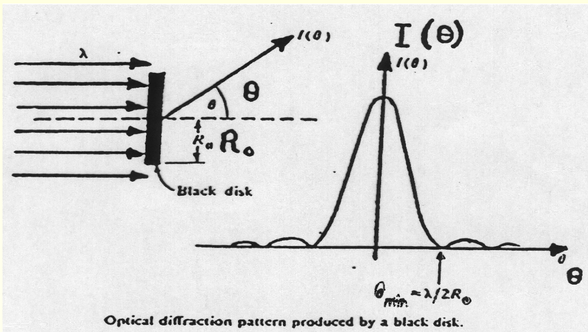
Hard Diffraction
at HERA and the Tevatron

- Introduction
- QCD Factorization
- Diffractive Structure Function @ HERA
- Diffractive Dijets and VM production @ HERA
- Diffractive Dijets @ Tevatron
- Effective Diffractive Structure @ Tevatron
- Summary

Diffraction

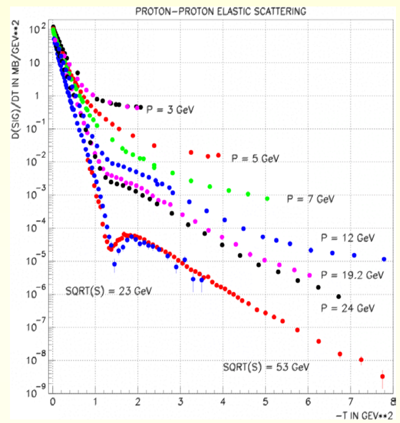
Optics

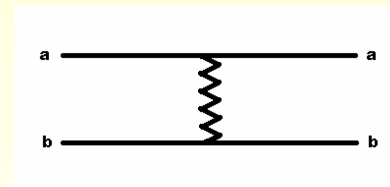
Diffraction of plane light waves on an absorbing disc



High Energy Physics

Analogy to Born approximation of high energy scattering reactions: a b → a b





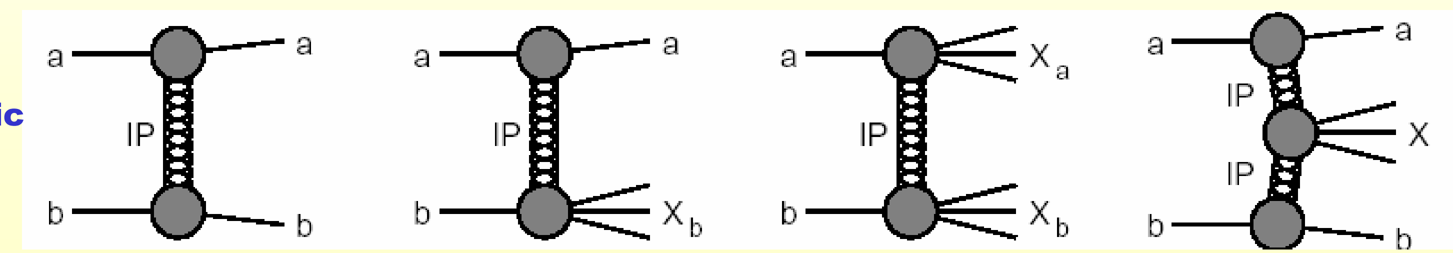
Similar scattering pattern

Today:

Diffractive interactions ≡ interactions without exchange of quantum numbers or color,

Identification : quasi-elastic scattered beam hadron with only small momentum loss, rapidity gaps due to color less exchange

elastic



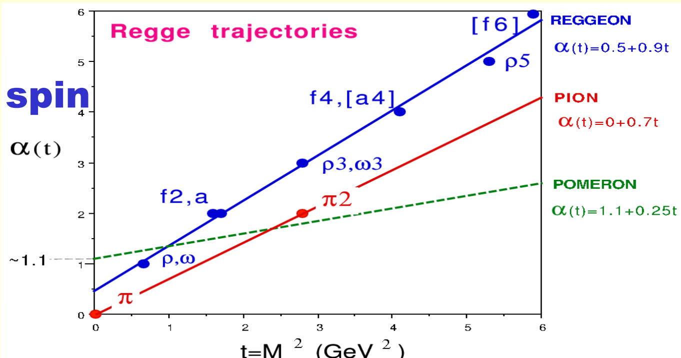
Double pomeron exchange

single diffr. dissociation **double diffr.dissociation**

Hadron-Hadron Scattering

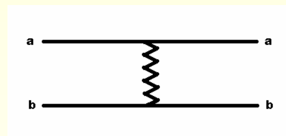
Experimental observation:

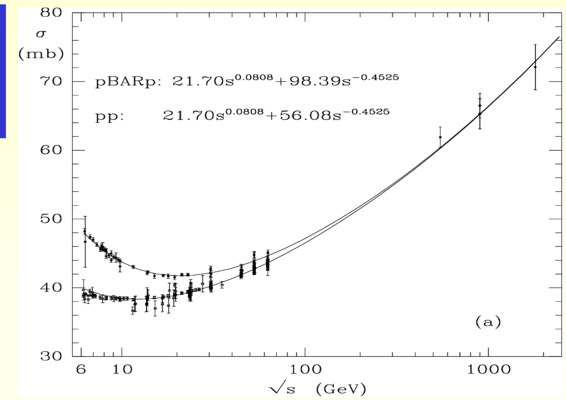
spin



mass

Regge Phenomenology





Exchange of Regge-Trajectory

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

Total cross section: $\sigma_{tot} \sim s^{\alpha_0 - 1}$

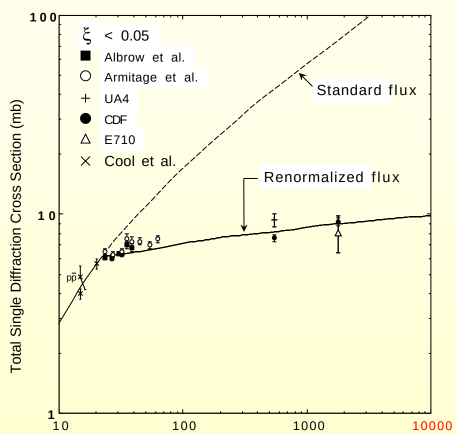
increasing with $\sqrt{s} \rightarrow \alpha_{IP}(0) = 1+\varepsilon > 1$

Soft Pomeron: $\alpha_{IP}(t) \approx 1.1 + 0.25\, t$

Complication:

Predictions with standard parameterizations too large:

$\sigma_{SD} > \sigma_{tot}$ **@ 40 TeV**



→ **renormalization,**

gap suppression, non-linear trajectory

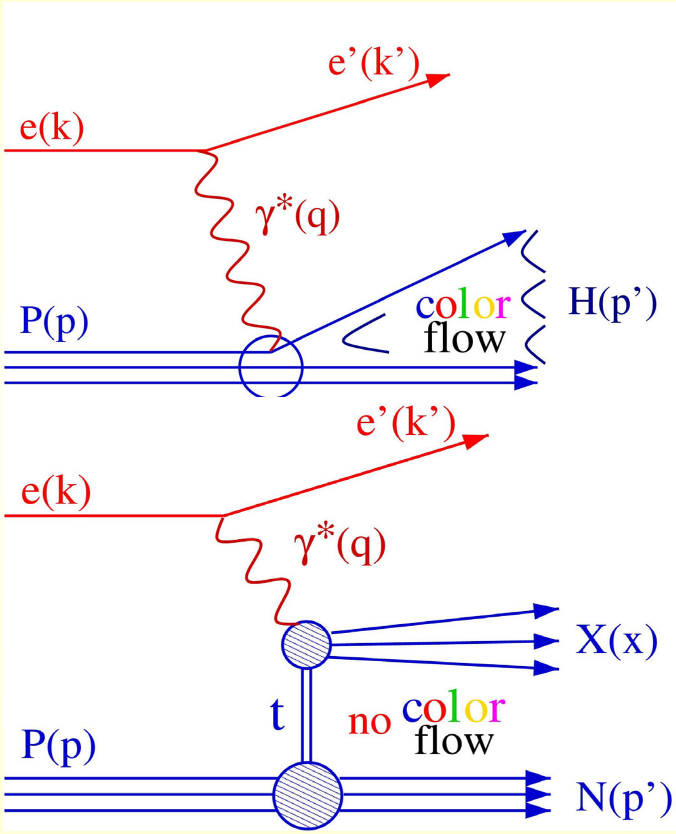
(→ M.Convery, D.Goulianos)

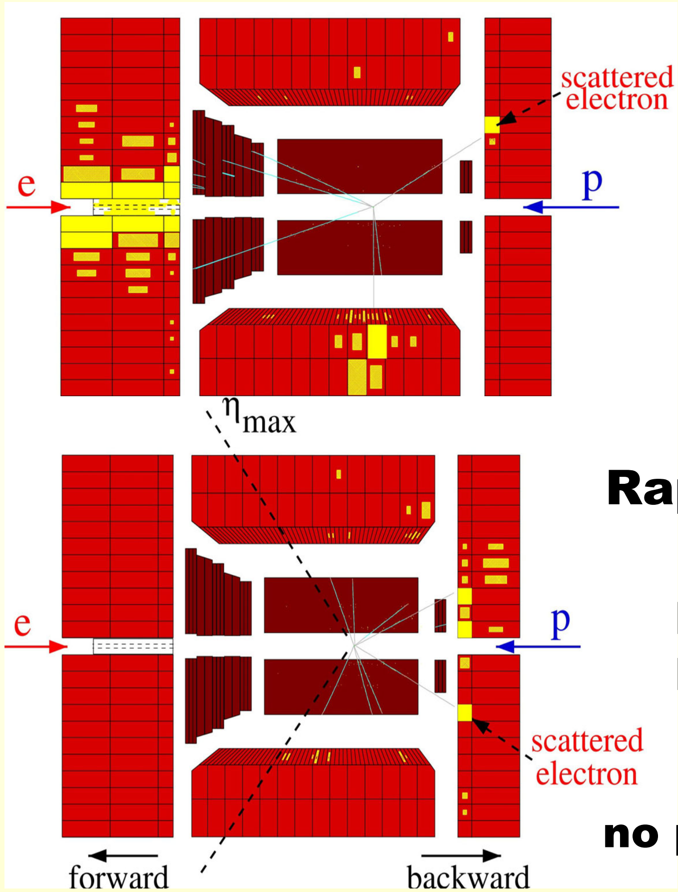
What is the nature of this colorless exchange ?

It has the quantum numbers of the vacuum, but spin 1

Rapidity Gaps in DIS @ HERA

y=1/2 log ((E+p$_z$)/(E-p$_z$)) $\approx \eta$ = - log tan (θ/2)



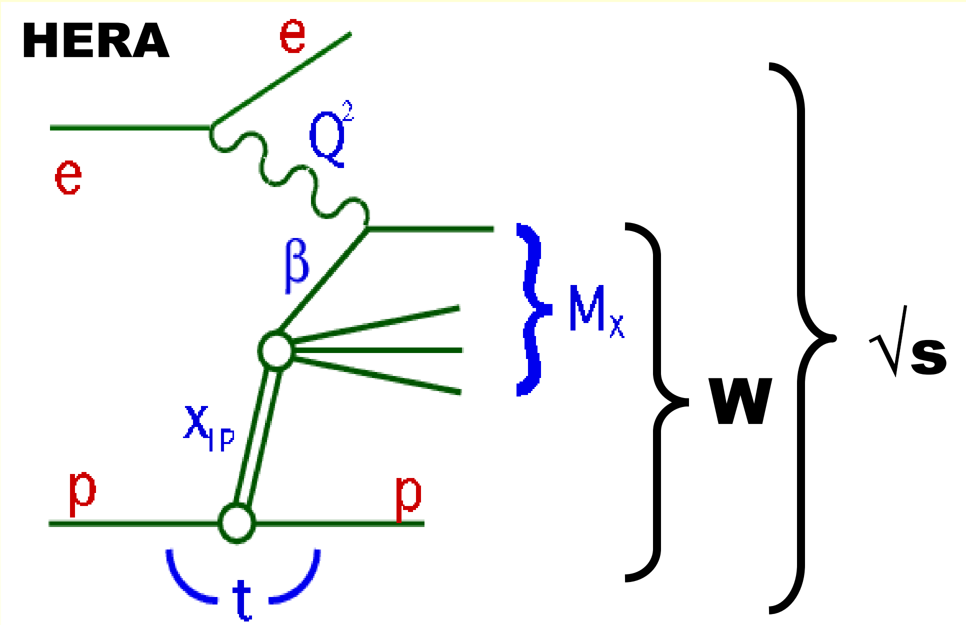


Rapidity gap:

no particle flow

Probe the structure of the diffractive exchange in DIS.

