Excited QCD 2011
20-25 February 2011
Les Houches (France)

The Pomeron and Vector Mesons at HERA

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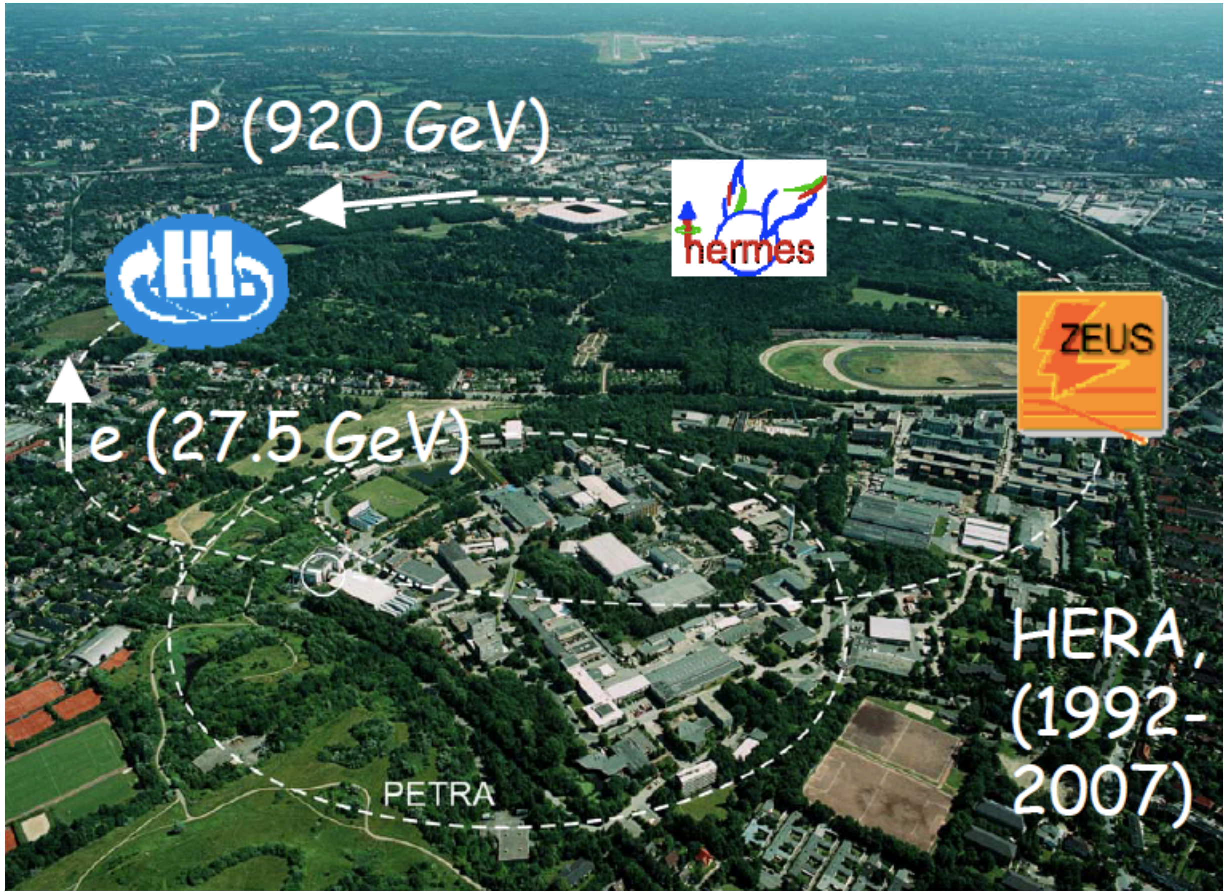
(Torino University and INFN)

- Diffraction in ep scattering
- Latest inclusive diffractive ep results
- QCD fits and diffractive PDFs extraction
- Latest results on exclusive VM production

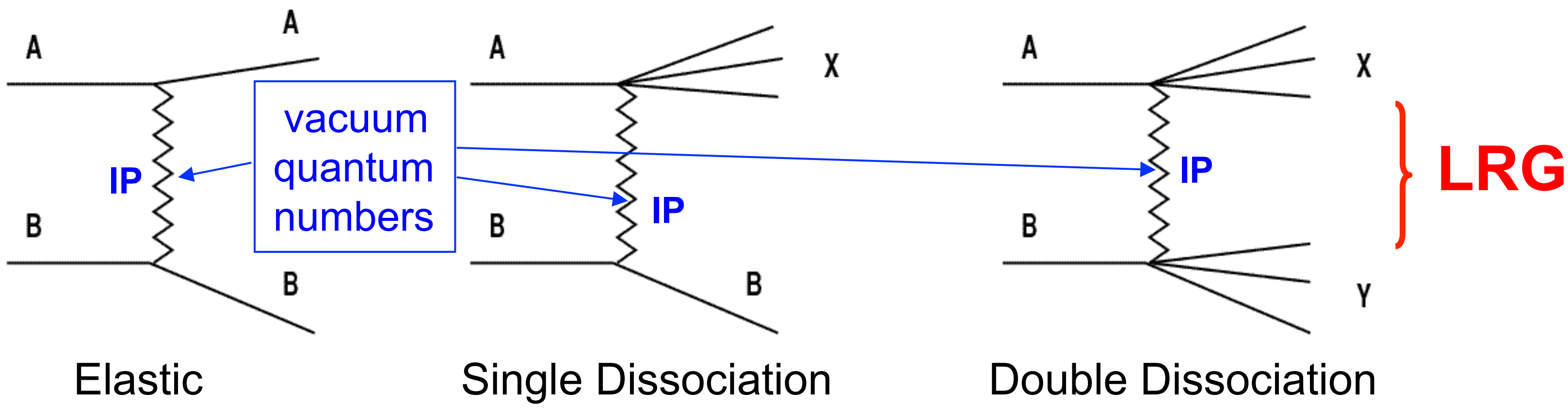
HERA Experiments



0.5 fb^{-1} collected by H1 and ZEUS experiments
Final analyses of HERA data are underway

Diffraction in Hadron Scattering

Diffraction is a feature of hadron-hadron interactions (30% of σ_{tot})



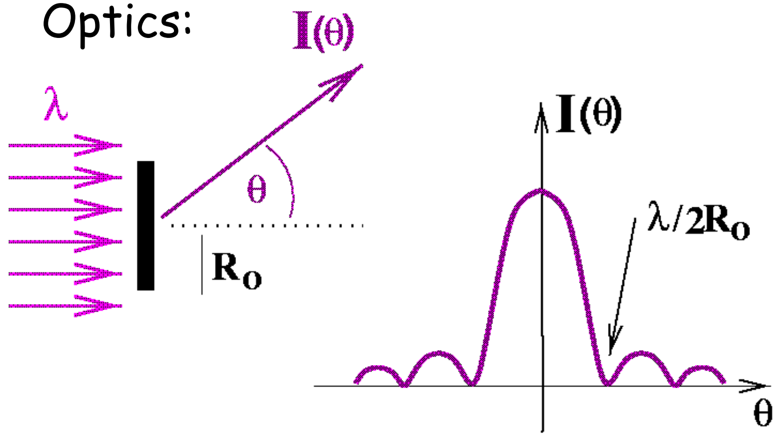
- ⇨ Beam particles emerge intact or dissociated into low-mass states
  → Very small fractional momentum losses (within a few %)

- ⇨ Final-state systems separated by a large polar angle
  (or pseudorapidity $\eta = -\ln[\tan(\theta/2)]$)
  → Large Rapidity Gap (LRG)

- ⇨ Interaction mediated by t-channel exchange of an object with vacuum quantum numbers (no colour)
  → Pomeron (IP)

Why Diffraction?

Optics:



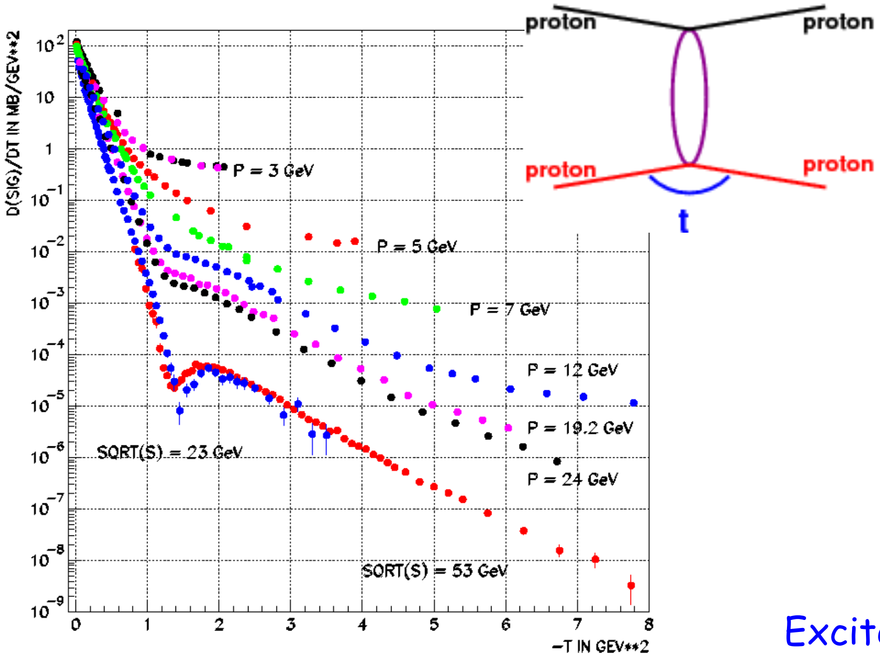
$$\frac{I(\theta)}{I(\theta_0)} \cong 1 - \frac{R_0^{\,2}}{4}(k\theta)^2 \qquad k = 2\pi/\lambda$$

Forward peak for q=0 (diffractive peak)

Diffraction pattern related to size of target and wavelength of beam

Particle Physics:

Propagation/interaction of a a hadron ⇨ absorption of its wave function



$$\frac{d\sigma/dt(t)}{d\sigma/dt(t=0)} \cong e^{-b|t|} \cong 1 - b(p\theta)^2$$

$|t| \approx (p\theta)^2$ 4-momentum transfer

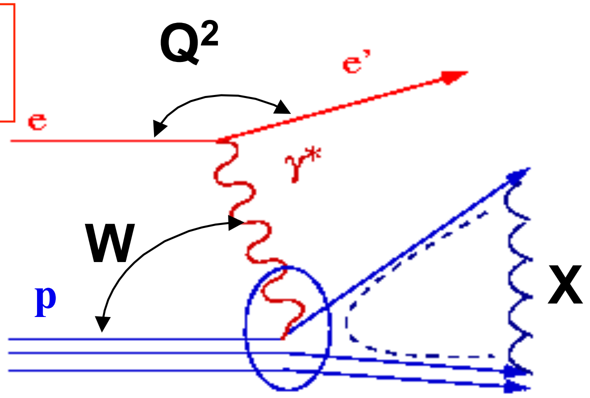
θ scattering angle

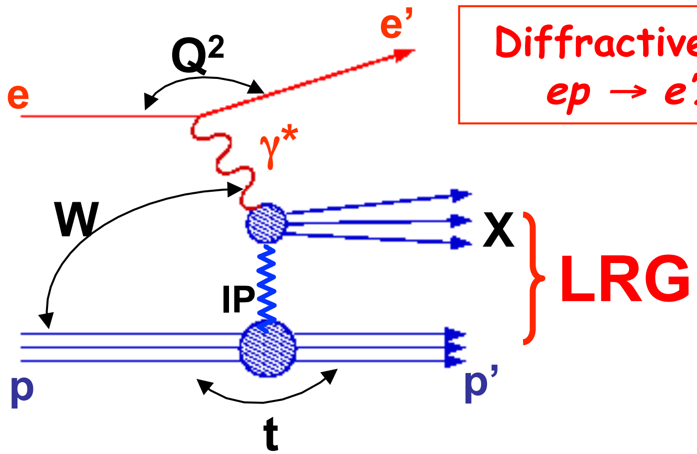
$b = R^2/4$

R transverse distance projectile-target

Diffraction at HERA

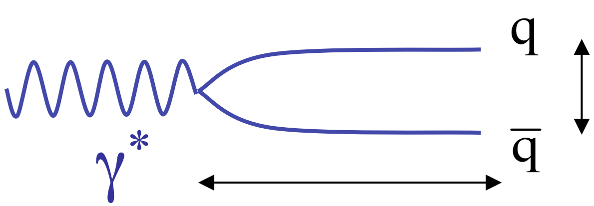
Standard DIS
ep → e'X





Diffractive DIS
ep → e'Xp'

Real and virtual photons can fluctuate in hadronic states ($q\bar{q}$, $q\bar{q}g$, ...)



$$\propto \frac{1}{\sqrt{Q^2 + M^2_{q\bar{q}}}}$$

$$\propto E_\gamma \sim W^2 \sim 1/x$$

(as seen in the proton rest-frame)

Q^2 = photon virtuality
x = Bjorken scaling variable

✓ Lifetime of $q\bar{q}$ dipole (hadron!) long because of large Lorentz boost (E_γ ~ 50 TeV at HERA)

