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

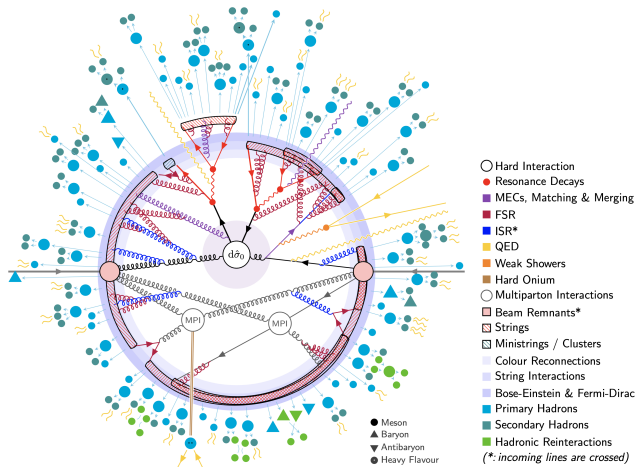**Marius Utheim**
in collaboration with Ilkka Helenius

University of Jyväskylä

DIS2023 – MSU – March 29

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.
- ▶ Can make future predictions, which may guide e.g. detector design.
- ▶ Includes ANGANTYR module for heavy ions.

○ Hard Interaction
● Resonance Decays
■ MECs, Matching & Merging
■ FSR
■ ISR*
■ QED
■ Weak Showers
■ Hard Onium
○ Multiparton Interactions
□ Beam Remnants*
□ Strings
□ Ministrings / Clusters
□ Colour Reconnections
□ String Interactions
□ Bose-Einstein & Fermi-Dirac
■ Primary Hadrons
■ Secondary Hadrons
■ Hadronic Reinteractions
(: incoming lines are crossed)*

● Meson
▲ Baryon
▼ Antibaryon
● Heavy Flavour

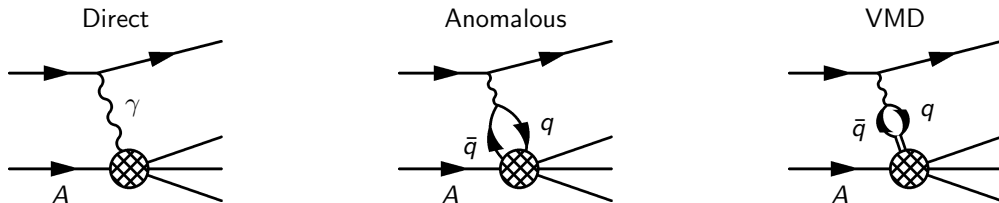(figure by S. Chakraborty and P. Skands)

Motivation

Overarching motivation: *we want a full minimum-bias photon-ion simulation*

Motivation

Overarching motivation: *we want a full minimum-bias photon-ion simulation*
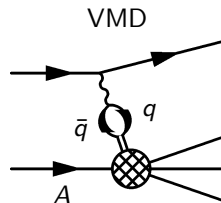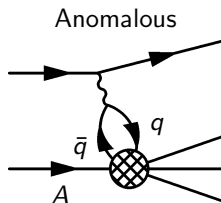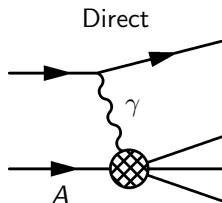
Motivation

Overarching motivation: *we want a full minimum-bias photon-ion simulation*

Direct	Anomalous	VMD
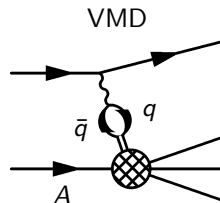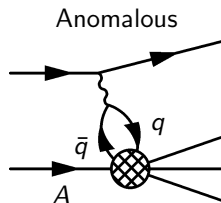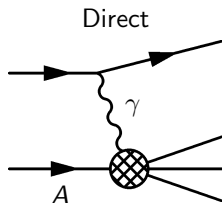
▶ The direct part is straightforward to model in ANGANTYR: the photon simply scatters off a single nucleon. At high Q^2, this corresponds to DIS.

