Searches at HERA

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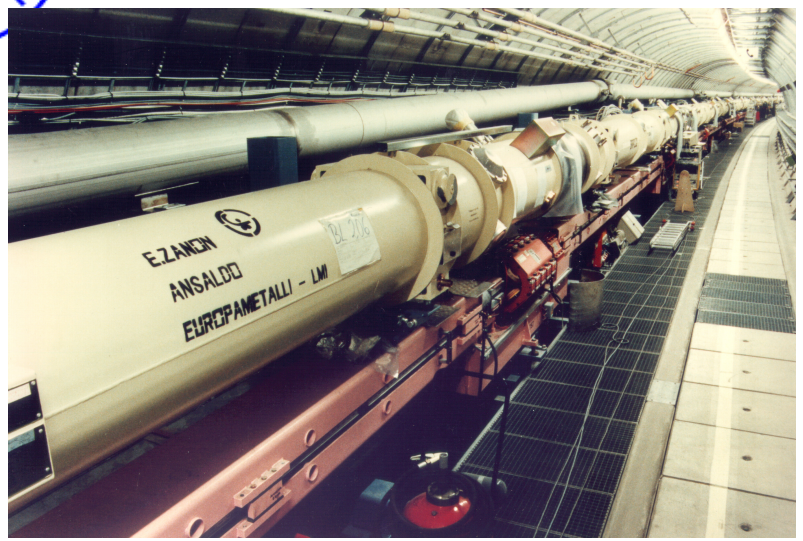
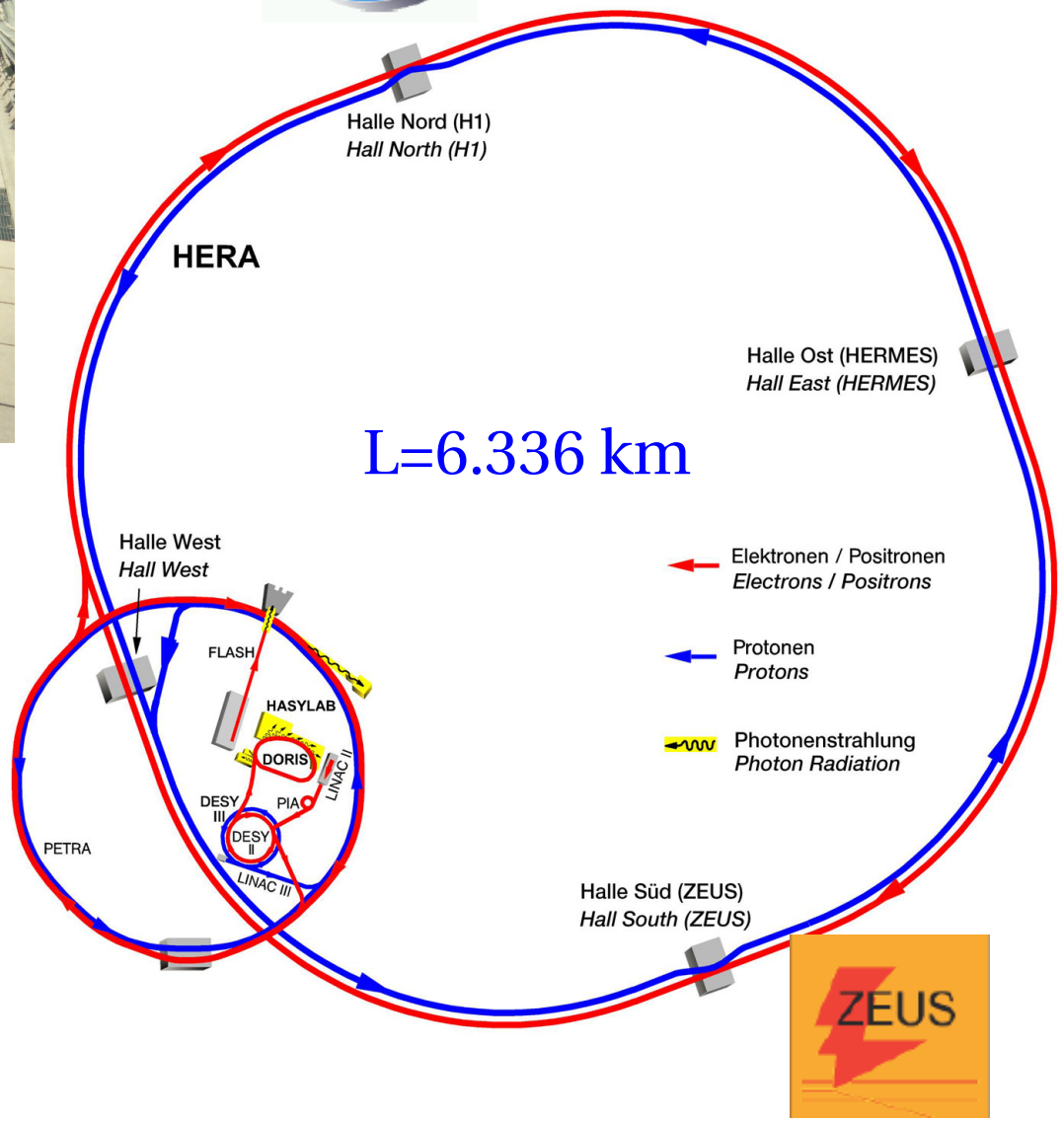
DESY
ISMD Gomel 2009

- HERA, H1, and ZEUS
- Inclusive signatures
- Model-based searches
- Lepton signatures
- General search
- Summary

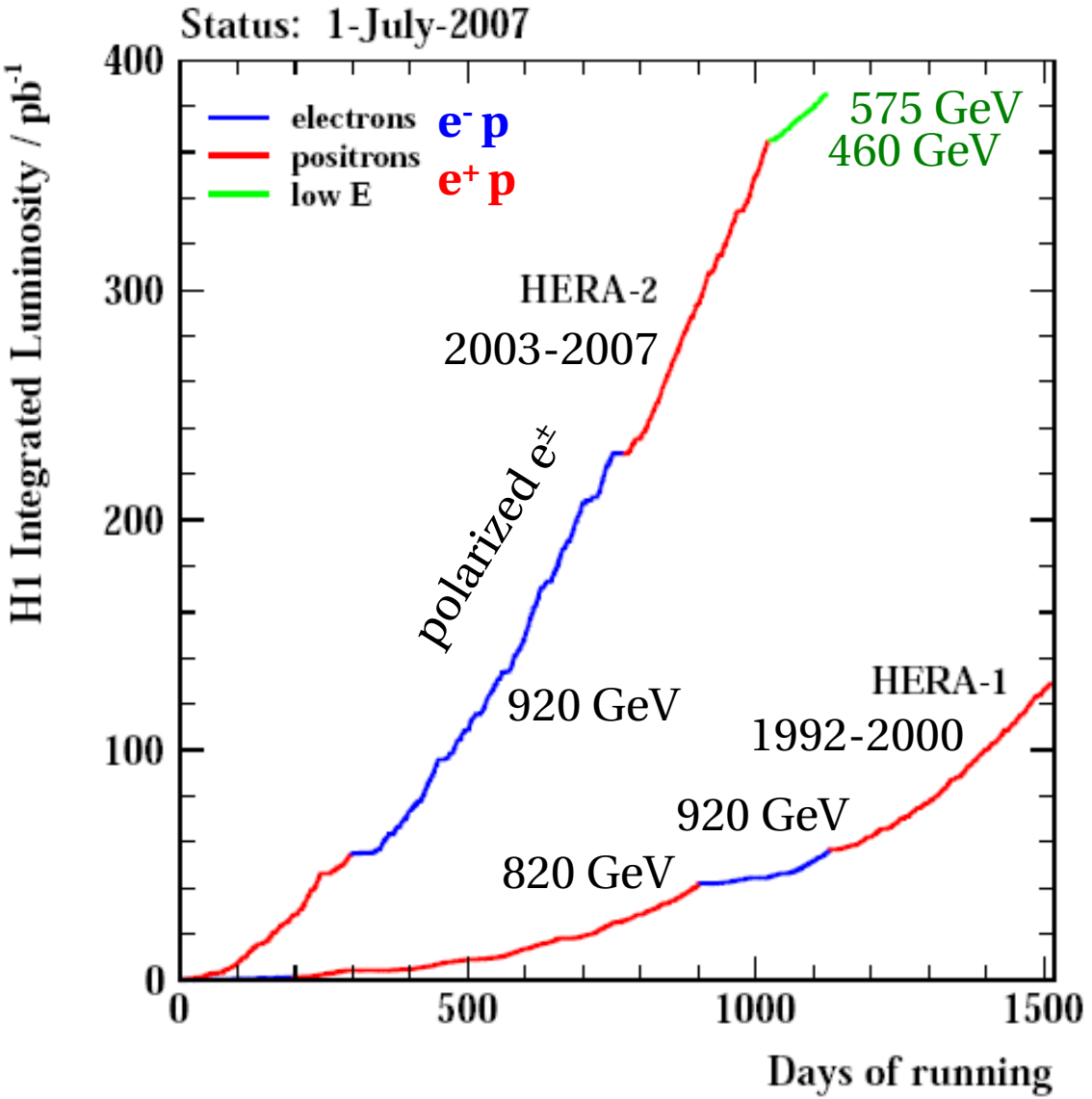
Hadron Elektron Ring Anlage HERA





- World's only ep accelerator and collider
- Operated 1992 - 2007
- p: 460-920 GeV, 110 mA
- e: 27.6 GeV, 45 mA
- 2 ep collider experiments: H1 and ZEUS.

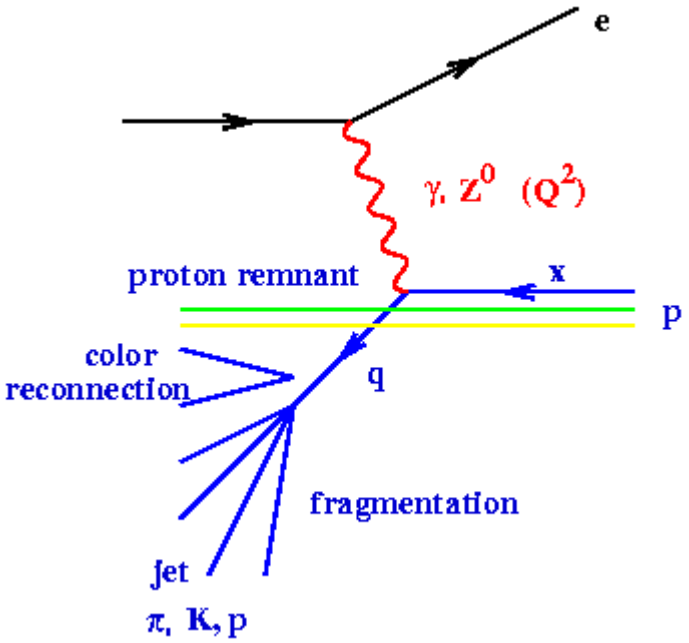
Luminosity collection

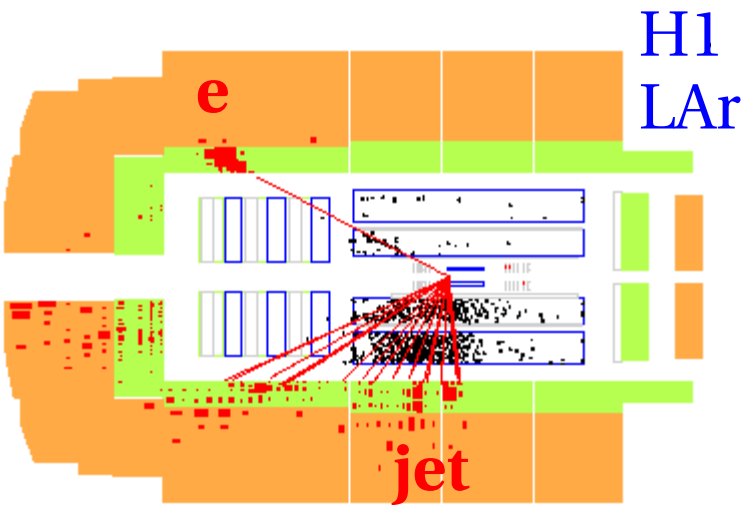


- H1 and ZEUS each have collected **0.5 fb^{-1}** of high quality physics data, balanced in e^+ and e^-.
- 72% of the luminosity is from HERA II, with longitudinally polarized $e^{\pm}$ beams.
- The detectors have been operated successfully and efficiently, including all upgrades.

Deep inelastic scattering

Neutral current: γ or Z exchange

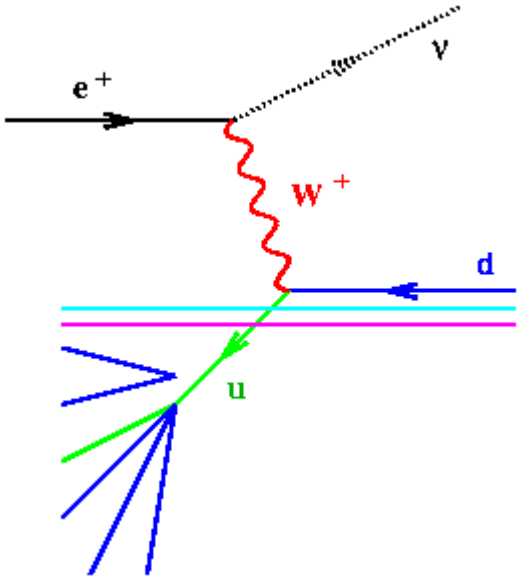




jet balanced by the electron: good calibration.
1% jet energy scale uncertainty above 20 GeV.

