# Diffractive pp cross sections at the LHC implemented in PYTHIA8


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http://cgc.physics.miami.edu/Miami2012.html

# 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

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
  - MBR produces only $\pi^{\pm}$ and $\pi^{0}$ '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

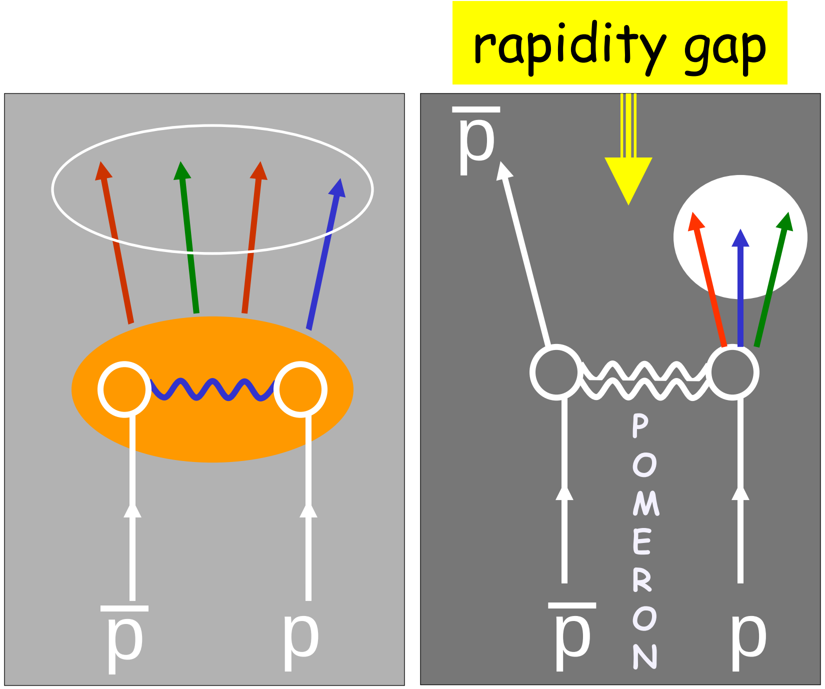
## Non-diffractive events

- color-exchange → η-gaps exponentially suppressed

## Diffractive events

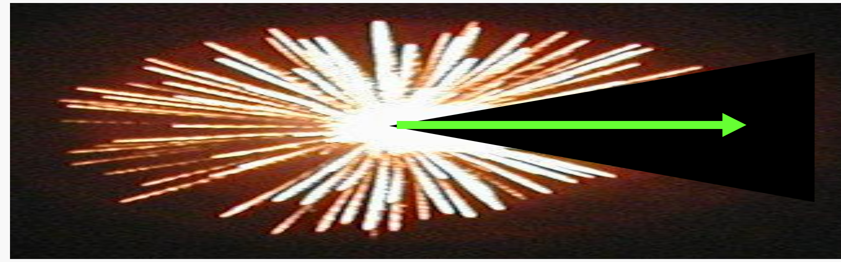
- Colorless vacuum exchange

→ η-gaps not exp'ly suppressed

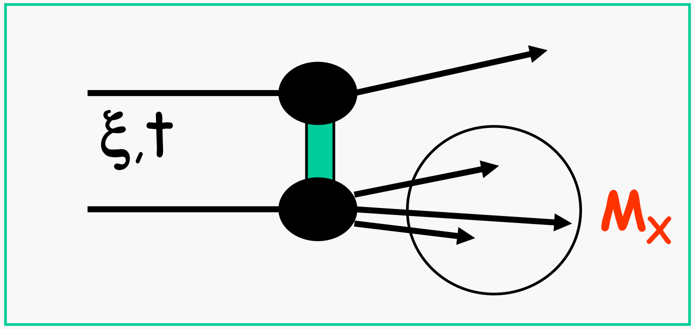



Goal: probe the QCD nature of the diffractive exchange

# DEFINITIONS



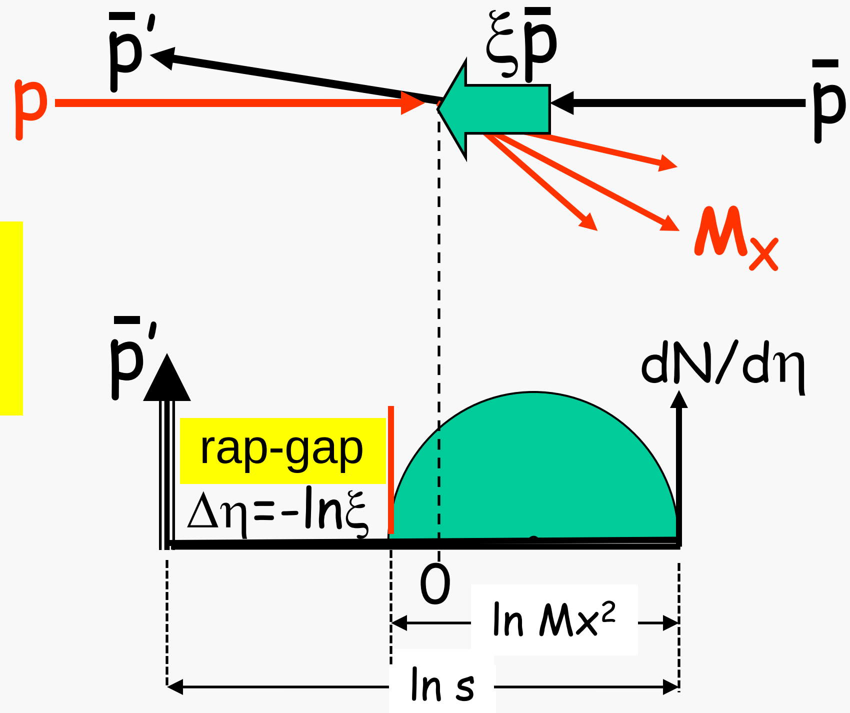
### SINGLE DIFFRACTION




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

Forward momentum loss

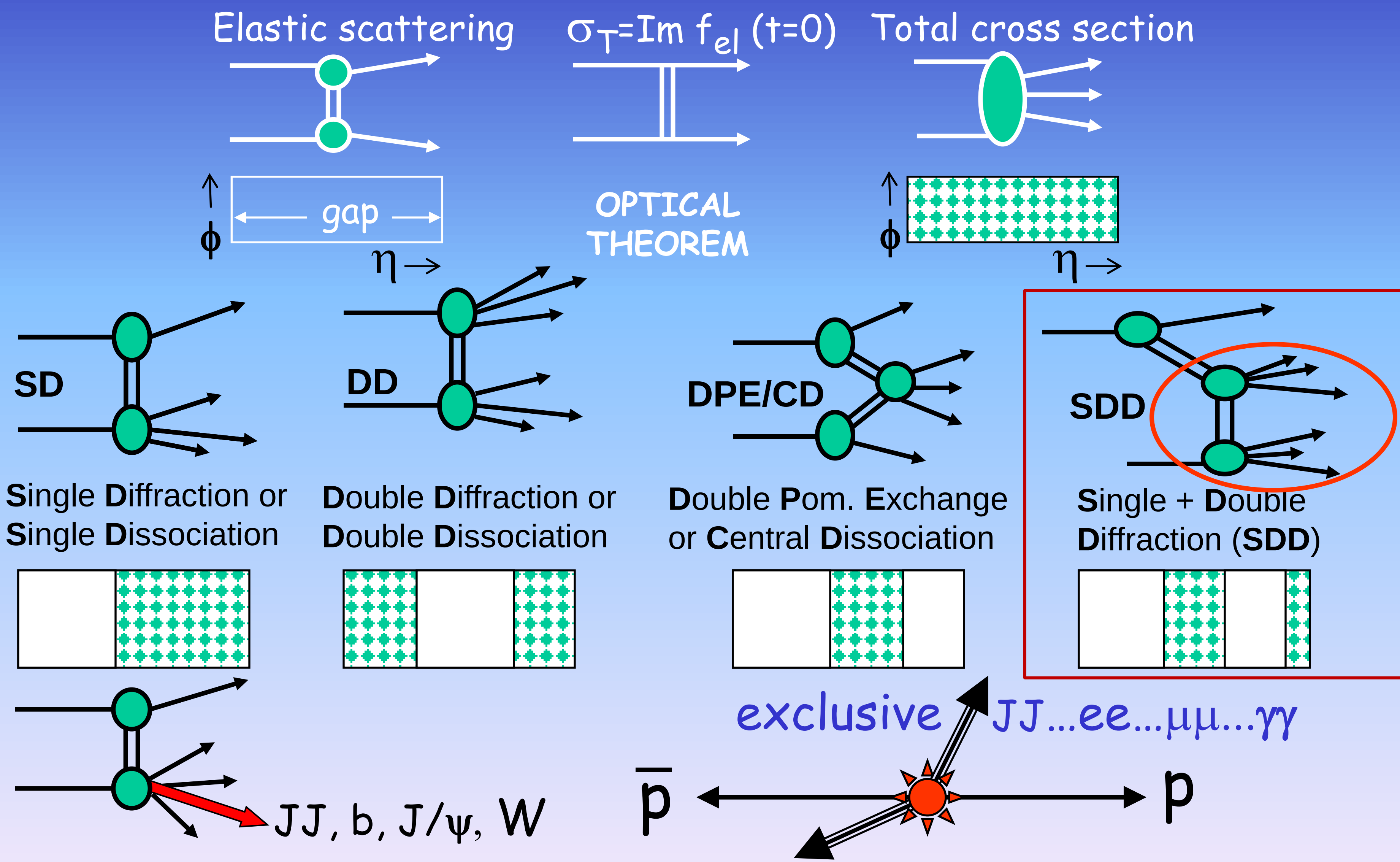
$$\xi^{CAL} = \frac{\sum_{i=1}^{all} E_T^{i\text{-tower}} e^{-\eta_i}}{\sqrt{s}}$$




