Coupled approach to solving the $R_{AA} \otimes v_2$ puzzle *and* the collectivity in ultra-peripheral Pb+Pb collisions

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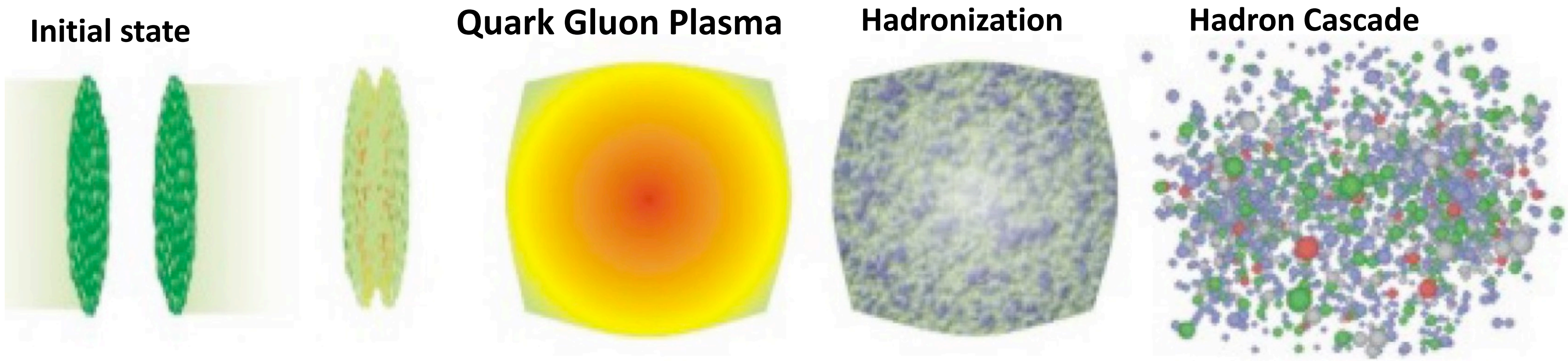
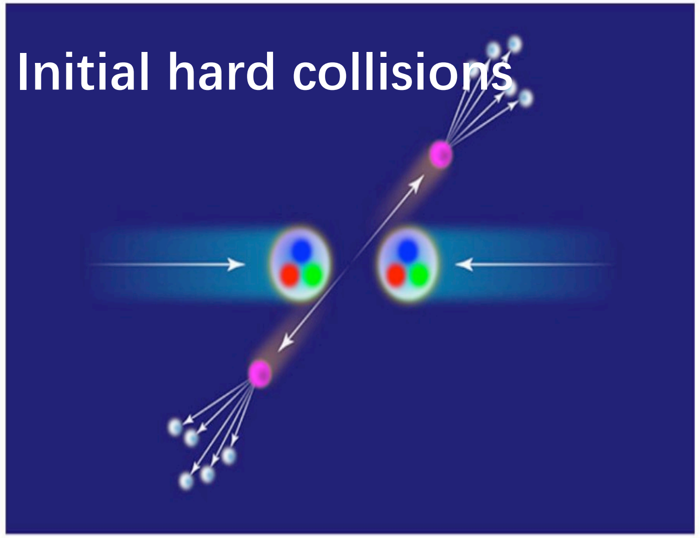
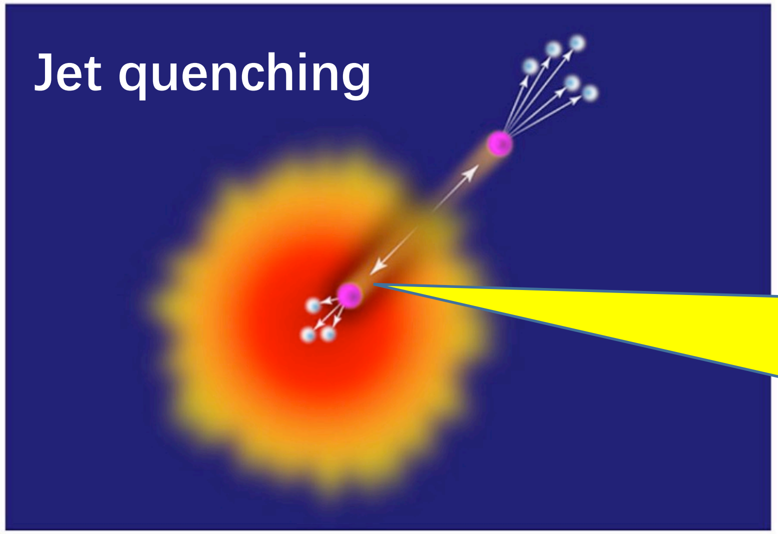
Wayne State University

HENPIC 161, 03.24.2022

Illustration of heavy-ion collisions



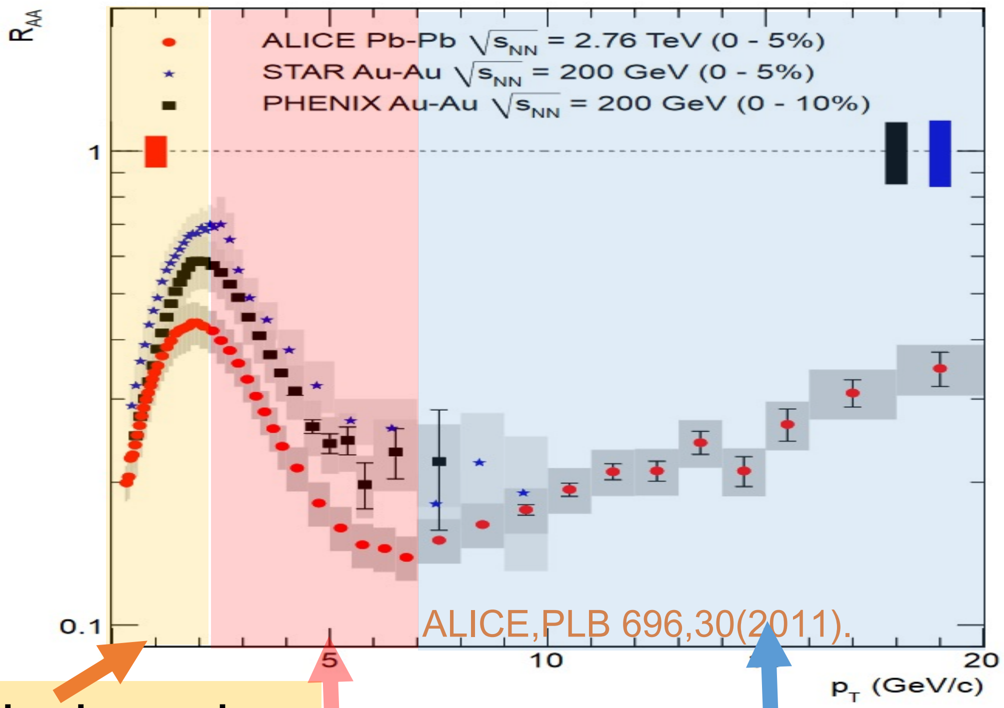




Jet quenching
Strong interaction with the energetic partons and the medium.

Different domains in heavy-ion collisions

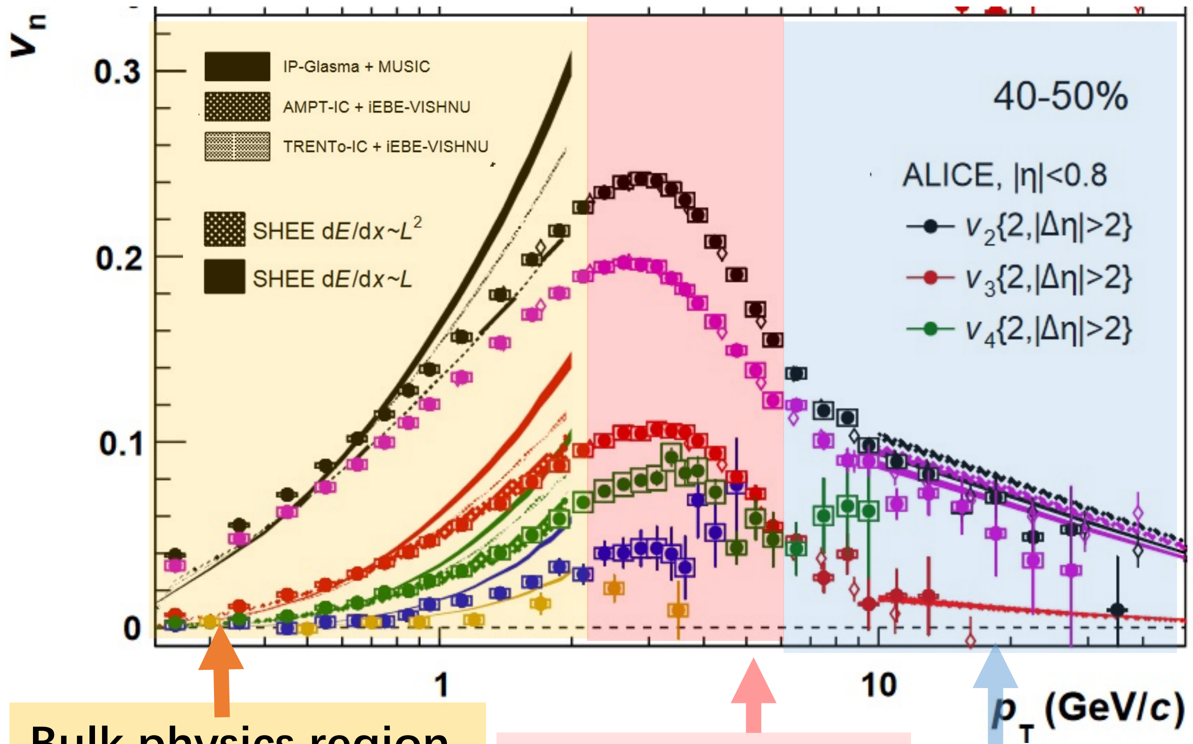
ALICE JHEP 1807,103 (2018)



Bulk physics region

Transition region

Jet physics region



Bulk physics region

Transition region

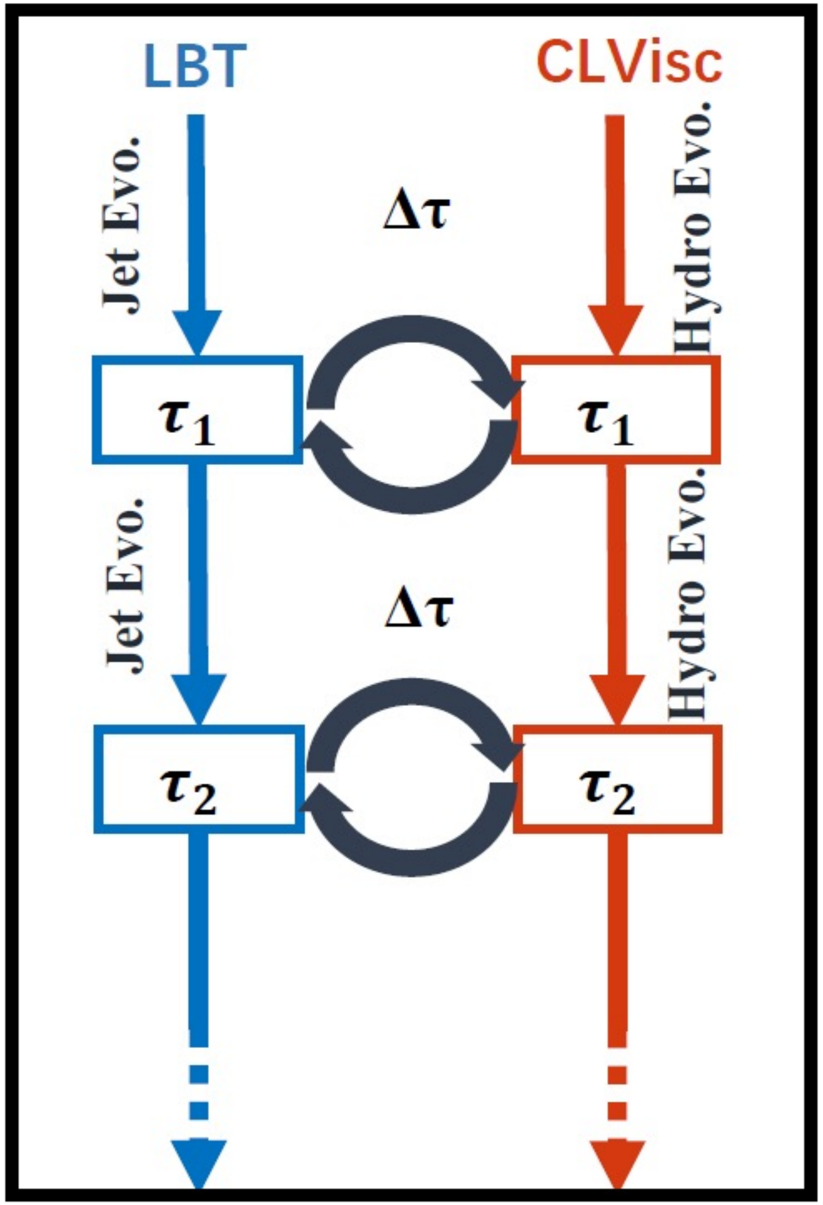
Jet physics region

$$R_{AA}(p_T, y, \phi) \equiv \frac{1}{\langle N_{coll}\rangle} \frac{\frac{dN_{AA}}{dp_T dy d\phi}}{\frac{dN_{pp}}{dp_T dy d\phi}},$$

$$v_2(p_T, y) \equiv \frac{\int d\phi \cos(2\phi) \frac{dN}{dp_T dy d\phi}}{\int d\phi \frac{dN}{dp_T dy d\phi}}$$

- Different domains are clearly observed in data in heavy-ion collisions.
- Low p_T (p_T<2-3 GeV): bulk physics; High p_T (p_T>10 GeV): jet physics.
- Intermediate p_T (3<p_T<8-10 GeV): transition regime; (Not well studied.)

CoLBT-hydro model



CoLBT-Hydro model

Linear Boltzmann Transport model (LBT) + 3+1D hydrodynamic model (CLVis)

Evolve the energetic partons and the bulk medium concurrently.

Hydrodynamics equations with the source terms:

$$\partial_\mu T^{\mu\nu}_{\text{fluid}} = J^\nu$$

$T^{\mu\nu}_{\text{fluid}}$: Energy-momentum tensor of the QGP fluid;

J^ν : Energy-momentum density deposited by energetic partons. with the Gaussian smearing:

$$J^\nu(\vec{x}_\perp, \eta_s) = \sum_i \frac{\theta(p^0_{\text{cut}} - p_i \cdot u)p^\nu}{\tau(2\pi)^{3/2}\sigma_r^2\sigma_{\eta_s}\Delta\tau} e^{-\frac{(\vec{x}_\perp - \vec{x}_{\perp i})^2}{2\sigma_r^2} - \frac{(\eta_s - \eta_{si})^2}{2\sigma_{\eta_s}^2}}$$

p^0_{cut} separates the soft and hard partons

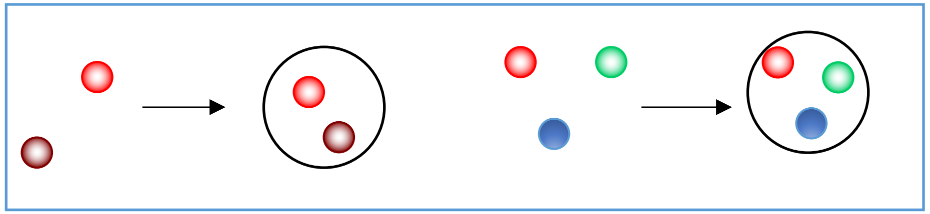
W. Chen, S. Cao, T. Luo, L.-G. Pang, and X.-N. Wang,Phys. Lett. B810, 135783 (2020), 2005.09678.

