Recent developments in PYTHIA 8

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- Cross sections in pp
- Heavy ions
- Space-time picture of hadronization
- Conclusion & outlook

Motivations for updates

Cross sections:

- Existing parametrizations failed to describe recent LHC data.
- Many models very old and outdated.

Heavy ions:

- Need for event generator that fully describes every step in heavy ion collision.
- Early attempts to describe heavy ions without QGP was reasonably successfull, but needed updating (eg. DIPSY and FRITIOF).

Space-time picture of hadronization:

- Collective effects seen in pp not described by current models.
- Large hadron density might might give reason for collective effects.

Total and elastic pp cross sections

pp total & elastic

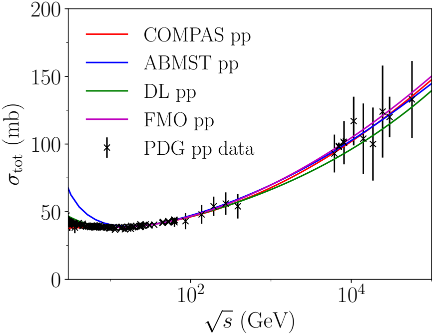
- All cross sections in PYTHIA 8 based on Regge theory.
- Default description of Schuler-Sjöstrand and Donnachie-Landshoff (SaSDL) parametrization uses a single Pomeron and a single Reggeon

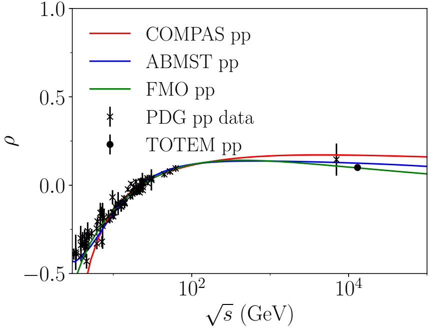
Two new parametrisations implemented:

- COMPAS parametrization: Froissaron, Pomeron, two Reggeons, several cuts, triple-gluon [PDG 2016] (corrected for misprints)
- DL-based parametrization from Appleby et.al. (ABMST): Two Pomerons, two reggeons, triple-gluon [EPJ C76 (2016) 520]

Other models available, but not shown here
(eg. MBR [PoS ICHEP2012 (2013) 301]).

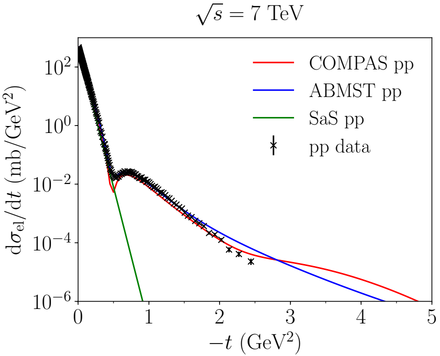
pp total & elastic

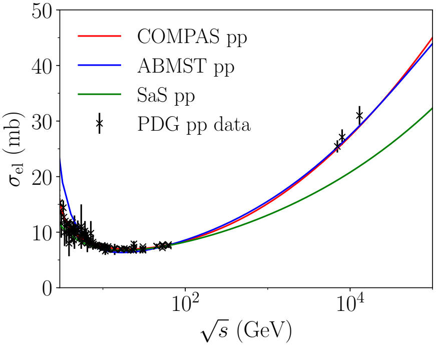




- Results from SaSDL, COMPAS, ABMST, FMO models.
- FMO includes Odderon, but not implemented in PYTHIA. [arXiv:1711.03288 [hep-ph]]
- New models improve description of $\sigma_{\rm tot}$ and ρ (const. in SaS, not shown).

pp total & elastic





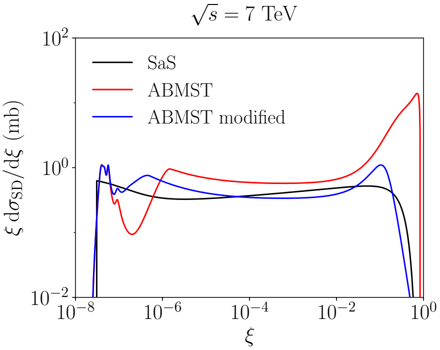
- FMO description not available when implemented
- SaS only exponential falloff, fail to describe high-t region
- COMPAS, ABMST describe structure in t well
- With new data at large t one might be able to exclude models
- Coulomb term can be included in all models

