Heavy ion collisions with Pythia/Angantyr, and a microscopic perspective on heavy ion physics

...a very biased view

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Introduction

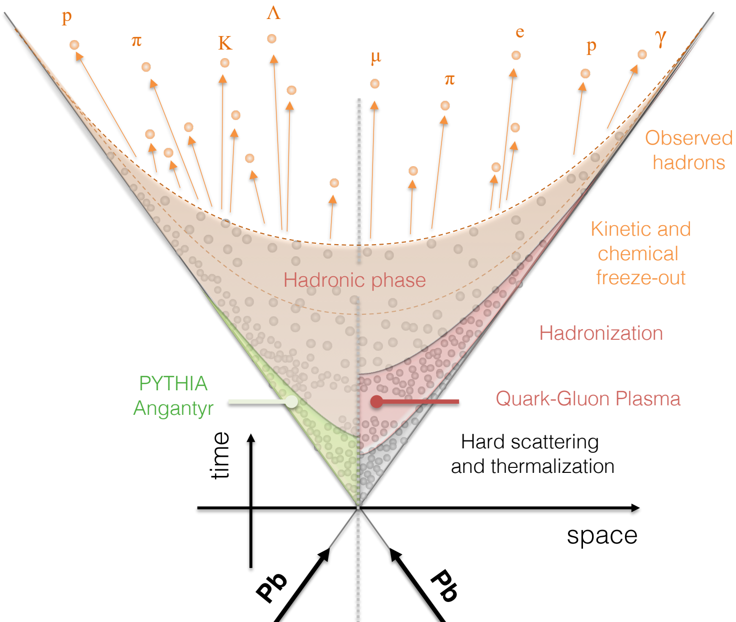
- A brief overview of Pythia's venture into heavy ion physics.
- Why?
  - Heavy ion phenomena in pp at LHC spurred interest.
  - Pythia often used as "baseline" tool.
- But!
  - Underlying models $! =$ Pythia implementation.
  - Can we deliver a better baseline?
  - ... or even make the Quark–Gluon Plasma redundant?

Most importantly:

◇ New opportunities for non-perturbative QCD

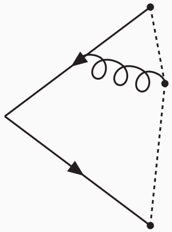
- This talk: a microscopic, plasma free approach.
  1. Basic ingredients of pp collisions & extensions.
     - ◇ string, MPIs, string shoving & rope hadronization.
  2. MPIs from pp to AA: The Angantyr model.
     - ◇ basic observables, final state rescatterings & towards EIC.

Heavy ion event generation without QGP



Start from e^+e^-, The Lund String

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



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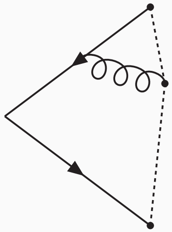

Lund symmetric fragmentation function

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

a and b related to total multiplicity.

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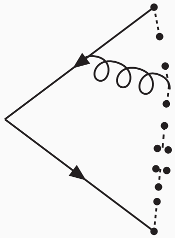

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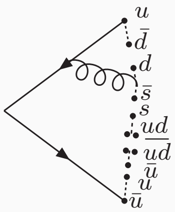

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Light flavour determination

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

Related to κ by Schwinger equation.

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

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

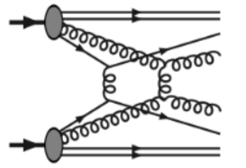

Figure T. Sjöstrand

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

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

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

- Picture blurred by CR, but holds in general.

Microscopic final state collectivity

- Clearly we need more! Where is the geometry?
- Proposal: Model microscopic dynamics with interacting Lund strings
- Additional input fixed or inspired by lattice, few tunable parameters.

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$\tau \approx 0$ **fm:** Strings no transverse extension. No interactions, partons may propagate.

$\tau \approx 0.6$ **fm:** Parton shower ends. Depending on "diluteness", strings may shove each other around.

$\tau \approx 1$ **fm:** Strings at full transverse extension. Shoving effect maximal.

$\tau \approx 2$ **fm:** Strings will hadronize. Possibly as a colour rope.

$\tau > 2$ **fm:** Possibility of hadronic rescatterings.

String shoving (CB, Gustafson, Lönnblad: 1612.05132, 1710.09725)

- Strings = interacting vortex lines in superconductor.
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$$\mathcal{E}(r_\perp) = C \exp\left(-r_\perp^2/2R^2\right)$$

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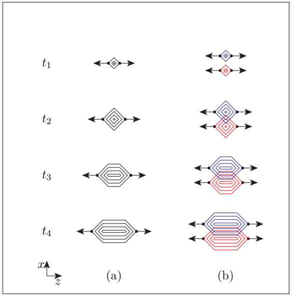

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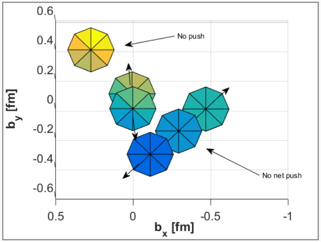
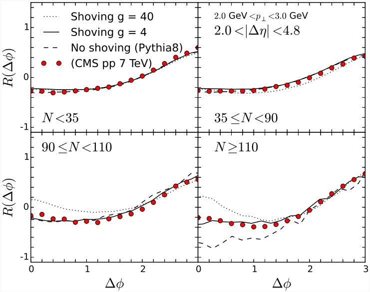
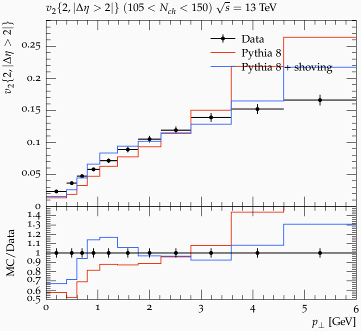


- All energy in electric field $\to g = 1$.
- Reality:
  Type 1 SC Energy to destroy vacuum.
  Type 2 SC Energy in current.

