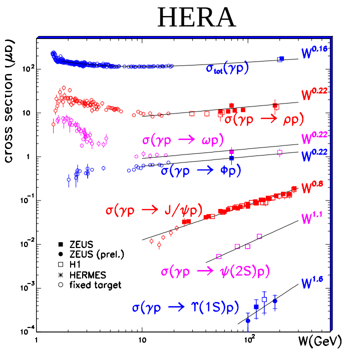
WE-Heraeus Physics School

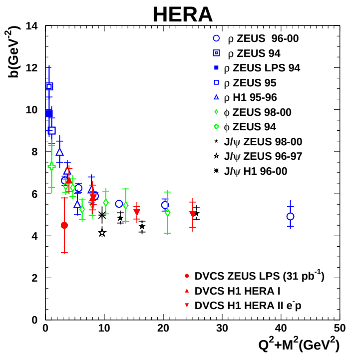
Diffractive and electromagnetic processes
at high energies

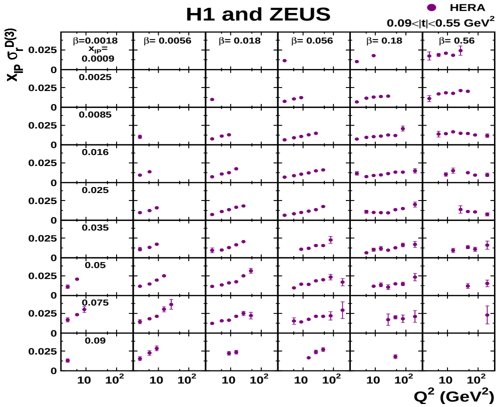
Bad Honnef, August 17 - 21, 2015

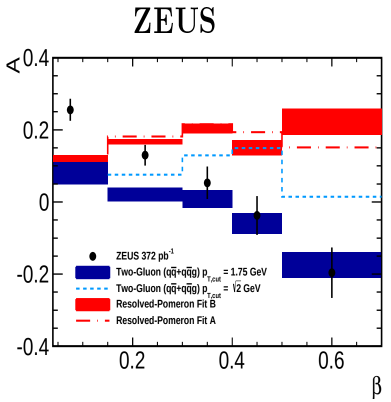
Diffraction and forward physics at HERA

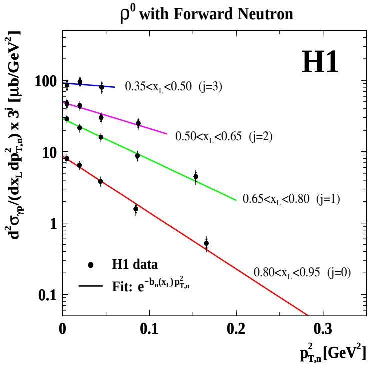
S. Levonian, DESY



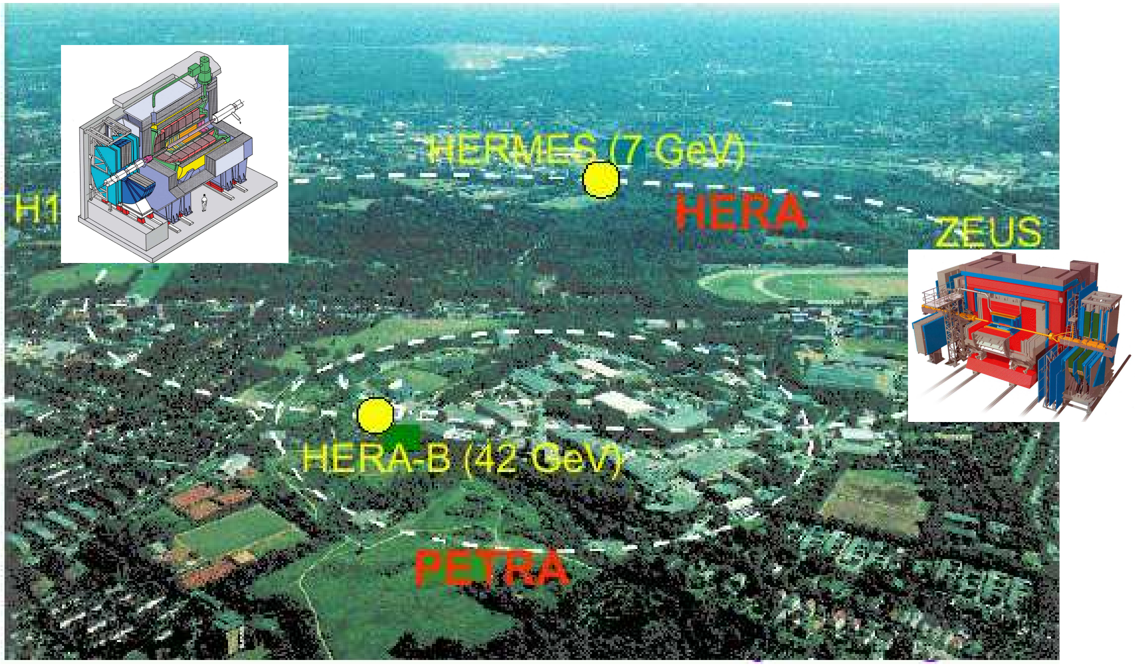








HERA: The World's Only ep Collider

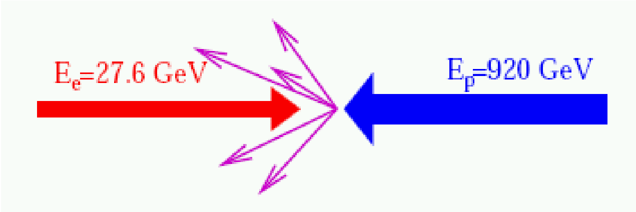


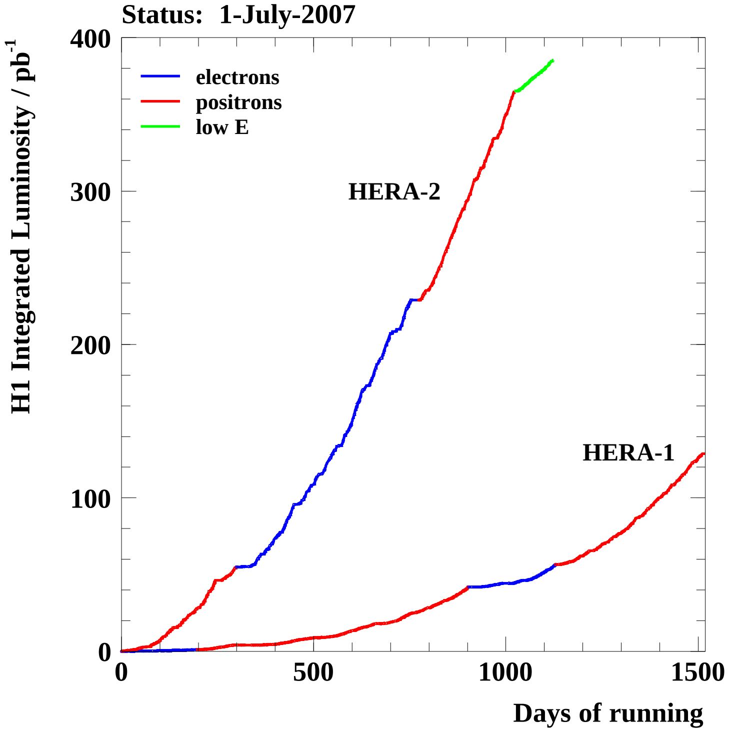
HERA-1 (1993-2000) $\simeq 120$ pb^{-1}

HERA-2 (2003-2007) $\simeq 380$ pb^{-1}

Final Data samples

H1+ZEUS: 2×0.5 fb^{-1}



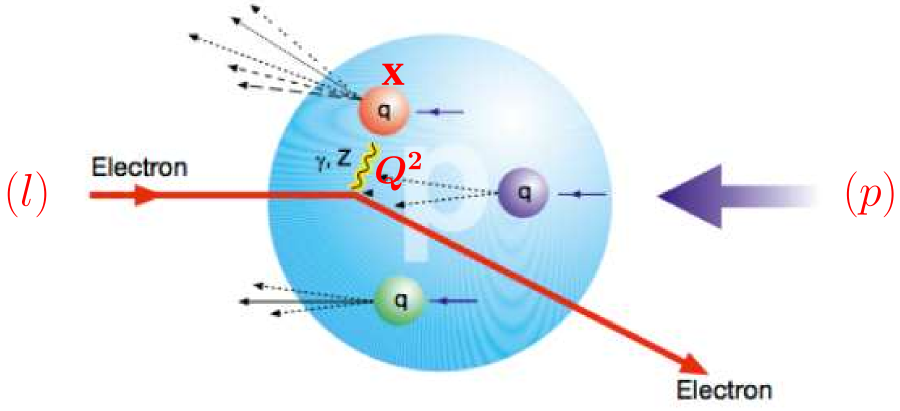


- 1998 E_p upgrade: $820 \Rightarrow 920$ GeV
  ($\sqrt{s}$: $301 \Rightarrow 319$ GeV)

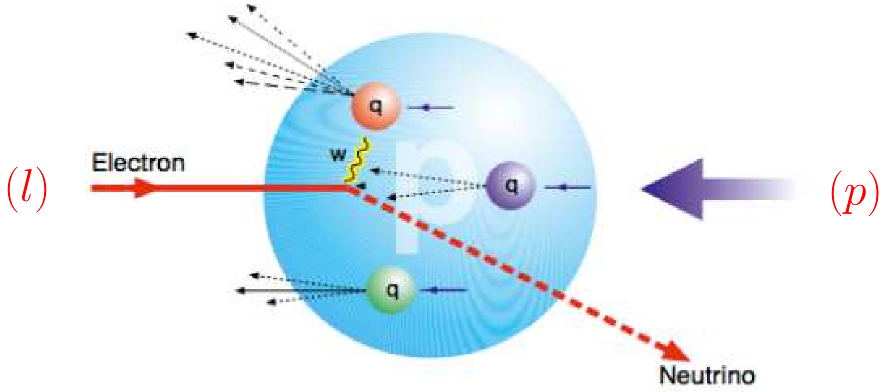
- 2001 HERA-2 upgrade: $\mathcal{L} \times 3$, Polarised e^+/e^-
  ($\langle P \rangle = 40\%$)

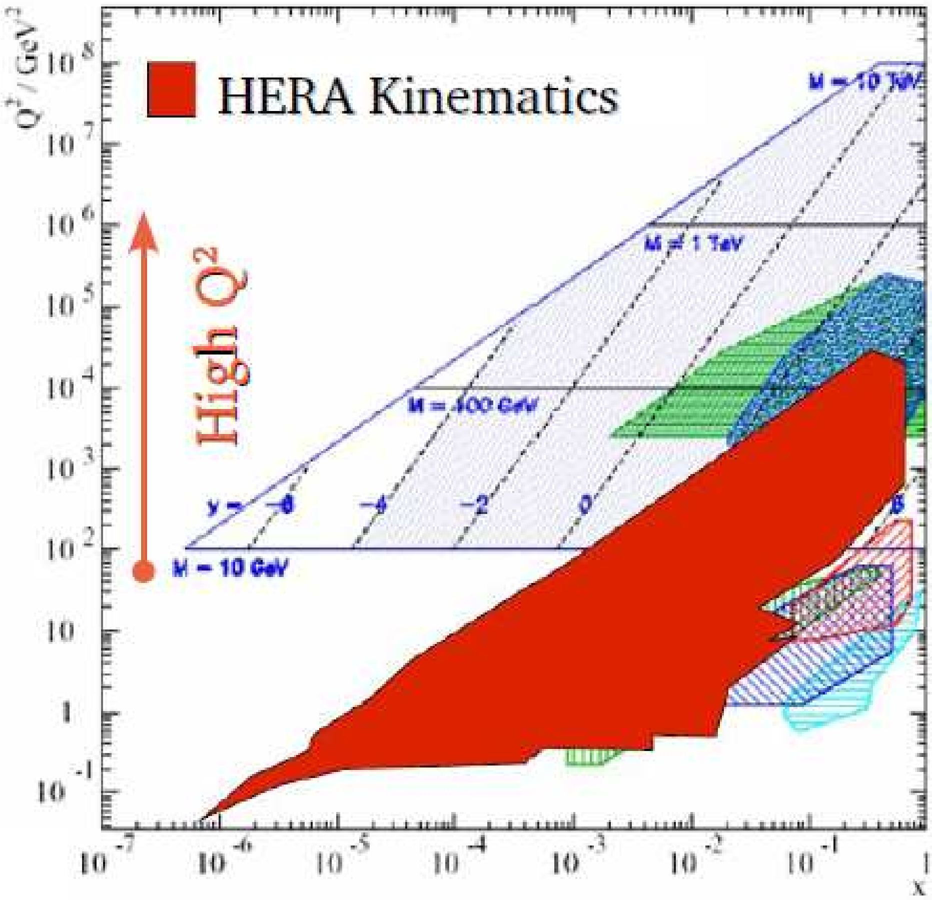
Deep-Inelastic Scattering at HERA

Neutral Current DIS: ep $\to$ e′X



Charged Current DIS: ep $\to \nu$X





Kinematics: (Momentum transfer)^2: $Q^2 = -q^2$

Bjorken x: $x = Q^2/(2p \cdot q)$

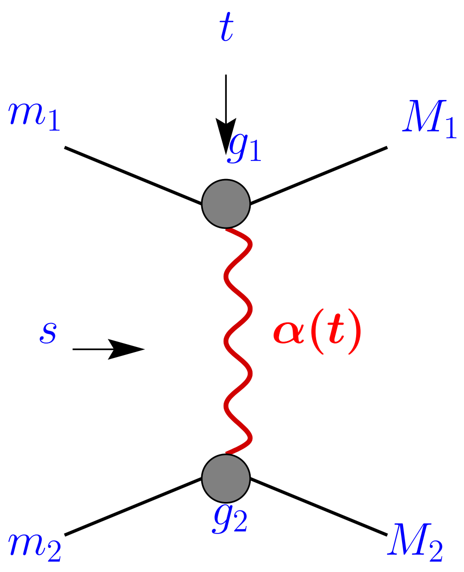
Inelasticity: $y = (p \cdot q)/(p \cdot l)$

(Total hadronic energy)^2: $W^2 = (p+q)^2$

$W^2 \simeq Q^2/x$

Two approaches to Strong Interactions

1. Regge Pole Model ⇒ RFT



$$A(s,t) =$$

$$g_1(m_1,M_1,t)g_2(m_2,M_2,t)\frac{s^{\alpha(t)}\pm(-s)^{\alpha(t)}}{\sin(\pi\alpha(t))}$$

hadronic language

2. Quark-Parton Model ⇒ QCD

$$\sigma_{ab} =$$

$$\int f_{i/a}(x_i,\mu^2)\cdot f_{j/b}(x_j,\mu^2)\cdot\hat{\sigma}_{ij}(x_i,x_j,\mu^2)$$

sub-hadronic language

Ultimate goal: derive (1) from (2)

RFT: soft hh scattering vs QCD: deep inelastic ep scattering

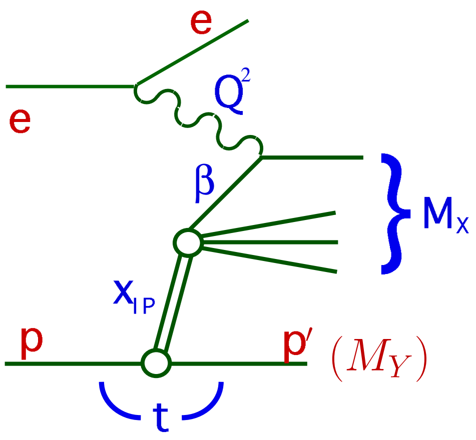
• Hadronic degrees of freedom	• Partonic degrees of freedom
• Validity: large $s \gg t$	• Low x: $W^2 \gg Q^2, t \ (Q^2/W^2 \simeq x \ll 1)$
• $\mathbb{P}$ dominates: $\alpha_{\mathbb{P}}(0) > \alpha_{\mathbb{R}}(0)$ $\longrightarrow \sigma_{\text{tot}} \propto s^{\alpha_{\mathbb{P}}(0)-1}$	• gluons dominate: $xg(x) \gg xq_{val}(x)$ $F_2(x, Q^2) \propto xg(x) \sim x^{-\lambda}$
• Unitarity corrections unavoidable $(\sigma_{\text{tot}} \leq \ln^2(s/s_0)$ at $s \to \infty)$	• Saturation of the $xg(x)$ (non-linear effects, shadowing, ...)
• When? $s_{sat} = ?$	• $x_{sat}(Q_{sat}) = ?$
• First to be seen in diffraction: $\sigma_D \propto s^{2(\alpha-1)}$	• First to be seen in diffraction: $\sigma_D \propto \lvert xg(x)\rvert^2$

$\Rightarrow$ Diffraction $\equiv$ Physics of the Pomeron, the essence of strong interactions	$\Rightarrow$ Diffraction $\equiv$ Gluodynamics, the essence of QCD

(in high energy limit)

Diffraction at HERA

- Fundamental aim: understand high energy limit of QCD (gluodynamics; CGC ?)
- Novelty: for the first time probe partonic structure of diffractive exchange
- Practical motivations: study factorisation properties of diffraction; try to transport to hh scattering (e.g. predict diffractive Higgs production at LHC)



$$x_{I\!P} = \xi = \frac{Q^2+M_X^2}{Q^2+W^2}$$

(momentum fraction of colour singlet exchange)

$$\beta = \frac{Q^2}{Q^2+M_X^2} = x_{q/I\!P} = \frac{x}{x_{I\!P}}$$

(fraction of exchange momentum, coupling to γ^*)

$$t = (p-p')^2$$

(4-momentum transfer squared)

Experimental methods:

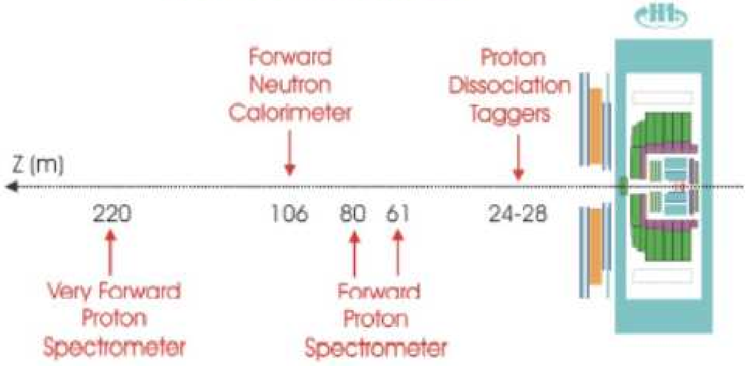
1) selecting LRG events

2) detecting p in Roman Pots
($60 - 220$ m from IP)

Selection of Diffractive Events

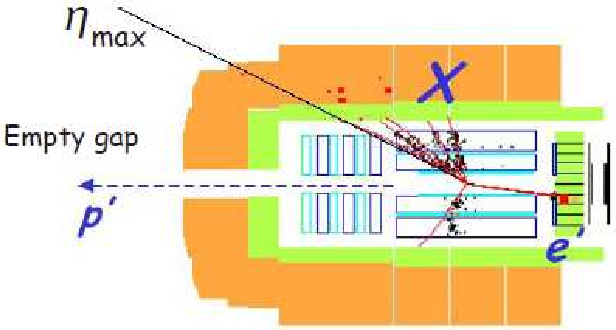
Measure the leading proton

→ Forward spectrometers
(H1 FPS/VFPS)



- x_{IP} and t measurements
- Less statistics
- p-tagging systematics

Measure a Large Rapidity Gap



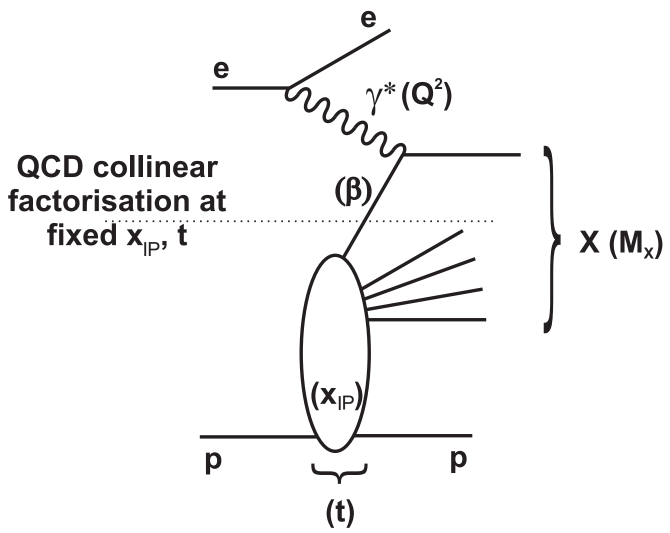
- Data integrated over |t| < 1 GeV^2
- High statistics
- Contamination from proton dissociation events

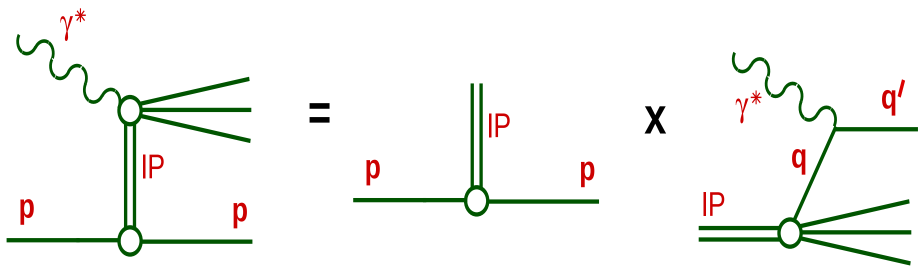
→ Needs to be controlled

↘ Different systematics

↘ Different kinematic coverage

Factorisation properties in diffraction





QCD versus Regge factorisation

QCD factorisation

(rigorously proven for DDIS by Collins et al.):

$$\sigma_r^{D(4)} \propto \sum_i \hat{\sigma}^{\gamma^* i}(x, Q^2) \otimes f_i^D(x, Q^2; x_{I\!P}, t)$$

- $\hat{\sigma}^{\gamma^* i}$ – hard scattering part, same as in inclusive DIS
- f_i^D – diffractive PDF's, valid at fixed $x_{I\!P}, t$ which obey (NLO) DGLAP

Regge factorisation

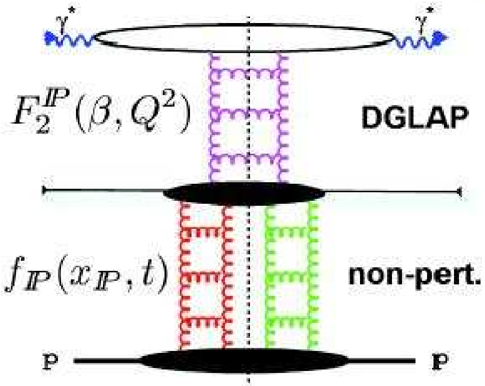
(conjecture, e.g. RPM by Ingelman,Schlein):

$$F_2^{D(4)}(x_{I\!P}, t, \beta, Q^2) = \Phi(x_{I\!P}, t) \cdot F_2^{I\!P}(\beta, Q^2)$$

- In this case shape of diffractive PDF's is independent of $x_{I\!P}, t$ while normalization is controlled by Regge flux $\Phi(x_{I\!P}, t)$

QCD based approaches to DDIS: Partons vs Dipoles

- Infinite momentum frame: partons



- Factorization is assumed.

$$F_2^D = f_{I\!P}(x_{I\!P},t)\,F_2^{I\!P}(\beta,Q^2)$$

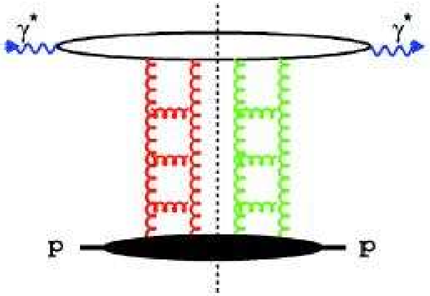
$$f_{I\!P} = \frac{e^{bt}}{x_{I\!P}^{2\alpha_{I\!P}-1}}$$

- Diffractive parton densities can be derived.

