Diffractive and total pp cross sections at the LHC and beyond

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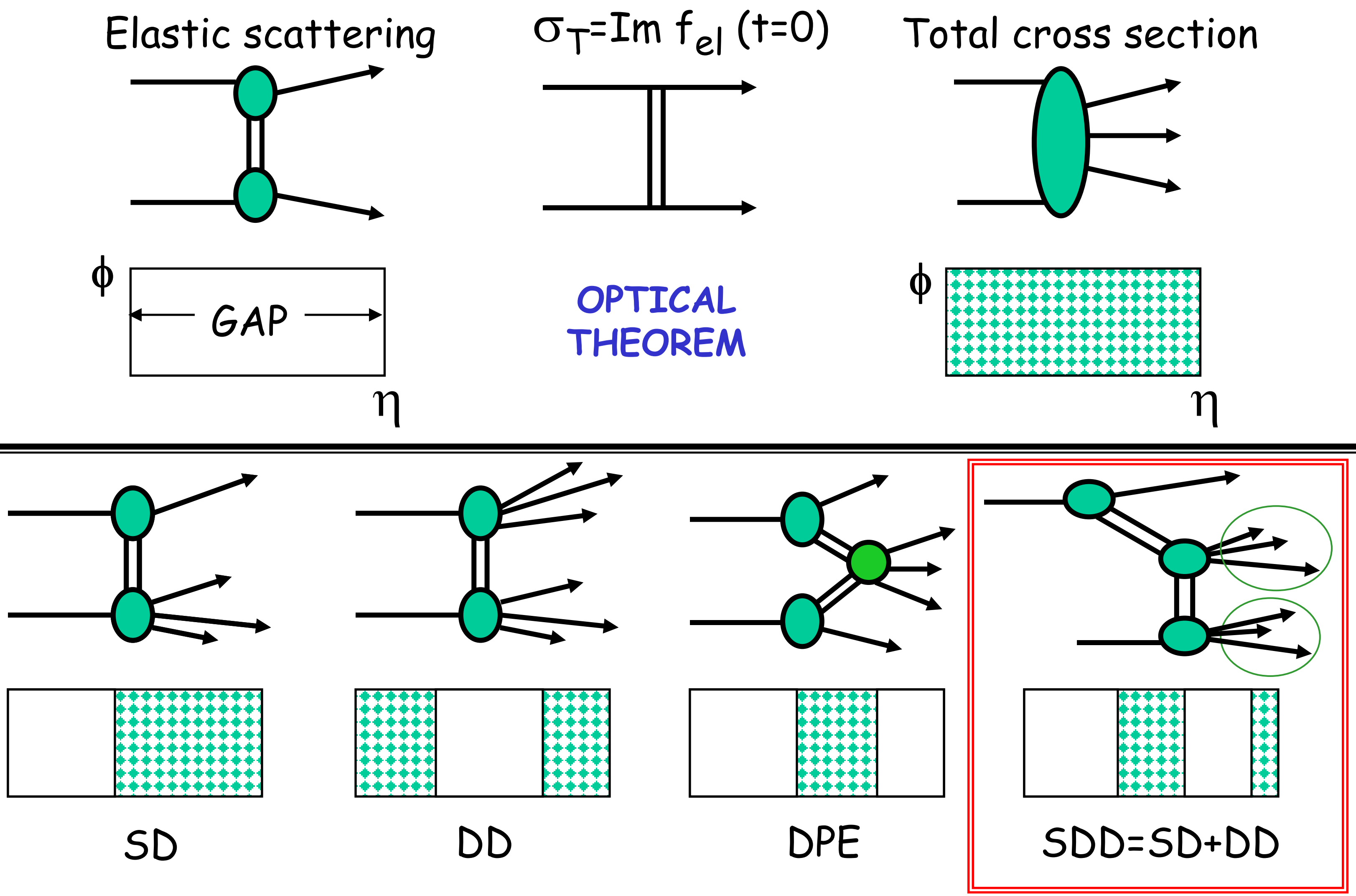
DIFFRACTION 2010
International Workshop on Diffraction in High-Energy Physics

CONTENTS

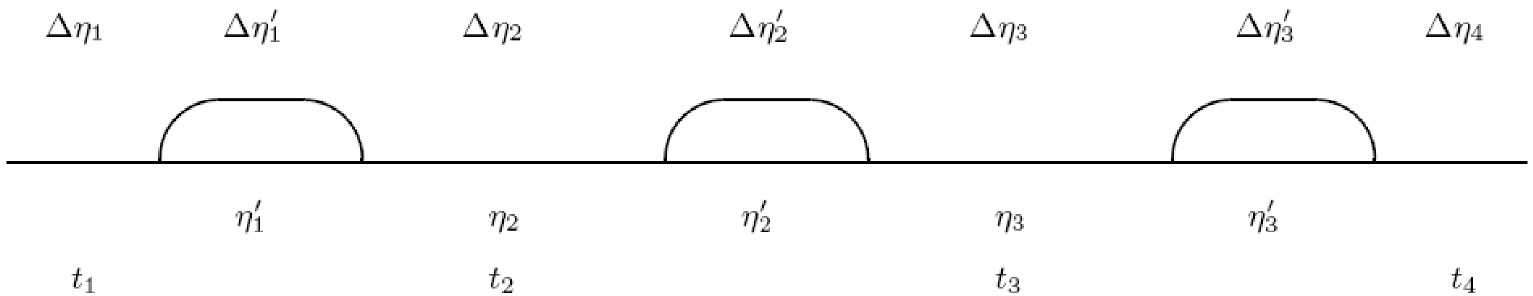
Diffractive pp/$\bar{p}$p Processes



Basic and combined (“nested”) diffractive processes

acronym	basic diffractive processes
$\mathbf{SD}_{\bar{p}}$	$\bar{p}p \to \bar{p} + \text{gap} + [p \to X_p]$,
$\mathbf{SD}_{p}$	$\bar{p}p \to [\bar{p} \to X_{\bar{p}}] + \text{gap} + p$,
DD	$\bar{p}p \to [\bar{p} \to X_{\bar{p}}] + \text{gap} + [p \to X_p]$,
DPE	$\bar{p}p \to \bar{p} + \text{gap} + X_c + \text{gap} + p$,
	2-gap combinations of SD and DD
$\mathbf{SDD}_{\bar{p}}$	$\bar{p}p \to \bar{p} + \text{gap} + X_c + \text{gap} + [p \to X_p]$,
$\mathbf{SDD}_{p}$	$\bar{p}p \to [\bar{p} \to X_{\bar{p}}]\text{gap} + X_c + \text{gap} + p$.

multi-gap “nested” process



The problem: the Regge theory description violates unitarity at high *s*

$$\left(\frac{d\sigma_{el}}{dt}\right)_{t=0} \sim \left(\frac{s}{s_o}\right)^{2\epsilon}, \quad \sigma_t \sim \left(\frac{s}{s_o}\right)^{\epsilon}, \quad \sigma_{sd} \sim \left(\frac{s}{s_o}\right)^{2\epsilon}$$

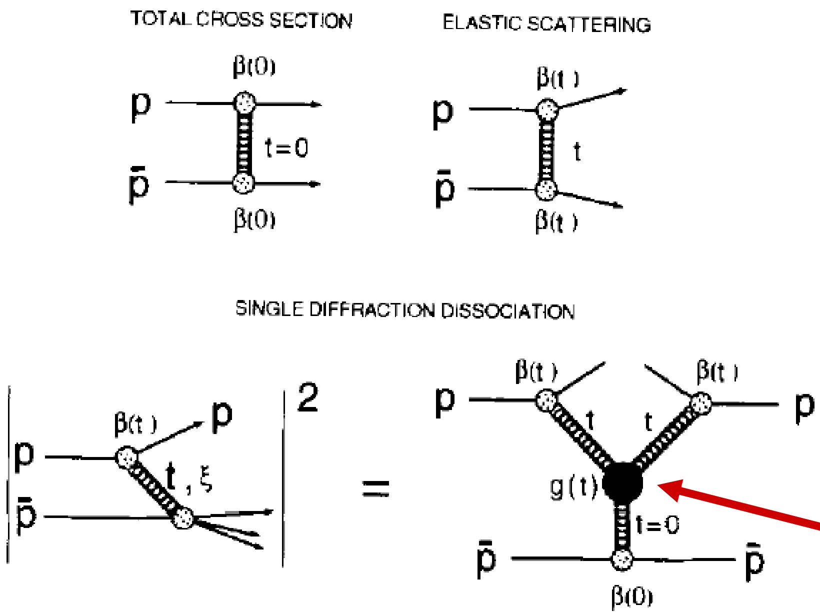
- $d\sigma/dt$ σ_{sd} grows faster than σ_t as *s* increases
  ➔ unitarity violation at high *s*

(similarly for partial x-sections in impact parameter space)