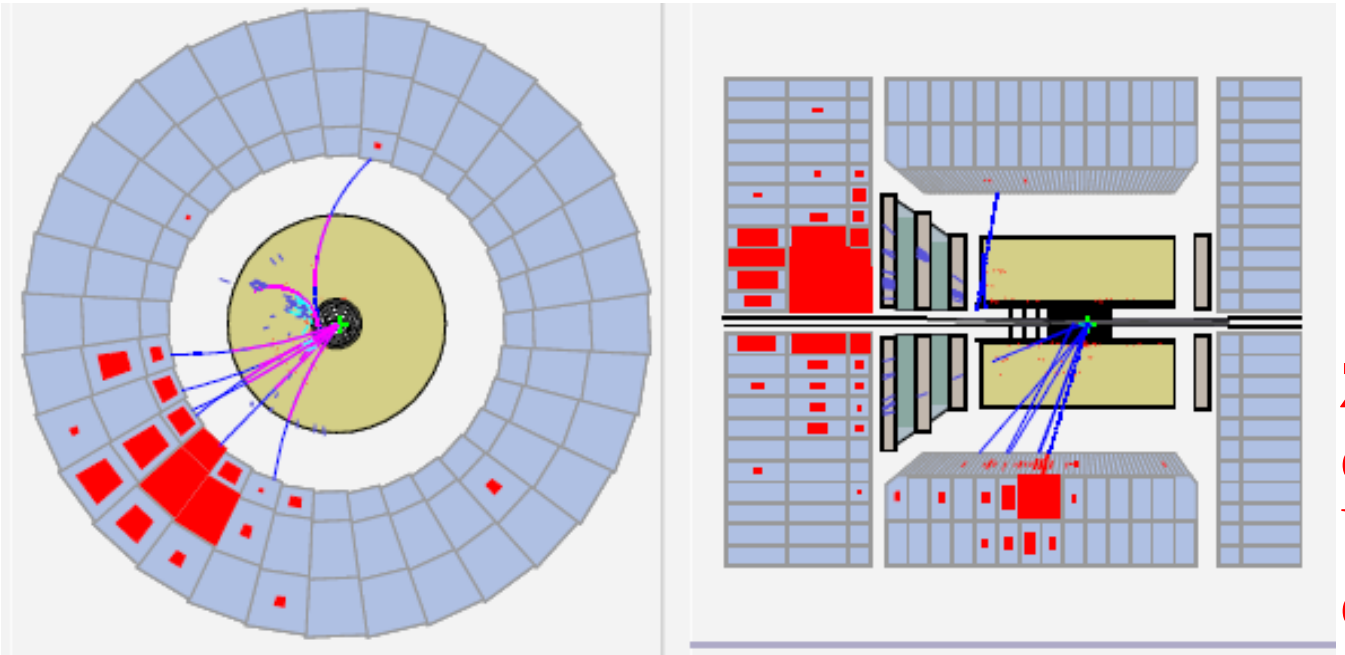
- Q^2: 4-momentum transfer from e to q by the boson.
- x = momentum fraction of the quark in the proton.
- $\sqrt{s} = 318$ GeV.

Charged current: W± exchange



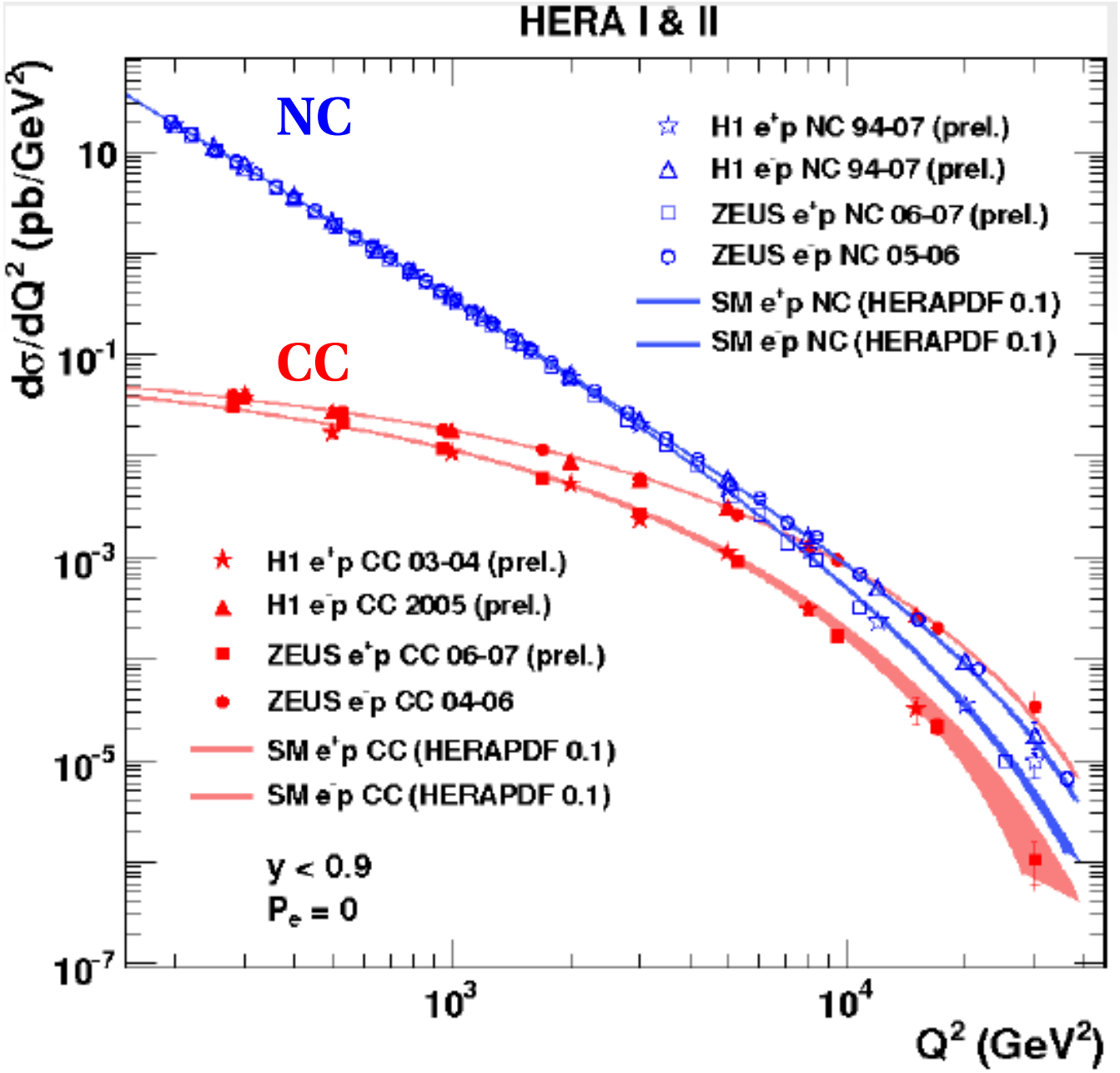
Q^2 and x can be reconstructed from the hadronic final state.

missing transverse momentum: neutrino



ZEUS compensating U-scintillator calorimeter

$e^+ p$ and $e^- p$ cross sections vs Q^2

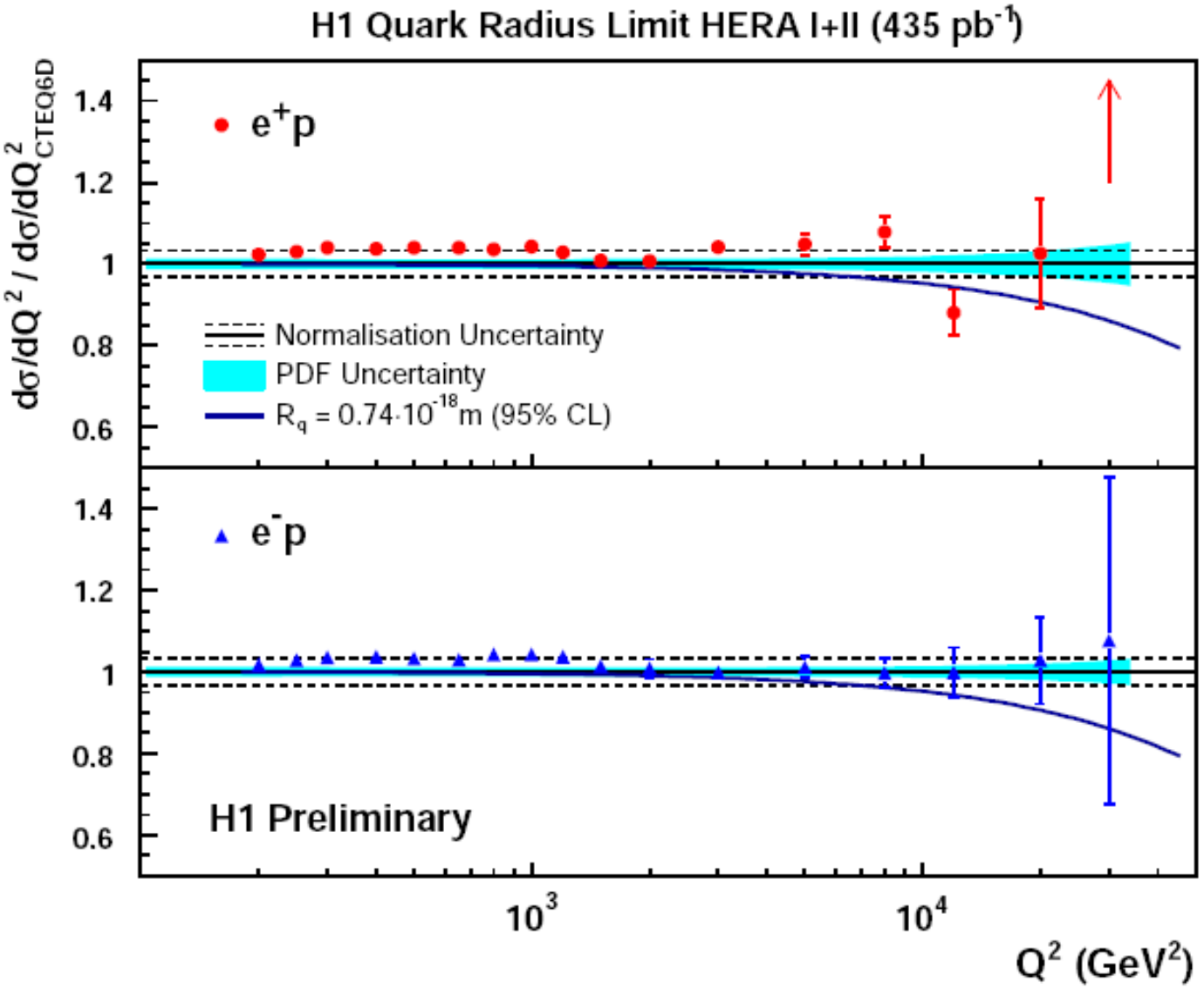


- Destructive (e^+) and constructive (e^-) γZ interference in Neutral Current.
- Well described over 6 orders of magnitude.
- Charged Current:

  e^- u enhanced

  e^+ d suppressed.
- Electroweak unification at $Q^2 \sim m_W^2$.

Quark radius limit



Quark radius form factor:
$(1 - R_q^2 Q^2/6)^2$

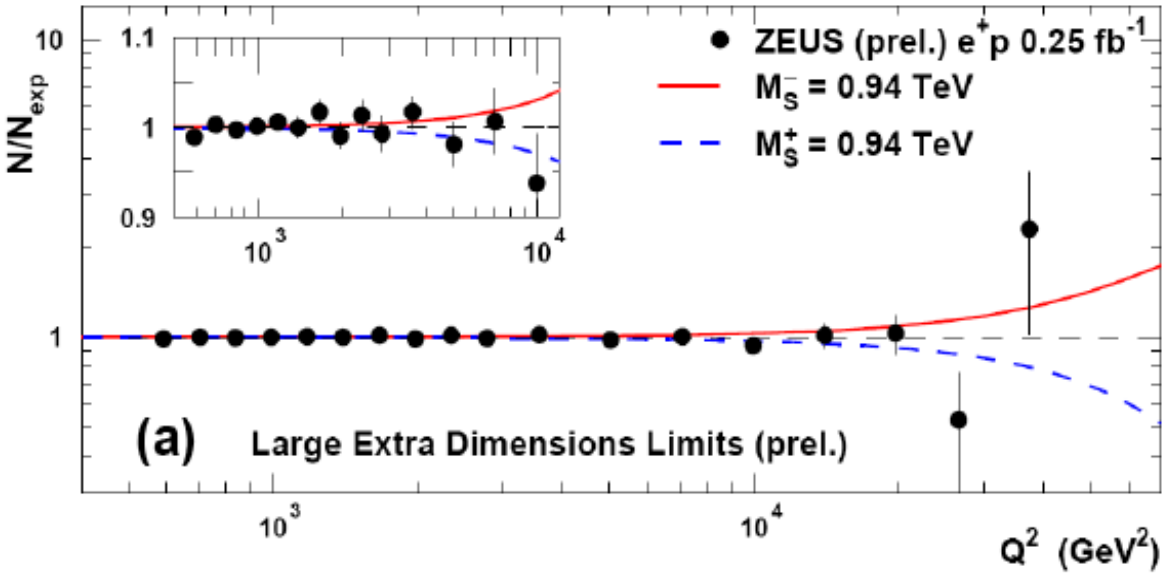
H1 limit:
$R_q < 0.74 \cdot 10^{-18}$ m

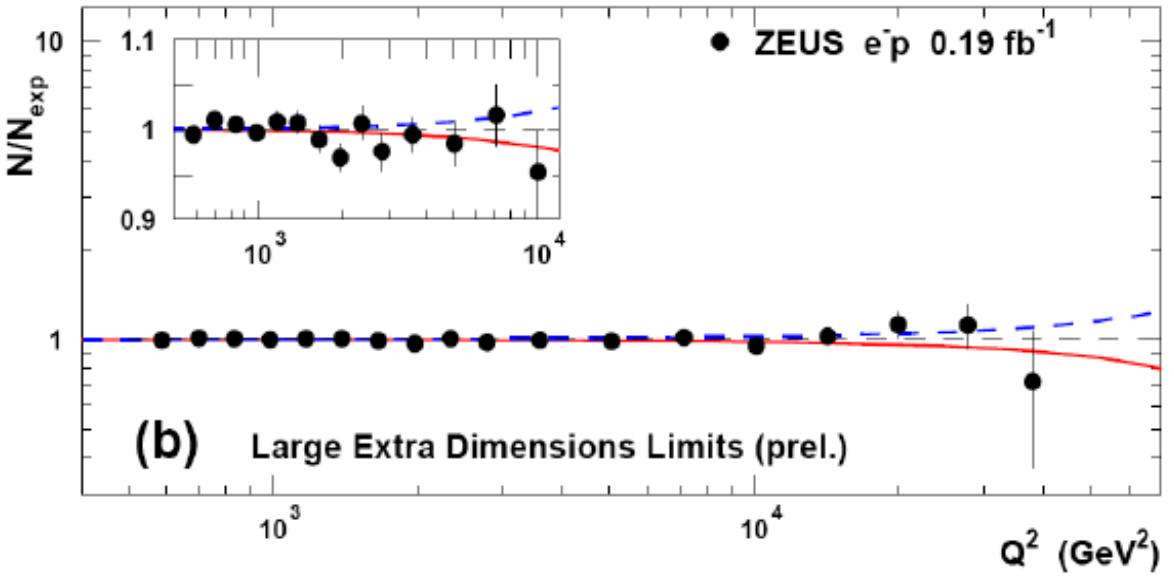
ZEUS limit:
$R_q < 0.62 \cdot 10^{-18}$ m

Large extra dimensions?

