(Multi)-strange hadrons in Pb+Pb collisions and correlations in p+Pb collisions at the LHC

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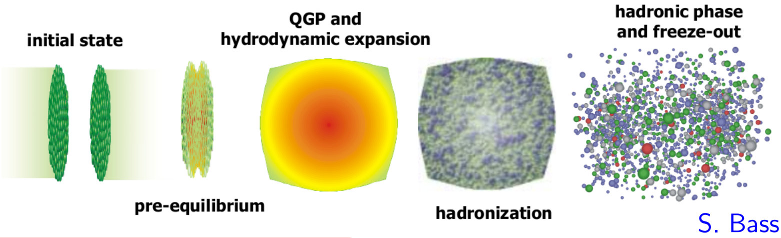
Main references:

- X. Zhu, F. Meng, H. Song, and Y. X. Liu, Phys. Rev. C **91**, no. 3, 034904 (2015).
- Y. Zhou, X. Zhu, P. Li and H. Song, Phys. Rev. C **91**, 064908 (2015).

Outline

- Introduction
  - Viscous hydrodynamics
  - Hybird approaches for heavy-ion collisions
- (Multi-)strange hadrons in Pb+Pb at $\sqrt{s_{\mathrm{NN}}}$=2.76 TeV
  - Multiplicities, p_{T}-spectra and elliptic flow of (multi-)strange hadrons
  - Chemical and thermal freeze-out of various hadrons species
- Correlations in p+Pb collisions at $\sqrt{s_{\mathrm{NN}}}$=5.02 TeV
  - Experimental measurements and hydrodynamic calculations
  - Correlations from hadronic cascade model, UrQMD
- Summary

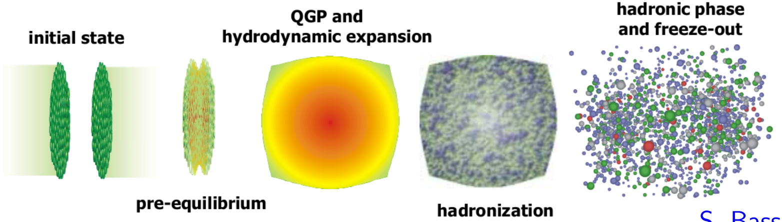
Stages of ultra-relativistic heavy ion collisions



Basics of viscous hydrodynamics

- Energy momentum tensor $T^{\mu\nu}(x)$: $\partial_\mu T^{\mu\nu}(x) = 0$
  where $T^{\mu\nu} = [e + p + \Pi]u^\mu u^\nu - (p + \Pi)g^{\mu\nu} + \pi^{\mu\nu}$ with
  - Viscous bulk pressure Π
    $\dot{\Pi} = -\frac{1}{\tau_\Pi}(\Pi + \zeta\partial\cdot u) - \frac{1}{2}\Pi\frac{\zeta T}{\tau_\Pi}\partial_\lambda(\frac{\tau_\Pi}{\zeta T}u^\lambda)$
  - Traceless viscous shear pressure tensor $\pi^{\mu\nu}$
    $\Delta^{\alpha\mu}\Delta^{\beta\nu}\dot{\pi}_{\alpha\beta} = -\frac{1}{\tau_\pi}(\pi^{\mu\nu} - 2\eta\sigma^{\mu\nu}) - \frac{1}{2}\pi^{\mu\nu}\frac{\eta T}{\tau_\pi}\partial_\lambda(\frac{\tau_\pi}{\eta T}u^\lambda)$
- Conserved charge current $N_i^\mu(x)$: $\partial_\mu N_i^\mu(x) = 0, \quad i = 1, ..., k$
  For simplicity, only consider the conserved net baryon number current.

Stages of ultra-relativistic heavy ion collisions



S. Bass

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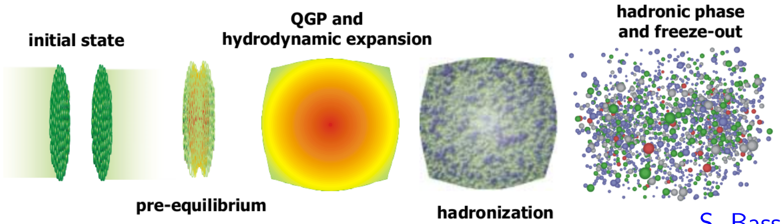
  Assume **zero** **net baryon density** at the LHC.

Stages of ultra-relativistic heavy ion collisions



S. Bass

Basics of viscous hydrodynamics

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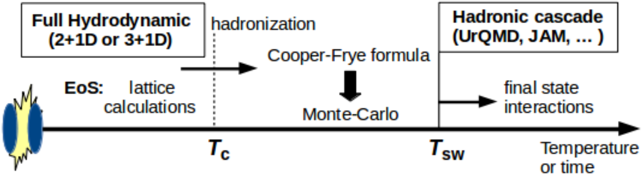
  For simplicity, only consider the conserved net baryon number current.
  Assume **zero net baryon density** at the LHC.

