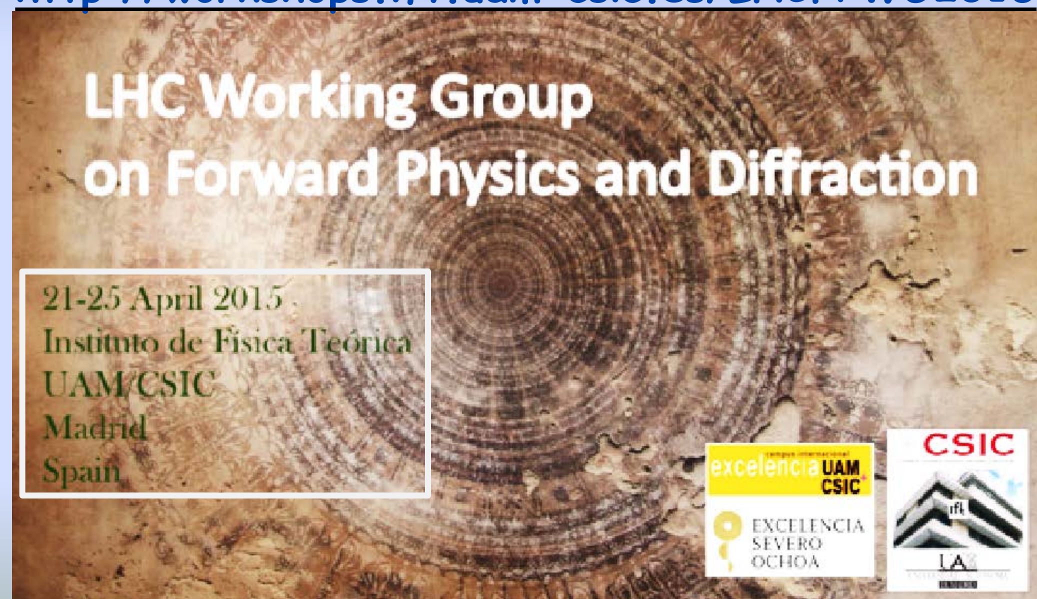
RENORM Diffractive Predictions Extended to Higher LHC and Future Accelerator Energies

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

http://workshops.ift.uam-csic.es/LHCFPWG2015



CONTENTS

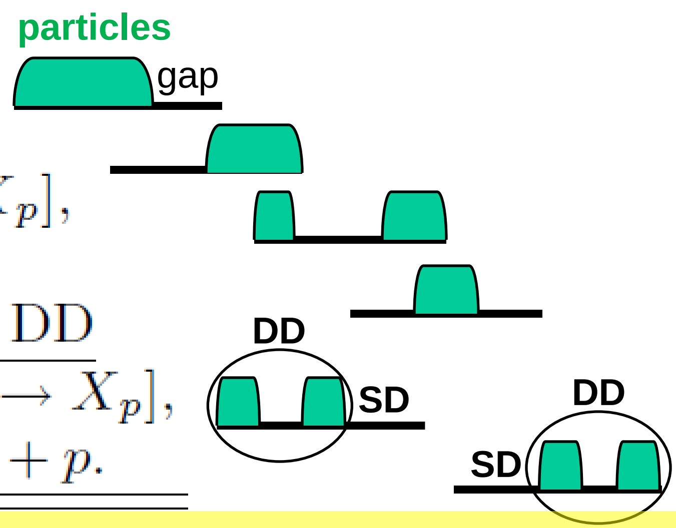
- Diffraction
  - SD1 $p_1p_2 \rightarrow p_1$+gap+X_2 Single Diffraction / Dissociation –1
  - SD2 $p_1p_2 \rightarrow X_1$+gap+p_2 Single Diffraction / Dissociation - 2
  - DD $p_1p_2 \rightarrow X_1$+gap+X_2 Double Diffraction / Double Dissociation
  - CD/DPE $p_1p_2 \rightarrow$gap+X+gap Central 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 (predictions compared to preliminary CMS results)
  - MIAMI 2014 (slides) https://cgc.physics.miami.edu/Miami2014/Goulianos2014.pdf (17-23 Dec 2014)
- Present talk (predictions compared to final CMS results)
  - CMS Soft Diffraction at 7 TeV: http://arxiv.org/format/1503.08689v1 (30 Mar 2015)

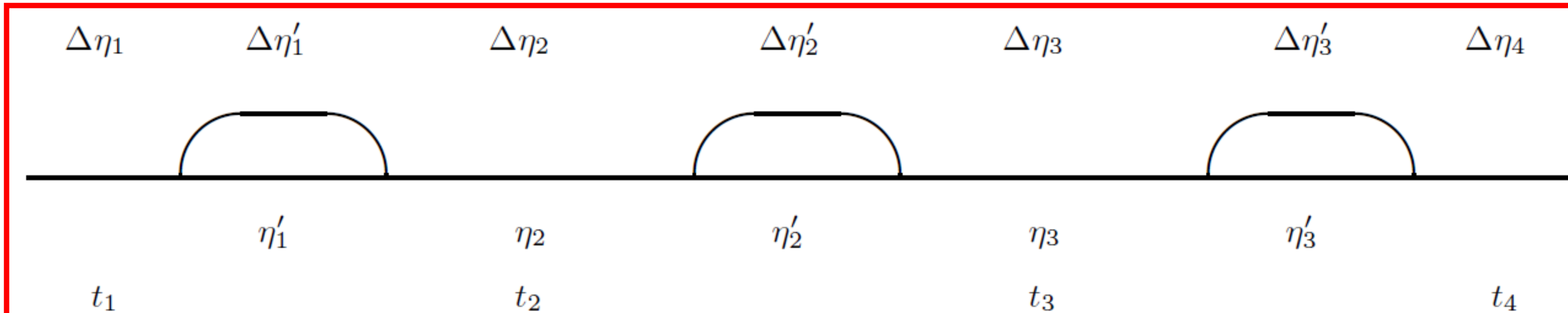
RENORM: Basic and Combined Diffractive Processes

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



Cross sections analytically expressed in arXiv below:

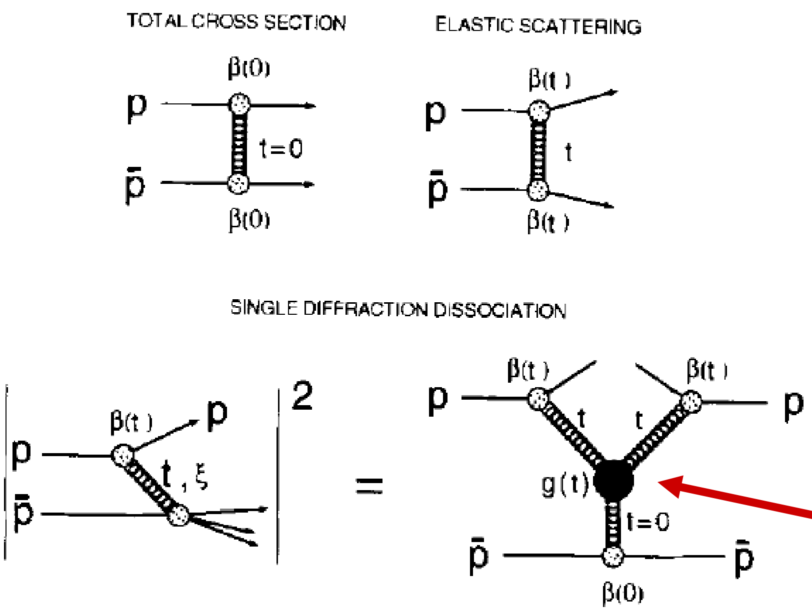
4-gap diffractive process-Snowmass 2001- **http://arxiv.org/pdf/hep-ph/0110240**



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

KG-PLB 358, 379 (1995)

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



Parameters:

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

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

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

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

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

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

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

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

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

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)

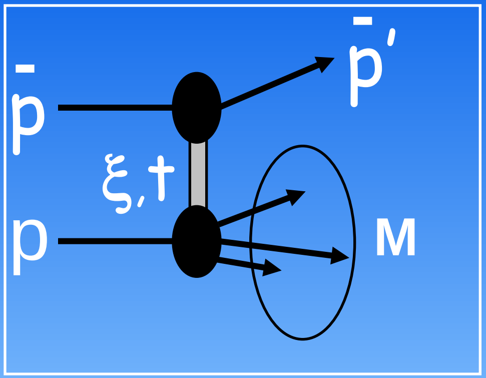
- the unitarity limit is already reached at $\sqrt{s}$ ~ 2 TeV !