- the unitarity limit is already reached at $\sqrt{s}\sim 2$ TeV

Standard Regge Theory

KG-1995: PLB 358, 379 (1995)



$$\sigma_T = \beta_1(0)\beta_2(0)\left(\frac{s}{s_0}\right)^{\alpha(0)-1} = \sigma_0^{p\bar{p}}\left(\frac{s}{s_0}\right)^{\epsilon} \qquad (1)$$

$$\frac{d\sigma_{el}}{dt} = \frac{\beta_1^2(t)\beta_2^2(t)}{16\pi}\left(\frac{s}{s_0}\right)^{2[\alpha(t)-1]}$$

$$= \frac{\sigma_T^2}{16\pi}\left(\frac{s}{s_0}\right)^{2\alpha' t} F^4(t) \approx \frac{\sigma_T^2}{16\pi} e^{b_{el}(s)t} \qquad (2)$$

$$F^4(t) \approx e^{b_{0,el}t} \Rightarrow b_{el}(s) = b_{0,el} + 2\alpha' \ln\left(\frac{s}{s_0}\right) \qquad (3)$$

$$\frac{d^2\sigma_{sd}}{dt\,d\xi} = \frac{\beta_1^2(t)}{16\pi}\xi^{1-2\alpha(t)}\left[\beta_2(0)\,g(t)\left(\frac{s'}{s'_0}\right)^{\alpha(0)-1}\right]$$

$$= f_{\mathcal{P}/p}(\xi,t)\,\sigma_T^{\mathcal{P}\bar{p}}(s',t) \qquad (4)$$

Parameters:

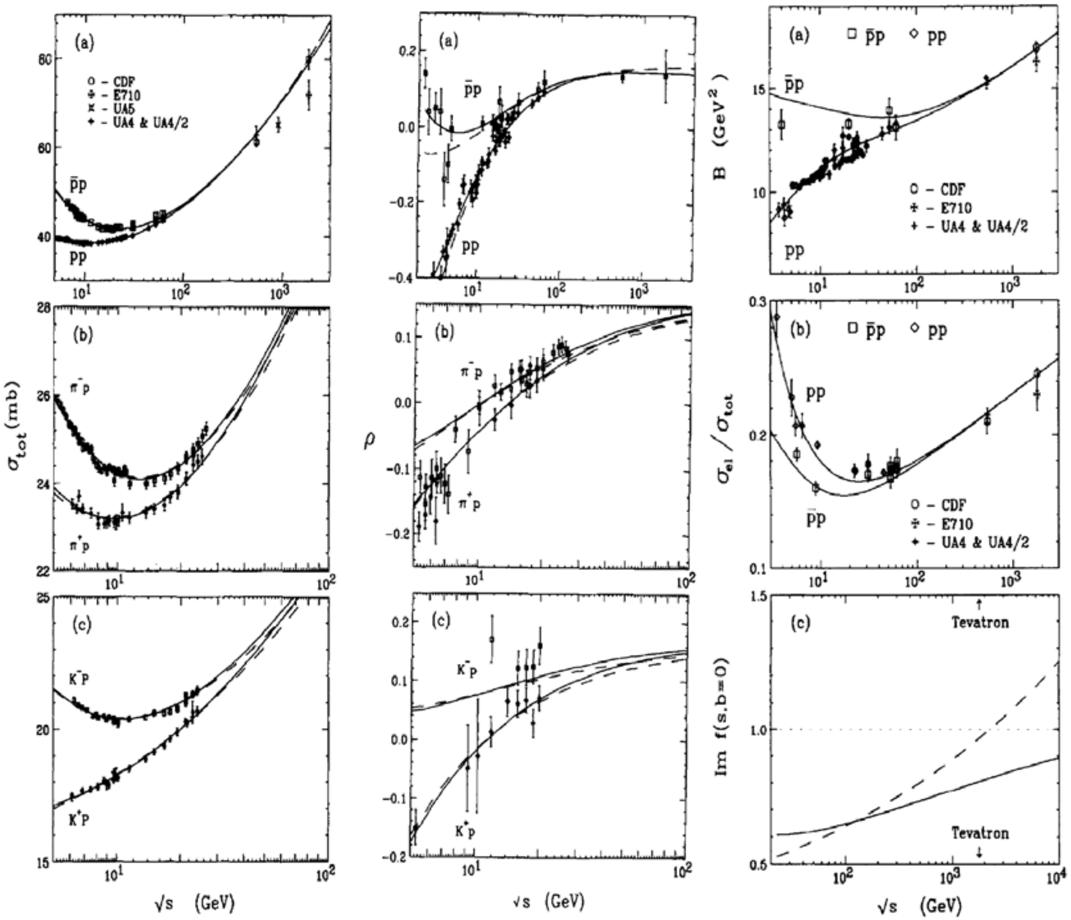
- s_0, s_0' and g(t)
- set $s_0' = s_0$ (universal IP)
- g(t) ➔ g(0) ≡ g_{PPP} →KG-1995
- determine s_0 and g_{PPP} – how?

Global fit to p±p, π±, K±p x-sections

CMG-1996
PLB 389, 176 (1996)

A new determination of the soft pomeron intercept

R.J.M. Covolan [1], J. Montanha [2], K. Goulianos [3]



Regge theory eikonalized

INPUT

$$\alpha_{f/a} = 0.68 + 0.82\,t$$

$$\alpha_{\omega/\rho} = 0.46 + 0.92\,t$$

$$\alpha'_{\mathbb{P}} = 0.25\ \mathrm{GeV}^{-2}$$

RESULTS

$$\alpha_{0,\mathbb{P}}^{\mathrm{Born}} = 1.104 \pm 0.002\,, \qquad \alpha_{0,\mathbb{P}}^{\mathrm{Eik}} = 1.122 \pm 0.002$$

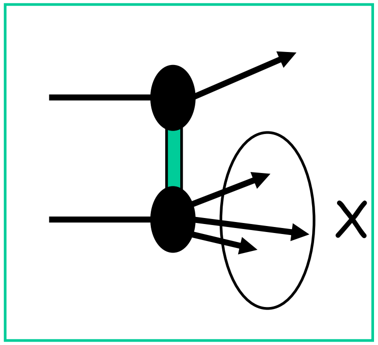
$$\sigma_{\mathrm{tot}}^{p^{\pm}p} = 16.79\, s^{0.104} + 60.81\, s^{-0.32} \mp 31.68\, s^{-0.54}$$

