Physics at HERA

Summer Student Lectures
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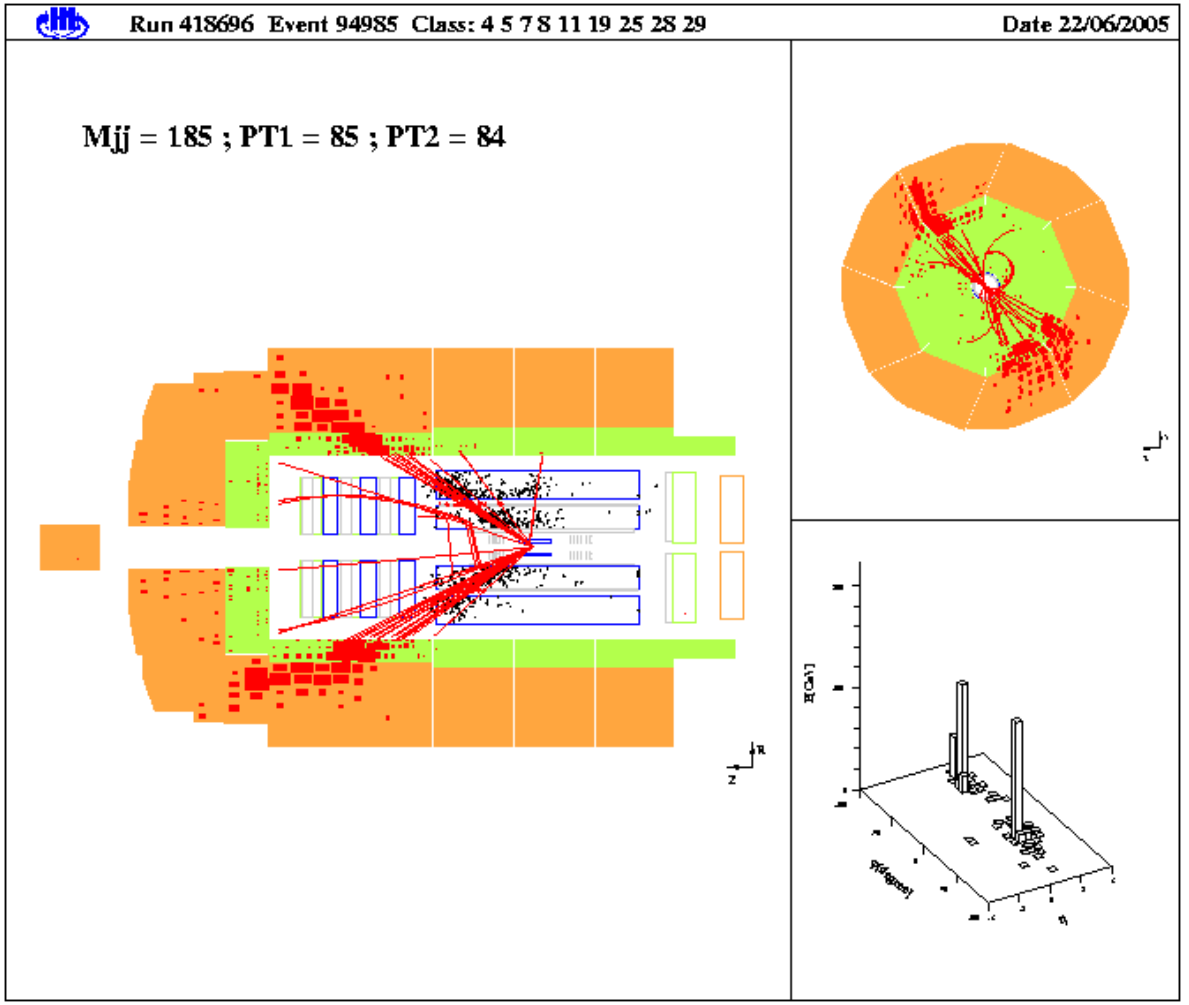
Overview Part 4

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

personal selection!
many more analyses
are done!

Jet Physics & the Strong Coupling α_S

What are Jets?



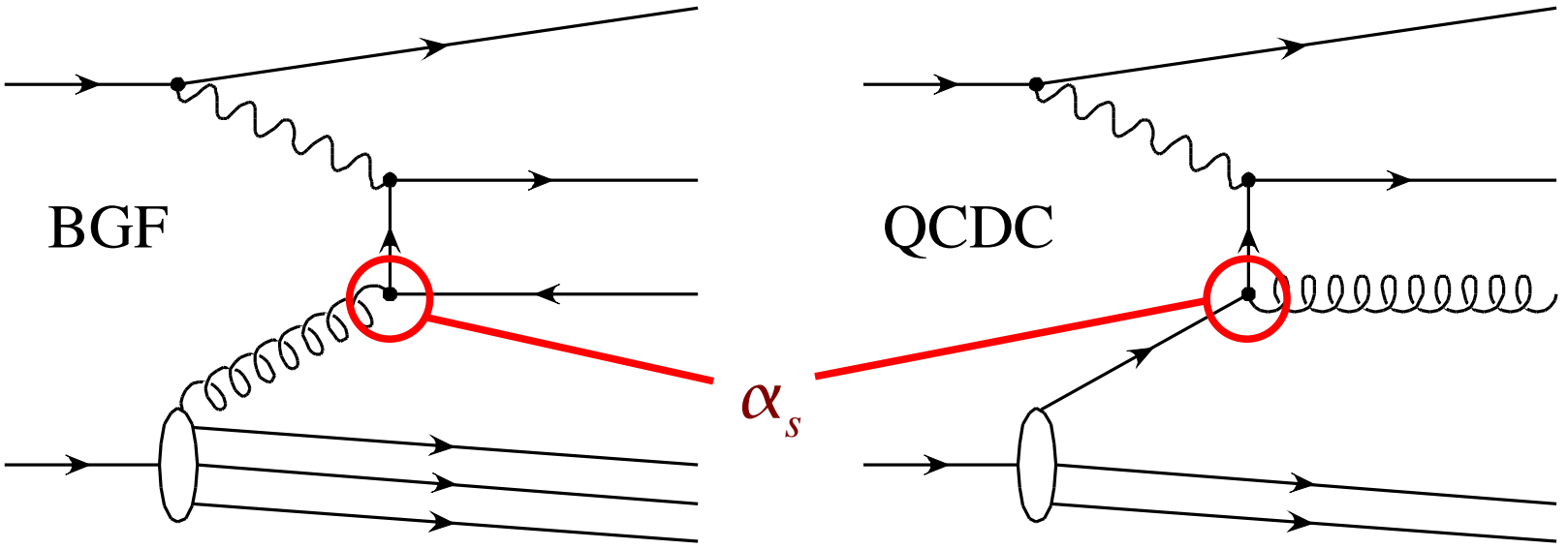
- jets are narrow bundles of hadrons originating from quarks or gluons
- can be used to study QCD and the strong coupling

How Are Jets Produced?

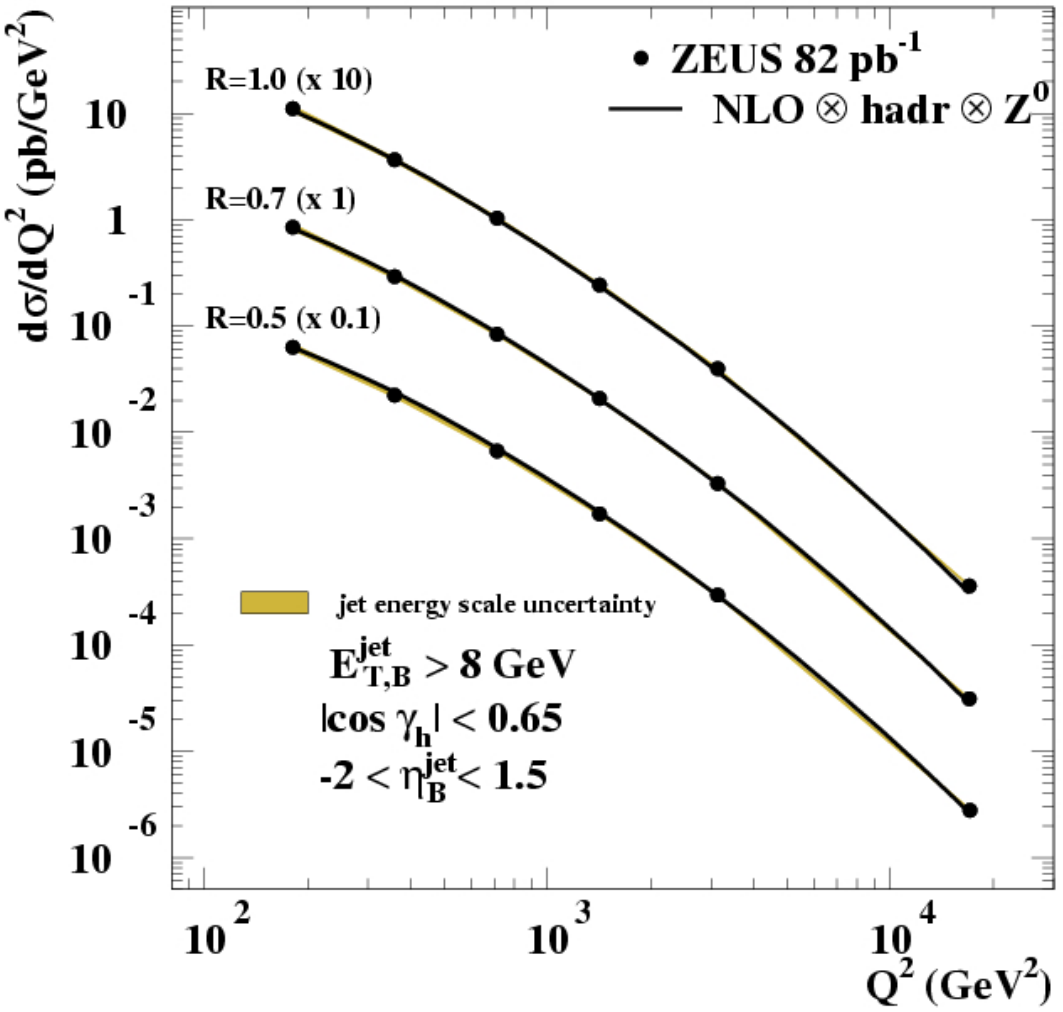
- do analysis in a frame where photon and proton collide head-on (e.g. Breit frame)

