LHCP2021

The Ninth Annual Conference on Large Hadron Collider Physics

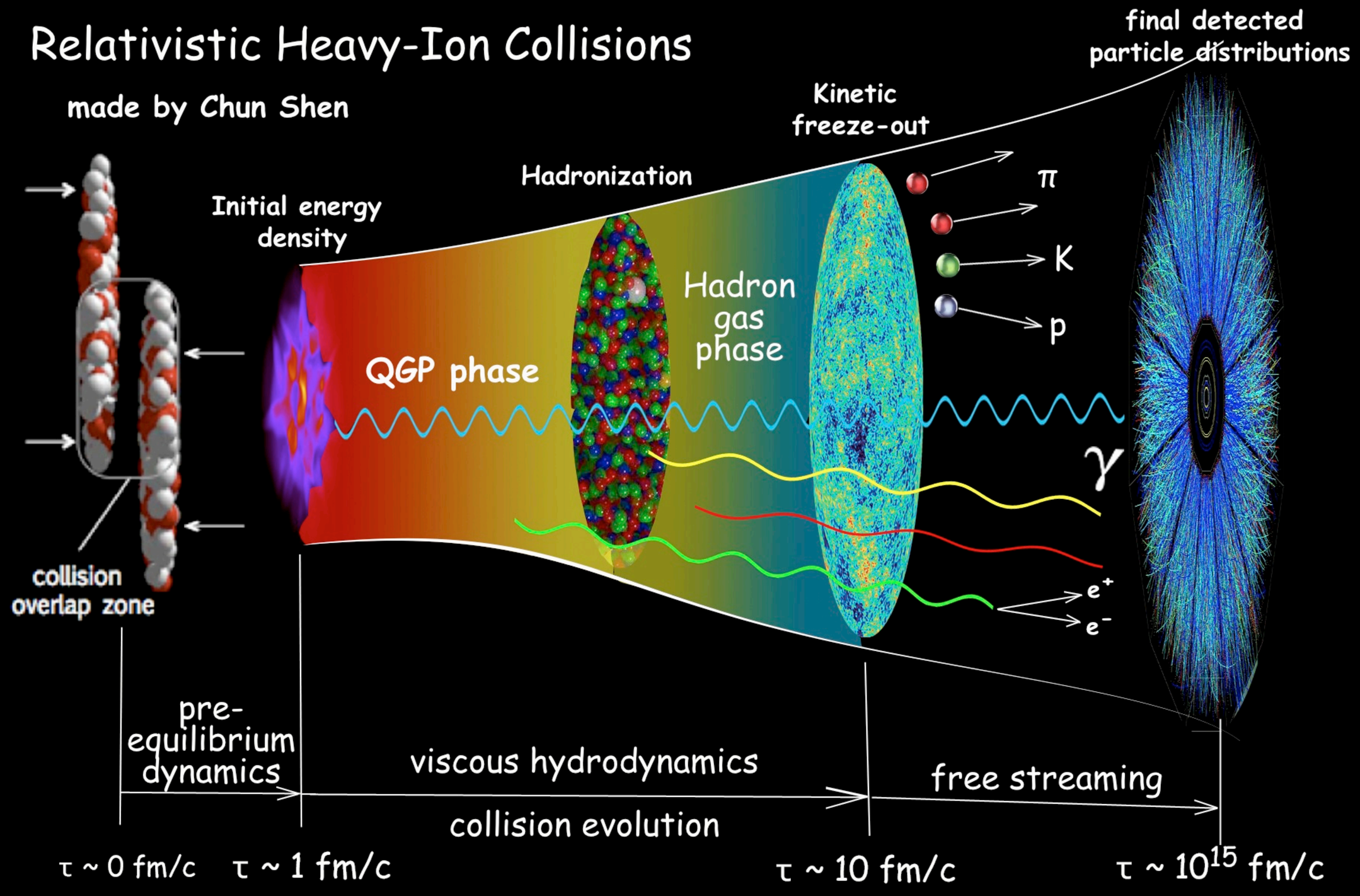
Soft particle production from the QGP

Alice Ohlson
Lund University

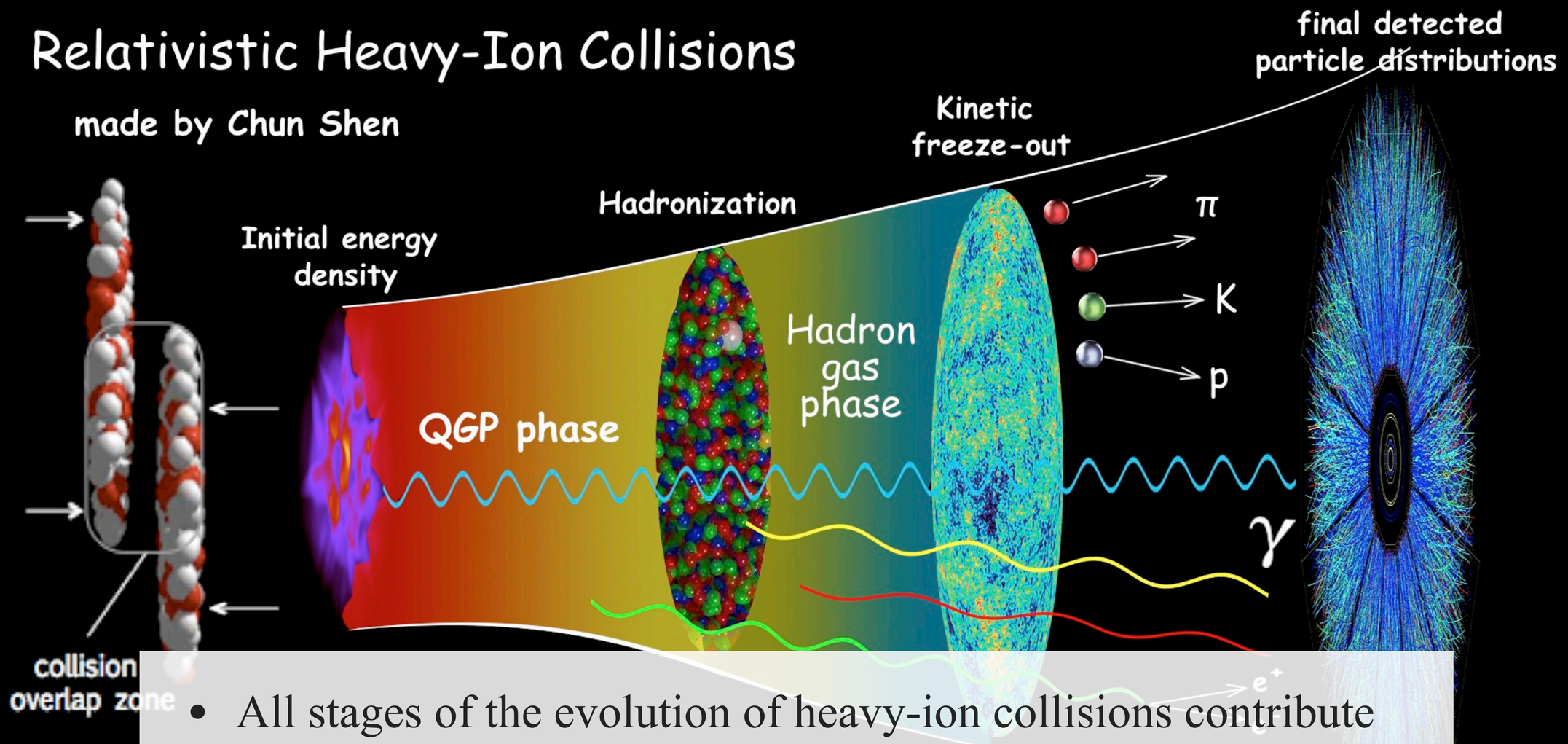
11 June 2021

Relativistic Heavy-Ion Collisions

made by Chun Shen



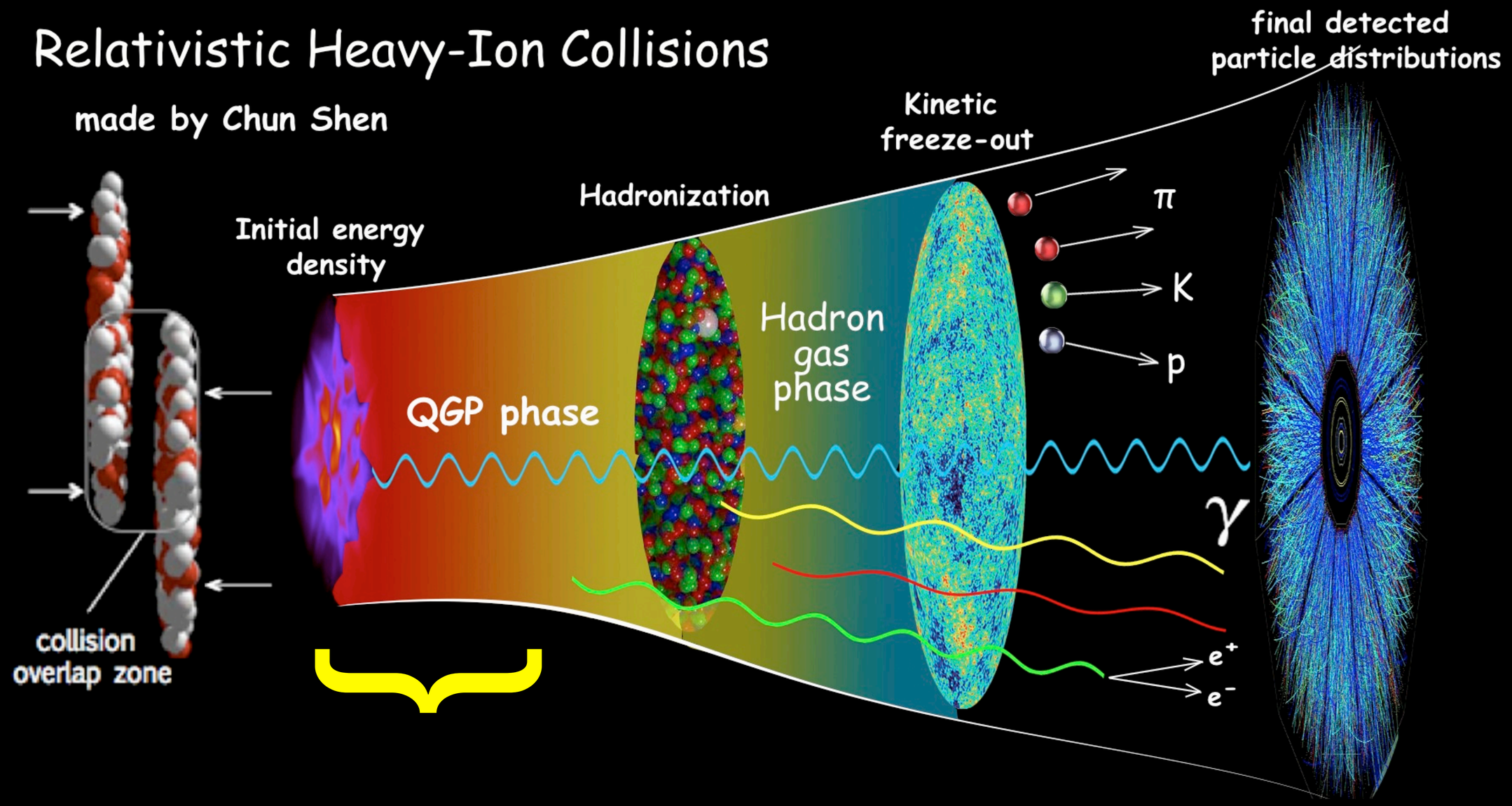
Relativistic Heavy-Ion Collisions



- All stages of the evolution of heavy-ion collisions contribute to the production and dynamics of soft final-state particles
- Precision measurements of soft particle production and kinematics give us information about the properties of the QGP and its evolution

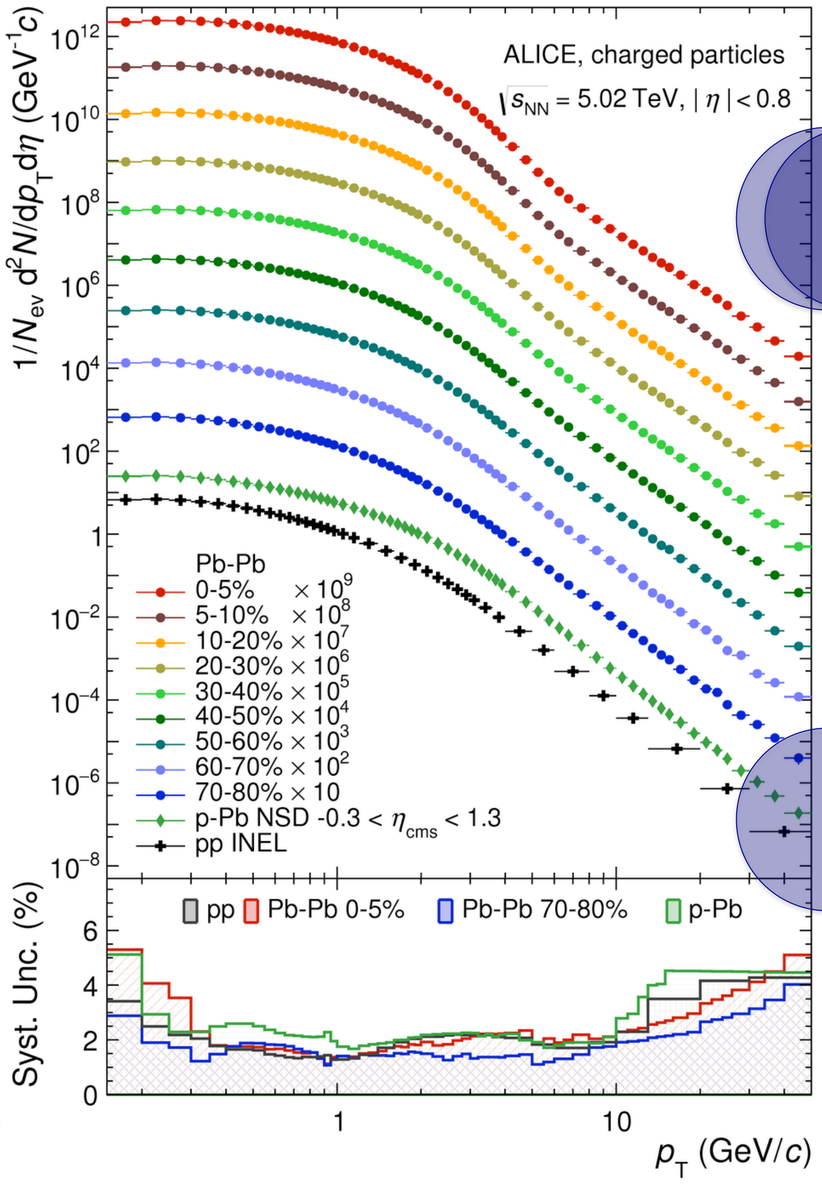
Relativistic Heavy-Ion Collisions

made by Chun Shen



