Diffractive Scattering

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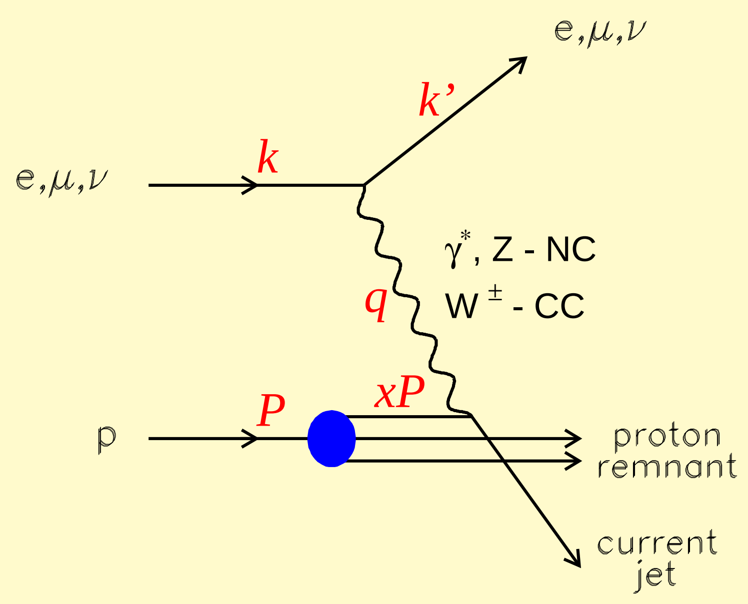
OUTLINE

- **Interest in diffraction**
- **Inclusive diffraction, from ep to $p\bar{p}$**
- **Exclusive processes, from VM to DVCS**
- **Summary**

DEEP INELASTIC SCATTERING



- Q^2 - virtuality of exchanged boson

$$Q^2 = -q^2 = -(k-k')^2$$

- s - lp centre of mass energy

$$s = (k+P)^2$$

- W - hadronic centre of mass energy

$$W^2 = (q+p)^2$$

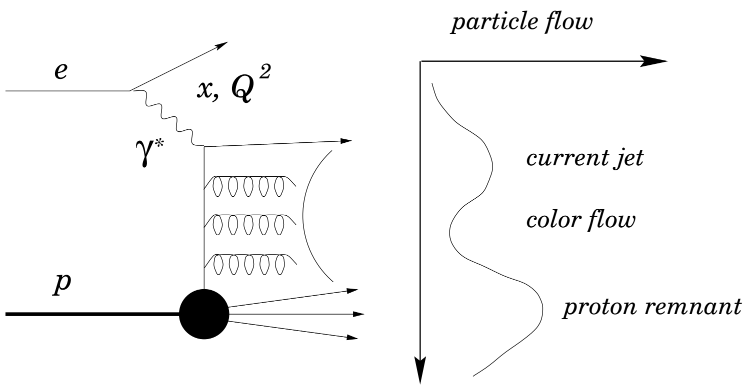
- x - Bjorken variable

$$x = \frac{Q^2}{2P\cdot q} = \frac{Q^2}{Q^2+W^2}$$

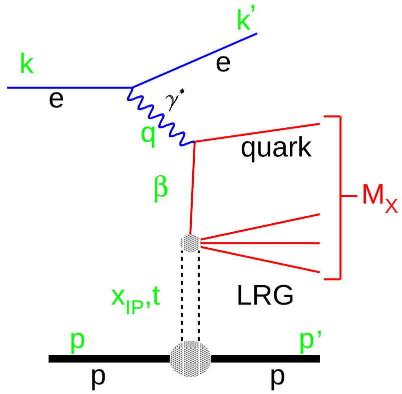
- y - inelasticity

$$y = \frac{P\cdot q}{P\cdot k}$$

Inclusive diffraction - large rapidity gaps



DIS-DGLAP



DIS-Diffraction

$$x_{I\!P} = \frac{q \cdot (p - p')}{q \cdot p} \simeq \frac{Q^2 + M_X^2}{Q^2 + W^2}$$

$$\beta = \frac{Q^2}{2q \cdot (p - p')} \simeq \frac{Q^2}{Q^2 + M_X^2}$$

$$t = (p - p')^2 \qquad x = x_{I\!P} \cdot \beta$$

DIFFRACTIVE STRUCTURE FUNCTIONS

$$\frac{d^3\sigma^D}{dx_{I\!P}dxdQ^2} = \frac{4\pi\alpha^2}{xQ^4}\left(1-y+\frac{y^2}{2}\right)\sigma_r^{D(3)}(x_{I\!P},x,Q^2)$$

$$\sigma_r^{D(3)} = F_2^{D(3)} - \frac{y^2}{1+(1-y)^2}F_L^{D(3)}$$

$$F_2^{D(3)} = \frac{dF_2^D}{dx_{I\!P}}$$

$$F_2^D = \frac{Q^2}{4\pi^2\alpha}\sigma^D(\gamma^* p)$$

- Is the origin of LRG of soft nature? Is the soft $I\!P$ responsible for LRG? $\rightarrow$ are LRG in the initial condition for DGLAP evolution?

REGGE FRAMEWORK

- At high energy, s, hadron-hadron interactions proceed through exchange of $I\!\!P$ trajectory:

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

$$\sigma_{\rm tot} \sim s^{\alpha_{I\!\!P}(0)-1}$$

$$\frac{d\sigma_{\rm el}}{dt} \sim \frac{\sigma^2_{\rm tot}}{16\pi} e^{2(b_0^{\rm el}+\alpha'_{I\!\!P}\ln s)t}$$

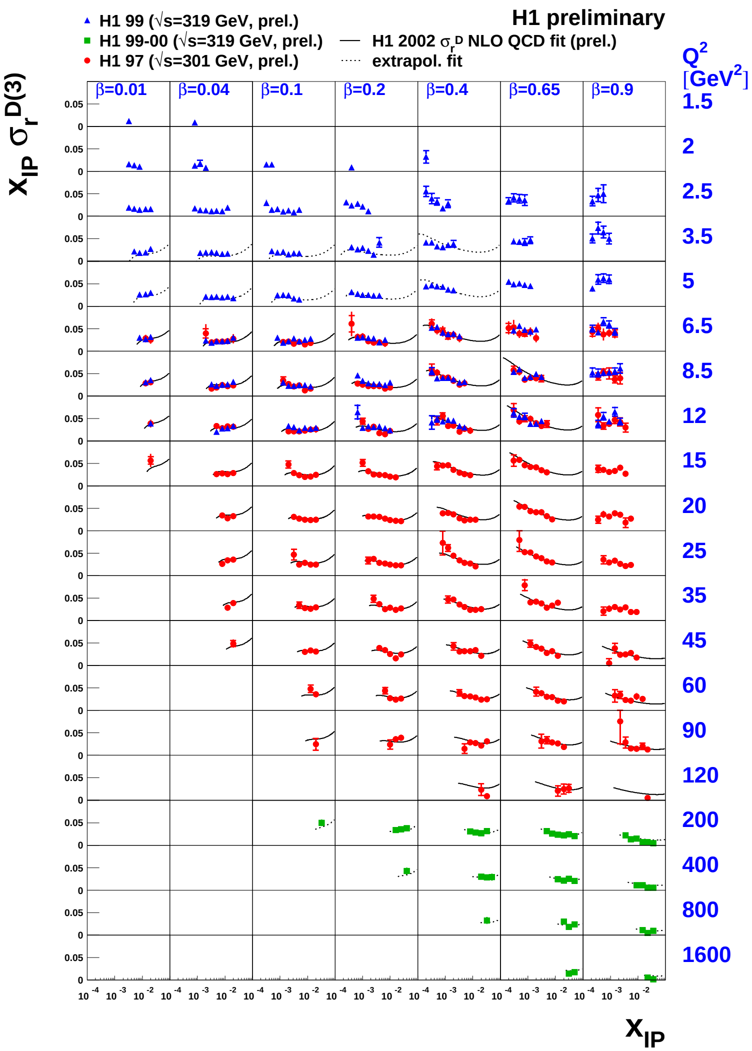
$$\frac{d^2\sigma_{\rm D}}{dt dx_{I\!\!P}} \sim \left(\frac{1}{x_{I\!\!P}}\right)^{2\alpha_{I\!\!P}(t)-1} e^{2(b_0^{\rm D}-\alpha'_{I\!\!P}\ln x_{I\!\!P})t}$$

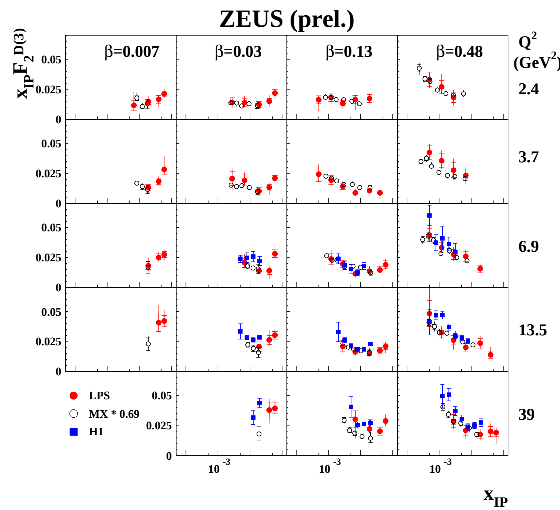
$$\frac{\sigma_{\rm el,diff}}{\sigma_{\rm tot}} \sim s^{\epsilon}$$

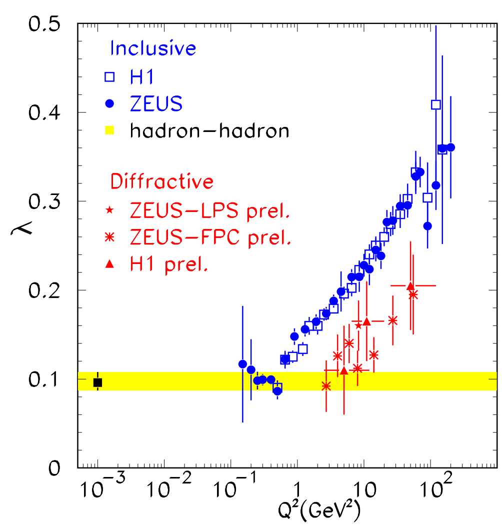
- shrinkage of t slope with s

- Experimentally $\alpha_{I\!\!P}(0) = 1 + \epsilon$ with $\epsilon = 0.08 - 0.10$ and $\alpha'_{I\!\!P} = 0.25({\rm GeV}^{-2})$