→ Dipole interacts hadronically with the proton

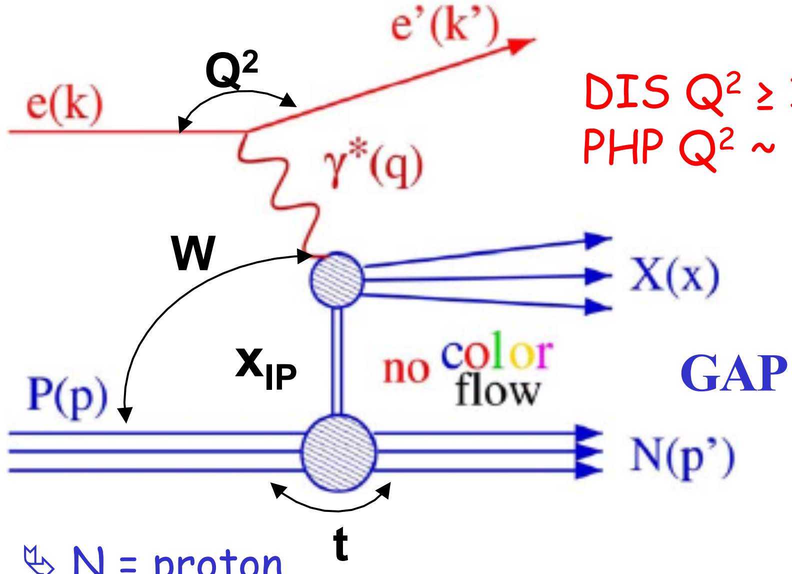
✓ Transverse size proportional to $1/\sqrt{(Q^2+M_{qq}^2)}$

→ If dipole size small, its interaction with the proton can be treated perturbatively

Diffractive events contribute up to 15% of the inclusive DIS cross section

Kinematics and Cross Sections

- Q^2 = virtuality of exchanged photon
- x = Bjorken scaling variable
- y = inelasticity of virtual photon
- W = invariant mass of γ^*-p system
- M_X = invariant mass of γ^*-IP system
- x_{IP} = fraction of proton momentum carried by IP
- $\beta = x/x_{IP}$ = fraction of IP momentum carried by struck parton
- t = (4-momentum exchanged at p vertex)^2 typically: $|t| < 1$ GeV^2



DIS $Q^2 \geq 1$ GeV^2
PHP $Q^2 \sim 0$

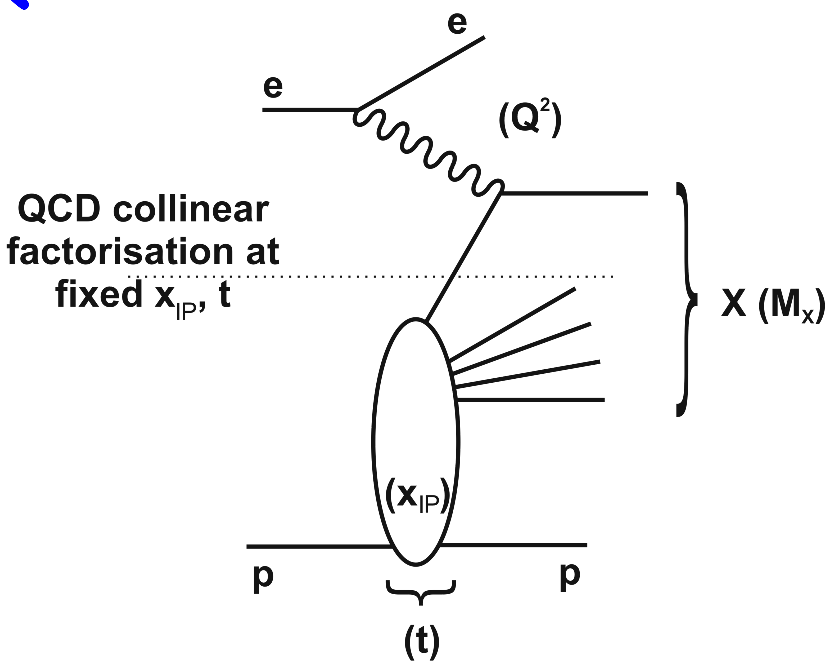
- N = proton → SD events
- N = proton dissociative system → DD events (background)

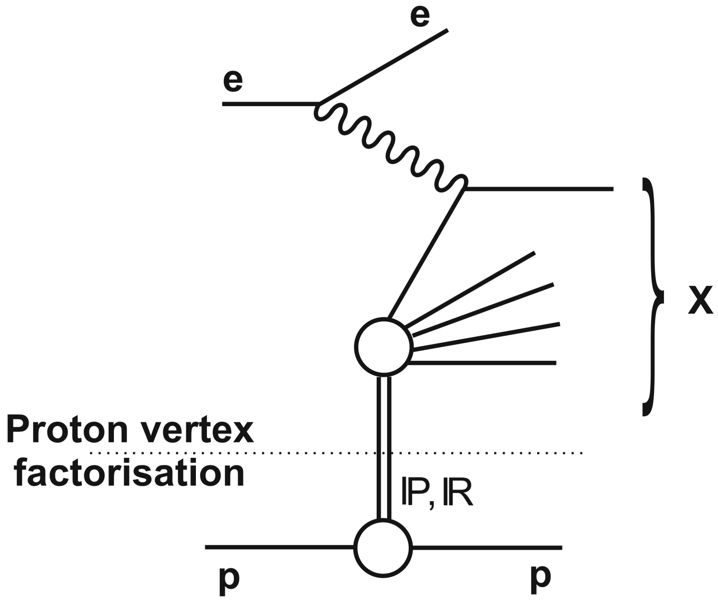
$$\frac{d^4\sigma^{ep\to e'Xp'}}{d\beta dQ^2 dx_{IP} dt} = \frac{2\pi\alpha^2}{\beta Q^4} Y_+ \left[F_2^{D(4)}(\beta,Q^2,x_{IP},t) - \frac{y^2}{Y_+} F_L^{D(4)}(\beta,Q^2,x_{IP},t)\right]$$

where $Y_+ = 1 + (1-y)^2$ $\quad = \sigma_r^{D(4)}(\beta,Q^2,x_{IP},t)$

When t is not measured $\sigma_r^{D(3)}(\beta, Q^2, x_{IP}) = \int \sigma_r^{D(4)}(\beta, Q^2, x_{IP}, t)\,dt$

QCD Factorization in Hard Diffraction





The QCD factorization theorem in diffractive DIS allows to write the diffractive cross section as a convolution of universal diffractive parton densities $f_i^D(x,Q^2,x_{IP},t)$ and partonic cross sections

$$\sigma^D(\gamma^* p \rightarrow Xp) \sim f_i^D(x, Q^2, x_{IP}, t) \otimes \sigma_{\gamma^* i}(x, Q^2)$$

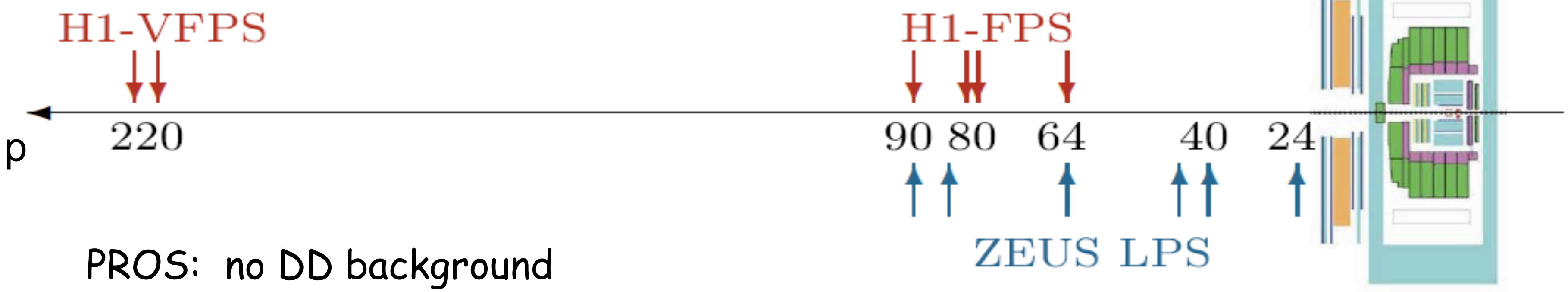
Additionally, assuming Regge factorization, the diffractive parton densities are written as a term depending on x_{IP} (Pomeron flux) times the Pomeron parton densities

$$f_i^D(x, Q^2, x_{IP}, t) \sim f_{IP/p}(x_{IP}, t) \otimes f_{i/IP}^D(x/x_{IP}, Q^2)$$

⇨ Universal DPDFs apply in DIS when vacuum quantum numbers are exchanged

Signatures and Selection Methods

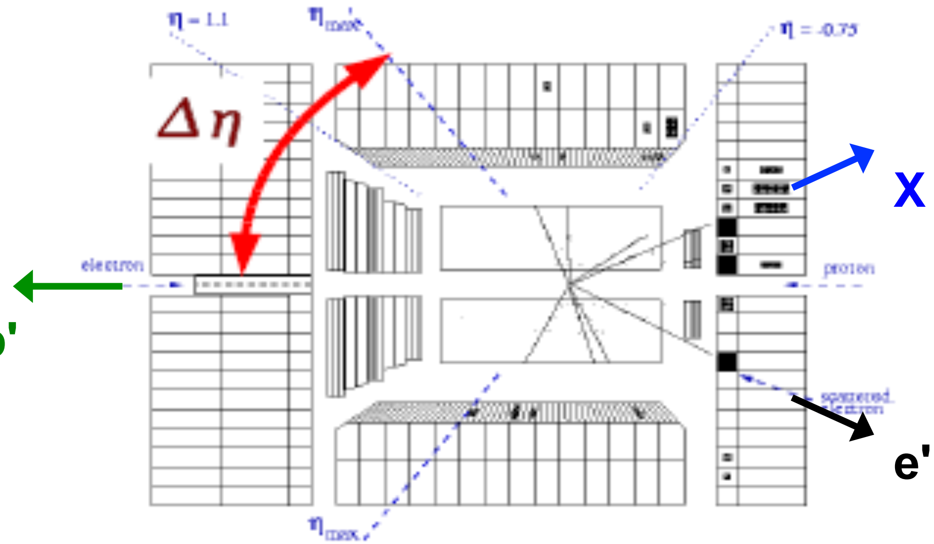
Proton Spectrometer (PS) method



PROS: no DD background
direct measurement of t, x_{IP}
high x_{IP} accessible

CONS: low statistics

Large Rapidity Gap (LRG) method



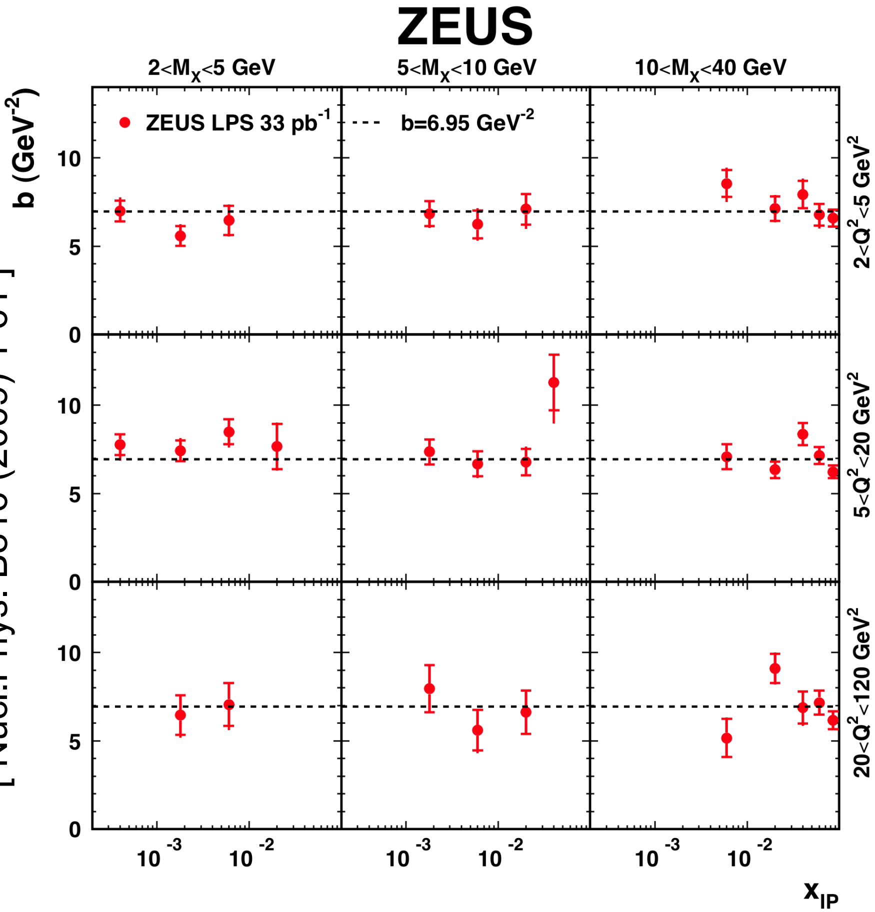
PROS: high statistics
near perfect acceptance
at low x_{IP}