Motivation

Overarching motivation: *we want a full minimum-bias photon-ion simulation*

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.

Motivation

Overarching motivation: *we want a full minimum-bias photon-ion simulation*

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.
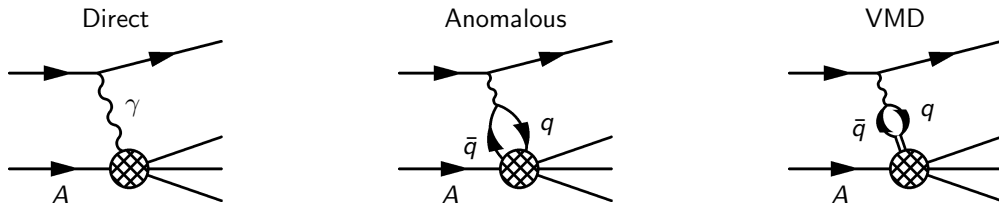
▶ The anomalous part is more complicated. The q and $\bar{q}$ can interact with different nucleons in A.

▶ 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.

Objective

Current objective: *To implement hadron-ion interactions for generic hadrons.*

Objective

Current objective: *To implement hadron-ion interactions for generic hadrons.*

▶ Primary use case is for the VMD part of the photon wave function.

Objective

Current objective: *To implement hadron-ion interactions for generic hadrons.*

▶ Primary use case is for the VMD part of the photon wave function.
▶ This feature also has other applications, such as modelling hadronic cascades.

Objective

Current objective: *To implement hadron-ion interactions for generic hadrons.*

▶ Primary use case is for the VMD part of the photon wave function.
▶ This feature also has other applications, such as modelling hadronic cascades.
  ▶ PYTHIA has already been used in CORSIKA 8 air shower [arXiv:2303.02792].

Objective

Current objective: *To implement hadron-ion interactions for generic hadrons.*

▶ Primary use case is for the VMD part of the photon wave function.
▶ This feature also has other applications, such as modelling hadronic cascades.
  ▶ PYTHIA has already been used in CORSIKA 8 air shower [arXiv:2303.02792].
  ▶ NA61/SHINE has provided data on $\pi^- C$ collisions [arXiv:2209.10561].

Objective

Current objective: *To implement hadron-ion interactions for generic hadrons.*

▶ Primary use case is for the VMD part of the photon wave function.

▶ This feature also has other applications, such as modelling hadronic cascades.
  ▶ PYTHIA has already been used in CORSIKA 8 air shower [arXiv:2303.02792].
  ▶ NA61/SHINE has provided data on $\pi^- C$ collisions [arXiv:2209.10561].

▶ One technical point is that in interactions like $e^- A \to e^- (\gamma A)$, the γA interaction is not at a fixed energy. We need to change the beam energies on an event-by-event basis, depending on the photon flux.

Objective

Current objective: *To implement hadron-ion interactions for generic hadrons.*

▶ Primary use case is for the VMD part of the photon wave function.
▶ This feature also has other applications, such as modelling hadronic cascades.
   ▶ PYTHIA has already been used in CORSIKA 8 air shower [arXiv:2303.02792].
   ▶ NA61/SHINE has provided data on $\pi^- C$ collisions [arXiv:2209.10561].
▶ One technical point is that in interactions like $e^- A \rightarrow e^- (\gamma A)$, the γA interaction is not at a fixed energy. We need to change the beam energies on an event-by-event basis, depending on the photon flux.

Objective

Current objective: *To implement hadron-ion interactions for generic hadrons.*

► Primary use case is for the VMD part of the photon wave function.
► This feature also has other applications, such as modelling hadronic cascades.
  ► PYTHIA has already been used in CORSIKA 8 air shower [arXiv:2303.02792].
  ► NA61/SHINE has provided data on $\pi^- C$ collisions [arXiv:2209.10561].
► One technical point is that in interactions like $e^- A \to e^- (\gamma A)$, the γA interaction is not at a fixed energy. We need to change the beam energies on an event-by-event basis, depending on the photon flux.

