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JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

Hadronic interactions in Angantyr

Marius Utheim
in collaboration with Ilkka Helenius

University of Jyväskylä

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Outline

Pythia overview

HardQCD in Angantyr

Generic hadronic interactions in Angantyr

Summary and outlook

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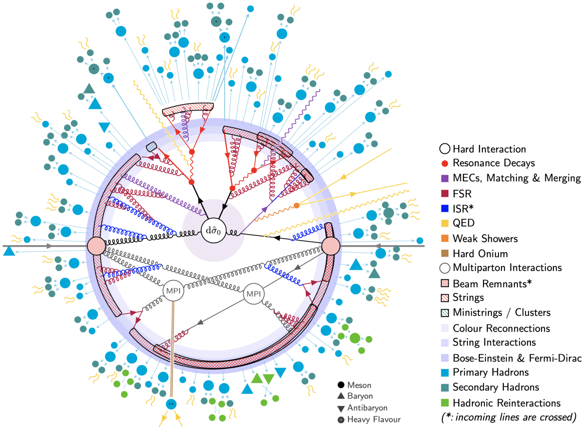
Pythia overview [arXiv:2203.11601]

PYTHIA is a general-purpose event generator.

- These generators combine models for each step of the event, to produce the most complete prediction of what a particle collision looks like.
- They tell us what our theoretical models predict at the end of the day
- Can make future predictions that may guide e.g. detector design.



(figure by S. Chakraborty and P. Skands)

Pythia overview

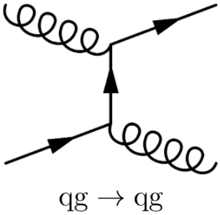
PYTHIA event generation is divided into three stages.

- Process level
  - Matrix elements and the hard process
- Parton level
  - Multiparton interactions
  - Matching and merging
  - Initial and final state radiation
  - Beam remnants
- Hadron level
  - String fragmentation
  - String shoving, rope formation, colour reconnection
  - Hadronic decays, hadronic rescattering

Originally, PYTHIA was intended for pp collisions, but I will give this overview from a perspective that is agnostic to the hadron species.

Process level – HardQCD vs. SoftQCD

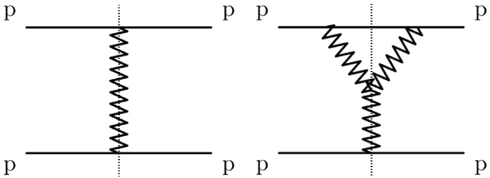
HardQCD



$$\frac{d\sigma_{AB\to kl}}{d\hat{t}dxdx'} = f_i^A(x,Q^2)\, f_j^B(x',Q^2)\, \frac{d\hat{\sigma}_{ij\to kl}}{d\hat{t}}$$

- Perturbative QCD, only at high scales
- Includes phase space constraints
- Useful for jet studies

SoftQCD

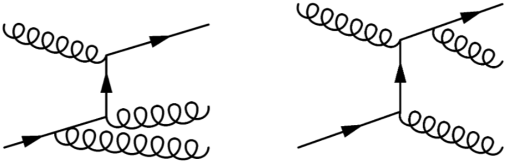


$$\sigma_{\text{total}} = X^{AB}s^{\epsilon} + Y^{AB}s^{-\eta}$$

- Minimum bias
- Based on Regge theory
- Non-diffractive, diffractive, elastic

Parton level

Beyond the hard process, additional gluons can be produced, such as in the diagrams



There are two approaches to including such effects.

- Fixed-order calculation: explicitly calculate the matrix element of each contributing diagram, using techniques such as matching and merging.
- Parton showers: using DGLAP evolution to add a variable number of additional partons as initial- or final-state radiation (ISR and FSR).

The interaction can also include additional parton-parton collisions. This is called *multiparton interactions* (MPIs).

Parton distribution functions

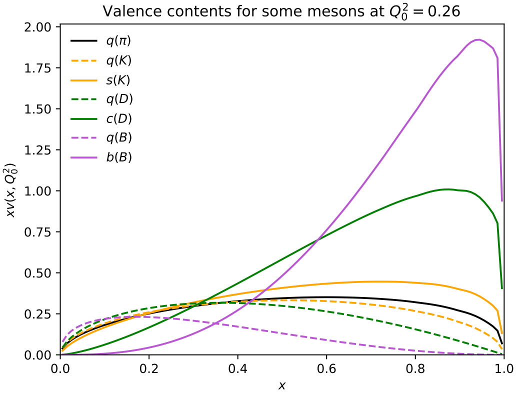
PDFs determine the contents of a hadron. For protons, detailed PDFs based on global fits exist, the Pythia default being NNPDF2.3 QCD+QED LO (with $\alpha_S = 0.130$).

