Overview of heavy ion features and strangeness enhancement in PYTHIA

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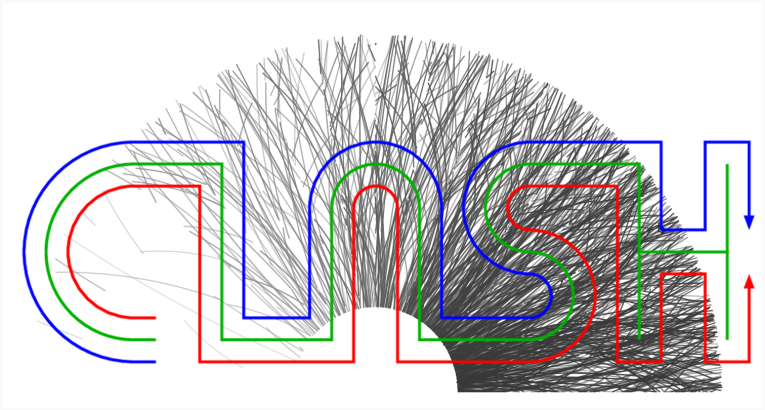
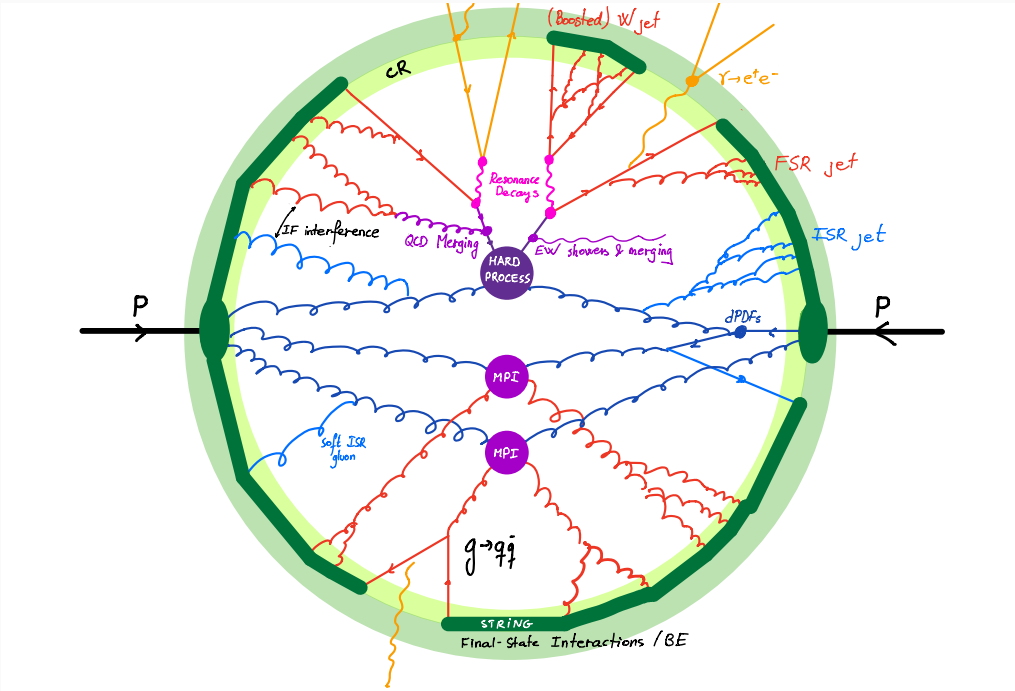


PYTHIA: Monte Carlo for e^+e^-, ep and pp

- General purpose event generator for pp collision physics and more.

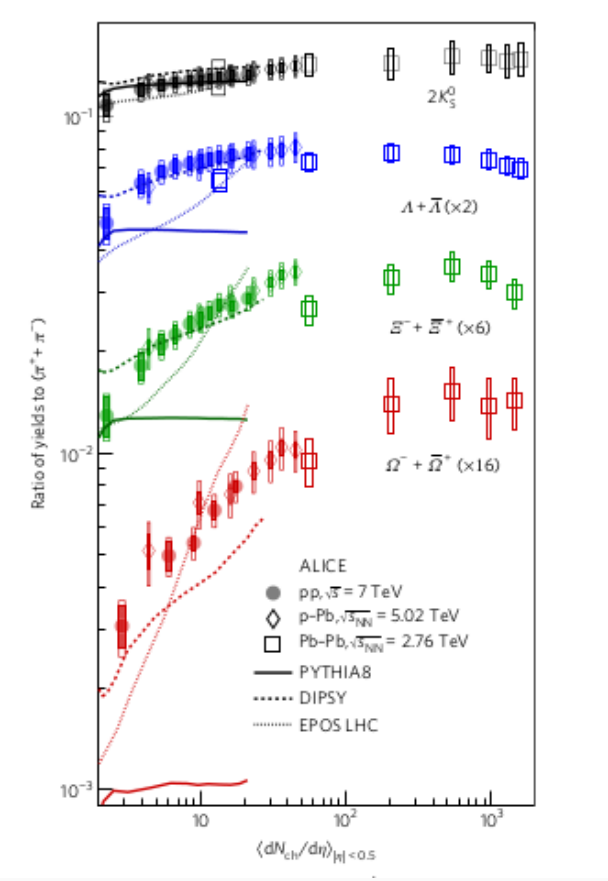


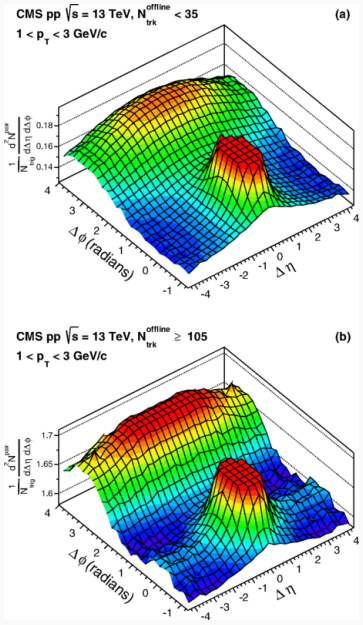
(Figure: Peter Skands)

- Focus on hard process + jets, parton showers, MPIs a sideshow, hadronization a necessity.
- *Jet universality* a cornerstone.