F_2^D MEASUREMENTS







$$F_2 \sim x^{-\lambda}$$

for F_2^D

$$\lambda = \alpha_{I\!P}(0)$$

$$\frac{\sigma^D}{\sigma} = \text{const}$$

$$\alpha_{I\!P} \sim Q^2?$$

DIFFRACTIVE PARTON DISTRIBUTIONS DPDF

- QCD factorization for diffractive DIS holds

(Collins, Berera &Soper, Trentadue & Veneziano)

$$\frac{d^2 F_2^D(x_{I\!P},t,x,Q^2)}{dx_{I\!P}dt} = \sum_i \int dz \frac{d^2 f_{i/p}^D(x_{I\!P},t,z,\mu^2)}{dx_{I\!P}dt} \hat{F}_i(\frac{x}{z}, \frac{Q^2}{\mu^2})$$

DPDF pQCD as F_2

- Diffractive parton distributions evolve in μ^2 following DGLAP equations

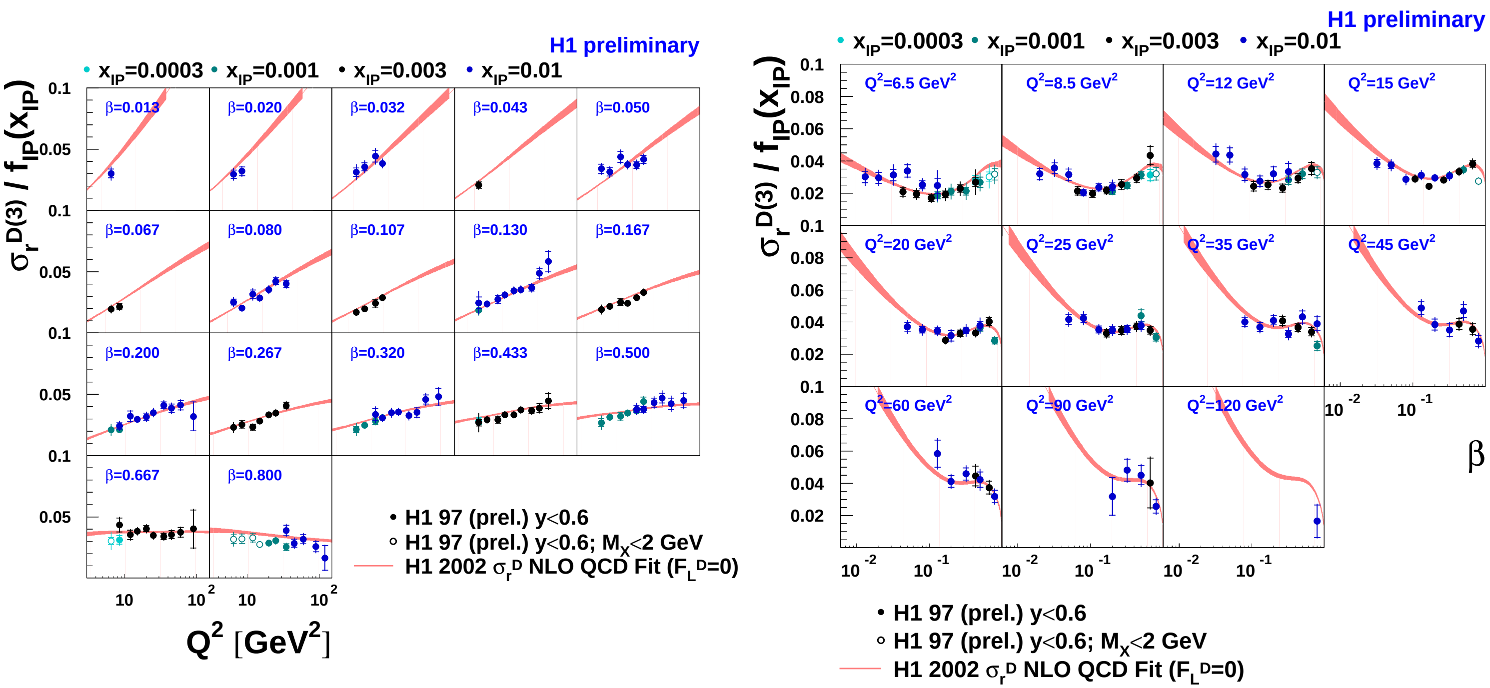
- If in addition postulate Regge factorization

(Ingelman & Schlein)

$$\frac{d^2 F_2^D(x_{I\!P},t,x,Q^2)}{dx_{I\!P}dt} = f_{I\!P/p}(x_{I\!P},t) F_2^{I\!P}(\beta, Q^2)$$

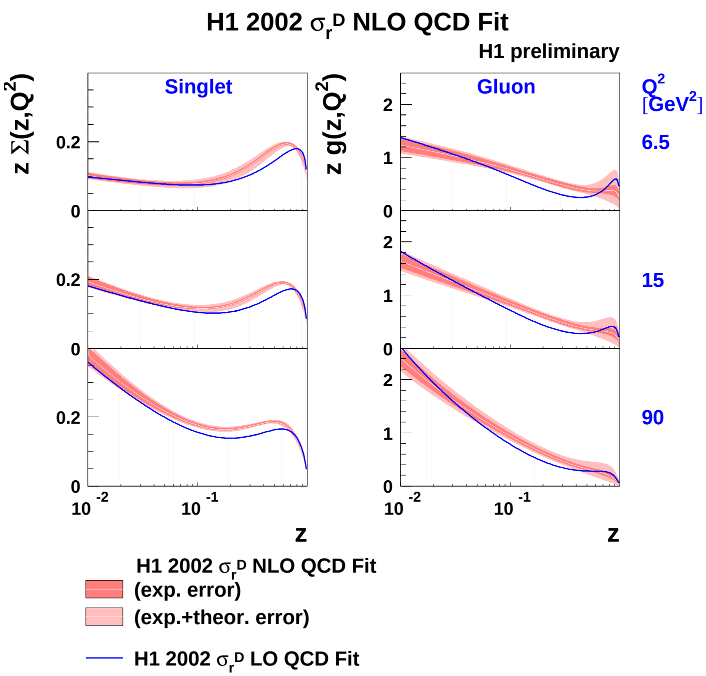
- $F_2^{I\!P}(\beta, Q^2)$ evolves following DGLAP equations

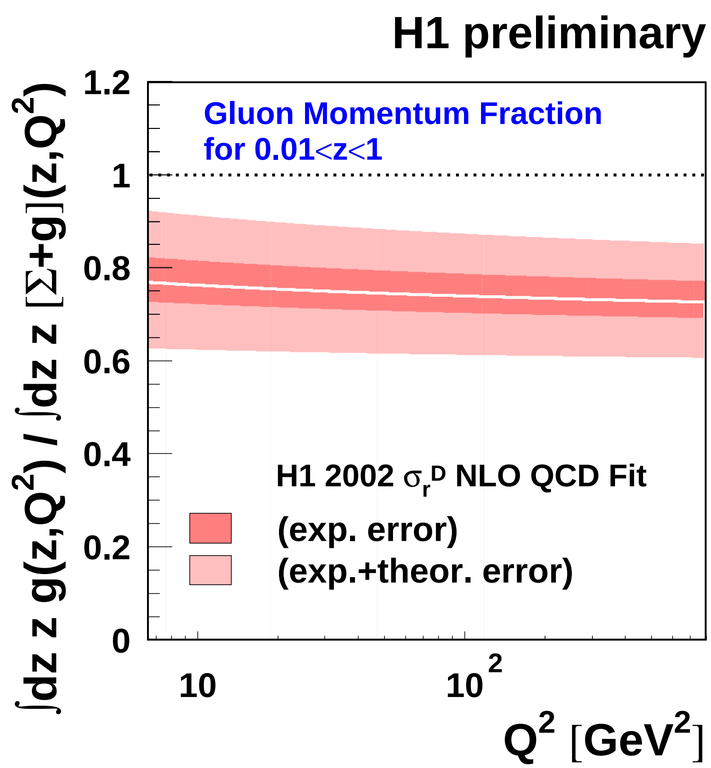
DIFFRACTIVE PARTON DISTRIBUTIONS



- Good description of data with NLO DGLAP evolution

DIFFRACTIVE PARTON DISTRIBUTIONS

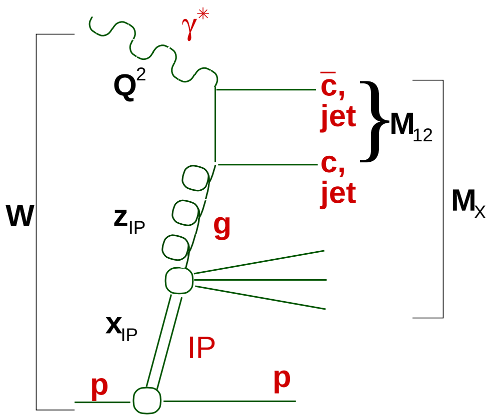


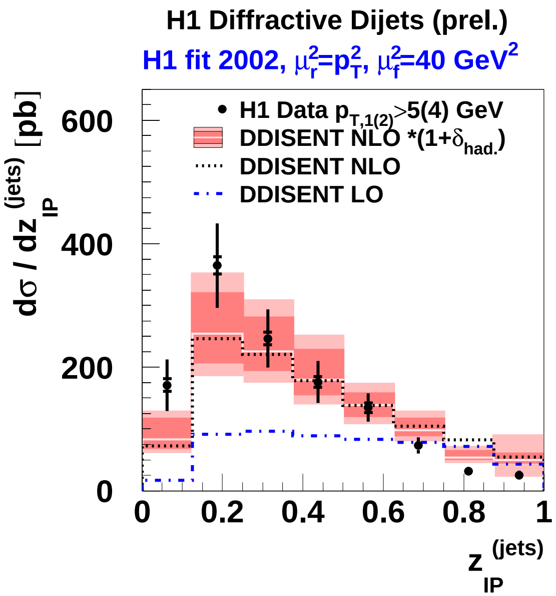


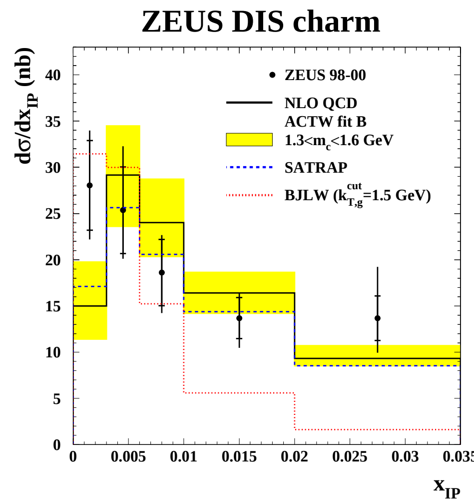
Summary

- Large contribution of DIS diffractive events (10 to 20 %)
- W dependence of LT diffraction as that of inclusive DIS !!!
- Diffractive events mainly originate from gluons

