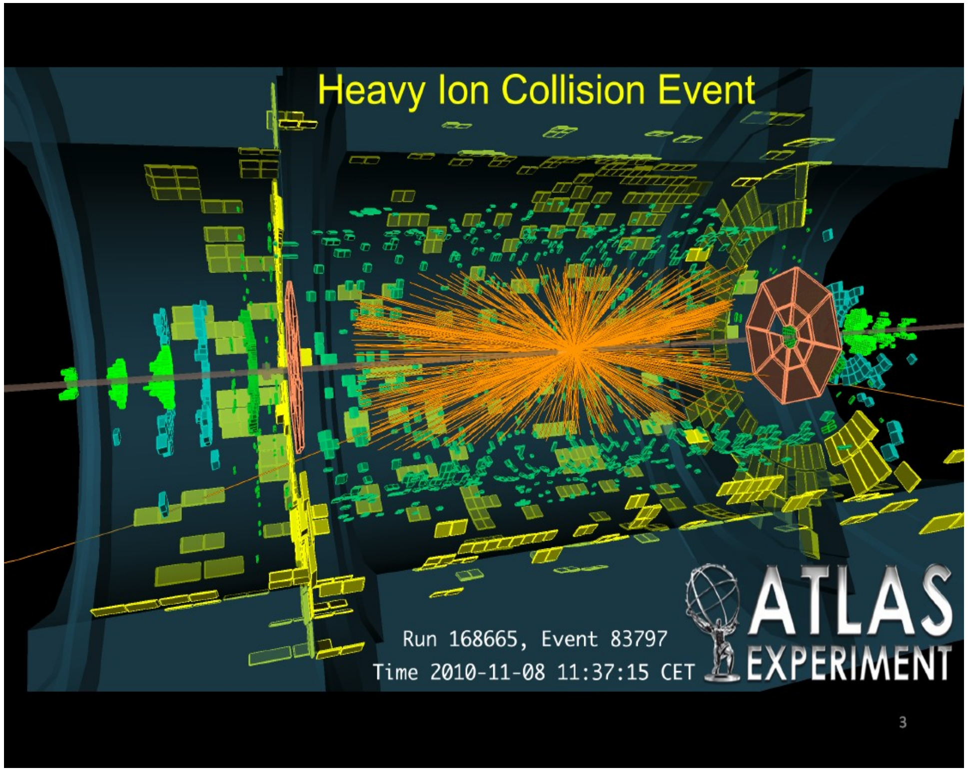
Physics Program
of the experiments at
Large Hadron Collider

Lecture 6

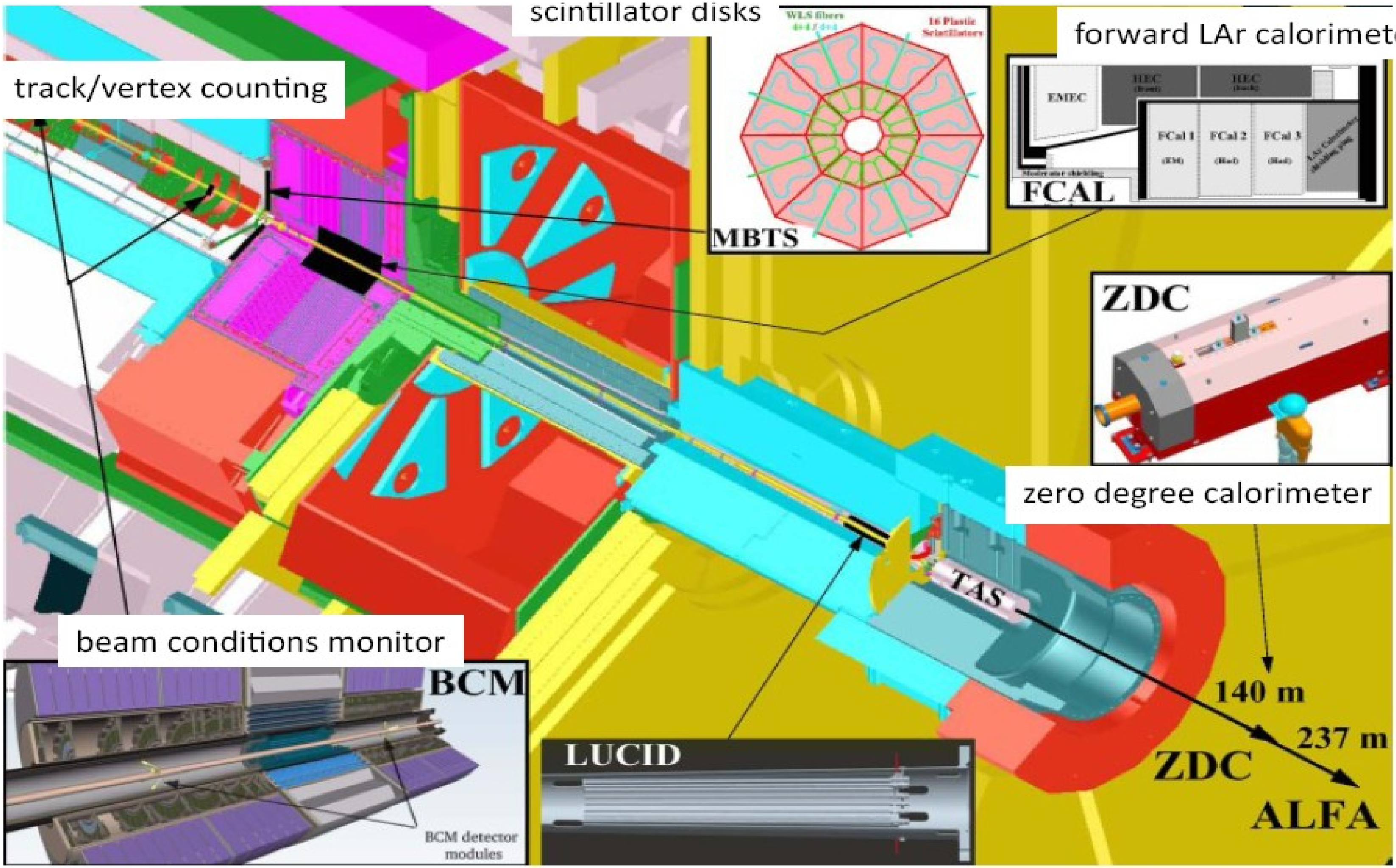
Physics with
W and Z bosons: part II

Latest news!!!

- The 50ns bunch spacing achieved but large electron background preventing going higher than 36 bunches per train.
- **First heavy ion collisions during night 6/7 November**
  - E_{beam} = 3.5 TeV x Z
    = 287 TeV,
    sqrt(s_{NN}) ~ 2.76 TeV
  - Peak luminosity: 1.3 10^{24}
  - Goal is up to 128 bunches

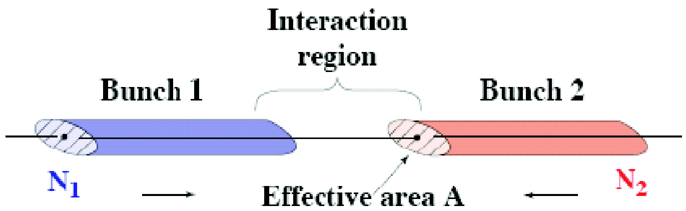


Luminosity measurement at ATLAS

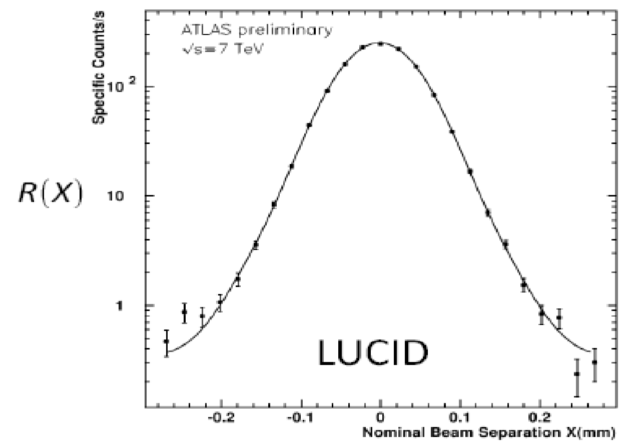


gas Cherenkov tubes

Luminosity measurement at ATLAS



- LHC provided three van der Meer scans
  - beams separated by known distances & interaction rate measured
  - measured transverse beam profile gives normalization from geometry
- Luminosity normalization now known to **11%**
  - Largest uncertainty from LHC beam current measurement (5% per beam)



$$\mathcal{L} = \frac{n_b f_r I_1 I_2}{2\pi \Sigma_x \Sigma_y}$$

$\longrightarrow$ n_b: number of bunches

$\longrightarrow$ f_r: revolution frequency

$\longrightarrow$ $I_{(1,2)}$: particles per bunch in beams 1, 2

$\longrightarrow$ $\Sigma_{(x,y)}$: effective convolved width in x, y
$= \int R(X)\, dX / (\sqrt{2\pi}\, R_{peak})$

Hadron colliders

Hera, Desy

- 319 GeV proton – electron collider

- Run 1992-2007
- Accumulated:
  - ~ 200pb-1 in e^-p
  - ~ 300pb-1 in e^+p

Tevatron, Fermilab

- 1.96 TeV p-anti p collider

- RunII started in 2002
- Delivered ~9fb^{-1}/exp.

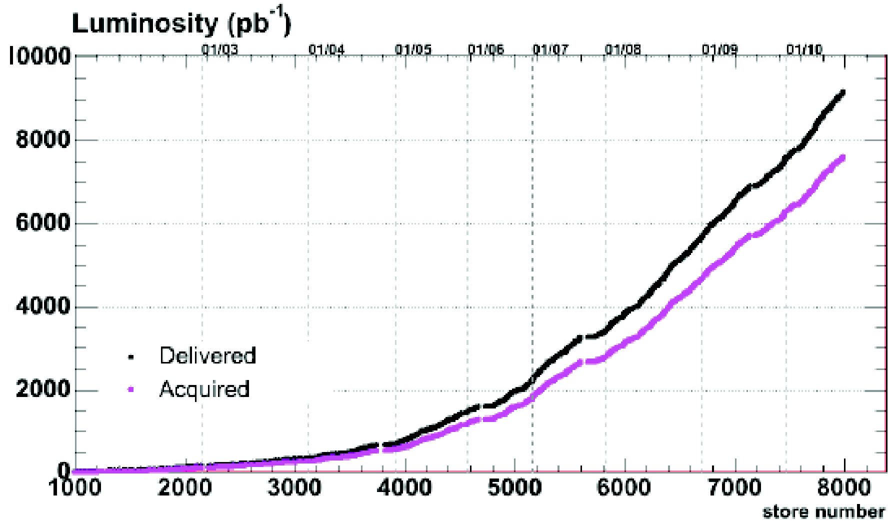
LHC, Cern

- ≤ 14 TeV p-p collisions

- Run phase I at sqrt(s)= 7 TeV started in 2010
- Delivered ~50pb^{-1}/exp.

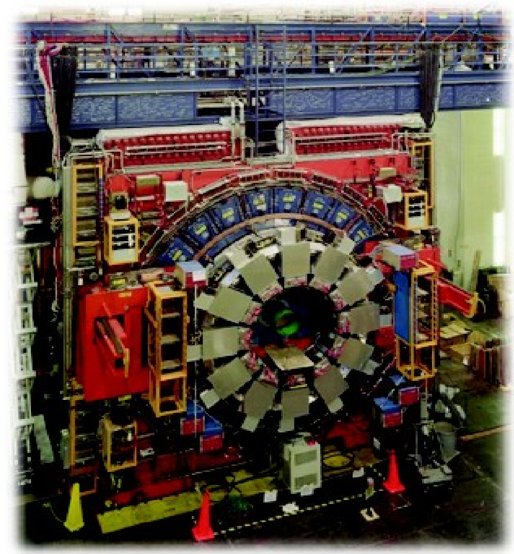
RHIC is also joining with polarised pp program

The Tevatron



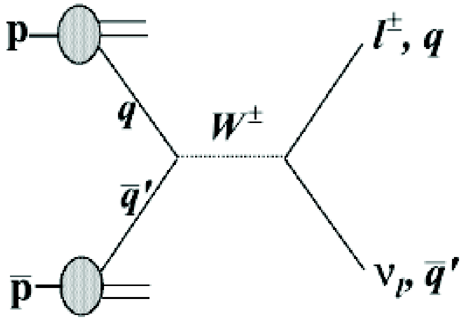
- 1.96 TeV p-anti p collider
- RunII since 2002,
  expect to end in 2011
- Further running
  2012-2014 is being considered
- Had delivered ~ 9fb^{-1} per experiment since 2002, and is running smoothly:
- Expect ~ 12fb^{-1} by end 2011

The Tevatron experiments

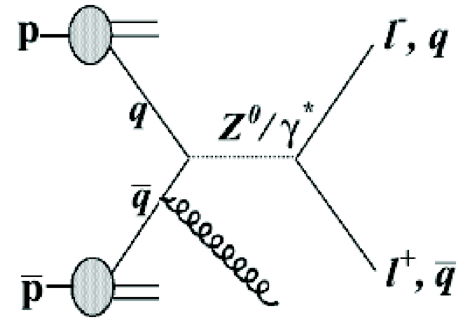


- Similar detectors in both experiments
  - Inner trackers
    - **CDF highlight:** large volume, high precision
  - Calorimeters
  - Outer muon detectors
    - **D0 highlight:** high acceptance & low background