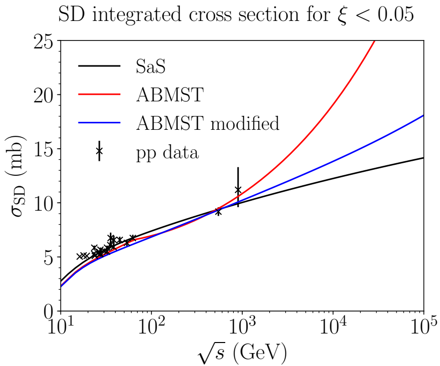
Diffractive pp cross sections

pp diffractive

- SaS provides a description for SD, DD, CD using a single Pomeron.
- COMPAS model provides no description here.
- ABMST provides a description for SD using a Pomeron and a Reggeon. Also includes sophisticated model for low-mass resonances.
- We have extended ABMST to DD and CD and provide a modified version fixing unwanted features.
- SaS gives too large SD, DD, CD cross sections at LHC energies, modification factor introduced to dampen growth

pp diffractive





- ABMST model has too much high-mass activity: Indistinguishable from non-diffractive events.
- ABMST model has large dip between low-mass resonances and high-mass region: Feature of background modelling in resonance-region, not physical.
- ABMST SD cross section too large.

pp results

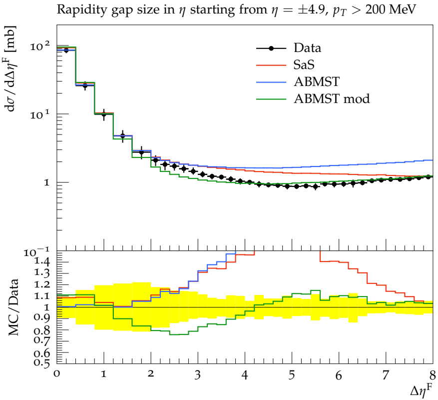
- Experimental results on cross section as function of gap-size.
- Small gap size is dominated by non-diffractive events, large gap-size dominated by diffractive events.
- Tests entire Soft QCD framework, including cross section description and hadronic event shapes in diffractive systems.
- Discrepancies between ATLAS and CMS data unresolved (25% difference in similar phase-space), so results from both experiments shown.

Soft QCD: Elastic, diffractive and non-diffractive QCD processes without hard scale

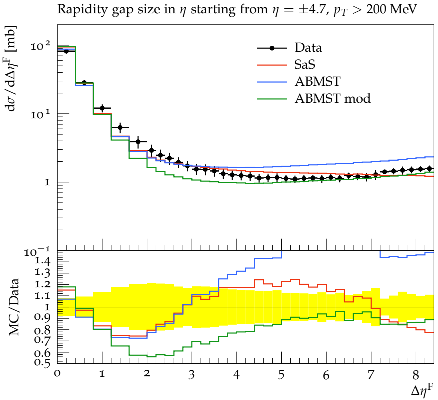
pp results

Before tuning:

ATLAS 2012:



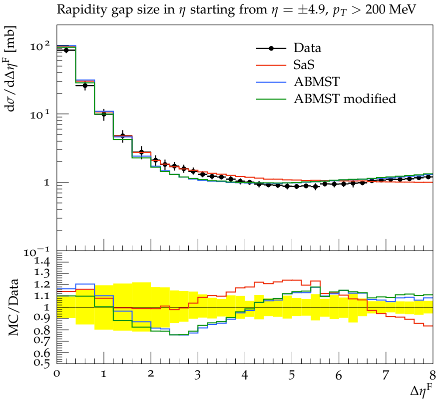
CMS 2015:



pp results

After tuning:

ATLAS 2012:



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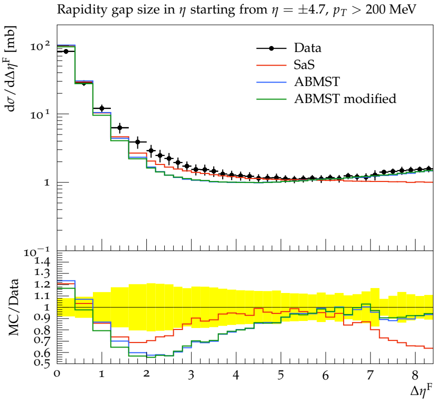
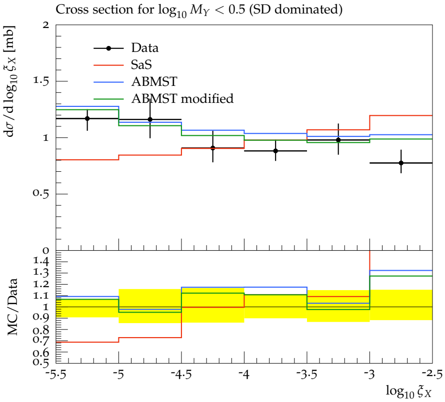


