Precision RENORM / MBR Predictions for Diffraction at LHC

Konstantin Goulianos

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

Miami 2015

Precision **predictions?** *Wow!*

CONTENTS

☐ Diffraction
- ☐ SD1 $p_1p_2 \to p_1+gap+X_2$ Single Diffraction / Dissociation –1
- ☐ SD2 $p_1p_2 \to X_1+gap+p_2$ Single Diffraction / Dissociation - 2
- ☐ DD $p_1p_2 \to X_1+gap+X_2$ Double Diffraction / Double Dissociation
- ☐ CD/DPE $p_1p_2 \to gap+X+gap$ Central Diffraction / Double Pomeron Exchange

☐ Renormalization→Unitarization
- ➤ RENORM Model

☐ Triple-Pomeron Coupling: unambiguously determined

☐ Total Cross Section:
- ➤ Unique prediction based on saturation and a tensor glue ball approach

☐ <u>References</u>

➤ <u>Previous talks:</u>
- ➤ LHCFPWG 2015 Madrid (21-25 Apr 2015) **http://workshops.ift.uam-csic.es/LHCFPWG2015/program**
- ➤ EDS BLOIS 2015 Borgo, Corsica, France 29 Jun-4 Jul, https://indico.cern.ch/event/362991/

➤ MBR MC Simulation in PYTHIA8, KG & R. Ciesielski, **http://arxiv.org/abs/1205.1446**

BASIC

COMBINED

particles

rapidity distributions

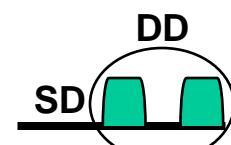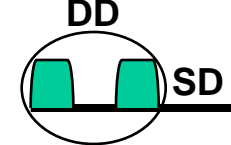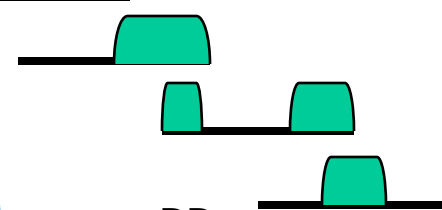| acronym	basic diffractive processes
$SD_{\bar{p}}$	$\bar{p}p \to \bar{p} + \text{gap} + [p \to X_p]$,
SD_p	$\bar{p}p \to [\bar{p} \to X_{\bar{p}}] + \text{gap} + p$,
DD	$\bar{p}p \to [\bar{p} \to X_{\bar{p}}] + \text{gap} + [p \to X_p]$,
DPE	$\bar{p}p \to \bar{p} + \text{gap} + X_c + \text{gap} + p$,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

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**

$\Delta\eta_1$ $\Delta\eta_1'$ $\Delta\eta_2$ $\Delta\eta_2'$ $\Delta\eta_3$ $\Delta\eta_3'$ $\Delta\eta_4$

η_1' η_2 η_2' η_3 η_3'

t_1 t_2 t_3 t_4
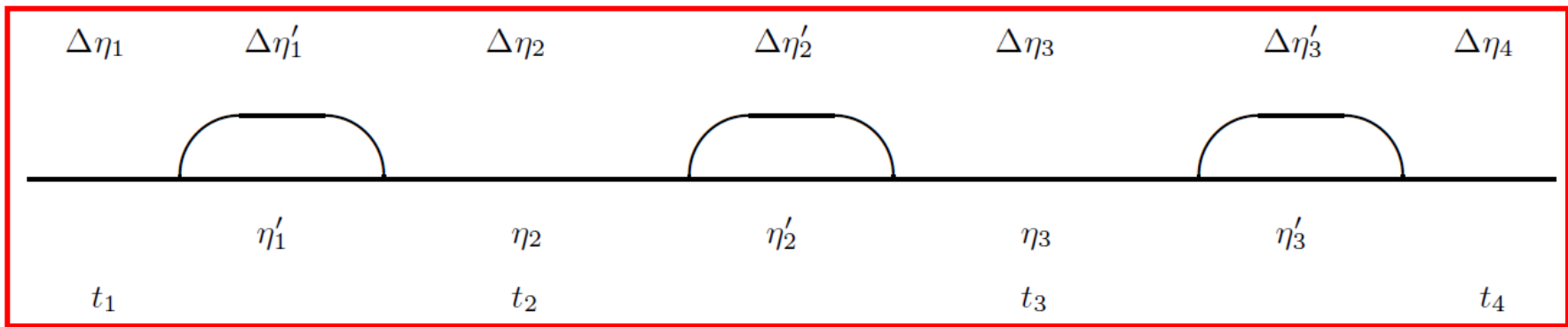
Regge Theory: Values of s_0 & g_{PPP}?

KG-PLB 358, 379 (1995)

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

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

TOTAL CROSS SECTION

$\beta(0)$
p
$\bar{p}$
$\beta(0)$
t=0

ELASTIC SCATTERING

$\beta(t)$
p
$\bar{p}$
$\beta(t)$
t

SINGLE DIFFRACTION DISSOCIATION

$$\left| \begin{array}{c} p \\ \bar{p} \end{array} \right|^2 = \begin{array}{c} p \\ \bar{p} \end{array}$$

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

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

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

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

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

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

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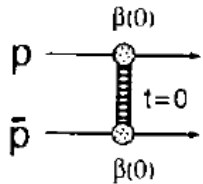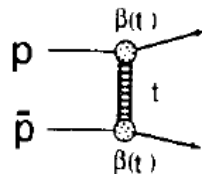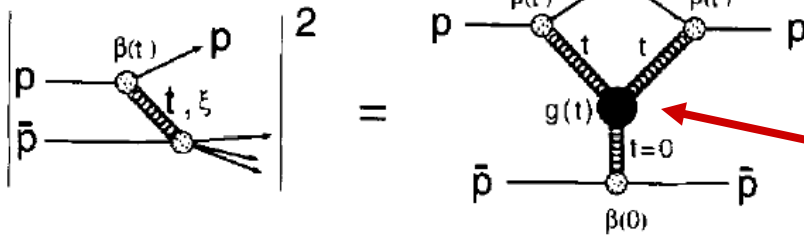
Parameters:

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

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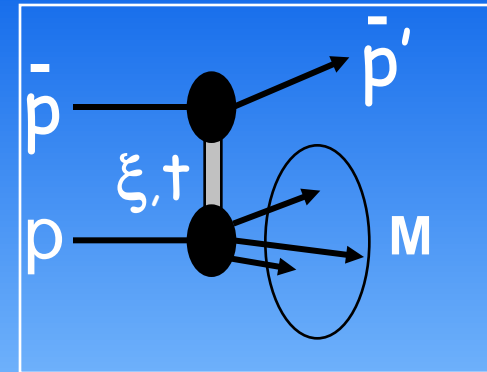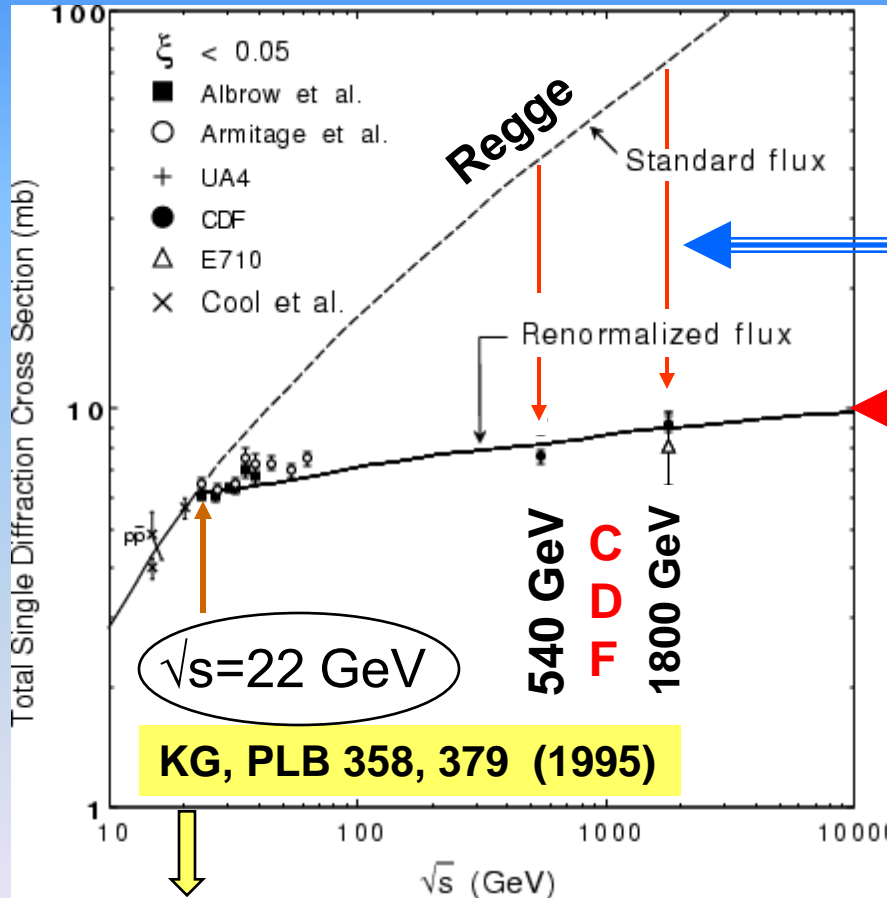(also true for partial x-sections in impact parameter space)

❑ the unitarity limit is already reached at √*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
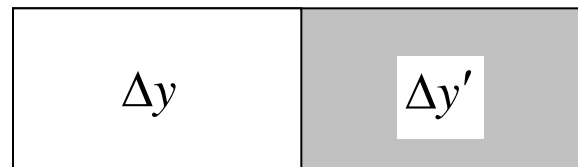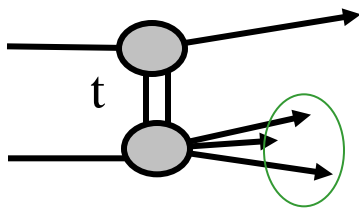

Factor of ~8 (~5) suppression at √s = 1800 (540) GeV

RENORMALIZATION

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

√s=22 GeV

KG, PLB 358, 379 (1995)

