DIFFRACTION AT THE TEVATRON IN PERSPECTIVE

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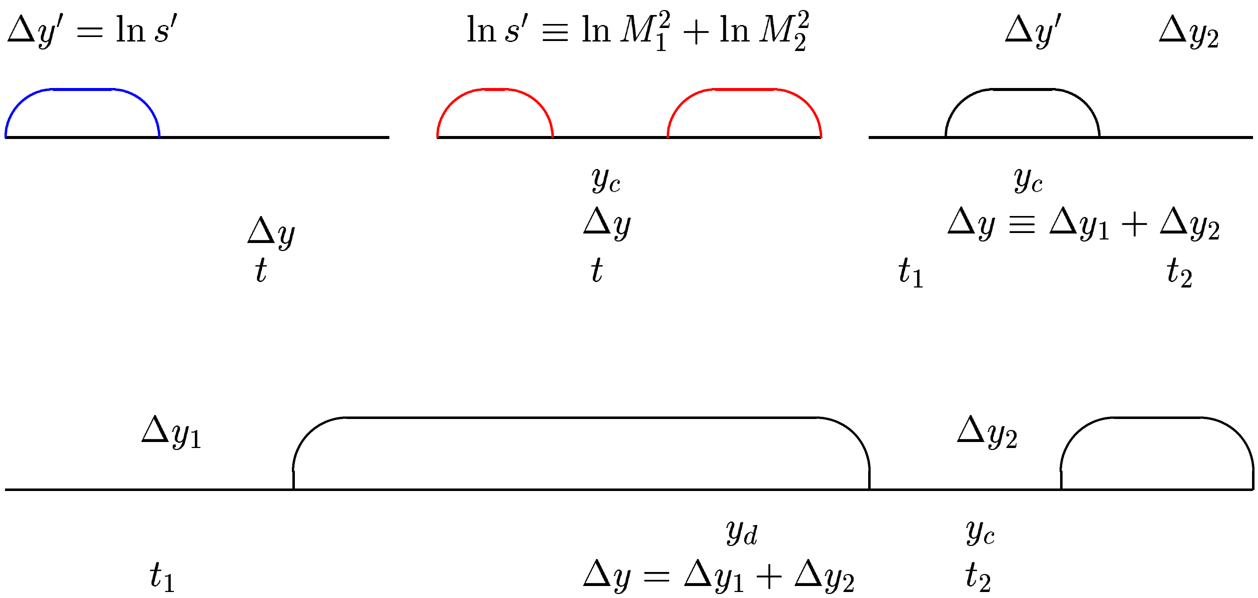
OUTLINE

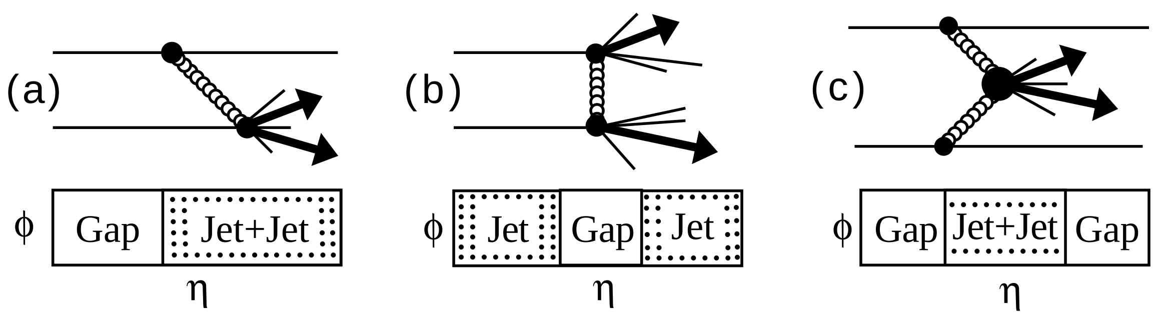
- Introduction
- **Outstanding issues in diffraction**
- **Soft diffraction**
  - **Multigap diffraction: NEW!**
    (hep-ph/0203141; hep-ph/0205217)
- **Hard diffraction**
- **Conclusions**

Thumbnails of Diffraction

Soft diffraction



Hard diffraction



Single Diffraction
W, JJ, b, J/ψ

Double Diffraction

Double Pomeron
Exchange

Tevatron Published Results on Diffraction

SOFT DIFFRACTION

Soft single diffraction	PRD 50 (1994) 5535	CDF
Soft double diffraction	PRL 87 (2001) 141802	CDF

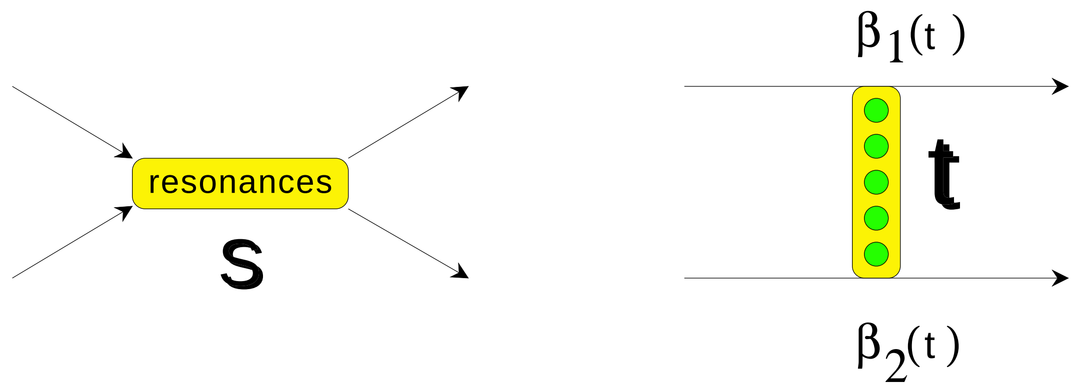
RAPIDITY GAP RESULTS

Diffractive W	PRL 78 (1997) 2698	CDF
Diffractive Dijets	PRL 79 (1997) 2636	CDF
Diffractive dijets	PLB 531 (2002) 52	DØ
Diffractive Beauty	PRL 84 (2000) 232	CDF
Diffractive J/ψ	PRL 87 (2001) 241802	CDF
Jet-Gap-Jet 1800	PRL 74 (1995) 855	CDF
Jet-Gap-Jet 1800	PRL 80 (1998) 1156	CDF
Jet-Gap-Jet 630	PRL 81 (1998) 5278	CDF
Jet-Gap-Jet 630	PRL 72 (1994) 2332	DØ
Jet-Gap-Jet 1800	PRL 76 (1996) 734	DØ
Jet-Gap-Jet 1800	PLB 440 (1998) 189	DØ

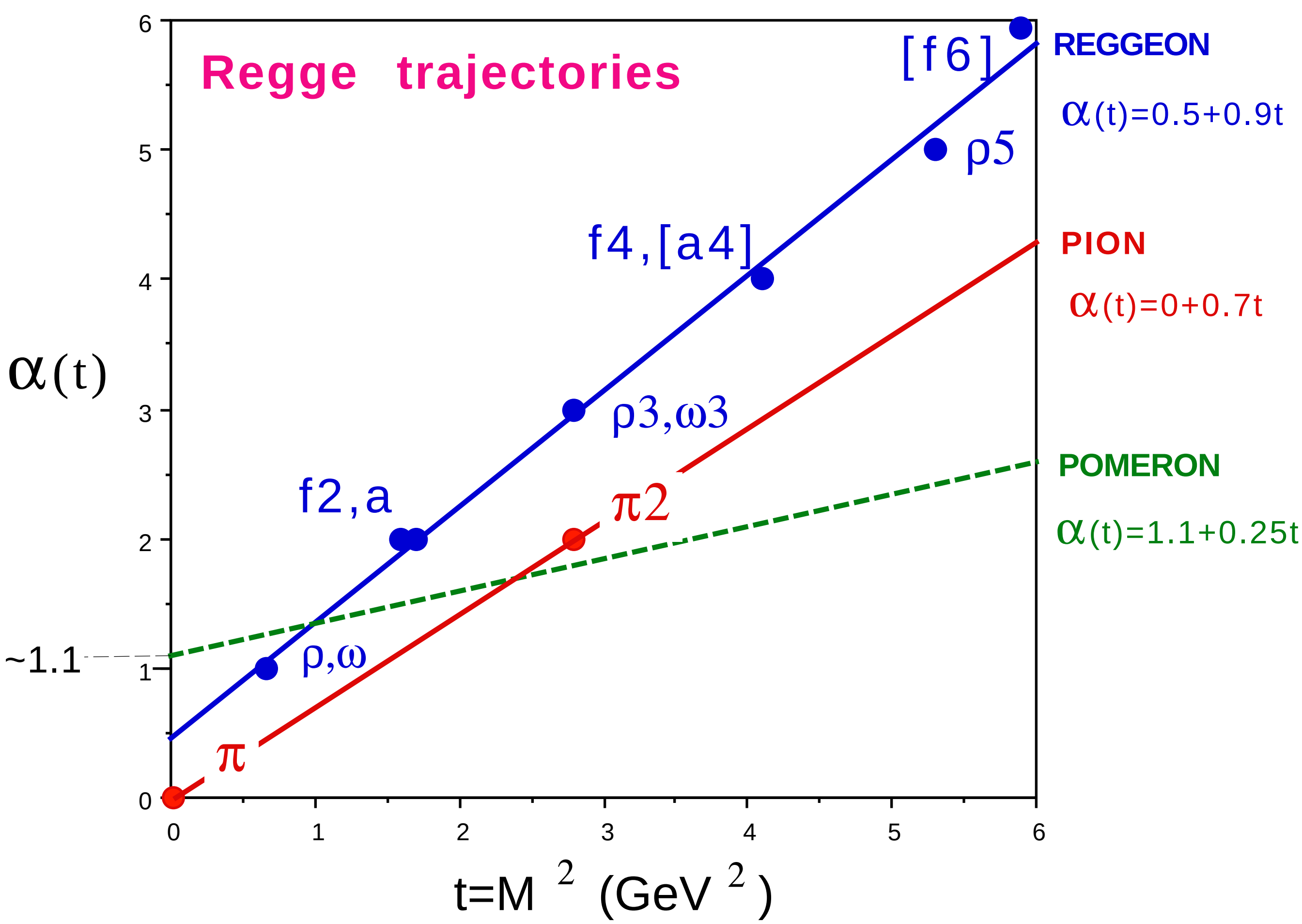
ROMAN POT RESULTS

Diffractive Dijets 1800	PRL 84 (2000) 5043	CDF
Diffractive Dijets 630	PRL 88 (2002) 151802	CDF
Double Pomeron Dijets	PRL 85 (2000) 4215	CDF

REGGE THEORY



$$T(s,t) = \frac{1}{s}\,\beta_1(t)\,\beta_2(t)\,s^{\alpha(t)}\,\phi_{a(t)} \qquad \sigma_T = \beta^2(0)\,s^{\alpha(0)-1}$$



