Physics at HERA

Summer Student Lectures
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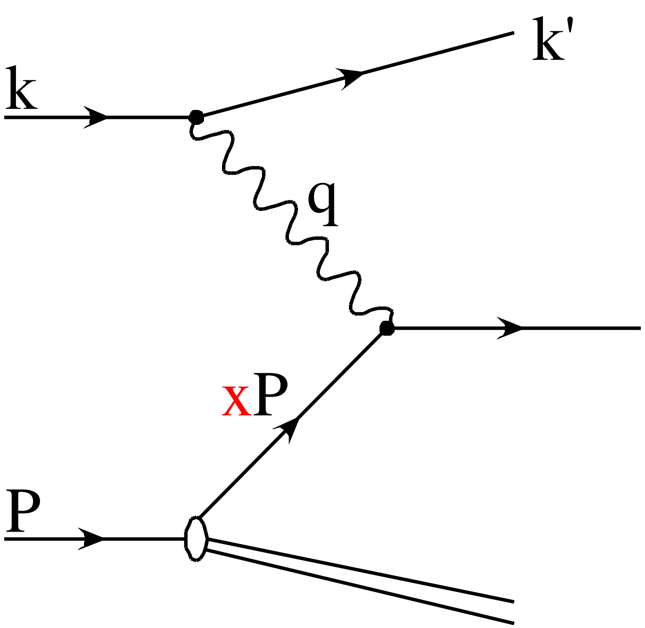
Overview Part 2

- Reminder
- Parton Density Fits
- High Q^2 and Electroweak Physics
  - Neutral Current
  - Charged Current
- Exotics
  - Model Dependent Searches
  - Model Independent Searches

Reminder: Deep Inelastic Scattering

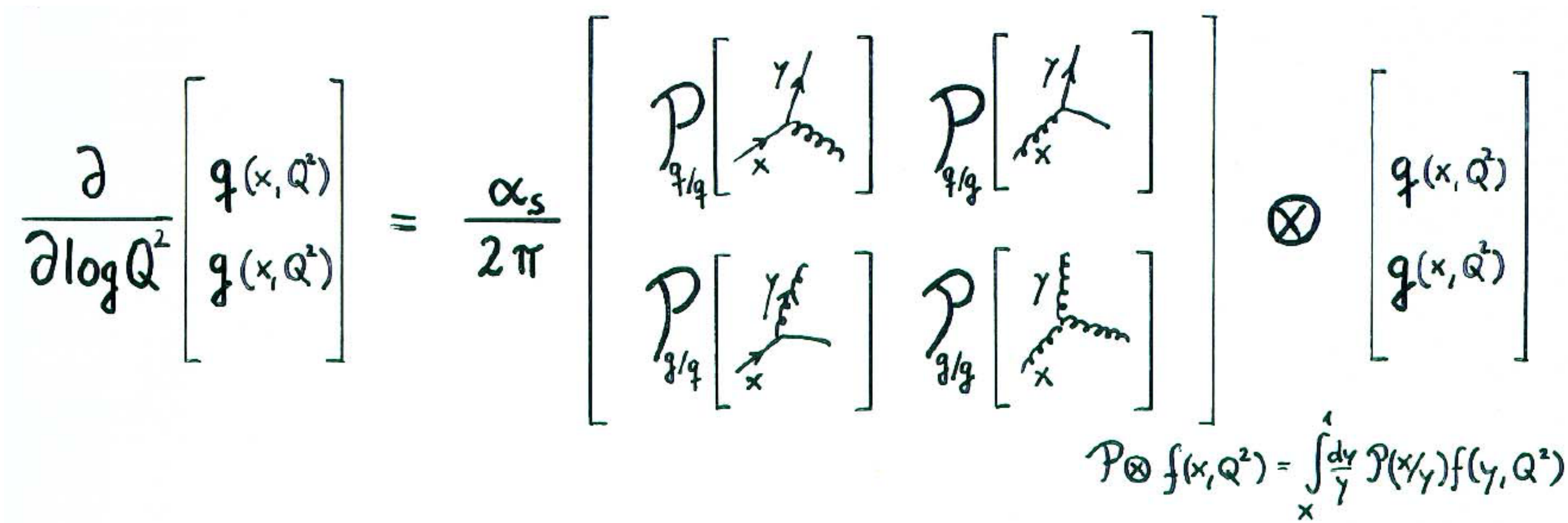
- $Q^2 = -q^2 = -(k - k')^2$ four-momentum transfer
- $y = \frac{q \cdot P}{k \cdot P}$ inelasticity
- $x = \frac{Q^2}{2\, q \cdot P} = \frac{Q^2}{ys}$ parton momentum fraction



$$\frac{d^2\sigma}{dx\, dQ^2} = \frac{4\pi\alpha^2}{Q^4}\frac{1}{x}\left[\left(1 - y + \frac{y^2}{2}\right) F_2(x, Q^2)\right]$$

$$F_2(x, Q^2) = x \sum e_q^2 \left(q(x) + \bar{q}(x)\right)$$

DGLAP Evolution Equations



- Q^2 dependence of quark densities $q(x,Q^2)$ and gluon density $g(x,Q^2)$ is predicted

Parton Density Fits

DGLAP predicts only Q^2 dependence

- ➔ assume parametrisation of the parton density functions (PDFs) as a function of x at a starting scale Q_0^2 (typically around 4-7 GeV^2):

$$x\ q(x, Q_0^2) = a\, x^b (1-x)^c [1 + d\, x]$$

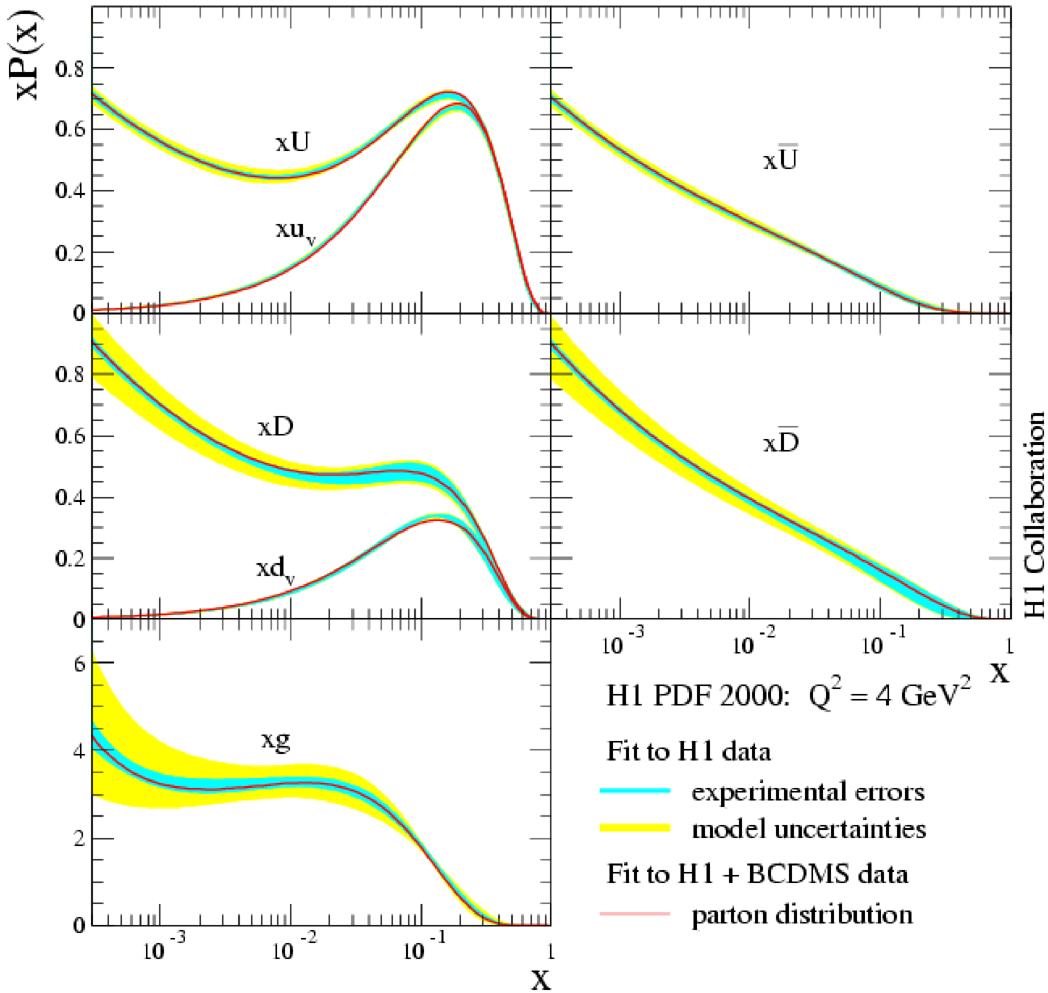
- ➔ evolve the PDFs to all measured Q^2, calculate F_2, and fit the parameters to match the data

- some freedom in the procedure!
  - how many parameters, which Q_0^2?
  - how to combine quark and antiquark densities?

