Soft and Hard Diffraction

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Small *x* and Diffraction 2003
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SOFT DIFFRACTION

- ✓ M^2-scaling
- ✓ Triple-pomeron coupling → relate to color factors
- ✓ Derive full differential cross section from parton model
- ✓ Multi-gap diffraction

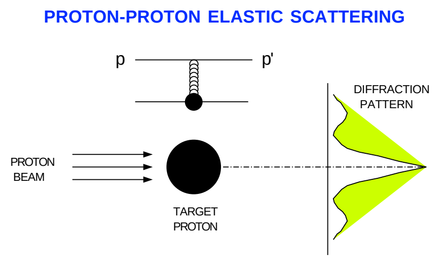
HARD DIFFRACTION

- ❖ Diffractive structure function → derive from proton PDFs
  - ➢ β and ξ dependence
  - ➢ Regge and QCD factorization

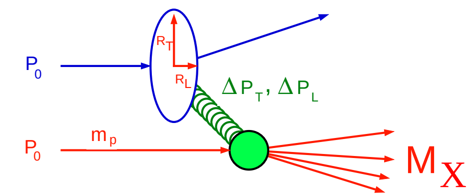
- ❑ HERA versus TEVATRON
  - ➢ Normalization
  - ➢ β dependence

Classical Picture of Diffraction

Elastic Scattering and Diffraction Dissociation



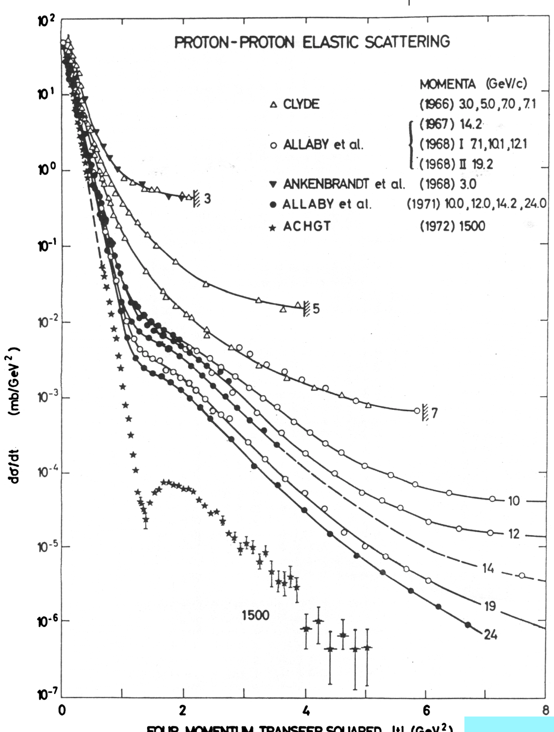
Diffraction dissociation



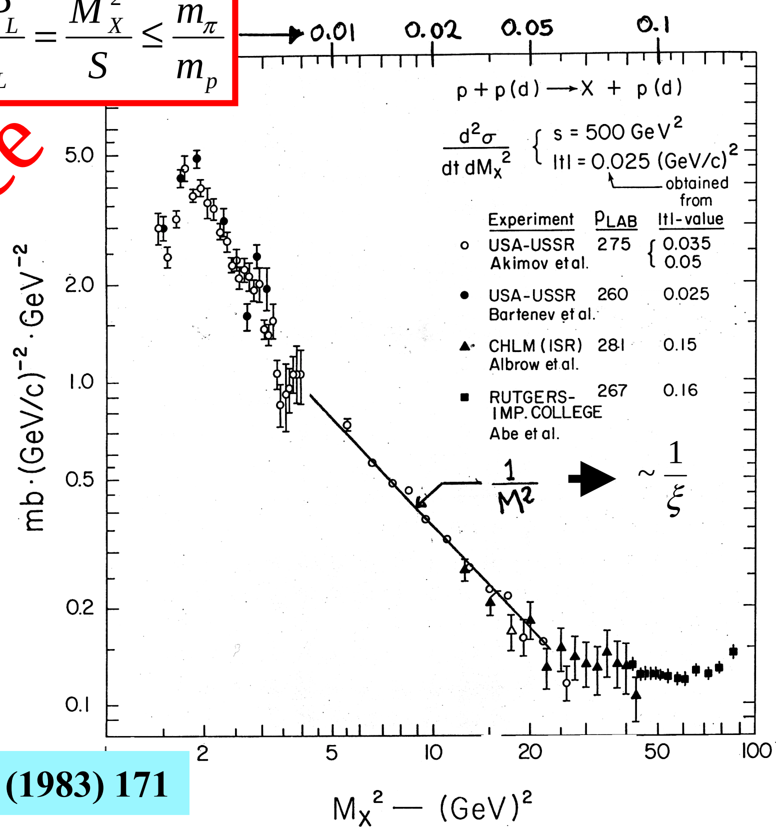
$$\xi = \frac{\Delta P_L}{P_L} = \frac{M_X^2}{S} \leq \frac{m_\pi}{m_p}$$

coherence

$\frac{d\sigma}{dt}$



$\frac{d^2\sigma}{dt\, dM^2}$



KG, Phys. Rep. 101 (1983) 171

Diffraction and Rapidity Gaps

✓**rapidity gaps are regions of pseudorapidity devoid of particles**

❑ **Non-diffractive interactions:**

Rapidity gaps are formed by multiplicity fluctuations.

From Poisson statistics:

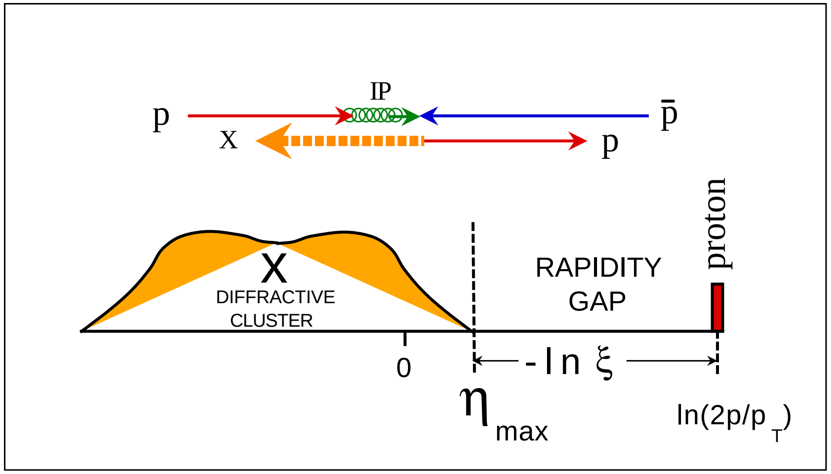
$$P(\Delta\eta) = e^{-\rho\Delta\eta} \quad \left(\rho = \frac{dN}{d\eta}\right)$$

(ρ=particle density in rapidity space)

Gaps are exponentially suppressed

❑ **Diffractive interactions:**

Rapidity gaps are due to absence of radiation in "vacuum exchange"



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

$$\frac{d\sigma}{dM^2} \sim \frac{1}{M^2} \quad \rightarrow \quad \frac{d\sigma}{d\Delta y} \sim \text{constant}$$

✓ large rapidity gaps are signatures for diffraction

The Pomeron in QCD

- **Quark/gluon exchange across a rapidity gap:**

  POMERON

- **No particles radiated in the gap:**

  the exchange is COLOR-SINGLET with quantum numbers of vacuum

- **Rapidity gap formation:**

  NON-PERTURBATIVE

- Diffraction probes the large distance aspects of QCD:

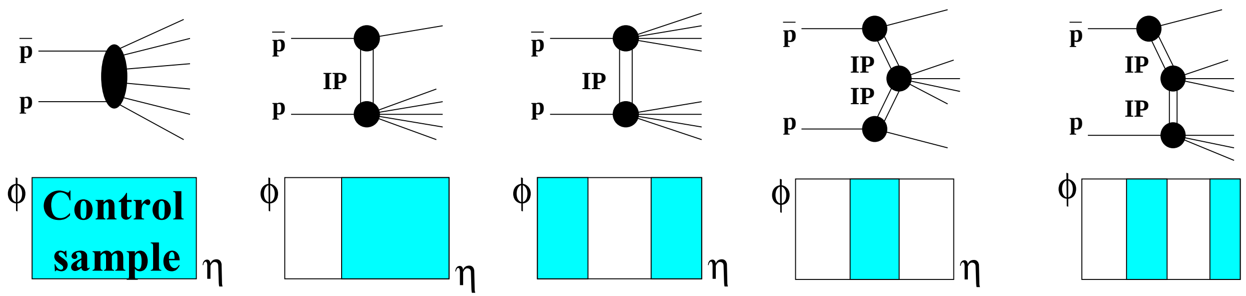
  POMERON ⟷ ? **CONFINEMENT**

  - **PARTONIC STRUCTURE**
  - **FACTORIZATION**

Diffraction at CDF in Run I

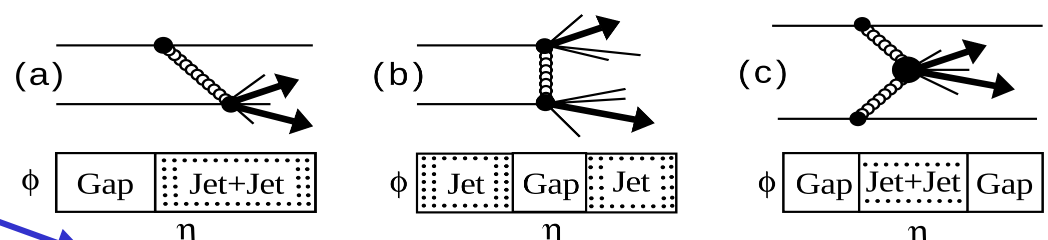
- Elastic scattering PRD 50 (1994) 5518
- Total cross section PRD 50 (1994) 5550
- Diffraction

