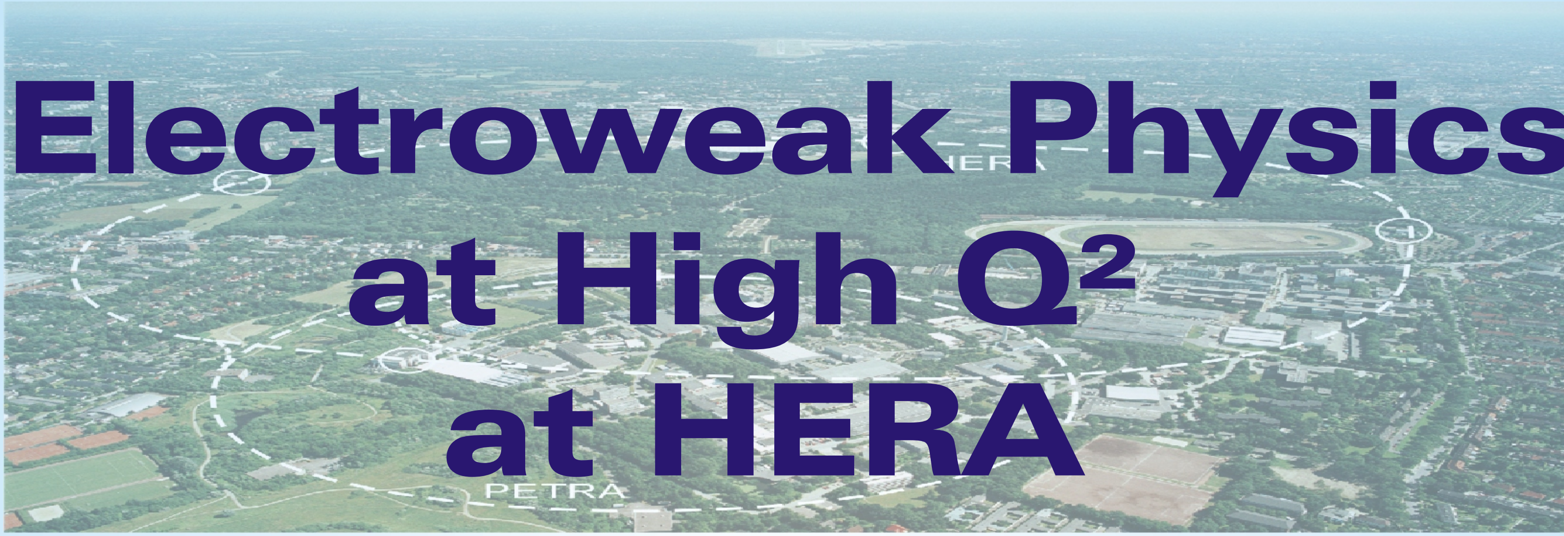
Electroweak Physics at High Q^2 at HERA



Iris Abt (MPI München)
on behalf of

Outline

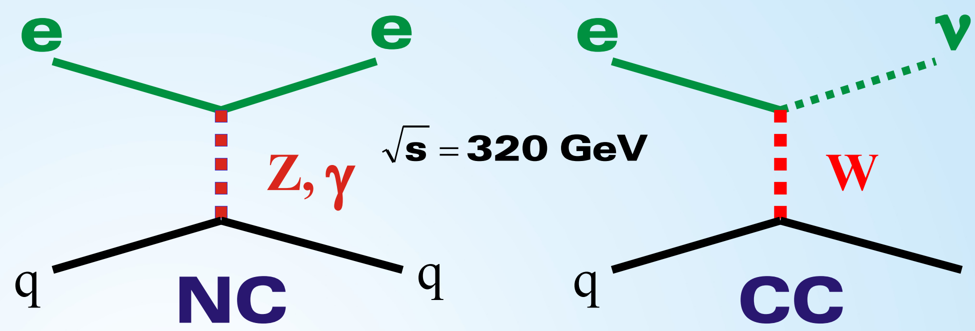
- Introduction
- HERA
- Deep Inelastic Scattering -- ep
- Kinematic Range and Experiments
- Polarization and DIS
- High Q^2 Results for CC and NC
- Elektroweak Plus QCD Fit Results
- Single W Production [Isolated Leptons]
- Health Bulletin of the SM, i.e. Summary

No attempt was made to be complete

ep Scattering

Only at HERA

27.5 GeV Electrons
probing
920 GEV Protons



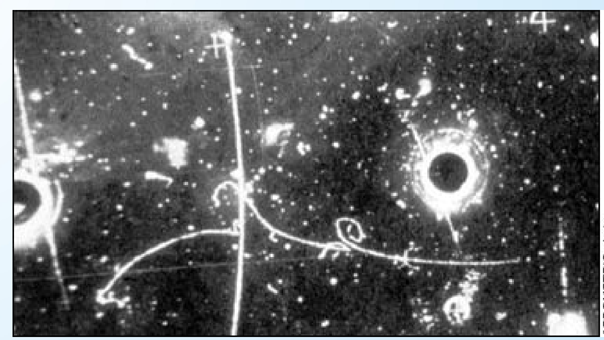
$\sqrt{s} = 320$ GeV

$Q^2_{MAX} \sim 10^5 \text{GeV}^2$

$\lambda_{MIN} \sim 1/1000 r_{proton}$

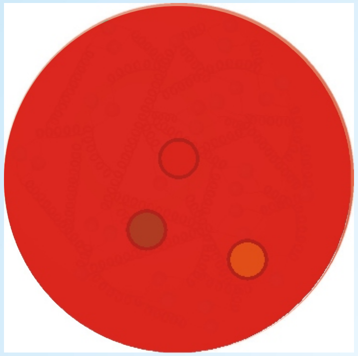
DIS at Q² ≈ EW-scale

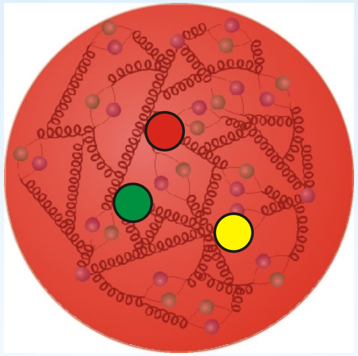
Note: DIS was not invented here, but at Q² ≈ 0
The Z, i.e. NC, was first seen in νN interactions.

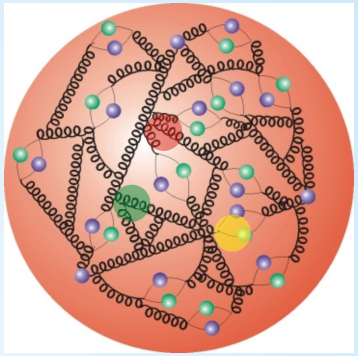


Would need a 50 TeV beam in a fixed target experiment

What Is High Q^2



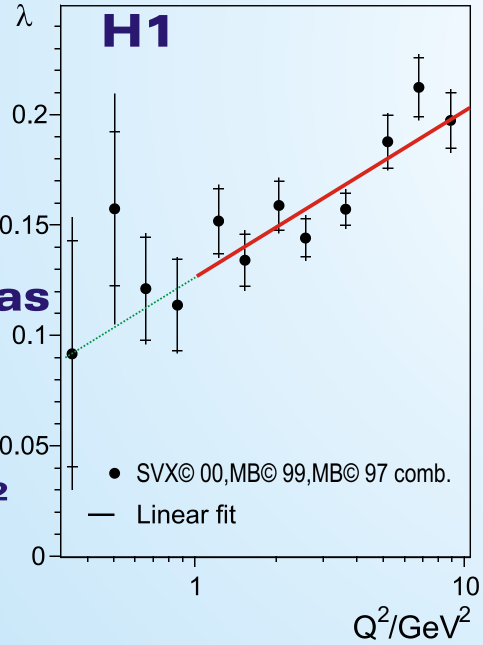




$\lambda \sim 1/\sqrt{Q^2}$

$F_2 \sim x^{\lambda}$

High Q^2 ideas work to pretty low Q^2

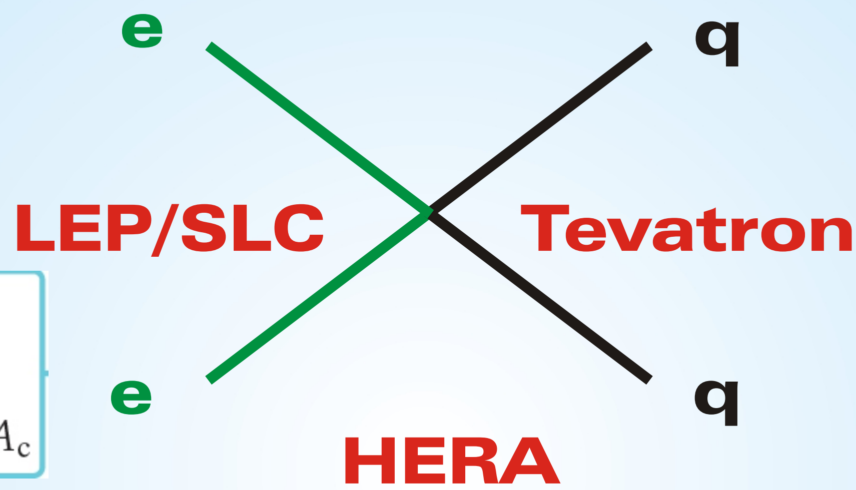


Anything that reveals the internal structure of the proton. Increasing Q^2 first reveals valence quarks and then sea quarks and glue.

Who Works at the EW Scale?

LEP: $m_Z, \Gamma_Z, \sigma_h^0, R_l^0, A_{FB}^{0,l}$
$P_\tau \longrightarrow A_l$
$Q_{FB} \longrightarrow \sin^2\theta_{eff}^{lept}$

SLD: A_l
LEP+SLD:
$R_b^0, R_c^0, A_{FB}^{0,b}, A_{FB}^{0,c}, A_b, A_c$



$p\bar{p}$: m_t
LEP+$p\bar{p}$: m_W, Γ_W

$$\sigma(ep) \propto \sum \sigma(eq) \otimes (pdf)$$
$$EW \otimes QCD$$

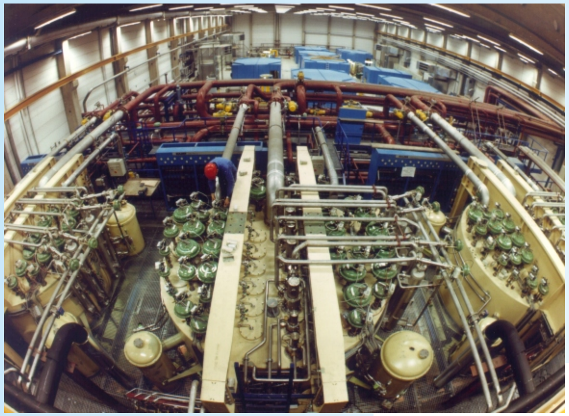
HERA:

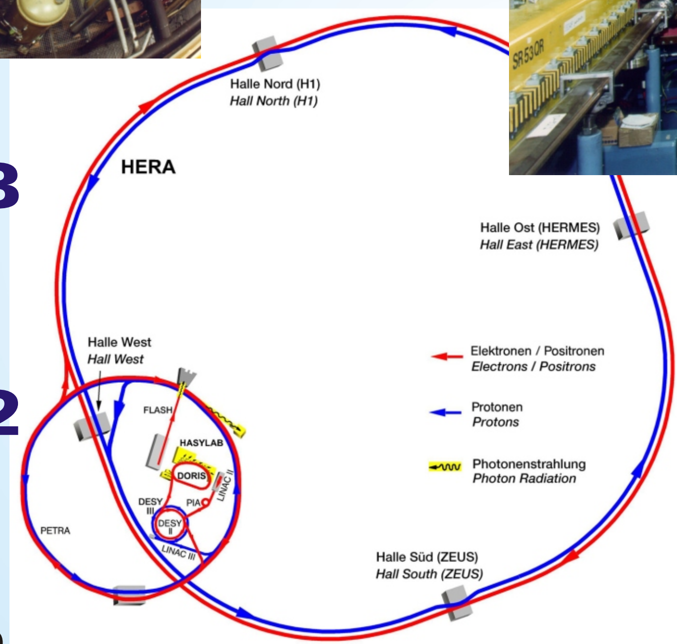
t-channel exchange of gauge bosons

- γZ interference
- propagator masses

Parton Distribution Functions needed

HERA in Memoriam





*

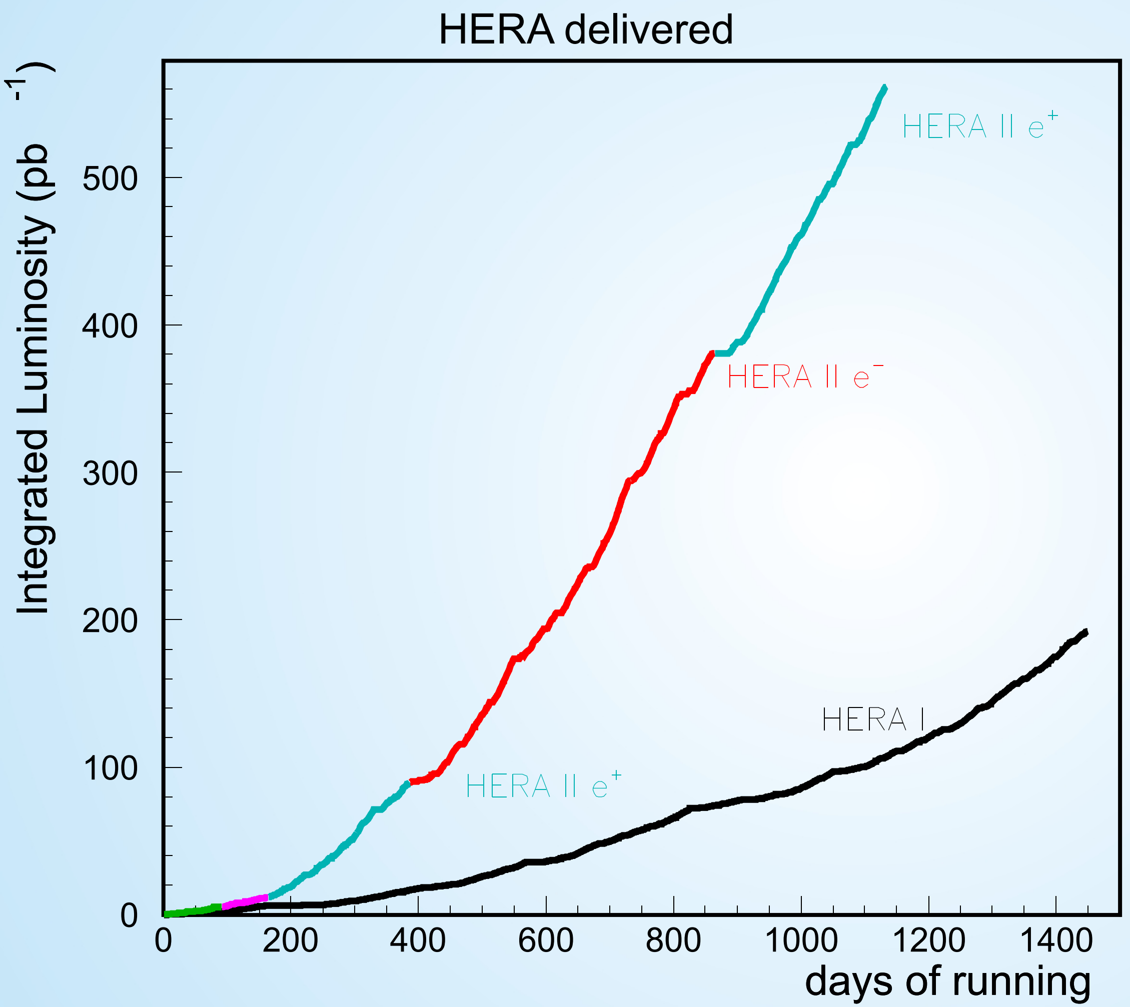
24.5.1993

* *

1.11.2002

last beam
30.6.2007

HERA Luminosity



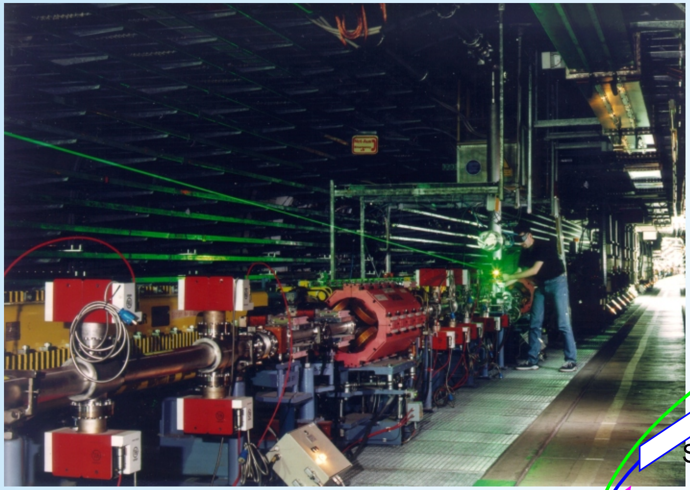
562 pb^{-1}

Nov. 2002
Mar. 2007

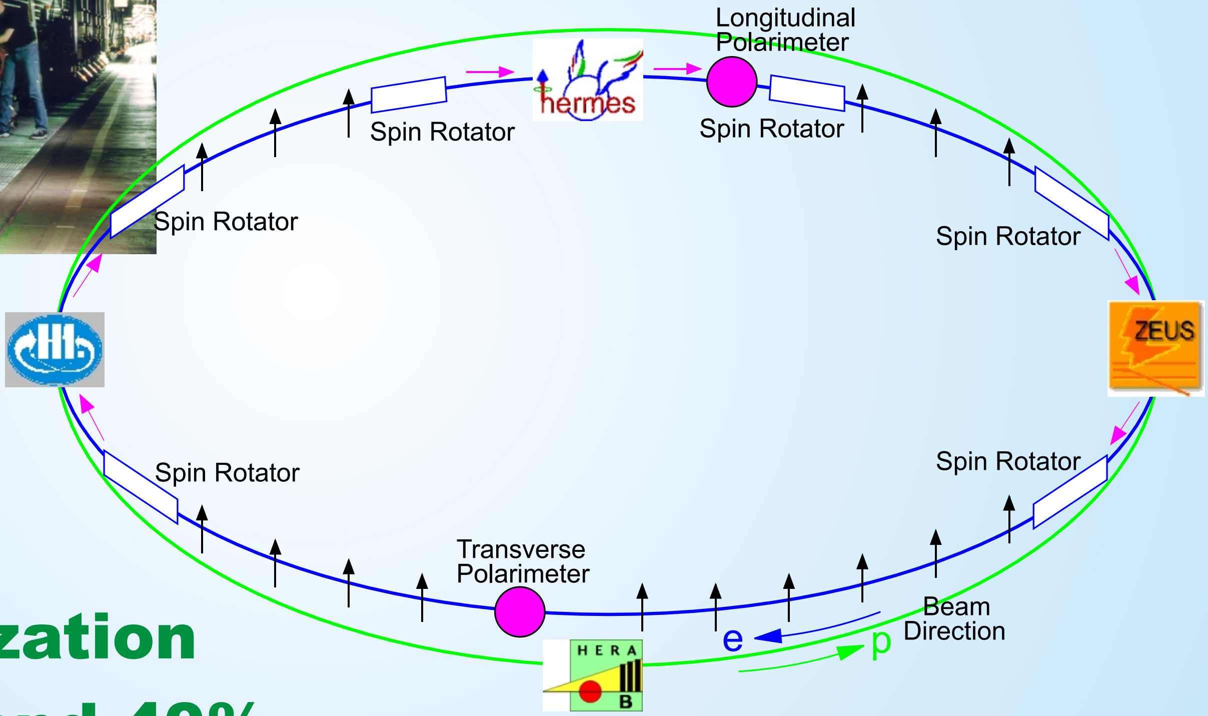
193 pb^{-1}

May 1993
Aug. 2000

Polarization at HERA



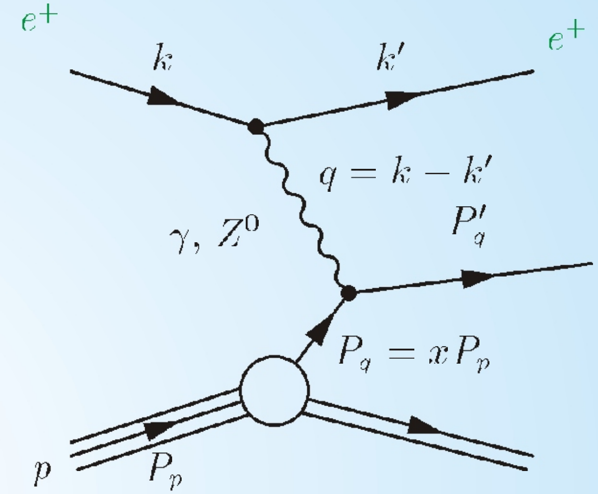
Longidtudinally polarized electrons and positrons.



Average polarization between 30% and 40%

Kinematics

- Virtuality: $Q^2 = -(k-k')^2$
  - ➔ Spatial resolution of probe $\lambda \sim 1/\sqrt{Q^2}$
- Bjorken scaling variable: $x = Q^2/2pq$
  - ➔ Momentum fraction of struck parton
- Inelasticity: $y = pk/pq$
  - ➔ Energy transfer to proton (in p rest frame)



$$Q^2 = xys$$

Experiment measures Cross-sections:
Structure Functions (SFs) are deduced.

$$\frac{d^2\sigma}{dxdQ^2} = \frac{2\pi\alpha^2}{Q^4} Y_+ F_2$$

If proton is point like → $\frac{d^2\sigma}{dxdQ^2} = \frac{2\pi\alpha^2}{Q^4} Y_+$

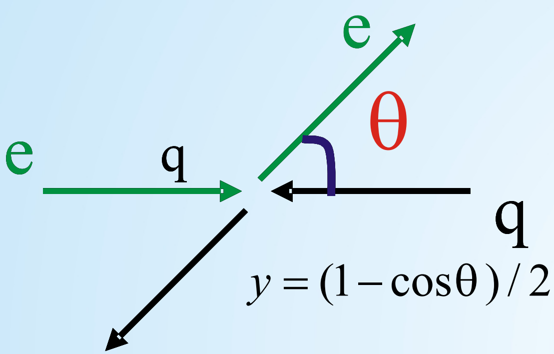
$$Y_+ = 1 + (1-y)^2$$

(The longitudinal SF, F_L, is neglected)

Deviation from pointlike behavior

Quark Parton Model -- QPM

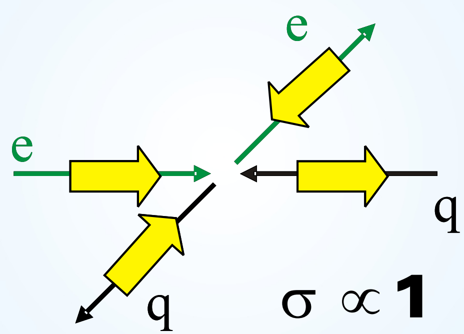
Kinematic variable y corresponds to angle θ between e and quark.



eq c.m.s.

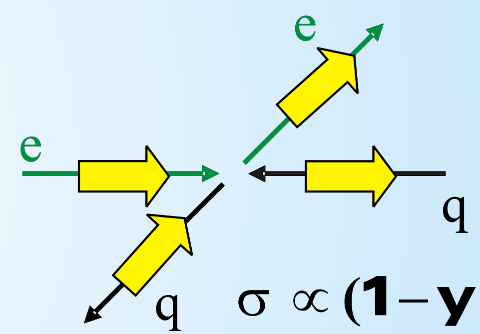
$$\frac{d^2\sigma}{dx\,dQ^2} = \frac{2\pi\alpha^2}{Q^4} Y_+ F_2$$

$$\text{V:} \quad Y_+ = 1 + (1-y)^2 \qquad \text{A:} \quad Y_- = 1 - (1-y)^2$$



$\sigma \propto \mathbf{1}$

LL(RR)



$\sigma \propto (\mathbf{1-y})^2$

LR

Low Q^2, i.e. photon exchange:

- **vector component only**
- **F_2 is based on based on quark charges**

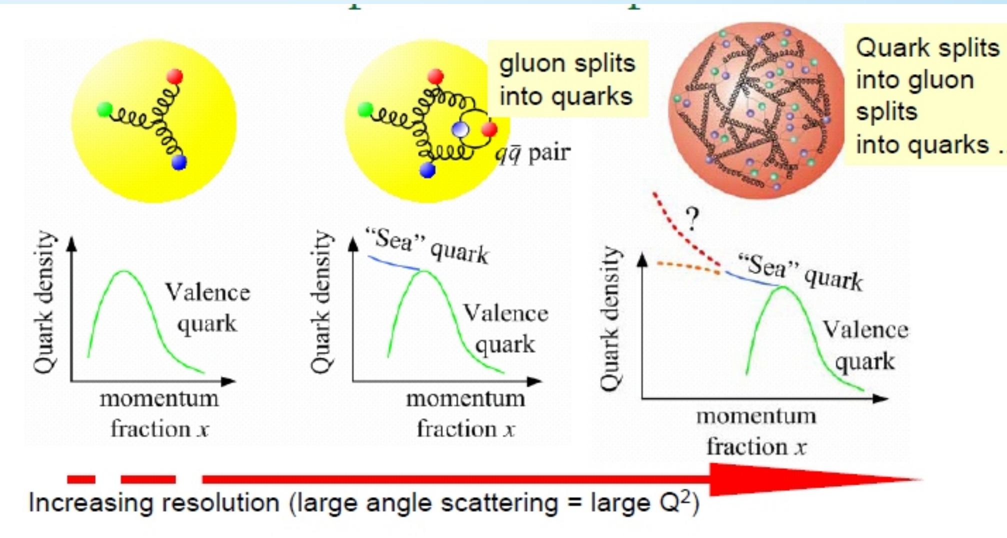
$$F_2 = x \Sigma e_q^2 (q + \bar{q})$$

$\sigma =$ **coupling • propagator • kinematic factor • charges² • PDFs**

QCD Evolution and Gluons

beyond QPM

-- PDFs are not static
→ "evolution" as Q^2 grows.
-- Structure depends on the power to see.
-- pQCD can describe this evolution: "DGLAP eq."



$$\frac{\partial}{\partial \ln Q^2}\begin{pmatrix}\Sigma \\ xg\end{pmatrix} = \alpha_s \begin{pmatrix} P_{qq} & P_{gq} \\ P_{gq} & P_{gg}\end{pmatrix} \otimes \begin{pmatrix}\Sigma \\ xg\end{pmatrix}$$

At low-x: $$\frac{\partial F_2}{\partial \ln Q^2} \propto \alpha_s xg$$

$$\frac{\partial}{\partial \ln Q^2} q_{NS} = \sigma_s P_{qq} \otimes q_{NS}$$

- F_2 is sum of q / qbar PDFs
  → Gluons not directly in F_2 (in LO)
- Gluons cause "slope" of F_2 in log Q^2 evolution

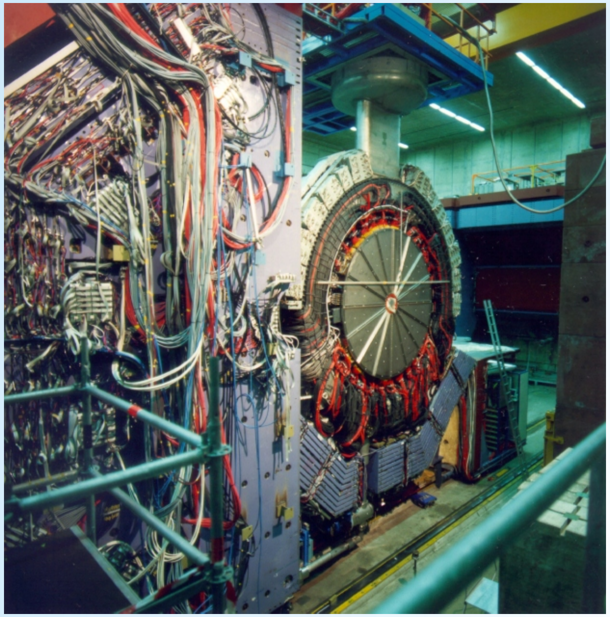
pQCD cannot predict x - dependence of PDFs a priori

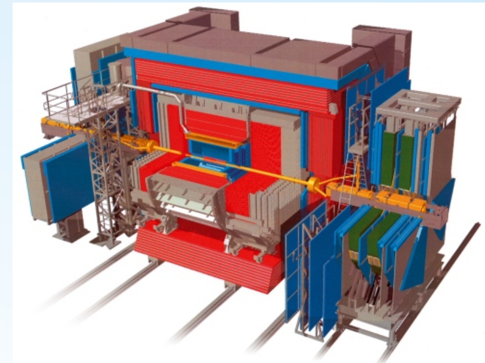
PDFs are determined by a global fit to experimental data