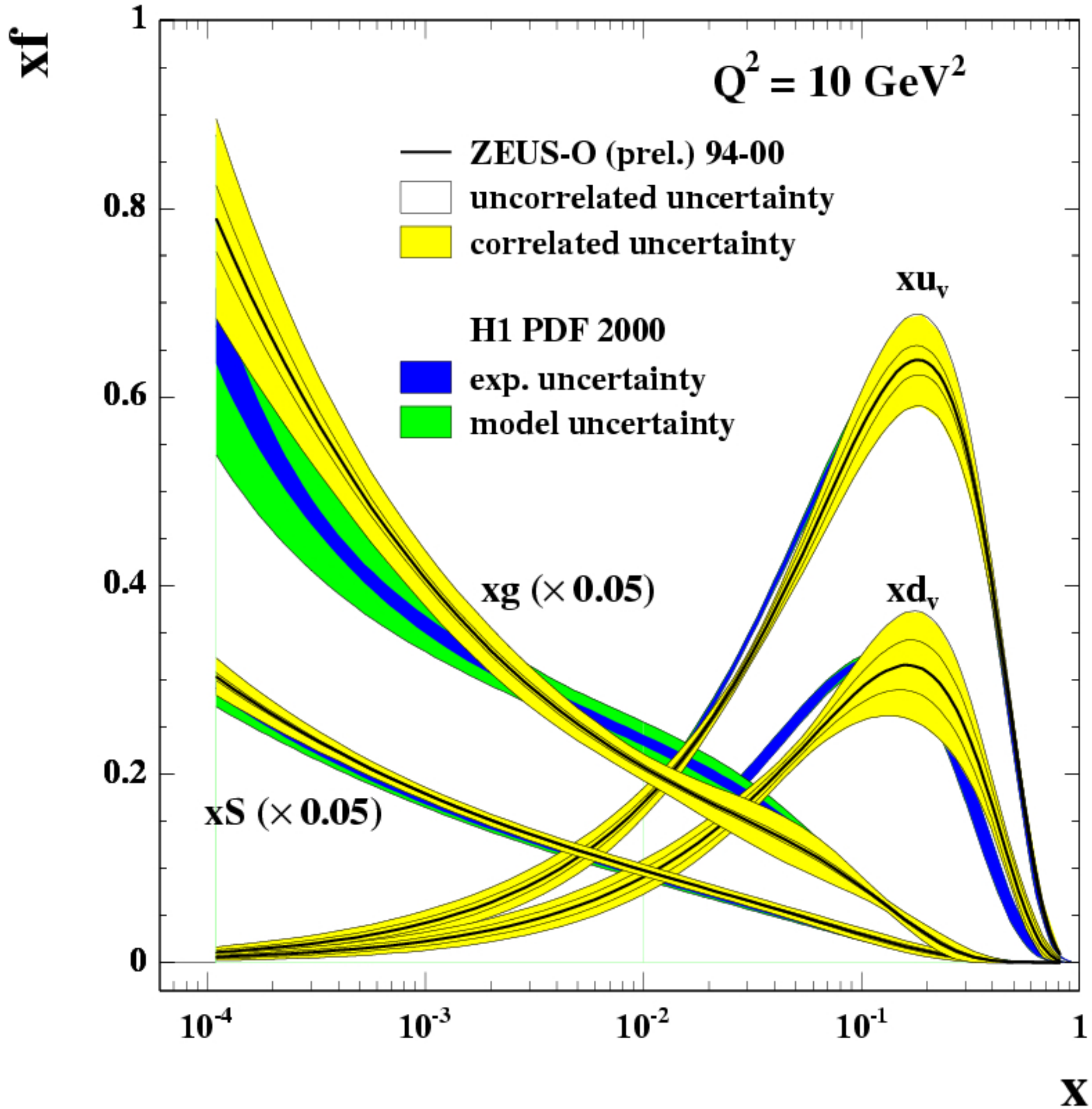
Parton Density Fits

quark and antiquark densities:

- most general: $u, \bar{u}, d, \bar{d}, s, \bar{s}, c, \bar{c}, (b, \bar{b})$
- distinguish valence and sea quarks: u_v, d_v, sea (some assumptions on de-composition of *sea* needed)
- distinguish *up*-type and *down*-type quarks:
  $U = u + c, \quad D = d + s (+b)$
  $\bar{U} = \bar{u} + \bar{c}, \quad \bar{D} = \bar{d} + \bar{s} (+\bar{b})$
  $\rightarrow u_v = U - \bar{U}, d_v = D - \bar{D}$



H1 & ZEUS Parton Densities



differences:

- H1:
  - $U, \overline{U}, D, \overline{D}, g$
  - $xU = a\,x^b(1-x)^c \left[1+d\,x+f\,x^3\right]$
  - 10 free parameters
- ZEUS:
  - u_v, d_v, sea, g
  - $x\,u_v = a\,x^b(1-x)^c\left[1+d\,x\right]$
  - 11 free parameters

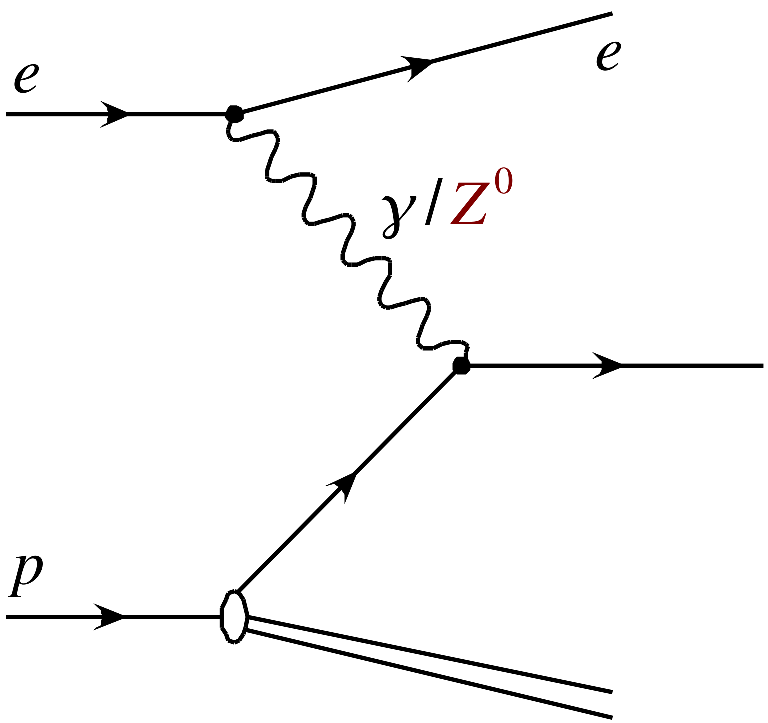
High Q^2 & Electroweak Physics

More Structure Functions

$F_L = F_2 - 2xF_1 = 0$ in the QPM

$$\frac{d^2\sigma^{\pm}_{NC}}{dx\,dQ^2} = \frac{2\pi\alpha^2}{Q^4}\frac{1}{x}Y_+\left[F_2(x,Q^2) - \frac{y^2}{Y_+}F_L(x,Q^2) \mp \frac{Y_-}{Y_+}xF_3(x,Q^2)\right]$$

$F_3 : \gamma - Z^0 -$ interference



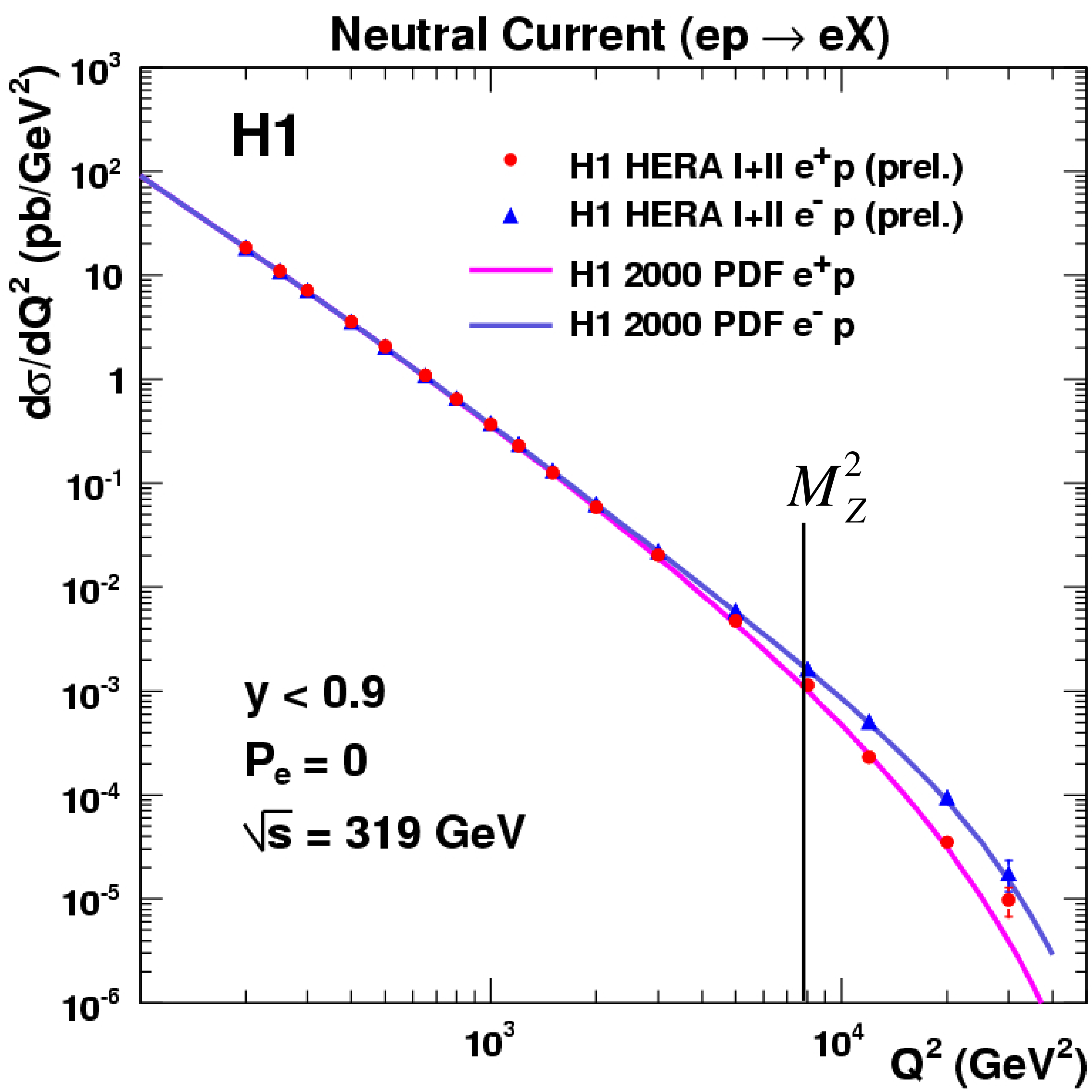
$$Y_{\pm} = 1 \pm (1-y)^2$$

- F_L relevant only at large y
- F_3 relevant only at large Q^2, different sign for e^+ and e^-