Sophisticated Coalescence model

$$\frac{dN_M}{d^3\mathbf{P}_M} = g_M \int d^3\mathbf{x}_1 d^3\mathbf{p}_1 d^3\mathbf{x}_2 d^3\mathbf{p}_2 f_q(\mathbf{x}_1,\mathbf{p}_1) f_{\bar{q}}(\mathbf{x}_2,\mathbf{p}_2) \times W_M(\mathbf{y},\mathbf{k})\delta^{(3)}(\mathbf{P}_M - \mathbf{p}_1 - \mathbf{p}_2),$$

$$\frac{dN_B}{d^3\mathbf{P}_B} = g_B \int d^3\mathbf{x}_1 d^3\mathbf{p}_1 d^3\mathbf{x}_2 d^3\mathbf{p}_2 d^3\mathbf{x}_3 d^3\mathbf{p}_3 f_{q_1}(\mathbf{x}_1,\mathbf{p}_1) \times f_{q_2}(\mathbf{x}_2,\mathbf{p}_2) f_{q_3}(\mathbf{x}_3,\mathbf{p}_3) W_B(\mathbf{y}_1,\mathbf{k}_1;\mathbf{y}_2,\mathbf{k}_2) \times \delta^{(3)}(\mathbf{P}_B - \mathbf{p}_1 - \mathbf{p}_2 - \mathbf{p}_3),$$

$g_{B(M)}$ is statistic factor, $f_{q/\bar{q}}$ is the phase-space distribution of (anti)quarks, $W_{M/B}$ is Wigner function of meson(baryon).
Here, we use the harmonic oscillator for wave functions of hadrons, then do the Wigner transformation to get the $W_{M/B}$.



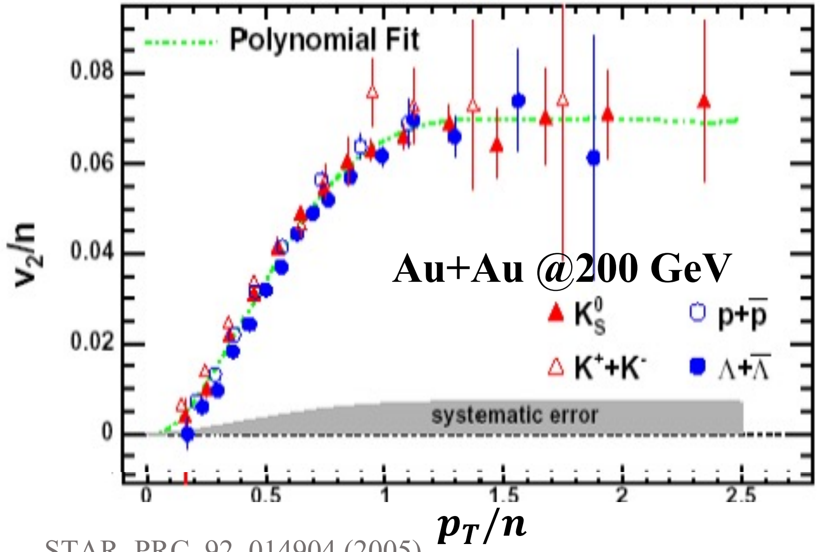
Thermal & hard Partons:

- *Thermal partons* generated by hydro
- *Hard partons* generated by PYTHIA8, then suffered with energy loss by CoLBT

Coalesence processes:

- thermal - thermal parton coalescence
- thermal - hard parton coalescence
- hard - hard parton coalescence

NCQ scaling



STAR, PRC, 92, 014904 (2005).

Han, Fries and Ko, PRC 93, 045207 (2016).
Zhao, Ko, Liu, Qin and Song, Phys.Rev.Lett. 125, 072301 (2020).
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String fragmentation

- **Colorless string fragmentation**

- Shower partons that do not coalesce will hadronize through string fragmentation using PYTHIA8.
- Shower partons have lost their original color configurations. We connect strings to minimizes the distance

$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

JETSCAPE framework: Phys. Rev. C 102, 054906 (2020).
W. Zhao, W. Ke, W. Chen, T. Luo and X. N.Wang, PRL. 128, 022302 (2022).

Framework of calculations

Hydro-Coal-Frag hadronization

Thermal hadrons, low p_T (CLVis):

- generated by hydro. with Cooper-Frye.
  Meson: $p_T < 2p_{T1}$; baryon: $p_T < 3p_{T1}$.

-initial shower partons from pythia8 with $p_T > p_{T2}$

Coalescence hadrons (Coal Model):

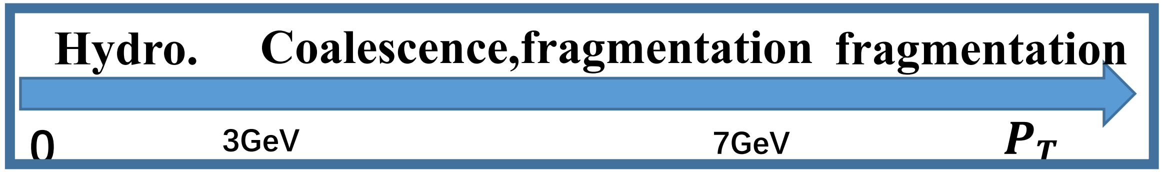
-generated by coalescence model including thermal-thermal, thermal-hard & hard-hard coalesence.

Fragmentation hadrons :

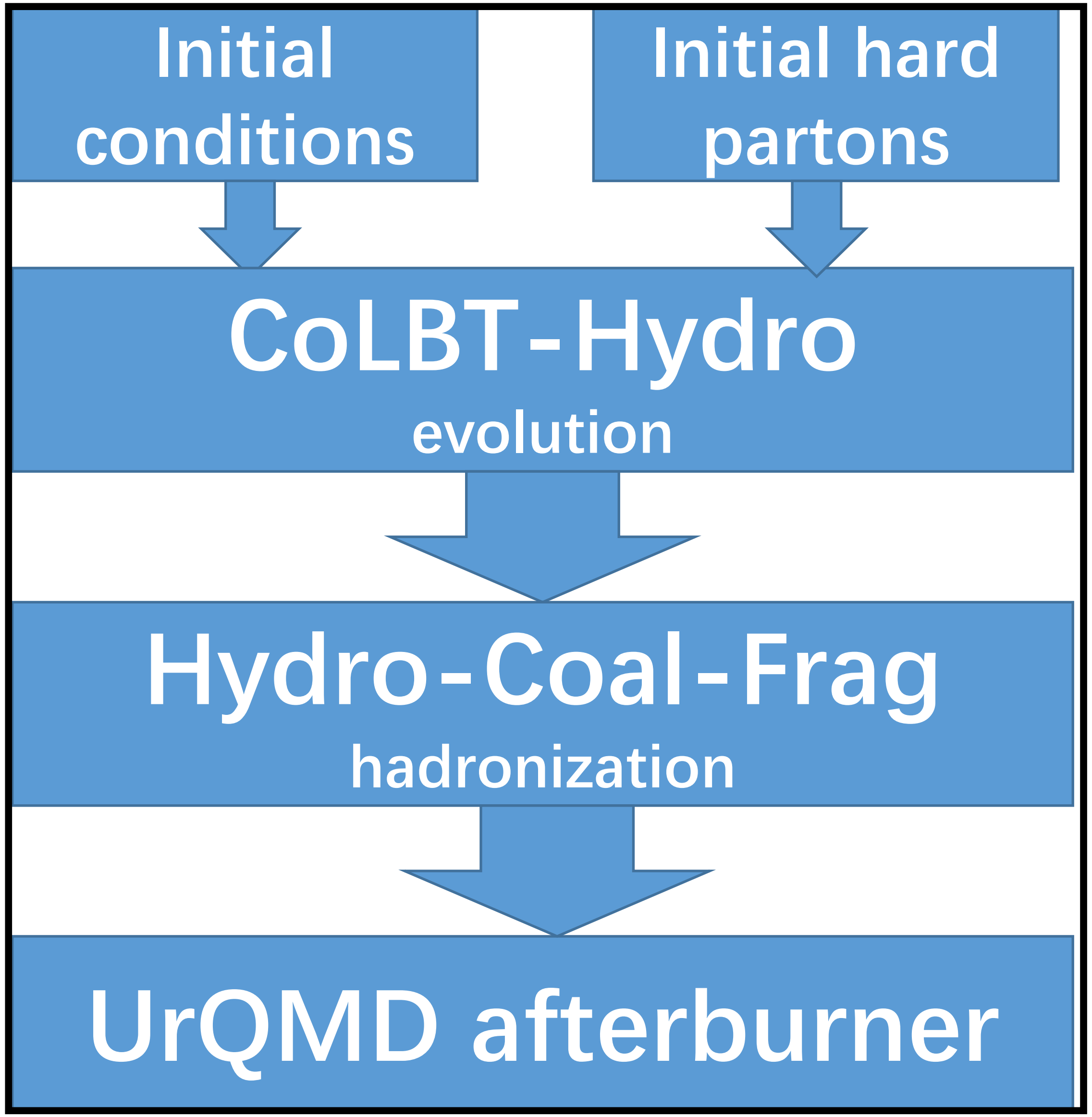
-the remnant hard quarks feed to fragmentation.

UrQMD afterburner:

-All hadrons are feed into UrQMD for hadronic evolution, scatterings and decays

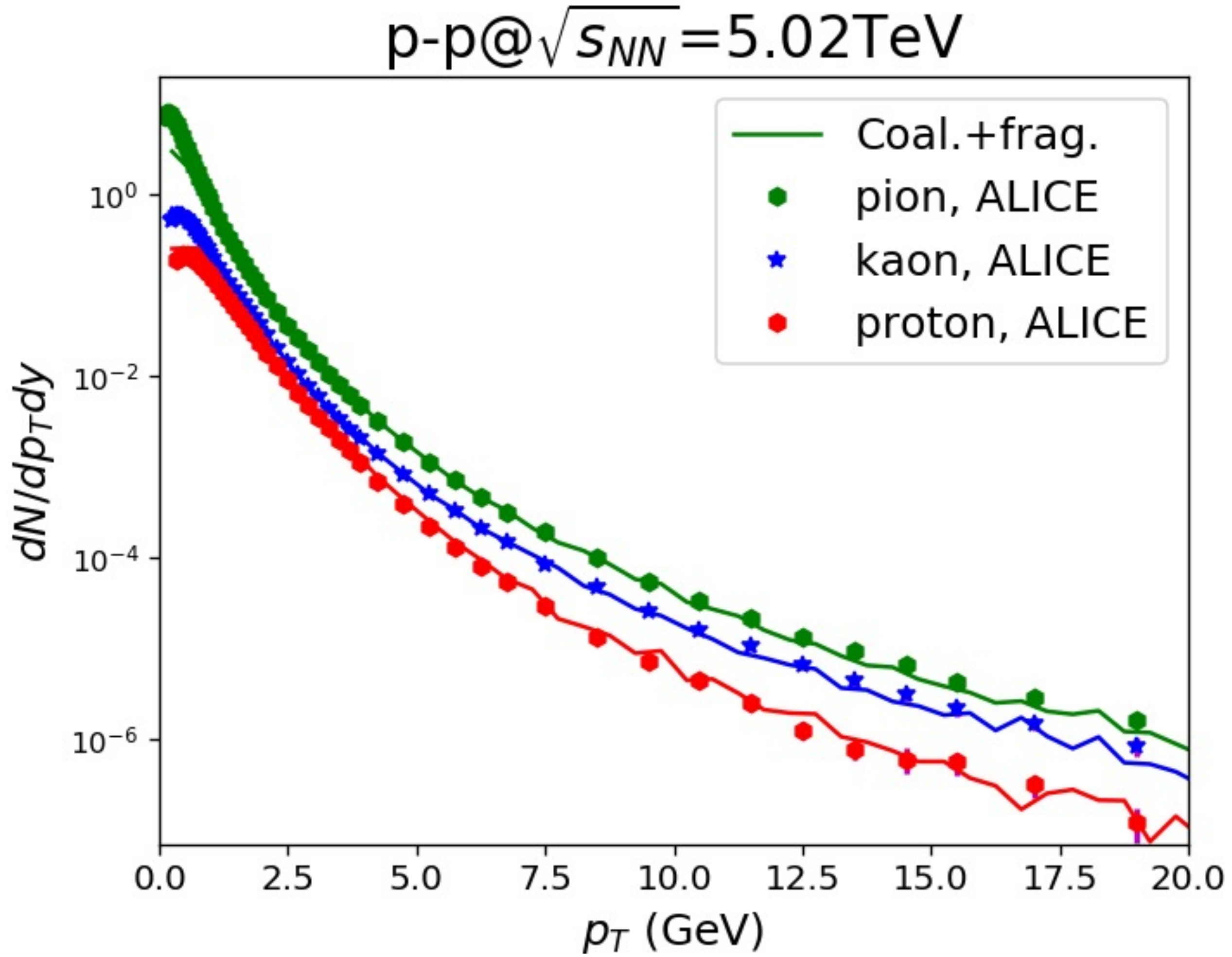


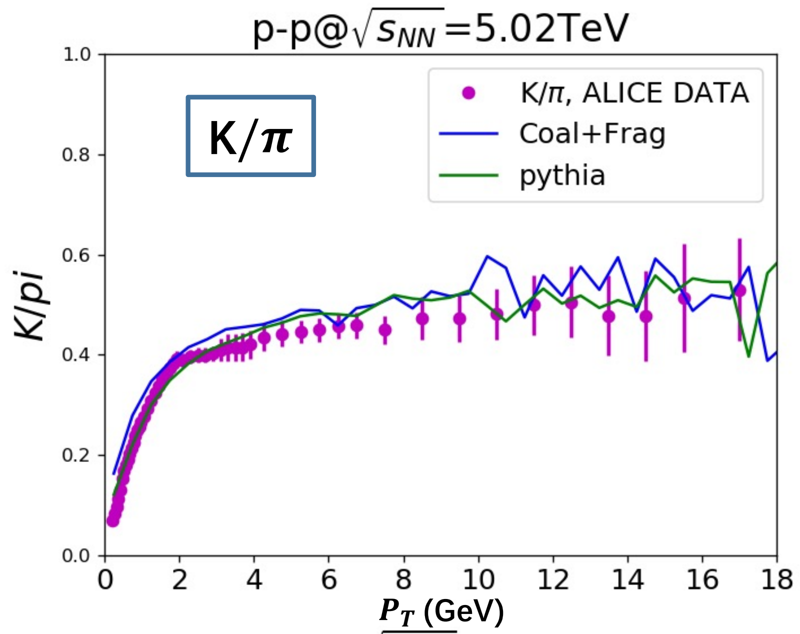
Framework

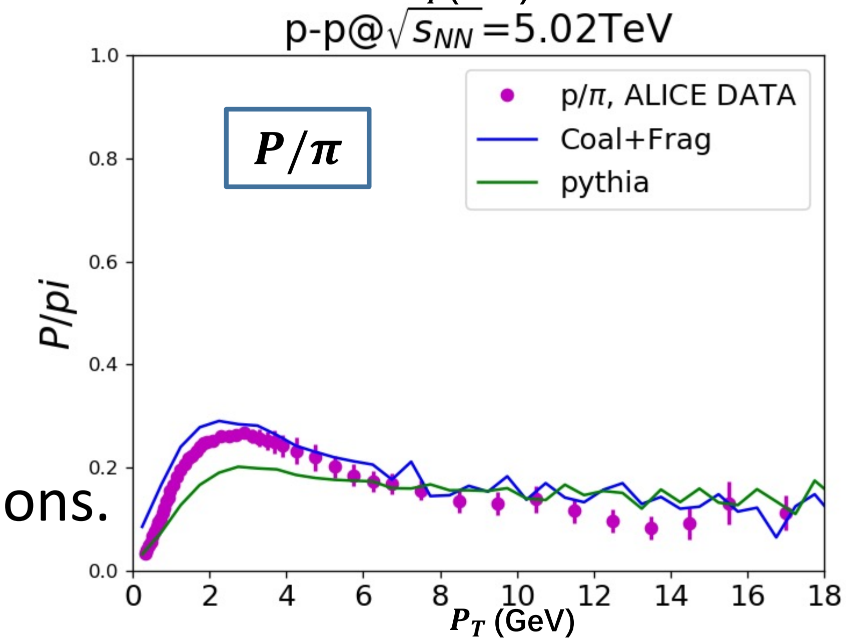


W. Zhao, Ko, Liu, Qin and Song, PRL. 125, 072301 (2020). W. Zhao, W. Ke, W. Chen, T. Luo and X. N.Wang, PRL. 128, 022302 (2022).

