The Structure of *Shadow* – Diffraction at HERA

I. Introduction - Characteristics of Diffractive Processes

II. Diffractive Structure Function

III. Final States in Hard Diffractive Scattering

IV. Vector Meson Production in Hard Diffractive Scattering

V. Summary

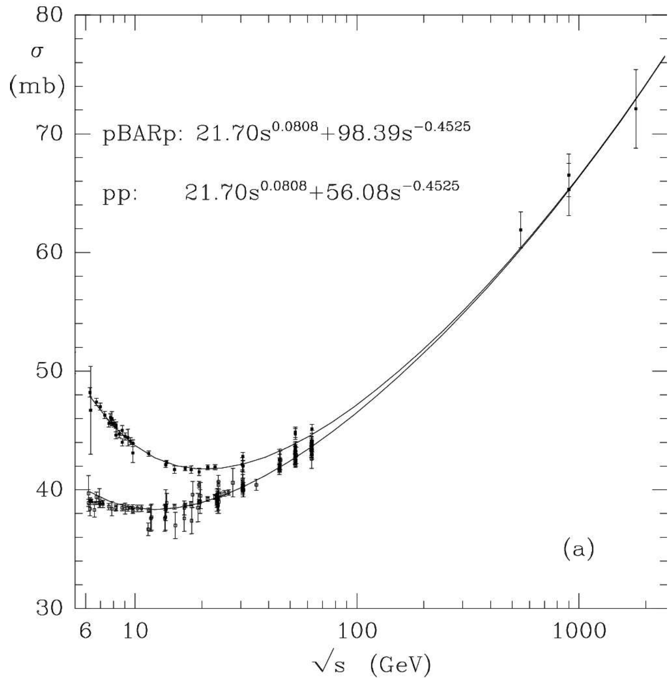
D. Wegener
X Mexican School of Particles and Fields
Playa del Carmen, Mexico
10/30 – 11/6/2002

I. Introduction – Diffraction in Soft Physics

pp – interactions at large s

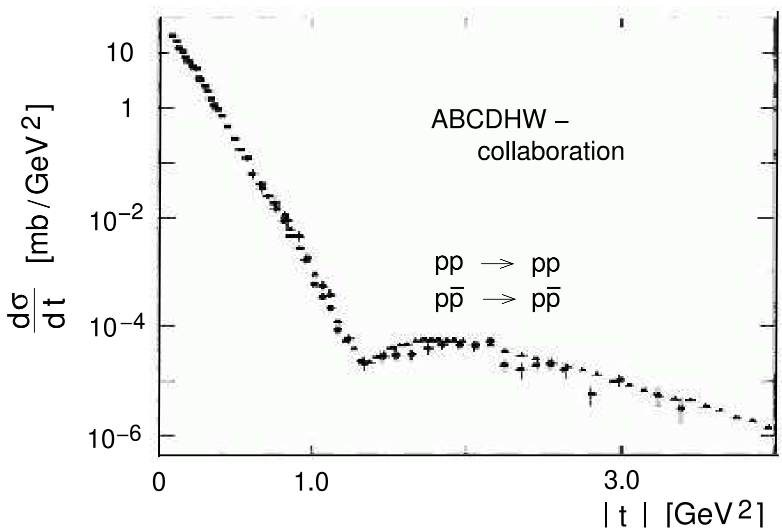
- σ_{tot} – universal behavior

$$\sigma_{tot} \;=\; a\; s^{-\alpha} + b\; s^{\lambda}$$



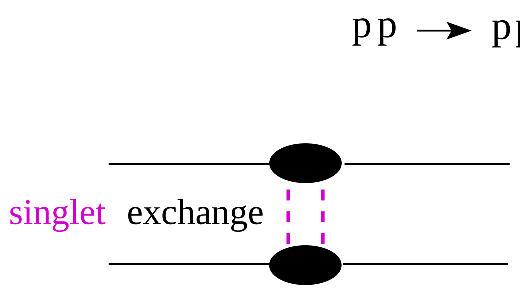
- $\frac{d\sigma}{dt}$ – diffractive structure

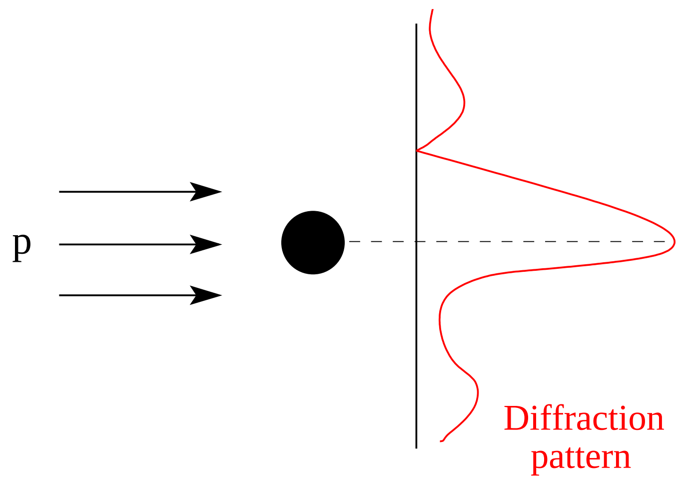
pp– and $p\bar{p}$–scattering : $\quad \frac{d\sigma}{dt} \;\sim\; s^{\,2\,\lambda}\; e^{Bt}$



s–rise fixed by

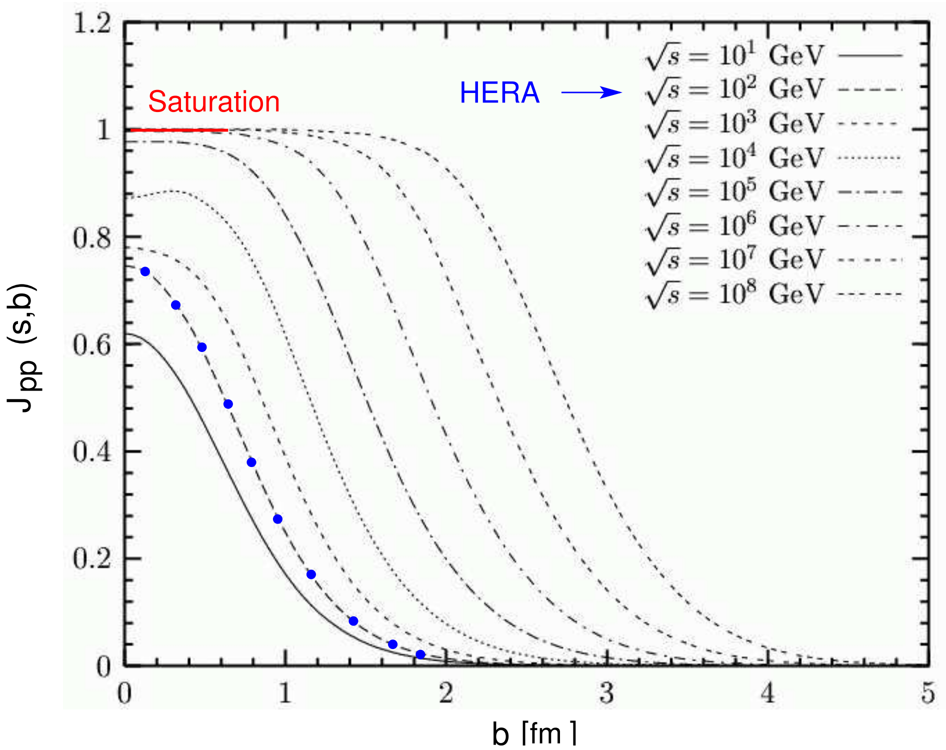
$$\lambda \;=\; 0.08$$

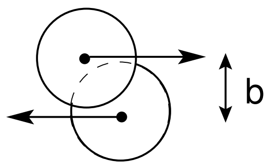




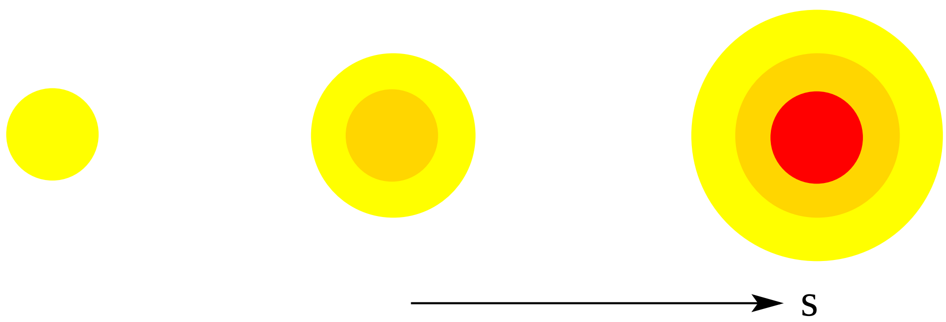
Geometrical picture of proton :

Impact parameter profile: H.J. Pirner et al. HD-THEP-02-04

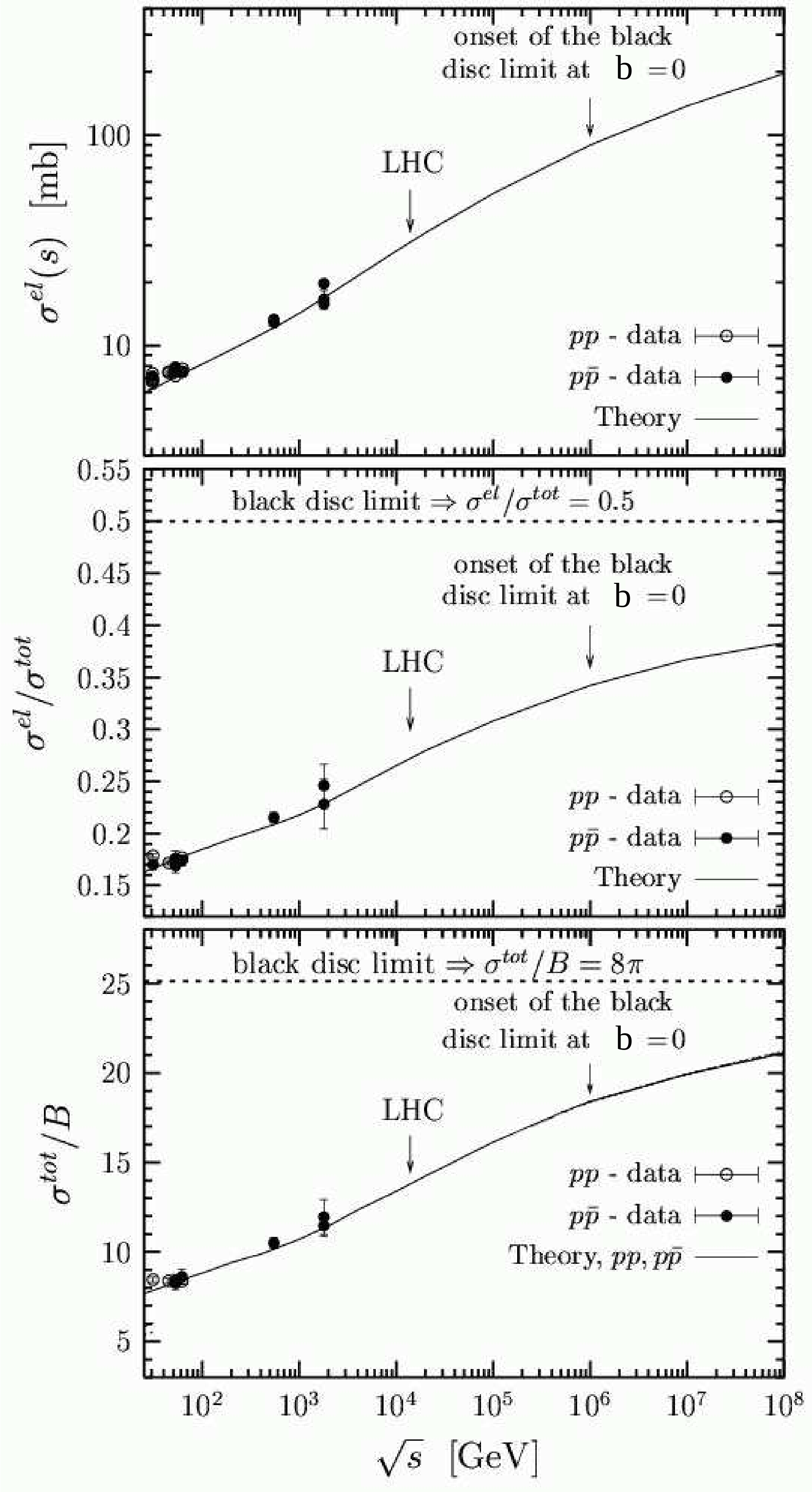




- gaussian shape of surface region
- grey disk $\rightarrow$ saturates at high s
- transverse size grows with s



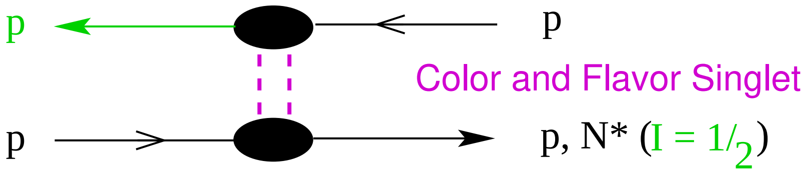
Predictions for soft physics

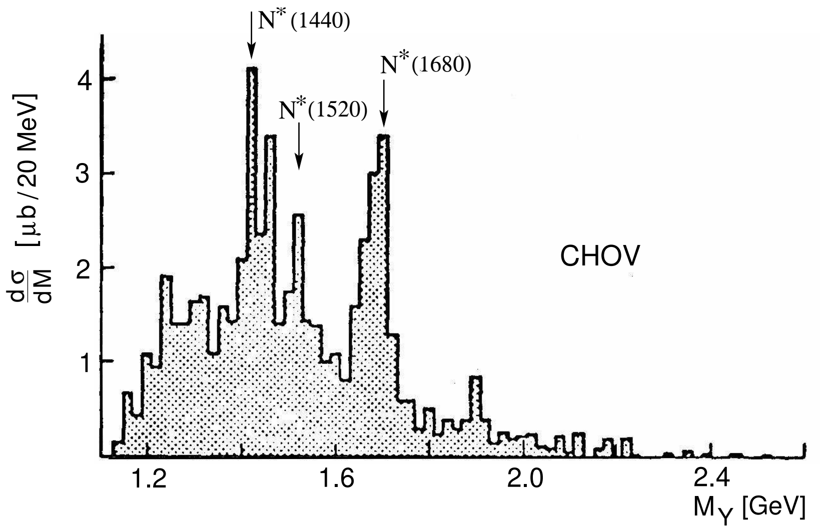


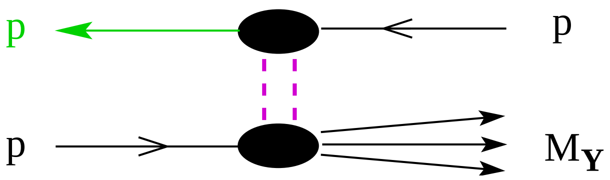
- Diffraction driven by absorption
- Complete absorption – only elastic scattering

