

Predictions of Diffraction at the LHC Compared to Experimental Results



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<http://indico.cern.ch/event/icnfp2013>





CONTENTS

- ❑ **Total pp cross section:** predicted in a unitarized parton model approach, which does not employ eikonalization and does not depend on the ρ -value.
- ❑ **Diffraction cross sections:**
 - ❑ SD - single dissociation: one of the protons dissociates.
 - ❑ DD - double dissociation: both protons dissociate.
 - ❑ CD – central diffraction: neither proton dissociates, but there is central diffractive production of particles.
- ❑ **Triple-Pomeron coupling:** uniquely determined.

➤ This is an updated version of a talk presented at EDS-2013.

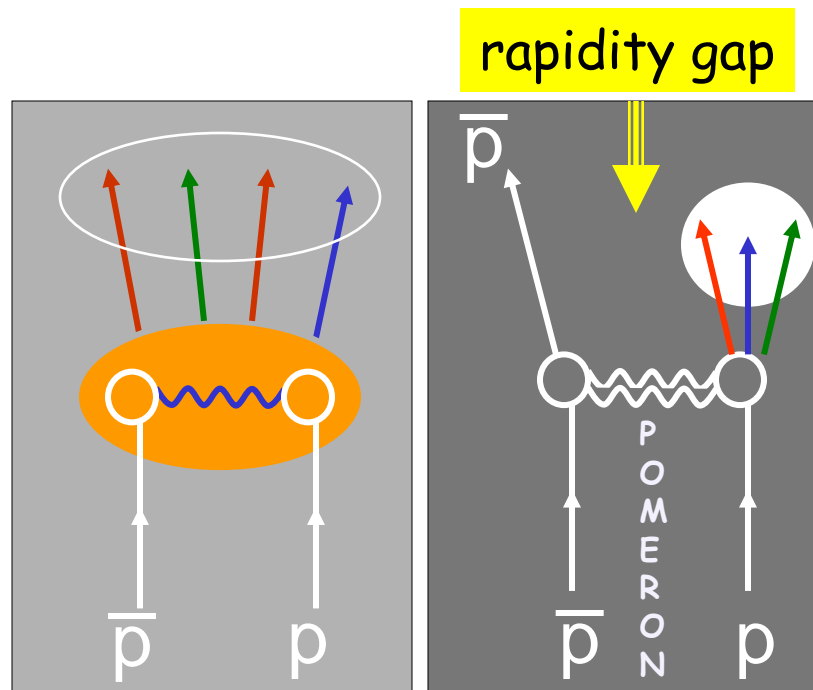
DIFFRACTION IN QCD

Non-diffractive events

- ❖ color-exchange \rightarrow η -gaps exponentially suppressed

Diffractive events

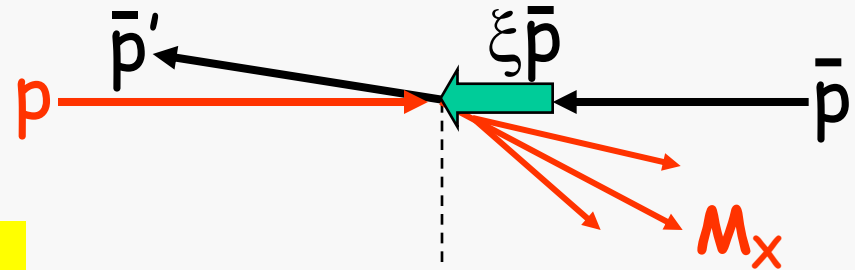
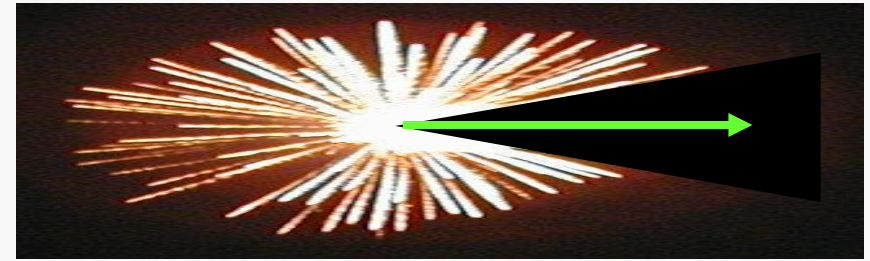
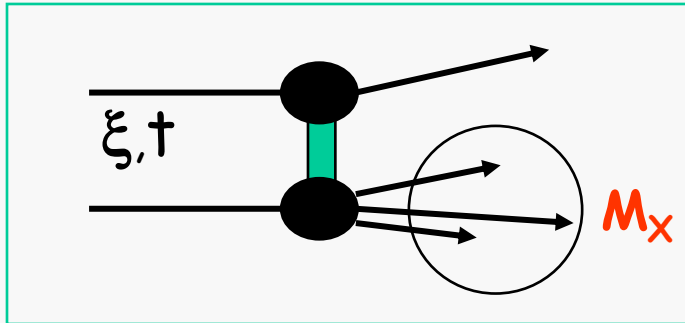
- ❖ Colorless vacuum exchange \rightarrow η -gaps not suppressed



Goal: probe the QCD nature of the diffractive exchange

DEFINITIONS

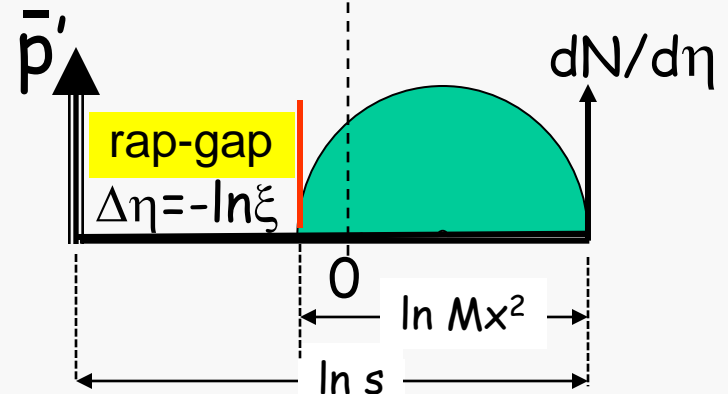
SINGLE DIFFRACTION



$$1 - x_L \equiv \xi = \frac{M_X^2}{s}$$

Forward momentum loss

$$\xi^{\text{CAL}} = \frac{\sum_{i=1}^{\text{all}} E_T^{i\text{-tower}} e^{-\eta_i}}{\sqrt{s}}$$



since no radiation \rightarrow
no price paid for increasing
diffractive-gap width

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

DIFFRACTION AT CDF

Elastic scattering

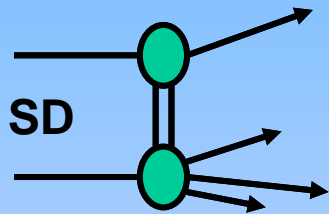
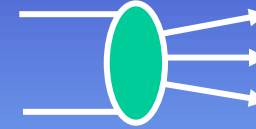


$\sigma_T = \text{Im } f_{el}(t=0)$

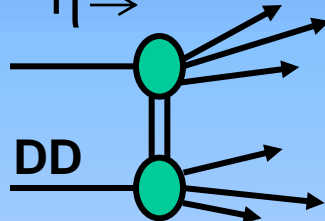
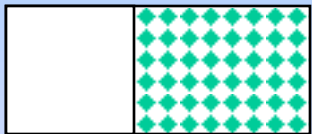


OPTICAL THEOREM

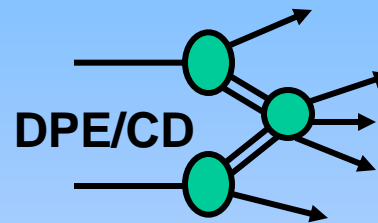
Total cross section



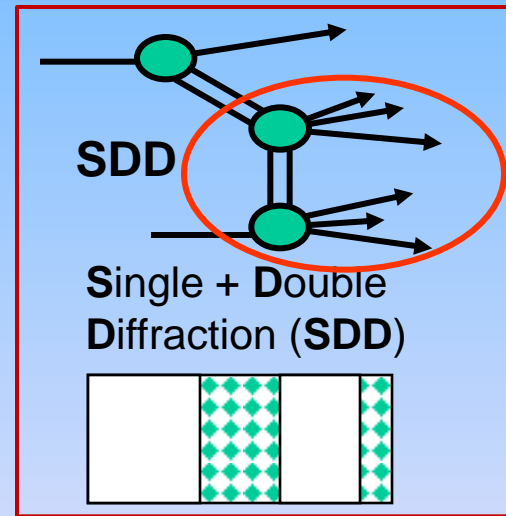
Single Diffraction or Single Dissociation