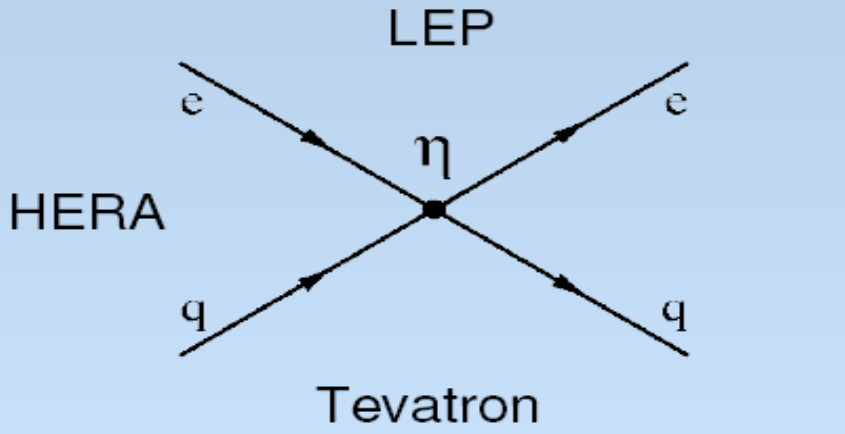
Arkani et al.:
n extra dimensions
compactified in R^n.
Scale: $M_S^{2+n} = M_{Pl}^2 / 8\,\pi\, R^n$

Graviton exchange with coupling ~$\pm 1/M_S^2$ interferes with the standard model.
Limit from a fit to e^+p and e^-p data: **$M_S > 0.94$ TeV**
($R < 500$ fm for $n = 6$).





Contact interactions



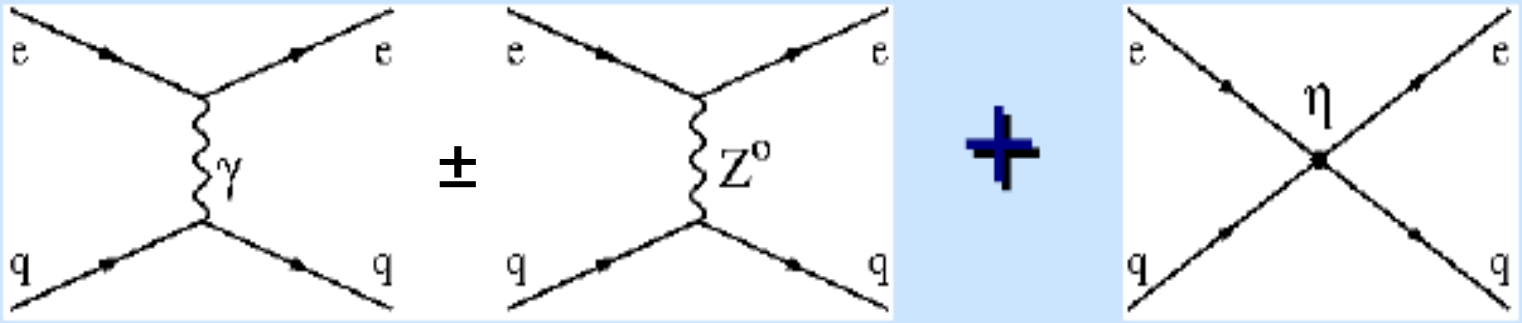
$$L_{CI} = \sum_{\alpha,\beta} \eta^{eq}_{\alpha\beta} (\bar{e}_\alpha \gamma^\mu e_\alpha)(\bar{q}_\beta \gamma^\mu q_\beta)$$

$$\eta_{\alpha\beta} = \frac{\pm 4\pi}{\Lambda^2_{\alpha\beta}} \qquad \alpha,\beta = \text{L,R helicities}$$

parity conservation: $\eta_{LL} + \eta_{LR} = \eta_{RL} + \eta_{RR}$

Model	η^{ed}_{LL}	η^{ed}_{LR}	η^{ed}_{RL}	η^{ed}_{RR}	η^{eu}_{LL}	η^{eu}_{LR}	η^{eu}_{RL}	η^{eu}_{RR}
VV	$+\eta$	$+\eta$	$+\eta$	$+\eta$	$+\eta$	$+\eta$	$+\eta$	$+\eta$
AA	$+\eta$	$-\eta$	$-\eta$	$+\eta$	$+\eta$	$-\eta$	$-\eta$	$+\eta$

At HERA:



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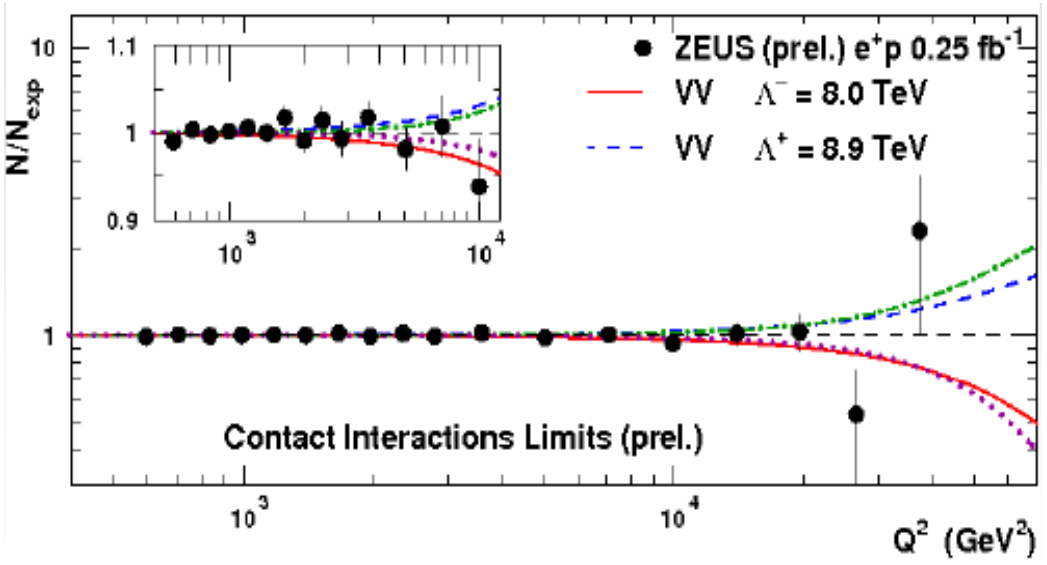
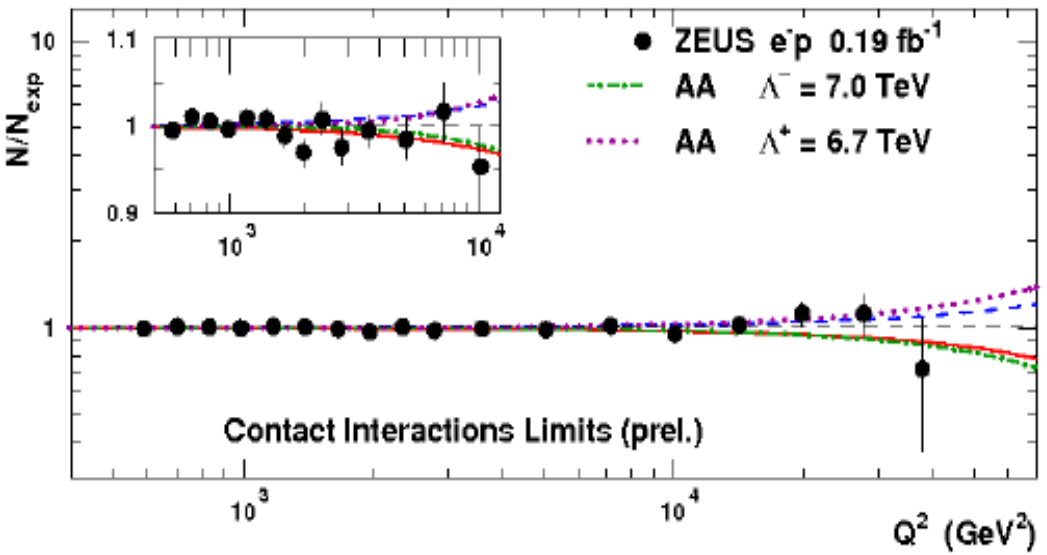
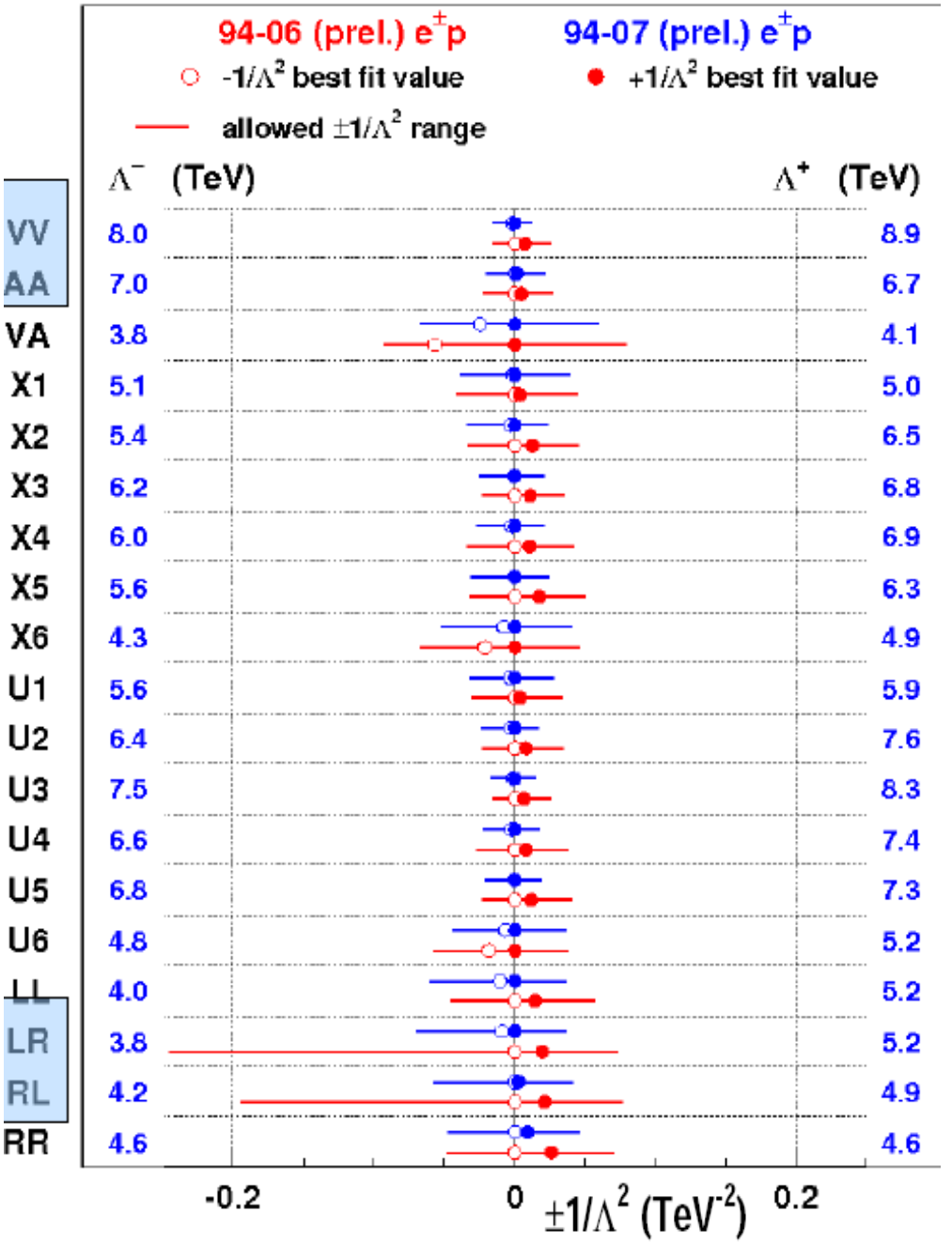
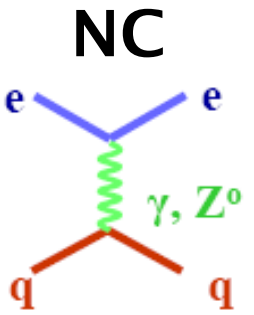


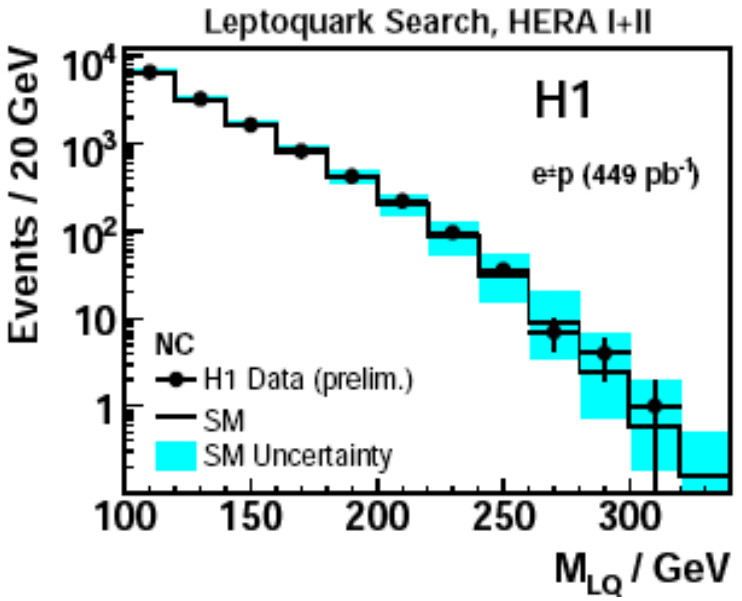


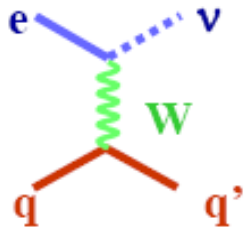


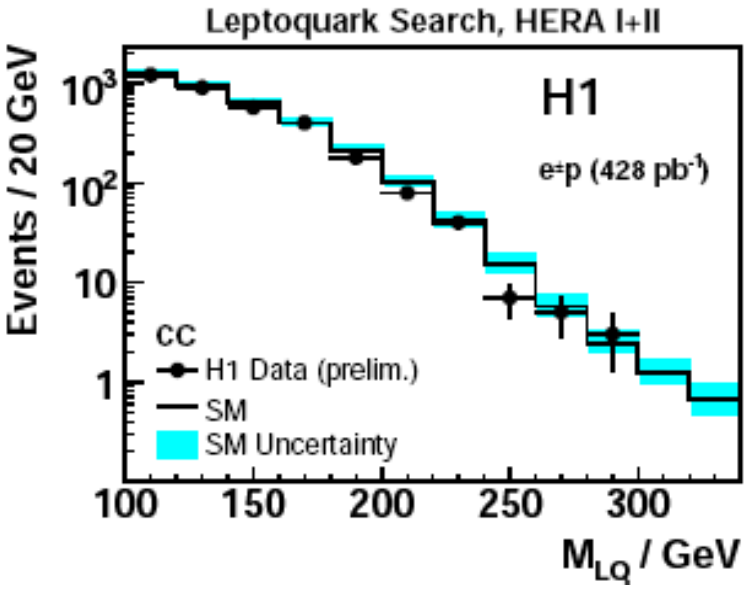
1st generation Leptoquarks?