SOFT diffraction



Non–Diffractive (ND)	Single–Diffractive (SD)	Double Diffractive (DD)	Double Pomeron Exchange (DPE)	Single + Double Diffractive (SDD)
	PRD 50 (1994) 5535	PRL 87 (2001)141802	PRL to be sub'd	PRL 91(2003)011802

HARD diffraction



PRL reference

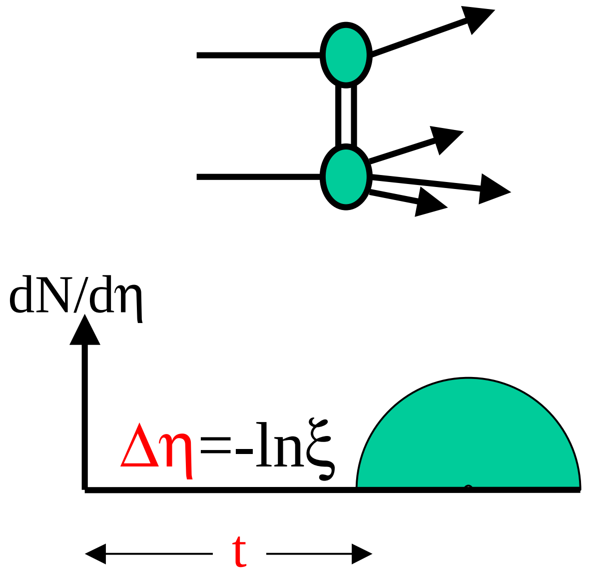
with roman pots

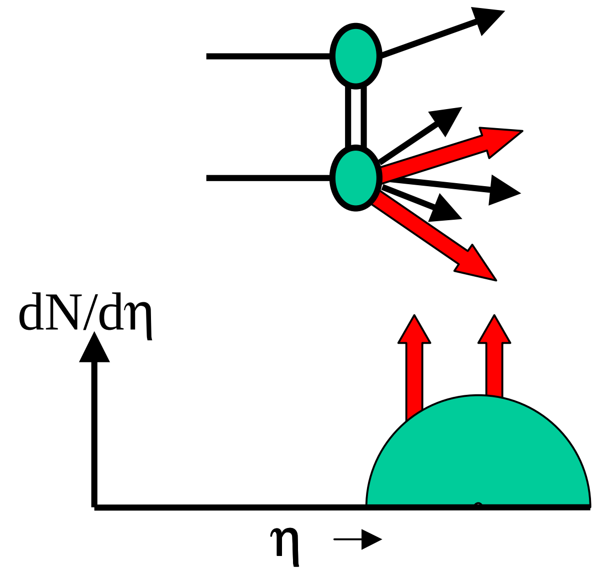
JJ	84 (2000) 5043
JJ	88 (2002) 151802

W 78 (1997) 2698	JJ 74 (1995) 855	JJ 85 (2000) 4217
JJ 79 (1997) 2636	JJ 80 (1998) 1156	
b-quark 84 (2000) 232	JJ 81 (1998) 5278	
J/ψ 87 (2001) 241802		

Single Diffraction

- SOFT DIFFRACTION
- HARD DIFFRACTION





$\xi = \Delta P_L / P_L$ fractional momentum loss of scattered hadron

Variables: (ξ, t) or (Δη, t)

Additional variables: ($\boldsymbol{x}$, Q^2)

$$x = \sum E_T^{jet} e^{-\eta^{jet}} / \sqrt{s}$$

$$x = \beta\,\xi \le \xi$$

Questions: universality of gap formation and of diffractive PDF’s

Soft diffraction

parton model

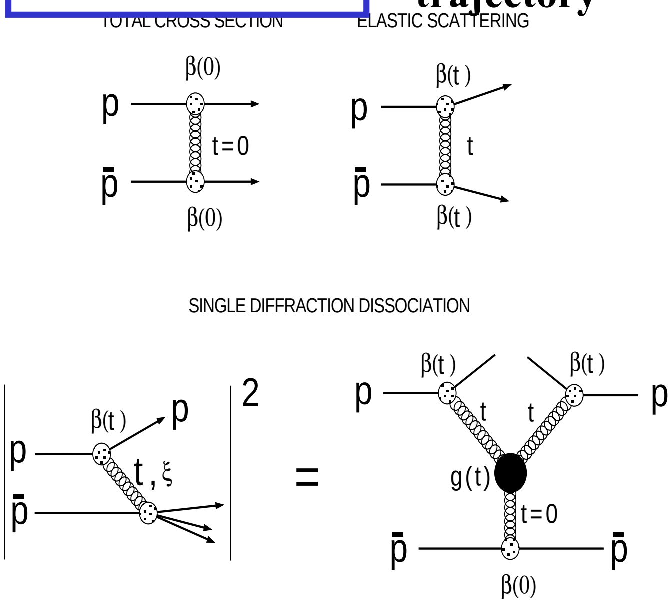
Regge

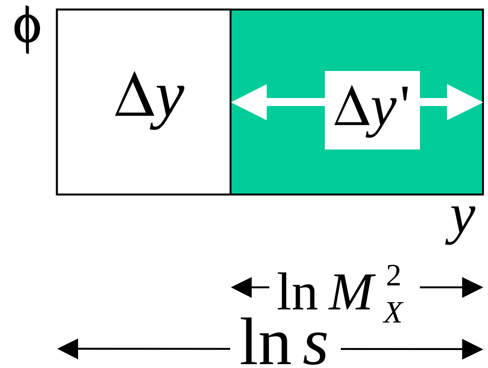
Factorization & (re)normalization

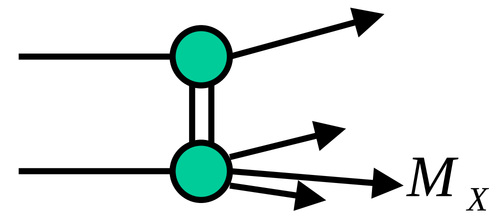
$$\sigma_T = \sigma_o s^{\varepsilon} = \sigma_o e^{\varepsilon \ln s} \Leftarrow \sigma_o s^{\alpha_{IP}(0)-1}$$

$$\alpha_{IP}(t) = 1 + \varepsilon + \alpha' t$$

Pomeron trajectory







$$\Delta y = \ln s - \Delta y'$$

$$\frac{d^2\sigma}{d\Delta y'\, dt} = f_{IP/p}(\Delta y, t) \times \sigma_{IP-p}(\Delta y')$$

$$C \cdot F_p^2(t) \cdot \left(e^{[\varepsilon + \alpha' t]\Delta y}\right)^2 \qquad \kappa \times \sigma_o e^{\varepsilon \Delta y'}$$

Renormalize to unity
KG, PLB 358 (1995) 379

Gap probability

$$\kappa = \frac{g_{IP-IP-IP}(t)}{\beta_{IP-p}(0)}$$

COLOR FACTOR

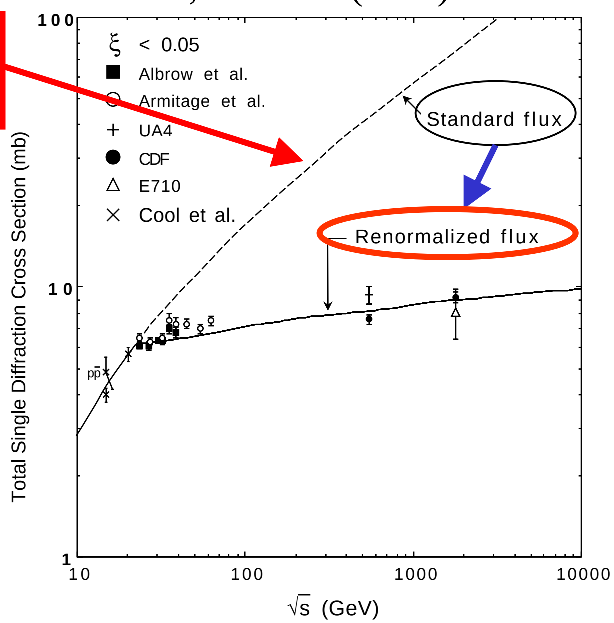
Soft Single Diffraction Data

$$p(\bar{p}) + p \rightarrow p(\bar{p}) + X$$

$$\sigma \sim s^{2\varepsilon}$$

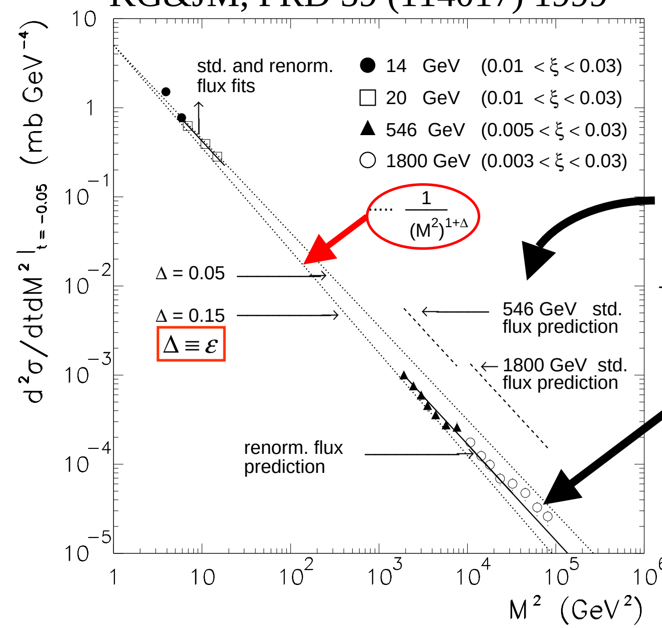
Total cross section

KG, PLB 358 (1995) 379



Differential cross section

KG&JM, PRD 59 (114017) 1999



REGGE

$$\frac{d\sigma}{dM^2} \propto \frac{s^{2\varepsilon}}{(M^2)^{1+\varepsilon}}$$

RENORM

$$\frac{d\sigma}{dM^2} \propto \frac{1}{(M^2)^{1+\varepsilon}}$$

s-independent

- Differential shape agrees with Regge
- Normalization is suppressed by factor $\propto s^{2\varepsilon}$
- Renormalize Pomeron flux factor to unity

