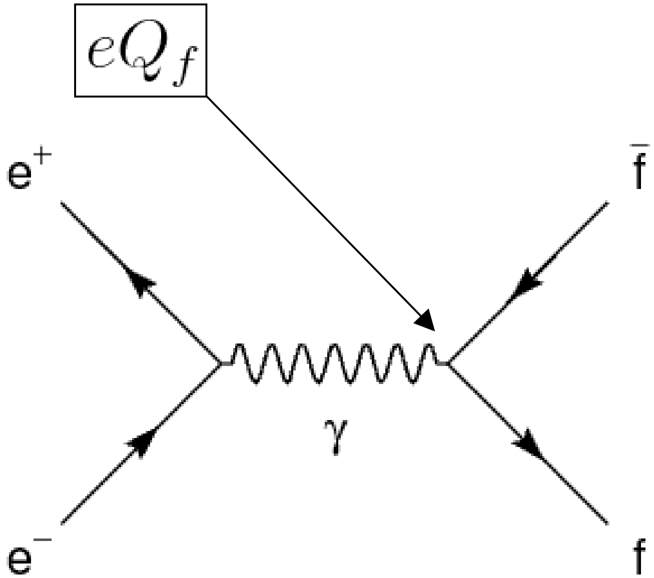
Electroweak Sector of the Standard Model

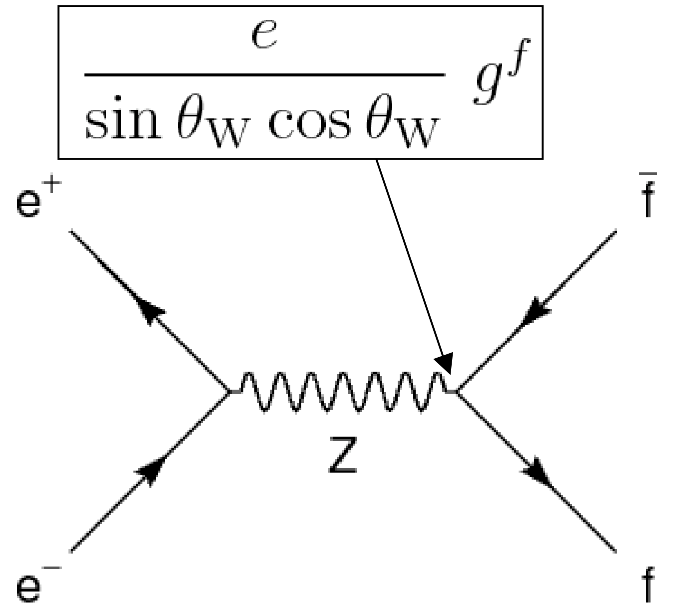
EPS Conference, HEP2007
23rd July 2007

Presented by
Terry Wyatt (University of Manchester)

- With my thanks to:
  - EW parallel session organizers
    - Giuseppe Degrassi, Jorgen D'Hondt, Chris Hays
  - >40 speakers in 14.5 hours of EW parallel sessions
    - special thanks to Martin Gruenewald
  - Scientific secretaries
    - Tim Coughlin, Tammy Yang

Introduction





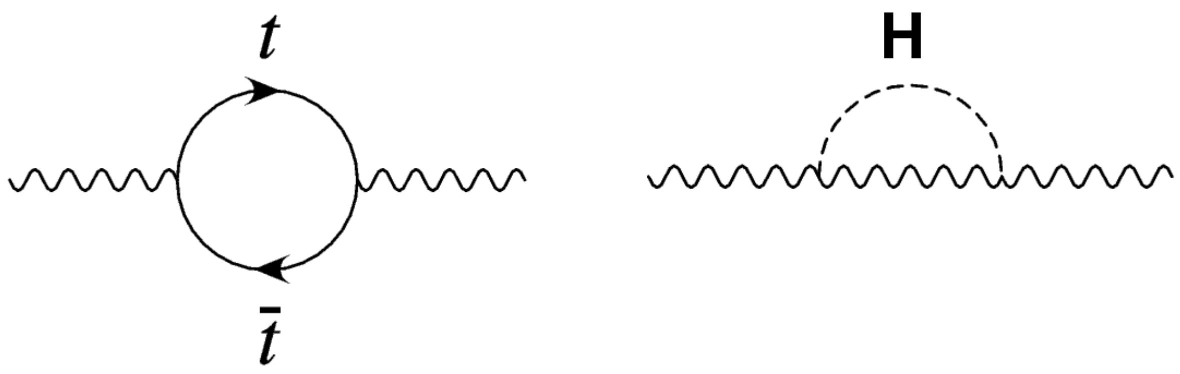
$$m_W{}^2 = m_Z{}^2 \cos^2\theta_W = \frac{\pi\alpha}{\sqrt{2} G_F \sin^2\theta_W}$$

$$g^f_{(L,R)} = T^f_{3,(L,R)} - Q_f \sin^2\theta_W$$

Fermion	$T^f_{3,L}$	$T^f_{3,R}$	Q_f
U	$+1/2$	0	$+2/3$
D	$-1/2$	0	$-1/3$
ν_ℓ	$+1/2$	0	0
ℓ	$-1/2$	0	-1

- At tree level EW theory determined by three "input" parameters
  - Most precisely known:
    - α, G_F, m_Z
- Add QCD: α_s

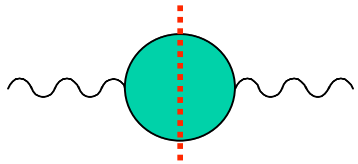
Loops



$$g^f_{(\mathrm{L,R})} = \sqrt{(1+\Delta\rho)}(T^f_{3,(L,R)} - Q_f \sin^2\theta^{\mathrm{eff}}_{\mathrm{W}})$$

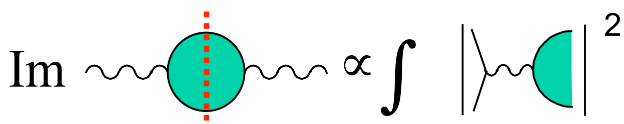
- EW observables then depend on:
  - α, G_F, m_Z, m_t, m_H
- Basic programme:
  - Measure precisely L and R couplings of each fermion to γ, Z, W
  - Measure precisely boson self-interactions
  - Measure precisely α_s, α, G_F, m_Z, m_t, m_W
  - Test consistency of measurements with SM predictions
  - Find the Higgs!

Running of α



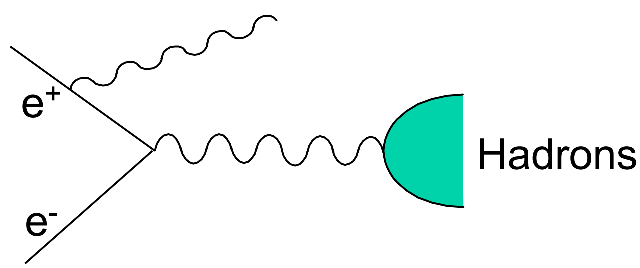
$$\alpha(q^2) = \alpha \,/\, \left(1 - \Delta\alpha_{\rm lep}(q^2) - \Delta\alpha_{\rm had}(q^2)\right)$$

- Uncertainty dominated by $\Delta\alpha_{had}(q^2)$
  - effect of qq loops at low q^2
- Cannot be calculated from first principles in pQCD
- Can be related to $\sigma^0_{had}(s)$ by dispersion relation



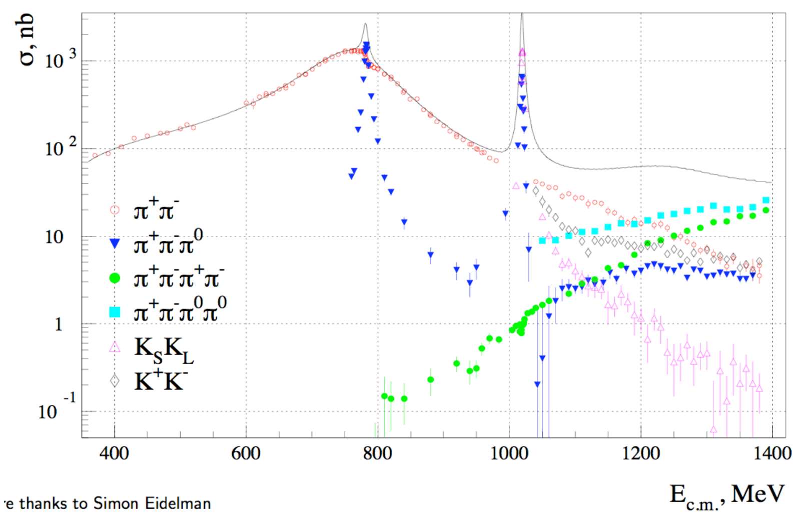
$$\Delta\alpha^{(5)}_{\rm had}(q^2) = -\frac{q^2}{4\pi^2\alpha} P \int_{m_\pi^2}^{\infty} \frac{\sigma^0_{\rm had}(s)\,{\rm d}s}{s-q^2}$$

- Experimentally accessible by:
  - direct scans
  - radiative return

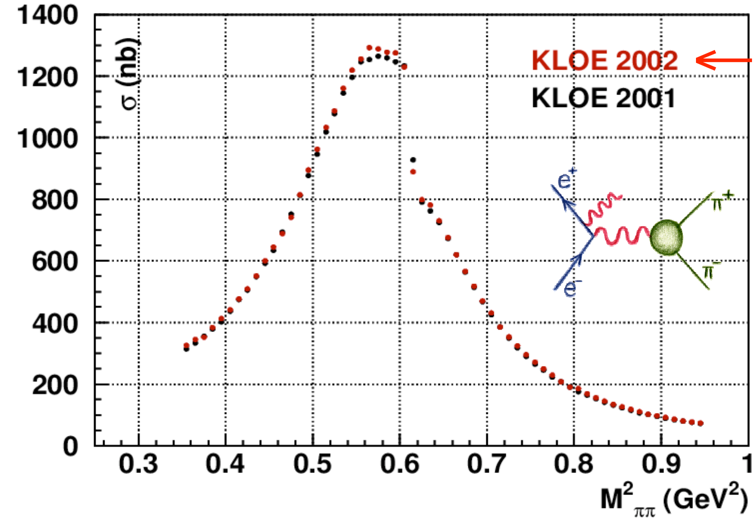


Data on $\sigma^0_{had}(s)$

- CMD-2 at Novosibirsk

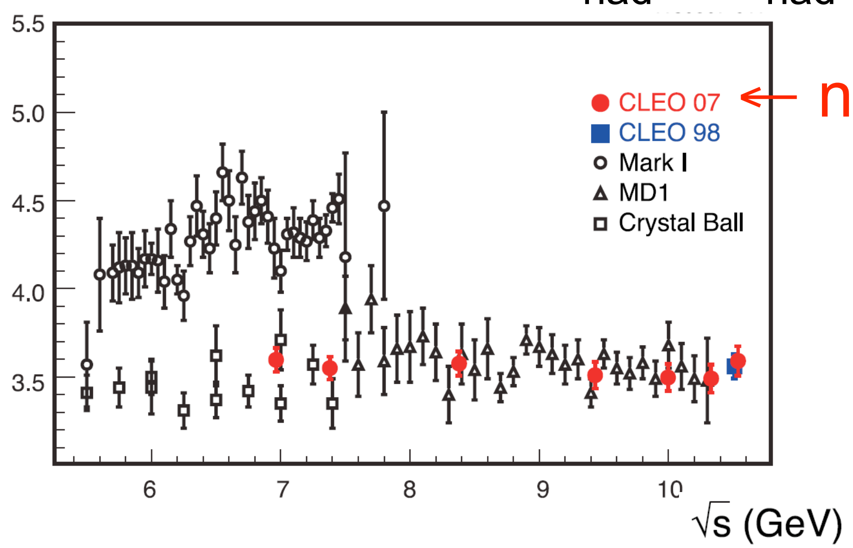


- KLOE at Frascati



← new!

- CLEO at Cornell: $R_{had} = \sigma_{had}/\sigma_{\mu\mu}$



← new!

+ new results from Babar expected soon (radiative return)

$\Delta\alpha_{had}(M_Z^2)$

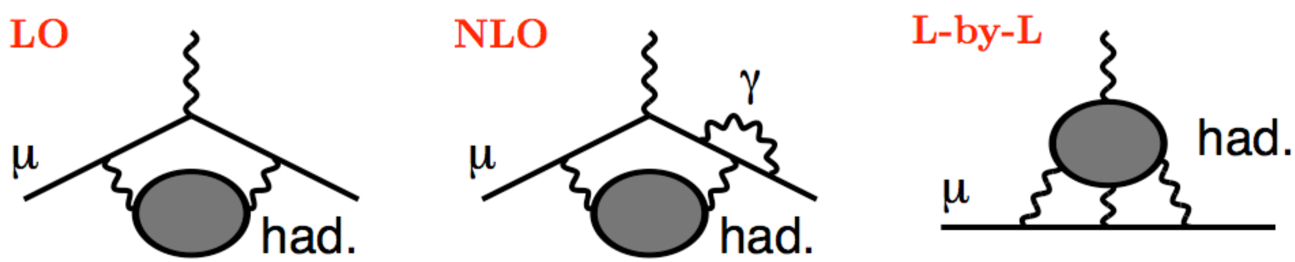
- Precise determination of $\Delta\alpha_{had}(M_Z^2)$ is a tricky business!
  - combination of results from many (sometimes old) experiments
  - treatment of correlated systematics, radiative corrections
  - close collaboration between expt. and theory essential!

Group	$\Delta\alpha^{(5)}_{\mathrm{had}}(M_Z^2)$
Burkhardt+Pietrzyk '05	0.02758 ± 0.00035
Troconiz+Yndurain '05	0.02749 ± 0.00012
Kühn+Steinhauser '98	0.02775 ± 0.00017
Jegerlehner '06	0.02761 ± 0.00023
($s_0^2 = (10\mathrm{GeV})^2$)	0.02759 ± 0.00017
HMNT '06	0.02768 ± 0.00022

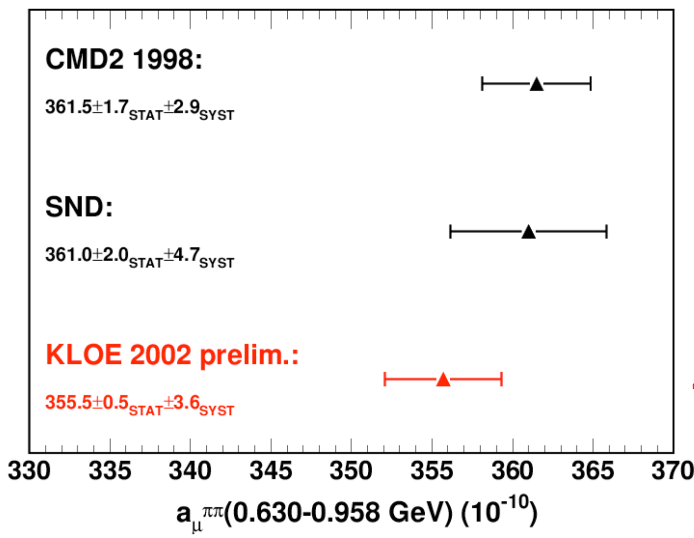
← currently used by LEPEWWG (Burkhardt+Pietrzyk '05)

g-2

- Hadronic corrections also dominate uncertainty in g-2



- $a_\mu = (g-2)/2$
- Comparison of $a_\mu^{\pi\pi}$
  – in the range 0.630-0.958 GeV



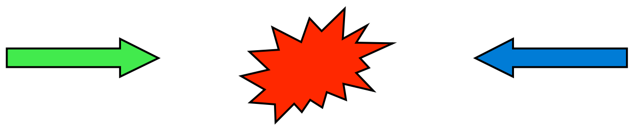
← new!

- Recent analyses confirm discrepancy at ~3.4 sigma level
  – $a_\mu^{expt} - a_\mu^{theory} = (27.6 \pm 8.1) \cdot 10^{-10}$
    - theory uncertainty (slightly) smaller than expt.

30th June 2007: The end of an ERA!