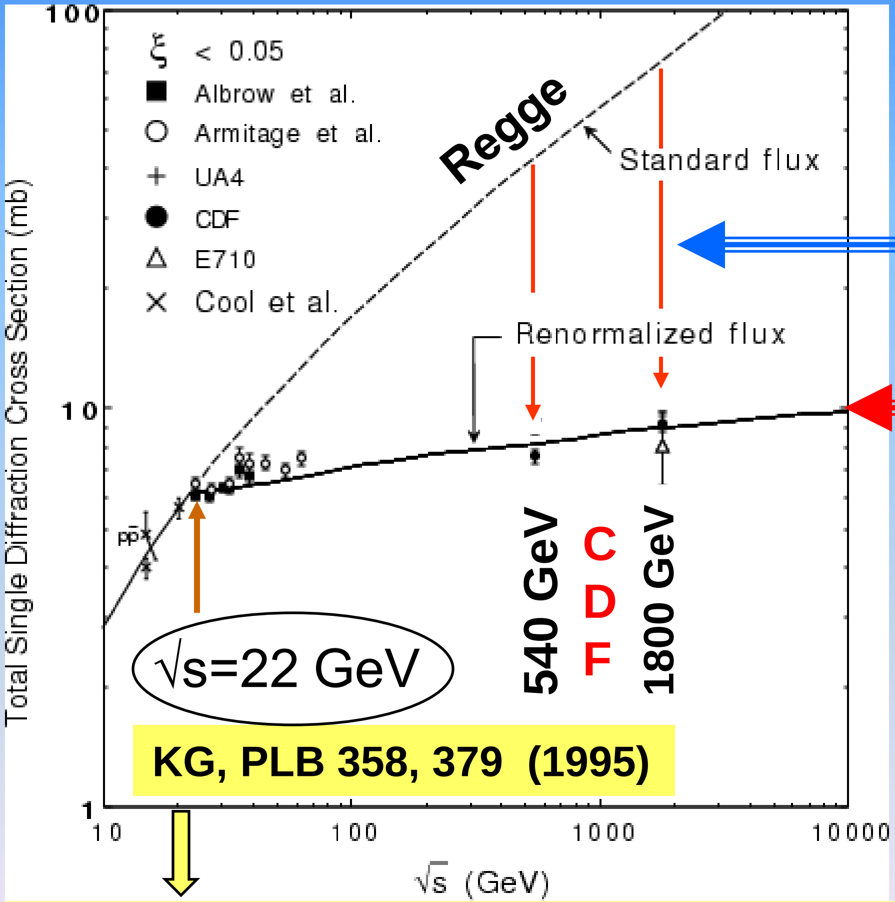
- need unitarization

* 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 √s increases





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

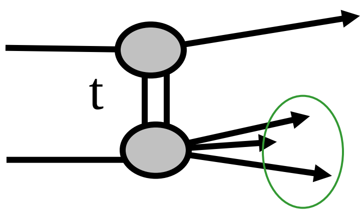
RENORMALIZATION

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

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

Single Diffraction Renormalized - 1

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



2 independent variables: $t, \Delta y$

color factor

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

$$\frac{d^2\sigma}{dt\, d\Delta y} = \underbrace{C \cdot F_p^2(t) \cdot \left\{ e^{(\varepsilon+\alpha' t)\Delta y} \right\}^2}_{\text{gap probability}} \cdot \kappa \cdot \underbrace{\left\{ \sigma_o\, e^{\varepsilon\, \Delta y'} \right\}}_{\text{sub-energy x-section}}$$

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

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

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

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

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

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

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

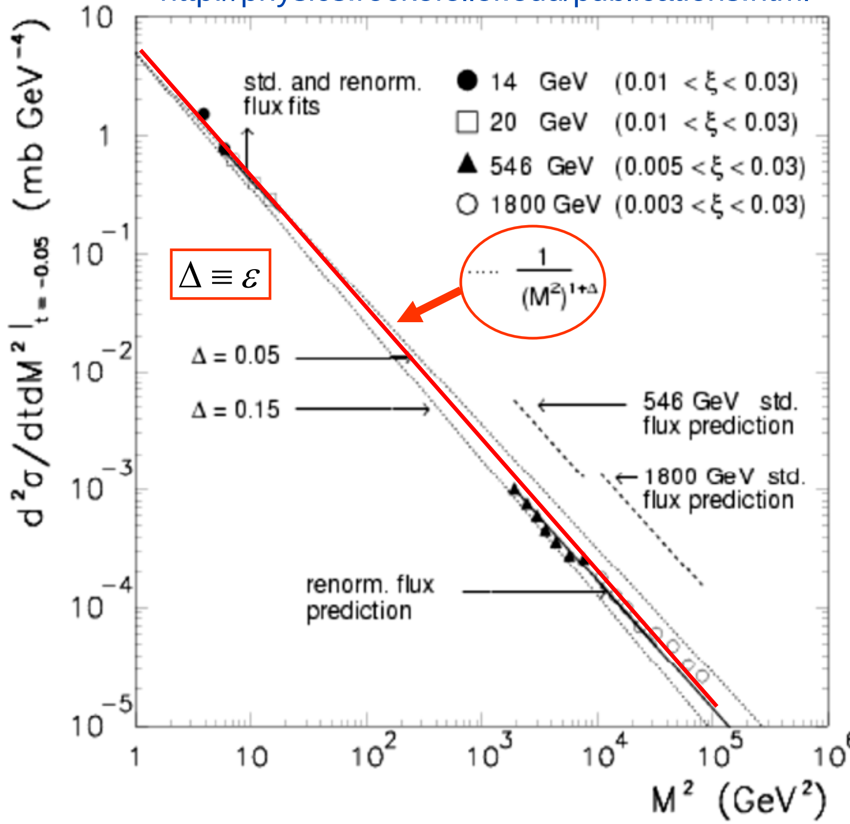
http://physics.rockefeller.edu/publications.html

Regge

data

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

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



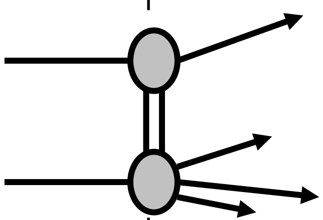
➔ factorization breaks down to ensure M^2 scaling

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



$$s_o^{\varepsilon}$$

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

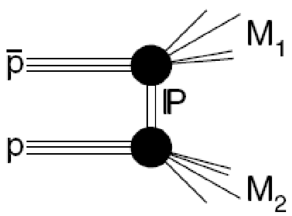
$$s_o^{-\varepsilon/2}\cdot g_{PPP}(t)$$

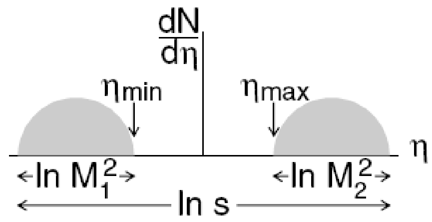
Pomeron-proton x-section

- ❑ 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

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

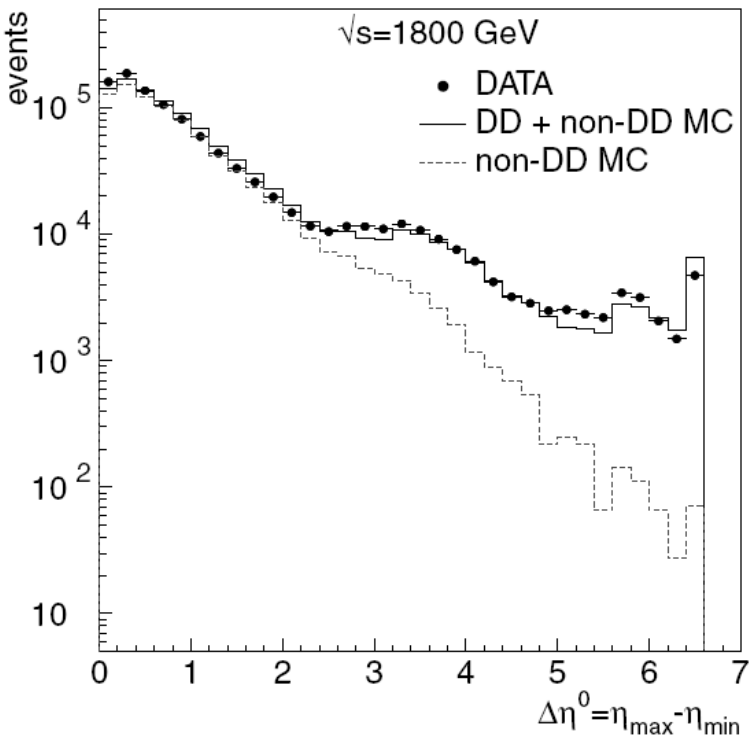


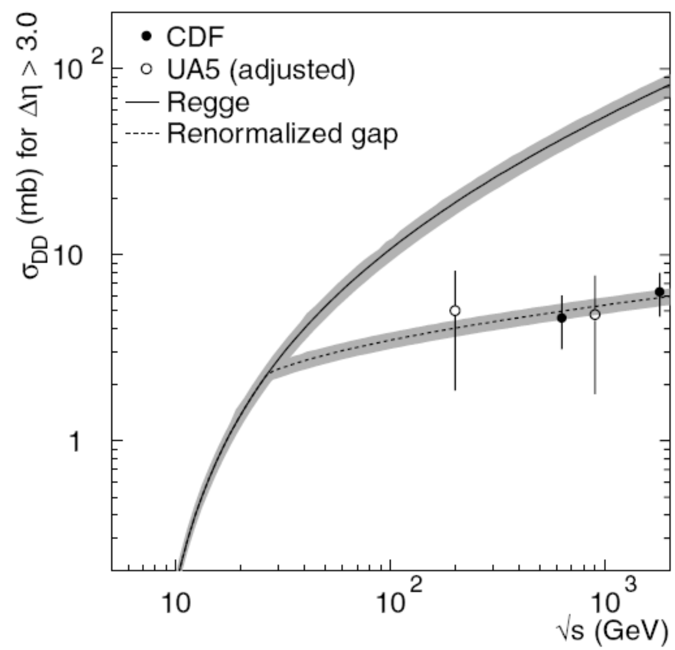


$$\frac{d^3\sigma_{\rm DD}}{dt\,dM_1^2\,dM_2^2} = \frac{d^2\sigma_{\rm SD}}{dt\,dM_1^2}\,\frac{d^2\sigma_{\rm SD}}{dt\,dM_2^2}\Big/\frac{d\sigma_{el}}{dt}$$
$$= \frac{[\kappa\beta_1(0)\beta_2(0)]^2}{16\pi}\,\frac{s^{2\epsilon}e^{b_{\rm DD}t}}{(M_1^2M_2^2)^{1+2\epsilon}}$$

