Updated RENORM / MBR Predictions for Diffraction at the LHC

Konstantin Goulianos

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

GAP
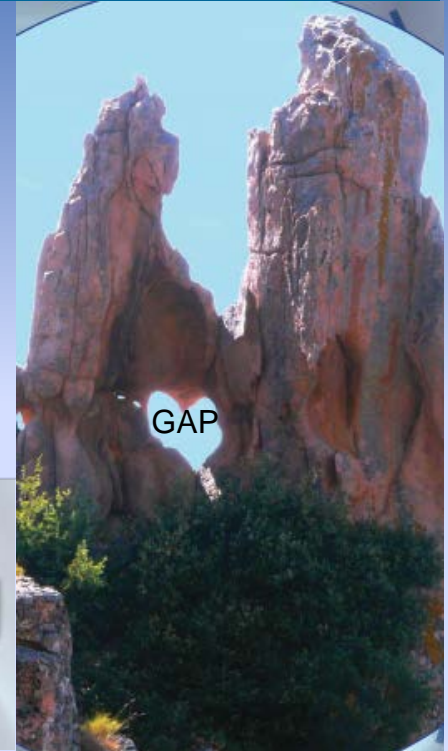
EDS Blois 2015, 16th International Conference on
Elastic and Diffractive Scattering
Borgo-Corsica, 29 June - 3 July 2015

http://indico.cern.ch/event/362991/

CONTENTS

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

□ Renormalization→Unitarization
  ➢ RENORM Model
□ Triple-Pomeron Coupling
□ Total Cross Section
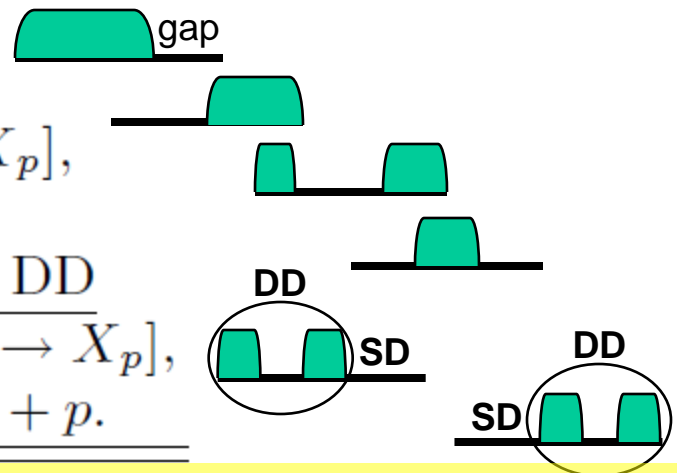□ RENORM / MBR Predictions Confirmed
□ RENORM / MBR Predictions Updated

□ References
- ➢ MBR MC Simulation in PYTHIA8, KG & R. Ciesielski, **http://arxiv.org/abs/1205.1446**
- ➢ Previous talk LHCFPWG 2015 Madrid (21-25 Apr 2015) **http://workshops.ift.uam-csic.es/LHCFPWG2015/program**
- ➢ Present talk Updated predictions are compared to data and models
  - ❖ ATLAS, CMS, TOTEM, various models

RENORM: Basic and Combined Diffractive Processes

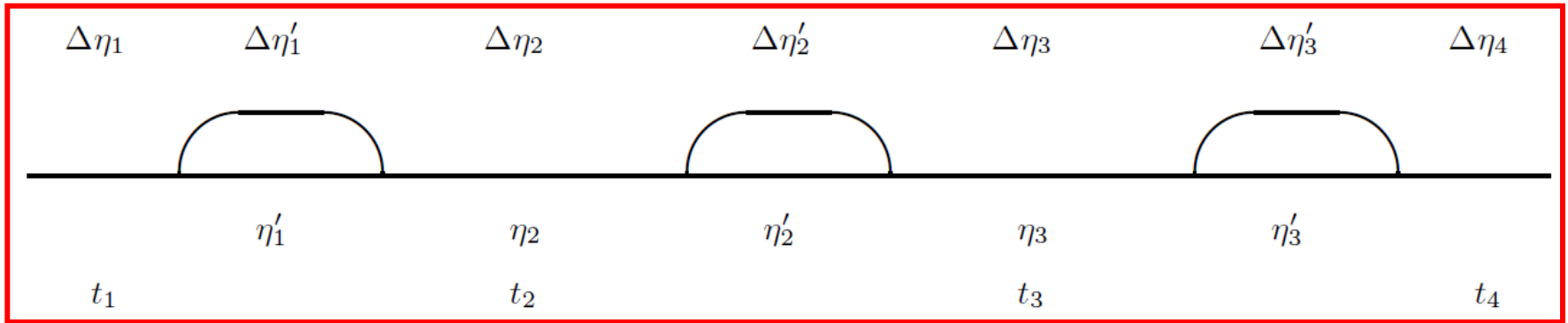| acronym	basic diffractive processes
$\mathbf{SD}_{\bar{p}}$	$\bar{p}p \rightarrow \bar{p} + \text{gap} + [p \rightarrow X_p]$,
$\mathbf{SD}_p$	$\bar{p}p \rightarrow [\bar{p} \rightarrow X_{\bar{p}}] + \text{gap} + p$,
$\mathbf{DD}$	$\bar{p}p \rightarrow [\bar{p} \rightarrow X_{\bar{p}}] + \text{gap}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

BASIC

COMBINED

particles

gap

DD

SD

DD

SD

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
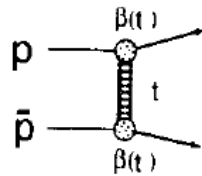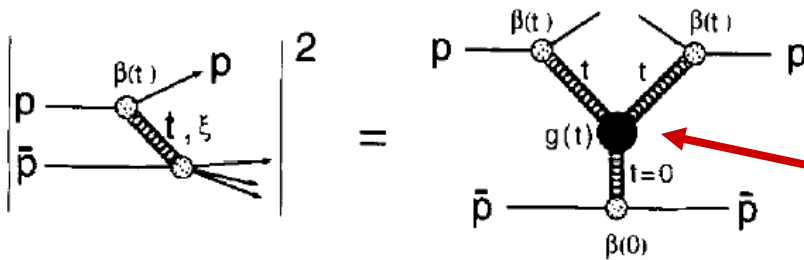

TOTAL CROSS SECTION
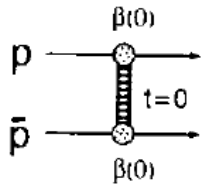
ELASTIC SCATTERING

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?**

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

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

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

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

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

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

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

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

Theoretical 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*

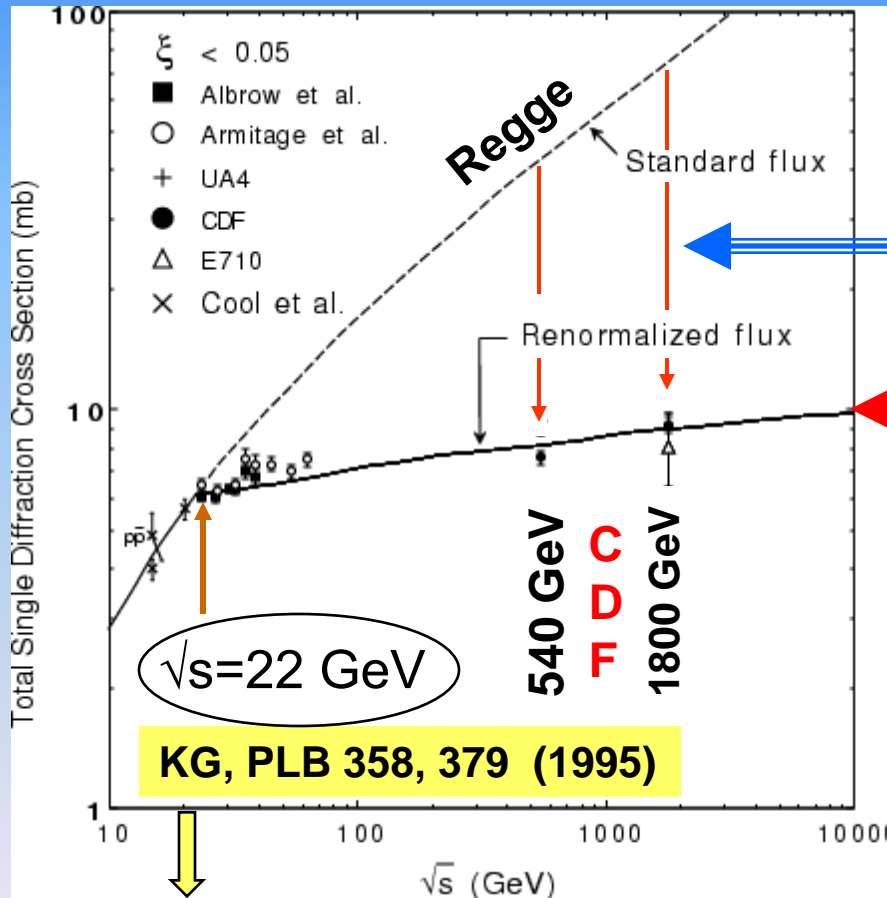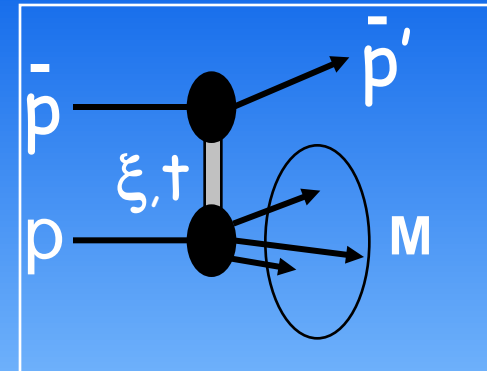(also true for partial x-sections in impact parameter space)

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

❑ need unitarization

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

FACTORIZATION BREAKING IN SOFT DIFFRACTION

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

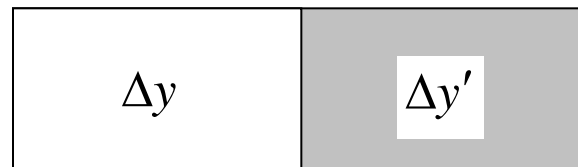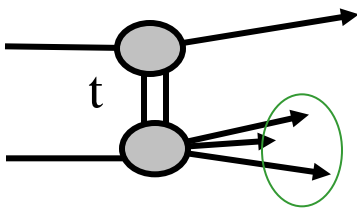Factor of ~8 (~5) suppression at $\sqrt{s}$ = 1800 (540) GeV