Collectivity in small systems (ALICE: 1606.07424, CMS: 1009.4122)

- LHC revealed that distinction between HI and pp is not simple.
- Probably most *surprising* discovery at LHC.





- Two paradigms at the prize of one!

1 If QGP is produced in pp collisions, can general purpose Monte Carlos stay general purpose?

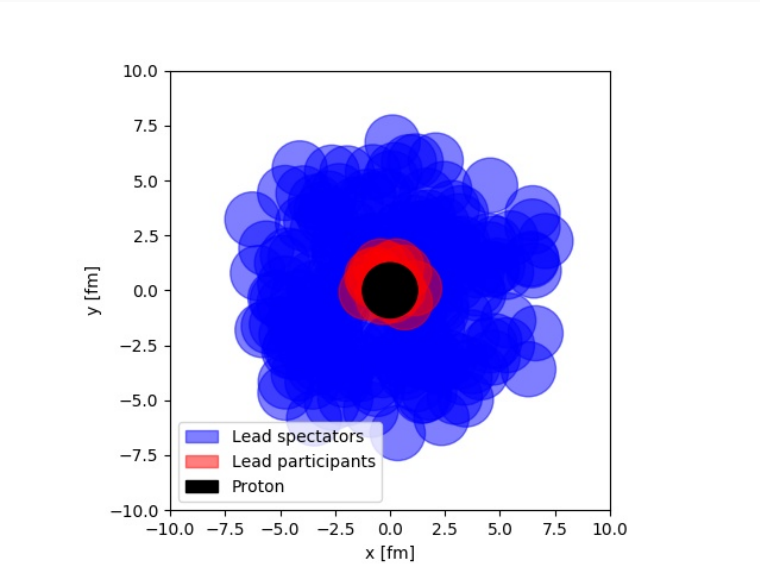
2 How "standard" is the standard model of heavy ion collisions, if QGP is not necessary for collectivity?

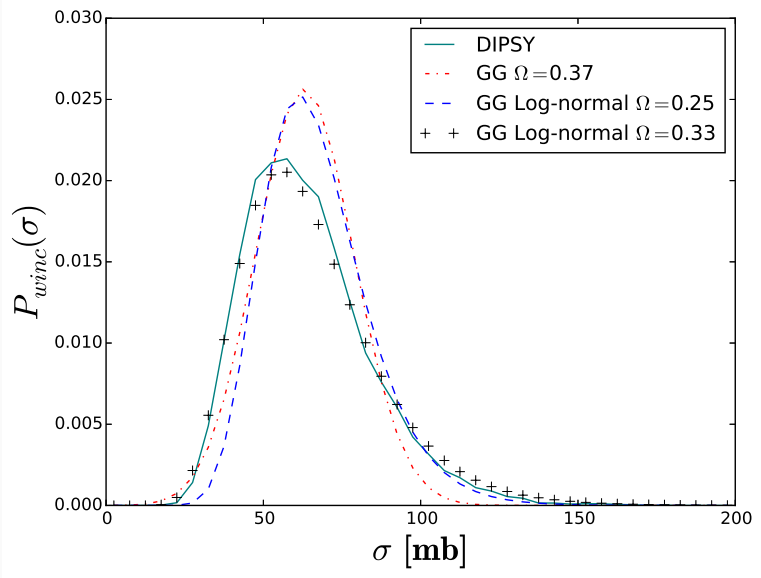
This talk

- *How to reconcile* heavy ion effects in pp with jet universality?
  - Key idea: Let Lund strings interact with each other.
  - Focus on strangeness enhancement, but work also existing for flow, charm, jet quenching...
- *What if* we could use this to construct QGP free heavy ion collisions as well?
  - The Angantyr heavy ion model allows this.
  - "Clean slate" to add collective effects.
  - Focus item: Hadronic rescattering in PYTHIA/Angantyr.
- New models/implementations:
  1. Angantyr heavy ion model.
  2. String fragmentation.
  3. Hadronic rescattering
- Results.

Heavy ion collisions: Angantyr (CB, Gustafson, Lönnblad, Shah: 1806.10820)

- Idea: Build a heavy ion collision by stacking nucleon–nucleon sub-collisions.
- Pay special attention to coherence effects.
- Step 1: Glauber calculation with fluctuating cross sections
  $\rightarrow$ ability to determine *type* of interaction

