A Pythia/Angantyr perspective on OO and pO collisions

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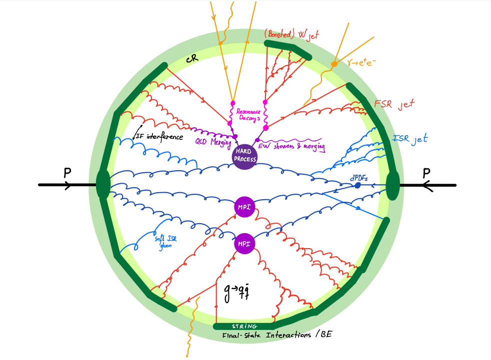
Feb 10th 2021, Opportunities of OO and pO collisions, CERN

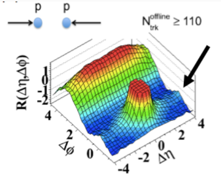
General purpose event generators for pp



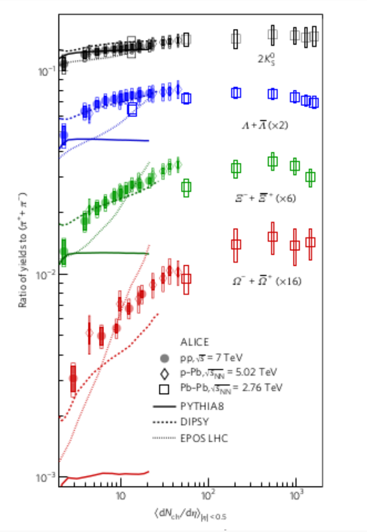
(Figure: Peter Skands)

- Traditional focus on hard processes (+ jets), QCD resummation by parton showers, MPIs a sideshow, hadronization a necessity.
- Jet universality! QGP production assumed a heavy ion phenomenon.

Small system collectivity a game changer



(CMS: JHEP 09 (2010) 091)



(ALICE: Nat. Phys.13 (2017))

- QGP the only game in town?
  1. Don't add QGP production: No more soft QCD physics!
  2. Add QGP production: Goodbye jet universality!
- Solution: Change the game.

This talk

- MPIs and The Lund string model for hadronization.
- Generalization to heavy ions: The Angantyr model.
  - Angantyr for oxygen collisions.
- Generating flow: string shoving.
  - String shoving in oxygen collisions.
- Early-time hadronic rescattering.
  - Hadronic rescattering in oxygen collisions.
- Looking ahead: cosmic cascades with Pythia.

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- Looking ahead: cosmic cascades with Pythia.
- OO Pythia perspective I: “untuned” test of models in new geometries
- OO Pythia perspective II: stepping stone for cosmic cascades
- Note: My biased view. Presentation of ongoing work.

MPIs in PYTHIA8 pp (Sjöstrand and Skands: arXiv:hep-ph/0402078)

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

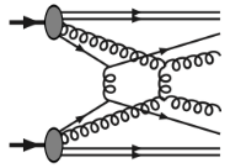


Figure T. Sjöstrand

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

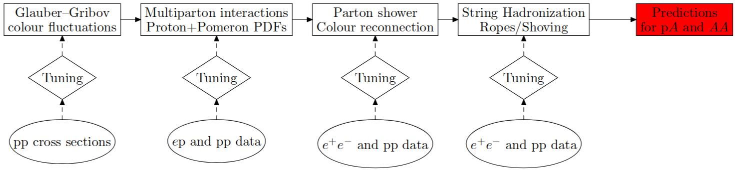
- Momentum conservation and PDF scaling.
- Ordered emissions: $p_{\perp 1} > p_{\perp 2} > p_{\perp 4} > \ldots$ from:

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

- $p_{\perp,0} \to$ retuned for RHIC energies. High energy OO better.

Angantyr – the Pythia heavy ion model (CB, G. Gustafson, L. Lönnblad: arXiv:1607.04434, += Shah: arXiv:1806.10820)

- Pythia MPI model extended to heavy ions since v. 8.235.
  1. Glauber initial state with Gribov colour fluctuations.
  2. Attention to diffractive excitation & forward production.
  3. Hadronize with Lund strings.



How to use?

