# Precision RENORM Tensor-Pomeron Cross Sections

Konstantin Goulianos
The Rockefeller University

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

5th International Conference on New Frontiers in Physics ICNFP2016
6-14 July 2016, Kolymbari, Crete, Greece ➔ http://indico.cern.ch/event/442094/









# 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: unambiguously determined
- Total Cross Section:
  - Unique prediction based on saturation and a tensor-Pomeron model



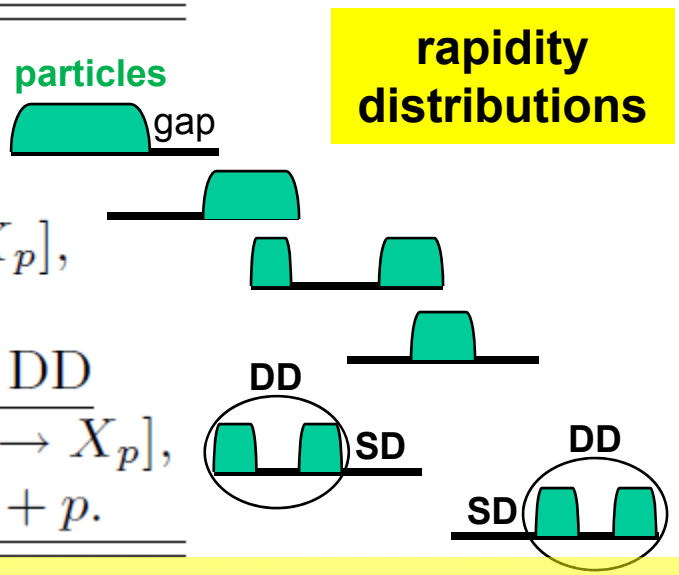
- Some previous papers/talks

- 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
- Moriond QCD 2016, La Thuile, Italy, March 19-26, http://moriond.in2p3.fr/QCD/2016/
- NPQCD16, Pris, June, https://www.brown.edu/conference/14th-workshop-non-perturbative-quantum-chromodynamics/

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

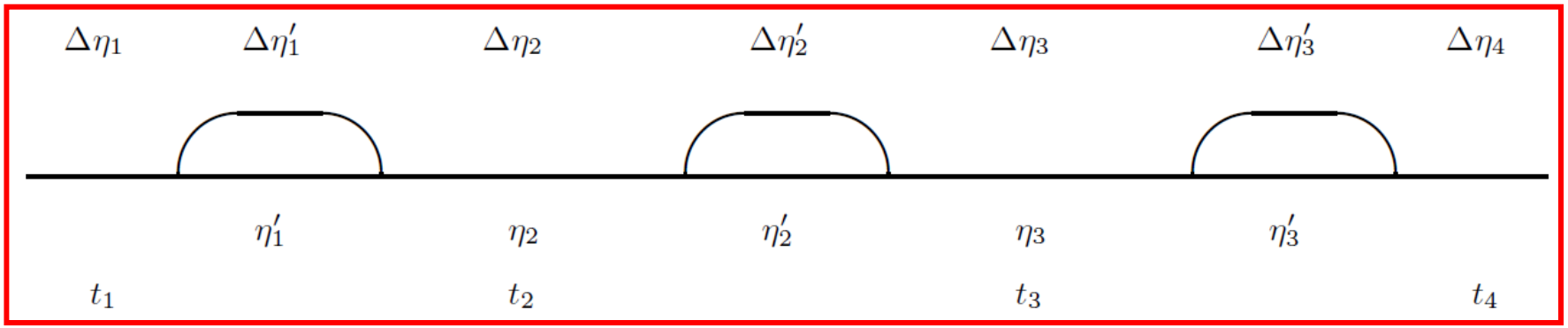
# RENORM: Basic and Combined Diffractive Processes

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




**Cross sections analytically expressed in arXiv::**

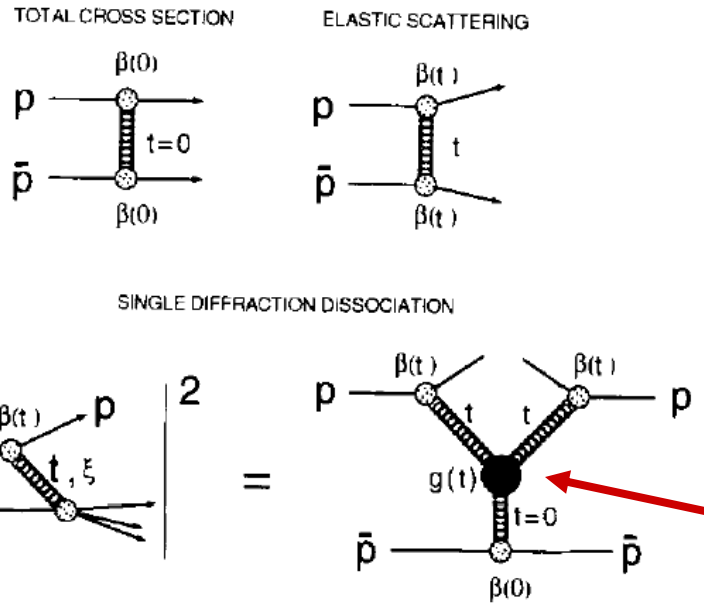
4-gap diffractive processes-Snowmass 2001 http://arxiv.org/abs/hep-ph/0110240



# 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?**

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

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

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

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

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

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

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

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

# Theoretical Complication: Unitarity!

$$\left(\frac{d\sigma_{el}}{dt}\right)_{t=0} \sim \left(\frac{s}{s_o}\right)^{2\epsilon}, \ \sigma_t \sim \left(\frac{s}{s_o}\right)^{\epsilon}, \ \text{and} \ \sigma_{sd} \sim \left(\frac{s}{s_o}\right)^{2\epsilon}$$

- $\sigma_{sd}$ grows faster than $\sigma_t$ as $s$ increases *
  ➔ unitarity violation at high $s$