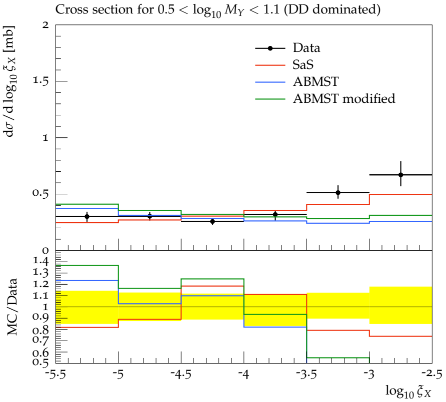
pp results

After tuning:

CMS 2015:



CMS 2015:



Heavy ions

Angantyr for heavy ions

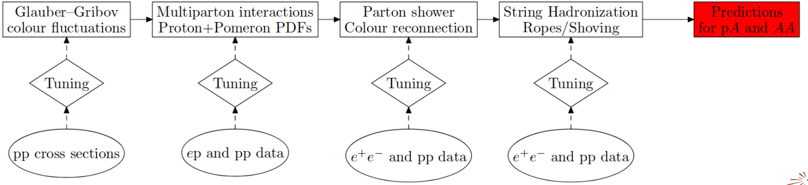
Event generators for heavy ions usually take one of two approaches

- Extrapolation of pp dynamics to pA and AA: HIJING, ANGANTYR
- Assume quark-gluon plasma (QGP): AMPT, EPOS

Several steps are taken in ANGANTYR:

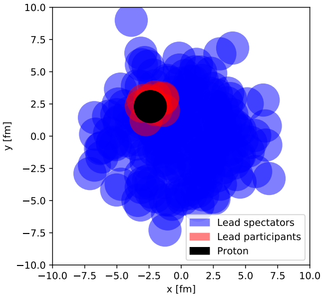
- Glauber model for number of collisions.
- Wounded nucleons for particle production.
- Possibility for additional subcollisions in an event (similar to MPIs in pp.)

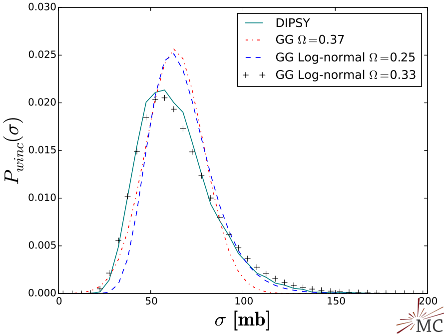
Only tuning to small systems.



Angantyr for heavy ions

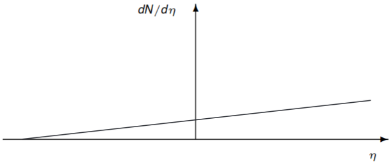
- Glauber-Gribov method to calculate number of interacting nucleons and binary collisions.
- Event-by-event colour fluctuations parametrized from DIPSY MC.
- DIPSY evolves initial-state dipoles in rapidity and calculates cross section from dipole-dipole scattering cross section.
- ANGANTYR is first model to include colour fluctuations in *both* target and projectile.





Angantyr for heavy ions

- Wounded nucleon model by Białas and Czyz used to create exclusive final-state.
- Wounded nucleons contribute equally to multiplicity in η.



$$\frac{dN}{d\eta} = \quad F(\eta) \qquad \text{(single wounded nucleon}$$

- Original model $F(\eta)$ fitted to data. ANGANTYR uses own model.
- $F(\eta)$ fitted to reproduce high-energy pp events, but **no** fitting to HI.

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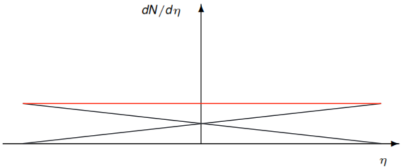

$$\frac{dN}{d\eta} = \quad F(\eta) + \quad F(-\eta) \qquad\qquad \text{(pp)}$$

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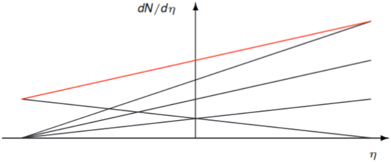

$$\frac{dN}{d\eta} = w_t F(\eta) + \quad F(-\eta) \qquad\qquad (pA)$$

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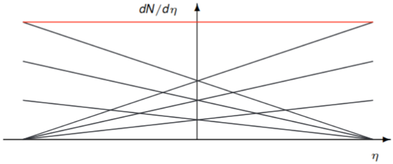

$$\frac{dN}{d\eta} = w_t F(\eta) + w_p F(-\eta) \qquad (AA)$$

- Original model $F(\eta)$ fitted to data. ANGANTYR uses own model.
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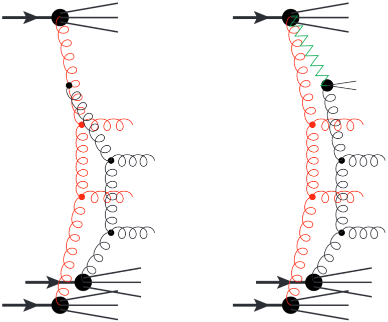
Angantyr for heavy ions