Experiments

H1

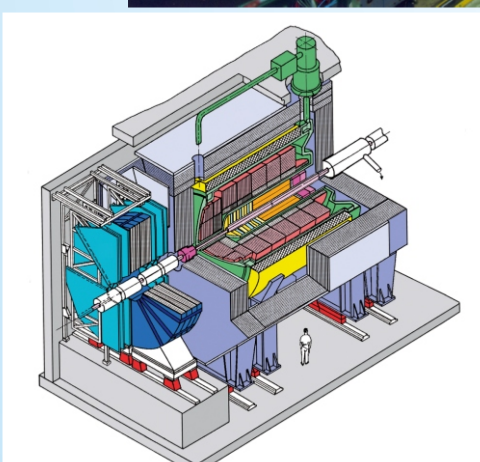
went
for
LAr



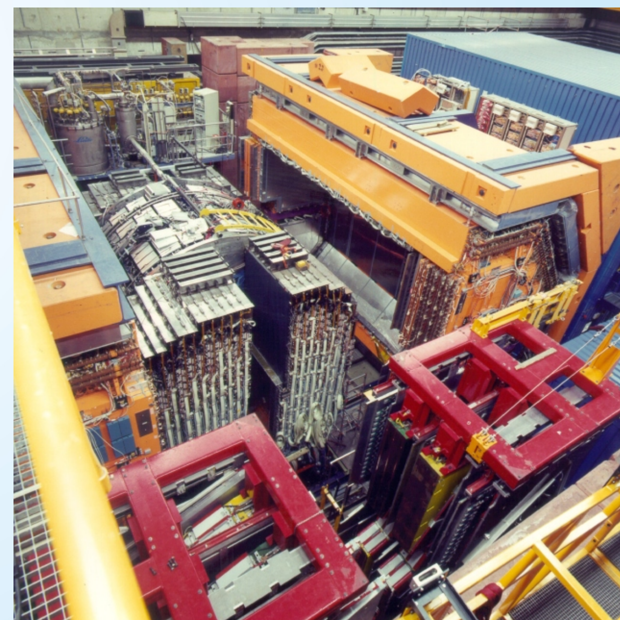


ZEUS

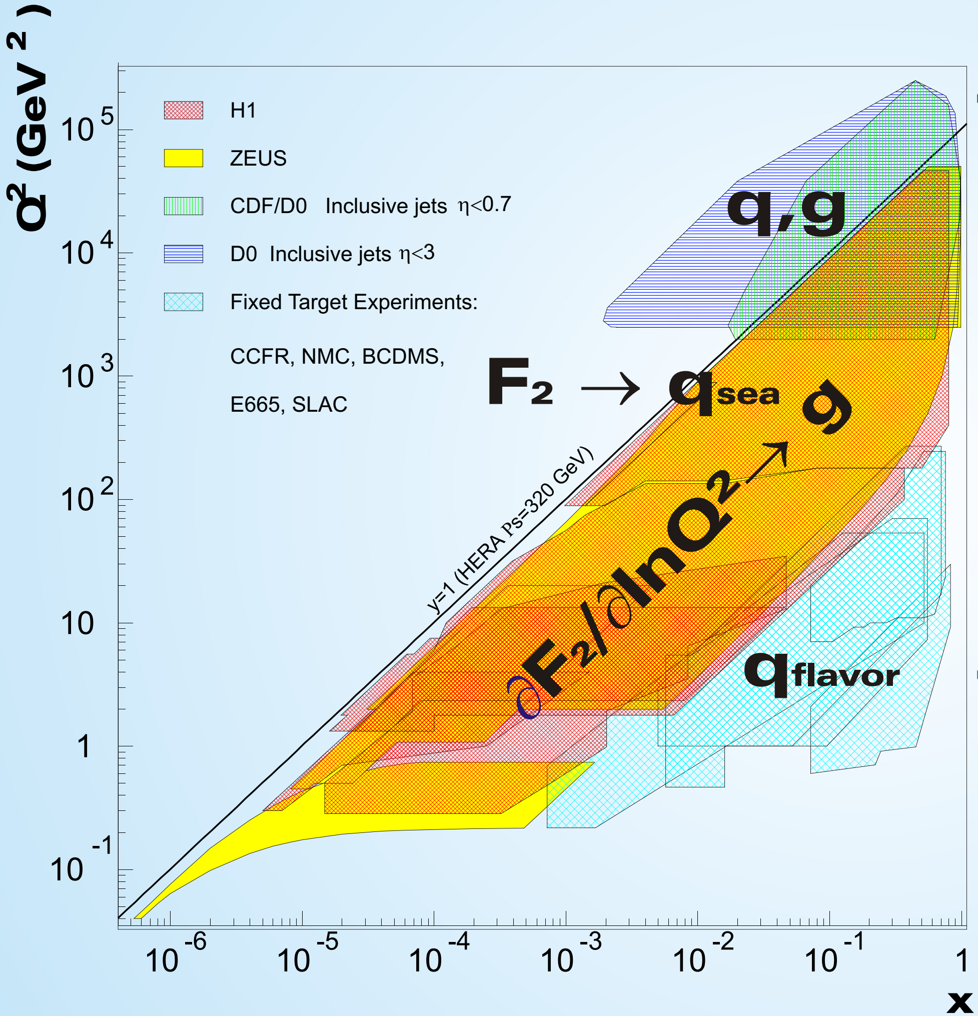
went
for
compen-
sation



Let's have a final look while they are still there....



Kinematic Range



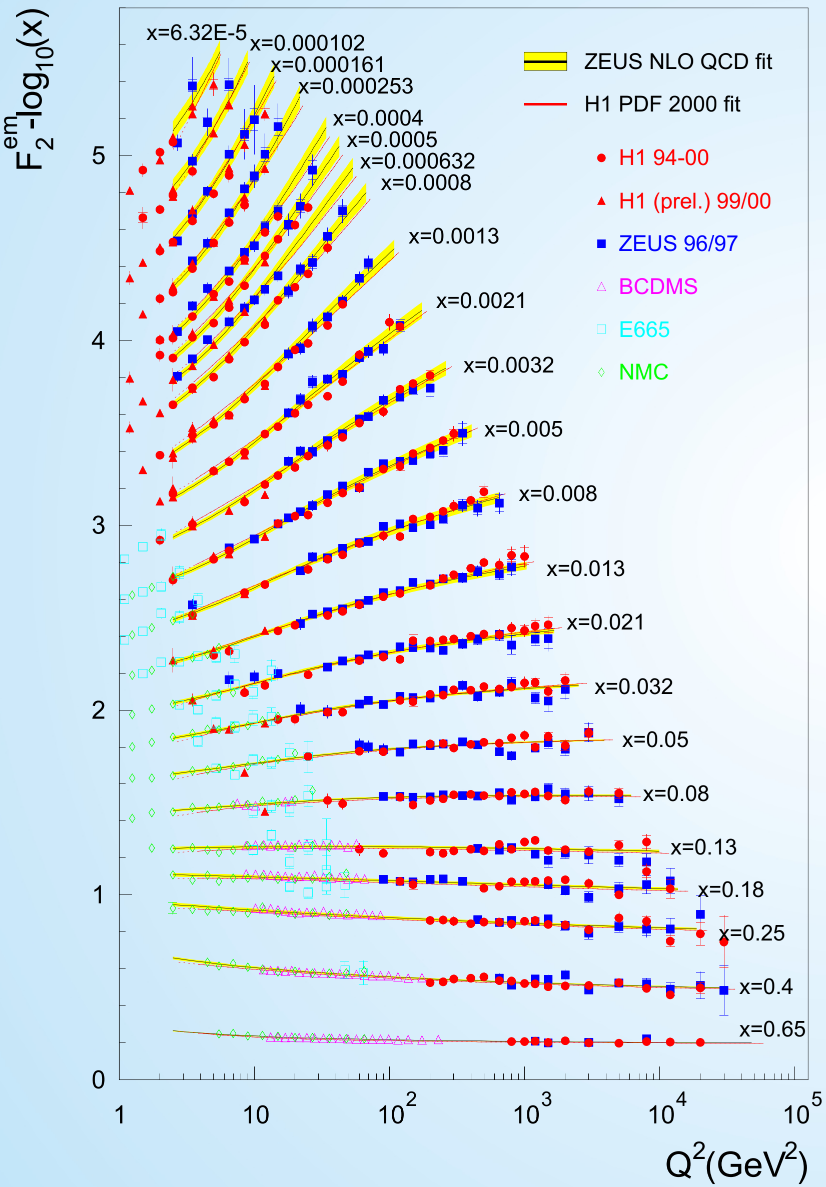
Tevatron Jet Distributions

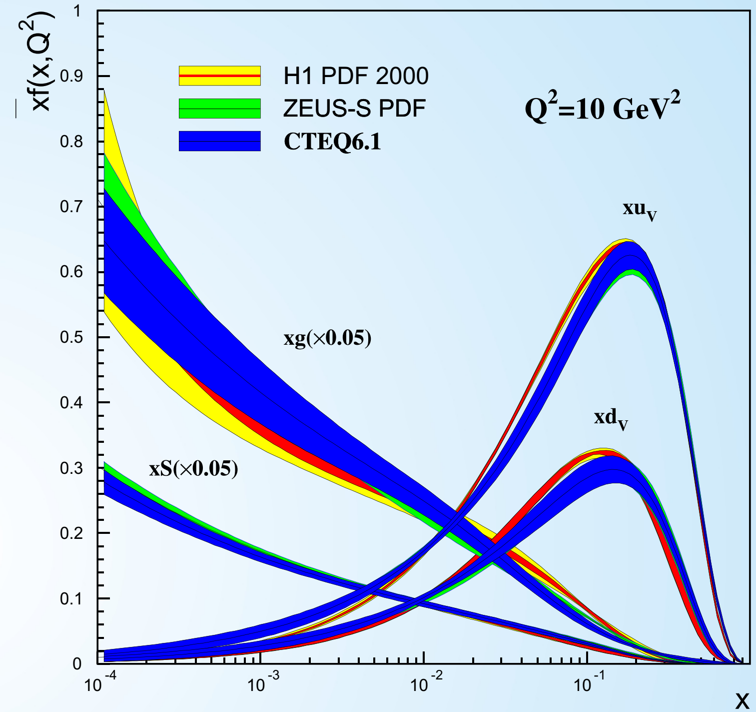
HERA: specialised in sea quarks determined via F_2.

Fixed Target

Note, that kinematic range is not static.

Structure Function F_2 and PDFs





NLO pQCD describes F_2 over

- **4 orders in Q^2**
- **3 orders in x**

Scaling Violations reveal the DIS invisible gluon.

PDFs known ⇒ EW can be studied

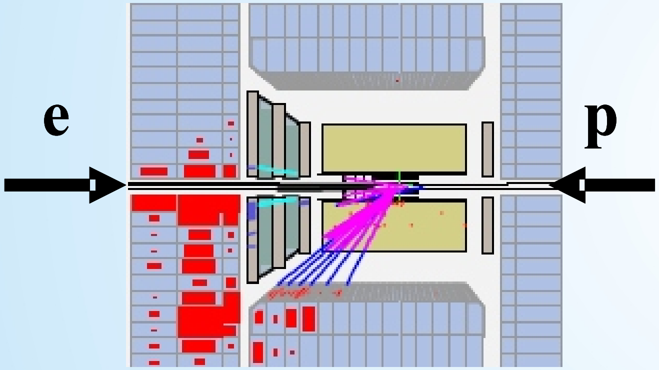
CC at High Q^2

CC ep $\rightarrow \nu X$: Pure Weak (only L)

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

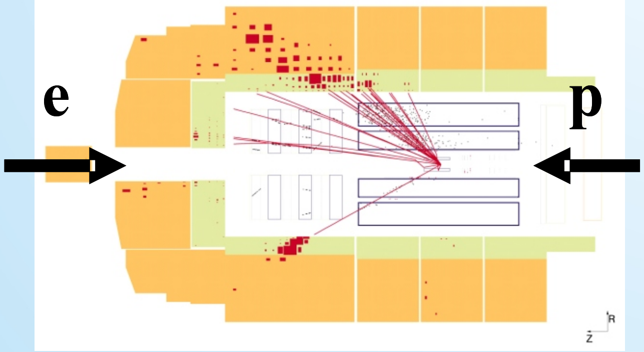
$$\frac{d^2\sigma(e^-p)}{dxdQ^2} = \frac{G_F^{\ 2}}{2\pi}\left(\frac{M_W^{\ 2}}{M_W^{\ 2}+Q^2}\right)^2\{(u+c)+(1-y)^2(\bar{d}+\bar{s})\}$$

e-p:
-- charge selecting nature: only up-type q (downtype anti-q)
-- anti-q receives $(1\text{-}y)^2$ helicity suppression



- Selection: large missing transverse energy: Pt,miss
- Kinematics reconstructed using hadrons (only possibility)

… while NC event looks like:



- Selection: presence of high p_T scattered electron, scattered at large angle
- Kinematics well reconstructed using either electrons or hadrons (or both)

NC at High Q²

- NC ep → eX: Z effects at high Q^2
  - -- F_2 receives additional terms
  - -- "Axial" SF, F_3, comes into

$$\frac{d^2\sigma(e^{\pm}P)}{dxdQ^2} = \frac{2\pi\alpha^2}{Q^4}\{Y_+\tilde{F}_2 \mp Y_- x\tilde{F}_3\}$$

For axial: sign flips between particles and anti-particles
-- Sign flips between e+/e-
-- q/qbar contributes to xF_3 with different sign
→ xF_3 is proportional to valence q

Nb.: xF_3 is written as F_3 in the equations below for simplicity

1st-order V — 2nd-order V

$$\tilde{F}_2 = \Sigma A_q x(q+\overline{q}) = F_2^{\gamma} - v_e\chi_Z F_2^{\gamma Z} + (v_e^2+a_e^2)\chi_Z^2 F_2^Z$$

$$\tilde{F}_3 = \Sigma B_q x(q-\overline{q}) = -a_e\chi_Z F_3^{\gamma Z} + 2v_e a_e\chi_Z^2 F_3^Z$$