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

gap probability x-section





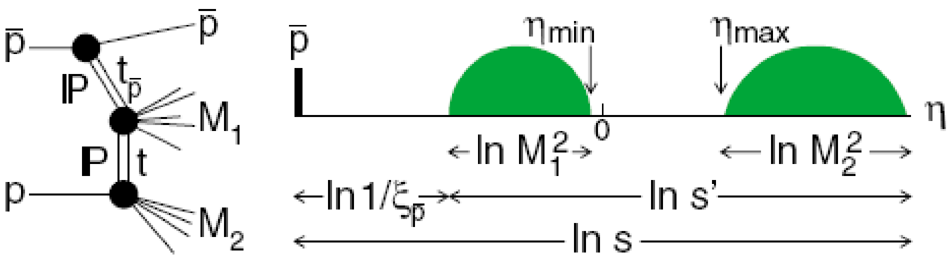
←Regge

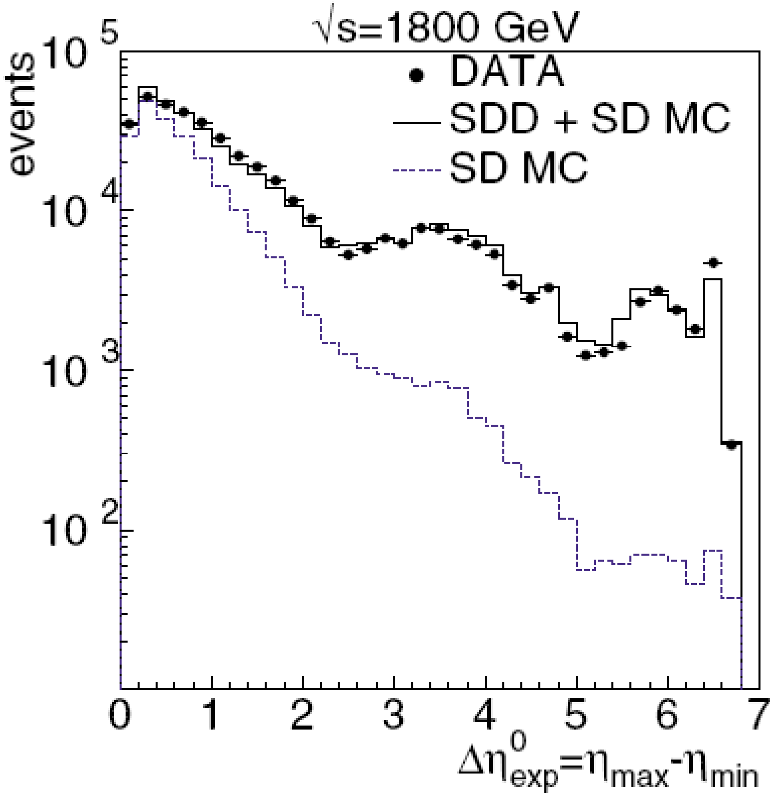
←Renor'd

x-section divided by integrated gap prob.

SDD at CDF

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



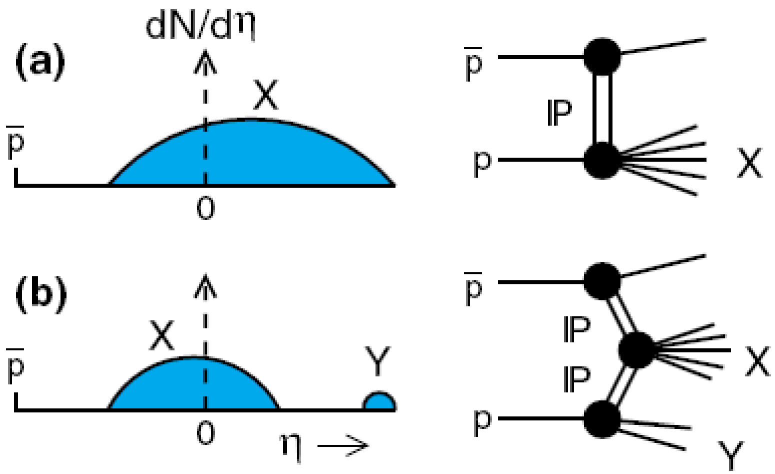


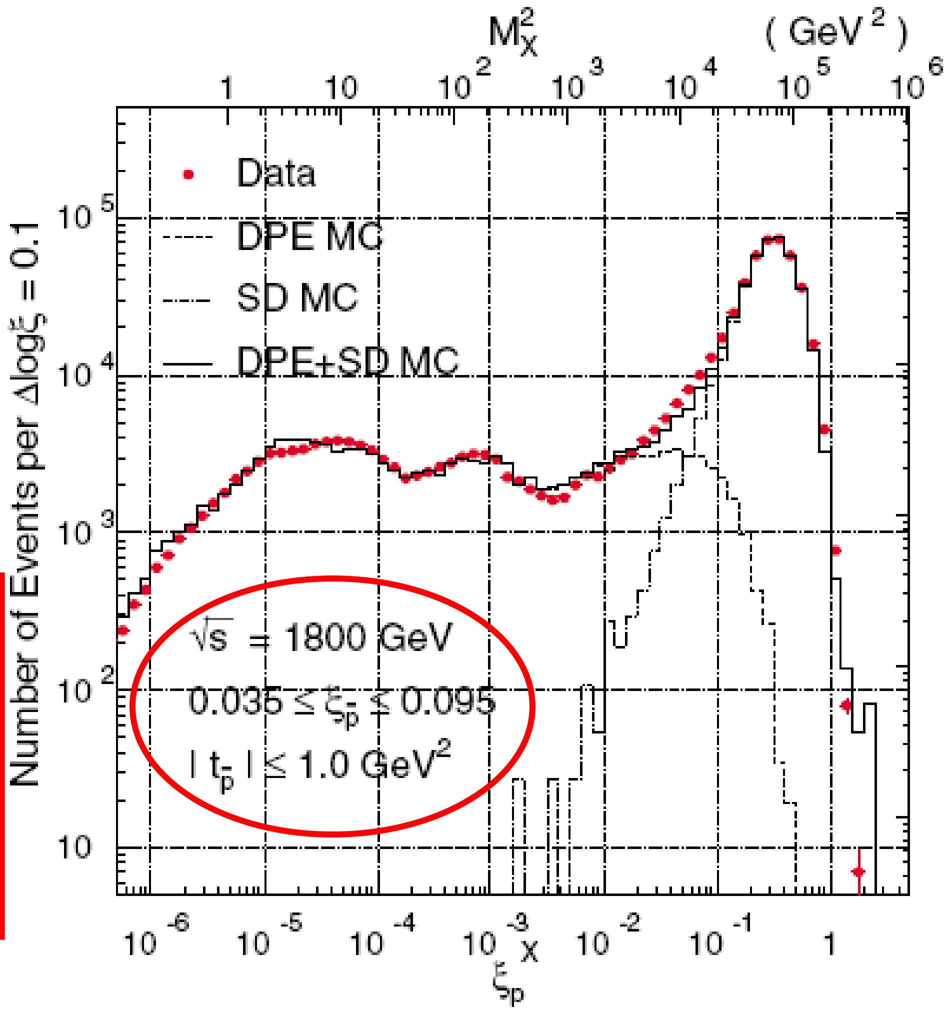
- Excellent agreement between data and MBR (MinBiasRockefeller) MC

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

CD/DPE at CDF

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

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

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

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

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

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

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)

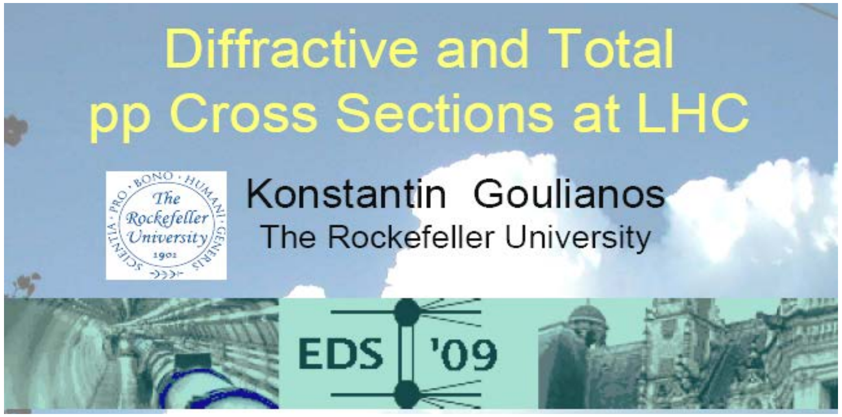
$$\sigma_{\rm tot}^{p^{\pm}p} = \begin{cases} 16.79 s^{0.104} + 60.81 s^{-0.32} \mp 31.68 s^{-0.54} & \text{for } \sqrt{s} < 1.8 \\ \sigma_{\rm tot}^{\rm CDF} + \frac{\pi}{s_0}\left[\left(\ln \frac{s}{s_F}\right)^2 - \left(\ln \frac{s^{\rm CDF}}{s_F}\right)^2\right] & \text{for } \sqrt{s} \geq 1.8 \end{cases}$$

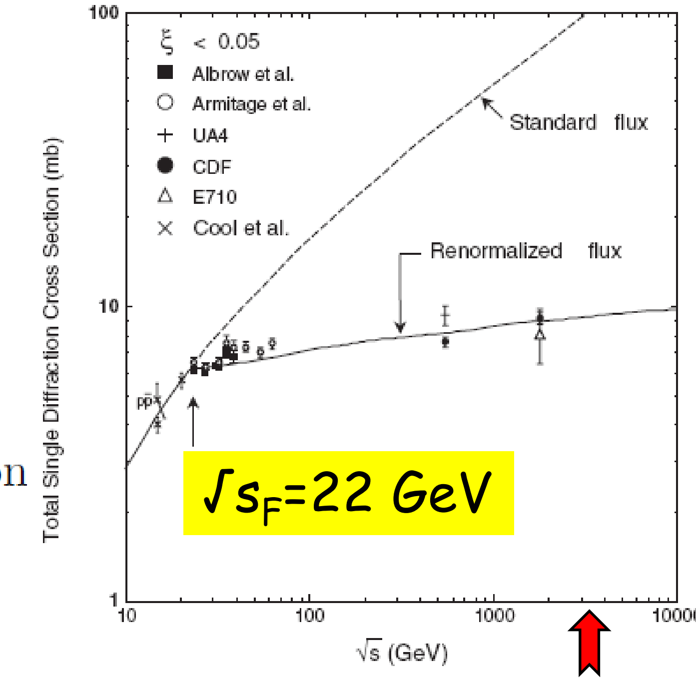
KG Moriond 2011, arXiv:1105.1916

$\sqrt{s^{\rm CDF}} = 1.8$ 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

$\sigma_{el}^{p\pm p} = \sigma_{tot}^{p\pm p} \times (\sigma_{el}/\sigma_{tot})^{p\pm p}$, 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].

