A MODEL OF DIFFRACTION

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MPI@LHC

Workshop on Multi-Parton Interactions at the LHC

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TOPICS

- Introduction:
- Diffractive ross sections: soft SD, DD, DPE or CD → **multigap diffraction?**
  - **also:** total, elastic → total-inelastic
  - **and:** hard dfiffraction
- Final states: pt, multiplicity (track-, total-), **particle ID**
- Issues: unitarization, factorization-breaking, "gap survival"
- Implementation in PYTHIA8 → talk of Robert Ciesielski in this session

For details of the model see talk and proceedings of:
DIFFRACTION 2010
"Diffractive and total *pp* cross sections at the LHC and beyond" (KG)
http://link.aip.org/link/doi/10.1063/1.3601406

REMARKS

- RENORM (renormalization model)
  - Tested using MBR (Minimum Bias Rockefeller) simulation at CDF
- Dffraction derived from inclusive PDFs and QCD color factors.
- Absolute normalization!
- HADRONIZATION

Robert's talk

  - MBR produces only $\pi^{\pm}$ and π^{0} 's using a modified gamma distribution
    - predicts distributions of multiplicity, $dN/d\eta$, and p_T
  - PYTHIA8-MBR is an update of PYTHIA8, as of PYTHIA8.165
    - MBR distributions with hadronization done by PYTHIA8
  - Work in progress: tune PYTHIA8-MBR to reproduce MBR distributions

- Total Cross section → formula based on a glue-ball-like saturated-exchange.

DIFFRACTION IN QCD

Non-diffractive events

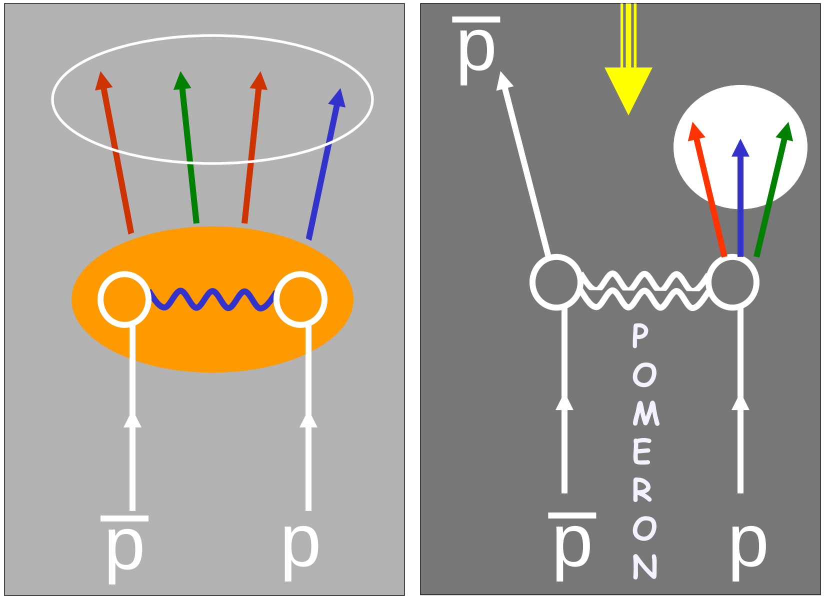
- color-exchange ➔ η-gaps exponentially suppressed