30th June 2007: The end of an (H)ERA!

p (920 GeV) e (27.5 GeV)



$\sqrt{s}$ = 318 GeV

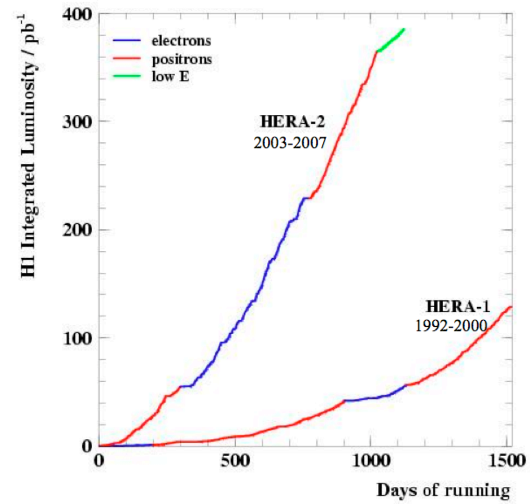
- Integrated luminosity

	HERA-1	HERA-2
e-	~20pb^{-1}	~200pb^{-1}
e+	~100pb^{-1}	~200pb^{-1}

- polarized electron beam

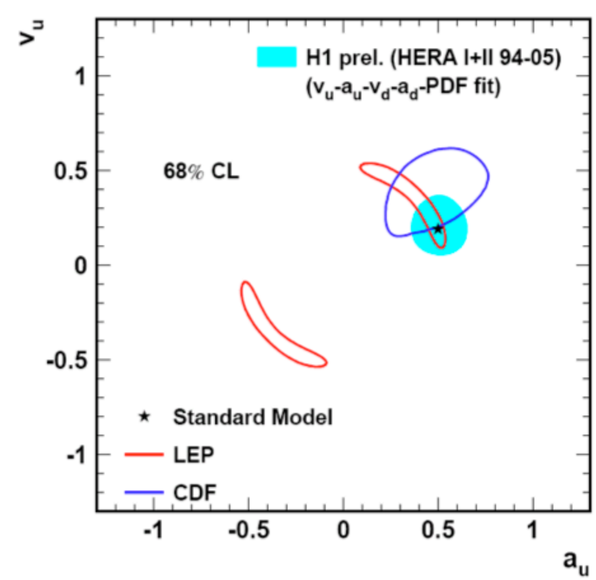
$$P_e = \frac{N_R - N_L}{N_R + N_L}$$

  - P_e typically 30-40%



- up quark couplings

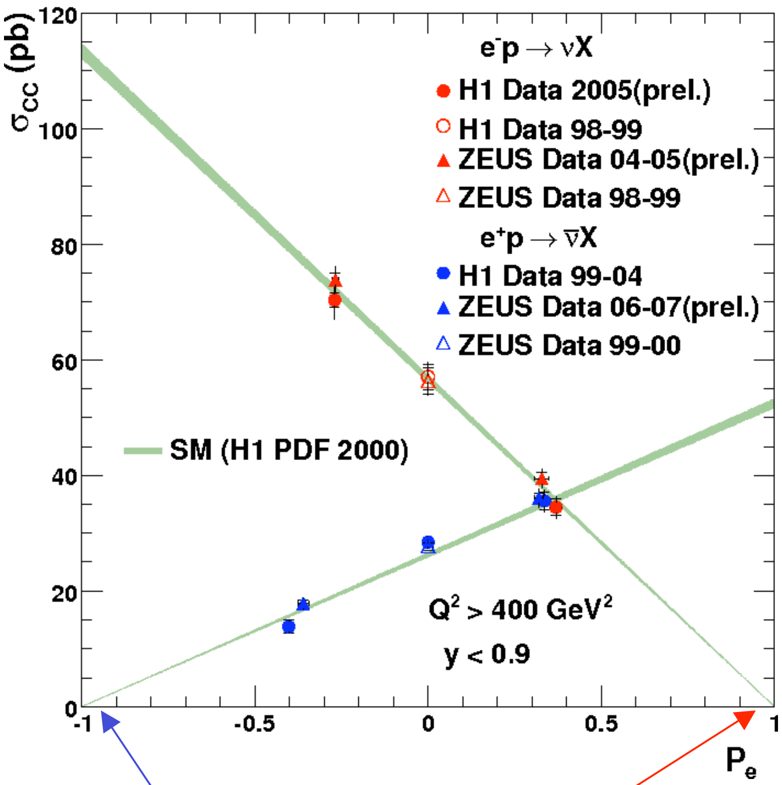
HERA-1+2 (94-05)



Results with Polarized Beams at HERA

Charged Current (CC)

exchange of $W^\pm$ ($e^\pm p \to \nu X$)



left-handed e^+ and right-handed e^-

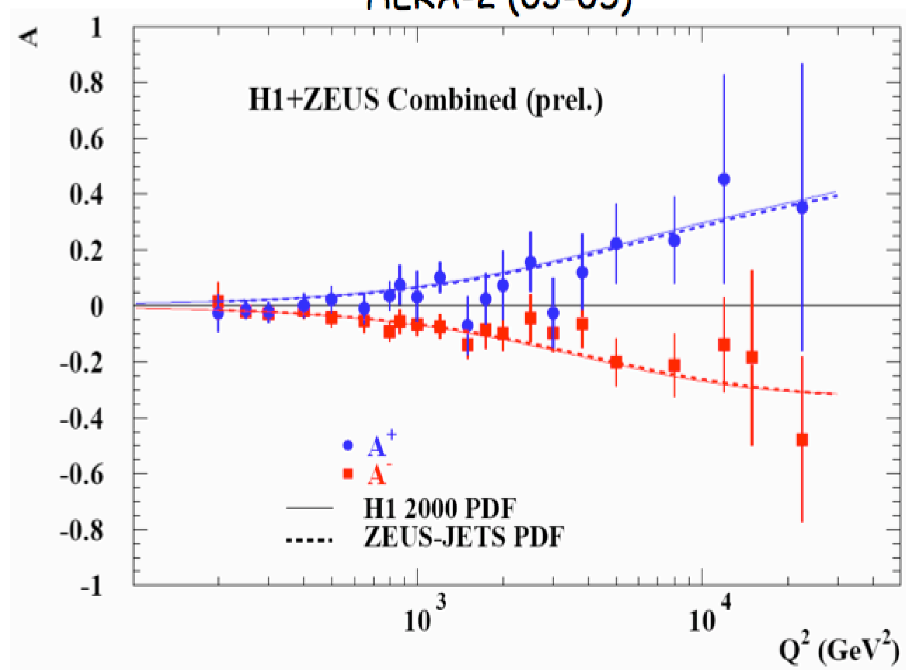
do not interact via $W^\pm$!

Neutral Current (NC)

exchange γ and Z^0 ($e^\pm p \to e^\pm X$)

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

HERA-2 (03-05)



- Directly tests the EW model at large <u>negative</u> Q^2
- Still a factor ~2 more HERA-2 data to be analyzed

The Fermilab Tevatron Collider

1992-95 Run I:

~ 100 pb^{-1}, 1.8 TeV

Major accelerator/detector upgrades

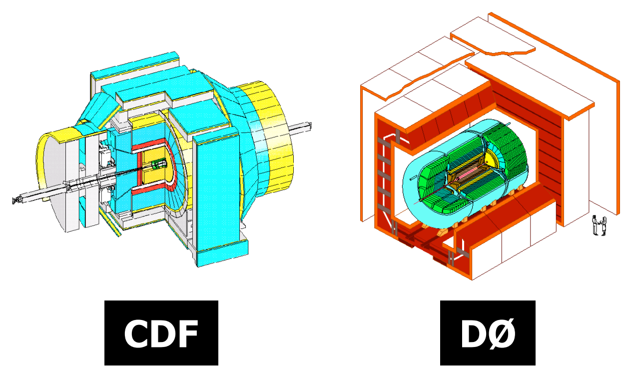
2002-06 Run IIa:

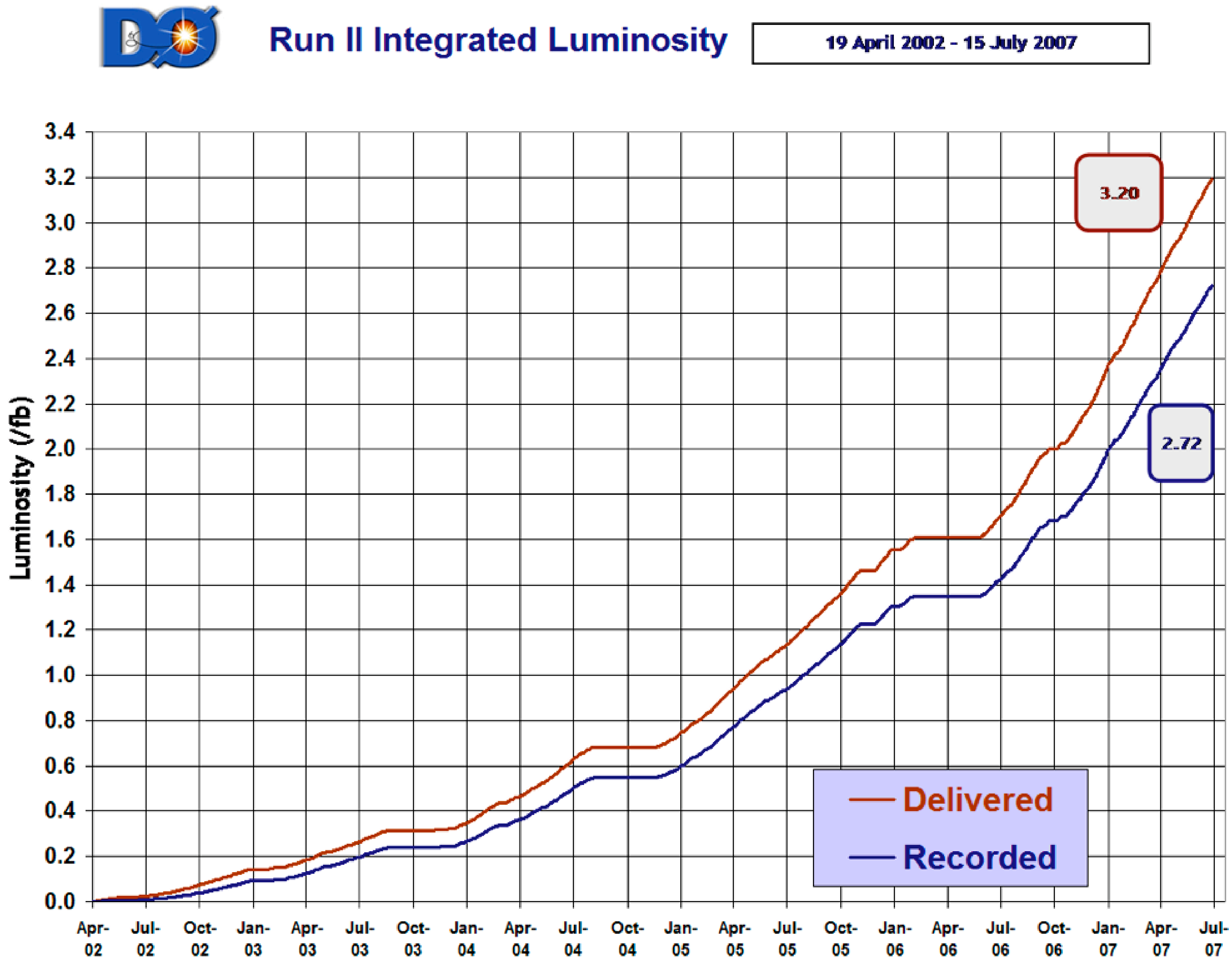
~ 1.6fb^{-1}, 1.96 TeV

Further upgrades

2006-09 Run IIb:

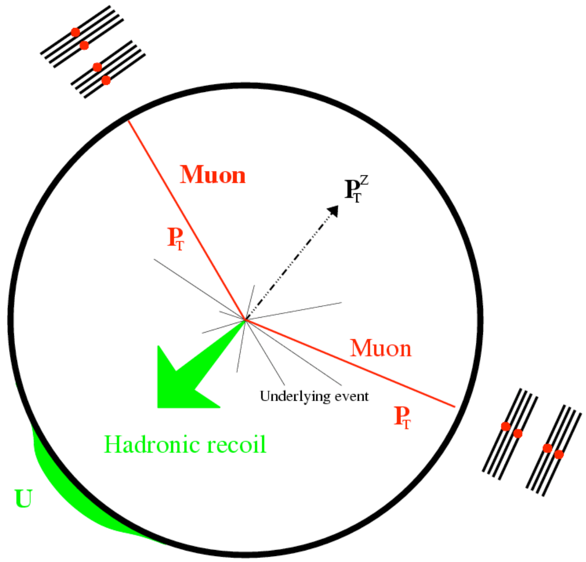
~ 6-8 fb^{-1}



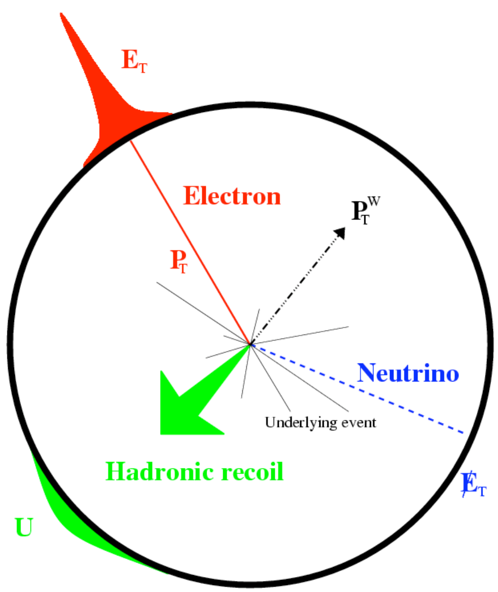


- ~85% data taking efficiency

Signatures of W and Z Production at the Tevatron



- Z: pair of charged leptons:
  - high p_T
  - isolated
  - opposite-charge



- W: single charged lepton:
  - high p_T
  - isolated
- E_T^{miss} (from neutrino)

transverse mass: $m_T = \sqrt{2 p_T^{\,l} p_T^{\,\nu} (1 - \cos\phi_{l\nu})}$

W Mass and Width from CDF

- 200 pb^{-1} data set

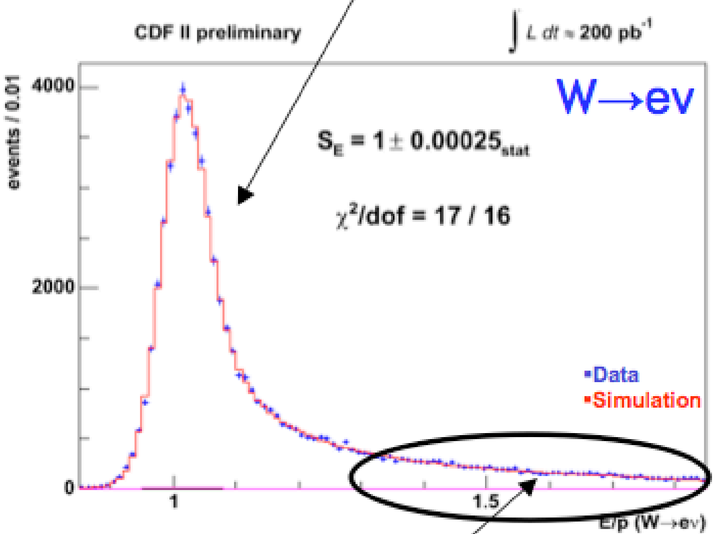
51,128 $W \to \mu\nu$ candidates

63,964 $W \to e\nu$ candidates

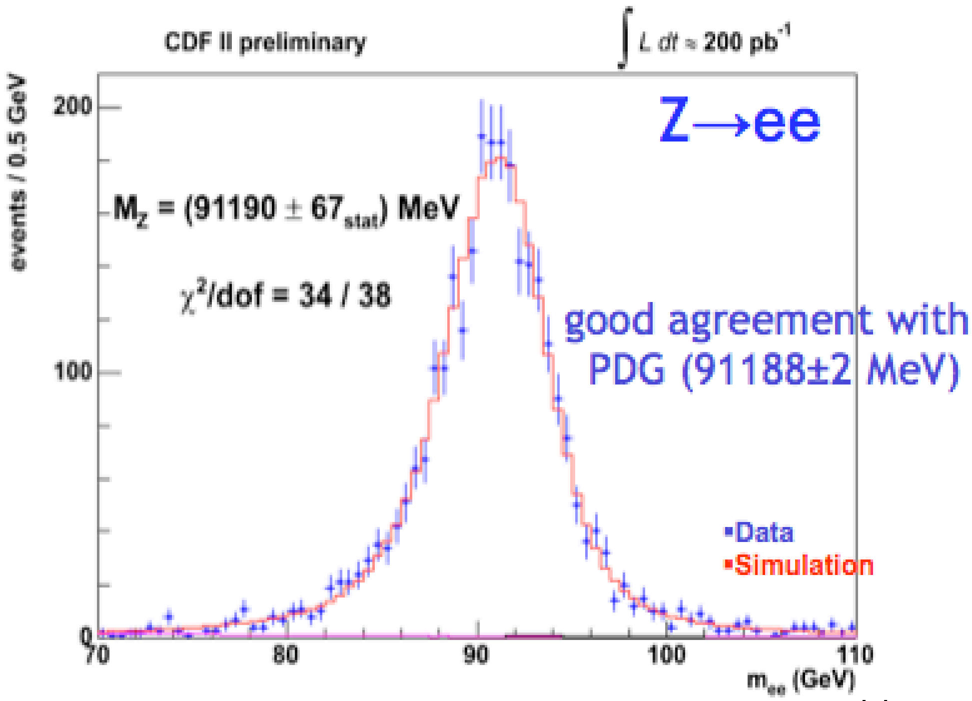
4,960 $Z \to \mu\mu$ candidates

2,919 $Z \to ee$ candidates

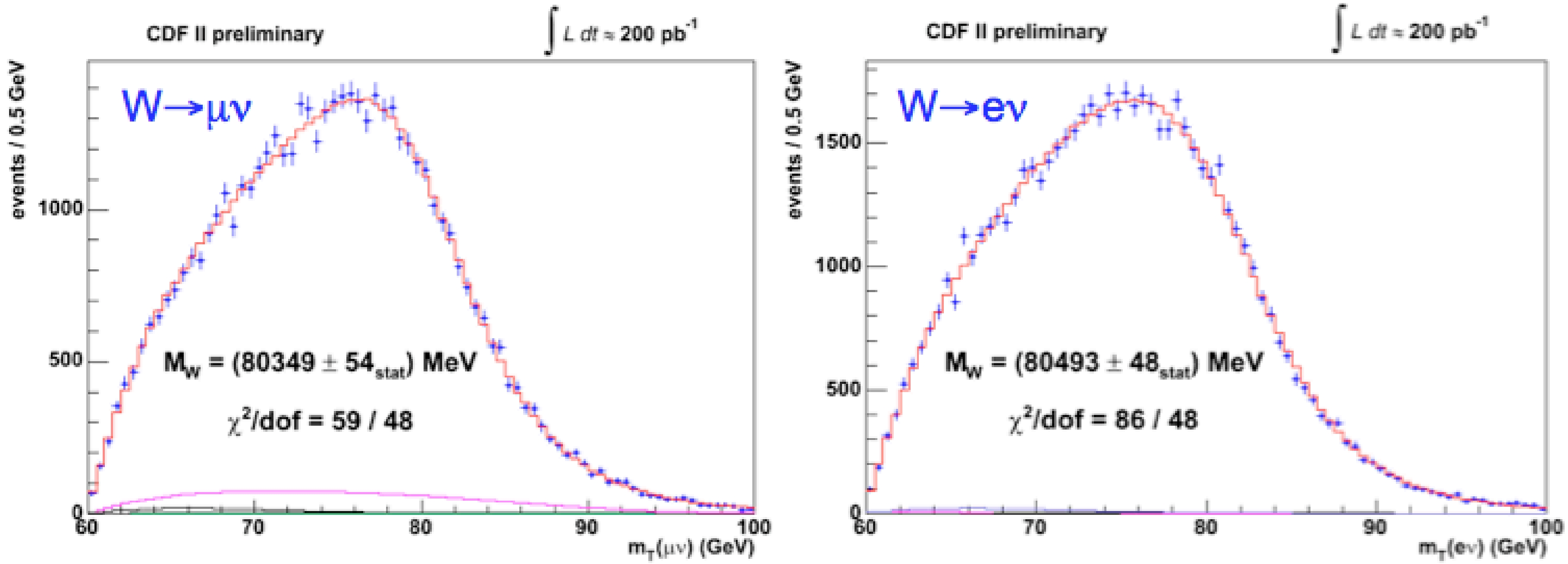
- Many handles to calibrate tracker and calorimeter p_T scale and resolution
  - $J/\psi, \Upsilon$, Z, E/p in $W \to e\nu$



dead material



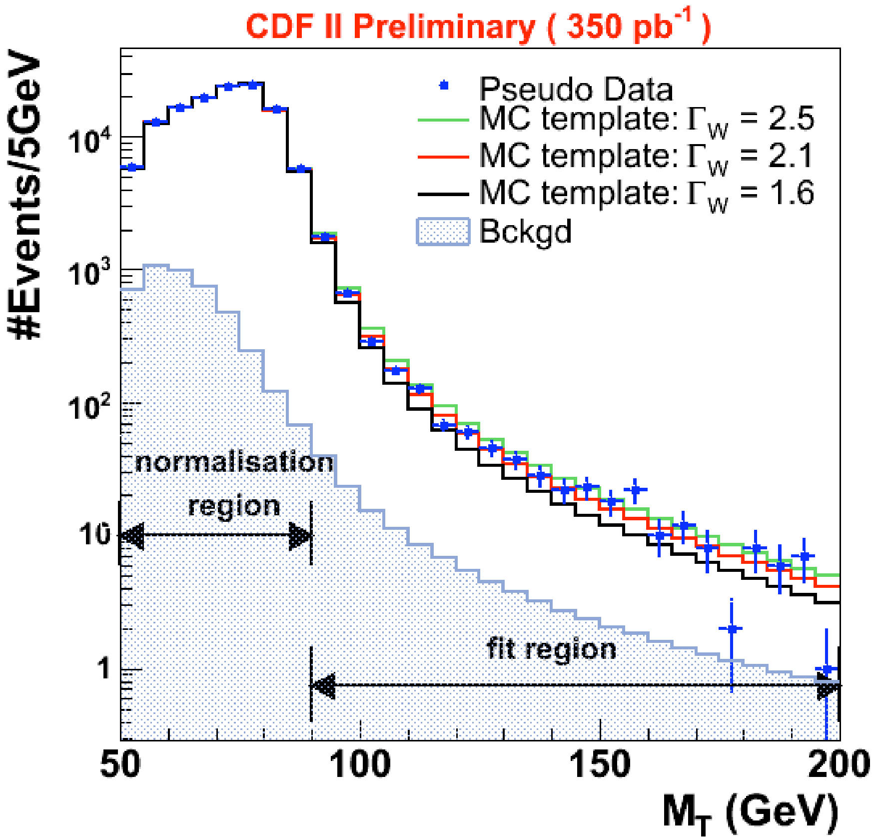
W Mass and Width from CDF



- m_W = 80413 ± 34(stat) ± 34(syst) MeV
- Major systematics:
  - lepton p_T scale and resolution, QED, PDFs

