Pythia, Angantyr, and the path towards a general-purpose electron–ion MC generator

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Overview

Pythia is a general-purpose event generator that has been invaluable for LHC physics.

- General-purpose event generators tell us what our theoretical models actually predict at the end of the day.
- Also useful for making future predictions, which may guide e.g. detector design.

Our long-term goal is to implement a full minimum-bias description of electron-ion processes at EIC energies.

- In this talk, I will first outline the basics of Pythia
- There will be a particular focus on generic hadronic interactions: collisions involving vector mesons are relevant for our recent work.
- Our recent work was to implement photon-ion collisions for photons in VMD states.

A brief history of Pythia

- **1978-1997** Early developments of the JETSET and PYTHIA programs
- **2006** PYTHIA 6.4 manual is published. It is one of the most cited papers on inspirehep with $>$ 10000 citations (S. Mrenna, T. Sjöstrand, P. Skands, [arXiv:hep-ph/0603175])
- **2007** PYTHIA 8.1 is released, porting from FORTRAN to C++.
- **2012** PYTHIA 6.4 is officially deprecated
- **2014** PYTHIA 8.2 is released. Since then, the size of the PYTHIA collaboration has more than doubled.
- **2019** PYTHIA 8.3 is released with many new developers and features, including new shower models, new soft physics, the heavy-ion framework Angantyr, etc.
- **2022** PYTHIA 8.3 manual is released [arXiv:2203.11601 [hep-ph]]

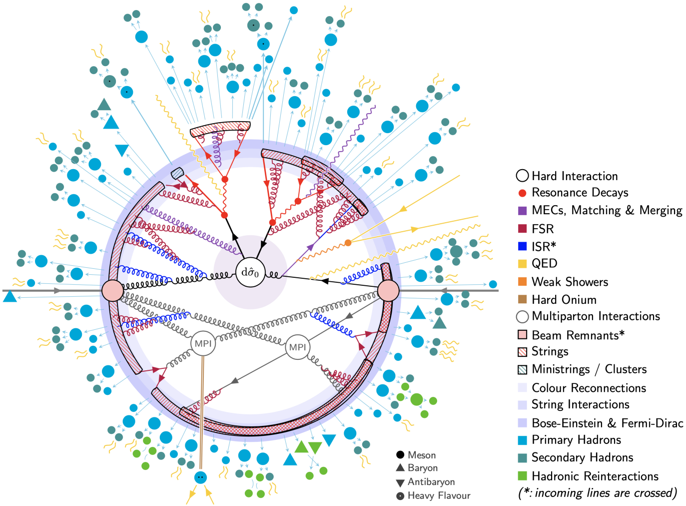
See www.pythia.org for more information

Pythia overview

Events in PYTHIA are generated in three phases:

- Process level
- Parton level
- Hadron level

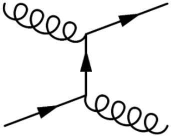
(figure by S. Chakraborty and P. Skands)



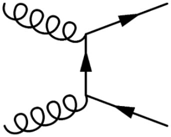
Process level

The first step in the generation is the hard process. In hadronic interactions, there are two categories of processes.

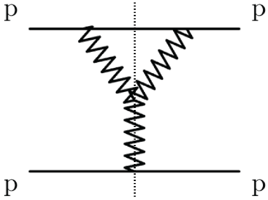
- `HardQCD` are, in short, perturbative QCD processes. These can have soft and collinear singularities, and are applicable only in a limited part of phase space. Also includes exclusive processes.
- `SoftQCD` are minimum-bias QCD processes. They rely on Regge theory to simulate non-perturbative interactions such as diffractive and elastic collisions.



$qg \to qg$



$gg \to q\bar{q}$

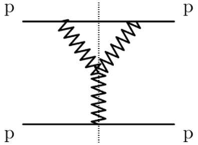


Total and partial cross sections

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.

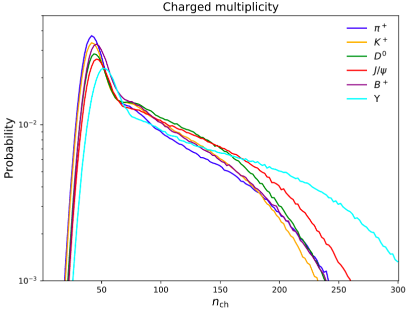


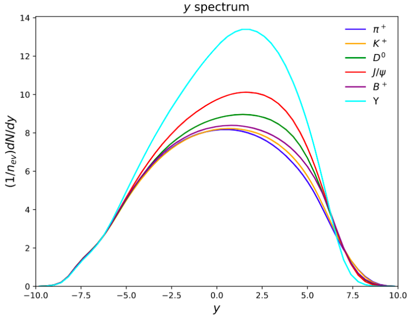
$$d\sigma = \frac{g_{3\mathbb{P}} \beta_{A\mathbb{P}} \beta_{B\mathbb{P}}^2}{16\pi} \frac{dM_X^2}{M_X^2} (e^{B_{XB} t} dt) \, F_{\mathrm{SD}}(M_X^2, s)$$