Diffractive events

- Colorless vacuum exchange

➔ η-gaps not exp'ly suppressed

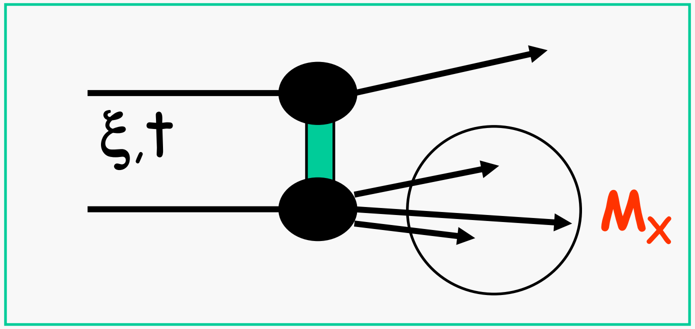
rapidity gap



Goal: probe the QCD nature of the diffractive exchange

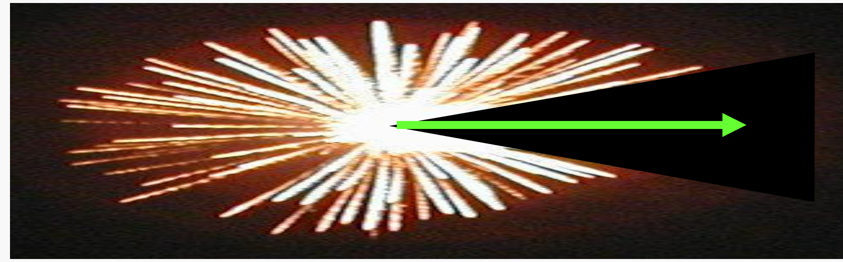
DEFINITIONS

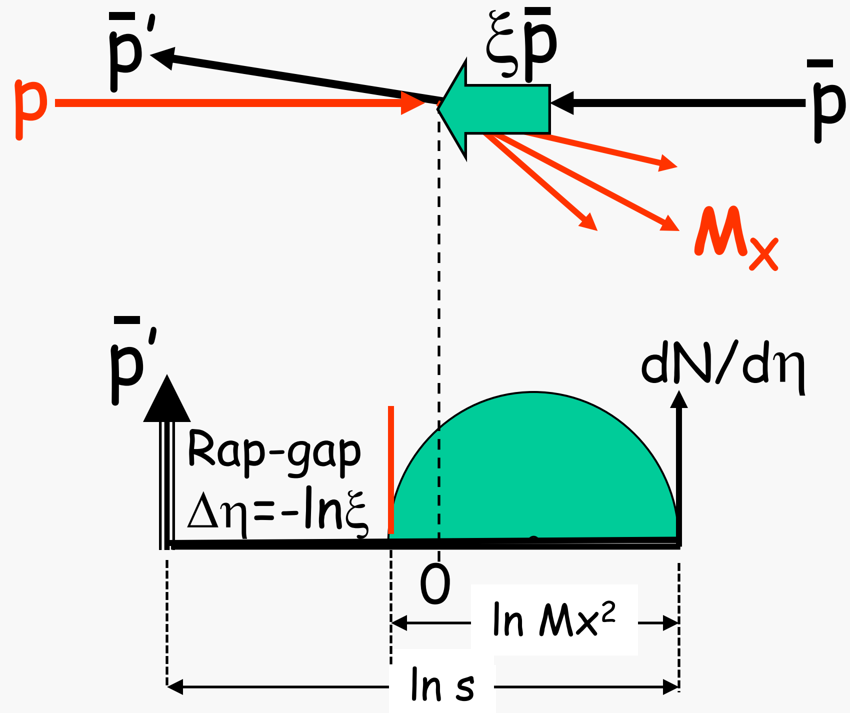
SINGLE DIFFRACTION



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

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

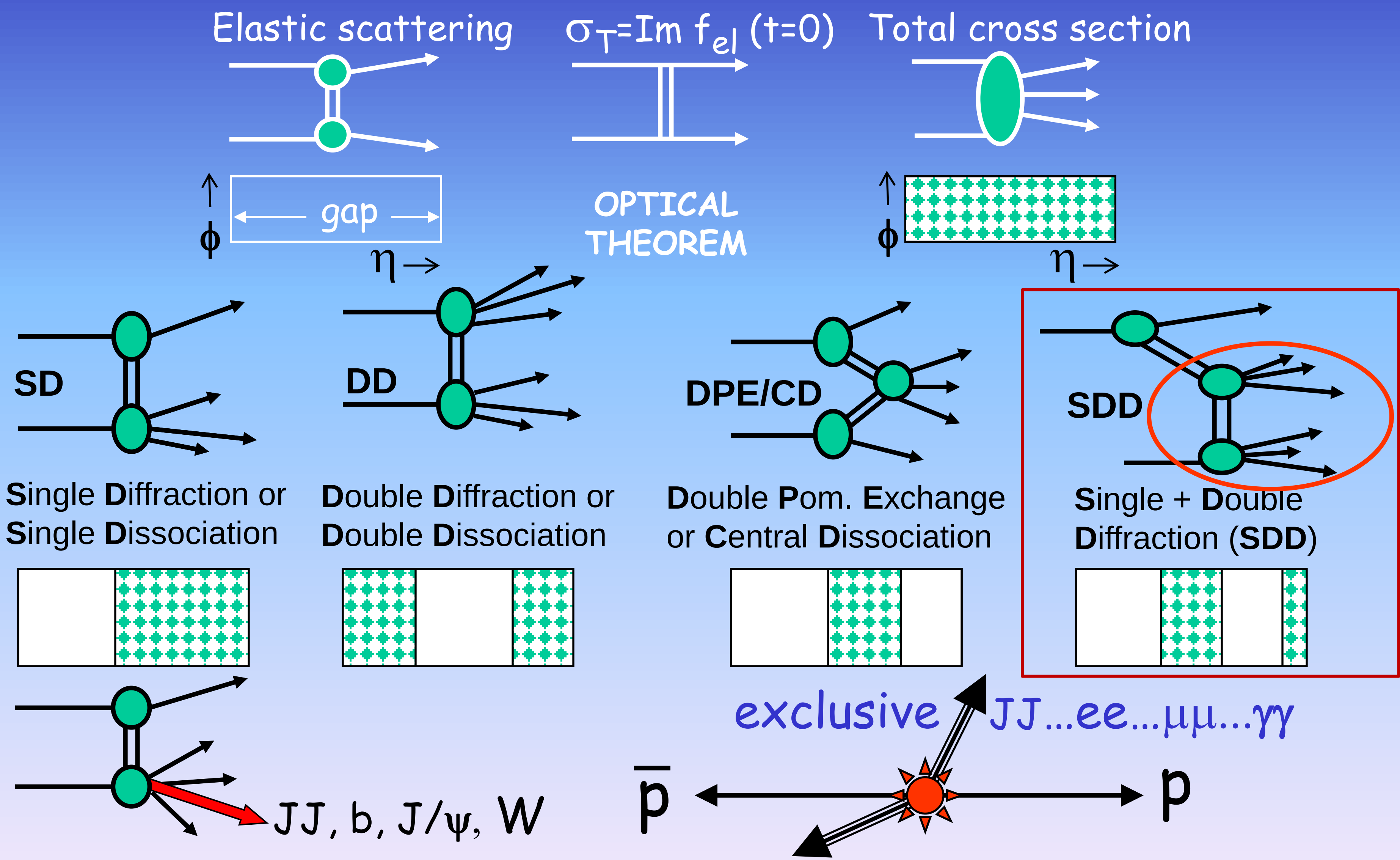




since no radiation →
no price paid for increasing diffractive-gap width

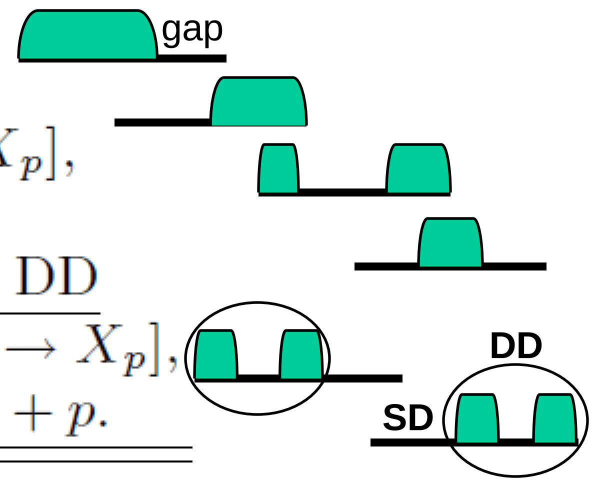
$$\left(\frac{d\sigma}{d\Delta\eta}\right)_{t=0} \approx \text{constant} \Rightarrow \frac{d\sigma}{d\xi} \propto \frac{1}{\xi} \Rightarrow \frac{d\sigma}{dM^2} \propto \frac{1}{M^2}$$

DIFFRACTION AT CDF

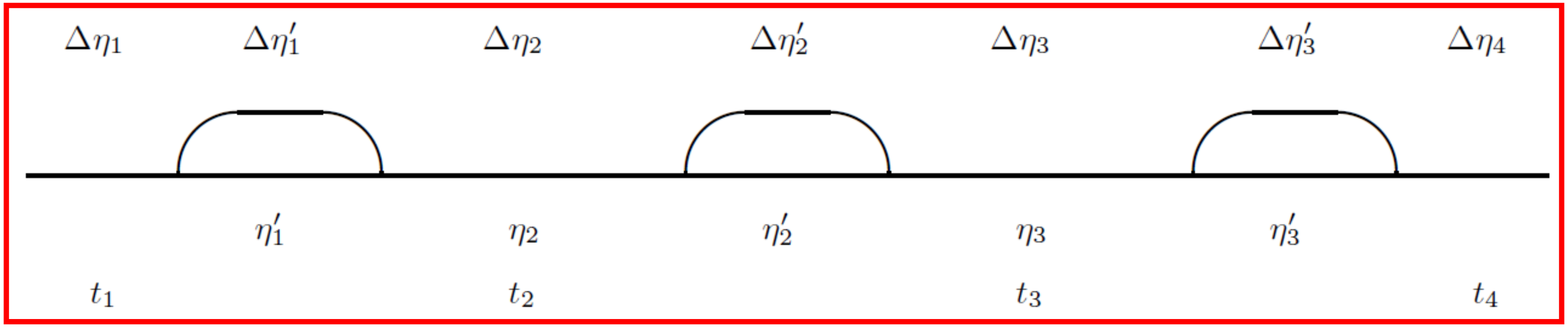


Basic and combined diffractive processes

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

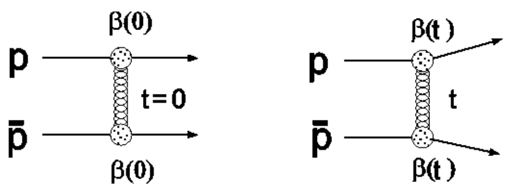


4-gap diffractive process-Snowmass 2001- http://arxiv.org/pdf/hep-ph/0110240

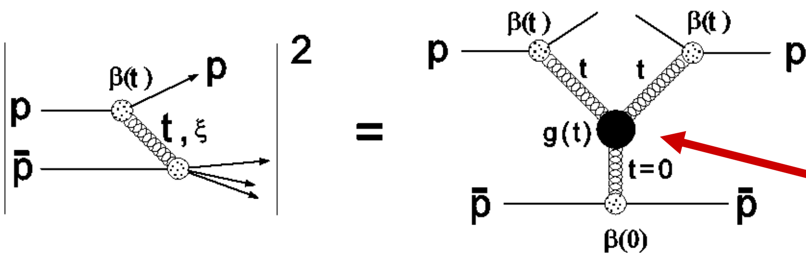


Regge theory – values of s_o & g_{PPP}?

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?**

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

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

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

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

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

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

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

A complication … → Unitarity!

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

- σ_{sd} grows faster than σ_t as *s* increases *

  → unitarity violation at high *s*

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

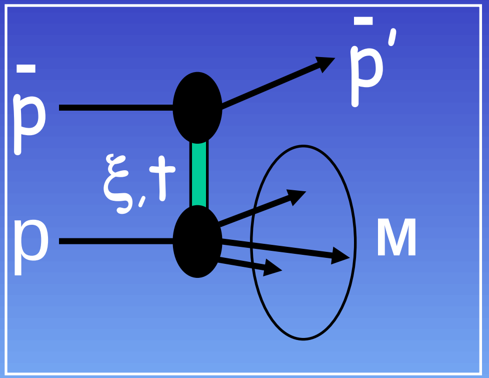
- the unitarity limit is already reached at $\sqrt{s} \sim 2$ TeV !

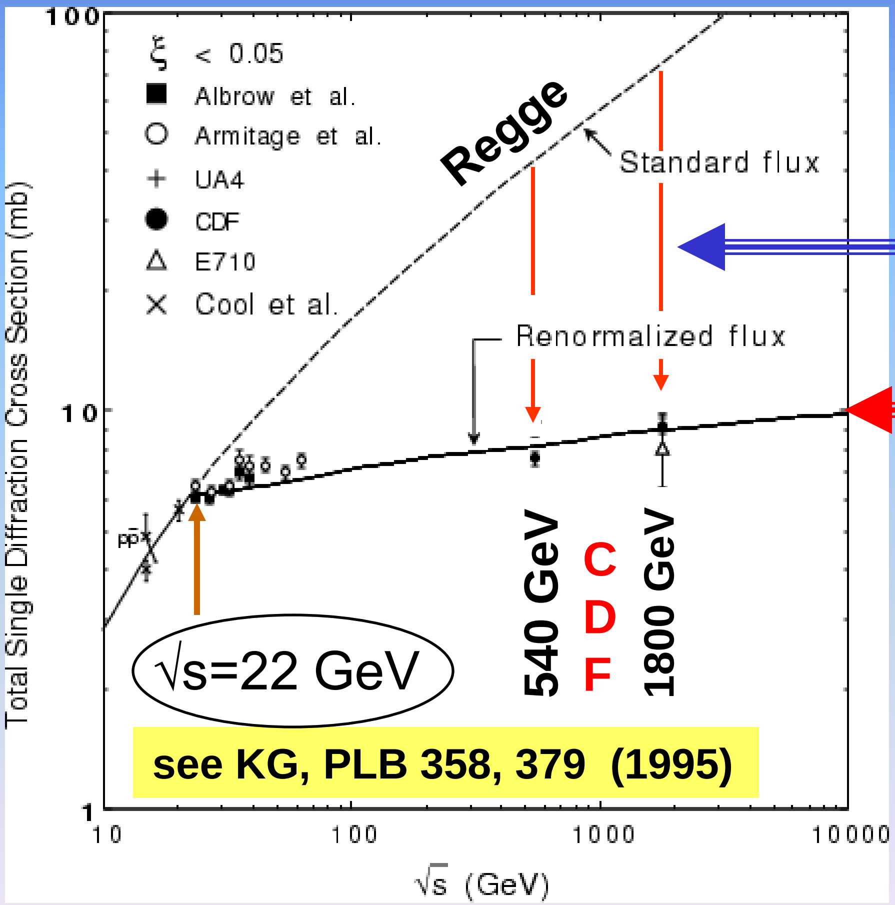
- need unitarization

* similarly for $(d\sigma_{el}/dt)_{t=0}$ vs σ_t, but this is handled differently in RENORM.

