Physics at HERA

Summer Student Lectures
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Overview Part 2

- High Q^2 and Electroweak Physics
- Polarization
- Exotics
- Jet Physics
- Heavy Quarks
- Diffraction

personal selection!
many more analyses
are done!

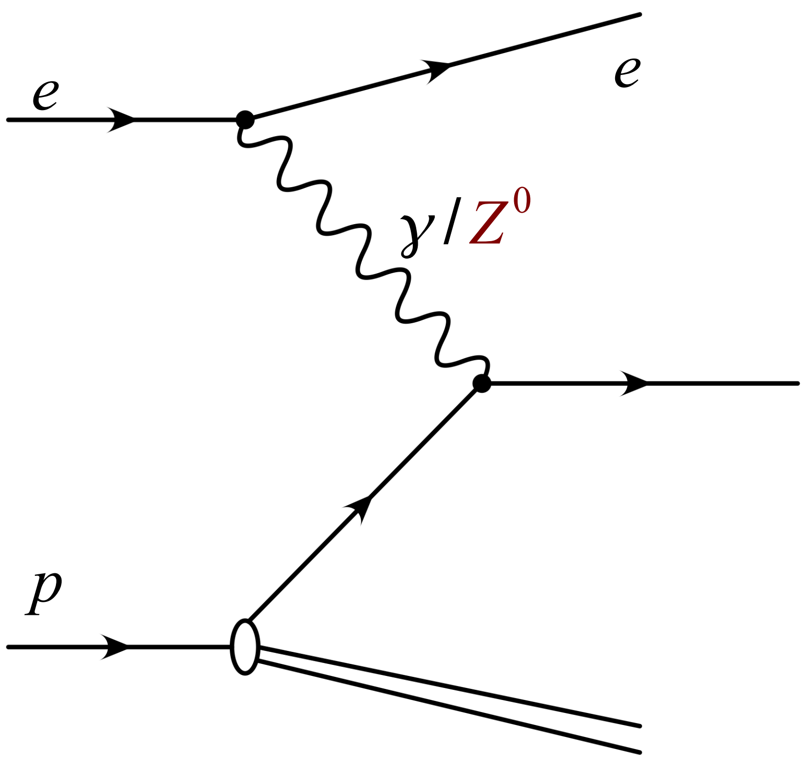
High Q^2 & Electroweak Physics

More Structure Functions

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

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

$F_3 : \gamma - Z^0 - \text{interference}$



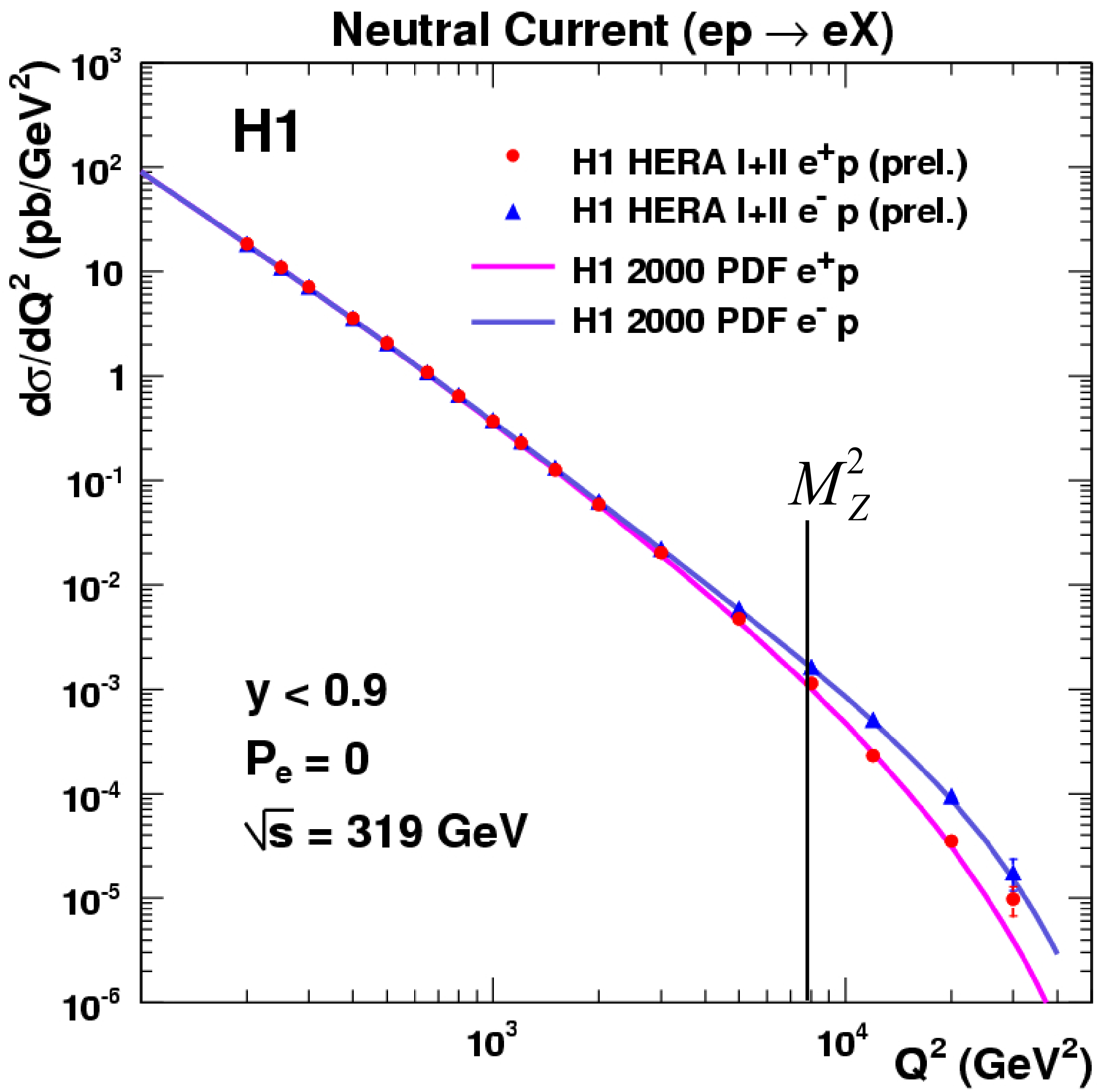
$$Y_{\pm} = 1 \pm (1-y)^2$$

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

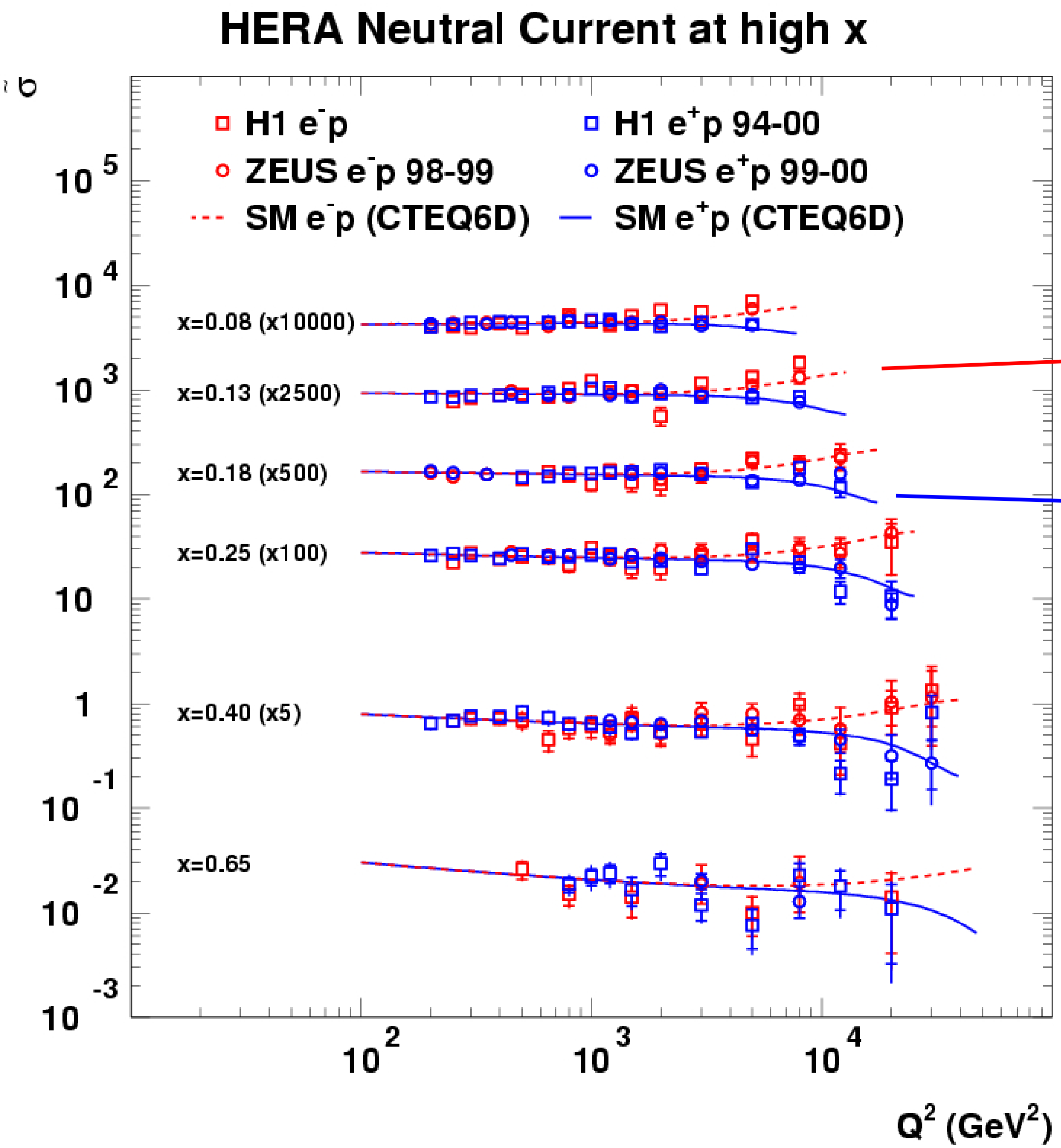
High Q^2 Neutral Current

- 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

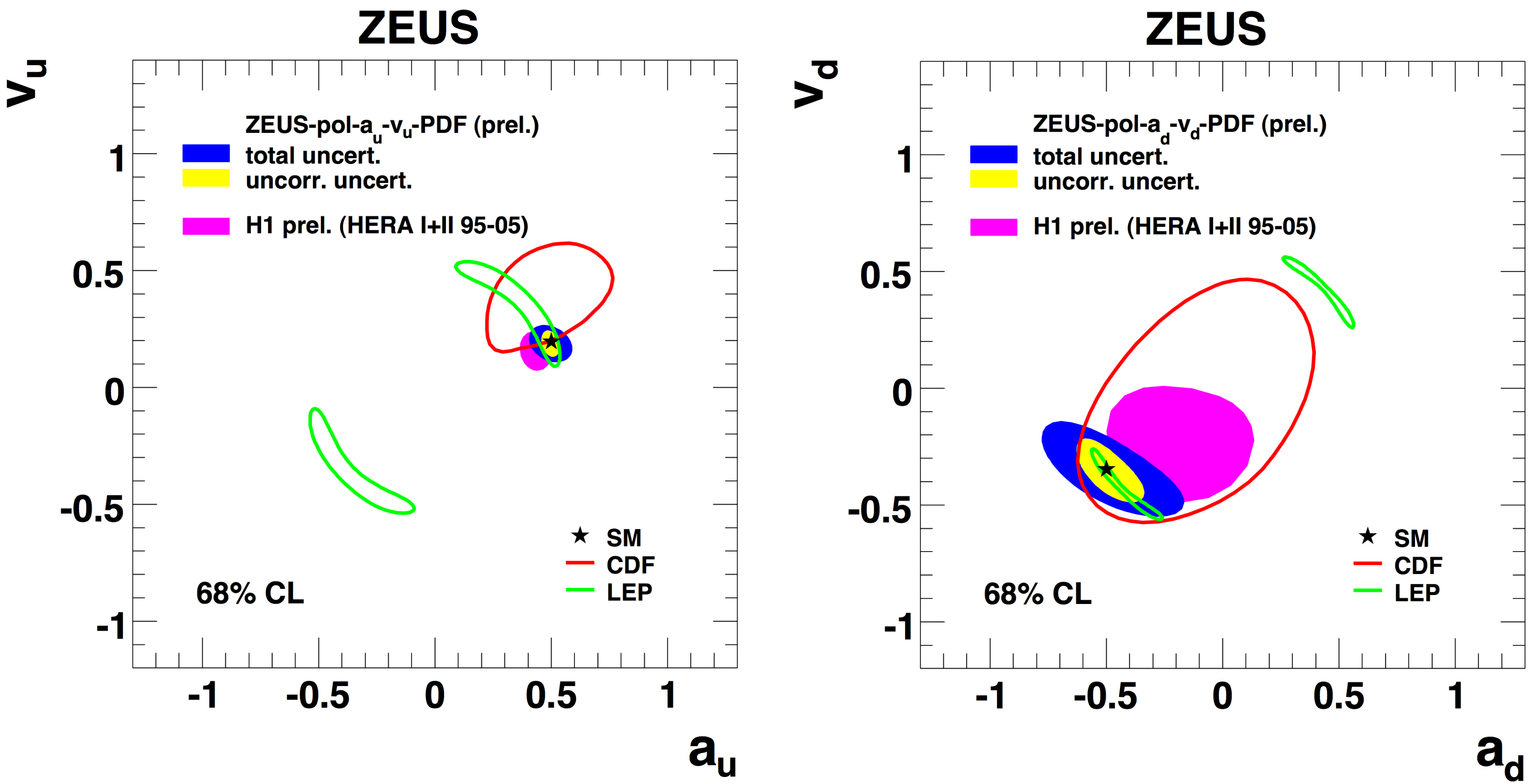
e^+ negative interference

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

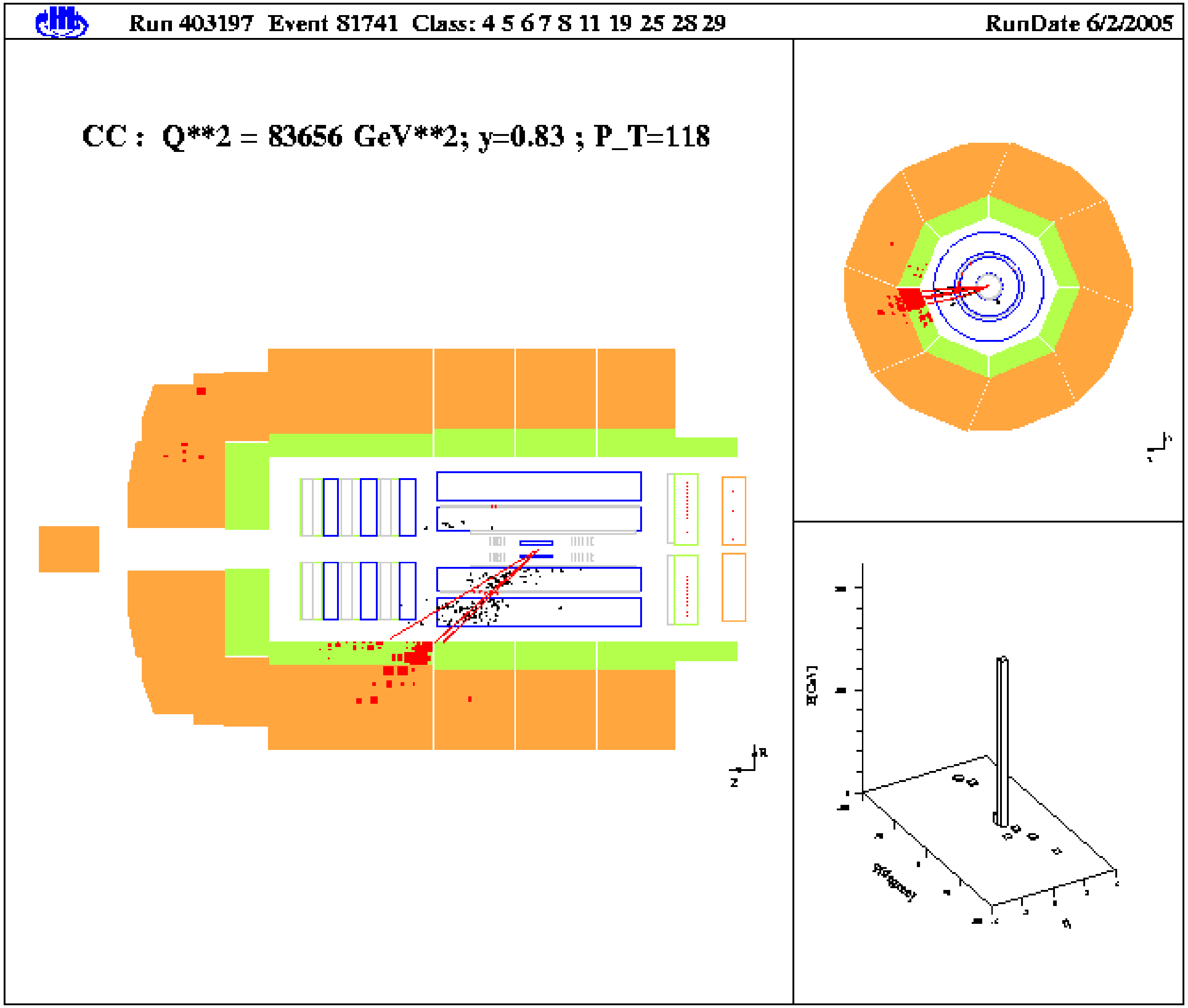
direct handle on valence quark distribution!

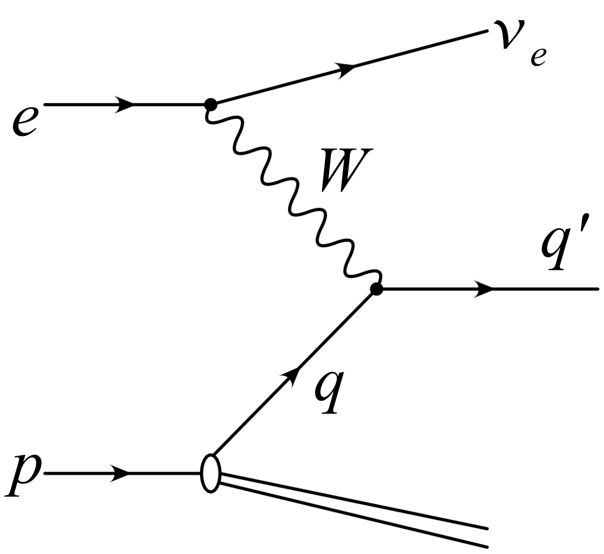
Electroweak Parameters: Z^0 Couplings

