Diffraction from HERA and Tevatron to LHC

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Workshop on physics with forward proton taggers
at the Tevatron and LHC
14-16 December 2003, Manchester, UK

- **results**
- **theory**
- **predictions**

Topics

Soft diffraction

- Elastic and total cross sections
- M^2-scaling
- Soft diffraction cross sections
- Multigap diffraction

Determine:
- triple-pomeron coupling
- pomeron intercept
- diffractive cross section

using soft parton densities

Diffractive DIS at HERA

- Derive F2D3
- Explain flat ratio of F2D3 / F2
- Explain rise of ε (or α_{IP}) with Q^2

Predict from hard plus soft parton densities

Hard diffraction at the Tevatron

- Explain ratio of $F_{jj}(SD)$ / $F_{jj}(ND)$ – magnitude and shape!
- Double-gap hard diffraction

Diffraction at the LHC

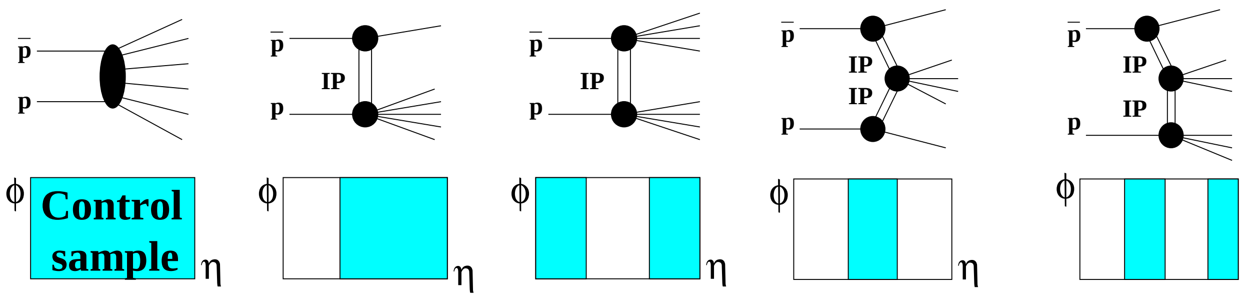
- Soft and hard single and multigap diffraction

Diffraction at CDF in Run I

16 papers

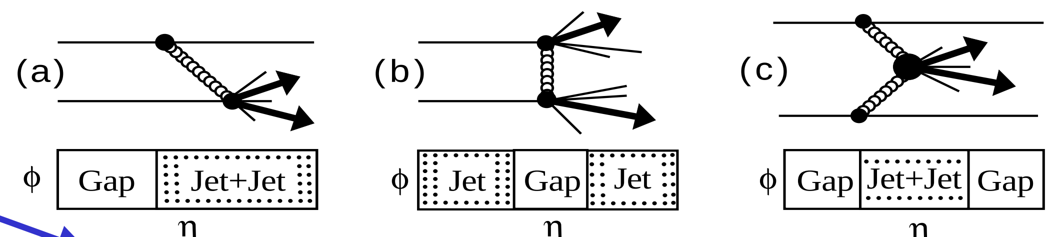
- Elastic scattering **PRD 50 (1994) 5518**
- Total cross section **PRD 50 (1994) 5550**
- Diffraction

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 submitted	PRL 91(2003)011802