Input EoS $p(e, n)$ for closure

Hybrid approaches

Hydrodynamic+hadronic cascade hybrid approach



- `VISHNU` **hybrid approach:**
  - Initial condicaitons: MC-Glauber, MC-KLN (this work)
  - Hydrodynamic: `VISH2+1`, $\eta/s = 0.16$, and EoS: `s95p-PCE`
  - Switching temperature: $T_{\mathrm{sw}} = 165$MeV
  - Hadronic cascade: `UrQMD`, hadronic rescattering and resonance decays
- **Other hybrid approaches:**
  - D. Teaney, J. Lauret and E. V. Shuryak, nucl-th/0110037.
  - C. Nonaka and S. A. Bass, Phys. Rev. C **75**, 014902 (2007).
  - T. Hirano *et al.*, Phys. Lett. B **636**, 299 (2006).
  - H. Petersen *et al.*, Phys. Rev. C **78**, 044901 (2008).
  - K. Werner *et al.*, Phys. Rev. C **82**, 044904 (2010).
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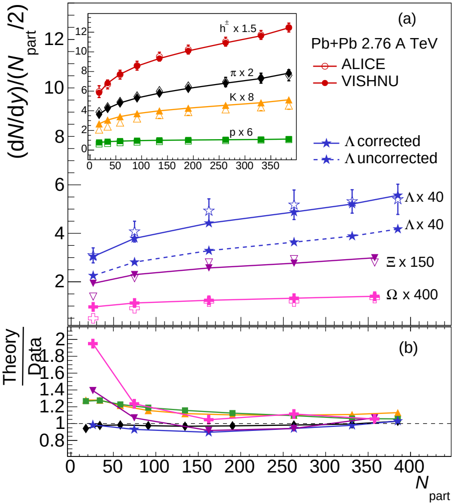
Multiplicities, spectra and elliptic flow for (multi-)strange hadrons

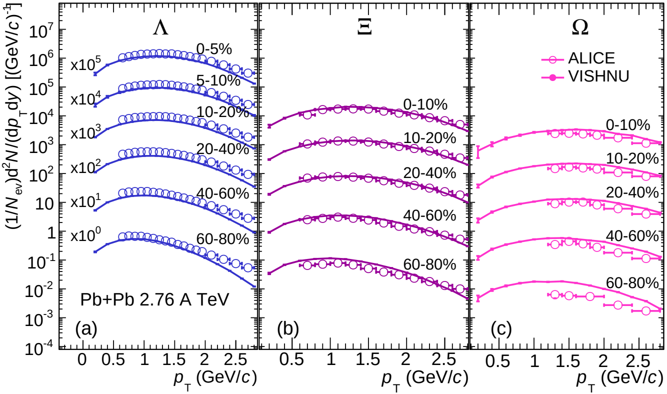
Multiplicities for identified hadrons in Pb-Pb collisions



X. Zhu, F. Meng, H. Song, and Y. X. Liu, PRC 2015.

- With baryon-antibaryon (B-$\bar{B}$) annihilations
  - Reduce dN_p/dy and $dN_{\bar{p}}/dy$ by $\mathcal{O}(30\%)$. H. Song *et al.*, PRC (2014).
- Λ results
  - ALICE results: contaminated by the feed-down decays of Σ^0 and $\Sigma(1385)$.
  - Λ corrected (solid line): summed weak decays from $\Sigma^0 \to \Lambda + \gamma$.
  - Λ uncorrected (dashed line): no weak decays of Σ^0.
- `VISHNU` nicely describes the multiplicities for various hadrons species at most centrality bins.

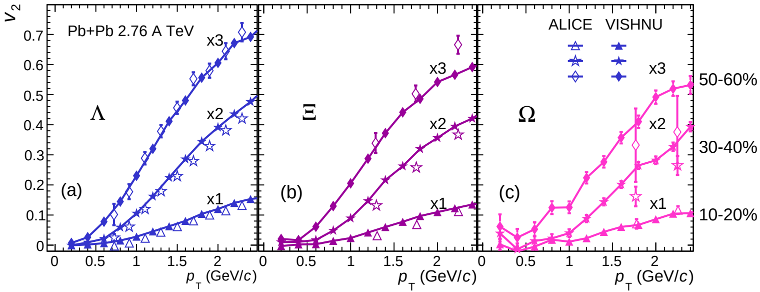
p_T-spectra for Λ, Ξ, and Ω in Pb-Pb collisions



X. Zhu, F. Meng, H. Song, and Y. X. Liu, PRC 2015.

- Λ results from `VISHNU` are without weak decays, ∼30% lower than the experimental measurements with weak decay contaminations.
- `VISHNU` nicely fits the slope of the spectra for Λ, Ξ, and Ω and at various centralities.

Elliptic flow for Λ, Ξ, and Ω in Pb-Pb collisions

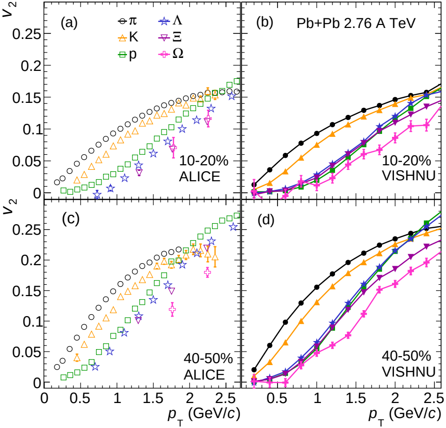


X. Zhu *et al.*, Phys. Rev. C **91**, no. 3, 034904 (2015).

- Below 2 GeV, v_2 for Λ, Ξ, and Ω are fairly well described by `VISHNU` within the statistical error bars.
- Above 2 GeV, the descriptions of v_2 for Ξ at 50-60% and Ω for at 30-40% and 50-60% become worse.

Mass ordering of elliptic flow for identified hadrons

X. Zhu, F. Meng, H. Song, and Y. X. Liu, PRC 2015.



- VISHNU nicely describes the mass ordering among π, K, p, and Ω.
- VISHNU fails to describe the mass ordering among p, Λ and Ξ.
- VISHNU slightly under-predicts the proton v_2 below 2 GeV, leading to inverse mass ordering between p and Λ.

Initial flow could enhance the radial flow

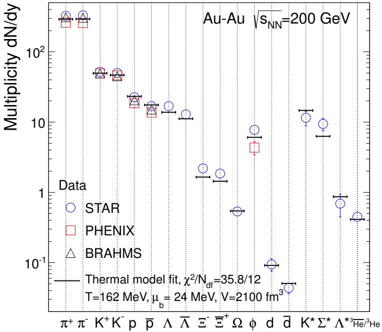
Improvement?