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

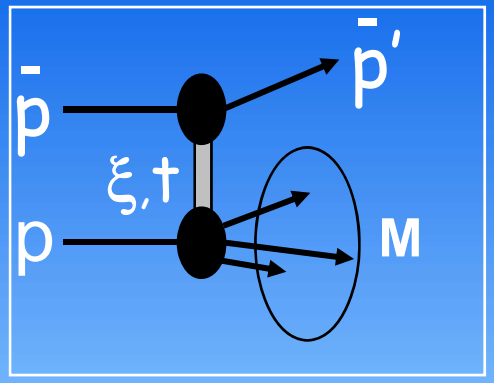
- the unitarity limit is already reached at $\sqrt{s} \sim 2$ TeV

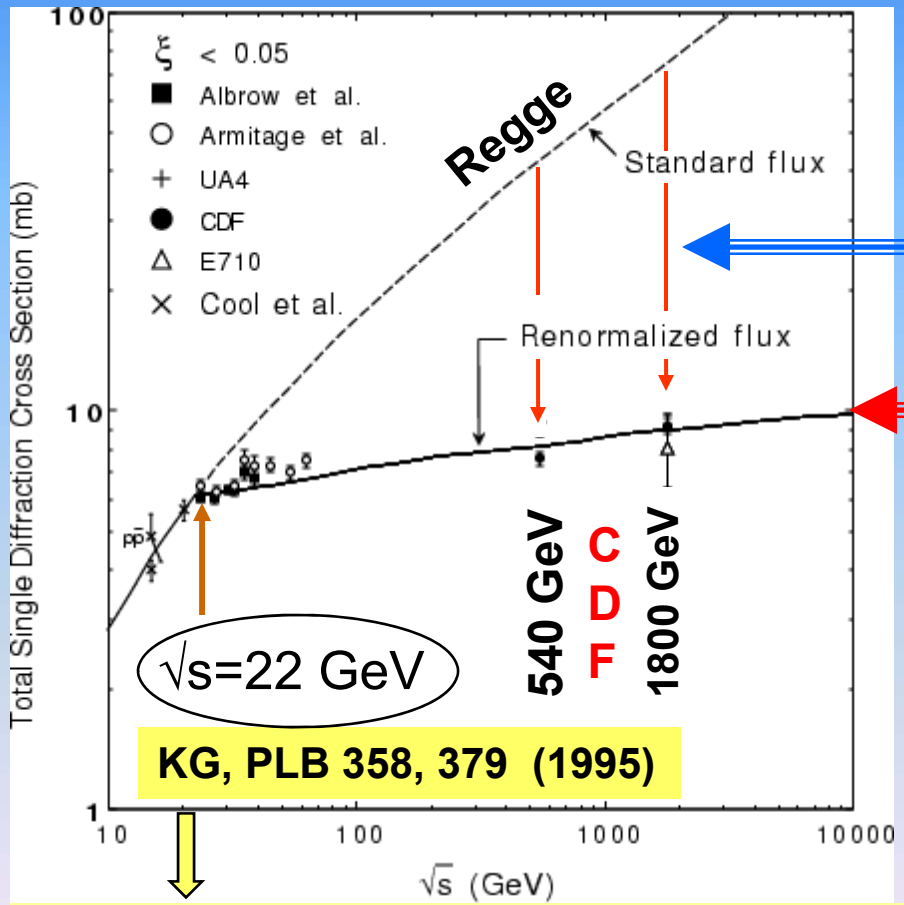
- need unitarization

* similarly for $(d\sigma_{el}/dt)_{t=0}$ w.r.t. $\sigma_t$, 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

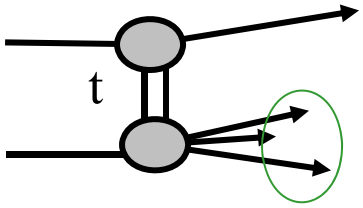
**RENORMALIZATION**

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

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

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

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 ➔

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

**KG&JM, PRD 59 (114017) 1999**
http://dx.doi.org/10.1103/PhysRevD.59.114017

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

# Single Diffraction Renormalized - 3

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

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

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

←affects only the s-dependence

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

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

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

# $M^2$ - Distribution: Data

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

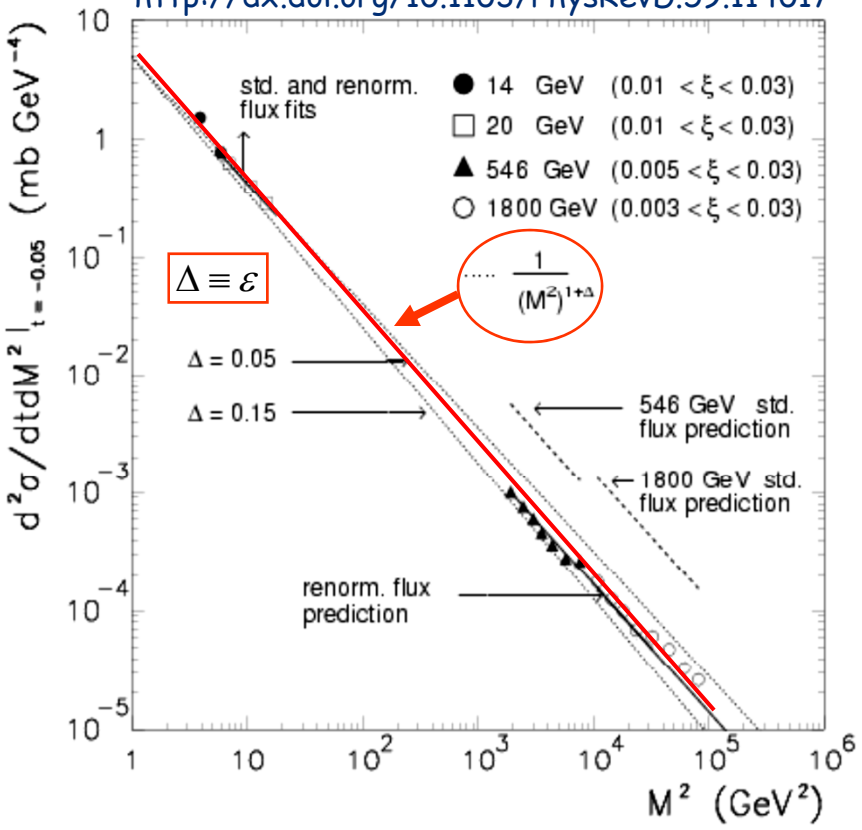
http://physics.rockefeller.edu/publications.html