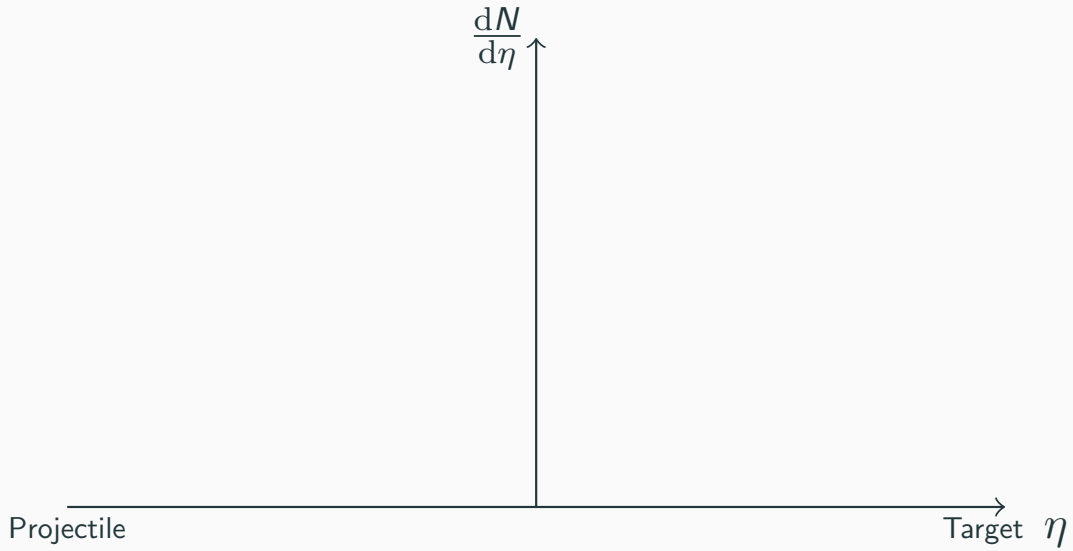




- Parameters fitted to pp cross sections
  $\rightarrow$ no AA input at this point.

Particle production (Inspired by Białas and Czyz: Nucl.Phys.B 111 (1976))

- Emission $F(\eta)$ per wounded nucleon
$$\rightarrow \frac{\mathrm{d}N}{\mathrm{d}\eta} = n_t F(\eta) + n_p F(-\eta).$$
- $F(\eta)$ modelled with even gaps in rapidity, as diffraction.
- Tuned to reproduce pp in the $n_t = n_p = 1$ case.
- No tunable parameters for AA – though some freedom in choices along the way.



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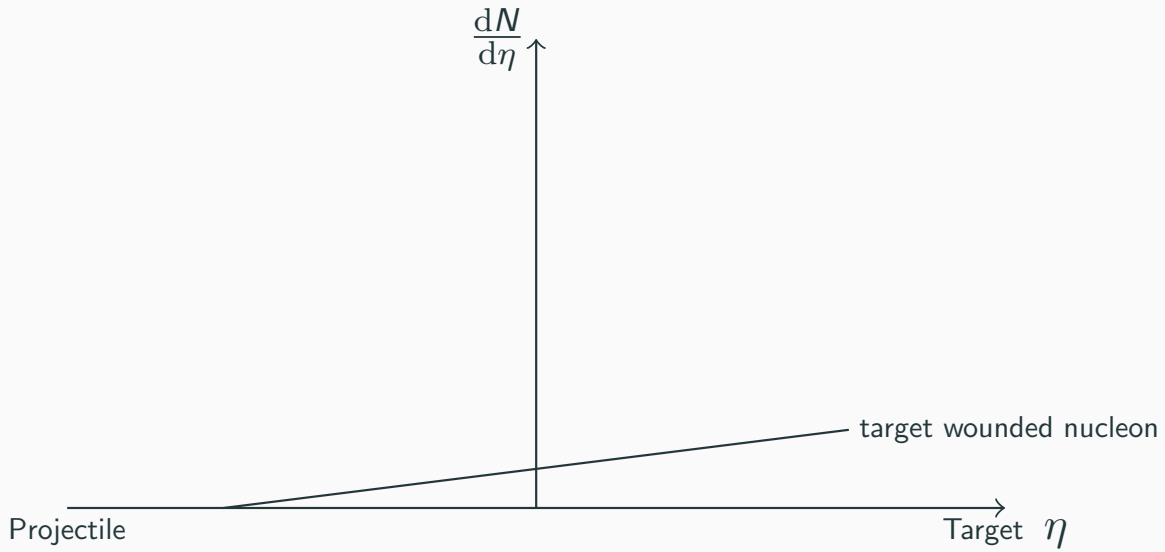

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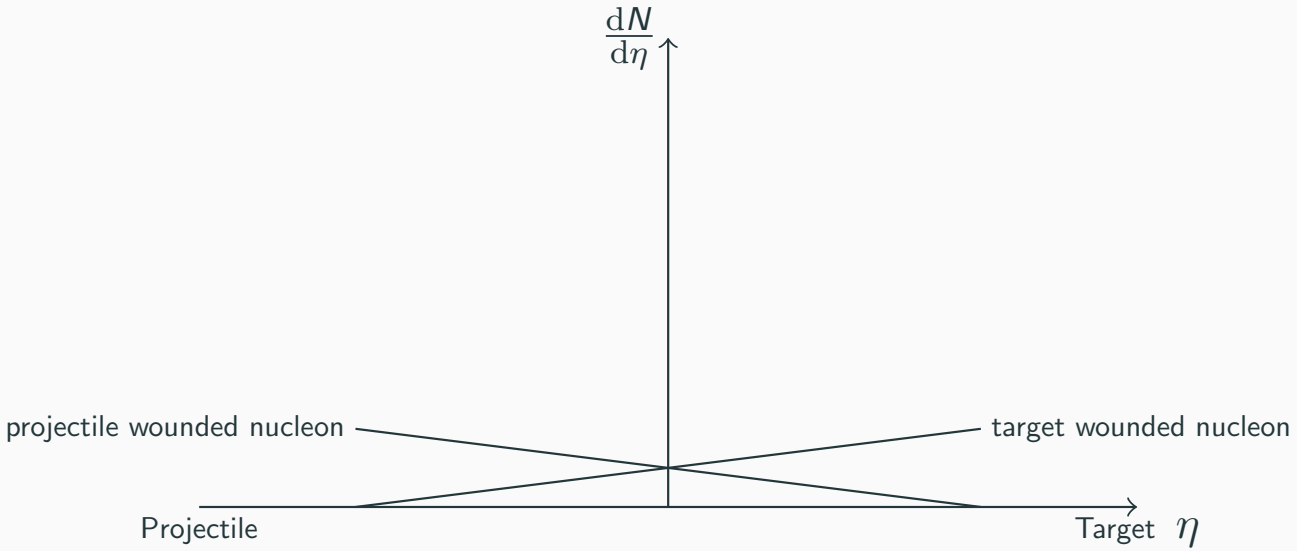