1st-order A — 2nd-order A

γZ interference — Pure Z

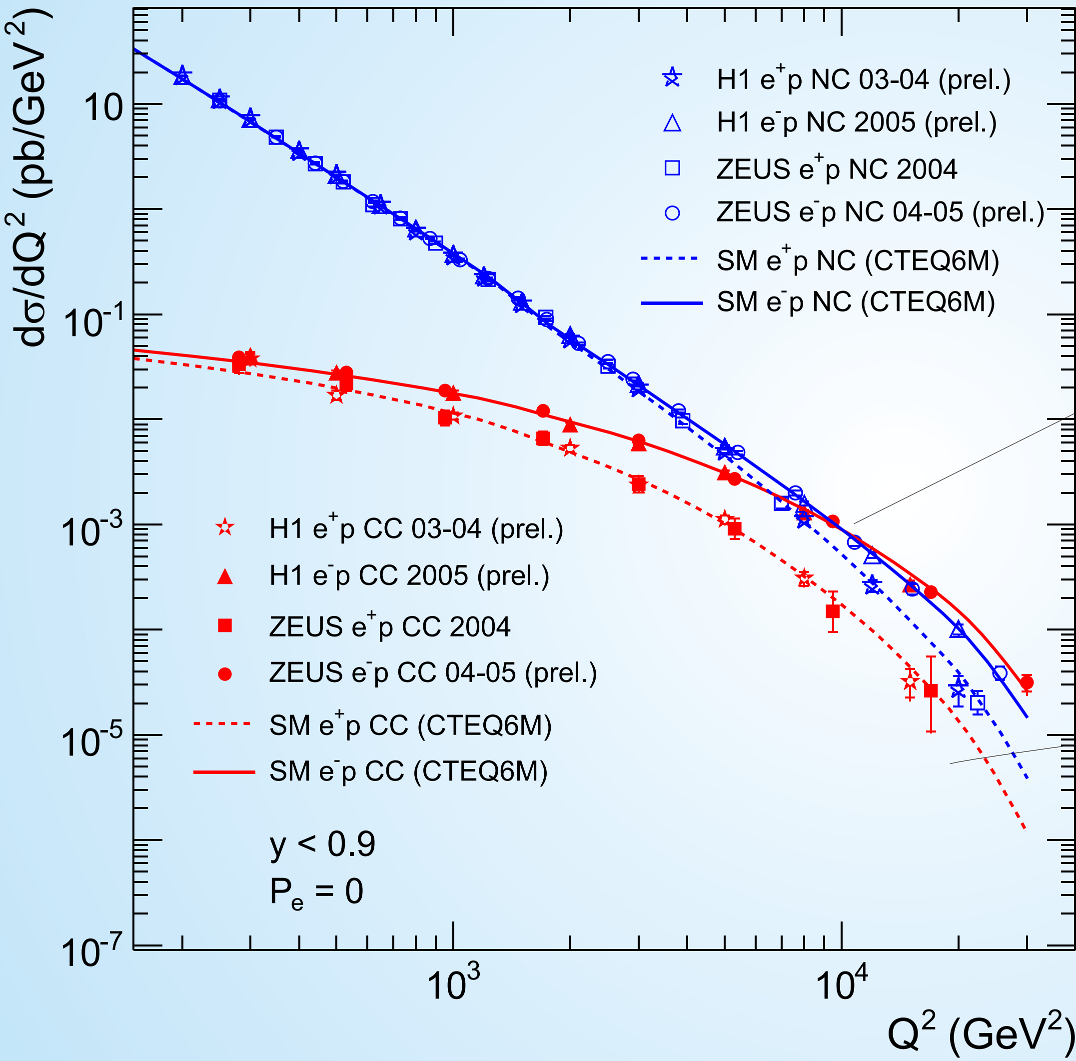
$$\chi_Z = \frac{1}{\sin^2 2\theta_w}\frac{Q^2}{M_Z^2+Q^2}$$

Propagator term

-- F_2 : 2nd order only $\sim a_e^2\chi_z^2 F_2^Z$

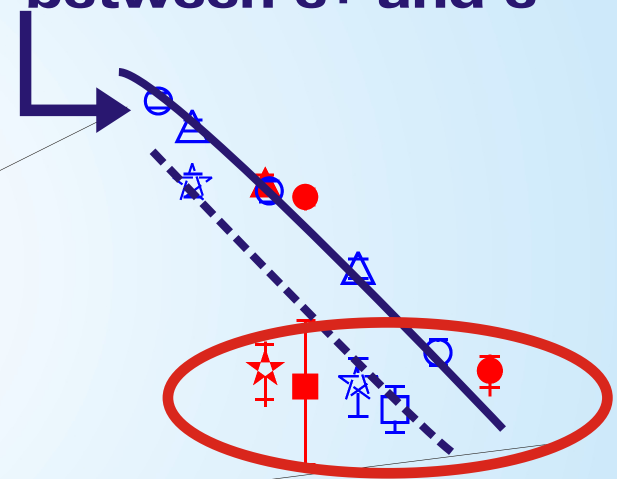
-- F_3 : 1st order γZ interf. $\sim a_e\chi_Z F_3^{\gamma Z}$

EW "unification"



HERA II

In NC axial component xF_3 is seen as difference between e+ and e-



NC and CC cross-sections become similar.

Remaining differences mainly due to PDFs

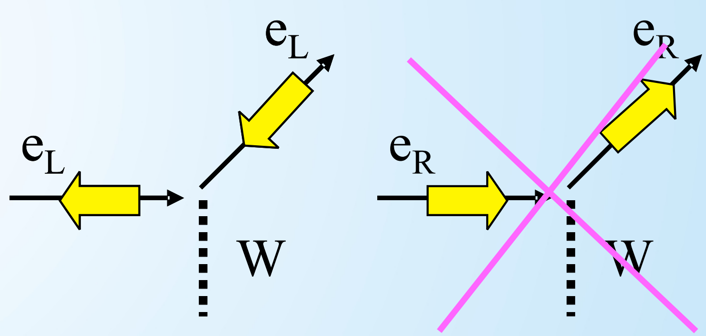
EW Physics With Polarized Leptons

Left-Handed **Right-Handed**

- Polarization = Asymmetry of Helicity states:
  $P = (N_R - N_L) / (N_R + N_L)$
- Helicity = Chirality (if mass is neglected)
  ➔ By means of Pol, chiral structure can be tested.
- RH ≠LH ⇔ parity violation

Charged-current DIS

- "Pure" Weak
  → Chiral structure of weak int. is directly visible as a function of Polarization
- Weak = "100% parity violated" (no RH)
  → Zero cross section @ Pol=1 (-1 for e+)
  ➔ $\sigma(\text{Pol}) = (1+\text{Pol})\,\sigma(\text{Unpol})$

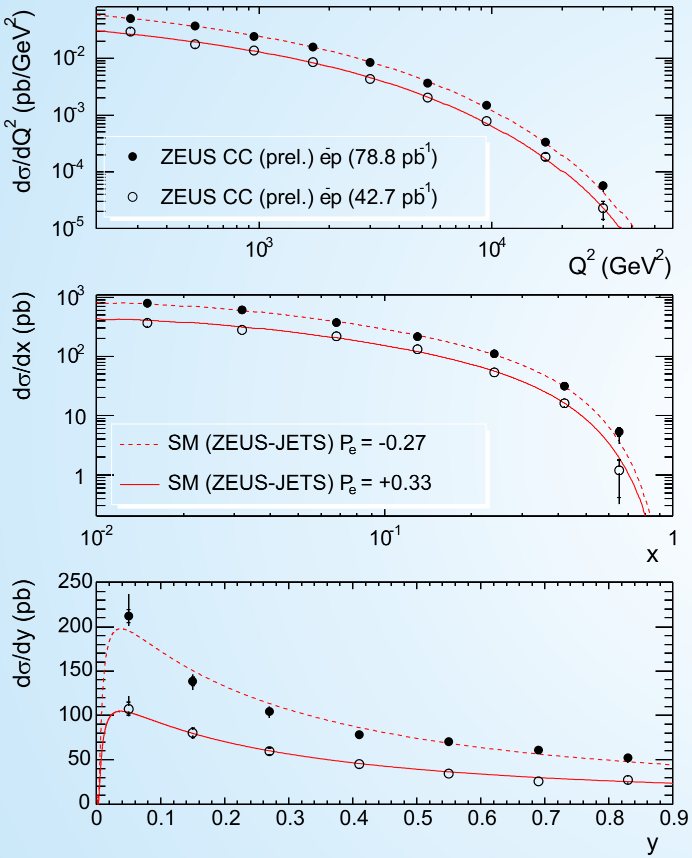


Neutral-current DIS

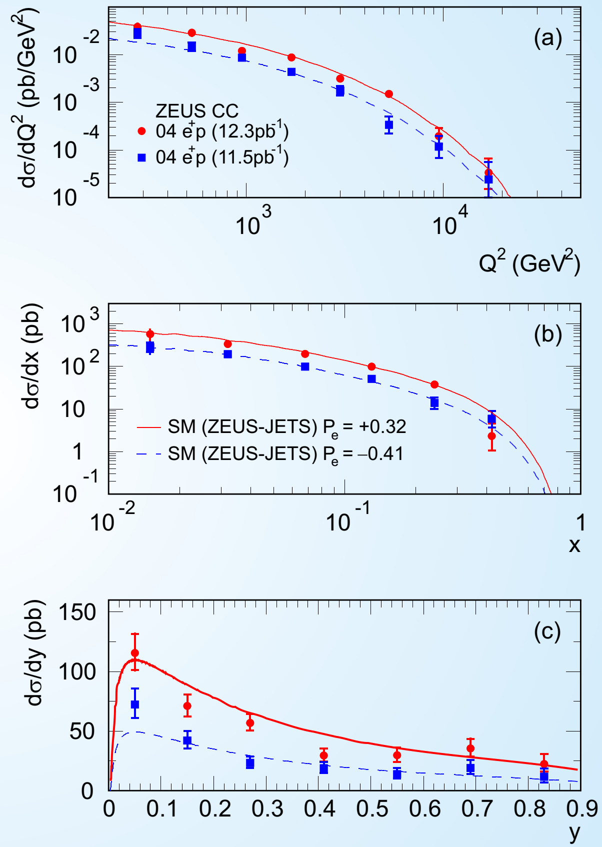
- Weak parity violating effect through γZ interference and pure Z
  → visible only at large Q^2
- Such γZ and Z terms contain EW parameters, i.e. quark couplings to Z, $\sin\theta_W$, M_Z