Some Results: shoving

- Reproduces the pp ridge with suitable choice of g parameter.
- Improved description of $v_2 2|\Delta eta| > 2.(p_\perp)$ at high multiplicity.
- Low multiplicity not reproduced well – problems for jet fragmentation?





A Z-boson changes the kinematics (CB: 1901.07447)

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- It *can* introduce kinematical biases: MC implementation will handle this.
- Recently measured by ATLAS (ATLAS-CONF-2017-068).

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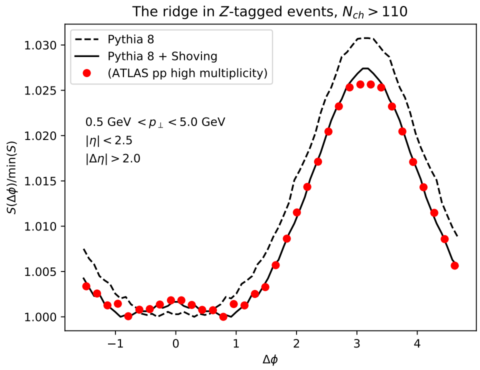

Rope Hadronization (JHEP 1503 (2015) 148 – explored heavily in 80's and 90's!)

- After shoving, strings (p and q) still overlap.
- 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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$$\{p, q\} \otimes \vec{3} = \{p+1, q\} \oplus \{p, q+1\} \oplus \{p, q-1\}$$

$$\underbrace{\begin{smallmatrix}\square\\ \square\end{smallmatrix} \otimes \begin{smallmatrix}\square\\ \square\end{smallmatrix} \otimes \ldots \otimes \begin{smallmatrix}\square\\ \square\end{smallmatrix}}_{\text{All anti-triplets}} \underbrace{\otimes \square \otimes \square \otimes \ldots \otimes \square}_{\text{All triplets}}$$

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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.

The highest multiplet

- Rope breaks one string at a time, reducing the *remaining* tension.
- String *junctions* carry baryon number.

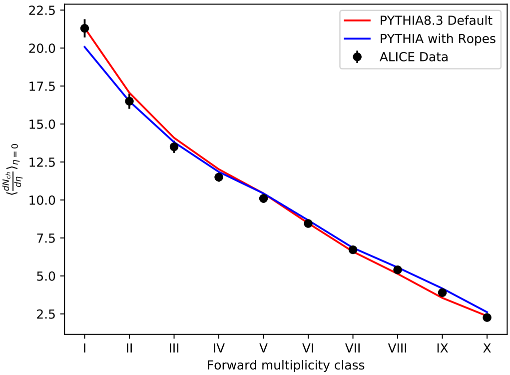
Strangeness enhanced by:

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

- QCD + geometric extrapolation from LEP.
- Can *never* do better than LEP description!

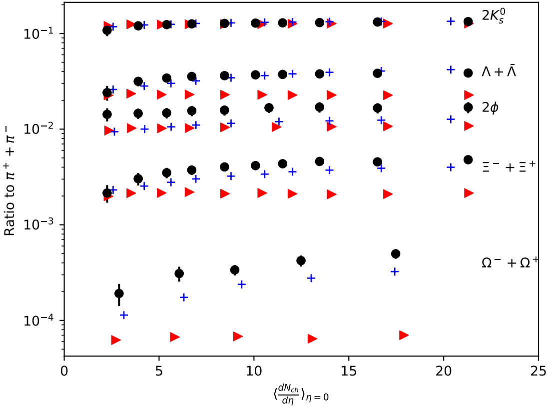
Forward/central multiplicity folding

- Full, honest comparison requires reproduction of centrality-measure.
- Recently possible in the Rivet project (rivet.hepforge.org, 2001.10737 [hep-ph])



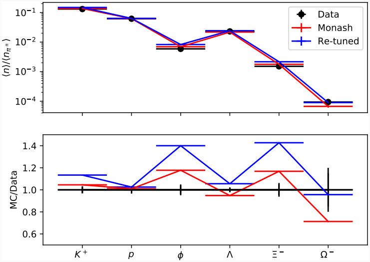
Strangeness enhancement (Data from ALICE (Nature Phys. 13 (2017) 535-53))

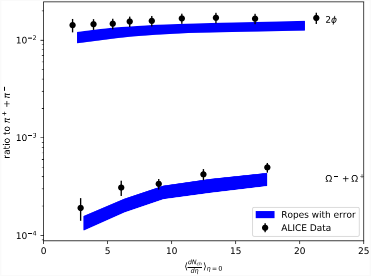
- Fair description, but quantitavely off in places.
- Most interesting for further microscopic development!
- RED: Pythia default, BLUE: Pythia + ropes, pp 7 TeV.



The LEP constraints (An aside, CB in prep.)

- Statement: Pythia describes LEP correctly!
- Truth: ... well, mostly!