RENORMALIZATION

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

KG, PLB 358, 379 (1995)

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

KG ➜ CORFU-2001: http://arxiv.org/abs/hep-ph/0203141

Δy $\Delta y'$

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

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

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

Single Diffraction Renormalized - 3

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

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

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

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

set to unity
➔ determines s_o

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

M² - Distribution: Data

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

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

Regge ➔ data

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

http://physics.rockefeller.edu/publications.html
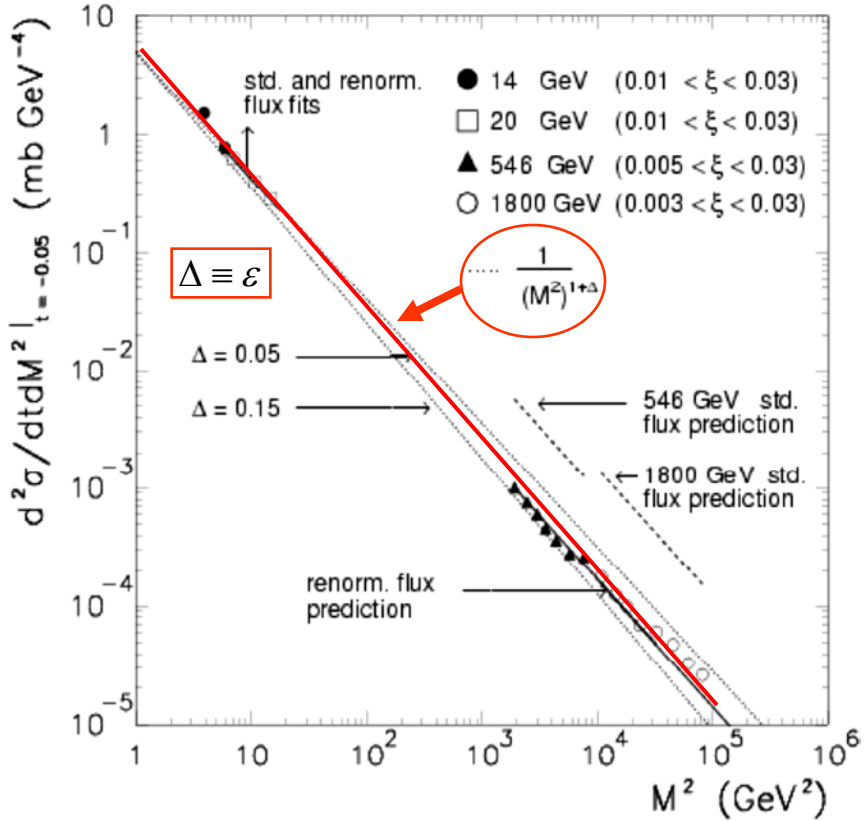
➔ factorization breaks down to ensure M² scaling

Scale s_0 and *PPP* Coupling

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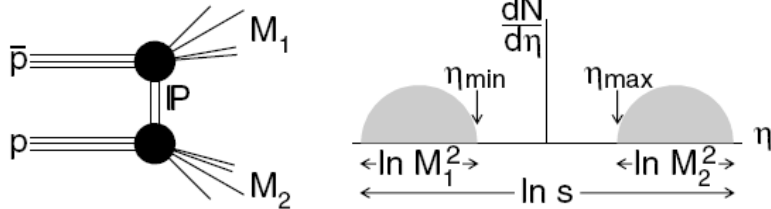→set to unity: determines g_{PPP} and s_0

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

$$s_o^{\varepsilon}$$

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

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

Pomeron-proton x-section

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

DD at CDF

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

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

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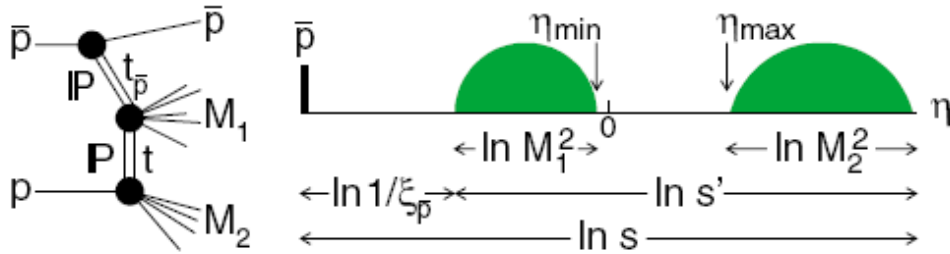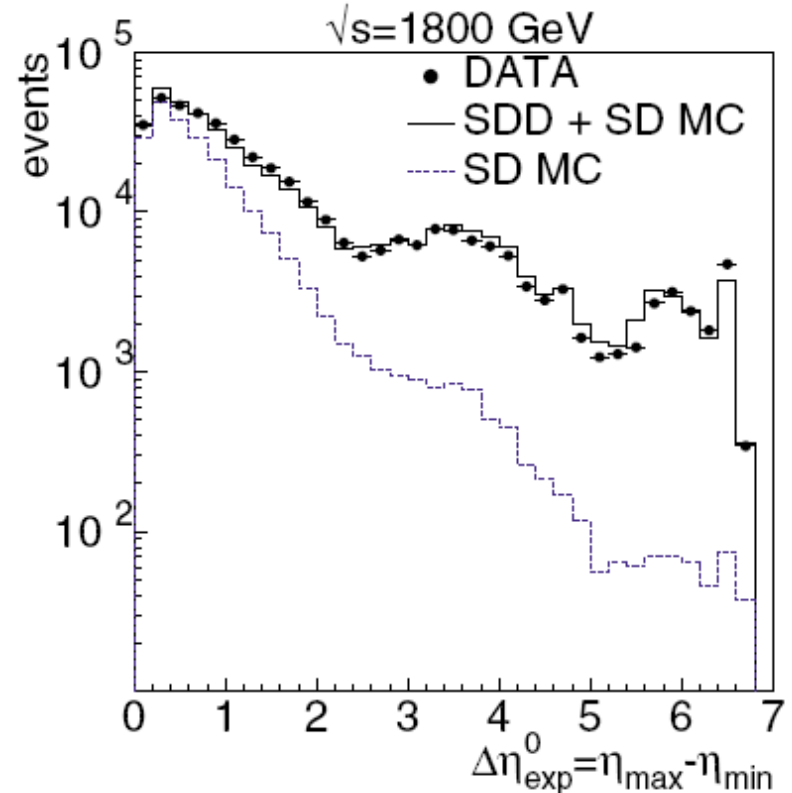
gap probability   x-section
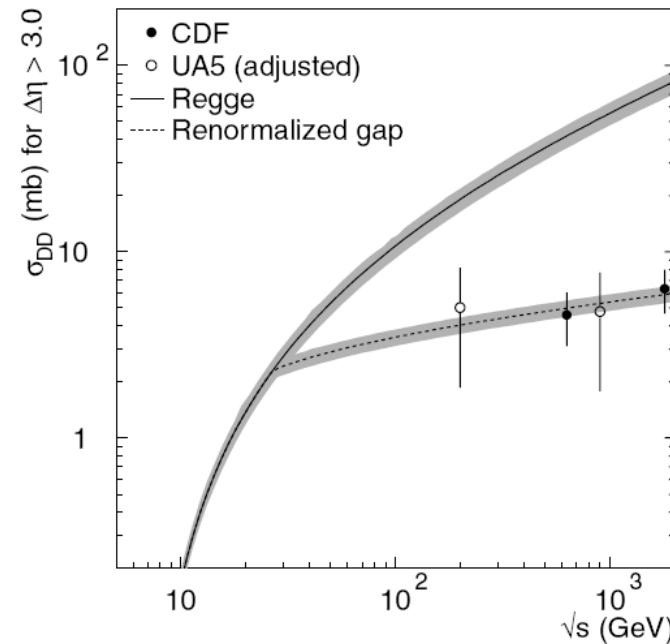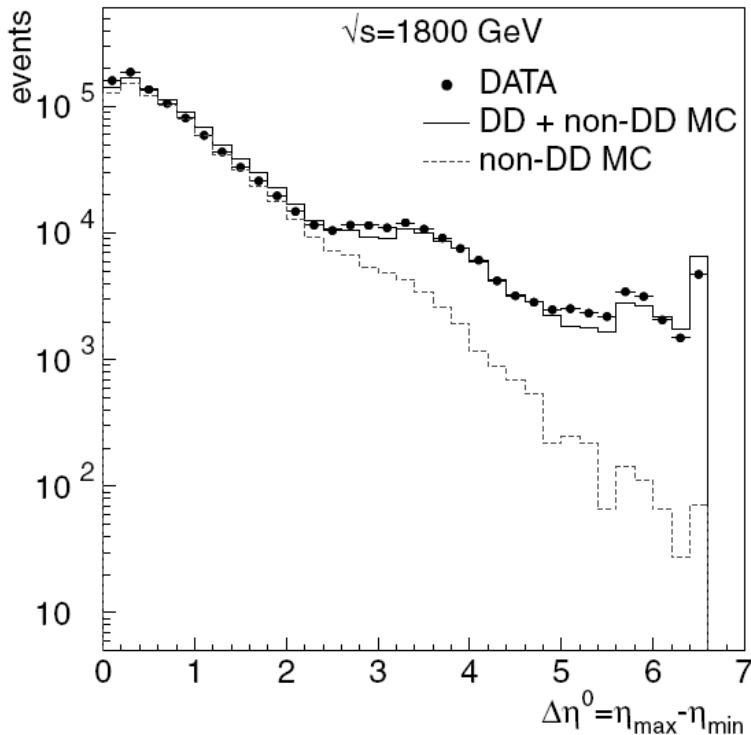
←**Regge**

←**Renor'd**

x-section divided by integrated gap prob.