The Original Pomeron

$$\boxed{\alpha_{I\!P}(0) = 1 + \alpha' t}$$

As $s \Rightarrow \infty$

- Total cross section

$$\sigma^{tot} \Rightarrow \text{ constant}$$

- Elastic scattering

$$\frac{d\sigma}{dt} \Rightarrow \text{ constant } \times e^{b+2\alpha'(\ln \frac{s}{s_0})t}$$

- Single diffraction

$$\frac{d\sigma}{d\xi dt} \Rightarrow \frac{\text{constant}}{\xi} \times e^{\frac{b}{2}+2\alpha'(\ln \frac{1}{\xi})t}$$

$$\boxed{\sigma_{sd} \Rightarrow \ln(\ln \frac{s}{s_0}) \Rightarrow \text{Unitarity Violation}}$$

The Supercritical Pomeron

$$\boxed{\alpha_{I\!P}(t) = 1 + \epsilon + \alpha'(t)}$$

- Total cross section

$$\sigma^{tot} \Rightarrow \text{ constant} \times \left(\frac{s}{s_0}\right)^{\epsilon}$$

- Elastic scattering slope

$$b_{el} = b_0 + 2\alpha' \ln \frac{s}{s_0}$$

- Single diffraction

$$\frac{d\sigma}{d\xi} \sim \frac{1}{\xi^{1+2\epsilon}} \cdot (\xi s)^{\epsilon}$$

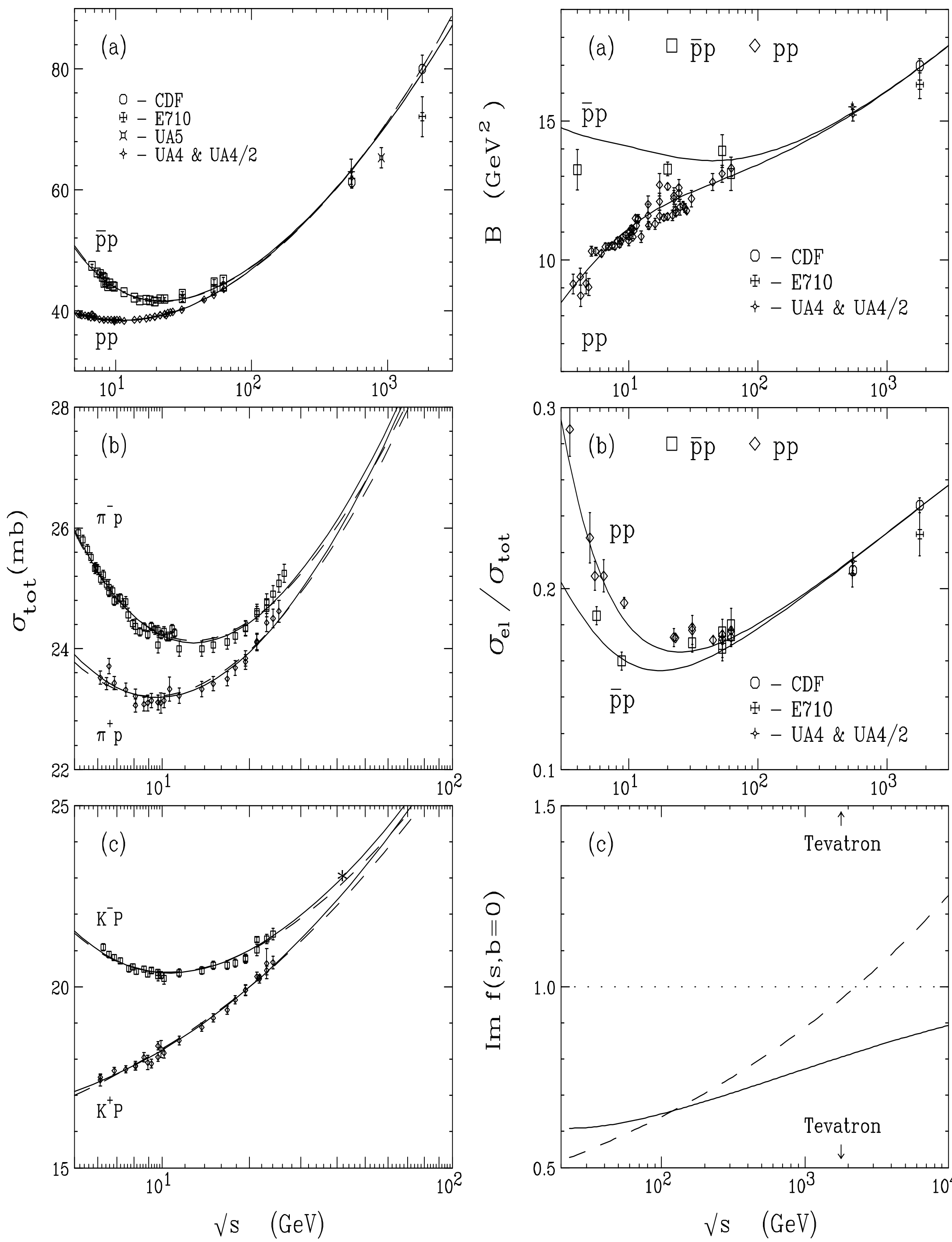
$$\boxed{\xi \Rightarrow \frac{M^2}{s}}$$

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

Total and Elastic Cross Sections

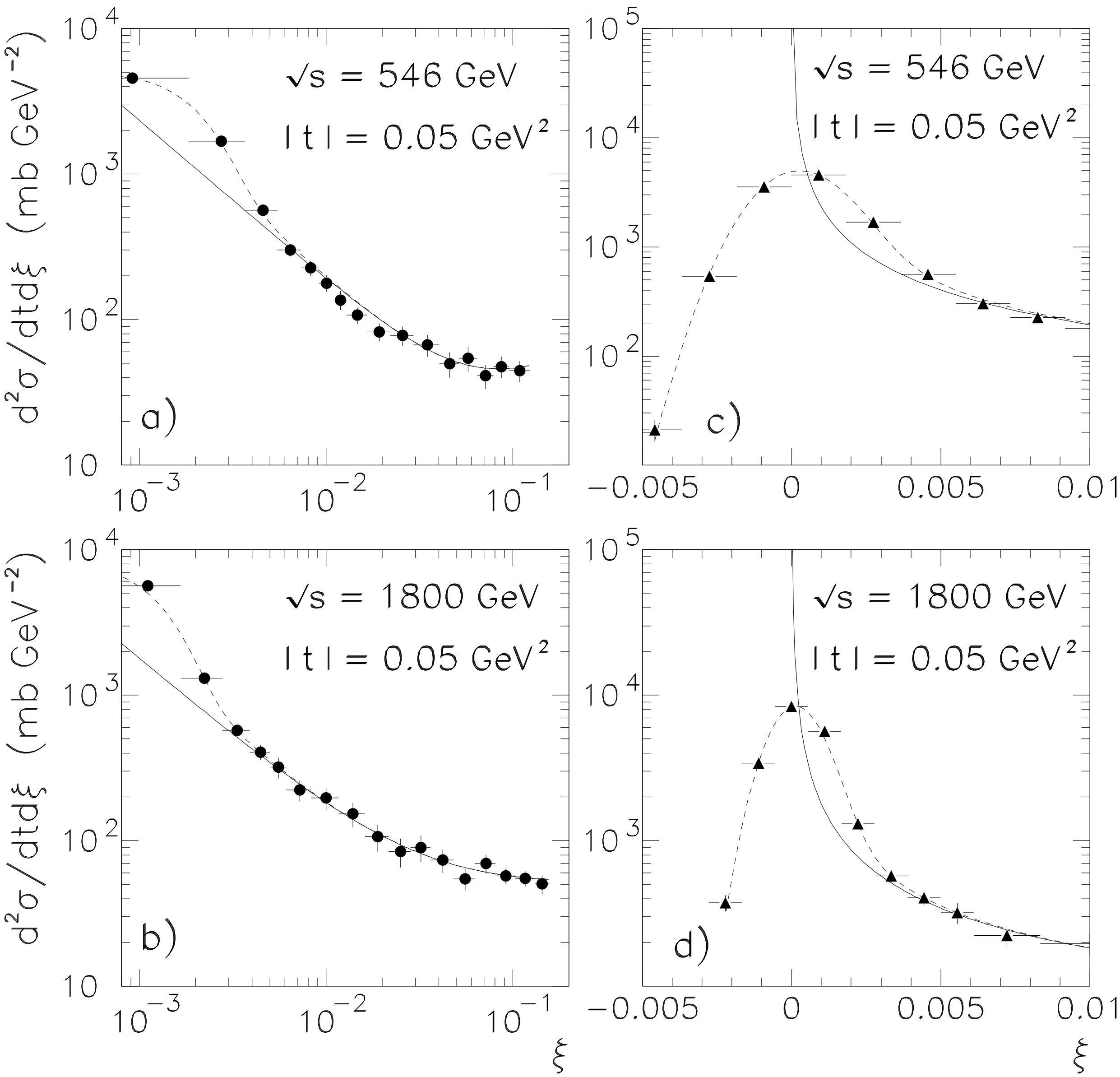
Covolan, Montanha and Goulianos, Phys. Lett. B 389 (1996) 176

$\alpha_{I\!P} = 1 + \epsilon\,(\Rightarrow 0.104) + 0.25t \quad \alpha_{f/a} = 0.68 + 0.82t \quad \alpha_{\omega/\rho} = 0.46 + 0.92t$



Single Diffraction at CDF

K. Goulianos and J. Montanha, PRD 59 (1999) 114017

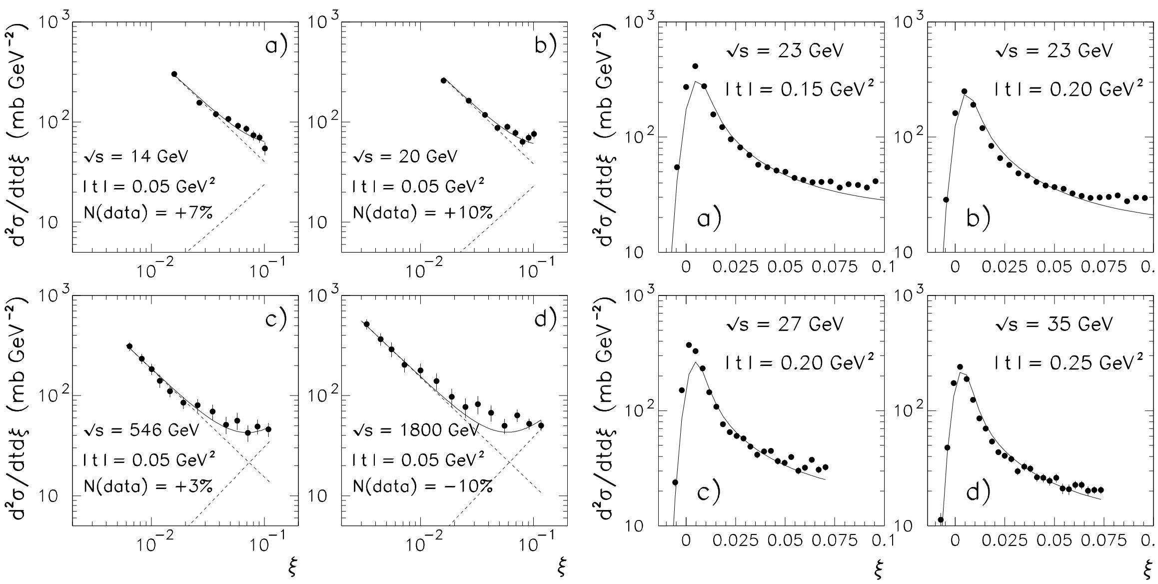


CDF cross sections $d\sigma/d\xi dt$ versus ξ at $t = -0.05$ GeV^2.
(solid) Input formula to CDF Monte Carlo fit.
(dashed) CDF formula convoluted with ξ resolution.

