Production mechanisms in Monte Carlo Event Generators

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Light flavours – soft physics from e^+e^- to AA

- Light flavour physics is a unique probe of fragmentation properties.
- In MC's *Jet Universality* has been the guiding principle.
- Strangeness enhancement wrt. e^+e^- opportunity to learn.
  1. Approach based on *corrections* in dense environments.
  2. A "colour reconnection" is neccesary.
  3. Pythia + DIPSY: Rope formation, stronger string tension.
  4. HERWIG: Cluster reconnections.
  5. EPOS: Core–corona interpolation (dedicated talk).

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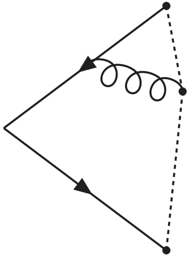
  5. EPOS: Core–corona interpolation (dedicated talk).
- Inclusive quantities provided a new insight.
- Now it is time to study the dynamics.

Hadronization in pp: Lund strings (See *e.g.* hep-ph/0603175)

- Non-perturbative phase of final state.
- Confined colour fields $\approx$ *strings* with tension $\kappa \approx 1$ GeV/fm.



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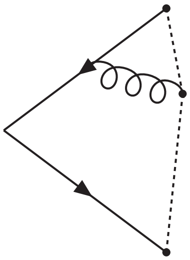

Lund symmetric fragmentation function

$$f(z) \propto z^{-1}(1-z)^a \exp\left(\frac{-bm_\perp}{z}\right).$$

a and b related to total multiplicity.

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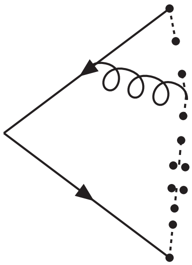

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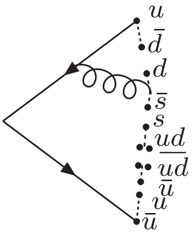

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Light flavours determined by relative probabilities

$$\rho = \frac{\mathcal{P}_{\text{strange}}}{\mathcal{P}_{\text{u or d}}}, \xi = \frac{\mathcal{P}_{\text{diquark}}}{\mathcal{P}_{\text{quark}}}$$

Probabilities related to κ by Schwinger equation.

MPIs in Pythia 8: proton collisions

Sjöstrand and Skands: arXiv:hep-ph/0402078

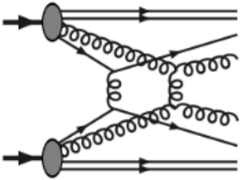

Figure T. Sjöstrand

- Several partons taken from the PDF.
- Hard subcollisions with $2 \rightarrow 2$ ME:

$$\frac{d\sigma_{2\rightarrow 2}}{dp_\perp^2} \propto \frac{\alpha_s^2(p_\perp^2)}{p_\perp^4} \rightarrow \frac{\alpha_s^2(p_\perp^2 + p_{\perp 0}^2)}{(p_\perp^2 + p_{\perp 0}^2)^2}.$$

- Momentum conservation and PDF scaling.
- Ordered emissions: $p_{\perp 1} > p_{\perp 2} > p_{\perp 4} > \ldots$ from:

$$\mathcal{P}(p_\perp = p_{\perp i}) = \frac{1}{\sigma_{nd}} \frac{d\sigma_{2\rightarrow 2}}{dp_\perp} \exp\left[-\int_{p_\perp}^{p_{\perp i-1}} \frac{1}{\sigma_{nd}} \frac{d\sigma}{dp'_\perp} dp'_\perp\right]$$

- Number distribution narrower than Poissonian (momentum and flavour rescaling).

