Electroweak studies and search for new phenomena at HERA

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for

H1 ZEUS

Outline

- Introduction

  HERA and experiments

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- Deep Inelastic $e^{\pm}p$ Scattering
    Measurement of high Q^2 NC and CC DIS

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  Observation of parity violation and polarization asymmetry
  QCD and Electroweak analysis of HERA data

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- Searches for new phenomena
   Contact Interactions and leptoquarks
    Isolated leptons

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  Contact Interactions and leptoquarks
  Isolated leptons

- Conclusions

Introduction
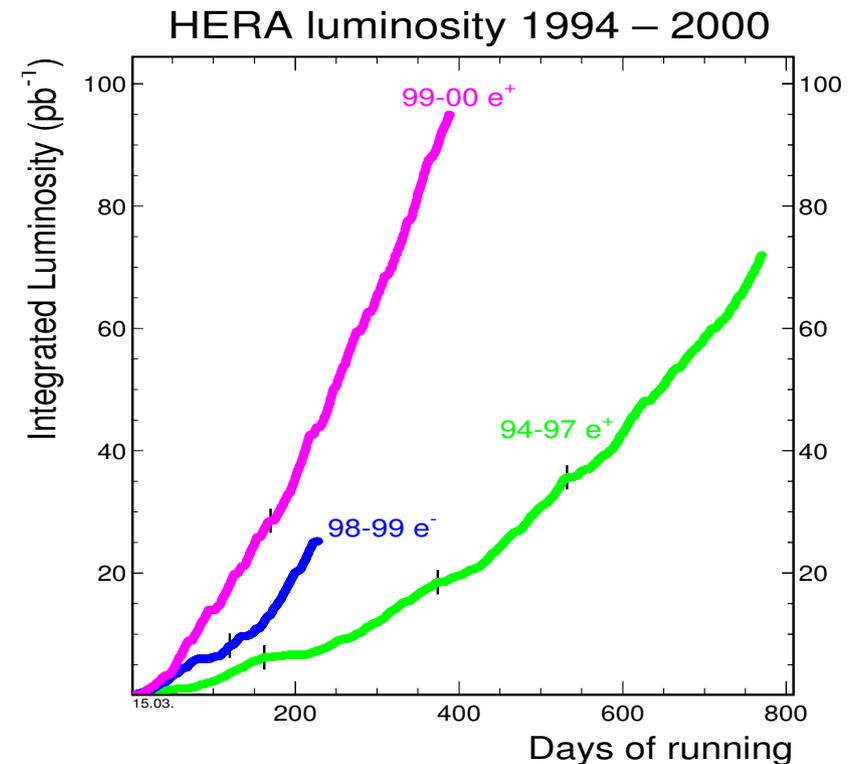
HERA
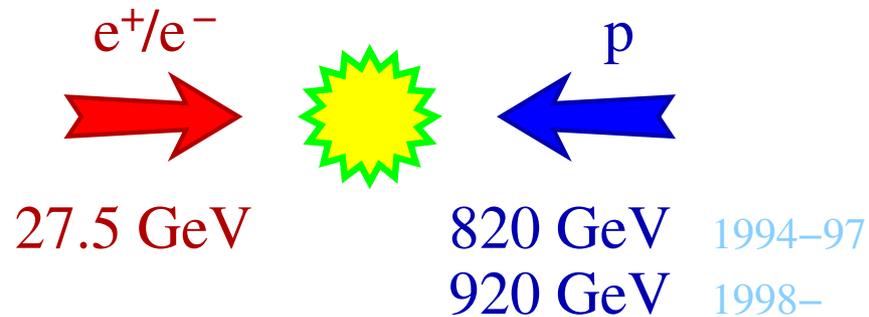
electron(positron)-proton collider at DESY

e^+/e^- p

27.5 GeV   820 GeV   1994–97
                920 GeV   1998–

HERA I   1994-2000

about $100 pb^{-1}$ collected per experiment

mainly e^+p data

HERA luminosity 1994 − 2000

Introduction

HERA
electron(positron)-proton collider at DESY

e^+/e^- p

27.5 GeV   820 GeV   1994–97
              920 GeV   1998–
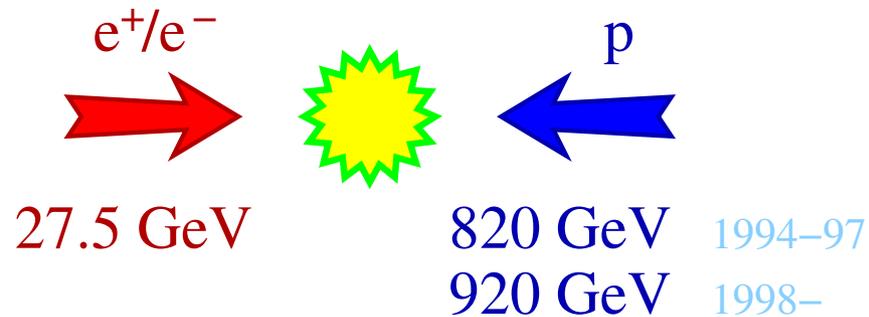
HERA I   1994-2000
about $100 pb^{-1}$ collected per experiment

mainly $e^+ p$ data

HERA II   2002-2007
over $300 pb^{-1}$ per experiment (so far)

more $e^- p$ data
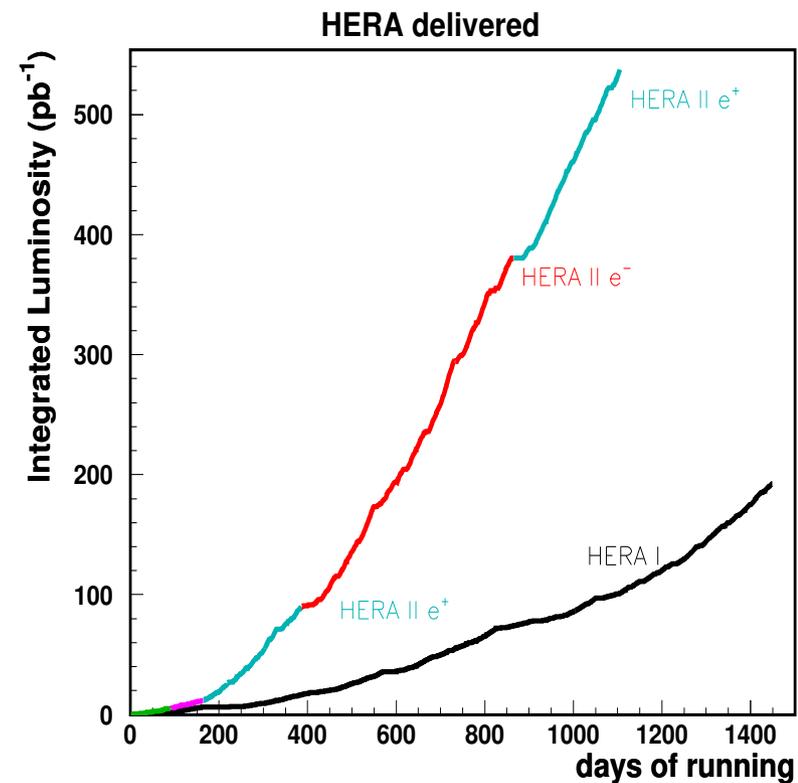
HERA delivered

HERA II e^+

HERA II e^-

HERA II e^+

HERA I

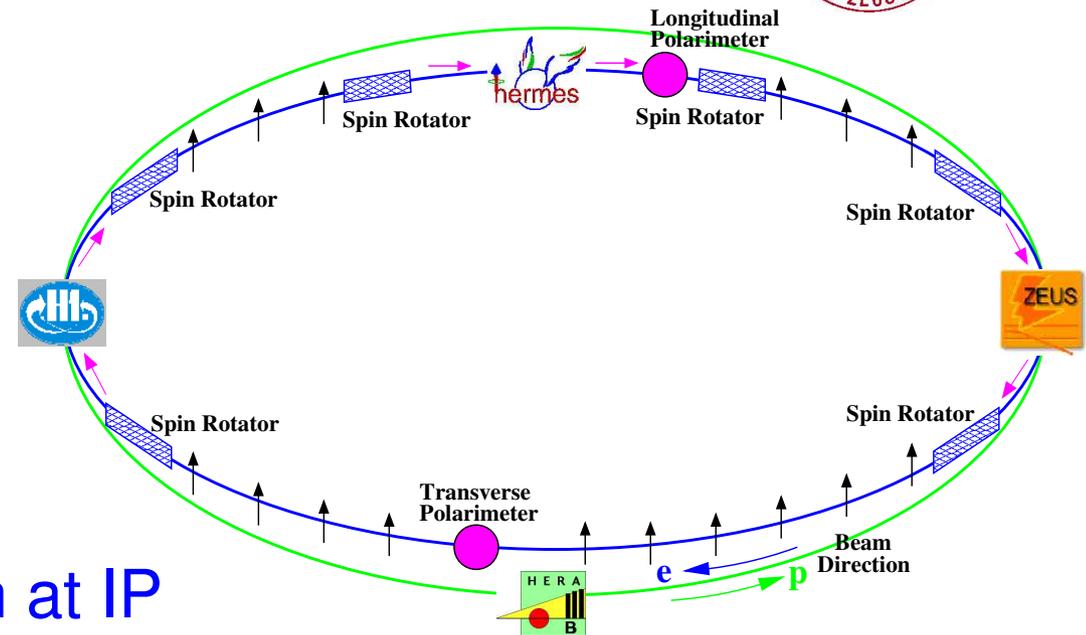Integrated Luminosity (pb^{-1})

days of running

co Uta Klein

Introduction

HERA II

Through the emission of synchrotron radiation electron beam at HERA becomes transversely polarized

Spin Rotators installed to obtain longitudinal polarization at IP

Introduction

HERA II

Through the emission of synchrotron radiation electron beam at HERA becomes transversely polarized

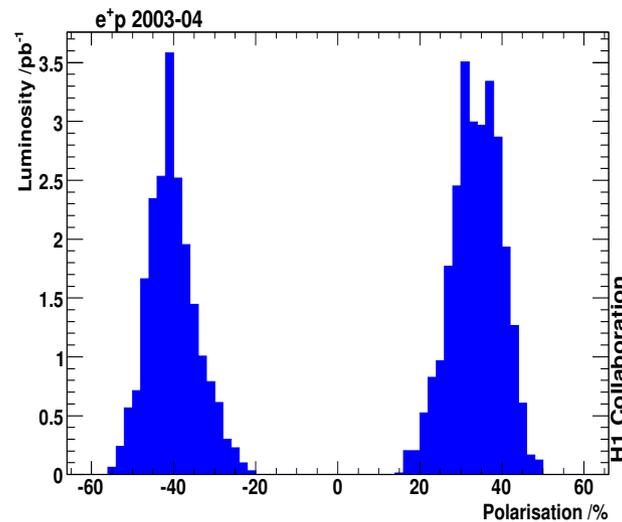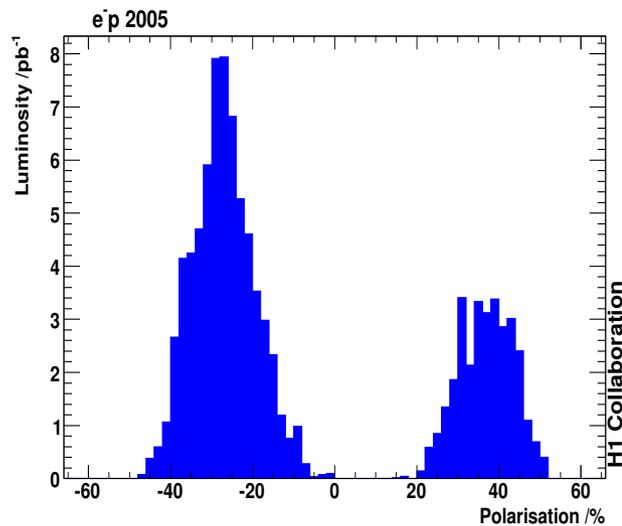Spin Rotators installed
to obtain longitudinal polarization at IP

