Hadronic Interactions at High and Low Energies

Marius Utheim

23rd MCnet meeting
This talk

This talk will be a review on the things I did during my PhD. I will present my perspectives on a few phenomena, results of what I did, and talk about some things that I did not have time to do.

- Hadronic rescattering
- Exotic hadrons
- Cosmic rays
Outline

Hadronic rescattering

Exotic hadrons

Cosmic rays
How I view rescattering
Features of rescattering

- Rescattering changes multiplicity and particle composition.
Features of rescattering

- Rescattering changes multiplicity and particle composition.
- Rescattering can give rise to collective flow.
Features of rescattering

- Rescattering changes multiplicity and particle composition.
- Rescattering can give rise to collective flow.
- To some extent it can also give rise to jet quenching.
Features of rescattering

- Rescattering changes multiplicity and particle composition.
- Rescattering can give rise to collective flow.
- To some extent it can also give rise to jet quenching.
- Resonances produced in rescattering can be hard to observe. Some resonances can be suppressed.
Multiplicities - pp vs. PbPb @ 5.02 TeV

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

"Rule of thumb": MultipartonInteractions:pT0Ref = 2.345
Particle composition is still changed, e.g. by $p\bar{p} \rightarrow \pi^+\pi^0\pi^-$
Flow and jet quenching

Phenomena such as collective flow has been observed, and are usually attributed to the formation of a *quark-gluon plasma* (QGP).

These phenomena have also been observed in $pA$ and $pp$ collisions. Open question: can this be explained by the QGP model?
Flow - PbPb @ 5.02 TeV

Pb-Pb $\sqrt{s_{NN}} = 5.02$ TeV, $v_2\{2, |\Delta \eta| > 1.4\}$

Pb-Pb $\sqrt{s_{NN}} = 5.02$ TeV, $v_2\{8\}$

(ALICE Data)

(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
Jets $I_{AA}$ - PbPb @ 2.76 TeV

$I_{AA}$ is the PbPb/pp ratio of associated particle yield per trigger

$8 \text{ GeV} < p_{\perp,\text{trig}} < 15 \text{ GeV}, \quad 4 \text{ GeV} < p_{\perp,\text{assoc}} < p_{\perp,\text{trig}}$
**Jets \(I_{AA}\) - PbPb @ 2.76 TeV**

\(I_{AA}\) is the PbPb/\(p\bar{p}\) ratio of associated particle yield per trigger:

\[
8 \text{ GeV} < p_{\perp,\text{trig}} < 15 \text{ GeV}, \quad 4 \text{ GeV} < p_{\perp,\text{assoc}} < p_{\perp,\text{trig}}
\]

(Data from arXiv:1110.0121)

NB: \(p_{\perp}\) spectrum is also modified by other mechanisms. Would be interesting to study in more detail.
Resonance formation and signal suppression

I did not have time to study resonance signal suppression, but this would be an interesting thing to study.

- In $\Lambda(1520) \rightarrow pK^-$ decays, the $pK^-$ will be correlated. If one of the outgoing particles rescatters, this correlation will be suppressed [arXiv:1805.04361]

Experiments indicate that $K^*$ signals are suppressed by rescattering, but $\phi$ signals are not. This puts limits on the duration of rescattering [arXiv:1910.14419]. How does this compare to rescattering in Pythia?

On the other side of the coin, rescattering produces new resonances, but they can be difficult to detect. For example, in the process $\pi K \rightarrow K^* \rightarrow \pi K$, the $\pi K$ mass spectrum is unchanged.
Resonance formation and signal suppression

I did not had time to study resonance signal suppression, but this would be an interesting thing to study.

- In $\Lambda(1520) \rightarrow pK^-$ decays, the $pK^-$ will be correlated. If one of the outgoing particles rescatters, this correlation will be suppressed [arXiv:1805.04361]

- Experiments indicate that $K^*$ signals are suppressed by rescattering, but $\phi$ signals are not. This puts limits on the duration of rescattering [arXiv:1910.14419]. How does this compare to rescattering in Pythia?
Resonance formation and signal suppression

I did not had time to study resonance signal suppression, but this would be an interesting thing to study.