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

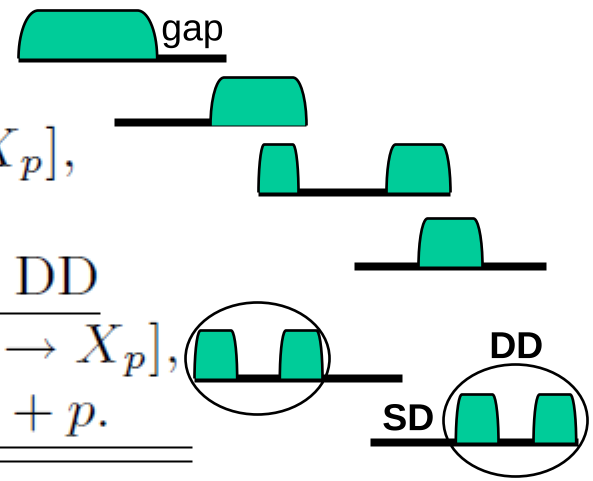
$$\left(\frac{d\sigma}{d\,\Delta\eta}\right)_{t=0} \approx \text{constant} \Rightarrow \frac{d\sigma}{d\xi} \propto \frac{1}{\xi} \Rightarrow \frac{d\sigma}{dM^2} \propto \frac{1}{M^2}$$

# DIFFRACTION AT CDF

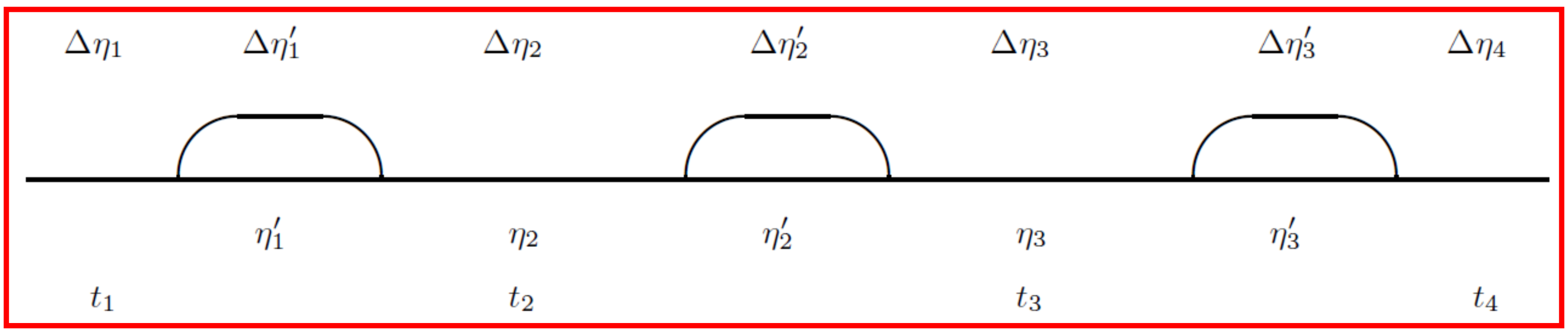


# Basic and combined diffractive processes

| acronym | basic diffractive processes |
|---|---|
| $\mathbf{SD}_{\bar{p}}$ | $\bar{p}p \to \bar{p} + \text{gap} + [p \to X_p]$, |
| $\mathbf{SD}_{p}$ | $\bar{p}p \to [\bar{p} \to X_{\bar{p}}] + \text{gap} + p$, |
| **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 |
| $\mathbf{SDD}_{\bar{p}}$ | $\bar{p}p \to \bar{p} + \text{gap} + X_c + \text{gap} + [p \to X_p]$, |
| $\mathbf{SDD}_{p}$ | $\bar{p}p \to [\bar{p} \to X_{\bar{p}}]\text{gap} + X_c + \text{gap} + p$. |

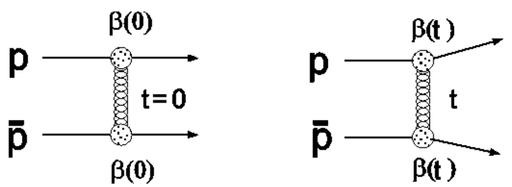



4-gap diffractive process-Snowmass 2001- http://arxiv.org/pdf/hep-ph/0110240

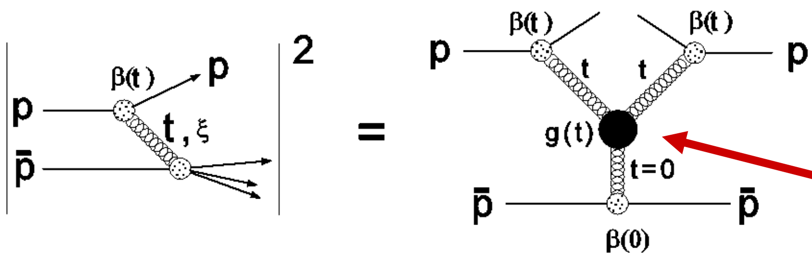


# Regge theory – values of $s_o$ & $g_{PPP}$?

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?**

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

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

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

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

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

$$\frac{d^2\sigma_{\rm sd}}{dt\,d\xi} = \frac{\beta_1^2(t)}{16\pi}\,\xi^{1-2\alpha(t)}\left[\beta_2(0)\,g(t)\left(\frac{s'}{s_0'}\right)^{\alpha(0)-1}\right]$$

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

# A complication … ➔ Unitarity!

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

- ❑ $\sigma_{sd}$ grows faster than $\sigma_t$ as *s* increases *
  ➔ unitarity violation at high *s*

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

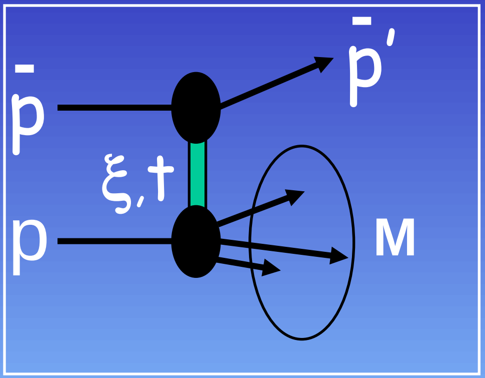
- ❑ the unitarity limit is already reached at $\sqrt{s}$ ~ 2 TeV !