Resolved Pomeron model

(Ingelman, Schlein - 1985)

- Proton rest frame: dipoles

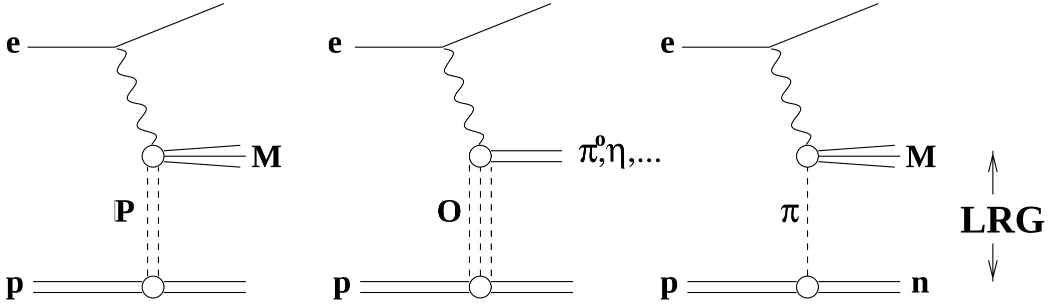


- Long-living quark pair interacts with the gluons from the proton.

$$d\sigma^{\gamma^* p}_{diff}/dt \propto \int dz\,dr^2\,\Psi^*\sigma^2_{qq}(x,r^2,t)\Psi$$

- Direct relation to inclusive DIS.
- Incorporates saturation dynamics.
- No extra parameters for diffraction are needed.

Selected Results



- Inclusive diffraction and DPDF: Pomeron under the microscope

- Diffractive dijets and QCD factorisation tests

- Vector Mesons and DVCS: soft vs hard Pomeron

- Leading neutrons and $\gamma\pi^+$ cross sections
  - ▷ forward neutrons and photons and CR models
  - ▷ inclusive neutrons in DIS and pion structure function
  - ▷ exclusive ρ^0 with forward neutron in PHP

- Summary and open questions

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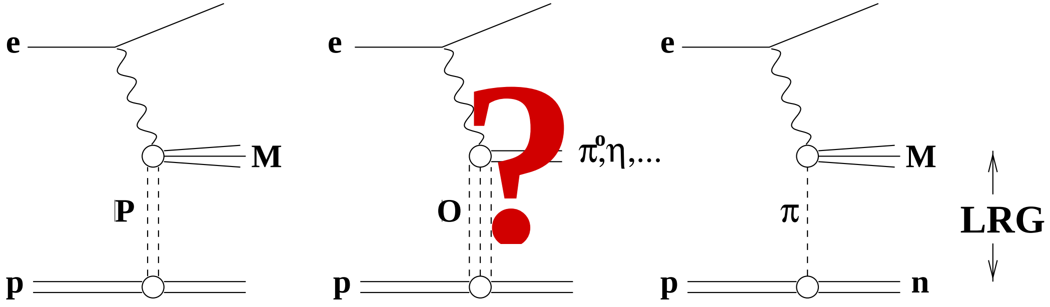

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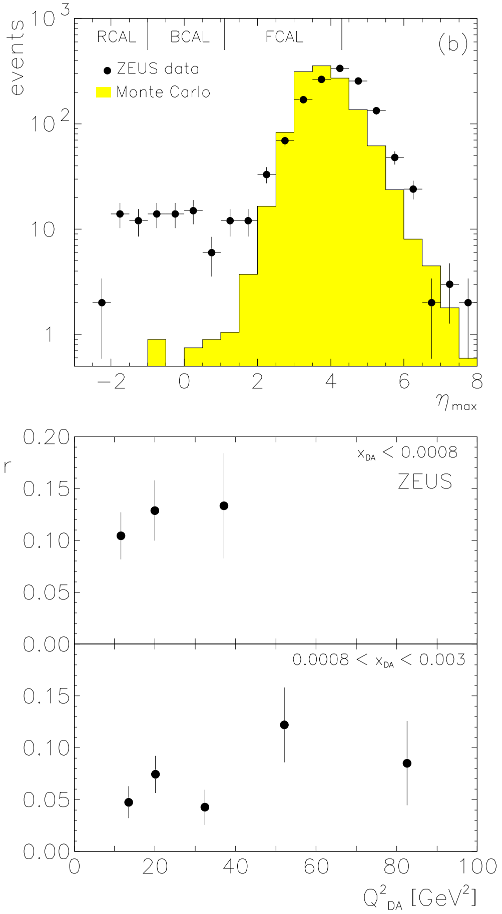
Inclusive diffraction in DIS

20 years of Diffraction in DIS

ZEUS-1993



First observation

of diffraction in DIS

1992 data, 24.7 nb^{-1}

20 years of Diffraction in DIS

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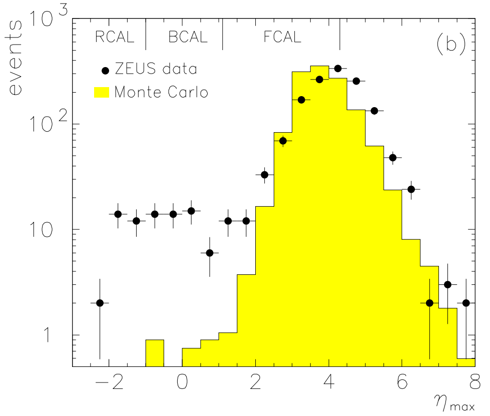
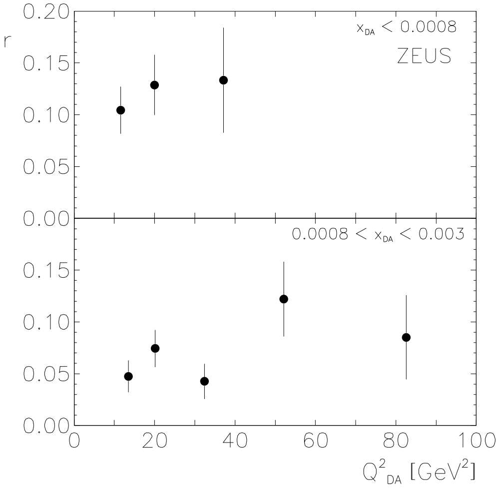
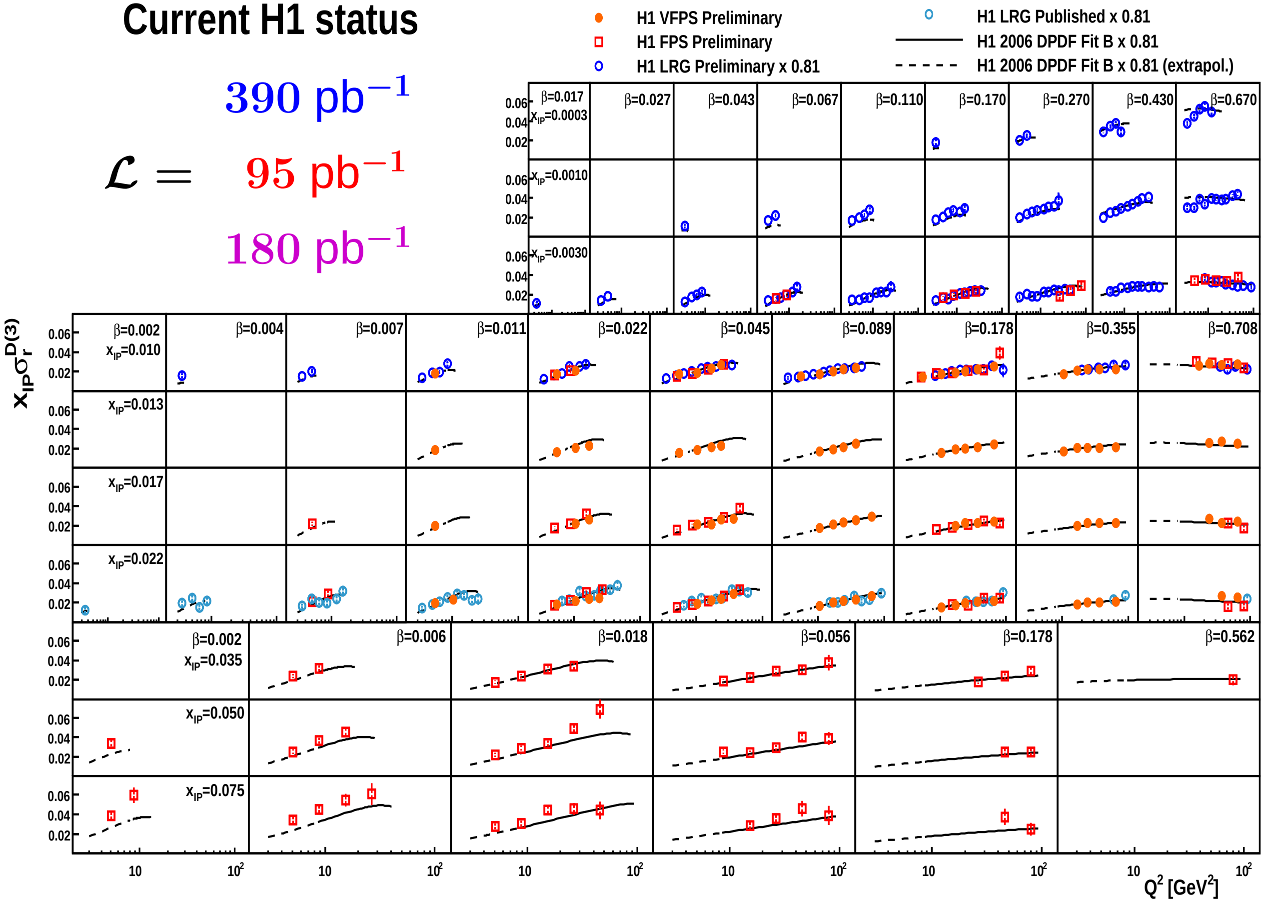




First observation
of diffraction in DIS
1992 data, 24.7 nb^{-1}

Current H1 status

$\mathcal{L} =$ 390 pb^{-1}
95 pb^{-1}
180 pb^{-1}



LRG

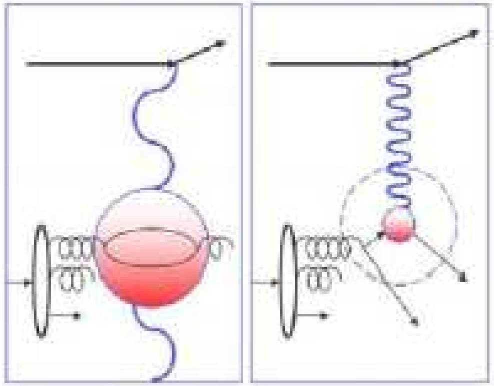
VFPS

FPS

- Compelling confirmation of the NLO QCD picture of diffraction over a wide kinematic range. Clear candidate for the textbook!
- Positive scaling violation up to large $\beta \Rightarrow$ gluon dominated $I\!P$

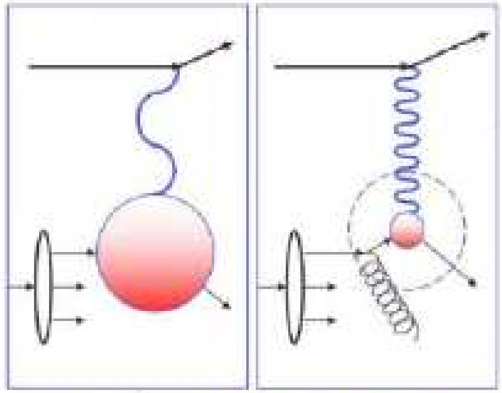
Compare to scaling violation in Inclusive NC DIS

Small x: Gluons, sea quarks

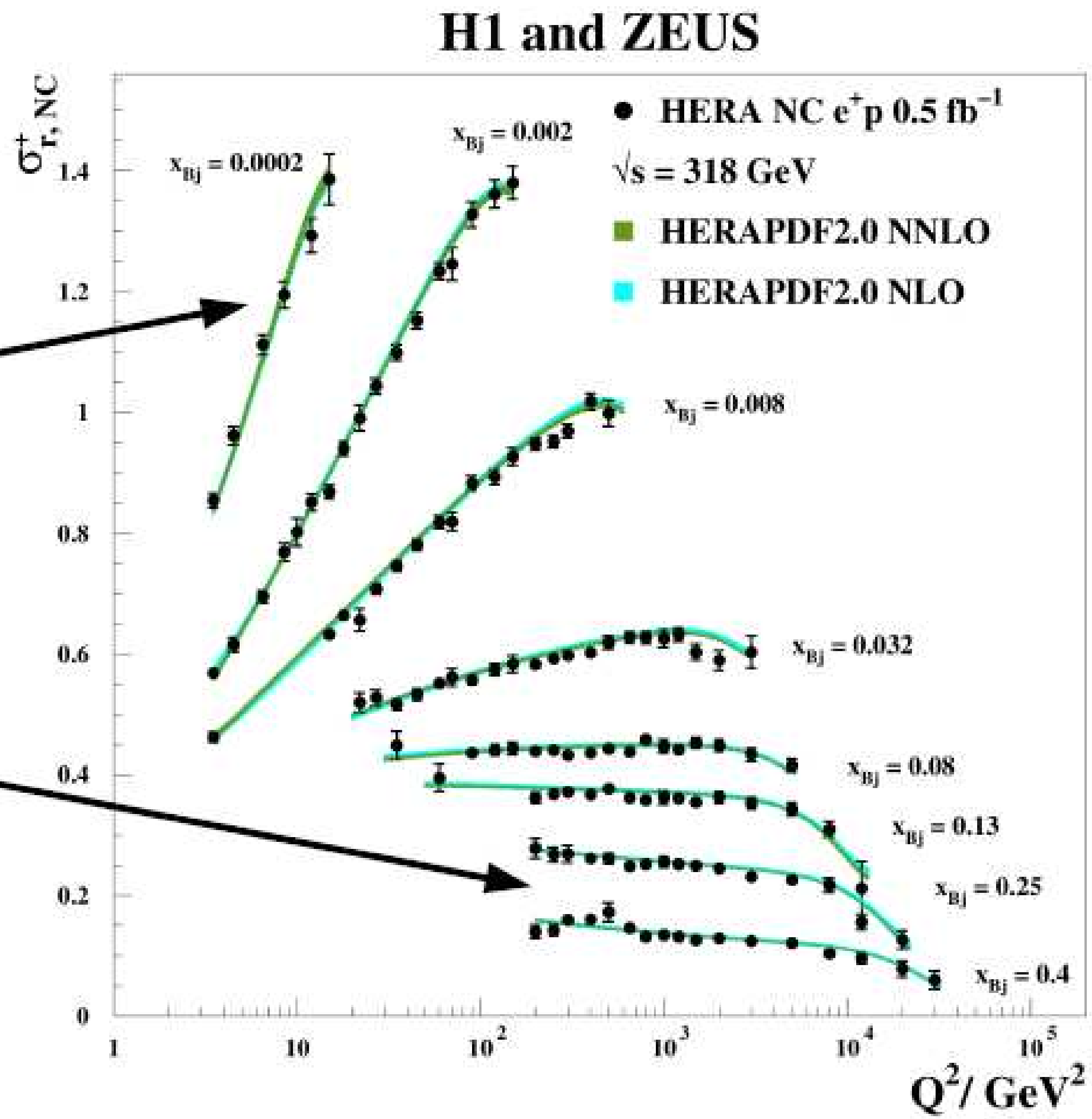


Q² ↑ ⇒ F_2 ↑ for fixed x

Large x: valence quarks

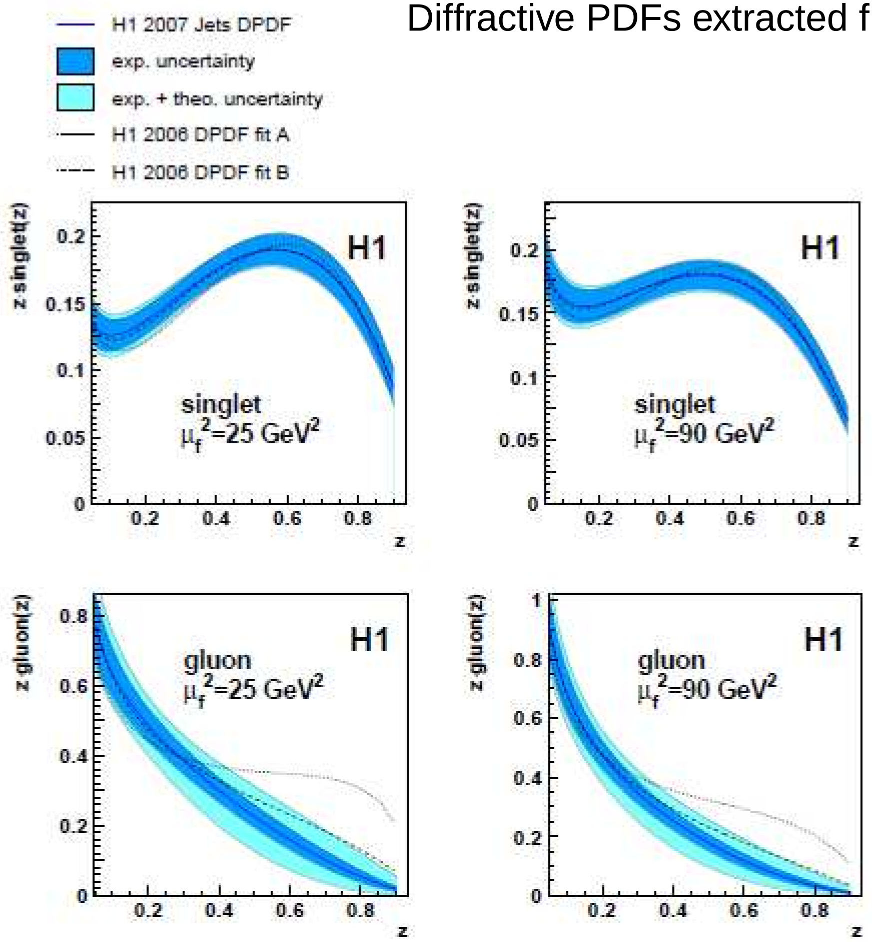


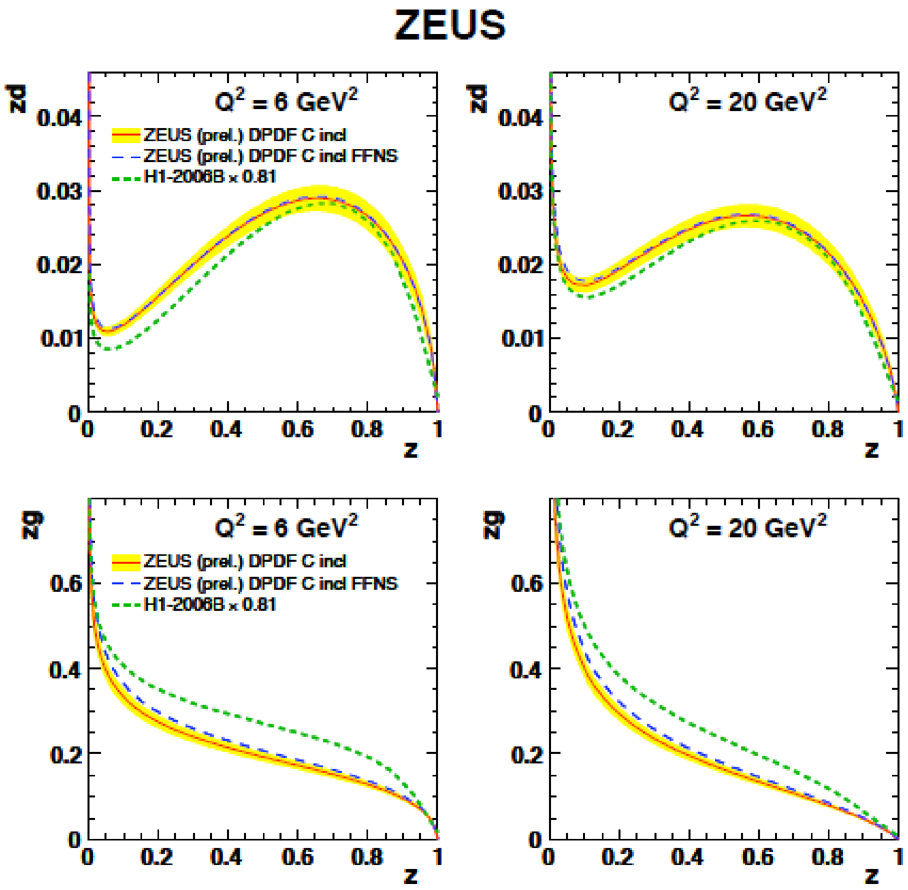
Q² ↑ ⇒ F_2 ↓ for fixed x



Diffractive PDFs as determined by H1 and ZEUS

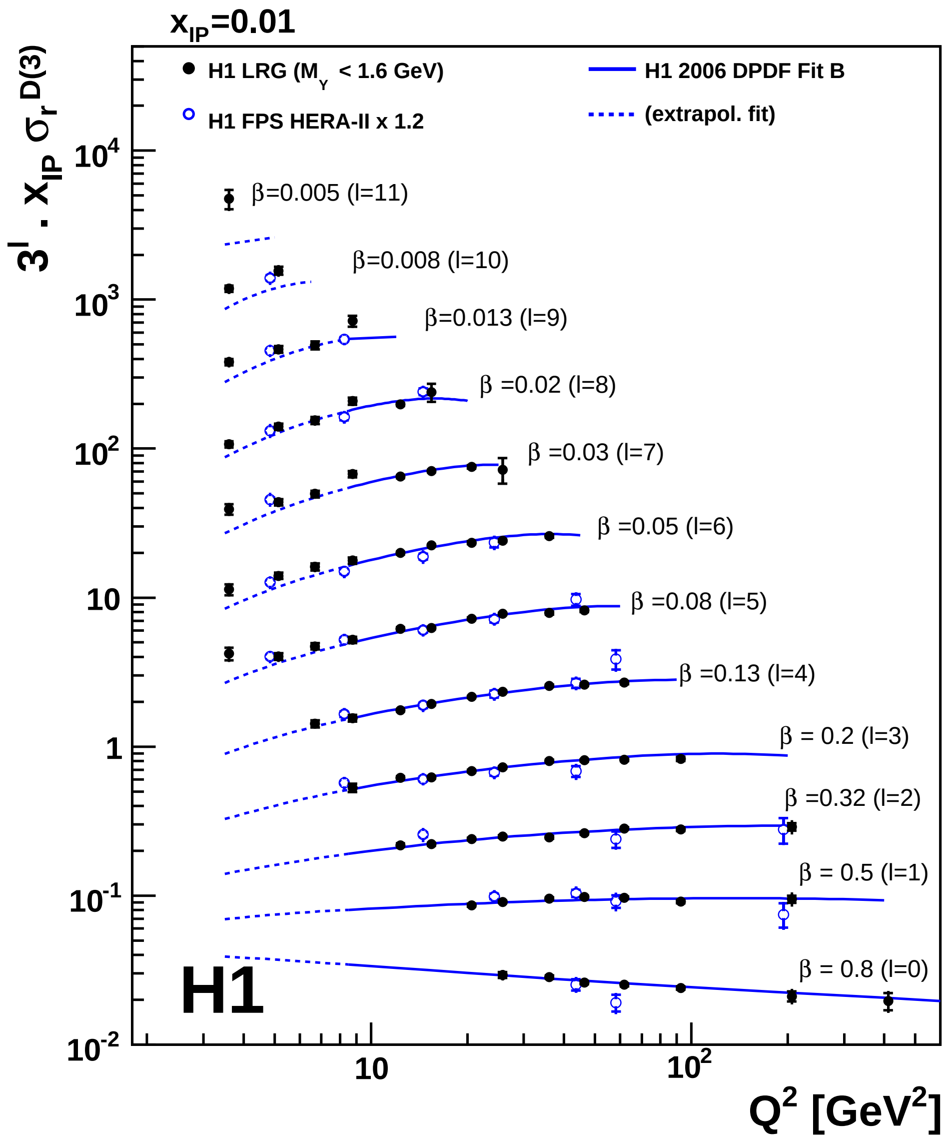
Diffractive PDFs extracted from NLO DGLAP fit, using Regge factorisation





