Hadronic Rescattering in Pythia/Angantyr

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Outline

Heavy ion research in Lund

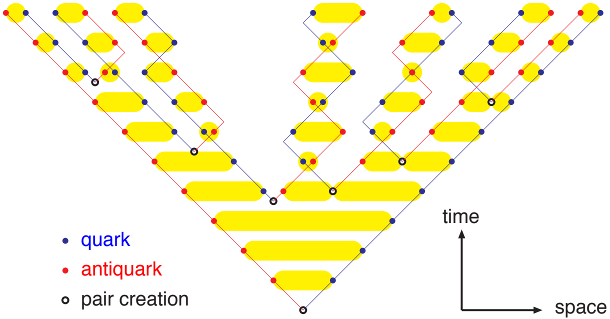
- Several projects in Lund are trying to explore heavy ion physics without a QGP, to see how well other effects can explain experimental data.
- Rescattering is one such effect. Other effects include string shoving, rope formation, and colour reconnection.
- Rescattering has been shown to give rise to collective effects such as flow (da Silva et al., arXiv:1911.12824).

Why rescattering in Pythia?

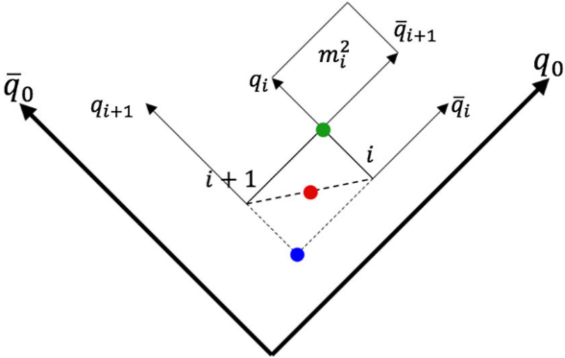
Other frameworks for hadronic transport already exist (UrQMD, SMASH, ...), so why implement rescattering in PYTHIA?

- Having our own framework integrated in PYTHIA is convenient
- Easy to use: `HadronLevel:Rescatter = on`
- We can implement our own physics features, such as interactions involving charm and bottom and relying on the Lund string model
- Can utilize the PYTHIA infrastructure, such as the event record to trace complete particle histories

The Lund string model



Spacetime picture of the Lund string model

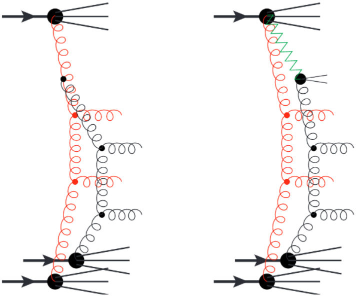


String tension $\kappa \sim 1$ GeV/fm

(Ferreres-Solé & Sjöstrand, arXiv:1808.04619)

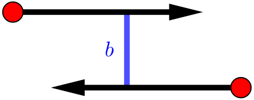
Angantyr

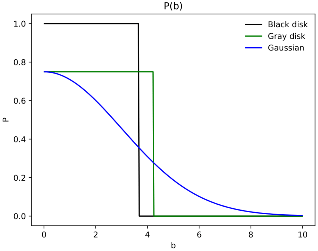
- Angantyr is the default heavy ion model for Pythia
- Basically Pythia's MPI model extended to heavy ions, using a Glauber model for the nucleon geometry
- First interaction modelled as non-diffractive pp event. Subsequent interactions modelled similar to single-diffractive.



The collision criterion

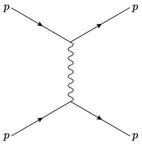
The probability of an interaction depends on the cross section σ and the impact parameter b



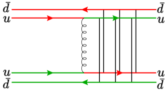


The characteristic range of the interaction is $b_{\text{crit}} = \sqrt{\sigma/\pi}$
The cross section σ depends on the particle types and the center-of-mass energy.

