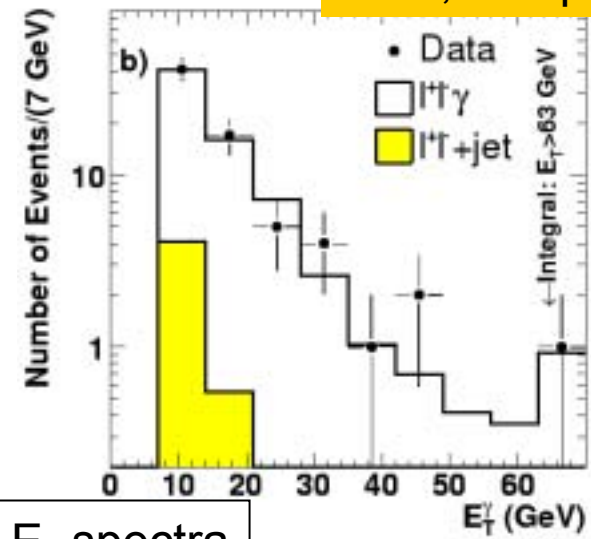
$g_1^Z = 0.991^{+0.022}_{-0.021}$

Z+γ at the Tevatron

- ZZγ, Zγγ vertices do no exist in SM
  - In SM, photon in Z+γ is events produced by initial or final state radiation (ISR/FSR)
  - Analyses require photon lepton separation to suppress FSR
- Cross section in good agreement with SM calculations (E_T^{γ}>7 GeV)
  - CDF (PRD 94, 041803)
    - 4.6±0.6 pb
  - DØ (preliminary)
    - 4.5±0.5 pb
  - Theory
    - 4.5±0.3 pb

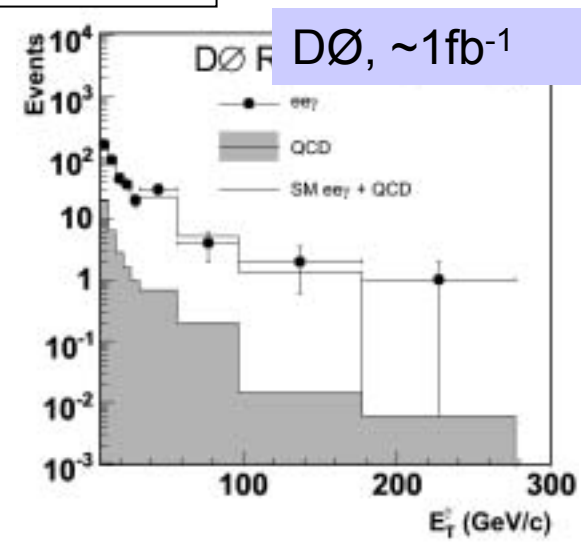
Baur & Berger, PRD 41, 1476, PRD 47,4889

CDF, 200 pb^{-1}



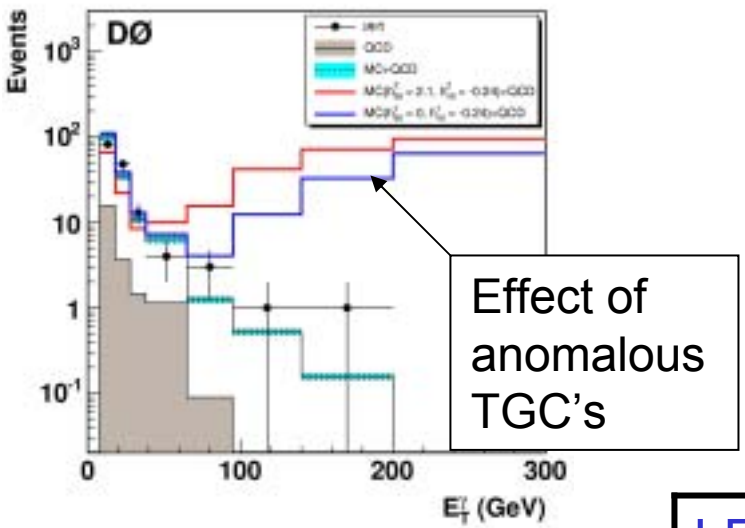
Photon E_T spectra

DØ, ~1fb^{-1}



Zγ Trilinear Coupling Limits

- Zγγ* (95% CL)



LEP	DØ (~300 pb^{-1})
$-0.13 < h_1^Z < 0.13$	$-0.23 < h_1^Z < 0.23$
$-0.078 < h_2^Z < 0.071$	$-0.02 < h_2^Z < 0.02$
$-0.20 < h_3^Z < 0.07$	$-0.23 < h_3^Z < 0.23$
$-0.05 < h_4^Z < 0.12$	$-0.019 < h_4^Z < 0.019$

- ZγZ* (95% CL)

LEP	DØ (~300 pb^{-1})
$-0.056 < h_1^\gamma < 0.055$	$-0.23 < h_1^\gamma < 0.23$
$-0.045 < h_2^\gamma < 0.045$	$-0.02 < h_2^\gamma < 0.02$
$-0.049 < h_3^\gamma < 0.008$	$-0.23 < h_3^\gamma < 0.23$
$-0.002 < h_4^\gamma < 0.034$	$-0.019 < h_4^\gamma < 0.019$

LEP: hep-ex/0511027
D0: PRL 95, 051802 (2005)

WW at the Tevatron

- WW→llνν
  - Good signal extraction
  - Theory (Campbell, Ellis):

$$\sigma = 12.4 \pm 0.8\text{pb}$$

  - CDF (825 pb^{-1}):

$$\sigma = 13.6 \pm 2.3(\text{stat}) \pm 1.6(\text{sys}) \pm 1.2(\text{lum})\text{pb}$$

  - DØ (~250 pb^{-1}):

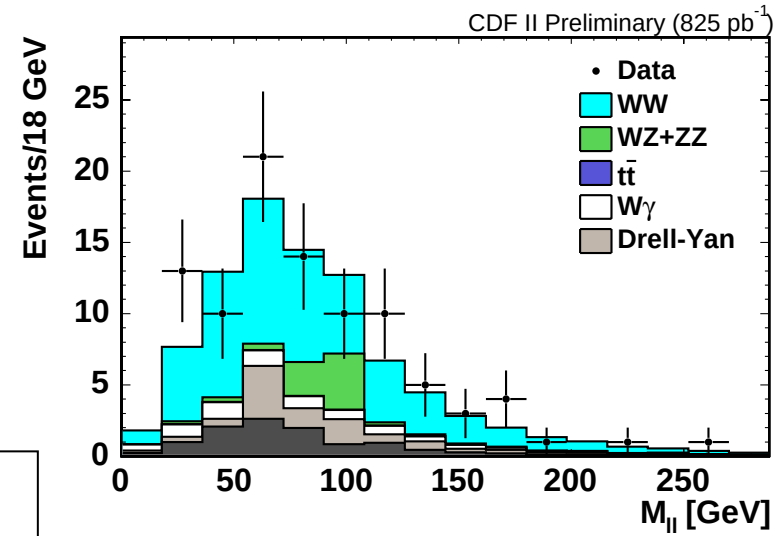
$$\sigma = 13.8^{+4.3}_{-3.8}(\text{stat})^{+1.2}_{-0.9}(\text{sys}) \pm 0.9(\text{lum})\text{pb}$$

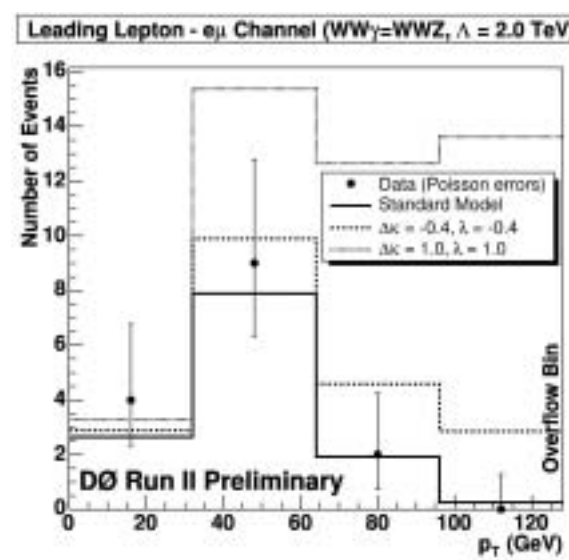
$$0.68 < \kappa < 1.45$$
$$-0.29 < \lambda < 0.30$$

- WW+WZ→lνjj
  - CDF (350 pb^{-1})

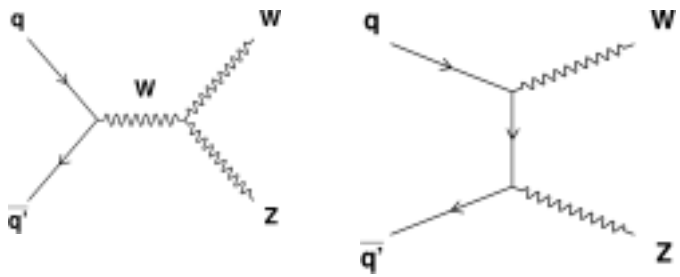
$$0.49 < \kappa < 1.44$$
$$-0.28 < \lambda < 0.28$$

$$\sigma(WW + WZ) < 36 \text{ pb @ } 95\% \text{ CL}$$





WZ at the Tevatron



Clean channel: WZ→*lll*ν

- CDF (825 pb^{-1})
  - 4.6 events expected (3.7 sig+0.9 bkg)
  - 2 events observed
  - Set limit:

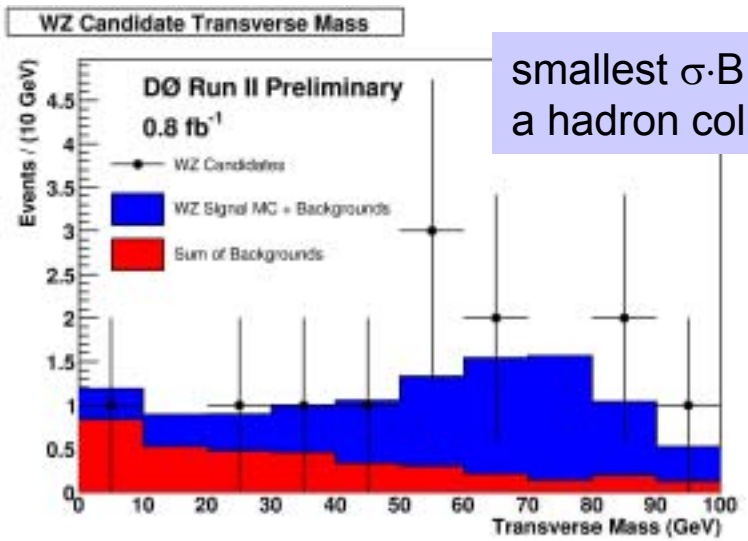
$$\sigma(WZ) < 6.3\text{pb} @ 95\%\text{CL}$$