Verification of the hadronization code in p-p



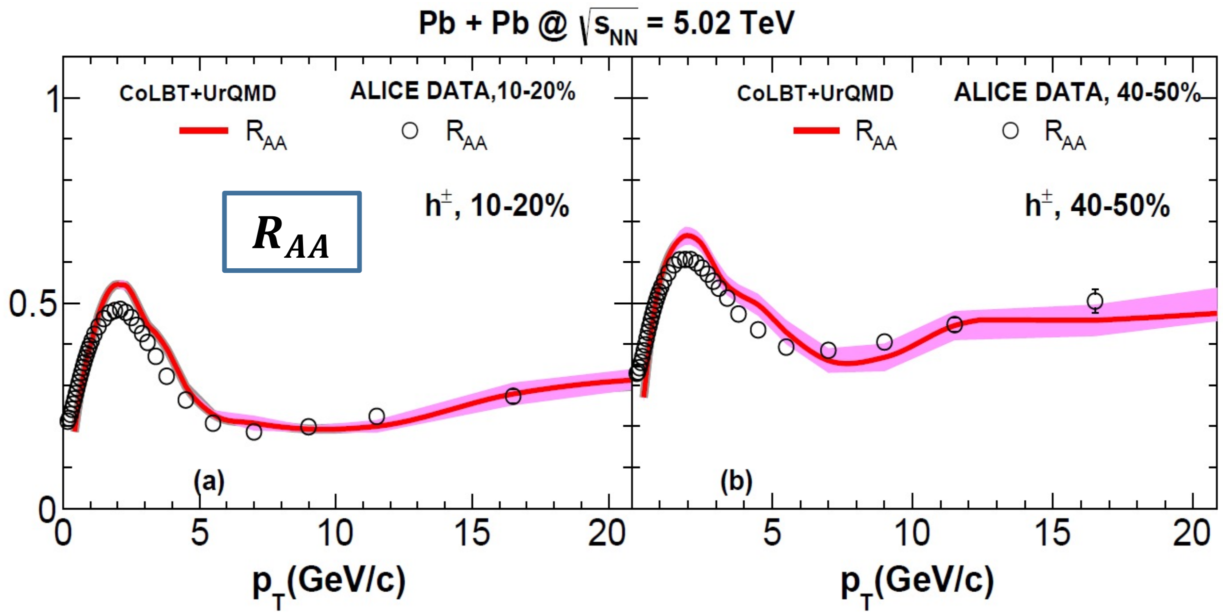


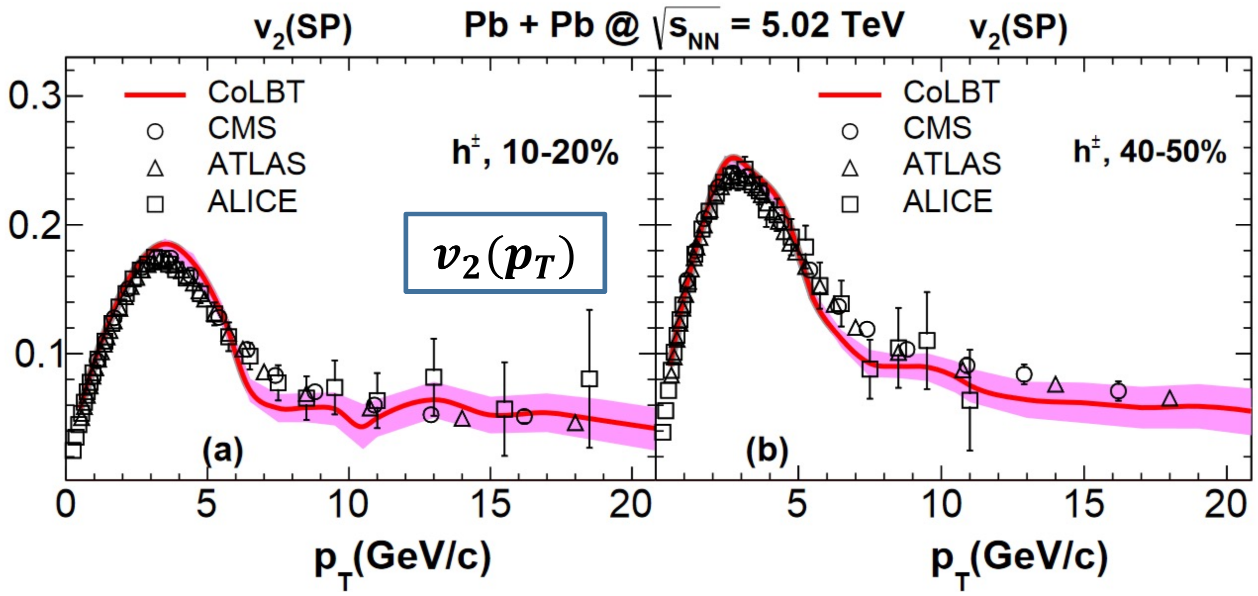


- Coal-Frag model can well reproduce the p_T-spectra of π, K and P as well as the K/π and P/π in p-p collisions.

W. Zhao, W. Ke, W. Chen, T. Luo and X. N.Wang, PRL. 128, 022302 (2022).

R_{AA} v.s. $v_2(p_T)$ from low p_T to high p_T

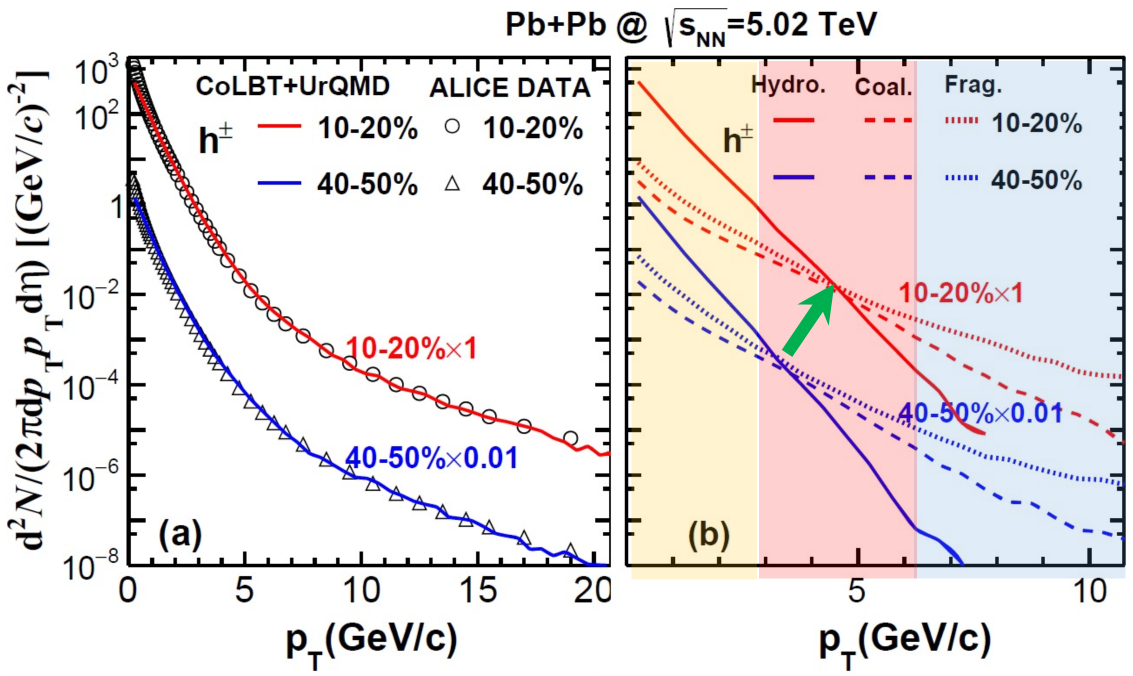


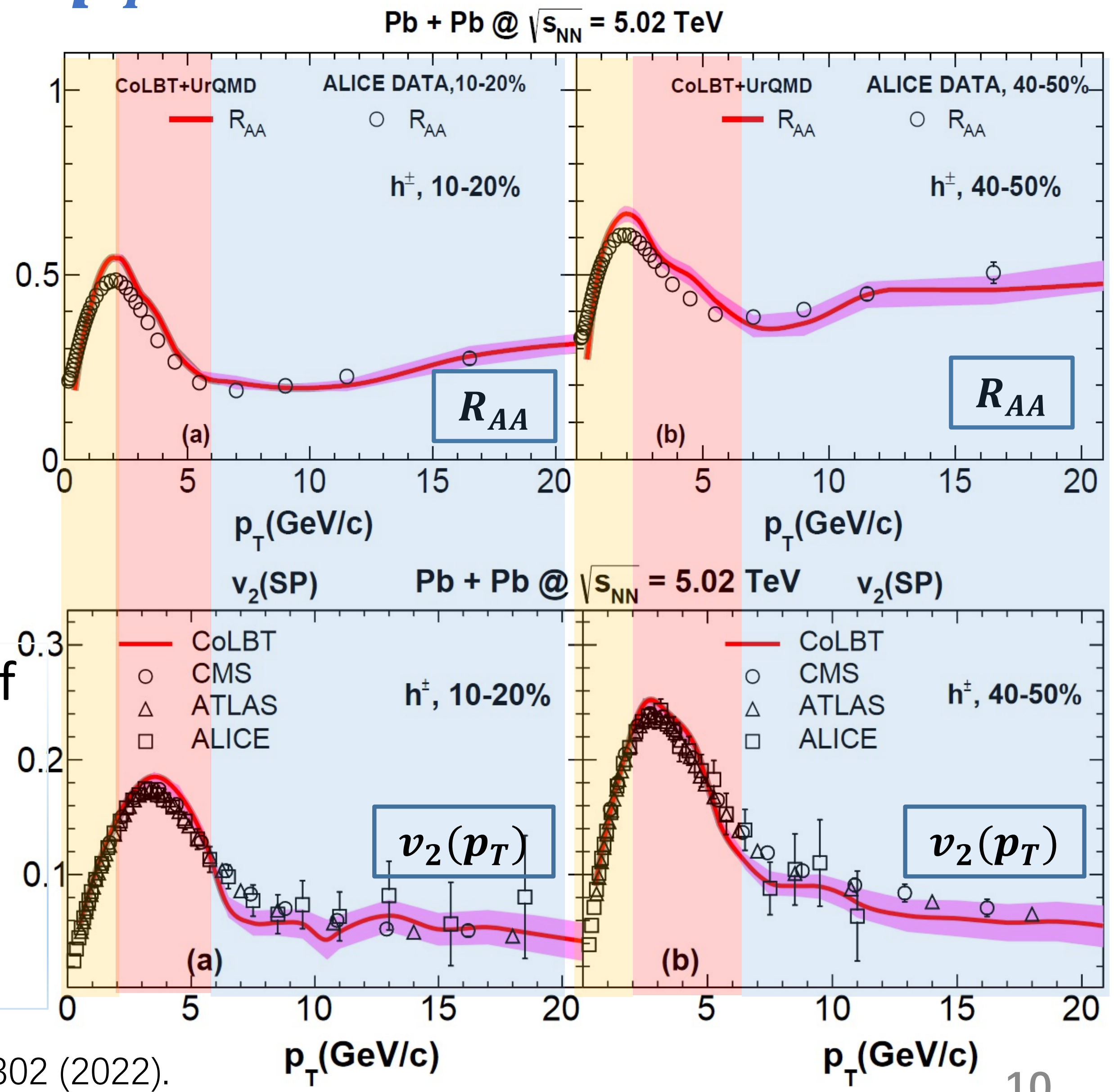


- CoLBT-hydro with Hydro-Coal-Frag hadronizations can simultaneously describe the R_{AA} and collective flow from low p_T to high p_T regions in Pb+Pb collisions.