Hadron-proton interactions already exist in PYTHIA [arXiv:2108.03481]. In this talk, I will present this framework, then introduce the changes we have made to extend this to ANGANTYR. Finally we look at some results, comparing to HERA and LHC data.
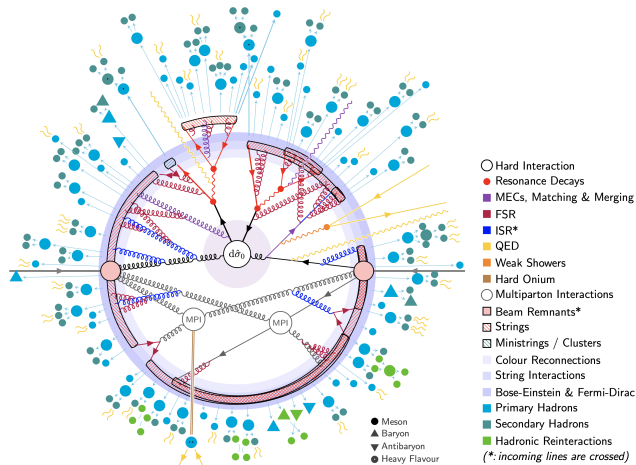
Outline

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.

- ○ Hard Interaction
- ● Resonance Decays
- ■ MECs, Matching & Merging
- ■ FSR
- ■ ISR*
- ■ QED
- ■ Weak Showers
- ■ Hard Onium
- ○ Multiparton Interactions
- □ Beam Remnants*
- □ Strings
- ⊡ Ministrings / Clusters
- ▫ Colour Reconnections
- ▫ String Interactions
- ▫ Bose-Einstein & Fermi-Dirac
- ■ Primary Hadrons
- ■ Secondary Hadrons
- ■ Hadronic Reinteractions
- *(*: incoming lines are crossed)*

- ● Meson
- ▲ Baryon
- ▼ Antibaryon
- ● Heavy Flavour

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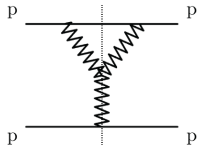
$$\sigma_{AB}(s) = X^{AB} s^{\epsilon} + Y^{AB} s^{-\eta}$$

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.

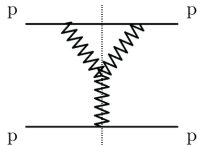$$d\sigma = \frac{g_{3\mathbb{P}}\beta_{A\mathbb{P}}\beta_{B\mathbb{P}}^2}{16\pi}\frac{dM_X^2}{M_X^2}(e^{B_{XB}t}dt)\, F_{\mathrm{SD}}(M_X^2, s)$$

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.
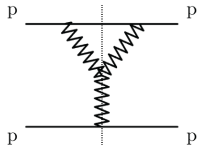
$$d\sigma = \frac{g_{3\mathbb{P}}\beta_{A\mathbb{P}}\beta_{B\mathbb{P}}^2}{16\pi}\frac{dM_X^2}{M_X^2}(e^{B_{XB}t}dt)\,F_{\mathrm{SD}}(M_X^2, s)$$
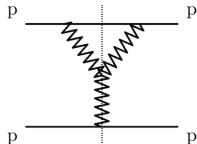
▶ If $\beta_{B\mathbb{P}}(t) = \beta_{B\mathbb{P}}\exp(b_B t)$, then with suitable normalization, $X^{AB} = \beta_{A\mathbb{P}}(0)\beta_{B\mathbb{P}}(0)$

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

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 $\alpha_S = 0.130$).