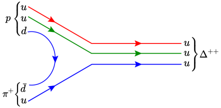
Low-energy interactions



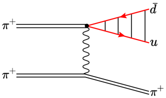
Elastic



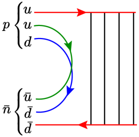
Non-diffractive



Resonant

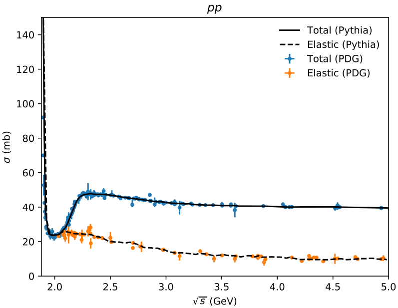


Diffractive



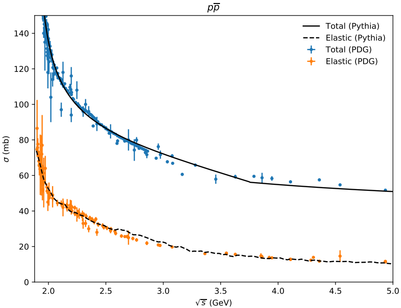
Annihilation

Cross sections



Based on PDG data and HPR_1R_2 parameterization

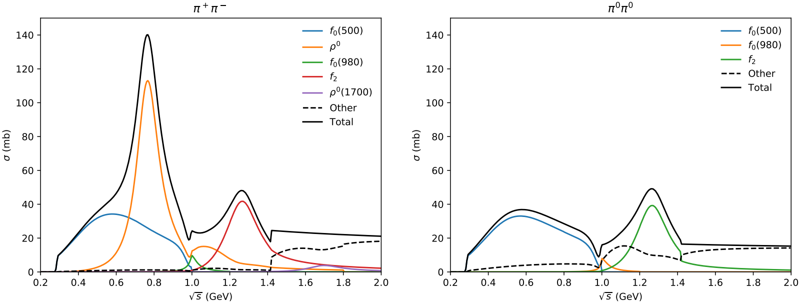
(DOI: 10.1103/PhysRevD.98.030001)



Based on UrQMD (arXiv:nucl-th/9803035) and CERN/HERA parameterization

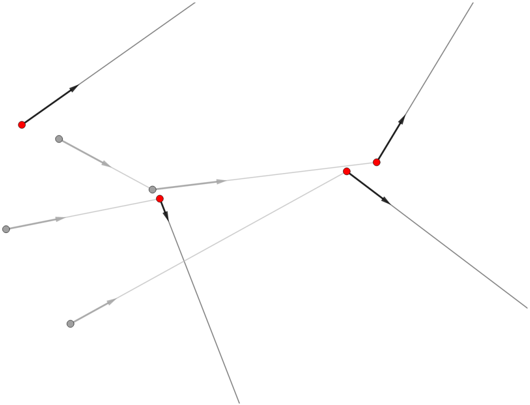
(DOI 10.1103/PhysRevD.50.1173)

Cross sections



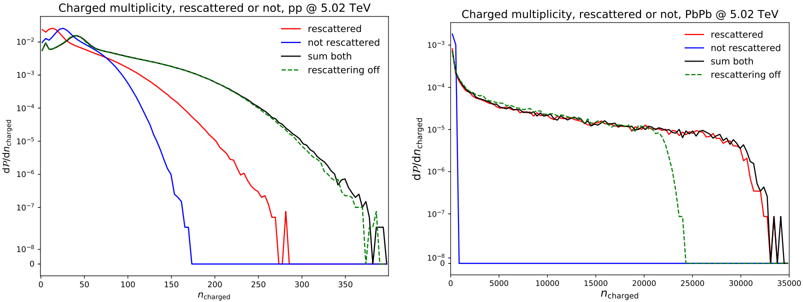
Based on work by Pelaez, Rodas, Ruiz de Elvira et al.
(arXiv:1102.2183, arXiv:1907.13162, arXiv:1602.08404)

Rescattering overview



Multiplicities - pp vs. PbPb @ 5.02 TeV

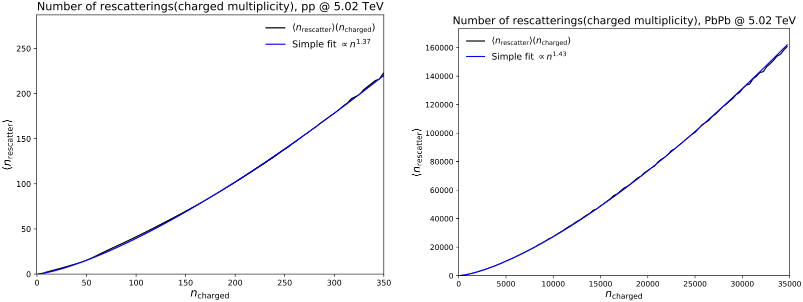
- Rescattering is implemented $2 \to n$ processes, but not $n \to 2$, so multiplicity will increase.