➔ LO DIS cannot produce transverse momentum

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

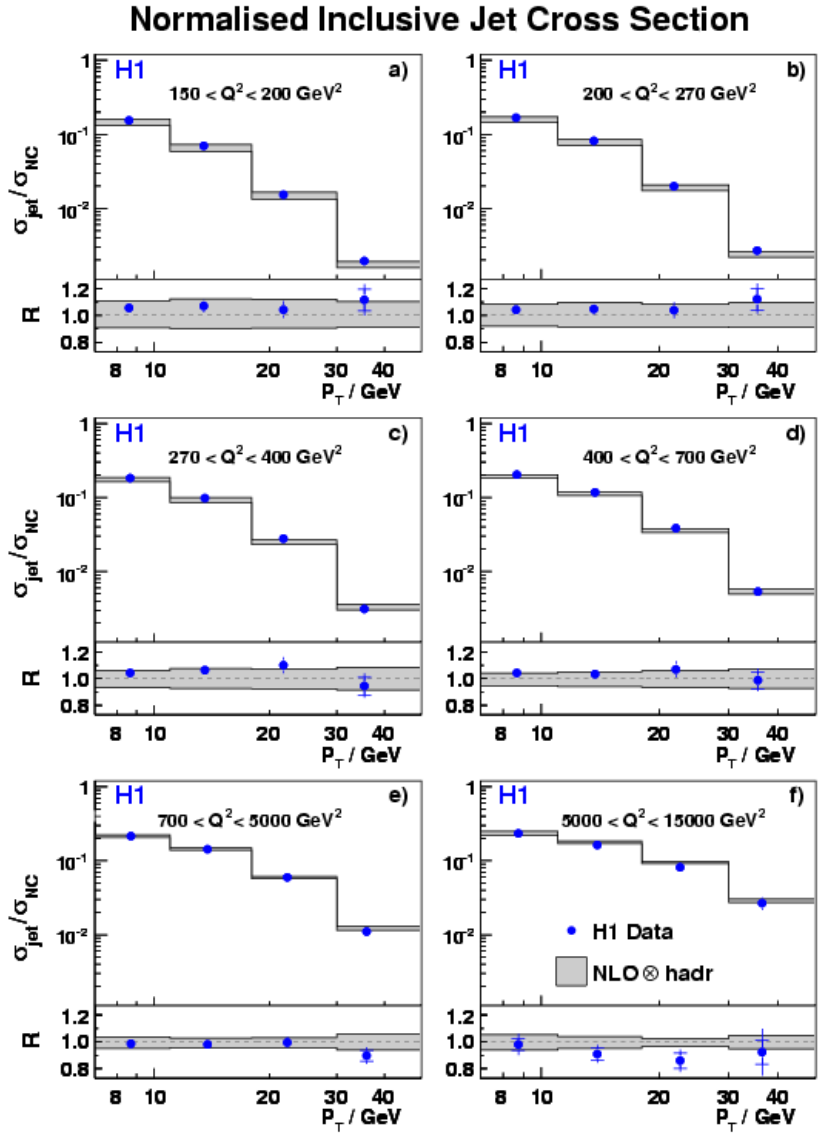


Jet Cross Sections



- 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

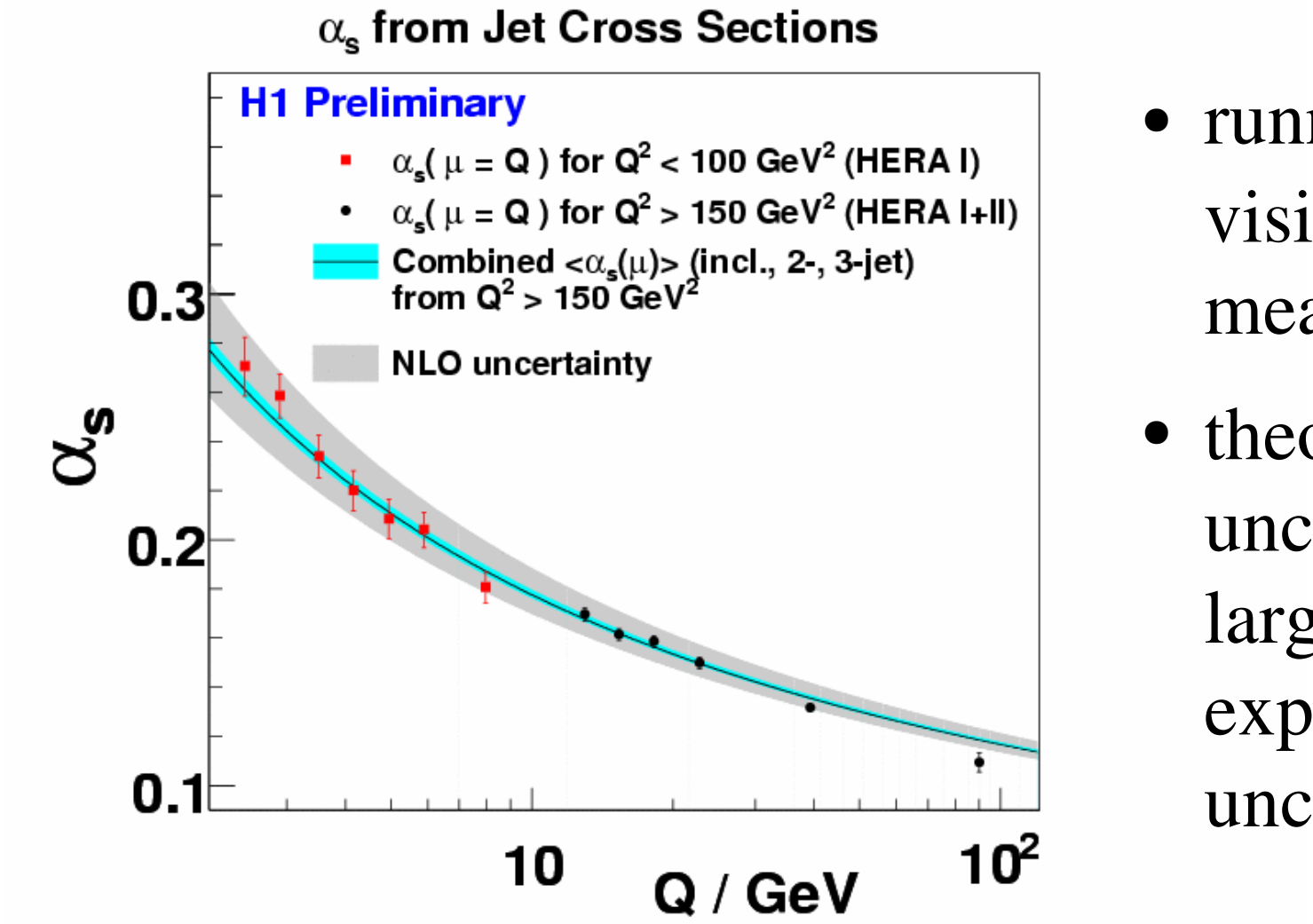
Jet Cross Sections



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

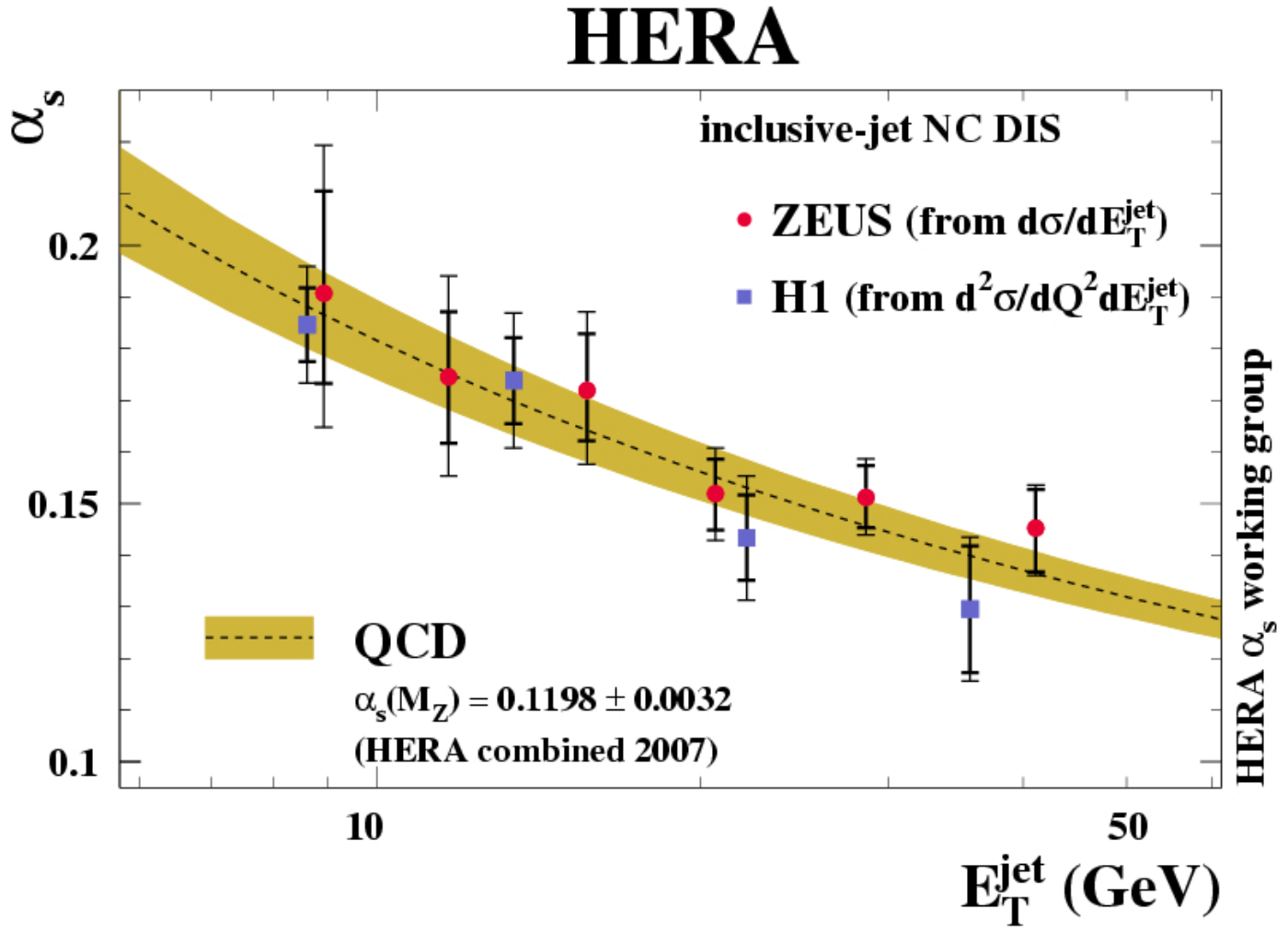
- systematic
- PDFs

α_S from Jets



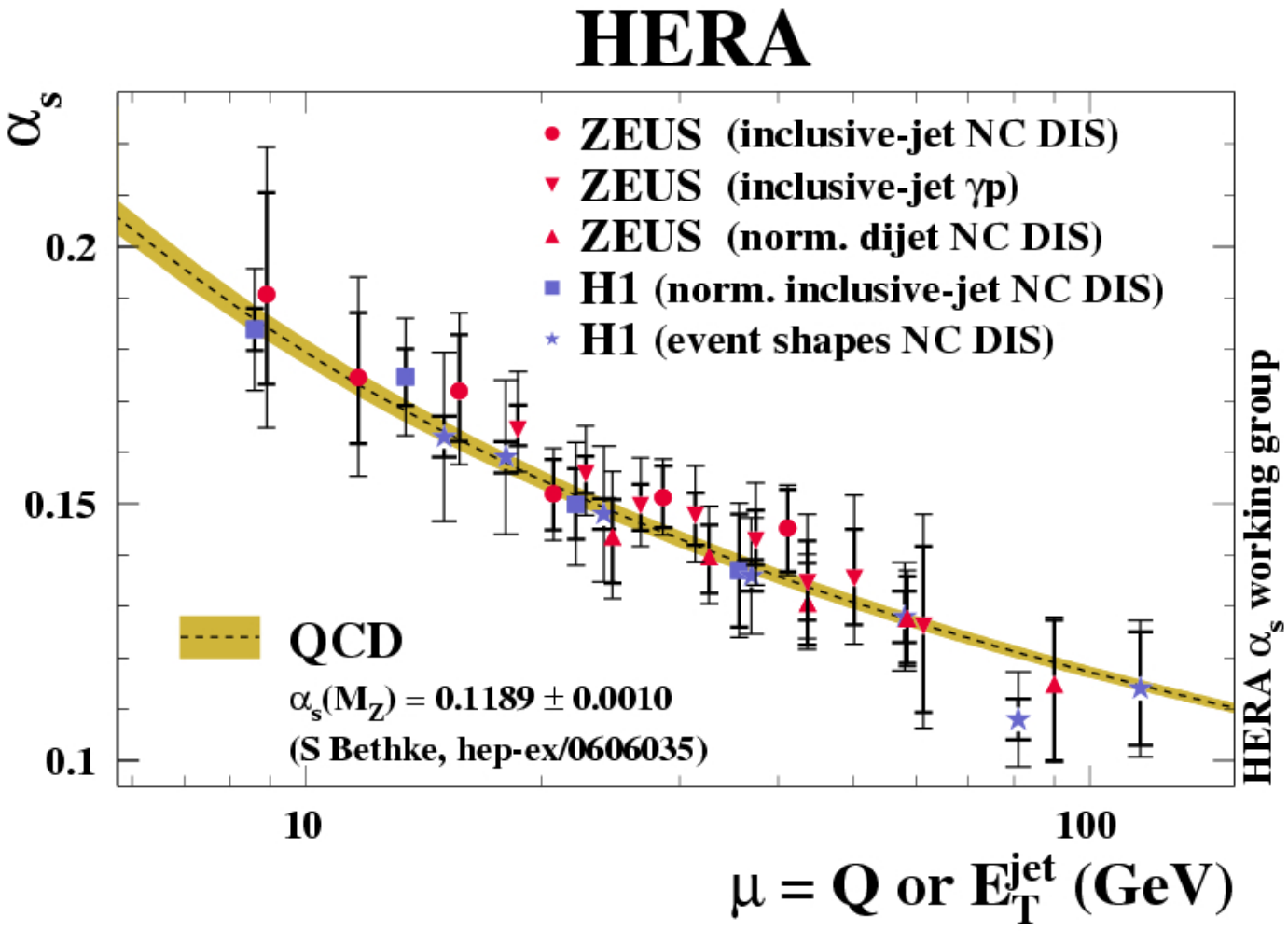
- running of α_S visible in one measurement
- theory uncertainties larger than experimental uncertainties