CDF chooses to treat CTEQ6 error sets as 1.6σ uncertainty

W Mass and Width from CDF



- Major systematics:
  - lepton p_T resolution ~30 MeV
  - recoil model ~50 MeV
  - backgrounds ~30 MeV
  - uncorrelated between electron and muon channels

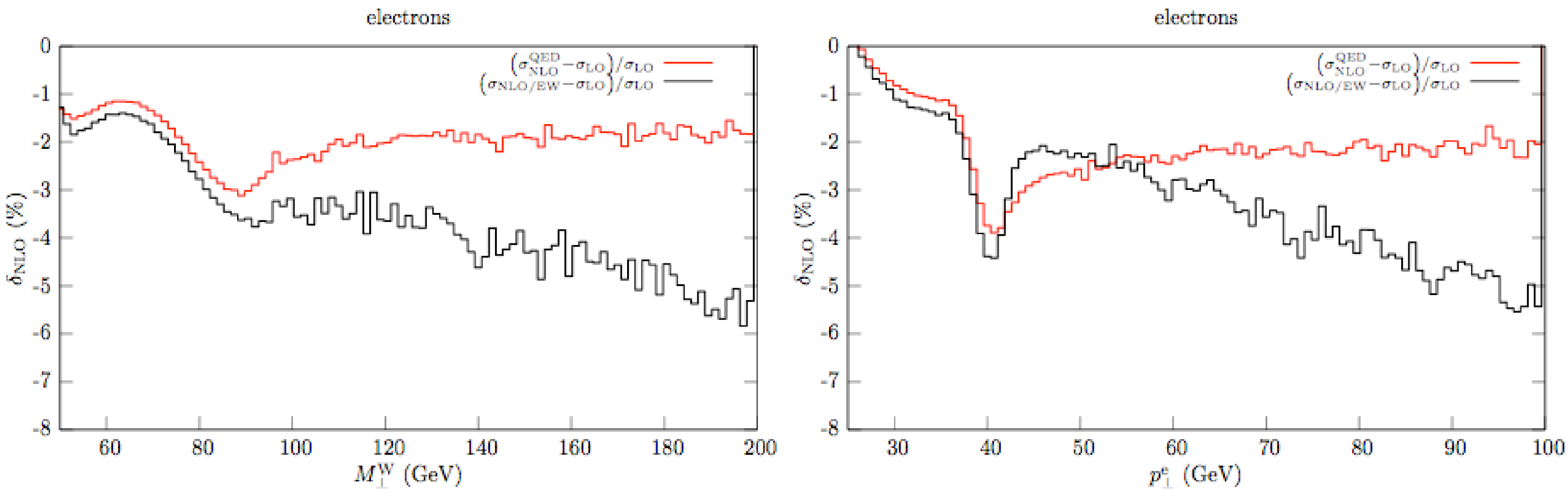
Γ_W = 2032 ± 71 (stat + syst) MeV (350 pb-1)

c.f. indirect measurement from cross sections:

$$R = \frac{\sigma \cdot BR\,(W \rightarrow l\nu)}{\sigma \cdot BR\,(Z \rightarrow ll)}$$

Γ_W = 2092 ± 42 MeV (stat + syst) MeV (72 pb-1)

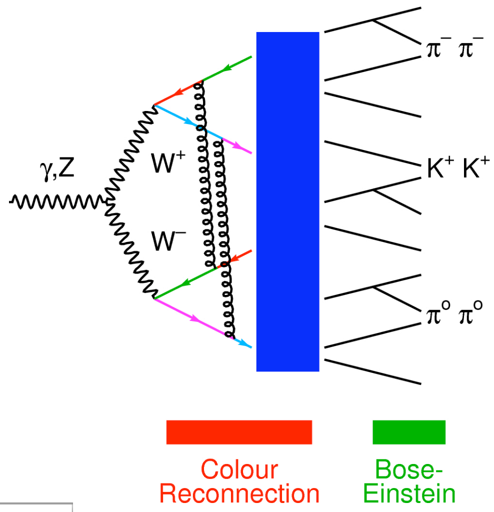
Watch Out for the Theoretical Uncertainty!

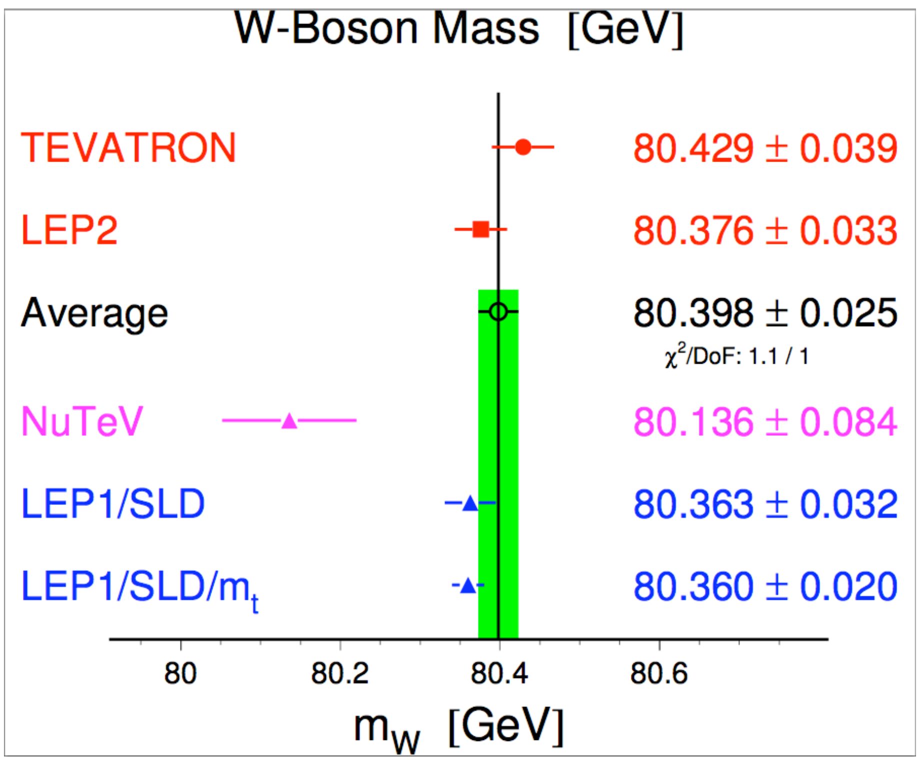


- In the hard tails of $M_\perp^W$ and $p_\perp^\ell$ predictions including QED FSR only differ at some % level from the complete NLO electroweak calculation $\longrightarrow$ important for precision W width measurement?

W Mass

- Final LEP2 M_W awaits:
  - final combination of colour reconnection limits
  - final M_W combination



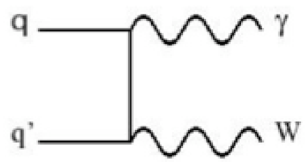


$\Delta m_W = 25$ MeV

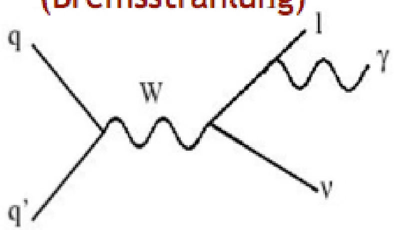
Di-Boson Physics at the Tevatron

- Wγ

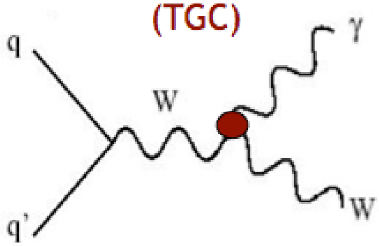
Initial State Radiation

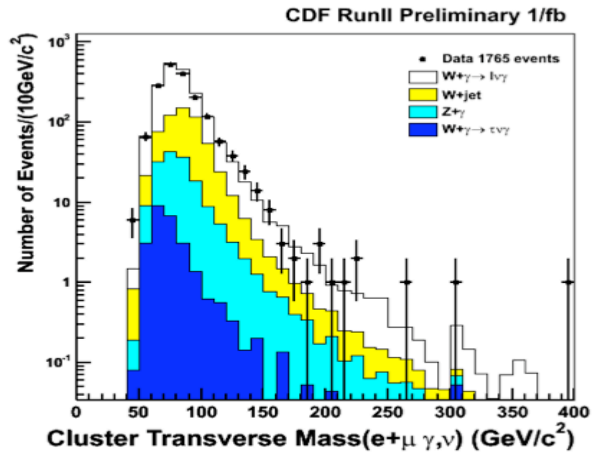


Final State Radiation (Bremsstrahlung)



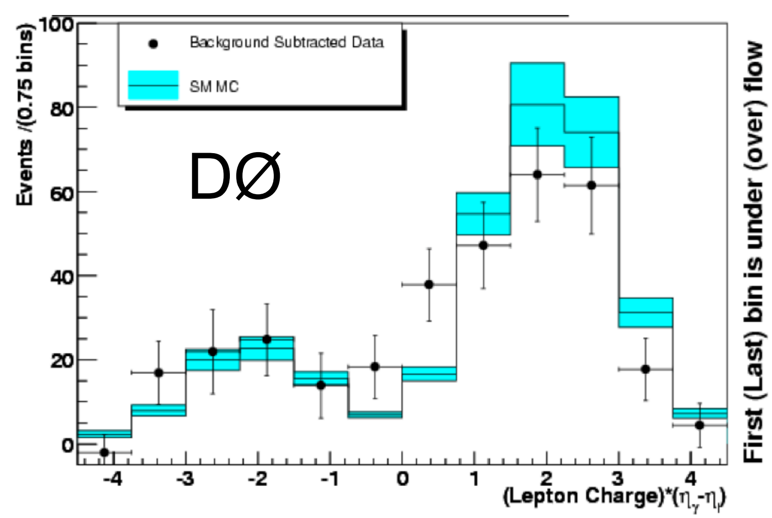
Photon Radiated from a W (TGC)





$\sigma(W\gamma)$*BR($W \rightarrow l\nu$) = 18.03±0.65(stat)±2.55(sys)±1.05(lumi) pb

NLO prediction: $\sigma(W\gamma)$*BR($W \rightarrow l\nu$) = 19.3±1.4 pb

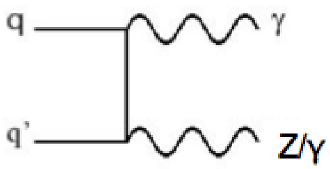


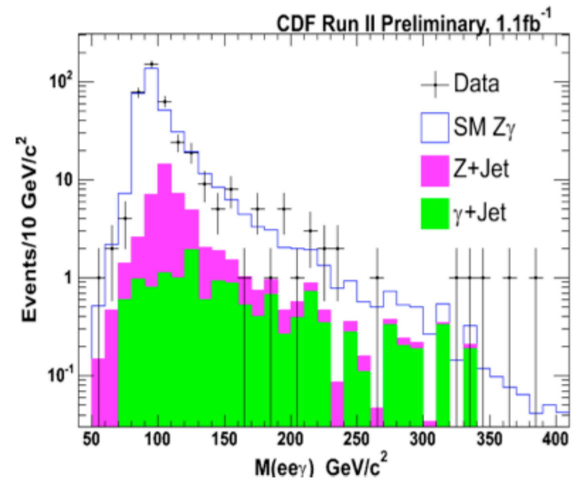
- Data consistent with SM
  - do not yet require "radiation zero"

Di-Boson Physics at the Tevatron

- $Z\gamma$

Initial State Radiation

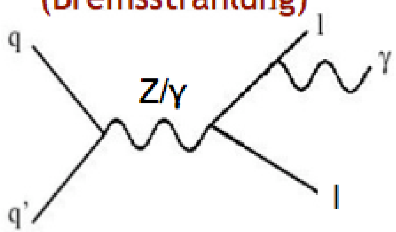




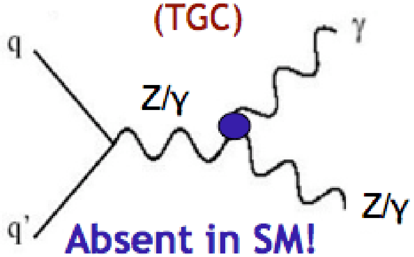
$\sigma(Z\gamma)$*BR($Z\rightarrow e^+e^-$) = 4.9±0.3(stat)±0.3(sys)±0.3(lumi) pb

NLO prediction: $\sigma(Z\gamma)$*BR($Z\rightarrow e^+e^-$) = 4.7±0.4 pb

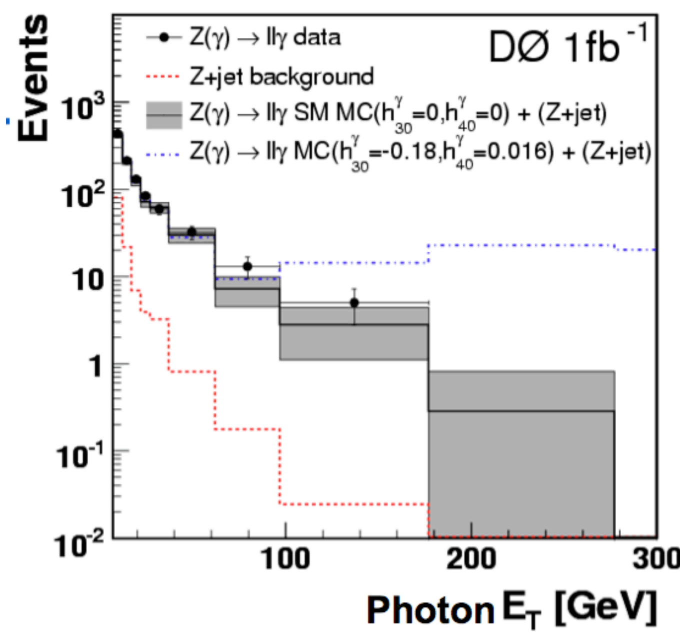
Final State Radiation (Bremsstrahlung)



Photon Radiated from a Z (TGC)



Absent in SM!



