Physics at HERA

Summer Student Lectures
20 -22 August 2007

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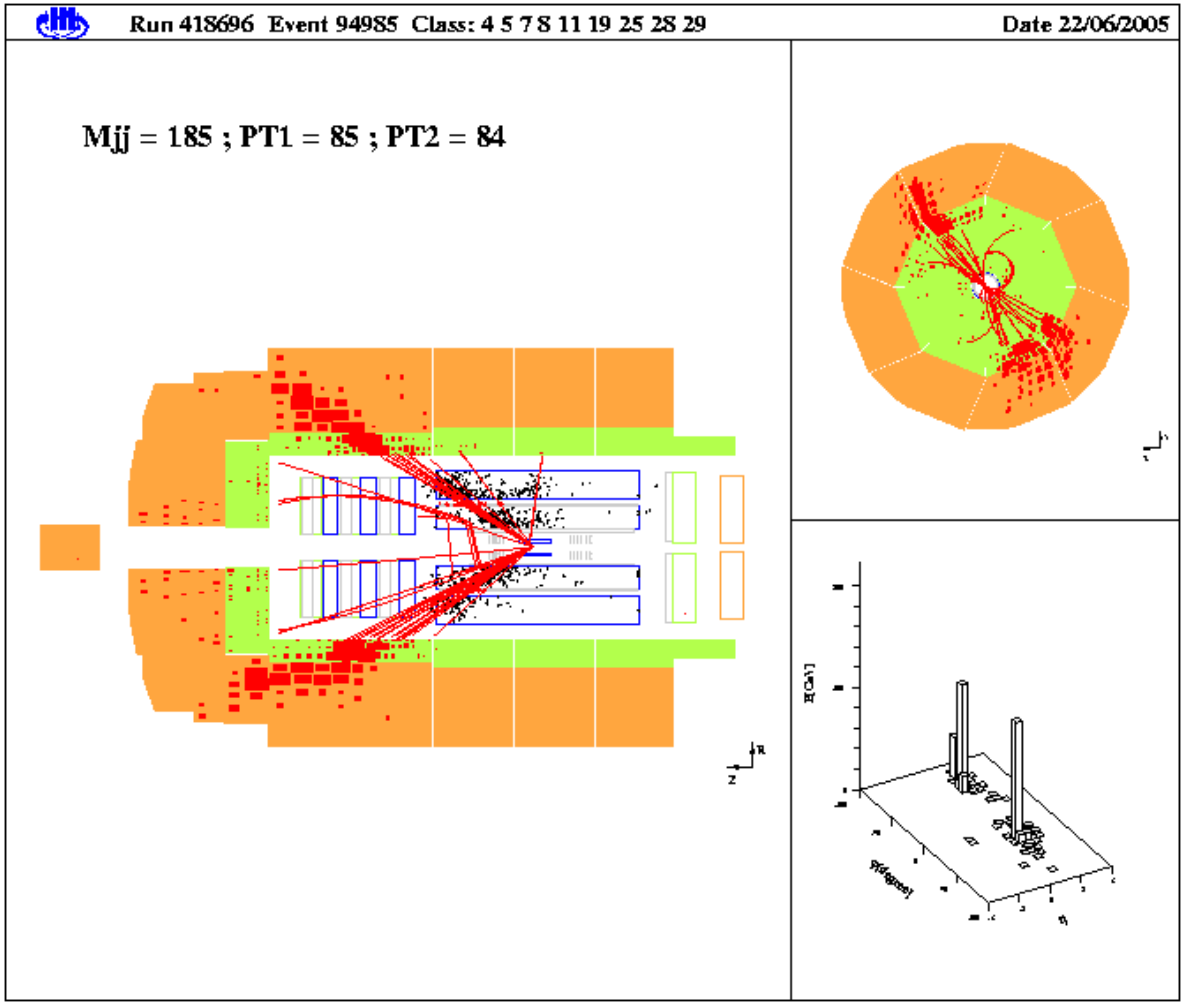
Overview Part 3

- Jet Physics
  - Cross Sections
  - Strong Coupling
- Heavy Quarks
  - Charm
  - Beauty
- Diffraction

Jet Physics & the Strong Coupling α_s

What are Jets?



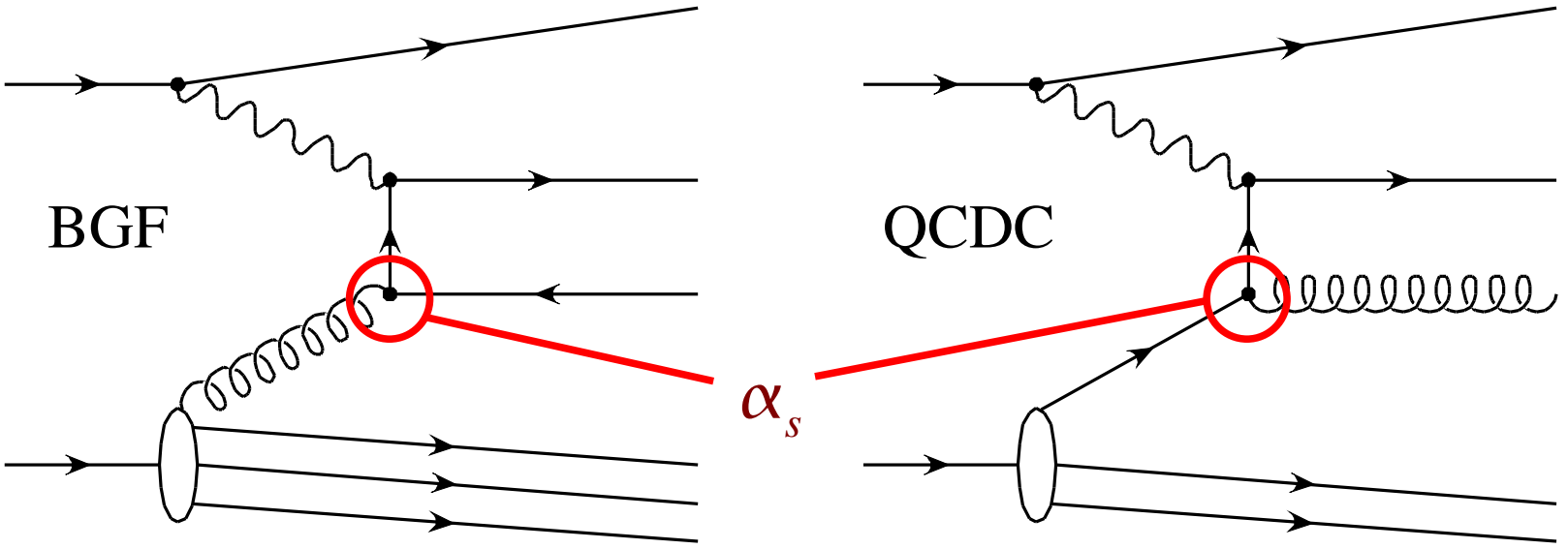
- jets are narrow bundles of hadrons originating from quarks or gluons
- can be used to study QCD and the strong coupling

How Are Jets Produced?

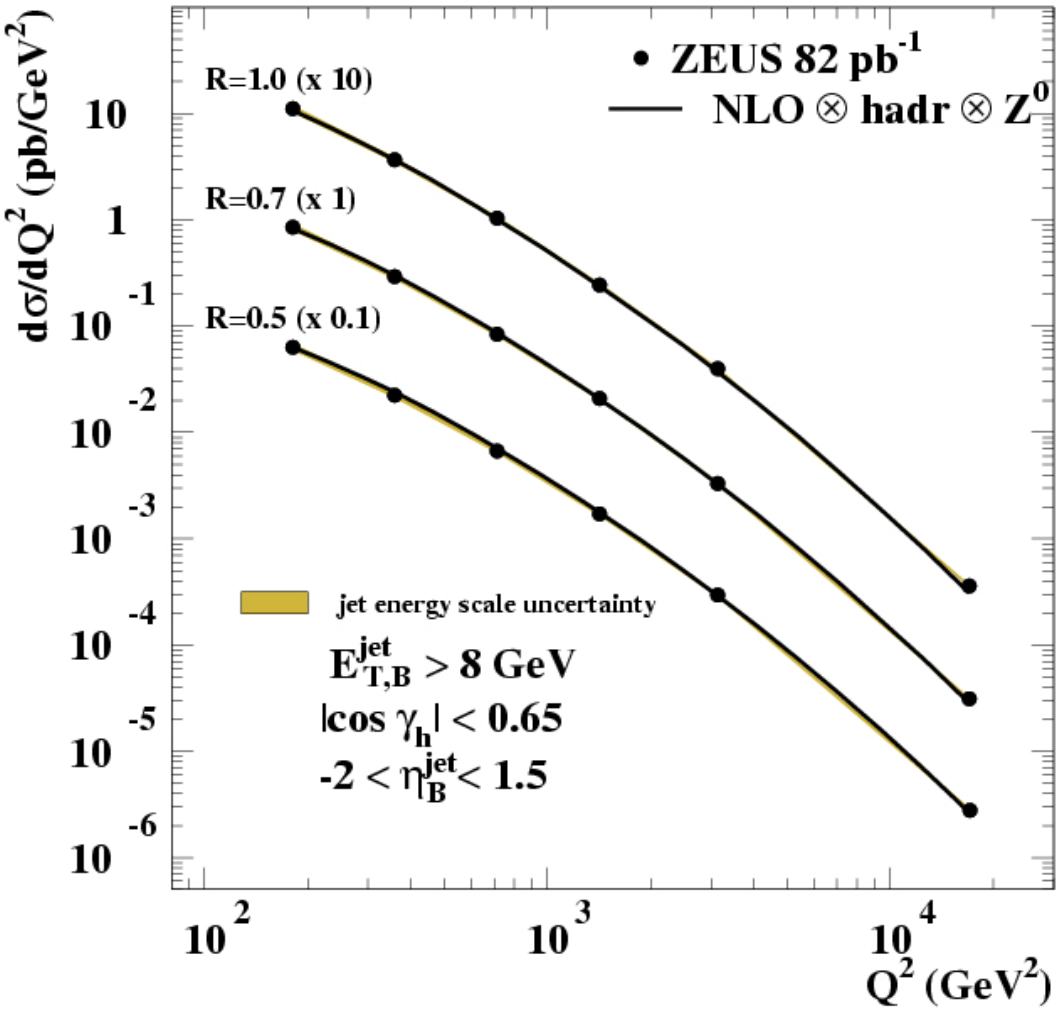
- do analysis in a frame where photon and proton collide head-on (e.g. Breit frame)