HARD diffraction



PRL reference

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		

with roman pots

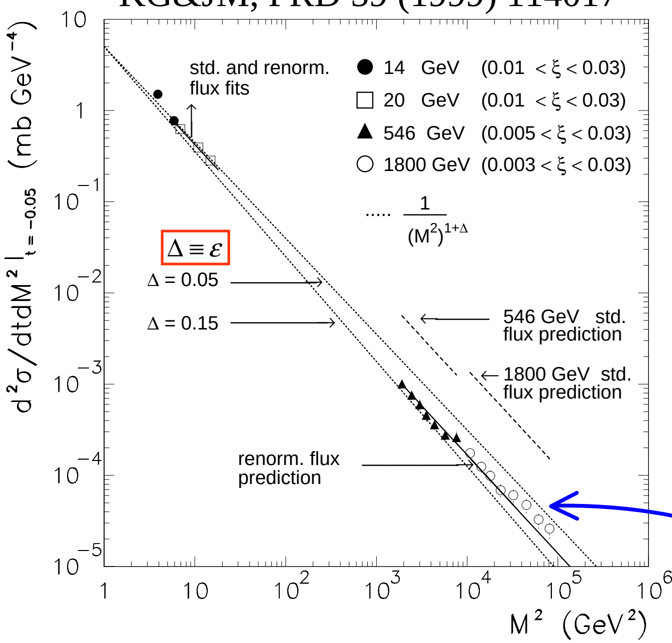
JJ	84 (2000) 5043
JJ	88 (2002) 151802

Two (most) important results

Soft Diffraction

M²SCALING

KG&JM, PRD 59 (1999) 114017

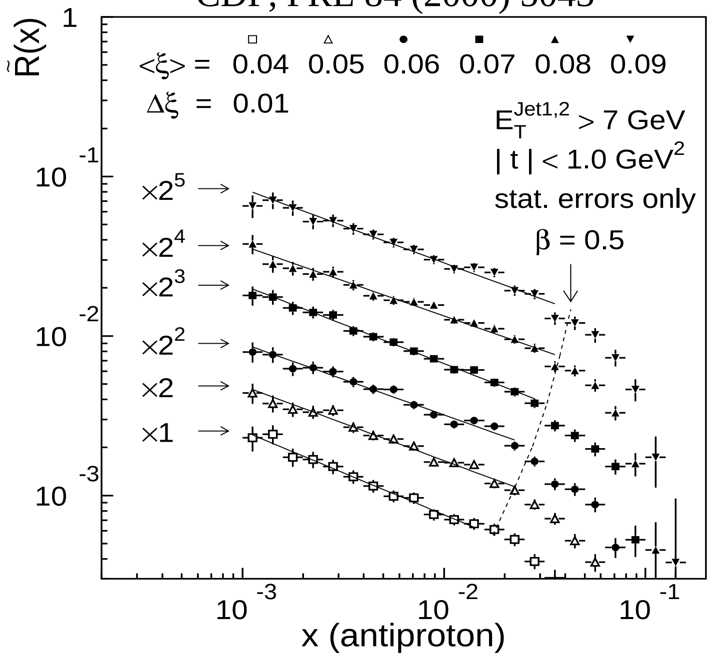


$$\frac{d\sigma}{dM^2} \propto \frac{1}{(M^2)^{1+\varepsilon}}$$

Hard Diffraction

POWER LAW

CDF, PRL 84 (2000) 5043



$$R_{jj}(x) = \frac{F_{jj}^{SD}(x)}{F_{jj}^{ND}(x)} \propto x^{-0.45}$$

Soft Double Pomeron Exchange

- Roman Pot triggered events
- 0.035 < ξ-pbar < 0.095

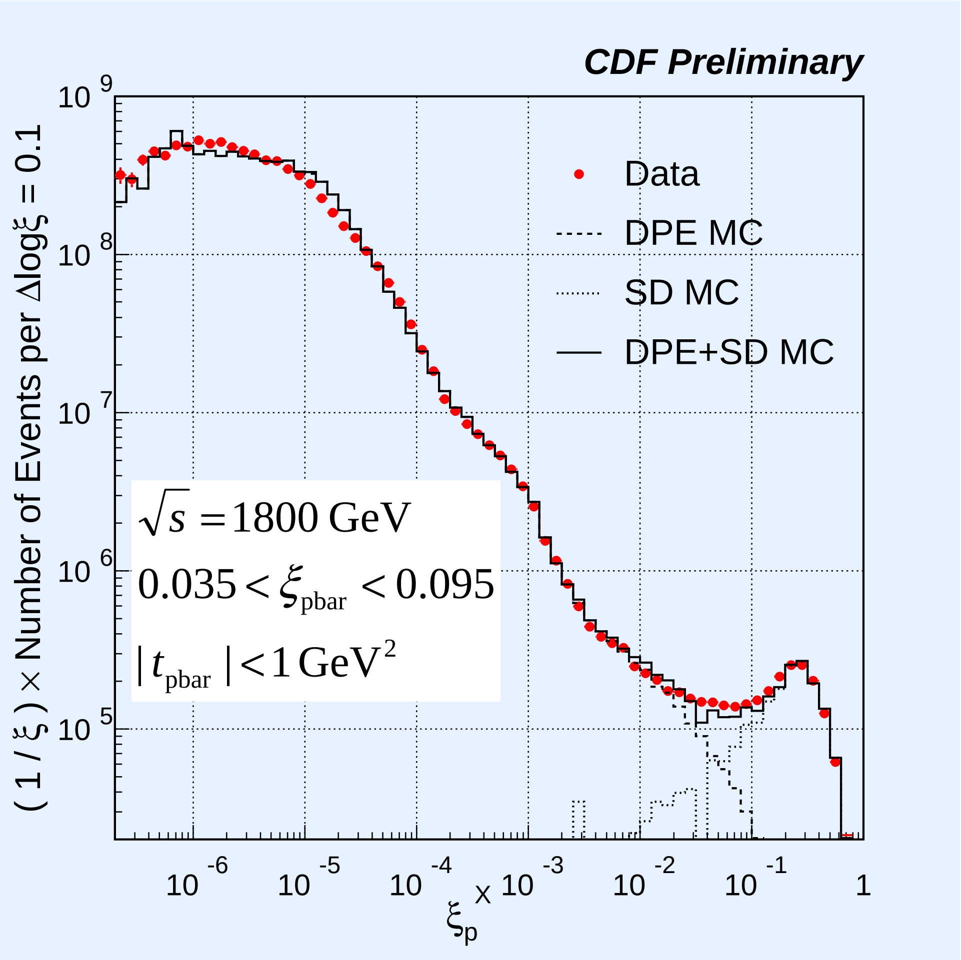
  |t-pbar| < 1 GeV ^{2}
- ξ-proton measured using

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

- Data compared to MC based

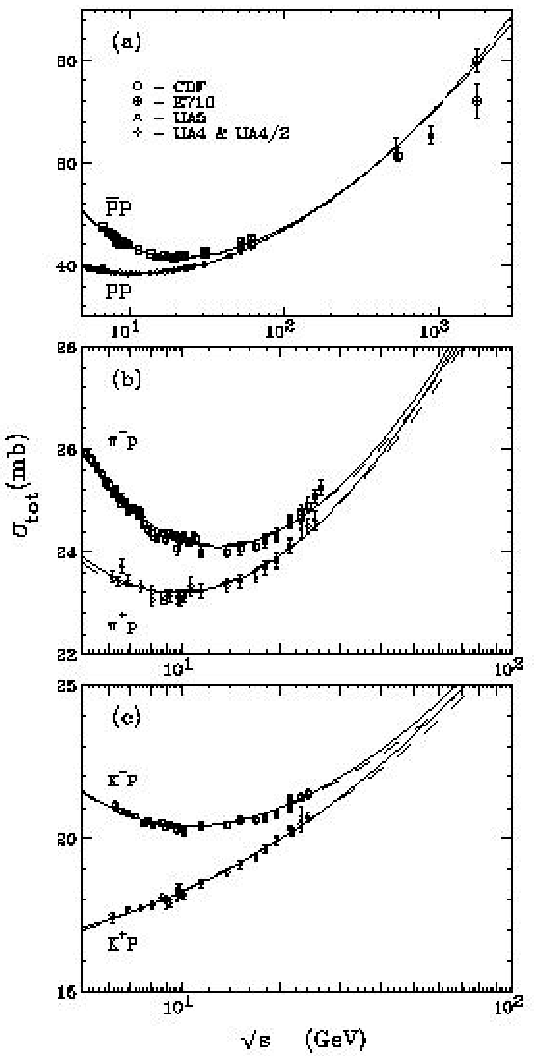
  on Pomeron exchange with

➔ Pomeron intercept ε=0.1



- Good agreement over 4 orders of magnitude!

Total Cross Section



- σ_t exhibits universal rise with energy
- the falling term at low energies has NOTHING to do with this rise!
- POWER LAW behavior:

$$\sigma_t = \beta^2_{IP-p}(0) \cdot s^{\varepsilon} = \sigma_o \, e^{\varepsilon \ln s} = \sigma_o \, e^{\varepsilon \, \Delta y'}$$

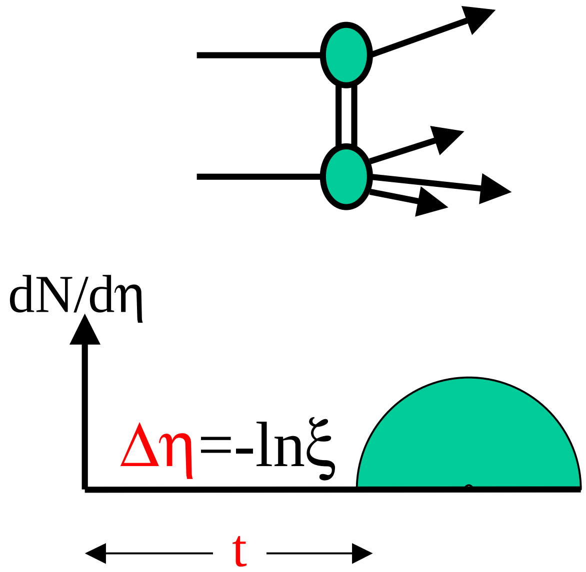
t=0 elastic scattering amplitude

Parton model: # of wee partons grows exponentially

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

Single Diffraction Variables

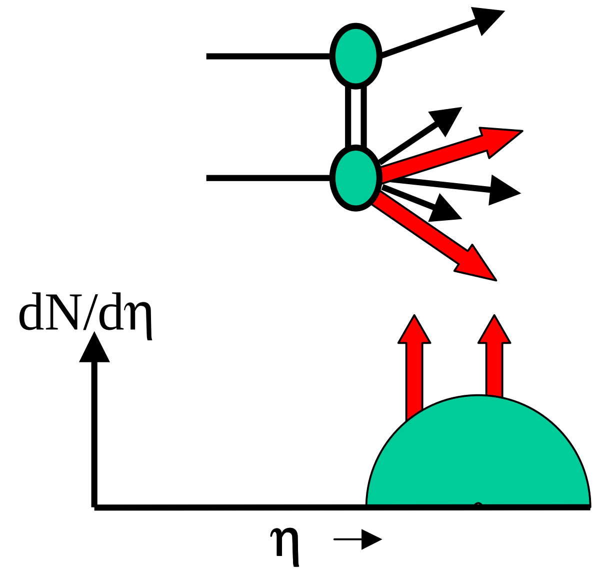
- SOFT DIFFRACTION



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

Variables: (ξ, t) or (Δη, t)

- HARD DIFFRACTION



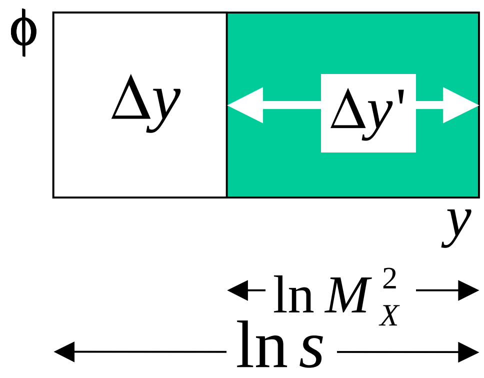
Additional variables: (***x***, Q^2)

