

Review of RENORM Diffractive Predictions for LHC up to 8 TeV and Extension to 13 TeV



Konstantin Goulios

<http://physics.rockefeller.edu/dino/my.html>

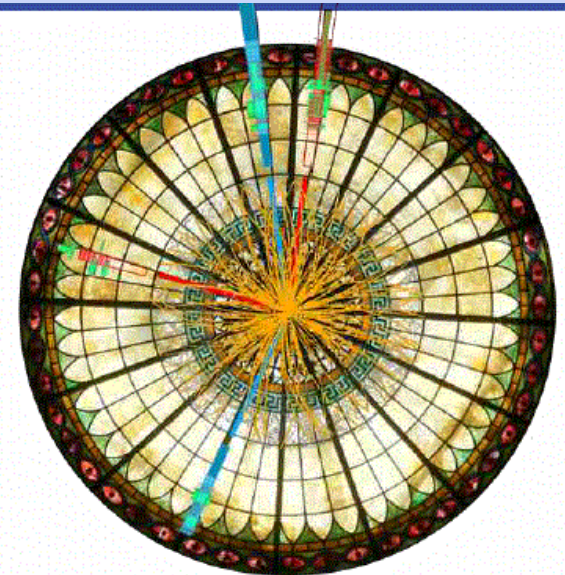


DIS 2015

XXIII International Workshop on
Deep-Inelastic Scattering and
Related Subjects

<http://www.dis2015.org>

Southern Methodist University
Dallas, TX, USA, April 27 - May 1, 2015



CONTENTS

□ Diffraction

- SD1 $p_1 p_2 \rightarrow p_1 + \text{gap} + X_2$ Single Diffraction / Dissociation –1
- SD2 $p_1 p_2 \rightarrow X_1 + \text{gap} + p_2$ Single Diffraction / Dissociation - 2
- DD $p_1 p_2 \rightarrow X_1 + \text{gap} + X_2$ Double Diffraction / Double Dissociation
- CD/DPE $p_1 p_2 \rightarrow \text{gap} + X + \text{gap}$ Central Diffraction / Double Pomeron Exchange

□ Renormalization → Unitarization

➤ RENORM Model

- Triple-Pomeron Coupling
- Total Cross Section
- RENORM Predictions Confirmed
- RENORM Predictions Extended

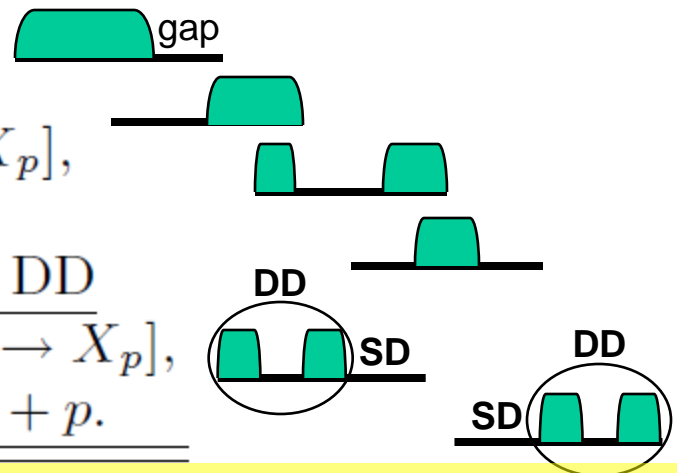
□ References

- MBR MC Simulation in PYTHIA8, KG & R. Ciesielski, <http://arxiv.org/abs/1205.1446>
- [Previous talk](#) (RENORM diffractive predictions extended to higher LHC and future accelerator energies) – similar to present talk
 - ❖ LHCFPWG 2015 Madrid (slides) <http://workshops.ift.uam-csic.es/LHCFPWG2015/program> (21-25 Apr 2015)
- [Present talk](#) (predictions compared to final CMS results)
 - ❖ CMS Soft Diffraction at 7 TeV: <http://arxiv.org/format/1503.08689v1> (30 Mar 2015)

RENORM: Basic and Combined Diffractive Processes

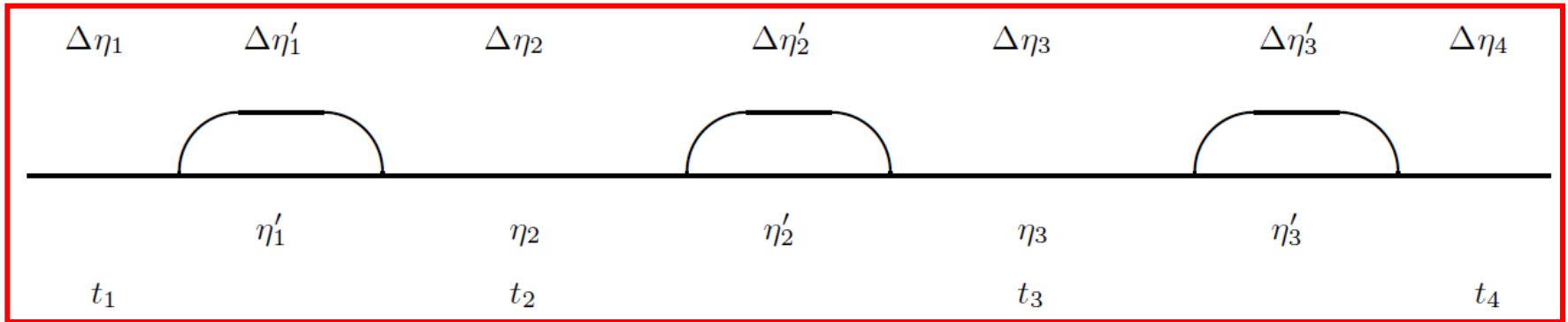
acronym	basic diffractive processes
$SD_{\bar{p}}$	$\bar{p}p \rightarrow \bar{p} + \text{gap} + [p \rightarrow X_p],$
SD_p	$\bar{p}p \rightarrow [\bar{p} \rightarrow X_{\bar{p}}] + \text{gap} + p,$
DD	$\bar{p}p \rightarrow [\bar{p} \rightarrow X_{\bar{p}}] + \text{gap} + [p \rightarrow X_p],$
DPE	$\bar{p}p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

particles



Cross sections analytically expressed in arXiv below:

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

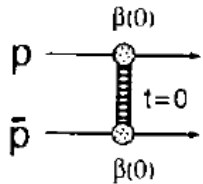


Regge Theory: Values of s_0 & g_{PPP} ?

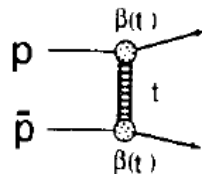
KG-PLB 358, 379 (1995)

<http://www.sciencedirect.com/science/article/pii/037026939501023J>

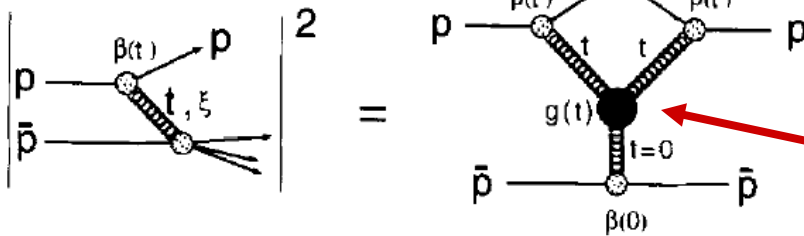
TOTAL CROSS SECTION



ELASTIC SCATTERING



SINGLE DIFFRACTION DISSOCIATION



Parameters:

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

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

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

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

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

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

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

Theoretical 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

(also true for partial x-sections in impact parameter space)

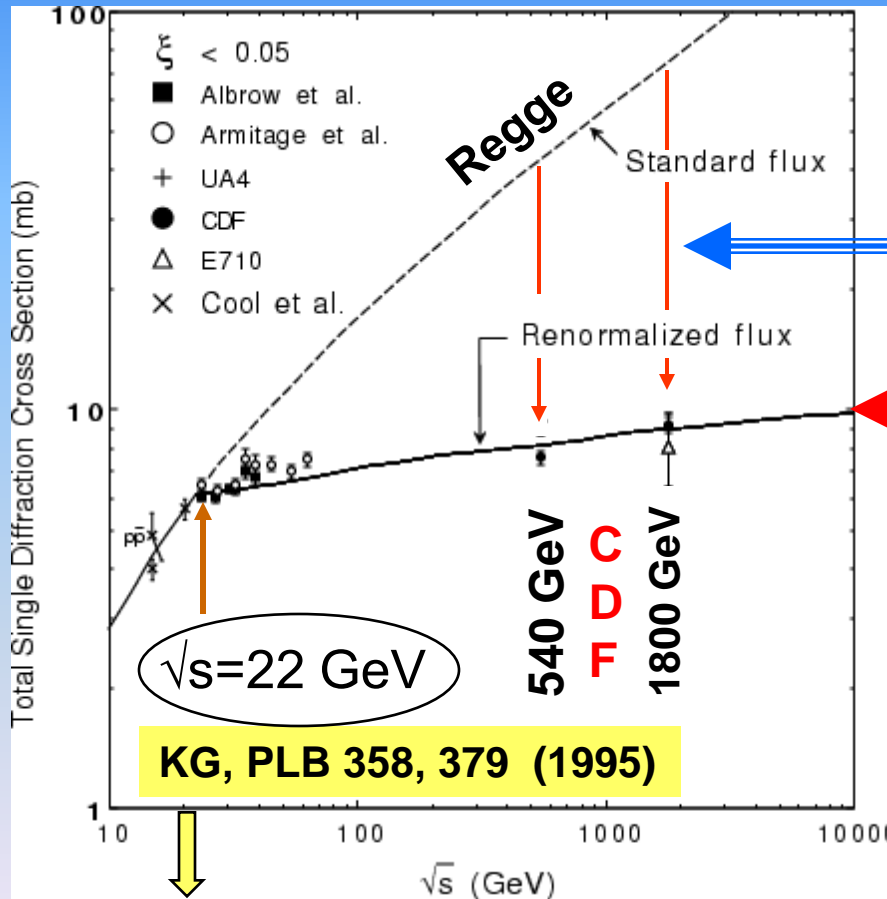
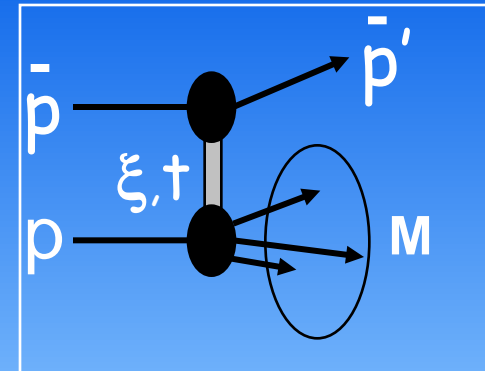
□ the unitarity limit is already reached at $\sqrt{s} \sim 2 \text{ TeV} !$