➔ LO DIS cannot produce transverse momentum

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

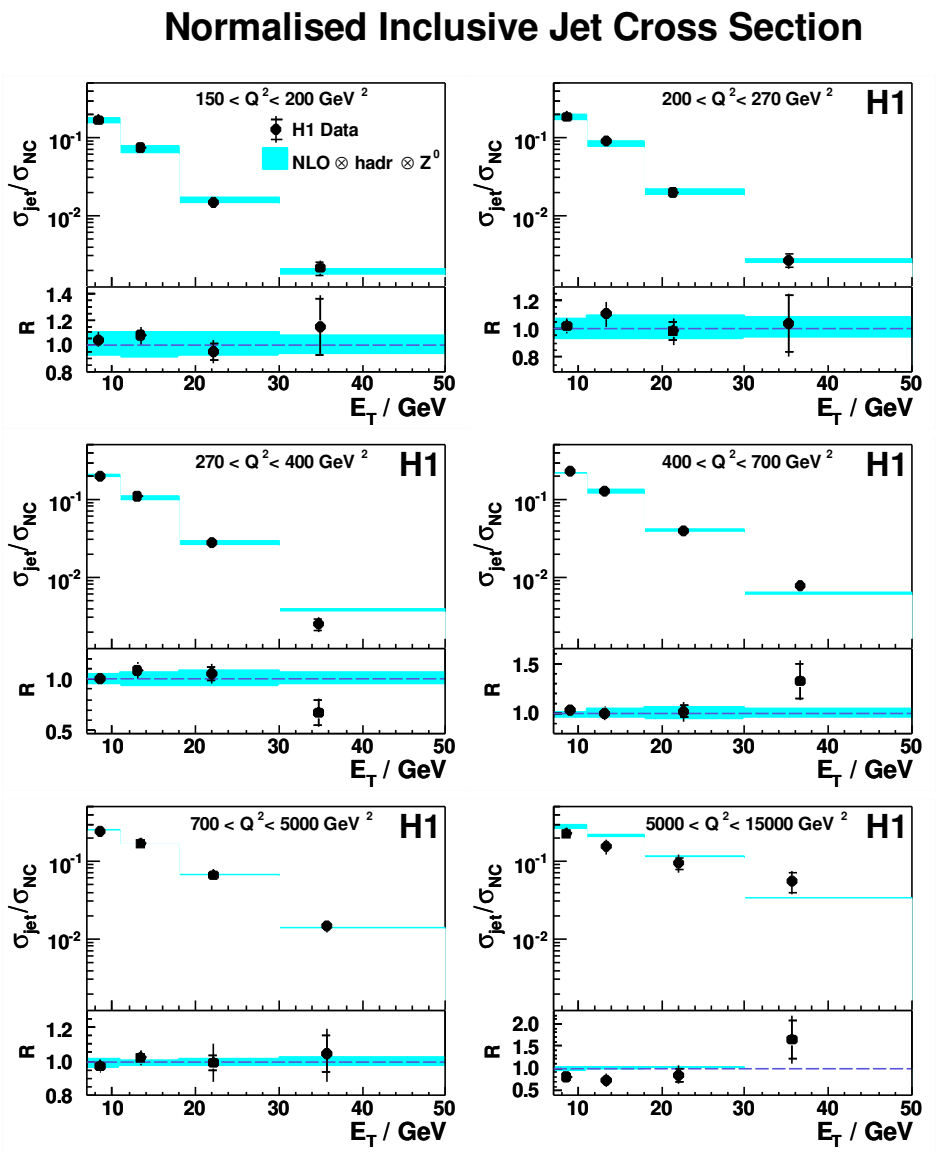


Jet Cross Sections



- theory curve:
  - NLO QCD calculation
  - PDFs
  - α_s
  - hadronisation
- very good agreement of theory and data
- uncertainty on PDF and theory input leads to uncertainty on α_s