W. Zhao, W. Ke, W. Chen, T. Luo and X. N.Wang, PRL. 128, 022302 (2022).

Transition from low p_T to high p_T

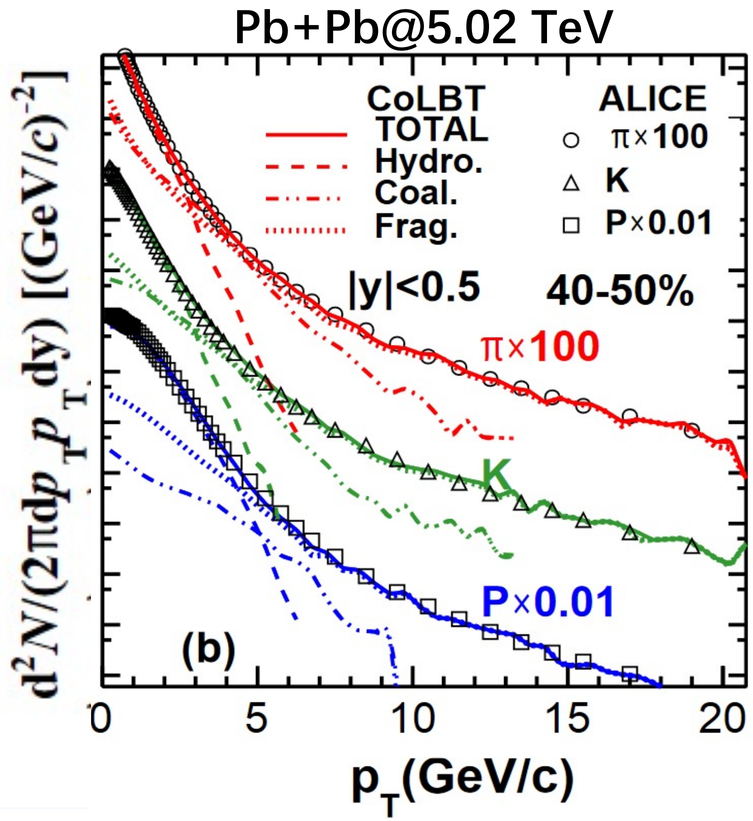


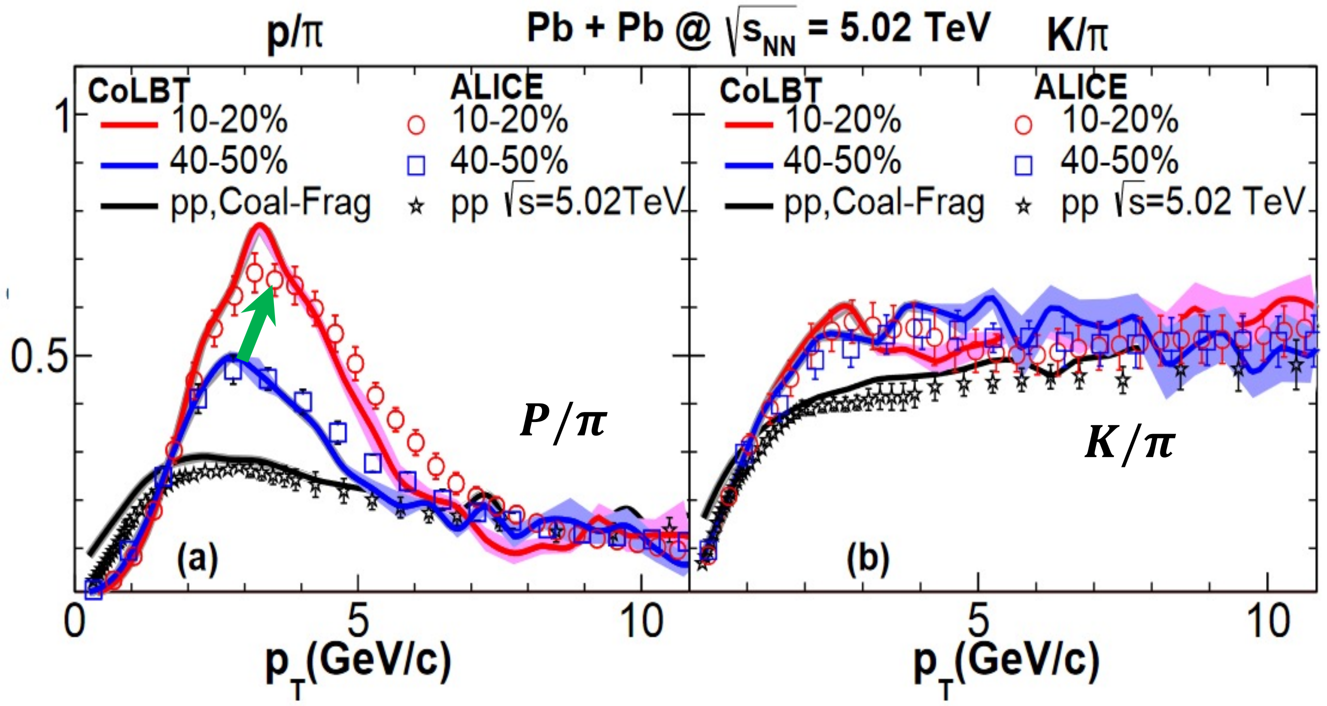


- CoLBT-hydro nicely describes the spectra of charged from 0 to 20 GeV.
- Low p_T: hydro; Intermediate p_T: transition regime; High p_T: jet physics.
- Transition p_T is higher in central collisions.

W. Zhao, W. Ke, W. Chen, T. Luo and X. N.Wang, PRL. 128, 022302 (2022).

Transverse momentum spectra of identified hadrons

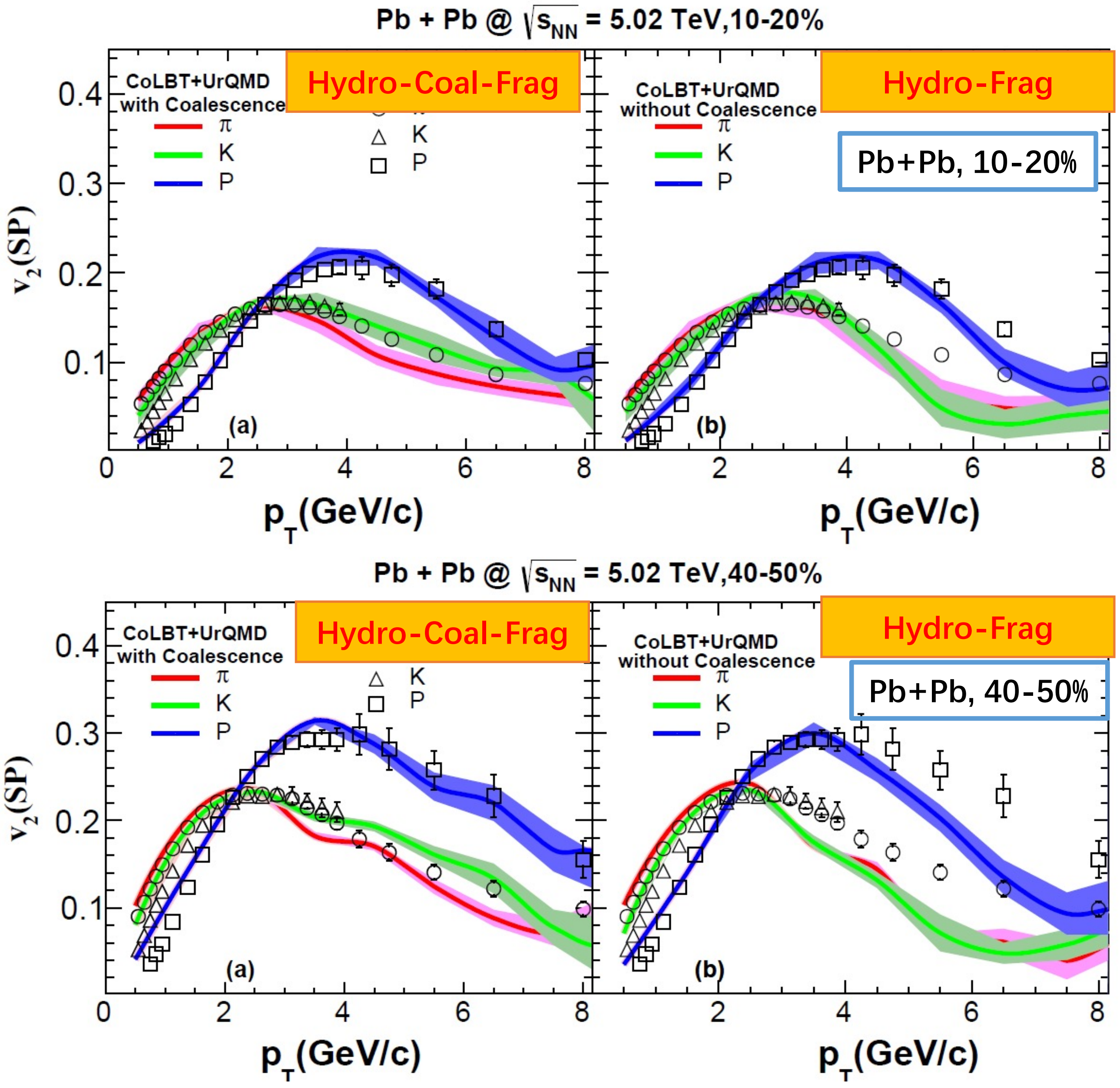




- CoLBT-hydro nicely describes the spectra of identified hadrons, $\boldsymbol{P/\pi}$ and $\boldsymbol{K/\pi}$ from 0 to 20 GeV.
- $\boldsymbol{P/\pi}$ in Pb+Pb is higher than pp; $\boldsymbol{P/\pi}$ peak moves to higher p_T in central collision.
- $\boldsymbol{P/\pi}$ and $\boldsymbol{K/\pi}$ approach to the p-p value at high p_T.

W. Zhao, W. Ke, W. Chen, T. Luo and X. N.Wang, PRL. 128, 022302 (2022).

Collective flow of identified hadrons

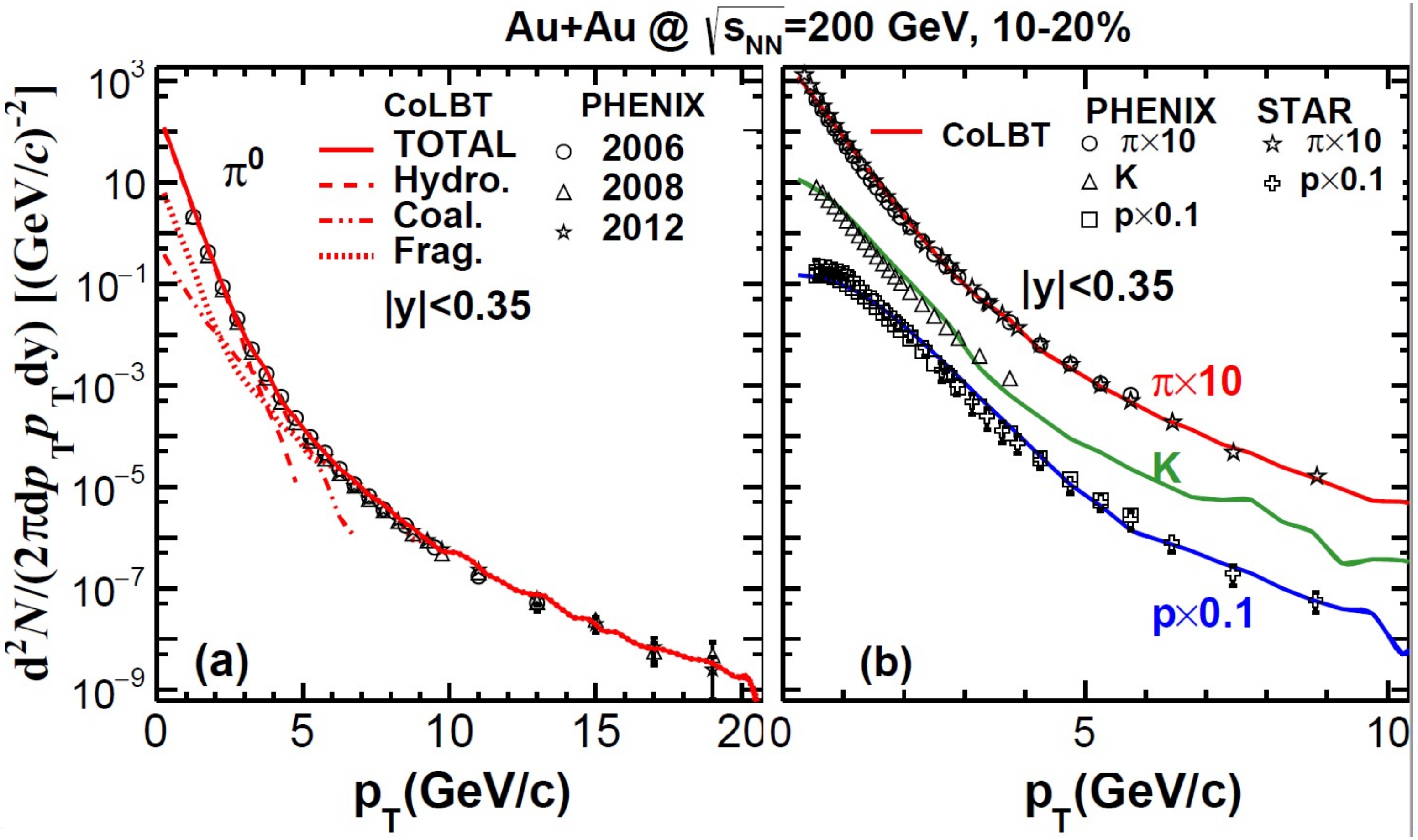


- CoLBT-hydro with Hydro-Coal-Frag works well for PID flow from 0 to 8 GeV.
- $v_2(p_T)$ of P larger than π and K at 3 GeV, caused by interplay between hydro. Coal. and frag.
- Quark coalescence is important for Pb+Pb collisions at intermediate p_T range.

