Bulk Dynamics - Hands-On

Post your questions, comments and complains in SLACK: [july19-hydrodynamics]

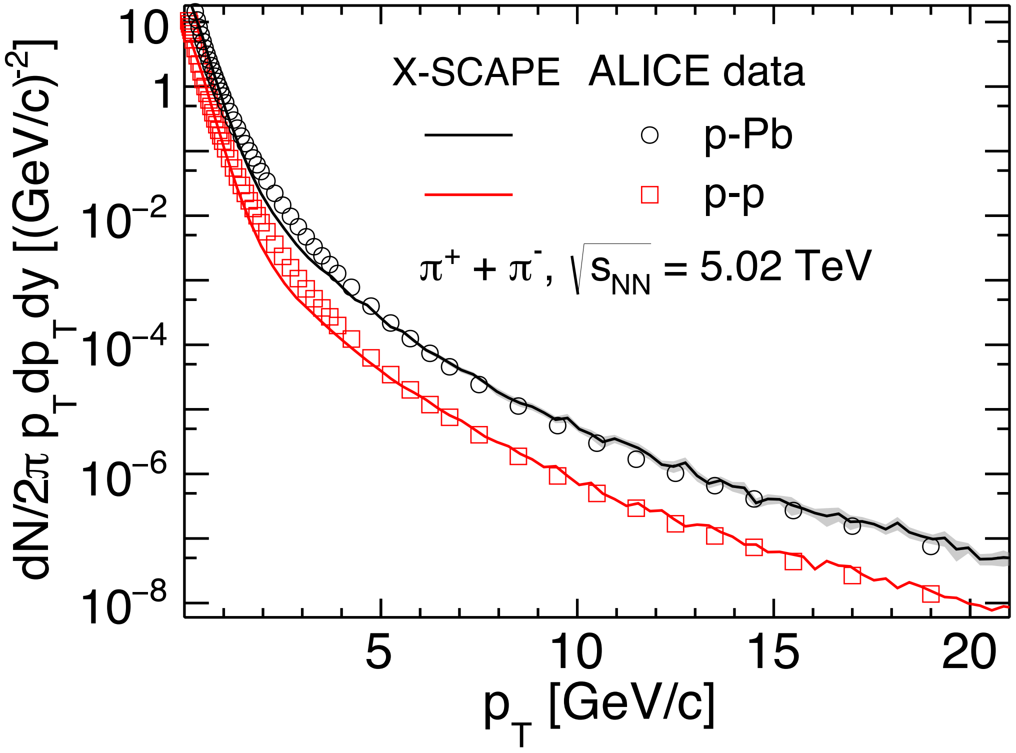
July 19th, 2023.