high Q^2 NC DIS allows the determination of the vector and axial-vector couplings of *up*- and *down*-type quarks to the Z^0



Charged Current Interactions





neutrino not visible in detector

→ imbalance in transverse plane

Charged Current Cross Section

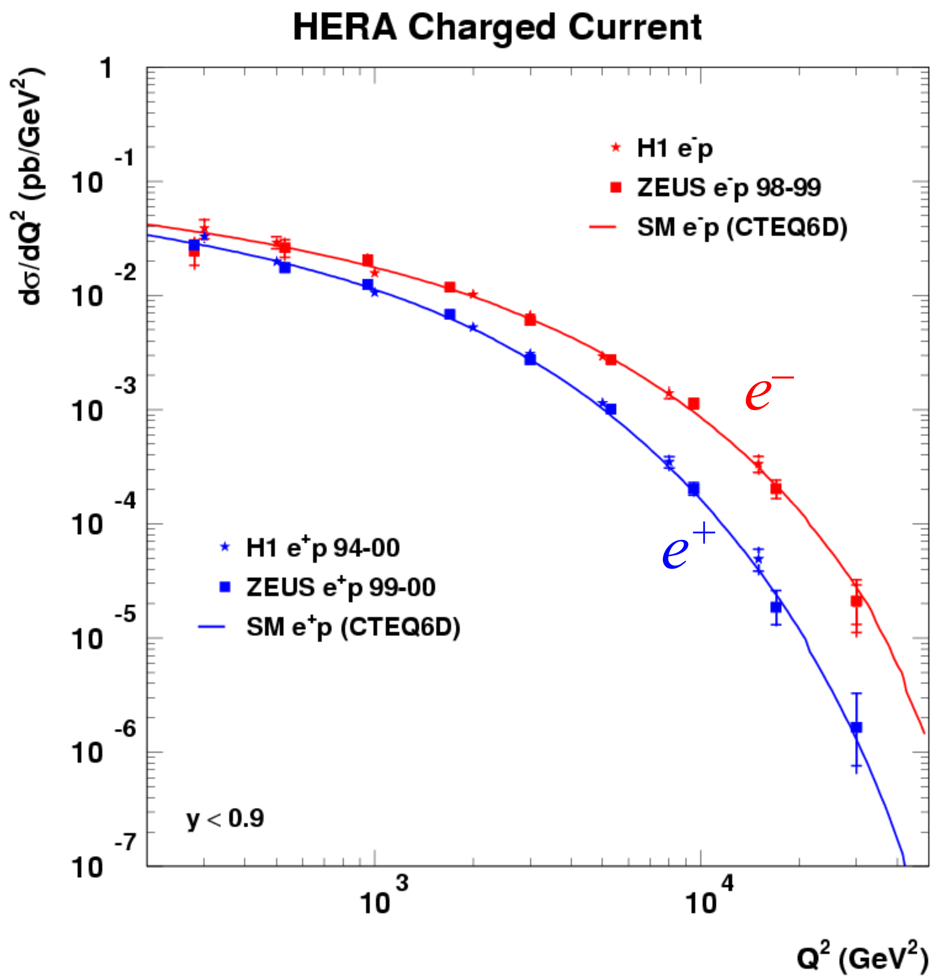
$$\frac{d^2\sigma^{\pm}_{CC}}{dx\,dQ^2} = \frac{G_F^2}{4\pi x}\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2 Y_+\left[W_2^{\pm} - \frac{y^2}{Y_+}W_L^{\pm} \mp \frac{Y_-}{Y_+}x\,W_3^{\pm}\right]$$

- W bosons couple differently to *up*- and *down*-type quarks
- in the QPM:

$$W_2^- = x(U+\overline{D}), \quad xW_3^- = x(U-\overline{D})$$
$$W_2^+ = x(\overline{U}+D), \quad xW_3^+ = x(D-\overline{U})$$
$$W_L^{\pm} = 0$$

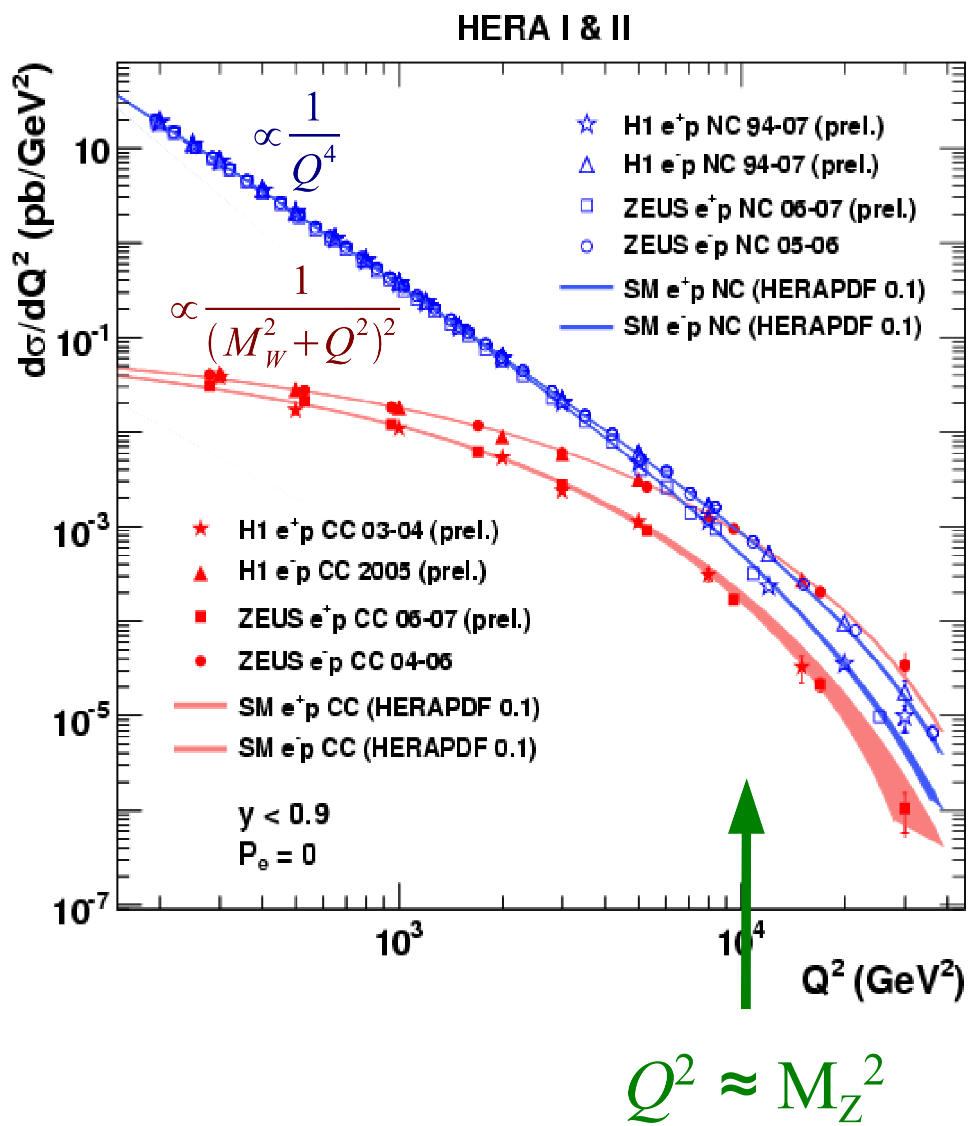
➔ $\sigma^-_{CC} \propto x\left[U + (1-y)^2\,\overline{D}\right]$

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



Comparison NC vs. CC

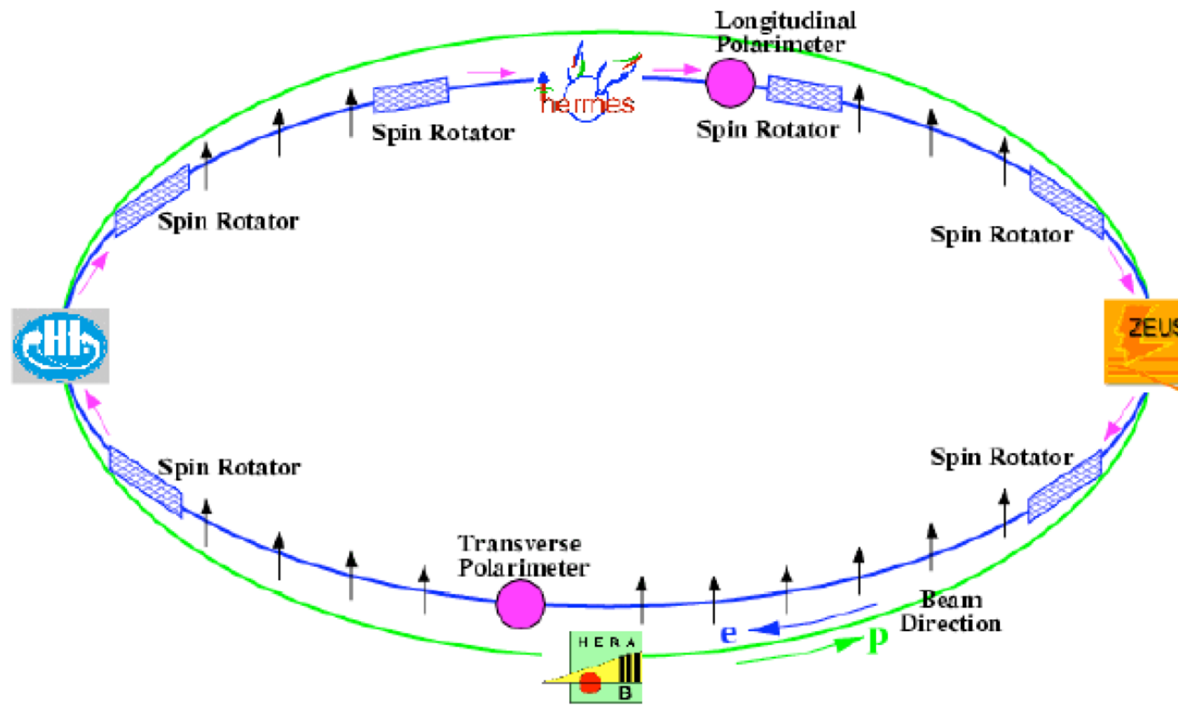
- at low Q^2: different dependences because of photon in NC
- at high $Q^2 \approx M_Z^2$: „electroweak unification“: electromagnetic and weak interactions have similar strength