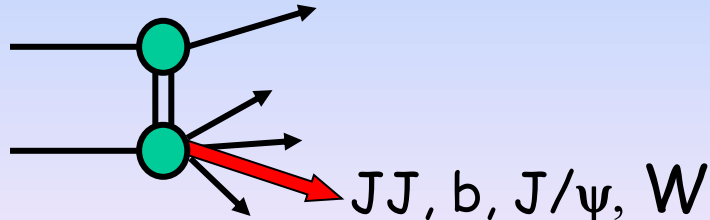
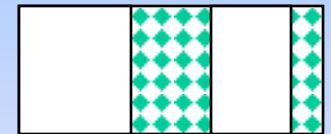
Double Diffraction or Double Dissociation



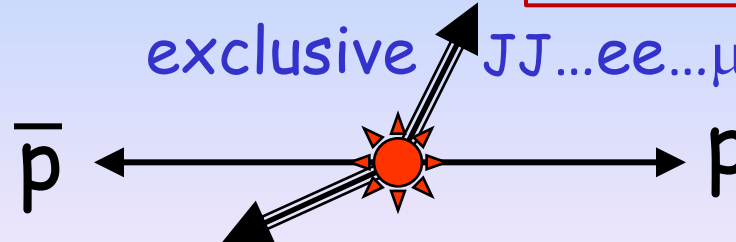
Double Pom. Exchange or Central Dissociation



Single + Double Diffraction (SDD)



exclusive $JJ \dots ee \dots \mu\mu \dots \gamma\gamma$



Basic and combined diffractive processes

acronym basic diffractive processes

$$\mathbf{SD}_{\bar{p}} \quad \bar{p}p \rightarrow \bar{p} + \text{gap} + [p \rightarrow X_p],$$

$$\mathbf{SD}_p \quad \bar{p}p \rightarrow [\bar{p} \rightarrow X_{\bar{p}}] + \text{gap} + p,$$

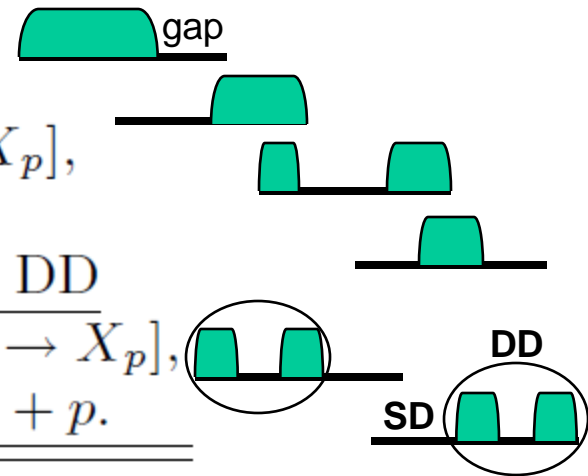
$$\mathbf{DD} \quad \bar{p}p \rightarrow [\bar{p} \rightarrow X_{\bar{p}}] + \text{gap} + [p \rightarrow X_p],$$

$$\mathbf{DPE} \quad \bar{p}p \rightarrow \bar{p} + \text{gap} + X_c + \text{gap} + p,$$

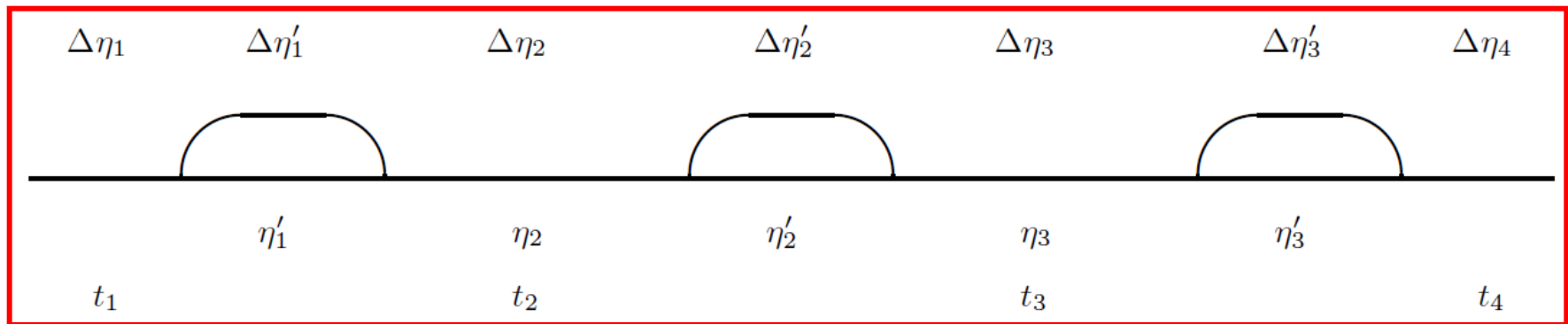
2-gap combinations of SD and DD

$$\mathbf{SDD}_{\bar{p}} \quad \bar{p}p \rightarrow \bar{p} + \text{gap} + X_c + \text{gap} + [p \rightarrow X_p],$$

$$\mathbf{SDD}_p \quad \bar{p}p \rightarrow [\bar{p} \rightarrow X_{\bar{p}}] \text{gap} + X_c + \text{gap} + p.$$

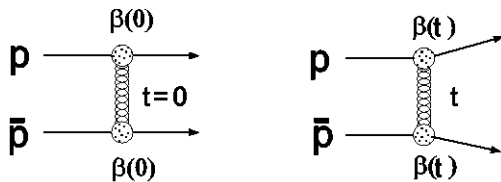


4-gap diffractive process-Snowmass 2001- <http://arxiv.org/pdf/hep-ph/0110240>

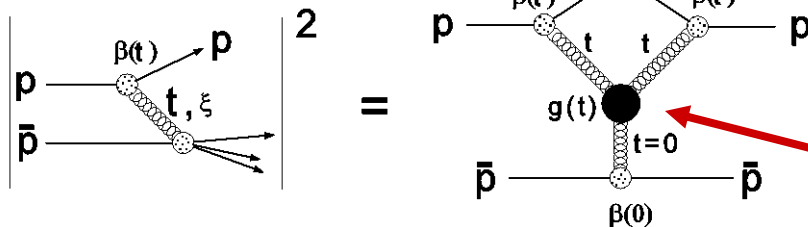


Regge theory – values of s_0 & g_{PPP} ?

KG-PLB 358, 379 (1995)



SINGLE DIFFRACTION DISSOCIATION



Parameters:

- s_0, s_0' and $g(t)$
- set $s_0' = s_0$ (universal IP)
- determine s_0 and g_{PPP} – **how?**

$$\alpha(t) = \alpha(0) + \alpha' t \quad \alpha(0) = 1 + \epsilon$$

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

$$\begin{aligned} \frac{d\sigma_{el}}{dt} &= \frac{\beta_1^2(t) \beta_2^2(t)}{16\pi} \left(\frac{s}{s_0} \right)^{2[\alpha(t)-1]} \\ &= \frac{\sigma_T^2}{16\pi} \left(\frac{s}{s_0} \right)^{2\alpha' t} F^4(t) \approx \frac{\sigma_T^2}{16\pi} e^{b_{el}(s)t} \end{aligned} \quad (2)$$

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

$$\frac{d^2 \sigma_{sd}}{dt d\xi}$$

$$\begin{aligned} &= \frac{\beta_1^2(t)}{16\pi} \xi^{1-2\alpha(t)} \left[\beta_2(0) g(t) \left(\frac{s'}{s_0'} \right)^{\alpha(0)-1} \right] \\ &= f_{p/p}(\xi, t) \sigma_T^{p\bar{p}}(s', t) \end{aligned} \quad (4)$$

A complication ... → Unitarity!

$$\left(\frac{d\sigma_{el}}{dt}\right)_{t=0} \sim \left(\frac{s}{s_0}\right)^{2\epsilon}, \quad \sigma_t \sim \left(\frac{s}{s_0}\right)^\epsilon, \quad \text{and} \quad \sigma_{sd} \sim \left(\frac{s}{s_0}\right)^{2\epsilon}$$