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

Hadron–proton collisions in Pythia

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



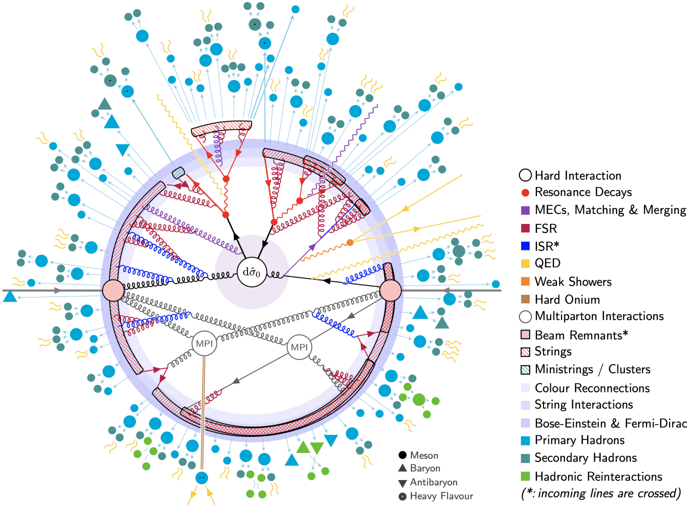


- Hadrons with heavier valence content generally lead to harder interactions and more activity
- Effect is particularly pronounced for J/ψ and Υ, which have no light valence.

[arXiv:2108.03481 [hep-ph]]

Multiparton interactions

- When two protons collide, more than one pair of partons can interact. Such interactions are referred to as MPI.
- Subsequent MPIs are modelled as non-diffractive SoftQCD interactions.
- MPIs have significant effects on the background.



Parton distribution functions

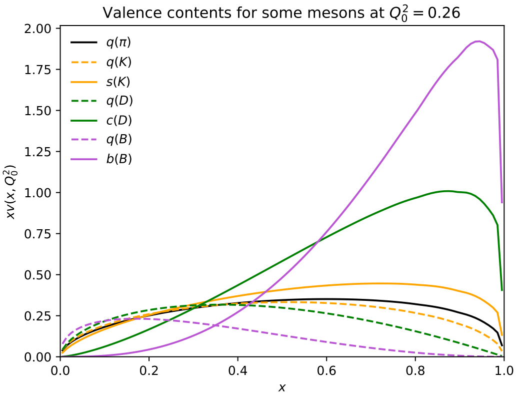
PDFs determine the contents of a hadron, and are central to modelling MPIs. For protons, detailed PDFs based on global fits exist, the Pythia default being NNPDF2.3 QCD+QED LO (with $\alpha_S = 0.130$).

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).

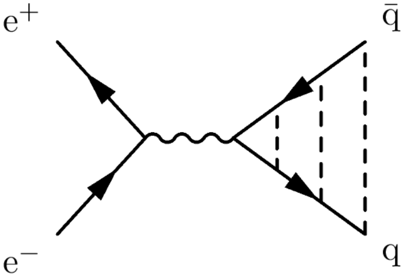
Parton showers

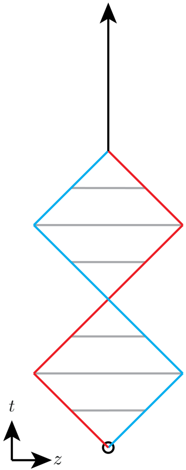
Pythia comes with three different models for parton showers.

1. The default PYTHIA shower is based on DGLAP evolution. It is the most basic and most flexible for use with external tools.
2. Vincia: based on antenna formalism
   - Coherent antennae, especially useful for UE
   - Recent developments include interleaved resonances and a detailed treatment of EW/QED [arXiv:2108.10786,arXiv:2002.04939]
   - Efficient LO merging at high multiplicity [arXiv:2008.09468]
3. Dire: dipole shower with close connection to DGLAP
   - Particularly accurate for uncorrelated jets
   - Includes NLO corrections to evolution [arXiv:1705.00742, arXiv:1705.00982, arXiv:1805.0375]
   - Recent developments include fixed colour [arXiv:2109.09706]

String hadronization

The Lund string model is PYTHIA's model for hadronization. The basic idea is to treat colour fields as strings. The colour field potential is $V(r) = \kappa r$, where κ can be interpreted as string tension.