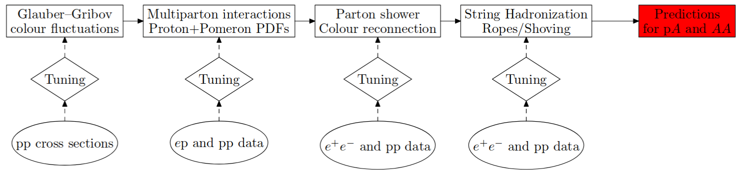




- Take home messages:
  1. Hadronization uncertainties are real, and can be quantified!
  2. ...but they rarely are!

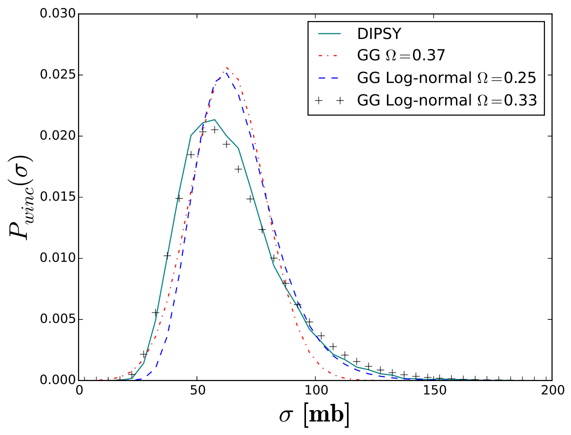
Angantyr – the Pythia heavy ion model (CB, G. Gustafson, L. Lönnblad: JHEP 1610 (2016) 139, += Shah: JHEP 1810 (2018) 134)

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



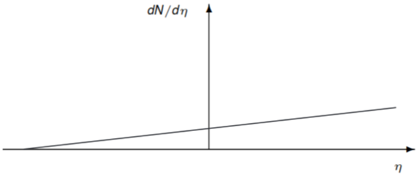
Glauber–Gribov colour fluctuations

- Cross section has EbE colour fluctuations.
- Parametrized in Angantyr, fitted to pp (total, elastic, diffractive).



Particle production: Wounded nucleons

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



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

- 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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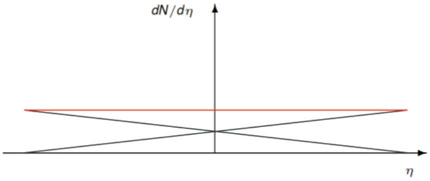

$$\frac{dN}{d\eta} = F(\eta) + F(-\eta) \qquad \text{(pp)}$$

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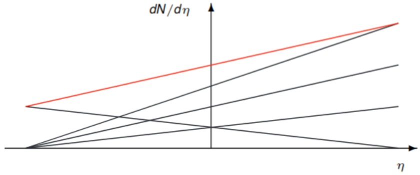

$$\frac{dN}{d\eta} = w_t F(\eta) + \quad F(-\eta) \qquad \text{(p}A\text{)}$$

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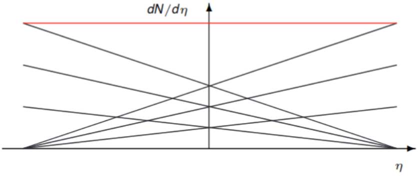

$$\frac{dN}{d\eta} = w_t F(\eta) + w_p F(-\eta) \qquad (AA)$$

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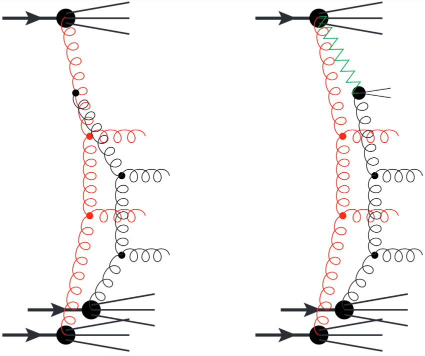
The emission function

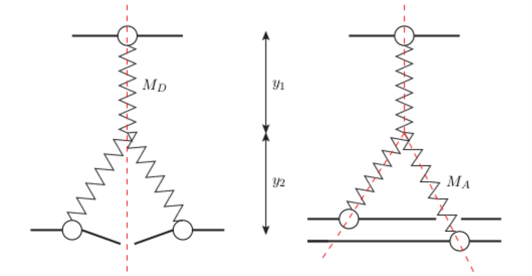
- A schematic view of a pD collision. Contains 3 wounded nucleons.
- First two are a normal non-diffractive pp event.
- The second one is modelled as a single diffractive event.
- Generalizes to all pA and AA collisions.



(a) (b)

Secondary absorptive interactions

- Similarity: triple-Pomeron diagrams.