- An initial flow is expected to improve the description of mass ordering.
- UrQMD hadronic cross sections also need to be reevaluated and improved.

Chemical and thermal freeze-out for identified hadrons

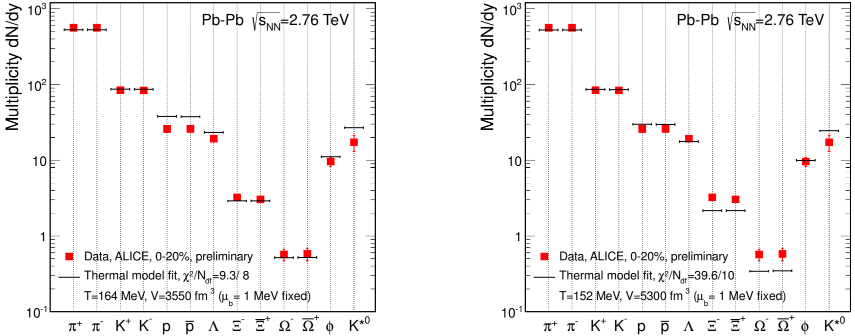
- **Chemical freeze-out**: hadron multiplicity no longer changes—termination of inelastic collisions.
- **Thermal freeze-out**: hadron momentum is fixed—end of elastic collisions.

Proton “puzzle” from statistical hadronization model



- **Statistical model:**
  three parameters
  - Chemical freeze-out temperature T
  - Baryo-chemical potential μ_b
  - Fireball volume V
- Temperature is about 162 MeV at 200 GeV.

Proton “puzzle” from statistical hadronization model



- Excluding $p/\bar{p}$, other data can be descriped by a temperature of 164 MeV.
- A good description of the $p/\bar{p}$ data with T around 150 MeV.
- This temperature results into the yield of Λ and Ω is under-predicted.

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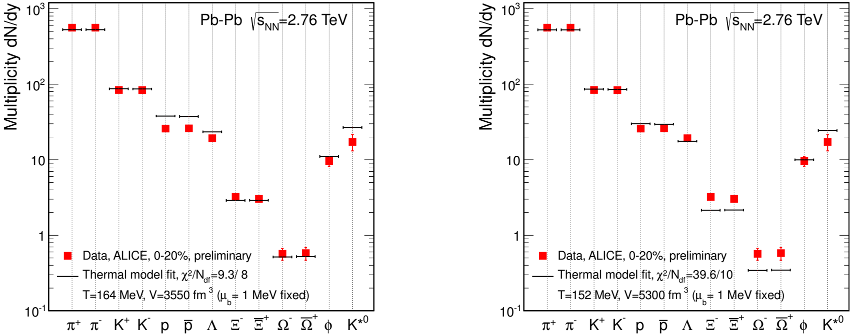

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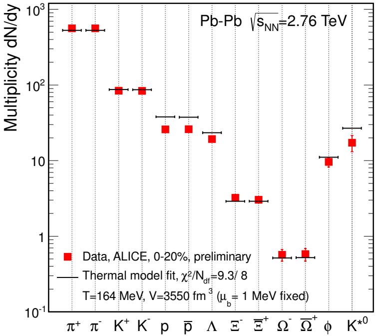
How about the result from `VISHNU`?

Proton “puzzle” from statistical hadronization model

Statistical Model



Proton "puzzle" from statistical hadronization model

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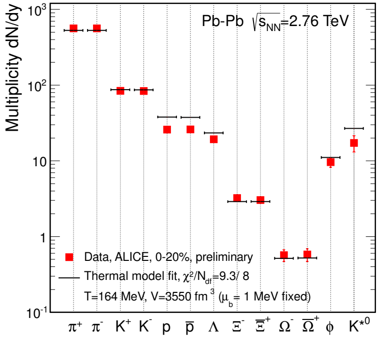
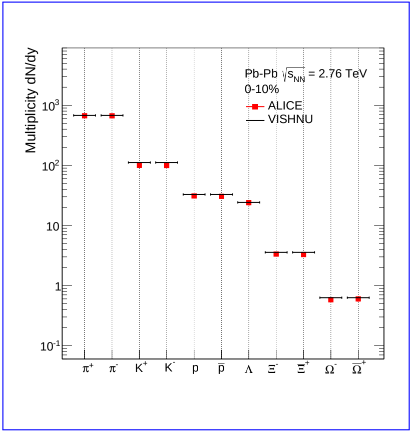


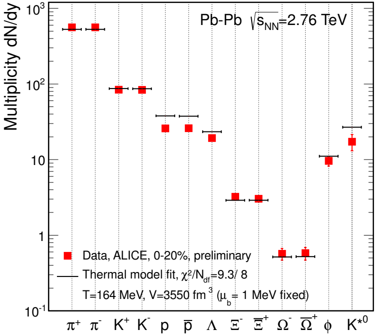
VISHNU



- Excluding $p/\bar{p}$, other data can be descriped by a temperature of 164 MeV.
- A good description of the $p/\bar{p}$ data with T around 150 MeV.
- `VISHNU` gives a nice description of all hadrons.

