Predictions of Diffractive and Total Cross Sections at LHC Confirmed by Recent Results

Konstantin Goulianos

The Rockefeller University, New York City, USA

Low-X 2014

YUKAWA INSTITUTE, KYOTO, JAPAN
June 17-21 2014

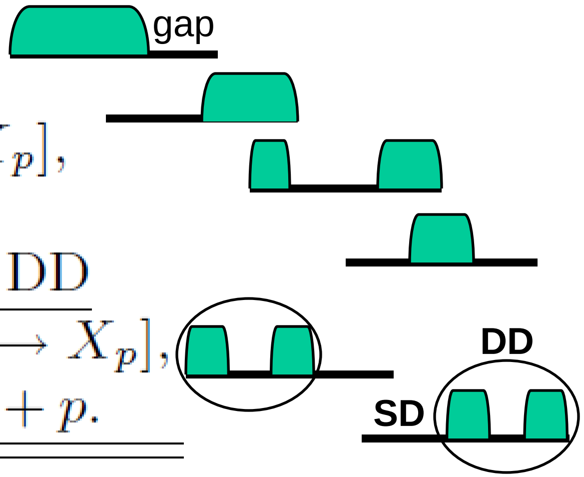
CONTENTS

- Diffraction
  - SD1 pp→p-gap-X
    SD2 p→X-gap-p Single Diffraction / Single Dissociation
  - DD pp→X-gap-X Double Diffraction / Double Dissociation
  - CD/DPE pp→gap-X-gap Cenral Diffraction / Double Pomeron Exchange
- Renormalization→unitarization
  - RENORM model
- Triple-Pomeron coupling
- Total Cross Section
- RENORM predictions Confirmed

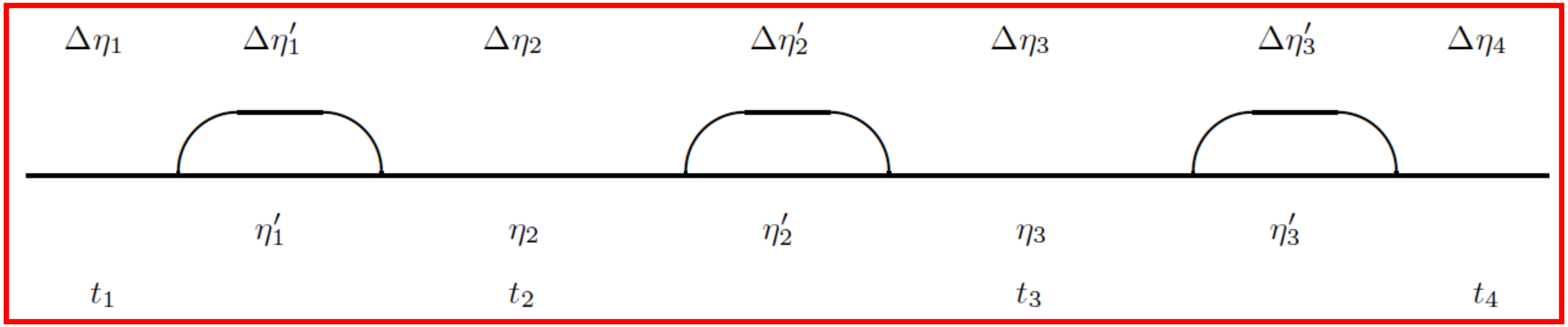
- References
- MBR in PYTHIA8 http://arxiv.org/abs/1205.1446
- *CMS PAS* *http://cds.cern.ch/record/1547898/files/FSQ-12-005-pas.pdf*
- DIS13 http://pos.sissa.it/archive/conferences/191/067/DIS%202013_067.pdf
- MPI@LHC 2013 summary: http://arxiv.org/abs/1306.5413
- CTEQ Workshop, "QCD tool for LHC Physics: From 8 to 14 TeV, what is needed and why"" *FINAL*, 14 November, 2013

Basic and combined diffractive processes

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

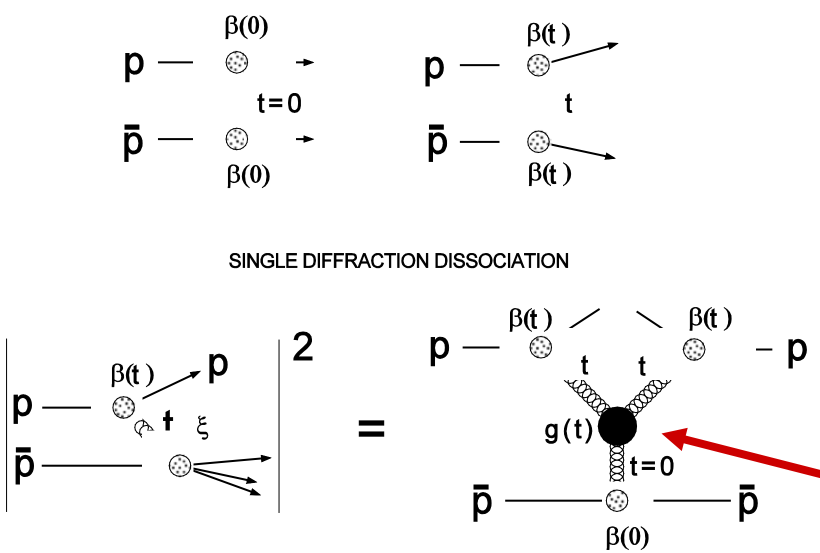


4-gap diffractive process-Snowmass 2001- **http://arxiv.org/pdf/hep-ph/0110240**



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

KG-PLB 358, 379 (1995)



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

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

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

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

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

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

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

Parameters:

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

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)

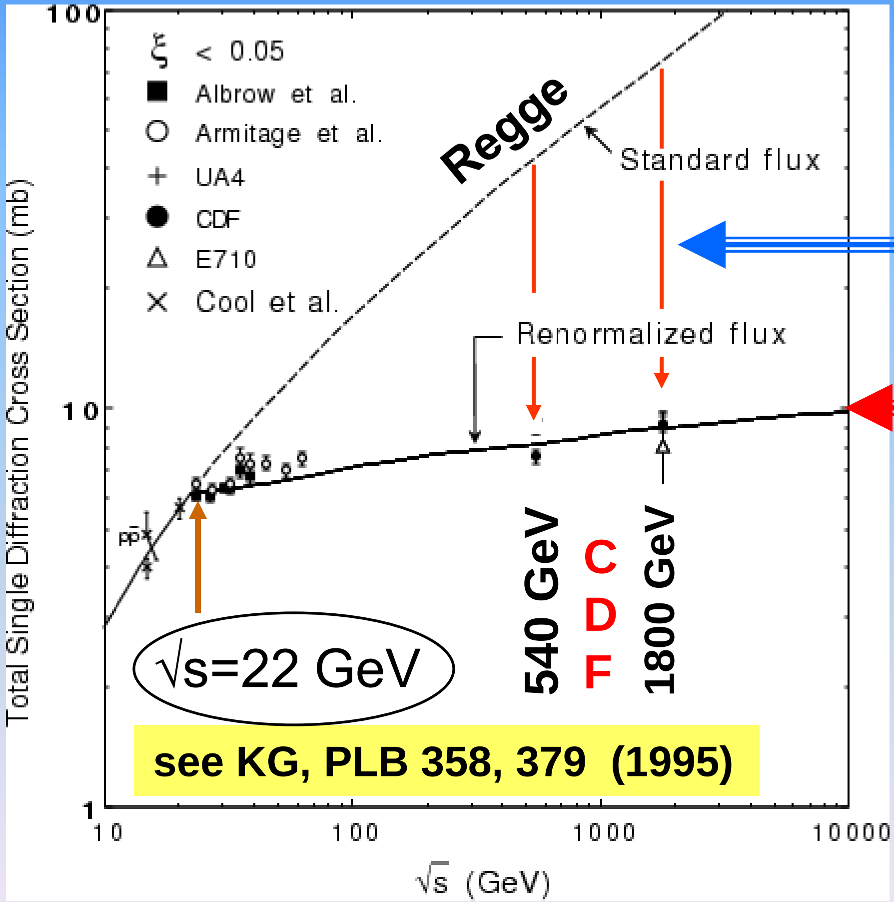
- the unitarity limit is already reached at √*s* ~ 2 TeV !

