Generic hadron-ion collisions in Pythia/Angantyr

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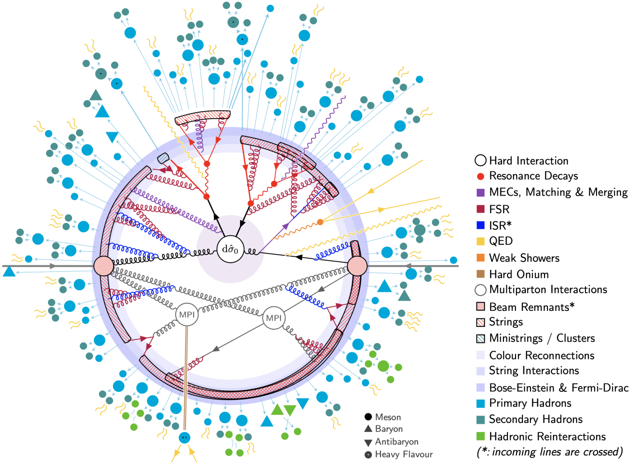
Pythia overview [arXiv:2203.11601]

PYTHIA is a general-purpose event generator.

- GPEGs tell us what our theoretical models predict at the end of the day.
- PYTHIA is one of the most detailed simulations we have.
- Includes ANGANTYR module for heavy ions.



(figure by S. Chakraborty and P. Skands)

Objective

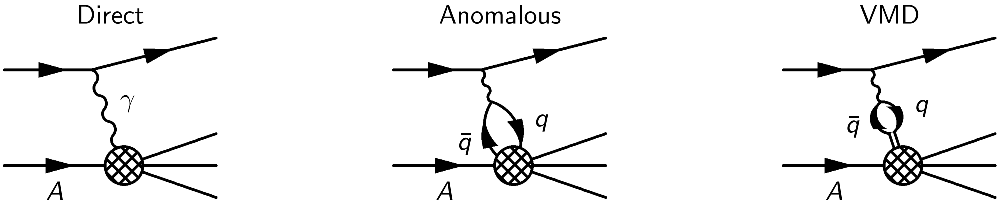
In our recent work, we have implemented generic hadron-ion collisions in Angantyr.

- This can be used to model collisions that are relevant for hadronic cascades.
- Pythia already has generic hadron-nucleon interactions [arXiv:2108.03481], and has been used in CORSIKA 8 air shower [arXiv:2303.02792], using a toy model for nuclear effects.
- Another main use case is for the VMD part of the photon wave function, which is relevant e.g. for ultraperipheral collisions and electron-ion physics.

In this talk, I will present the framework for hadron-nucleon interactions, then introduce the changes we have made to extend this to Angantyr. Finally we look at some results, comparing to data from NA61/SHINE, HERA, and LHC.

Sidenote: Photon-induced processes

Another important application of this framework is modelling the photon wavefunction.

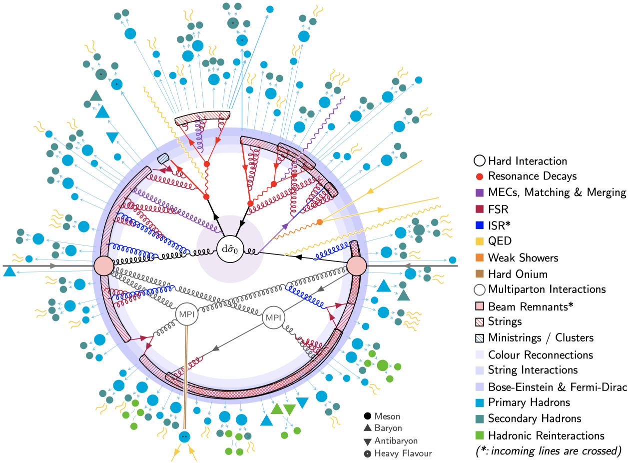


- The direct part is straightforward to model in ANGANTYR: the photon simply scatters off a single nucleon. At high Q^2, this corresponds to DIS.
- The anomalous part is more complicated. The q and $\bar{q}$ can interact with different nucleons in A.
- The VMD part can be described as a hA interaction, analogous to pA. This is the component with highest multiplicity, due to MPIs and multiple subcollisions.