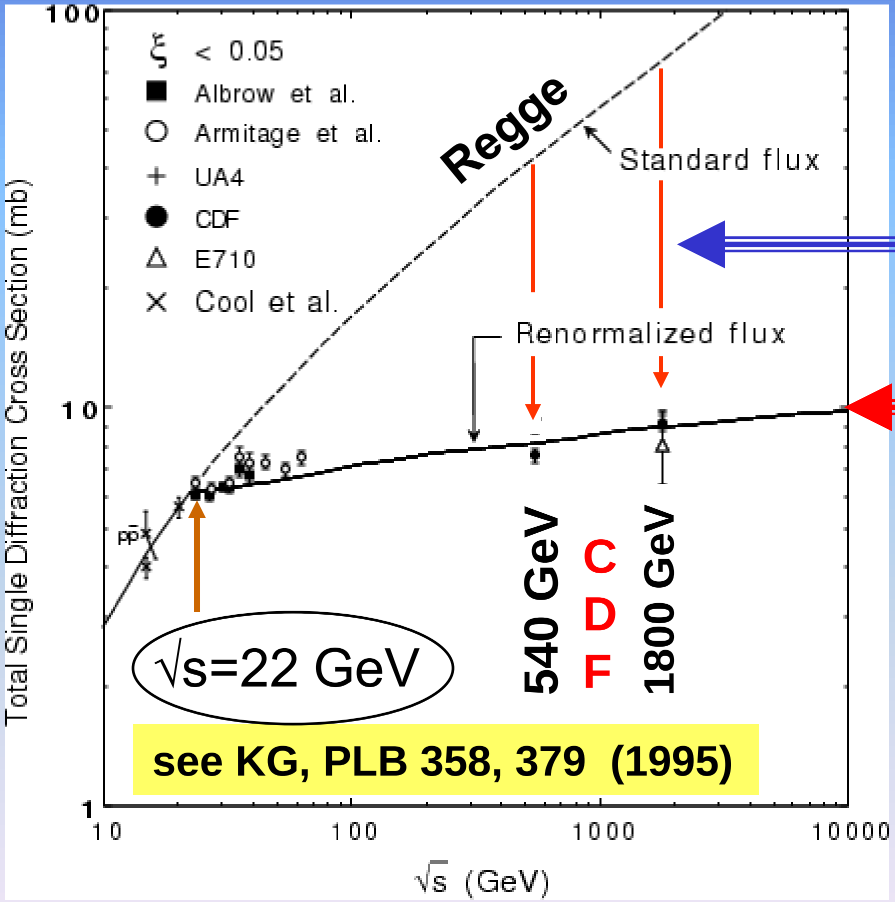
- ❑ need unitarization

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

# FACTORIZATION BREAKING IN SOFT DIFFRACTION

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



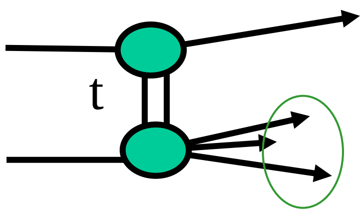

Factor of ~8 (~5) suppression at √s = 1800 (540) GeV

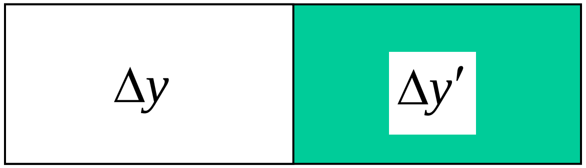
**RENORMALIZATION**

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:**

**KG&JM, PRD 59 (114017) 1999**

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

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

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

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

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

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

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

set to unity
➔ determines $s_o$

# Single diffraction renormalized - 4

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

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

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

grows slower than $s^{\varepsilon}$

→ 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!

**KG&JM, PRD 59 (1999) 114017**

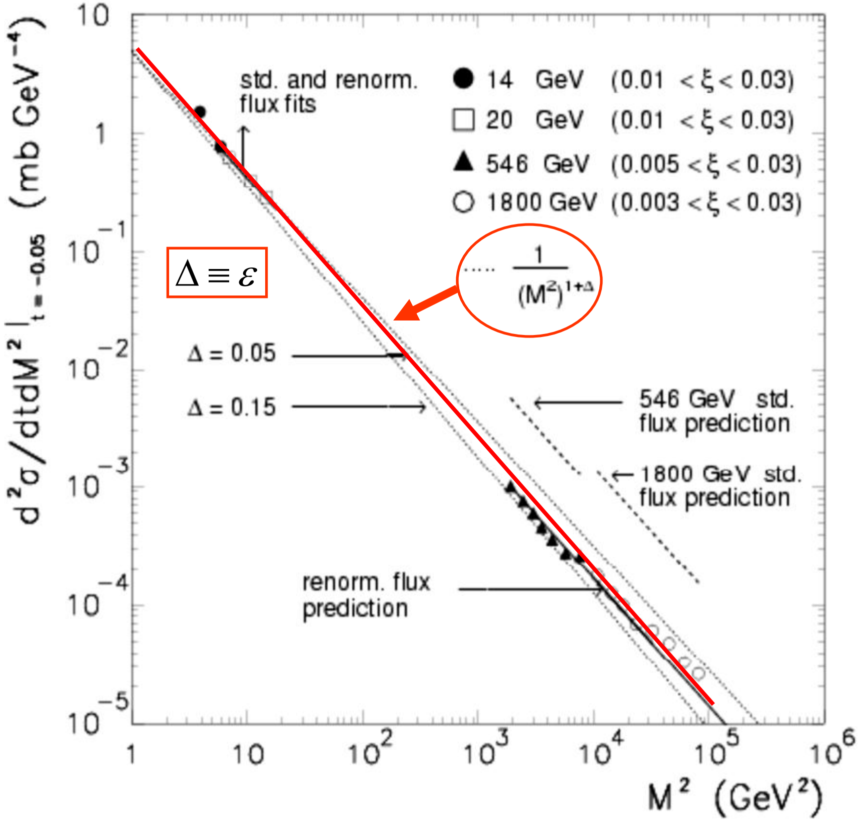
Regge

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



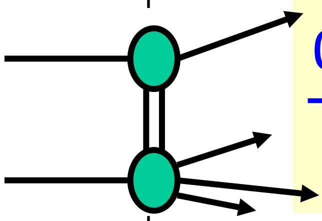

➔ factorization breaks down to ensure $M^2$ scaling

# 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



$$s_o^{\varepsilon}$$

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

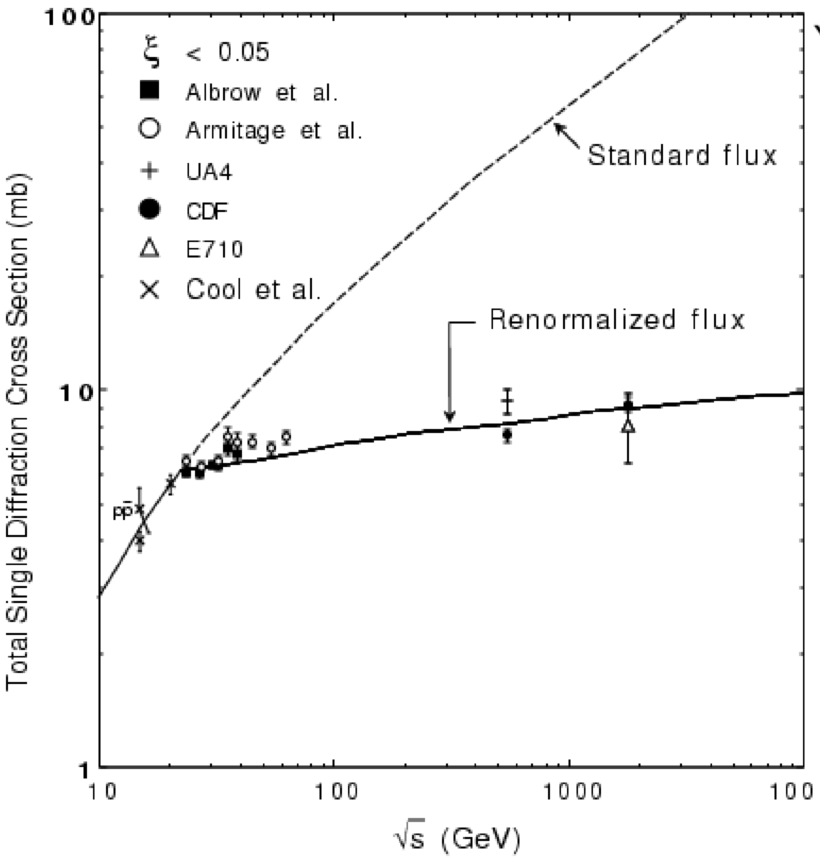
$$s_o^{-\varepsilon/2}\cdot g_{PPP}(t)$$

Pomeron-proton x-section

- ❑ Two free parameters: $s_o$ and $g_{PPP}$
- ❑ Obtain product $g_{PPP}\bullet s_o^{\varepsilon/2}$ from $\sigma_{SD}$
- ❑ 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