TEST OF FACTORIZATION IN DIS



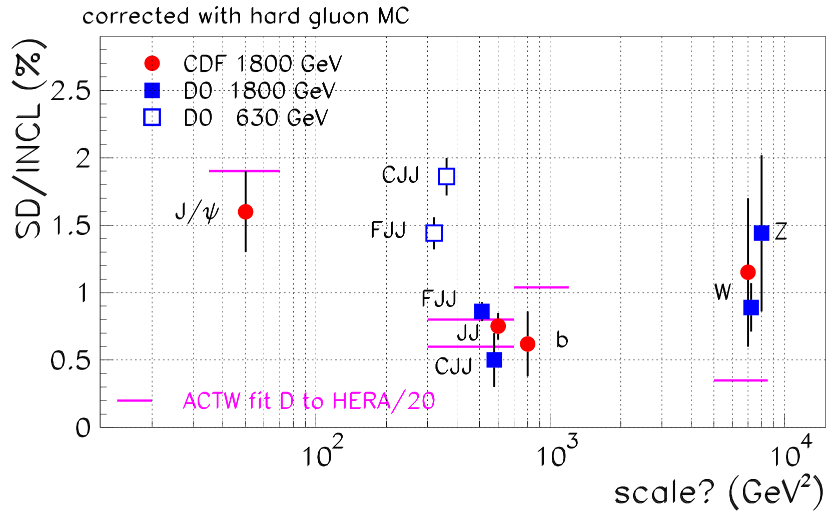


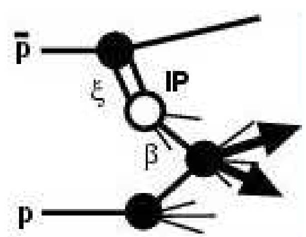


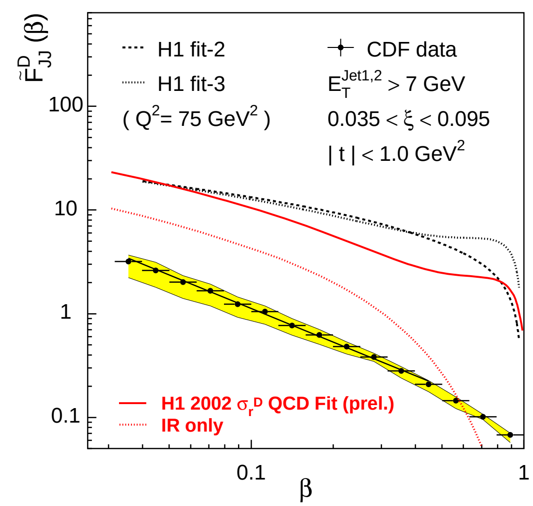
- Diffractive dijet and charm rates in DIS well reproduced by NLO calculations with DPDFs - factorization holds

FACTORIZATION BREAKING IN HARD DIFFRACTIVE $p\bar{p}$

RUN I results

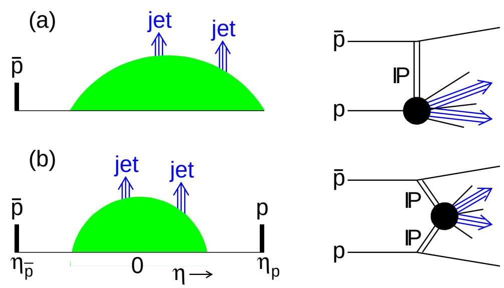


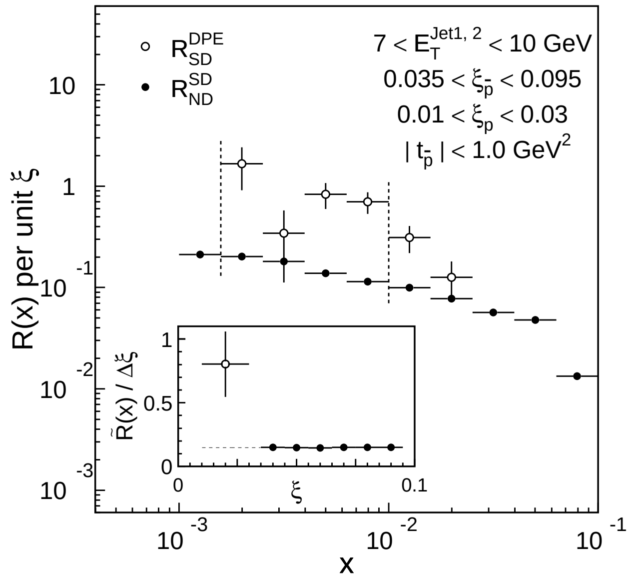


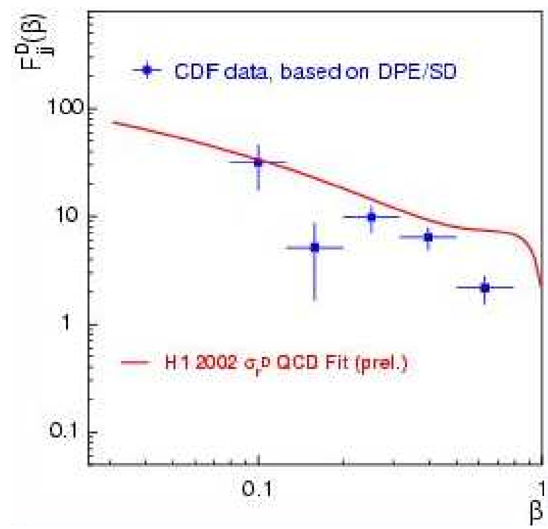


$$F^D_{jj}(x_{\bar{p}}) = \frac{\sigma(SD_{jj})}{\sigma(ND_{jj})} F_{jj}(x_{\bar{p}})$$