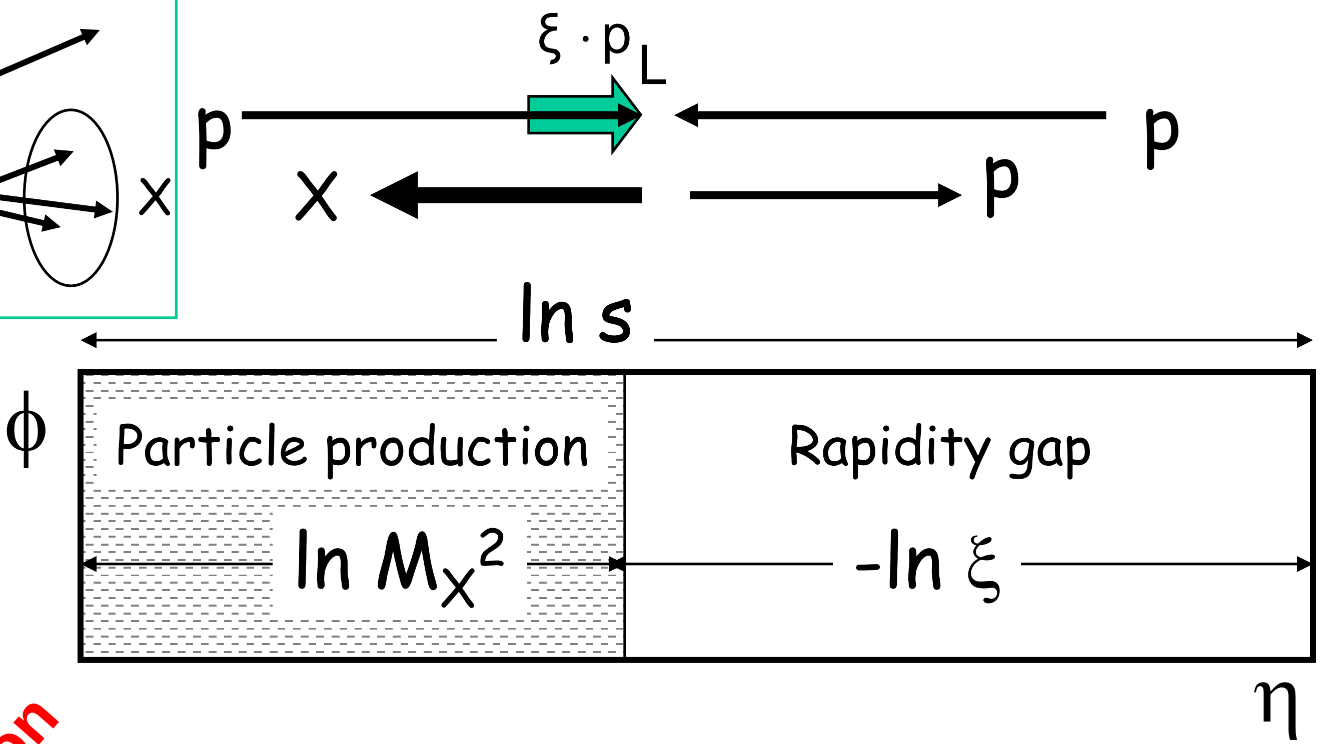
negligible

Renormalization
→ the key to diffraction in QCD

Diffractive gaps

definition: gaps not exponentially suppressed



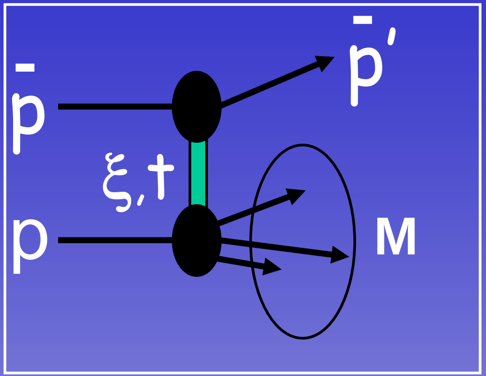


No radiation

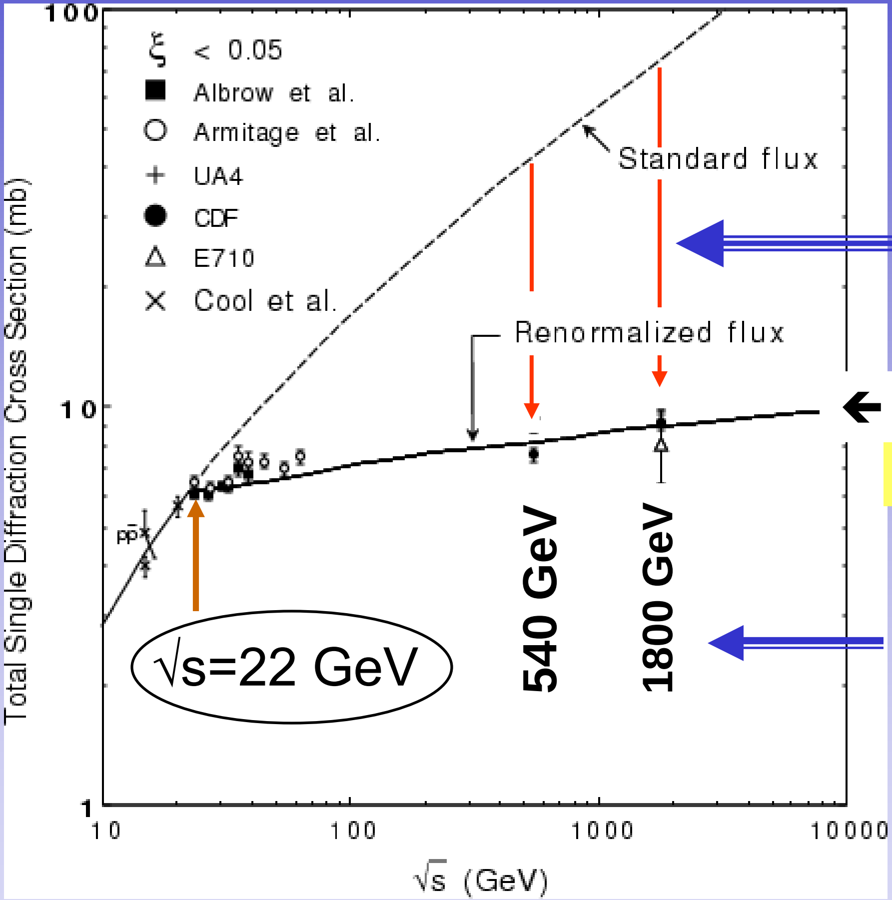
$$\left(\frac{d\sigma}{d\Delta\eta}\right)_{t=0} \approx \text{constant} \Rightarrow \frac{d\sigma}{dM^2} \sim \frac{1}{M^2} \quad \Rightarrow \frac{d\sigma}{d\xi} \sim \frac{1}{\xi}$$

σ^T_{SD} ($\bar{p}p$ & pp) - data

➔ suppressed relative to Regge for √s>22 GeV



σ^T_{SD} mb



Factor of ~8 (~5) suppression at √s = 1800 (540) GeV

← RENORMALIZATION MODEL

KG, PLB 358, 379 (1995)

CDF Run I results

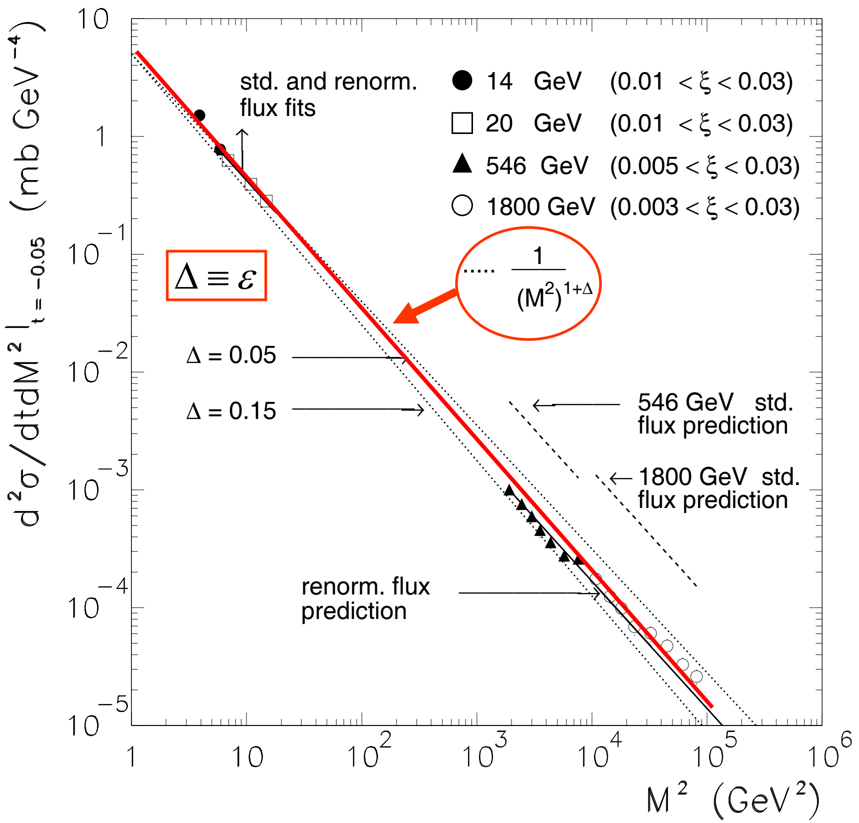
M^2 distribution: data

➔ $d\sigma/dM^2|_{t=-0.05}$ ~ independent of s over 6 orders of magnitude!

KG&JM, PRD 59 (1999) 114017

Regge ➔ data

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



Independent of S over 6 orders of magnitude in M^2

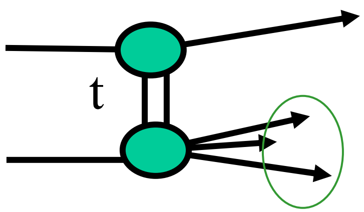
➔ M^2 scaling

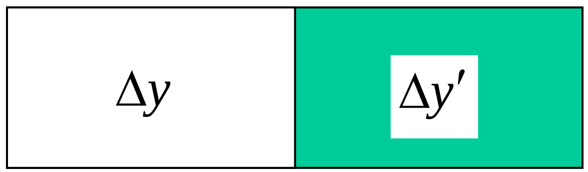
➔ factorization breaks down to ensure M^2 scaling

Single diffraction renormalized – (1)

CORFU-2001: hep-ph/0203141

EDS 2009: http://arxiv.org/PS_cache/arxiv/pdf/1002/1002.3527v1.pdf





2 independent variables: $t, \Delta y$

color factor

$$\kappa = \frac{g_{IP-IP-IP}(t)}{\beta_{IP-p-p}(0)} \approx 0.17$$

$$\frac{d^2\sigma}{dt\, d\Delta y} = \underbrace{C \cdot F_p^2(t) \cdot \left\{ e^{(\varepsilon+\alpha' t)\Delta y} \right\}^2}_{\text{gap probability}} \cdot \kappa \cdot \left\{ \underbrace{\sigma_o\, e^{\varepsilon\, \Delta y'}}_{\text{sub-energy x-section}} \right\}$$

Gap probability ➔ (re)normalize to unity

Single diffraction renormalized – (2)

color factor

$$\kappa = \frac{g_{IP-IP-IP}(t)}{\beta_{IP-p-p}(0)} \approx 0.17$$

Experimentally:

KG&JM, PRD 59 (114017) 1999

$$\kappa = \frac{g_{IP-IP-IP}}{\beta_{IP-p}} = 0.17 \pm 0.02, \quad \varepsilon = 0.104$$

