RENORM Tensor-Pomeron Diffractive Predictions

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Rencontres de Moriond
QCD and High Energy Interactions

50th anniversary meeting

thanks to **Tran & Kim!**

photo credit: Emmanuelle Tran

CONTENTS

- Diffraction
  - SD1 $p_1p_2 \rightarrow p_1+\text{gap}+X_2$ Single Diffraction / Dissociation –1
  - SD2 $p_1p_2 \rightarrow X_1+\text{gap}+p_2$ Single Diffraction / Dissociation - 2
  - DD $p_1p_2 \rightarrow X_1+\text{gap}+X_2$ Double Diffraction / Double Dissociation
  - CD/DPE $p_1p_2 \rightarrow \text{gap}+X+\text{gap}$ 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-Pomeron** model

- References

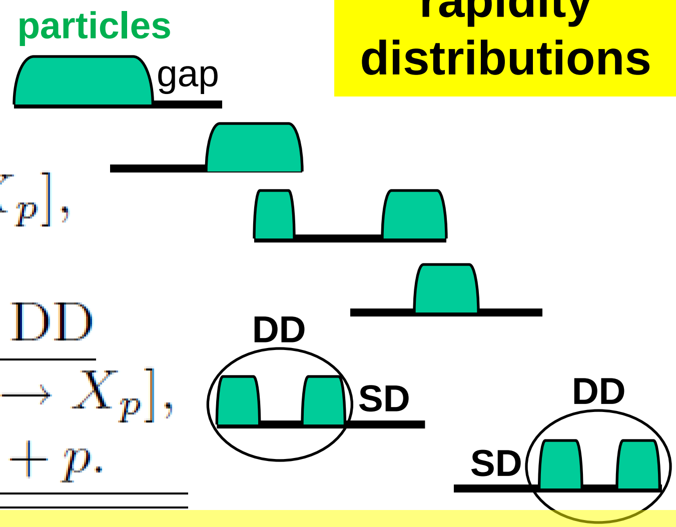
- MBR MC Simulation in PYTHIA8, KG & R. Ciesielski, **http://arxiv.org/abs/1205.1446**
- LHCFPWG 2015 Madrid (21-25 Apr 2015) **http://workshops.ift.uam-csic.es/LHCFPWG2015/program**
- EDS BLOIS 2015 Borgo, Corsica, France Jun 29-Jul 4, https://indico.cern.ch/event/362991/
  KG, Updated RENORM/MBR-model Predictions for Diffraction at the LHC, http://dx.doi.org/10.5506/APhysPolBSupp.8.783

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

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
	$\mathbf{SDD}_{\bar{p}}$	$\bar{p}p \to \bar{p} + \text{gap} + X_c + \text{gap} + [p \to X_p],$
	$\mathbf{SDD}_{p}$	$\bar{p}p \to [\bar{p} \to X_{\bar{p}}]\text{gap} + X_c + \text{gap} + p.$

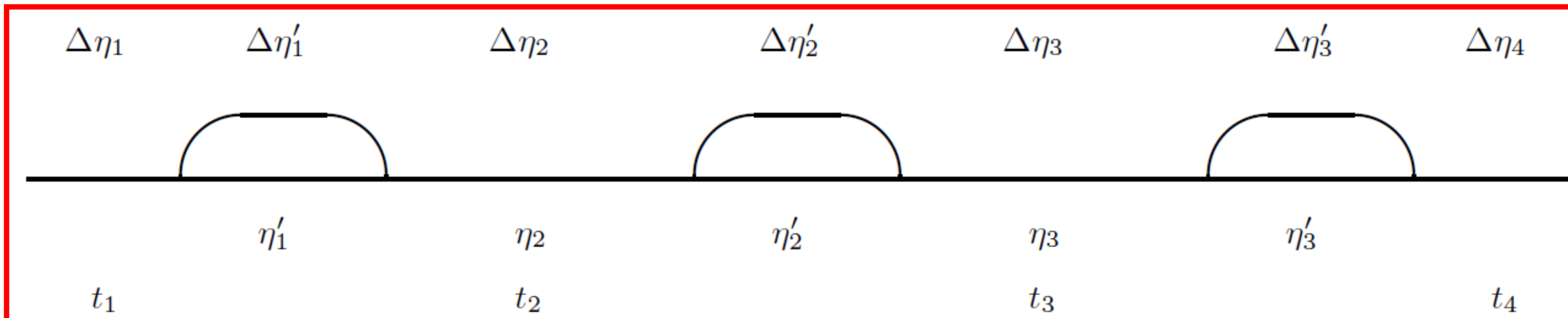
rapidity distributions



Cross sections analytically expressed in arXiv below:

http://arxiv.org/abs/hep-ph/0110240

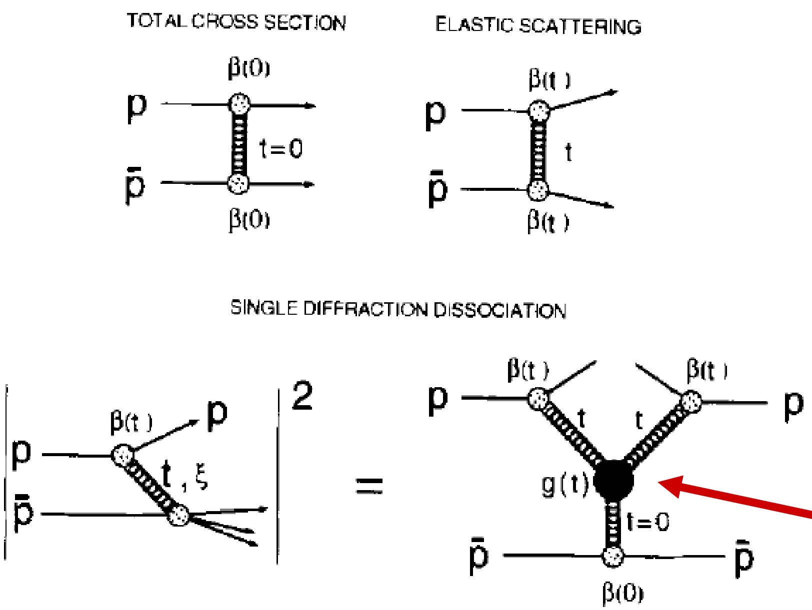
4-gap diffractive process-Snowmass 2001



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

KG-PLB 358, 379 (1995)