From pp to hp

Going from *pp* to *hp* requires two changes:

1. Modified cross sections.
2. Parton distribution functions (PDFs) for the new hadrons.

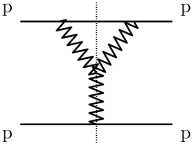


Total and partial cross sections

Several models for total cross sections are available in Pythia. The most generic is the Donnachie-Landshoff model, which is available for most hadron–nucleon combinations:

$$\sigma_{AB}(s) = X^{AB} s^{\epsilon} + Y^{AB} s^{-\eta}$$

Elastic and diffractive cross sections are based on parameterizations by SaS, e.g.



$$d\sigma = \frac{g_{3\mathbb{P}} \beta_{A\mathbb{P}} \beta_{B\mathbb{P}}^2}{16\pi} \frac{dM_X^2}{M_X^2} (e^{B_{XB} t} dt) F_{\mathrm{SD}}(M_X^2, s)$$

- If $\beta_{B\mathbb{P}}(t) = \beta_{B\mathbb{P}} \exp(b_B t)$, then with suitable normalization, $X^{AB} = \beta_{A\mathbb{P}}(0)\beta_{B\mathbb{P}}(0)$
- $B_{XB} = 2b_B + 2\alpha'_{\mathbb{P}} \log(s/M_X^2)$ with $b = 1.4$ for mesons and 2.3 for baryons
- F_{SD} is a fudge factor (out of scope for this talk)

Parton distribution functions

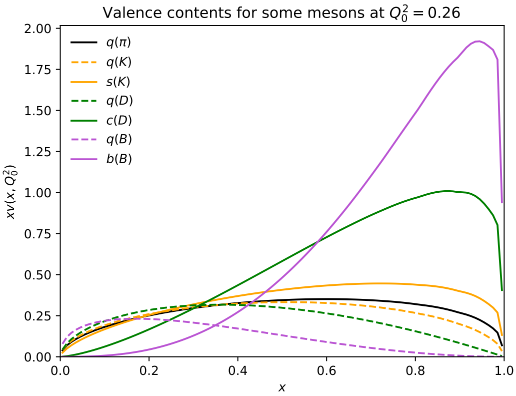
PDFs determine the contents of a hadron, and are central to modelling MPIs. For protons, detailed PDFs based on global fits exist, the Pythia default being NNPDF2.3 QCD+QED LO (with $\alpha_S = 0.130$).

For other species, very little data exists, and we base our valence distributions on an ansatz by Glück, Reya et al.:

$$f(x, Q_0^2 = 0.26\ \mathrm{GeV}^2) = Nx^a(1-x)^b(1 + A\sqrt{x} + Bx)$$

and evolve to higher scales using the QCDNUM program. The parameters are fixed by flavour- and momentum sum relations, and some heuristic guesses. In particular, heavier valence quarks should have larger x, as they must all have similar velocities in order for the hadron to stay intact.

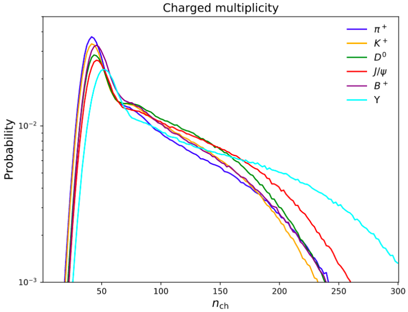
Parton distribution functions

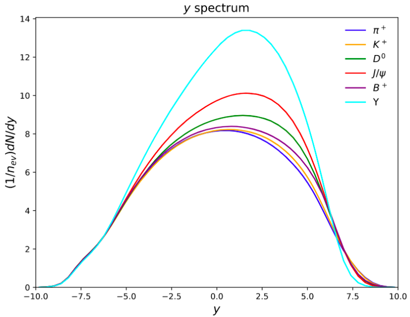


- $\langle x \rangle$ is higher for heavy valence content (solid lines), and correspondingly lower for light content (dashed lines).

Hadron–proton collisions in Pythia [arXiv:2108.03481]

The following plots are for meson–proton nondiffractive events at 6 TeV





- Hadrons with heavier valence content generally lead to harder interactions and more activity
- Effect is particularly pronounced for J/ψ and Υ, which have no light valence.

Sidenote: baryon production and the forward direction

In cosmic rays, the forward direction is particularly important.