SDD at CDF
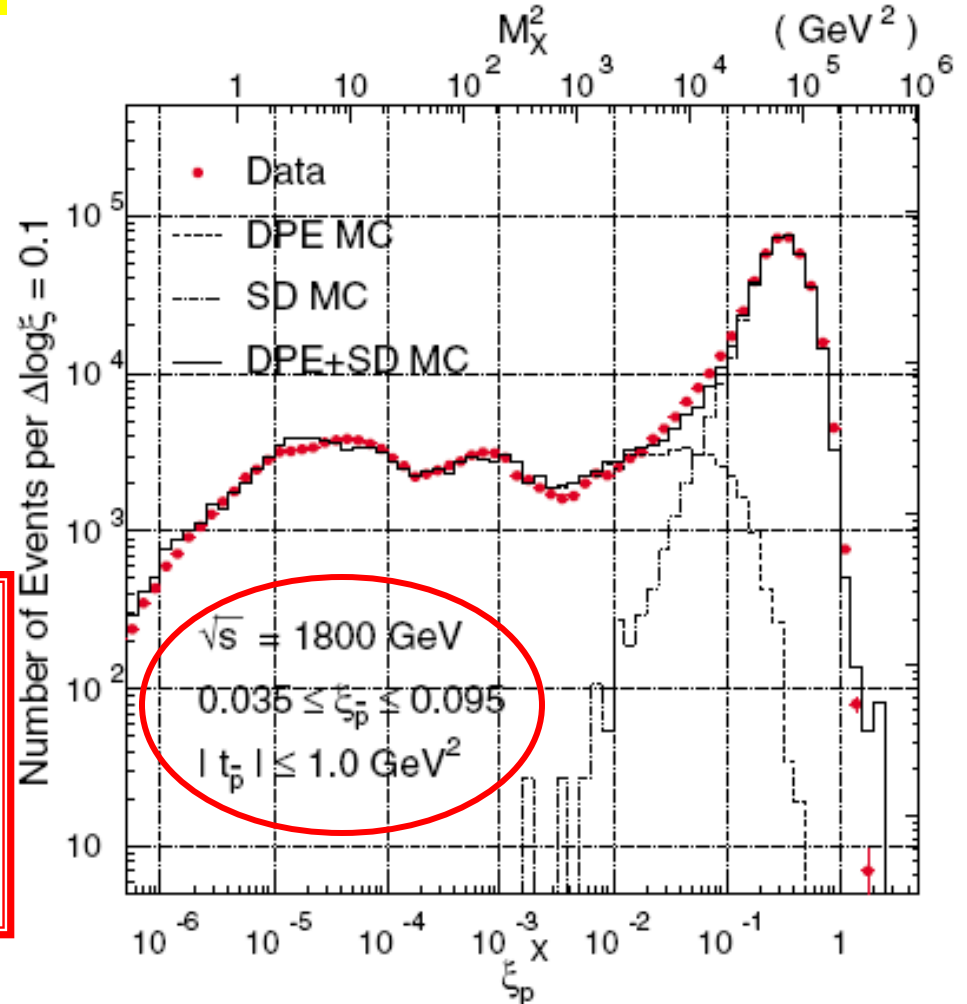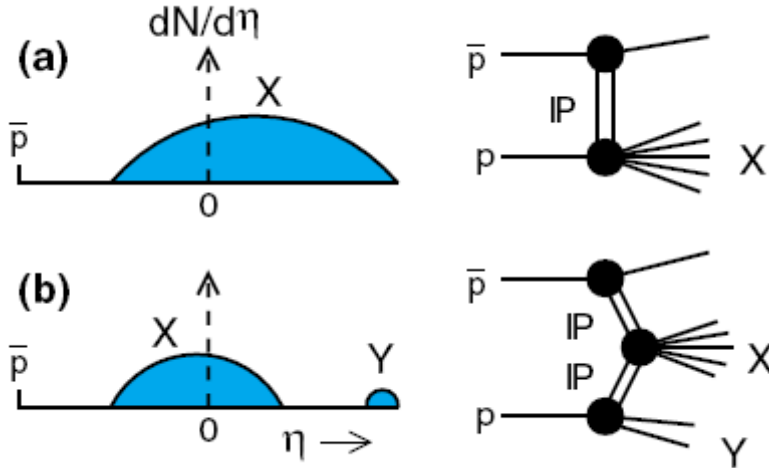

http://physics.rockefeller.edu/publications.html

- ■ Excellent agreement between data and MBR (MinBiasRockefeller) MC

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

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 Difractive Cross Sections

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

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

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

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

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

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

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

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

http://www.sciencedirect.com/science/article/pii/S0370269396013627

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

KG   MORIOND-2011 http://moriond.in2p3.fr/QCD/2011/proceedings/goulianos.pdf

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

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

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

Diffractive and Total pp Cross Sections at LHC

Konstantin Goulianos
The Rockefeller University

EDS '09
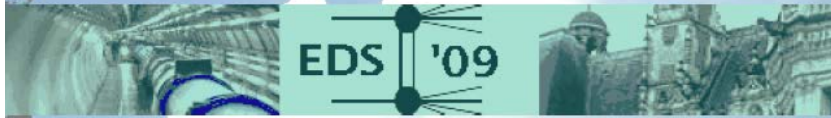
√s$_F$=22 GeV

- 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:

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

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

Uncertainty is due to s$_0$
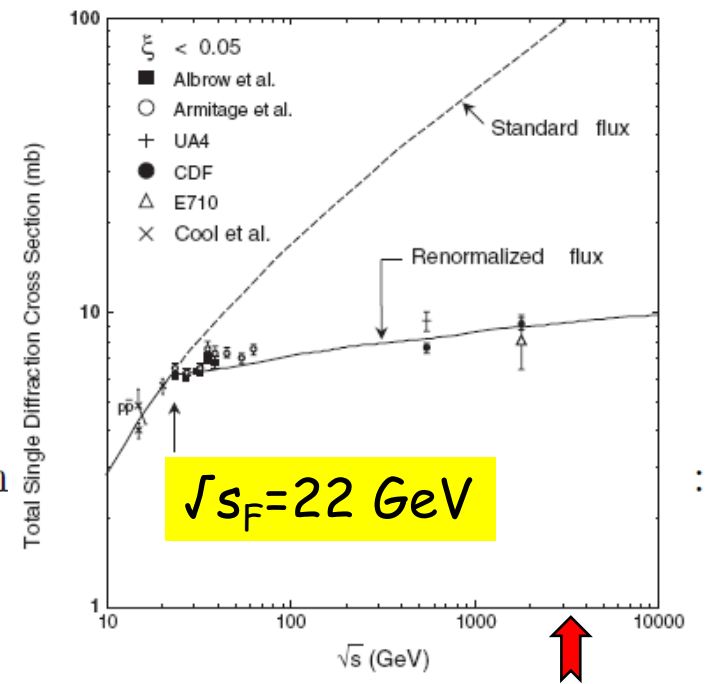
TOTEM (2012) vs PYTHIA8-MBR
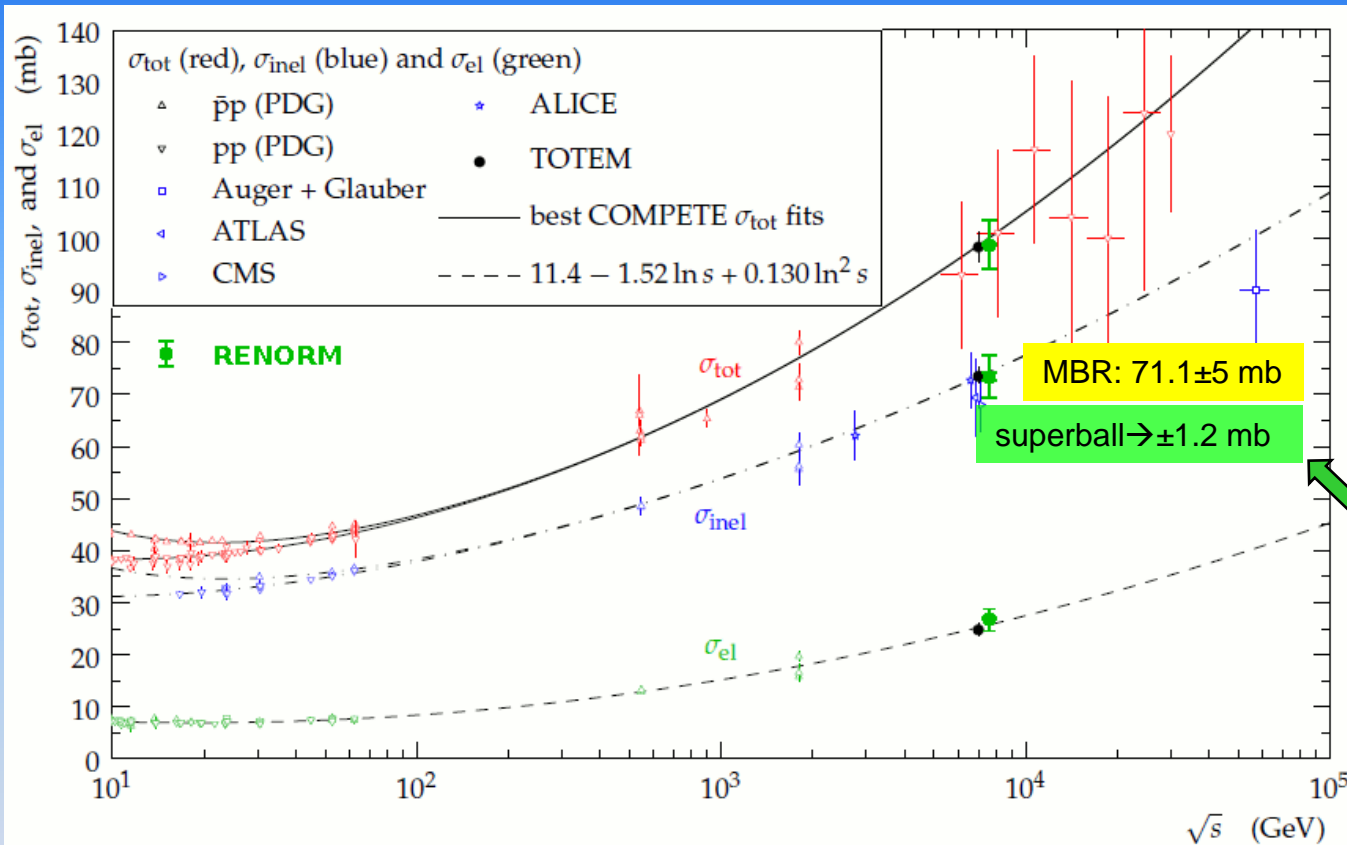
$\sigma_{inel}^{7\,TeV} = $ **72.9 ±1.5 mb**