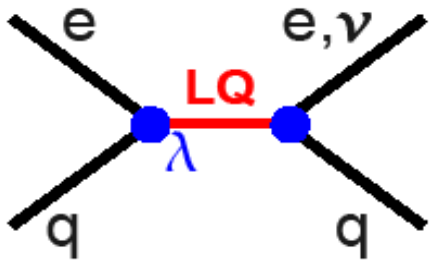
Peak at $M^2_{LQ} = xs$?

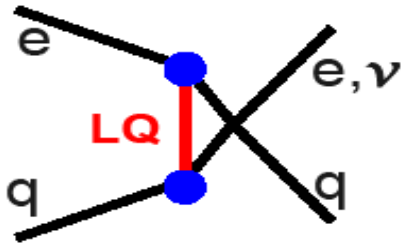


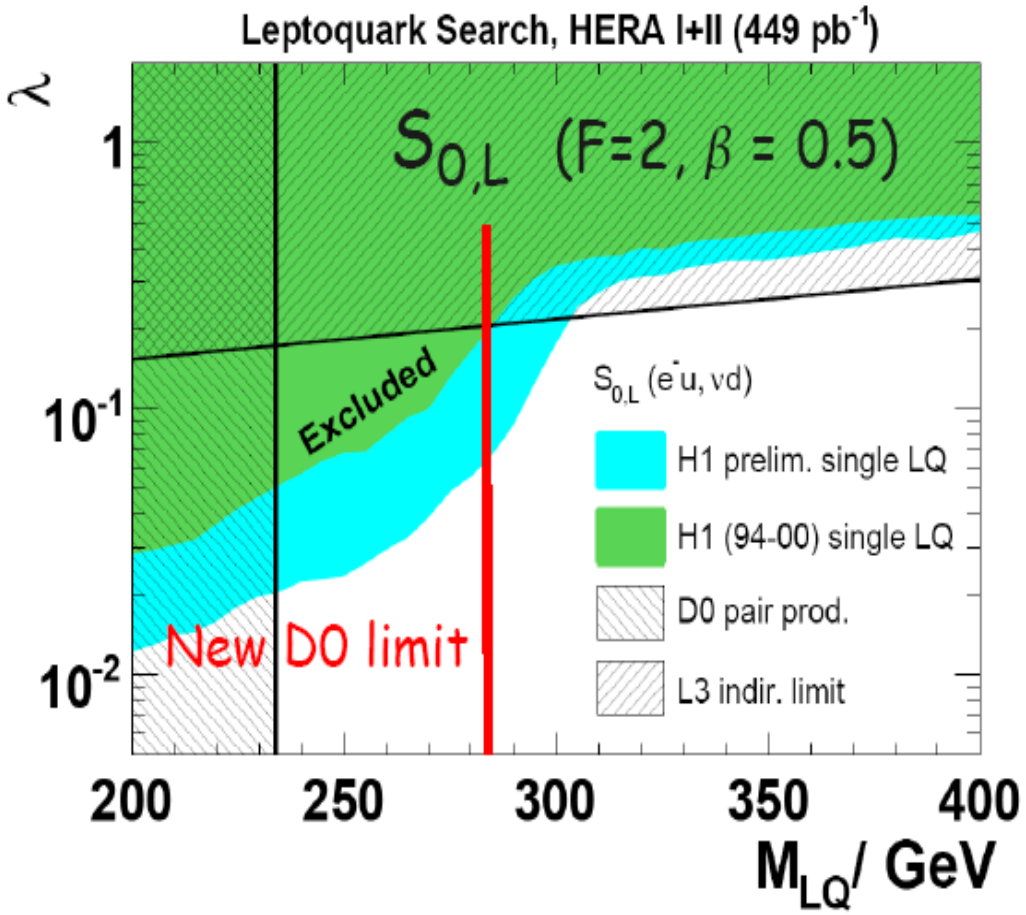






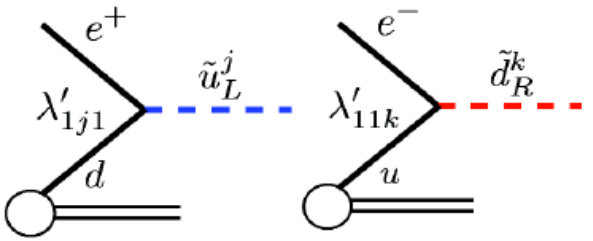




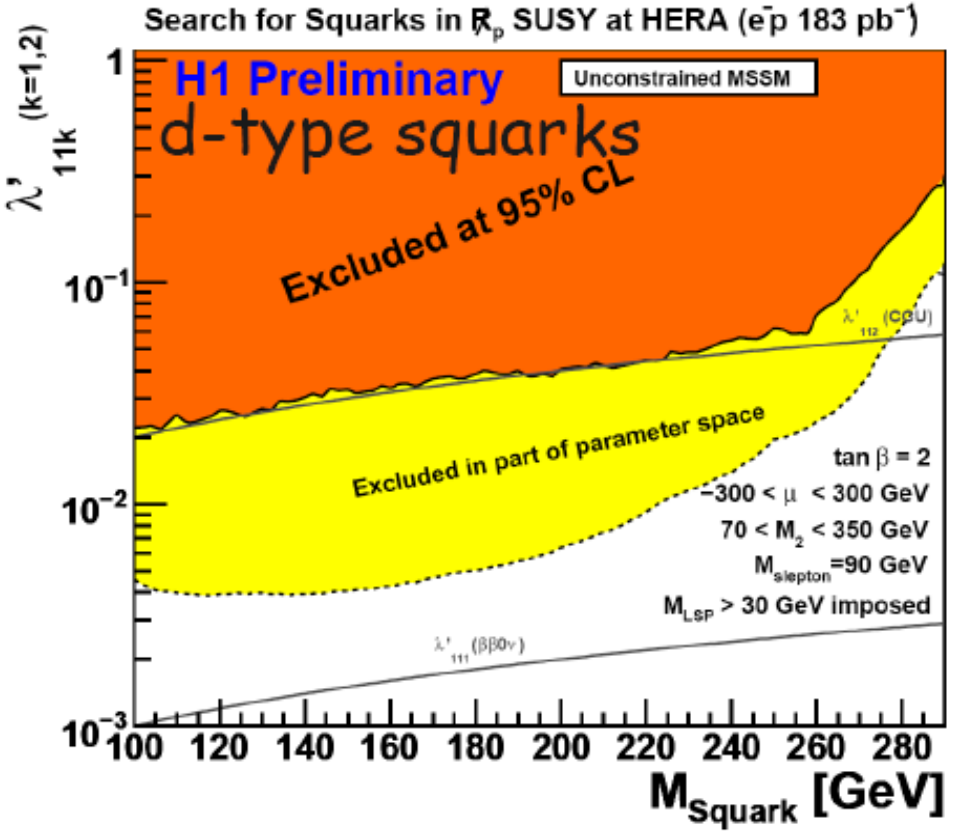


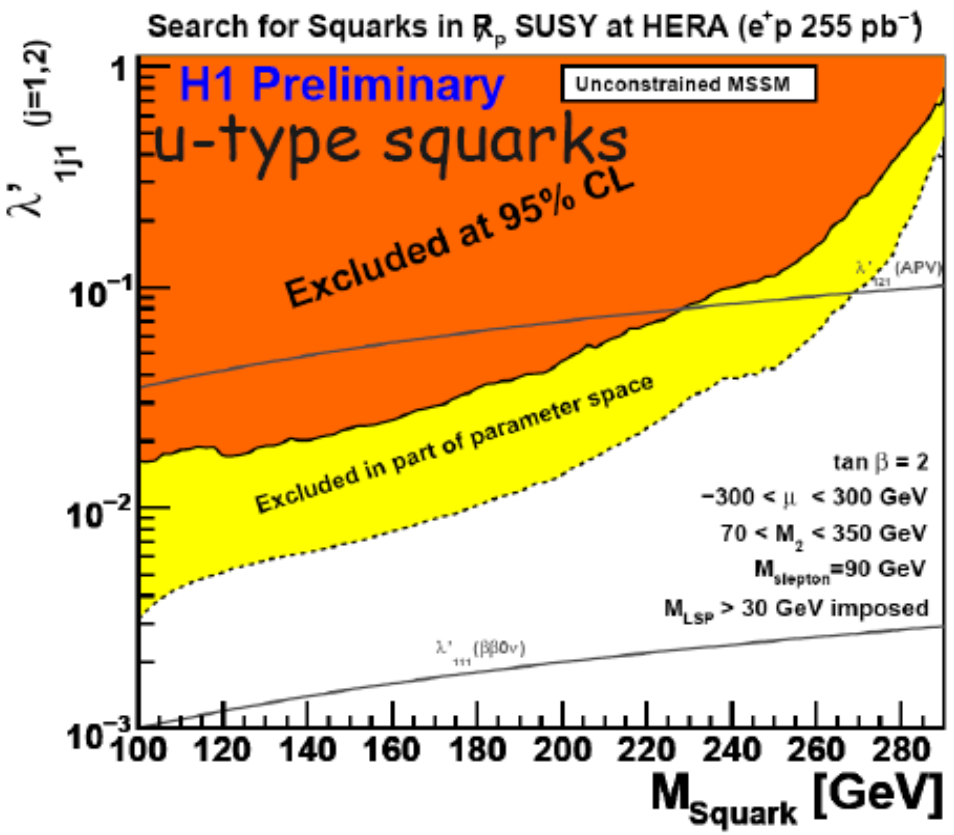
R_P-violating SUSY hat HERA?

$$R_P = (-1)^{3B + L + 2S}$$

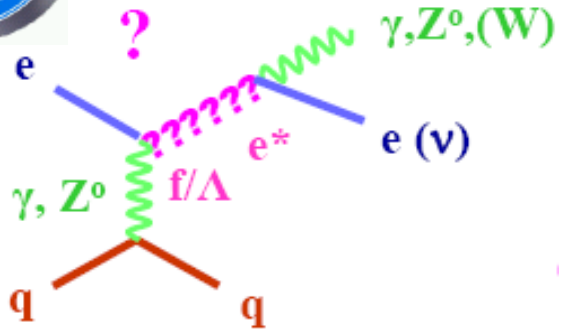


SUSY with R-parity violation:
resonant squark production at HERA?
Many decay channels searched: direct or via cascades with neutralinos and charginos.