For other species, very little data exists, and we base our valence distributions on an ansatz by Glück, Reya et al. [`arXiv:hep-ph/9806404`]:

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

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

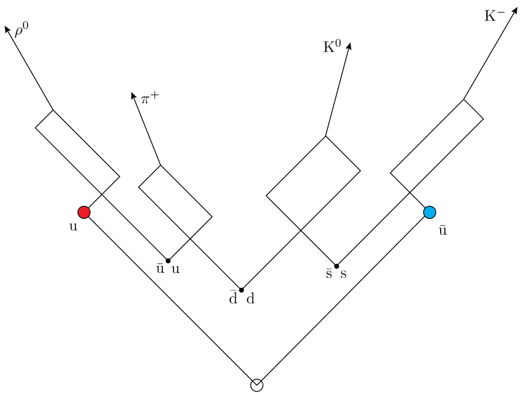


- $\langle x \rangle$ is higher for heavy valence content (solid lines), and correspondingly lower for light content (dashed lines).

Hadronization [DOI:10.1007/BF01407824, DOI:10.1016/0550-3213(84)90607-2]

Hadronization is a non-perturbative process. In PYTHIA, it is implemented using the Lund string model.

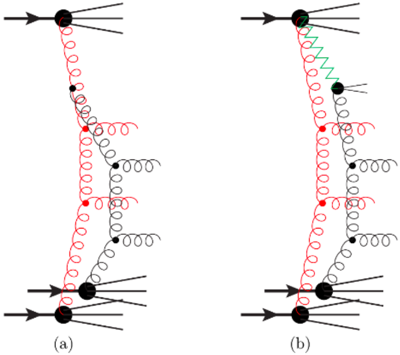
- Strings (colour fields) are stretched between outgoing partons.
- Strings can break to produce new quark-antiquark pairs.
- The details of the model include flavour selection, baryon production, string interactions, etc.



Angantyr [arXiv:1806.10820]

In a nutshell, ANGANTYR sets up the spatial configuration of each nucleus, then proceeds by simulating individual nucleon-nucleon interactions using PYTHIA.

- Nuclear geometry is given by Glauber model. 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.



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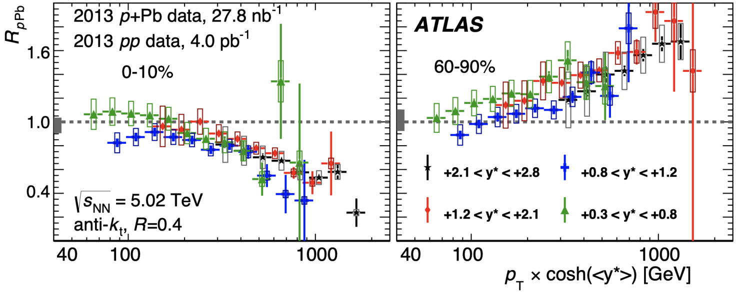
Motivation

Project in collaboration with Hannu Paukkunen

ATLAS data has observed interesting nuclear effects at high $p_\perp$ [`arXiv:1412.4092v2`]



- This is believed to be due to bias in the centrality measure. We want to investigate with PYTHIA.
- The highest-energy events are $\sim 10^{-10}$ times as likely as the most probably ones. There is an optimization issue here.

HardQCD in Pythia

On the process level, we must sample the impact parameter b and the transverse momentum transfer $\hat{p}_\perp$. The distribution is on the form

$$\frac{d\sigma}{db d\hat{p}_\perp} = f(b) g(\hat{p}_\perp) \exp\left(- \int_{\hat{p}_\perp}^{\infty} d\hat{p}'_\perp \, S(b, \hat{p}'_\perp) \right), \tag{1}$$

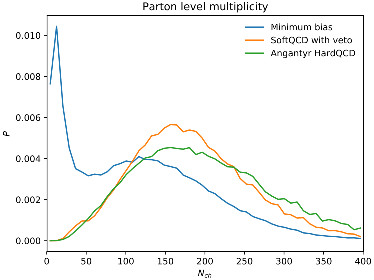
where the exponential corresponds to a Sudakov factor. In the limit of large $\hat{p}_\perp$ ($\gtrsim 15$ GeV), the exponential becomes 1 and b and $\hat{p}_\perp$ decouple.