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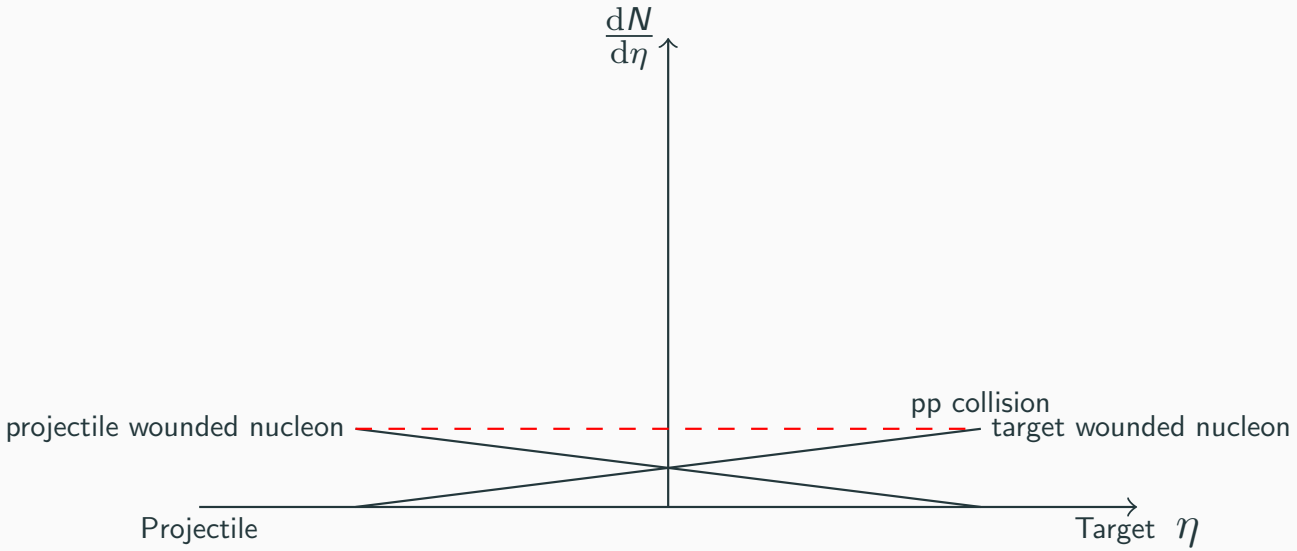

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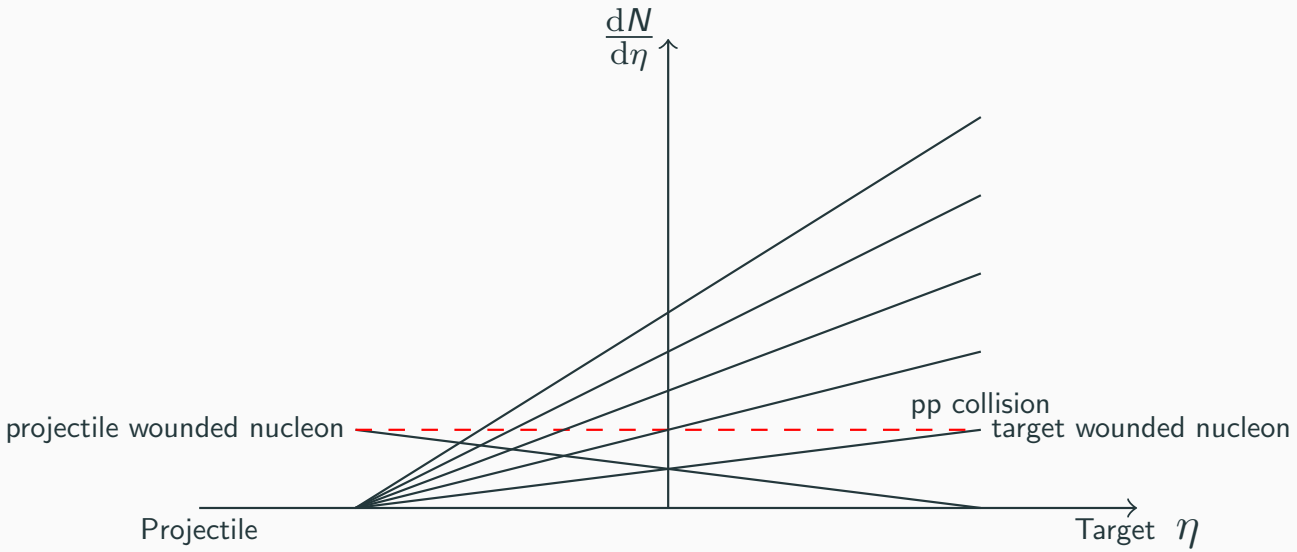