Color reconnection

- Many partonic subcollisions ⇒ Many hadronizing strings.
- But! $N_c = 3$, not $N_c = \infty$ gives interactions.
- Easy to merge low-$p_\perp$ systems, hard to merge two hard-$p_\perp$.

$$\mathcal{P}_{merge} = \frac{(\gamma p_{\perp 0})^2}{(\gamma p_{\perp 0})^2 + p_\perp^2}$$

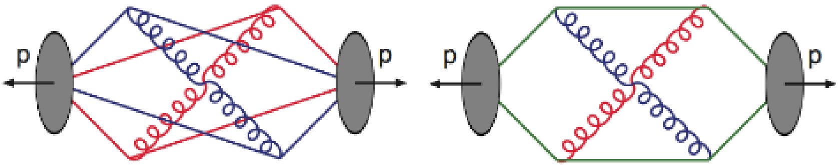

Figure T. Sjöstrand

- Actual merging is decided by minimization of "potential energy":

$$\lambda = \sum_{dipoles} \log(1 + \sqrt{2}E/m_0)$$

Colour reconnection 5-10 years ago

CR = short range in rapidity. Little effect on *inclusive* flavour composition.

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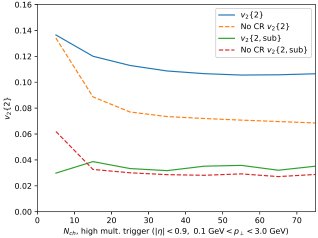
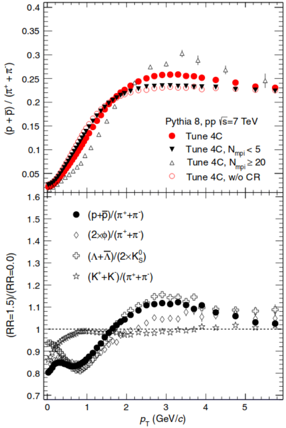
Quantifying its contribution

- Moves protons to measured phase space (Velasquez *et al.* PRL 111 (2013) 042001).
- But "flow like" does not mean long range in y (CB, V. Pacík, Y. Zhou, in prep.)





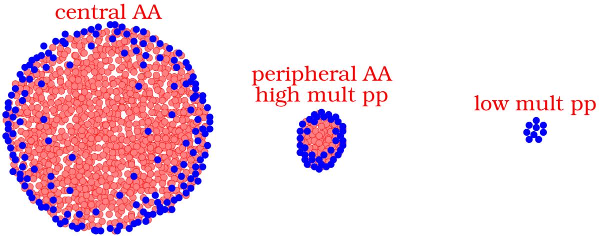
Contribution to $v_2\{2\}$ disappears: CR not long range.

EPOS: Core–corona (dedicated talk)

- Interpolation between the LEP extreme and the statistical fit extreme, allows for smooth transition.
- Adding also hydro and URQMD on top – many effects compete.

Core-corona picture in EPOS

Gribov-Regge approach => (Many) kinky strings
=> core/corona separation (based on string segments)



core => hydro => statistical decay ($\mu = 0$)
corona => string decay

(Klaus Werner, MCnet Summer School, Lund, 2017)

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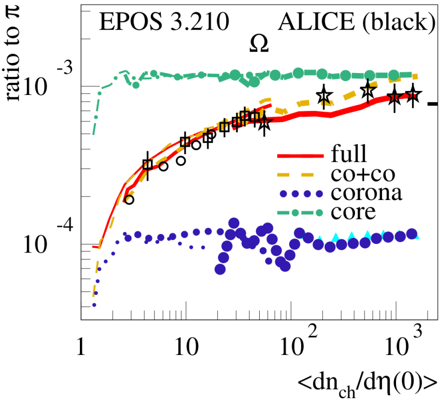
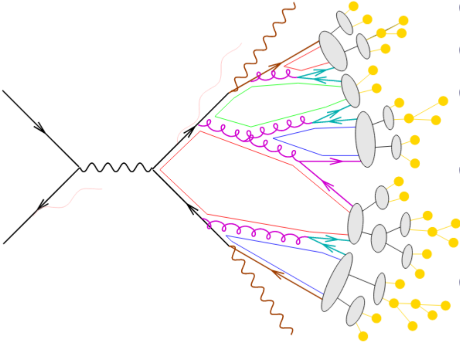
Omega to pion ratio