**KG&JM, PRD 59 (1999) 114017**

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

Regge → data

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



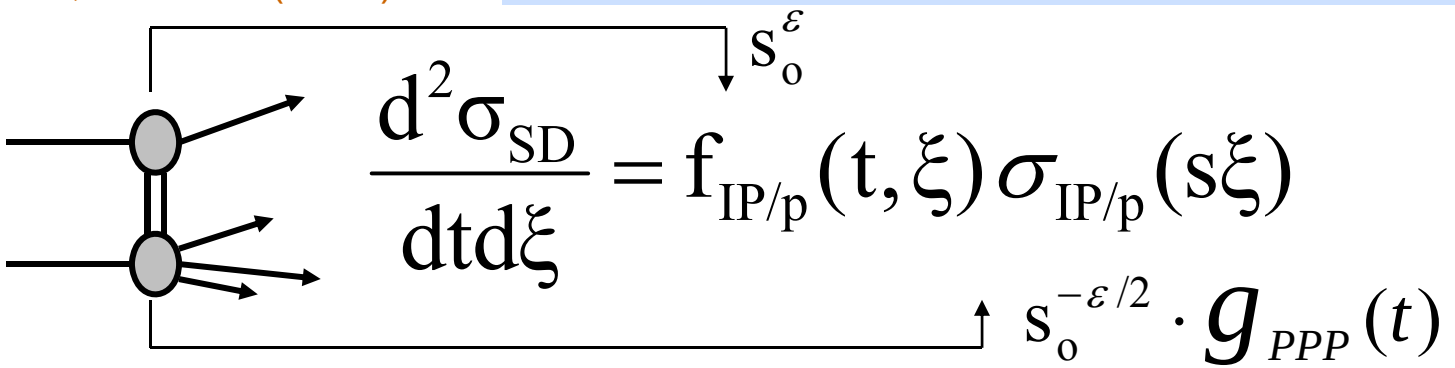

➔ factorization breaks down to ensure $M^2$-scaling

# 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

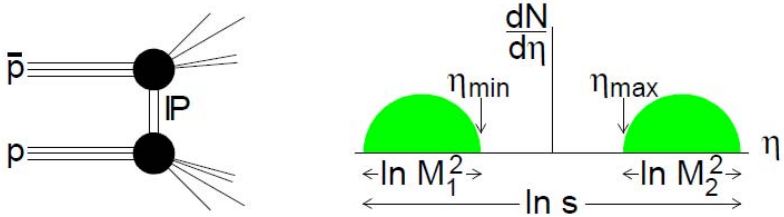



Pomeron-proton x-section

- Two free parameters: $s_o$ and $g_{PPP}$
- Obtain product $g_{PPP}\, s_o^{\varepsilon/2}$ from $\sigma_{SD}$
- 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



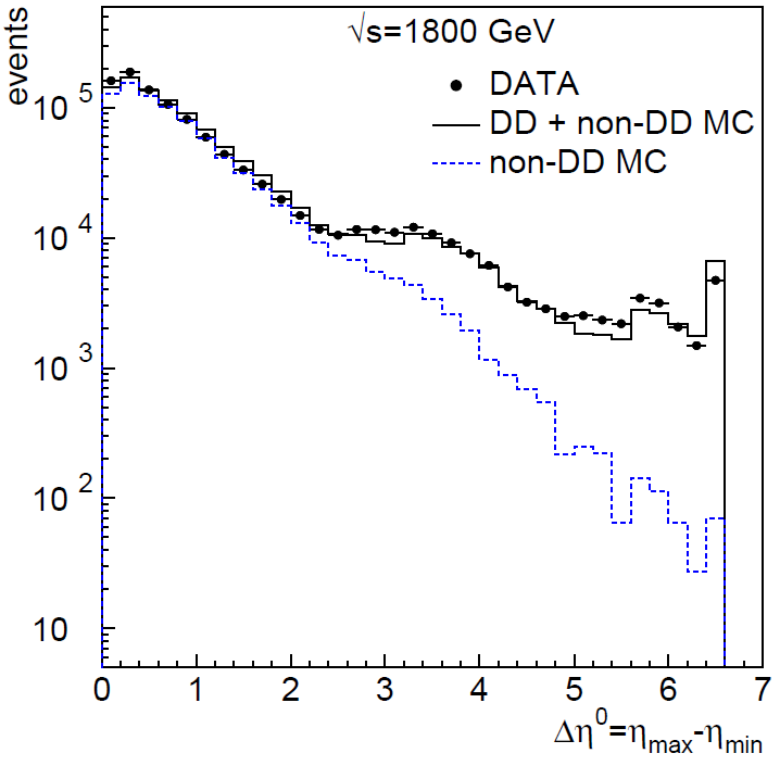

$$\frac{d^3\sigma_{DD}}{dtdM_1^2dM_2^2} = \frac{d^2\sigma_{SD}}{dtdM_1^2}\frac{d^2\sigma_{SD}}{dtdM_2^2} \Big/ \frac{d\sigma_{el}}{dt}$$

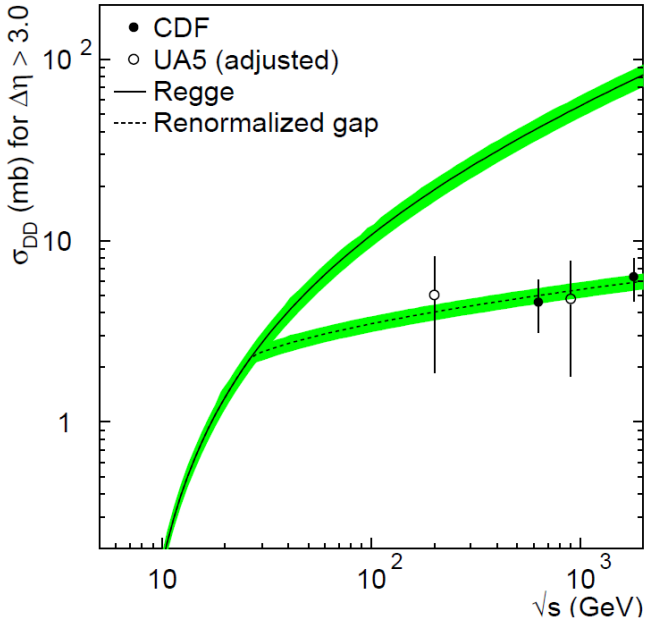
$$= \frac{[\kappa\beta_1(0)\beta_2(0)]^2}{16\pi} \frac{s^{2[\alpha(0)-1]}\, e^{b_{DD}t}}{(M_1^2M_2^2)^{1+2[\alpha(0)-1]}}$$