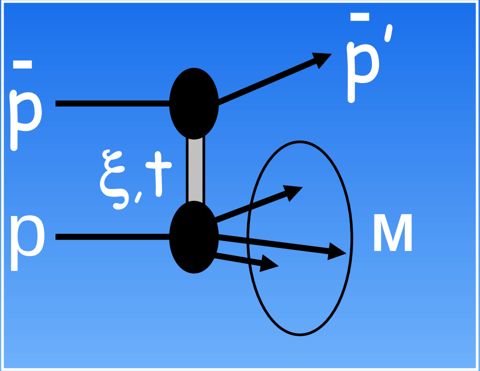
- need unitarization

* similarly for $(d\sigma_{el}/dt)_{t=0}$ w.r.t. 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





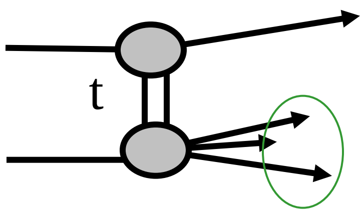
Factor of ~8 (~5) suppression at √s = 1800 (540) GeV

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

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

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

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

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

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

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

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

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

set to unity
➔ determines s_o

M^2 distribution: data

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

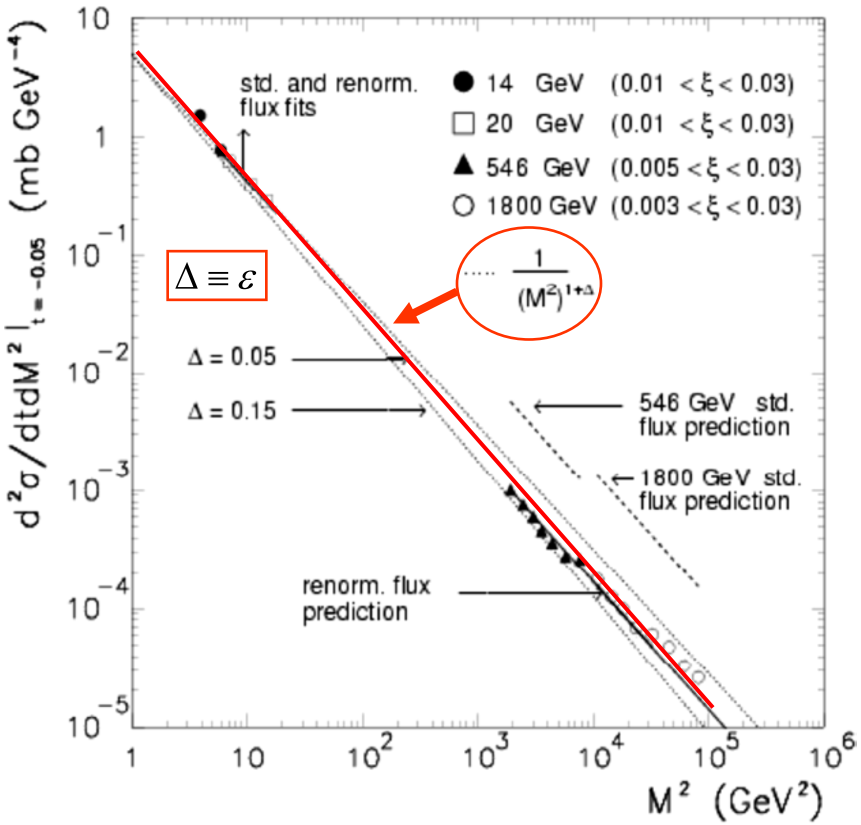
KG&JM, PRD 59 (1999) 114017

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

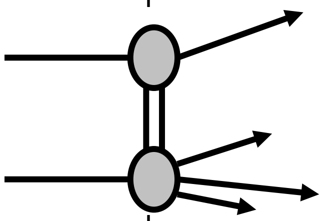


➔ factorization breaks down to ensure M^2 scaling

Scale s_0 and *PPP* coupling

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

KG, PLB 358 (1995) 379



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

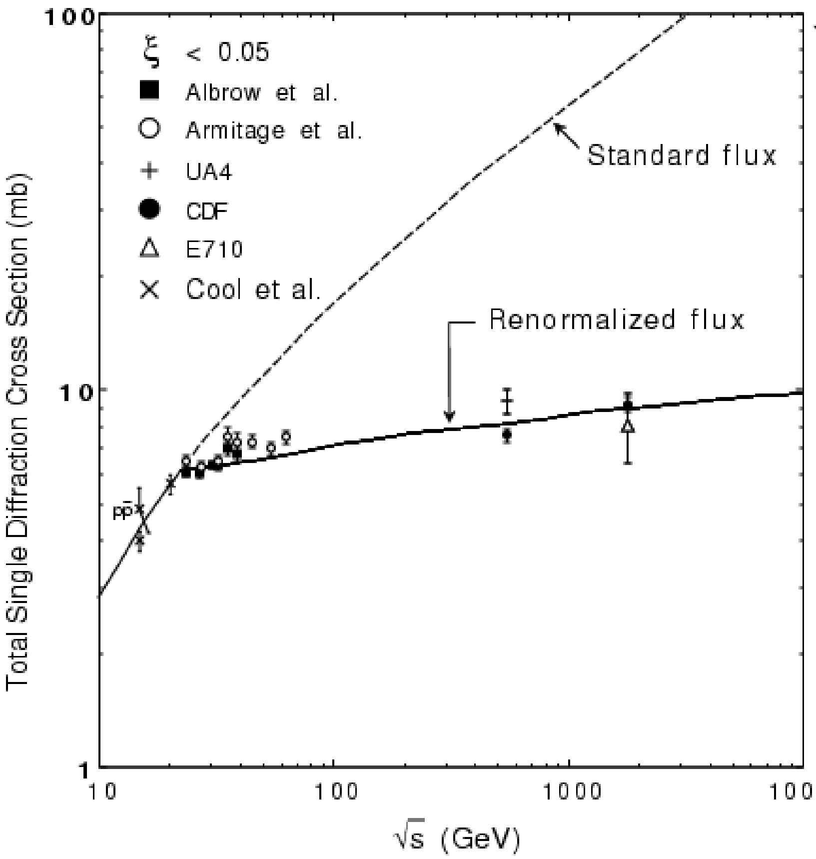
s_o^{ε}

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

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}

Saturation at low Q^2 and small-x



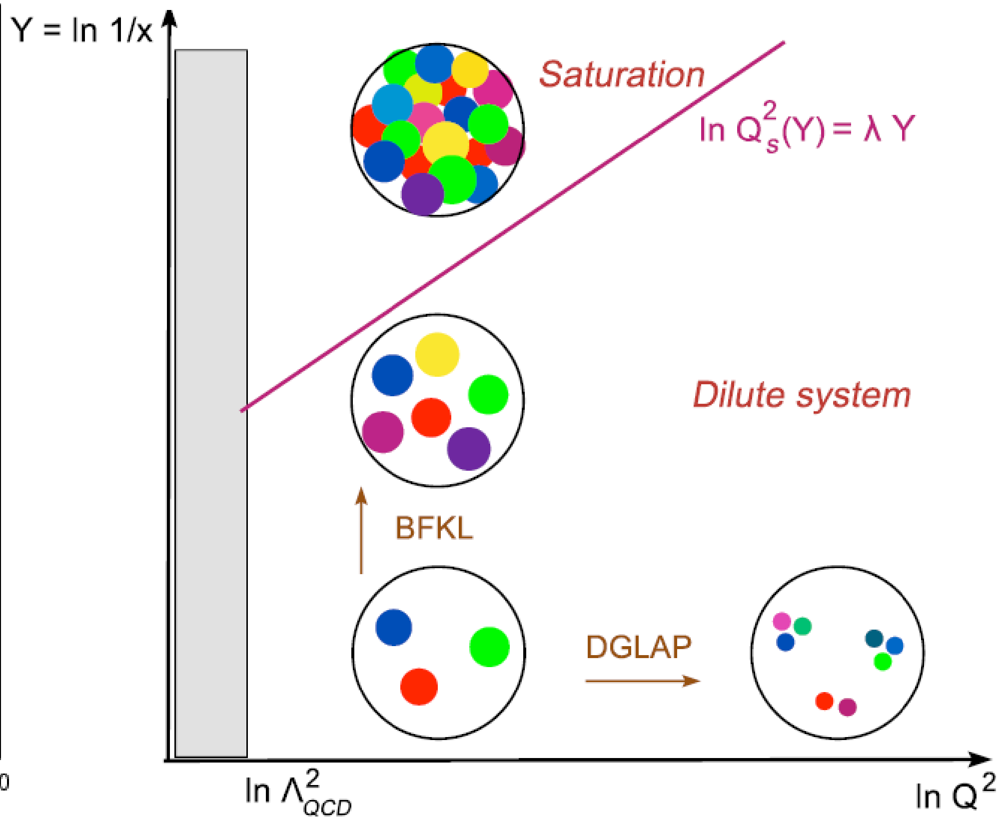
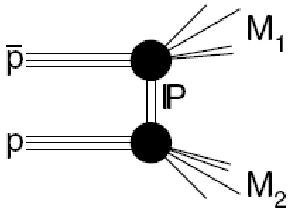
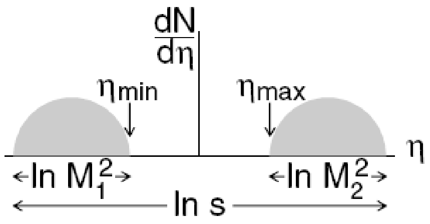