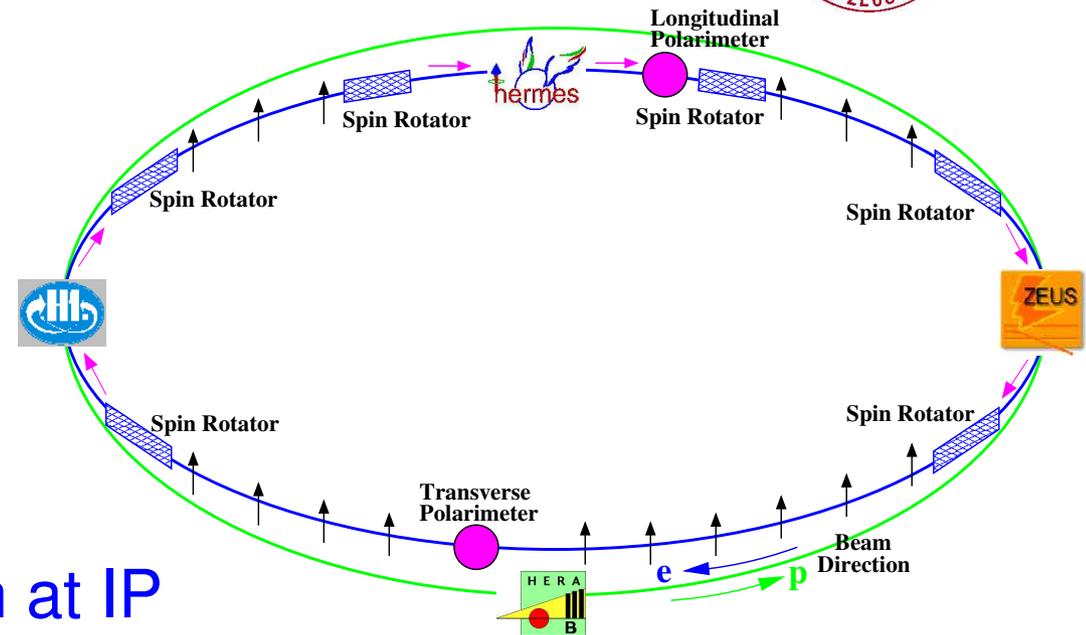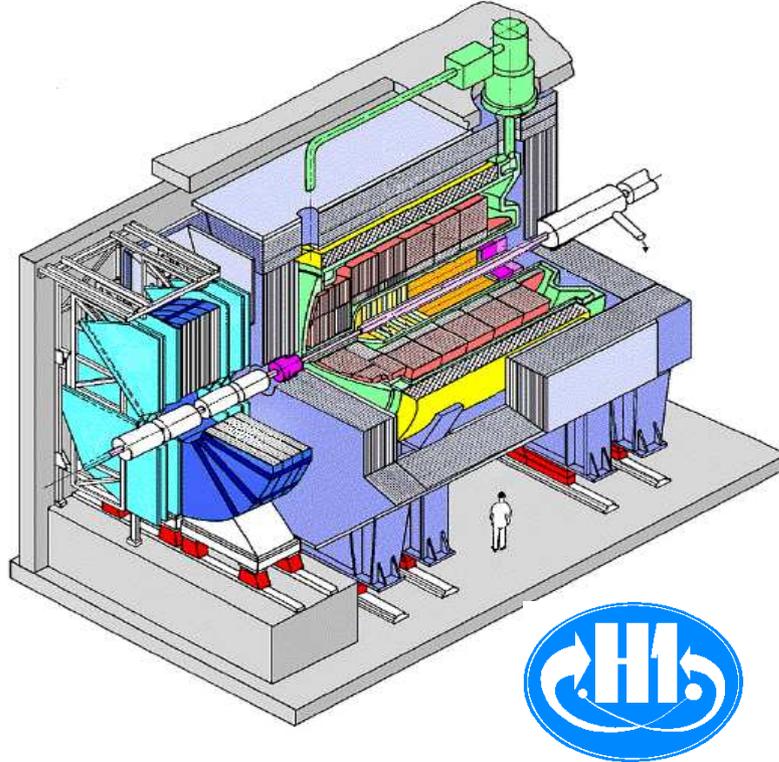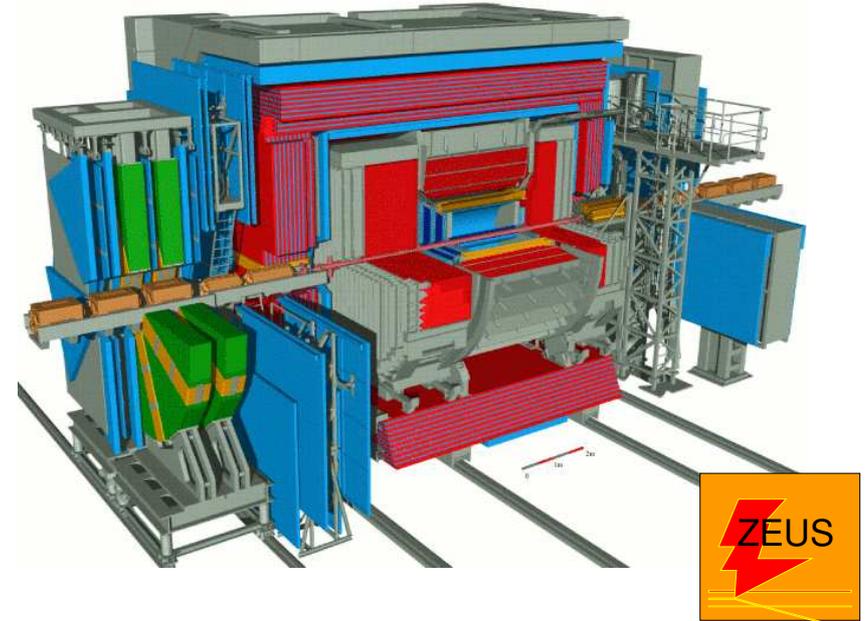Polarization measured in dedicated polarimeters
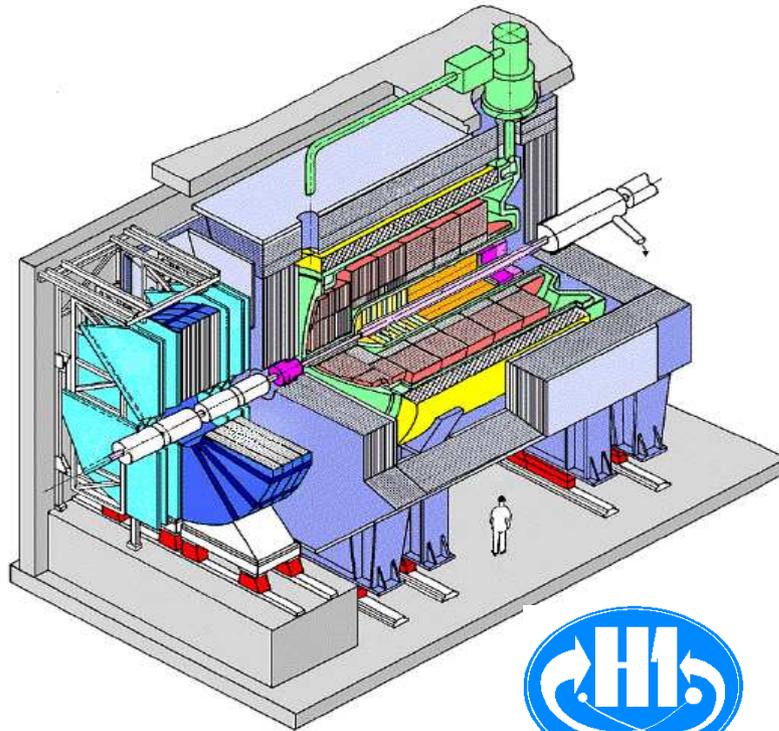
Average polarization
30-40%

Introduction

H1

ZEUS

Two omni-purpose detectors

Both equipped with silicon tracking, drift chambers, hermetic calorimetry and muon detector system

Introduction

H1
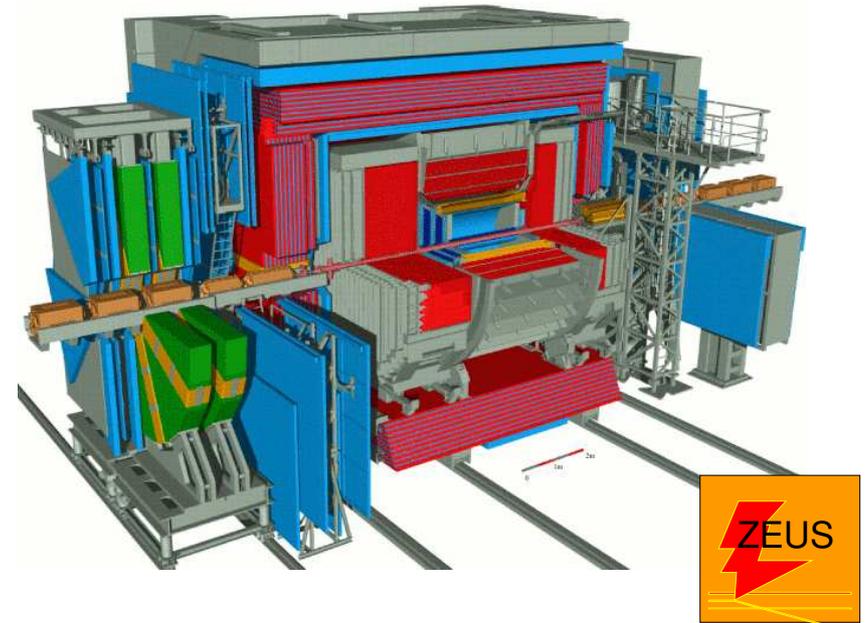

ZEUS

Fine-grained LAr calorimeter:

$$\sigma_E/E \quad = \quad 12\%/\sqrt{E} \oplus 1\% \quad (\text{ele})$$

$$\sigma_E/E \quad = \quad 55\%/\sqrt{E} \oplus 1\% \quad (\text{had})$$

Backward lead-scintillator calorimeter:

$$\sigma_E/E \quad = \quad 7\%/\sqrt{E} \oplus 1\% \quad (\text{ele})$$

Uranium-scintillator calorimeter:

$$\sigma_E/E \quad = \quad 18\%/\sqrt{E} \quad (\text{ele})$$

$$\sigma_E/E \quad = \quad 35\%/\sqrt{E} \quad (\text{had})$$

Deep Inelastic $e^{\pm}p$ Scattering

Main process studied at H1 and ZEUS

Scattering of electron/positron off proton with:

- large four-momentum transfer and
- large invariant mass of hadronic final state.

In the QPM it is described by exchange of gauge boson between lepton and quark.

Kinematic variables:

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

$$x = \frac{Q^2}{2P \cdot (k - k')}$$

$$y = \frac{P \cdot (k - k')}{P \cdot k}$$

|virtuality| of the exchanged boson

$\Rightarrow$ spatial resolution $\lambda \sim 1/Q$

$\Rightarrow$ sensitivity to mass scales $\Lambda \sim Q$
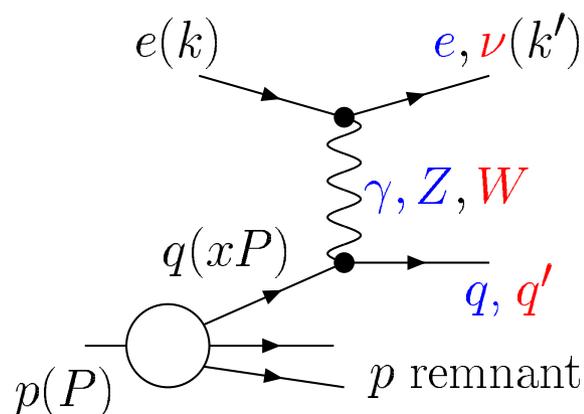
Deep Inelastic $e^{\pm}p$ Scattering

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$$x = \frac{Q^2}{2P \cdot (k - k')}$$

fraction of proton momenta carried by stuck quark

$\Rightarrow eq$ invariant mass $M_{eq} = \sqrt{x \cdot s}$

$$y = \frac{P \cdot (k - k')}{P \cdot k}$$

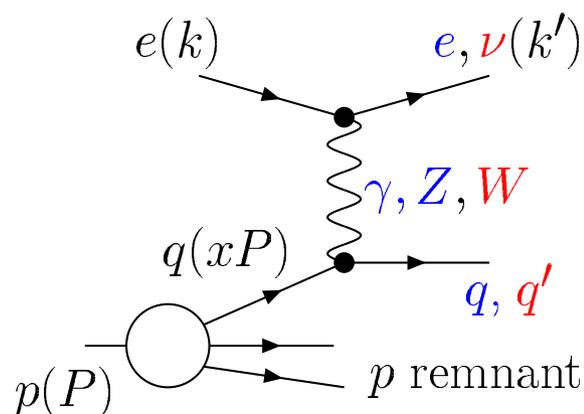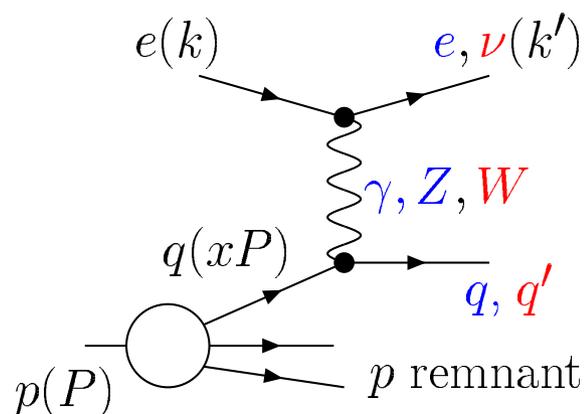# Deep Inelastic $e^{\pm}p$ Scattering

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$$y = \frac{P \cdot (k - k')}{P \cdot k}$$

fraction of lepton energy transfered in the proton rest frame

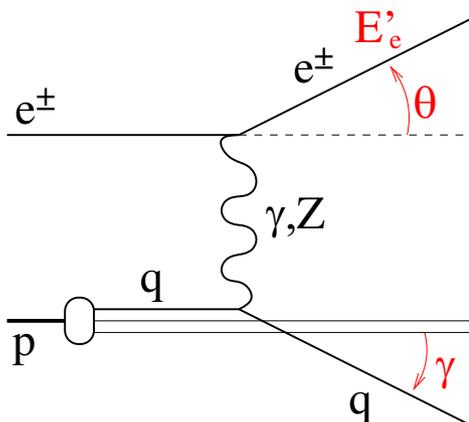$\Rightarrow$ scattering angle in the eq CMS

Deep Inelastic $e^{\pm}p$ Scattering

NC DIS (Neutral Currents)

γ/Z° exchange:

Scattered lepton AND current jet measured in the final state.