Experimental characteristics of diffraction

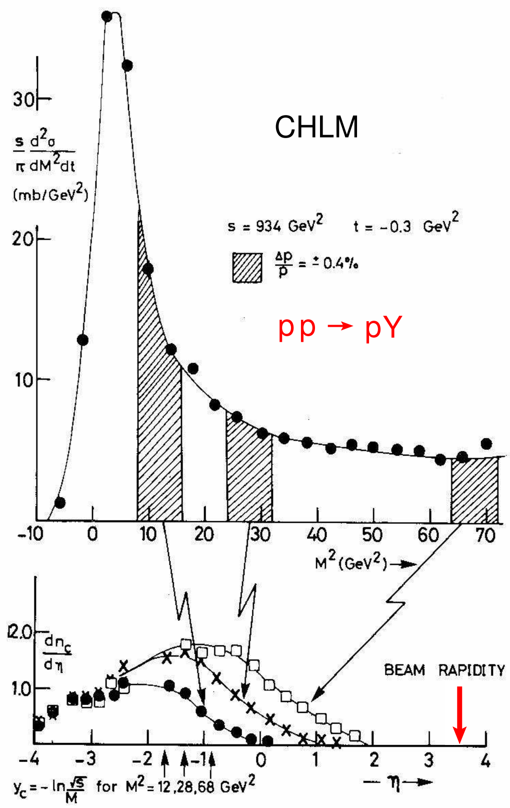
- $\frac{d\sigma}{dt} \sim e^{Bt}$

- 



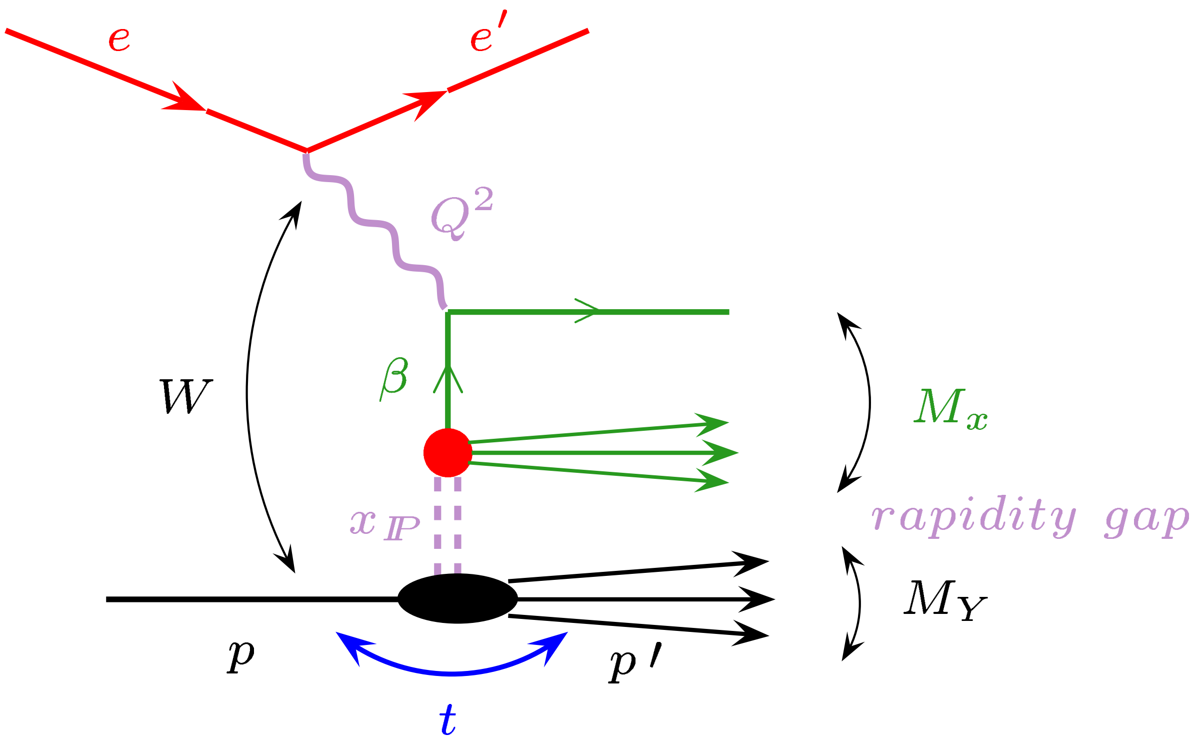
- 

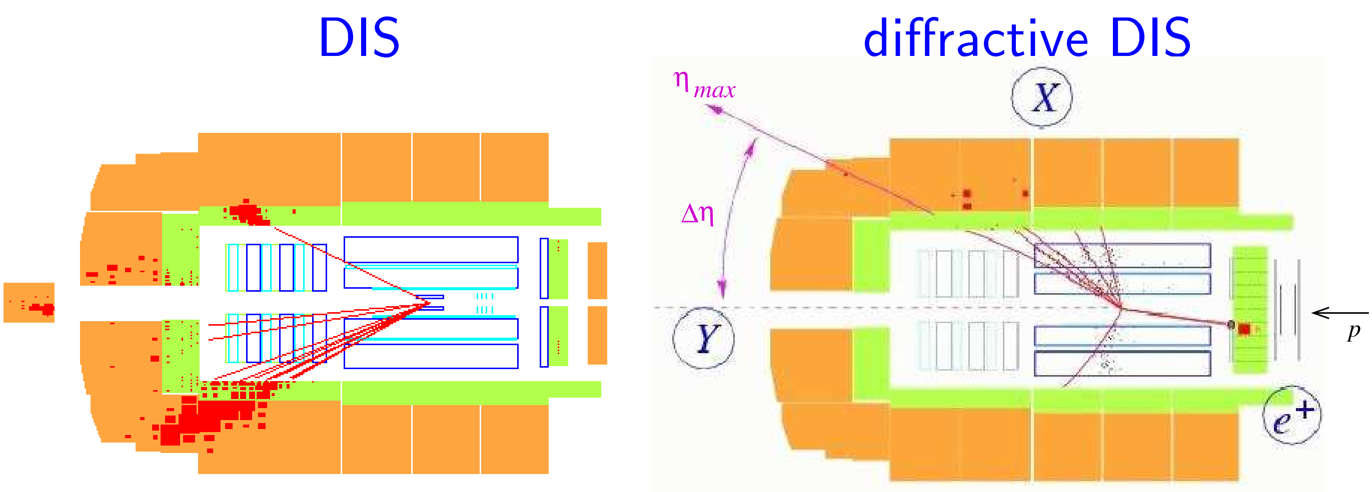
$$x_F = \frac{|\vec{p}\,|}{|\vec{p}_{Max}|} \approx 1$$



Rapidity gap

Hard diffraction at HERA





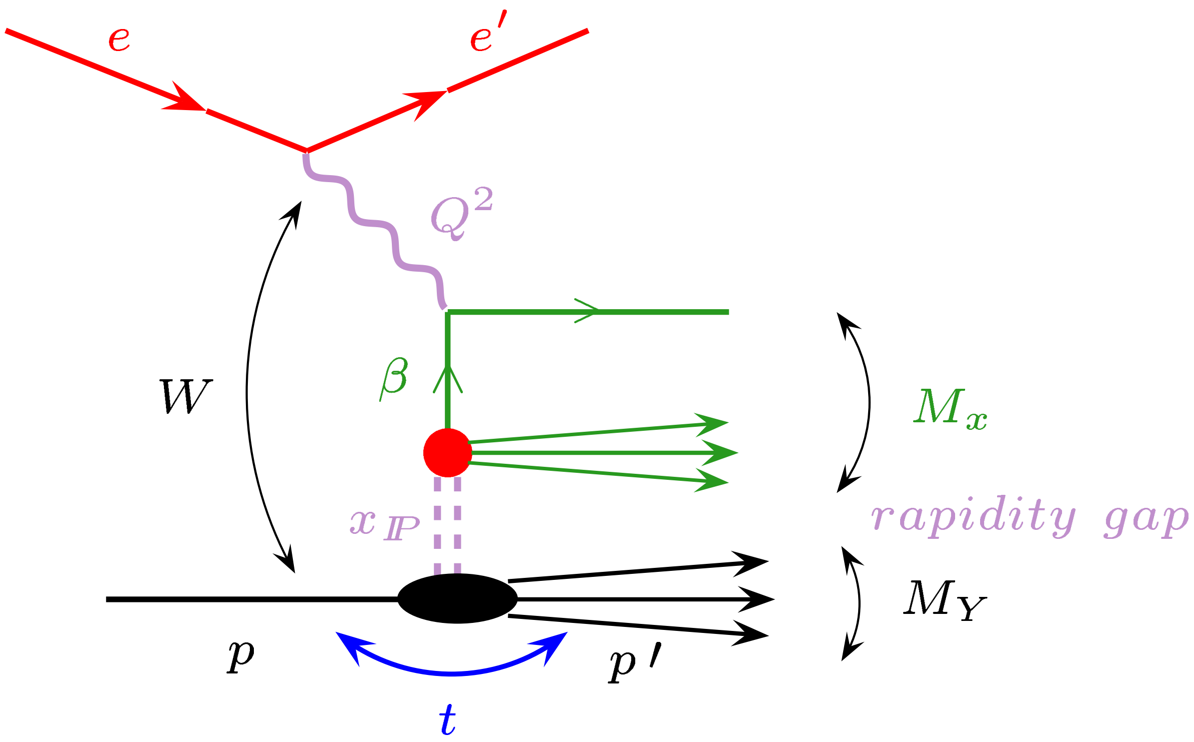
Tagging of hard diffractive events :

- $Q^2 \gg 1\ GeV^2$
- rapidity gap in forward direction

or

- proton with $x_F > 0.5$ in forward direction $(Y = p)$

Kinematics



$$
\begin{aligned}
Q^2 &= -\,q^2 = (e - e')^2 \\
t &= (p - p')^2 \\
W^2 &= (q + p)^2 = -\,Q^2 + 2\,q\,p
\end{aligned}
$$

$$\beta = \frac{Q^2}{2(p - p')q} = \frac{Q^2}{M_x^2 + Q^2 - t} \approx \frac{Q^2}{M_x^2 + Q^2}$$

β = fraction of exchanged singlet momentum carried by struck quark

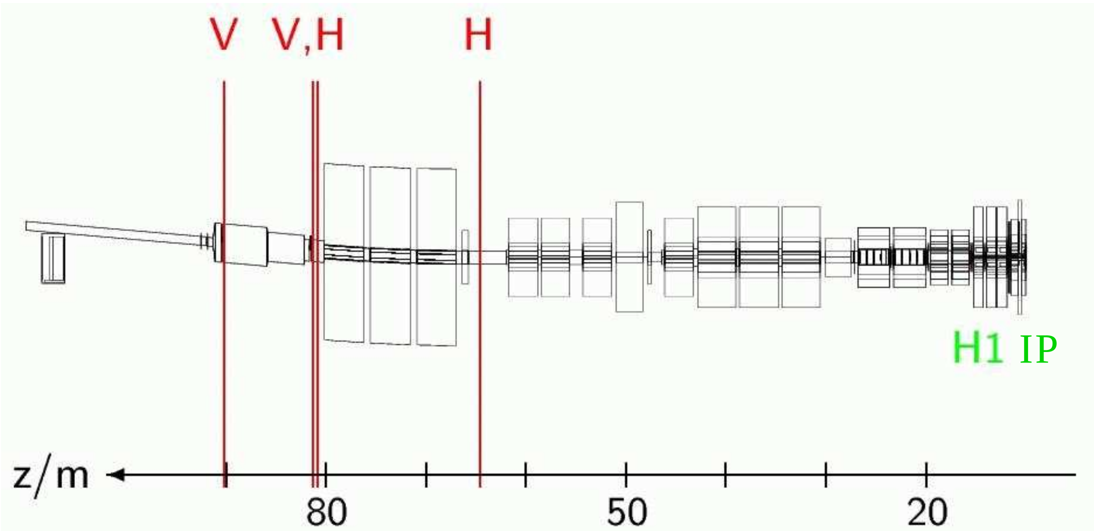
$$x_{I\!P} = \frac{M_x^2 + Q^2}{W^2 + Q^2}$$

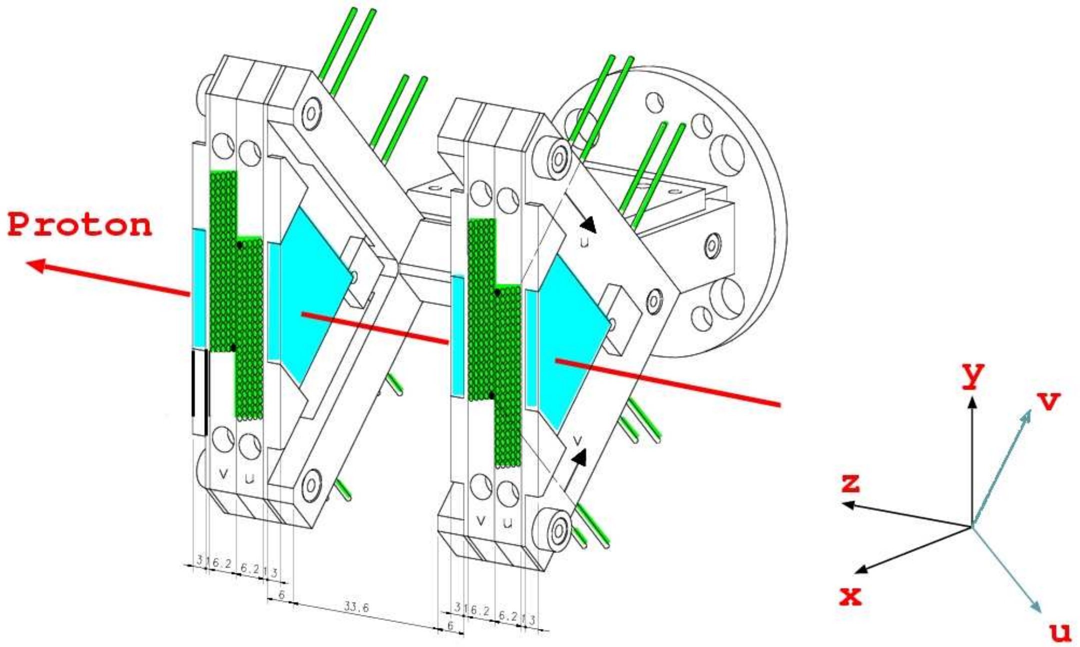
$x_{I\!P}$ = fraction of proton momentum carried by singlet

$$
\begin{aligned}
x_{Bj} &= x = \beta \cdot x_{I\!P} \\
y &= \frac{q\,p}{e\,p} = \frac{W^2 + Q^2}{s} \approx \frac{W^2}{s}
\end{aligned}
$$

Tagging forward proton : Forward proton spectrometer

Accelerator magnets used as forward spectrometer





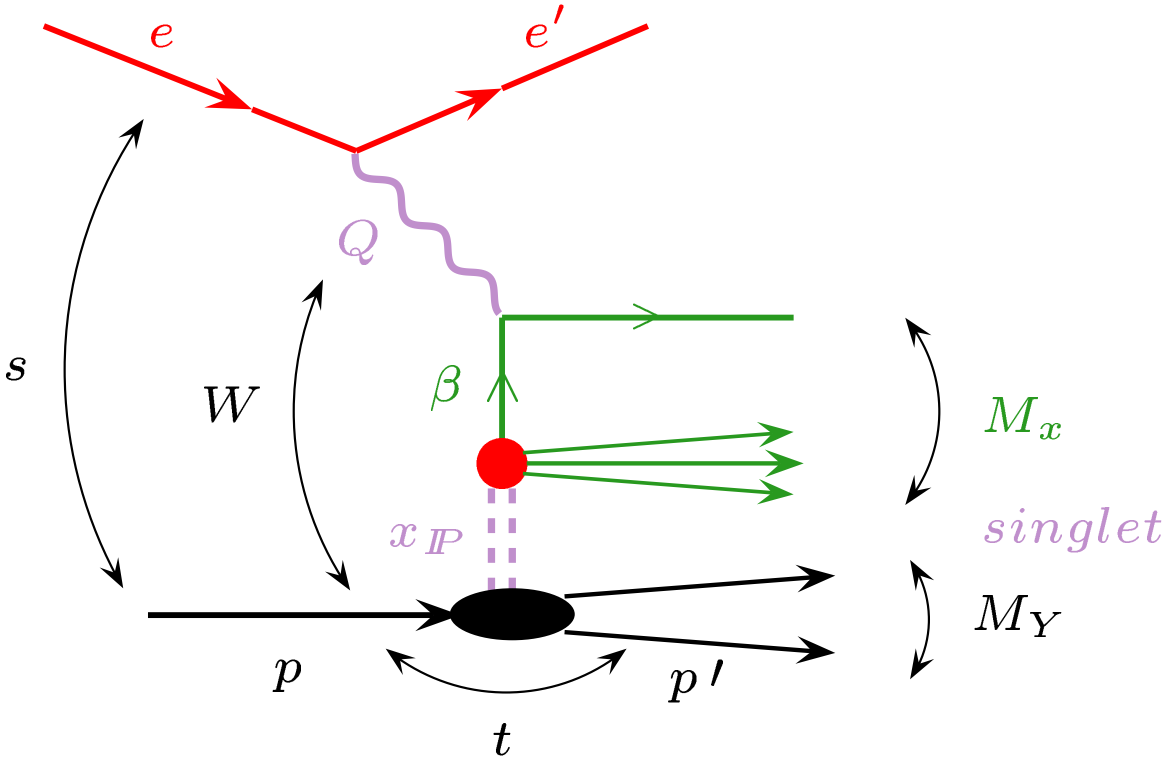
Acceptance $-0.45 < t < -0.08\ GeV^2$

$$E_{p'}/E_p > 0.9$$

$$x_{I\!P} = 1 - \frac{E_{p'}}{E_p} > 0.01$$

$$t = -\frac{p_t^2}{1 - x_{I\!P}} - t_{Min}$$

II. Diffractive Structure Function



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

Reduced cross–section

$$\sigma_r^{D(4)} = F_2^{D(4)}(x,Q^2,x_{I\!P},t) - \frac{y^2}{1+(1-y)^2}\,F_L^{D(4)}(x,Q^2,x_{I\!P},t)$$

$$\approx\ F_2^{D(4)}(x,Q^2,x_{I\!P},t)\quad (\text{small } y \text{ or } F_L^D = 0)$$

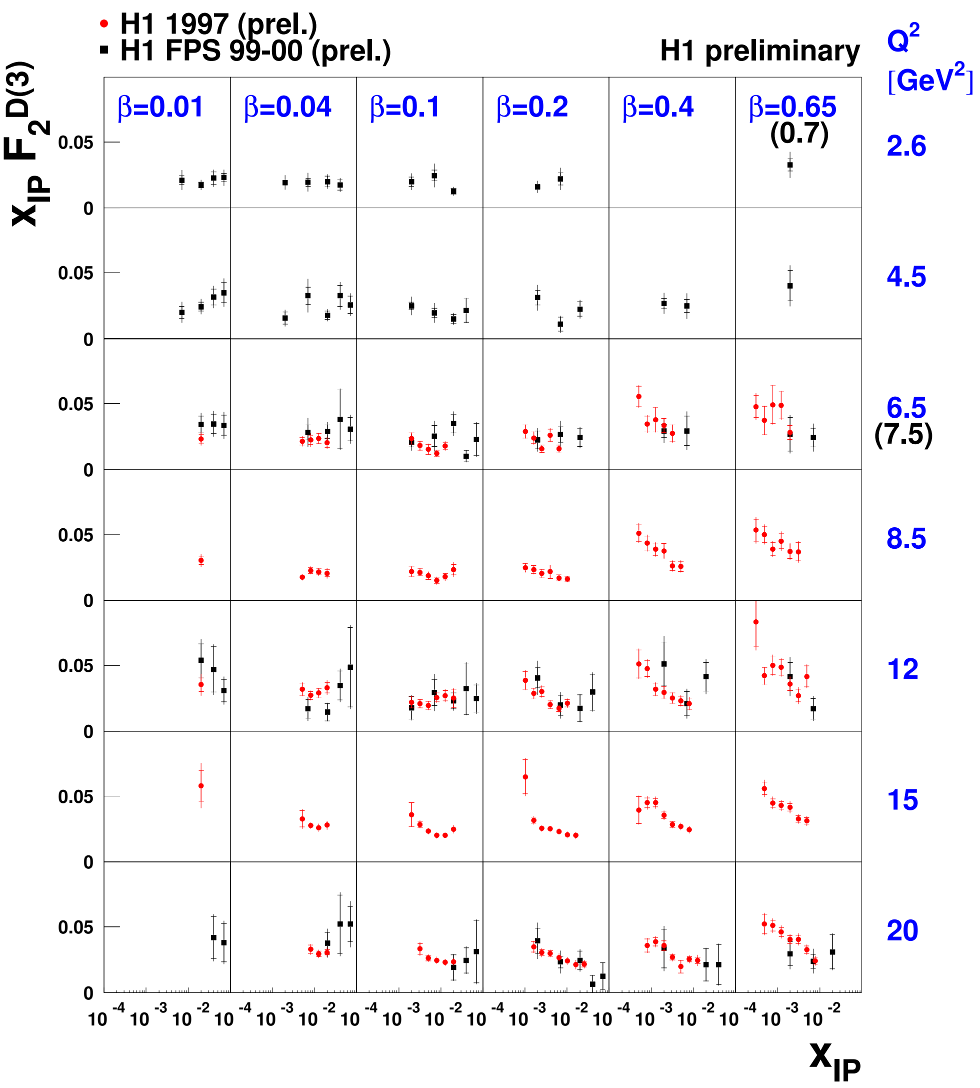
$$x = x_{Bjorken} = \beta\cdot x_{I\!P}$$