Polarization

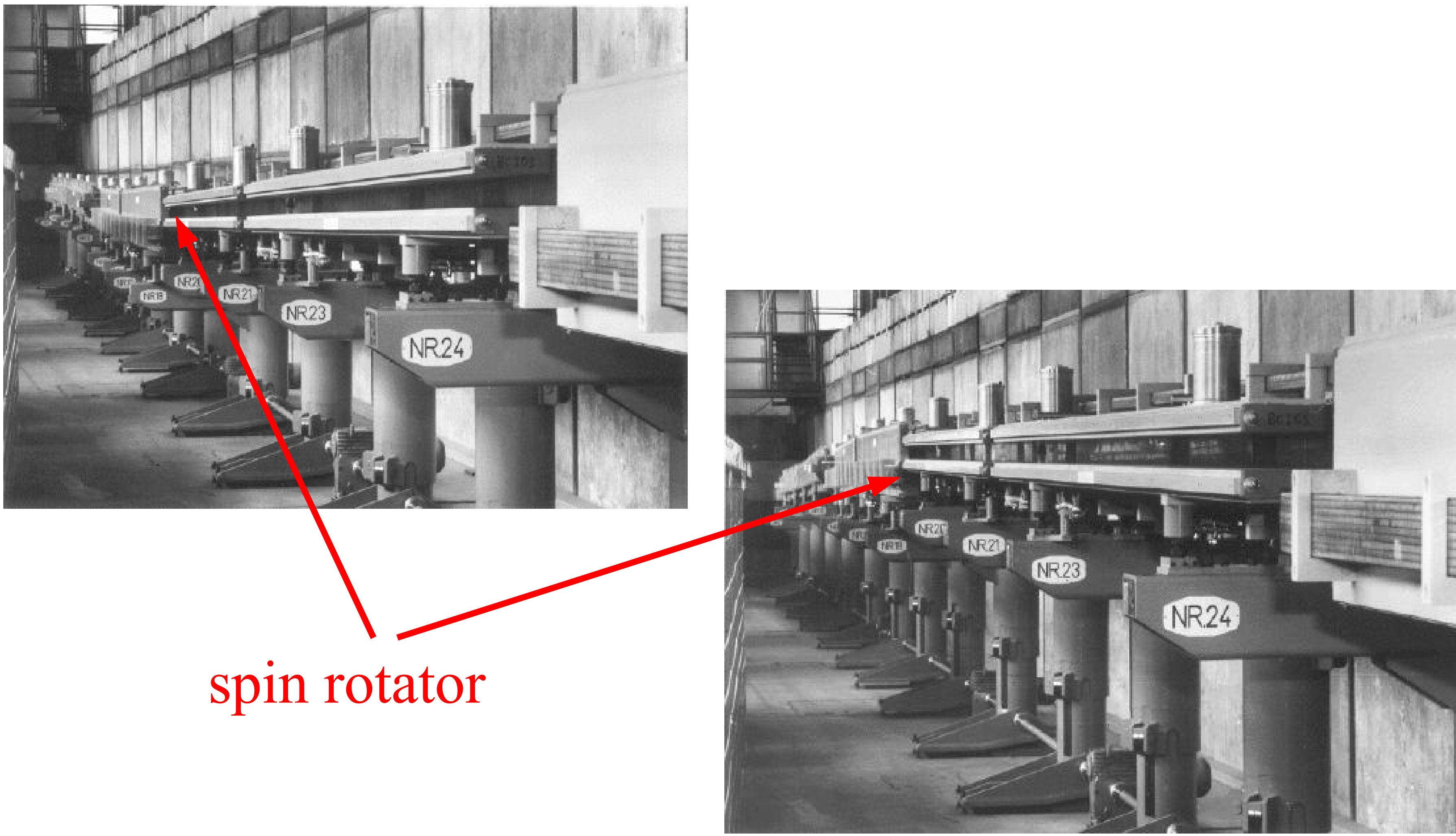
Polarization @ HERA

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



- 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

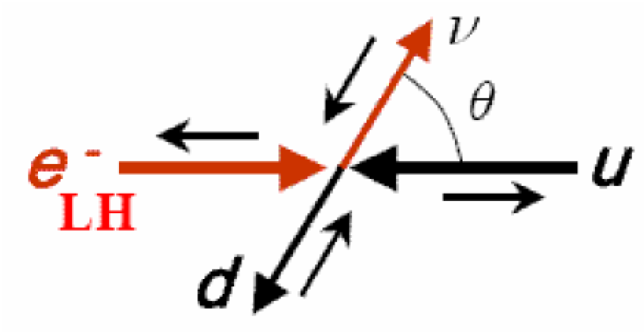


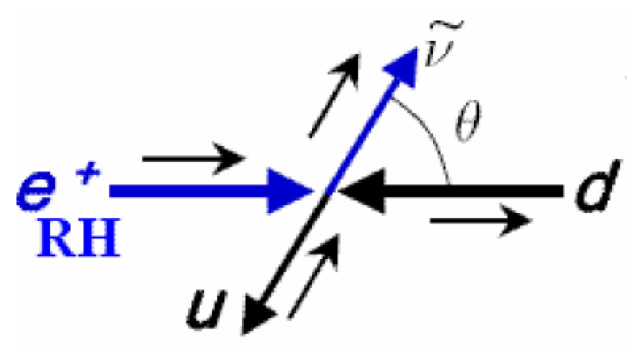
CC & Polarization

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

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

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





CC: Polarization Dependence

- Standard Modell expectation:

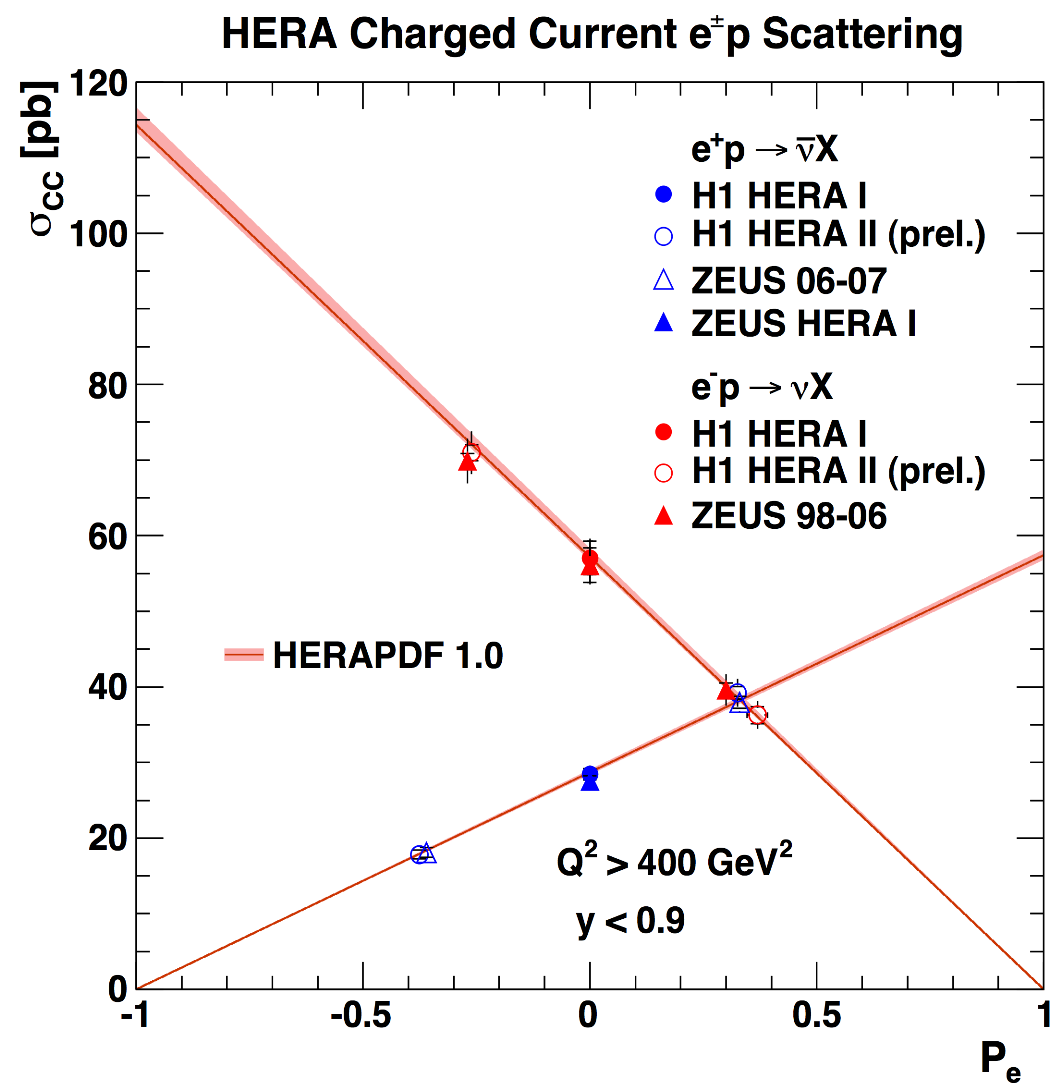
$$\sigma^-_{CC}(P_e = +1) = 0$$

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

- experimental result: (H1)

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

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



Exotics or Beyond the Standard Modell

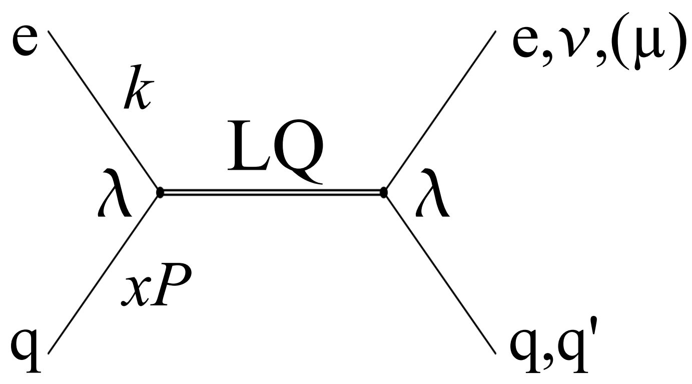
New Particles

many theories predict more particles than the SM:

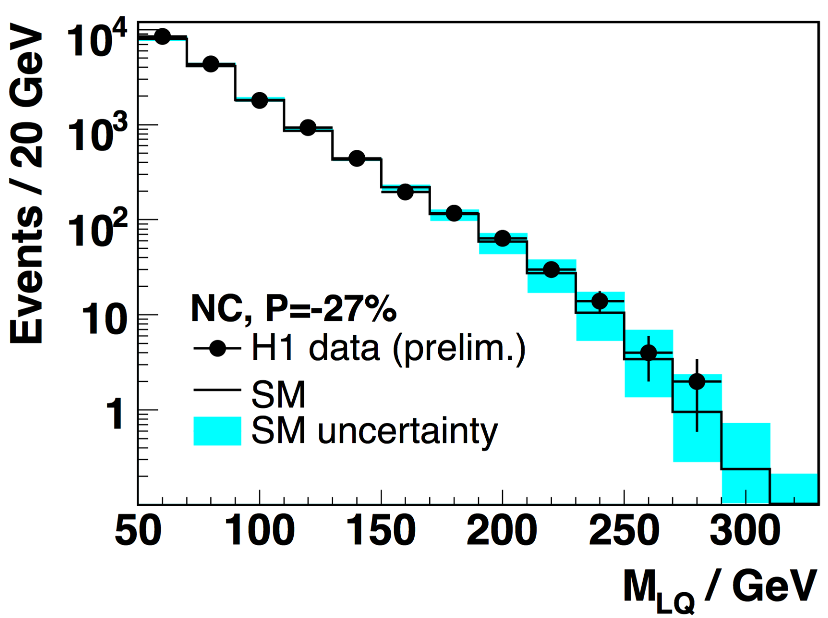
- SUSY
- leptoquarks
  - particle with lepton and quark properties
  - can be produced resonantly in *ep* collisions
- ... exited fermions, contact interactions, large extradimensions ...

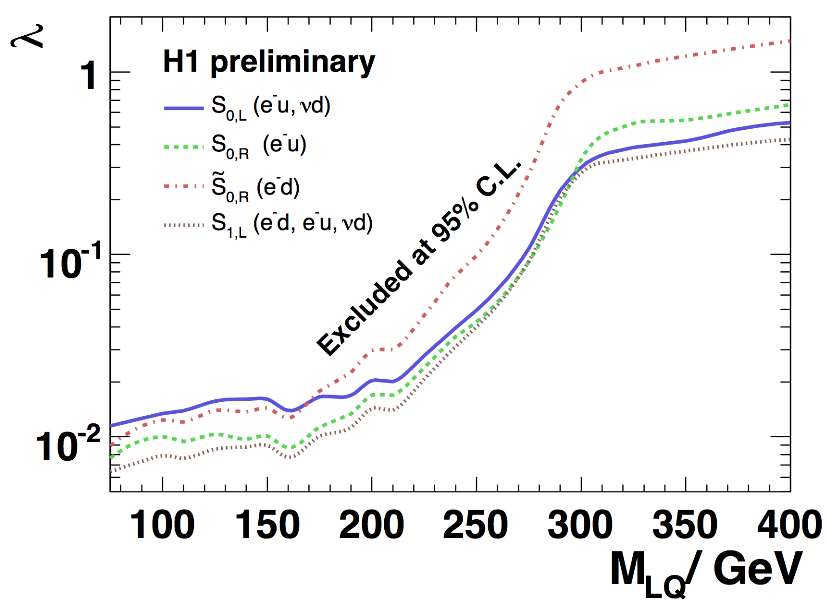
but experimentally search also model-independent!