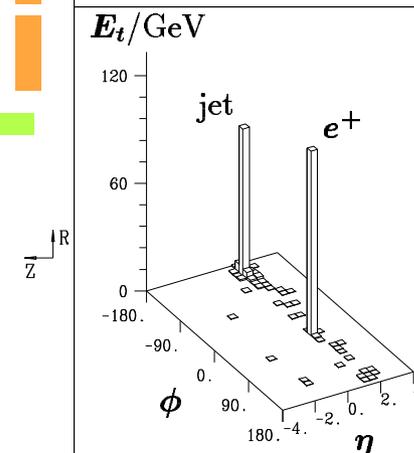Kinematic Reconstruction

- electron: E'_e, θ H1

H1   Run 122145   Event 69506   Date 19/09/1995

$Q^2 = 25030 \text{ GeV}^2, \quad y = 0.56, \quad M = 211 \text{ GeV}$
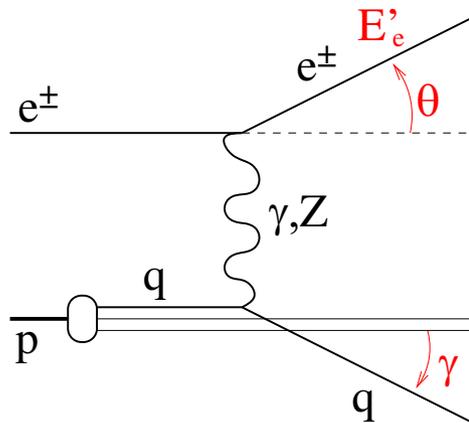
E_t/GeV

jet

e^+

Deep Inelastic $e^{\pm}p$ Scattering

NC DIS   (Neutral Currents)

γ/Z° exchange:

Scattered lepton AND current jet measured in the final state.
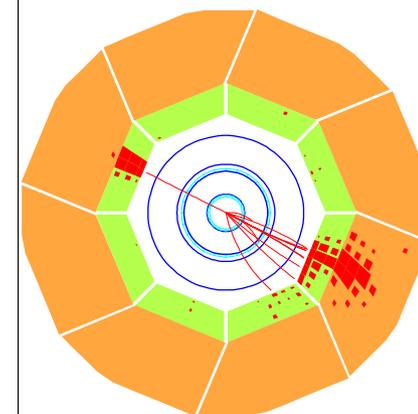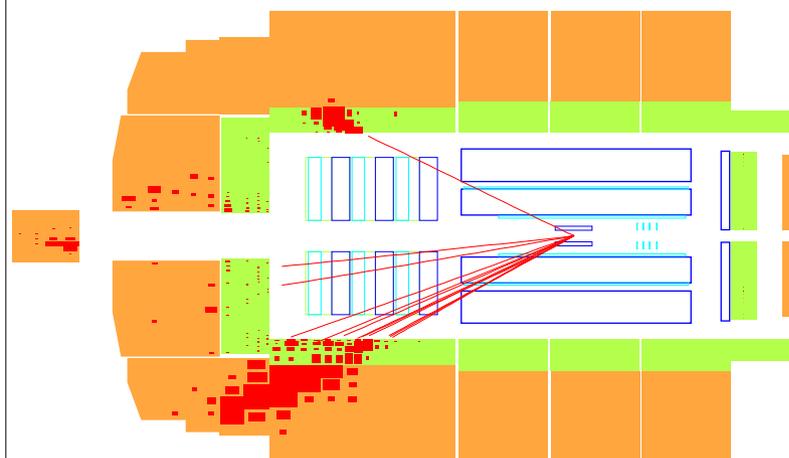
Kinematic Reconstruction

- electron: E'_e, θ H1

- angles: θ, γ ZEUS

Deep Inelastic $e^{\pm}p$ Scattering

CC DIS (Charged Currents)

$W^{\pm}$ exchange:

Only current jet
measured in the final state.

Kinematic Reconstruction

- hadronic final state
  $\Rightarrow E_j,\ \gamma$

Run 221734   Event 6105   Class: 26   Date 12/10/1998

...just from the HOTLINE

Q**2 = 21475   y = 0.55   M = 198

Deep Inelastic $e^{\pm}p$ Scattering

CC DIS   (Charged Currents)
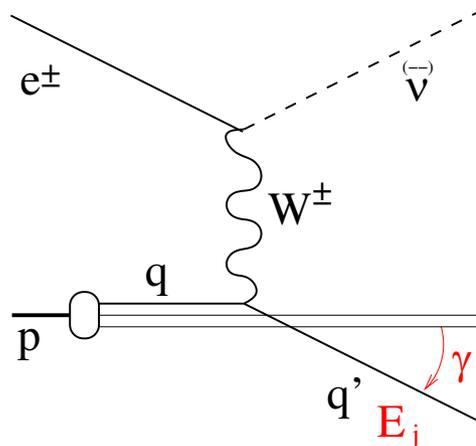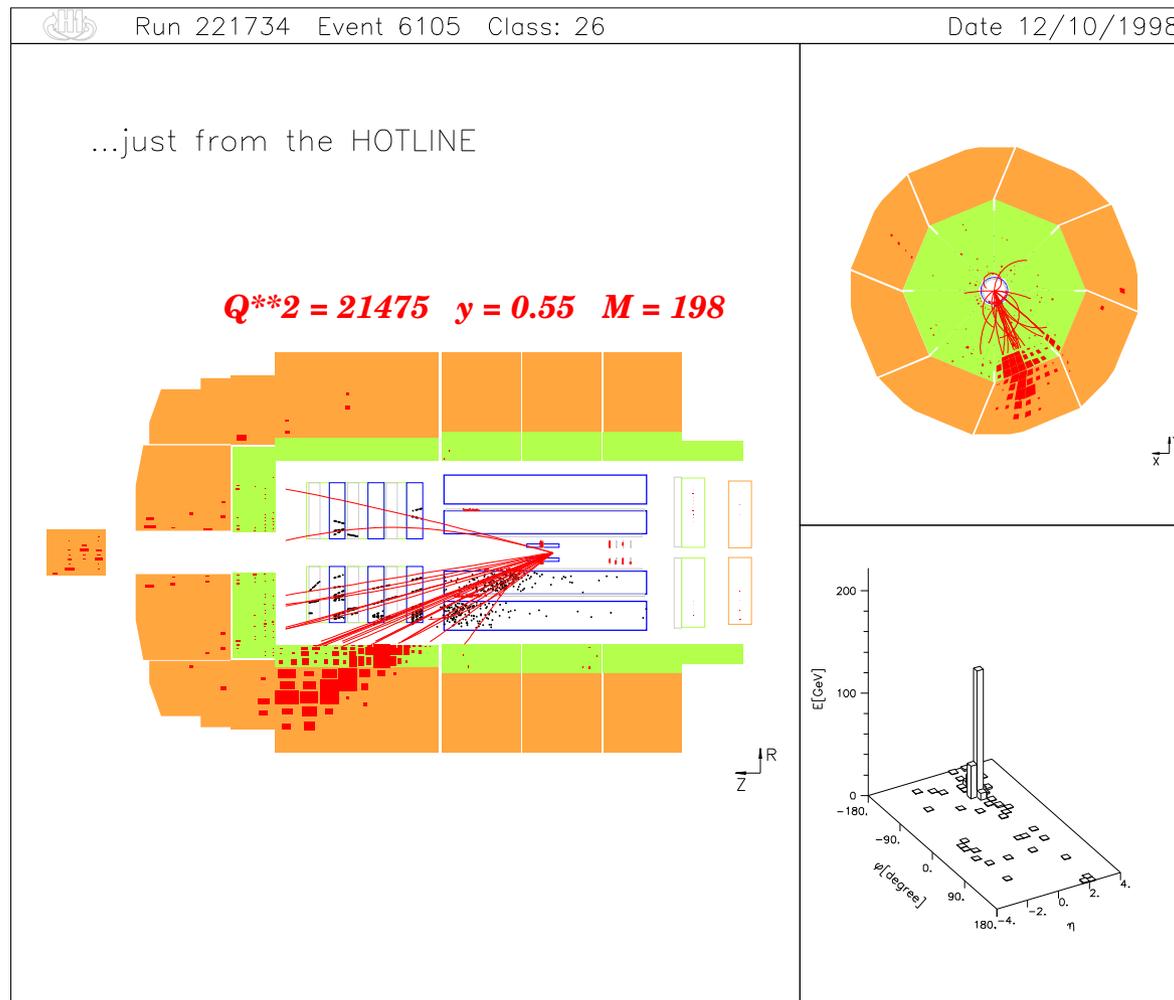
$W^{\pm}$ exchange:

Only current jet
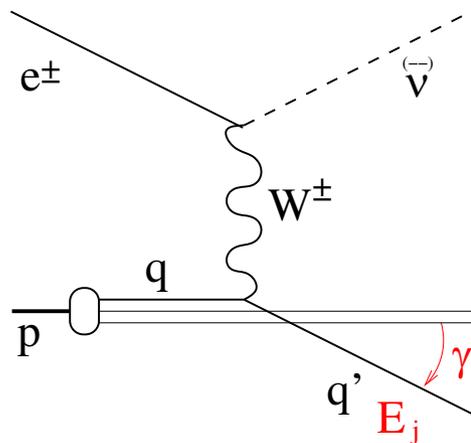measured in the final state.

Kinematic Reconstruction

- hadronic final state
  $\Rightarrow E_j, \gamma$
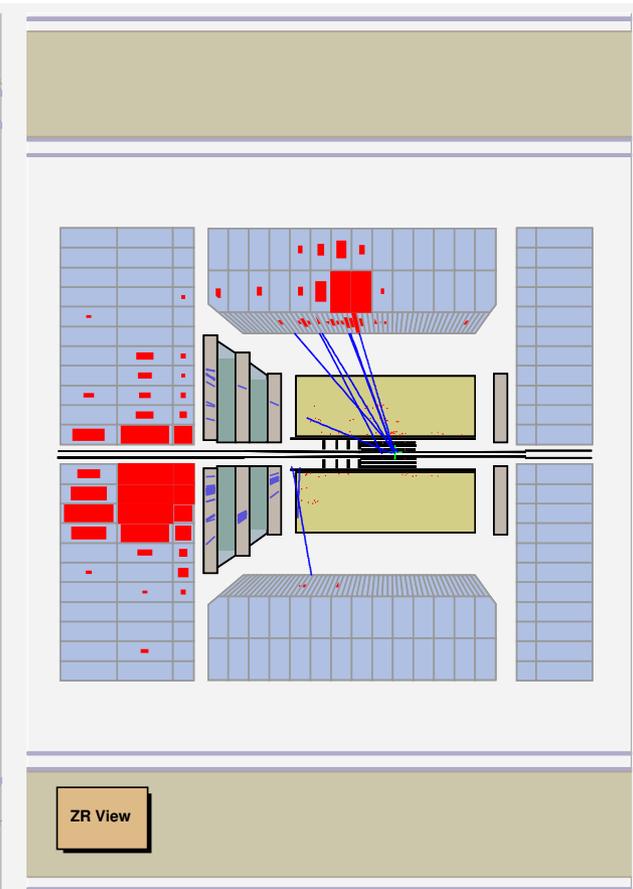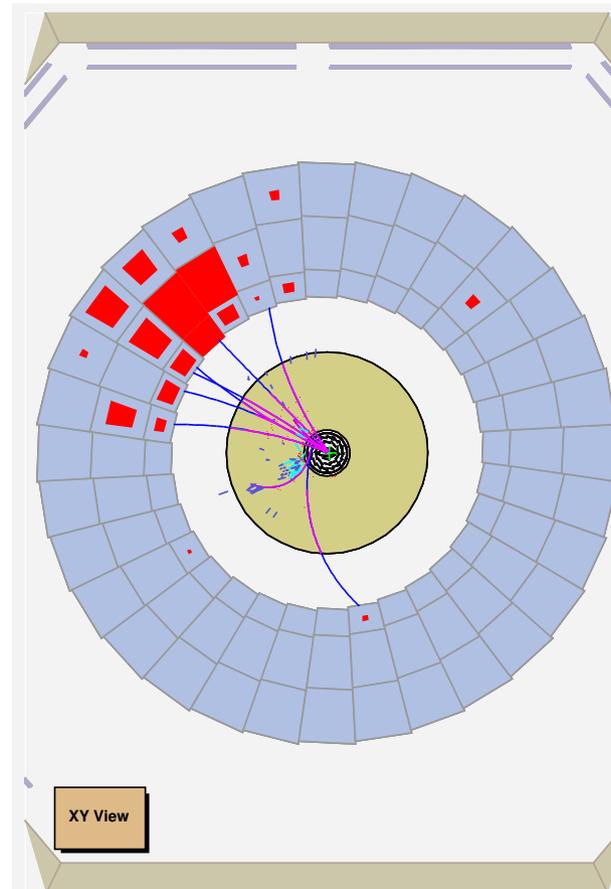
Deep Inelastic $e^{\pm}p$ Scattering