For pp we compensate by tuning $p_{\perp,0}$ from the MPI framework.
Other cases need a more detailed treatment

Rescattering rates - pp vs. PbPb @ 5.02 TeV

Naïvely expect $n_{\text{rescattering}} \sim n^2_{\text{hadron}}$.
In practice, assume n^p scaling for some other p

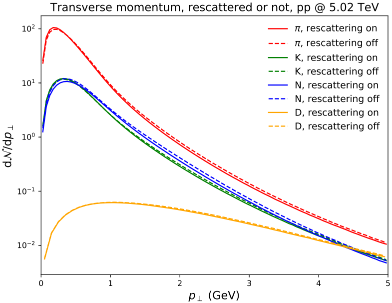


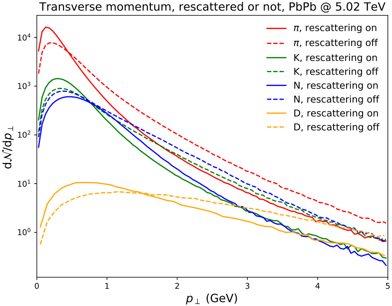
Case	p
pp	1.37
pPb	1.47
PbPb	1.43

- Scaling is faster for pPb than for pp.
- But slower for PbPb than pPb, since then higher multiplicity implies larger volume.

pT spectra - pp vs. PbPb @ 5.02 TeV

- Rescattering reduces mean $p_\perp$ since multiplicity increases
- D mesons start out at higher $p_\perp$ because charm is not produced in string fragmentation

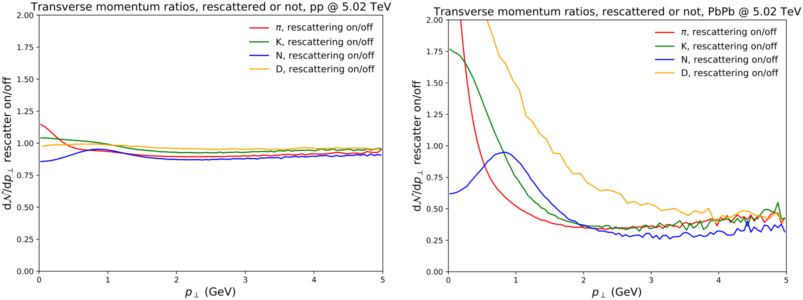

Transverse momentum, rescattered or not, pp @ 5.02 TeV


Transverse momentum, rescattered or not, PbPb @ 5.02 TeV

To study this closer, let look at ratios between the two spectra...

pT spectrum ratios - pp vs. PbPb @ 5.02 TeV

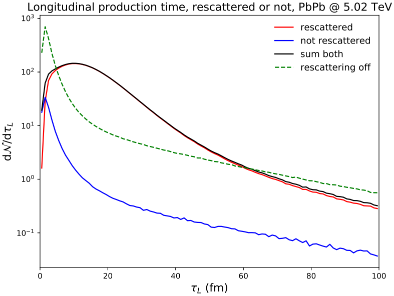
$dN/dp_\perp$ ratios with rescattering on : off

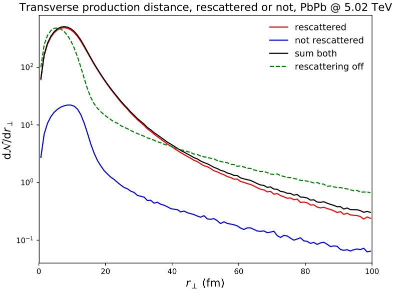


- Pion wind pushes pions to lower $p_\perp$ and nucleons to higher
- Nucleon depletion due to baryon–antibaryon annihilation
- D mesons start out at higher $p_\perp$ and are pushed to lower velocities