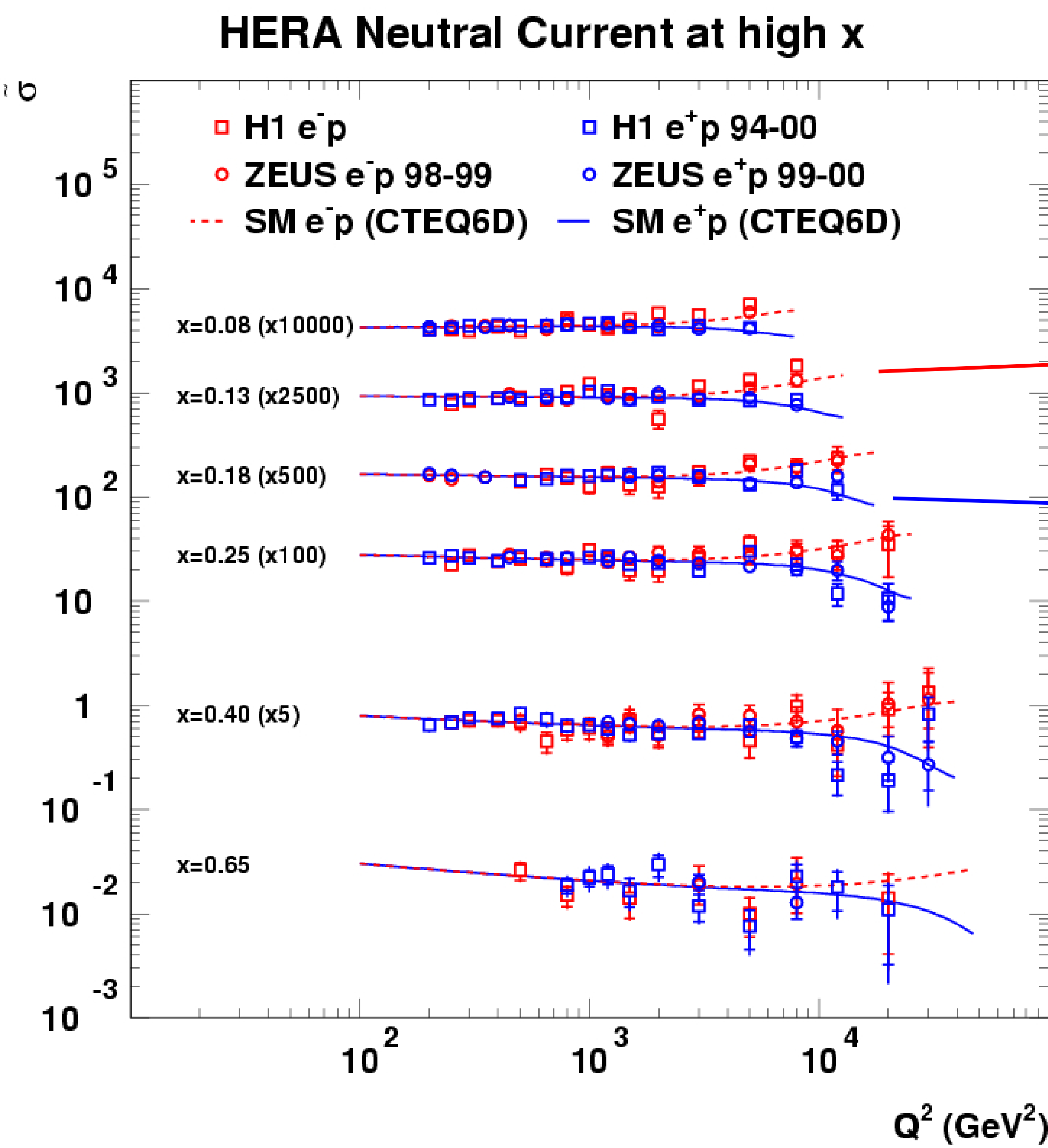
High Q^2 Neutral Current

- difference between e^+p and e^-p only at large $Q^2 \approx M_Z^2$

➔ $\gamma - Z^0 -$ interference



High Q^2 Neutral Current



$$\tilde{\sigma} = \frac{x Q^4}{2\pi\alpha^2} \frac{1}{Y_+} \frac{d^2\sigma^{\pm}_{NC}}{dx\,dQ^2}$$

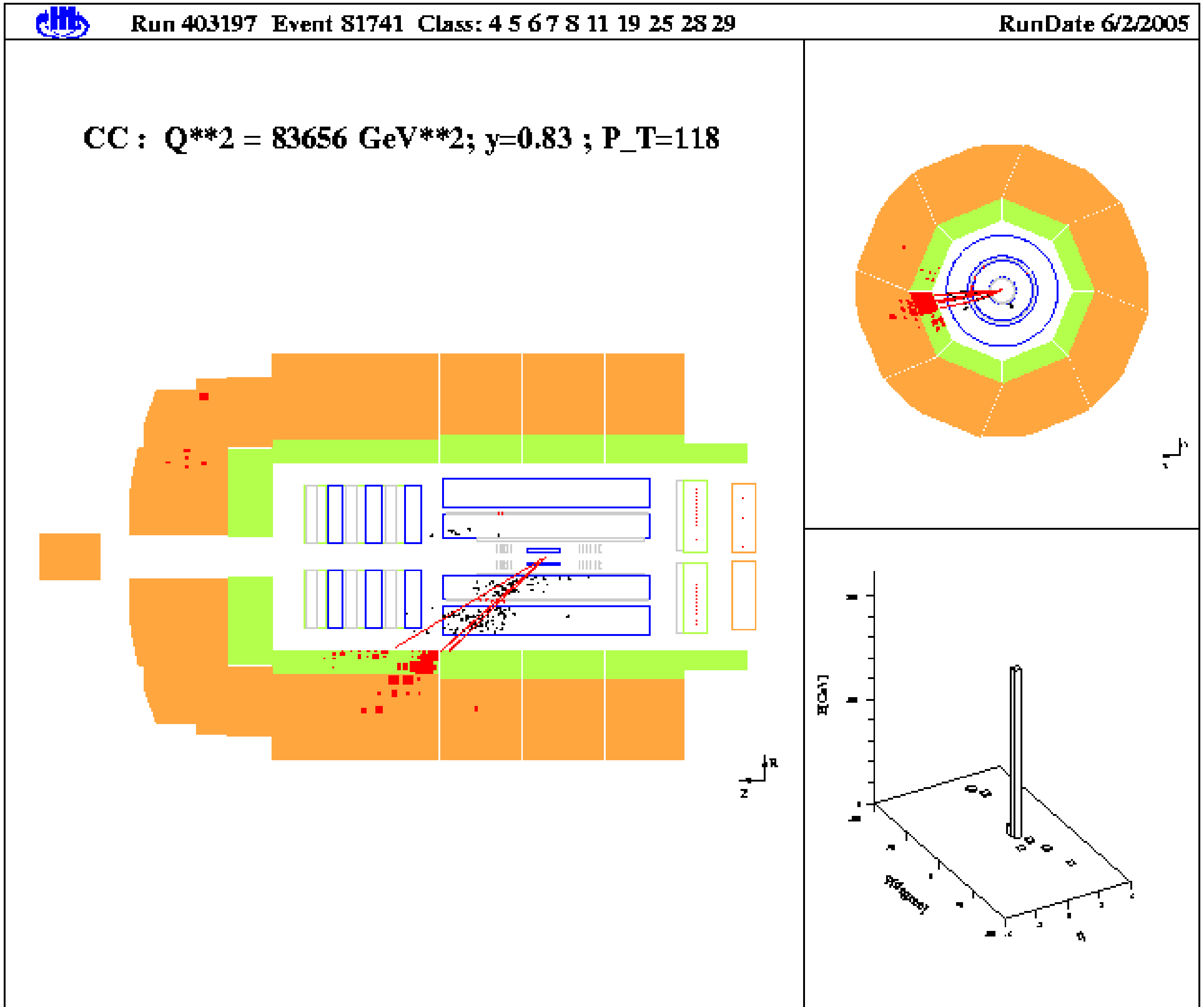
e⁻ positive interference

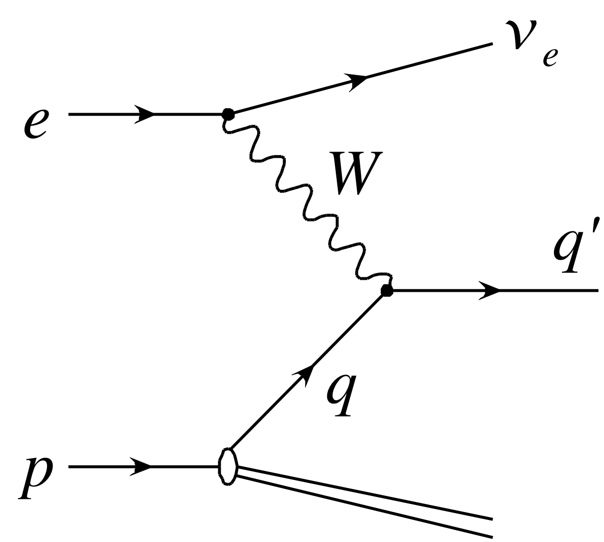
e⁺ negative interference

$$x F_3 \propto x \sum e_q^2 (q - \bar{q})$$

direct handle on valence quark distribution!

Charged Current Interactions





neutrino not visible in detector

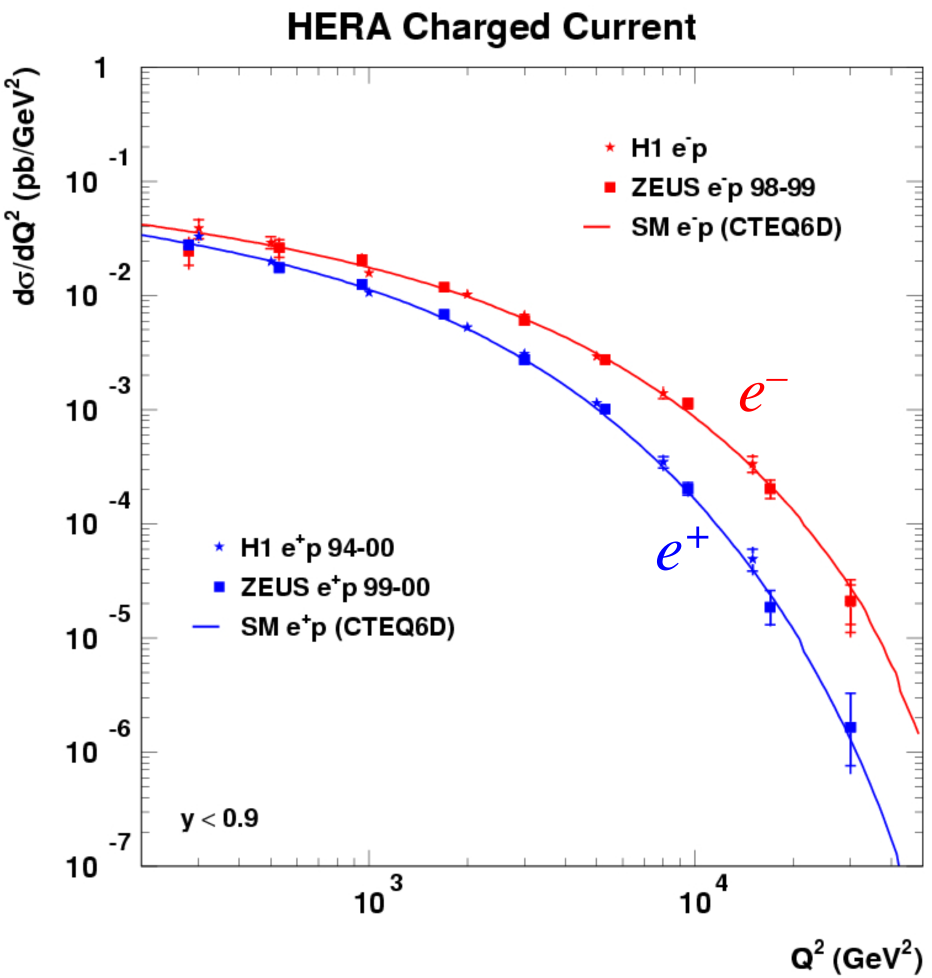
→ imbalance in transverse plane

Charged Current Cross Section

$$\frac{d^2\sigma^{\pm}_{CC}}{dx\,dQ^2} = \frac{G_F^2}{4\pi x}\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2 Y_+\left[W_2^{\pm} - \frac{y^2}{Y_+}W_L^{\pm} \mp \frac{Y_-}{Y_+}x\,W_3^{\pm}\right]$$