- In $\Lambda(1520) \rightarrow pK^-$ decays, the $pK^-$ will be correlated. If one of the outgoing particles rescatters, this correlation will be suppressed \[arXiv:1805.04361\]

- Experiments indicate that $K^*$ signals are suppressed by rescattering, but $\phi$ signals are not. This puts limits on the duration of rescattering \[arXiv:1910.14419\]. How does this compare to rescattering in PYTHIA?

- On the other side of the coin, rescattering produces new resonances, but they can be difficult to detect. For example, in the process $\pi K \rightarrow K^* \rightarrow \pi K$, the $\pi K$ mass spectrum is unchanged.
Hadronic rescattering - Summary

- Rescattering changes multiplicity. Can partially compensate by setting `MultipartonInteractions:pT0Ref = 2.345`. In the future, $n \to 2$ processes may also be implemented.
Hadronic rescattering - Summary

- Rescattering changes multiplicity. Can partially compensate by setting `MultipartonInteractions:pT0Ref = 2.345`. In the future, $n \rightarrow 2$ processes may also be implemented.

- Hadronic rescattering can give rise to collective flow.
Hadronic rescattering - Summary

- Rescattering changes multiplicity. Can partially compensate by setting `MultipartonInteractions:pT0Ref = 2.345`. In the future, $n \rightarrow 2$ processes may also be implemented.
- Hadronic rescattering can give rise to collective flow
- To what extent does rescattering lead to jet quenching?

Marius Utheim
Hadronic Interactions at High and Low Energies
Hadronic rescattering - Summary

- Rescattering changes multiplicity. Can partially compensate by setting `MultipartonInteractions:pT0Ref = 2.345`. In the future, $n \rightarrow 2$ processes may also be implemented.

- Hadronic rescattering can give rise to collective flow

- To what extent does rescattering lead to jet quenching?

- To what extent does rescattering lead to resonance signal suppression?
Outline

Hadronic rescattering

Exotic hadrons

Cosmic rays
Motivation: what is the nature of exotic hadrons?

Bag model or molecular state?
Pentaquarks - background

- In 2015, LHCb observed two peaks when studying $\Lambda_b \rightarrow J/\psi pK^-$ ($J\psi \rightarrow \mu^+\mu^-$) decays, designated $P_c^+(4380)$ and $P_c^+(4450)$.

- Another study with a larger LHCb data set in 2019 further resolved this into three states: $P_c^+(4312)$, $P_c^+(4440)$ and $P_c^+(4457)$.

- Interpretation:
  - $P_c^+(4312)$ is a $\Sigma_c^0D_m$ molecular state.
  - $P_c^+(4440)$ and $P_c^+(4457)$ are $\Sigma_c^0D_m^*$ molecular states with spins $1/2$ and $3/2$, respectively.

In our work, we also studied the $\chi_{c1}(3872)$ tetraquark.
In 2015, LHCb observed two peaks when studying $\Lambda_b \rightarrow J/\psi pK^- \ (J\psi \rightarrow \mu^+\mu^-)$ decays, designated $P_c^+(4380)$ and $P_c^+(4450)$.

Another study with a larger LHCb data set in 2019 further resolved this into three states: $P_c^+(4312)$, $P_c(4440)$ and $P_c^+(4457)$.
Pentaquarks - background

- In 2015, LHCb observed two peaks when studying $\Lambda_b \rightarrow J/\psi p K^-$ ($J/\psi \rightarrow \mu^+ \mu^-$) decays, designated $P_c^+(4380)$ and $P_c^+(4450)$.

- Another study with a larger LHCb data set in 2019 further resolved this into three states: $P_c^+(4312)$, $P_c(4440)$ and $P_c^+(4457)$.

- Interpretation:
Pentaquarks - background

- In 2015, LHCb observed two peaks when studying $\Lambda_b \rightarrow J/\psi pK^-$ ($J\psi \rightarrow \mu^+\mu^-$) decays, designated $P_c^+(4380)$ and $P_c^+(4450)$.