Running of α_S



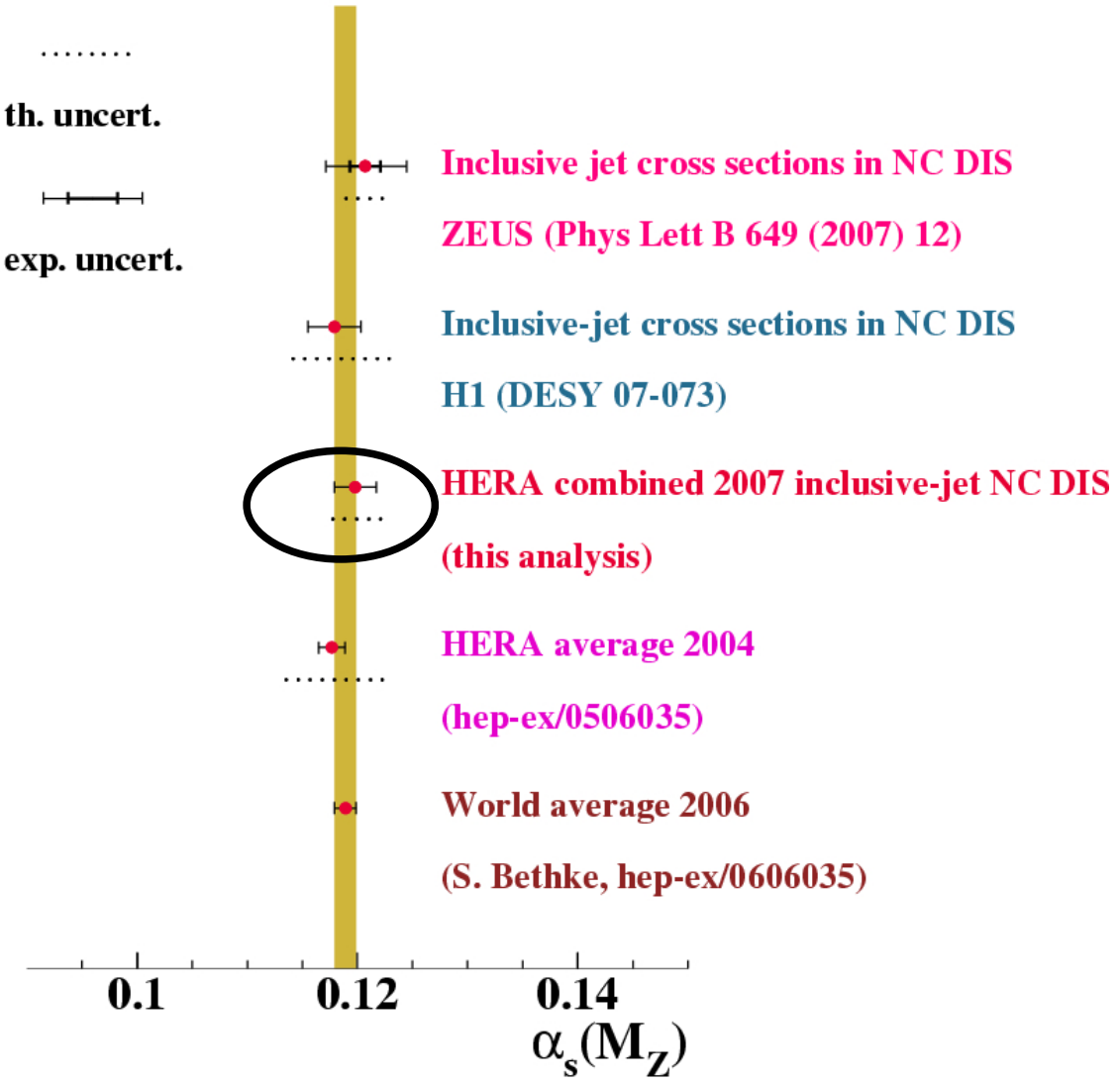
combine α_S measurements with smallest errors in fit

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

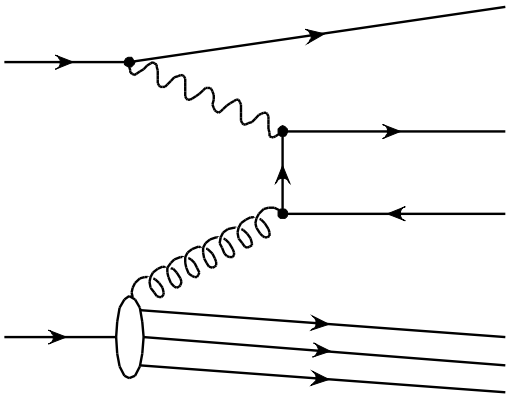
→ HERA value very competitive

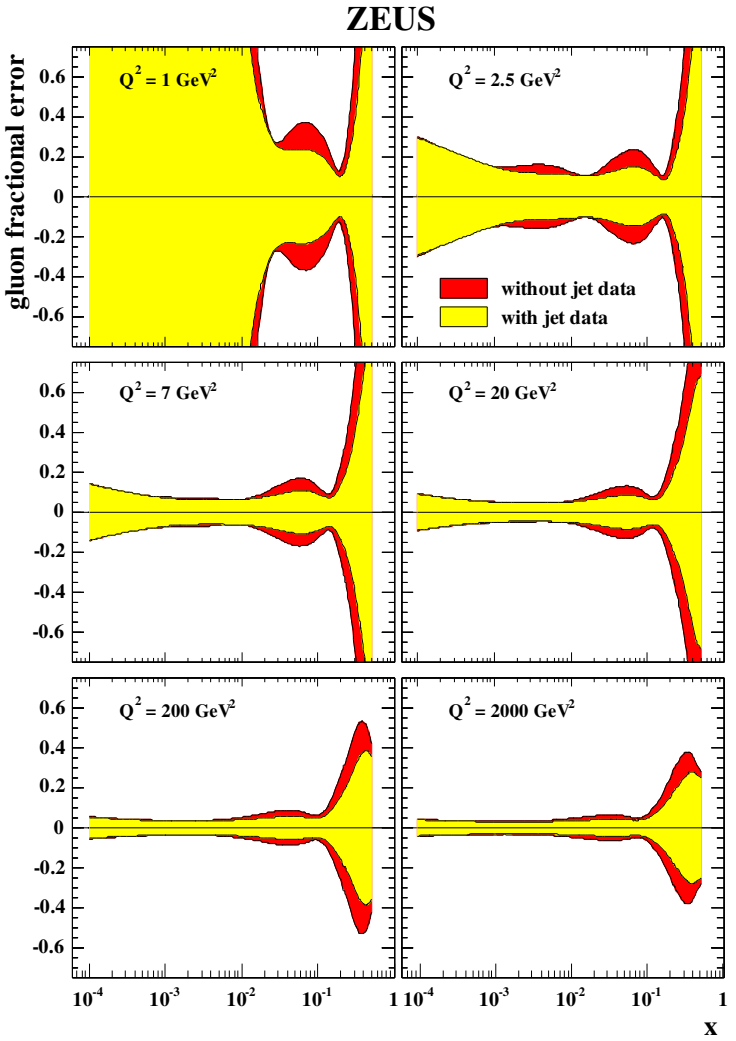
Improved Parton Densities

- F_2 is only indirectly sensitive to the gluon

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

➔ alternative: use HERA (di-)jet data

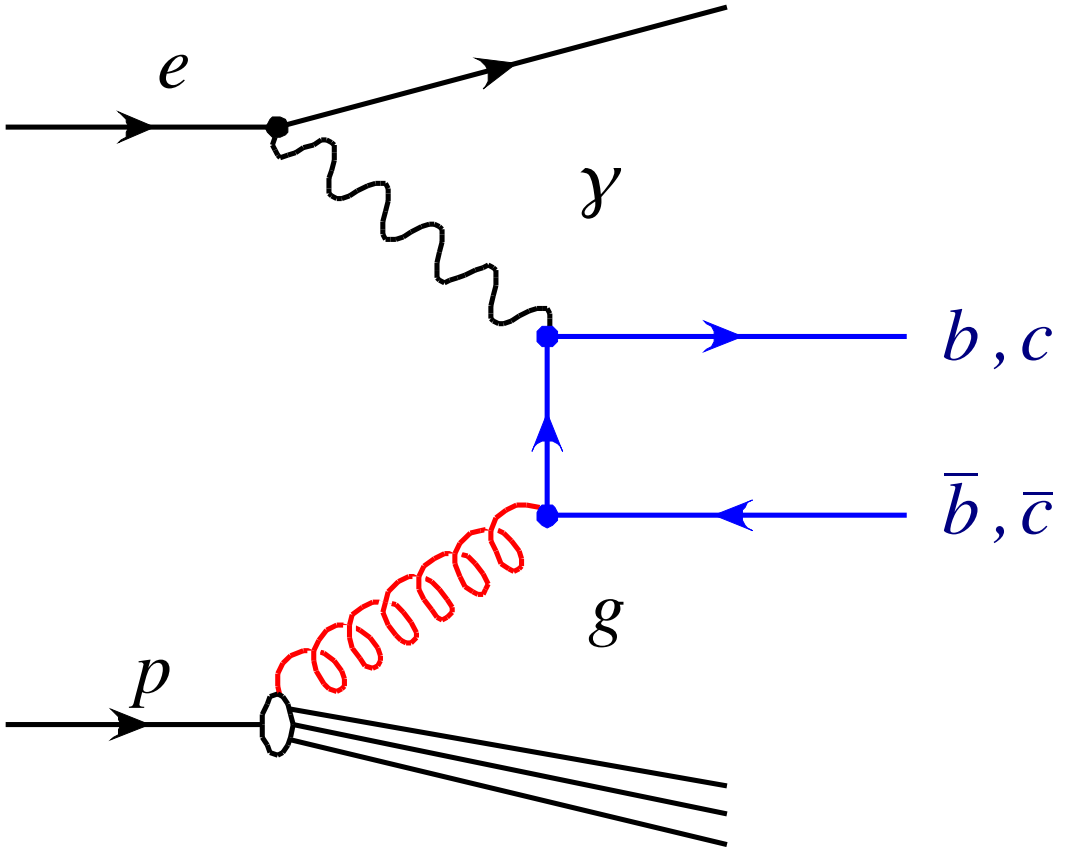




improvement at medium to large x

Heavy Quarks

Production of Heavy Quarks



predominantly via boson gluon fusion

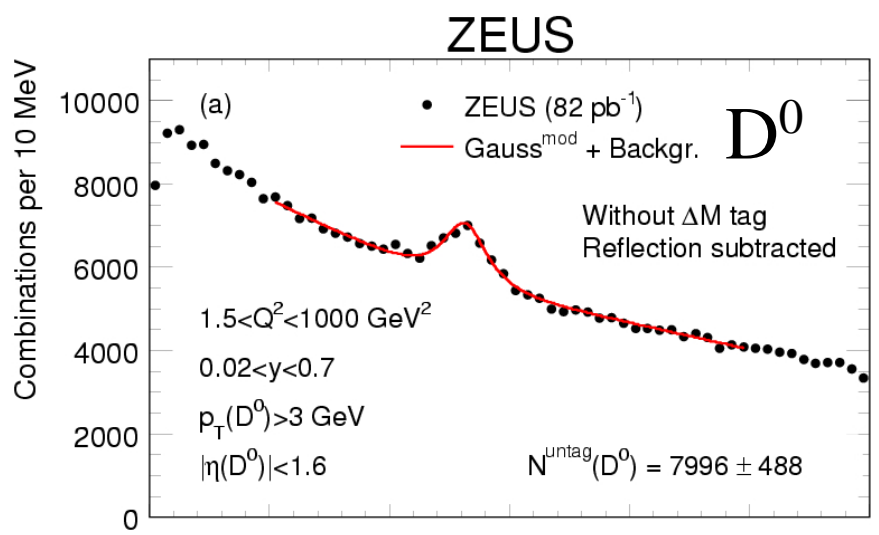
large quark mass allows pQCD calculations

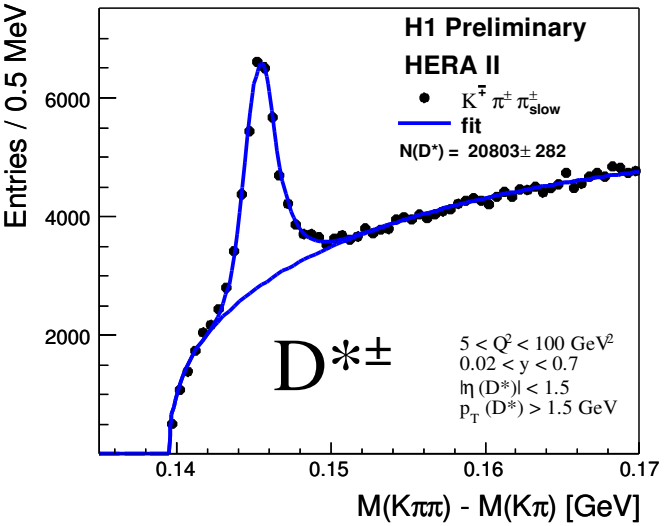
directly sensitive to gluon density in the proton

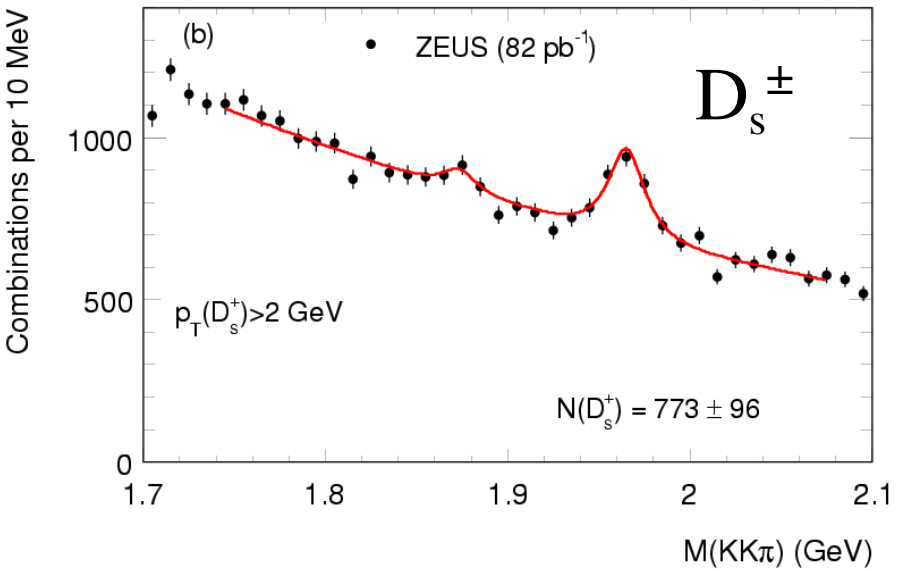
heavy quark contribution to structure function