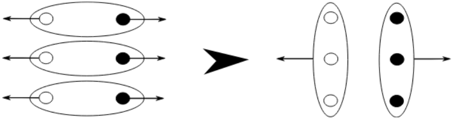


thick lines = pp (7TeV)
thin lines = pPb (5TeV)
circles = pp (7TeV)
squares = pPb (5TeV)
stars = PbPb (2.76TeV)

(Klaus Werner, MCnet Summer School, Lund, 2017)

Herwig cluster reconnection (EPJ C78 (2018) 99)





- Create clusters by forcing $g \to q\bar{q}$.
- Decay high-mass clusters.
- Decay to hadrons according to phase space and spin.
- New: Allow $g \to s\bar{s}$ quarks.
- New: Allow clusters to reconnect to baryonic junctions.

Improvement!

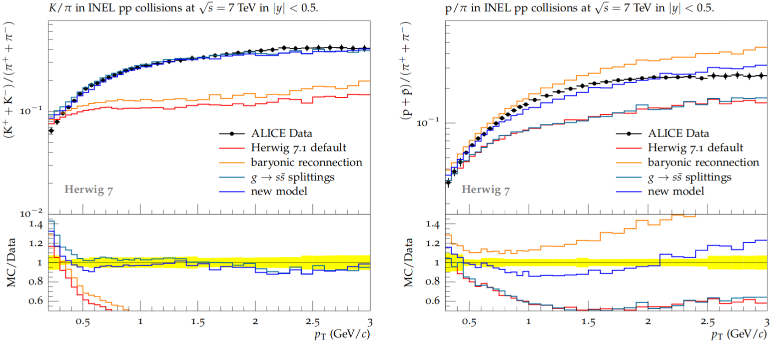
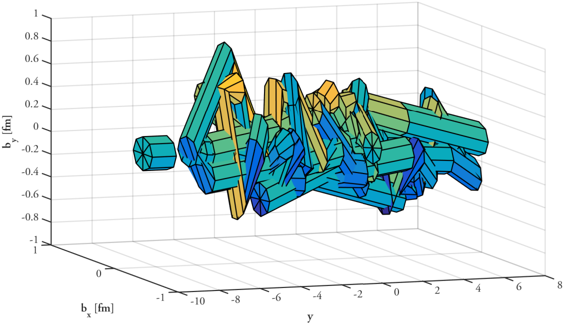


Fig. 9. Transverse momentum spectra for the ratios p/π and K/π as measured by ALICE at $\sqrt{s} = 7$ TeV [25] in the very central rapidity region $|y| < 0.5$.

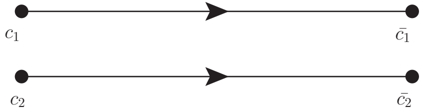
- Minimum bias greatly improved.
- Multiplicity dependence not neccesarily...
- ...but this still needs a comparison similar to experimental analysis (Centrality definition, Levy-Tsallis fits...).

Ropes build on a space time picture

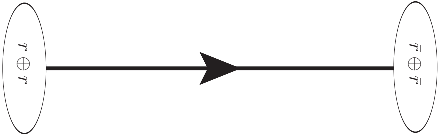
- If strings are colour fields with colour ends...
- ...then they should be able to act coherently



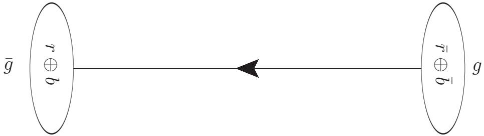
Simple example



Case (a), $c_1 = c_2$:



Case (b), $c_1 \neq c_2$:



DIPSY/Pythia – Rope Hadronization (JHEP 1503 (2015) 148)

- Triplet strings (p and q) overlaps in space.
- Combines into *multiplet* with effective string tension $\tilde{\kappa}$.