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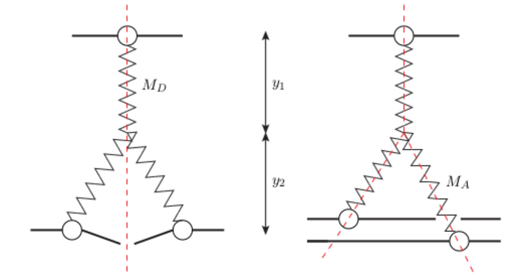


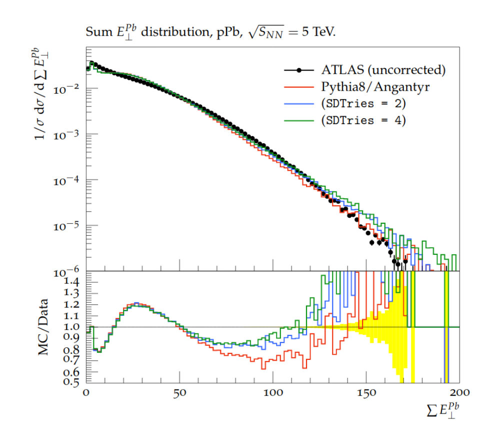
Diagram weight proportial to $(1+\Delta = \alpha_{\mathbb{P}}(0))$

$$\frac{\mathrm{d}s}{s^{(1-2\Delta)}} \frac{dM_D^2}{(M_D^2)^{(1+\Delta)}} \text{ diffractive excitation,}$$

$$\frac{\mathrm{d}s}{s^{(1-\Delta)}} \frac{dM_A^2}{(M_A^2)^{(1-\Delta)}} \text{ secondary absorption.}$$

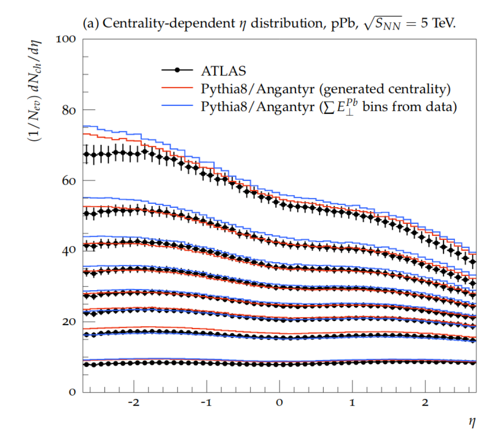
Some results - pPb

- Centrality measures are delicate, but well reproduced.

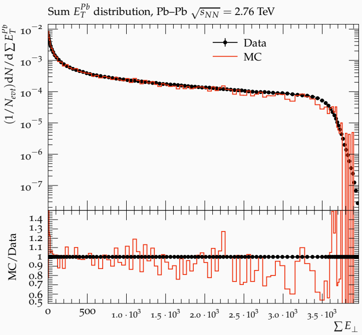


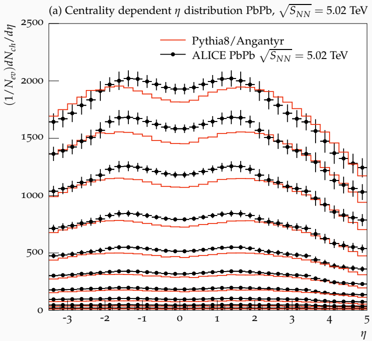
Some results - pPb

- Multiplicity distributions well reproduced.



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

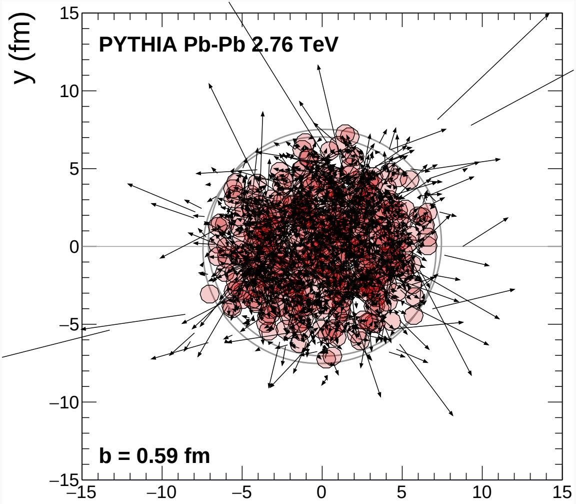




- Necessary baseline for any full model.
- Ropes and shoving work in progress.

Final state interactions in AA (CB, et al. 2002.10236 [hep-ph])

- Hadronic final state interactions matters in AA.
- Especially in non-fluid scenario, with short times.
- Pythia/Angantyr + URQMD.



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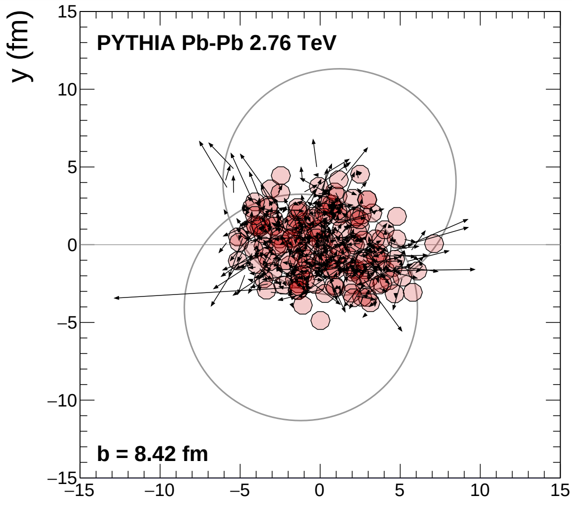