$\sigma_{inel}^{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

Comparison with previous measurements
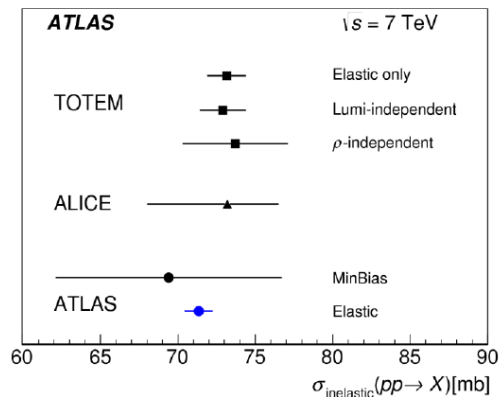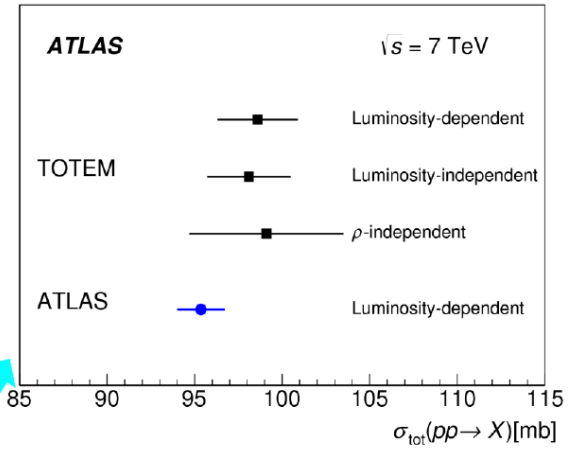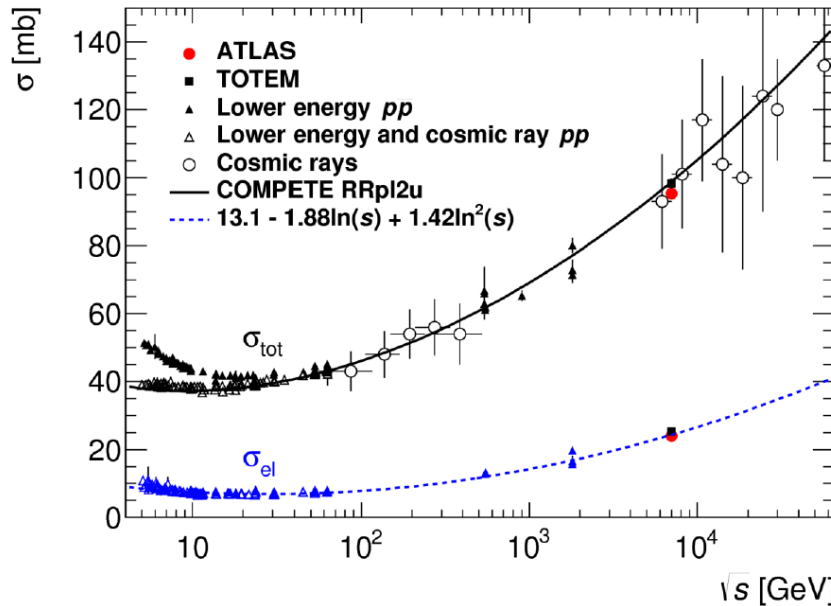
RENORM: 98.0±1.2 mb

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

The same run in 2011, Lumi-dependent method:

ATLAS: σ_{tot} = 95.4 ± 1.4 mb (Lumi unc=2.3%)
TOTEM: σ_{tot} = 98.6 ± 2.2 mb (Lumi unc=4%)
→ Difference = 1.3 σ

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

ATLAS: σ_{el} = 24.0 ± 0.6 mb (Lumi unc=2.3%)
Totem: σ_{el} = 25.4 ± 1.1 mb (Lumi unc=4%)
→ Difference = 1.1 σ

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http://www.cs.infn.it/en/web/external_community/home

Reduce Uncertainty in s_0

Exclusive $\pi^+\pi^-$
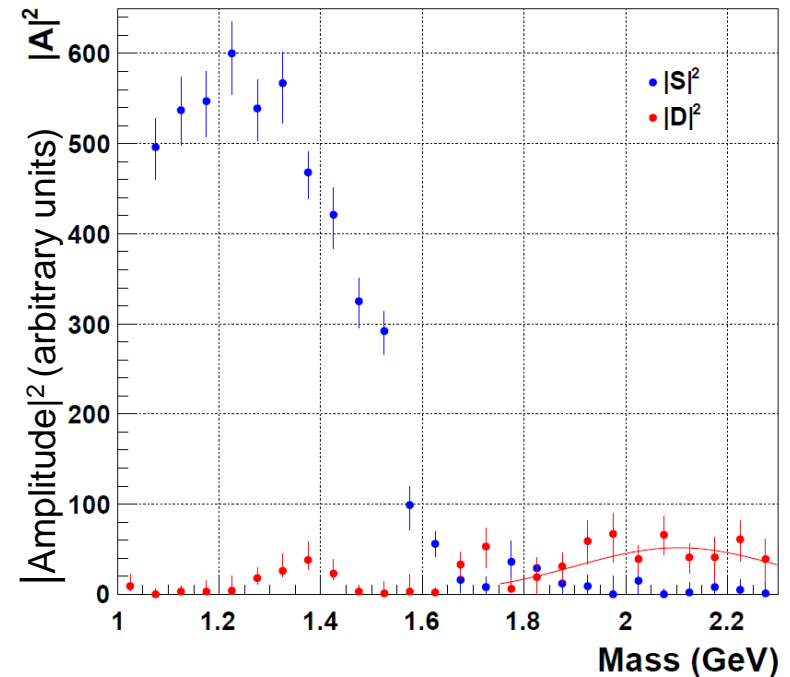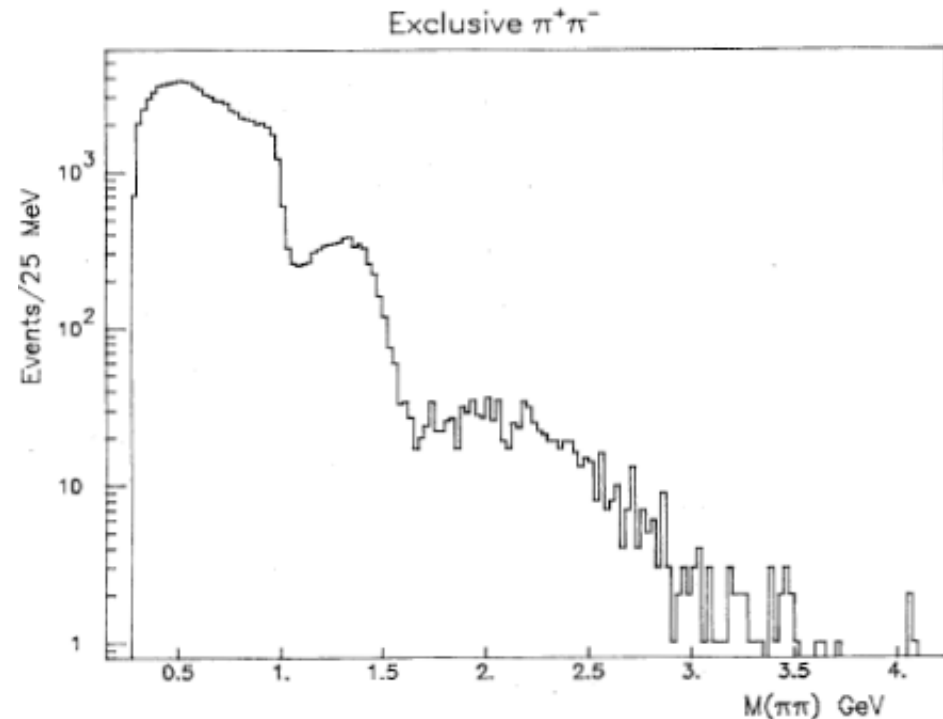
Review of CEP by Albrow, Coughlin, Forshaw http://arxiv.org/abs/1006.1289
Fig. from **Axial Field Spectrometer** at the CERN Intersecting Storage Rings

- $|S|^2$
- $|D|^2$

Data: Peter C. Cesil, ASF thesis
   (courtesy Mike Albrow)
   ➔ analysis: S and D waves
Conjecture: **tensor glue ball** (spin 2)
Fit: Gaussian
❑ $<M_{tgb}> = \sqrt{s_0} = 2.10 \pm 0.68$ GeV
   ❑ ➔ $s_0 = 4.42 \pm 0.34$ GeV^2

20% increase in s_0
➔ x-sections decrease

Reduce Uncertainty in s_0

Energy	Total	Elastic	Inelastic	MBR Exp
7 TeV	95.4±1.2	26.4±0.3	69.0±1.0	MBR
	98.4±2.2		73.7±3.4	TOTEM
	95.35±1.36	24.00±0.60	71.34±0.90	ATLAS
				CMS
8 TeV	97.1±1.4	27.2±0.4	69.9±1.0	MBR
	101.7±2.9	27.1±1.4	74.7±1.7	TOTEM
				ATLAS
				CMS
13 TeV	103.7±1.9	30.2±0.8	73.5±1.3	MBR

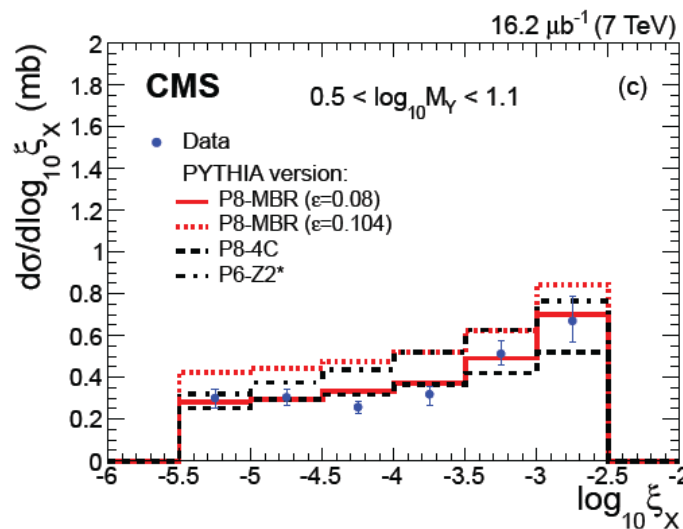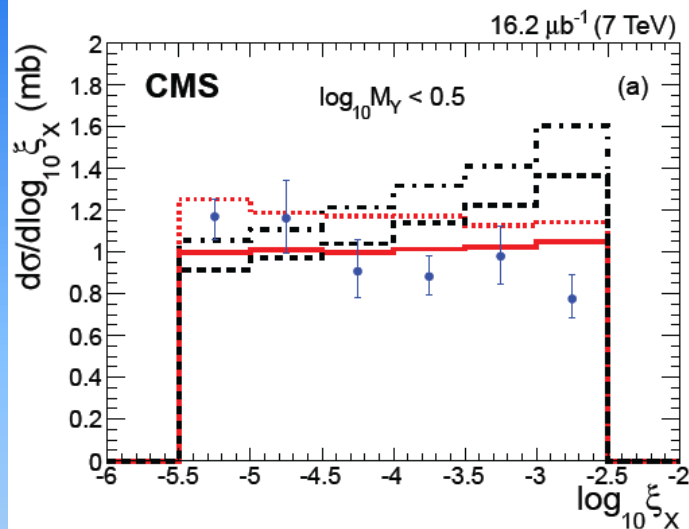# The CMS Detector