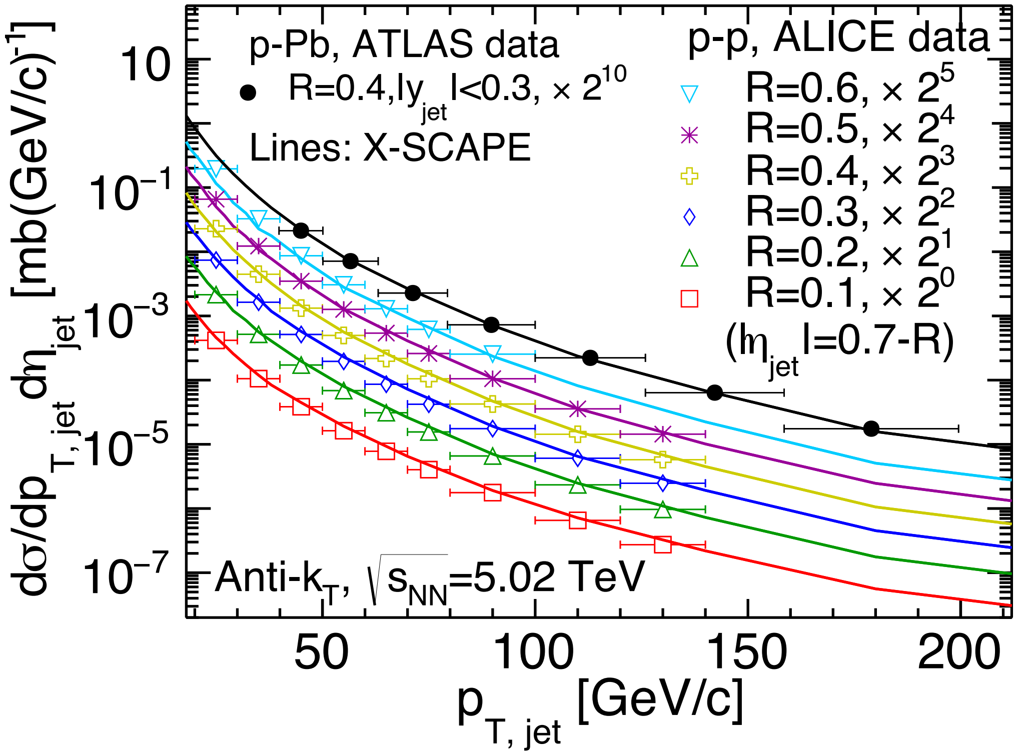
Wenbin Zhao wenbinzhao@wayne.edu

JETSCAPT Summer School 2023

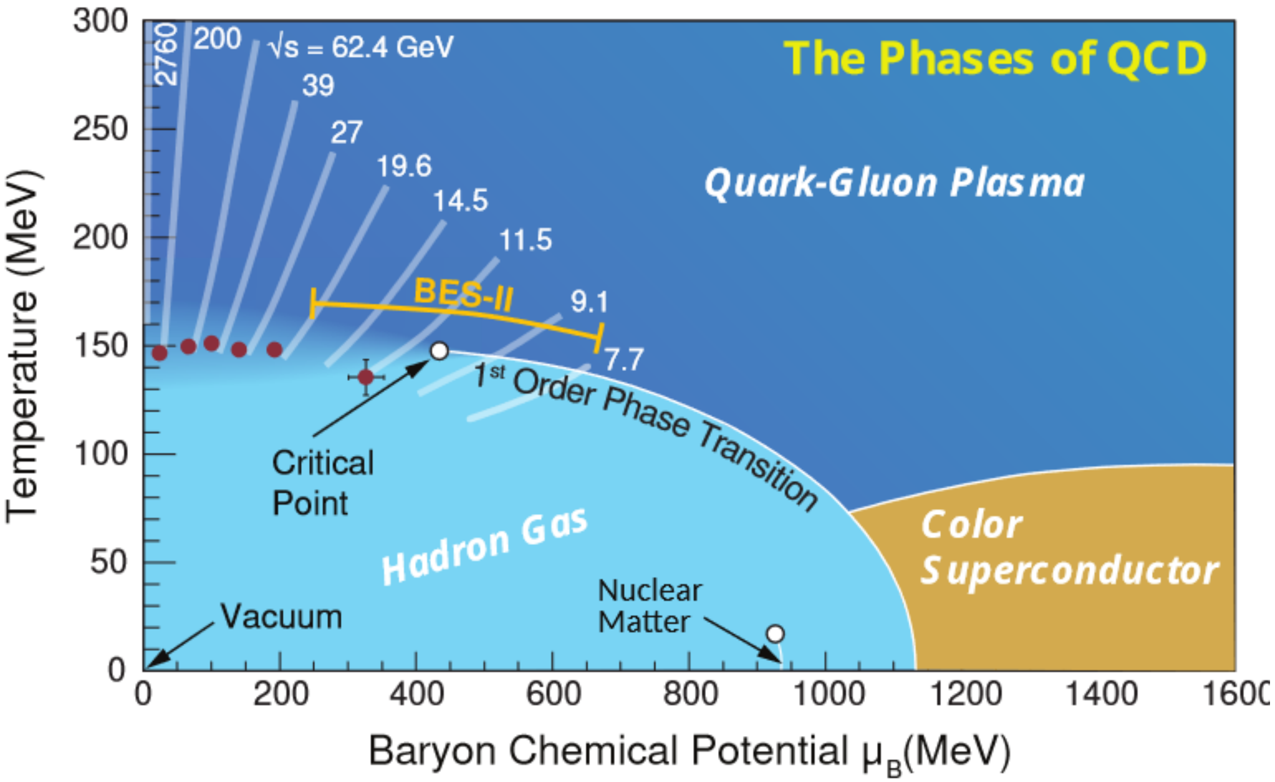
Contents

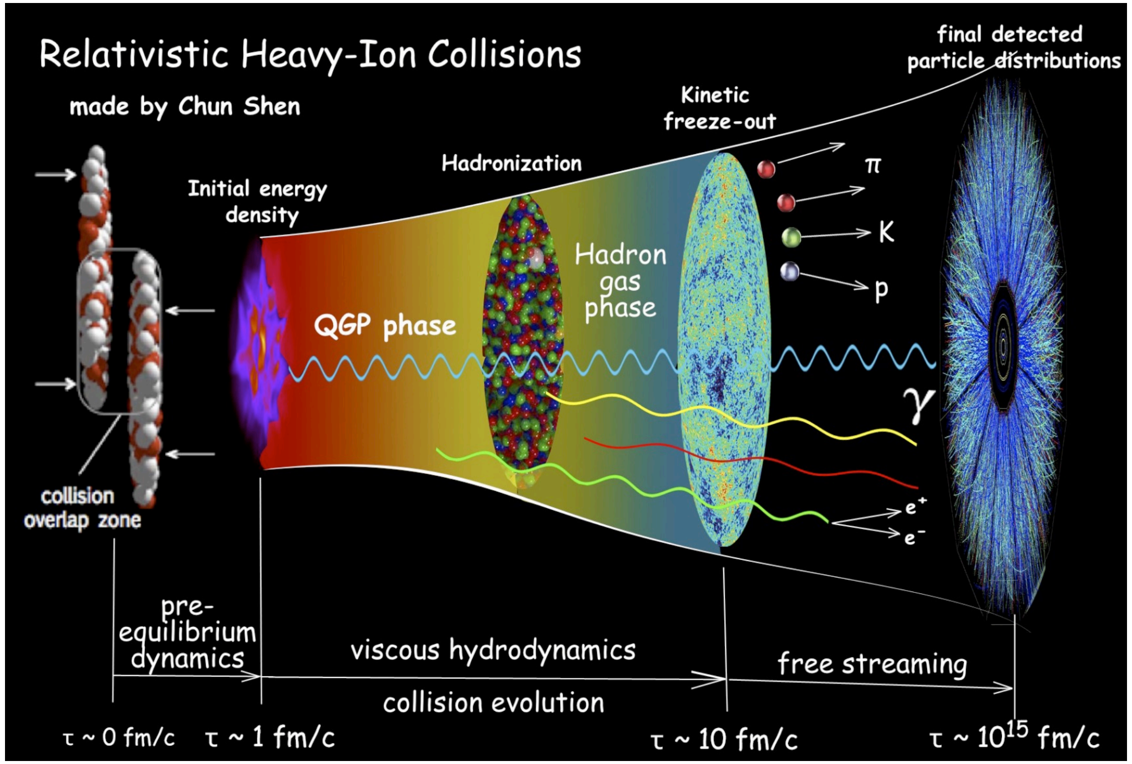
- Brief introduction of 3D-Glauber model, coupled with MUSIC hydrodynamic model.
- Brief introduction of the X-SCAPE framework.
- Get familiar with the X-SCAPE code, do some test run. Build some intuitions on the soft-hard correlations in small systems.
- **Homework**: reproduce the hadron and jet p_T-spectra in p-p at 5.02 TeV.





Nuclear matter phase diagram

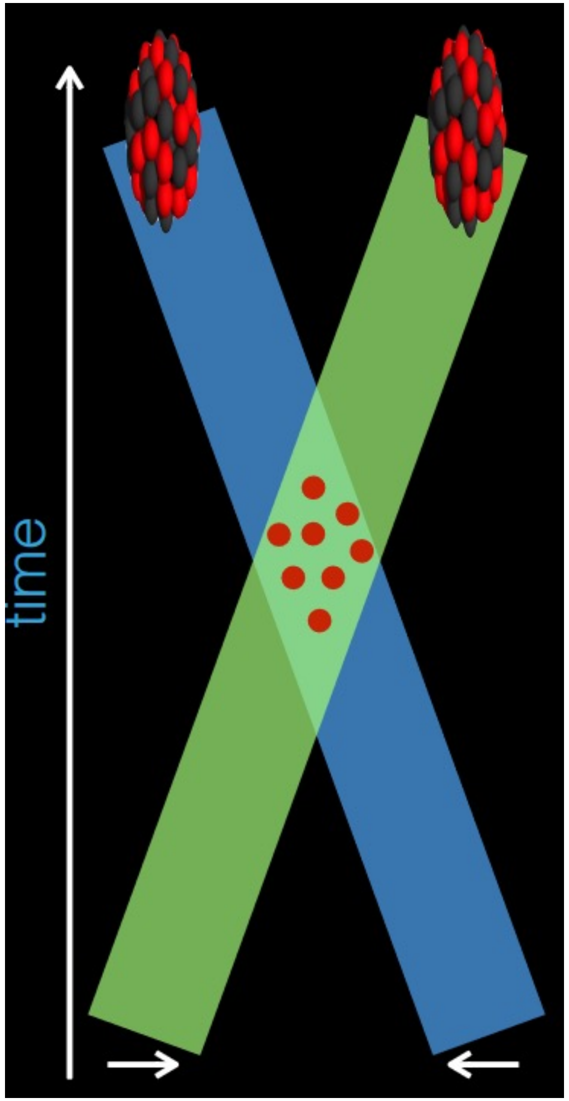


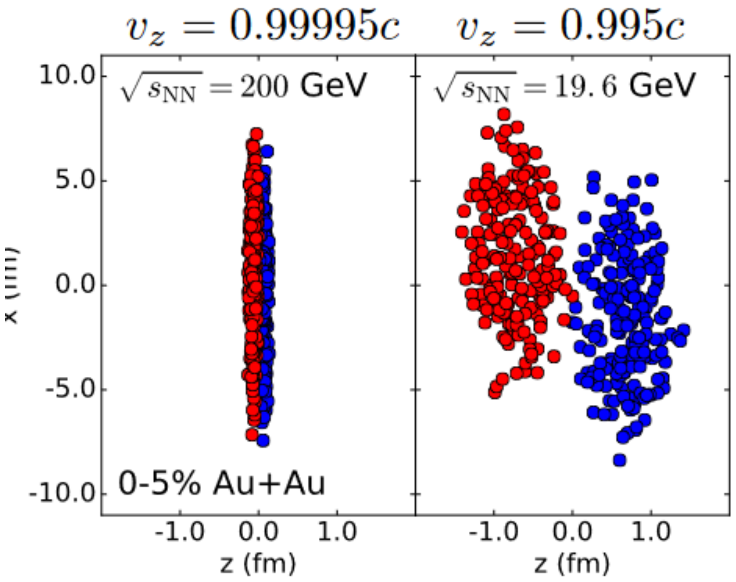


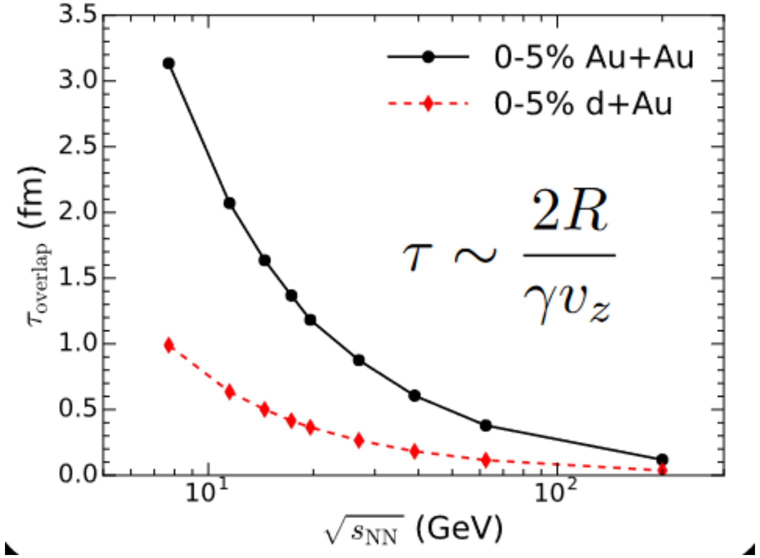
credit: Chun Shen

- First order phase transition line? Critical point?
- How do the QGP transport properties change in a large baryon density environment? $\eta/s(T,\mu_B)$, $\zeta/s(T,\mu_B)$
- What's the smallest QGP fluid?

3D Dynamics







Overlap time of two nuclei in the laboratory frame:

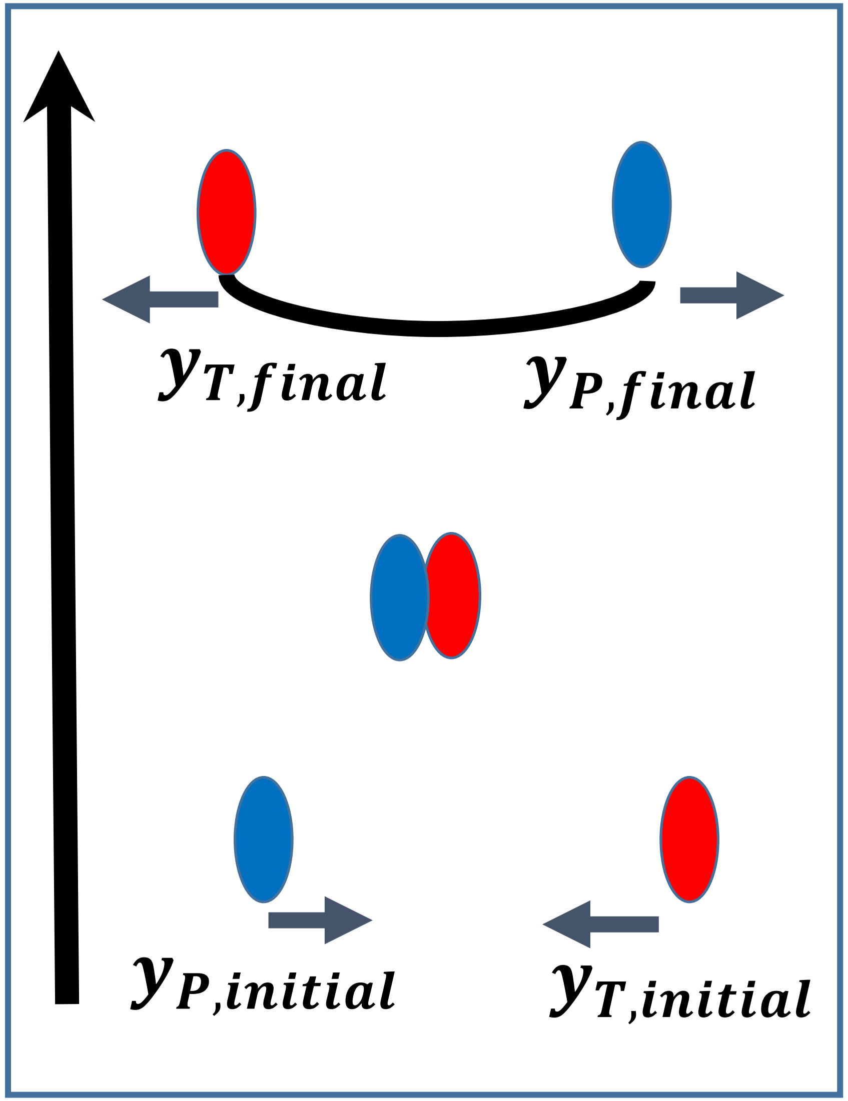
$$\tau_{\rm overlap} = \frac{2R}{\gamma v_z} = \frac{2R}{\sinh(y_{\rm beam})},$$

R: nuclear radius, γ : Lorentz factor, v_z moving velocities, $y_{beam} = \mathrm{arccosh}(\sqrt{s_{NN}}/(2m_p))$ beam rapidity, m_p : nucleon mass.