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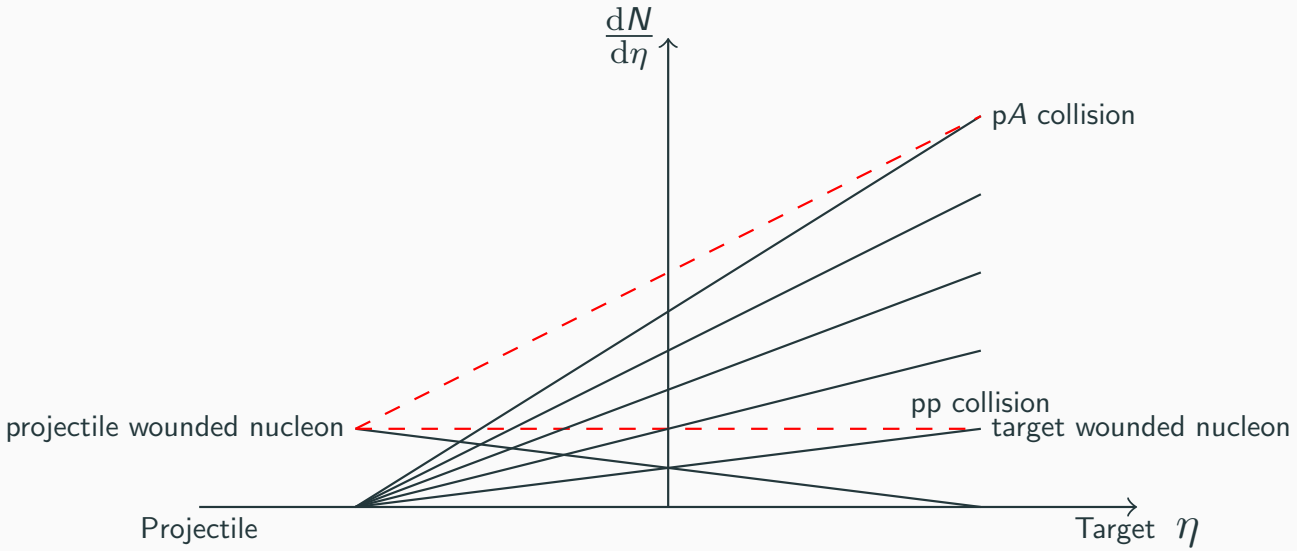

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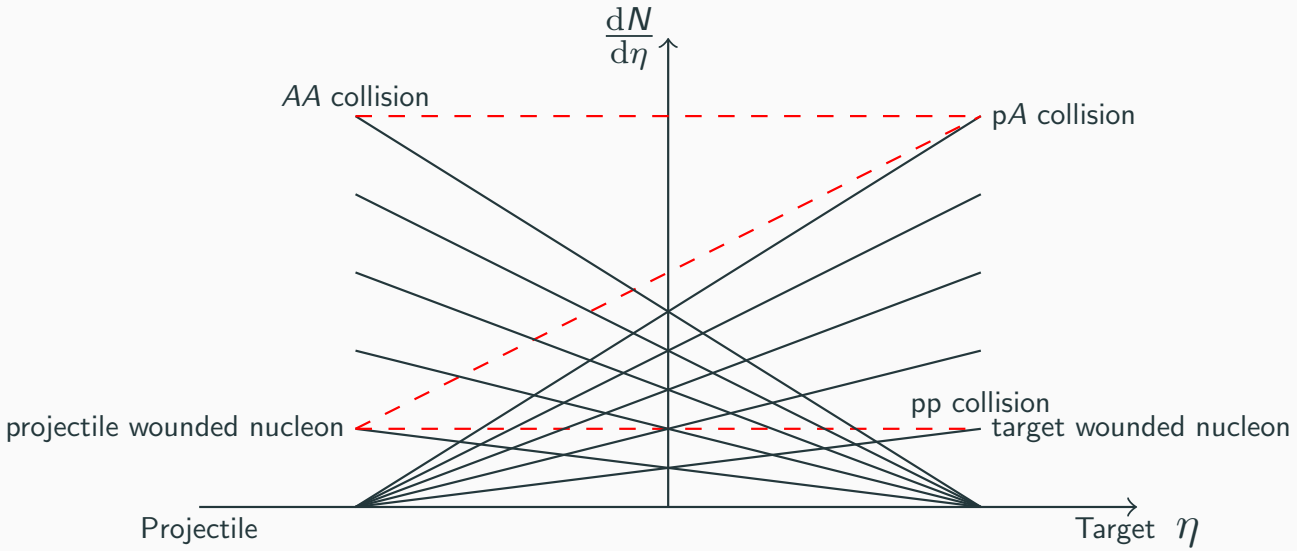
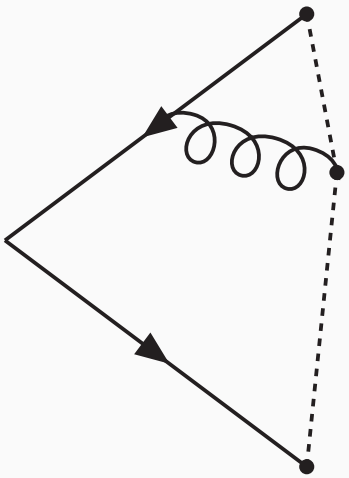


Fragmentation of a single string (Lund strings: Phys.Rept. 97 (1983) 31-145)

- Non-perturbative fragmentation, Lund strings, $\kappa \approx 1$ GeV/fm.



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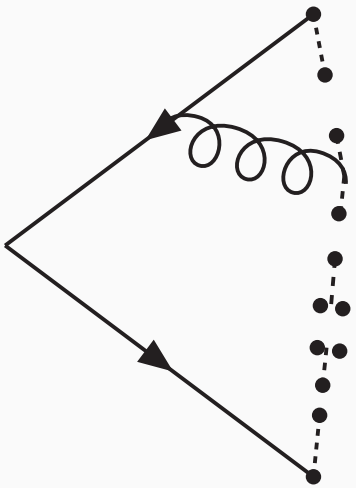
Flavour by tunnelling

$\mathcal{P} \propto \exp\left(-\frac{\pi m_\perp^2}{\kappa}\right)$, where m is the quark mass $\rightarrow$ parameter.