□ need unitarization

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

FACTORIZATION BREAKING IN SOFT DIFFRACTION

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



KG, PLB 358, 379 (1995)

<http://www.sciencedirect.com/science/article/pii/037026939501023J>

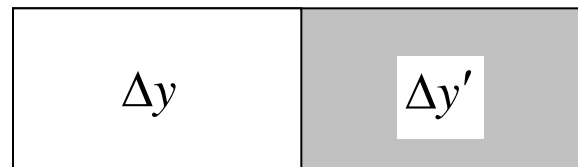
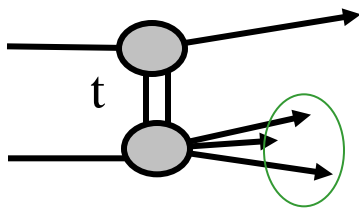
Factor of ~ 8 (~ 5)
suppression at
 $\sqrt{s} = 1800$ (540) GeV

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

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

gap probability

sub-energy x-section

Gap probability → (re)normalize it 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
 → determines s_o

M² - Distribution: Data

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

Regge

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

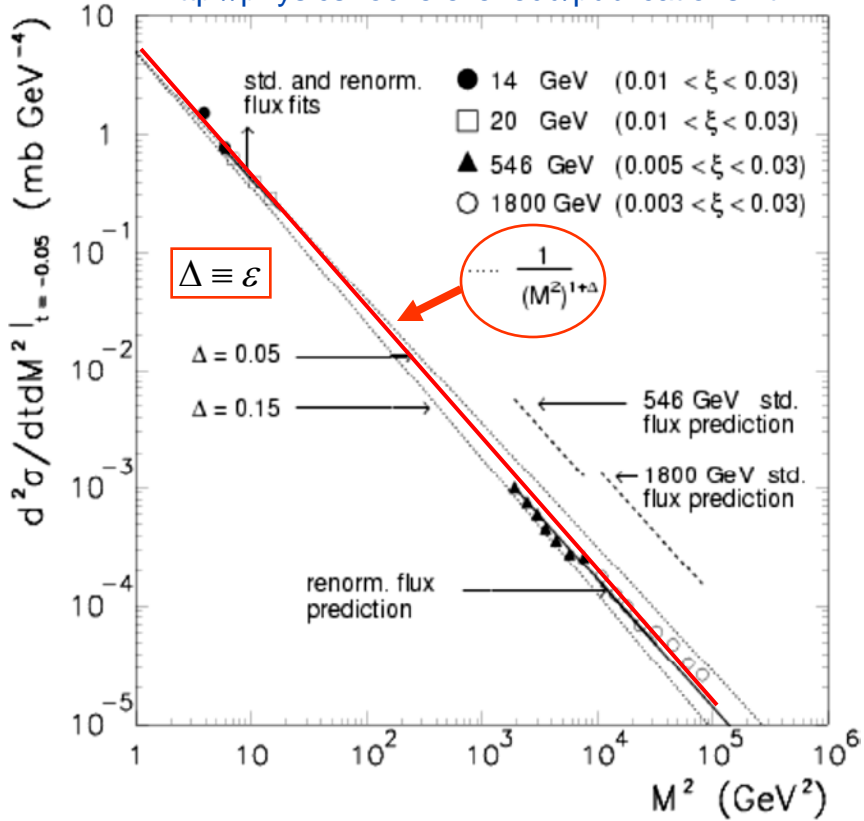
$s^{2\varepsilon} \rightarrow 1$

data

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

KG&JM, PRD 59 (1999) 114017

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



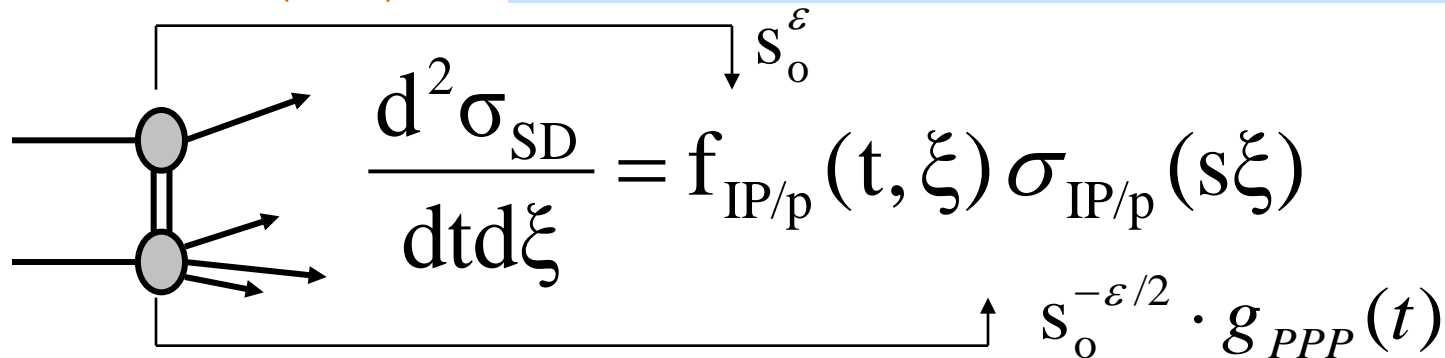
→ factorization breaks down to ensure M² scaling

Scale s_0 and PPP Coupling

Pomeron flux: interpret it as gap probability

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

KG, PLB 358 (1995) 379 <http://www.sciencedirect.com/science/article/pii/037026939501023J>



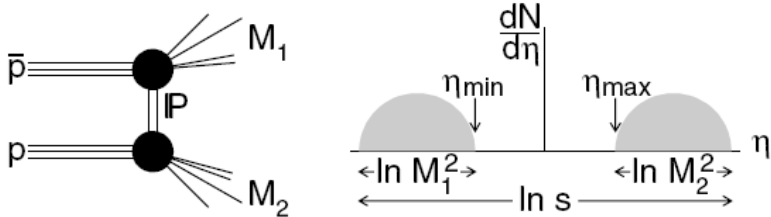
$$\frac{d^2 \sigma_{SD}}{dt d\xi} = f_{IP/p}(t, \xi) \sigma_{IP/p}(s\xi)$$

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}

DD at CDF

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

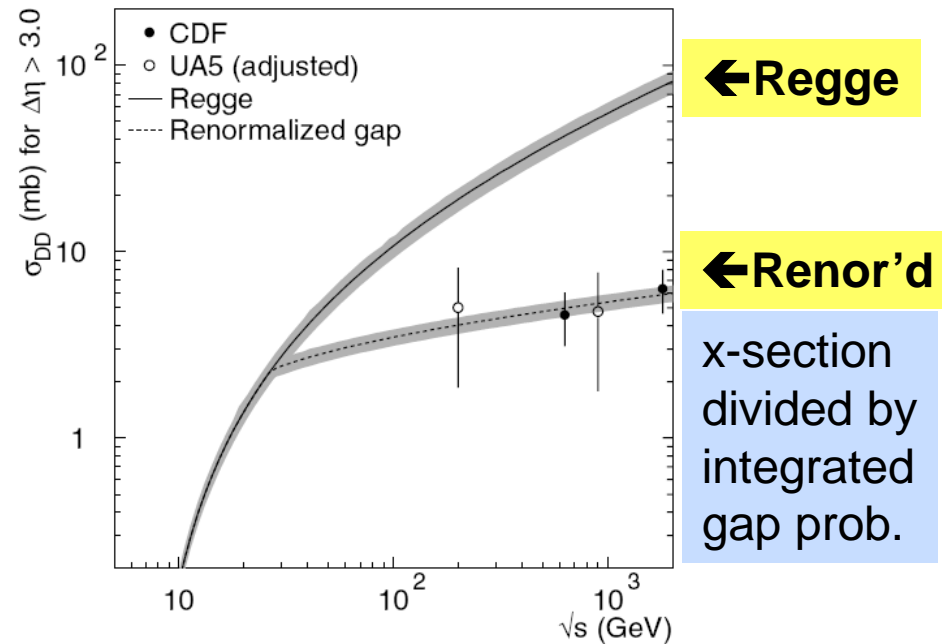
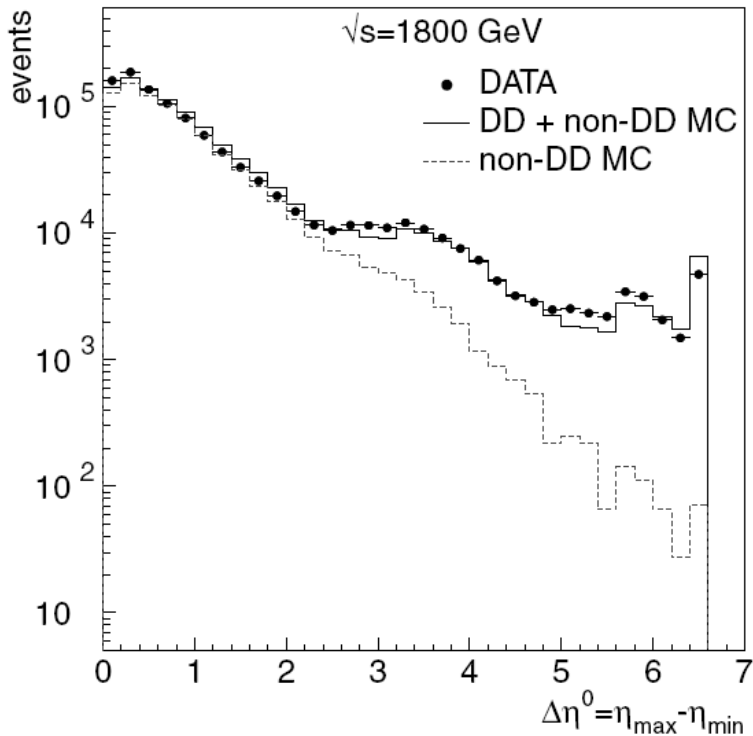


$$\frac{d^3\sigma_{DD}}{dt dM_1^2 dM_2^2} = \frac{d^2\sigma_{SD}}{dt dM_1^2} \frac{d^2\sigma_{SD}}{dt dM_2^2} \bigg/ \frac{d\sigma_{el}}{dt}$$