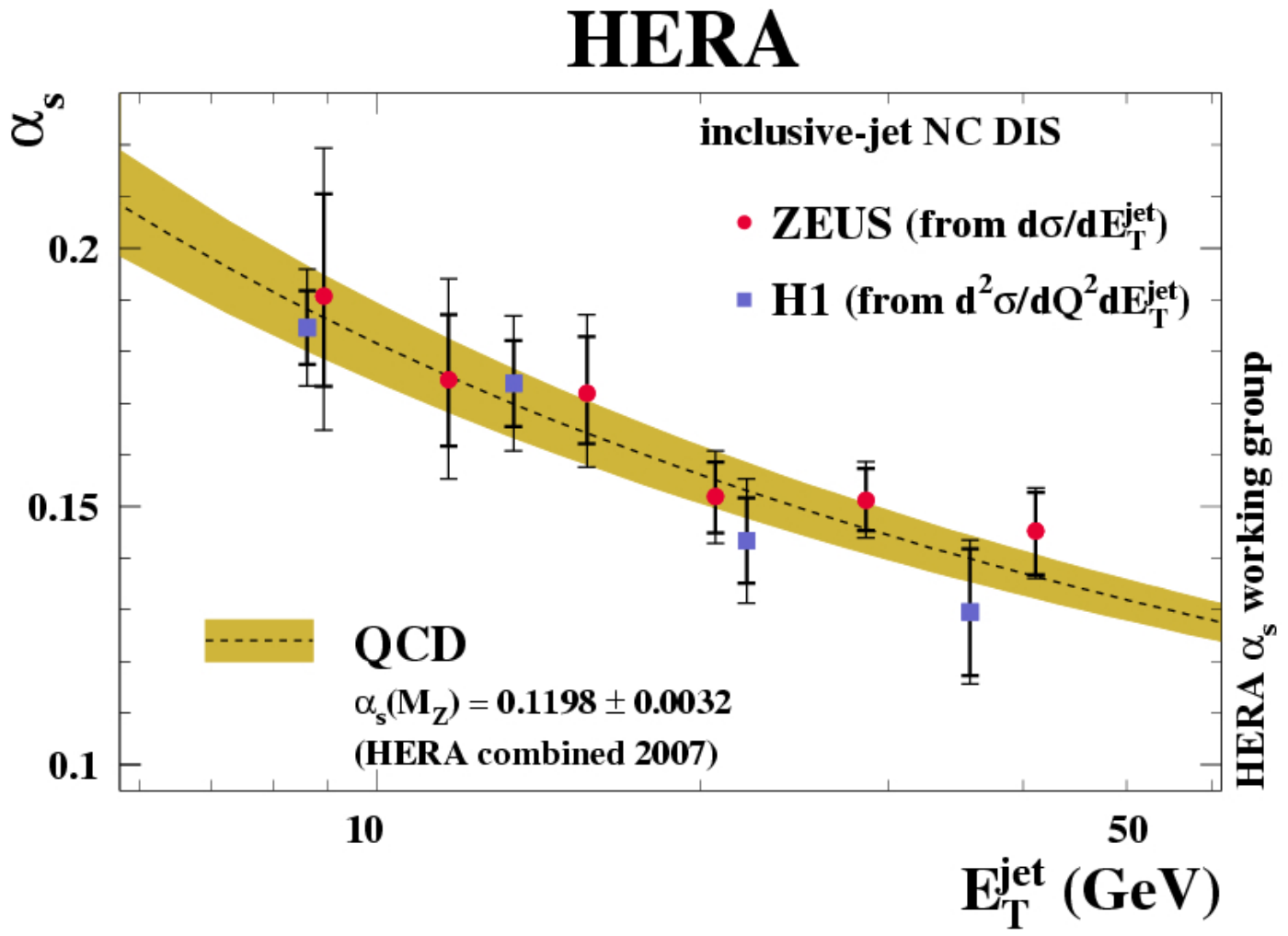
Jet Cross Sections



ratio of jet cross section to inclusive cross section has reduced uncertainties

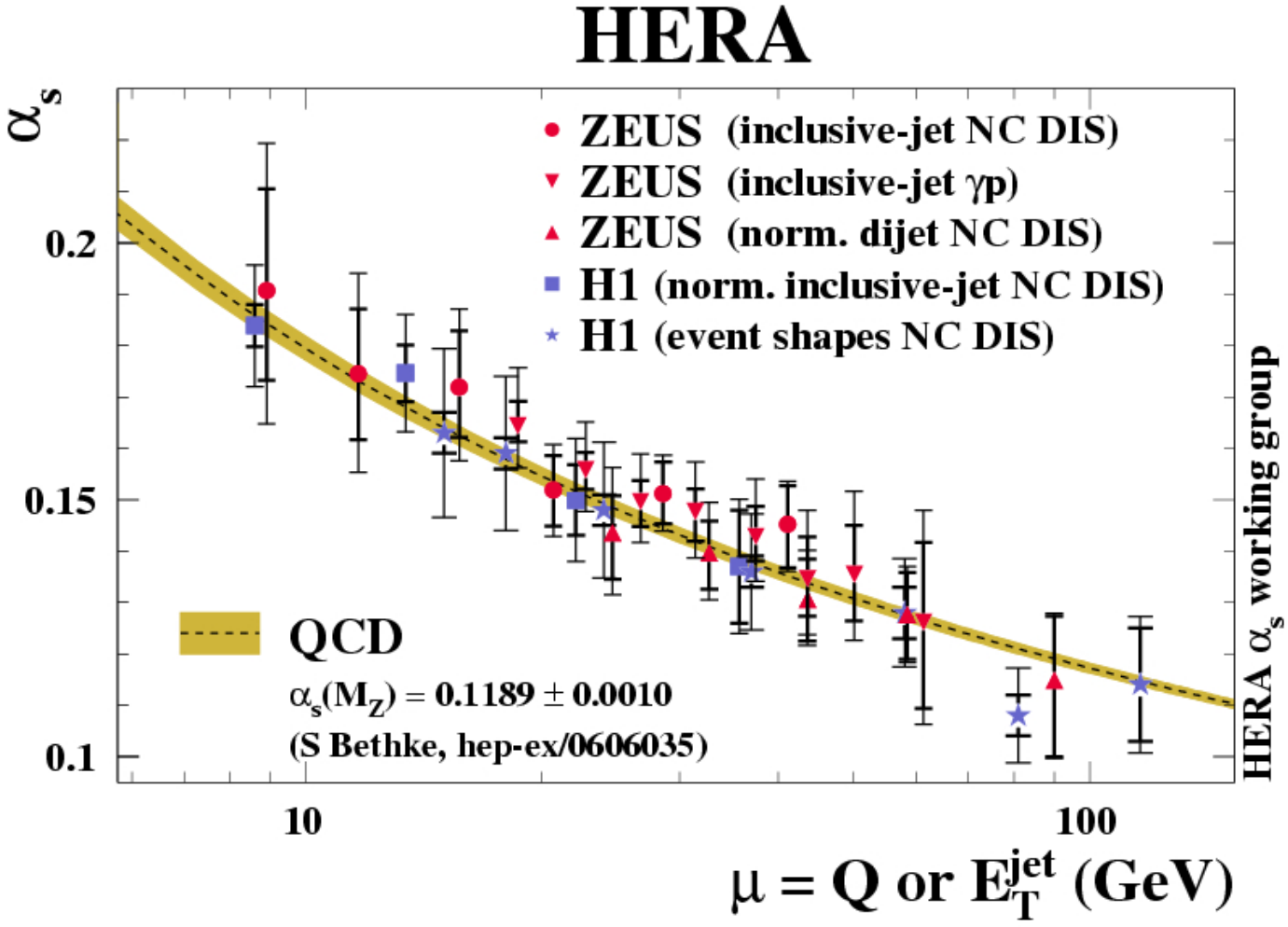
- systematic
- PDFs

Running of α_s



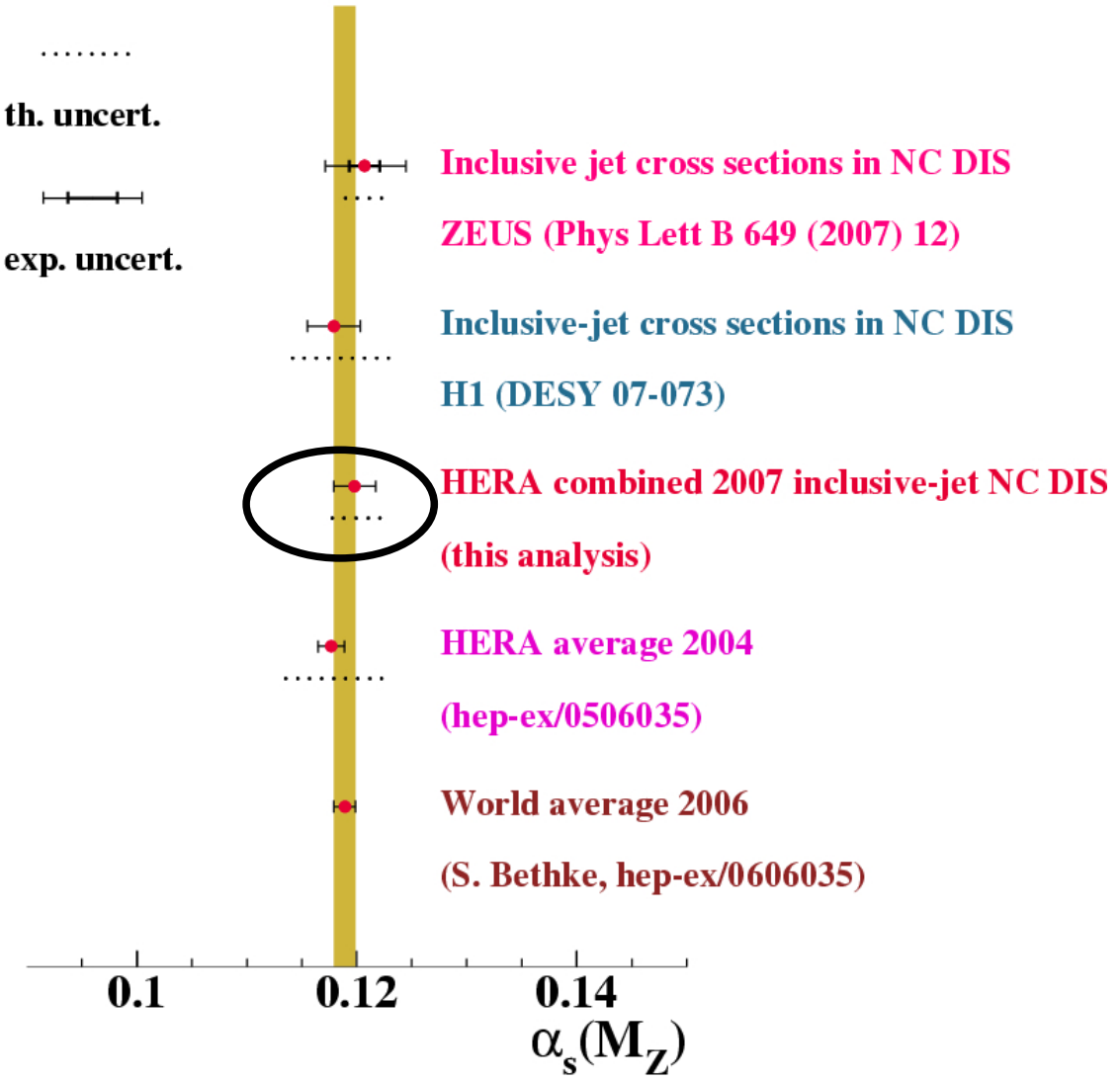
running of the strong coupling visible in one measurement