□ σ_{sd} grows faster than σ_t as s increases

→ **unitarity violation at high s**

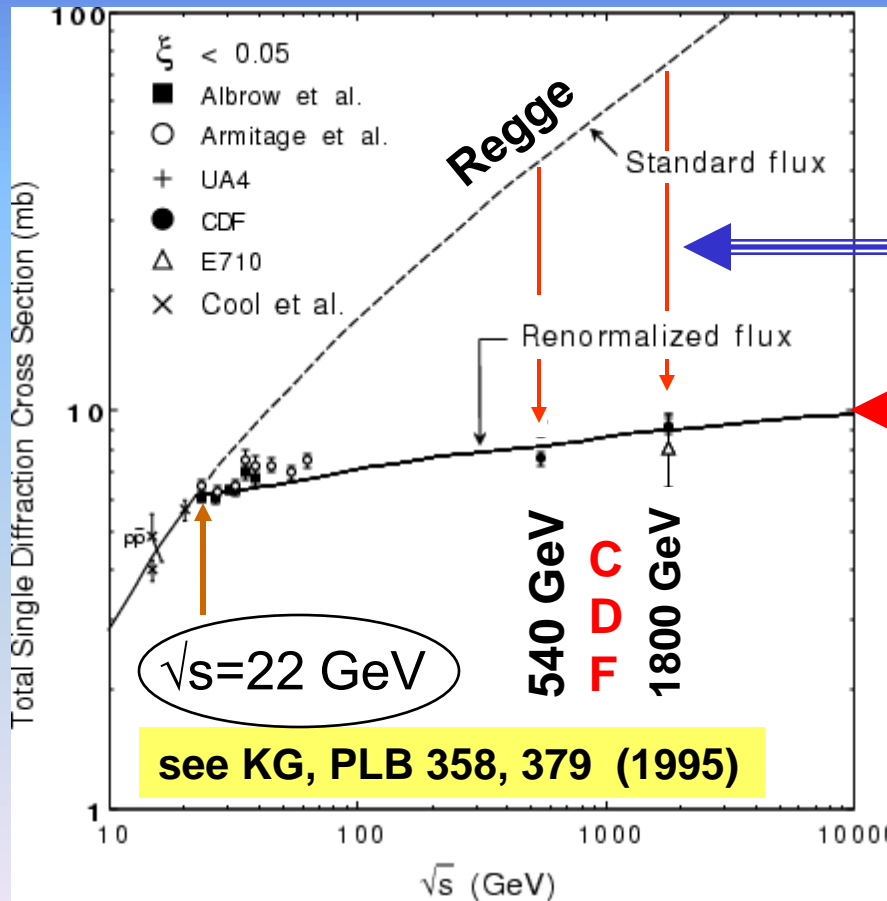
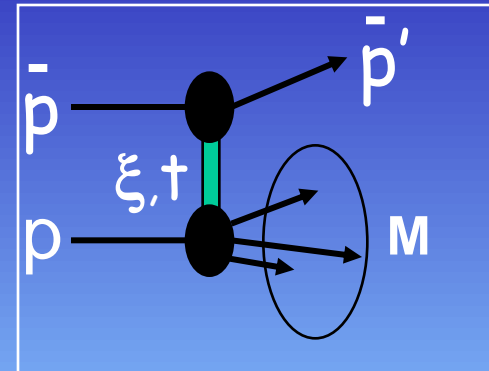
(similarly for partial x-sections in impact parameter space)

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

□ **need unitarization**

FACTORIZATION BREAKING IN SOFT DIFFRACTION

→ diffractive x-section suppressed relative to Regge prediction as \sqrt{s} increases



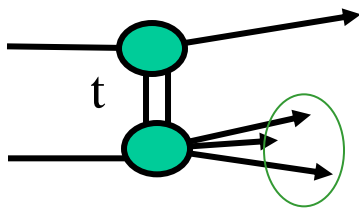
Factor of ~ 8 (~ 5)
suppression at
 $\sqrt{s} = 1800$ (540) GeV

RENORMALIZATION

Interpret flux as gap
formation probability
that saturates when it
reaches unity

Single diffraction renormalized - 1

KG → CORFU-2001: <http://arxiv.org/abs/hep-ph/0203141>



2 independent variables: $t, \Delta y$

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

$$\frac{d^2 \sigma}{dt d\Delta y} = C \cdot F_p^2(t) \cdot \left\{ e^{(\varepsilon + \alpha' t) \Delta y} \right\}^2 \cdot \kappa \cdot \left\{ \sigma_0 e^{\varepsilon \Delta y'} \right\}$$

gap probability

sub-energy x-section

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

Single diffraction renormalized - 3

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

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

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

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

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

set to unity
 \rightarrow determines s_o

M² distribution: data

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

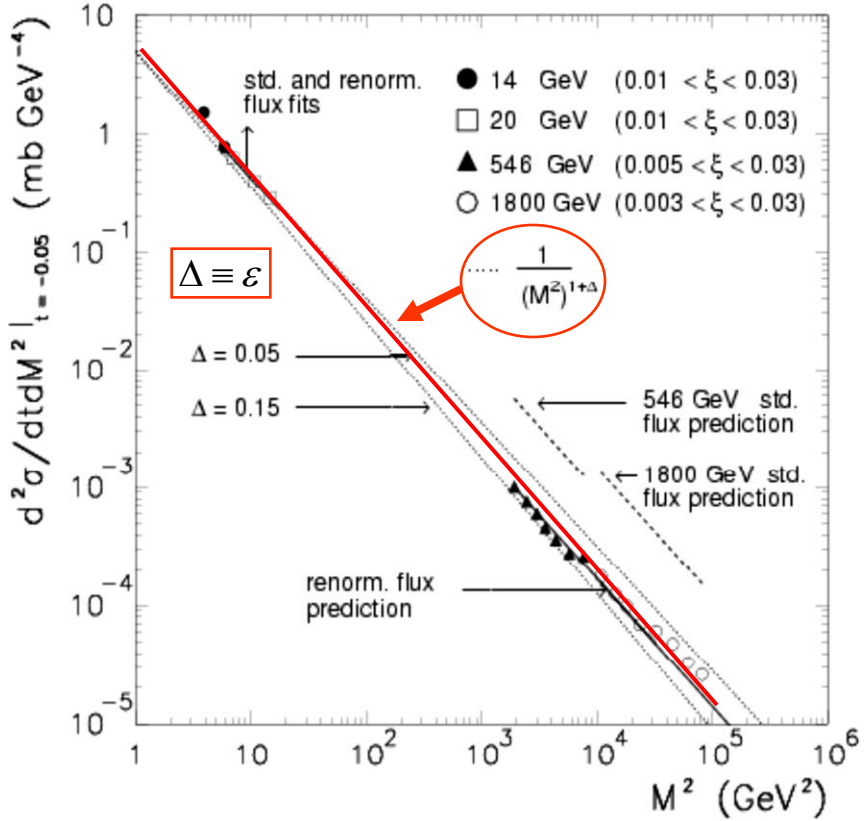
Regge

data

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

Independent of s over 6 orders of magnitude in M^2
 → M^2 scaling

KG&JM, PRD 59 (1999) 114017

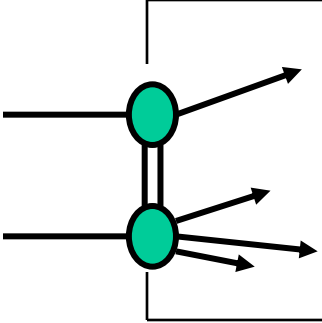


→ factorization breaks down to ensure M^2 scaling!

Scale s_0 and PPP coupling

Pomeron flux: interpret as gap probability

→ set to unity: determines g_{PPP} and s_0 KG, PLB 358 (1995) 379



The diagram shows two incoming lines from the left entering two green circular vertices. From each vertex, two lines branch out to the right. A large arrow points from the top vertex to the equation, labeled s_0^ϵ . A large arrow points from the bottom vertex to the equation, labeled $s_0^{-\epsilon/2} \cdot g_{PPP}(t)$.