- At low energies, the overlapping time is close to hydro life-time.

C. Shen and B. Schenke, Phys. Rev. C,105 (2022), 064905, Phys. Rev. C 97, 024907 (2018).

3DGlauber dynamical initial condition



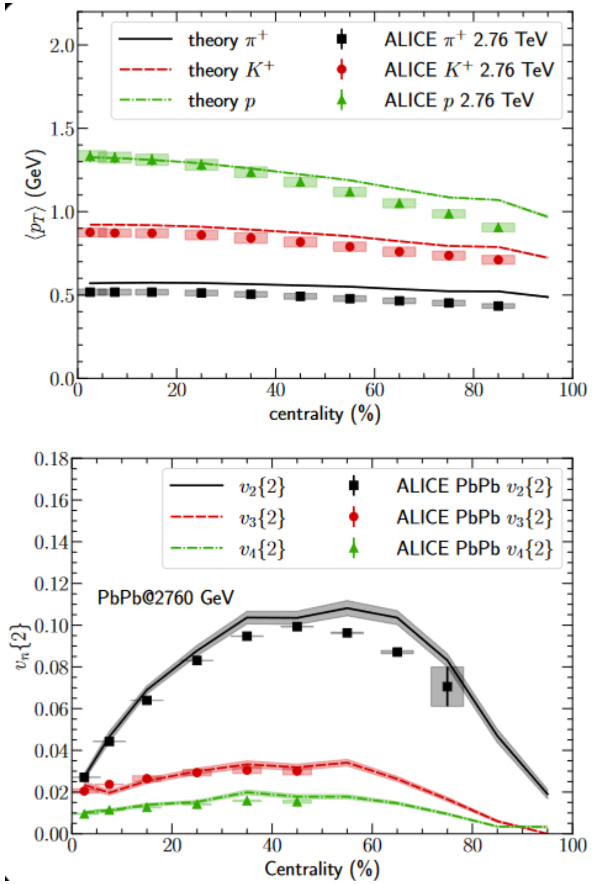
- Collision geometry is determined by MC-Glauber model.
- Incoming quarks are decelerated with a classical string tension.
- Conservation for energy, momentum, and net baryon density is imposed. Energy-momentum current and net baryon density are fed into the hydrodynamic simulations as the source terms.