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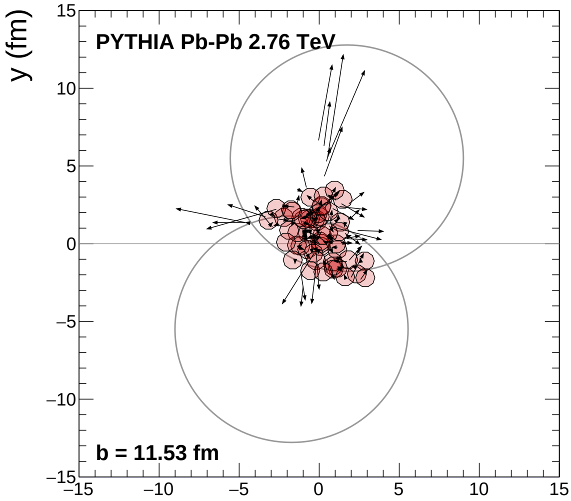
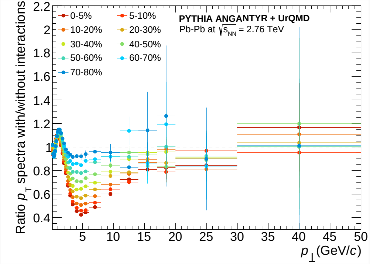
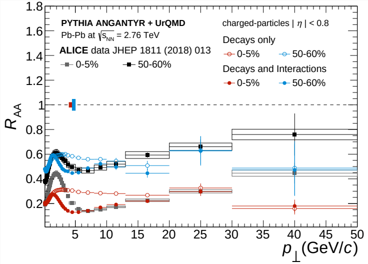


Effects on $p_\perp$-spectra

- Pythia will hadronize early, compared to eg. hydro.
- Denser state $\rightarrow$ more hadronic rescatterings.





- Not quantitative *description* of data, but improved baseline.
- Note: No free parameters for AA.

Summary of the AA part

- pA and AA collisions in PYTHIA.
- Focus on soft productions.
- Key: Cross section fluctuations & secondary absorption.
- Early results PYTHIA + URQMD promising aspects.
- Easy to use: Download and run.
- To come: microscopic collectivity in AA.

```
#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;
}
```

Towards EIC (WIP: with Ilkka Helenius; CB & C. O. Rasmussen: 1907.12871 [hep-ph])

- Extending Angantyr to EIC requires knowledge of fluctuating $\sigma_{abs}(Q^2)$.
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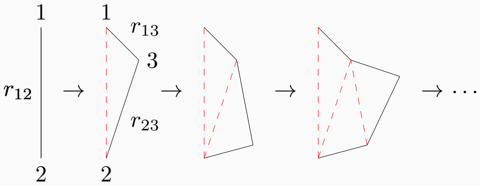

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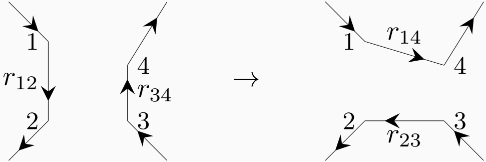

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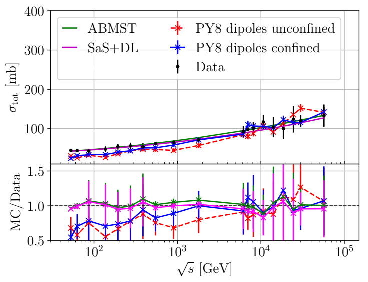
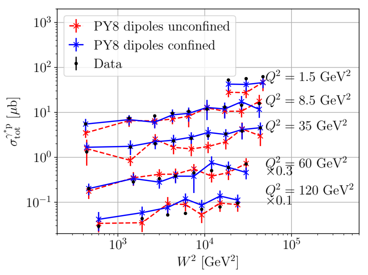




Glauber for $\gamma^* A$

- Results in fluctuating γ^*-nucleon absorptive cross section.

Wounded nucleon cross section gets frozen

1st:

$$\int \mathrm{d}z \int \mathrm{d}^2\vec{r}\,(|\psi_L(z,\vec{r})|^2 + |\psi_T(z,\vec{r})|^2)(2\langle T(\vec{b})\rangle_{t,p} - \langle\langle T(\vec{b})\rangle_t^2\rangle_p).$$

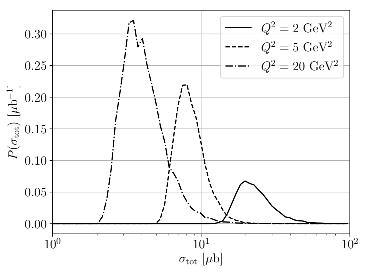
Further:

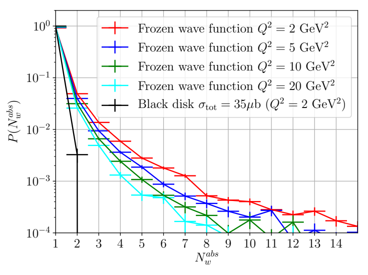
$$2\langle T(\vec{b})\rangle_{t,p} - \langle\langle T(\vec{b})\rangle_t^2\rangle_p,$$

- First ingredient of "soft QCD" EIC generator.

Glauber for $\gamma^* A$ II

- Correct fluctuations and freezing is neccesary.
- Next steps: Sampling of photon flux (UPCs) and full integration with final states.





Summary

Heavy ion collisions without the plasma

◇ How far can we get without a QGP?

- Combined effort of:
  - ◇ pp & HI, low & high energy.
  - ◇ theory, phenomenology and experimental input.
- Key elements.
  - ◇ extending string description with ropes & shoving.
  - ◇ extending MPIs to AA with Angantyr.
  - ◇ extending Angantyr to EIC with fluctuating cross sections.

Thank you for the invitation!

Some additional material

Color reconnection? What's that?