- DPDFs are consistent in shape, $\sim 10\%$ difference in normalisation
- Jets help to constrain high z gluons
- Gluons carry $\sim (70-75)\%$ of the Pomeron momentum

Inclusive DDIS: LRG vs p-tagged methods



Compare LRG and FPS cross sections

Ratio LRG/FPS:

$$\frac{\sigma(M_Y<1.6\text{GeV})}{\sigma(Y=p)} =$$

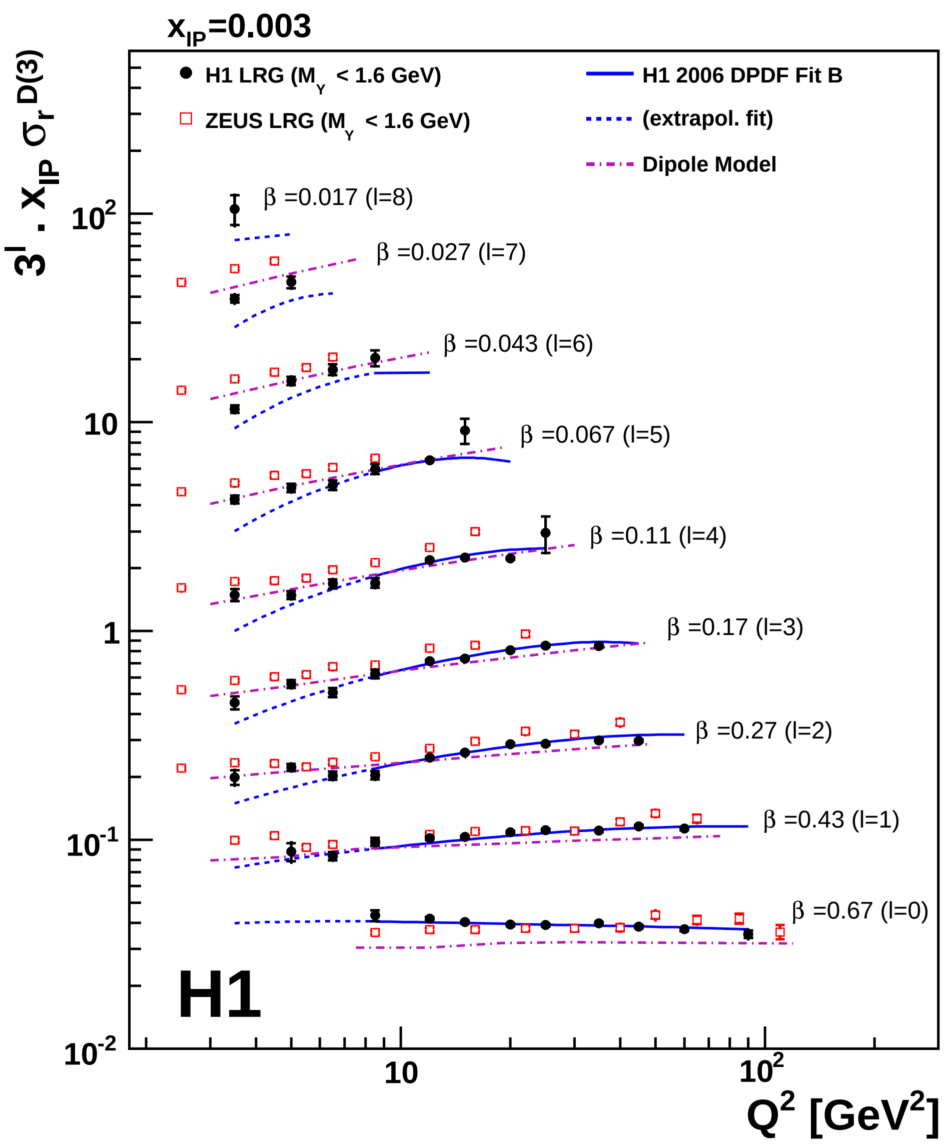
$$1.203 \pm 0.019(exp) \pm 0.087(norm)$$

$$(1.6\%) \qquad (7.2\%)$$

- Experimental control on the amount of proton dissociation in LRG data

- No Q^2 or β dependent differences observed

Inclusive DDIS: Confronting Data and Models



Compare H1 and ZEUS LRG data to H1 DPDF Fit B and Dipole model

Normalisation difference of $\sim 10\%$ between **H1** and **ZEUS** – within norm. uncertainties of each experiment

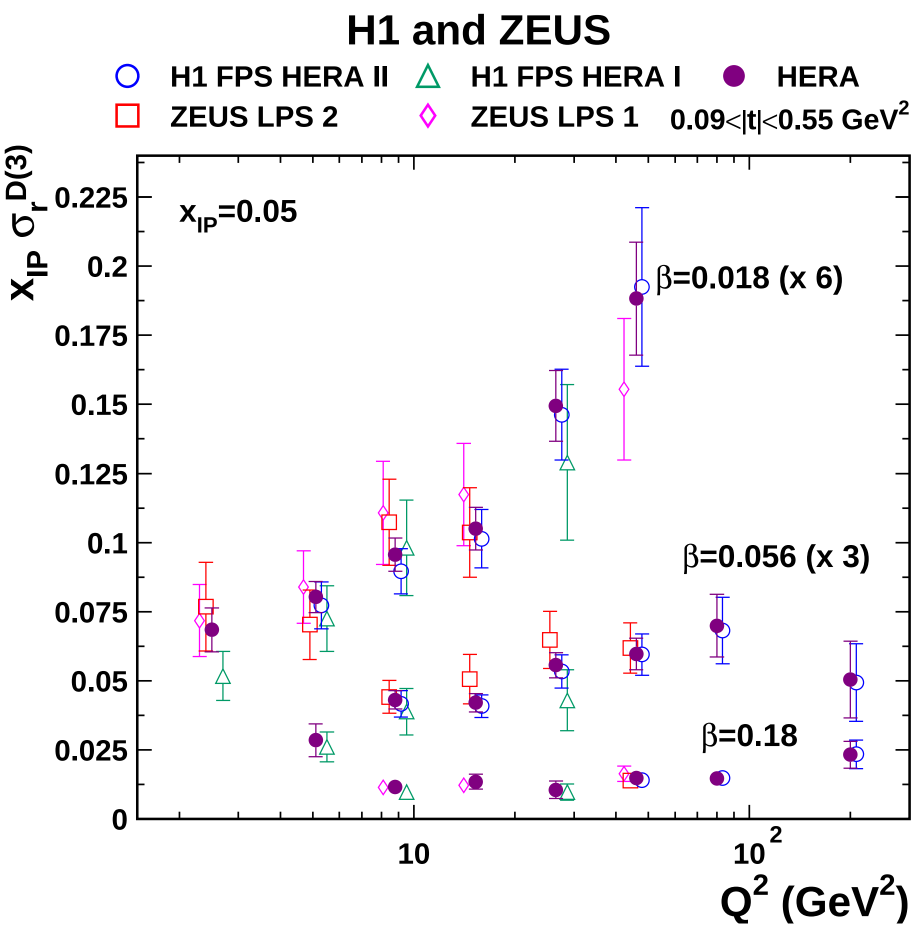
Dipole model describes better low Q^2 trend

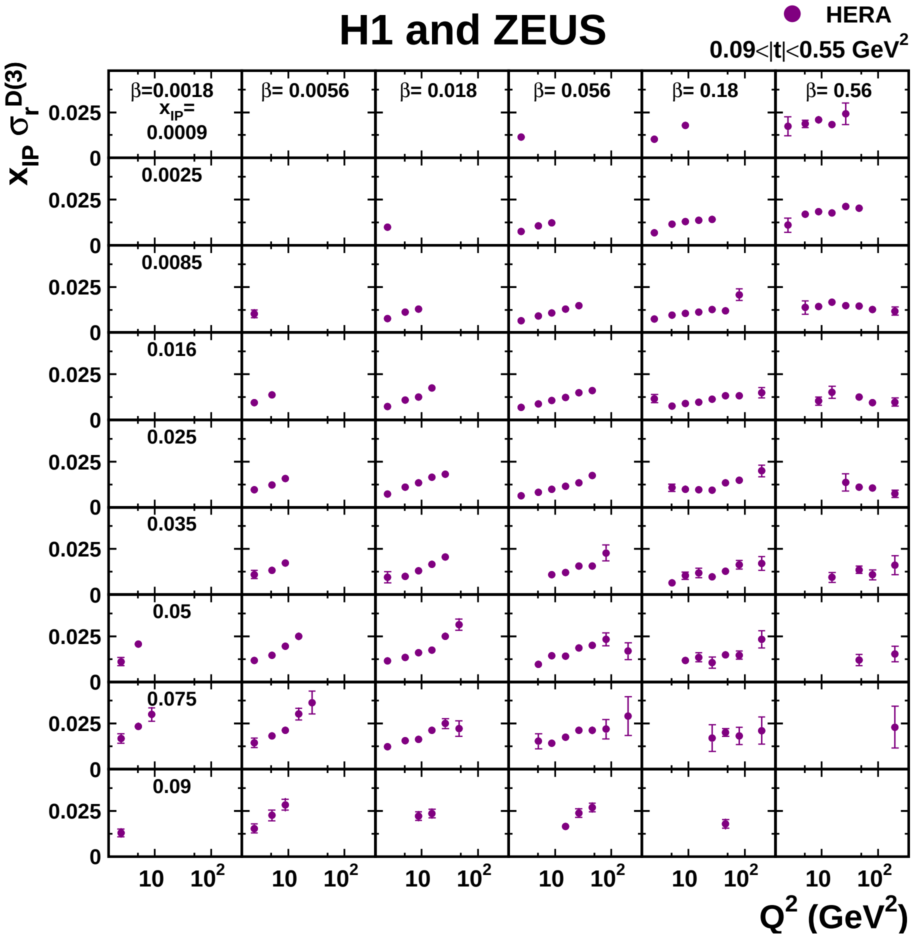
DPDF is better at higher Q^2

Final precise data challenge models

First H1 + ZEUS combination in diffraction

Eur. Phys. J. C72 (2012) 2175



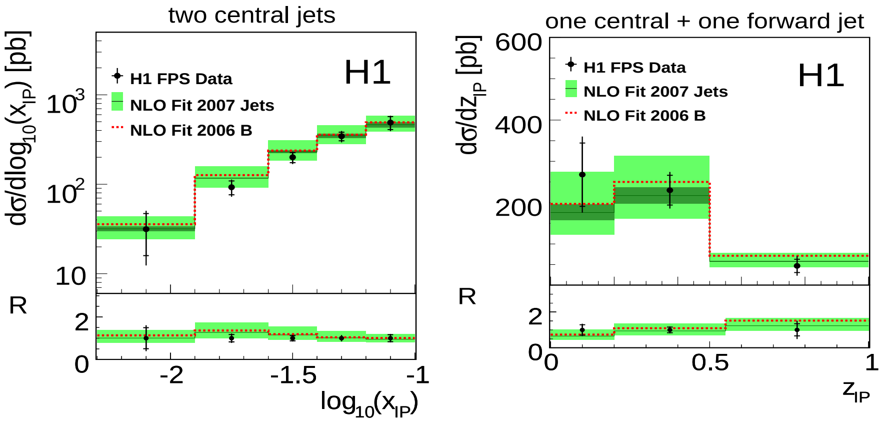


➡ To do: final QCD analysis of all H1 + ZEUS data (LRG and p-tagged) ⇒ DPDF

Diffractive dijets

QCD Factorisation Tests in Diffraction at HERA

QCD Factorisation holds in DIS regime *(EPJ, C72, 2012)*



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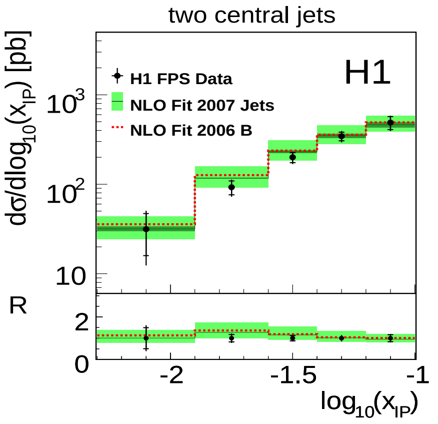
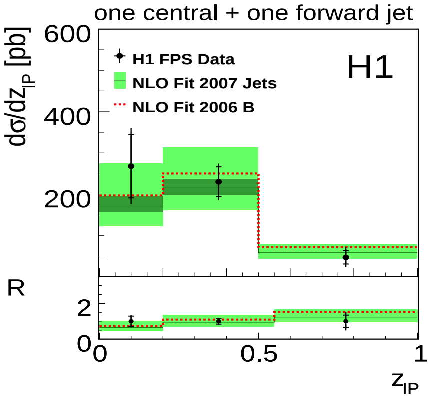
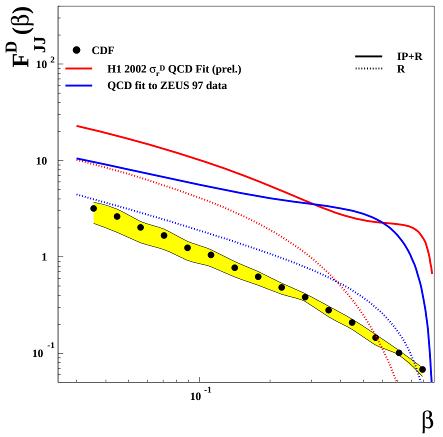
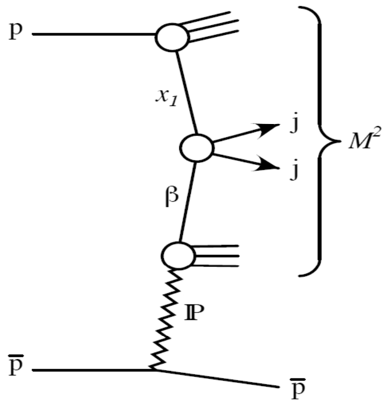




However, it breaks down at Tevatron ...

Tevatron vs HERA





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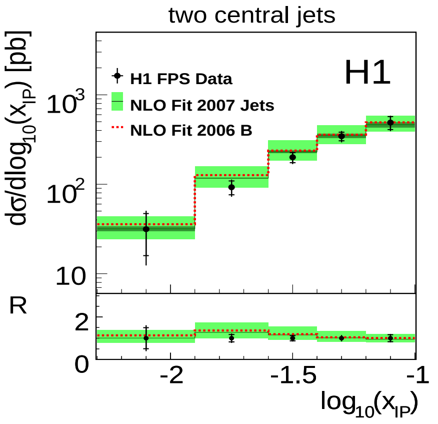
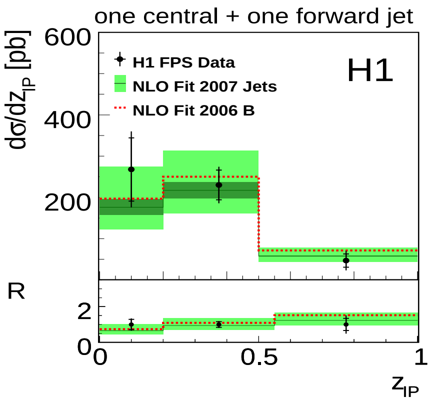
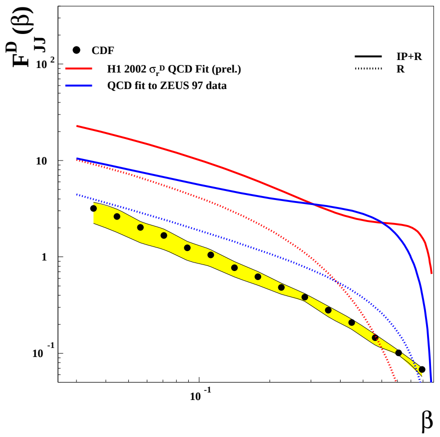


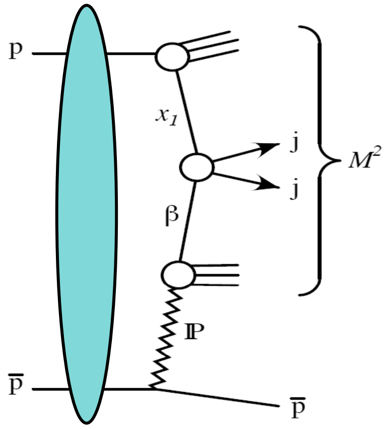


However, it breaks down at Tevatron ...

...due to soft remnant rescattering ($S \sim 0.15$)

Tevatron vs HERA





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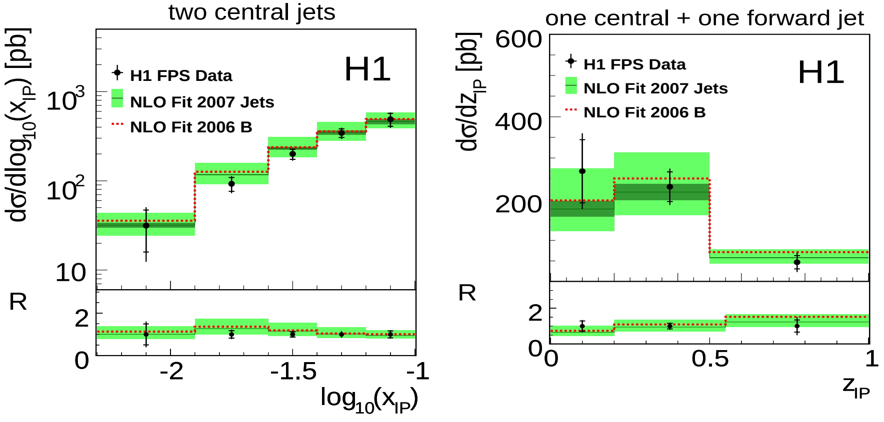
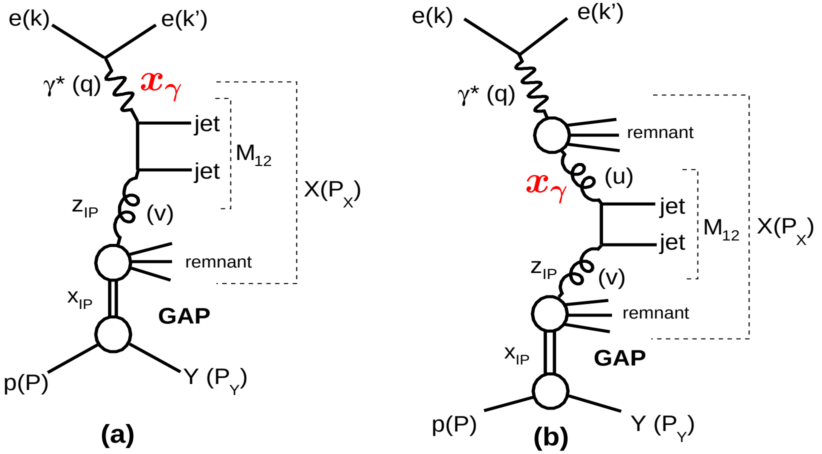


⇒ Test it in photoproduction:



(a) direct, $x_\gamma = 1$ (DIS-like)

(b) resolved, $x_\gamma < 1$ (hadron-like)

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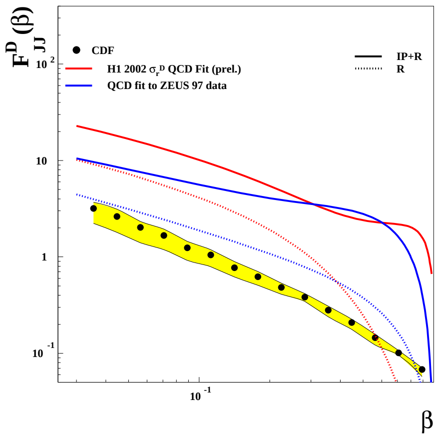
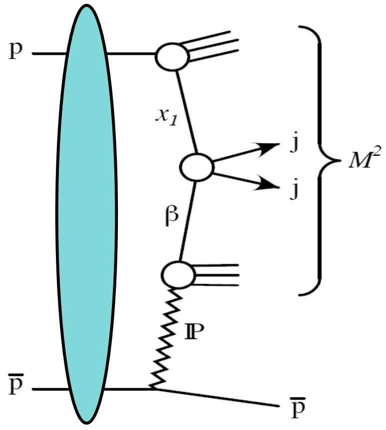
Tevatron vs HERA





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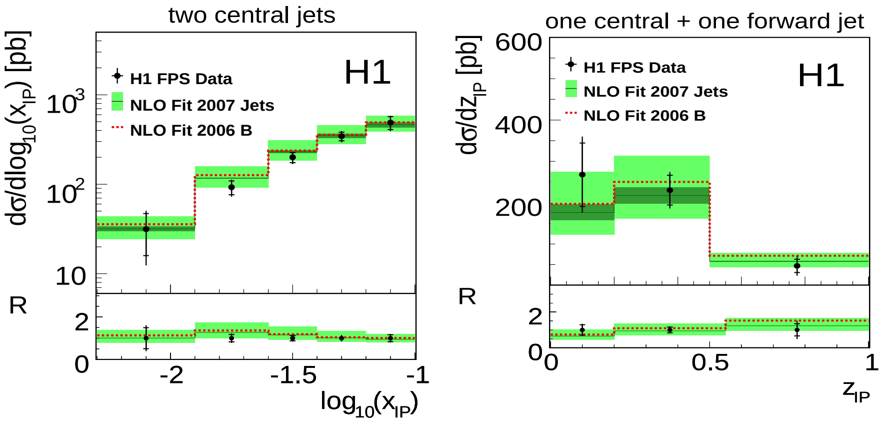

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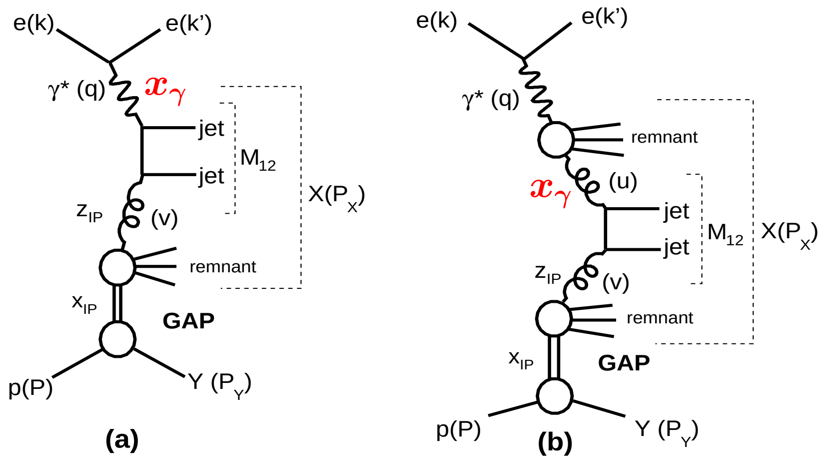

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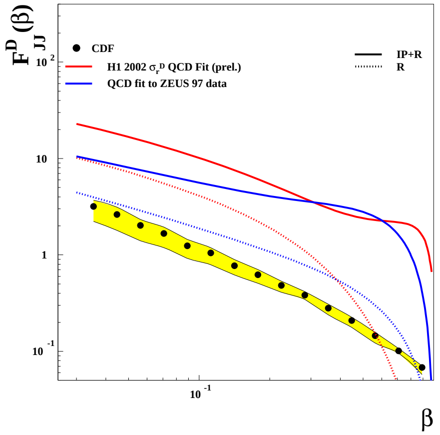
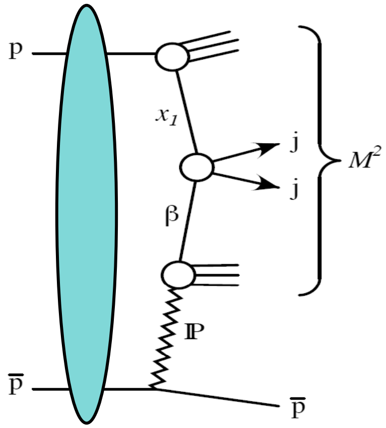
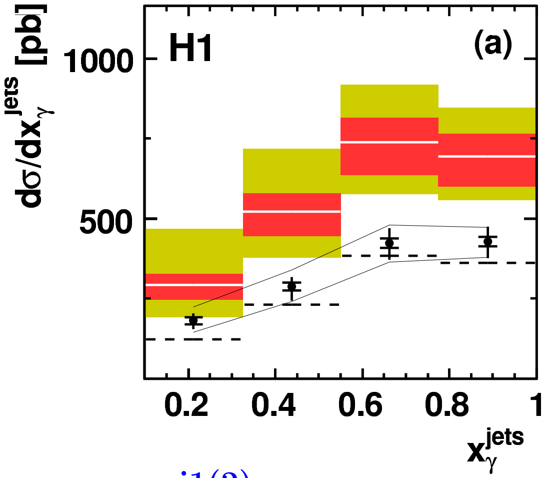
However, it breaks down at Tevatron ...