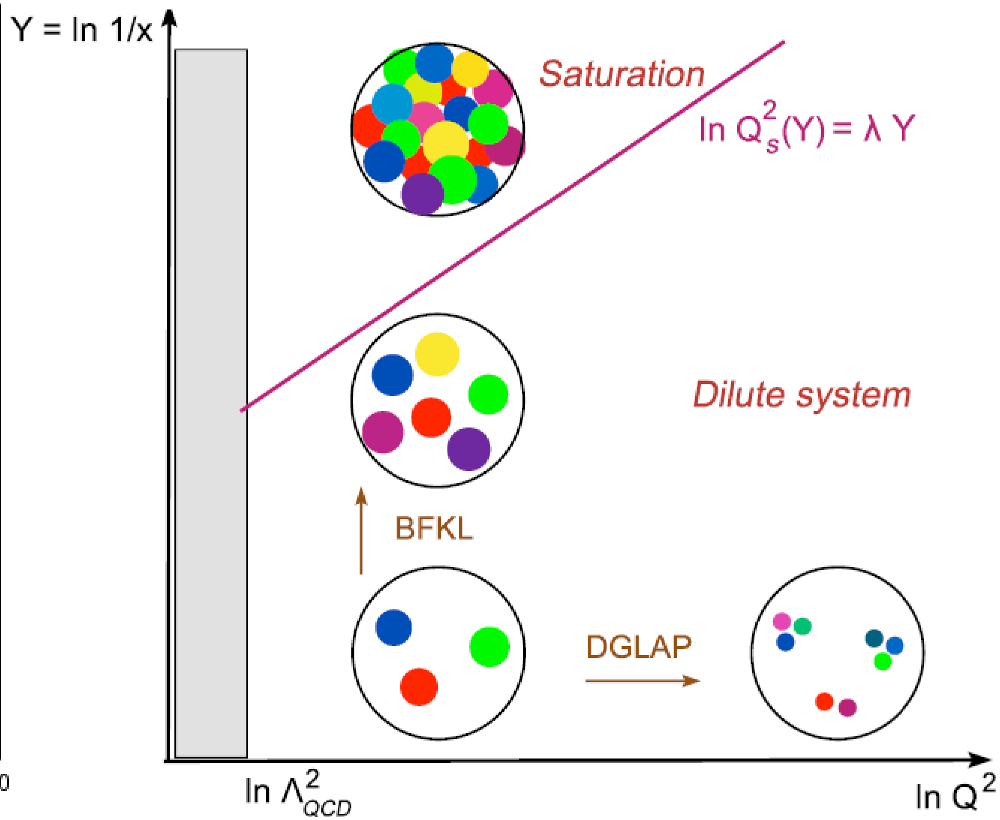
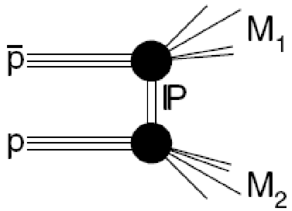
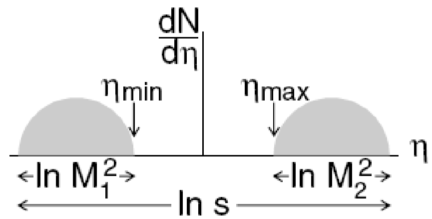




figure from a talk by Edmond Iancu

# DD at CDF

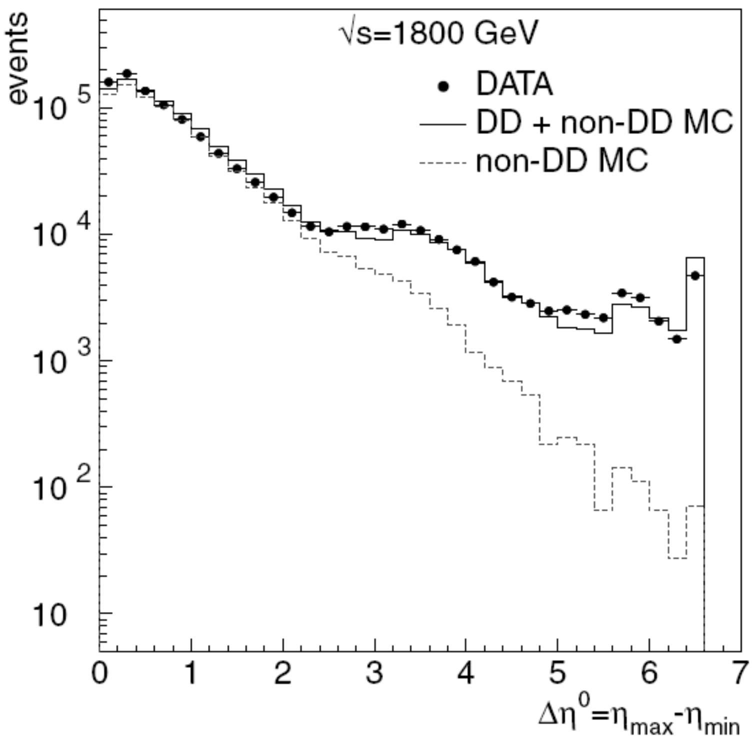


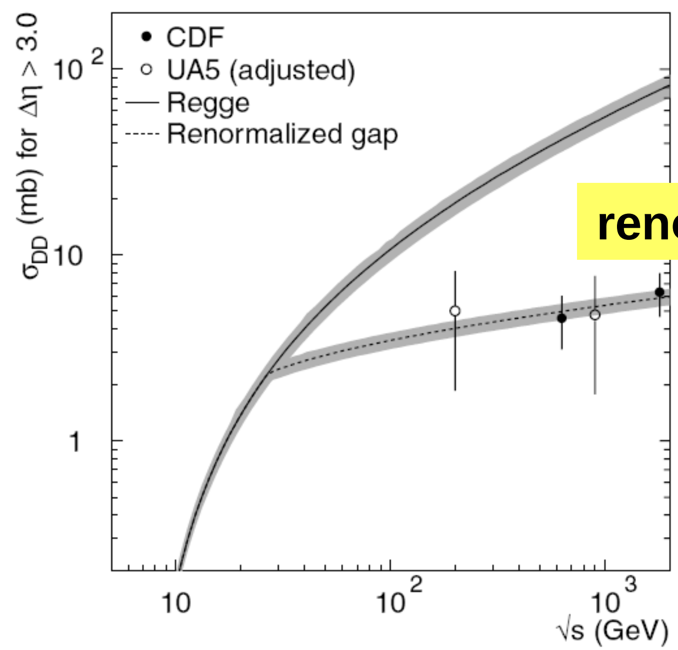




$$\frac{d^3\sigma_{\rm DD}}{dt\,dM_1^2\,dM_2^2} = \frac{d^2\sigma_{\rm SD}}{dt\,dM_1^2}\,\frac{d^2\sigma_{\rm SD}}{dt\,dM_2^2}\Big/\frac{d\sigma_{el}}{dt}$$
$$= \frac{[\kappa\beta_1(0)\beta_2(0)]^2}{16\pi}\,\frac{s^{2\epsilon}e^{b_{\rm DD}t}}{(M_1^2M_2^2)^{1+2\epsilon}}$$