High Q^2 NC & CC DIS

HERA II

Contribution from weak boson exchange become important for:

$$Q^2 \quad \sim \quad M_Z^2, \, M_W^2$$

Electroweak "unification"
NC & CC comparable in size

Charge asymmetry in NC DIS:
difference between e^+p and e^-p

Excellent agreement with Standard
Model prediction over many orders
of magnitude
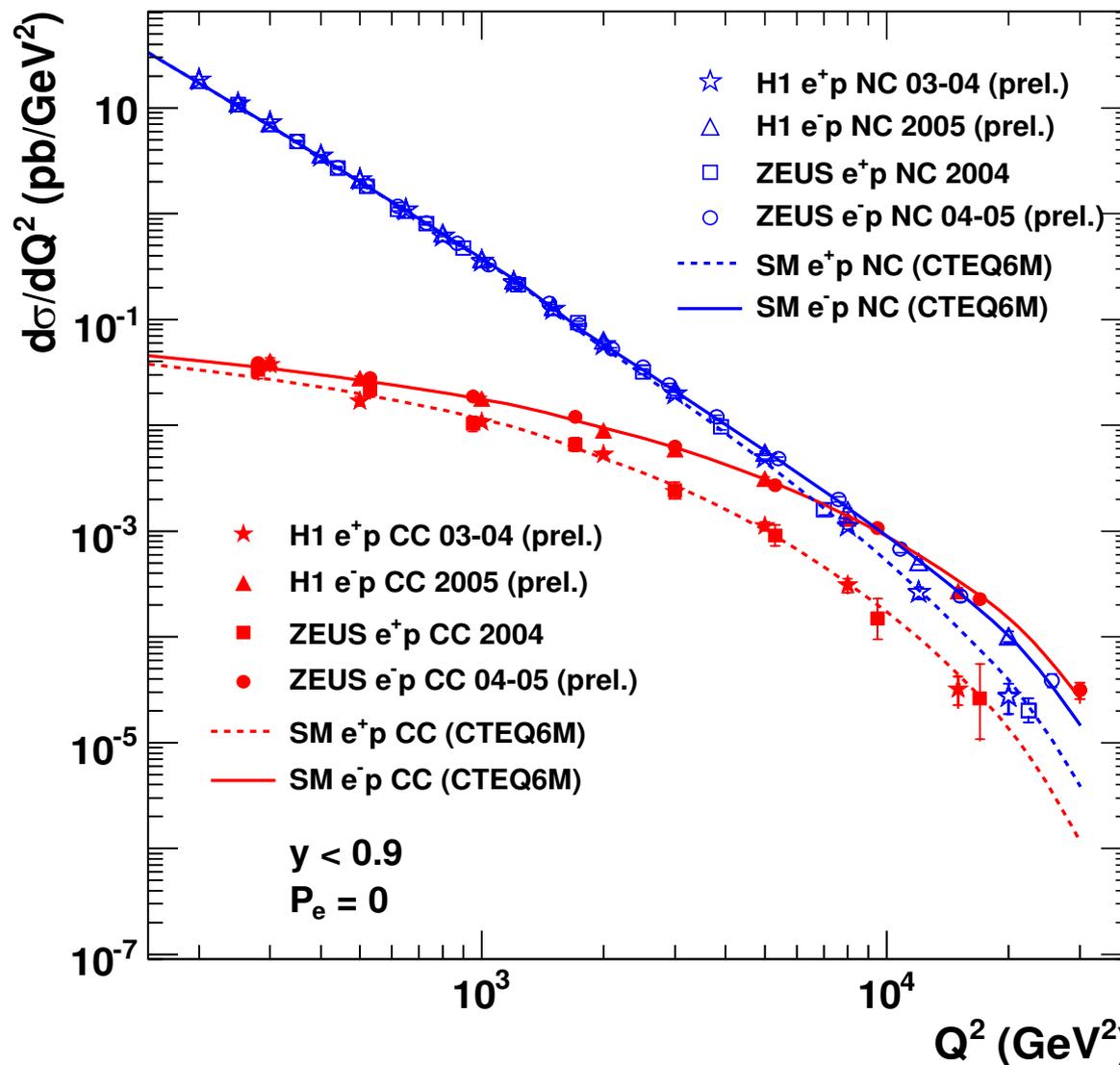
Legend within plot:
- ☆ H1 e^+p NC 03-04 (prel.)
- △ H1 e^-p NC 2005 (prel.)
- □ ZEUS e^+p NC 2004
- ○ ZEUS e^-p NC 04-05 (prel.)
- - - SM e^+p NC (CTEQ6M)
- —— SM e^-p NC (CTEQ6M)

- ★ H1 e^+p CC 03-04 (prel.)
- ▲ H1 e^-p CC 2005 (prel.)
- ■ ZEUS e^+p CC 2004
- ● ZEUS e^-p CC 04-05 (prel.)
- - - SM e^+p CC (CTEQ6M)
- —— SM e^-p CC (CTEQ6M)

y < 0.9
$P_e = 0$

dσ/dQ^2 (pb/GeV^2) — Q^2 (GeV^2)

Electroweak studies

High Q^2 NC DIS cross section, neglecting contributions from F_L

$$\frac{d^2\sigma^{\mathrm{NC}}(e^{\pm}p)}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+ F_2^0 \mp Y_- xF_3^0\right]$$

where: $Y_{\pm} = 1 \pm (1-y)^2$

Unpolarized structure functions:

$$F_2^0 = \sum_q x(q+\bar{q})\left(e_q^2 - 2e_q v_q v_e P_Z + (v_q^2 + a_q^2)(v_e^2 + a_e^2)P_Z^2\right)$$

$$xF_3^0 = \sum_q x(q-\bar{q})\left(-2e_q a_q a_e P_Z + 4v_q a_q v_e a_e P_Z^2\right)$$

$\Rightarrow$ Measurement of xF_3^0 sensitive to axial quark couplings, a_q.

$$P_Z = \frac{1}{\sin^2 2\theta_W}\left(\frac{Q^2}{M_Z^2 + Q^2}\right)$$

Electroweak studies

High Q^2 NC DIS cross section, neglecting contributions from F_L

$$\frac{d^2\sigma^{\mathrm{NC}}(e^\pm p)}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+F_2^0 \mp Y_-xF_3^0 + P_e\left(Y_+F_2^P \mp Y_-xF_3^P\right)\right]$$

where: $Y_\pm = 1 \pm (1-y)^2$

Polarized structure functions: P_e - lepton beam polarization

$$F_2^P = \sum_q x(q+\bar{q})\left(2e_qv_qa_eP_Z - 2(v_q^2+a_q^2)v_ea_eP_Z^2\right)$$

$$xF_3^P = \sum_q x(q-\bar{q})\left(2e_qa_qv_eP_Z - 2v_qa_q(v_e^2+a_e^2)P_Z^2\right)$$

$\Rightarrow$ Measurement of xF_3^0 sensitive to axial quark couplings, a_q.

$\Rightarrow$ Measurement of F_2^P sensitive to vector quark couplings, v_q.

$$P_Z = \frac{1}{\sin^2 2\theta_W}\left(\frac{Q^2}{M_Z^2+Q^2}\right)$$
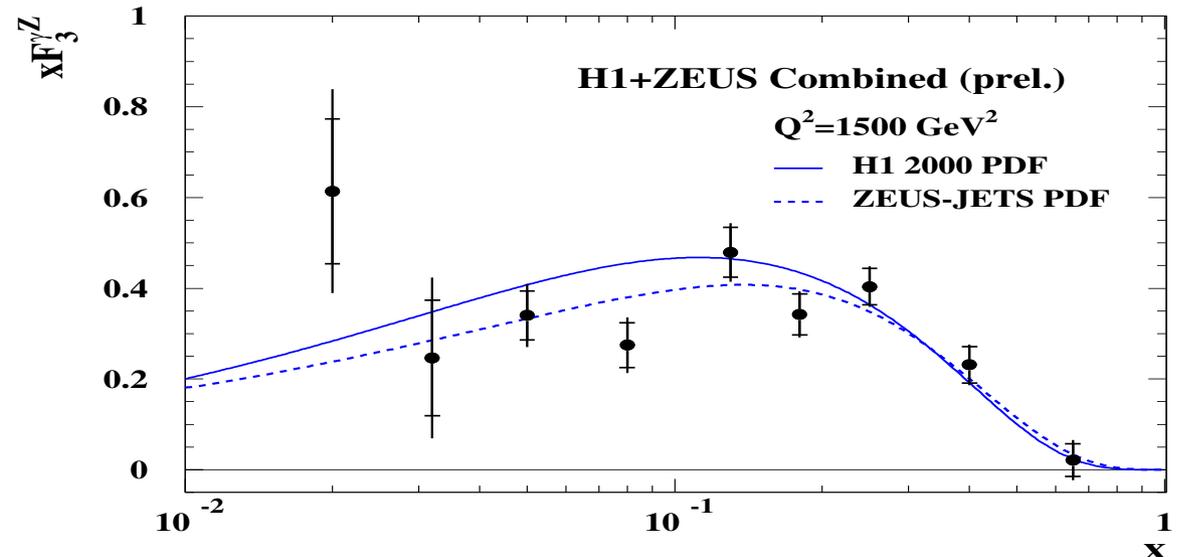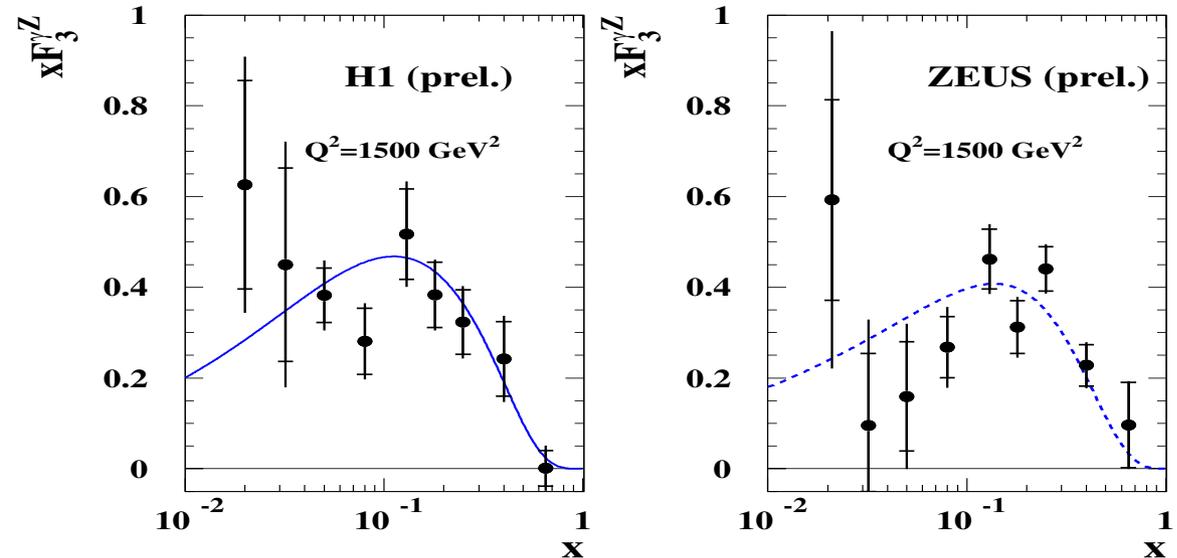
Electroweak studies

HERA I + HERA II

Combined measurement of the proton structure function $xF_3^0(x, Q^2)$

Assuming SM couplings:

$$xF_3^0 \approx \left(\frac{2}{3}u_v + \frac{1}{3}d_v\right) xP_Z$$

⇒ can be used to constrain valence quark densities

Electroweak studies

HERA II

Combined measurement of NC DIS polarization asymmetries:

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

Direct measurement of parity violation due to $\gamma - Z$ interference.
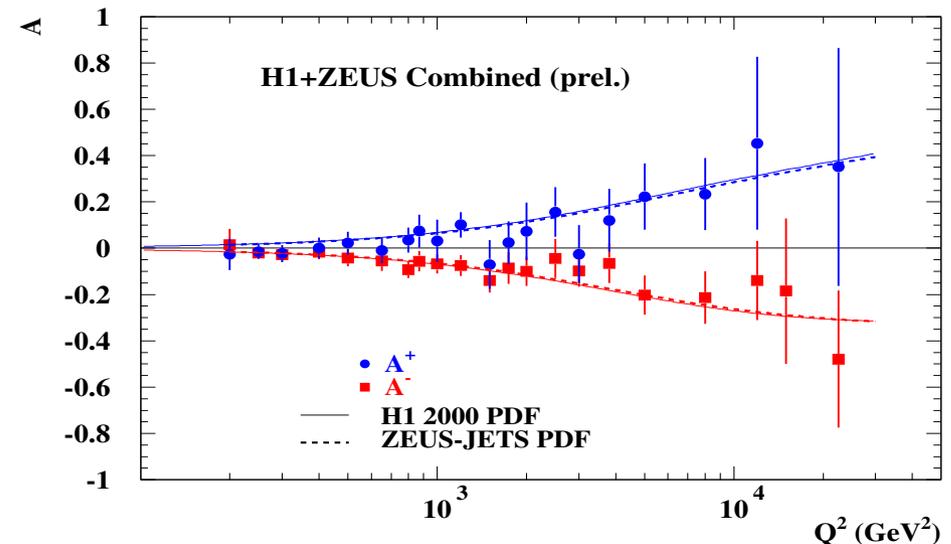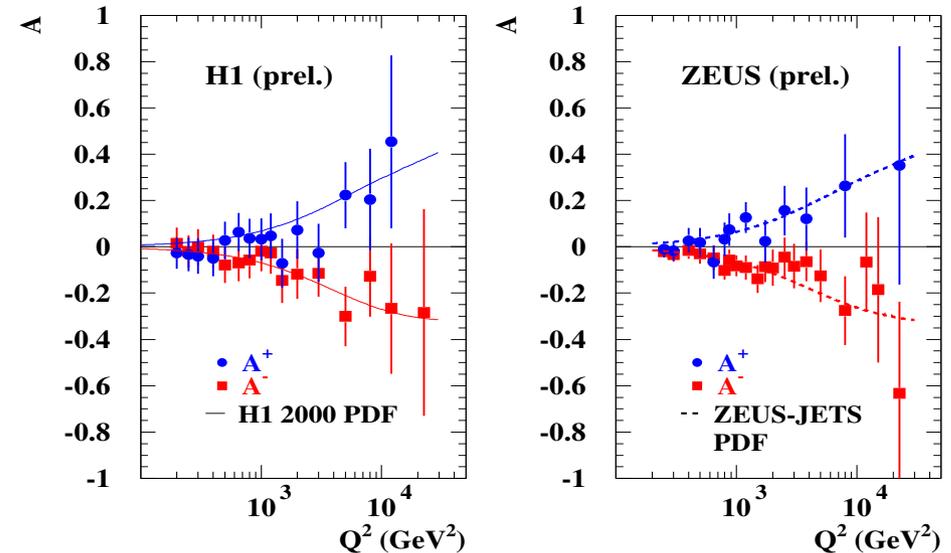
To the first approximation