**Regge factorization**

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

gap probability  x-section



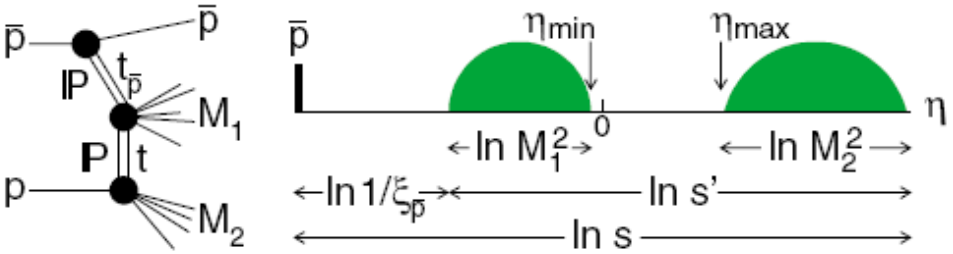




**←Regge**

**Regge ← RENORM**

x-section divided by integrated gap prob.

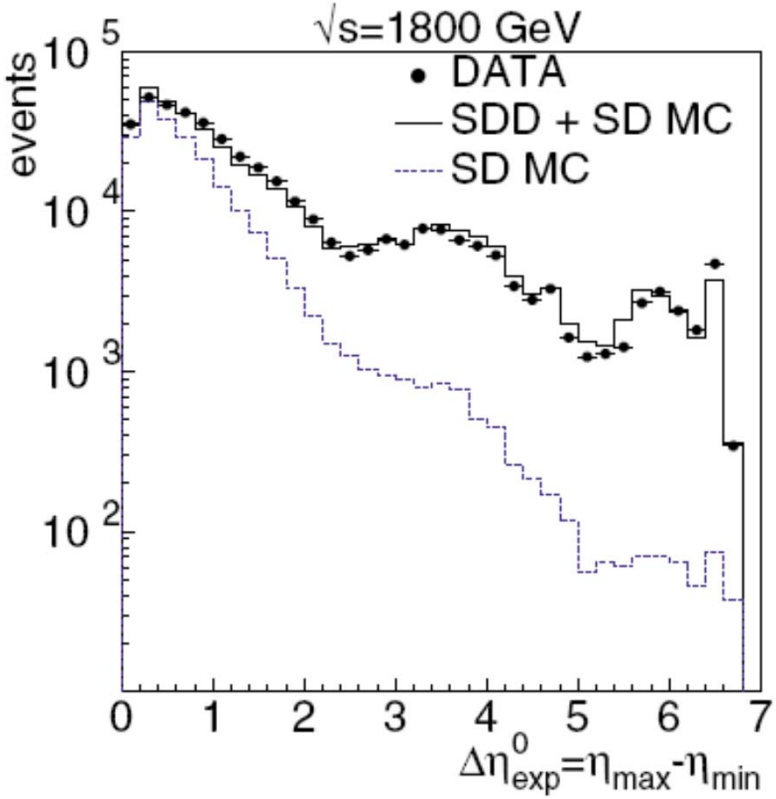
# SDD at CDF




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

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

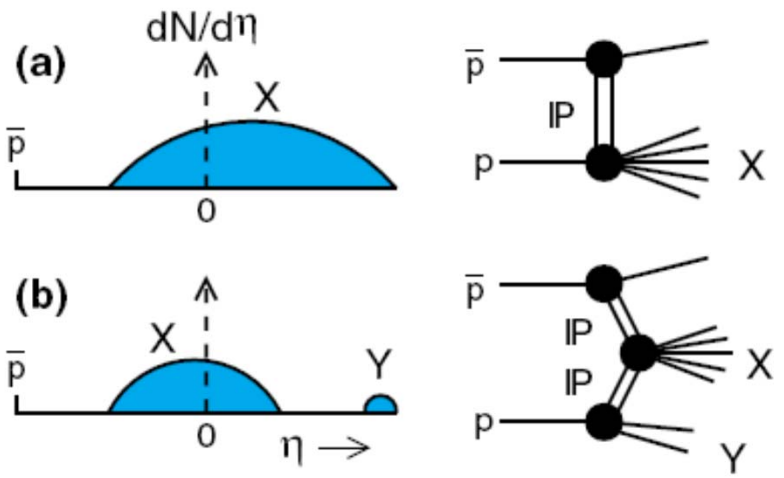
- Excellent agreement between data and MBR (MinBiasRockefeller) MC