Global one parameter fit to $\bar{p}(p) + p \to \bar{p}(p) + X$ cross sections

K. Goulianos and J. Montanha, PRD 59 (1999) 114017

$$\frac{d^2\sigma}{d\xi\, dt} = f^N_{I\!P/p}(\xi, t) \cdot \sigma^{I\!Pp}(s\xi) + f_{\pi/p}(\xi, t) \cdot \sigma^{\pi p}(s\xi)$$



Differential single diffractive cross sections compared with the results of a simultaneous one parameter fit with a renormalized $I\!P I\!P I\!P$ amplitude and a pion exchange ($\pi\pi I\!P$) contribution (convoluted with the experimental ξ resolution in the figure on the right).

Renormalization and M^2-scaling

Single diffraction

$$\alpha_{I\!P}(t=0) = 1+\epsilon$$

$$\frac{d\sigma}{d\xi} \sim \frac{1}{\xi^{1+2\epsilon}} \cdot (\xi s)^{\epsilon}$$

$$\xi = \frac{M^2}{s}$$

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

Experimentally: $s^{2\epsilon} \;\Rightarrow\; 1$

A scaling law in diffraction

RENORMALIZATION

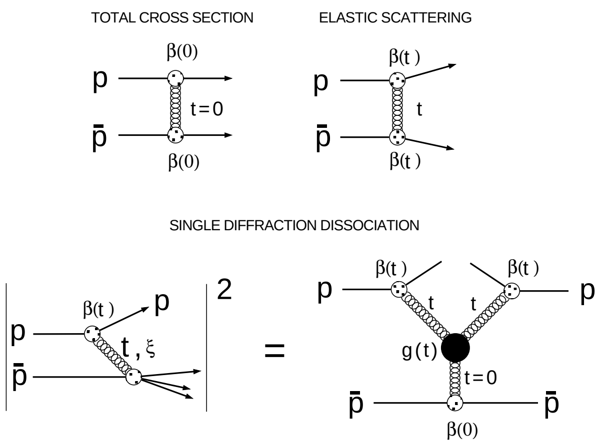
KG, PLB 358 (1995) 379

$$N_{\rm ren}^{-1} = \int_{\xi_{min}\approx 1/s}^{\xi_{max}\approx 1} \frac{d\xi}{\xi^{1+2\epsilon}} \propto s^{2\epsilon}$$

$$\frac{d\sigma}{dM^2} \sim N_{\rm ren} \times \frac{s^{2\epsilon}}{(M^2)^{1+\epsilon}} \sim \frac{1}{(M^2)^{1+\epsilon}}$$

Outstanding issues in diffraction

Soft Diffraction: Regge factorization?



$$\alpha_{I\!P}(t) = 1+\epsilon+\alpha' t$$

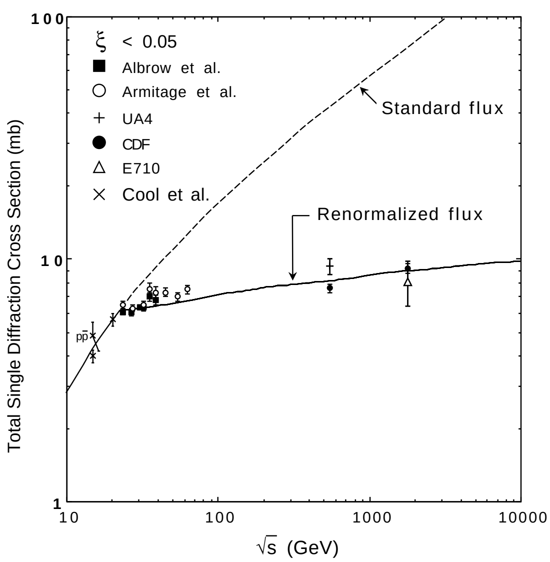
$$\xi \frac{d^2\sigma_{sd}}{d\xi dt} = \underbrace{\left(\frac{\beta(t)}{4\sqrt{\pi}}\cdot\frac{1}{\xi^{\epsilon+\alpha' t}}\right)^2}_{\xi\cdot f_{I\!P/p}(\xi,t)} \underbrace{\beta(0)g(t)\cdot(s')^{\epsilon}}_{\sigma_T^{I\!Pp}(s')}$$

$$\xi = \frac{\Delta p}{p} = \frac{M^2}{s} = e^{-\Delta y}$$

Hard Diffraction: QCD factorization?

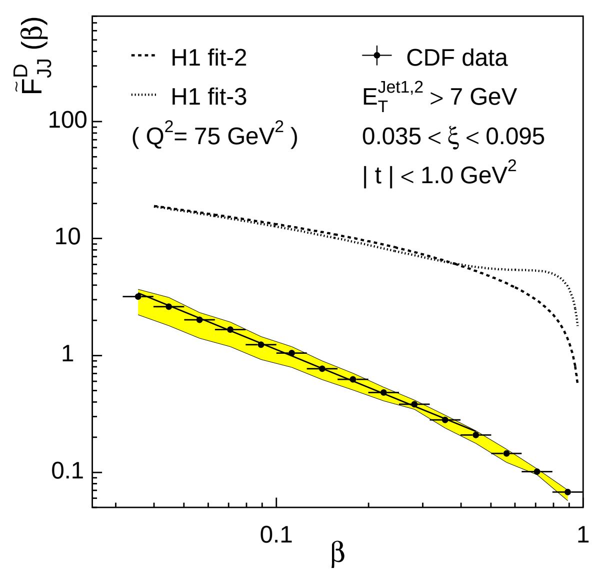
Can diffractive cross sections be obtained by convoluting parton level cross sections with diffractive structure functions of hadrons?

Both Regge and QCD factorization break down



The $\bar{p}p/pp\ \sigma_{SD}^T$ vs $\sqrt{s}$

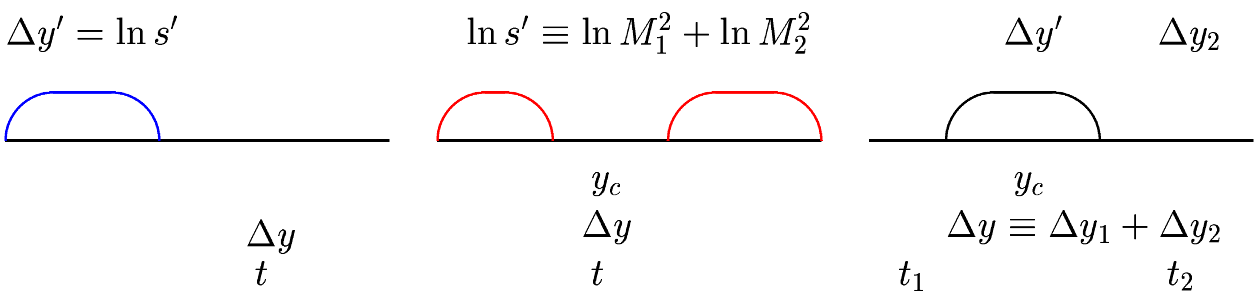
KG: PLB **358**, 379 (1995)



Diffractive structure function vs β

CDF: PRL **84**, 5083 (2000)

Soft diffraction predictions



$$\kappa \equiv \frac{g_{I\!P I\!P I\!P}}{\beta(0)} = 0.17, \qquad \frac{1}{\xi} = e^{\Delta y}, \qquad (s')^{\epsilon} = e^{\epsilon \Delta y'}$$

REGGE THEORY

Process		Gap Probability	$\sigma^{tot}(s')$
SD:	$\frac{d^2\sigma}{dt\,d\Delta y} =$	$\left[\frac{\beta(t)}{4\sqrt{\pi}}\, e^{(\epsilon+\alpha' t)\Delta y}\right]^2$	$\kappa \left[\beta^2(0)\, e^{\epsilon \Delta y'}\right]$
DD:	$\frac{d^3\sigma}{dt\,d\Delta y\,dy_c} =$	$\kappa \left[\frac{\beta(0)}{4\sqrt{\pi}}\, e^{(\epsilon+\alpha' t)\Delta y}\right]^2$	$\kappa \left[\beta^2(0)\, e^{\epsilon \Delta y'}\right]$
DPE:	$\frac{d^4\sigma}{dt_1 dt_2 d\Delta y dy_c} =$	$\Pi_i \left[\frac{\beta(t_i)}{4\sqrt{\pi}}\, e^{(\epsilon+\alpha' t_i)\Delta y_i}\right]^2$	$\kappa^2 \left[\beta^2(0)\, e^{\epsilon \Delta y'}\right]$

PARTON MODEL AMPLITUDE

$$f(\Delta y, t) \sim e^{(\epsilon + \alpha' t)\Delta y}$$

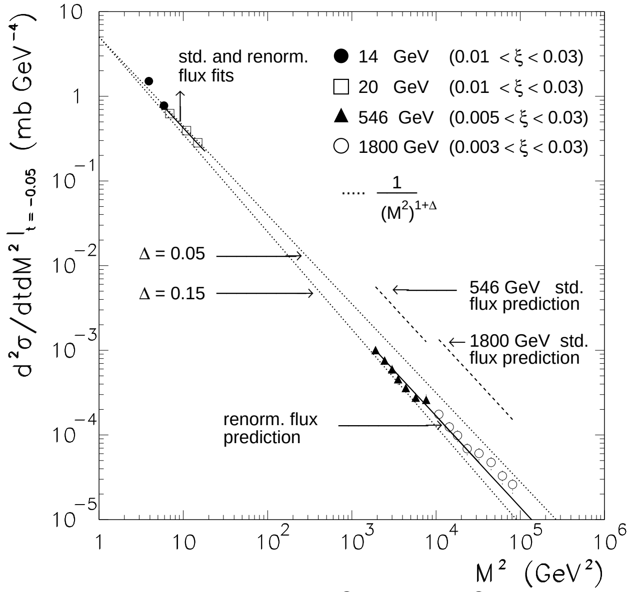
CROSS SECTION: $\sim \Pi_i f_i^2(\Delta y_i, t_i) \times f(\Delta y', t' = 0)$

