EDS Blois 2015:

The 16th conference on Elastic and Diffractive Scattering

Review of HERA results on exclusive production

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(Univ. Piemonte Orientale & INFN-Torino, Italy)

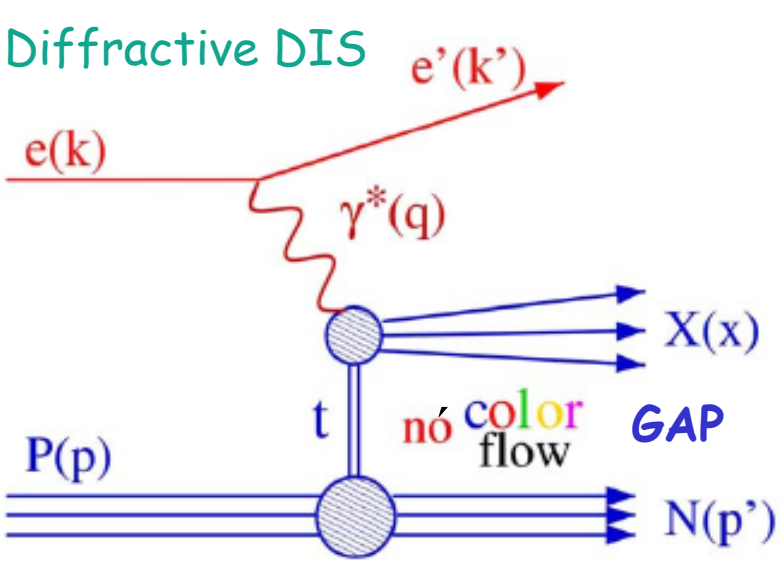
on behalf of the ZEUS and H1 Collaborations

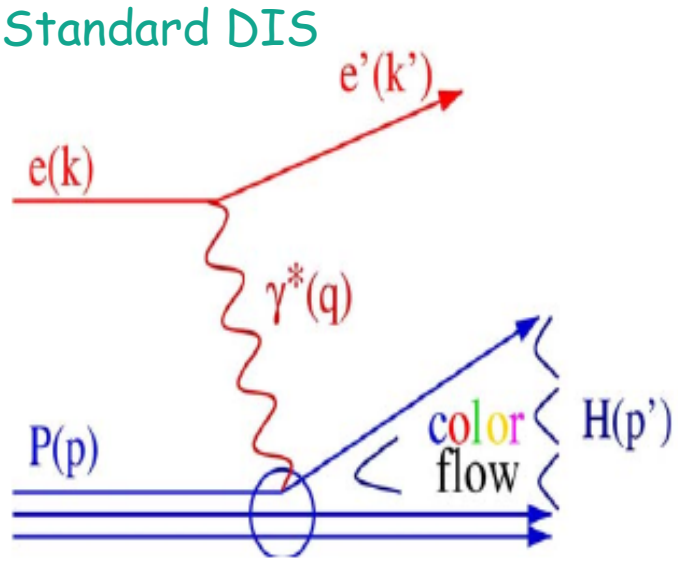
Outline

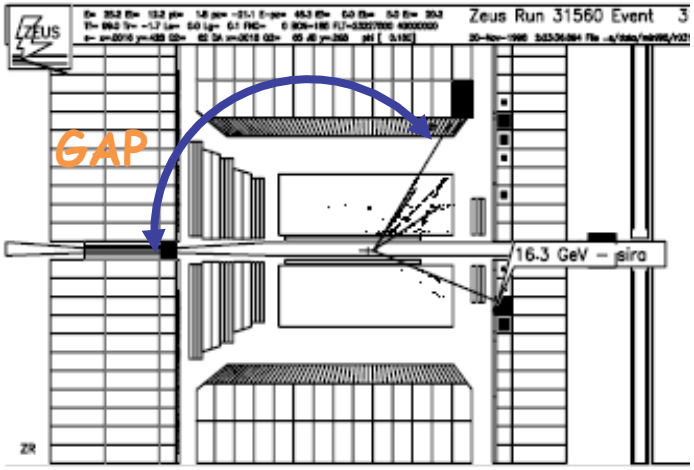
- Review of exclusive (vector meson production) processes at HERA: a window on soft-hard transition
  - W dependence
  - t dependence
  - Pomeron (IP) trajectory
  - angular distributions
  - elastic vs proton dissociative production
  - vertex factorization

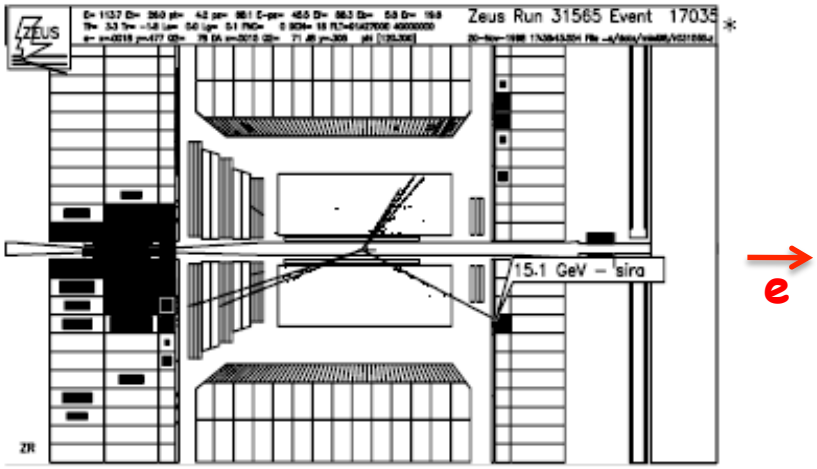
- Recent H1/ZEUS results
  - Exclusive dijet production] [DESY 15-070]
  - Ψ'/J/psi [ZEUS prel-15-002]
  - ρ production with a leading neutron [H1prelim-14-013]

Diffractive dissociation of the (virtual) photon at HERA

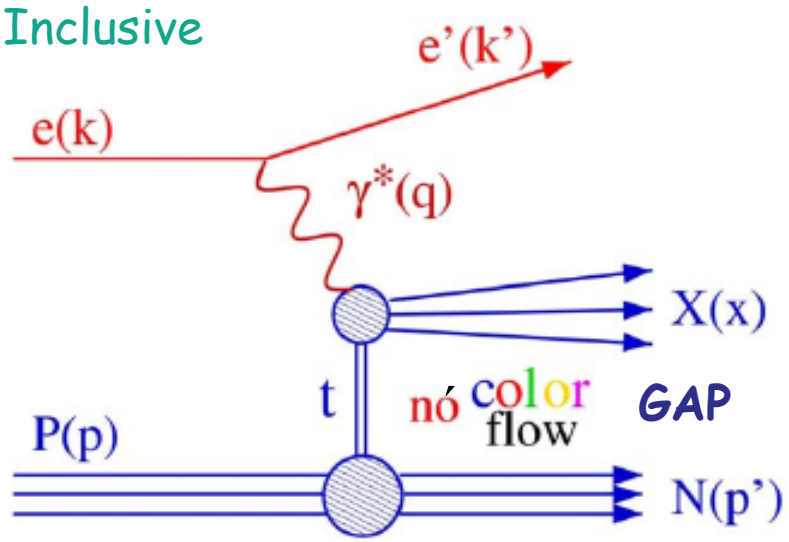


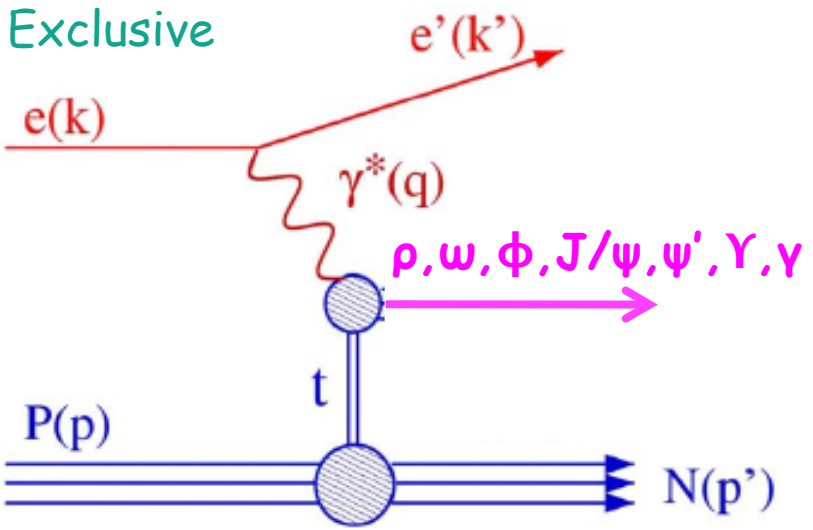






Inclusive and exclusive diffraction





Q^2 = virtuality of photon =
= (4-momentum exchanged at e vertex)^2

W = invariant mass of γ^*-p system

t = (4-momentum exchanged at p vertex)^2
typically: $|t|<1$ GeV^2

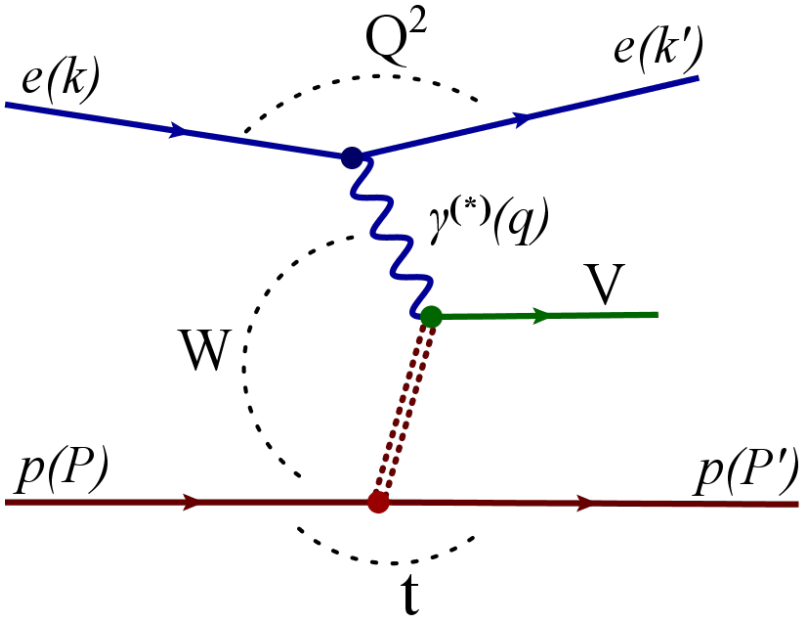
M_X = invariant mass of γ^* -IP system

x_{IP} = fraction of proton's momentum carried by IP

β = Bjorken's variable for the IP
= fraction of IP momentum carried by struck quark
= x/x_{IP}

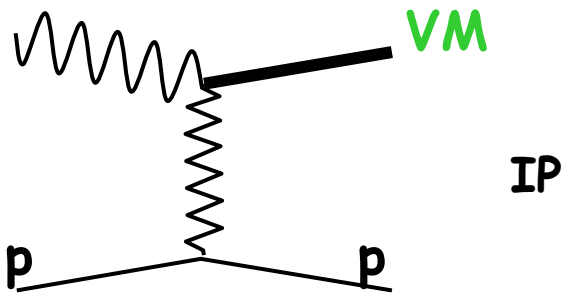
- **Single diffraction/elastic:** **N=proton**
- **Double diffraction:** **proton-dissociative system N**

Vector meson (VM) production

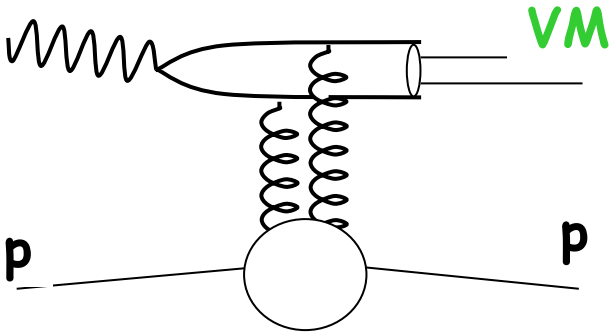


Transition soft → hard

Soft - Regge



Hard - QCD



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

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

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

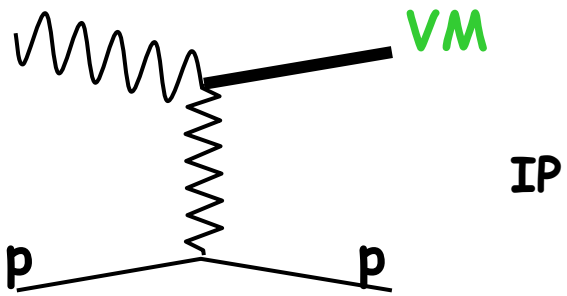
- Expect δ to increase from soft (~0.2, 'soft Pomeron' value) to hard (~0.8, reflecting large gluon density at low x)

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

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

Transition soft → hard

Soft - Regge



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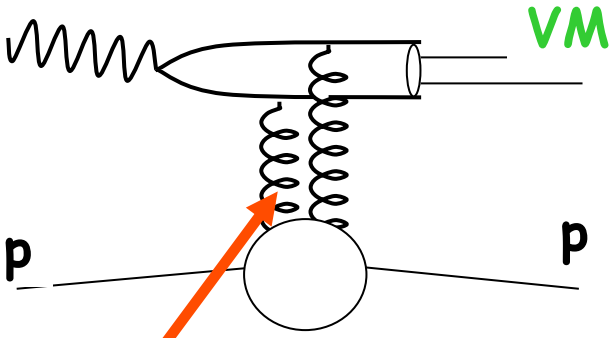


VM ($J^{PC}=1^{--}$): γ, ρ, ϕ, J/ψ, Υ,...