Proton "puzzle" from statistical hadronization model

Statistical Model



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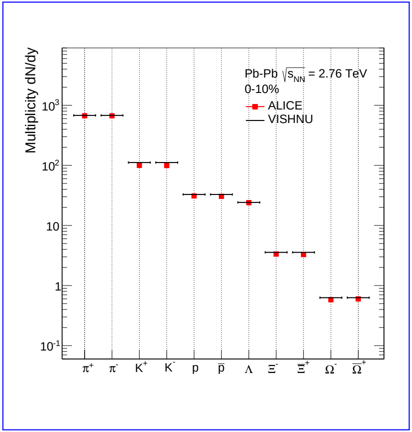

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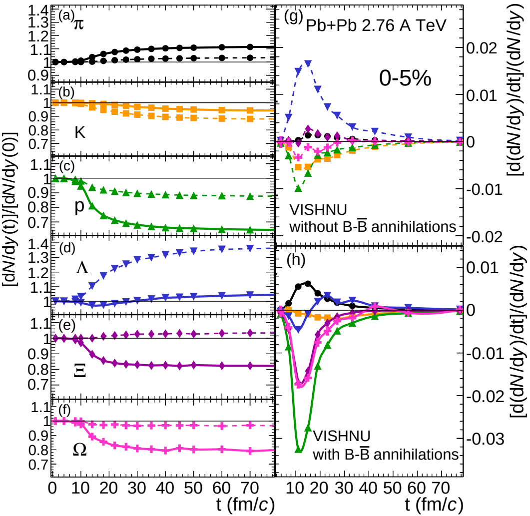
It is significant to further investigate the freeze-out with the hybrid model.

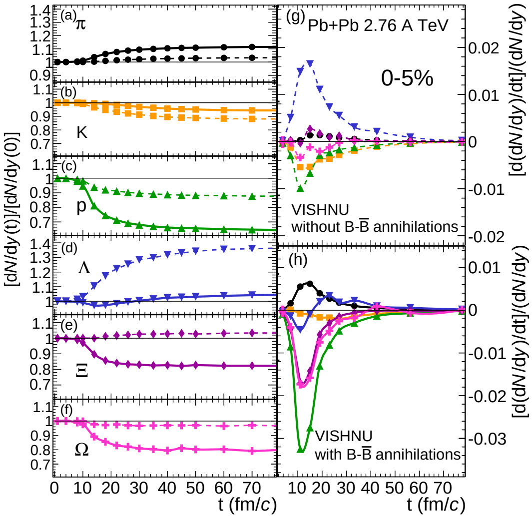
Chemical freeze-out for identified hadrons (I)



- With and without B-$\bar{B}$ annihilations.
- **Method**: define different times of the calculation and output in `UrQMD`.
  - ▶ Left panels: the ratio of multiplicity density at t to at $t = 0\ \mathrm{fm}/c$.
  - ▶ Right panels: the change rate of multiplicity density scaled by the multiplicity density at t.

X. Zhu, F. Meng, H. Song, and Y. X. Liu, PRC 2015.

Chemical freeze-out for identified hadrons (II)

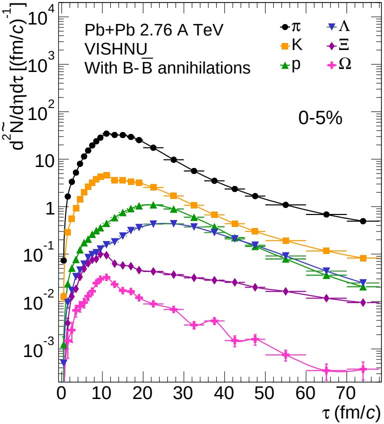


- With B-$\bar{B}$ annihilations
  - ♦ influence baryons
  - ⇒∼30% reductions for p, ∼20% reductions for Λ, and Ω.
- With and without B-$\bar{B}$
  - ♦ Ξ and Ω experience earlier chemical freeze-out.
- Different hadrons may have different effective chemical freeze-out temperature.

X. Zhu, F. Meng, H. Song, and Y. X. Liu, PRC 2015.

Further analysis of **effective chemical freeze-out** T, is needed to do when the `UrQMD` is updated to record more intermediate evolution information.

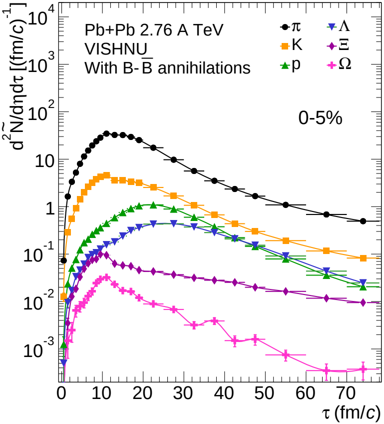
Thermal freeze-out for identified hadrons (I)



X. Zhu, F. Meng, H. Song, and Y. X. Liu, PRC 2015.

- Only with B-$\bar{B}$ annihilations
- **Thermal freeze-out time**: time of last elastic collision or decay for various hadrons species.

Thermal freeze-out for identified hadrons (II)



X. Zhu, F. Meng, H. Song, and Y. X. Liu, PRC 2015.

- The peaks of Ξ and Ω are located around 10 fm/c.
- The peaks of p and Λ are shifted to 20-30 fm/c.

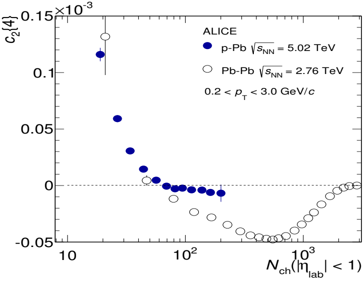
  ⇒ Multistrange hadrons experience earlier thermal freeze-out.
- Freeze-out time distributions of π and K spread widely along the time axis.

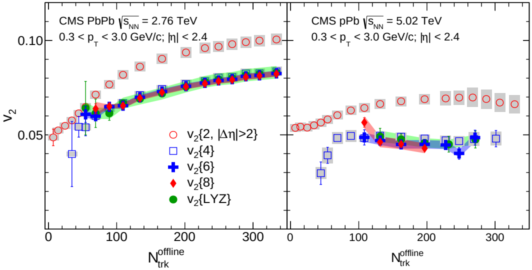
  ⇒ Meson species still suffer hadronic scattering even during the late stage.

