MBR (Minimum-Bias Rockefeller) simulation in Pythia8

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Introduction

- About 30% of the total pp cross section at LHC is attributed to diffractive events (rapidity gaps).
- Large uncertainties in the modelling of diffractive component.
- MBR (Minimum-Bias Rockefeller) Monte Carlo simulation - an event generator addressing the contribution from diffractive processes:
  - Predicts energy dependence of the total, elastic and total-inelastic cross sections.
  - Fully simulates diffractive components (SD, DD, CD → next slide) of total-inel. cross section.
  - Originally written for, and tested at CDF (Tevatron).
  - Recently implemented in Pythia8.165.

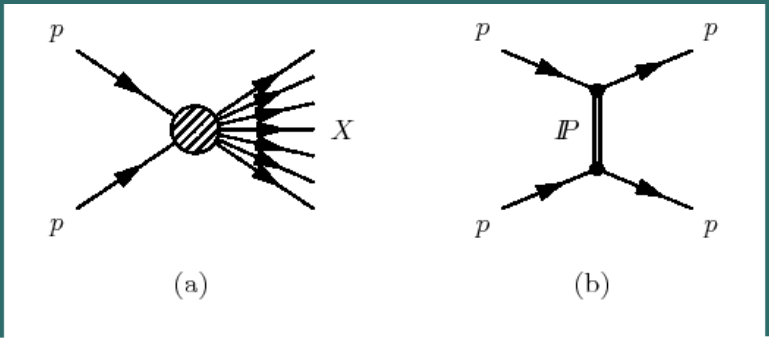
Documented in arXiv:1205.1446.

Main processes contributing to the total *pp* cross section

Non-diffractive:

pp → X

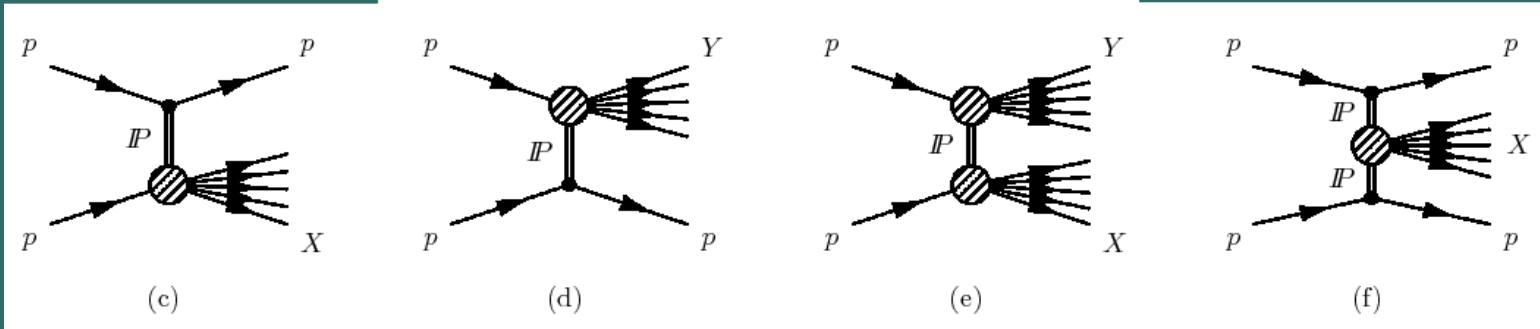
(exponentially-suppressed rapidity gap)



:Elastic

pp → pp

Diffractive:



Single dissociation (SD),

pp → Xp , pp → pY

Double dissociation (DD),

pp → XY

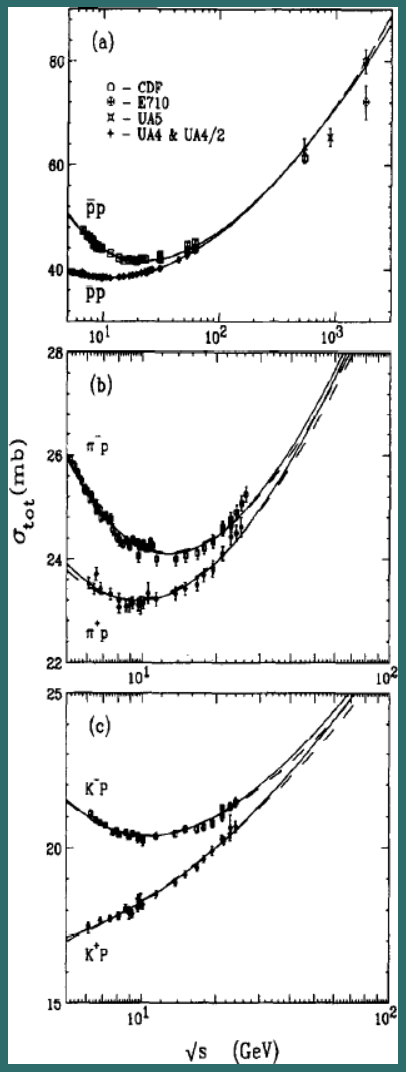
Central dissociation (CD)

pp → pXp

or double-Pomeron exchange (DPE)

(a) and (c)-(f) contribute to the total-inelastic cross section

Total, elastic and total-inelastic cross sections



- **Total pp cross section**

Energy dependence:

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

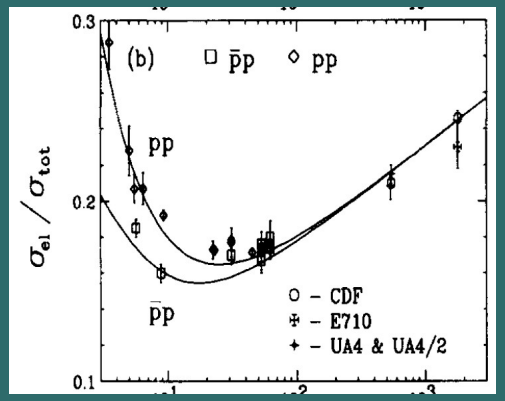
- **For √s < 1.8 TeV – global fit to pre-LHC data on $p^\pm p$, $K^\pm p$, $\pi^\pm p$ cross-sections.** Phys.Lett B389, 176 (1996)

- **For √s > 1.8 TeV (LHC and beyond) – model based on a saturated Froissart bound.** arXiv:1105.4916

Froissart bound with two parameters: s_F = 22 GeV, s_0 = 3.7±1.5 GeV^{-2}, normalized to the CDF measurement @1.8 TeV: 80.03 ±2.24 mb.

Total, elastic and total-inelastic cross sections

Phys.Lett B389, 176 (1996)



- **Elastic cross section**

$$\sigma_{el} = r \bullet \sigma_{tot}$$

with $r = \sigma_{el}/\sigma_{tot}$ from the global fit. →

Linear *log(s)* dependence at higher energies not expected to obey black-disk limit → model valid up to energies of O(50 TeV).

- **Total-inelastic cross section**

$$\sigma_{inel} = \sigma_{tot} - \sigma_{el}$$

Diffractive cross sections

- **Calculated based on renormalized-Regge theory.**

hep-ph/0407035
arXiv:hep-ph/020314

- **Differential cross sections vs. rapidity gap width, Δy, and 4-momentum transfer squared, t:**

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

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

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

$$\Delta y = \Delta y_1 + \Delta y_2$$

DD: y_0 – center of rapidity gap, DPE: y_c – rapidity of dissociated system

$$\alpha(t) = 1 + \epsilon + \alpha' t = 1.104 + 0.25\ (\mathrm{GeV}^{-2})\cdot t$$

$$\beta^2(t) = \beta^2(0)F^2(t) \qquad \kappa \equiv g(t)/\beta(0)$$

$$\xi = e^{-\Delta y} \qquad \xi_{\rm SD} = M^2/s$$

$$\xi_{\rm DD} = M_1^2 M_2^2/(s\cdot s_0)$$

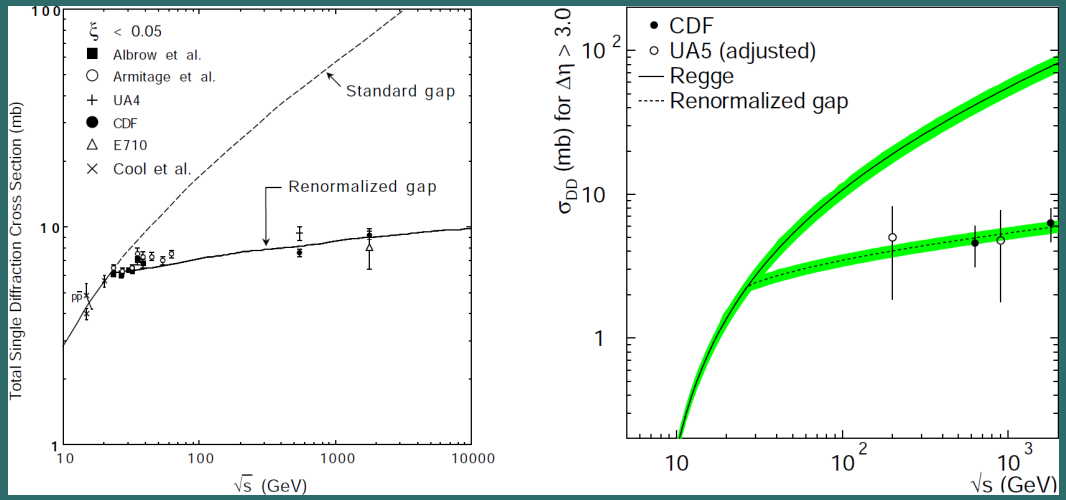
$$\mathrm{DPE}\ \xi = \xi_1\xi_2 = M^2/s$$

- **Term in { } brackets: total Pomeron-p cross section at a reduced energy $s'=s\cdot e^{-dy}$.**
- **Term in [ ] brackets: Pomeron flux.**
- ***$N_{gap}(s)$*: renormalization factor: *min(1,f)*, with *f* := integral of Pomeron flux**

  → allows to interpret the flux as (diffractive) gap-formation probability.