- Another study with a larger LHCb data set in 2019 further resolved this into three states: $P_c^+(4312)$, $P_c(4440)$ and $P_c^+(4457)$.

- Interpretation:
  - $P_c^+(4312)$ is a $\Sigma_c^+\bar{D}^0$ molecular state.
Pentaquarks - background

- In 2015, LHCb observed two peaks when studying $\Lambda_b \rightarrow J/\psi pK^-$ ($J\psi \rightarrow \mu^+\mu^-$) decays, designated $P_c^+(4380)$ and $P_c^+(4450)$.

- Another study with a larger LHCb data set in 2019 further resolved this into three states: $P_c^+(4312)$, $P_c(4440)$ and $P_c^+(4457)$.

- Interpretation:
  - $P_c^+(4312)$ is a $\Sigma_c^+ D^0$ molecular state.
  - $P_c^+(4440)$ and $P_c^+(4457)$ are $\Sigma_c^+ D^{*0}$ molecular states with spins 1/2 and 3/2, respectively.
Pentaquarks - background

- In 2015, LHCb observed two peaks when studying $\Lambda_b \to J/\psi pK^-$ ($J\psi \to \mu^+\mu^-$) decays, designated $P_c^+(4380)$ and $P_c^+(4450)$.
- Another study with a larger LHCb data set in 2019 further resolved this into three states: $P_c^+(4312)$, $P_c^+(4440)$ and $P_c^+(4457)$.
- Interpretation:
  - $P_c^+(4312)$ is a $\Sigma^+_c \bar{D}^0$ molecular state.
  - $P_c^+(4440)$ and $P_c^+(4457)$ are $\Sigma^+_c \bar{D}^{*0}$ molecular states with spins $1/2$ and $3/2$, respectively.
Pentaquarks - background

- In 2015, LHCb observed two peaks when studying $\Lambda_b \rightarrow J/\psi pK^{-}$ ($J/\psi \rightarrow \mu^+\mu^-$) decays, designated $P_c^+(4380)$ and $P_c^+(4450)$.

- Another study with a larger LHCb data set in 2019 further resolved this into three states: $P_c^+(4312)$, $P_c(4440)$ and $P_c^+(4457)$.

- Interpretation:
  - $P_c^+(4312)$ is a $\Sigma_c^+ \bar{D}^0$ molecular state.
  - $P_c^+(4440)$ and $P_c^+(4457)$ are $\Sigma_c^+ \bar{D}^*0$ molecular states with spins 1/2 and 3/2, respectively.

In our work, we also studied the $\chi_{c1}(3872)$ tetraquark.
My work

The objective of my work was to create a framework for studying exotic hadrons in *Pythia*. Specifically, we studied these pentaquarks and the $\chi_{c1}(3872)$ tetraquark.

We implemented pentaquark production them through $\Lambda_b \rightarrow P_c^+ K^-$ decays, as well as exotic hadron resonances in rescattering, e.g. $\Sigma_c^+ \bar{D}^0 \rightarrow P_c^+(4312)$ or $D^0 \bar{D}^{*0} \rightarrow \chi_{c1}(3872)$. 
Results - the $P_c^+$ pentaquarks

Rescattering cross section is somewhat model-dependent.

Rate of production from $\Lambda_b^0 \rightarrow P_c^+ K^-$ decays is model dependent, specifically on $P_c^+ \rightarrow p J/\psi$ branching ratio.
Recall that rescattering resonances are hard to observe directly. The experimental pentaquark signal comes from the $P_c^+ \rightarrow p J/\psi \rightarrow p \mu^+ \mu^-$ channel

$(p_{\perp,p} > 1 \text{ GeV} \text{ and } p_{\perp,\mu} > 0.5 \text{ GeV}, \text{ and } 2 < \eta_{p,\mu} < 5)$
Results - experimental signal

Recall that rescattering resonances are hard to observe directly. The experimental pentaquark signal comes from the $P_c^+ \rightarrow p \ J/\psi \rightarrow p\mu^+\mu^-$ channel