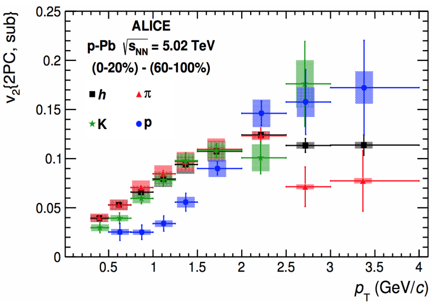
- Thermal freeze-out is strongly hadron species dependent.
- Multistrange hadrons Ξ and Ω experience earlier thermal freeze-out, as expected, due to their much smaller hadronic cross sections.

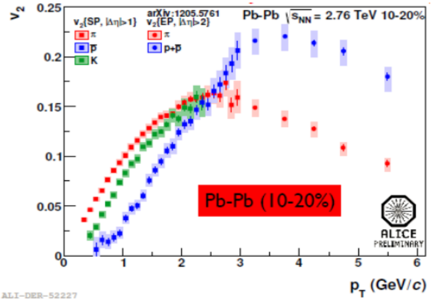
Correlations in p+Pb collisions at $\sqrt{s_{\mathrm{NN}}}$=5.02 TeV

Collective flow in p+Pb? – Experimental Observations





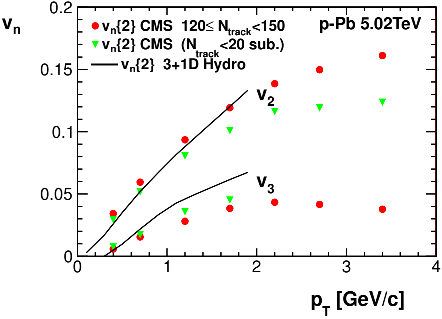


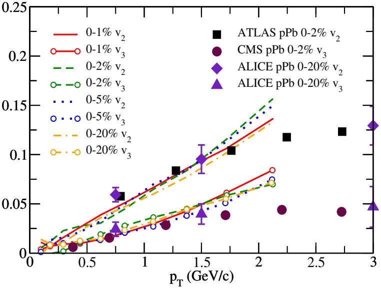


ALICE Collaboration, PRC (2014), PLB (2013); CMS Collaboration PRL (2015)

Collective flow in p+Pb? – Hydrodynamics simulations

Elliptic and triangular flow from 3+1-dimensional hydrodynamics

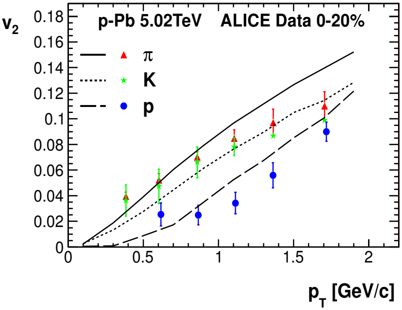


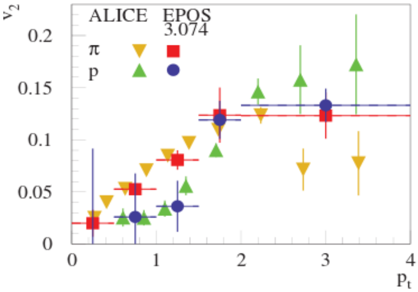


- P. Bożek *et al.*, NPA **926**, 16 (2014).
- G. Y. Qin *et al.*, PRC **89**, 044902 (2014).

Collective flow in p+Pb? – Hydrodynamics simulations

Mass ordering of v_2 for π, K, and p





- P. Bożek *et al.*, NPA **926**, 16 (2014).
- K. Werner,*et al.*, PRL **112**, 232301 (2014).

- Where does the correlations (collective flow) in 5.02 TeV p+Pb collisions come from?
  - Initial State or/and QGP?
- Is it possible to generate such flow-like correlations through pure hadronic interaction?

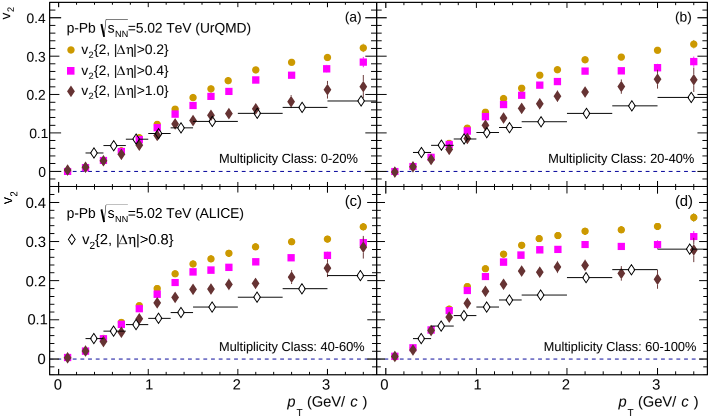
UrQMD Baseline Calculations

Y. Zhou, X. Zhu, P. Li and H. Song, Phys. Rev. C **91**, 064908 (2015).

Assumption:

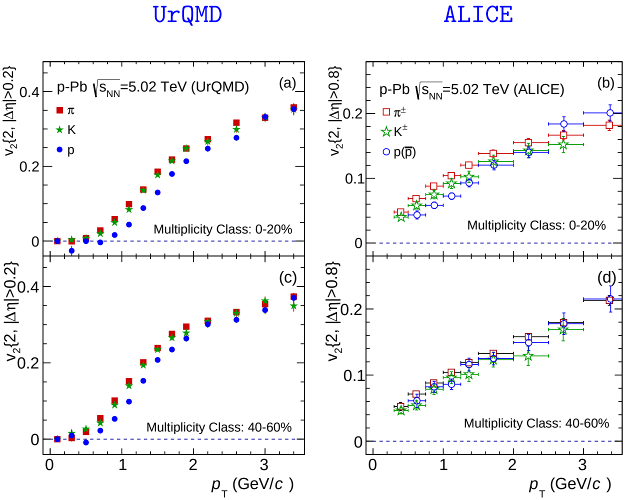
p+Pb collisions only produce hadronic systems without reach the threshold of the QGP formation