Kinematic Variables



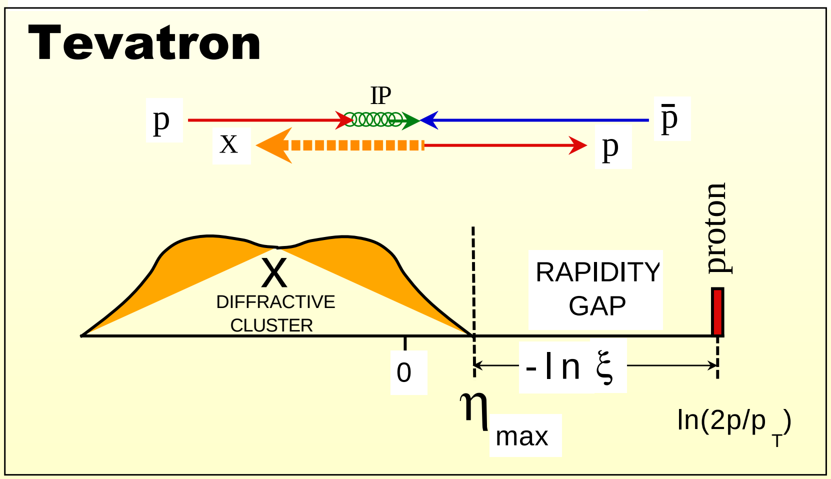
$Q^2 = \gamma$ virtuality

$x = x_{q\,/\,p}$ or $x_{g\,/\,p}$

$x_{IP} = x_{IP\,/\,p}$

$\beta = x_{q\,/\,IP}$ or $x_{g\,/\,IP}$

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



$\xi = x_{IP} = M^2 / s$

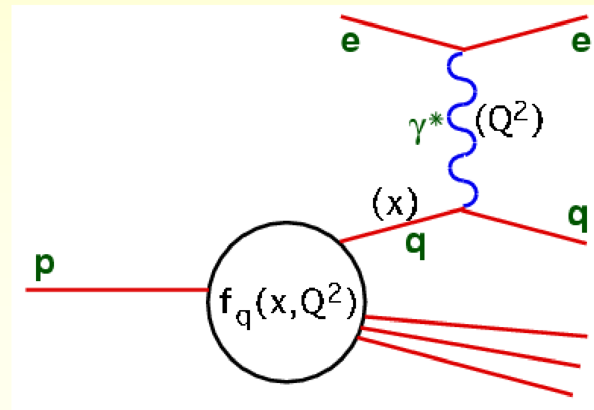
$$\Delta\eta \approx -\ln\xi = \ln s - \ln M^2$$

QCD Factorization

Inclusive DIS:

- **Theory: QCD Factorization holds**

- $\sigma^{DIS}(x,Q^2) \sim F_2(x,Q^2) \sim f_q(x,Q^2) \times \sigma_{pQCD}$

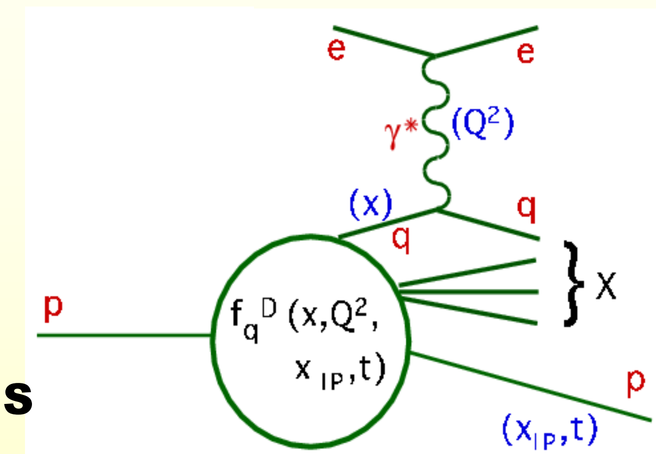


Diffractive DIS:

- **Theory: QCD Factorization holds**

- $\sigma^{DDIS}(x_{IP},t,\beta,Q^2) \sim F_2^D(x_{IP},t,\beta,Q^2)$

$$\sim f_q^D(x_{IP},t,\beta,Q^2) \times \sigma_{pQCD}$$



parton densities universal

same QCD evolution with DGLAP

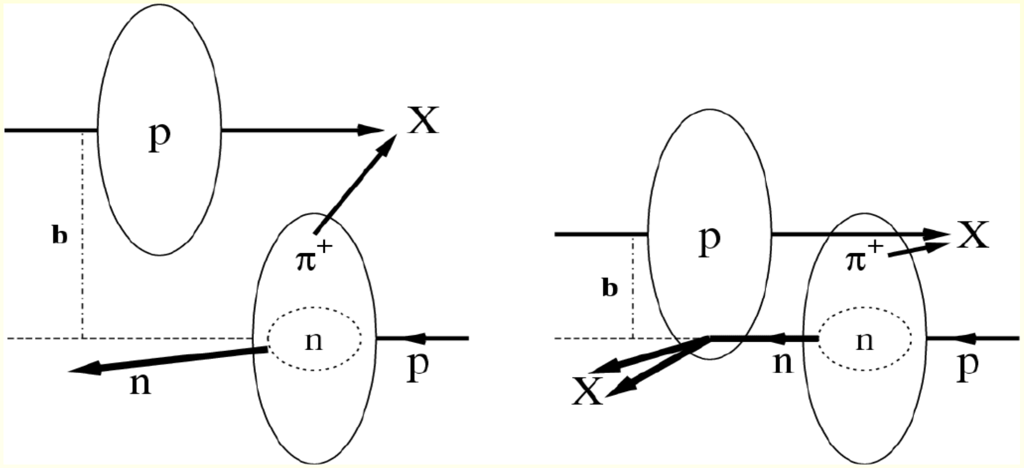
hard scattering in DDIS = hard scattering in DIS

same parton densities for other processes at the same (x_{IP},t)

Possibility for experimental tests

QCD Factorization in $\bar{p}p$ and resolved γp ?

Theory: QCD Factorization not proven and not expected to hold:



Modeled by:

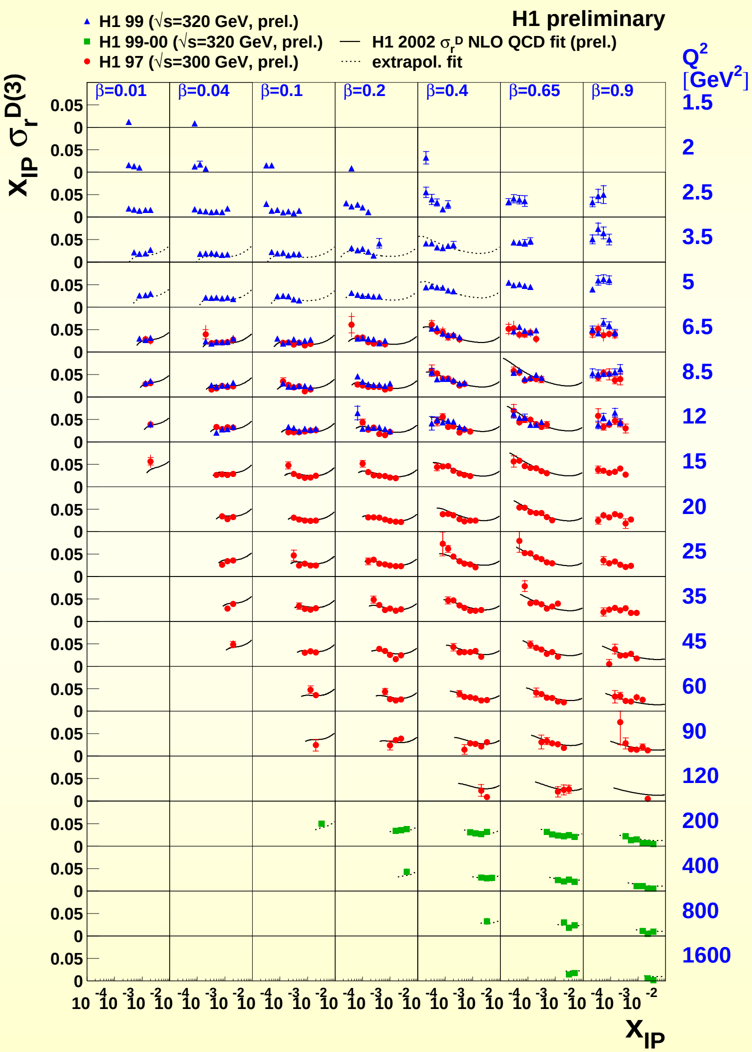
absorption in target fragmentation,

rapidity gap suppression via multiple pomeron exchange,

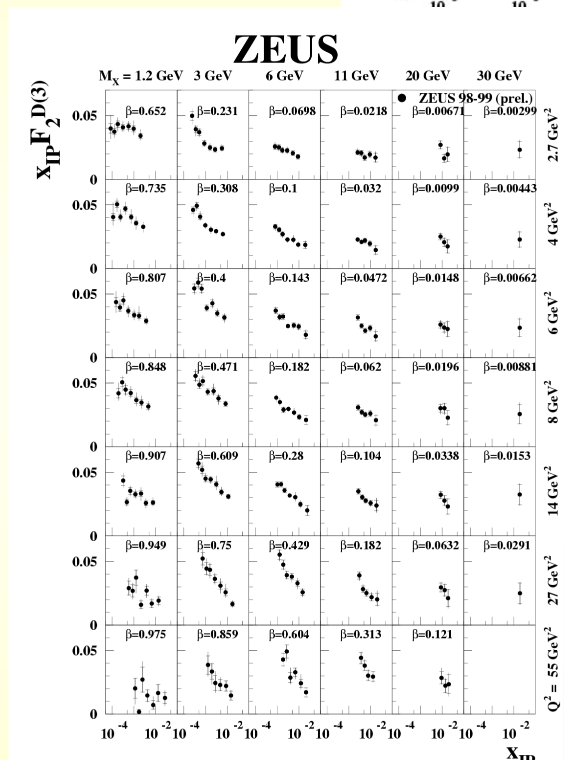
renormalization of rapidity gap probability, ...

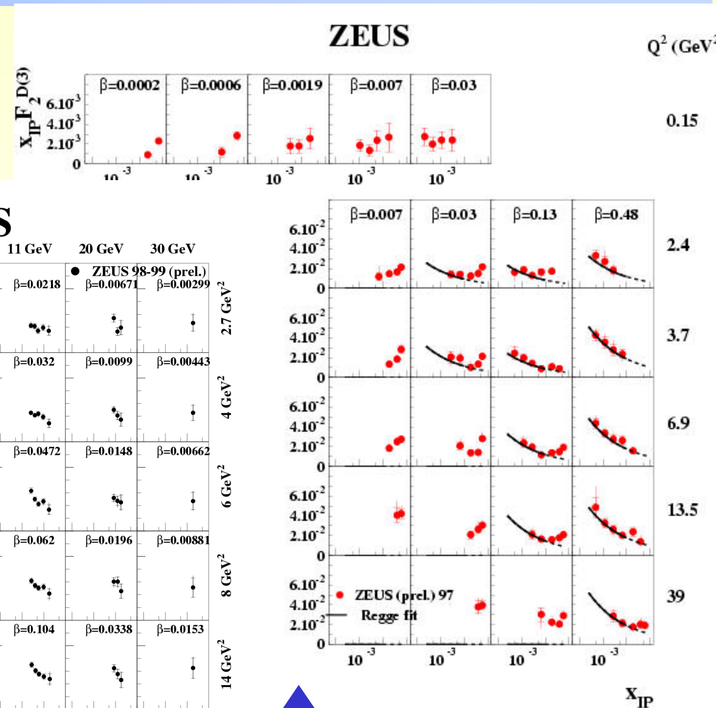
Experimental and theoretical challenge !

Inclusive DIS Data



Rapidity gap selection





Leading protons

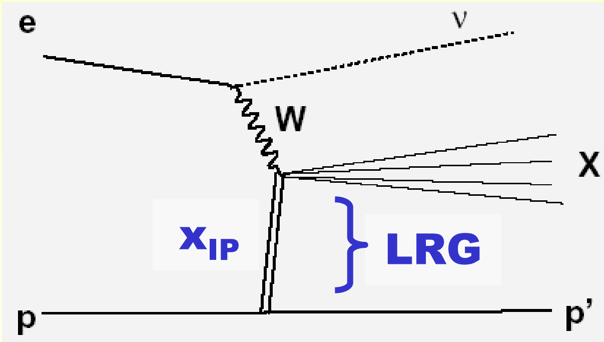
M_X Method

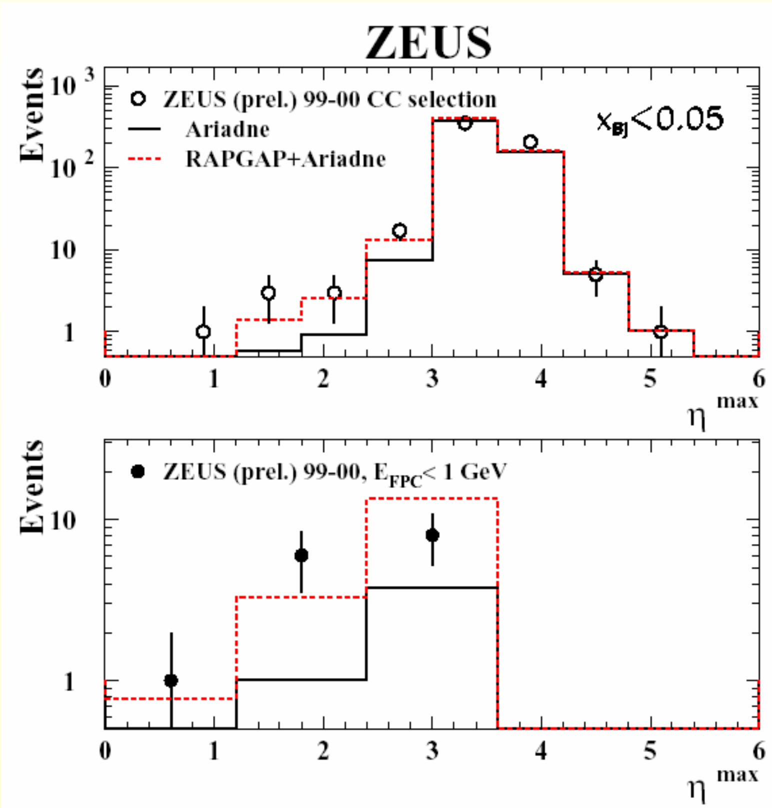
Large data sets available

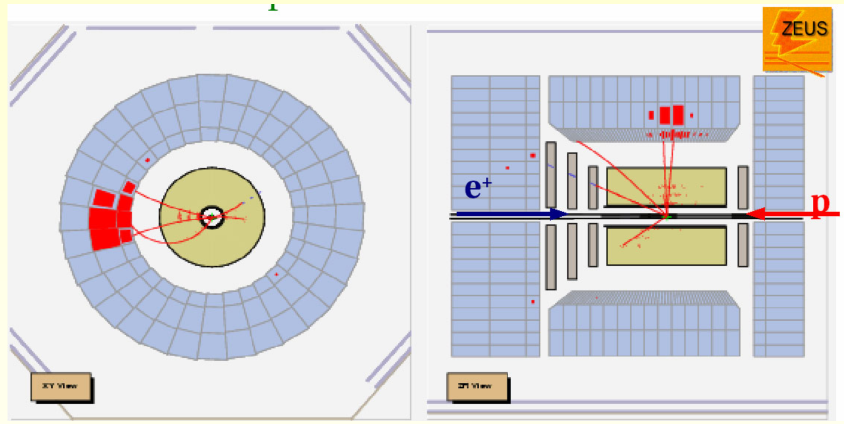
→ high precision

→ even rapidity gaps observed in CC events

Rapidity Gaps in Charged Current Events





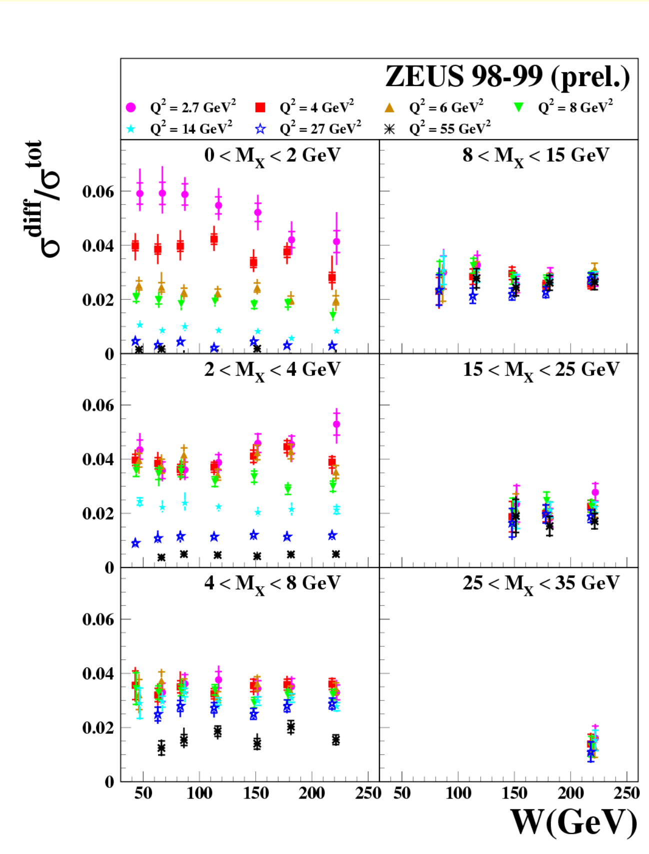


9 events observed, data consistent with expectation

$$\sigma^{cc,diff}\ (Q^2>200\,\mathrm{GeV}^2,\ x_{IP}<0.05) = 0.49\pm0.20(\mathrm{stat})\pm0.13(\mathrm{syst})\,\mathrm{pb}$$

$$\frac{\sigma^{cc,diff}\ (Q^2>200\,\mathrm{GeV}^2,\ x_{IP}<0.05)}{\sigma^{cc,tot}\ (Q^2>200\,\mathrm{GeV}^2,\ x_{bj}<0.05)} = 2.9\pm1.2(\mathrm{stat})\pm0.8(\mathrm{syst})\ \%$$