$\sigma_{\gamma Z} = 4.96 \pm 0.30_{(stat+syst)} \pm 0.30_{(lumi)}$ pb

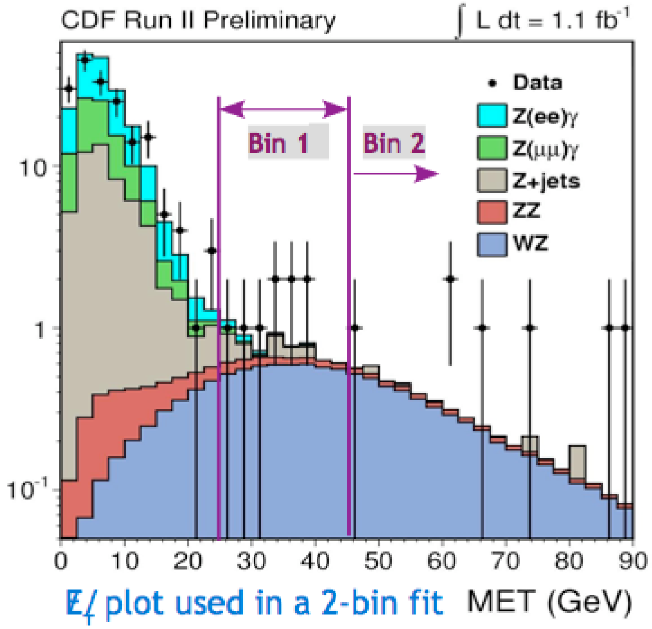
SM NLO: $\sigma_{Z\gamma} = 4.74 \pm 0.22$ pb

($E_T^\gamma > 7$ GeV; $dR_{\gamma l} > 0.7$; $M_{ll} > 30$ GeV)

95% C.L. $h_{30,40}^{\gamma,Z}$ limits ($h_{10,20}^{\gamma,Z} = 0$):

	h^γ ($h^Z = 0$)	h^Z ($h^\gamma = 0$)
	$-0.085 < h_{30} < 0.084$	$-0.083 < h_{30} < 0.082$
	$-0.0053 < h_{40} < 0.0054$	$-0.0053 < h_{40} < 0.0054$

WZ and ZZ



E̸T plot used in a 2-bin fit

Expected number of signal events

9.75±0.03(stat)±0.31(sys)±0.59(lumi)

Expected number of background events

2.65±0.28(stat)±0.33(sys)±0.09(lumi)

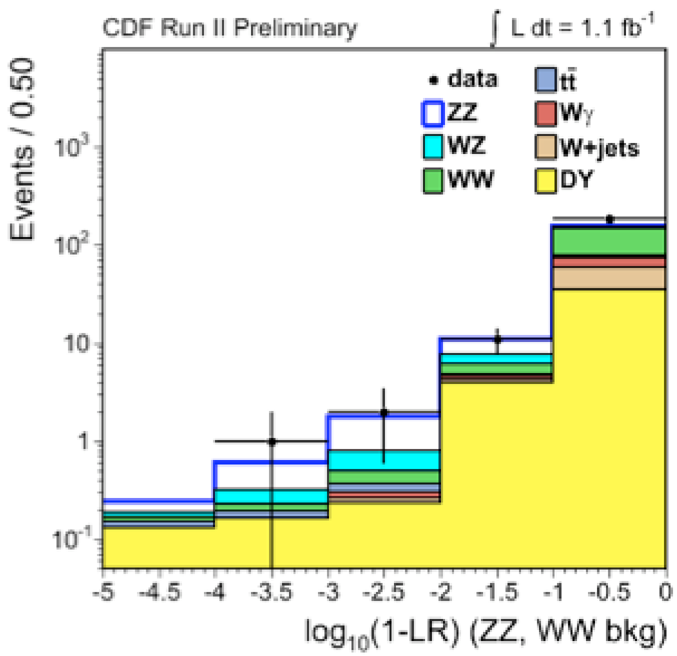
Observed

16 events

⇒ significance 6σ

$$\sigma(WZ) = 5.0^{+1.8}_{-1.6} \text{ (stat.+syst.) pb}$$

NLO prediction: σ(WZ) = 3.7 ± 0.3 pb



ZZ→llll (1.5 fb⁻¹)

- Very clean but very small BR
- 1 4-lepton event observed!

ZZ→llνν (1.1 fb⁻¹)

Combined result

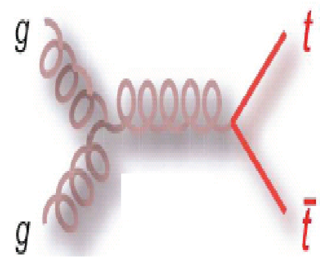
3σ significance

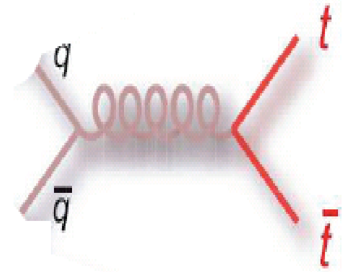
$$\sigma(ZZ) = 0.75^{+0.71}_{-0.54} \text{ (stat.+syst.) pb}$$

NLO prediction: σ(WZ) = 1.4 ± 0.1 pb

Top Quark Pair Production and Decay at Tevatron

- Production: 85% 15%

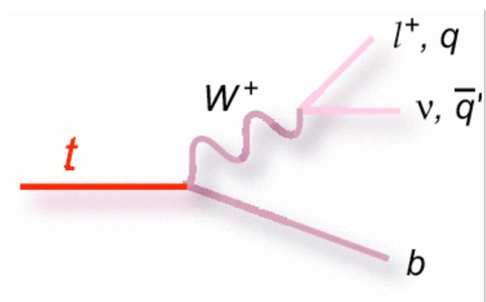




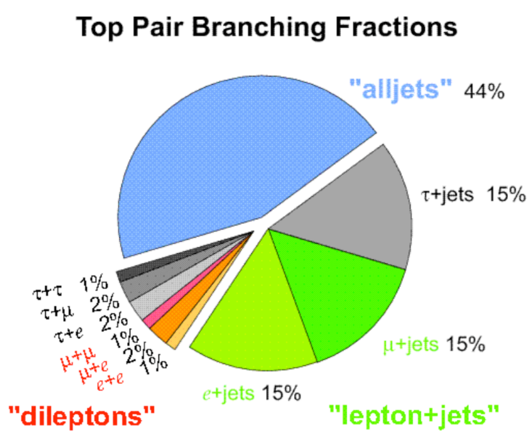
CDF measurement

$$\frac{\sigma(gg \to t\bar{t})}{\sigma(p\bar{p} \to t\bar{t})} = 0.01 \pm 0.16(stat) \pm 0.07(syst)$$

- Decay



- Final state determined by decay of the two Ws



"lepton+jets"

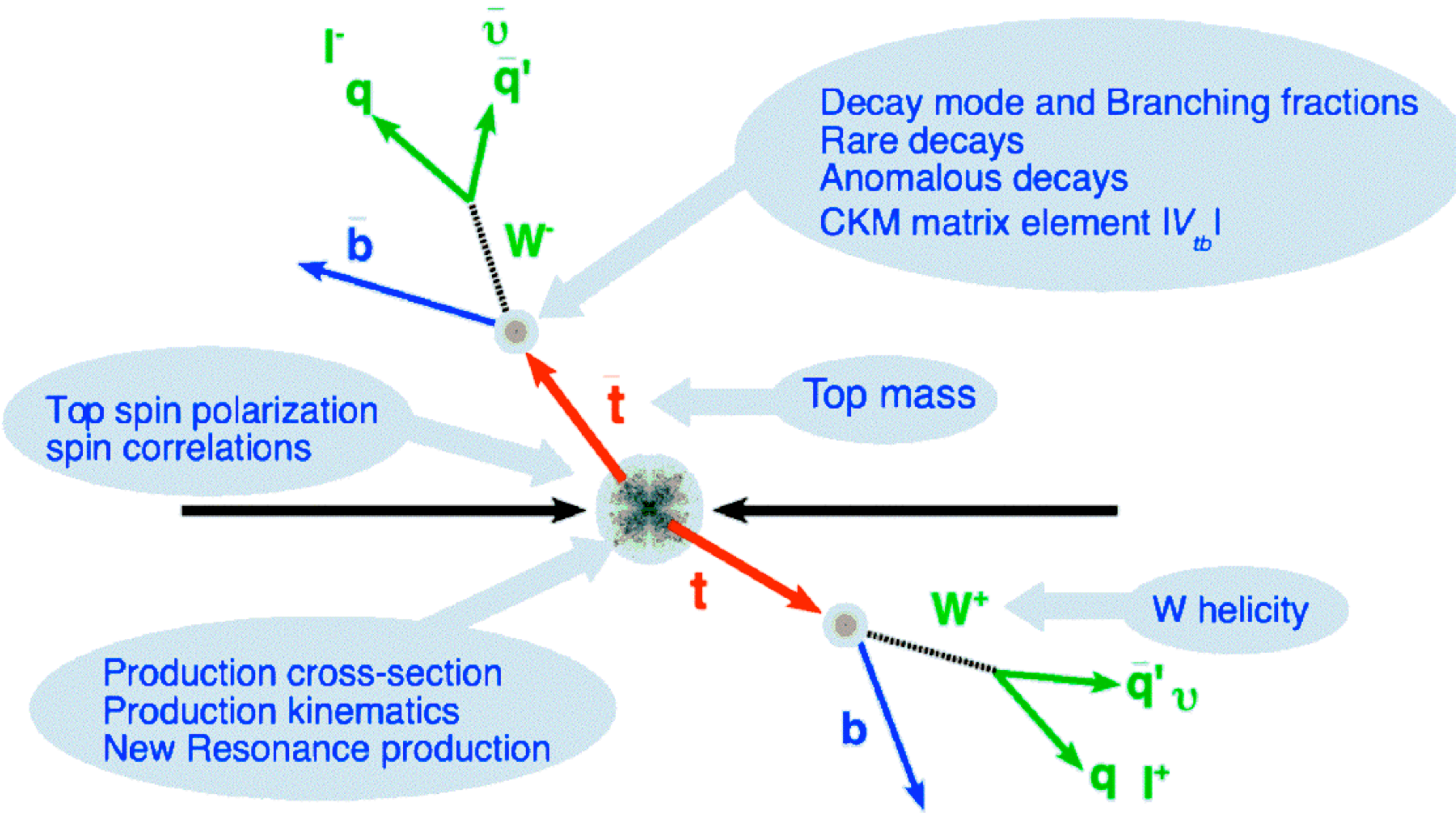
(e or μ), υ, W→qq, two b-jets

30% of tt decays

moderate background

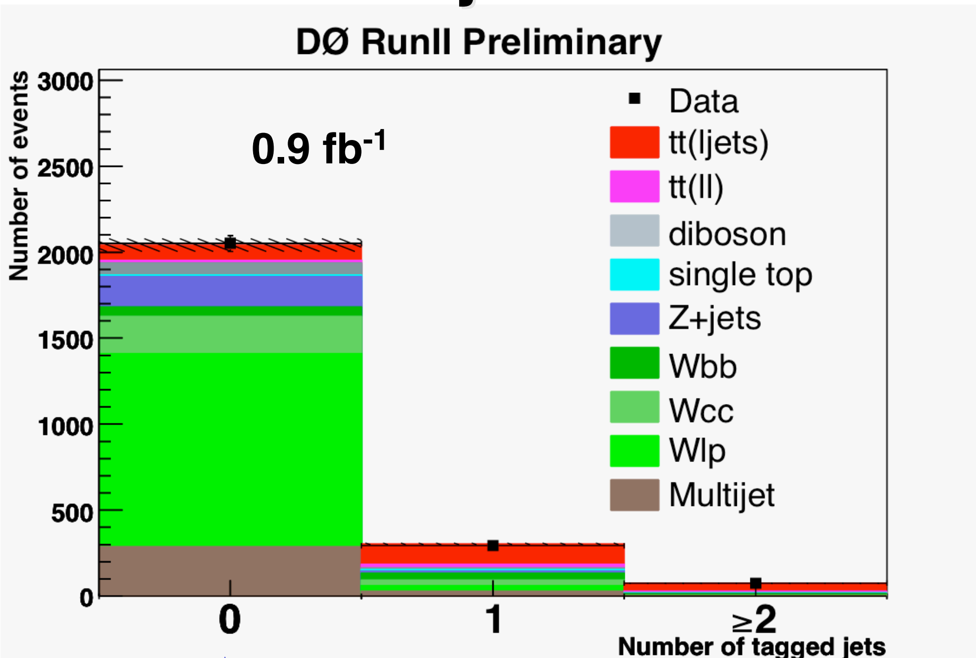
→ usually yields most precise measurements

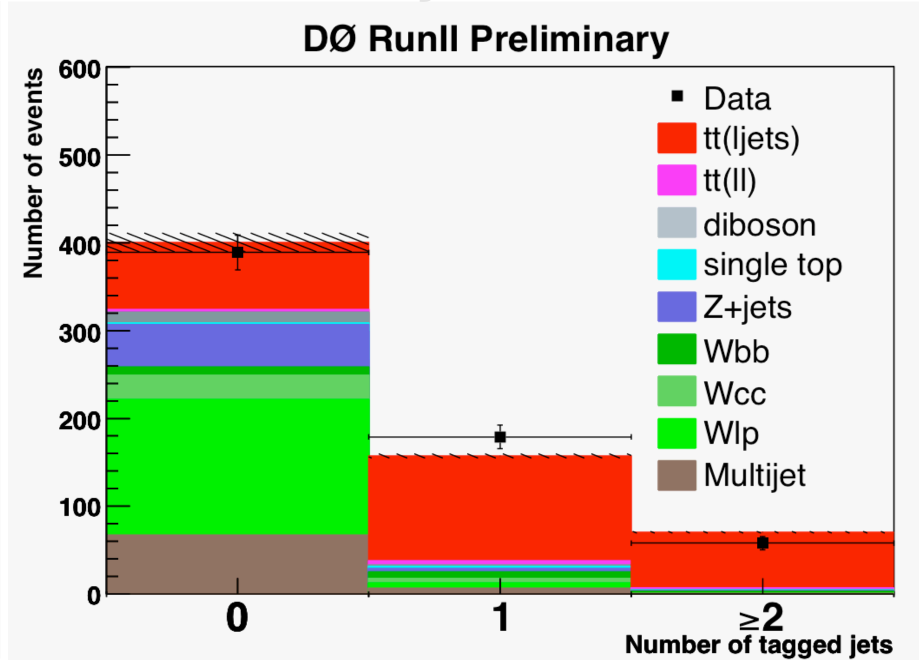
A Rich Programme of Top Physics to Explore!



Production Cross Section and Br(t→bX)

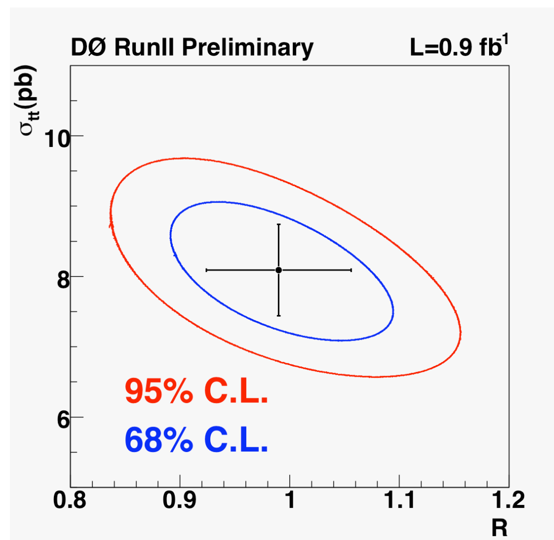
= 3 jets | **≥ 4 jets**





- Use additional kinematic discriminant in 0-tag bins to enhance tt
- Simultaneous fit to σ_{tt} and R

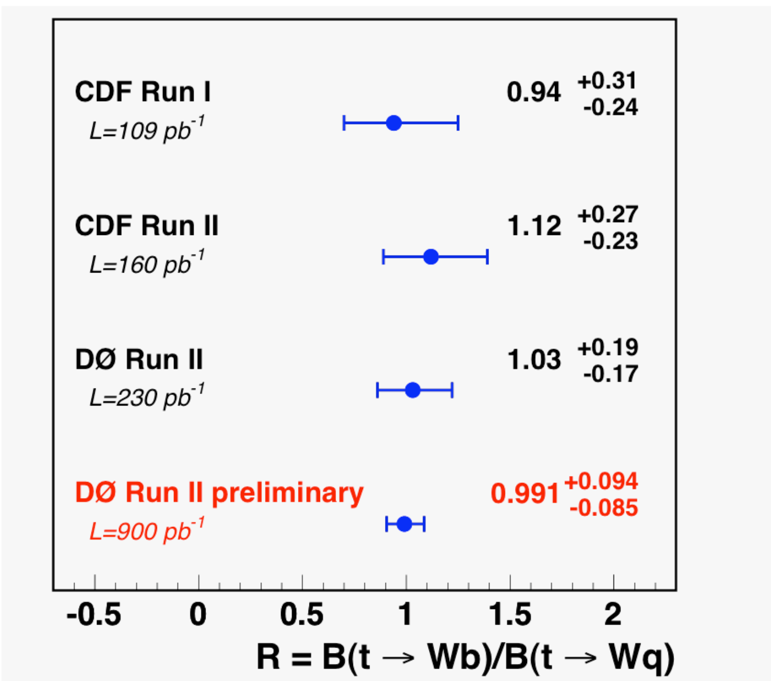
$$R = \frac{Br(t \to Wb)}{Br(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{tb}|^2 + |V_{ts}|^2 + |V_{td}|^2}$$



Production Cross Section and Br($t \rightarrow bX$)

$\Delta\sigma_{tt} / \sigma_{tt}$ (%)

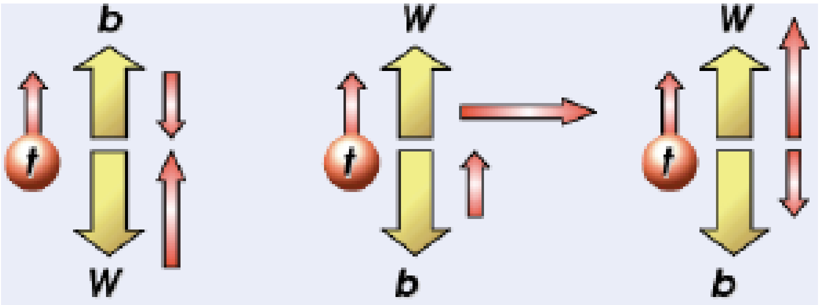
- DØ preliminary (900 pb-1)
  - $\sigma_{tt} = 8.08^{+0.85}_{-0.82}$ (stat+syst) ± 0.49 (lumi) pb — **12%**
- CDF preliminary (1120 pb-1)
  - $\sigma_{tt} = 8.2 \pm 0.5$ (stat) ± 0.8 (syst) ± 0.5 (lumi) pb — **13%**
- SM prediction
  - $\sigma_{tt} = 6.7 \pm 0.8$ pb — **12%**