$v_2(p_T)$ in p+Pb collisions at 5.02 TeV



- Multi-particle cumulant method. Y. Zhou *et al*, PRC **91**, 064908 (2015)
- Sizeable values of $v_2\{2\}$ with different peseudorapidity gap cuts.
- With large pseudo-rapidity gap cuts, $v_2\{2\}$ from UrQMD is comparible to the experimental data

$v_2(p_T)$ mass ordering in p+Pb collisions at 5.02 TeV



Y. Zhou *et al*, PRC **91**, 064908 (2015)

- Remarkable mass ordering is produced by `UrQMD` like ALICE data, but with larger magnitude.

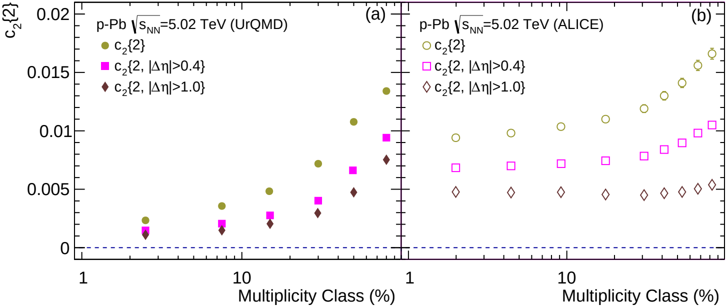
Does the Hadronic p+Pb system really flow?

Does the Hadronic p+Pb system really flow?

Check with the multi-particle method

- $v_n\{2\} = \sqrt{c_n\{2\}} \Rightarrow$ 2-particle cumulant should be **positive**.
- $v_n\{4\} = \sqrt[4]{-c_n\{4\}} \Rightarrow$ 4-particle cumulant should be **negative**.

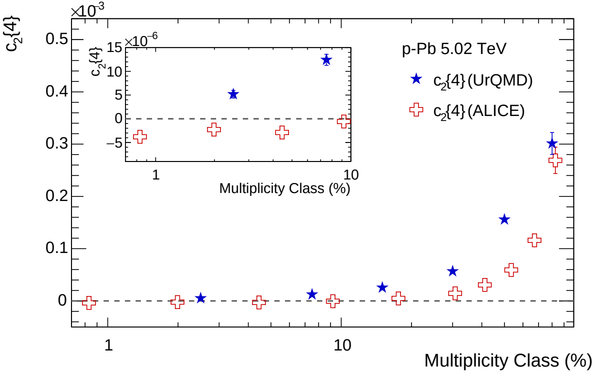
Multi-particle cumulants of v_2 from UrQMD



Y. Zhou *et al*, PRC **91**, 064908 (2015)

- 2-particle cumulant of v_2: $c_2\{2\} = \langle\langle 2\rangle\rangle = \langle\langle e^{i2(\phi_1-\phi_2)}\rangle\rangle = \langle v_2^2 + \delta_2^2\rangle$
- The UrQMD systems are largely influenced by non-flow effects
- Non-flow effects: $\delta \sim 1/M$, M multiplicity in one event
- $c_2\{2\}$ is **positive**.

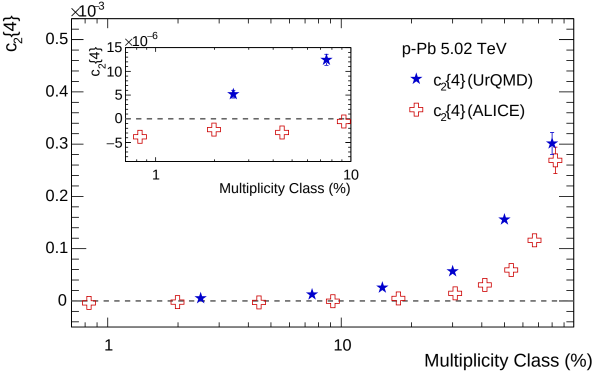
Multi-particle cumulants of v_2 from `UrQMD`



Y. Zhou *et al*, PRC **91**, 064908 (2015)

- ALICE results of $c_2\{4\}$ becomes negative when centrality $< 10\%$.
- But, $c_2\{4\}$ of `UrQMD` keeps **positive** at all centrality bins.

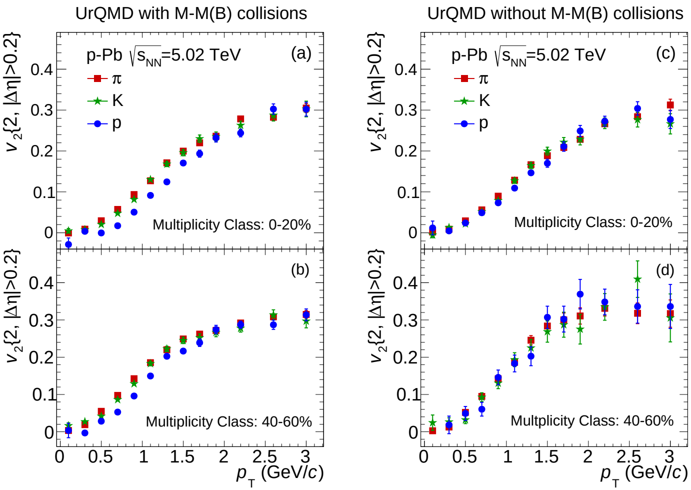
Multi-particle cumulants of v_2 from UrQMD



Y. Zhou *et al*, PRC **91**, 064908 (2015)

- ALICE results of $c_2\{4\}$ becomes negative when centrality $< 10\%$.
- But, $c_2\{4\}$ of UrQMD keeps **positive** at all centrality bins.
- UrQMD simulations for p+Pb collisions can not generate the collective flow!
- In p+Pb collisions, effects from initial state and/or QGP are needed to generate collective.