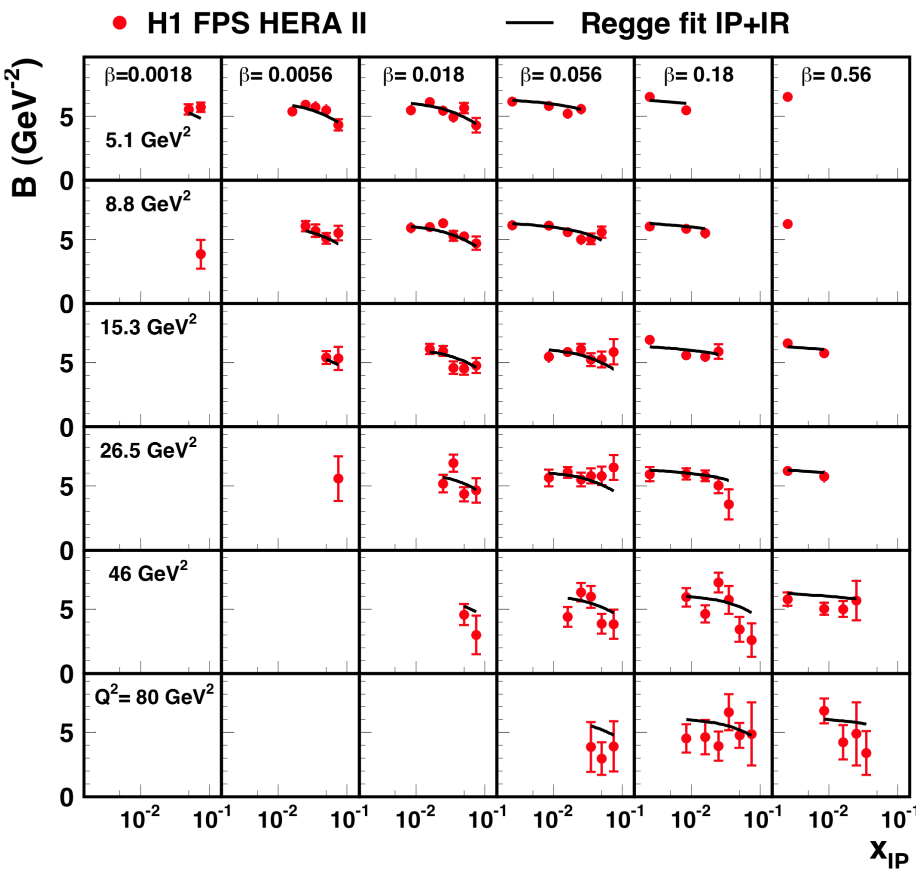
CONS: DD background

t-slope

$d\sigma/dt \sim e^{bt}$

[Nucl.Phys. B816 (2009) 1-61]

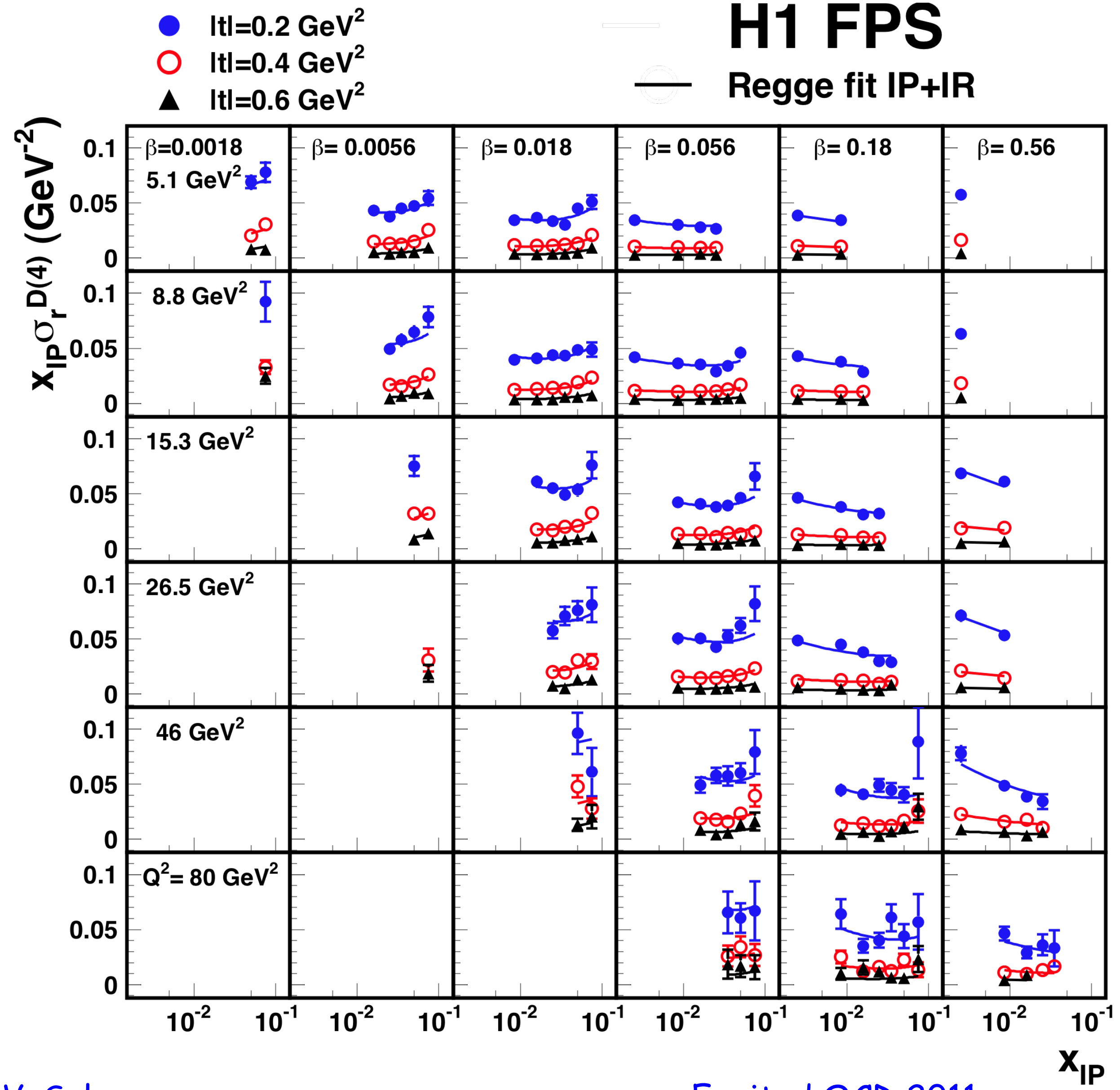




[arXiv: 1010.1476]

- t-slope does not change with Q^2 and M_X (or β) at fixed x_{IP}
  → data consistent with Regge factorization
- H1 results exibit an x_{IP} dependence of t-slope in (Q^2, β) bins
  → contributions other than IP at high x_{IP}

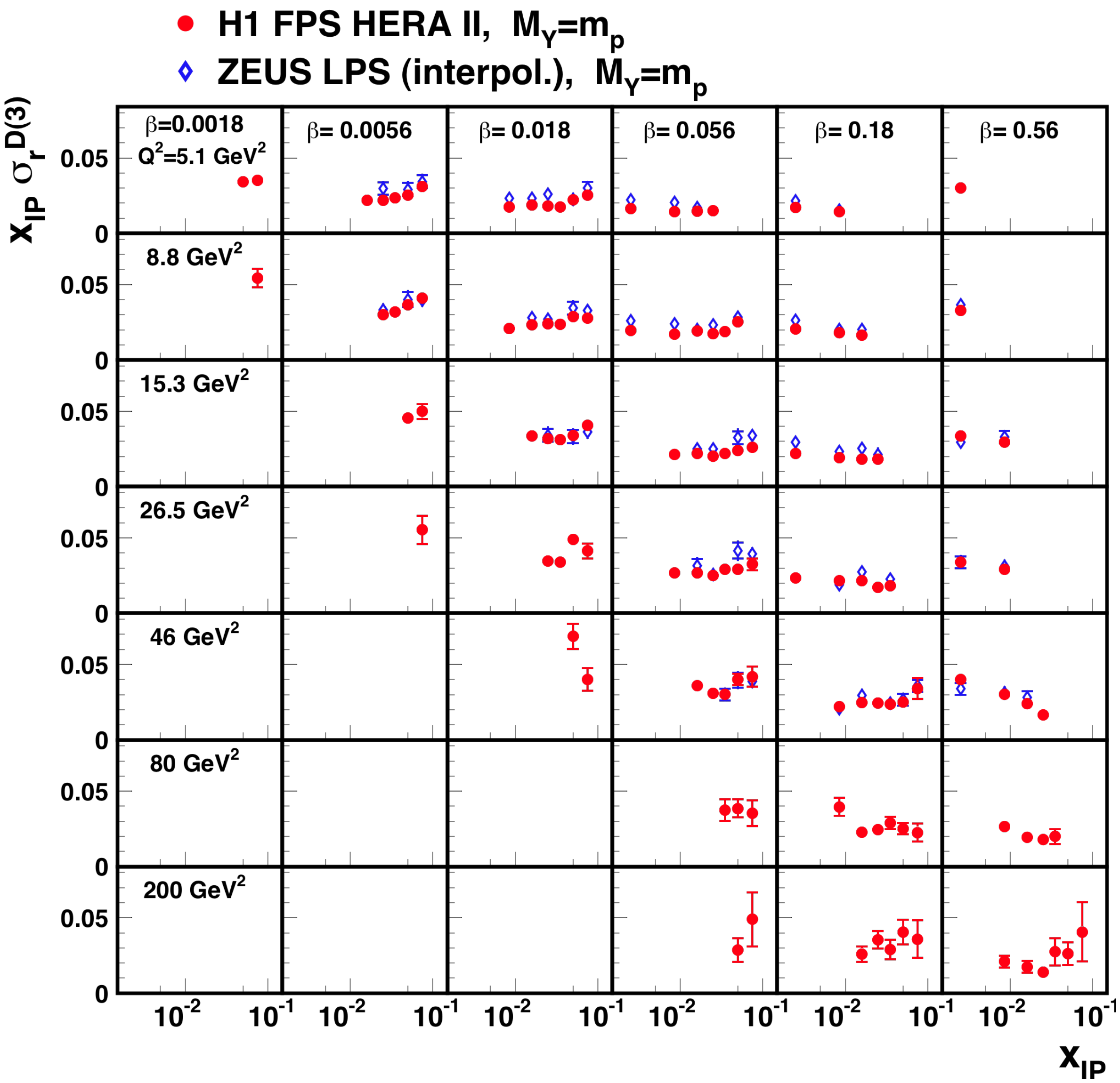
x_{IP} Dependence of $\sigma_r^{D(4)}$



H1 HERA-II FPS data ($156\ pb^{-1}$) improve stats by factor of 20 and reach higher Q^2

syst uncertainty ~ 8%
norm uncertainty ~ 4.3%

x_{IP} Dependence of $\sigma_r^{D(3)}$



All available PS data used by both Collaborations (integrated over t)

Fair agreement in normalization between H1 and ZEUS

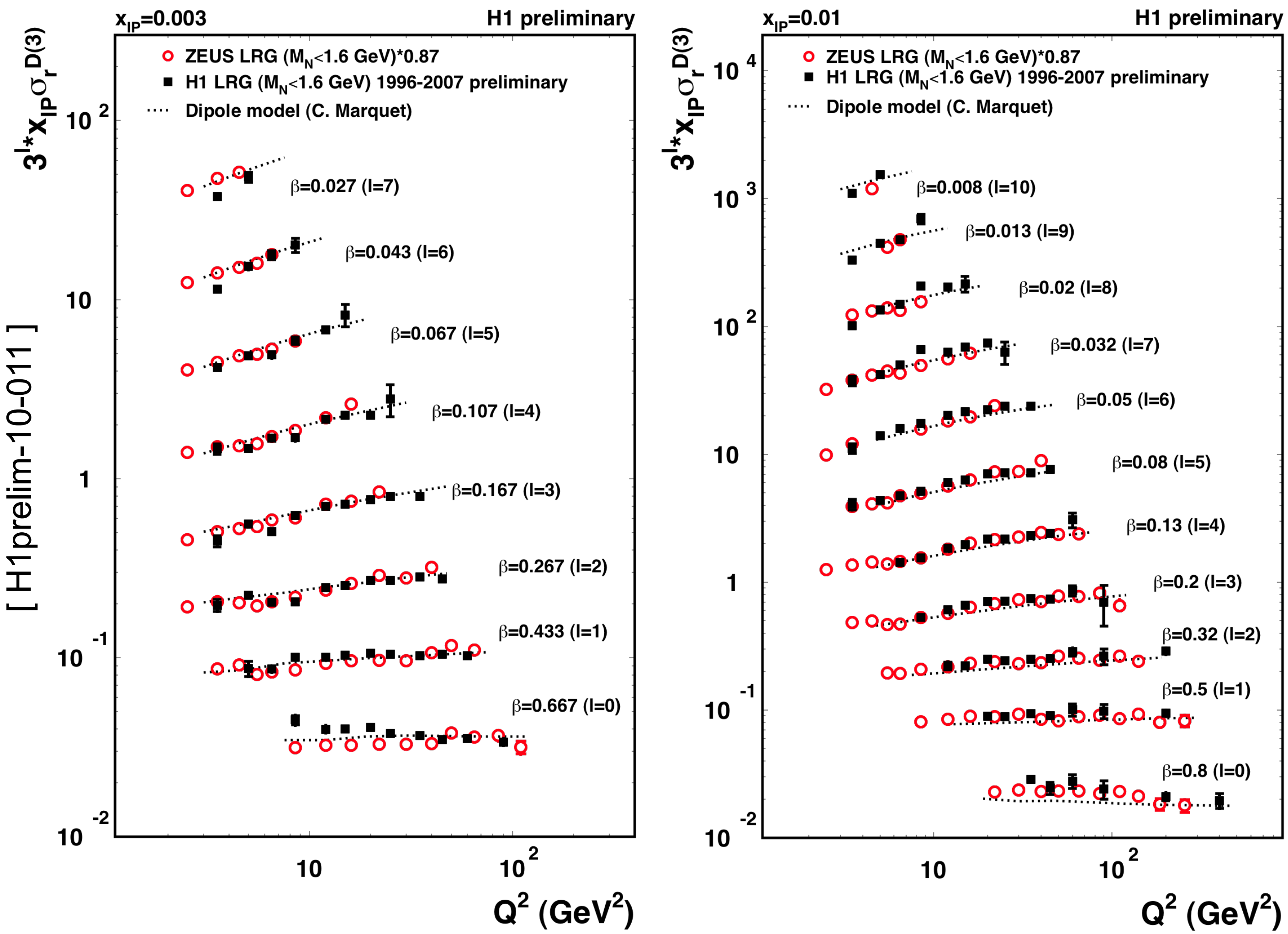
H1 FPS norm unc ~ ± 6%

ZEUS LPS norm unc ~ + 11% - 7%

H1/ZEUS = 0.85 ± 0.01 (stat) ± 0.03(syst) + 0.09 – 0.12 (norm)