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

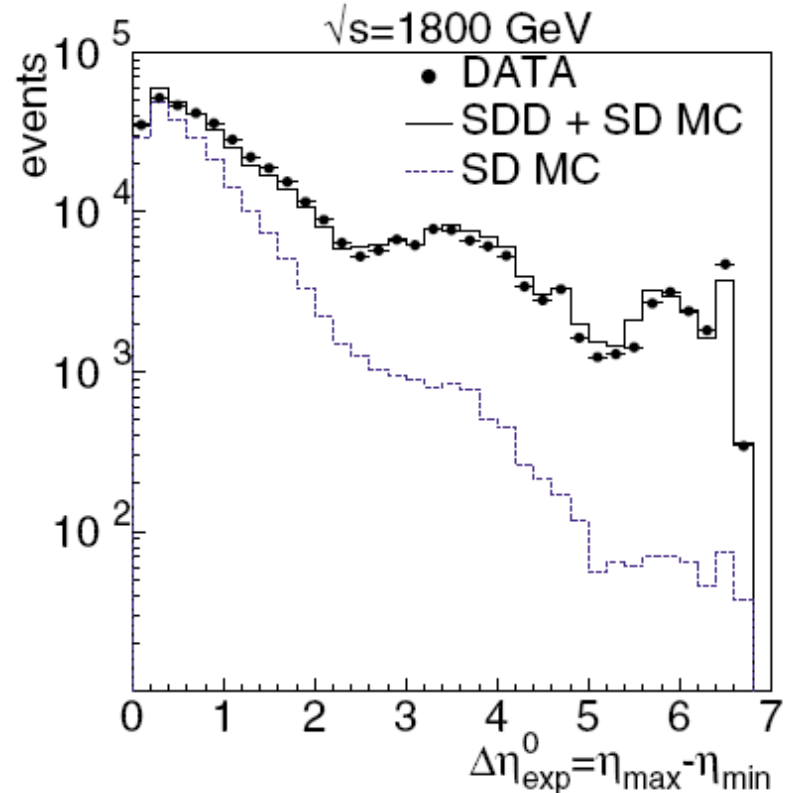
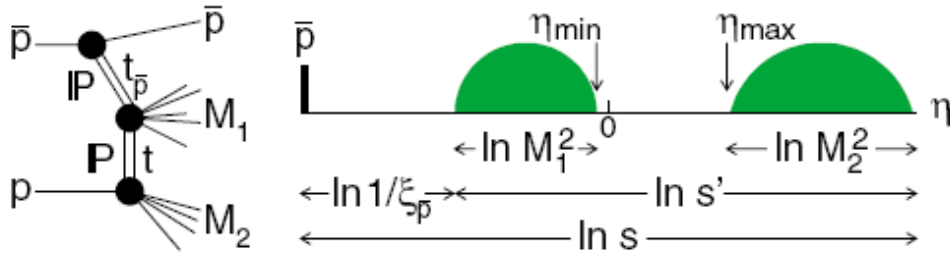
$$\frac{d^3\sigma_{DD}}{dt d\Delta\eta d\eta_c} = \left[\frac{\kappa \beta^2(0)}{16\pi} e^{2[\alpha(t)-1]\Delta\eta} \right] \left[\kappa \beta^2(0) \left(\frac{s'}{s_0} \right)^\epsilon \right]$$

gap probability x-section



SDD at CDF

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

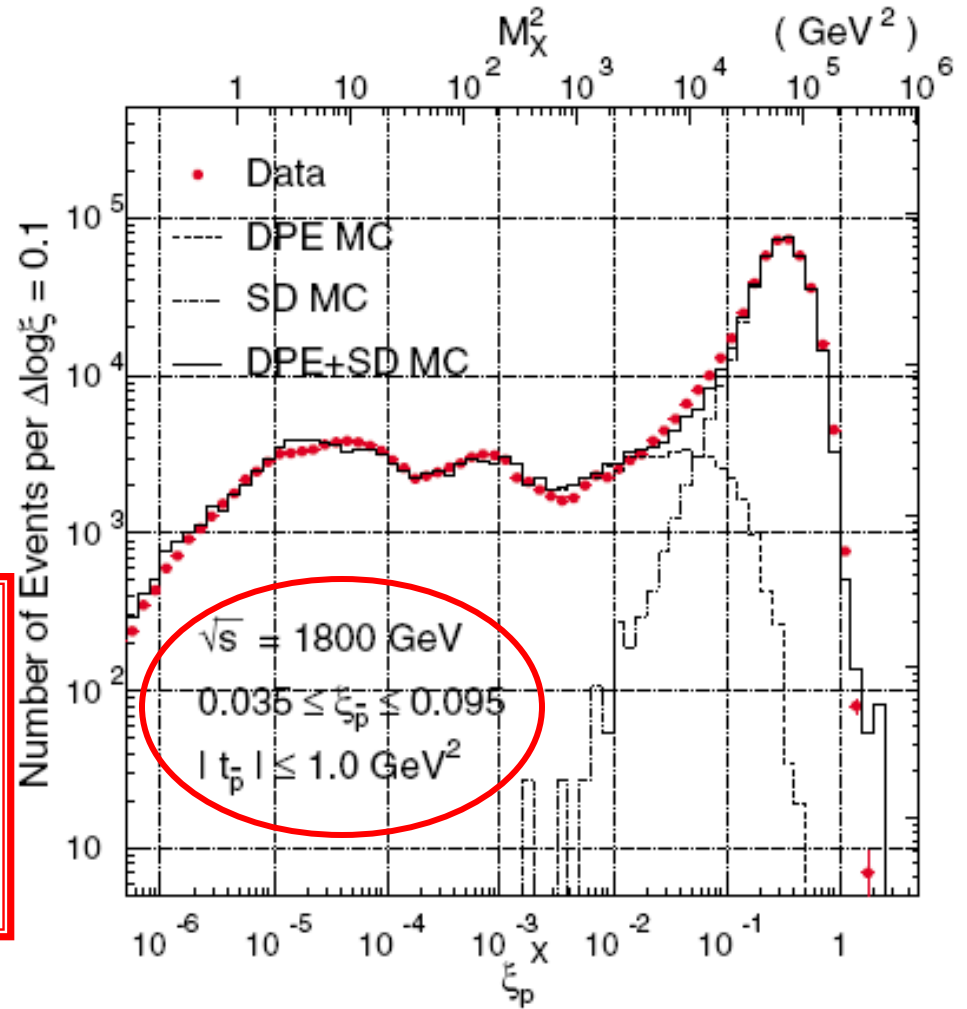
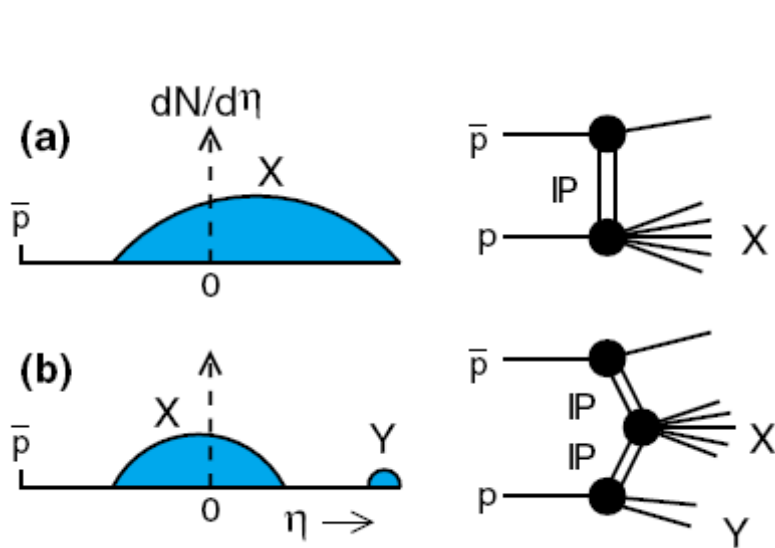


- Excellent agreement between data and MBR (MinBiasRockefeller) MC

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

CD/DPE at CDF

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



- Excellent agreement between data and MBR based MC
- ➔ Confirmation that both **low and high mass x-sections** are correctly implemented

RENORM Diffractive Cross Sections

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

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

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

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

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

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

Total, Elastic, and Inelastic x-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

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

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

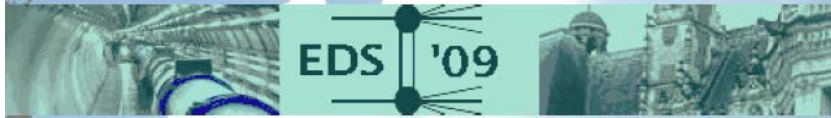
$$\sigma_{\text{el}}^{p\pm p} = \sigma_{\text{tot}}^{p\pm p} \times (\sigma_{\text{el}}/\sigma_{\text{tot}})^{p\pm p}, \text{ with } \sigma_{\text{el}}/\sigma_{\text{tot}} \text{ from CMG}$$

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

Diffraction and Total pp Cross Sections at LHC



Konstantin Goulios
The Rockefeller University



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

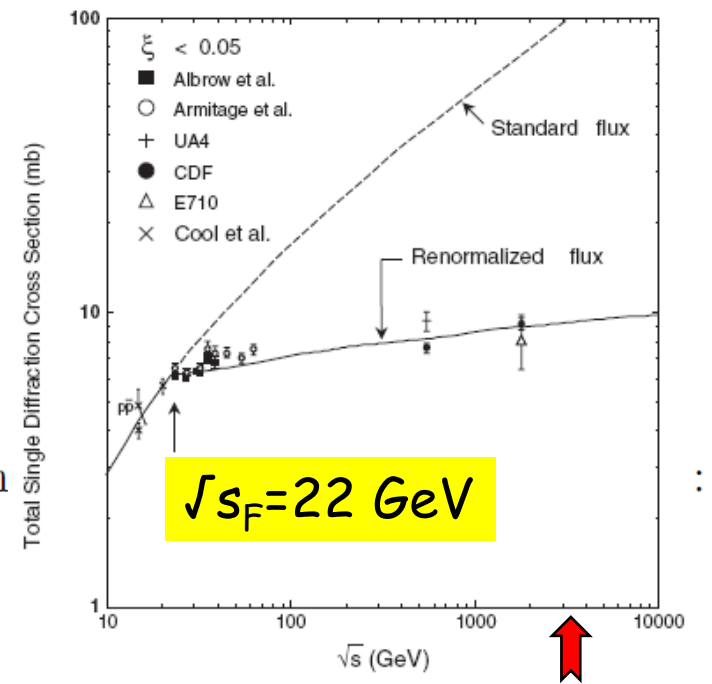
$$\sigma_t(s > s_F) = \sigma_t(s_F) + \frac{\pi}{m^2} \cdot \ln^2 \frac{s}{s_F}$$