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.:

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

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.
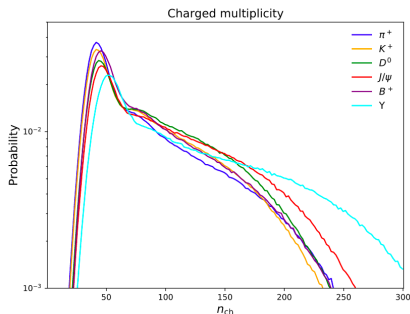
Parton distribution functions

Valence contents for some mesons at $Q_0^2 = 0.26$
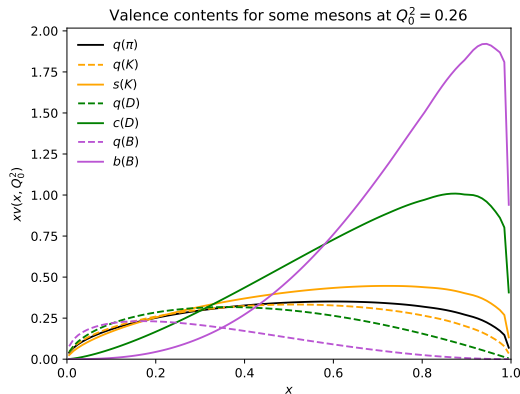
▶ $\langle x \rangle$ is higher for heavy valence content (solid lines), and correspondingly lower for light content (dashed lines).

Hadron–proton collisions in Pythia [arXiv:2108.03481]

The following plots are for meson–proton nondiffractive events at 6 TeV
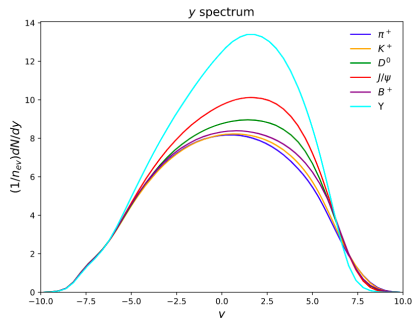
▶ Hadrons with heavier valence content generally lead to harder interactions and more activity

▶ Effect is particularly pronounced for J/ψ and Υ, which have no light valence.

From hp to hA

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

From hp to hA

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

▶ Nuclear geometry is given by Glauber model. Each subcollision is assigned a type (absorptive, diffractive, elastic) based on the impact parameter b_{NN}.
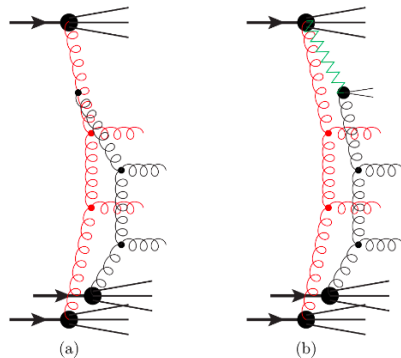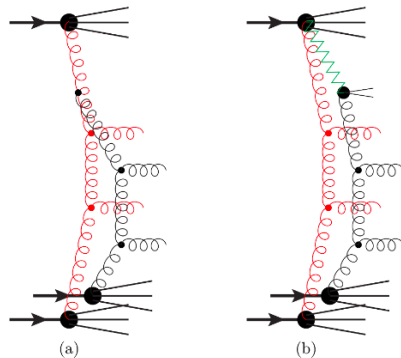

(a)   (b)

arXiv:1806.10820

From hp to hA

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

▶ 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.

(a)   (b)

`arXiv:1806.10820`

From hp to hA

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

▶ 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.
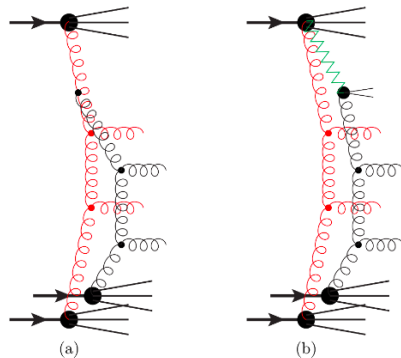

(a)   (b)

arXiv:1806.10820

From hp to hA

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

▶ 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.