Effective string tension from the lattice

$$\kappa \propto C_2 \Rightarrow \frac{\tilde{\kappa}}{\kappa_0} = \frac{C_2(\text{multiplet})}{C_2(\text{singlet})}.$$

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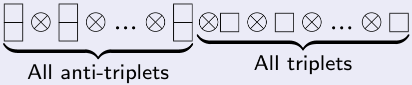
Easily calculable using SU(3) recursion relations

$$\{p, q\} \otimes \vec{3} = \{p+1, q\} \oplus \{p, q+1\} \oplus \{p, q-1\}$$



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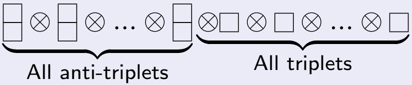

- Transform to $\tilde{\kappa} = \frac{2p+q+2}{4}\kappa_0$ and $2N = (p+1)(q+1)(p+q+2)$.
- N serves as a state's weight in the random walk.

Old idea – new in PS event generators

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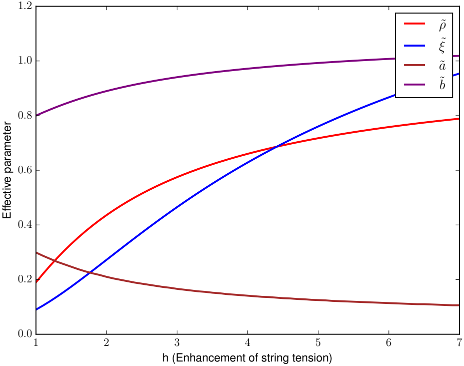
- As well as the ones I forgot.

Effect on parameters

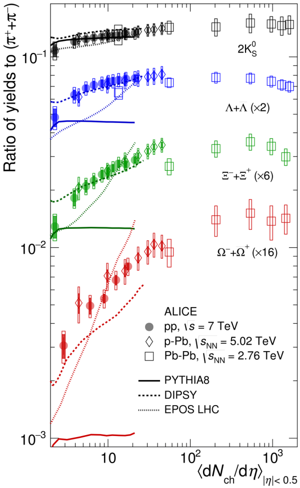
- Parameters:

  ρ strangeness.
  ξ diquarks / baryons.
  a, b multiplicity through fragmentation function.



Strangeness enhancement

- Less sensitive on geometry – a game of *density*.
- Described strangeness enhancement from pp to *AA*.
- No direct comparison to unfolded data ... yet.



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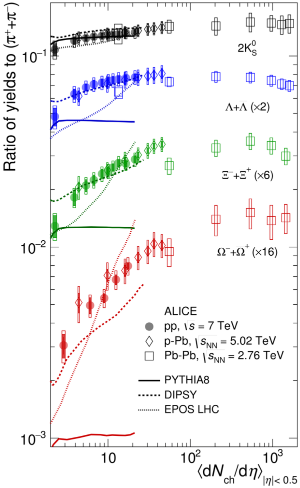
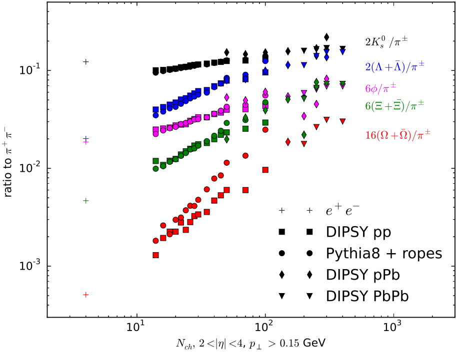
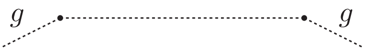


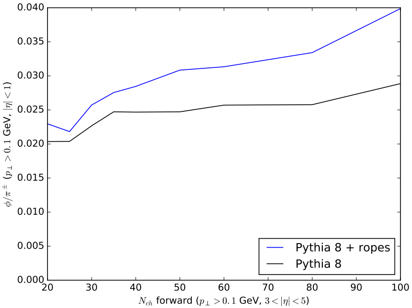


The importance of ϕ production

Very interesting new data!

- The ϕ is an excellent laboratory for strangeness effects.
- Two s-breaks means squared suppression and added sensitivity.