- 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:

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

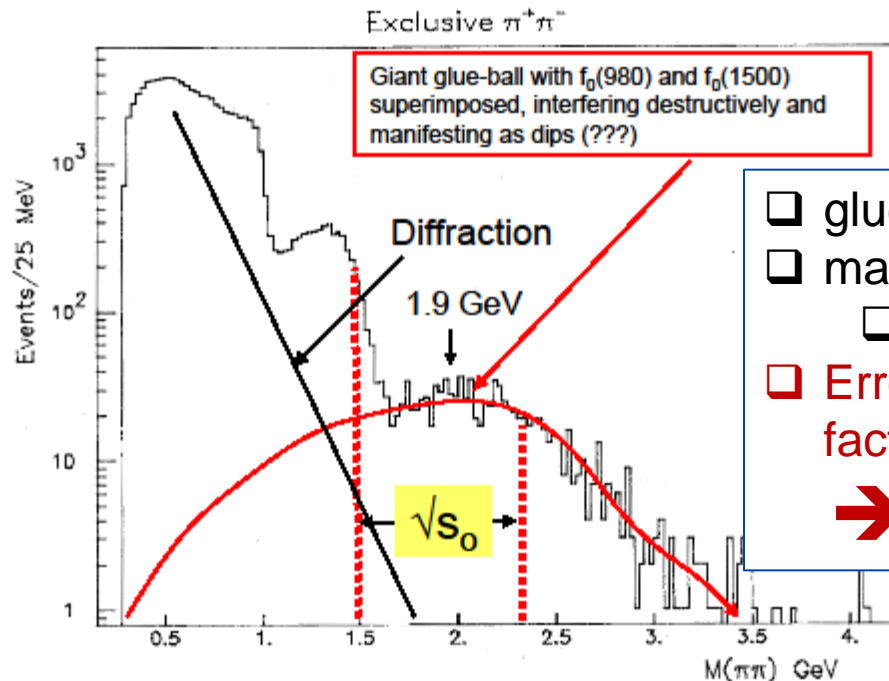
**98 ± 8 mb at 7 TeV
 109 ± 12 mb at 14 TeV**

Main error is due to s_0



How to Reduce Uncertainty in s_0

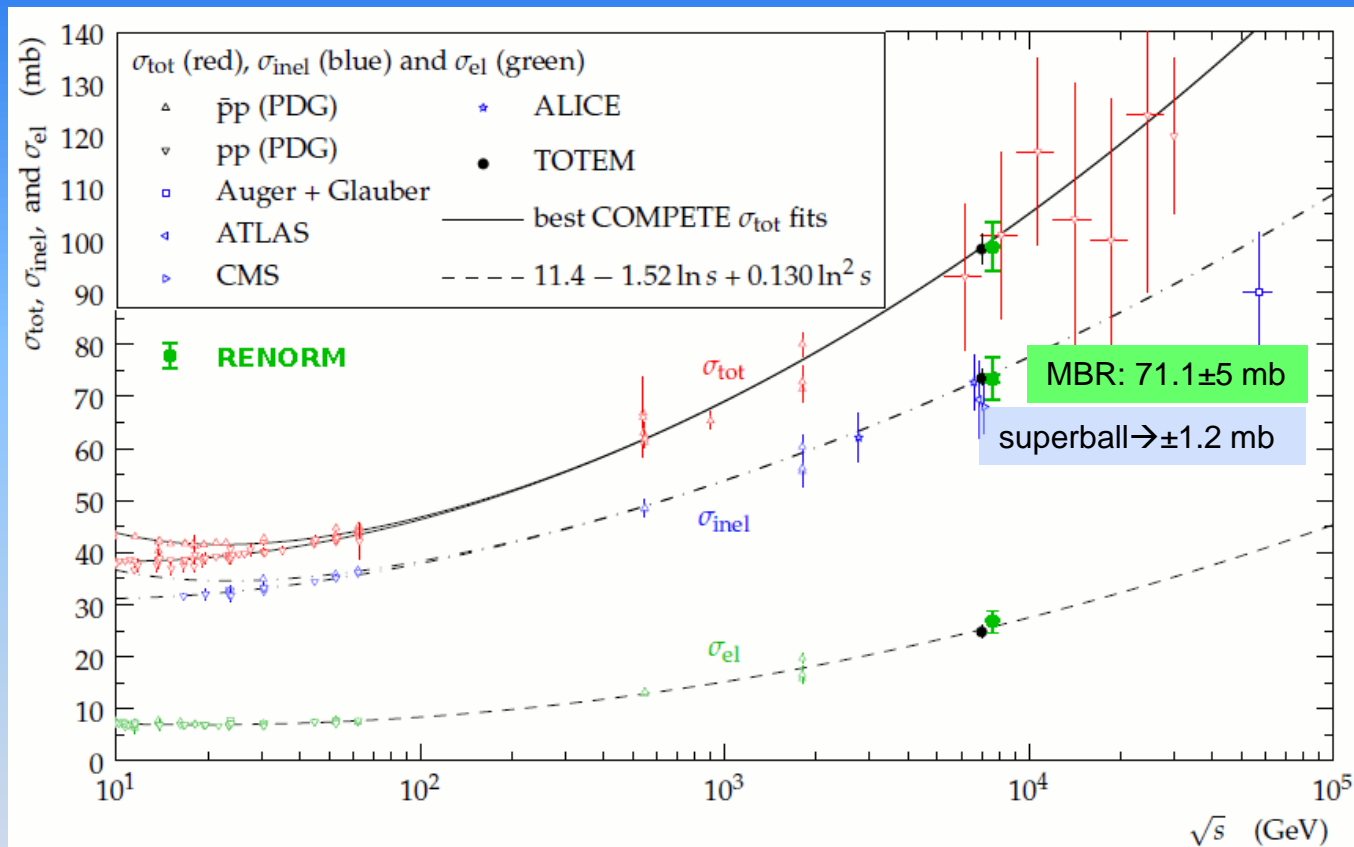
Saturation glueball?



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

Figure 8: $M_{\pi^+\pi^-}$ spectrum in *DPE* 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 (2012) vs PYTHIA8-MBR



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

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

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

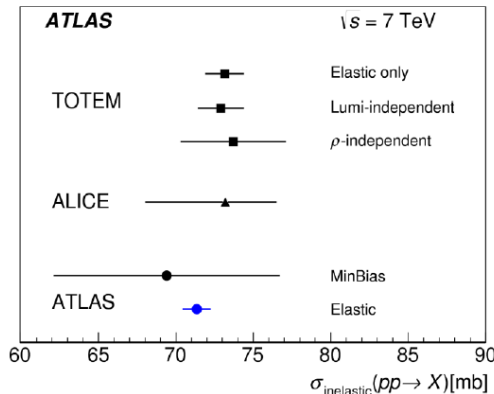
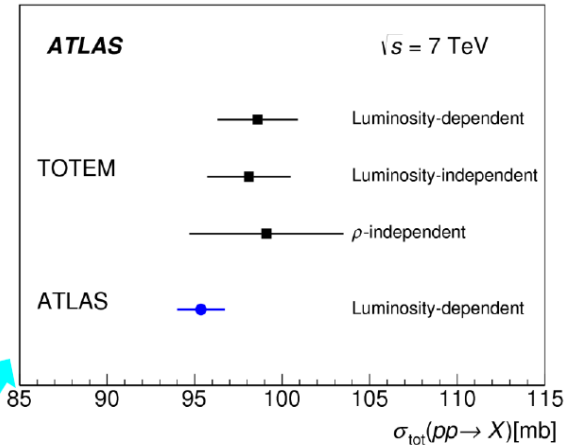
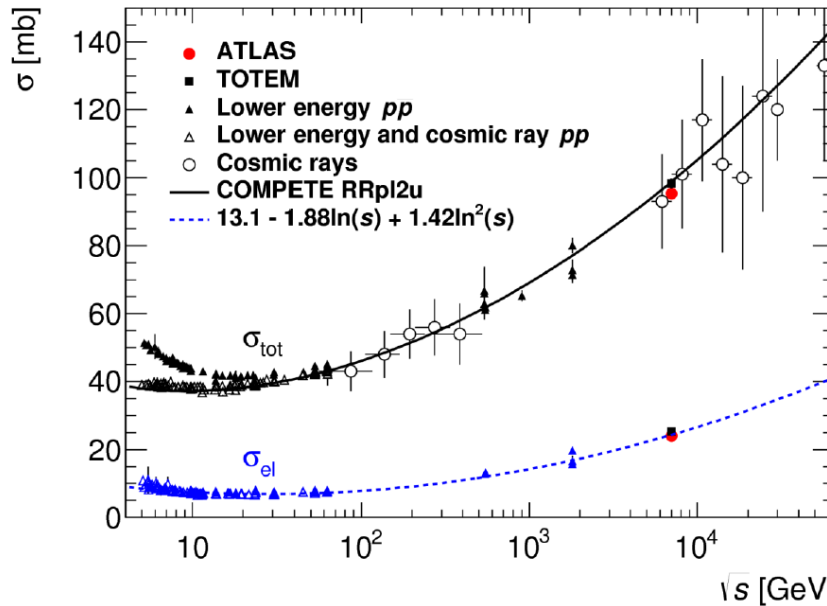
$$\text{RENORM: } 71.1 \pm 1.2 \text{ mb}$$

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

ATLAS - in Diffraction 2014

(Talk by Marek Taševský, slide#19)

Comparison with previous measurements



RENORM:
98.0 ± 1.2 mb

σ_{inel} :
ALFA significantly improves precision of the previous ATLAS σ_{inel} measurement

The same run in 2011, Lumi-dependent method:

ATLAS: $\sigma_{tot} = 95.4 \pm 1.4$ mb (Lumi unc=2.3%)
TOTEM: $\sigma_{tot} = 98.6 \pm 2.2$ mb (Lumi unc=4%)
→ Difference = 1.3 σ

ATLAS value ~2 σ below COMPETE fit, but closer to predictions by Block & Halzen, KMR, Softer.