Isotropic expansion of the fireball

- Pressure gradients build up in the fireball
- Particles boosted in the radial direction
  → "radial flow"
  → higher mean p_T



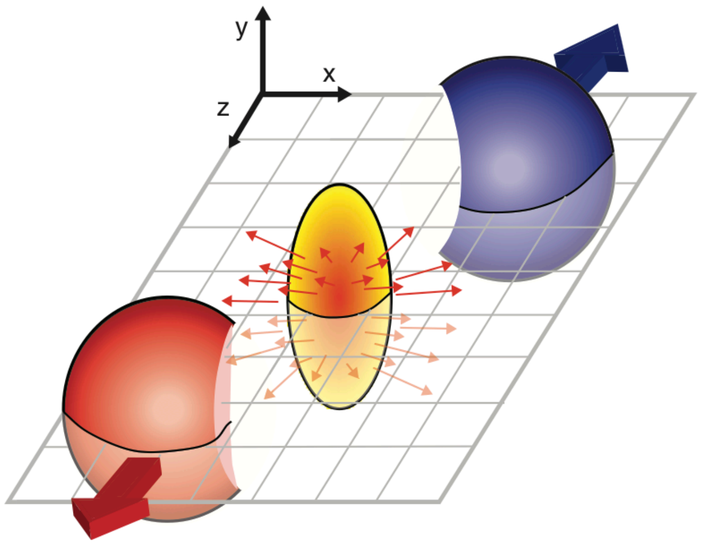
ALICE, JHEP 11 (2018) 013,
arxiv: 1802.09145 [nucl-ex]

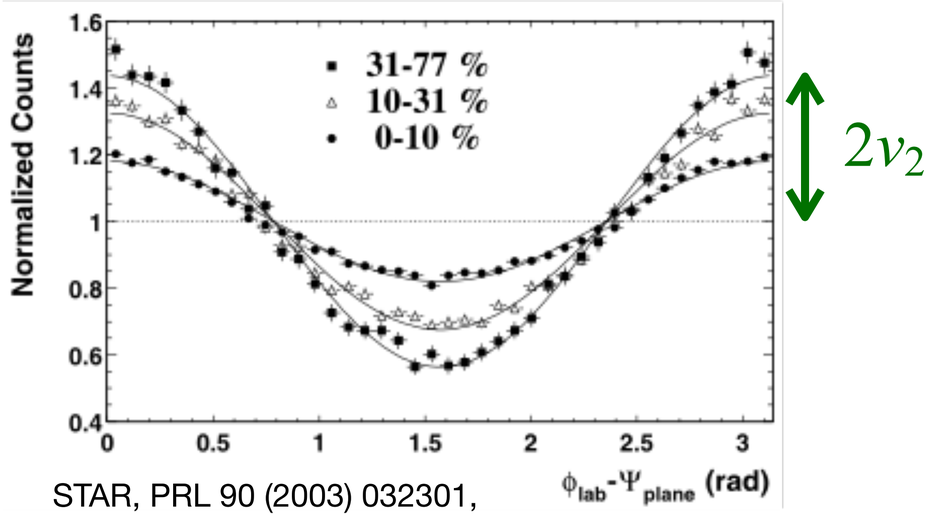
Anisotropic expansion of the fireball

- Pressure gradients build up in the fireball
- Particles boosted in the radial direction
  → "radial flow"
  → higher mean p_T
- Anisotropic interaction region in non-central collisions
  → Particles boosted in-plane more than out-of-plane
- Particle distribution described by a Fourier cosine series

$$dN/d\varphi \sim 1 + 2v_2\cos(2(\varphi-\Psi_2))$$

- v_2 → "elliptic flow"