Running of α_s



comparison with other HERA measurements

$\alpha_s(M_Z)$



HERA measurements often dominated by systematic and theoretical uncertainties

→ use only selected datasets to extract α_s with minimal uncertainty

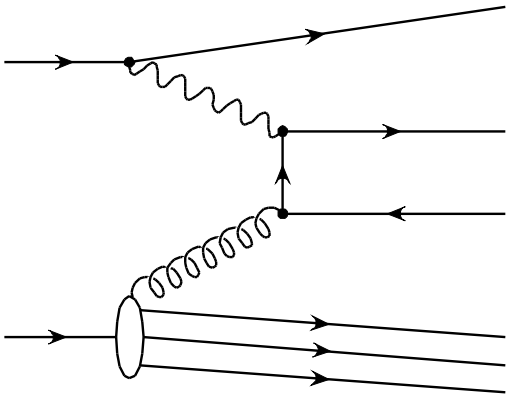
→ HERA value very competitive

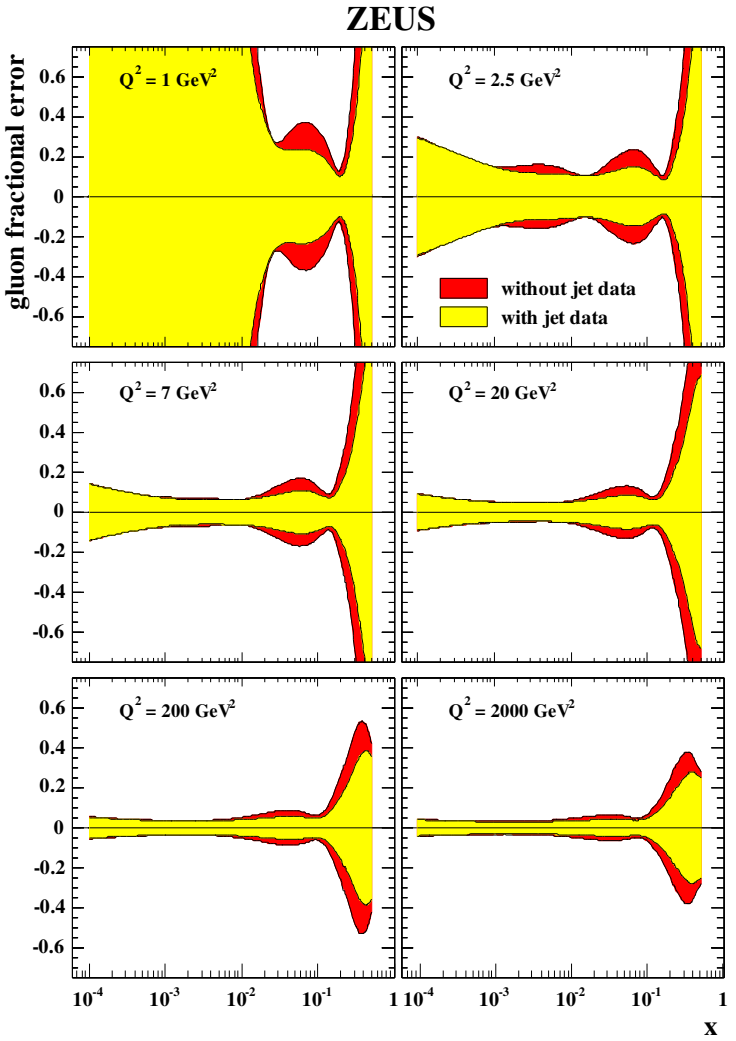
Improved Parton Densities

- F_2 is only indirectly sensitive to the gluon

➔ global fits (MRST, CTEQ) use Tevatron jet data

➔ alternative: use HERA (di-)jet data

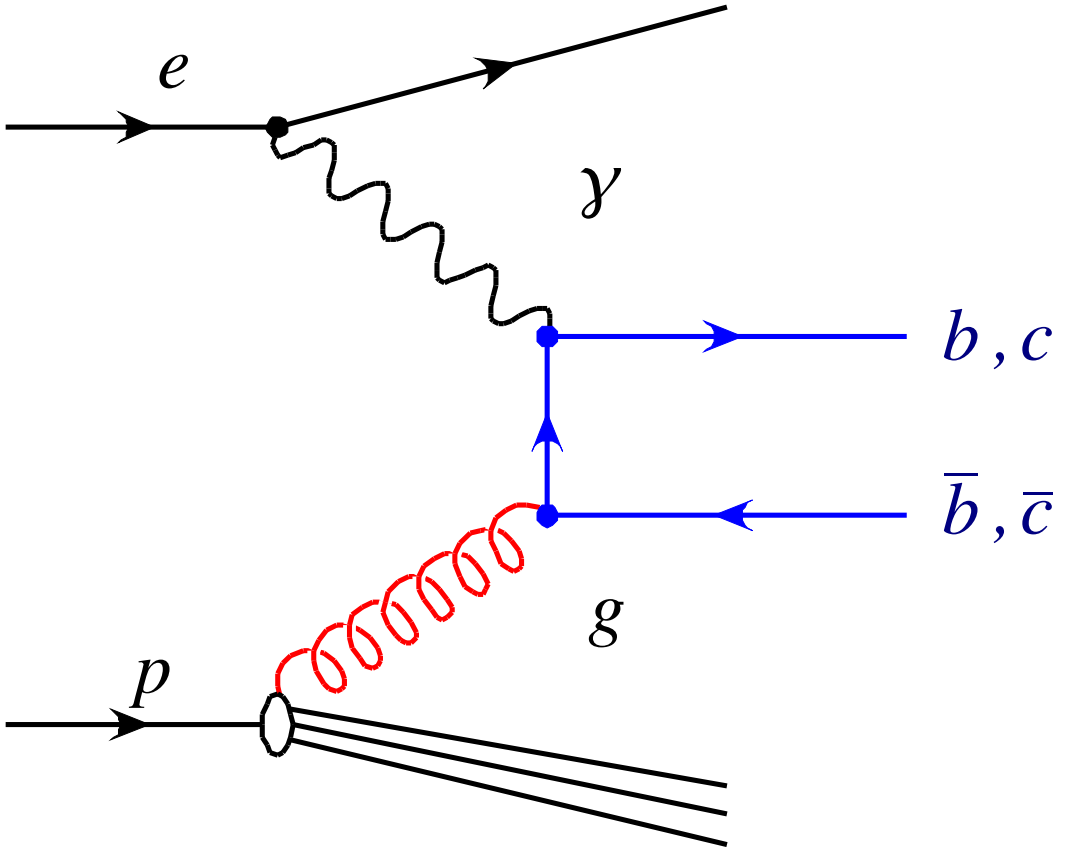




improvement at medium to large x

Heavy Quarks

Production of Heavy Quarks



predominantly via boson gluon fusion

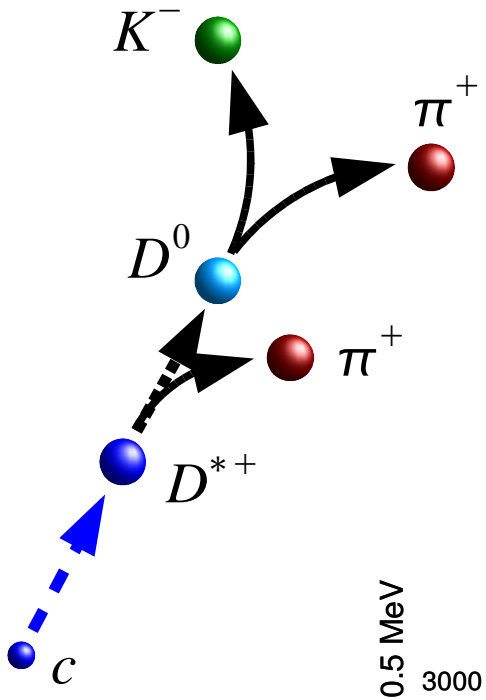
large quark mass allows pQCD calculations

directly sensitive to gluon density in the proton

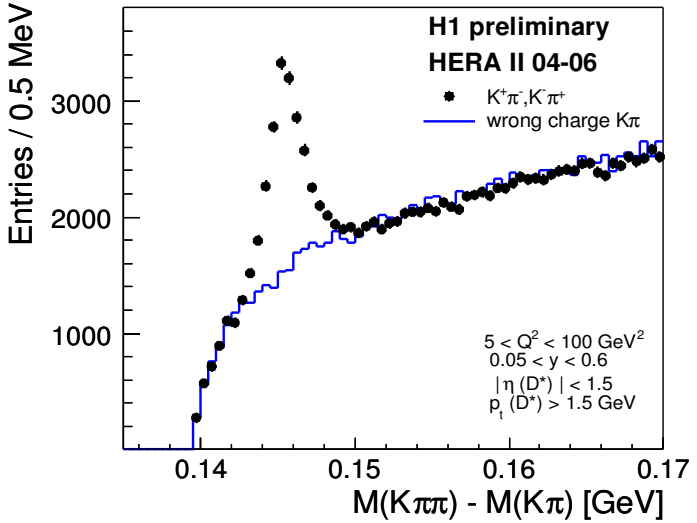
heavy quark contribution to structure function

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

Reconstruction of *charm* Quarks

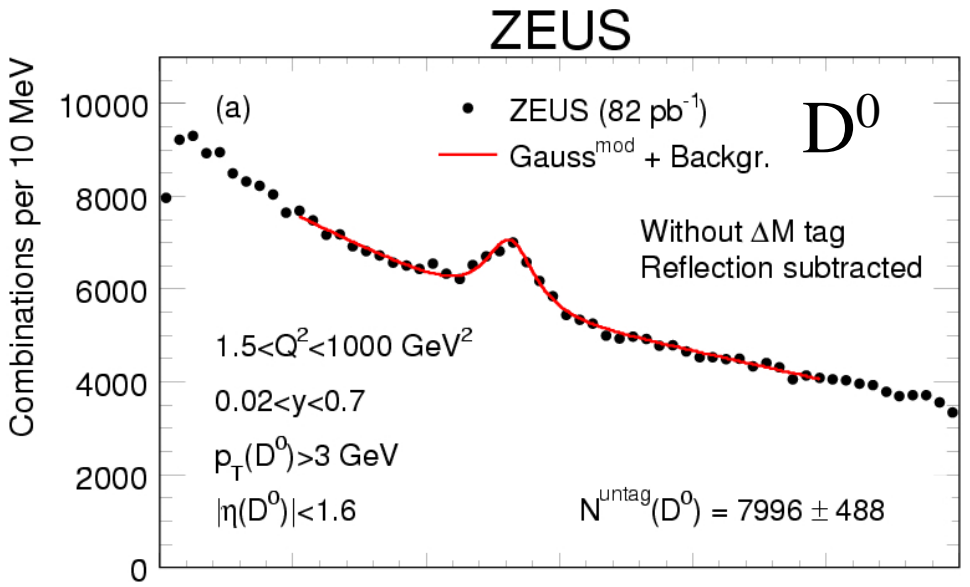


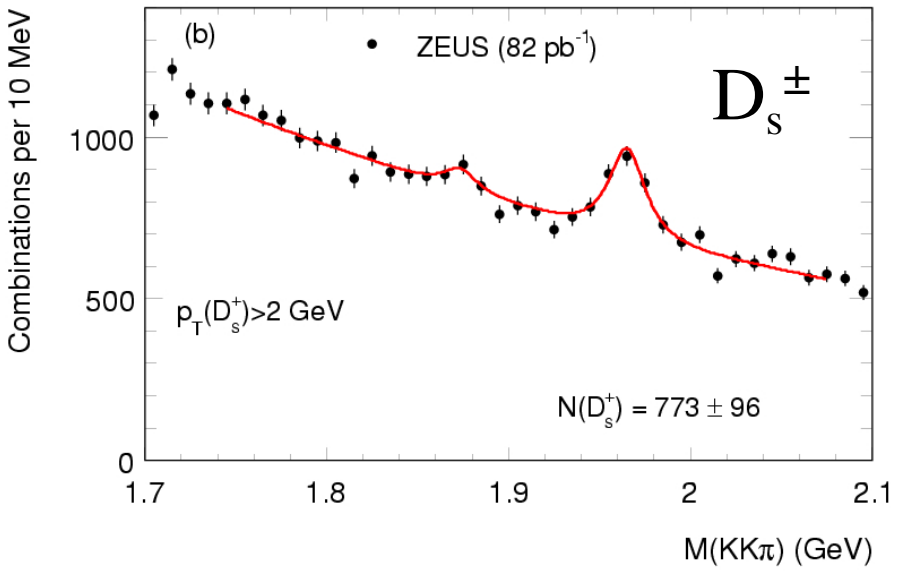
- fragmentation $c \to D^*$ meson (25,5%)
- „golden decay“ (2,6%)
  $D^{*+} \to D^0 \pi_s^+ \to K^- \pi^+ \pi_s^+$
  - only charged decay particles
  - small mass difference $\Delta M = m(D^*) - m(D^0)$