- W bosons couple differently to *up*- and *down*-type quarks
- in the QPM:
  $W_2^- = x(U+\overline{D}), \quad xW_3^- = x(U-\overline{D})$
  $W_2^+ = x(\overline{U}+D), \quad xW_3^+ = x(D-\overline{U})$
  $W_L^{\pm} = 0$

➔ $\sigma^-_{CC} \propto x\left[U + (1-y)^2\overline{D}\right]$
$\sigma^+_{CC} \propto x\left[\overline{U} + (1-y)^2 D\right]$



Comparison NC vs. CC

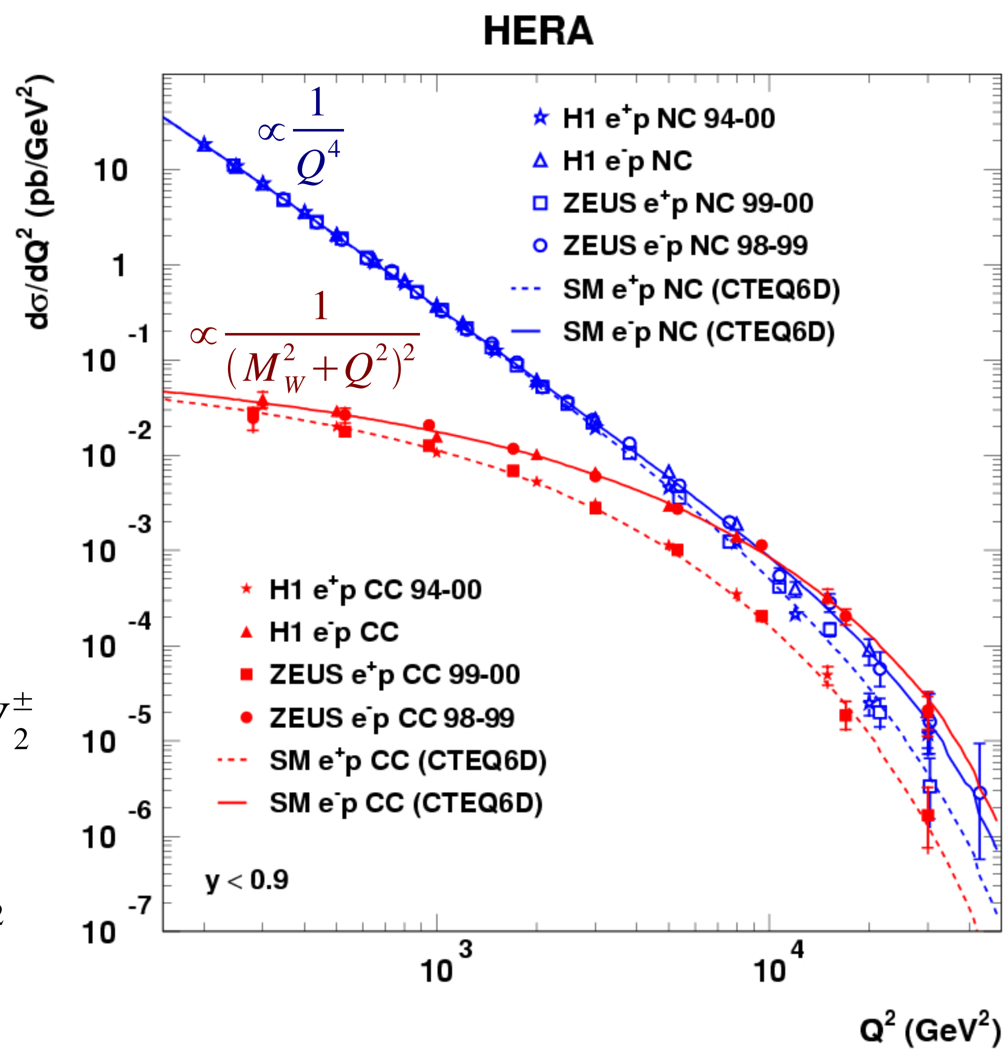
- at low Q^2: different dependences because of photon in NC
- at high Q^2: „electroweak unification"

but:

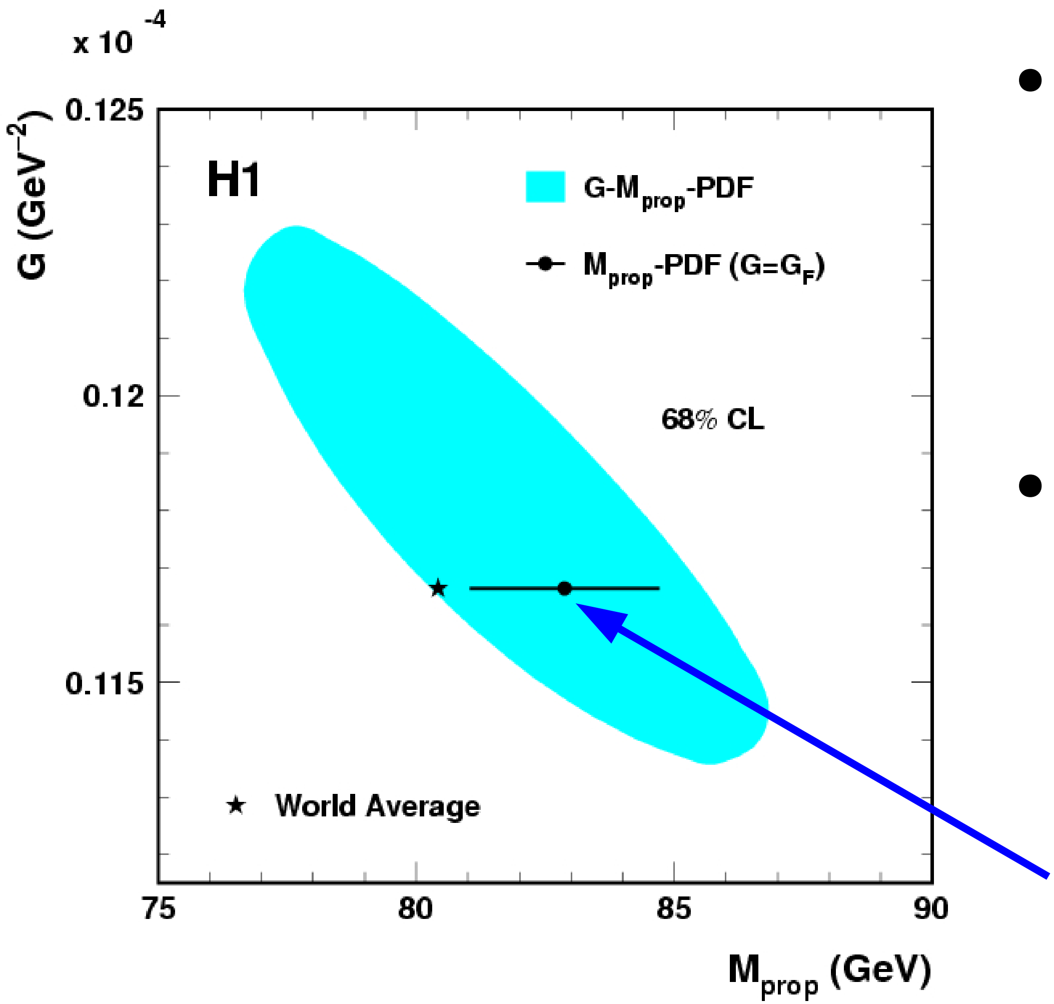
$$\frac{d^2\sigma^{\pm}_{CC}}{dx\,dQ^2} \approx \frac{G_F^2}{4\pi x}\cdot\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2 \cdot Y_+ W_2^{\pm}$$

$$\frac{d^2\sigma^{\pm}_{NC}}{dx\,dQ^2} \approx \frac{2\pi\alpha^2}{x}\cdot \quad \frac{1}{Q^4} \quad \cdot Y_+ F_2$$

similar because $G_F \approx \frac{4\pi\alpha}{\sqrt{2}M_W^2}$



Electroweak Parameters: *W* Mass



- $G = G_F$ determined by normalization of the CC cross section
- $M_{prop} = M_W$ determined by the Q^2 dependence of the CC cross section

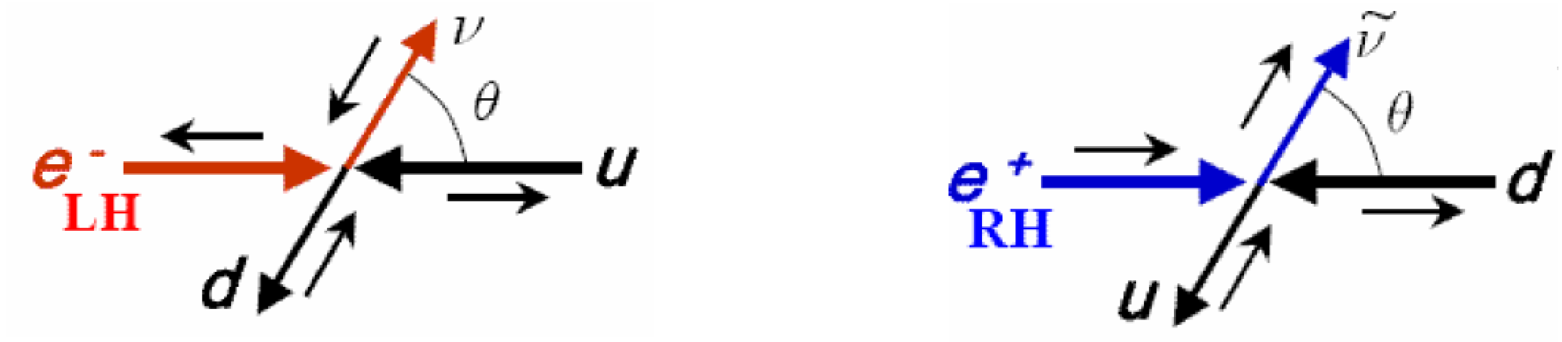
$$82.87 \pm 1.82_{exp} \begin{pmatrix} +0.30 \\ -0.16 \end{pmatrix}_{model} \text{GeV}$$