W and Z at Tevatron



$\sigma(p\bar{p} \to W^{\pm} \to l\nu) \sim 2700$ pb

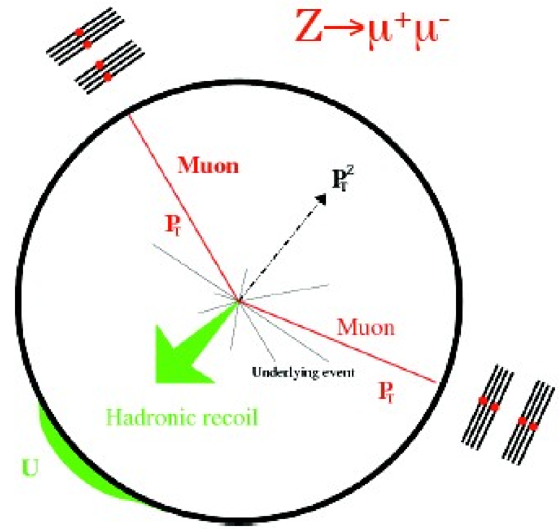


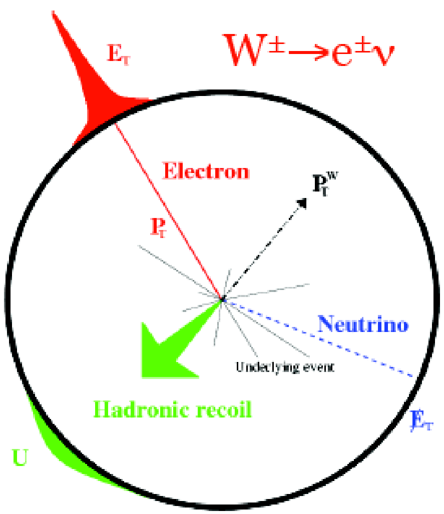
$\sigma(p\bar{p} \to Z^0 \to l^+l^-) \sim 250$ pb

- Probe QCD and EW interactions
  - Hard and soft gluon emission
  - Sensitive to parton distribution
- Leptonic decay used for precision measurements
  - Extract Electro-weak (EW) parameters: $\sin^2\Theta_w$ and m_W
- In $1fb^{-1}$/experiment: $W\to l\nu$ 10^6 events, $Z\to ee$ 10^5 events
  - High statistics samples and low background

Detecting W and Z

- $Z \rightarrow l^+l^-$
  - **Signature:** pair of charged leptons with opposite sign charge
    - Leptons are high p_T and isolated
  - Peak in l^+l^- invariant mass



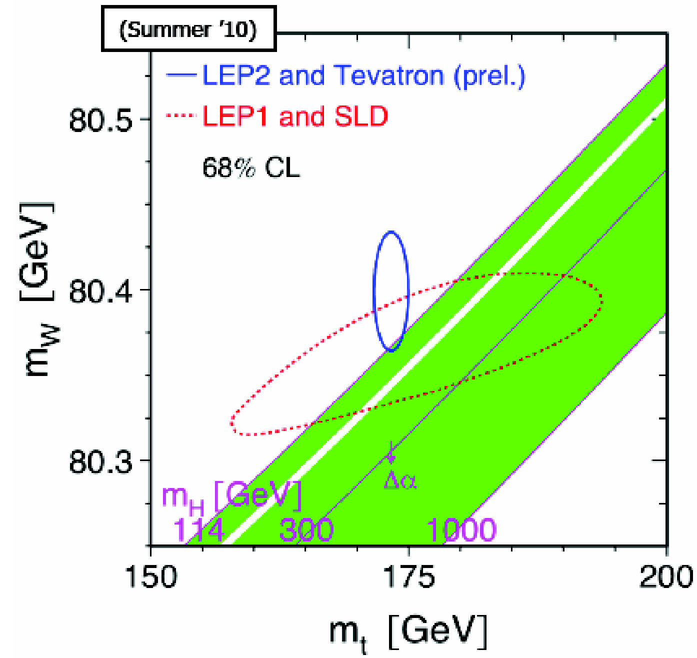


- $W \rightarrow l^\pm \nu^\pm$
  - **Signature:** single charged lepton and missing transverse energy (MET)
    - Leptons are high p_T and isolated
    - MET from neutrino
      - $p_T \nu$ is inferred
  - Peak in transverse invariant mass

W mass:

SM consistency check

- Derive W boson mass from precisely measured electroweak quantities
- Measuring the W boson mass and to quark mass precisely allows for predictions of the mass of the Higgs boson
- **Δr – large** radiative corrections
  - Dominated by tb and Higgs loops
  - Sensitive to new physics



m_{top}=(173.3 ± 1.1) GeV (0.6%)

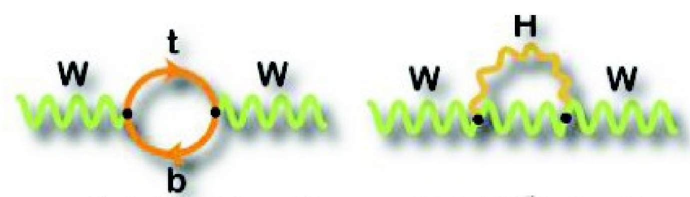
m_W =(80.399±0.023) GeV (0.028%)

$\Delta m_W \sim 0.006 \times \delta m_{top} \sim 7$ MeV for equal weights in Higgs limits

known to 0.015%

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

known to 0.0009% M_Z known to 0.002%

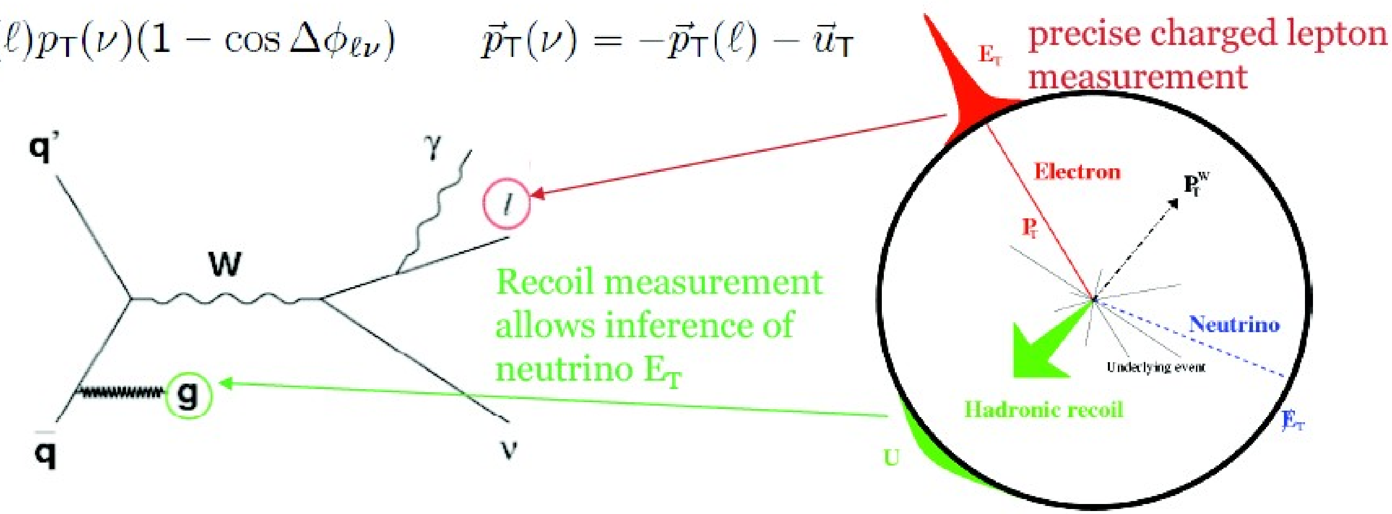


$\Delta r \propto m_{top}^2$ **$\Delta r \propto \log m_H$**

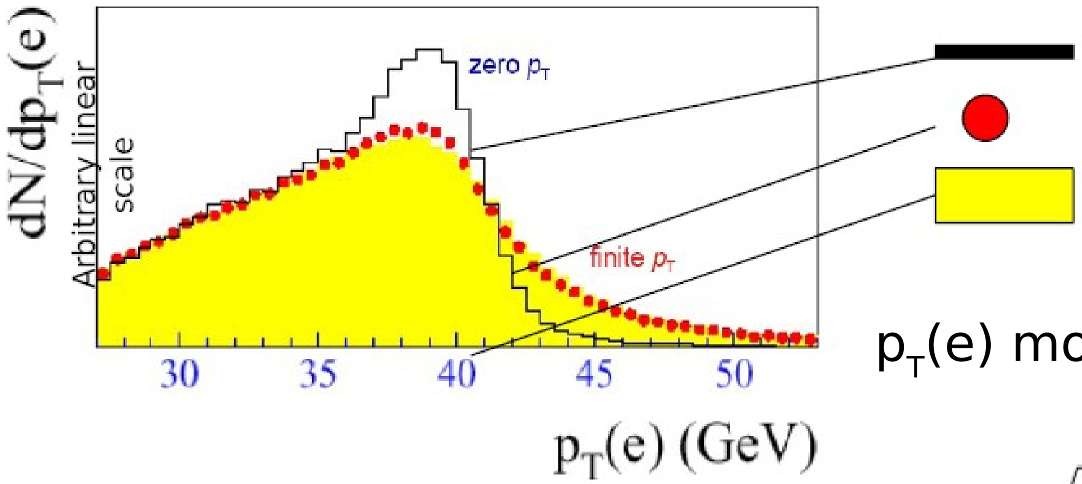
W mass measurement strategy

- At hadrons colliders, rely on transverse variables: m_T, p_T^l , MET (inferred neutrino p_T)
  - Requires precise measure of charged lepton p_T and hadronic recoil
  - Requires detailed knowledge of the detectors

$$m_T^2 = 2p_T(\ell)p_T(\nu)(1 - \cos\Delta\phi_{\ell\nu}) \qquad \vec{p}_T(\nu) = -\vec{p}_T(\ell) - \vec{u}_T$$