Reasonable agreement in shape between H1 and ZEUS

Q^2 Dependence of $\sigma_r^{D(3)}$



ZEUS corrected to M_N < 1.6 GeV with PYTHIA MC

All available LRG data used by both Collaborations

Very precise measurements of the scaling violation for diffraction

Reduced cross section constrains quark density

$\ln Q^2$ dependence constrains gluon density

⇨ QCD fits to data provide sets of diffractive PDFs

Diffractive PDFs from NLO Fits

Inclusive Data

NLO QCD Fits:
- parametrize quark singlet and gluon at Q^2_0 = 1.8 GeV^2

$$z\, f_{u,d,s}(z, Q^2_0) = A_q\, z^{B_q} (1-z)^{C_q}$$
$$z\, f_g(z, Q_0^2) = A_g\, z^{B_g} (1-z)^{C_g}$$

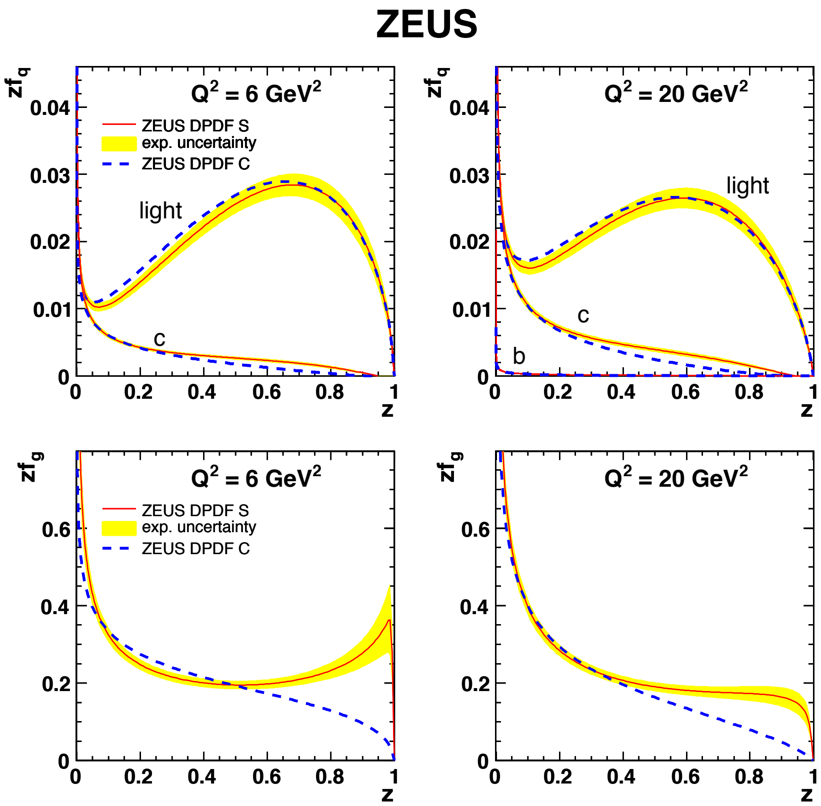
- evolve with NLO DGLAP and fit

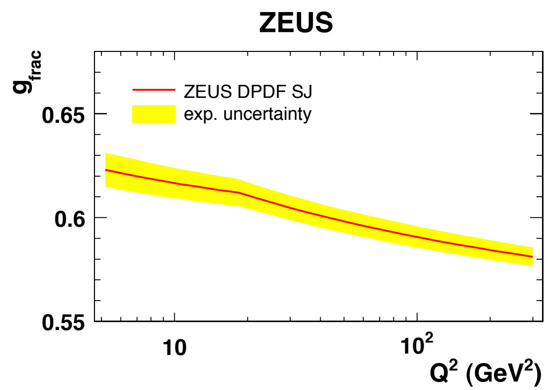
Different parametrizations

Well constrained singlet
Gluon weakly constrained in the high z_{IP} region (gluon density from $\ln Q^2$ dependence of σ_r^D)

DPDFs are gluon dominated

(z = momentum fraction of the diffr exchange entering the hard scattering)

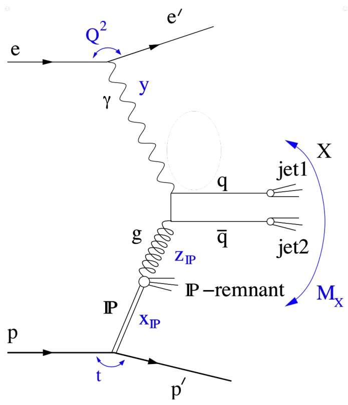




[Nucl.Phys. B831 (2010) 1-25]

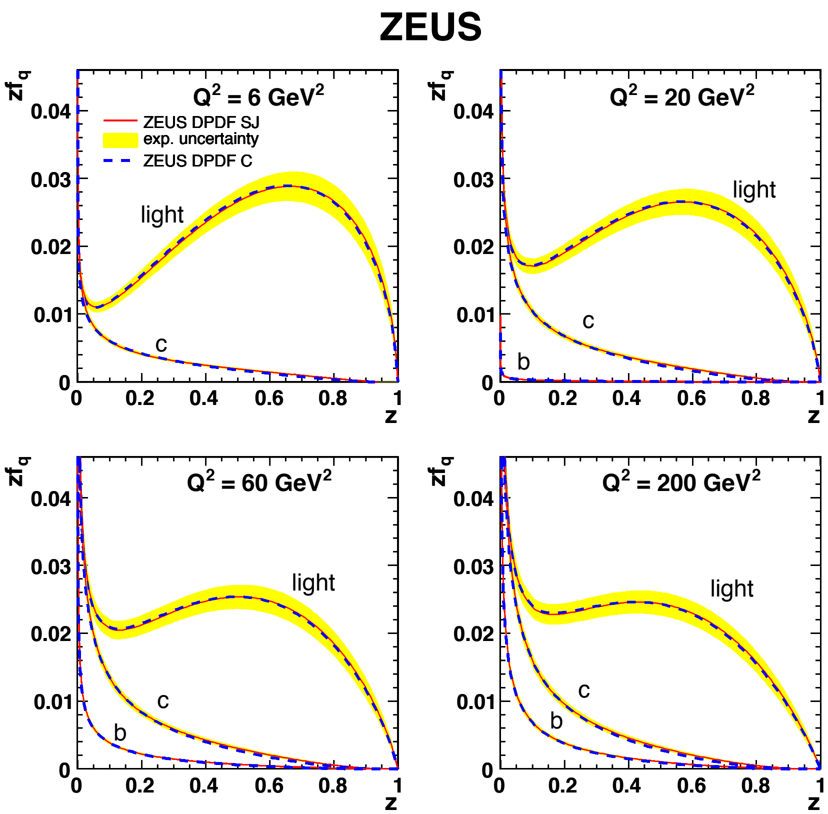
Diffractive PDFs from NLO Fits

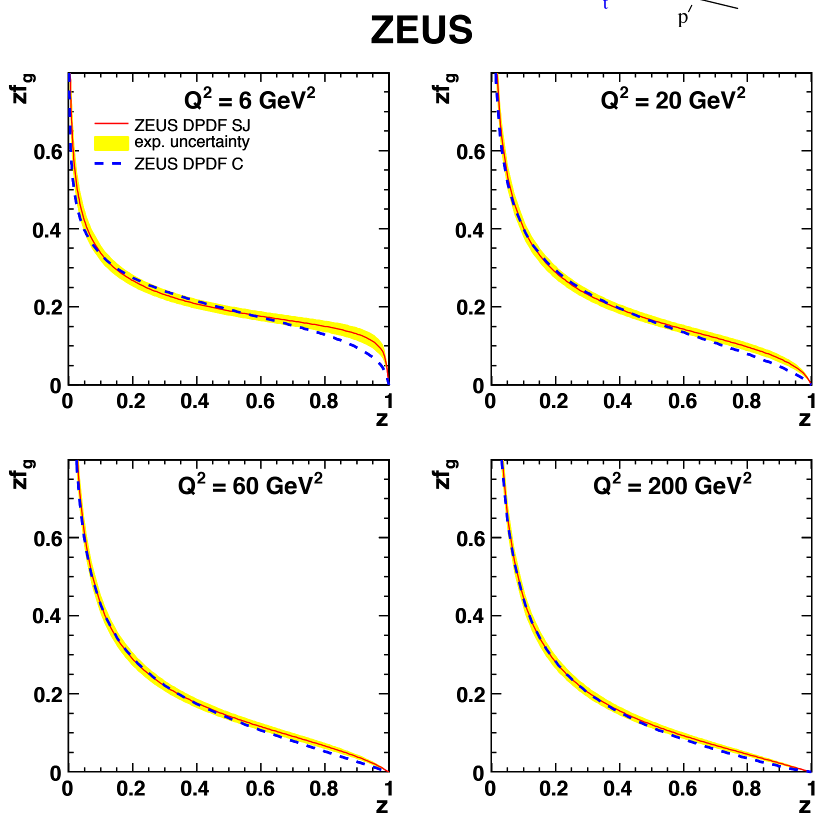
Inclusive and Dijet Data



Diffractive dijiet data are directly sensitive to the gluon as the photon-gluon fusion contributes at first order

Singlet and gluon constrained with similar precision across the whole kinematic range

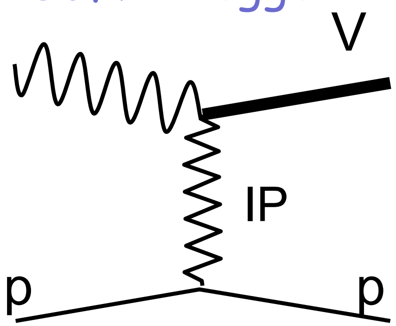




Vector Meson Production

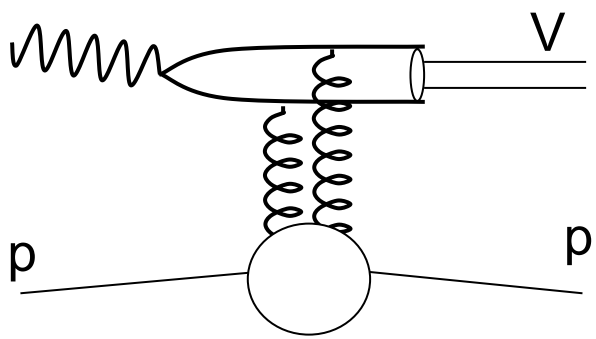
ep → eVMp
VM ($J^{PC} = 1^{--}$): ρ, φ, J/ψ, Υ, ...
DVCS: real γ

Soft - Regge



IP exchange
(Regge trajectory)

Hard - pQCD



2-gluon exchange
(LO realization of vacuum quantum numbers in QCD)

Cross section proportional to probability of finding 2 gluons in the proton → $\sigma \propto [x\,g]^2$

With increasing scale (Q^2, M_{VM}, t)

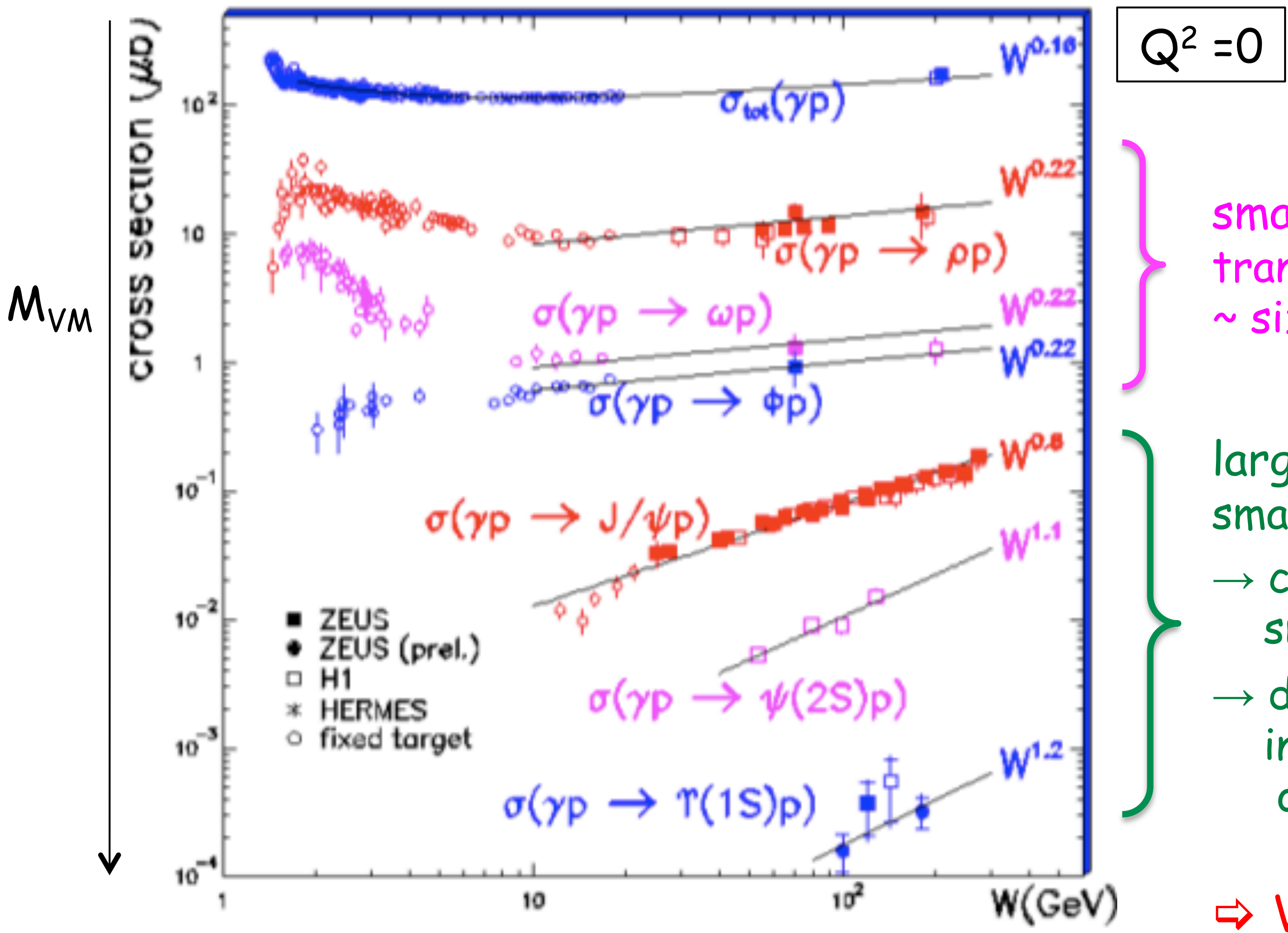
$$\sigma(W) \propto W^{\delta}$$

- Expect δ to increase from soft (~0.2 'soft Pomeron' value) to hard (~0.8 reflecting large gluon density at low x)

$$\frac{d\sigma}{dt} \propto e^{-b|t|}$$

- Expect b to decrease from soft (~10 GeV^{-2}) to hard (~4-5 GeV^{-2})