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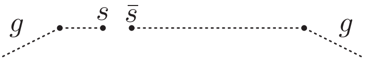

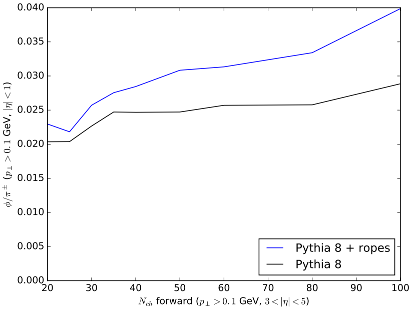

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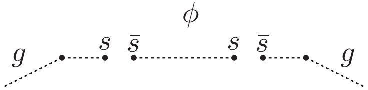
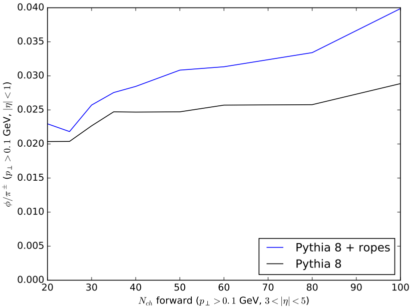
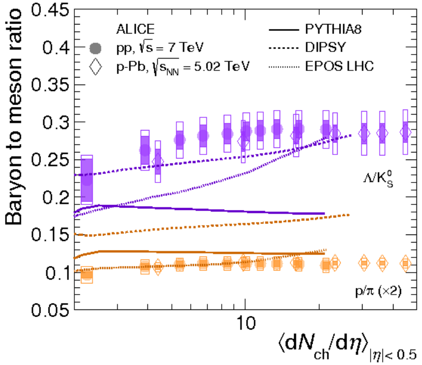




The baryon problem or the proton problem?

- Statement: No baryon enhancement – is it true?.
- A proton rather than a baryon effect.
- Hadronic rescatterings? Or something else.
- Can be approximated by playing with fragmentation dynamics (so–called popcorn).



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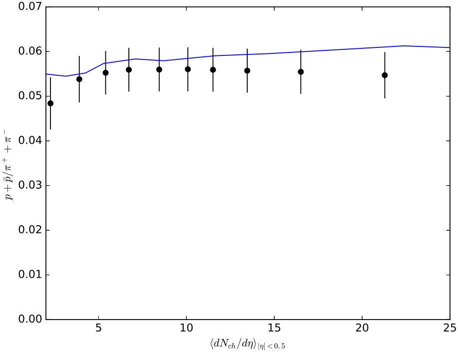
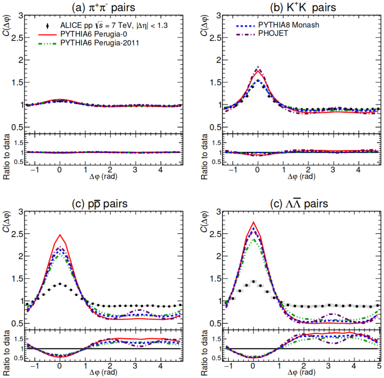


But really, our understanding is lacking!

- We don't want to describe just one curve at the time.
- As long as production dynamics is poorly understood, we cannot claim dynamical understanding.
- Baryon correlations carries much information (ALICE: Eur. Phys. J. C77 (2017) 569).



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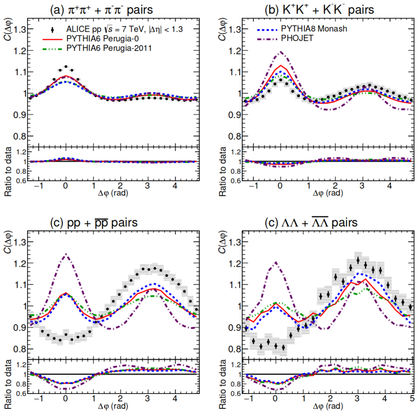
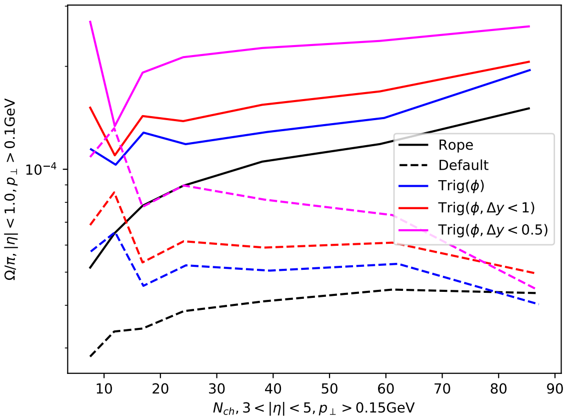


Assessing the smallest QGP droplet (CB, in prep.)