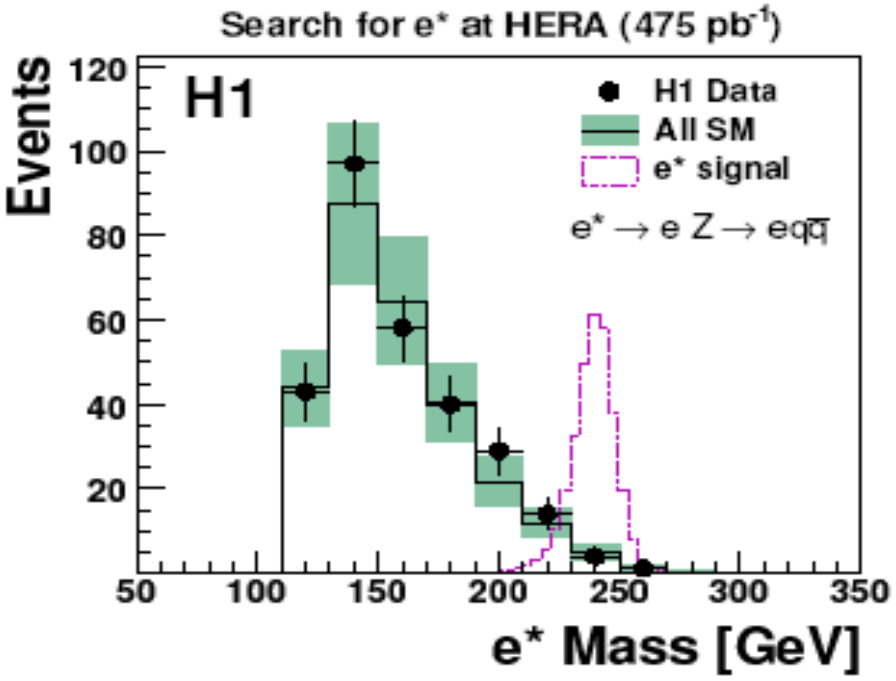


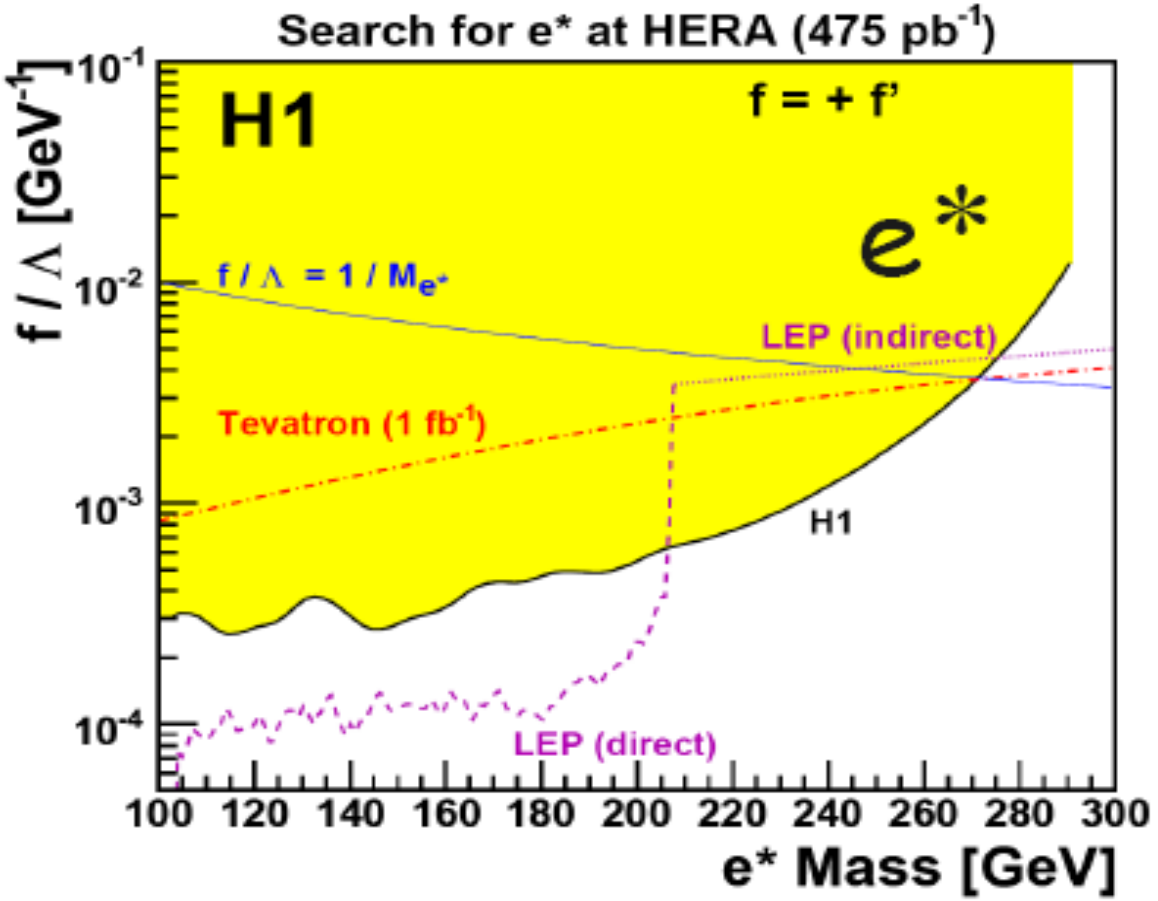
Excited electrons?



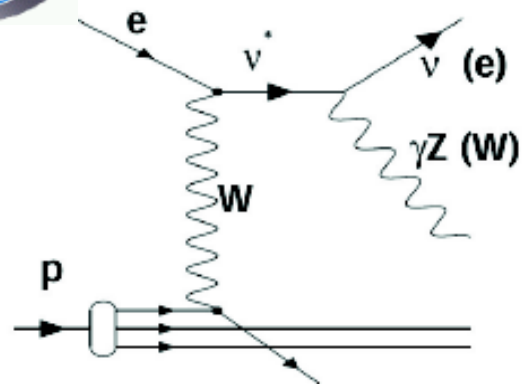
Channel	Data	SM	Signal Efficiency [%]
$e^* \to e\gamma$ (ela.)	42	48 ± 4	60–70
$e^* \to e\gamma$ (inel.)	65	65 ± 8	60–70
$e^* \to \nu W \to \nu q\bar{q}$	129	133 ± 32	20–55
$e^* \to \nu W \to \nu e\nu$	4	4.5 ± 0.7	60
$e^* \to eZ \to e\nu\nu$			35
$e^* \to eZ \to eq\bar{q}$	286	277 ± 62	20–55
$e^* \to eZ \to eee$	0	0.72 ± 0.06	60
$e^* \to eZ \to e\mu\mu$	0	0.52 ± 0.05	40–15

Hagiwara et al. model:
U(1) coupling f
SU(2) coupling f'.



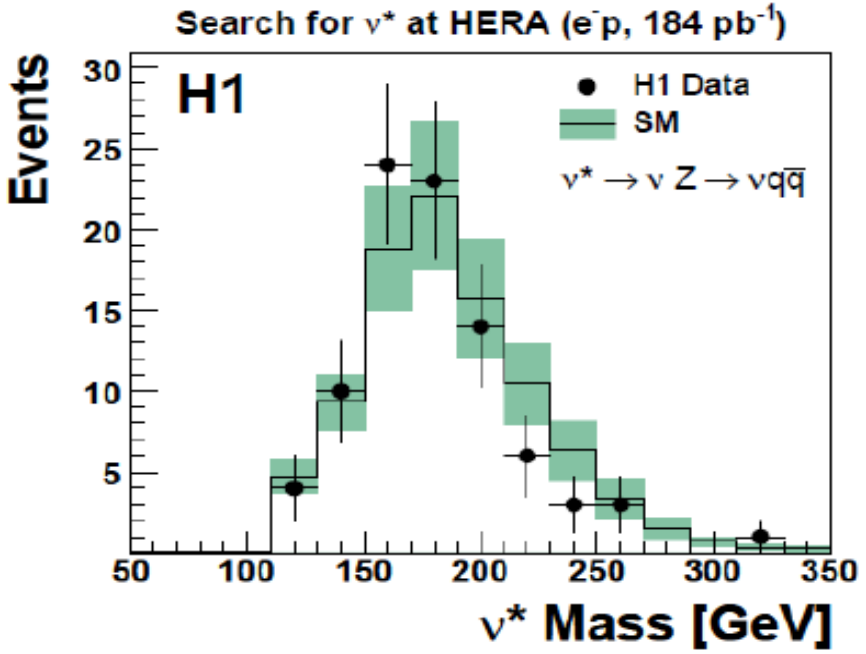


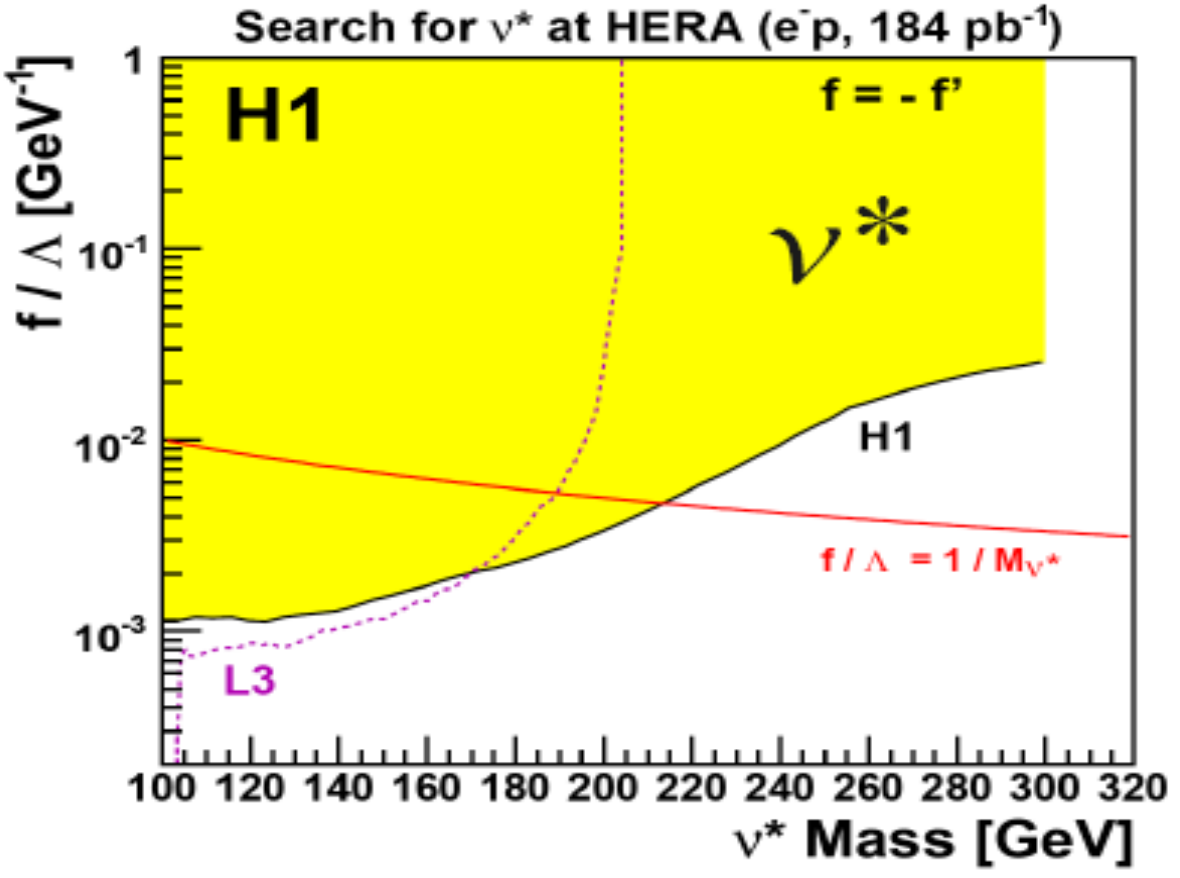
Excited neutrinos?



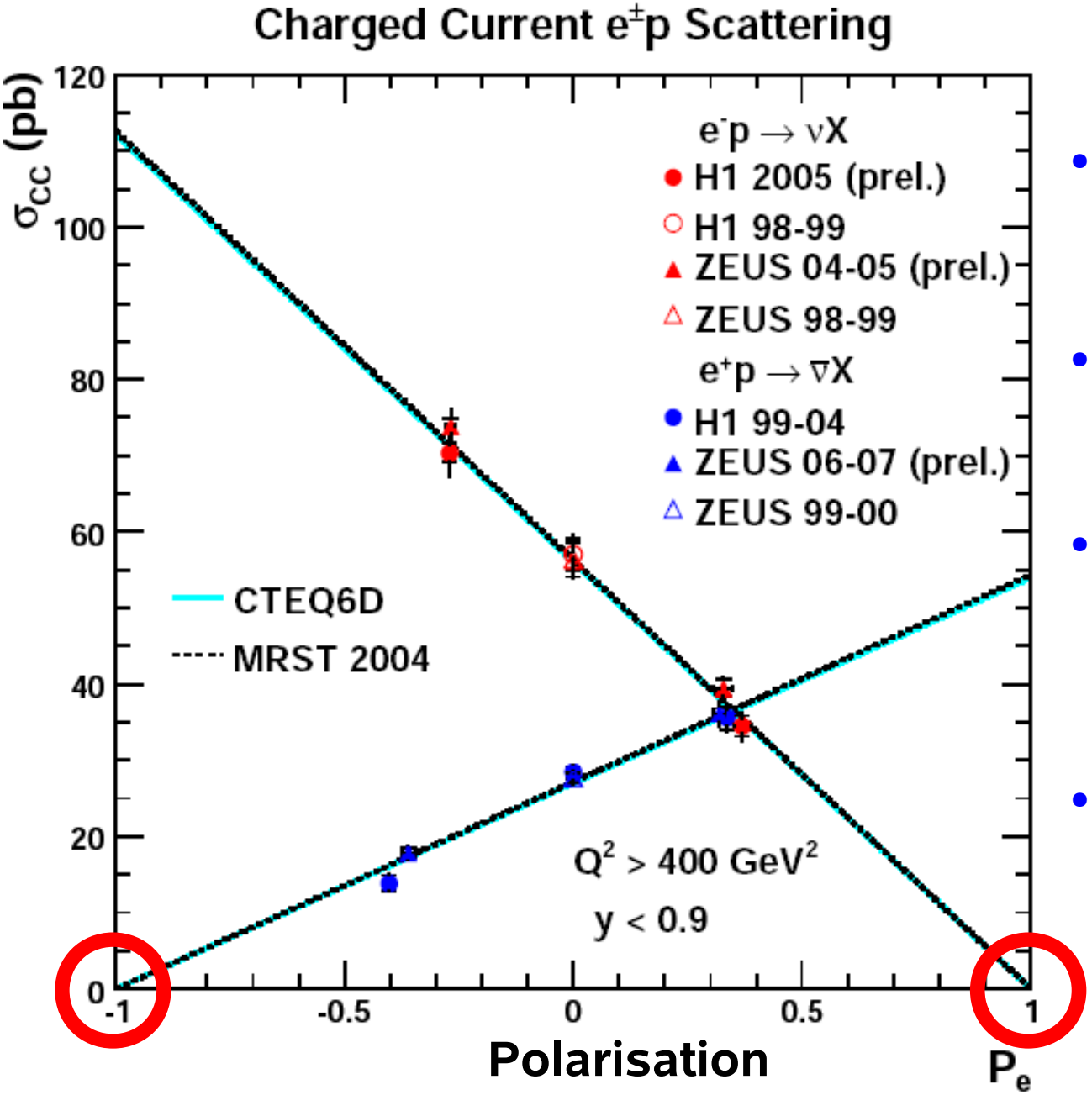
Channel	Data	SM	Signal Efficiency [%]
$\nu^* \to \nu\gamma$	7	12.3 ± 3.0	50–55
$\nu^* \to eW \to eq\bar{q}$	220	223 ± 47	40–65
$\nu^* \to eW \to e\nu\mu$	0	0.40 ± 0.05	35
$\nu^* \to eW \to e\nu e$	0	0.7 ± 0.1	45
$\nu^* \to \nu Z \to \nu q\bar{q}$	89	95 ± 21	25–55
$\nu^* \to \nu Z \to \nu ee$	0	0.19 ± 0.05	45

e^-p data used: enhanced charged current cross section.





Charged current with polarized e±



- Standard model:

  $\sigma = (1 \pm P_e) \cdot \sigma_0$

- Extrapolation to $P_e = \pm 1$:

  σ consistent with zero.

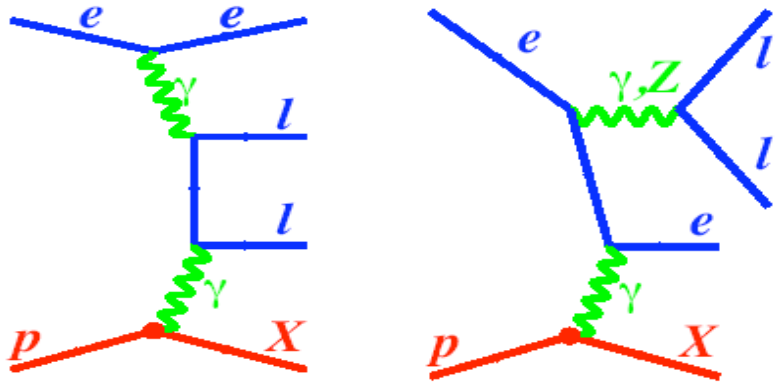
- Direct limit on right-handed W:

  $M(W_R) > 208$ GeV.