W. Zhao, W. Ke, W. Chen, T. Luo and X. N.Wang, PRL. 128, 022302 (2022).

Predictions for Au-Au at RHIC

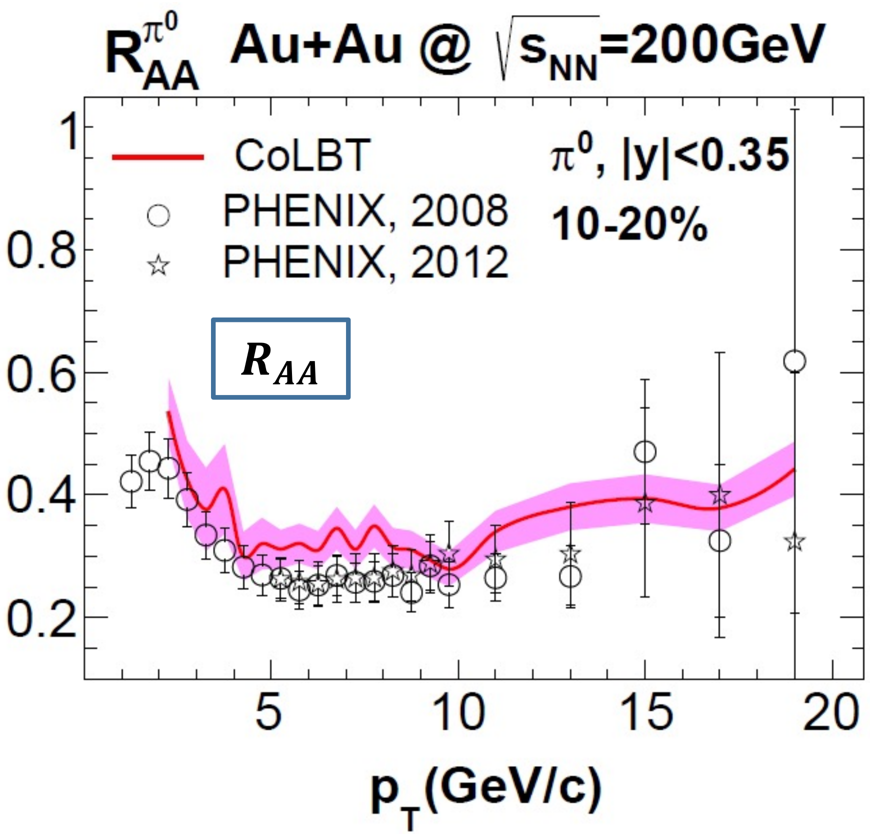
Spectra at Au-Au at RHIC

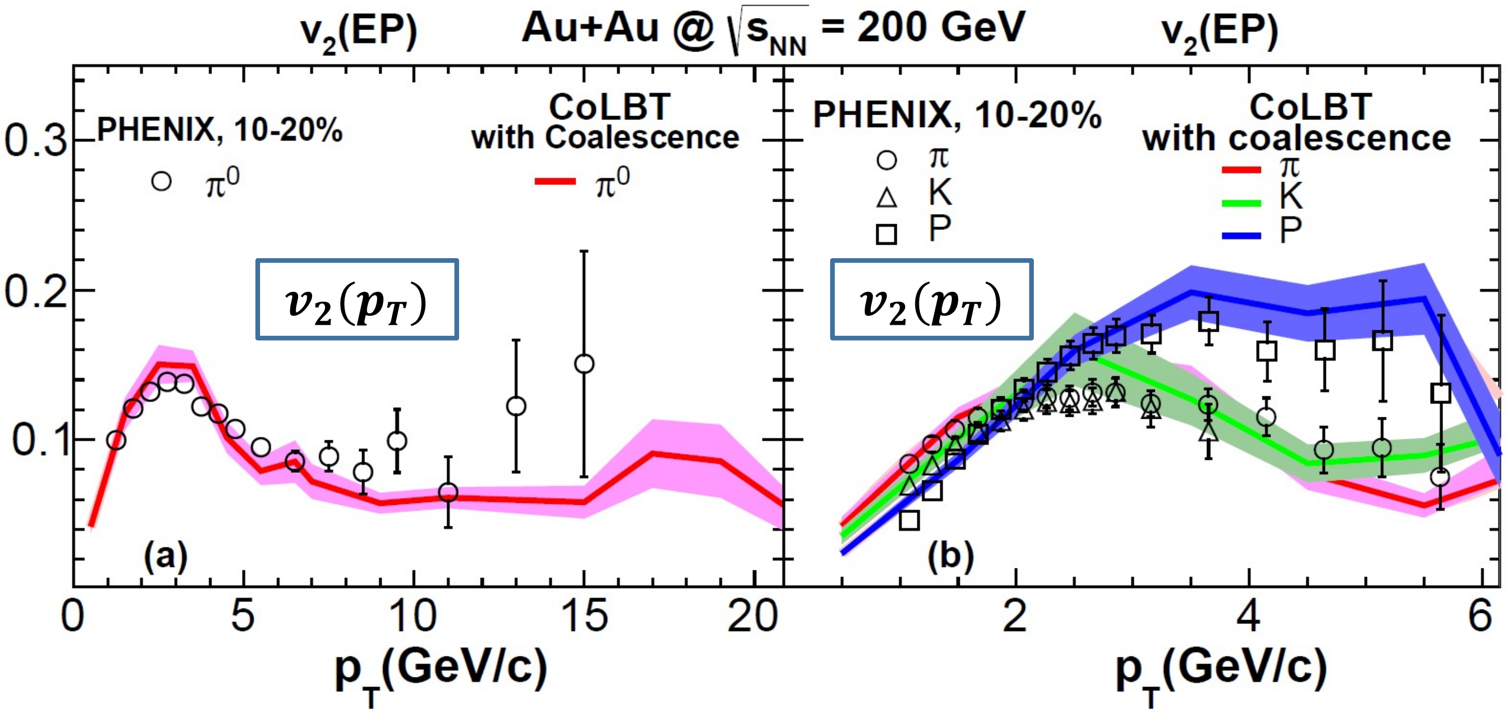


- With parameters fixed at LHC, CoLBT-hydro nicely predicts the spectra of π^0 and of $\pi^{\pm}$, K and P from low p_T to high p_T in Au-Au at 200 GeV.
- Low p_T: hydro; Intermediate p_T: transition region; High p_T: fragmentation.

W. Zhao, W. Ke, W. Chen, T. Luo and X. N.Wang, PRL. 128, 022302 (2022).
W. Zhao, W. Ke, W. Chen, T. Luo and X. N.Wang, in preparation.

R_{AA} and $v_2\,(p_T)$ at Au-Au at RHIC

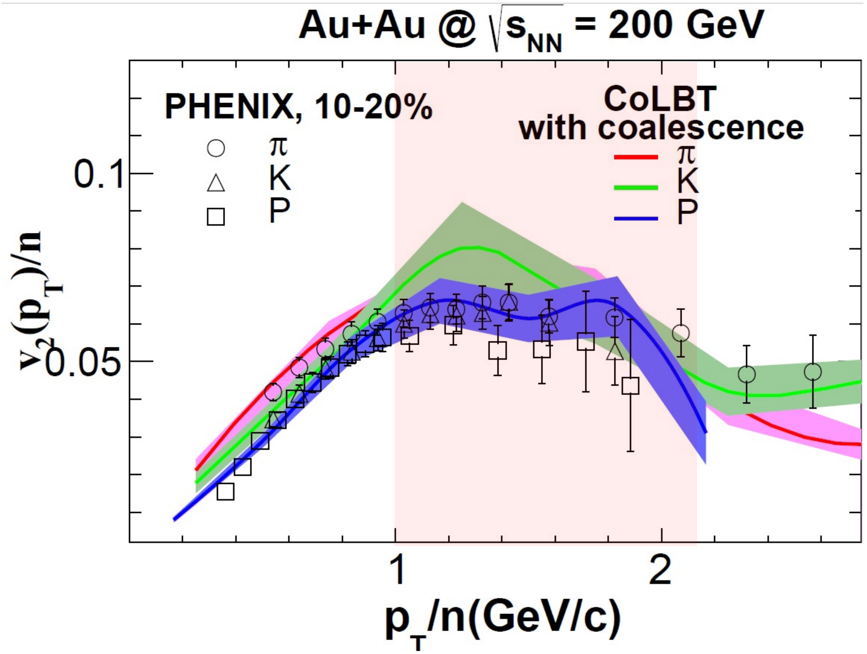


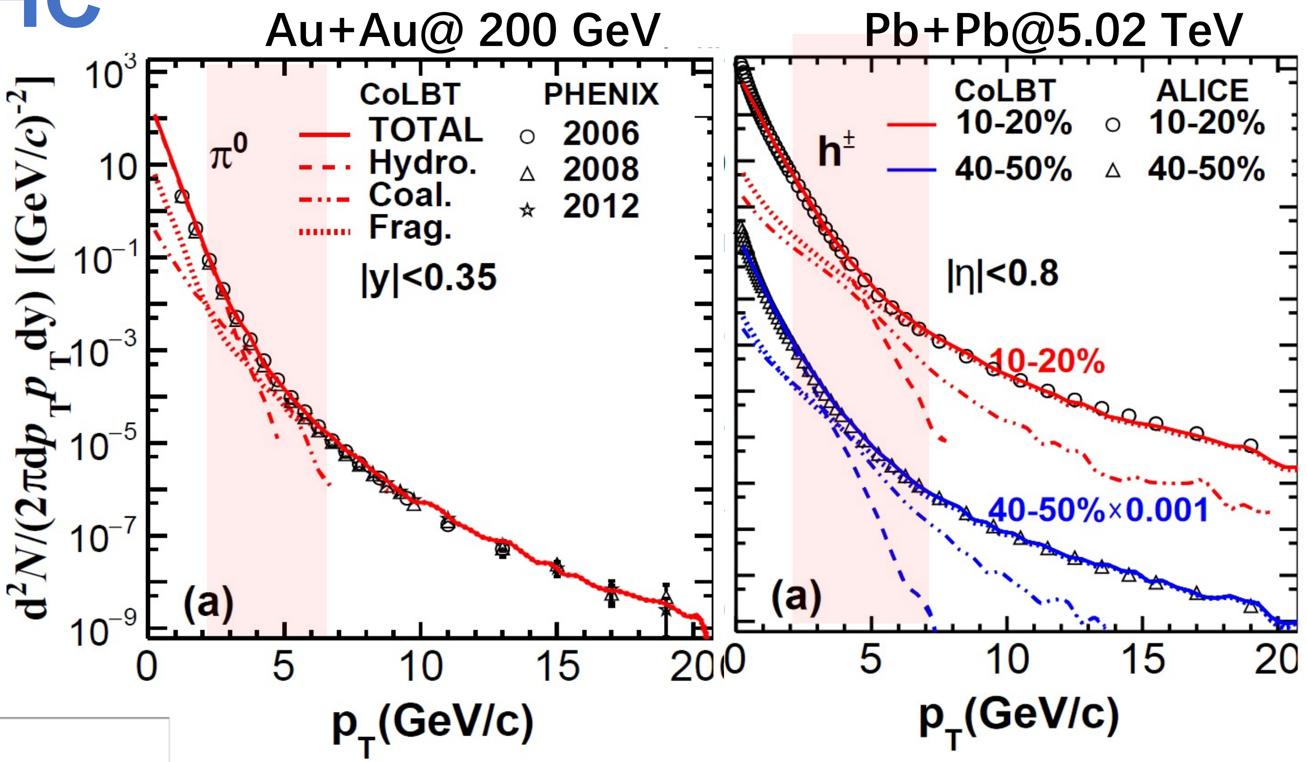


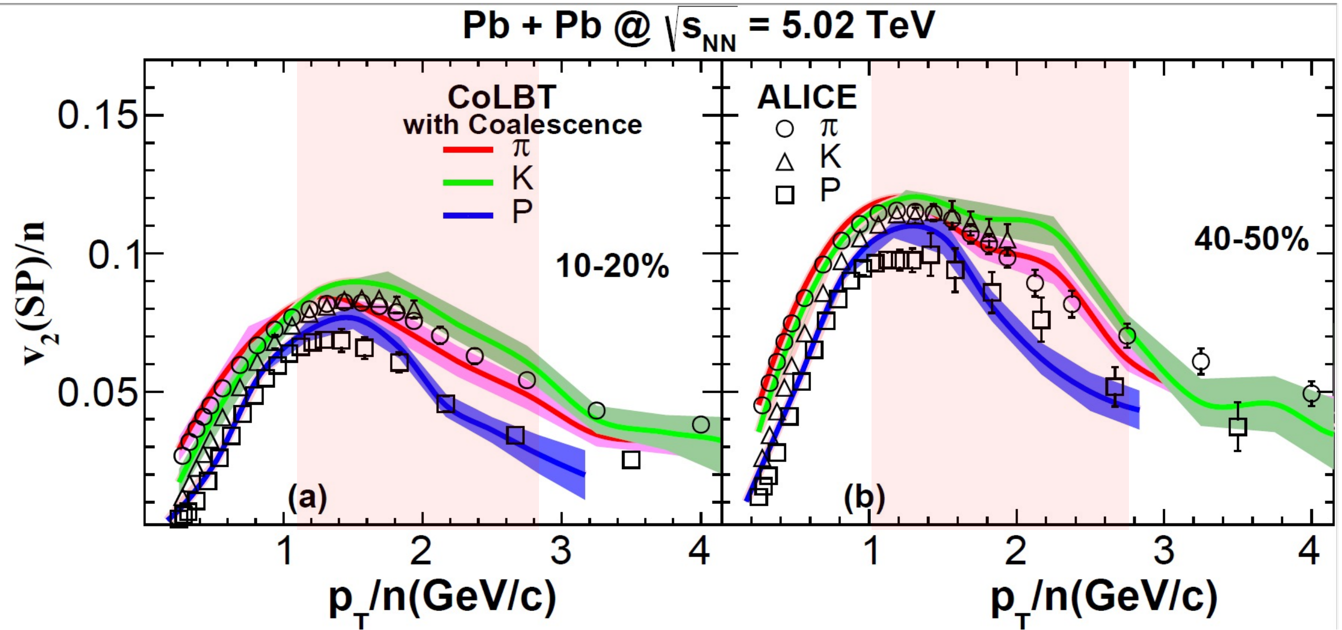
- With parameters fixed at LHC, CoLBT-hydro nicely predicts the $\mathrm{R_{AA}}$ and $v_2(p_T)$ from 0 to 20 GeV in Au-Au at 200 GeV.
- CoLBT-hydro nicely predicts the $v_2(p_T)$ of π, K and P from 0 to 6 GeV in RHIC.

W. Zhao, W. Ke, W. Chen, T. Luo and X. N.Wang, PRL. 128, 022302 (2022).
W. Zhao, W. Ke, W. Chen, T. Luo and X. N.Wang, in preparation.

NCQ scaling at RHIC and LHC







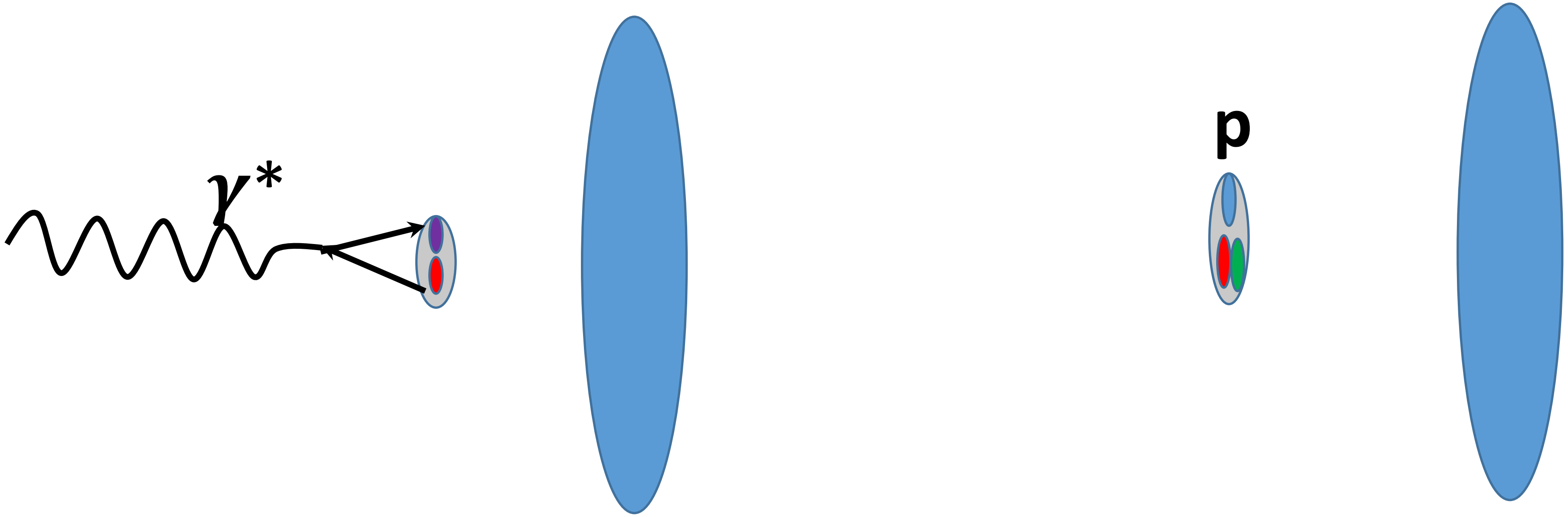
- NCQ scaling at intermediate p_T are caused by interplay of hydro, coal. and frag.

W. Zhao, W. Ke, W. Chen, T. Luo and X. N.Wang, PRL. 128, 022302 (2022).
W. Zhao, W. Ke, W. Chen, T. Luo and X. N.Wang, in preparation.