ATLAS: $\sigma_{el} = 24.0 \pm 0.6$ mb (Lumi unc=2.3%)
Totem: $\sigma_{el} = 25.4 \pm 1.1$ mb (Lumi unc=4%)
→ Difference = 1.1 σ

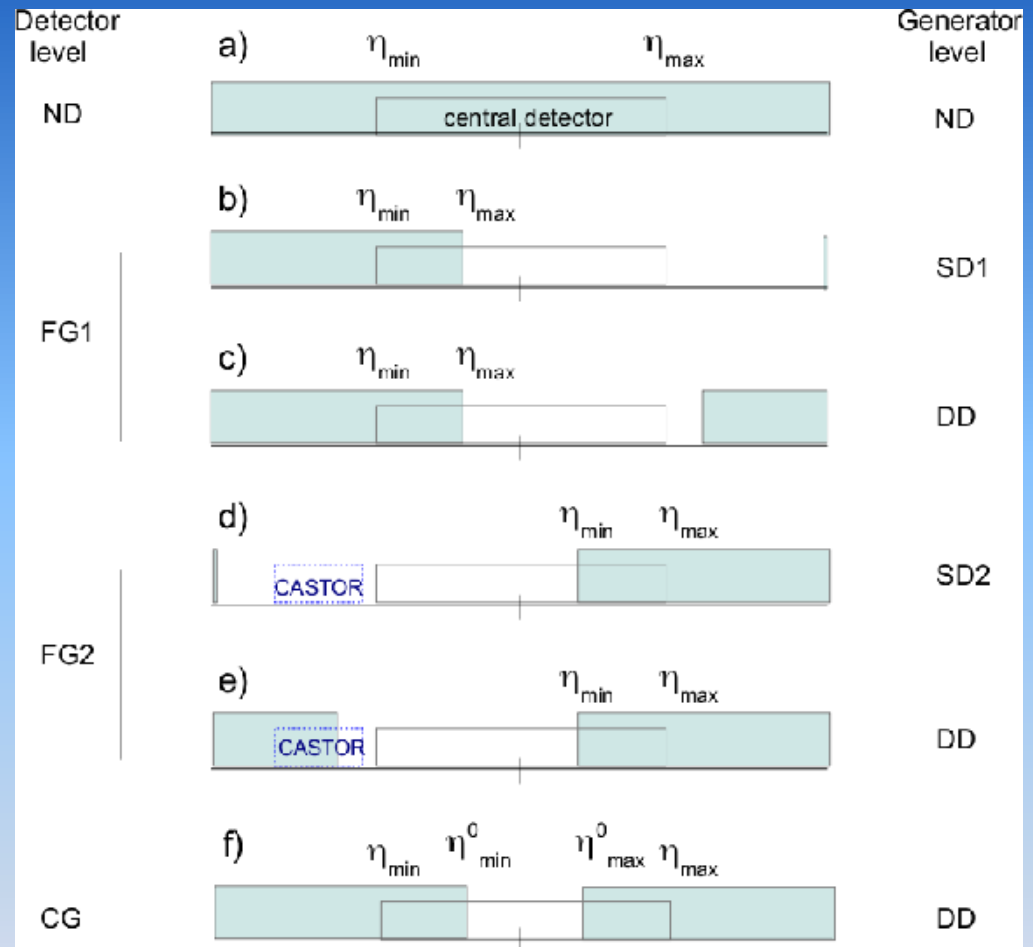
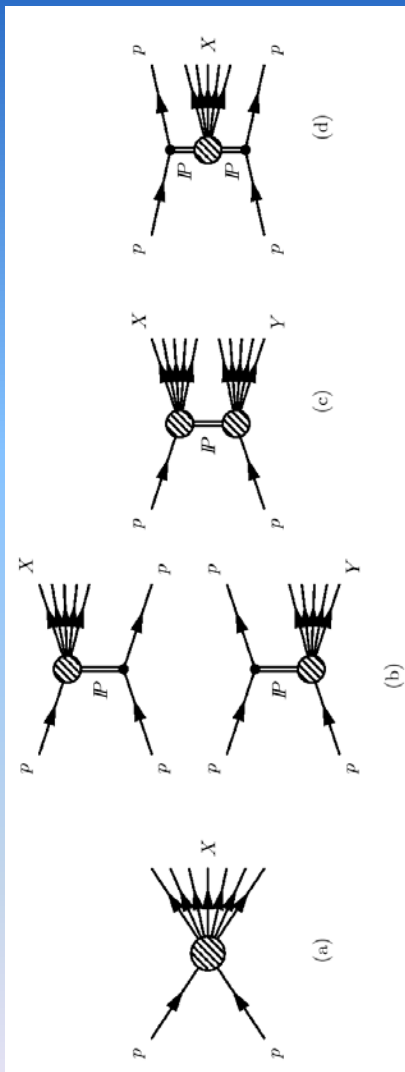
The CMS Detector