Leptoquarks



- can look the same as NC or CC process
- $M_{LQ}{}^2 = (xP + k)^2 = xs$
- compare measured cross section with SM expectation
- derive limits on coupling λ

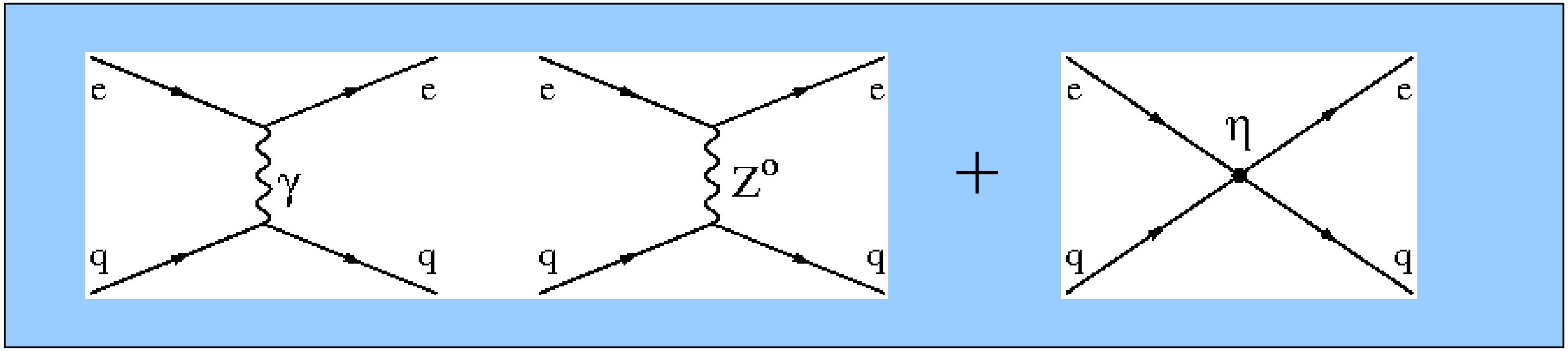




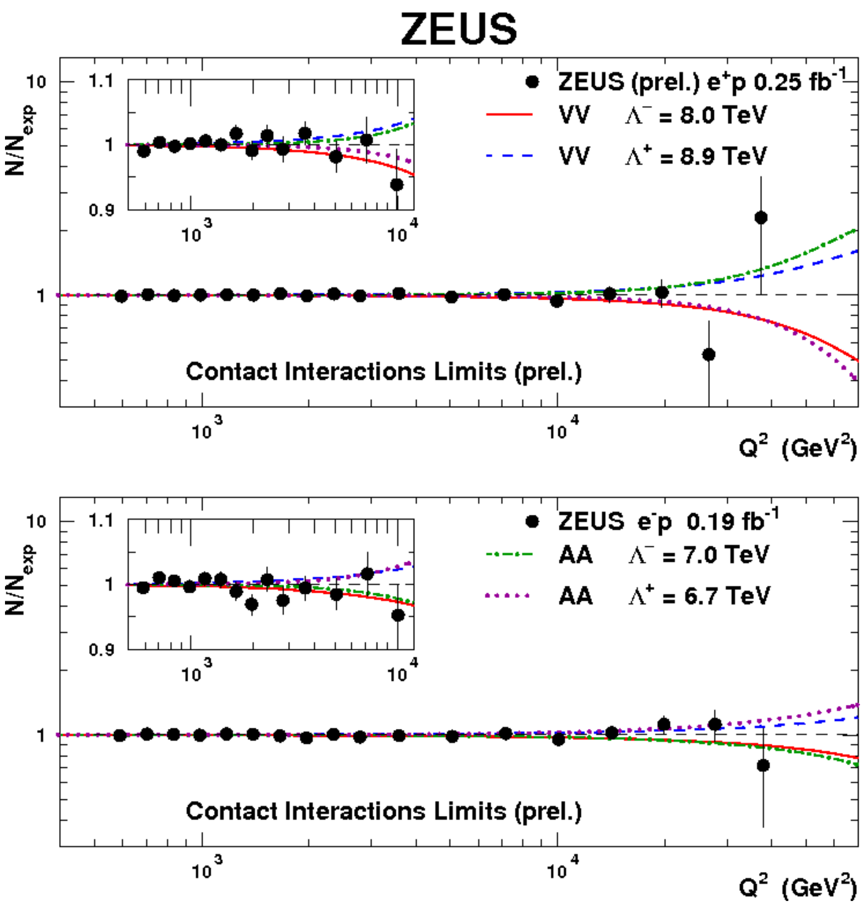
Contact Interactions

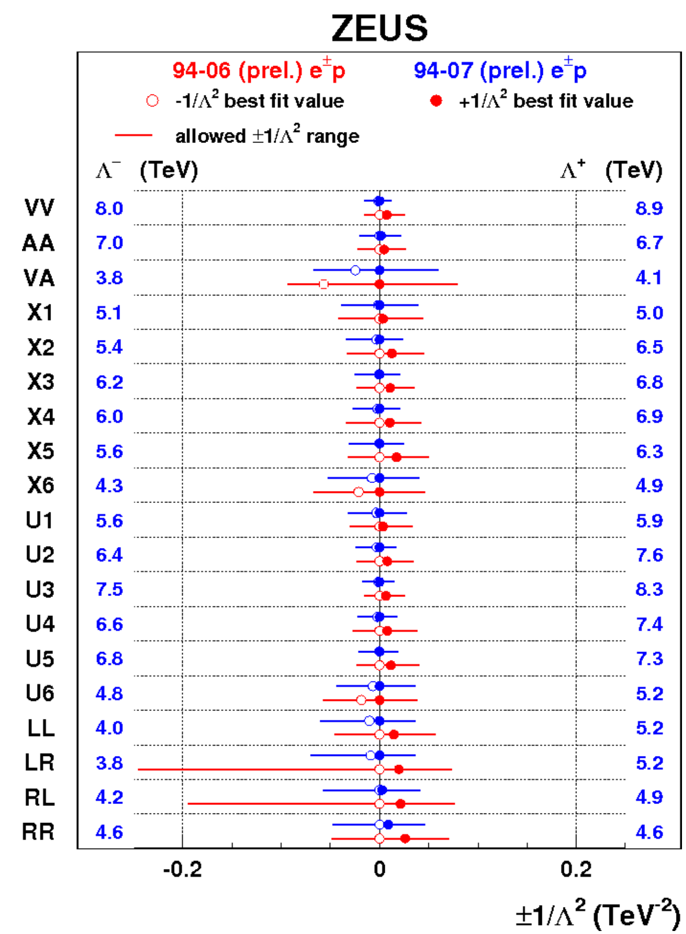
- New interactions at higher scale ($\Lambda >> \sqrt{s}$) can be effectively described at lower energies as 4-fermion *eeqq* Contact Interactions
- Reminder: before W and Z^0 were discovered, weak interactions ($\Lambda \approx M_W$) were described as 4-fermion Contact Interactions with Fermi constant $G_F = g^2/M^2_W$

➔ Contact Interactions would modify the DIS cross section



Contact Interactions

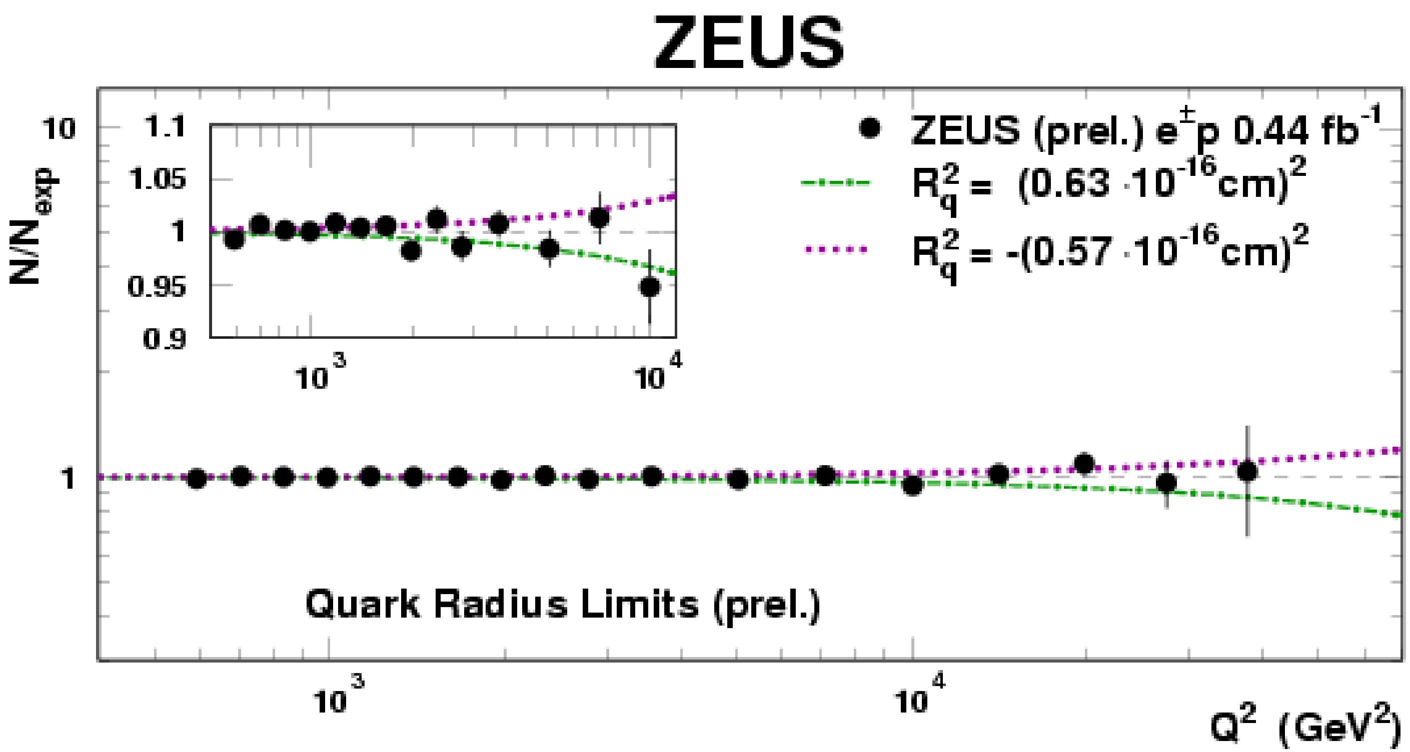




- No sign for Contact Interactions found
- masses much larger than √s excluded

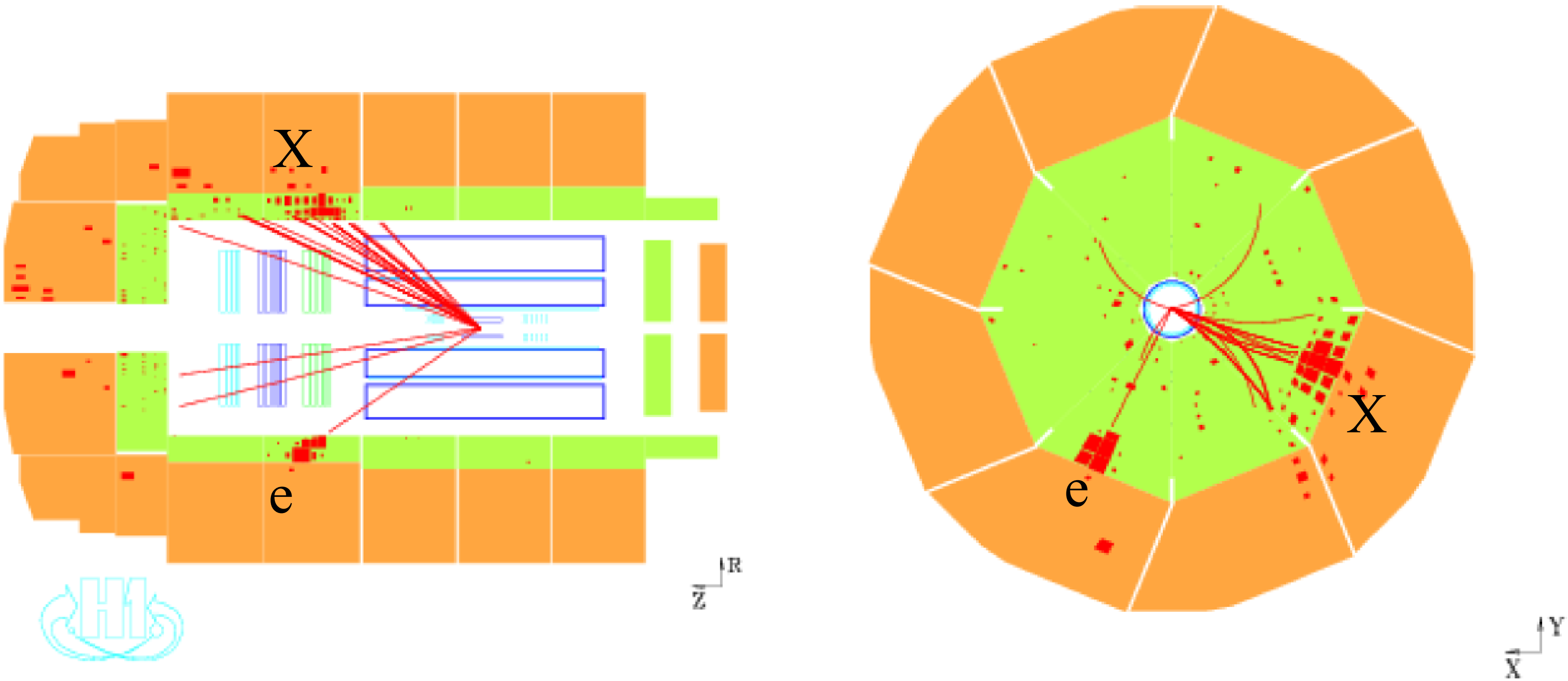
ZEUS (94-07 data):
$\Lambda > 3.8$ - 8.9 TeV

Quark Radius



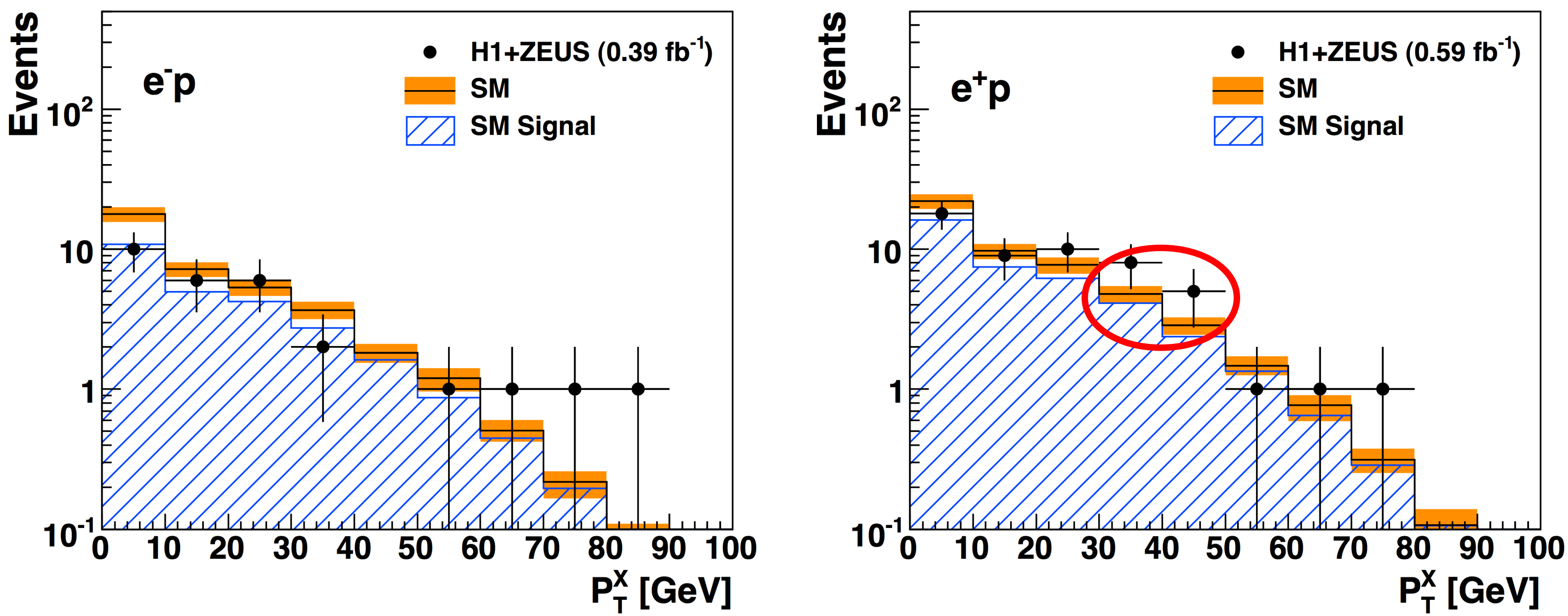
- if quarks have a size, a quark Form Factor would modify the NC cross section at high Q^2
- limit on quark size: $< 0.6 \cdot 10^{-18}$ m