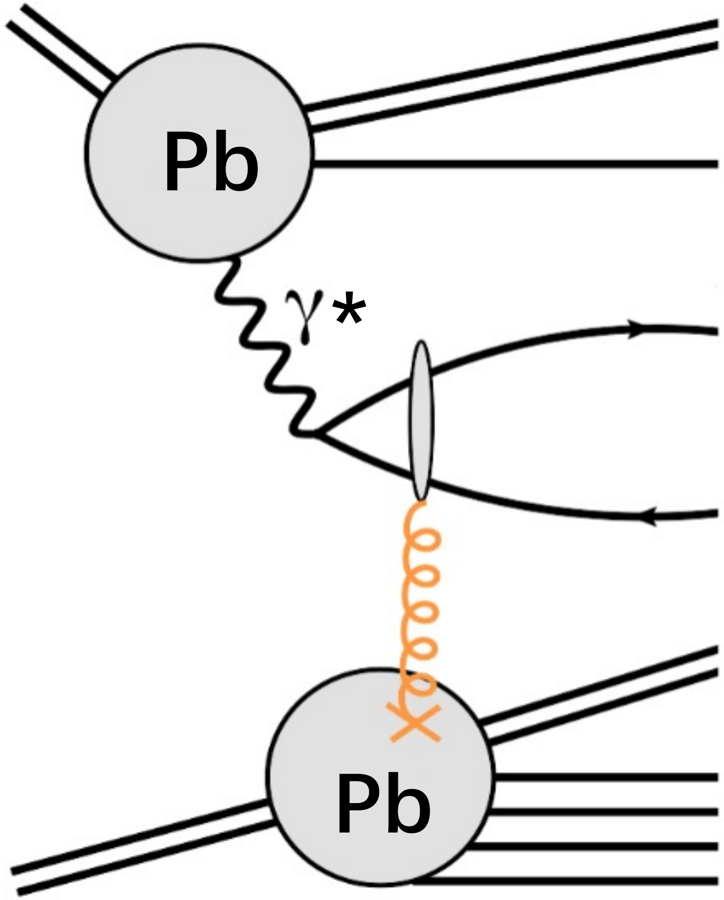
Summary for part-I

- CoLBT-hydro with Hydro-Coal-Frag hadronization simultaneously describe the R_{AA} and collective flow from low p_T to high p_T in Pb+Pb collisions.
- CoLBT-hydro also nicely describes the collective flow of identified hadrons with p_T from 0 to 8 GeV.
- Quark coalescence is important in heavy-ion collisions.
- With parameters fixed at LHC, CoLBT-hydro excellently predicts the R_{AA} and collective flow from low p_T to high p_T in Au+Au collisions at RHIC.

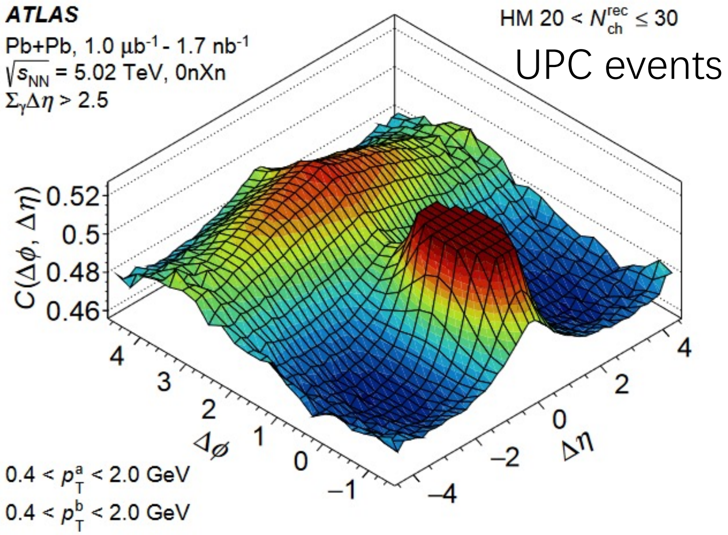
Collectivity in ultra-peripheral Pb+Pb pollisions

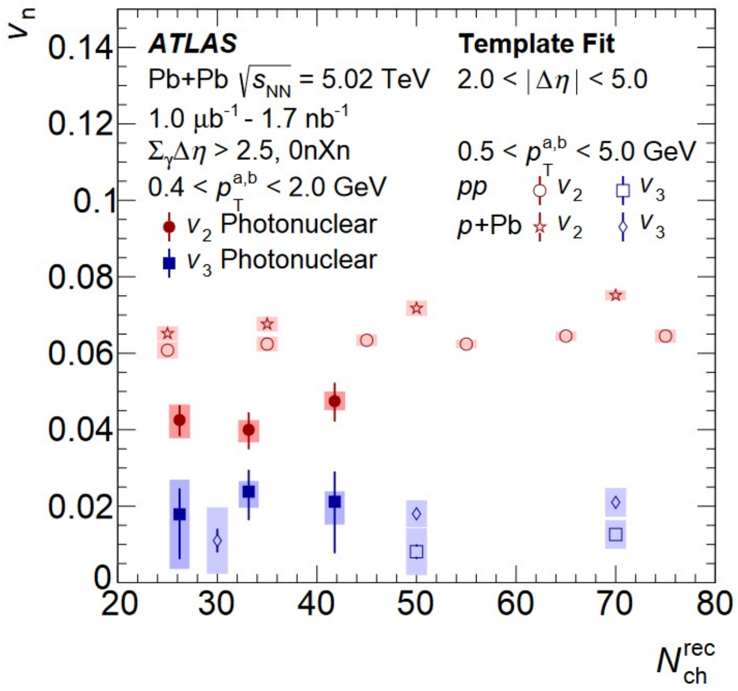


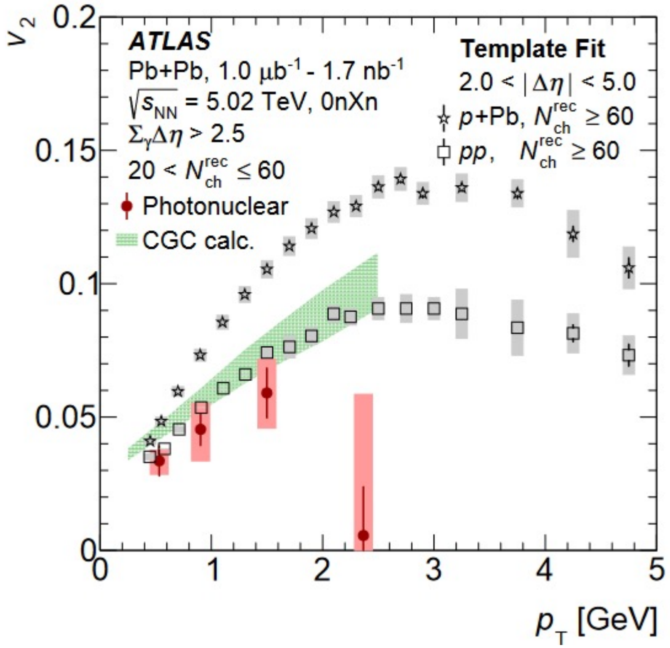
“Collectivity” in UPC



Borrow from Nicole Lewis’s slide



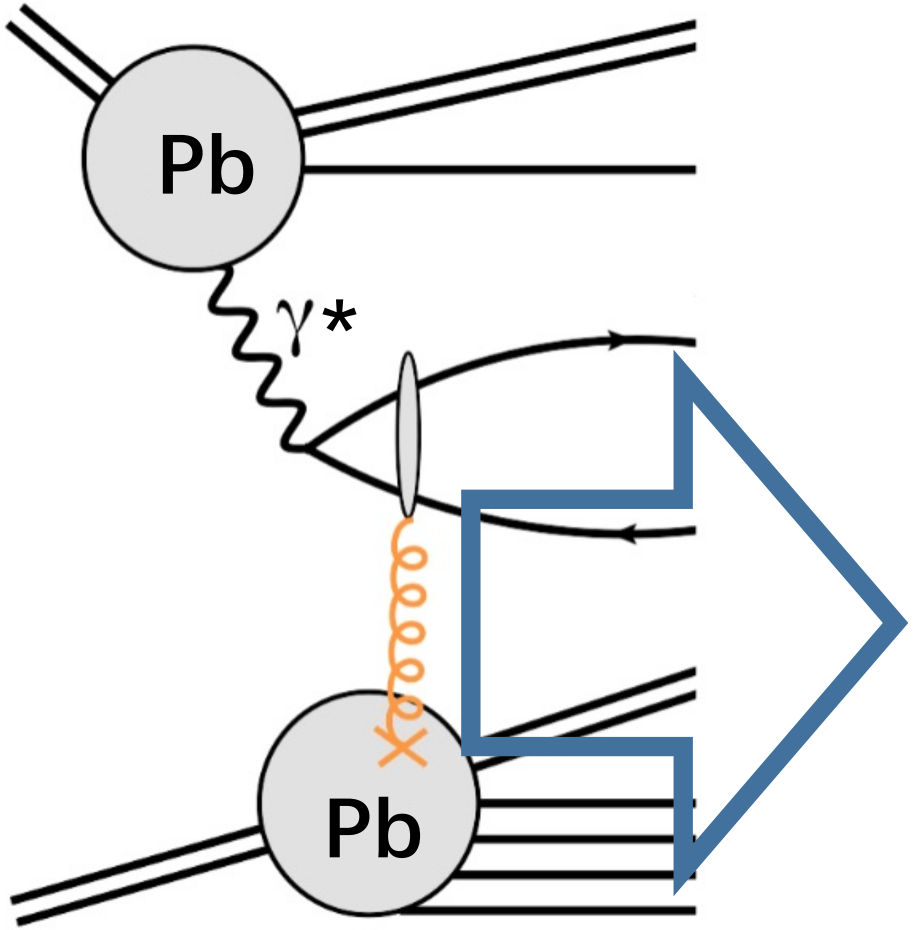




- UPCs has a similar order of magnitude and trends of collectivity as other previously measured hadronic systems

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

Hydrodynamic simulation of UPC



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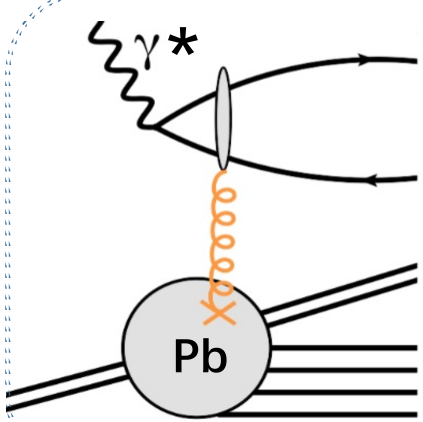
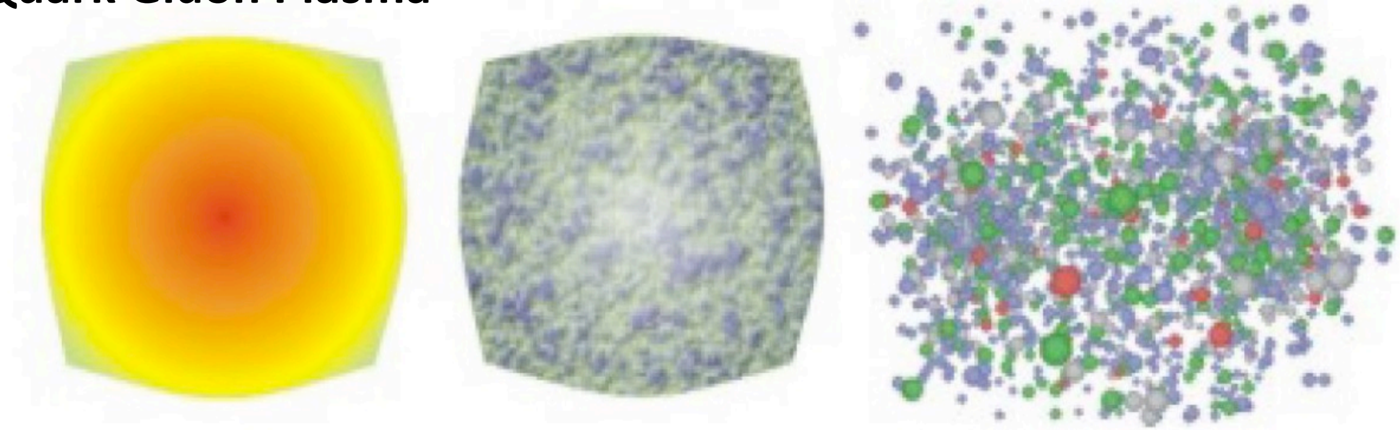


The transverse positions of the valence partons are sampled from a 2D Gaussian

$$\boldsymbol{P(x,y) \propto exp[-\frac{x^2+y^2}{2}Q^2]}$$

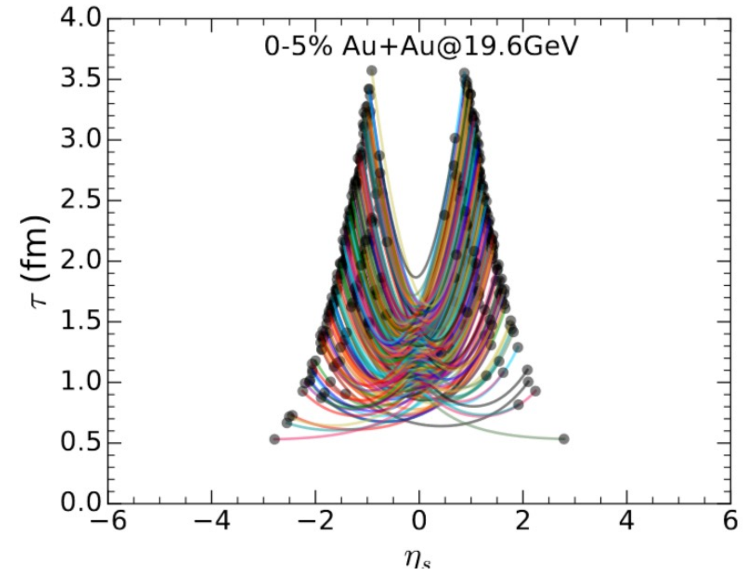
Q: the virtuality of virtual photon.