RENORMALIZE the gap probability $\Pi_i f_i^2(\Delta y_i, t_i)$ to unity

Single and double diffraction

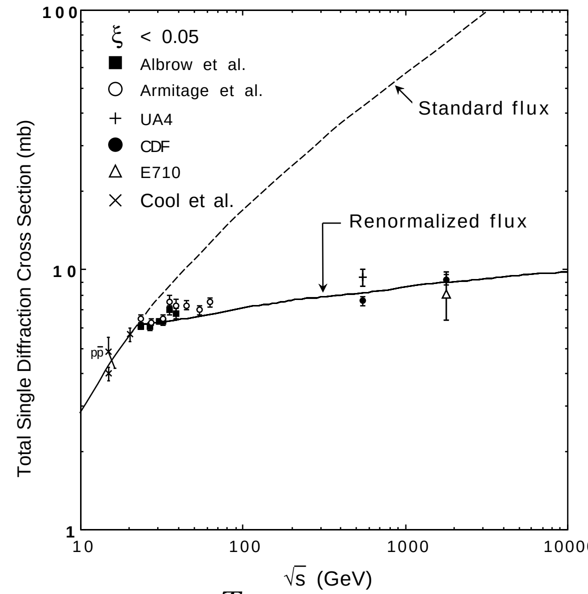
Single Diffraction

KG & JM: PRD 59 (1999) 114017



$d\sigma_{SD}/dM^2$ vs M^2

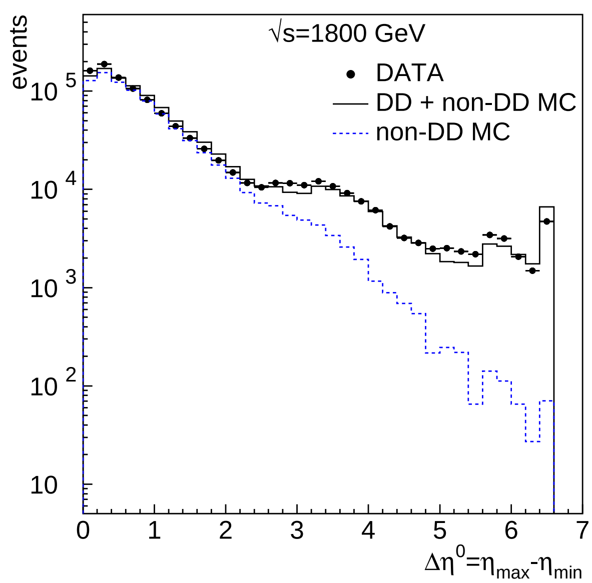
KG: PLB 358 (1995) 379



σ_{SD}^T vs $\sqrt{s}$

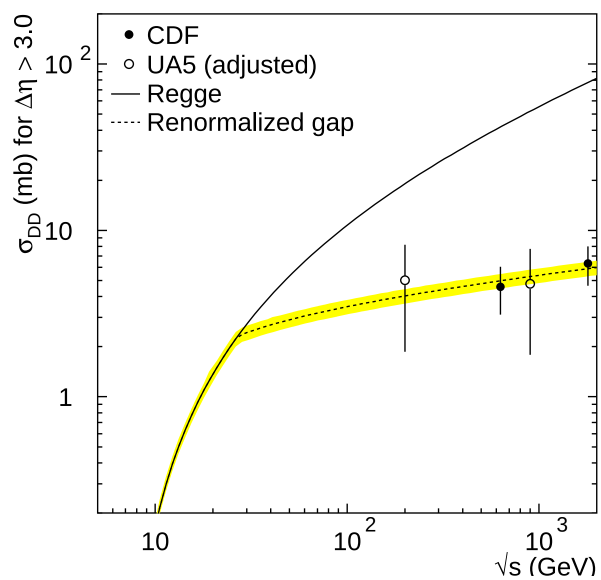
Double diffraction

CDF: PRL 87 (2001) 141802



Δy^0 distribution

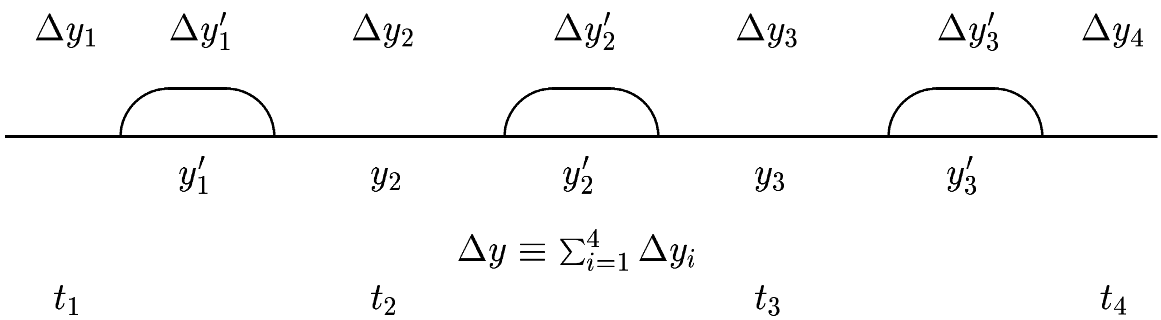
CDF: PRL 87 (2001) 141802



σ_{DD}^T vs $\sqrt{s}$

Distributions: shapes agree with Regge predictions
Normalization: suppressed by rapidity gap probability integral

Multigap diffraction



Differential cross-section

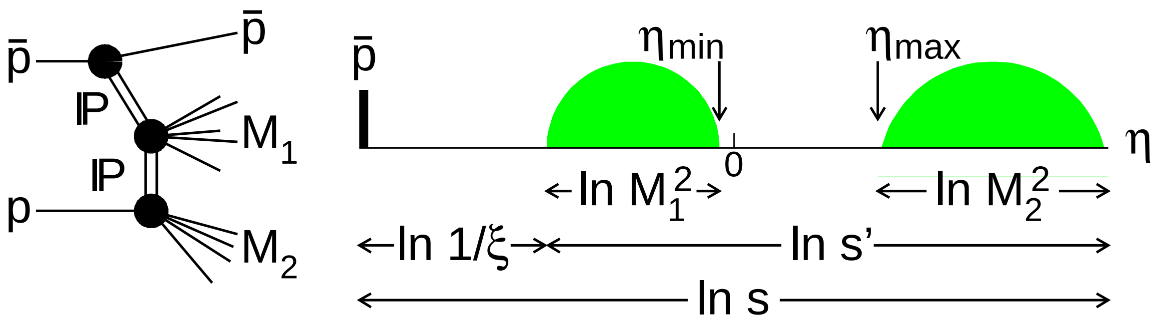
- There are 10 independent variables, V_i, shown below the figure.
- $\dfrac{d^{10}\sigma}{\Pi_{i=1}^{10} dV_i} = P_{gap} \times \sigma(\mathrm{sub-energy})$
- $\sigma(\mathrm{sub-energy}) = \kappa^4 \left[\beta^2(0) \cdot e^{\epsilon \Delta y'}\right]$
  $(\Delta y' = \Sigma_{i=1}^{3} \Delta y'_i)$
- $P_{gap} = N_{gap} \times \Pi_{i=1}^{4} \left[e^{(\epsilon + \alpha' t_i)\Delta y_i}\right]^2 \times [\beta(t_1)\beta(t_4)]^2$

$$P_{gap} = N_{gap} \cdot e^{2\epsilon \Delta y} \cdot f(V_i)|_{i=1}^{10}$$

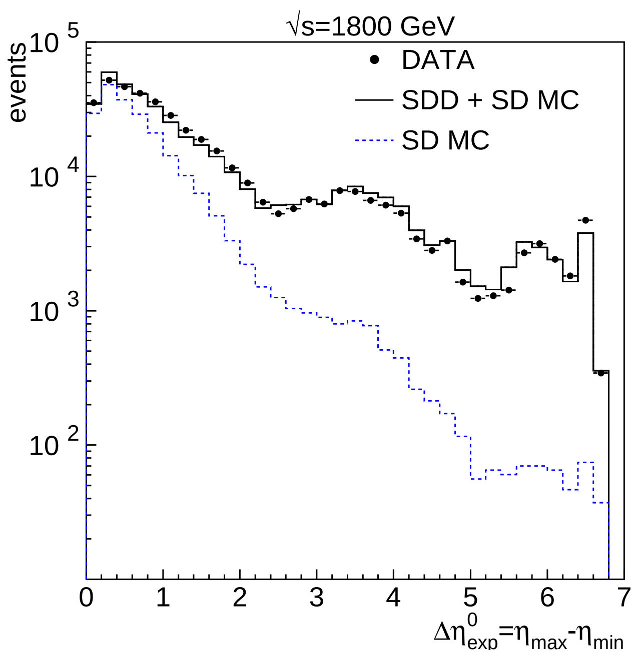
- N_{gap} : factor that normalizes P_{gap} over all phase space to unity. Note that N_{gap} depends on the sum of all gaps and therefore on the s-value independent of the number of gaps!

SDD: single + double diffraction

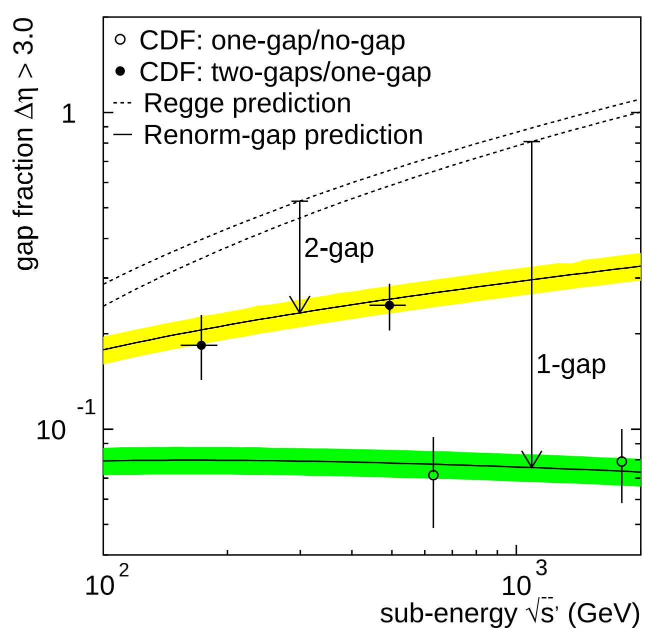
$$\bar{p} + p \to \bar{p} + \mathrm{GAP}_1 + X + \mathrm{GAP}_2 + Y$$