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



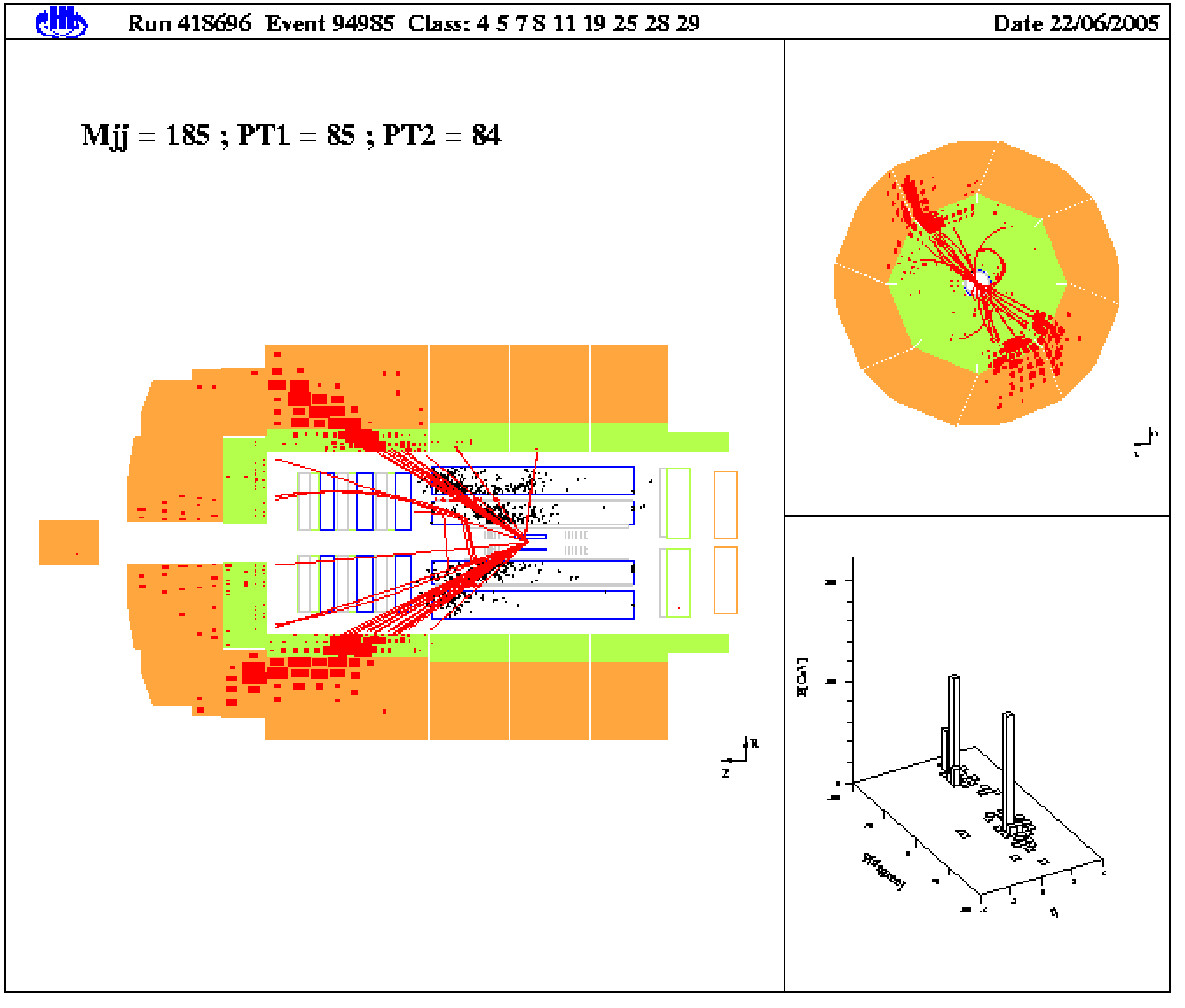
- no excess in e^- data
- e^+:H1+ZEUS combined: 1.9 σ excess
- H1 alone: 2.4 σ excess

?

H1+ZEUS 1994–2007 e^+p 0.59 fb^{-1}		Data	SM Expectation
Combined	Total	53	49.8 ± 6.2
	$P_T^X > 25$ GeV	23	14.0 ± 1.9

Jet Physics & the Strong Coupling α_S

What are Jets?



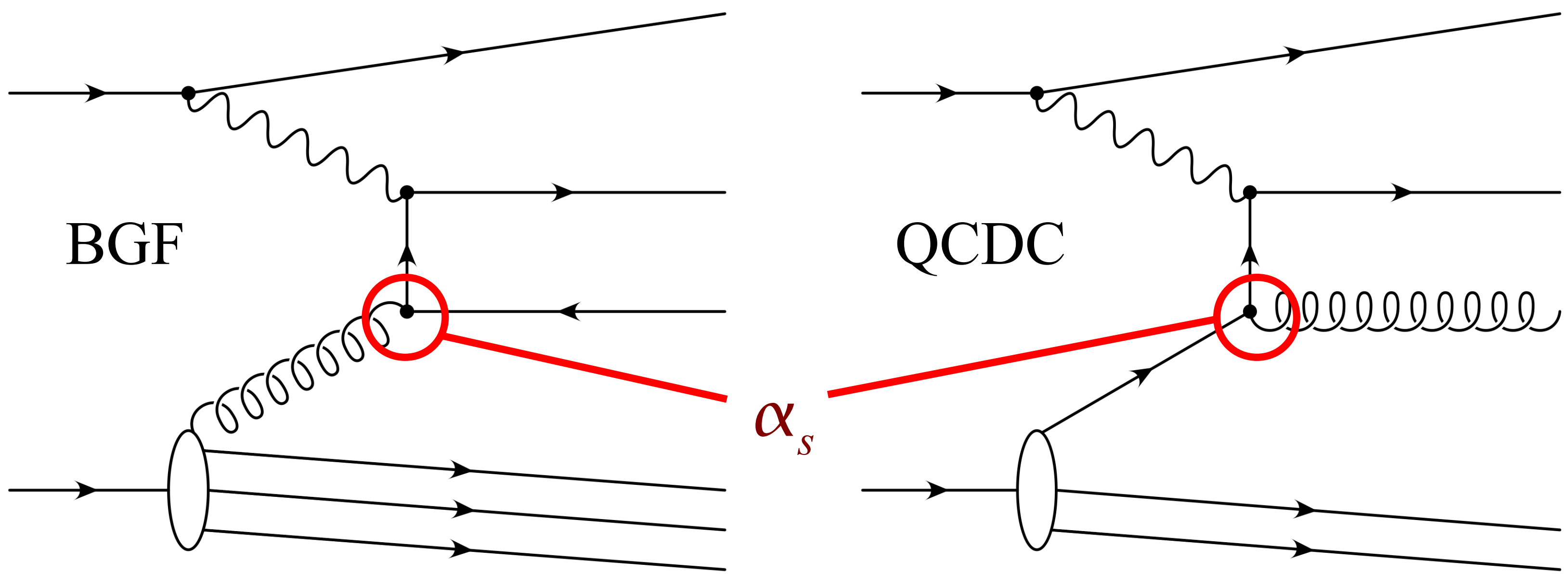
- jets are narrow bundles of hadrons originating from quarks or gluons
- can be used to study QCD and the strong coupling

How Are Jets Produced?

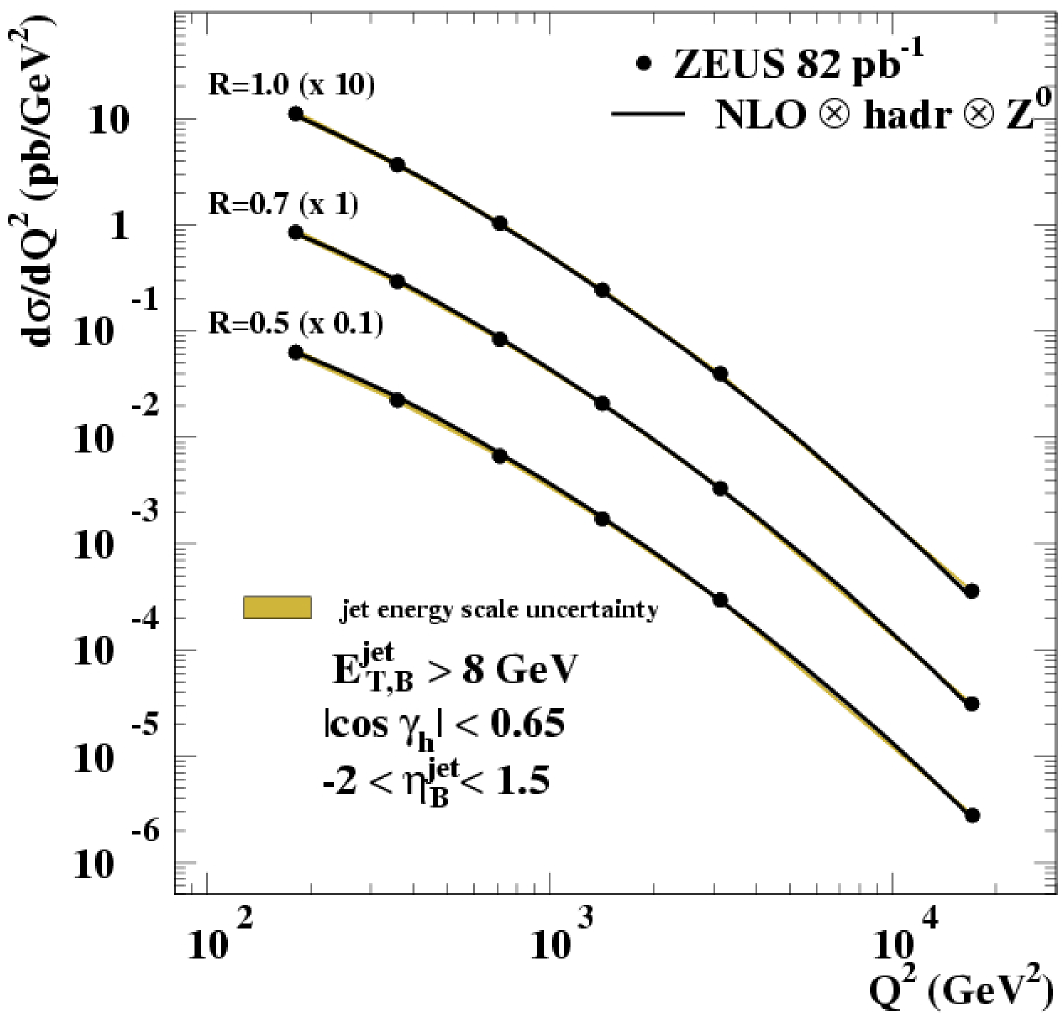
- do analysis in a frame where photon and proton collide head-on (e.g. Breit frame)

➔ LO DIS cannot produce transverse momentum

➔ jets with transverse momentum can originate from boson-gluon fusion (BGF) or QCD-Compton (QCDC) processes

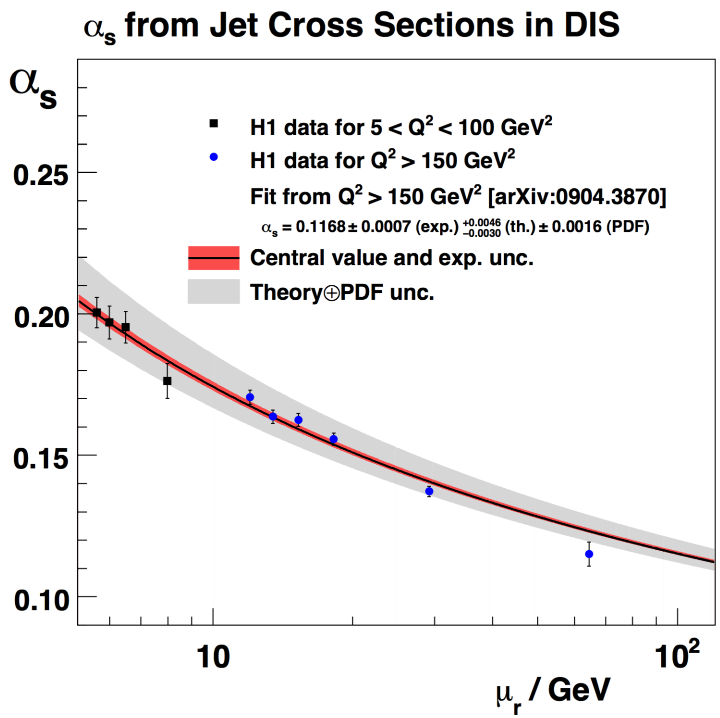


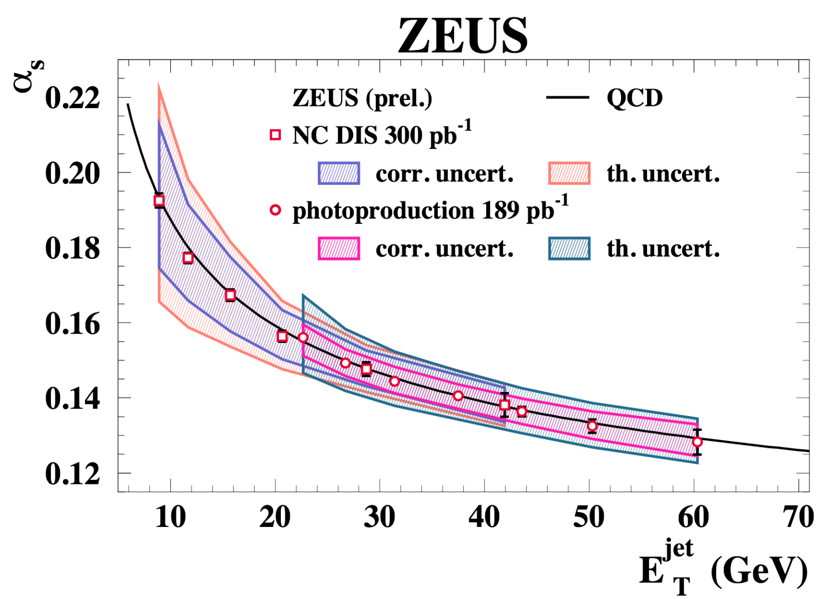
Jet Cross Sections



- theory curve:
  - NLO QCD calculation
  - PDFs
  - α_s
  - hadronisation
- very good agreement of theory and data, PDFs extracted from F_2 describe jet prod.
- uncertainty on PDF and theory input leads to uncertainty on α_s