Experimental observables

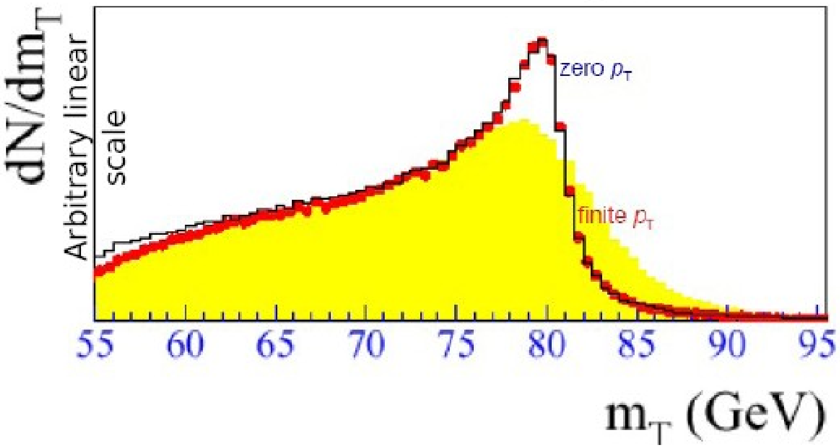


No $P_T(W)$

$P_T(W)$ included

Detector Effects added

$p_T(e)$ most affected by $p_T(W)$

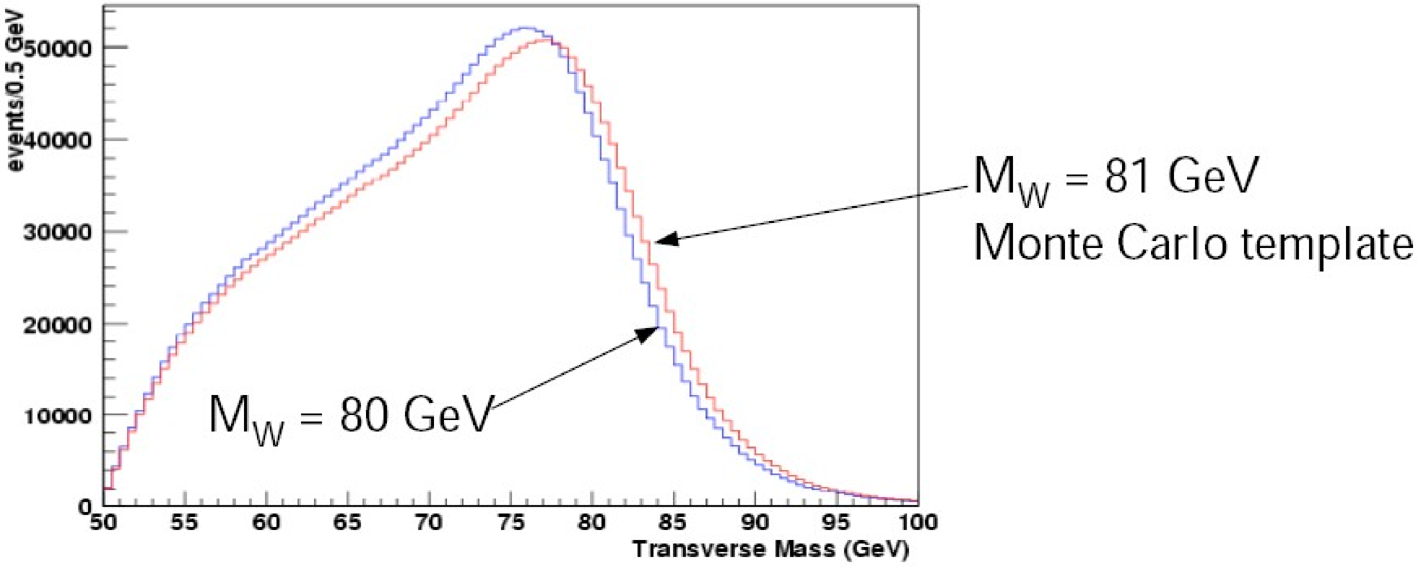


$$m_T = \sqrt{2 p_T^l p_T^\nu (1 - \cos\Delta\phi)}$$

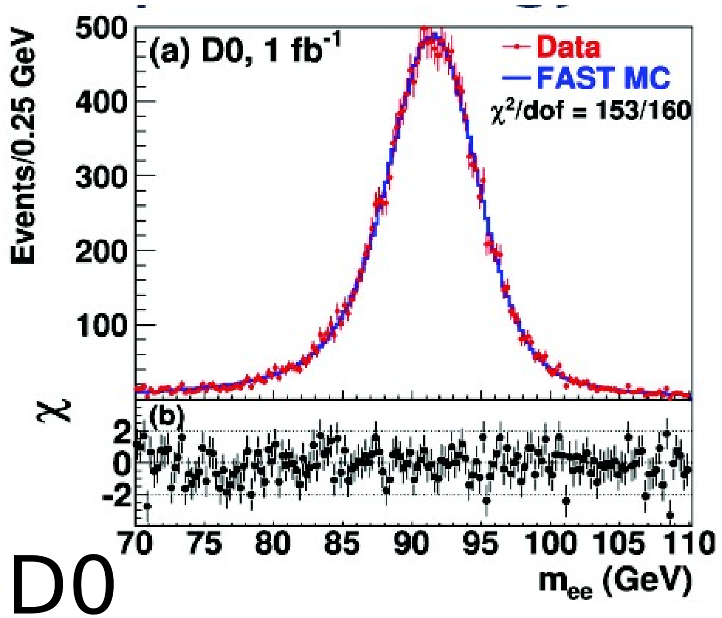
m_T most affected by measurement of MET

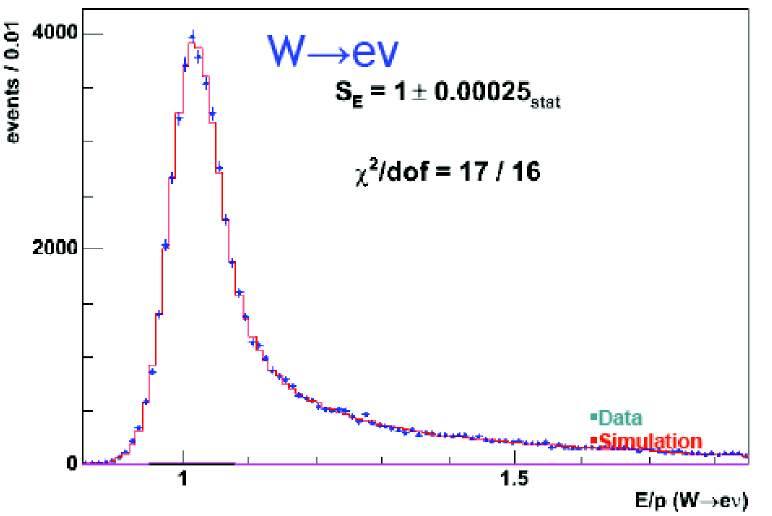
Template fitting

- Custom fast Monte Carlo makes smooth high-statistics templates. Perform binned maximum likelihood fits to the data
  - And provides analysis control over key ingredient of the simulation



Lepton energy/momentum scale

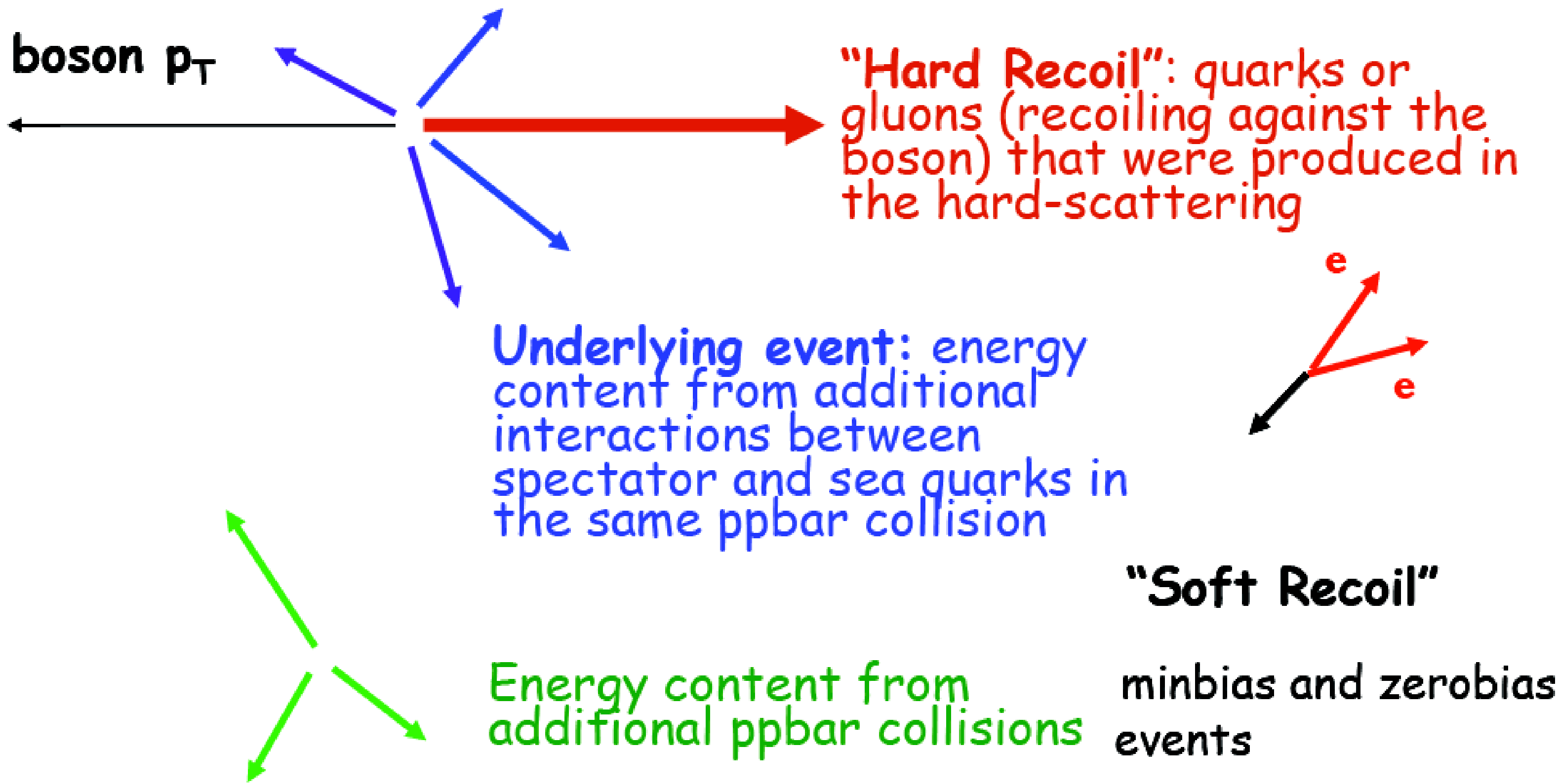




- D0
  - Calibrate calorimeter using precisely M_Z from LEP
  - Detailed corrections for uninstrumented regions
- CDF
  - Calibrate lepton momentum scale using Υ, J/Ψ, m_Z
  - Calibrate calorimeter against precision tracker (E/p), M_Z

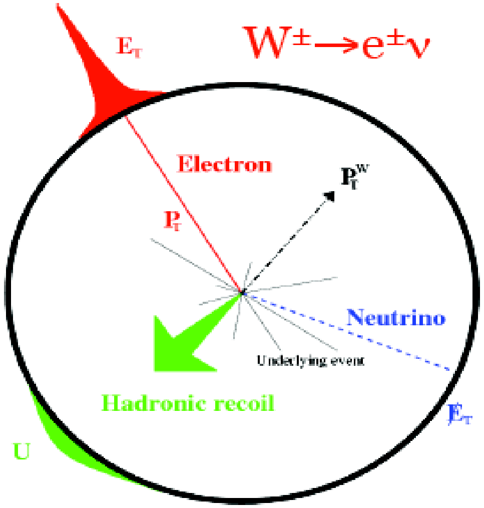
Dominant systematic uncertainty (D0: 34 MeV, CDF: 17/30 MeV e/μ)

Recoil model

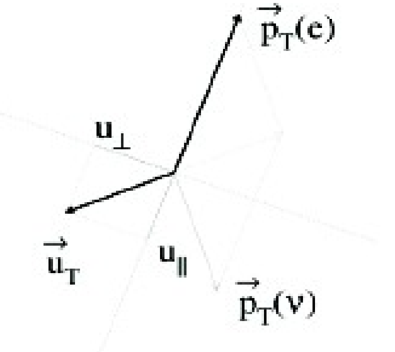


Final adjustment of free parameters in the recoil model is done **in situ** using $Z \to ee$ events

Recoil model

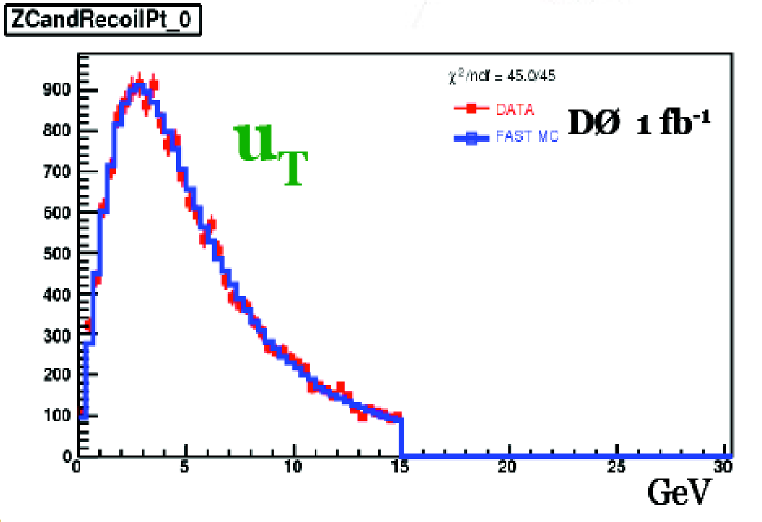


- **Recoil due to:**
  - QCD radiation “recoil” against W
  - Underlying event
  - Overlapping min bias



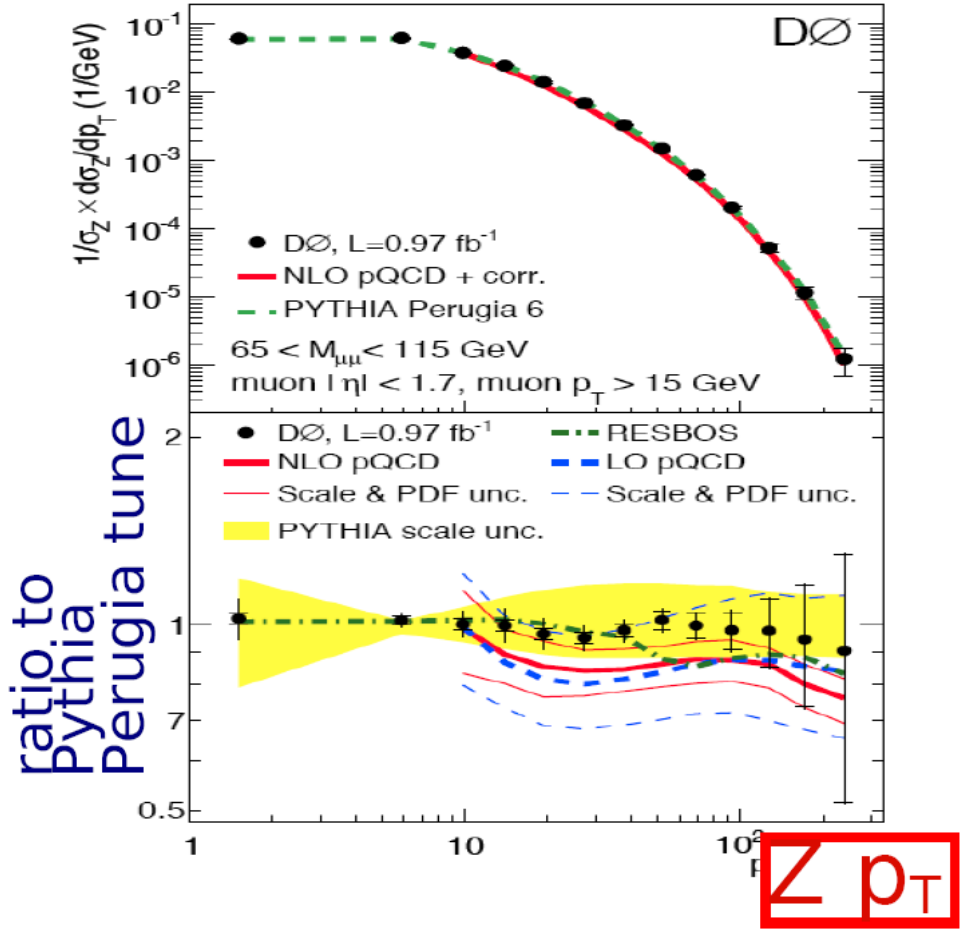
- Use Z→ ee (D0 and CDF) + Z→ μμ (CDF) balancing to calibrate recoil energy scale and to model resolution