Diffractive cross sections

- **Flux renormalization procedure brings the standard Regge theory predicitons in agreement with the CDF data.**



from arXiv:hep-ph/020314

- **Small gap widths, diffractive limit**

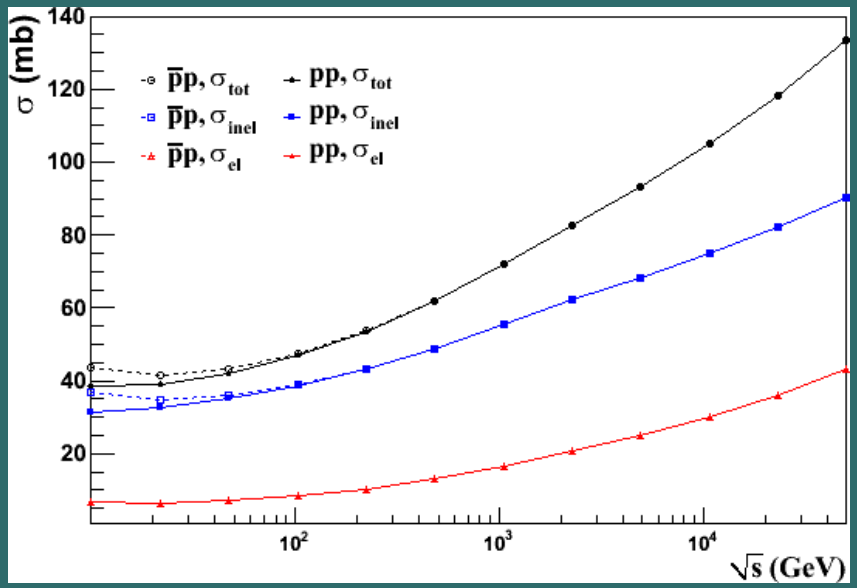
Cross section formulae are used to generate events with large (diffractive) rapidity gaps. Small gaps are suppressed by convoluting the formulae with the error function (cumulative Gauss distribution) centered at $\Delta y_s = 2$ with a width of $\sigma_s = 0.5$:

$$S = \frac{1}{2}\left[1 + erf\left(\frac{\Delta y - \Delta y_S}{\sigma_S}\right)\right]$$

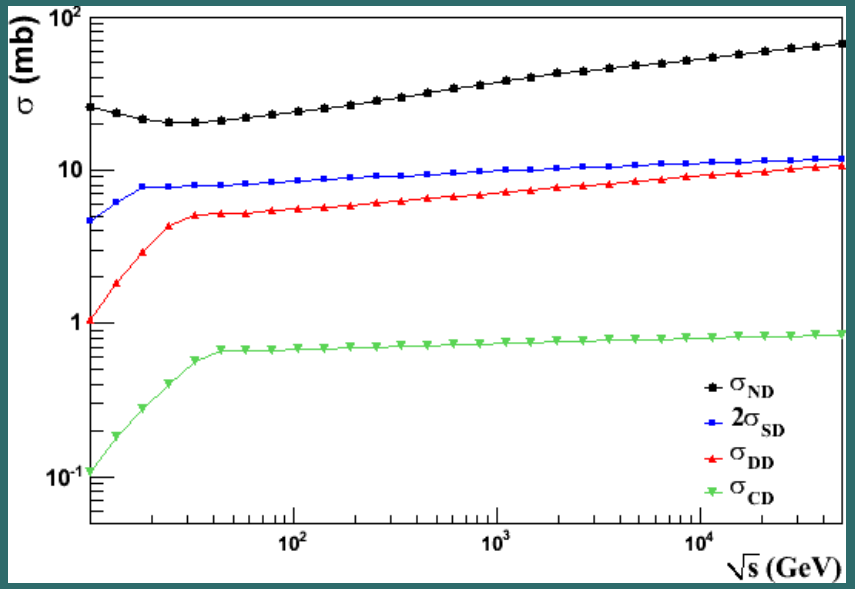
SD events: coherence limit ($\xi \leq 0.135$)
DD events: arbitrary choice, because small gaps in DD and ND events cannot be unambiguously distinguished.
CD events: suppression applied on total gap width, $\Delta y = \Delta y_1 + \Delta y_2$.

Cross section predictions

Total, elastic, total-inel. xsecs



Components of total-inel. xsec: diffractive (SD,DD,CD) and non-diffractive (ND) xsecs