FACTORIZATION BREAKING IN SOFT DIFFRACTION

➔diffractive x-section suppressed relative to Regge prediction as √s increases





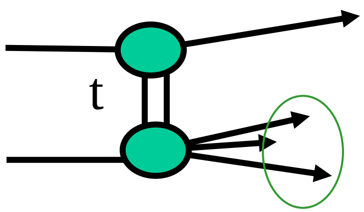
Factor of ~8 (~5) suppression at √s = 1800 (540) GeV

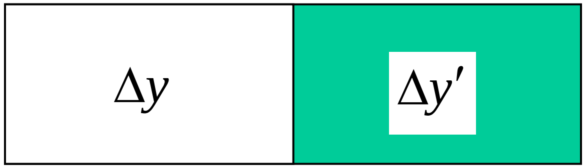
RENORMALIZATION

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

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

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

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

KG&JM, PRD 59 (114017) 1999

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

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

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

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

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

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

set to unity
➔ determines 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

M^2 distribution: data

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

Regge

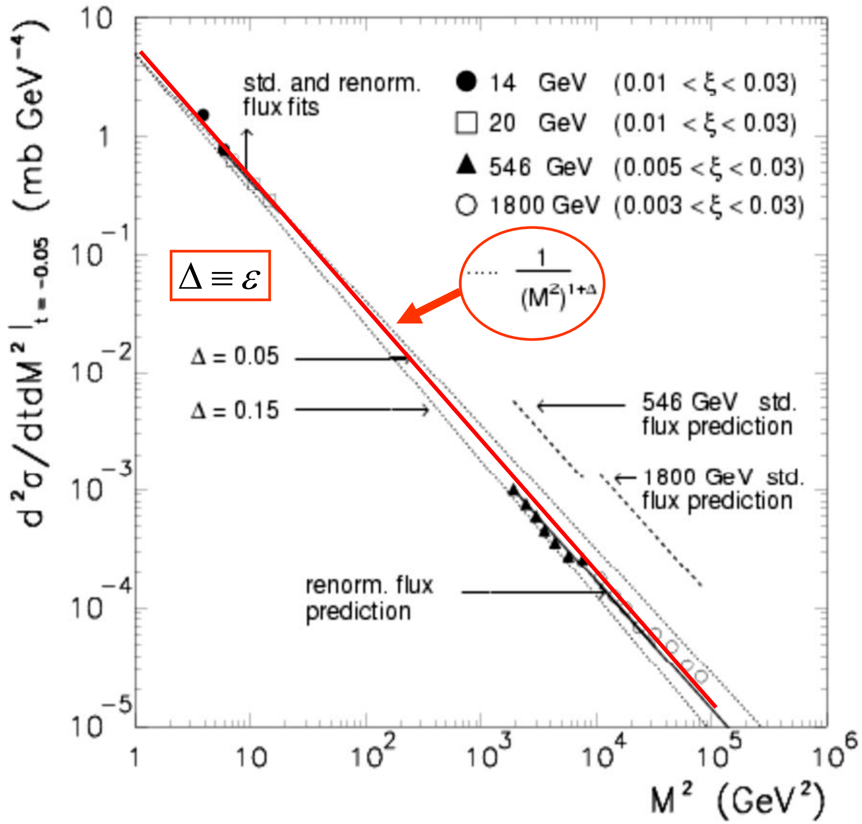
data

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

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

➔ M^2 scaling

KG&JM, PRD 59 (1999) 114017



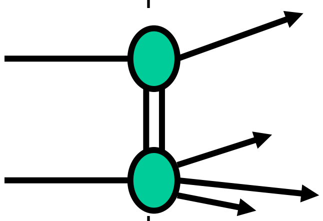
➔ factorization breaks down to ensure M^2 scaling

Scale s_o and *PPP* coupling

Pomeron flux: interpret as gap probability

➔set to unity: determines g_{PPP} and s_0

KG, PLB 358 (1995) 379



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

s_o^{ε}

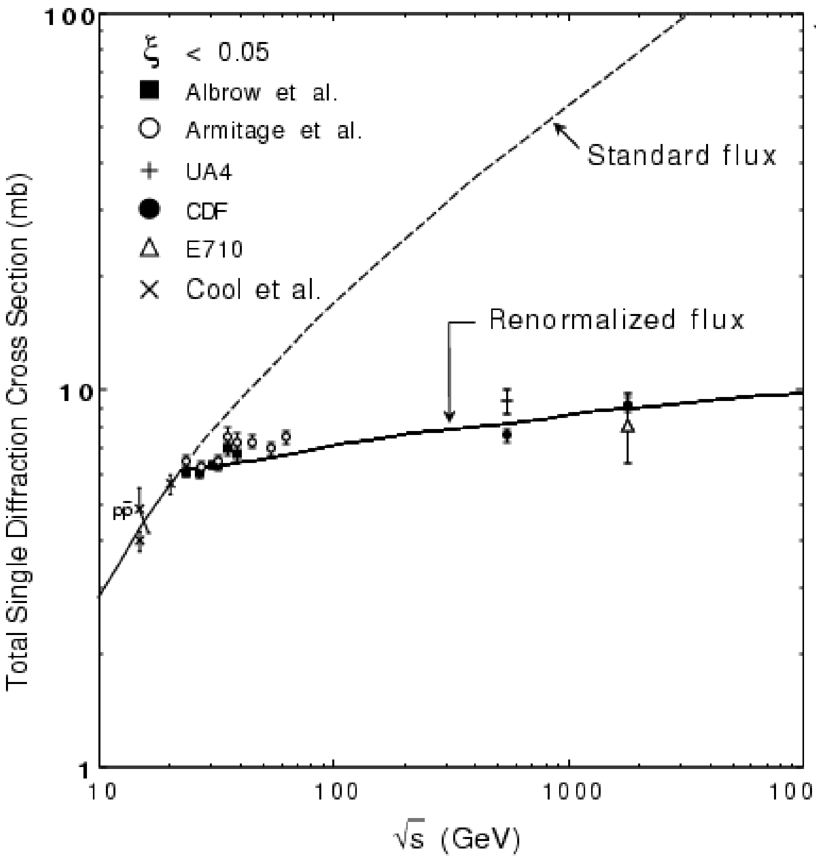
$s_o^{-\varepsilon/2}\cdot g_{PPP}(t)$

Pomeron-proton x-section

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

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

Saturation at low Q^2 and small-x



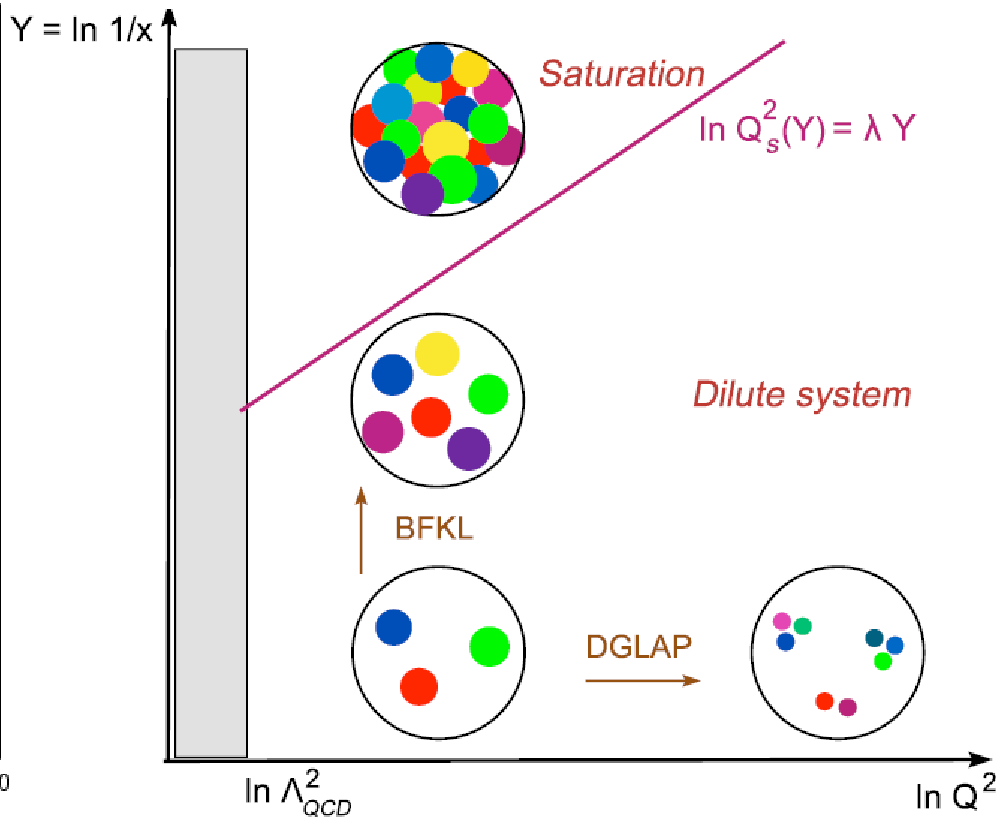
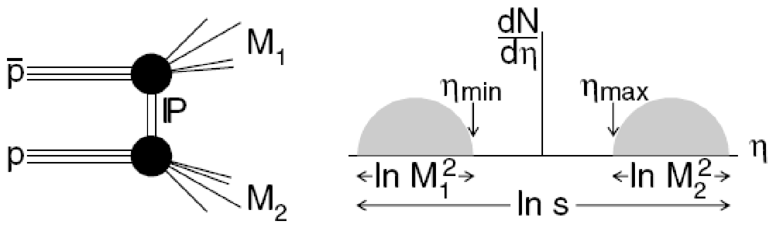