2-gluon exchange:
LO realisation of vacuum
quantum numbers in QCD

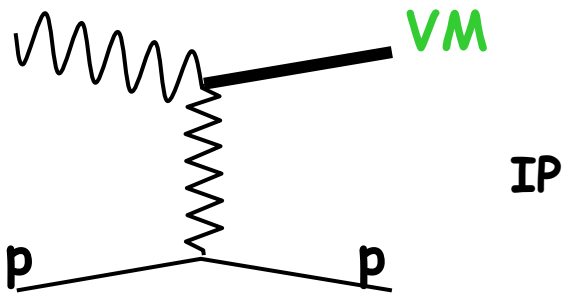
Cross section proportional to probability of finding 2 gluons in the proton

$$\sigma \propto [x\, g]^2$$!

Gluon density in the proton

Transition soft → hard

Soft - Regge



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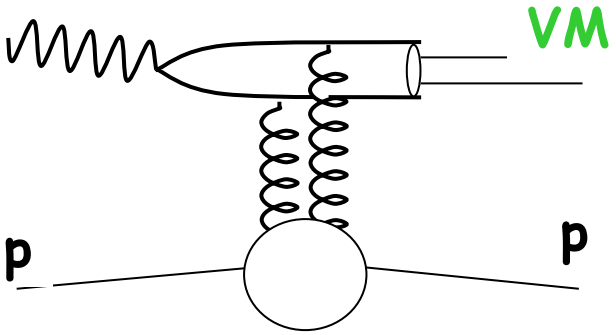

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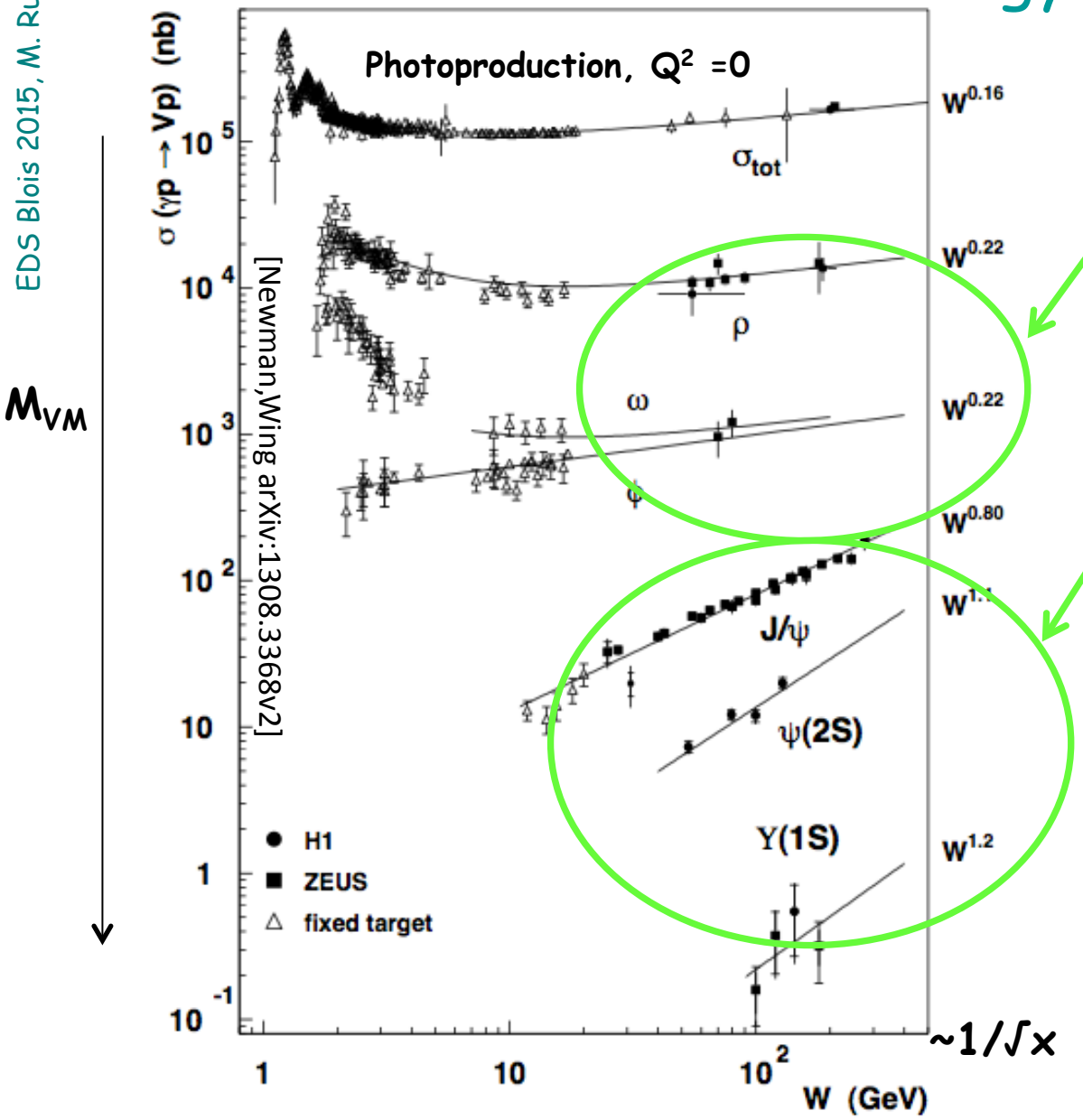
Transition soft → hard: energy dependence



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

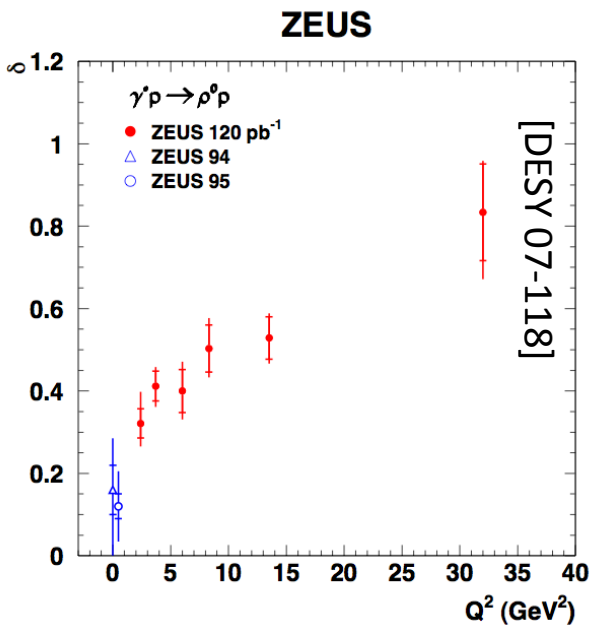
large M_{VM} : small dipole size

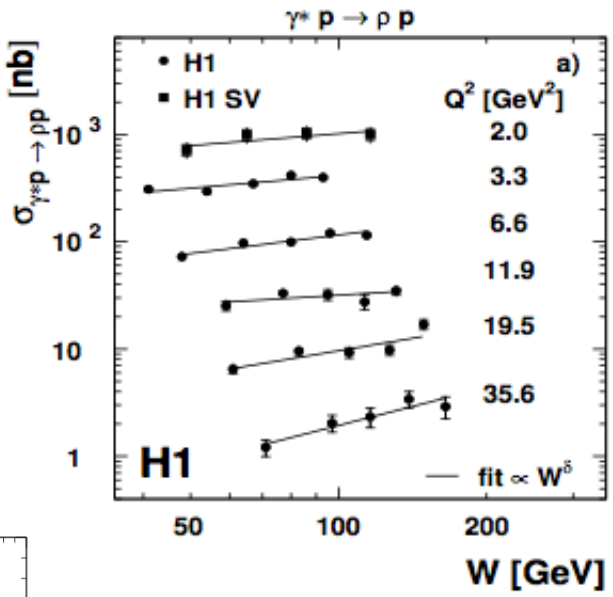
→cross section much smaller

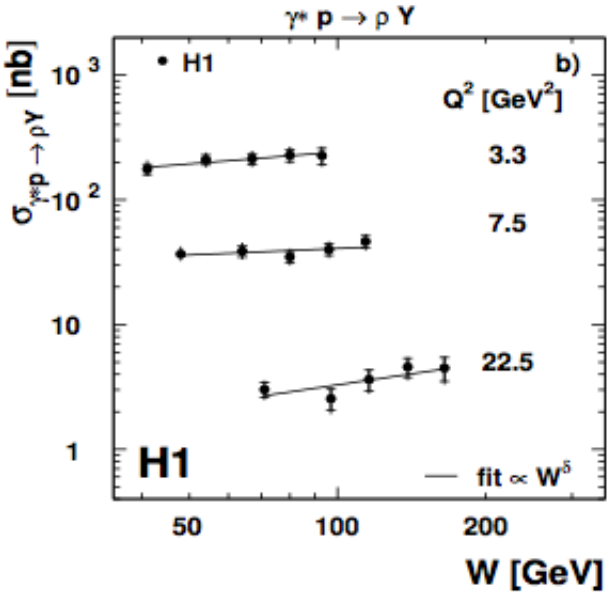
→dipole resolves partons in the proton:
$\sigma \sim (xg)^2$ → large δ

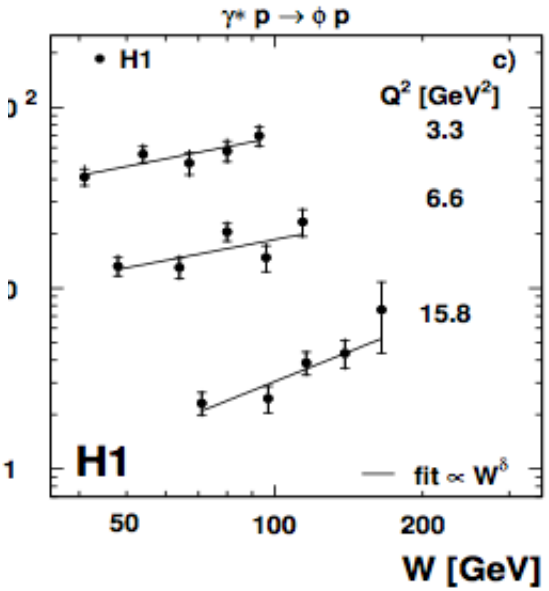
VM data can help determine gluon density!

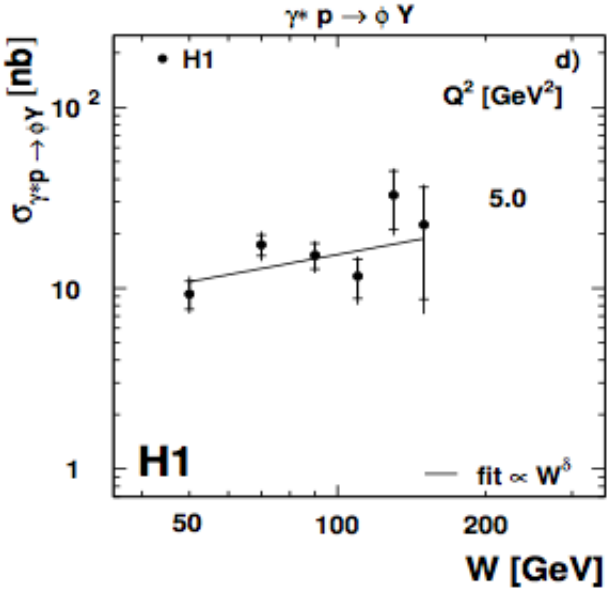
Here scale is M_{VM} – same observed when varying Q^2 for a given VM


ZEUS
γ*p→ρ⁰p
ZEUS 120 pb⁻¹
ZEUS 94
ZEUS 95
δ
Q² (GeV²)
[DESY 07-118]


γ* p → ρ p
H1
H1 SV
a)
Q² [GeV²]
2.0
3.3
6.6
11.9
19.5
35.6
H1
fit ∝ W^δ
σ_γ*p→ρp [nb]
W [GeV]


γ* p → ρ Y
H1
b)
Q² [GeV²]
3.3
7.5
22.5
H1
fit ∝ W^δ
σ_γ*p→ρY [nb]
W [GeV]

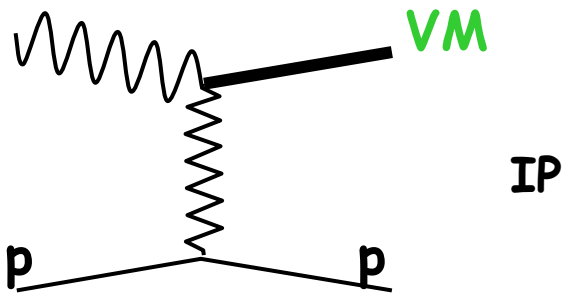

γ* p → φ p
H1
c)
Q² [GeV²]
3.3
6.6
15.8
H1
fit ∝ W^δ
W [GeV]


γ* p → φ Y
H1
d)
Q² [GeV²]
5.0
H1
fit ∝ W^δ
σ_γ*p→φY [nb]
W [GeV]

[DESY 09-093]

Transition soft → hard

Soft - Regge



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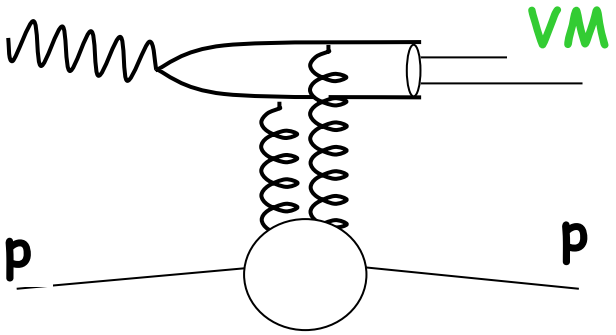