LRG SURVIVAL IN $p\bar{p}$





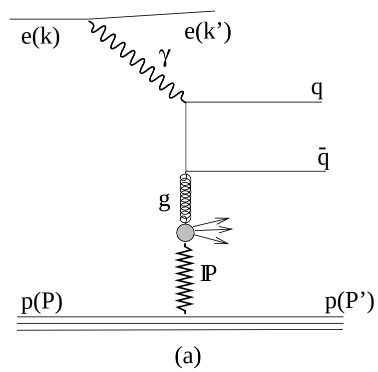


$$\frac{R^{SD}_{ND}}{R^{DPE}_{SD}} = 0.19 \pm 0.07$$

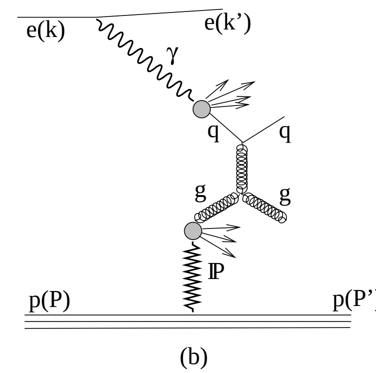
Factorization holds

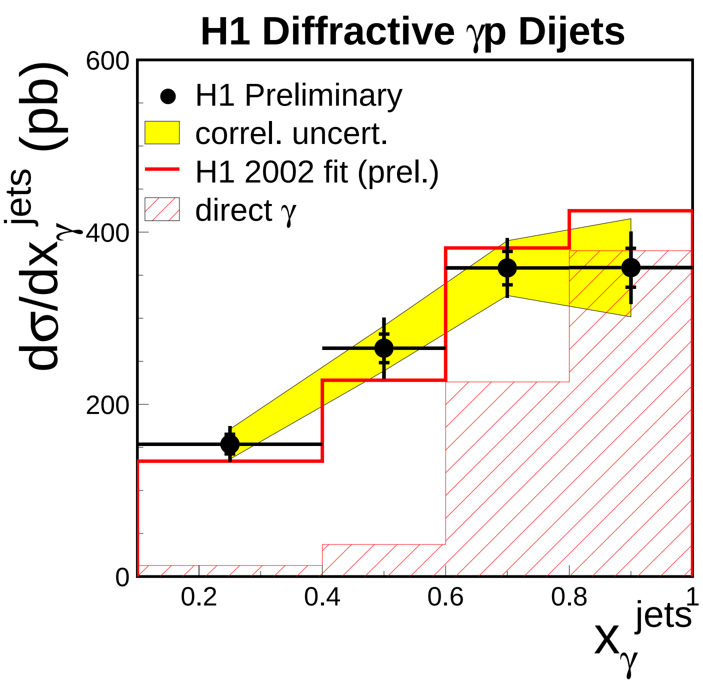
FACTORIZATION TESTS IN γp

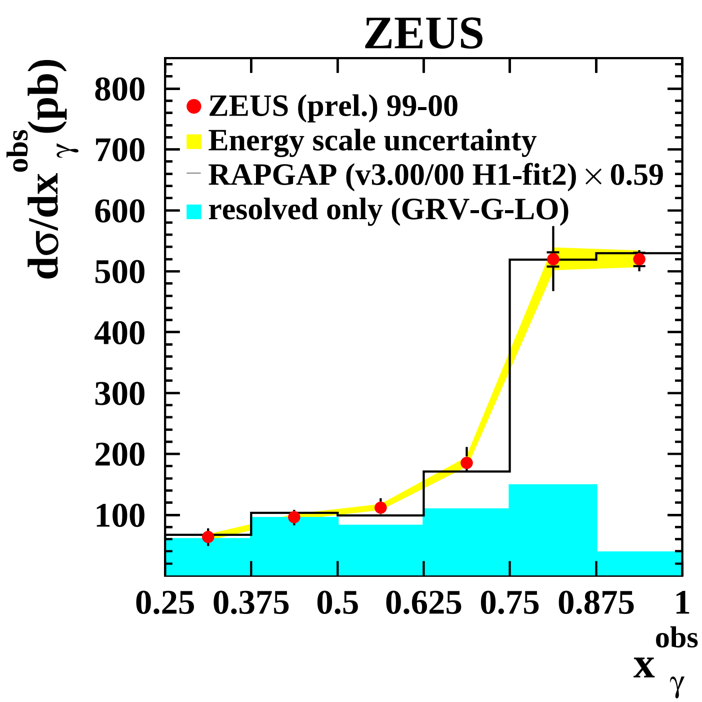
direct γ



resolved γ

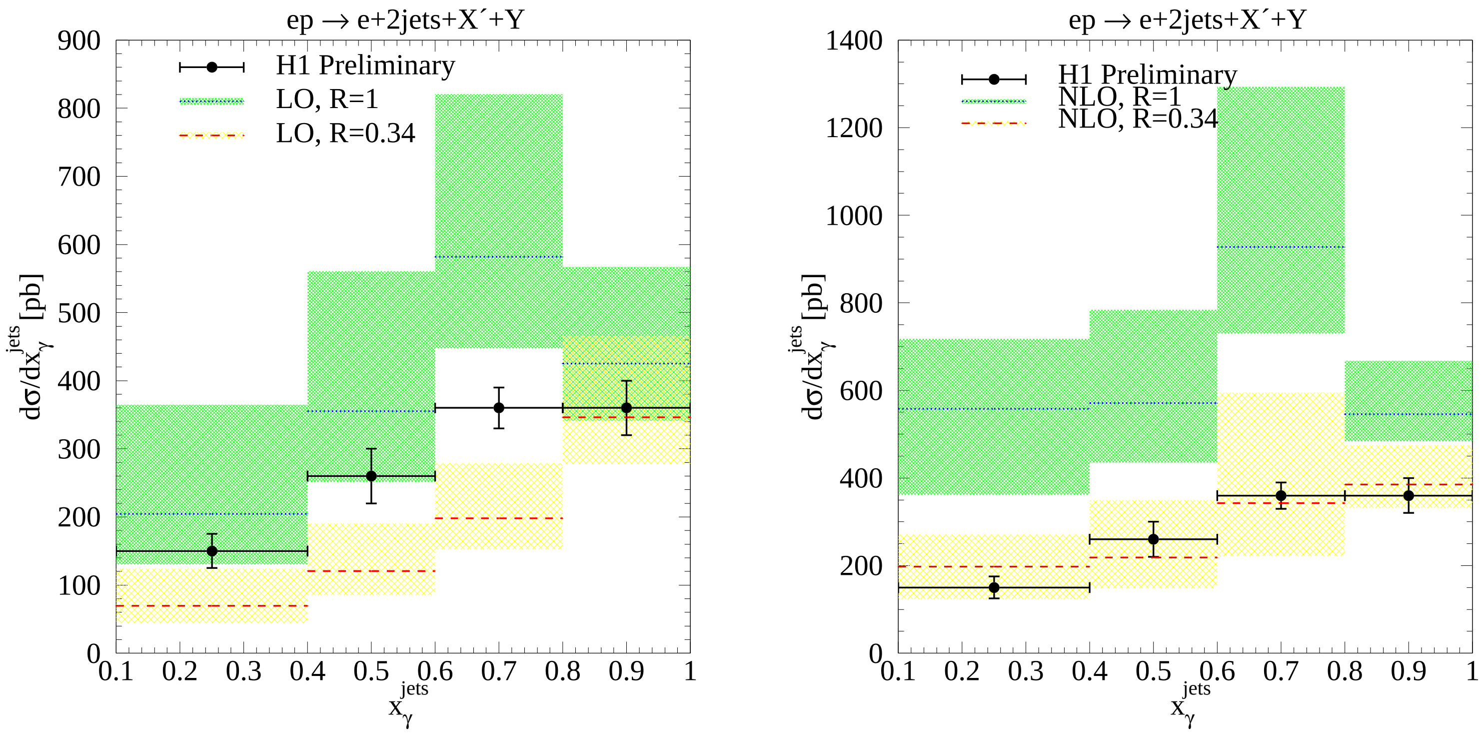






FACTORIZATION TESTS IN γp

Calculations by Klasen and Kramer



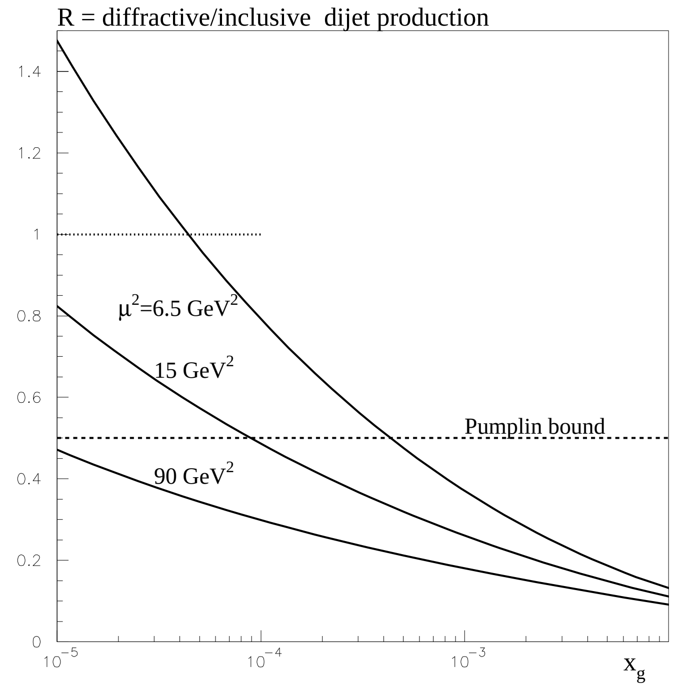
- For calculation to agree with data, in NLO resolved contribution suppressed by factor 3 relative to direct

UNITARITY PROBLEM

- At low x the gluon density in the proton is known to be large
- Diffraction in DIS is driven by gluons and does not rise with W as fast as expected
- Could it be that in the gluon sector unitarity effects are already present?

Estimates by Kaidalov et al.

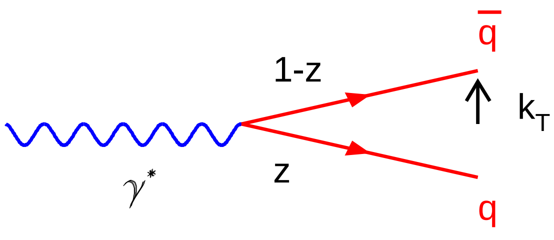
- Pumplin limit: $\sigma^D/\sigma \leq 0.5$
- With the present diffractive gluon pdf, limit exceeded in 2 jet production by gluons.
- Indication that unitarity effects may be present in the gluon sector



GLUODYNAMICS - SATURATION

Dipole picture of ep interactions

In the target rest frame:



$$\tau_{\text{fluctuation}} \simeq \frac{1}{2mx} \gg 1\,\text{fm}$$

The color dipole interacts with the target T

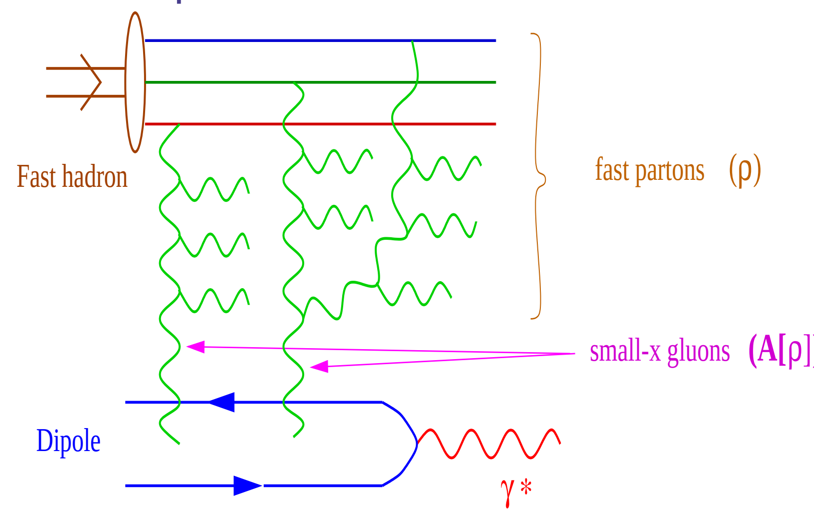
- k_T large, small transverse size $r \to$ pQCD

$$\sigma_{q\bar{q}T} = \frac{\pi^2}{3} r^2 \alpha_S(Q^2) x G_T(x, Q^2 \simeq \frac{\lambda}{r^2})$$

Color transparency/opacity

- k_T small, large transverse r
  $\to$ non-perturbative

In the dipole frame:

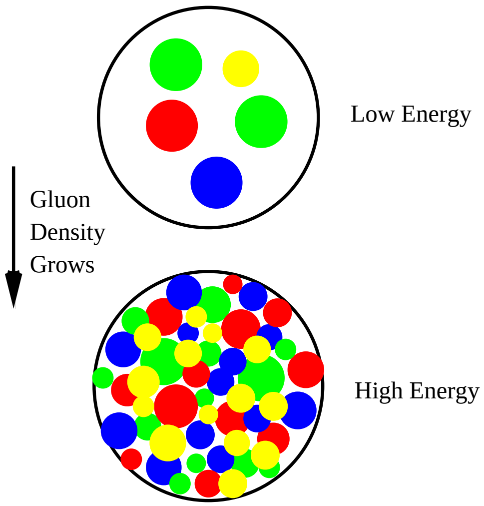


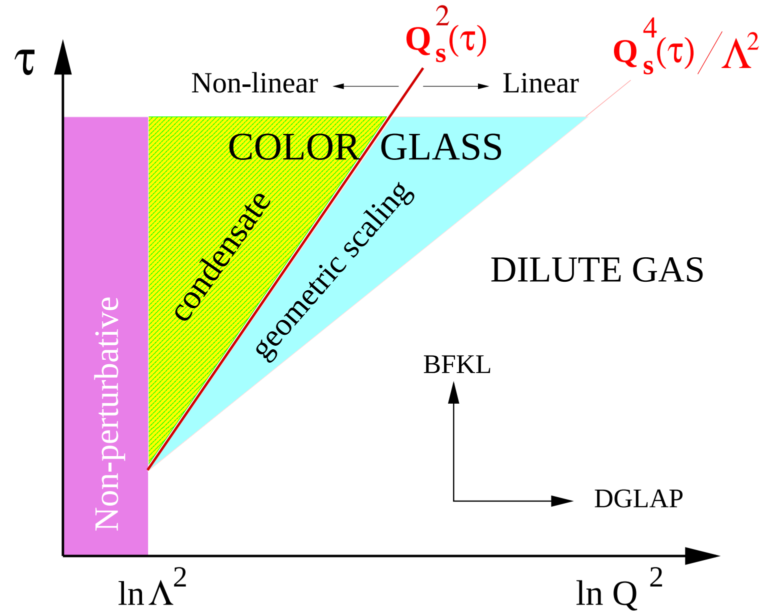
fast partons produce a random color source - $\rho^a(x)$ seen by soft gluons as frozen over short time scale $\to$ glass
gluons are densely packed - density $\sim 1/\alpha_S \to$ Bose condensate

Color Glass Condensate

New form of matter

Overlapping gluons





$$\tau = \ln\frac{1}{x}$$

With increasing energy gluons are forced to occupy higher momenta, so the coupling becomes weaker and the gluons are not seen by the probe

- Saturation and Unitarization are related

Saturation Model for DIS

Golec-Biernat-Wuesthoff Model

$$F_2(x,Q^2) = \frac{Q^2}{4\pi^2\alpha}(\sigma_T + \sigma_L)$$

$$\sigma_{T,L} = \int dz d^2r |\psi_{T,L}(z,r,Q^2)|^2 \sigma_{\rm dipole}$$

$$\sigma_{\rm dipole} = \sigma_0(1 - e^{-r^2 Q_s^2(x)/4})$$

$$Q_s^2(x) = \left(\frac{x_0}{x}\right)^\lambda$$

GBW model very successfull in reproducing F_2, F_2^D and the constant ratio F_2^D/F_2...