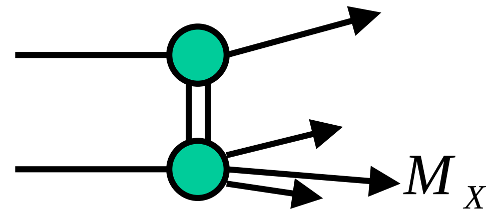
$$x_{Bj} = \sum E_T^{jet} e^{-\eta^{jet}} / \sqrt{s}$$

$$x = \beta\, \xi \leq \xi$$

Soft Single Diffraction Phenomenology

Factorization & (re)normalization





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

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

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

Gap probability:
Normalize to unity
KG, PLB 358 (1995) 379

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

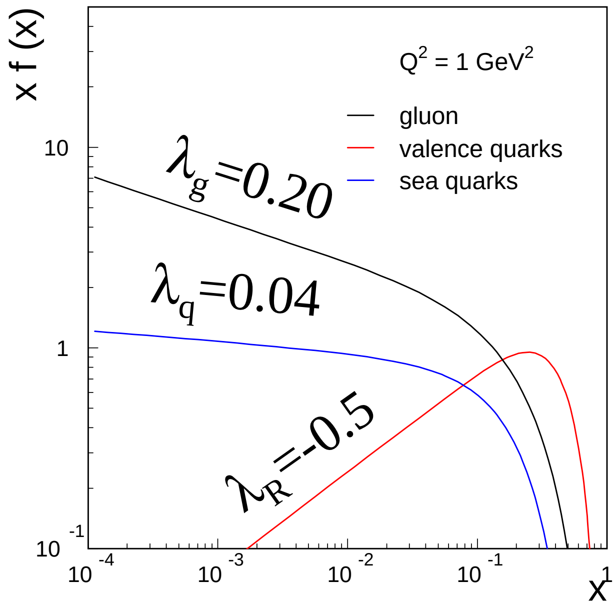
COLOR FACTOR

The factors κ and ε

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

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

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



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

Soft Single Diffraction Data

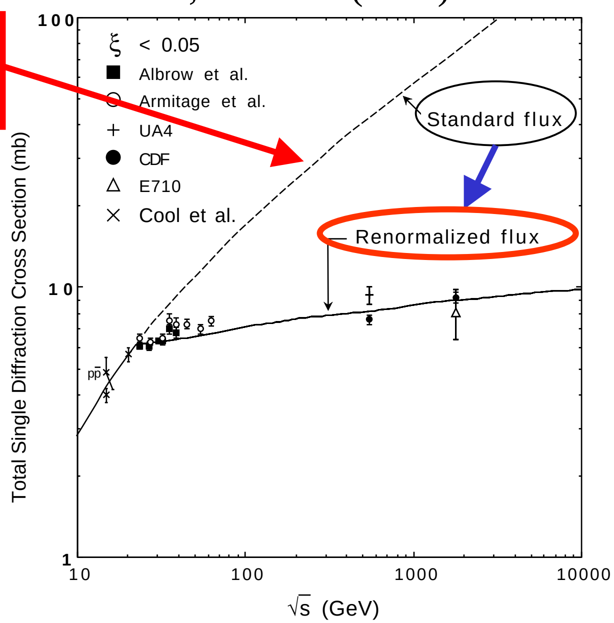
$$p(\bar{p}) + p \rightarrow p(\bar{p}) + X$$

Regge

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

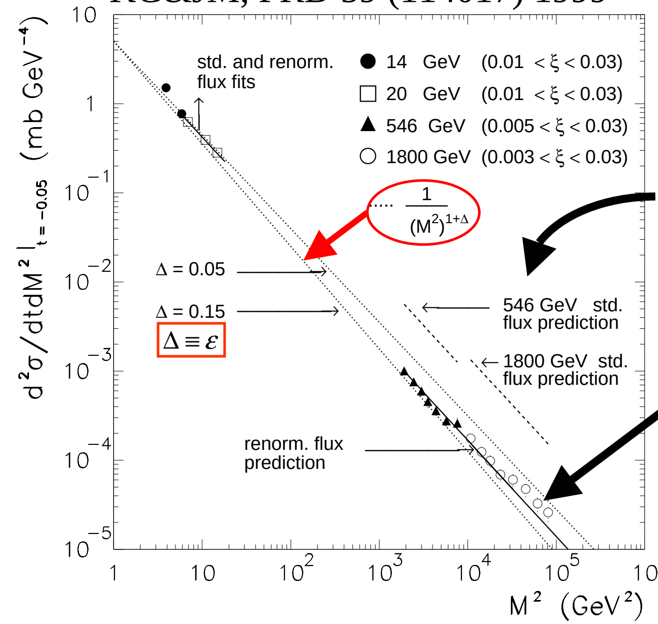
Total cross section

KG, PLB 358 (1995) 379



Differential cross section

KG&JM, PRD 59 (114017) 1999



REGGE

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

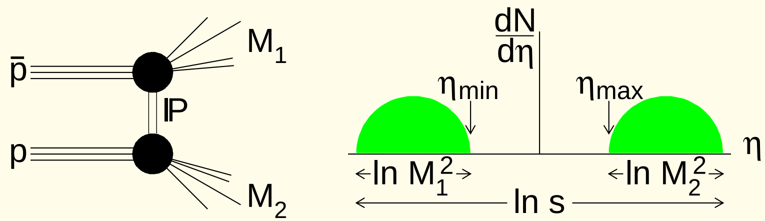
RENORM

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

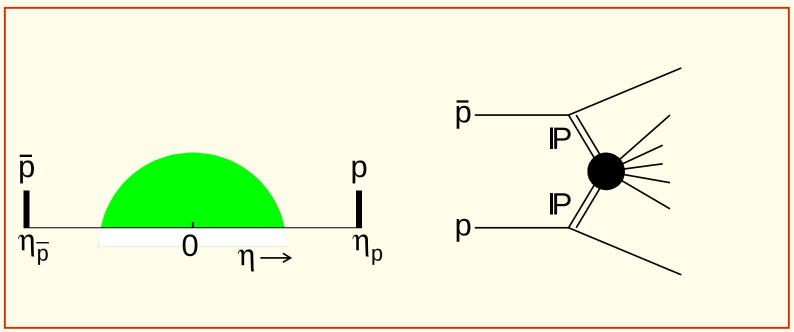
s-independent

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

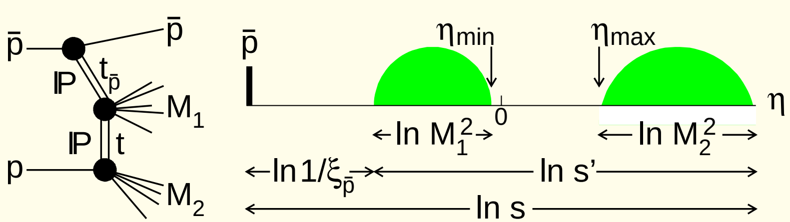
Central and Double Gaps



- **Double Diffraction Dissociation**
  - **One central gap**

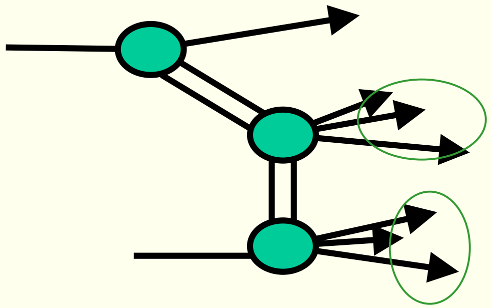


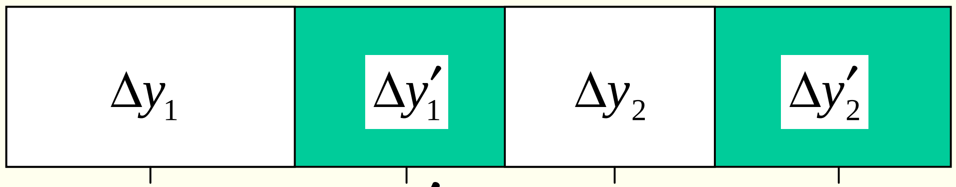
- **Double Pomeron Exchange**
  - **Two forward gaps**