figure from a talk by Edmond Iancu

DD at CDF

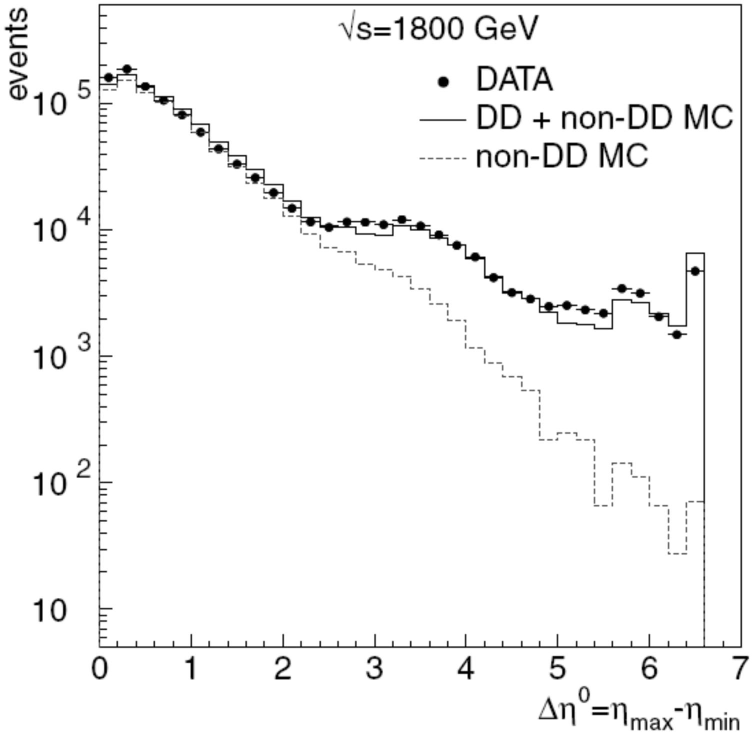


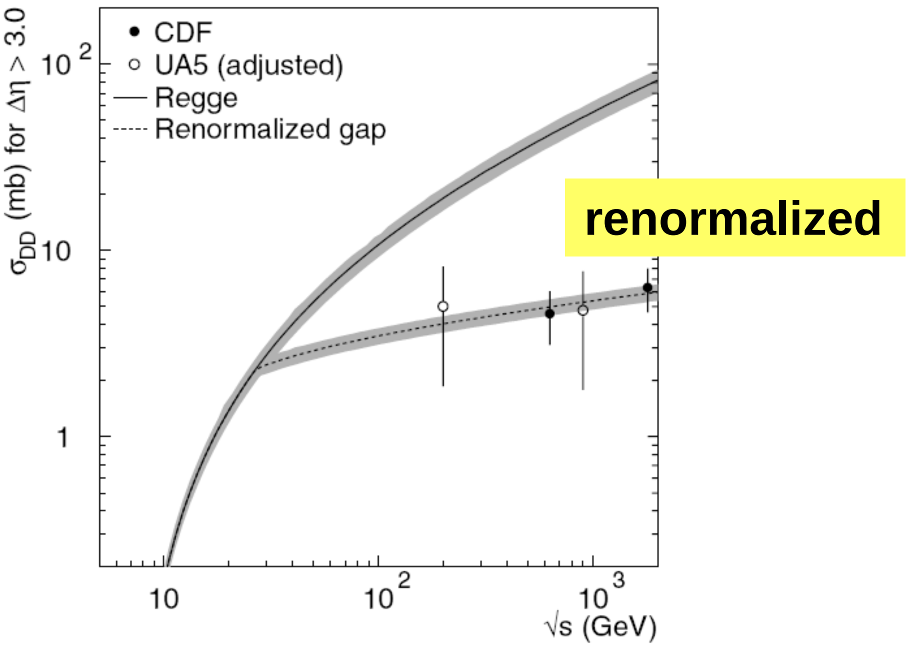


$$\frac{d^3\sigma_{DD}}{dt dM_1^2 dM_2^2} = \frac{d^2\sigma_{SD}}{dt dM_1^2}\frac{d^2\sigma_{SD}}{dt dM_2^2} \Big/ \frac{d\sigma_{el}}{dt}$$
$$= \frac{[\kappa\beta_1(0)\beta_2(0)]^2}{16\pi}\frac{s^{2\epsilon}e^{b_{DD}t}}{(M_1^2M_2^2)^{1+2\epsilon}}$$

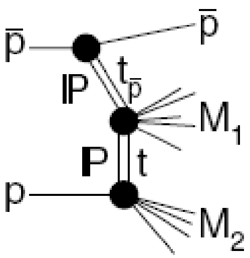
$$\frac{d^3\sigma_{DD}}{dt\,d\Delta\eta\,d\eta_c} = \left[\frac{\kappa\beta^2(0)}{16\pi}e^{2[\alpha(t)-1]\Delta\eta}\right]\left[\kappa\beta^2(0)\left(\frac{s'}{s_0}\right)^{\epsilon}\right]$$