Cross section values [mb] vs. energy

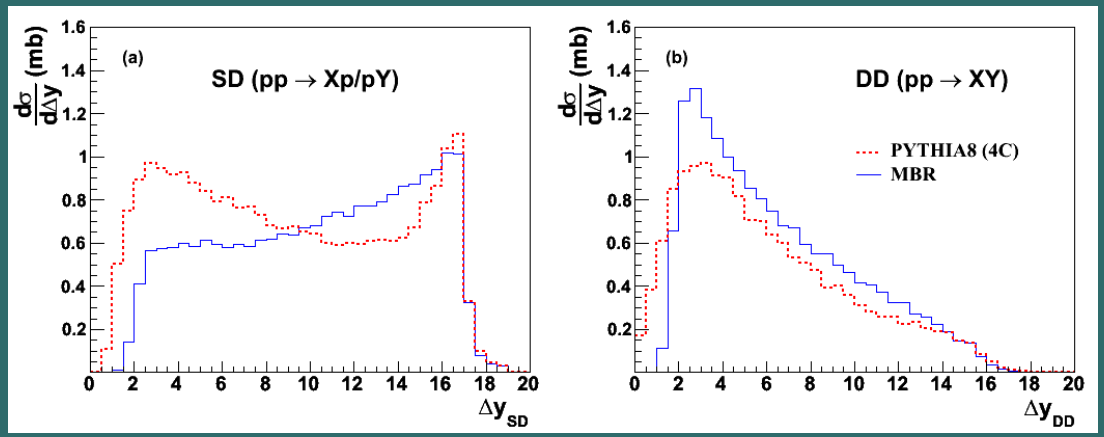
$\sqrt{s}$ (TeV)	0.3	0.9	1.96	2.76	7	8	14
σ_{tot}	56.50	69.87	81.03	85.25	98.29	100.35	109.49
σ_{el}	11.28	15.83	19.97	21.70	27.20	28.09	32.10
σ_{inel}	45.23	54.04	61.06	63.55	71.10	72.26	77.39
σ_{ND}	29.19	36.50	42.41	44.39	50.57	51.54	55.84
σ_{2SD}	9.10	9.76	10.22	10.41	10.91	10.98	11.26
σ_{DD}	6.21	7.03	7.67	7.97	8.82	8.94	9.47
σ_{CD}	0.718	0.746	0.766	0.776	0.800	0.804	0.818

Implementation in Pythia8.165

- **MBR simulation activated with Diffraction:PomFlux = 5**
- **SD, DD processes**

MBR code added to the already existing simulation of processID =103,104 and 105.

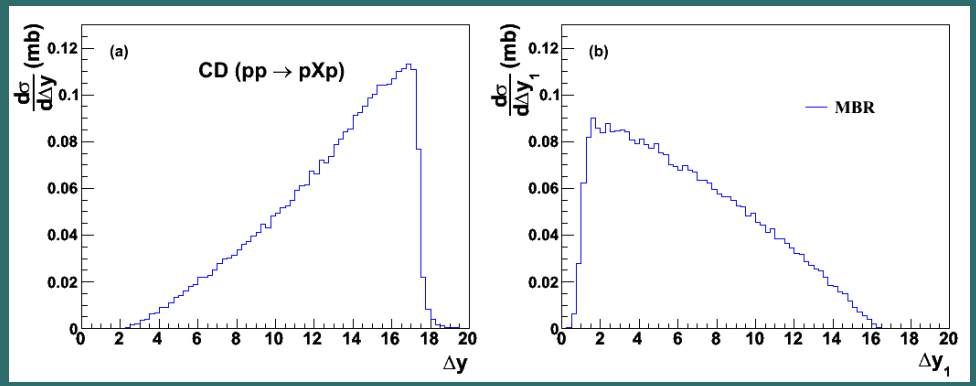
Comparison with Pythia8-4C (rescaled Schuler&Sjostrand model, Diffraction:PomFlux=1) →



- **CD (DPE) process**

Implemented in PYTHIA for the first time. ProcessID=106, SoftQCD:centralDiffractive = on .

4-vector of centrally-produced inclusive hadronic system propagated to PYTHIA for hadronization



→ possible to extend the simulatation to CD processes such as exclusive di-hadron or exclusive di-jet production (hadronization step).

Implementation in Pythia8.165

When option 5 is selected, the following parameters of the MBR model [Cie12] are used:

```
parm  Diffraction:MBRepsilon  (default = 0.104; minimum = 0.02; maximum = 0.15)

parm  Diffraction:MBRalpha  (default = 0.25; minimum = 0.1; maximum = 0.4)
```
the parameters of the Pomeron trajectory.

```
parm  Diffraction:MBRbeta0  (default = 6.566; minimum = 0.0; maximum = 10.0)

parm  Diffraction:MBRsigma0  (default = 2.82; minimum = 0.0; maximum = 5.0)
```
the Pomeron-proton coupling, and the total Pomeron-proton cross section.