- **SDD: Single+Double Diffraction**
  - **Forward + central gaps**

Two-Gap Diffraction (hep-ph/0205141)





y'_1 y_2

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

color factor

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

Gap probability

Sub-energy cross section (for regions with particles)

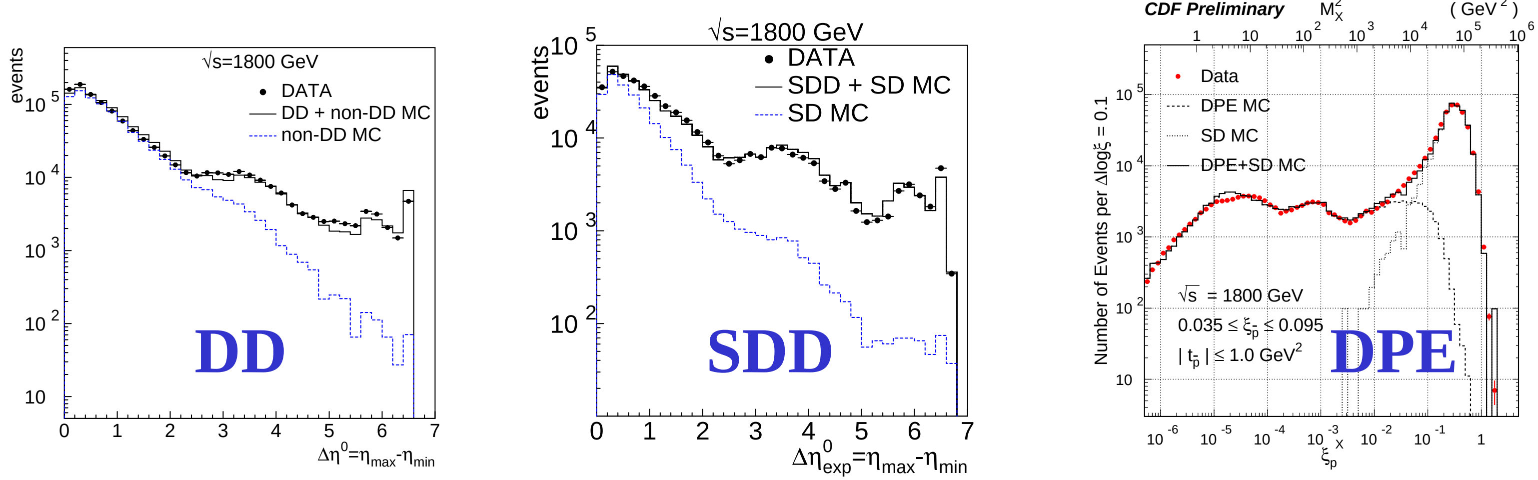
Integral $\sim s^{2\varepsilon}$

$\leftarrow \sim e^{2\varepsilon \Delta y}$

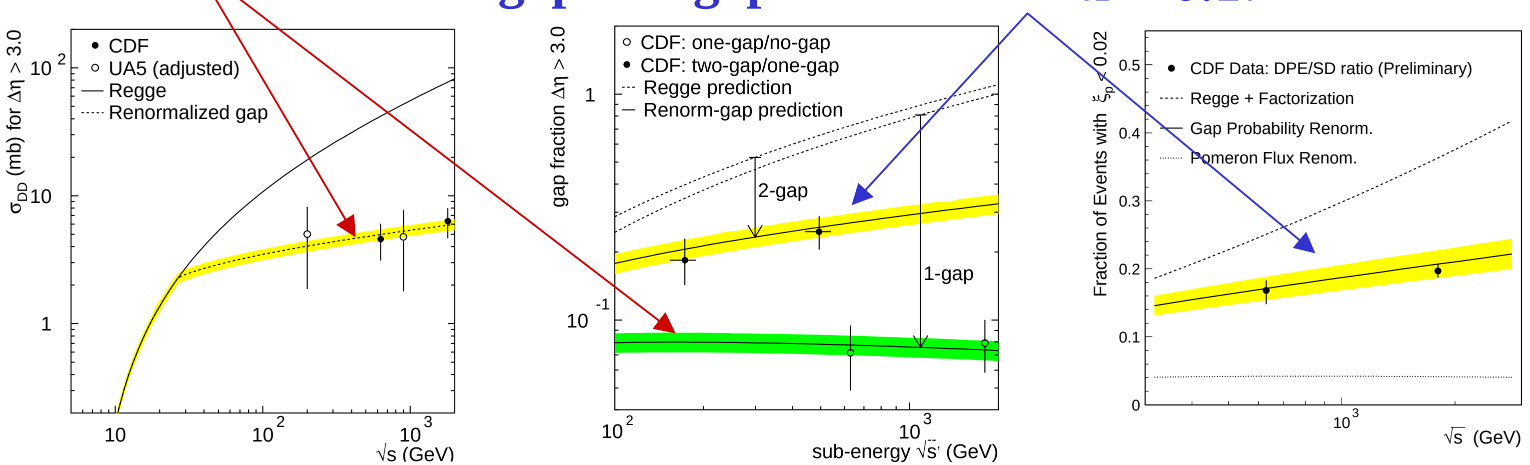
Renormalization removes the s-dependence → SCALING

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 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