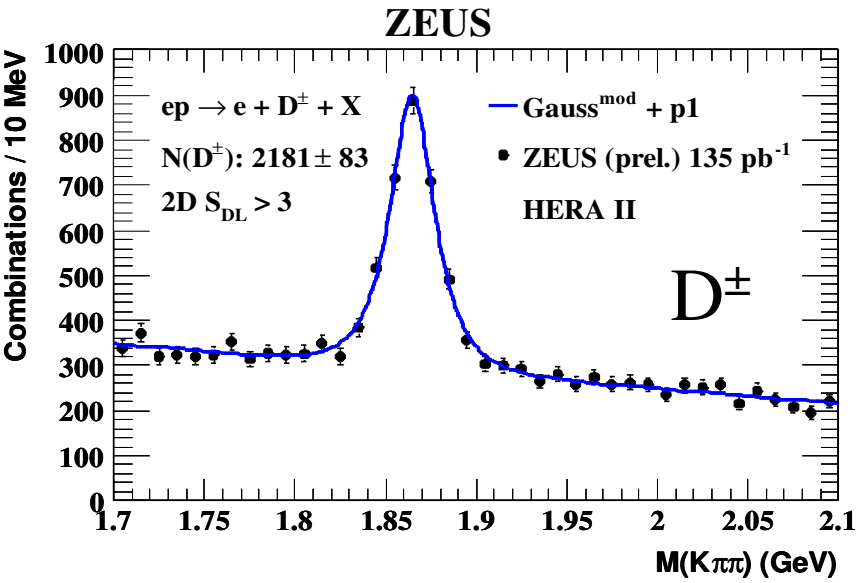
$$\frac{d^2\sigma^{b\bar{b}}}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4} Y_+ \left[F_2^{b\bar{b}}(x,Q^2) - \frac{y^2}{Y_+} F_L^{b\bar{b}}(x,Q^2) \right]$$

charm Signals

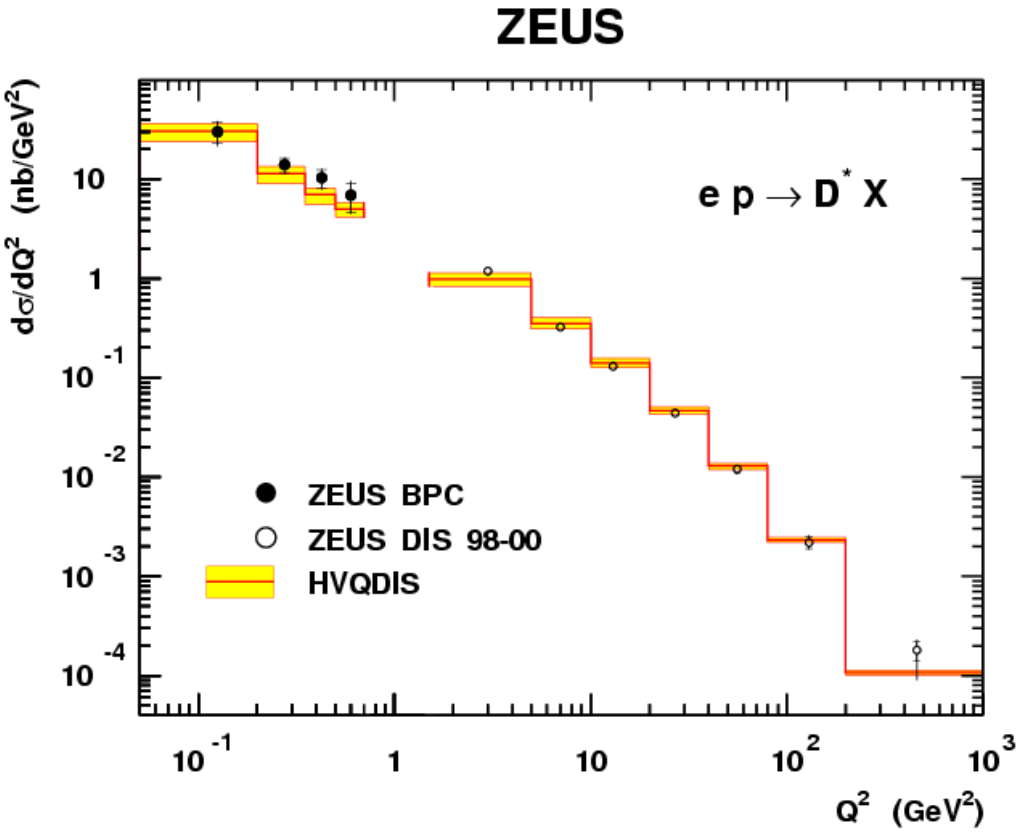


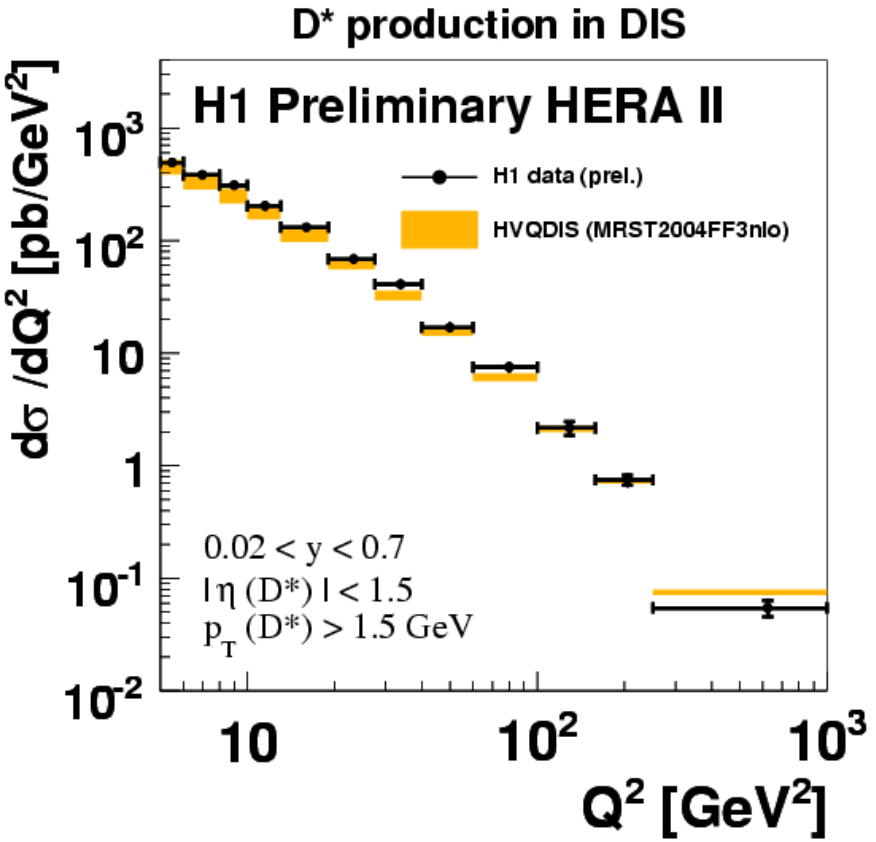






D* Cross Section



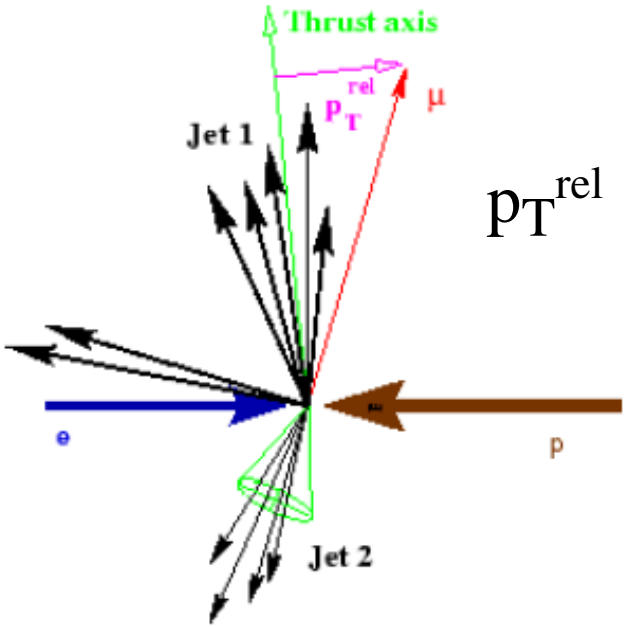


good description by NLO pQCD calculation (HVQDIS) in full measured Q^2 range (> 4 orders of magnitude)