- DØ (~800 pb^{-1})
  - 11.1 events expected (7.5sig +3.6 bkg)
  - 12 observed
  - 3.3σ significance
  - Measure cross section:

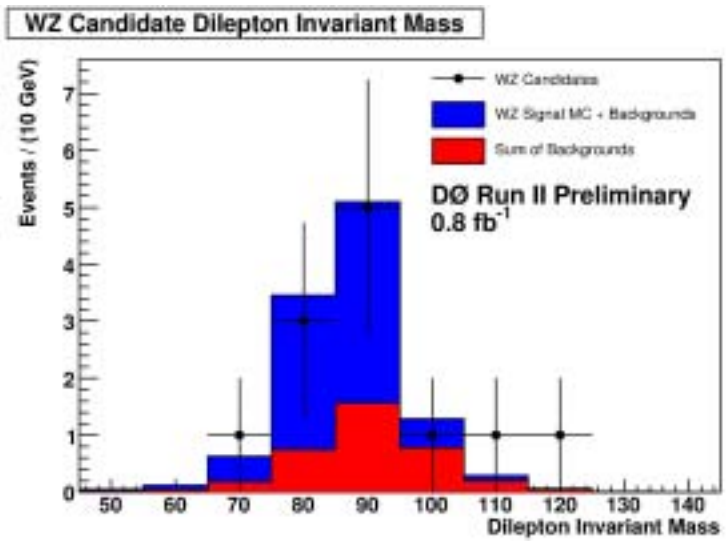
$$\sigma(WZ) = 4.0^{+1.9}_{-1.5}\text{pb}$$

- Theory

$$\sigma(WZ) = 3.7 \pm 0.1\text{pb}$$

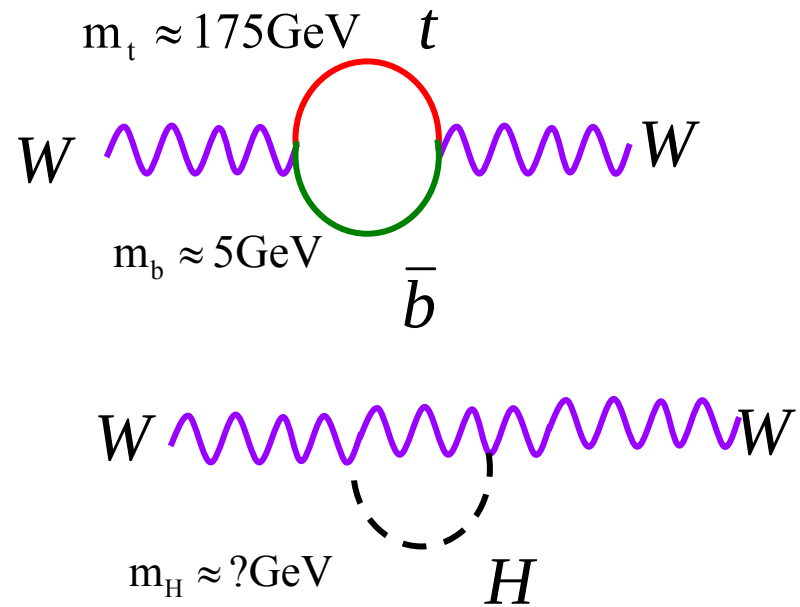


smallest σ·B seen at a hadron collider



Critical EW mass measurements

$$M_W^2 = \frac{\pi \alpha_{EM}}{\sqrt{2} G_F \left(1 - M_W^2 / M_Z^2\right)\left(1 - \Delta r\right)}$$

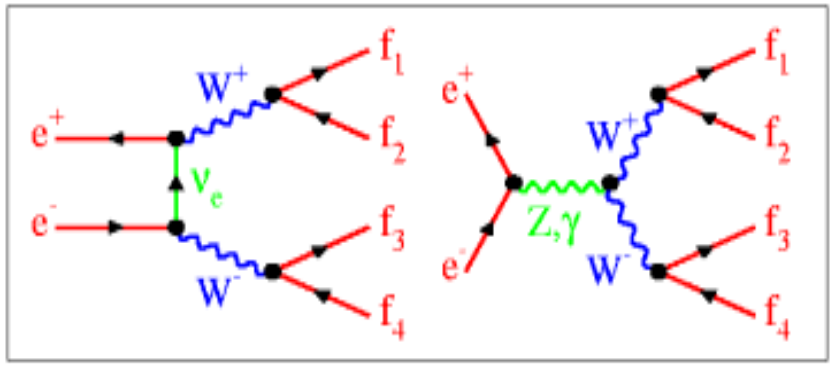


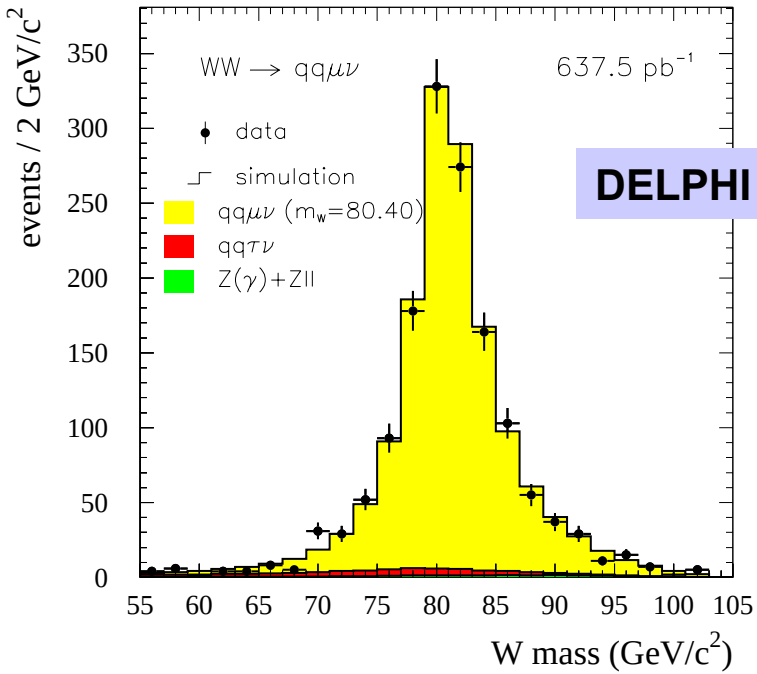
- W mass has quadratic dependence on top mass, logarithmic dependence on Higgs mass through radiative corrections

- top mass and W mass are essential in
  - testing the consistency of the SM
  - predicting Higgs mass
  - further testing SM if Higgs is found

W mass update from LEP 2

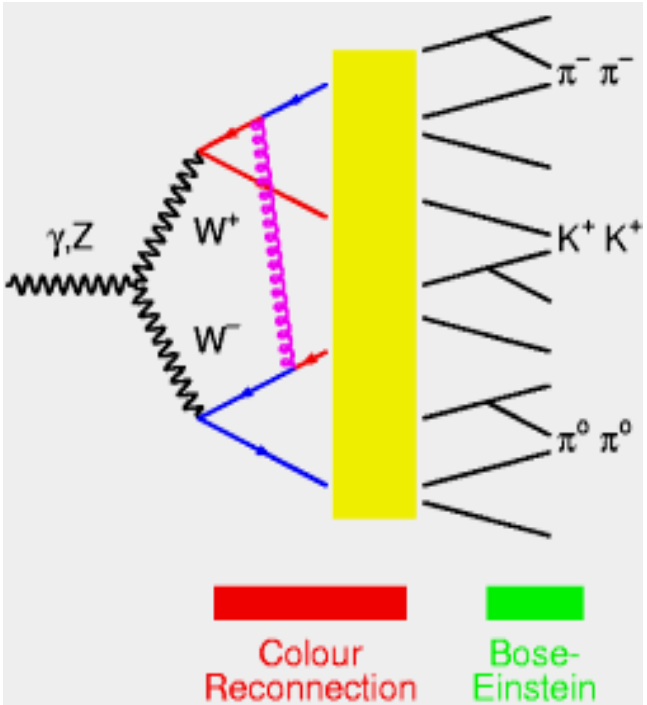
- LEP W mass measured in W pair production
  - Most important channels:
    - WW→lνqq (weight=76%)
    - WW→qqqq (weight=22%)
- W mass measurements from all four LEP experiments are now final
  - DELPHI final result is new
- LEPEWWG combination is not yet final
  - Possible reduction of uncertainty by use of common final state interatction constraints

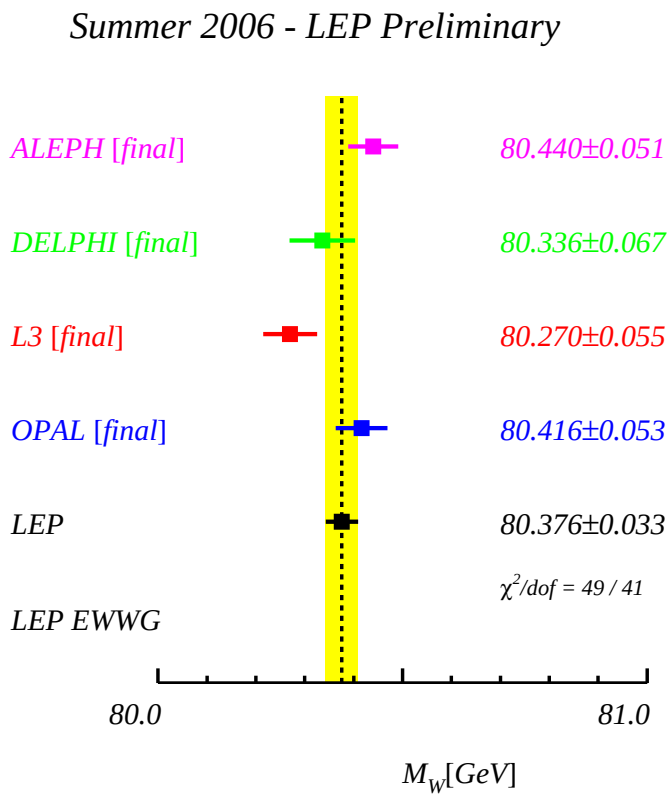




DELPHI final

W mass at LEP





prob. fit: 11.1%

- **Main area of recent work: Final State Interactions (FSI)**
  - **Mainly effects qqqq channel**
    - **"color reconnection"**
    - **Bose-Einstein correlations**