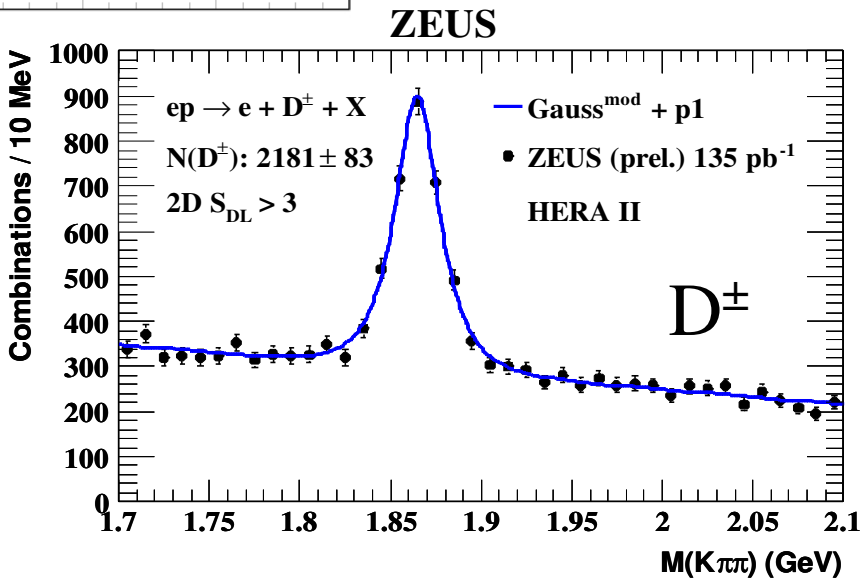


- small momentum of the „slow“ π_s
- good experimental resolution (~1 MeV)

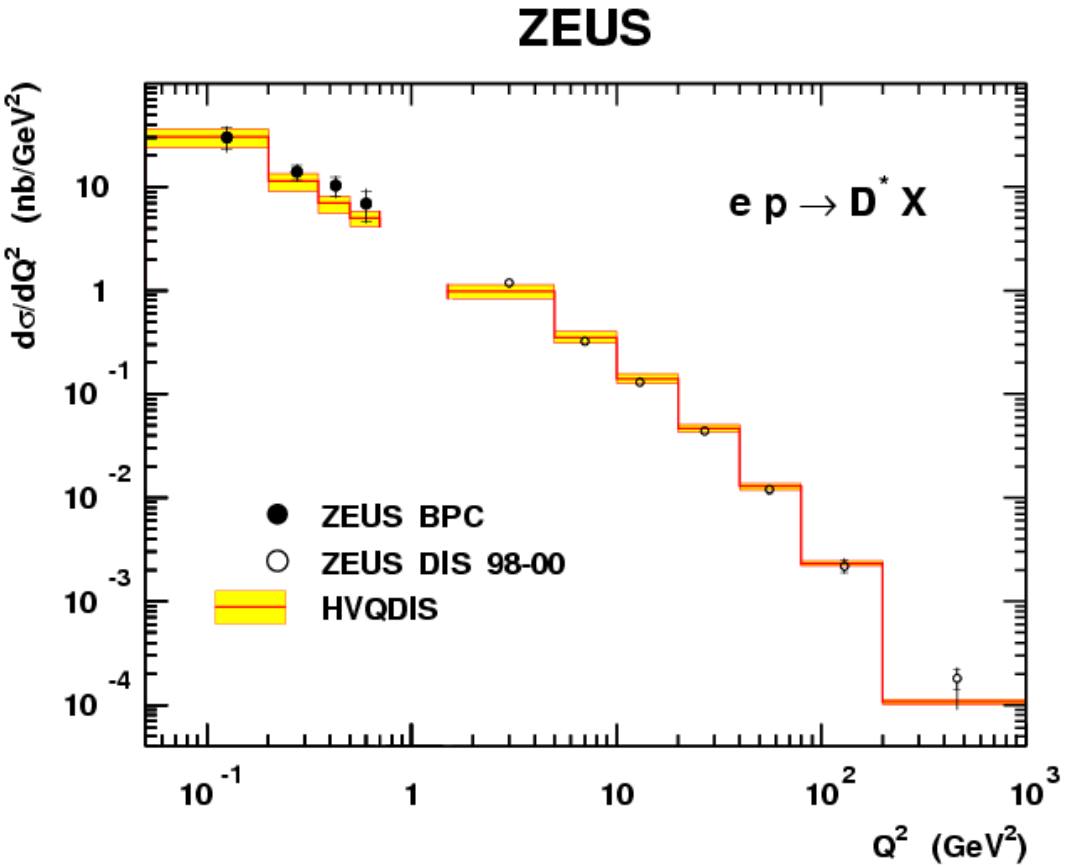
More *charm* Signals







D* Cross Section

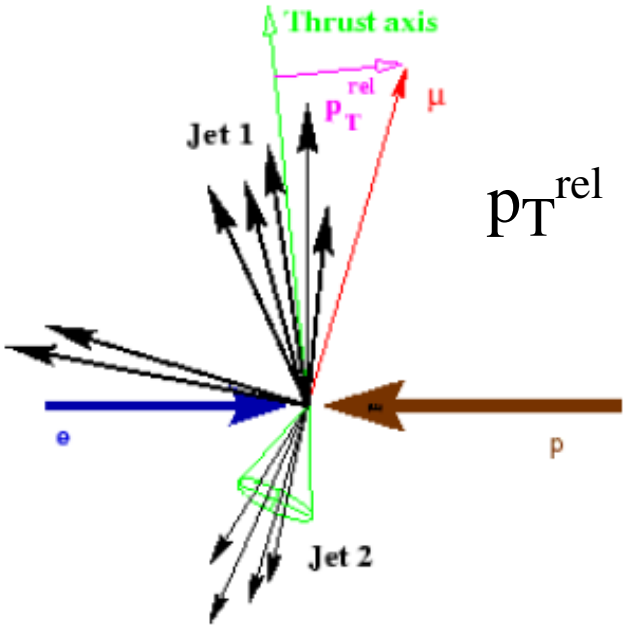


good description by NLO pQCD calculation (HVQDIS) in full measured Q^2 range (> 4 orders of magnitude)