CD

DD

SD

ND
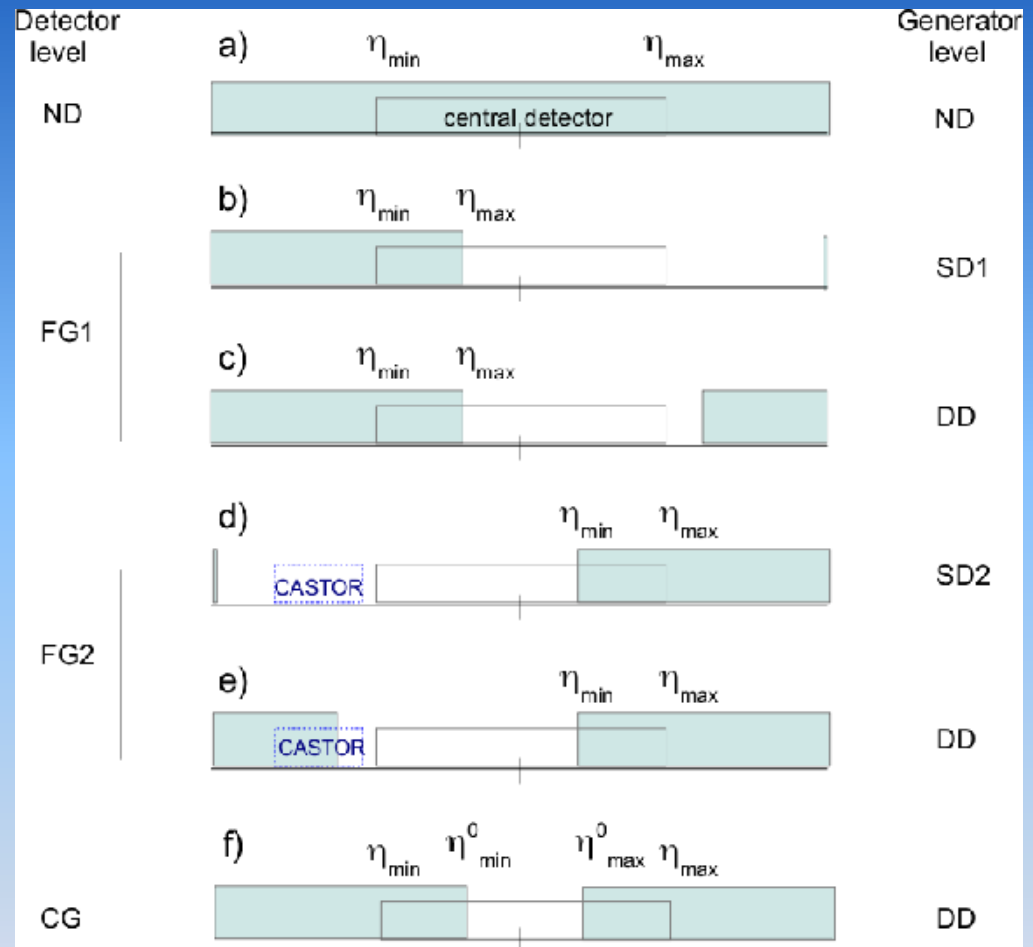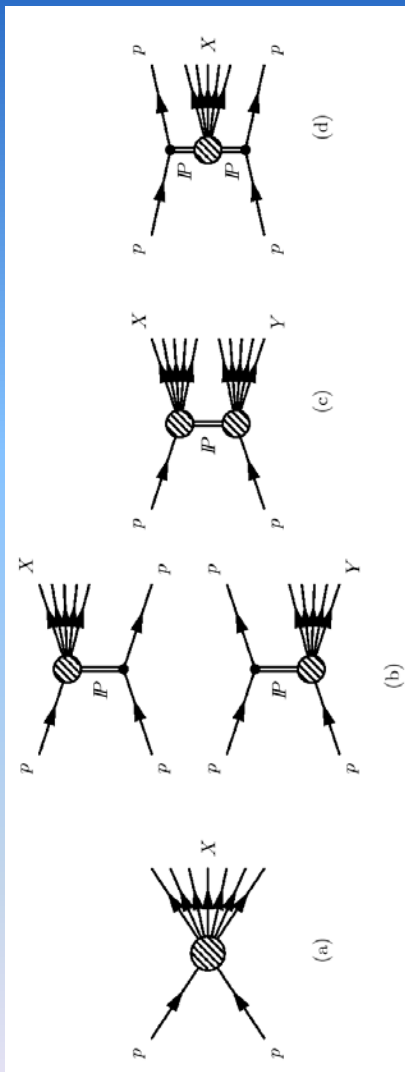
CASTOR forward calorimeter important for separating SD from DD contributions

CMS Data vs MC Models (2015)-1
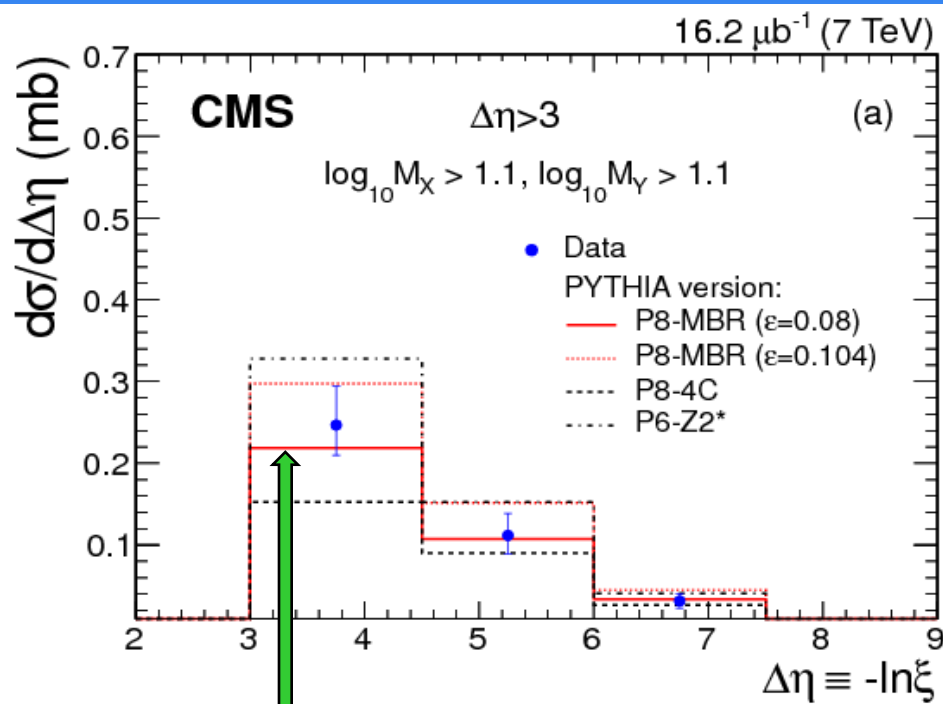
SD dominated data

DD dominated data
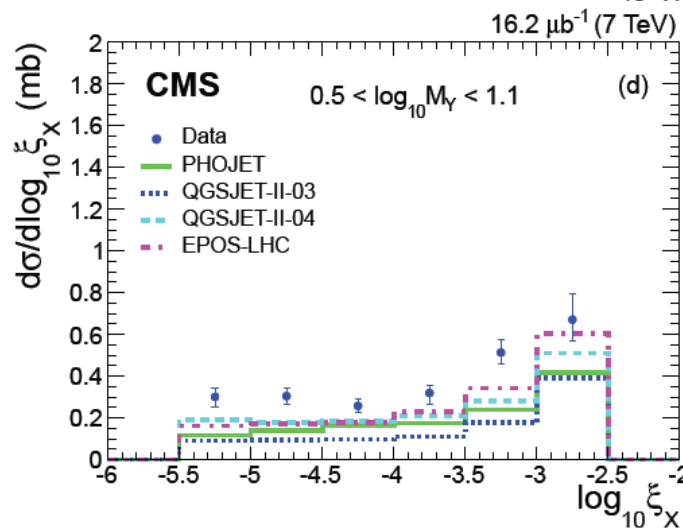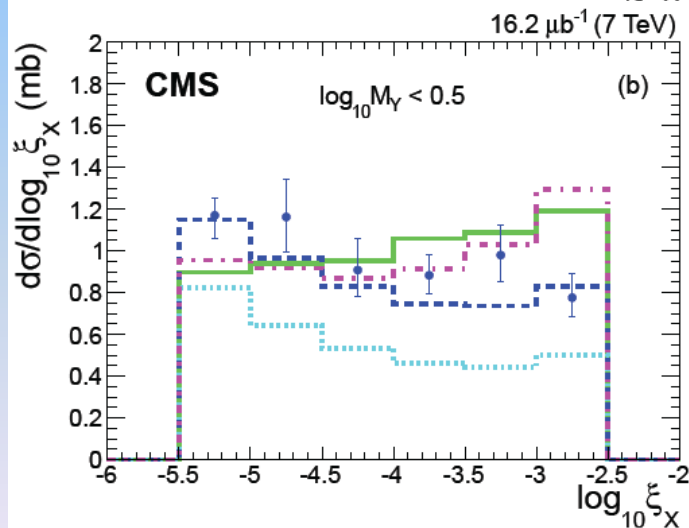
□ Error bars are dominated by systematics