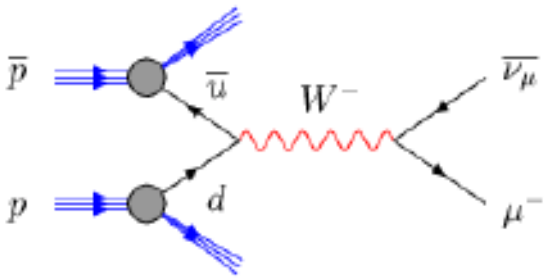
Difference between channels:

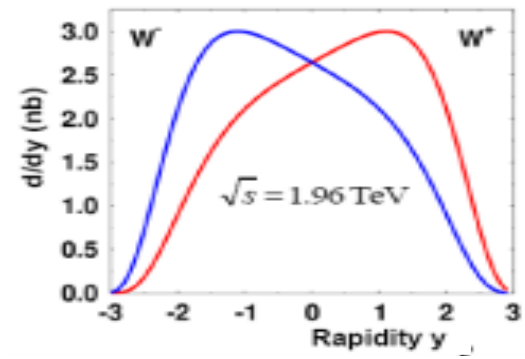
M_W(4q-2q) = -11.7 ± 44.6 MeV/c2

W mass at the Tevatron

- No results yet for Run II
  - Tevatron Run I: M_W=80.452±0.059 GeV
- Related Run II measurements used to constrain model of W production at the Tevatron
  - W charge asymmetry
  - W forward vs. central cross sections
    - Constrain parton distribution functions using W sample itself
  - Z rapidity distribution
    - W and Z production mechanisms are almost identical

W charge asymmetry

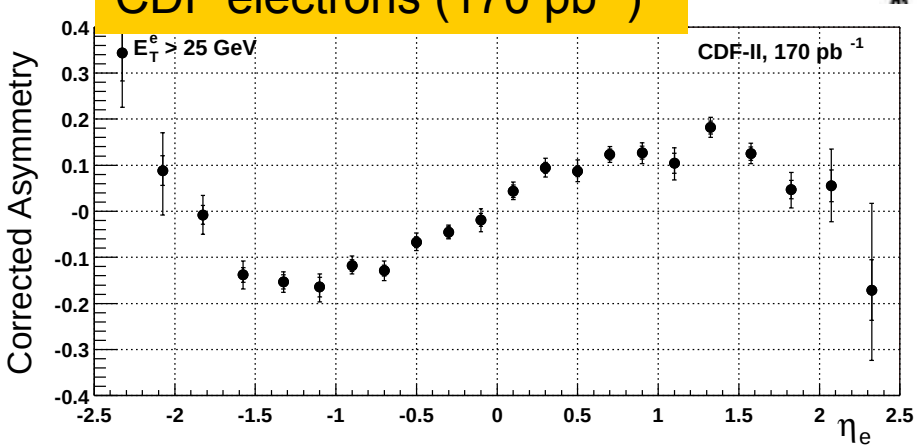




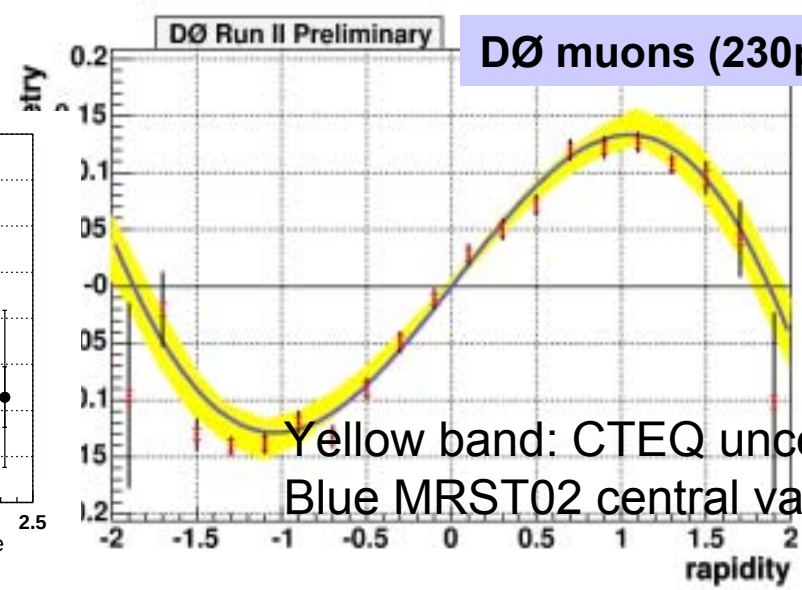
Typically the u quark carries more of the proton momentum → W^+ is boosted in the direction of the proton

$$A(y_\mu) = \frac{N_{\mu^+}(y_\mu) - N_{\mu^-}(y_\mu)}{N_{\mu^+}(y_\mu) + N_{\mu^-}(y_\mu)}$$

CDF electrons (170 pb^{-1})



DØ muons (230pb^{-1})



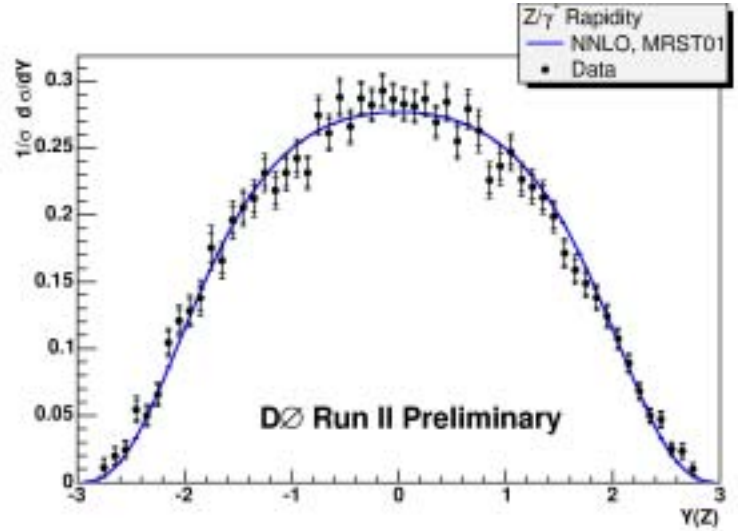
Yellow band: CTEQ uncertainty
Blue MRST02 central value

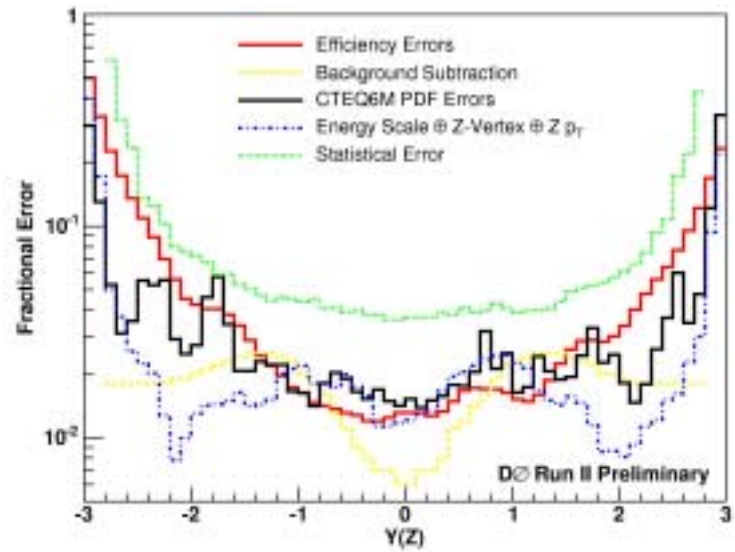
DØ Z rapidity

$$y = \frac{1}{2}\ln\left(\frac{E^Z + p_z^Z}{E^Z - p_z^Z}\right)$$

- At leading order :

$$x_p, x_{\bar{p}} = \left(\frac{M}{\sqrt{s}}\right)e^{\pm y}$$





Not yet enough statistics to constrain PDF uncertainties, but should be possible in foreseeable future

Forward W cross section (CDF)

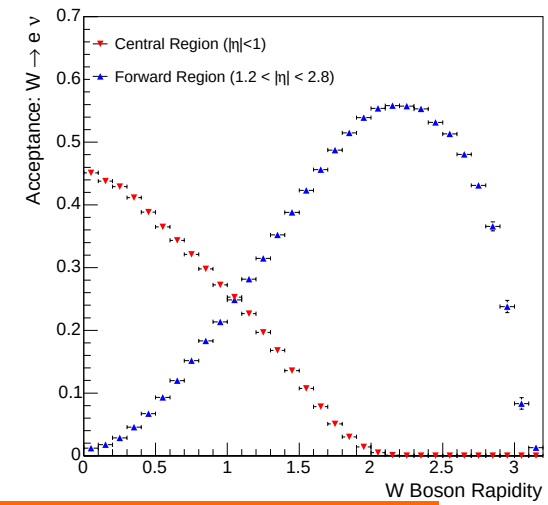
Similar to Z rapidity, a comparison of W cross section from central and forward electrons constrains W production model

- **longitudinal momentum distribution of W boson is important because acceptance affects couples this to observed transverse momentum distribution**

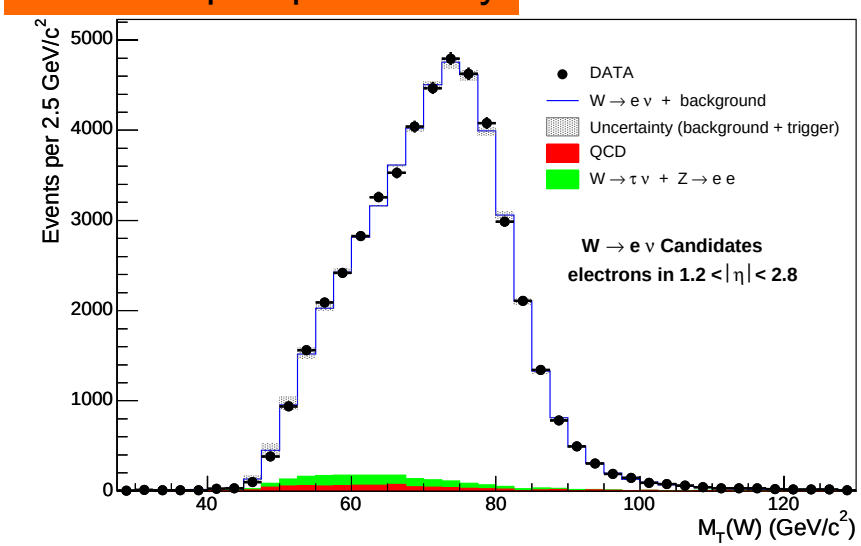
$$R_{\exp}^{central/forward} = 0.925 \pm 0.033$$