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$$\frac{d\sigma}{dt} \propto e^{-b|t|}$$

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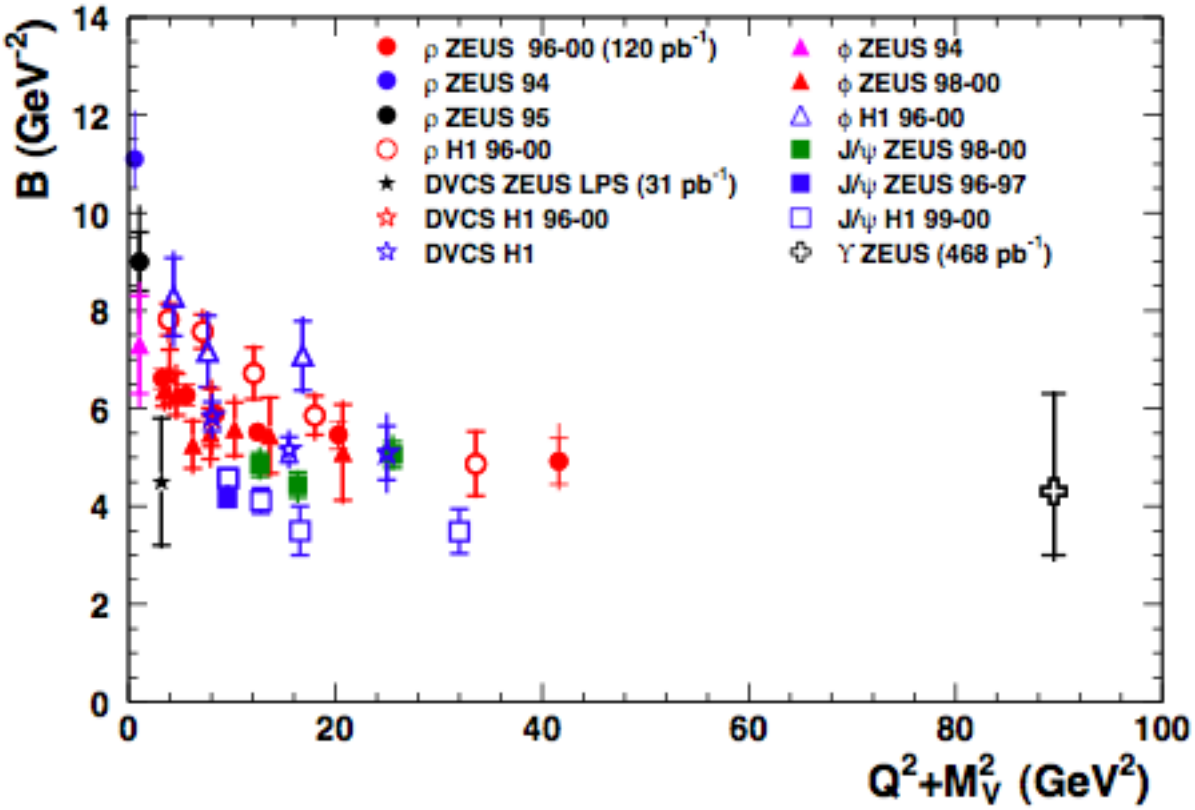
Transition soft → hard: t-slope dependence



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

As in optical diffraction, size of diffractive cone related to size of interacting objects

$b \approx b_{VM} + b_p$

Transition soft → hard: Pomeron trajectory

From Regge phenomelonogy

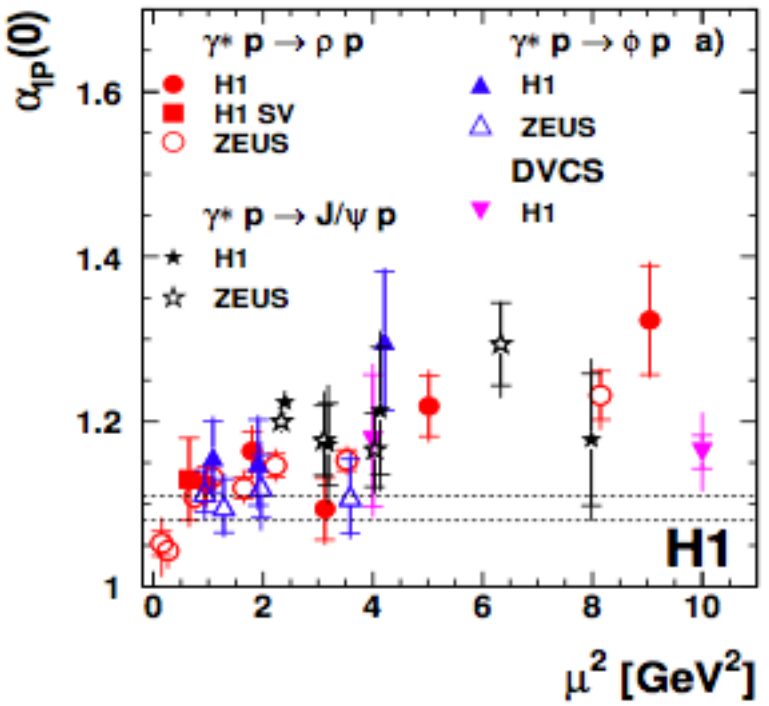
$$\alpha_{IP}(t) = \alpha_{IP}(0) + \alpha'_{IP}(t)$$

Transition soft → hard: Pomeron intercept

From Regge phenomelonogy

$$\alpha_{IP}(t) = \alpha_{IP}(0) + \alpha'_{IP}(t)$$

$$\sigma^{\gamma p \to Vp}(W) \propto (W^2)^{2\alpha_{IP}(t)-2}$$



[DESY 09-093]

Relationship between W dependences of inclusive DIS and vector meson production in presence of a sufficiently large scale

$$\alpha_{IP}(0) = 1 + \lambda \qquad F_2(x,Q^2) \propto x^{-\lambda(Q^2)}$$

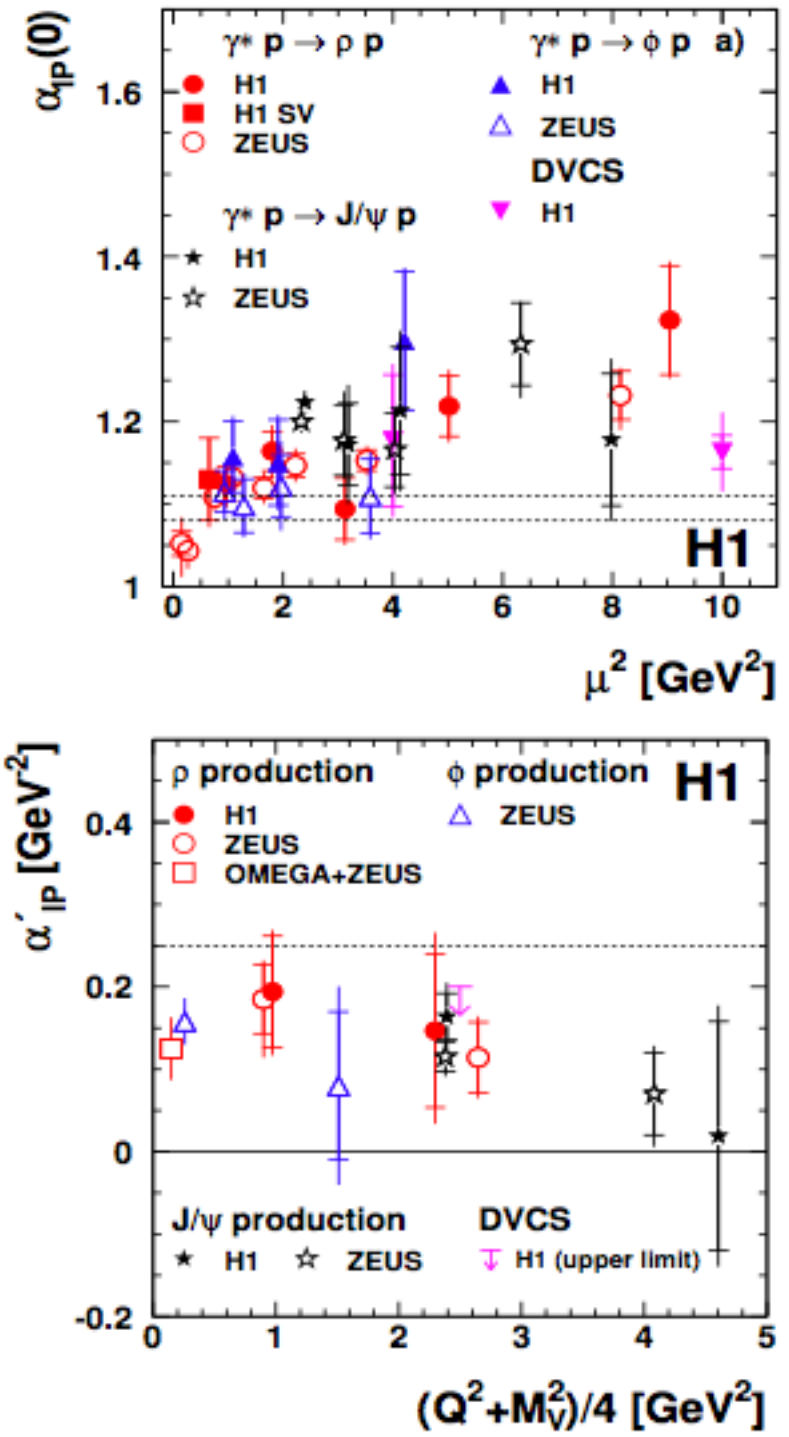
Transition soft → hard: Pomeron slope

From Regge phenomelonogy

$$\alpha_{IP}(t) = \alpha_{IP}(0) + \alpha'_{IP}(t)$$

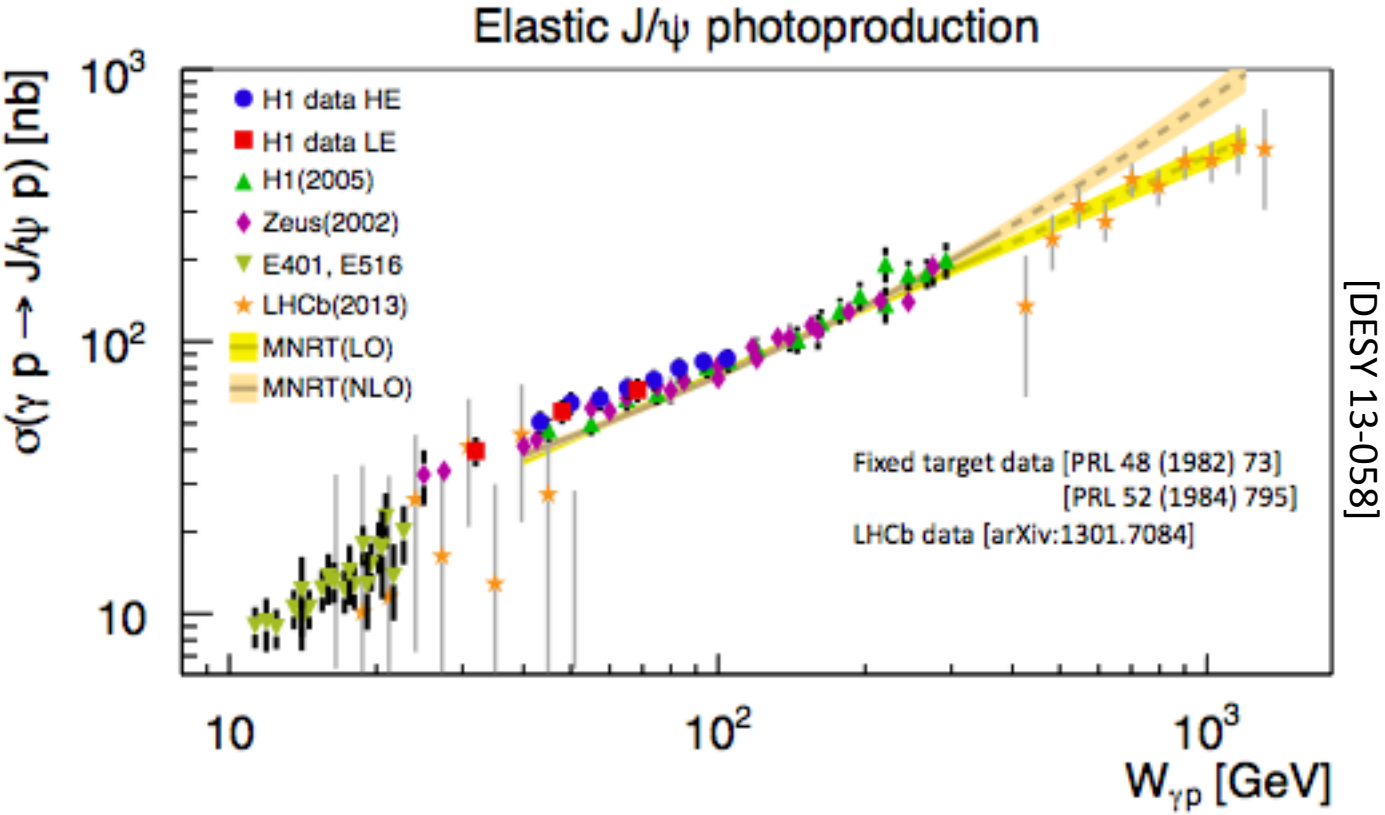
$$\sigma^{\gamma p \to Vp}(W) \propto (W^2)^{2\alpha_{IP}(t)-2}$$

$$b(W) = b_0 + 4\alpha'_{IP} \ln \frac{W}{W_0}$$



[DESY 09-093]