PDF: ZEUS PDF extracted from inclusive DIS

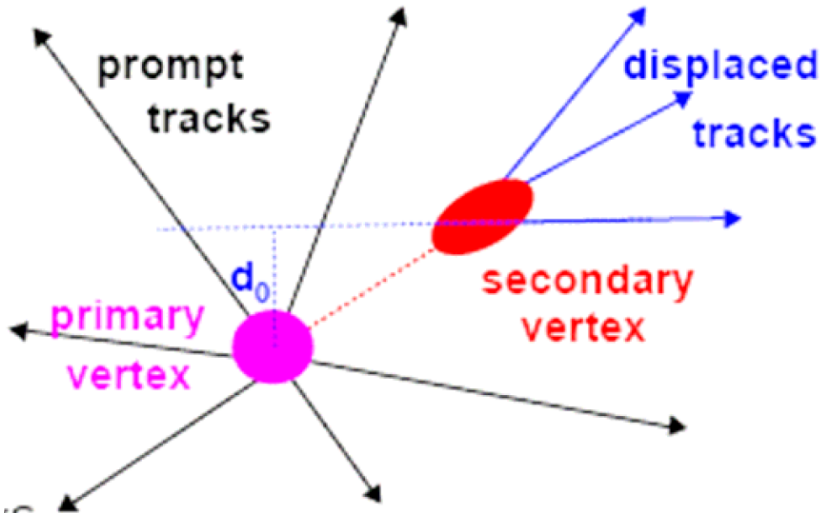
Tagging of *beauty* Quarks

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

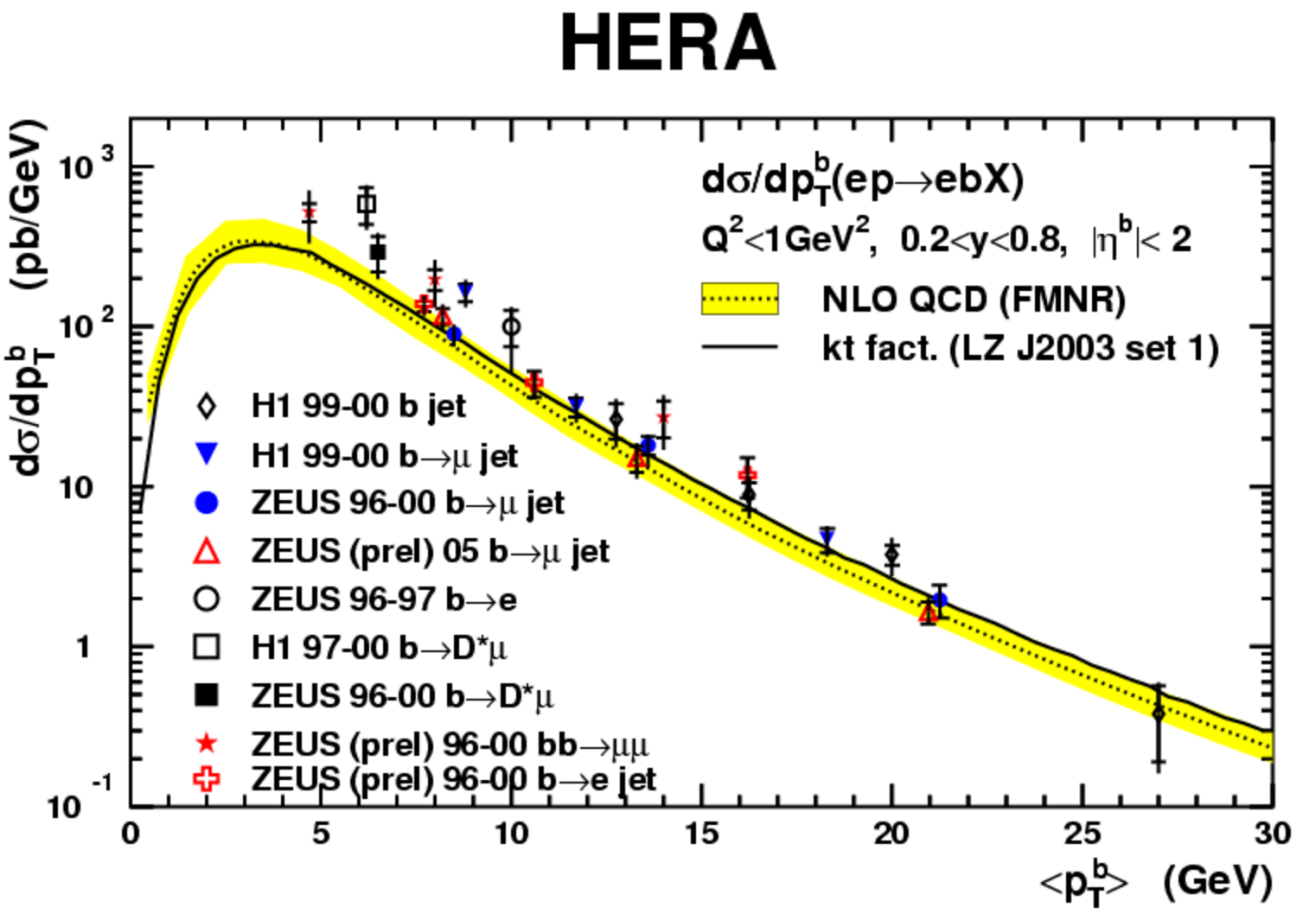


p_T^{rel}

lifetime tagging



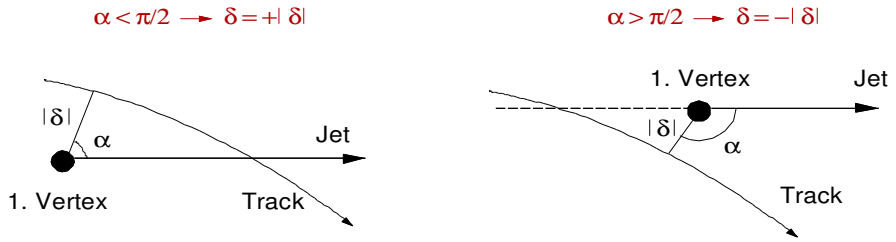
beauty Cross Section Results

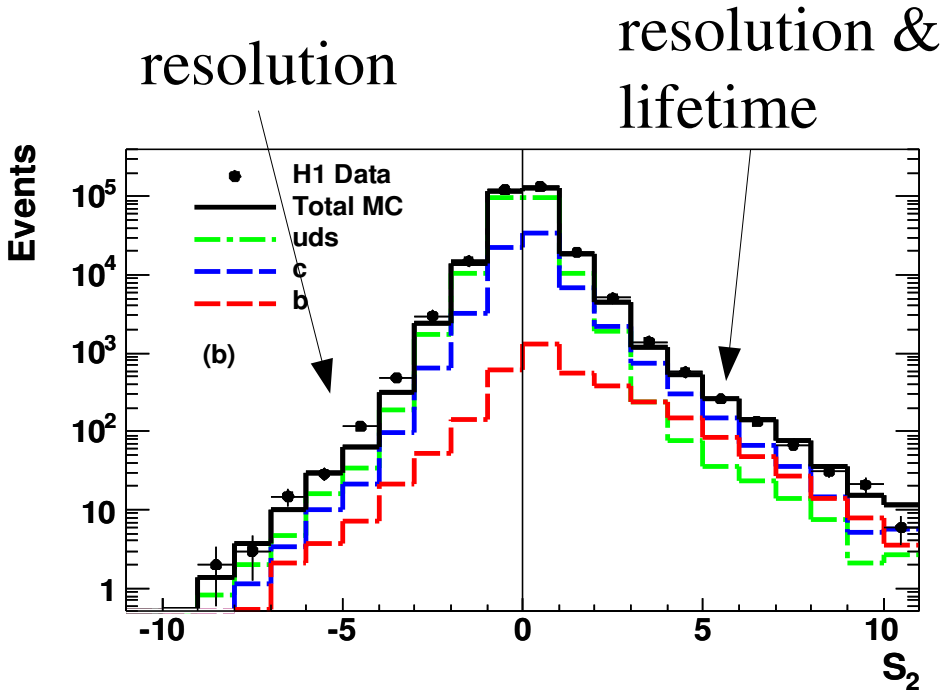


some data higher than NLO QCD theory, but reasonable agreement for the most precise data

Inclusive Lifetime Tagging

signed impact parameter δ

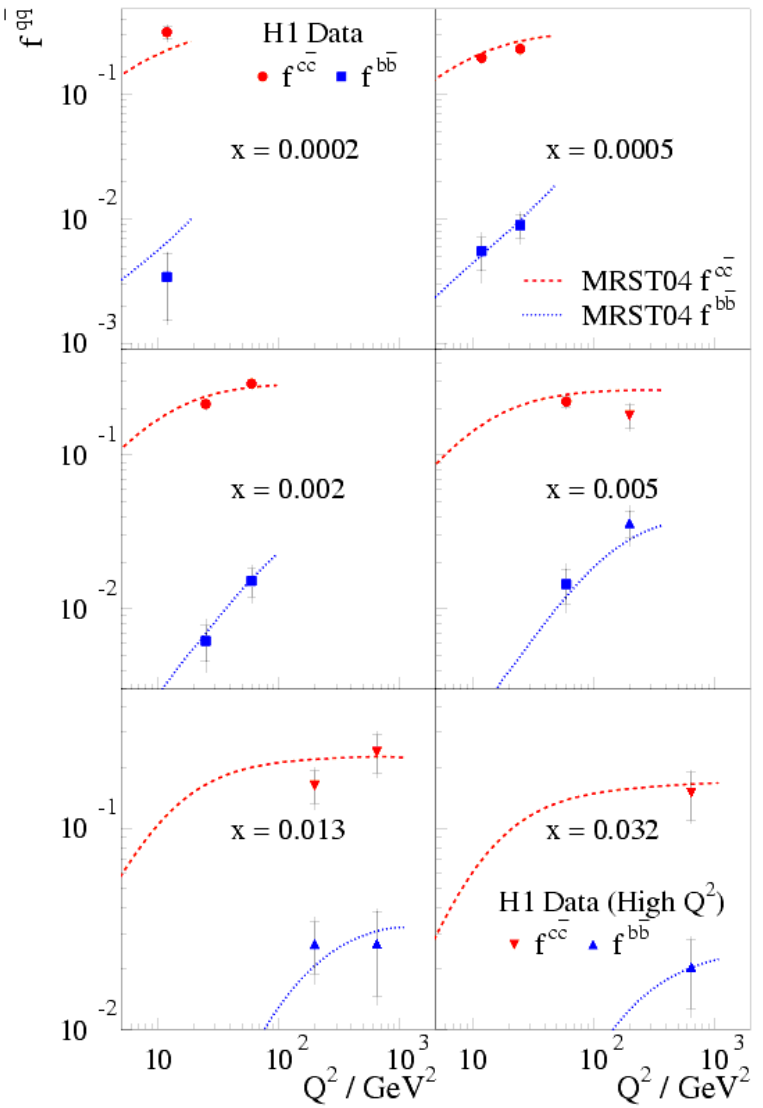




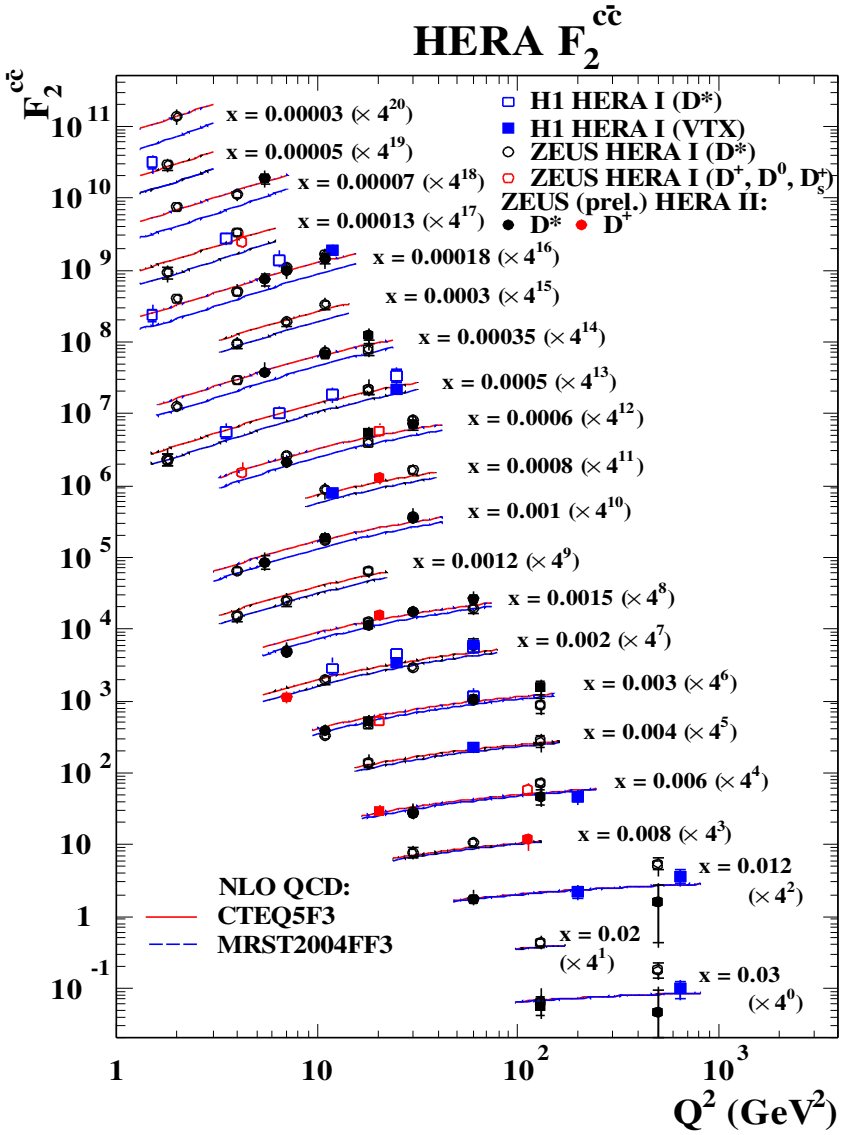
- both experiments have silicon vertex detectors
- inclusive method: use all tracks
- study significance of the (signed) impact parameter: $S = \delta / \sigma(\delta)$
- allows separation of beauty, charm and light quarks