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

Normalized gap probability

Sub-energy cross section

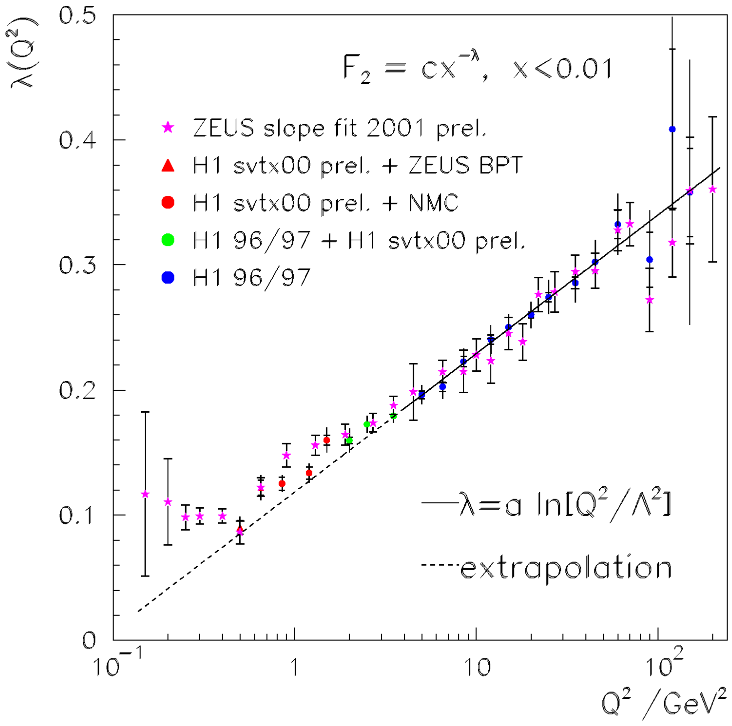
form factor for surviving nucleon

color factor: one κ for each gap

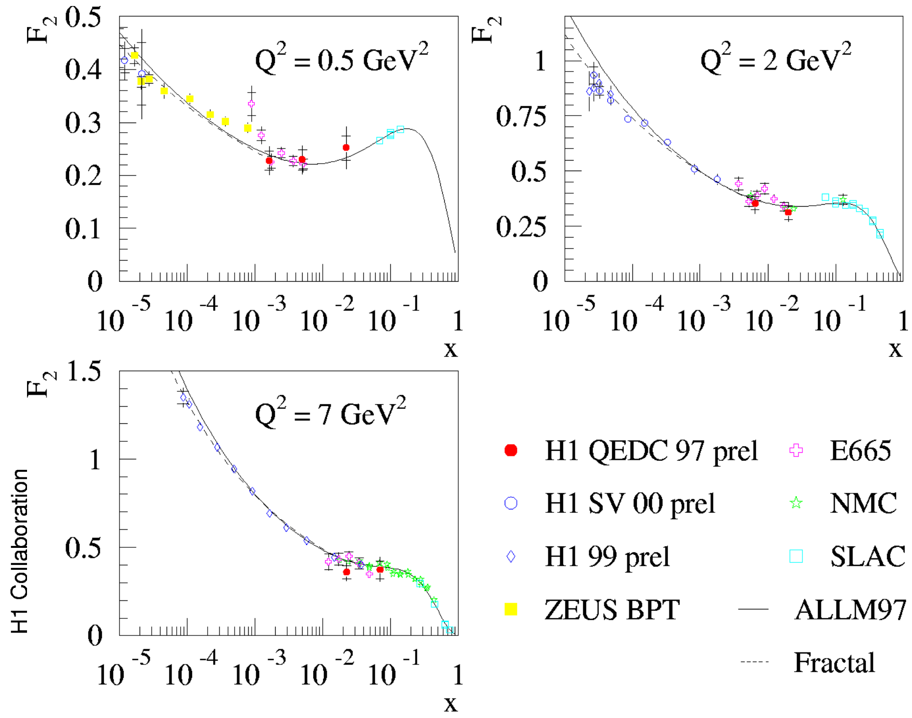
enter $F_2(x,Q^2) = c\, x^{-\lambda}$ HERA

[from the talk of E. Tassi @ Small-x and Diffraction 2003, Fermilab]

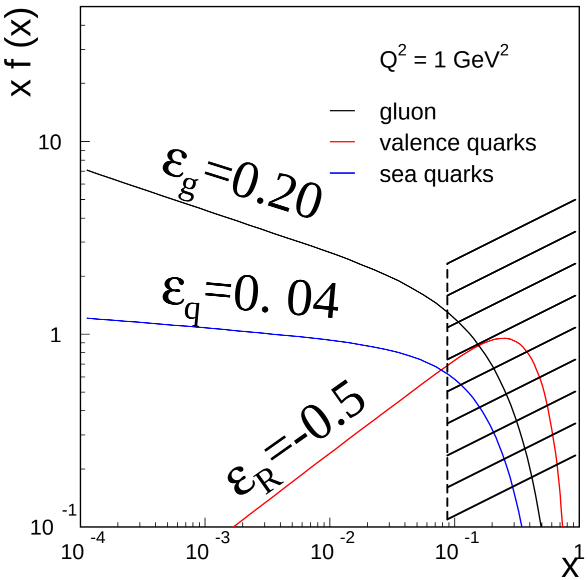
$\lambda(Q^2)$ versus Q^2



F_2 from Compton analysis (H1)



Diffractive DIS @ HERA



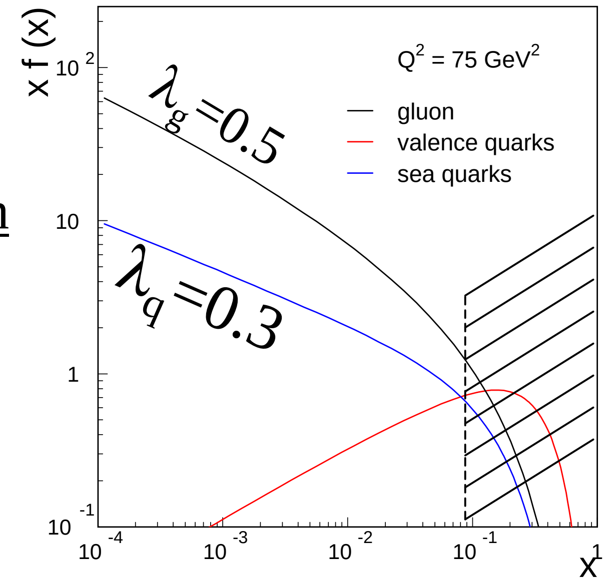
$$x \cdot f(x) = \frac{1}{x^{\varepsilon}}$$

Power-law region

$$\xi_{max} = 0.1$$

$$x_{max} = 0.1$$

$$\beta < 0.05\xi$$

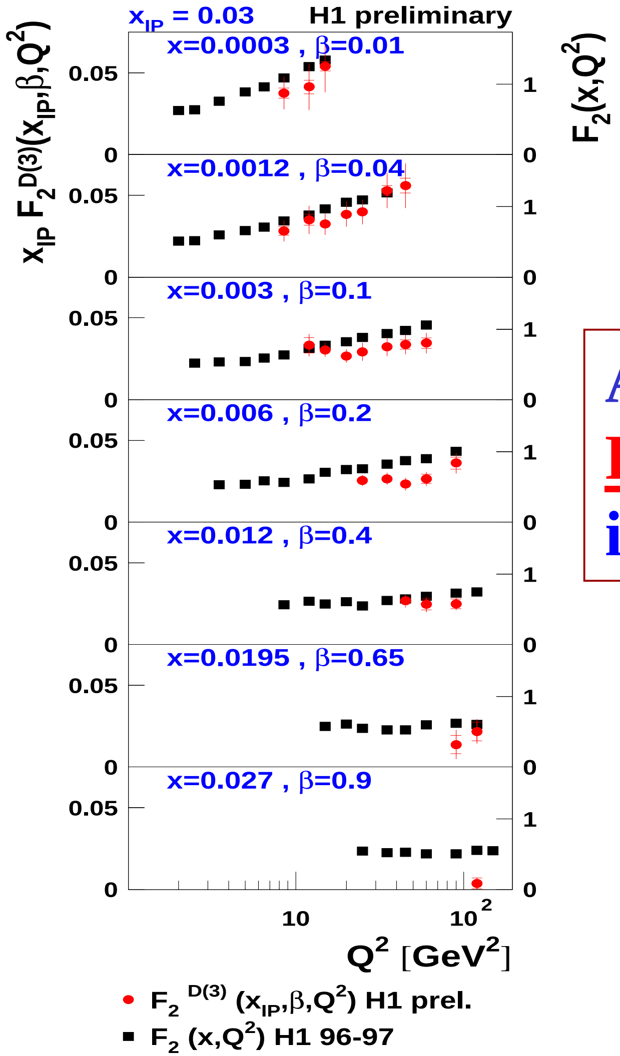


$$F_2^{D3}(Q^2, x, \xi) \propto \frac{1}{\xi^{1+\varepsilon}} \cdot F_2(Q^2, x) \propto \frac{1}{\xi^{1+\varepsilon}} \cdot \frac{C(Q^2)}{(\beta\xi)^{\lambda(Q^2)}} \Rightarrow \frac{A}{\xi^{1+\varepsilon+\lambda}} \cdot \kappa \cdot \frac{C}{\beta^{\lambda}}$$

$$R_{ND}^{SD} \equiv \frac{F_2^{D3}(Q^2, x, \xi)}{F_2(Q^2, x)} = \frac{A}{\xi^{1+\varepsilon}} \cdot \kappa \xrightarrow{\text{fixed}\,\xi} \text{constant}$$