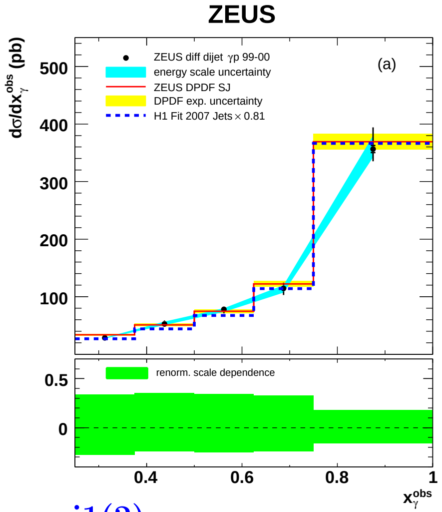
...due to soft remnant rescattering ($S \sim 0.15$)

Tevatron vs HERA





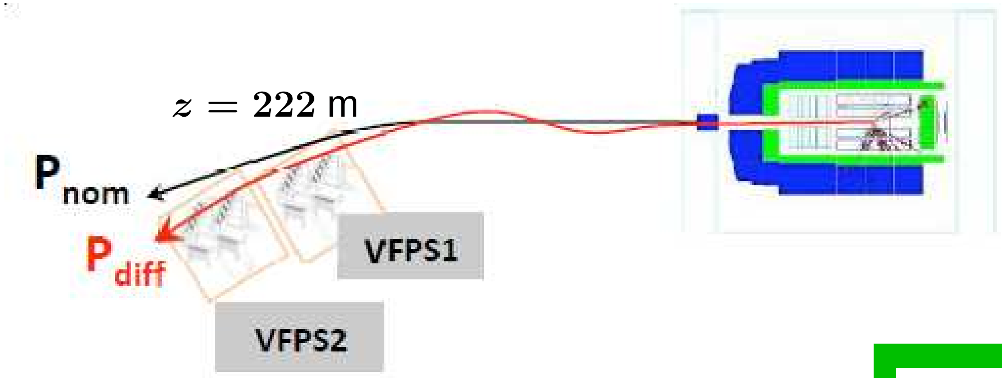




$E_T^{j1(2)} > 5(4)$ GeV $E_T^{j1(2)} > 7.5(6.5)$ GeV

$\boxed{S \approx 0.6}$ $\boxed{S \approx 1.0}$

New analysis: VFPS Dijets in DIS and PHP



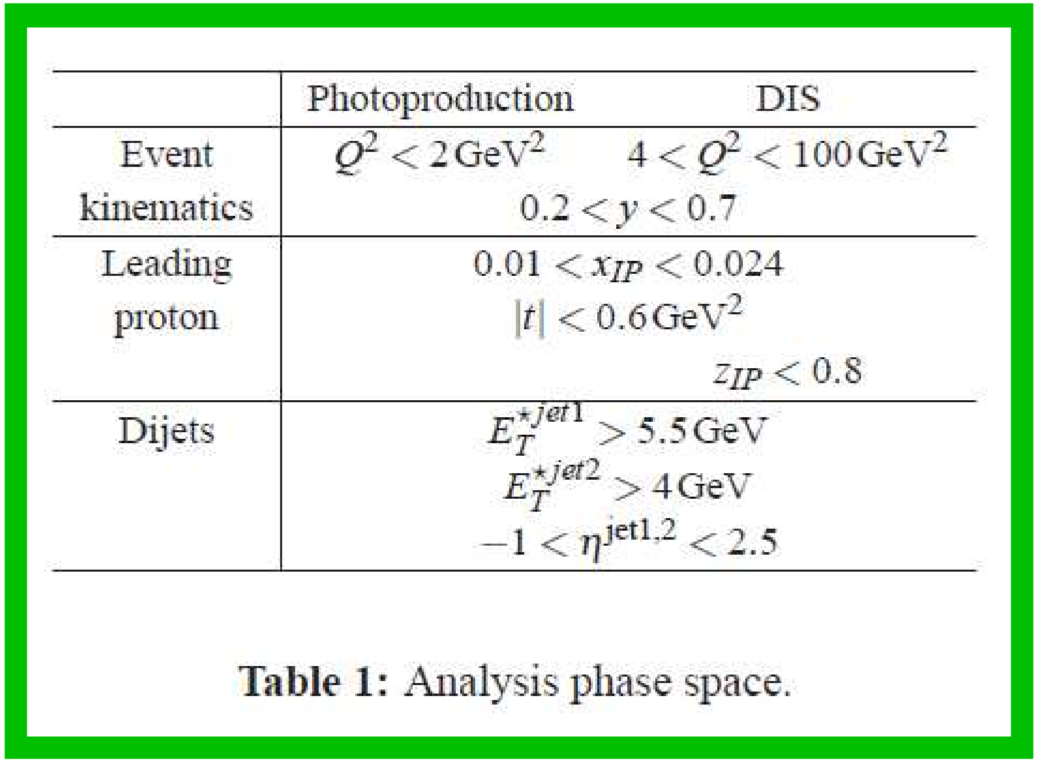
- 2006/07 e^+p data, $\mathcal{L} \approx 30(50)$ pb^{-1}
- Leading proton measured by VFPS
- Untagged photoproduction
  (e^+ escapes in the beampipe)

Statistics: 3800 dijet events in PHP
550 dijet events in DIS

Data unfolded to the level of stable hadrons using *TUnfold* program

Results are compared to NLO QCD

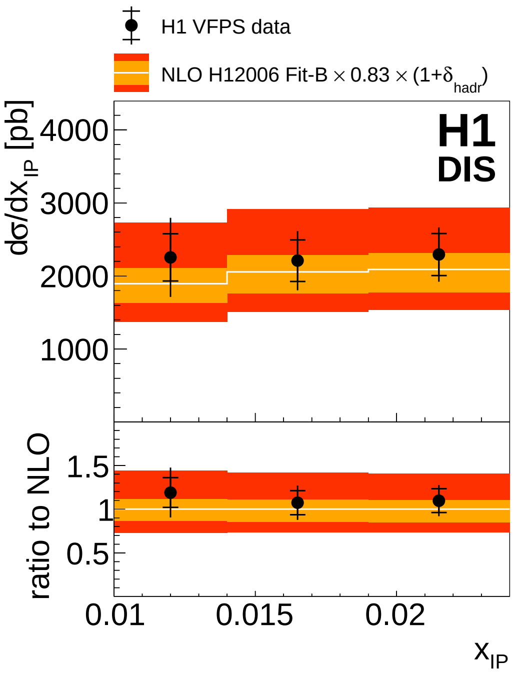
- Scales: $\mu_r^2 = \mu_f^2 = \langle E_{T,\mathrm{jet}}^2 \rangle + Q^2$
- DPDF H1 2006 Fit B and GRV-HO γ-PDF used
- Different scale choices and γ-PDF studied

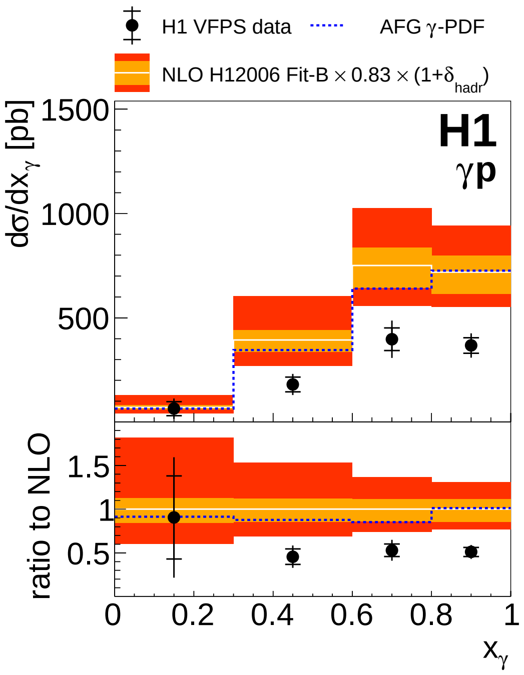


	Photoproduction	DIS
Event kinematics	$Q^2 < 2\,\mathrm{GeV}^2$	$4 < Q^2 < 100\,\mathrm{GeV}^2$
	$0.2 < y < 0.7$	
Leading proton	$0.01 < x_{IP} < 0.024$	
	$\lvert t \rvert < 0.6\,\mathrm{GeV}^2$	
		$z_{IP} < 0.8$
Dijets	$E_T^{*jet1} > 5.5\,\mathrm{GeV}$	
	$E_T^{*jet2} > 4\,\mathrm{GeV}$	
	$-1 < \eta^{\mathrm{jet1,2}} < 2.5$	

Table 1: Analysis phase space.

VFPS Dijets: Data vs NLO QCD



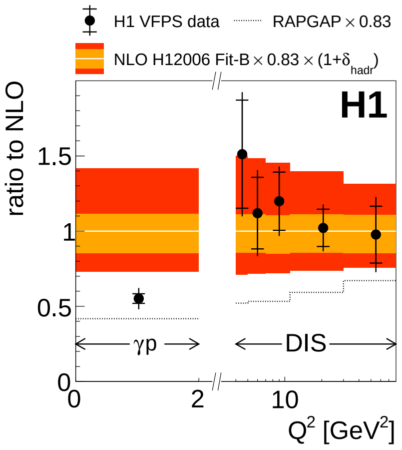


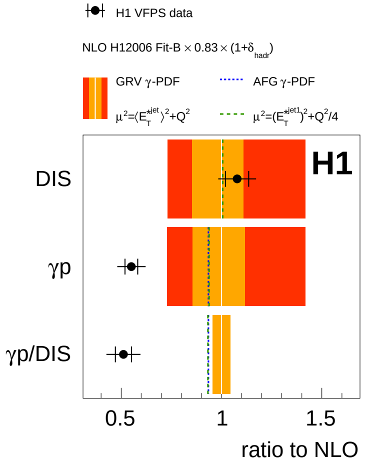
- DIS dijets in agreement with QCD factorisation

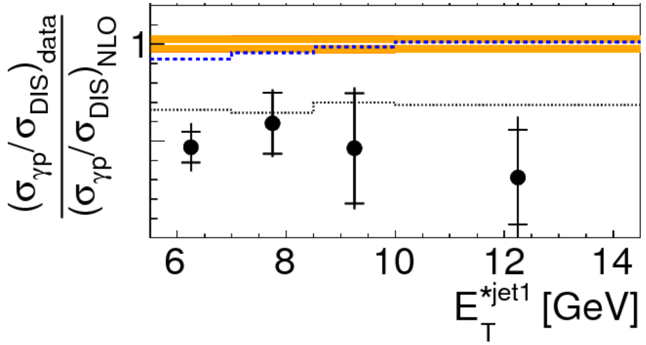
- Factorisation is broken in PHP
$\langle S^2 \rangle = 0.51 \pm 0.09$

- This is not related to p diss.
(p tagged in VFPS)

- Independence on x_γ confirmed
No jet E_T dependence observed



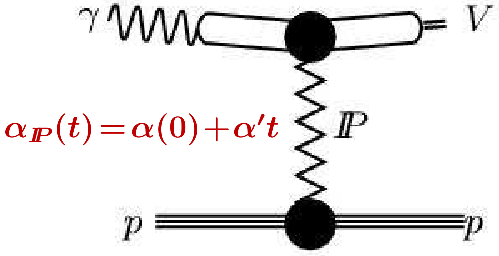




Vector Mesons and DVCS

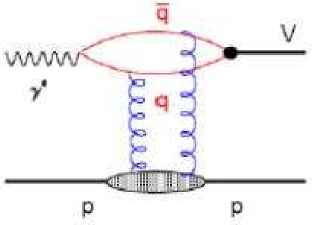
Vector Mesons at HERA

soft $I\!\!P$omeron exchange

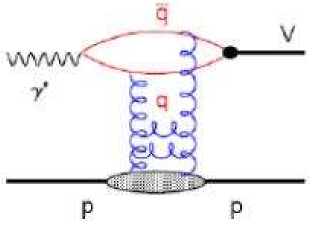


$\alpha_{I\!\!P}(t) = \alpha(0) + \alpha' t$

hard $I\!\!P$omeron diagrams



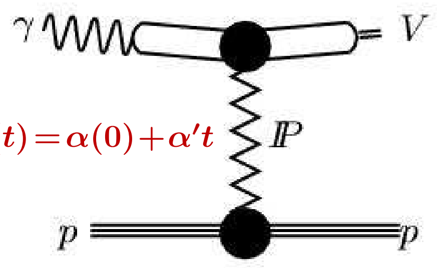
LO 2 gluons



LL1/x ladder

Vector Mesons at HERA

soft $I\!\!P$omeron exchange



$\alpha_{I\!\!P}(t) = \alpha(0) + \alpha' t$

$\sigma \propto W_{\gamma p}^{4(\alpha_{I\!\!P}-1)}$

Hard scales: Q^2, M_V, t

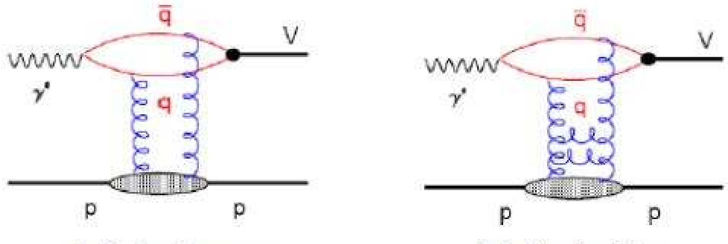
Predictions

$\alpha_{I\!\!P}(0) \simeq 1.08$ / 1.20

$\alpha'_{I\!\!P} \simeq 0.25$ / 0.0

Universal scale $\mu^2 = (Q^2 + M_V^2)/4$

hard $I\!\!P$omeron diagrams



LO 2 gluons

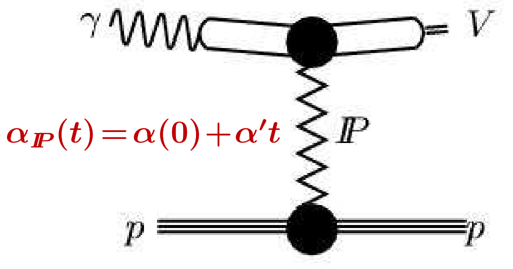
LL1/x ladder

$\sigma \propto [xg(x, Q^2)]^2$

Exclusive VM production at HERA – a nice tool to study ‘soft’ vs ‘hard’ Pomeron regimes

Vector Mesons at HERA

soft $I\!P$omeron exchange



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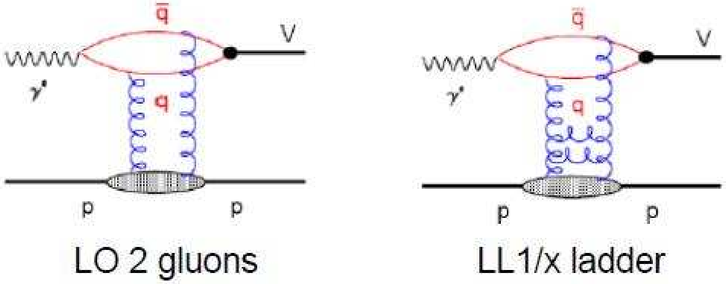

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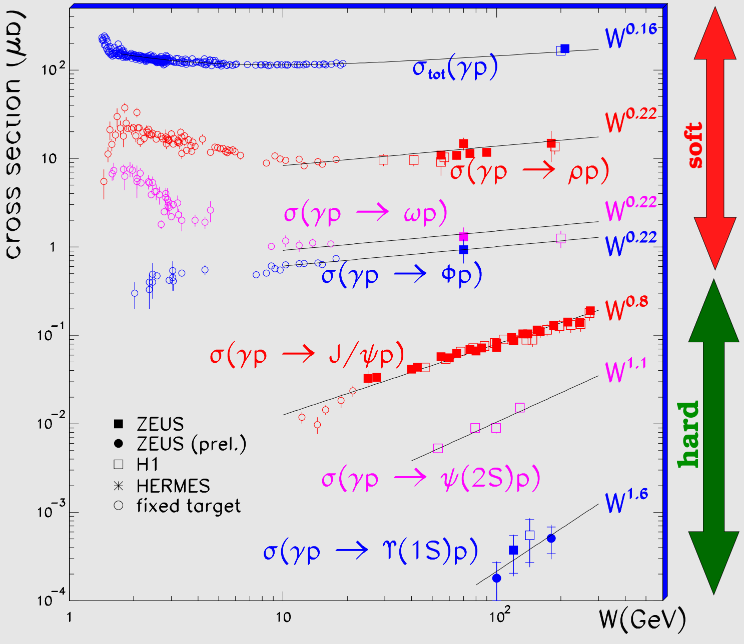
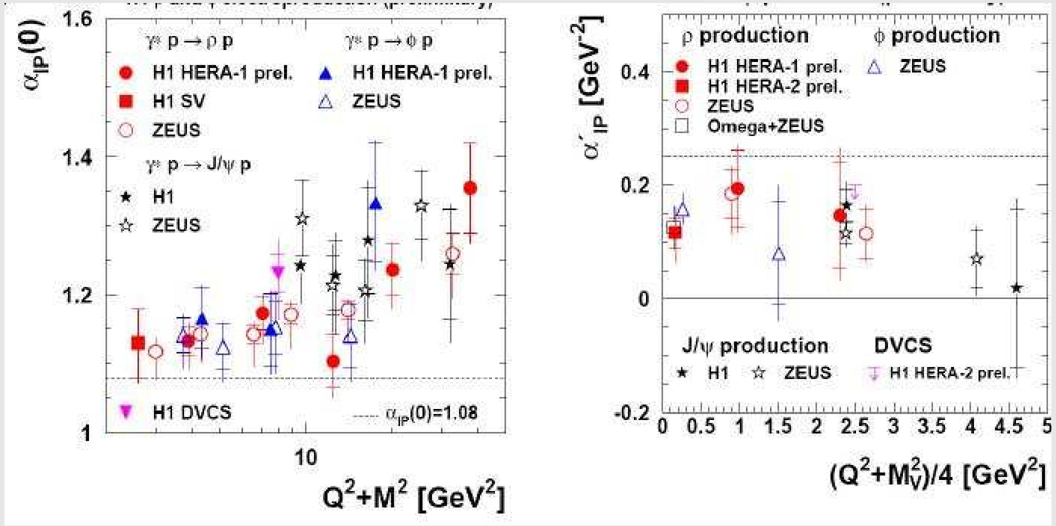
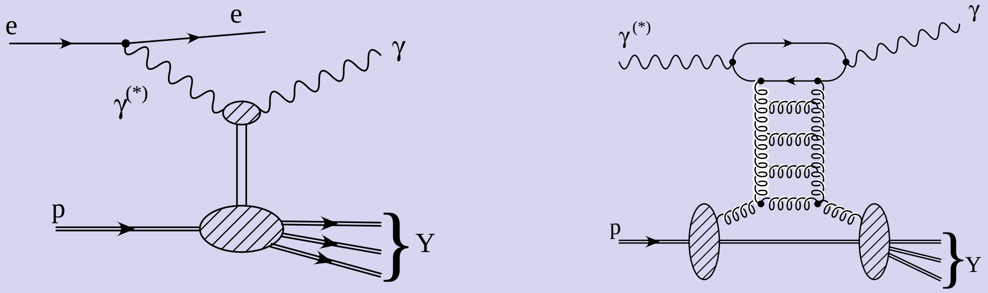
Exclusive VM production at HERA – a nice tool to study ‘soft’ vs ‘hard’ Pomeron regimes



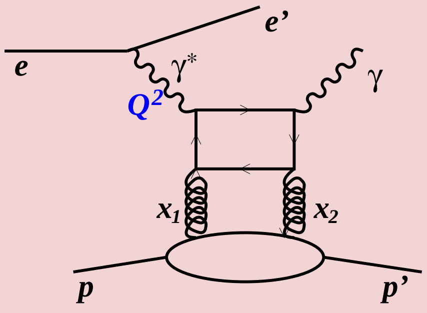
transition from soft to hard regime at $\mu^2 \simeq 4 \div 5$ GeV^2