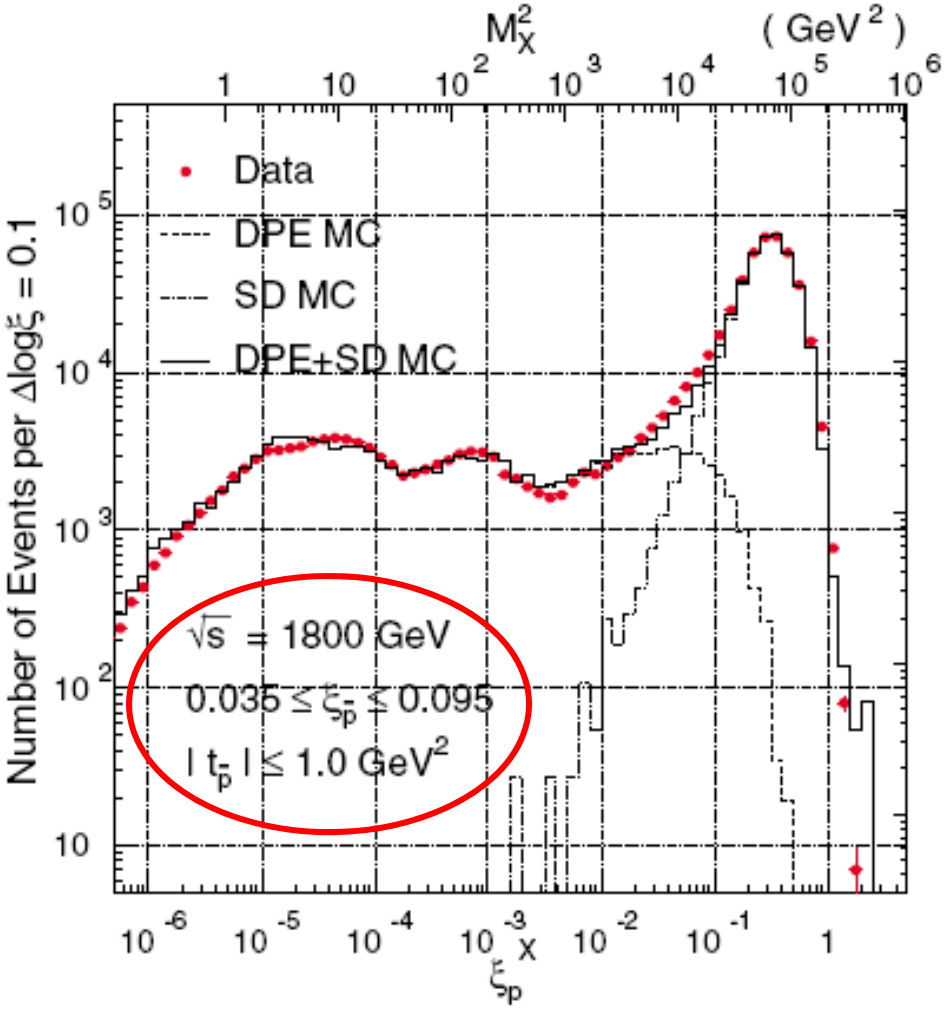



$$\frac{d^5\sigma}{dt_{\bar{p}}dtd\xi_{\bar{p}}d\Delta\eta d\eta_c} = \left[\frac{\beta(t)}{4\sqrt{\pi}}\, e^{[\alpha(t_{\bar{p}})-1]\ln(1/\xi)}\right]^2 \times \kappa\left\{\kappa\left[\frac{\beta(0)}{4\sqrt{\pi}} e^{[\alpha(t)-1]\Delta\eta}\right]^2 \kappa\left[\beta^2(0)\left(\frac{s''}{s_\circ}\right)^{\epsilon}\right]\right\}$$

# 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

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

$$\frac{d^3\sigma_{DD}}{dtd\Delta ydy_0} = \frac{1}{N_{\rm gap}(s)}\left[\frac{\kappa\beta^2(0)}{16\pi}e^{2[\alpha(t)-1]\Delta y}\right]\cdot\left\{\kappa\beta^2(0)\left(\frac{s'}{s_0}\right)^{\epsilon}\right\},$$

$$\frac{d^4\sigma_{DPE}}{dt_1dt_2d\Delta ydy_c} = \frac{1}{N_{\rm gap}(s)}\left[\Pi_i\left[\frac{\beta^2(t_i)}{16\pi}e^{2[\alpha(t_i)-1]\Delta y_i}\right]\right]\cdot\kappa\left\{\kappa\beta^2(0)\left(\frac{s'}{s_0}\right)^{\epsilon}\right\}$$

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

$$F^2(t) = \left[\frac{4m_p^2-2.8t}{4m_p^2-t}\left(\frac{1}{1-\frac{t}{0.71}}\right)^2\right]^2 \approx a_1e^{b_1t}+a_2e^{b_2t}$$

$\alpha_1$=0.9, $\alpha_2$=0.1, $b_1$=4.6 GeV$^{-2}$, $b_2$=0.6 GeV$^{-2}$, s′=s $e^{-\Delta y}$, $\kappa$=0.17, $\kappa\beta^2(0)=\sigma_0$, $s_0$=1 GeV$^2$, $\sigma_0$=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 [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

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

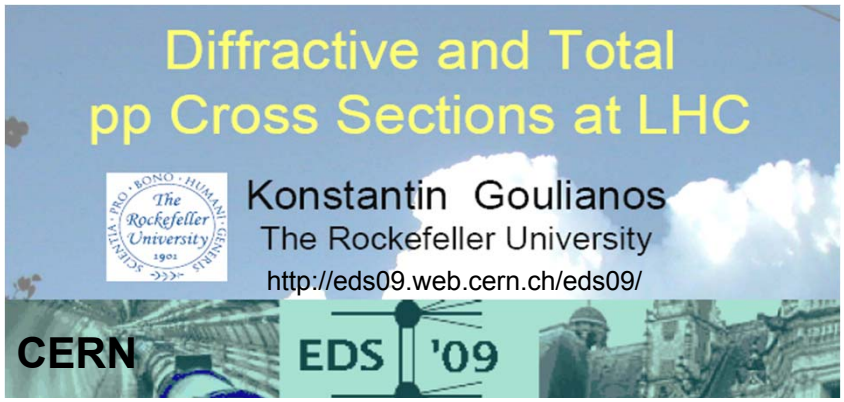
KG MORIOND-2011 http://moriond.in2p3.fr/QCD/2011/proceedings/goulianos.pdf

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

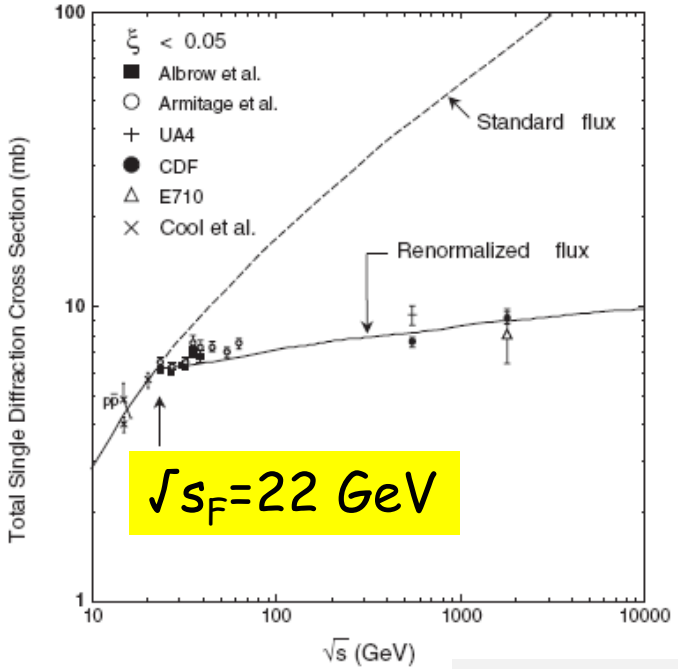
$$\sqrt{s_F} = 22 \text{ GeV} \qquad s_0 = 3.7 \pm 1.5 \text{ GeV}^2$$