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

Single Diffraction Renormalized - 1

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

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

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

Single Diffraction Renormalized - 3

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

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

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

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

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

set to unity
➔ determines s_o

M² - Distribution: Data

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

Regge ➡ data

$$\frac{d\sigma}{dM^2} \propto \frac{s^{2\varepsilon} \rightarrow 1}{(M^2)^{1+\varepsilon}}$$
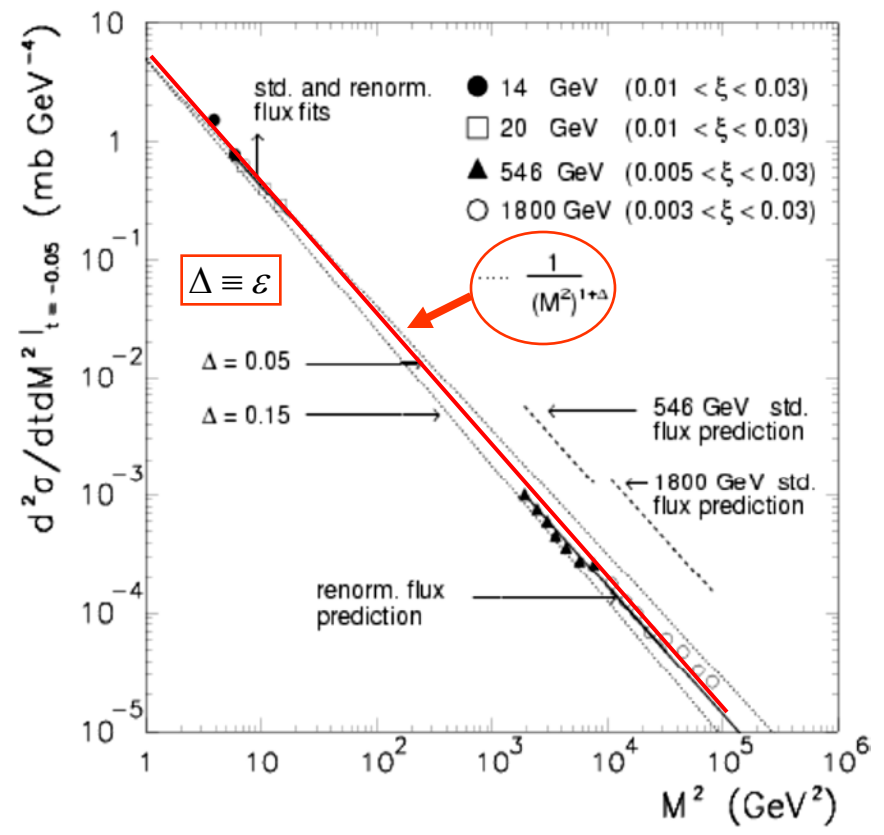
➡ factorization breaks down to ensure M² scaling

Scale s_0 and *PPP* Coupling

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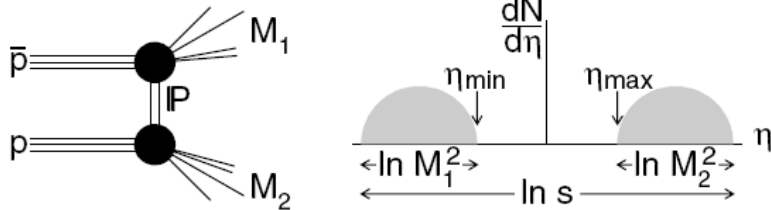→set to unity: determines g_{PPP} and s_0

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

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

$$s_o^{\varepsilon}$$

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

Pomeron-proton x-section

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

DD at CDF

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

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

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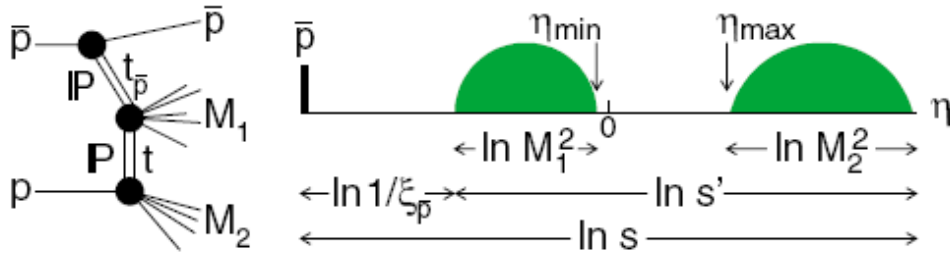
gap probability   x-section
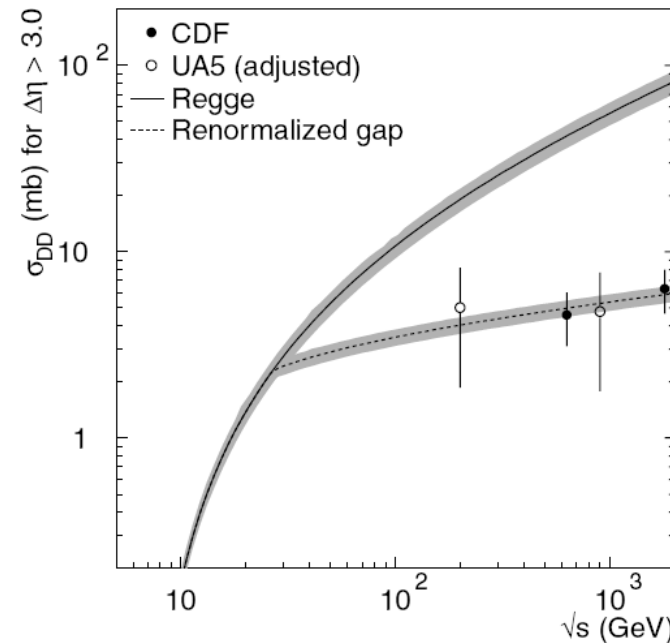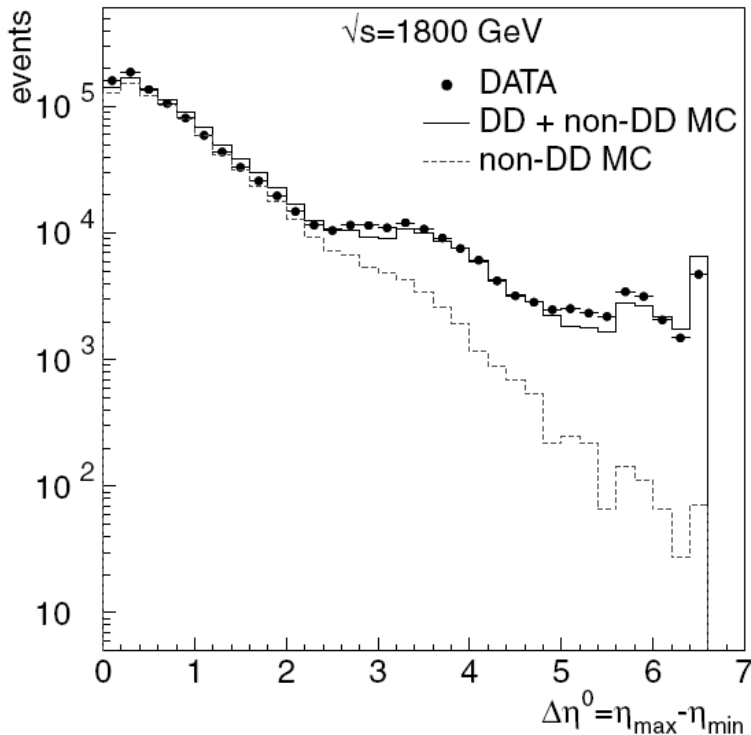
←**Regge**

←**Renor'd**

x-section divided by integrated gap prob.

SDD at CDF

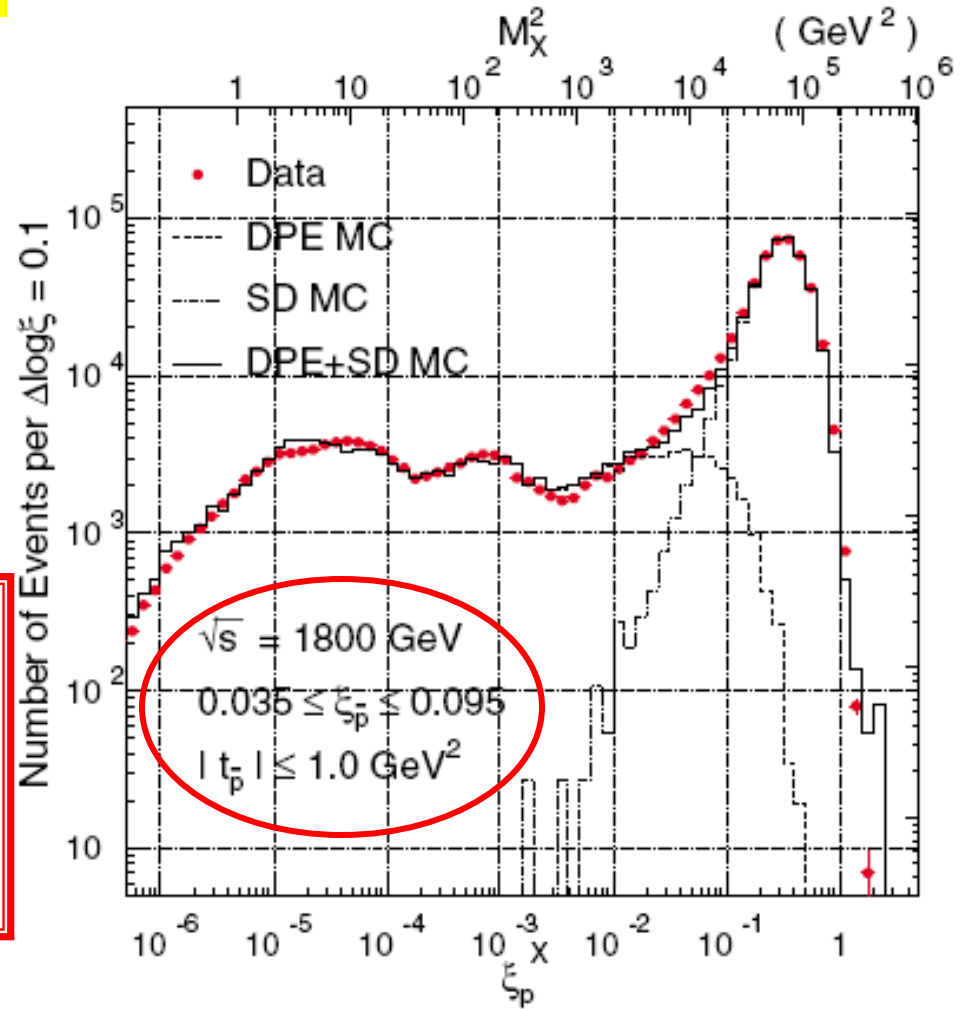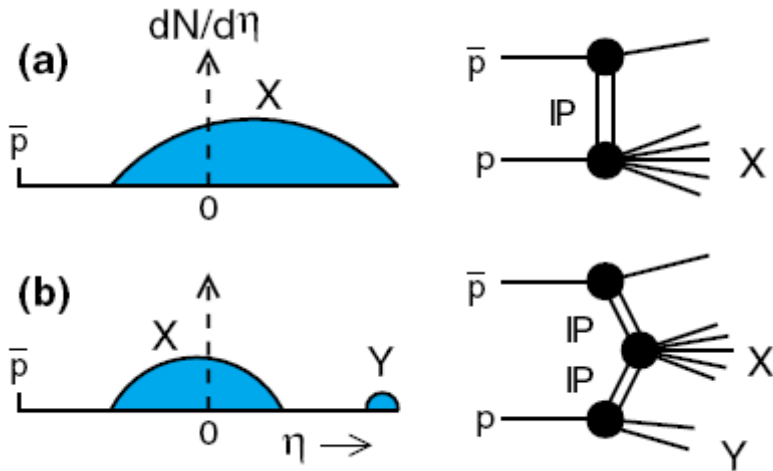http://physics.rockefeller.edu/publications.html