CC & Polarization

- CC cross section depends on longitudinal electron/positron polarization P_e

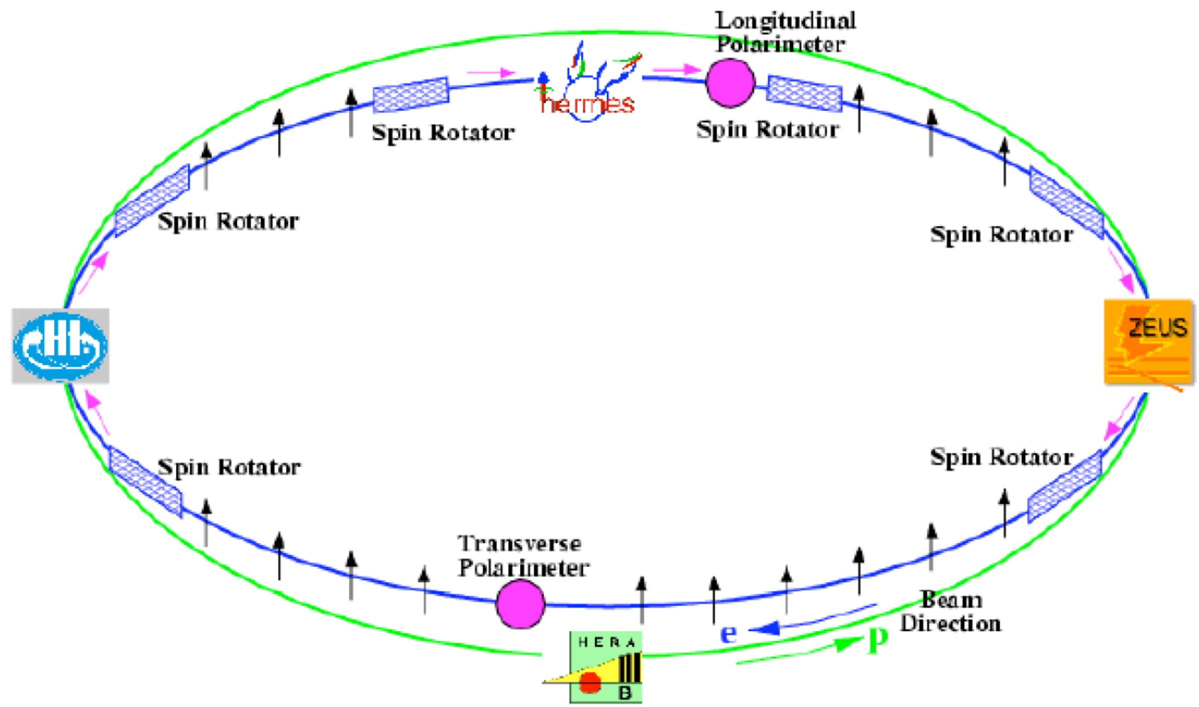
$$\frac{d^2\sigma_{CC}^{\pm}}{dx\,dQ^2}(P_e) \approx (1 \pm P_e)\frac{G_F^2}{4\pi x}\cdot\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2 \cdot Y_+ W_2^{\pm}$$

- reason: *W* boson couples only to left-handed (LH) particles and right-handed (RH) antiparticles:



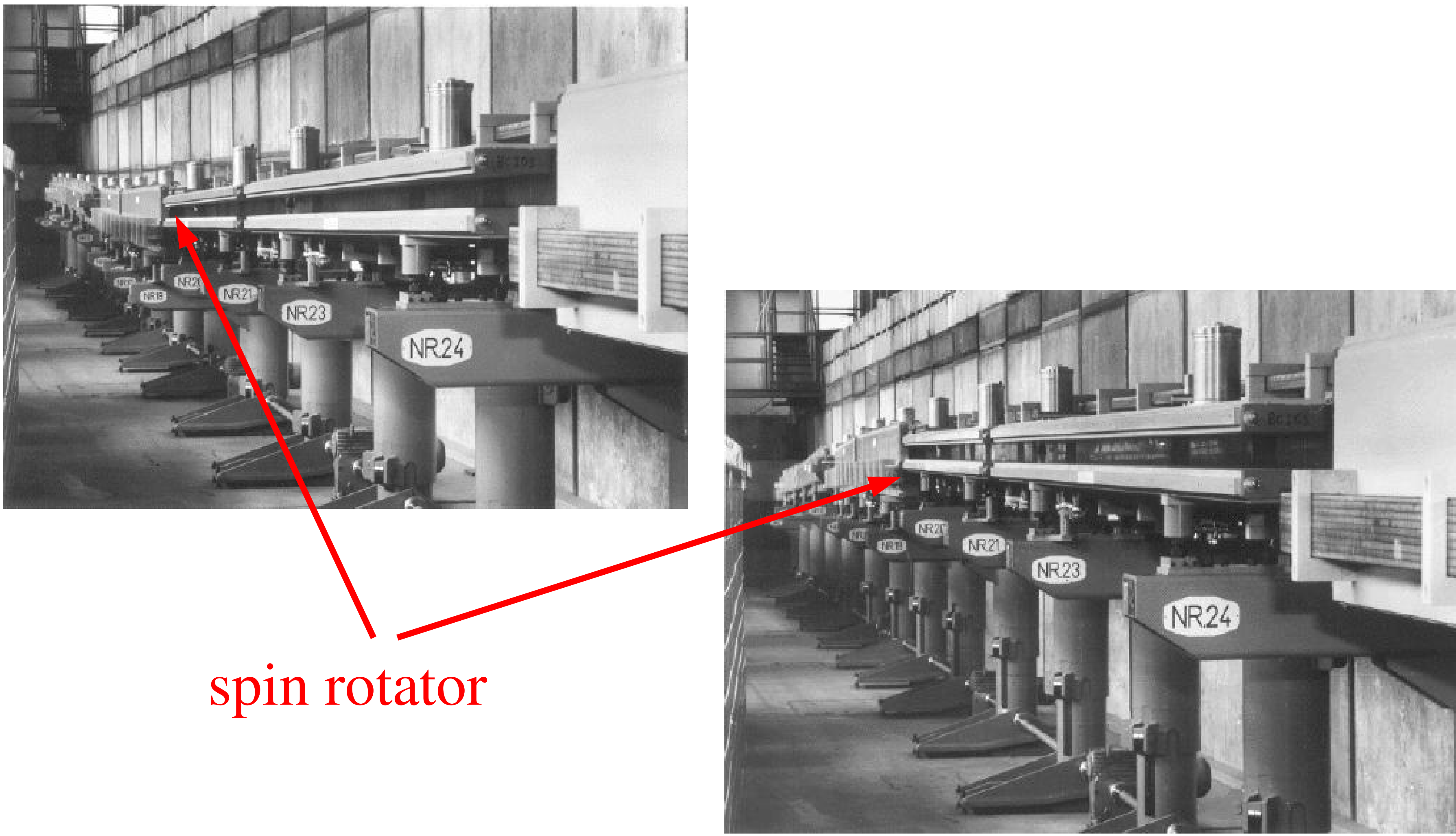
Polarization @ HERA

$$P_e = \frac{N_{RH} - N_{LH}}{N_{RH} + N_{LH}}$$



- transverse polarization builds up in ~40 minutes through synchrotron radiation (Sokolov-Ternov effect)
- spin rotators flip transverse ⟶ longitudinal before experiments and back after

Polarization @ HERA



CC: Polarization Dependence

- Standard Modell expectation:

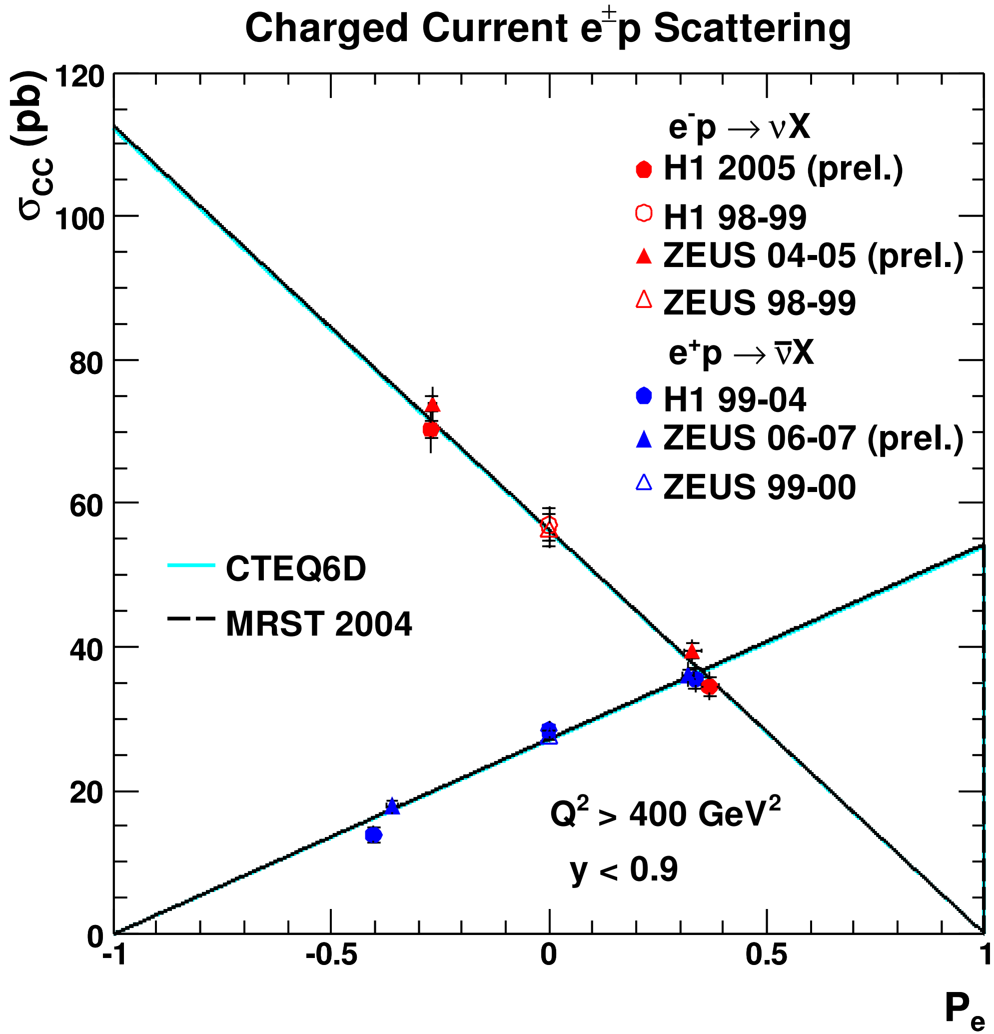
$$\sigma^{-}_{CC}(P_e=+1) = 0$$

$$\sigma^{+}_{CC}(P_e=-1) = 0$$

- experimental result: (H1)