- Not so fond of "providing predictions".
- We provide the code, experiments generate their own.
- Reproduction of experimental conditions crucial.
- Blind implementation of analyses good practise.
- We prefer validating with Rivet (1912.05451,2001.10737).

```cpp
#include "Pythia8/Pythia.h"
#include "Pythia8/HeavyIons.h"

using namespace Pythia8;

// This is a one-slide example program demonstrating Heavy Ion
// functionality.
int main() {
  Pythia pythia;
  // Setup the beams.
  pythia.readString("Beams:idA = 1000822080");
  pythia.readString("Beams:idB = 1000822080"); // The lead ion.
  pythia.readString("Beams:eCM = 2760.0");
  // Sum up the weights of all generated events.
  double sumw = 0.0;
  // Count the number of charged particles.
  double ncEvent = 0.0;
  // Initialise Pythia.
  pythia.init();
  for ( int iEvent = 0; iEvent < 1000; ++iEvent ) {
    if ( !pythia.next() ) continue;
    double nc = 0.0;
    for (int i = 0; i < pythia.event.size(); ++i) {
      Particle & p = pythia.event[i];
      if ( p.isFinal() ) {
        if ( p.isCharged() && p.pT() > 0.1 && abs(p.eta()) < 0.5 ) ++nc;
      }
    }
    sumw += pythia.info.weight();
    ncEvent += nc * pythia.info.weight();
  }
  cout << "Charged multiplicity density at mid-eta: " << ncEvent / sumw << endl;
  return 0;
}
```

Nucleus geometry

- Fairly standard Woods-Saxon à la GLISSANDO.
- Easy to plug new geometries yourself (`HeavyIonUserHooks`).
- Upcoming: Harmonic Oscillator Shell, α-clustering and Hulthén.
- Current release only WS, HOS test in this presentation:

$$\rho(r) = \frac{4}{\pi^{3/2} C^3} \left(1 + \frac{(A-4)r^2}{6C^2}\right) \exp(-r^2/C^2)$$

$$C^2 = \left(\frac{5}{2} - \frac{4}{A}\right)^{-1} (\langle r^2 \rangle_A - \langle r^2 \rangle_p)$$

Cross section colour fluctuations

- NN cross section fluctuates event by event: important for pA, $\gamma^* A$ and less AA.
- Projectile remains frozen through the passage of the nucleus.
- Consider fixed state (k) projectile scattered on single target nucleon:

$$\Gamma_k(\vec{b}) = \langle \psi_S | \psi_I \rangle = \langle \psi_k, \psi_t | \hat{T}(\vec{b}) | \psi_k, \psi_t \rangle =$$

$$(c_k)^2 \sum_t |c_t|^2 T_{tk}(\vec{b}) \langle \psi_k, \psi_t | \psi_k, \psi_t \rangle =$$

$$(c_k)^2 \sum_t |c_t|^2 T_{tk}(\vec{b}) \equiv \langle T_{tk}(\vec{b}) \rangle_t$$

- And the relevant amplitude becomes $\langle T^{(nN_i)}_{t_i,k}(\vec{b}_{ni}) \rangle_t$

Fluctuating nucleon-nucleon cross sections

- Let nucleons collide with total cross section $2\langle T\rangle_{p,t}$
- Inserting frozen projectile recovers total cross section.
- Consider instead inelastic collisions only (color exchange, particle production):

$$\frac{\mathrm{d}\sigma_{\mathrm{inel,pp}}}{\mathrm{d}^2\vec{b}} = 2\langle T(\vec{b})\rangle_{p,t} - \langle T(\vec{b})\rangle^2_{p,t}.$$

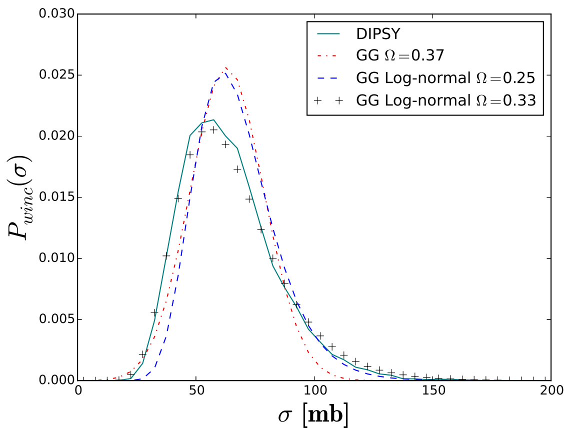
- Frozen projectile will not recover original expression, but require target average first.

$$\frac{\mathrm{d}\sigma_w}{\mathrm{d}^2\vec{b}} = 2\langle T_k(\vec{b})\rangle_p - \langle T_k^2(\vec{b})\rangle_p = 2\langle T(\vec{b})\rangle_{t,p} - \langle\langle T(\vec{b})\rangle_t^2\rangle_p$$

- Increases fluctuations! But pp can be parametrized.