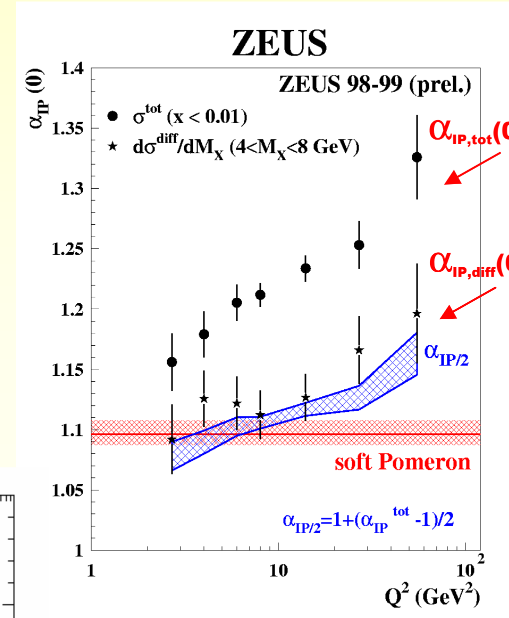
Inclusive Cross Section as a function of W

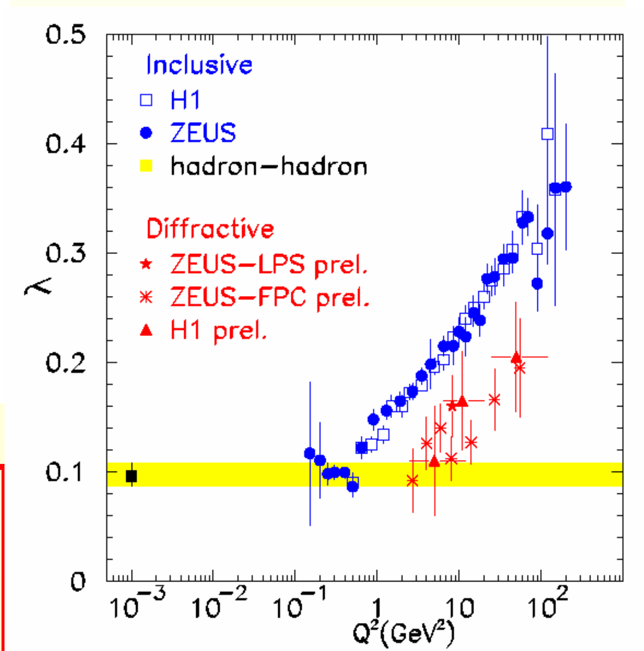


$\sigma^{tot} \sim F_2 \sim x^{-\lambda}$

$\sigma^{tot} \sim (W^2)^{\alpha_{IP,tot}(0)-1}$

$\sigma^{diff} \sim (W^2)^{2(\overline{\alpha_{IP,diff}}-1)}$





Ratio flat with W

Ratio decreasing with increasing Q^2

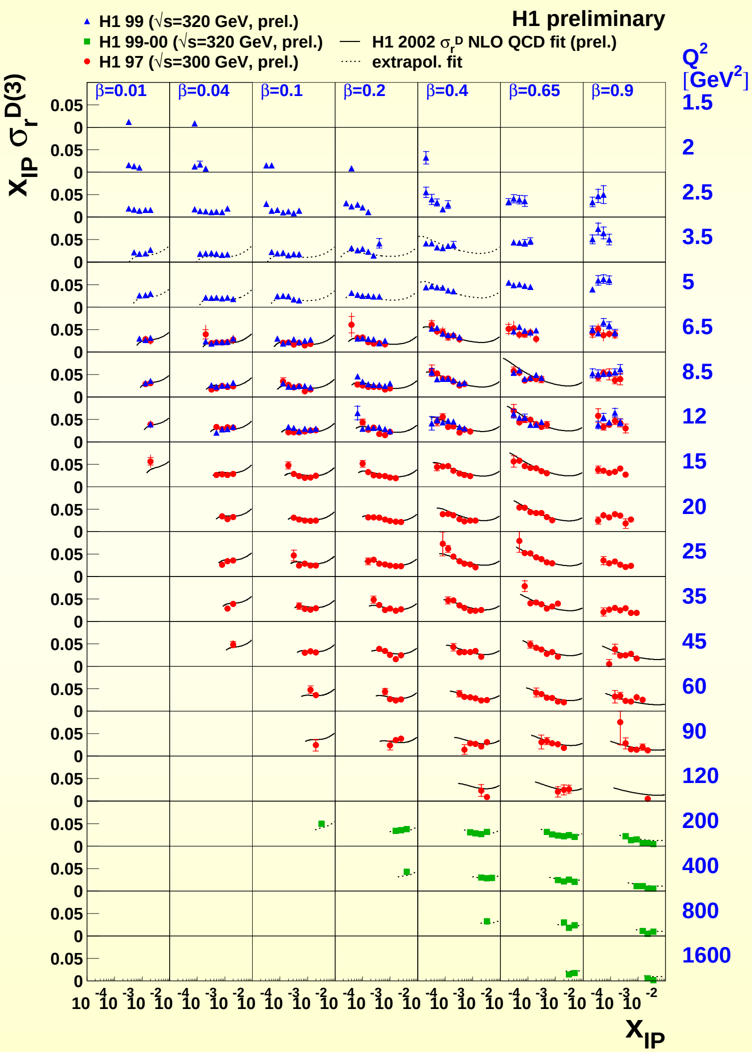
$\alpha_{IP,diff}(0) > \alpha_{IP,soft}(0)$

$\alpha_{IP,diff} = \alpha_{IP,diff}(Q^2)$?

$\alpha_{IP,tot}(0) = 1 + \lambda$

$\alpha_{IP,diff}(0) \approx 1 + \lambda/2$

Diffractive Structure Function



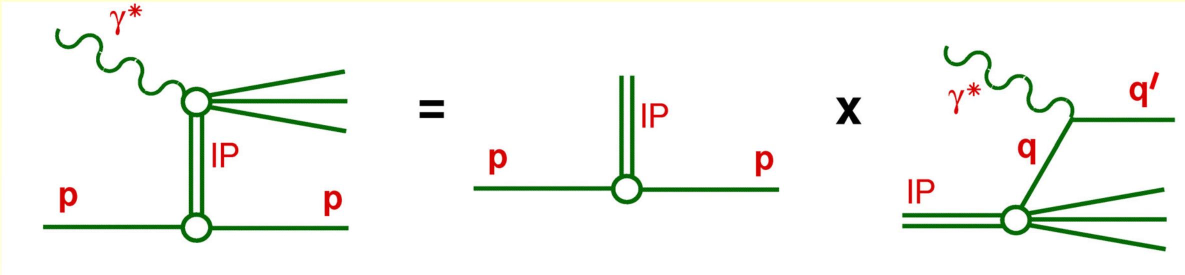
Measure F_2^D analog to F_2 with two more variables: x_{IP} and t (integrated):

$$F_2^{D(3)}(\beta, Q^2, x_{IP}) = \frac{\beta Q^4}{4\pi\alpha^2(1 - y + y^2/2)} \cdot \frac{d\sigma^D{}_{ep\to e'Xp'}}{d\beta dQ^2 dx_{IP}}$$

Parameterizations:

- **Resolved Pomeron** (→ Ch. Kiesling)
- **Color Dipole Models (for example BEKW)**
- **Deep Sea Model** (→ D.Goulianos)

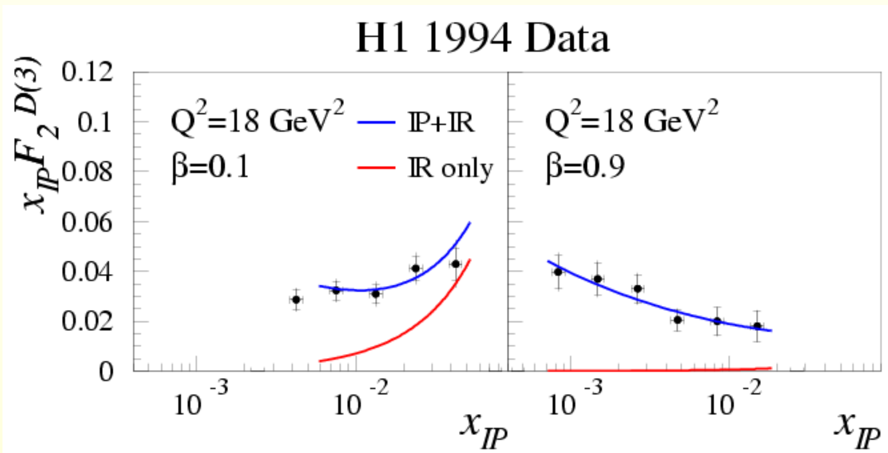
Resolved Pomeron Model



$$F_2^{D(3)} = f_{IP}(x_{IP}) \cdot F_2^{IP}(\beta, Q^2)$$

$$f_{IP}(x_{IP}) \propto \int \frac{e^{b_t t}}{x_{IP}^{2\alpha_{IP}(t)-1}} dt$$

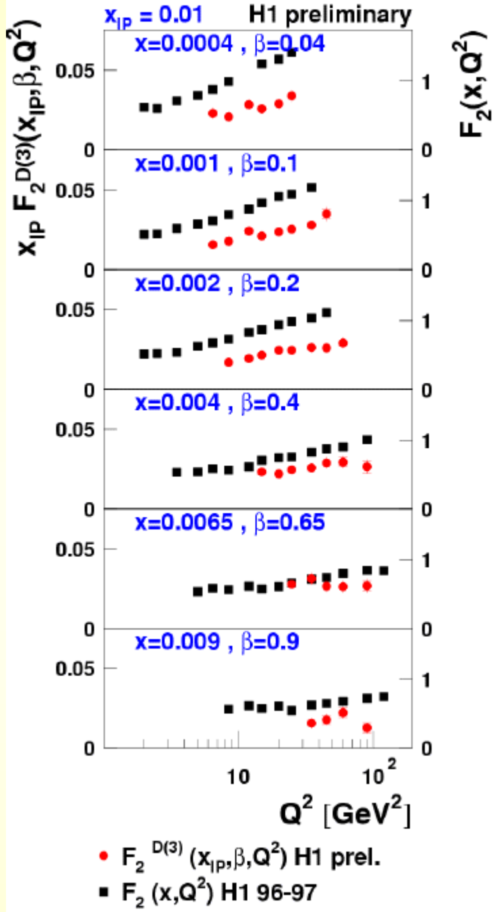
$$\alpha_{IP}(t) = \alpha_{IP}(0) + \alpha_{IP}' \cdot t$$



→ **Need sub-leading trajectory exchange**

$$F_2^{D(3)} = \underbrace{f_{IP}(x_{IP}) \cdot F_2^{IP}(\beta, Q^2)}_{\textbf{Pomeron}} + \underbrace{f_{IR}(x_{IP}) \cdot F_2^{IR}(\beta, Q^2)}_{\textbf{Reggeon}}$$

Parton Densities for Pomeron Part



$$F_2^D \sim q^D(x) + \overline{q}^D(x)$$

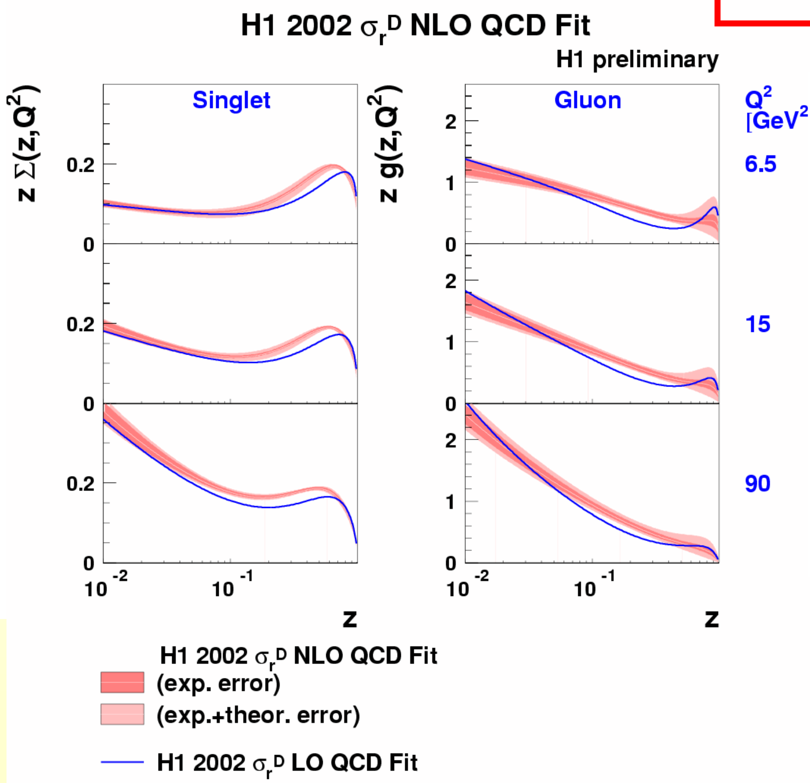
$$\partial F_2^D / \partial \ln Q^2 \sim g^D(x)$$