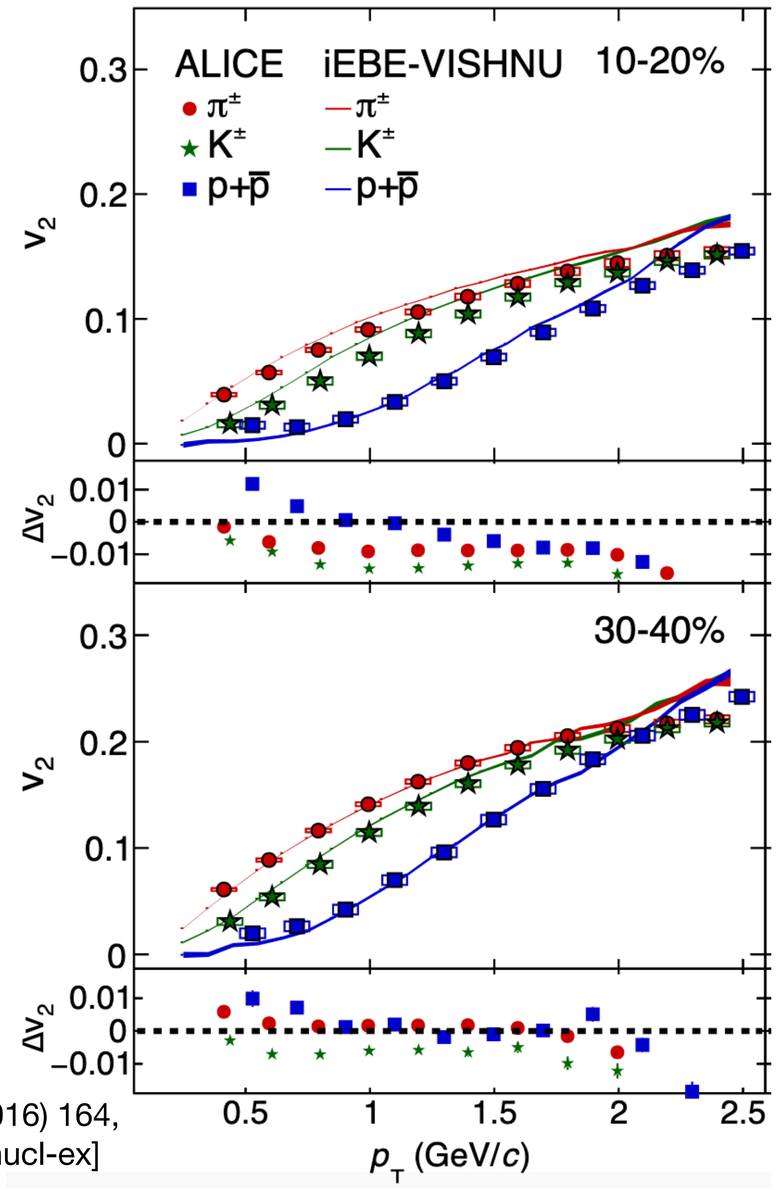
STAR, PRL 90 (2003) 032301, arXiv:nucl-ex/0206006

Anisotropic expansion of the fireball

- Pressure gradients build up in the fireball
- Particles boosted in the radial direction
  → "radial flow"
  → higher mean p_T
- Anisotropic interaction region in non-central collisions
  → Particles boosted in-plane more than out-of-plane
- Particle distribution described by a Fourier cosine series

$$dN/d\varphi \sim 1 + 2v_2\cos(2(\varphi-\Psi_2))$$

- v_2 → "elliptic flow"
- Measurements of v_2 are described very well by hydrodynamic models
  → QGP behaves as a liquid with viscosity (η/s) near the quantum lower bound, the "perfect liquid"



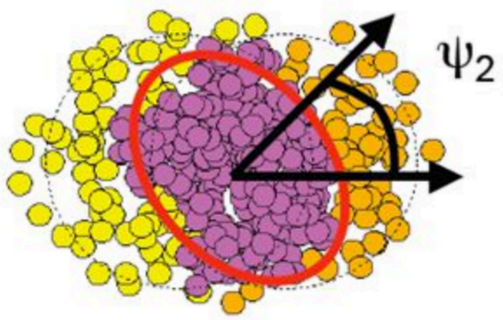
ALICE, JHEP 09 (2016) 164, arXiv:1606.06057 [nucl-ex]

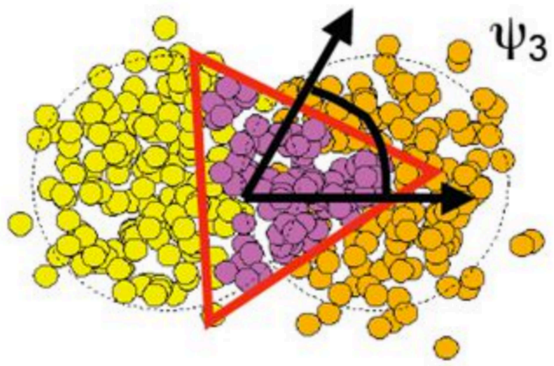
Anisotropic expansion of the fireball

- Pressure gradients build up in the fireball
- Particles boosted in the radial direction
  → "radial flow"
  → higher mean p_T
- Anisotropic interaction region in non-central collisions
  → Particles boosted in-plane more than out-of-plane
- Particle distribution described by a Fourier cosine series

$$dN/d\varphi \sim 1 + 2v_2\cos(2(\varphi-\Psi_2))$$

- v_2 → "elliptic flow"
- Measurements of v_2 are described very well by hydrodynamic models
  → QGP behaves as a liquid with viscosity (η/s) near the quantum lower bound, the "perfect liquid"

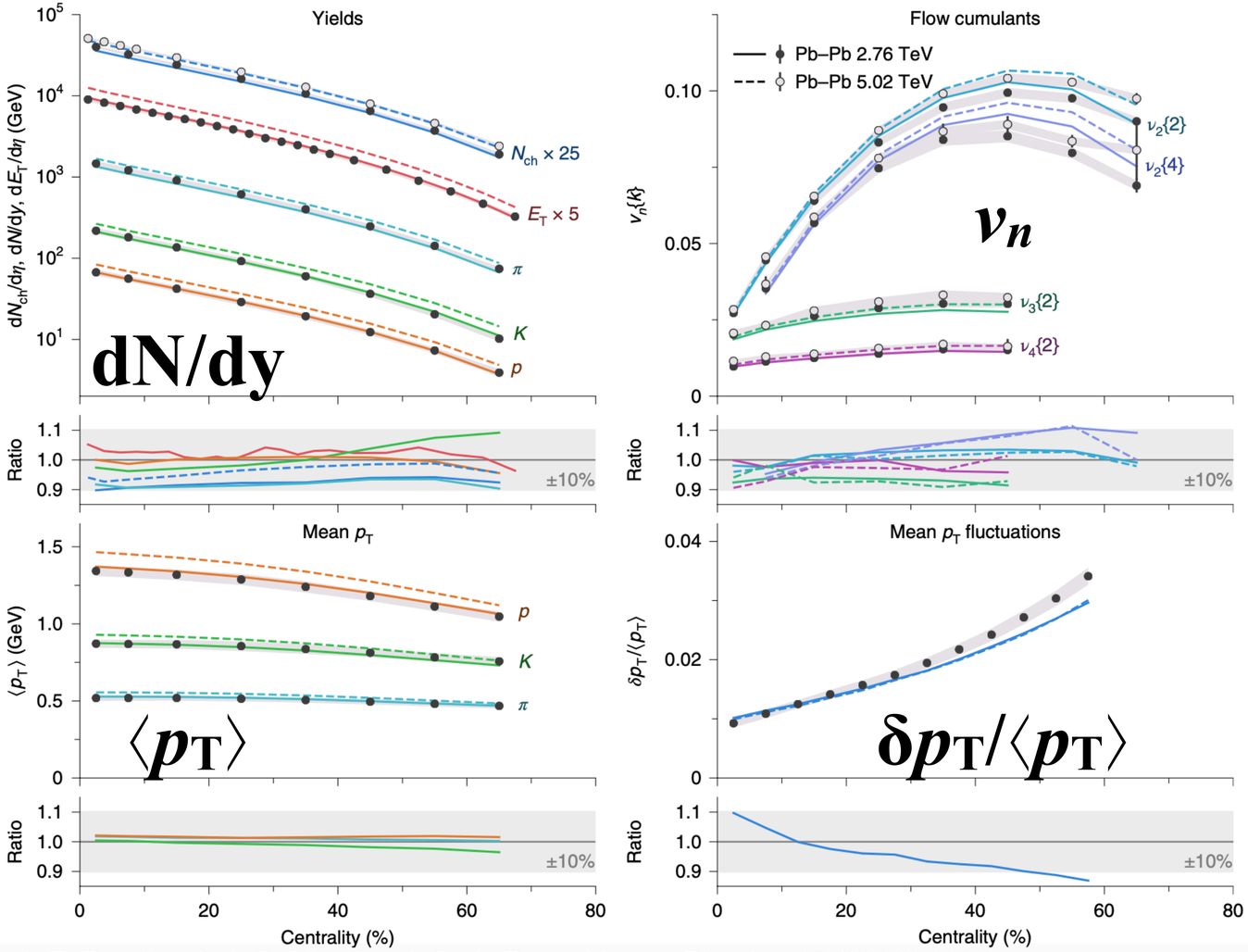




- Fluctuations of the positions of nucleons lead to higher-order flow coefficients
  → v_3, v_4, v_5…

Extracting QGP properties with flow

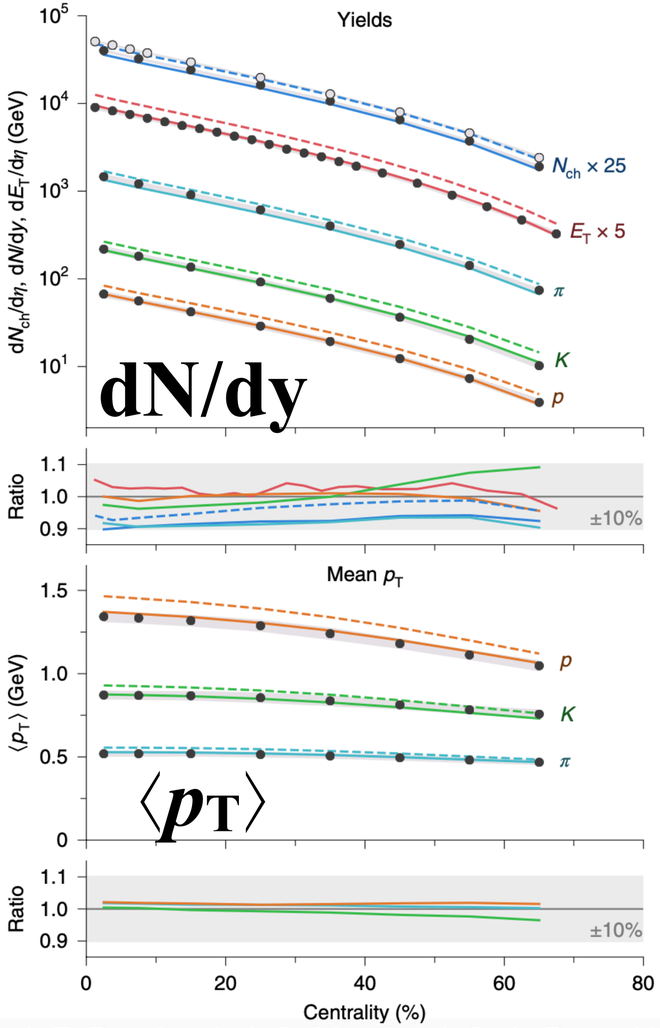
- Bayesian analysis of particle yields, mean p_T, v_2, v_3, v_4 measured by ALICE