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

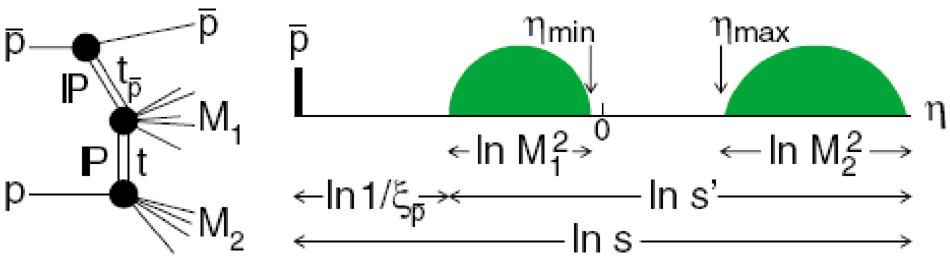
gap probability x-section

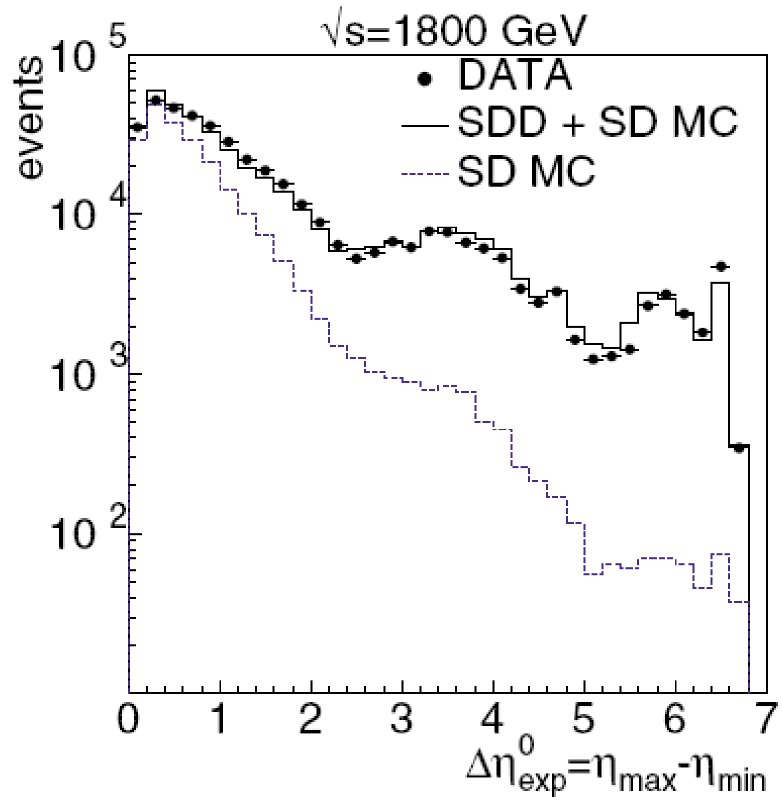



**renormalized**

# SDD at CDF

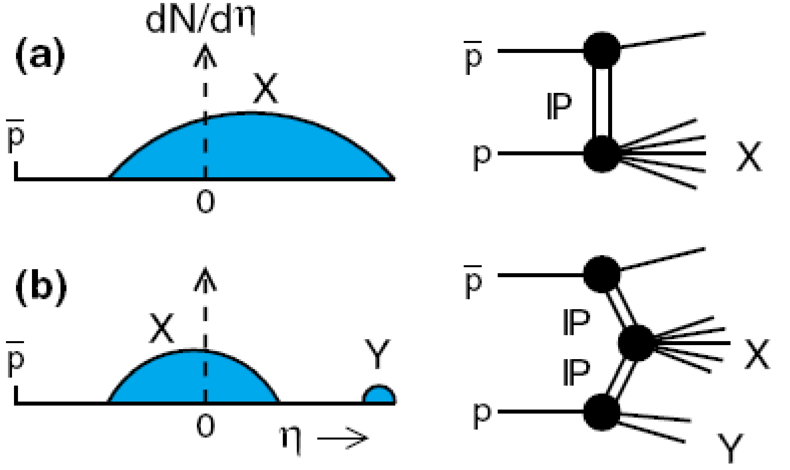


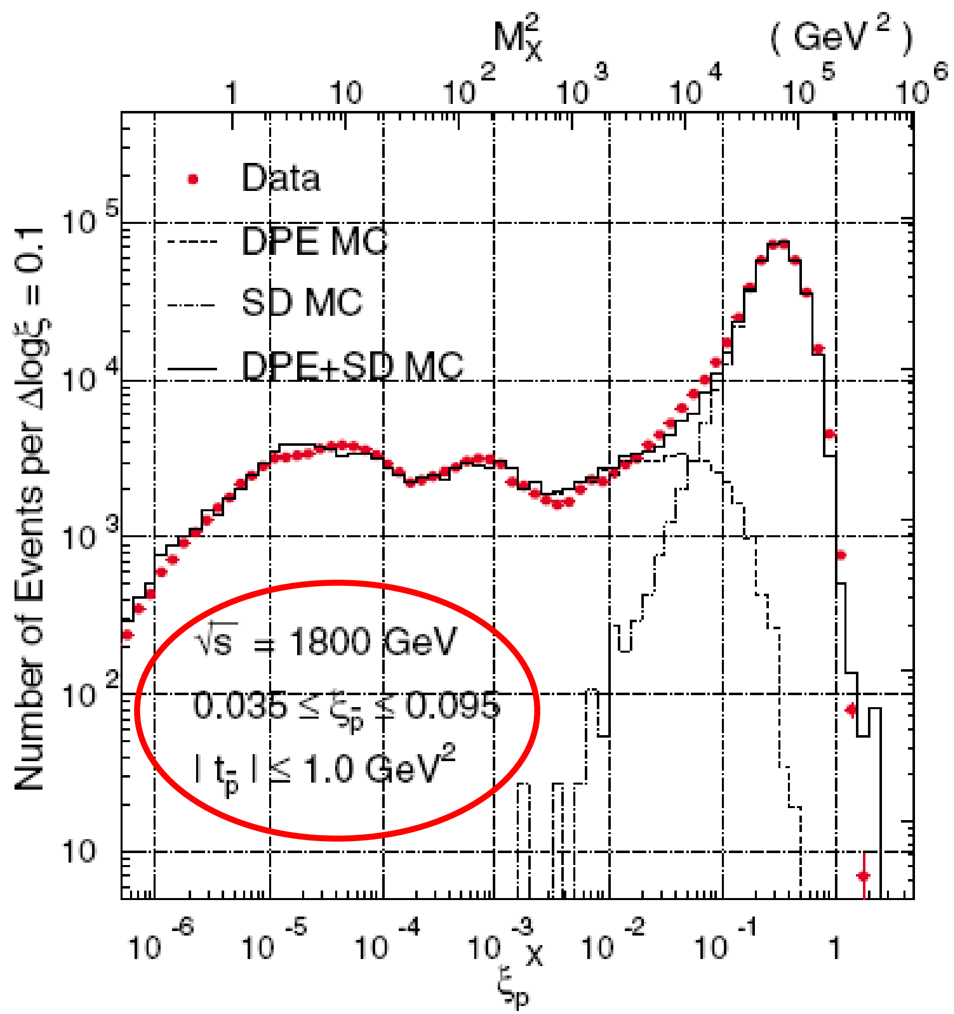




- Excellent agreement between data and MBR (MinBiasRockefeller) MC

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

# CD/DPE at CDF




- Excellent agreement between data and MBR

➔ low and high masses are correctly implemented

# Difractive x-sections

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

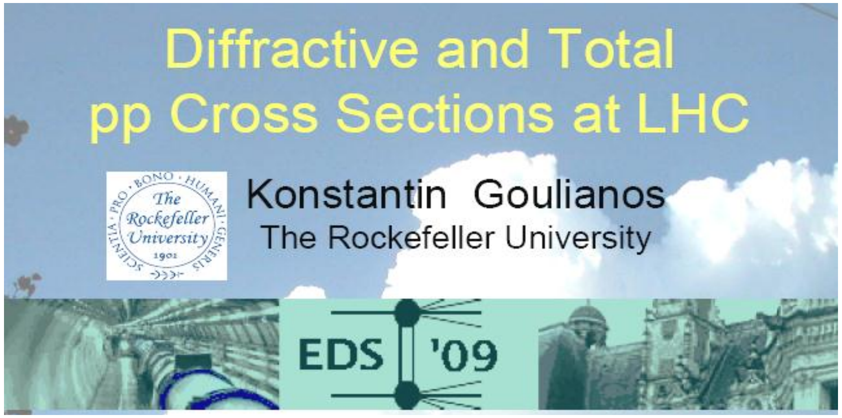
$$\frac{d^3\sigma_{DD}}{dt d\Delta y dy_0} = \frac{1}{N_{\rm gap}(s)}\left[\frac{\kappa\beta^2(0)}{16\pi}e^{2[\alpha(t)-1]\Delta y}\right]\cdot\left\{\kappa\beta^2(0)\left(\frac{s'}{s_0}\right)^{\epsilon}\right\},$$

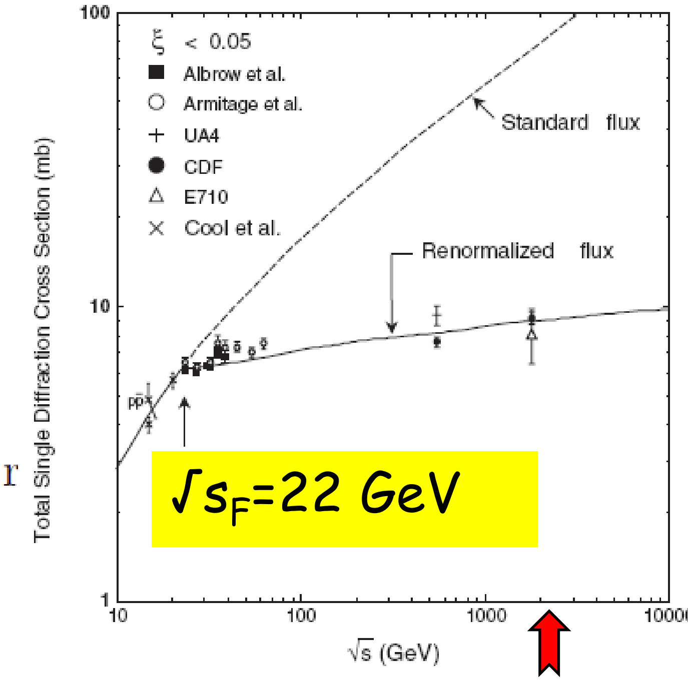
$$\frac{d^4\sigma_{DPE}}{dt_1 dt_2 d\Delta y dy_c} = \frac{1}{N_{\rm gap}(s)}\left[\Pi_i\left[\frac{\beta^2(t_i)}{16\pi}e^{2[\alpha(t_i)-1]\Delta y_i}\right]\right]\cdot\kappa\left\{\kappa\beta^2(0)\left(\frac{s'}{s_0}\right)^{\epsilon}\right\}$$

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

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

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




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

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

- This formula should be valid above the *knee* in $\sigma_{sd}$ 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].