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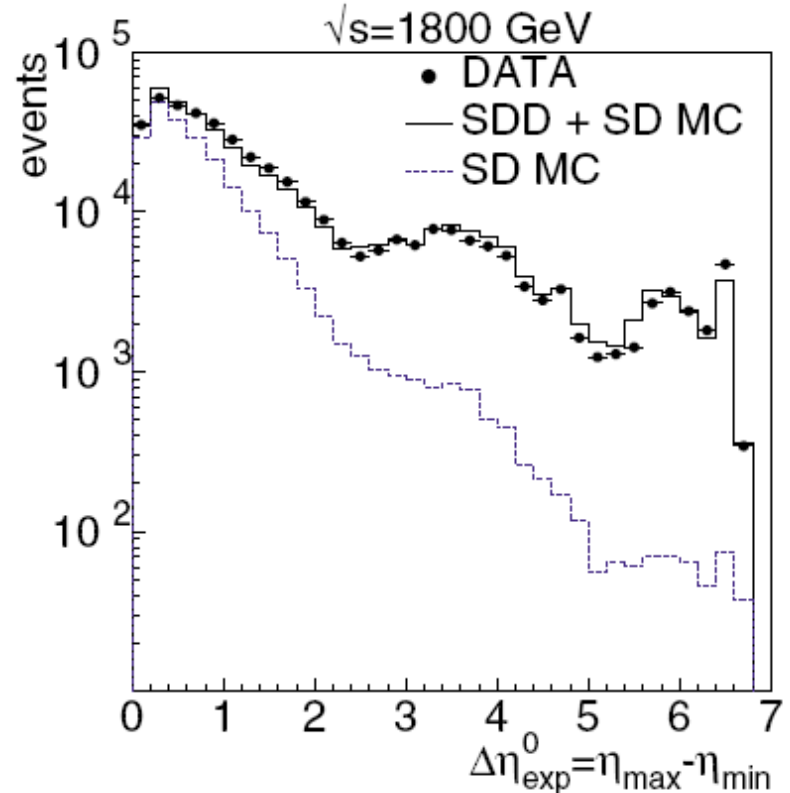
$$\frac{d^5\sigma}{dt_{\bar{p}}dt d\xi_{\bar{p}} d\Delta\eta d\eta_c} = \left[\frac{\beta(t)}{4\sqrt{\pi}} e^{[\alpha(t_{\bar{p}})-1]\ln(1/\xi)}\right]^2 \times \kappa\left\{\kappa\left[\frac{\beta(0)}{4\sqrt{\pi}} e^{[\alpha(t)-1]\Delta\eta}\right]^2 \kappa\left[\beta^2(0)\left(\frac{s''}{s_\circ}\right)^\epsilon\right]\right\}$$

CD/DPE at CDF

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

RENORM Diffractive Cross Sections

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

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

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

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

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

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, $\kappa\beta^2(0)$=σ_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

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

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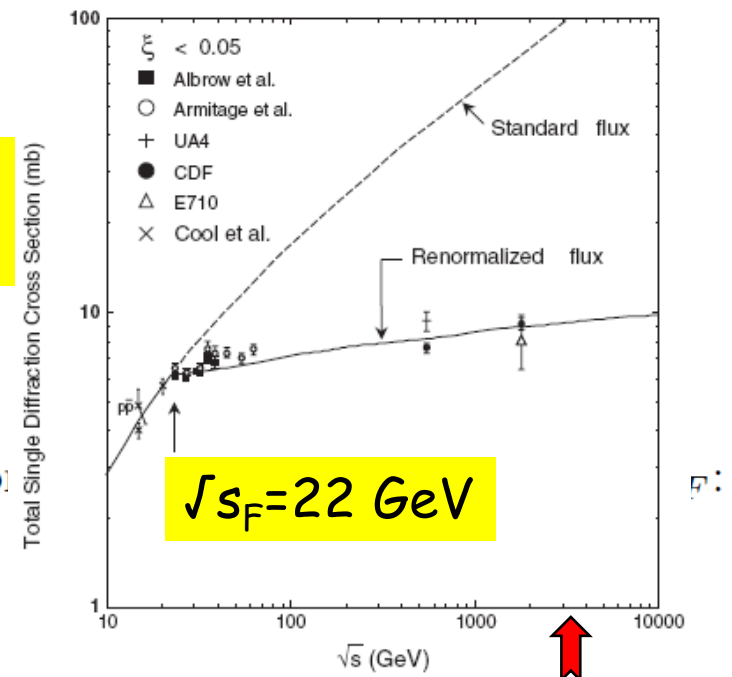
$$\sigma_t^{LHC} = \sigma_t^{CDF} + \frac{\pi}{s_o} \cdot \left(\ln^2 \frac{s^{LHC}}{s_F} - \ln^2 \frac{s^{CDF}}{s_F} \right)$$

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

Uncertainty is due to s_0

TOTEM (2012) vs PYTHIA8-MBR
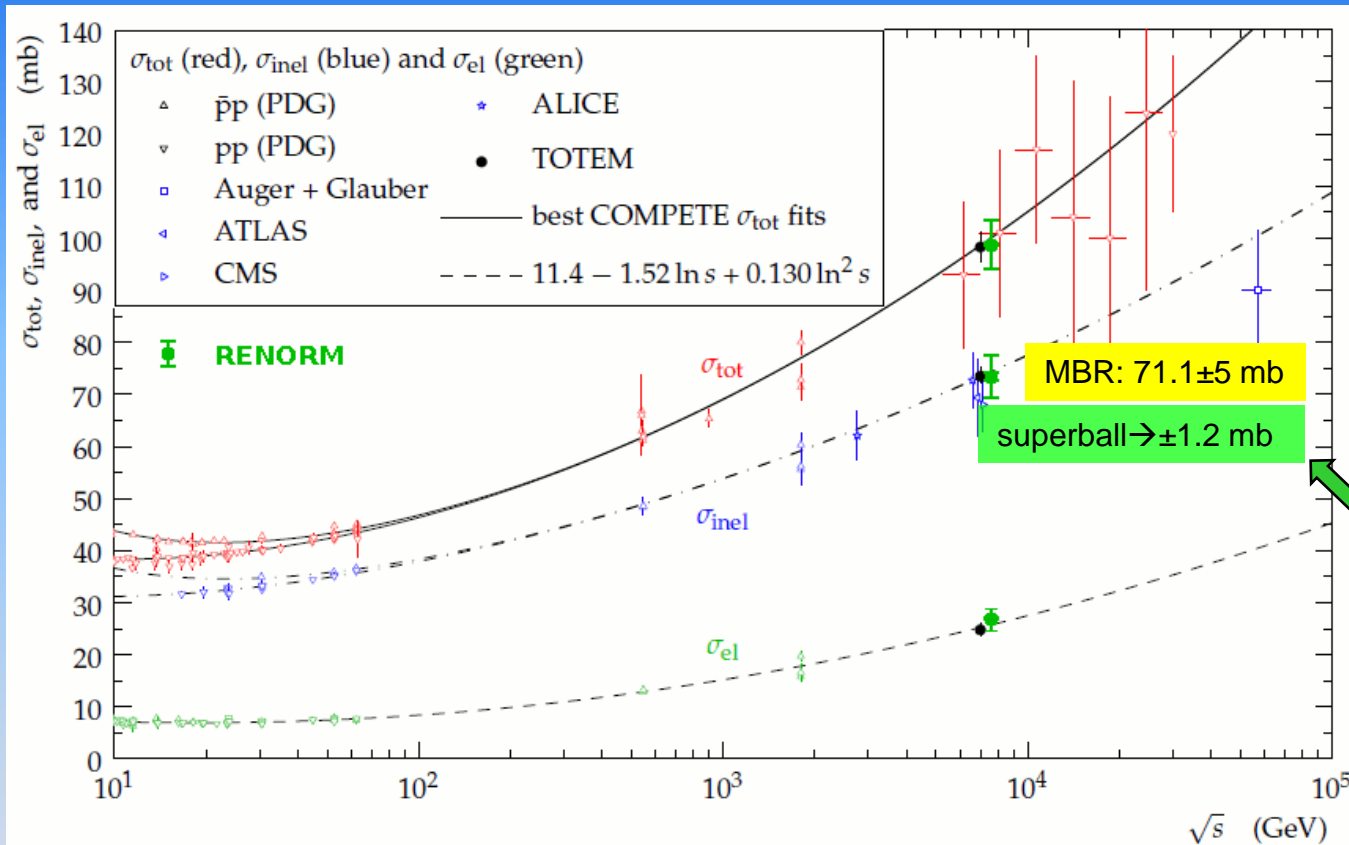
$\sigma_{inel}^{7\,TeV} = 72.9 \pm 1.5$ mb