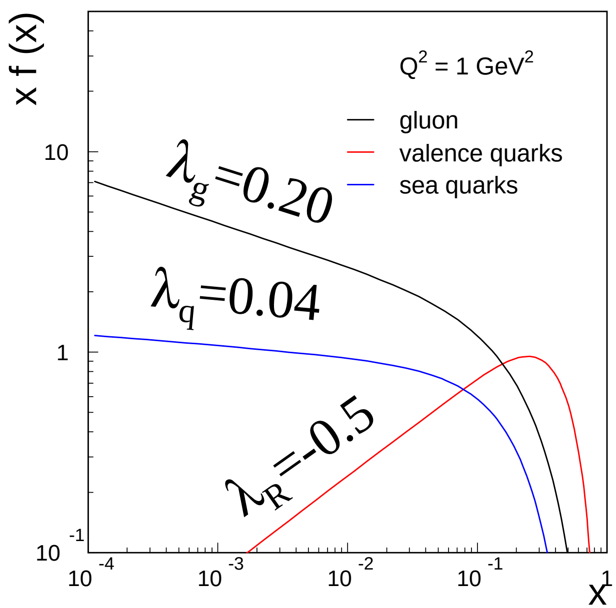
M² SCALING

The color factor κ

Experimentally: $\kappa = \dfrac{g_{IP-IP-IP}}{\beta_{IP-p}} = 0.17 \pm 0.02$ $\leftarrow$ KG&JM, PRD 59 (114017) 1999

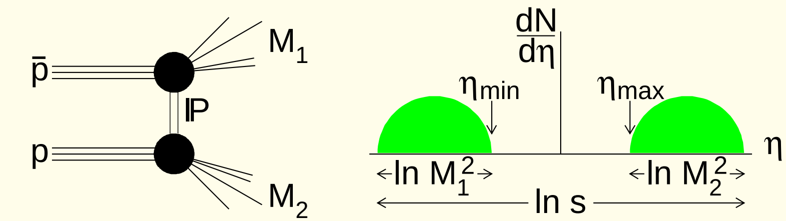
Theoretically: $\kappa = f_g \times \dfrac{1}{N_c^2 - 1} + f_q \times \dfrac{1}{N_c} \xrightarrow{Q^2 \to 0} \approx 0.75 \times \dfrac{1}{8} + 0.25 \times \dfrac{1}{3} = 0.18$

$$x \cdot f(x) = \frac{1}{x^{\lambda}}$$

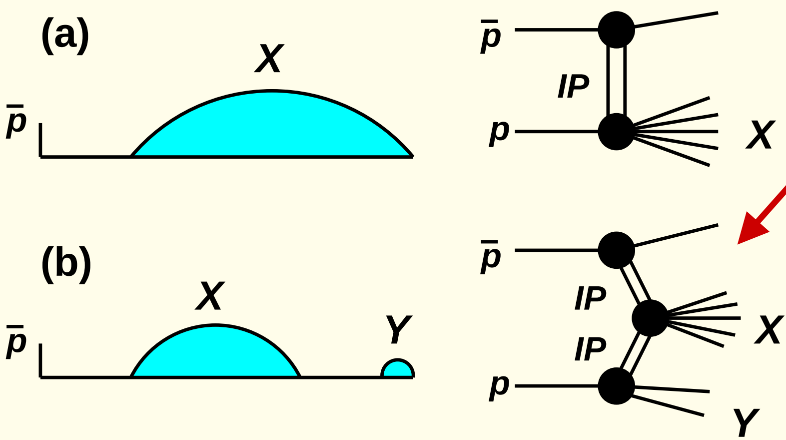


$$\varepsilon = \lambda_g \cdot w_g + \lambda_q \cdot w_q = 0.12$$

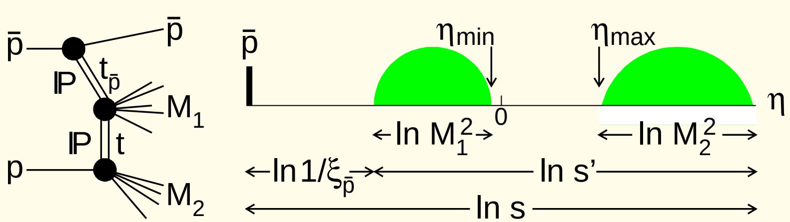
Central and Double Gaps



- **Double diffraction**
  - **Plot #Events versus Δη**

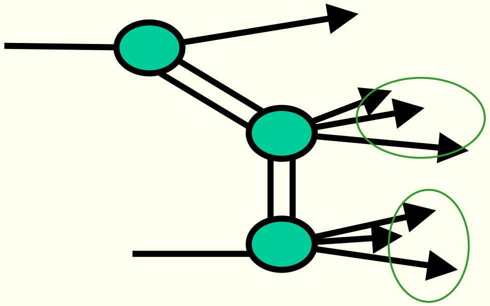


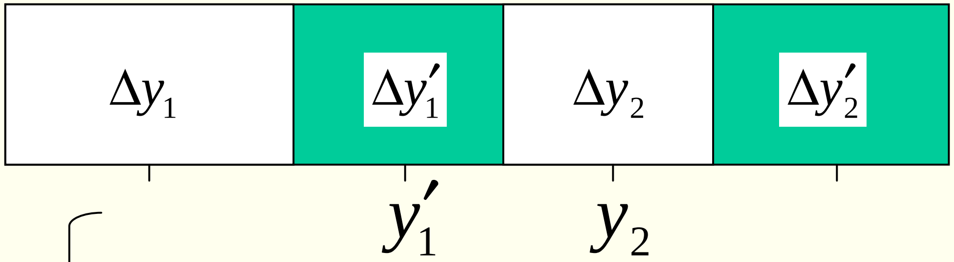
- **Double Pomeron Exchange**
  - **Measure** $$\xi_p = \frac{1}{\sqrt{s}} \sum_{\text{all particles}} E_T^i \cdot e^{\eta_i}$$
  - **Plot #Events versus log(ξ)**



- **SDD: single+double diffraction**
  - **Central gaps in SD events**

Two-Gap Diffraction (hep-ph/0205141)





5 independent variables $\left\{ t_1 \quad \Delta y = \Delta y_1 + \Delta y_2 \quad t_2 \right.$

color factor

$$\frac{d^5\sigma}{\prod\limits_{i=1-5} dV_i} = C \times F_p^2(t_1) \prod_{\mathrm{i=1\text{-}2}} \left\{ e^{(\varepsilon+\alpha' t_i)\Delta y_i} \right\}^2 \times \kappa^2 \left\{ \sigma_o \, e^{\varepsilon(\Delta y'_1 + \Delta y'_2)} \right\}$$

Gap probability

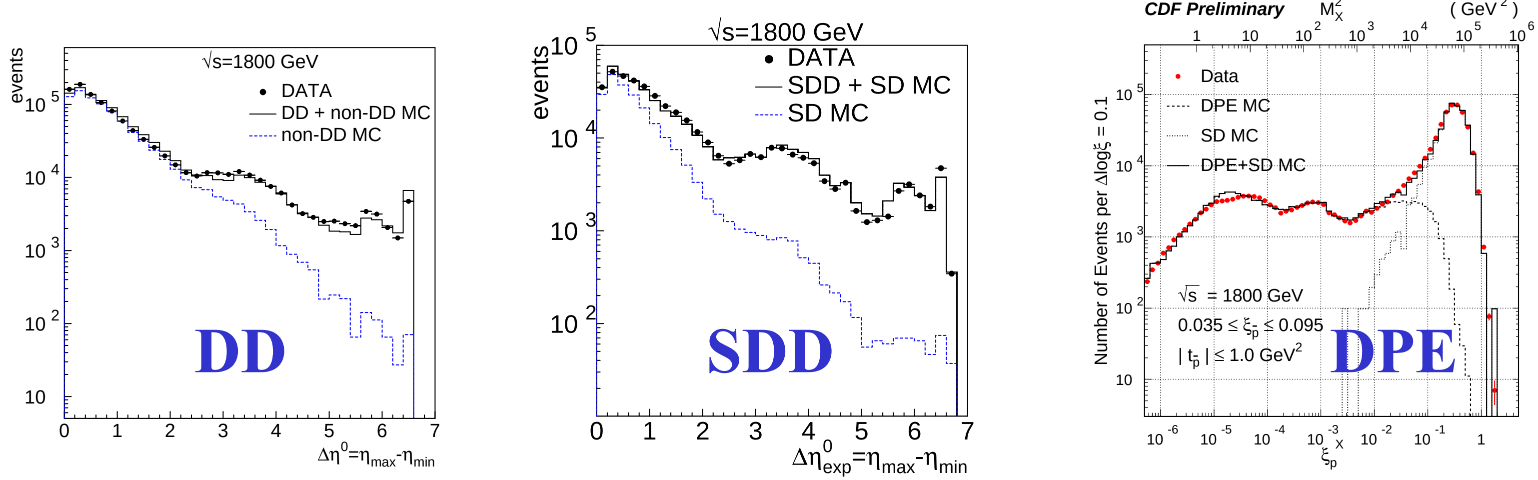
Sub-energy cross section (for regions with particles)