With HardQCD, we set a lower limit $\hat{p}_{\perp,\mathrm{min}}$ and oversample certain parts of phase space to get better statistics. This means the rate of events in this region will be too high, and we must rescale to compensate:

$$w = \frac{\sigma_{\mathrm{Hard}}}{\sigma_{\mathrm{Total}}} = \frac{\int_0^\infty db \int_{\hat{p}_{\perp,\mathrm{min}}}^\infty d\hat{p}'_\perp \frac{d\sigma}{db d\hat{p}'_\perp}}{\int_0^\infty db \int_0^\infty d\hat{p}'_\perp \frac{d\sigma}{db d\hat{p}'_\perp}} \tag{2}$$

What does "HardQCD" mean in Angantyr?

In pp, a HardQCD event is characterized by a phase space restriction like $\hat{p}_\perp > \hat{p}_{\perp,\mathrm{min}}$.
We call a pA event "hard" if the primary collision is absorptive with $\hat{p}_\perp > \hat{p}_{\perp,\mathrm{min}}$.



The "gold standard" way to produce HardQCD events is to generate SoftQCD and reject the ones that don't fulfil the phase space restriction. Although HardQCD is already available in ANGANTYR 8.310, it does not account for the fact that hard processes are more likely at low impact parameters.

Impact parameter-dependent weights

For a subcollision i at impact parameter b_i, the probability that it is hard can be written as

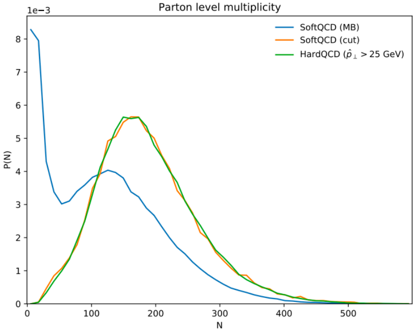
$$P_i(b_i) = \frac{\int_{\hat{p}_{\perp,\min}}^{\infty} d\hat{p}'_\perp \frac{d\sigma}{dbd\hat{p}'_\perp}}{\int_0^{\infty} d\hat{p}'_\perp \frac{d\sigma}{dbd\hat{p}'_\perp}}. \tag{3}$$

The total probability of an event with a given nuclear configuration is hard is thus

$$P_{\mathrm{Hard}} = 1 - \prod_i (1 - P_i). \tag{4}$$

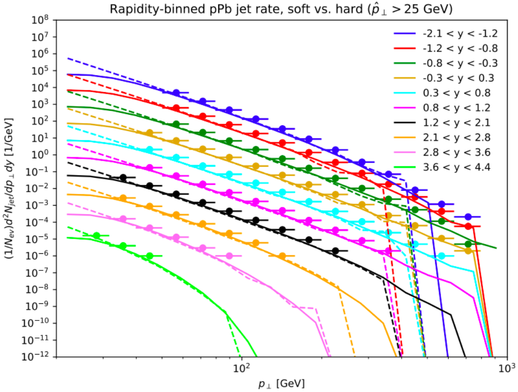
In our implementation, we replace a random subcollision by a HardQCD event, and reweight the event according to P_{Hard}.

Model validation



- HardQCD now gives behaviour that is in accordance with the “gold standard”.
- When starting from SoftQCD, around ~ 99.7 % of events are vetoed due to the $\hat{p}_\perp > 25$ GeV requirement.
- Here, $P_i(b)$ was obtained using MC to generate the necessary $d\sigma/db$ distributions. The missing piece is to do this efficiently.

Results: Jet spectra [arXiv:1412.4092v2]



- Solid lines indicate HardQCD, dashed lines are SoftQCD.
- Overall, the fit is within error bars, but the scale is logarithmic and compressed.
- The HardQCD overlaps with SoftQCD in the middle, and extends to higher $p_\perp$.

Outline

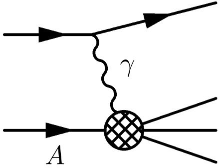
Motivation

On a technical level, our objective is *to generate hadron-ion collisions for projectile hadrons other than protons and neutrons*.