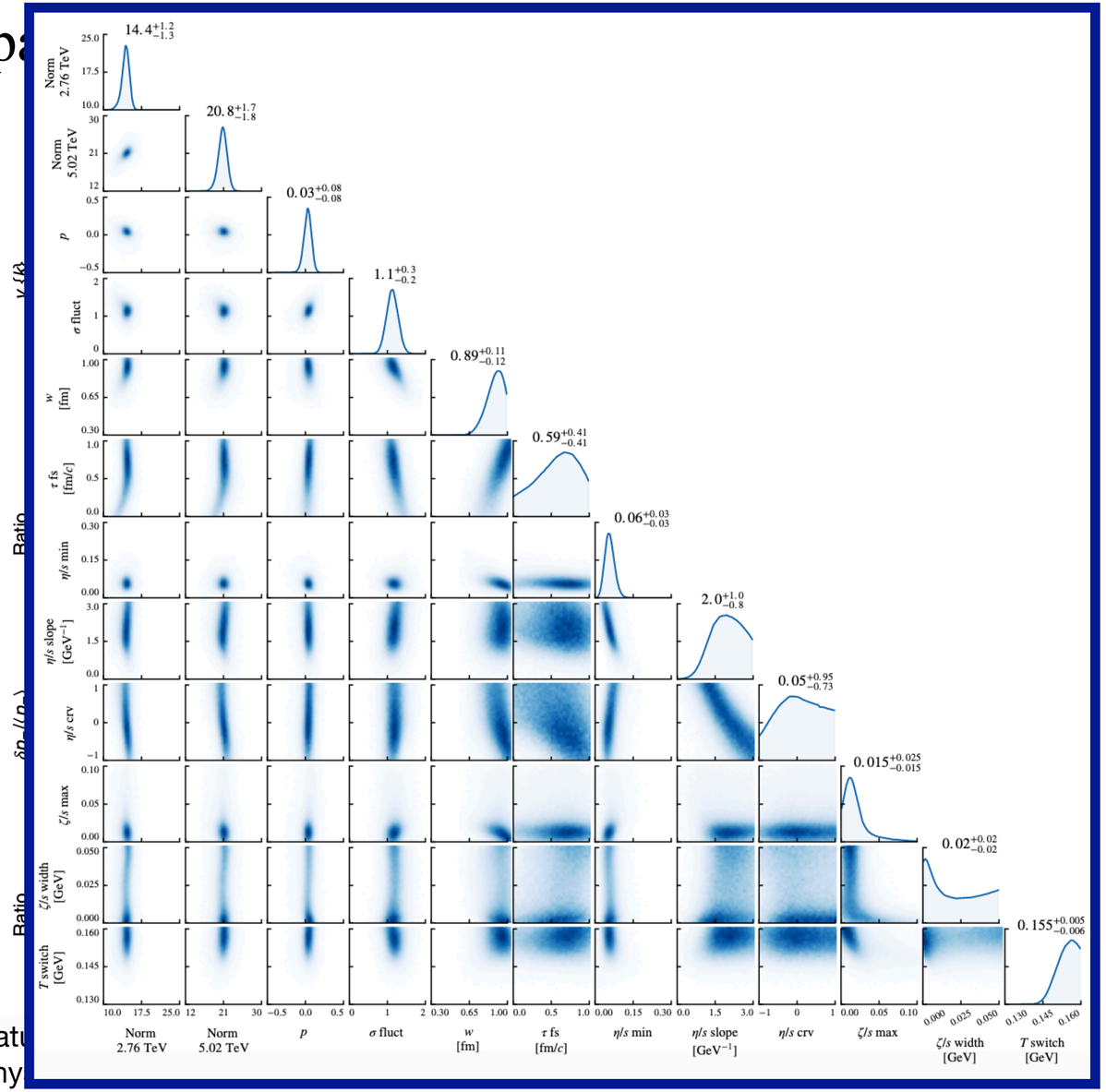


J. E. Bernhard, J. S. Moreland, S. A. Bass, Nature Physics 15 (2019) 1113
J. S. Moreland, J. E. Bernhard, S. A. Bass, Phys. Rev. C 101 (2020) 024911, arXiv:1808.02106 [nucl-th]

Extracting QGP properties with flow

- Bayesian analysis of pa ALICE



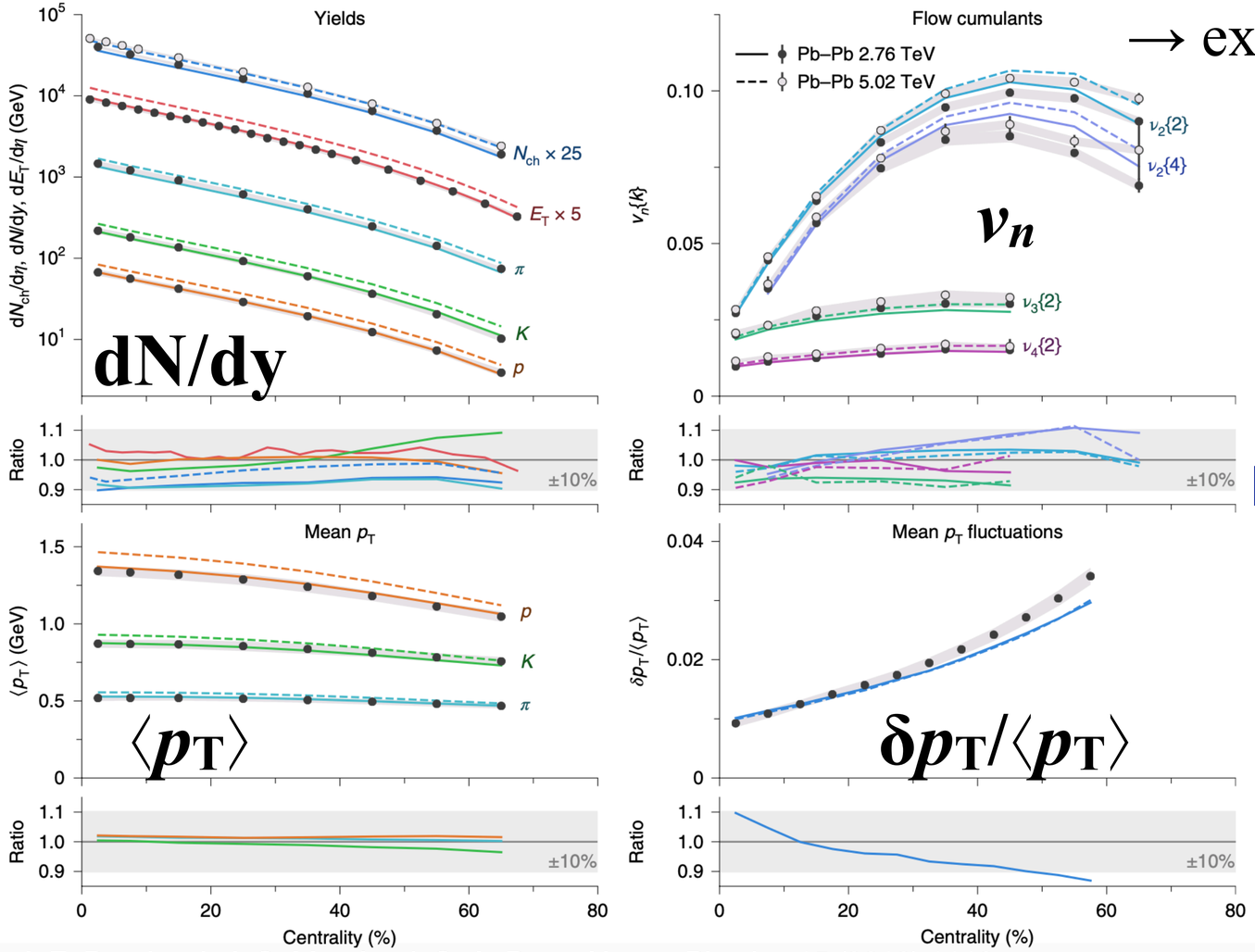


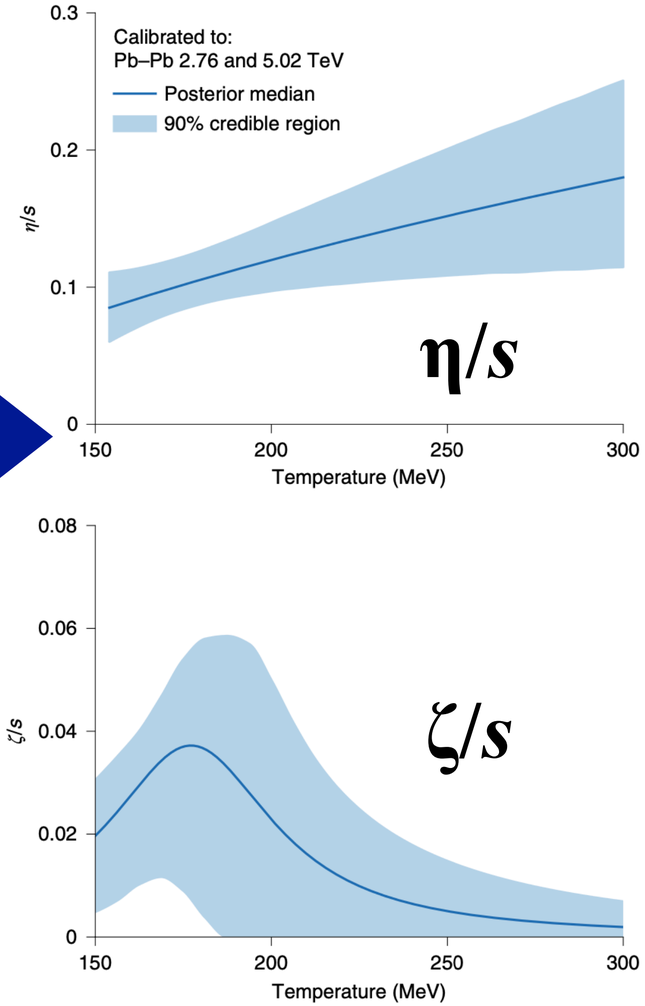
J. E. Bernhard, J. S. Moreland, S. A. Bass, Natu
J. S. Moreland, J. E. Bernhard, S. A. Bass, Phy