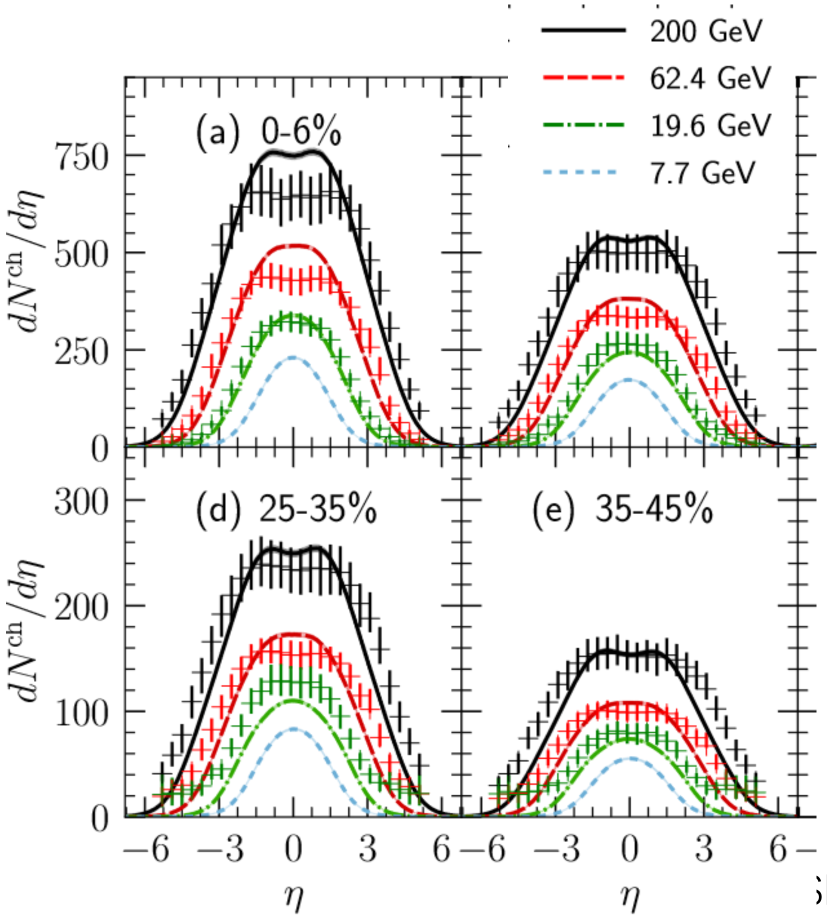
$$\partial_\mu T^{\mu\nu} = J^\nu$$

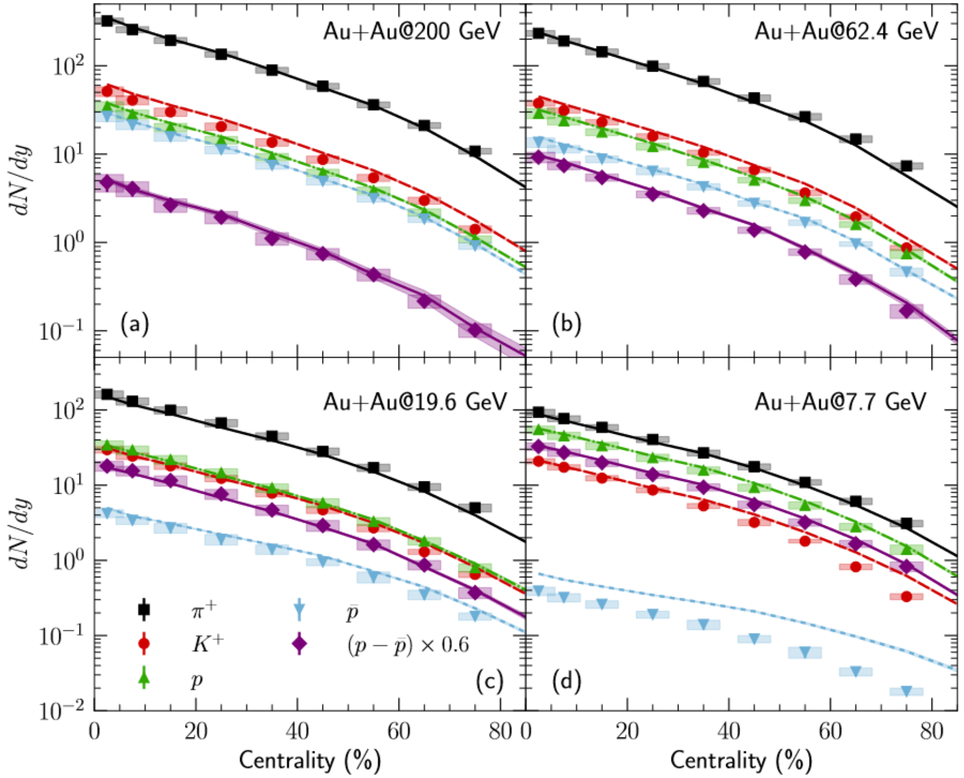
$$\partial_\mu J_B^\mu = \rho_B,$$

C. Shen and B. Schenke, Phys. Rev. C,105 (2022), 064905, Phys. Rev. C 97, 024907 (2018).

3DGlauber + MUSIC + UrQMD



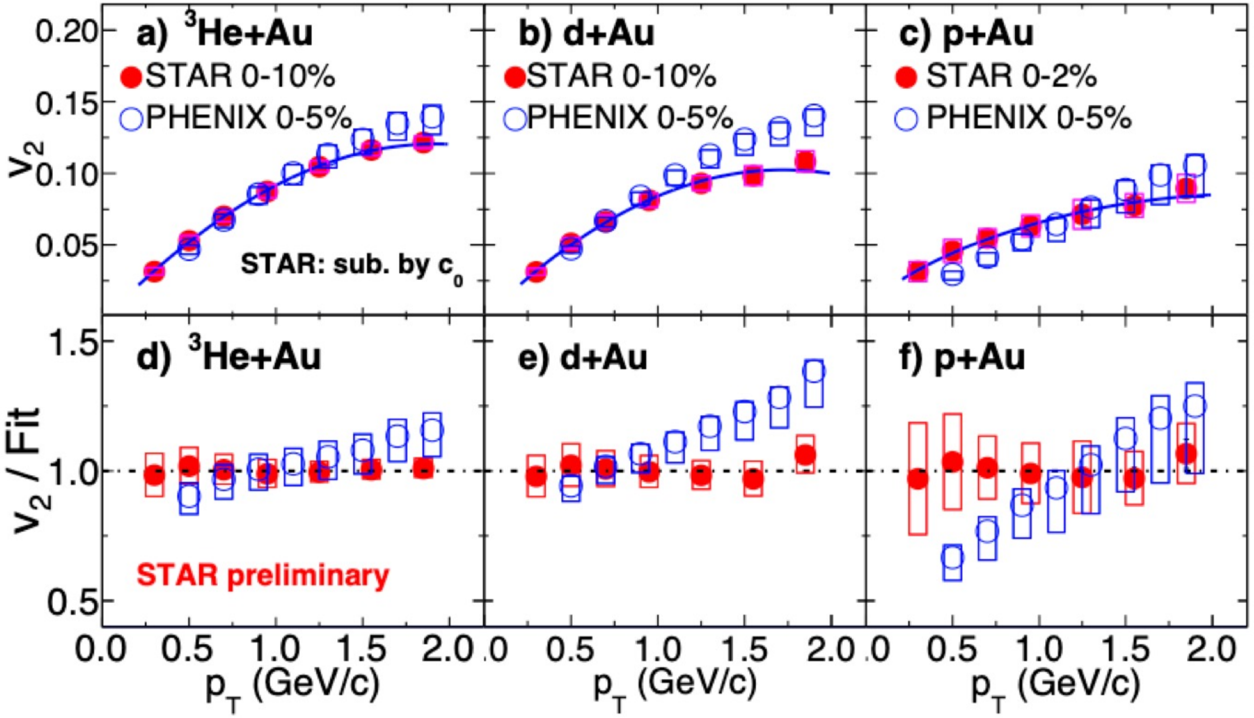


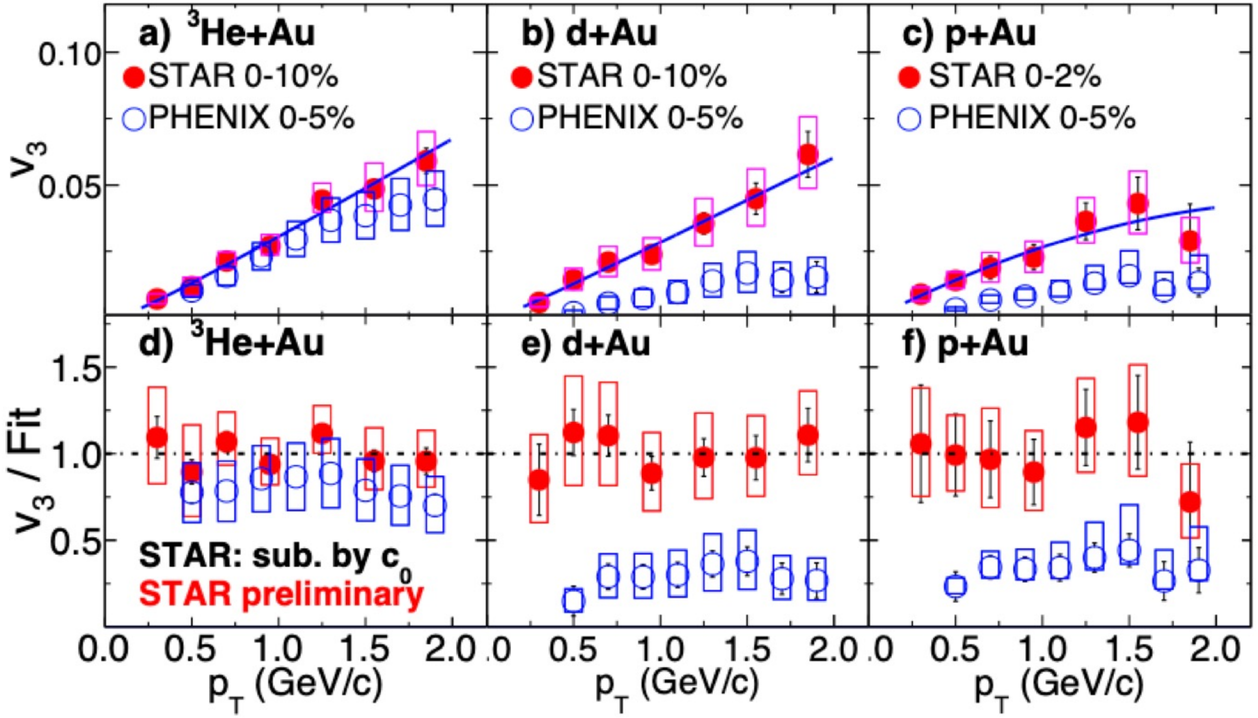


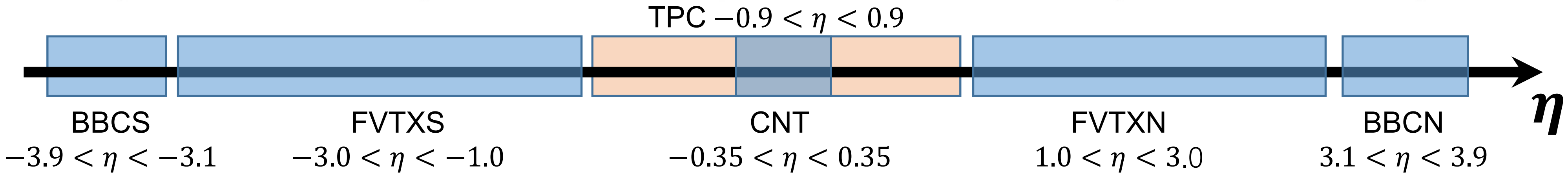
Shen and B. Schenke, Phys. Rev. C,105 (2022), 064905.
C. Shen and B. Schenke Phys. Rev. C 97, 024907 (2018).

- 3D-Glauber + MUSIC + UrQMD works well in describing various identified particle productions, anisotropic flow from low energies to high energies in heavy-ion collisions.

Small System Scan at RHIC (STAR and PHENIX)







TPC $-0.9 < \eta < 0.9$

BBCS $-3.9 < \eta < -3.1$

FVTXS $-3.0 < \eta < -1.0$

CNT $-0.35 < \eta < 0.35$

FVTXN $1.0 < \eta < 3.0$

BBCN $3.1 < \eta < 3.9$

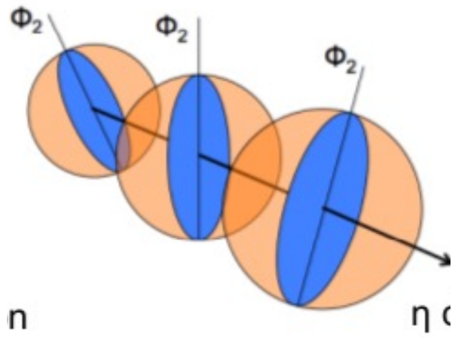
η

PHENIX: two-particle correlations between BBCS-CNT or FVTXS-CNT. STAR: TPC, ($|\eta| < 0.9$ and $|\Delta\eta| > 1.0$)

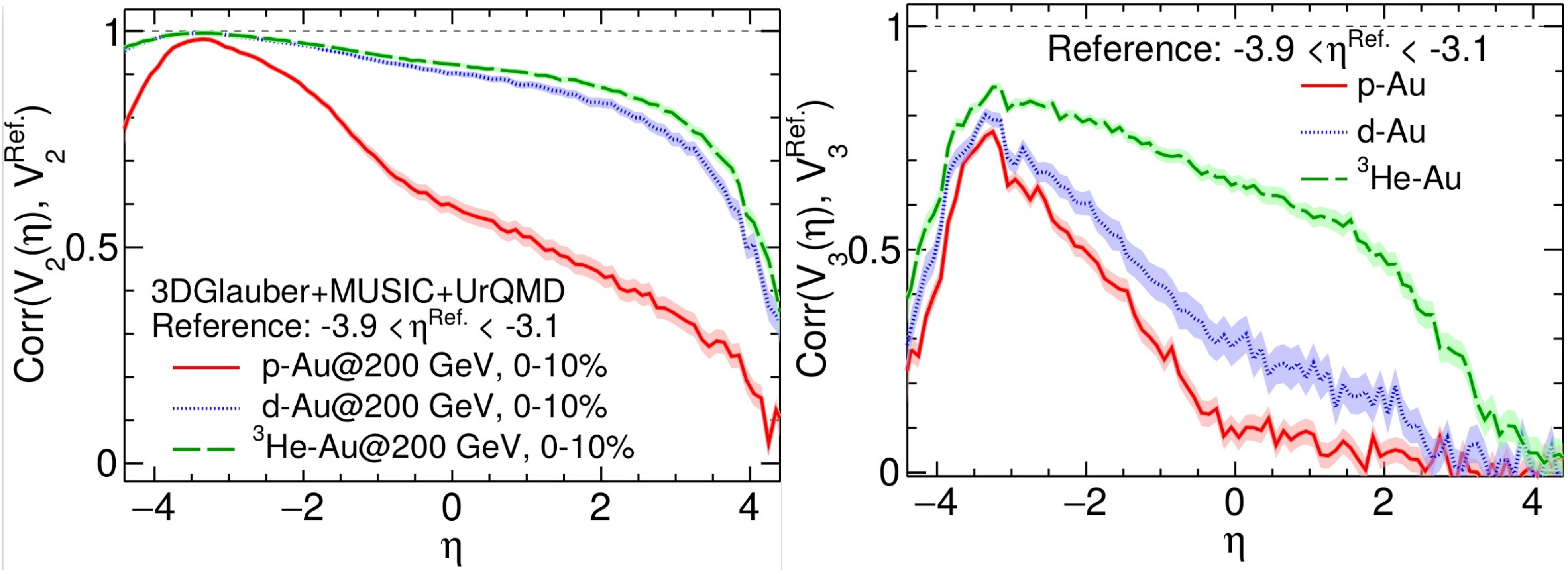
- (3+1)D simulations are essential to understand the difference between PHENIX and STAR measurements

Nature Physics **15**, pages214–220 (2019); Roy, A. Lacey (For the STAR) QM 2019., STAR, [arXiv:2210.11352 [nucl-ex]].