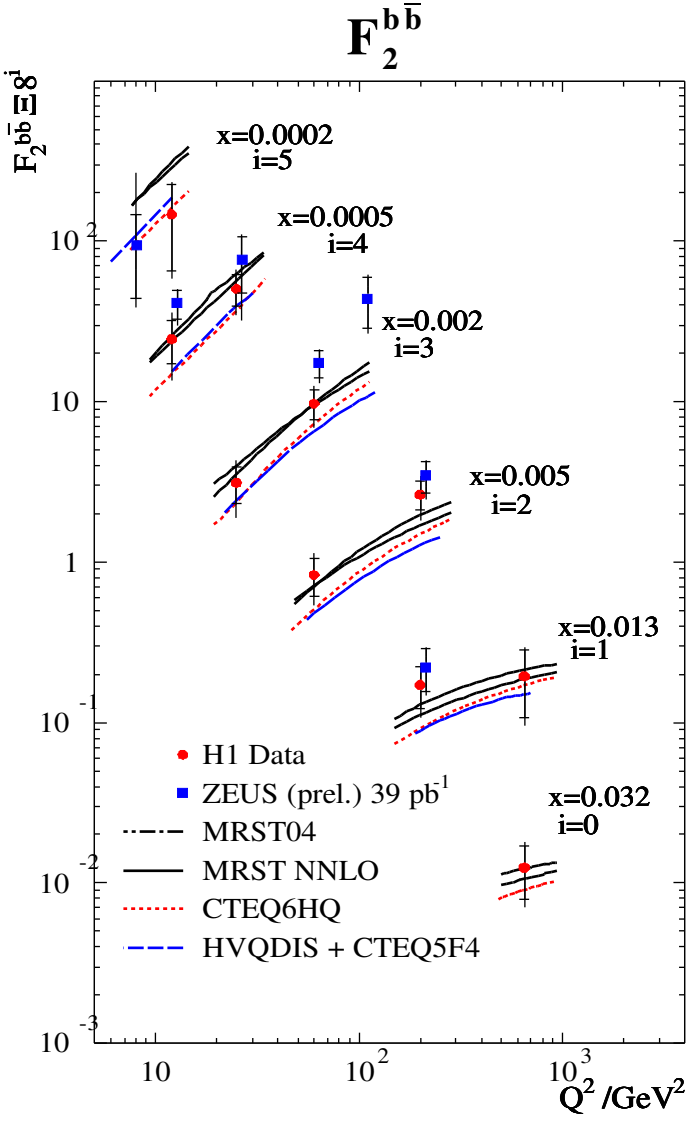
Contribution to the Cross Section

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



Contribution to the Structure Function

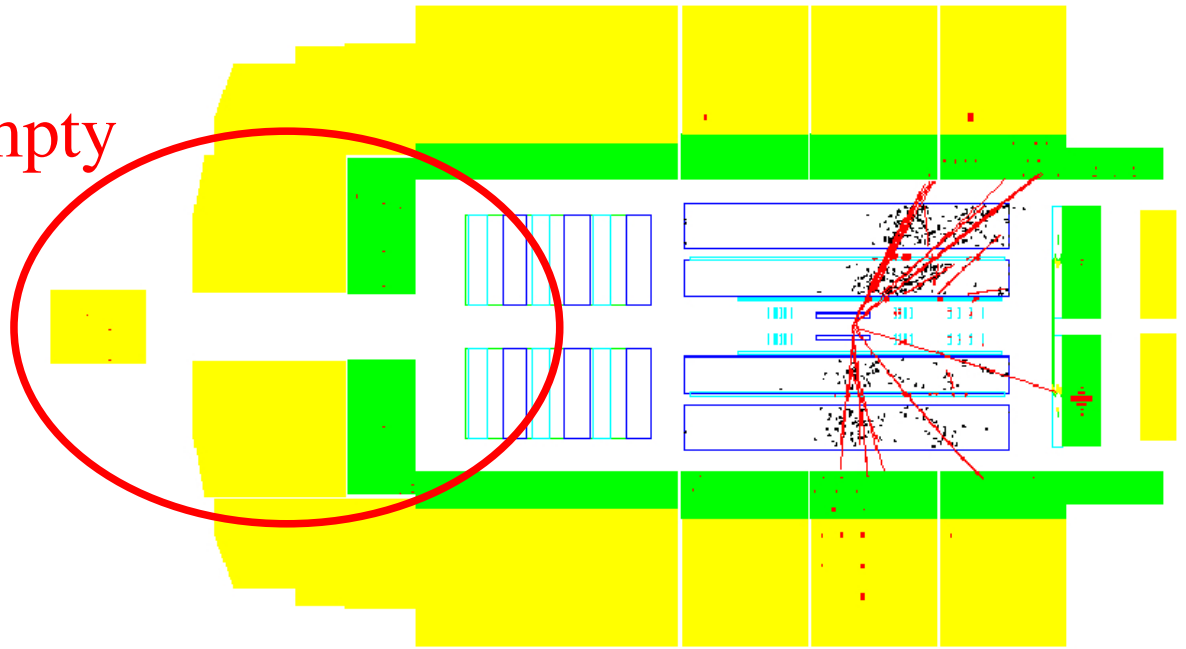




Diffraction

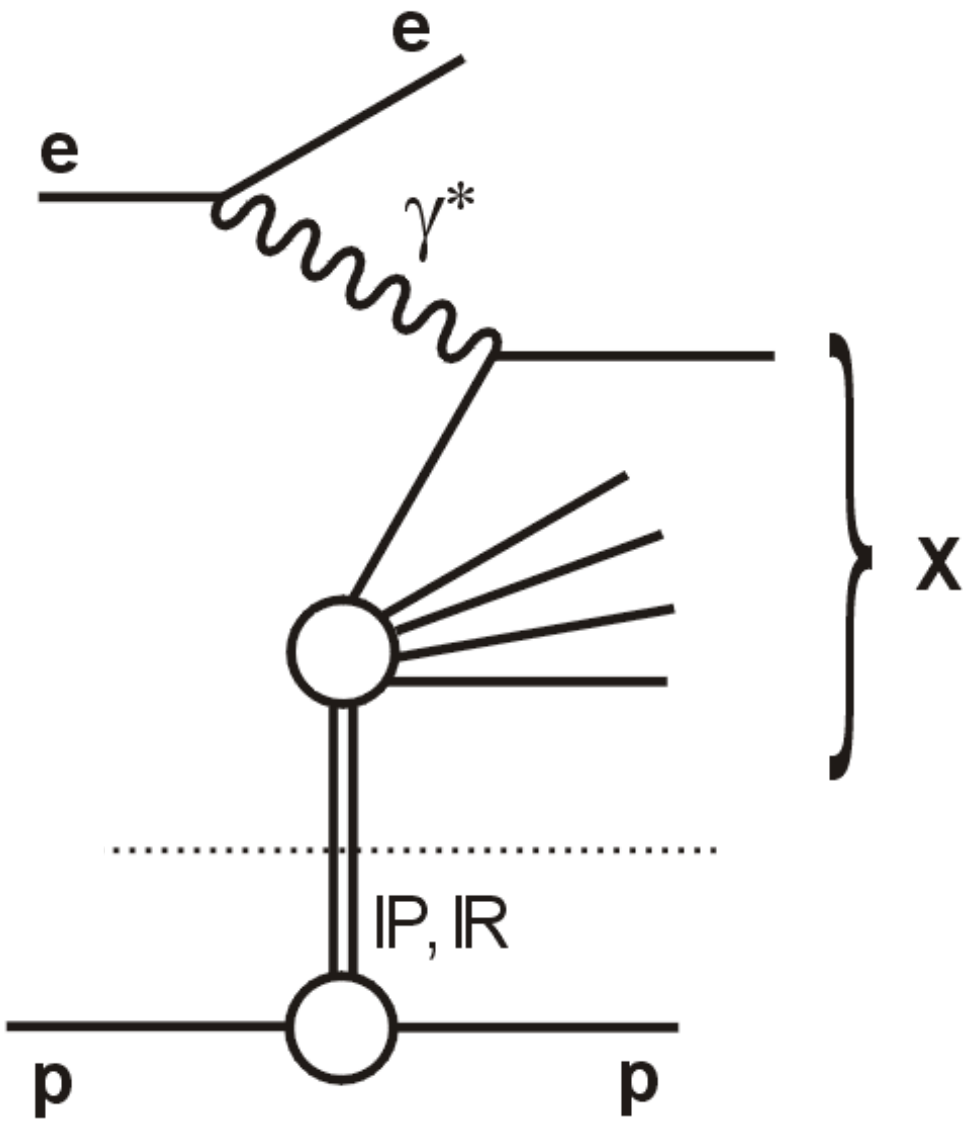
What is Diffraction?