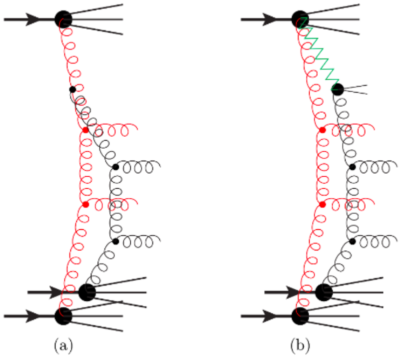
- Comparison with LHCf data shows that PYTHIA has a too soft neutron spectrum, and too hard π^0/γ.
- The popcorn model is a mechanism to produce baryons in hadronization. Disabling it for string endpoints might improve results in the forward direction (`StringFlav:suppressLeadingB = off`)
- The default tune is focused on the central region, and retuning can improve the results. Especially parameters in the Lund string model,

$$f(z) = \frac{(1-z)^a}{z} e^{-bm_\perp^2/z}$$

From hp to hA

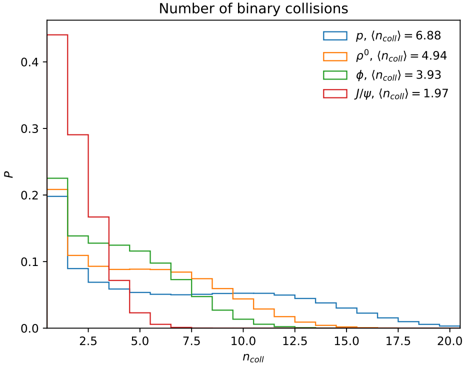
Now, let us look at how this fits in with ANGANTYR.

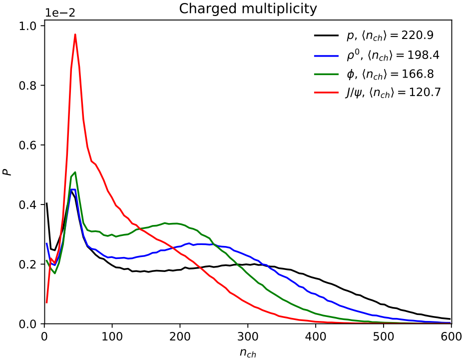
- Nuclear geometry is given by Glauber model. By default, nucleons can fluctuate.
- Each subcollision is assigned a type (absorptive, diffractive, elastic) based on the impact parameter b_{NN}.
- Perform absorptive subcollisions with smallest b_{NN} first. Generate events to parton level.
- Secondary absorptive collisions are modelled like diffractive interactions.
- Combine partons from all subevents, then do color reconnection, string interactions, string hadronization, etc.



arXiv:1806.10820

Hadron-ion collisions in Angantyr (lead target, 5.02 TeV)





- Heavier quark content implies fewer subcollisions with more activity per collision.
- Because of this, ρ and ϕ show more prominent peaks.
- Including fluctuations might lead to a more bimodal shape.

Technical remark: variable beams and energies

One technical point is that in hadronic cascades, all collisions are at different energies and with different hadrons. We need to change the beams on an event-by-event basis.

- Variable energies are implemented, and will be released in the upcoming PYTHIA 8.310
- Variable beam species will probably not be implemented in time.

This is a technical implementation,

$\pi^- C$ at NA61/SHINE [arXiv:1707.07902]

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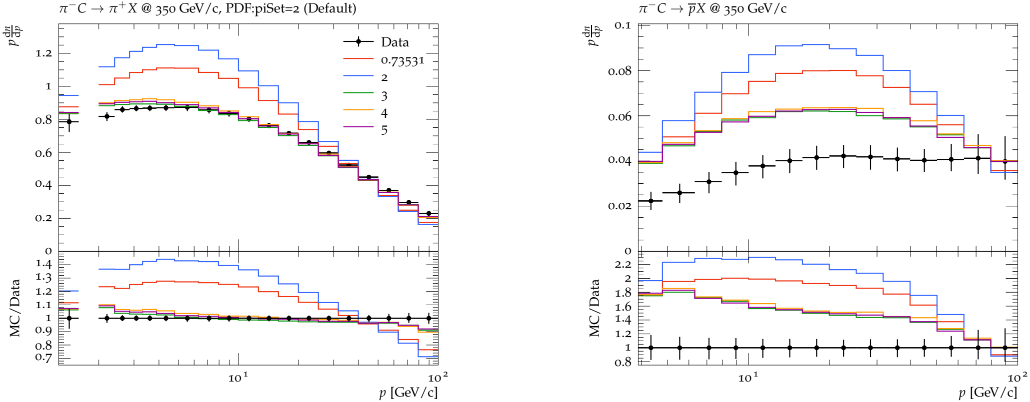
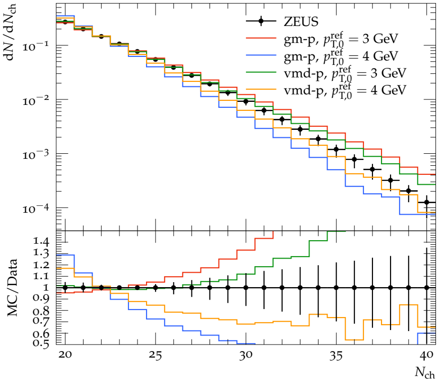
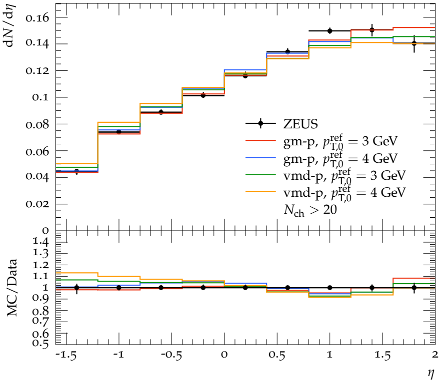