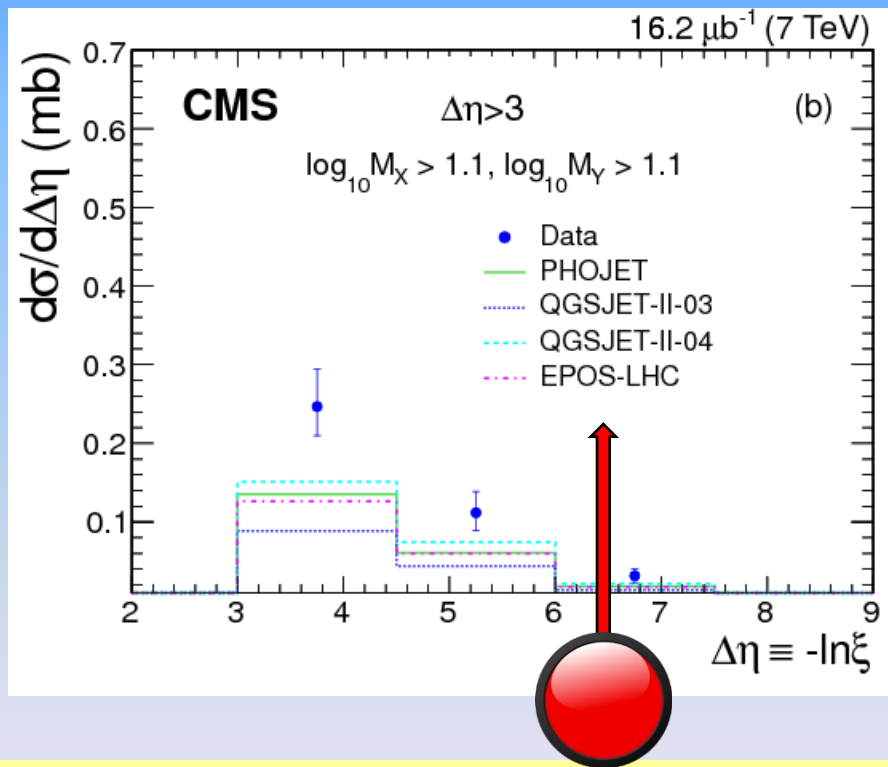□ DD data scaled downward by 15% (within MBR and CDF data errors)

PYTHIA8-MBR is the only model that describes well both the SD and DD data

CMS Data vs MC Models (2015) -2
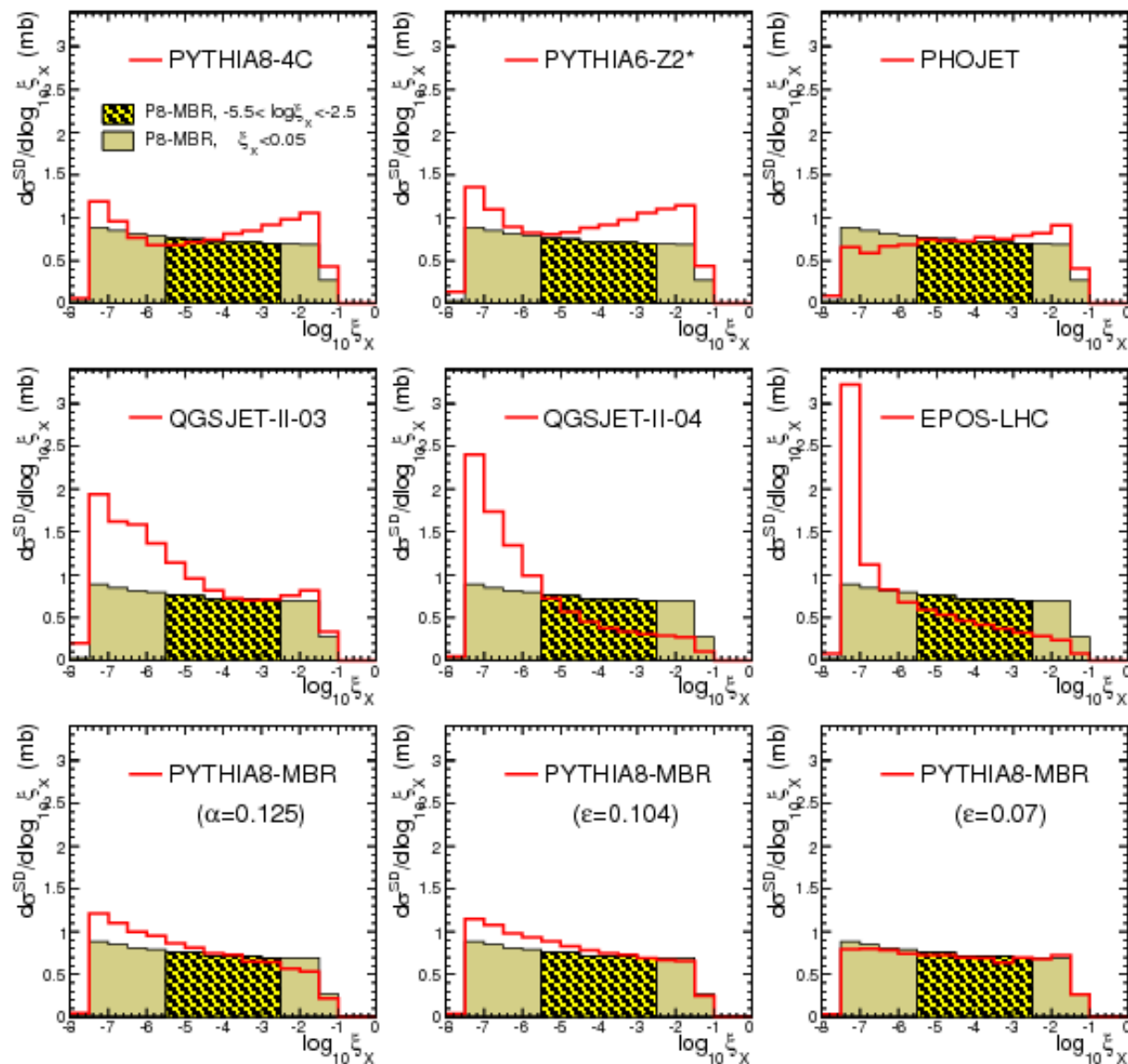
Central η-gap x-sections (DD dominated)

❑ P8-MBR provides the best fit to the data

❑ All other models too low at small $\Delta\eta$

- ❑ P8-MBR describes the normalization and shape of the CMS data and is used to extrapolate to the unmeasured regions to obtain σ^{SD} for $\xi < 0.05$
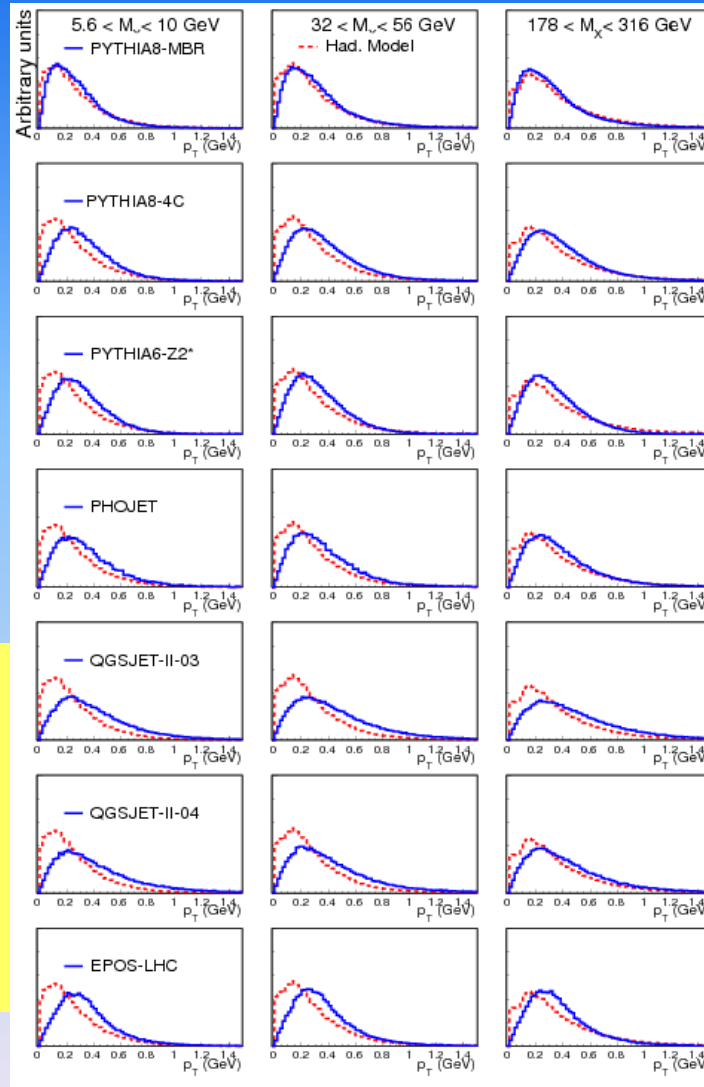
p_T Distr's of MCs vs Pythia8 Tuned to MBR

□ COLUMNS

Mass Regions
□ Low 5.5<MX<10 GeV
□ Med. 32<MX<56 GeV
□ High 176<MX<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

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

Diffractive data vs MGD

Mass Regions
- ☐ Low   5.5<MX<10 GeV
- ☐ Med. 32<MX<56 GeV
- ☐ High 176<MX<316 GeV