σ_{tt} and R consistent with SM expectations

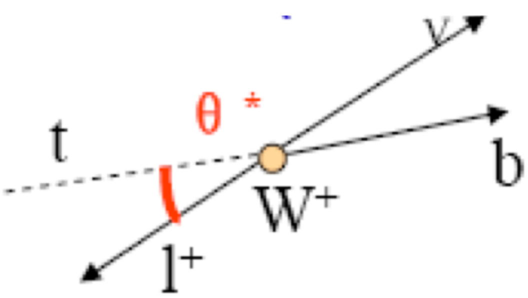
W Helicity in Top Decays

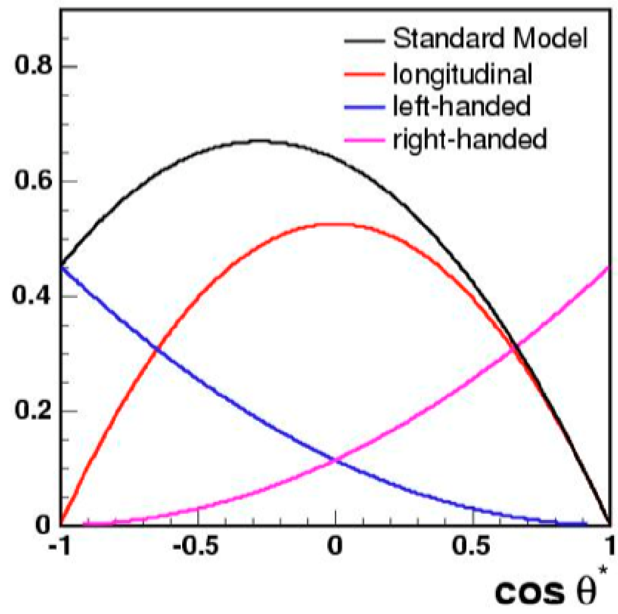
- Test left-handed t→Wb coupling



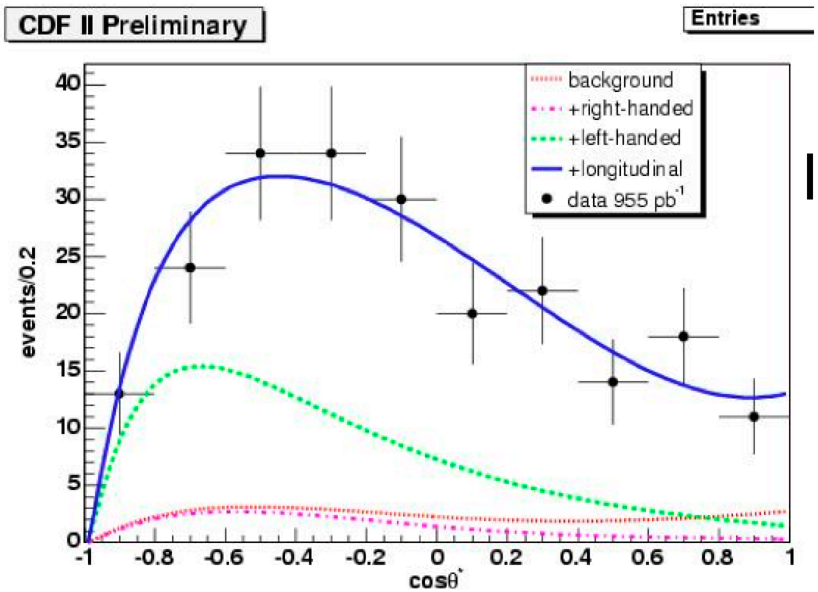
left handed	longitudinal	right handed
SM: $f_-=0.3$	$f_0=0.7$	$f_+\sim10^{-4}$

- θ*: angle between $l^\pm$ momentum in W rest frame and W momentum in top rest frame

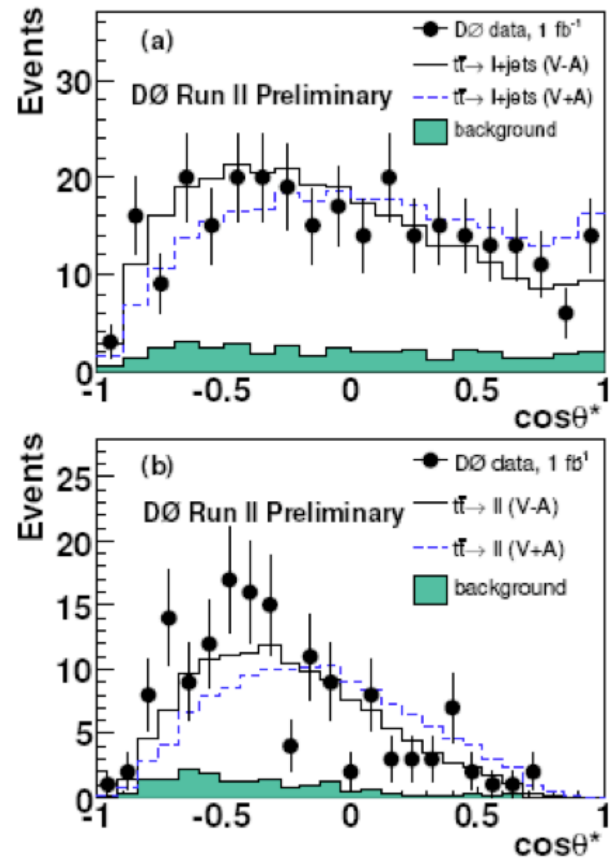




W Helicity in Top Decays



l+jets



l+jets

di-lepton

- **Simultaneous fit:**
- **$f_0 = 0.74 \pm 0.25(stat) \pm 0.06(syst)$**
- **$f_+ = -0.06 \pm 0.10(stat) \pm 0.03(syst)$**
- **Fixing $f_0 = 0.7$**
- **$f_+ = -0.06 \pm 0.06(stat) \pm 0.03(syst)$**

- **Fixing $f_0 = 0.7$**
- **$f_+ = 0.017 \pm 0.048(stat) \pm 0.047(syst)$**

Top Mass Measurement

Example Technique: Matrix Element (ME)

- Form event probability P_{evt}

$$P_{evt} = f_{sgn} P_{sgn}(x; m_{top}, JES) + (1 - f_{sgn}) P_{bkg}(x)$$

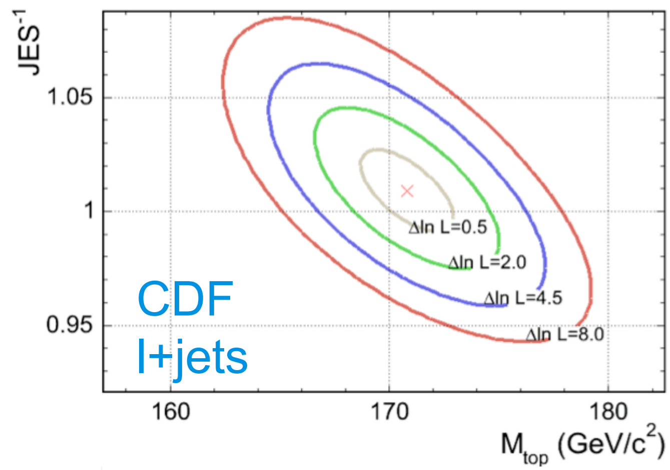
- Where P_{sgn} is the probability to observe x for given values of m_{top} and JES (Jet Energy Scale calibration factor)

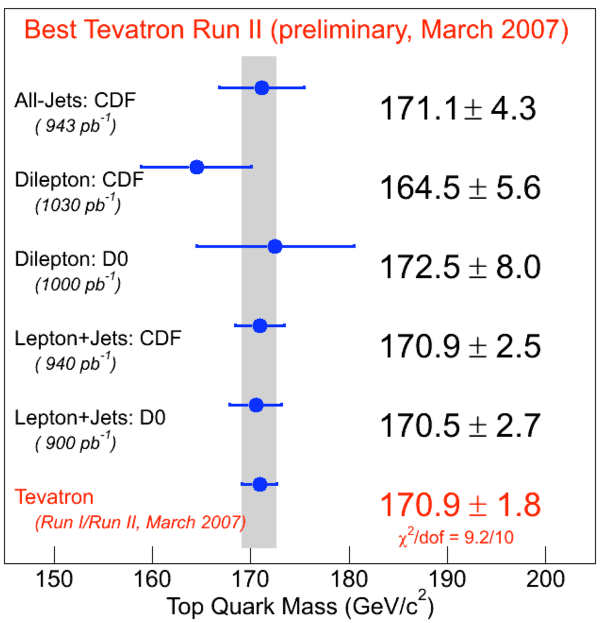
$$P_{sgn}(x; m_{top}, JES) = \frac{1}{\sigma} \underbrace{\sum w_i}_{\text{b-tag weights}} \int \underbrace{T(x, y, JES)}_{\text{transfer function}} \underbrace{d\sigma^n(y, m_{top})}_{\text{from ME}} \underbrace{f(q_1) f(q_2)}_{\text{PDFs}} dq_1 dq_2$$

- Integrate over all unmeasured quantities and experimental resolutions
- Fit simultaneously m_{top} and JES
  - using m_W constraint

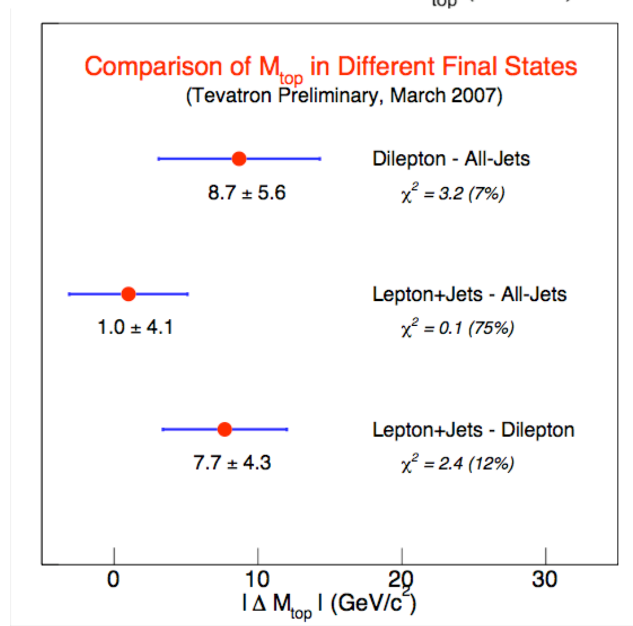
Top Mass Measurement

- Dominant systematics
  - ISR
  - FSR
  - PDFs
  - b-jet energy scale
  - b fragmentation





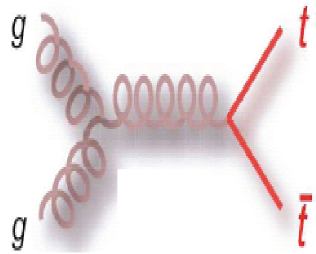
$\Delta m_{top} / m_{top} \sim 1\%$



- Is m_{top} in Monte Carlos used by experiments the same as m_{top} (pole) used in the EW fits?
  - e.g., colour reconnection effects?

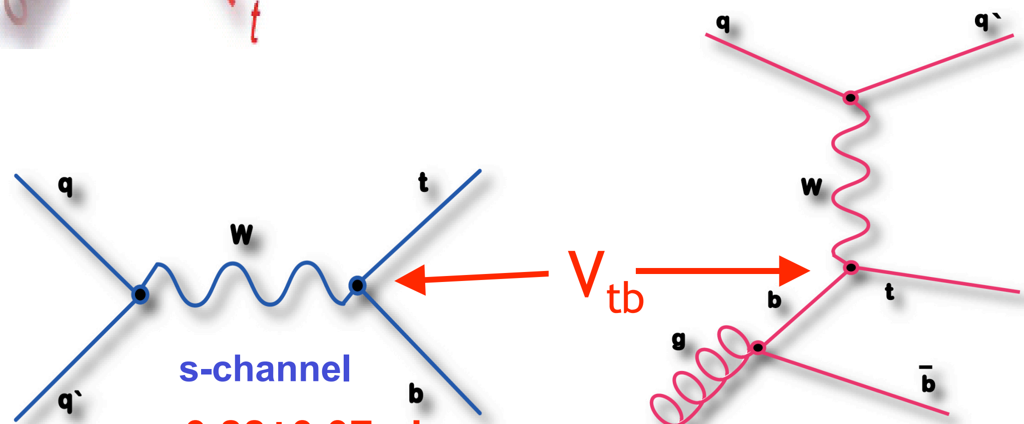
Evidence for Single Top Production

- Top pairs:



σ_{tt} **= 6.7 ± 0.8 pb**

- Single top:



σ_s **= 0.88±0.07 pb**

t-channel

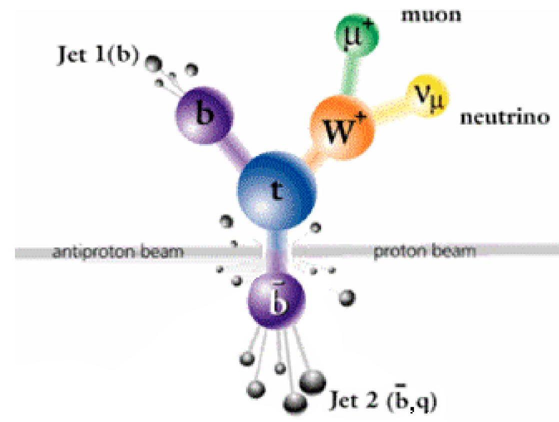
σ_t **= 1.98±0.21 pb**

- Motivation
  - Top pairs
    - can measure only ratio of couplings to kinematically allowed final states

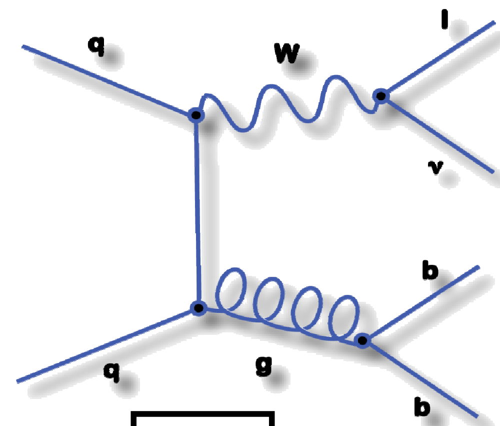
$$R = \frac{Br(t \to Wb)}{Br(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{tb}|^2 + |V_{ts}|^2 + |V_{td}|^2}$$

  - Single top
    - $\sigma_{s+t} \propto |Vtb|^2$
    - $|Vtb|^2$ can be determined with assumptions of 3 generations, unitarity

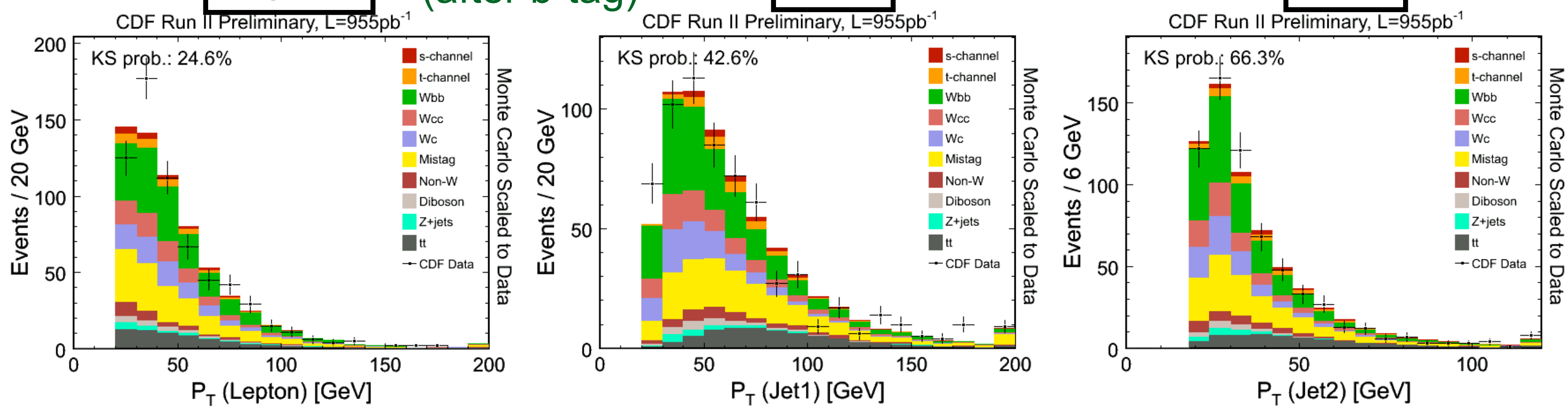
Backgrounds to Single Top



- σ_{s+t} only a factor of two lower than σ_{tt}
  - signal event signature less pronounced
    - fewer high p_T objects

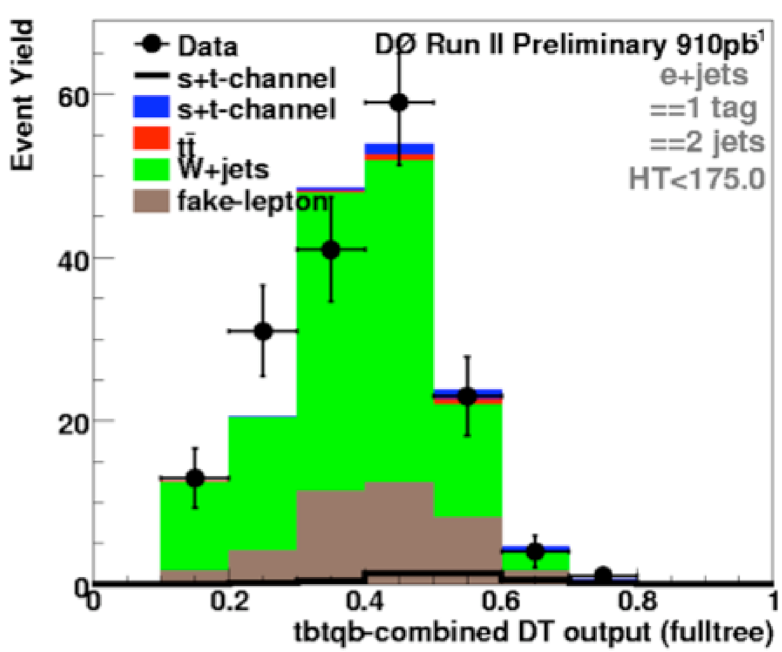


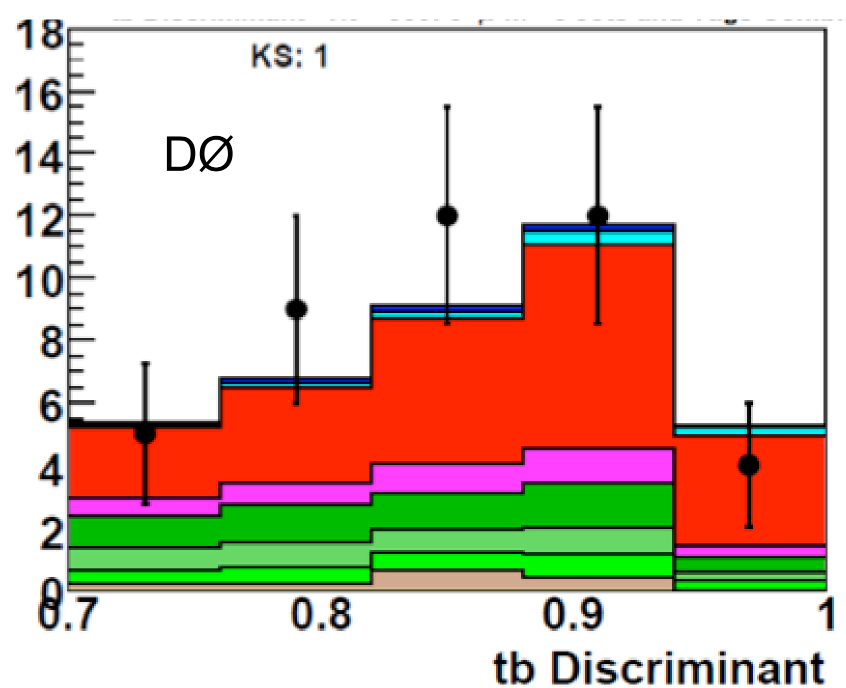
- Backgrounds much more of a challenge!
- W+jets poorly understood
  - especially W+heavy flavour
  - considerable tuning of MC to data required
  - Lepton (after b-tag) Jet1 Jet2