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

Pomeron-proton x-section

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

Saturation at low Q^2 and small x

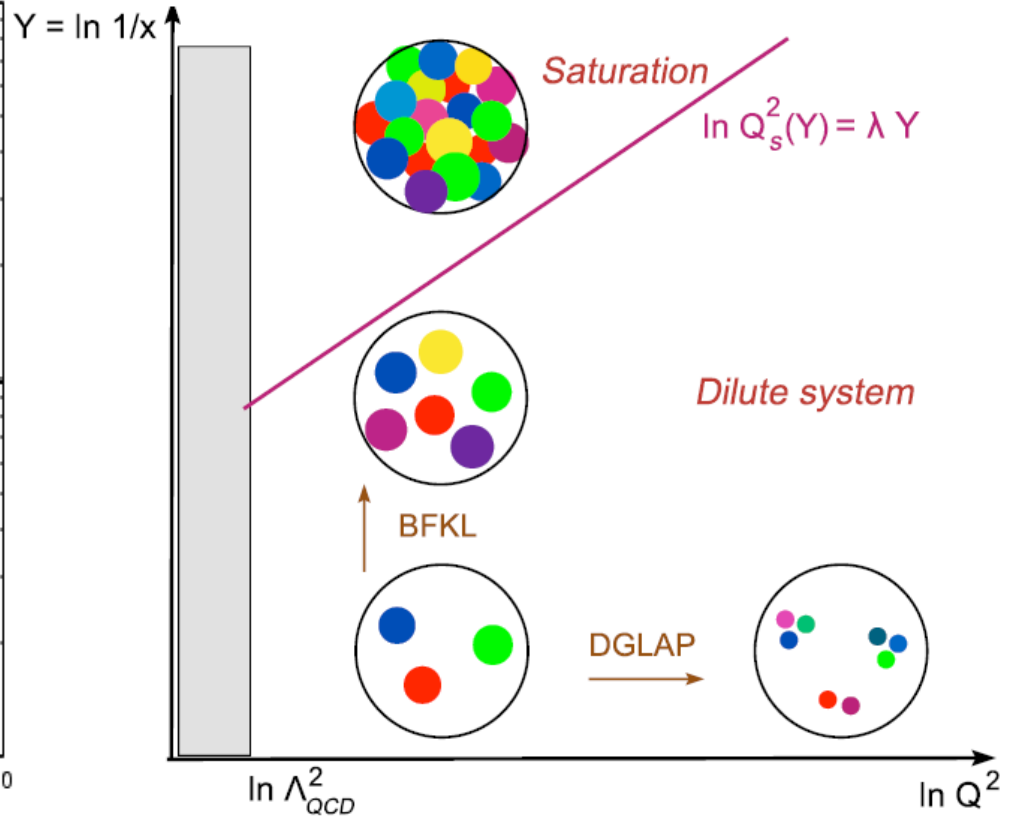
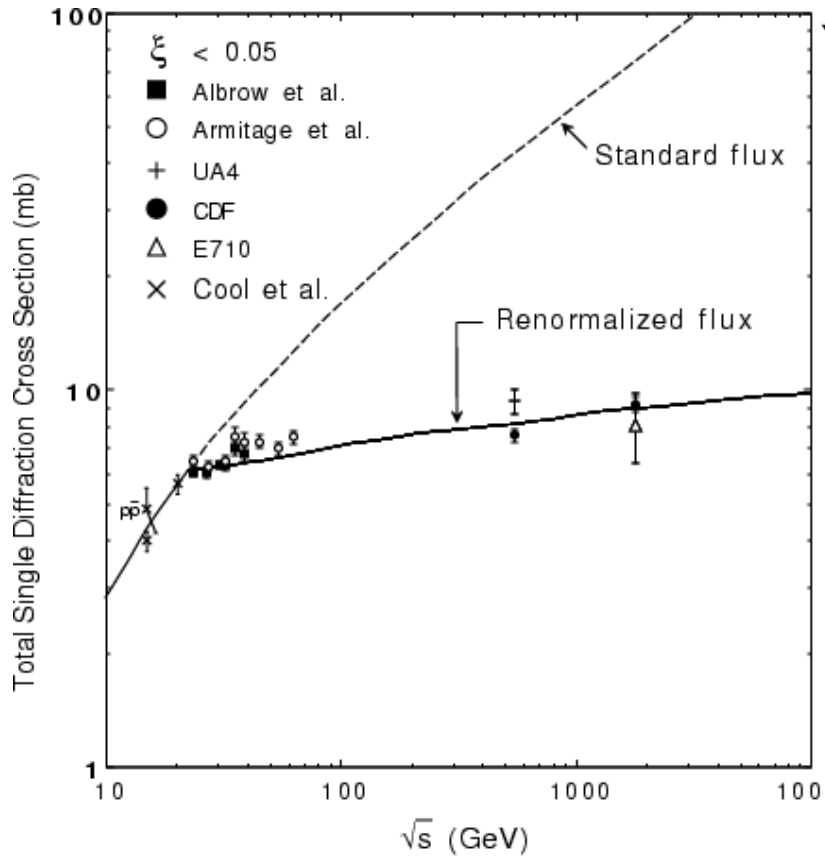
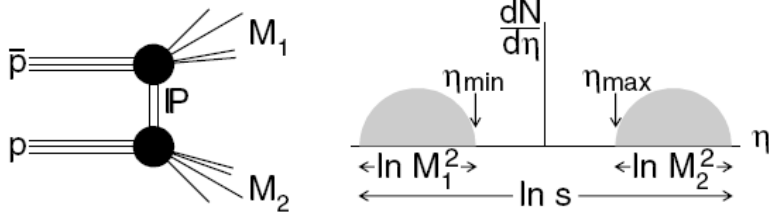


figure from a talk by Edmond Iancu

DD at CDF

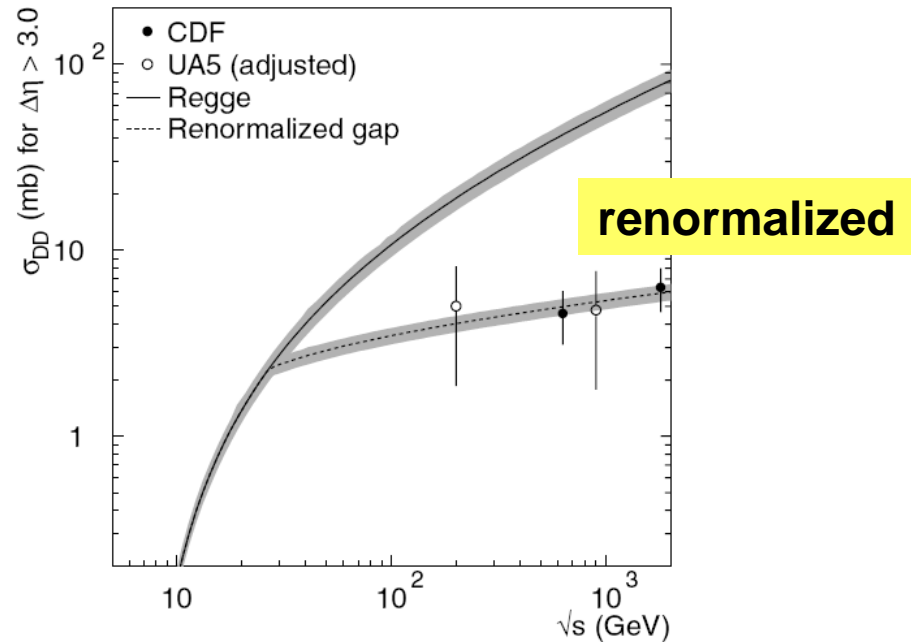
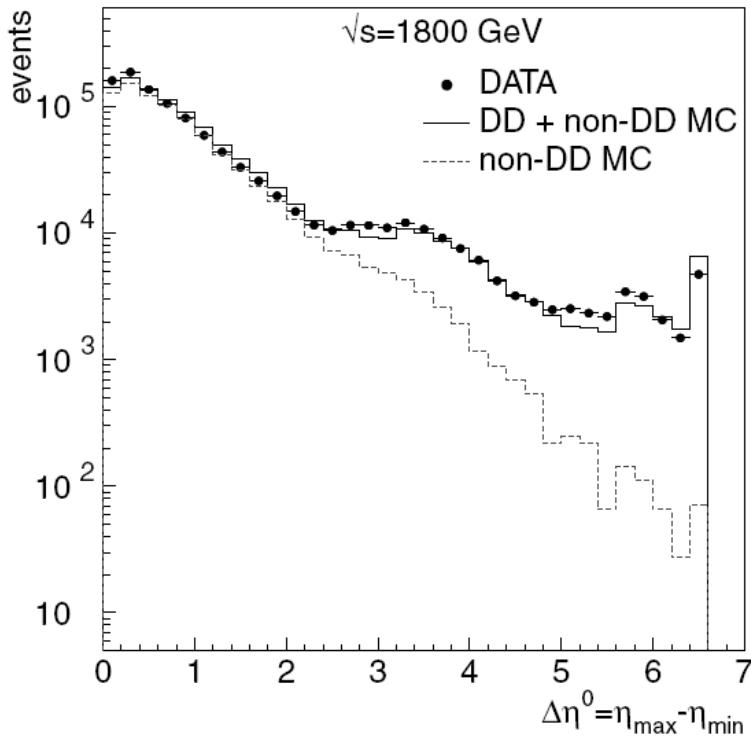


$$\frac{d^3\sigma_{DD}}{dt dM_1^2 dM_2^2} = \frac{d^2\sigma_{SD}}{dt dM_1^2} \frac{d^2\sigma_{SD}}{dt dM_2^2} / \frac{d\sigma_{el}}{dt}$$

$$= \frac{[\kappa \beta_1(0) \beta_2(0)]^2}{16\pi} \frac{s^{2\epsilon} e^{b_{DD}t}}{(M_1^2 M_2^2)^{1+2\epsilon}}$$

$$\frac{d^3\sigma_{DD}}{dt d\Delta\eta d\eta_c} = \left[\frac{\kappa \beta^2(0)}{16\pi} e^{2[\alpha(t)-1]\Delta\eta} \right] \left[\kappa \beta^2(0) \left(\frac{s'}{s_0} \right)^\epsilon \right]$$