New Data of H1

FPS	Rapidity Gap
$2\ GeV^2 < Q^2 < 50\ GeV^2$	$6.5\ GeV^2 < Q^2 < 120\ GeV^2$
$5 \cdot 10^{-3} < \beta < 1$	$0.01 < \beta < 0.9$
$x_{I\!P} < 0.09$	$10^{-4} < x_{I\!P} < 0.05$
$-0.45\ GeV^2 < t < -0.08\ GeV^2$	–
$28.8\ pb^{-1}$	$10.6\ pb^{-1}$
1999 – 2000	1997

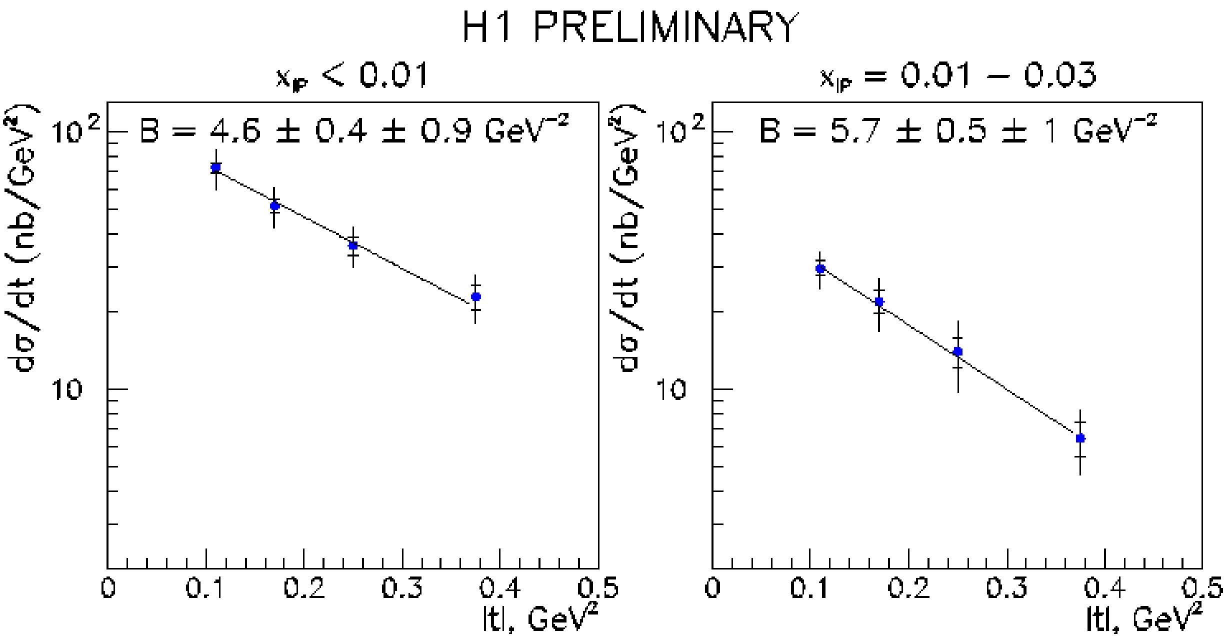
Compare data : good agreement

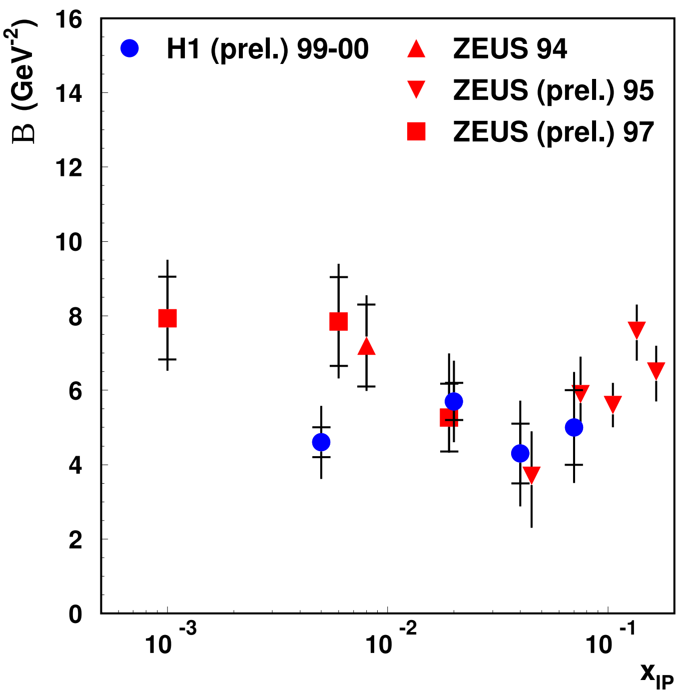
(t–extrapolation for FPS data)



t–dependence of diffractive cross section :

FPS–data : $e\,p \;\to\; e\,p\,X$





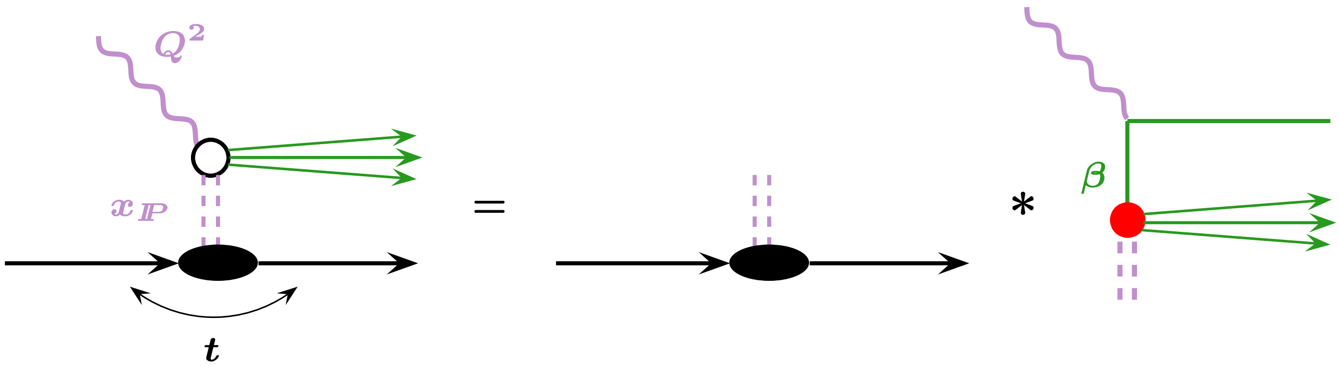
- $B \;=\; (5.0 \pm 0.3 \pm 0.8)\;GeV^2$
- No visible $x_{I\!P}$–dependence
- comparison to $pp \;\to\; pp$ (ABCDHW–Coll.) :

$$B \;=\; (11.0 \pm 0.1)\;GeV^2$$

Factorization of F_2^D :

- QCD hard scattering factorization for diffractive DIS : Collins, Phys.Rev. D57 (1998) 3051
  - $\sigma\,(\gamma * p \;\rightarrow\; Xp) \;\sim$ $P_{q/p}\,(x, Q^2, x_{I\!P}, t) \otimes\; \sigma_{\gamma * q}\,(x, Q^2)$
  - fixed $x_{I\!P}$, t : diffractive pdf's evolve with Q^2 at given x according to DGLAP
- Regge factorization

  Additional assumptions : shape of pdf's independent of $x_{I\!P}$, t :



$$\sigma(\gamma{*}p \rightarrow Xp) \sim f_{I\!P/p}\,(x_{I\!P}, t) \otimes P_{q/I\!P}(\beta, Q^2) \otimes \sigma_{\gamma * q}\,(\beta, Q^2)$$

diffractive flux — pomeron pdf's — hard process

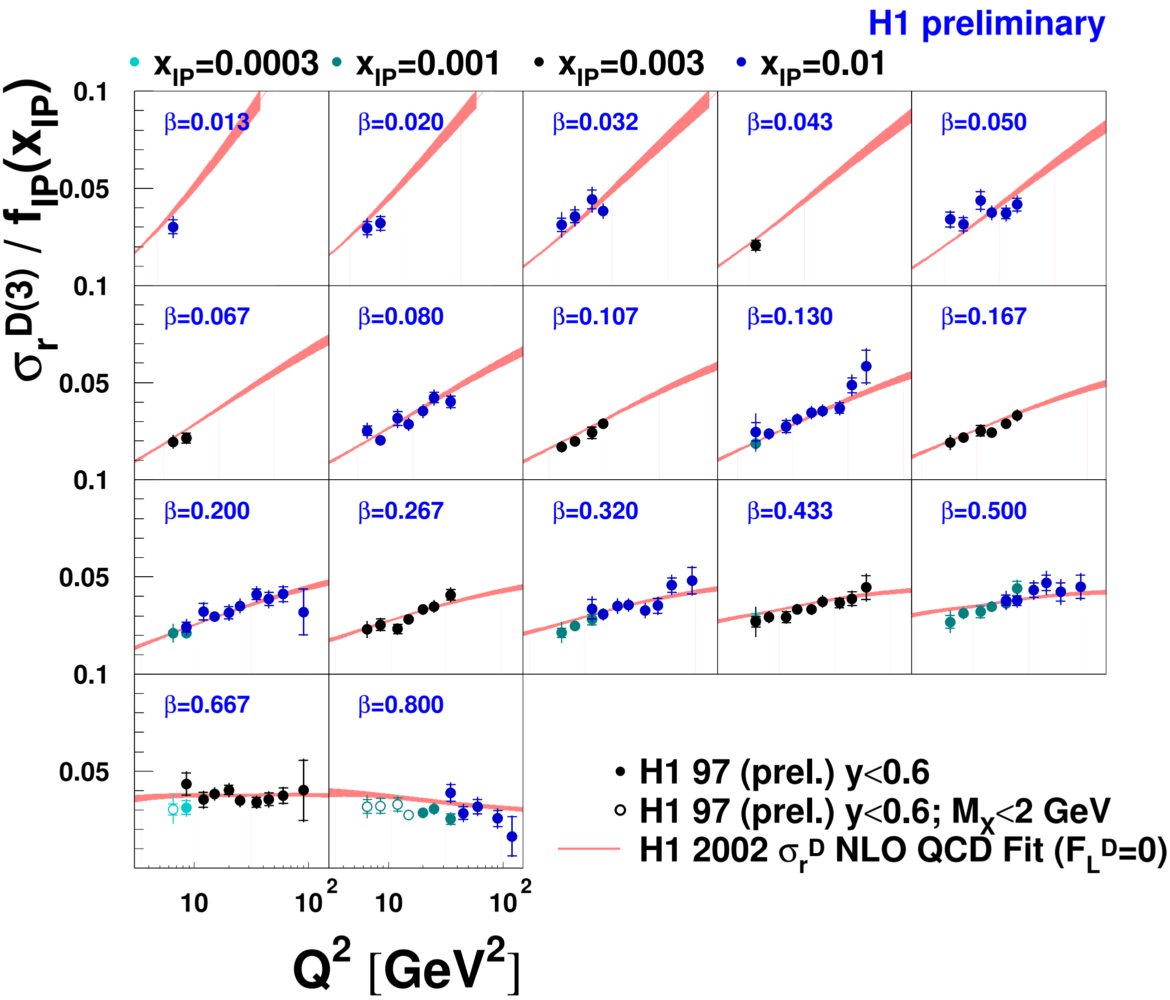
Regge Factorization Works

$$\sigma_r^{D(3)}(\beta, Q^2, x_{I\!P}) = f_{I\!P/p}(x_{I\!P})\, \sigma_r^{D(2)}(\beta, Q^2)$$

$$f_{I\!P/p}(x_{I\!P}) = \int dt\, x_{I\!P}^{1-2\,\alpha_{I\!P}(t)}\, e^{Bt}$$

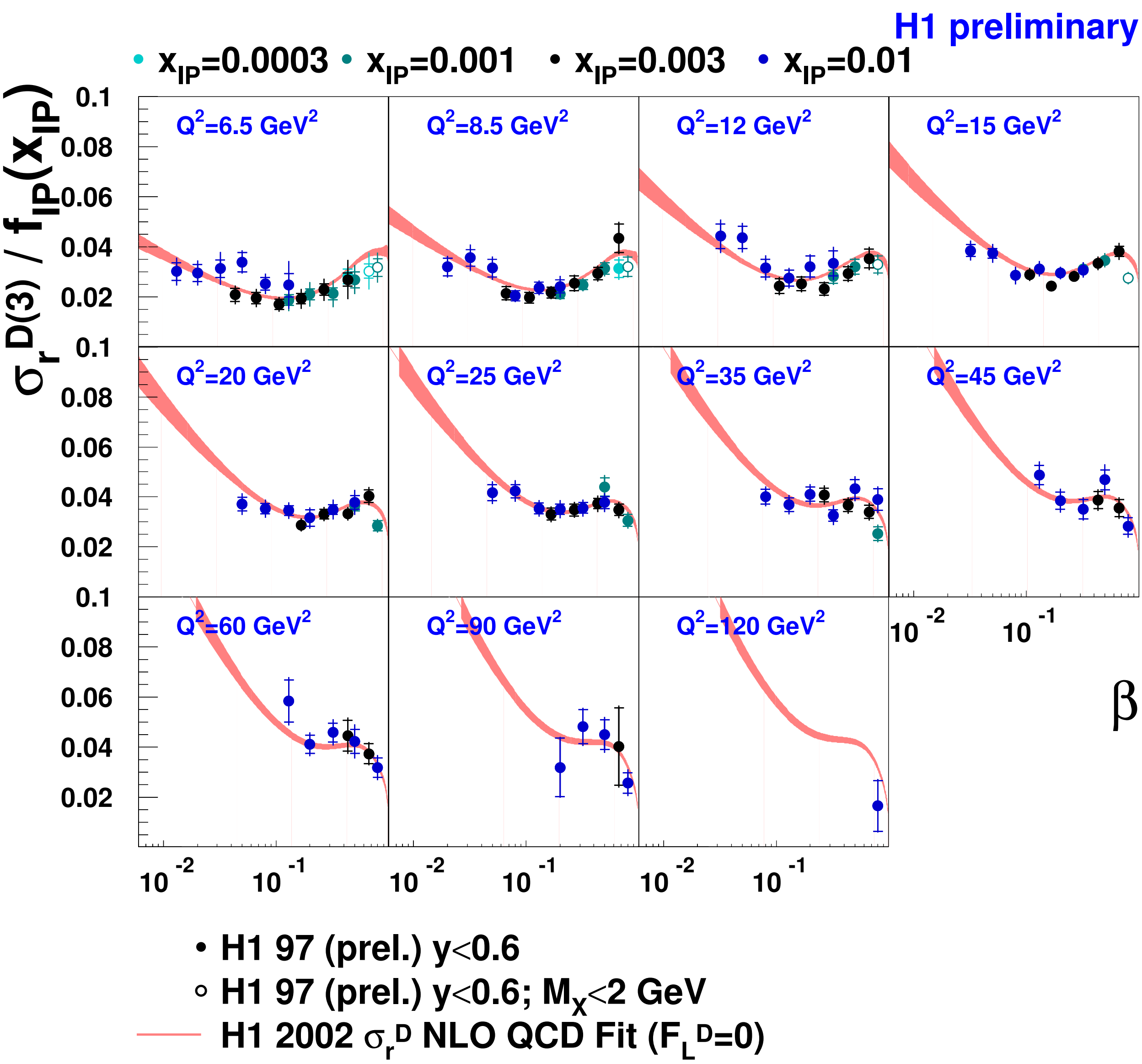
$$\alpha_{I\!P}(t) = \alpha_{I\!P}(0) + \alpha'_{I\!P}(0) \cdot t$$

$$\alpha_{I\!P}(0) = 1.173 \pm 0.018, \quad \alpha'_{I\!P}(0) = 0.26 \pm 0.26$$



- Scaling violation similar at all $x_{I\!P}$ $\rightarrow$ Regge factorization
- Large positive scaling violation for $\beta \lesssim 0.5$ $\rightarrow$ gluon dominates
- QCD fit describes data