Where is the mass ordering from?



Y. Zhou *et al*, PRC **91**, 064908 (2015)

- Hadronic interaction can generate a mass ordering for 2-particle correlations.
- Some unkown cross sections are calculated by the additive quark model
  ⇒ cross sections of meson-baryon are ∼50% larger than meson-meson.

Summary

- **Multiplicity, spectra, and elliptic flow for (multi-)strange hadrons**
  - `VISHNU` gives nicely discription of the multiplicity, spectra and elliptic flow in most of centrality bins.
  - `VISHNU` nicely describes the mass ordering among π, K, p, and Ω, but fails among p, Λ and Ξ.
- **Chemical and thermal freeze-out**
  - Ξ and Ω experience earlier chemical freeze-out.
  - Thermal freeze-out is strongly hadron species dependent.
  - Ξ and Ω also experience earlier thermal freeze-out, as expected, due to their much smaller hadronic cross sections.
- **Correlations in p+Pb collisions**
  - Experimental results strongly indicate the development of collective flow.
  - Hydrodynamics semi-quantitatively reproduce these experimental data
  - `UrQMD` simulations shows hadronic interactions can not produce flow data measured in experiments; effects from initial state and /or QGP are needed
  - v_2 mass-ordering is observed in `UrQMD`, which is the consequence of hadronic interactions and not necessarily associated with strong fluid-like expansions.

Summary

- **Multiplicity, spectra, and elliptic flow for (multi-)strange hadrons**
  - `VISHNU` gives nicely discription of the multiplicity, spectra and elliptic flow in most of centrality bins.
  - `VISHNU` nicely describes the mass ordering among π, K, p, and Ω, but fails among p, Λ and Ξ.
- **Chemical and thermal freeze-out**
  - Ξ and Ω experience earlier chemical freeze-out.
  - Thermal freeze-out is strongly hadron species dependent.
  - Ξ and Ω also experience earlier thermal freeze-out, as expected, due to their much smaller hadronic cross sections.
- **Correlations in p+Pb collisions**
  - Experimental results strongly indicate the development of collective flow.
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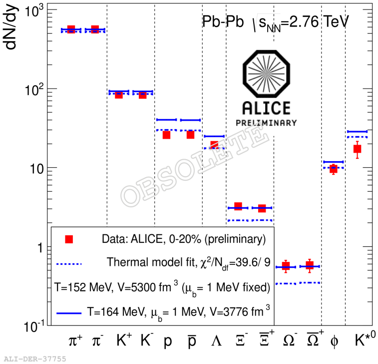
Thanks for your attention!

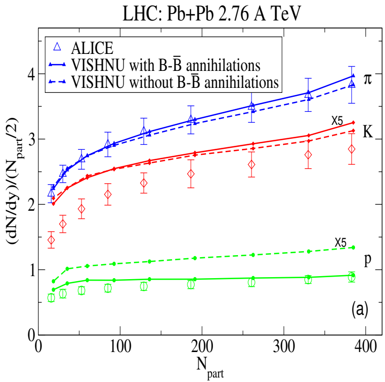
Backup

Baryon-antibaryon annihilations influence

A. Andronic *et al.*, Nucl. Phys. A **904-905**, 535c (2013).



H. Song *et al.*, PRC **89**, no. 3, 034919 (2014).

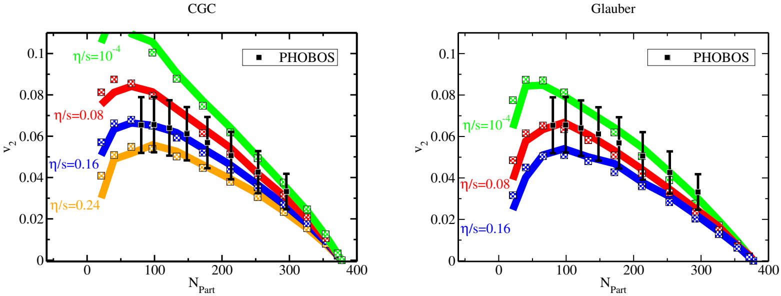


- Statistical Model does not include Baryon-antibaryon (B-$\bar{B}$) annihilations!
- B-$\bar{B}$ annihilations mainly reduce dN_p/dy and $dN_{\bar{p}}/dy$ by $\mathcal{O}(30\%)$.

B-$\bar{B}$ annihilations play an important role for a nice fit of the proton data.

η/s from viscous hydrodynamics

Specific shear viscosity η/s (how "perfect" is the created matter)

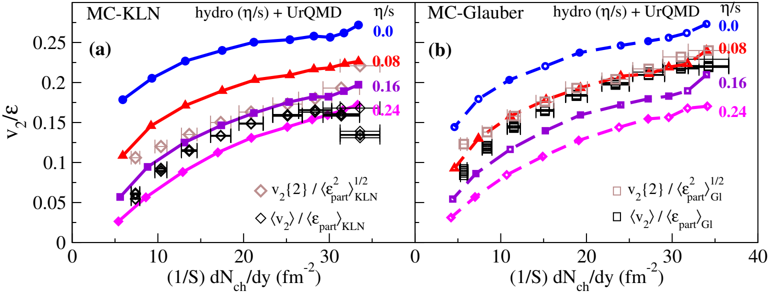


M. Luzum and P. Romatschke, Phys. Rev. C **78**, 034915 (2008).

- The mean value of η/s extracted is very small but existence.
- **No** finite chemical potential, bulk viscosity, heat flow, **hadron cascades**, three-dimensional fluid dynamic effects.