Comparison with (pQCD) models



[DESY 13-058]

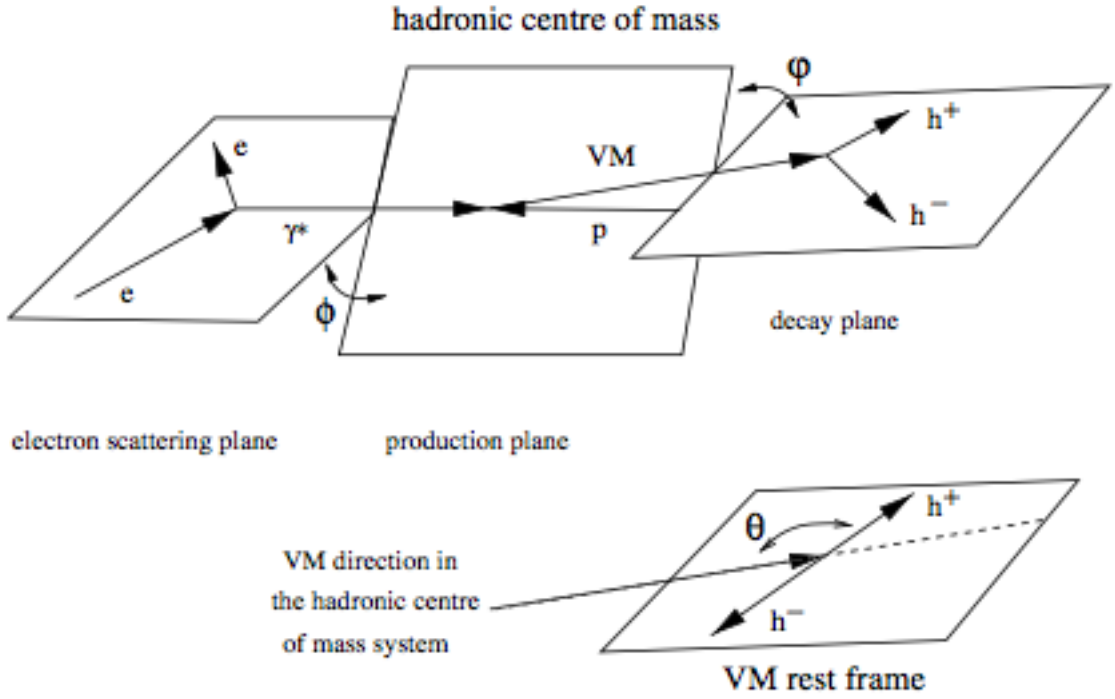
LO and NLO fits to previous J/ψ measurements at HERA [PLB 662 (2008) 252]

Fits extrapolated to higher $W_{\gamma p}$

LO fit describes LHCb data

Angular distributions

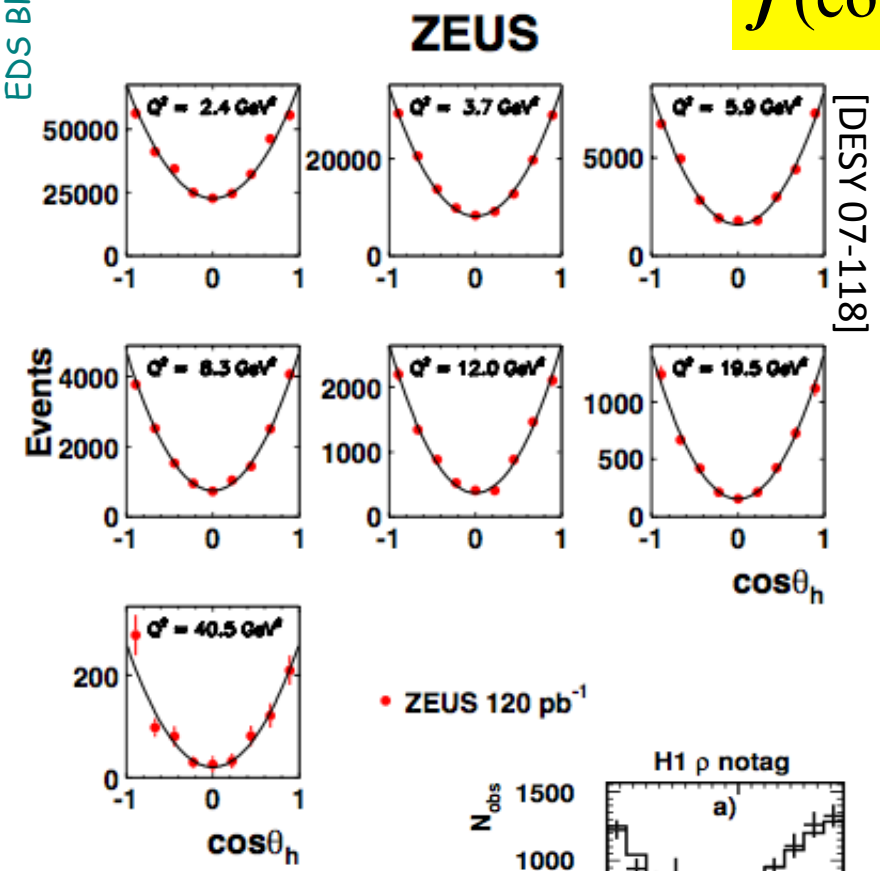
Production and decay angles



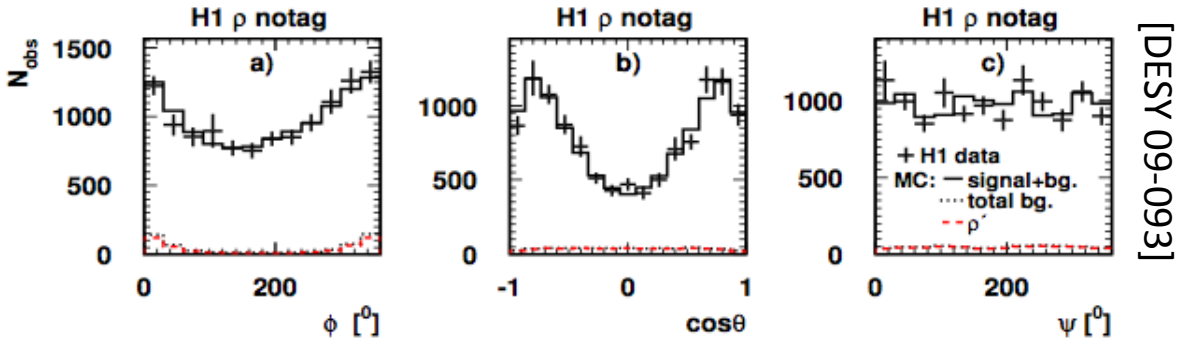
Angles parameterized with spin density matrix elements (SDME)

Angular distributions → SDME

$$f(\cos\theta_h) \propto (1 - r_{00}^{04}) + (3r_{00}^{04} - 1)\cos^2\theta_h$$



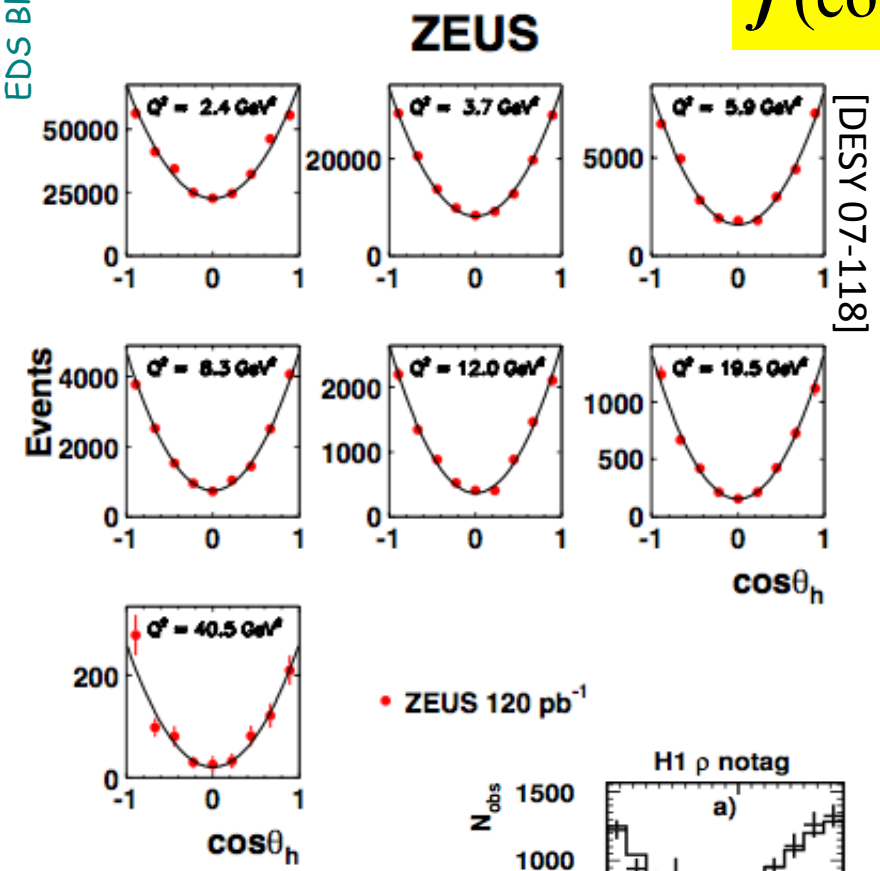
[DESY 07-118]



[DESY 09-093]

Angular distributions → σ_L/σ_T

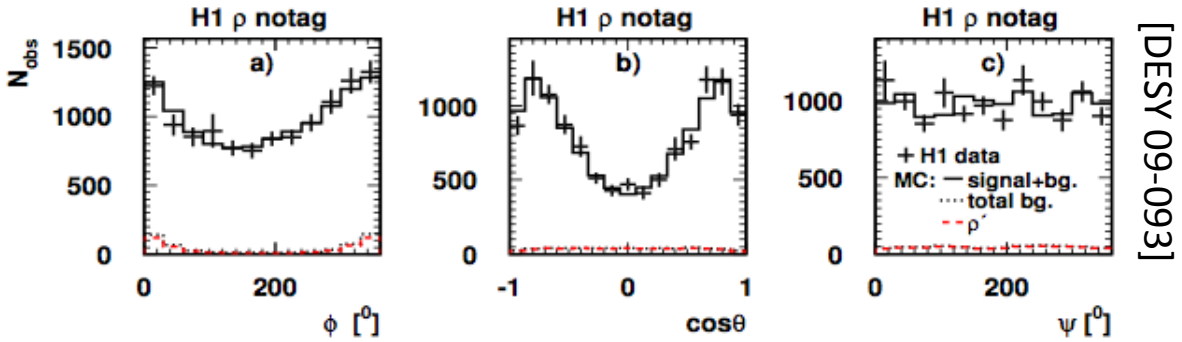
$$f(\cos\theta_h) \propto (1 - r_{00}^{04}) + (3r_{00}^{04} - 1)\cos^2\theta_h$$



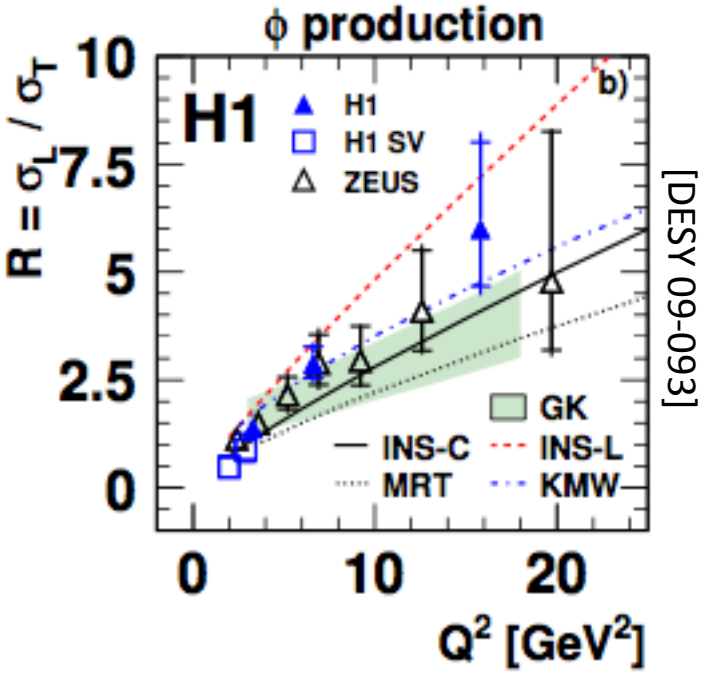
$$R \equiv \frac{\sigma_L}{\sigma_T} = \frac{1}{\varepsilon}\frac{r_{00}^{04}}{1 - r_{00}^{04}}$$ using SCHC

ε - ratio of longitudinal- to transverse-photon fluxes (<ε> = 0.996)

$$r_{00}^{04} = \frac{\sigma_L}{\sigma_L + \sigma_T} = \frac{\sigma_L}{\sigma_{tot}}$$