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



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

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

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

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

$$\frac{d^2\sigma_{\rm sd}}{dt\,d\xi} = \frac{\beta_1^2(t)}{16\pi}\,\xi^{1-2\alpha(t)}\left[\beta_2(0)\,g(t)\left(\frac{s'}{s'_0}\right)^{\alpha(0)-1}\right] = f_{\mathcal{P}/p}(\xi,t)\;\sigma_T^{\mathcal{P}\bar{p}}(s',t) \quad (4)$$

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)

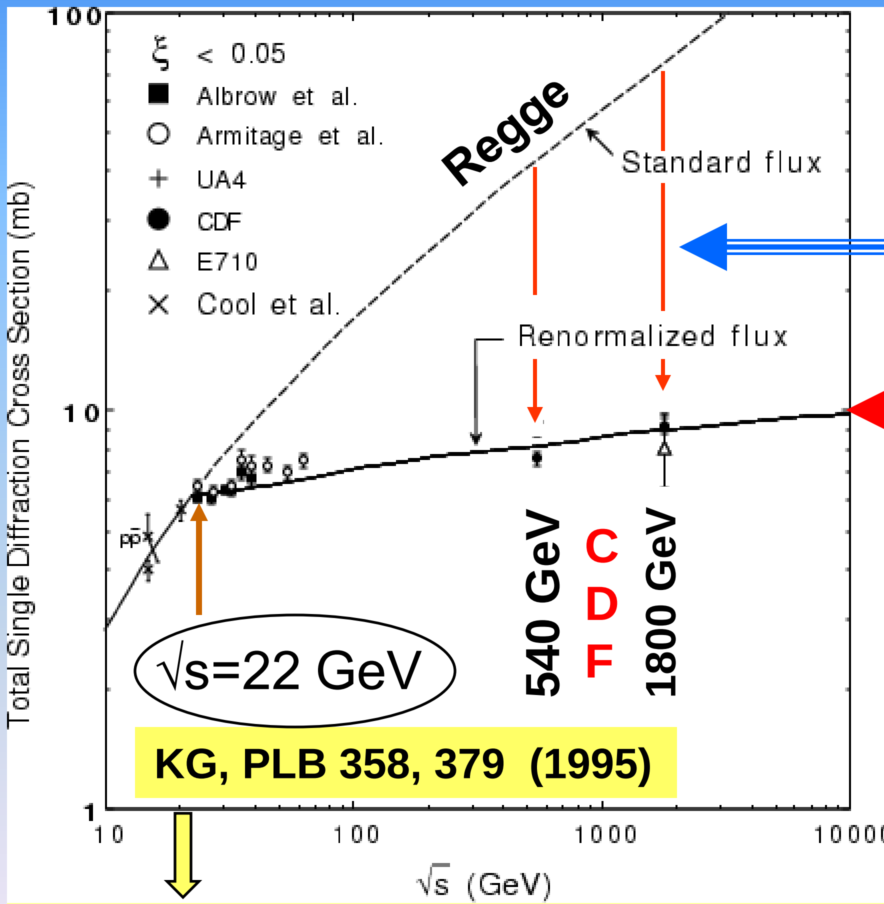
- ❑ the unitarity limit is already reached at $\sqrt{s}$ ~ 2 TeV

- ❑ need unitarization

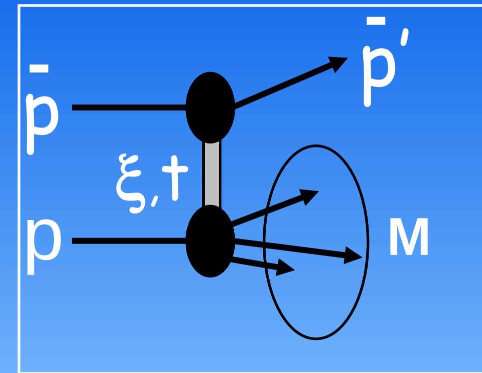
* similarly for $(d\sigma_{el}/dt)_{t=0}$ w.r.t. σ_t, but this is handled differently in RENORM

FACTORIZATION BREAKING IN SOFT DIFFRACTION

Diffractive x-section suppressed relative to Regge prediction as √s increases



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



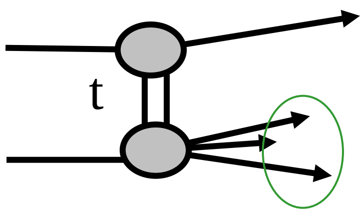
Factor of ~8 (~5) suppression at √s = 1800 (540) GeV

RENORMALIZATION

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

Single Diffraction Renormalized - 1

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



2 independent variables: $t, \Delta y$

color factor

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

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

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 ➔

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

KG&JM, PRD 59 (114017) 1999

http://dx.doi.org/10.1103/PhysRevD.59.114017

QCD: $\kappa = \mathrm{f}_g \times \frac{1}{N_c^2 - 1} + \mathrm{f}_q \times \frac{1}{N_c} \xrightarrow{Q^2 = 1} \approx 0.75 \times \frac{1}{8} + 0.25 \times \frac{1}{3} = 0.18$