- Tevatron:

  $M(W_R) > 790$ GeV.

HERA Multi-leptons



$l = e$ or μ.

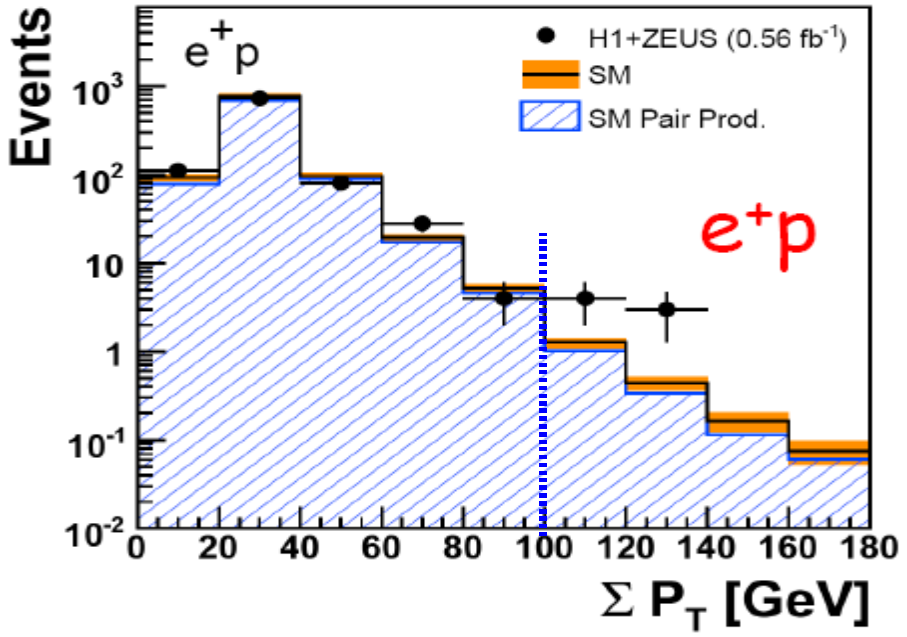
H1 and ZEUS combined in common phase space.

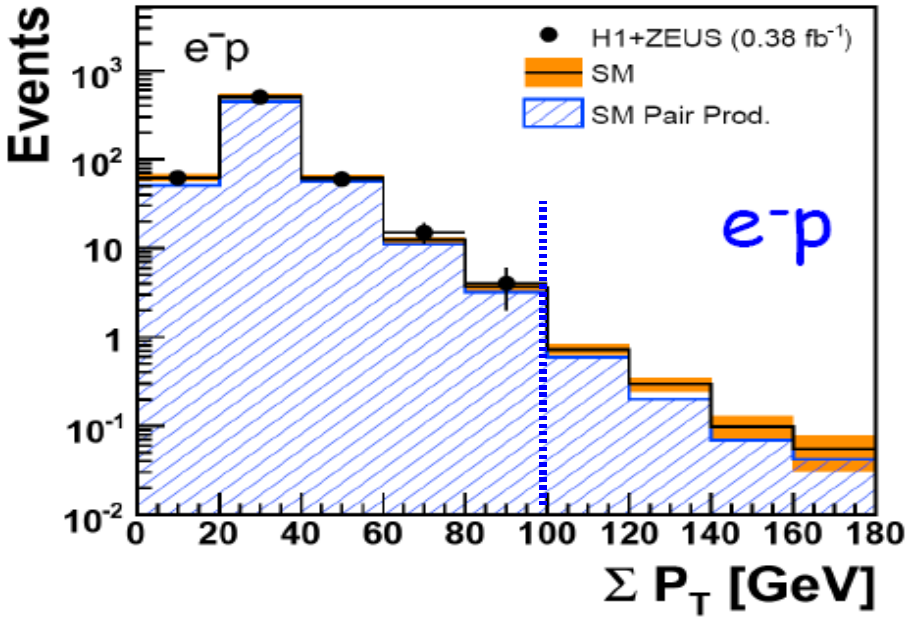
Rate well described by the Standard model below 100 GeV.

For $\sum P_T > 100$ GeV:

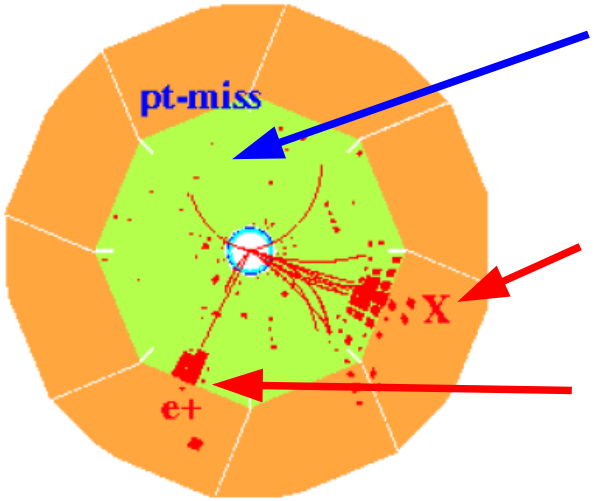
$e^+ p$: 7 for 1.9 expected (2.6σ)

$e^- p$: 0 for 1.2 expected.





High p_t leptons and missing p_t

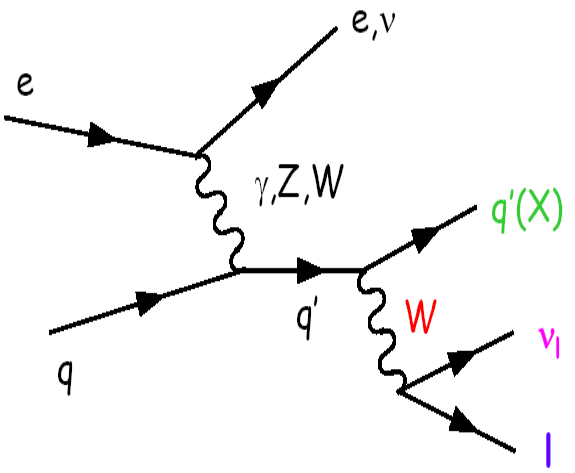


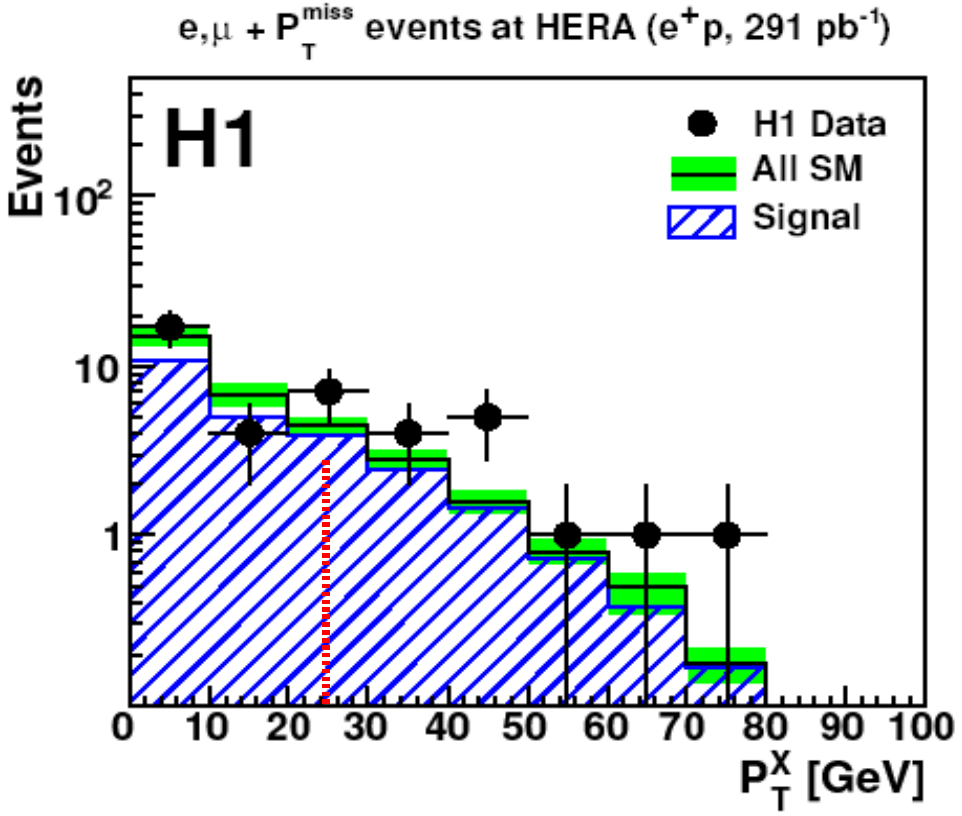
Missing momentum

Hadronic system X

Isolated high p_t e or μ

Standard model:
W production, ~1 pb.
but: expect small P_T^X

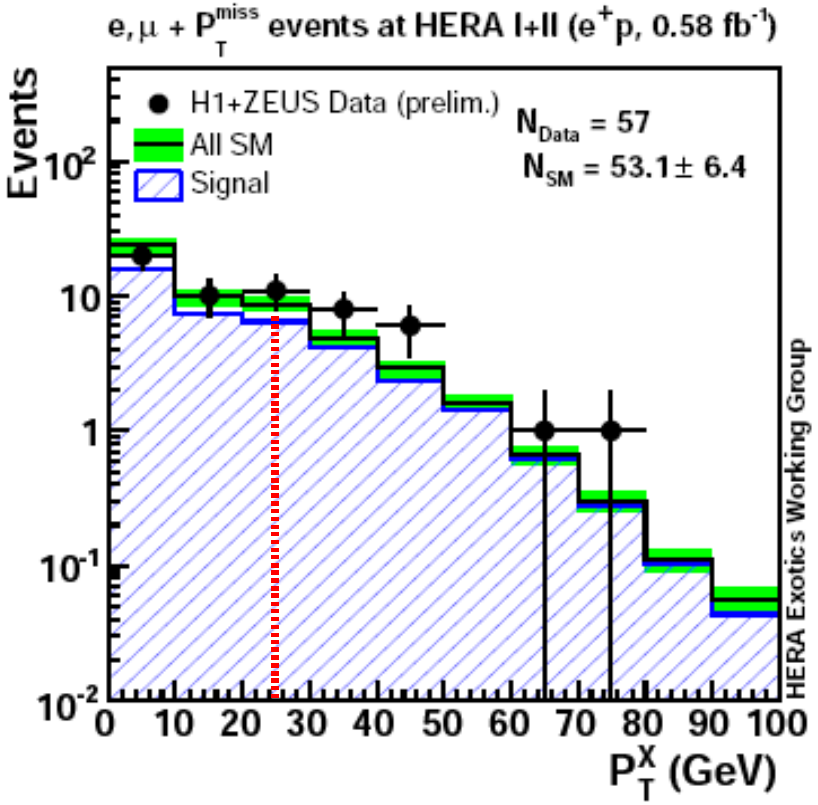




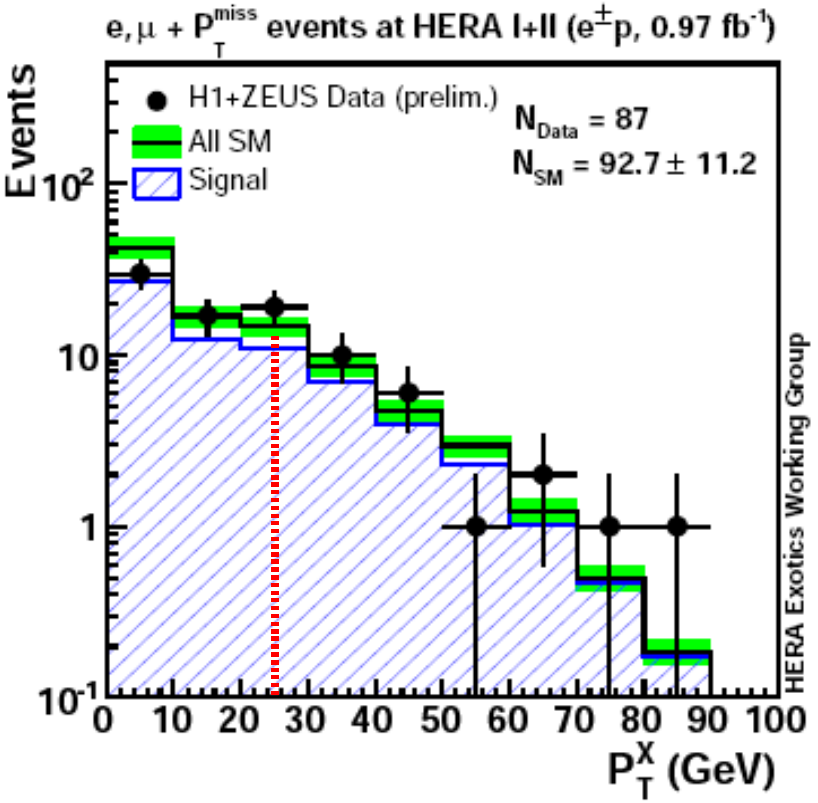
in **$e^+ p$**,
for $P_T^X > 25$ GeV:
H1 sees 17 events for
8 ± 1.3 expected: **$2.4\,\sigma$**.

High p_t leptons and missing p_t

H1 and ZEUS combined in a common phase space:

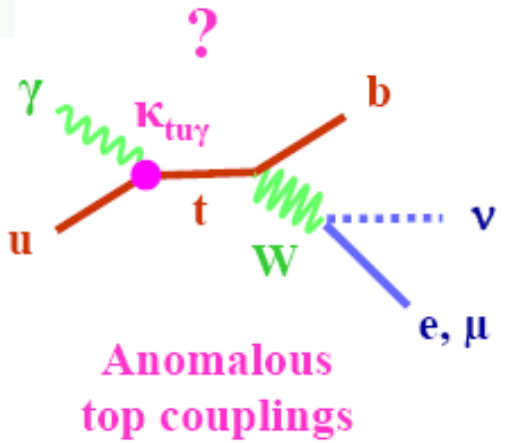


in **$e^+ p$**, for $P_T^X > 25$ GeV:
H1 and ZEUS combined
see 23 events for 15±2
expected: **1.8 σ**.