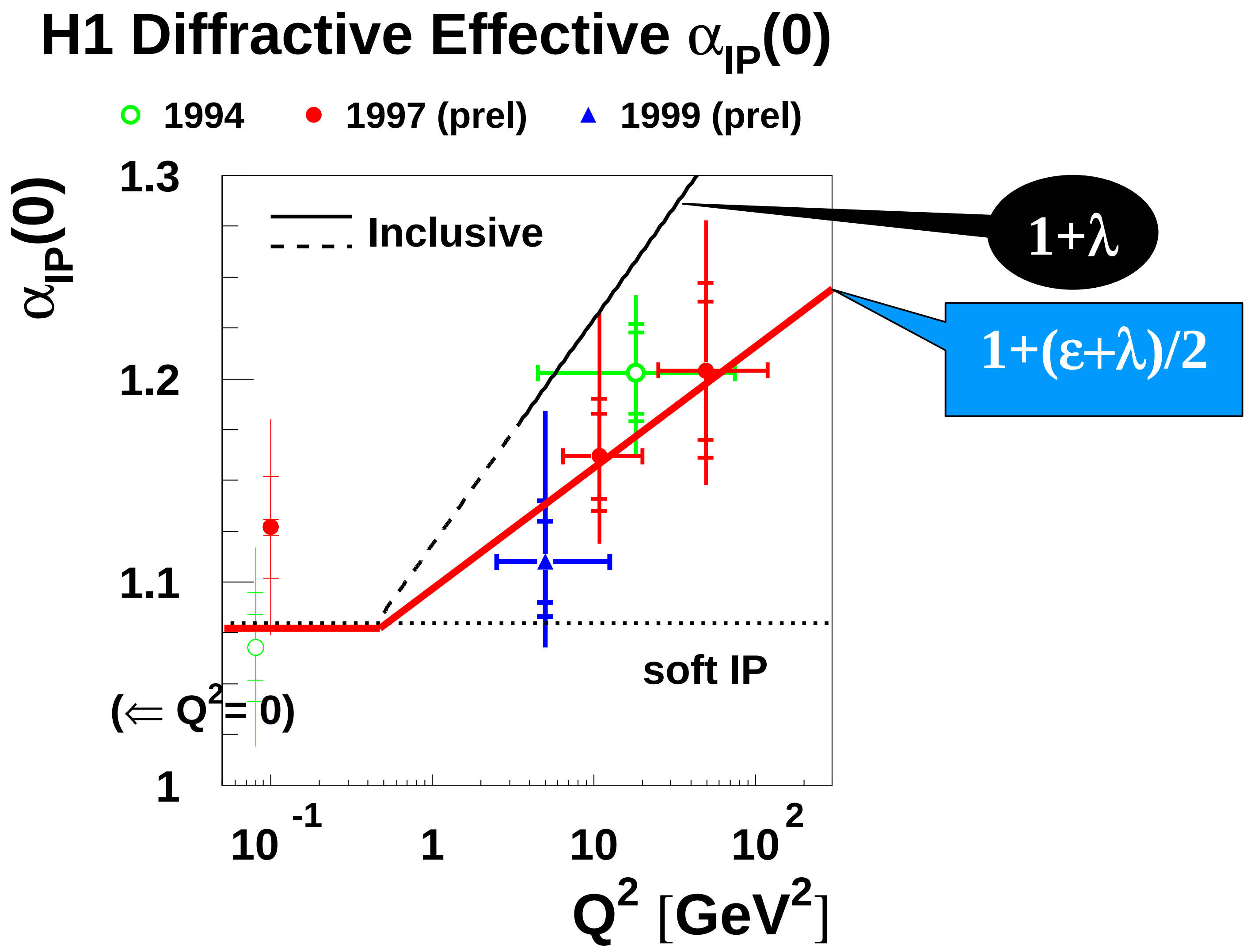
$$2\varepsilon_{DIS}^{D} = \varepsilon + \lambda(Q^2)$$

$F_2^{D3}(x_{IP},x,Q^2)/F_2(x,Q^2)$



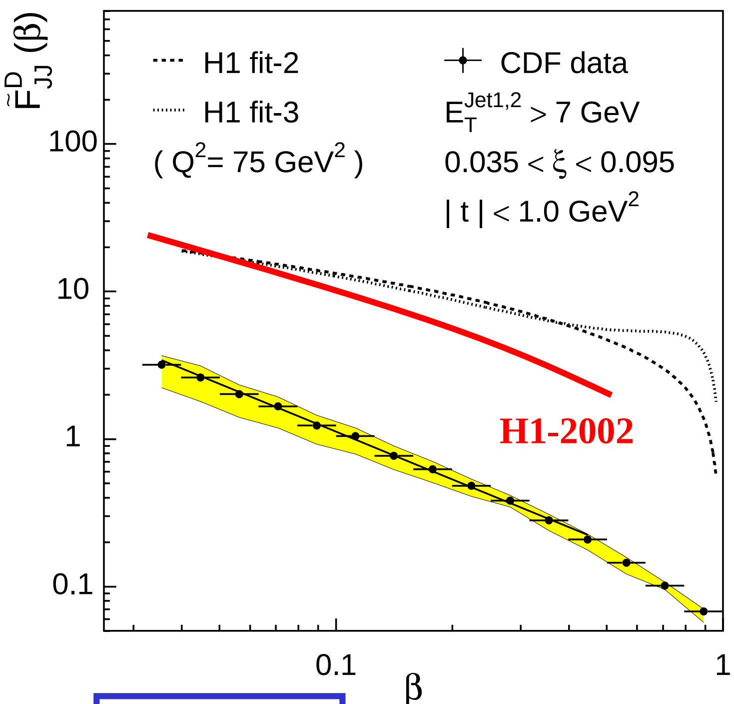
At fixed x_{IP}:
$F_2^{D3}(x_{IP},x,Q^2)$ evolves as $F_2(x,Q^2)$ independent of the value of x