Systematic uncertainty on M_W :
D0: 6 MeV m_{TW}, 12 MeV p_T
CDF: 9 MeV m_{TW}, 17 MeV p_T

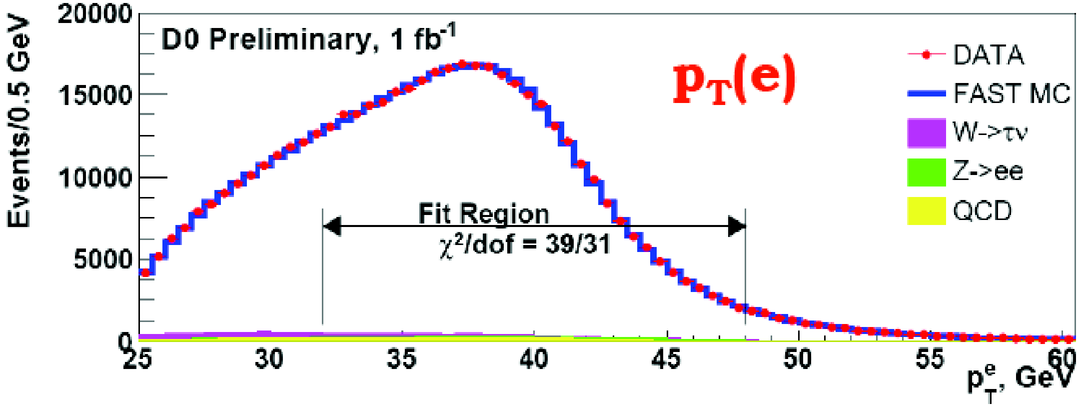


Z/γ* transverse momenta

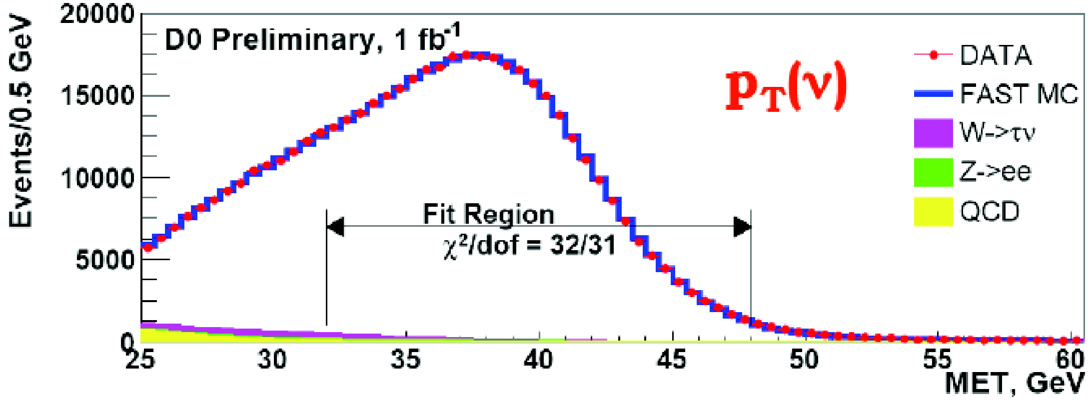
- Sensitive to parton initial state radiation => stringent test on QCD
- Low p_T spectrum sensitive to multiple soft gluon emission => requires resummation techniques/models



Mass fit



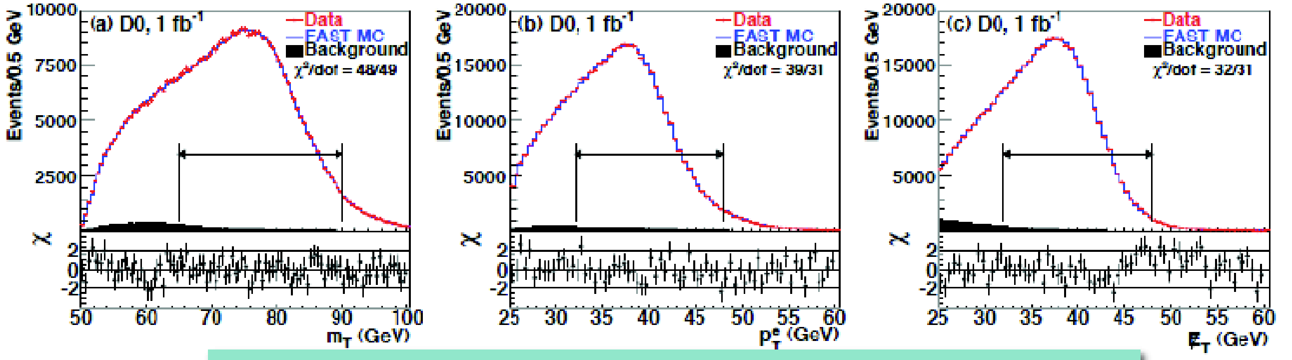
$M_W = 80.400 \pm 0.027$ (stat) GeV



$M_W = 80.402 \pm 0.023$ (stat) GeV

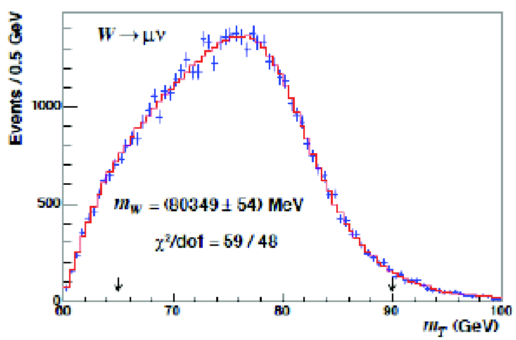
W mass results (presented at PIC2010)

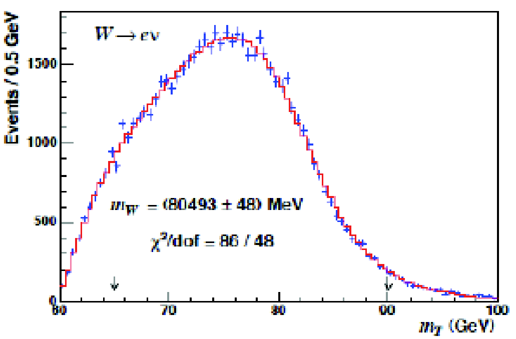
- D0 combination of 3 results



D0 (1fb^{-1}) m_W=80401±21(stat)±38(syst) MeV

- CDF combination of 6 results





CDF (200 pb^{-1}) m_W=80413±34(stat)±34(syst) MeV

W mass systematic uncertainties

Limited by the size of the Z sample. Will improve with more data

Tevatron measurements improving the precision of parton distributions functions (ex. W charge asymmetry

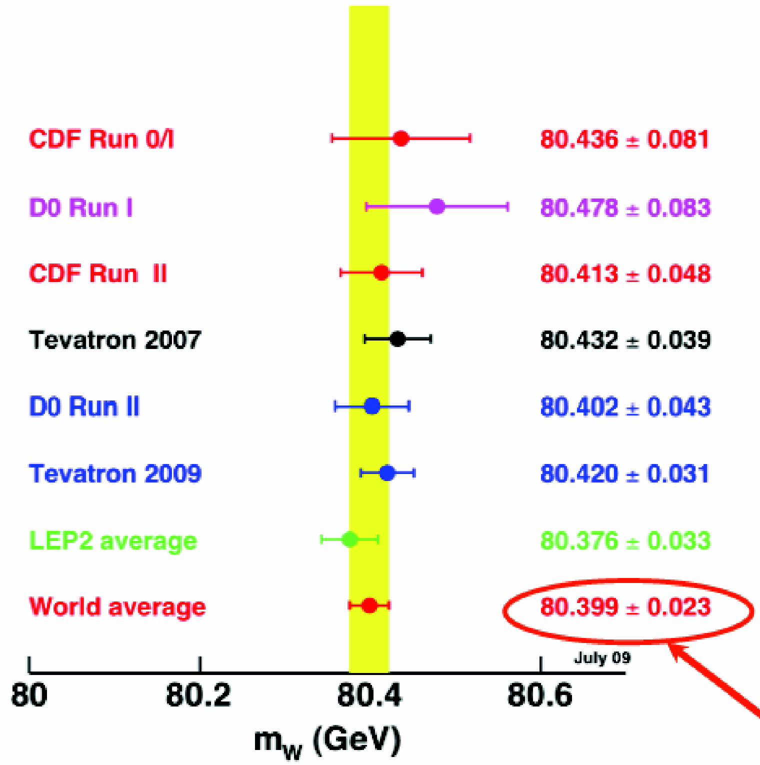
Tevatron goal Δm_W < 25 MeV per experiment

D0 m_W Systematic Uncertainties (1 fb^{-1})

Systematic Source	δm_W (MeV)
Electron energy scale	34
Electron energy resolution model	2
Electron energy nonlinearity	4
W and Z electron energy loss differences	4
Recoil model	6
Electron efficiencies	5
Backgrounds	2
PDF	9
QED	7
Boson p_T	2
Total	**37**

W mass combination
(presented at PIC2010)

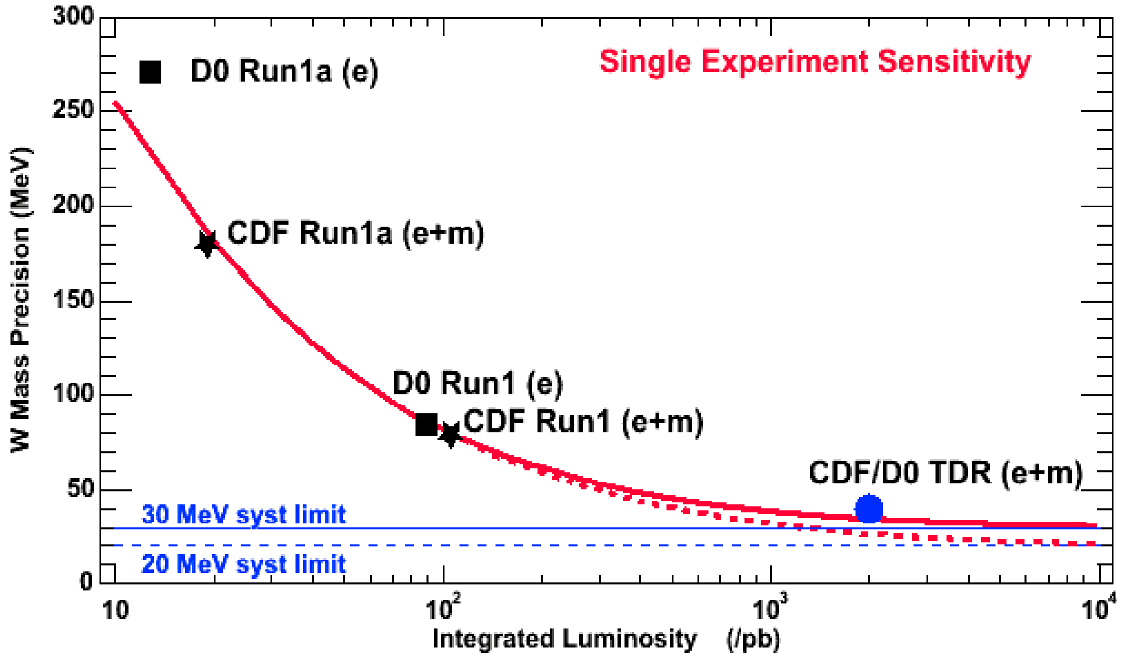
Tevatron m_W=80420±31 MeV



- Update previous CDF result to modern PDFs
- Correct to same Γ_W
- PDF, QED, Γ_W uncertainties correlated
- More precise than LEP II combination!