CD

DD

SD

ND

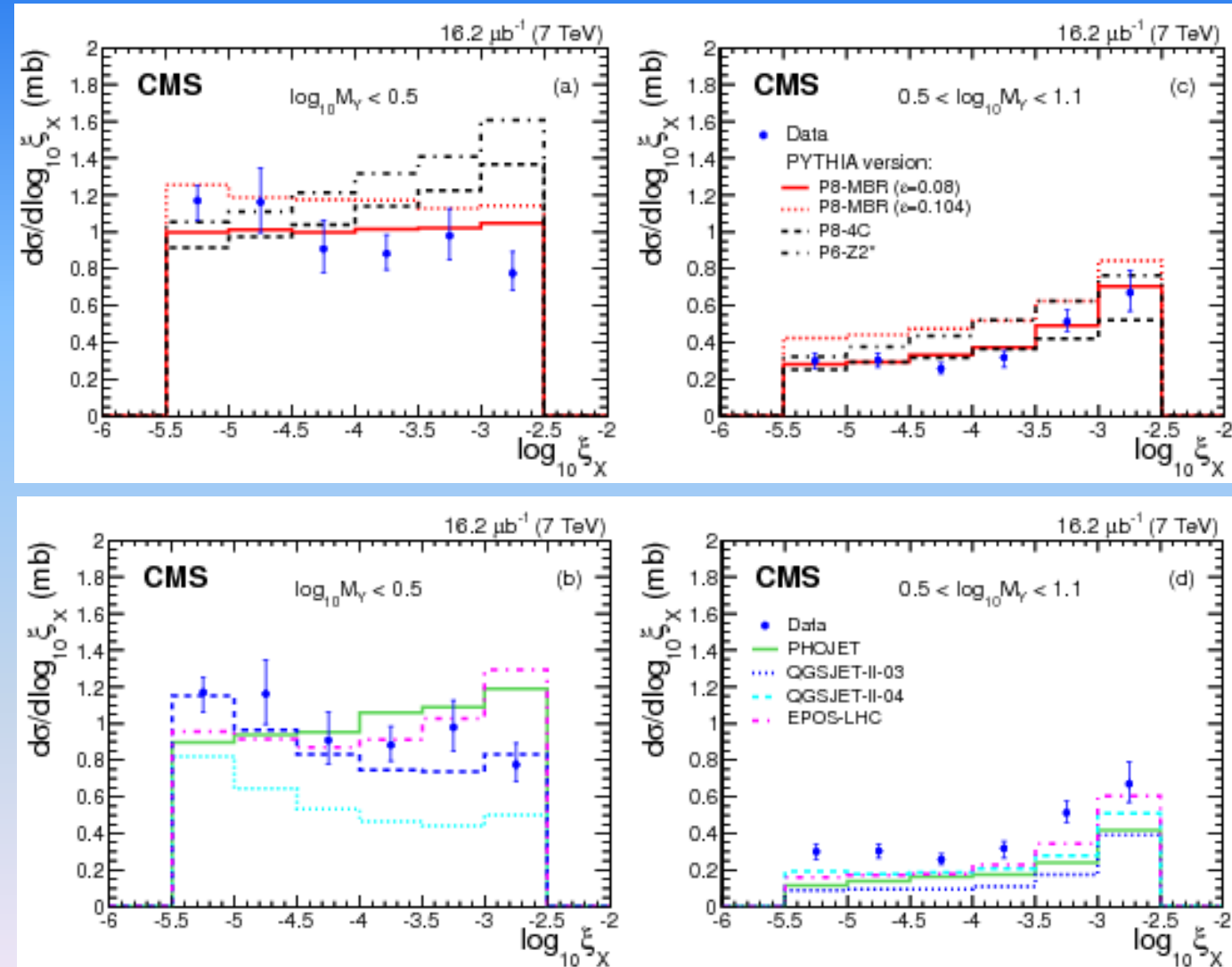


CASTOR forward calorimeter important for separating SD from DD contributions

CMS Data vs MC Models (2015)-1

SD dominated data

DD dominated data

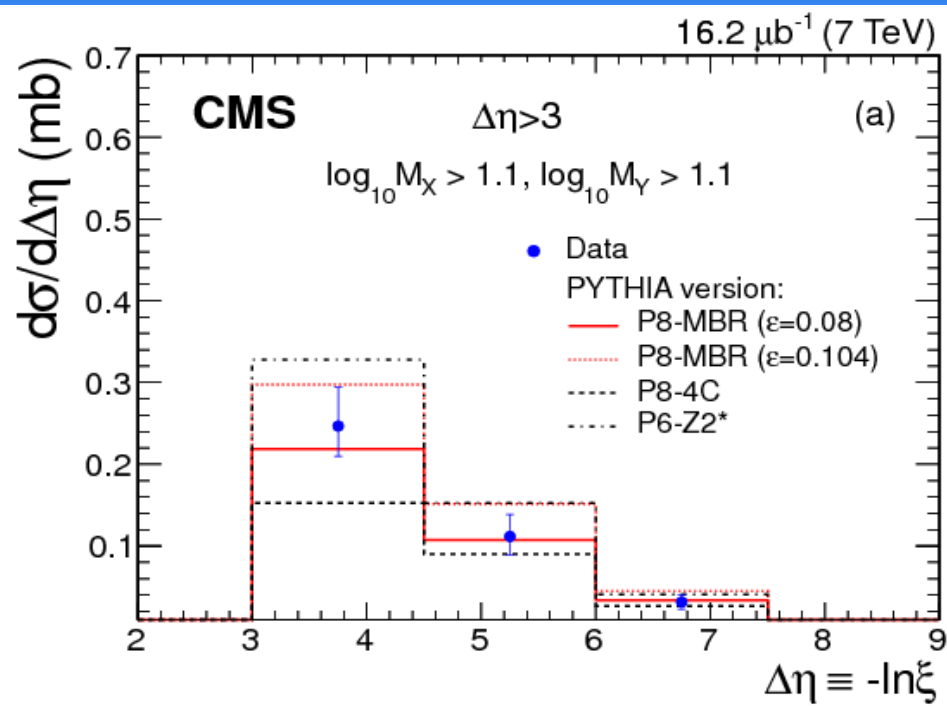


❑ Error bars are dominated by systematics

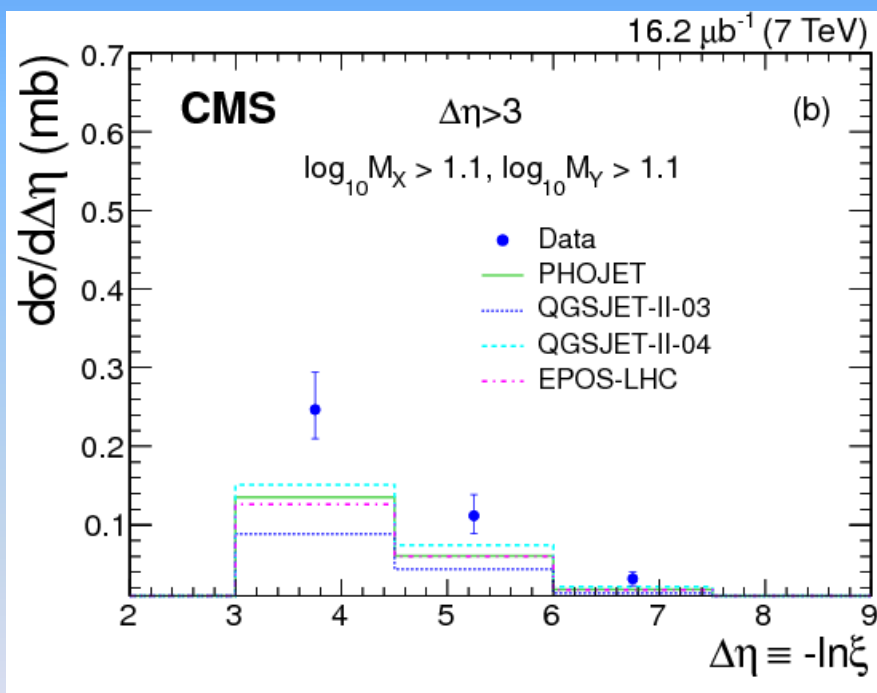
❑ DD data scaled downward by 15% (within MBR and CDF data errors)

CMS Data vs MC Models (2015) -2

Central η -gap x-sections (DD dominated)

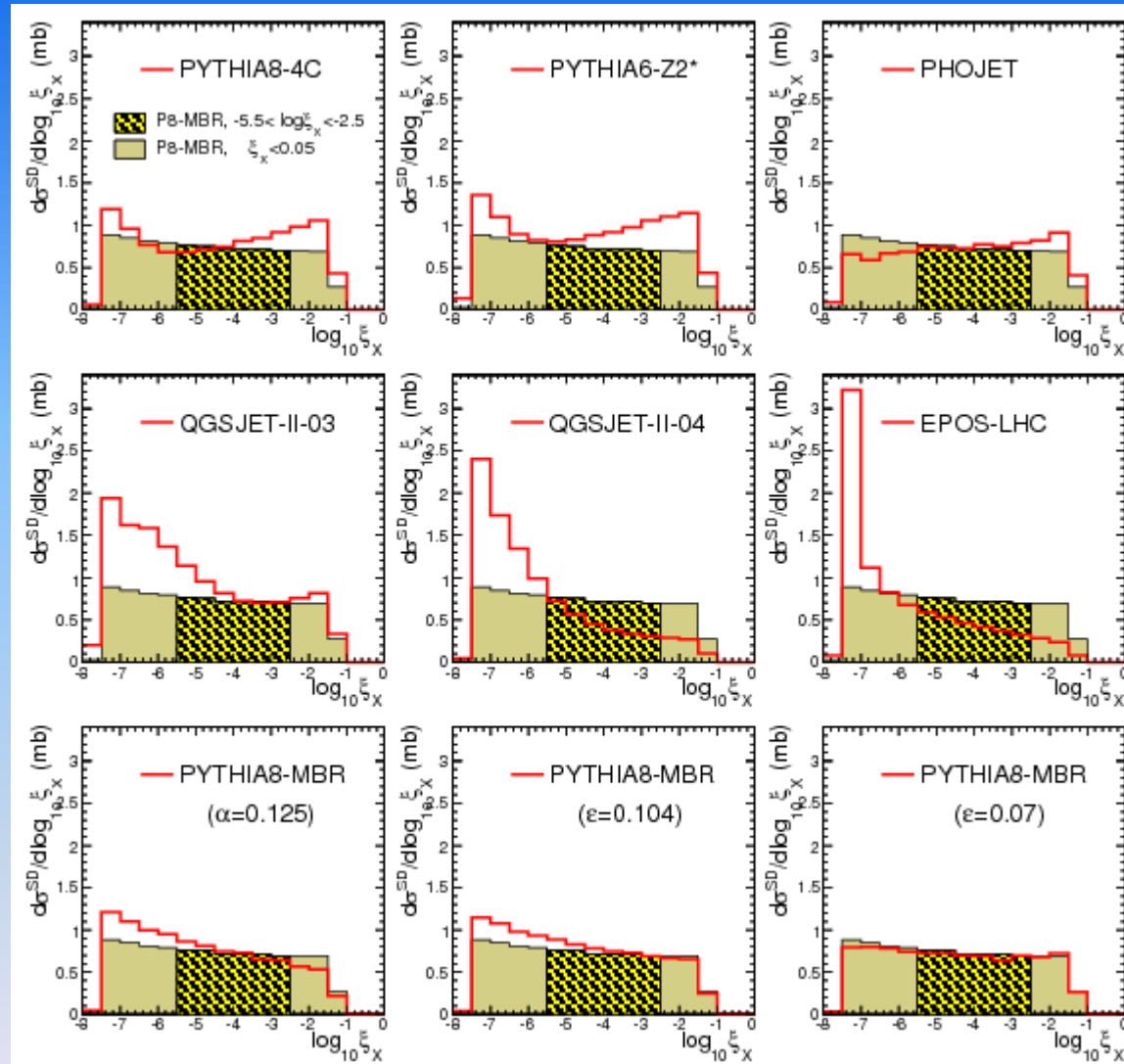


□ .P8-MBR provides the best fit to data



□ .All above models too low at small $\Delta\eta$

SD/DD Extrapolations to $\xi_x \leq 0.05$ vs MC Models



p_T Distr's of MCs vs Pythia8 Tuned to MBR

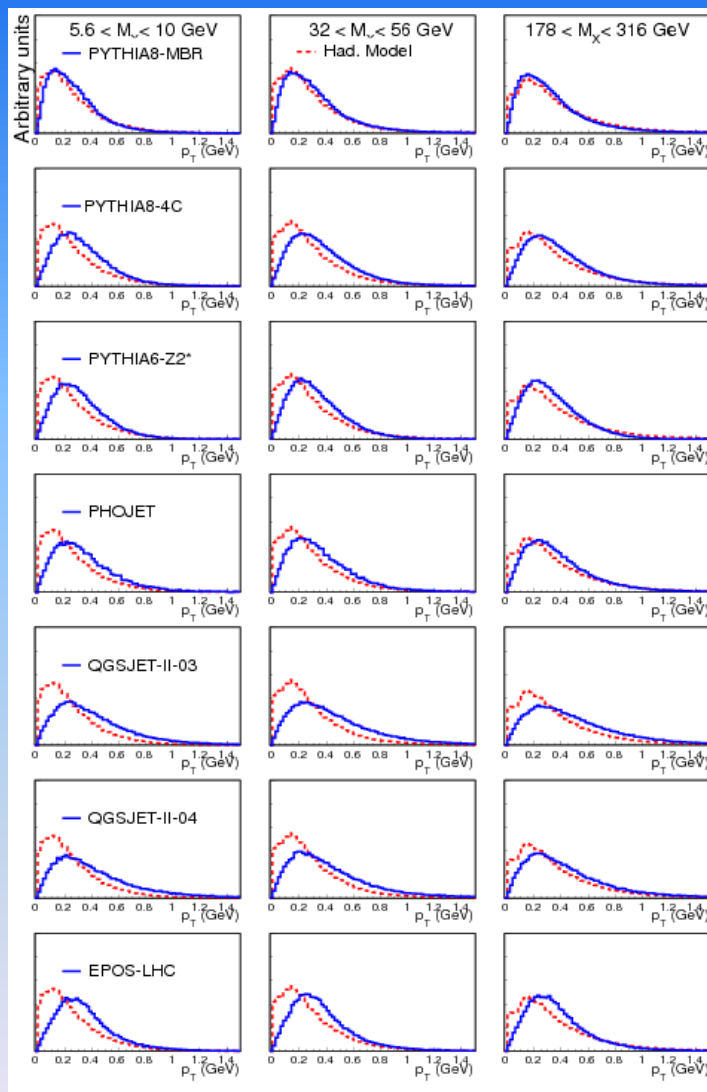
COLUMNS

Mass Regions

- Low $5.5 < M_X < 10$ GeV
- Med. $32 < M_X < 56$ GeV
- High $176 < M_X < 316$ GeV

CONCLUSION

- PYTHIA8-MBR agrees best with the reference model and is used by CMS in extrapolating to the unmeasured regions.