Integral $\sim s^{2\varepsilon}$ ← $\sim e^{2\varepsilon \Delta y}$

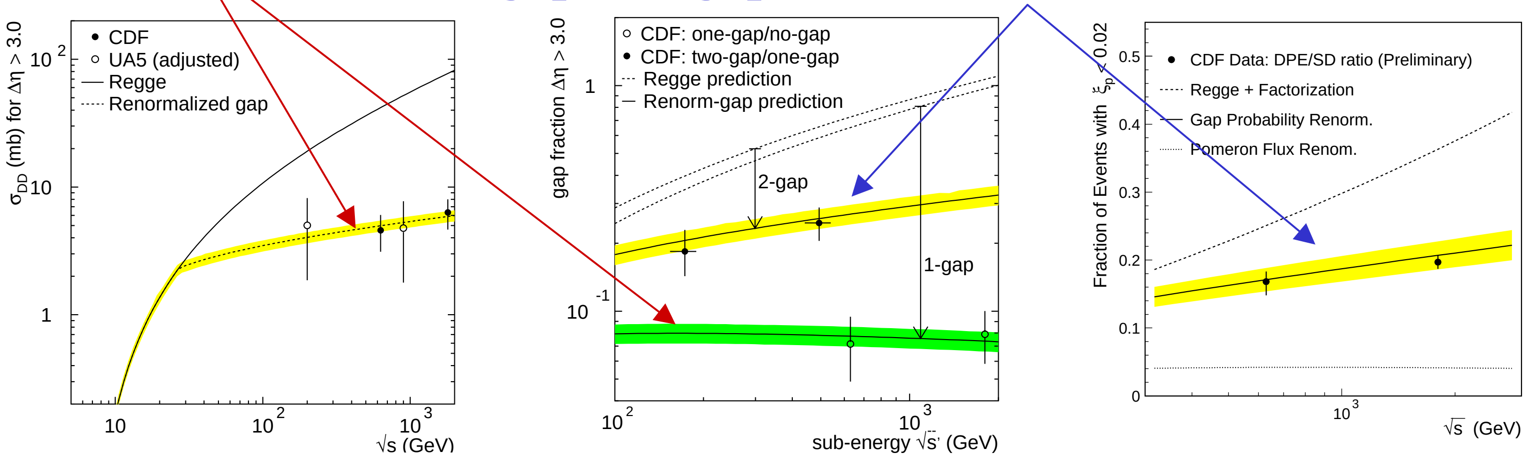
Renormalization removes the s-dependence → SCALING

Central and Double-Gap CDF Results

Differential shapes agree with Regge predictions



- **One-gap cross sections require renormalization**
  - **Two-gap/one-gap ratios are** $\approx \kappa = 0.17$



Soft Double Pomeron Exchange

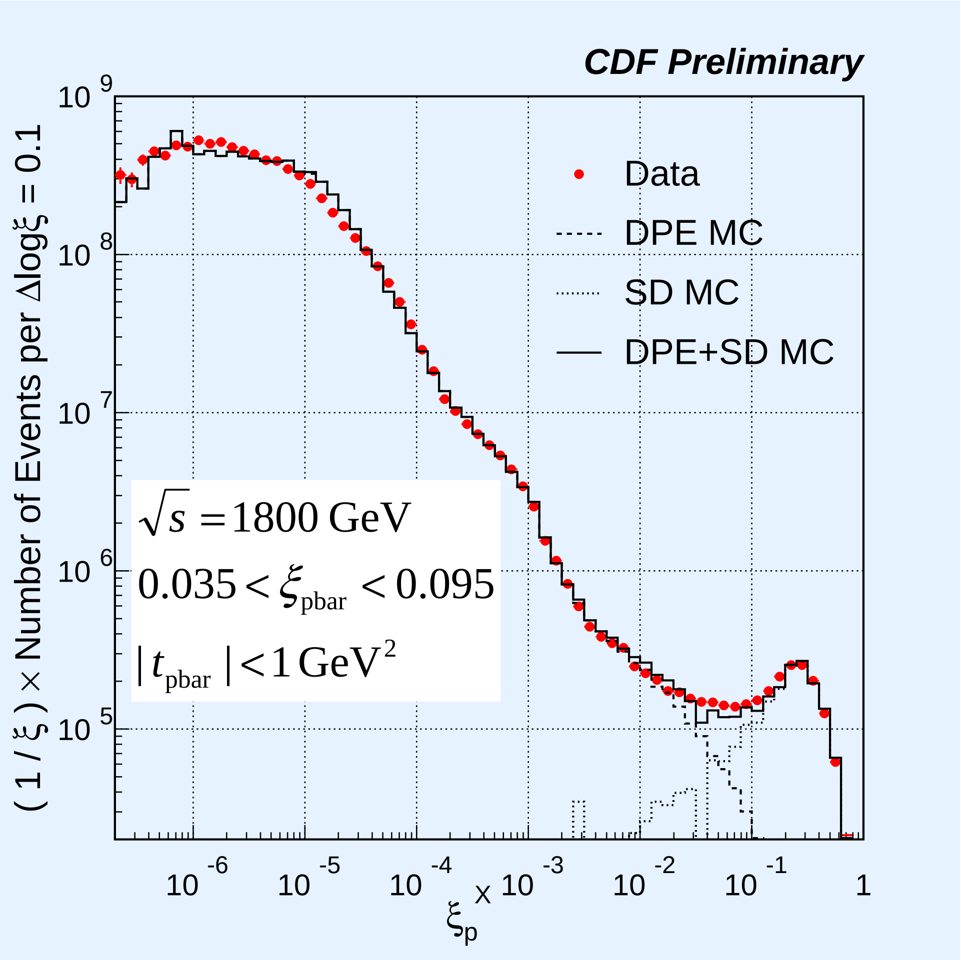
- Roman Pot triggered events
- $0.035 < \xi\text{-pbar} < 0.095$

  $|t\text{-pbar}| < 1\ \text{GeV}^2$
- ξ-proton measured using

$$\xi_p = \frac{1}{\sqrt{s}} \sum_{\text{all particles}} E_T^i \cdot e^{\eta_i}$$

- Data compared to MC based on Pomeron exchange with

➔ Pomeron intercept $\varepsilon=0.1$



- Good agreement over 4 orders of magnitude!

Soft Diffraction Summary

Multigap variables

Δy_i – rapidity gap regions

κ – color factor = 0.17

$\Delta y'_j$ – particle cluster regions

also:

t_i – t-across gap

$\eta^o_{i,j}$ – centers of floating gap/clusters

Parton model amplitude

$$f_{(\Delta y,t)} \propto e^{(\varepsilon+\alpha' t)\Delta y}$$

Differential cross section

$$\frac{d^{\text{var}}\sigma}{\prod_{i-\text{var}} dV_i} = C \times F_p^2(t_1) \prod_{\text{i-gaps}} \left\{ e^{(\varepsilon+\alpha' t_i)\Delta y_i} \right\}^2 \times \kappa^{\text{n}} \left\{ \sigma_o \, e^{\varepsilon \Sigma_j \Delta y'_j} \right\}$$