Diffractive scattering of γ at large $|t|$ and DVCS

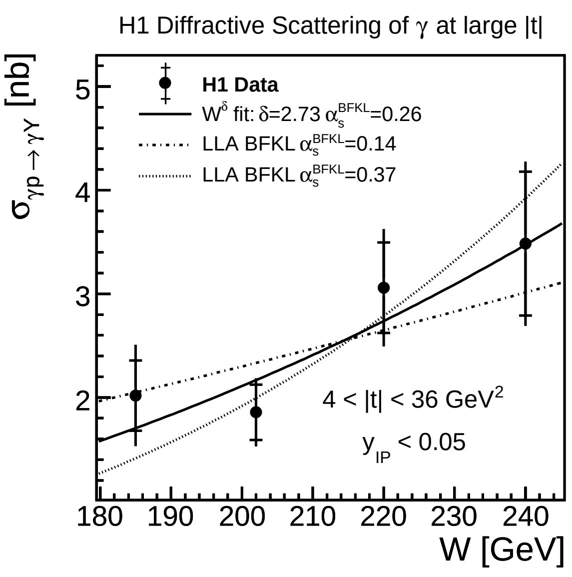


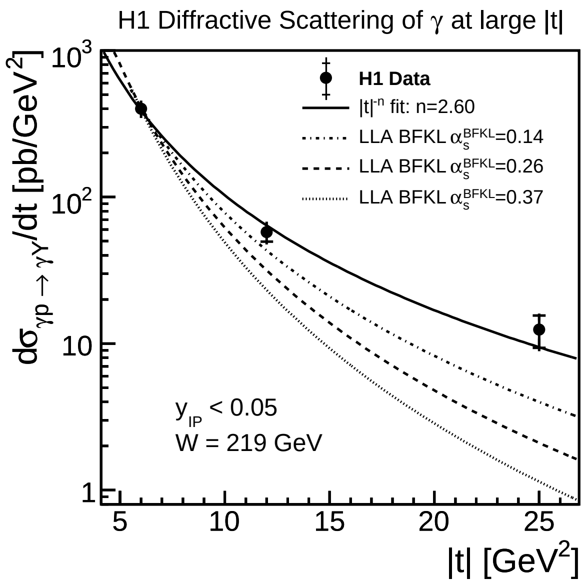
PHP ($Q^2 < 0.01$ GeV^2)



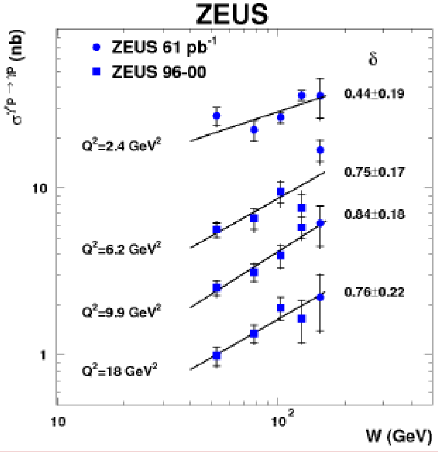
DIS ($Q^2 > 2$ GeV^2)

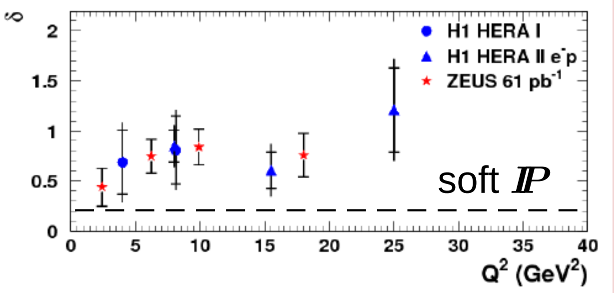
$$\sigma(W) \propto W^{4\omega_0} \qquad \omega_0 = 4N_c\frac{\alpha_s^{BFKL}}{\pi}\ln 2 \qquad \frac{d\sigma}{dt} \propto |t|^{-n}$$



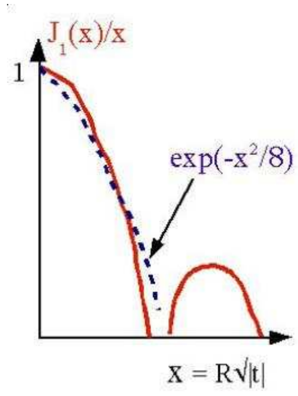


Hard Pomeron at work





Vector Mesons at HERA: $t-$dependence



$d\sigma/dt \sim e^{-b|t|}$ → diffractive peak (approximated from Bessel function)

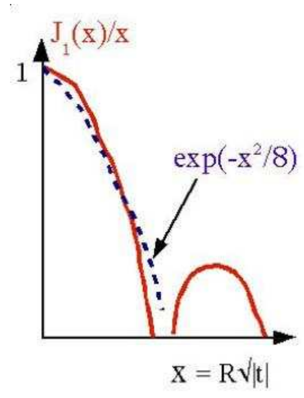
$b = (R/2)^2$ → transverse size of the target (geometric picture)

Predictions: $b = b_0 + 4\alpha'_{I\!P}\ln(W/W_0)$;

soft $I\!P$: shrinkage of diffractive peak ($\alpha'_{I\!P}=0.25$); large $b_0 \approx 10$ GeV^{-2}

hard $I\!P$: no (or small) shrinkage ($\alpha'_{I\!P}<0.1$); small $b_0 \approx 5$ GeV^{-2}

Vector Mesons at HERA: $t-$dependence



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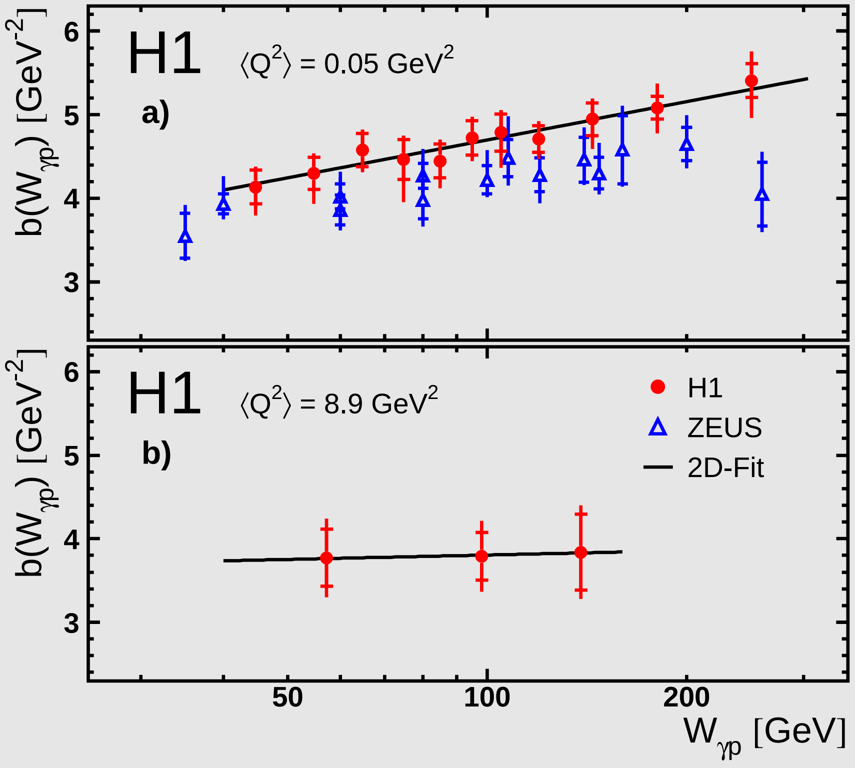

Example: shrinkage in $\gamma^* p \to J/\psi p$

$Q^2 < 1$ GeV^2:

$$\alpha'_{I\!P} = 0.164 \pm 0.028 \pm 0.030$$

$Q^2 = 2 - 80$ GeV^2:

$$\alpha'_{I\!P} = 0.019 \pm 0.139 \pm 0.076$$

Vector Mesons at HERA: $t-$dependence

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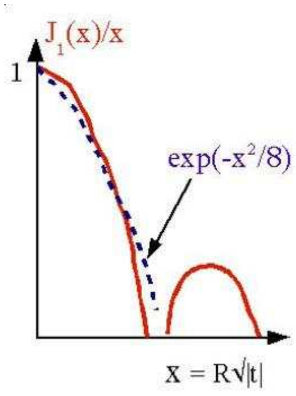

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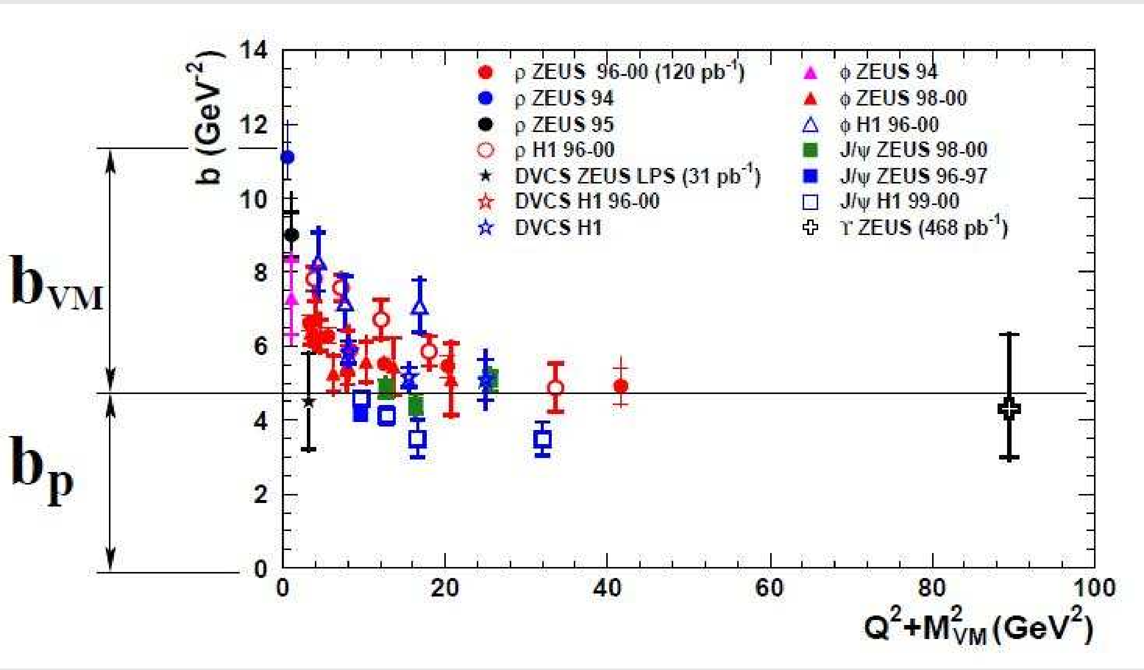
Dipole picture interpretation:

$b = b_{VM} + b_{\rm p}$

$b_{VM} \sim 1/(Q^2 + M^2_{VM})$

$b_{\rm p}$ ⟶ size of the gluons area:

$\langle r^2 \rangle = 2b_{\rm p} \cdot (\hbar c)^2 \simeq 0.6$ fm



Gluons confinement area (0.6 fm) is smaller than the proton size (0.8 fm)

Exclusive Photoproduction of J/ψ Mesons

- Simultaneous unfolding of EL and PD channels

- Use high $E_p = 920$ GeV and low $E_p = 460$ GeV data

  thus extending $W_{\gamma p}$ range

- Both e^+e^- and $\mu^+\mu^-$ decay channels ⇒

  cross check of systematics, better statistics

- t dependence:

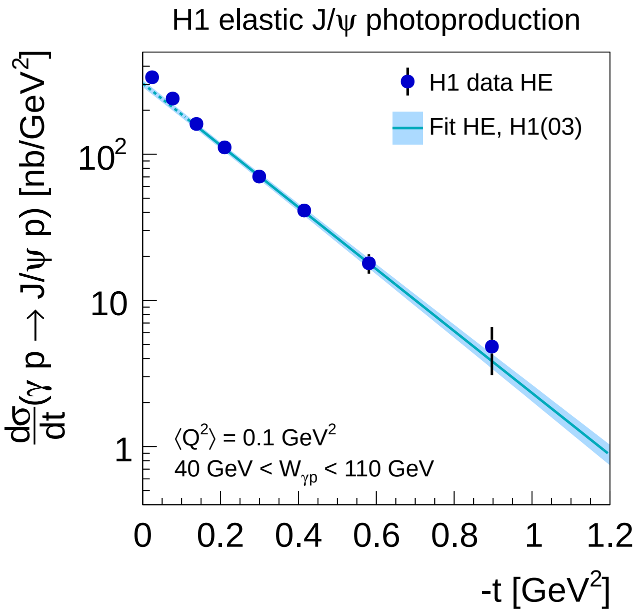
  EL – exponential; $b_{el} = 4.9(4.3)$ GeV^{-2} for HE(LE)

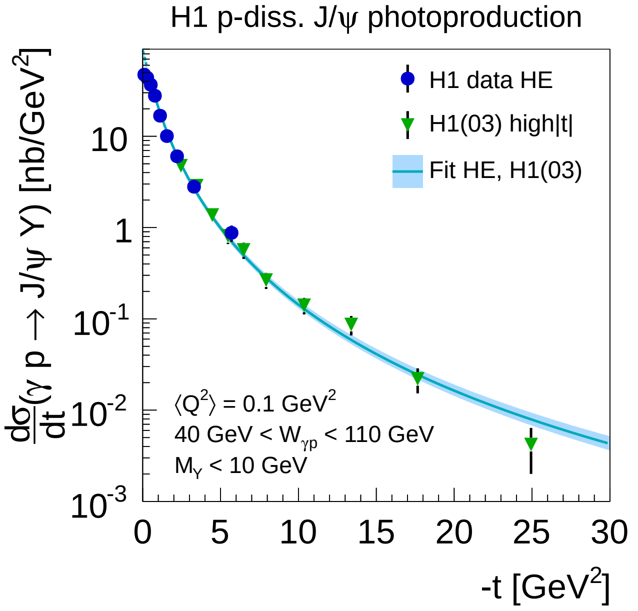
  PD – $d\sigma/dt \propto (1 + (b_{pd}/n)|t|)^{-n}$;

- Energy dependence: $\sigma \propto W_{\gamma p}^{\delta}$

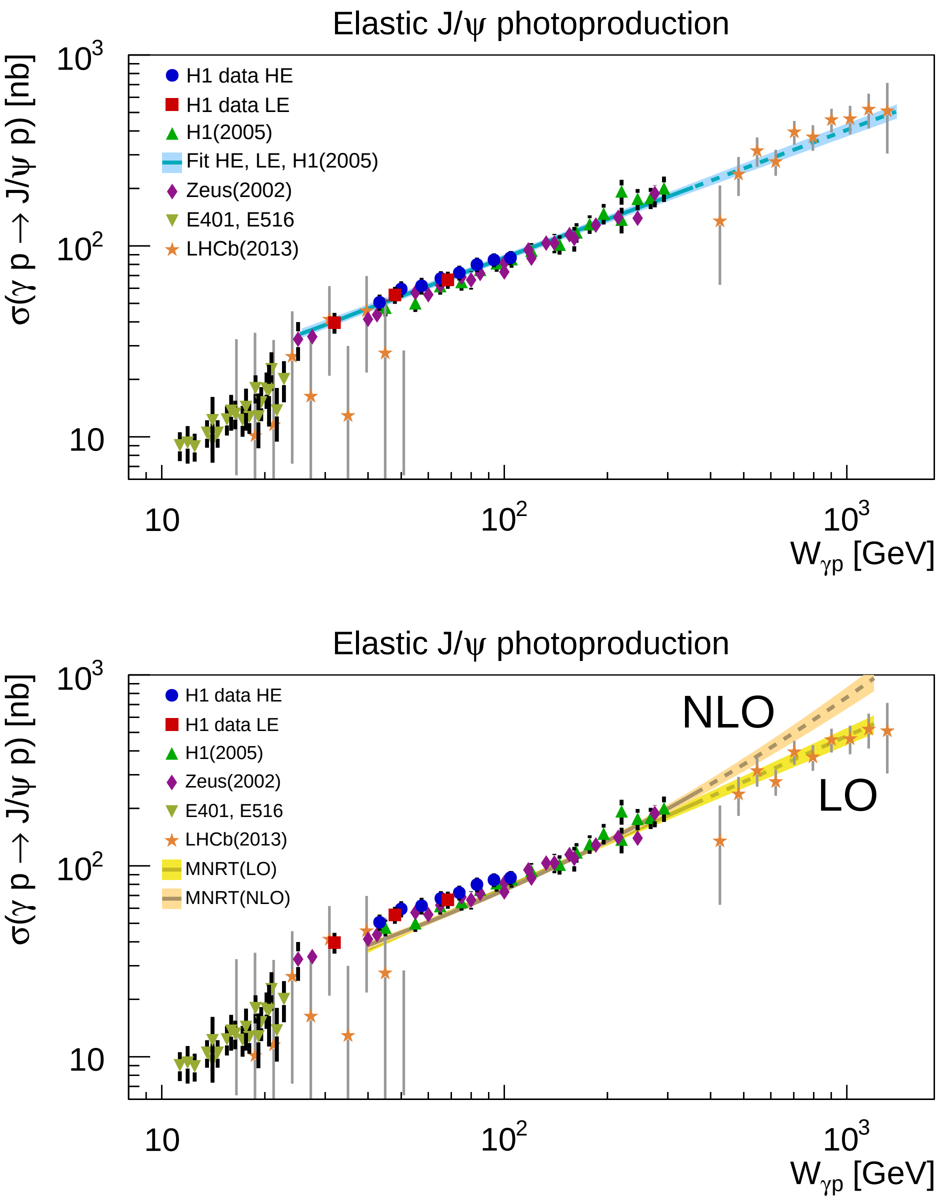
  $\delta_{el} = 0.67 \pm 0.03$; $\delta_{pd} = 0.42 \pm 0.05$

  (possible explanation: $S_{gap}(W) < 1$ for PD case)





Exclusive Photoproduction of J/ψ Mesons



- Extrapolating HERA fit describes LHCb
- Low x gluon, based on old HERA data (A. Martin et al, 2008). NLO too steep

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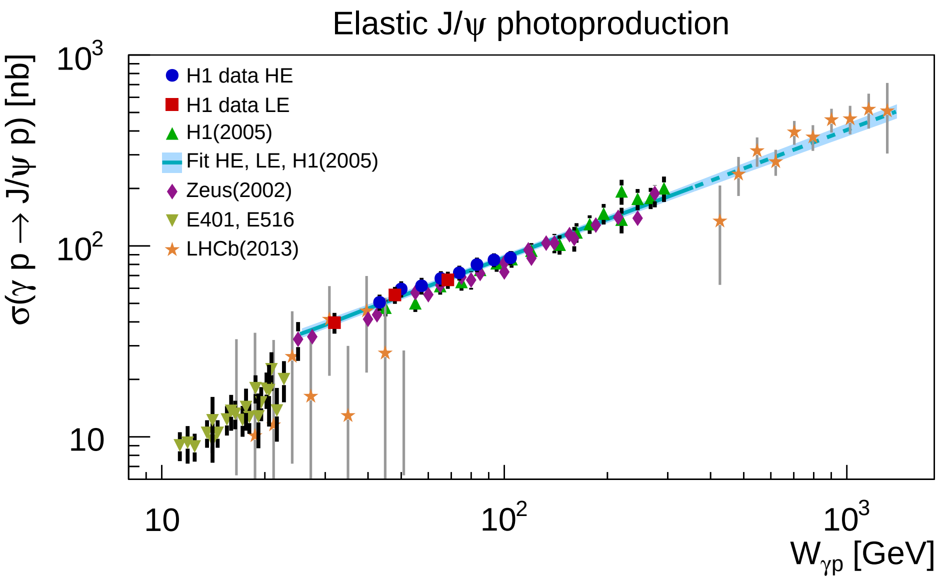

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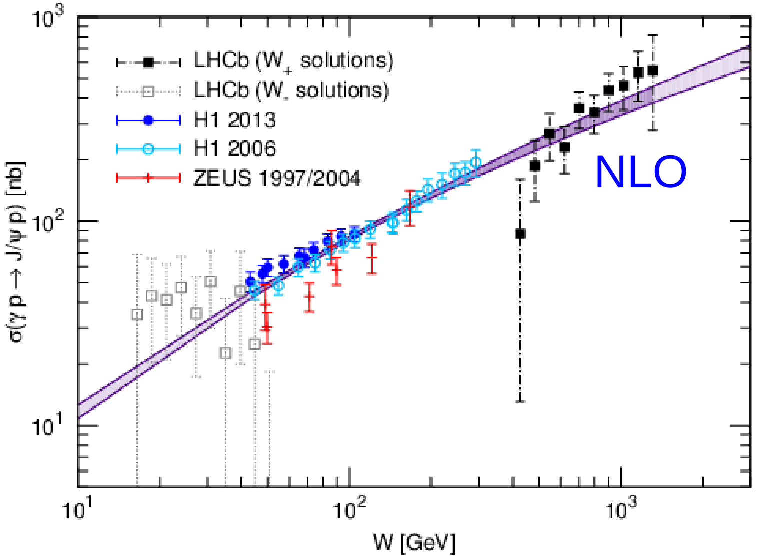

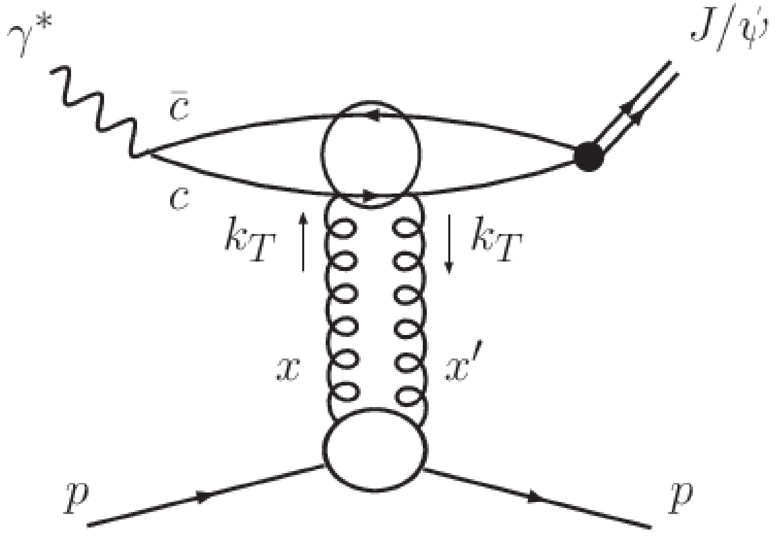

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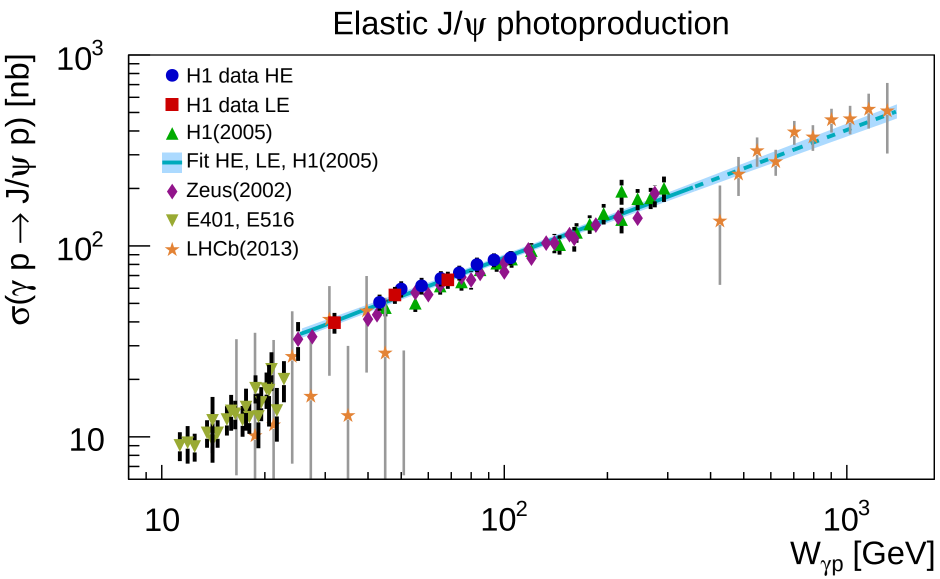