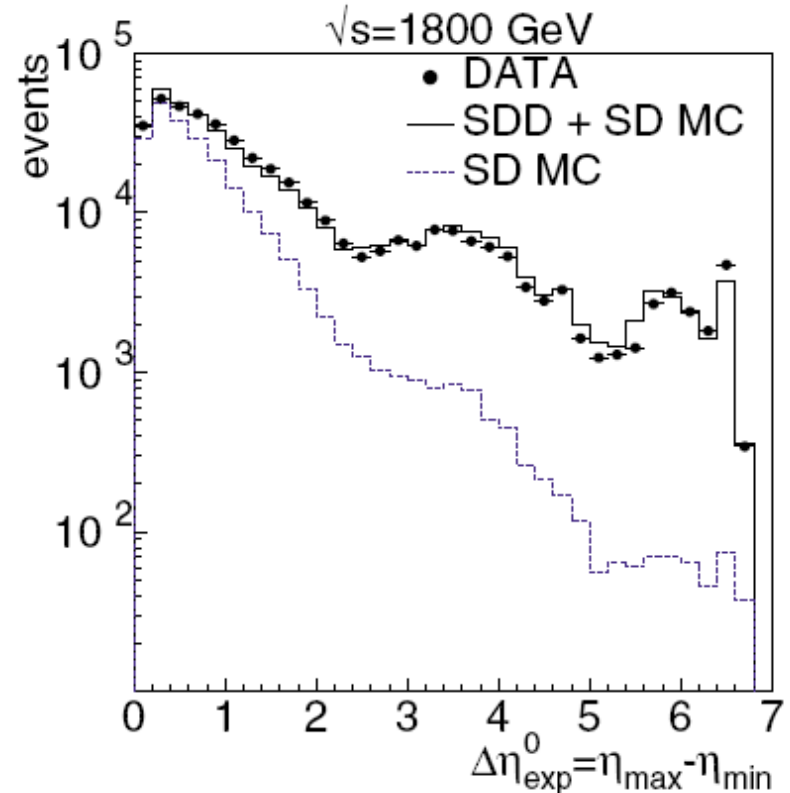
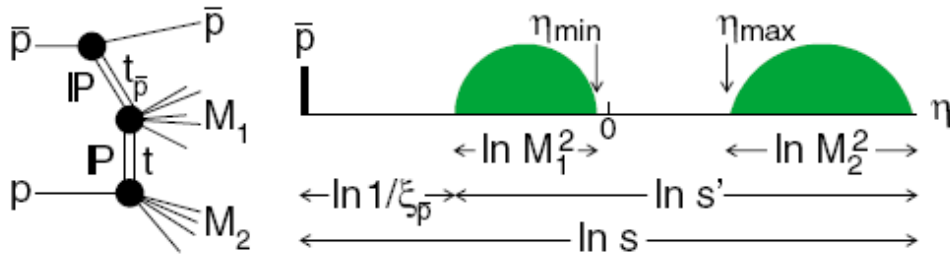
gap probability x-section



Rapidity Gaps in Fireworks



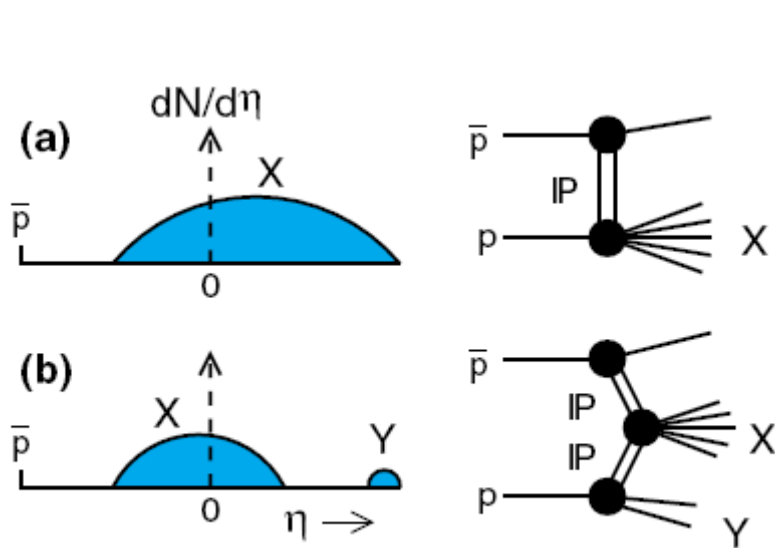
SDD at CDF



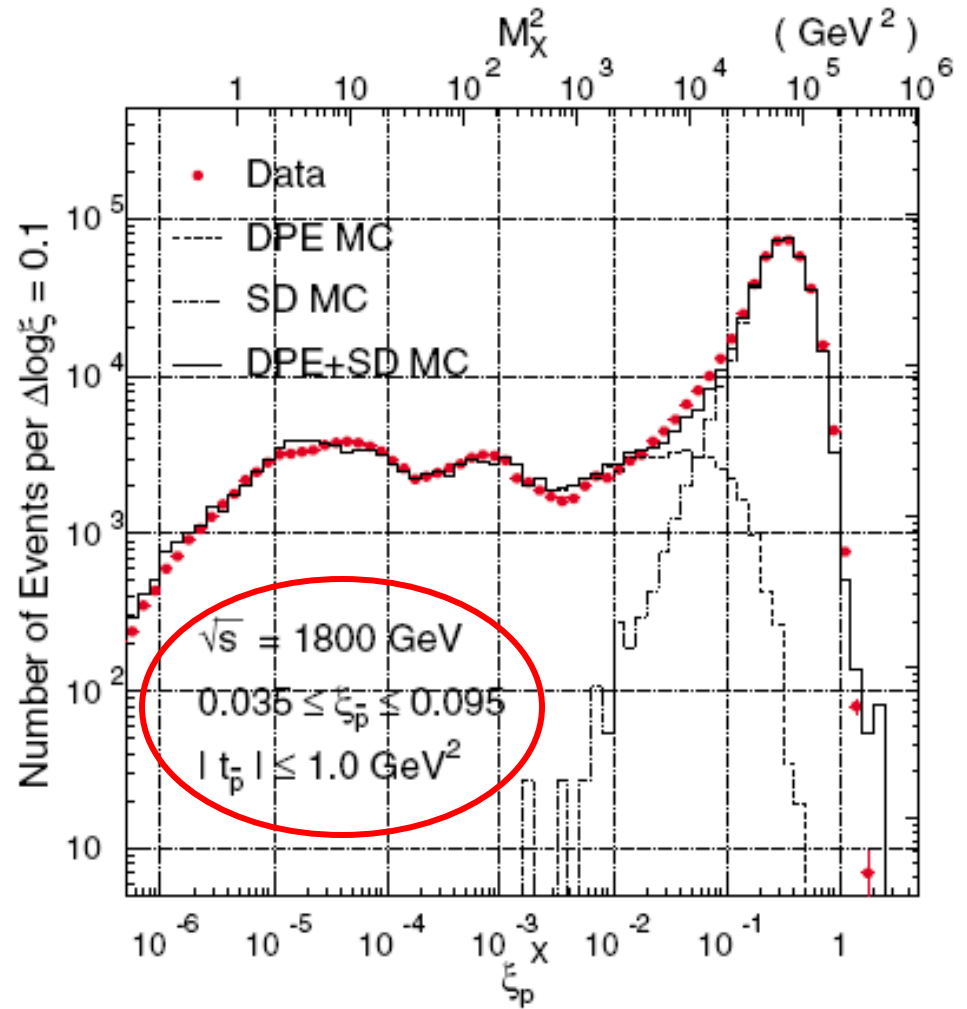
■ Excellent agreement between data and MBR (MinBiasRockefeller) MC

$$\frac{d^5\sigma}{dt_{\bar{p}} dt d\xi_{\bar{p}} d\Delta\eta d\eta_c} = \left[\frac{\beta(t)}{4\sqrt{\pi}} e^{[\alpha(t_{\bar{p}})-1]\ln(1/\xi)} \right]^2 \times \kappa \left\{ \kappa \left[\frac{\beta(0)}{4\sqrt{\pi}} e^{[\alpha(t)-1]\Delta\eta} \right]^2 \kappa \left[\beta^2(0) \left(\frac{s''}{s_0} \right)^\epsilon \right] \right\}$$

CD/DPE at CDF



■ Excellent agreement between data and MBR
 → low and high masses are correctly implemented



Diffractive cross sections

$$\begin{aligned} \frac{d^2\sigma_{SD}}{dt d\Delta y} &= \frac{1}{N_{\text{gap}}(s)} \left[\frac{\beta^2(t)}{16\pi} e^{2[\alpha(t)-1]\Delta y} \right] \cdot \left\{ \kappa \beta^2(0) \left(\frac{s'}{s_0} \right)^\epsilon \right\}, \\ \frac{d^3\sigma_{DD}}{dt d\Delta y dy_0} &= \frac{1}{N_{\text{gap}}(s)} \left[\frac{\kappa \beta^2(0)}{16\pi} e^{2[\alpha(t)-1]\Delta y} \right] \cdot \left\{ \kappa \beta^2(0) \left(\frac{s'}{s_0} \right)^\epsilon \right\}, \\ \frac{d^4\sigma_{DPE}}{dt_1 dt_2 d\Delta y dy_c} &= \frac{1}{N_{\text{gap}}(s)} \left[\prod_i \left[\frac{\beta^2(t_i)}{16\pi} e^{2[\alpha(t_i)-1]\Delta y_i} \right] \right] \cdot \kappa \left\{ \kappa \beta^2(0) \left(\frac{s'}{s_0} \right)^\epsilon \right\} \end{aligned}$$

$$\beta^2(t) = \beta^2(0) F^2(t)$$

$$F^2(t) = \left[\frac{4m_p^2 - 2.8t}{4m_p^2 - t} \left(\frac{1}{1 - \frac{t}{0.71}} \right)^2 \right]^2 \approx a_1 e^{b_1 t} + a_2 e^{b_2 t}$$

$$\alpha_1=0.9, \alpha_2=0.1, b_1=4.6 \text{ GeV}^{-2}, b_2=0.6 \text{ GeV}^{-2}, s'=s e^{-\Delta y}, \kappa=0.17, \kappa\beta^2(0)=\sigma_0, s_0=1 \text{ GeV}^2, \sigma_0=2.82 \text{ mb or } 7.25 \text{ GeV}^{-2}$$