Charged Current Cross-Section

Electron

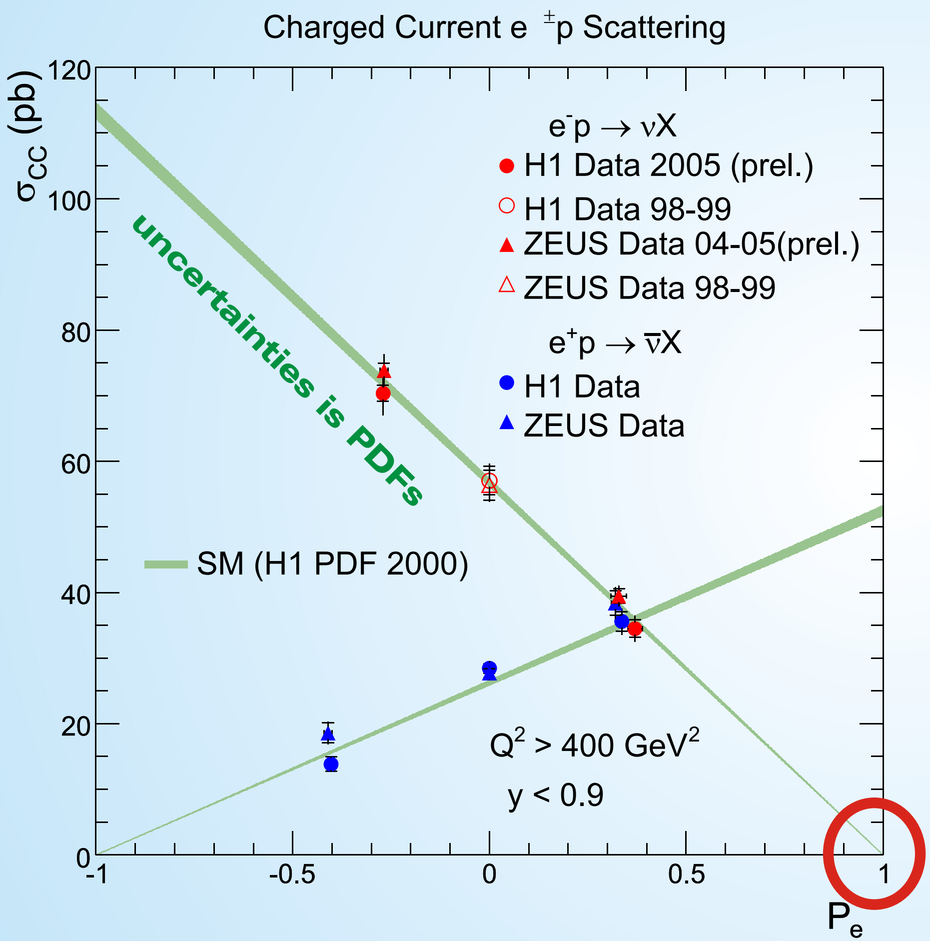


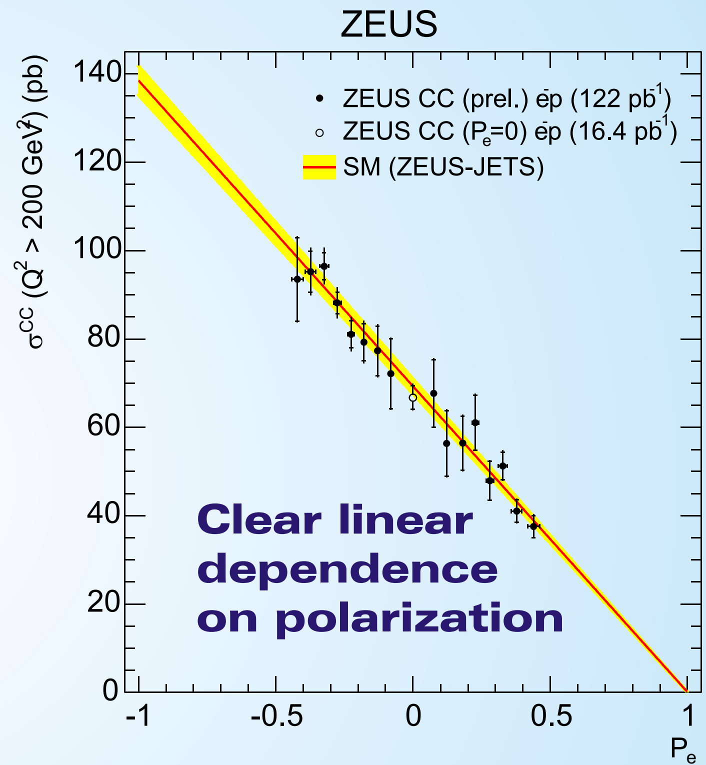
Positron



Clear difference in cross-sections between negative and positive polarization

Polarization Dependence of CC Cross-Section



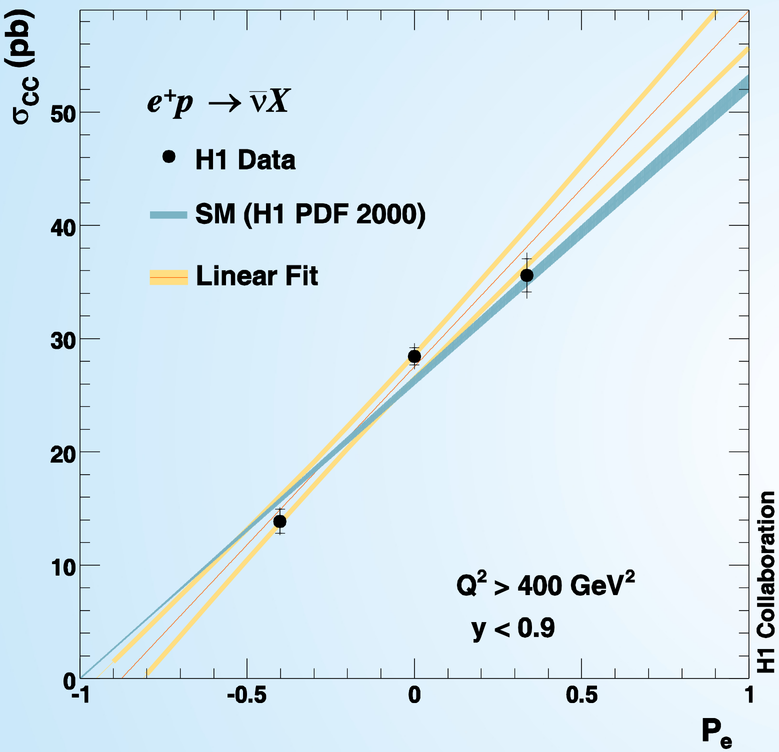


Consistent with SM prediction

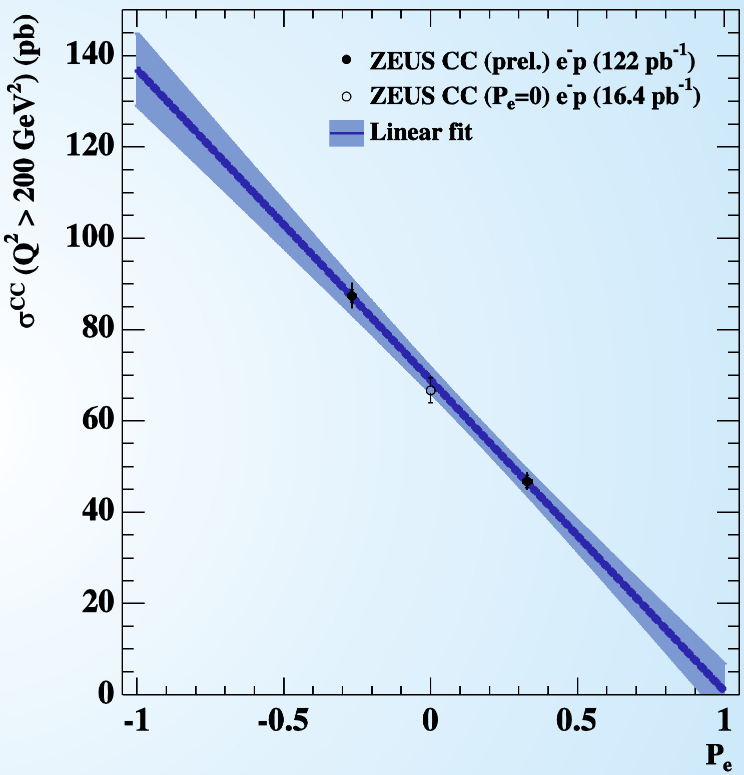
$\sigma(CC_{RH}) = 0$

W_R Mass Limit

H1 positron



ZEUS electron



Assume $g_L = g_R$ and ν_R is light:

H1 e- → W_R > 186 GeV

H1 e+ → W_R > 208 GeV

ZEUS e- → W_R > 180 GeV

> 310 GeV from polarized ^{12}N β decay

> 786 GeV from W' → eν , μν

Polarization Effects in NC

$$\tilde{F}_2 = F_2^{\gamma} - (v_e \pm P_e a_e)\chi_Z F_2^{\gamma Z} + ((v_e^2 + a_e^2) \pm P_e 2 v_e a_e))\chi_Z^2 F_2^Z$$
$$\tilde{F}_3 = - (a_e \pm P_e v_e)\chi_Z F_3^{\gamma Z} + ((2 v_e a_e \pm P_e (v_e^2 + a_e^2))\chi_Z^2 F_3^Z$$

Nb.: xF_3 is written as F_3 for simplicity

- Polarization modifies γZ and Z terms:
  - -- Axial in F_2, vector in F_3
  - -- dependent on size of P_e

$v_e \approx 0$

-- F_2 : 1st order, ~ $\pm P_e a_e \chi_Z F_2^{\gamma Z}$

-- F_3 : 2nd order only, ~ $\pm P_e a_e^2 \chi_Z^2 F_3^Z$

Unpol:

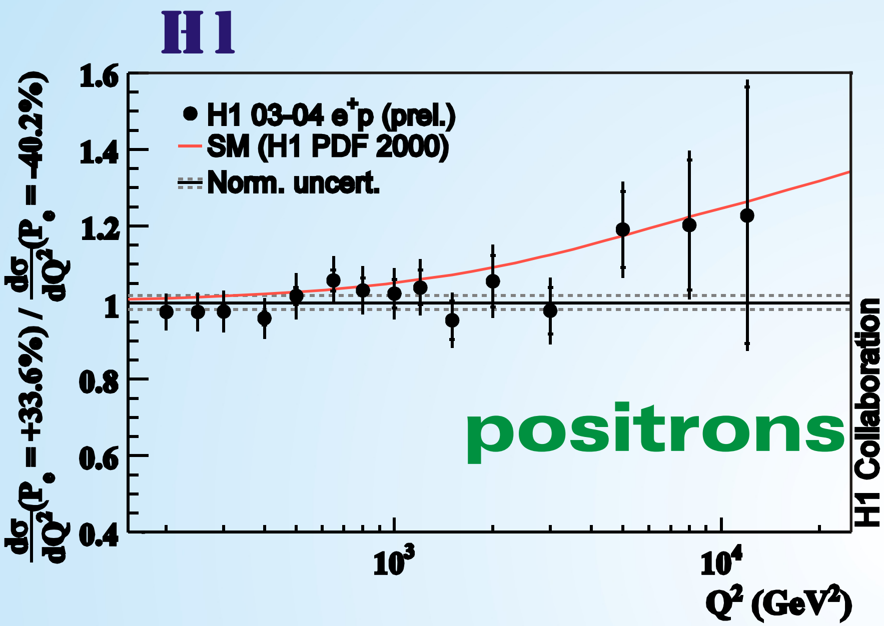
$\sigma(e^+) - \sigma(e^-) \rightarrow F_3^{\gamma Z}$

Pol :

$\sigma(P_e \rightarrow) - \sigma(P_e \leftarrow) \rightarrow F_2^{\gamma Z}$

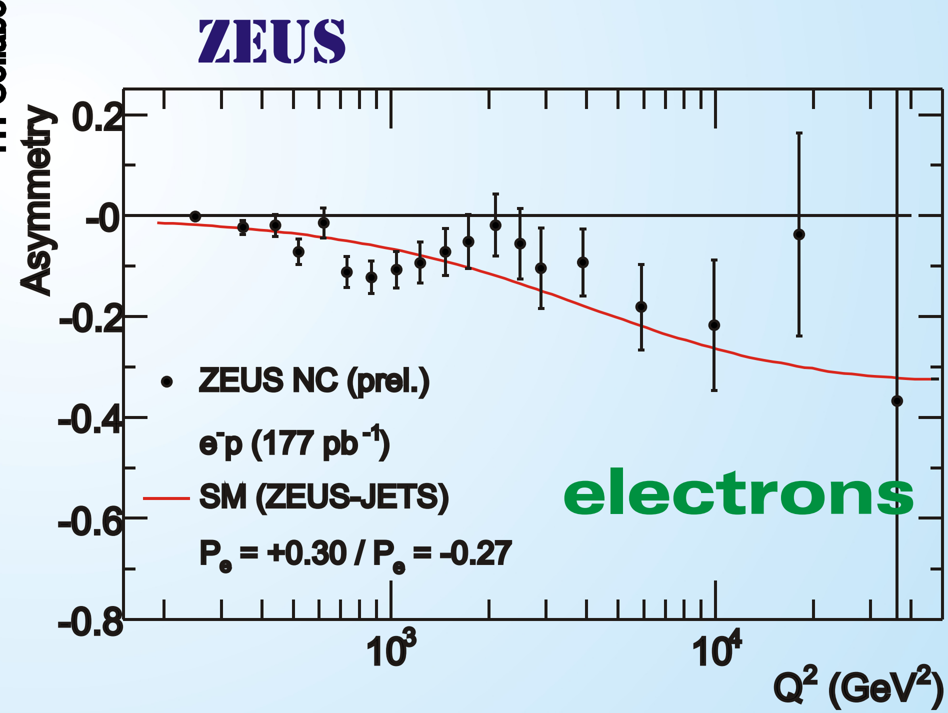
- Polarization effects expected only at EW scale, i.e large Q^2