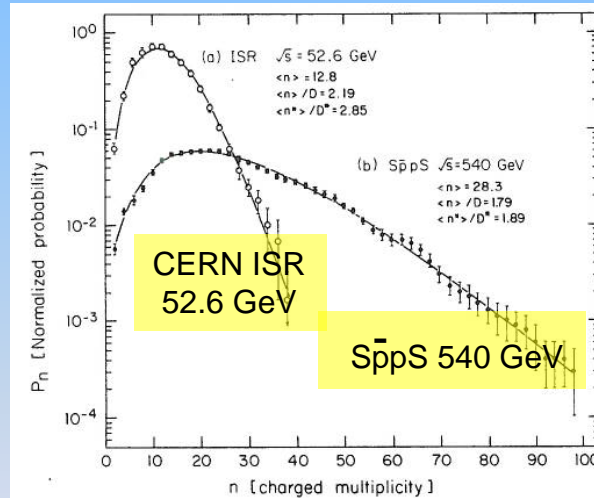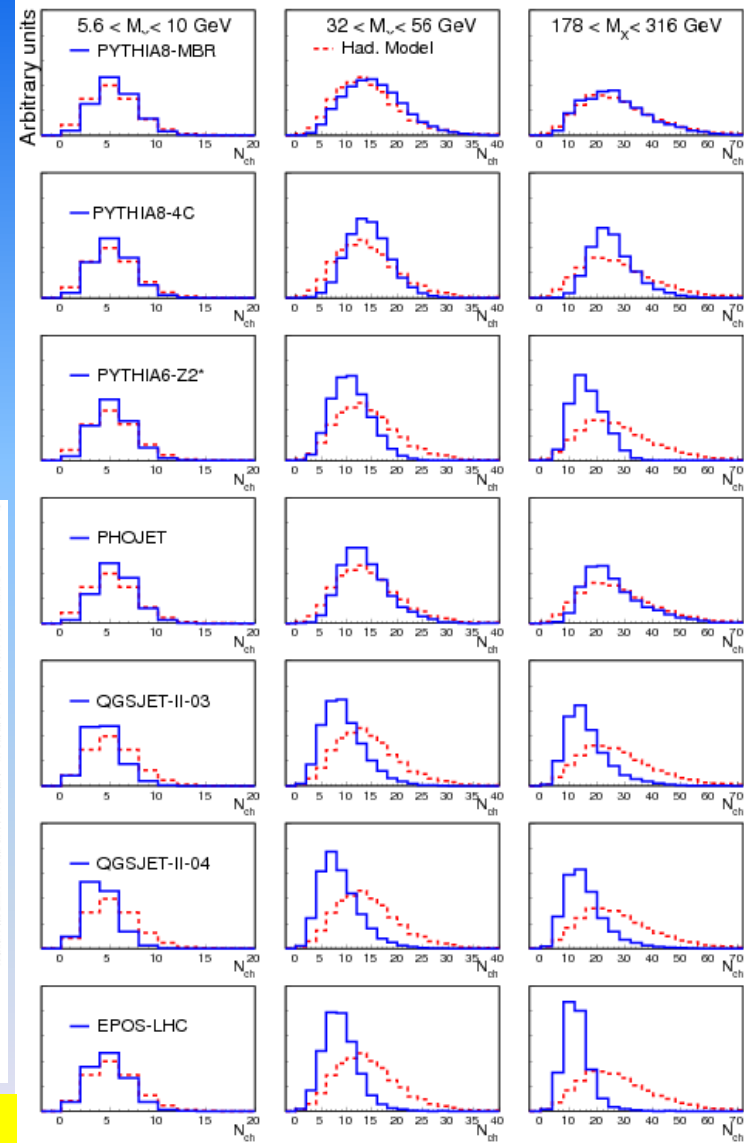CERN ISR 52.6 GeV

S$\bar{\text{p}}$pS 540 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.
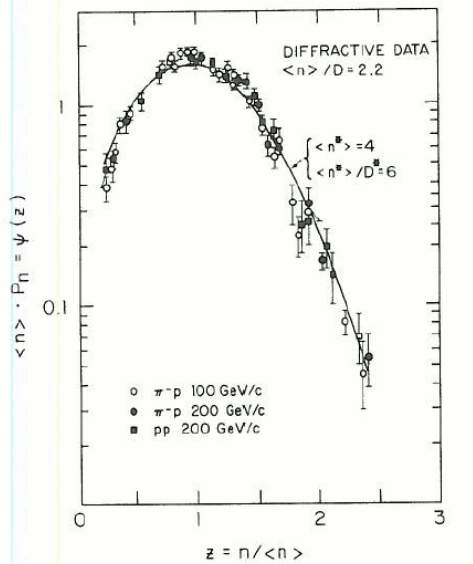
CERN ISR & S$\bar{\text{p}}$pS w/MGD fit
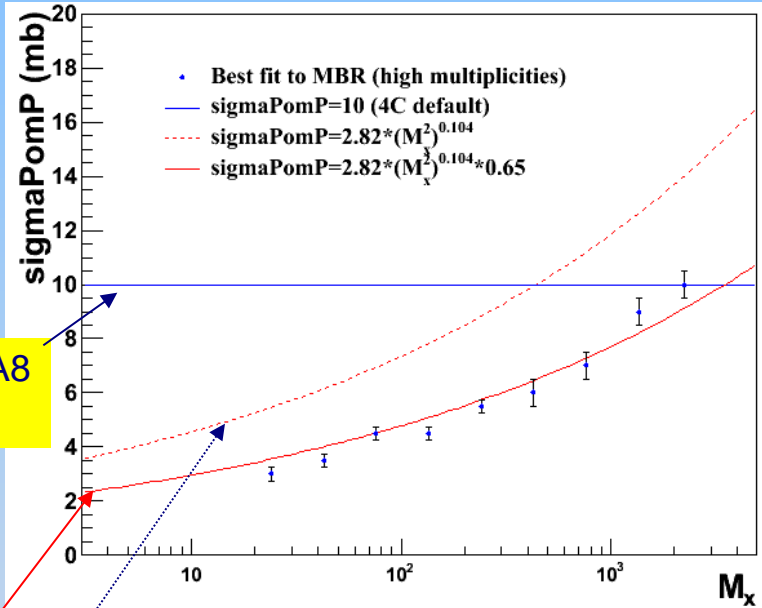

$0 < p_T < 1.4$ GeV

Pythia8-MBR Hadronization Tune

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

- Best fit to MBR (high multiplicities)
- sigmaPomP=10 (4C default)
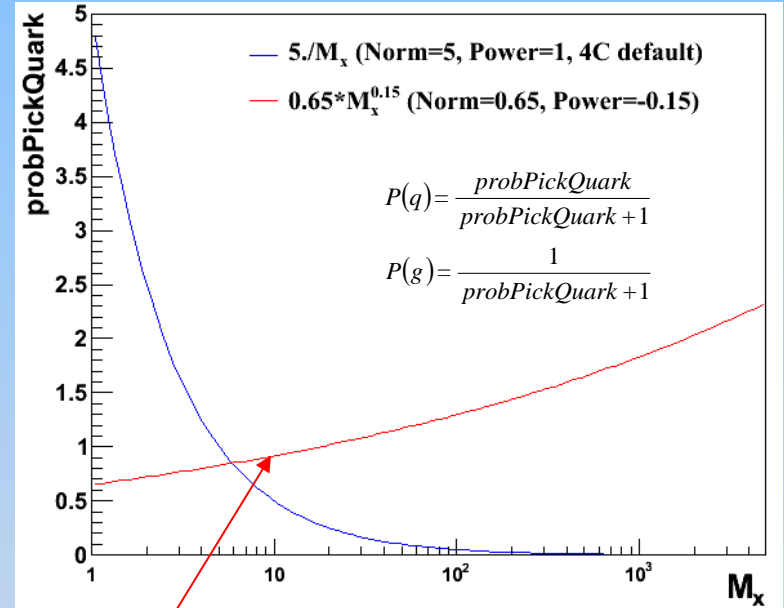- sigmaPomP=2.82*(M²)^0.104
- sigmaPomP=2.82*(M_x³)^0.104*0.65

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)
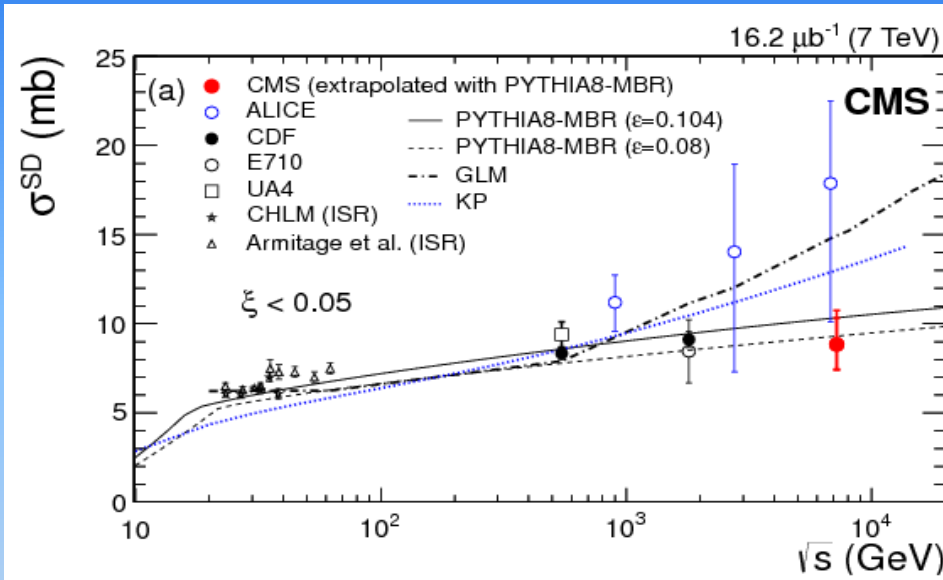
Diffraction: QuarkNorm/Power parameter

- 5./M_x (Norm=5, Power=1, 4C default)
- 0.65*M_x^0.15 (Norm=0.65, Power=-0.15)