- We can do better than inclusive rates.
- Accessing longitudinal (rapidity) structure: Correlation measurements.
- Consider ropes in a ϕ-triggered event.
  1. Even in e^+e^- we bias to more strange production,
  2. In pp we can assess the difference wrt. default strings.
  3. Moving closer to the ϕ production rapidity gives larger string tension.
- Statistics hungry analysis – something for HL-LHC?

Preliminary: pp @ 13 TeV (Pythia8 + ropes)

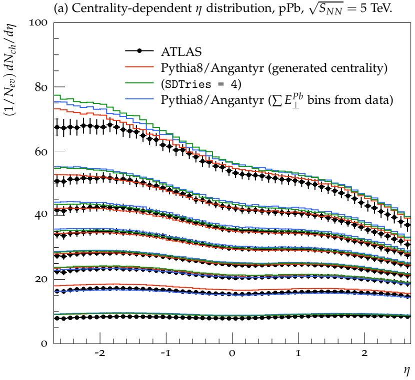
- Input for discussion:
  1. Sensible measurement?
  2. What does thermal models say?
  3. Can we remove the neigbor bias? (require neighbor etc.)

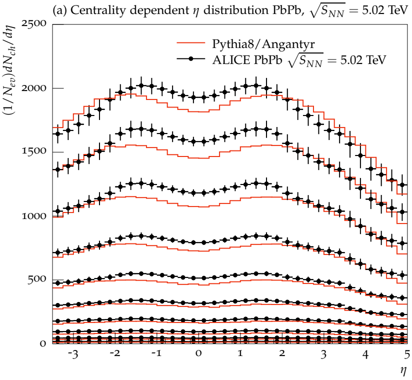


Perspective: Angantyr – PYTHIA8 for AA collisions

- Initial state geometry less fluctuation dominated.
- ... but MPI model must be extended to nuclear collisions.

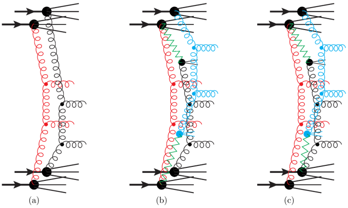
(CB, G. Gustafson, L. Lönnblad: JHEP 1610 (2016) 139; CB, G. Gustafson, L. Lönnblad, H. Shah: in prep.).



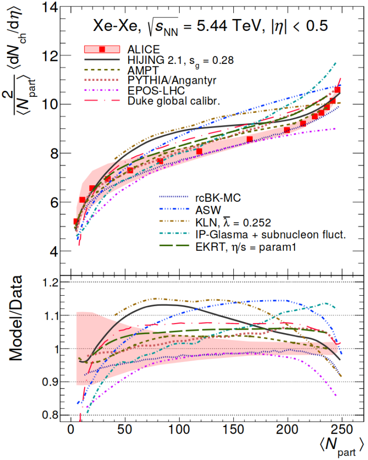


The model

- Initial Glauber calculation + Gribov fluctuations (fitted to pp).
- Sub–collisions which minimize total string length (a la CR), inspired by "wounded nucleon model".
- Hadronize it all together.
- Collective effects (Ropes + shoving) will come.



A window to ultra–high final state densities? (ALICE: 1805.04432)



Summary

- Light flavour hadron production modified from e^+e^- – crucial for MC EG.
- Herwig: Cluster reconnection.
- Pythia CR and ropes.

Dynamical	could provide dynamical insight to the QGP.
Universal	parameters which can be fixed in e^+e^- are.
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  Prospects initial studies on AA collisions are promising.
- Outlook:
  - Can we identify more good observables for pp at HL-LHC?
  - For light flavours: Is there really a physics case for more pA collisions?

Thank you!