Single Diffraction Renormalized - 3

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

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

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

← affects only the *s*-dependence

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

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

set $N(s,s_o)$ to unity
➔ determines s_o

M^2 - Distribution: Data

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

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

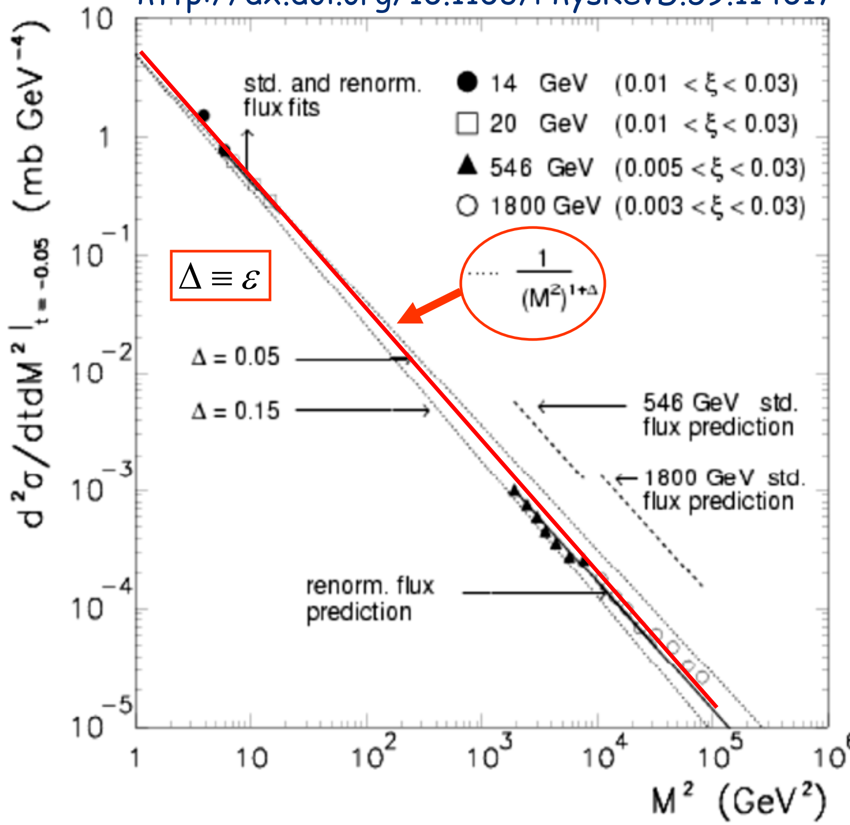
KG&JM, PRD 59 (1999) 114017

http://dx.doi.org/10.1103/PhysRevD.59.114017

Regge

data

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



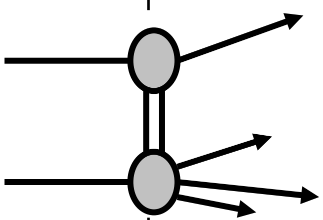
➔ factorization breaks down to ensure M^2-scaling