$\sigma_{inel}^{8\,TeV} = 74.7 \pm 1.7$ mb
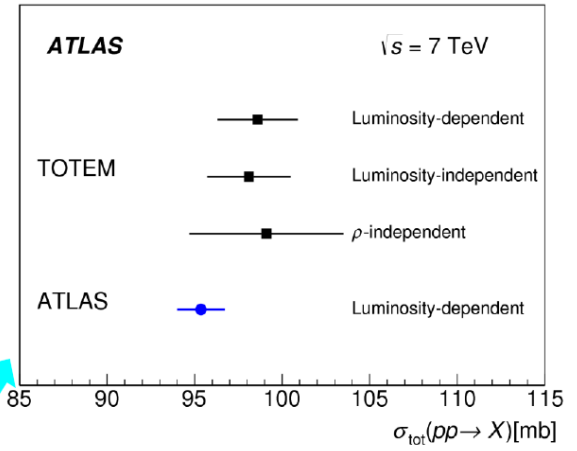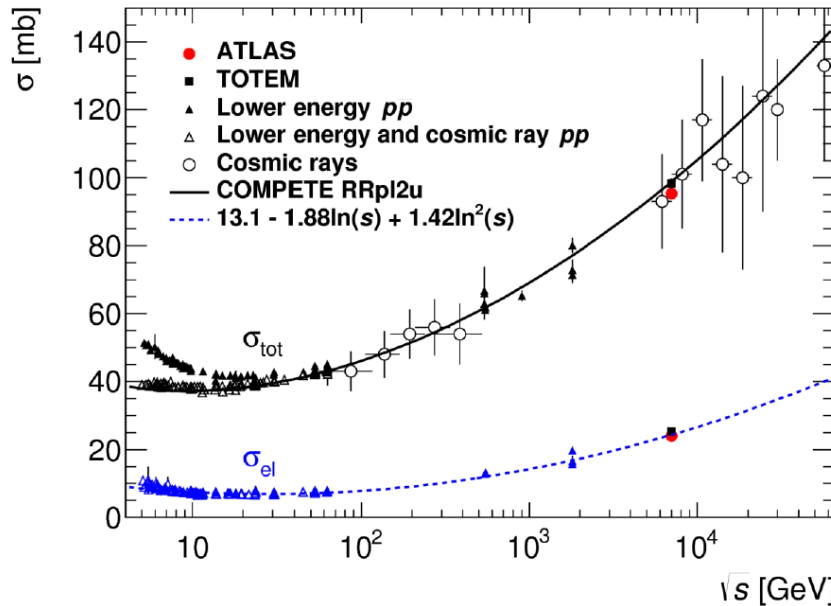
TOTEM, G. Latino talk at MPI@LHC, CERN 2012

RENORM: 71.1±1.2 mb

RENORM: 72.3±1.2 mb

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

Comparison with previous measurements

RENORM: 98.0±1.2 mb

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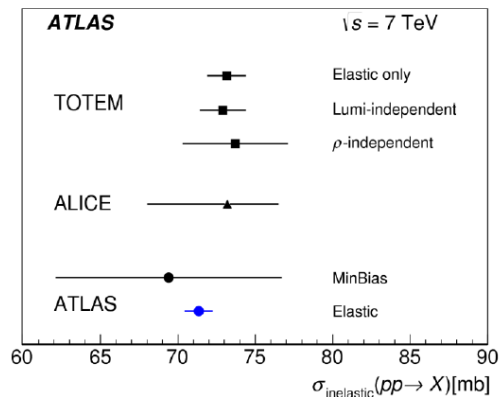
σ_{inel}:
ALFA significantly improves precision of the previous ATLAS σ_{inel} measurement

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Reduce Uncertainty in s_0

2015

Exclusive $\pi^+\pi^-$

$|S|^2$
$|D|^2$
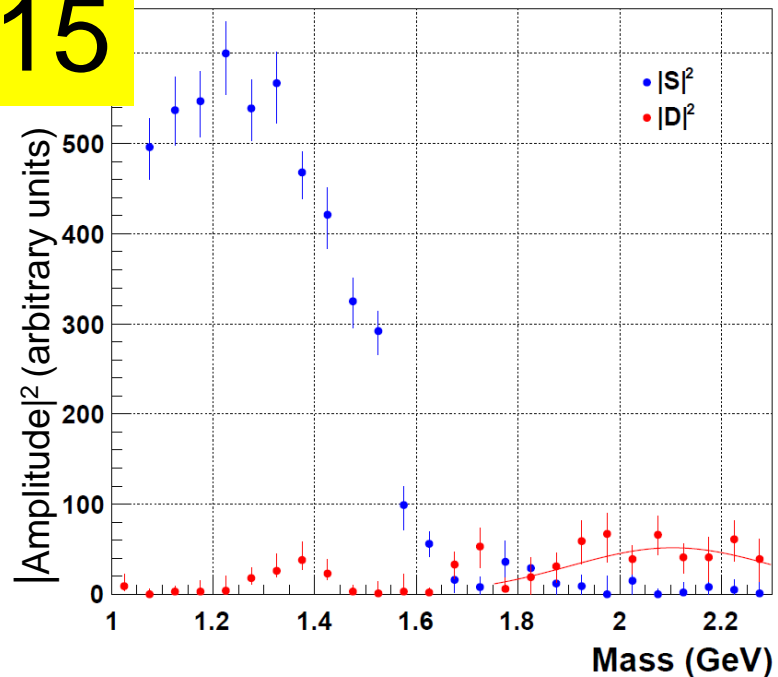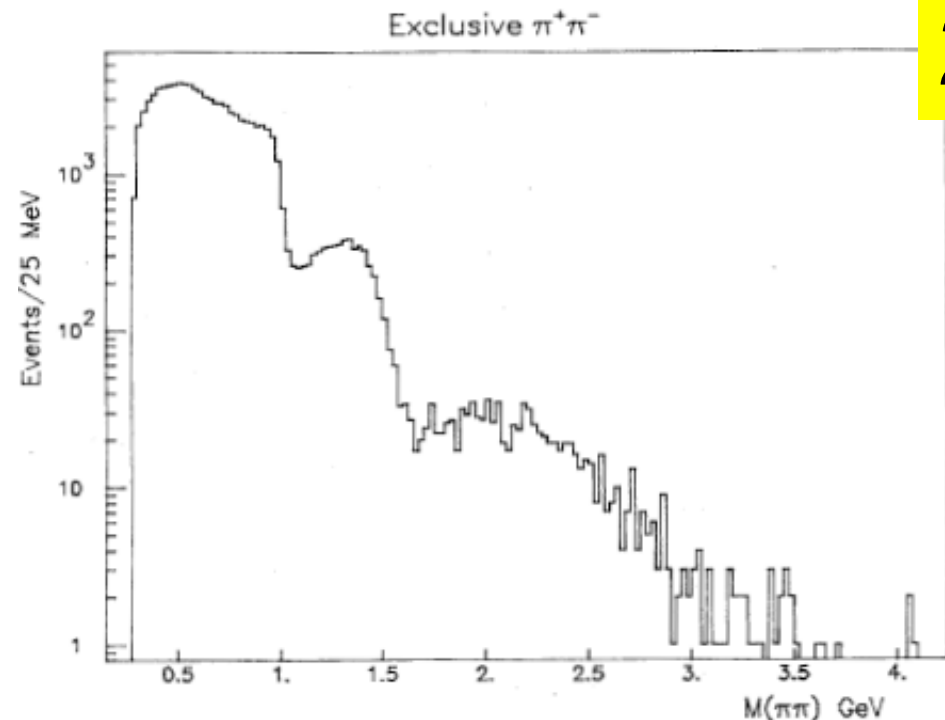
Review of CEP by Albrow, Coughlin, Forshaw http://arxiv.org/abs/1006.1289
Fig. from **Axial Field Spectrometer** at the CERN Intersecting Storage Rings