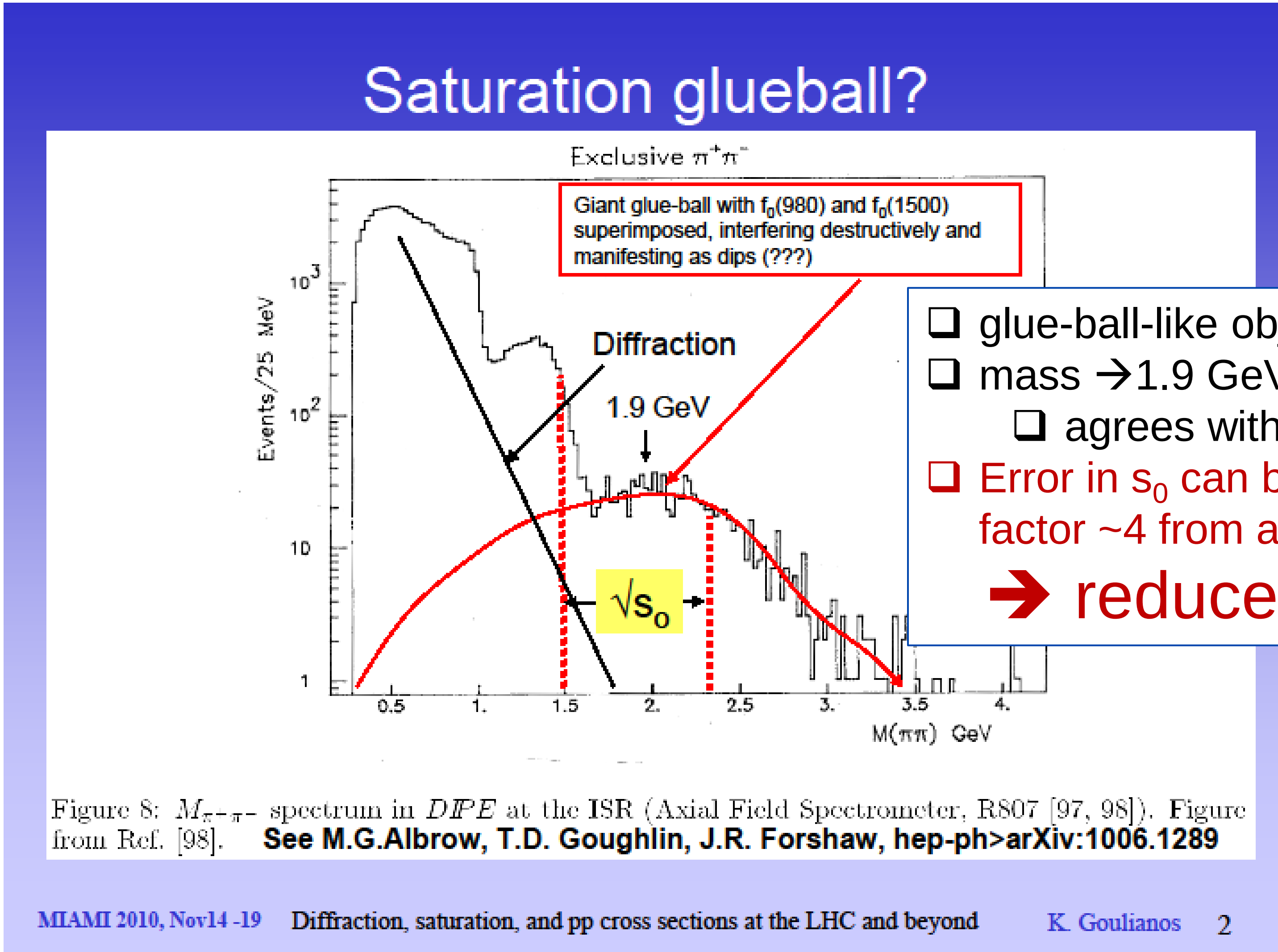
- Obtain the total cross section at the LHC:

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

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

Main error is due to s_0

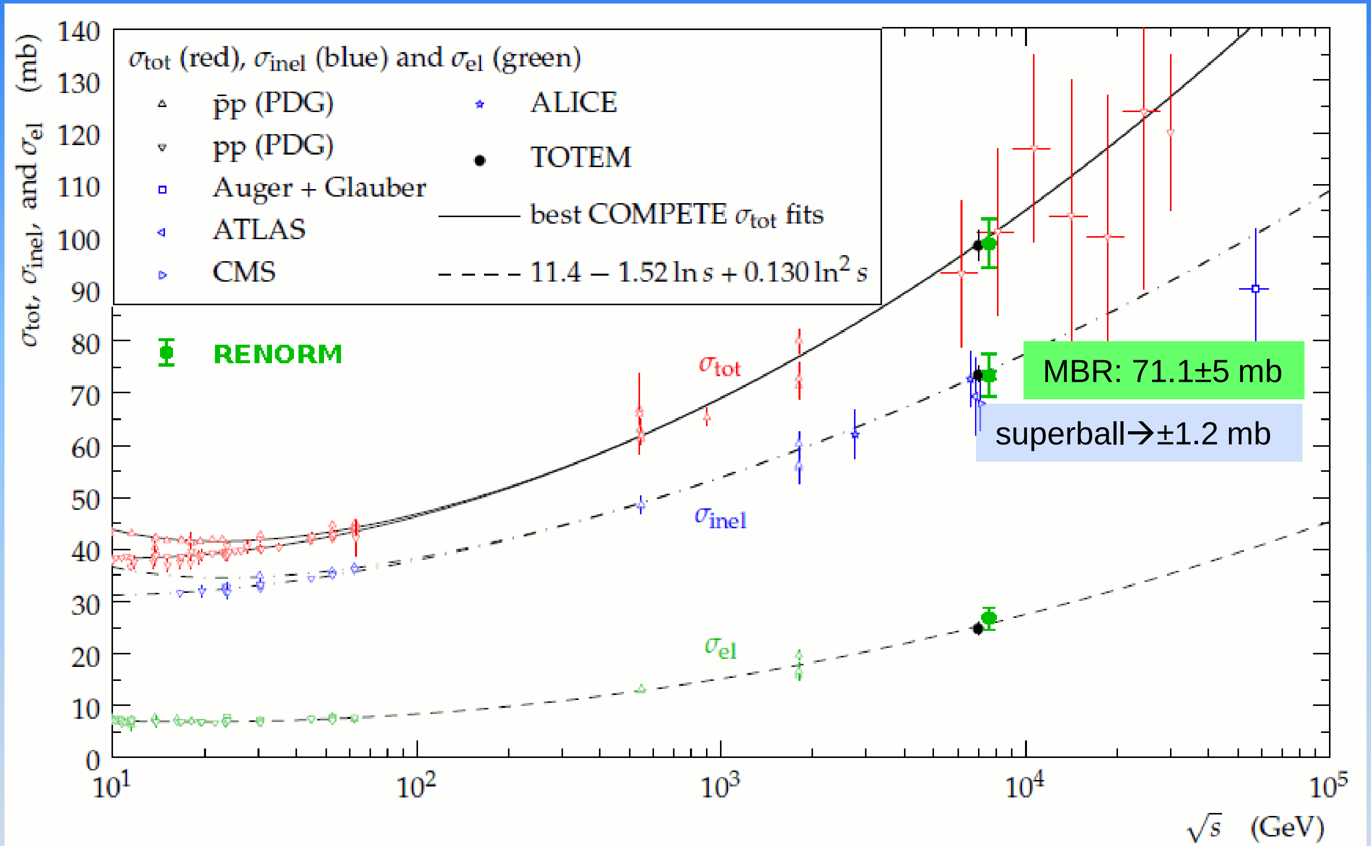
How to Reduce Uncertainty in s_0



- ❑ 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 (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

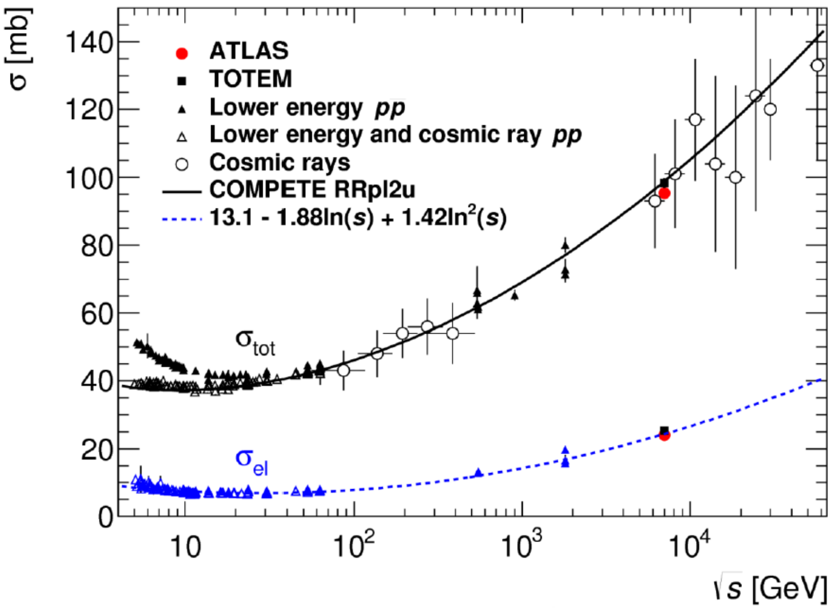
RENORM: 72.3±1.2 mb

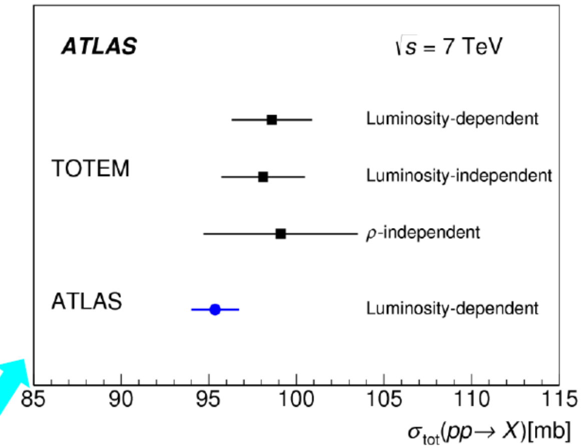
ATLAS - in Diffraction 2014

(Talk by Marek Taševský, slide#19)

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

Comparison with previous measurements



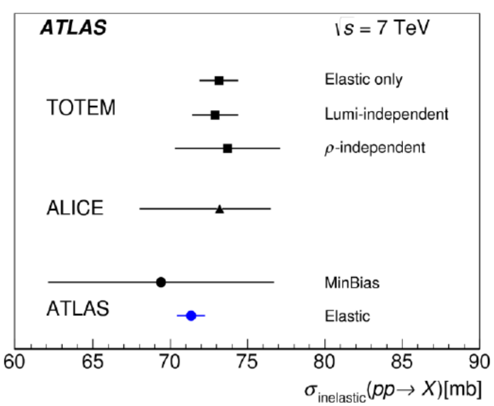


The same run in 2011, Lumi-dependent method:

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

RENORM: 98.0±1.2 mb



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

19

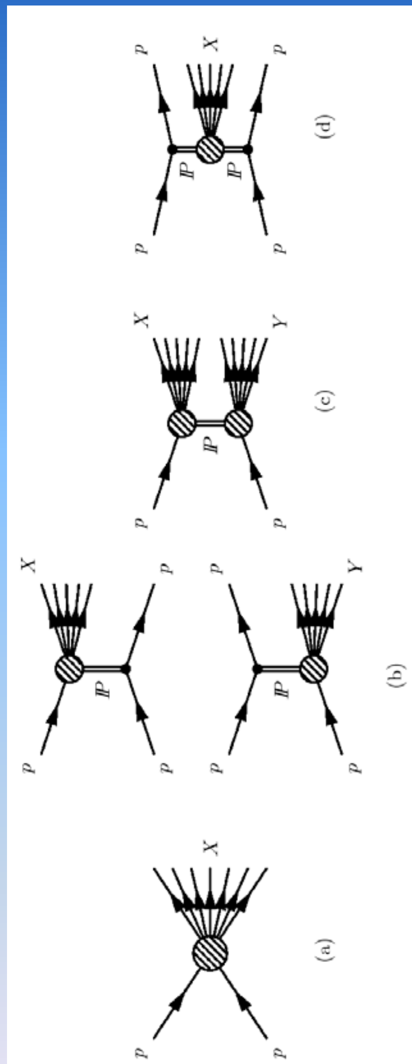
The CMS Detector

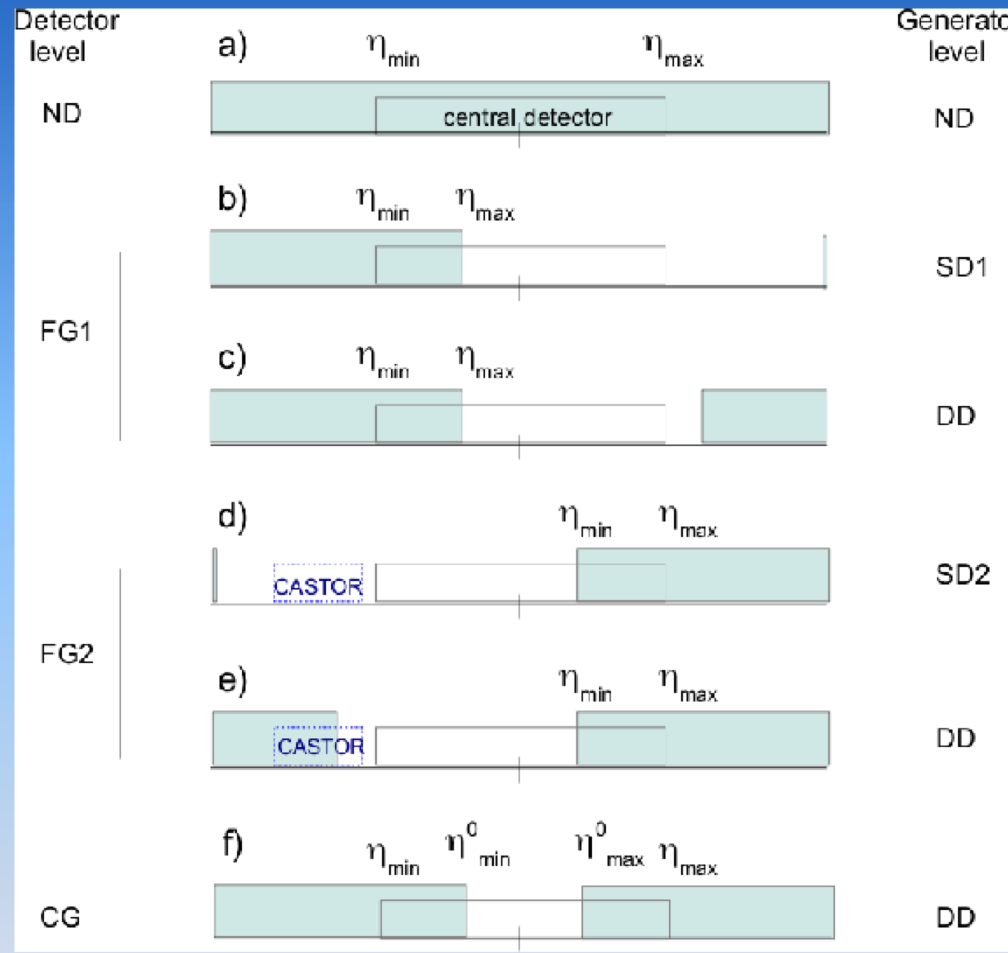
CD

DD

SD

ND



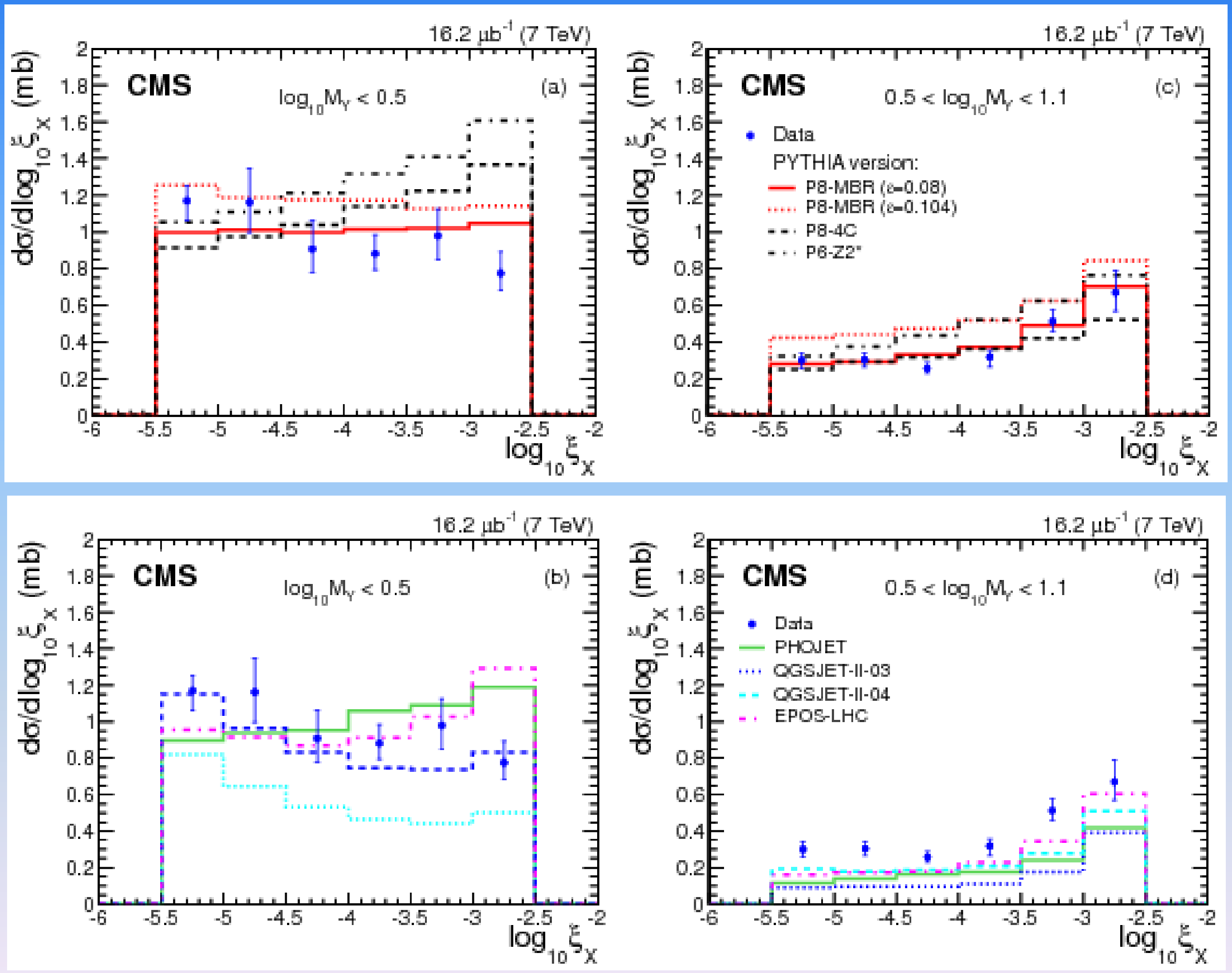


CASTOR forward calorimeter important for separating SD from DD contributions

CMS Data vs MC Models (2015)-1

SD dominated data

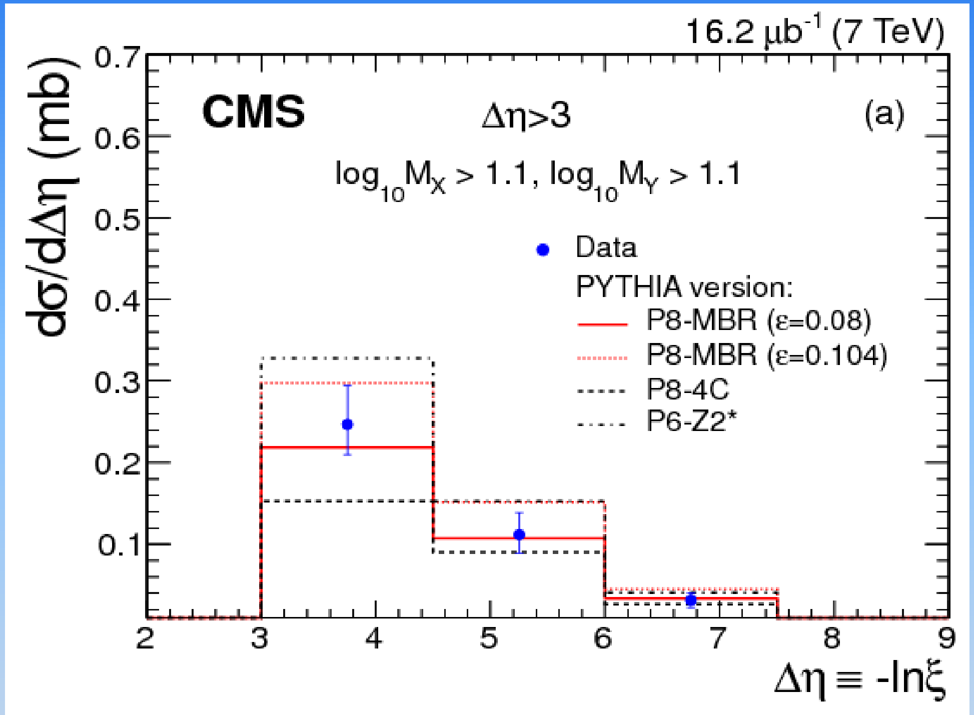
DD dominated data

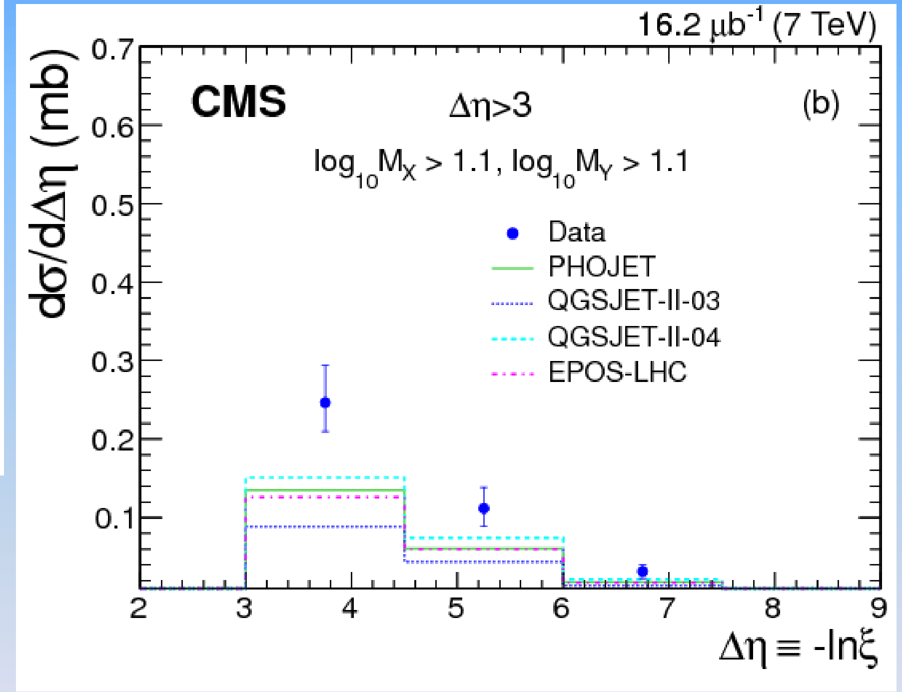


- ❑ Error bars are dominated by systematics