Status and prospects

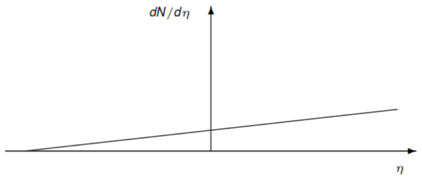
- Fluctuating cross section event-by-event.
- Dynamically generated or parametrized.



- OO size and α clusters: possible discovery venue?

Particle production: Wounded nucleons

- Simple model by Białas, Bleszyński and Czyż,
- Wounded nucleons contribute equally to multiplicity in η.
- Originally: Emission function $F(\eta)$ fitted to data.



$$\frac{dN}{d\eta} = F(\eta)$$ (single wounded nucleon

- Angantyr: No fitting to HI data, but include model for emission function.
- Model fitted to reproduce pp case, high $\sqrt{s}$, can be retuned down to 10 GeV.

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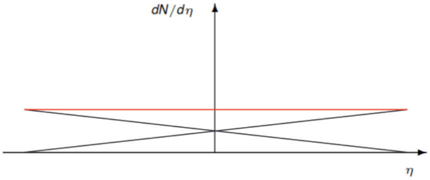

$$\frac{dN}{d\eta} = F(\eta) + F(-\eta) \qquad \text{(pp)}$$

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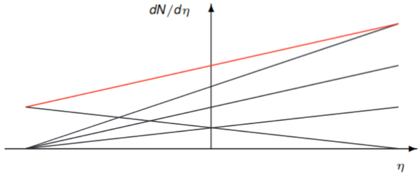

$$\frac{dN}{d\eta} = w_t F(\eta) + \quad F(-\eta) \qquad \text{(p}A\text{)}$$

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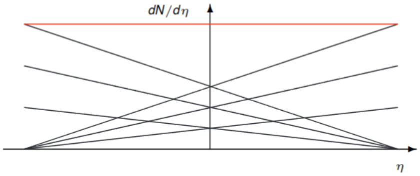
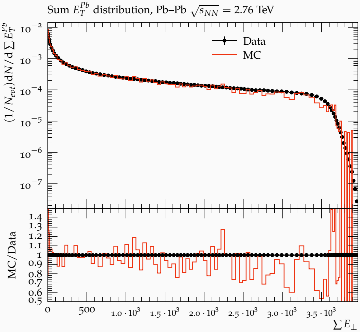


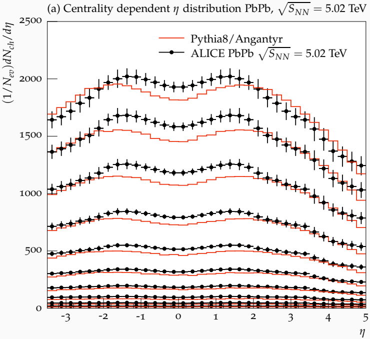
$$\frac{dN}{d\eta} = w_t F(\eta) + w_p F(-\eta) \qquad (AA)$$

- Angantyr: No fitting to HI data, but include model for emission function.
- Model fitted to reproduce pp case, high $\sqrt{s}$, can be retuned down to 10 GeV.

Basic quantities in PbPb

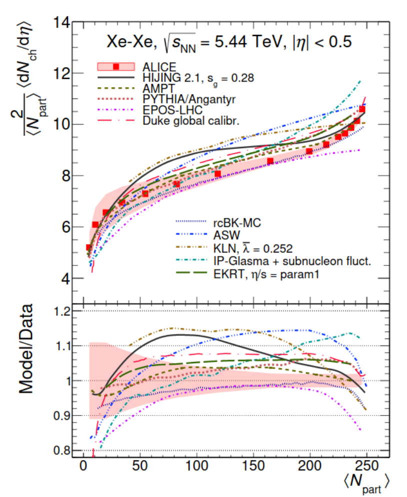
- Reduces to normal Pythia in pp. In AA:
    1. Good reproduction of centrality measure.
    2. Particle density at mid–rapidity.