Longitudinal decorrelations



S. Mohapatra QM 2017

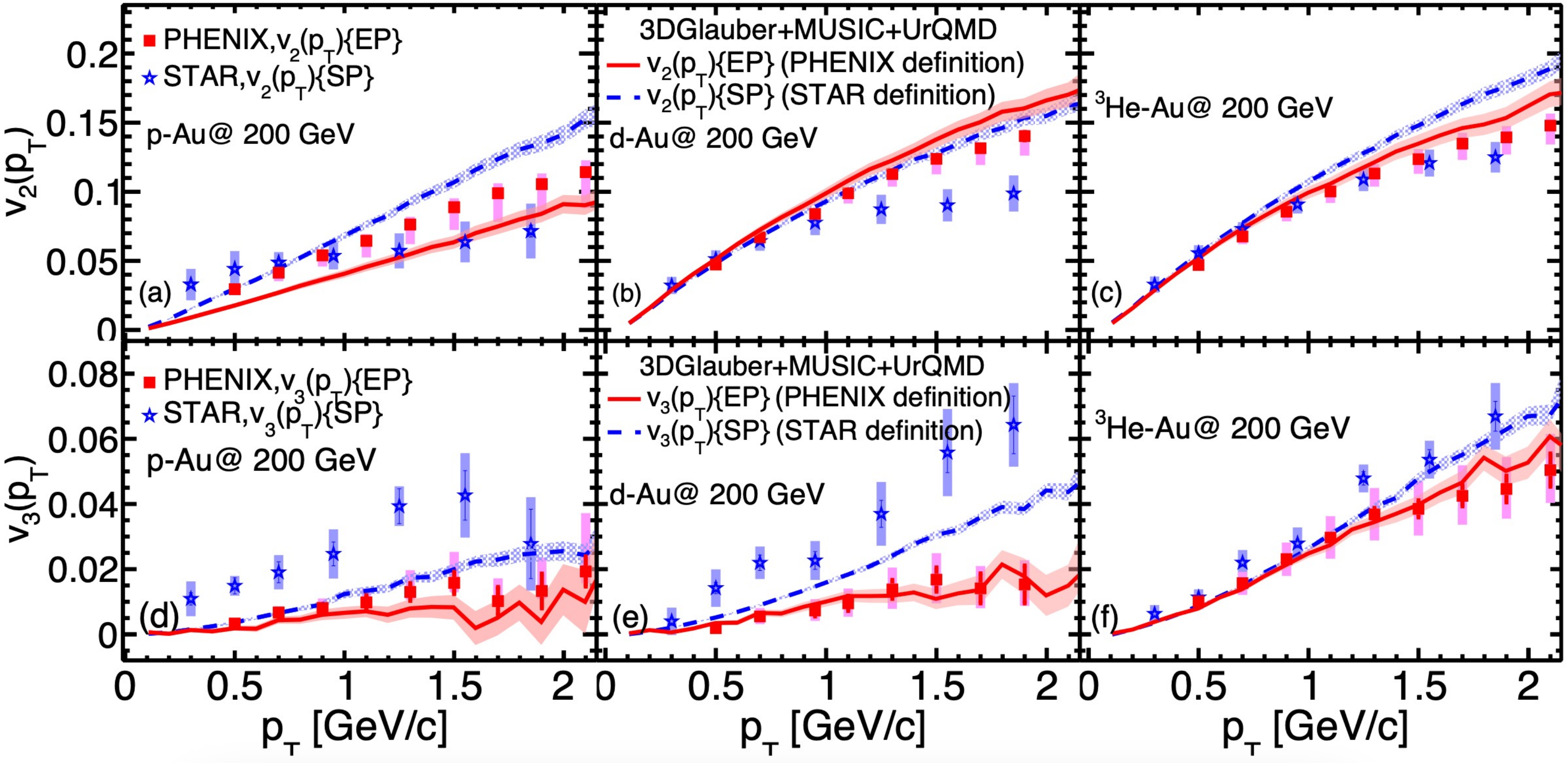


$$\mathrm{Corr}\left(V_n(\eta),\ V_n^{\mathrm{Ref.}}\right) = \frac{\langle V_n^*(\eta) V_n^{\mathrm{Ref.}}\rangle}{\sqrt{\langle |V_n(\eta)|^2\rangle}\sqrt{\langle |V_n^{\mathrm{Ref.}}|^2\rangle}},$$

- The elliptic flow correlations in (d, ^{3}He)+Au remain strong with increasing η difference, which ensures strong geometric response in the PHENIX measurements.
- Flow correlations of v_3 of all systems are significantly below 1, indicating the choice of reference flow angle is crucial for the two-particle flow measurements

W. Zhao, S. Ryu, C. Shen and B. Schenke Phys. Rev. C 107, 014904 (2023).

STAR and PHENIX



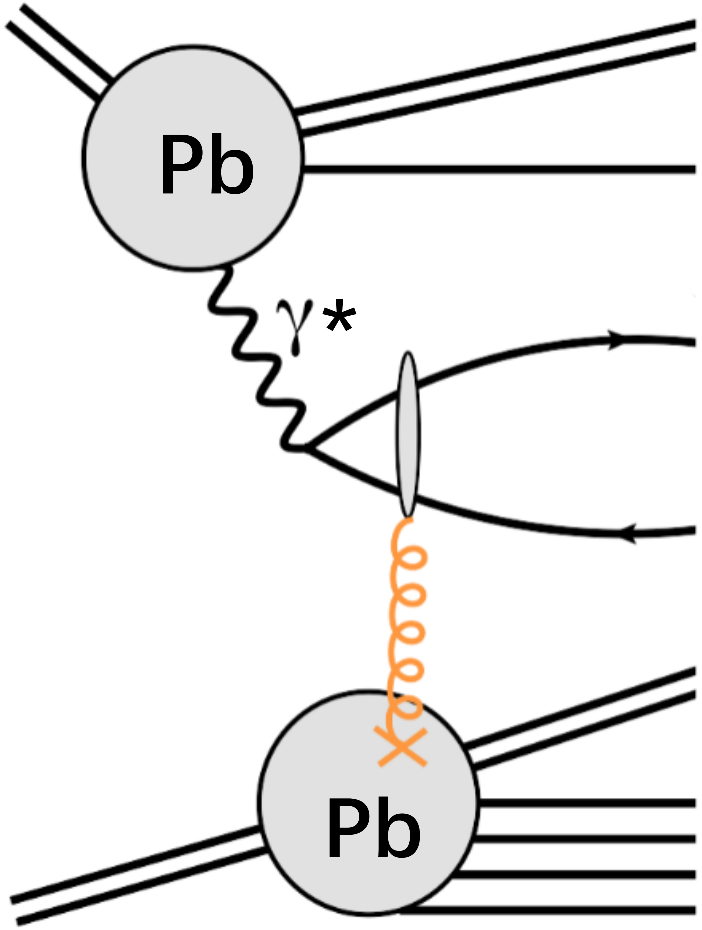
PHENIX η range:
$[-3.9, -3.1]$ $v.s.$ $[-0.35, 0.35]$
$[-3.0, -1.0]$ $v.s.$ $[-0.35, 0.35]$;

STAR η range:
$[-0.9, 0.9]$ and $|\Delta\eta| > 1.0$

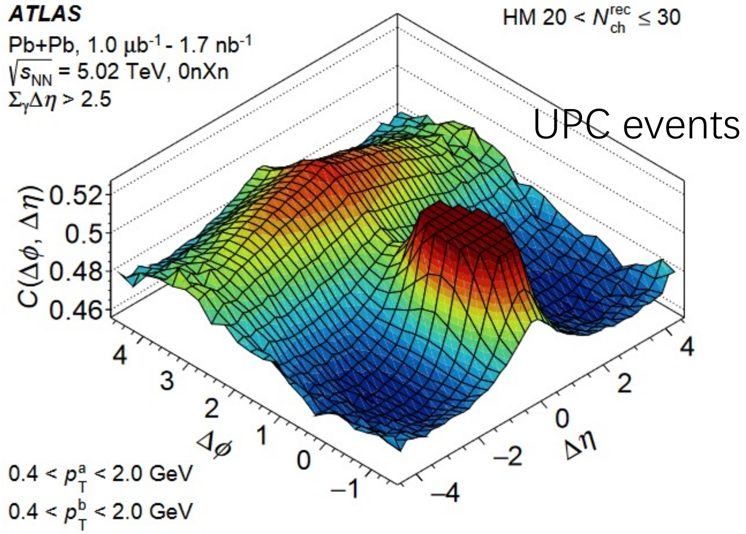
W. Zhao, S. Ryu, C. Shen and B. Schenke Phys. Rev. C 107, 014904 (2023).

- 3D hybrid model reproduces the PHENIX $\boldsymbol{v_2(p_T)}$ and $\boldsymbol{v_3(p_T)}$ for all three systems.
- The 3D hybrid model gives larger $\boldsymbol{v_3(p_T)}$ with the STAR definition than those from PHENIX, explaining 50% difference between PHENIX and STAR $\boldsymbol{v_3}$ measurements.