NC Cross-Section vs. Polarization



dσ/dx and dσ/dy do not strongly depend on P_e

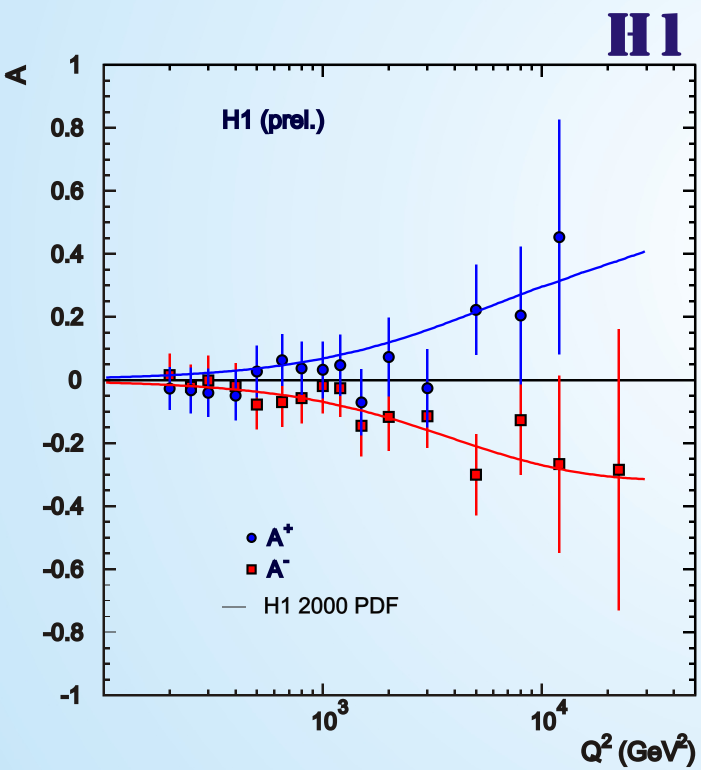
dσ/dQ² does

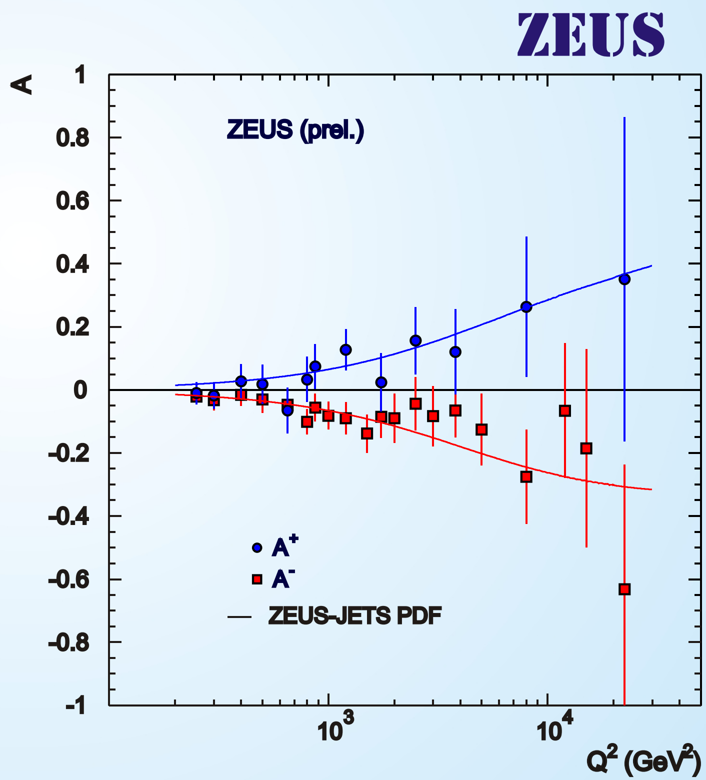


Observation of Parity Violation at EW scale

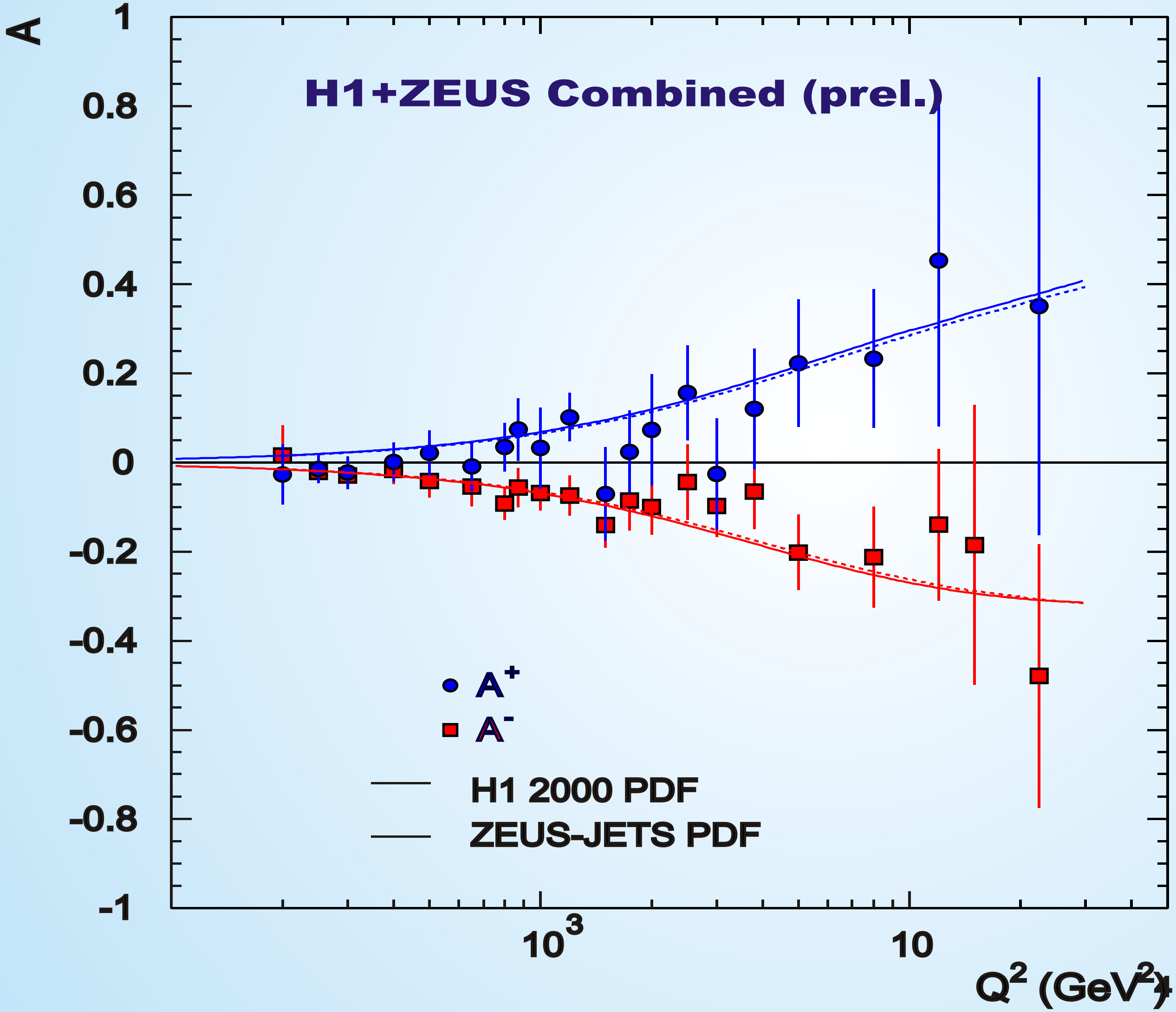
NC Cross-Section Asymmetries

$$A_{\pm} = \frac{2}{P_R - P_L} \; \frac{\sigma_{\pm}(P_R) - \sigma_{\pm}(P_L)}{\sigma_{\pm}(P_R) + \sigma_{\pm}(P_L)}$$





NC Cross-Section Asymmetries



Parity Violation due to γZ interference

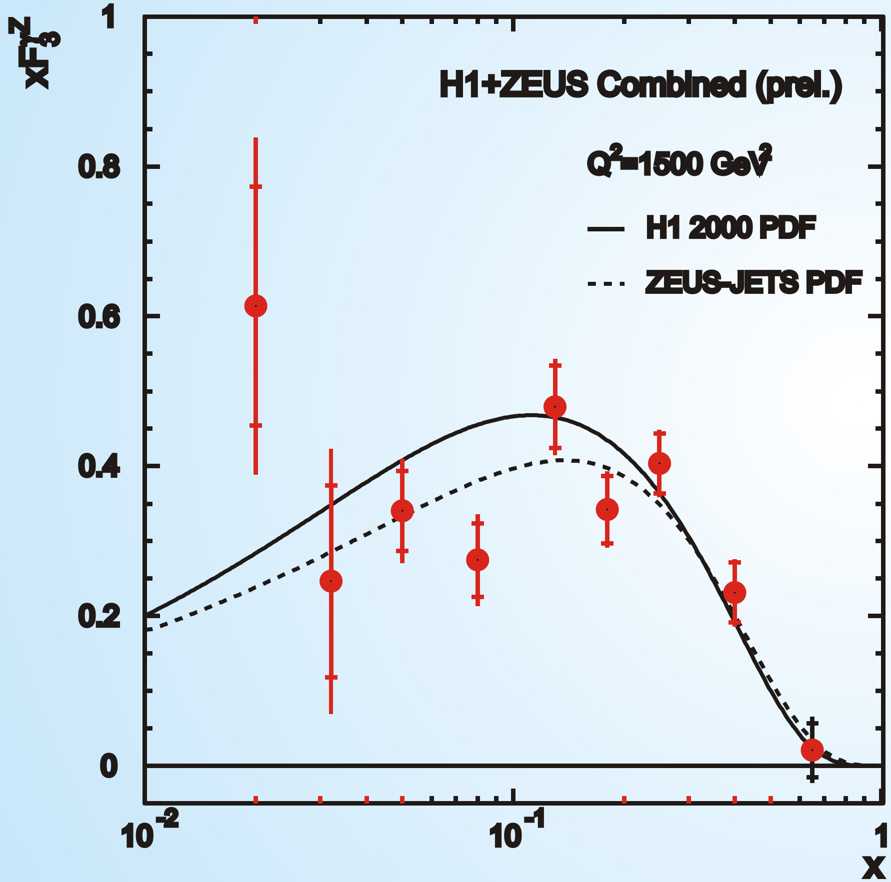
At high x, assuming SM couplings

$$A_{\pm} \sim \frac{u_v + d_v}{4u_v + d_v}$$

constrain d/u

xF_3

H1 + ZEUS



Combine all data and correct to zero polarization.

Assuming SM couplings

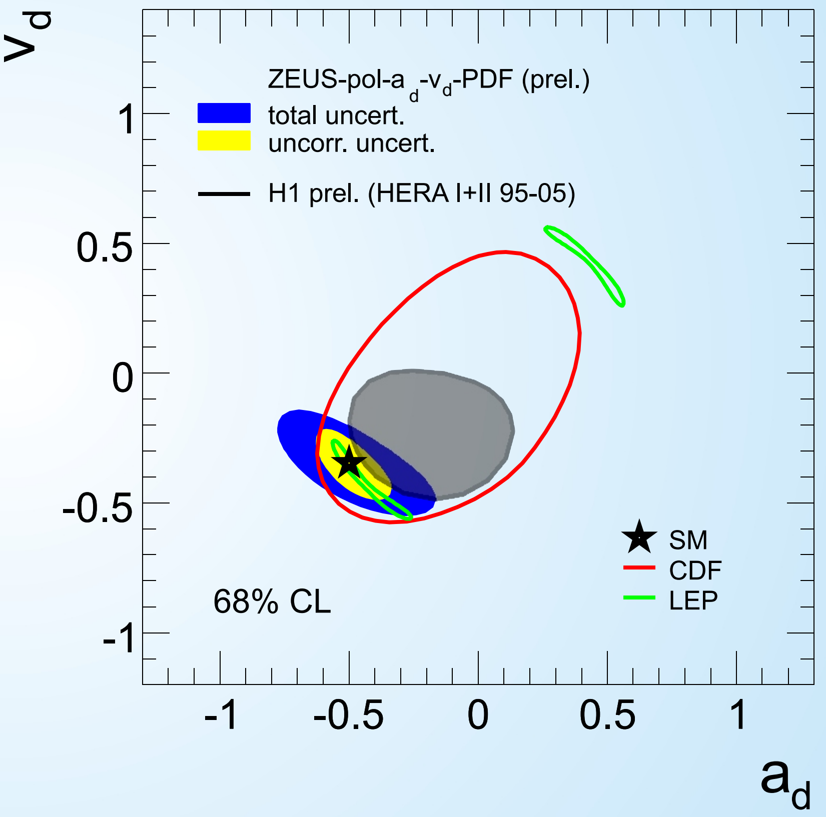
$F_3 \sim 2/3\, u_v + 1/3\, d_v$

Constrain valence quarks

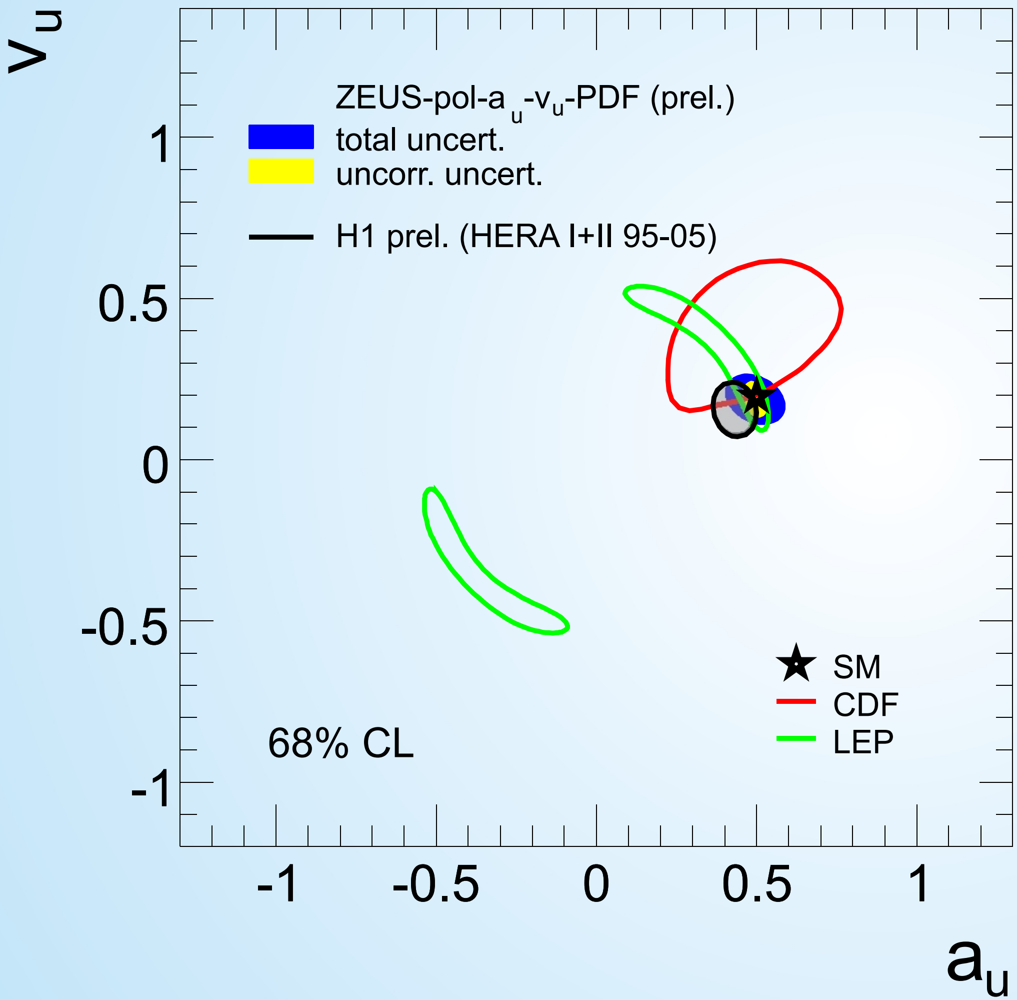
EW plus QCD Fit

Fit both PDFs and EW parameters simultaniously

Experiments fit seperately to simplify handling of systematic errors



EW plus QCD Fits



Precise determination of light quark couplings to Z

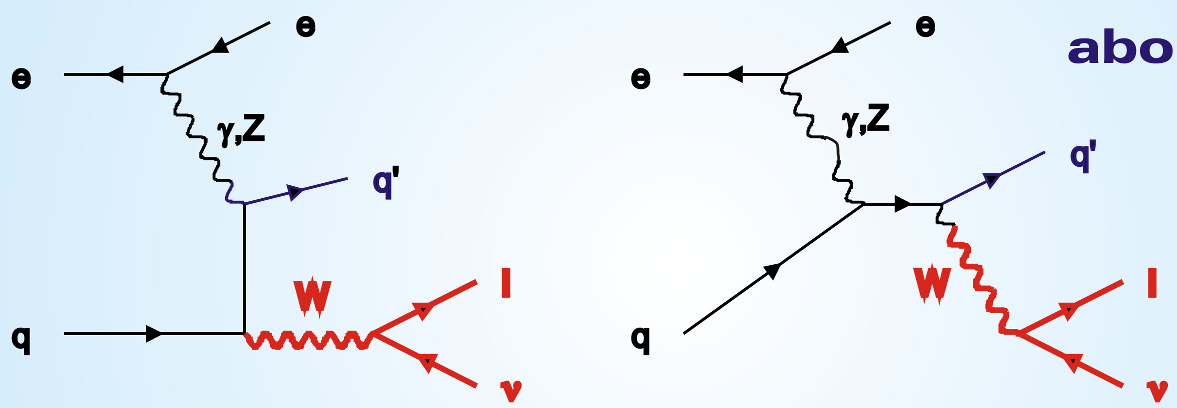
Luminosity helps with a

Polarization helps with v

Smack on SM prediction...