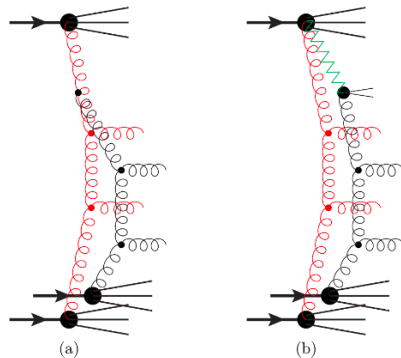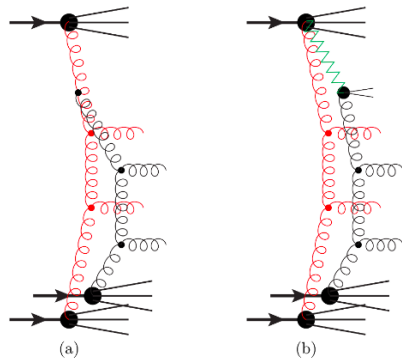▶ Combine partons from all subevents, then do color reconnection, string interactions, string hadronization, etc.

`arXiv:1806.10820`

From hp to hA

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

▶ 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.

arXiv:1806.10820

From hp to hA

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

▶ 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.

arXiv:1806.10820

Once we have *hp* and ANGANTYR, no further physics modelling is needed.

Hadron-ion collisions in Angantyr
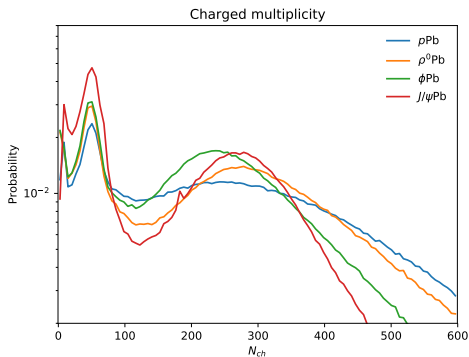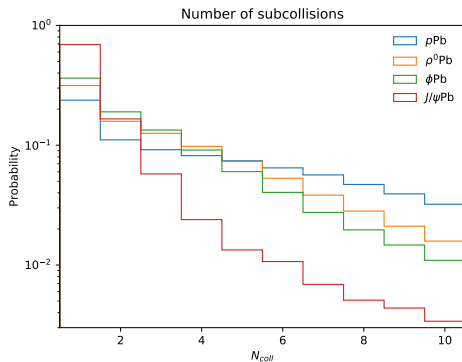
▶ Heavier quark content implies fewer subcollisions with more activity per collision.

▶ In hA, there is one or zero absorptive interactions, giving a bimodal spectrum.

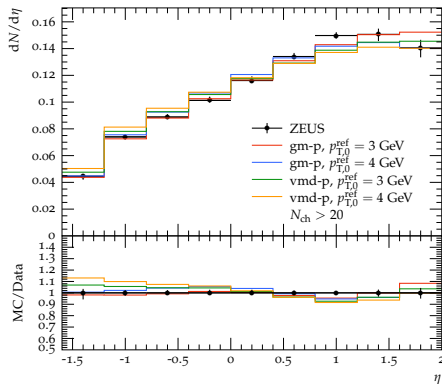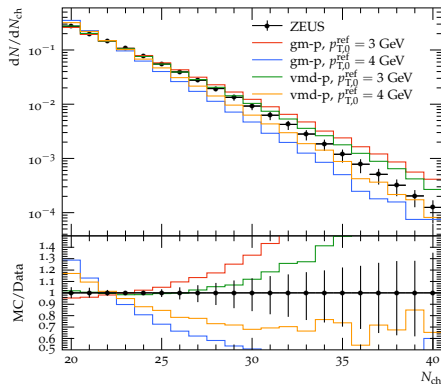▶ Note that ϕ peak is not between ρ^0 and J/ψ.

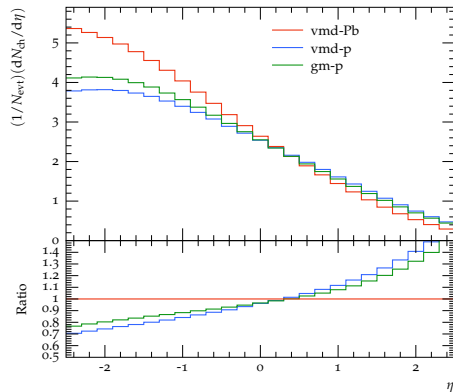# Outline

# γp at HERA [arXiv:2106.12377]

- ▶ $p_{\perp,0}^{\rm ref}$ 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 $p_{\perp,0}^{\rm ref}$ is larger on average in the full photoproduction than in just the VMD component.