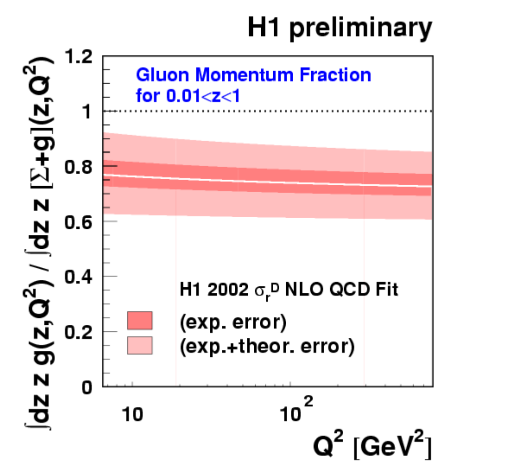
DGLAP QCD fit

large gluon density

large uncertainty at high β

good description of data



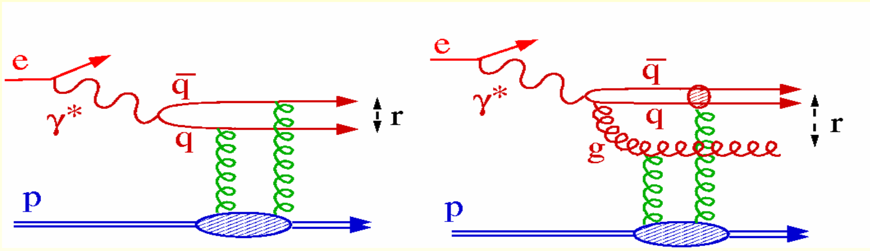


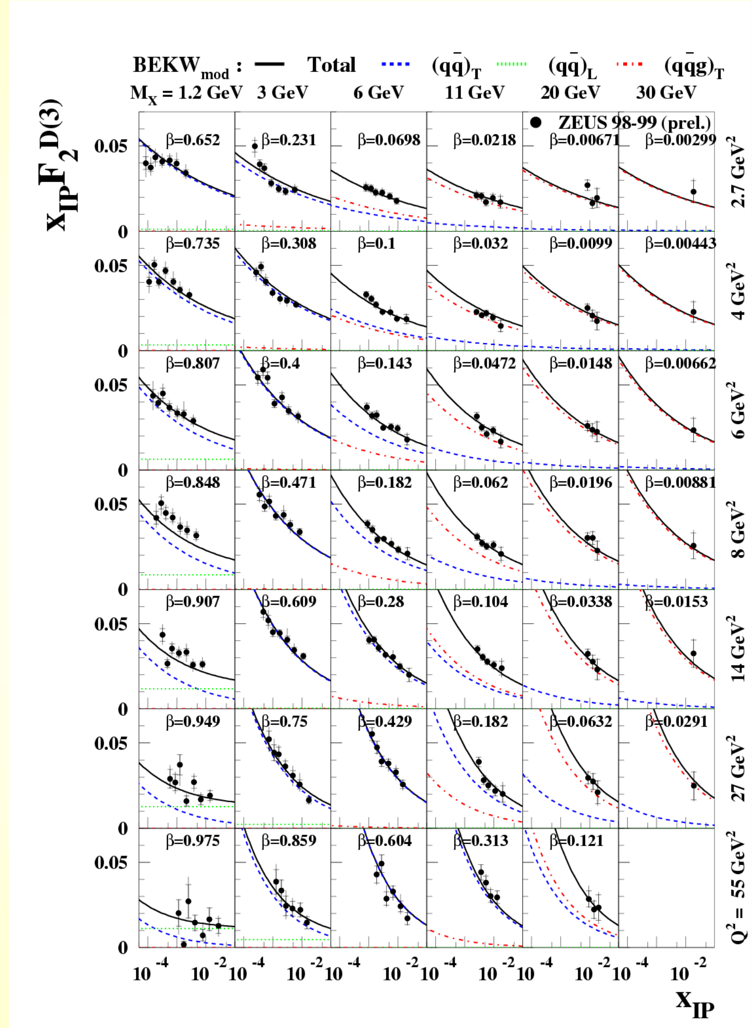
x: similar to proton

β: large scaling violations→ gluons

(→ Ch. Kiesling)

Color Dipole Models





(→ J.Bartels)

BEKW model :

- **at medium β** $F^T_{q\bar{q}} \sim \beta(1-\beta)$
- **at small β** $F^T_{q\bar{q}g} \sim (1-\beta)^\gamma$

Saturation model : $\sigma_{q\bar{q}} \propto r^2 \propto 1/Q^2$

for $Q^2 \to 0$ → $\sigma_{q\bar{q}} \to \infty$

growth tamed by requiring saturation

Deep Sea Model

Restrict the validity of the model to the partonic sea region

→ **small x, small x_{IP} , small β**

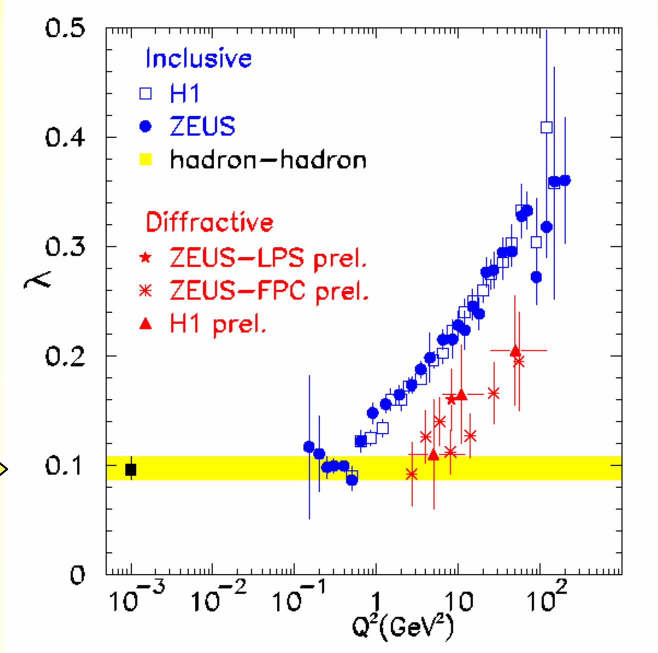
→ **asymtotic behavior**

$$F^D(x_{IP}, x, Q^2) \sim \frac{1}{x_{IP}^{1+\varepsilon}} F(x, Q^2)$$

$$\sim \frac{1}{x_{IP}^{1+\varepsilon}} \cdot \frac{C}{(\beta \cdot x_{IP})^{\lambda(Q^2)}}$$

λ(Q²) →

ε →



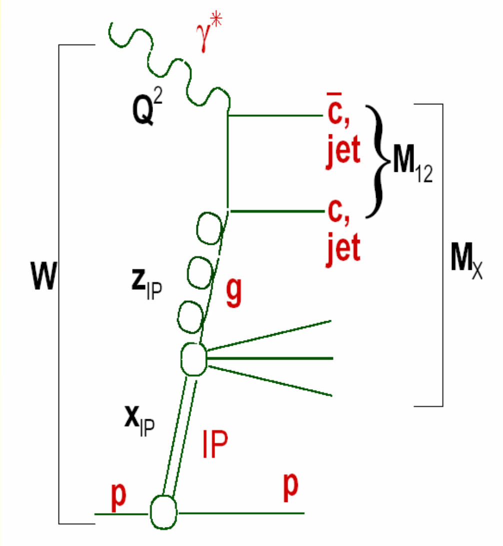
Expectation seen in the data:

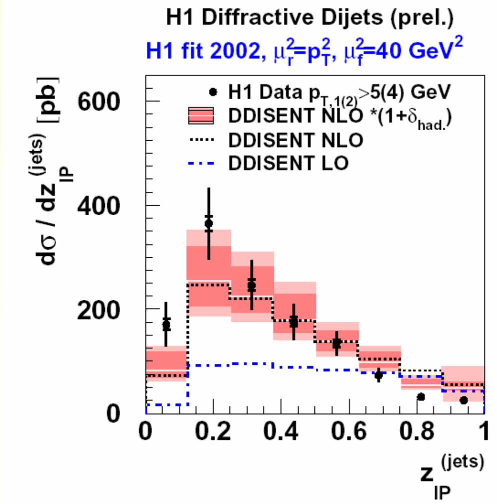
F_2^D / F_2 = constant   for fixed x_{IP}

(→ D.Goulianos)

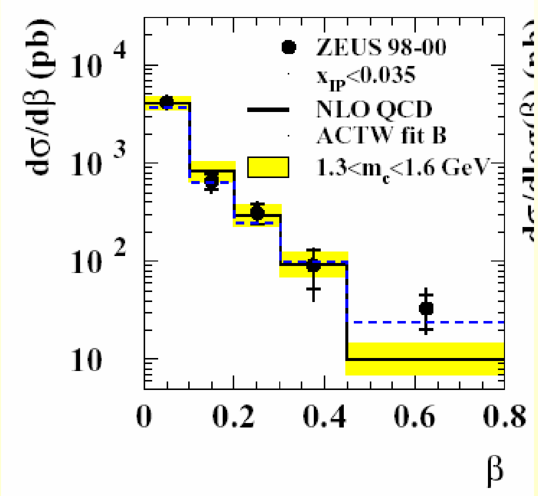
$\alpha_{IP,diff}(0) = 1 + ½(\varepsilon+\lambda(Q^2))$

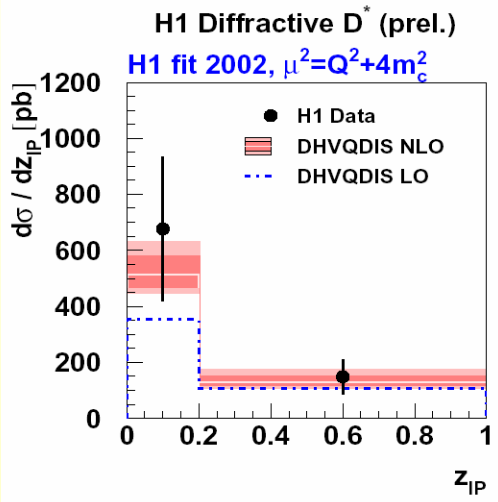
QCD Factorization in DDIS





Diffractive Dijet and D* production rates well reproduced by NLO calculations





Factorization holds!

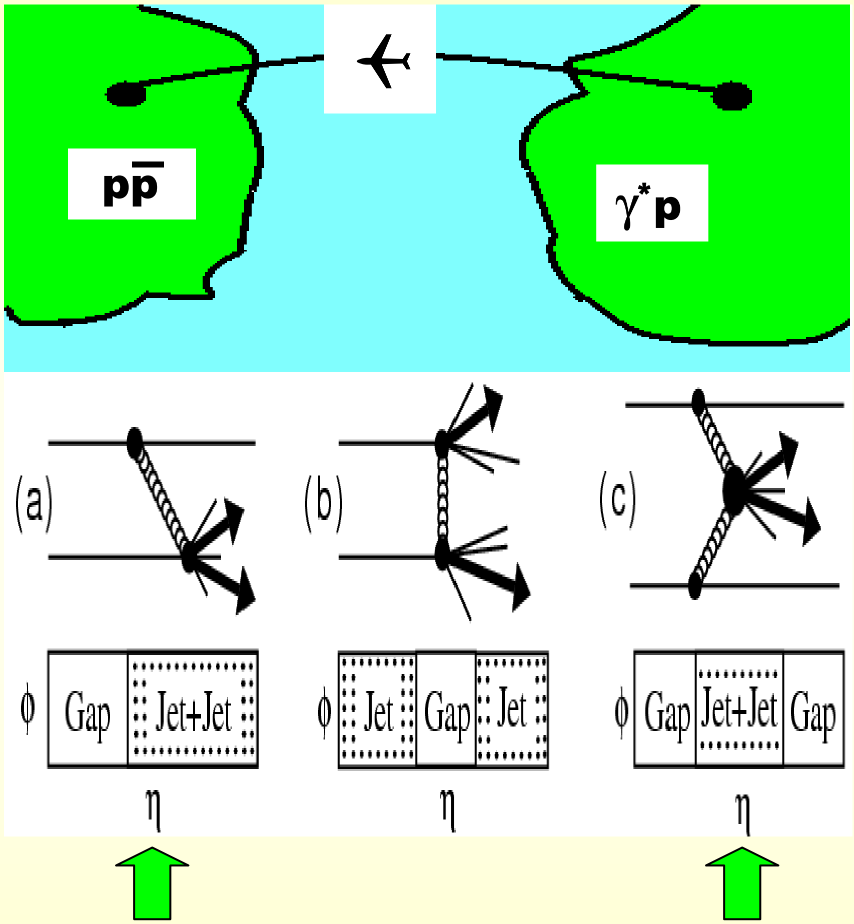
(→ Ch. Kiesling)

Summary HERA

- **Large data sets analyzed → high precision achieved**
- **Models available to describe the data**
- **QCD Factorization holds in DDIS**

Consistent description in the framework of QCD achieved

Hard Diffraction in $\bar{p}p$ Collisions



SD

DPE

Concentrate on dijet production

Results from rapidity gaps:

W / Z, beauty, J/Ψ, jets

Tevatron: 1% diffraction

HERA: 10% diffraction

Factorization tests with leading proton data:

SD dijet Fjj $\leftrightarrow$ Fjj from HERA

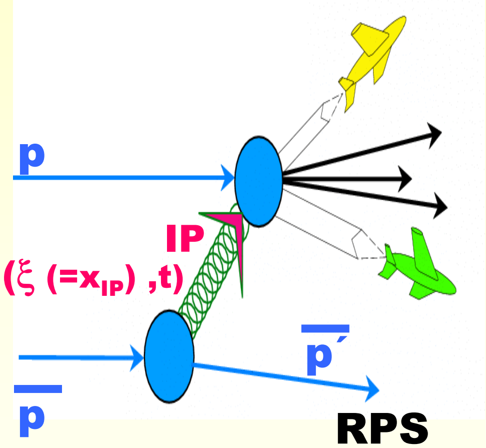
SD dijets: @ 1800 $\leftrightarrow$ @ 630