$$R_{CTEQ\ 6.1}^{central/forward} = 0.924 \pm 0.037$$

$$R_{MRST\ 01E}^{central/forward} = 0.941 \pm 0.012$$



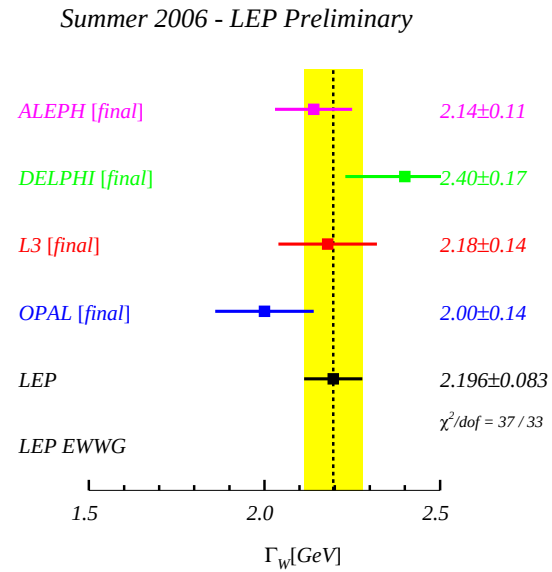
CDF 223 pb^{-1} preliminary



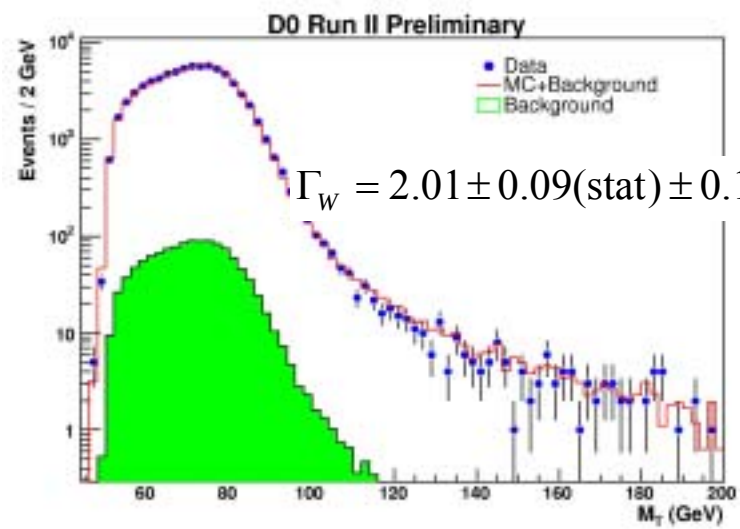
W Boson width

- From LEP
  - Determined from the kinematic fits of WW events (same fits that give mass)
  - All four measurement now final
  - Preliminary combination:

$$\Gamma_W = 2.196 \pm 0.083 \text{ GeV}$$



- From Tevatron
  - Fits to the high tail of the transverse mass distribution for W→lν events
  - Also measured indirectly from ratio



$$\Gamma_W = 2.01 \pm 0.09(\text{stat}) \pm 0.11(\text{syst}) \text{ GeV}$$

$$R = \frac{\sigma(p\bar{p} \to W + X) B(W \to \ell\nu)}{\sigma(p\bar{p} \to Z + X) B(Z \to \ell^+\ell^-)} = \frac{\sigma(W)}{\sigma(Z)} \cdot \frac{\Gamma(W \to \ell\nu)}{\Gamma_W B(Z \to \ell^+\ell^-)}$$

$$\Gamma_W = 2.092 \pm 0.042 \text{ GeV}$$

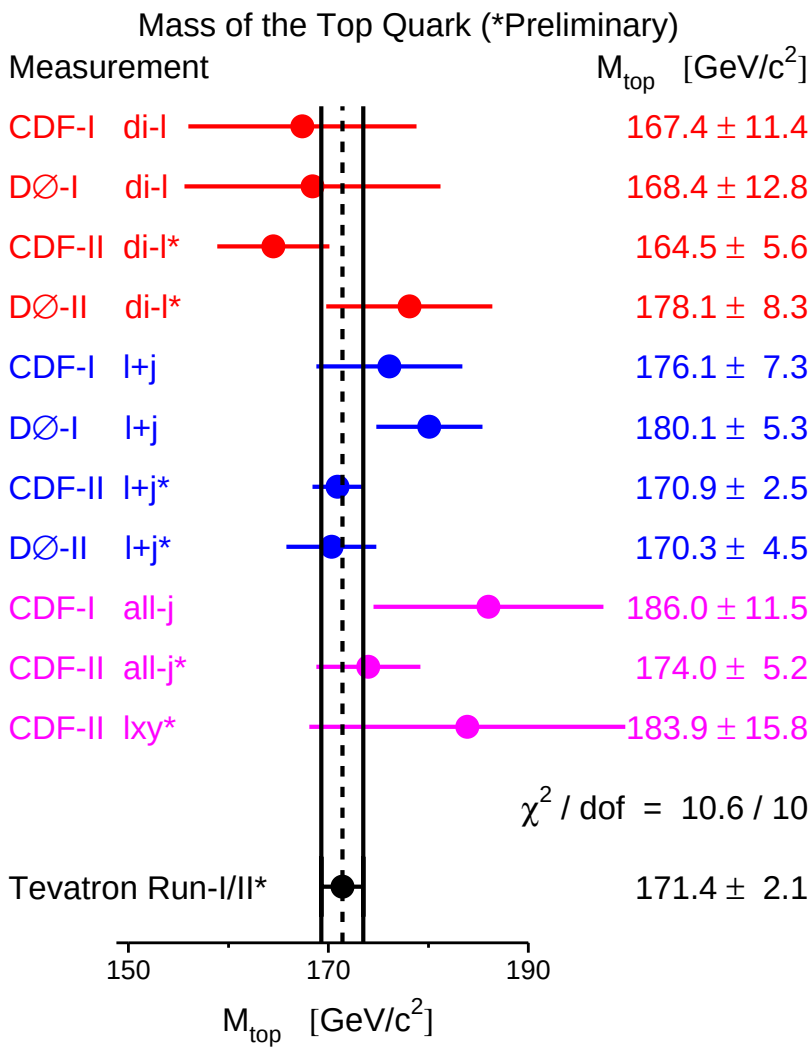
CDF e+μ, 72 pb^{-1}
PRL 94, 091803 (2005)

Top quark mass

- Measured at the Tevatron in modes:
  - Dilepton $t\bar{t} \rightarrow \ell \nu \ell \nu b\bar{b}$
  - Lepton + jets $t\bar{t} \rightarrow \ell \nu jjb\bar{b}$
  - All jets $t\bar{t} \rightarrow jjjjb\bar{b}$
- Many new results since last year
- New preliminary Tevatron average:

$$M_{top} = 171.4 \pm 2.1\,\text{GeV}$$

See Doug Glenzinski's talk (following directly) for description of top mass measurements

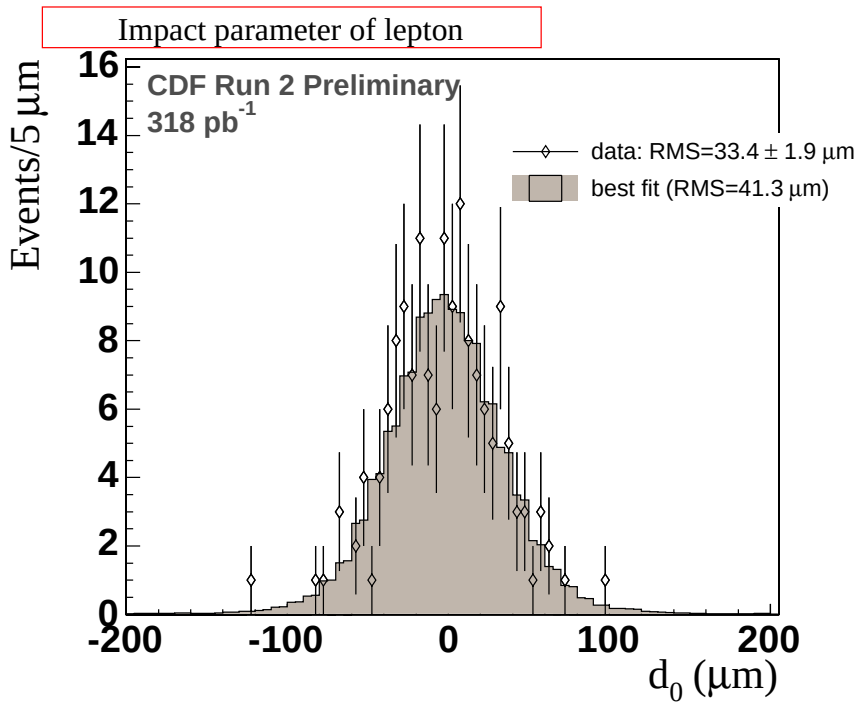


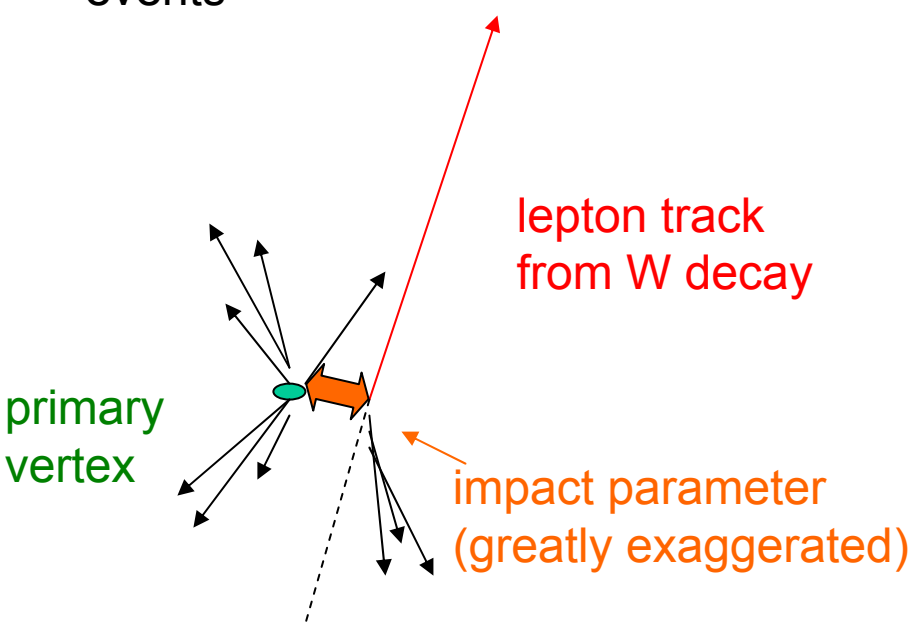
Top quark lifetime

SM:

top quark width = 1.5 GeV
$\Rightarrow c\tau_{top} \sim 130$ fm

Measure upper limit on τ_{top} by looking at impact parameter of leptons from W-decays in $t\bar{t}$ events





$$c\tau_{top} < 53\mu\text{m} \ @\ 95\%\ \text{CL}$$

τ Lepton mass

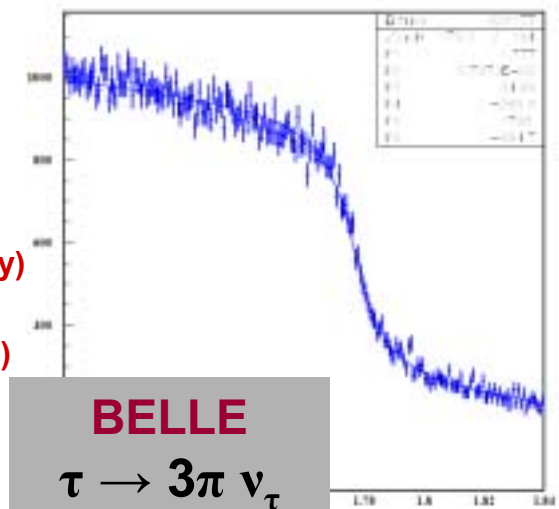
New preliminary measurement of the τ mass from lower energy e^+e^- experiments