QCD: $\kappa = \mathrm{f}_g \times \frac{1}{N_c^2 - 1} + \mathrm{f}_q \times \frac{1}{N_c} \xrightarrow{Q^2 = 1} \approx 0.75 \times \frac{1}{8} + 0.25 \times \frac{1}{3} = 0.18$

Single diffraction renormalized - (3)

$$\frac{d^2\sigma_{sd}(s,M^2,t)}{dM^2dt} = \left[\frac{\sigma_\circ}{16\pi}\sigma_\circ^{I\!Pp}\right] \frac{s^{2\epsilon}}{N(s,s_o)} \frac{e^{bt}}{(M^2)^{1+\epsilon}}$$

$$b = b_0 + 2\alpha' \ln\frac{s}{M^2} \qquad s_o^{\mathrm{CMG}} = (3.7 \pm 1.5)\ \mathrm{GeV}^2$$

$$N(s,s_o) \equiv \int_{\xi_{\min}}^{\xi_{\max}} d\xi \int_{t=0}^{-\infty} dt\, f_{I\!P/p}(\xi,t) \overset{s\to\infty}{\to} \sim s_o^{\epsilon}\frac{s^{2\epsilon}}{\ln s}$$

$$\frac{d^2\sigma_{sd}(s,M^2,t)}{dM^2dt} \overset{s\to\infty}{\to} \sim \ln s\, \frac{e^{bt}}{(M^2)^{1+\epsilon}}$$

$$\sigma_{sd} \xrightarrow{s\to\infty} \sim \frac{\ln s}{b \to \ln s} \Rightarrow const$$

set to unity
➔ determine s_o

Single diffraction renormalized – (4)

$$\frac{d^2\sigma}{dt\,d\Delta y} = N_{gap} \cdot \underbrace{C \cdot F_p^2(t) \cdot \left\{ e^{(\varepsilon+\alpha' t)\Delta y} \right\}^2}_{P_{gap}(\Delta y, t)} \cdot \kappa \cdot \left\{ \sigma_o \, e^{\varepsilon \, \Delta y'} \right\}$$

$$N_{gap}^{-1}(s) = \int_{\Delta y, t} P_{gap}(\Delta y, t)\, d\Delta y\, dt \xrightarrow{s\to\infty} C' \cdot \frac{s^{2\varepsilon}}{\ln s}$$

$$\frac{d^2\sigma}{dt\,d\Delta y} = C'' \left[e^{\varepsilon(\Delta y - \ln s)} \cdot \ln s \right] e^{(b_0 + 2\alpha' \Delta y)t}$$

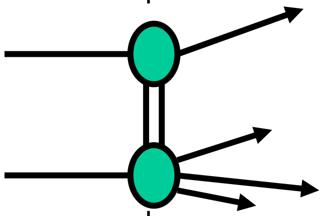
Grows slower than s^{ε}

→ Pumplin bound obeyed at all impact parameters

Scale s_o and triple-pom coupling

Pomeron flux: interpret as gap probability
➔set to unity: determines g_{PPP} and s_0

KG, PLB 358 (1995) 379



s_0^{ε}

$$\frac{d^2\sigma_{SD}}{dt\,d\xi} = f_{IP/p}(t,\xi)\cdot\sigma_{IP-\bar{p}}(s\xi)$$

$s_0^{-\varepsilon/2}\cdot g_{PPP}(t)$

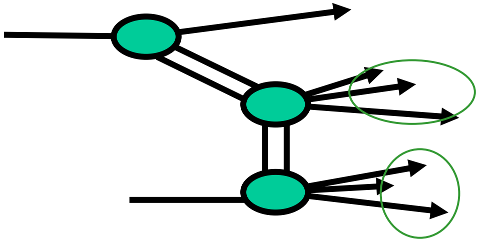
Pomeron-proton x-section

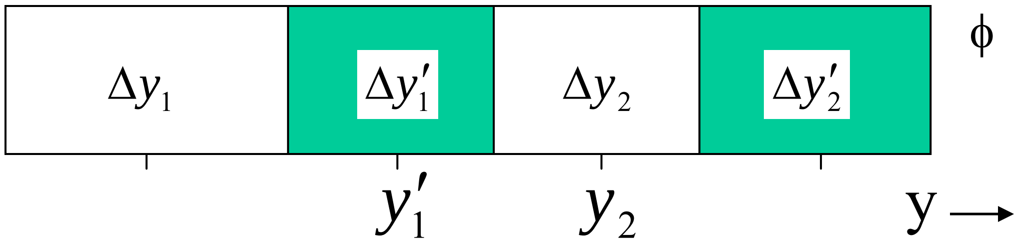
- ❑ Two free parameters: s_0 and g_{PPP}
- ❑ Obtain product $g_{PPP}\bullet s_0^{\varepsilon/2}$ from σ_{SD}
- ❑ Renormalized Pomeron flux determines s_0
- ❑ Get unique solution for g_{PPP}

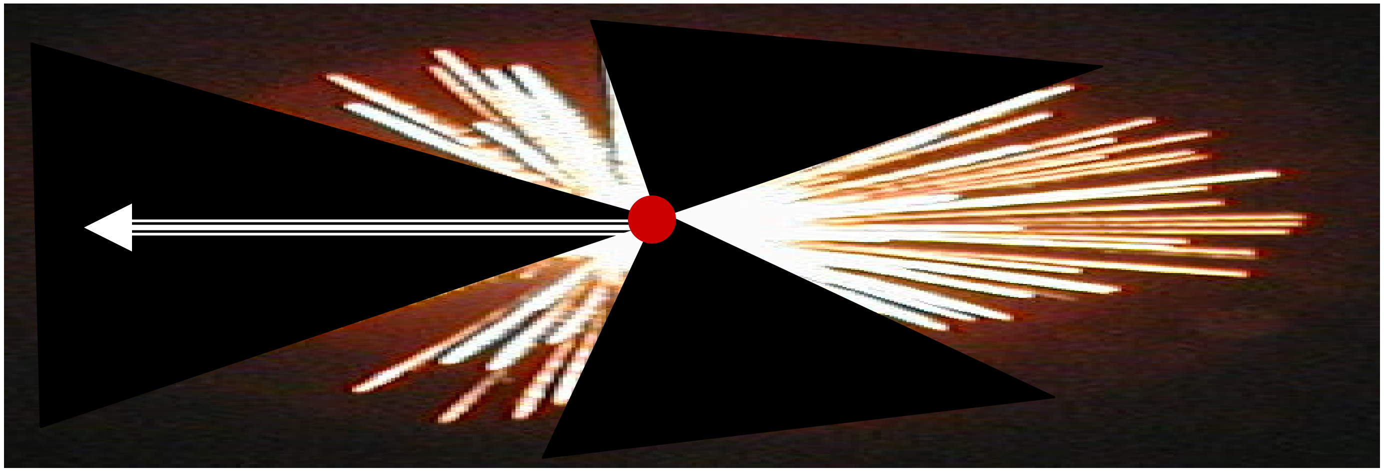
$g_{PPP}=0.69\ \mathrm{mb}^{-1/2}=1.1\ \mathrm{GeV}^{-1}$ $S_o=3.7\pm1.5\ \mathrm{GeV}^2$

Multigap diffraction

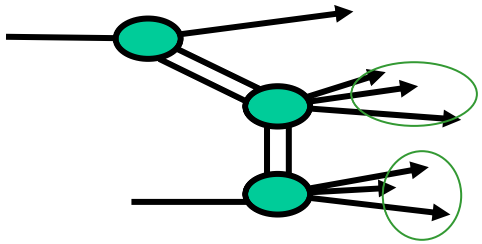
KG, hep-ph/0203141

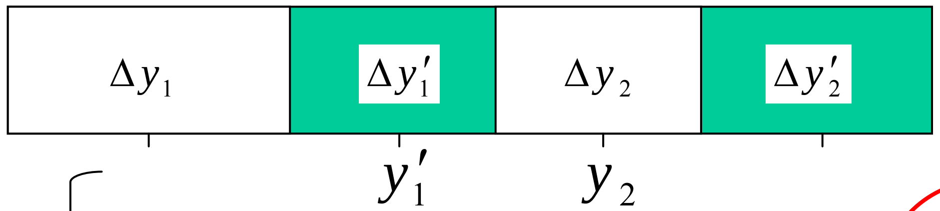






Multigap cross sections





5 independent variables $\left\{ y'_1,\ y_2,\ t_1,\ \Delta y = \Delta y_1 + \Delta y_2,\ t_2 \right.$