Results: CDF Preliminary

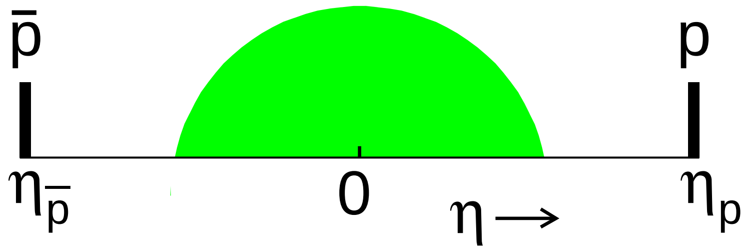


$\Delta\eta^0$ distribution



Rapgap ratios

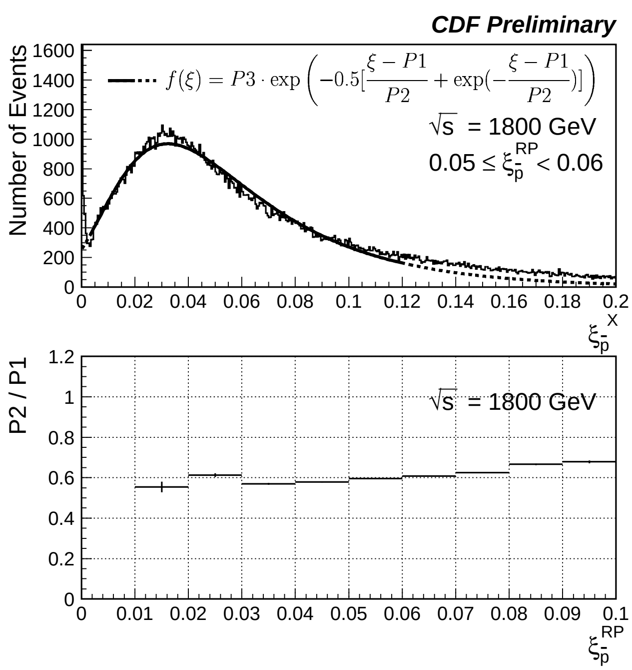
DPE: topology and data analysis

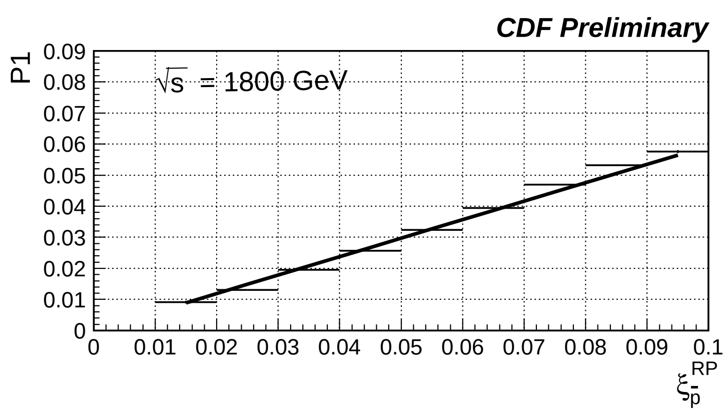


- $\xi(\bar{p})$ is measured by the Roman Pot Spectrometer: $\xi_{\bar{p}}^{RP}$
- Measure $\xi(p)$ from calorimeter and BBC information:

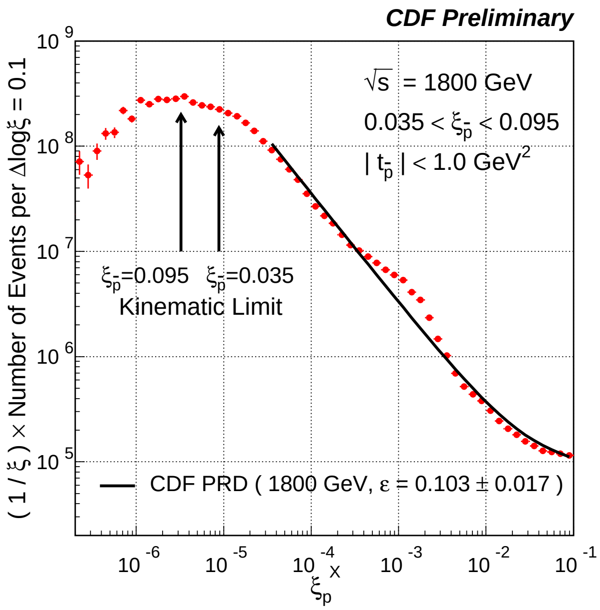
$$\xi_p^{\mathrm{X}} = \frac{M_{\mathrm{X}}^2}{\xi_{\bar{p}} \cdot s} = \frac{\Sigma_i E_{\mathrm{T}}^i \ \exp(+\eta^i)}{\sqrt{s}}$$

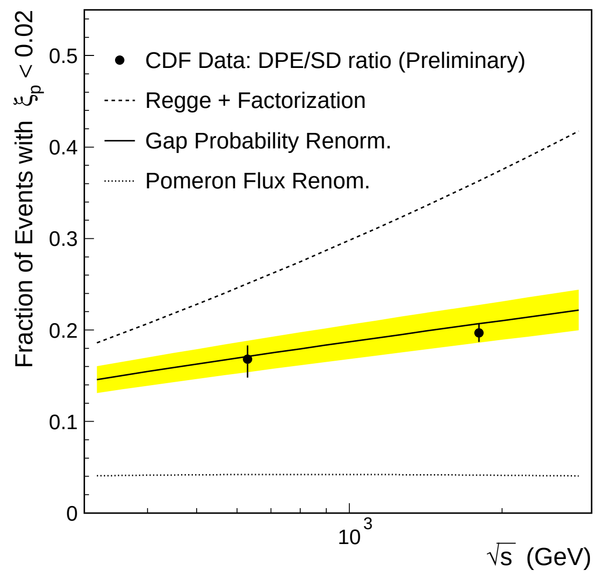
- Calibrate ξ^X by comparing $\xi^X(\bar{p})$ with $\xi_{\bar{p}}^{RP}$





DPE: results

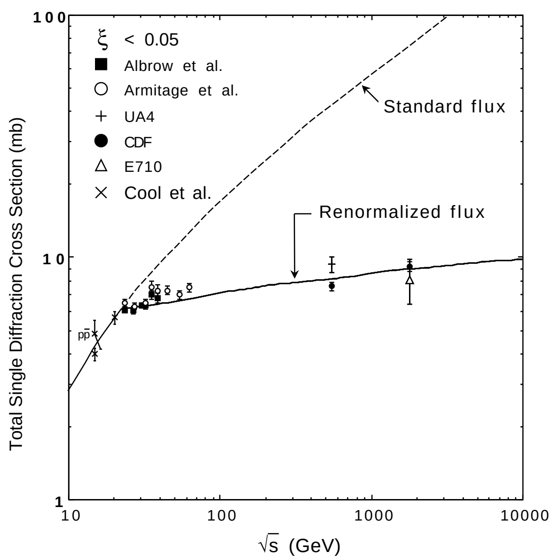




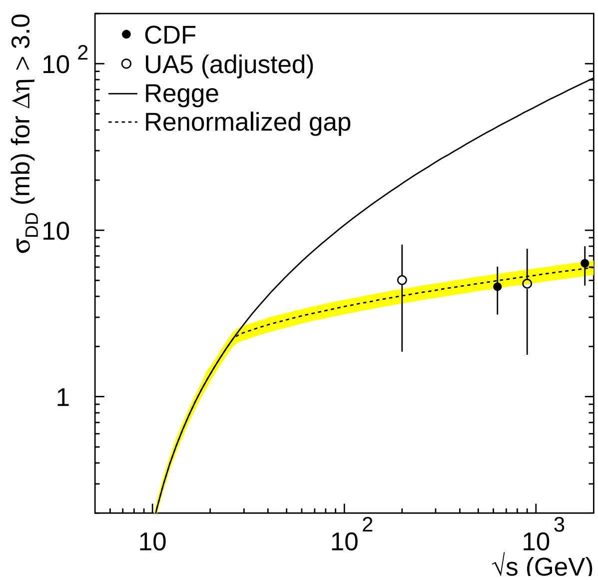
Comments on the ξ-distribution

- $dN/d\xi \sim 1/\xi$ for $\xi_p < 0.02$ down to $\xi_{min} = 1/(s\xi_{\bar{p}})$
- The ξ-resolution has little effect on the $dN/d\xi$ shape
- The bump at $\xi \sim 10^{-3}$ is caused by central calorimeter noise shifting events from low to high ξ (NO EVENTS ARE LOST!)
- In the region $5 \times 10^{-4} < \xi_p < 10^{-2}$ the ξ_p-distribution agrees with the form $1/\xi^{1.103}$ (solid curve) obtained from a fit to the CDF single diffraction data reported in PRD (1994) 5536.

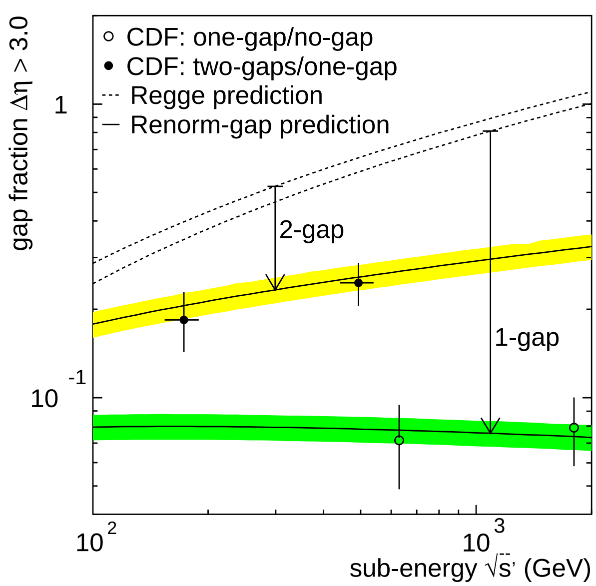
Summary of soft diffraction results



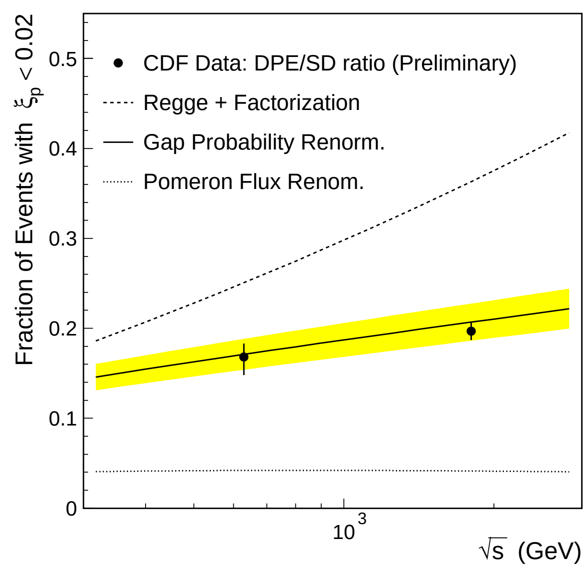
SD



DD



SDD



DPE

- The shaded bands are the “renormalized gap” predictions.

Soft diffraction conclusions

$\Rightarrow$ ξ and/or rapidity gap distributions:

agree in shape with Regge predictions disagree in normalization

RENORMALIZATION yields correct rates.

$\Rightarrow$ The ξ_p distribution in DPE is $\sim 1/\xi_p$
down to $\xi_{min} = 1/s\langle\xi_{\bar{p}}\rangle \approx \underbrace{10^{-5} \text{ at } 1800 \text{ GeV}}$

This result challenges the validity of models proposing
"ξ-damping" at low ξ or variation of ϵ with ξ and/or s.

$\Rightarrow$ Two-gap to one-gap ratio

$$R\left(\frac{\text{two}-\text{gap}}{\text{one}-\text{gap}}\right) \approx \kappa$$

In events with a gap the formation of a second gap is "unsuppressed".

$\Rightarrow$ The factor κ

$$\kappa = \frac{\text{triple}-\text{pomeron coupling}}{\text{pomeron}-\text{proton coupling}}$$

may be interpreted as the color factor required to neutralize the color flow and form a rapidity gap.