- KEDR at VEPP-4M
- BELLE at KEK

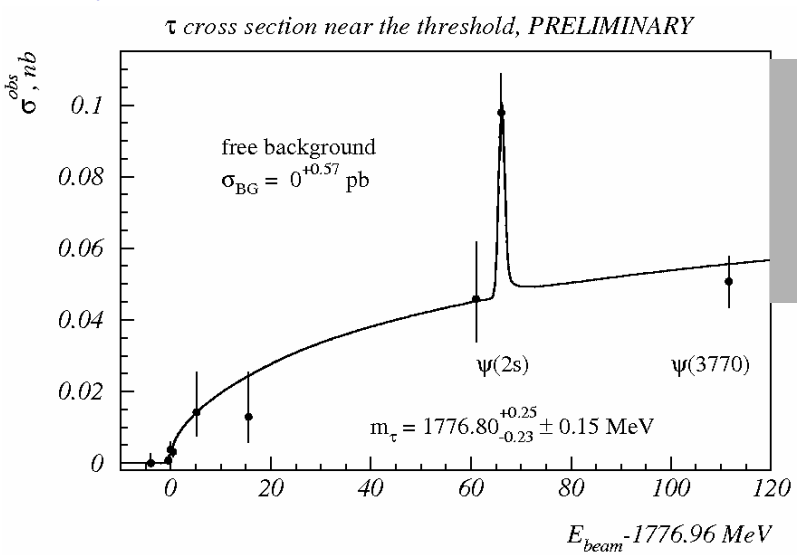
$$M_\tau = 1776.71 \pm 0.13(\text{stat}) \pm 0.32(\text{syst})\ \text{MeV}$$ **(BELLE, preliminary)**

$$M_\tau = 1776.80 \pm^{0.25}_{0.22}(\text{stat}) \pm 0.15(\text{syst})\ \text{MeV}$$ **(KEDR, preliminary)**

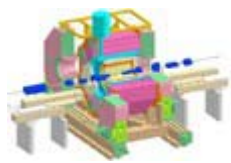
$$M_\tau = 1776.99 \pm^{0.29}_{0.26}\ \text{MeV}$$ **(PDG)**

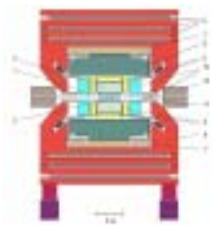


BELLE
$\tau \rightarrow 3\pi\ \nu_\tau$
pseudomass reconstruction



KEDR
τ+τ- cross section near threshold



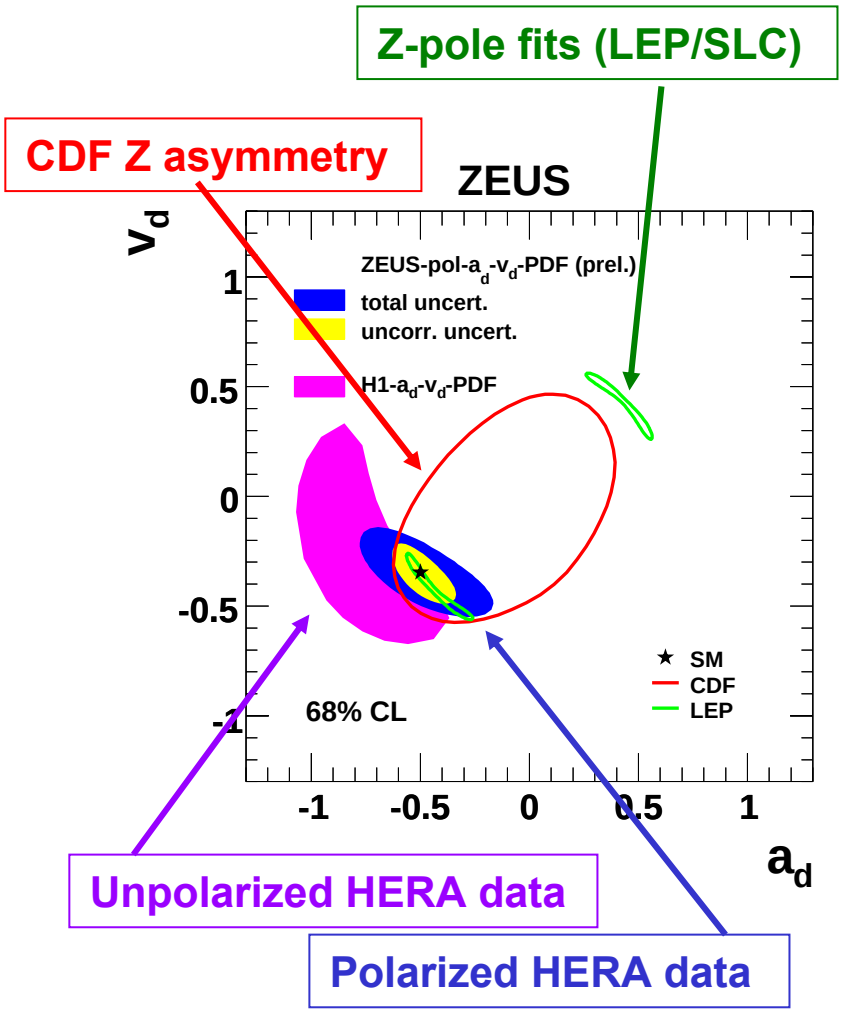


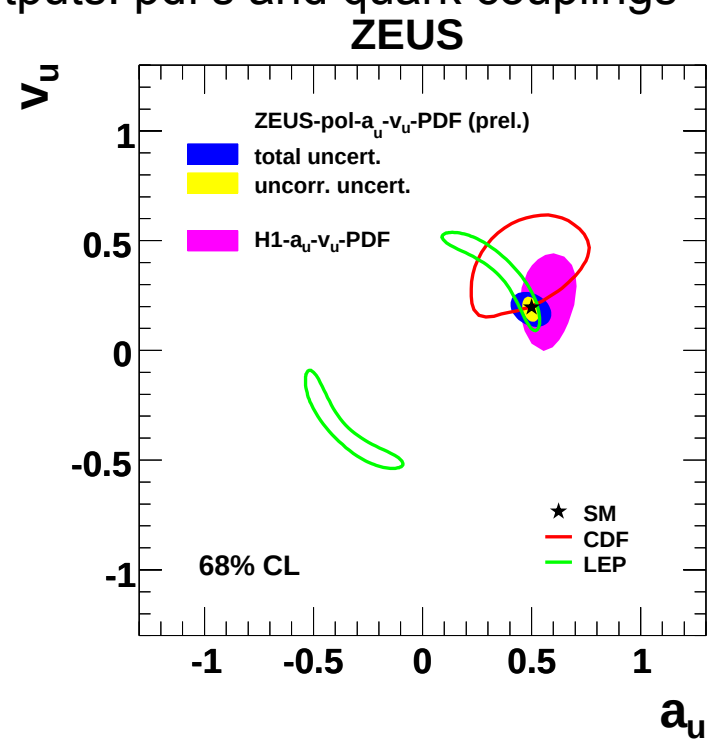
Fits 1: HERA fit to QCD+EW

HERA fit

inputs: (polarized) $e^{\pm}p$ cross sections (charged, neutral, x, Q^2)

outputs: pdf's and quark couplings



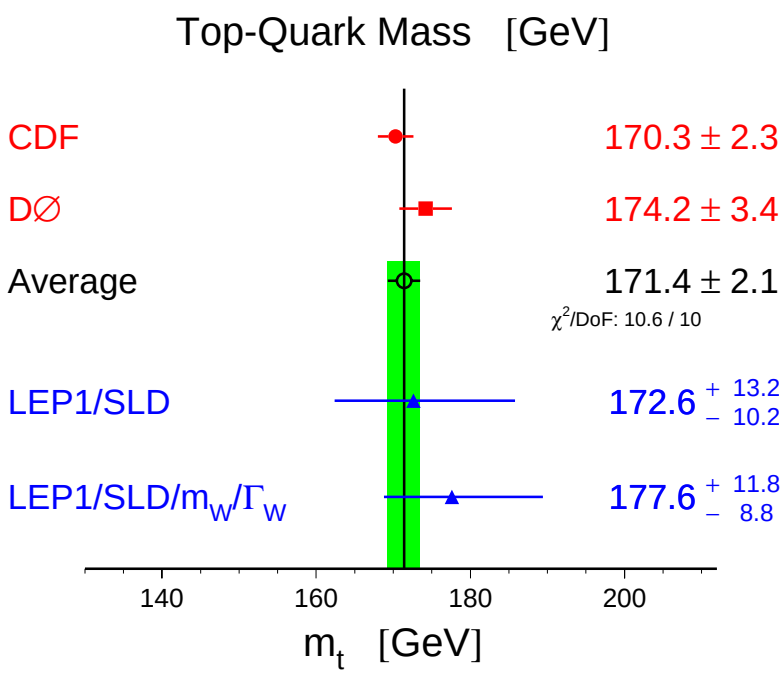


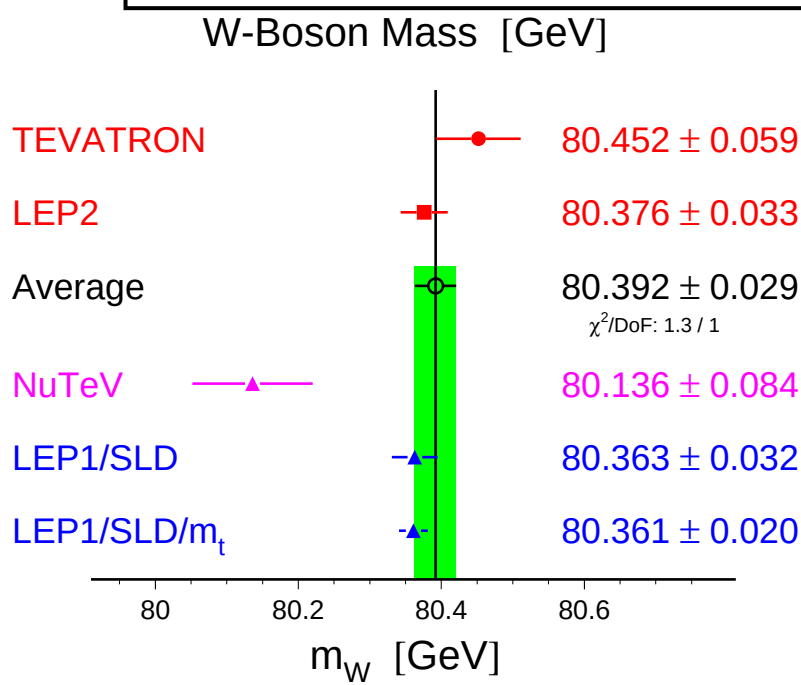
Fits 2: EW fits from LEPEWWG

Fits assume minimal standard model with one Higgs
inputs include: 5 Z lineshape and FB asym.,2 Polarized leptonic asymmetries, 1 Hadronic charge asymmetry, 6 Heavy quark Flavour results, + (top mass, W mass, W width)