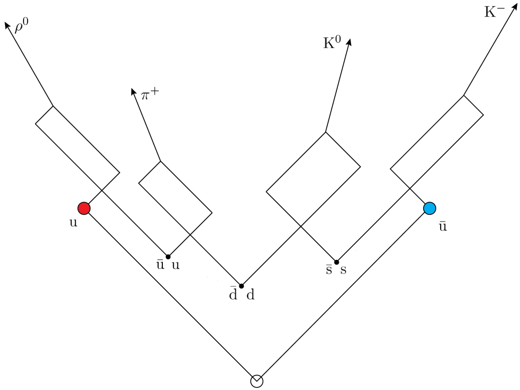




String fragmentation

In the string model, hadrons are produced through string fragmentation.

- Strings fragment to form $q\bar{q}$ pairs. Eventually, strings are converted into hadrons based on their endpoint flavours.
- Heavy flavours are suppressed by a factor $e^{-\pi m_\perp^2/\kappa}$.
- Baryons can be produced strings fragmenting into dipole-pairs, through junctions, or through the popcorn model.



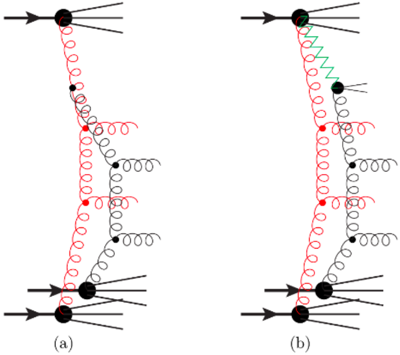
String interactions

One of the greatest powers of the Lund string model is that it invites a picture of strings as physical objects that can interact with each other.

- Colour reconnection can rearrange the string topology.
- Overlapping strings produce stronger fields called *ropes*, with a larger κ. This can lead to strangeness enhancement, in accordance with the suppression factor $e^{-\pi m_\perp^2/\kappa_{\mathrm{rope}}}$ [arXiv:2202.12783]
- Fields can also attract or repulse each other. We call this phenomenon *shoving*, and it can give rise to collective flow [arXiv:2207.14186 [hep-ph]]

Angantyr overview

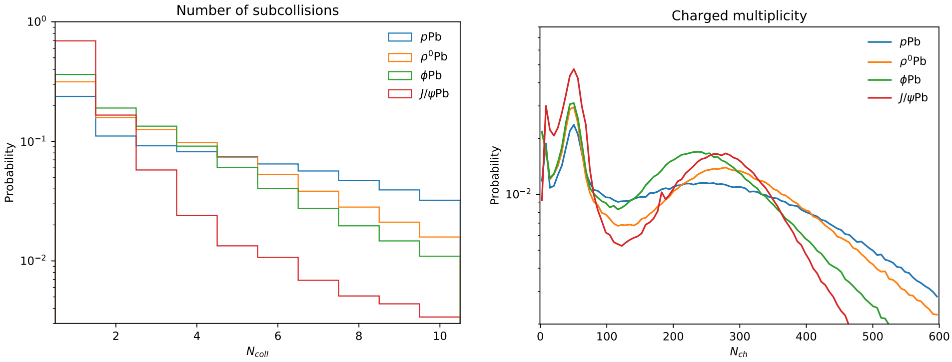
- Nuclear geometry is given by Glauber model. Each subcollision is assigned a type based on the impact parameter b_{NN}.
- Perform absorptive subcollisions with smallest b_{NN} first. Generate events to parton level.
- Secondary absorptive collisions are modelled like diffractive interactions.
- Combine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



[arXiv:1806.10820]

One objective of Angantyr is to investigate a QGP-less paradigm.

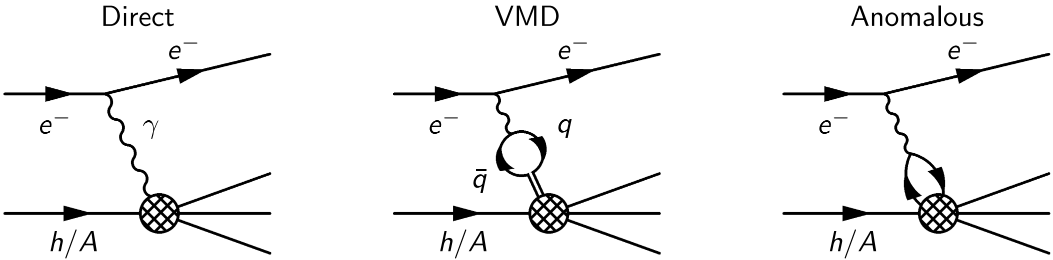
Hadron-ion collisions in Angantyr (NEW)



- Heavier quark content implies fewer subcollisions with more activity per collision.
- In hA, there is one or zero absorptive interactions, giving a bimodal spectrum.
- Note that ϕ peak is not between ρ^0 and J/ψ.

Photon-induced processes

The photon wavefunction has three components.