σ_L/σ_T



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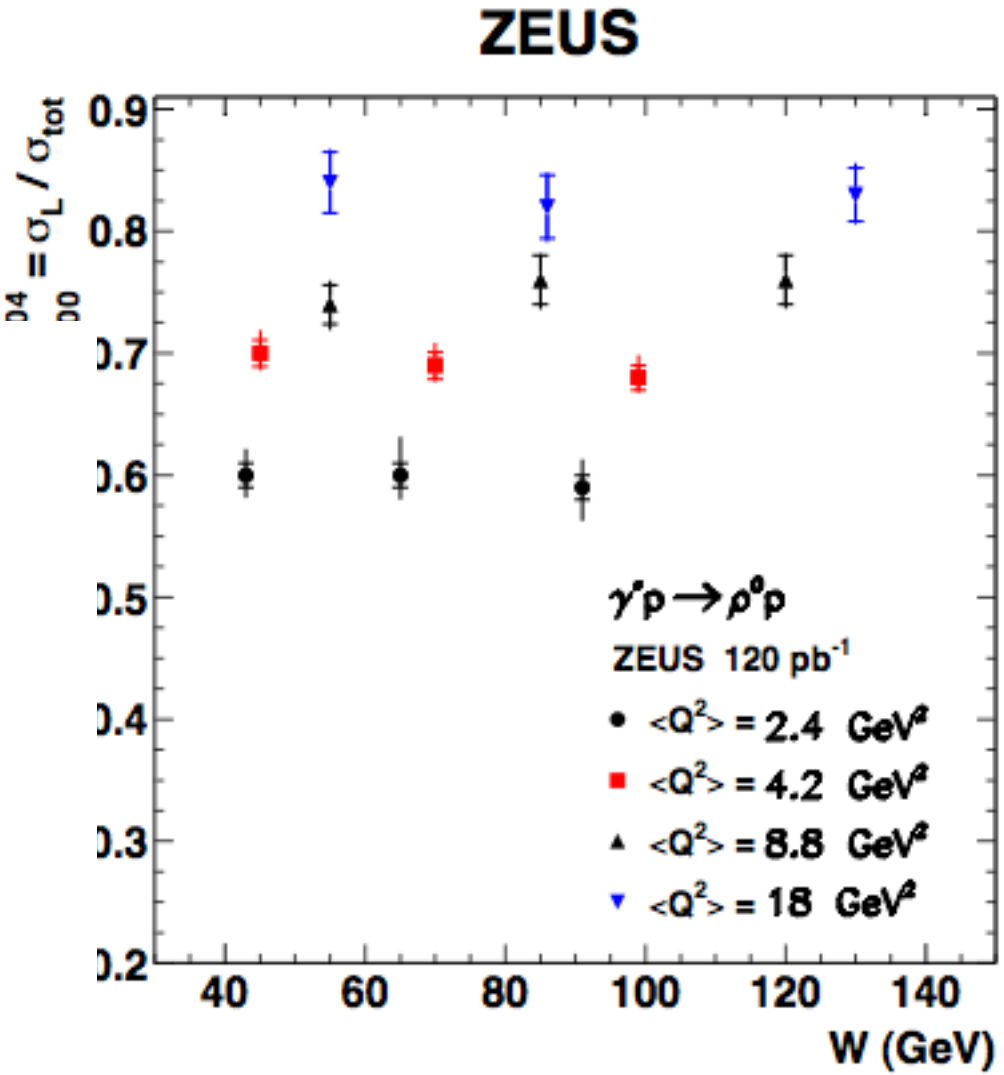
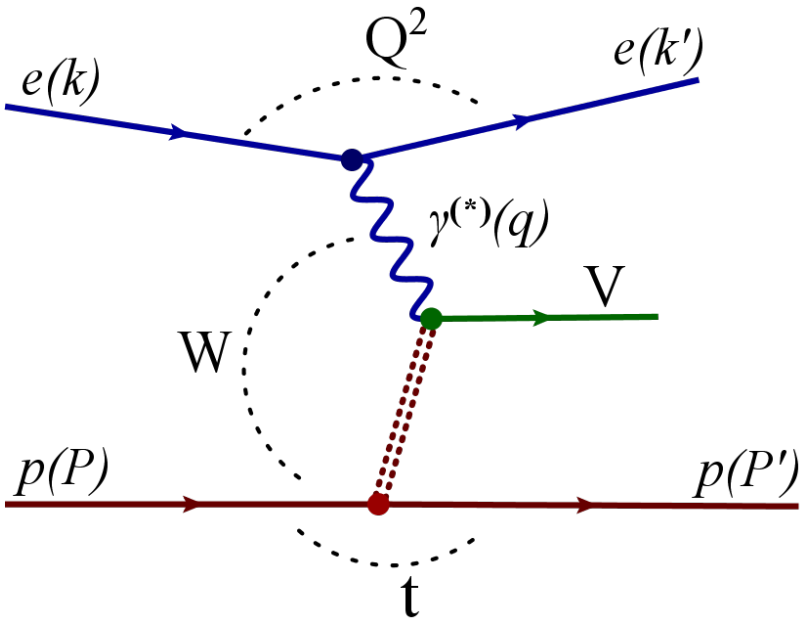


[DESY 07-118]

Vertex factorisation

Test factorization of VM production amplitudes into
- photon vertex governing Q^2 dependence
- proton vertex governing t dependence



Vertex factorisation : ratio $\sigma_{p.\ diss.}/\sigma_{el.}$ at $|t| = 0$

Test factorization of VM production amplitudes into
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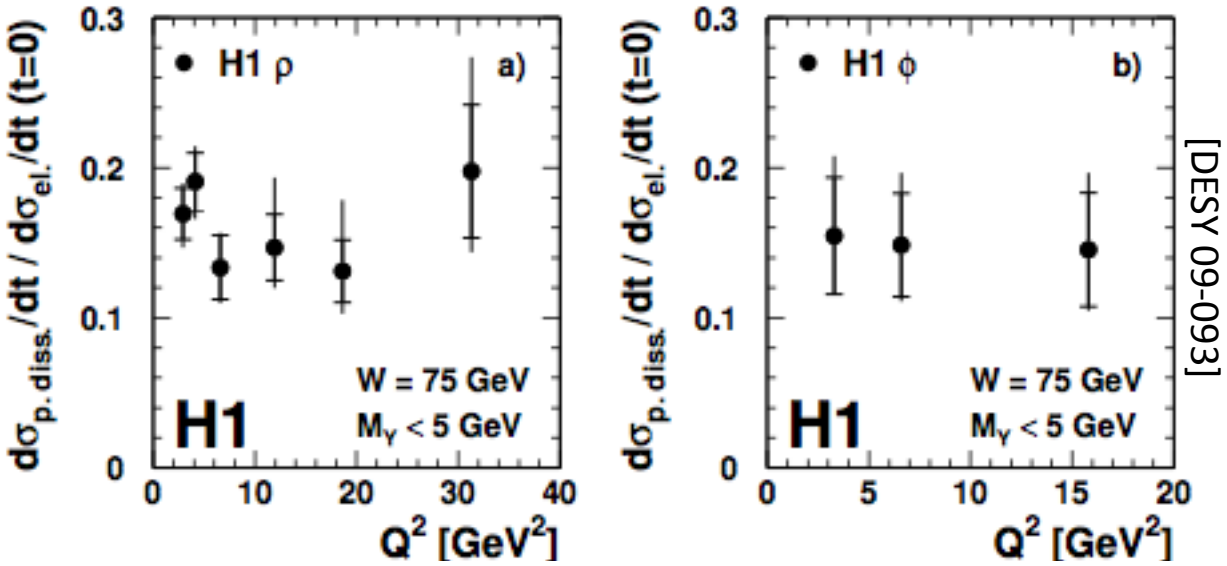


[DESY 09-093]

$$\frac{d\sigma_{p.\ diss.}^{M_Y<5\ GeV}/dt}{d\sigma_{el.}/dt}(t=0)(\rho) = 0.159 \pm 0.009\ (stat.)\ ^{+0.011}_{-0.025}\ (syst.) \pm 0.004\ (norm.)\ ,$$

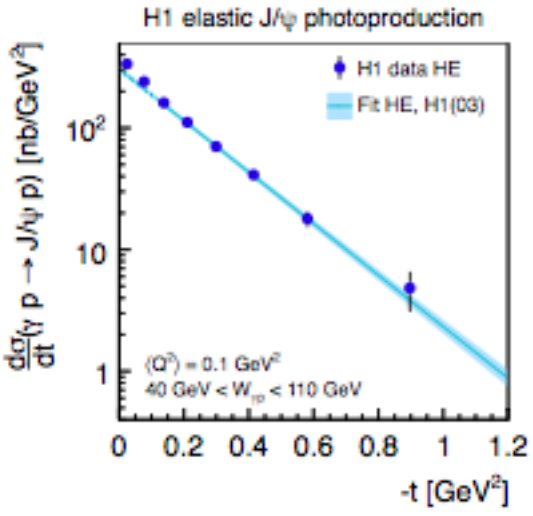
$$\frac{d\sigma_{p.\ diss.}^{M_Y<5\ GeV}/dt}{d\sigma_{el.}/dt}(t=0)(\phi) = 0.149 \pm 0.021\ (stat.)\ ^{+0.035}_{-0.036}\ (syst.) \pm 0.003\ (norm.)\ .$$

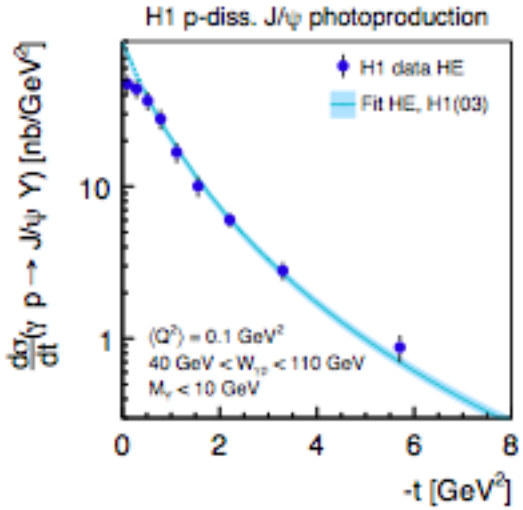
No Q^2 dependence

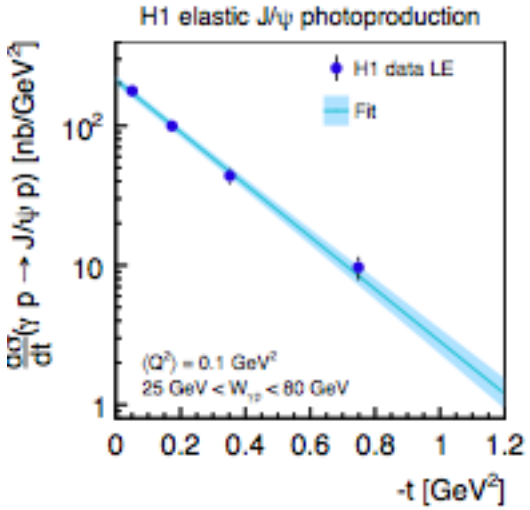
Within uncertainties, ratios for ρ and ϕ are compatible

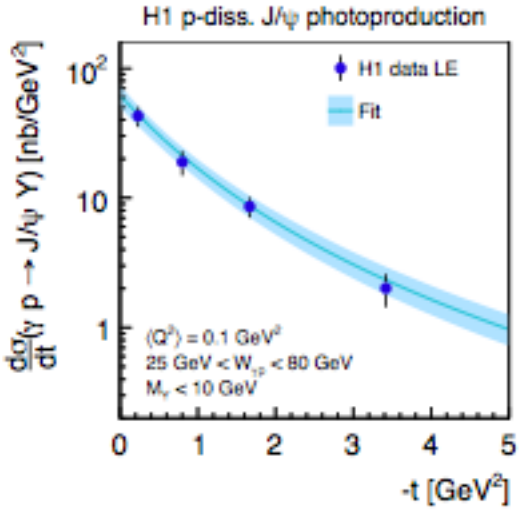
→ Vertex factorisation

Elastic vs pdiss: t-slope dependence







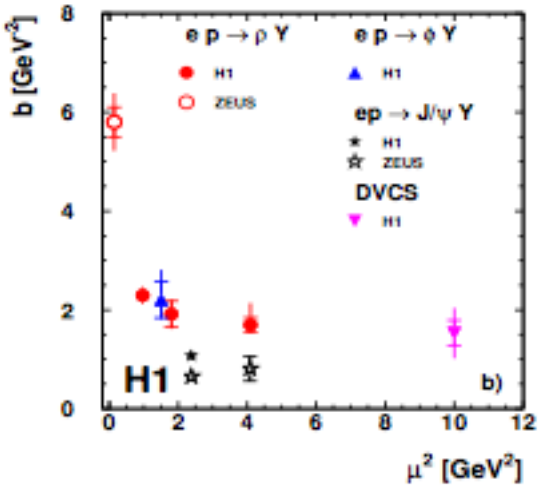


Simultaneous* fit to the forms

- $\frac{d\sigma_{el}}{dt} = N_{el} e^{-b_{el}|t|}$ elastic
- $\frac{d\sigma}{dt} = (N_{pd}(1+\frac{b_{pd}}{n})|t|)^{-n}$ p-diss