figure from a talk by Edmond Iancu

DD at CDF: comparison with MBR

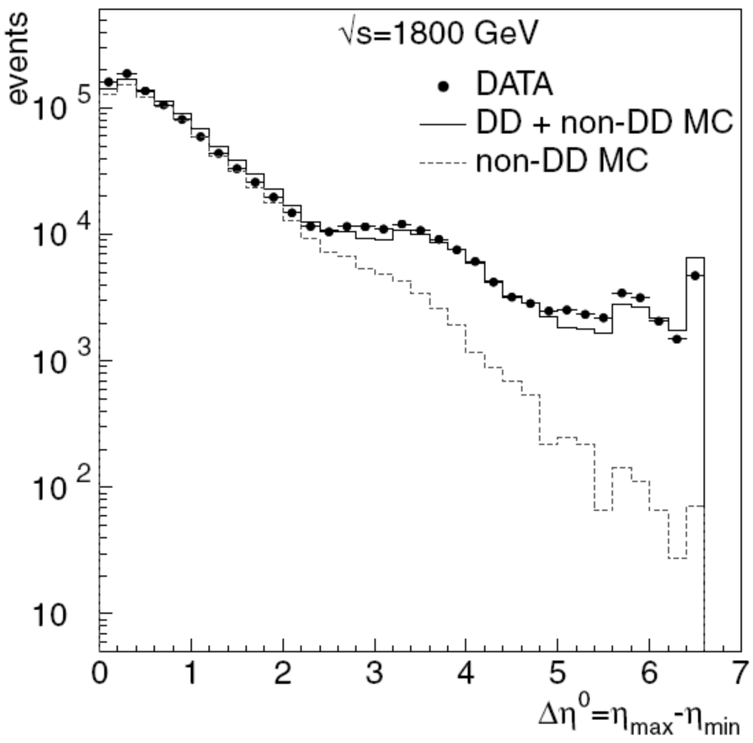
http://physics.rockefeller.edu/publications.html

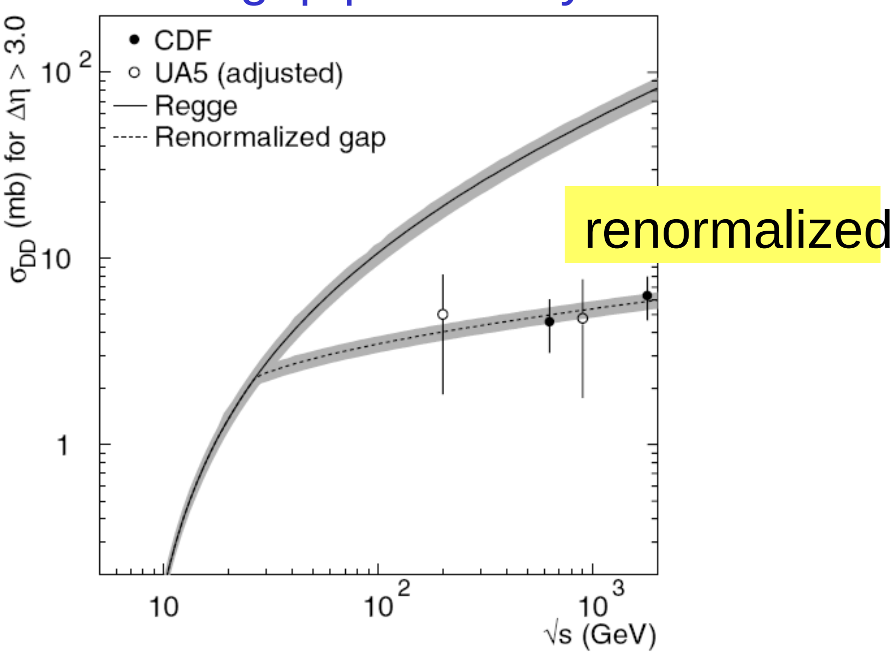


$$\frac{d^3\sigma_{DD}}{dt\,dM_1^2\,dM_2^2} = \frac{d^2\sigma_{SD}}{dt\,dM_1^2}\,\frac{d^2\sigma_{SD}}{dt\,dM_2^2}\Big/\frac{d\sigma_{el}}{dt} = \frac{[\kappa\beta_1(0)\beta_2(0)]^2}{16\pi}\,\frac{s^{2\epsilon}e^{b_{DD}t}}{(M_1^2M_2^2)^{1+2\epsilon}}$$

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

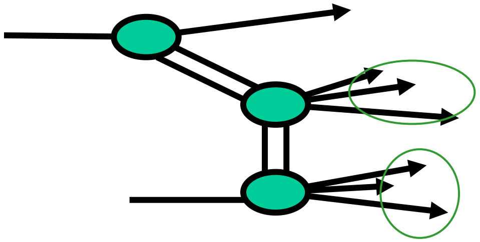
gap probability x-section

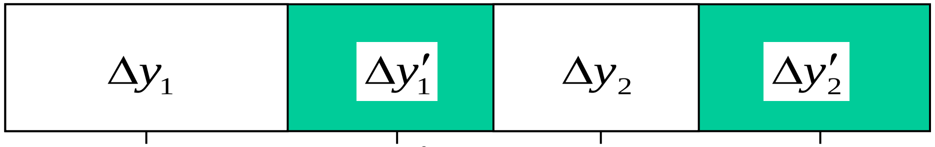




Multigap cross sections, e.g. SDD

KG, hep-ph/0203141





y_1' $\quad y_2$

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

color factor

$$\frac{d^5\sigma}{\prod_{i=1-5} dV_i} = \underbrace{C\times F_p^2(t_1)\prod_{i=1\text{-}2}\left\{e^{(\varepsilon+\alpha' t_i)\Delta y_i}\right\}^2}_{\text{Gap probability}} \times \kappa^2 \underbrace{\left\{\sigma_o\, e^{\varepsilon(\Delta y_1'+\Delta y_2')}\right\}}_{\text{Sub-energy cross section}}$$

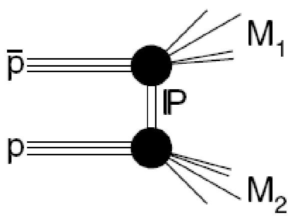
Gap probability

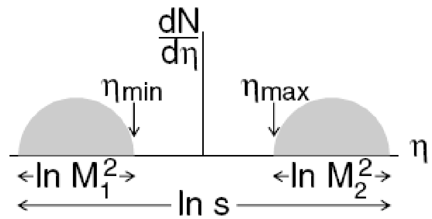
$$\int_{\Delta y,t} \sim s^{2\varepsilon}/\ln s$$

Sub-energy cross section
(for regions with particles)

Same suppression
as for single gap!

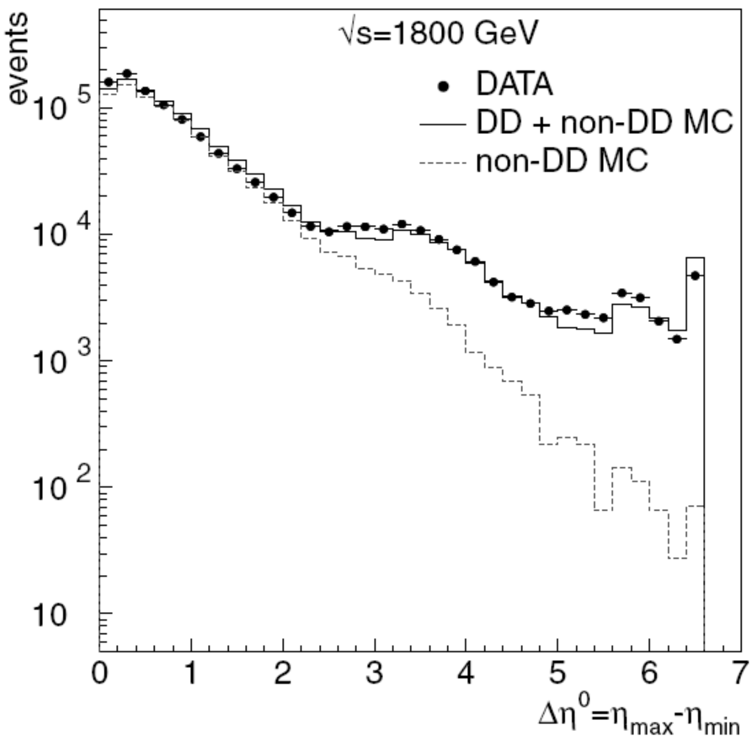
DD at CDF

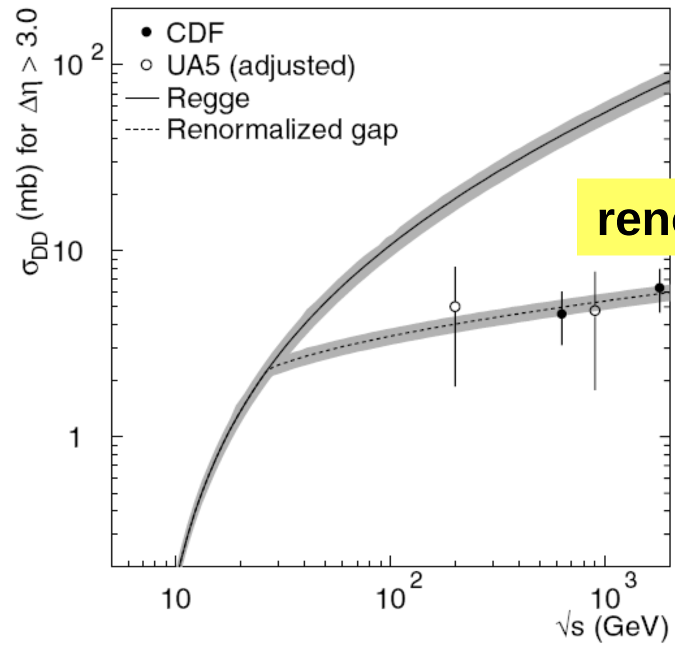




$$\boxed{\begin{aligned}\frac{d^3\sigma_{\rm DD}}{dt\,dM_1^2\,dM_2^2} &= \frac{d^2\sigma_{\rm SD}}{dt\,dM_1^2}\,\frac{d^2\sigma_{\rm SD}}{dt\,dM_2^2}\Big/\frac{d\sigma_{el}}{dt}\\ &= \frac{[\kappa\beta_1(0)\beta_2(0)]^2}{16\pi}\,\frac{s^{2\epsilon}e^{b_{\rm DD}t}}{(M_1^2M_2^2)^{1+2\epsilon}}\end{aligned}}$$