Uptick in XeXe

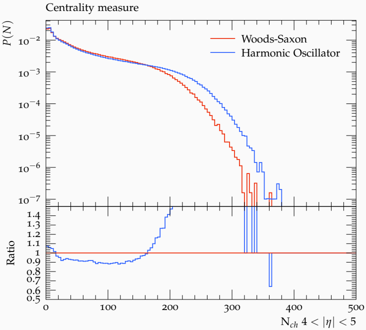
- Good description of XeXe uptick.
- OO runs out of participants quicker.
- Accurate comparison/projection (N_{part} definition) crucial!
- Sensitivity to geometry to be explored.

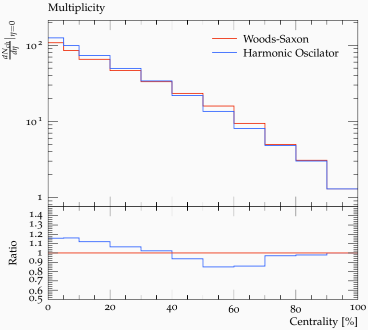


(ALICE: PLB 790 (2019) 35)

Predictions for OO

- Mock centrality measure: N_{ch} in $4 < |\eta| < 5$.
- Tuning effort necessary (in pipeline), results using GLISSANDO default parameter.
- $\sqrt{s_{NN}} = 5020$ GeV, $\tau_{0max} = 10$ mm/c, $\approx$ 3K events/minute/thread.

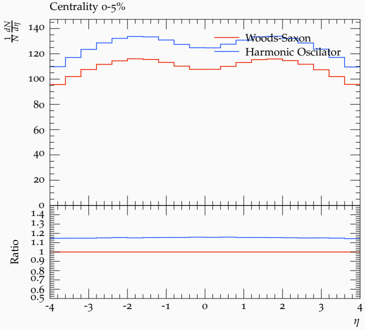


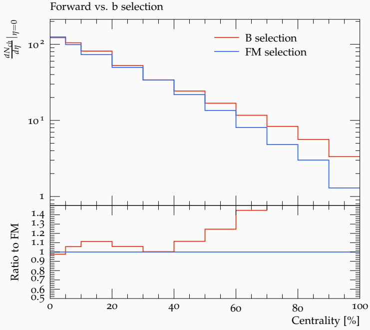


- Dedicated study of α clustering warranted!

Geometry control

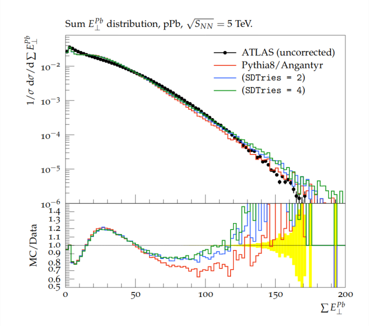
- Projected difference between IS geometries at level of model precision.
- Measured vs. initial centrality has large impact (like pA).

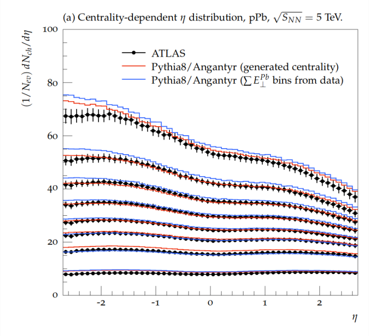




Basic quantities in pPb

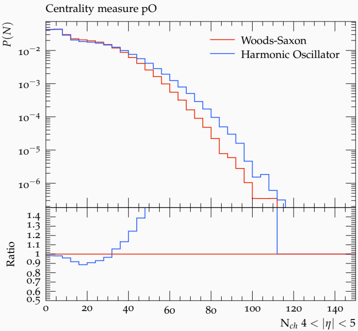
- Centrality measures are delicate, but well reproduced.
- So is charged multiplicity.