ATLAS $\gamma + Pb$ multiplicities [arXiv:2101.10771]
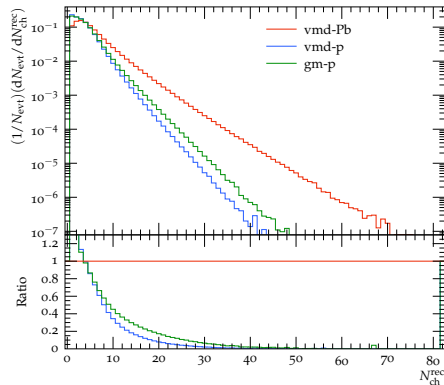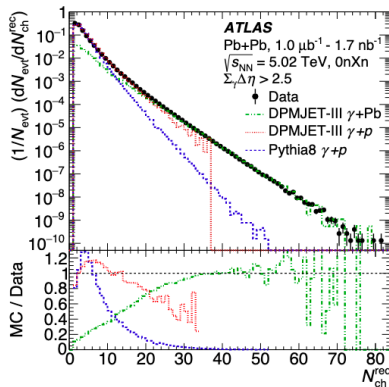
- ▶ Our analysis is not exactly the same as in the experimental paper.
- ▶ Qualitatively speaking, the shift from γp to γPb is consistent with data.
- ▶ In γp, the VMD component has less average multiplicity than in full photoproduction. This could be the other way around for γPb.

ATLAS eta spectrum [arXiv:2101.10771]
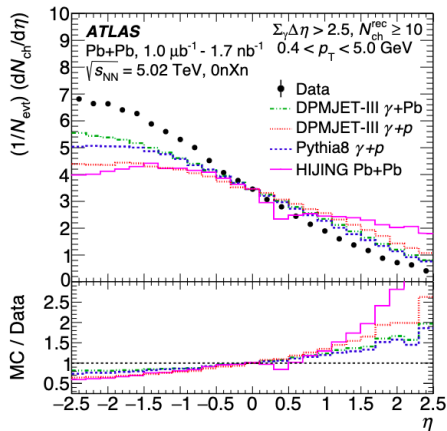
► The ratios between γp and γPb is similar for our simulation and in data.

► VMD components have a slight bias in the photon-going direction.

Outline

Summary and outlook

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

▶ With this new feature, we can study photon-induced processes with VMD photons. Our long-term goal is a minimum-bias γA simulation.

Summary and outlook

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

▶ With this new feature, we can study photon-induced processes with VMD photons. Our long-term goal is a minimum-bias γA simulation.

▶ We have validated our approach against HERA data. The shift from VMD-p to VMD-Pb is qualitatively in line with ATLAS UPC data.

Summary and outlook

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

► With this new feature, we can study photon-induced processes with VMD photons. Our long-term goal is a minimum-bias γA simulation.

► We have validated our approach against HERA data. The shift from VMD-p to VMD-Pb is qualitatively in line with ATLAS UPC data.

► We have also implemented variable energies in ANGANTYR.

Summary and outlook

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

► With this new feature, we can study photon-induced processes with VMD photons. Our long-term goal is a minimum-bias γA simulation.

► We have validated our approach against HERA data. The shift from VMD-p to VMD-Pb is qualitatively in line with ATLAS UPC data.

► We have also implemented variable energies in ANGANTYR.

Summary and outlook

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

▶ With this new feature, we can study photon-induced processes with VMD photons. Our long-term goal is a minimum-bias γA simulation.

▶ We have validated our approach against HERA data. The shift from VMD-p to VMD-Pb is qualitatively in line with ATLAS UPC data.

▶ We have also implemented variable energies in ANGANTYR.