- Many partonic subcollisions $\Rightarrow$ 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-$p_\perp$.

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

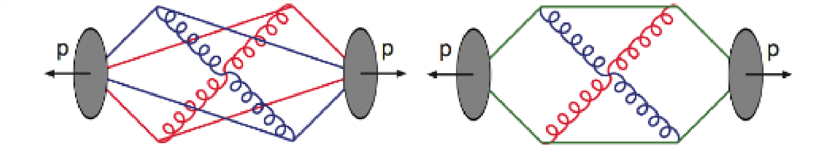


Figure T. Sjöstrand

- Actual merging by minimization of "potential energy":

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

Colour Reconnection – microscopic collectivity?

(Ortiz et al.: 1303.6326, CB QM18: 1807.05217 & mcplots.cern.ch)

- 👍 Mechanism allows cross–talk over an event.
- 👍 Based on physics effect.
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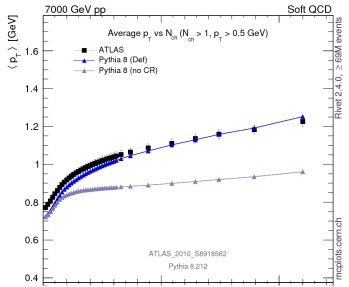
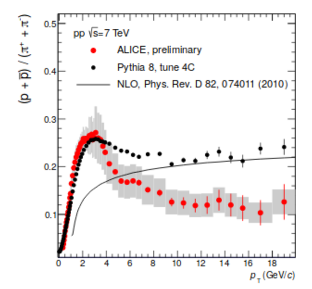
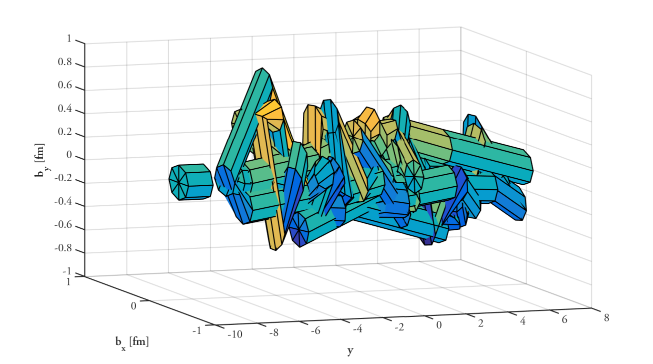




The importance of the initial state

- Space–time information is important: We rely on models! Also true for hydro.
- Here: Overlapping 2D Gaussians (p mass distribution).
- Figure string $R = 0.1$ fm, reality $R \sim 0.5$ fm.



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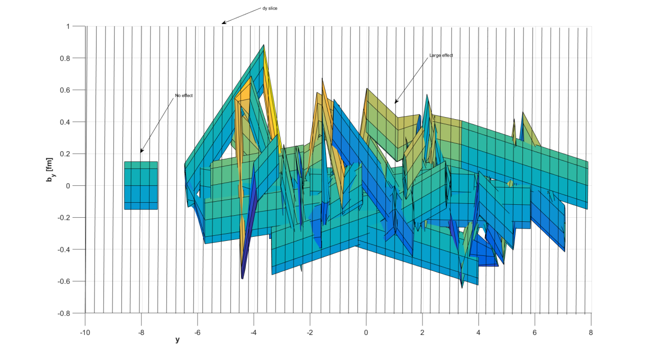

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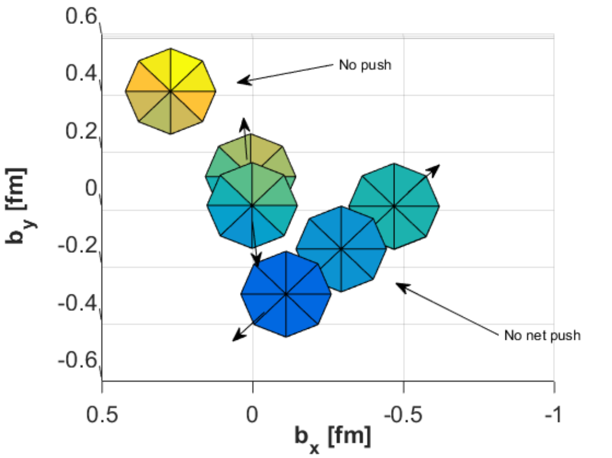

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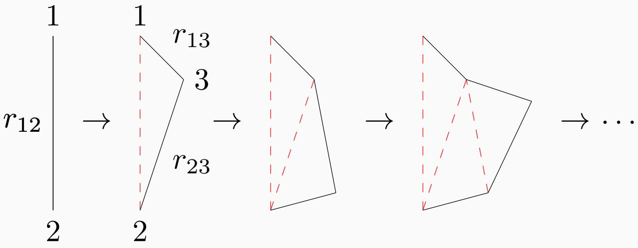

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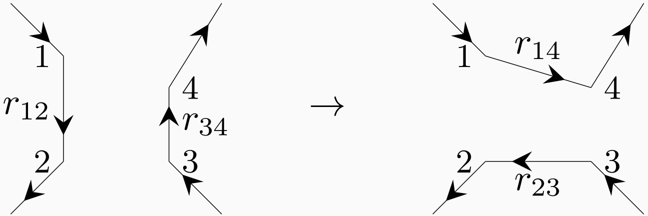