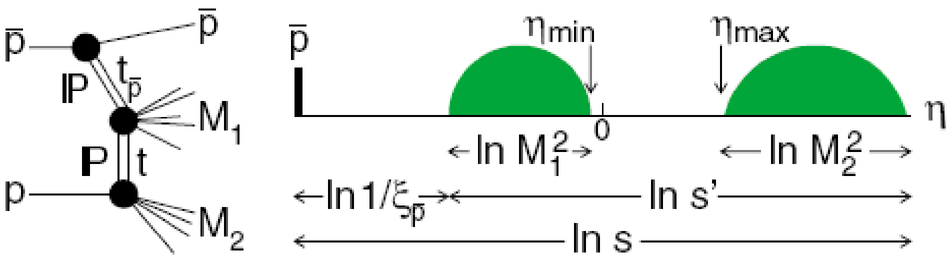
$$\frac{d^3\sigma_{\rm DD}}{dt\,d\Delta\eta\,d\eta_c} = \underbrace{\left[\frac{\kappa\beta^2(0)}{16\pi}\,e^{2[\alpha(t)-1]\Delta\eta}\right]}_{\text{gap probability}}\underbrace{\left[\kappa\beta^2(0)\left(\frac{s'}{s_0}\right)^{\epsilon}\right]}_{\text{x-section}}$$

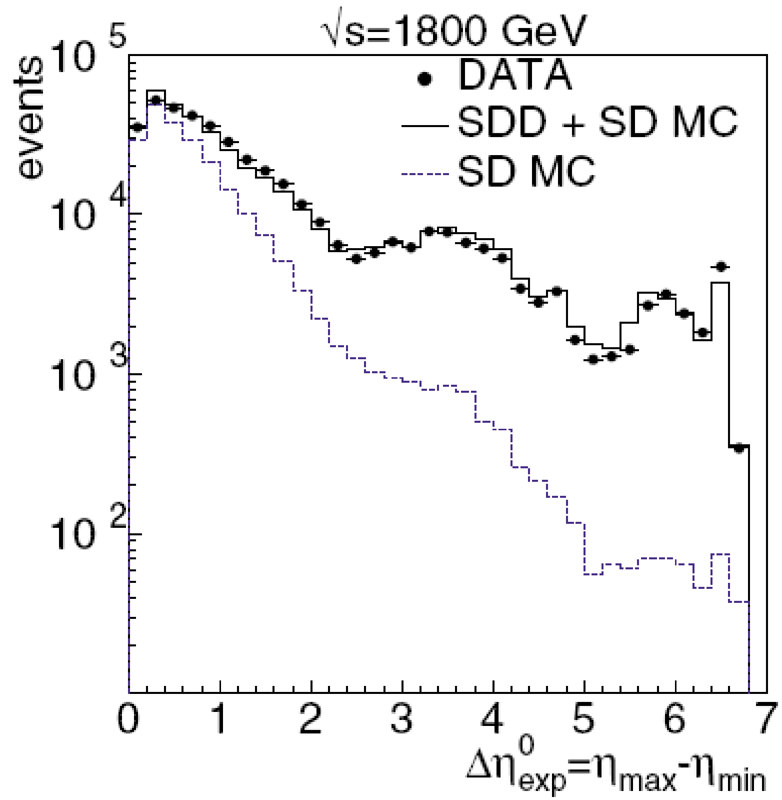




renormalized

SDD at CDF

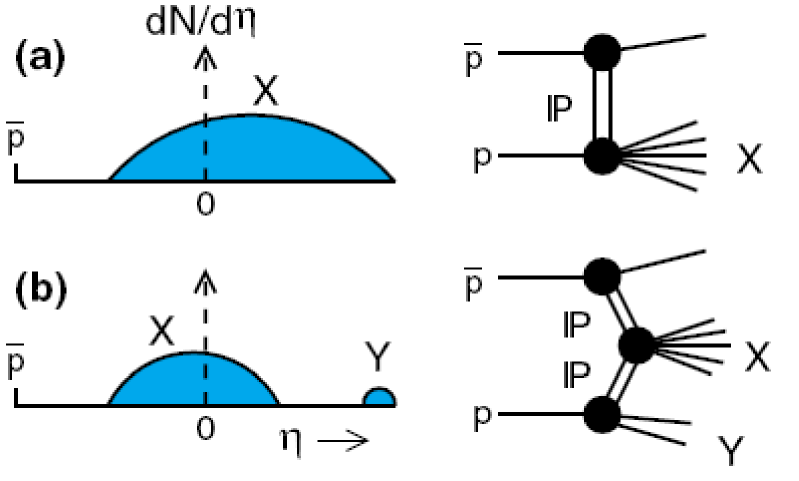




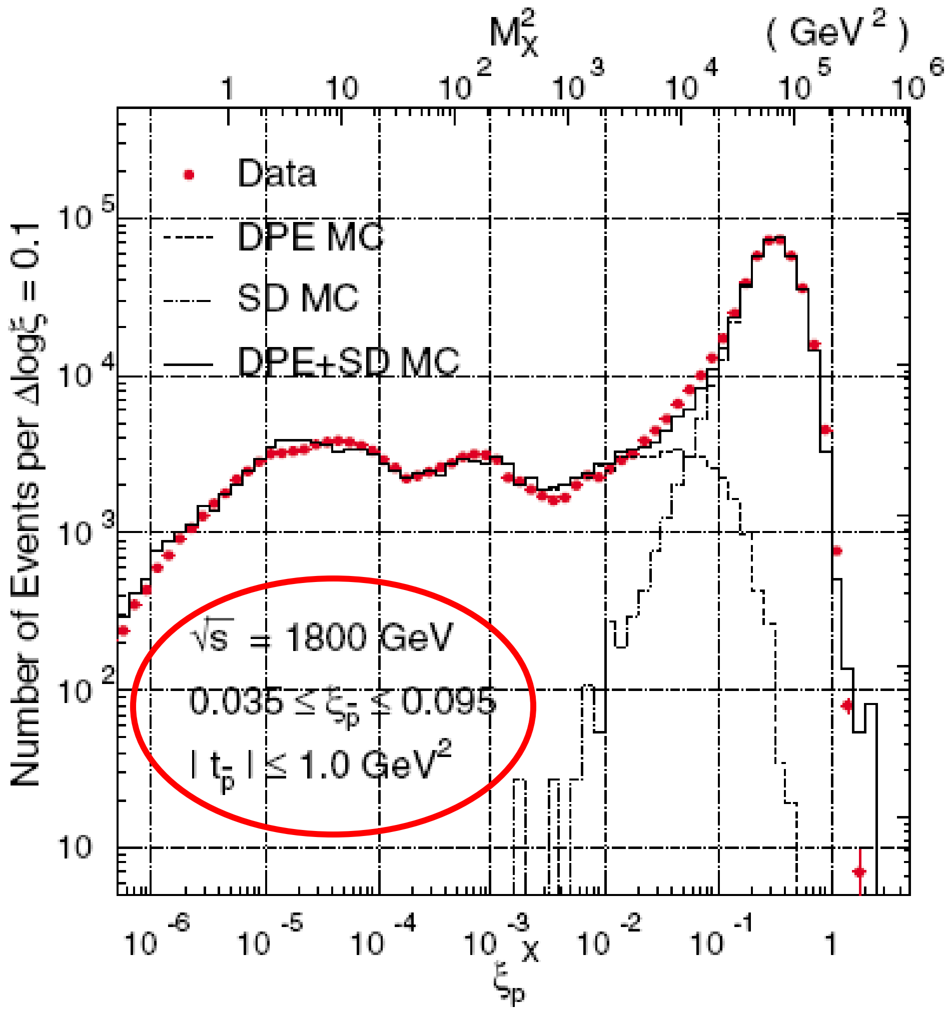
- Excellent agreement between data and MBR (MinBiasRockefeller) MC

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

CD/DPE at CDF



- Excellent agreement between data and MBR
➔ low and high masses are correctly implemented



Difractive x-sections

$$\frac{d^2\sigma_{SD}}{dt\,d\Delta y} = \frac{1}{N_{\rm gap}(s)}\left[\frac{\beta^2(t)}{16\pi}e^{2[\alpha(t)-1]\Delta y}\right]\cdot\left\{\kappa\beta^2(0)\left(\frac{s'}{s_0}\right)^{\epsilon}\right\},$$