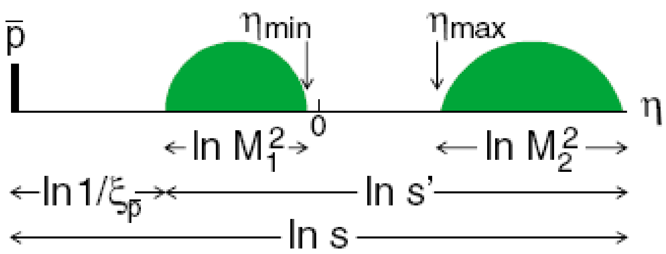
gap probability x-section

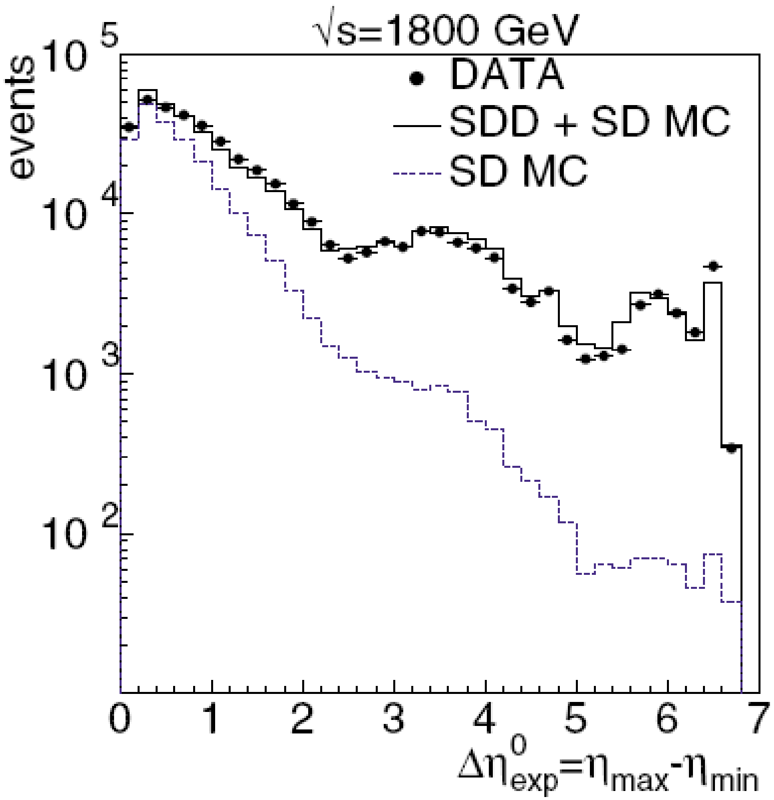




SDD at CDF



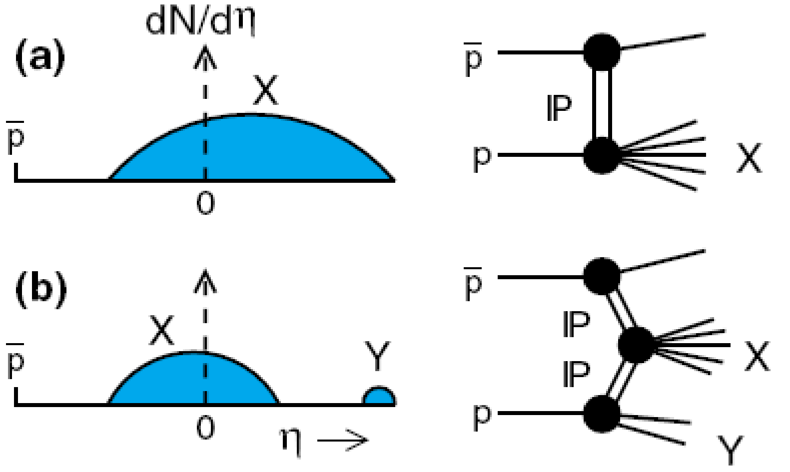


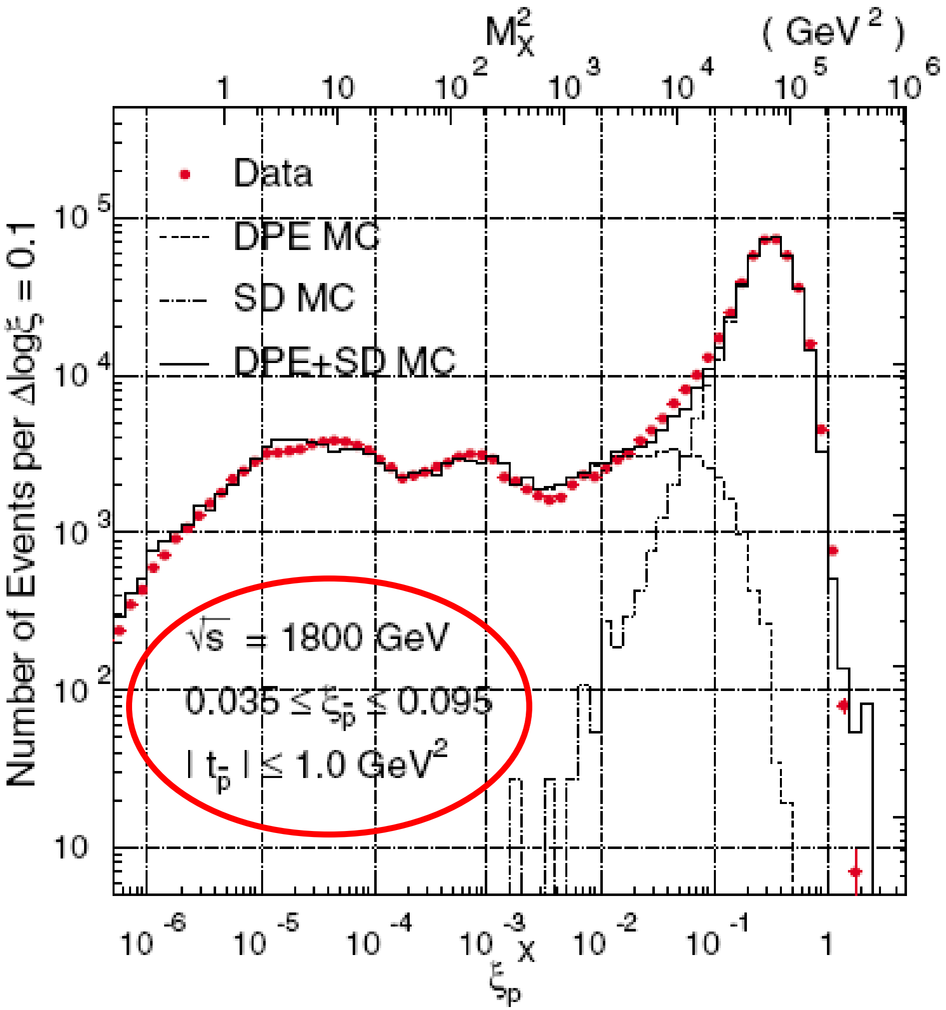


- Excellent agreement between data and MBR (MinBiasRockefeller) MC

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

CD/DPE at CDF





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

Difractive x-sections

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

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

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

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

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

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}

Total, elastic, and inelastic x-sections

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

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

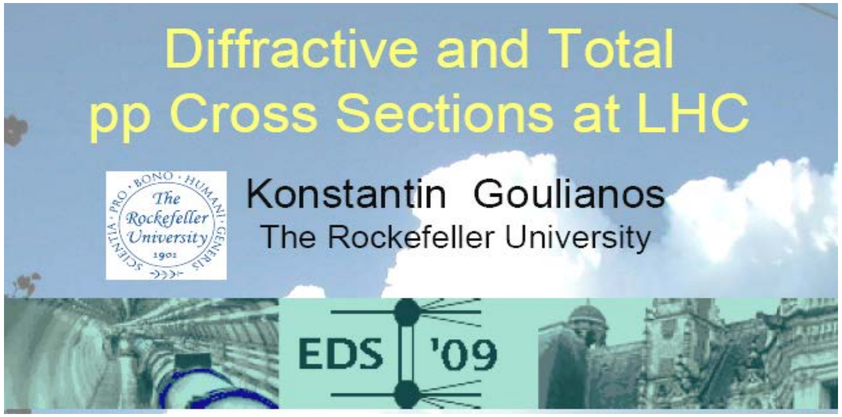
$$\sigma_{\rm tot}^{p^\pm p} = \begin{cases} 16.79 s^{0.104} + 60.81 s^{-0.32} \mp 31.68 s^{-0.54} & \text{for } \sqrt{s} < 1.8 \\ \sigma_{\rm tot}^{\rm CDF} + \frac{\pi}{s_0}\left[\left(\ln\frac{s}{s_F}\right)^2 - \left(\ln\frac{s^{\rm CDF}}{s_F}\right)^2\right] & \text{for } \sqrt{s} \geq 1.8 \end{cases}$$

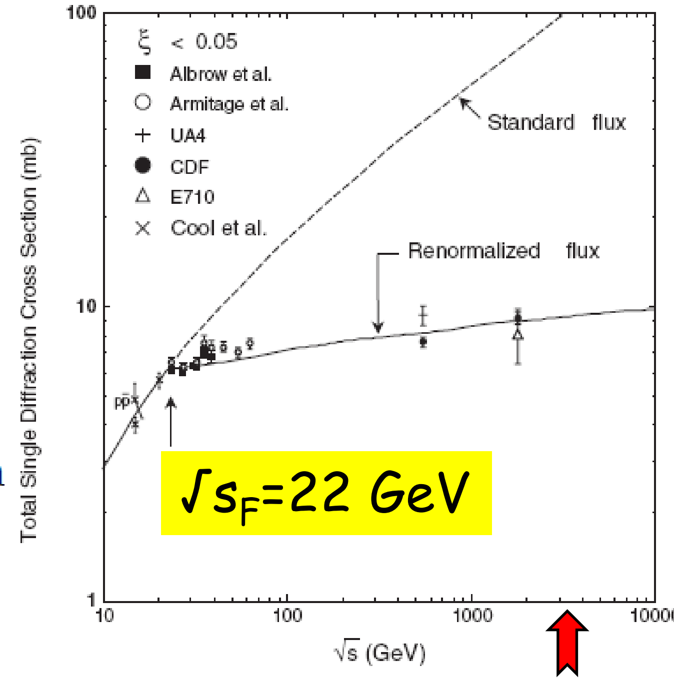
KG Moriond 2011, arXiv:1105.1916

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

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

$\sigma_{el}^{p\pm p} = \sigma_{tot} \times (\sigma_{el}/\sigma_{tot})$, with σ_{el}/σ_{tot} from CMG
small extrapol. from 1.8 to 7 and up to 50 TeV)





- 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].