- $\Delta\alpha_{had}$ =0.02766 ± 0.00034
- $\alpha_s(Mz)$ = 0.1186 ± 0.00027
- M_z = 91.1874 ± 0.0021 GeV

Since summer '05:
- **M_w direct changed by -0.56σ**, w/ 10% improvement
- **M_t direct changed by -0.49σ**, w/ 28% improvement



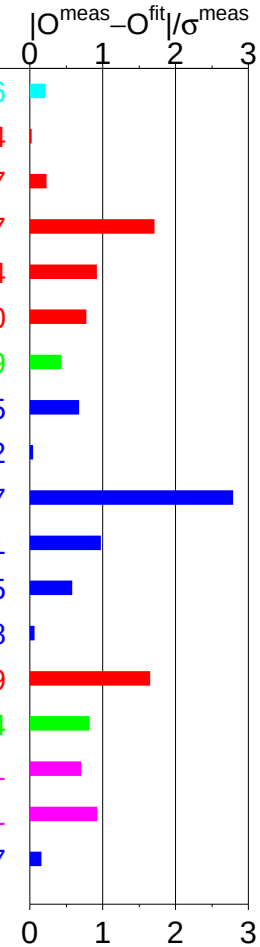


Pulls on the EW fit

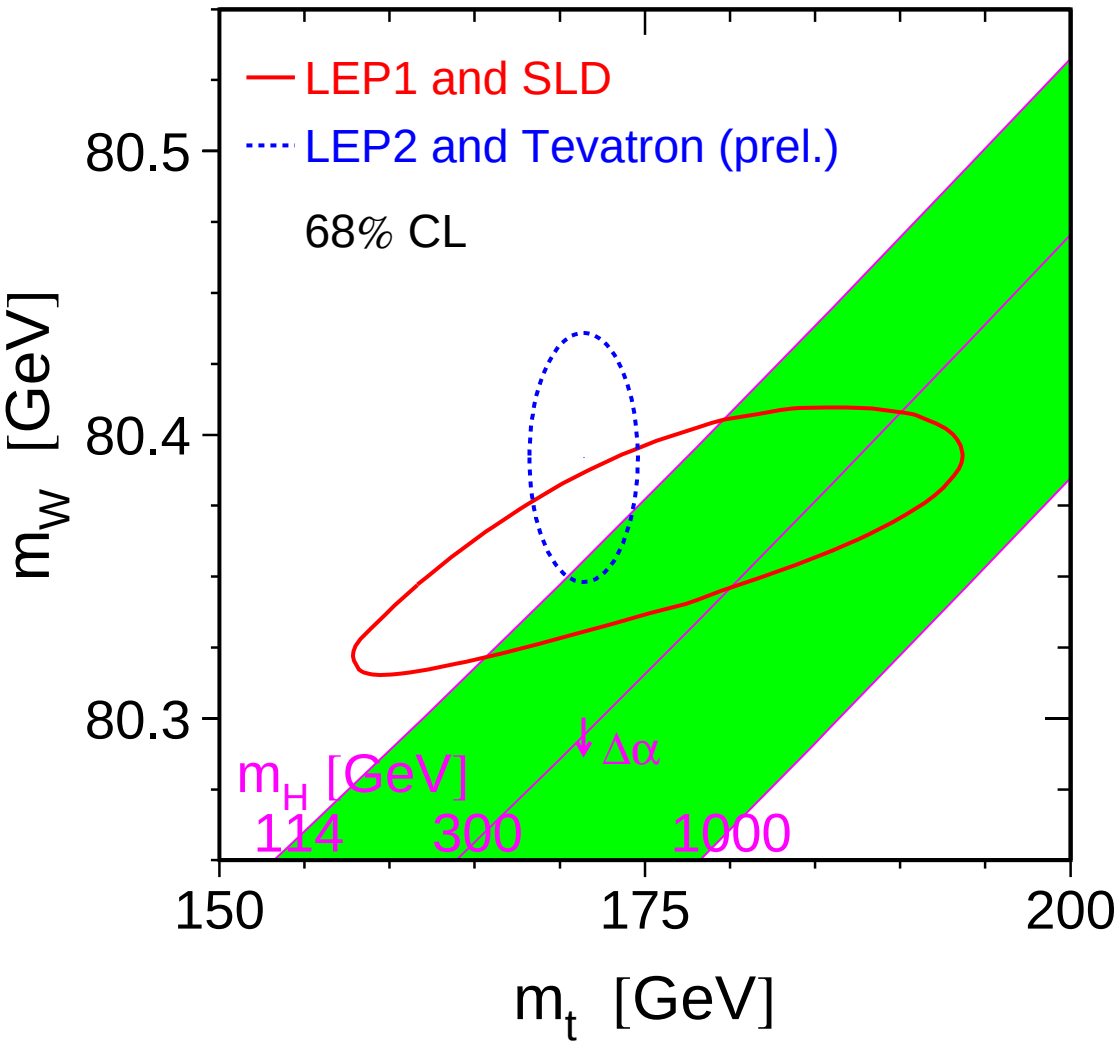
χ^2/dof=17.8/13 (16.6%)

Largest pull is from LEP b-quark forward/backward asymmetry.

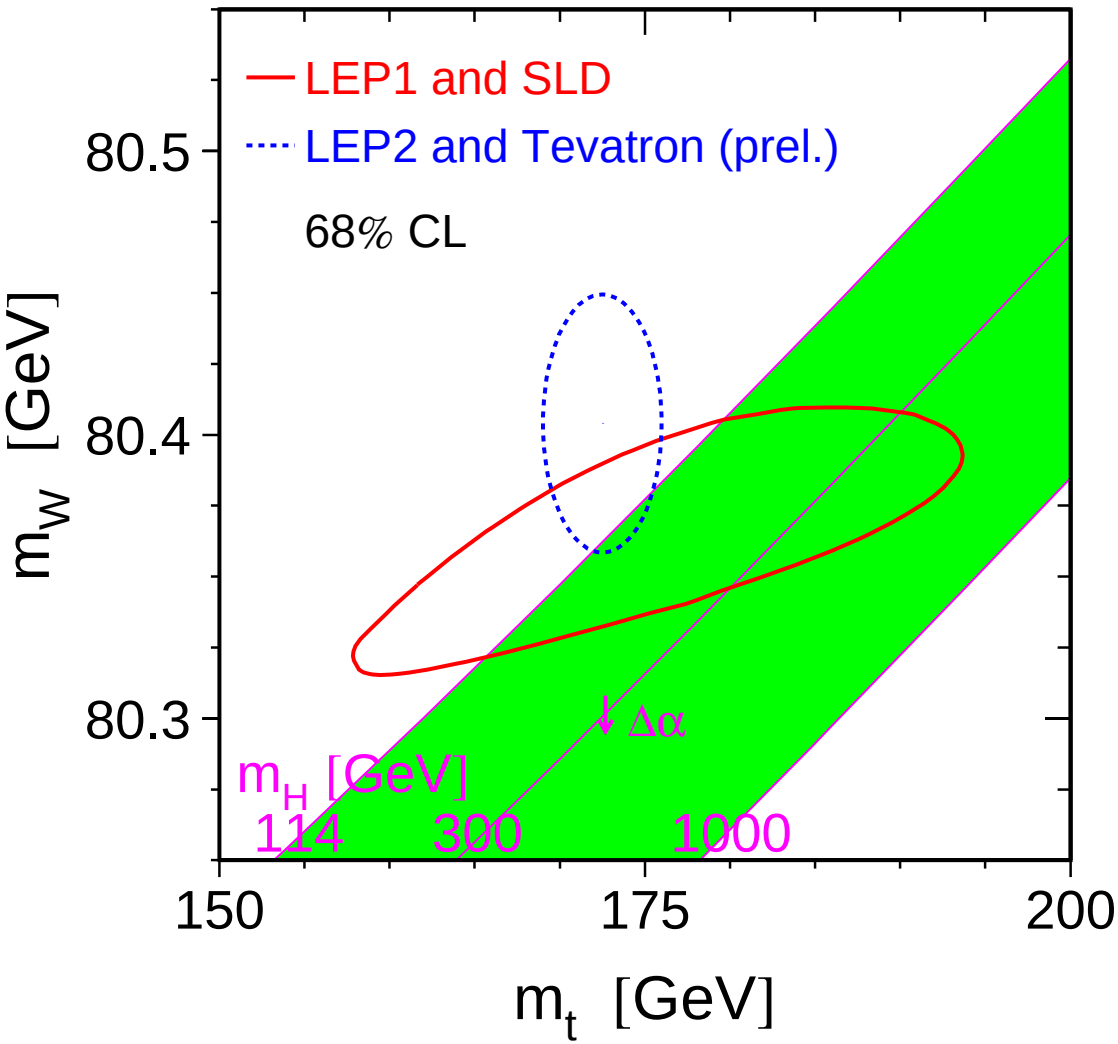
	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02766
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
σ_{had}^0 [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01640
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1479
R_b	0.21629 ± 0.00066	0.21585
R_c	0.1721 ± 0.0030	0.1722
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1037
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0741
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1479
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.392 ± 0.029	80.371
Γ_W [GeV]	2.147 ± 0.060	2.091
m_t [GeV]	171.4 ± 2.1	171.7