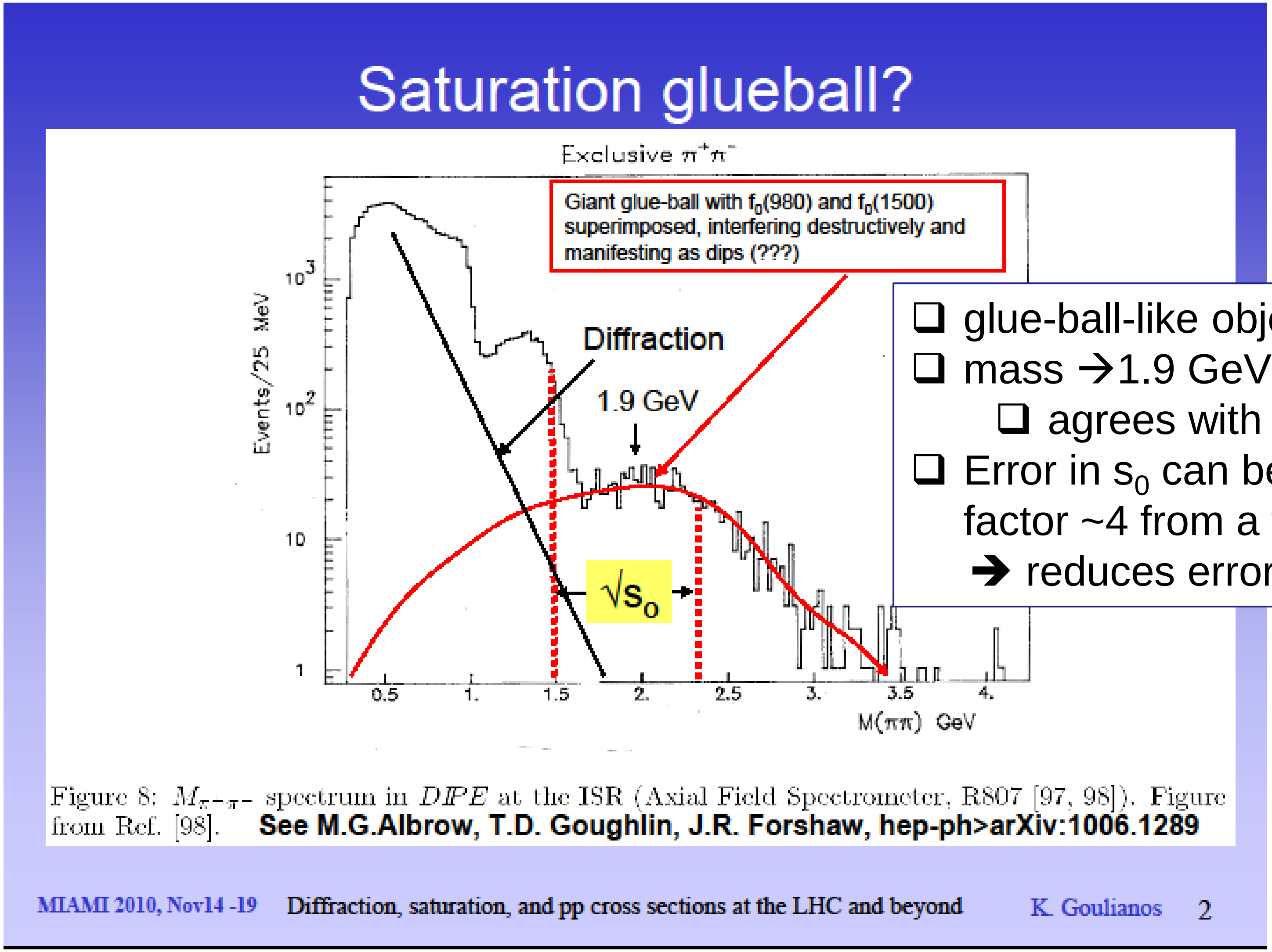
- Obtain the total cross section at the LHC:

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

**SUPERBALL MODEL**

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

# Reduce the uncertainty in $s_0$




- 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!
  → reduces error in $\sigma_t$.

# Total, elastic, and inelastic x-sections

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

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

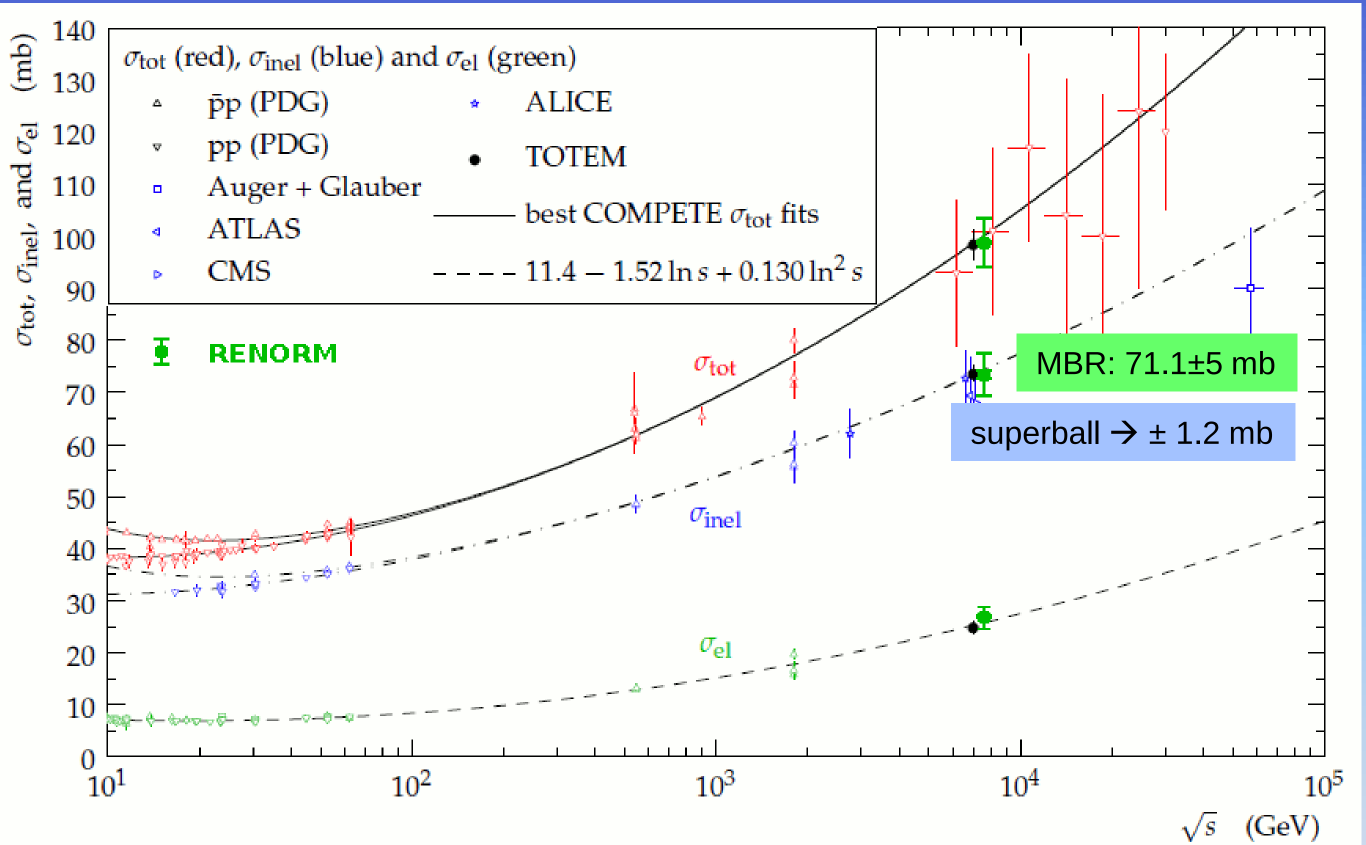
$$\sigma_{\mathrm{tot}}^{p^{\pm}p} = \begin{cases} 16.79 s^{0.104} + 60.81 s^{-0.32} \mp 31.68 s^{-0.54} & \text{for } \sqrt{s} < 1.8 \\ \sigma_{\mathrm{tot}}^{\mathrm{CDF}} + \frac{\pi}{s_0}\left[\left(\ln \frac{s}{s_F}\right)^2 - \left(\ln \frac{s^{\mathrm{CDF}}}{s_F}\right)^2\right] & \text{for }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