color factor

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

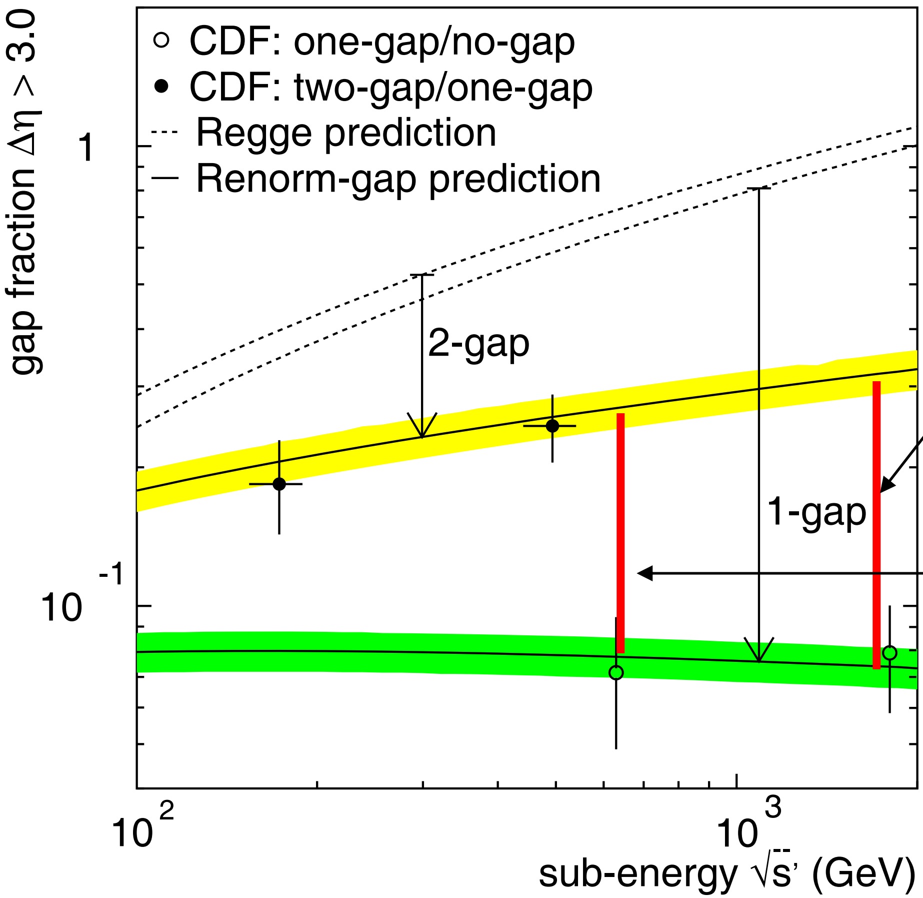
Gap probability

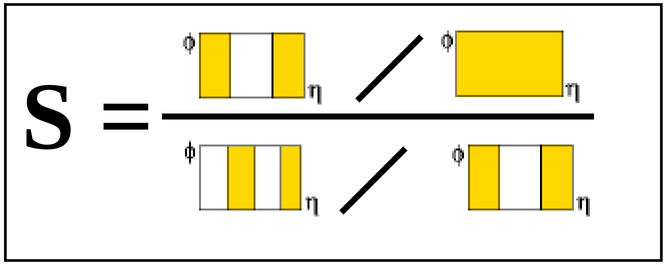
$$\int_{\Delta y, t} \sim s^{2\varepsilon} / \ln s$$

Sub-energy cross section (for regions with particles)

Same suppression as for single gap!

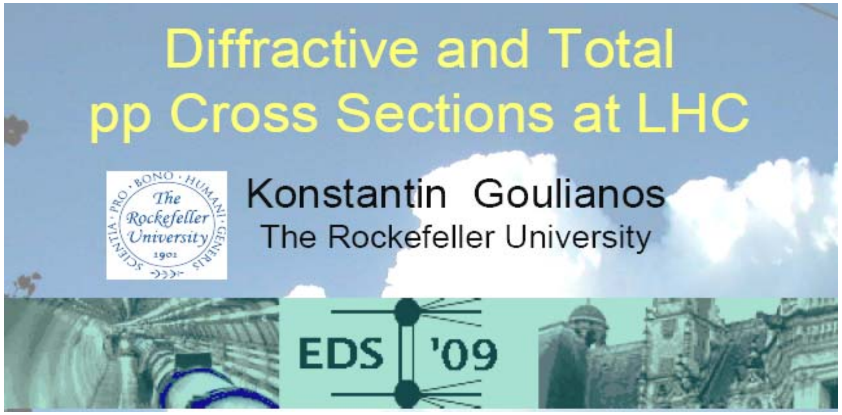
Gap survival probability

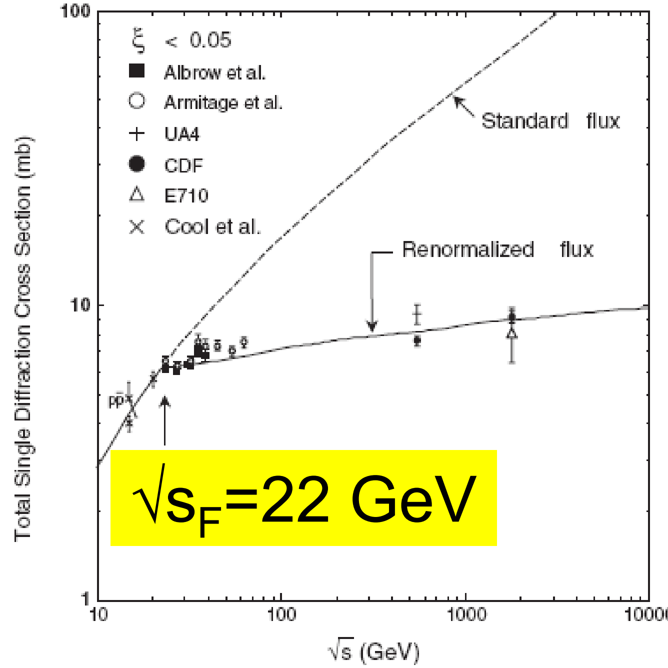




$$S^{1-gap/0-gap}_{2-gap/1-gap}(1800\ \mathrm{GeV}) \approx 0.23$$

$$S^{1-gap/0-gap}_{2-gap/1-gap}(630\ \mathrm{GeV}) \approx 0.29$$





- Use the Froissart formula as a *saturated* cross section

$$\sigma_t(s > s_F) = \sigma_t(s_F) + \frac{\pi}{m^2} \cdot \ln^2 \frac{s}{s_F}$$

- This formula should be valid above the *knee* in σ_{sd} vs. $\sqrt{s}$ at $\sqrt{s_F} = 22$ GeV (Fig. 1) and therefore valid at $\sqrt{s} = 1800$ GeV.

- Use $m^2 = s_o$ in the Froissart formula multiplied by 1/0.389 to convert it to mb^{-1}.

- Note that contributions from Reggeon exchanges at $\sqrt{s} = 1800$ GeV are negligible, as can be verified from the global fit of Ref. [7].

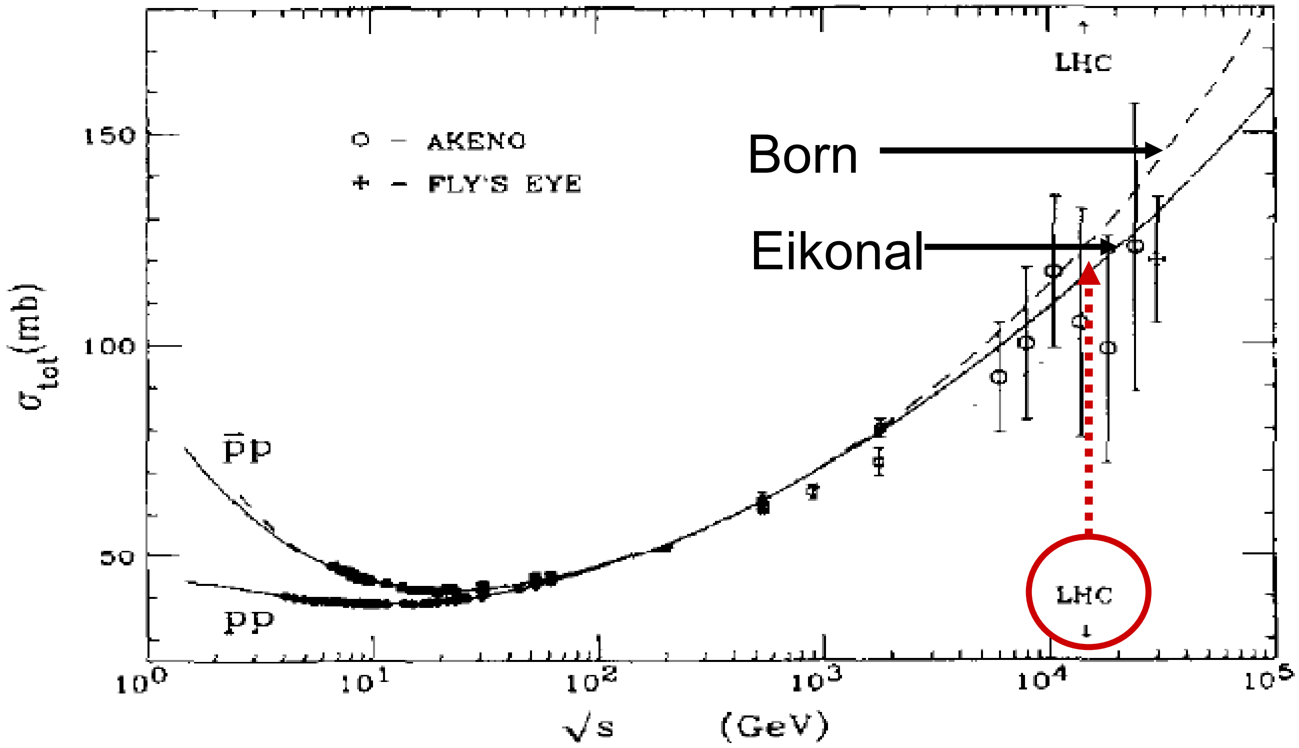
- Obtain the total cross section at the LHC:

$$\sigma_t^{\rm LHC} = \sigma_t^{\rm CDF} + \frac{\pi}{s_o} \cdot \left(\ln^2 \frac{s^{\rm LHC}}{s_F} - \ln^2 \frac{s^{\rm CDF}}{s_F} \right)$$

SUPERBALL MODEL

98 ± 8 mb at 7 TeV
109 ±12 mb at 14 TeV

σ^T at LHC from CMG global fit



- σ @ LHC $\sqrt{s}$=14 TeV: 122 ± 5 mb Born, 114 ± 5 mb eikonal
  ➔ error estimated from the error in ε given in CMG-96

Compare with **SUPERBALL** σ(14 TeV) = 109 ± 6 mb

caveat: s_o=1 GeV^2 was used in global fit!