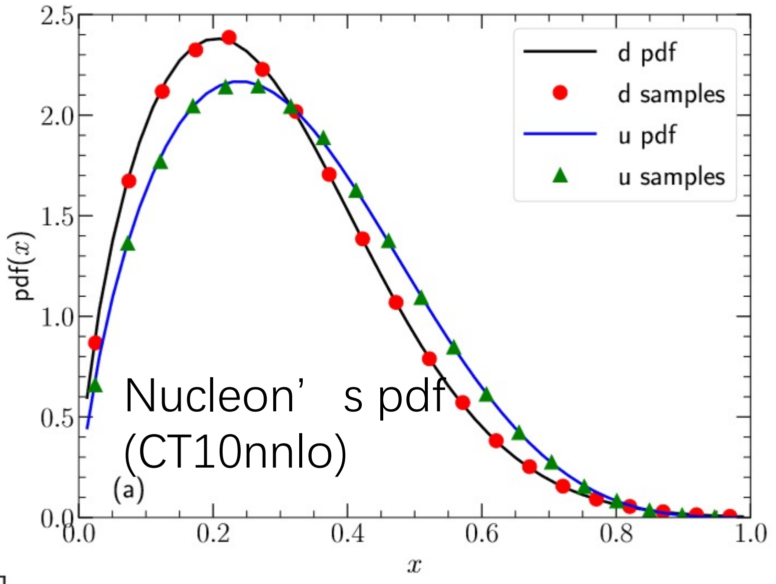


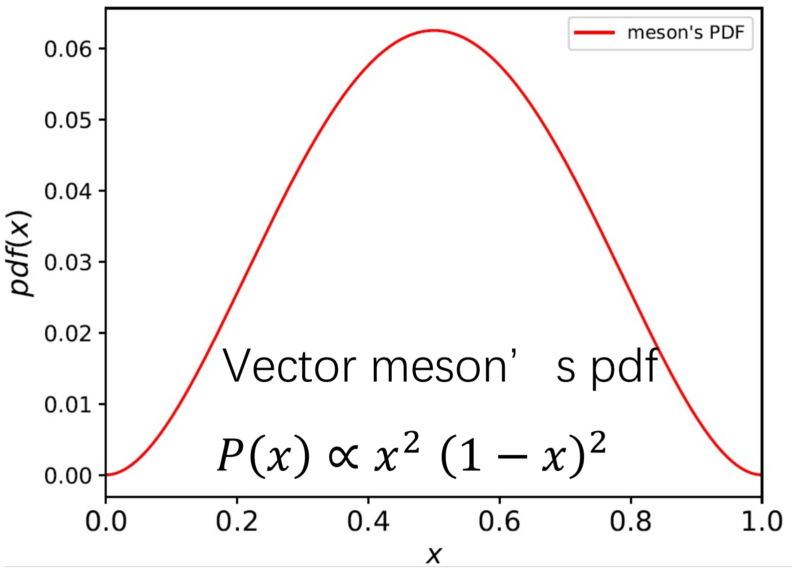
3DGlauber + MUSIC + UrQMD

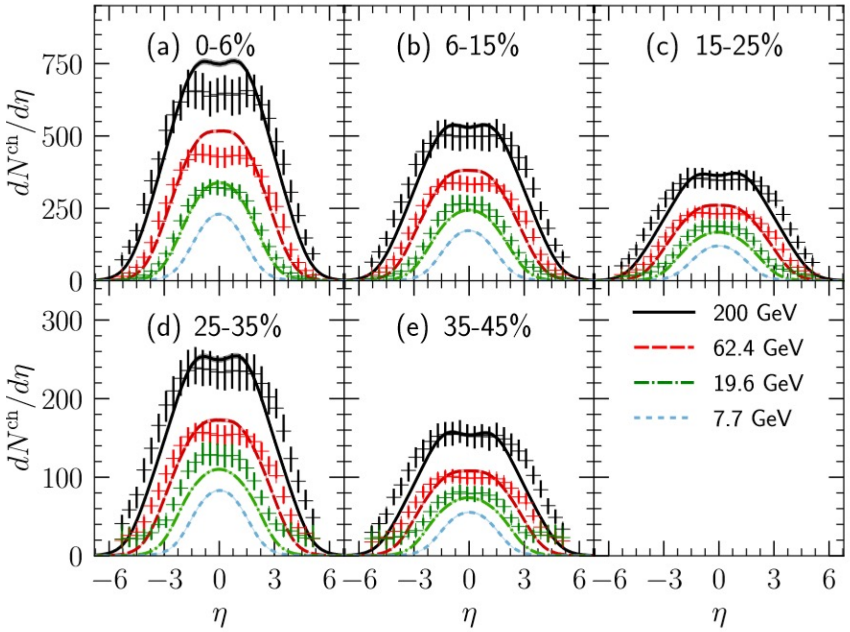
C. Shen and B. Schenke, [arXiv:2203.04685 [nucl-th]].
C. Shen and B. Schenke Phys. Rev. C 97, 024907 (2018).
W. Zhao, C. Shen and B. Schenke [arXiv:2203.06094].

3DGlauber + MUSIC + UrQMD





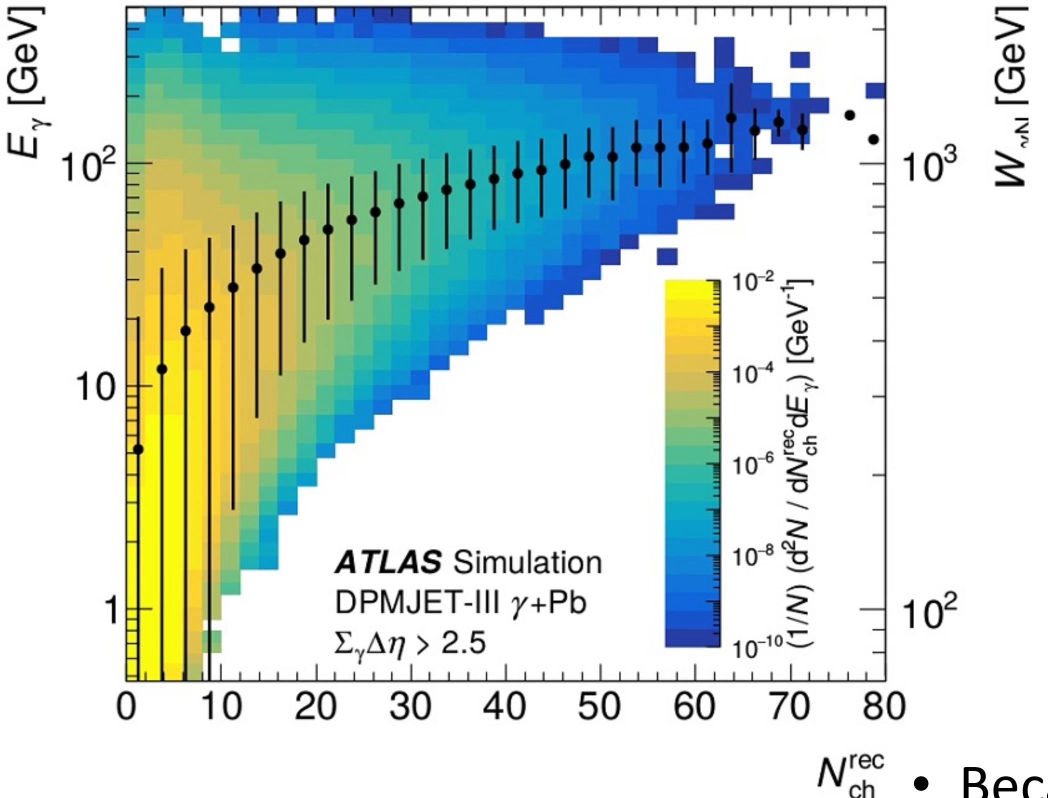




- 3D-Glauber + MUSIC + UrQMD works well in description various soft observables from low energies to high energies.
- Nucleon's pdf peaks around x~0.33, vector meson's pdf peaks at x~0.5.

C. Shen and B. Schenke, [arXiv:2203.04685 [nucl-th]].
C. Shen and B. Schenke Phys. Rev. C 97, 024907 (2018).
W. Zhao, C. Shen and B. Schenke [arXiv:2203.06094].

Kinematics



ATLAS PhysRevC.104.014903.
R. Engel, Z. Phys. C 66, 203 (1995)

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The physics of ultraperipheral collisions at the LHC

A.J. Baltz[a], G. Baur[b], D. d'Enterria[c], L. Frankfurt[d], F. Gelis[e], V. Guzey[f,w], K. Hencken[g,h,1], Yu. Kharlov[i], M. Klasen[j], S.R. Klein[k], V. Nikulin[l], J. Nystrand[m], I.A. Pshenichnov[n,o], S. Sadovsky[i], E. Scapparone[p], J. Seger[q], M. Strikman[r,*,1], M. Tverskoy[l], R. Vogt[k,s,t,1], S.N. White[a], U.A. Wiedemann[u], P. Yepes[v,1], M. Zhalov[l]

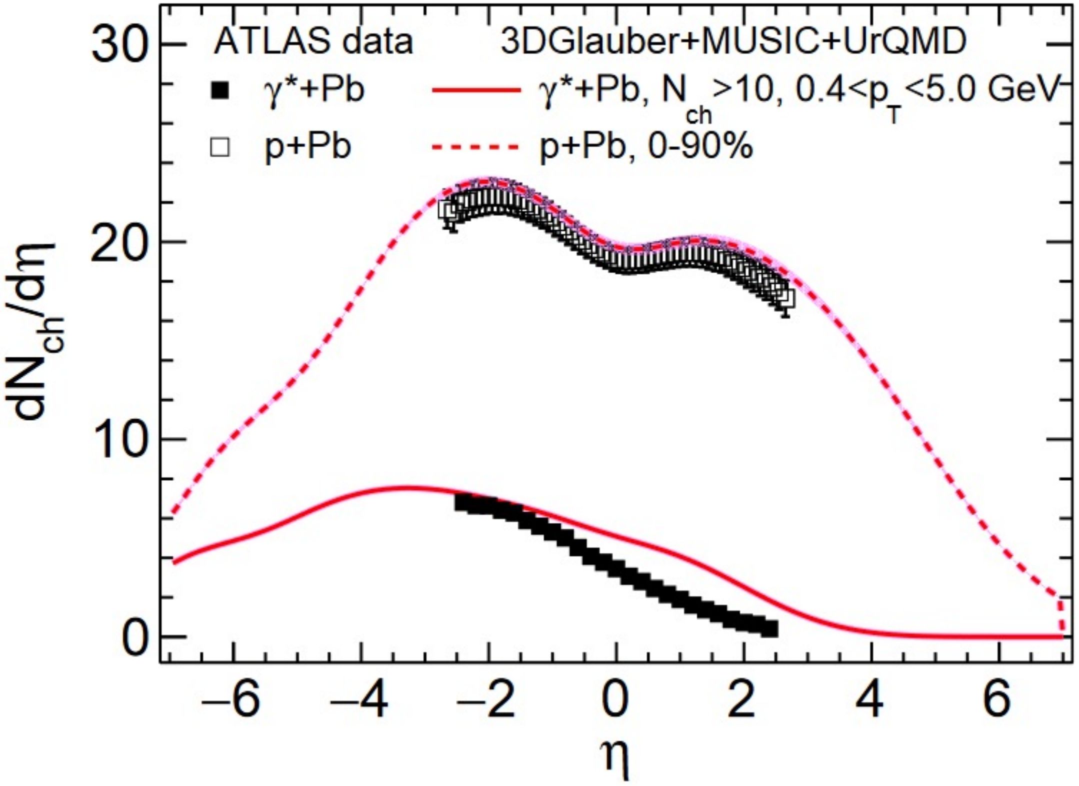
$\sqrt{s_{\gamma N}}$ =894 GeV for Pb+Pb at $\sqrt{s_{NN}}$ =5.02 TeV;
$\sqrt{s_{\gamma N}}$ =9.88 GeV for Au+Au at $\sqrt{s_{NN}}$ =54.4 GeV.

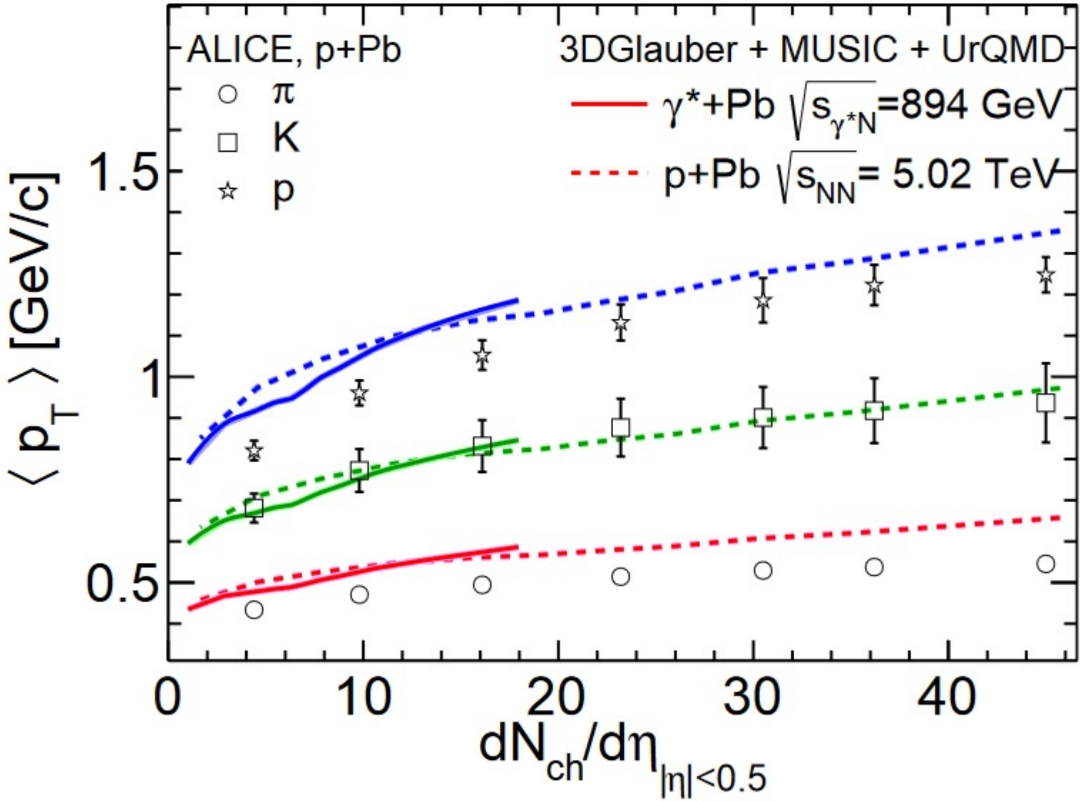
- Because of the unequal energies of incoming Pb and γ^* in the lab frame, we need to do a global rapidity shift to all final-state.

$\gamma^* + Pb$: $\Delta y = 1.756$ in the Pb-going direction;