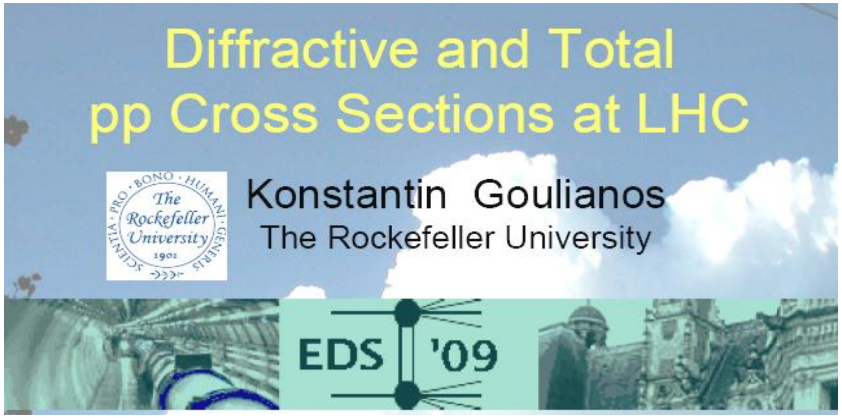
$$\frac{d^3\sigma_{DD}}{dt\,d\Delta y\,dy_0} = \frac{1}{N_{\rm gap}(s)}\left[\frac{\kappa\beta^2(0)}{16\pi}e^{2[\alpha(t)-1]\Delta y}\right]\cdot\left\{\kappa\beta^2(0)\left(\frac{s'}{s_0}\right)^{\epsilon}\right\},$$

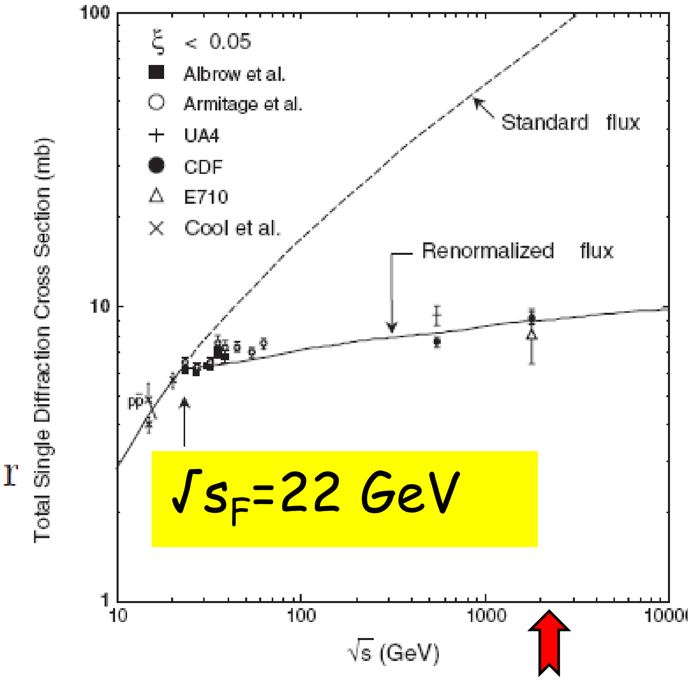
$$\frac{d^4\sigma_{DPE}}{dt_1\,dt_2\,d\Delta y\,dy_c} = \frac{1}{N_{\rm gap}(s)}\left[\Pi_i\left[\frac{\beta^2(t_i)}{16\pi}e^{2[\alpha(t_i)-1]\Delta y_i}\right]\right]\cdot\kappa\left\{\kappa\beta^2(0)\left(\frac{s'}{s_0}\right)^{\epsilon}\right\}$$

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

$$F^2(t) = \left[\frac{4m_p^2-2.8t}{4m_p^2-t}\left(\frac{1}{1-\frac{t}{0.71}}\right)^2\right]^2 \approx a_1e^{b_1t}+a_2e^{b_2t}$$

α_1=0.9, α_2=0.1, b_1=4.6 GeV^{-2}, b_2=0.6 GeV^{-2}, s'=s $e^{-\Delta y}$, κ=0.17, $\kappa\beta^2(0)=\sigma_0$, s_0=1 GeV^2, σ_0=2.82 mb or 7.25 GeV^{-2}





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

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

- 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:

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

SUPERBALL MODEL

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

Reduce the uncertainty in s_0

Saturation glueball?

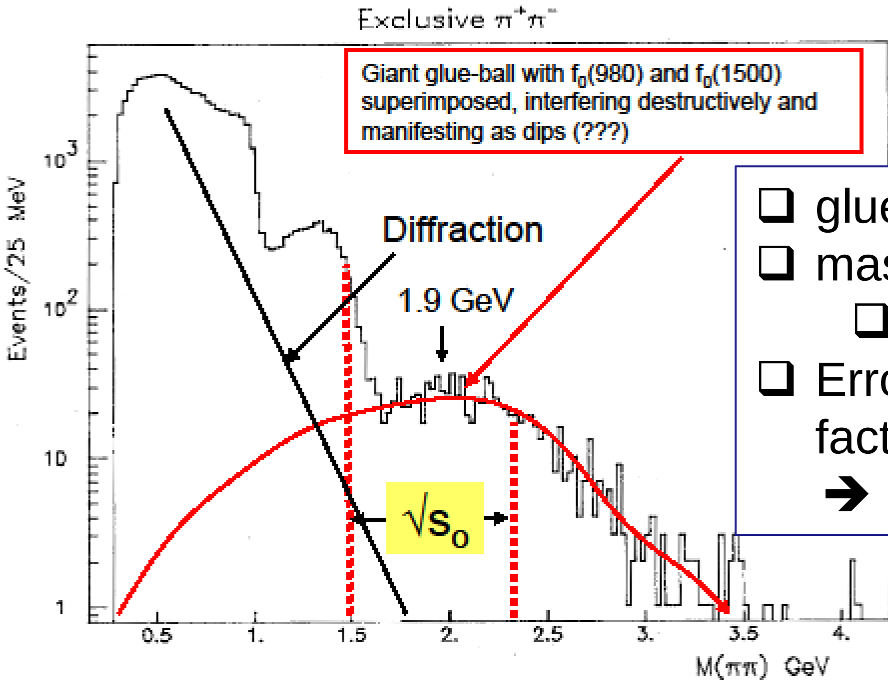


Figure 8: $M_{\pi^+\pi^-}$ spectrum in $DIPE$ at the ISR (Axial Field Spectrometer, R807 [97, 98]). Figure from Ref. [98]. **See M.G.Albrow, T.D. Goughlin, J.R. Forshaw, hep-ph>arXiv:1006.1289**

MIAMI 2010, Nov14 -19 Diffraction, saturation, and pp cross sections at the LHC and beyond K. Goulianos 2

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

Total, elastic, and inelastic x-sections

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

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

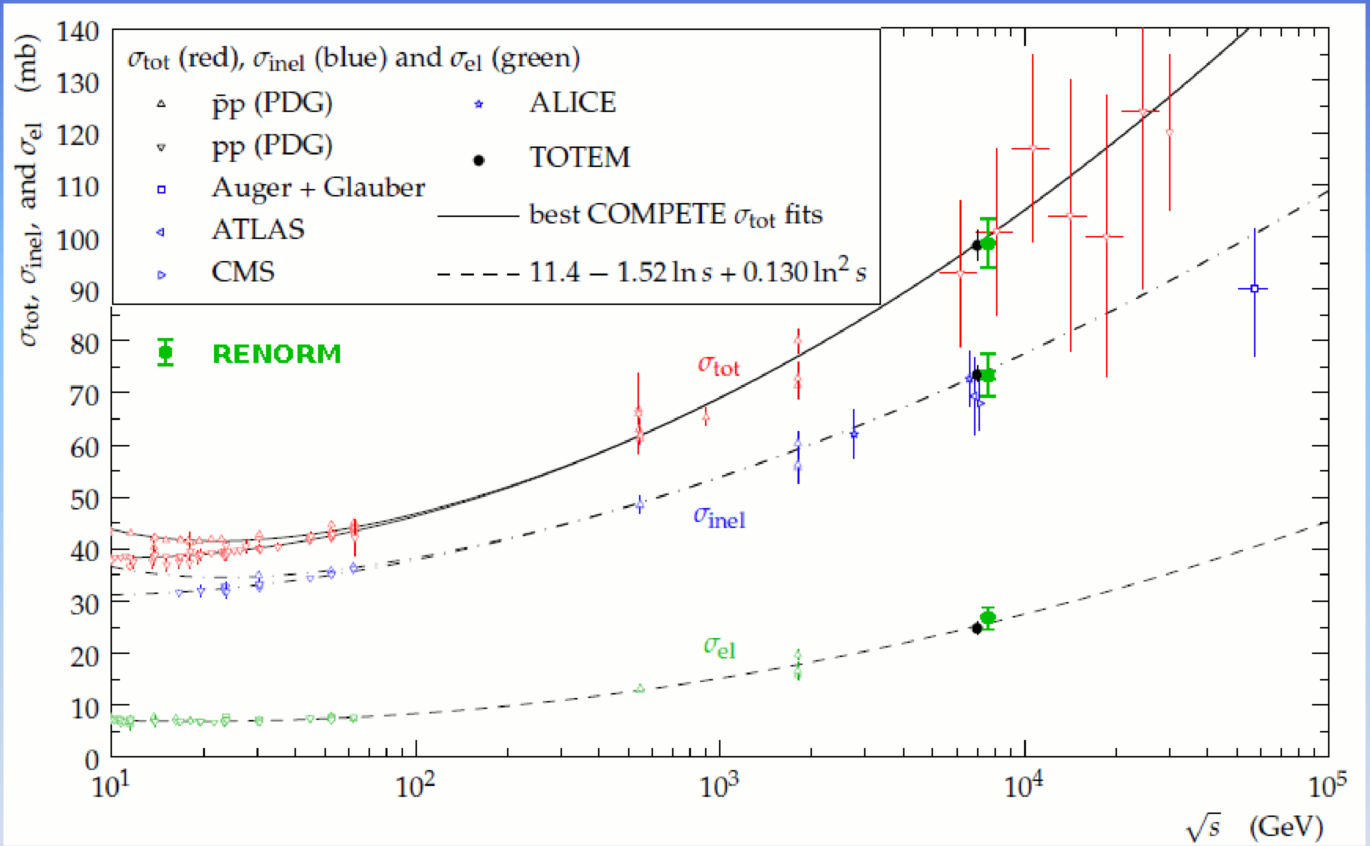
$$\sigma_{\rm tot}^{p^{\pm}p} = \begin{cases} 16.79 s^{0.104} + 60.81 s^{-0.32} \mp 31.68 s^{-0.54} & \text{for } \sqrt{s} < 1.8 \\ \sigma_{\rm tot}^{\rm CDF} + \frac{\pi}{s_0}\left[\left(\ln \frac{s}{s_F}\right)^2 - \left(\ln \frac{s^{\rm CDF}}{s_F}\right)^2\right] & \text{for } \sqrt{s} \geq 1.8 \end{cases}$$