Isolated leptons

In the SM isolated leptons are only produced through single W production:



about 1.1 pb

Select

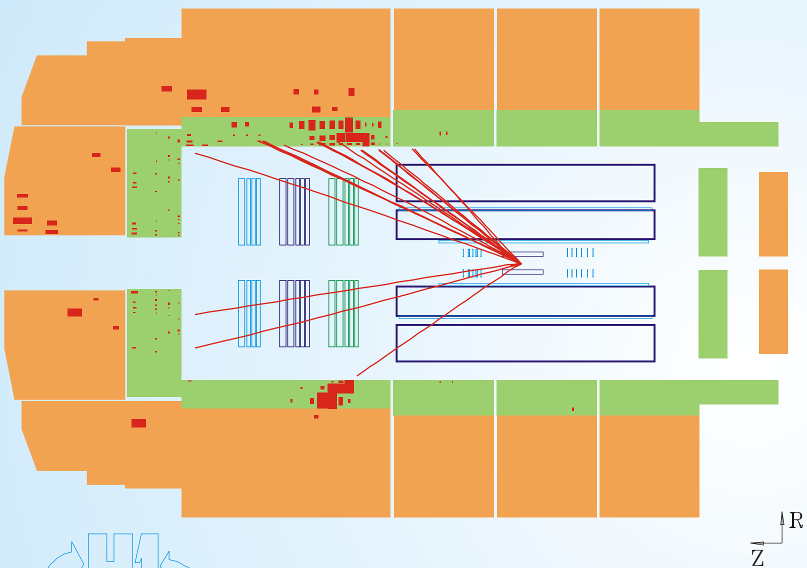
quark jet with large transverse momentum p_{Tx}

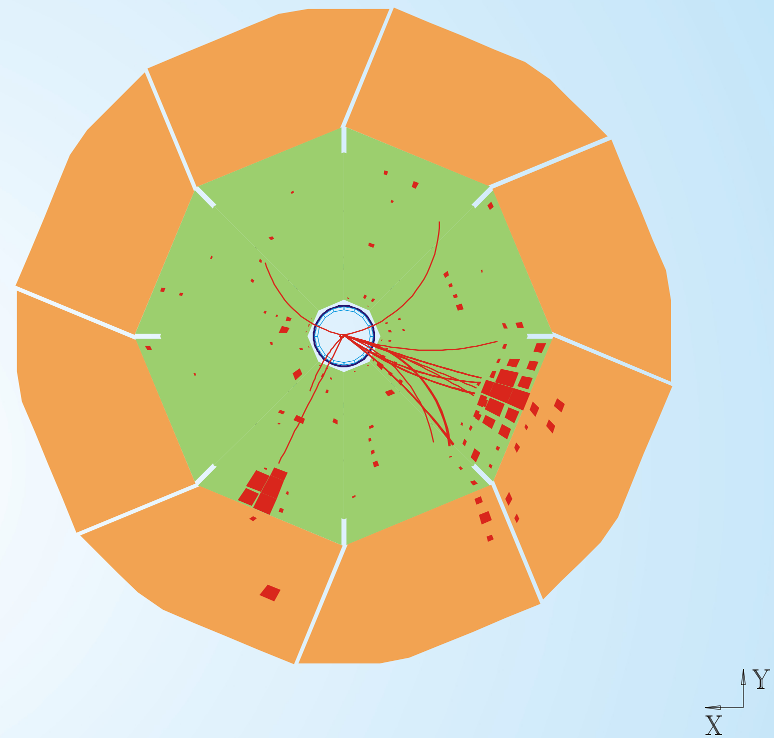
only small fraction of SM events/expected for single t

isolated lepton with large transverse momentum p_{Tl}

large missing transverse momentum p_{Tmiss}

Event in H1

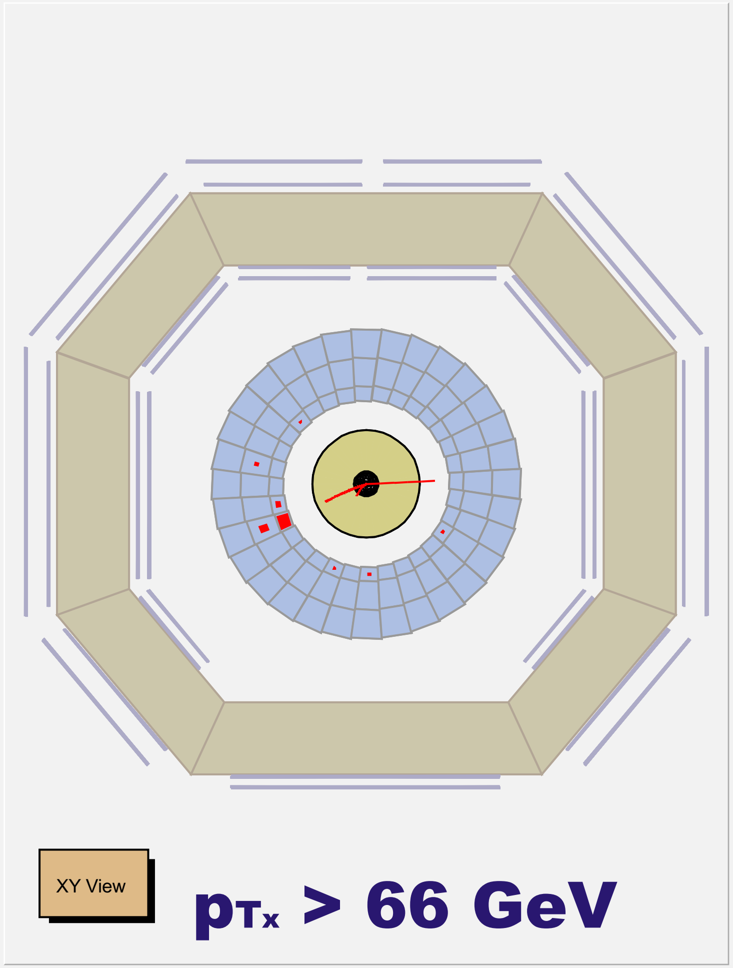




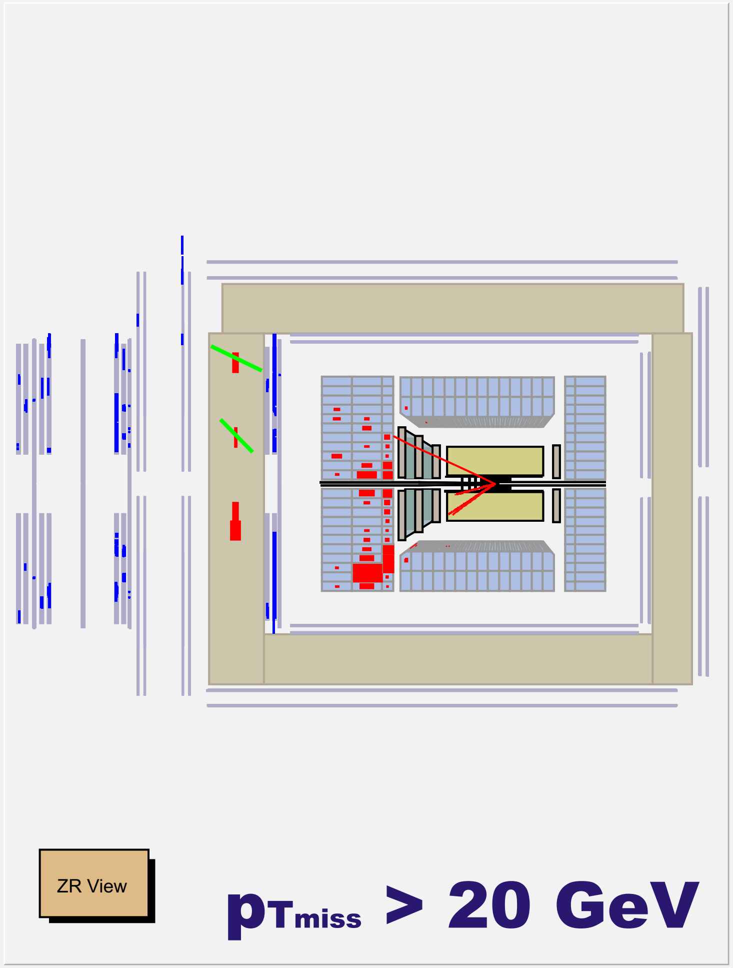
$p_{Tx} > 29$ GeV **$p_{Tmiss} > 44$ GeV** **$p_{Tl} > 37$ GeV**

large acoplanarity

Event in ZEUS



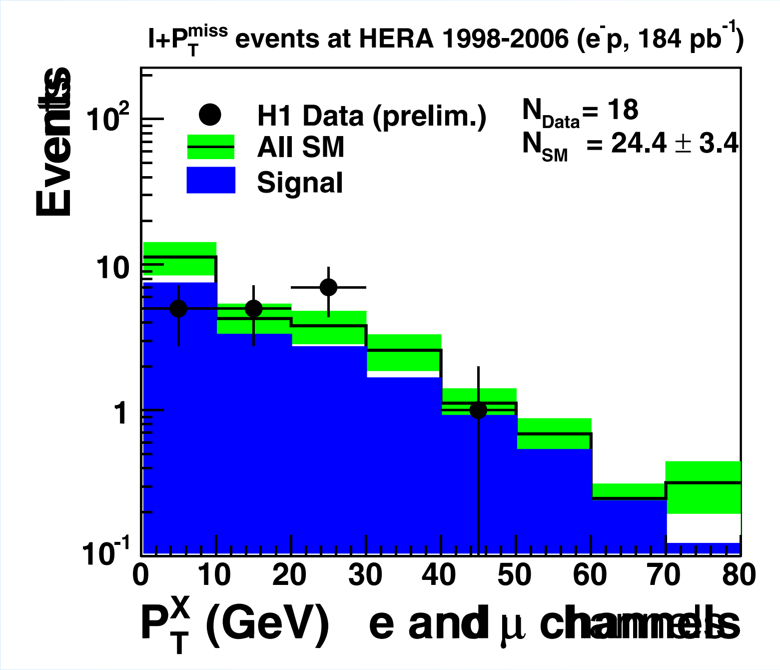
$p_{Tx} > 66$ GeV

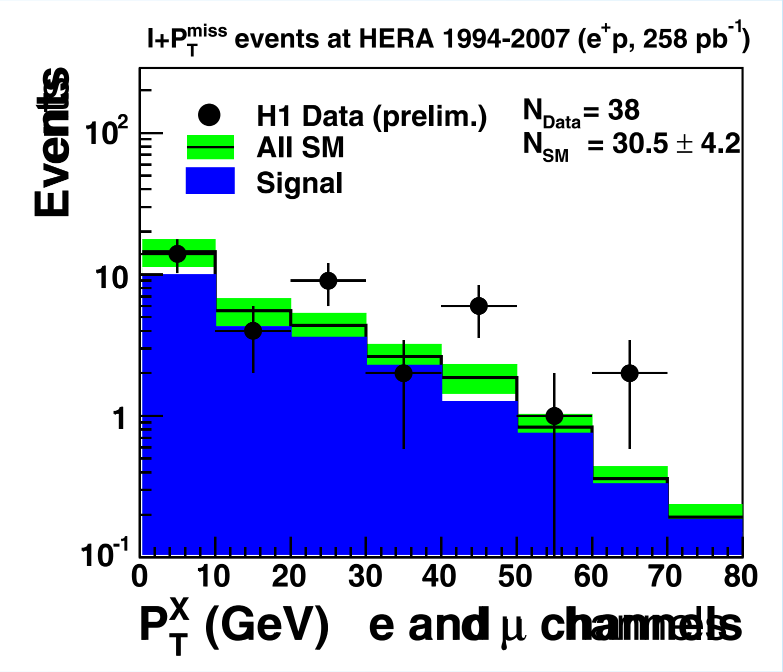


$p_{Tmiss} > 20$ GeV

large acoplanarity

Transverse Momentum Distributions



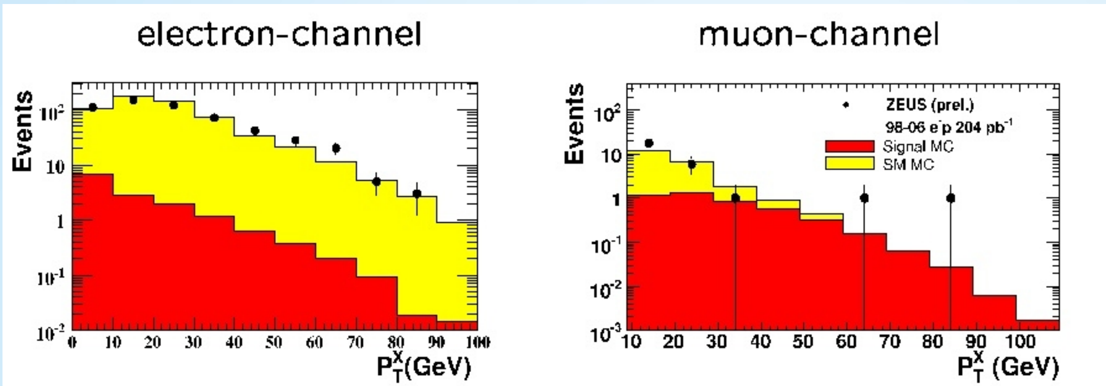


electrons **positrons**

Clean single W signal

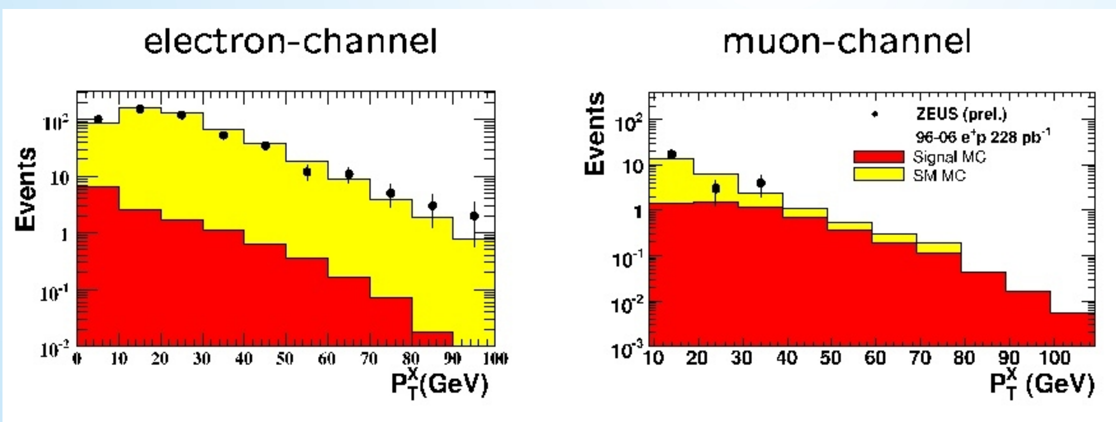
Transverse Momentum Distributions

ZEUS



positrons

misidenified NC is main background in electron channel



electrons

muon channel is a lot cleaner

Isolated Leptons

$P_T^X > 25$ GeV			electrons Data/SM	muons Data/SM
e^+p	H1	294 pb^{-1}	11/4.7±0.9	10/4.2±0.7
	ZEUS	228 pb^{-1}	1/3.2±0.4	3/3.1±0.5
e^-p	H1	184 pb^{-1}	3/3.8±0.6	0/3.1±0.5
	ZEUS	204 pb^{-1}	5/3.8±0.6	2/2.2±0.3

Cristinel Diaconu
DIS 2007

Experiments are checking on things like acceptance:

- **H1 has larger accpetance, but the extra events are in common region.**

like different cuts:

- **Sample purities are, however, similar.**

Statistics struck again?