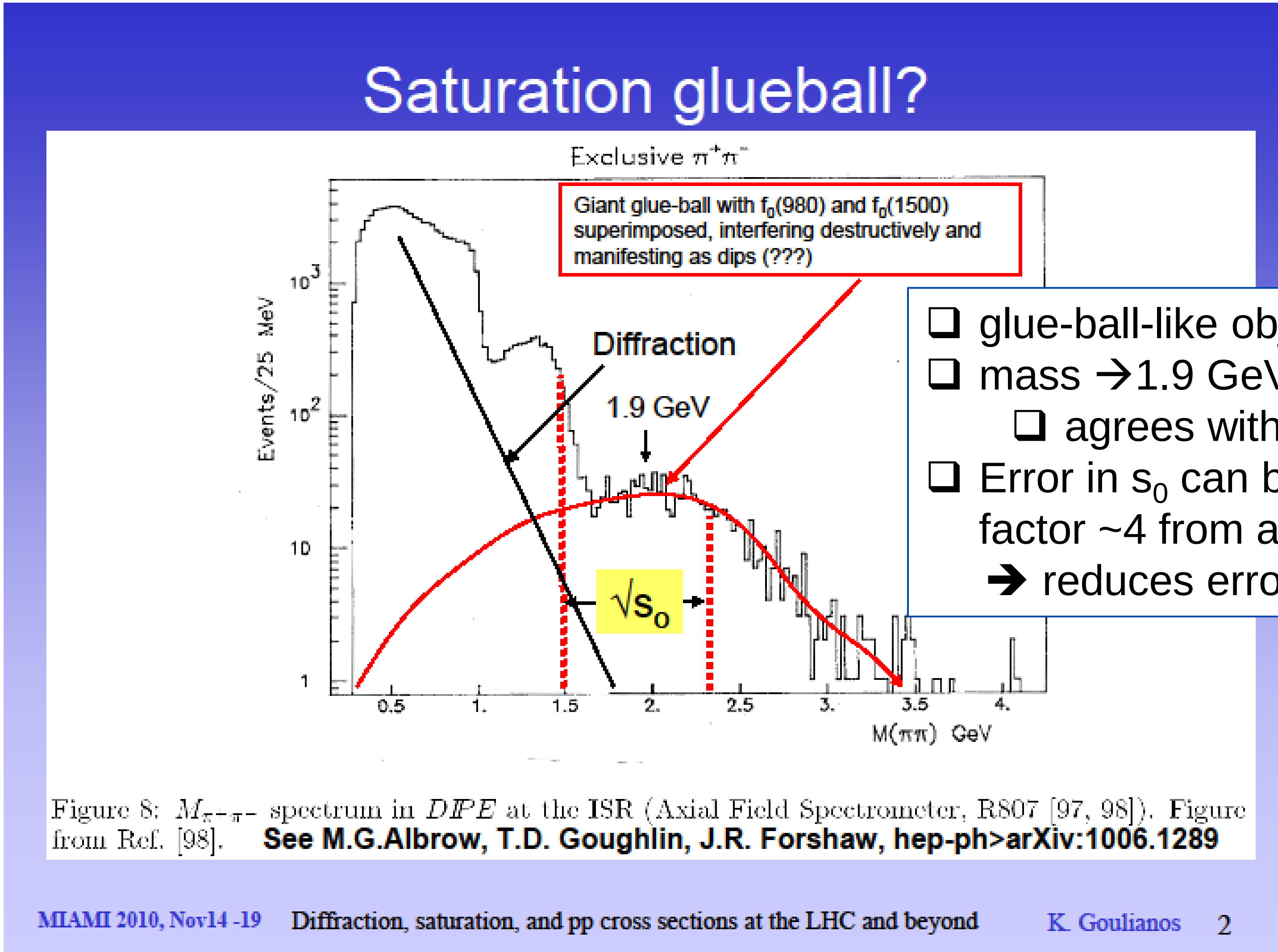
- Obtain the total cross section at the LHC:

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

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

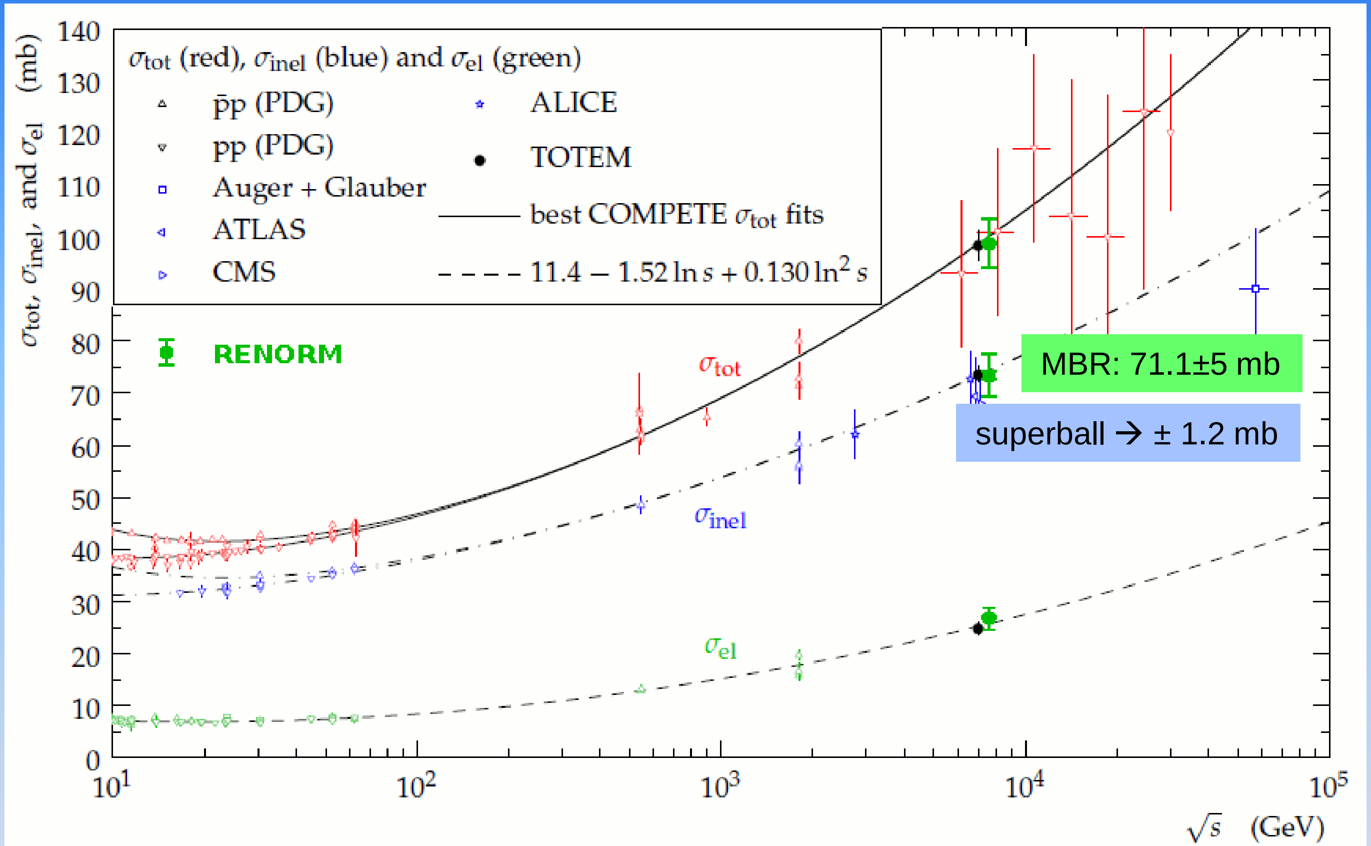
Main error from s_0

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 σ_t.