Extracting QGP properties with flow

- Bayesian analysis of particle yields, mean p_T, v_2, v_3, v_4 measured by ALICE

→ extract shear and bulk viscosity $\eta/s(T)$, $\zeta/s(T)$

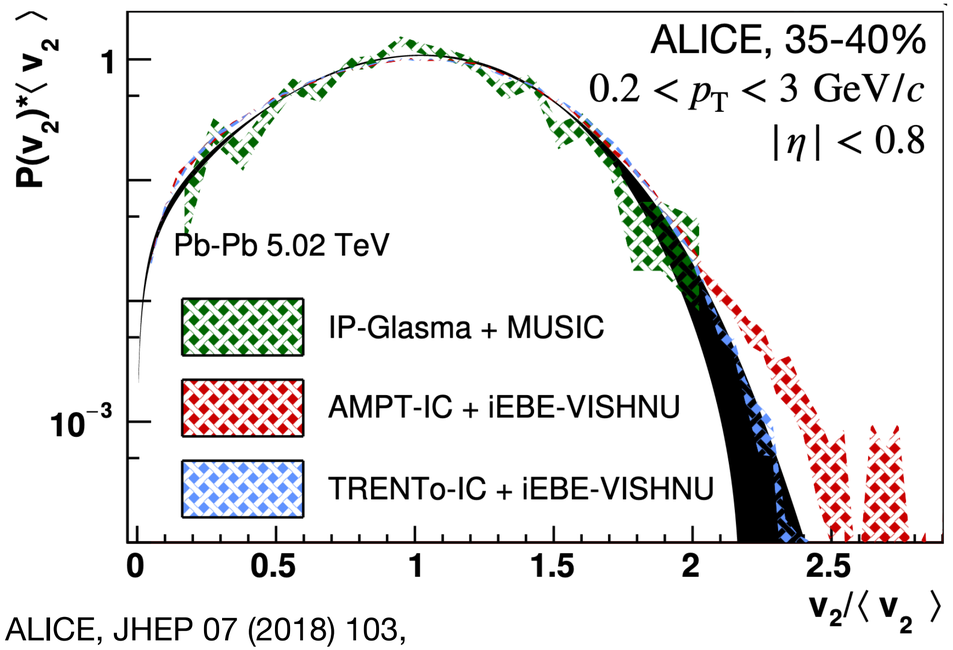




J. E. Bernhard, J. S. Moreland, S. A. Bass, Nature Physics 15 (2019) 1113
J. S. Moreland, J. E. Bernhard, S. A. Bass, Phys. Rev. C 101 (2020) 024911, arXiv:1808.02106 [nucl-th]

Beyond v_n: flow fluctuations

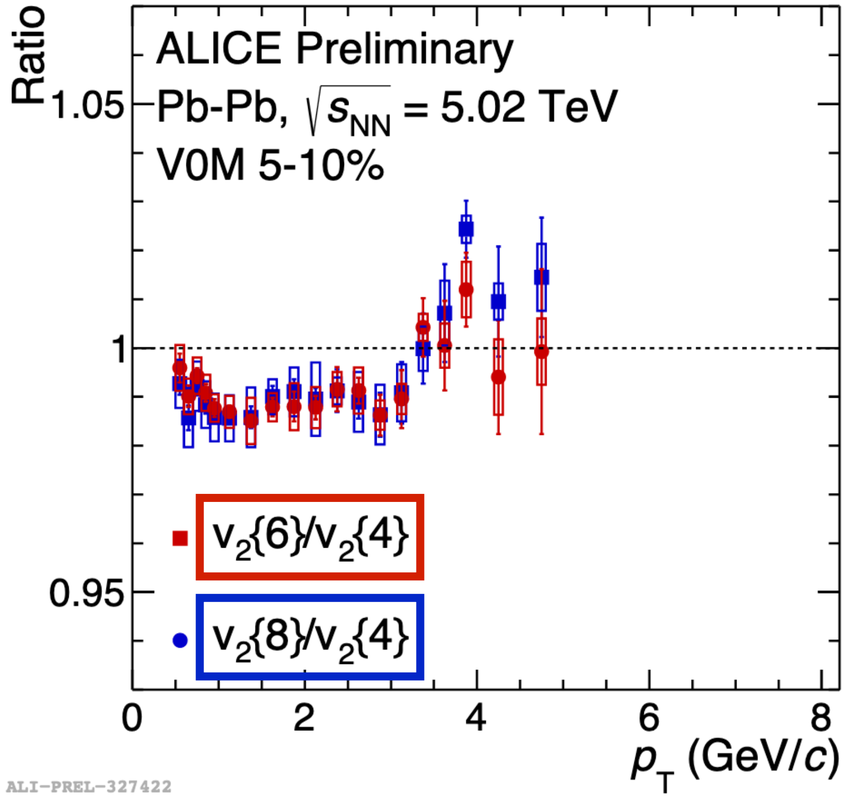
- Measure non-Bessel-Gaussian nature of flow distribution using cumulants

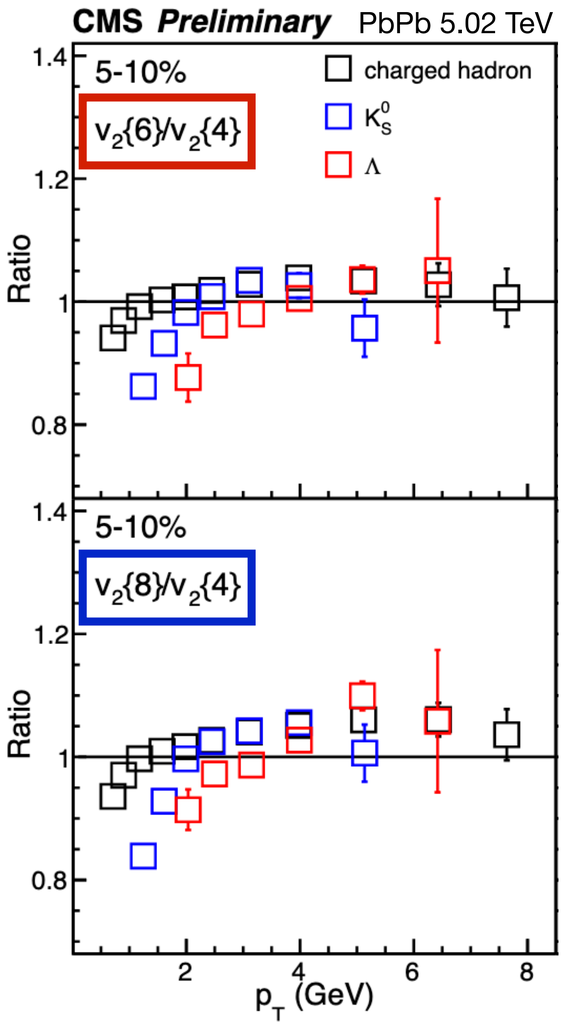


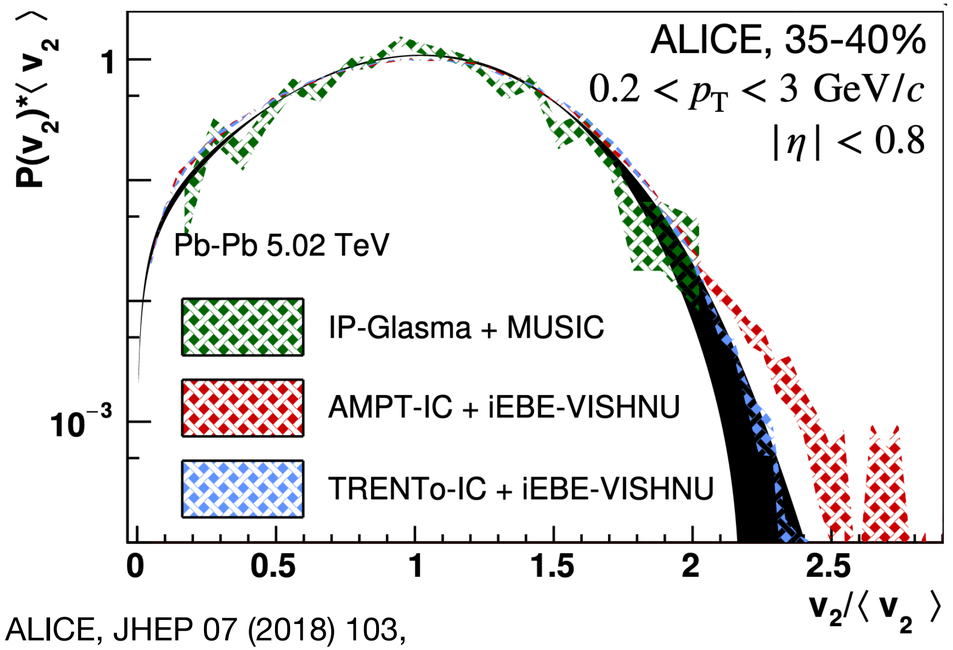
ALICE, JHEP 07 (2018) 103, arXiv:1804.02944 [nucl-ex]