Scale s_0 and *PPP* Coupling

Pomeron flux: interpreted 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



$$s_o^{\varepsilon}$$

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

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

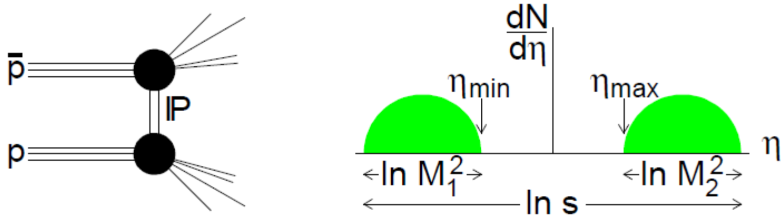
Pomeron-proton x-section

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

DD at CDF

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

http://dx.doi.org/10.1103/PhysRevLett.87.141802

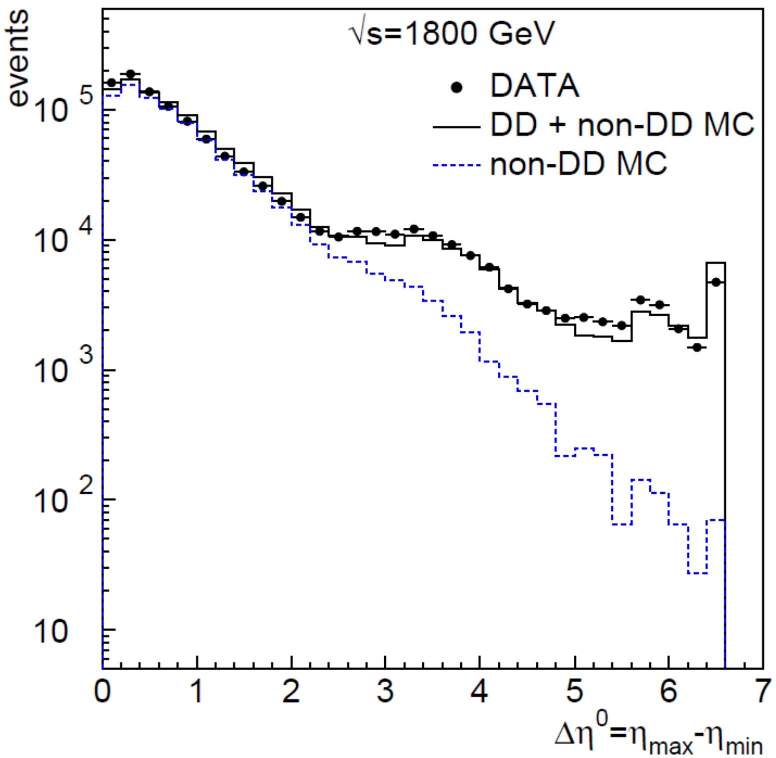


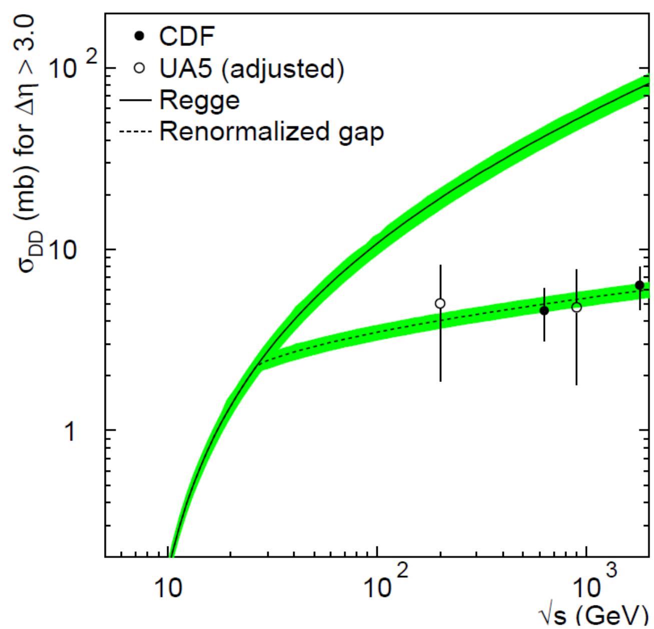
$$\frac{d^3\sigma_{DD}}{dt\,dM_1^2\,dM_2^2} = \frac{d^2\sigma_{SD}}{dt\,dM_1^2}\,\frac{d^2\sigma_{SD}}{dt\,dM_2^2}\Big/\frac{d\sigma_{el}}{dt}$$

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

Regge factorization

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



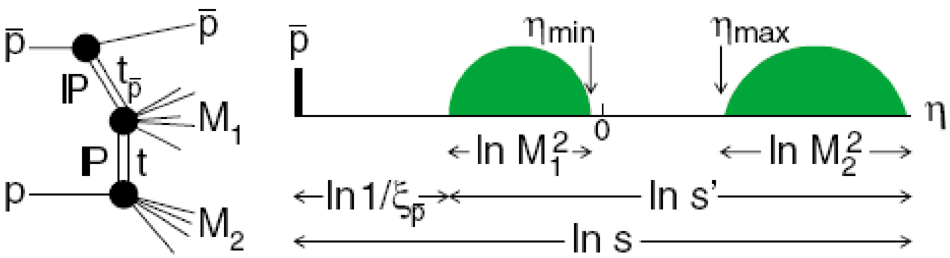


🡐Regge

Regge
🡐 RENORM

x-section divided by integrated gap prob.

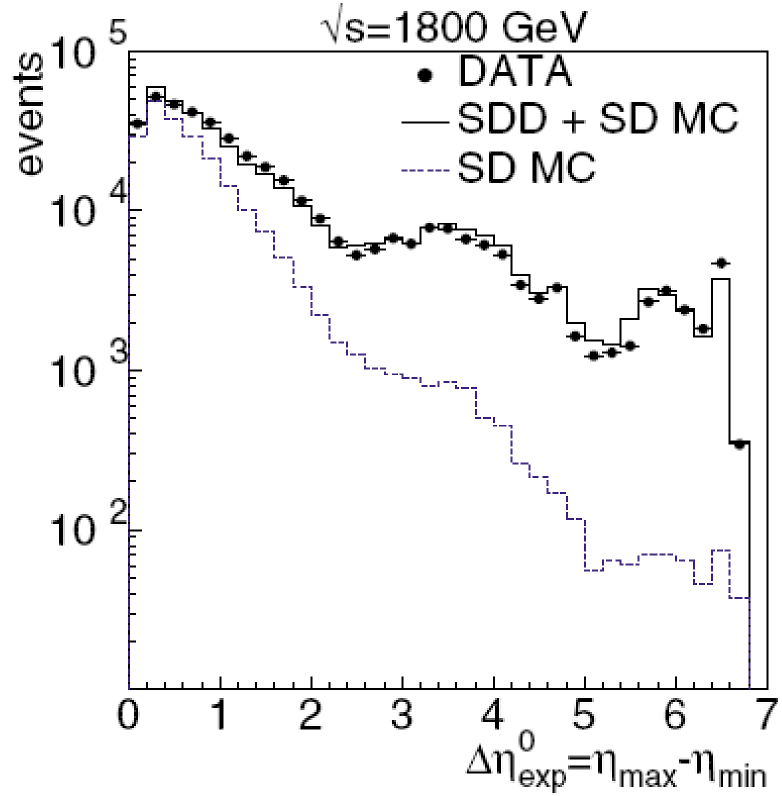
SDD at CDF



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

http://dx.doi.org/10.1103/PhysRevLett.91.011802

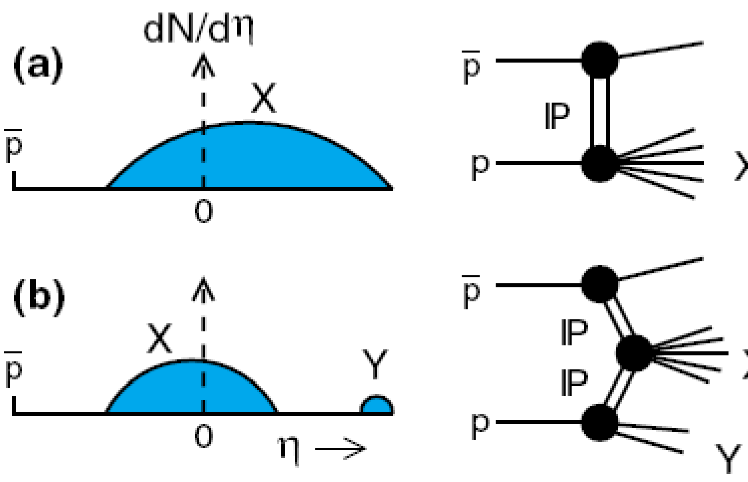
- Excellent agreement between data and MBR (MinBiasRockefeller) MC