TOTEM vs PYTHIA8-MBR



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

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

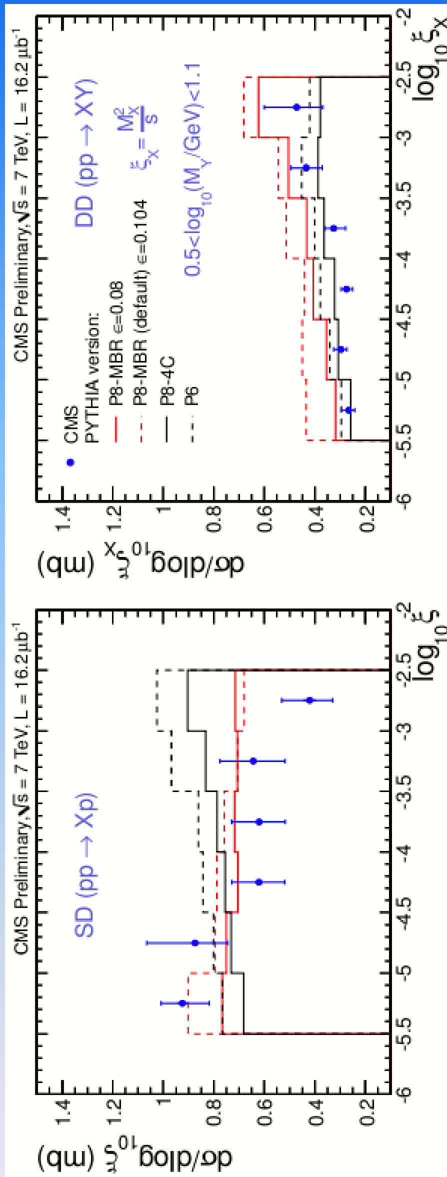
TOTEM, G. Latino talk at MPI@LHC, CERN 2012

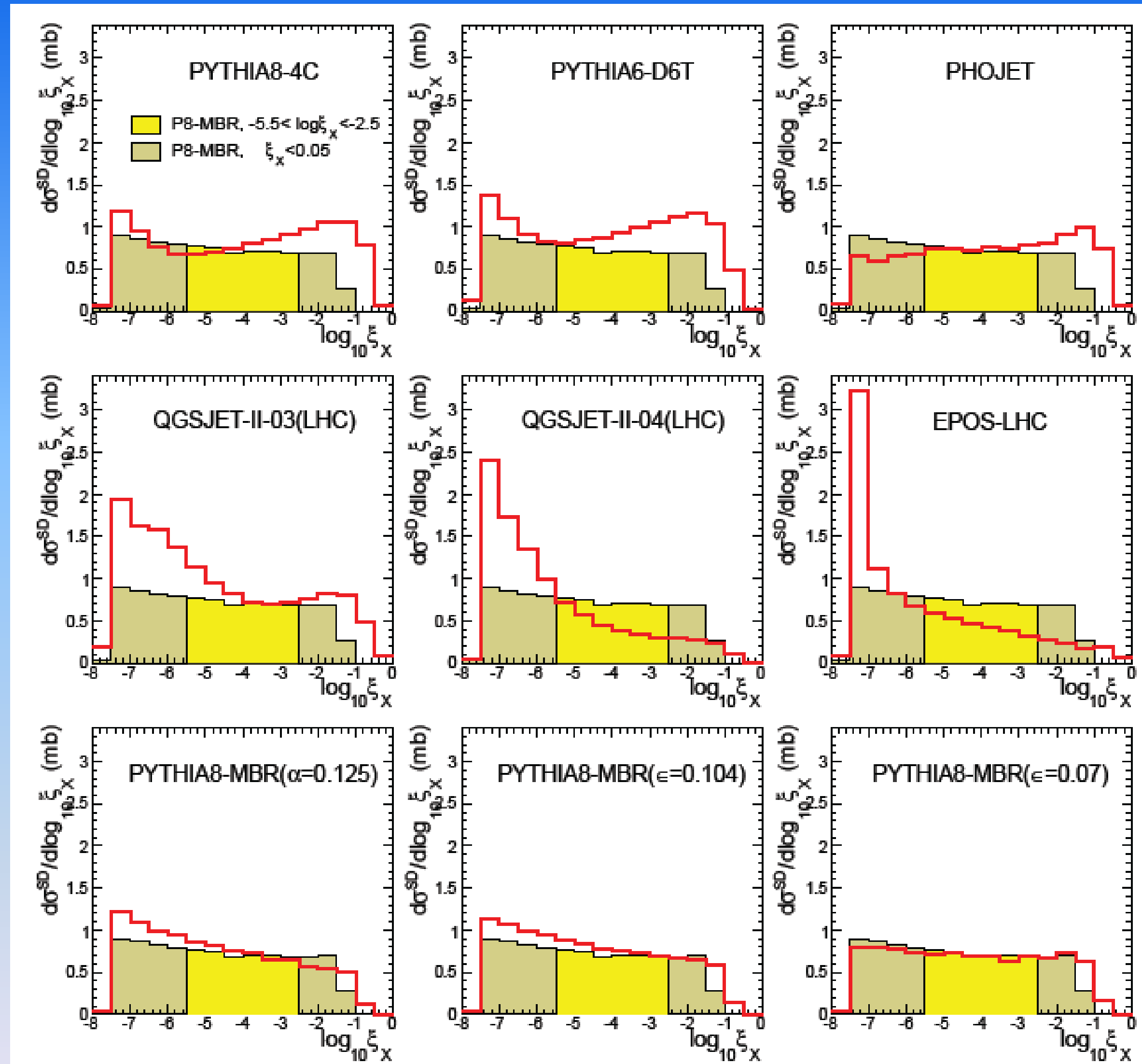
RENORM: 71.1±1.2 mb

RENORM: 72.3±1.2 mb

SD/DD extrapolation to ξ ≤ 0.05 vs MC model

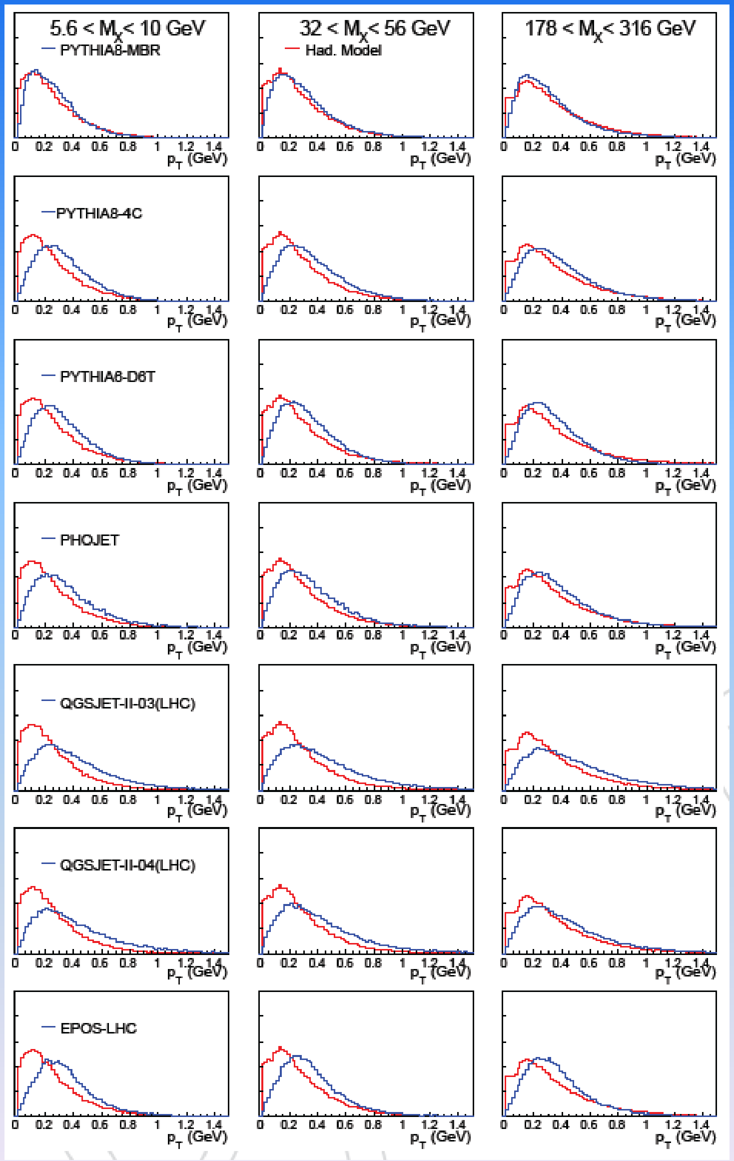
CMS data best described by PYTHIA8-MBR





Central yellow-filled box is the data region (see left figure)

p_T distr's of MCs vs Pythia8 tuned to MBR



← Pythia8 tuned to MBR

- ❑ COLUMNS

<u>Mass Regions</u>

- ❑ Low 5.5<MX<10 GeV
- ❑ Med. 32<MX<56 GeV
- ❑ High 176<MX<316 GeV

- ❑ ROWS

<u>MC Models</u>

- ❑ PYTHIA8-MBR
- ❑ PYTHIA8-4C
- ❑ PYTHIA8-D6C
- ❑ PHOJET
- ❑ QGSJET-II-03(LHC)
- ❑ QGSJET-04(LHC)
- ❑ EPOS-LHC

- ❑ CONCLUSION
- ❑ PYTHIA8-MBR agrees best with reference model and can be trusted to be used in extrapolating to the unmeasured regions.