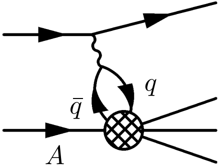
- Direct studies: the NA61/SHINE experiment studies pion beams on a carbon target.
- Hadronic cascades: when energetic particles move through a medium, such as cosmic particles inducing air showers in our atmosphere, many different hadrons are produced and subsequently collide with atoms in the medium. We want to simulate these interactions.
- Photon-ion interactions: interactions where a photon interacts with an ion occur in the context of ultra-peripheral collisions (UPCs), and are central for the future Electron-Ion Collider (EIC). In these interactions, the photon can fluctuate into a vector meson (ρ^0, ω, ϕ, or J/ψ), leading to an essentially QCD interaction.

The photon wavefunction

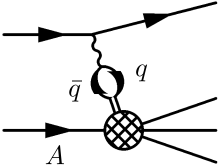
Direct



Anomalous



VMD



- 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, and it dominates the cross section for minimum bias events.

Hadronic fluctuations

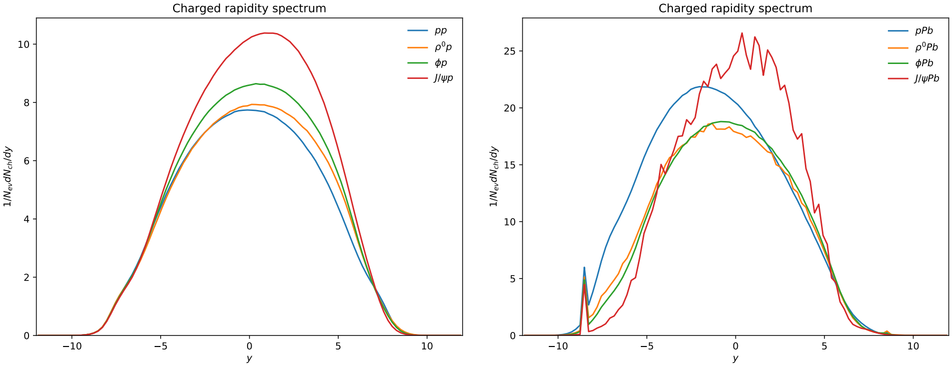
Hadron-hadron interactions already exist in PYTHIA, including their PDFs and cross sections. The only non-trivial hadronic effect left to consider is hadronic fluctuations.

As hadrons travel through space, the size of the wavefunction fluctuates. In pp collisions, this effect can be compensated with tuning. In pA it is more important, since a large projectile will interact with more nucleons in the target, which gives a longer tail in multiplicity distributions.

In ANGANTYR, the fluctuations are controlled by three parameters. The size of the fluctuations fix the cross sections. The fluctuation parameters are fitted with a genetic algorithm to reproduce these cross sections.

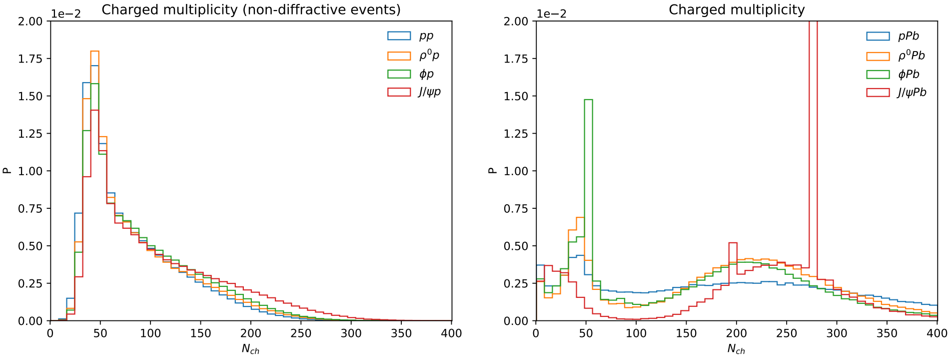
Applying this procedure to the asymmetric meson-nucleon case gives mediocre results. The fitting targets are insensitive to asymmetric fluctuations. Furthermore, the model gives unphysically large fluctuations for J/ψ, which is expected to have a small wavefunction. Clearly there is room for improvement.

Model test: Rapidity spectra at 5.02 TeV



- For heavier mesons, the rapidity spectrum is pushed in the meson-going direction.
- Relation between p and ρ^0 is unexpected – it is a model uncertainty due to PDFs.
- pPb has more subcollisions, and is thus pushed harder in the ion-going direction.
- Due to fluctuations and impact parameter sampling, J/ψ gets some events with extremely high weight.