HARD DIFFRACTION

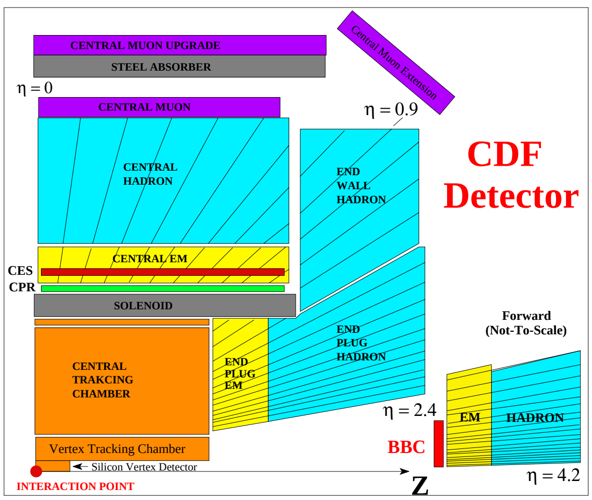
- Rapidity gap results
  - Hard double diffraction (jet-gap-jet)
  - Hard single diffraction (W, JJ, b, J/ψ)
- Roman pot results
  - Dijets in single diffraction
  - Dijets in double pomeron exchange

QCD and Regge factorization tests

- Conclusions

Diffraction studies using rapidity gaps

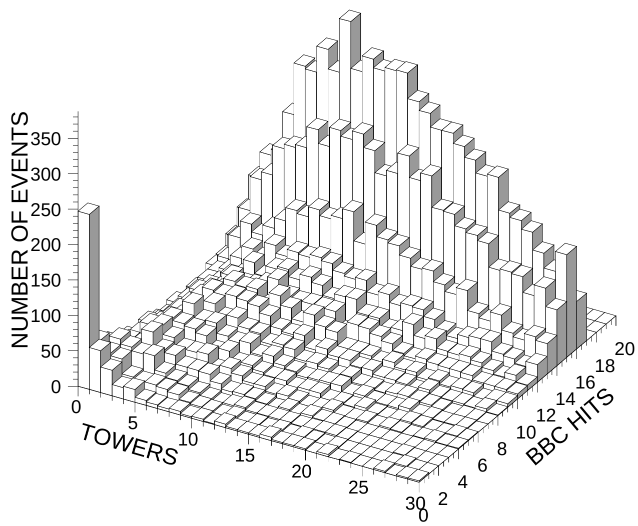
CDF Detector



BBC $3.2 < \eta < 5.9$

FCAL $2.4 < \eta < 4.2$

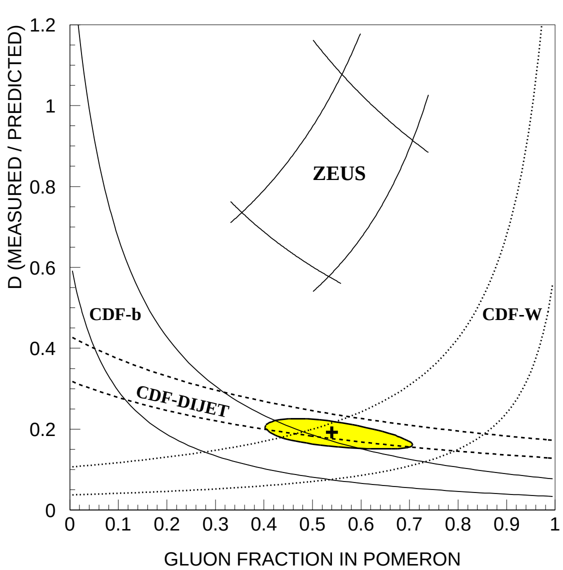
Diffractive dijet signal



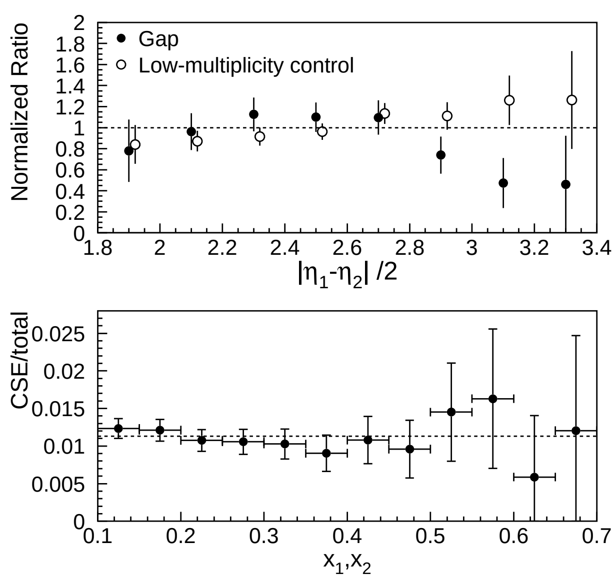
CDF rapidity gap results

Hard process	$\sqrt{s}$ (GeV)	$R = \frac{\text{DIFF}}{\text{TOTAL}}$ (%)	Kinematic region
SD			
$W(\to e\nu)$+G	1800	1.15 ± 0.55	E_T^e, $\not{E}_T > 20$ GeV
Jet+Jet+G	1800	0.75 ± 0.1	$E_T^{jet} > 20$ GeV, $\eta^{jet} > 1.8$
$b(\to e + X)$+G	1800	0.62 ± 0.25	$\|\eta^e\| < 1.1$, $p_T^e > 9.5$ GeV
$J/\psi(\to \mu\mu)$+G	1800	1.45 ± 0.25	$\|\eta^\mu\| < 0.6$, $p_T^\mu > 2$ GeV
DD			
Jet-G-Jet	1800	1.13 ± 0.16	$E_T^{jet} > 20$ GeV, $\eta^{jet} > 1.8$
Jet-G-Jet	630	2.7 ± 0.9	$E_T^{jet} > 8$ GeV, $\eta^{jet} > 1.8$

Diffractive gluon fraction



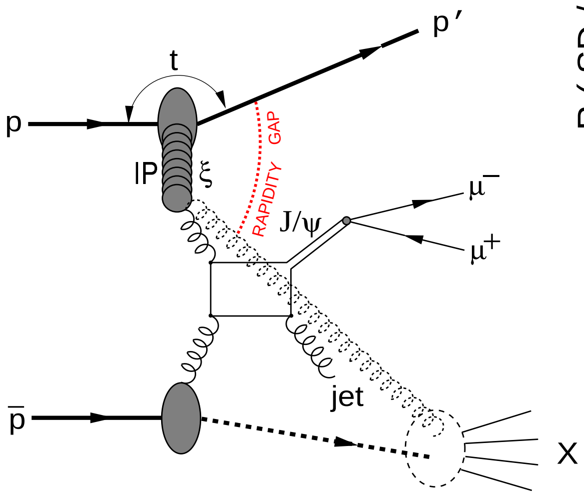
Jet-Gap-Jet 1800 GeV

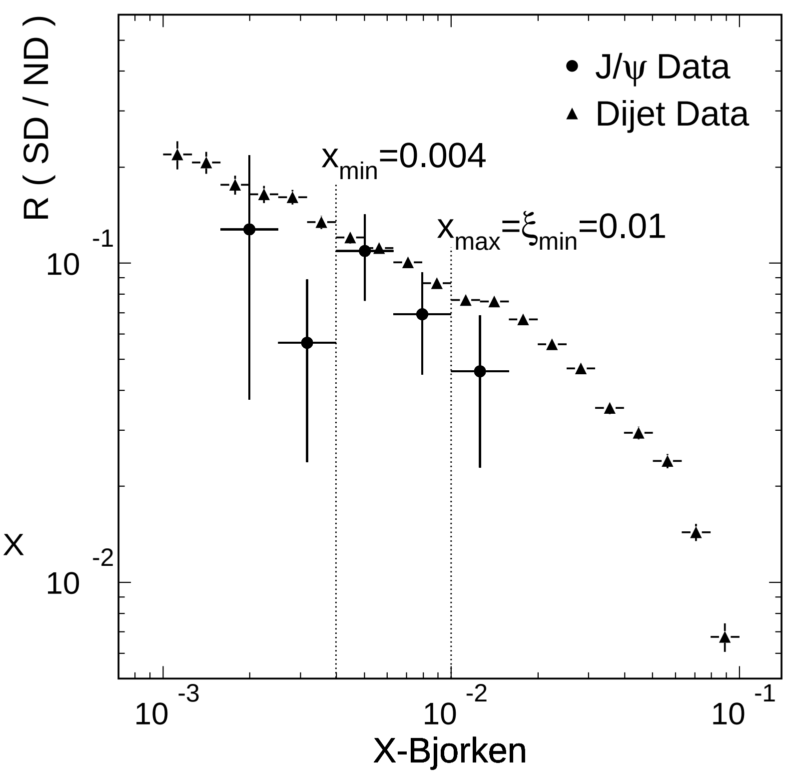


Diffractive J/ψ Production

Ratio of SD to ND rates versus x_{bj}

$$x_{bj}^{\pm} = \frac{1}{\sqrt{s}} \times p_T^{J/\psi} \left(e^{\pm\eta^{J/\psi}} + e^{\pm\eta^{jet}} \right)$$