$\beta / x_{Bjorken}$ – dependence

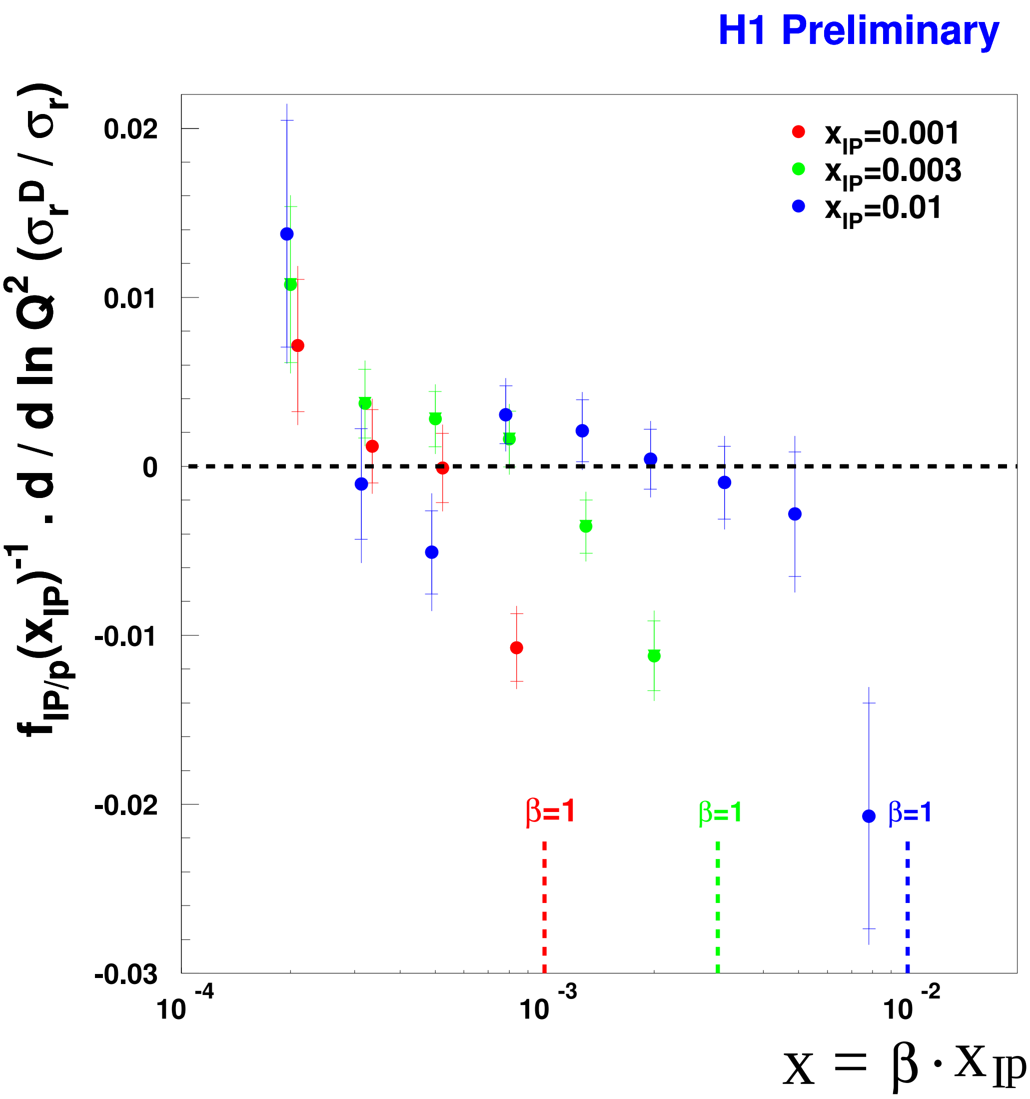


- Same structure at all $x_{I\!P}$ –
  Regge factorization works

- Measure quark density $(\gamma^* q)$
  Large at high $x_{Bjorken}$

- Structure function different from inclusive DIS

Comparison of inclusive and diffractive DIS



- $\frac{\sigma_r^{D(2)}}{\sigma_r} \sim$ constant
- $\beta \to 1$: negative Log. derivative $\to$ hint for 2–gluon exchange (higher twist)
- Similar QCD dynamics of inclusive and diffractive DIS
- $\frac{diffractive}{inclusive} \approx 0.1$ independent of Q^2

Non–leading order DGLAP fits :

INPUT :

- $M_X > 2\ GeV$ – leading twist selected
- σ_r^D fitted

  F_L^D : LO $\quad y < 0.45 \ \rightarrow \ F_L^D$ negligible

  NLO $\quad$ via g^D
- 284 data points $\quad 6.8\ GeV^2 \leq Q^2 \leq 120\ GeV^2$

  29 data points $\quad 200\ GeV^2 \leq Q^2 \leq 800\ GeV^2$
- Regge factorization assumed
- subleading Regge exchange: pdf's of π–meson
- diffractive exchange : flavor singlet

  $$\sum\nolimits^D (z) = u\,(z) + d\,(z) + s\,(z) + \bar{u}\,(z) + \ \ldots$$
  $$= 6\,u\,(z)$$

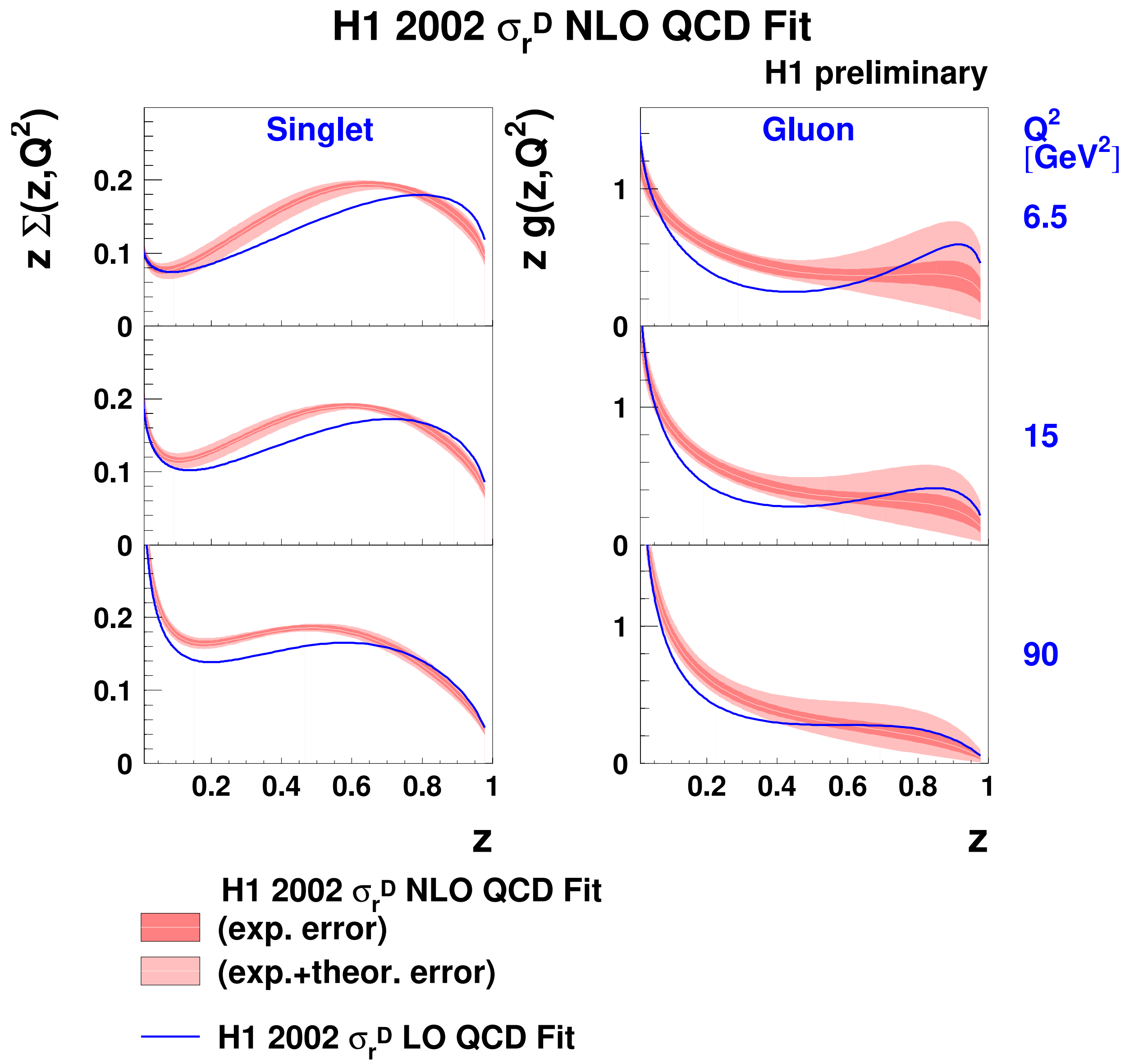
  $g^D(z)$

  $z = \beta$ in LO; $0 < \beta < z$ in HO
- pdf's : starting scale $Q_0^2 \ = \ 3\ GeV^2$

  Chebychev polynomial ansatz

  Evolved with DGLAP to $Q^2 > 3\ GeV^2$

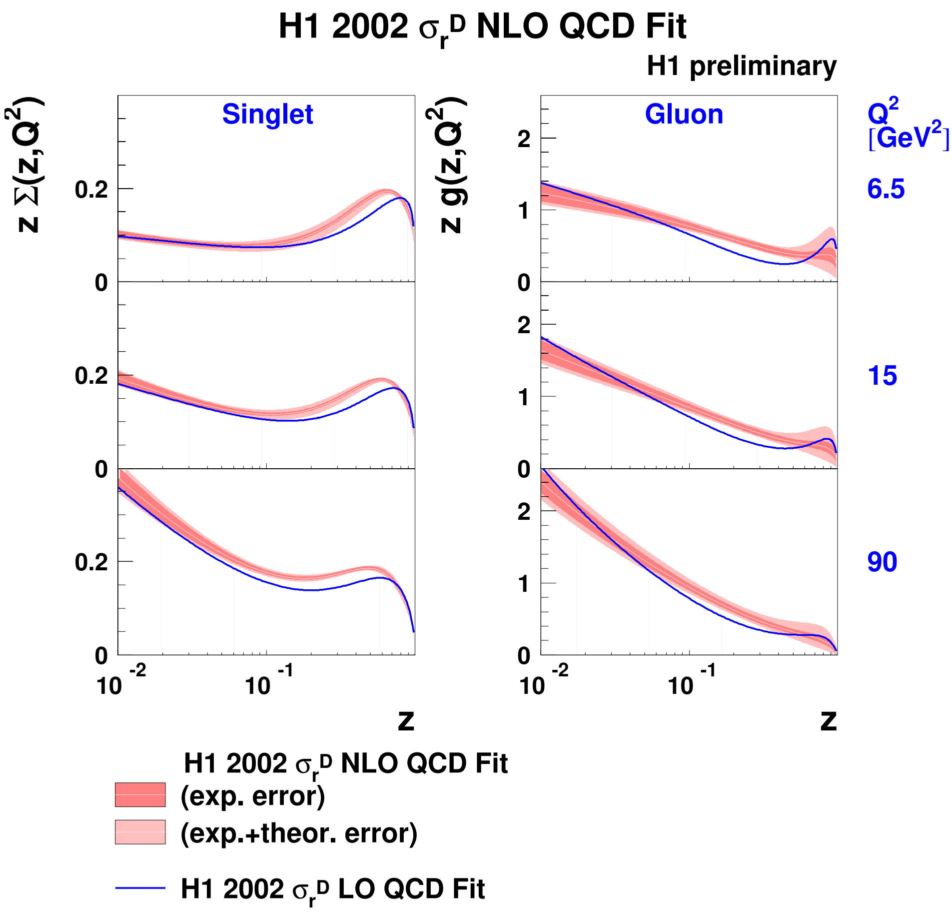
Resulting structure functions



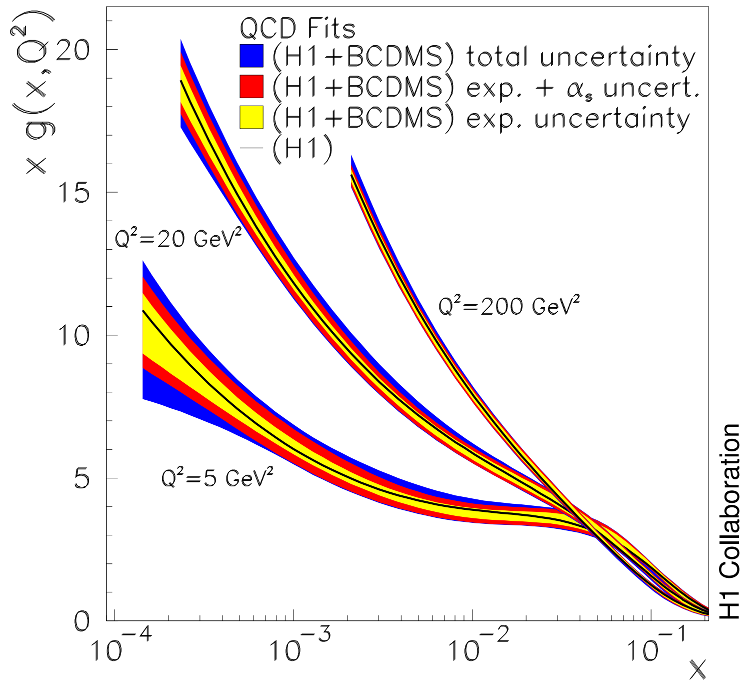
- $\Sigma^D(z)$ well defined
  $g^D(z)$ uncertainty large for $z > 0.5$
- LO and NLO no large difference
- shape of $\Sigma^D(z)$ reflects shape of $\sigma_r^D(\beta, Q^2)$
  $g^D(z)$ determined from scaling violations
- gluons dominate for all z

Comparison inclusive and diffractive DIS

diffractive DIS



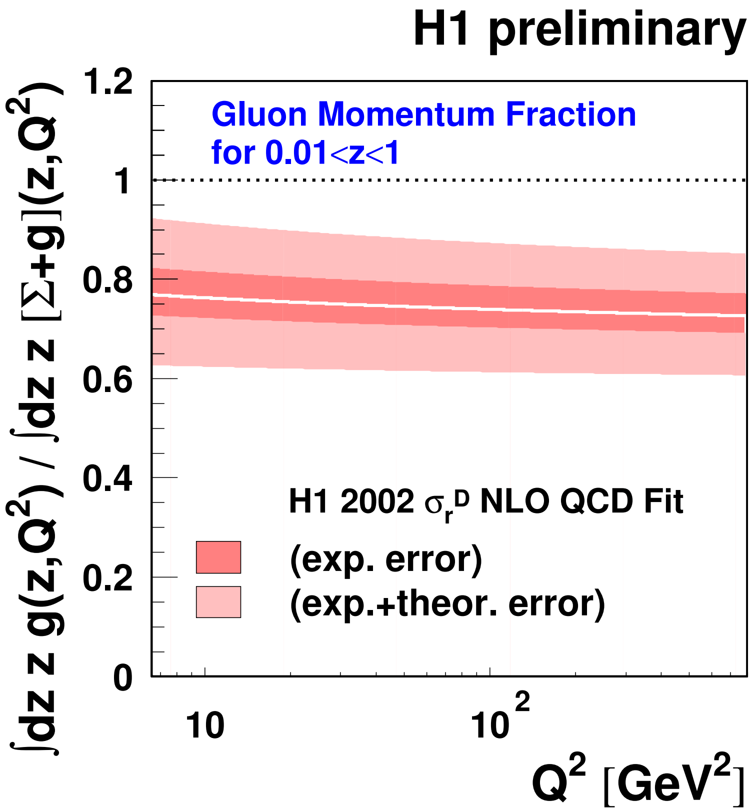
DIS



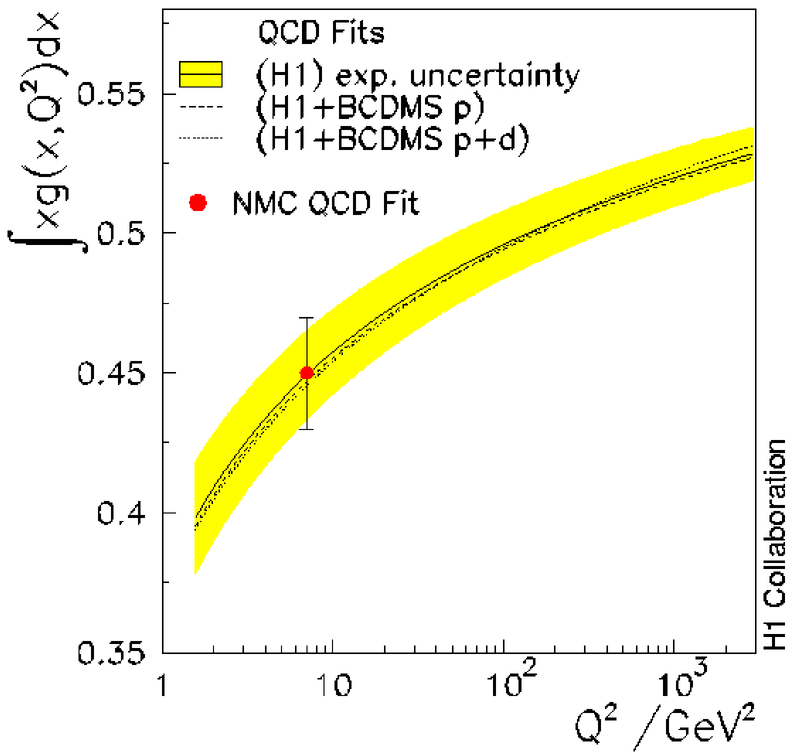
- Large $z > 0.1$ major difference
  gluons strong contribution up to $z \approx 0.5$
- Similar Q^2–dependence at $z =$ const.