PDF: extracted from inclusive DIS

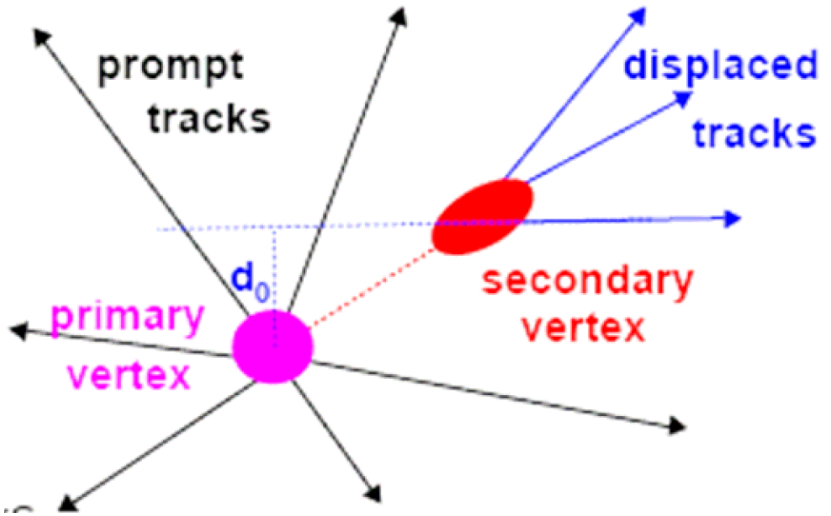
Tagging of *beauty* Quarks

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

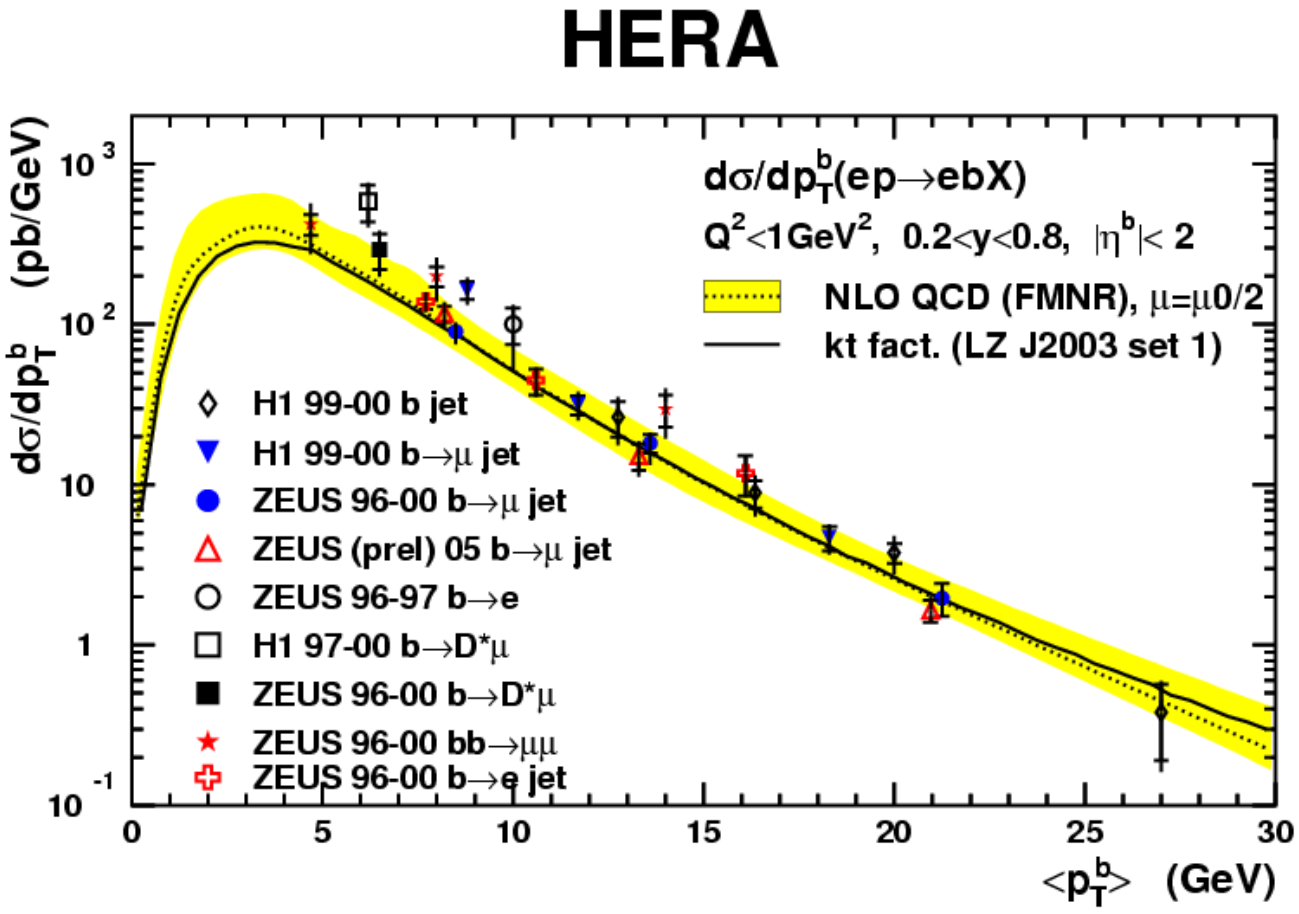


p_T^{rel}

lifetime tagging



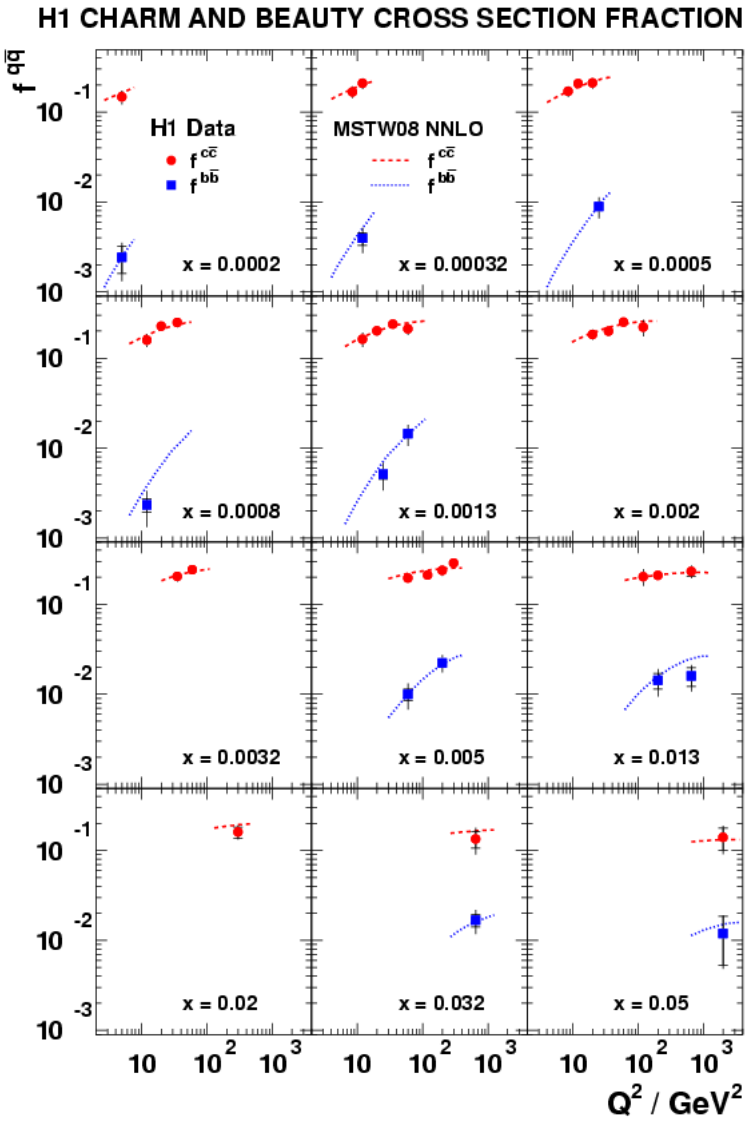
beauty Cross Section Results



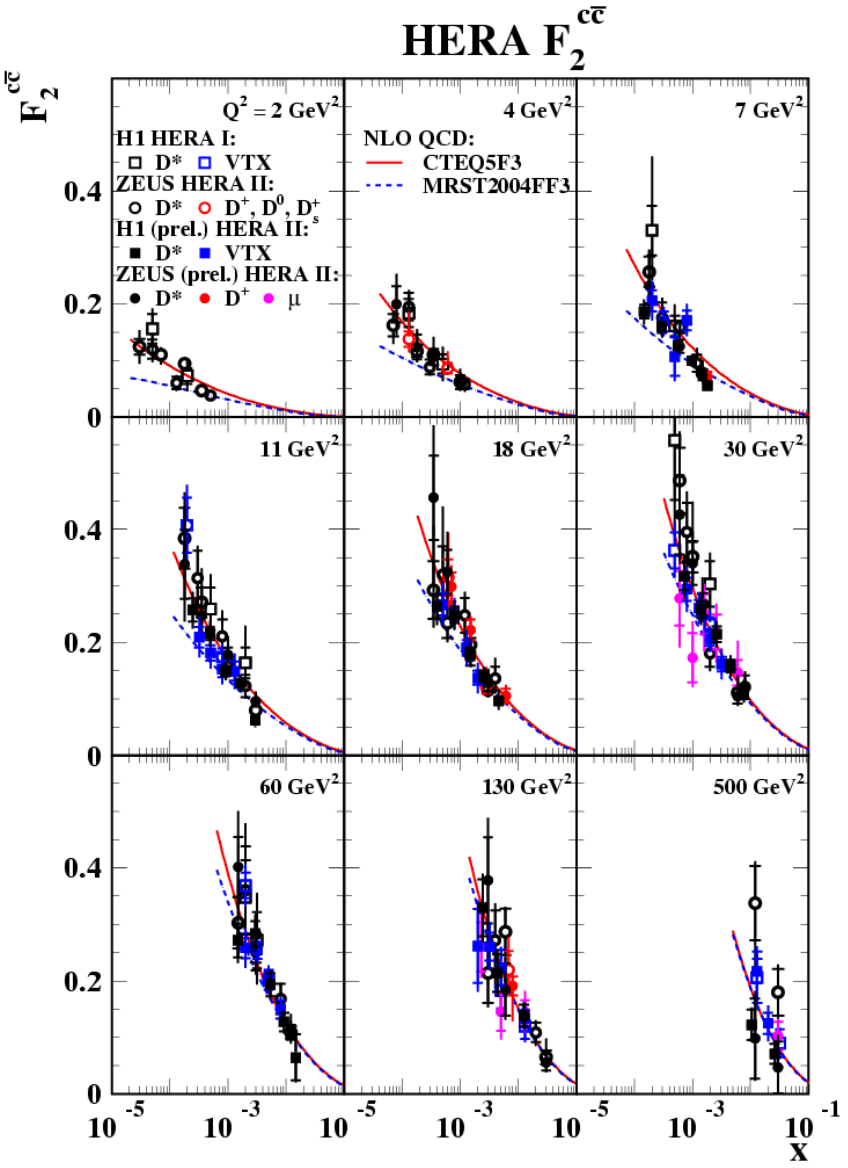
some data higher than NLO QCD theory,
but good agreement for the most precise data