($p_{\perp,p} > 1 \text{ GeV}$ and $p_{\perp,\mu} > 0.5 \text{ GeV}$, and $2 < \eta_{p,\mu} < 5$)

<table>
<thead>
<tr>
<th></th>
<th>$P_c^+(4312)$</th>
<th>$P_c^+(4440)$</th>
<th>$P_c^+(4457)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>model 1</td>
<td>$1 \times 10^{-6}$</td>
<td>$1 \times 10^{-6}$</td>
<td>$5 \times 10^{-7}$</td>
</tr>
<tr>
<td>model 2</td>
<td>$5 \times 10^{-5}$</td>
<td>$3 \times 10^{-5}$</td>
<td>$4 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

Ratio of signal to background

- Contributions are too small to be observed at LHCb
- But this study shows that there is an order of magnitude difference between the two models
Results - the $\chi_{c1}(3872)$ tetraquark

For $\chi_{c1}(3872)$, we measured the production cross sections in $pp$ collisions at $\sqrt{s} = 7$ TeV. ($\sigma_{pp} \approx 90$ mb)

- The inclusive production cross section has been measured by LHCb$^1$, and found to be $5.4 \pm 1.3 \pm 0.8$ nb.

- Our measured exclusive cross section from rescattering is $0.04$ nb, which is $\sim 1\%$ of the total production cross section.

Results - the $\chi_{c1}(3872)$ tetraquark

For $\chi_{c1}(3872)$, we measured the production cross sections in $pp$ collisions at $\sqrt{s} = 7$ TeV. ($\sigma_{pp} \approx 90$ mb)

- The inclusive production cross section has been measured by LHCb$^1$, and found to be $5.4 \pm 1.3 \pm 0.8$ nb.

- Our measured exclusive cross section from rescattering is $0.04$ nb, which is $\sim 1\%$ of the total production cross section.

While the overall contribution is small, future LHCb data may make it possible to separate cross sections by production mechanism. This could provide insights on how to model tetraquark formation.

---

Conclusions

- Overall, rescattering does not seem to be a major production mechanism for exotic hadrons.
Conclusions

▶ Overall, rescattering does not seem to be a major production mechanism for exotic hadrons.

▶ Rescattering will probably have a negligible effect on $P_c^+$ pentaquark formation, but future data from LHCb can provide insights on how to model $\chi_{c1}(3872)$. 
Conclusions

- Overall, rescattering does not seem to be a major production mechanism for exotic hadrons.
- Recattering will probably have a negligible effect on $P_{c}^{+}$ pentaquark formation, but future data from LHCb can provide insights on how to model $\chi_{c1}(3872)$.
- But this framework is just the beginning – the framework can be extended to include other exotic hadrons, or other particles such as deuterons.
Outline

Hadronic rescattering

Exotic hadrons

Cosmic rays
Cosmic rays

Image credit: A. Chantelauze, S. Staffi, L. Bret
Objectives

Programs such as CORSIKA\(^2\) are used to simulate hadronic cascades. These programs need models for generic hadron–nucleon collisions.

Objectives

Programs such as CORSIKA\(^2\) are used to simulate hadronic cascades. These programs need models for generic hadron–nucleon collisions.

Our goal is to implement such collisions in \textit{PyTHIA}, so that it can be used as a plugin to hadronic cascade simulations.

Objectives

Programs such as CORSIKA$^2$ are used to simulate hadronic cascades. These programs need models for generic hadron–nucleon collisions.

Our goal is to implement such collisions in PYTHIA, so that it can be used as a plugin to hadronic cascade simulations.

To do this, we need to total and partial cross section at perturbative energies, and describing PDFs for the relevant hadron species.