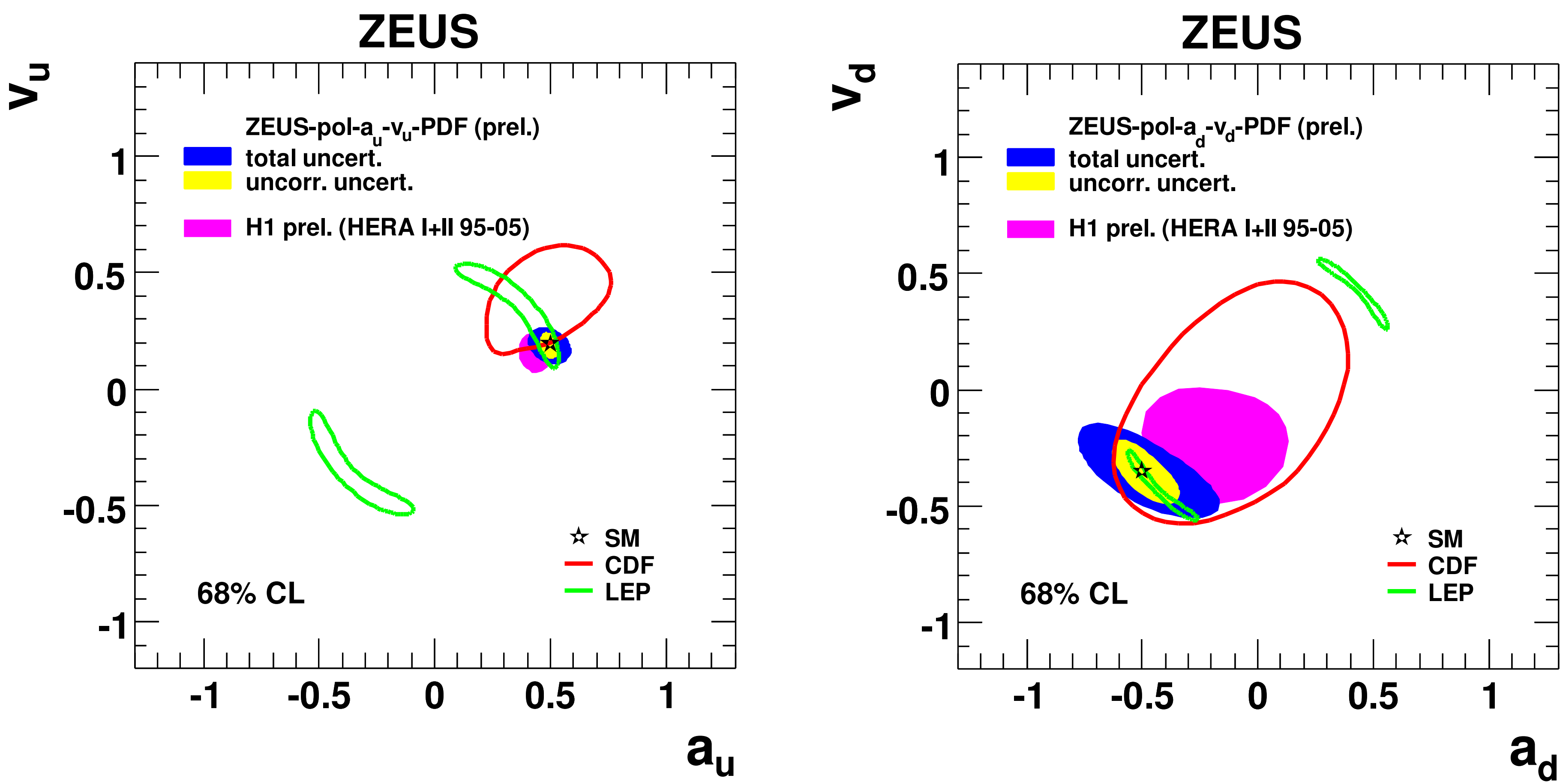
$$\sigma^{-}_{CC}(+1) = -0.9 \pm 2.9_{stat} \pm 1.9_{syst} \pm 1.9_{pol}\ \text{pb}$$

$$\sigma^{+}_{CC}(-1) = -3.9 \pm 2.3_{stat} \pm 0.7_{syst} \pm 0.8_{pol}\ \text{pb}$$



Electroweak Parameters: Z^0 Couplings

polarization also allows better sensitivity to vector and axial-vector couplings of *up*- and *down*-type quarks to the Z^0



Exotics or
Beyond the Standard Modell

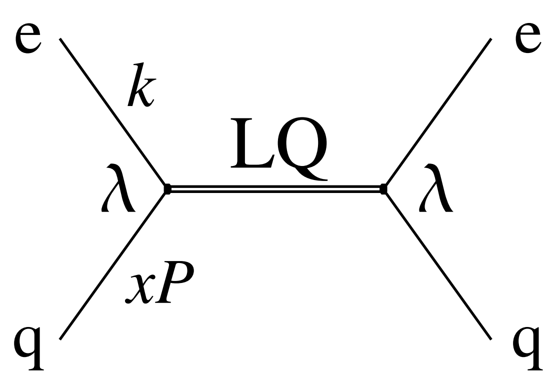
New Particles

many theories predict more particles than the SM:

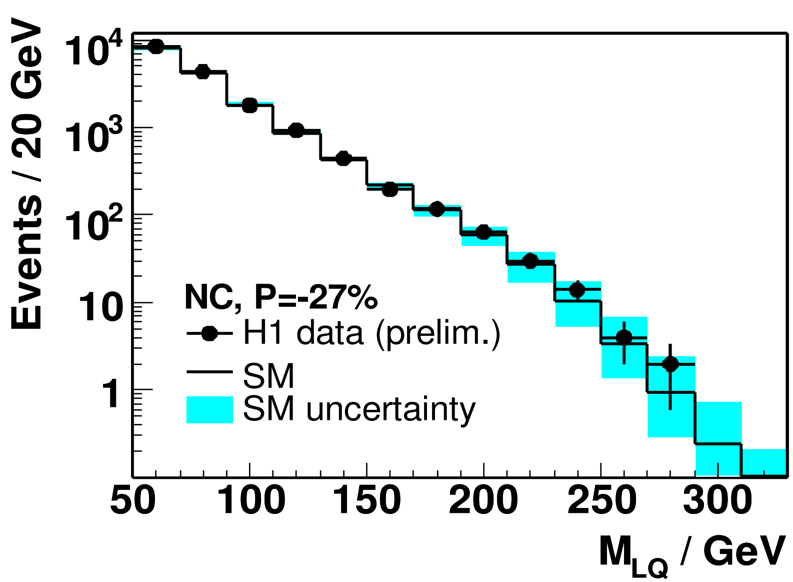
- SUSY:
  - every Standard Model particles has a supersymmetric partner
  - fermion partners are bosons, boson partners fermions
- leptoquarks
  - particle with lepton and quark properties
  - can be produced resonantly in *ep* collisions
- ... exited fermions, contact interactions, large extradimensions ...

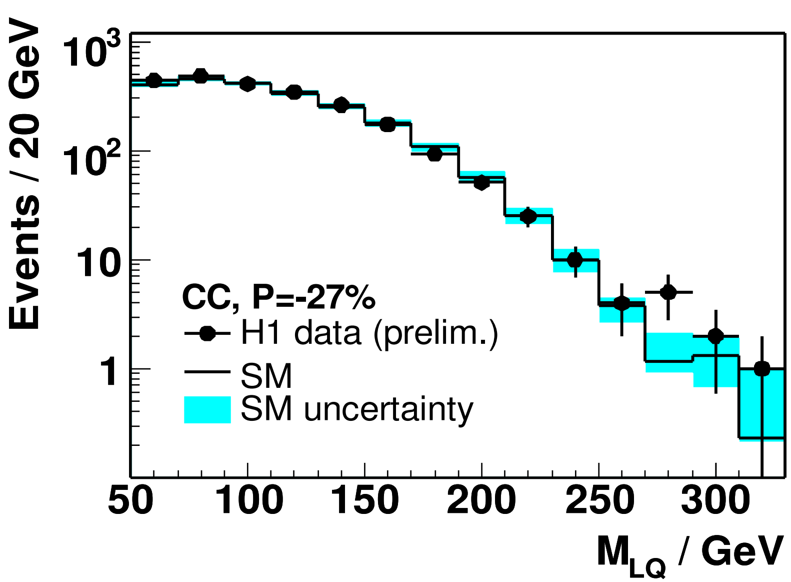
but experimentally search also model-independent!

Leptoquarks

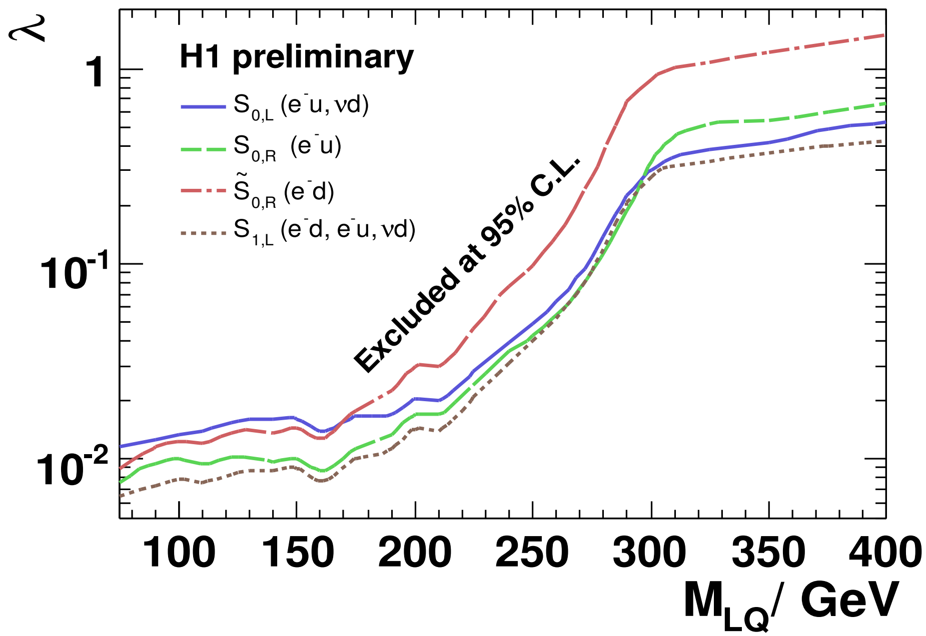


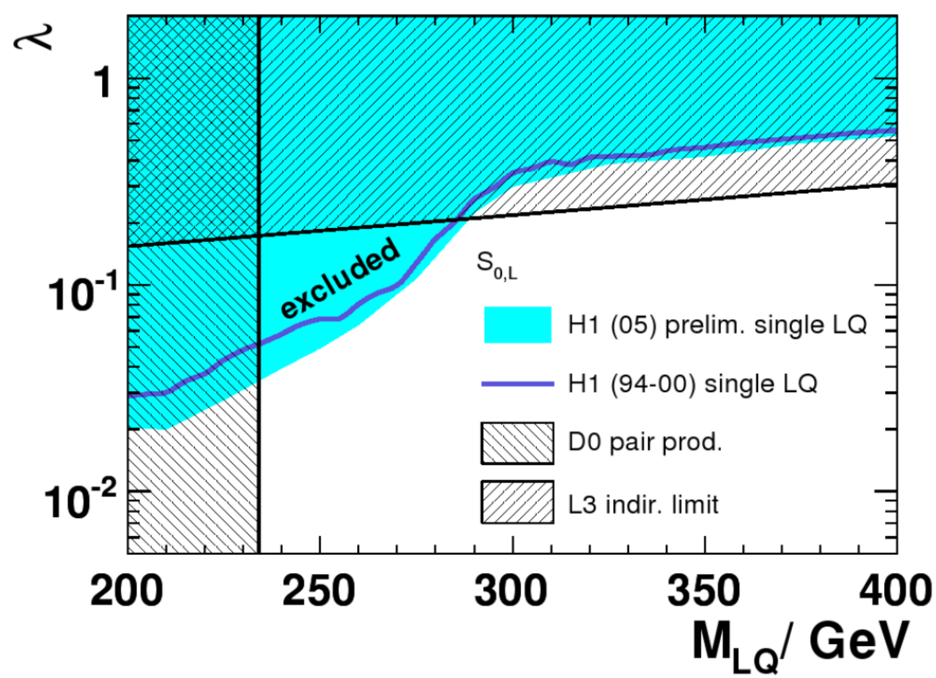
- $M_{LQ}{}^2 = (xP + k)^2 = xs$
- compare measured cross section with SM expectation
- derive limits on coupling λ