- ❑ DD data scaled downward by 15% (within MBR and CDF data errors)

CMS Data vs MC Models (2015) -2

Central η-gap x-sections (DD dominated)

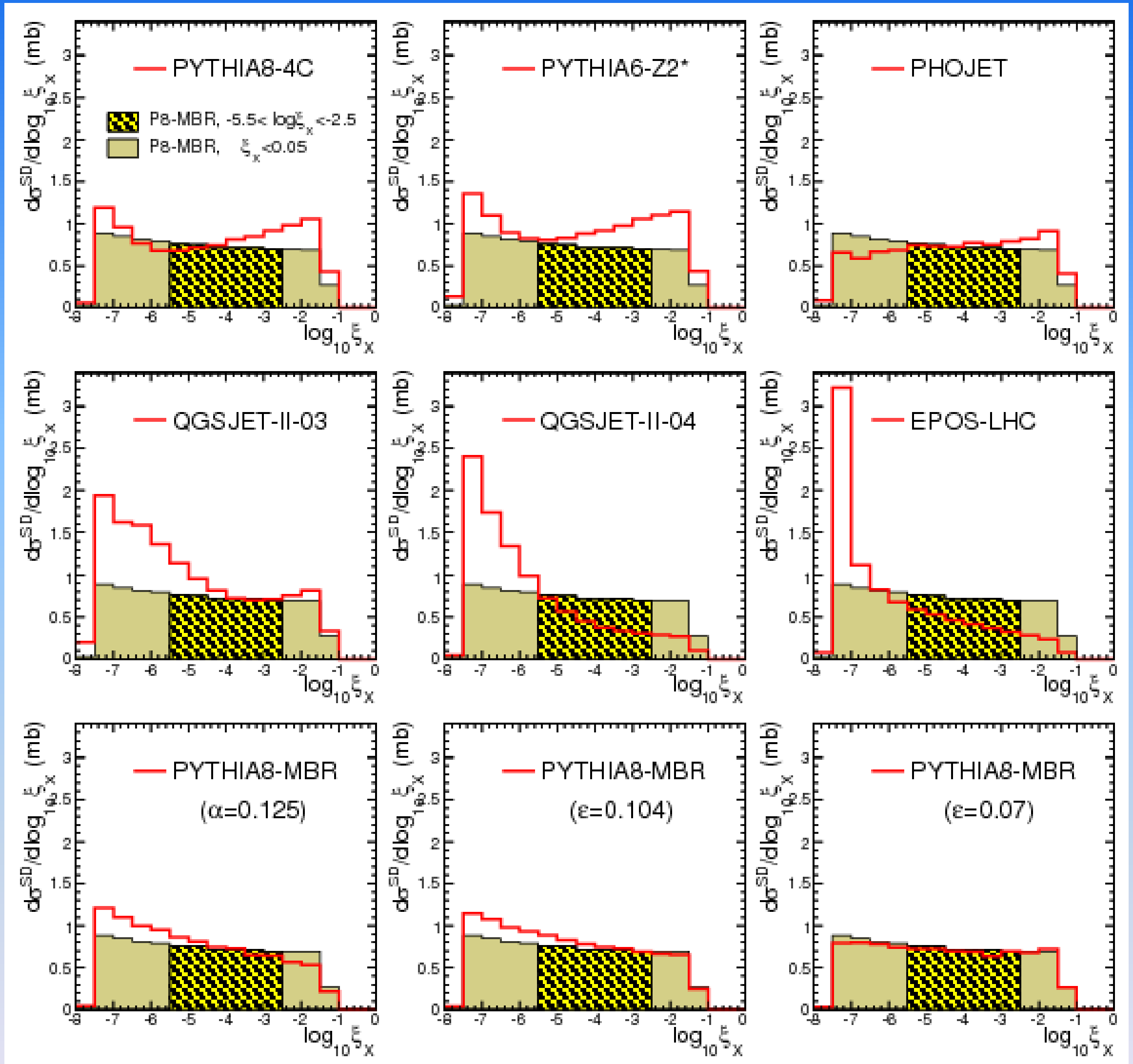




- .P8-MBR provides the best fit to data

- .All above models too low at small Δη

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



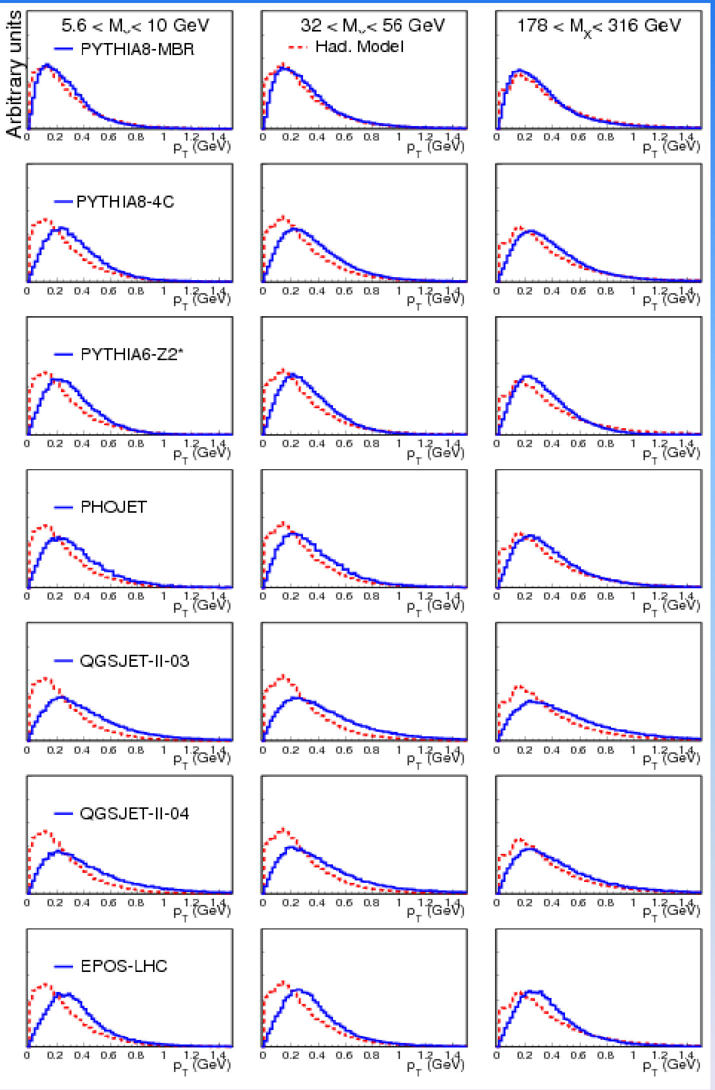
p_T Distr's of MCs vs Pythia8 Tuned to MBR

- ❑ 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

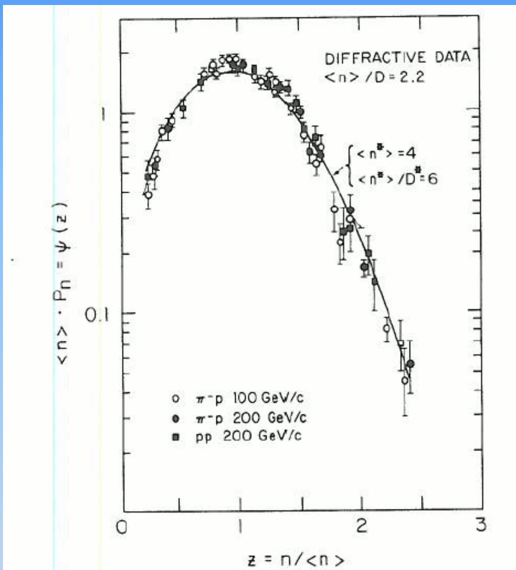


Fig. 1. The diffractive data of ref. [3] fitted with the modified gamma function.