Hadronic cross sections

For total cross sections, we use the Donnachie-Landshoff model:

\[ \sigma_{AB}(s) = X^{AB}s^\epsilon + Y^{AB}s^{-\eta} \]
Hadronic cross sections

For total cross sections, we use the Donnachie-Landshoff model:

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

The coefficient \(X\) does not care about flavour, and is taken to be proportional to the effective number of quarks in accordance with the Additive Quark Model (AQM),

\[
n_{\text{eff}} = n_d + n_u + 0.6n_s + 0.2n_c + 0.07n_b
\]
Hadronic cross sections

For total cross sections, we use the Donnachie-Landshoff model:

\[ \sigma_{AB}(s) = X^{AB} s^\varepsilon + Y^{AB} s^{-\eta} \]

The coefficient \( X \) does not care about flavour, and is taken to be proportional to the effective number of quarks in accordance with the Additive Quark Model (AQM),

\[ n_{\text{eff}} = n_d + n_u + 0.6n_s + 0.2n_c + 0.07n_b \]

The \( Y \) coefficients are more complicated, and I won’t go into technical details here.
Parton distribution functions

Based on the ansatz by Glück and Reya,\(^3\)

\[
f(x, Q_0^2 = 0.26 \text{ GeV}^2) = N x^a (1 - x)^b,\]

and evolve to higher scales using the QCDNUM program.

\(^3\)arXiv:hep-ph/9903288
Parton distribution functions

Based on the ansatz by Glück and Reya,\(^3\)

\[
f(x, Q_0^2 = 0.26 \text{ GeV}^2) = N x^a (1 - x)^b,
\]

and evolve to higher scales using the QCDNUM program.

---

\(^3\)arXiv:hep-ph/9903288
A simplified nuclear model

The atmosphere is made of nuclei, not nucleons. Angantyr is not equipped to flexibly handle variable energies. Instead, we use a simplified model where the highest $p_z$ produced hadron may immediately interact again.
A simplified nuclear model

The atmosphere is made of nuclei, not nucleons. **Angantyr** is not equipped to flexibly handle variable energies. Instead, we use a simplified model where the highest $p_z$ produced hadron may immediately interact again.
Features of hadronic cascades

For a particle propagating in a medium of uniform density $\rho$, the mean free path is $l_0 = 1/\sigma \rho$. 
Features of hadronic cascades

For a particle propagating in a medium of uniform density \( \rho \), the mean free path is \( l_0 = \frac{1}{\sigma \rho} \).

In our article, we also study a toy model where the atmosphere depends on the height \( h \) according to \( \rho(h) = \rho_0 e^{-h/H} \).
Features of hadronic cascades

For a particle propagating in a medium of uniform density $\rho$, the mean free path is $l_0 = 1/\sigma \rho$.

In our article, we also study a toy model where the atmosphere depends on the height $h$ according to $\rho(h) = \rho_0 e^{-h/H}$. 

![Graph showing number of hadrons at depth for different conditions](image-url)
Outlook

With this work, also high energy interactions are available for important hadron–nucleon combinations (yay!)

There is some room for improvement in ANGANTYR:

- Variable energies are not yet supported
- There is no detailed handling of nuclear remnants
- Collisions below $\sim 100$ GeV are not modelled accurately

Despite these shortcomings, PYTHIA is around the level of state-of-the-art models used by CORSIKA.
Overall summary

- Implemented more general hadronic interactions in *Pythia*, both at low and high energies.
Overall summary

- Implemented more general hadronic interactions in Pythia, both at low and high energies.
- Implemented hadronic rescattering in Pythia. It can give rise to QGP-signatures, especially collective flow.
Overall summary

- Implemented more general hadronic interactions in Pythia, both at low and high energies
- Implemented hadronic rescattering in Pythia. It can give rise to QGP-signatures, especially collective flow.
- First steps towards studying exotic hadrons with MC generators (negative result: rescattering is probably not that significant production mechanism)
Overall summary

- Implemented more general hadronic interactions in Pythia, both at low and high energies
- Implemented hadronic rescattering in Pythia. It can give rise to QGP-signatures, especially collective flow.
- First steps towards studying exotic hadrons with MC generators (negative result: rescattering is probably not that significant production mechanism)
- With these general hadronic interactions, Pythia offers a plugin to hadronic cascade simulators