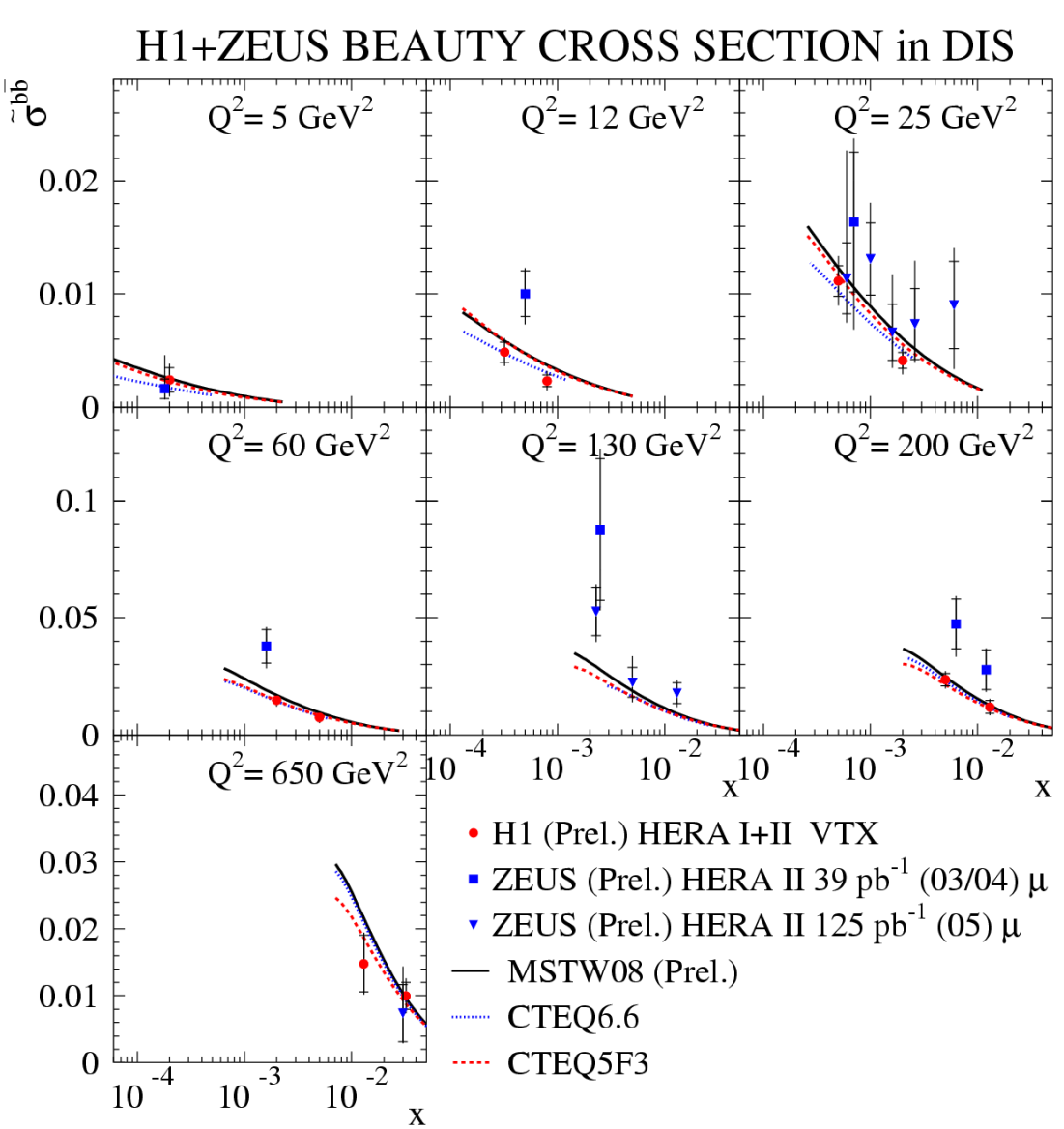
Contribution to the Cross Section

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



Contribution to the Structure Function

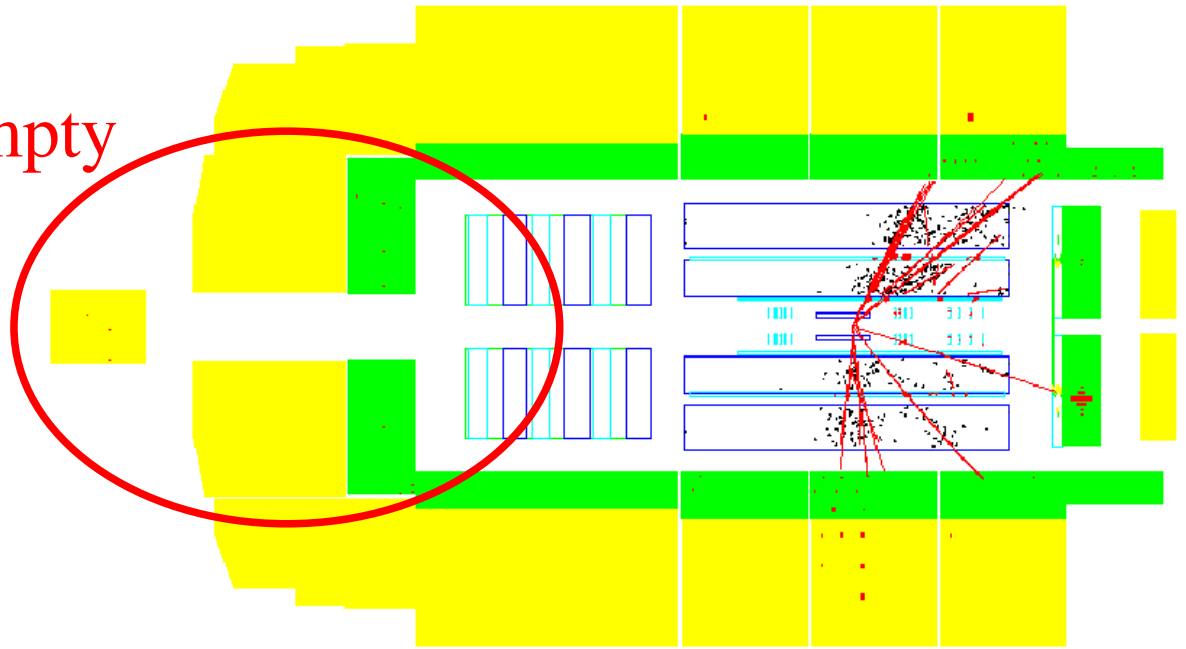




Diffraction

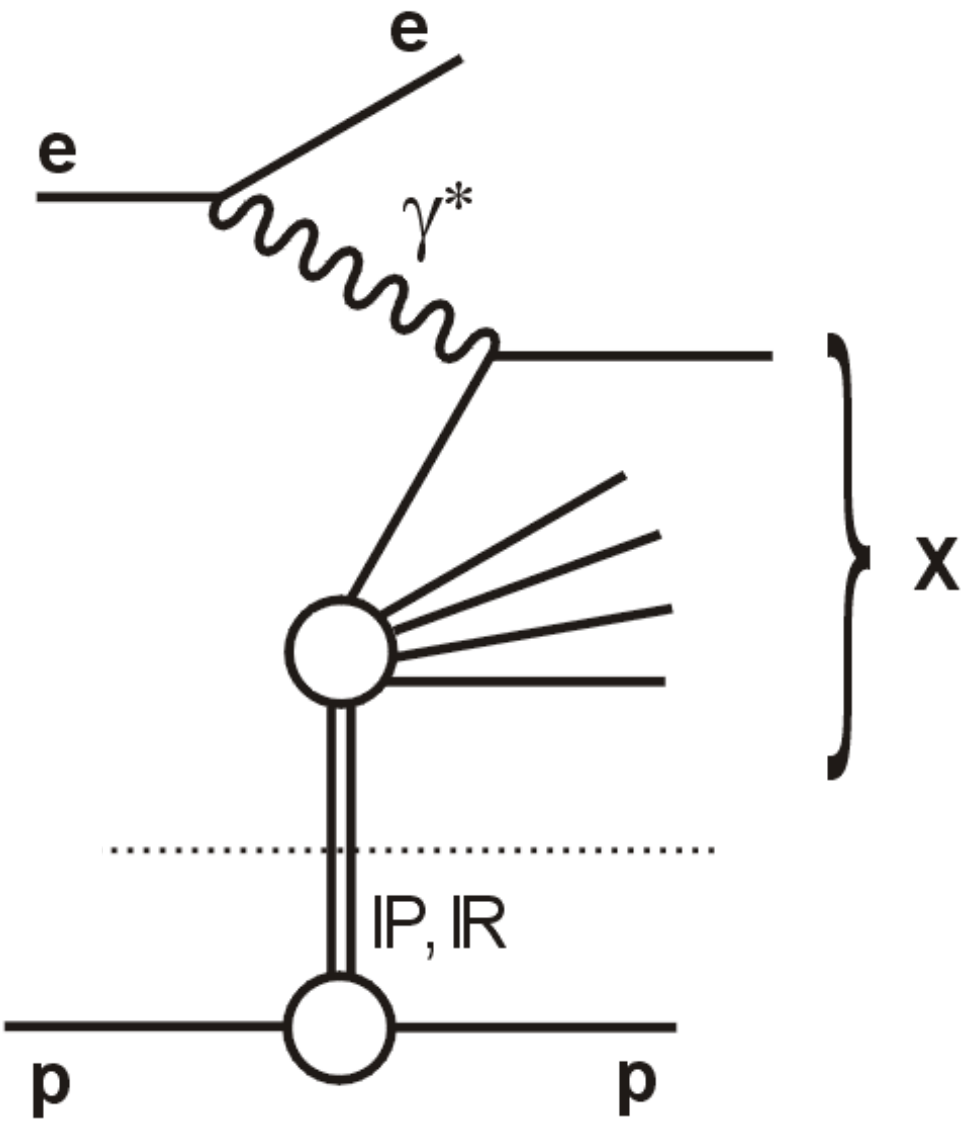
What is Diffraction?

- 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

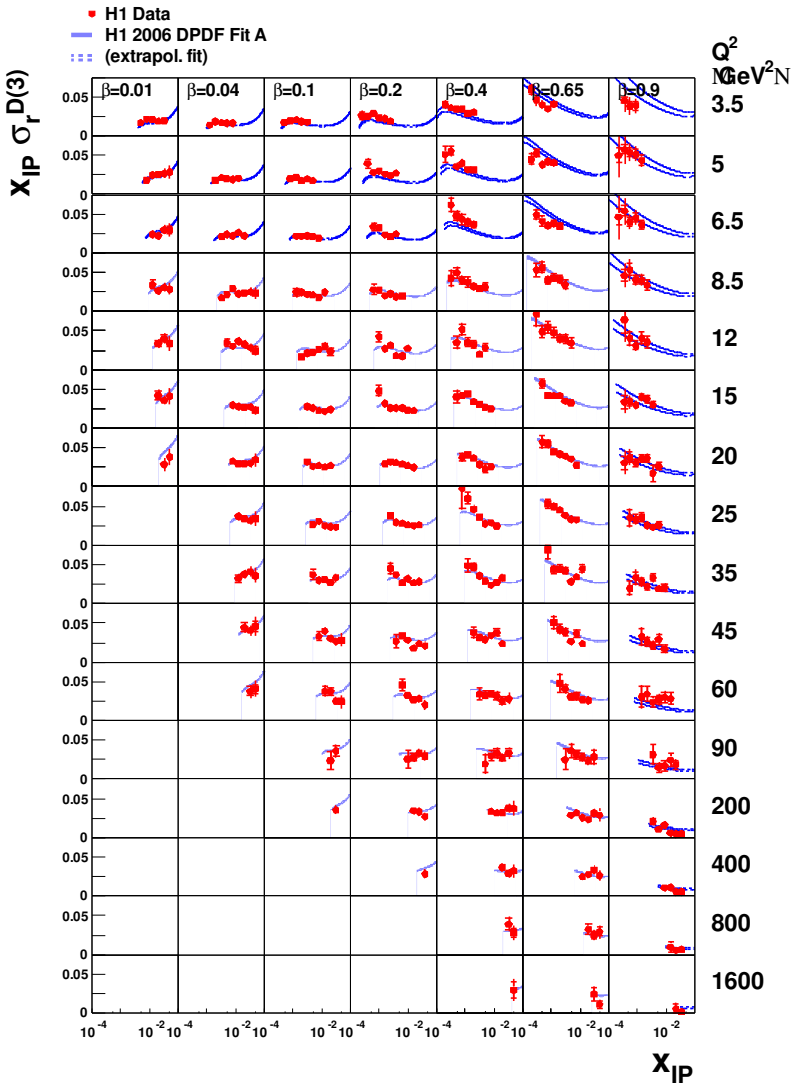


- idea: interaction between photon and proton by a „Pomeron“
  - colourless
  - already used to describe low energy hadron-hadron scattering
  - no particle!

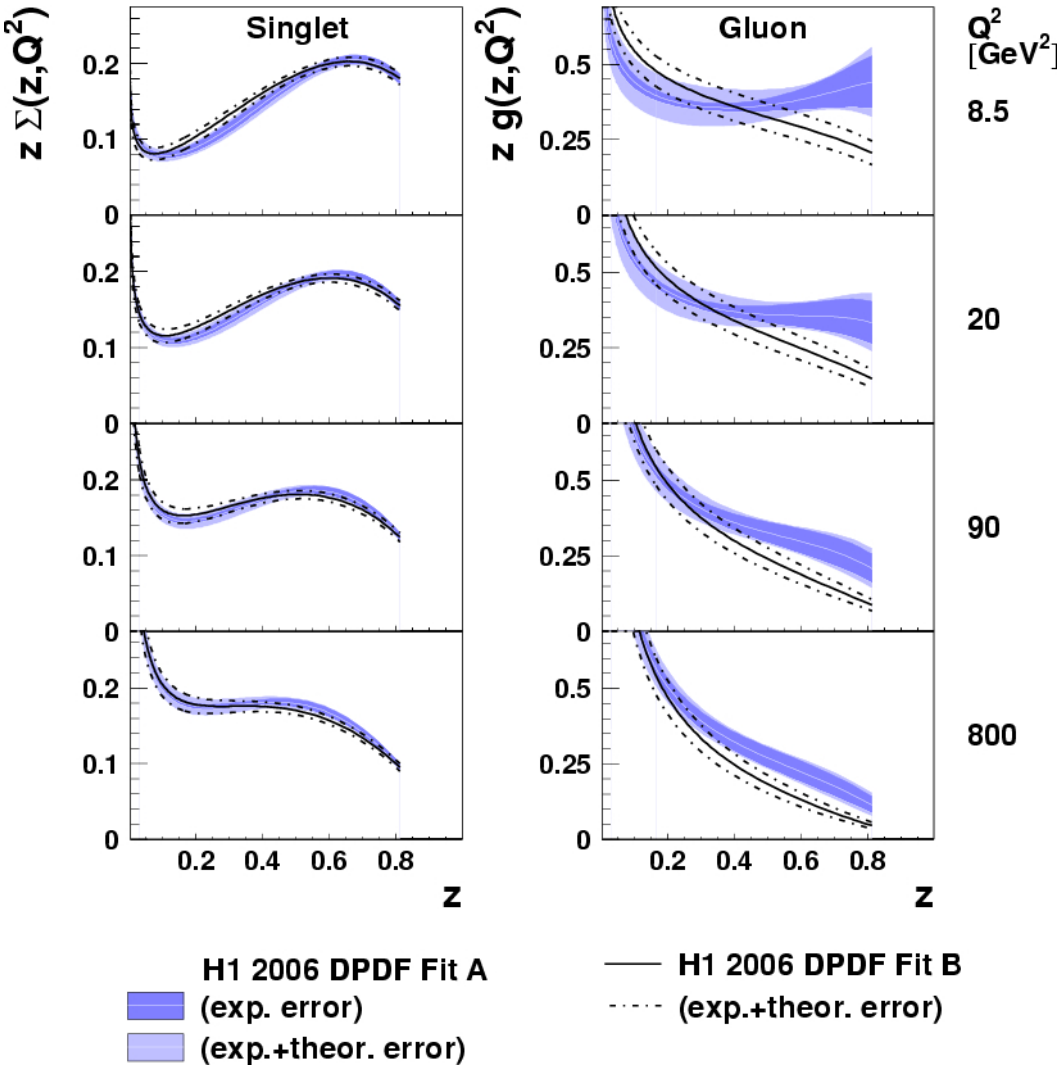
Physics in Diffraction

- 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?