W Dependence in Photoproduction



M_{VM} is the scale
→ same feature observed when varying Q^2 for a given VM

small M_{VM} (~ 1 GeV^2)
transverse size of dipole
~ size of proton

large M_{VM}
small dipole size

→ cross section much smaller (color screening)

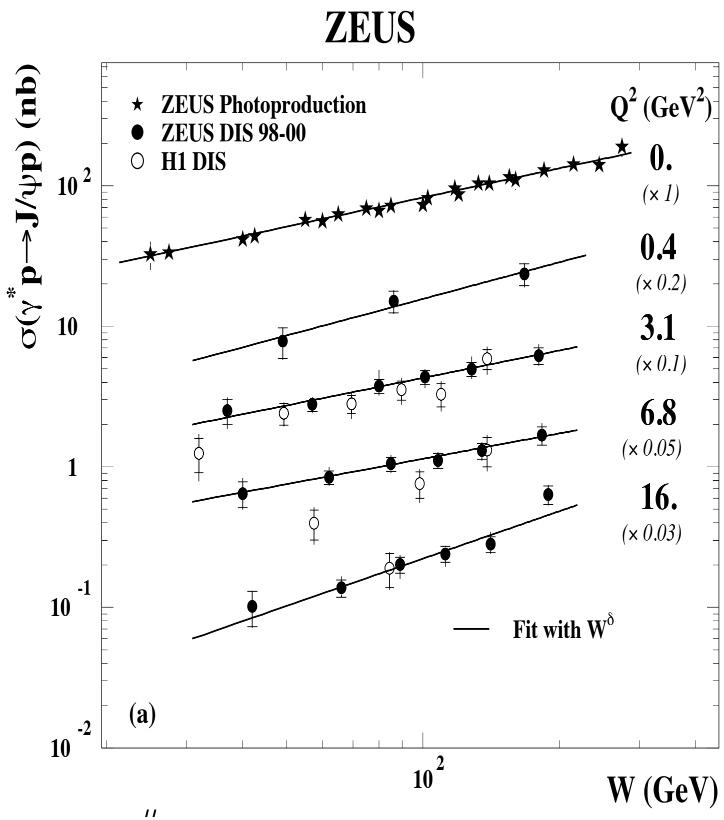
→ dipole resolves partons in the proton
$\sigma \sim (xg)^2$ ⇨ large δ

⇨ VM data can help determine gluon density!

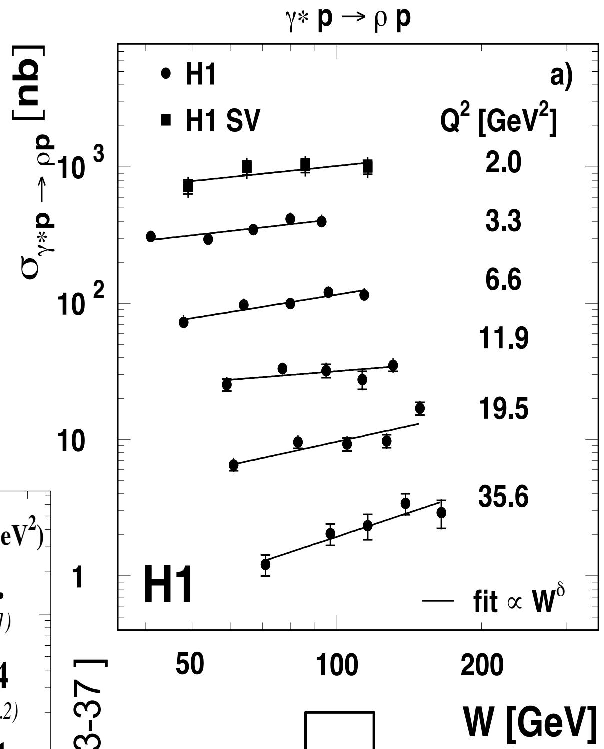
W Dependence in Bins of Q^2

At fixed M_{VM}
→ the value of the slope δ increase with Q^2

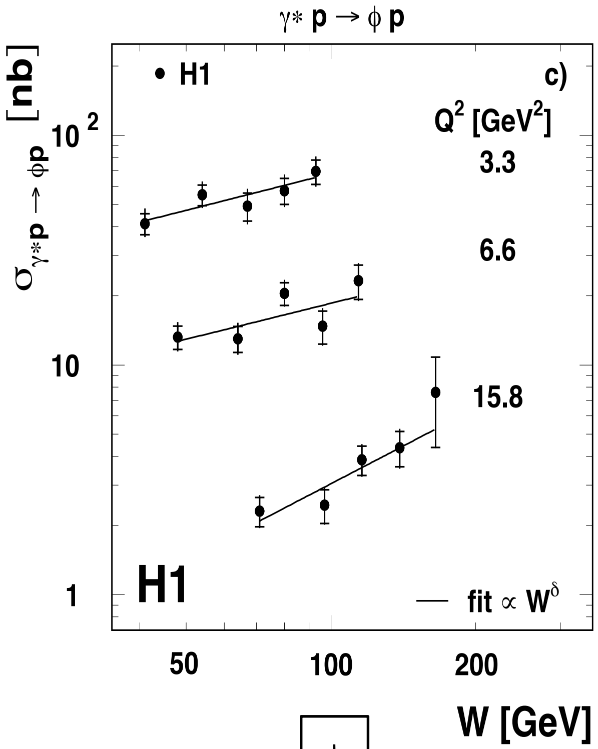
J/ψ



[Nucl.Phys. B695 (2004) 3-37]



ρ

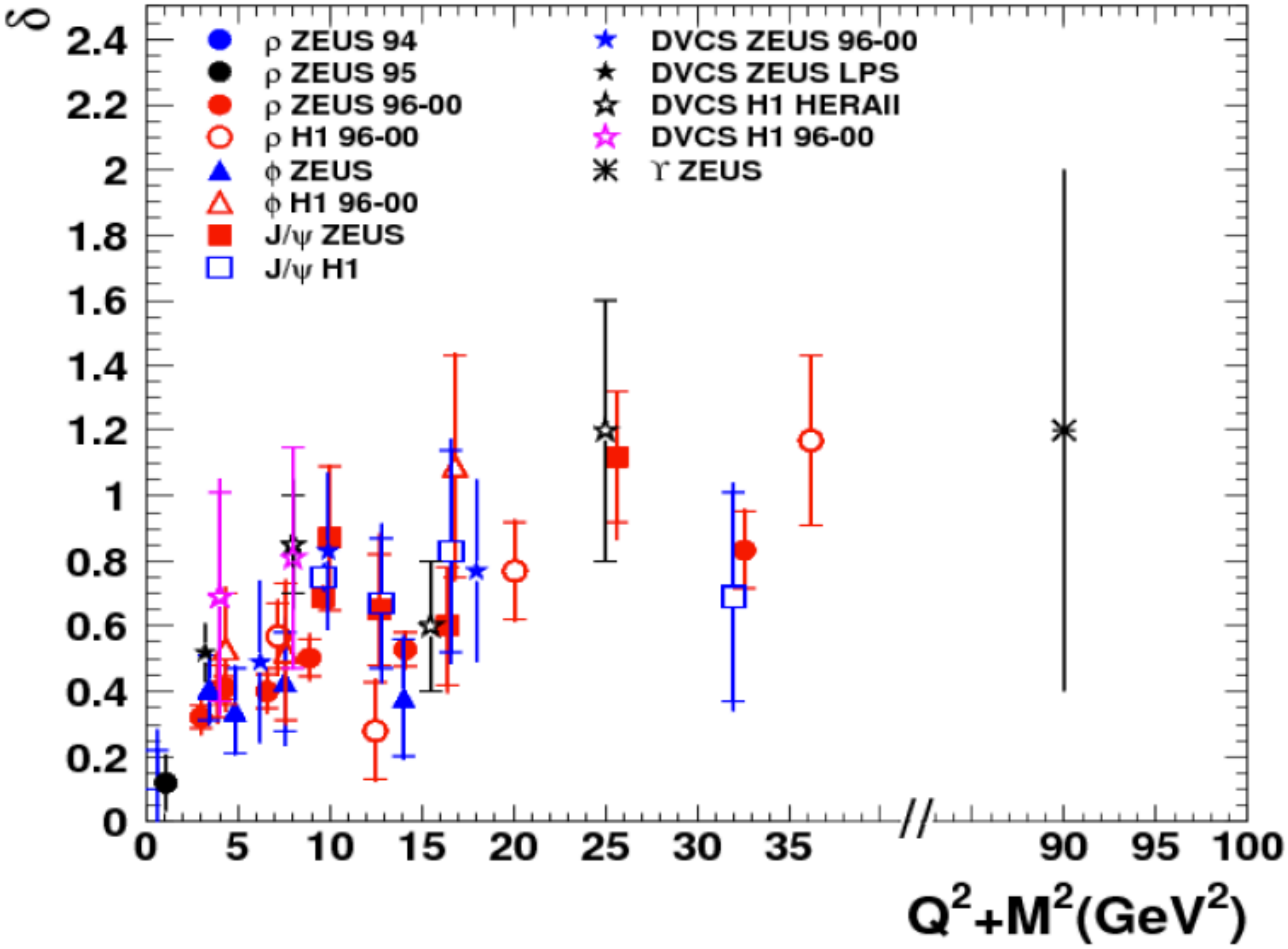


φ

[JHEP05 (2010) 032]

The W dependence of the J/ψ cross section does not change with Q^2 up to 16 GeV^2
→ the value of $(M_{J/\psi})^2$ already provide a sufficient hard scale

Soft to Hard Transition - σ(W)

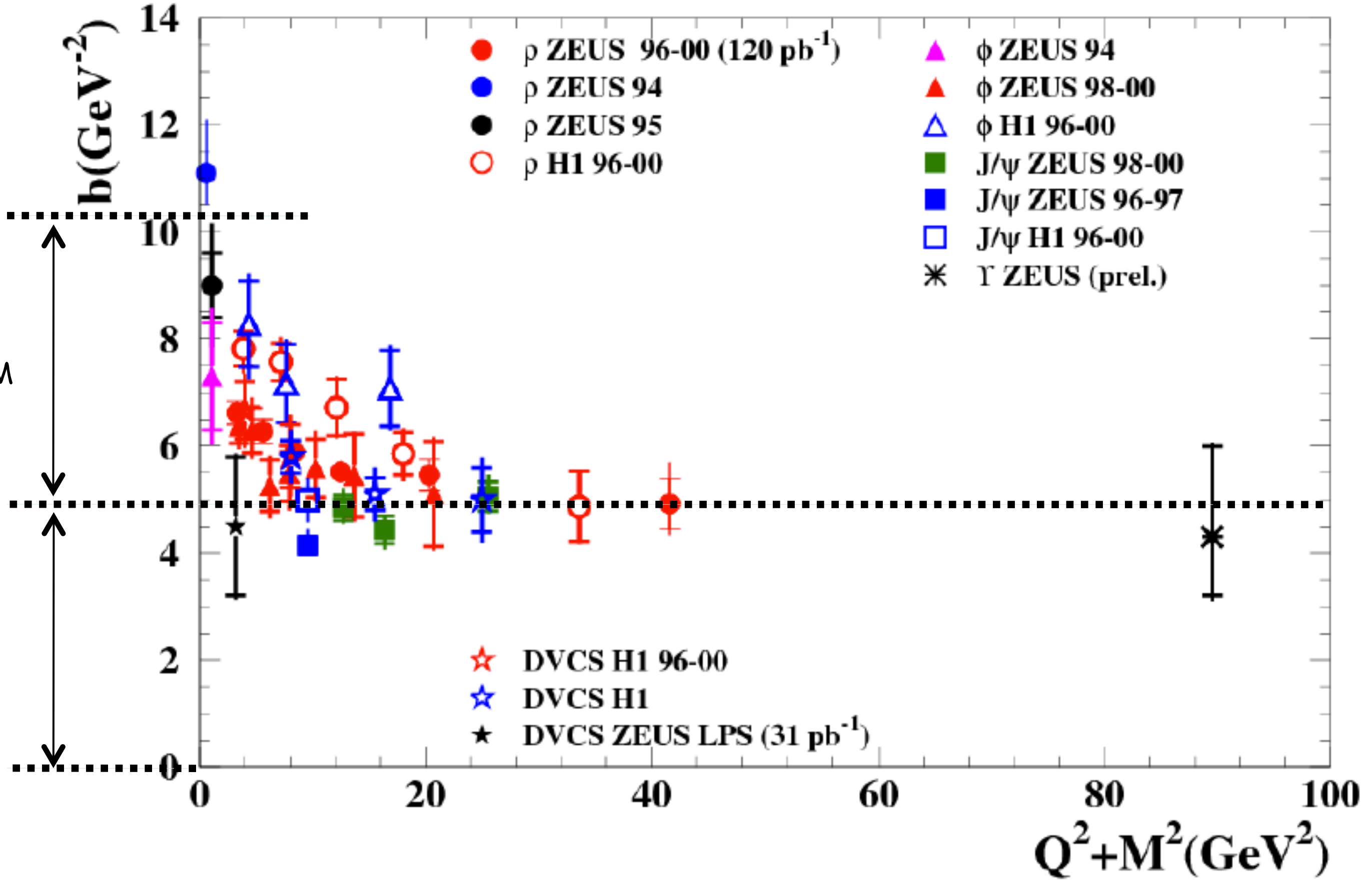


⇨ Process becomes harder as the scale (Q^2 + M^2) becomes larger

Soft to Hard Transition - t-slope

$$\frac{d\sigma}{dt} \propto e^{-b|t|}$$

Slope b becomes smaller as the scale increases



Size of diffractive cone related to size of interacting objects (as in optical diffraction)