Kinematic Discriminants

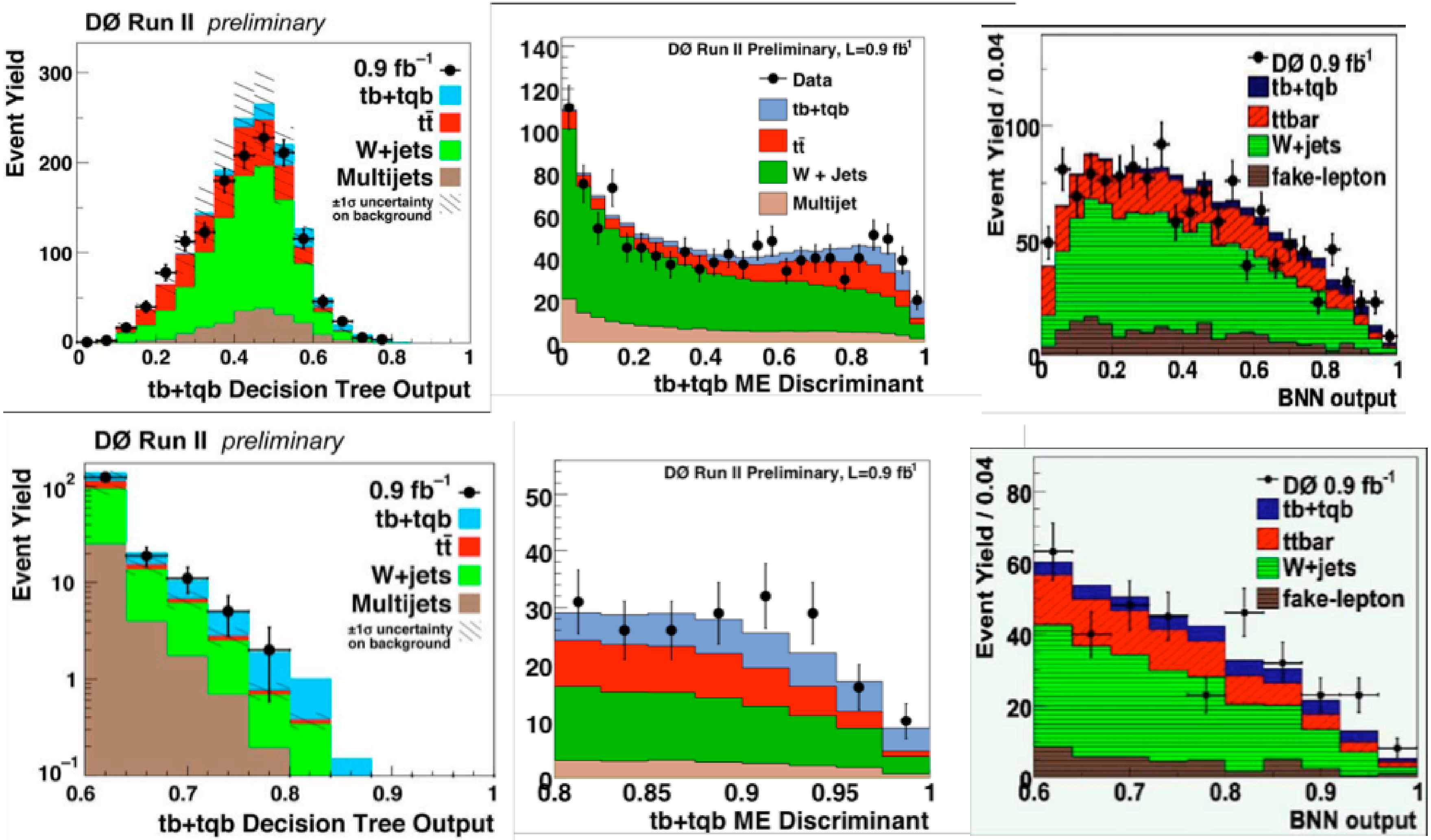
- Even after b-tagging signal swamped by background
- Use multivariate kinematic discriminants
  - e.g., Likelihood, Matrix Element, Neural Networks, Boosted Decision Trees
- Validate on "background-enriched" sub-samples
  - "W-like" (low total visible E_T) "tt-like" (very high total visible E_T)





DØ Evidence for Single Top

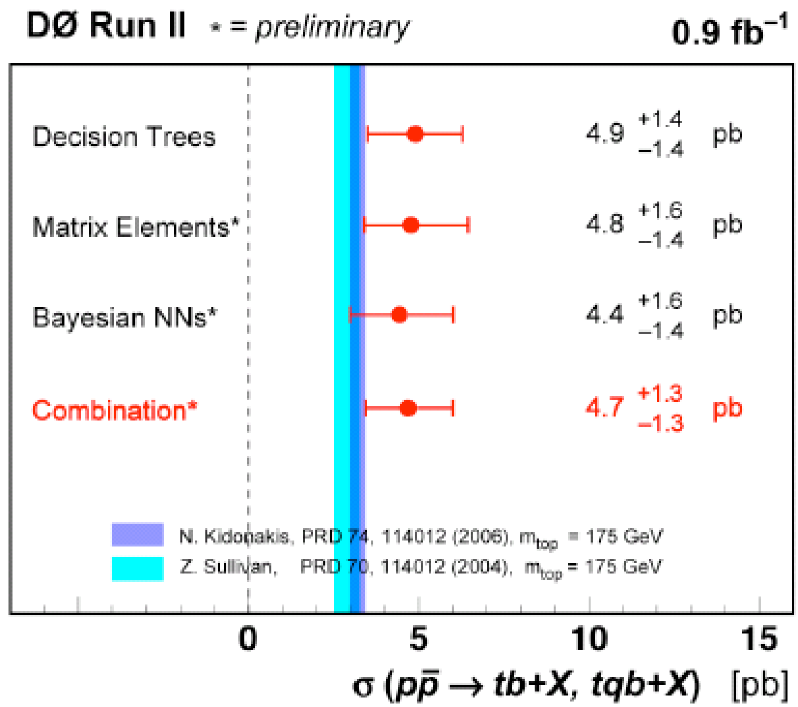
Decision Tree   Matrix Element   Bayesian NN



- Consistent excess seen in all three analyses

DØ Evidence for Single Top

- Combined result
  - σ_{s+t} consistent with SM
  - 3.6σ significance
  - 2.4σ expected significance

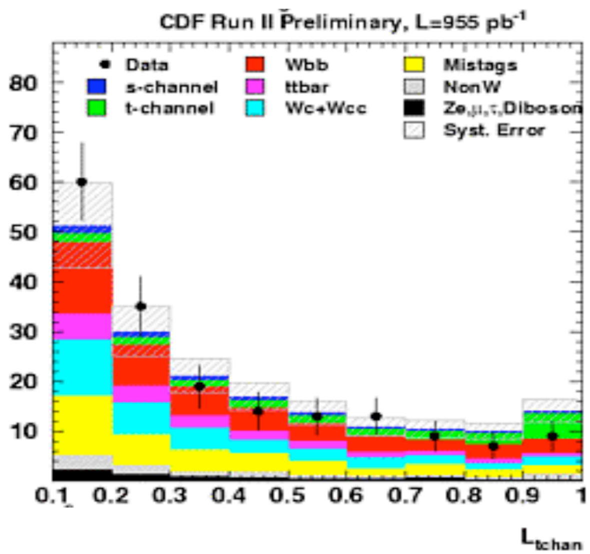


- First direct measurement of $|V_{tb}|$
  - Assuming standard model production:
    - Pure left-handed coupling
    - $|V_{td}|^2 + |V_{ts}|^2 << |V_{tb}|^2$
    - Additional theoretical errors needed (top mass, scale, PDF etc…)
  - Measurement does not assume 3 generations or unitarity

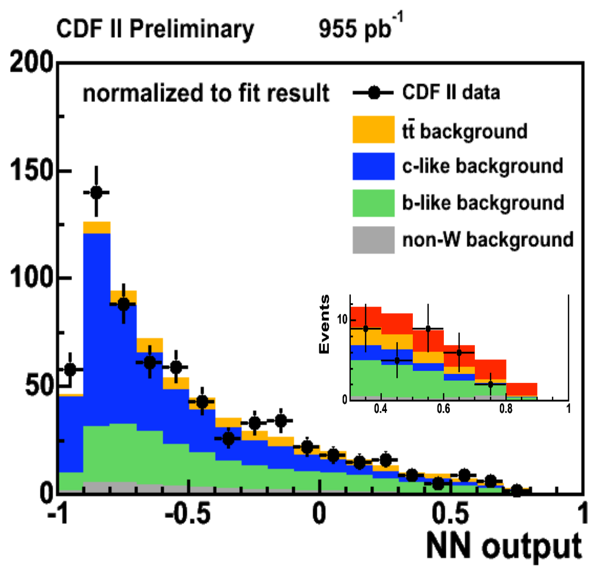
$|V_{tb}| = 1.3 \pm 0.2$ or $0.68 < |V_{tb}| < 1$ at 95%CL

CDF Single Top Results

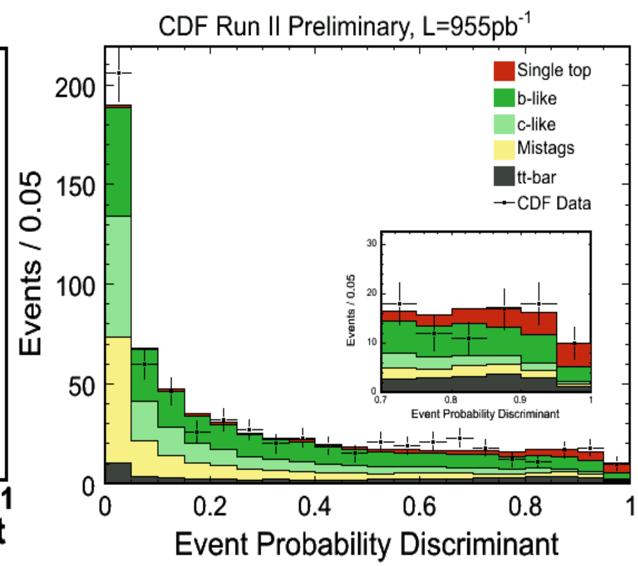
Likelihood



Neural Networks



Matrix Element



No evidence of signal
σ_{s+t}<2.7pb at 95% C.L.

Expected signal significance 2.0σ

No evidence of signal
σ_{s+t}<2.6pb at 95% C.L.

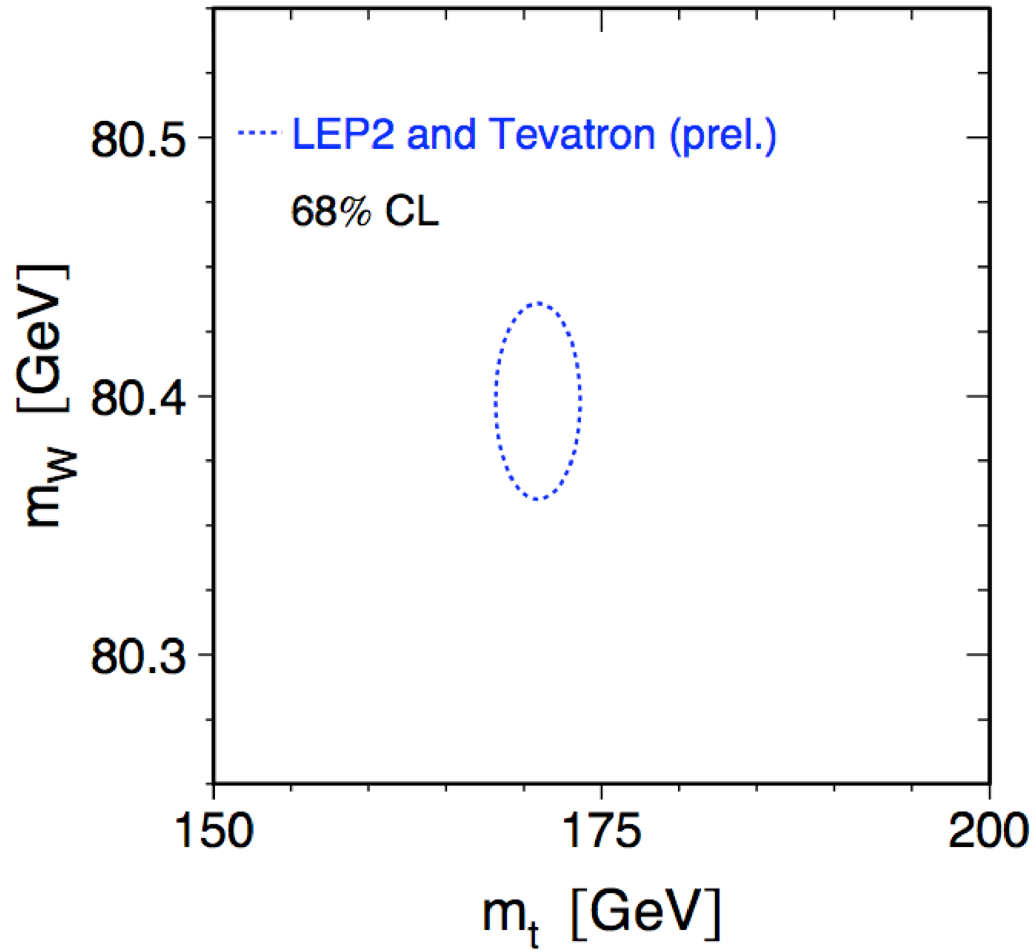
Expected signal significance 2.6σ

p−value = 1.0% (2.3σ)
σ_{s+t}=2.7(+1.5/−1.3)pb

Expected signal significance 2.5σ

1.2% of pseudo−experiments fluctuated as unluckily as the observed data

m_W and m_t (direct)



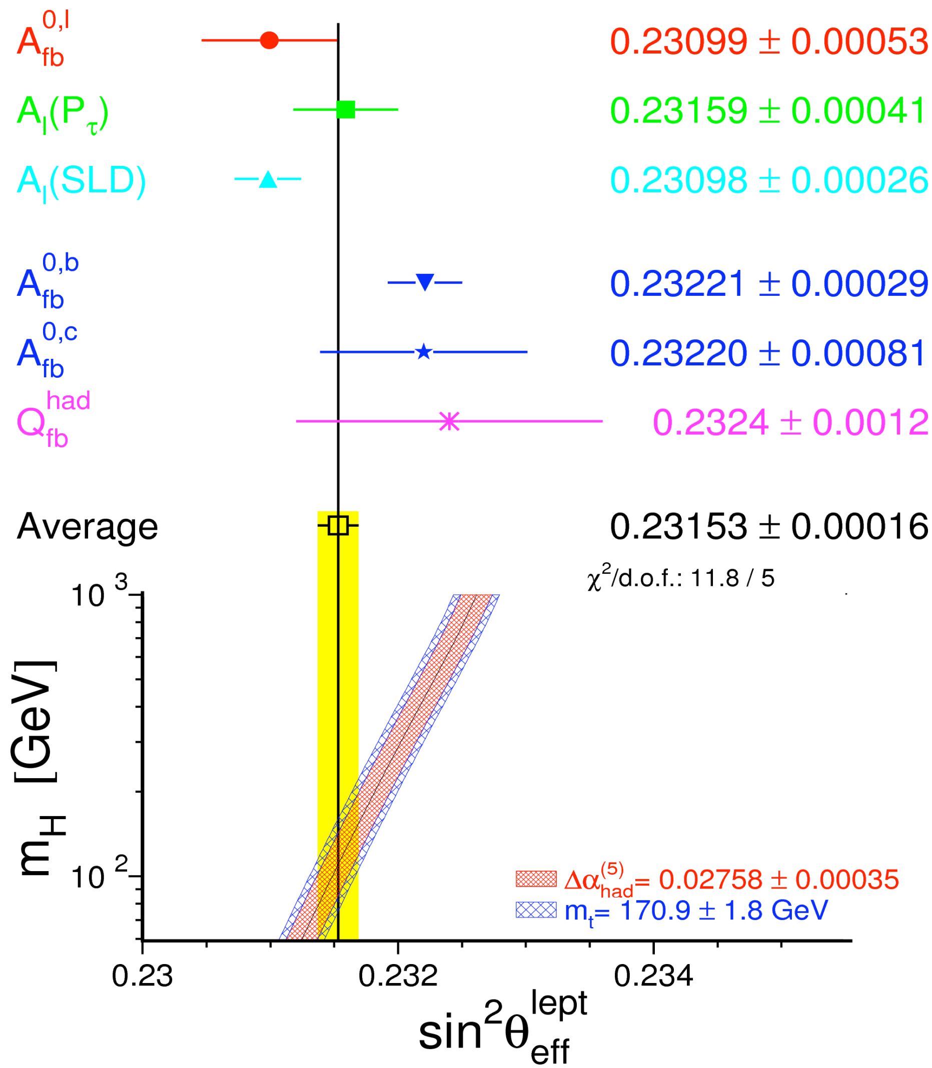
- Important parameters of SM
- Real interest is to compare with other information