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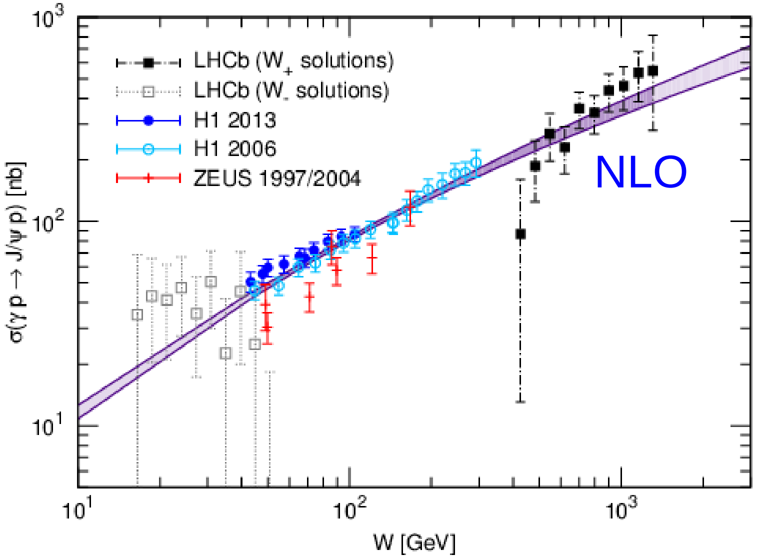
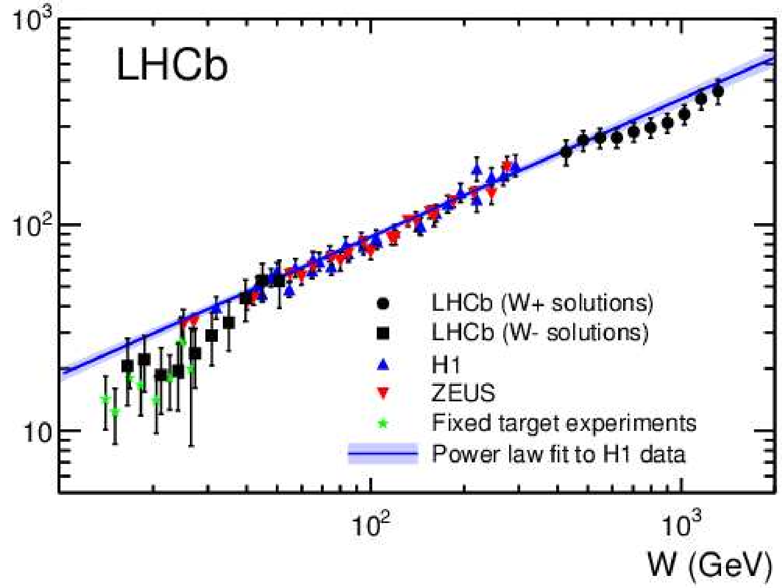
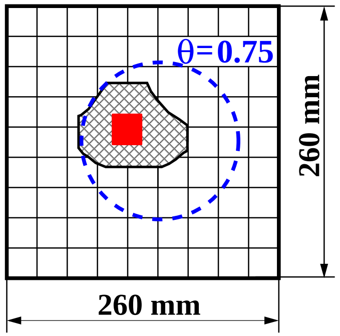
- New LHCb data (930pb^{-1}) [arXiv:1401.3288]

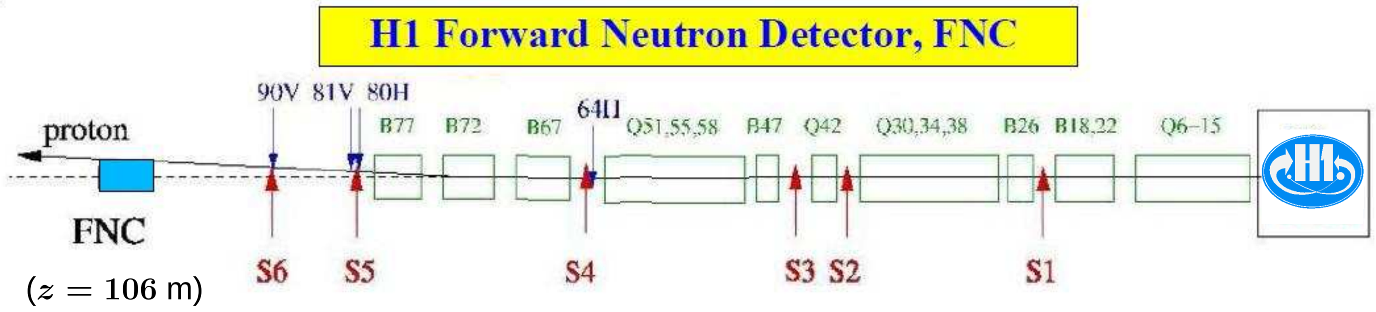


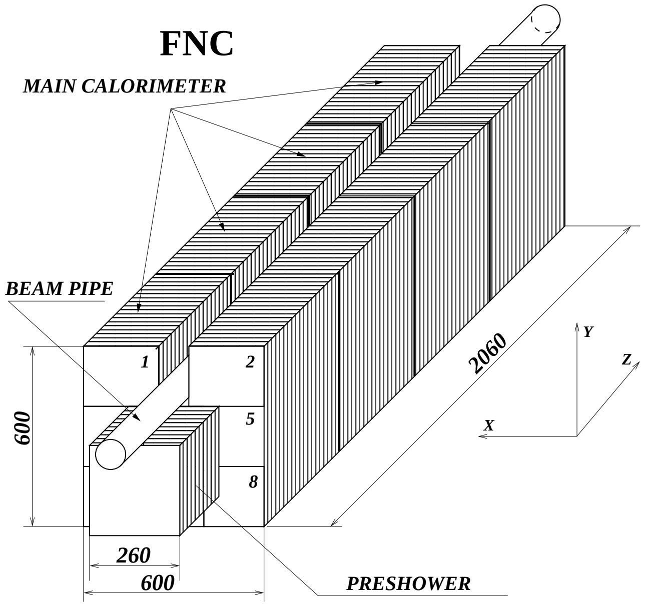


Leading Neutrons at HERA

Physics with Forward Neutral Particles







HERA-I

- Similar H1 and ZEUS calorimeters, only n, located at $z = 106$ m from IP
- $\langle A \rangle \simeq 30\%$ for $\theta_n < 0.8$ mrad

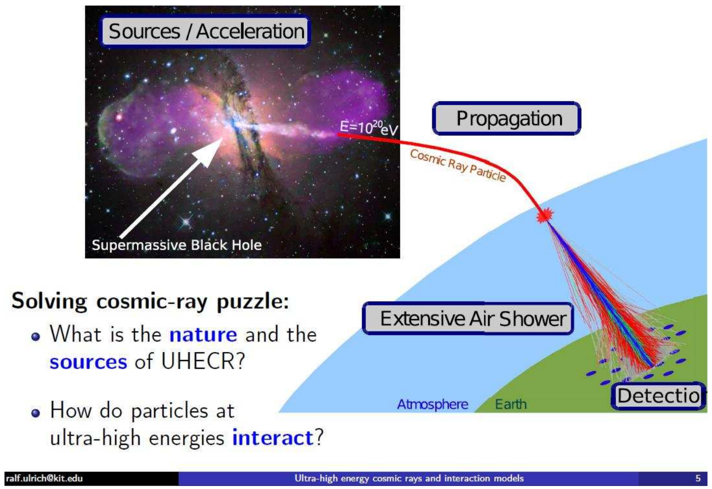
HERA-II

- Improved H1 FNC: distinguish ($\langle P \rangle = 98\%$) and measure n and γ/π^0
- Preshower: $60X_0$, Main Calo: 8.9λ

Motivation and Challenges

- Extreme forward region in particle collisions is still poorly understood
  - ▷ Theory: No (or few) firm predictions from first principles
  - ▷ Experiment: Difficult to measure due to detector acceptance limitations

- Important for correct analysis of (ultra-high energy) Cosmic Rays
  - ▷ Two pieces of the puzzle:
    – Sources/Propagation (prime interest)
    – Interaction/Detection (extensive air shower)
  - ▷ To understand the former one needs good MC models for the latter

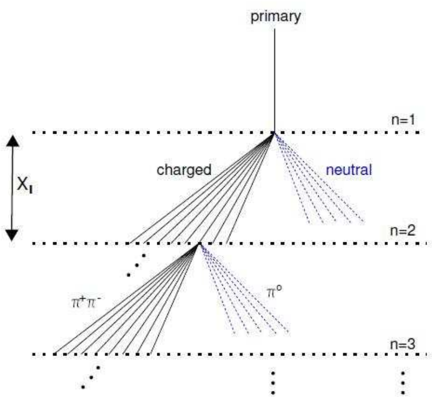


Solving cosmic-ray puzzle:

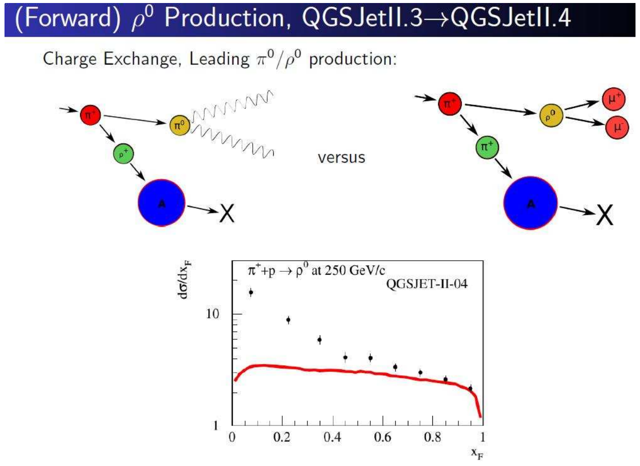
- What is the **nature** and the **sources** of UHECR?
- How do particles at ultra-high energies **interact**?

ralf.ulrich@kit.edu Ultra-high energy cosmic rays and interaction models 5

Extended Heitler Model:



(Ralf Ulrich, PANIC-2014)



(Forward) ρ^0 Production, QGSJetII.3→QGSJetII.4

Charge Exchange, Leading π^0/ρ^0 production:

S. Ostapchenko, ISVHECRI 2012

Motivation and Challenges

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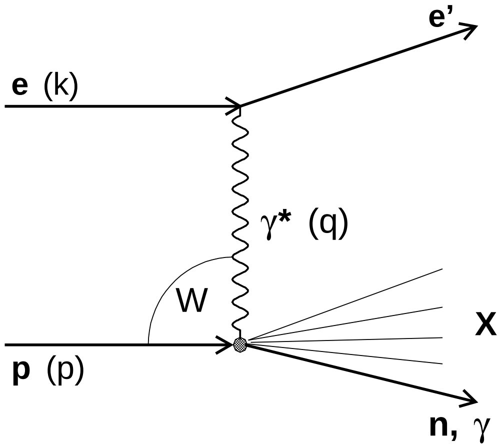
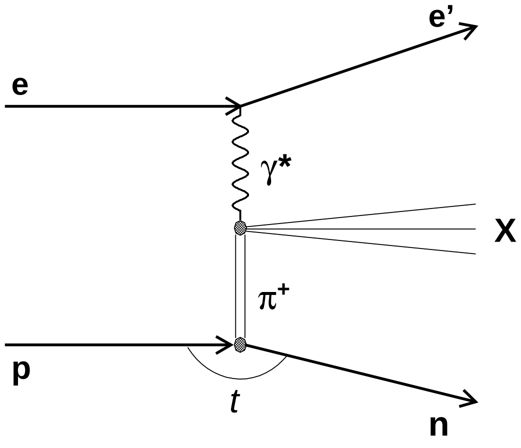
  - ▷ Two pieces of the puzzle:
    - – Sources/Propagation (prime interest)
    - – Interaction/Detection (extensive air shower)
  - ▷ To understand the former one needs good MC models for the latter
- Current situation (from PANIC summary):
  - ▷ Recent LHC data are very valuable for CR MC tuning but still no fully consistent picture yet
  - ▷ UHECR data becomes more precise and require also better precision of hadronic interaction modelling
- Specifics of HERA
  - ▷ Additional constraints for different kinematical regimes wrt hadron colliders (smaller collision energy can be ”compensated” by studying scaling properties and transporting the measurements to higher energies)
  - ▷ Some observables are unique (e.g. possible extraction of $\gamma\pi$ cross sections)

Inclusive forward γ, n production in DIS

$$e^+ + p \longrightarrow e^+ \binom{n}{\gamma} X$$





Data

$\mathcal{L} = 131\ \text{pb}^{-1}$, $\sqrt{s} = 319$ GeV

$6 < Q^2 < 100\ \text{GeV}^2$

$70 < W < 245$ GeV

$\eta_{\text{lab}} > 7.9$, $x_F = 2p^*_{||}/W > 0.1$

γ : 83000 ev. n : 230000 ev.

MC models

DIS: LEPTO/CDM (γ, n)

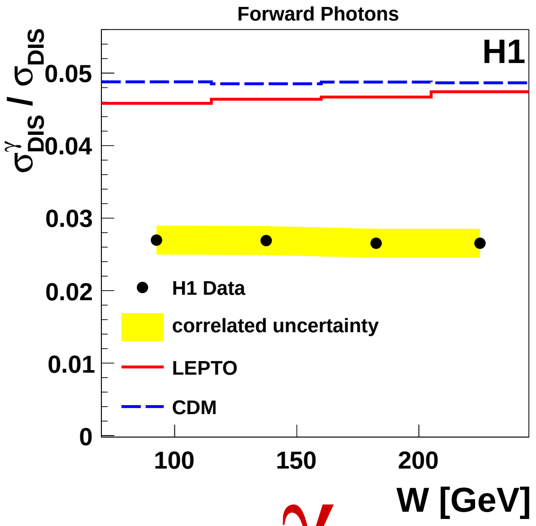
RAPGAP-π (n)

CR: EPOS LHC

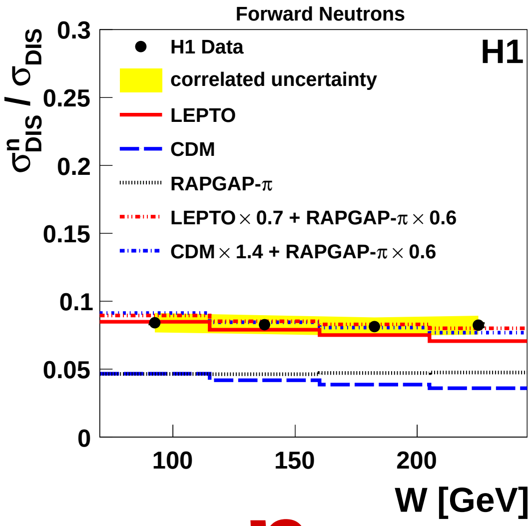
SYBILL 2.1

QGSJET (3 versions)

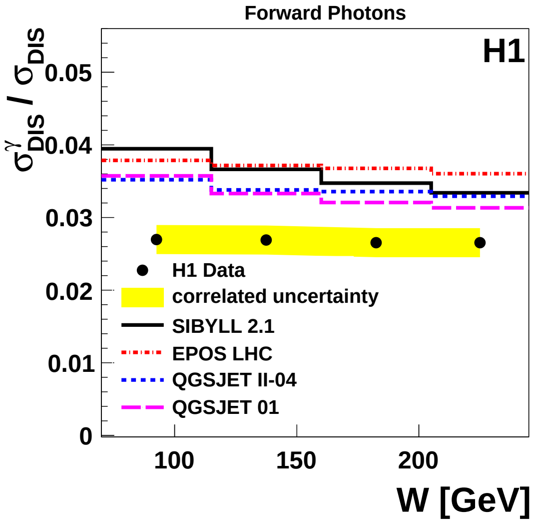
W dependence

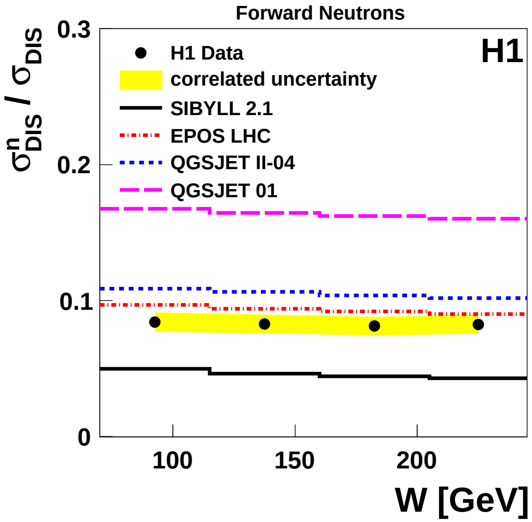


γ



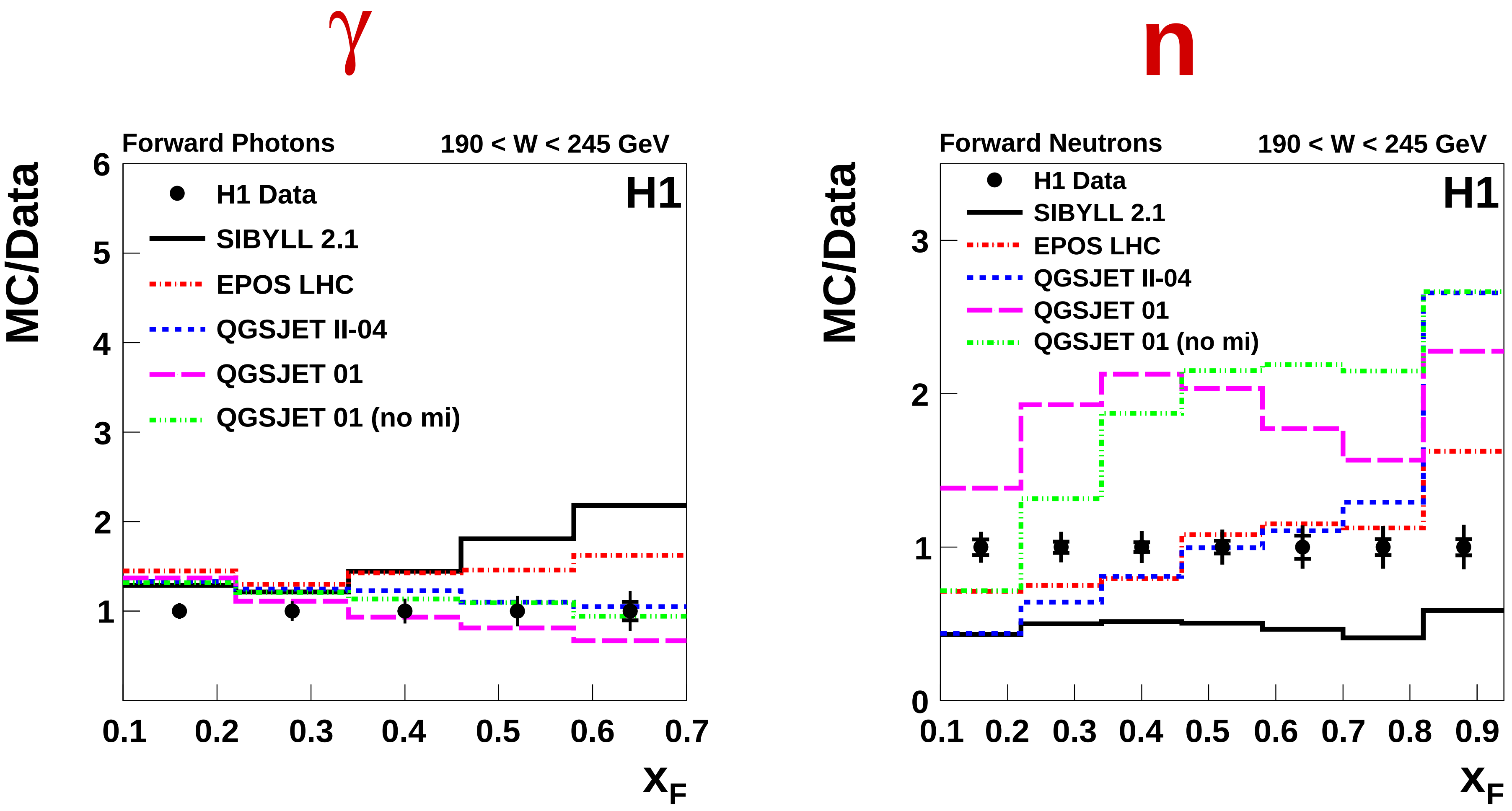
n





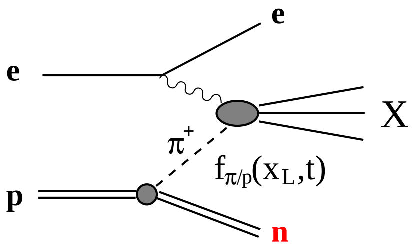
- (γ, n) yields are independent on W
- DIS MC overestimate photon rate by $\sim 70\%$ and describe neutrons
- CR MC overestimate photon rate by $30-40\%$ EPOS LHC is best for n

x_F spectra vs CR MC models



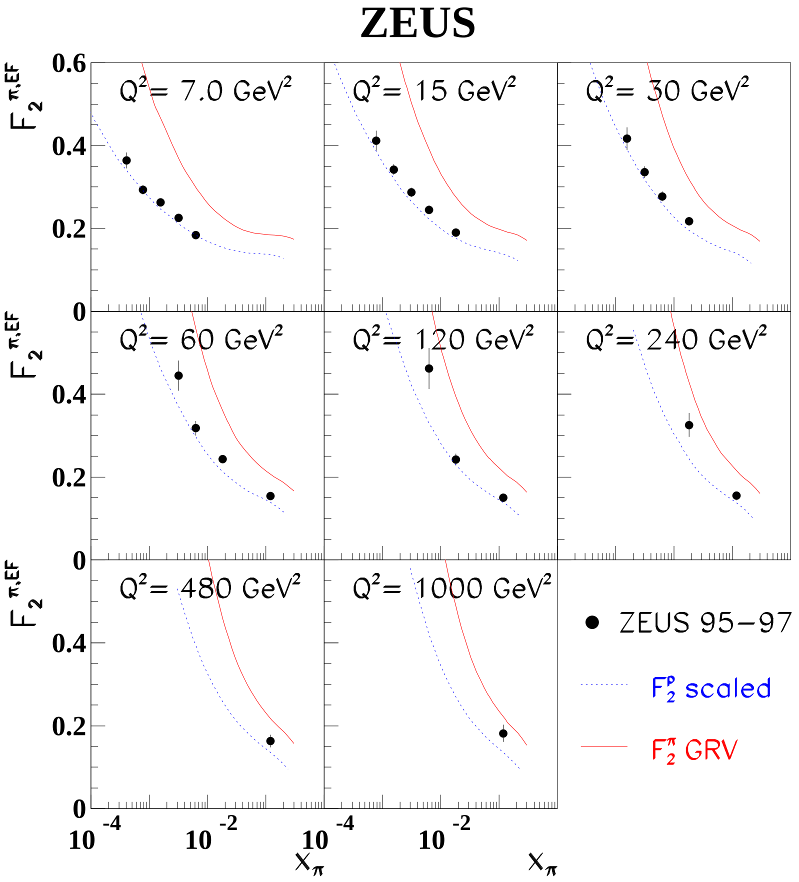
- None of the models describes simultaneously γ and n
- EPOS LHC gives best shape description for γ and resonable for n