Data: Peter C. Cesil, AFS 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

Reduced Uncertainty in s_0

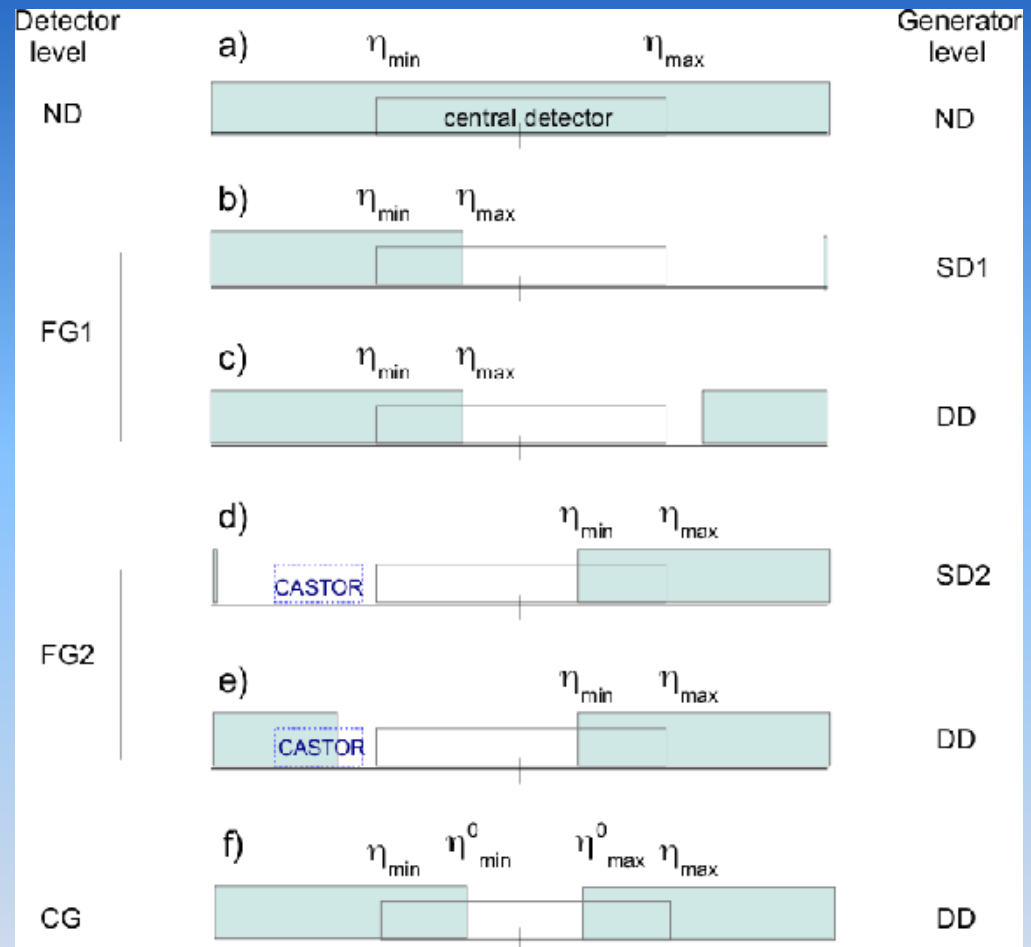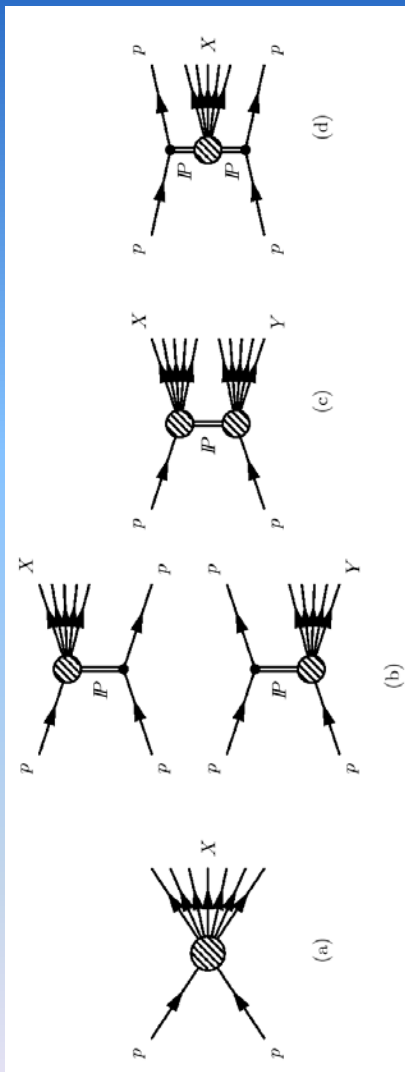| Energy	Total	Elastic	Inelastic	MBR Exp
7 TeV	95.4±1.2	26.4±0.3	69.0±1.0	MBR
	98.4±2.2		73.7±3.4	TOTEM
	95.35±1.36	24.00±0.60	71.34±0.90	ATLAS
				CMS
8 TeV	97.1±1.4	27.2±0.4	69.9±1.0	MBR
	101.7±2.9	27.1±1.4	74.7±1.7	TOTEM
			73. 1±0.9±0.9syst±3.3extr (this conference)	ATLAS
				CMS
13 TeV	103.7±1.9	30.2±0.8	73.5±1.3	MBR

The CMS Detector

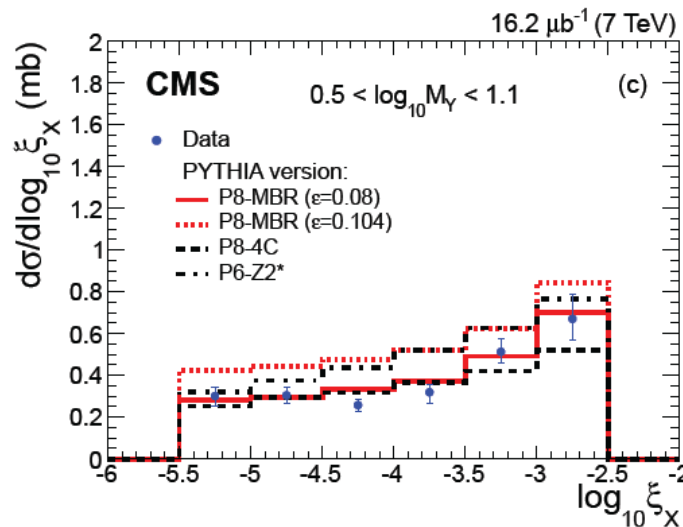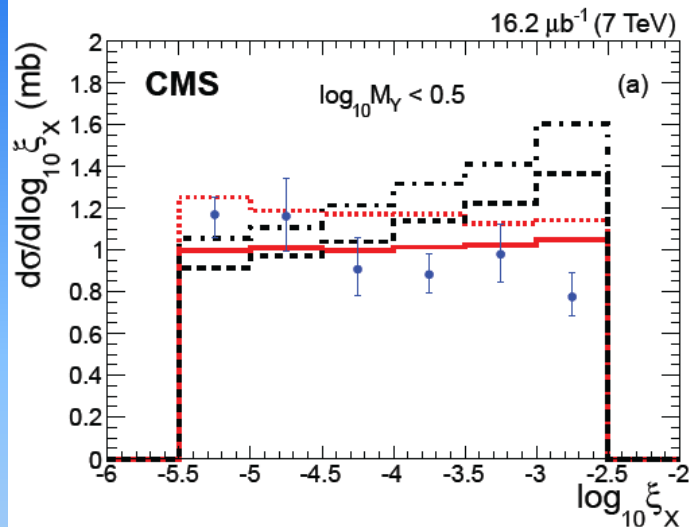

CD

DD

SD

ND

CASTOR forward calorimeter: important for separating SD from DD contributions

CMS Data vs MC Models (2015)-1
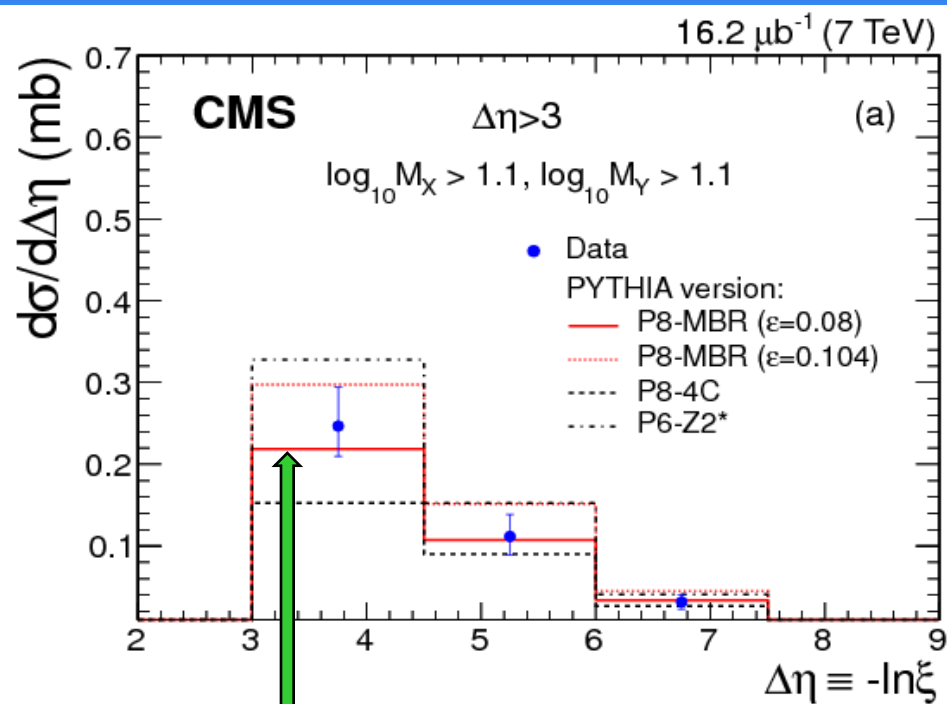
SD dominated data   DD dominated data
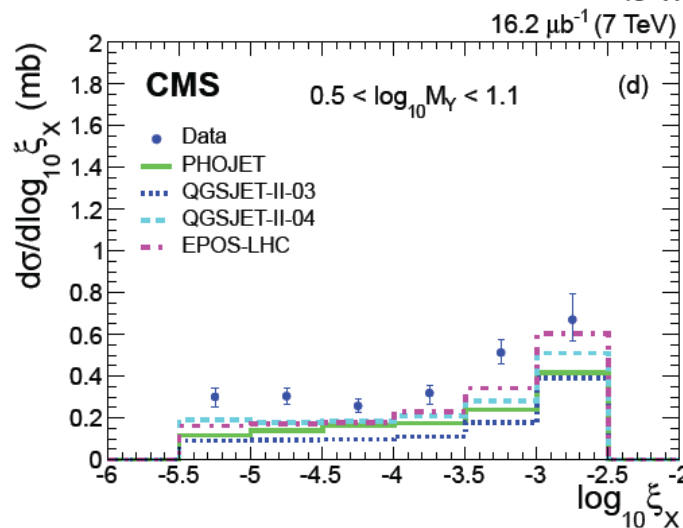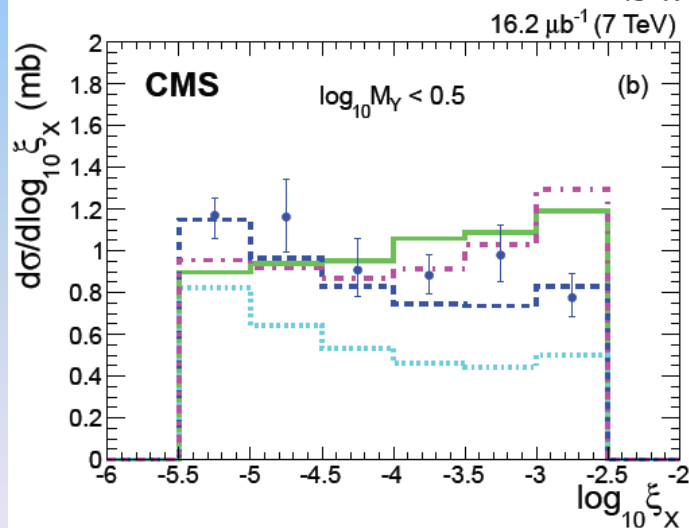
☐ Error bars are dominated by systematics