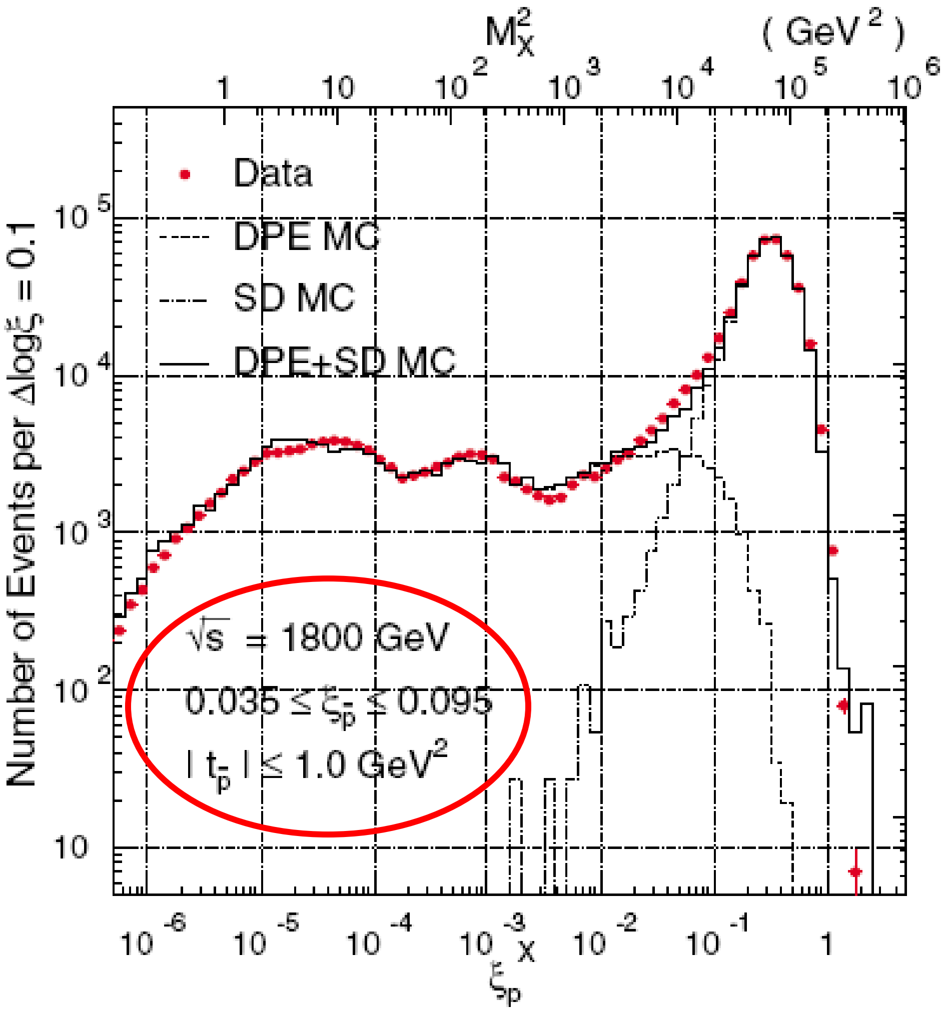


$$\frac{d^5\sigma}{dt_{\bar{p}}\,dt\,d\xi_{\bar{p}}\,d\Delta\eta\,d\eta_c} = \left[\frac{\beta(t)}{4\sqrt{\pi}}\, e^{[\alpha(t_{\bar{p}})-1]\ln(1/\xi)}\right]^2 \times \kappa\left\{\kappa\left[\frac{\beta(0)}{4\sqrt{\pi}}\, e^{[\alpha(t)-1]\Delta\eta}\right]^2 \kappa\left[\beta^2(0)\left(\frac{s''}{s_\circ}\right)^{\epsilon}\right]\right\}$$

CD/DPE at CDF

http://dx.doi.org/10.1103/PhysRevLett.93.141601





- Excellent agreement between data and MBR-based MC

➔ Confirmation that both **low and high mass x-sections** are correctly implemented

RENORM Difractive Cross Sections

http://arxiv.org/abs/1205.1446

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

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

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

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

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

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

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

CMG➔

R.J.M. Covolan [1], J. Montanha [2], K. Goulianos [3]
The Rockefeller University, 1230 York Avenue, New York, NY 10021, USA

PLB 389, 196 (1996)

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

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

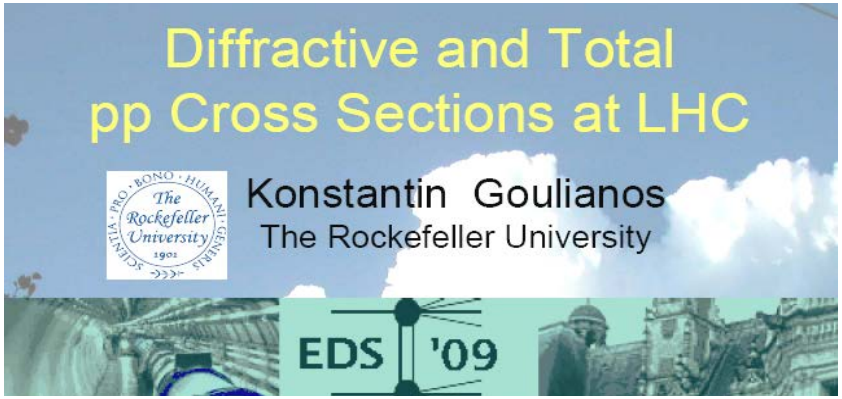
KG MORIOND-2011 http://moriond.in2p3.fr/QCD/2011/proceedings/goulianos.pdf