$b \sim b_{VM} + b_p$

$\langle r^2 \rangle = b(\hbar c)^2$

r_{gluons} ~ 0.6 fm - radius of gluon density in proton

r_{proton} ~ 0.8 fm – radius of charge density in the proton

Summary

- ✓ After 15 years of running HERA provided unique diffractive data
- ✓ Consistency reached between different experiments, methods and data sets
  - ⇨ Ready to combine inclusive cross sections between experiments
- ✓ DPDFs well constrained which can be used to predict other processes in DDIS
  - ⇨ Inclusion of dijet data in the QCD fits provides a much better constraint of the gluon density at high fractional momentum
- ✓ Lots of inputs from exclusive vector meson production
  - ⇨ Precision measurements can constrain the gluon density
  - ⇨ Transition from soft to hard regime is visible

Thank You

QCD Factorization in Hard Diffraction

QCD factorisation theorem, proven for DDIS by **J.Collins [PR D57 (1998) 3051]**

$$\sigma^D(\gamma^* p \to Xp) = \sum_i \hat{\sigma} \otimes f_i^D(x_{IP}, t, z, Q^2)$$

Hard subprocess ME
pQCD calculable

DPDFs, universal for diffractive DIS processes

Proton-vertex factorisation assumption, supported by H1 and ZEUS data

$$f_i^D(x_{IP}, t, z, Q^2) = f_{IP}(x_{IP}, t) f_i^{IP}(z, Q^2) + f_{IR}(x_{IP}, t) f_i^{IR}(z, Q^2)$$

Flux parametrisation

$$f(x_{IP}, t) = \frac{Ae^{Bt}}{x_{IP}^{2\alpha(t)-1}}$$

with $\alpha(t) = \alpha(0) + \alpha' t$

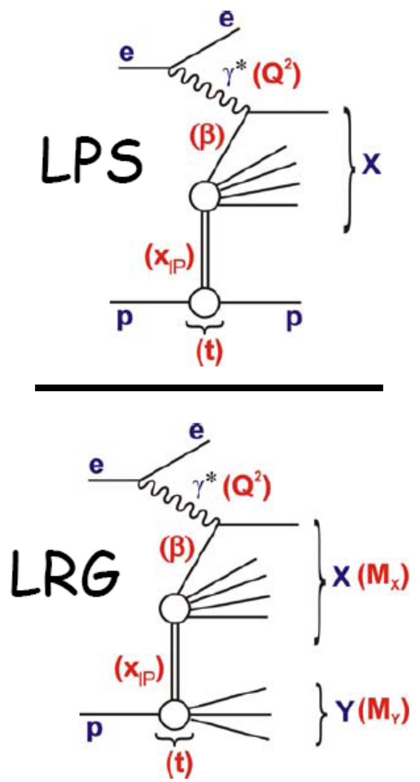
Pomeron PDFs

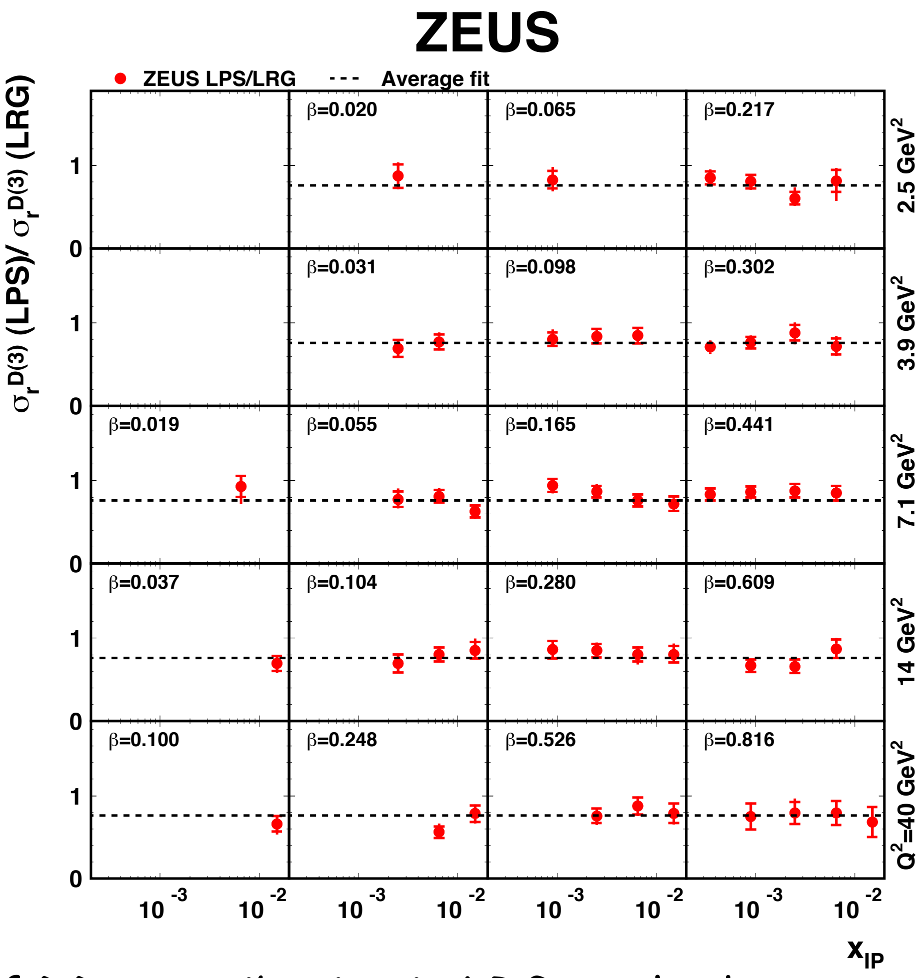
Reggeon PDFs taken from pion (GRV)

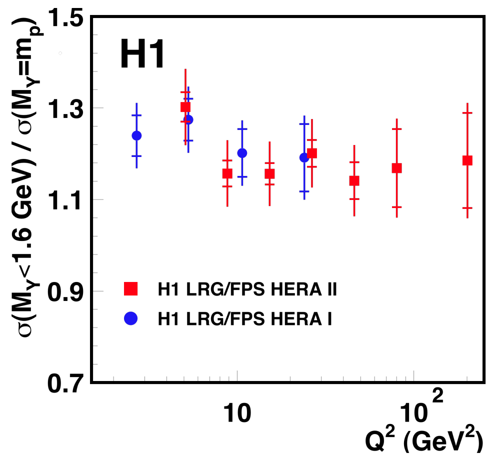
→ Fit z and Q^2 dependence at fixed x_{IP} and t

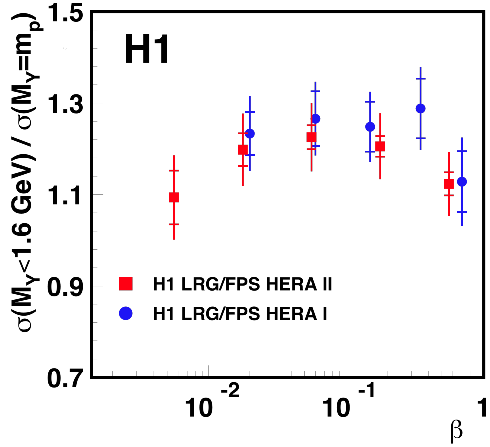
(z = momentum fraction of the diffr exchange entering the hard scattering)

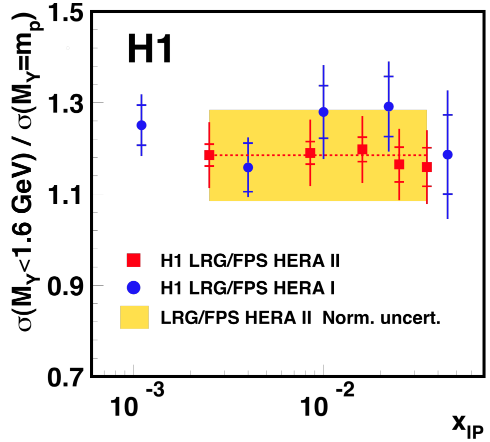
LRG vs PS









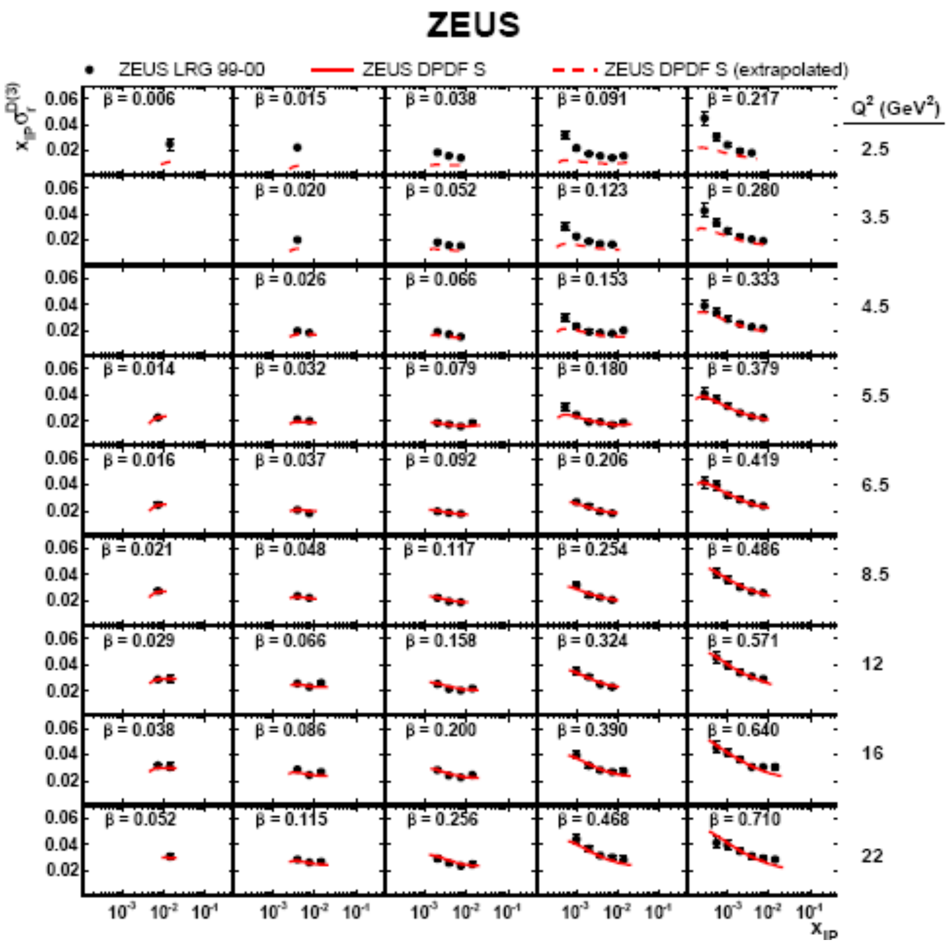


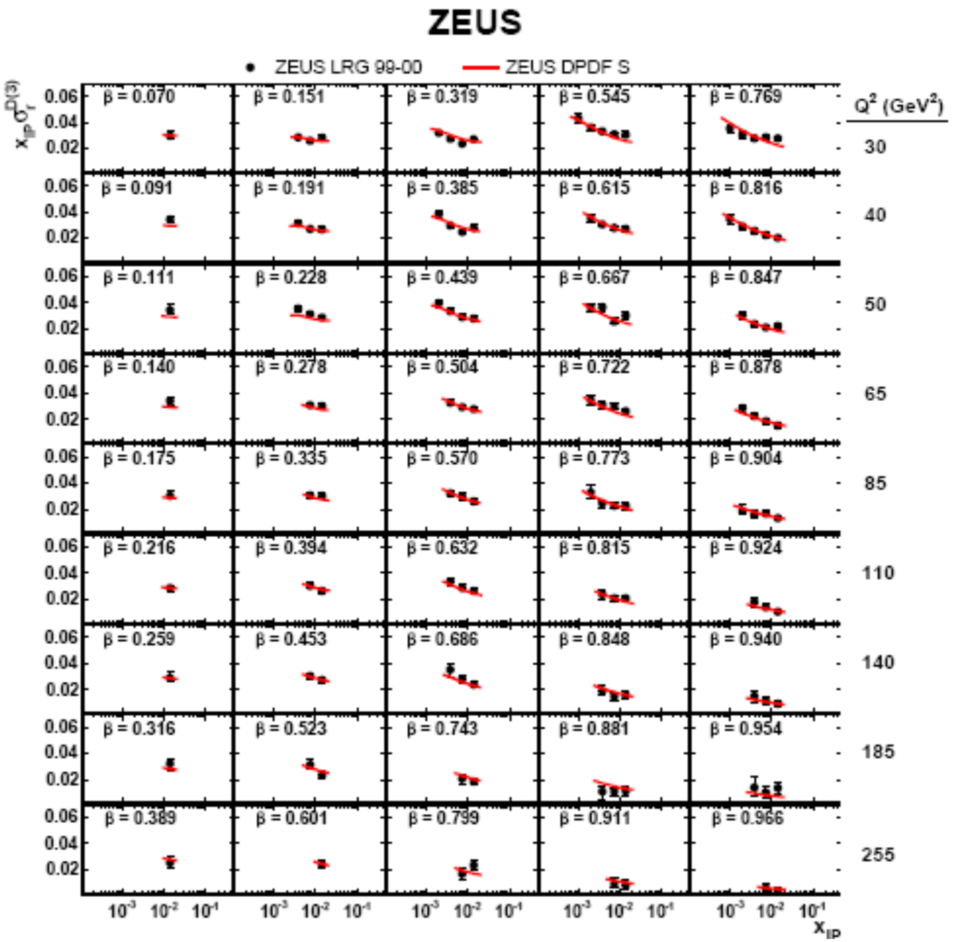
Estimation of DD contribution in LRG method