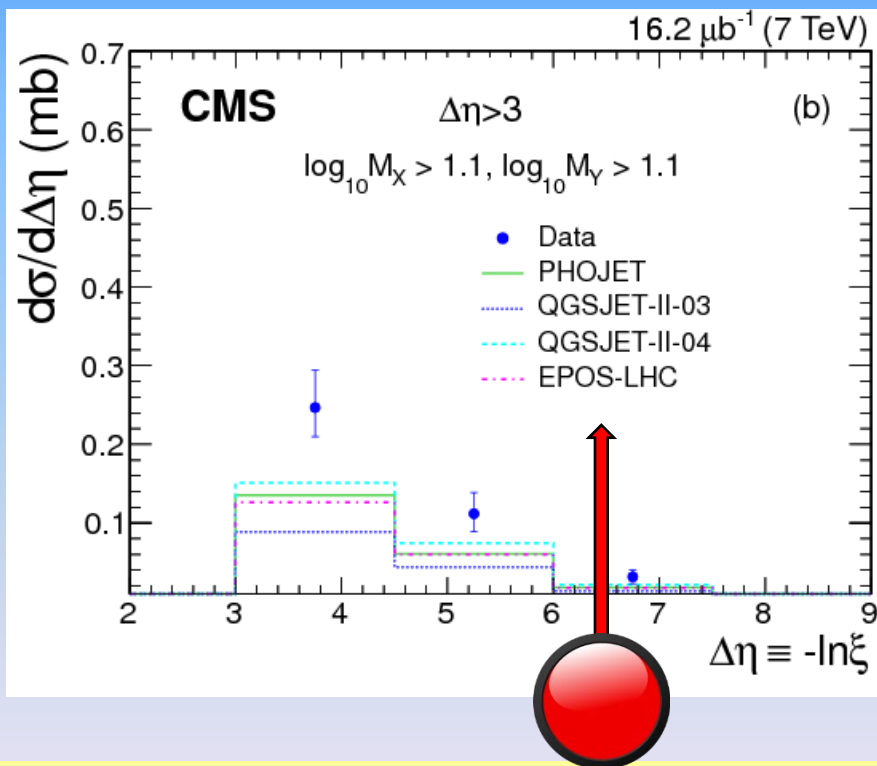☐ DD data scaled downward by 15% (within MBR and CDF data errors)

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

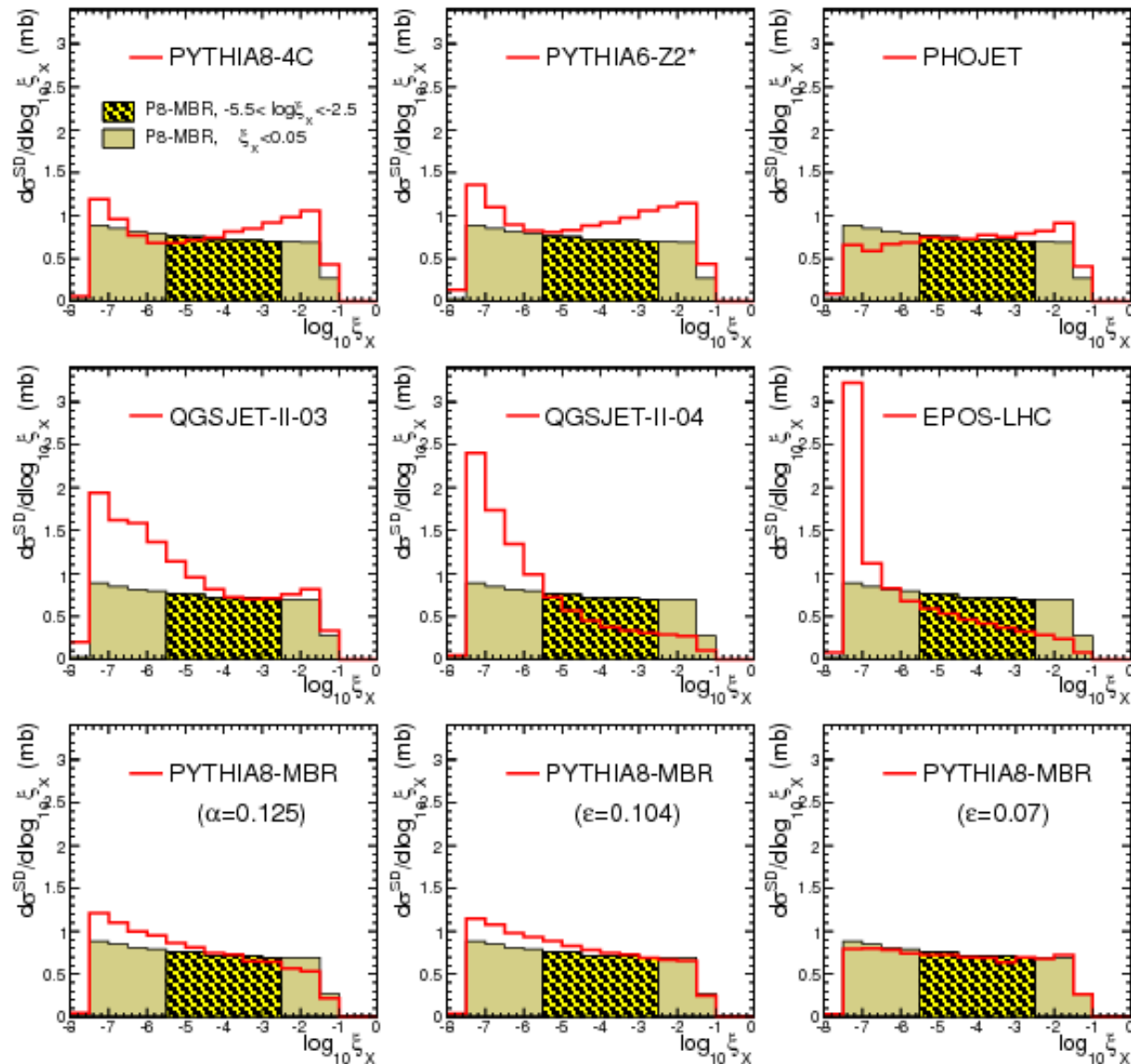# CMS Data vs MC Models (2015) -2

Central η-gap x-sections (DD dominated)

❑ P8-MBR provides the best fit to the data

❑ All other models too low at small Δη

SD Extrapolation to $\xi_x \leq 0.05$ vs MC Model

☐ 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 $\xi<0.05$
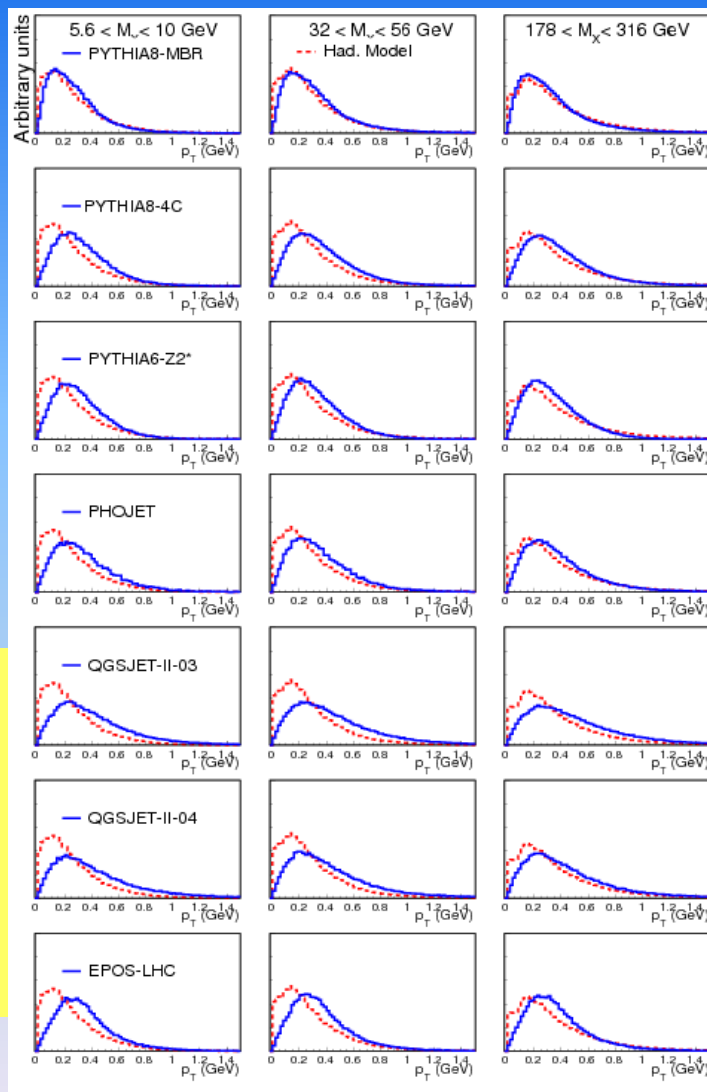
p$_T$ Distr's of MCs vs Pythia8 Tuned to MBR