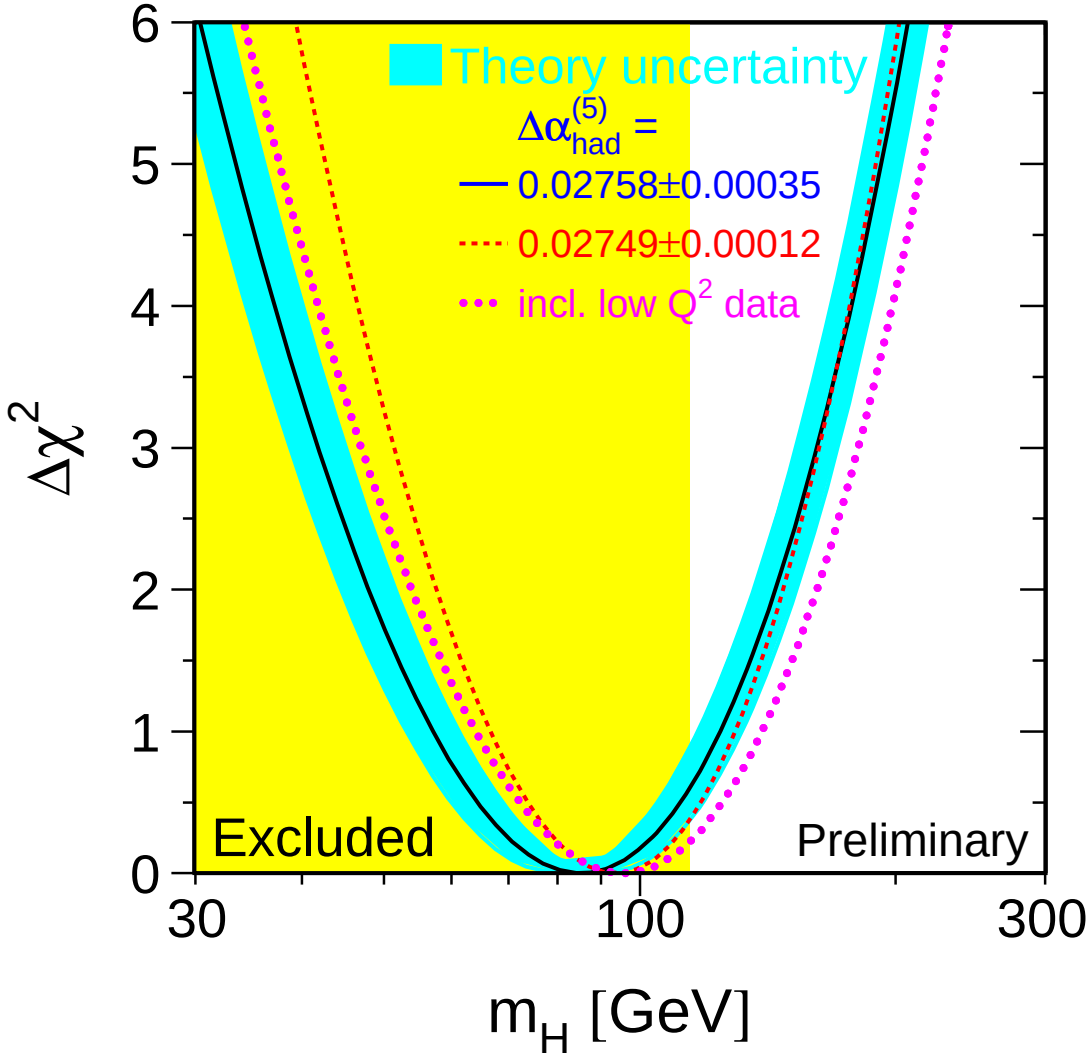
Fit Constraints in M_W-M_t plane – July 06



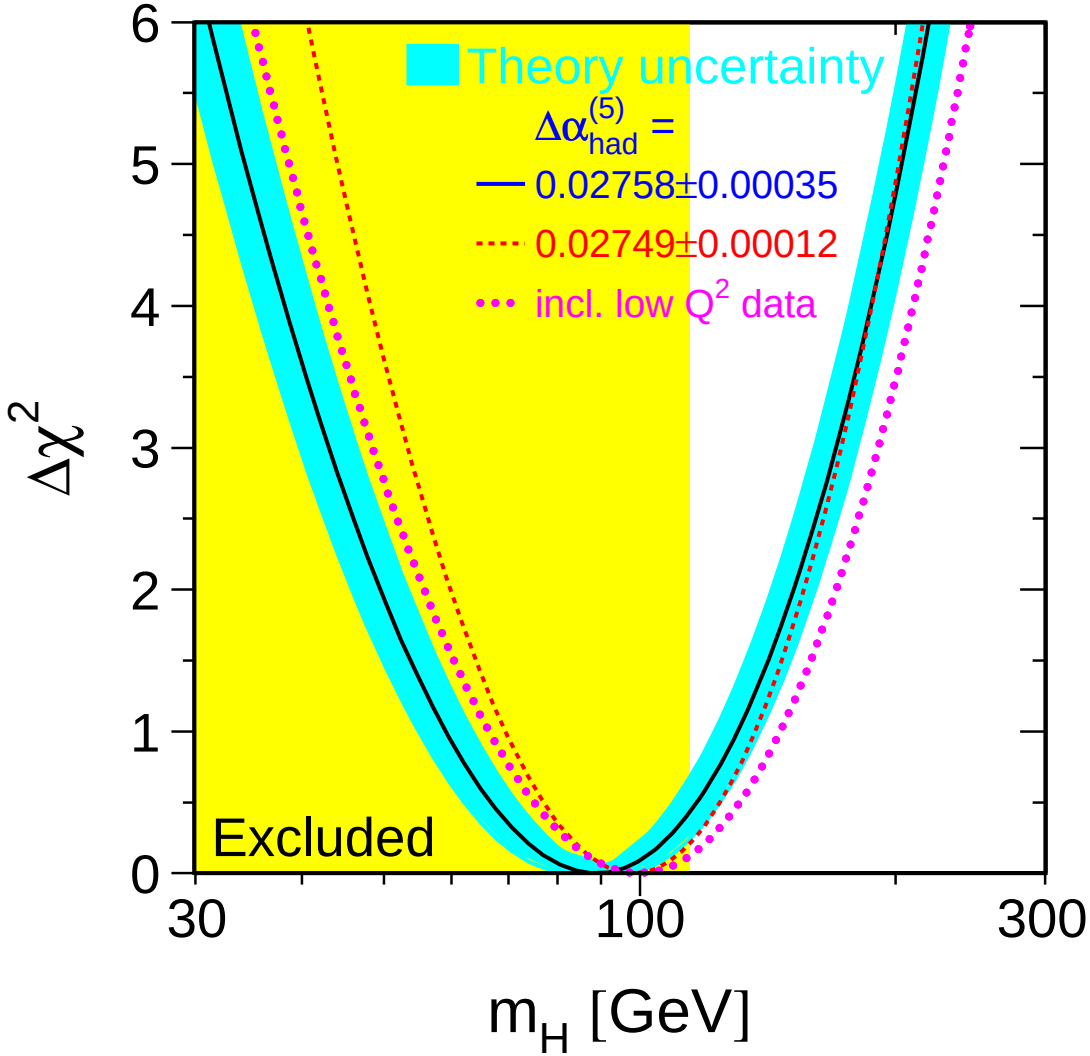
Fit Constraints in M_W-M_t plane – March 06



Constraints on SM Higgs mass – July 06

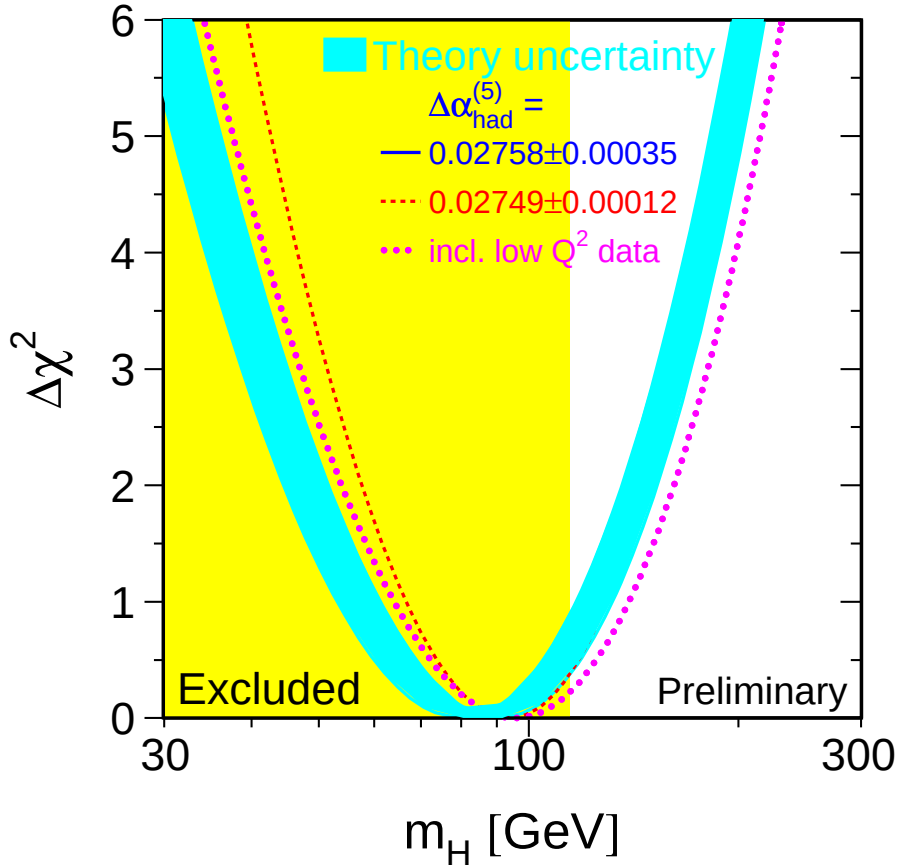


Constraints on SM Higgs mass – March 06



SM Higgs Constraints

- EW fits alone, without theory uncertainties: MH=$85\pm^{39}_{28}$ GeV (68% CL)
- 95% one-sided CL including theory uncertainties ("blue band"):
  - **M_H<166 GeV (ignoring direct limit)**
  - **M_H<199 GeV (including 114 GeV limit)**
- Blue band uncertainties due to uncalculated higher order corrections, estimated by ZFITTER



Outlook – past & present experiments

- LEP analysis is reaching the end
  - final W mass combination still to come
  - LEP/SLD data will continue make up much of the foundation of EW precision fits for some time
- HERA
  - more polarized positron data coming
- Tevatron
  - >1 fb^{-1} recorded, but only a fraction analyzed in some cases
  - expect 4-8 fb^{-1} by end of RunII