SD dijets $\leftrightarrow$ J/Ψ @ 1800

SD dijets $\leftrightarrow$ DPE dijets

DPE dijet Fjj $\leftrightarrow$ Fjj from HERA

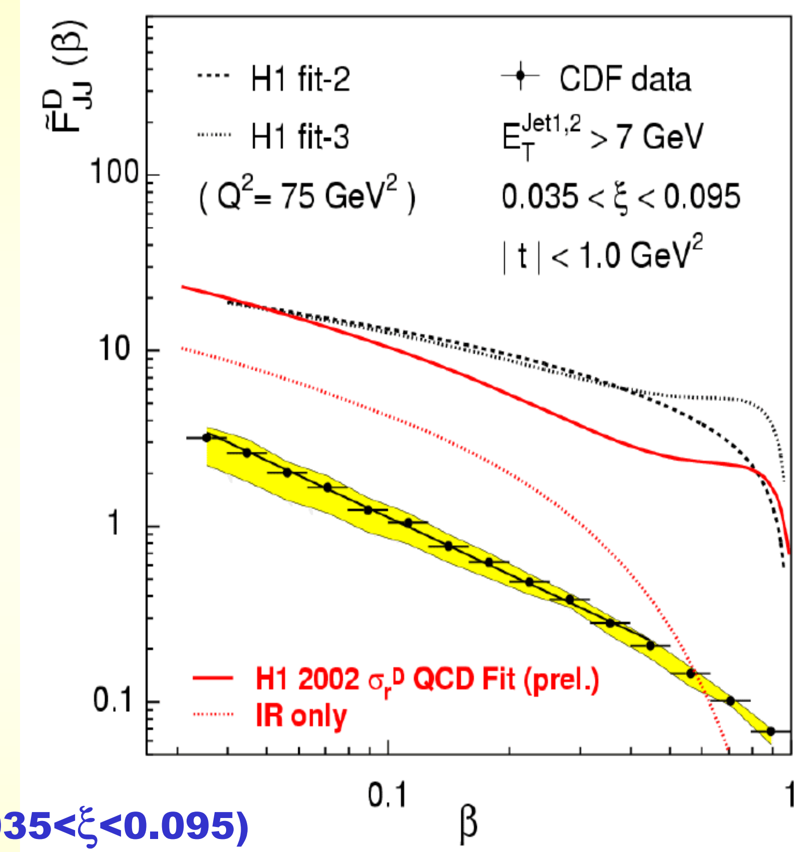
SD dijets @ 1800 GeV



$x = 1/\sqrt{s} \bullet \Sigma_i E_{T,i} \, e^{-\eta_i}$

ξ (=x_{IP}) from RPS

$\beta = x/\xi$



Effective structure function for dijet production:

$F_{jj}(x) = x\,[\,g(x) + 4/9\,\Sigma(q(x)+\overline{q}(x))\,]$

Tevatron: unfold from ratio

$R^{SD}_{ND} \sim F^D_{jj}/F_{jj}$ **& Fjj from proton pdf**

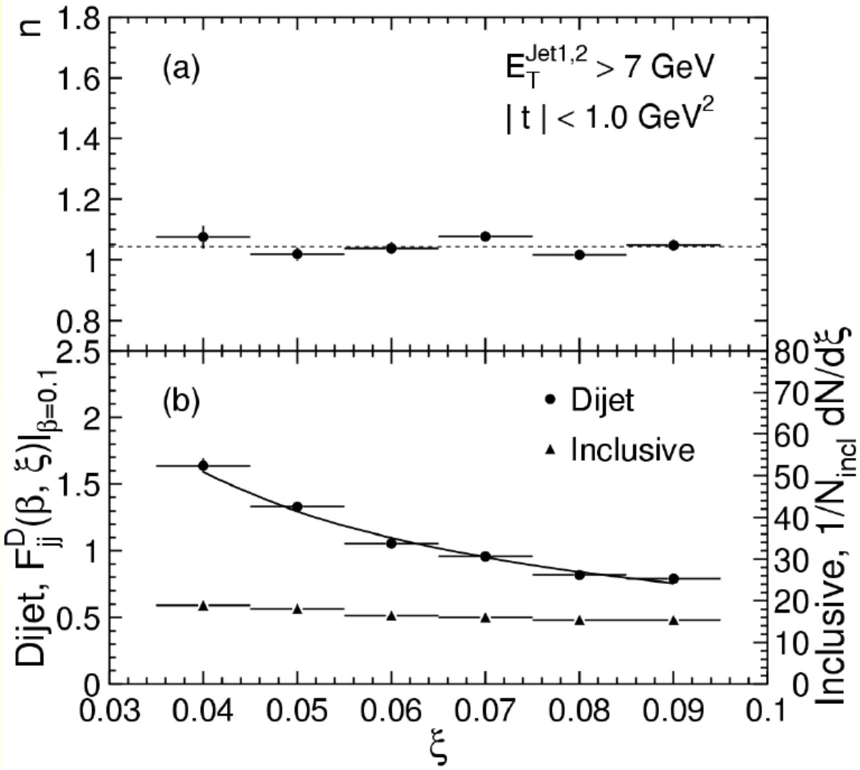
HERA: use diffractive pdf ($x_{IP}<0.05 \rightarrow 0.035<\xi<0.095$)

Fjj ~ $1/\beta^n$ with n=1.0±0.1 for β<0.5

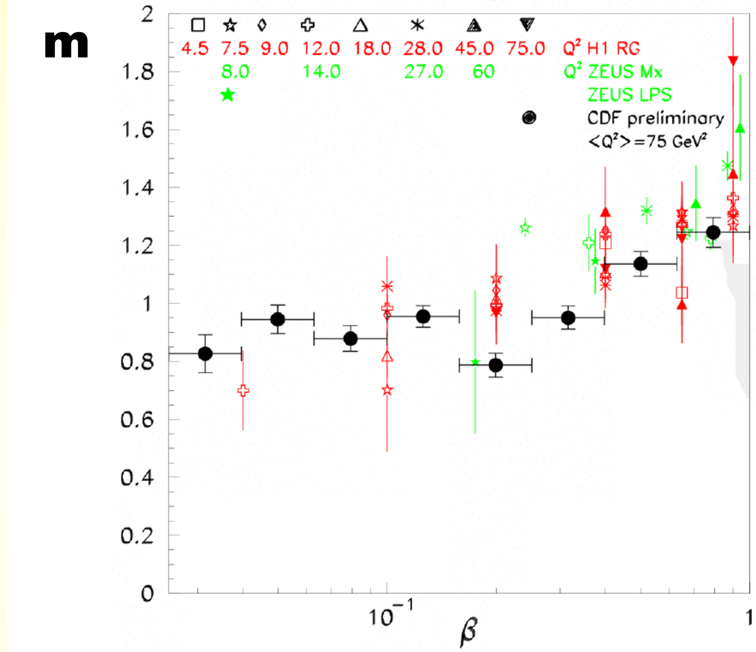
Tevatron ↔ HERA: shape similar → same evolution,

normalization off by a factor ≈ 10 → Factorization broken !

Diffractive Characteristics



$F_{jj}^D(\beta, \xi) \sim 1/\ \xi^m$



$F_{jj}^D(\beta, \xi) \sim 1/\ \beta^n$ independent of ξ

$F_{jj}^D(\beta=0.1, \xi) \sim 1/\ \xi^m$, $m=1.0\pm0.1$,
$m > m_{soft}$

$F_{jj}^D(\beta, \xi) \sim 1/\ \beta^n \bullet 1/\ \xi^m$?

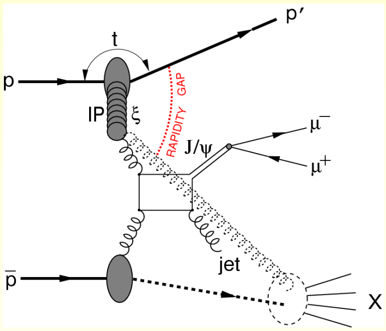
($F_2 \sim 1/x^\lambda$, $f_{IP/p} \sim 1/\ \xi^{(2\alpha-1)}$)

$F_{jj}^D(\beta, \xi) \sim 1/\ \beta^n \bullet 1/\ \xi^m$ for $\beta < 0.5$

Although $0.035<\xi<0.095$:
no 50% reggeon contribution
($m_{IP}\approx1.1$, $m_{IR}\approx0$, $m_\pi\approx-1$)

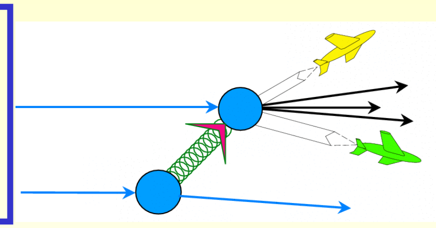
Same ξ dependence at HERA ($x_{IP}<0.05$)
and CDF ($0.035<\xi<0.095$)

Further Factorization Tests



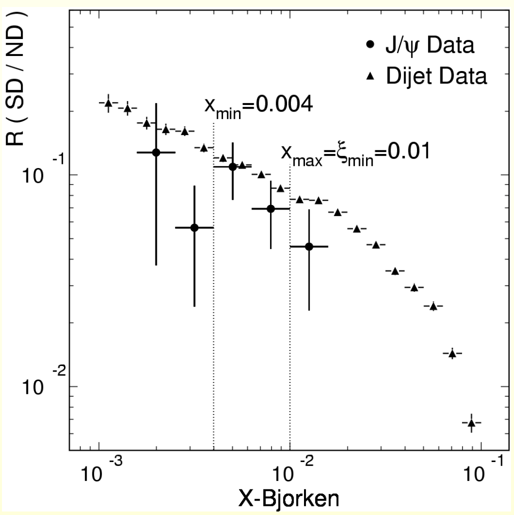
Different process, same √s:

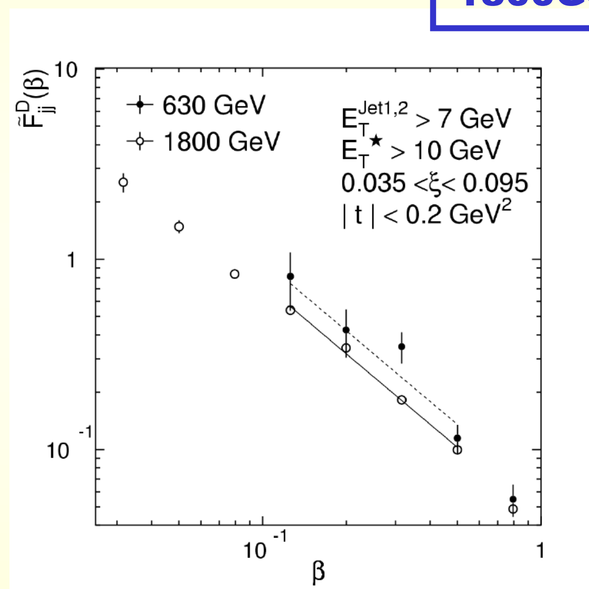
J/Ψ → μ+ μ- (+jet)



Dijets at different center of mass energy:

1800GeV ↔ 630GeV





Ratio jj / J/Ψ = 1.17±0.27(stat)

Factorization holds

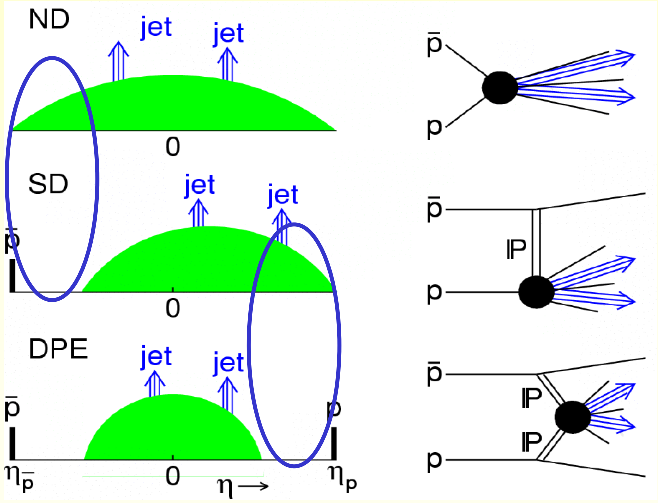
Similar structure 1/ β^n

n(630)=1.4 ±0.2, n(1800)=1.23 ±0.04

Ratio 630 / 1800 = 1.3 ±0.2(stat) ±0.3(syst)

Factorization ?

Factorization Test with DPE



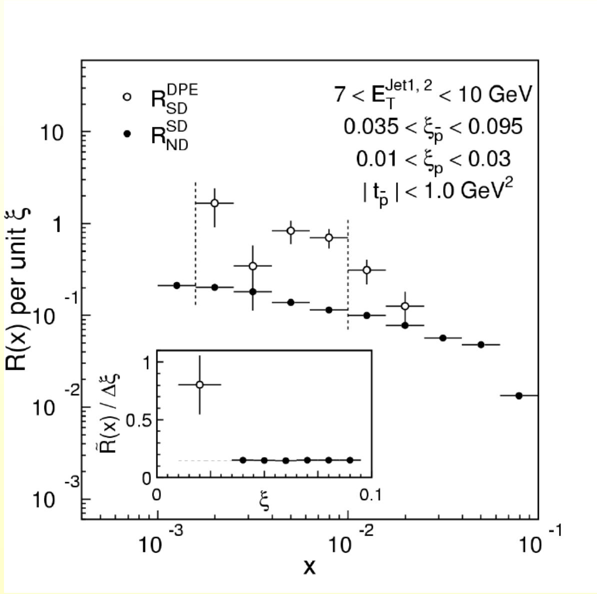
Lower effective √s ↔ multiple rap. gaps

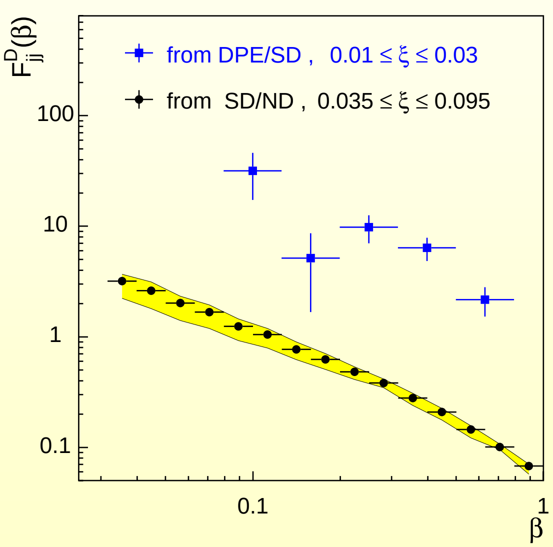
Factorization: $$F_{jj}\left[R^{SD}_{ND}\right] = F_{jj}\left[R^{DPE}_{SD}\right]$$