→ ratio flat both in ZEUS and H1

→ quantity of DD ~ 20%

x_{IP} Dependence of $\sigma_r^{D(3)}$





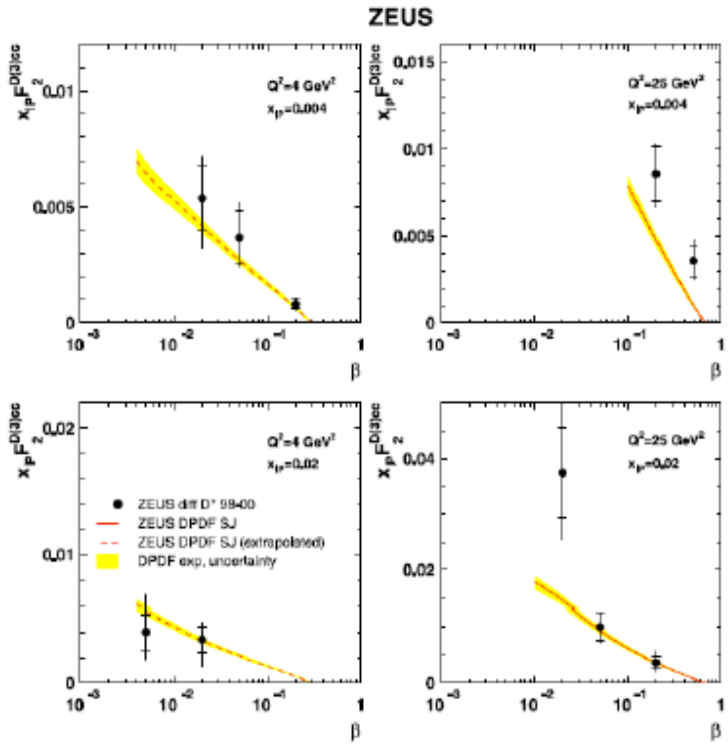
Wide kinematic coverage and very good statistical precision

Factorization Test in Diffractive DIS

Use DPDFs extracted from inclusive DDIS for calculating NLO predictions to semi-inclusive final states: **test universality of DPDFs**

→ Open charm and dijets in DIS: hard scales in the process ensure use of pQCD

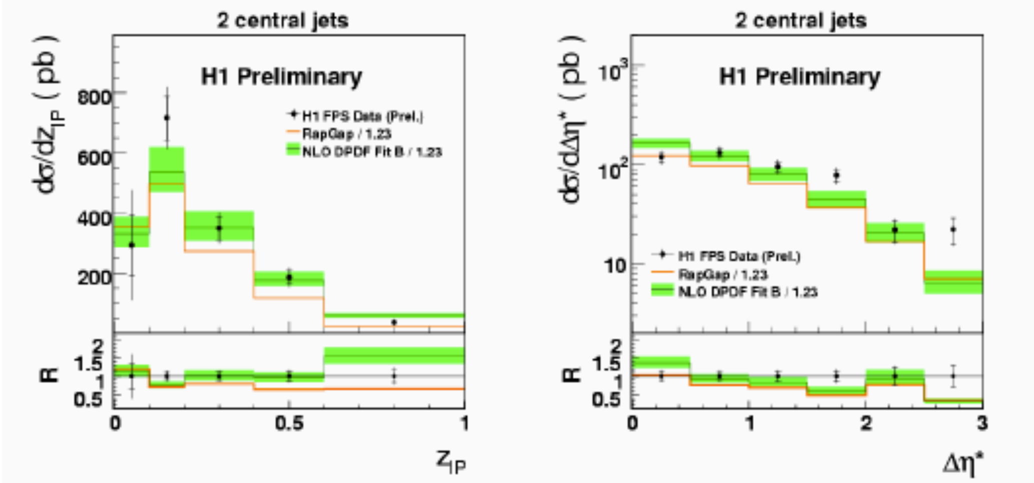
Open charm: H1, EPJ C50 (2007) 1
ZEUS, NP B672 (2003) 3



→ **QCD factorisation holds in DDIS!**

Dijets: H1, JHEP 0710:042 (2007)
ZEUS, EPJ C52 (2007) 813

First measurement of dijets in DDIS with a **tagged proton** (H1 FPS) - **H1prelim-10-013**

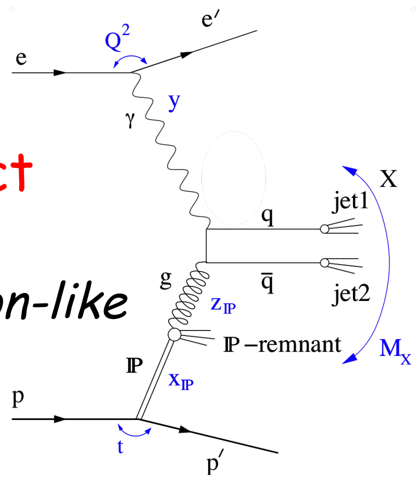


Deviations might be related to missing pomeron remnant in NLO predictions (NLOJET++)
Deviations at high $\Delta\eta^*$ → interesting to look at forward jets

Factorization Test in PHP at HERA

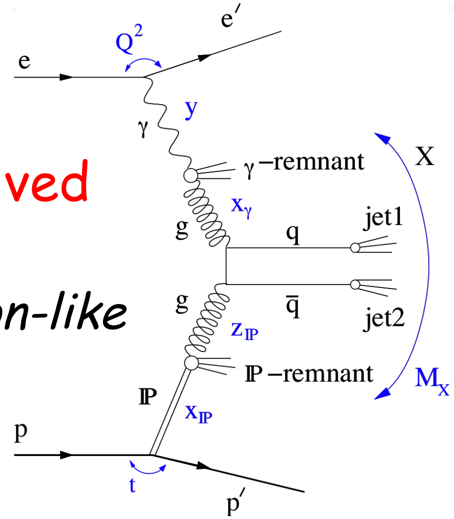
Direct

Less hadron-like



Resolved

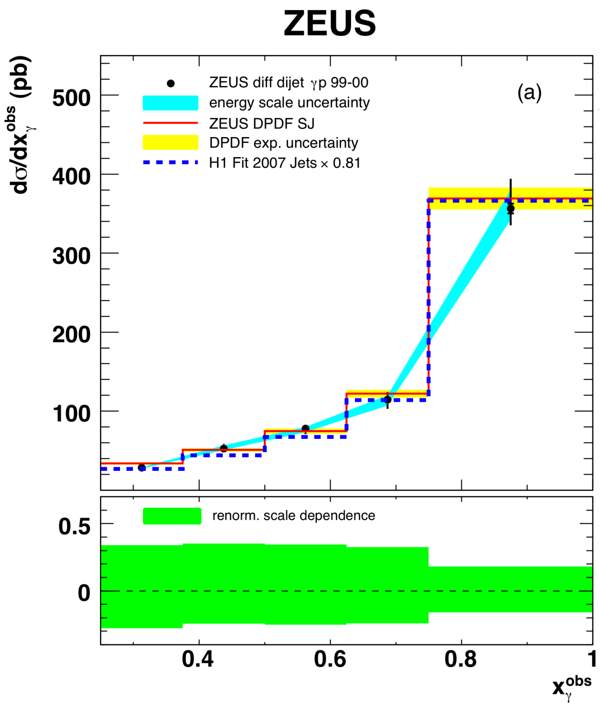
More hadron-like

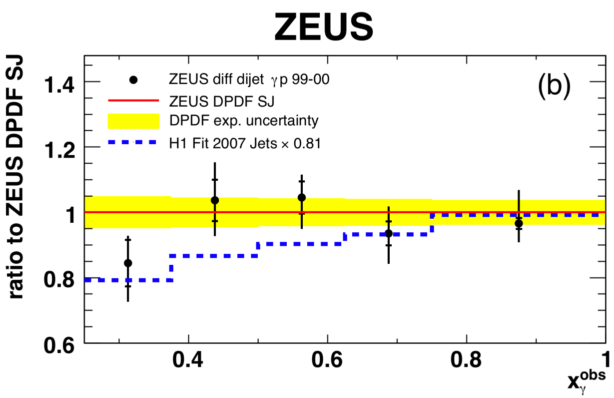


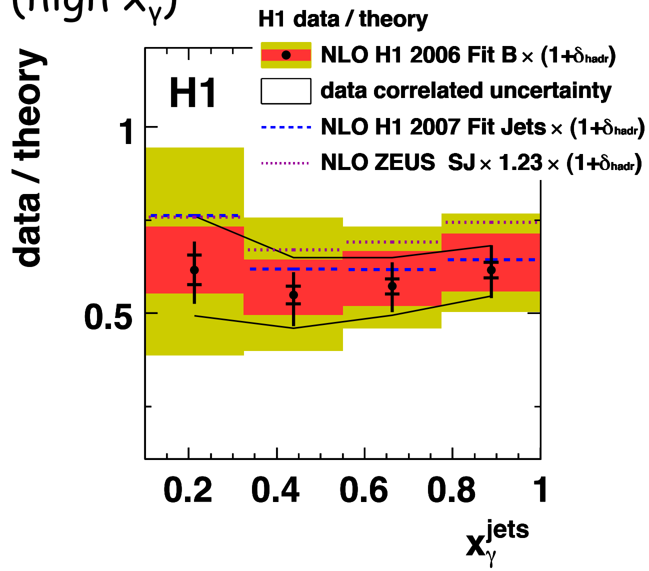
Use photoproduction at HERA as a hadron-hadron process

How hadron-like the proton is depends on the x_γ variable

Expect Resolved (low x_γ) to be more suppressed than Direct (high x_γ)





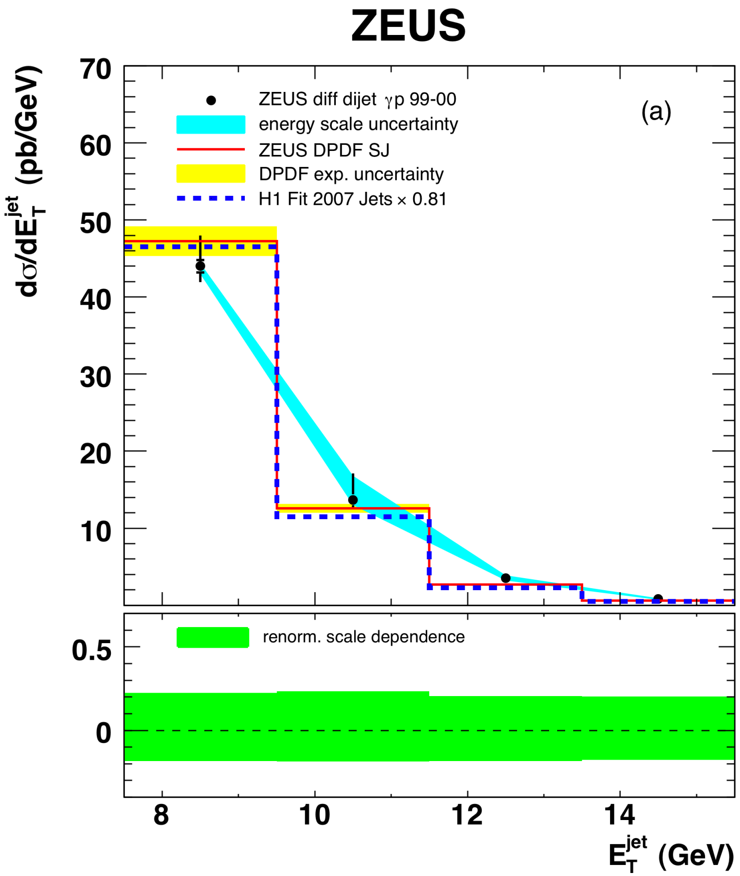


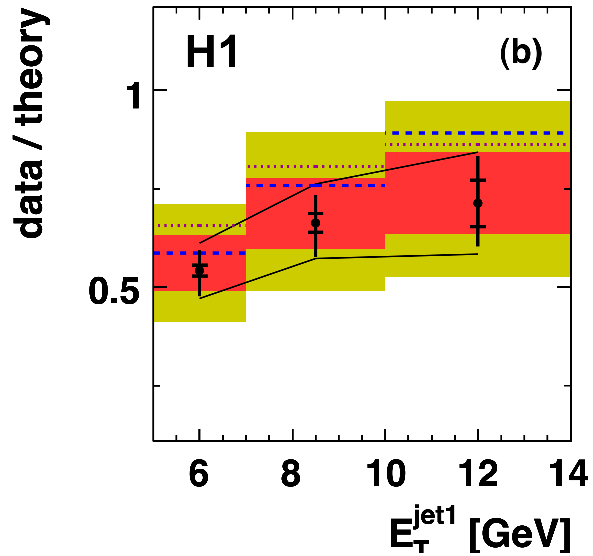
(different E_T region and different sets of DPDFs between ZEUS and H1)