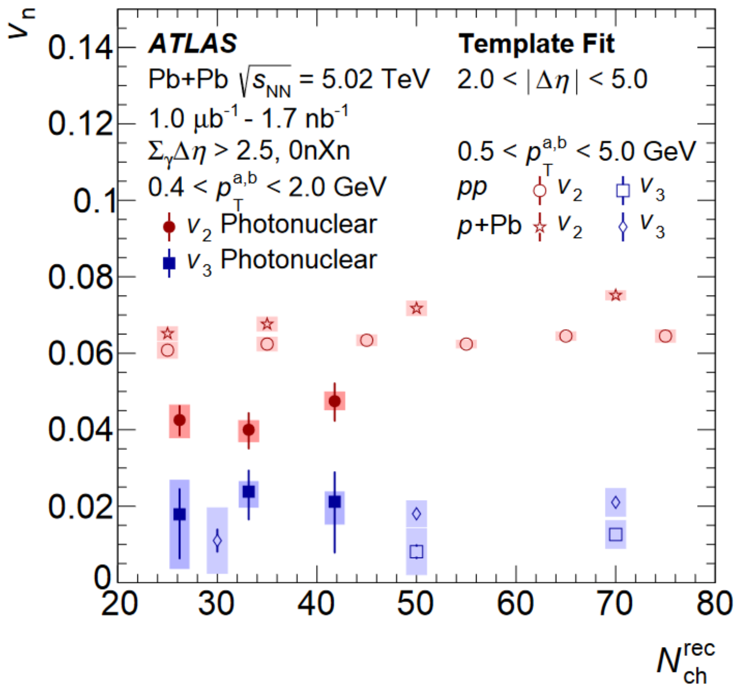
“Collectivity” in UPC

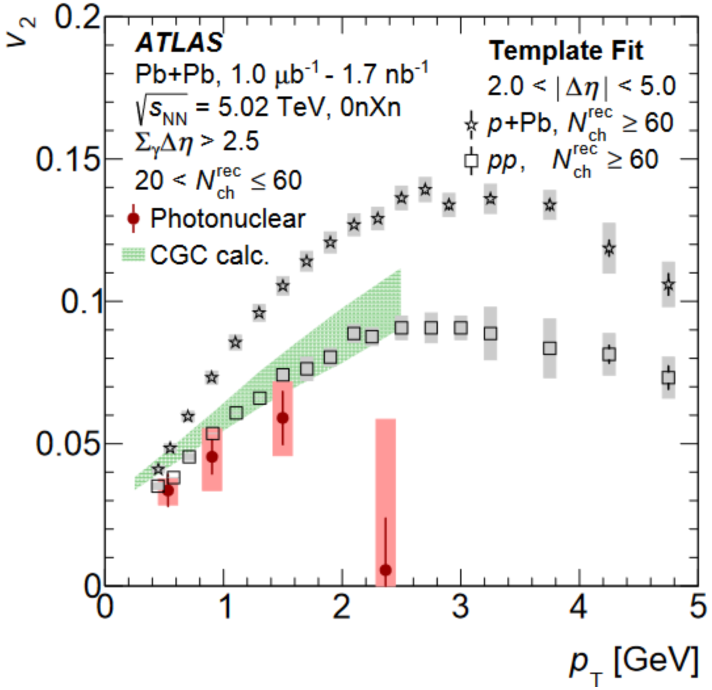


Taken from Nicole Lewis’s slide



UPC events

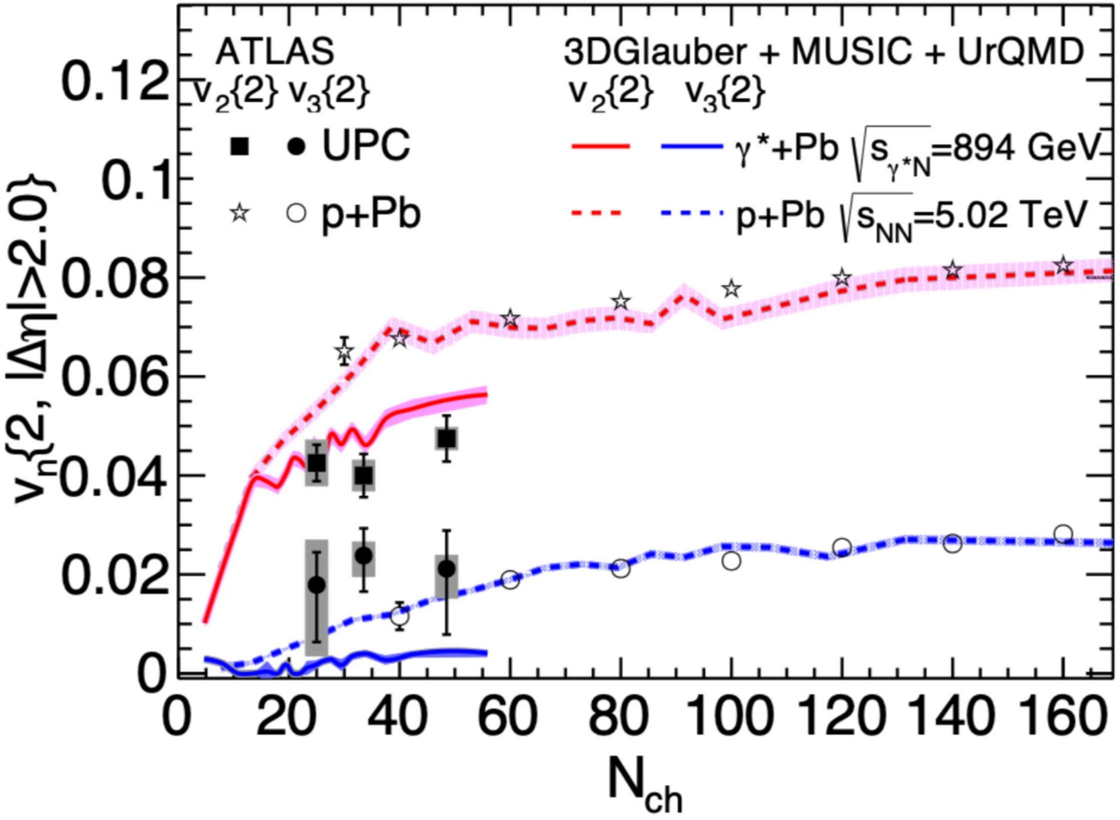


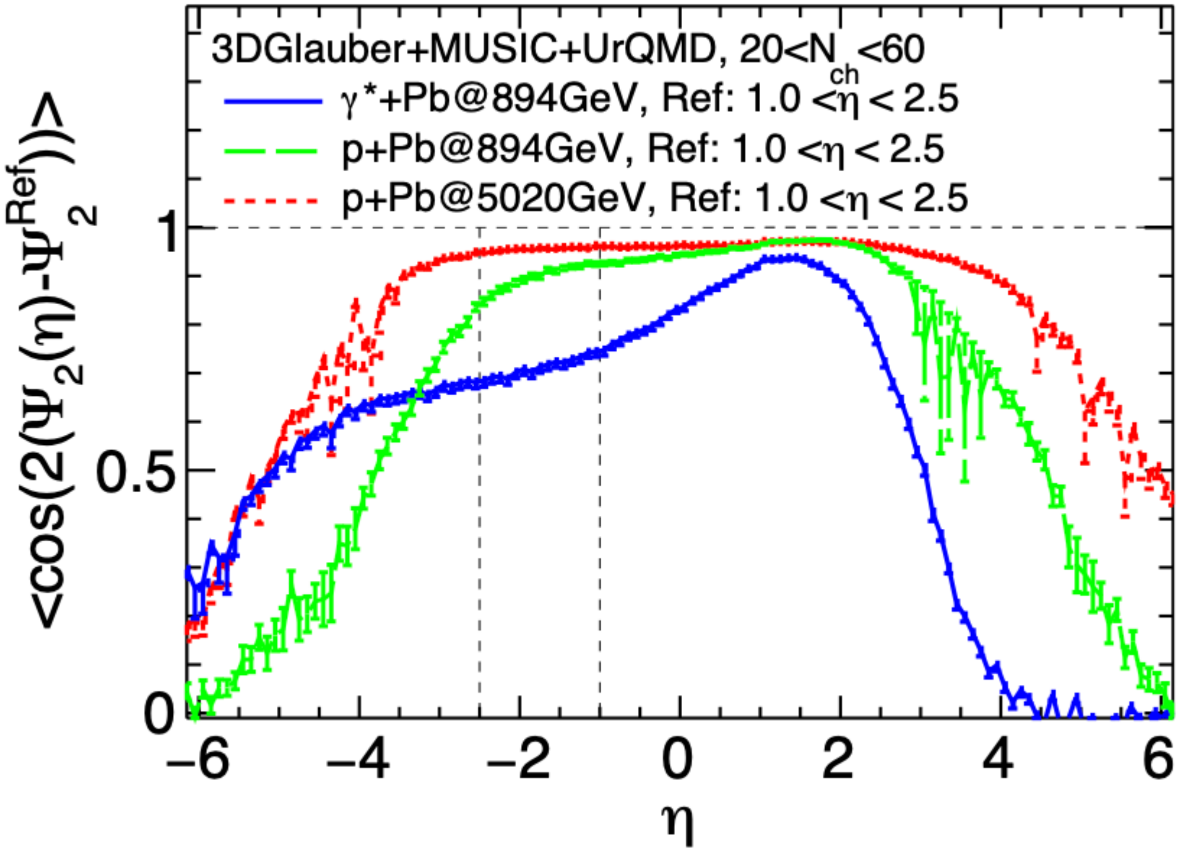


- UPCs have a similar order of magnitude and trends of collectivity as other previously measured hadronic systems

ATLAS Phys. Rev. C 104, 014903 (2021).
Y. Shi, etc.al,Phys. Rev. D 103, 054017 (2021).