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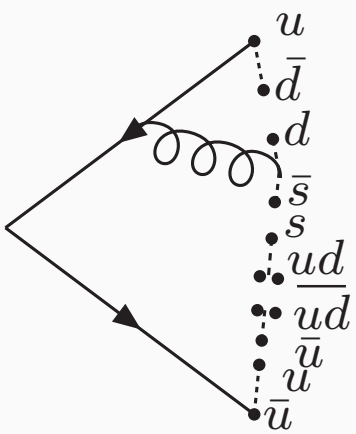

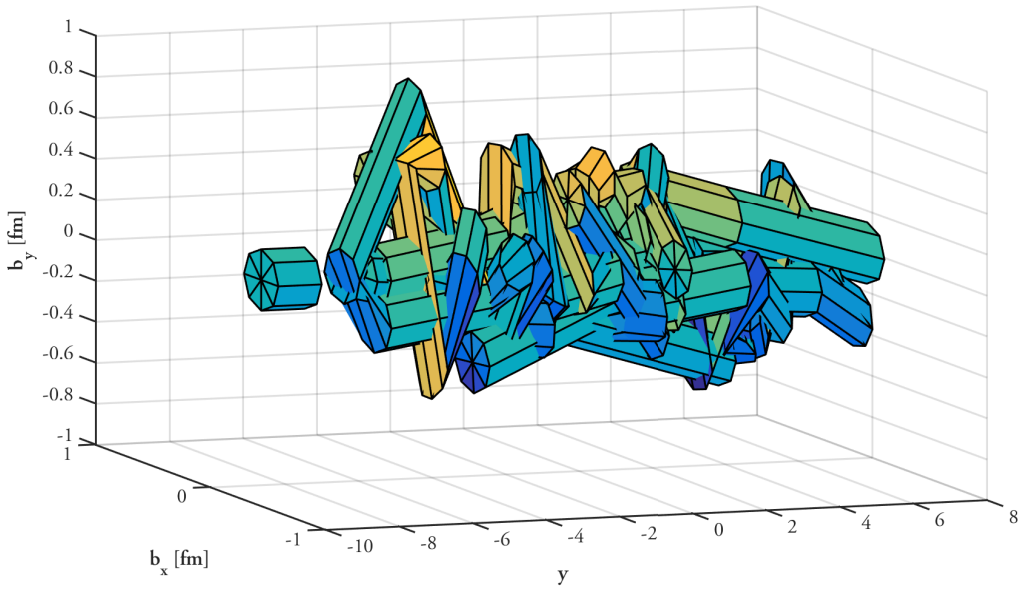

But many strings overlap in pp collisions!

Rope Hadronization (CB, Gustafson, Lönnblad, Tarasov: 1412.6259 – explored heavily in 80's and 90's!)

- Overlapping strings combine 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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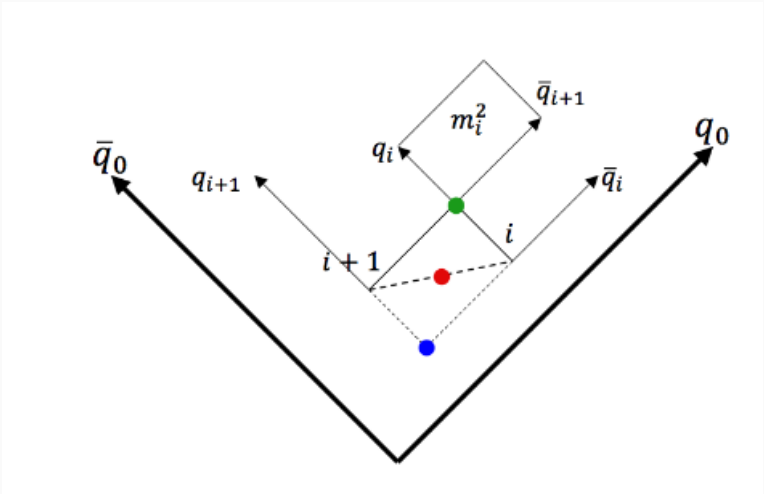
Strangeness enhanced by:

$$\rho_{LEP} = \exp\left(-\frac{\pi(m_s^2 - m_u^2)}{\kappa}\right) \rightarrow \tilde{\rho} = \rho_{LEP}^{\kappa_0/\kappa}$$

- QCD + geometry extrapolation from LEP.
- Can *never* do better than LEP initial conditions!

Rescattering (CB, Utheim, Sjöstrand, Ferreres-Solé: 2103.09665, 2005.05658, 1808.04619)