W. Zhao, C. Shen and B. Schenke [arXiv:2203.06094].

Multiplicity and mean p_T

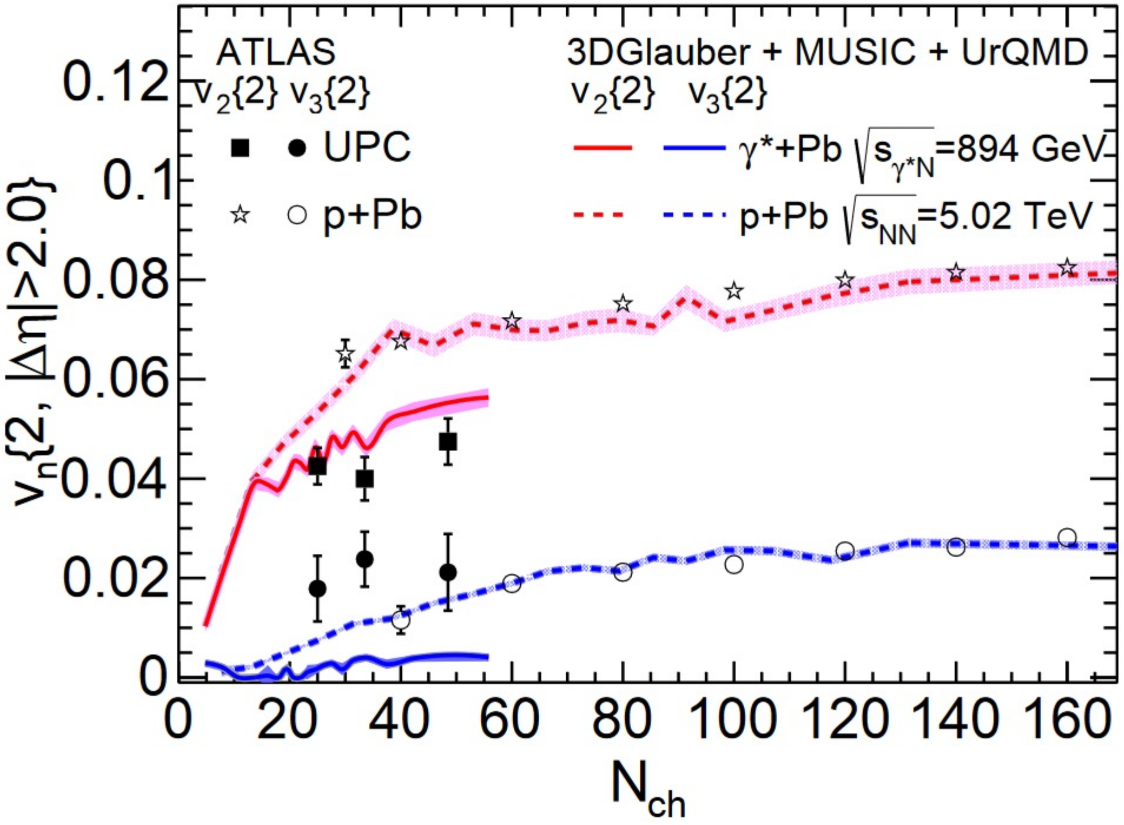


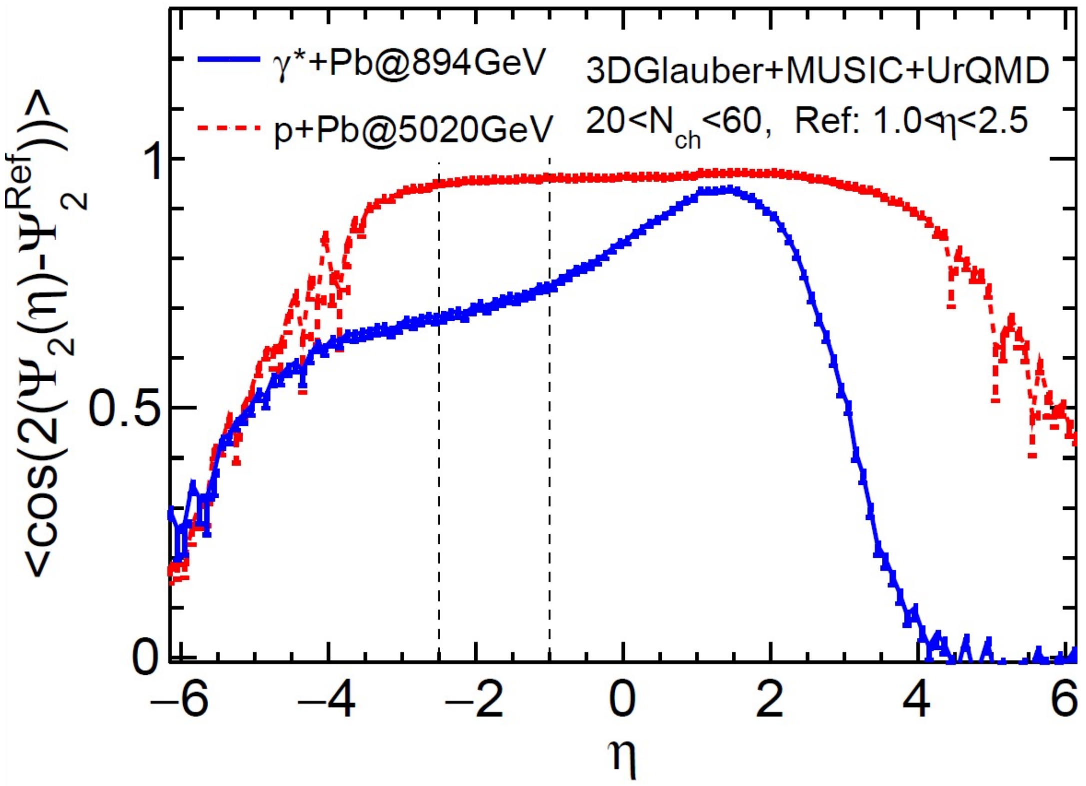


- 3D-Glauber + MUSIC + UrQMD reasonably describe the $dN_{ch}/d\eta$ in $\boldsymbol{\gamma}^*$+Pb and p+Pb .
- The $dN_{ch}/d\eta$ of $\boldsymbol{\gamma}^*$+Pb shows a strong asymmetry in the η direction, which demonstrates the strong violation of longitudinal boost-invariance.
- Clear mass hierarchy of the $<p_T>$ of π, K and P is calculated in $\boldsymbol{\gamma}^*$+Pb and p+Pb.

W. Zhao, C. Shen and B. Schenke [arXiv:2203.06094].
C. Shen and B. Schenke, [arXiv:2203.04685 [nucl-th]].

$v_n\{2\}$ in γ^*+Pb and p+Pb

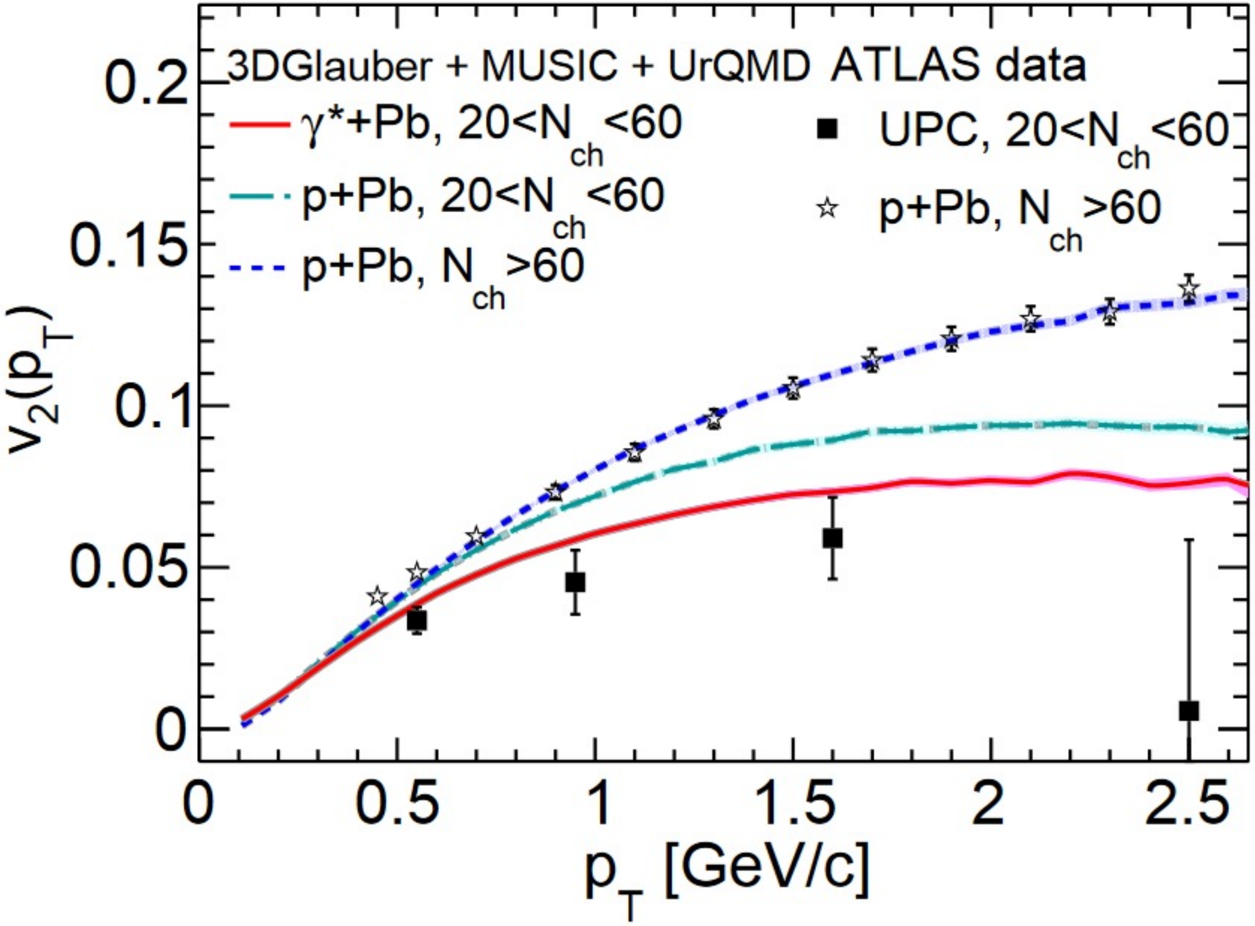




- 3D-Glauber + MUSIC + UrQMD describes the $\boldsymbol{v_2\{2\}}$ in $\boldsymbol{\gamma^*}$+Pb and p+Pb well.
- The v_2 hierarchy between p+Pb and γ∗+Pb is dominated by the difference in longitudinal flow decorrelations.
- More efforts are required for v_3 in $\boldsymbol{\gamma^*}$+Pb.

W. Zhao, C. Shen and B. Schenke [arXiv:2203.06094].
C. Shen and B. Schenke, [arXiv:2203.04685 [nucl-th]].

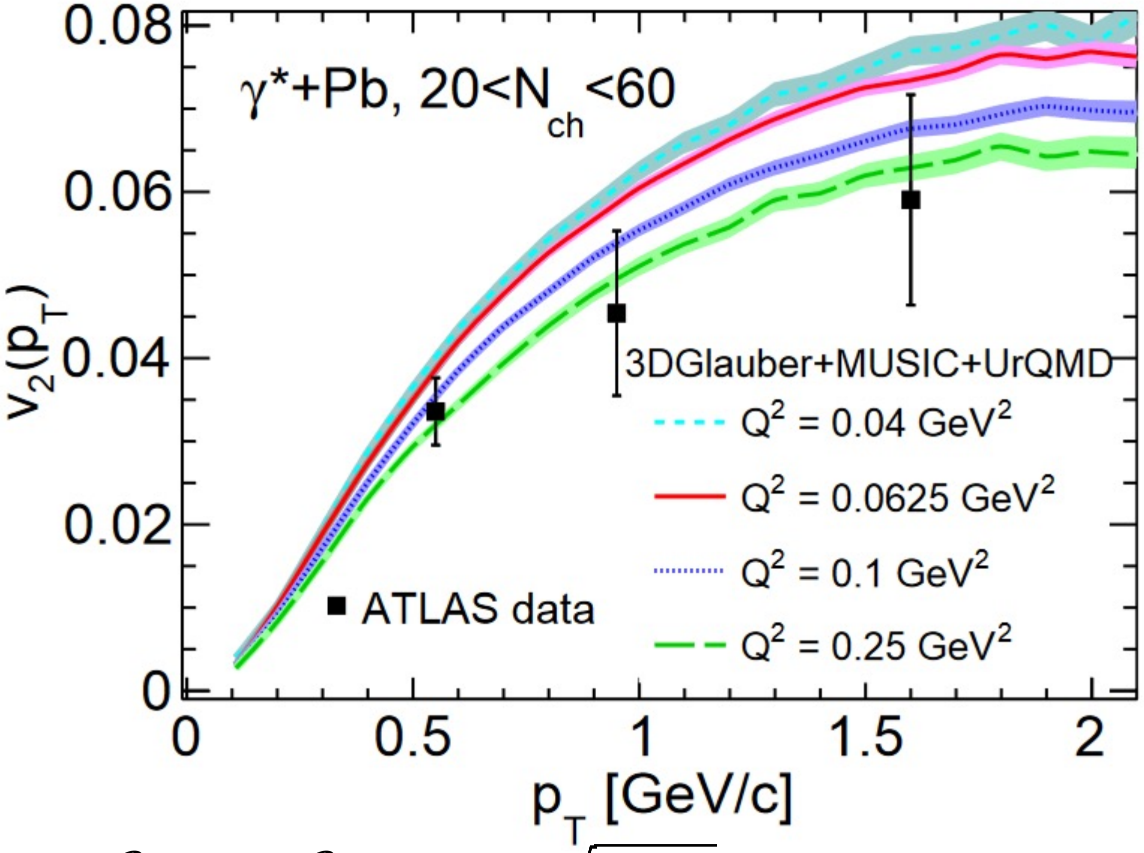
$v_2(p_T)$ in γ^*+Pb and p+Pb

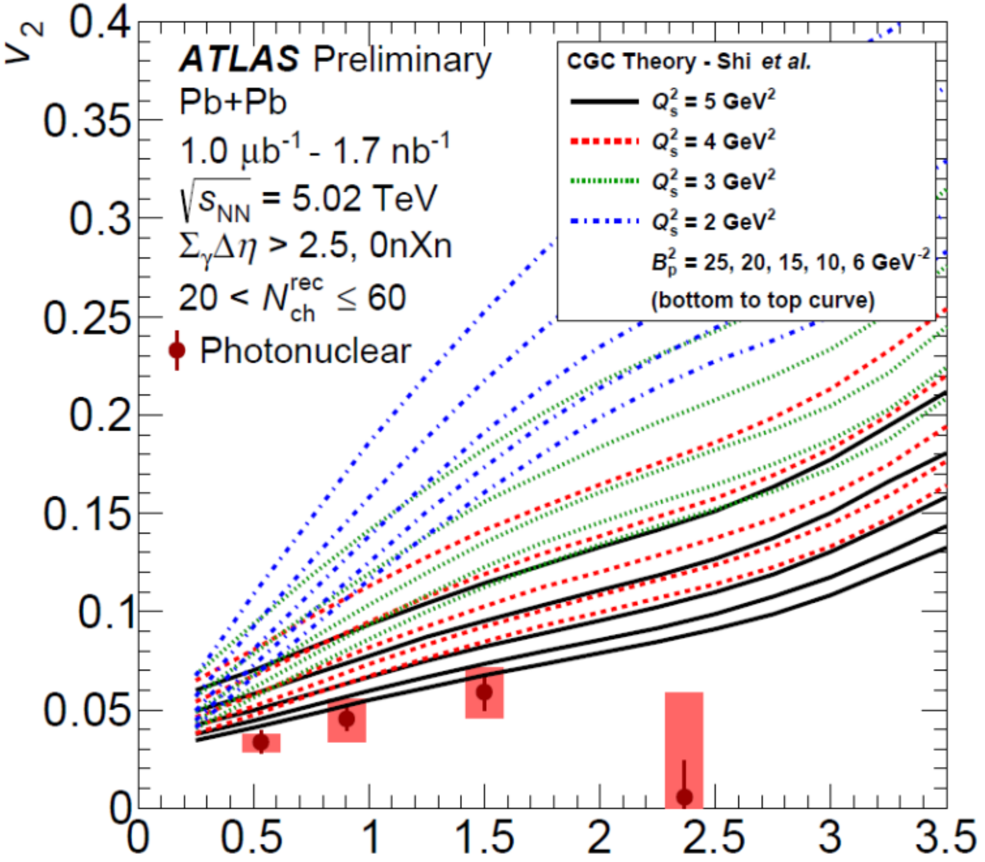


- 3D-Glauber + MUSIC + UrQMD describes the $\boldsymbol{v}_2(p_T)$ in $\boldsymbol{\gamma}^*$+Pb and p+Pb well.

W. Zhao, C. Shen and B. Schenke [arXiv:2203.06094].

Photon virtuality dependence of flow





($Q^2 = 1/B_p^2,\ r_{rms} = \sqrt{2/Q^2}$. i.e. $r_{rms} = 0.557$ fm for $Q^2 = 0.25\ GeV^2$)

- Hydro: larger transverse space for the geometry allows more fluctuate and the v_2 are larger.
- CGC: Larger number of independent domains leads to lower v_2.

W. Zhao, C. Shen and B. Schenke [arXiv:2203.06094]. Y. Shi, etc.al,Phys. Rev. D 103, 054017 (2021). B. D. Seidlitz. QM2019.

Summary for part-II

- We carried out the first dynamical (3+1)D hydro simulations that quantitatively study the collectivity in p+Pb and ultra-peripheral Pb+Pb collisions at LHC energies
- Due to different longitudinal flow decorrelation, which results in a smaller v_2 in $\gamma *$+Pb collisions than p+Pb in a given multiplicity bin.
- The v_2 of $\gamma *$+Pb collisions increases with the decreasing virtualities of photons in the hydro framework.
- Our work bridges the phenomenological studies of collectivity in relativistic heavy-ion collisions with the future electron+nucleus collisions.

Thanks for Your Attenation!

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