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

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




2009




$\sqrt{s_F}$=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 $\sigma_{sd}$ vs. $\sqrt{s}$ at $\sqrt{s_F} = 22$ GeV 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 $\text{mb}^{-1}$.

- 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

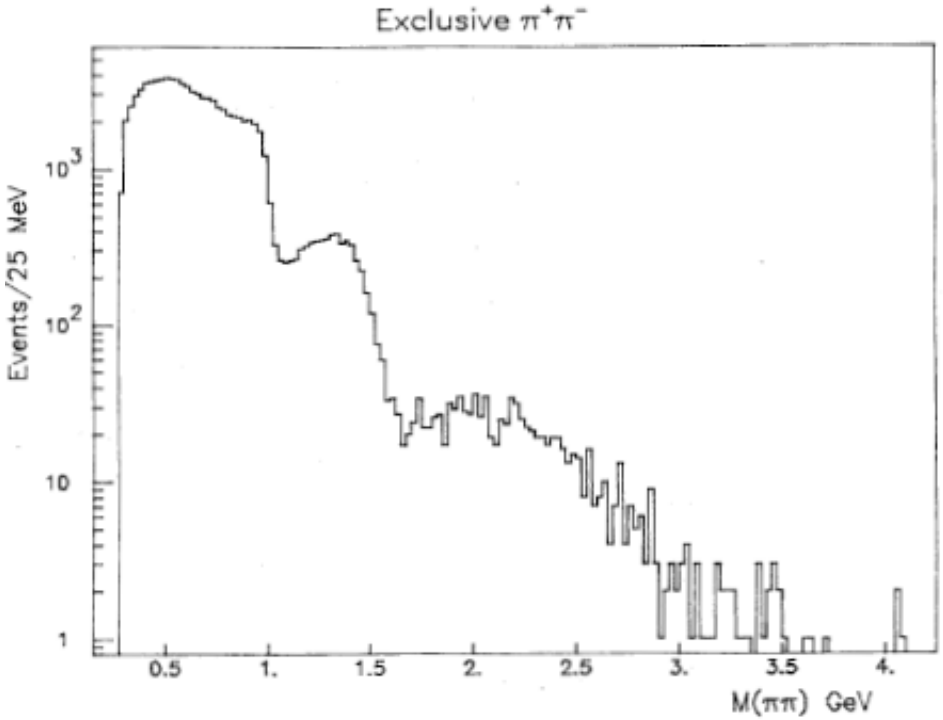
Uncertainty is due to $s_o$

2015

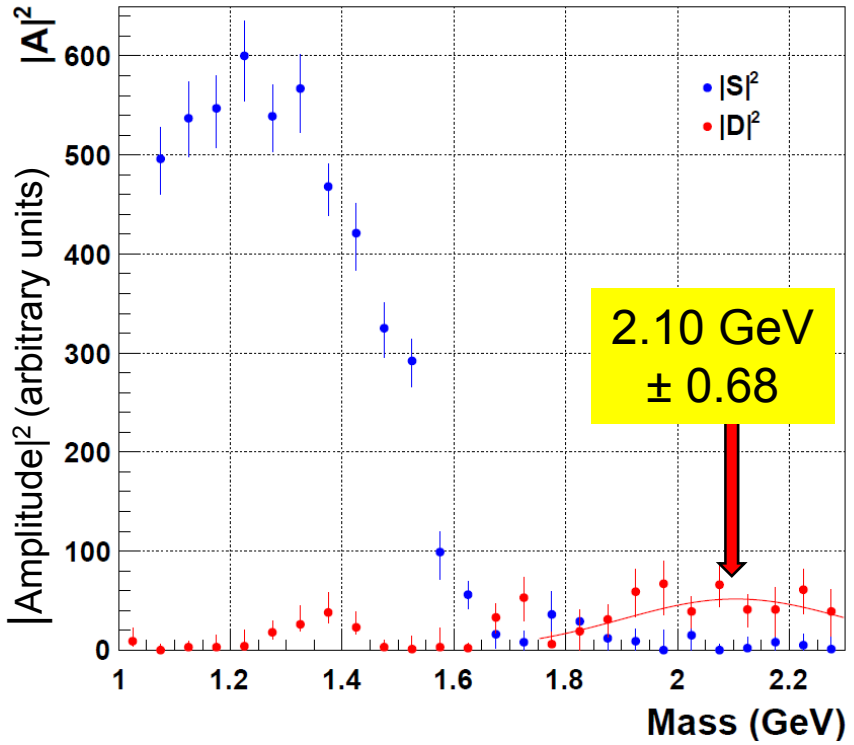
# Reduce Uncertainty in $s_0$

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
- $\langle M_{tgb} \rangle = \sqrt{s_0} = 2.10 \pm 0.68$ 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 $s_o$

From my Moriond-2016 Talk

| $\sqrt{s}$ | MBR/Exp | $\sigma_{tot}$ | $\sigma_{el}$ | $\sigma_{inel}$ |
|---|---|---|---|---|
| 7 TeV | MBR | 95.4±1.2 | 26.4±0.3 | 69.0±1.0 |
| | TOTEM<br>totem-lumInd | 98.3±0.2±2.8<br>98.0±2.5 | 24.8±0.2±1.2<br>25.2±1.1 | 73.7±3.4<br>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 | | $\sigma_{inel}$=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

Totem-Lum-Ind 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

Atlas13 TeV Aspen 2016 Doug Schafer https://indico.cern.ch/event/473000/timetable/#all.detailed