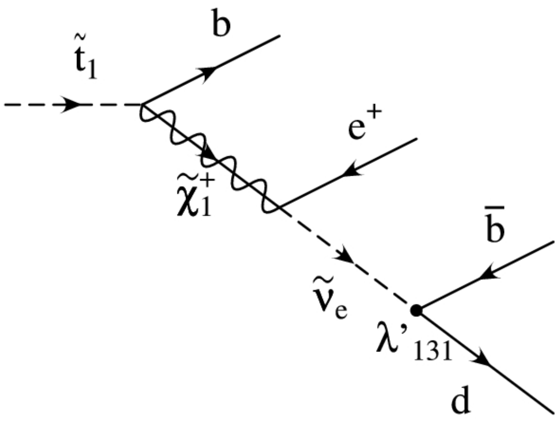
Limits on Leptoquarks

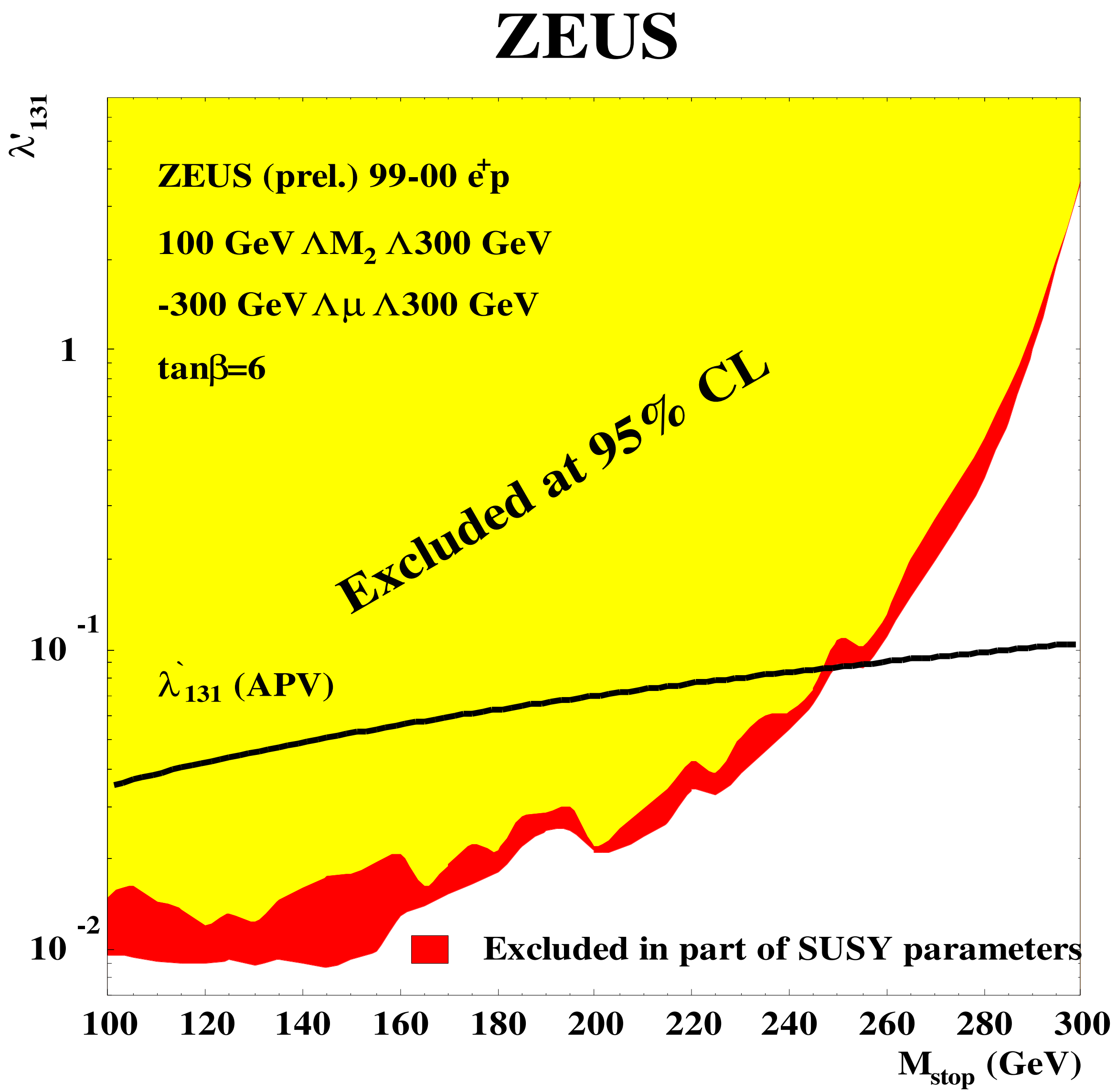




SUSY

- R parity violation: single SUSY particle can be produced
- limits depend on many parameters (masses, couplings)
- example: stop





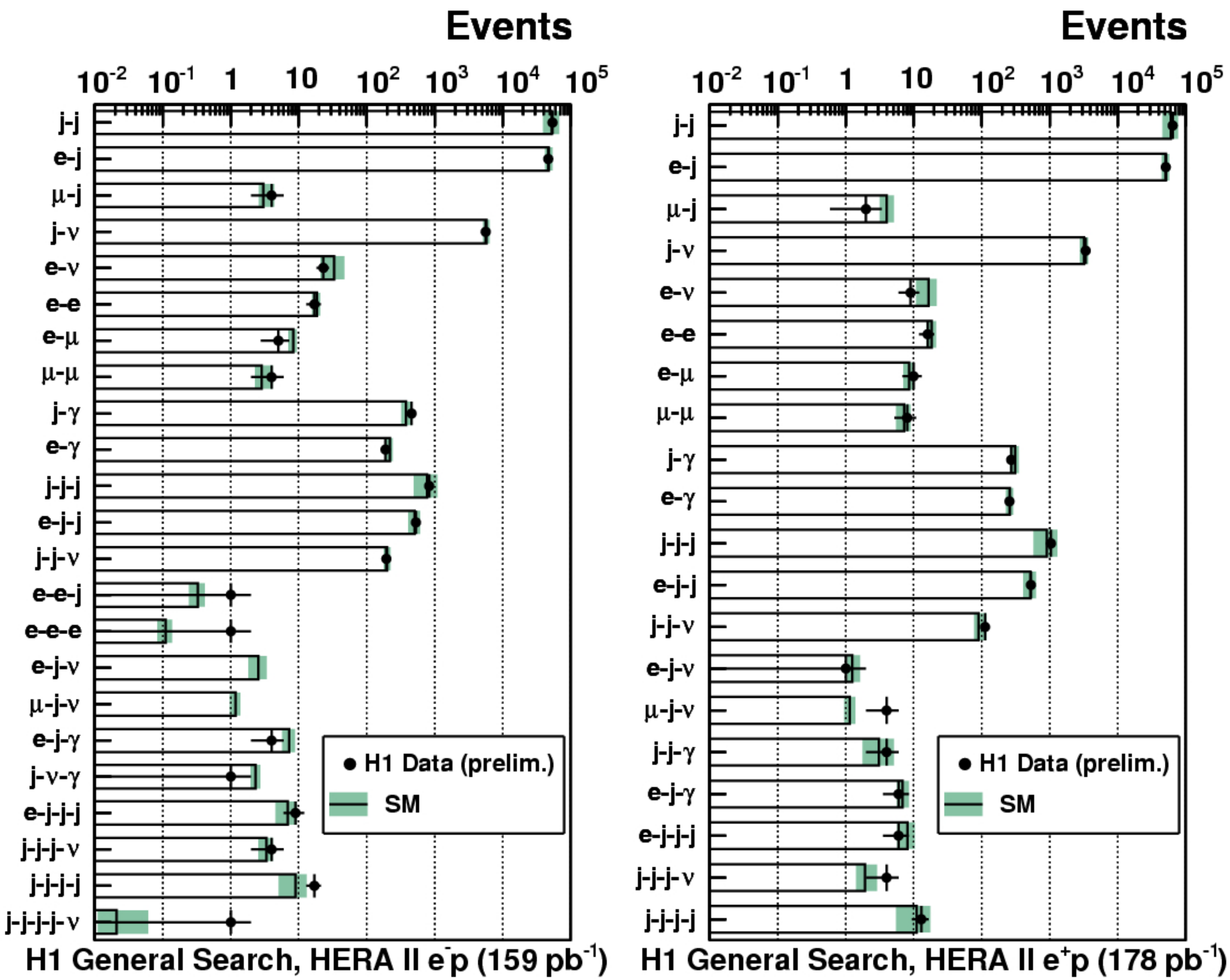
General Searches

- idea: new particles have typically large mass

➔ final state should contain particles with large transverse momentum from the decay

  - jets
  - electrons
  - muons
  - photons
  - neutrinos (missing transverse momentum)