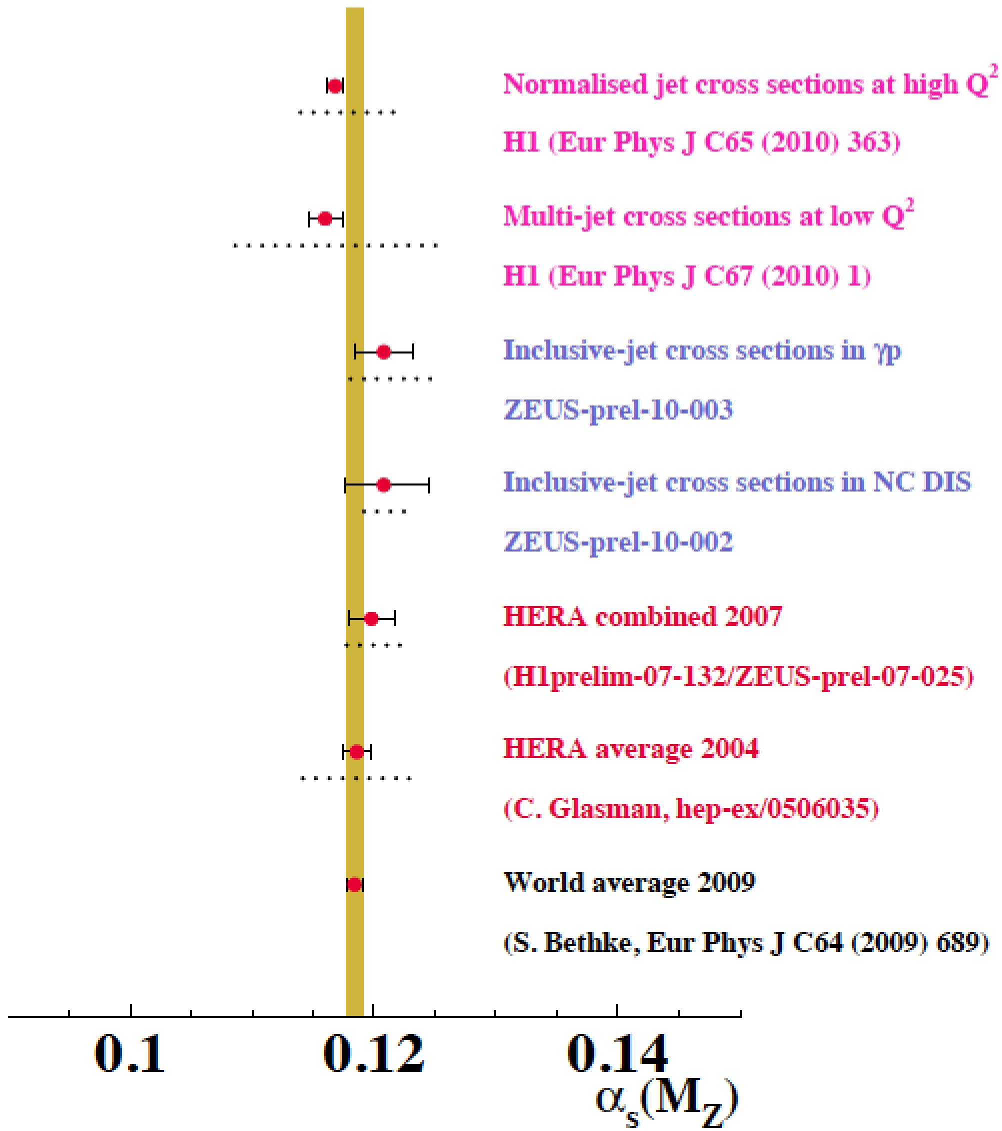
α_s from Jets





- running of α_s visible in one experiment
- theory uncertainties larger than experimental uncertainties

$\alpha_s(M_Z)$

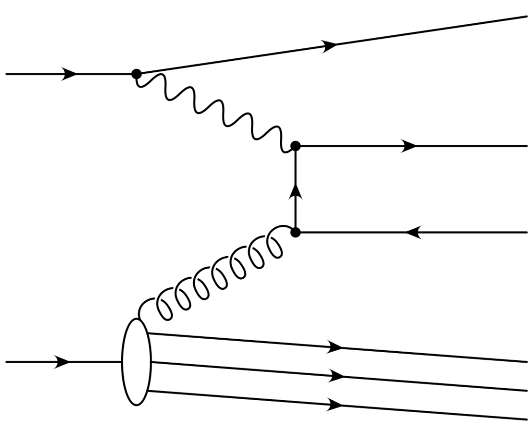


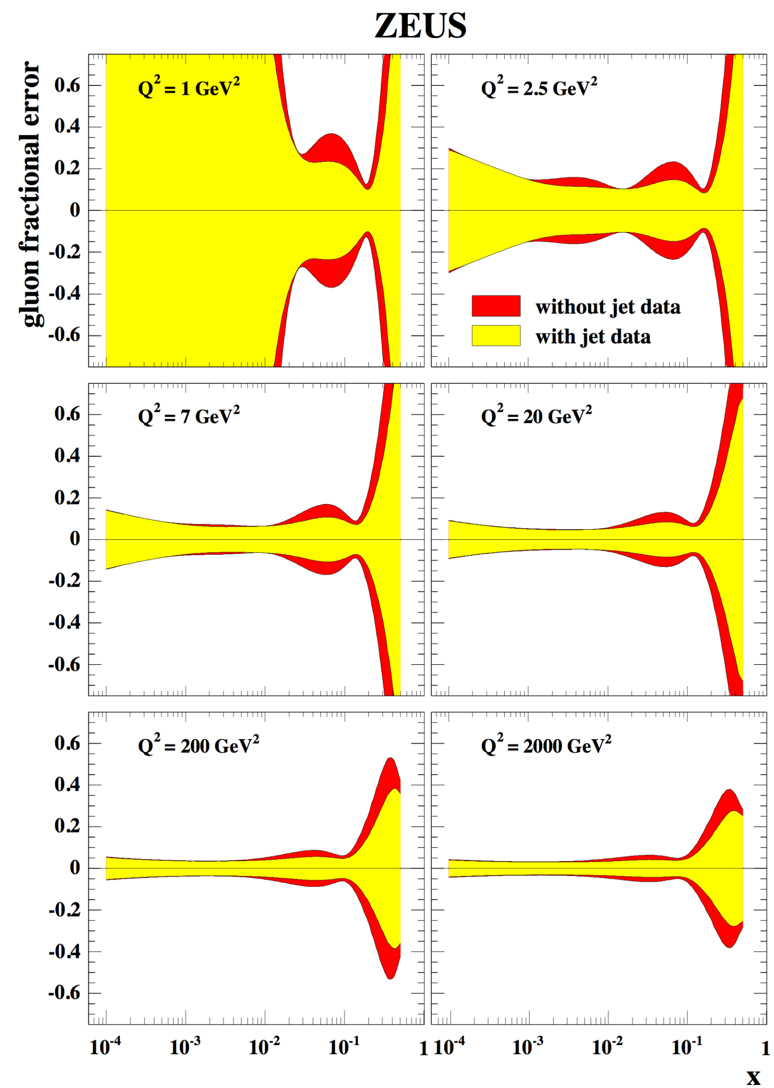
HERA measurements often dominated by systematic and theoretical uncertainties

➔ HERA value very competitive

Improved Parton Densities

- F_2 is only indirectly sensitive to the gluon
- ➔ global fits (MRST, CTEQ) use Tevatron jet data
- ➔ alternative: use HERA (di-)jet data

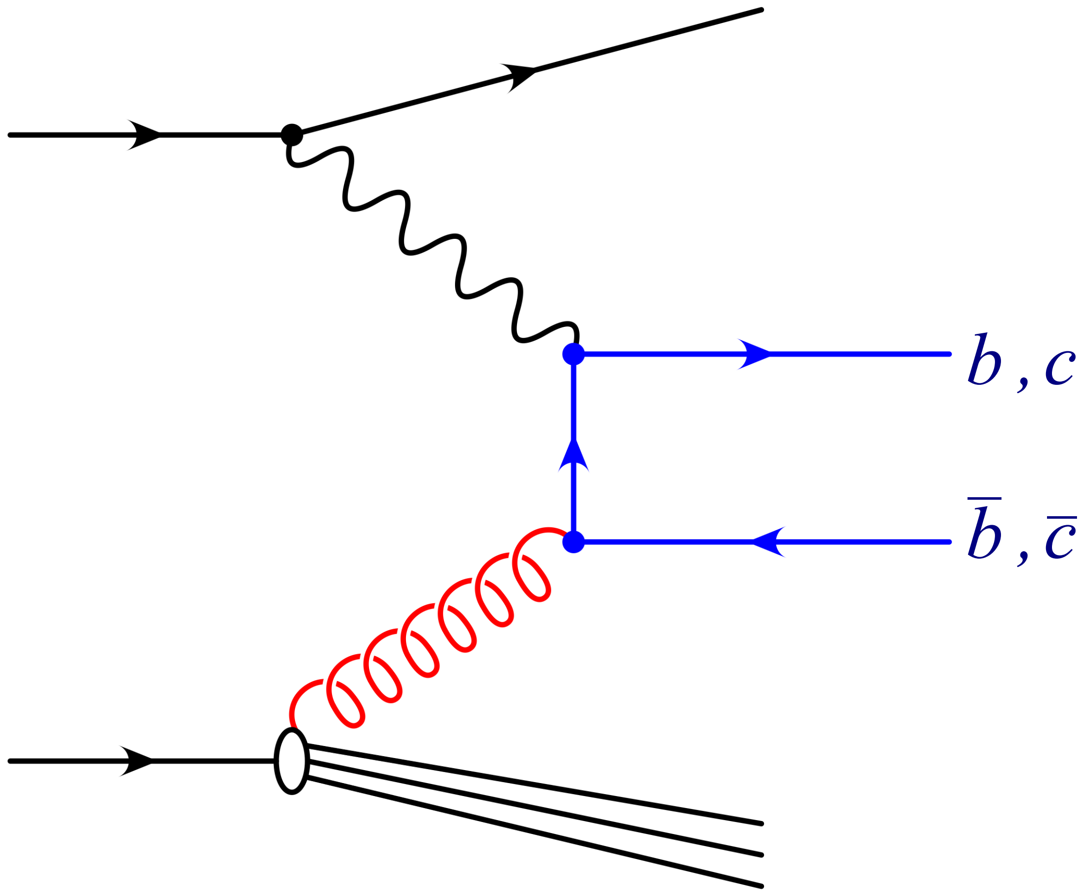




improvement at medium to large x

Heavy Quarks

Production of Heavy Quarks



predominantly via boson gluon fusion

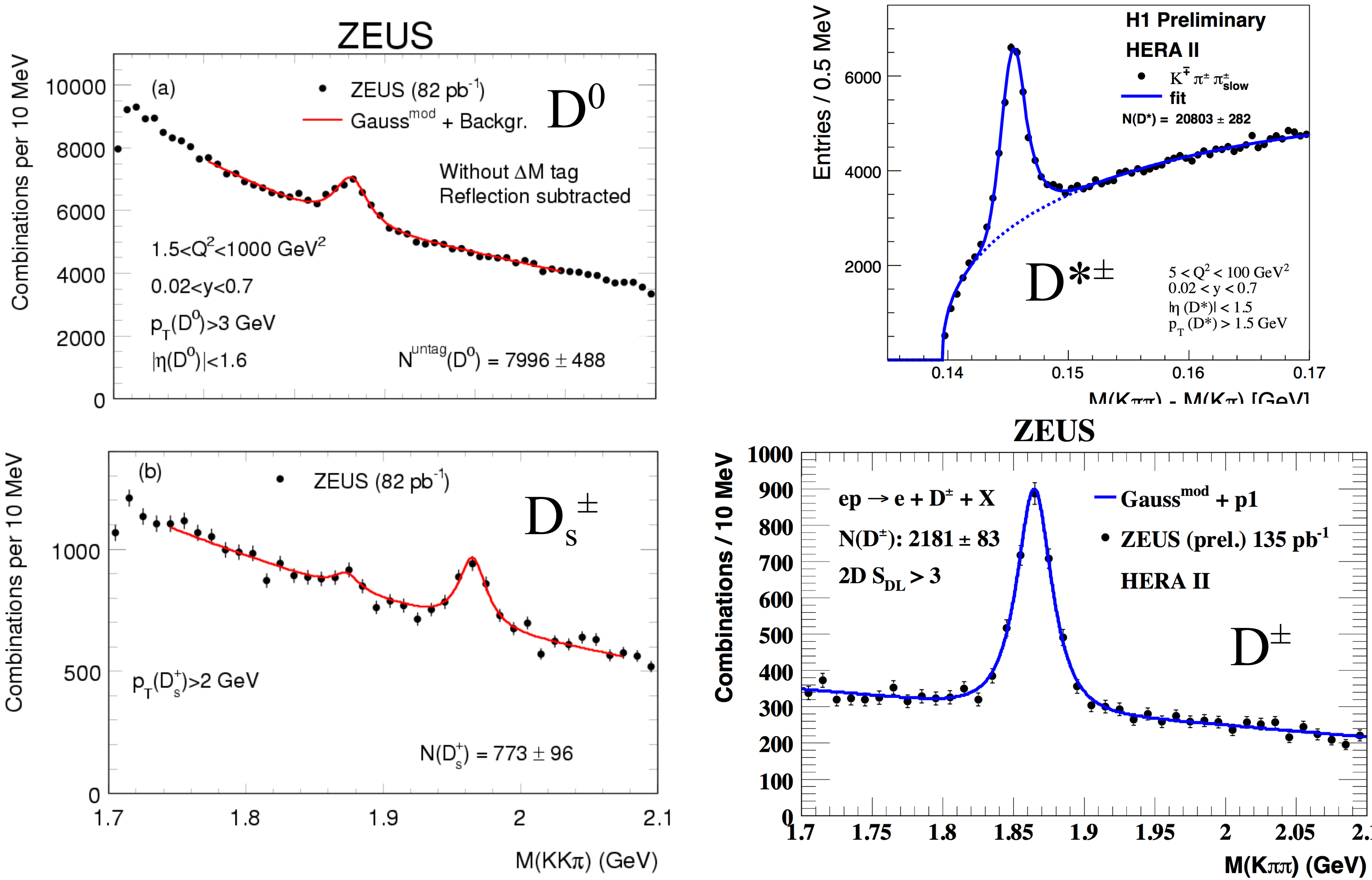
large quark mass allows pQCD calculations