- Gives good fit to π and K spectra after tuning the $p_{\perp,0}^{\mathrm{Ref}}$ parameter.
- Poor description of $p/\bar{p}$.

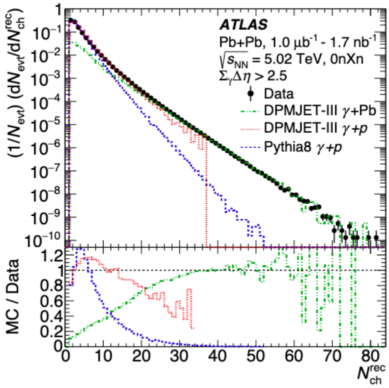
γp at HERA [arXiv:2106.12377]

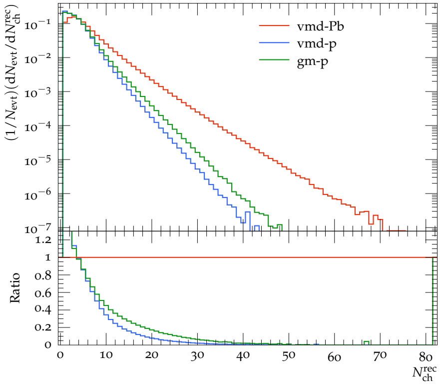




- $p_{\perp,0}^{\mathrm{ref}}$ is the regularization scale for MPI evolution. Larger value means fewer MPIs. The variation gives a sense of the model uncertainty.
- The shift due to changing $p_{\perp,0}^{\mathrm{ref}}$ is larger on average in the full photoproduction than in just the VMD component.

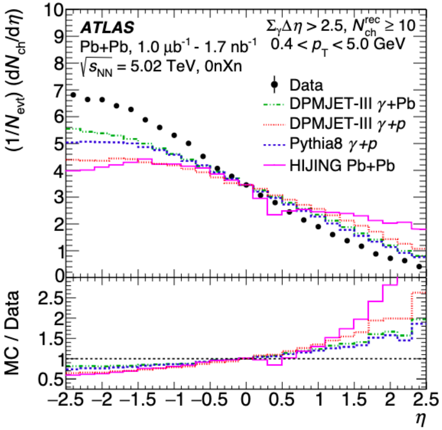
ATLAS γ + Pb multiplicities [arXiv:2101.10771]

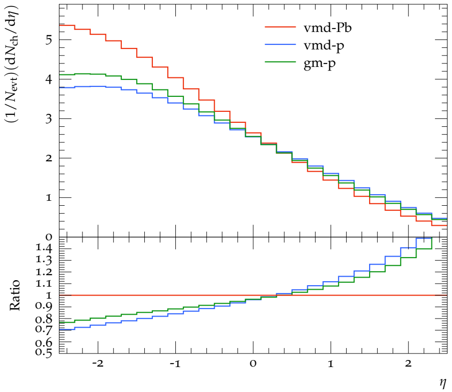




- Our analysis is not exactly the same as in the experimental paper.
- Qualitatively speaking, the shift from γp to γPb is consistent with data.
- In γp, the VMD component has less average multiplicity than in full photoproduction. This could be the other way around for γPb.

ATLAS eta spectrum [arXiv:2101.10771]





- The ratios between γp and γPb is similar for our simulation and in data.
- VMD components have a slight bias in the photon-going direction.