Diffractive data vs MGD

Mass Regions

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

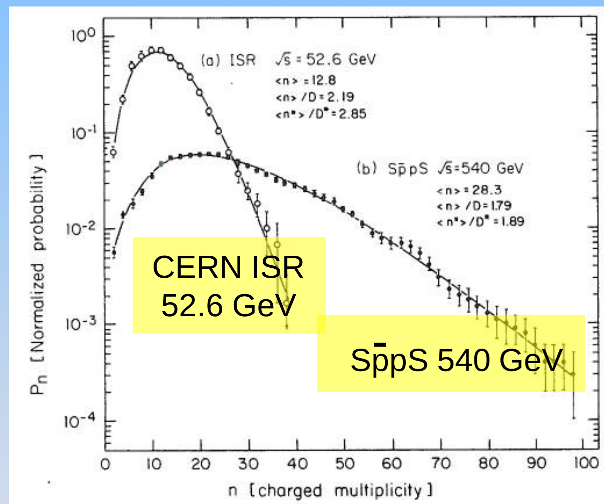
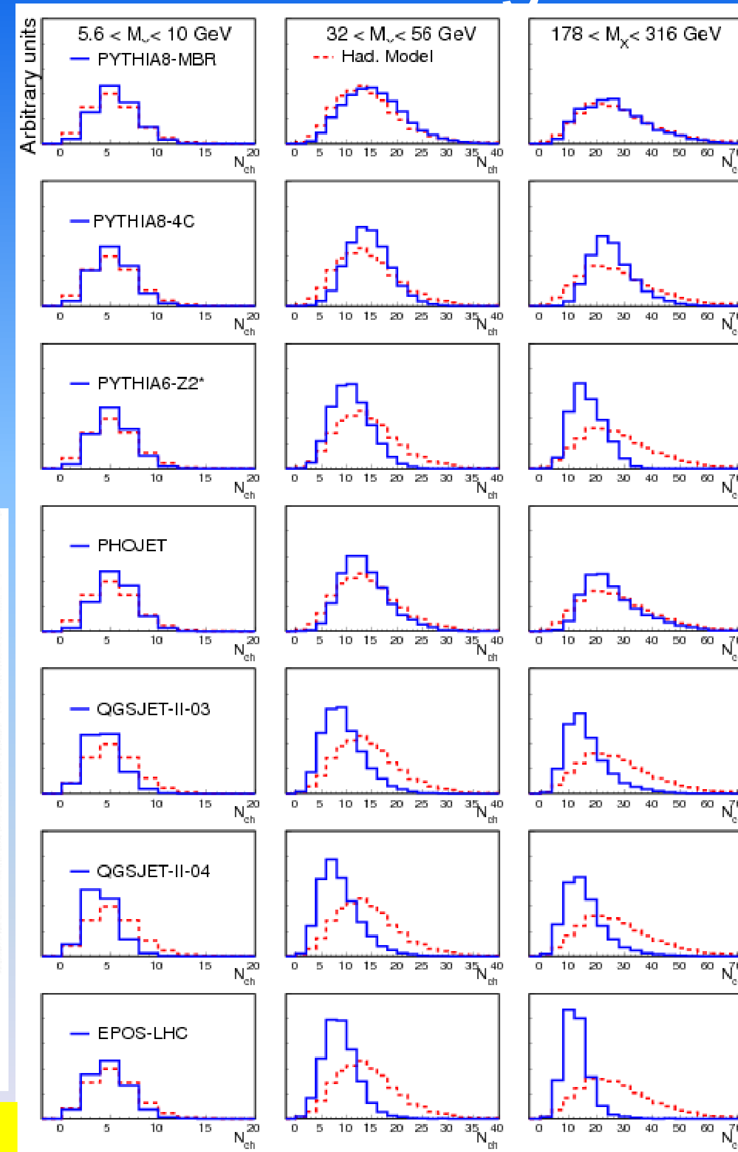


Fig. 2. Full phase space inelastic non-single-diffractive data fitted with the modified gamma function: (a) ISR data [5] at $\sqrt{s}$=52.6 GeV and (b) collider data [7] at $\sqrt{s}$=540 GeV.

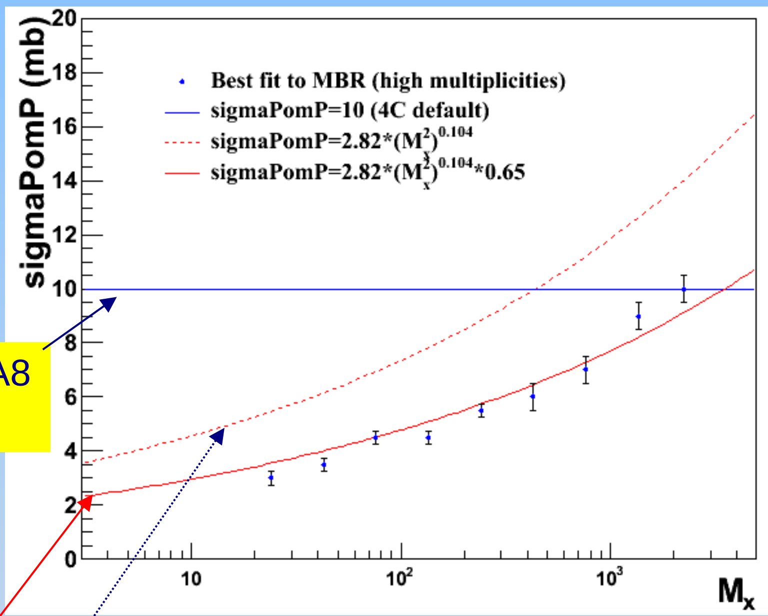
CERN ISR & $S\bar{p}pS$ w/MGD fit



$0 < p_T < 1.4$ GeV

Pythia8-MBR Hadronization Tune

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

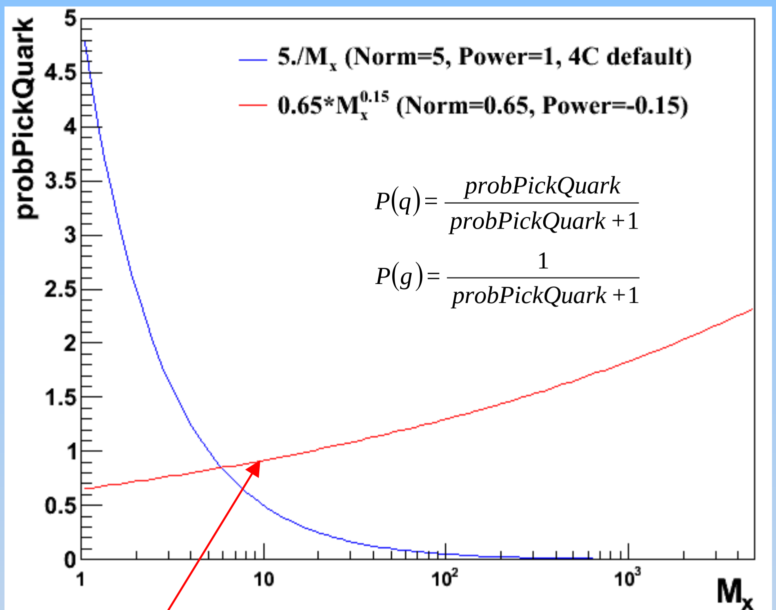


PYTHIA8 default

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

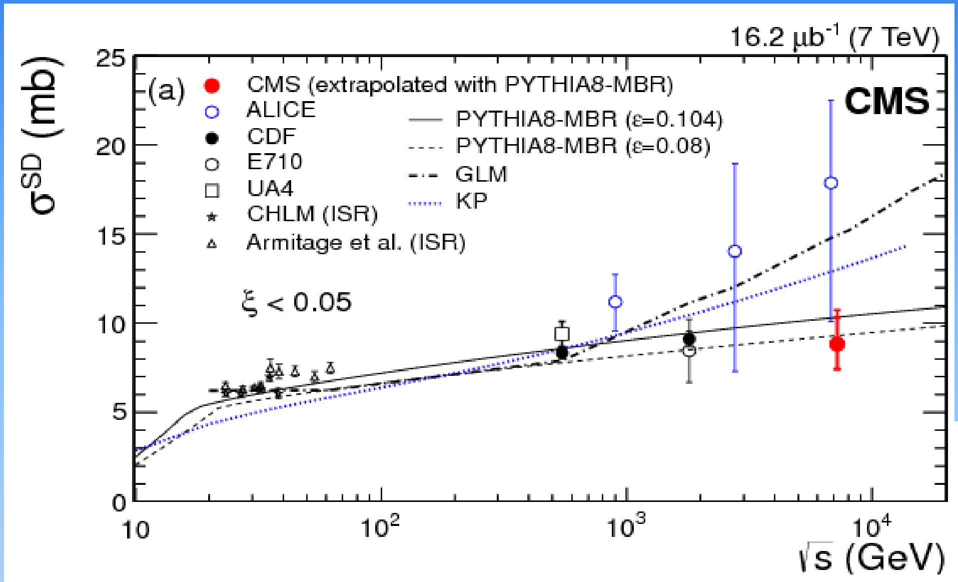
Red line: best fit to multiplicity distributions.
(in bins of Mx, fits to higher tails only, default pT spectra)