directly sensitive to gluon density in the proton

heavy quark contribution to structure function

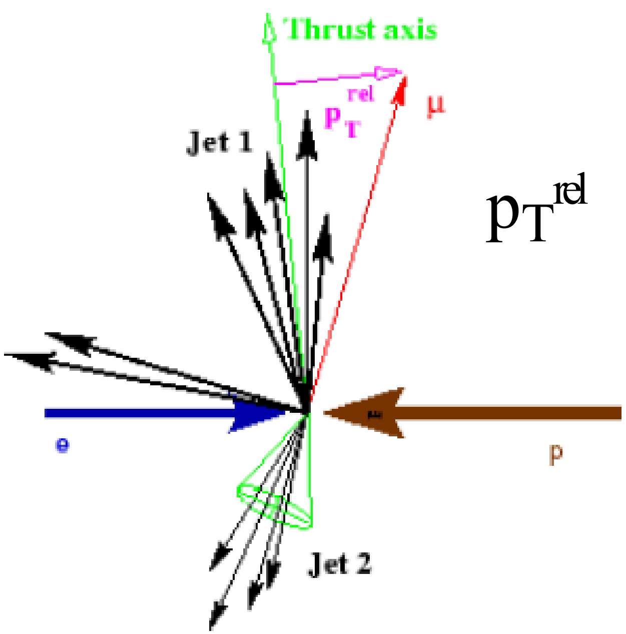
$$\frac{d^2\sigma^{b\bar{b}}}{dx\,dQ^2}=\frac{2\pi\alpha^2}{xQ^4}Y_+\left[F_2^{b\bar{b}}(x,Q^2)-\frac{y^2}{Y_+}F_L^{b\bar{b}}(x,Q^2)\right]$$

charm Signals



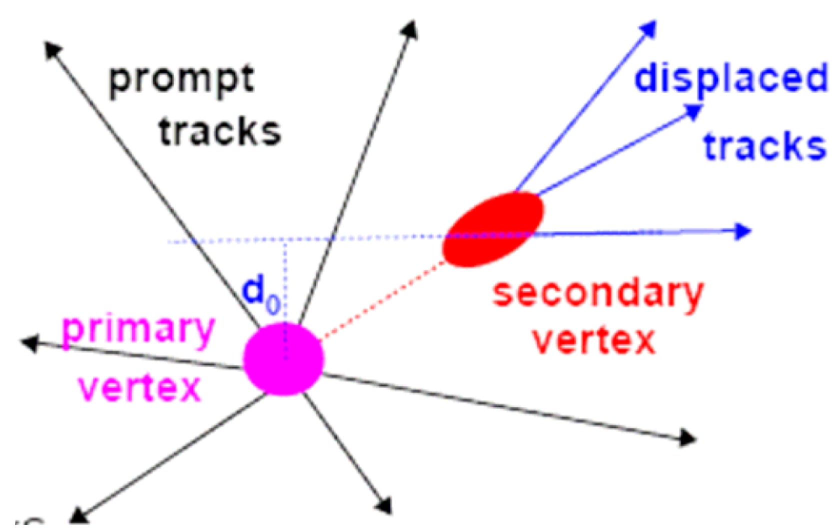
Tagging of *beauty* Quarks

- large transverse momenta due to large mass
- semileptonic decay
- long lifetime (*beauty* ~500 µm, *charm* ~100-300 µm)

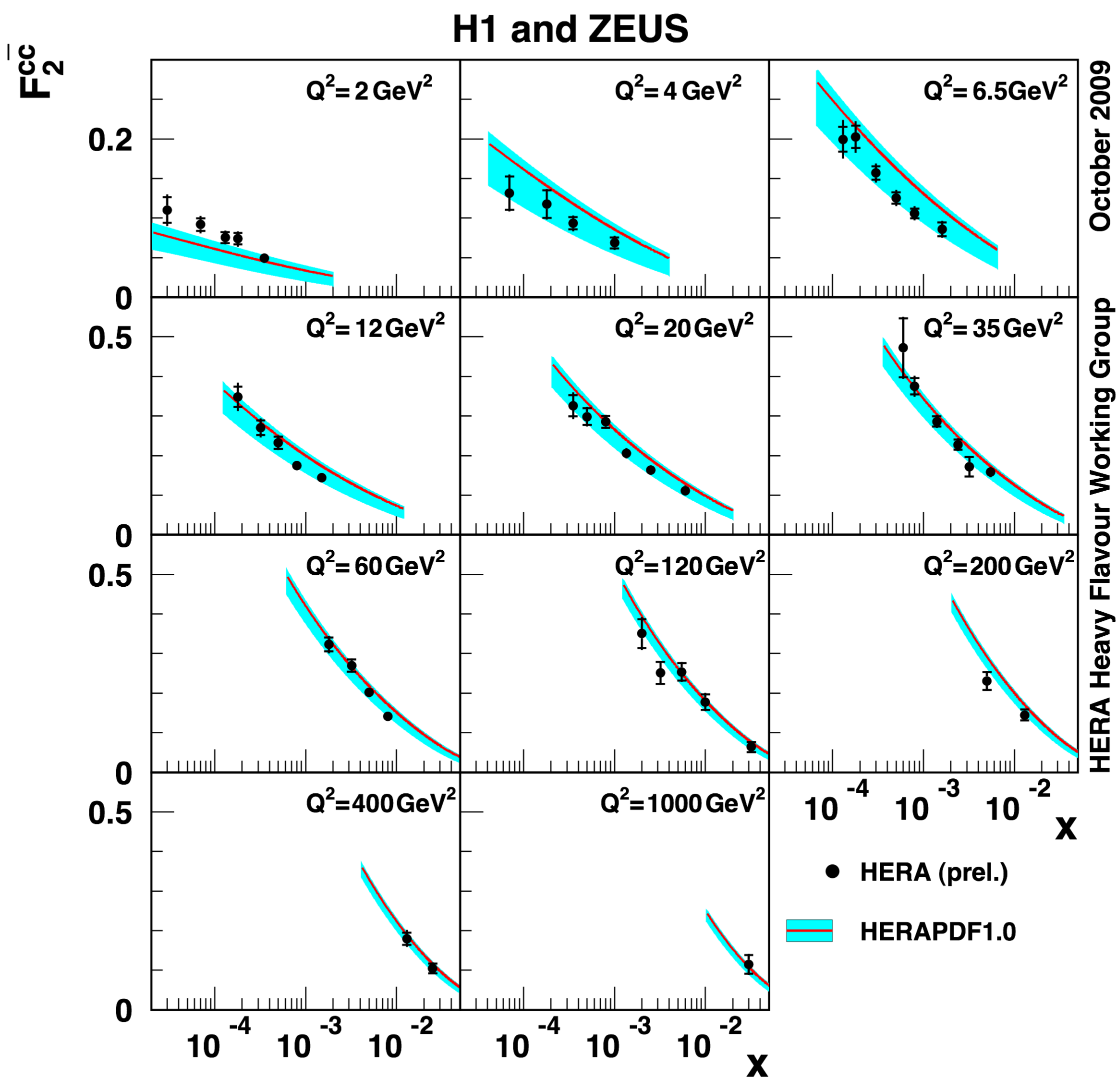


p_T^{rel}

lifetime tagging



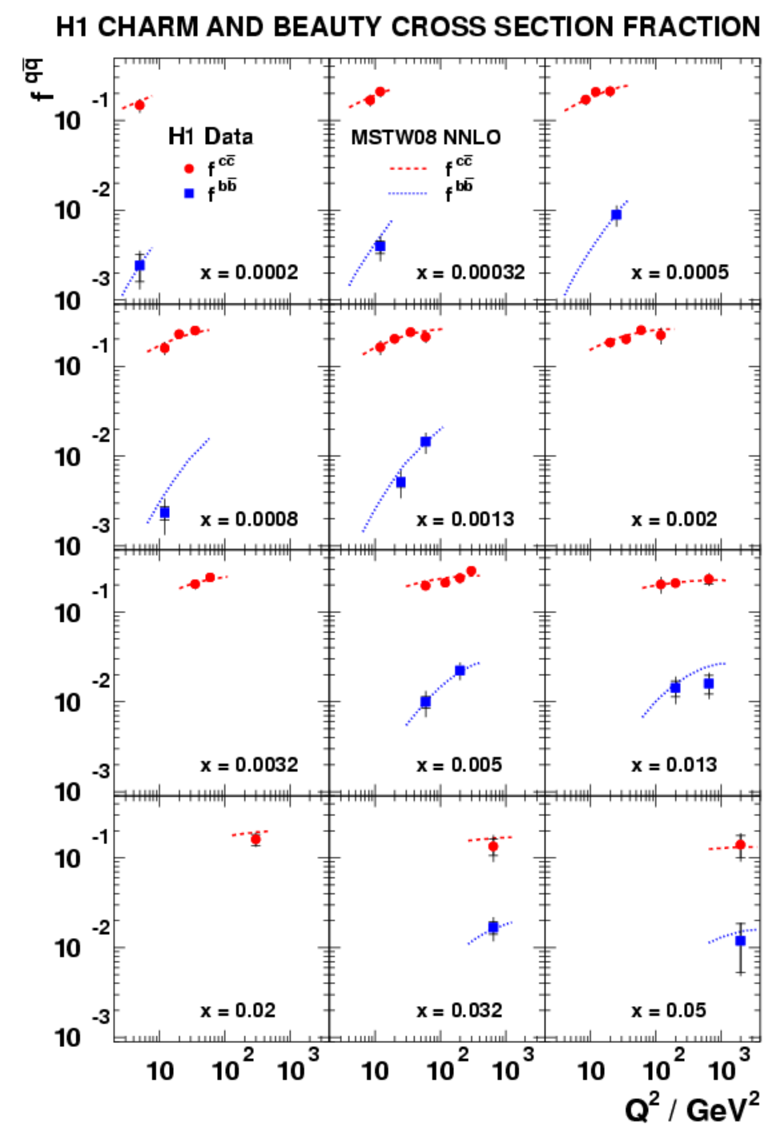
charm contribution to F_2



- good experimental precision by com-bining measure-ments with different methods
- *charm* data in agreement with predictions with PDF from F_2

Contribution to the Cross Section

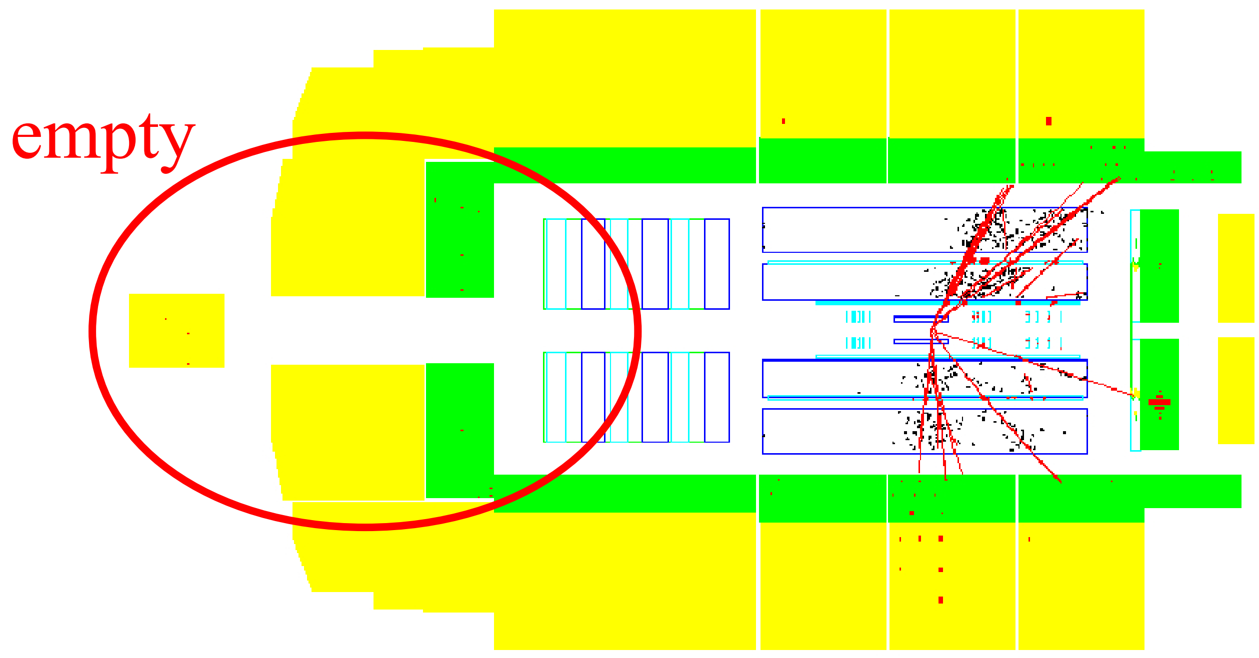
- large charm fraction (up to ~30%)
- small beauty fraction (‰ to few %)
- charm and beauty thresholds
- reasonable description by theory