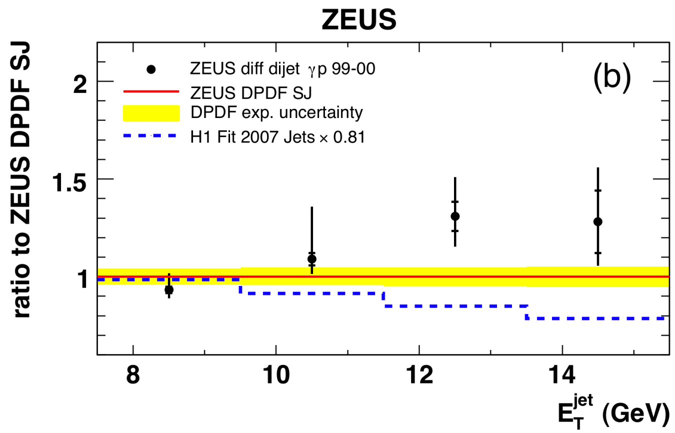
⇨ No evidence of suppression of resolved contribution

Factorization Test in PHP at HERA

Dijet photoproduction vs E_T



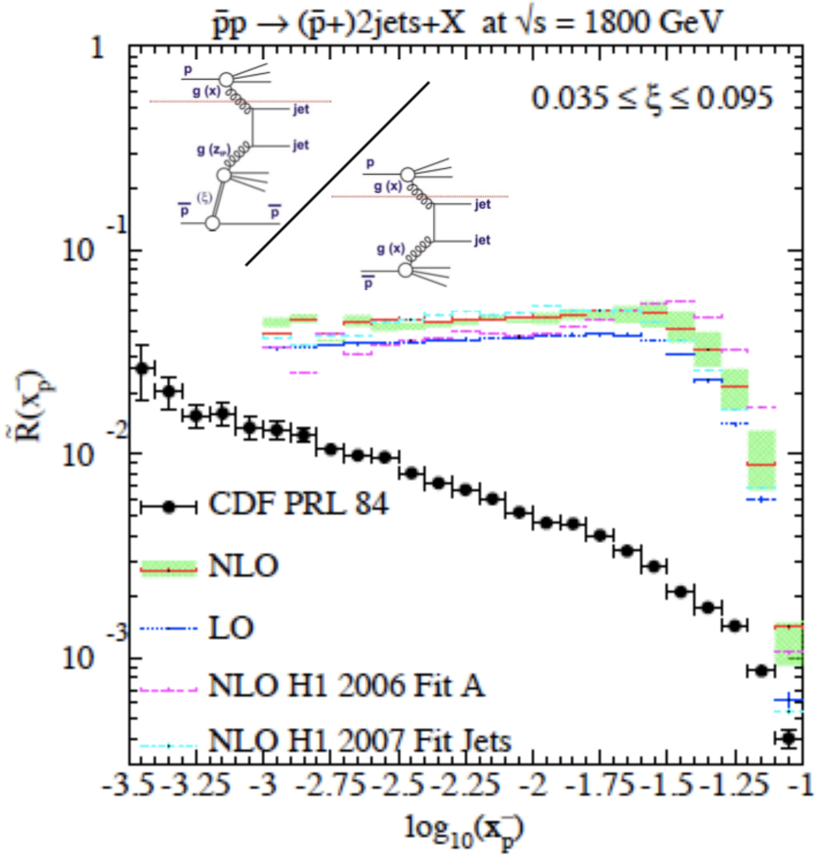




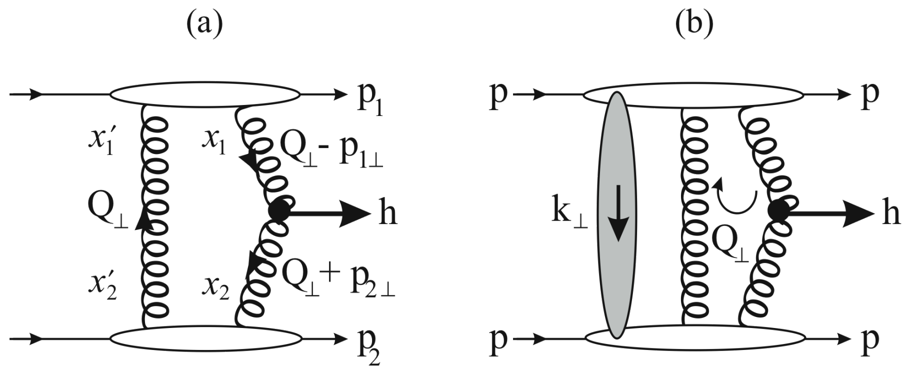
Data compared to NLO calculations using HERA DPDFs to test E_T dependence

Small suppression at small E_T
Both data still compatible

Factorisation Test at Tevatron



When trying to use universal DPDFs extracted at HERA to predict diffractive dijets at CDF we find a large suppression factor



Suppression expected in QCD and understood in terms of soft interactions between the hadrons and their remnants suppressing the Large Rapidity Gap

⇨ To understand diffraction at LHC a detailed undertanding on this mechanism is needed

First Measurement of F_L^D

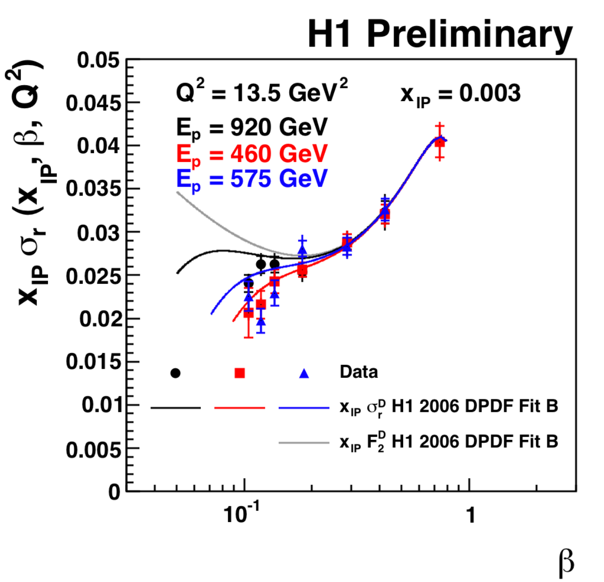
$$\sigma_r^D = F_2^D - \frac{y^2}{Y_+} F_L^D \qquad F_L^D \sim \alpha_S \times g(x)$$

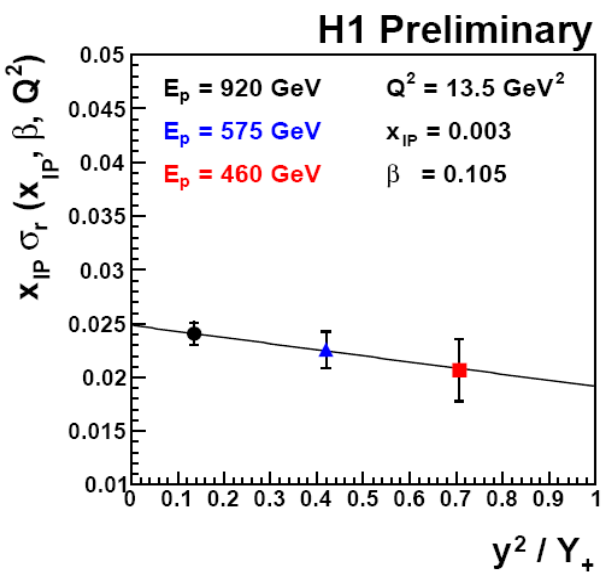
Challenging measurement, requires good understanding of the detector

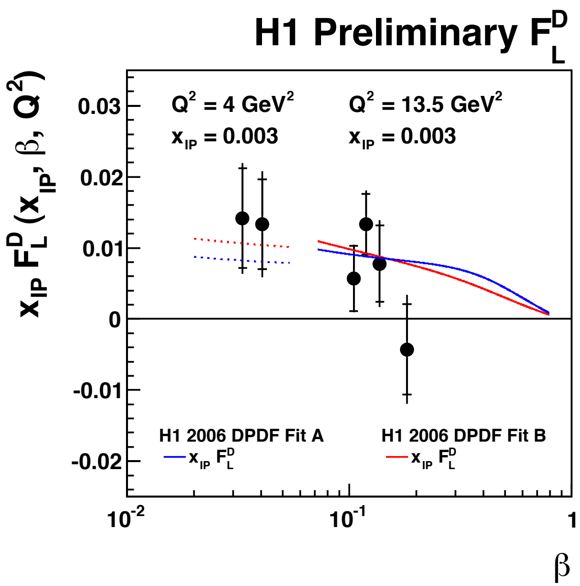
Measurement is performed with data taken at 3 proton beam energies: 920, 460 and 575 GeV

($Q^2 = sxy$, $x = \beta x_{IP}$)

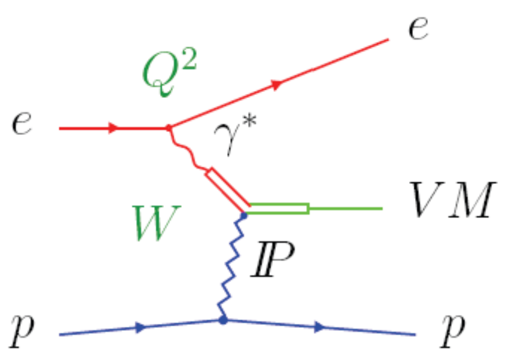
⇨ At fixed Q^2 and x_{IP}, high y corresponds to low β





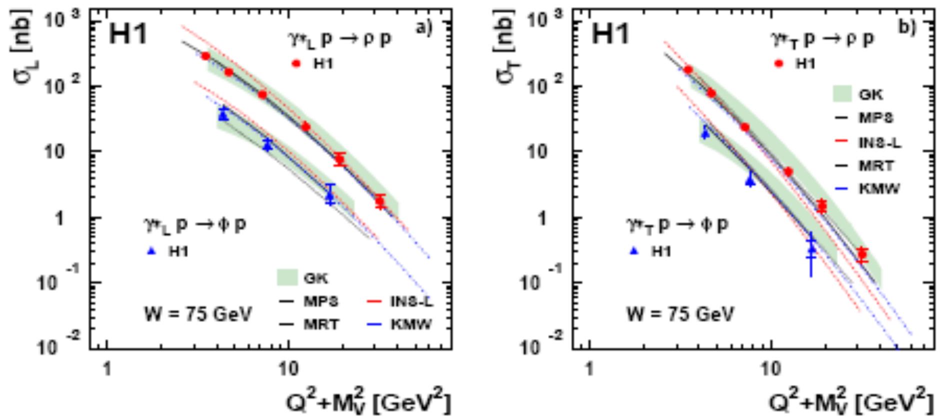


Flash on Exclusive Results (ep → ep VM)

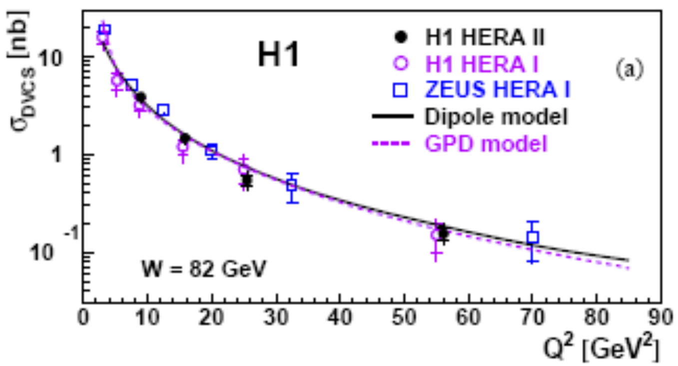


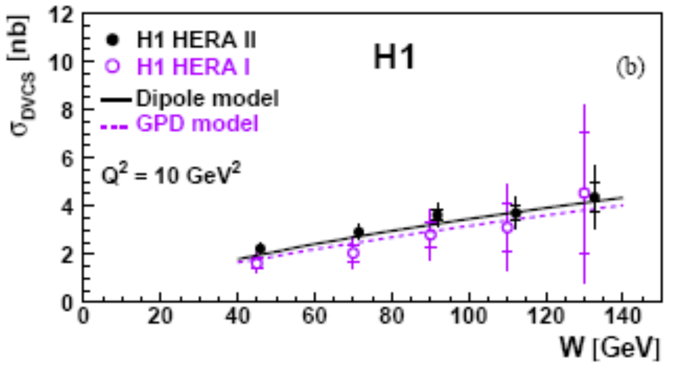
ρ and φ production

γ*p → ρp
γ*p → φp

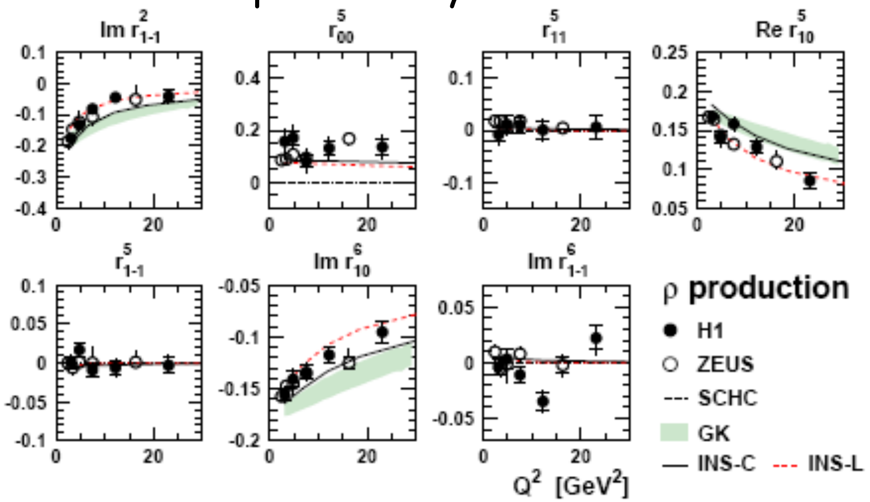


DVCS γ*p → γp





Some spin density martix elements



⇨ Lot of new physics results on this subject