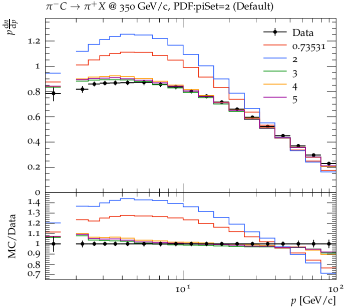
Model test: Multiplicities at 5.02 TeV

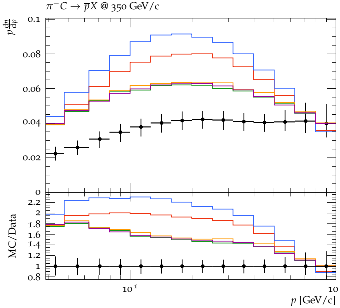


- Bimodal peaks are due to the presence or absence of an absorptive subcollision.
- Long proton tail is driven by larger cross section and more subcollisions.
- Heavier mesons produce fewer subcollisions, but each subcollision produces more particles, leading to a non-trivial progression from ρ^0 to ϕ to J/ψ.

Results: $\pi^- C$ at NA61/SHINE [`arXiv:2209.10561v1`]

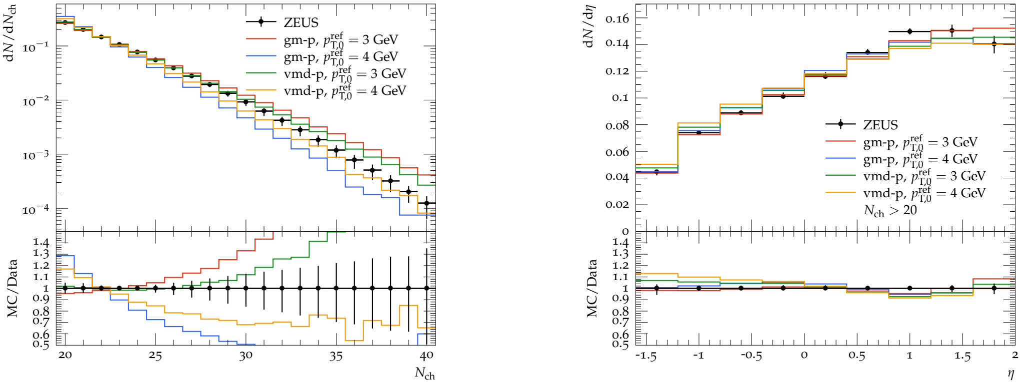
In collaboration with Chloé Gaudu





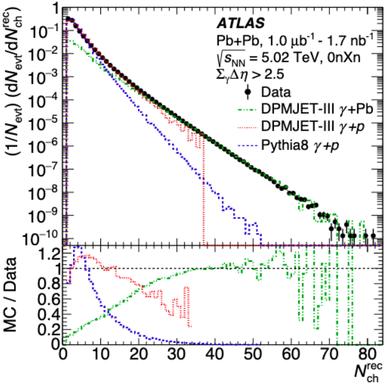
- The different colours refer to different values of the $p_{0,\perp}^{\mathrm{ref}}$ parameter, which represents a saturation scale in MPI evolution.
- Angantyr shows good agreement in pion spectra. The same holds for other meson spectra such as K.
- Baryons are less well described.

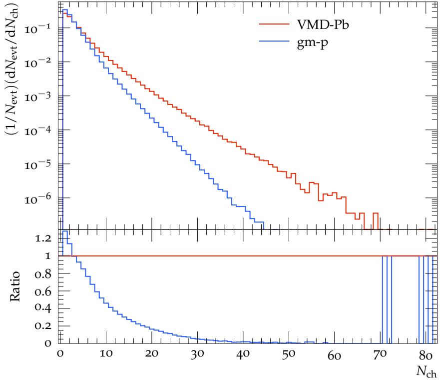
Results: γp at HERA [`arXiv:2106.12377`]



- The $p_{0,\perp}^{\mathrm{ref}}$ variation gives a sense of the model uncertainty.
- The shift due to changing $p_{0,\perp}^{\mathrm{ref}}$ is larger on average in the full photoproduction than in just the VMD component.