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

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

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

# TOTEM vs PYTHIA8-MBR




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

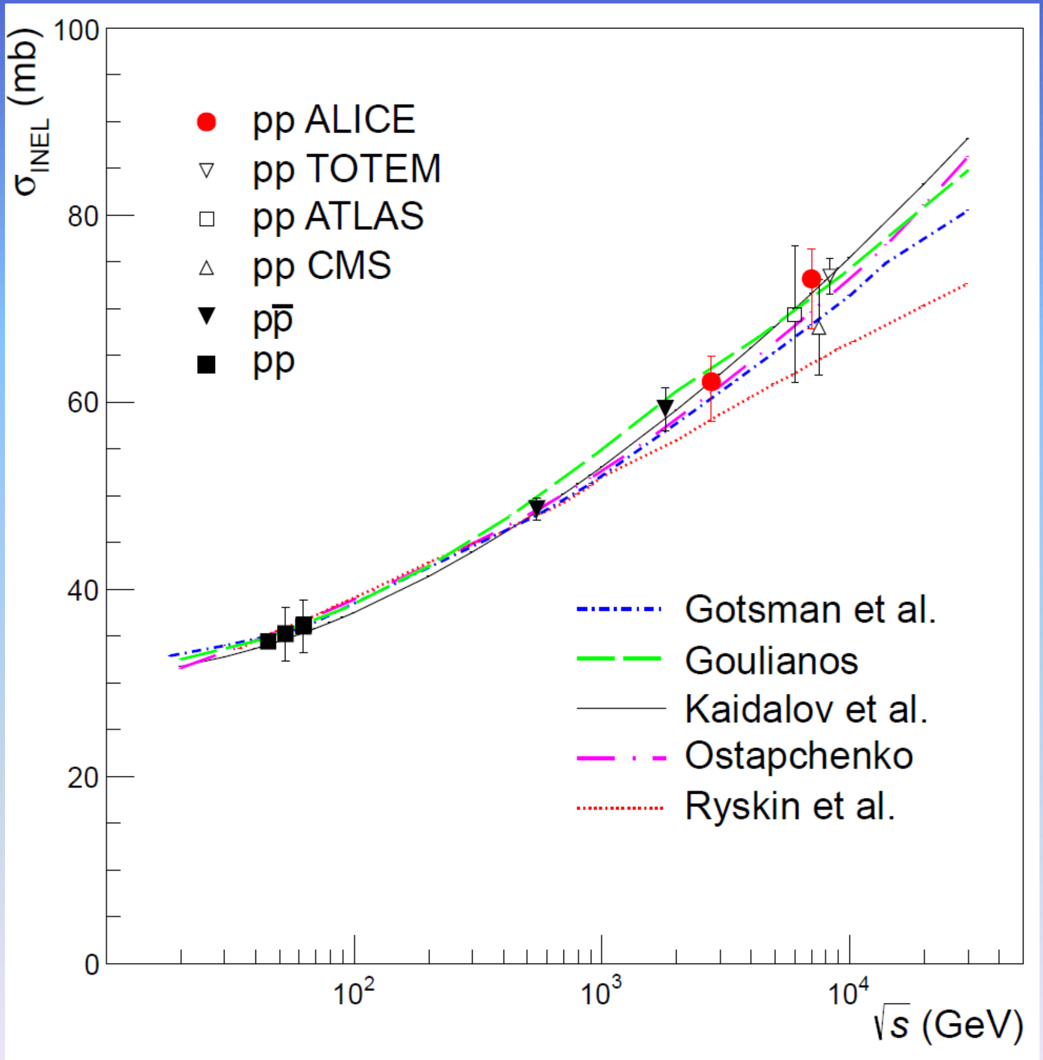
$\sigma_{inrl}^{8\ TeV}$ = 74.7 ±1.7 mb

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

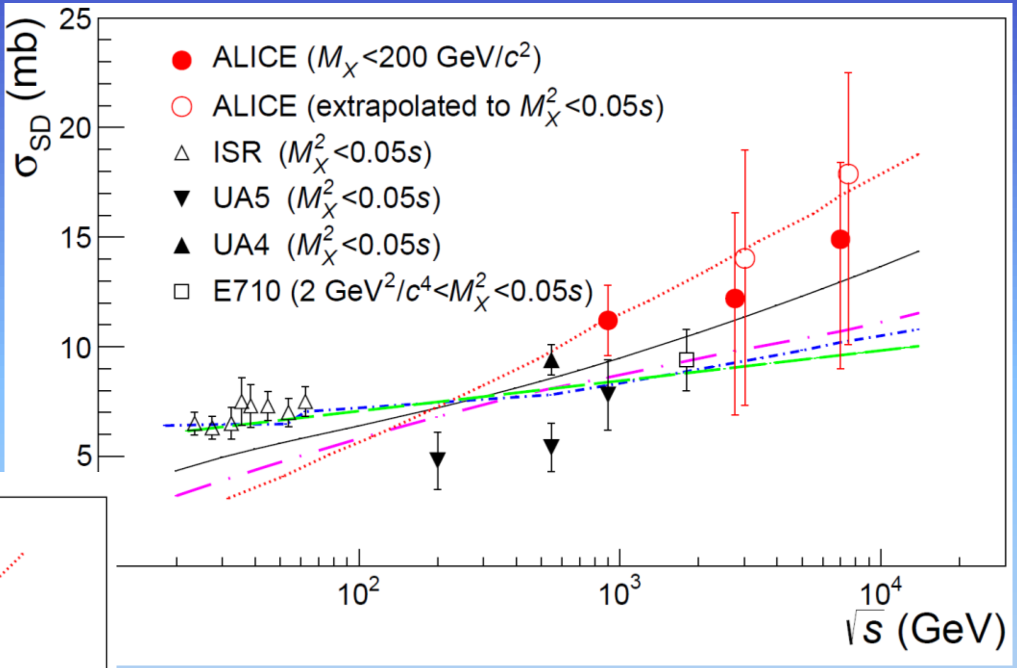
RENORM: 71.1±1.2 mb

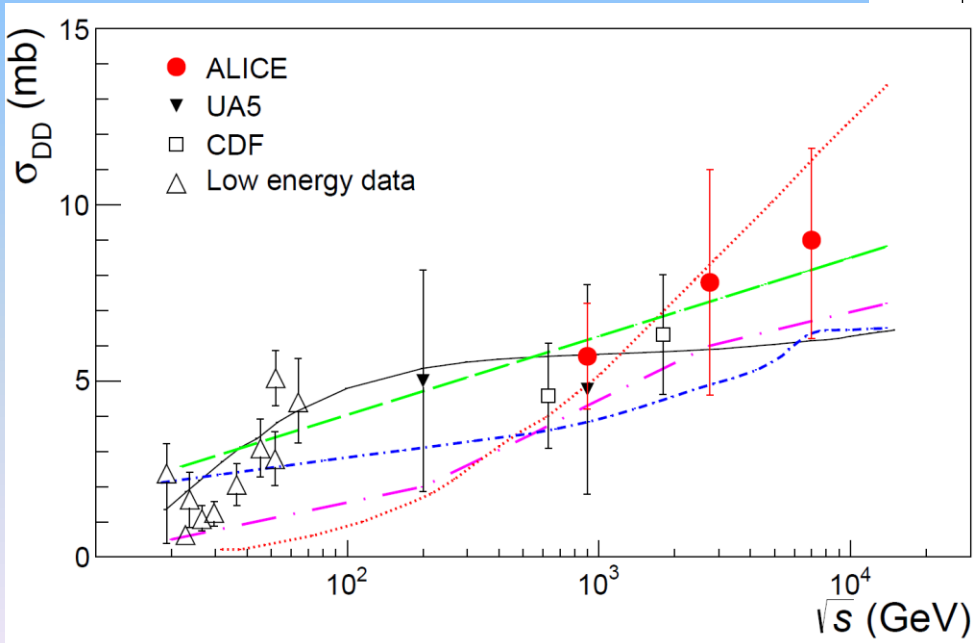
RENORM: 72.3±1.2 mb

# ALICE tot-inel vs PYTHIA8-MBR



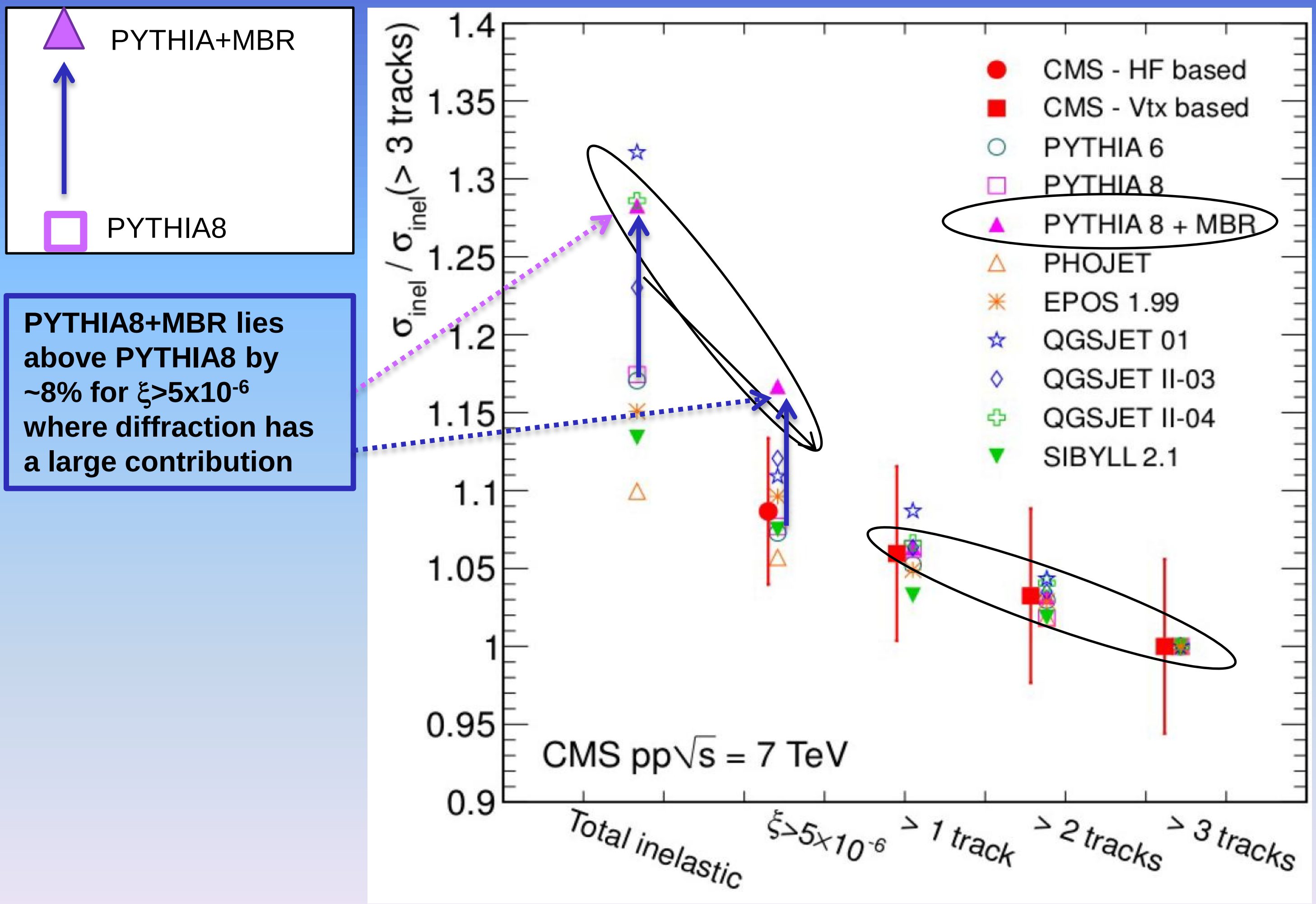