← Pythia8 tuned to MBR

ROWS

MC Models

- PYTHIA8-MBR
- PYTHIA8-4C
- PYTHIA6-Z2*
- PHOJET
- QGSJET-II-03
- QGSJET-04
- EPOS-LHC

Charged Mult's vs MC Model – 3 Mass Regions

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

<http://www.sciencedirect.com/science/article/pii/0370269387904746>

Mass Regions

- ❑ Low $5.5 < M_X < 10$ GeV
- ❑ Med. $32 < M_X < 56$ GeV
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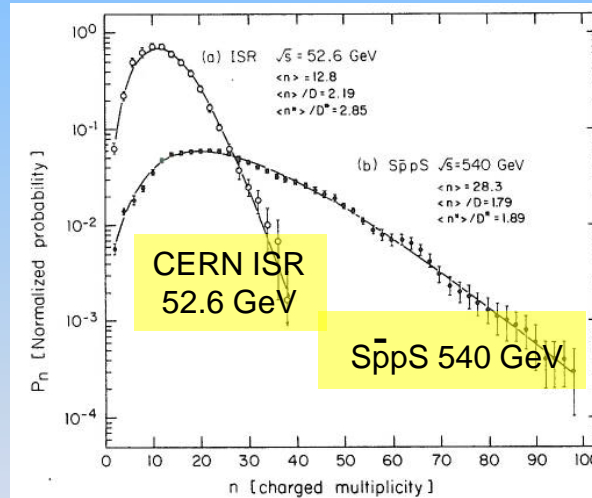
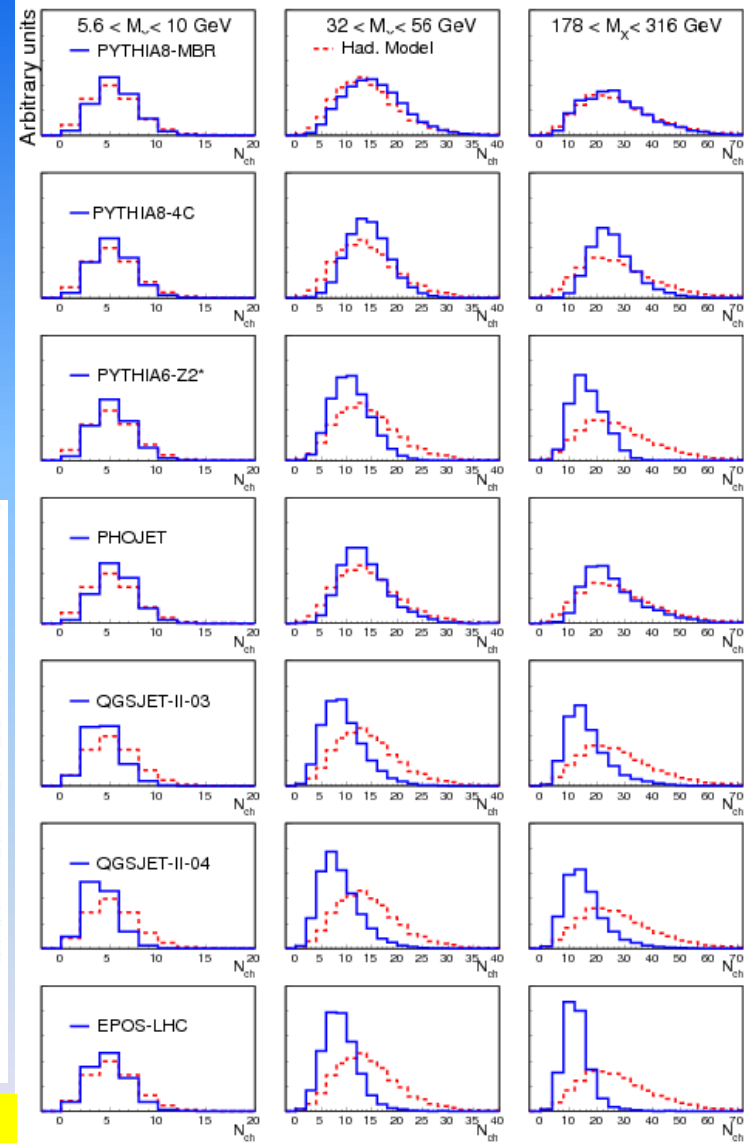


Fig. 2. Full phase space inelastic non-single-diffractive data fitted with the modified gamma function: (a) ISR data [5] at $\sqrt{s}=52.6$ GeV and (b) collider data [7] at $\sqrt{s}=540$ GeV.

CERN ISR & SppS w/MGD fit



$0 < p_T < 1.4$ GeV

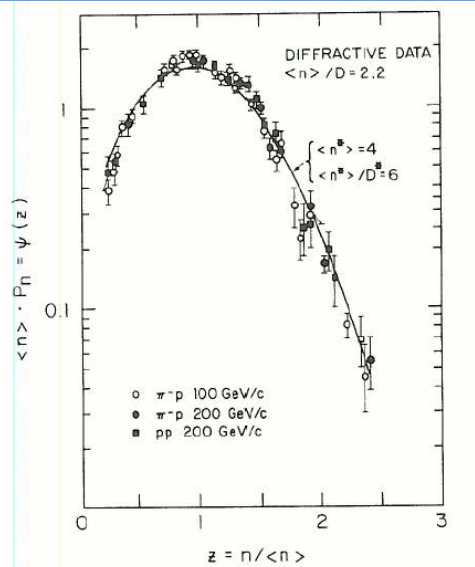
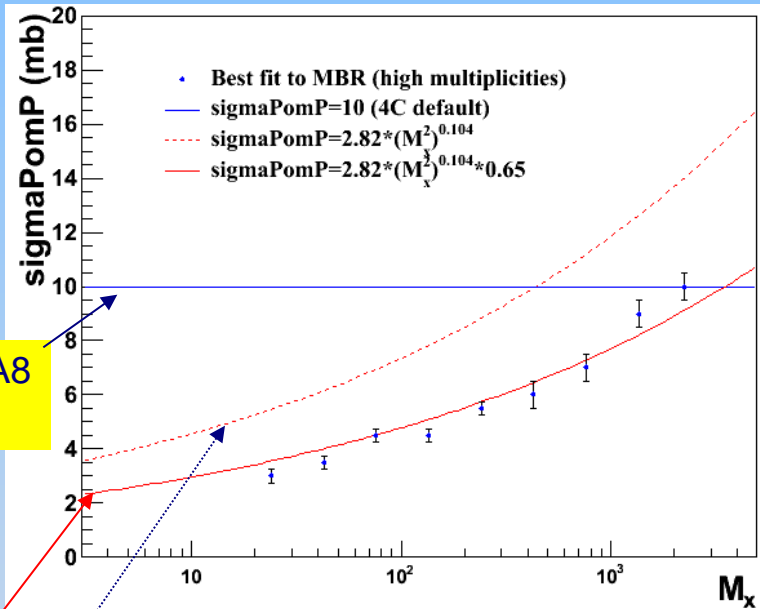


Fig. 1. The diffractive data of ref. [3] fitted with the modified gamma function.

Diffractive data vs MGD

Pythia8-MBR Hadronization Tune

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

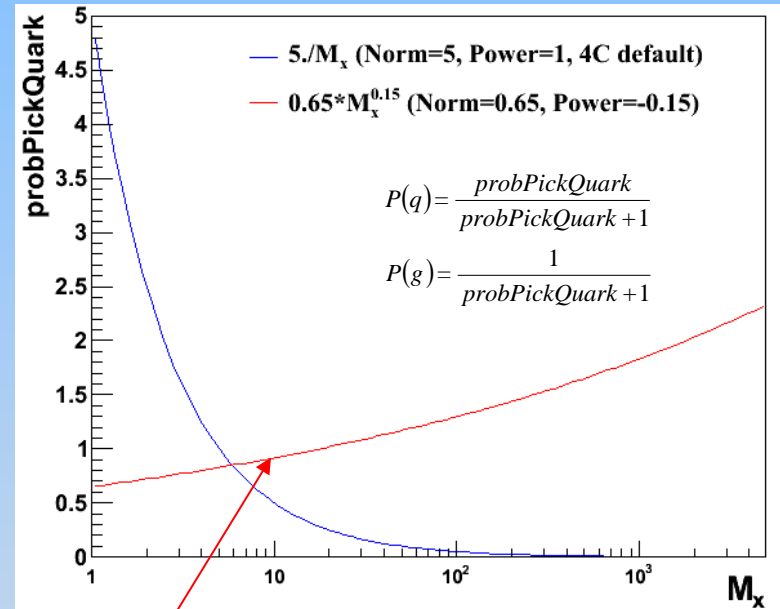


PYTHIA8 default

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

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

Diffraction: QuarkNorm/Power parameter

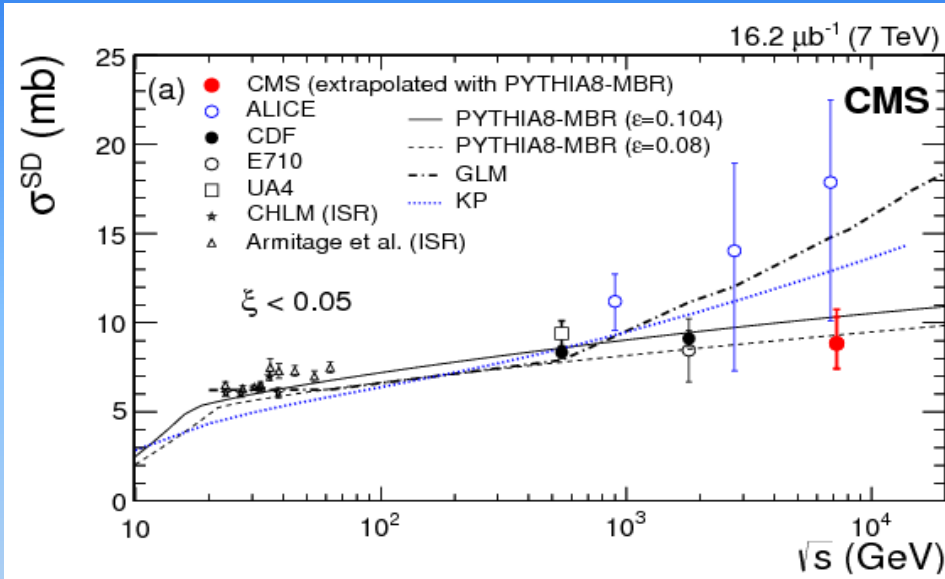


$$P(q) = \frac{\text{probPickQuark}}{\text{probPickQuark} + 1}$$

$$P(g) = \frac{1}{\text{probPickQuark} + 1}$$

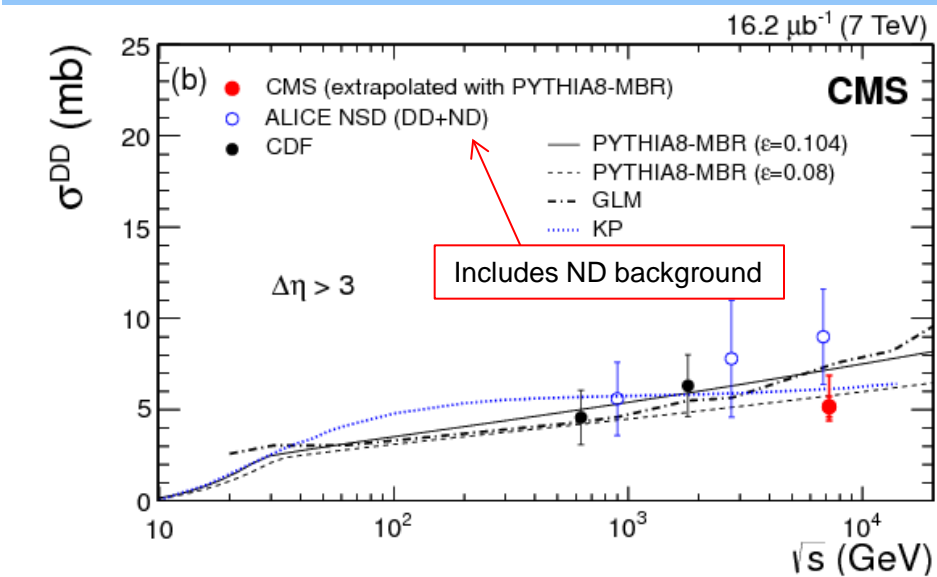
☐ good description of low multiplicity tails