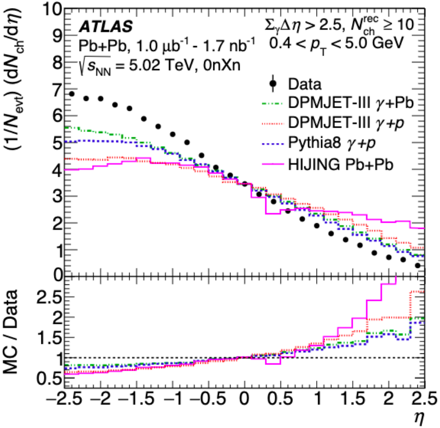
Results: ATLAS $\gamma + \mathrm{Pb}$ multiplicities [`arXiv:2101.10771`]

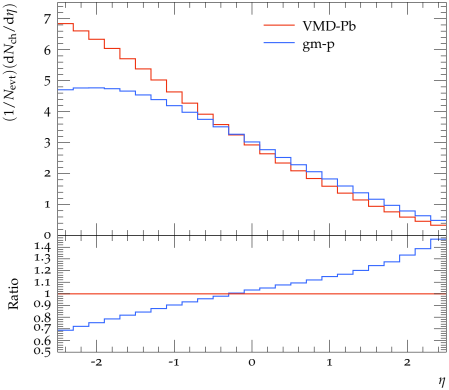




- The ATLAS data is not corrected for the limited efficiency, estimated to ~ 80 %.
- Qualitatively speaking, the shift from γp to γPb is consistent with data.
- In γp, the VMD component has less average multiplicity than in full photoproduction. This could be the other way around for γPb.

Results: ATLAS eta spectrum [`arXiv:2101.10771`]





- Again, we cannot make a direct comparison, but the fit is still good when accounting for the limited efficiency in the multiplicity cut.

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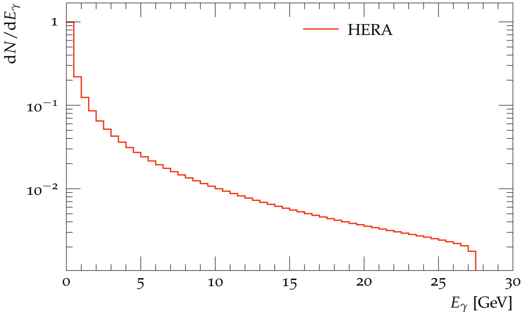
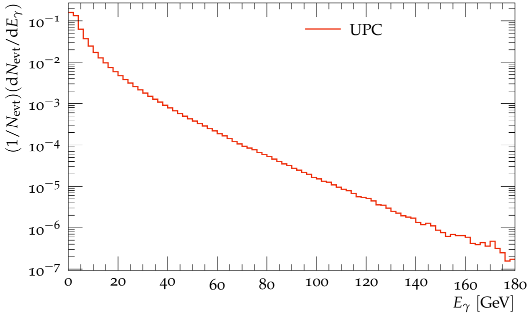
Summary and outlook

1. Simulating hard events in ANGANTYR.
   - Implementation is not complete. The main missing piece is calculating $d\sigma^{\text{Hard}}/db$.
   - Preliminary results show a decent agreement with jet data.
   - Next step is to compare to centrality-dependent ATLAS data.
2. Simulating hadron-ion collisions for all hadron species.
   - Has applications to cosmic rays and photo-induced processes.
   - Relies on existing PYTHIA hadron-hadron framework. The main non-trivial new physics feature is hadron size fluctuations. The current model has some flaws, particularly noticeable for J/ψ.
   - The work also includes technical features, in particular energy and beam switching.
   - Our model shows a good agreement with data from NA61/SHINE, HERA, and ATLAS UPCs.
   - In our paper, we will also compare to v_2 data from ATLAS UPCs.

Outline

Photon flux [arXiv:1901.05261]



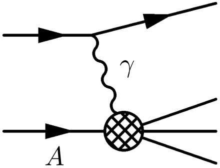


$$f_{\gamma/e}(x) = \frac{\alpha_{EM}}{2\pi}\frac{1+(1-x)^2}{x}\log\left[\frac{Q^2_{\max}(1-x)}{m_2^2x^2}\right]$$

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

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

Direct



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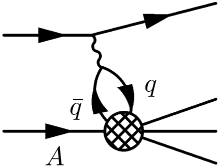
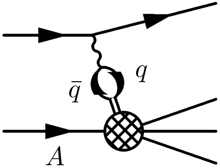


VMD



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

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

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

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