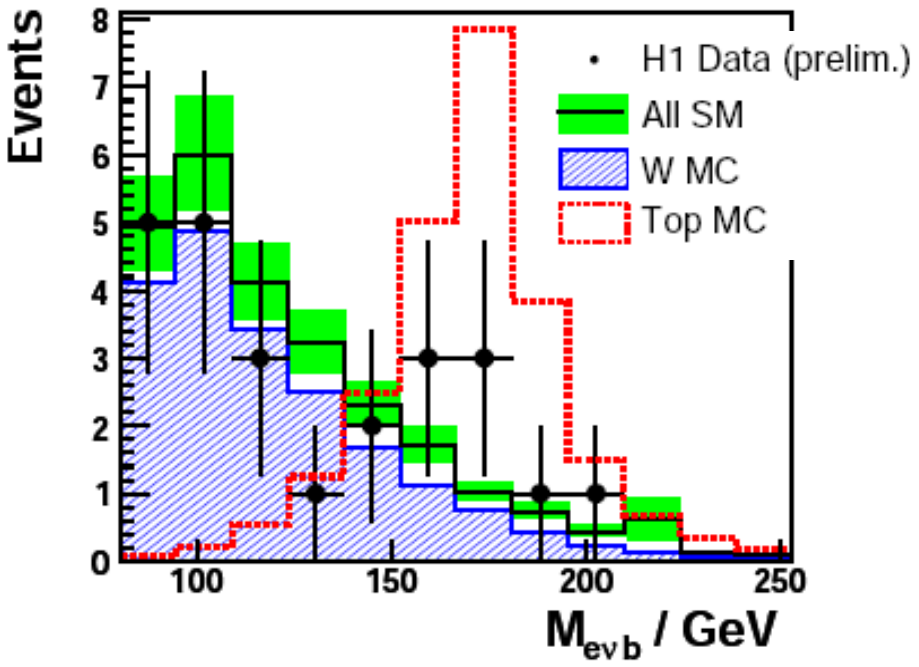
all ep, for $P_T^X > 25$ GeV:
H1 and ZEUS combined
see 29 events for 26±3
expected.

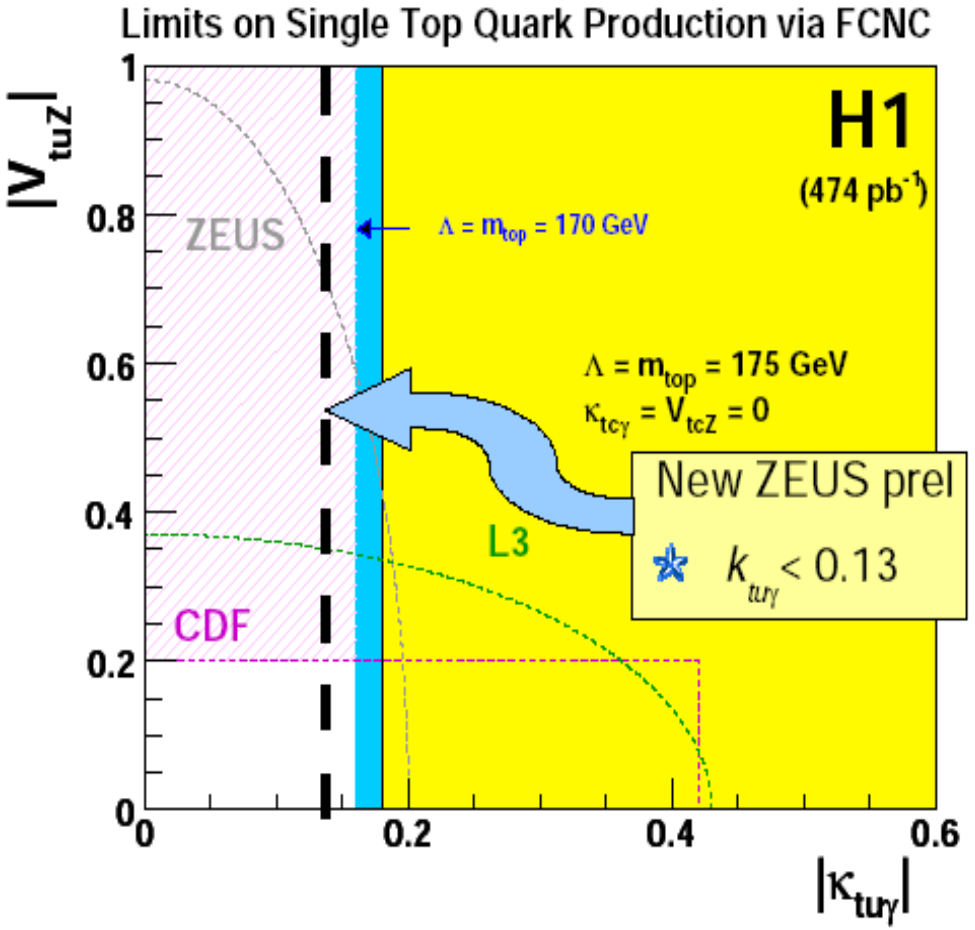
Anomalous top production?



Single top at HERA: ~1 fb.

Flavour changing neutral current





HERA has the most stringent limits on t-u-γ coupling.

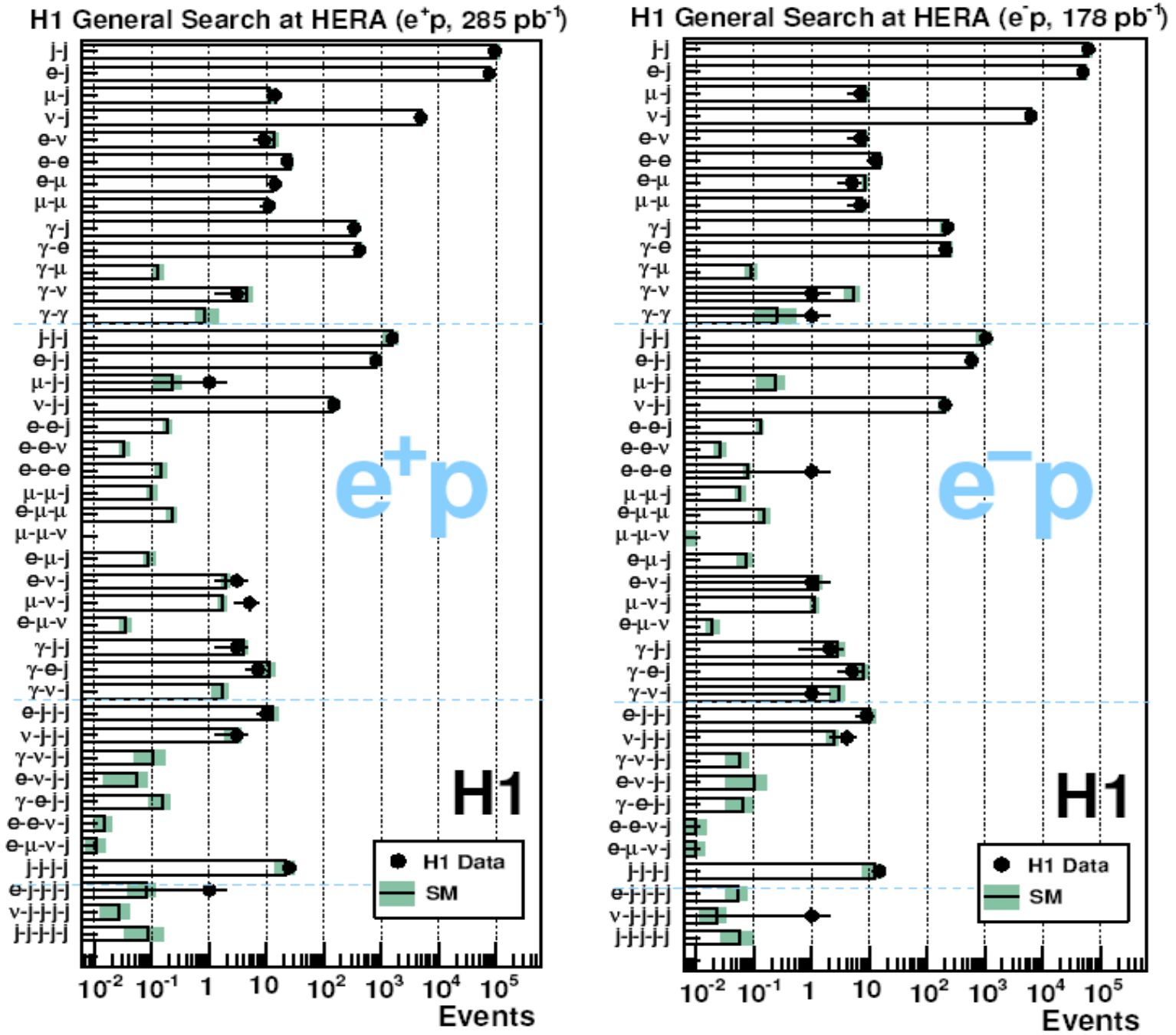
General search with high p_t objects

e, μ, γ, jets, ν with $p_t > 20$ GeV, isolated.

41 channels

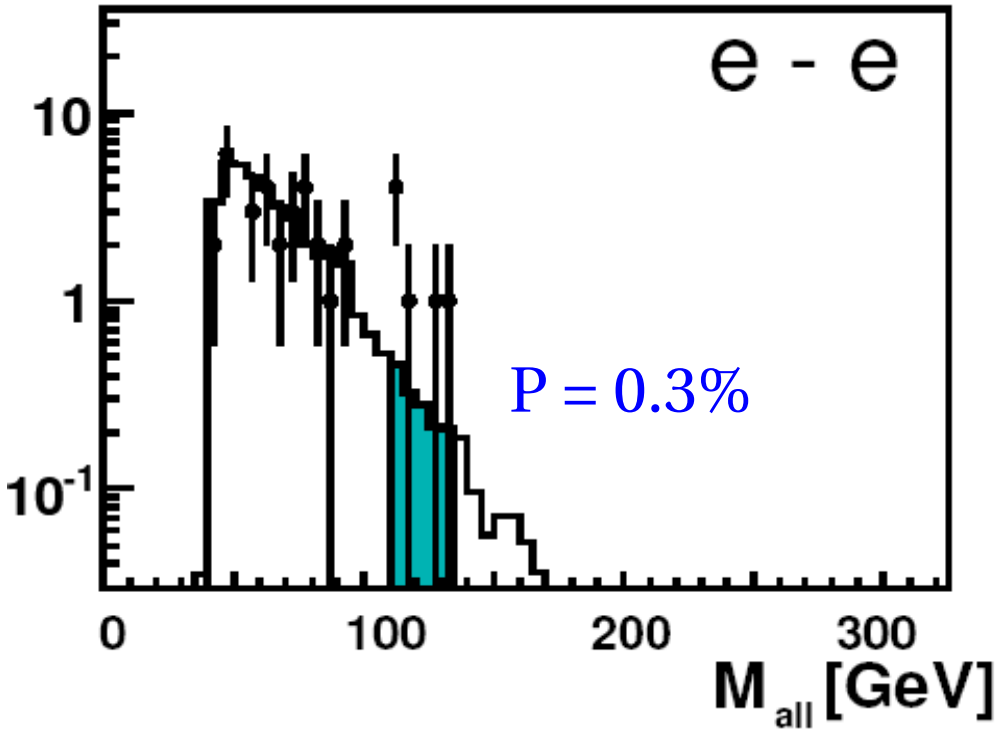
largest rate fluctuation: μ-jet-ν.

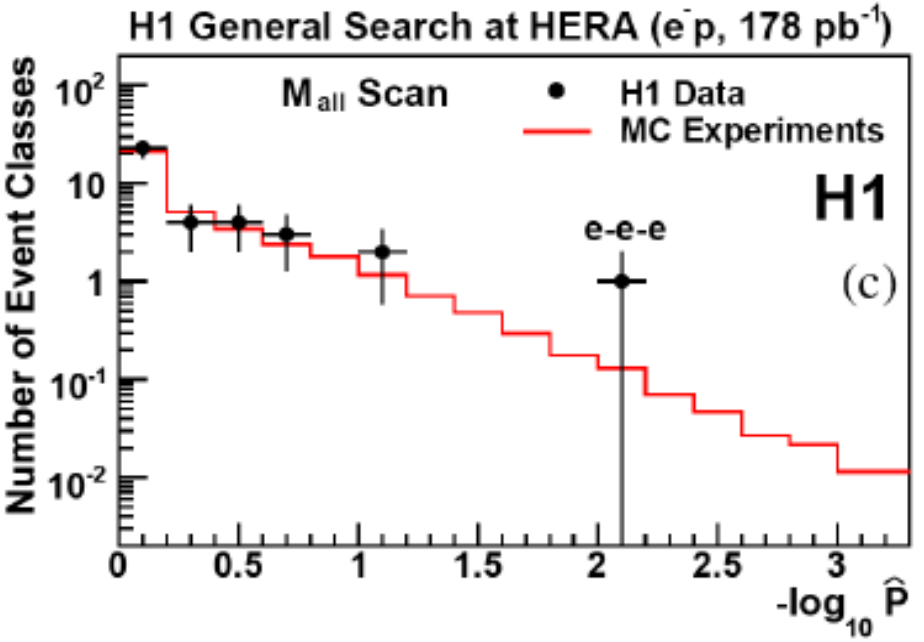
All channels described by Standard Model physics.