Total, elastic & inelastic cross sections

$$\sigma_{\text{ND}} = (\sigma_{\text{tot}} - \sigma_{\text{el}}) - (2\sigma_{\text{SD}} + \sigma_{\text{DD}} + \sigma_{\text{CD}})$$

CMG

R. J. M. Covolan, K. Goulios, J. Montanha, Phys. Lett. B **389**, 176 (1996)

$$\sigma_{\text{tot}}^{p\pm p} = \begin{cases} 16.79s^{0.104} + 60.81s^{-0.32} \mp 31.68s^{-0.54} & \text{for } \sqrt{s} < 1.8 \\ \sigma_{\text{tot}}^{\text{CDF}} + \frac{\pi}{s_0} \left[\left(\ln \frac{s}{s_F} \right)^2 - \left(\ln \frac{s^{\text{CDF}}}{s_F} \right)^2 \right] & \text{for } \sqrt{s} \geq 1.8 \end{cases}$$

KG Moriond 2011, arXiv:1105.1916

$$\sqrt{s^{\text{CDF}}} = 1.8 \text{ TeV}, \sigma_{\text{tot}}^{\text{CDF}} = 80.03 \pm 2.24 \text{ mb}$$

$$\sqrt{s_F} = 22 \text{ GeV} \quad s_0 = 3.7 \pm 1.5 \text{ GeV}^2$$

$$\sigma_{\text{el}}^{p\pm p} = \sigma_{\text{tot}} \times (\sigma_{\text{el}}/\sigma_{\text{tot}}), \text{ with } \sigma_{\text{el}}/\sigma_{\text{tot}} \text{ from CMG}$$

small extrapol. from 1.8 to 7 and up to 50 TeV)

Diffraction and Total pp Cross Sections at LHC



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

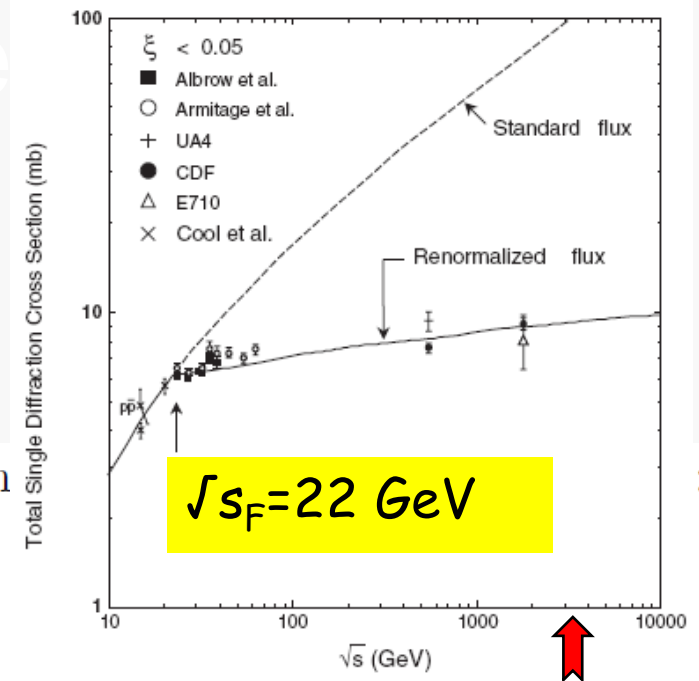
$$\sigma_t(s > s_F) = \sigma_t(s_F) + \frac{\pi}{m^2} \cdot \ln^2 \frac{s}{s_F}$$

- 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 $m^2 = s_0$ 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:

$$\sigma_t^{\text{LHC}} = \sigma_t^{\text{CDF}} + \frac{\pi}{s_0} \cdot \left(\ln^2 \frac{s^{\text{LHC}}}{s_F} - \ln^2 \frac{s^{\text{CDF}}}{s_F} \right)$$

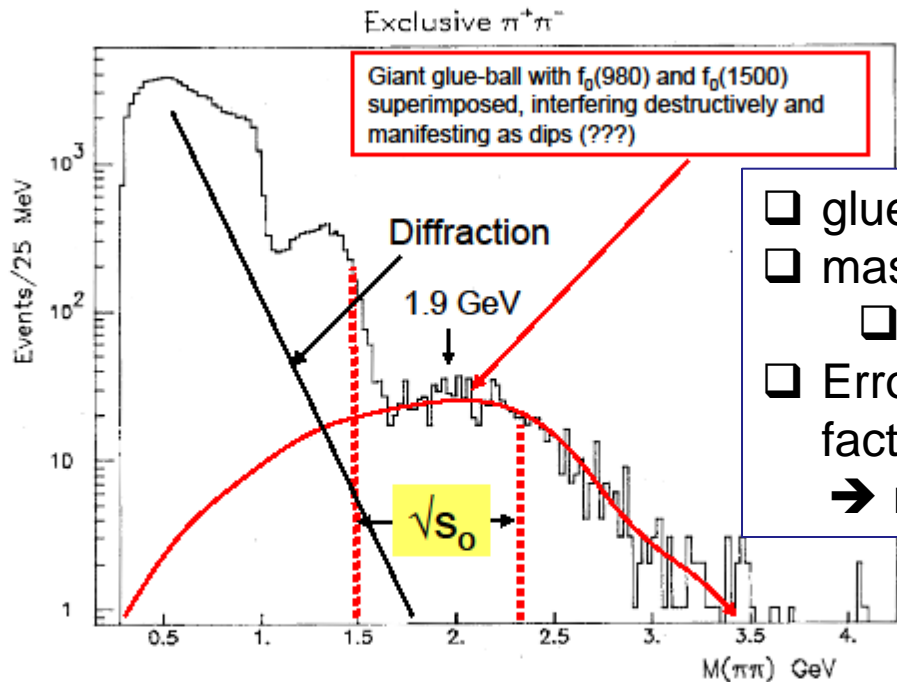
**98 ± 8 mb at 7 TeV
 109 ± 12 mb at 14 TeV**

Main error from s_0



Reducing the uncertainty in s_0

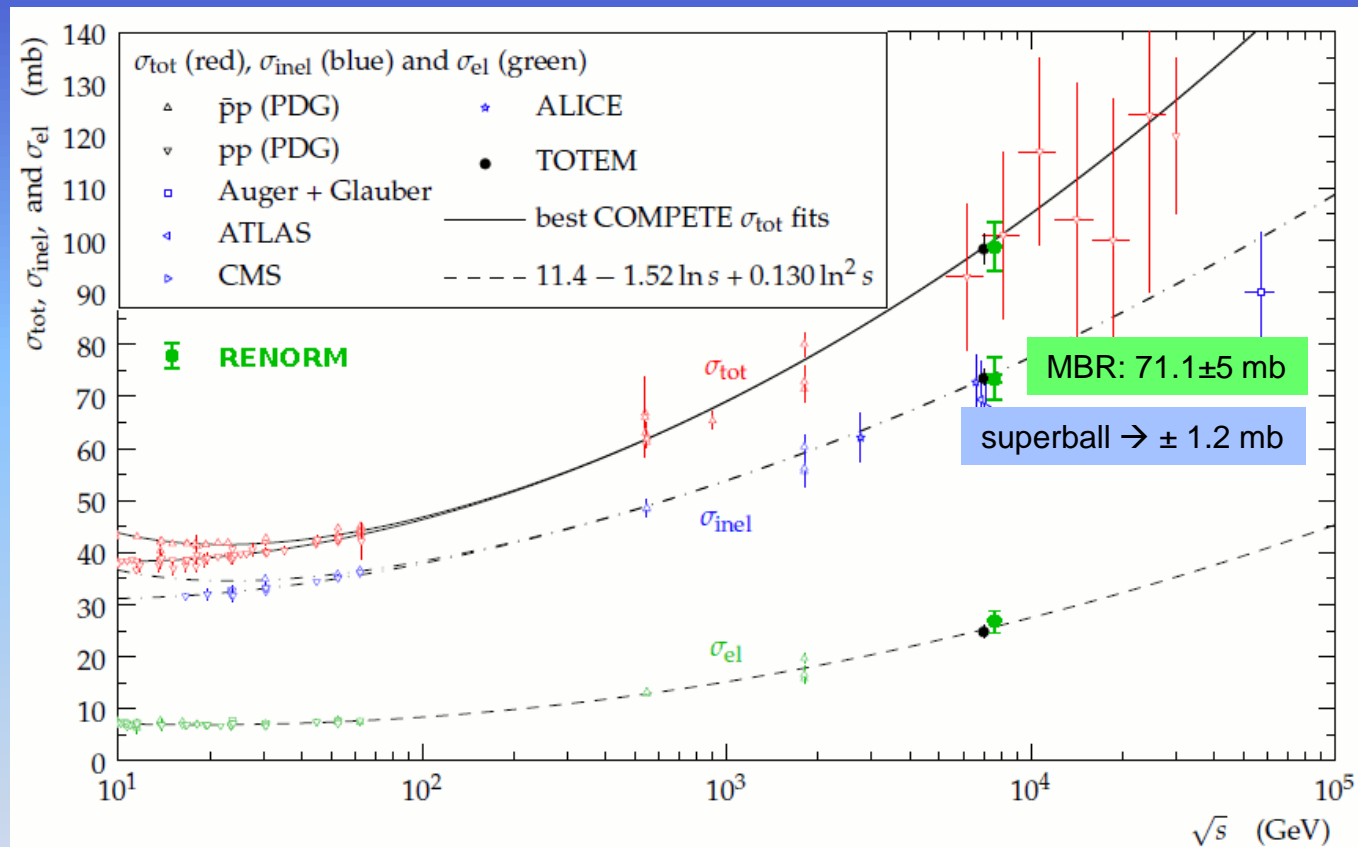
Saturation glueball?



