Hadronic Interactions at High and Low Energies

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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

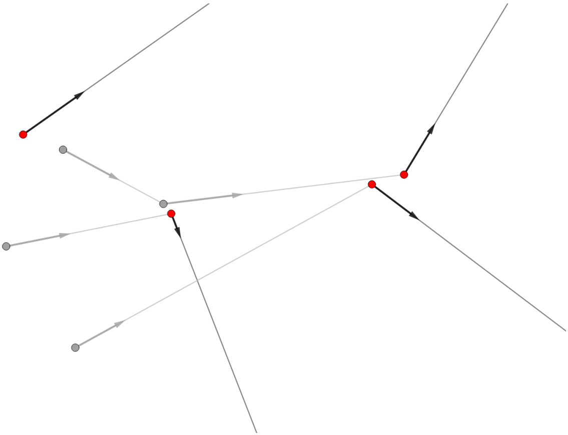
Outline

Hadronic rescattering

Exotic hadrons

Cosmic rays

How I view rescattering



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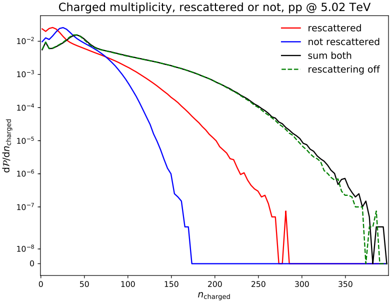
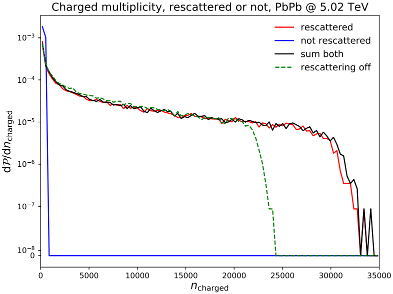
- To some extent it can also give rise to jet quenching.
- Resonances produced in rescattering can be hard to observe. Some resonances can be suppressed.

Multiplicities - pp vs. PbPb @ 5.02 TeV

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

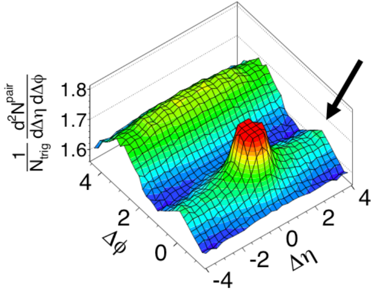


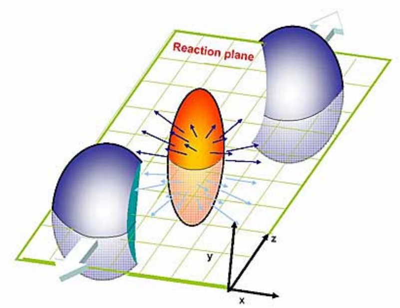


"Rule of thumb": `MultipartonInteractions:pT0Ref = 2.345`
Particle composition is still changed, e.g. by $p\bar{p} \to \pi^+\pi^0\pi^-$

Flow and jet quenching

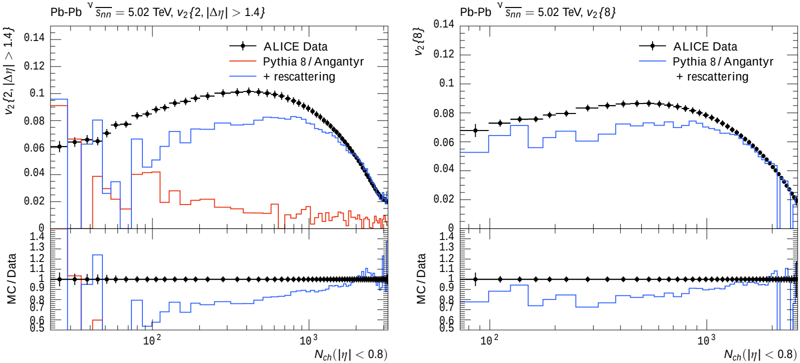
Phenomena such as collective flow has been observed, and are usually attributed to the formation of a *quark-gluon plasma* (QGP)





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



(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 GeV < $p_{\perp,\text{trig}}$ < 15 GeV, 4 GeV < $p_{\perp,\text{assoc}}$ < $p_{\perp,\text{trig}}$