Normalized gap probability

Sub-energy cross section

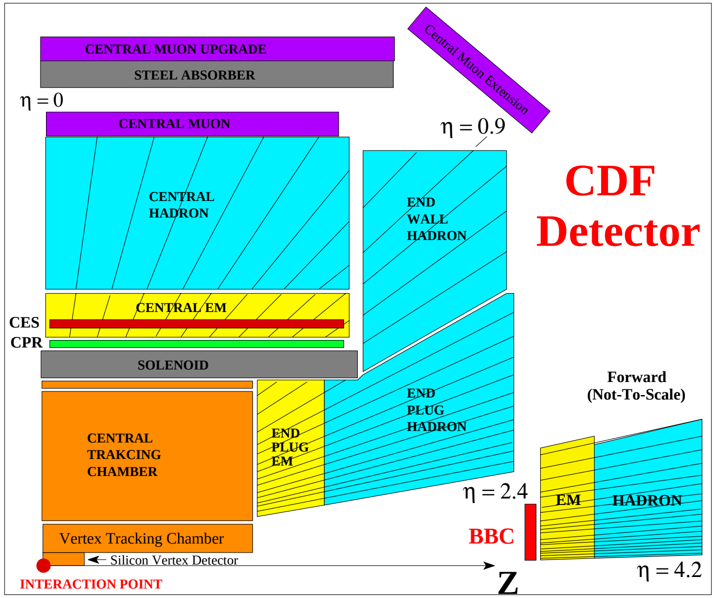
form factor for surviving nucleon

color factor: one κ for each gap

Hard diffraction at CDF in Run I

CDF Forward Detectors

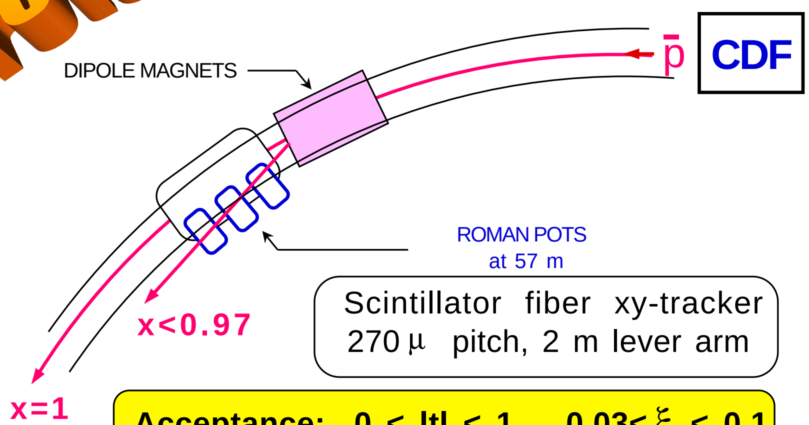
Rapidity gaps



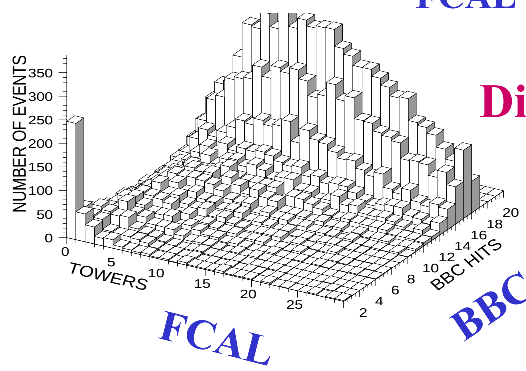
BBC $3.2<\eta<5.9$

FCAL $2.4<\eta<4.2$

Antiproton tag



Acceptance: $0 < |t| < 1$, $0.03 < \xi < 0.1$



Diffractive dijets

Hard Diffraction ^{w}/Rapgaps

❑ SINGLE DIFFRACTION

$$\bar{p}p \rightarrow X + \text{gap}$$

SD/ND gap fraction (%) at 1800 GeV

X	CDF	D0
W	1.15 (0.55)	
JJ	0.75 (0.10)	0.65 (0.04)
b	0.62 (0.25)	
J/ψ	1.45 (0.25)	

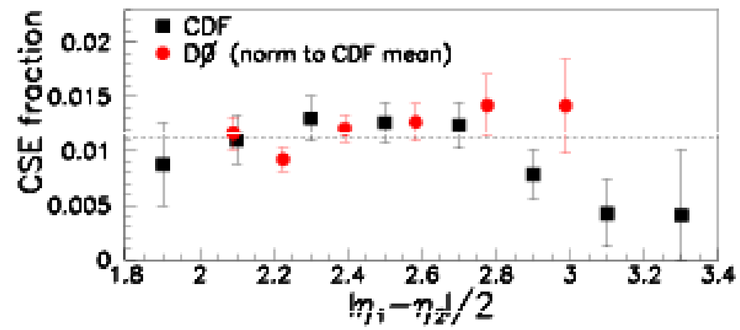
- **All SD/ND fractions ~1%**
- **Gluon fraction** $f_g = 0.54 \pm 0.15$
- **Suppression by ~5 relative to HERA**

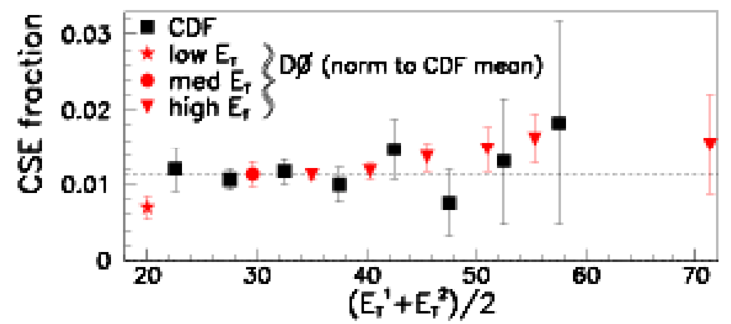
Just like in ND except for the suppression due to gap formation

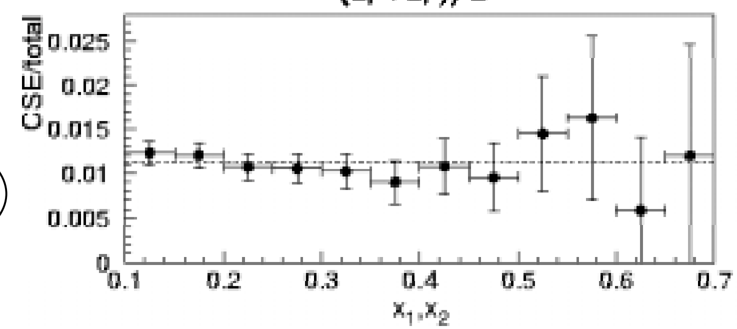
❑ DOUBLE DIFFRACTION

$$\bar{p}p \rightarrow Jet - \text{gap} - Jet$$

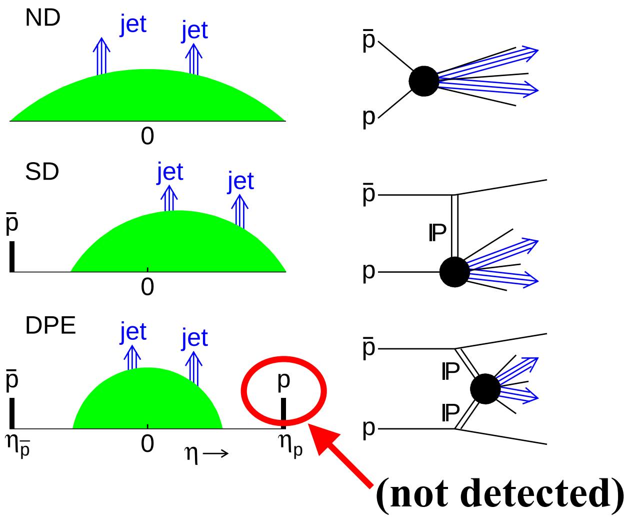
DD/ND gap fraction at 1800 GeV







Diffractive Dijets with Leading Antiproton



The diffractive structure function

$x_{Bj}^{\bar{p}}$ **Bjorken-x of antiproton**

$$x_{Bj}^{\bar{p}} = \frac{1}{\sqrt{s}} \sum_{\# jets} E_T^i \, e^{-\eta^i}$$

$F^{ND}(x, Q^2)$ **Nucleon structure function**

$F^{SD}(\xi, t, x, Q^2)$ **Diffractive structure function**

ISSUES: **1) QCD factorization** > $F^{SD}(\xi, t, x, Q^2)$ **is F^{SD} universal?**

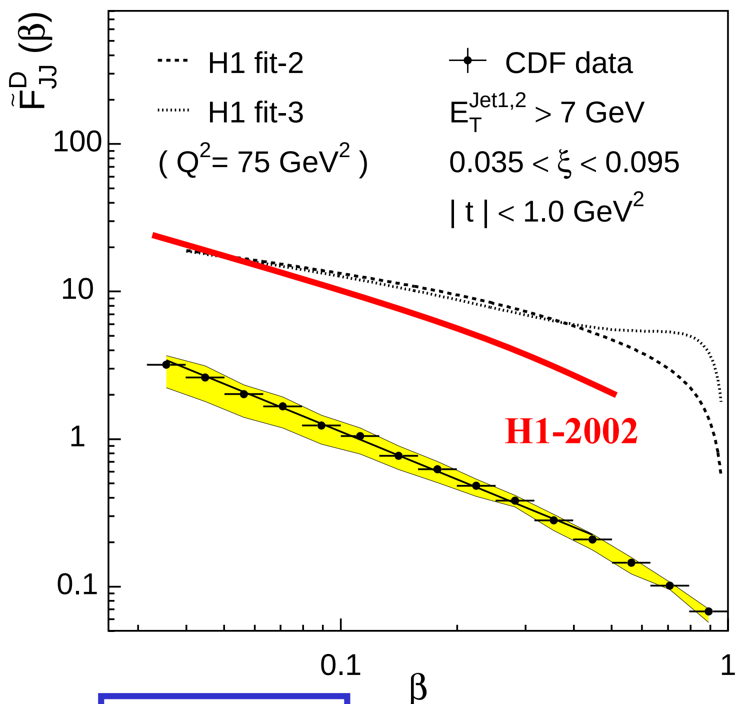
2) Regge factorization > $F^{SD}(\xi, t, \beta, Q^2) = f_{IP-\text{flux}}(\xi, t) \times f_{IP}(\beta, Q^2)$ **?**

$\beta \equiv x / \xi$ **momentum fraction of parton in *IP***

METHOD of measuring F^{SD} : measure ratio R(ξ,t) of SD/ND rates for given ξ,t
set $R(\xi,t)=F^{SD}/F^{ND}$
evaluate $F^{SD} = R * F^{ND}$