Beyond v_n: flow fluctuations

- Measure non-Bessel-Gaussian nature of flow distribution using cumulants





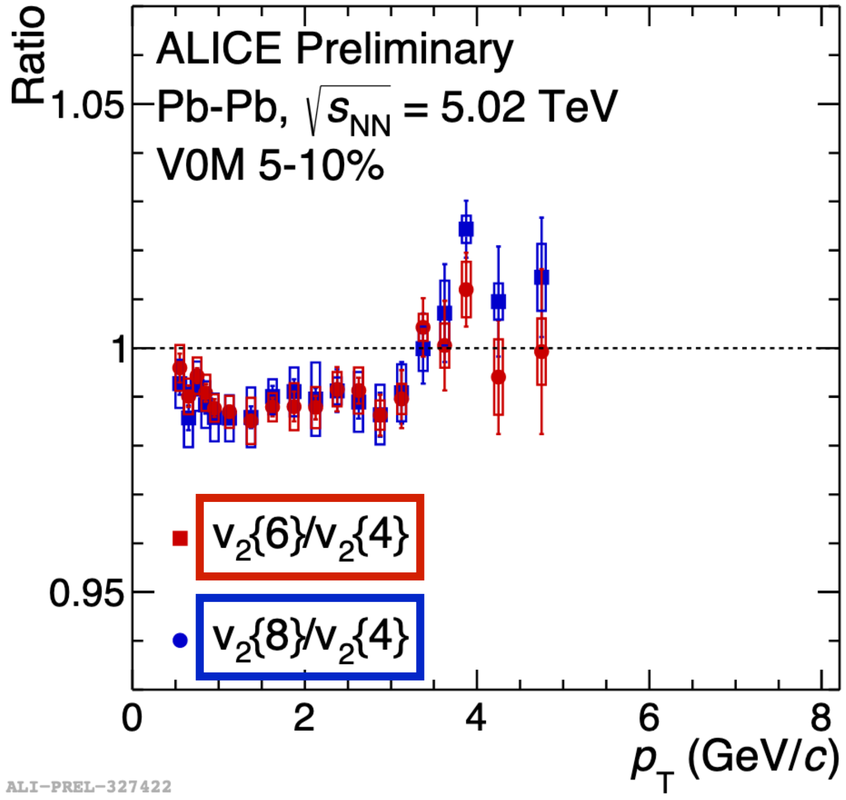


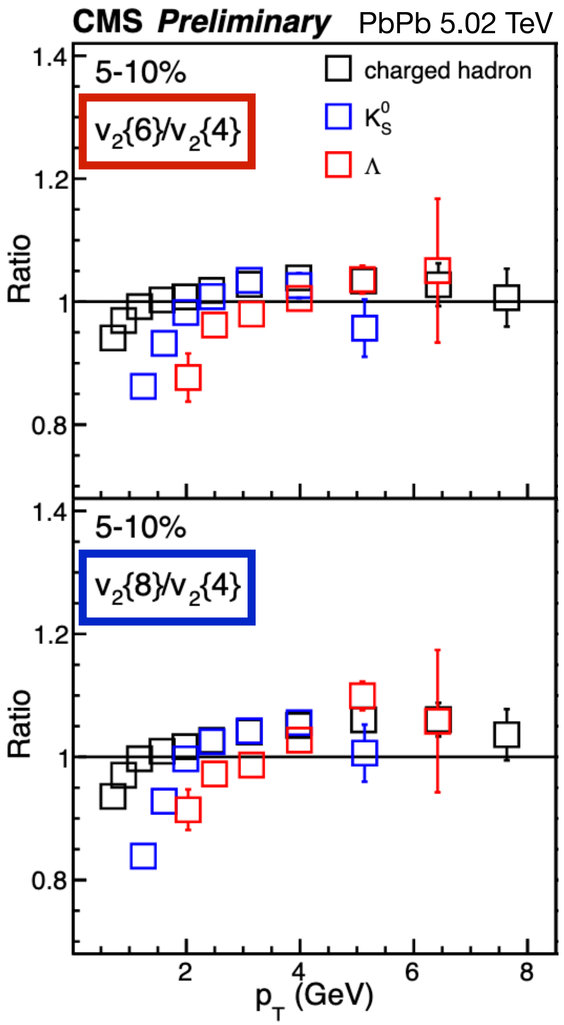
ALICE, JHEP 07 (2018) 103, arXiv:1804.02944 [nucl-ex]

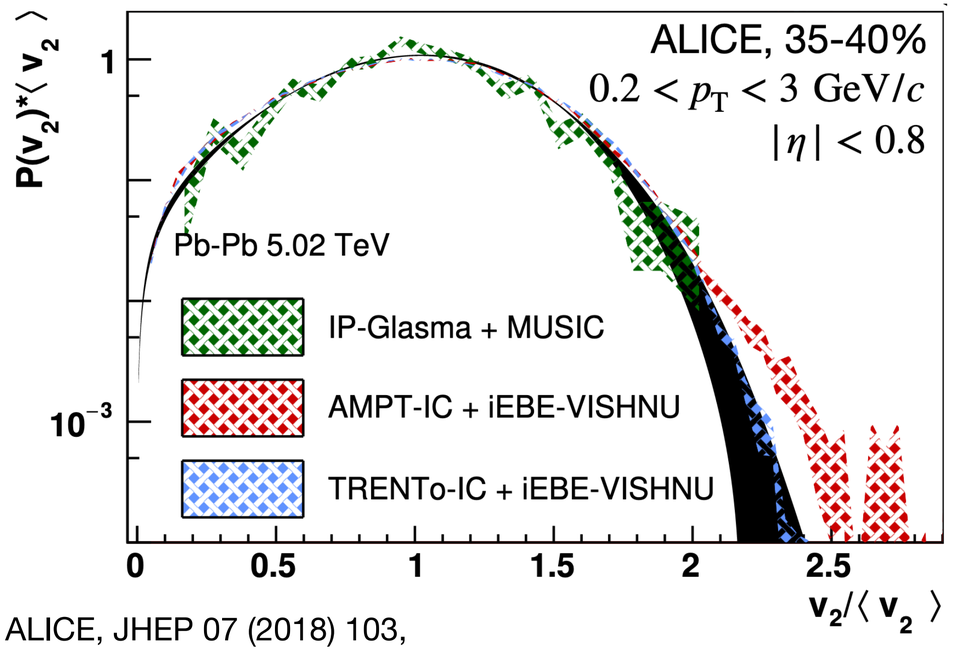
V. Vislavicius
Heavy ion parallel session
Wednesday 16:15

Beyond v_n: flow fluctuations

- Measure non-Bessel-Gaussian nature of flow distribution using cumulants







ALICE, JHEP 07 (2018) 103, arXiv:1804.02944 [nucl-ex]

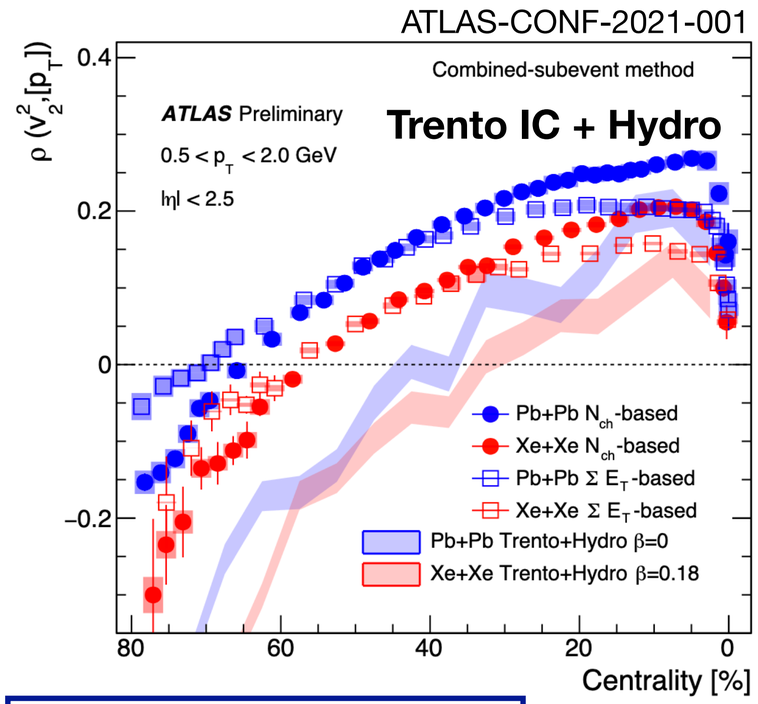
- Precision measurements of v_n distribution provide strong constraints on models of expansion dynamics and medium properties

V. Vislavicius
Heavy ion parallel session
Wednesday 16:15

Beyond v_n: flow correlations

- Correlations between radial flow and anisotropic flow
  - sensitive to initial energy deposition, nuclear deformation, and interplay between system expansion and anisotropy

$$\rho\left(v_n^2, \langle p_T \rangle\right) = \frac{cov\left(v_n^2, \langle p_T \rangle\right)}{\sqrt{var\left(v_n^2\right)}\sqrt{var\left(\langle p_T \rangle\right)}}$$



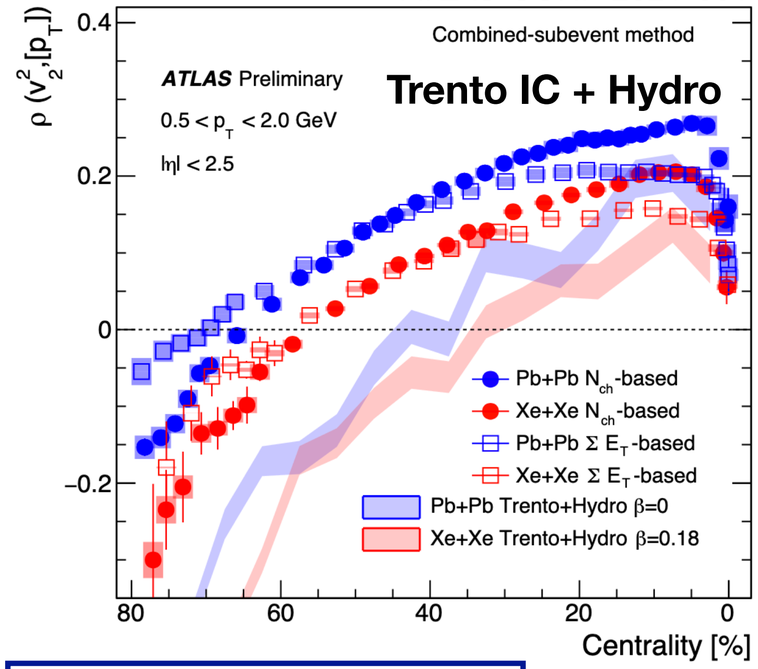
V. Vislavicius
Heavy ion parallel session
Wednesday 16:15