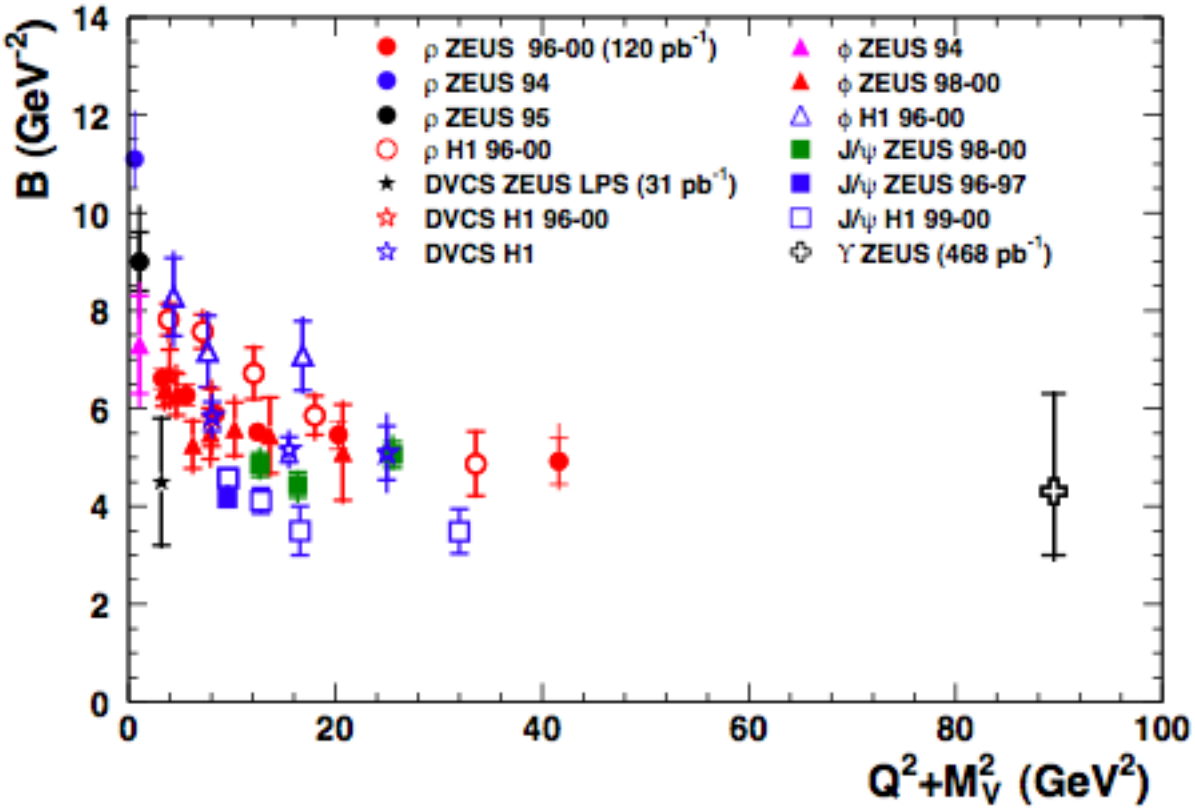
*Fit includes old data H1(03) [PLB 568 (2003) 205]

→ b_{el} = 4.88 ± 0.15 GeV^{-2}(HE)
b_{pd} = 1.79 ± 0.12 GeV^{-2}(HE)
b_{el} = 4.3 ± 0.2 GeV^{-2} (LE)
b_{pd} = 1.6 ± 0.2 GeV^{-2} (LE)



[EPJ C73 (2013) 2466]

Transition soft → hard: t-slope dependence



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

As in optical diffraction, size of diffractive cone related to size of interacting objects

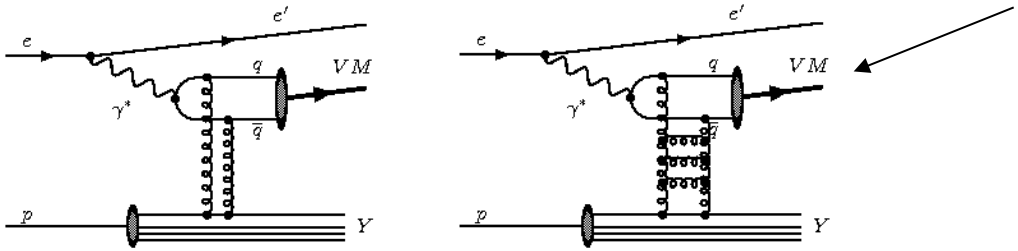
$b \approx b_{VM} + b_{ps}$

For p.diss. proton breaks → $b_{p.diss.}$ smaller than $b_{el.}$

High |t| vector mesons and photons

Among best processes to see BFKL pomeron

standard DGLAP or BFKL evolution equations

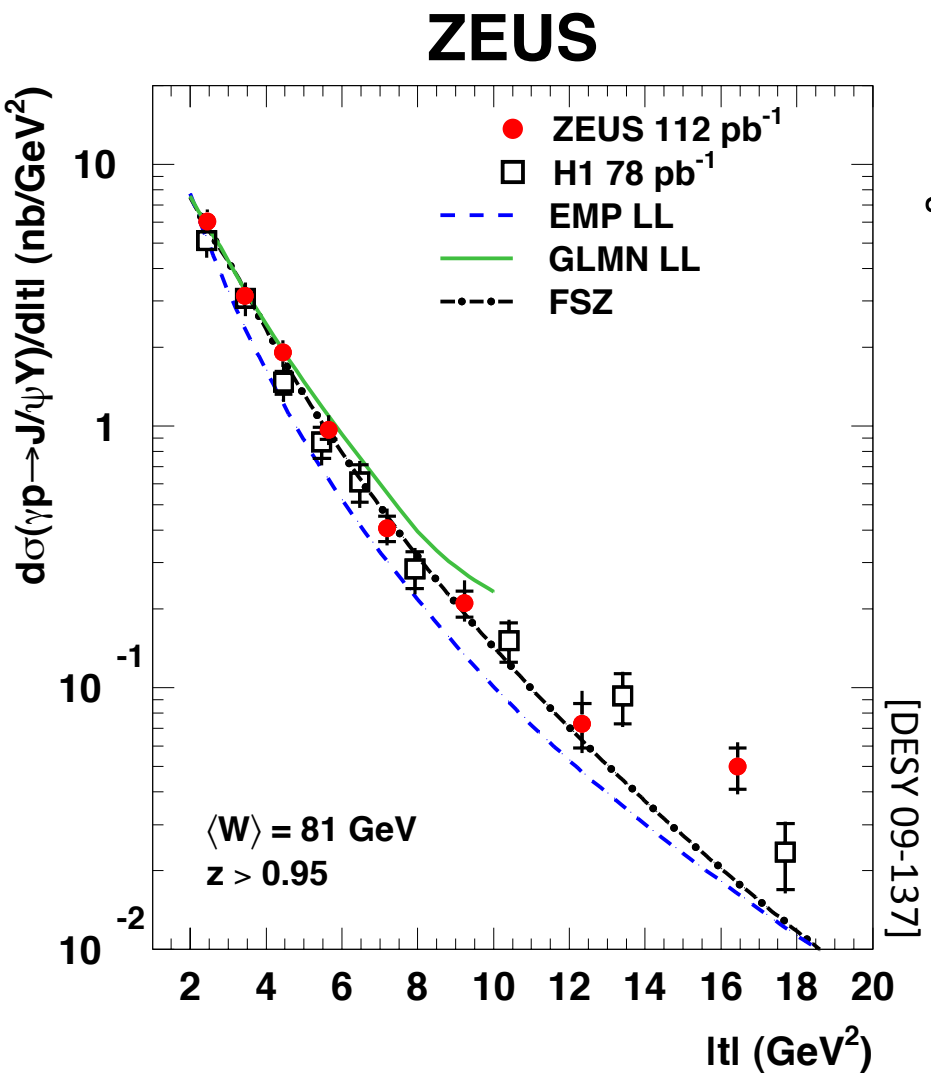


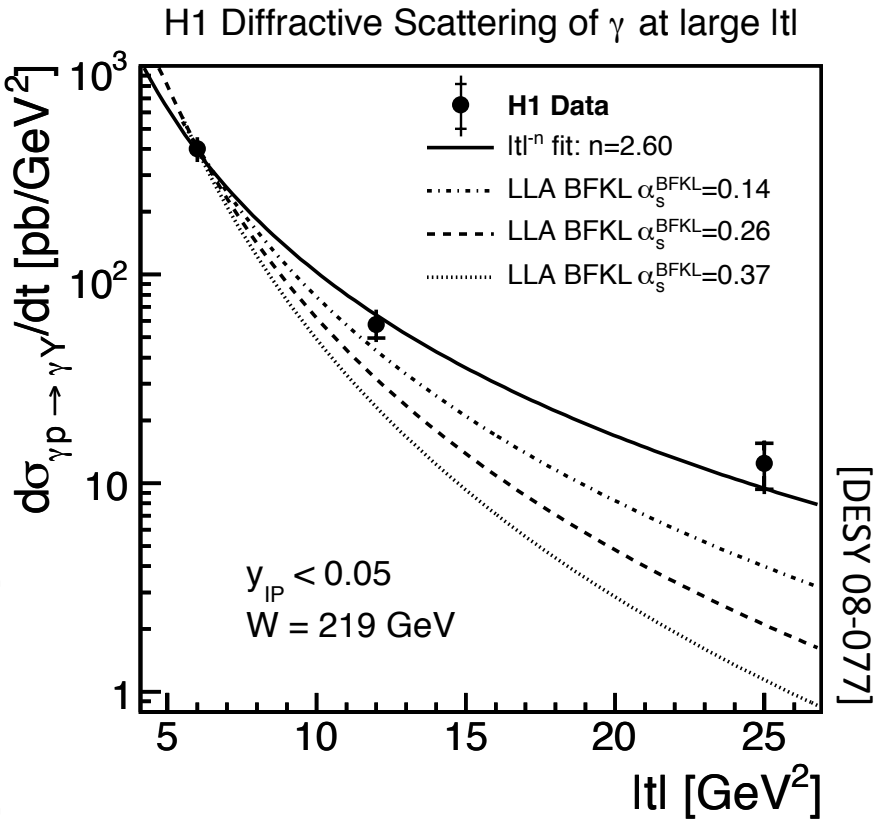
High t domain little explored so far

Proton dissociative processes dominate at high t

ZEUS and H1 results with light VM, J/psi, exclusively produced photons

High |t| vector mesons and photons





Vector meson production at HERA, whatsapp

Rich harvest documented by tens of papers

Large W interval

Wide range of several scales (Q^2, t, M_{VM})

Presently H1 and ZEUS are finalizing analyses of post-upgrade data

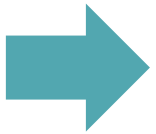
- key measurements repeated with full statistics

- runs at reduced center of mass energy originally devoted to F_L extraction allow studies with different kinematics

- low cross section processes benefit from higher lumi

☐ **Recent H1/ZEUS results**

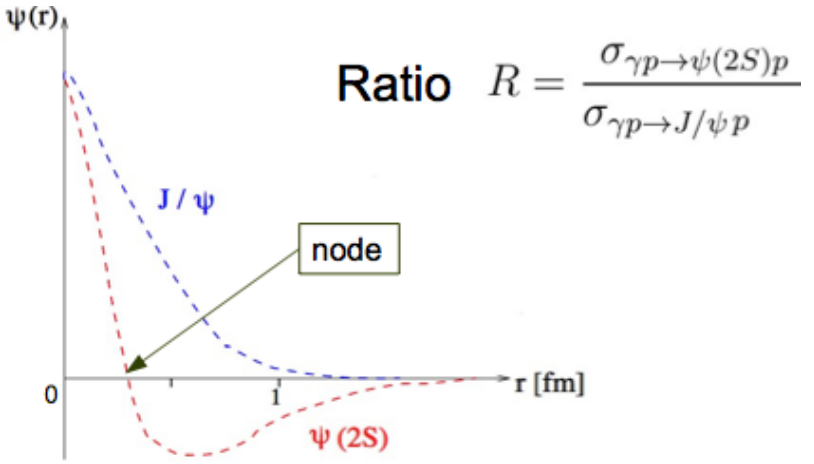
- Exclusive dijet production [DESY 15-070]
- Ψ'/J/psi [ZEUS prel-15-002]
- ρ^0 production with a leading neutron [H1prelim-14-013]



Ψ'/ψ ratio

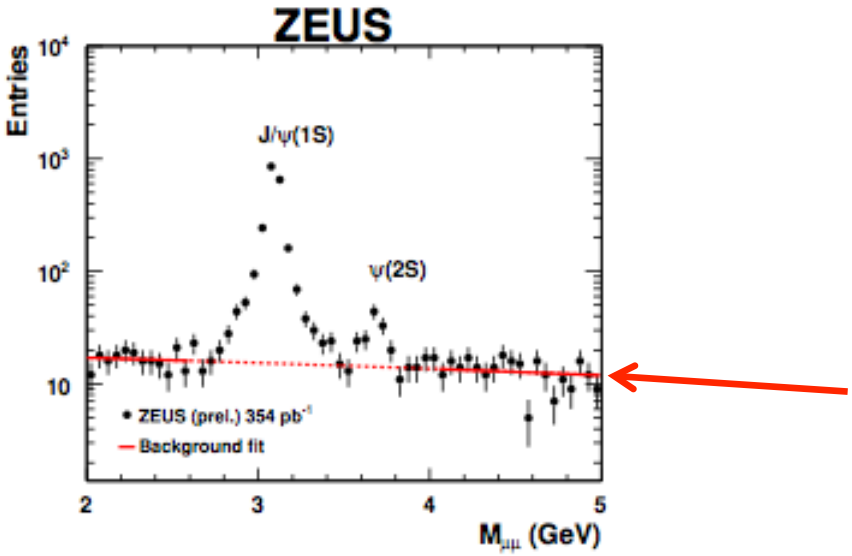
Motivation and event selection

[ZEUS prel-15-002]