Thus the photon wave function can be written as

$$|\gamma\rangle = c_0 \, |\gamma_{\mathrm{direct}}\rangle + \sum_{V=\rho^0,\omega,\phi,J/\psi} c_V \, |V\rangle + \sum_f c_f \, |f\bar{f}\rangle$$

Photon-induced processes

Direct processes: $d\sigma_{\text{direct}} = f_{\gamma}^{e}(x_{\gamma}) \otimes f_{q}^{p}(x_{q}) \otimes d\sigma_{\gamma q}$

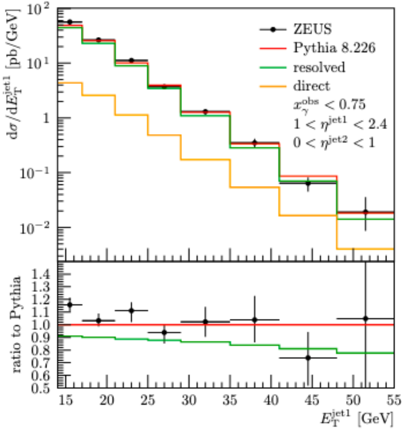
Resolved processes: $d\sigma_{\text{resolved}} = f_{\gamma}^{e}(x_{\gamma}) \otimes f_{q}^{\gamma}(x) \otimes f_{q'}^{p}(x') \otimes d\sigma_{qq'}$

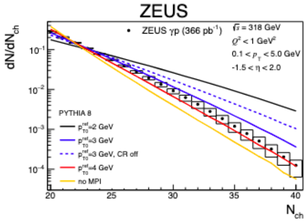
- Direct interactions tend to be harder, since the entire photon participates in the hard process.
- For resolved processes, low Q^2 is associated with VMDs, and large Q^2 with the anomalous part.
- VMDs tend to have higher multiplicity than anomalous processes due to multiparton interactions.

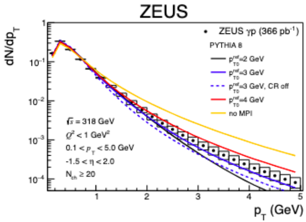
Photon–proton interactions with Pythia

In Pythia, γp interactions are accurately modelled [arXiv:hep-ex/0112029]

However, there is a number of technicalities that must be dealt with when extending this to heavy ions.





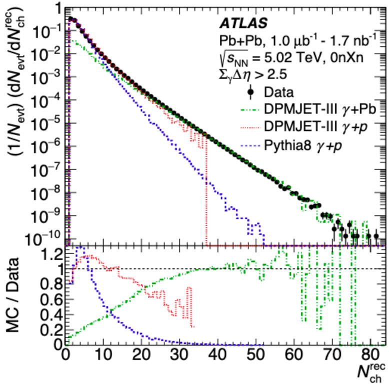


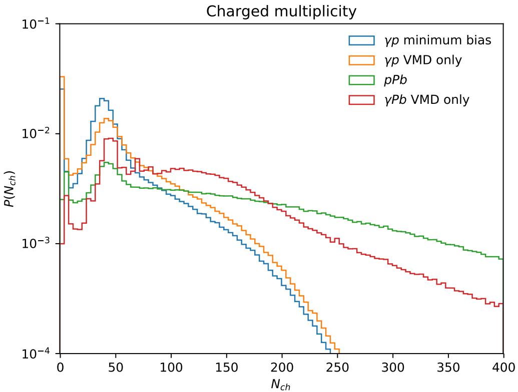
Photon–ion interactions with Angantyr

- The direct part is straightforward to model in Angantyr. It is just a matter of actually implement it in the code.
- In γp, the VMD part is modelled by PDFs describing the photon content. In γA, this is insufficient since it doesn't explain how to implement secondary collisions. We solve this by simulating it as a hA interaction, using the wounded nucleon model as with pA.
- The anomalous part is more complicated in γA than γp, because the q and $\bar{q}$ can interact with different nucleons in A. We still need to work out these details.

Another technical issue is that Angantyr does not support changing the collision energy on an event-by-event basis. Variable energy is required because in $e^- A \to e^-(\gamma A)$ interactions, the γA interaction is not at a fixed energy.

Angantyr with VMD photons – Preliminary results (NEW)





- γPb VMD modelled as weighted sum of VPb collisions.
- Differences between shapes for γPb and pPb
- Qualitatively speaking, the shift from γp to γPb is consistent with data.

Outlook

Our goal is to implement full $e^- A$ interactions in Pythia.

- For the direct part, the physics are understood, but the implementation is missing.
- The VMD part is under implementation in this current work.
- For the anomalous part, we need to work out the details of how the $q\bar{q}$ system interacts with nuclei.
- There are also some other technical issues, like supporting variable beam energies.