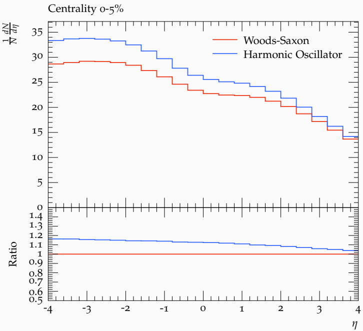




Predictions for pO

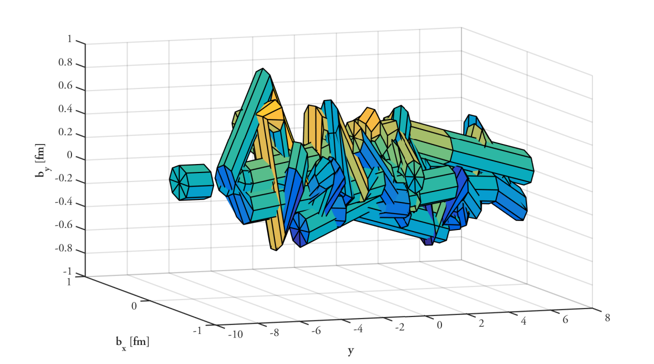
- Same story, increased effect.
- Note again: tuning to 1 and 2-nucleon densities necessary.





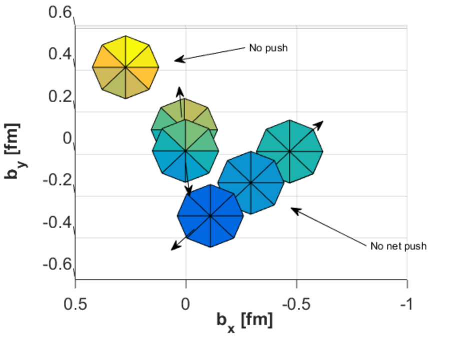
How to add space-time dependence to Lund strings?

- Shopping list:
    1. Space time structure (KISS for now, convolution of 2D Gaussians, Lorentz contracted in z-direction).
    2. This talk: Flow effects with string shoving.
    3. (Proper extension of rope hadronization to AA in pipeline, no results yet).



Shoving: The cartoon picture (CB, Gustafson, Lönnblad: 1710.09725, +=Chakraborty: 2010.07595)

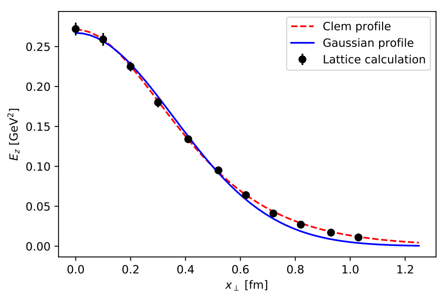
- Strings push each other in transverse space.
- Colour-electric fields → classical force.



👍 Transverse-space geometry.
👍 Particle production mechanism.
?? String radius and shoving force

MIT bag model, dual superconductor or lattice?

- Easier analytic approaches, eg. bag model: $\kappa = \pi R^2[(\Phi/\pi R^2)^2/2 + B]$
- Bad R 1.7 and dual sc. 0.95 respectively, shape of field is input.
- Lattice can provide shape, but uncertain R.



- Solution: Keep shape fixed, but R ballpark-free.

The shoving force

- Energy in field, in condensate and in magnetic flux.
- Let g determine fraction in field, and normalization N is given:

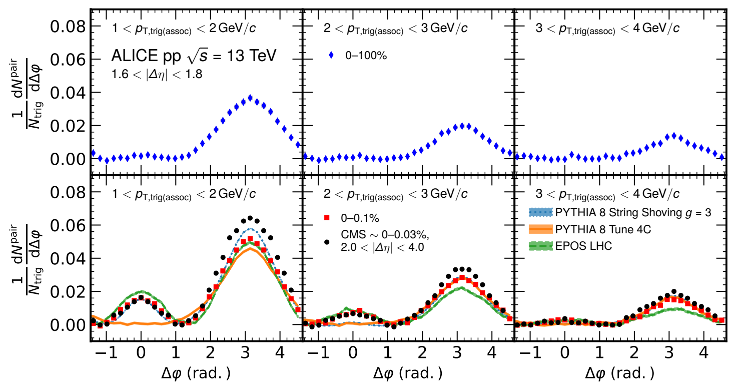
$$E = N \exp(-\rho^2/2R^2)$$

- Interaction energy calculated for transverse separation $d_\perp$, giving a force:

$$f(d_\perp) = \frac{g\kappa d_\perp}{R^2} \exp\left(-\frac{d_\perp^2}{4R^2}\right)$$