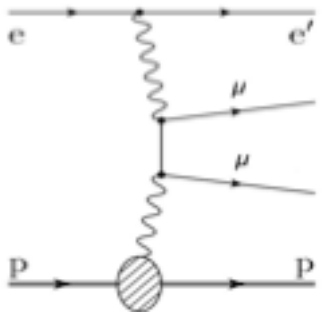


Ψ(2s) wave function different from J/ψ wave function

pQCD models predict R ≈ 0.17 (photoproduction) and rise of R with Q^2

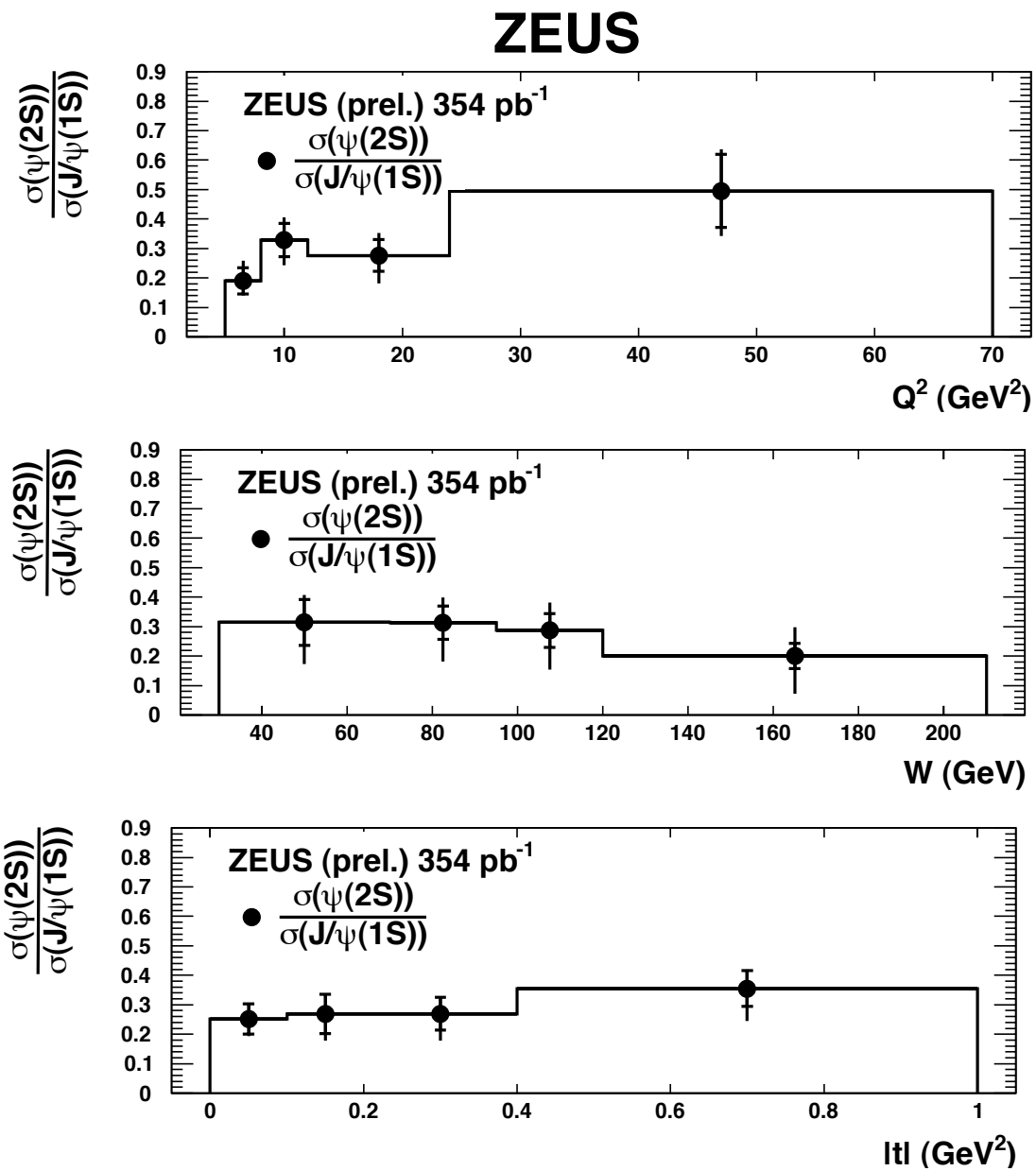


Ψ(2S) → J/ψ π⁺ π⁻; J/ψ → μ⁺ μ⁻
Ψ(2S) → μ⁺ μ⁻
J/ψ → μ⁺ μ⁻



Results

[ZEUS prel-15-002]



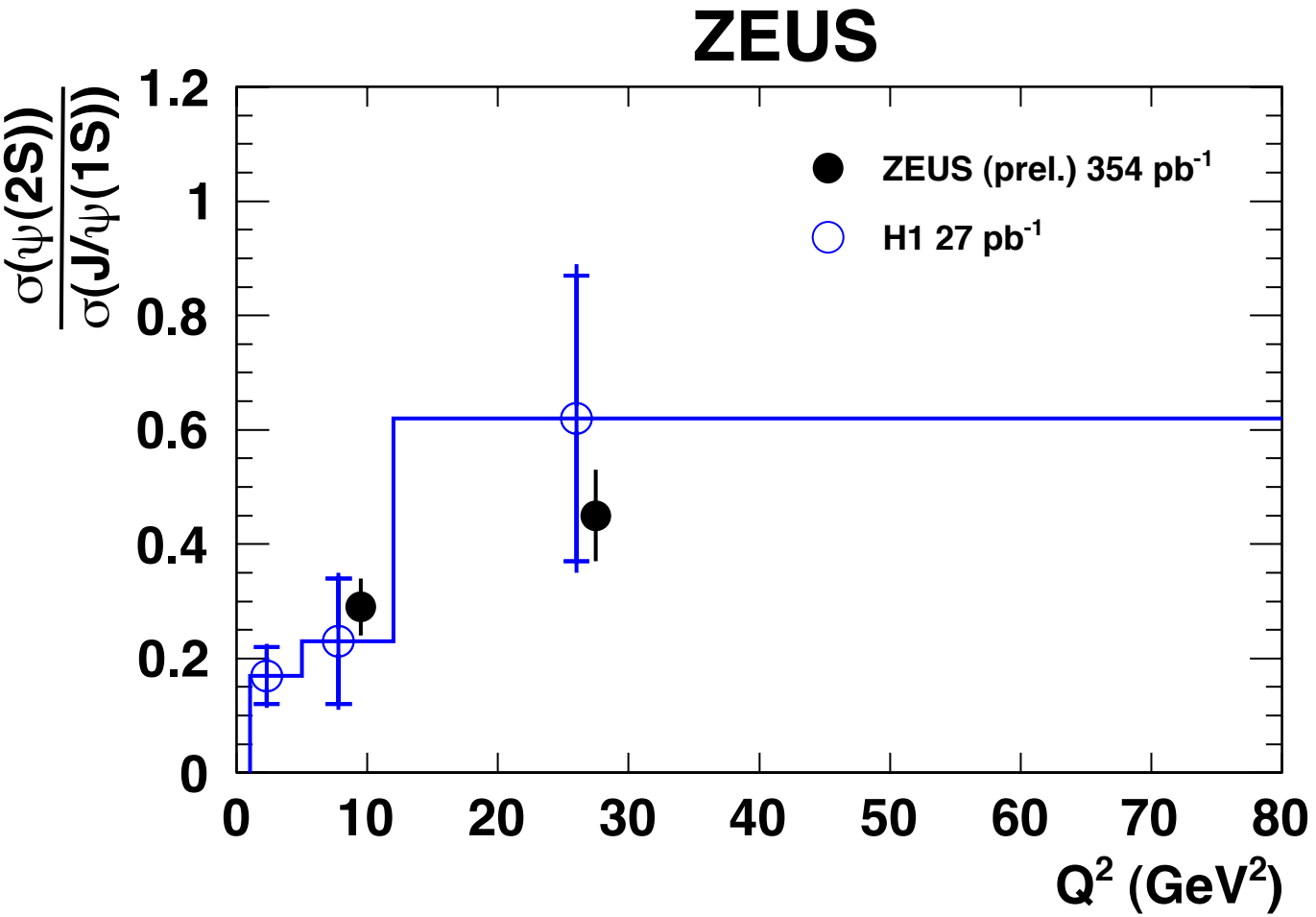
→Increase with Q^2

→Independent of W

→ Independent of |t|

[ZEUS prel-15-002]

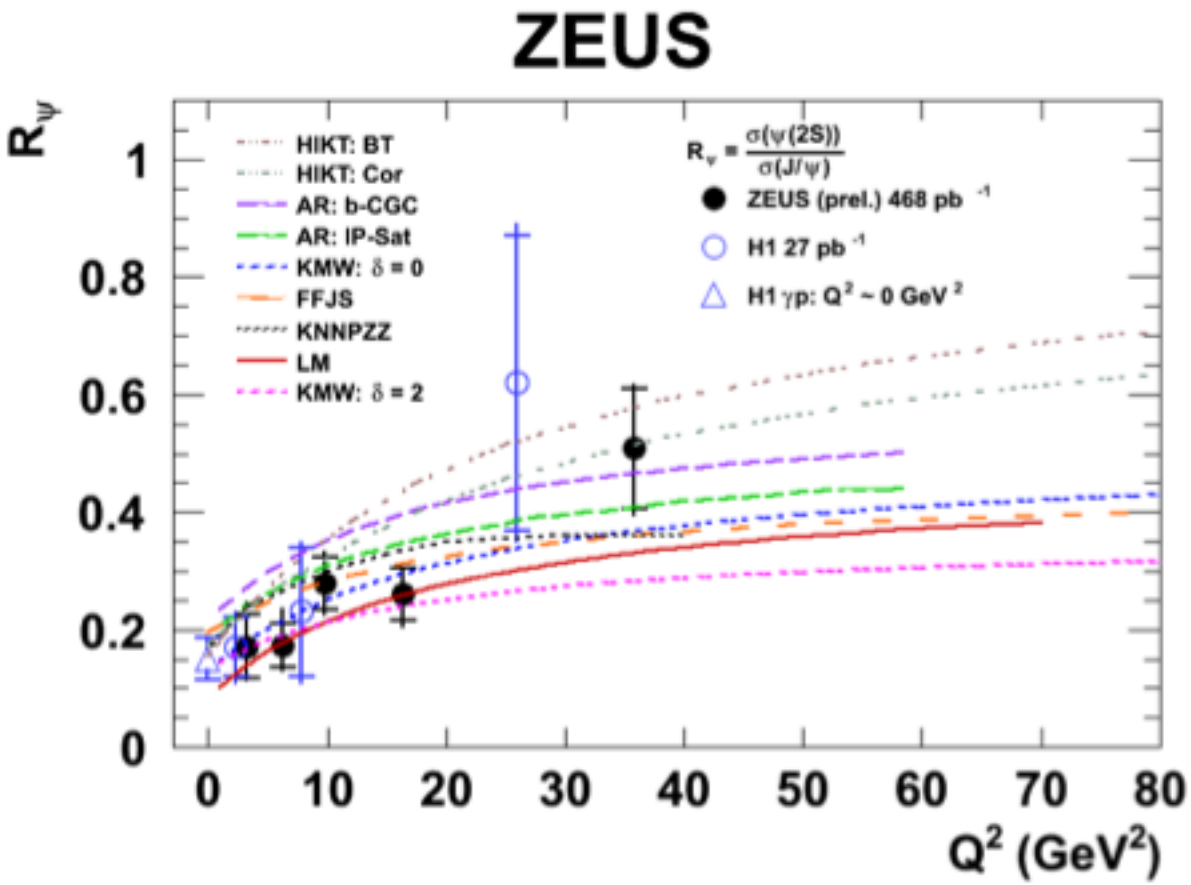
Comparison with H1 earlier measurements



→Much larger luminosity in ZEUS measurement (HERA I + HERA II)

Comparison with models

[ZEUS prel-15-002]

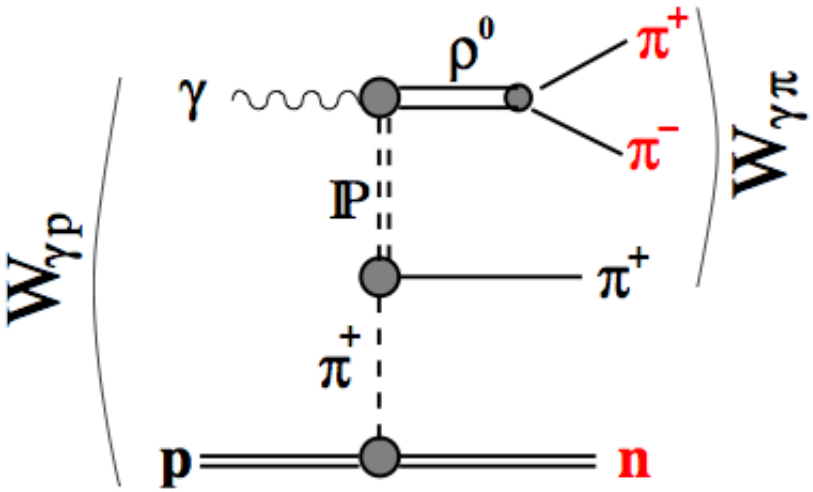


HIKT, Hufner et al.:dipole model, dipole-proton constrained by inclusive DIS data
AR, Armesto and Rezaeian: impact parameter dependent CGC and IP-Sat model
KMW,Kowalski Motyka Watt: QCD description and universality of quarkonia production
FFJS, Fazio et al.: two component Pomeron model
KNNPZZ, Nemchik et al.: color-dipole cross section derived from BFKL generalised eq.
LM, Lappi and Mäntysaari : dipole picture in IP-Sat model