Diffraction: QuarkNorm/Power parameter



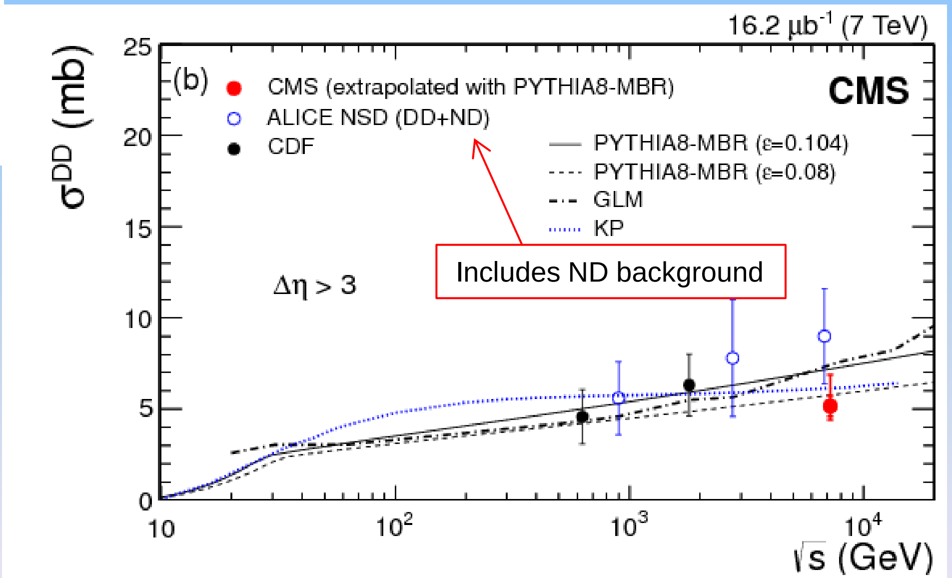
- good description of low multiplicity tails

SD and DD x-Sections vs Models

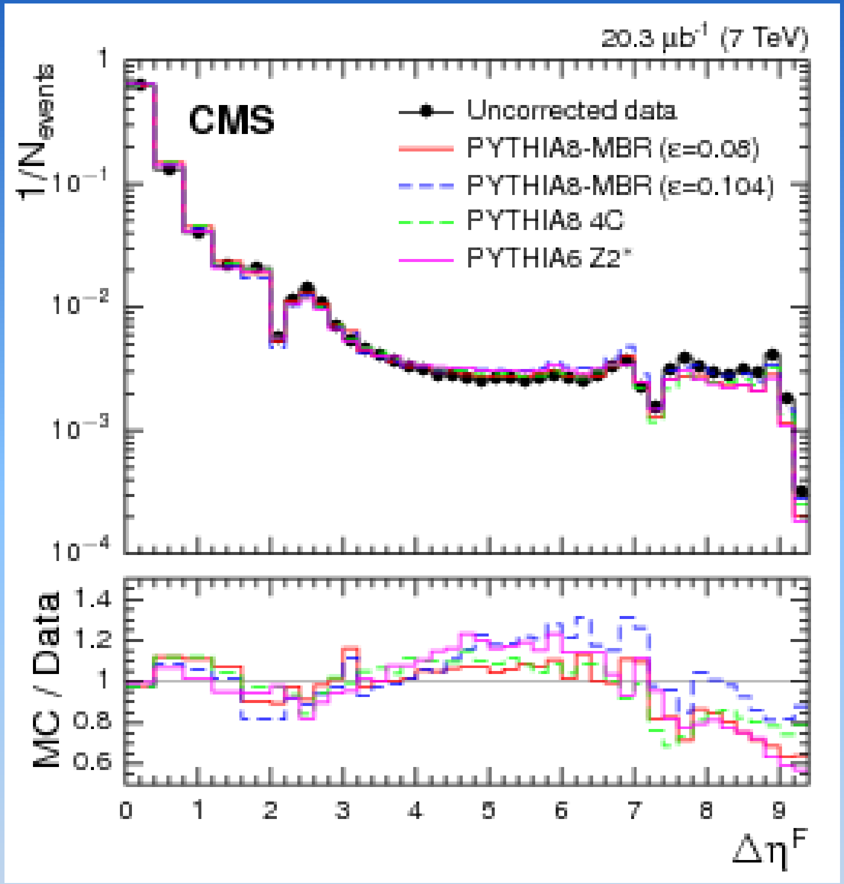


Single Diffraction

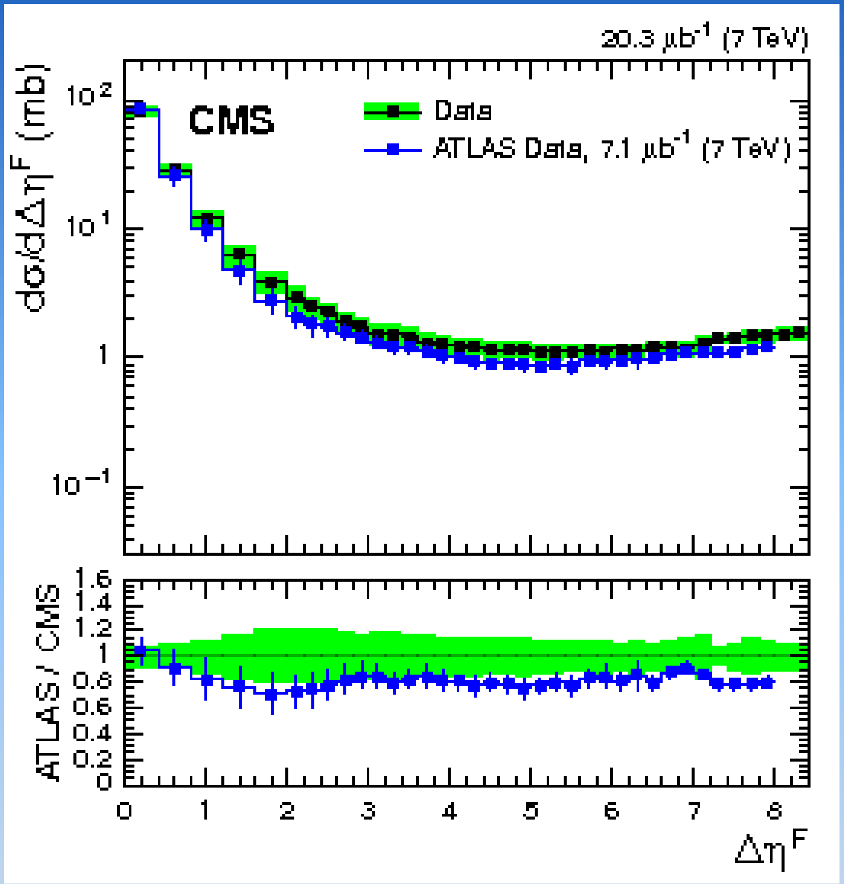
Double Diffraction



CMS vs MC & ATLAS



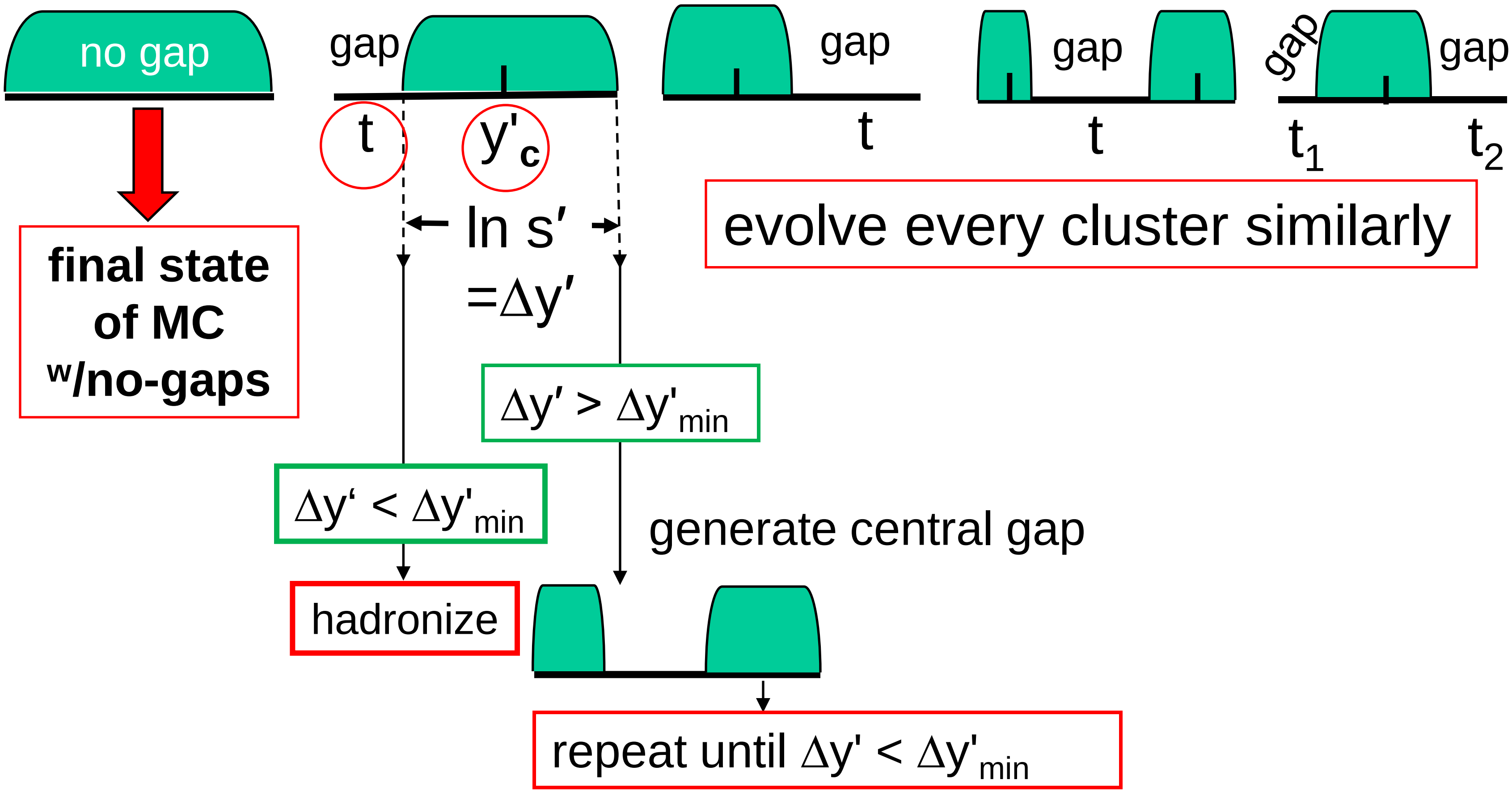
Uncorrected $\Delta\eta^F$ distribution vs MCs



Stable-particle x-sections for pT>200 MeV and $|\eta|<4.7$ 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:
    - ❖ this is the only final state to be tuned

derived from ND and QCD color factors (applies to the three items above)

- ❑ 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!