Charged mult's vs MC model – 3 mass regions

Pythia8 parameters tuned to reproduce multiplicities of modified gamma distribution
KG, PLB 193, 151 (1987)

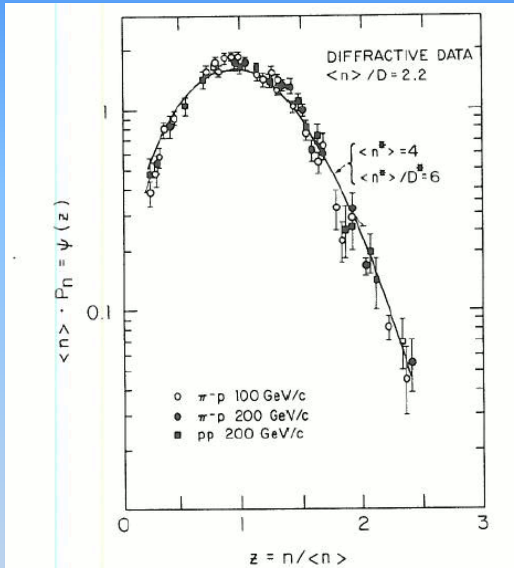


Fig. 1. The diffractive data of ref. [3] fitted with the modified gamma function.

<u>Mass Regions</u>

- ❑ Low 5.5<MX<10 GeV
- ❑ Med. 32<MX<56 GeV
- ❑ High 176<MX<316 GeV

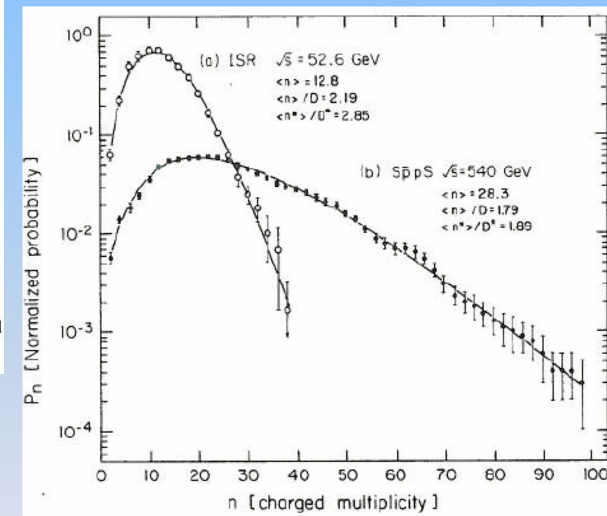
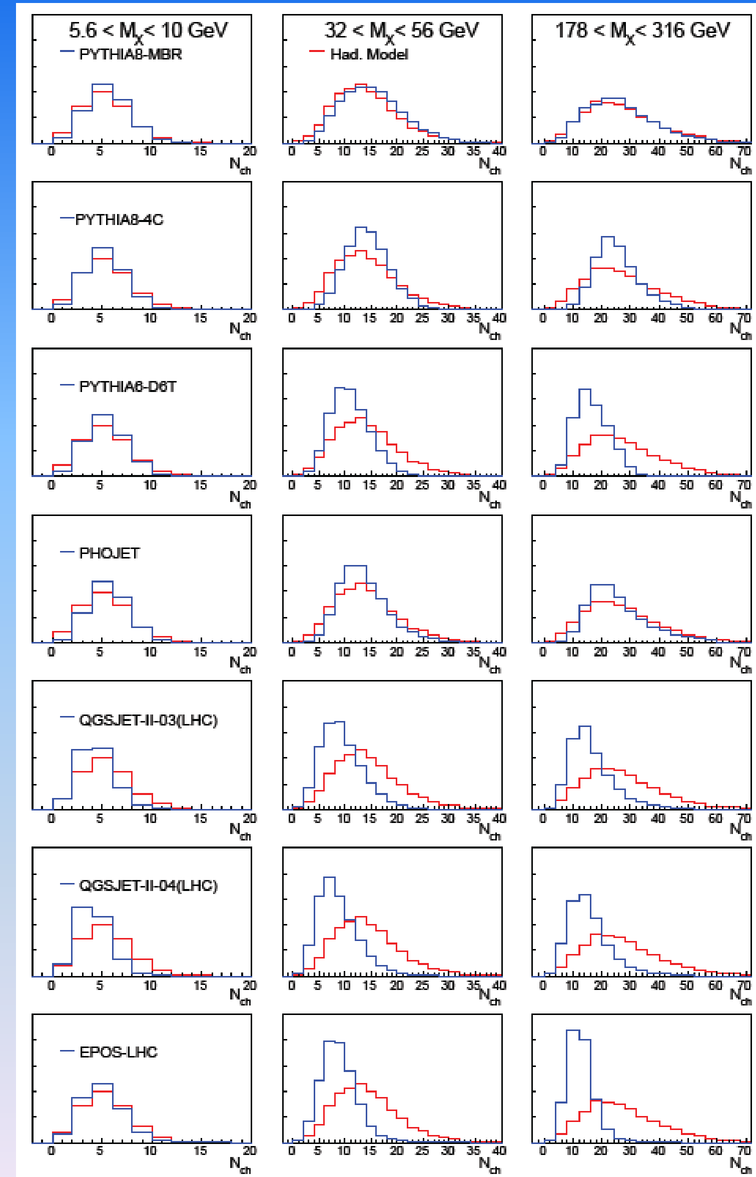
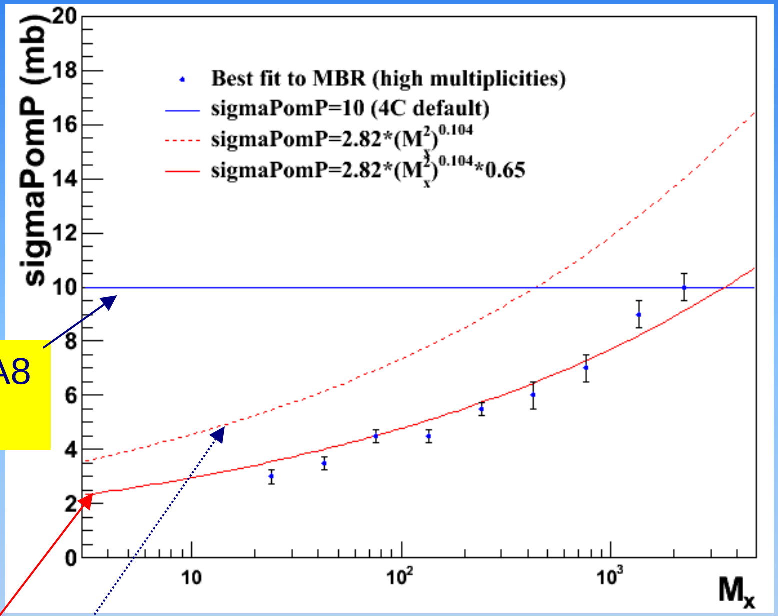


Fig. 2. Full phase space inelastic non-single-diffractive data fitted with the modified gamma function: (a) ISR data [5] at $\sqrt{s}=52.6$ GeV and (b) collider data [7] at $\sqrt{s}=540$ GeV.



Pythia8-MBR hadronization tune

Diffraction: tune SigmaPomP $n_{ave} = \frac{\sigma_{QCD}}{\sigma_{IPp}}$

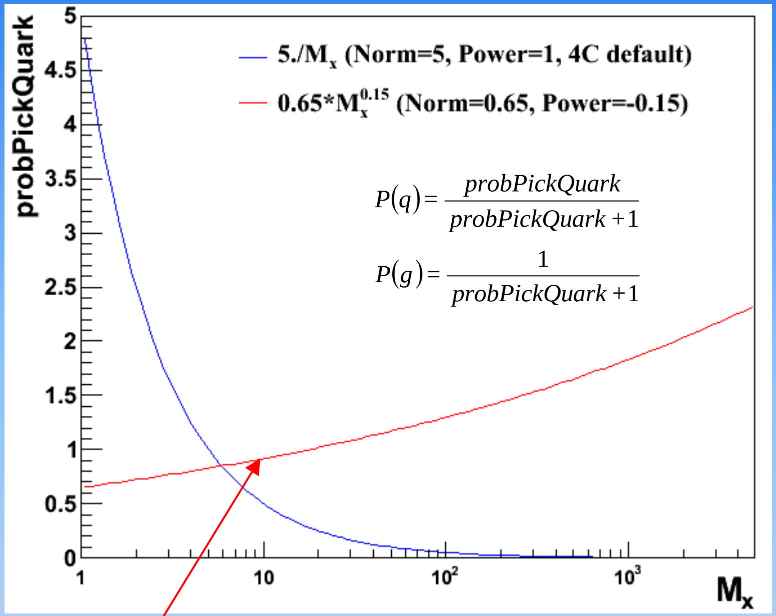


PYTHIA8 default

$\sigma^{Pp}(s)$ expected from Regge phenomenology for s_0=1 GeV^2 and DL t-dependence.