ρ^0 photoproduction with a leading neutron

[H1prelim-14-01]

Exclusive ρ^0 photoproduction with forward n



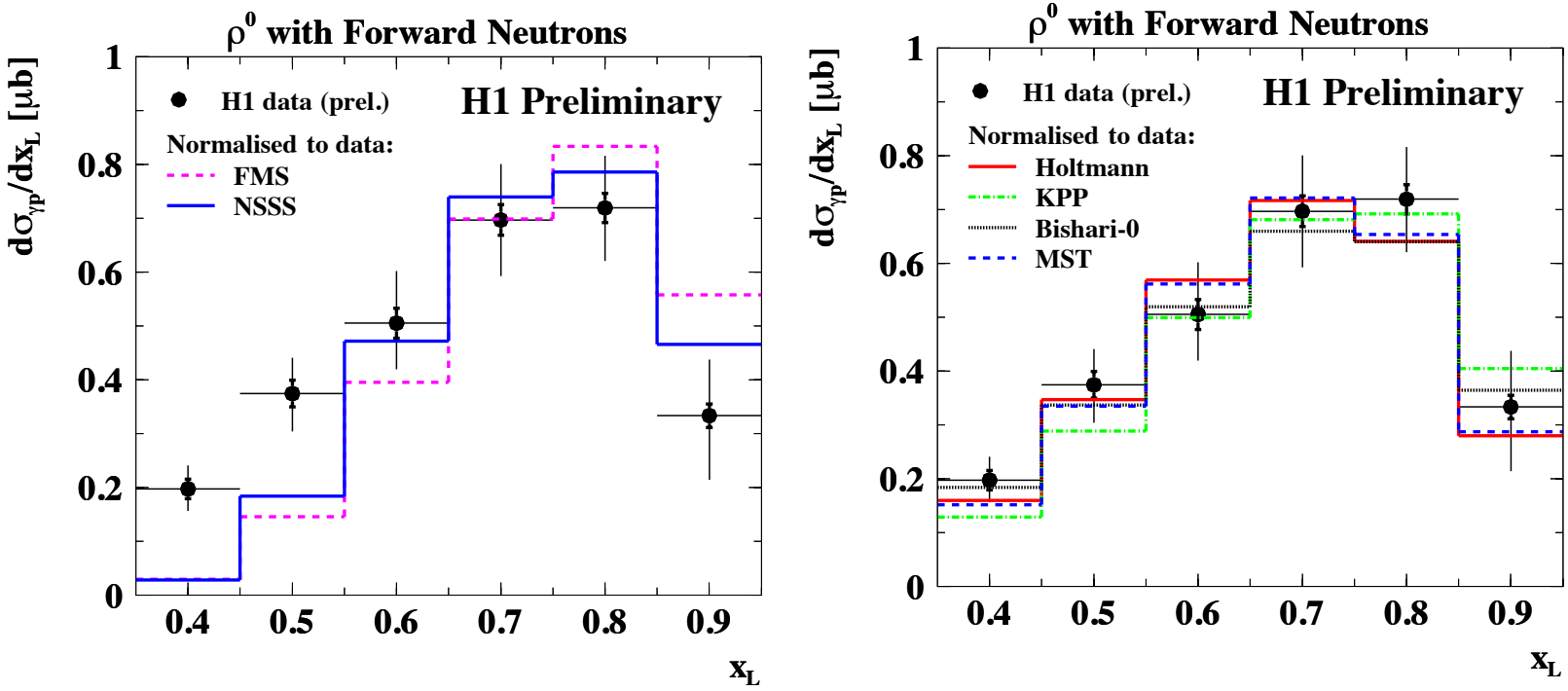
x_L = fraction of incoming p momentum carried by n

Mean W of 22 GeV → soft regime

- The photon emitted from the electron beam scatters elastically on the pion emitted from the proton producing a ρ^0
- Theoretically: exchange of two Regge trajectories in a double-peripheral scattering process

[H1prelim-14-01]

Exclusive ρ^0 photoproduction with forward n

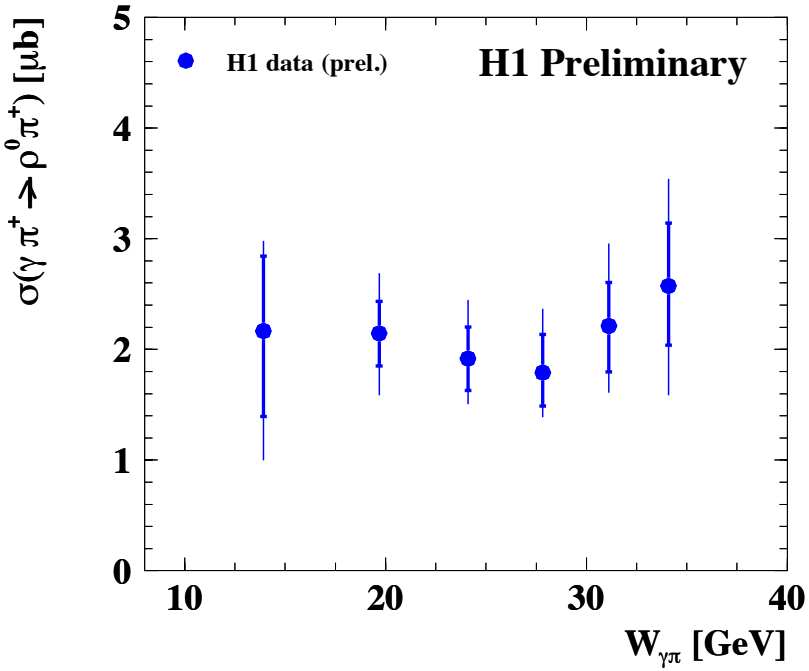


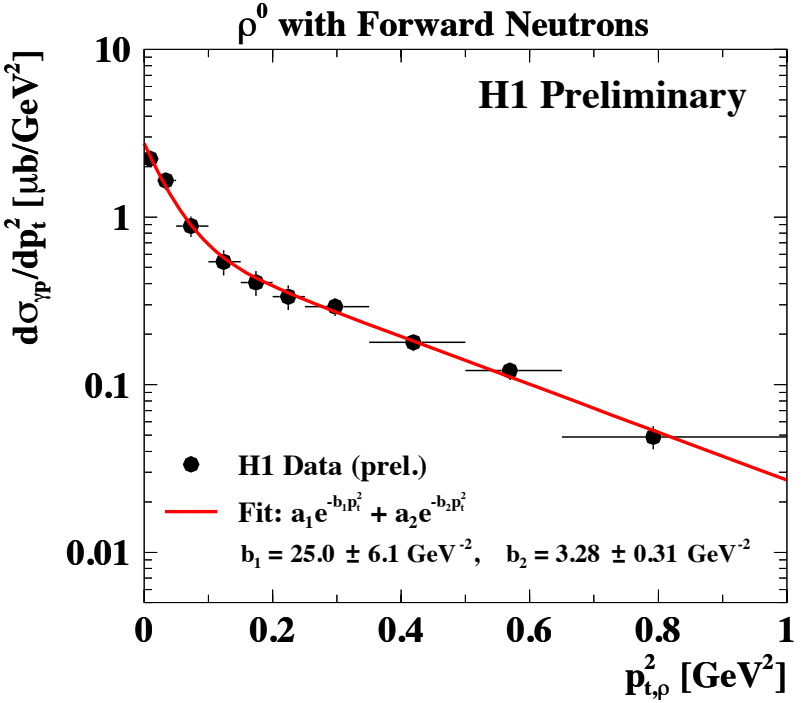
Models differ in the implementation of the pion flux

→ Shape generally well described by predictions

[H1prelim-14-01]

Exclusive ρ^0 photoproduction with forward n





$\sigma(\gamma\pi)/\sigma(\gamma p) = 0.25 \pm 0.06$

In agreement with a previous ZEUS result

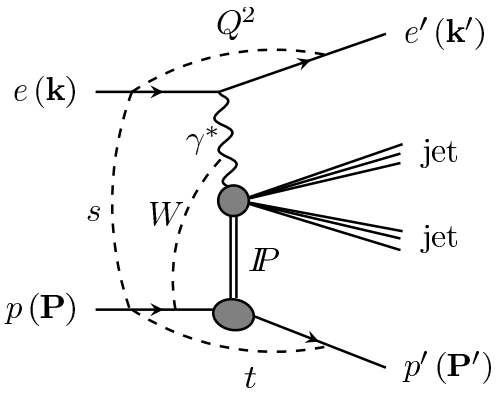
Lower than expectations
→ absorption?

Two slopes as predicted for a double-peripheral process

Exclusive dijet production in DIS

Discussed by A. Valkarova

Comparison to model predictions: A parameter

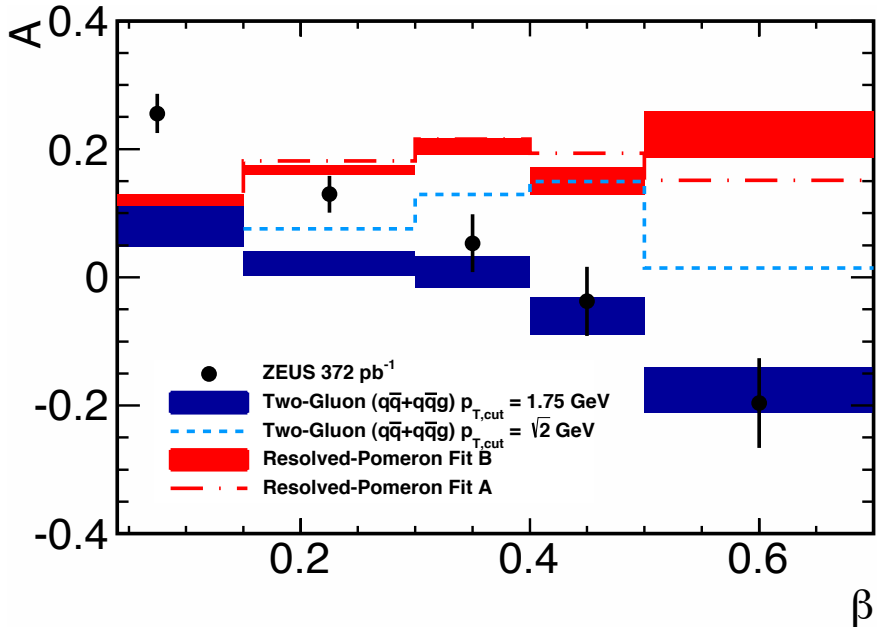


Resolved Pomeron model

Predictions based on diffractive g(x) from fits to the H1 data (H1 Fit A and B)

→ **Almost constant positive A through full β range**

ZEUS [DESY 15-070]



Two-gluon exchange model

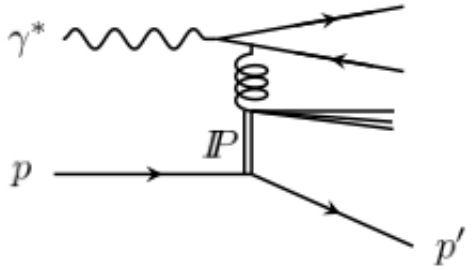
Predictions based on the GRV parameterisation of the gluon density

→ **A varies from positive to negative**

→ **Qualitative agreement for 0.3 < β < 0.7**

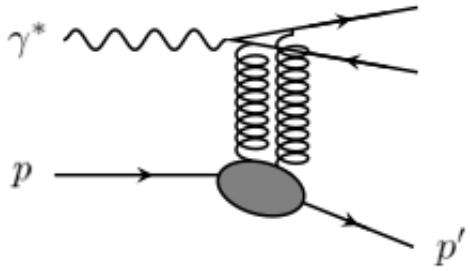
Models of qqbar production in diffractive DIS

Resolved Pomeron model



- Gluon emitted from the IP
- qqbar pair produced via boson-gluon fusion
- **Positive A**
- Cross section sensitive to the **diffractive gluon distribution in the proton**

Two-gluon exchange model



- Virtual photon fluctuates into qqbar, which then fluctuates to two gluons from the proton
- **Negative A**
- Cross section sensitive to the **gluon distribution in the proton**
- Emission of additional gluon also contributes to qqbar production

In summary

- Unique HERA data on exclusive processes providing new insights for the understanding of QCD and the interplay of soft and hard diffraction
- Presently H1 and ZEUS are finalizing their analyses of post-upgrade data
  - key measurements repeated with full statistics
  - low cross section processes benefit from higher lumi
- First HERA measurement of **exclusive dijets in DIS**: two-gluon exchange model agrees with the data within (large) uncertainties
- **$\psi'/J/\psi$** measured by ZEUS with full available statistics: ratio grows with Q^2 and is constant with W and t
- Exclusive ρ^0 photoproduction associated with leading neutron, measured by H1, used to extract the **elastic cross section $\sigma(\gamma\pi^+ \rightarrow \rho^0\pi^+)$** for the first time at HERA

What HERA VM data taught us (and still teach)

- The cross section rises with W and its logarithmic derivative in W, δ, increases with Q^2
- The effective Pomeron trajectory has a larger intercept than that extracted in soft interactions
- The exponential slope of the t distribution decreases with Q^2 and levels off at about b of 5 GeV^{-2}
- Proton and photon vertex factorize
- Where applicable, perturbative QCD calculations are a complementary source of information on the gluon content in the proton
- The ratio of cross sections induced by longitudinally and transversely polarised virtual photons increases with Q^2 , but is independent of W and |t|