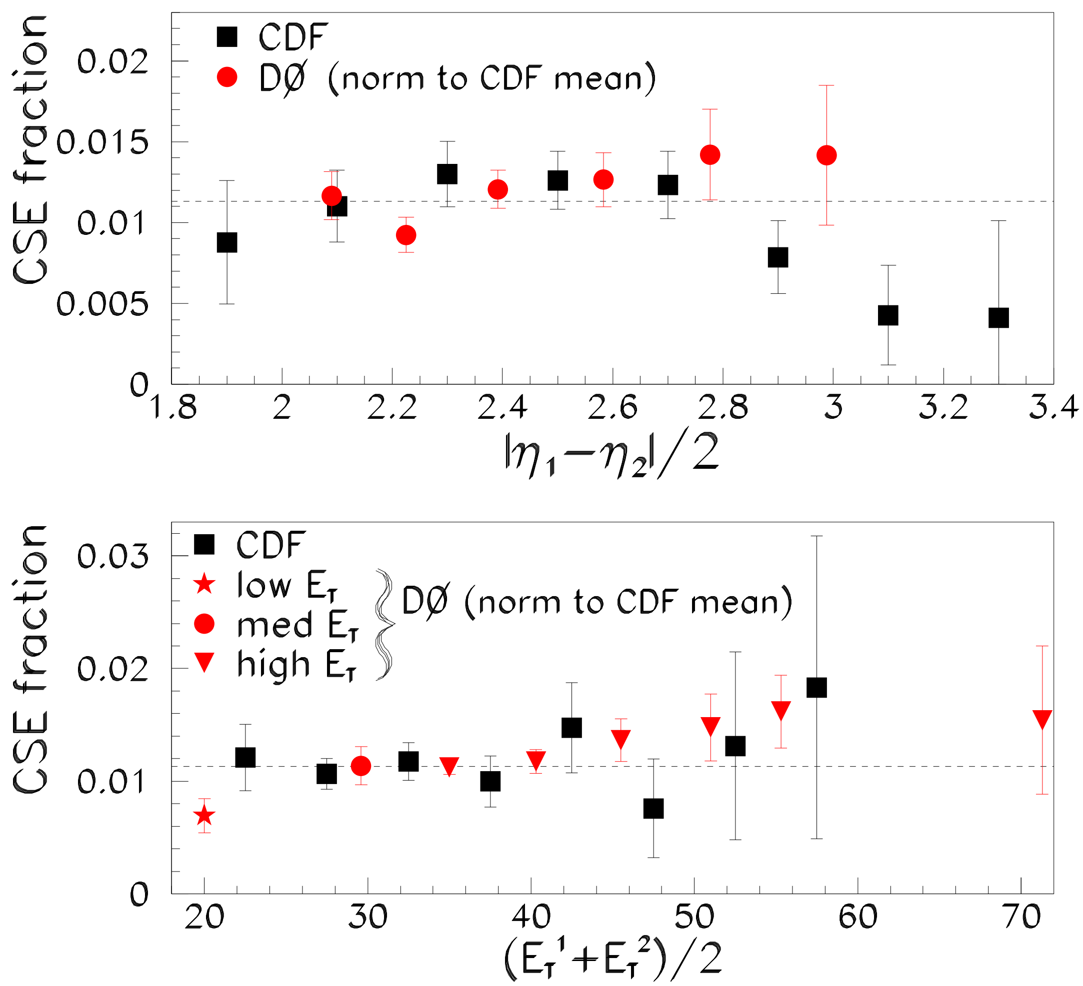


$$\left(\frac{R_{JJ}}{R_{J/\psi}}\right)_{exp} = \frac{g^D + \frac{4}{9}q^D}{g^{ND} + \frac{4}{9}q^{ND}} / \frac{g^D}{g^{ND}} = 1.17 \pm 0.27\,(\text{stat})$$

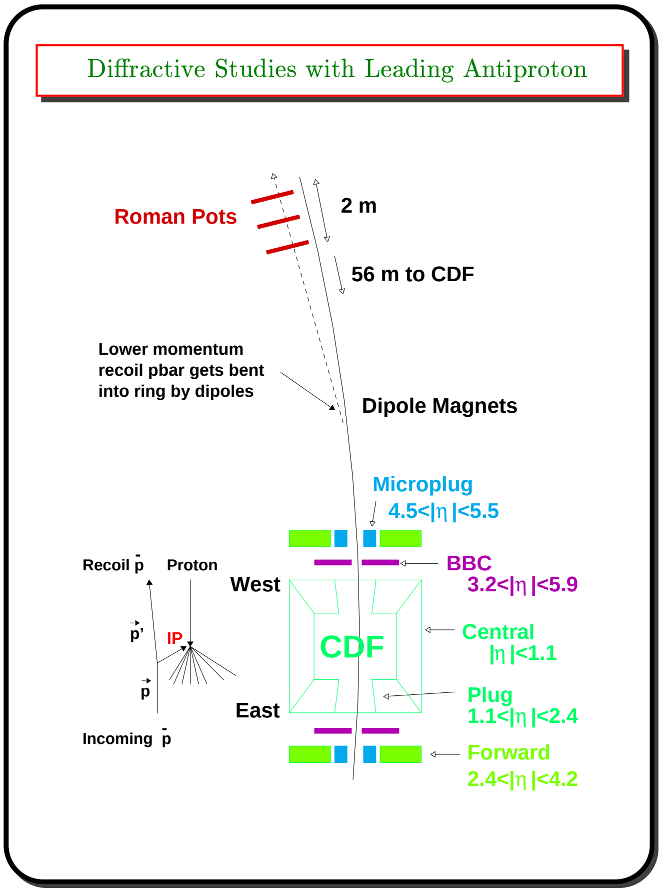
Gluon fraction : $f_g^D = 0.59 \pm 0.15\,(\text{stat} \oplus \text{syst})$

(compare to 0.54 ± 0.15 from W, JJ, and b)

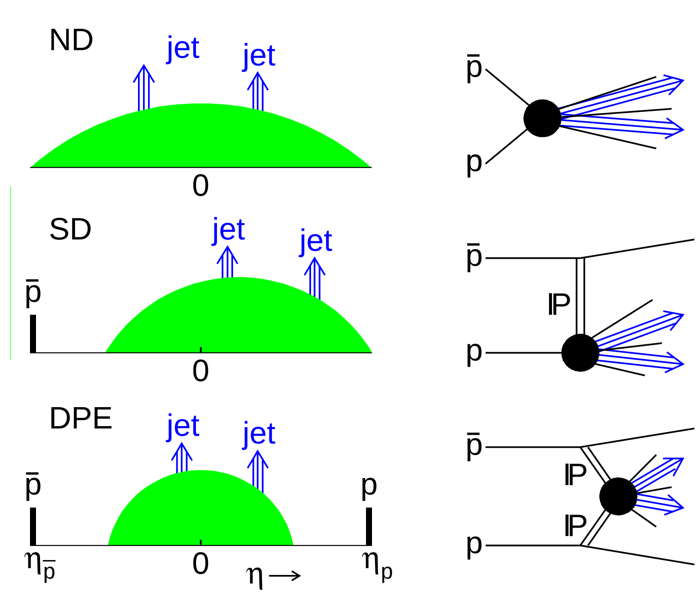
Jet-Gap-Jet Events
$\sqrt{s}$ =1800 GeV



Diffraction studies using roman pots



Facrorization tests



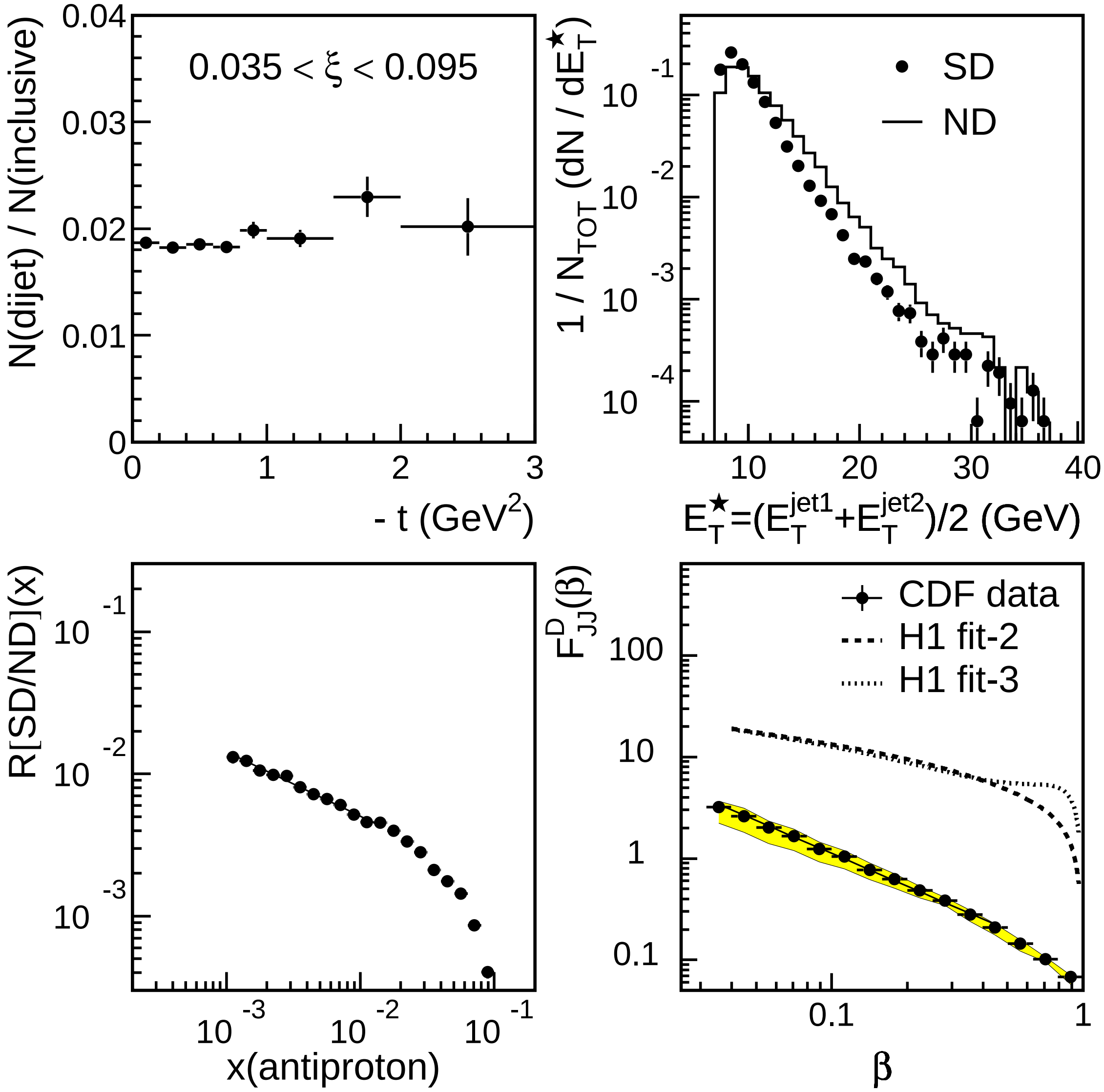
Structure function measurement

- $$x_{\bar{p}} = \frac{\Sigma_{i=1,2(3)} E_{\rm T}^{i} \exp(-\eta^{i})}{\sqrt{s}}$$

  (sum over jet1 and jet2, include jet3 if $E_T^{(3)} > 5$ GeV)
- $R_{\frac{\rm SD}{\rm ND}}(x_{\bar{p}}, \xi) = F_{jj}^{D}(x_{\bar{p}}, \xi)/F_{jj}(x_{\bar{p}})$
- $F_{jj}^{D}(x_{\bar{p}}) = x_{\bar{p}}\left[g^{D}(x_{\bar{p}}) + \frac{4}{9}\Sigma\left\{q_i^{D}(x_{\bar{p}}) + \bar{q}_i^{D}(x_{\bar{p}})\right\}\right]$
- $$F_{jj}^{D}(x_{\bar{p}}, \xi) = R_{\frac{\rm SD}{\rm ND}}(x_{\bar{p}}, \xi) \times F_{jj}(x_{\bar{p}})$$
- $$F_{jj}^{D}(x_{\bar{p}}, \xi) \;\Rightarrow\; \boxed{\beta = x_{\bar{p}}/\xi} \Rightarrow \; F_{jj}^{D}(\beta, \xi)$$

Roman pot dijets

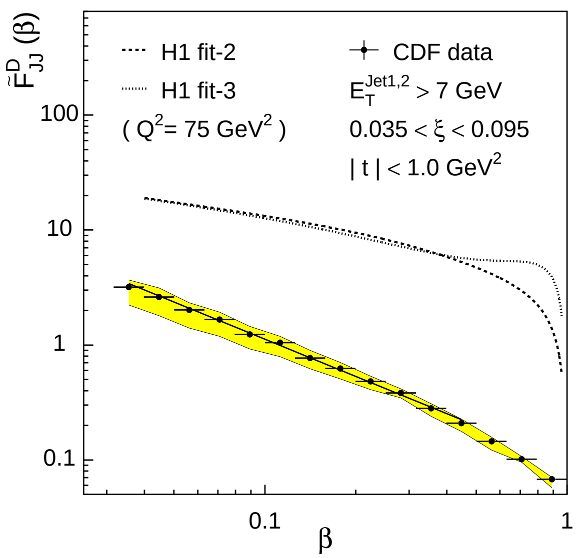
diffractive structure function



- Dijet to inclusive production ratio is t-independent
- Regge factorization for $\beta < 0.5$