$$A^{\pm} \;\; = \;\; \frac{F_2^P}{F_2^0}$$

At high-x, assuming SM couplings:

$$A^{\pm} \;\; \sim \;\; \frac{u_v + d_v}{4u_v + d_v}$$

$\Rightarrow$ can be used to constrain d/u ratio

HERA

Electroweak studies

HERA I + HERA II

Measurement of the polarization dependence of CC DIS

$$\frac{d^2\sigma^{e^\pm p}}{dxdQ^2} = (1 \pm P_e)\frac{G_F^2}{4\pi x}\left(\frac{M_W^2}{M_W^2 + Q^2}\right)^2$$

$$\times \begin{cases} x\left[u + c + (1-y)^2(\bar{d} + \bar{s} + \bar{b})\right] \\ \qquad\qquad\qquad\qquad for \quad e^- p \\ x\left[(1-y)^2(d + s + b) + \bar{u} + \bar{c}\right] \\ \qquad\qquad\qquad\qquad for \quad e^+ p \end{cases}$$

$\Rightarrow$ independent constraints on u and d densities at high x

Charged Current $e^\pm p$ Scattering

$e^- p \to \nu X$
- H1 Data 2005 (prel.)
- H1 Data 98-99
- ZEUS Data 04-05(prel.)
- ZEUS Data 98-99

$e^+ p \to \bar{\nu}X$
- H1 Data
- ZEUS Data

SM (H1 PDF 2000)

$Q^2 > 400$ GeV^2

$y < 0.9$
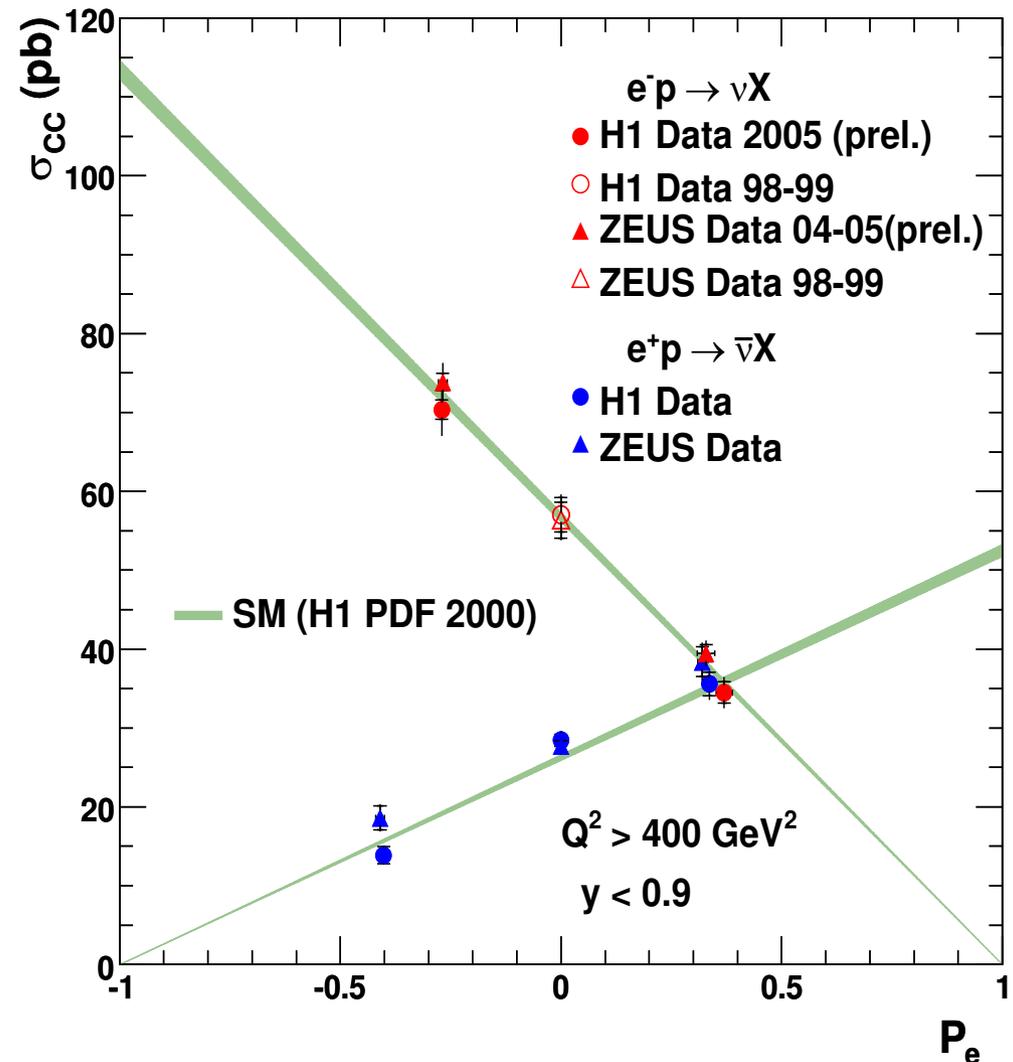
Electroweak studies

HERA I

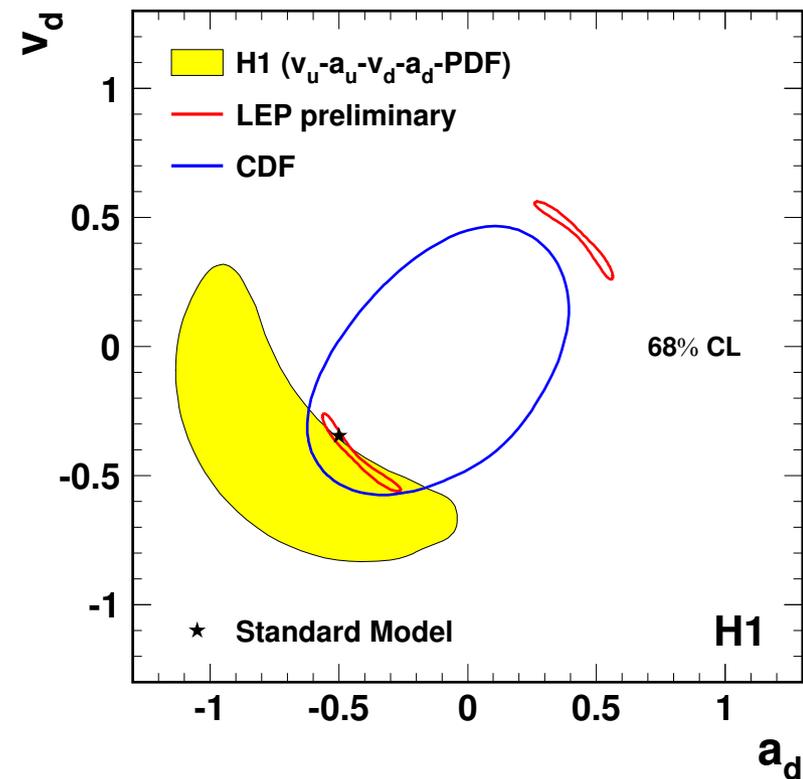Combined QCD and Electroweak analysis of H1 data only.

High precision of NC and CC DIS measurements allows for simultaneous determination of PDFs and electroweak parameters:
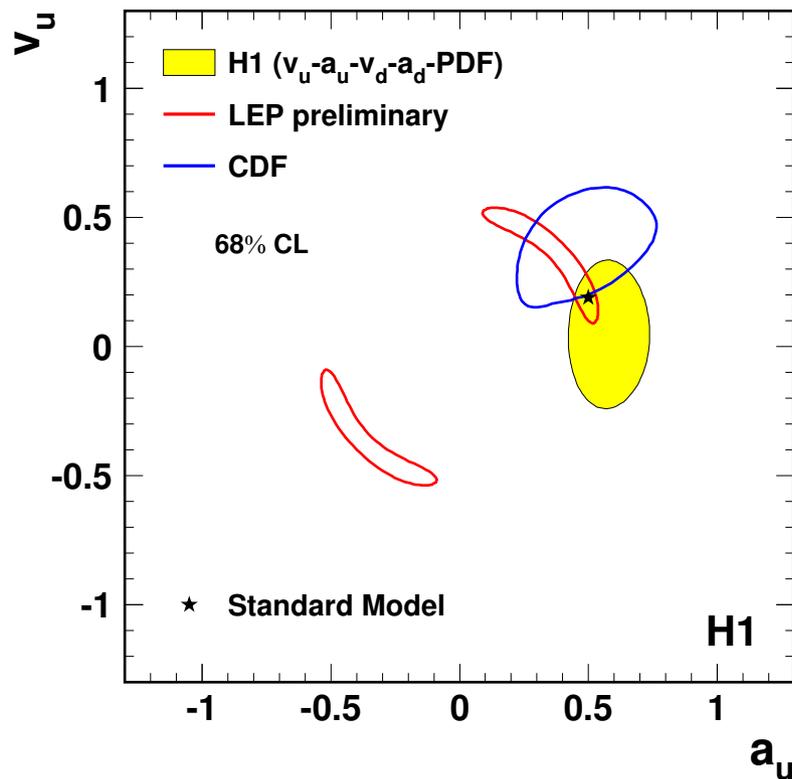
$\Rightarrow$ Precision of light quark coupling determination similar to Tevatron
No sign ambiguity.

Electroweak studies

HERA I + HERA II

Combined QCD and Electroweak analysis of ZEUS data.

Much higher statistics of e^-p data (xF_3 / a_q) and lepton beam polarization (F_2^P / v_q)
$\Rightarrow$ significant improvement of coupling determination
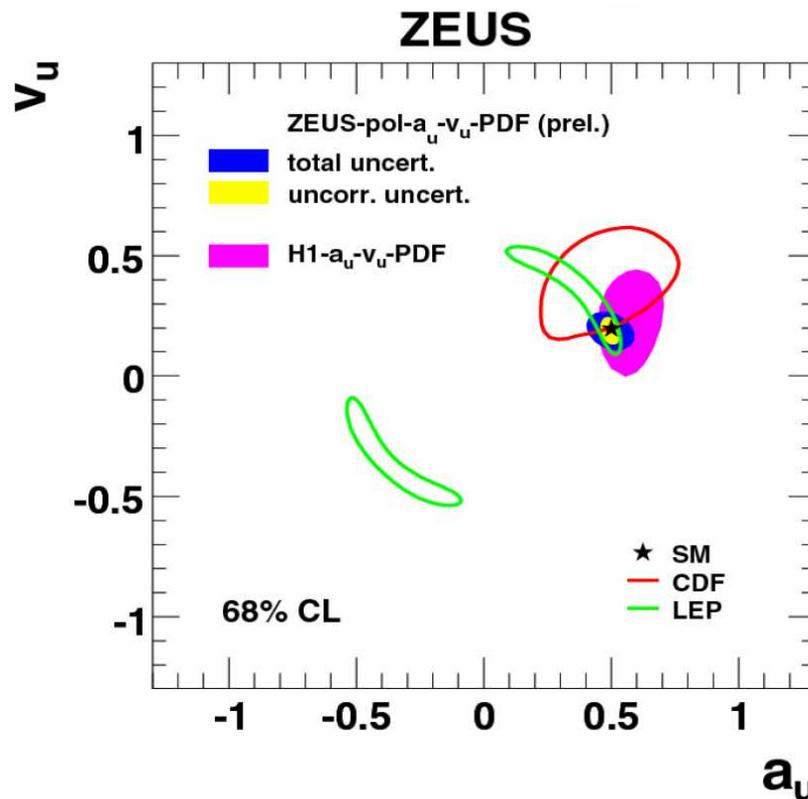
Results consistent with SM predictions, precision comparable with LEP.