η/s from hybrid approaches

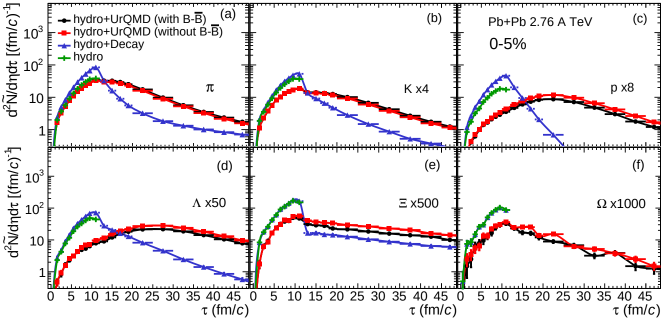
Specific shear viscosity η/s (how “perfect” is the created matter)



H. Song *et al.*, Phys. Rev. Lett. **106**, 192301 (2011).

- v_2/ε only depends on the viscosity.
- η/s is estamiated at $1 < 4\pi(\eta/s) < 2.5$.

Thermal freeze-out for identified hadrons

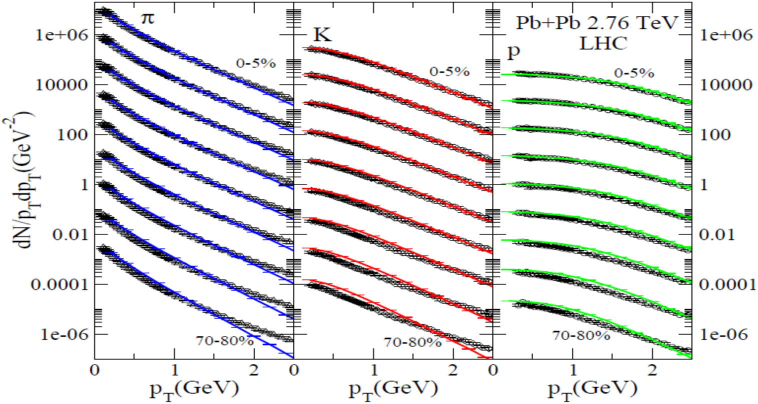


For comparisons, four simulations, `hydro`, `hydro+Decay`, `hydro+UrQMD with and without` B-$\bar{B}$, are done.

1. `hydro`: thermal freeze-out time distributions for all hadrons stop ∼10 fm/c.
2. `hydro+Decay`: resonance decays ⇒remarkable enhancement for π and p at before 10 fm/c and a long tail for π, K, p, Λ and Ξ after 10 fm/c.
3. `hydro+UrQMD`: `UrQMD` hadronic scatterings broaden thermal freeze-out time distributions of all hadron species.

What is the difference among all particle species in `hydro+UrQMD`? **Please see next** ···

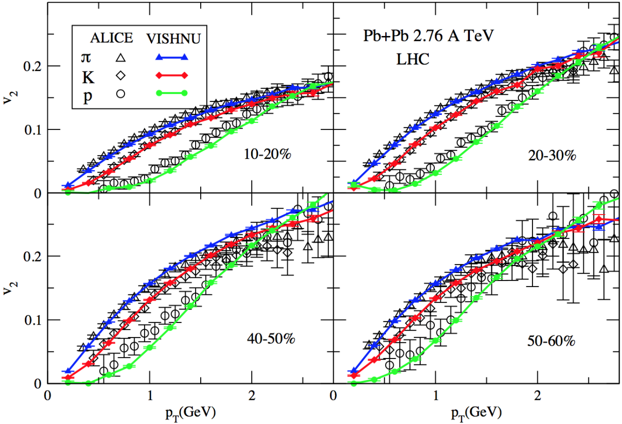
p_{T}-spectra for π, K, and p in Pb-Pb collisions



H. Song *et al.*, PRC **89**, no. 3, 034919 (2014).

`VISHNU` hybrid model gives a good discription of spectra for π, K, and p at central and semi-central collisions.

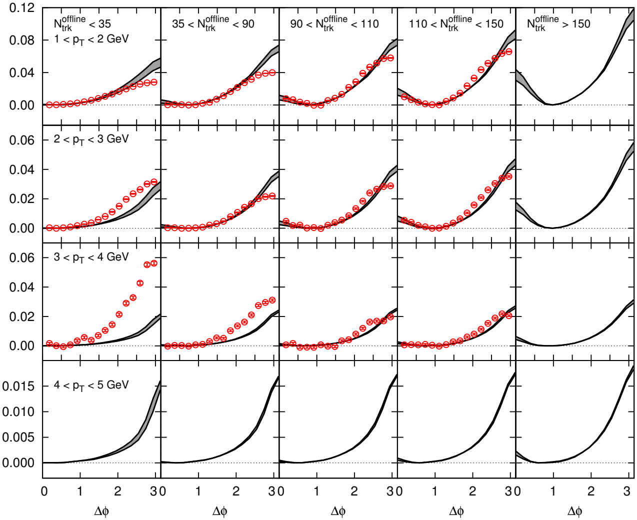
Elliptic flow for π, K, and p in Pb-Pb collisions



H. Song *et al.*, PRC **89**, no. 3, 034919 (2014).

- `VISHNU` gives a good discription of elliptic flow data for π, K and p.

Correlations from Initial States



K. Dusling and R. Venugopalan, Phys. Rev. D **87**, no. 9, 094034 (2013)