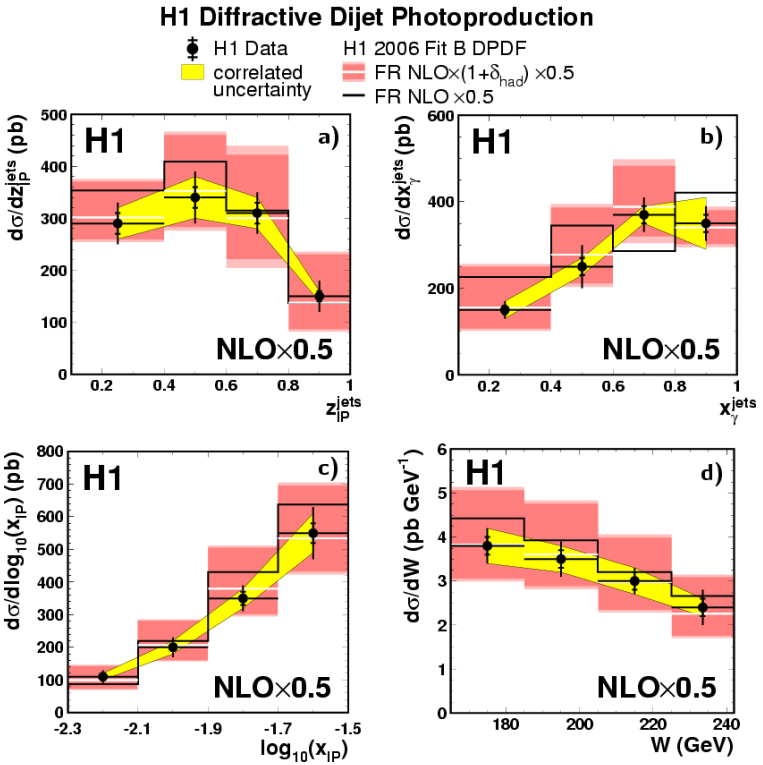
Diffractive Parton Densities

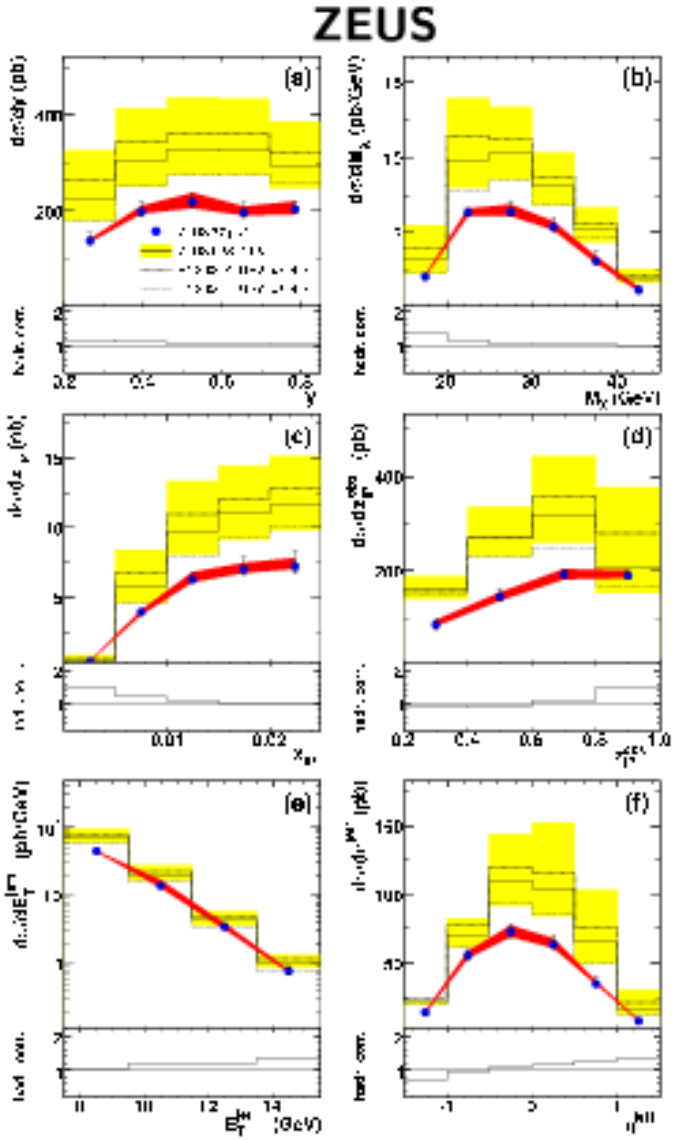


Singlet = Quark



Diffractive Dijet Cross Sections





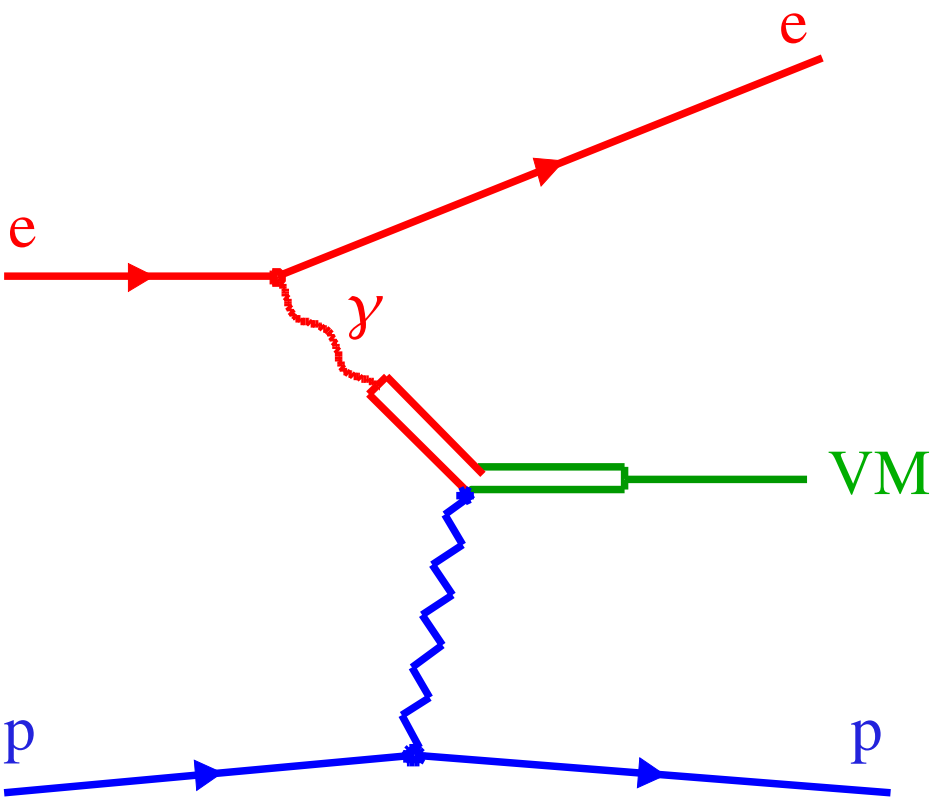
- shape of the QCD theory prediction agrees with the data
- normalization is wrong
- ➔ factorization is broken!

Vector Mesons in Diffration

- vector mesons (VM= ρ, ω, φ, J/ψ, ...) have the same quantum numbers as the photon

➔ photon can fluctuate into a VM, afterwards the VM can scatter off the proton

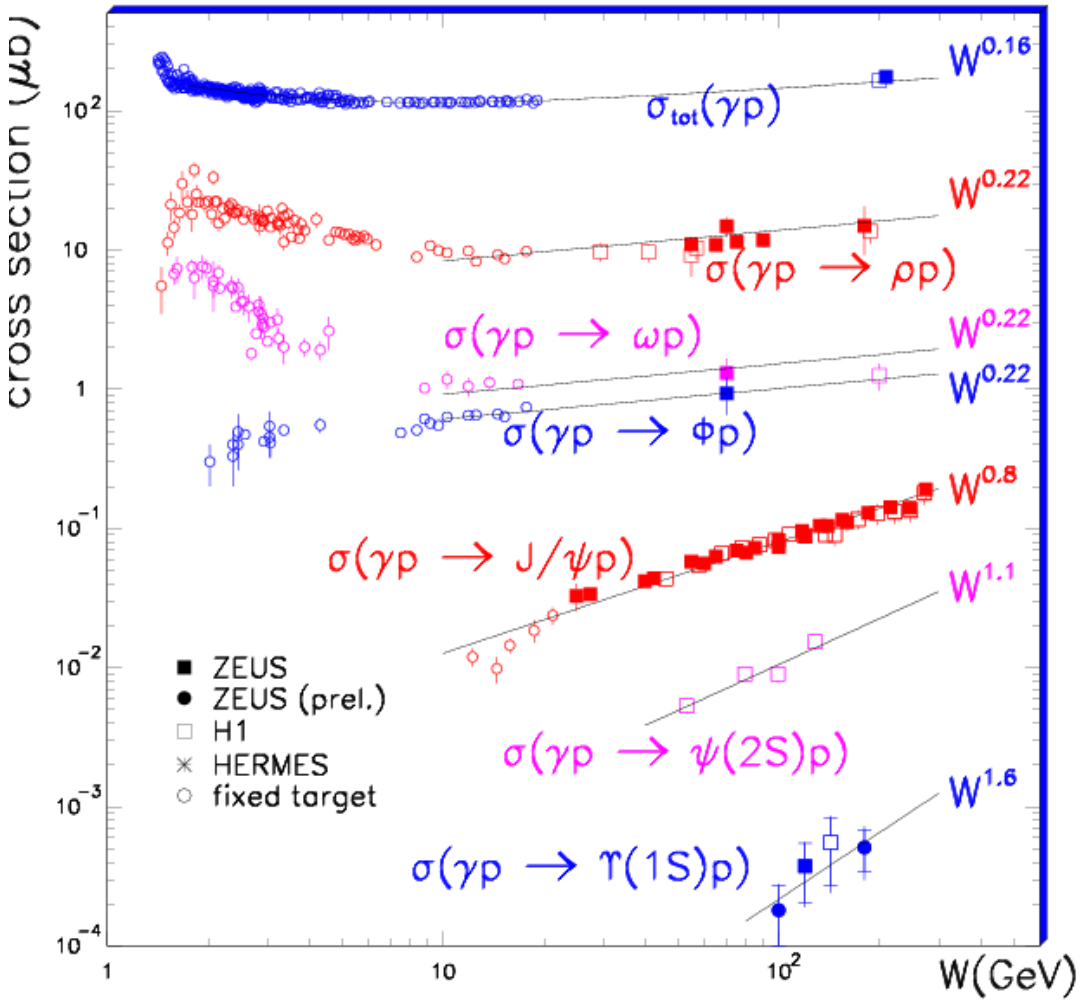
➔ „hadron-hadron“ scattering



Vector Mesons in Diffraction

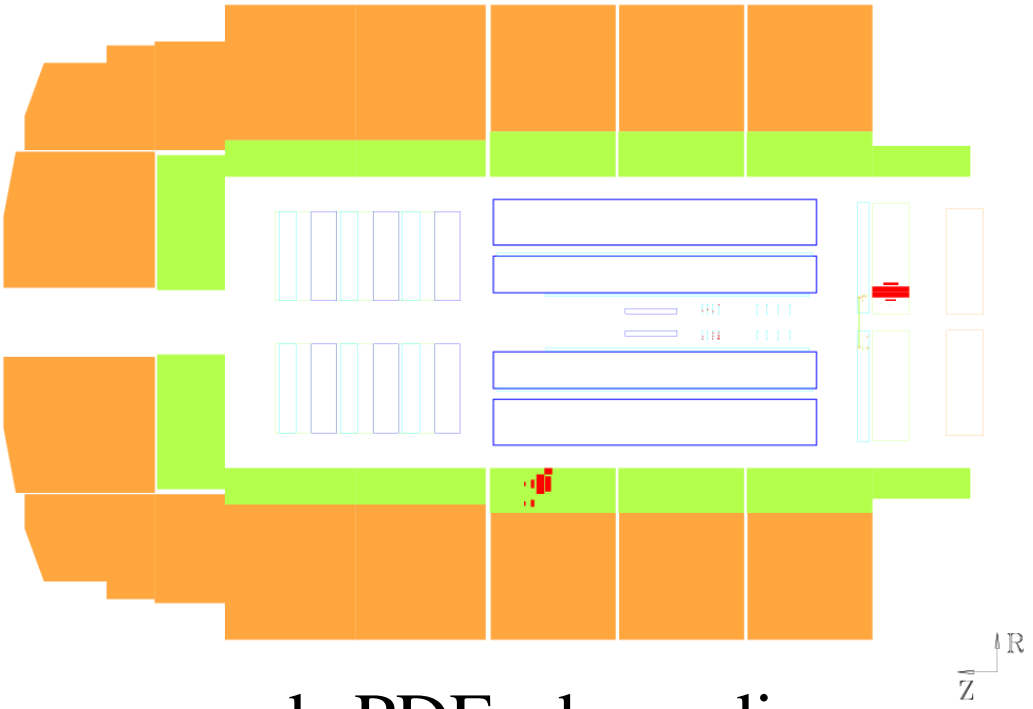
- light VMs (ρ, ω, φ) show the same dependence on the γp center-of-mass energy W
- heavier VMs (J/ψ, Υ) show increasing W dependence with mass

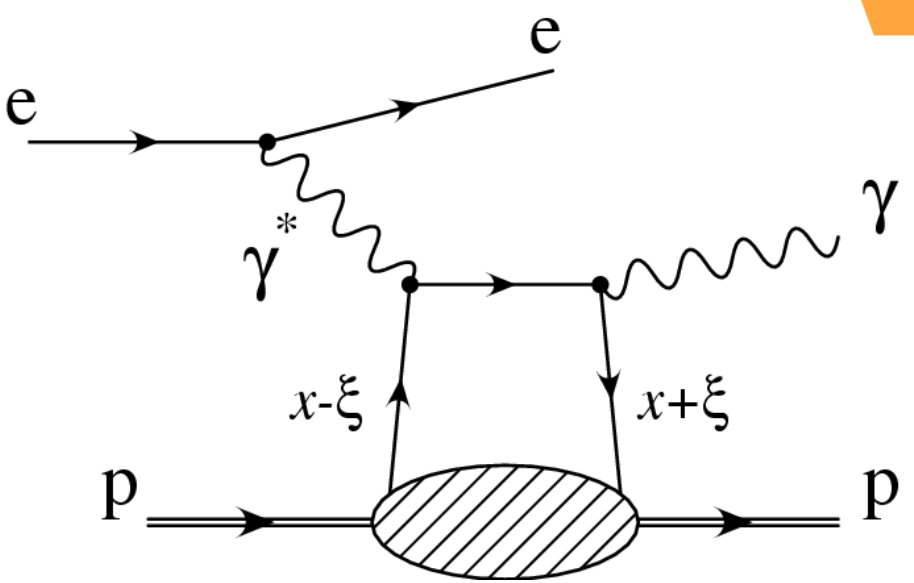
➔ simple „Pomeron“ picture doesn't work!