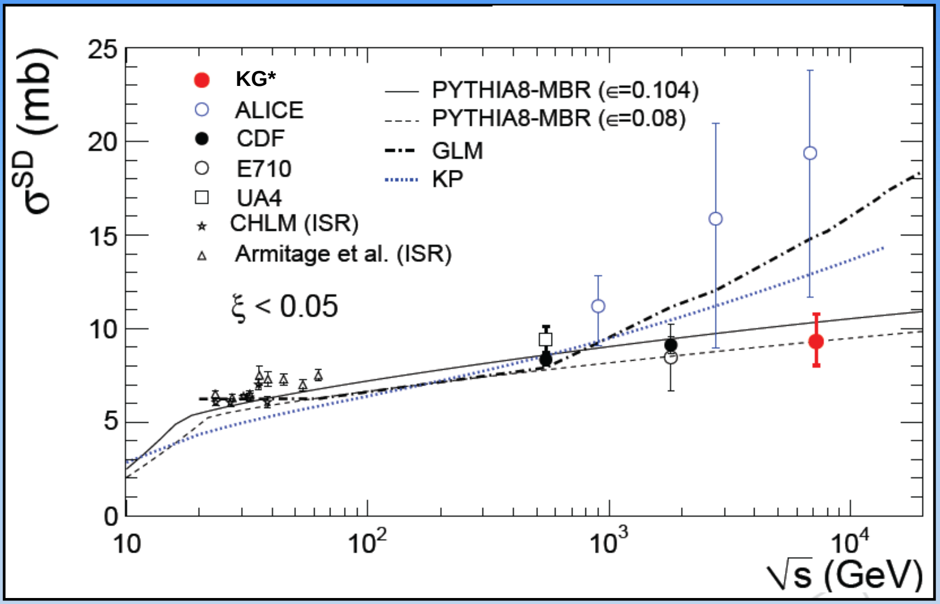
Red line: best fit to multiplicity distributions.
(in bins of Mx, fits to higher tails only, default pT spectra)

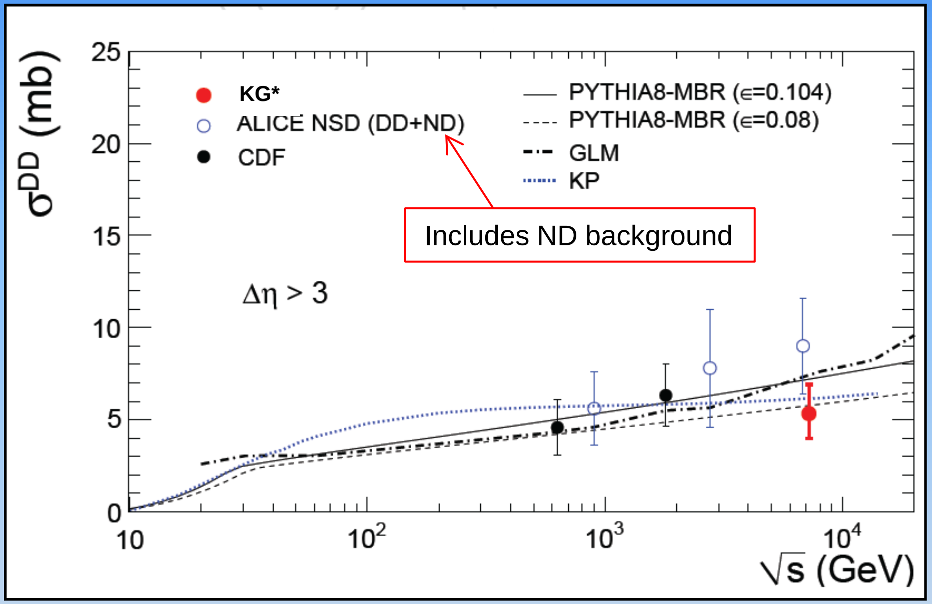
Diffraction: QuarkNorm/Power parameter



good description of low multiplicity tails

SD and DD x-sections vs theory

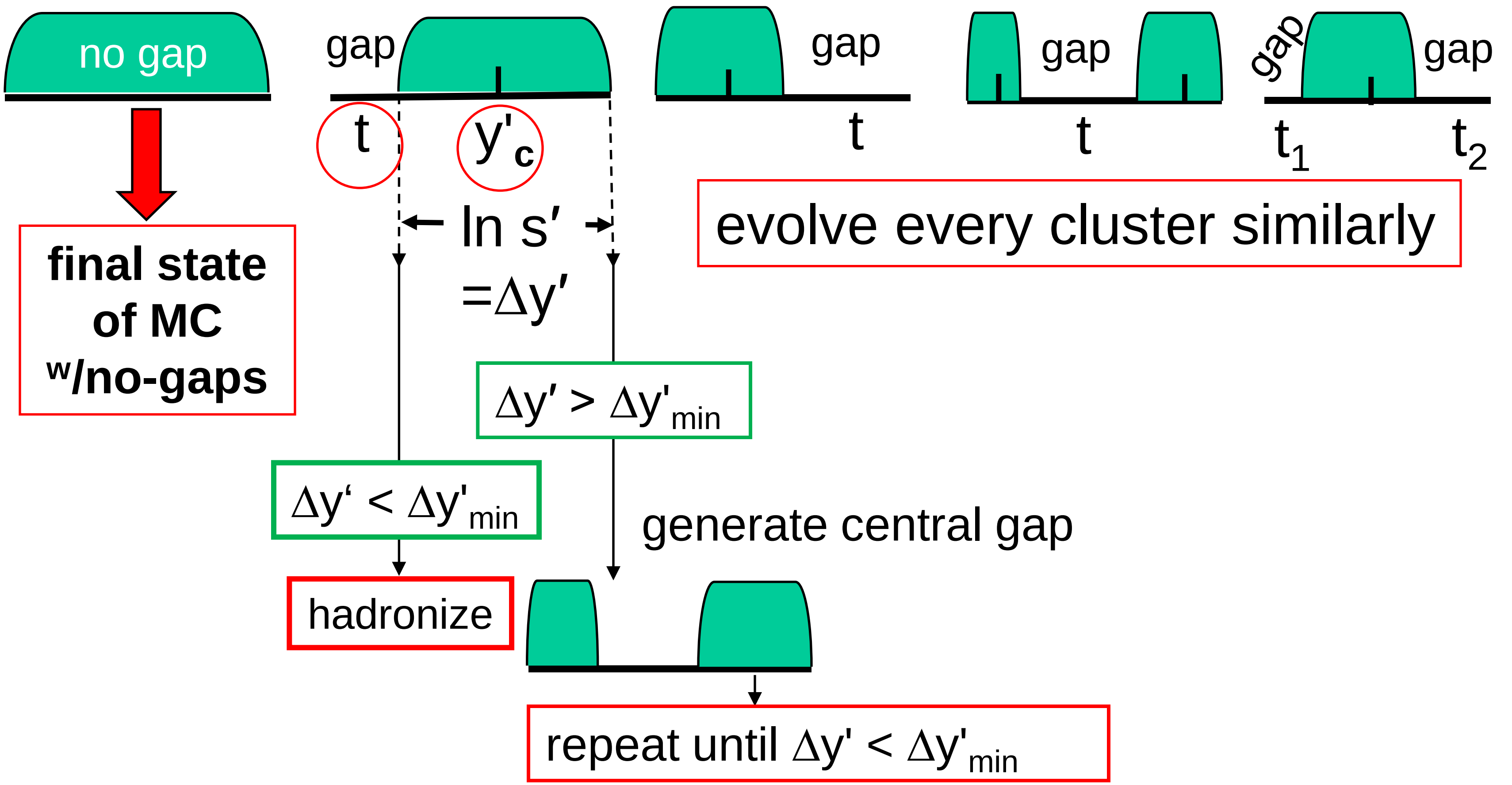




- ❑ KG*: after extrapolation into low ξ from the measured CMS data using MBR model

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
- Monte Carlo strategy for the LHC – “nesting”

Thank you for your attention