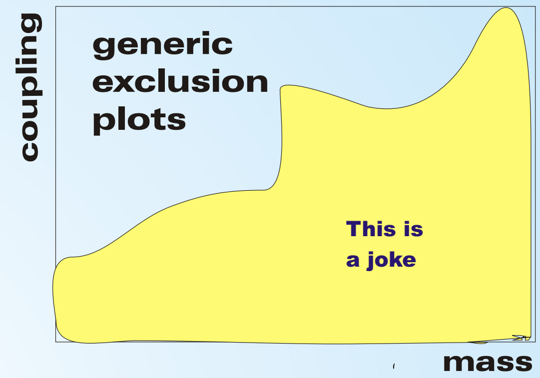
Searches

Leptoquarks

Compositeness

Extra Dimensions

Quark Form Factors



Sorry,
NOTHING

Resonance Production

Anomalous Whatever

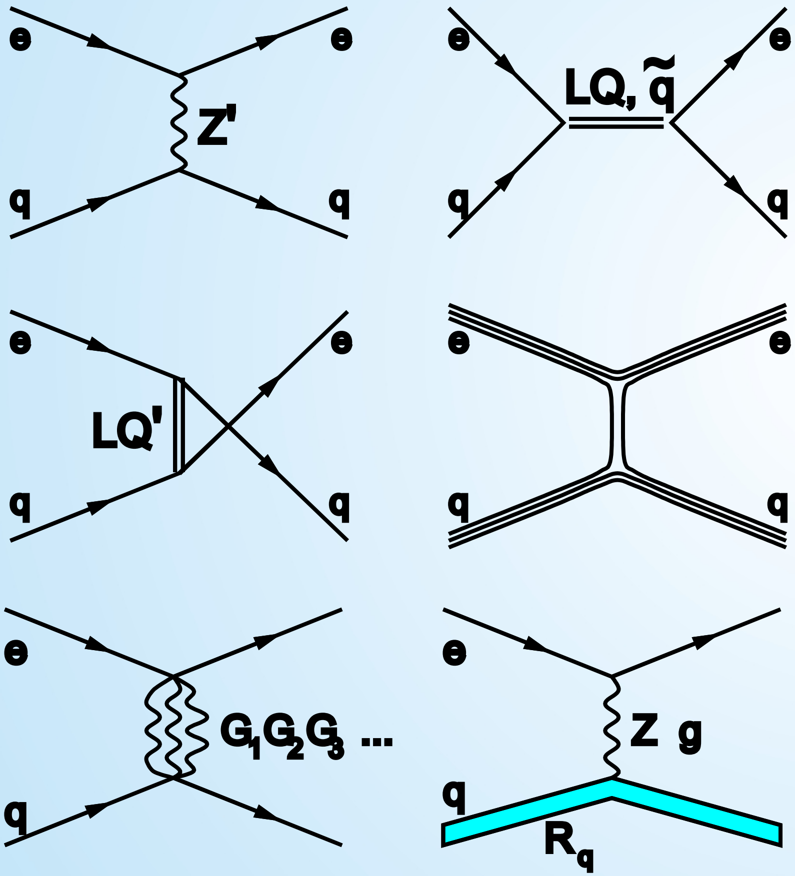
H1 → see extra talk

ZEUS → some examples

Supersymmetry

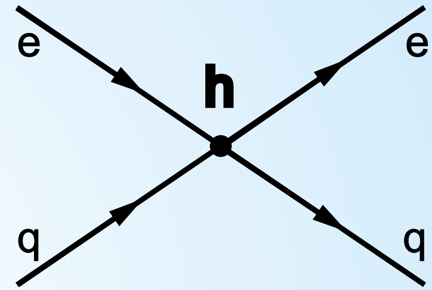
Contact Interactions

Possible "new physics" in NC DIS:



$\sqrt{s} \ll$ **process scale** Λ

$\Rightarrow$ **effective parametrization**



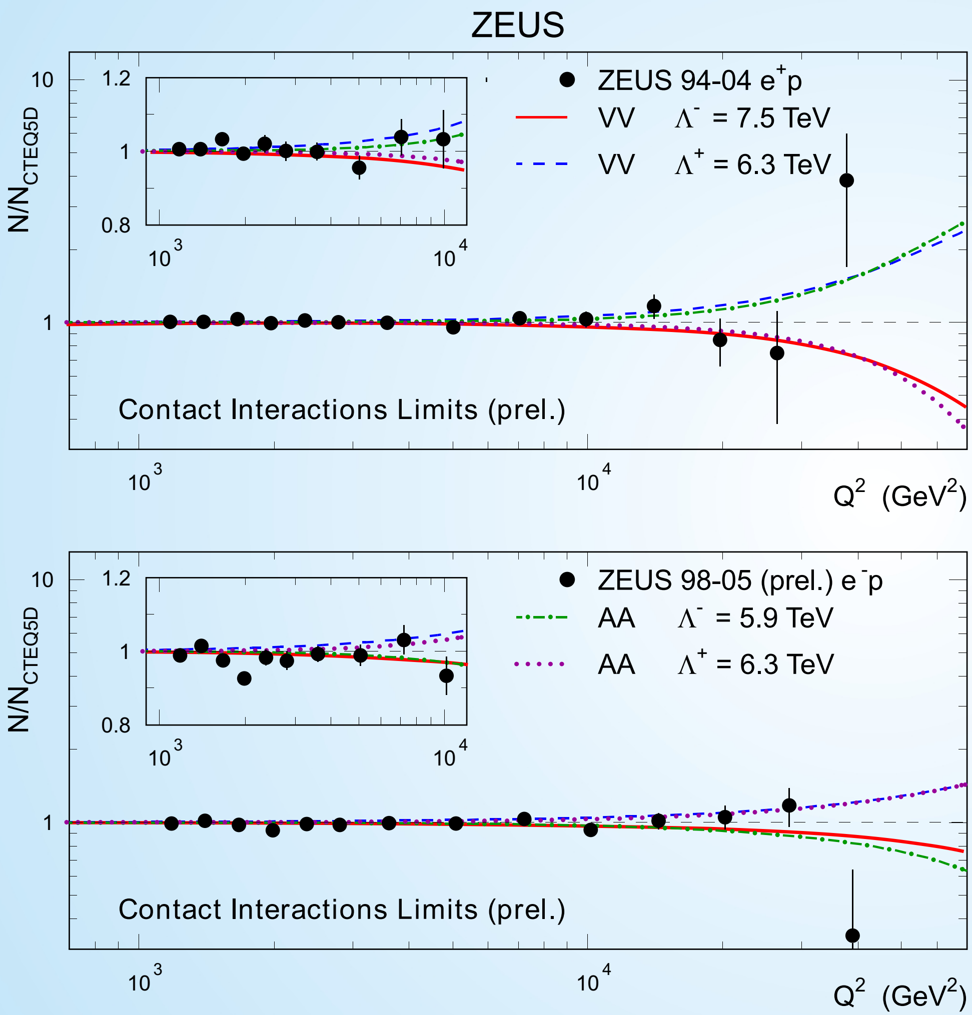
eeqq contact interactions (CI)

Contribution to the NC cross-section:

$$\frac{d\sigma}{dxdQ^2}(\eta) = \frac{d\sigma^{SM}}{dxdQ^2} \cdot [1 + A(x, Q^2)\,\eta + B(x, Q^2)\,\eta^2]$$

General formula for all CI type models

Compositeness Models



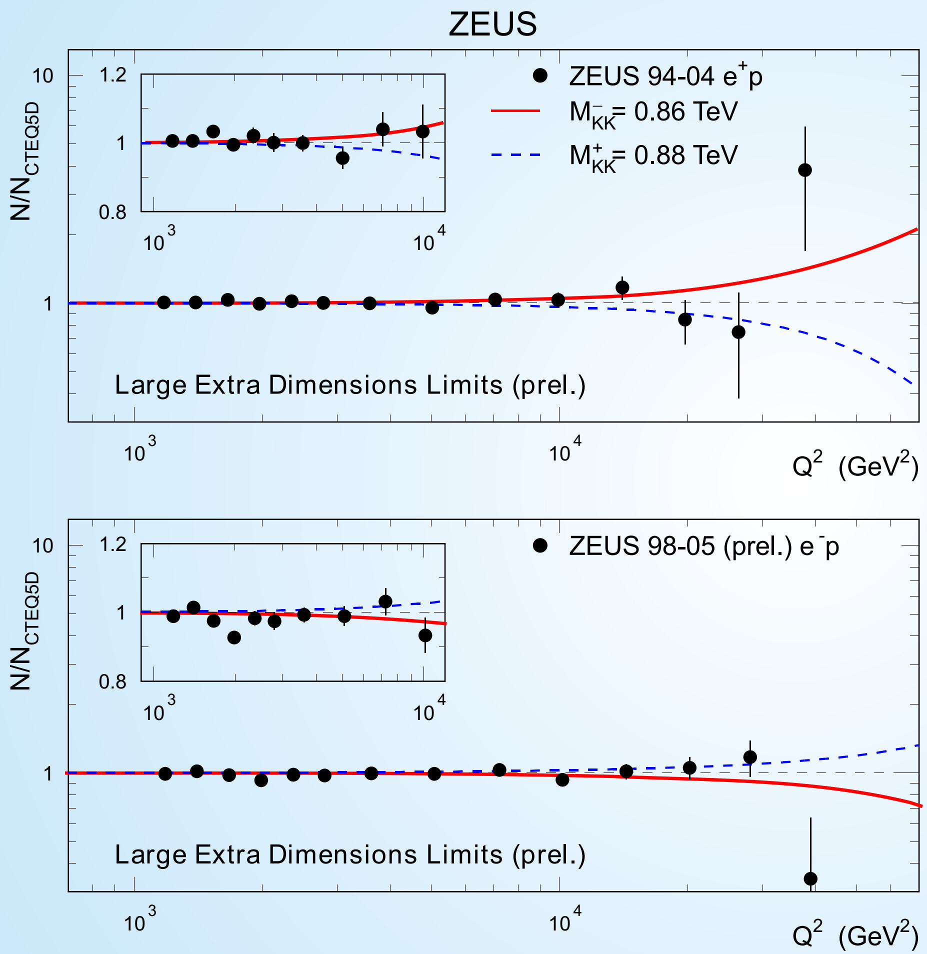
Contact interaction coupling given by:

$$\eta = \pm\, 4\pi \,/\, \Lambda^2$$

Λ: **compositeness scale**

Limits range from 2.0 to 7.5 TeV

Large Extra Dimensions



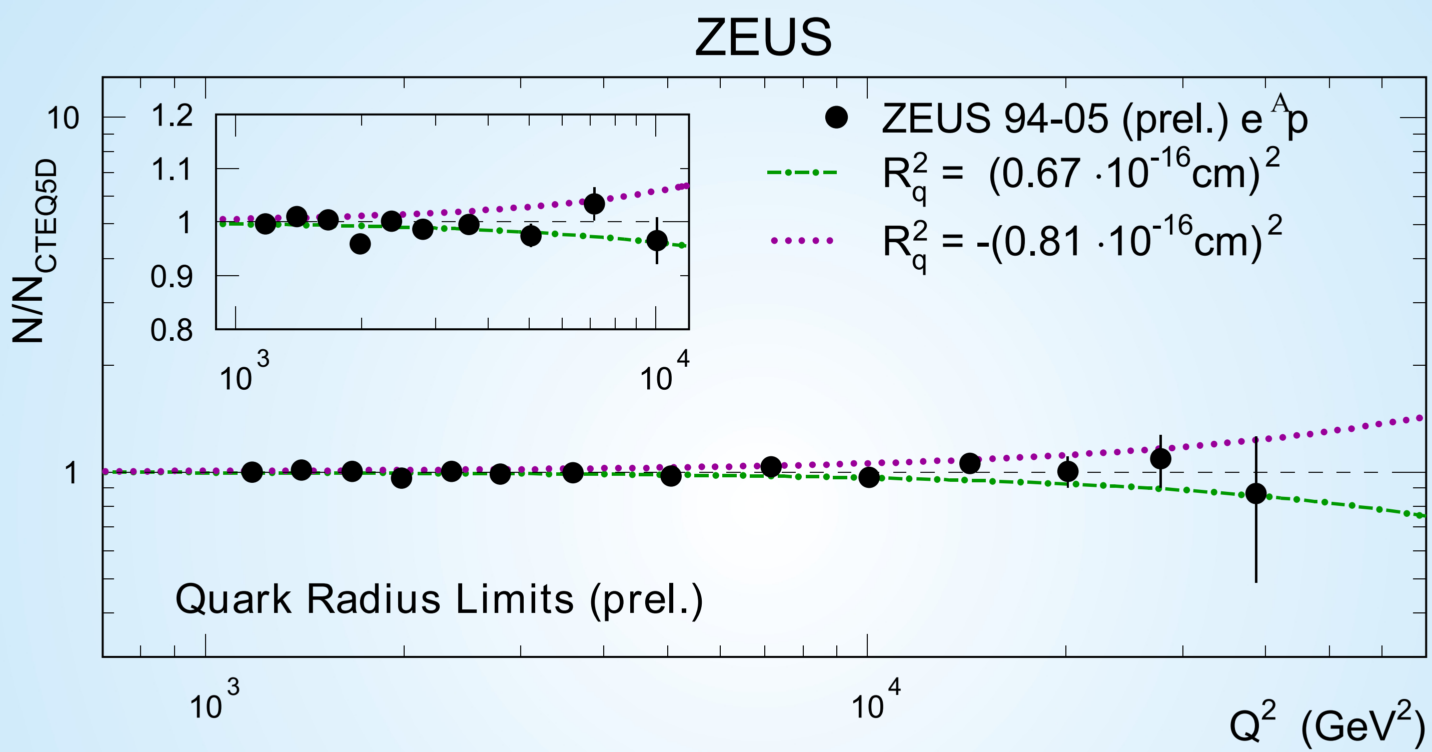
Kaluza-Klein Graviton Exchange

Effective Scale

$\eta \sim s / M_{KK}^4$

$M_{KK}^{+} > 0.88$ **TeV**

Quark Form Factor



Semi-classical model:

R_q – quark radius

$$\frac{d\sigma}{dQ^2} = \frac{d\sigma^{SM}}{dQ^2}\left(1 - \frac{R_q^2}{6} Q^2\right)$$

$$R_q < 0.67 \cdot 10^{-16}\,\mathrm{cm}$$

Summary

HERA II has provided a large amount of high Q^2 data
We are in the middle of an exciting period of analysis.

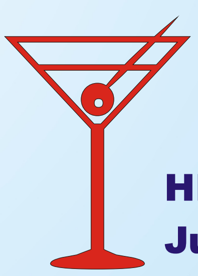
The PDFs will be the legacy and stand for a long time.

The Standard Model has survived HERA without a scratch.

Unfortunately [?] nothing unexpected has happened at HERA.

Still doing the low energy run for gluons.

Shut down June 30, i.e. this Saturday.



HERA-Fest
June 28/29