# ALICE SD and DD vs PYTHIA8-MBR



# CMS Total-Inelastic Cross Section

## compared to PYTHIA8 and PYTHIA8+MBR




**PYTHIA8+MBR lies above PYTHIA8 by ~8% for $\xi$>5x10$^{-6}$ where diffraction has a large contribution**

# 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 |
| $\sigma_{tot}$ | 94.2 | 97.4 | 95.4 | 104.0 | 107.5 | 107.3 | 125.0 | 134.8 | 134.0 | 138.8 | 147.1 | 393 | 2067 |
| $\sigma_{inel}$ | 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

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

$\sigma_T$

↕ **optical theorem**

**Im $f_{el}(t=0)$**

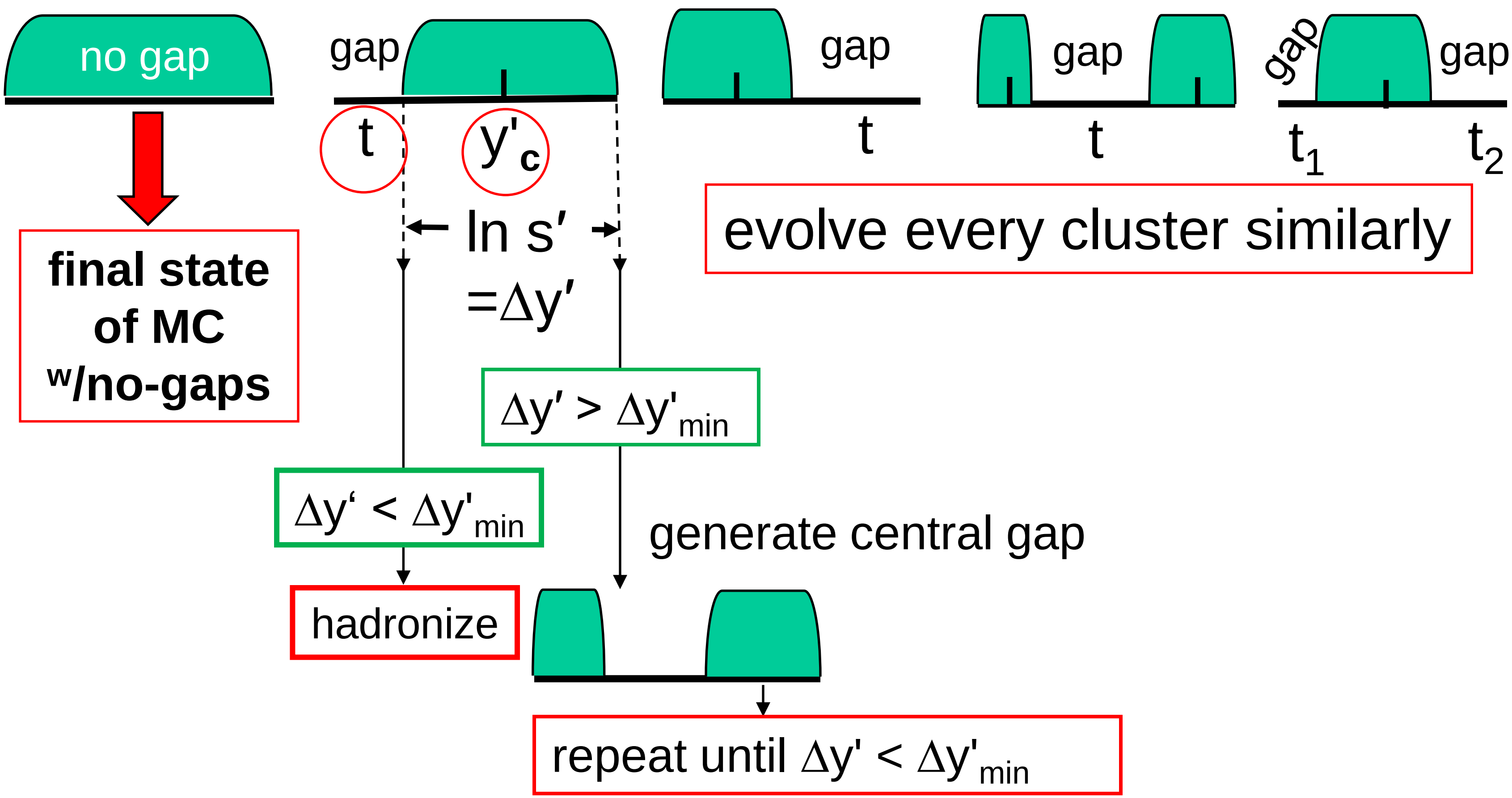
↕ **dispersion relations**

**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*