- ❑ glue-ball-like object \rightarrow “superball”
- ❑ mass $\rightarrow 1.9$ GeV $\rightarrow m_s^2 = 3.7$ GeV
 - ❑ agrees with RENORM $s_0 = 3.7$
- ❑ Error in s_0 can be reduced by factor ~ 4 from a fit to these data!
 - \rightarrow reduces error in σ_t .

Figure 8: $M_{\pi^+\pi^-}$ spectrum in *DIFE* at the ISR (Axial Field Spectrometer, R807 [97, 98]). Figure from Ref. [98]. See M.G.Albrow, T.D. Goughlin, J.R. Forshaw, hep-ph>arXiv:1006.1289

TOTEM results vs PYTHIA8-MBR



$$\sigma_{\text{inrl}}^{7 \text{ TeV}} = 72.9 \pm 1.5 \text{ mb}$$

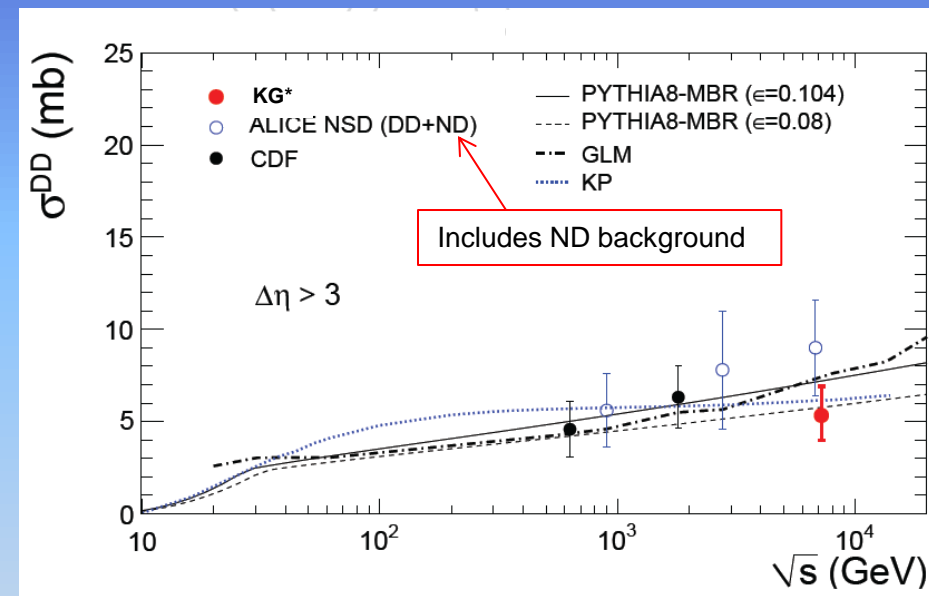
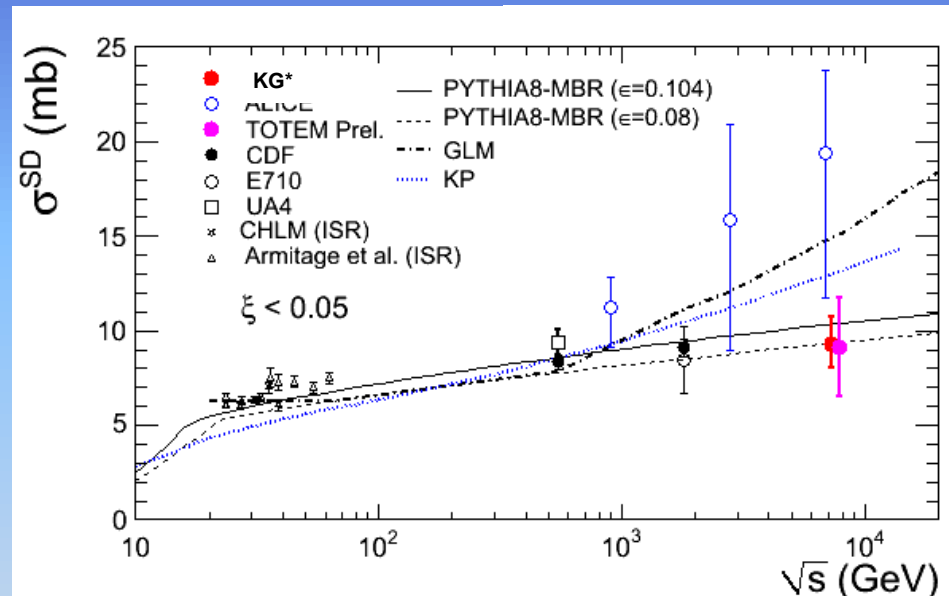
$$\sigma_{\text{inrl}}^{8 \text{ TeV}} = 74.7 \pm 1.7 \text{ mb}$$

TOTEM, G. Latino talk at MPI@LHC, CERN 2012

$$\text{RENORM: } 71.1 \pm 1.2 \text{ mb}$$

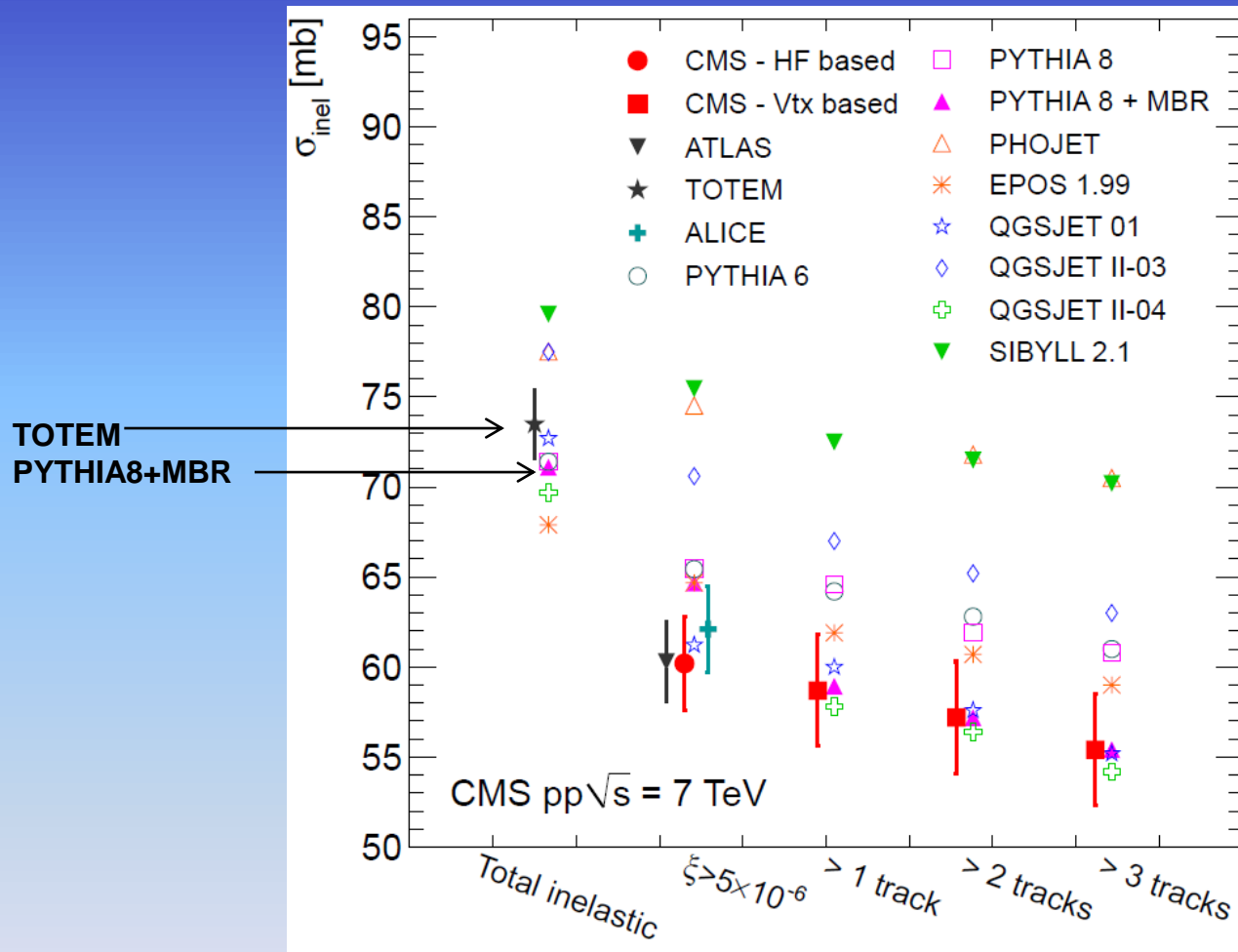
$$\text{RENORM: } 72.3 \pm 1.2 \text{ mb}$$

SD and DD cross sections vs predictions



❖ KG*: from CMS measurements after extrapolation into low ξ using the MBR model

Inelastic cross sections at LHC vs predictions



Monte Carlo Strategy for the LHC ...