Diffraction

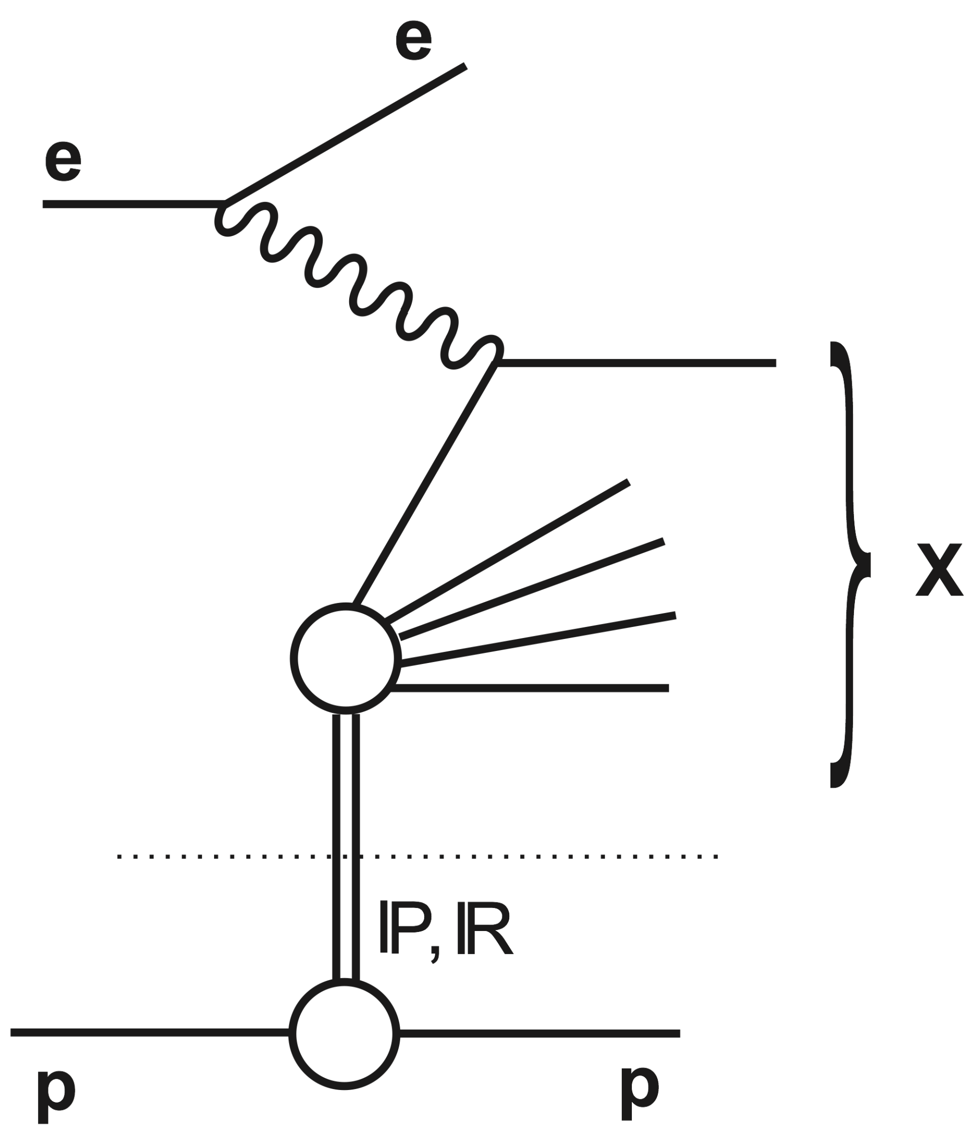
What is Diffraction?

- in general: in DIS events the proton breaks up
- in diffraction: the proton stays intact
  (but nevertheless $W>M_P$)



surprise: ~10% of all events at HERA are diffractive!

Diffraction

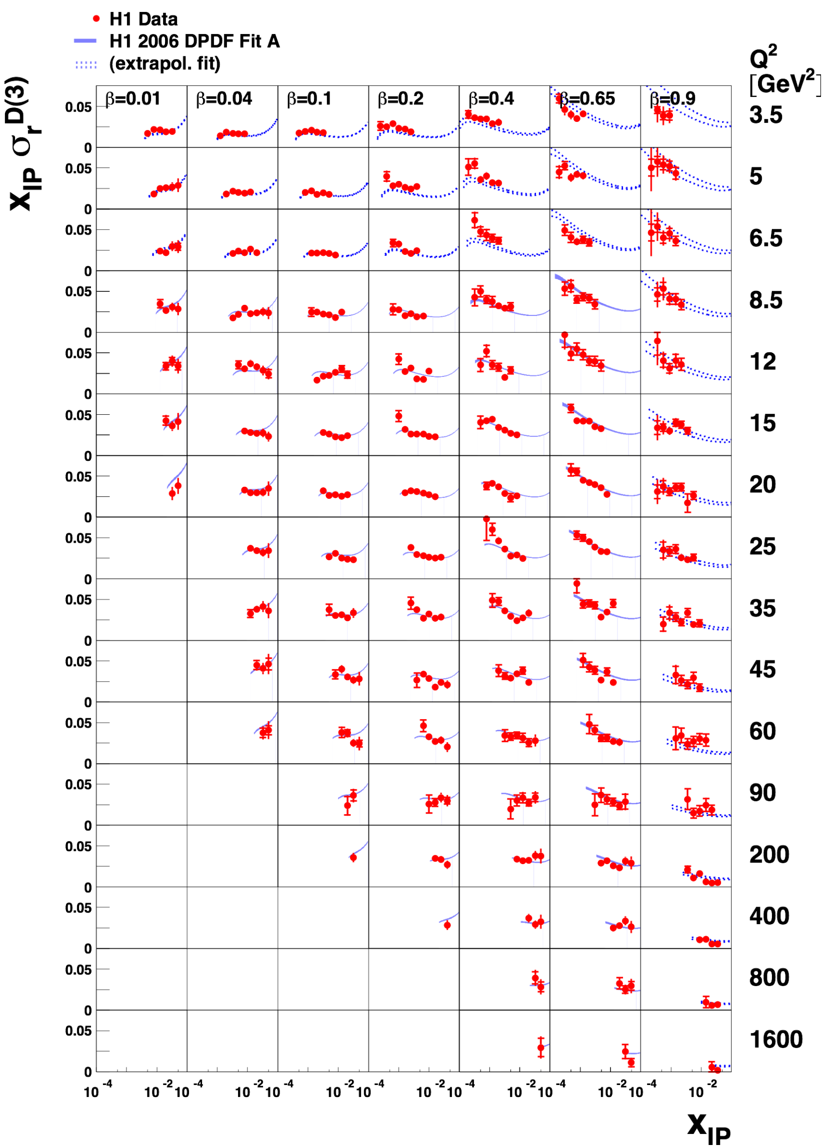


- idea: interaction between photon and proton by a „Pomeron“
  - colourless
  - already used to describe low energy hadron-hadron scattering
  - no particle!

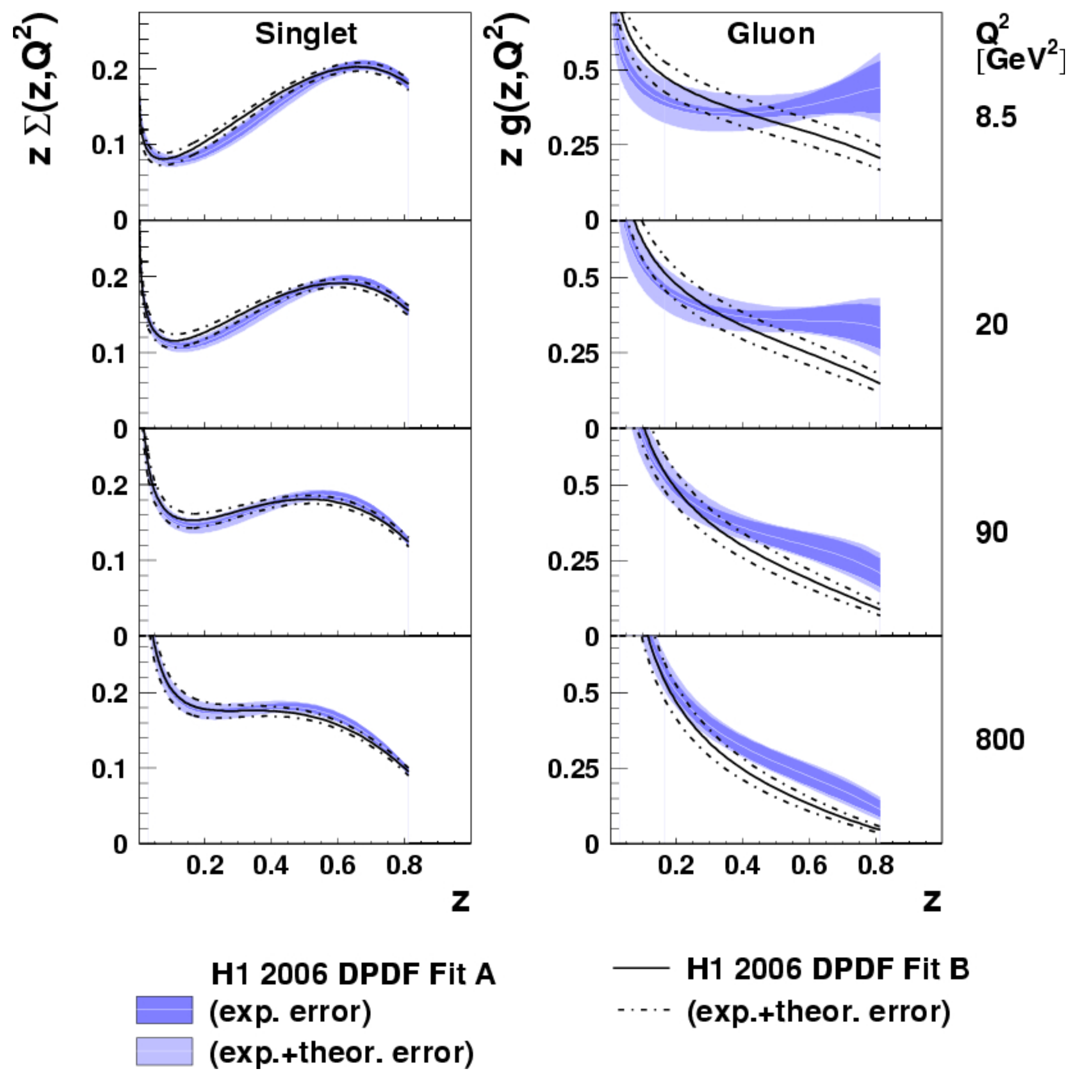
Physics in Diffraction

- many things similar to inclusive DIS
  - diffractive parton densities
  - jets in diffraction
  - heavy flavour in diffraction
- test of factorization
  - are the parton densities the same for all diffractive processes?
  - or: does the Pomeron know what happens at the photon vertex?

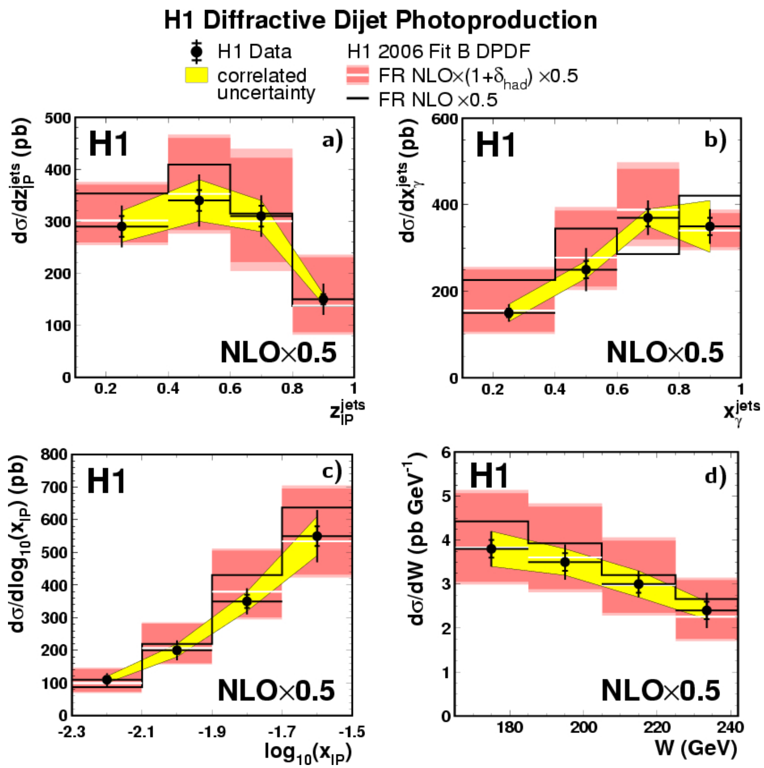
Diffractive Parton Densities

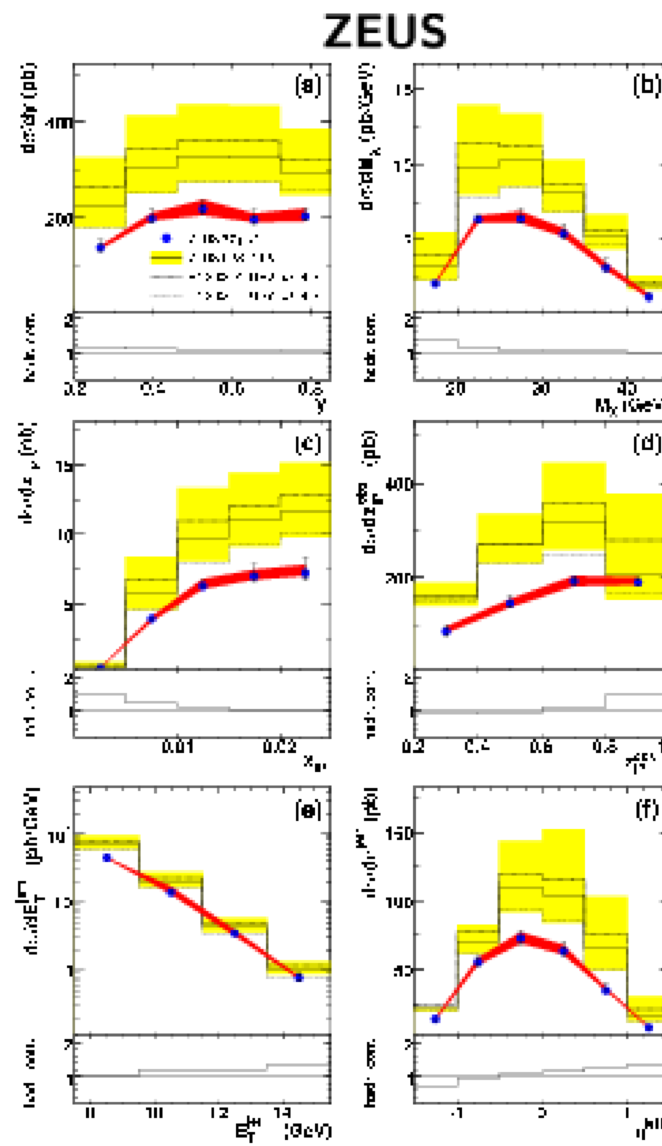


Singlet = Quark



Diffractive Dijet Cross Sections





- shape of the QCD theory prediction agrees with the data
- normalization is wrong

➔ factorization broken?!

Summary

- HERA offered unique possibilities to study the structure of the proton
- perturbative QCD is a big success to describe HERA data
- no significant deviation from the Standard Model found
- always prepare for the unexpected!