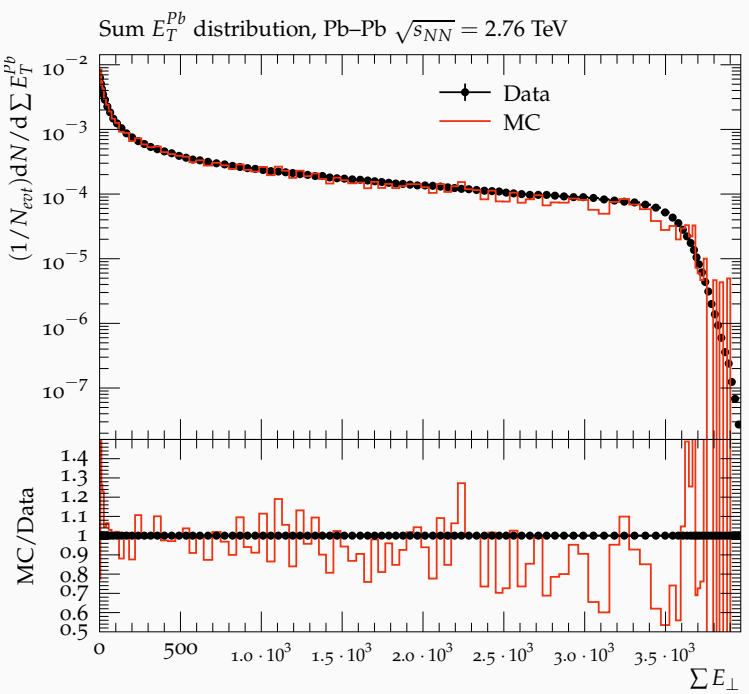
- Rescattering requires hadron space–time vertices.
- Key difference to existing approaches: Earlier hadronization $\tau \approx 2$ fm.
- Momentum-space to space-time breakup vertices through string EOM: $v_i = \frac{\hat{x}_i^+ p^+ + \hat{x}_i^- p^-}{\kappa}$
- Hadron located between vertices: $v_i^h = \frac{v_i + v_{i+1}}{2} \left(\pm \frac{p_h}{2\kappa} \right)$

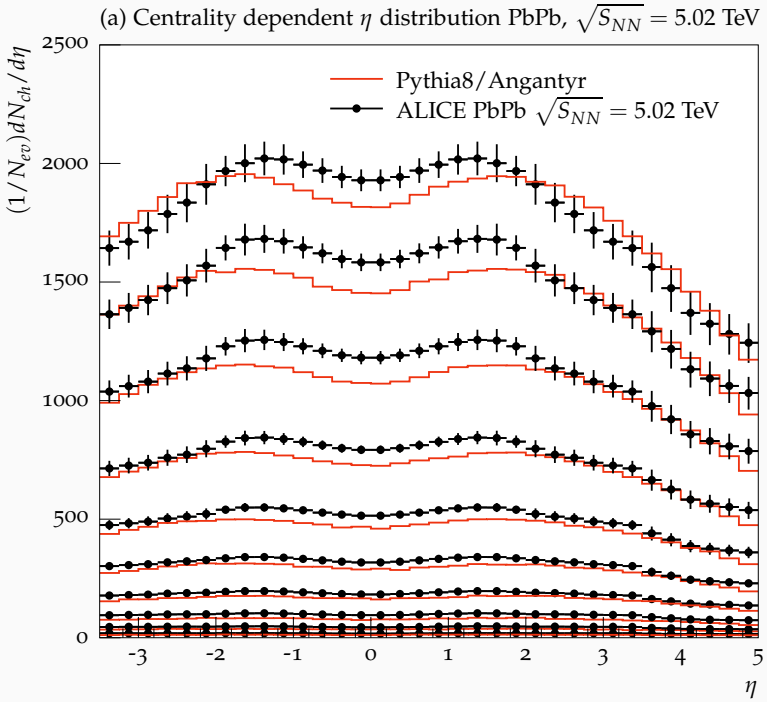


- Formalism also handles complex topologies.
- Hadron cross sections from Regge theory or data.
- Note recent extension for prompt pentaquark production (Ilten, Utheim: 2108.03479).

Angantyr particle production

- Reduces to normal Pythia in pp. In AA:
  1. Good reproduction of centrality measure (forward measurement ATLAS).
  2. Particle density at mid–rapidity.