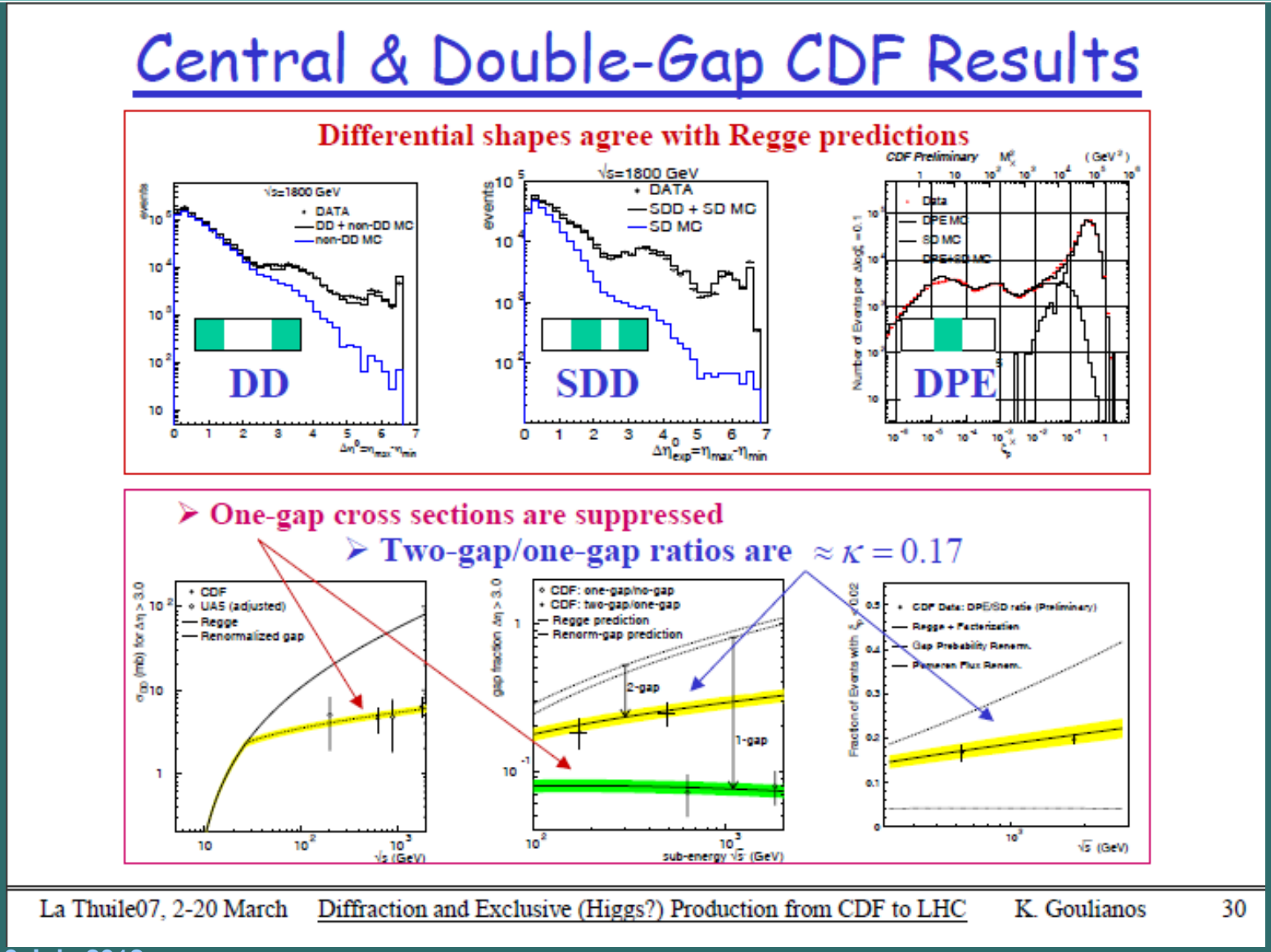
```
parm  Diffraction:MBRm2Min  (default = 1.5; minimum = 0.0; maximum = 3.0)
```
the lowest value of the mass squared of the dissociated system.

```
parm  Diffraction:MBRdyminSDflux  (default = 2.3; minimum = 0.0; maximum = 5.0)

parm  Diffraction:MBRdyminDDflux  (default = 2.3; minimum = 0.0; maximum = 5.0)

parm  Diffraction:MBRdyminCDflux  (default = 2.3; minimum = 0.0; maximum = 5.0)
```
the minimum width of the rapidity gap used in the calculation of *Ngap(s)* (flux renormalization).