- Possibility for OO: $R/R_{\mathrm{O}} \approx 1/5$ and $R/R_{\mathrm{Pb}} \approx 1/14$

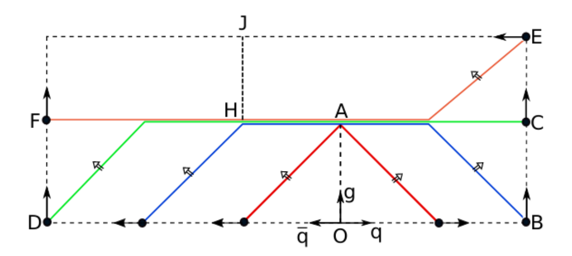
- The pp ridge (and much more, see 2010.07595).
- Here compared to ALICE: apply cuts and biases as you wish (even Z tags, see 1901.07447)



(ALICE: 2101.03110)

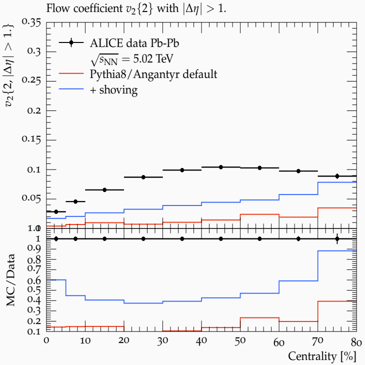
Recent progress: shoving in AA

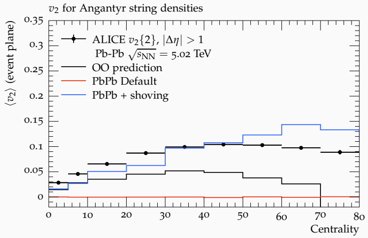
- Adding small pushes propagating along the string is difficult!
- Current problem: "secondary" string pieces arising from origami regions.
- If only there were no soft gluons around...



Shoving results PbPb and OO

- Missing origami regions, realistic initial states (left).
- Toy model configuration (right)
- Both lacking hadronic rescattering, which also plays a role.





Early time hadronic rescattering

- Hadronic rescattering framework recently in Pythia.
- Besides physics: Fast re-initialization of of low-energy collisions. Useful for cosmic shower programs.
- In place for pp (Sjö strand and Utheim: 2005.05658), AA work in progress.
- Running time: t_{res}/t_{def}: pp: 1.8, pPb: 4.0, PbPb: 250.
- Full event history (where was the particle produced).
- Includes charm processes, extension option (pentaquarks, deuterons, ...) work in progress.

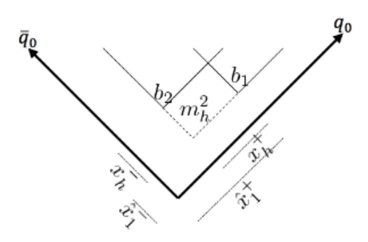
String kinematics (B. Andersson et al.: Phys. Rept.97(1983) 31)

- Lund string connects $q\bar{q}$, tension $\kappa = 1\text{GeV/fm}$.
- String obey yo–yo motion:

$$p_{q_0/\bar{q}_0} = \left(\frac{E_{cm}}{2} - \kappa t\right)(1;0,0,\pm 1).$$

- String breaks to hadrons with 4-momenta:

$$p_h = x_h^+ p^+ + x_h^- p^- \text{ with } p^\pm = p_{q_0/\bar{q}_0}(t=0)$$



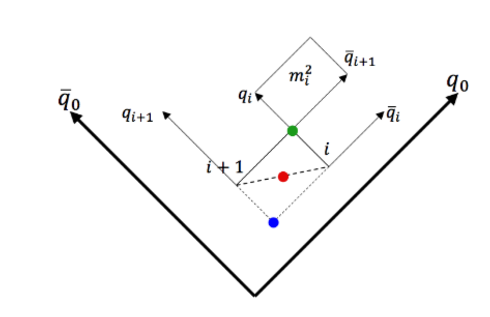
- ... which gives breakup vertices in momentum picture.