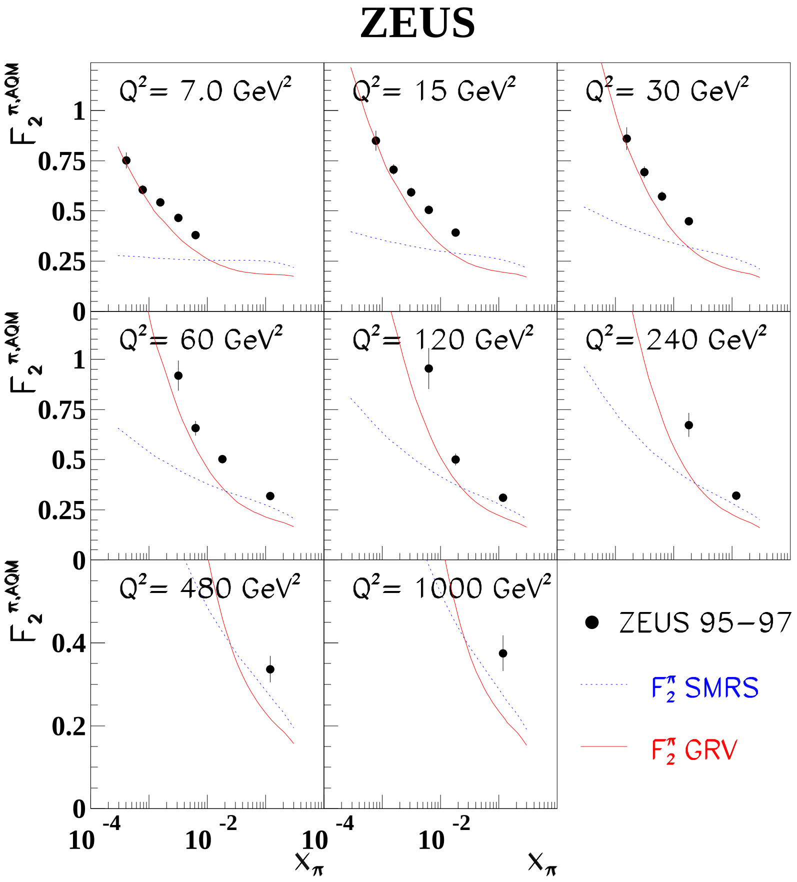
Pion structure function from LN DIS



$$F_2^{\mathrm{LN}(4)}(x,Q^2,x_L,t) = f_{\pi/p}(x_L,t)F_2^{\pi}(x/(1-x_L),Q^2,t)(1-\Delta_{\mathrm{abs}}(Q^2,x_L,t))$$

$$\Delta_{\mathrm{abs}}^{\mathrm{theo}} = (0.1 \div 0.4)$$





Important to determine absorptive corrections experimentally

HERA as a ‘4P’ facility

HERA enables us to study structure of

Proton – $F_2, F_L, \ldots$

Photon – g/γ

Pomeron – F_2^D, F_L^D

Pion – F_2^π

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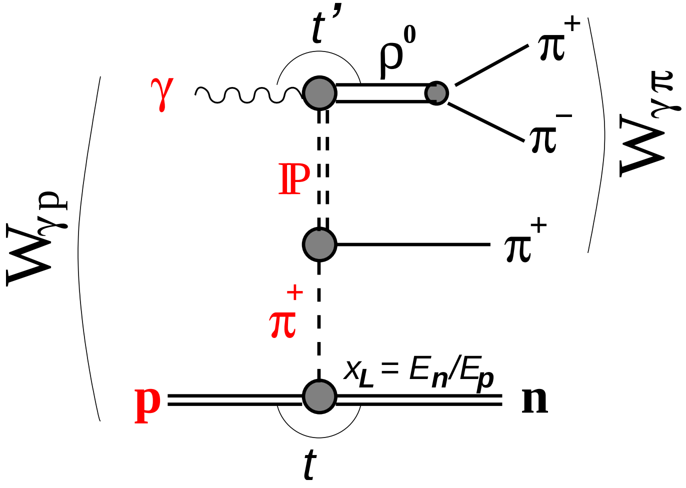
Here for the first time we investigate the reaction involving all these objects simultaneously:

$$\gamma + \mathbf{p} \longrightarrow \rho^0 \pi^+ \mathbf{n}$$



HERA as a ‘4P’ facility

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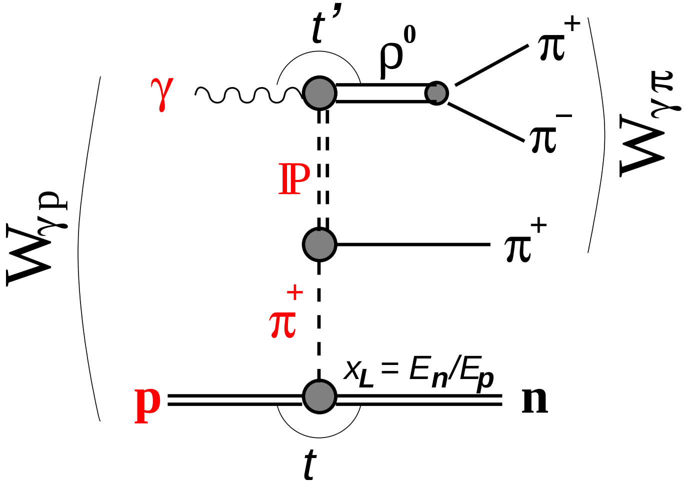
Pomeron – F_2^D, F_L^D
Pion – F_2^π

Here for the first time we investigate the reaction involving all these objects simultaneously:

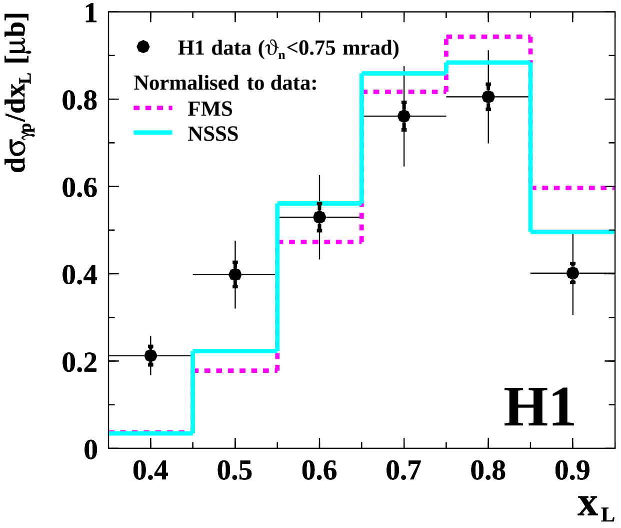
$$\gamma + \mathbf{p} \longrightarrow \rho^0 \pi^+ \mathbf{n}$$

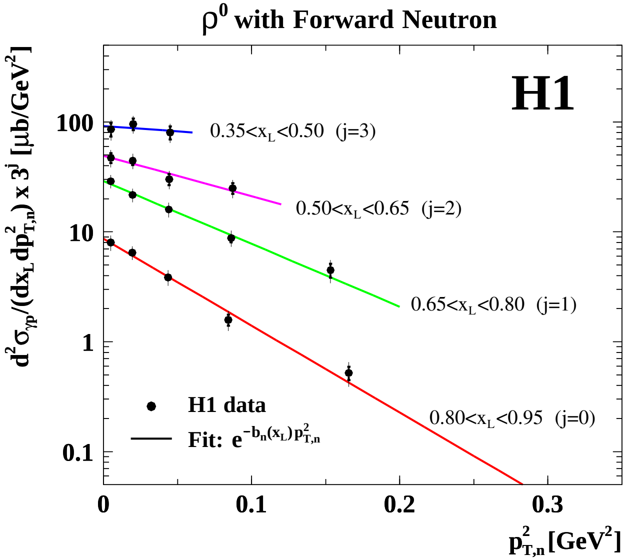
$Q^2 < 2$ GeV^2 $(\langle Q^2\rangle = 0.04)$
$|t'| < 1$ GeV^2 $(\langle |t'|\rangle = 0.20)$
$0.35 < x_L < 0.95$;
$\theta_n < 0.75$ mrad
$p_{t,n} < 0.2$ GeV (OPE)

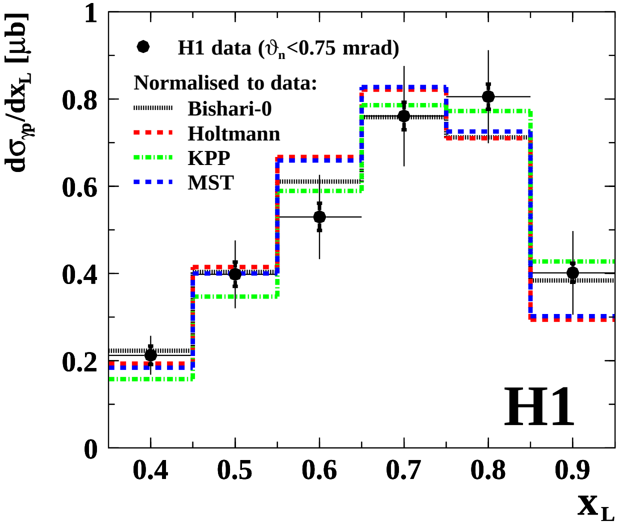


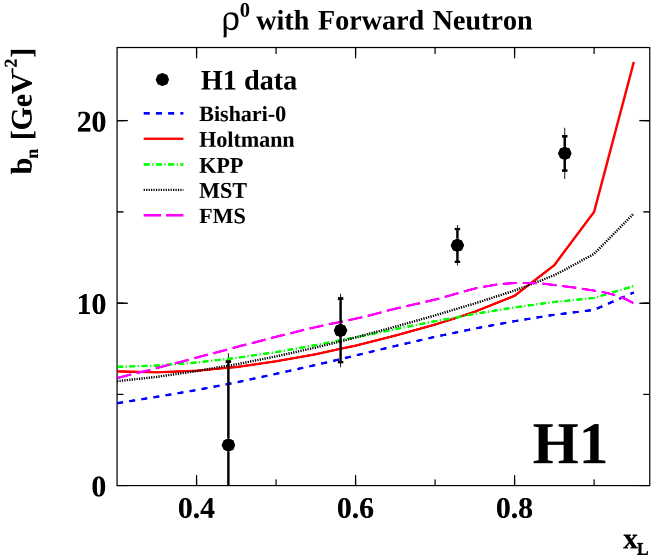
$$\frac{d^2\sigma_{\gamma p}(W_{\gamma p}, x_L, t)}{dx_L dt} = f_{\pi/p}(x_L, t)\, \sigma_{\gamma\pi}(W_{\gamma\pi})$$

Constraining pion flux



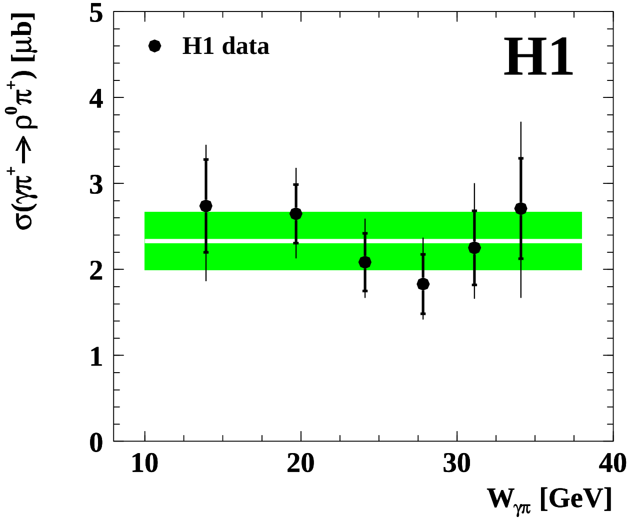


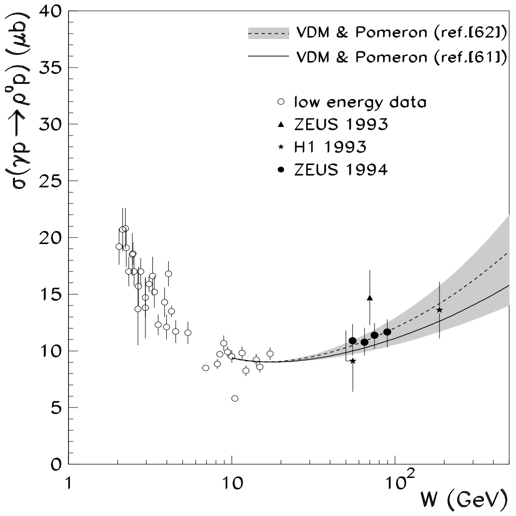




Estimate of absorption corrections

γπ





γp

$$r_{\rm el} = \frac{\sigma_{\gamma\pi\to\rho^0\pi}}{\sigma^{\gamma p\to\rho^0 p}} = \begin{cases} 0.25 \pm 0.06 & \text{(exp.extracted)} \\ 0.57 \pm 0.03 & \text{(theo.expected)} \end{cases}$$

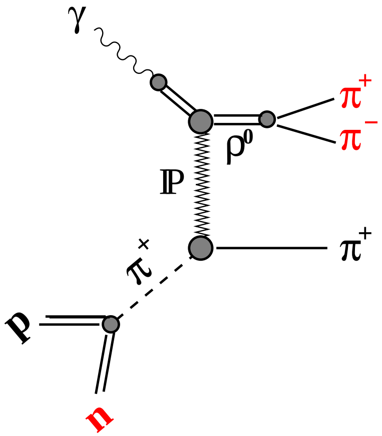
➡

$$K_{\rm abs} = 0.44 \pm 0.11$$

Look into other processes. What do we see there?

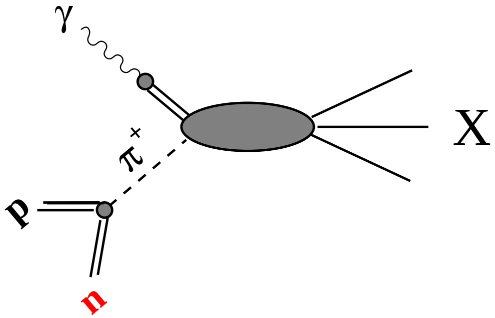
Cross sections ratio

H1 (2015)



$\sigma^{\gamma\pi}_{el}$ (W=24 GeV)

ZEUS (2002)



$\sigma^{\gamma\pi}_{tot}$ (W=107 GeV)

$\sigma_{\rm el}^{\gamma\pi}/\sigma_{\rm el}^{\gamma p} = 0.25 \pm 0.06$	Exp.result	$\sigma_{\rm tot}^{\gamma\pi}/\sigma_{\rm tot}^{\gamma p} = 0.32 \pm 0.03$
OT+eikonal approach+data: $r_{\rm el} \simeq 0.57$	Theory	AQM: $r_{\rm tot} \simeq 2/3$

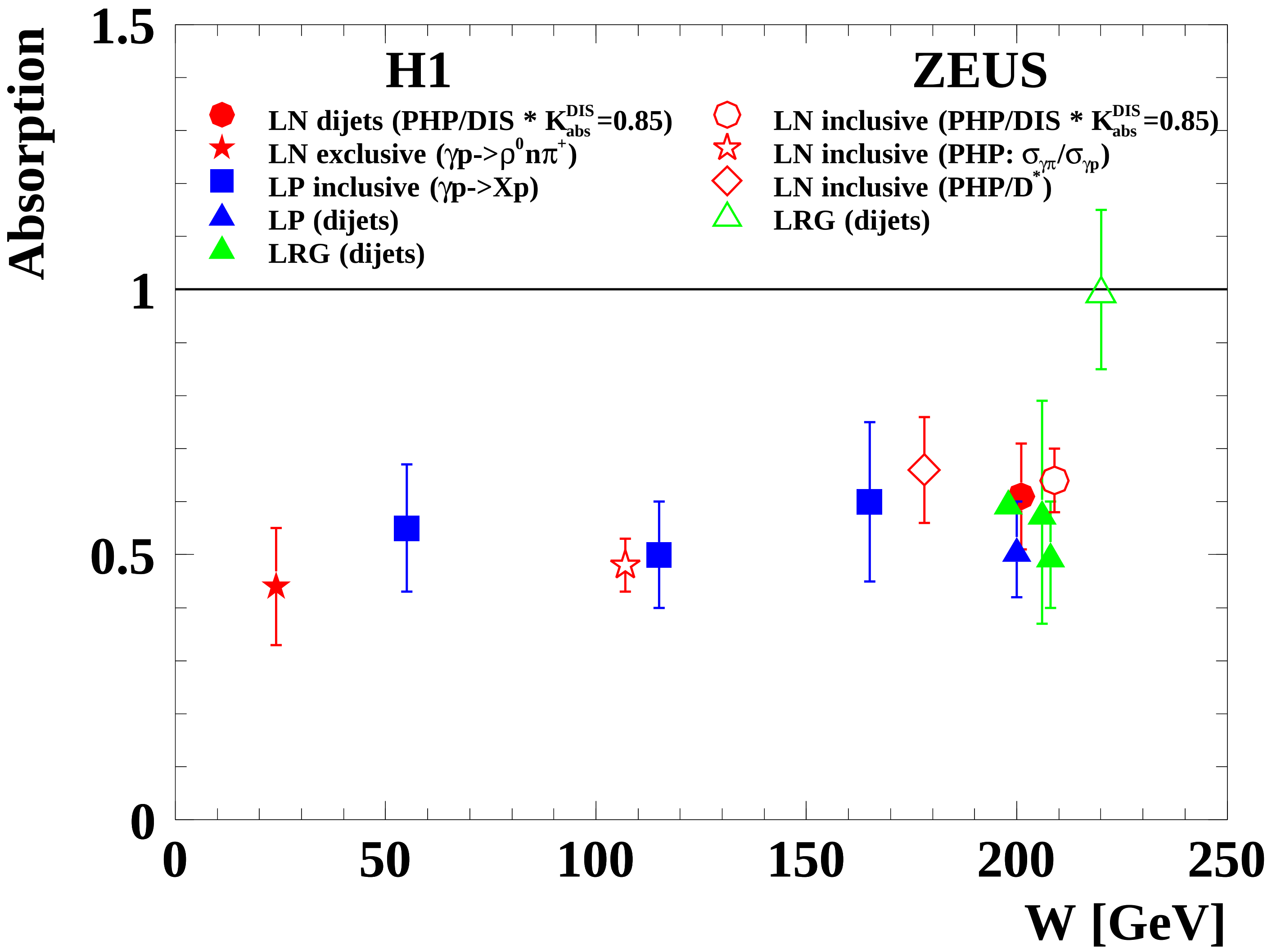
Large absorption effects!

Optical Theorem: $\frac{d\sigma_{el}}{dt}\,|_{t=0} = b_{\rm el}\sigma_{\rm el} \propto \sigma^2_{\rm tot}$ ⇒ $r_{\rm el} = (\frac{b_{\gamma p}}{b_{\gamma\pi}}) \cdot (\sigma_{\rm tot}^{\gamma\pi}/\sigma_{\rm tot}^{\gamma p})^2$

Eikonal approach: $b = \langle R^2 \rangle; \quad b_{12} = b_1 + b_2$

World data: $(b_{pp} \simeq 11.7, \;\; b_{\pi^+ p} \simeq 9.6, \;\; b_{\gamma p} \simeq 9.75)$ GeV^{-2}

Absorptive factors, K_{abs}, in different PHP reactions



Summary

- Diffraction is an important area of HERA physics landscape.
  It represents a complicated interplay of soft and hard phenomena.

- Pomeron is a gluon dominated object.
  Diffractive DIS is fairly well described by both RP model and CD approach.

- QCD factorisation holds in DDIS, but is broken in PHP regime.
  The exact mechanism still to be revealed (x_γ independence).

- Very forward neutral particle production is still a challenge for Cosmic Ray models.

- Absorptive effects in Leading Neutron production are essential both in DIS and PHP regimes. They have to be taken into account when extracting F_2^π from LN in DIS and for $\gamma\pi$ cross section extraction from LN in PHP.