Momentum carried by gluons

diff. inclusive DIS



DIS



Proton

$< x_g >$ increasing with Q^2

$$< x_g > = 0.4 \ldots 0.55$$

Pomeron

slowly decreasing with Q^2

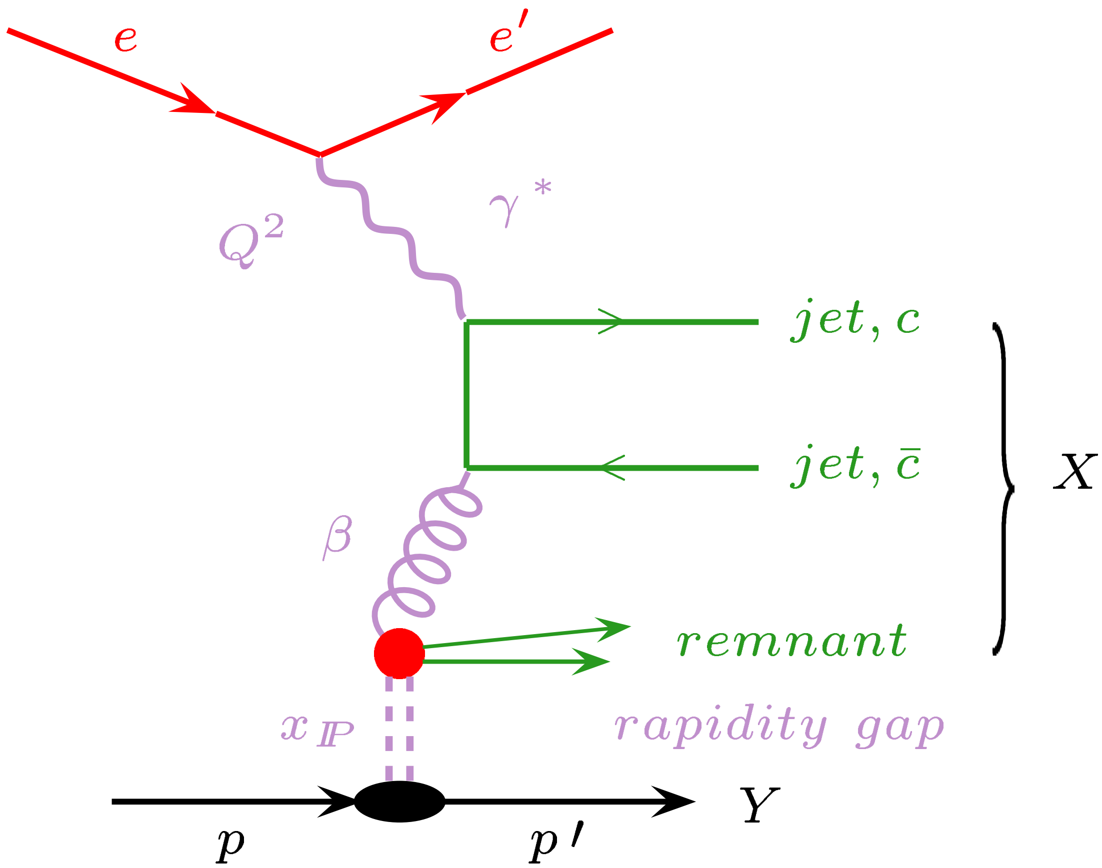
$$< z_g > = 0.75$$

III. Final States in Diffractive DIS

QCD factorization tested

Dijet – final state
D^* – production
} in diffractive DIS

Described by photon–gluon fusion –
directly sensitive to gluon component

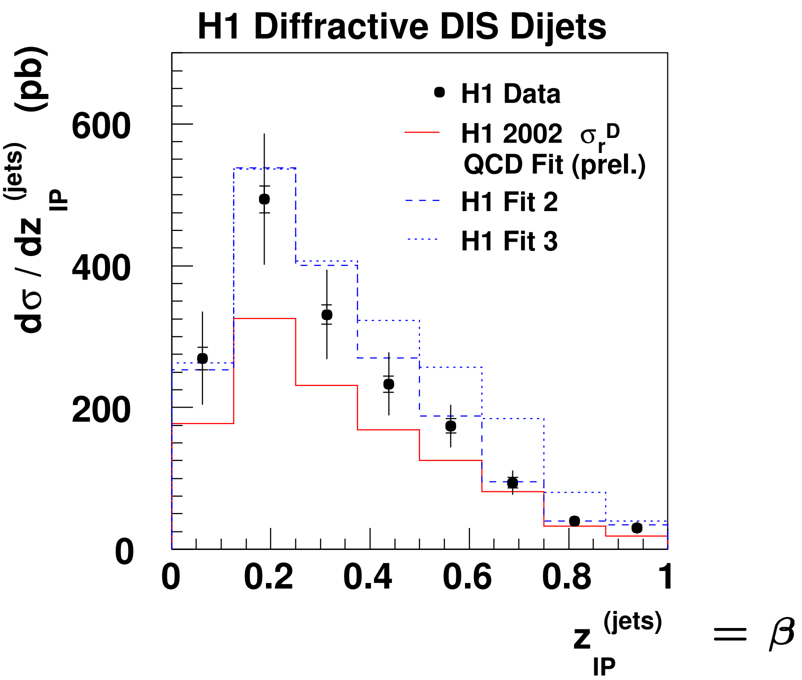


Input :

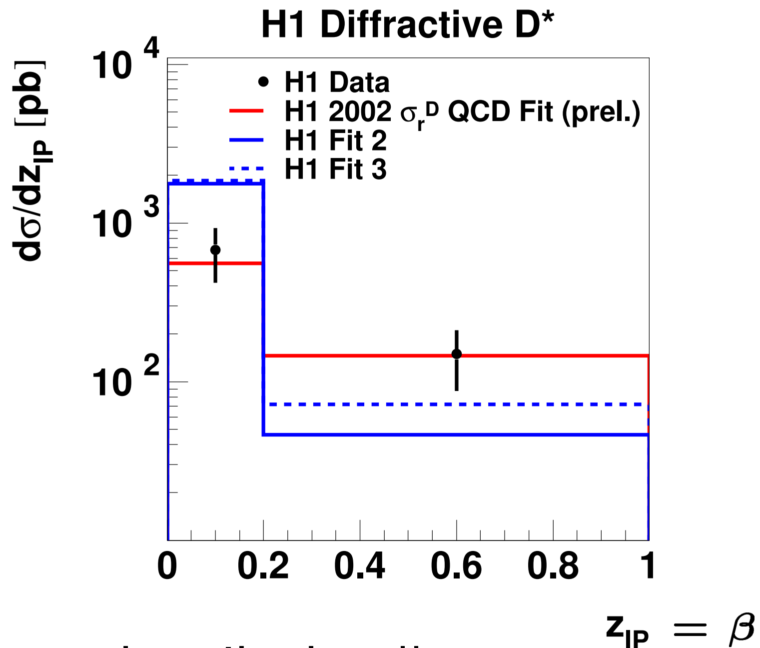
- pdf's from leading order fit
- Renormalization/factorization scale:
  $\mu^2 = Q^2 + p_T^2 + m_q^2$
- RAPGAP Monte Carlo

Direct sensitivity to gluon in Pomeron

H1 : Dijets in diffractive DIS



H1 : D^* in diffractive DIS



- Shapes described well

- Magnitude improved description for D^*
  worse description for dijets

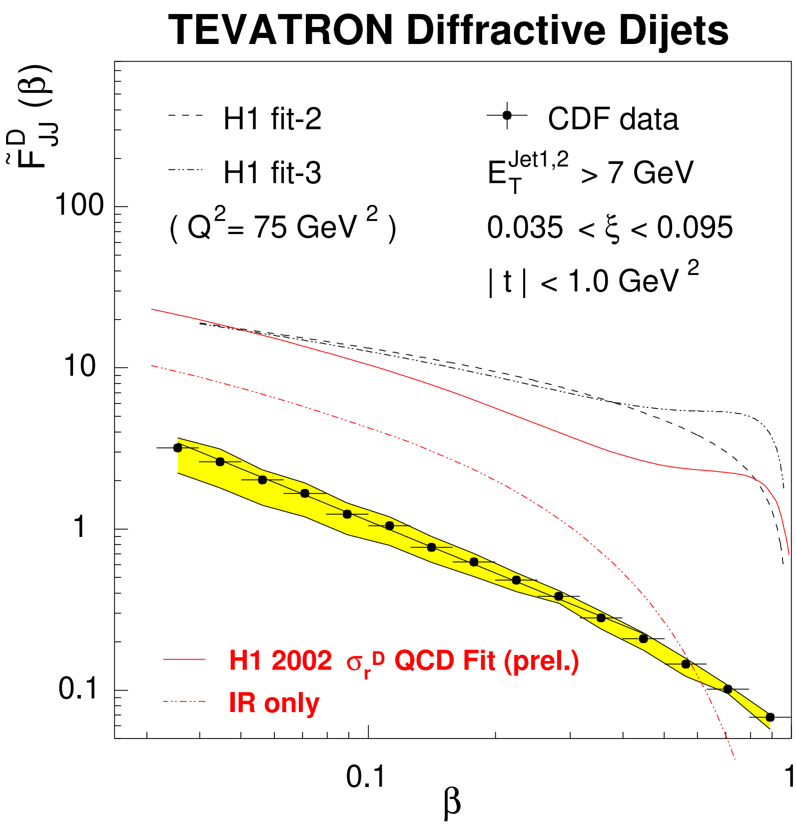
but only LO simulation
uncertainty of diffractive pdf's
not yet propagated

CDF : diffractive Dijet cross–section

tagged with leading $\bar{p}$ at Tevatron

Effective diffractive structure function at $Q^2 = 75$ GeV^2

$$\tilde{F}^{D}_{jj}(\beta) = f(x_{I\!P}, t) \otimes \beta \left\{ g^{D}(\beta, Q^2) + \frac{4}{9} \sum{}^{D}(\beta, Q^2) \right\}$$

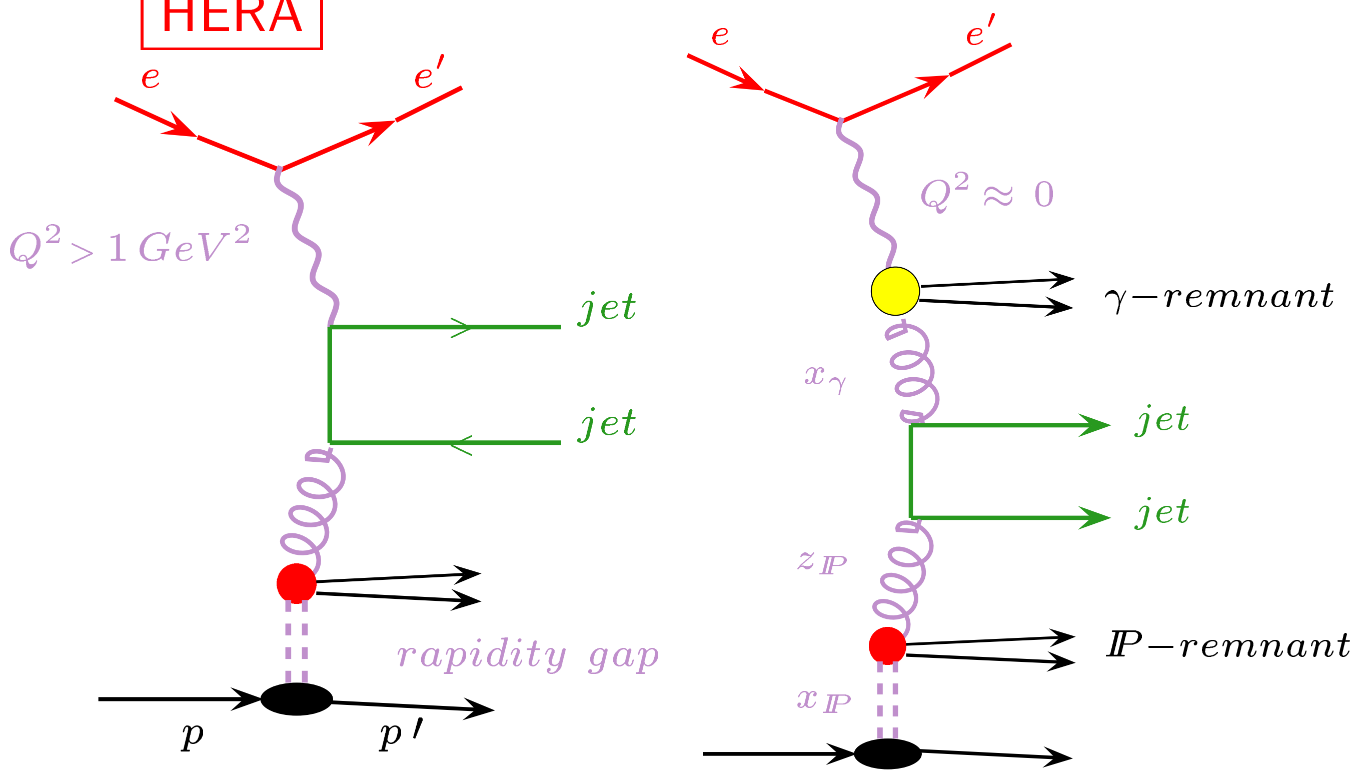


Use new H1 pdf's :

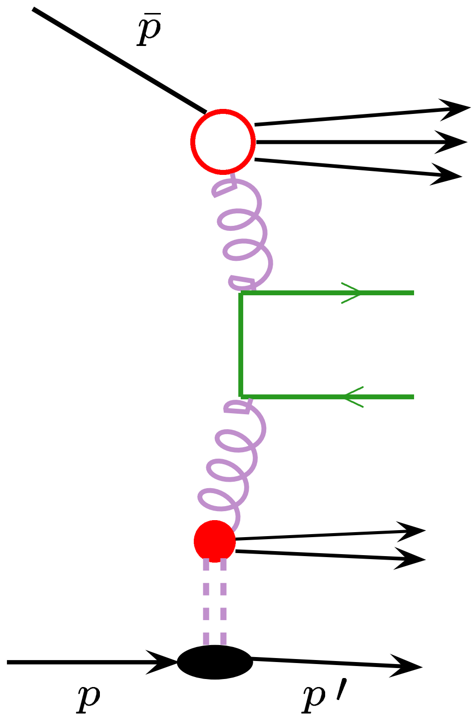
- New fit confirms serious breakdown of QCD factorization, new prediction slightly closer
- β–dependence similar (except hightest β)
- Note : 50 % contribution from subleading terms in $x_{I\!P}$–regime of CDF data at low β
- Explanation : Additional spectator interactions ?

Dijet in diffractive photoproduction

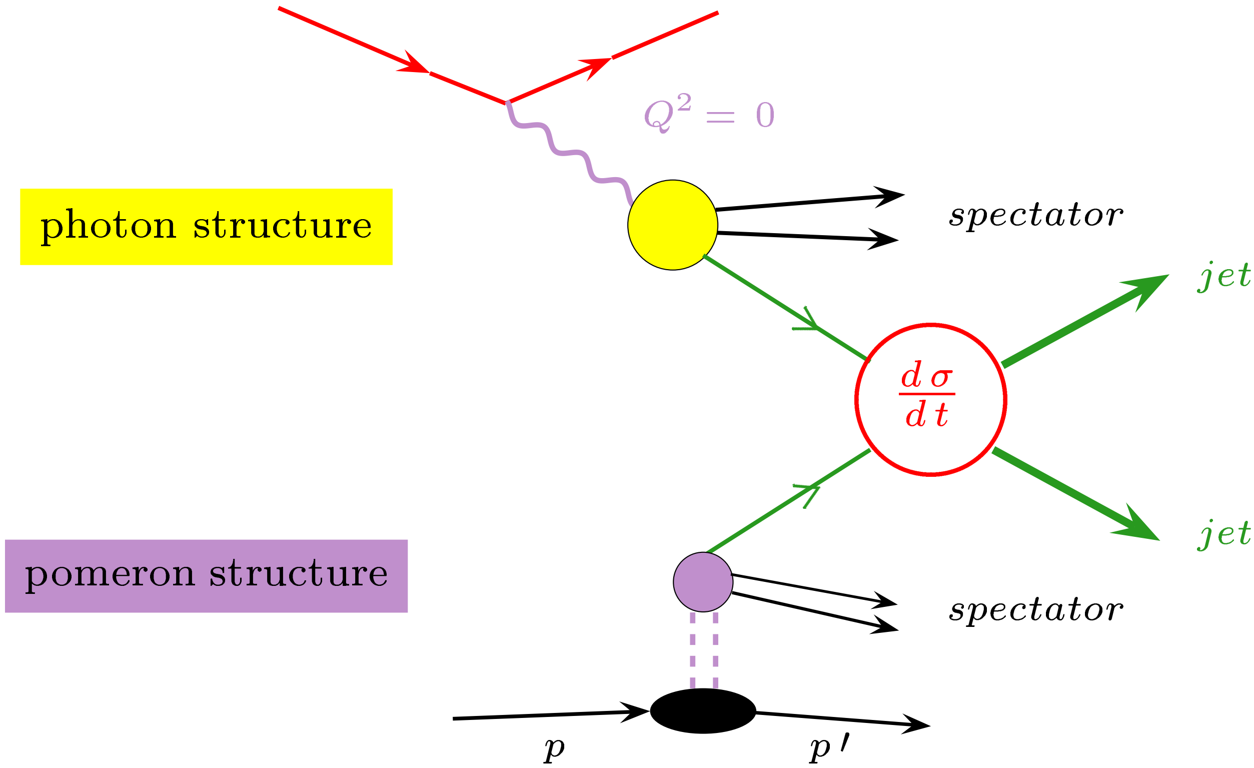
HERA



Tevatron

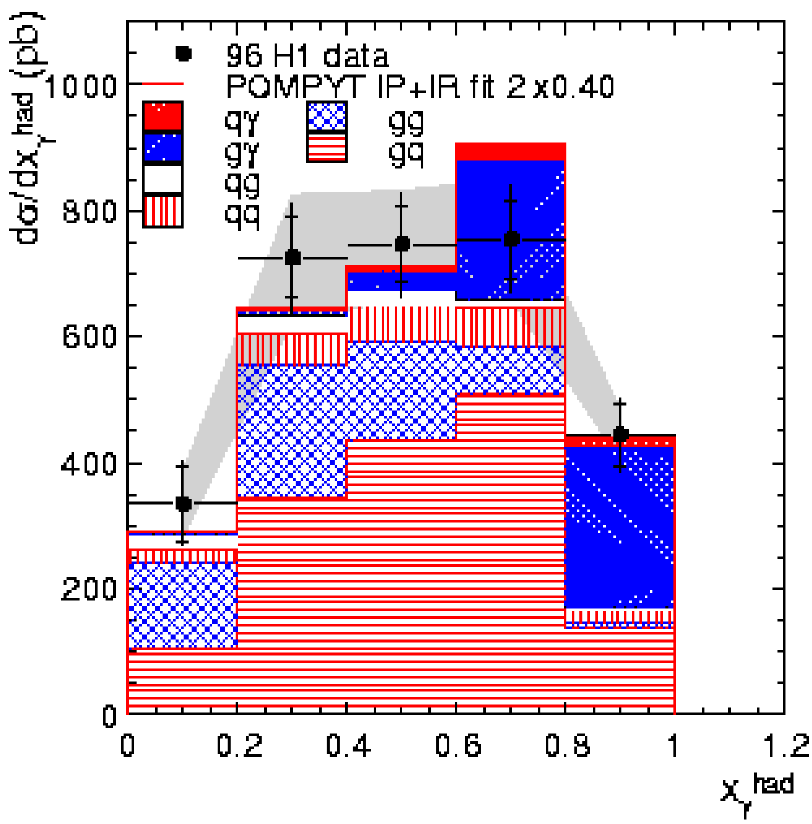


<u>IDEA</u> : real photon : transition from diffractive DIS to hard diffractive $p\bar{p}$–collisions