Spacetime distributions - PbPb @ 5.02 TeV

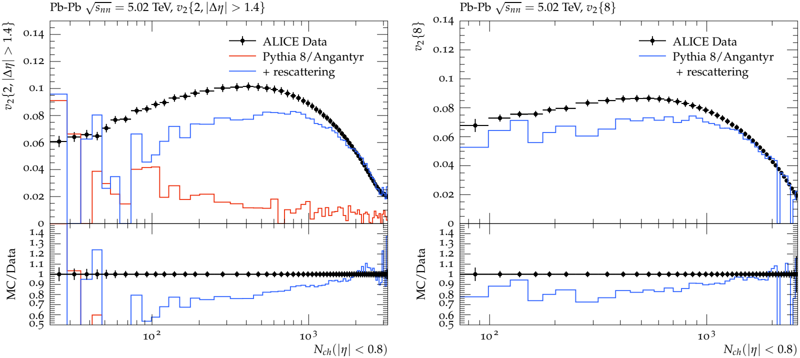
$$\tau_L^2 = t^2 - z^2, \qquad r_\perp^2 = x^2 + y^2$$


Longitudinal production time, rescattered or not, PbPb @ 5.02 TeV


Transverse production distance, rescattered or not, PbPb @ 5.02 TeV

- Reduction in number of hadrons produced very early or late
- Particles produced at higher $r_\perp$ are less likely to rescatter
- Mean production time with rescattering $\langle \tau_L \rangle = 15.4$ fm

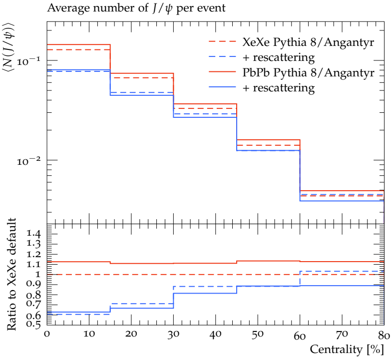
Flow - PbPb @ 5.02 TeV

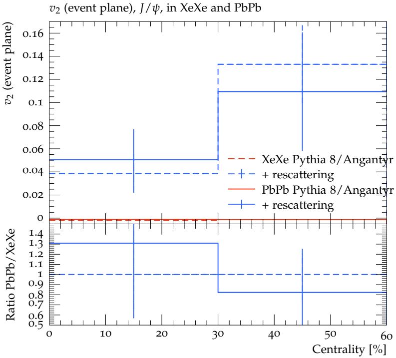


(Data from arXiv:1903.01790)

- Very good description at high multiplicities, where there is more rescattering activity
- Other effects like ropes and shoving should also contribute, so the result with only rescattering should be below data

Flow for J/ψ - PbPb @ 2.76 TeV / XeXe @ 5.44 TeV

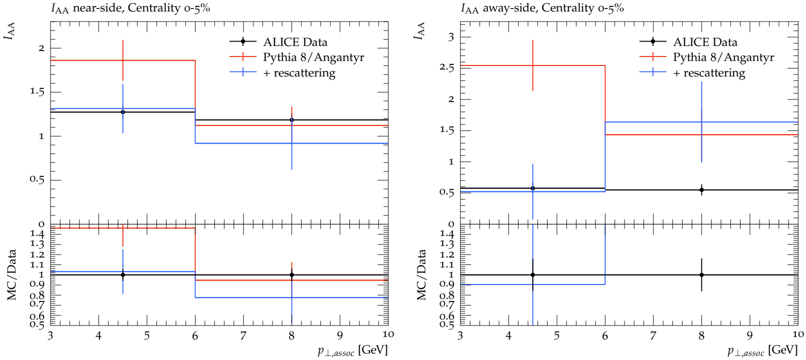




- Number of J/ψ depleted in rescattering
- Rescattering gives a flow effect for J/ψ

Jets I_{AA} - PbPb @ 2.76 TeV

I_{AA} is the PbPb/pp ratio of associated particle yield per trigger
$8\text{ GeV} < p_{\perp,\text{trig}} < 15\text{ GeV}, \qquad 4\text{ GeV} < p_{\perp,\text{assoc}} < p_{\perp,\text{trig}}$



(Data from arXiv:1110.0121)

NB: $p_\perp$ spectrum modified by other mechanisms, and result must be taken with a grain of salt.

Outlook

- Rescattering in pp collisions is available in PYTHIA 8.303. Heavy ions will also be supported in 8.304.
- We have seen that rescattering has non-negligible effects, perhaps most significantly giving rise to collective flow
- Framework still under development. Especially $3 \to 2$ processes are a high priority
- There are also other ways to go from here, such as cosmic ray physics and pentaquark formation
- The future of Angantyr will involve shoving, ropes, and other effects. The question is, *how far can one get without a QGP?*