Searches for new phenomena
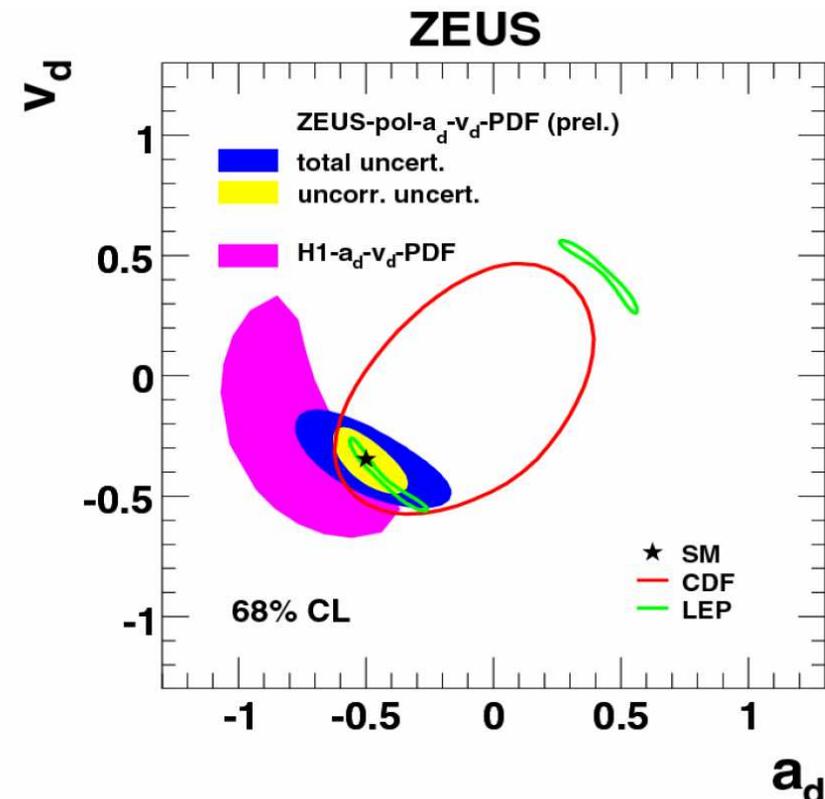
Contact Interactions

Possible "new physics" in NC DIS:
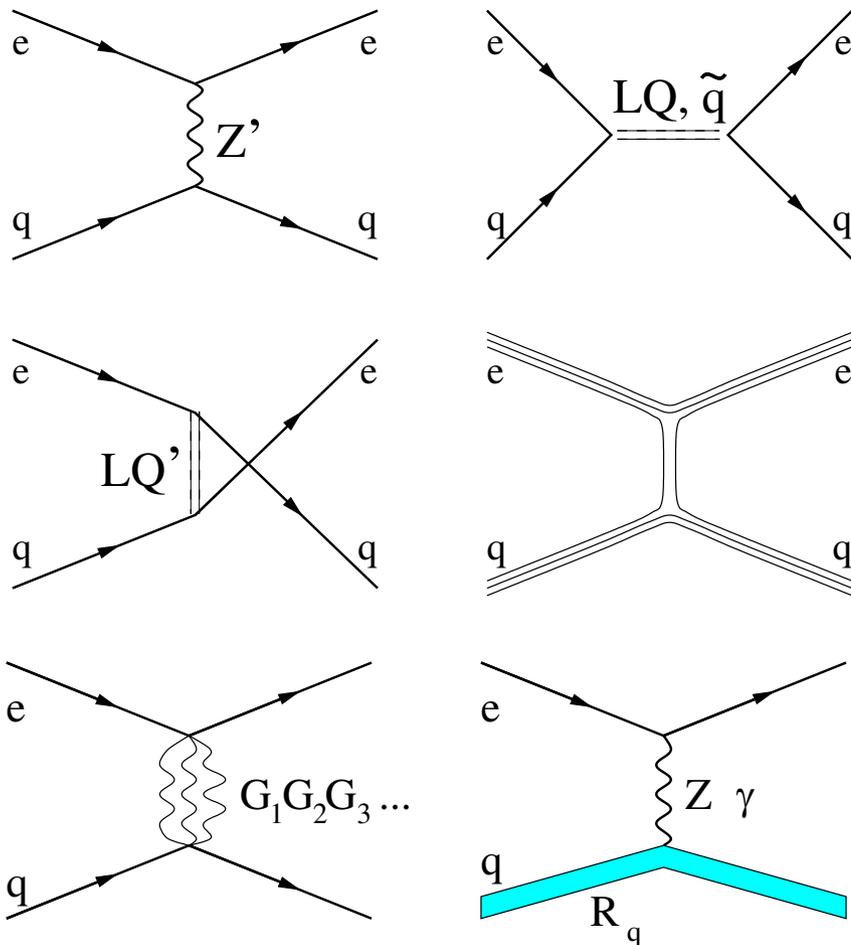
For $\sqrt{s}$ much smaller than process scale Λ
$\Rightarrow$ effective parameterization:
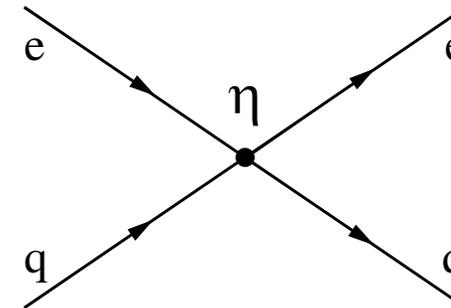
$eeqq$ contact interactions (CI)

Contribution to the NC cross-section:

$$\frac{d\sigma}{dx\,dQ^2}(\eta) = $$

$$\frac{d\sigma^{SM}}{dx\,dQ^2} \cdot \left[1 + A(x, Q^2)\,\eta + B(x, Q^2)\,\eta^2 \right]$$

General formula for all CI type models

Searches for new phenomena

Compositeness models

ZEUS analysis of HERA I + HERA II data

Contact interaction coupling given by

$$\eta \;\; = \;\; \pm \frac{4\pi}{\Lambda^2}$$

where: Λ - compositeness scale

Limits on Λ determined from
Q^2 distribution of NC DIS events

Compositeness models

ZEUS analysis of HERA I + HERA II data

Contact interaction coupling given by

$$\eta = \pm\frac{4\pi}{\Lambda^2}$$

where: Λ - compositeness scale

Limits on Λ determined from Q^2 distribution of NC DIS events

Limits range from 2.0 to 7.5 TeV

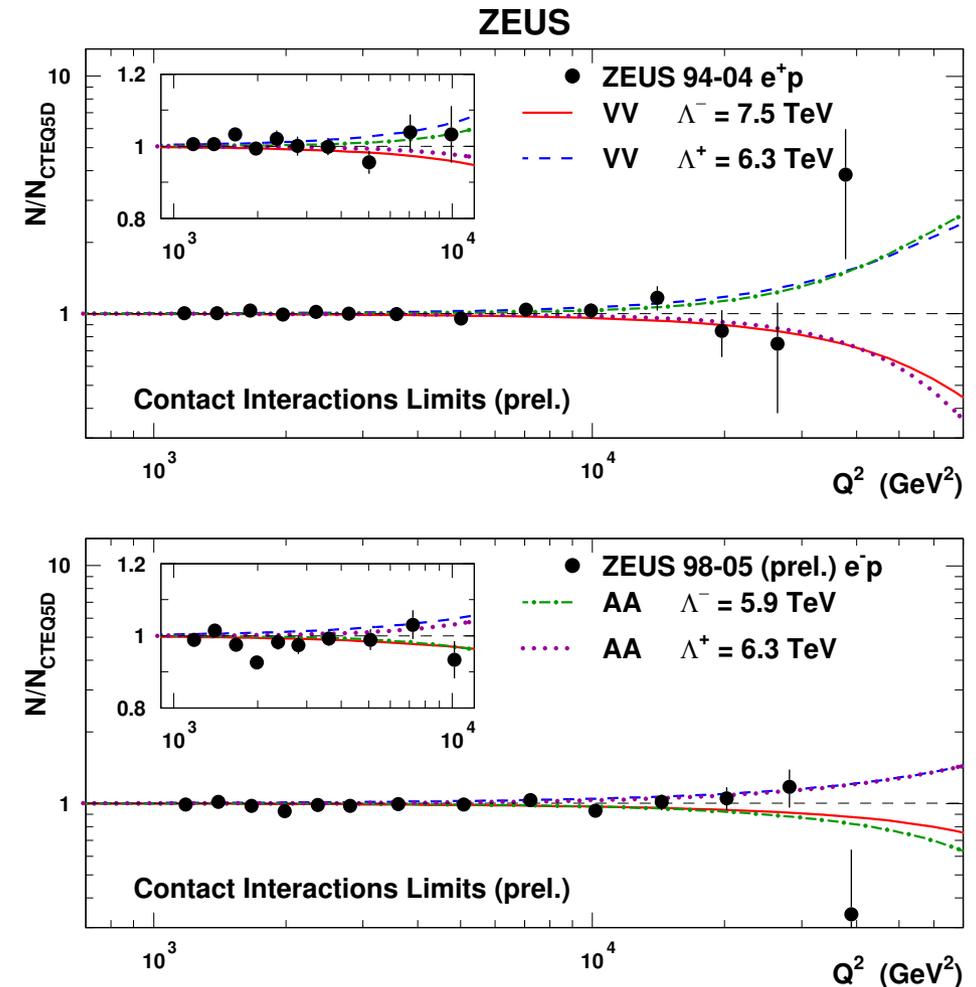Significant improvement from HERA II data

ZEUS

	94-00 e^+p	94-05 (prel.) e^+p
○	-1/Λ^2 best fit value	● +1/Λ^2 best fit value
—	allowed ±1/Λ^2 range	

	Λ^- (TeV)	Λ^+ (TeV)
VV	7.5	6.3
AA	5.9	6.3
VA	3.3	3.5
X1	4.3	4.7
X2	5.1	4.7
X3	5.9	5.3
X4	5.4	4.8
X5	5.1	4.5
X6	4.3	4.1
U1	5.2	5.5
U2	6.1	5.2
U3	7.1	6.1
U4	6.1	5.0
U5	6.2	5.0
U6	4.5	4.7
LL	4.2	4.2
LR	2.0	3.6
RL	2.3	3.6
RR	4.0	3.8

±1/Λ^2 (TeV^{-2})
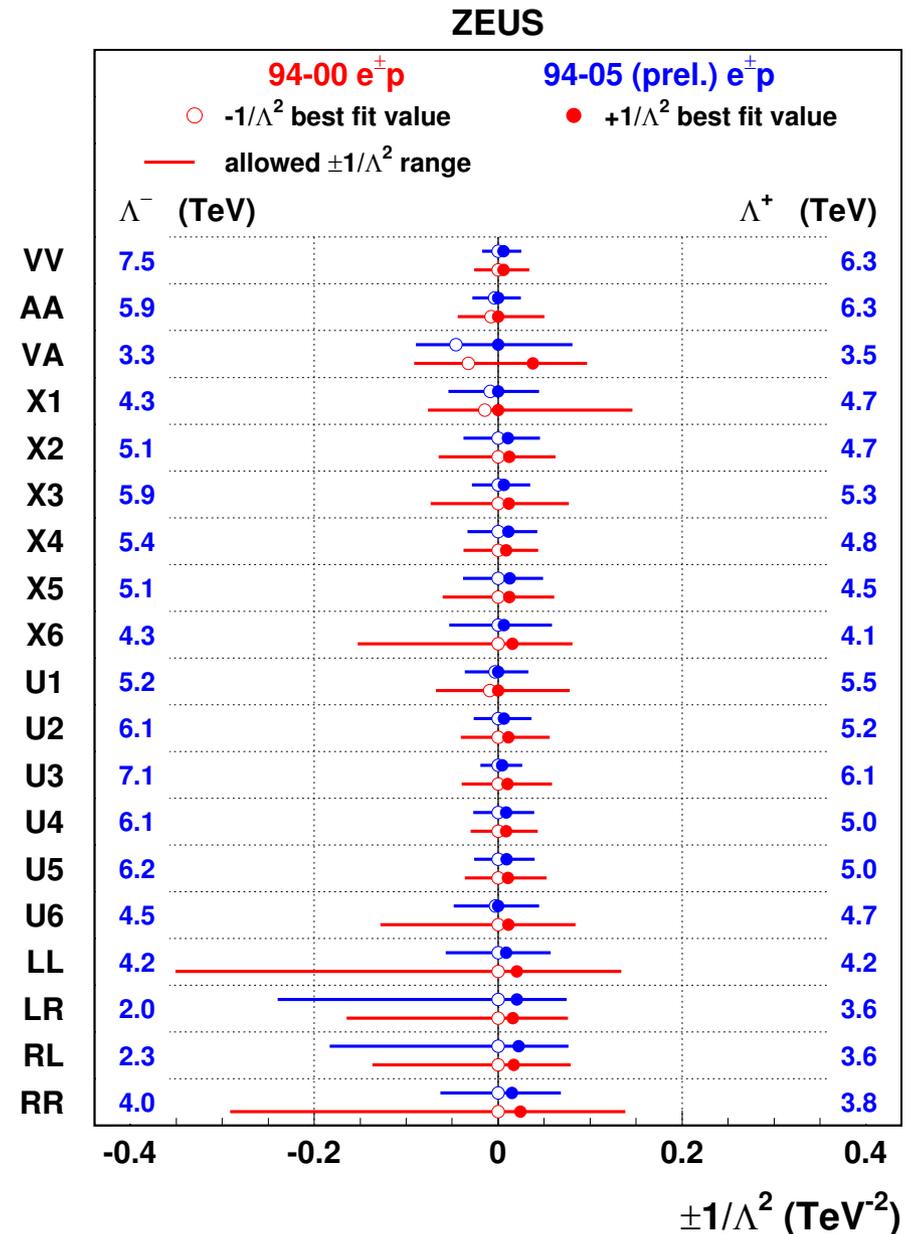
Searches for new phenomena