Saturation scale

gluon recombination:$\sigma \sim \alpha_s/Q^2$
gluon density: $\rho \sim xG(x,Q^2)/\pi R^2$
saturation scale Q_s^2: $\sigma\rho = 1$

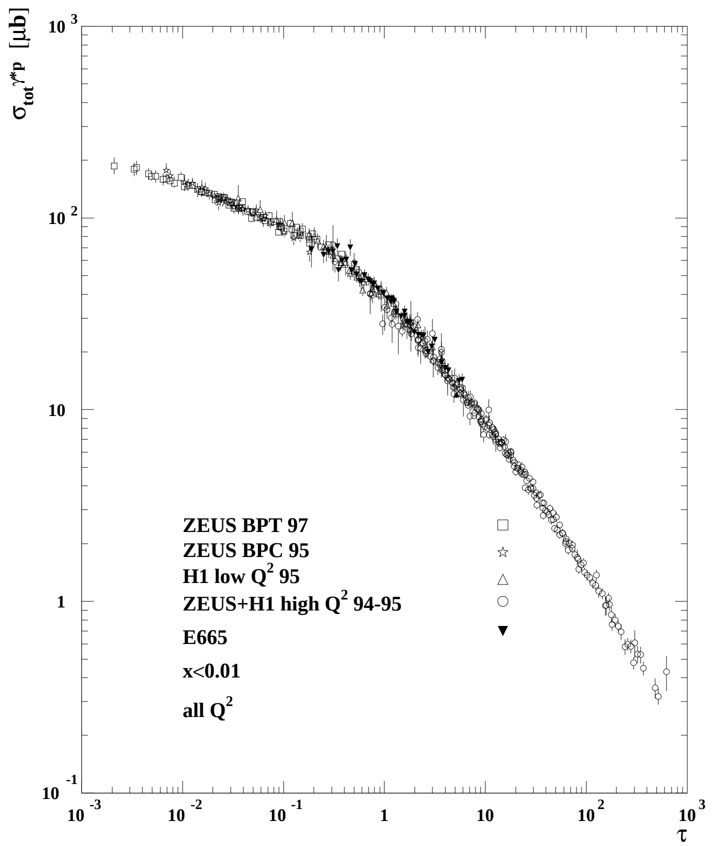
$$Q_s^2 = \alpha_s \frac{xG(x,Q^2)}{\pi R^2}$$

$xG(x,Q^2)$ may be calculated from evolution equations
In linear evolution $xG(x,Q^2) \sim x^{-\lambda}$

The theory behind CGC legitimizes the GBW model

GEOMETRICAL SCALING

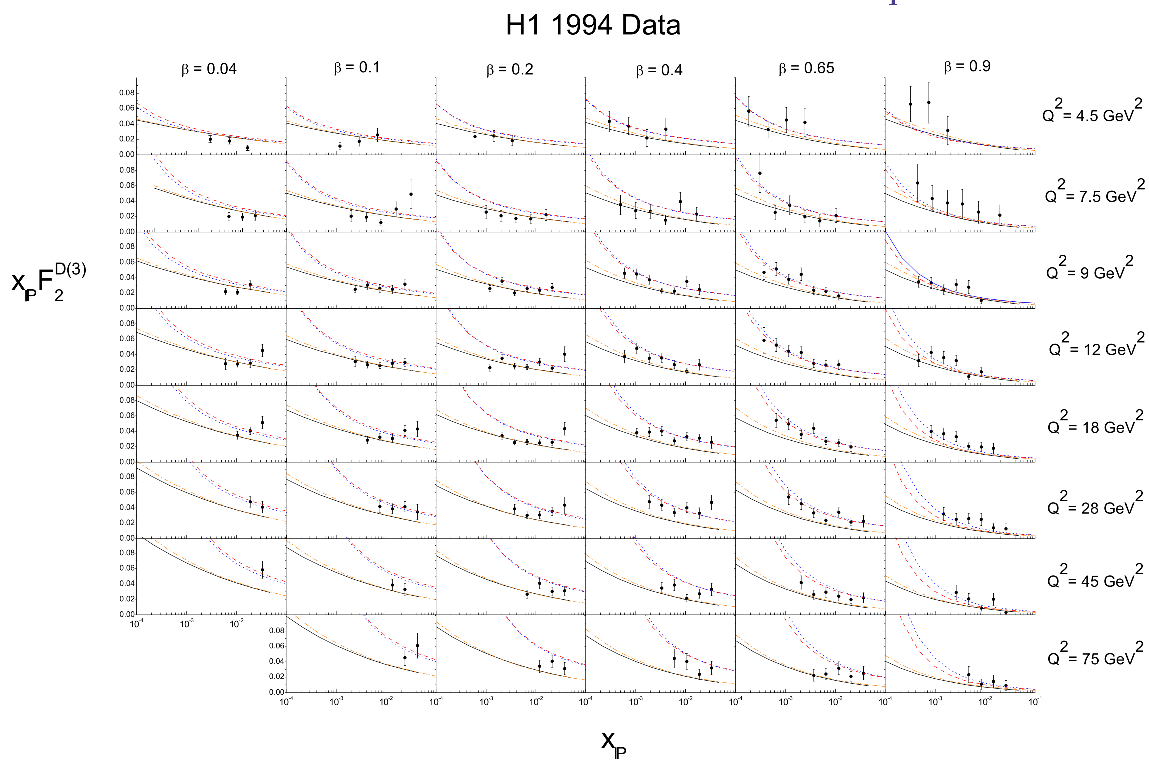
$$\sigma_{\gamma^* p} = \sigma_T + \sigma_L = f(\tau = Q^2/Q_s^2)$$



- $Q_s^2 > 1\,\mathrm{GeV}^2$ for $x < 10^{-4}$
- Cure to F_2 growth in pQCD?
- Geometrical scaling valid for $Q^2 < 450\,\mathrm{GeV}^2$ and $x < 10^{-2}$, beyond saturation regime as expected for BFKL evolution with saturation bound

DIFFRACTION AND SATURATION MODELS

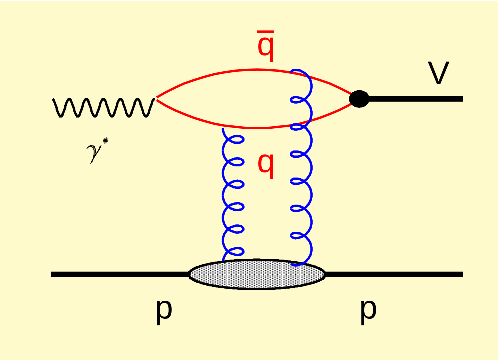
Calculations by Forshaw, Sandapen and Shaw with $\sigma_{\rm dipole}$ qfrom F_2 fits



- Forshaw, Kerley and Shaw (soft/hard components) – red and blue
- Iancu, Itakura and Munier (CGC) – black
- Golec-Biernat and Wuesthoff – orange

EXCLUSIVE PROCESSES IN ep

Candidate for a hard process ⇒ pQCD



If $q\bar{q}$ form small configuration ⇒ resolves gluons

either γ^*_L or $V = c\bar{c},\ \ b\bar{b}$

Expectations:

- SU(4) restoration

$$\rho : \omega : \Phi : J/\psi = 9 : 1 : 2 : 8$$

- $\sigma_L \sim \frac{\alpha_S^2}{Q^6} \mid xG(x, Q^2) \mid^2$

⇒ fast increase of $\sigma(\gamma^* p \to V p)$ with W^2

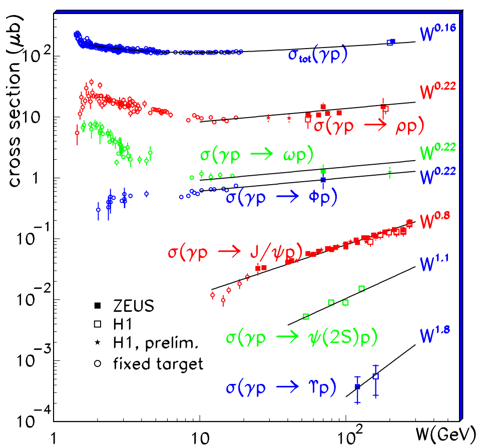
⇒ universality of t dependence $\sim e^{b_{2g}t}$