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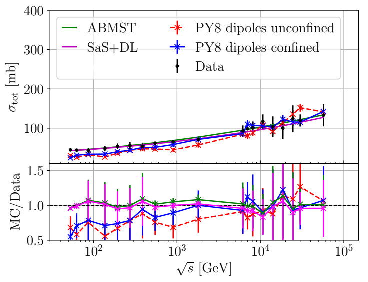
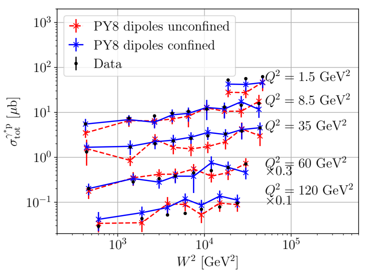
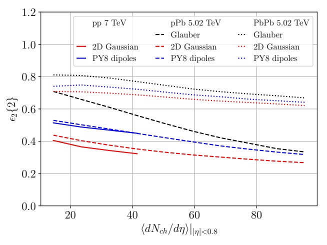
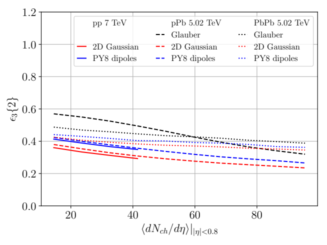




Geometry in pp, pA and AA

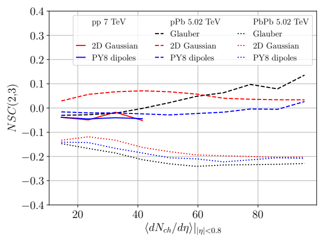
- Assuming $\epsilon_{2,3} \propto v_{2,3}$.
- Dipole model: $\epsilon_{2,3}$ equal for pp and pPb.

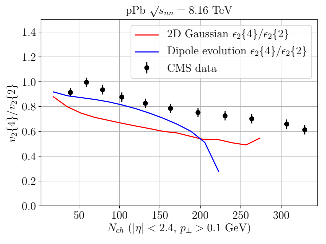




Flow fluctuations: Looking inside

- Flow fluctuations and normalized symmetric cumulants.
- Best discrimination in pPb.
- Dipole evolution $\rightarrow$ negative $NSC(2,3)$ in pPb.





- *Important to develop realistic initial states.*
- *Point stands also for hydro.*

Jet shoving: Hadrochemistry

- Hadrochemistry indirectly affected through basic string equations.
- Study inclusive quantities: Average hadron mass and total jet charge: $\langle m_h \rangle = \frac{1}{N_p} \sum_i^{N_p} m_{h,i}$, $Q_j = \sum_i^{N_p} q_{h,i}$

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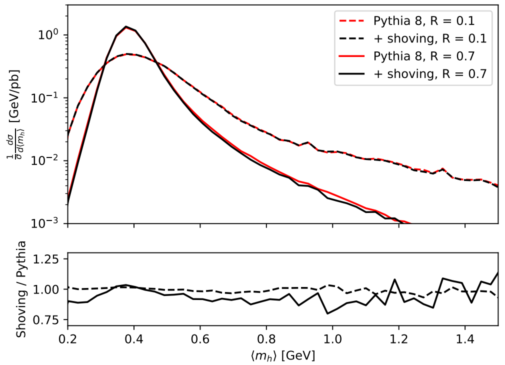

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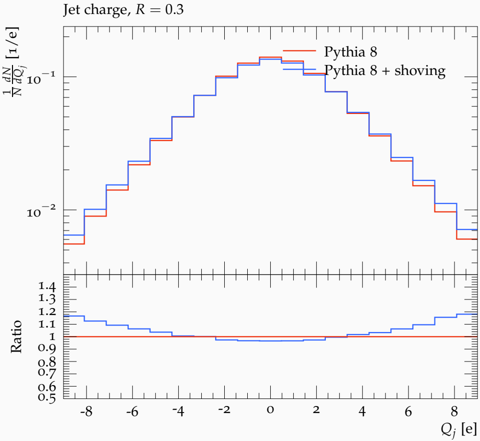

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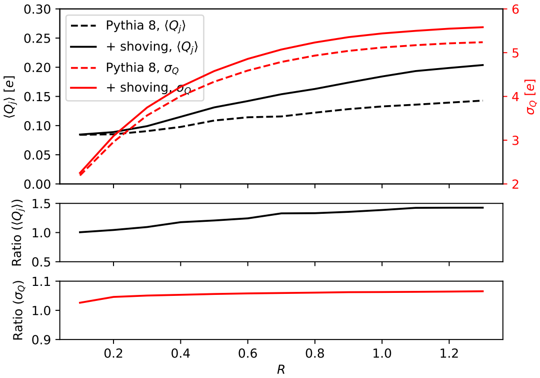
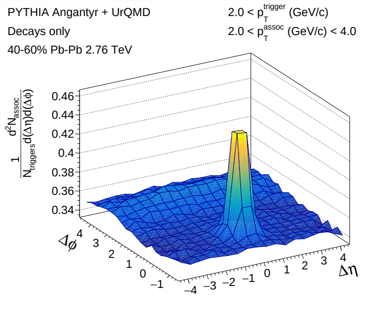
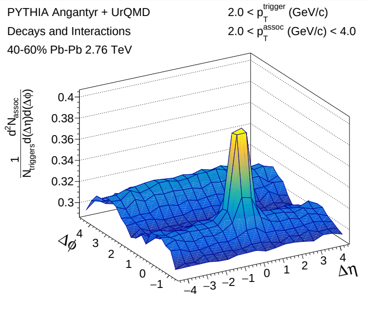


- Rescattering produces correlations long-range in η (the double ridge).
- Previously seen, but not at these energies, with general purpose MC input (Bleicher *et al.* arXiv:nucl-th/0602009).