Dijets in Single Diffraction - Data

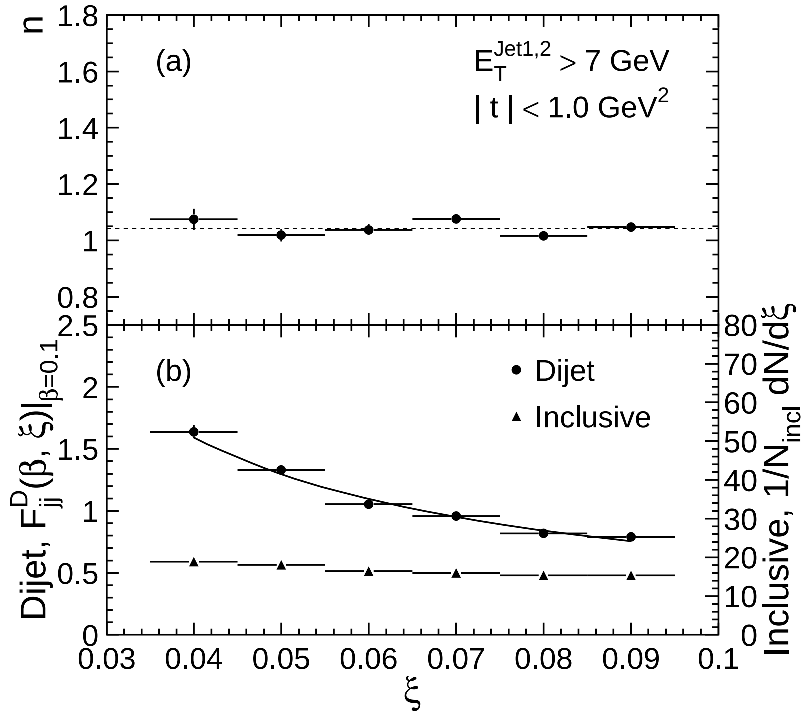
Test QCD factorization



$F^D_{JJ}(\beta)$

suppressed at the Tevatron relative to extrapolations from HERA parton densities

Test Regge factorization



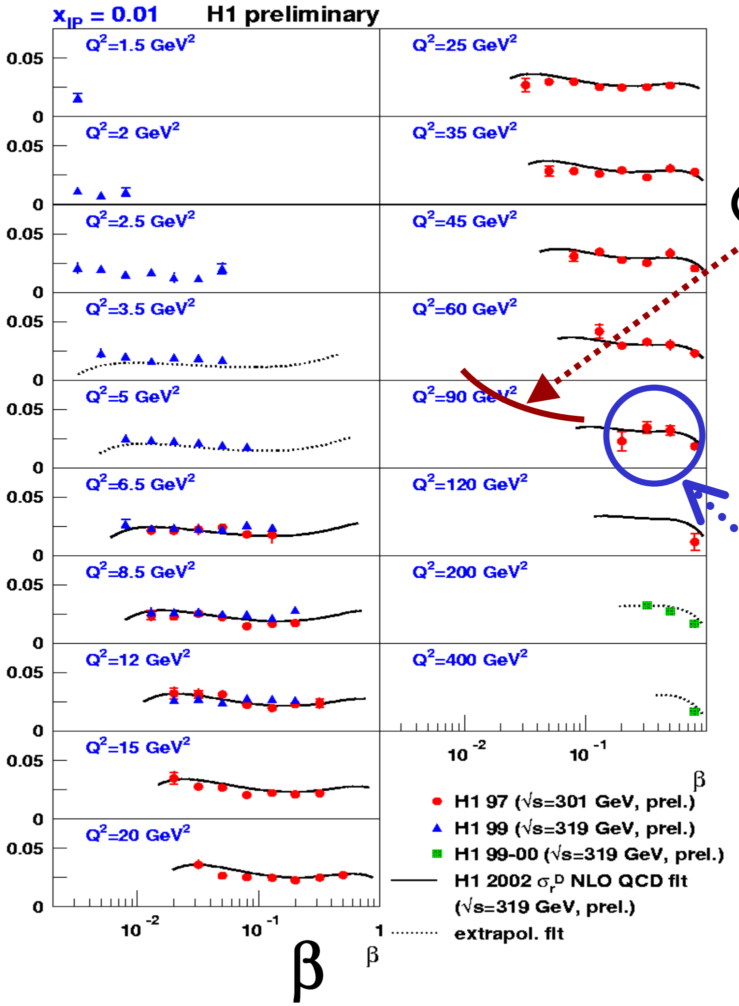
$$F^D_{JJ}(\xi, \beta) = C\ \beta^{-n}\ \xi^{-m}$$

Regge factorization holds

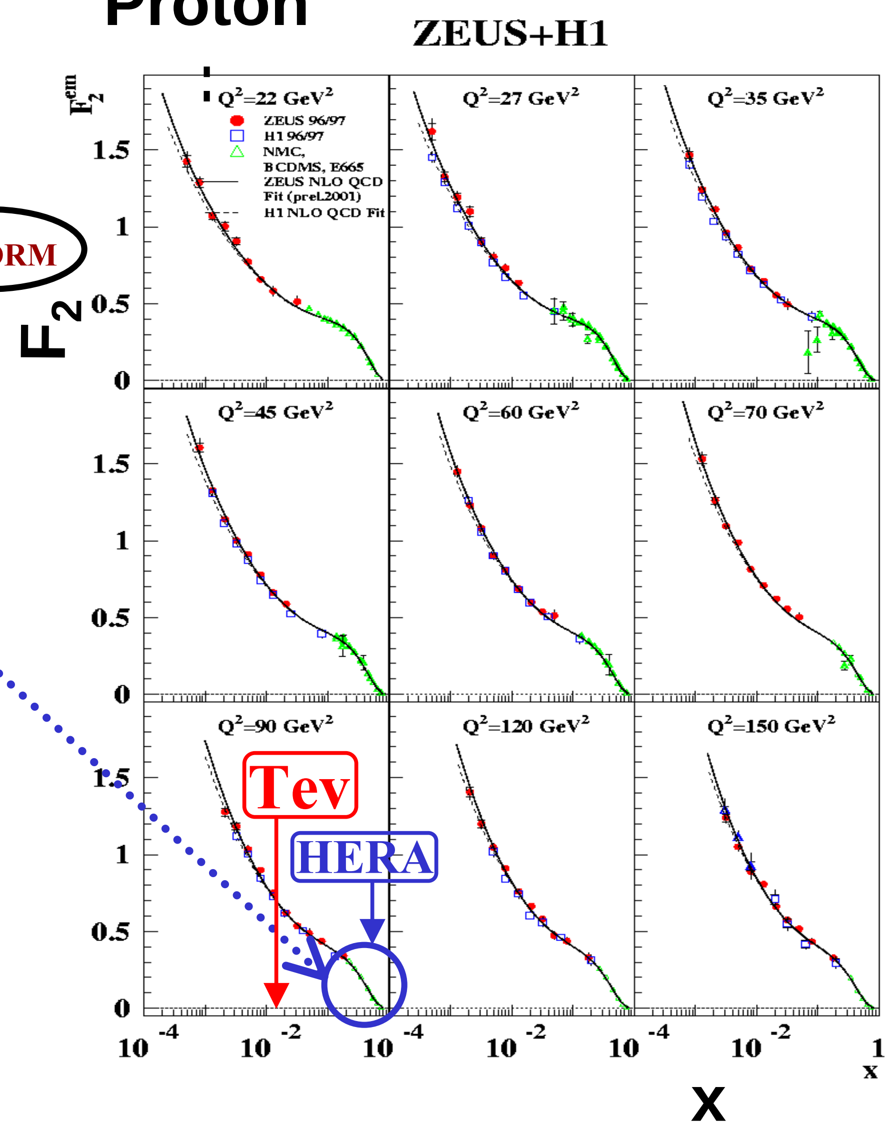
$m \approx 1 \Rightarrow$ Pomeron exchange

DDIS vs DIS at HERA

Pomeron:

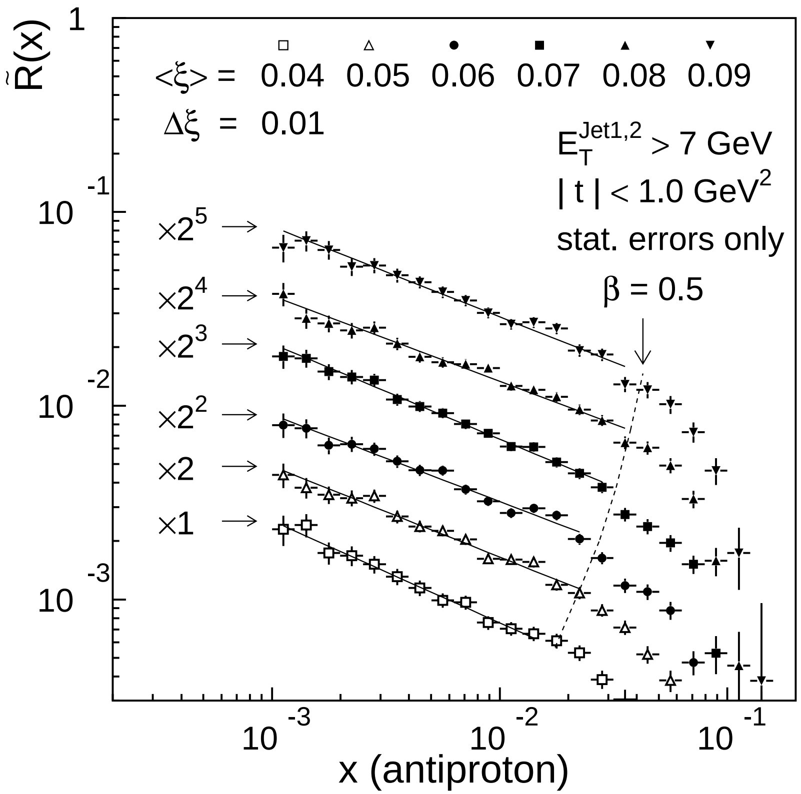


Proton



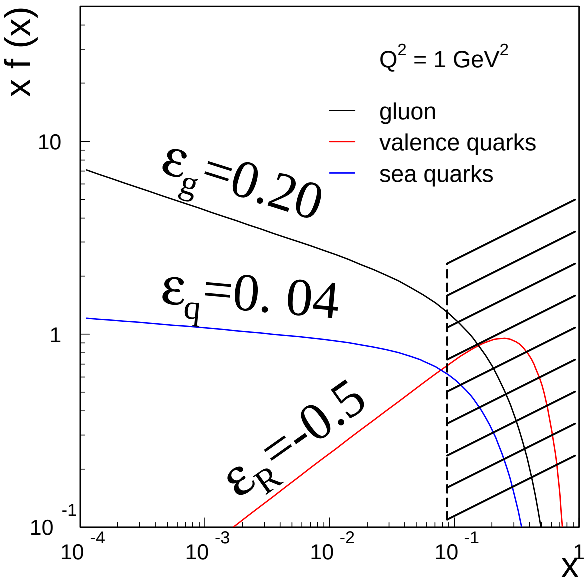
Dijets in Single Diffraction – R(x)

$$R(x) = \frac{F_{jj}^{SD}(x)}{F_{jj}^{ND}(x)}$$



$$R(x)\Big|_{0.035<\xi<0.095} = \frac{(6.1\times10^{-4})}{x^{0.45}}$$

R(x) predicted from pronton PDFs



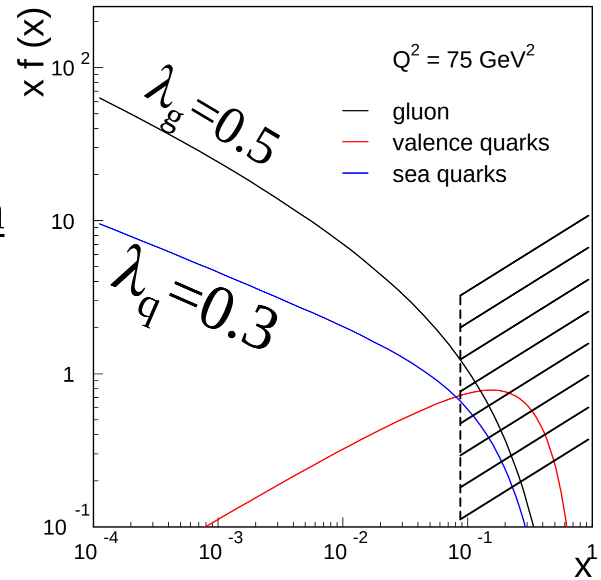
$$x \cdot f(x) = \frac{1}{x^{\varepsilon}}$$

Power-law region

$\xi_{max} = 0.1$

$x_{max} = 0.1$

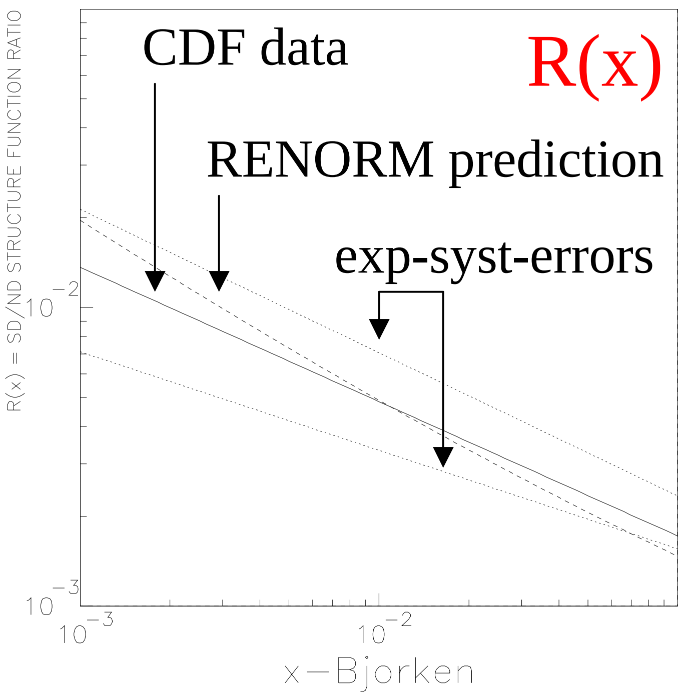
$\beta < 0.05\xi$



$$F^{D}(Q^2, x, \xi) \propto \frac{1}{\xi^{1+\varepsilon}} \cdot F^{ND}(Q^2, x) \sim \frac{1}{\xi^{1+\varepsilon}} \cdot \frac{C(Q^2)}{(\beta\xi)^{\lambda(Q^2)}} \Rightarrow \frac{A_{\text{NORM}}}{\xi^{1+\varepsilon+\lambda}} \cdot \kappa \cdot \frac{C}{\beta^{\lambda}}$$

$$A = 1 / \int_{\xi-\min}^{\xi=0.1} \frac{d\xi}{\xi^{1+\varepsilon+\lambda}} = (\varepsilon+\lambda)\left(\frac{M_{jj}^{2}}{\beta\, x_{\max}\, s}\right)^{\varepsilon+\lambda} \Rightarrow R_{jj} = \frac{A}{\xi^{1-\lambda}} \cdot \frac{1}{x^{\varepsilon+\lambda}}$$

RENORM prediction of R(x) vs data



- Ratio of diffractive to non-diffractive structure functions is predicted from PDF's and color factors with no free parameters.

→$F_{jj}(\beta,\xi)$ correctly predicted

→Test: processes sensitive to quarks will have more flat R(x) – diff W?

$$R(x)\Big|_{0.035<\xi<0.095}^{\text{DATA}} = \frac{(6.1\times10^{-4})}{x^{0.45}}$$

$$R(x)\Big|_{0.035<\xi<0.095}^{\text{RENORM}} \approx \frac{(4.0\times10^{-4})}{x^{0.55}}$$

HERA vs Tevatron

$$F^D(Q^2,\beta,\xi) \xrightarrow{\text{TEVATRON}} (\varepsilon+\lambda)\left(\frac{M_{jj}^2}{\beta\, x_{\max}\, s}\right)^{\varepsilon+\lambda} \underbrace{\frac{1}{\xi^{1+\varepsilon+\lambda}}\cdot\kappa}_{\text{normalized gap probability}}\cdot\frac{C}{\beta^\lambda}$$

normalized gap probability

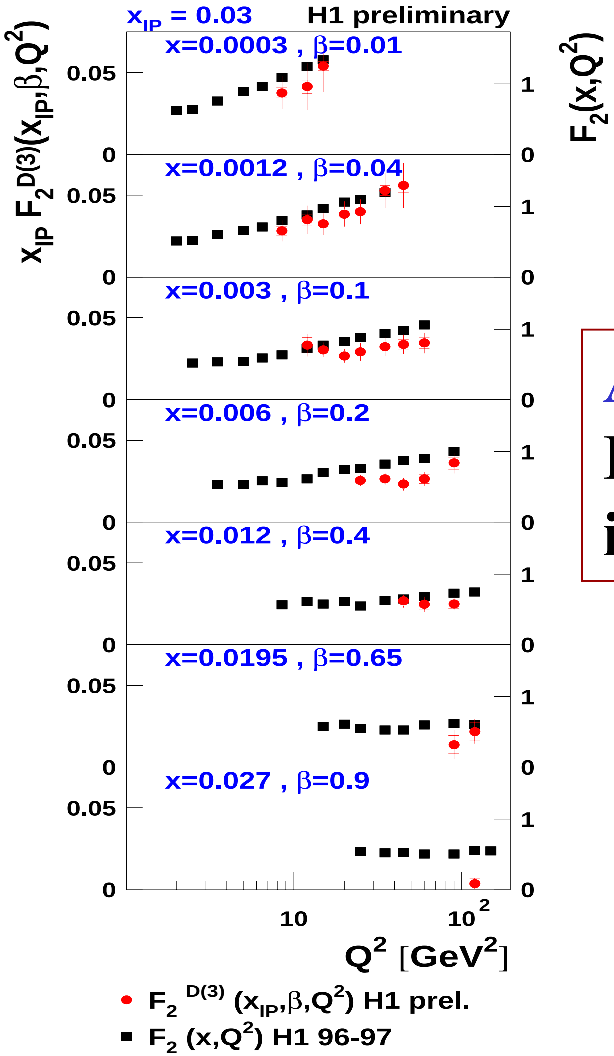
$$F^D(Q^2,\beta,\xi) \xrightarrow{\text{HERA}} 0.76\times\underbrace{\frac{1}{\xi^{1+\varepsilon+\lambda}}}_{\text{Pomeron flux}}\cdot\kappa\cdot\frac{C}{\beta^\lambda}$$

Pomeron flux

RENORM PREDICTIONS

	HERA	Tevatron	Tev/HERA
$(\varepsilon+\lambda)$_effective	--	0.55	--
Normalization	0.76	0.042	0.06
$R(x)=F^D(x)/F(x)$	flat	$x^{-(\varepsilon+\lambda)\_eff}$	$\simeq x^{-0.5}$
ε_eff = $[\varepsilon+\lambda(Q^2)]/2$	~ 0.2	--	--