σ^{SD} and ratio of α'/ε

PHYSICAL REVIEW D **80**, 111901(R) (2009)

Pomeron intercept and slope: A QCD connection

Konstantin Goulianos

$$\frac{d^2\sigma_{sd}(s,M^2,t)}{dM^2dt} = \left[\frac{\sigma_\circ}{16\pi}\sigma_\circ^{\mathbb{P}p}\right]\frac{s^{2\epsilon}}{N(s)}\frac{1}{(M^2)^{1+\epsilon}}e^{bt}$$

$$\stackrel{s\to\infty}{\Rightarrow}\left[2\alpha' e^{(\epsilon b_0)/\alpha'}\sigma_\circ^{\mathbb{P}p}\right]\frac{\ln s^{2\epsilon}}{(M^2)^{1+\epsilon}}e^{bt}$$

$$\sigma_{pp/\bar{p}p}^{\rm tot} = \sigma_\circ \cdot e^{\epsilon\Delta\eta}.$$

$$\sigma_{sd}^{\infty} = 2\sigma_\circ^{\mathbb{P}p}\exp\left[\frac{\epsilon b_\circ}{2\alpha'}\right] = \sigma_\circ^{pp}$$

$$\sigma_\circ^{\mathbb{P}p} = \beta_{\mathbb{P}pp}(0)\cdot g(t) = \kappa\sigma_\circ^{pp}$$

$$\kappa = \frac{f_g^\infty}{N_c^2 - 1} + \frac{f_q^\infty}{N_c}$$

$$b_\circ = R_p^2/2 = 1/(2m_\pi^2).$$

$$r = \frac{\alpha'}{\epsilon} = -[16m_\pi^2\ln(2\kappa)]^{-1}$$

$$r_{\rm pheno} = 3.2 \pm 0.4\ ({\rm GeV}/c)^{-2}$$

$$r_{\rm exp} = 0.25\ ({\rm GeV}/c)^{-2}/0.08 = 3.13\ ({\rm GeV}/c)^{-2}$$

Monte Carlo Strategy for the LHC

MONTE CARLO STRATEGY

- ❑ σ^T → from SUPERBALL model
- ❑ optical theorem → Im $f_{el}(t=0)$
- ❑ dispersion relations → Re $f_{el}(t=0)$
- ❑ differential σ^{SD} → from RENORM
- ❑ use *nested* pp final states for

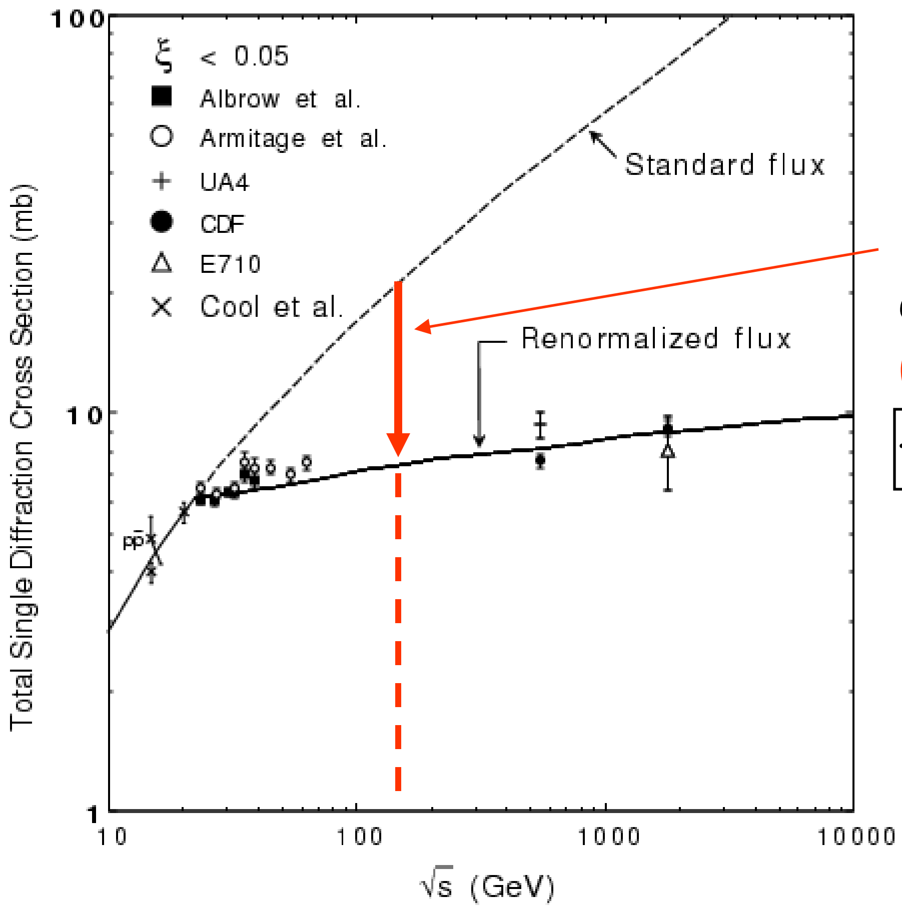
pp collisions at the IP - p sub-energy √s'

σ_T
↕ **optical theorem**
Im $f_{el}(t=0)$
↕ **dispersion relations**
Re $f_{el}(t=0)$

Strategy similar to that employed in the MBR (Minimum Bias Rockefeller) MC used in CDF based on multiplicities from:
K. Goulianos, Phys. Lett. B 193 (1987) 151 pp
"A new statistical description of hardonic and e^+e^- multiplicity distributions "

Dijets in γp at HERA from RENORM

K. Goulianos, POS (DIFF2006) 055 (p. 8)



Factor of ~3 suppression expected at W~200 GeV (just as in pp collisions)

for both direct and resolved components

SUMMARY

- Froissart bound $\sigma \le (\pi / m^{2)} \cdot \ln^2 s$
- Valid above the “knee” at √s = 22 GeV in σ_T^{SD} vs. √s

and therefore valid at √s = 1.8 TeV of the CDF measurement

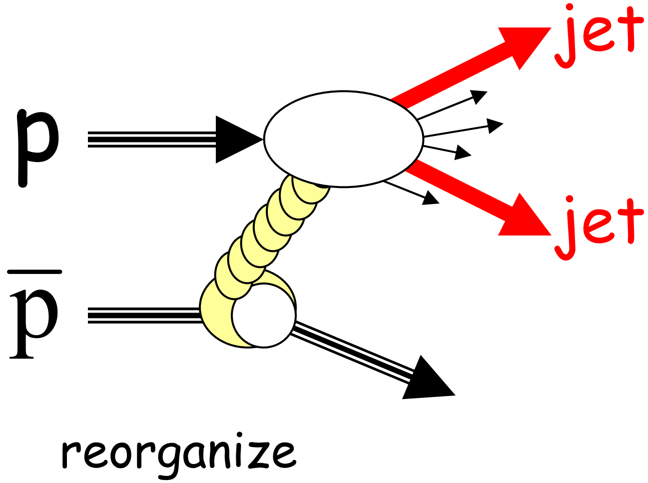
- Use superball scale s_0 (saturated exchange) in the Froissart formula, where s_0= 3.7±1.5 GeV²as determined from setting the integral of the Pomeron flux to unity at the “kneee” of s√s = 22 GeV

  ➔ $m^2 = s_0 = (3.7 \pm 1.5\ \mathrm{GeV}^2$

- At √s 1.8 TeV Reggeon contributions are negligible (see global fit)
- $$\sigma_{14000}^{LHC} = \sigma_{1800}^{CDF} + \frac{\pi}{s_0} \cdot \left(\ln^2 \frac{s^{LHC}}{s_F} - \ln^2 \frac{s^{CDF}}{s_F} \right) = (80.03 \pm 2.24) + (29 \pm 12) = 109 \pm 12 \text{ mb}$$
- compatible with CGM-96 global fit result of 114 ± 5 mb
- σ_t= (98 ± 8) mb at 7 TeV – wait and see!