Outlook - LHC

Long-term goals include

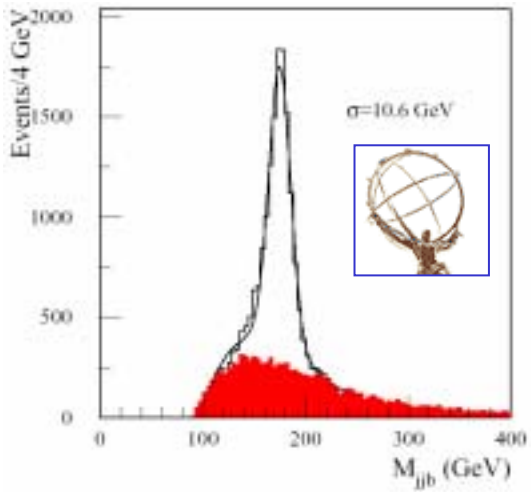
- **top mass measured to <2 GeV**
- **W mass measured to ~15 MeV**
- **improve measurement of λ TGC's**

Strategy: Use statistics (e.g. 10^7 Z→ee in $10fb^{-1}$) to drive down systematic uncertainties

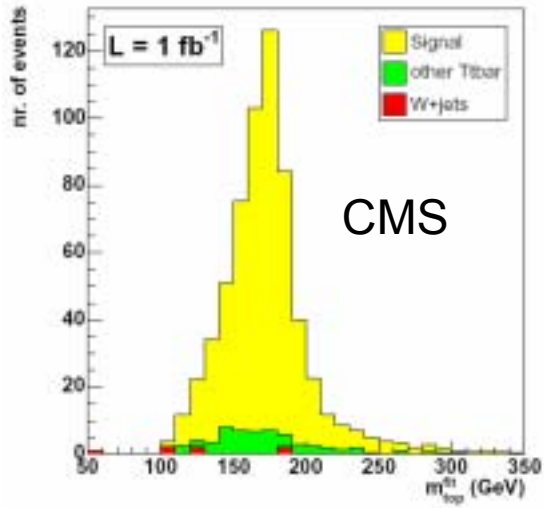
Important initial steps

- **establish W and Z signals, and use to calibrate, align, constrain pdf's**
  - **examples: W rapidity distribution, Z asymmetry vs. direction of travel, hadronic W in top decays**

Extensive studies and strategies are in hand – real data will soon allow the next level of understanding



Examples of top mass distributions in tt→lepton+jet Monte Carlo events

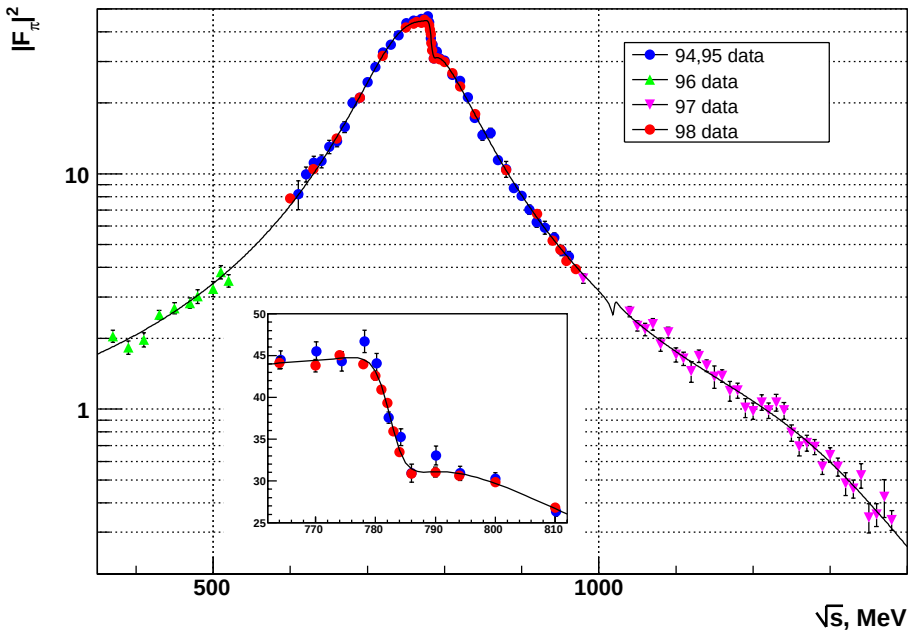


Conclusion

- EW gauge bosons have been studies under wide variety of conditions
  - real and virtual, spacelike and timelike, high and low Q^2
  - couplings to hadrons, leptons, other gauge bosons
- The improvements in the top mass and W mass measurements are the most important for indirect Higgs constraints.
  - Further top mass precision improvements are imminent, but it will take some time to improve significantly the measurement of the W mass.
  - Already, the error on indirect M_H due to M_W is about three times larger than that due to M_t.
- Look forward to one or another dramatic development from direct Higgs searches
  - exclusion up to ~170 GeV would exclude the minimal SM at 95%
  - a observed Higgs mass would allow new types of precision EW tests
  - For Higgs detection status/prospects see talks from **Doug Glenzinski** (Tevatron) today and **Fabiola Gianotti** (LHC) tomorrow.

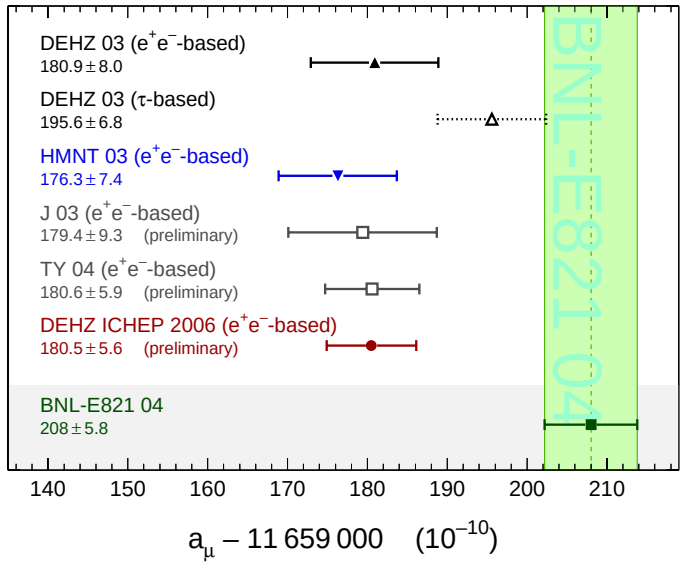
backups

muon g-2



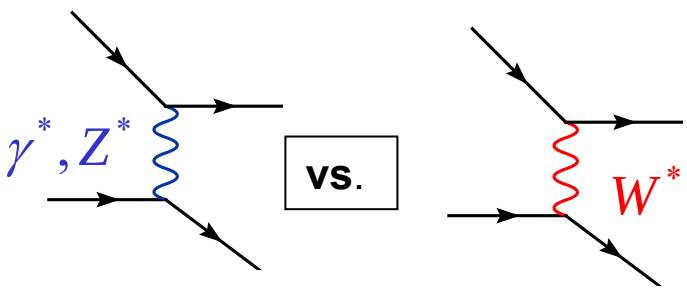
Final results from CMD-2 in Novosibirsk on pion form factor from E_{cm}=370 MeV to E_{cm}=1400 MeV

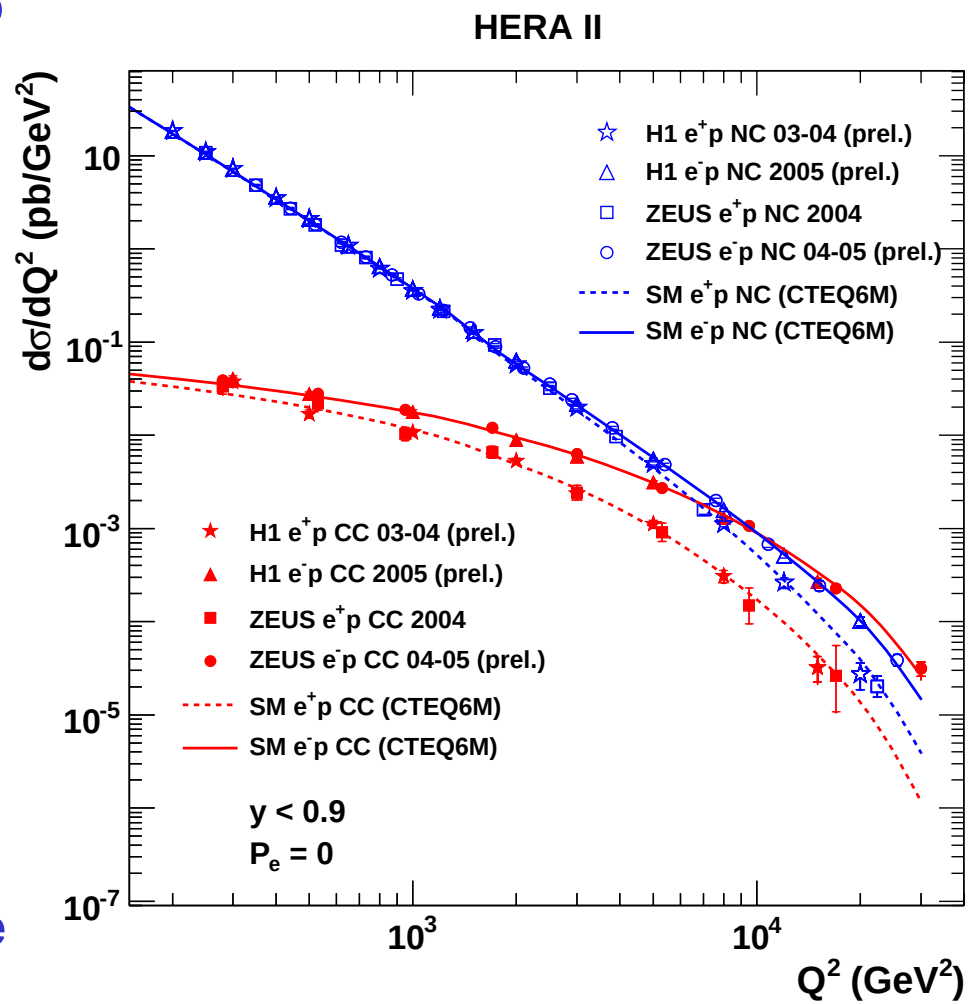
g-2 theory and experiment



EW unification: neutral vs. charged currents at HERA

- Charged and neutral deep inelastic scattering cross sections become comparable when Q^2 reaches the electroweak scale





- Quantitatively, LEP data test unification much more strongly, but DIS plot is beautiful demonstration