Deeply Virtual Compton Scattering

production of a real photon by scattering of a virtual photon on a proton

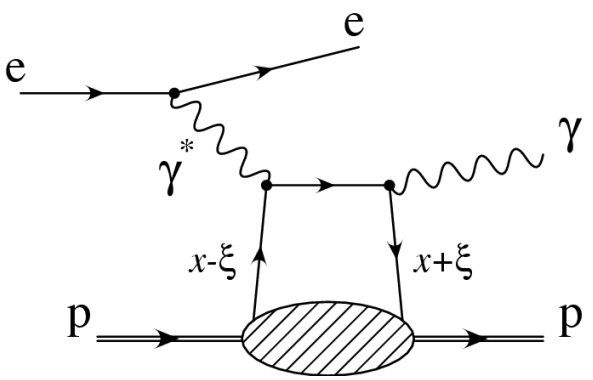


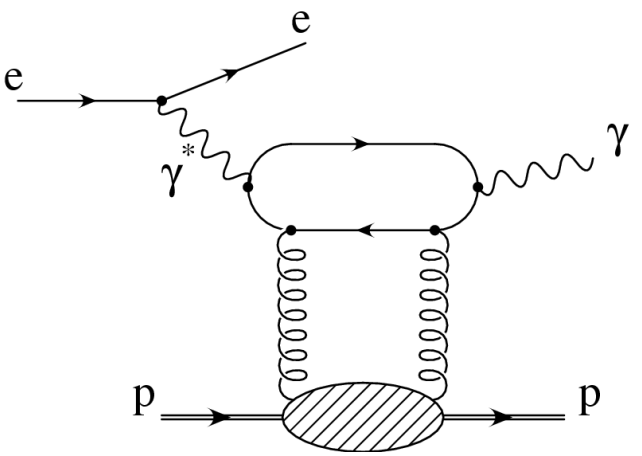


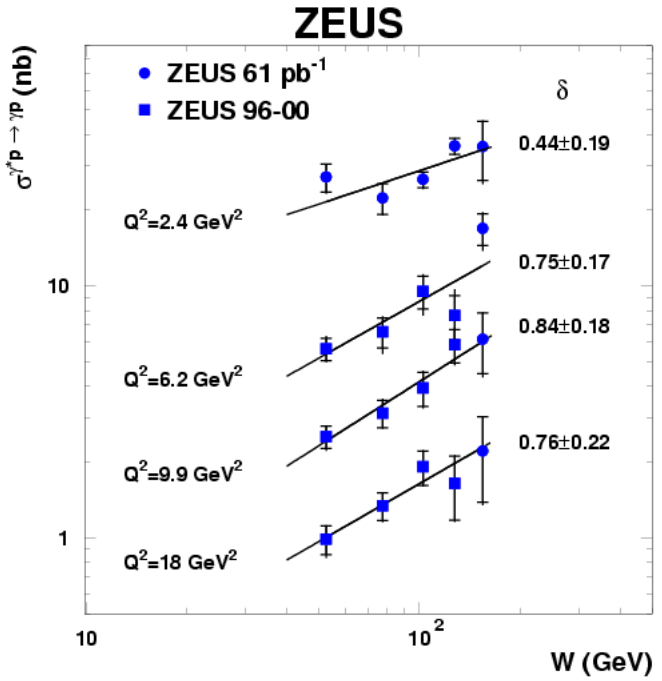
needs PDFs depending on x and „skewedness“ ξ

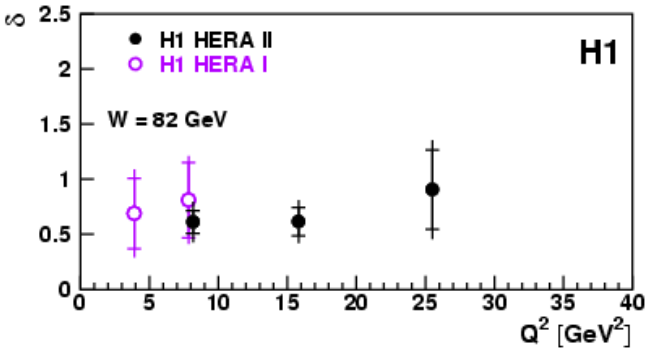
→ Generalized PDFs, extending standard PDFs to elastic form factors

Deeply Virtual Compton Scattering





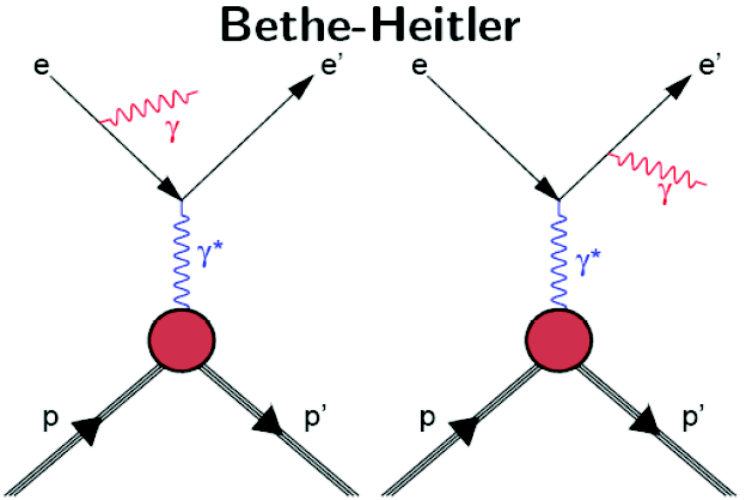


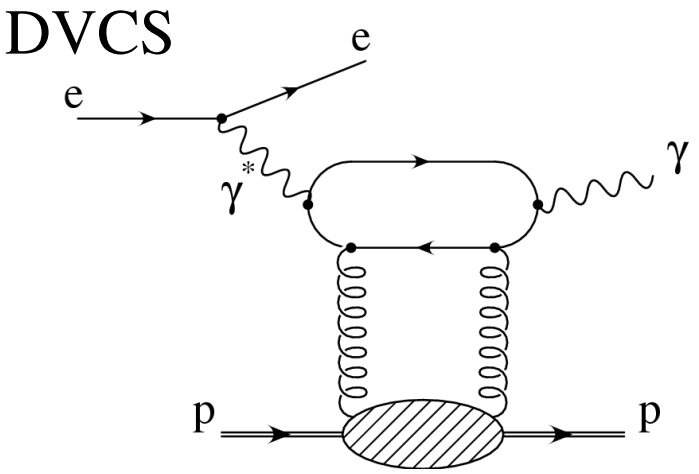


similar W dependence as heavy vector mesons

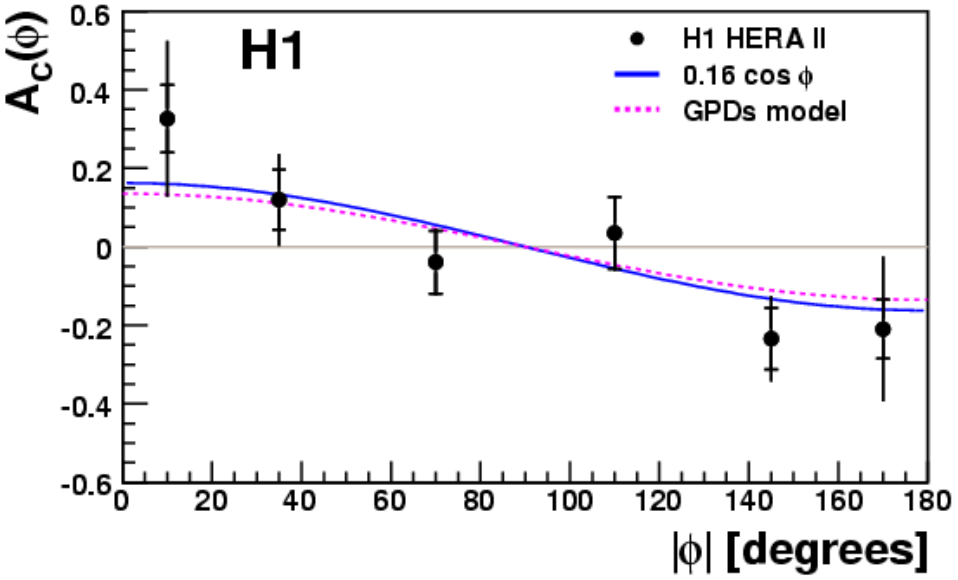
→ 2-gluon-exchange dominates

DVCS: Beam Charge Asymmetry

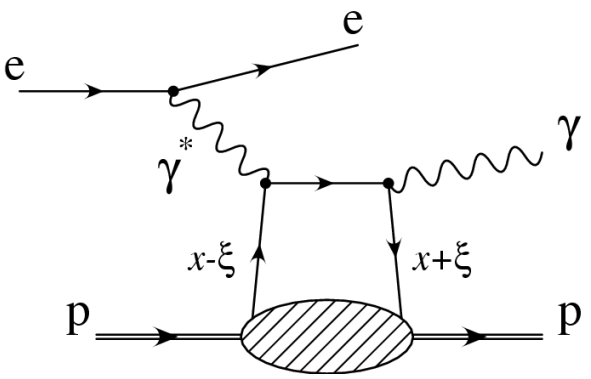




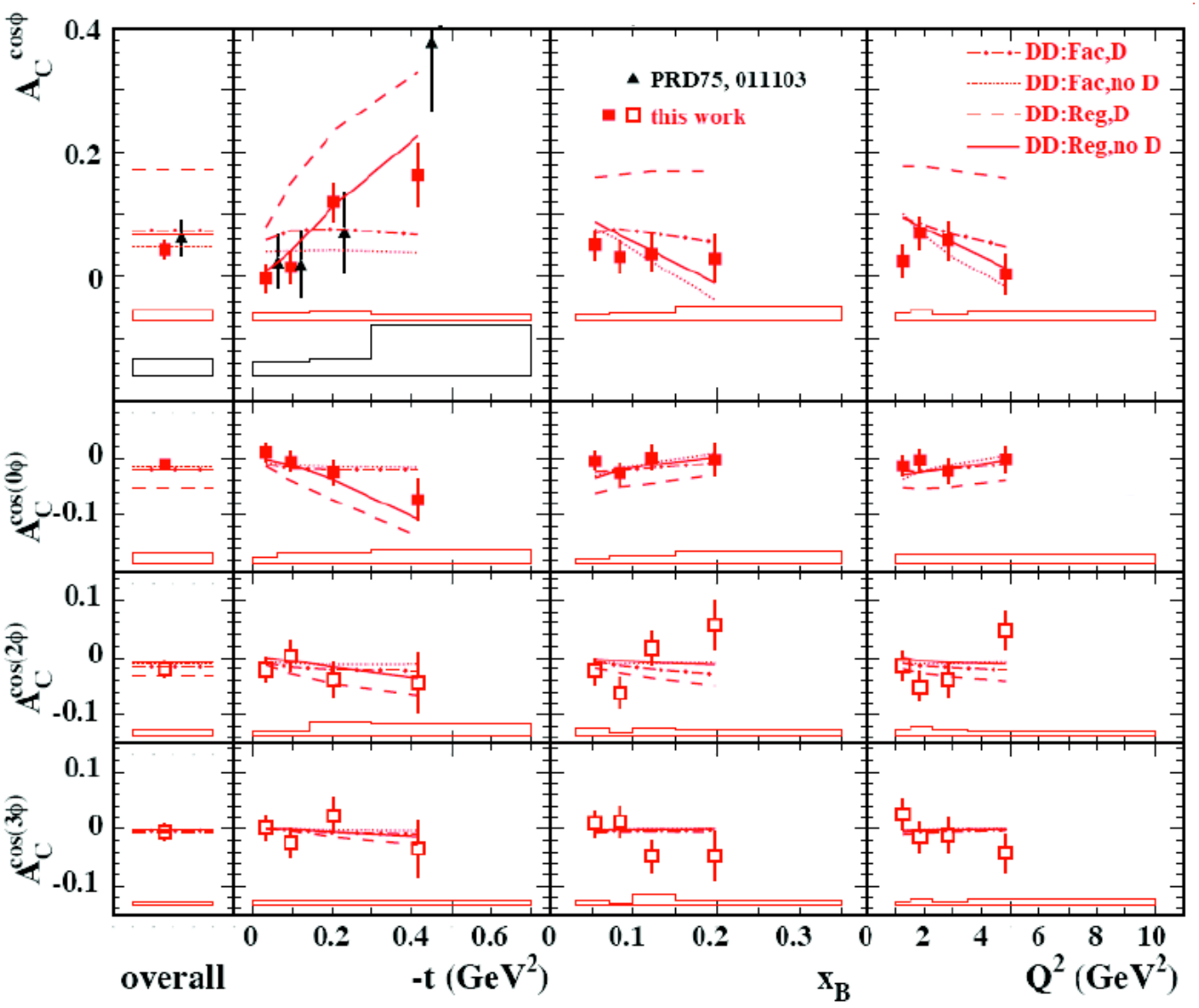
- same final state for DVCS and Bethe Heitler
- ➔ interference
- ➔ azimuthal asymmetry



DVCS: HERMES



- HERMES kinematic domain dominated by quark contribution
- Bethe-Heitler amplitude much larger than DVCS
- measure DVCS via interference with Bethe-Heitler



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
- always prepare for the unexpected!