K. Goulianos, *Diffraction, Saturation and pp Cross Sections at the LHC*, arXiv:1105.4916.

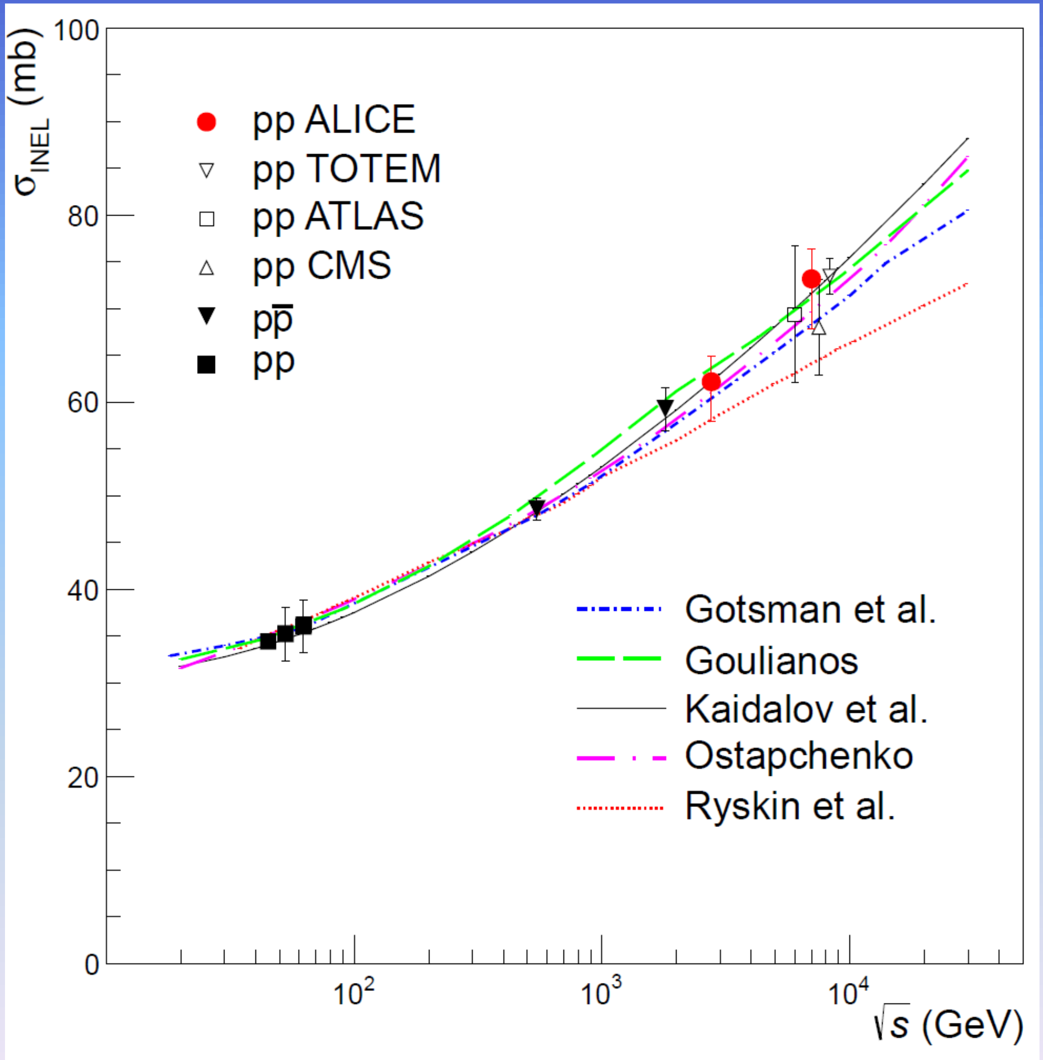
$$\sqrt{s^{\rm CDF}} = 1.8 \text{ TeV}, \ \sigma_{\rm tot}^{\rm CDF} = 80.03 \pm 2.24 \text{ mb}$$