Large Extra Dimensions

Kaluza-Klein graviton exchange

$\Rightarrow$ CI with effective scale $\eta \sim s/M_S^4$

$$M_S^+ > 0.88 \text{ TeV}$$

Quark form factor
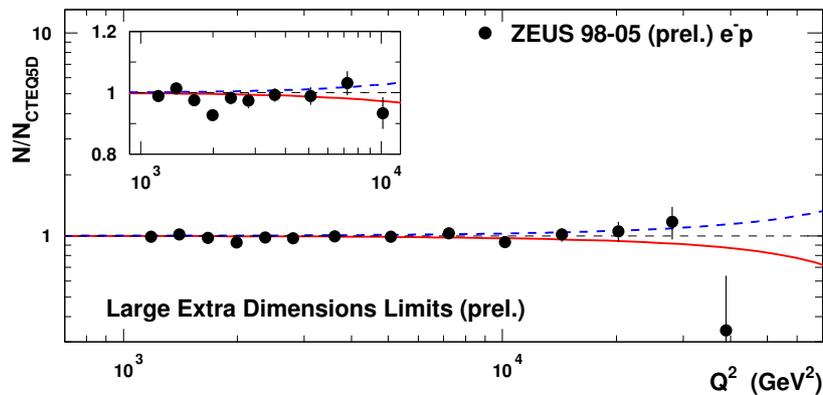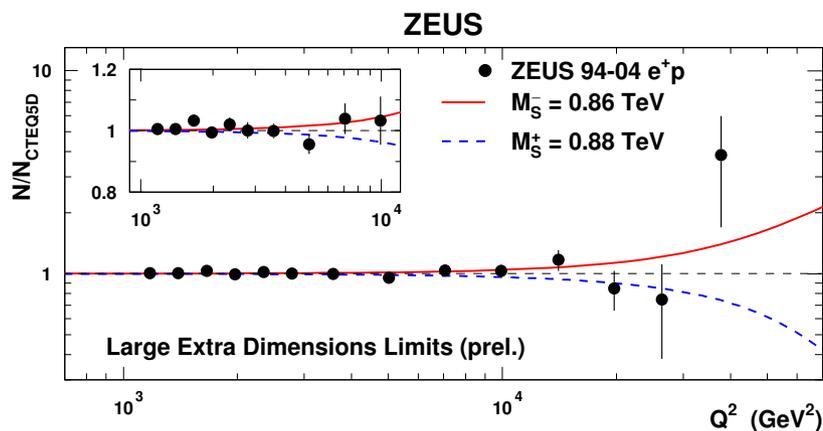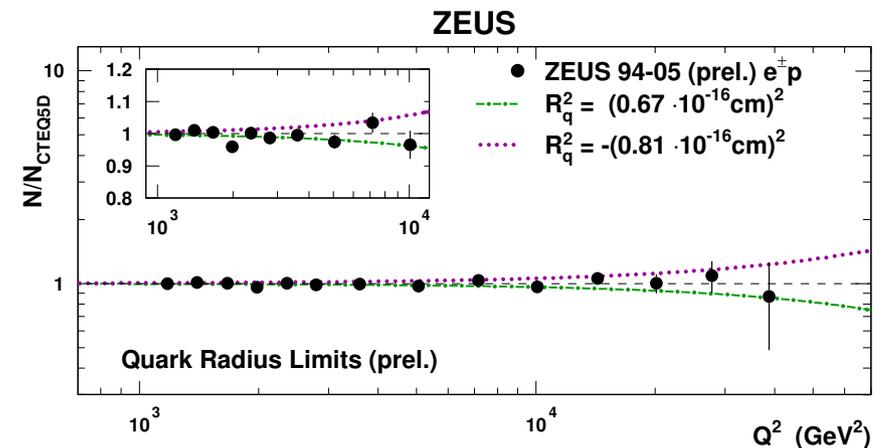
Semi-classical model: R_q - quark "radius"

$$\frac{d\sigma}{dQ^2} = \frac{d\sigma^{SM}}{dQ^2} \cdot \left[1 - \frac{R_q^2}{6} Q^2 \right]^2$$

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

Searches for new phenomena

Resonance production

Search for resonant states in eq scattering
leptoquarks or squarks in models
with R-parity violation

H1 analysis of HERA II data
factor 6 increase in e^-p luminosity

Invariant mass distribution for NC and CC DIS
in very good agreement with SM predictions

NC, P=-27%
H1 data (prelim.)
SM
SM uncertainty

Events / 20 GeV

M_{LQ} / GeV

CC, P=-27%
H1 data (prelim.)
SM
SM uncertainty
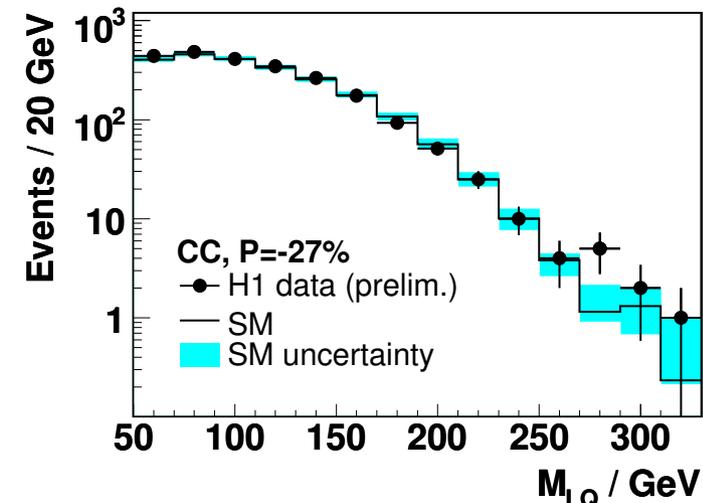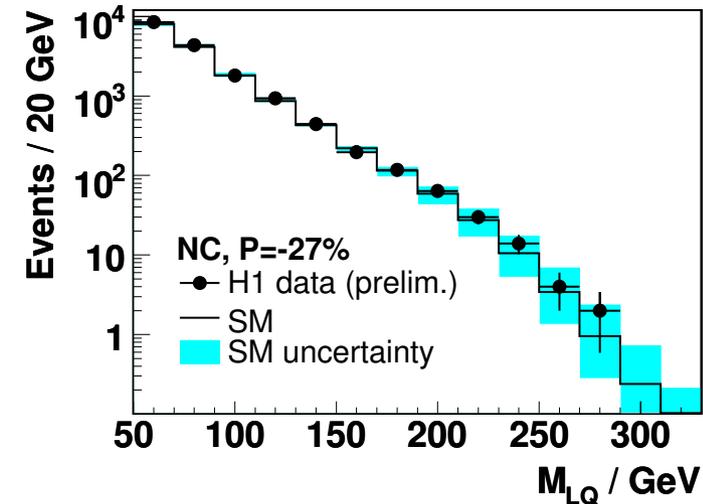
Events / 20 GeV

M_{LQ} / GeV

Searches for new phenomena

Resonance production

Search for resonant states in eq scattering
leptoquarks or squarks in models
with R-parity violation

H1 analysis of HERA II data
factor 6 increase in e^-p luminosity

Invariant mass distribution for NC and CC DIS
in very good agreement with SM predictions

$\Rightarrow$ Exclusion limits in mass-coupling plane

For electromagnetic coupling F=2 leptoquarks below 276-304 GeV excluded

Searches for new phenomena

Isolated leptons

Most prominent excess over SM observed in HERA ?
Events with isolated lepton and large missing transverse momentum:

$$p_T^e = 37 \text{ GeV} \qquad p_T^{had} = 29 \text{ GeV} \qquad p_T = 44 \text{ GeV}$$

Require also large acoplanarity $\Rightarrow$ significant suppression of SM background

Searches for new phenomena

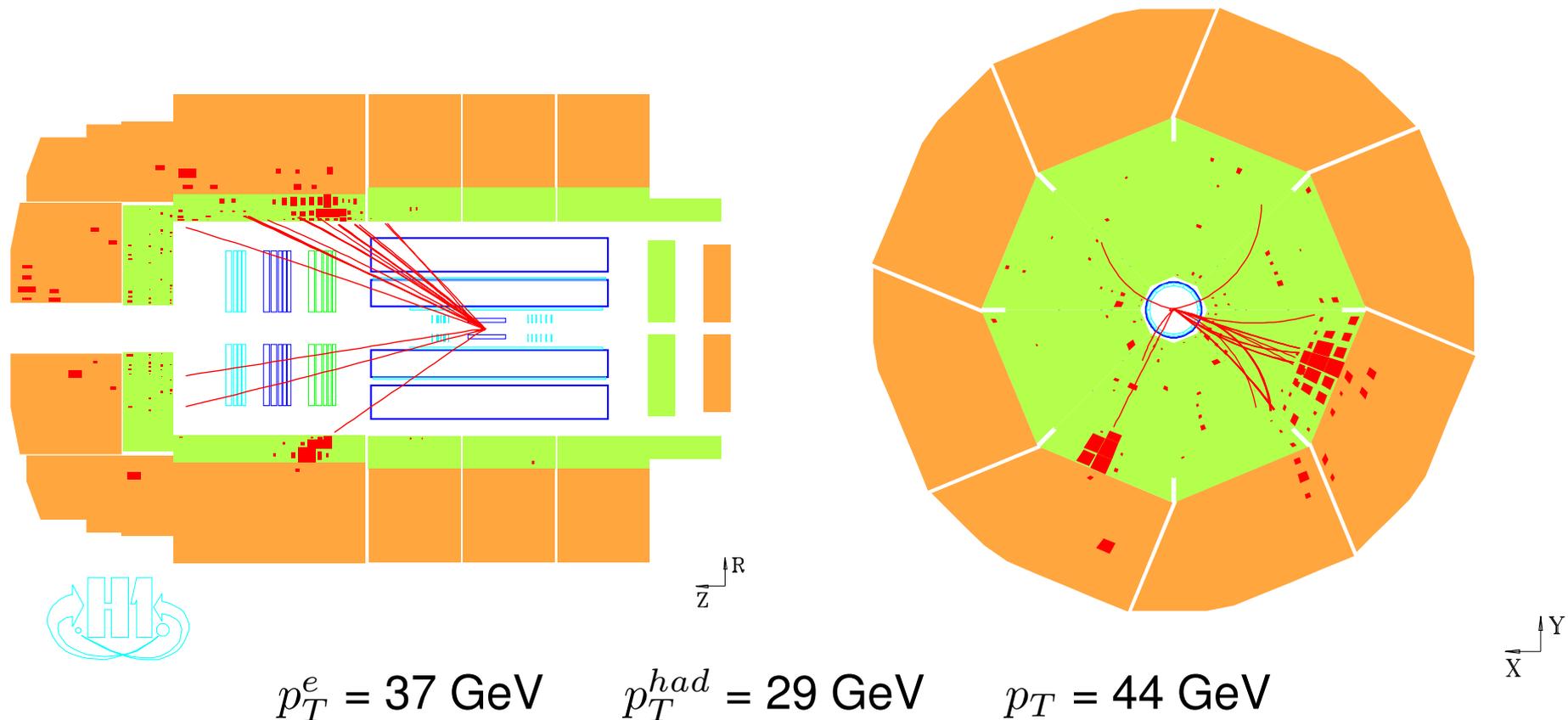## Isolated leptons

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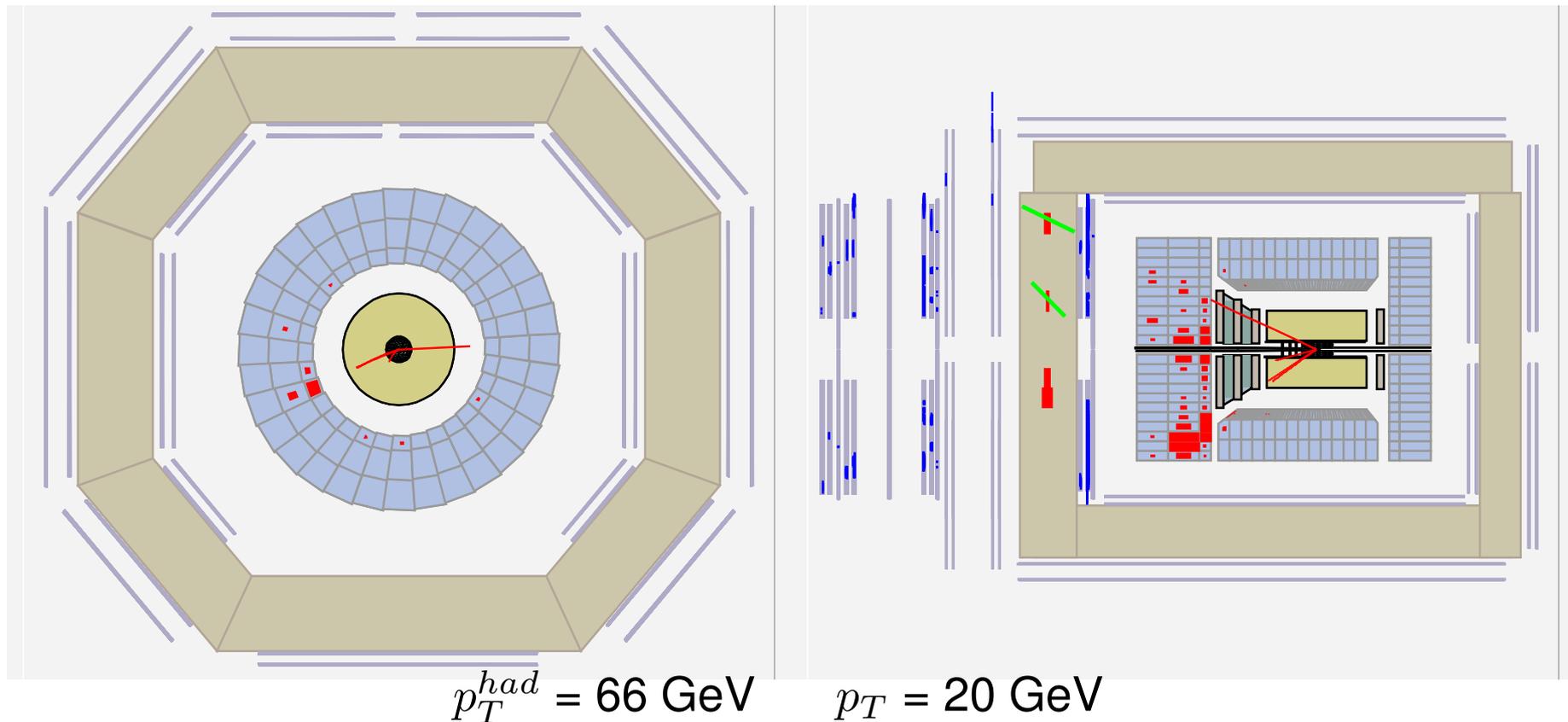
$$p_T^{had} = 66 \text{ GeV} \qquad p_T = 20 \text{ GeV}$$