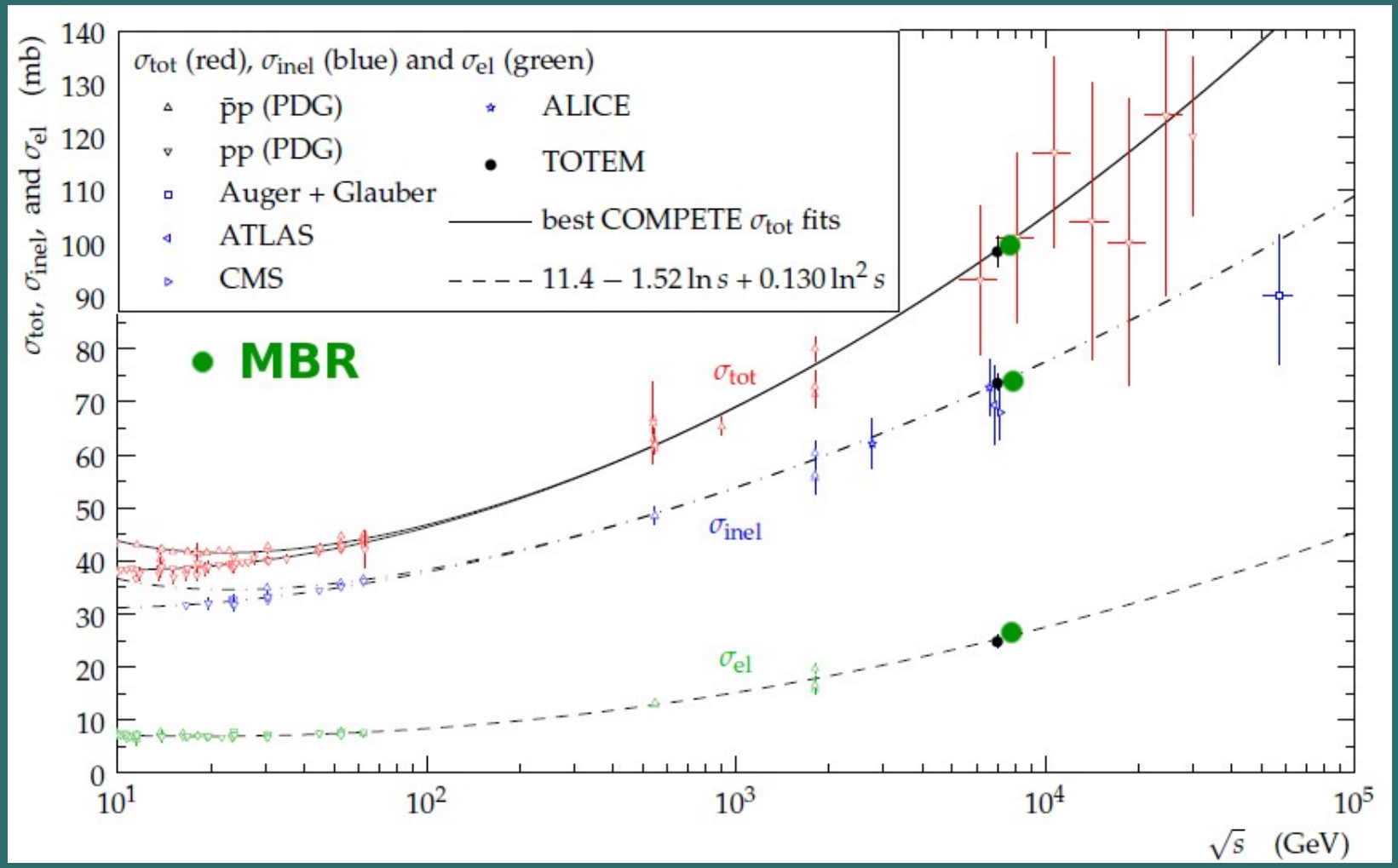
```
parm  Diffraction:MBRdyminSD  (default = 2.0; minimum = 0.0; maximum = 5.0)

parm  Diffraction:MBRdyminDD  (default = 2.0; minimum = 0.0; maximum = 5.0)

parm  Diffraction:MBRdyminCD  (default = 2.0; minimum = 0.0; maximum = 5.0)
```
the minimum width of the rapidity gap used in the calculation of cross sections, i.e. the parameter *dy_S*, which suppresses the cross section at low *dy* (non-diffractive region).

```
parm  Diffraction:MBRdyminSigSD  (default = 0.5; minimum = 0.001; maximum = 5.0)

parm  Diffraction:MBRdyminSigDD  (default = 0.5; minimum = 0.001; maximum = 5.0)

parm  Diffraction:MBRdyminSigCD  (default = 0.5; minimum = 0.001; maximum = 5.0)
```
the parameter *sigma_S*, used for the cross section suppression at low *dy* (non-diffractive region).