BACKUP

Diffractive dijets @ Tevatron



$$F^D(\xi, x, Q^2) \propto \frac{1}{\xi^{1+2\varepsilon}} \cdot F(x/\xi, Q^2)$$

$F^D_{JJ}(\xi,\beta,Q^2)$ @ Tevatron

$$F^D(\xi,\beta,Q^2) = N_{renorm}\frac{1}{\xi^{1+2\varepsilon}}\cdot\frac{C(Q^2)}{(x/\xi)^{\lambda(Q^2)}} = \frac{2\varepsilon}{(\beta\, s)^{2\varepsilon}}\cdot\frac{1}{\xi^{1+2\varepsilon}}\cdot\frac{C(Q^2)}{\beta^{\lambda(Q^2)}}$$

$$N_{renorm}^{-1} = \int_{\xi_{min}}^{1}\frac{d\xi}{\xi^{1+2\varepsilon}} \xrightarrow{\xi_{min}=\frac{x_{min}}{\beta}\approx\frac{1}{\beta\, s}} \frac{(\beta\, s)^{2\varepsilon}}{2\varepsilon}$$

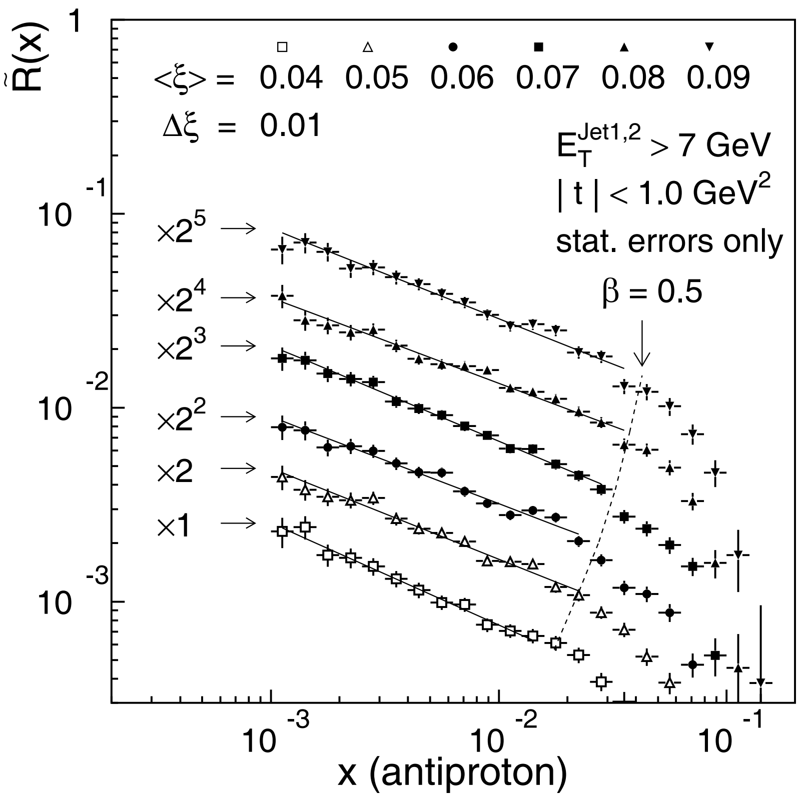
$$\text{RENORM} \Rightarrow R^{SD}_{ND}(x) = \frac{2\varepsilon}{s^{2\varepsilon}}\frac{1}{\xi^{1-\lambda(Q^2)}}\cdot x^{-(2\varepsilon)}$$

$$\varepsilon_g = 0.2 \rightarrow x^{-0.4}$$

SD/ND dijet ratio vs. x_{Bj}@ CDF

CDF Run I

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



0.035 < ξ < 0.095

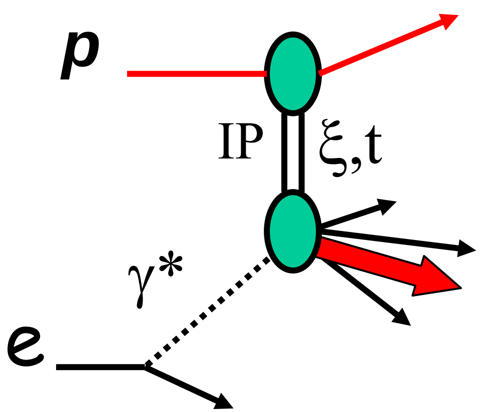
Flat ξ dependence for β < 0.5

$$R(x) = x^{-0.45}$$

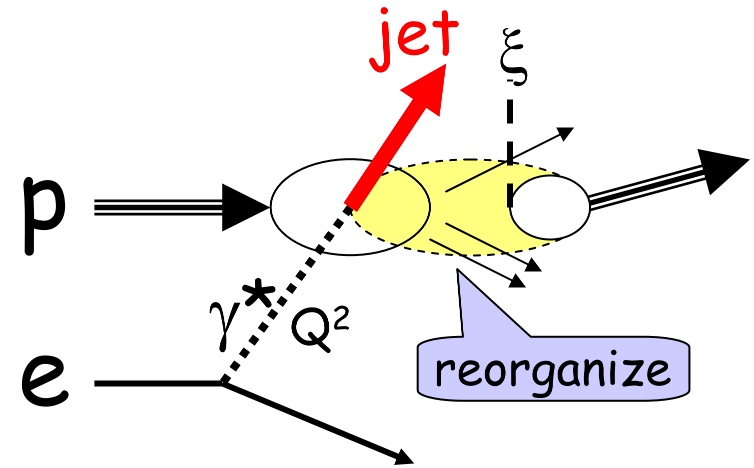
Diffractive DIS @ HERA

J. Collins: factorization holds (but under what conditions?)

Pomeron exchange



Color reorganization

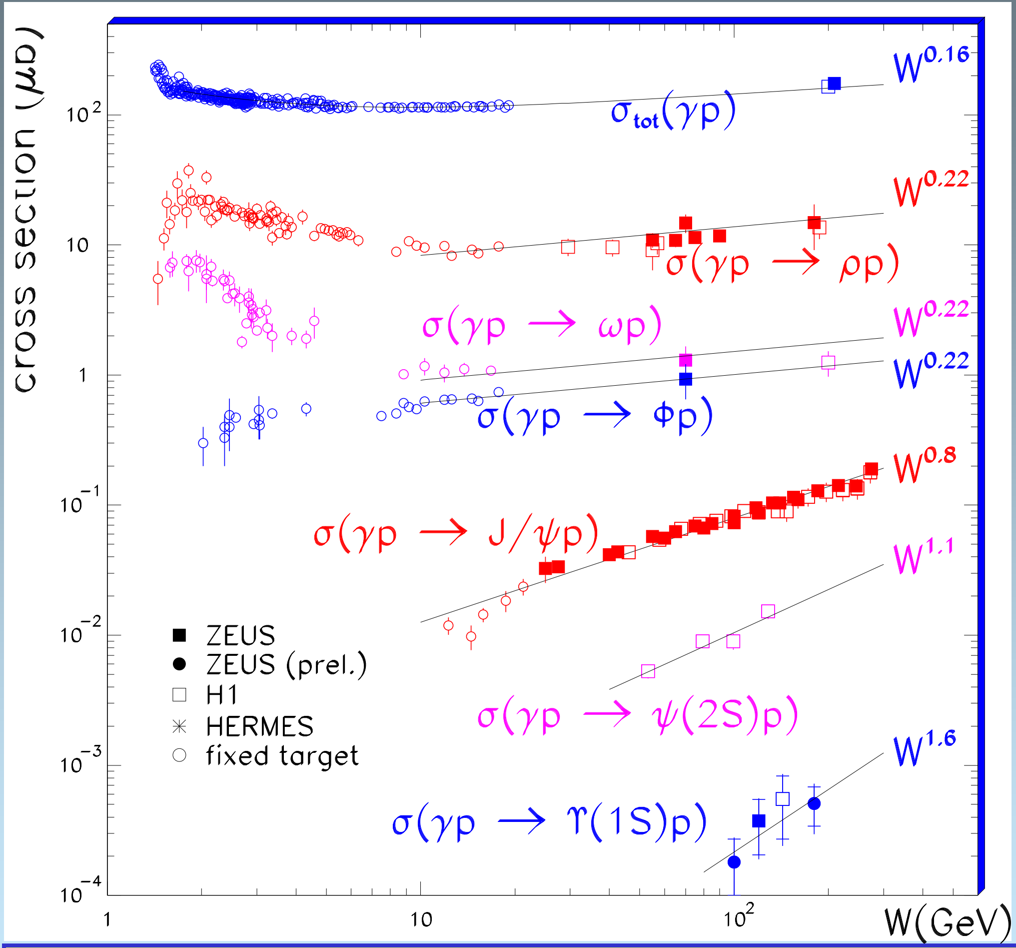


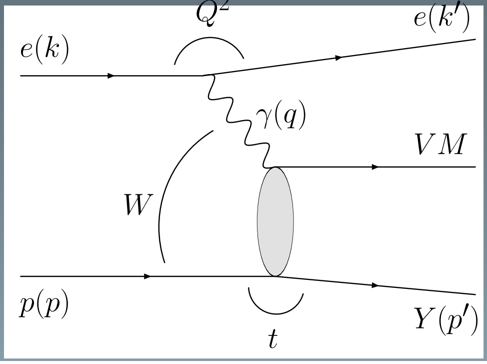
$$F_2^{D(3)}(\xi, x, Q^2) \propto \frac{1}{\xi^{1+\varepsilon}} \cdot F_2(x, Q^2)$$