SD and DD x-Sections vs Models

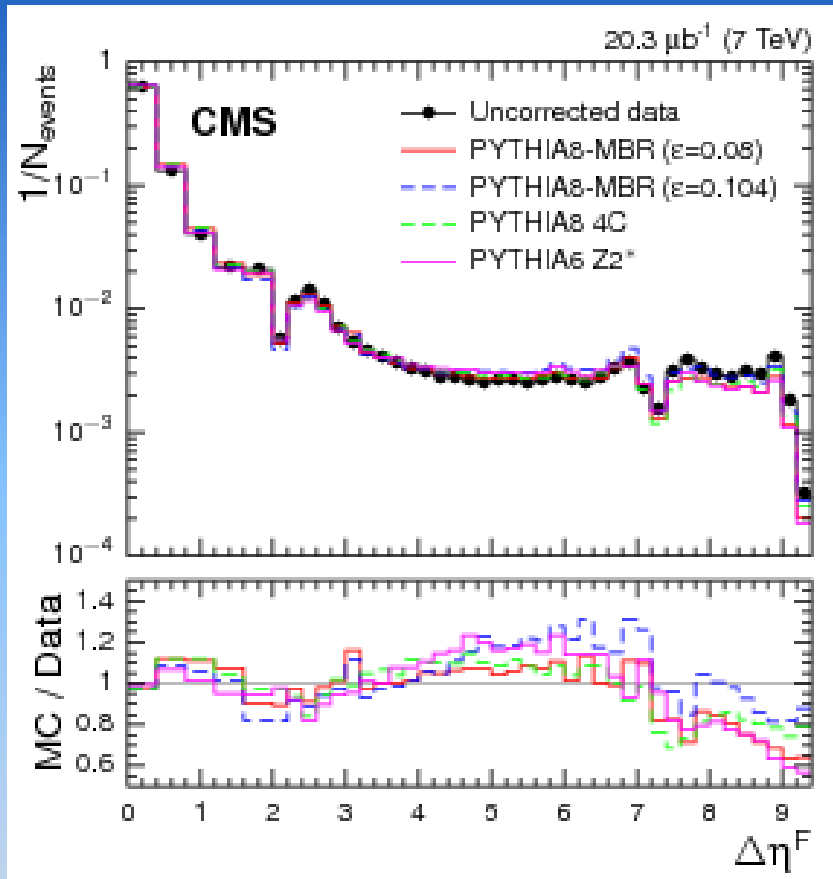


Single Diffraction

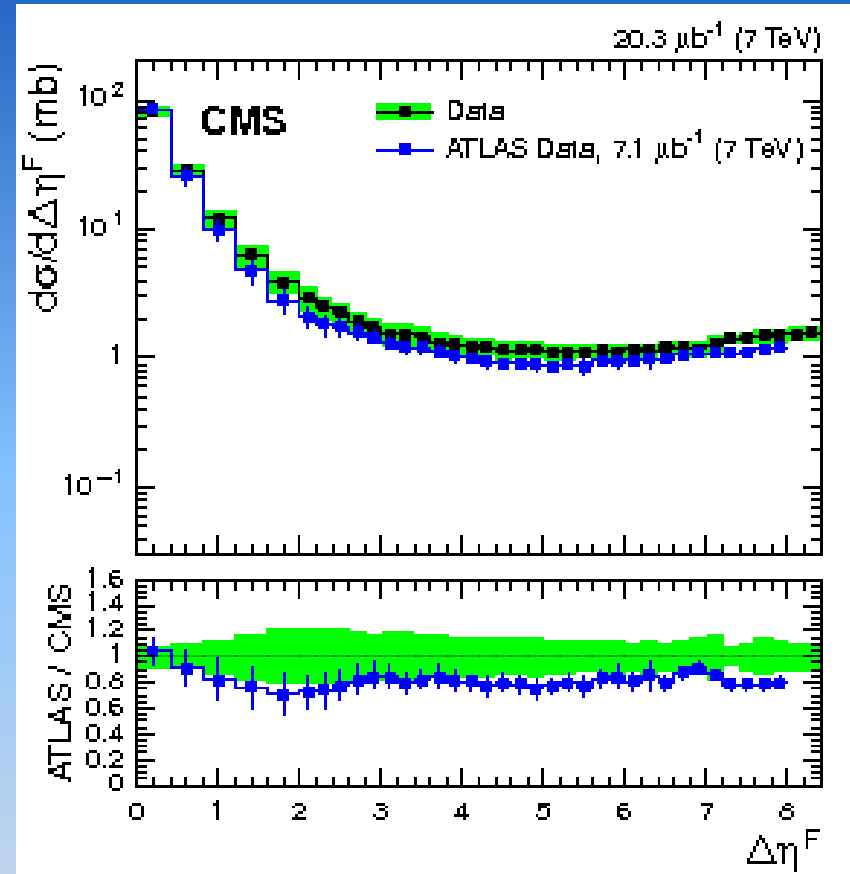
Double Diffraction



CMS vs MC & ATLAS



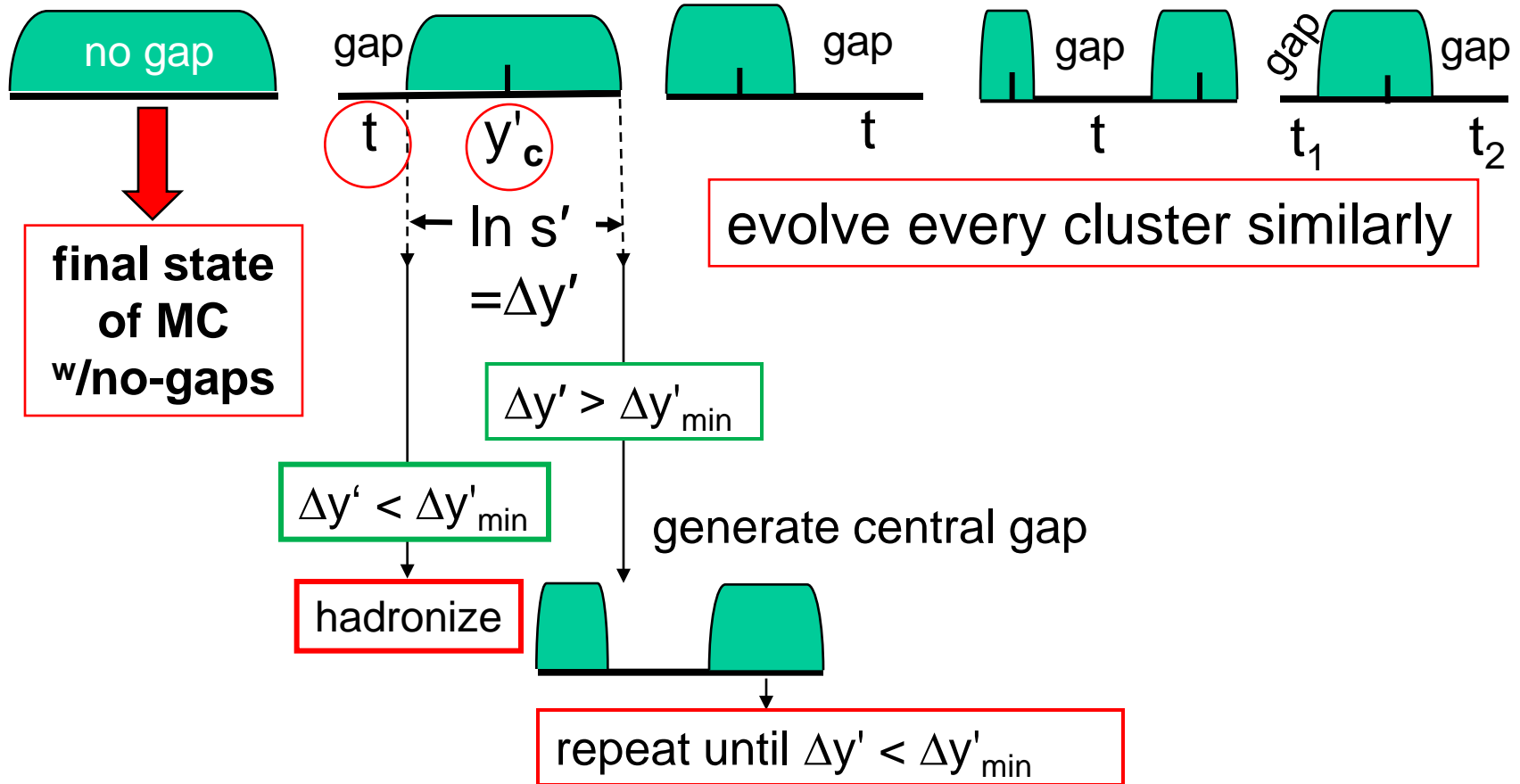
Uncorrected $\Delta\eta^F$ distribution vs MCs



Stable-particle x-sections for $p_T > 200$ MeV and $|\eta| < 4.7$ compared to the ATLAS 2012 result similar result

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

- ND → no diffractive gaps:

} **derived from ND
and QCD color factors**

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

- Monte Carlo strategy for the LHC – “nesting”

Warm thanks to my CDF and CMS colleagues, and to Office of Science of DOE

Special thanks to Robert A. Ciesielski, my collaborator in the PYTHIA8-MBR project

Thank you for your attention!