Next steps...

▶ For the direct part of the photon wavefunction, modelling is straightforward, but the implementation is missing. The anomalous part is a little more complicated.

Summary and outlook

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

- ▶ With this new feature, we can study photon-induced processes with VMD photons. Our long-term goal is a minimum-bias γA simulation.
- ▶ We have validated our approach against HERA data. The shift from VMD-p to VMD-Pb is qualitatively in line with ATLAS UPC data.
- ▶ We have also implemented variable energies in ANGANTYR.

Next steps...

- ▶ For the direct part of the photon wavefunction, modelling is straightforward, but the implementation is missing. The anomalous part is a little more complicated.
- ▶ This work also has other applications, such as hadronic showers and $\pi^- C$ scattering experiments.

Summary and outlook

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

▶ With this new feature, we can study photon-induced processes with VMD photons. Our long-term goal is a minimum-bias γA simulation.

▶ We have validated our approach against HERA data. The shift from VMD-p to VMD-Pb is qualitatively in line with ATLAS UPC data.

▶ We have also implemented variable energies in ANGANTYR.

Next steps...

▶ For the direct part of the photon wavefunction, modelling is straightforward, but the implementation is missing. The anomalous part is a little more complicated.

▶ This work also has other applications, such as hadronic showers and $\pi^- C$ scattering experiments.

Summary and outlook

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

▶ With this new feature, we can study photon-induced processes with VMD photons. Our long-term goal is a minimum-bias γA simulation.

▶ We have validated our approach against HERA data. The shift from VMD-p to VMD-Pb is qualitatively in line with ATLAS UPC data.

▶ We have also implemented variable energies in ANGANTYR.

Next steps...

▶ For the direct part of the photon wavefunction, modelling is straightforward, but the implementation is missing. The anomalous part is a little more complicated.

▶ This work also has other applications, such as hadronic showers and $\pi^- C$ scattering experiments.

Code expected to be released in PYTHIA 8.310.
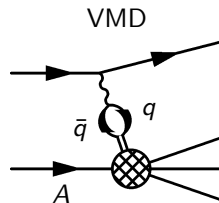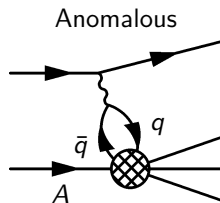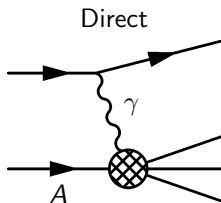
Outline

Backup slides

Photon flux [arXiv:1901.05261]
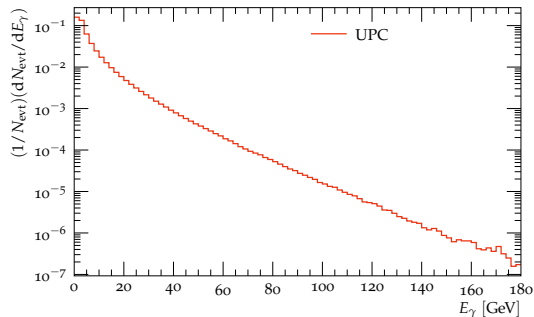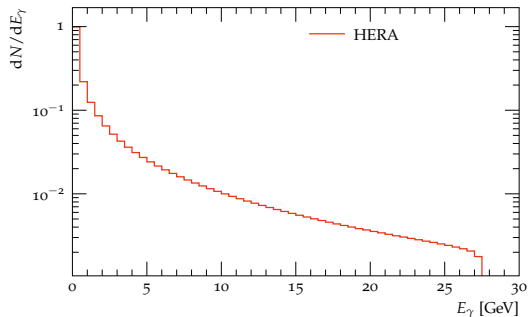
$$f_{\gamma/e}(x) = \frac{\alpha_{EM}}{2\pi} \frac{1 + (1-x)^2}{x} \log\left[\frac{Q_{\max}^2(1-x)}{m_2^2 x^2}\right]$$

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

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

| | Direct | Anomalous | 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

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