$$\frac{d\sigma}{dt} : \; gg \to gg, \quad qg \to qg, \quad qq \to qq$$

$$\text{direct process}: \quad \gamma g \to q\bar{q}$$

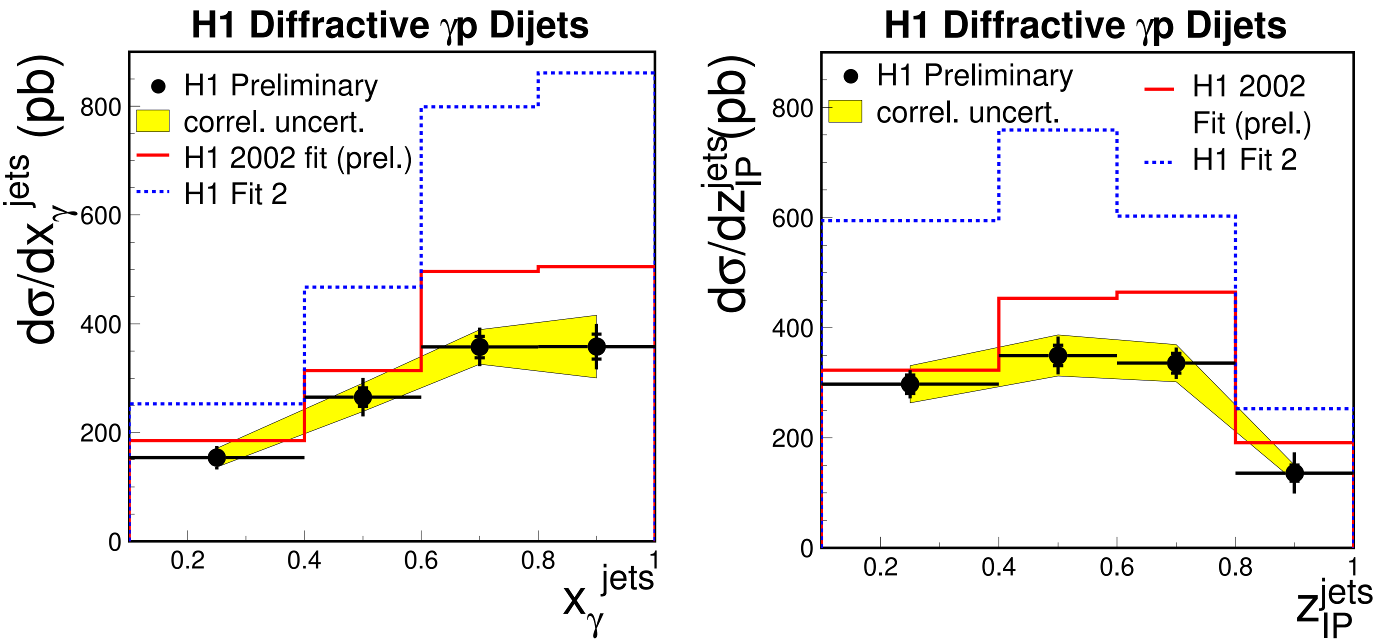


Subprocesses can be separated

Diffractive dijet photoproduction

$$Q^2 < 0.01\ GeV^2, \quad E_T^{jet} > 5\ GeV, \quad x_{I\!P} < 0.03$$
$$M_Y < 1.6\ GeV, \quad -t < 1\ GeV^2$$

RAPGAP : LO photon + Pomeron structure

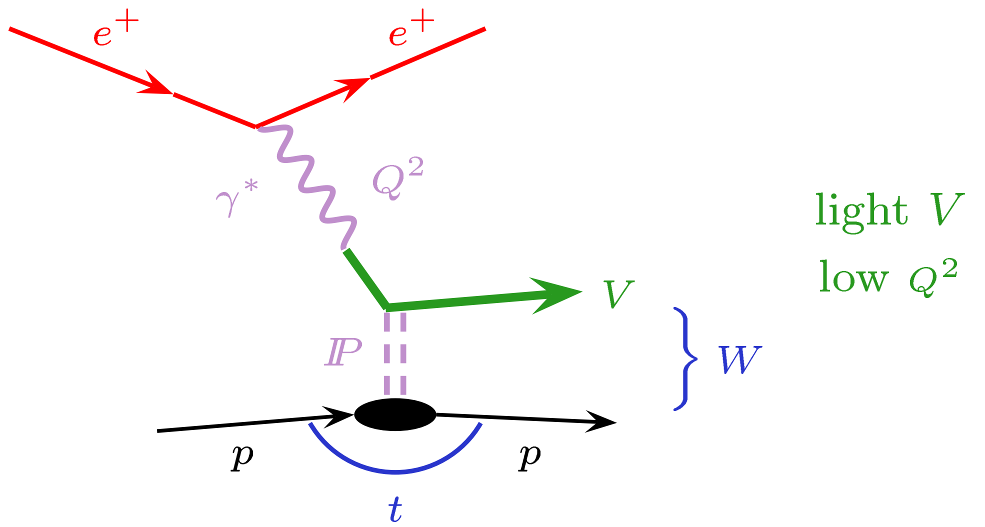


- Shape well described
- Normalization :
  LO calculation/data ≈ 1.3
  reminder : DIS diffraction ratio < 1
- Photoproduction/DIS $= (1.8 \pm 0.45)$
  same suppression for direct/resolved photons
- Smaller suppression in photoproduction
  than for Tevatron data
- Note : LO calculation !

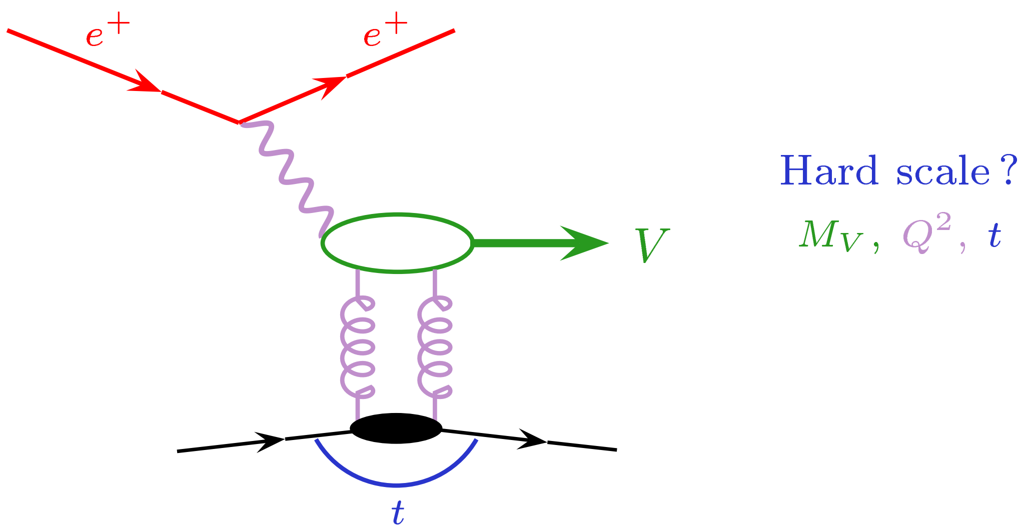
IV. Vector Meson Production in Hard Diffraction Scattering

$$e^+ p \;\to\; e^+ V p, \qquad V = \rho^0, \omega, \phi, \psi, \Upsilon$$

Regge theory :

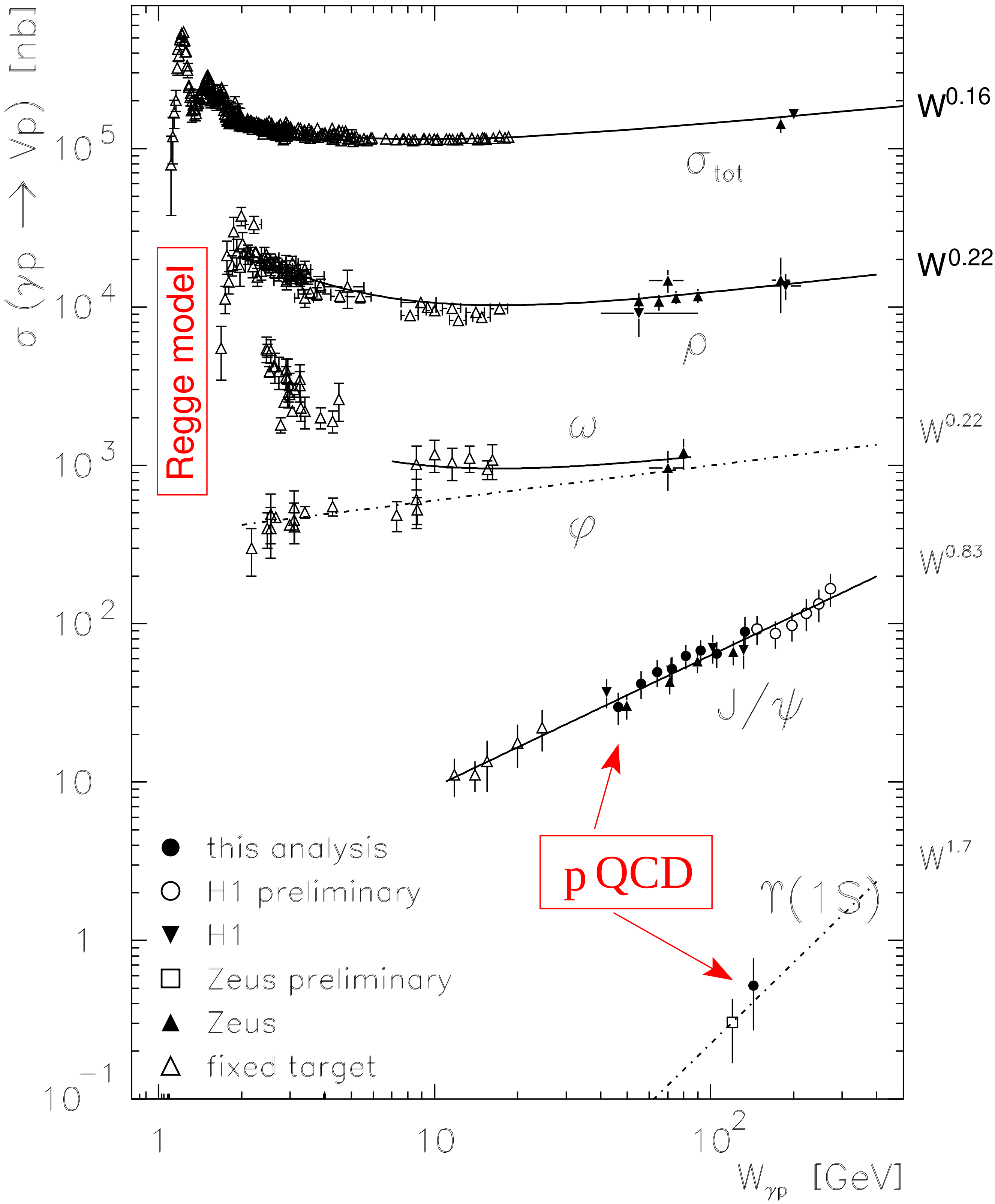


$p\,QCD$–models



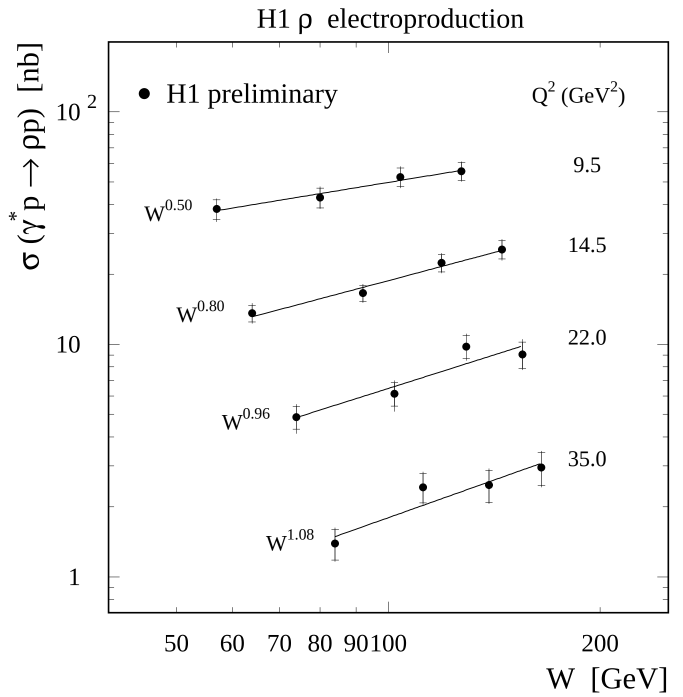
- $\sigma_r \;\sim\; \left(x\, g\,(x, Q^2)\,\right)^2$
- Steep rise with $W \approx \frac{Q^2}{x}$ due to gluon
- $\sigma \;\sim\; |\,t\,|^n$
- ρ^0 : at high Q^2 transition soft $\to$ hard physics

- Photoproduction

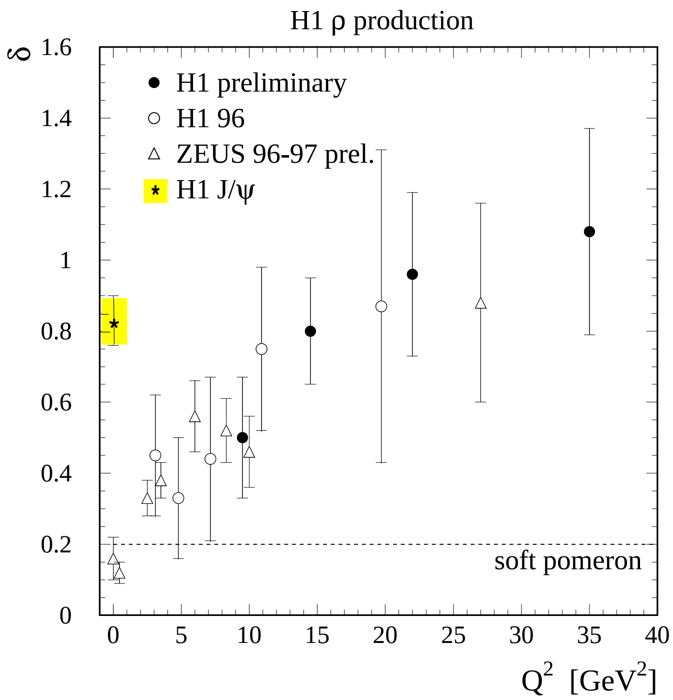


$M_\psi, \ M_\Upsilon$ hard scale

- Electroproduction of ρ^0–mesons :
  W–dependence for different Q^2



Parametrization $\sigma\,(W, Q^2)\ \sim\ W^{\delta\,(Q^2)}$:



Q^2 hard scale

- Transition soft $\rightarrow$ hard physics
- $\delta_\rho\,(Q^2 \gg 1\ GeV^2)\ \approx\ \delta_\psi\,(Q^2 = 0)$