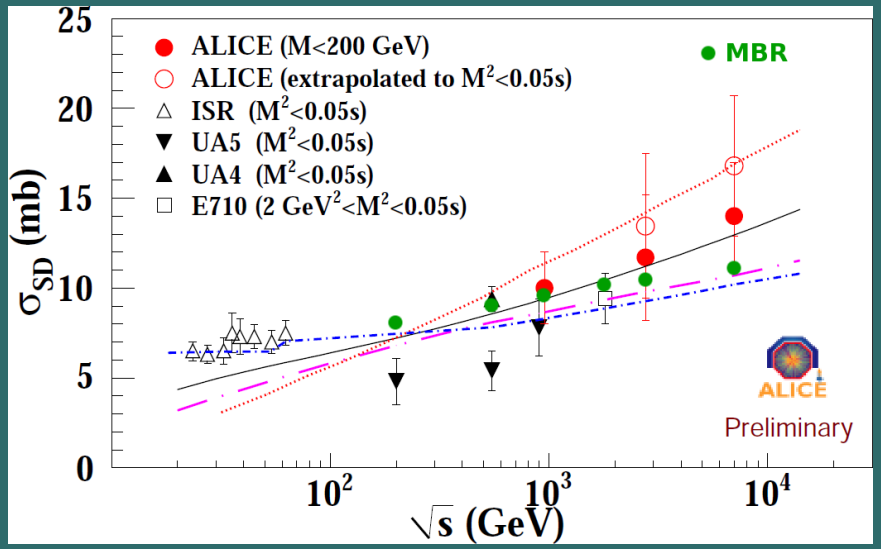
MBR vs. CDF data

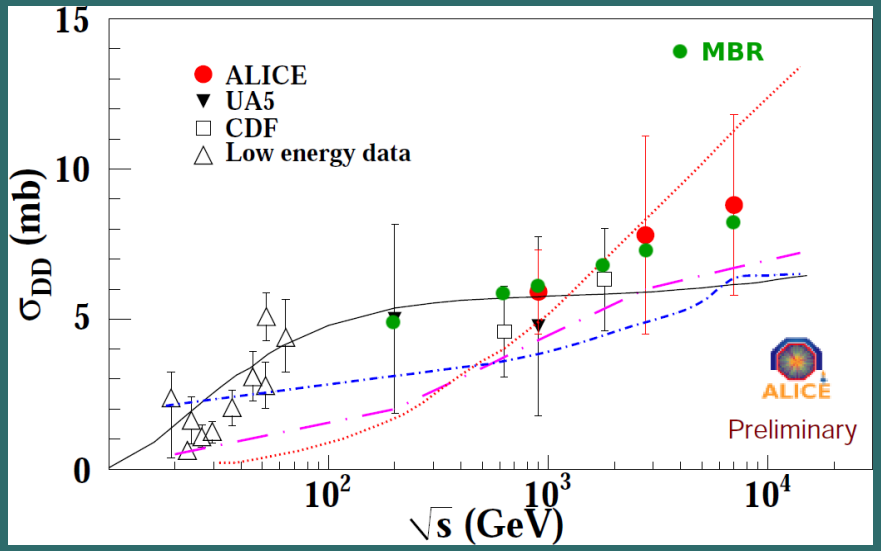


MBR vs. LHC data

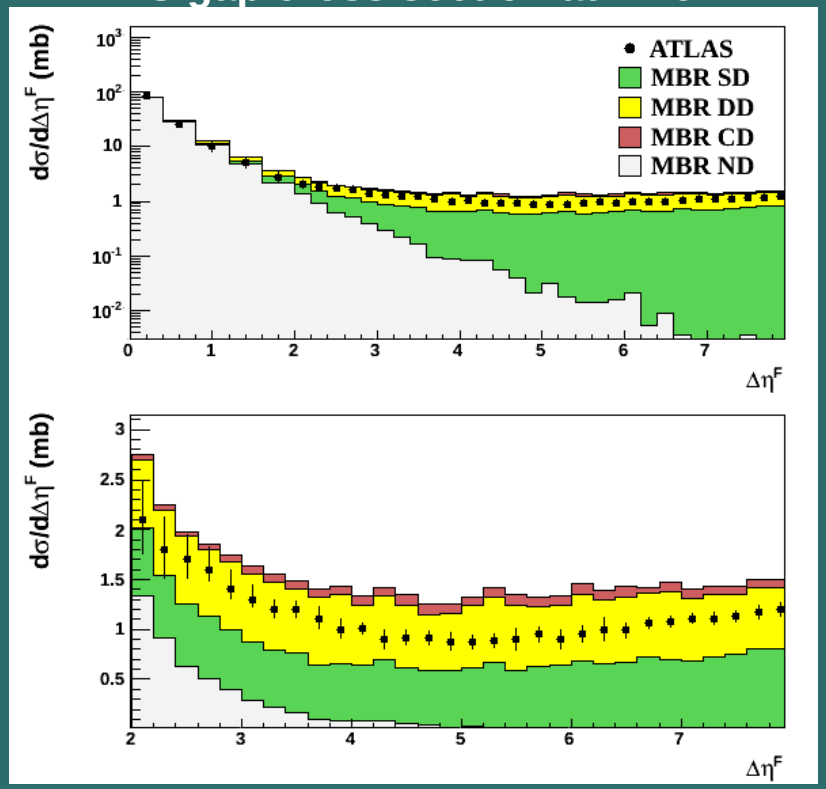


MBR vs. LHC data





ATLAS gap cross section at 7 TeV



Default Pythia8-4C hadronization

Summary

- MBR (Minimum-Bias Rockefeller) simulation, developed and successfully tested at CDF, has been implemented in Pythia8.165.
- MBR predicts the total, elastic and total-inelastic cross sections and fully simulates diffractive processes with single-, double- and central-dissociation.
- Central-dissiociation (double-Pomeron exchange) process included in PYTHIA for the first time.
- Good agreement with CDF and LHC data.
- Future development: tune of hadronization step using original MBR hadronization model, based on pre-LHC and pre-Tevatron low-energy data.

Thank you for your attention!

Backup slides

Event generation, SD

3.1 Single-diffractive events

Events are generated by first choosing the rapidity-gap width, Δy, according to Eq. (3) integrated over t:

$$\frac{d\sigma_{SD}}{d\Delta y} \sim e^{\epsilon \Delta y} \cdot \left(\frac{a_1}{b_1 + 2\alpha' \Delta y} + \frac{a_2}{b_2 + 2\alpha' \Delta y} \right) \cdot S. \tag{9}$$

The range of the generation is defined by $\Delta y_{min} = 0$ and $\Delta y_{max} = -\ln M_0^2/s$, where $M_0^2 =$`MBRm2Min`. The term:

$$S = \frac{1}{2} \left[1 + erf \left(\frac{\Delta y - \texttt{MBRdyminSD}}{\texttt{MBRdyminSigSD}} \right) \right], \tag{10}$$

is added to suppress events at low values of Δy, as explained in Sec. 2.2.

A value of t is then chosen according to:

$$\frac{d\sigma_{SD}}{dt} \sim F^2(t) \cdot e^{2\alpha' \Delta y t}, \tag{11}$$

where $F^2(t)$ is given by Eq. (7) and the integration is performed up to $t_{max} = -m_p^2 \cdot \frac{\xi^2}{1-\xi}$, with $\xi = e^{-\Delta y}$. The diffractive mass is calculated as $M = \sqrt{s\xi}$. The four-momenta of the outgoing proton and the dissociated mass system are calculated using Mandelstam variables for a two-body scattering process, as implemented in PYTHIA8 for other `Diffraction:PomFlux` options.