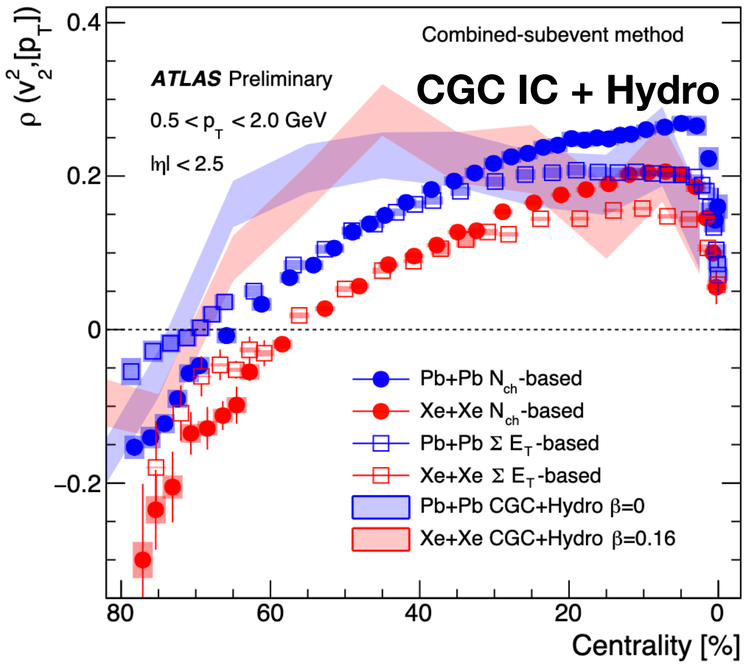
Beyond v_n: flow correlations

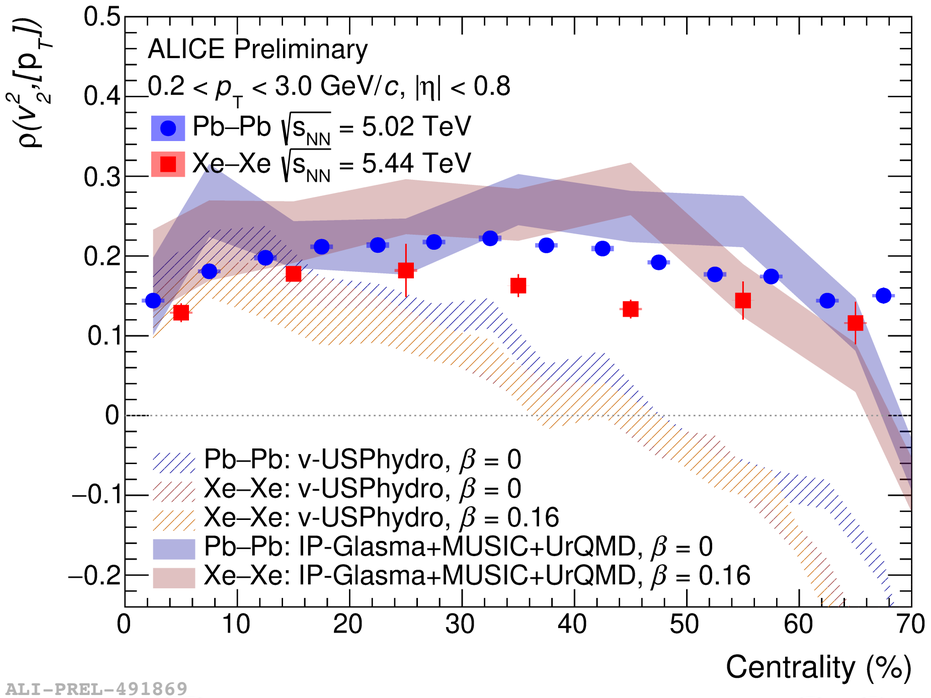
- Correlations between radial flow and anisotropic flow
  - sensitive to initial energy deposition, nuclear deformation, and interplay between system expansion and anisotropy

$$\rho\left(v_n^2, \langle p_T \rangle\right) = \frac{cov\left(v_n^2, \langle p_T \rangle\right)}{\sqrt{var\left(v_n^2\right)}\sqrt{var\left(\langle p_T \rangle\right)}}$$

ATLAS-CONF-2021-001



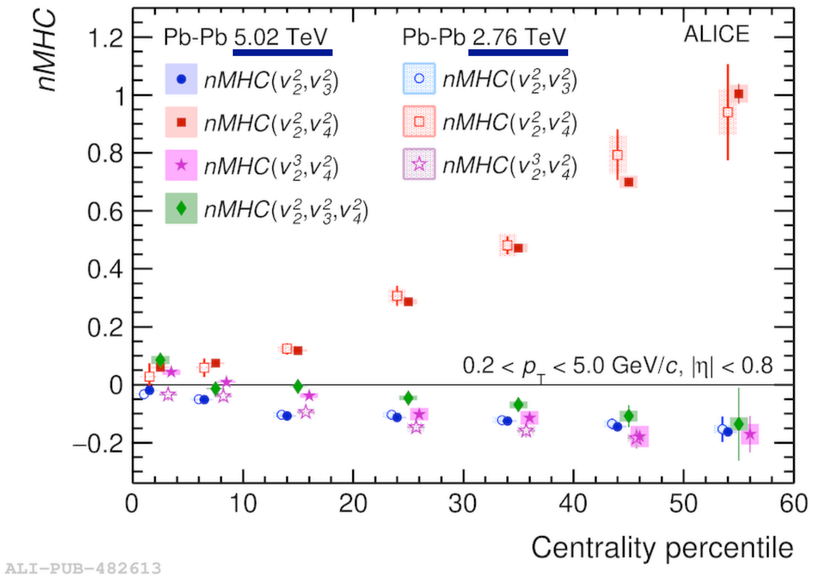




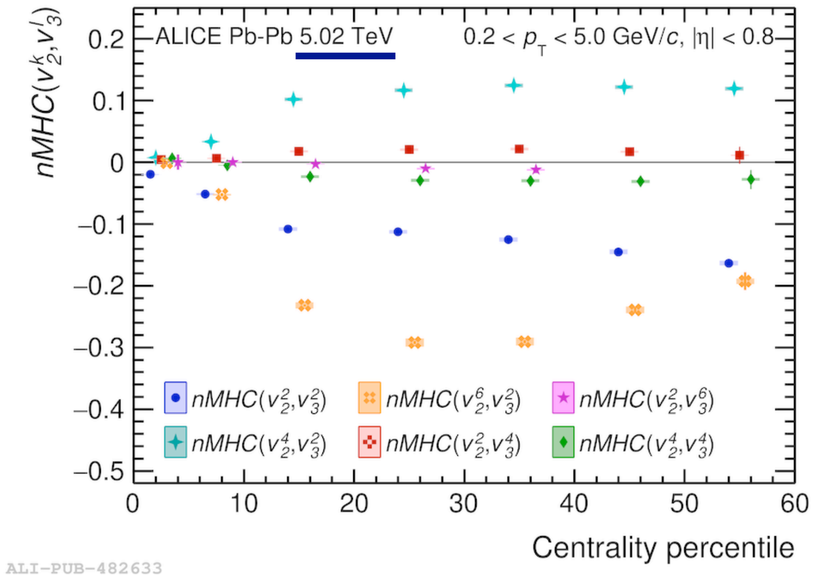
V. Vislavicius
Heavy ion parallel session
Wednesday 16:15

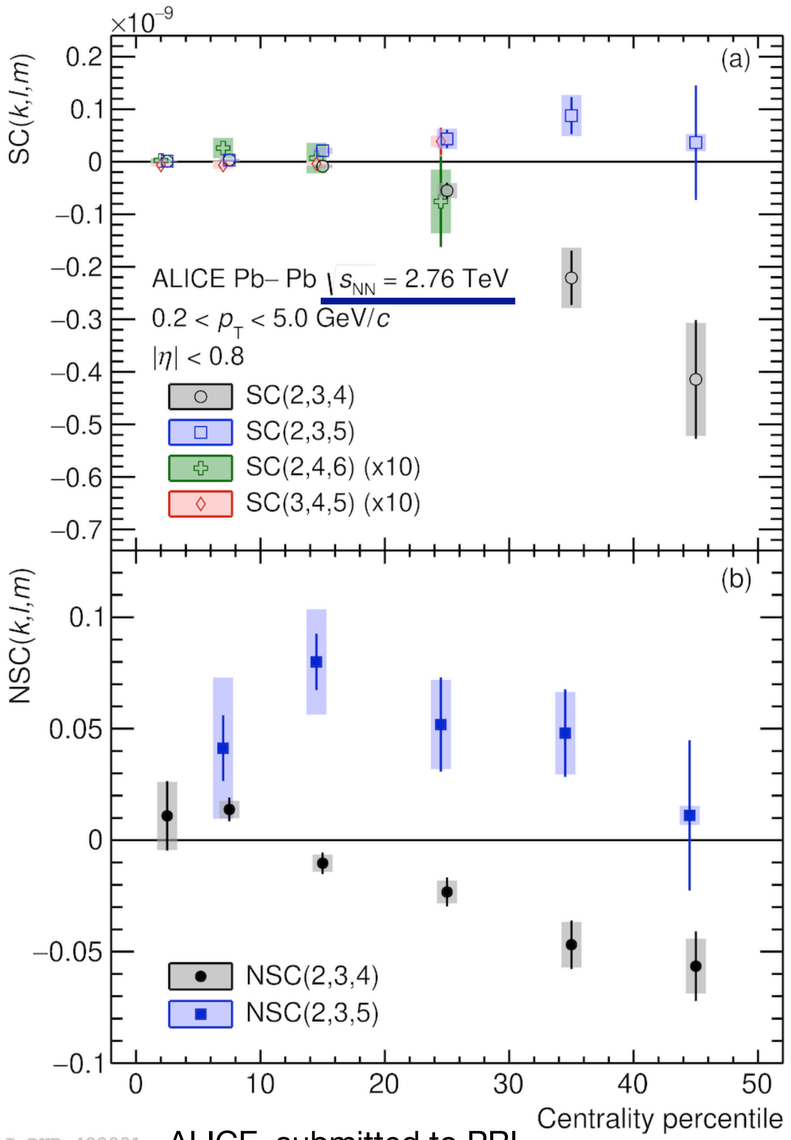
Beyond v_n: flow correlations

- Correlations between flow harmonics of different orders
  - sensitive to initial conditions and final state interactions
  - measurements now extended to correlations between three harmonics, and eight-particle correlations