MONTE CARLO STRATEGY

- $\sigma_{\text{tot}} \rightarrow$ from SUPERBALL model
- optical theorem $\rightarrow \text{Im } f_{\text{el}}(t=0)$
- dispersion relations $\rightarrow \text{Re } f_{\text{el}}(t=0)$
- $\sigma_{\text{el}} \leftarrow$ using global fit
- $\sigma_{\text{inel}} = \sigma_{\text{tot}} - \sigma_{\text{el}}$
- differential $\sigma_{\text{SD}} \rightarrow$ from RENORM
- use *nesting* of final states for pp collisions at the P - p sub-energy \sqrt{s}'

σ_T



optical theorem

$\text{Im } f_{\text{el}}(t=0)$



dispersion relations

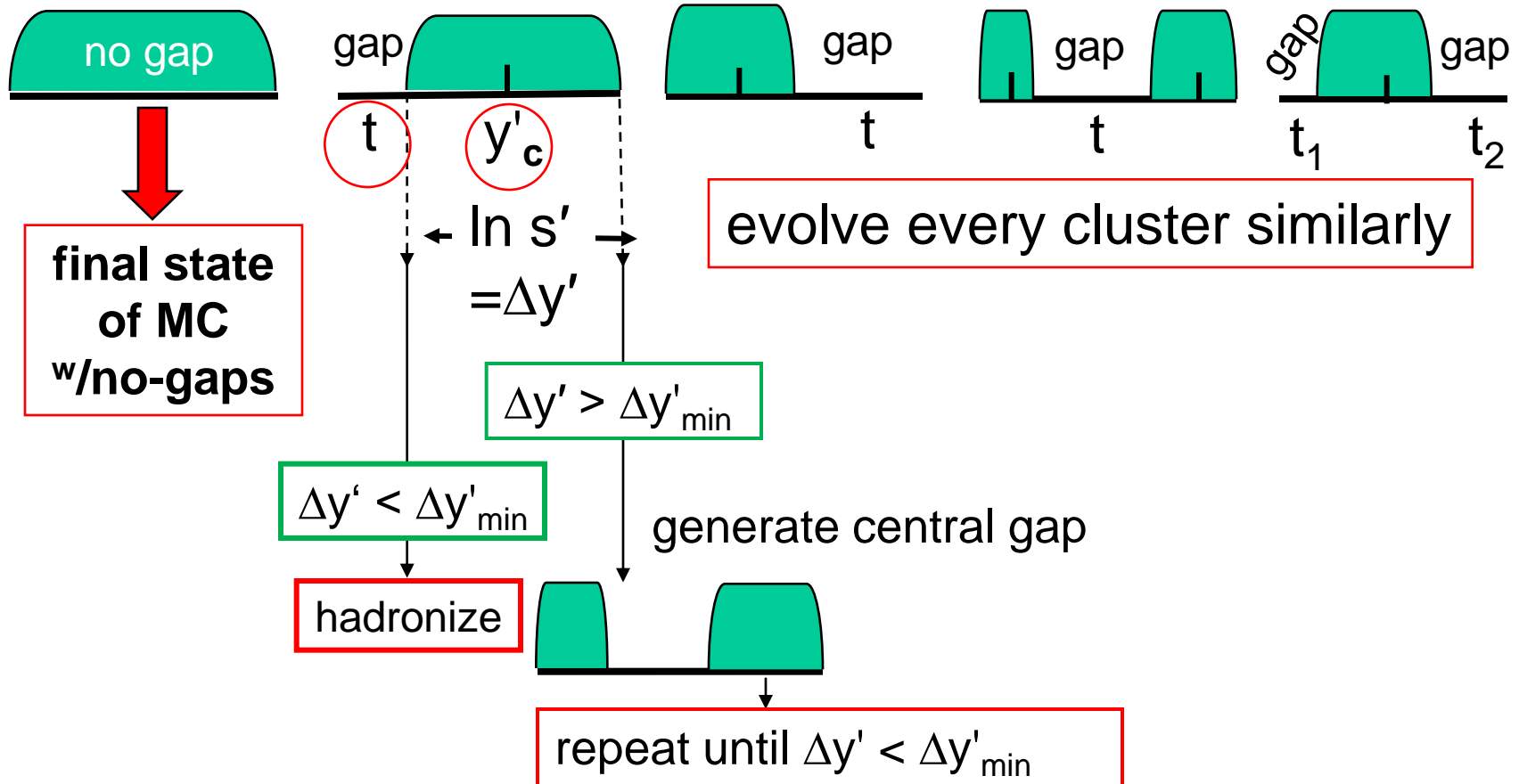
$\text{Re } f_{\text{el}}(t=0)$

*Strategy similar to that of MBR used in CDF based on multiplicities from:
K. Goulios, Phys. Lett. B 193 (1987) 151 pp*

“A new statistical description of hadronic and e^+e^- multiplicity distributions”

Monte Carlo algorithm - nesting

Profile of a pp inelastic collision



SUMMARY

- Introduction

- Diffractive cross sections:

- basic: SD1, SD2, DD, CD (DPE)
 - combined: multigap x-sections
- } **derived from ND and QCD color factors**
- ND → no diffractive gaps:

- ❖ **this is the only final state to be tuned**

- Total, elastic, and total inelastic cross sections

- Monte Carlo strategy for the LHC – “nesting”

Thank you for your attention

Images

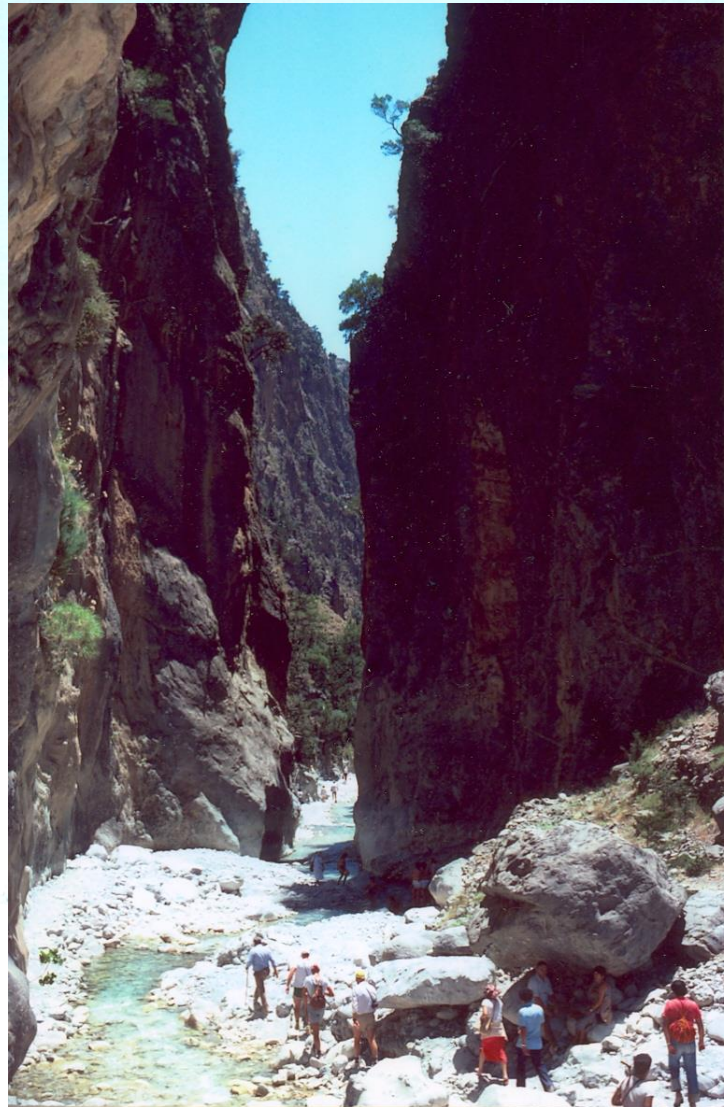
Fermilab 1971

First American-Soviet Collaboration

Elastic, diffractive and total cross sections



At the gorge of Samaria (1980)



Fermilab1989

Opening night at Chez Leon



The End

The End!