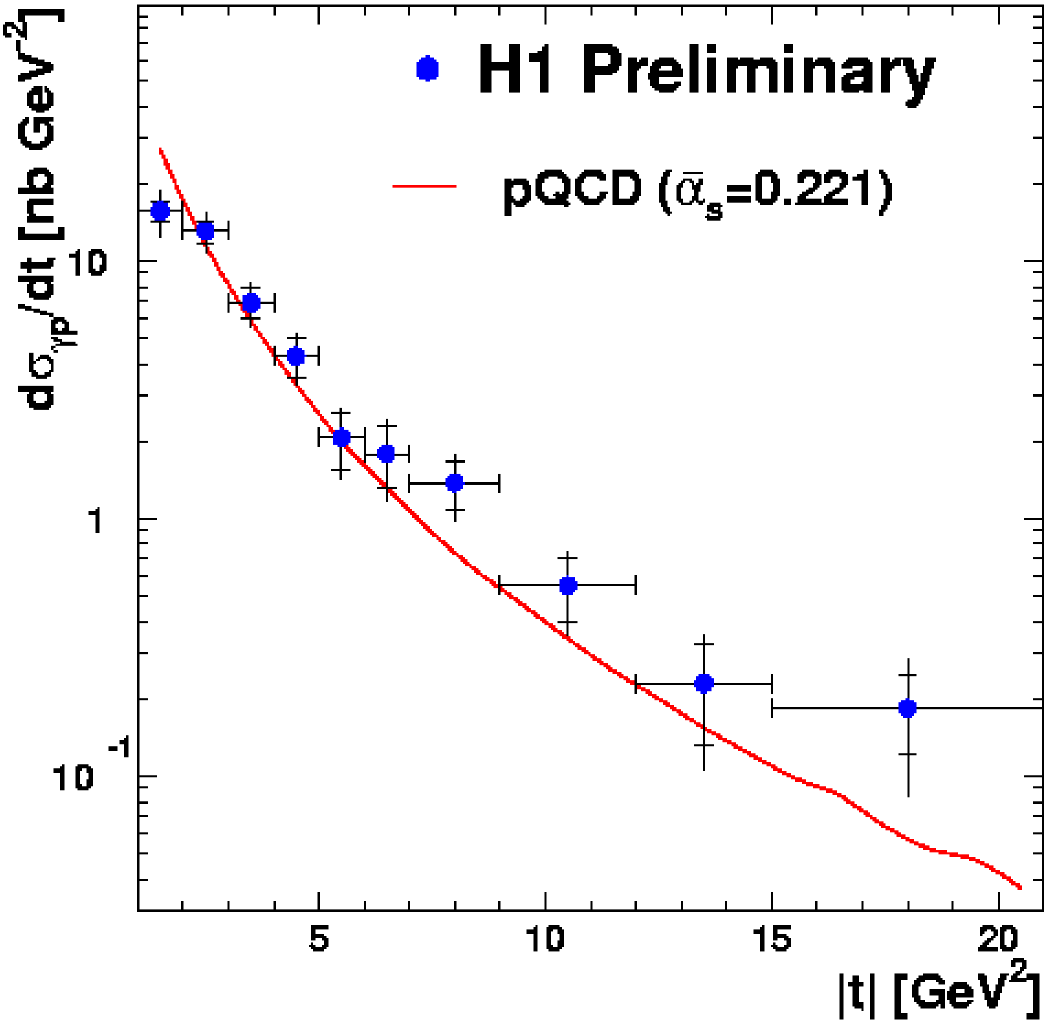
- Photoproduction $\gamma p \to \psi Y$

At high t: proton dissociation dominates

Expectation: *Regge* $\frac{d\sigma}{dt} \sim e^{Bt}$

hard process $\frac{d\sigma}{dt} \sim |t|^n$

$Q^2 < 1\,\text{GeV}^2;\ 50 < W < 160\,\text{GeV}$



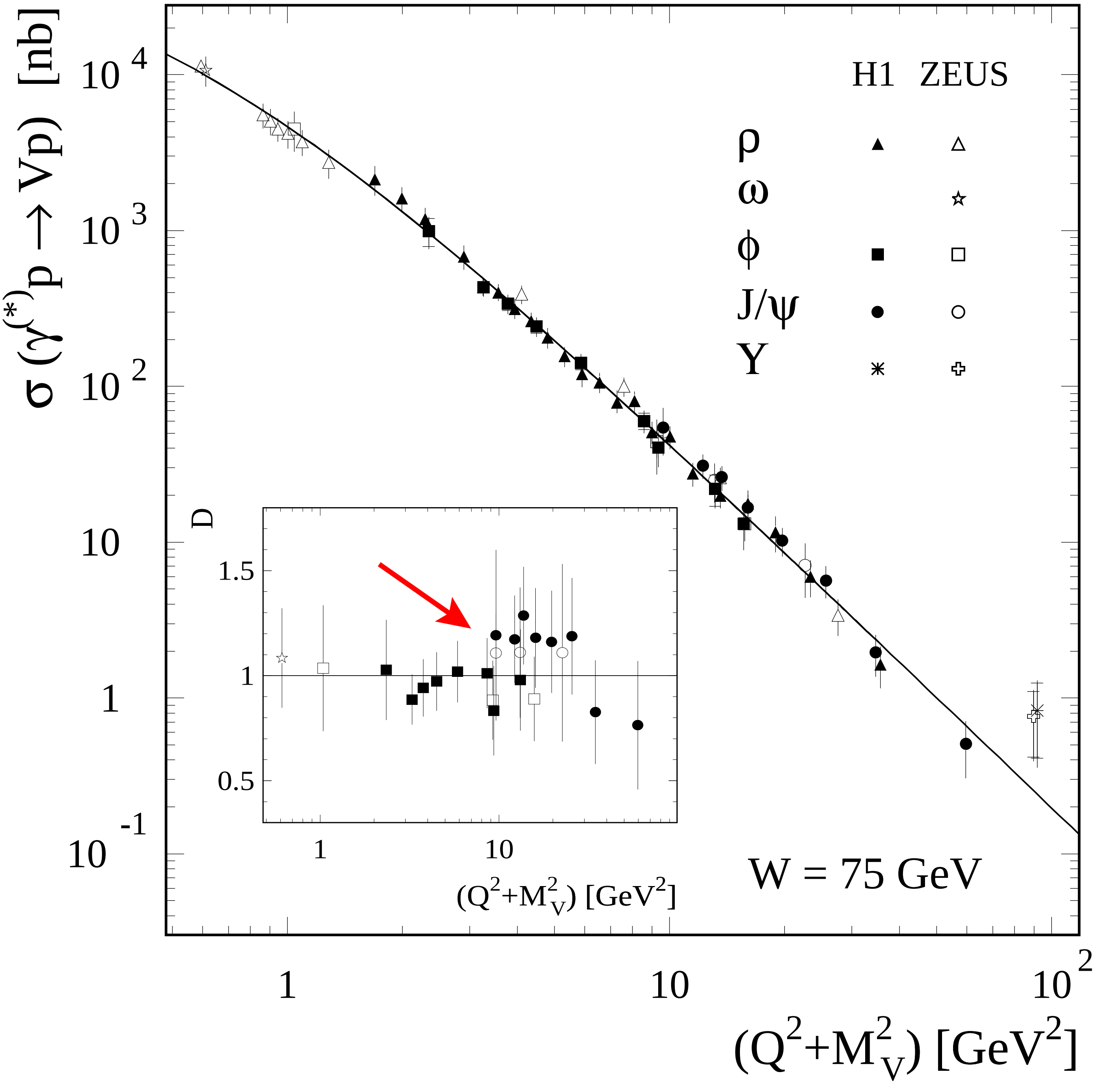
- at large $\frac{d\sigma}{dt} \sim |t|^n$
- described by $pQCD$
  (Large normalization uncertainties)

  Indication: t is hard scale

- Interplay between Q^2 and M_V^2 scales :

  Approximate flavor independence: SU(4)–factors

  $\rho^0 : \omega : \phi : \psi = 9 : 1 : 2 : 8$



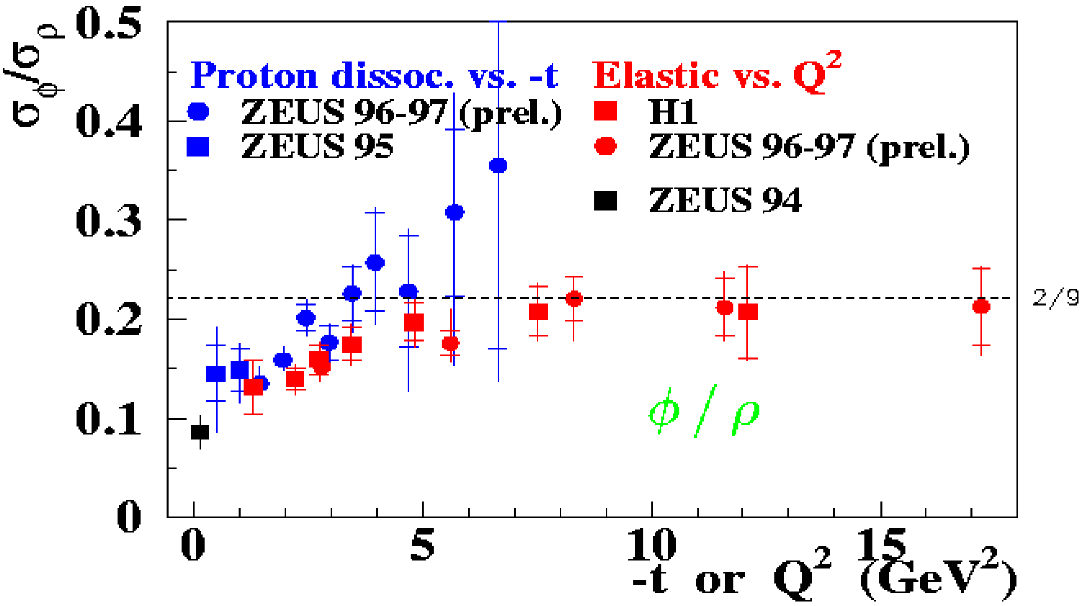
- $\sigma(\gamma^* p \to \psi p)$ slightly larger $\longrightarrow$

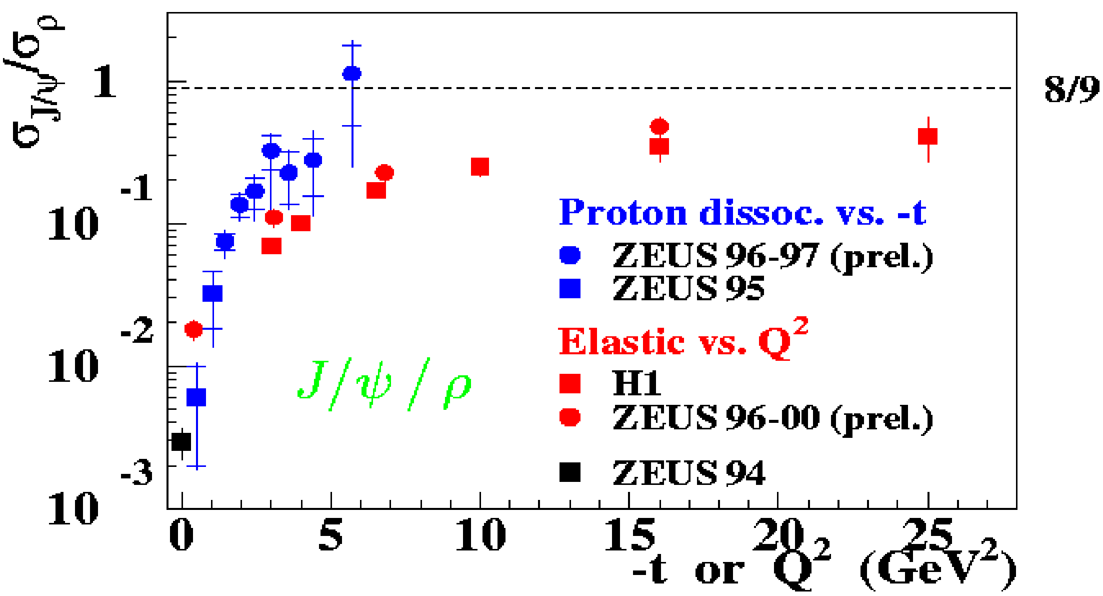
  masses not negligible in $pQCD$

- Comparison of Q^2- and $t-$dependence

$\gamma^* p \rightarrow V p$: Q^2-dependence

$\gamma\, p \rightarrow V N^*$: $t-$dependence

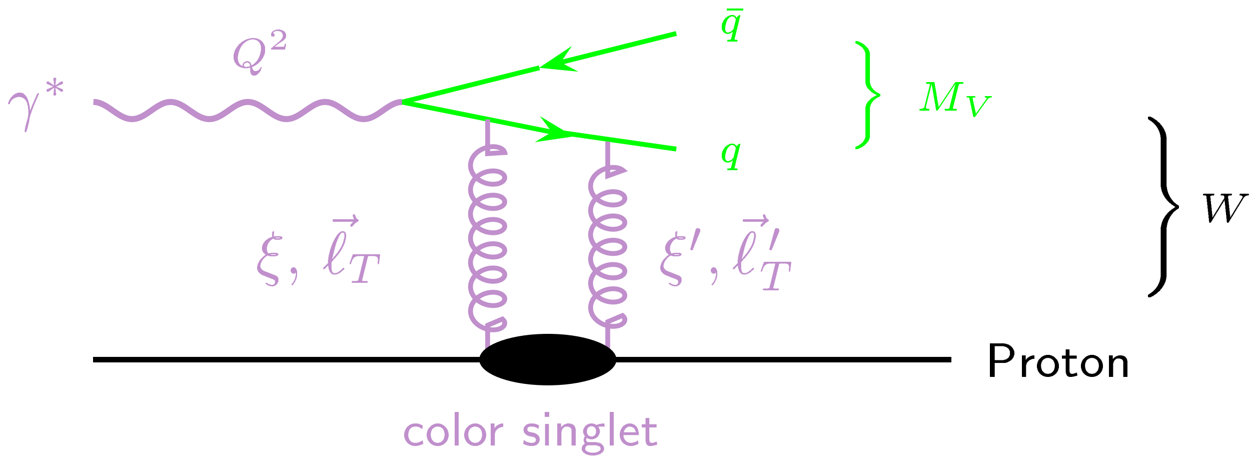




- Large $-t,\, Q^2$: SU(4) ratios
- Small $-t,\, Q^2$: Steeper rise in $|\, t\,|$
- Large $-t,\, Q^2$: Hard scale
- factorization at p–Vertex

Interpretation

- nonperturbative : hard Pomeron
- perturbative QCD model



$$\delta\,\xi \;=\; \frac{M_V^2 + Q^2}{W^2 + Q^2}$$

$$\left(\frac{d\sigma}{dt}\right)_{t=0} \;\sim\; |\ \xi\ g\,(\xi, \bar{Q}^2)\ |^2$$

Skewed gluon distribution: $\delta\,\xi(\Upsilon)$ large

Model assumptions :

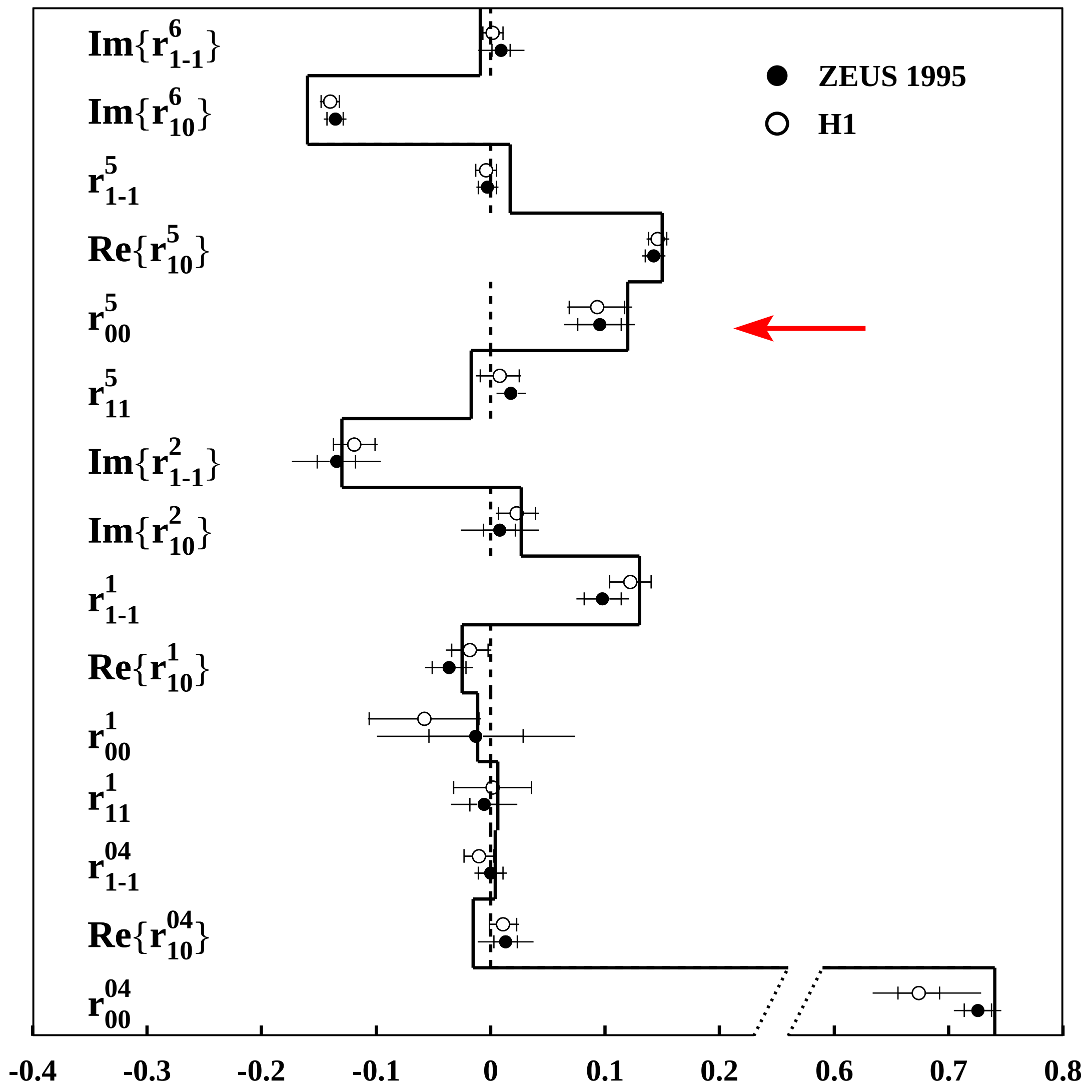
- $q\bar{q}$ − state
- 2 gluon exchange
- $q\bar{q} \;\rightarrow\; V$ wave function
  parton hadron duality

Comparison with model predictions

- Spin density matrix elements

  $(1\ GeV^2 < Q^2 < 60\ GeV^2)$

  $\gamma^* p \ \rightarrow\ \rho^0 p,\ \gamma^* p \ \rightarrow\ \phi p$



——— $pQCD$ 2 gluon

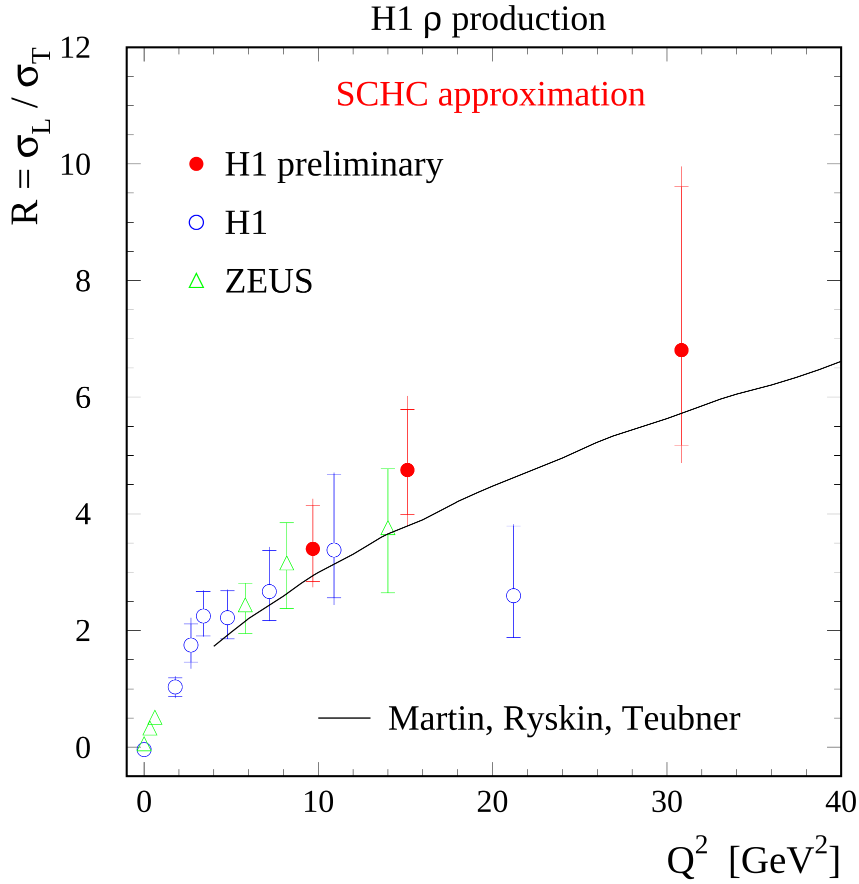
- - - - - SCHC

- $r^5_{00} \ \sim\ T_{00}\, T^*_{01} \ +\ T_{01}\, T^*_{00} \neq 0$

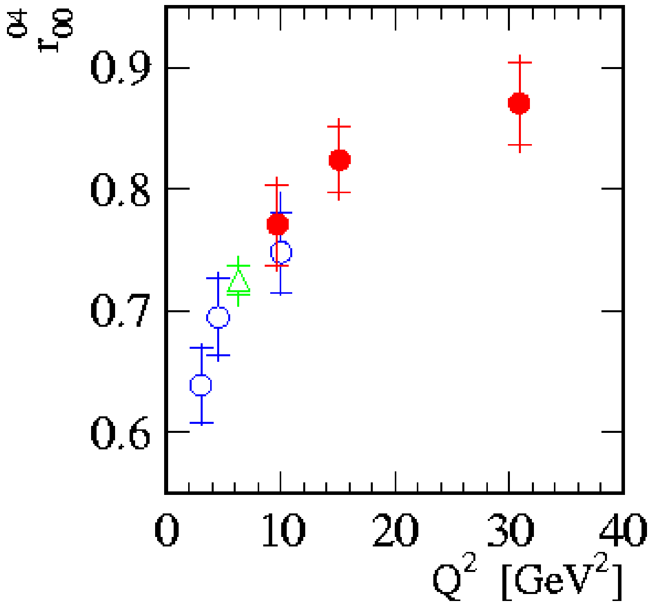
  $\boldsymbol{\gamma_T \ \rightarrow\ \rho_L}$ transition measured