World average (Summer 2009):
m_W=80399 ± 23 MeV

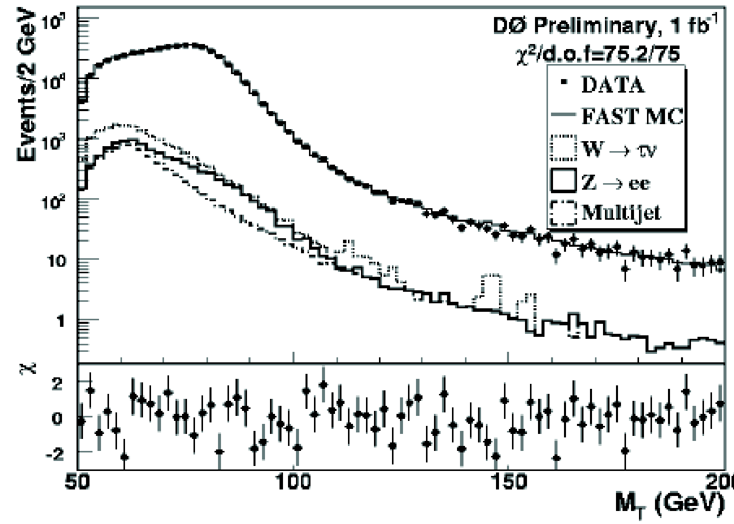
W mass from Tevatron

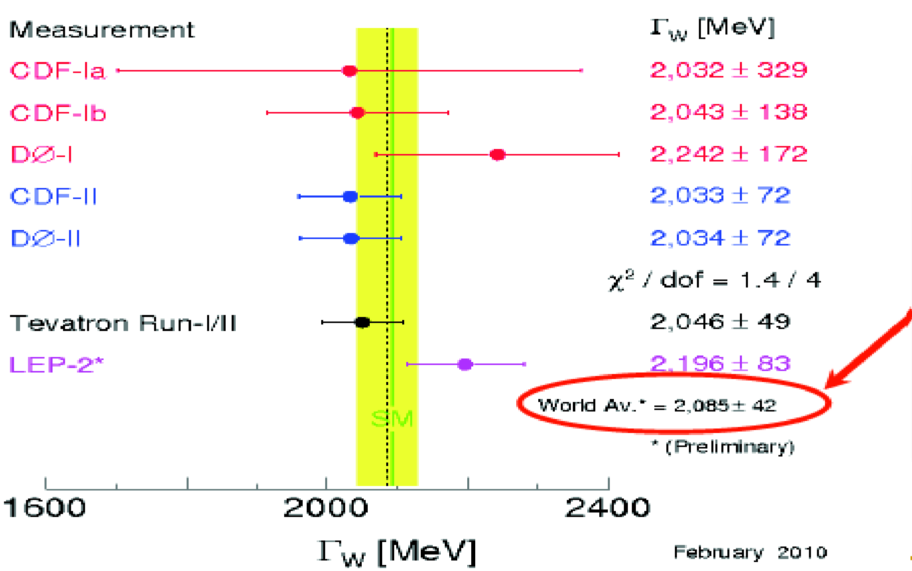


- Beyond few fb^{-1} overall uncertainty does not improve significantly without better understanding of systematics, but energy scale systematics still statistically limited.
- Goal: $\delta m_W < 25$ GeV per experiment by the end of Run II

W-width Γ_W

- Don't expect new physics here
- The high m_T tail contains information on Γ_W
  - Exploit slower falloff of Breit-Wigner compared to Gaussian resolution





World average (Winter 2010):

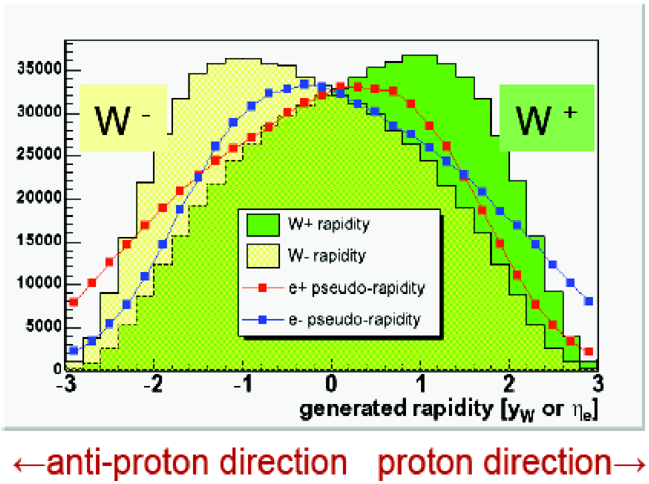
$\Gamma_W = 2085 \pm 42$ (stat + syst) MeV

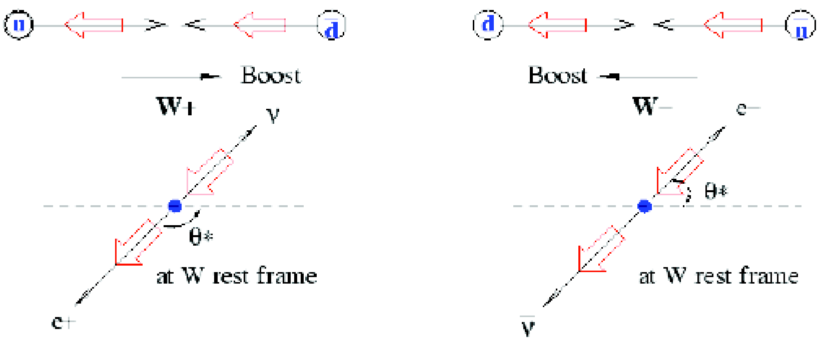
Theory: $\Gamma_W = 2089 \pm 2$ MeV

(Rosner, Phys. Rev. D49, 1363 (1994) Renton: *arXiv*:0804.4779(2008), Denner: Fortsch. Phys. 41, 307 (1993))

W charge asymmetry

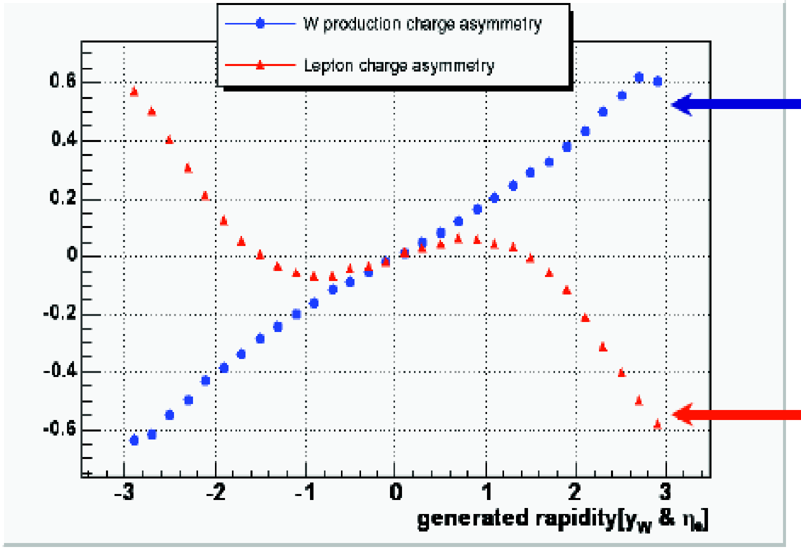
- At the Tevatron mainly produced by the valence quarks
- On average, u quark carries higher momentum than d quarks
  - W^+ boosted in proton direction
  - W^- boosted in anti-proton direction
- W asymmetry $[A(y_W)]$
  - Sensitive probe of the difference between u and d quarks at $Q^2 = m_W^2$





Lepton charge asymmetry

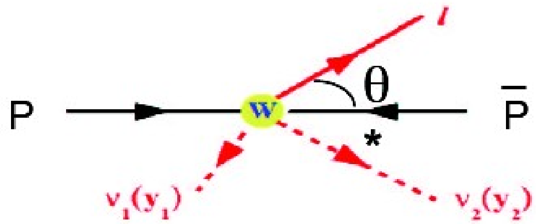
- Experimentally more accessible is lepton charge asymmetry
- Convolution of both the W charge asymmetry and V-A decay structure



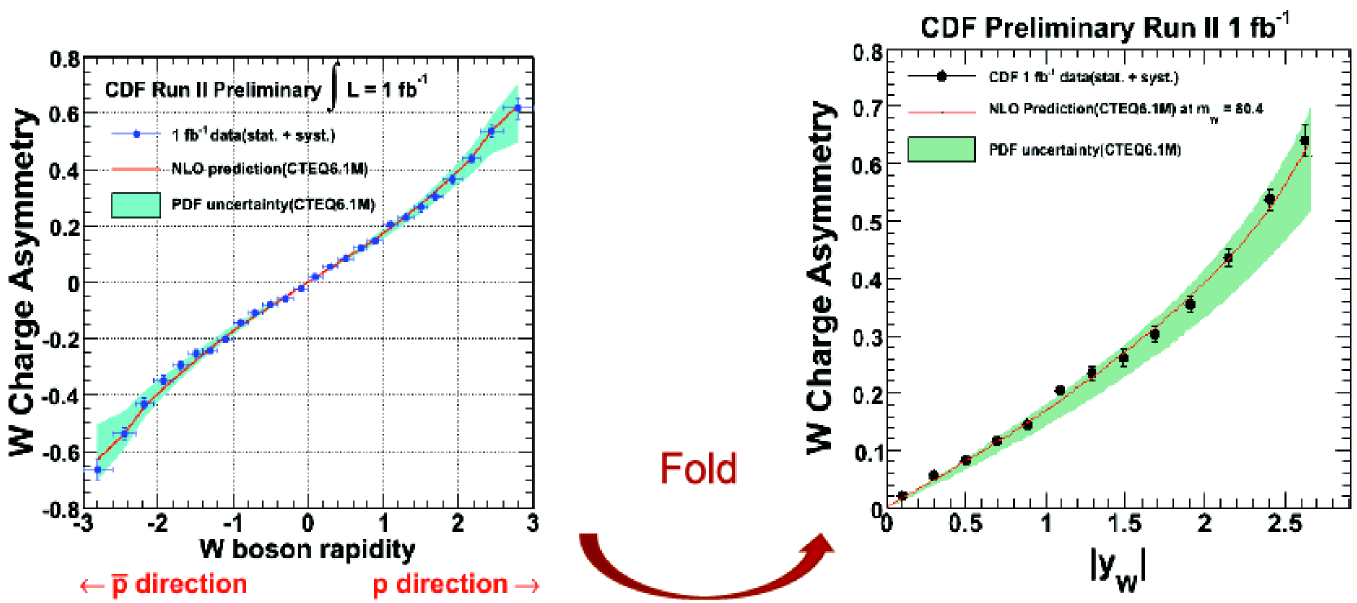
$$A(y_W) = \frac{d\sigma_+/dy_W - d\sigma_-/dy_W}{d\sigma_+/dy_W + d\sigma_-/dy_W}$$

$$A_l(\eta) = \frac{d\sigma(l^+)/d\eta - d\sigma(l^-)/d\eta}{d\sigma(l^+)/d\eta + d\sigma(l^-)/d\eta}$$

$A(y_W)$ measurement



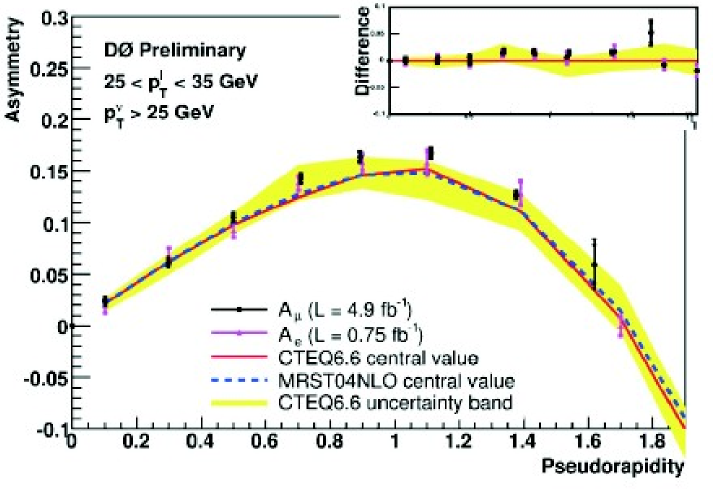
- CDF measurement using $W \rightarrow e\nu$ in $1fb^{-1}$
  - Use W mass constrain to infer p_Z^ν (weights)
  - Applying weighting method i.e. calculate 2 solutions and weight them with matrix element