- 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

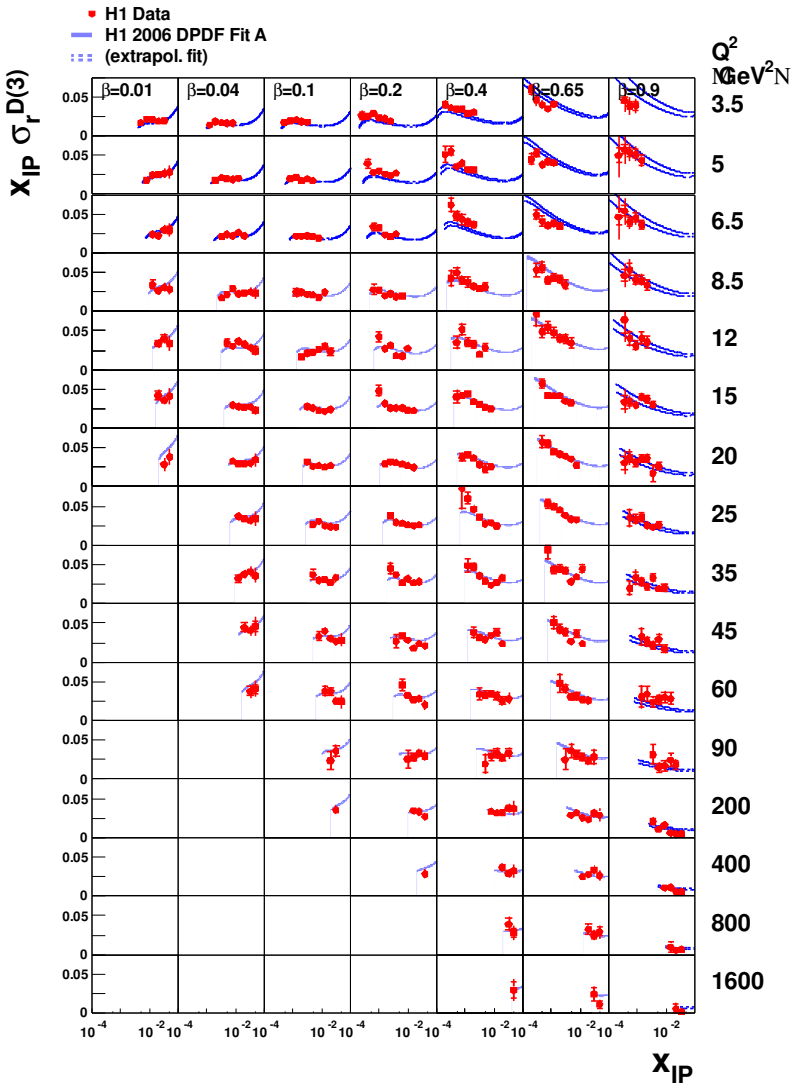


- idea: interaction between photon and proton by a „Pomeron“
  - colourless
  - already used to describe low energy hadron-hadron scattering
  - no particle!

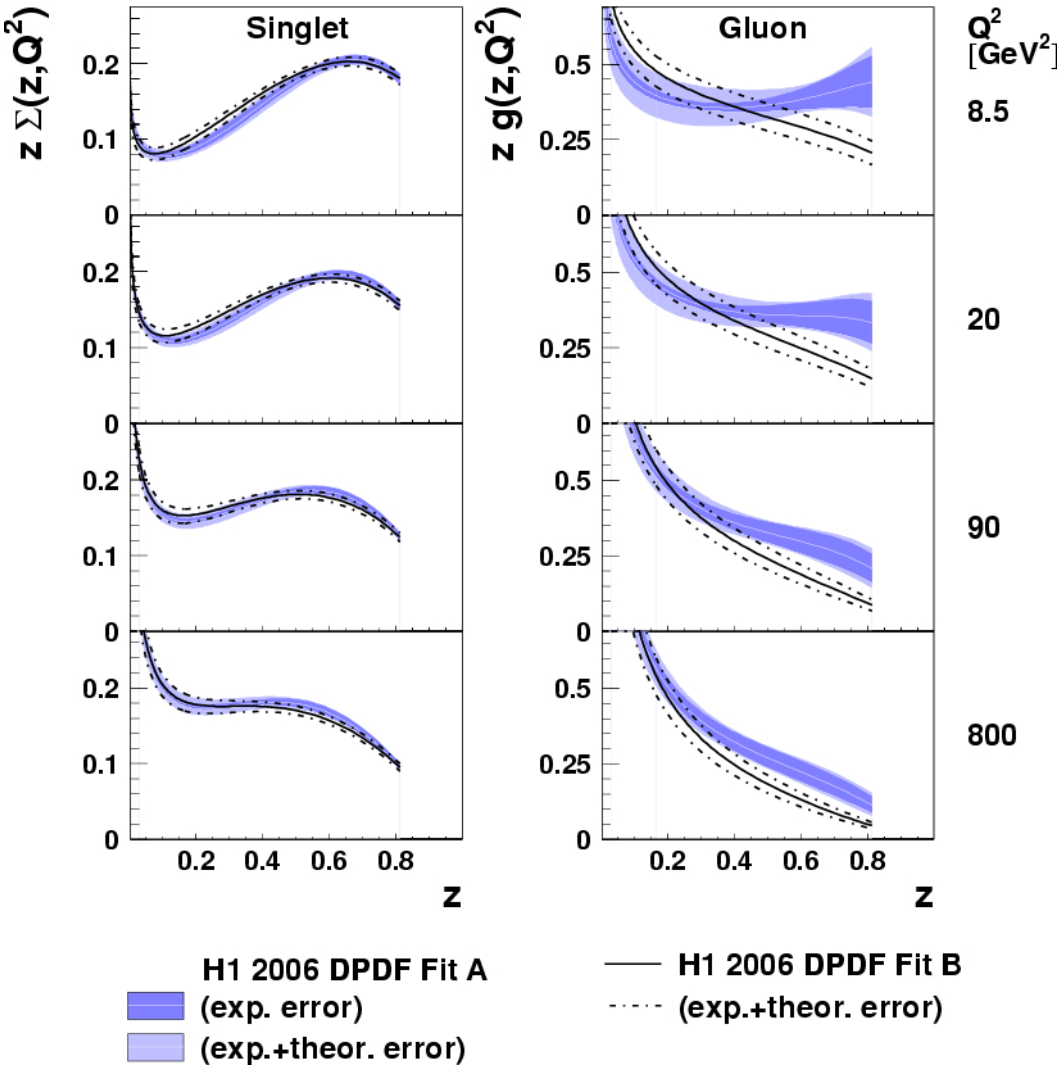
Physics in Diffraction

- 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?

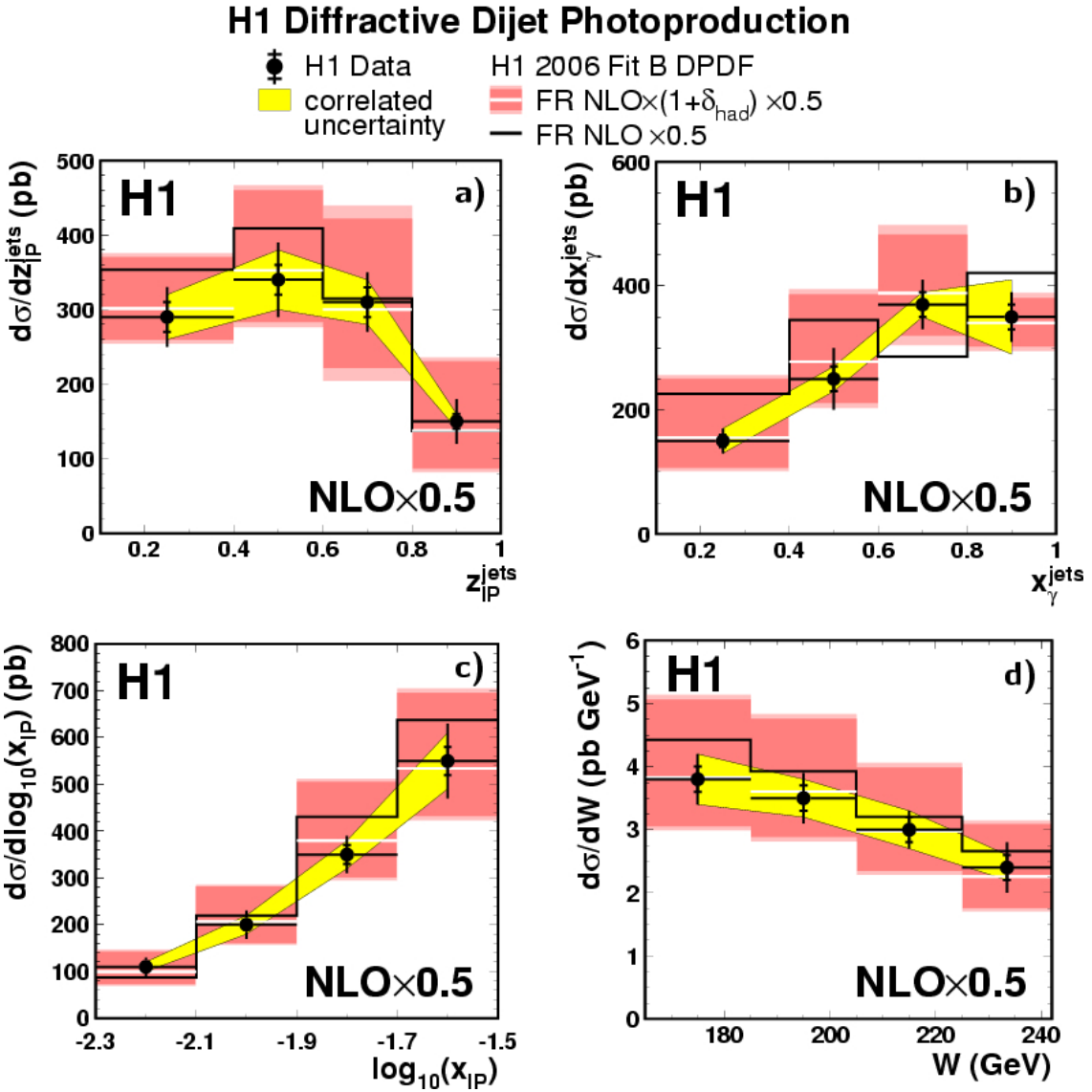
Diffractive Parton Densities



Singlet = Quark



Diffractive Dijet Cross Sections



- shape of the QCD theory prediction agrees with the data
- normalization is wrong by a factor 2

➔ factorization is broken!

Summary

- HERA offered unique possibilities to study the structure of the proton
- perturbative QCD is a big success to desribe HERA data
- no significant deviation from the Standard Model found