Precision EW Data from LEP/SLC

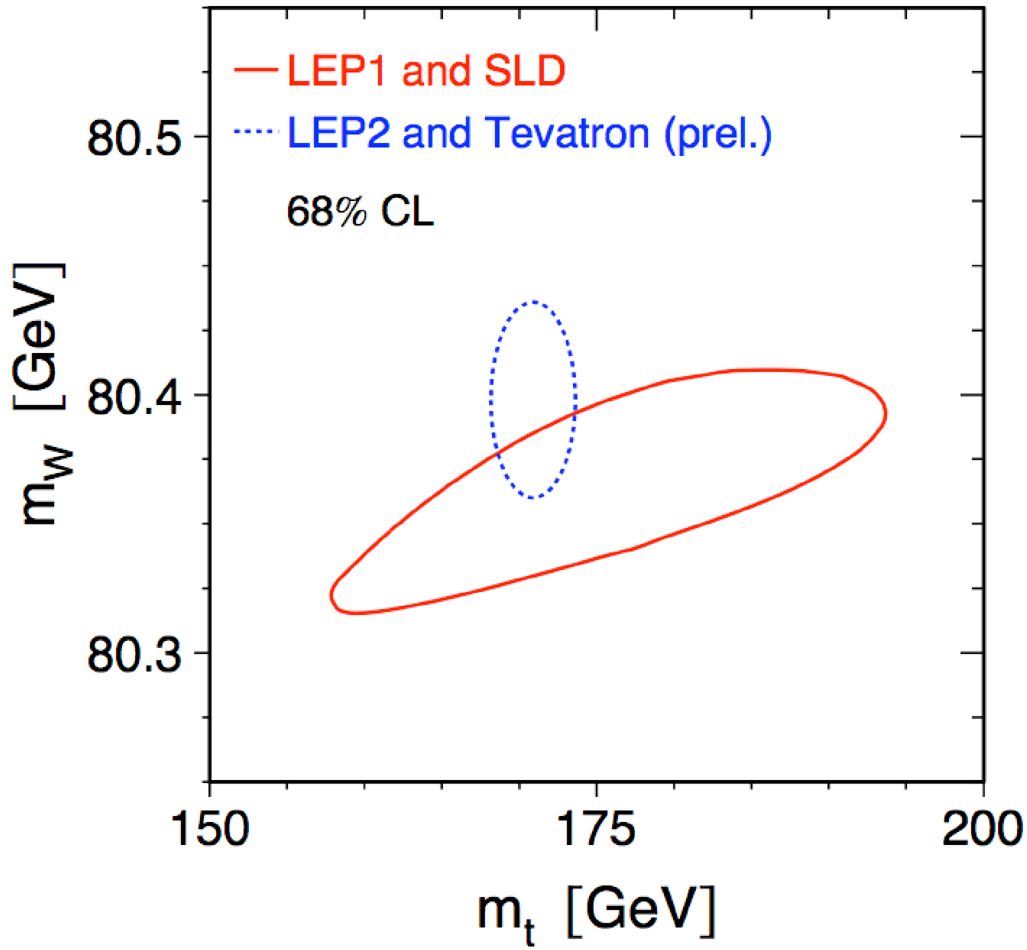
- Asymmetries measure:

$$\frac{(g_L^f)^2 - (g_R^f)^2}{(g_L^f)^2 + (g_R^f)^2}$$

- Longstanding issue:
  - "leptonic" and "hadronic" asymmetries consistent only at ~3α level
    - (may not be resolved until the ILC!)

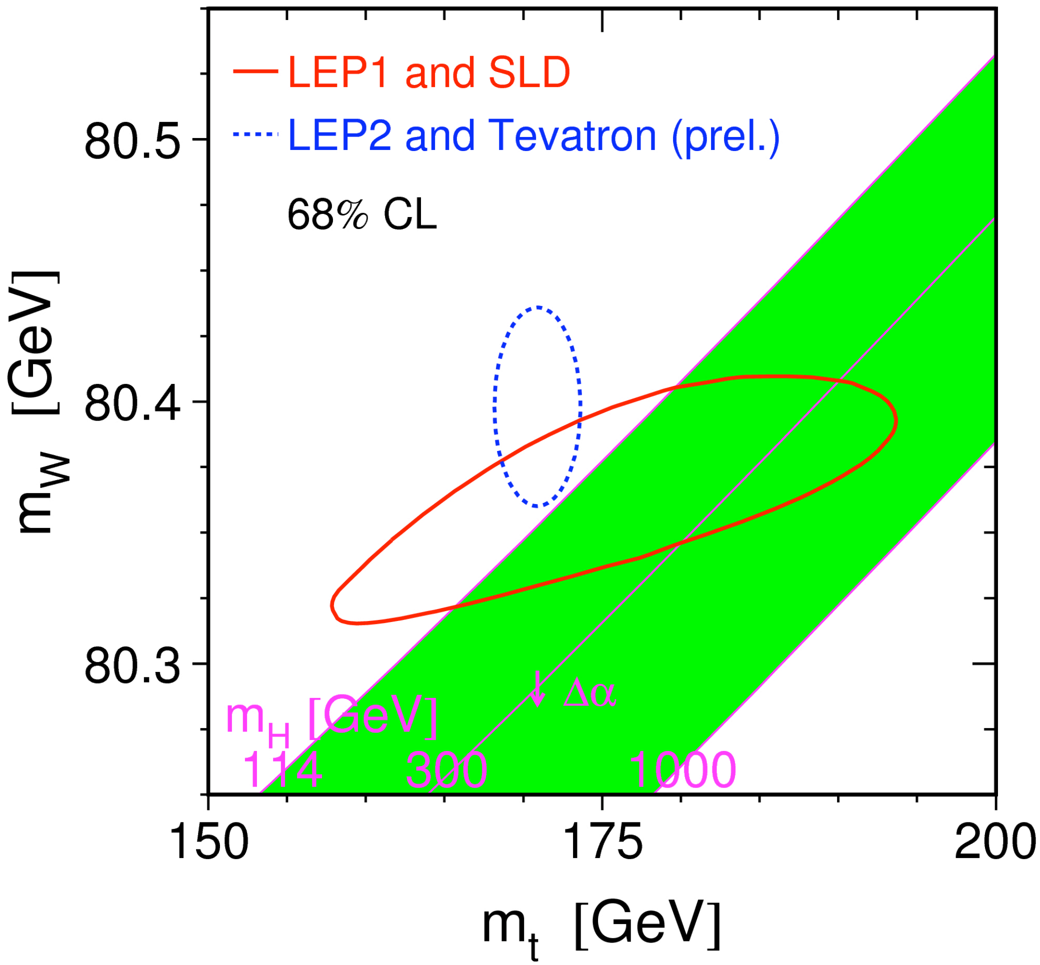


m_W and m_t (direct and indirect)



- Powerful consistency check of SM
- Decreasing Δm_W is the priority!

m_W and m_t (compared to m_H)



- Data prefer light Higgs
- Decreasing Δm_W is the priority!

Limits on m_H

$m_H = 76^{+33}_{-24}$ GeV

$m_H < 144$ GeV (95%CL)

Direct search limit (LEP-2):

$m_H > 114$ GeV (95%CL)

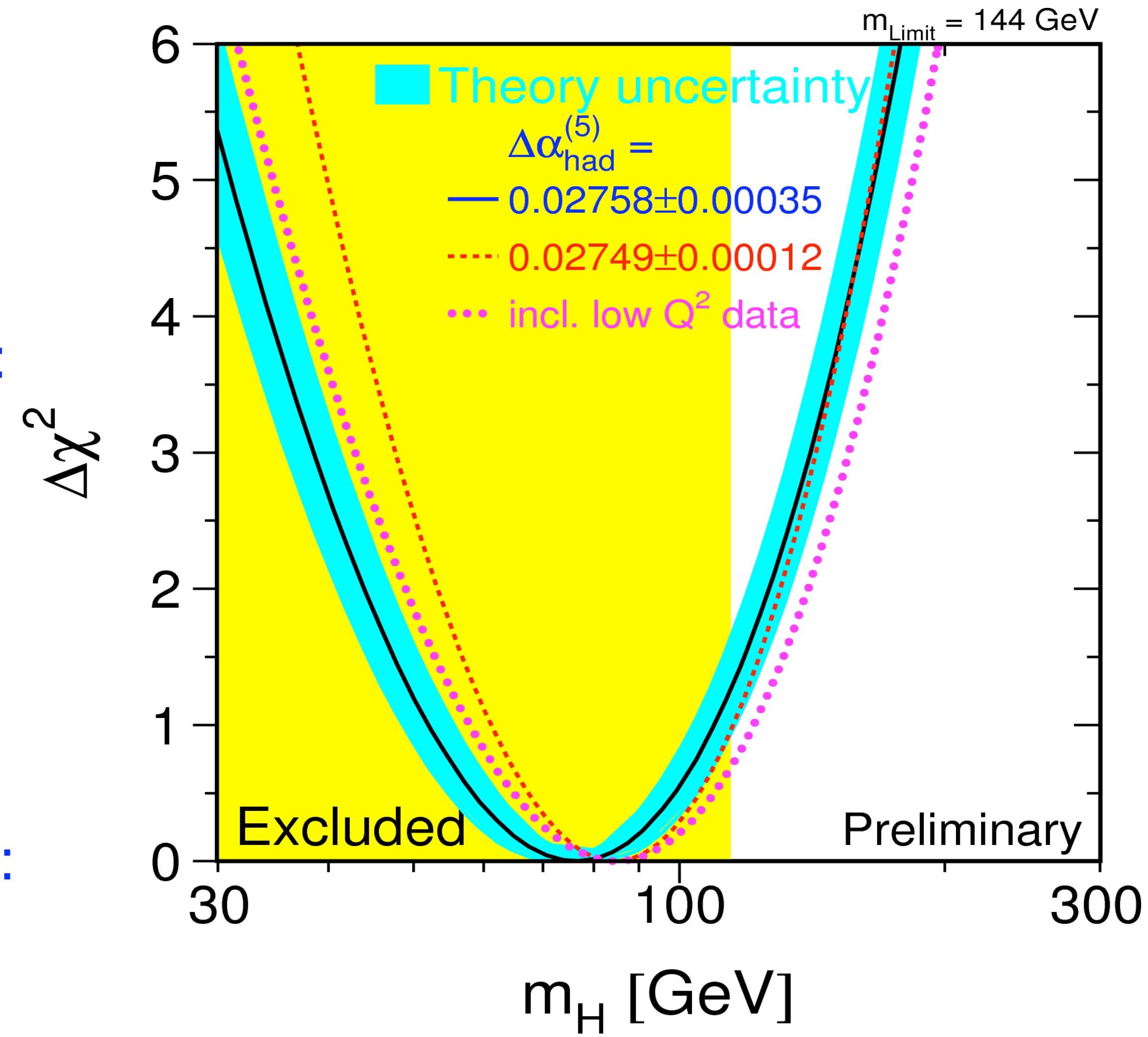
Probability M_H>114 GeV:

15%

Renormalise probability for m_H>114 GeV to 100%:

$m_H < 182$ GeV (95%CL)

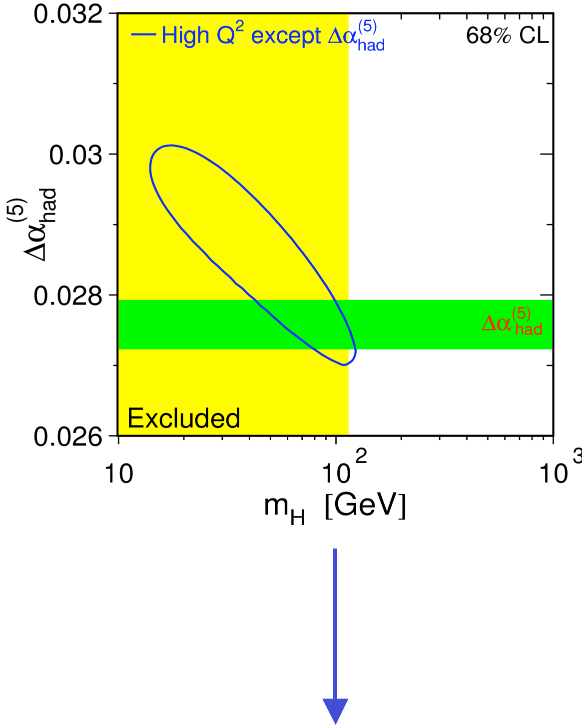
- **So let's find it!**



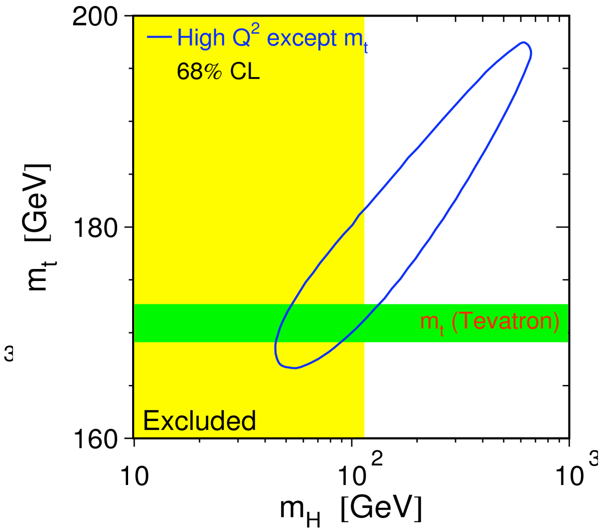
The Crucial Observables

Fit to all measurements but excluding:

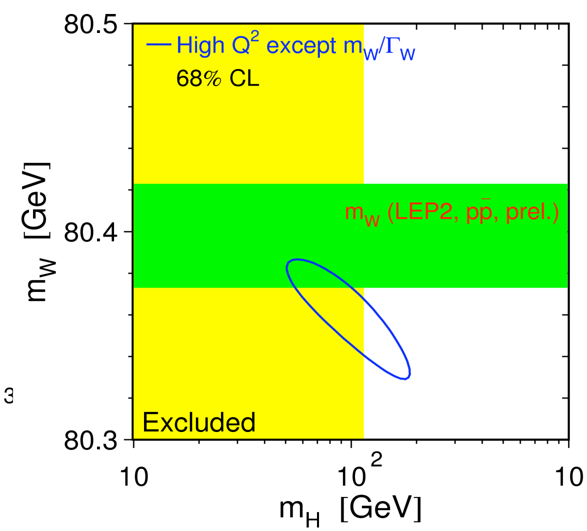
$\Delta\alpha_{had}(M_Z)$



M_{top}



M_W

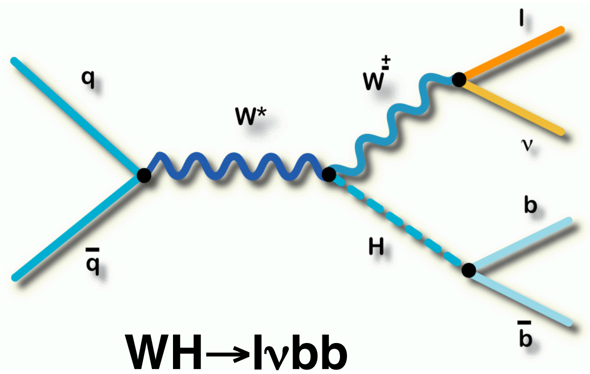


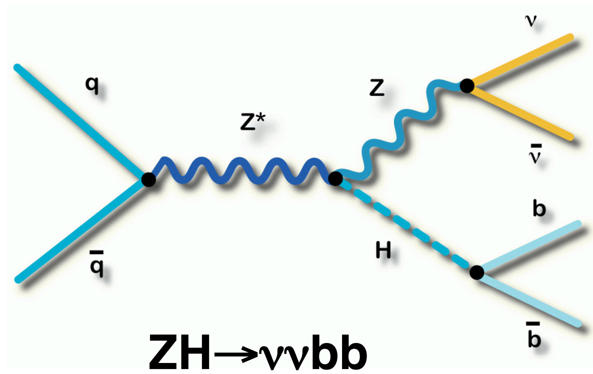
Yields $M_H < 140$ GeV (95%CL)

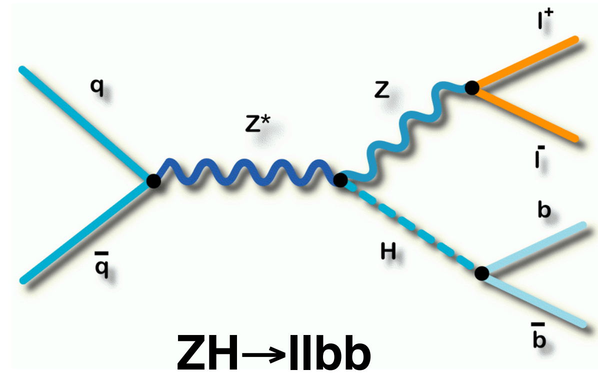
cf $M_H < 144$ GeV (95%CL) including external $\Delta\alpha_{had}(M_Z)$

Searches for the SM Higgs Boson at the Tevatron

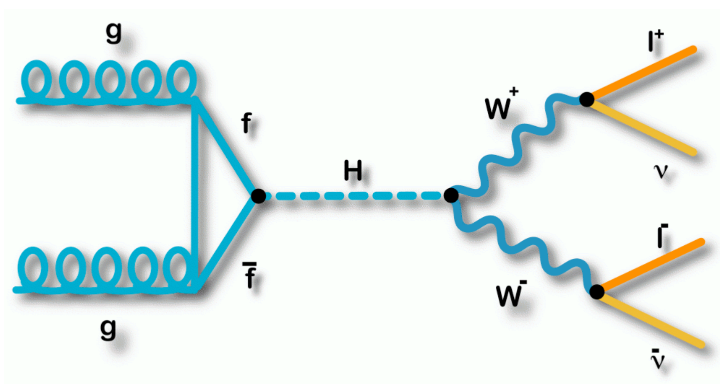
Associated Production: Low mass only, three final states







Gluon Fusion: Most interesting at intermediate to high masses

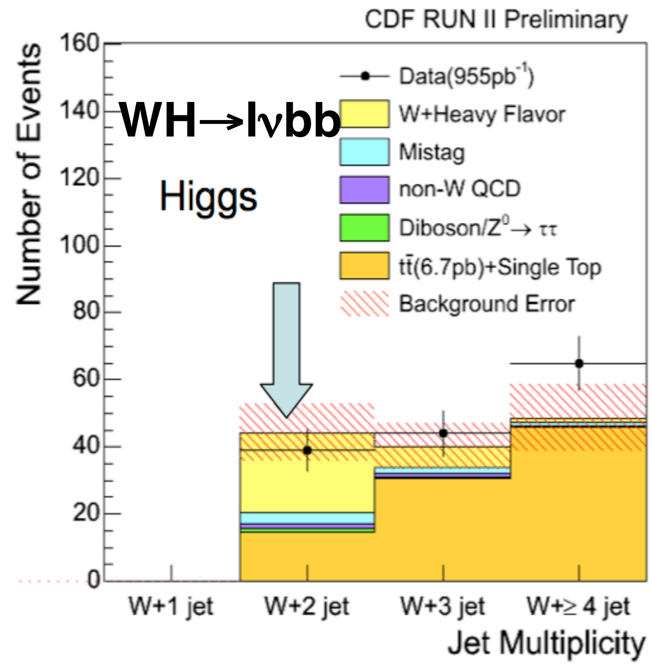


Higher cross section
 - but can only distinguish from backgrounds with H→WW decay