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

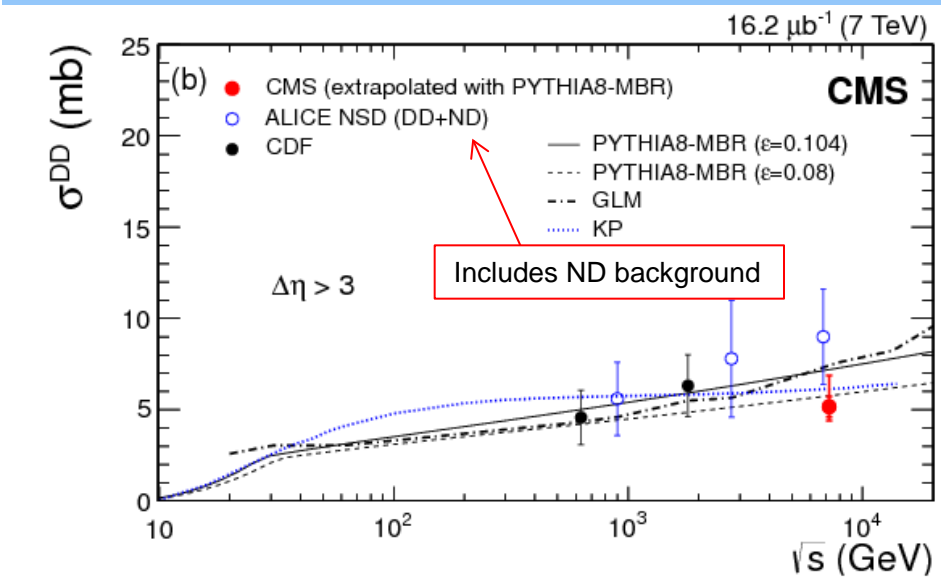$P(g) = \dfrac{1}{probPickQuark + 1}$

❑ good description of low multiplicity tails

SD and DD x-Sections vs Models

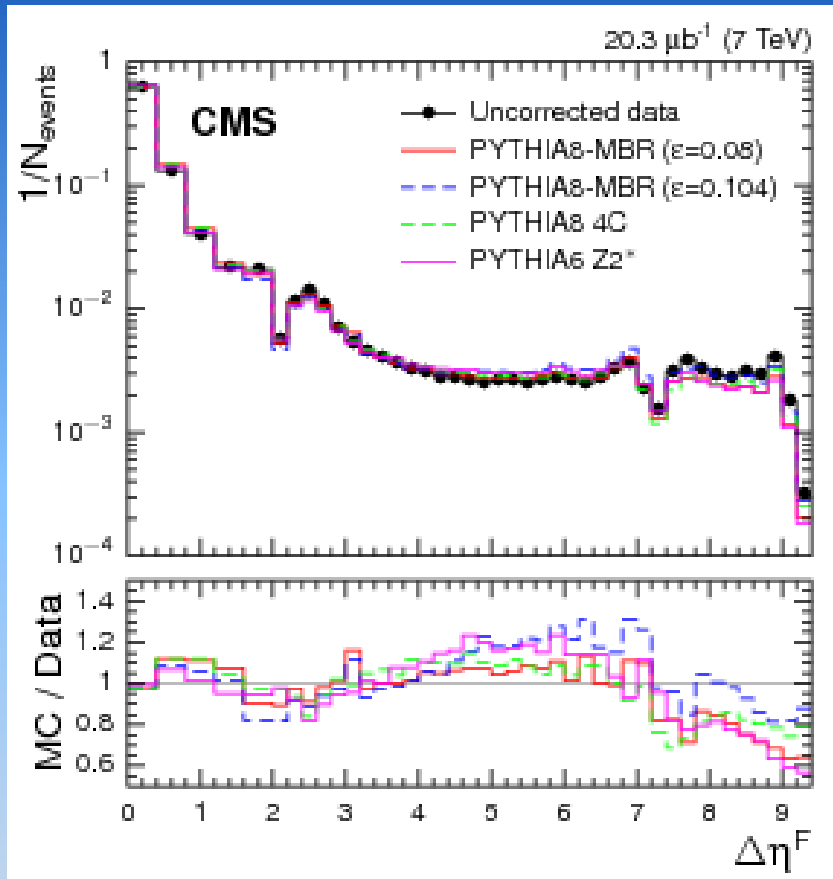Single Diffraction

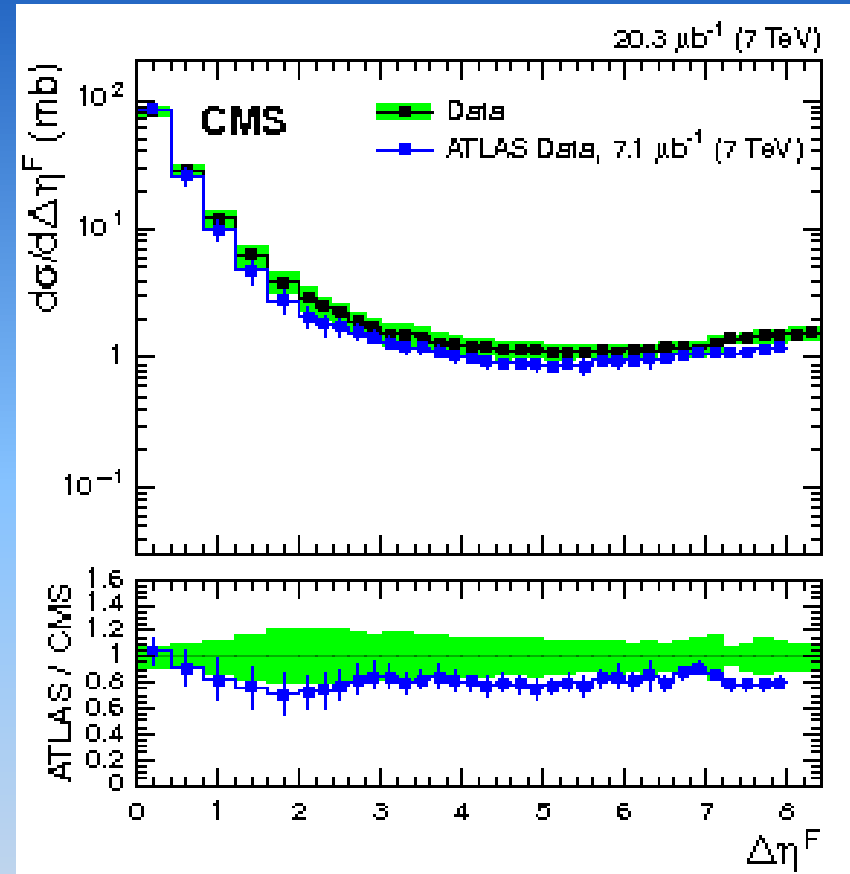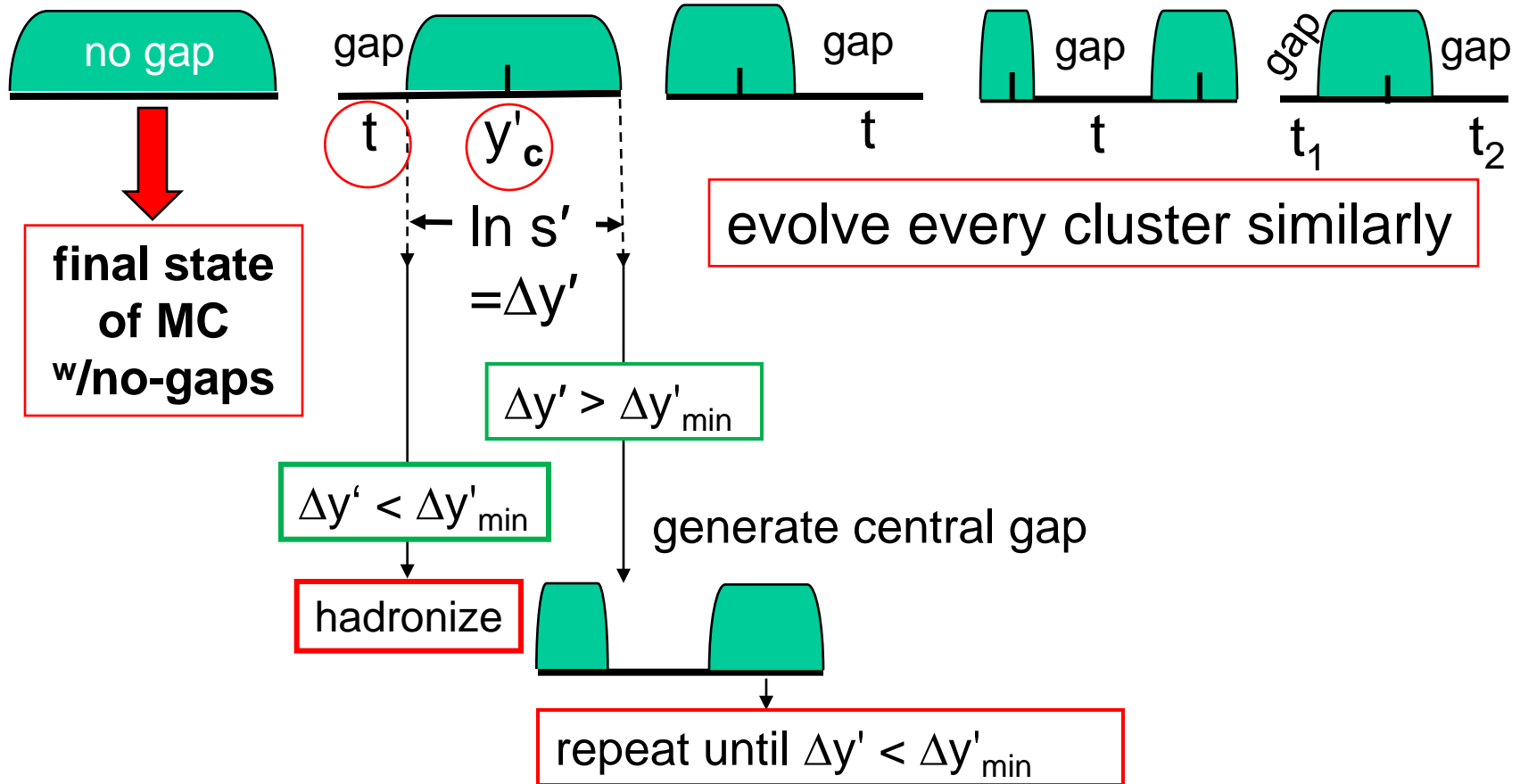Double Diffraction

CMS vs MC & ATLAS

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

Stable-particle x-sections for pT>200 MeV and |η|<4.7 compared to the ATLAS 2012 result similar result

Monte Carlo Algorithm - Nesting

Profile of a pp Inelastic Collision

no gap — t — y'_c — $\ln s' = \Delta y'$ — gap — gap — gap — gap — t_1 — t_2

evolve every cluster similarly

final state of MC ^{w}/no-gaps

$\Delta y' > \Delta y'_{min}$

$\Delta y' < \Delta y'_{min}$

hadronize

generate central gap

repeat until $\Delta y' < \Delta y'_{min}$

SUMMARY

❑ Introduction
❑ Review of RENORM predictions of diffractive physics
➢ basic processes: SD1,SD2, DD, CD (DPE)
  ➢ combined processes: multigap x-sections
  ➢ ND ➜ no diffractive gaps
      ❖ this is the only final state to be tuned
❑ Monte Carlo strategy for the LHC – "nesting"
❑ Updated RENORM parameters
  ➜ Good agreement with existing measurements
  ➜ Predictions of cross sections at 13 TeV

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

Thank you for your attention!