❑ COLUMNS

<u>Mass Regions</u>
❑ 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

<u>MC Models</u>
❑ 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

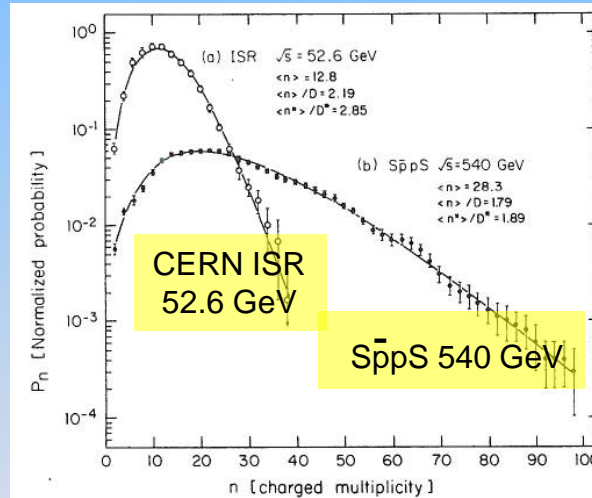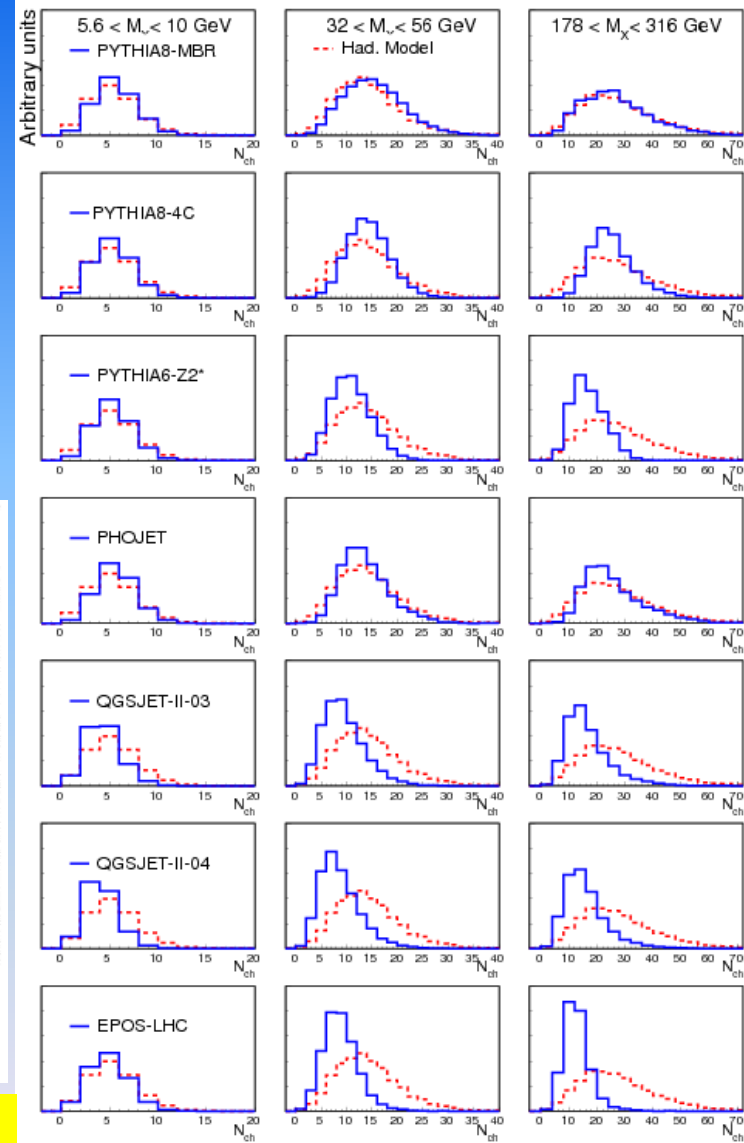CERN ISR 52.6 GeV

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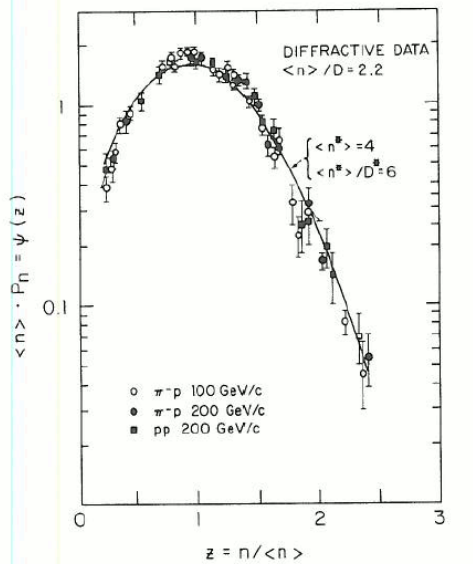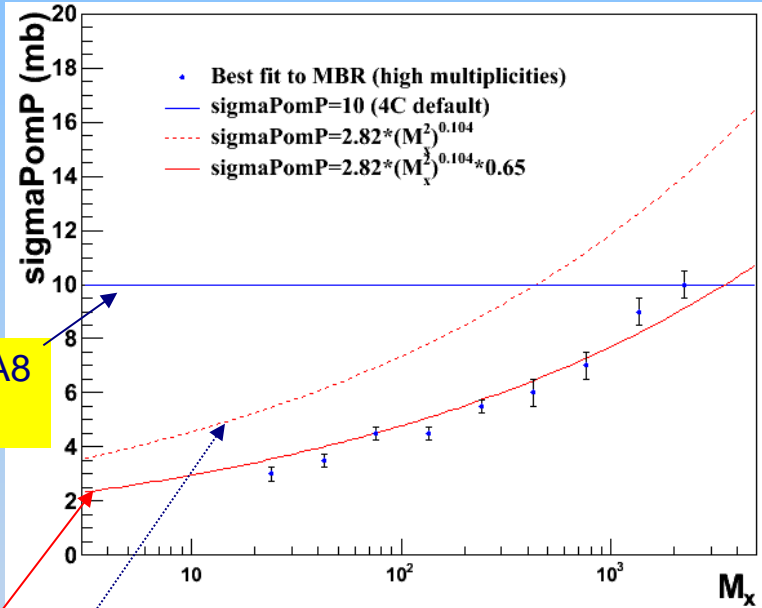
CERN ISR & S$\bar{p}$pS w/MGD fit

$0 < p_T < 1.4$ 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)
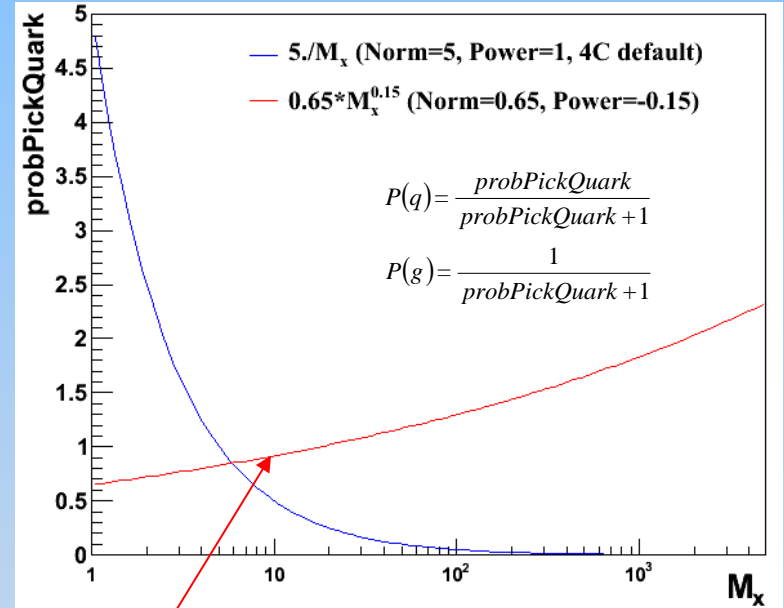sigmaPomP=2.82*$(M^2)^{0.104}$
sigmaPomP=2.82*$(M_x^2)^{0.104}$*0.65

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)
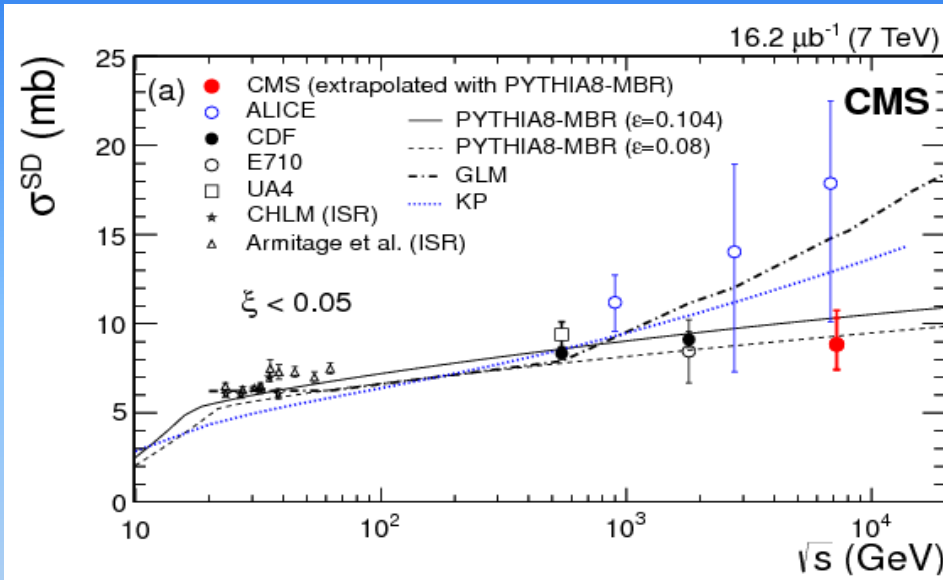
Diffraction: QuarkNorm/Power parameter