Open questions

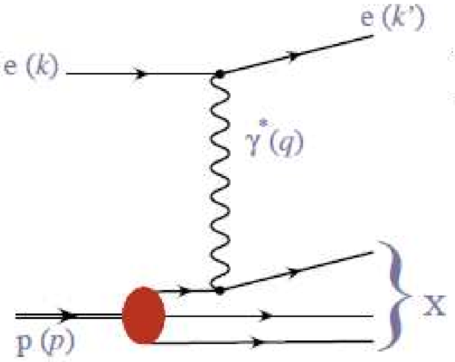
- $F_2^{D(4)}$ from HERA-II VFPS data and final DPDF determination without assumption on Regge factorisation.
- Explain factorisation breaking mechanizm in PHP, in particular independence of Gap Survival Probability on x_γ.
- Multiscale problem: (Q^2, E_T, M_V, t).
- Where is an Odderon ?
- Can one observe Glueball in a double Pomeron reaction in PHP?
  $\gamma p \longrightarrow (I\!P I\!P) \longrightarrow M_X \quad (M_X = \sqrt{x_{I\!P1} x_{I\!P2}} W_{\gamma p} = 2 \div 4\ \mathrm{GeV})$

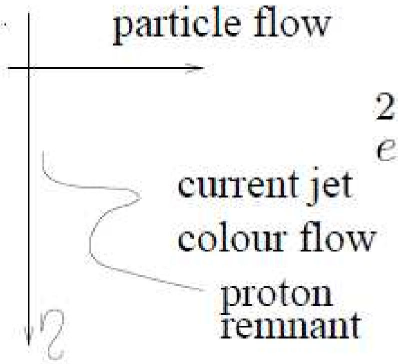
HERA has finished, but not DIS physics.
What's next? **eRHIC ?** **LHeC ?**

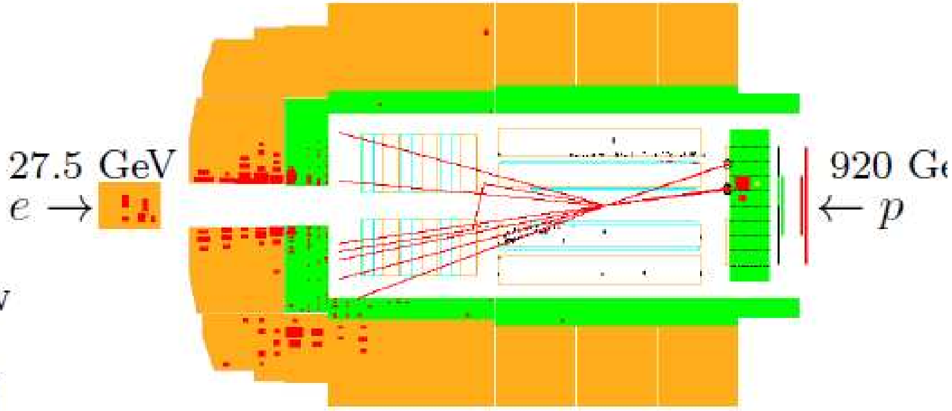
Backup Slides

Iclusive vs Diffractive DIS

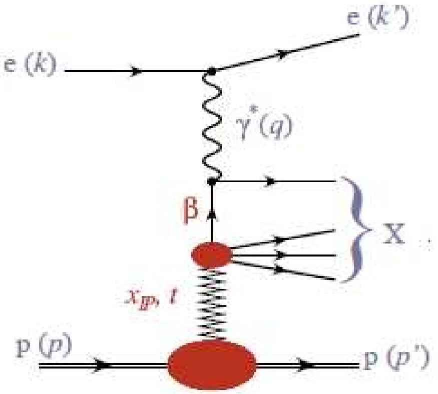
Deep Inelastic Scattering (DIS)

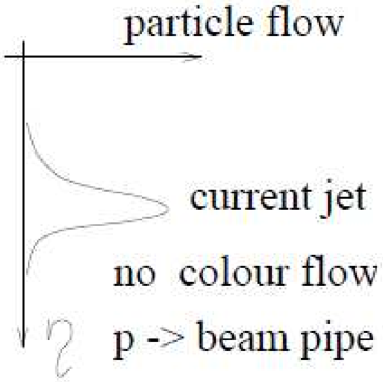


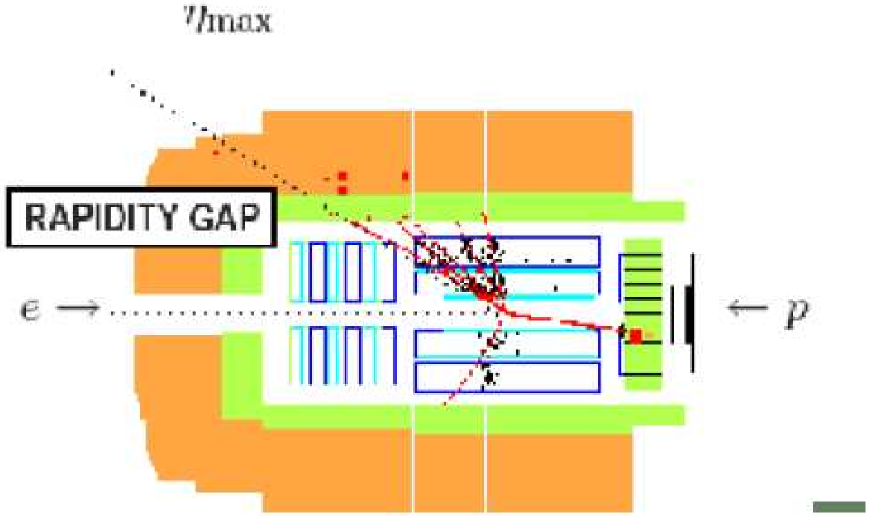




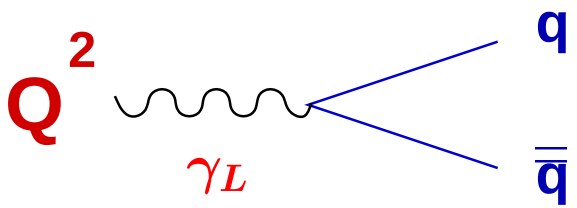
Diffractive Scattering (DDIS)

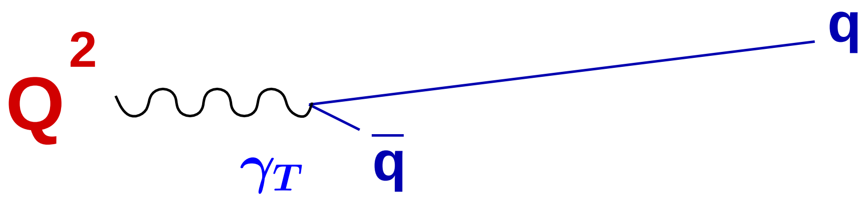






Interplay of soft and hard contributions





$$\gamma_L\ (z \simeq 0.5):\ \langle r_t^2\rangle \simeq (z(1-z)Q^2+m_q^2)^{-1} \simeq 1/[(Q/2)^2+m_q^2]$$

$$\gamma_T\ (z \simeq 0;1):\ \langle r_t^2\rangle \simeq (z(1-z)Q^2+m_q^2)^{-1} \simeq 1/m_q^2$$

Small dipole

Large dipole

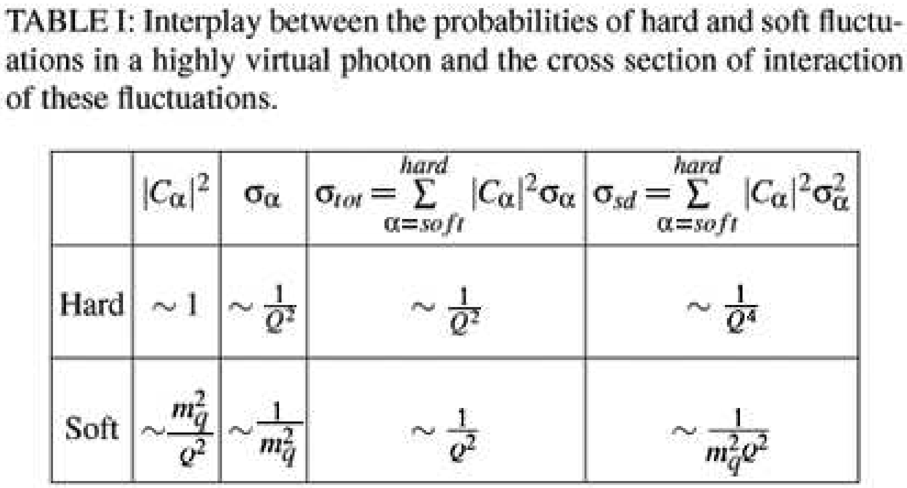


TABLE I: Interplay between the probabilities of hard and soft fluctuations in a highly virtual photon and the cross section of interaction of these fluctuations.

	$\lvert C_\alpha\rvert^2$	σ_α	$\sigma_{tot}=\sum_{\alpha=soft}^{hard}\lvert C_\alpha\rvert^2\sigma_\alpha$	$\sigma_{sd}=\sum_{\alpha=soft}^{hard}\lvert C_\alpha\rvert^2\sigma_\alpha^2$
Hard	~ 1	$\sim\frac{1}{Q^2}$	$\sim\frac{1}{Q^2}$	$\sim\frac{1}{Q^4}$
Soft	$\sim\frac{m_q^2}{Q^2}$	$\sim\frac{1}{m_q^2}$	$\sim\frac{1}{Q^2}$	$\sim\frac{1}{m_q^2Q^2}$

Inclusive DDIS: Extracting Pomeron trajectory

- Regge fit to LRG cross section:

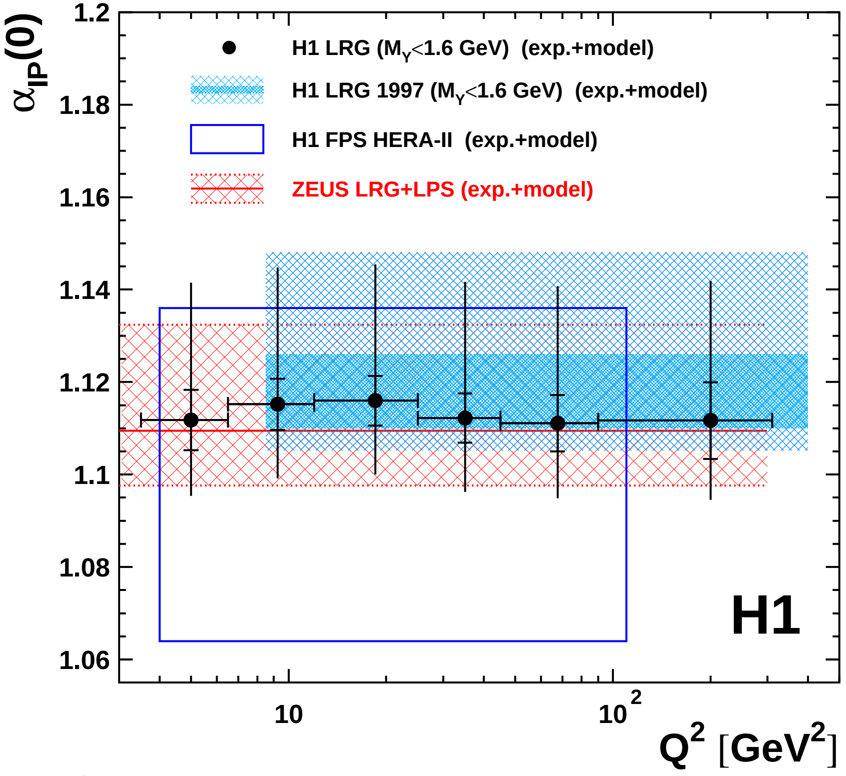
$$\boxed{F_2^{D(3)}(Q^2,\beta,x_{\mathbb{P}}) = f_{\mathbb{P}/p}(x_{\mathbb{P}})F_2^{\mathbb{P}}(Q^2,\beta) + n_{\mathbb{R}} f_{\mathbb{R}/p}(x_{\mathbb{P}})F_2^{\mathbb{R}}(Q^2,\beta)}$$

$$f_{\mathbb{P}/p,\mathbb{R}/p}(x_{\mathbb{P}}) = \int_{t_{cut}}^{t_{min}} \frac{e^{B_{\mathbb{P},\mathbb{R}}t}}{x_{\mathbb{P}}^{2\alpha_{\mathbb{P},\mathbb{R}}(t)-1}}dt \qquad \alpha_{\mathbb{P},\mathbb{R}}(t) = \alpha_{\mathbb{P},\mathbb{R}}(0) + \alpha'_{\mathbb{P},\mathbb{R}}t$$

- Mean value of the Pomeron intercept:

$$\alpha_{\mathbb{P}}(0) = 1.113 \pm 0.002(\mathrm{exp})^{+0.029}_{-0.015}(\mathrm{model})$$

- No Q^2 dependence observed
- Consistent with other determinations
- Supports proton-vertex factorisation hypothesis



$\alpha_{\mathbb{P}}(0)$ – consistent with 'soft $\mathbb{P}$'

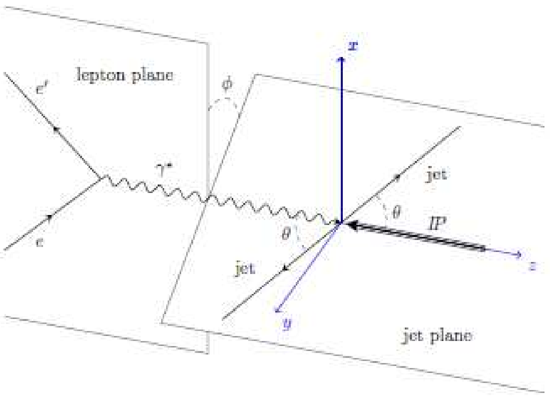
$\alpha'_{\mathbb{P}} \leq 0.1$ is typical for 'hard $\mathbb{P}$'

Complicated interplay of hard and soft phenomena

Exclusive dijets in DDIS

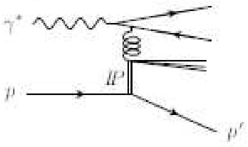
$\boxed{\text{LRG: } Q^2 > 25\ \text{GeV}^2,\ x_{I\!P} < 0.01,\ N_{\text{jet}} = 2,\ P_T^{\text{jets}} > 2\ \text{GeV}}$

- using Durham jet algorithm in $\gamma^* - I\!P$ rest frame in exclusive mode (all objects are in jets), $y_{cut} = 0.15$.
- test the nature of the exchanged object in diffractive interactions
- reconstruct ϕ angle between lepton and jet planes

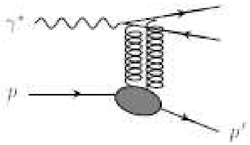


→ $d\sigma/d\phi \sim 1 + A(P_T^{\text{jet}})\cos 2\phi$ [J.Bartels et al.,PLB386,(1996)389]

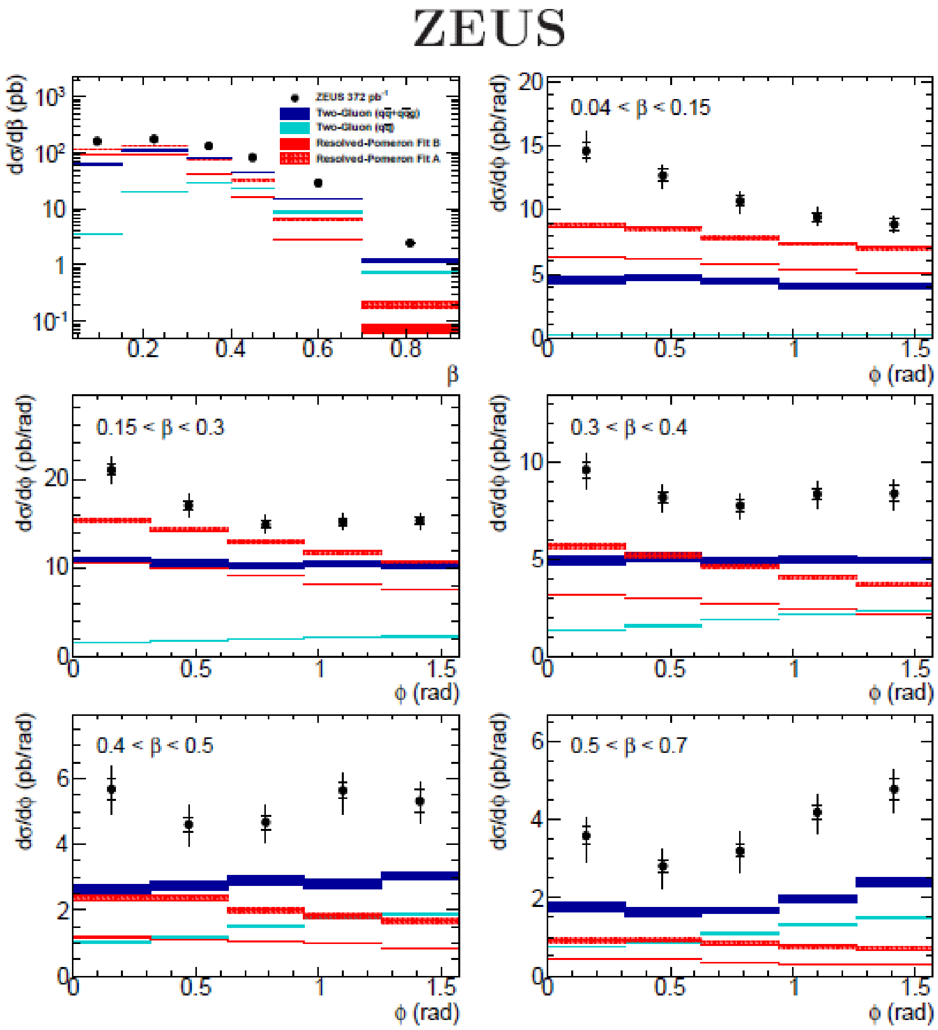
$A > 0$ for $q\bar{q}$ produced from single gluon



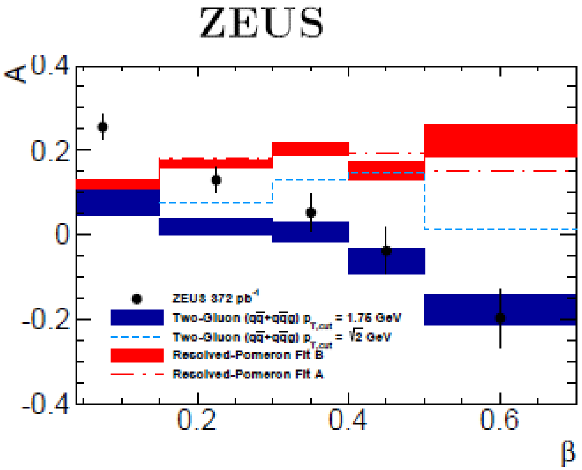
$A < 0$ two gluons exchange.



Exclusive dijets in DDIS

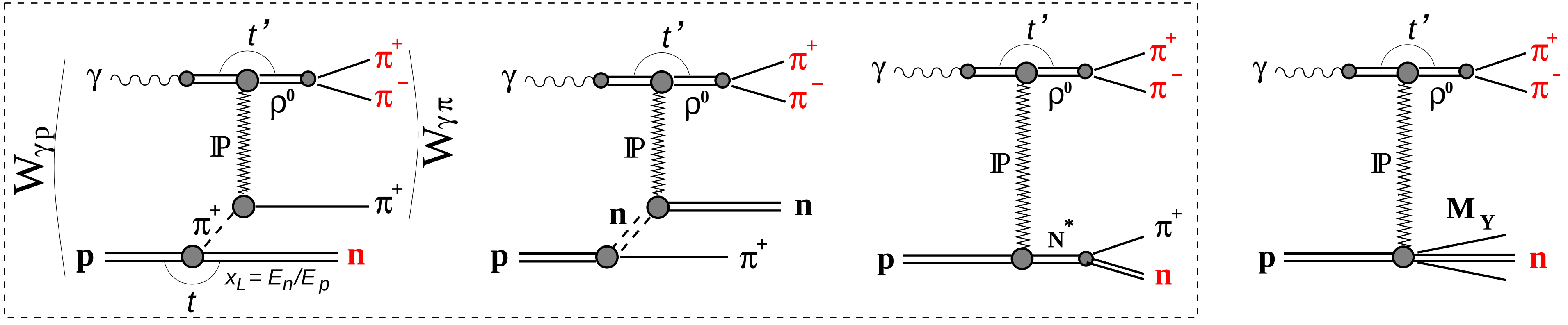


- $d\sigma/d\phi$ fitted in each β bin



- normalisation discrepancy of factor two (NLO large ?)
- A vs ϕ: good description by the two gluon model for $\beta > 0.3$ (i.e. towards exclusive dijets).

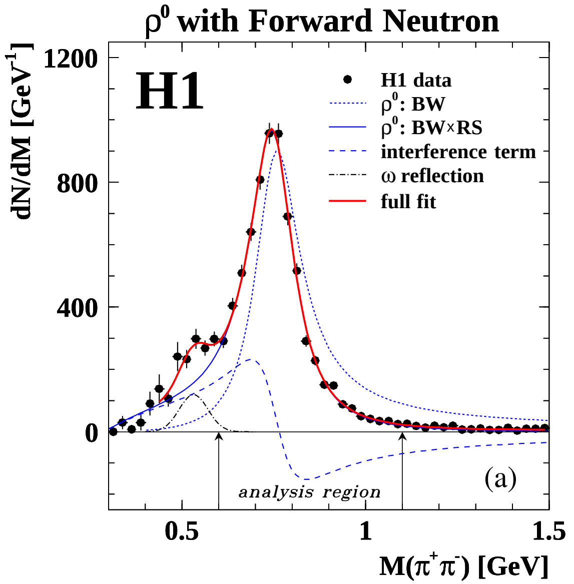
Exclusive ρ^0 with Forward Neutron

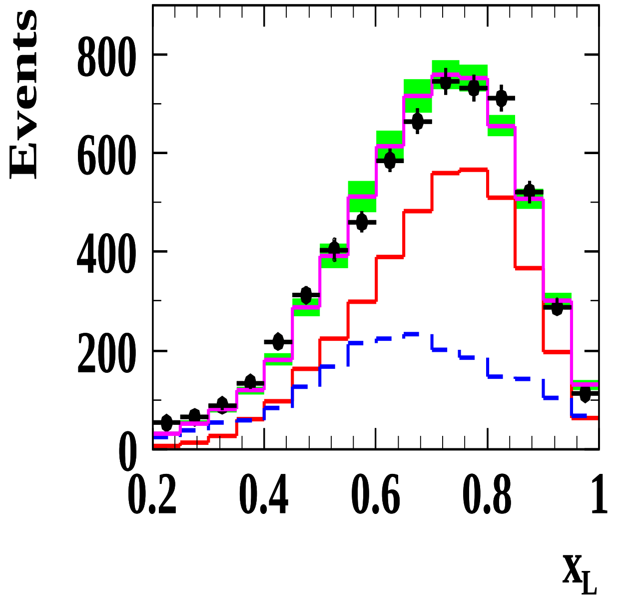


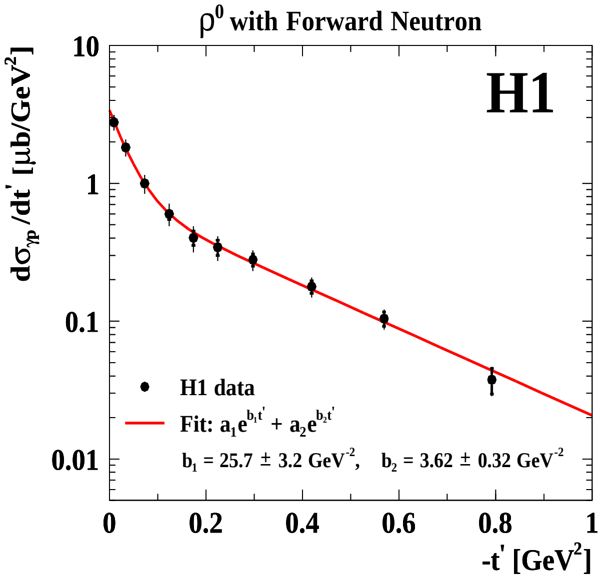
(a) (b) (c) (d)

Signal (DHD model)

Bgr (DIFFVM MC)







Taking an estimate of K_{abs} seriousely

- Optical Theorem (plus exponential t dependence):

$$d\sigma_{el}/dt\,|_{t=0} = b_{\rm el}\sigma_{\rm el} \propto \sigma_{\rm tot}^2; \quad \Rightarrow \quad \sigma_{\rm el} \propto \sigma_{\rm tot}^2/b_{\rm el}$$

- Relations between elastic slopes ($b \propto \langle R^2\rangle; \quad b_{ij} = b_i + b_j$):

$$r_b \equiv \frac{b_{12}}{b_{13}} = \frac{b_1 + b_2}{b_1 + b_3} = \frac{b_1 + b_2}{(b_1 + b_2) + (b_2 + b_3) - 2b_2} = \frac{b_{12}}{b_{12} + b_{23} - b_{22}} = \frac{1}{1 - \frac{b_{22} - b_{23}}{b_{12}}}$$

- Data at $\sqrt{s} \simeq 24$ GeV (for $\gamma p \longrightarrow \rho^0 p$ an interpolated value of $b_{\gamma p}$ is given):

$$b_{pp} = (11.7 \pm 0.2)\ \mathrm{GeV}^{-2}; \quad b_{\pi^+ p} = (9.6 \pm 0.25)\ \mathrm{GeV}^{-2}; \quad b_{\gamma p} = (9.75 \pm 0.50)\ \mathrm{GeV}^{-2}$$

- Ratio r_{el} $(1 = \gamma,\ 2 = p,\ 3 = \pi^+)$:

$$r_{el} = \left(\frac{b_{\gamma p}}{b_{\gamma\pi}}\right) \cdot \left(\frac{\sigma_{\rm tot}^{\gamma\pi}}{\sigma_{\rm tot}^{\gamma p}}\right)^2 = \left(\frac{1}{1 - (2.1/9.75)}\right) \cdot \left(\frac{2}{3}\right)^2 = (0.57 \pm 0.03)$$

- Absorption factor:

$$K_{abs} = \frac{r_{el}(\mathrm{measured})}{r_{el}(\mathrm{estimated})} = \frac{0.25 \pm 0.06}{0.57 \pm 0.03} = 0.44 \pm 0.11$$