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

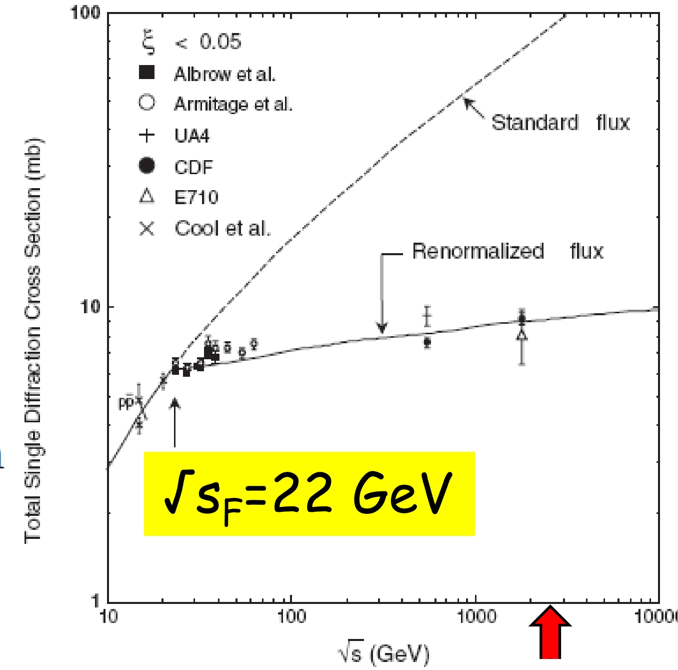
$$\sqrt{s_F} = 22\ \mathrm{GeV} \qquad s_0 = 3.7 \pm 1.5\ \mathrm{GeV}^2$$

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

- small extrapolation from 1.8 to 7 and up to 50 TeV



2009



- 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 (see Fig.) 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 CGM.

- Obtain the total cross section at the LHC:

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

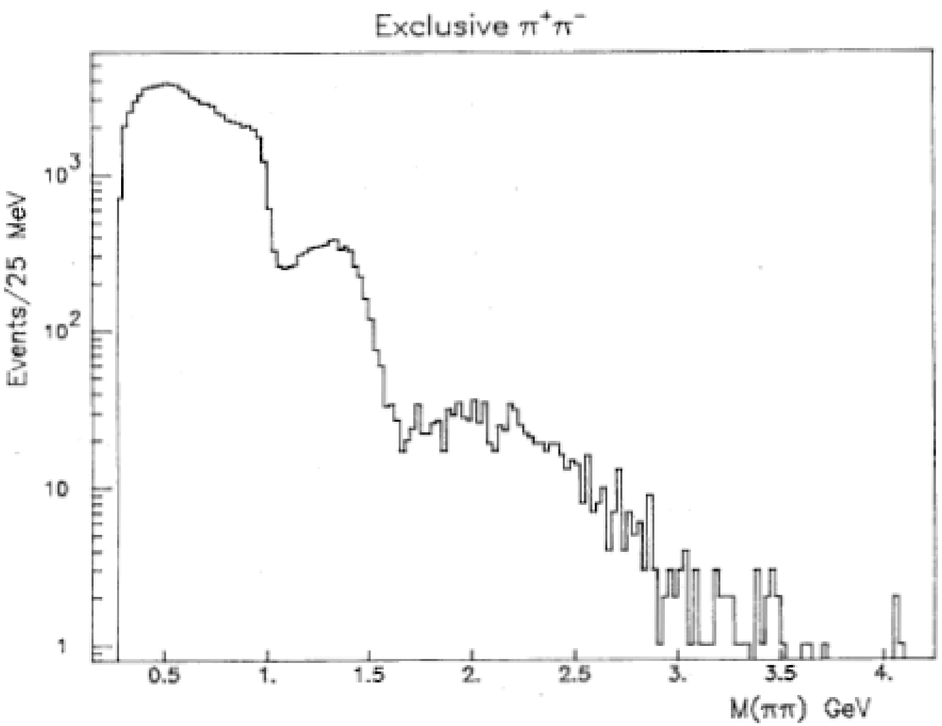
98 ± 8 mb at 7 TeV
109 ±12 mb at 14 TeV

Uncertainty is due to s_o

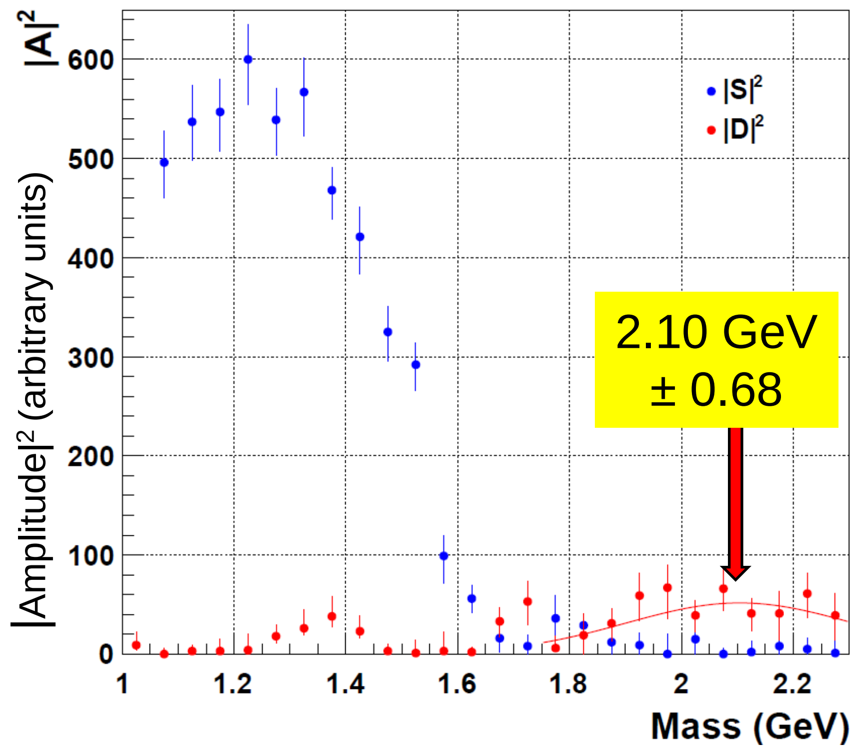
2015 Reduce Uncertainty in s_0

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

EDS 2015: http://dx.doi.org/10.5506/APhysPolBSupp.8.783



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_o
→x-sections decrease

Predictions vs Measurements ^{with}/reduced Uncertainty in s_o

$\sqrt{s}$	MBR/Exp	σ_{tot}	σ_{el}	σ_{inel}
7 TeV	MBR	95.4±1.2	26.4±0.3	69.0±1.0
	TOTEM totem-lumInd	98.3±0.2±2.8 98.0±2.5	24.8±0.2±1.2 25.2±1.1	73.7±3.4 72.9±1.5
	ATLAS	95.35±1.36	24.00±0.60	71.34±0.90
8 TeV	MBR	97.1±1.4	27.2±0.4	69.9±1.0
	TOTEM	101.7±2.9	27.1±1.4	74.7±1.7
13 TeV	MBR	103.7±1.9	30.2±0.8	73.5±1.3
	ATLAS		σ_{inel}=73.1±0.9(exp)±6.6(lumi) ±3.8(extra.)mb	

- RENORM/MBR with a **tensor-Pomeron model** predicts measured cross sections to the ~1% level
- **Test of RENORM/MBR**: ATLAS results using the ALFA and RP detectors to measure the cross sections

Stay tuned!

totem 7 TeV: http://arxiv.org/abs/1204.5689

totemLumInd 7 TeV http://iopscience.iop.org/article/10.1209/0295-5075/101/21004

atlas 7 TeV: http://arxiv.org/abs/1408.5778

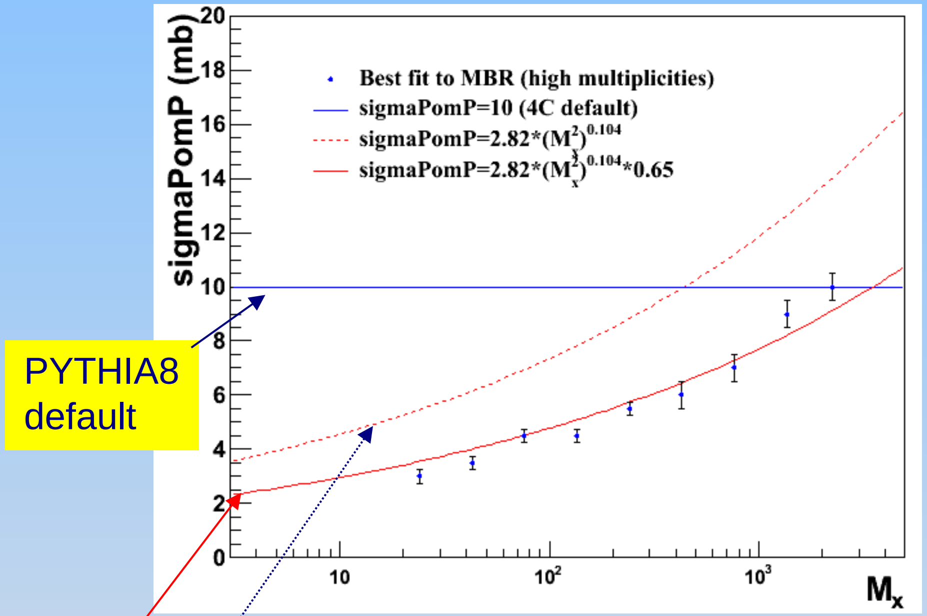
totem 8 TeV: http://dx.doi.org/10.1103/PhysRevLett.111.012001

atllas2016 13 TeV Aspen 2016 Doug Schafer talk:: https://indico.cern.ch/event/473000/timetable/#all.detailed

Pythia8-MBR Hadronization Tune

An example of the diffractive tuning of PYTHIA-8 to the RENORM-NBR model

$$n_{ave} = \frac{\sigma_{QCD}}{\sigma_{IPp}}$$



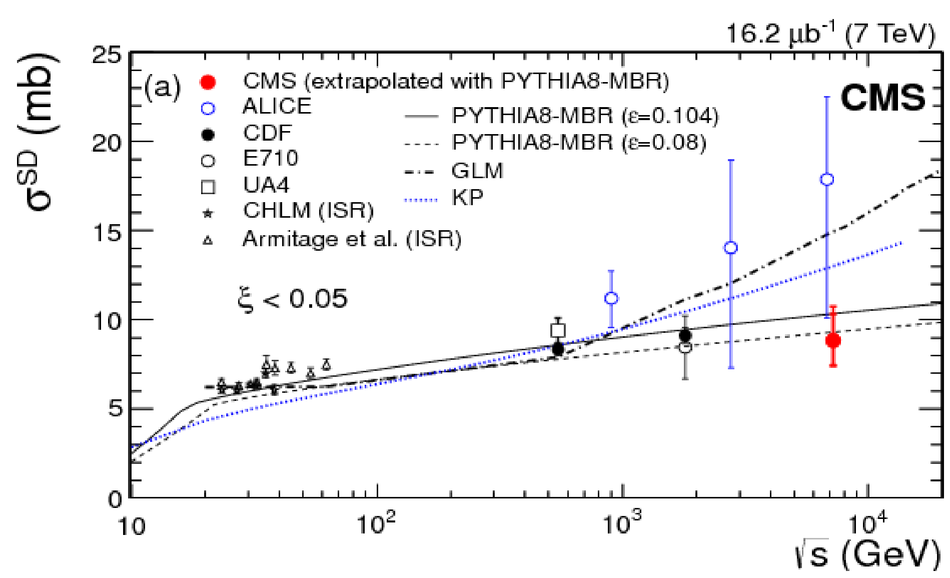
$\sigma^{Pp}(s)$ expected from Regge phenomenology for s_0=1 GeV^2 and DL t-dependence.