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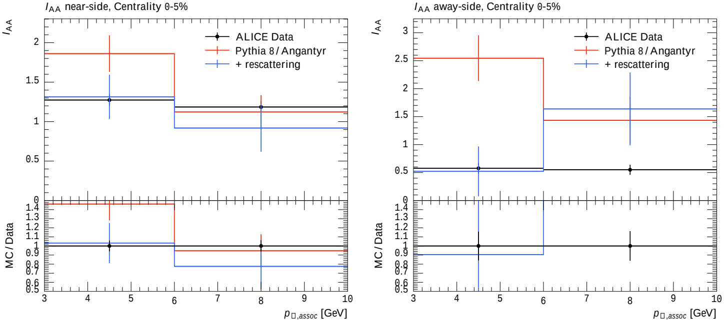

(Data from arXiv:1110.0121)

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 had time to study resonance signal suppression, but this would be an interesting thing to study.

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

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

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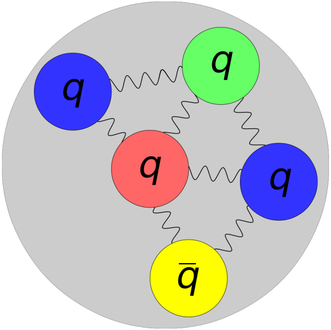
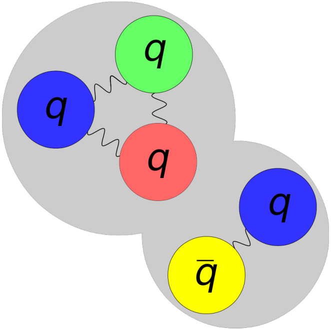
- To what extent does rescattering lead to resonance signal suppression?

Outline

Motivation: what is the nature of exotic hadrons?





Bag model or molecular state?

Pentaquarks - background

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

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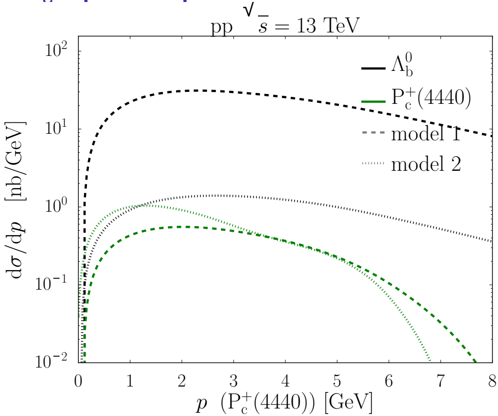
In our work, we also studied the $\chi_{c1}(3872)$ tetraquark.

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 $\Lambda_b \to P_c^+ K^-$ decays, as well as exotic hadron resonances in rescattering, e.g. $\Sigma_c^+ \bar{D}^0 \to P_c^+(4312)$ or $D^0 \bar{D}^0 \to \chi_{c1}(3872)$.

Results - the P_c^+ pentaquarks



- Rescattering cross section is somewhat model-dependent.
- Rate of production from $\Lambda_b^0 \to P_c^+ K^-$ decays is model dependent, specifically on $P_c^+ \to p J/\psi$ branching ratio.

Results - experimental signal

Recall that rescattering resonances are hard to observe directly.
The experimental pentaquark signal comes from
the $P_c^+ \to p\,J/\psi \to p\mu^+\mu^-$ channel
($p_{\perp,p} > 1$ GeV and $p_{\perp,\mu} > 0.5$ GeV, and $2 < \eta_{p,\mu} < 5$)

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	$\mathrm{P_c^+}(4312)$	$\mathrm{P_c^+}(4440)$	$\mathrm{P_c^+}(4457)$
model 1	1×10^{-6}	1×10^{-6}	5×10^{-7}
model 2	5×10^{-5}	3×10^{-5}	4×10^{-5}

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 1 % of the total production cross section.

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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.

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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 $\chi_{c1}(3872)$.
- But this framework is just the beginning – the framework can be extended to include other exotic hadrons, or other particles such as deuterons.