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

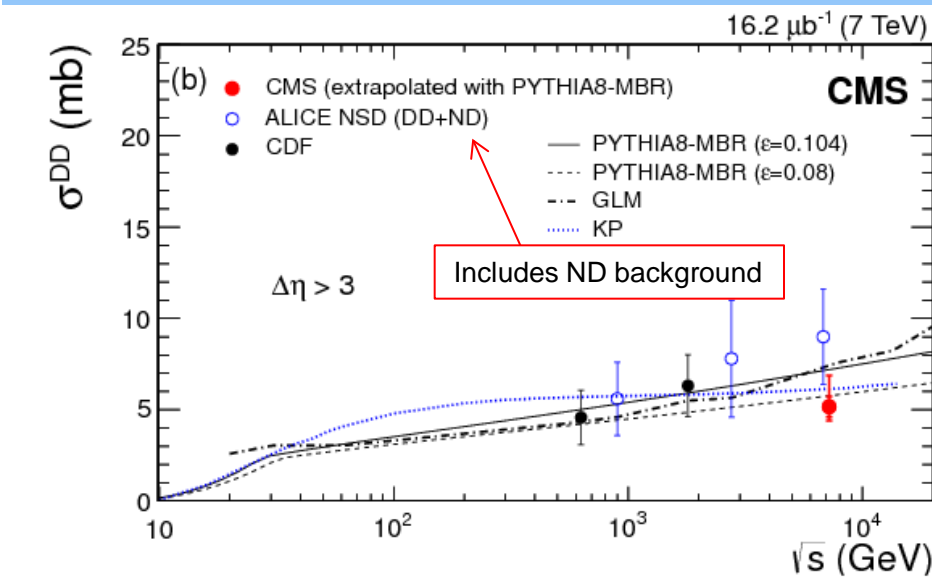$$P(q) = \frac{probPickQuark}{probPickQuark + 1}$$

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

❑ good description of low multiplicity tails

SD and DD x-Sections vs Models

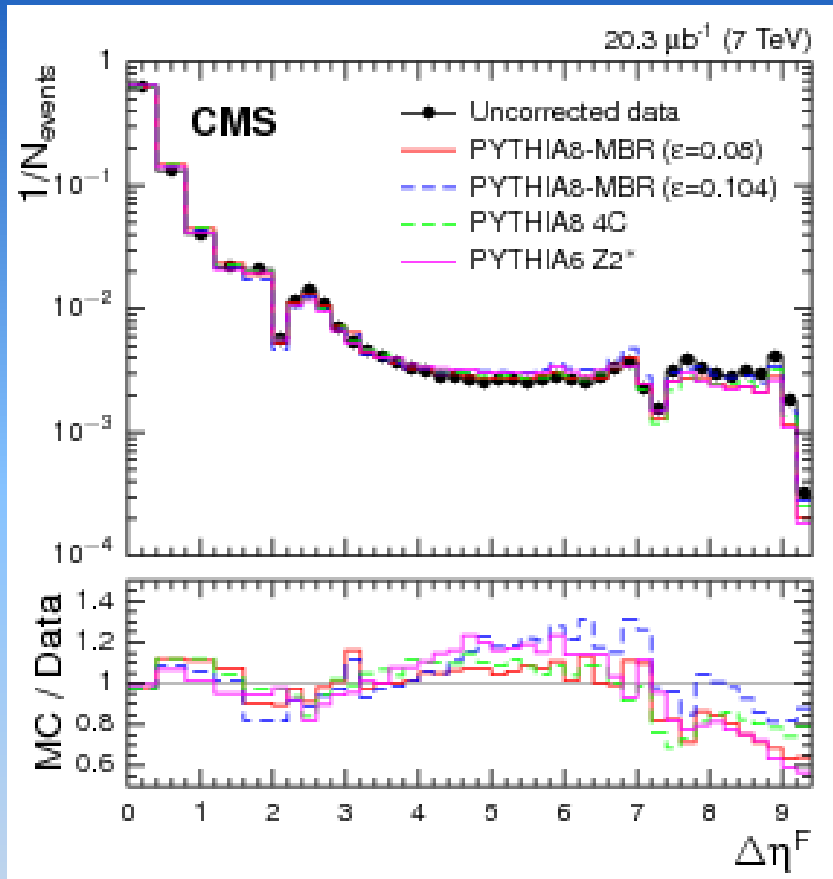Single Diffraction

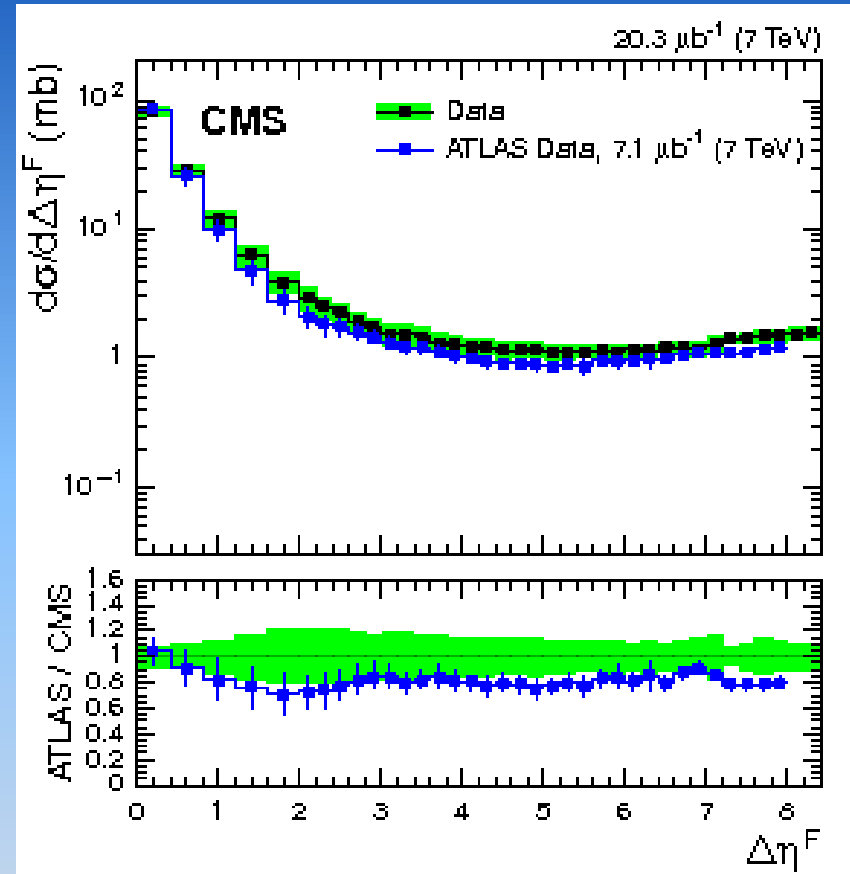Double Diffraction

Includes ND background

CMS vs MC & ATLAS

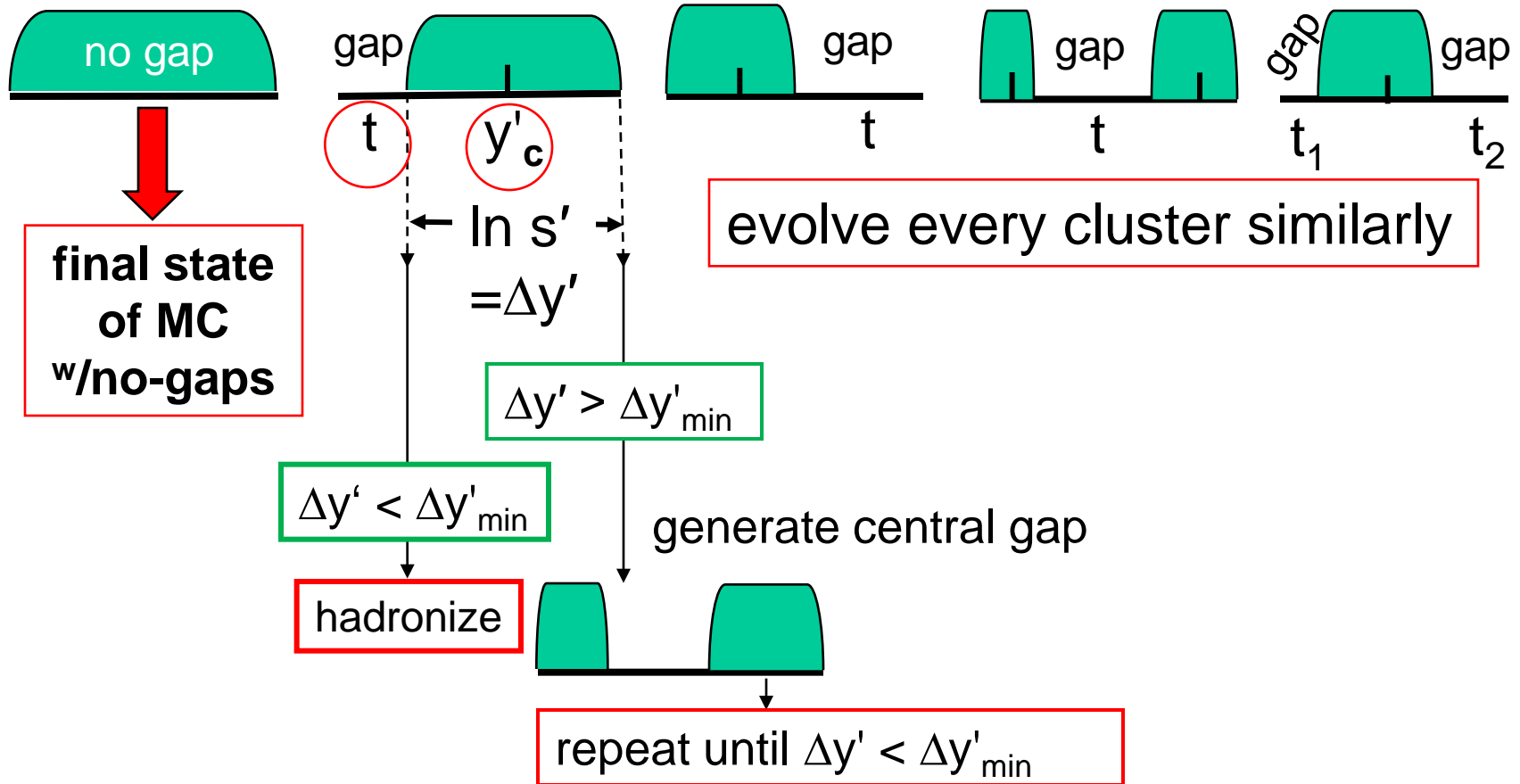

Uncorrected $\Delta\eta^F$ distribution vs MCs

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

Monte Carlo Algorithm - Nesting

Profile of a pp Inelastic Collision

no gap

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

gap t y'_c

$\leftarrow \ln s' \rightarrow$
$= \Delta y'$

evolve every cluster similarly

gap t

gap t

gap t_1 t_2 gap

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

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

generate central gap

hadronize

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!