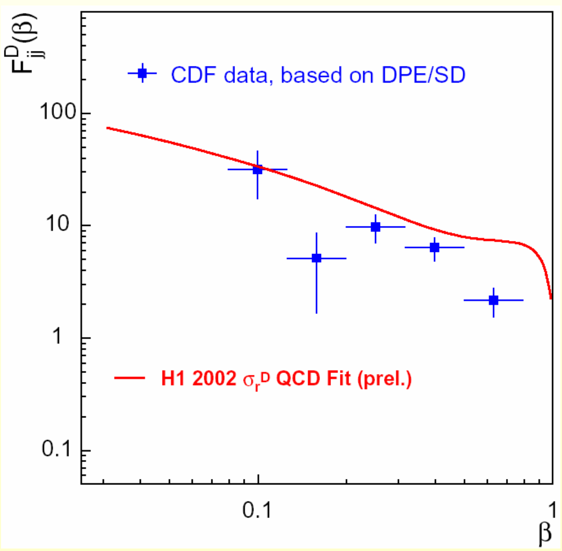
Ratio: ≈ factor 5

Fjj: ≈ factor 10 between SD and DPE,

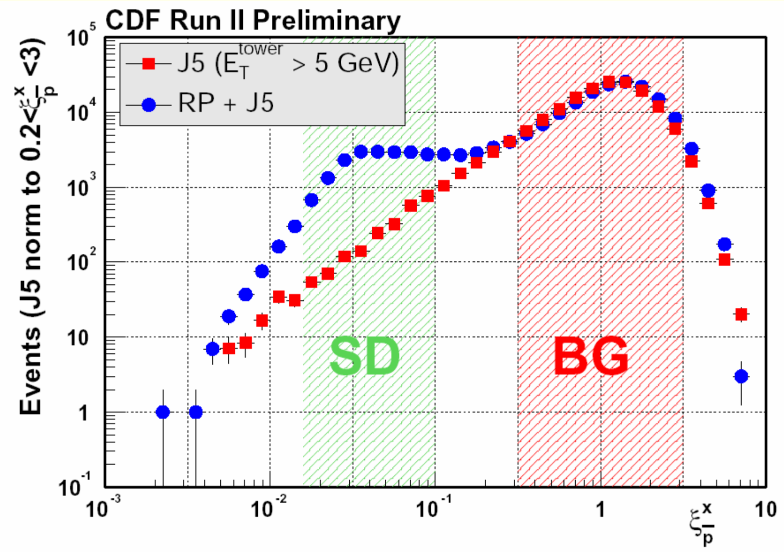
but DPE similar to HERA **(→ M.Convery)**







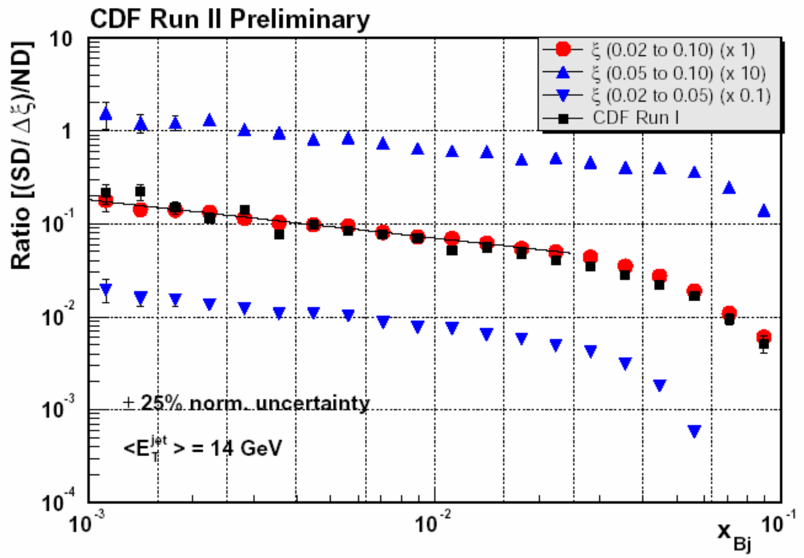
Results from Run II

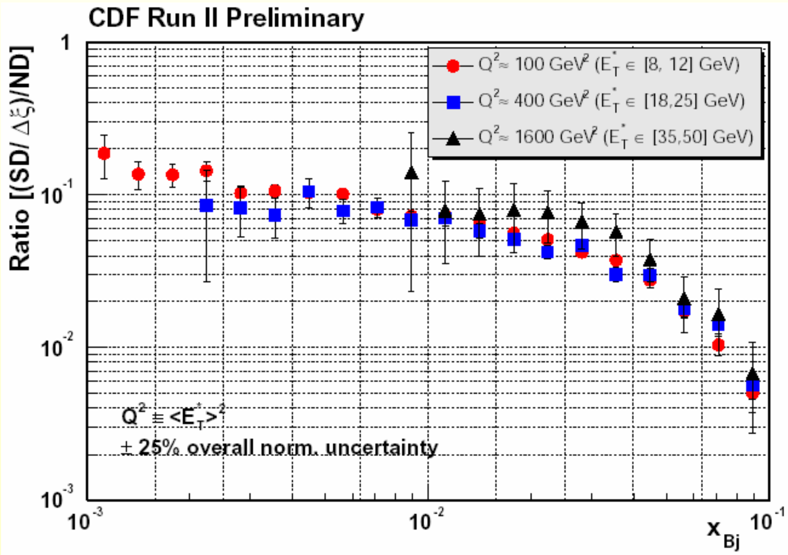


Non diffractive background is exponentially suppressed

Results from Run I confirmed

No Q^2 dependence seen
→ Fjj^D similar evolution as Fjj



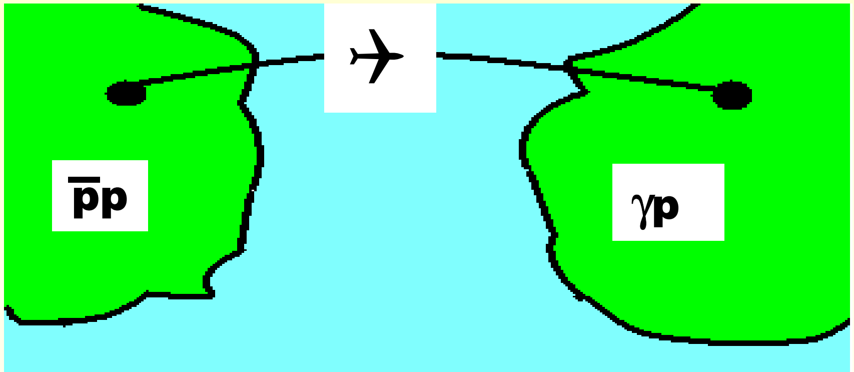


Summary Tevatron

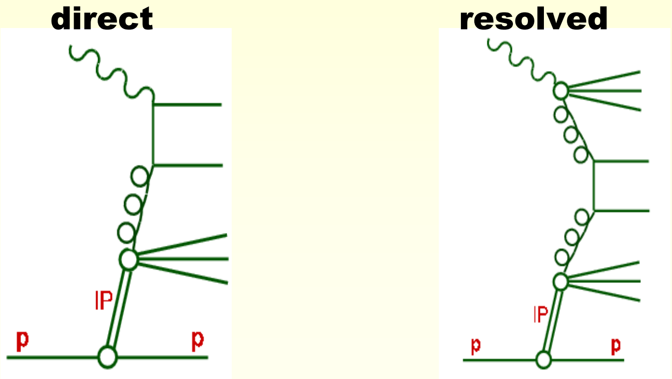
- **Precise data available, statistic even more increasing with Run II data**
- **QCD Factorization not expected to hold:**
  - **Factorization breaking in normalization between Tevatron and HERA established,**
    but similar diffractive characteristic seen
  - **Factorization holds, when changing processes**
  - **Factorization broken between SD/ND and DPE/SD**
  - **Factorization re-established between DPE/SD and HERA**

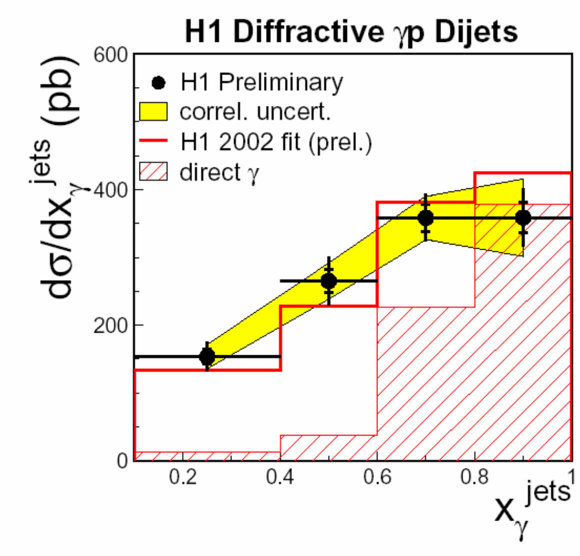
Factorization breaking found,
but re-established under certain circumstances
(same $\sqrt{s}$ or multiple rapidity gaps)

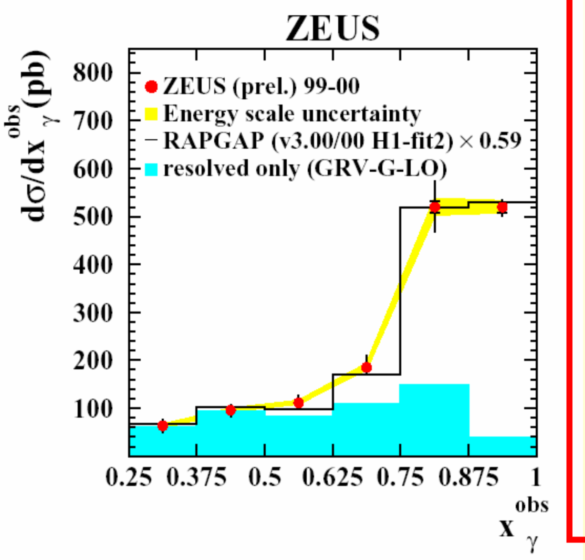
Going back to PHP @ HERA



Factorization not expected to hold:







In LO:

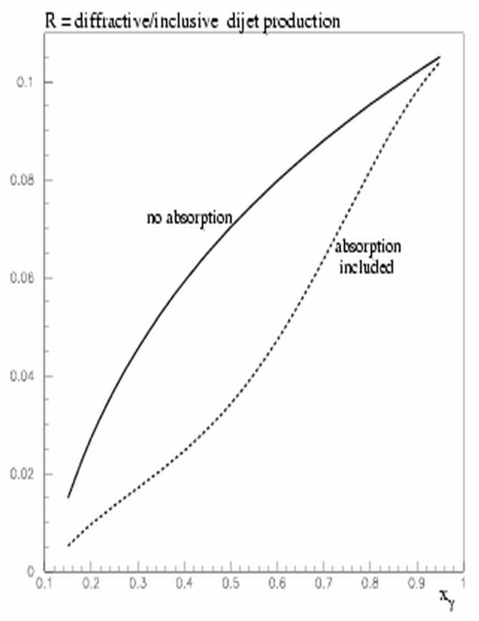
- **published diffractive pdf's: rescaling of MC by ≈0.6 independent of xγ needed**
- **new preliminary pdf's: good description**
- **ratio MC/data for PHP larger by 1.3±0.3 compared to DIS**

Expectation from Theory

Calculation by KKMR using multiple IP exchange:

PHP(resolv.)≈0.34 DIS

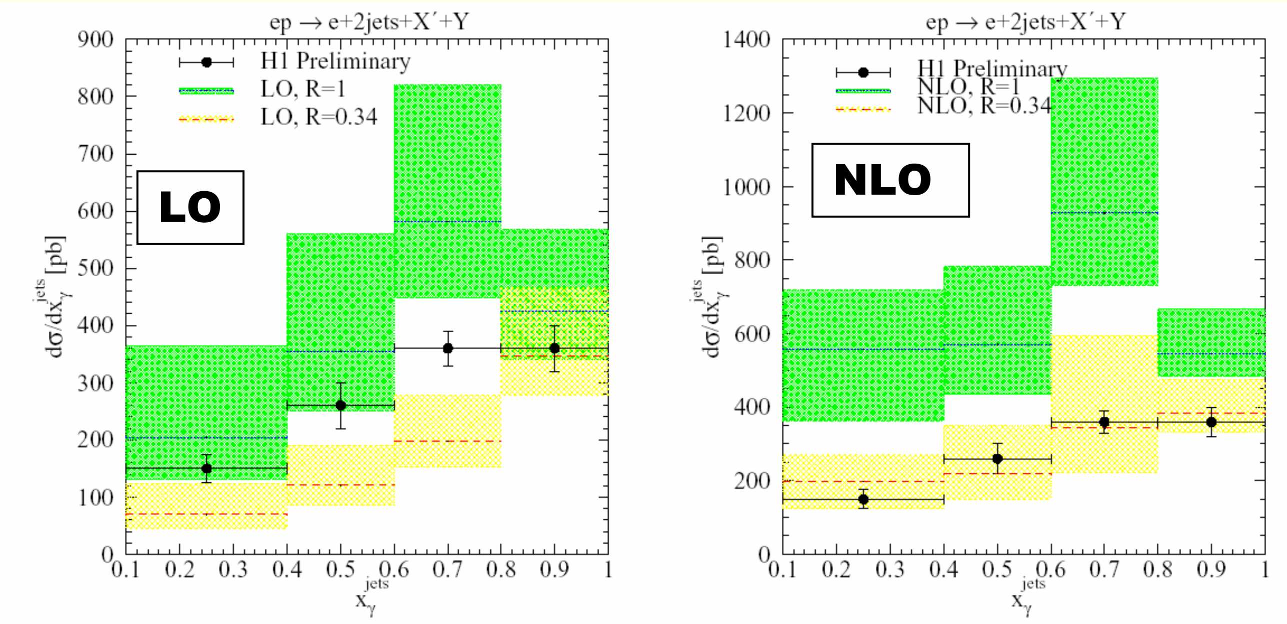
& exp. smearing



Calculation by Klasen & Kramer using no suppression (R=1) or suppression (R=0.34) for resolved part:

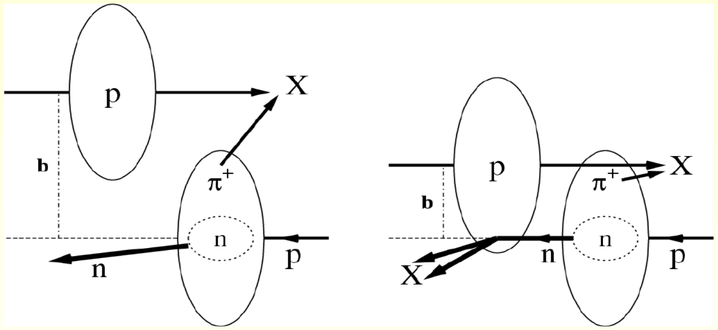
- **No suppression in LO**
- **Suppression needed in NLO**

(but large uncertainty in diffractive pdf's)