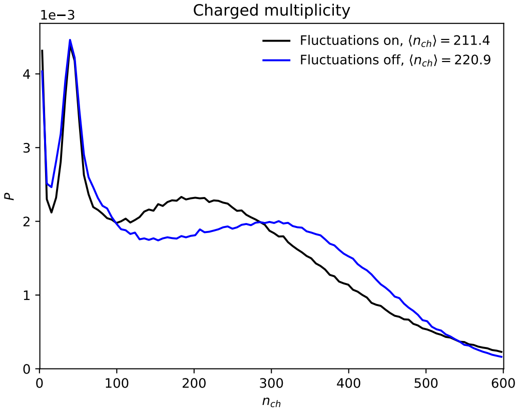
Summary and outlook

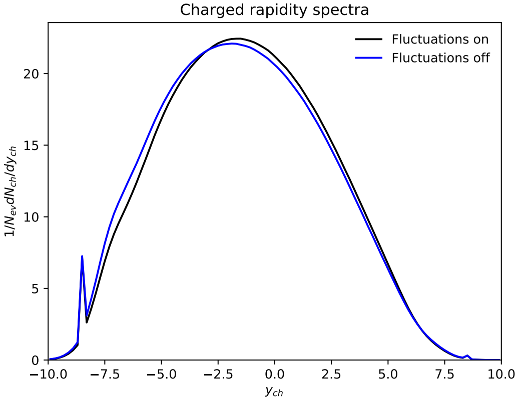
In this work, we have implemented generic hadron-ion collisions in PYTHIA.

- We have validated our approach against data from NA61/SHINE, HERA, and ATLAS. Our model generally fits data well.
- Nucleon fluctuations are not yet modelled for non-nucleon hadrons.
- Some details to improve upon (forward direction, $p/\bar{p}$ spectra, ...)
- We have also implemented variable energies in ANGANTYR. Changing beam particles will probably not make it before the next release.
- With this new feature, we can study photon-induced processes with VMD photons. One long-term goal is a minimum-bias γA simulation.

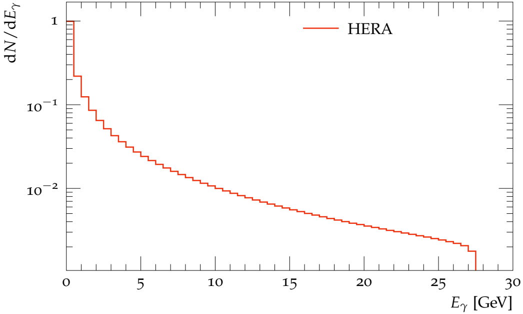
Code to be released in PYTHIA 8.310.

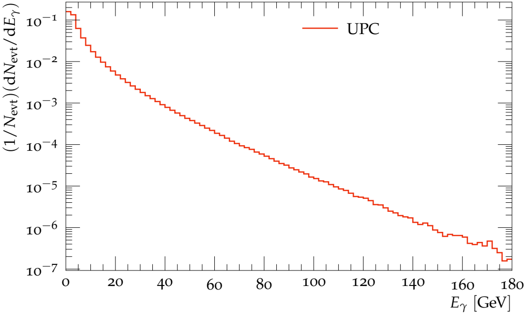
The effect of fluctuations





Photon flux [arXiv:1901.05261]

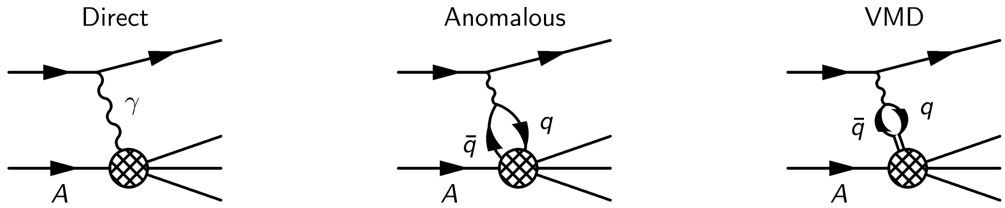




$$f_{\gamma/e}(x) = \frac{\alpha_{EM}}{2\pi}\frac{1+(1-x)^2}{x}\log\left[\frac{Q^2_{\mathrm{max}}(1-x)}{m_2^2x^2}\right]$$

$$f_{\gamma/A}(x) = \frac{\alpha_{EM}Z^2}{\pi x}\left[2\xi K_1(\xi)K_0(\xi) - \xi^2(K_1^2(\xi) - K_0^2(\xi))\right]$$

Photon wavefunction details [arXiv:hep-ph/9403393]



$$|\gamma\rangle = c_{\text{bare}} |\gamma_{\text{bare}}\rangle + \sum_q c_q |q\bar{q}\rangle + \sum_{V=\rho^0,\omega,\phi,J/\psi} c_V |V\rangle$$

$$c_V = \frac{4\pi\alpha_{EM}}{f_V^2}$$

V	$f_V^2/4\pi$
ρ^0	2.20
ω	23.6
ϕ	18.4
J/ψ	11.5

$p_{\perp,0}^{\mathrm{Ref}}$ variations