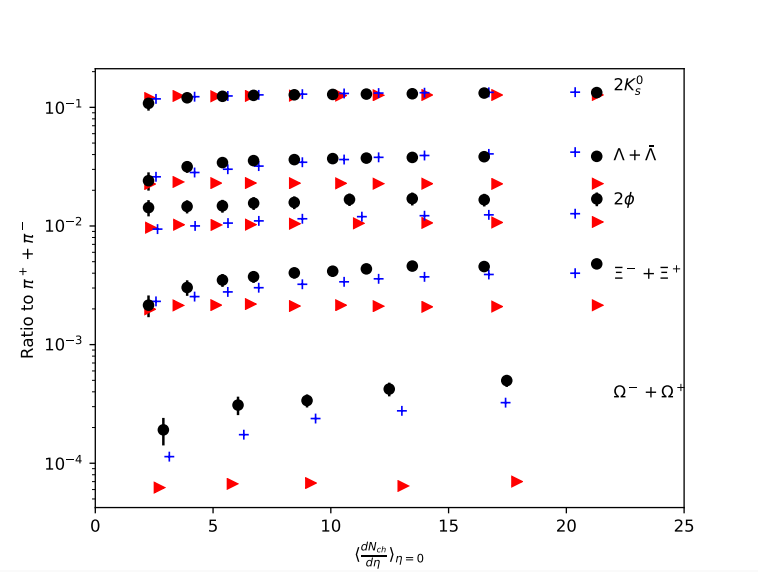




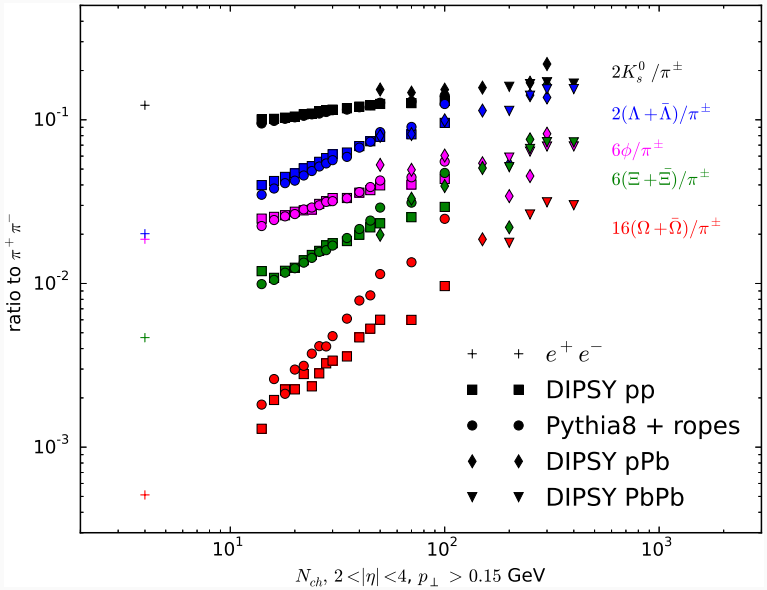
- Same for other geometries, also pA.
- Would like: Similar in LHCb acceptance, SMOG fixed target would be great! Preferably in RIVET (1912.05451, 2001,10737)

Strangeness enhancement from ropes

- Good description of strangeness enhancement.
- Left pp (in release), right pp-AA preliminary results (WiP).



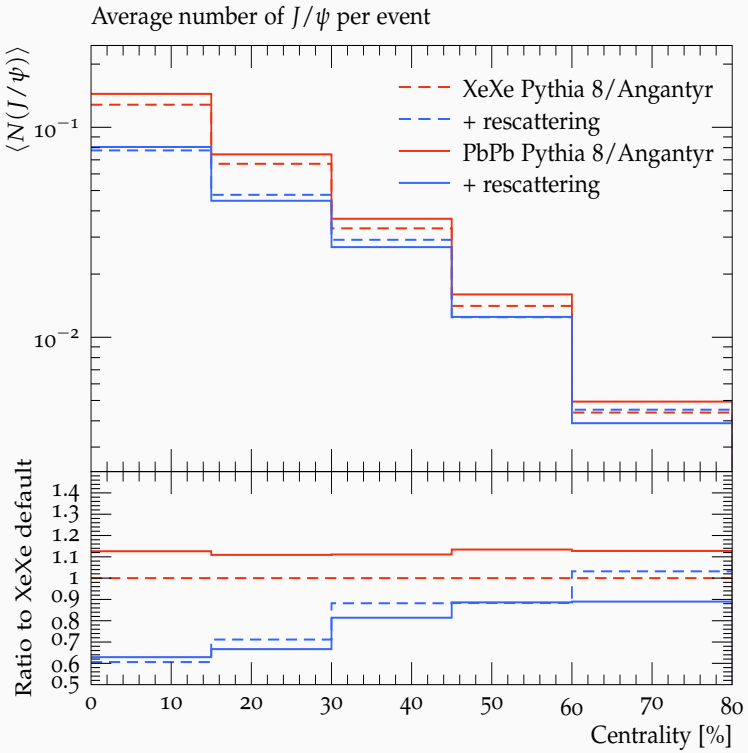
(Black ALICE data, red PYTHIA default, blue PYTHIA with ropes)

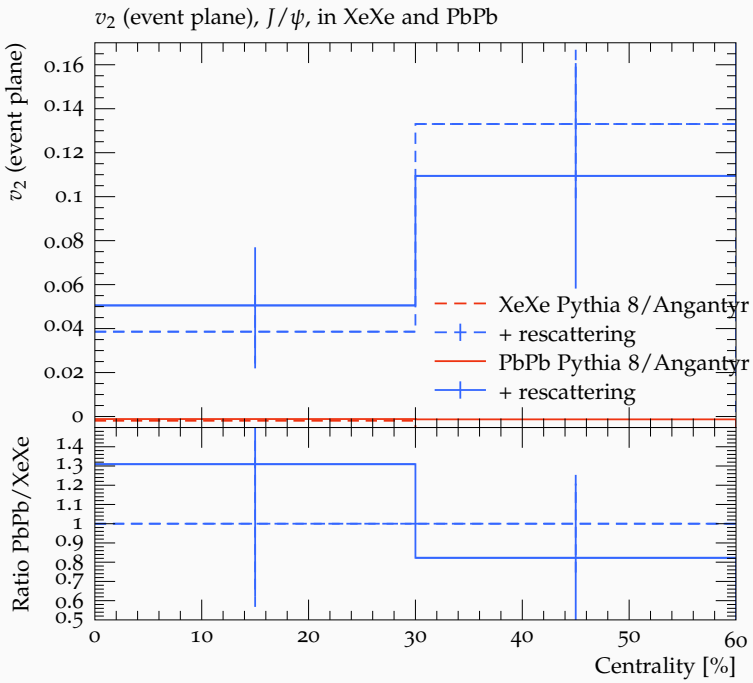


- Would like: To what degree is the multiplicity phase space choice necessary? Similar effects for cs states D_s, Λ_c etc.? Maybe even B_s/B?

Hadronic rescattering, closed charm

- Includes additive quark model for charm cross sections.
- Large effect for J/ψ (dissociation, flow). Early production.
- Full comparison to data needed, preferably RIVET.





Summary and future

- Many developments concerning heavy ion physics in PYTHIA!
  1. Model for collective behaviour, still mostly pp, AA in pipeline.
  2. Angantyr model for heavy ion collisions, just specify your ion and run.
  3. Internal rescattering framework, includes charm, allows origin extraction and extendible to eg. pentaquarks.
- Model(s) needs stress-testing and further development!
- Removing QGP from the equation is drastic, but a neccesary null-test.
  1. Geometry variation, SMOG results unique, prospects?
  2. LHCb phase space, model should work out to remnant region.
  3. Precision comparisons required, RIVET is our preferred tool.

Thank you for the invitation!