Outline

Cosmic rays

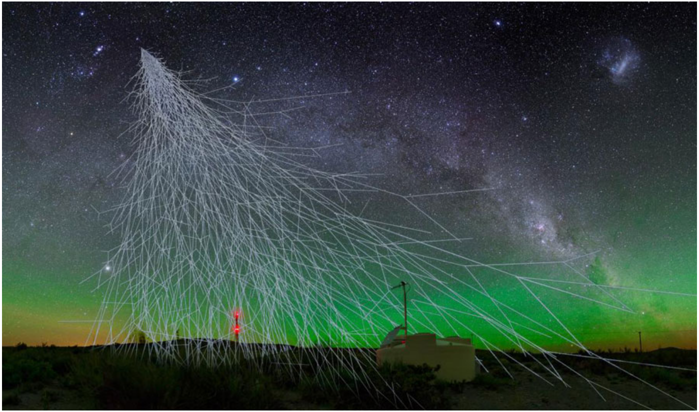

Image credit: A. Chantelauze, S. Staffi, L. Bret

Objectives

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

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

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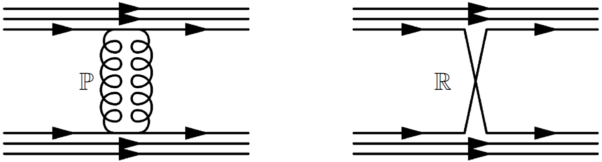
Hadronic cross sections

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

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



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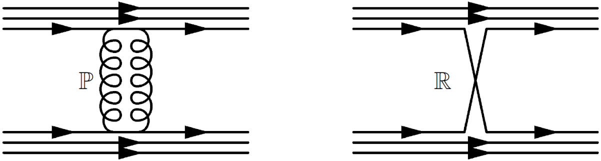

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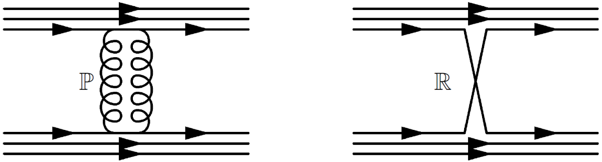

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The Y coefficients are more complicated, and I won't go into technical details here.

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.

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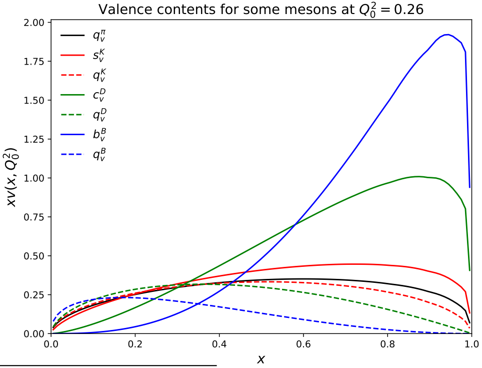

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A simplified nuclear model

The atmosphere is made of nuclei, not nucleons. Angantyr is not equipped to flexibly handle variable energies.

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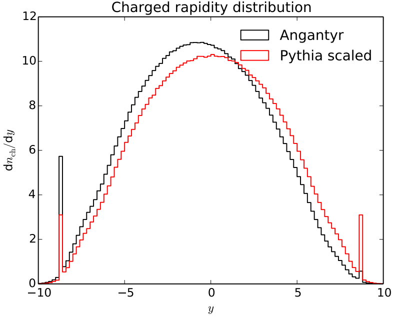

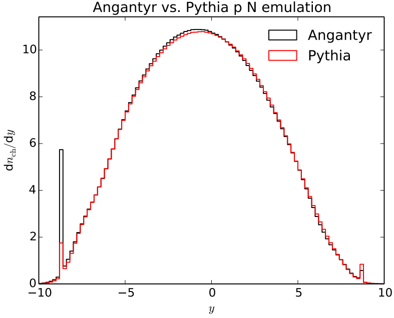

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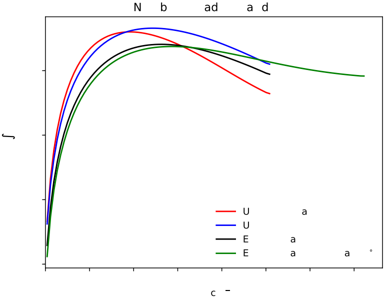

Outlook

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 100 GeV are not modelled accurately

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

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- 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