Hadron vertex positions (Ferreres-Solé & Sjöstrand: 1808.04619)

- Translate to space–time breakup vertices through string EOM.

$$v_i = \frac{\hat{x}_i^+ p^+ + \hat{x}_i^- p^-}{\kappa}$$

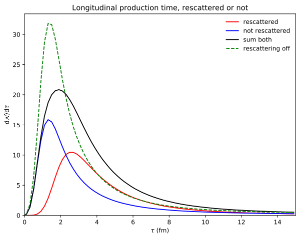
- Hadron located between vertices: $v_i^h = \frac{v_i + v_{i+1}}{2} \left(\pm \frac{p_h}{2\kappa} \right)$

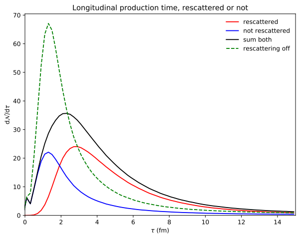


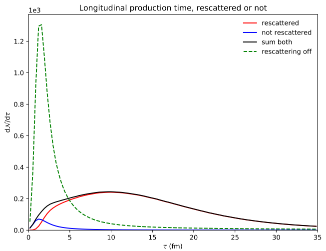
- Formalism also handles complex topologies.

Why “early time”?

- Particle production time pp (upper left) pPb (upper right) and PbPb (bottom).
- Freezeout time is not an instant! $\tau^2 = \tau_L^2 = t^2 - z^2$.

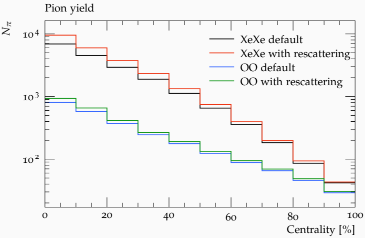


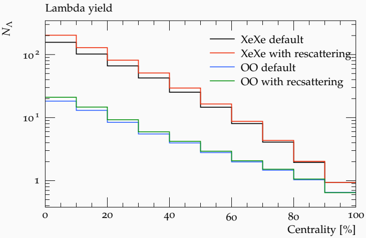




Some results (light flavour)

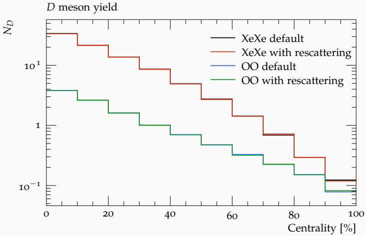
- Some light flavour (π and Λ) yields.
- Take home: Smaller system, smaller effect: from 30% to 15%.
- Isolating pre-hadronization effects (also on flow, R_{AA}, ...)?
- Note: untuned – rescattering gives higher total multiplicity.
- $\Rightarrow$ might not be so dramatic as shown.

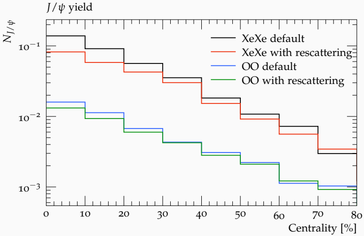




Some results (heavy flavour)

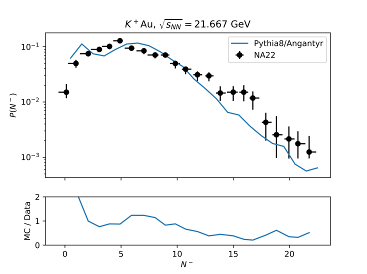
- Pythia rescattering includes heavy flavours.
- Sizeable effect on J/ψ: source of R_{AA}? Need distinct geometries at high energies to test! (= OO run).
- Note: Only perturbative charm in Pythia.

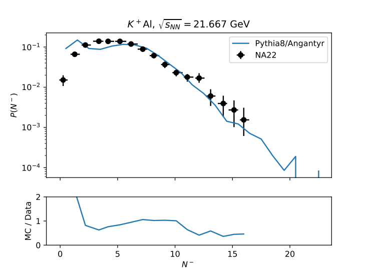




Outlook: cosmic cascades (Ida Storehaug, then ICECUBE, now ALICE)

- Important aspect, way out of my comfort zone.
- Neutrino flux very dependent on hadronic cascade, MC used.
- Pythia not a direct contender yet, but used indirectly.
- Wish list: Intermediate geometries (pO!), N fragmentation region (see LHCf talks), strange projectiles (one can dream...).





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    3. (not covered) Strangeness with rope hadronization.
- Another geometry at high energies will provide valuable input.

Thank you for the workshop!