Atlas/Totem 13TeV DIS15 https://indico.desy.de/contributionDisplay.py?contribId=330&confId=12482

# Predictions vs Measurements w/reduced Uncertainty in $s_o$ #1

**NEW!**

| $\sqrt{s}$ | MBR/Exp | Reference ➔next slide | $s_{tot}$ | $s_{el}$ | $S_{inel}$ |
|---|---|---|---|---|---|
| 7 TeV | MBR | | 95.4±1.2 | 26.4±0.3 | 69.0±1.0 |
| | ATLAS | 1 | 95.35±1.36 | 24.00±0.60 | 71.34±0.90 |
| | TOTEM | 2 | 101.7±2.9 | 27.1±1.4 | 74.7±1.7 |
| | TOTEM_Lum_Ind | 3 | 98.0±2.5 | 24.00±0.60 | 72.9±1.5 |
| 8 TeV | MBR | | 97.1±1.4 | 27.2±0.4 | 69.9±1.0 |
| | TOTEM | 4 | 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 | 5 & 6 | | | 73.1±0.9 (exp) ±6.6 (lumi) ±3.8 (extr) |
| | CMS | 7 | | | **71.3±0.5 (exp) ±2.1 (lumi) ±2.7 (extr)** |

CONT➔

# Predictions vs Measurements w/reduced Uncertainty in $s_o$ #2

*Caveat*

The MBR $\sigma_{el}$ is larger than the ATLAS and the TOTEM_lum_Ind measurements by ~2 mb at $\sqrt{s}$=7 TeV, which might imply a higher MBR prediction at $\sqrt{s}$=13 TeV by 2-3 mb. Lowering the MBR $\sigma_{el}$ prediction would lead to a larger $\sigma_{inel}$ . This interplay between $\sigma_{el}$ and $\sigma_{inel}$ should be kept in mind as more results of $\sigma_{el}$ and $\sigma_{tot}$ at $\sqrt{s}$ = 13 TeV become available.

- 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!*


1) Atlas 7 TeV: http://arxiv.org/abs/1408.5778

2) Totem 7 TeV http://arxiv.org/abs/1204.5689

3) Totem-Lum-Ind 7 TeV http://iopscience.iop.org/article/10.1209/0295-5075/101/21004

4) Totem 8 TeV http://dx.doi.org/10.1103/PhysRevLett.111.012001

5) Atlas13 TeV Aspen 2016 D. Schafer https://indico.cern.ch/event/473000/timetable/#all.detailed

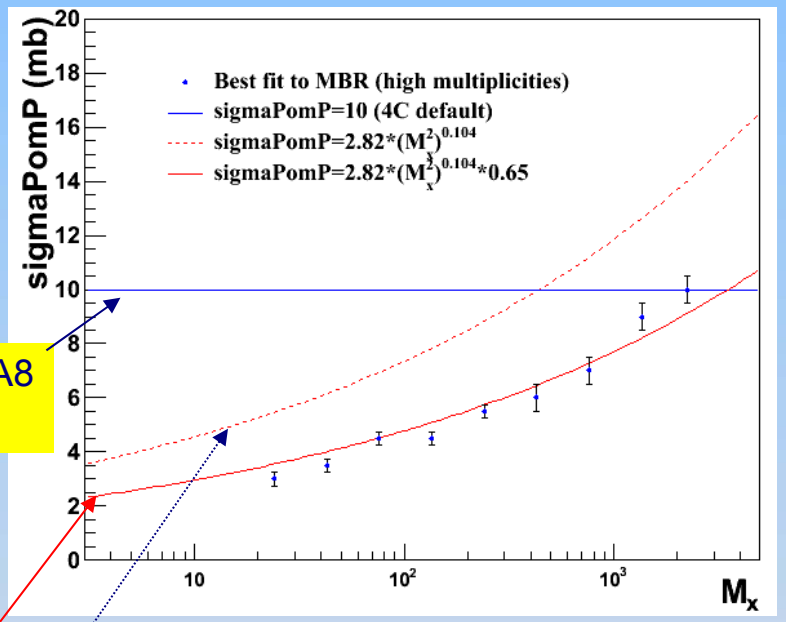
6) Atlas 13TeV DIS-2016 M. Trzebinski ttps://indico.desy.de/contributionDisplay.py?contribId=330&confId=12482

7) CMS 13TeV DIS-2016 H. Van Haevermaet https://indico.desy.de/contributionDisplay.py?contribId=105&confId=12482

# Pythia8-MBR Hadronization Tune

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

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




PYTHIA8 default

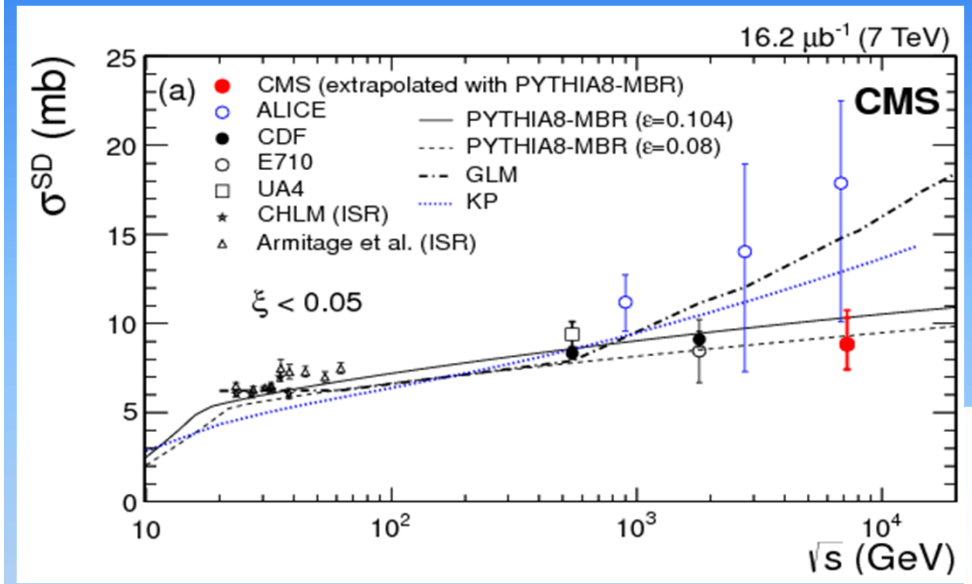
$\sigma^{Pp}(s)$ expected from Regge phenomenology for $s_0$=1 GeV$^2$ and DL t-dependence.