$b_{2g} \simeq 4\ \mathrm{GeV}^{-2}$ and $\alpha'_{I\!P} \simeq 0$

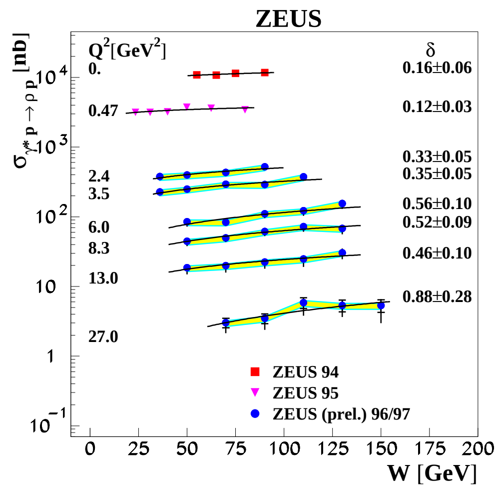
⇒ Q^2 dependence slower than $1/Q^6$

EXCLUSIVE VM PRODUCTION - W DEPENDENCE

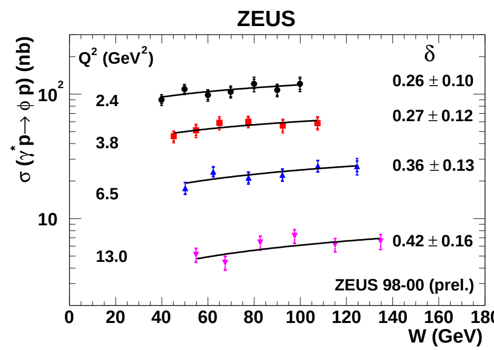
$Q^2 \simeq 0\,\mathrm{GeV}^2$



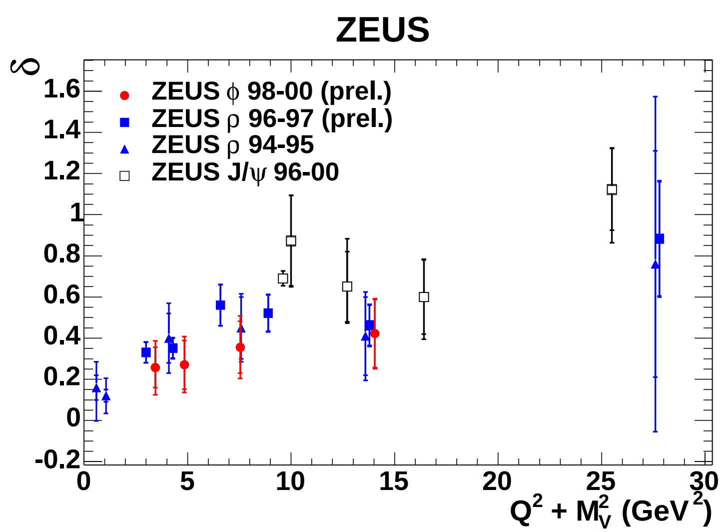
ρ^0



ϕ

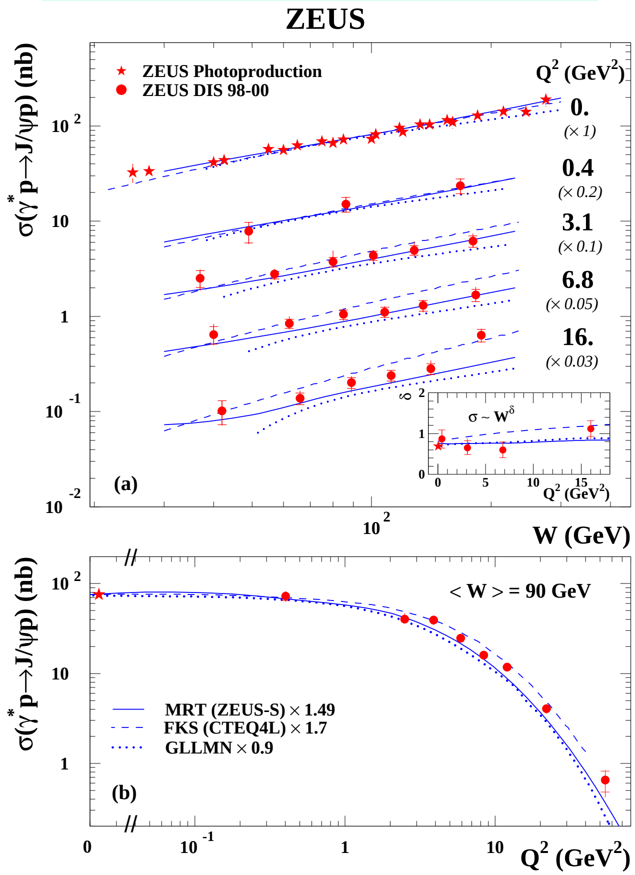


$\sigma \sim W^\delta$ $\Rightarrow$

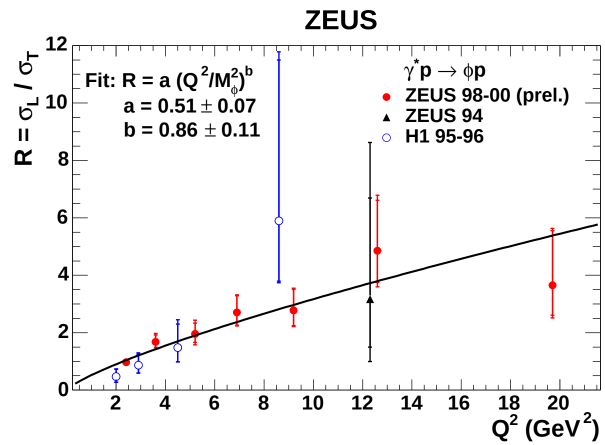


EXCLUSIVE VM PRODUCTION - SMALL DIPOLES

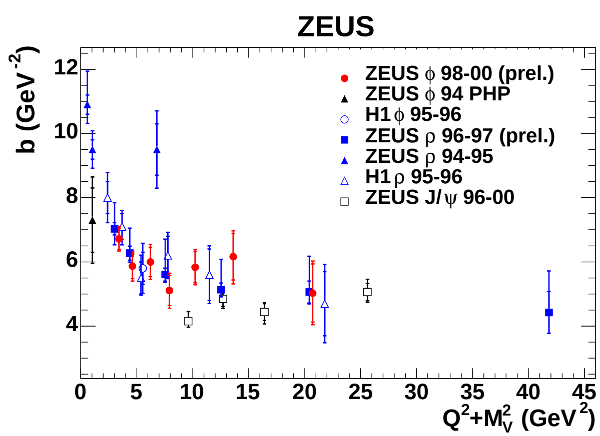
pQCD calculations for J/ψ



σ_L dominates at high Q^2

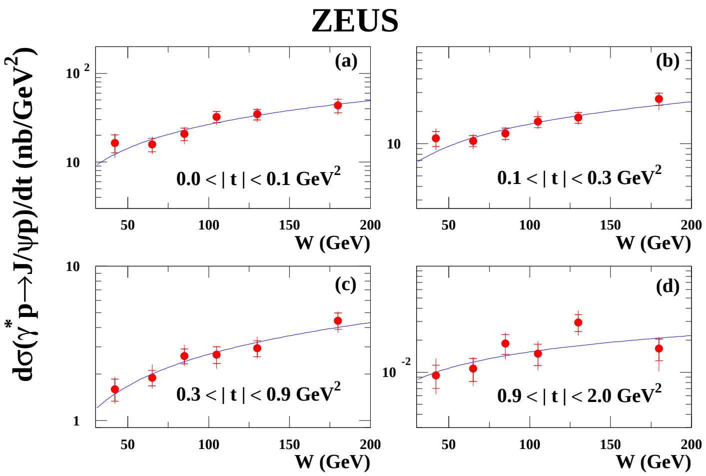


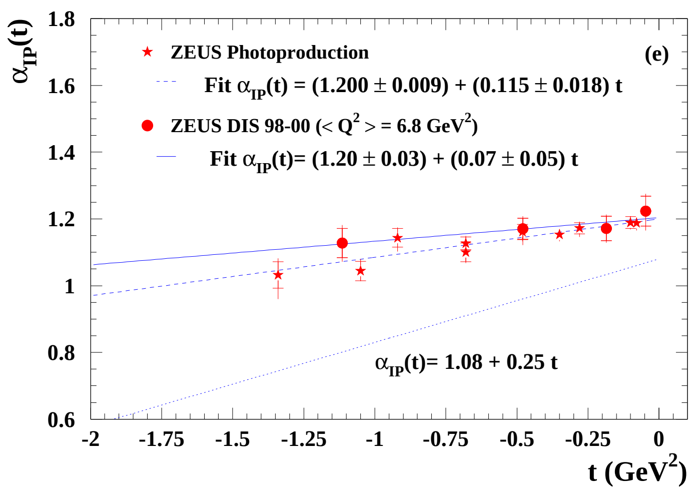
Effective size of $\gamma^\star$ becomes smaller with Q^2

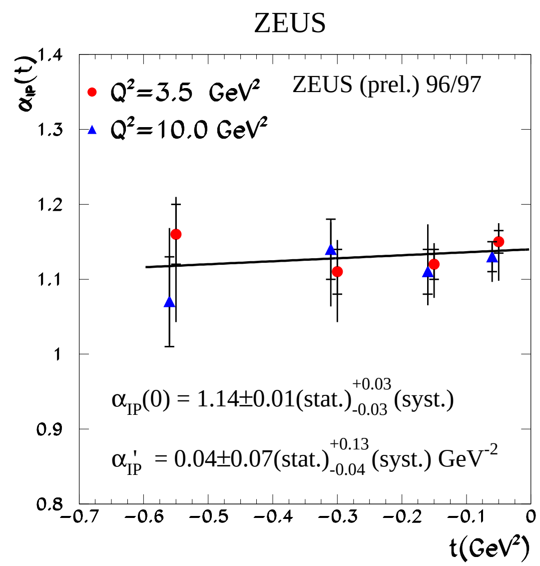


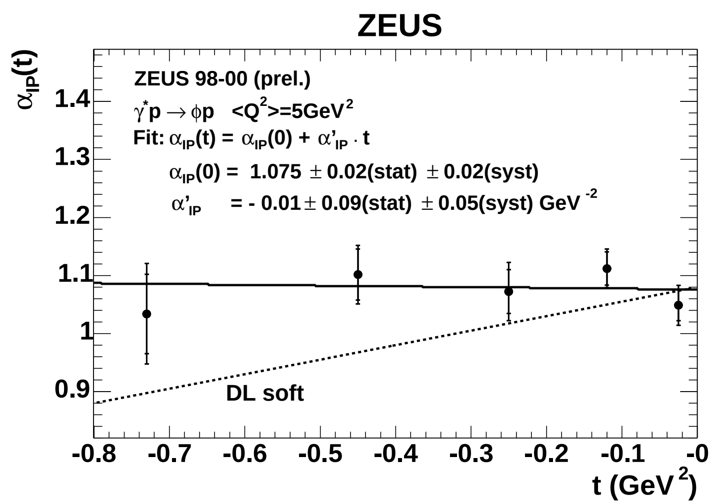
Exclusive VM production - Pomeron trajectory