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

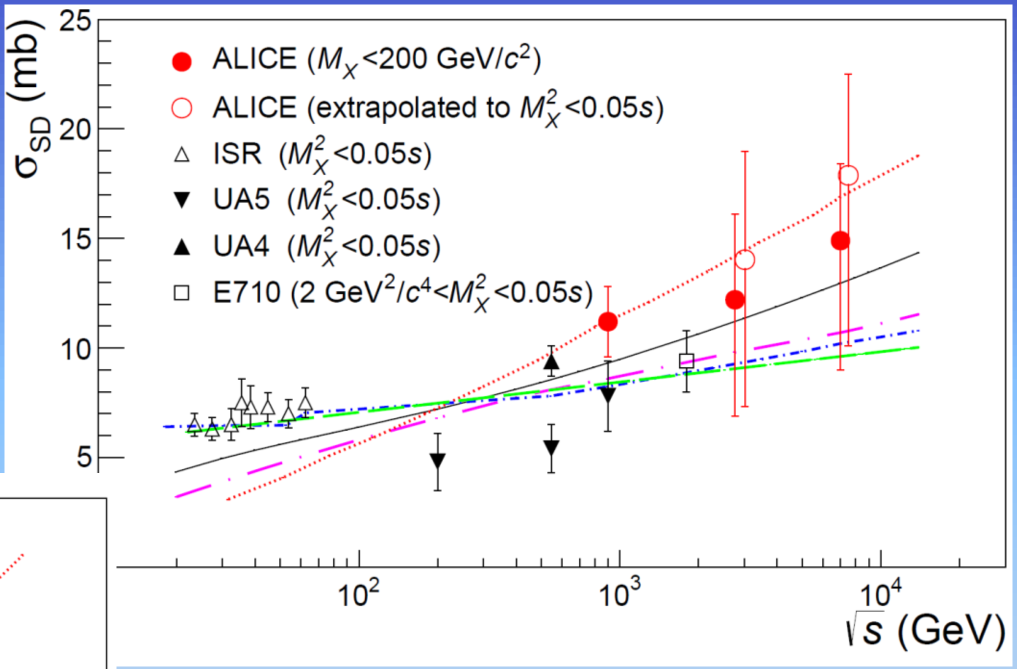
TOTEM vs PYTHIA8-MBR

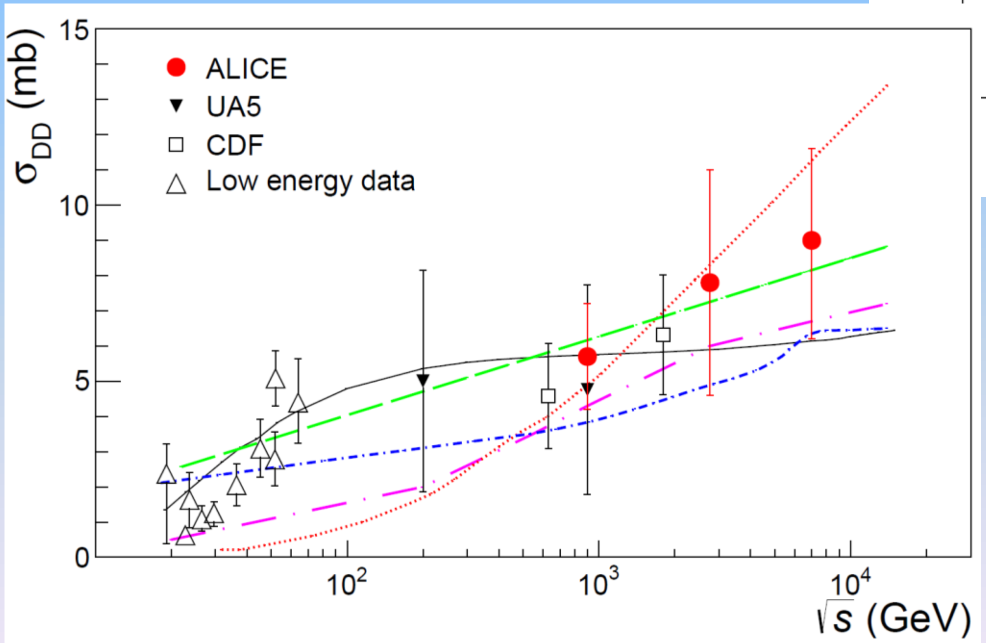


ALICE tot-inel vs PYTHIA8-MBR

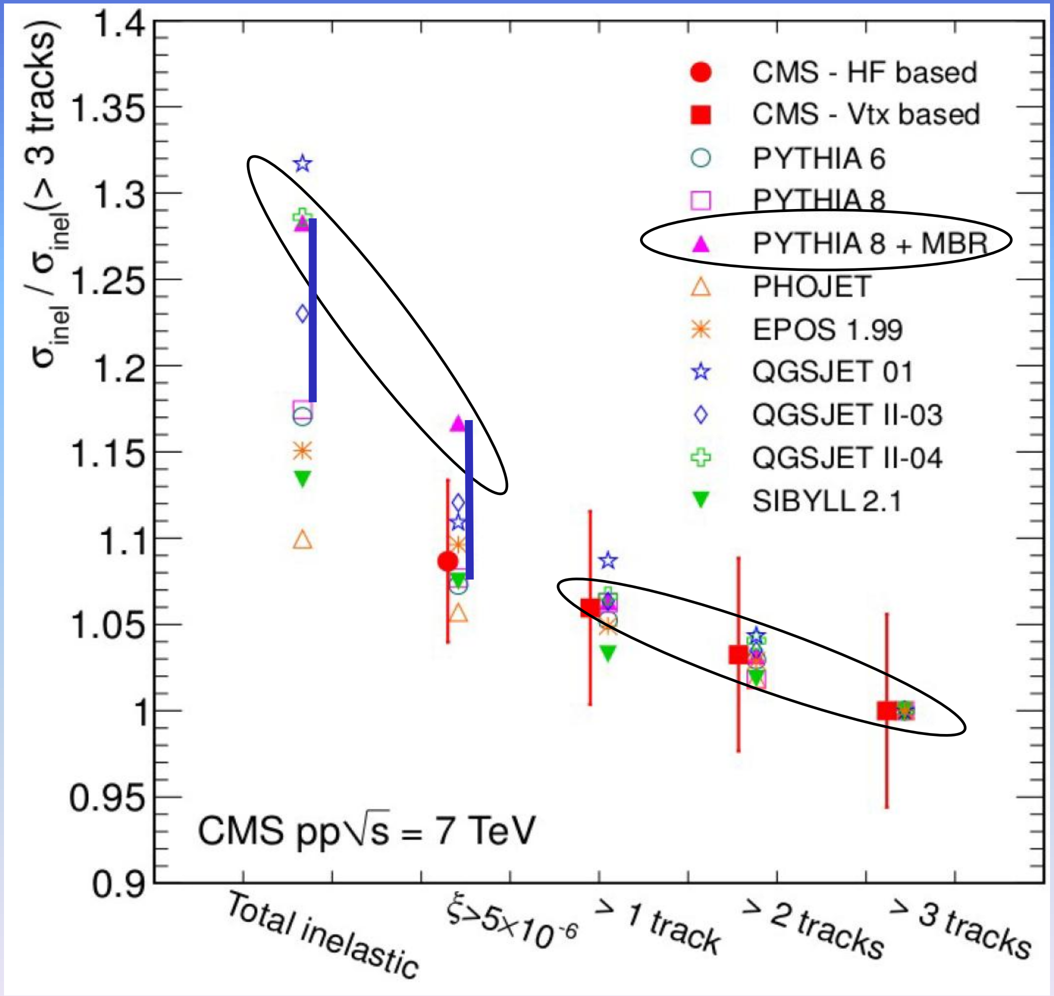


ALICE SD and DD vs PYTHIA8-MBR





CMS Total-Inelastic Cross Section
compared to PYTHIA8 and PYTHIA8-MBR



More on cross sections

Slide 12 from Uri Maor's talk at the LowX-2012

	7 TeV			14 TeV			57 TeV		100 TeV			$1.2 \cdot 10^{16}$ TeV	
	GLM	KMR	BH	GLM	KMR	BH	GLM	BH	GLM	KMR	BH	GLM	BH
σ_{tot}	94.2	97.4	95.4	104.0	107.5	107.3	125.0	134.8	134.0	138.8	147.1	393	2067
σ_{inel}	71.3	73.6	69.0	77.9	80.3	76.3	92.2	92.9	98.5	100.7	100.0	279	1131
$\frac{\sigma_{inel}}{\sigma_{tot}}$	0.76	0.76	0.72	0.75	0.75	0.71	0.74	0.70	0.74	0.73	0.68	0.71	0.55
MBR sigma_tot			98			109		136			144		2257

Monte Carlo Strategy for the LHC …

MONTE CARLO STRATEGY

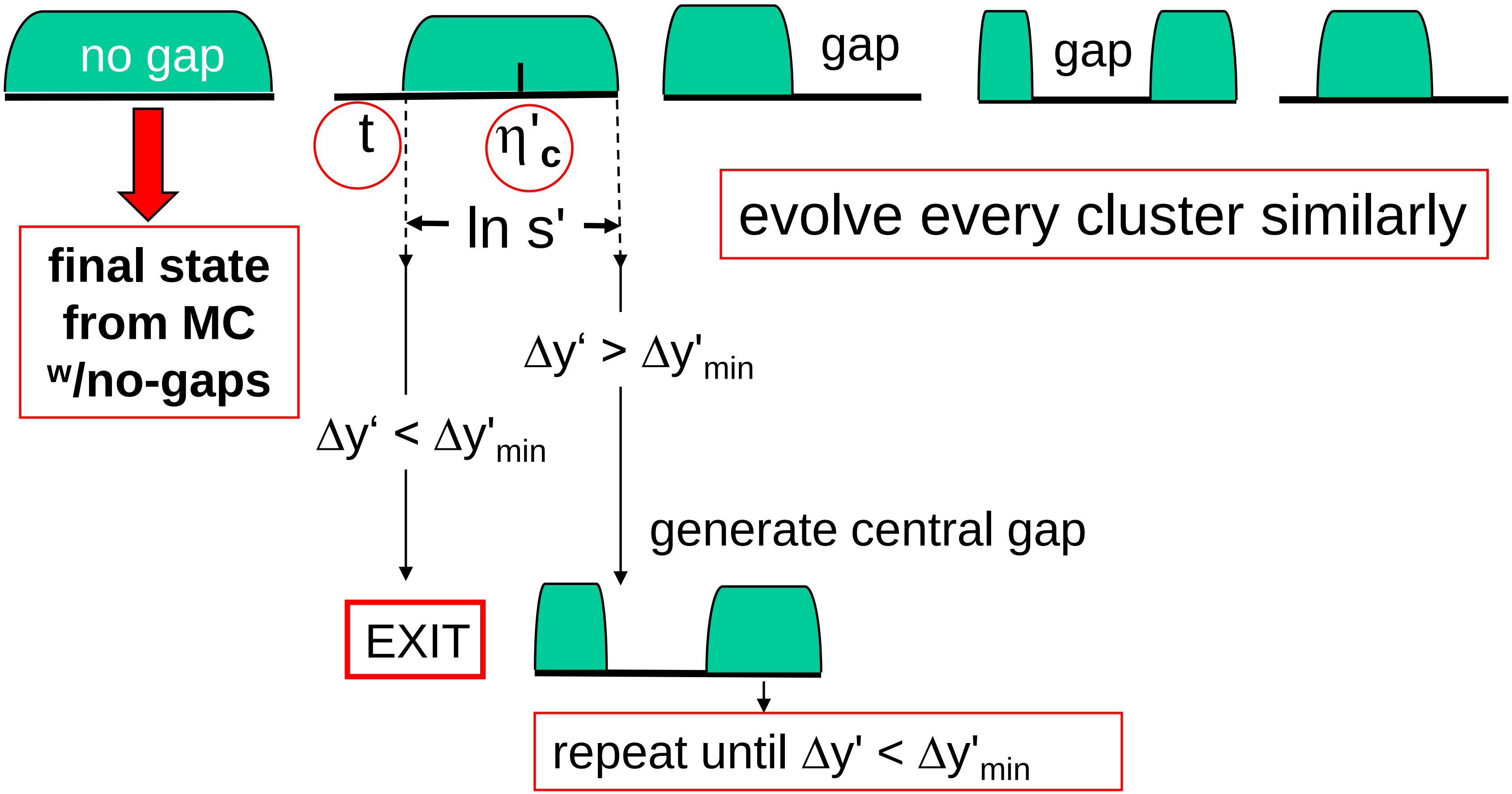
- ❑ σ^T → from SUPERBALL model
- ❑ optical theorem → Im $f_{el}(t=0)$
- ❑ dispersion relations → Re $f_{el}(t=0)$
- ❑ σ^{el}
- ❑ σ^{inel}
- ❑ differential σ^{SD} → from RENORM
- ❑ use *nesting* of final states (FSs) for *pp* collisions at the *IPp* sub-energy √s'

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

Strategy similar to that of MBR 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 distributios "

Monte Carlo algorithm - nesting

Profile of a *pp* inelastic collision



SUMMARY

- Introduction
- Diffractive cross sections
  - basic: SD_p, $SD_{\bar{p}}$, DD, DPE
  - combined: multigap x-sections

  derived from ND and QCD color factors
  - ND ➔ no-gaps: final state from MC with no gaps
    - this is the only final state to be tuned
- Total, elastic, and inelastic cross sections
- Monte Carlo strategy for the LHC – "nesting"

Thank you for your attention