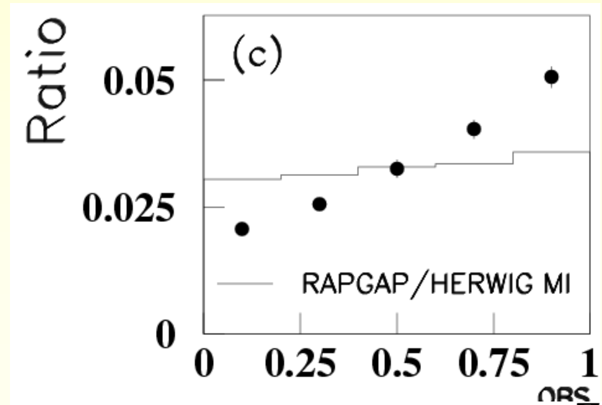


Equivalent: Leading Baryons

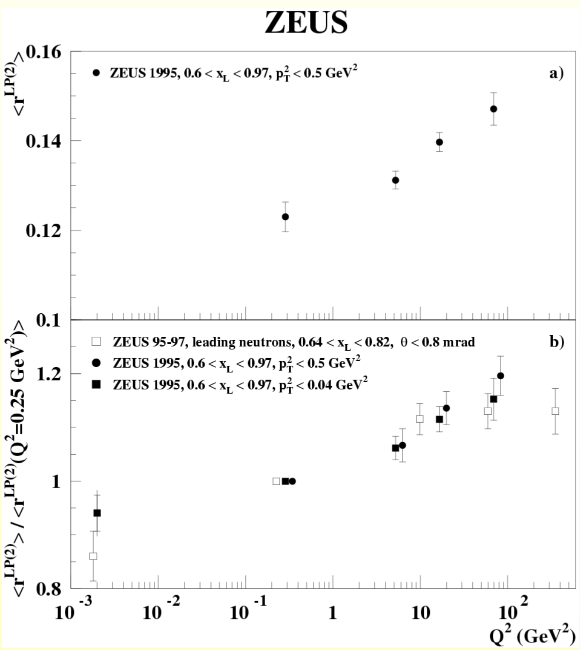
Absorption for Leading Neutrons:



Dijet PHP with Leading Neutron:

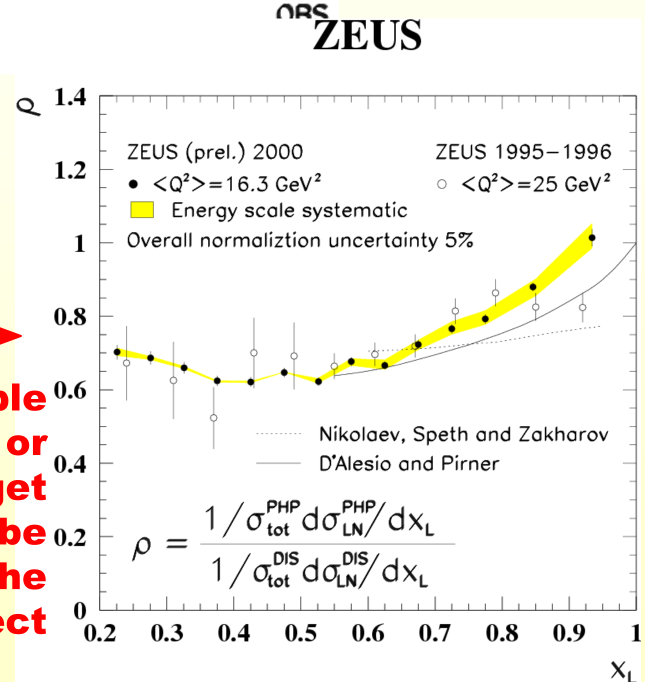


Evidence for factorization breaking



Production of Leading Neutrons and Leading Protons is Q2 dependent

Models with multiple pomeron exchange or rescattering in target fragmentation describe tendency, but not yet the full effect



Unitarity Effects in hard diffraction at HERA

Further calculations from KKMR:

$$R = \frac{\sigma_{jj}^{D}}{\sigma_{jj}} = \frac{\iint_{t,x_{IP}} F_{IP}^{g}(x_g, \mu^2)}{x_g f_p^g(x_g, \mu^2)}$$

increases quickly for x→0, but should be <1 by definition

Pumplin bound:

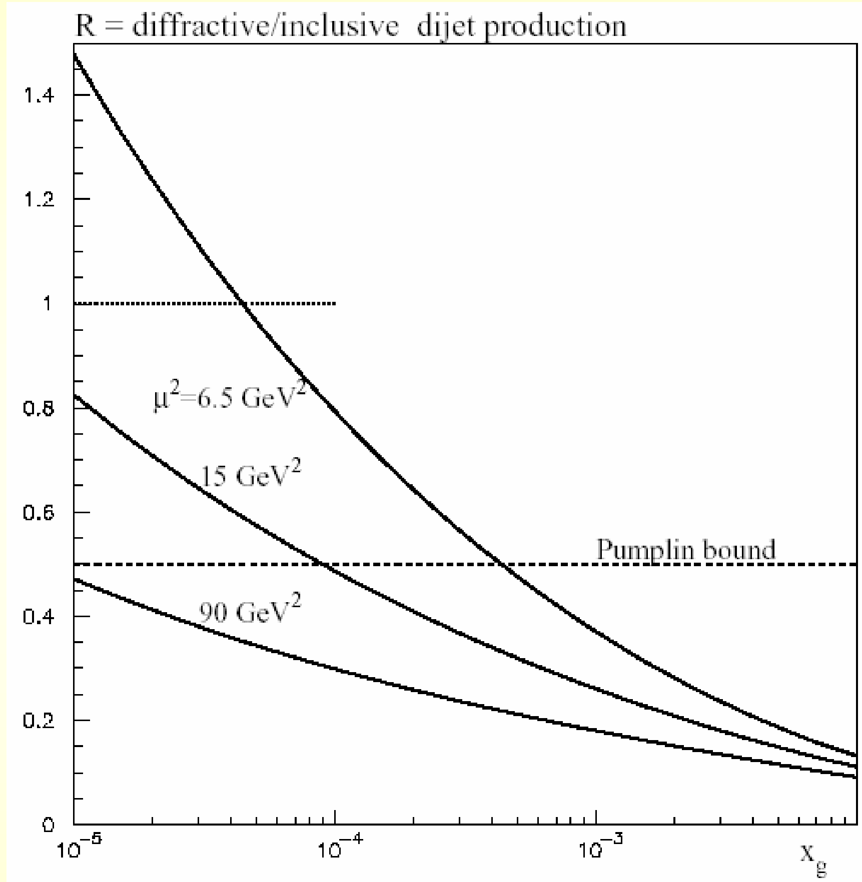
$\sigma^D / \sigma \leq 0.5 \rightarrow R \leq 0.5$

violated even at low scale μ^2 for $xg<10^{-3}$

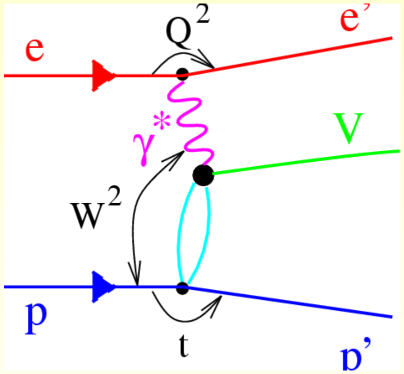
→ unitarity violation, saturation

→ To be checked experimentally

One possibility: exclusive vector meson production probing the gluon density



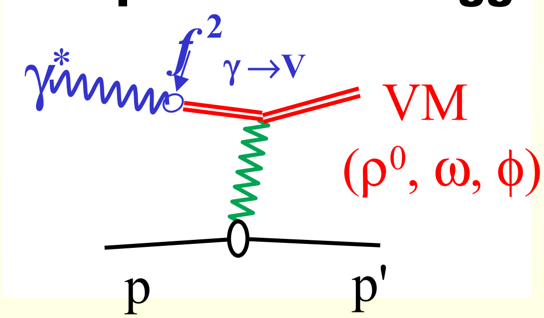
Exclusive Vector Meson Production @ HERA



Advantage:
- **Few particles in final state → clear signal**
- **Different hard scales available:**

Q^2	$0 < Q^2 < 100$ GeV^2
$W_{\gamma p}$	$20 < W_{\gamma p} < 290$ GeV
t	$0 < \|t\| < 20$ GeV^2
VM	$\rho^0, \omega, \phi, J/\psi, \psi', \Upsilon$

Soft production: Regge+VDM

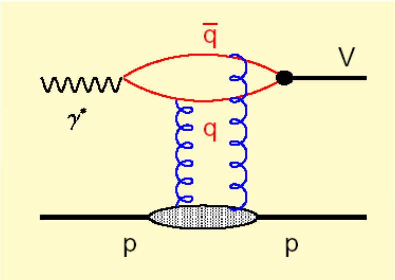


$\sigma_{\gamma p \to Vp} = f^2_{\gamma \to V} \otimes \sigma_{Vp \to Vp}$

$d\sigma_{Vp \to Vp}/dt = e^{-b_0 t} \cdot W^{4(\alpha_{IP}(t)-1)}$

$\sigma_{Vp \to Vp} \sim W^{4(\alpha_{IP}(0)-1)} \sim W^{0.22}$

Production with hard scale: pQCD



small $q\bar{q}$ configuration
→ resolve gluons
→ γ^*_L or VM=$c\bar{c}$,$b\bar{b}$

$\sigma_{\gamma^* p \to Vp} \sim 1/Q^6\,[x\,G(x,Q^2)]^2$

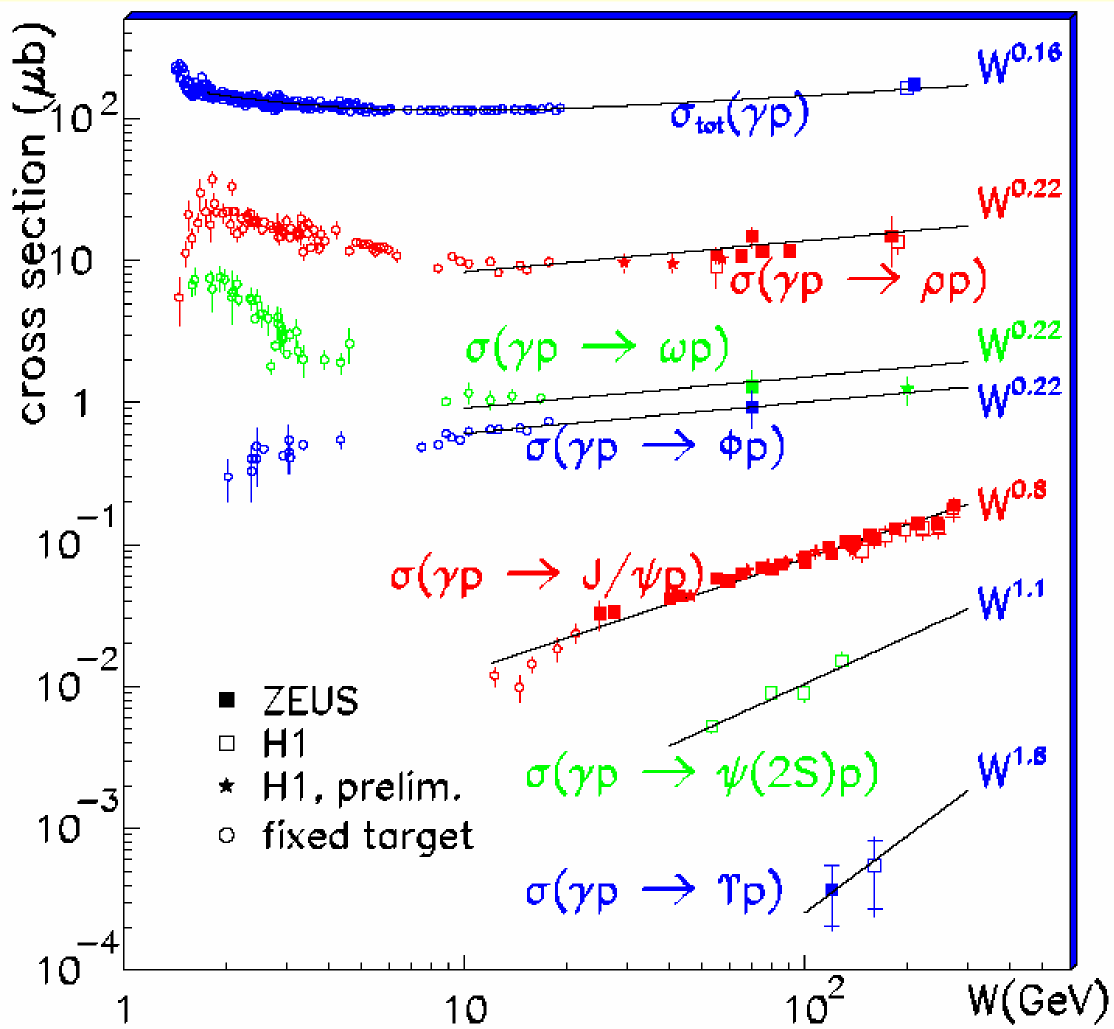
fast increase with $W^{0.8}$

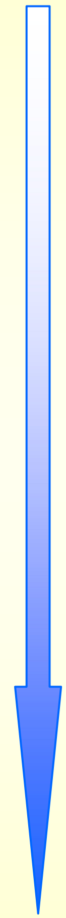
Q^2 dependence slower than $1/Q^6$

Universality of t dependence:

$b_{2g} \approx 4$GeV^{-2} and $\alpha' \approx 0$

Vector Meson Production in PHP

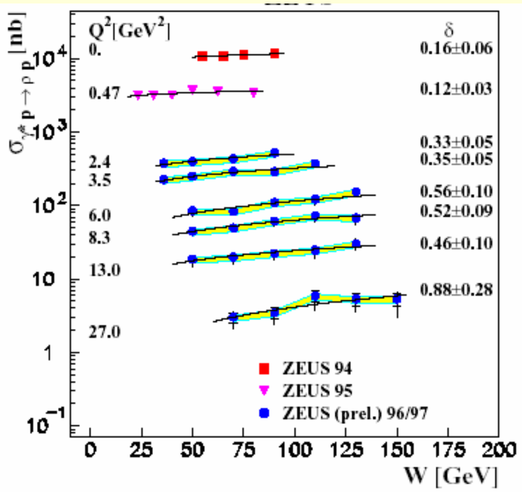




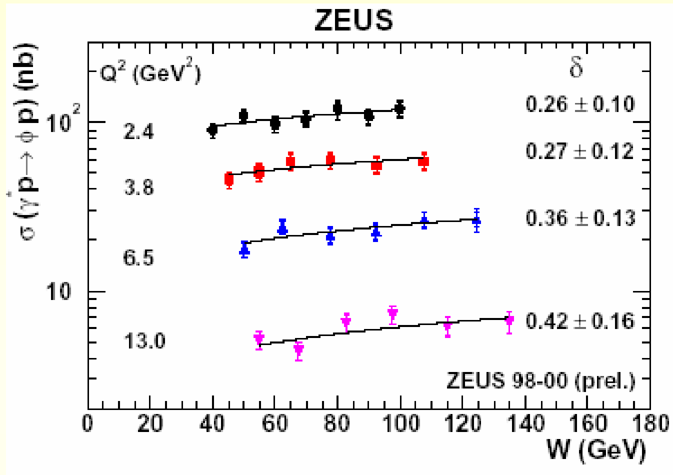
Increasingly harder scale by mass of the vector meson