Pomeron Intercept in DDIS



Diffractive Dijets @Tevatron

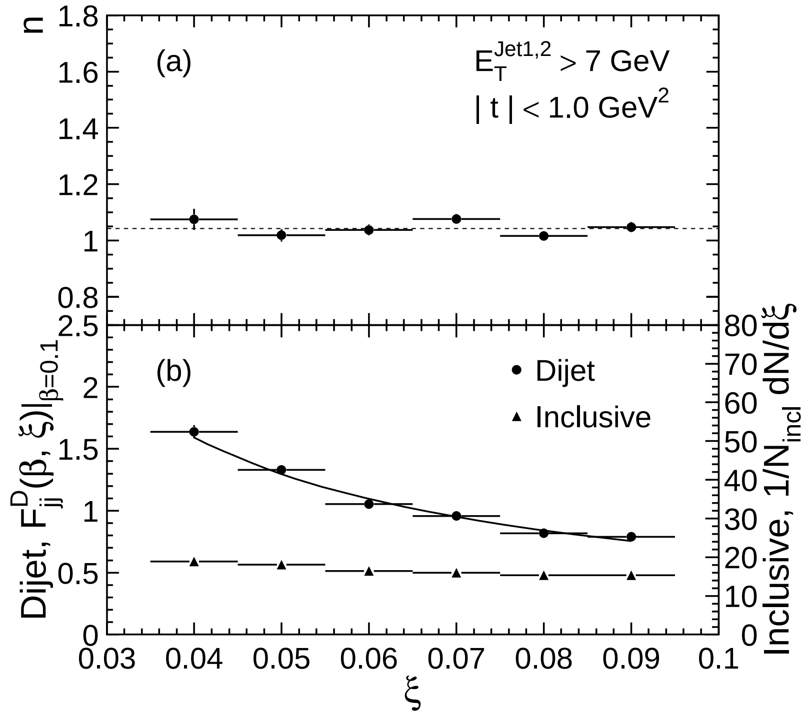
Test QCD factorization



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

suppressed at the Tevatron
relative to extrapolations
from HERA parton densities

Test Regge factorization



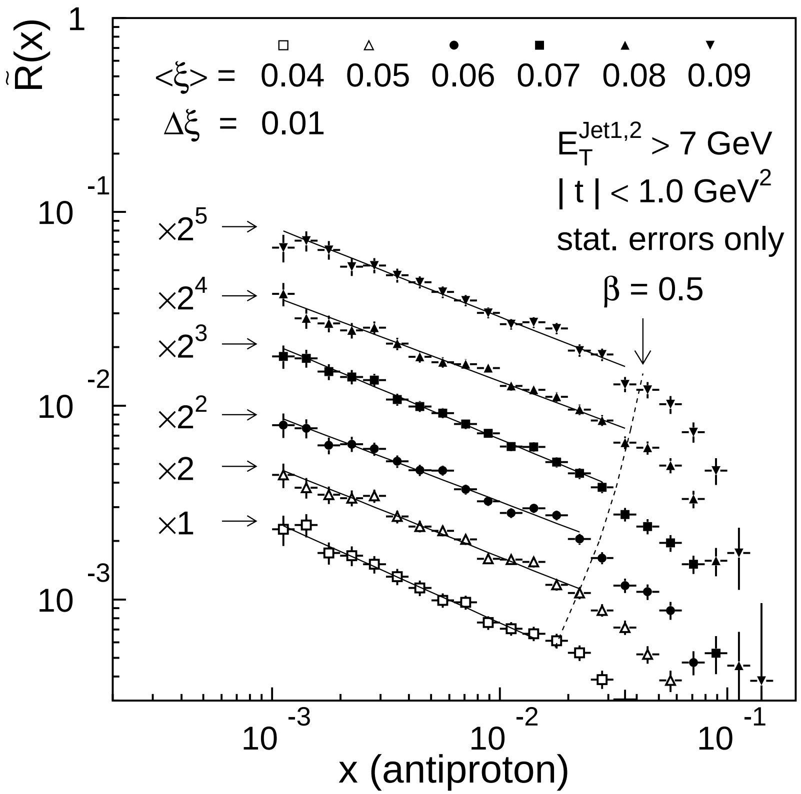
$$F^D_{JJ}(\xi, \beta) = C\ \beta^{-n}\ \xi^{-m}$$

Regge factorization holds

$m \approx 1 \Rightarrow$ Pomeron exchange

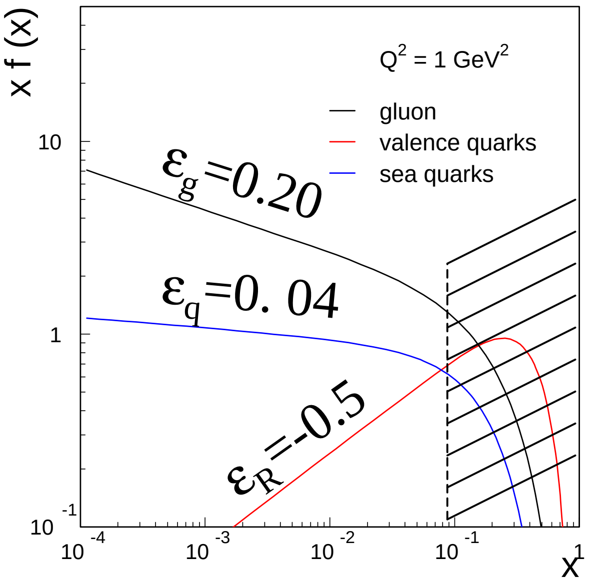
$R_{jj}(x)$ @Tevatron

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



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

$R_{jj}=F_{jj}^{SD}/F_{jj}^{ND}$

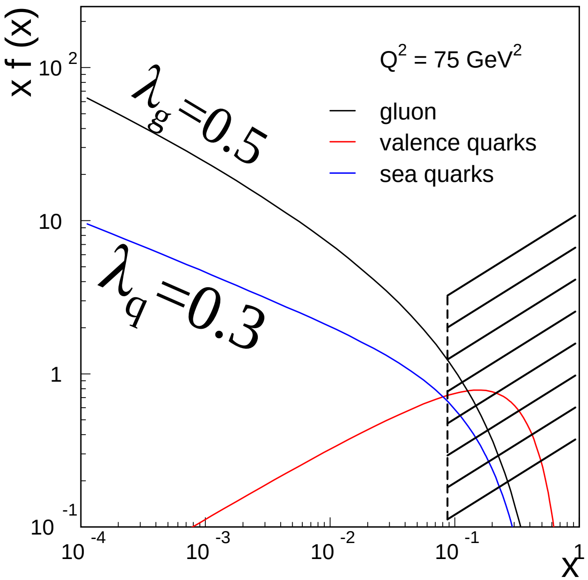


$$x\cdot f(x)=\frac{1}{x^{\varepsilon}}$$

<u>Power-law region</u>

$\xi_{max}=0.1$

$\beta<0.05\xi$

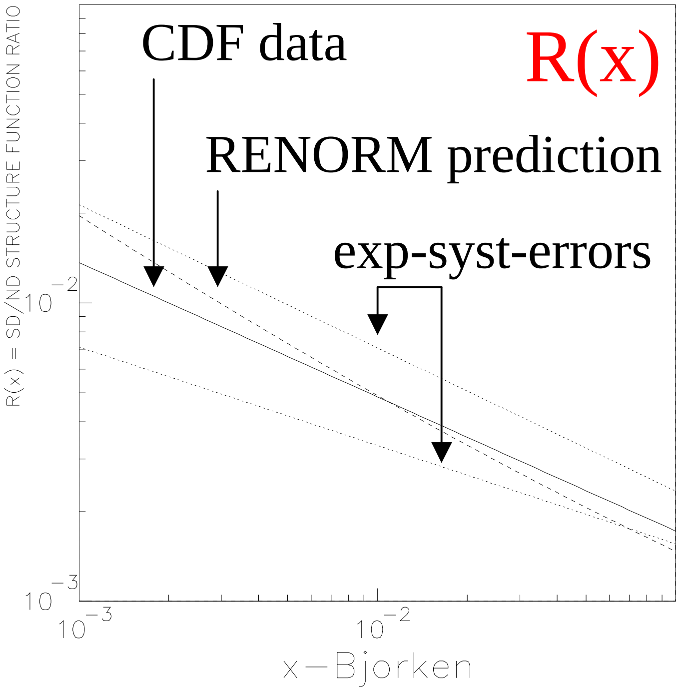


$$F^{SD}(Q^2,x,\xi)\propto\frac{1}{\xi^{1+\varepsilon}}\cdot F^{ND}(Q^2,x)\propto\frac{1}{\xi^{1+\varepsilon}}\cdot\frac{C(Q^2)}{(\beta\xi)^{\lambda(Q^2)}}\Rightarrow\frac{A_{\mathrm{RENORM}}}{\xi^{1+\varepsilon+\lambda}}\cdot\kappa\cdot\frac{C}{\beta^{\lambda}}$$

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

$$R_{jj}=\frac{A}{\xi^{1-\lambda}}\cdot\frac{1}{x^{\varepsilon+\lambda}}$$

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?