Collectivity in γ^*+Pb and p+Pb





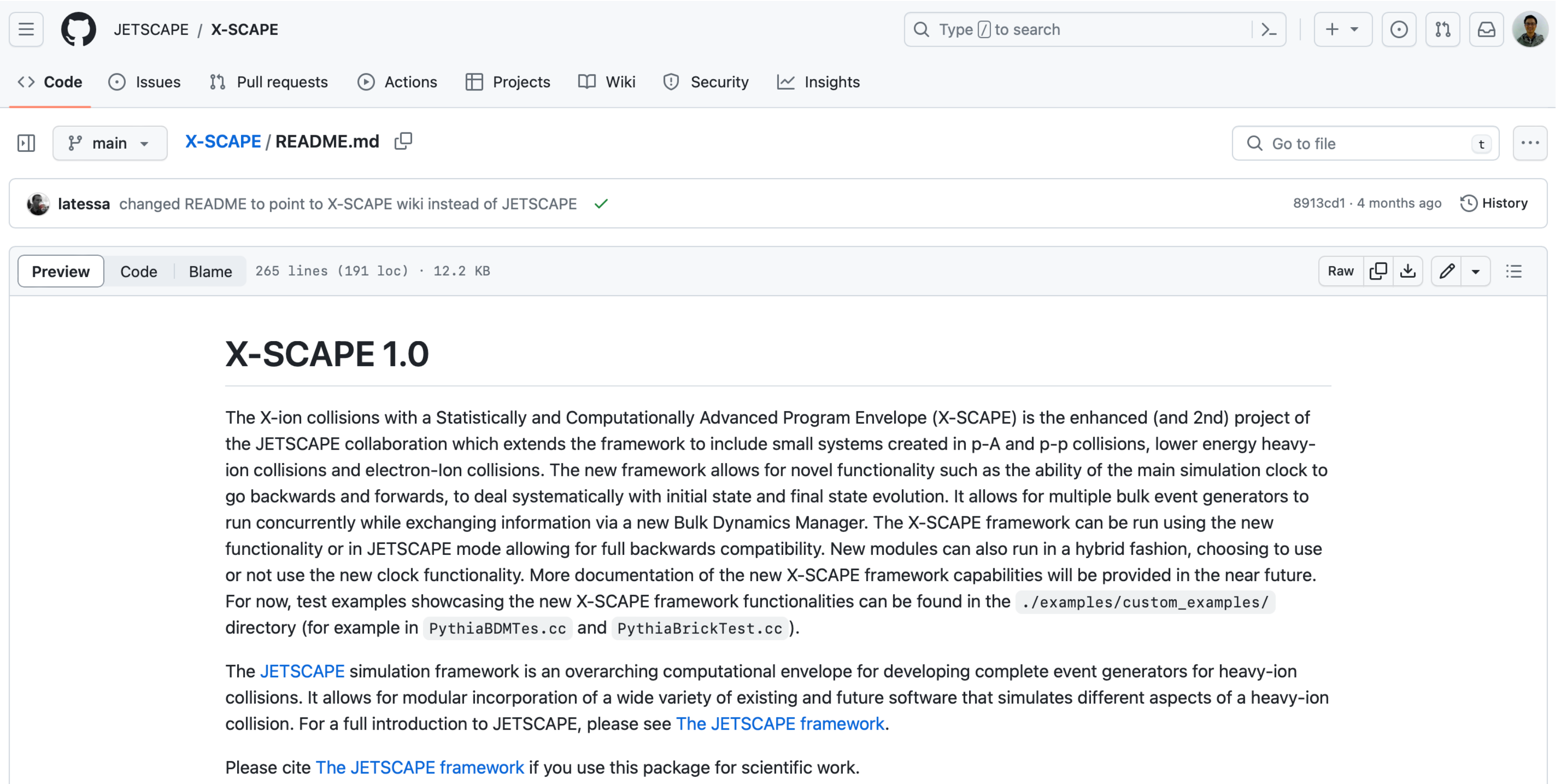
- The v_2 hierarchy between p+Pb and γ^*+Pb is reproduced by our model calculations.
- The longitudinal flow decorrelation is stronger in the $\boldsymbol{\gamma^*}$+Pb than p+Pb, resulting in the v_2 hierarchy between γ^*+Pb and p+Pb .
- v_3 is not well described in $\boldsymbol{\gamma^*}$+Pb yet.

W. Zhao, C. Shen and B. Schenke PhysRevLett.129.252302.
C. Shen and B. Schenke, Phys. Rev. C,105 (2022), 064905.

iEBE-MUSIC: https://github.com/chunshen1987/iEBE-MUSIC

X-ion collisions with a **S**tatistically and **C**omputationally **A**dvanced **P**rogram **E**nvelop

X-SCAPE: https://github.com/JETSCAPE/X-SCAPE



latessa changed README to point to X-SCAPE wiki instead of JETSCAPE ✓

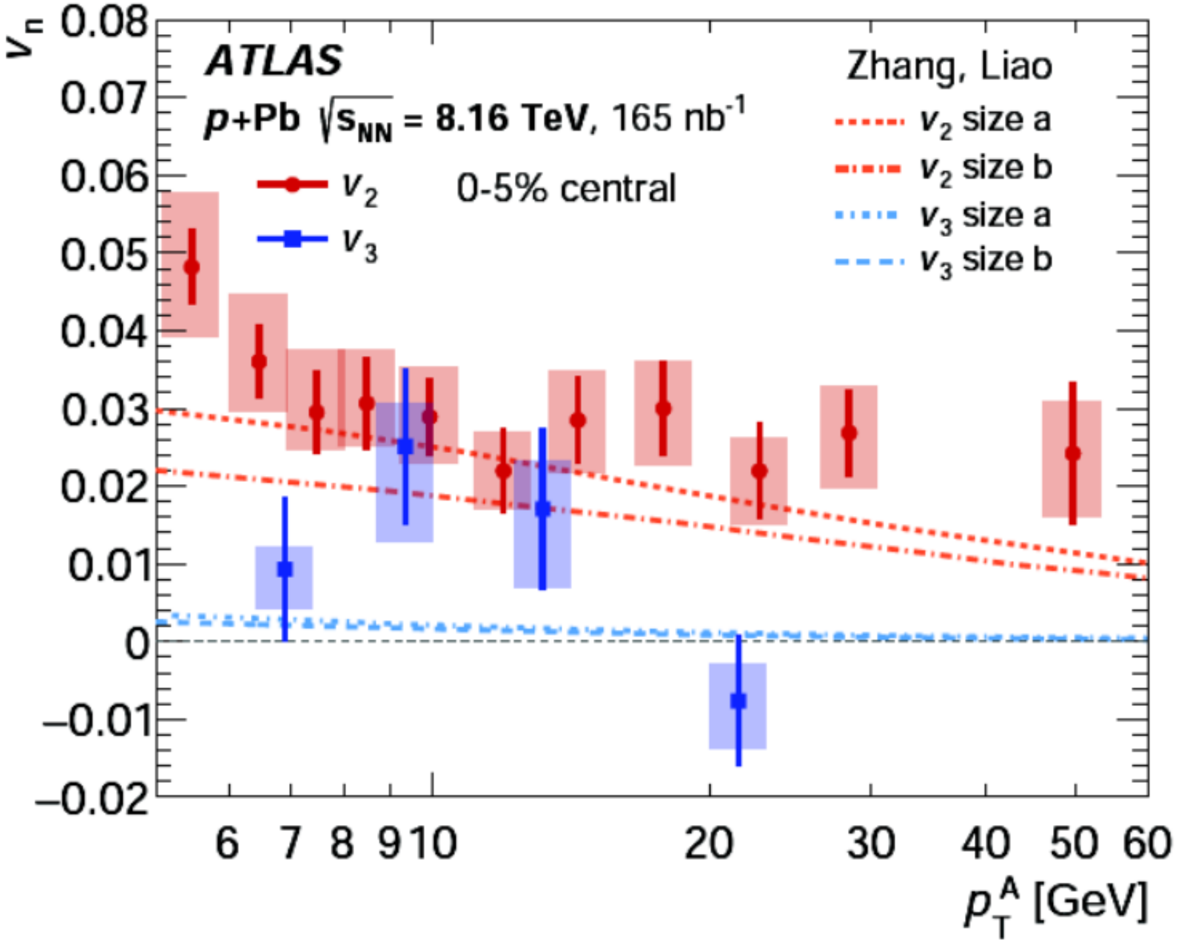
X-SCAPE 1.0

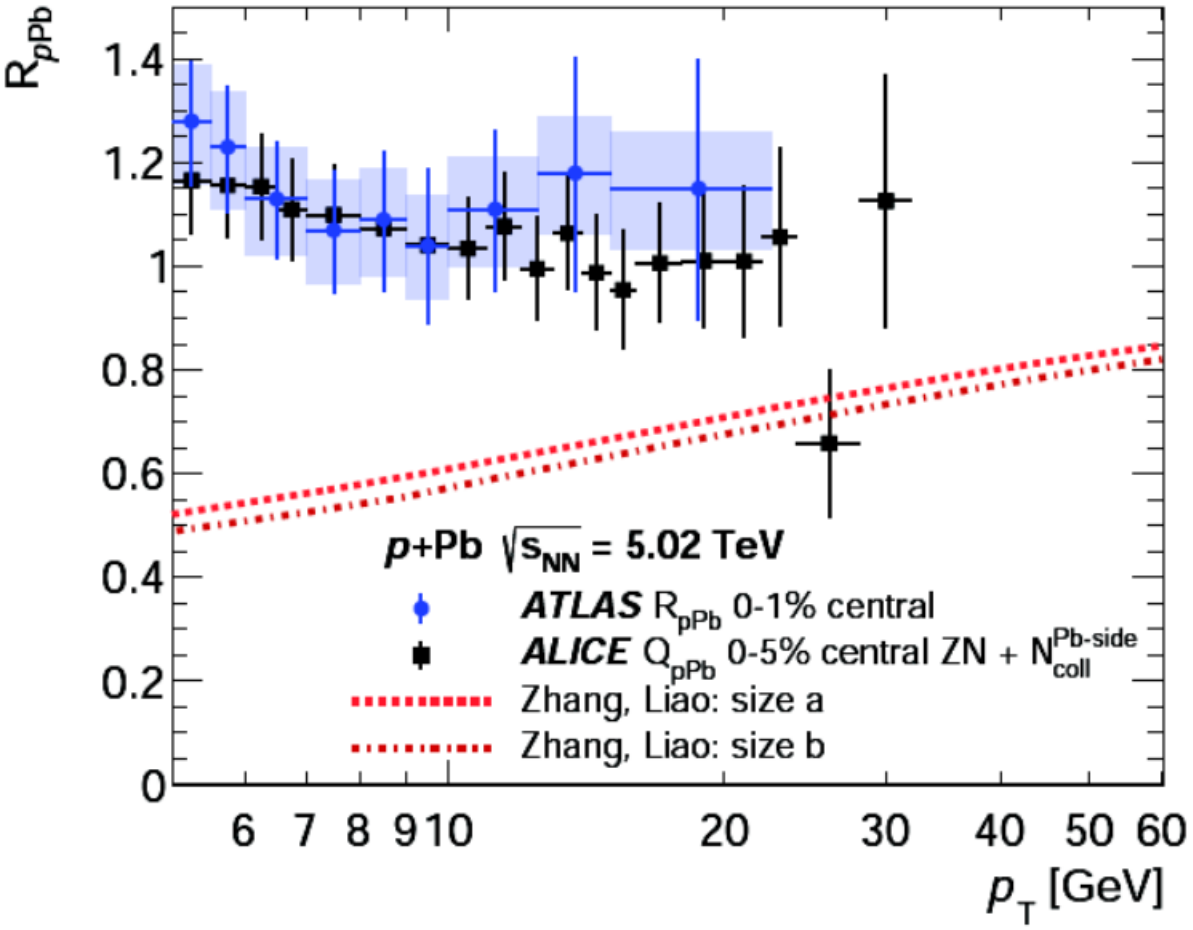
The X-ion collisions with a Statistically and Computationally Advanced Program Envelope (X-SCAPE) is the enhanced (and 2nd) project of the JETSCAPE collaboration which extends the framework to include small systems created in p-A and p-p collisions, lower energy heavy-ion collisions and electron-Ion collisions. The new framework allows for novel functionality such as the ability of the main simulation clock to go backwards and forwards, to deal systematically with initial state and final state evolution. It allows for multiple bulk event generators to run concurrently while exchanging information via a new Bulk Dynamics Manager. The X-SCAPE framework can be run using the new functionality or in JETSCAPE mode allowing for full backwards compatibility. New modules can also run in a hybrid fashion, choosing to use or not use the new clock functionality. More documentation of the new X-SCAPE framework capabilities will be provided in the near future. For now, test examples showcasing the new X-SCAPE framework functionalities can be found in the `./examples/custom_examples/` directory (for example in `PythiaBDMTes.cc` and `PythiaBrickTest.cc`).