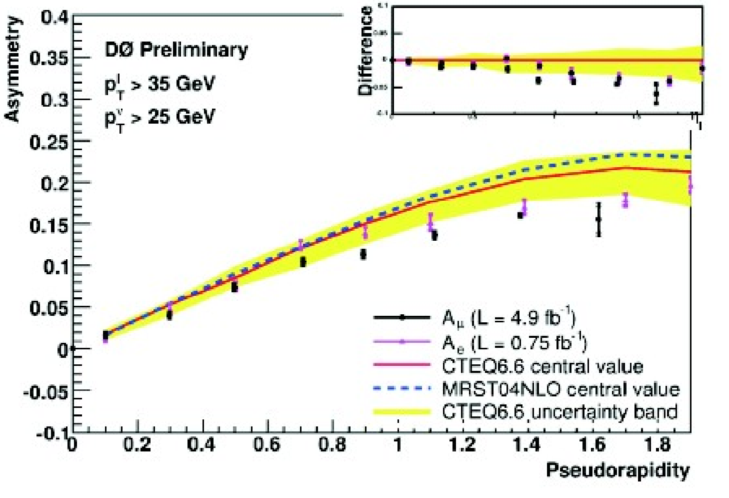


Precision MUCH better than error band => Improve global fits

A(η^l) measurement

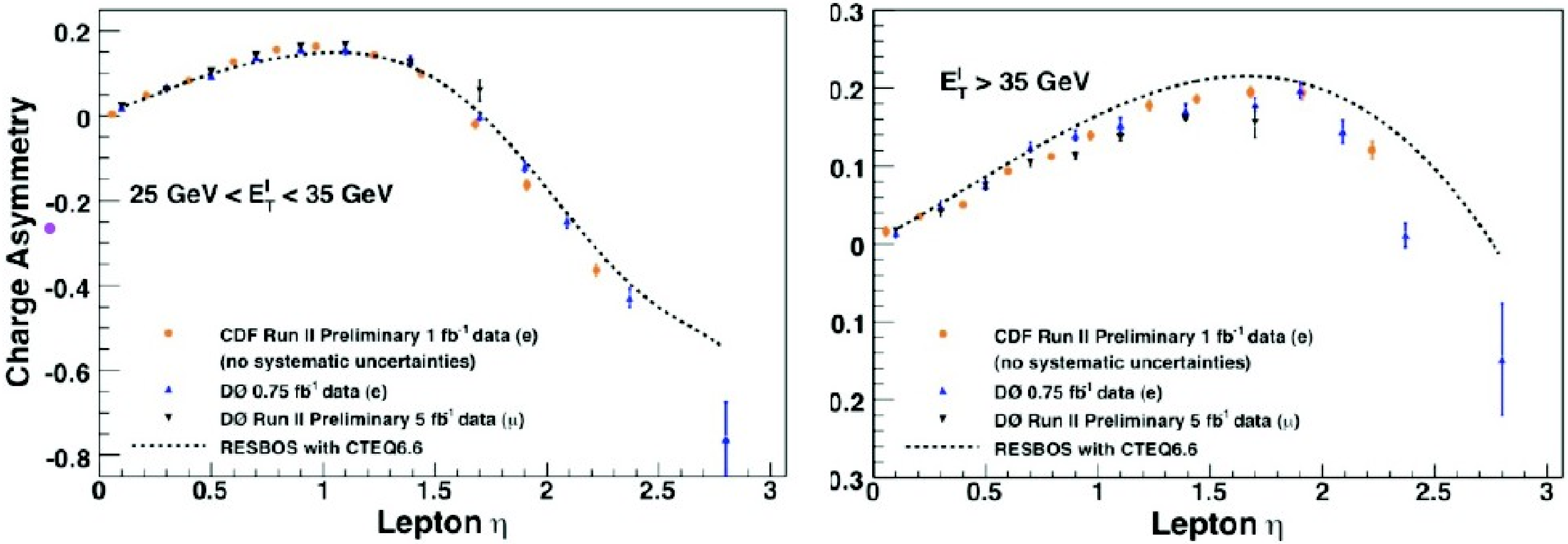
- D0 measurement using $W \rightarrow \mu\nu$ in 4.3 fb^{-1}
- Observed deviation from theory (reported already in previous measurements by CDF (0.17 fb^{-1}) in electron channel
- Global fitters (MSTW, CTEQ) have problem incorporating those data.
  - Tension with low-x data





W and lepton charge asymmetry

- Preliminary re-analysis from CDF confirms those results (presented at PIC2010)



The data for leptonic asymmetries are agree among channels and experiments but theory does not reproduce the leptonic asymmetries even though they do agree with the W boson asymmetry

Z cross-section and rapidity

- CDF measurement, Z->ee in 2.1 fb^{-1}
- Electron coverage up to |η|<2.8
- Select ~170k events
- Cross section measurements (|y| <2.9)

σ=256.6±0.7(stat)±2.0(syst) pb
+ 15.4 (lum) pb

Theory:

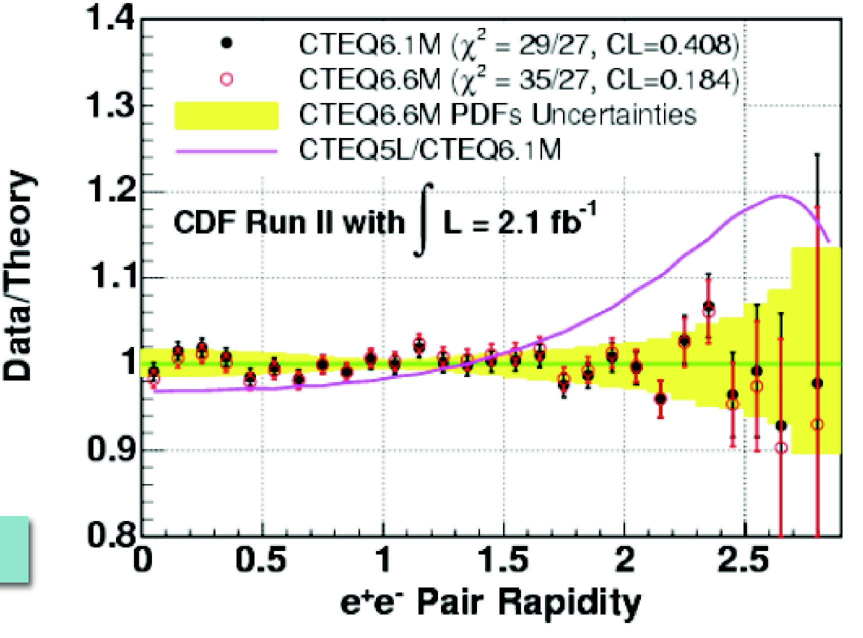
$\sigma = 238.7^{+7.1}_{-7.0}$ pb (CTEQ6.6M NLO)

$\sigma = 248.7^{+5.1}_{-4.0}$ pb (MSTW2008E NNLO)

- dσ/dy
  - High rapidity (y) probes high-x parton region

$$x_1, x_2 = (M/\sqrt{s})e^{\pm y}.$$

  - Z-boson rapidity reconstructed from leptonic decay



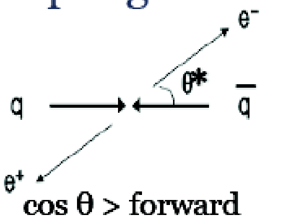
Shape well described by NLO QCD

Z forward backward asymmetry

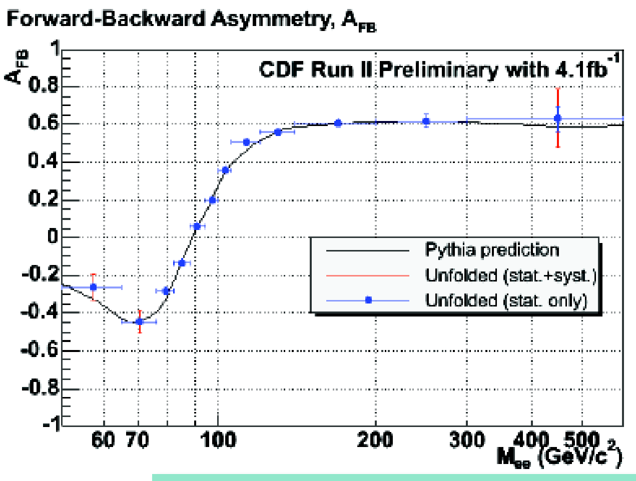
- A_{fb} determines the relative strengths of V-A boson-fermion couplings as well as $\sin^2\theta_W$

$$A_{fb} = (NF - NB) / (NF + NB)$$

- Sensitive to new resonance (f.g Z') via interference with Z/γ^*



cos θ > forward
cos θ < backward

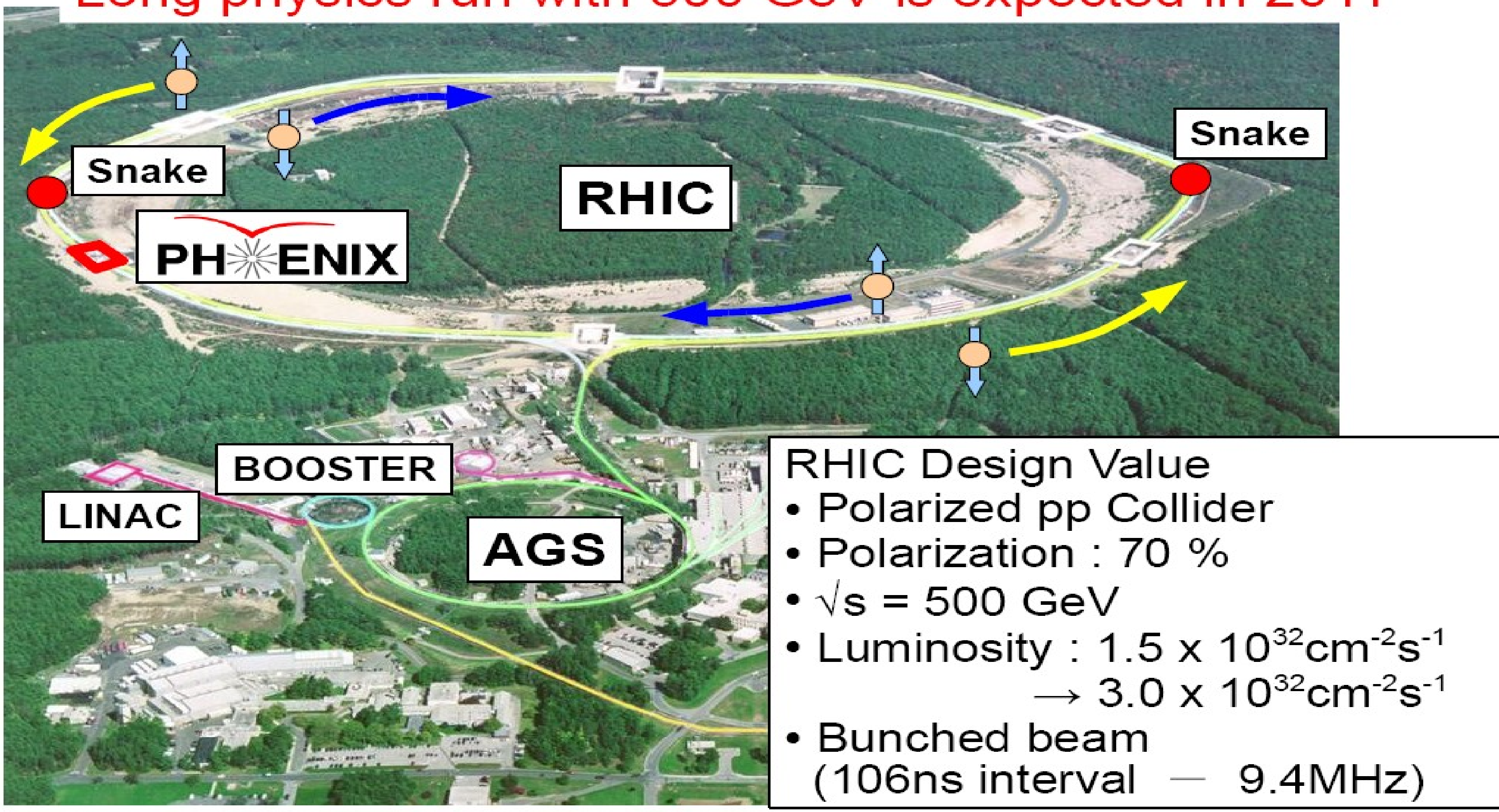


New CDF measurement with 4.1 fb^{-1}

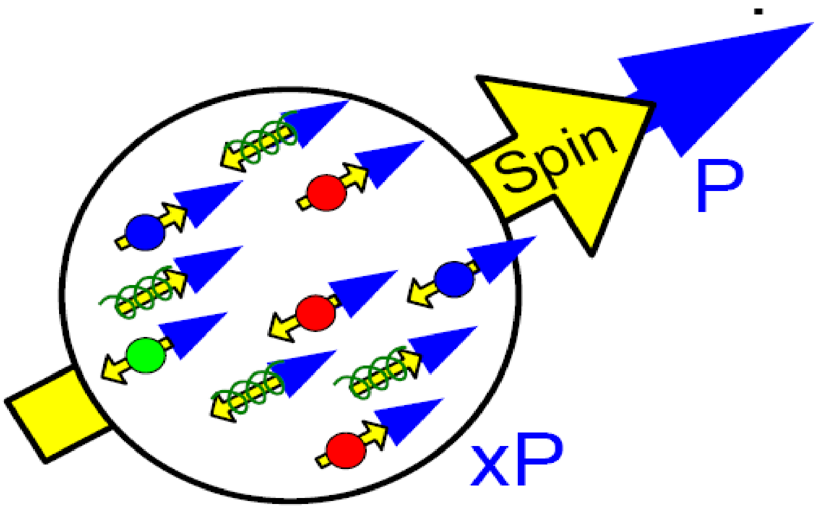
$\sin^2\theta_W$ ($1fb^{-1}$)= 0.2326±0.0018(stat.)±0.0006(syst.)
World = 0.23153 ±0.00016
Future Tevatron precision (10 fb^{-1}) ~ 0.0005