$$d\sigma/dt \propto W^{4(\alpha_{I\!P}(t)-2)}$$





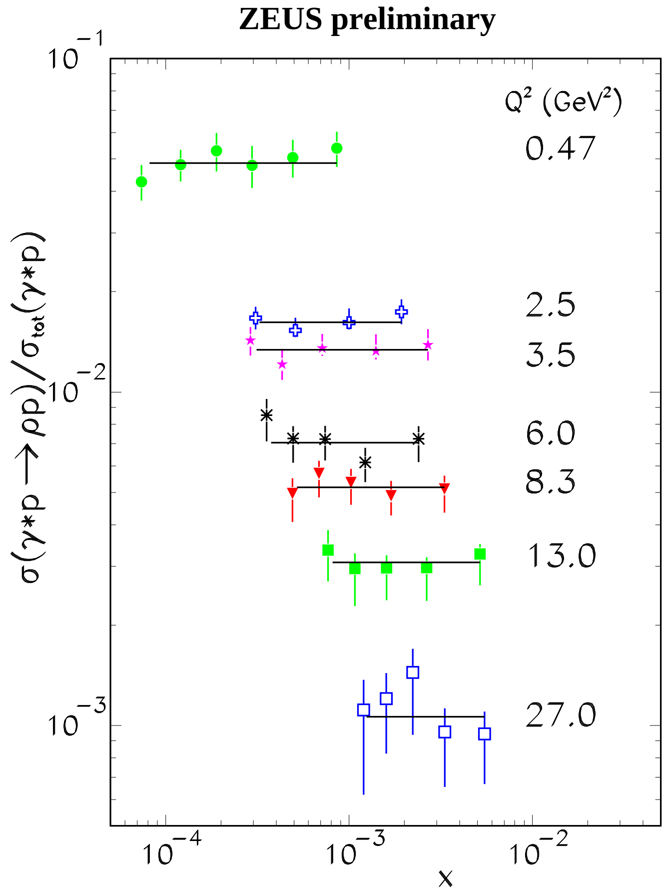


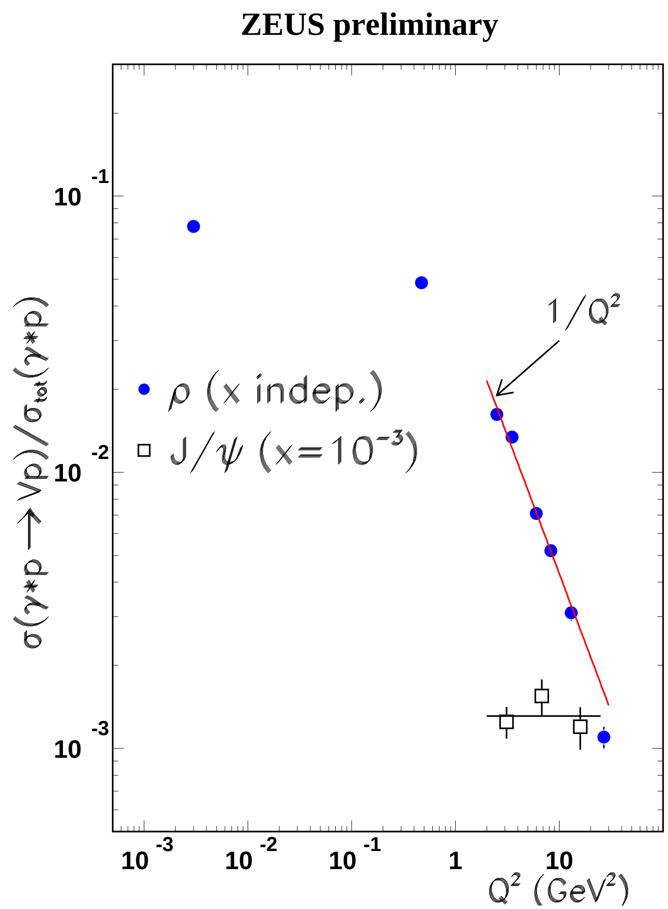


EXCLUSIVE VM PRODUCTION - HT CONTRIBUTION

σ_ρ/σ_{tot} independent of x

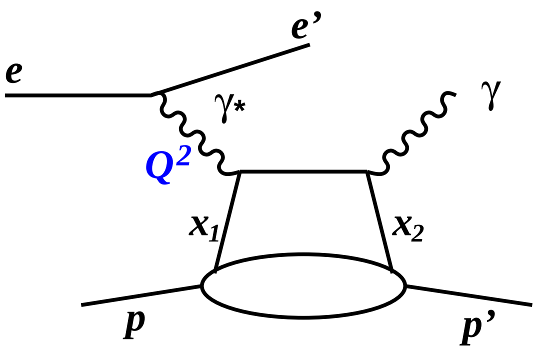
- ρ contribution is HT, J/ψ very small



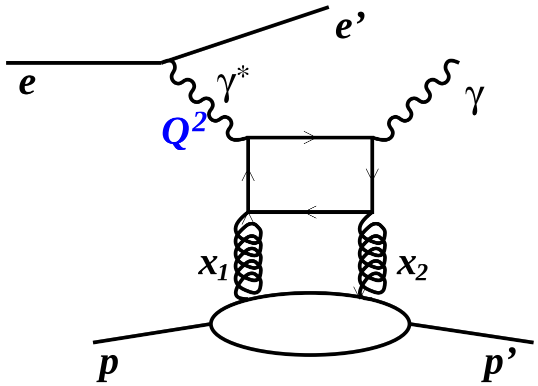


DVCS PROCESS IN QCD

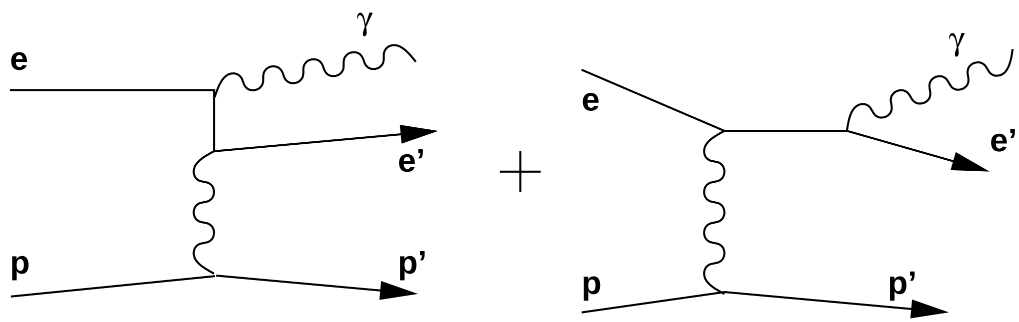
Handbag diagram, $x_1 \neq x_2$



Dominant contribution at low-x



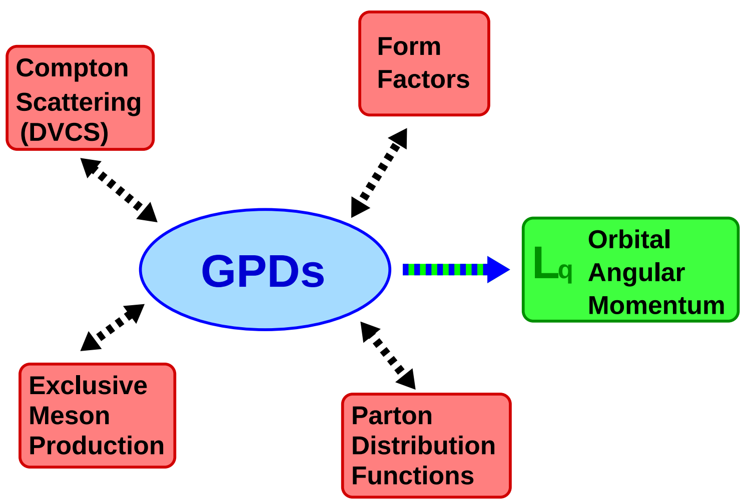
Competing: QED Bethe-Heitler process



WHY IS DVCS INTERESTING?

- Interference between QCD with QED amplitudes $\rightarrow$ rich structure in ϕ, angle between the hadronic and leptonic planes $\rightarrow$ asymmetries (angular, charge)
- BH-DVCS Interference term $\propto Re\mathcal{A}_{\rm QCD}$
- $Re\mathcal{A}_{\rm QCD}(x,Q^2) \sim \int \frac{dx_1}{x_1} ReC_i(x/x_1,Q^2)G_i(x_1,x,Q^2) \rightarrow$

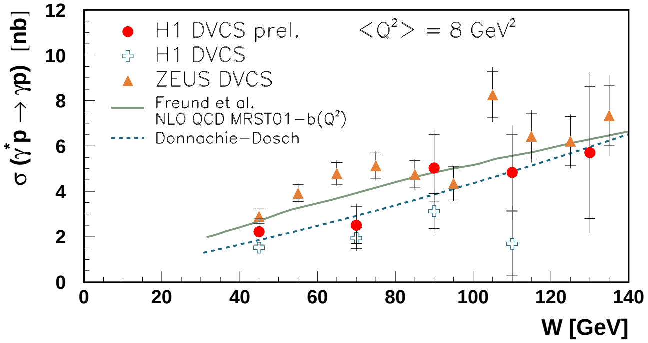
  Generalized Parton Distributions GPD

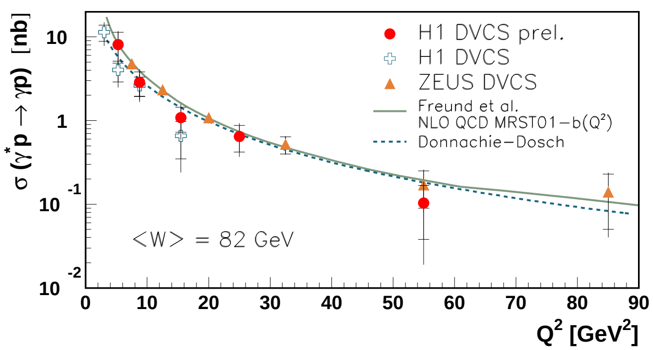


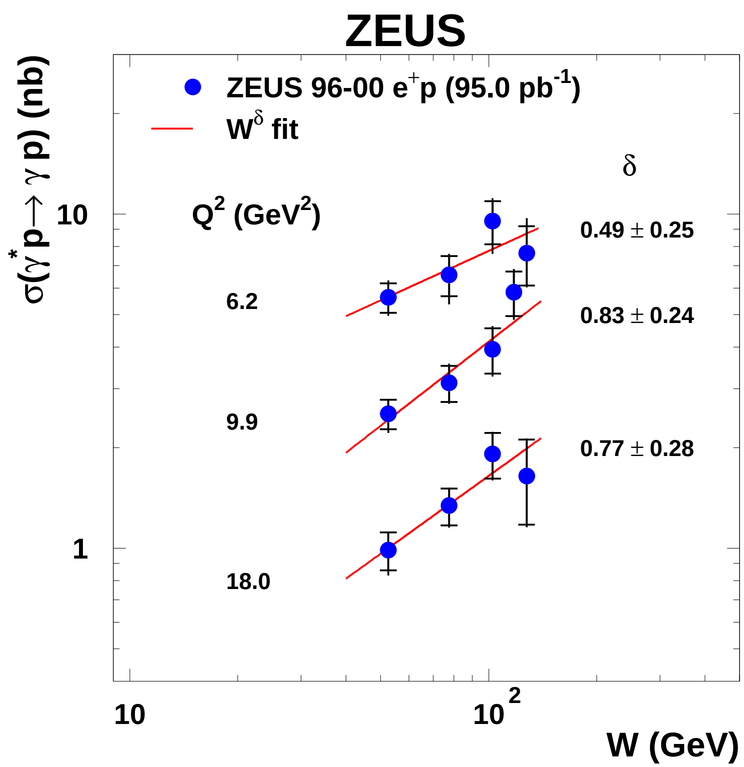
If t dependence included:

3-dimensional picture of the proton

DVCS CROSS SECTION

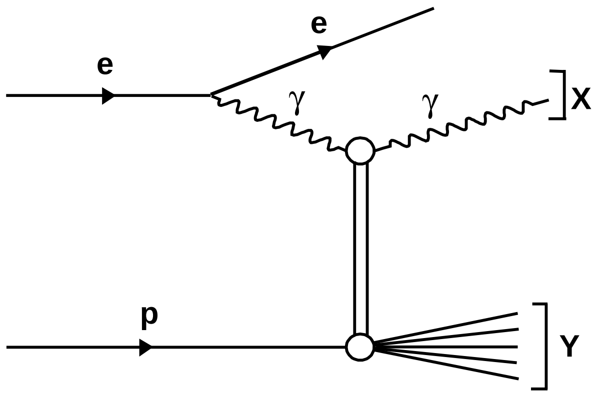


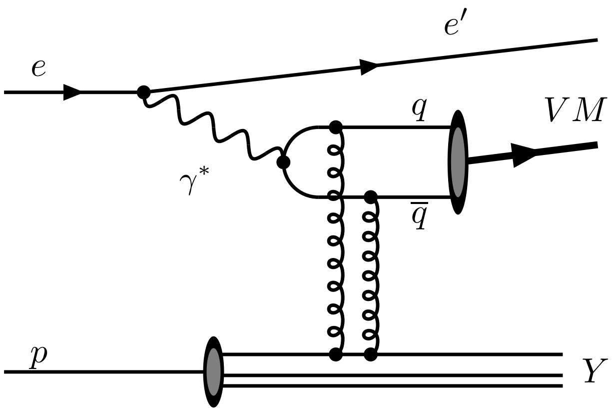


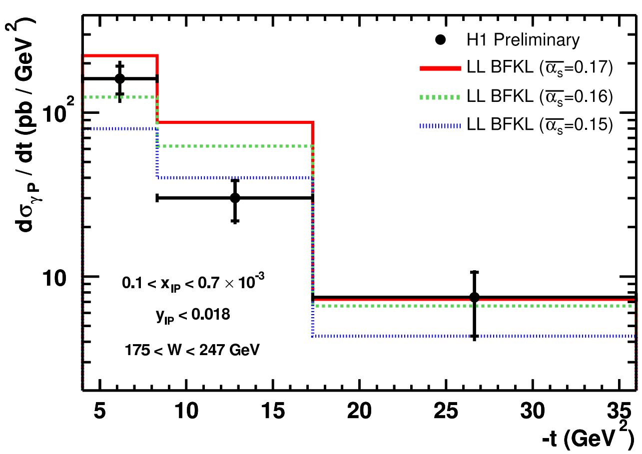


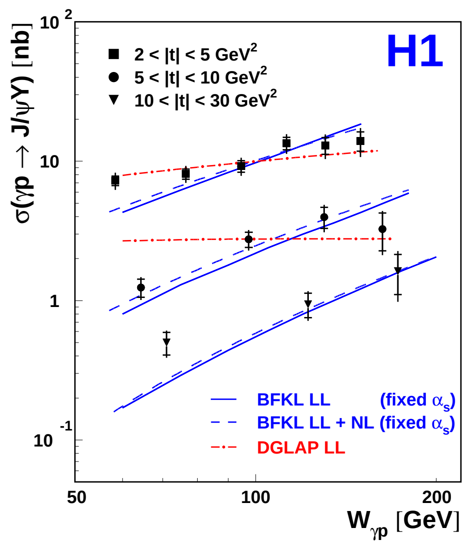
- DVCS hard process in spite of $\gamma_T^\star$

LARGE t EXCLUSIVE STATES - BFKL DYNAMICS



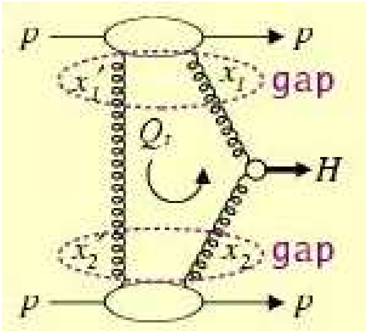




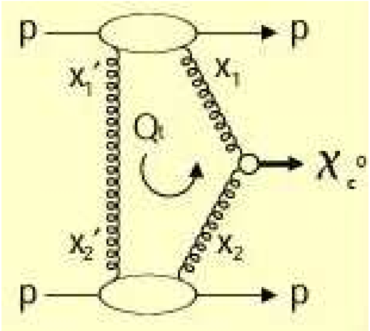


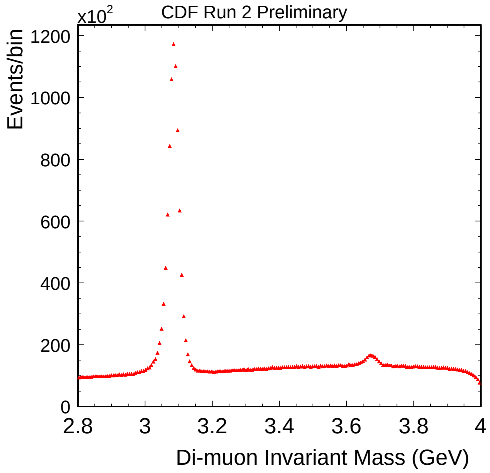
EXCLUSIVE STATES IN $p\bar{p}$

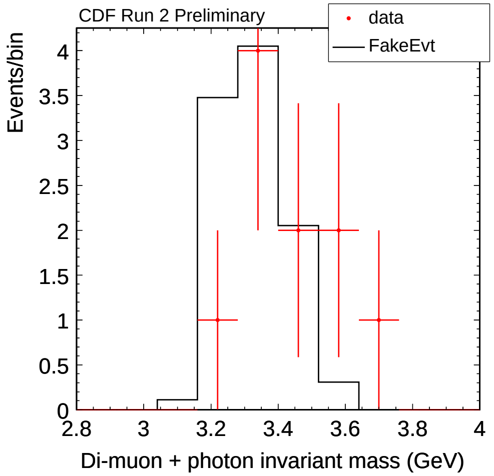
Interesting for light H at LHC



Calibrate with χ_c^0





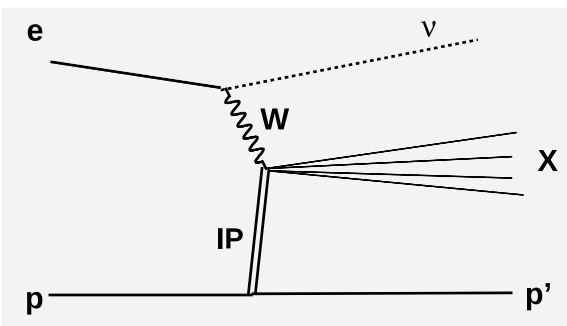


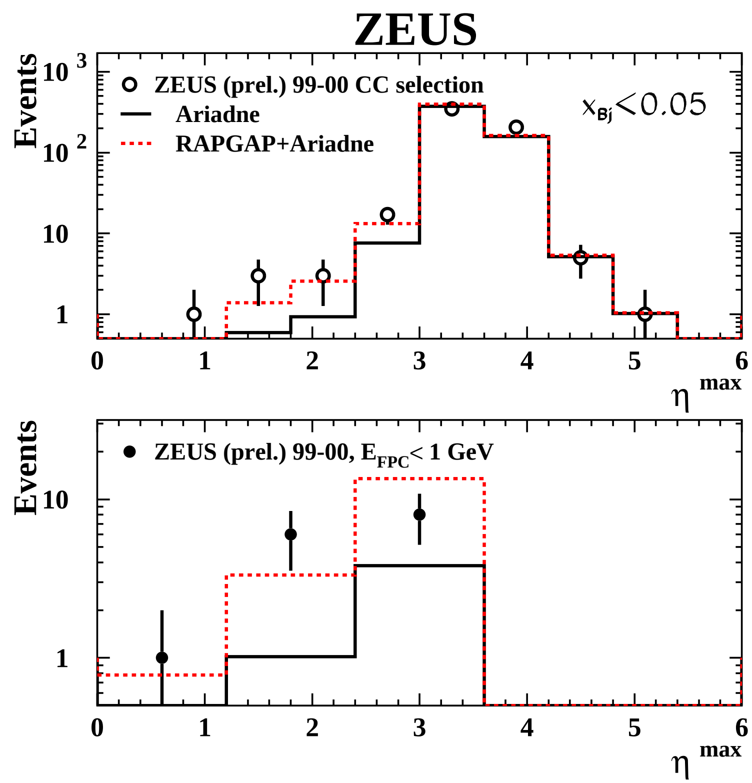
Expected cross section 600 nb

measured $\sigma(p\bar{p} \rightarrow p + J/\psi + \gamma + \bar{p}) = 58 \pm 18(\mathrm{stat}) \pm (\mathrm{syst})\ \mathrm{pb}$

DIFFRACTION AT HIGH Q^2

Charged Currents





Diffraction shows up whenever x is small enough

SUMMARY

- Diffractive scattering in the presence of a hard scale offers a unique opportunity to study
  - the structure of the proton in 3-dimensions,
  - the helicity struture of the proton,
  - the structure of strong interactions,
  - the wave functions of vector mesons.
- Diffraction may signal the signs of the onset of unitarity effects.
- A new form of weakly interacting hadronic matter may have been discovered.
- Diffractive scattering may facilitate the discovery of the light Higgs.
- Diffraction appears whenever x Bjorken is small enough.