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

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

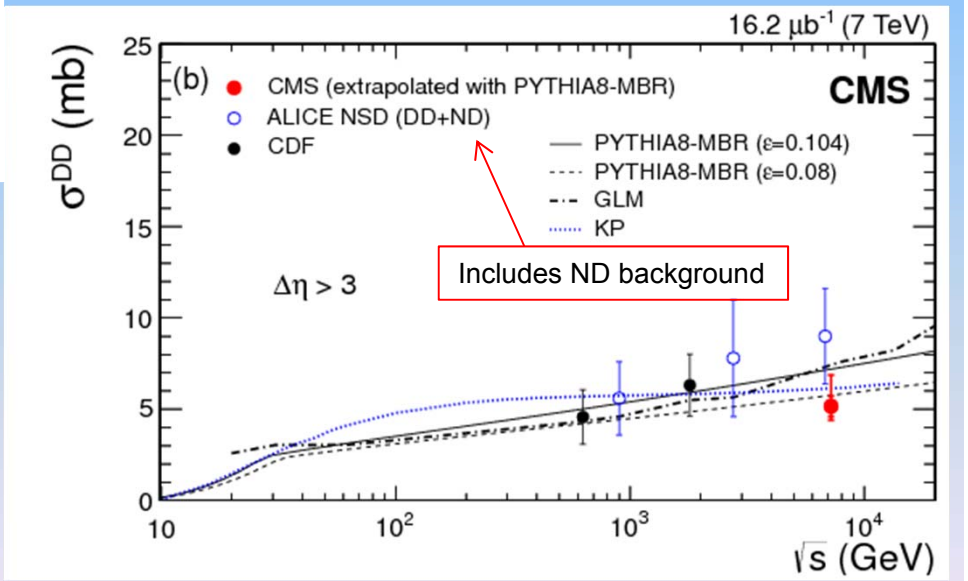
# SD and DD x-Sections vs Models

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

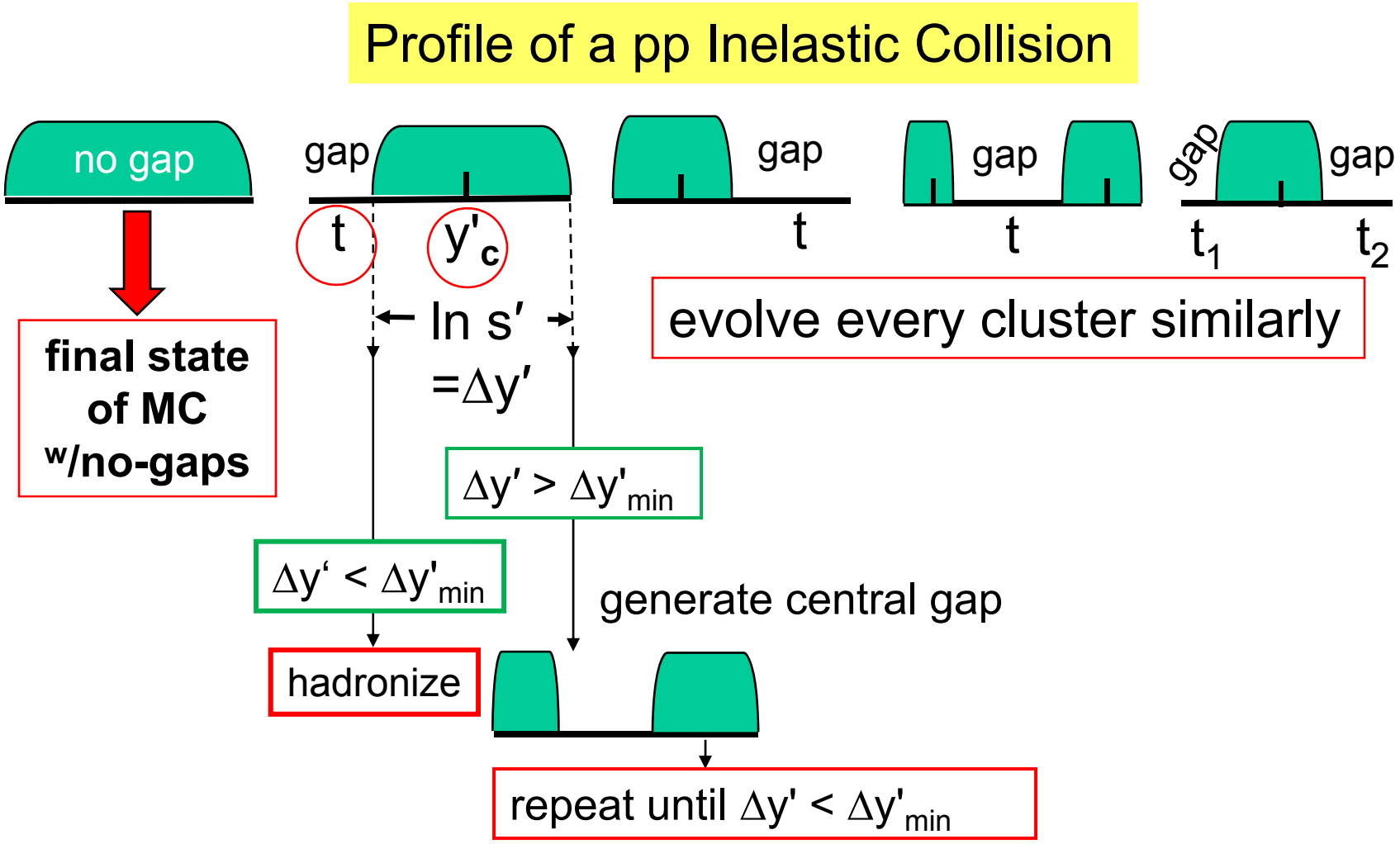



Single Diffraction

Double Diffraction



# Monte Carlo Algorithm - Nesting



# 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!*