The JETSCAPE simulation framework is an overarching computational envelope for developing complete event generators for heavy-ion collisions. It allows for modular incorporation of a wide variety of existing and future software that simulates different aspects of a heavy-ion collision. For a full introduction to JETSCAPE, please see The JETSCAPE framework.

Please cite The JETSCAPE framework if you use this package for scientific work.

One of the Goals of small system





- High p_T R_{pPb} v.s. v_2 (p_T) “puzzle” in p-Pb

ATLAS: arXiv:1910.13978.
Model: arXiv:1311.5463.

Workflow of the X-SCAPE for small system

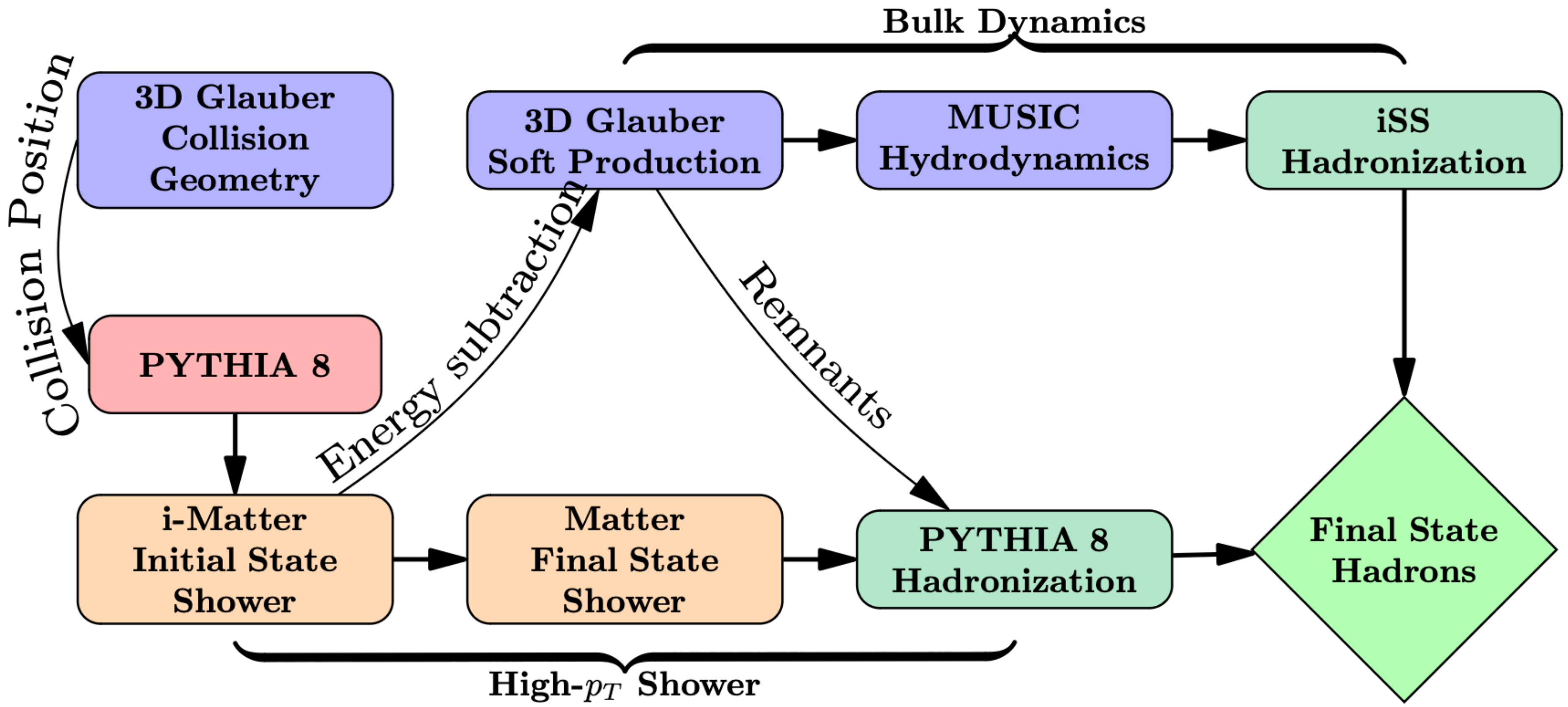


Figure 11: The workflow of the X-SCAPE event generator. The hard scattering is sampled using PYTHIA, and the scattering location is sampled according to the collision geometry provided by the 3D-Glauber initial state model. The i-Matter and Matter modules model the initial-state and final-state parton shower for the produced high-energy particles. After subtracting the energy and momentum of hard scatterings in the 3D Glauber, the 3D Glauber + MUSIC + iSS provides soft particle production. Finally, PYTHIA is used to hadronize the shower particles from Matter with the collision remnants provided by the 3D-Glauber model.

Questions ?

YES ✓ or 👍 means completed the preparation

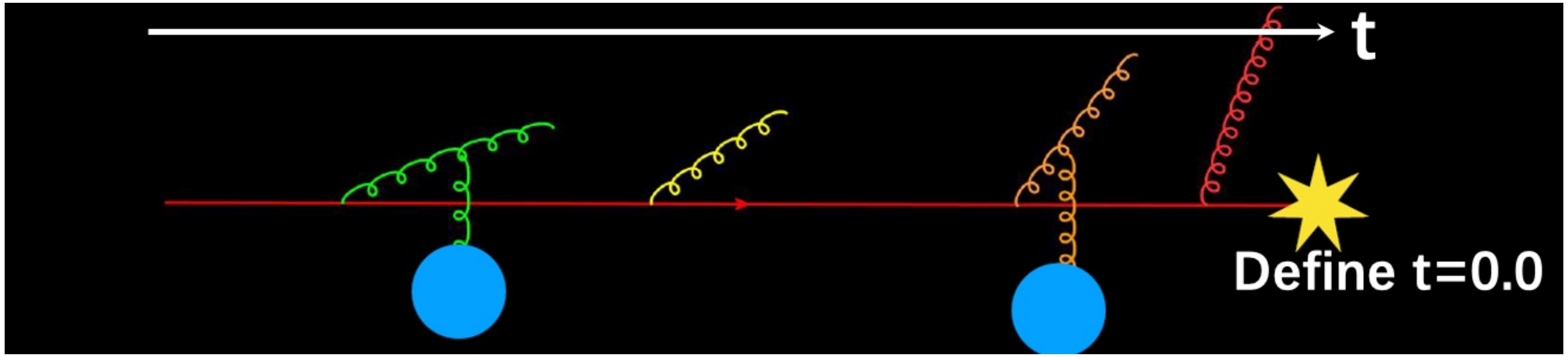
NO ✗ or 😮 means partially finished or Incomplete

X-SCAPE module iMATTER

Ismail Soudi, 21st. July

- Call Pythia (ISR-FSR-OFF) generate MPI scatterings.
- Start each parton at high and negative Q^2 and evolve back to $Q^2 = -1\ GeV^2$.
- A well-established method of generating ISR*
- i-MATTER : run parton shower backwards in time.
- Final parton at most negative time is the parent.
- Its hard energy removed from 3DGlauber, not available for hydro evolution.

It introduces the non-trivial soft-hard correlations.



Use power law for sampling hard scattering

```
<Hard>
  <PythiaGun>
    <pTHatMin>4</pTHatMin>
    <pTHatMax>-1</pTHatMax>
    <eCM>5020</eCM>
    <LinesToRead>
     PhaseSpace:bias2Selection = on
     PhaseSpace:bias2SelectionPow = 4
     PhaseSpace:bias2SelectionRef = 10
    </LinesToRead>
  </PythiaGun>
</Hard>
```

$$\frac{d\sigma}{dp_T^{jet}} = \frac{\sigma_{ptHat}}{w^{sum}} \sum_{i=1}^{Nevents} w_i \frac{dN_i^{jet}}{dp_T^{jet}}; \qquad w^{sum} = \sum_{i=1}^{N_{events}} w_i$$

Pythia output variables for each event:

w_i = `pythia.info.weight()`
w^{sum} = `pythia.info.weightSum()`
$\hat{p}_T$ = `pythia.info.pTHat()`

$$Weight = \left(\frac{p_T^{ref}}{p_T^{Hat}}\right)^{pow}$$

Pythia output variables with average over all events:

σ_{ptHat} = `pythia.info.sigmaGen()`
$\sigma_{ptHatError}$ = `pythia.info.sigmaErr()`