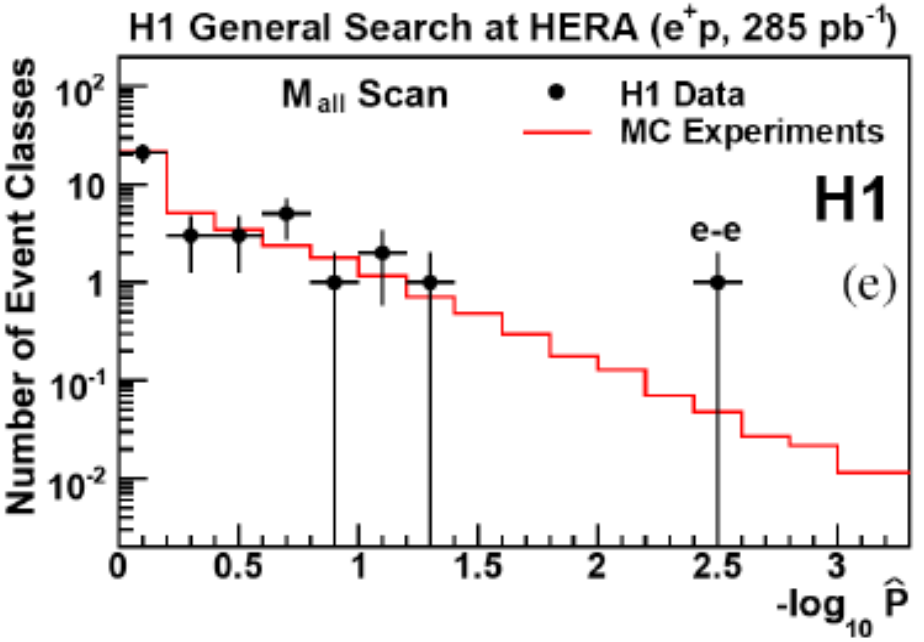


General search with high p_t objects

Mass window scan in each class, search for maximum deviation, calculate P-value w.r.t. SM. Distribution of 41 P-values as expected from MC experiments. Largest deviation in multi-electrons:







Summary

- HERA ep beams ended on June 30, 2007, after 15 years of successful operation.
- Each collider experiment has collected close to 0.5 fb^{-1} of high quality data with precision detectors.
- A comprehensive search for new physics phenomena using all data and combining H1 and ZEUS is being completed and published.
- Overall, no significant deviation from the standard model was found.
- For several channels and signatures the most stringent limits for new physics come from HERA.

Backup

Excited Fermions

Gauge mediated interactions of excited fermions:

$$\mathcal{L}_{GM} = \frac{1}{2\Lambda} F_R^* \bar{\sigma}_R^{\mu\nu} \left(g f \frac{\tau^a}{2} W^a_{\mu\nu} + g' f' \frac{Y}{2} B_{\mu\nu} + g_s f_s \frac{\lambda^a}{2} G^a_{\mu\nu} \right) F_L$$

SU(2) U(1) SU(3)

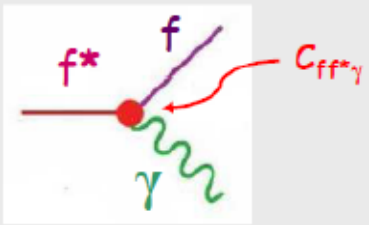
scale of the substructure

weight factors parametrizing different scales for the 3 gauge groups

$$F^*_{L,R} = \left(\nu^*_e, e^* \right)_{L,R}$$

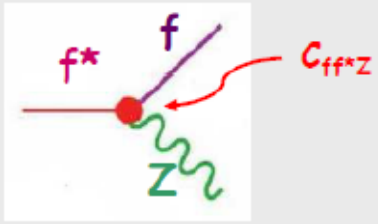
K. Hagiwara et al.
ZfP C29(1985)115

○ ff*γ vertex



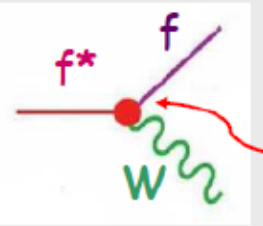
$$C_{\gamma ff^*} = \frac{1}{2}(f I_3 + f' \frac{Y}{2})$$

○ ff*Z vertex



$$C_{Zff^*} = \frac{1}{2}(f I_3 \cot\theta_W - f' \frac{Y}{2} \tan\theta_W)$$

○ ff*W vertex



$$C_{Wff^*} = \frac{f}{2\sqrt{2}\sin\theta_W}$$

$$C_{\gamma\nu\nu^*} = \frac{1}{4}(f - f') = 0|_{f=f'}$$

$$C_{\gamma ee^*} = -\frac{1}{4}(f + f') = 0|_{f=-f'}$$

I_3: third isospin component

Y: hypercharge (±1 for ℓ^*)

θ_W: Weinberg angle

High p_t leptons and missing p_t

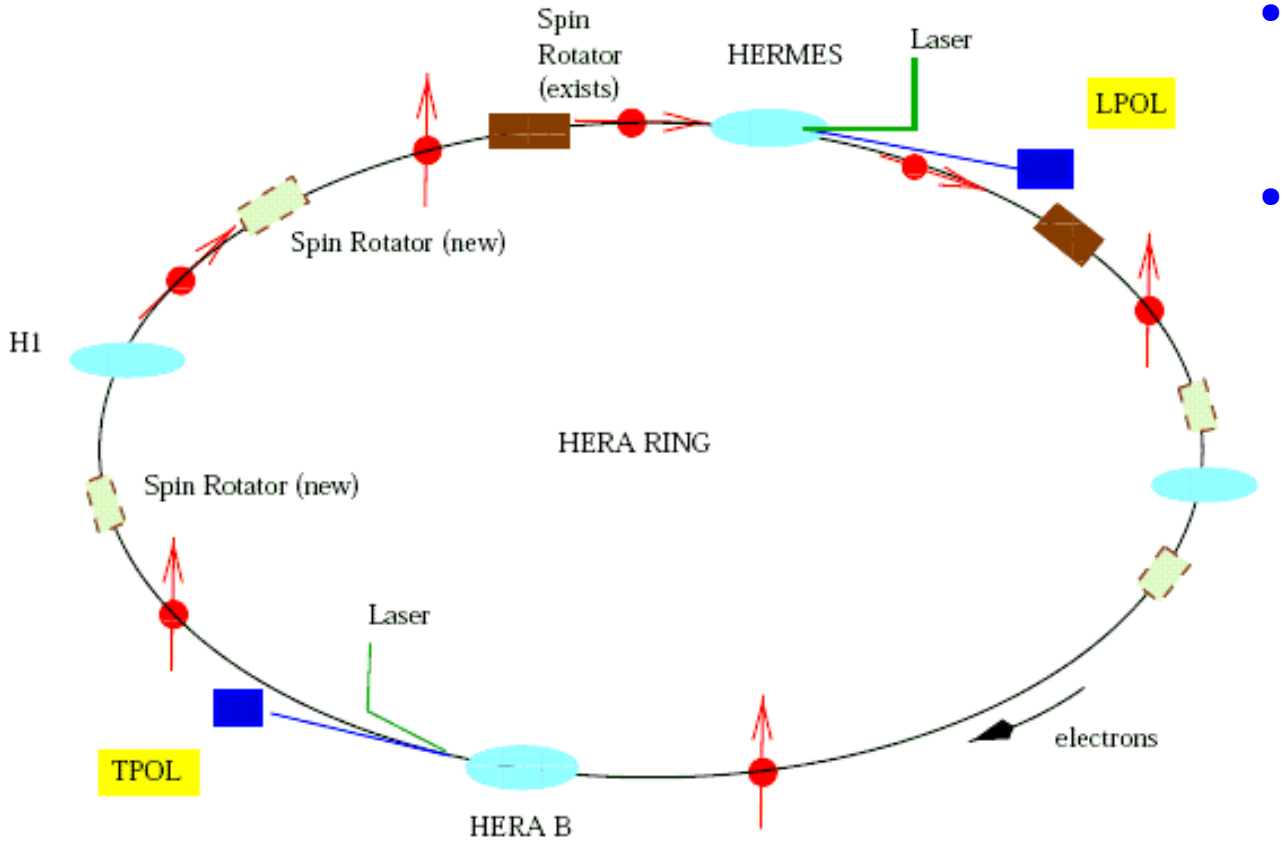
H1 and ZEUS combined in a common phase space:

H1+ZEUS Preliminary l+P_T^{miss} events at HERA I+II		Electron obs./exp. (Signal contribution)	Muon obs./exp. (Signal contribution)	Combined obs./exp. (Signal contribution)
1994-2007 e^+p	Full Sample	39 / 41.3 ± 5.0 (70%)	18 / 11.8 ± 1.6 (85%)	57 / 53.1 ± 6.4 (73%)
0.58 fb^{-1}	$P_T^X > 25$ GeV	12 / 7.4 ± 1.0 (78%)	11 / 7.2 ± 1.0 (85%)	23 / 14.6 ± 1.9 (81%)
1998-2006 e^-p	Full Sample	25 / 31.6 ± 4.1 (63%)	5 / 8.0 ± 1.1 (86%)	30 / 39.6 ± 5.0 (68%)
0.39 fb^{-1}	$P_T^X > 25$ GeV	4 / 6.0 ± 0.8 (67%)	2 / 4.8 ± 0.7 (87%)	6 / 10.6 ± 1.4 (76%)
1994-2007 $e^\pm p$	Full Sample	64 / 72.9 ± 8.9 (67%)	23 / 19.9 ± 2.6 (85%)	87 / 92.7 ± 11.2 (71%)
0.97 fb^{-1}	$P_T^X > 25$ GeV	16 / 13.3 ± 1.7 (73%)	13 / 12.0 ± 1.6 (86%)	29 / 25.3 ± 3.2 (79%)

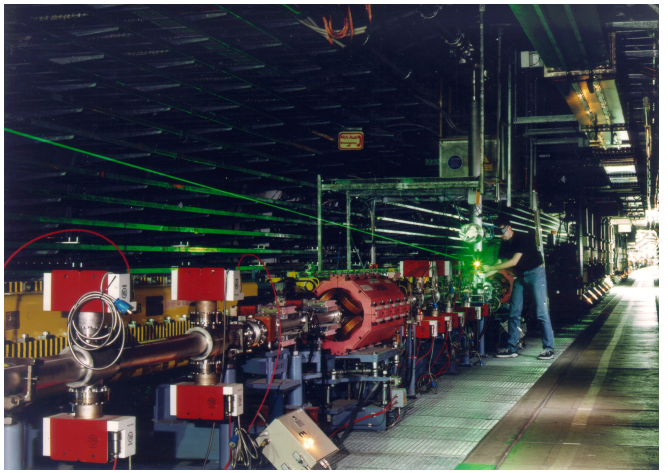
Polarized e±

e beam acquires transverse polarization by the Sokolov-Ternov effect (magnetic moment couples to the dipole B field, spin flip by synchrotron radiation emission).

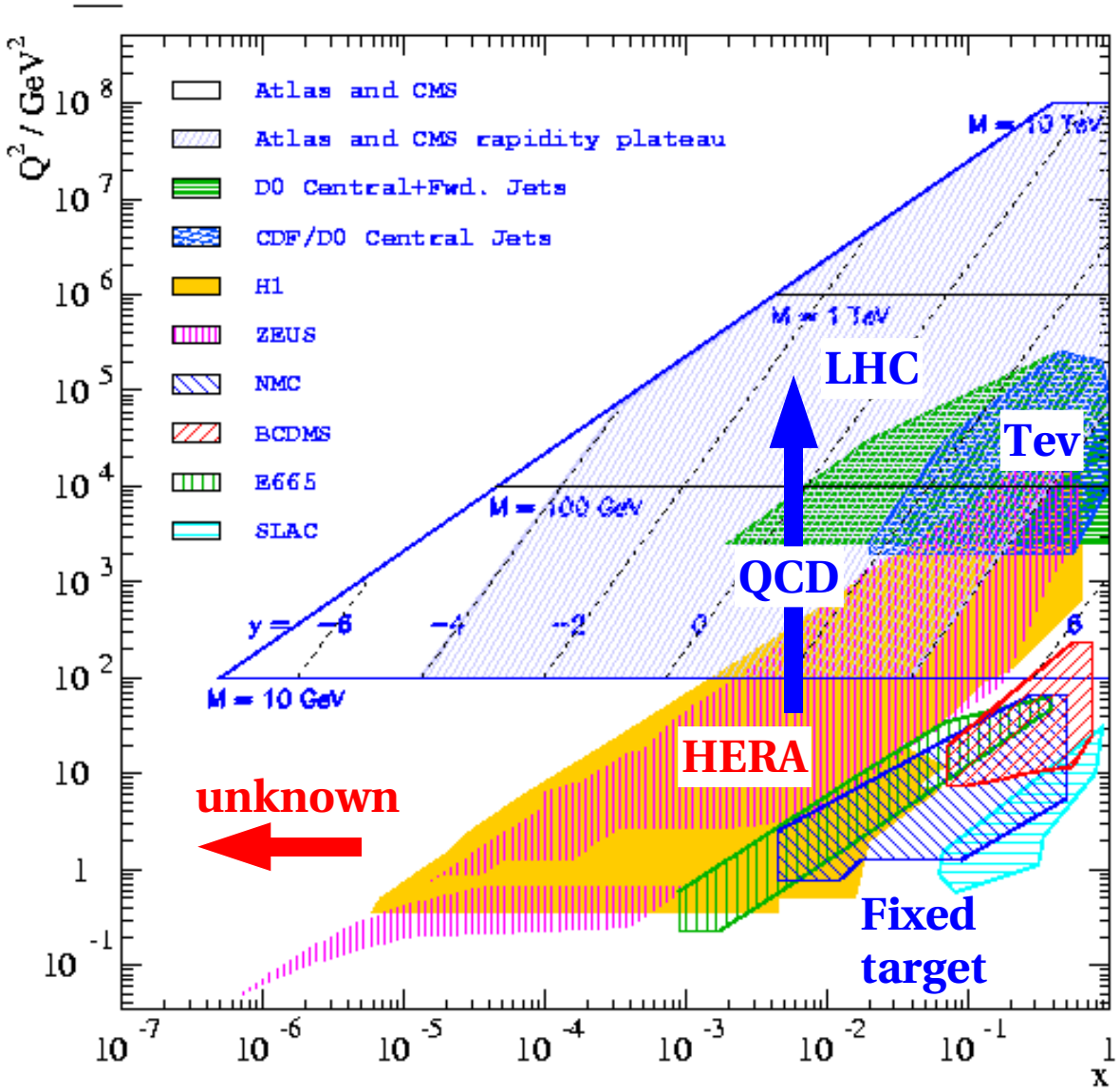
Spin rotators provide longitudinal polarization at the experiments (Hermes since 1995, H1 and ZEUS since 2003).



- Polarization typically 30-40%.
- Polarization monitored by Compton backscattering of laser beams.

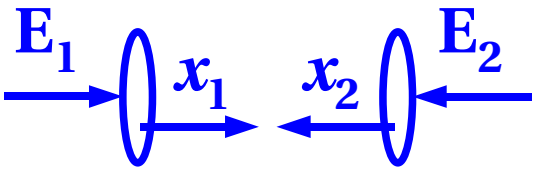


From HERA to LHC kinematics



QCD evolution (DGLAP equation).

Proton-proton collisions:



$s = 4\,E_1\,E_2$

$\hat{s} = x_1\,x_2\,s \geq M^2.$

$M^2 \triangleq Q^2.$

$$x_{1,2} = M/\sqrt{s}\cdot\exp(\pm y)$$

Rapidity y.

HERA covers the x-range for central production of heavy particles at the LHC.