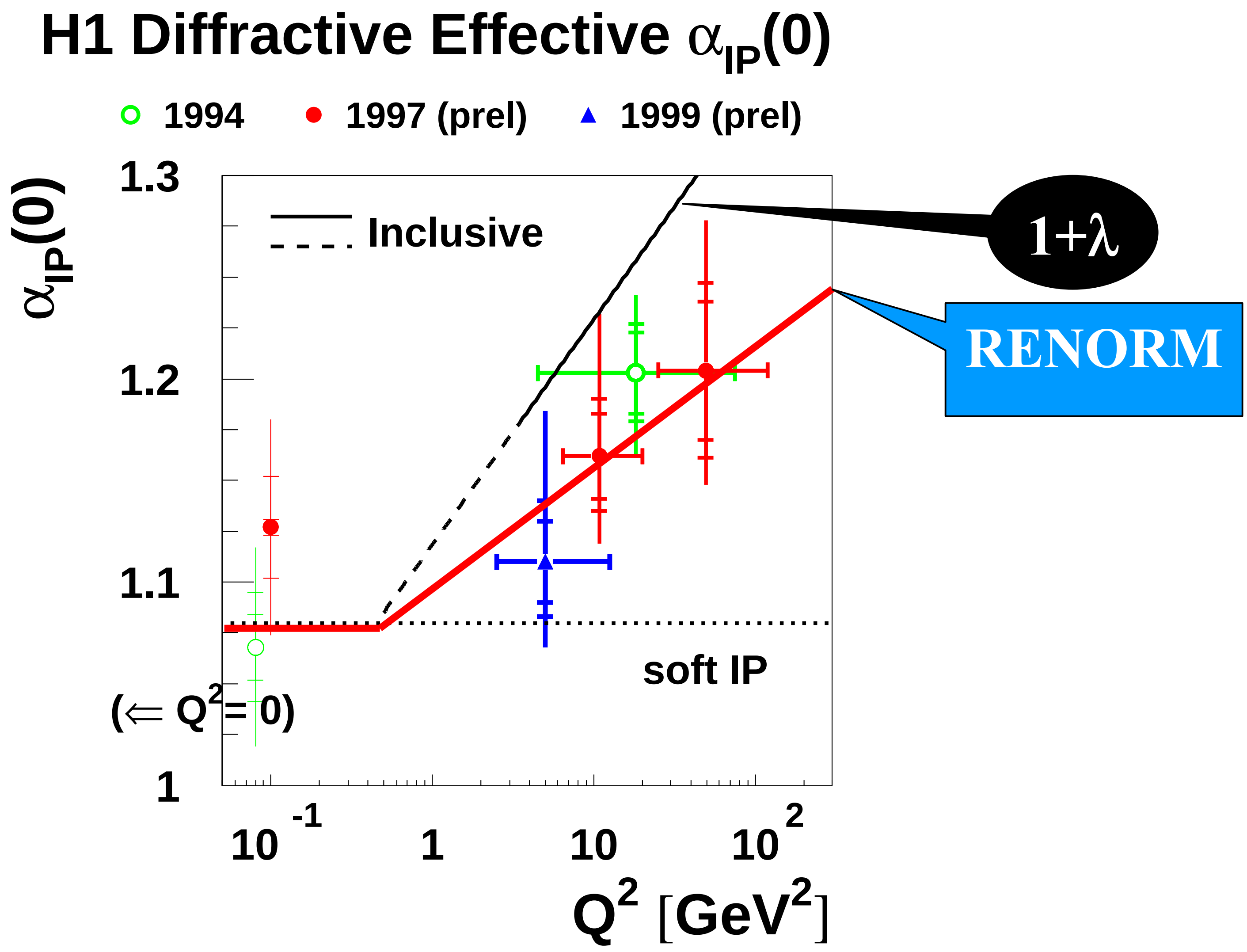
$F_2^D(x,Q^2)$ vs $F_2(x,Q^2)$ at HERA



At fixed x_{IP}:

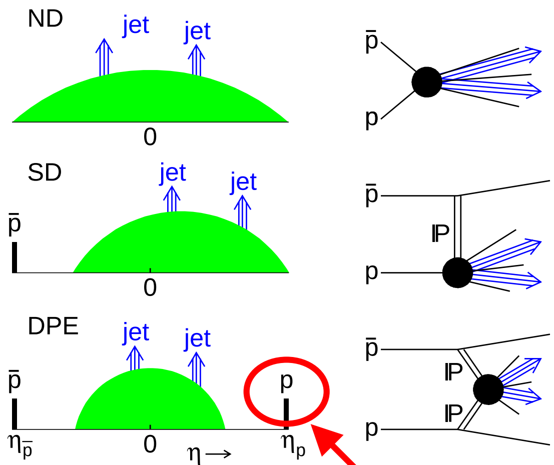
$F_2^D(x,Q^2)$ evolves like $F_2(x,Q^2)$ independent of the value of x

Pomeron Intercept in DDIS



Dijets in Double Pomeron Exchange

Test of factorization

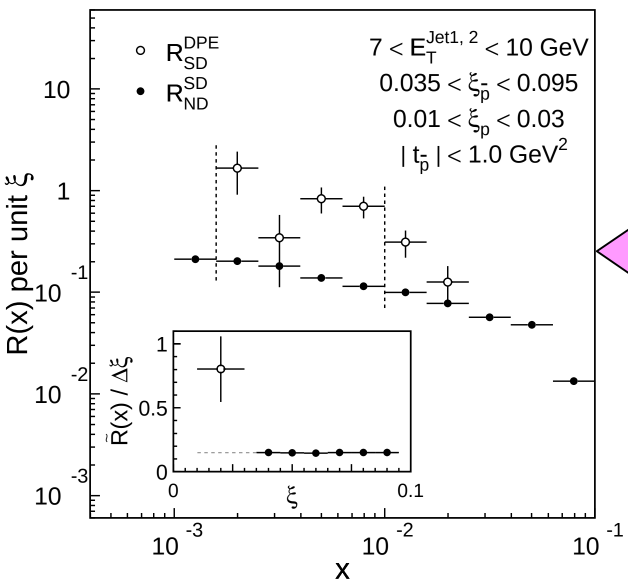


R(SD/ND)

R(DPE/SD)

equal?

(not detected)



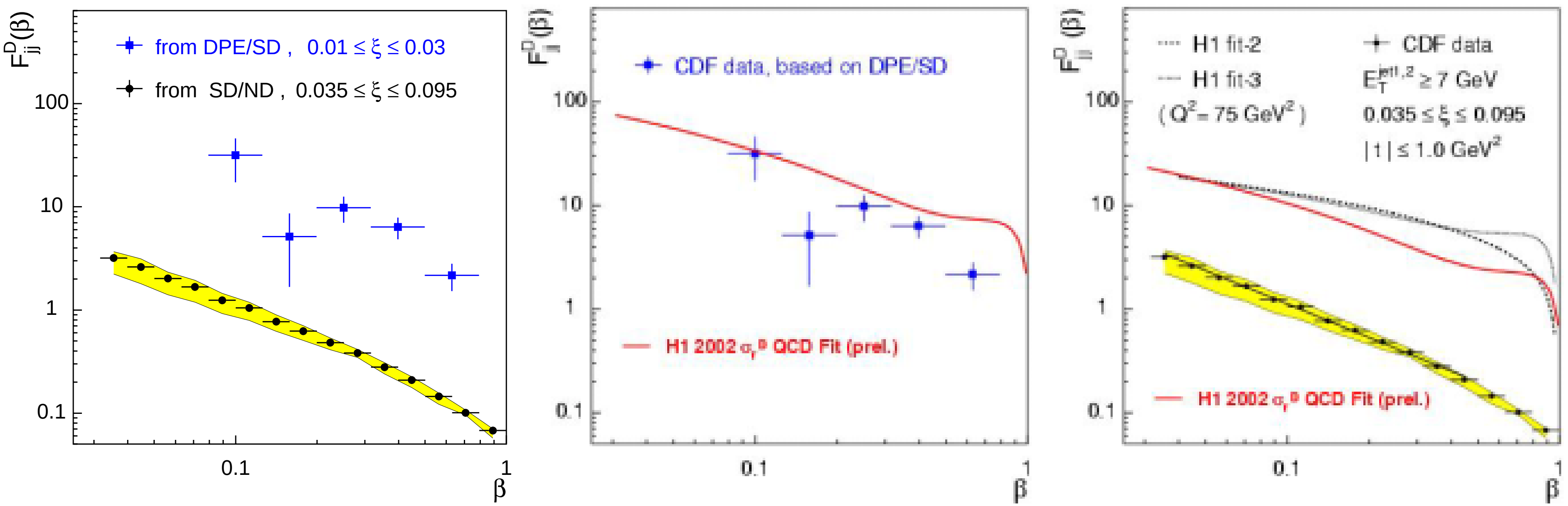
$$R^{DPE}_{SD} \approx 5\times R^{SD}_{ND}$$

The second gap is less suppressed!!!

Factorization breaks down, **but…**

see next slide(Hatakeyama's talk)

DSF: Tevatron double-gaps vs HERA



The diffractive structure function derived from double-gap events approximately agrees with expectations from HERA

SUMMARY

Soft and hard conclusions

Soft Diffraction

Hard Diffraction

Use reduced energy cross section

☞ Pay a color factor **κ** for each gap

Get gap size from renormalized P_{gap}

Diffraction is an interaction between low-x partons subject to color constraints