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

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

HERA vs Tevatron

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

(re)normalized gap probability

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

Pomeron flux

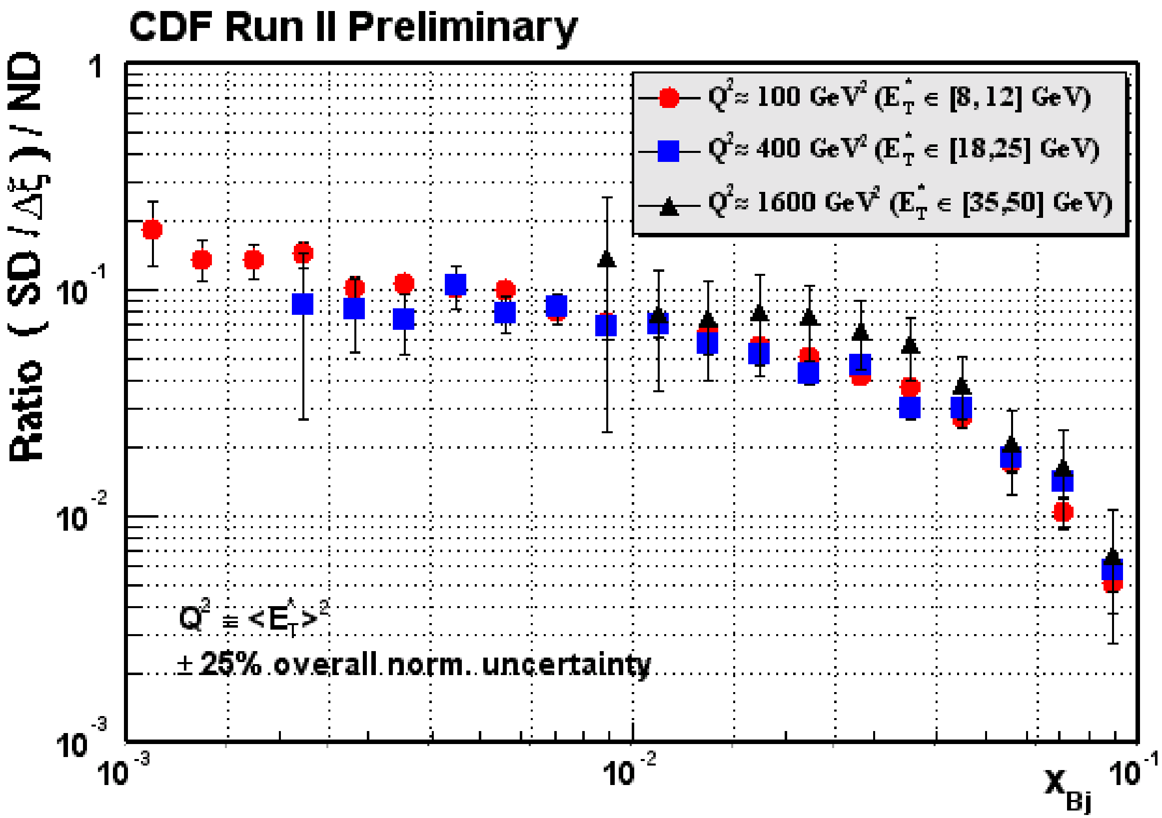
RENORM PREDICTIONS

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

Another issue

QCD evolution

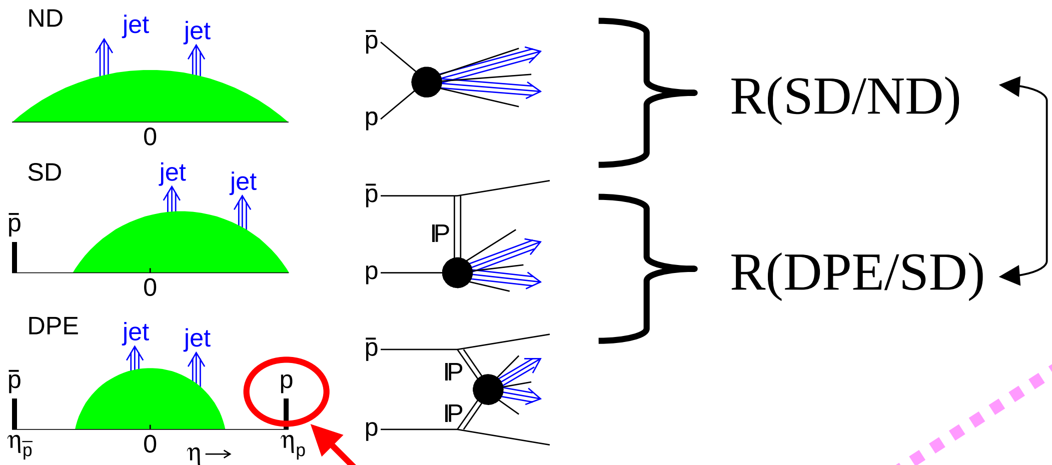
$R_{jj}(x_{Bj})$ vs Q^2



No appreciable E_T^2 dependence observed within $100 < E_T2 < 1600\ \mathrm{GeV}^2$

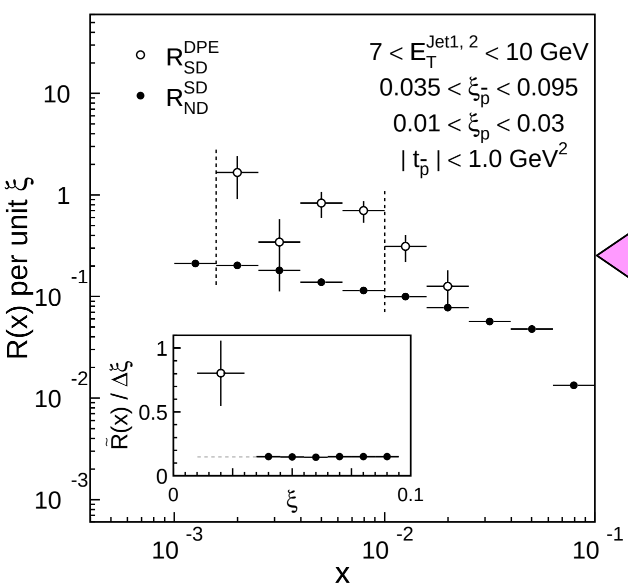
Dijets in Double Pomeron Exchange

Test of factorization



equal?

(not detected)



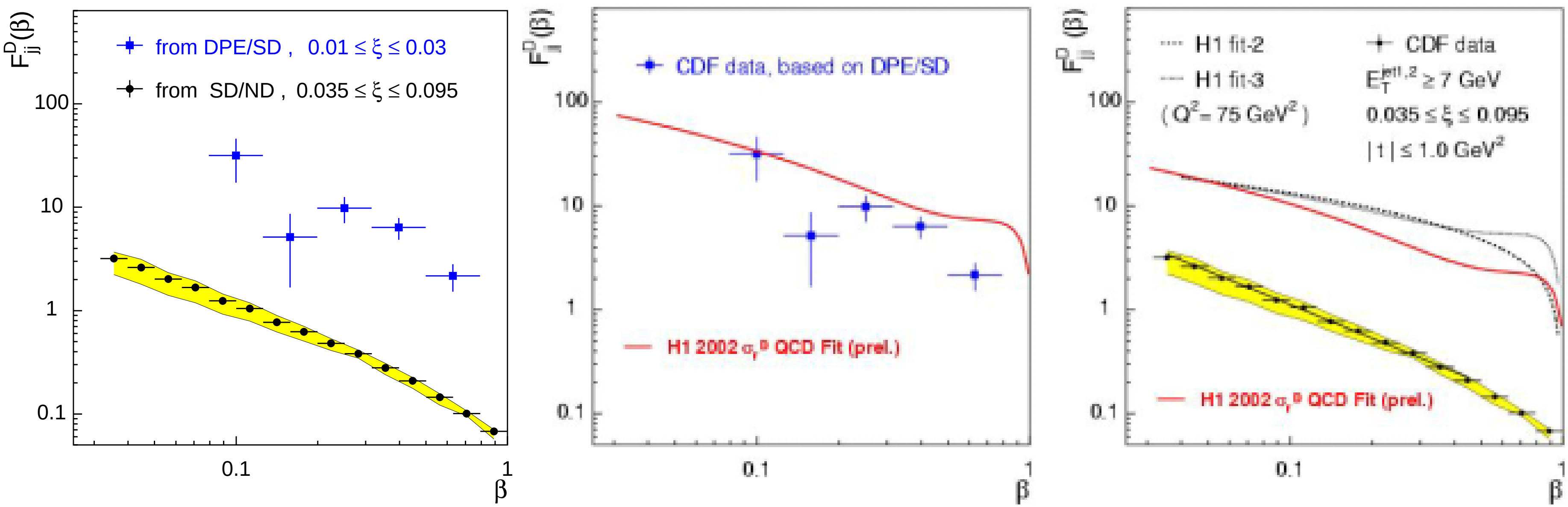
$$R^{DPE}_{SD} \approx 5\times R^{SD}_{ND}$$

The second gap is less suppressed!!!

Factorization breaks down,

but see next slide!

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

enter LHC

Inclusive Diffractive Higgs at the LHC

p+p → p-gap-(H+X)-gap-p

$$\ln s'_{LHC} \approx \ln s_{Tevatron}$$

σ^{D}(LHC) ~ κ^2 * σ^{ND} (Tevatron)

=> $(0.17)^2$ * 1 pb = 30 fb