- Method to combine nucleon-nucleon events needed as collision can contain scatterings that are hard to describe in large systems.
- Simplest system pD-collision with three wounded nucleons:



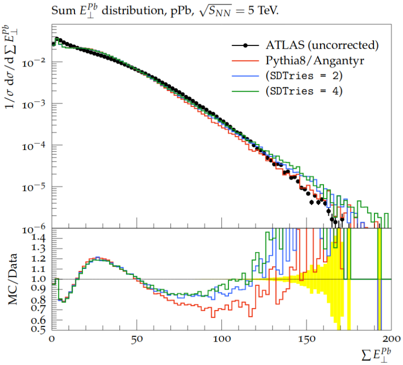
(a) (b)

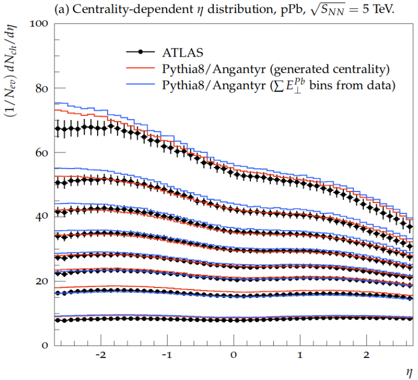
ANGANTYR cheat-sheet:

- First scattering modelled as a normal non-diffractive pp event.
- Second is modelled as a single diffractive event.
- Generalizes to all pA and AA collisions.

Angantyr for heavy ions

Results from pPb:

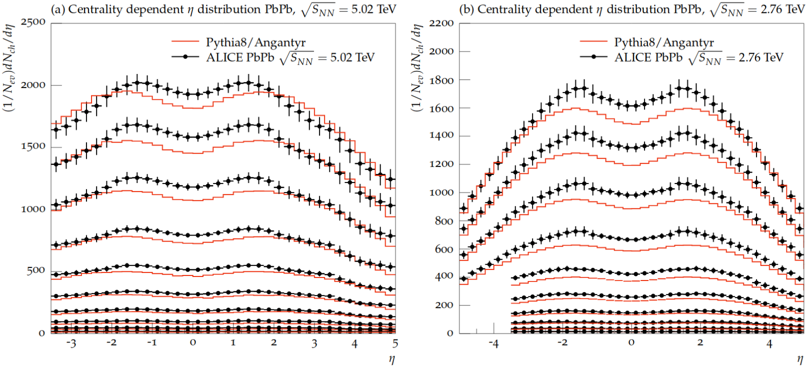




- Centrality often described by binning in $\sum E_\perp$.
- ANGANTYR can use experimental centrality definition or internal centrality measure.
- Centrality and multiplicity well reproduced by ANGANTYR.

Angantyr for heavy ions

Results from PbPb:

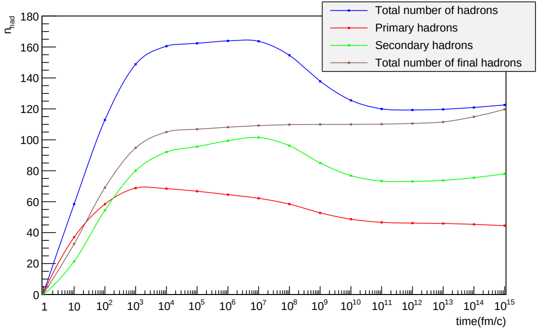


- Multiplicity well described by ANGANTYR.
- Dip around $\eta = 0$ caused by PYTHIA pp not describing $p_\perp < 500$ MeV (ALICE claims to measure to $p_\perp = 0$ MeV).

Space-time picture of hadronization

Space-time picture of hadronization

- Energy-momentum picture and space-time picture proportional when assuming linear confinement.
- Usually hadronization described in energy-momentum picture.
- Recently developed space-time picture as first step towards hadronic rescattering.
- Hadron density can become very high, motivating collective effects in pp.



Conclusion and outlook

- New models for total and elastic pp cross sections available.
- New models for diffractive pp cross sections available.
- Full generation of pA and AA events with ANGANTYR.
- Space-time picture of hadronization developed.

Conclusion and outlook

Future plans:

- Adding Odderon model to PYTHIA 8 if experiments requests this.
- Extend from ep to eA with Angantyr.
- Full space-time picture of hadronic rescattering.
- Rope hadronisation and shoving in ANGANTYR.
- Colour-reconnections between subcollisions in ANGANTYR.
- Fluctuating initial stage in pp events using a dipole evolution.
- Good-Walker description of cross sections for fluctuating initial stage.

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Thank you!