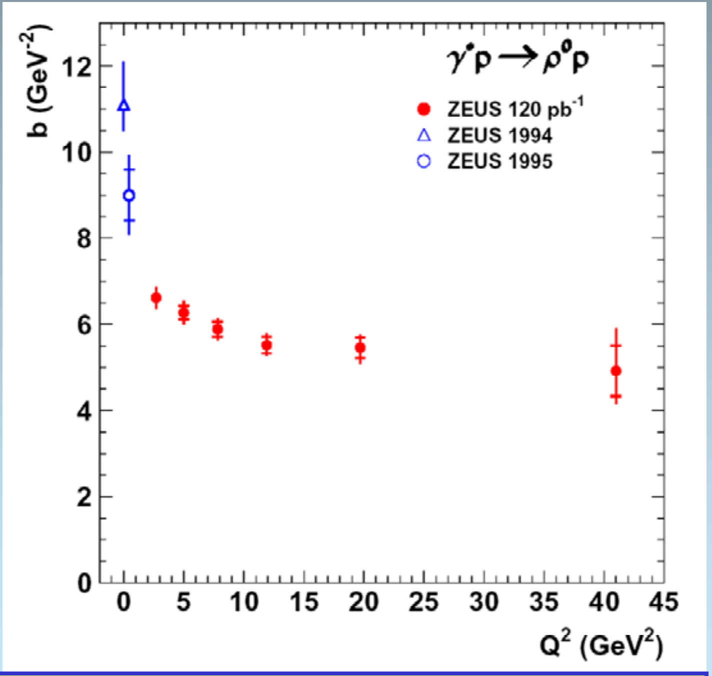
Results favor color reorganization

Vector meson production

(Pierre Marage, HERA-LHC 2008)

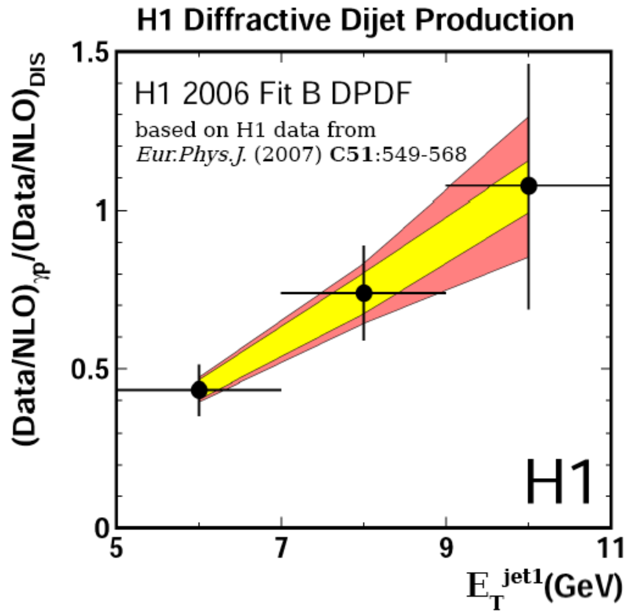




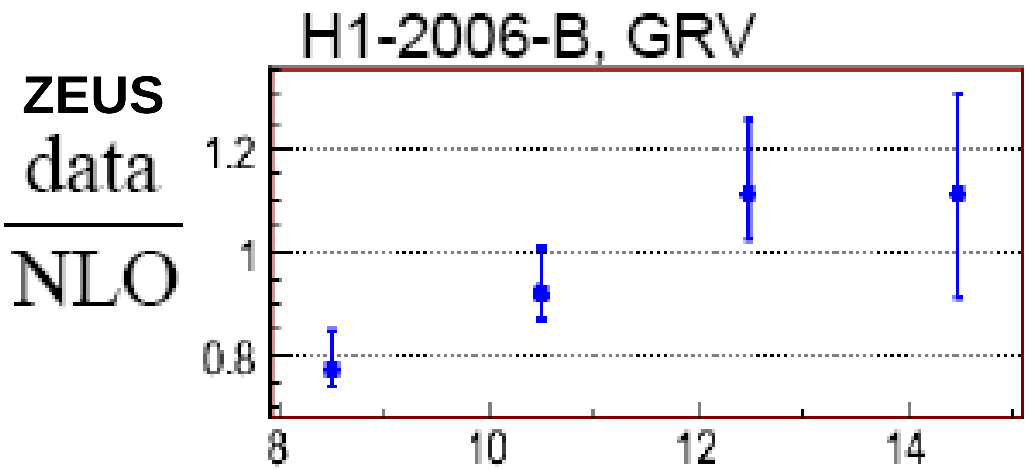


- *left* - why different σ vs. W slopes? ➔ more room for particles
- *right* - why smaller b-slope in γ*p? ➔ same reason

Dijets in γp at HERA - 2008



DIS 2008 talk by W. Słomiński,



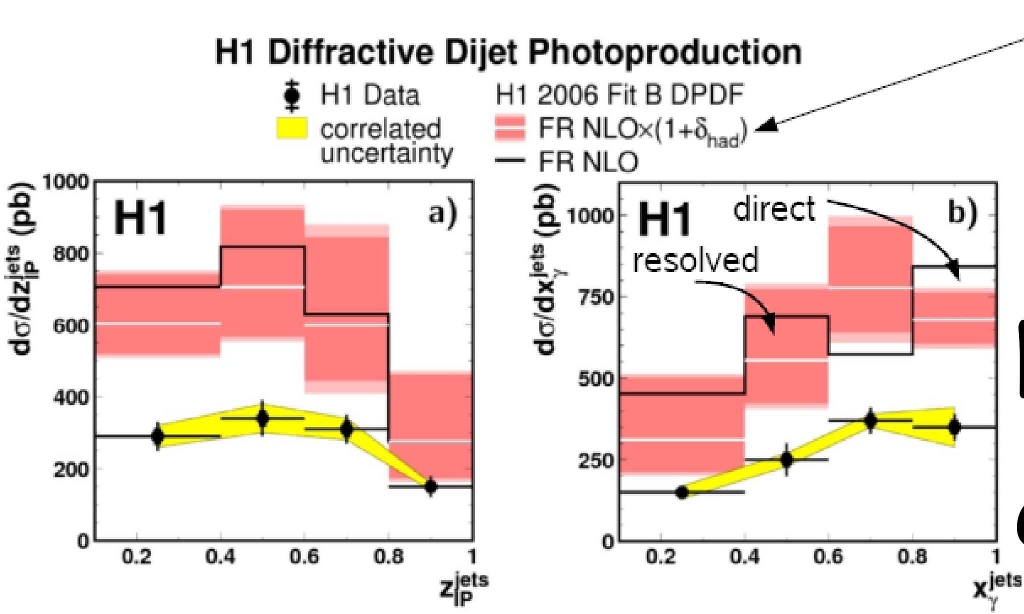
❑ 20-50 % apparent rise when E_T^{jet} 5→10 GeV

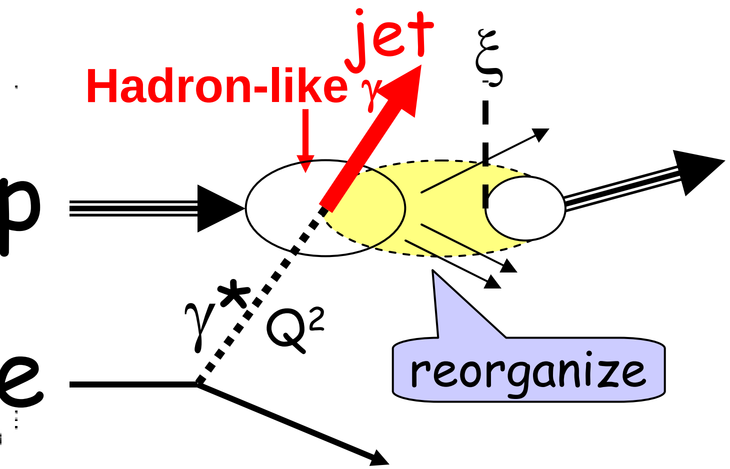
➔ due to suppression at low E_T^{jet} !!!

Dijets in γp at HERA – 2007

Dijets in γp

Direct vs. resolved





- the reorganization diagram predicts:
  - ➔ suppression at low Z_{IP}^{jets}, since larger $\Delta\eta$ is available for particles
  - ➔ same suppression for direct and resolved processes

The end