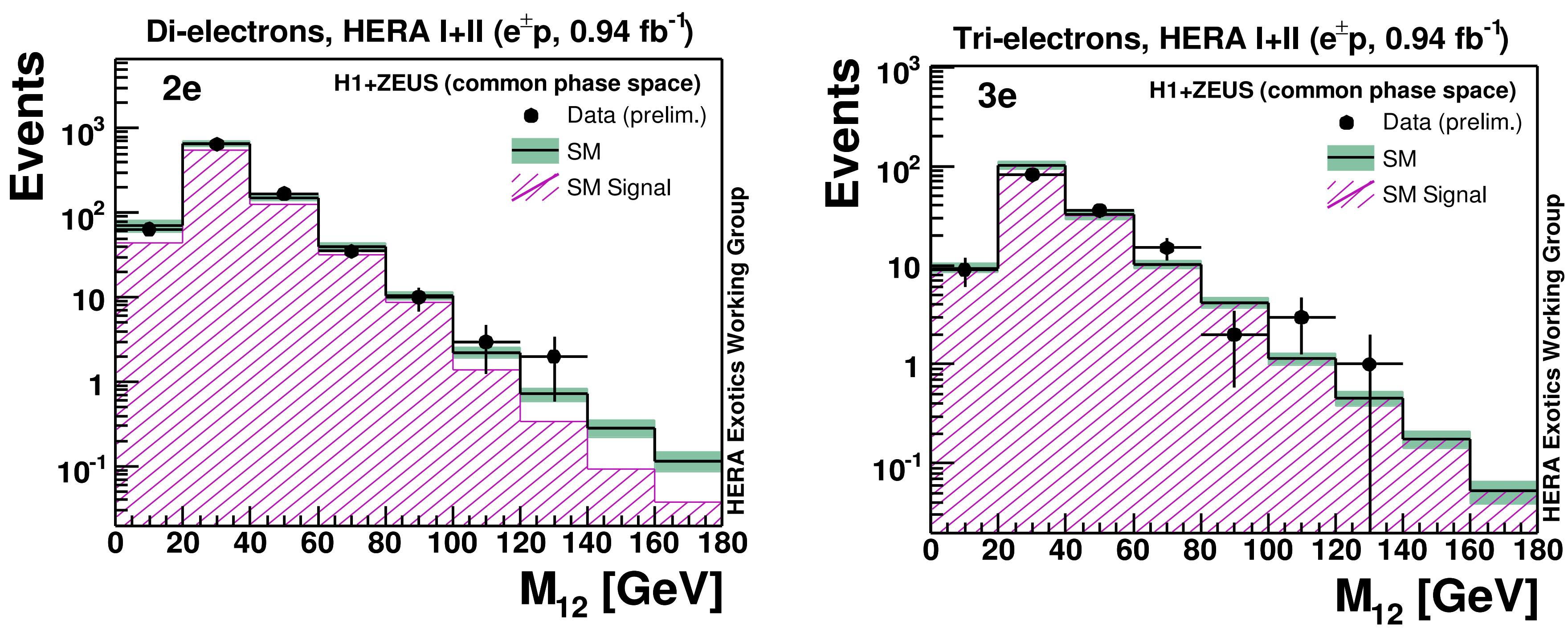
General Searches



every channel in reasonable agreement with the standard model

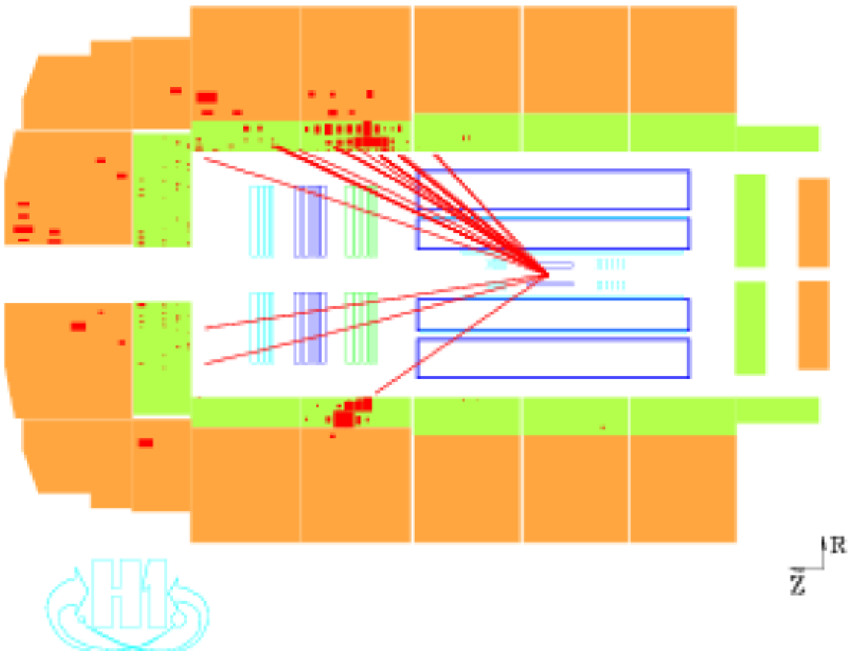
Multi-Leptons

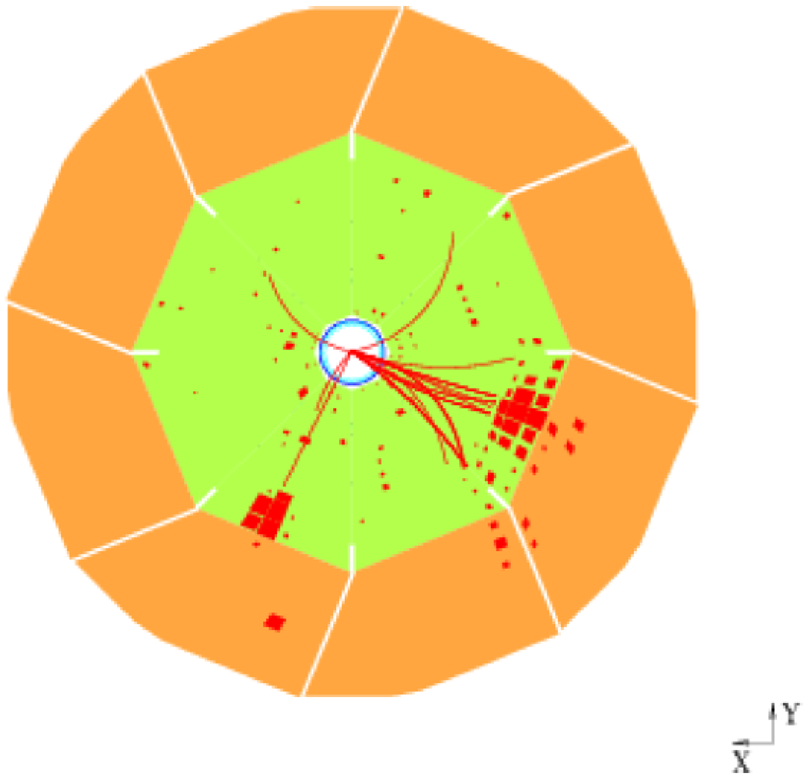
in HERA1 a small excess of di- and tri-electron events at high transverse momenta observed by H1



HERA2 data show no significant excess

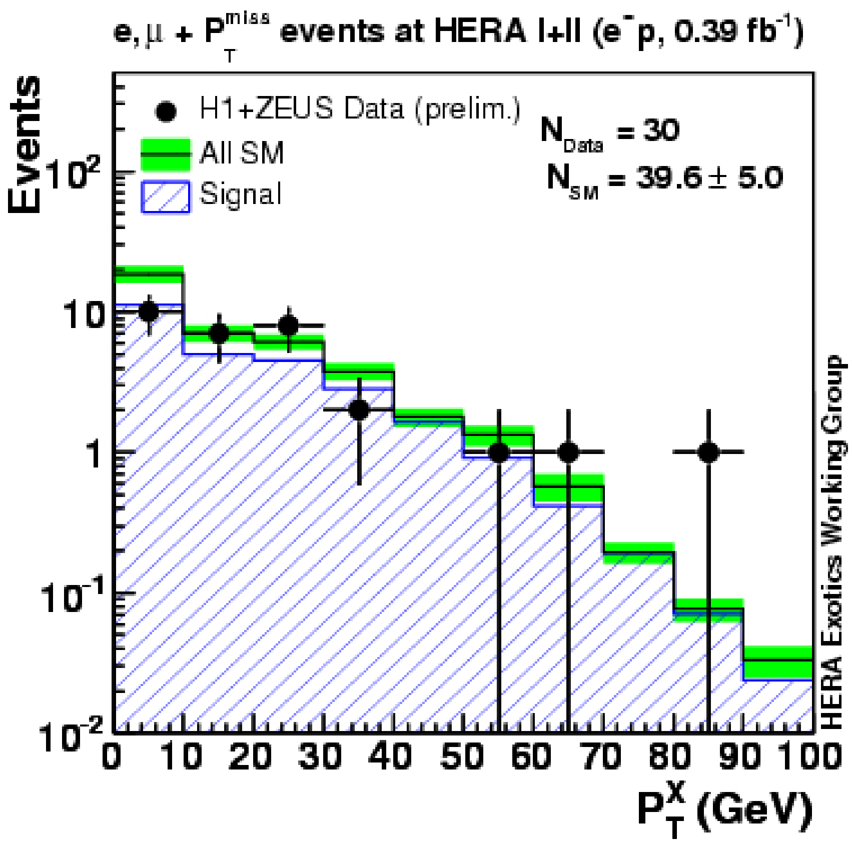
Isolated Leptons and Missing P_T

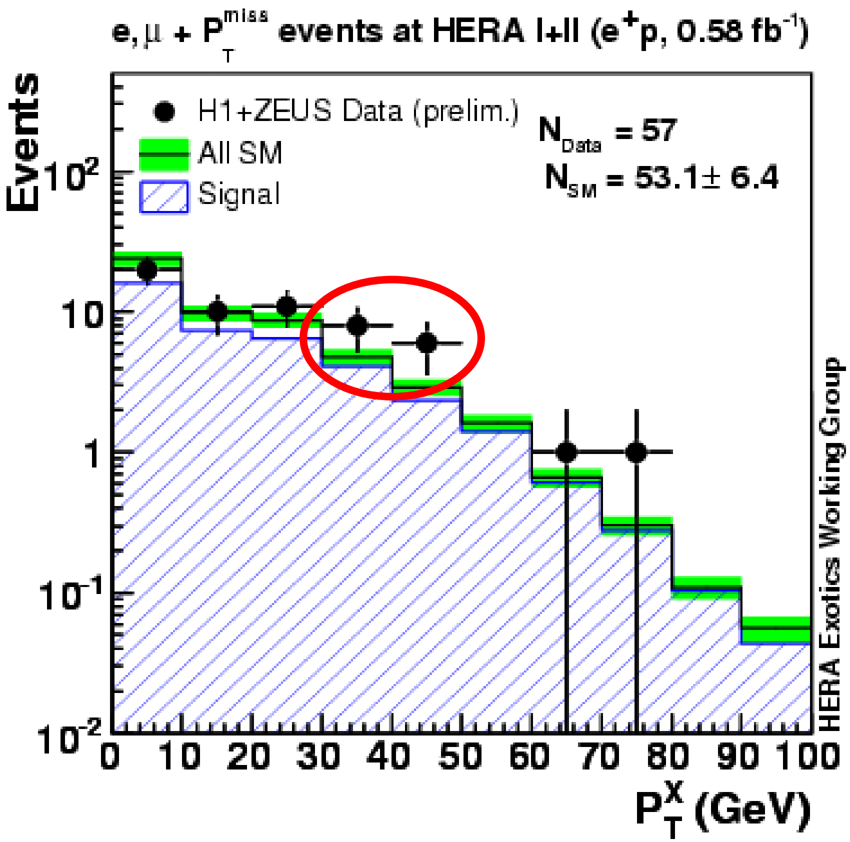




- spectacular events
- excess in HERA1 data at large transverse momenta of the hadronic system (P_T^X) seen by H1

Isolated Leptons and Missing P_T





- no excess in e^- data
- what about e^+?

Isolated Leptons and Missing P_T

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

- H1+ZEUS combined: 1.8 σ excess
- H1 alone: 2.9 σ excess

?