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Isolated leptons

Only significant contribution to this signal in the SM is expected from W production with leptonic decays. Main leading order diagrams:

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quark jet $\Rightarrow$ hadron transverse momentum p_T^X

isolated lepton $\Rightarrow$ large transverse momentum p_T^l

neutrino $\Rightarrow$ large missing transverse momentum p_T

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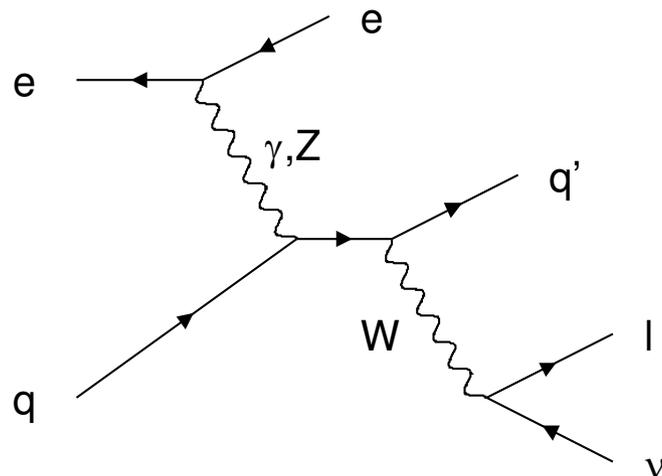
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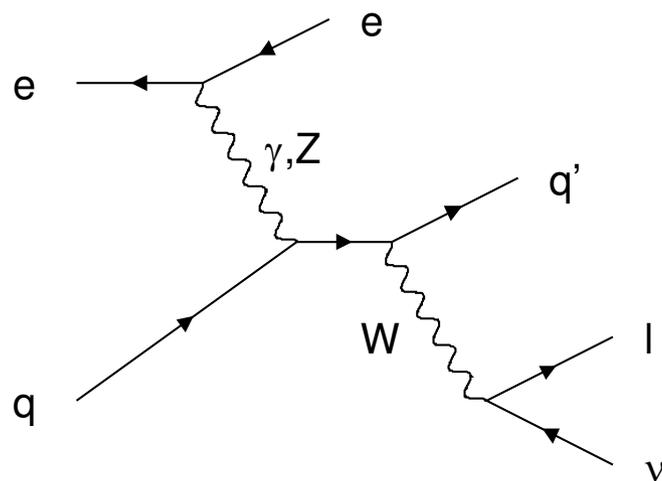
neutrino $\Rightarrow$ large missing transverse momentum p_T

Standard Model prediction $\sigma(ep \to eW^\pm X) \approx 1.1$ pb.

But only small fraction with large hadron transverse momentum, p_T^X.
Large p_T^X expected e.g. from anomalous single top production (FCNC).

Searches for new phenomena

Isolated leptons

H1 results from combined HERA I + HERA II data, $e^{\pm}$ and $\mu^{\pm}$ channel.

Reconstructed distribution of the hadron transverse momenta p_T^X:

$e^- p$
98-06
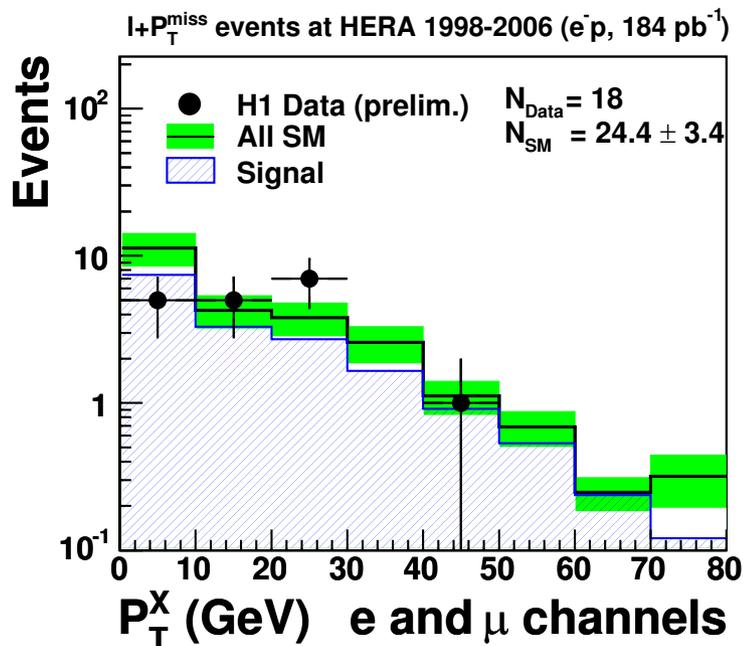
$e^+ p$
94-07
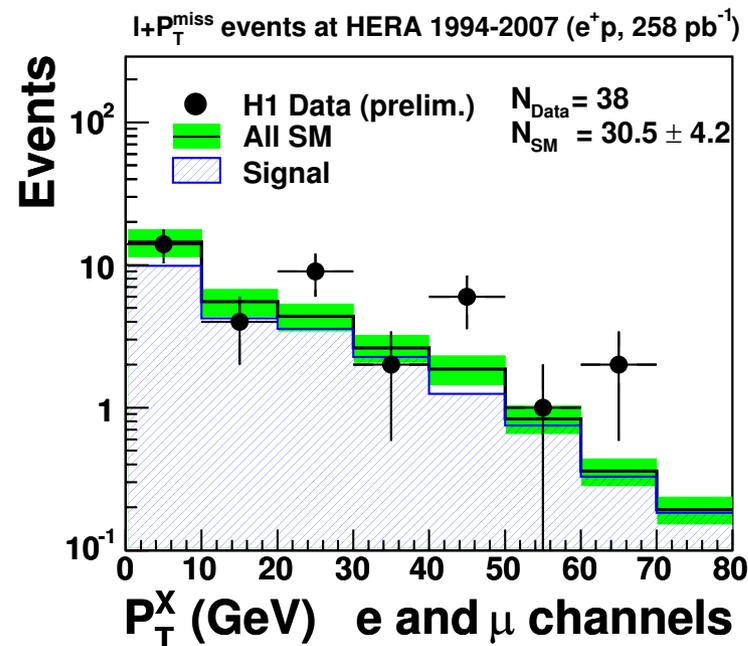
Good agreement with SM

$\sim 3\sigma$ excess for $p_T^X > 25$ GeV

$N_{obs} = 18$ for $N_{exp} = 7.8 \pm 1.3$

Searches for new phenomena
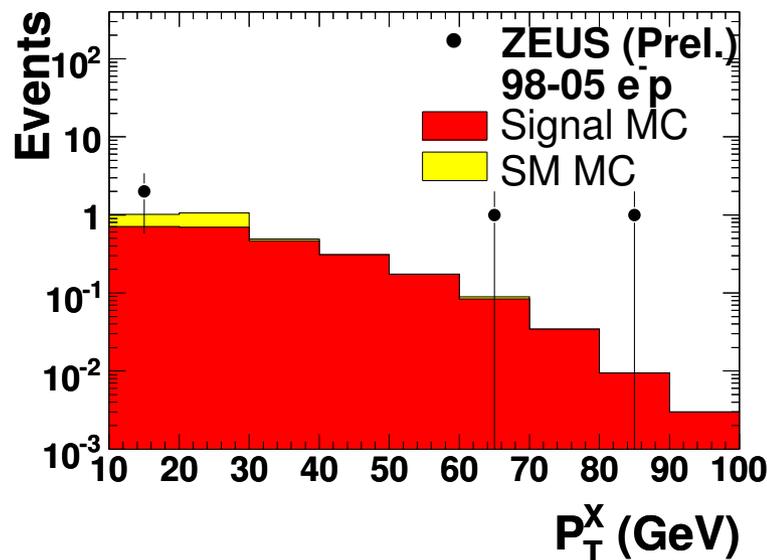
Isolated leptons

Result not confirmed by ZEUS analysis of HERA I + HERA II data !

Reconstructed distribution of the hadron transverse momenta p_T^X:

e^-p
98-06

e^+p
96-04
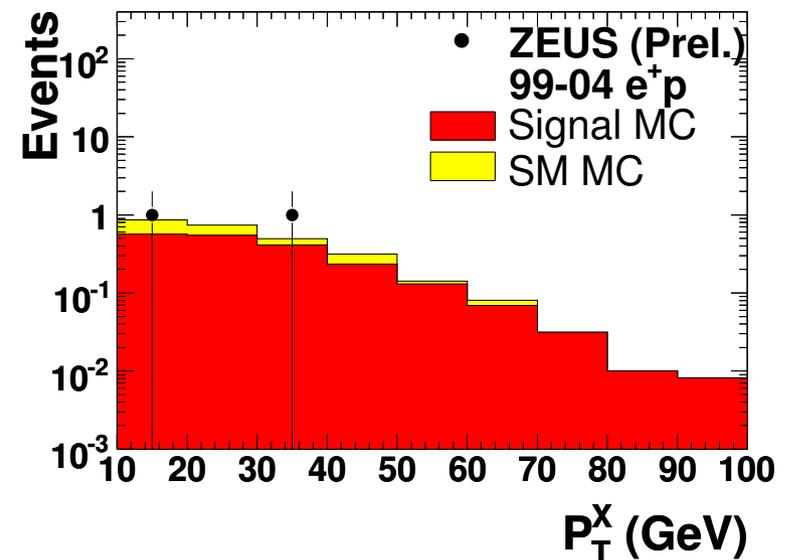
Isolated leptons with high transverse momentum observed,
but with rate consistent with SM expectations !

Searches for new phenomena

Isolated leptons

Summary of H1 and ZEUS results, $P_T^X > 25$ GeV   (status Feb 13th 2007)

H1 (prel.)	e channel	μ channel	e & μ comb.
e^-p (184 pb^{-1})	$3/3.8 \pm 0.6$ (61%)	$0/3.1 \pm 0.5$ (74%)	$3/6.9 \pm 1.0$ (67%)
e^+p (258 pb^{-1})	$10/4.1 \pm 0.8$ (75%)	$8/3.7 \pm 0.6$ (85%)	$18/7.8 \pm 1.3$ (80%)
$e^{\pm}p$ (442 pb^{-1})	$13/7.9 \pm 1.4$ (67%)	$8/6.8 \pm 1.1$ (79%)	$21/14.7 \pm 2.3$ (72%)

ZEUS (prel.)	e channel	μ channel
e^-p (204 pb^{-1})	$5/3.8 \pm 0.6$ (55%)	$2/2.2 \pm 0.3$ (86%)
e^+p (228 pb^{-1})	$1/3.2 \pm 0.4$ (75%)	$3/3.1 \pm 0.5$ (80%)
$e^{\pm}p$ (432 pb^{-1})	$6/7.0 \pm 0.7$ (64%)	$5/5.3 \pm 0.6$ (82%)

Excess observed in e and μ channel, but only in H1 e^+p data

Updated ZEUS results still in good agreement with SM predictions

Consistent SM expectations for both experiments

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$e^\pm p$ (432 pb^{-1})	$6/7.0 \pm 0.7$ (64%)	$5/5.3 \pm 0.6$ (82%)	$11/12.3$

H1+ZEUS

e^-p	$8/7.6$	$2/5.3$	$10/12.9$
e^+p	$11/7.3$	$11/6.8$	$22/14.1$
$e^\pm p$	$19/14.9$	$13/12.1$	$32/27.0$

No significant excess observed in the combined H1 + ZEUS data

Conclusions

HERA II

High luminosity + polarization $\Rightarrow$ new window for precise EW studies.

measurements of parity violation and polarization asymmetries in NC and CC DIS

Proton PDF and EW parameters can be constrained from HERA data only

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$\Rightarrow$ limits on deviations from SM set in different models

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HERA running coming to an end soon

Large samples of data collected with polarized lepton beams
still being analyzed. Many more interesting results expected.