RHIC: World's only polarised proton collider

Long physics run with 500 GeV is expected in 2011



Proton spin structure

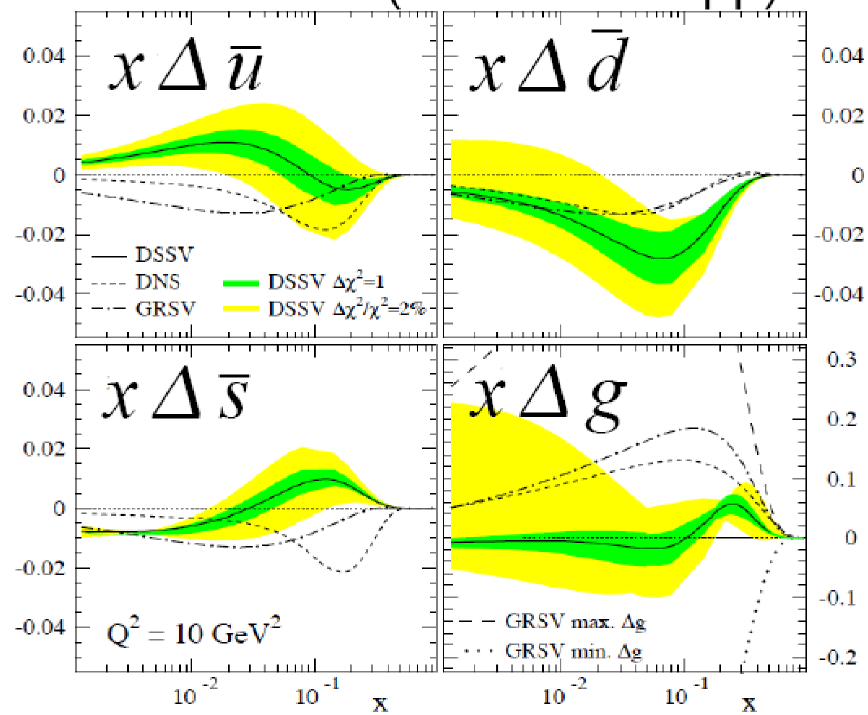


$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L$$

- ΔQ_v : Well known
- ΔG : Being revealed
- $\Delta \bar{Q}$: **Less well-known**
- L : Unknown

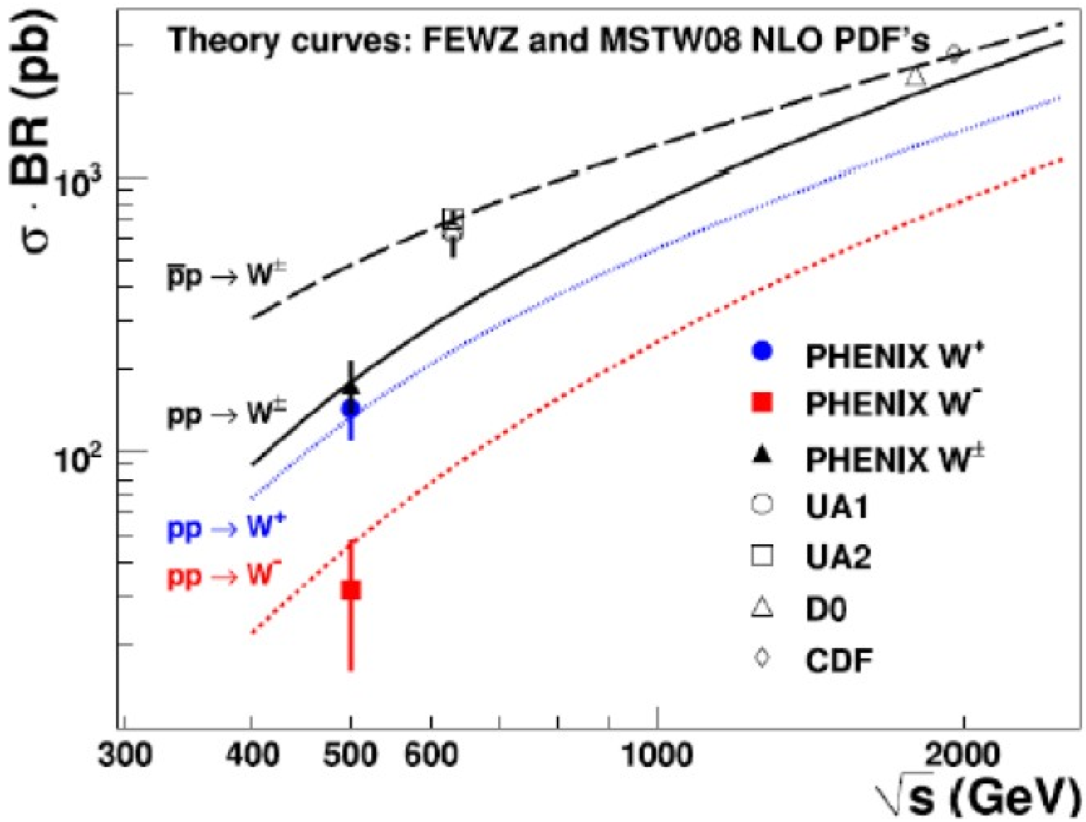
Spin of parton is parallel or anti-parallel to proton?

DSSV2008 (DIS+SIDIS+pp)

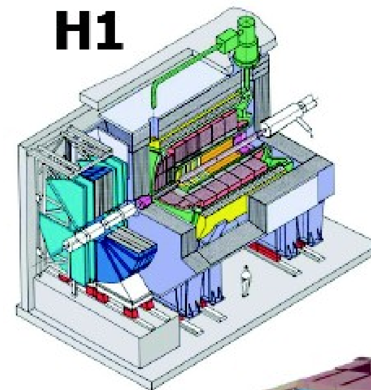


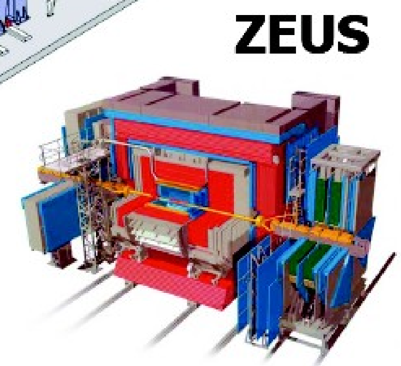
PHENIX

- First published measurement in pp collision
- Main interest is polarised beam
  - Sensitivity to the polarised sea structure functions
  - Single longitudinal asymmetry.

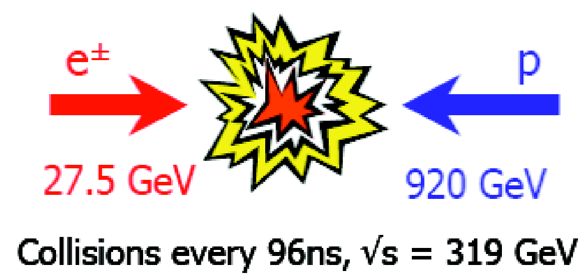


The H1 and Zeus exp. at HERA

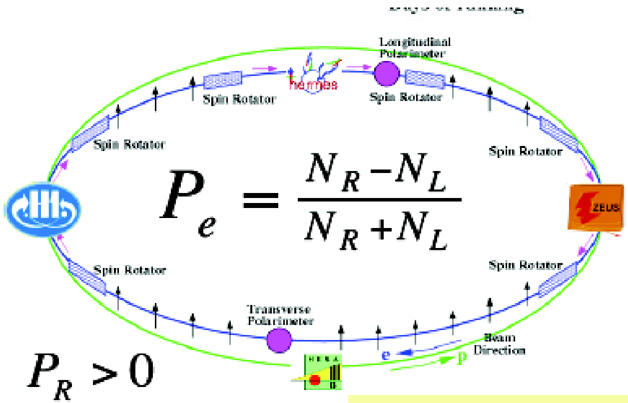




- 6.3 km long accelerator
- Two multi-purpose detectors
- Particle energies allow to probe proton structure down to $\Delta x \sim 10^{-18}$m



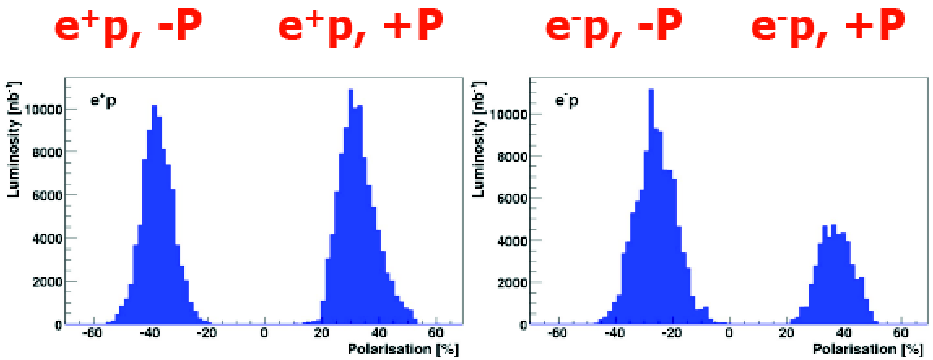
Polarised lepton beam



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

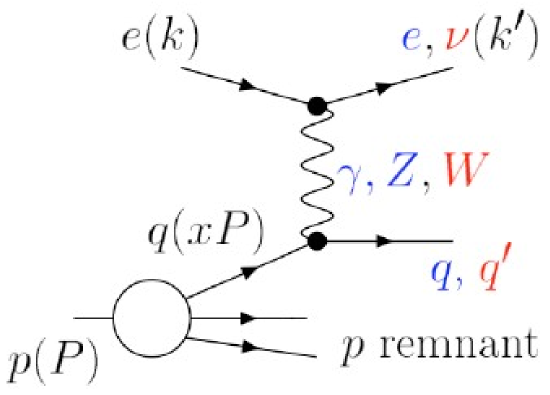
$P_R > 0$

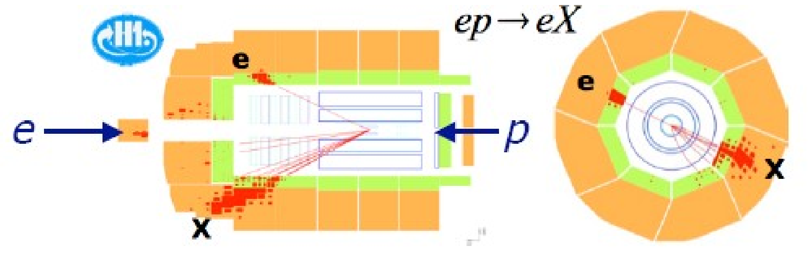
$P_L < 0$



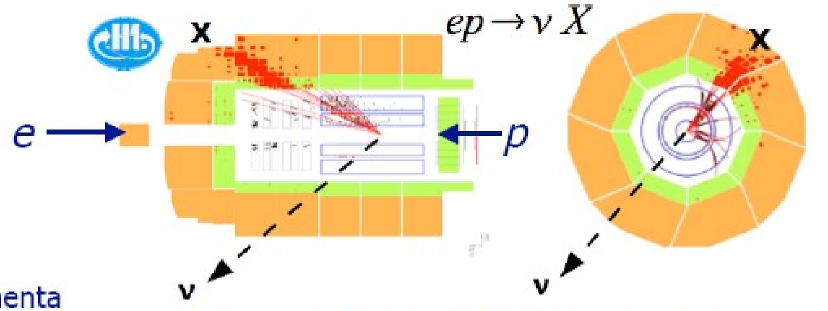
HERA II: Longitudinally Polarised Lepton Beam: 4 modes of running

Deep inelastic scattering





Neutral Current interaction



Charged Current interaction

$Q^2 = -(k - k')^2$ — Virtuality of the exchanged boson

$x = \frac{Q^2}{2P \cdot (k - k')}$ — Fraction of proton momenta carried by the struck quark

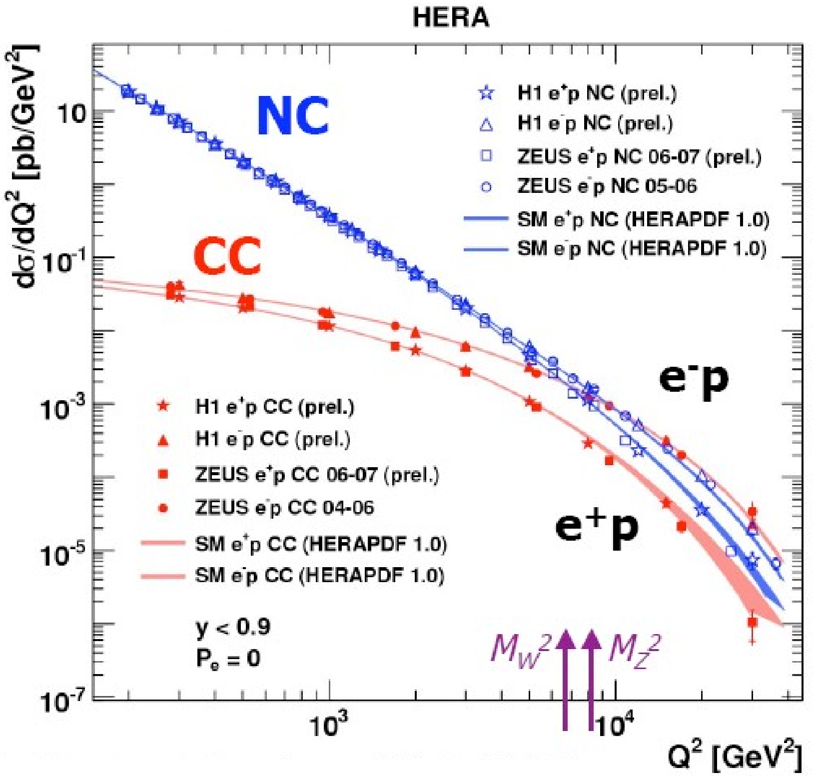
$y = \frac{P \cdot (k - k')}{P \cdot k}$ — Inelasticity: fraction of lepton energy transferred in the proton rest frame