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

R. Ciesielski, "Status of diffractive models", CTEQ Workshop 2013

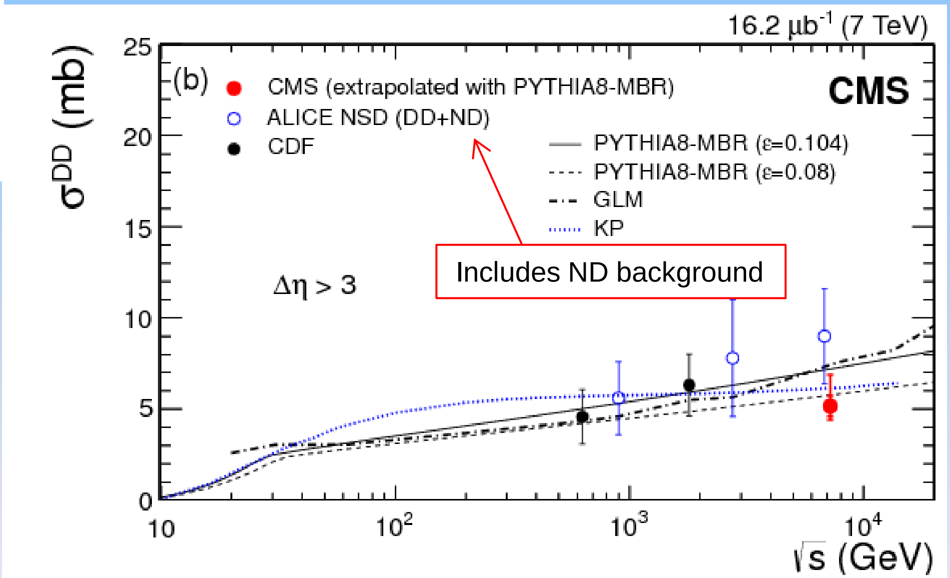
SD and DD x-Sections vs Models

http://dx.doi.org/10.1103/PhysRevD.92.012003



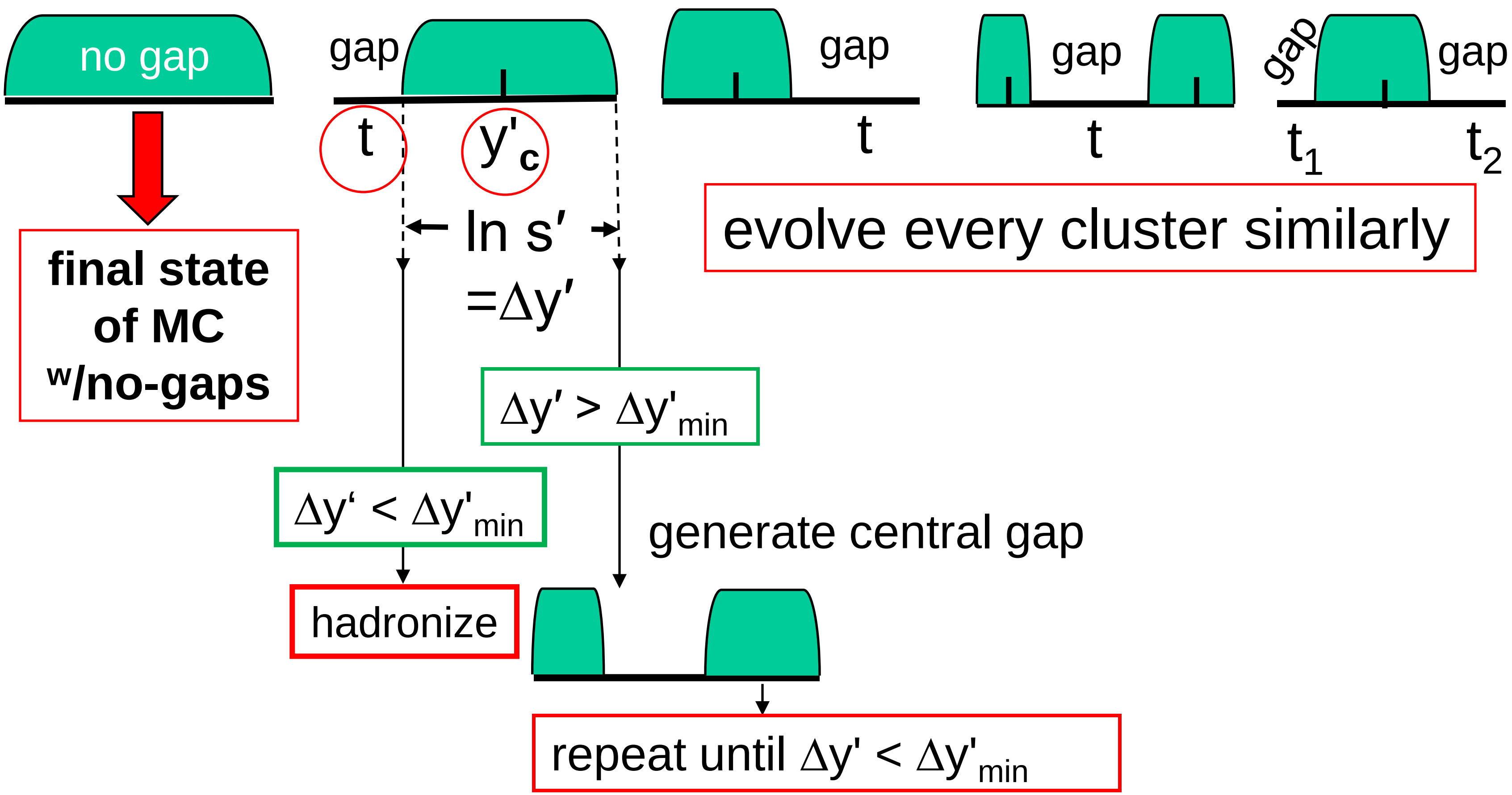
Single Diffraction

Double Diffraction



Monte Carlo Algorithm - Nesting

Profile of a pp Inelastic Collision



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 confirmed!

Thank you for your attention!