W Dependence for VM in pQCD

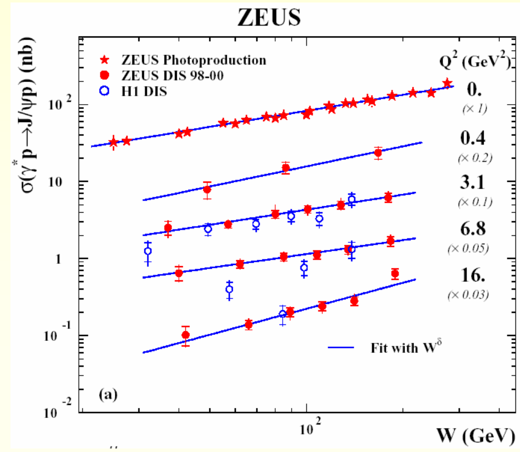
ρ

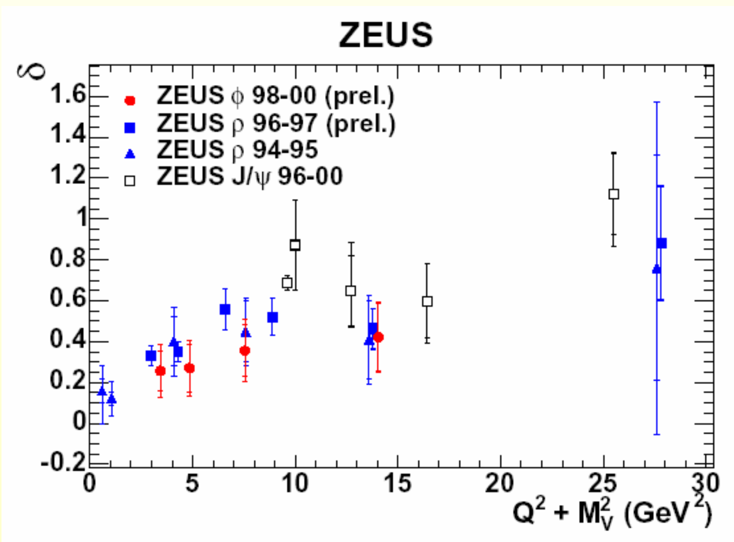


Φ



J/Ψ



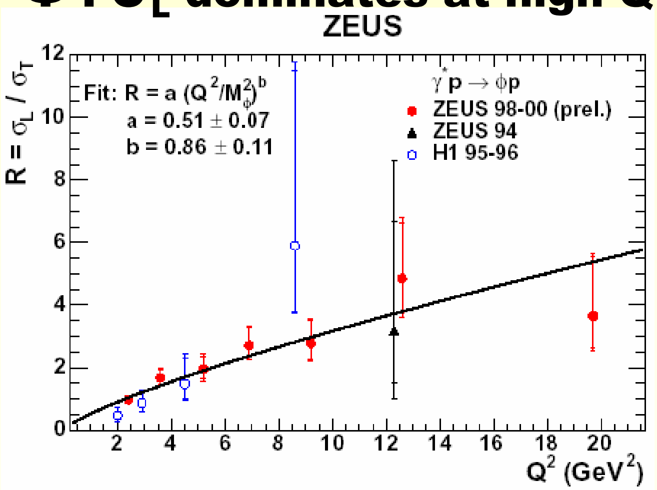


$\sigma \sim W^\delta$

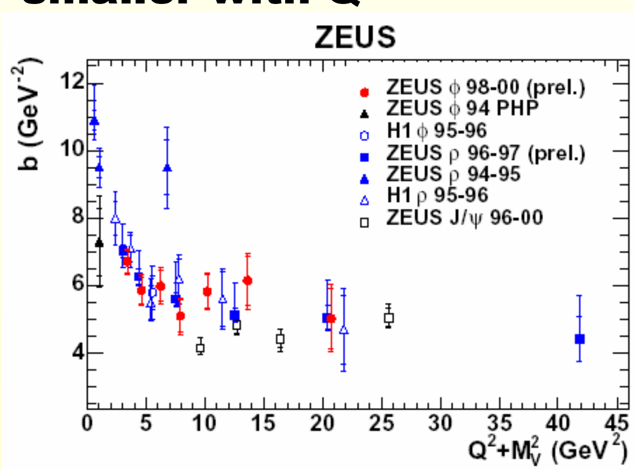
δ increasing with (Q^2+M^2)

Vector Meson Production in pQCD

Φ : σ_L dominates at high Q^2

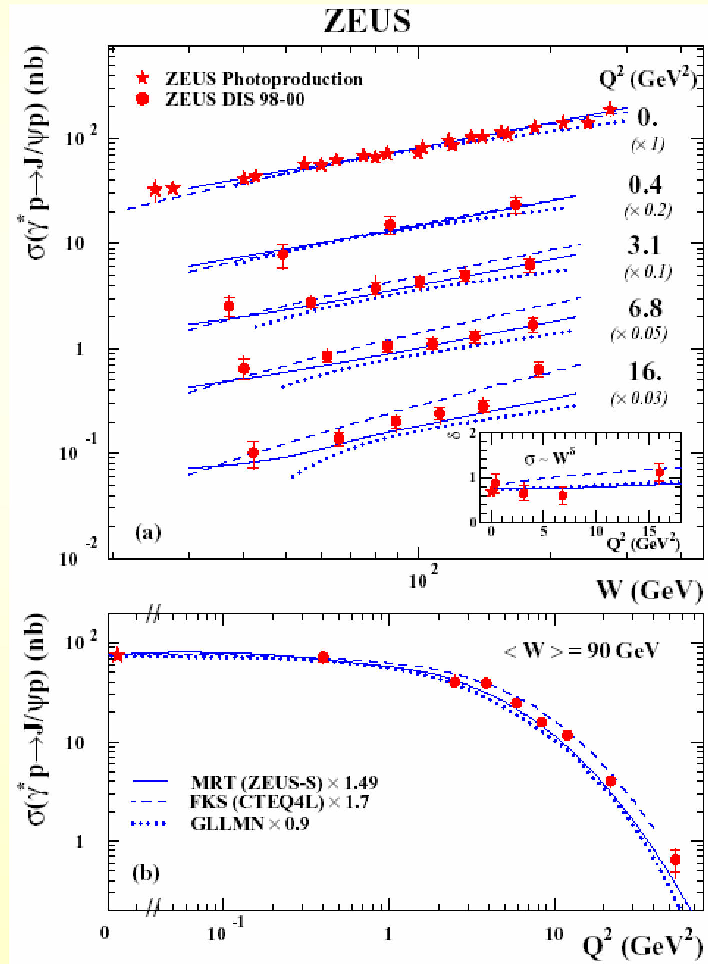


Effective size of γ* becomes smaller with Q^2



b_{2g}

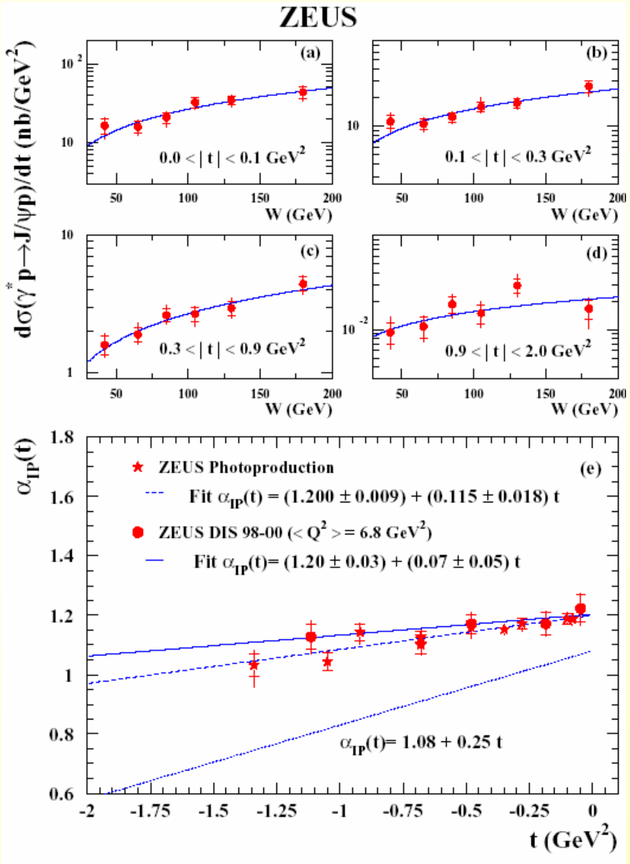
pQCD calculations for J/Ψ describe data:



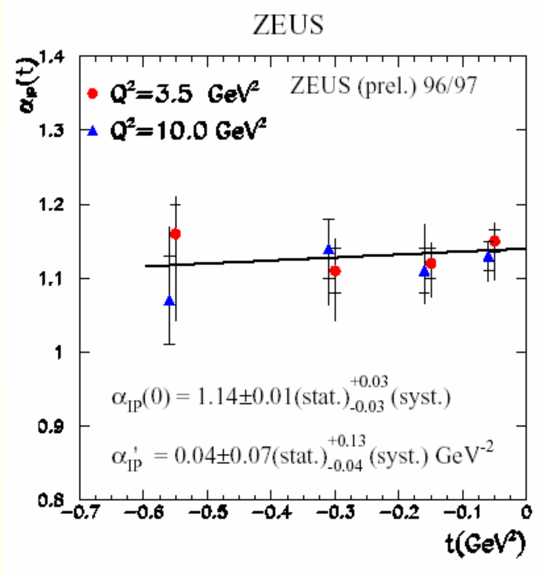
Vector Meson Production in pQCD

$d\sigma_{Vp\to Vp}/dt = e^{-b_0 t} \cdot W^{4(\alpha_{IP}(t)-1)}$

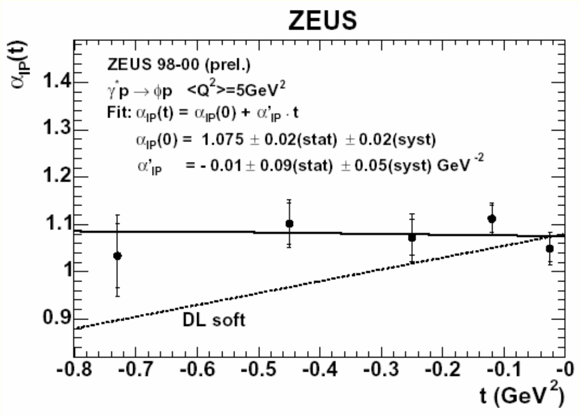
J/Ψ



Φ

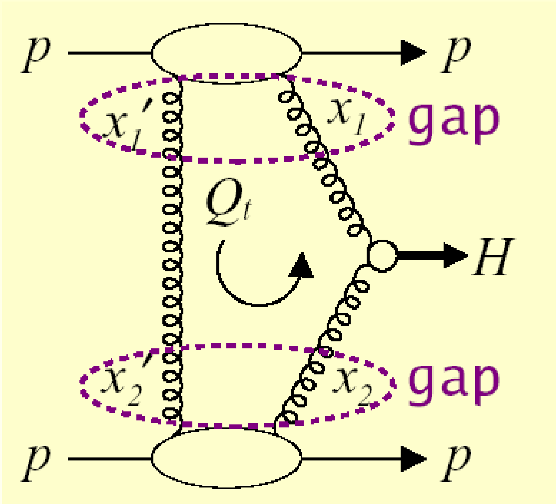


ρ



$\boxed{\alpha' \approx 0}$

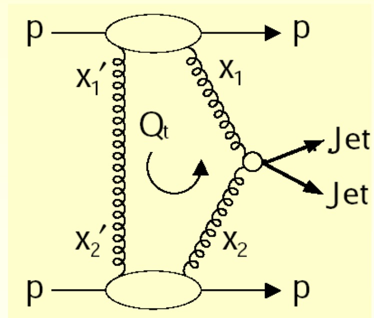
Exclusive States in $\bar{p}p$ Collisions

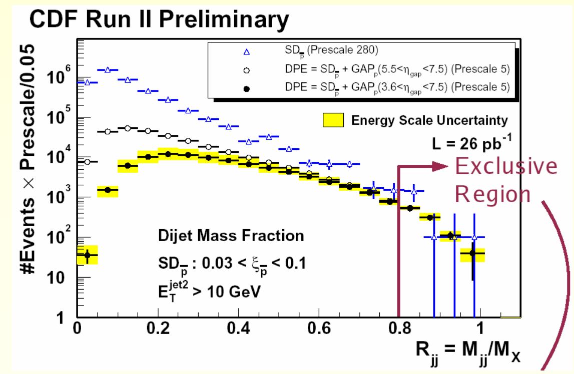


Diffractive Higgs production hot topic for LHC

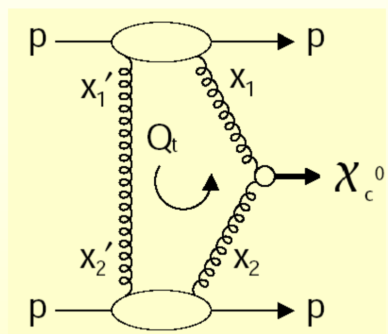
→ Something to learn from Tevatron?

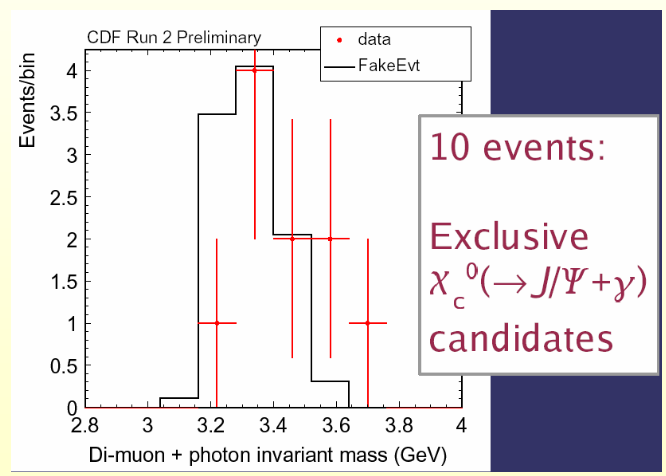
Exclusive dijet production:





Exclusive Xc production:





(→ M.Convery)

Summary

- **Data have reached a high level of precision**
- **HERA:**
  - **Models for diffractive structure function available**
  - **Factorization holds in diffractive DIS, under study in PHP**
  - **Exclusive Vector Meson production described by pQCD calculations**
- **Tevatron:**
  - **Factorization breaking found:**
    Fjj (SD 1800) $\leftrightarrow$ HERA, dijets in SD $\leftrightarrow$ DPE
  - **But factorization also holds :**
    SD 1800: Fjj $\leftrightarrow$ J/Ψ , DPE $\leftrightarrow$ HERA
  - **Models exist to calculate features of the data**

A lot of progress has been achieved so far, but still a lot remains to be understood.

Looking forward to even more precise data in different kinematic regions from HERA II and Tevatron Run II and of course to first diffractive events at LHC