$Q^2 = sxy$, $Q^2_{max} \sim 10^5$

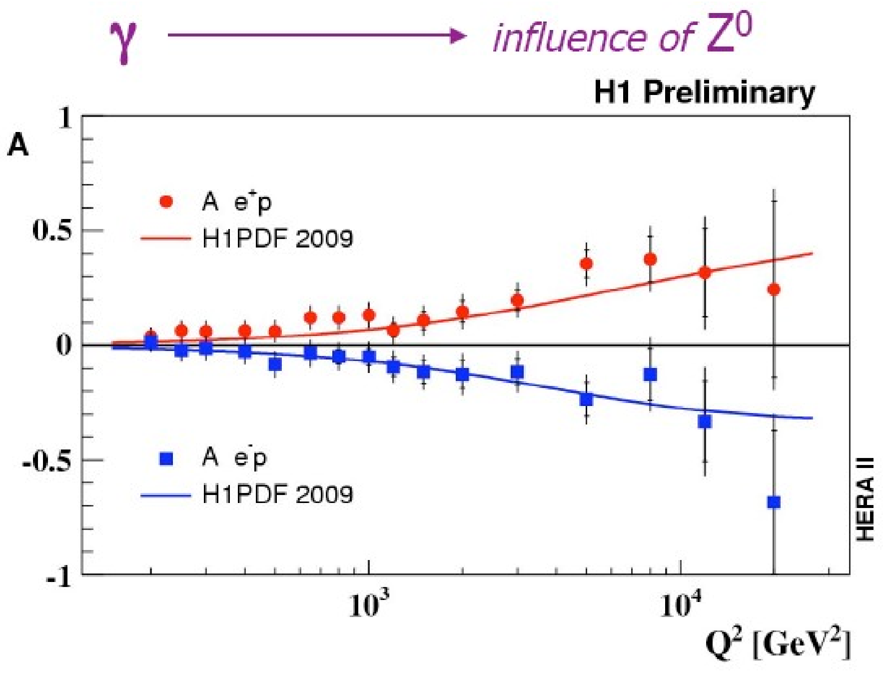
NC and CC cross section measurements done using up to the full HERA I+II data in the range $200 < Q^2 < 30{,}000$ GeV^2

Electroweak physics

- Inclusive differential cross-section at $Q^2 \sim m_{W,Z}$



Polarisation asymmetry in NC



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

$$P_e = \frac{N_R - N_L}{N_R + N_L} \qquad P_R > 0 \qquad P_L < 0$$

- From polarisation asymmetry clear observation of parity violation of NC electroweak exchange
- Well described by SM predictions

Charged current cross-section

e⁺p cross section:

Sensitive to the density of the d quark

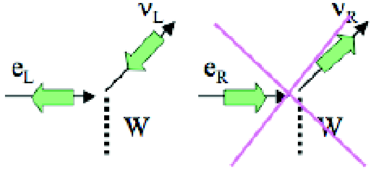
$$\frac{d^2\sigma^{CC}(e^+p)}{dxdQ^2} = \frac{G_F^2}{2\pi}\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2\left[\bar{u}+\bar{c}+(1-y)^2(d+s)\right]$$

e⁻p cross section:

$$\tilde{\sigma}(x,Q^2)/x$$

$$\frac{d^2\sigma^{CC}(e^-p)}{dxdQ^2} = \frac{G_F^2}{2\pi}\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2\left[u+c+(1-y)^2(\bar{d}+\bar{s})\right]$$

Sensitive to the density of the u quark



Standard Model weak interaction left-handed:
only LH Particles (RH anti-particles) interact

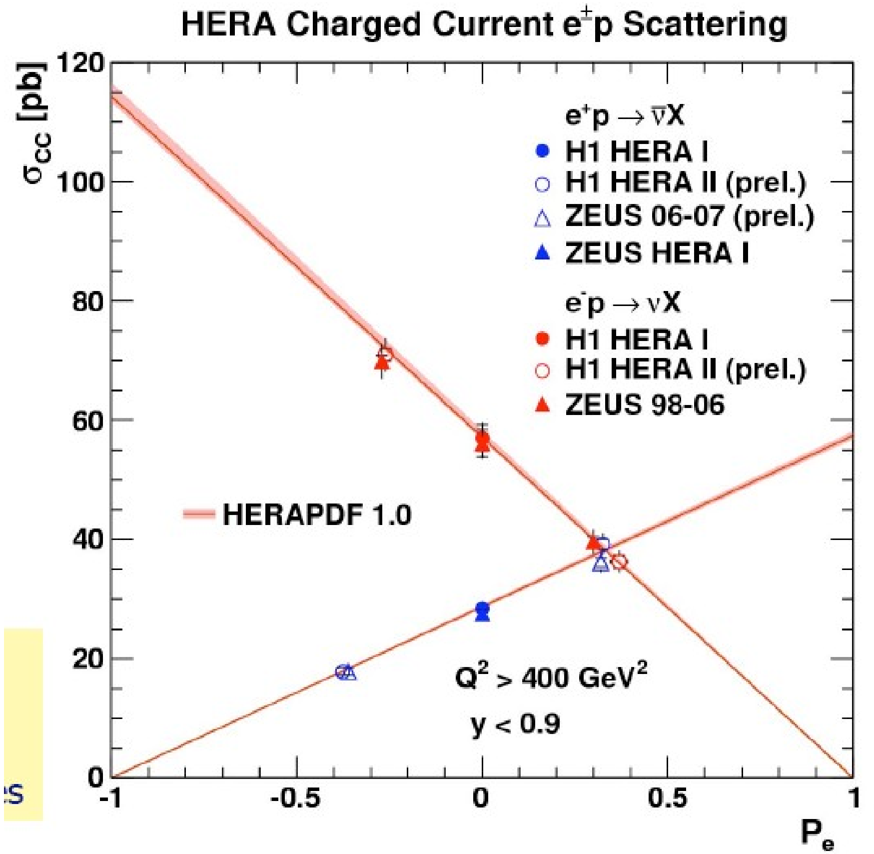
CC cross section modified by polarisation P_e:

$$\sigma_{CC}^{e^\pm p}(P_e) = (1 \pm P_e)\cdot\sigma_{CC}^{e^\pm p}(P_e = 0)$$

Polarisation scales the P_e=0 cross section linearly: *clear and large effect at HERA*
SM predicts zero cross section for P_e=+1(-1) in $e^{-(+)}$p scattering

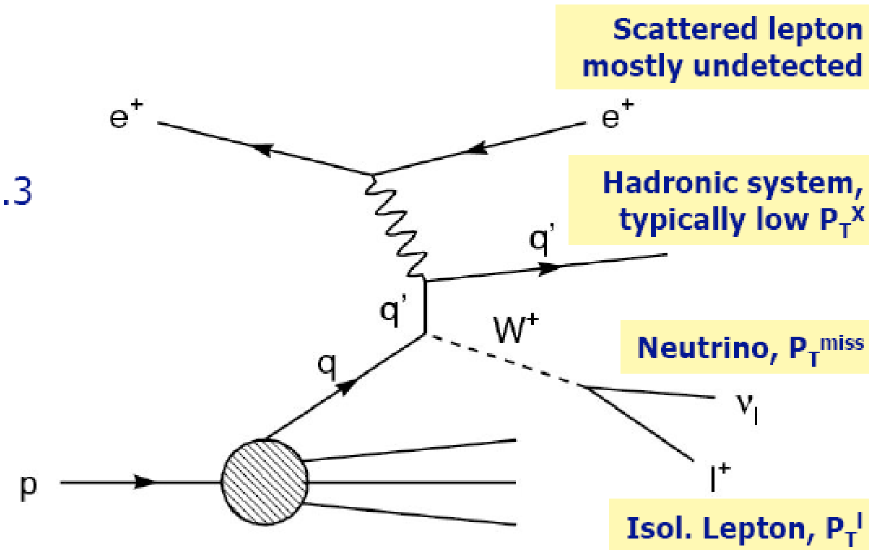
CC cross section vs polarisation

- Linear dependence on average polarisation
- Measurements agree with SM predictions



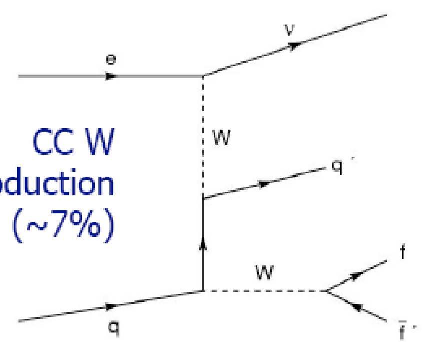
W at HERA: high p_T isolated lepton

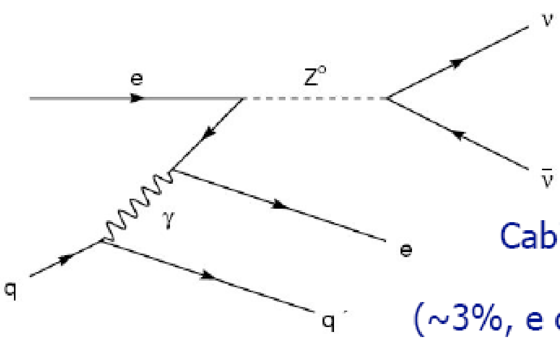
- Main SM contribution to signal from *real W production* with subsequent decay to leptons
  - Total cross section of about 1.3 pb, with 10% of W decays to each lepton flavour: very few events expected at HERA
  - Hadronic system typically has ***low*** transverse momentum
  - Modelled using EPVEC, re-weighted to a NLO calculation



- Two additional processes included that contribute to the signal topology:

CC W Production (~7%)





Cabibbo-Parisi Z^0 production (~3%, e channel only)

W at HERA: high p_T isolated lepton

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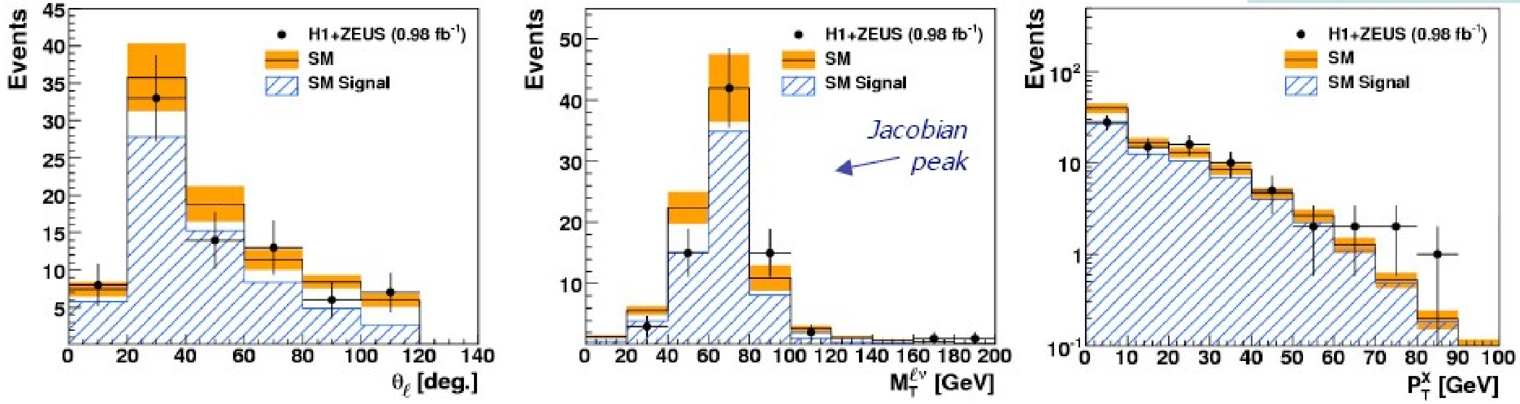

H1+ZEUS 1994–2007 $e^{\pm}p$ 0.98 fb^{-1}		Data	SM Expectation	SM Signal	Other SM Processes
Electron	Total	61	69.2 ± 8.2	48.3 ± 7.4	20.9 ± 3.2
	$P_T^X > 25$ GeV	16	13.0 ± 1.7	10.0 ± 1.6	3.1 ± 0.7
Muon	Total	20	18.6 ± 2.7	16.4 ± 2.6	2.2 ± 0.5
	$P_T^X > 25$ GeV	13	11.0 ± 1.6	9.8 ± 1.6	1.2 ± 0.3
Combined	Total	81	87.8 ± 11.0	64.7 ± 9.9	23.1 ± 3.3
	$P_T^X > 25$ GeV	29	24.0 ± 3.2	19.7 ± 3.1	4.3 ± 0.8

Good overall agreement with the Standard Model

SM expectation dominated W production
→ *Cross section*

Next topics

- 17.11 –
  - W + jets
  - Tops: xsection, mass
- 24.11 – Hot topics: new exclusion limits
- 1.12 – dibosons and anomalous couplings
- 8.12, 15.12 – Higgs
- 5.01 - Hot topics: ???