- SCHC (holds for $\gamma\, p \ \rightarrow\ \rho^0\, p$) broken predicted by models

Q^2– dependence of σ_L, σ_t :



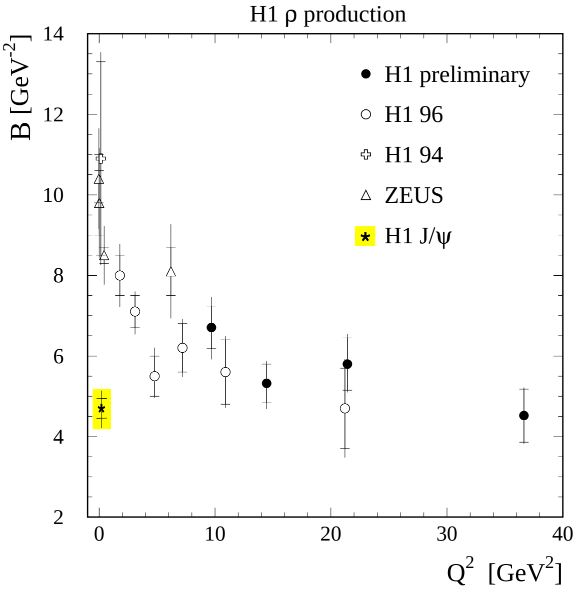
- σ_L dominates at high Q^2
- σ_T $\sim$ 15 % contribution at high Q^2
- Rise described by $p\,QCD$



$$R = \frac{\sigma_L}{\sigma_T} = \frac{1}{\varepsilon}\;\frac{r^{04}_{00}}{1 - r^{04}_{00}}$$

Electroproduction of ρ^0-mesons : $t-$dependence

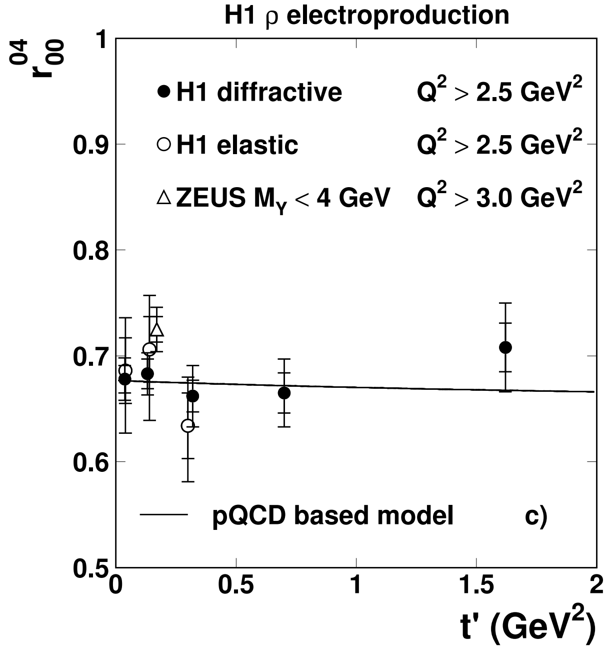
$$d\sigma/dt \sim e^{Bt}$$



$$B\,(Q^2) \sim r_p^2 + r_V^2$$

- transverse size of $q\bar{q}$ – pair decreases
- $B_\rho\,(Q^2 = 35\ GeV^2) \approx B_\psi\,(Q^2 = 0)$
- $\frac{\hbar\, c}{2}\sqrt{B_\rho\,(Q^2 = 35\ GeV^2)} \approx r_p$

- $r^{04}_{00} \sim |\, T_{01}\,|^2 + |\, T_{00}\,|^2$

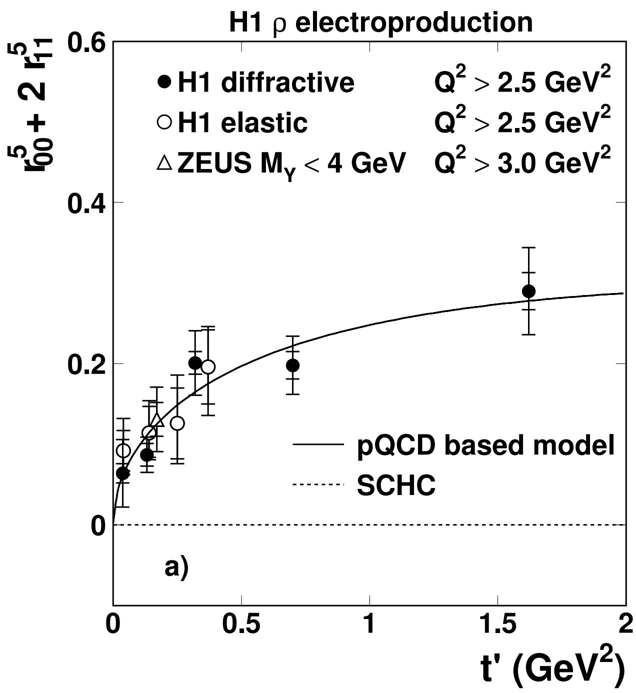


- flat t–dependence
- proton dissociation $\approx$ elastic data
  Factorization of p–vertex

- $r^5_{00} \sim T_{00}\, T^*_{01}$

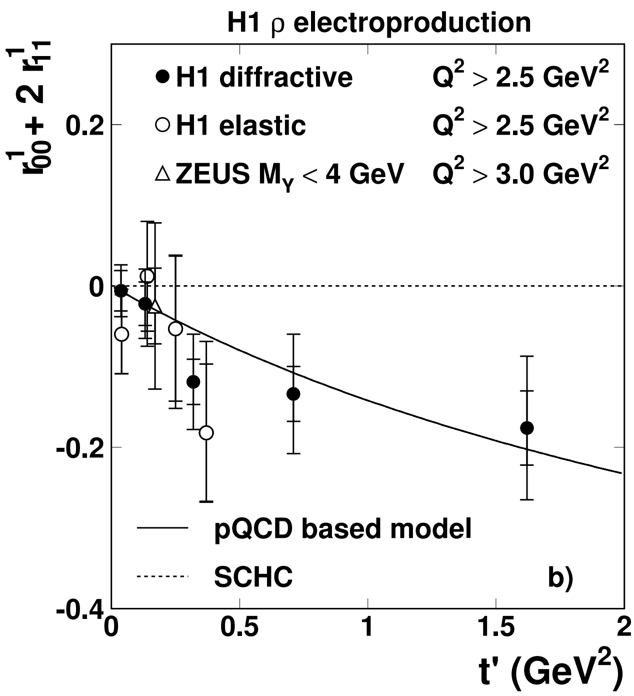
  $r^5_{11} \sim T_{10}\, T^*_{11} + T_{10}\, T^*_{1-1}$

  —— $\sqrt{t}$ – dependence



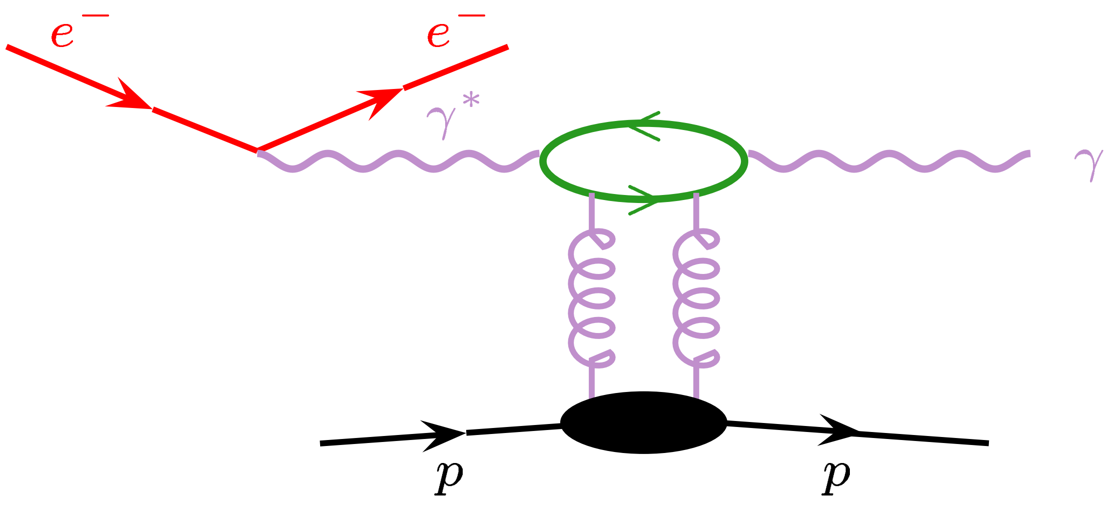
- $r^1_{00} \sim |\, T_{01}\,|^2$ $\gamma_T \rightarrow \rho_L$ dominates

  $r^1_{11} \sim T_{1-1}\, T^*_{11} + T_{11}\, T^*_{1-1}$ double flip ?



Data described by $pQCD$ based model predictions

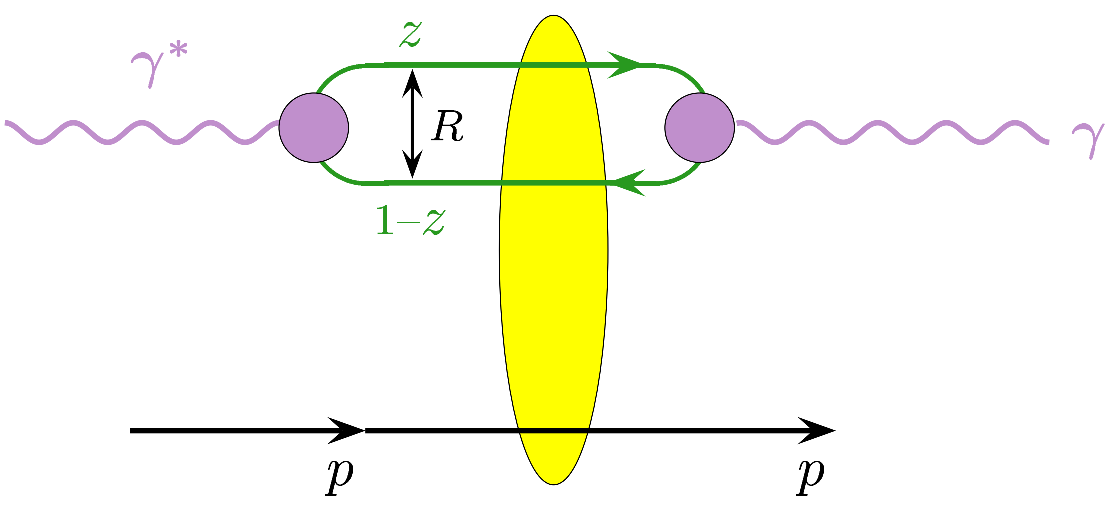
- Deeply Virtual Compton Scattering (DVCS)



Interferes with QED–Compton process

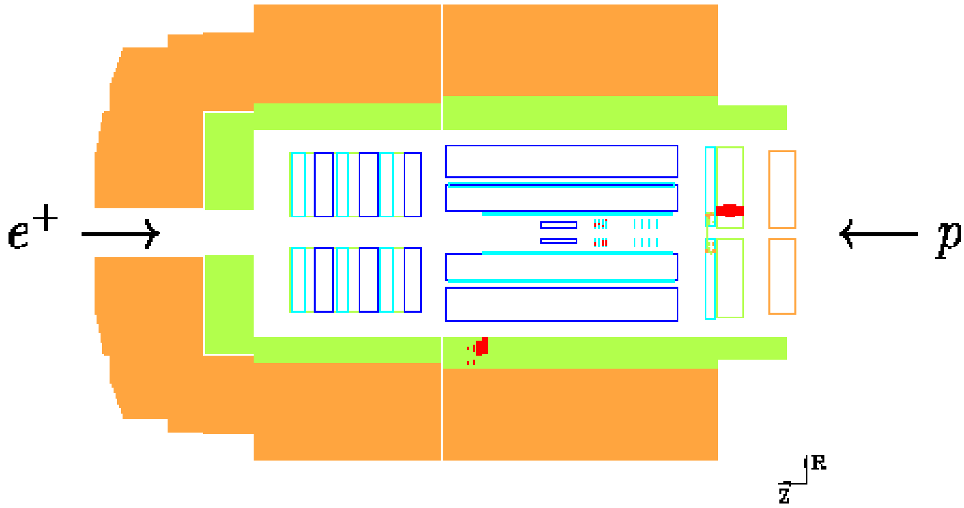
- factor Q^2 less than V–production
- no problem with $q\bar{q} \rightarrow V$

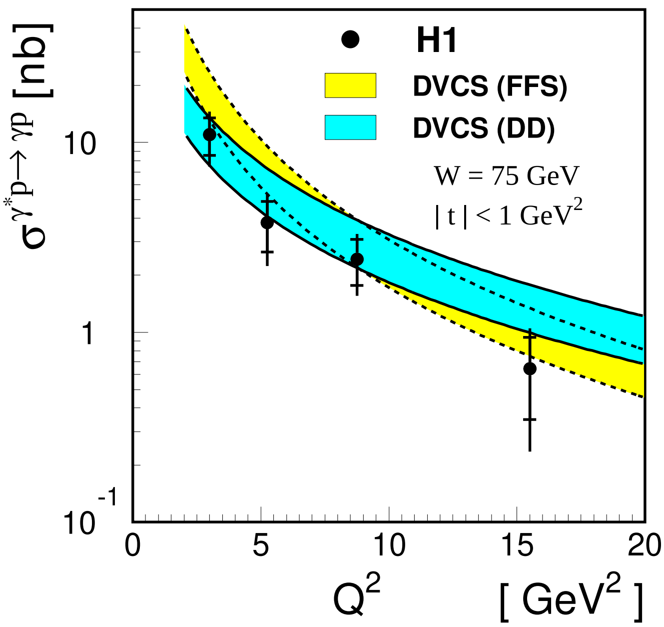
Models: ▸ skewed (generalized) parton distribution
▸ color dipole model :

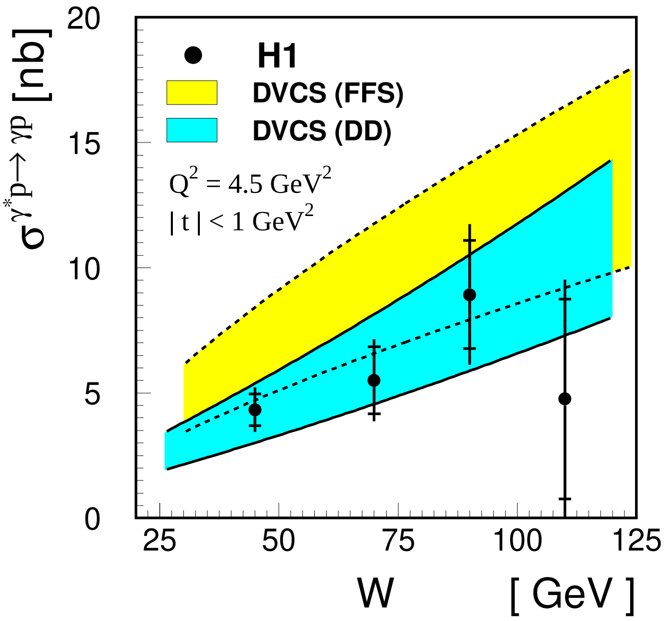


$$\text{Ampl} \sim \int \psi_i \ \sigma_{Dip} \ \psi_0$$

• DVCS







Good description of data by both

QCD based calculations DD

Semiclassical dipole model FFS

Summary vector mesons :

- promising agreement between 1^{st} generation data and models
- more work necessary to extract $g_p\,(x, Q^2)$
- skewed parton distributions measurable

V. Summary

- Hard diffraction observed
  (events with rapidity gap/leading p)

- QCD factorization works for inclusive diffractive scattering

- QCD fit describes data
  gluon dominates for all β
  $$< \beta_{gluon} > \approx 0.75$$

- Dijet and D*–production allow to measure gluon of Pomeron directly – reasonable agreement

- Q^2, M_V^2 and t hard scale for elastic vector meson production

- DVCS cross–section measured

- Skewed (generalized) parton distribution measurable

H1