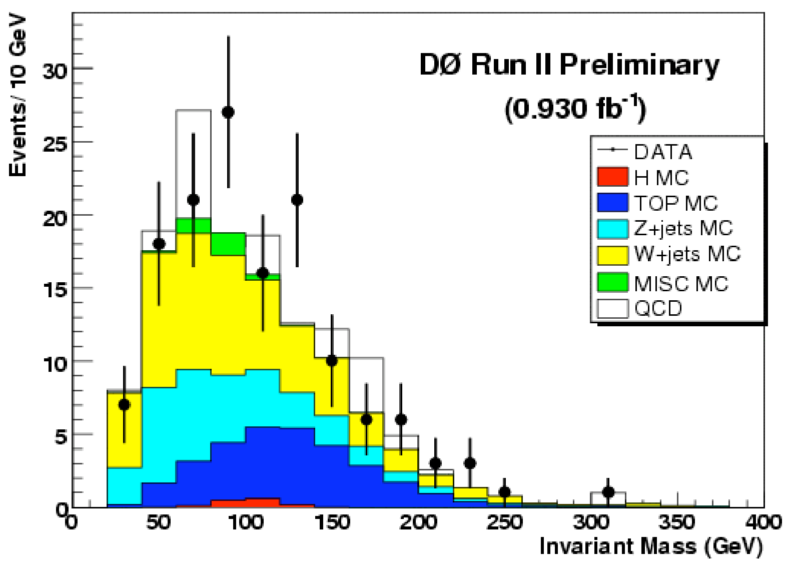
"The Higgs is underneath the needle in the haystack"

Associated Production

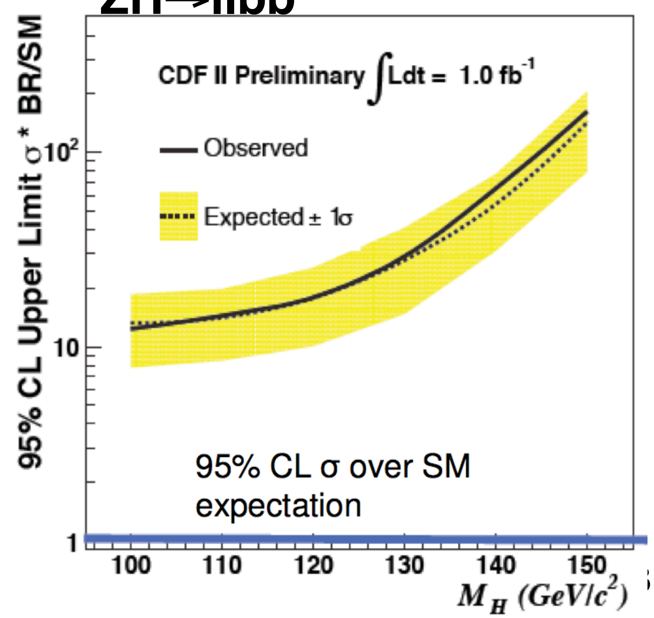
- Many improvements:
  - increased lepton acceptance
  - improved b-tagging
  - improved bb mass resolution



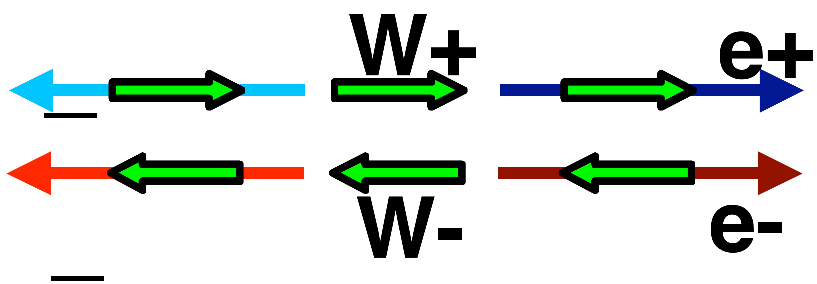
ZH→ννbb: 2 b-Tags

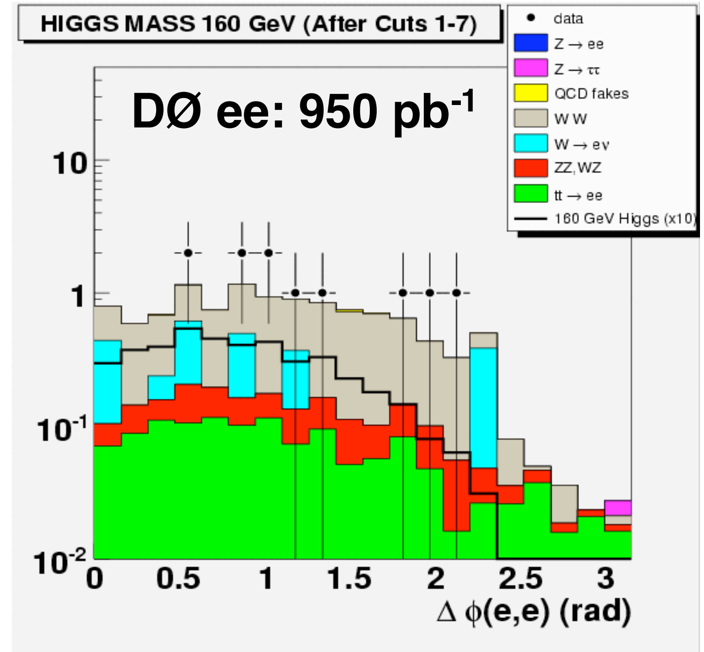


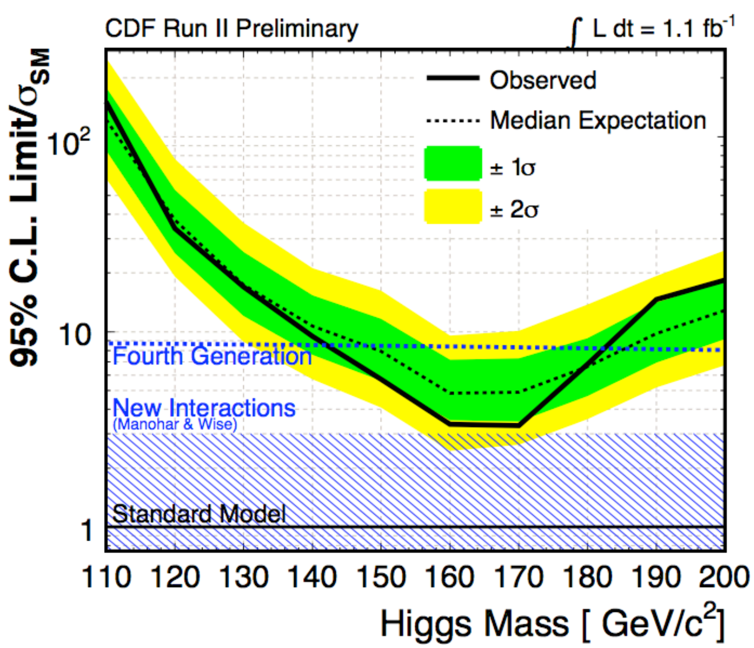
ZH→llbb



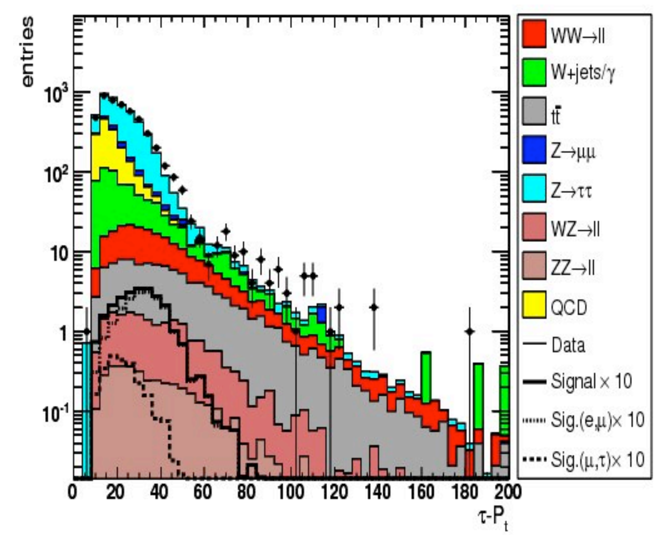
High Mass



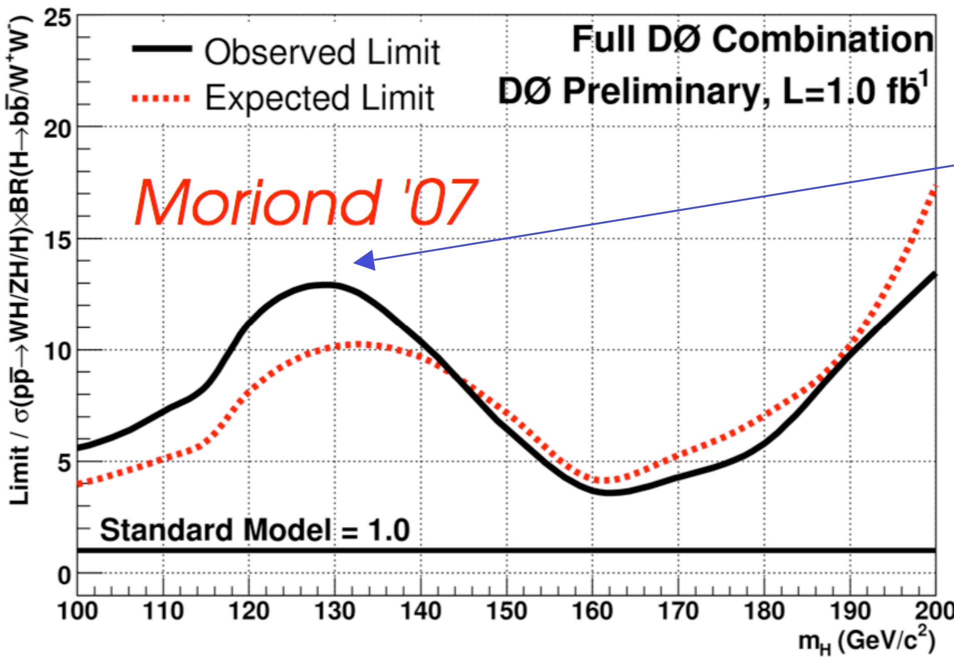




- New DØ search in H →WW →μτ



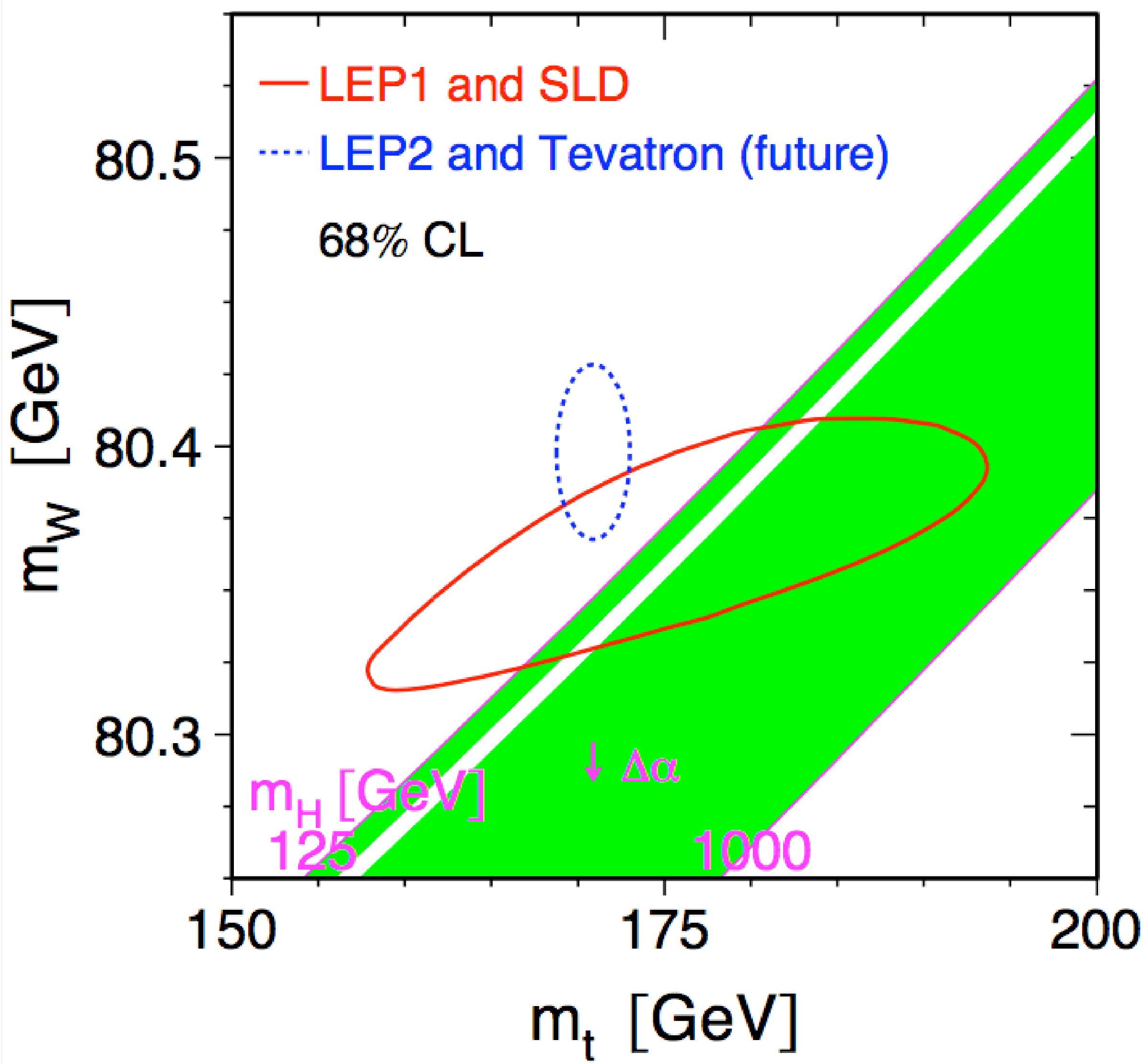
DØ Combined 1 fb^{-1} Limit



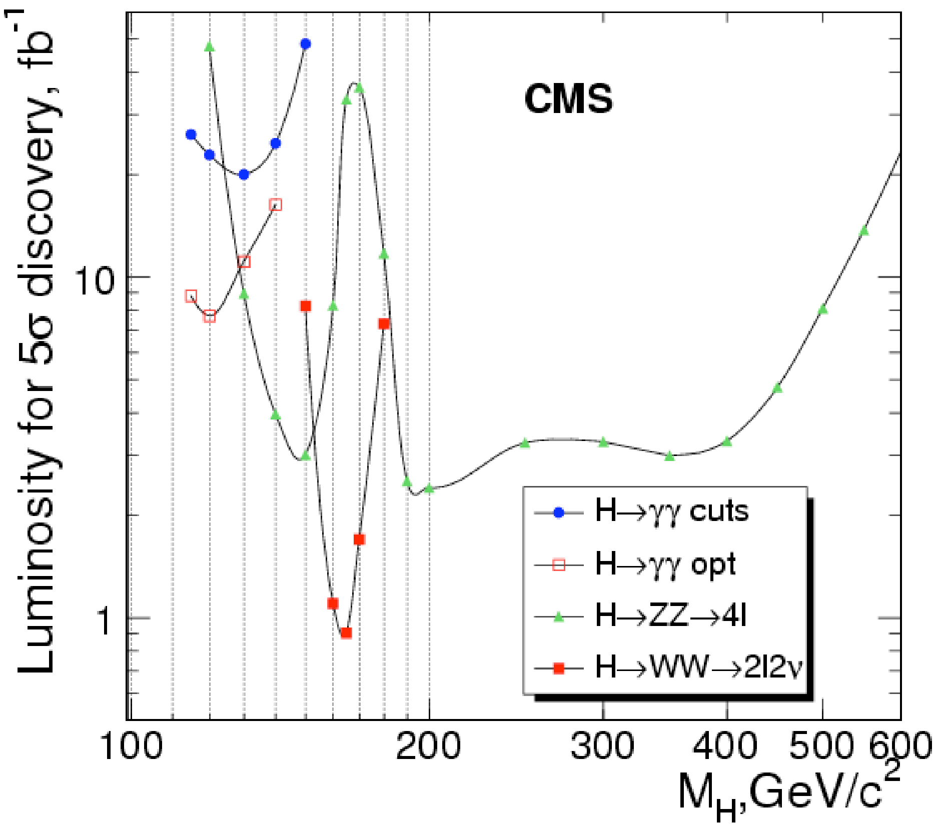
WH →WWW will help fill gap in sensitivity around m_H= 130 GeV

- Single experiment sensitivity
  - within factor 6 (4) of SM for m_H=~115 GeV (m_H=~160 GeV)
- Many improvements in pipeline
  - more data, combine experiments, more channels, get cleverer
  - expect sensitivity to continue to improve ~L and not √L !
- Success with low cross section, high background SM signals:
  - WZ, ZZ, single top
- Direct limits, or direct hints, from Tevatron with ~2-4 fb^{-1}?!

Outlook for EPS2009?



LHC Sensitivity



- Huge EW event samples crucial to commission detector, trigger and event reconstruction
  - in 1 fb-1
    - 250k l+jet tt events
    - 1M Z→ll events

- Intense theoretical activity in this area
  - QCD is under control at 10% level
  - Need to consider EW corrections ~5-8%

Summary

- Precise EW physics requires close interplay
  - precise experiment ↔ precise Monte Carlo ↔ precise theory
- Stay tuned for many new results from Tevatron experiments
  - 1 $fb^{-1} \rightarrow 6\ fb^{-1}$
- With the start up of the LHC the next year or two will be exciting times for EW physics!
  - Longer term prospects
    - $\Delta m_t \sim 1$ GeV, $\Delta m_W \sim 10$ MeV
    - will require a heroic effort!

Outlook for EPS2009?