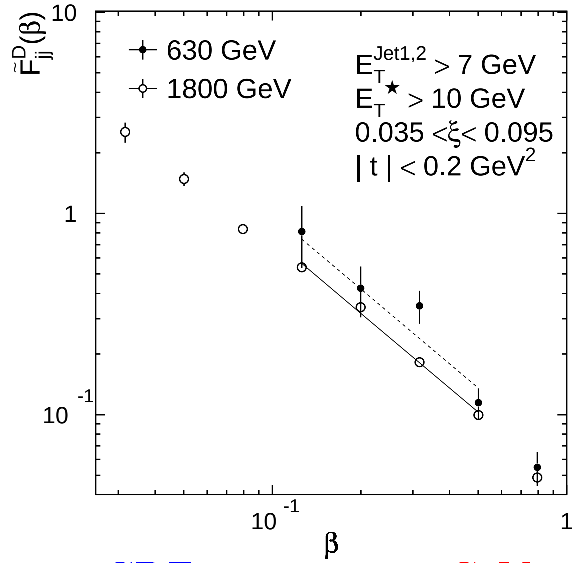
$$F_{jj}^{D}(\xi,\beta) \propto \frac{1}{\xi^m} \cdot \frac{1}{\beta^n} \quad (m \approx n \approx 1)$$

Factorization tests



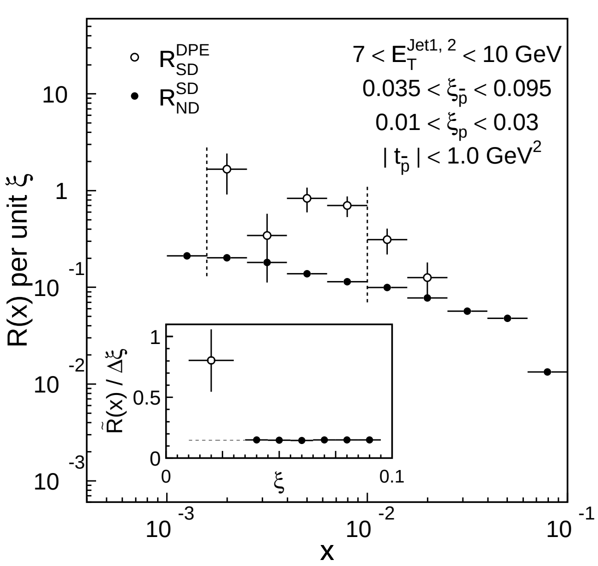
H1 vs CDF 1800 GeV

$$R^{CDF}_{H1}|_{\beta<0.5} = 0.06 \pm 0.02$$



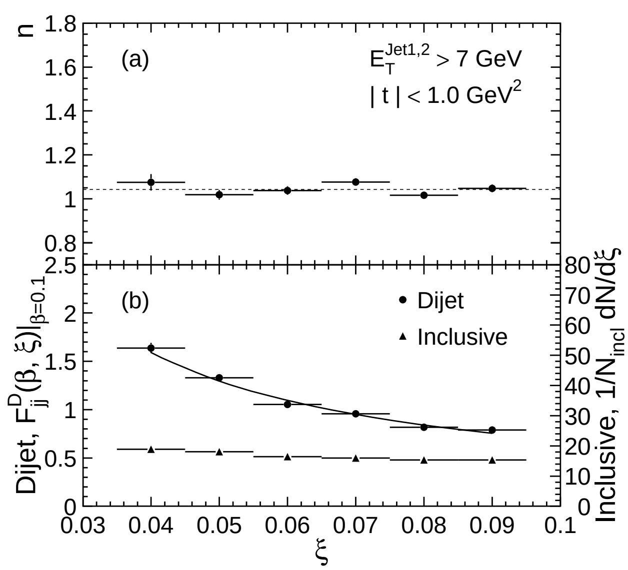
CDF: 630 vs 1800 GeV

$$R^{630}_{1800} = 1.3 \pm 0.2^{+0.4}_{-0.3}$$



CDF: DPE vs SD 1800 GeV

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

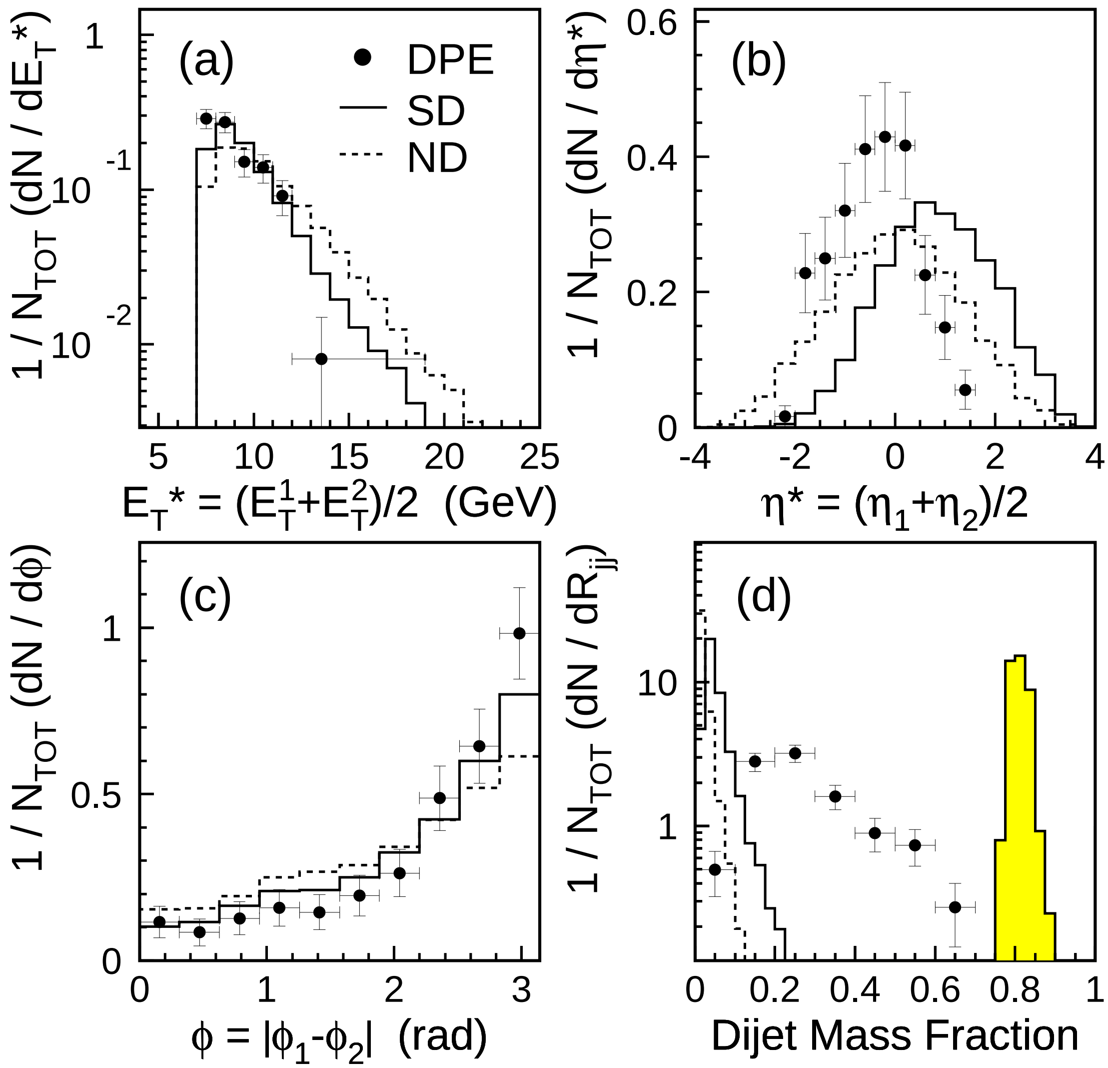


CDF: Regge factorization

$$F^D_{jj}(\beta,\xi) = C \cdot \frac{1}{\beta^n} \cdot \frac{1}{\xi^m}$$

$$n = 1.0 \pm 0.1 \quad m = 0.9 \pm 0.1$$

Double Pomeron Dijet Kinematics



(a) Average dijet E_T
(b) Average dijet pseudorapidity
(c) $\phi \equiv |\phi^{jet1} - \phi^{jet2}|$
(d) Dijet mass fraction: $R_X^{JJ} = M_{JJ}(cone)/M_X$
$M_{JJ}(cone)$ $\Rightarrow$ dijet mass from $E_T^{jet1,2}$ within cone of 0.7
$M_X = \sqrt{\xi_{\bar{p}}^{RPS} \cdot \xi_p^X \cdot s}$ $\Rightarrow$ total DPE c.m.s. energy

Double Pomeron Dijet Cross Sections

$$0.01 < \xi_p < 0.03$$
$$0.035 < \xi_{\bar{p}} < 0.095$$
$$-4.2 < \eta^{jet1,2} < +2.4$$

$$\sigma(E_T^{jet1,2} > 7\ \text{GeV}) = 43.6 \pm 4.4(\text{stat}) \pm 21.6(\text{syst})\ \text{nb}$$
$$\sigma(E_T^{jet1,2} > 10\,\text{GeV}) = 3.4 \pm 1.0(\text{stat}) \pm 2.0(\text{syst})\ \text{nb}$$

Exclusive dijet production

$$p + \bar{p} \to p' + (jet1 + let2) + \bar{p}'$$

$$E_T^{jet1,2} > 7\ \text{GeV}$$

$$\sigma(95\%\ \text{C.L.}) < 3.7\ \text{nb}$$

Predictions:

- A Berera, hep-ph/991045

$\sigma \sim \mathcal{O}(1\ \mu\text{b})$

- V.A. Khoze, A.D. Martin and M.G. Ryskin, hep-ph/0007083

$\sigma \approx 2$ nb

Hard diffraction conclusions

- Tevatron: SD at $\sqrt{s}$ =1800 GeV
  - QCD factorization:
    (1) all diffractive rate fractions $\approx 1\%$
    (2) diffractive gluon fraction $\approx$ same as in proton
    (3) diffractive gluon fraction process independent
    QCD factorization OK
  - Regge factorization:
    $\beta - \xi$ factorization in diffractive structure function
    Regge factorization OK
- Tevatron: SD at $\sqrt{s}$ =630 vs 1800 GeV
  - $R(630/1800) = 1.3 \pm 0.2^{+0.4}_{-0.3}$
    consistent with factorization
    also consistent with renormalization
- Tevatron: DPE vs SD at 1800 GeV
  - DPE/SD $>>$ SD/ND $\Rightarrow$ second gap not suppressed
- H1 vs Tevatron
  - QCD factorization breaks down
    consistent with renormalization