Event generation, DD

3.2 Double-diffractive events

Events are generated by first choosing the rapidity-gap width according to Eq. (4) integrated over t. Eq. (4) is divergent as $\Delta y \to 0$. In order to remove the divergence, the integration over t is performed within the limits from $t_{min} = -e^{\Delta y}$ to $t_{max} = -e^{-\Delta y}$. Then, Δy is chosen from the distribution:

$$\frac{d\sigma_{DD}}{d\Delta y} \sim e^{\epsilon \Delta y} \cdot \frac{\ln \frac{ss_0}{M_0^4} - \Delta y}{2\alpha' \Delta y} \left(e^{-2\alpha' \Delta y e^{-\Delta y}} - e^{-2\alpha' \Delta y e^{\Delta y}} \right) \cdot S, \tag{12}$$

and the range of the generation is defined by $\Delta y_{min} = 0$ and $\Delta y_{max} = -\ln M_0^4/(ss_0)$, where $M_0^2 =$ `MBRm2Min` and $s_0 = 1$ GeV^2. To further suppress events at low values of Δy the term:

$$S = \frac{1}{2}\left[1 + erf\left(\frac{\Delta y - \texttt{MBRdyminDD}}{\texttt{MBRdyminSigDD}}\right)\right], \tag{13}$$

is used as explained in Sec. 2.2.

The variable t is chosen according to:

$$\frac{d\sigma_{DD}}{dt} \sim e^{2\alpha' \Delta y t}, \tag{14}$$

in the range from $t_{min} = -e^{\Delta y}$ to $t_{max} = -e^{-\Delta y}$.

Then, the center of the rapidity gap, y_0, is selected uniformly within the limits:

$$-\frac{1}{2}\left(\ln \frac{ss_0}{M_0^4} - \Delta y\right) < y_0 < \frac{1}{2}\left(\ln \frac{ss_0}{M_0^4} - \Delta y\right), \tag{15}$$

and the diffractive masses are calculated as:

$$M_1^2 = \sqrt{s \cdot e^{-\Delta y - y_0}}, \tag{16}$$

$$M_2^2 = \sqrt{s \cdot e^{-\Delta y + y_0}}. \tag{17}$$

The four-momenta of the outgoing dissociated mass systems are calculated using Mandelstam variables for a two-body scattering process, as implemented in PYTHIA8 for other options of `Diffraction:PomFlux` .

Event generation, CD (DPE)

3.3 Central-diffractive (DPE) events

Events are generated by first choosing the total rapidity gap width, Δy, according to Eq. (5), integrated over t_1 and t_2:

$$\frac{d\sigma_{CD}}{d\Delta y} \sim e^{\epsilon \Delta y} \int_{-\Delta y/2+y_0}^{\Delta y/2-y_0} dy_0 \; f_- \cdot f_+ \cdot S_1 S_2, \tag{18}$$

where:

$$f_\pm = \left(\frac{a_1}{b_1 + \alpha' \Delta y \pm 2\alpha' y_0} + \frac{a_2}{b_2 + \alpha' \Delta y \pm 2\alpha' y_0} \right), \tag{19}$$

and the integration is performed from $\Delta y_{min} = 0$ to $\Delta y_{max} = -\ln M_0^2/s$, where M_0^2 =`MBRm2Min`. For events at low values of Δy we suppress individual gaps with the factor:

$$S = \frac{1}{2} \left[1 + erf \left(\frac{\Delta y - \texttt{MBRdyminCD}/2}{\texttt{MBRdyminSigCD}/\sqrt{2}} \right) \right]. \tag{20}$$

Then, the direction of the centrally-produced hadronic system, y_c, is selected uniformly within the region:

$$-\frac{1}{2}(\Delta y - \Delta y_{min}) < y_c < \frac{1}{2}(\Delta y - \Delta y_{min}), \tag{21}$$

and rapidity gaps corresponding to each of the two Pomerons are calculated as:

$$\Delta y_1 = \Delta y/2 + y_0, \tag{22}$$

$$\Delta y_2 = \Delta y/2 - y_0. \tag{23}$$

The four-momentum transfers squared at each proton vertex, t_1 and t_2, are generated according to:

$$\frac{d\sigma_{CD,i}}{dt} \sim F^2(t_i) \cdot e^{2\alpha' \Delta y_i t_i}, \tag{24}$$

up to $t_{max,i} = -m_p^2 \cdot \frac{\xi_i^2}{1-\xi_i}$, where $\xi_i = e^{-\Delta y_i}$ and $i = 1, 2$. Then, the p_T and p_z of outgoing protons are calculated as $p_{T,i}^2 = (1-\xi_i)|t_i| - m_p^2 \xi_i^2$ and $|p_{z,i}| = p(1-\xi_i)$, where $p = \sqrt{s/4 - m_p^2}$ is the incoming proton momentum.

Finally, the four-momentum of the hadronic system is calculated from the sum of the four-momenta of the Pomerons, each calculated as a difference between the incoming and outgoing proton four-vectors.