Results – flow

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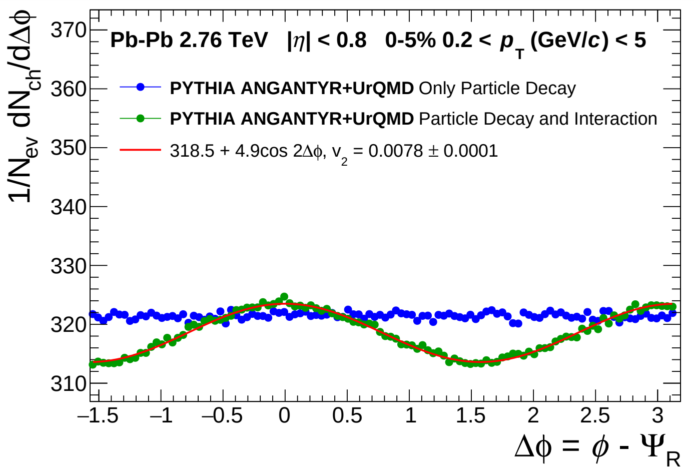
- Automatic removal of jet peak.



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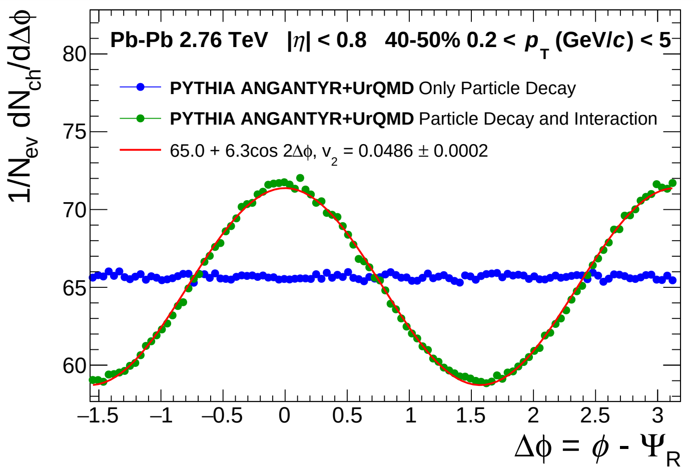

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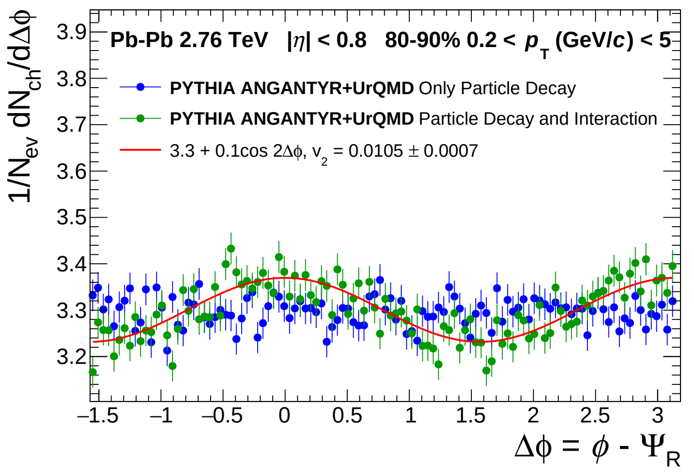
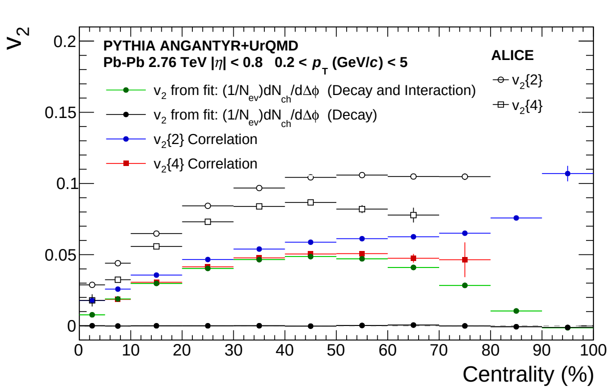


Results – elliptic flow coefficients

- v_2 vs centrality: same dynamics as in ALICE data, but 50% magnitude; v_2 via cumulants similar to v_2 with correlations wrt. event plane



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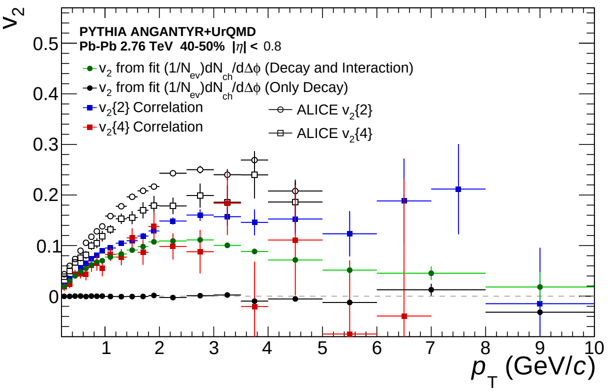

- Similar conclusion from $v_2(p_\perp)$