ALICE, PLB 818 (2021) 136354, arXiv:2102.12180 [nucl-ex]

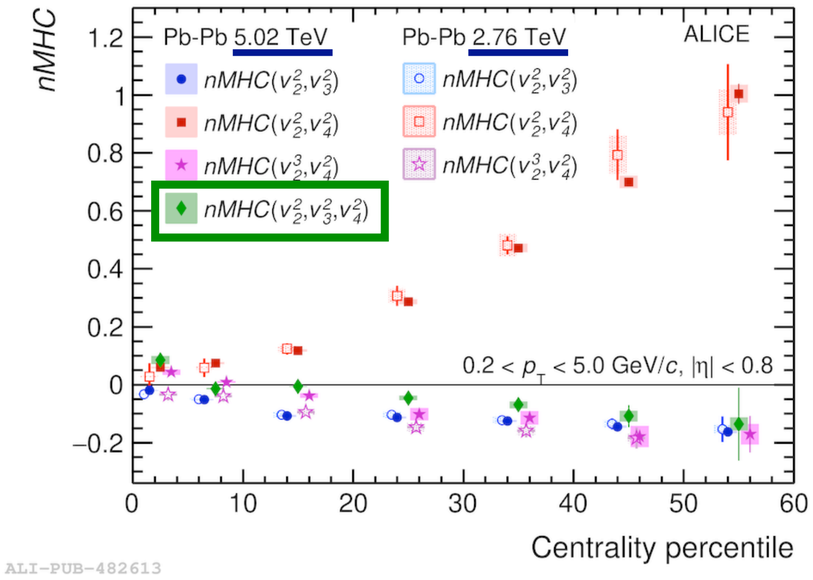




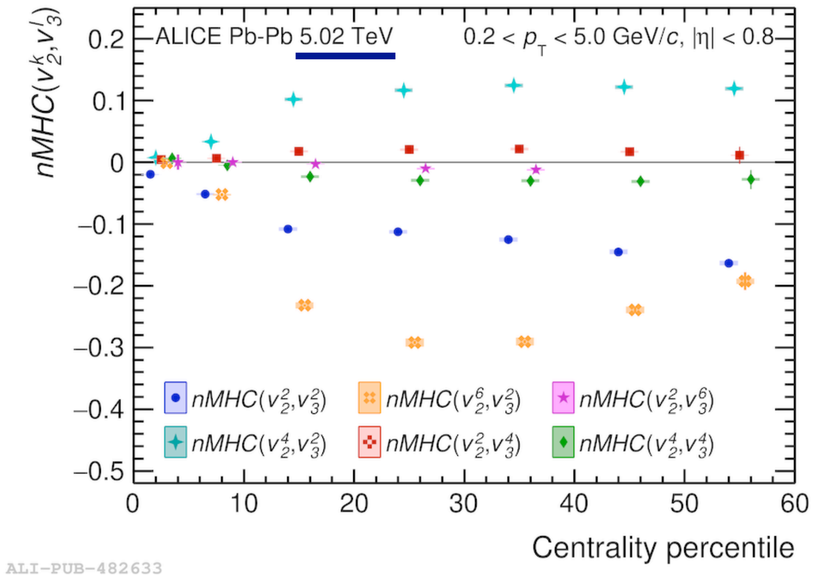
ALICE, submitted to PRL, arXiv:2101.02579 [nucl-ex]

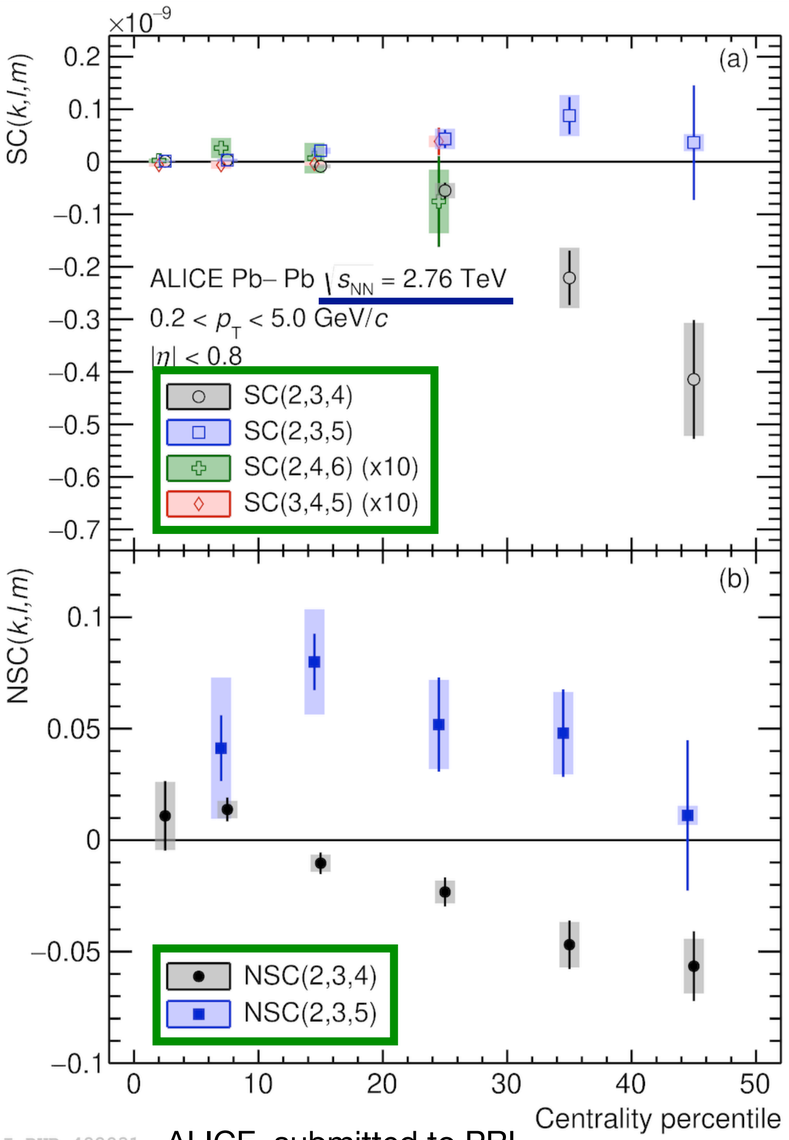
Beyond v_n: flow correlations

- Correlations between flow harmonics of different orders
  - sensitive to initial conditions and final state interactions
  - measurements now extended to correlations between three harmonics, and eight-particle correlations



ALICE, PLB 818 (2021) 136354, arXiv:2102.12180 [nucl-ex]

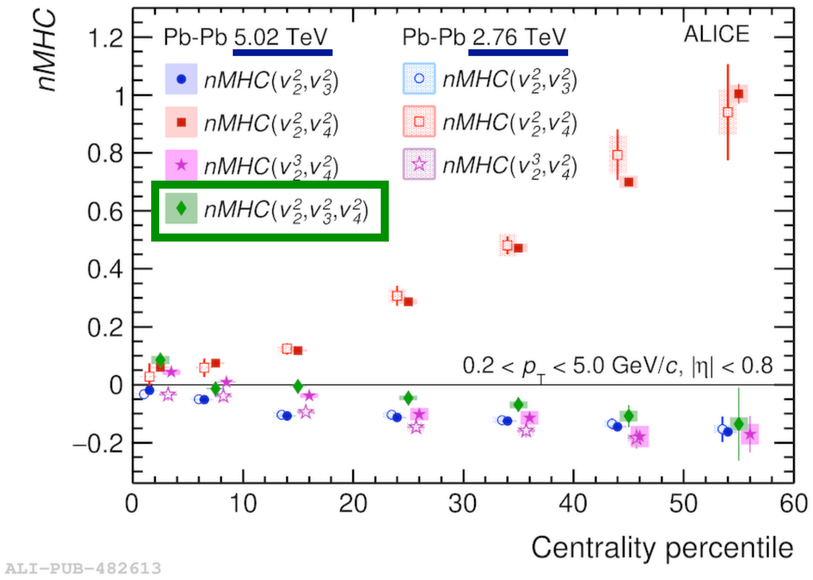




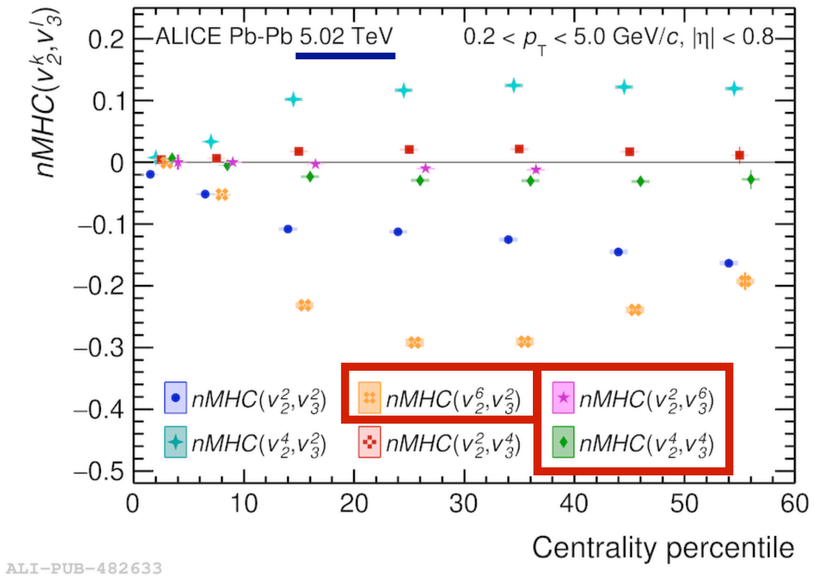
ALICE, submitted to PRL, arXiv:2101.02579 [nucl-ex]

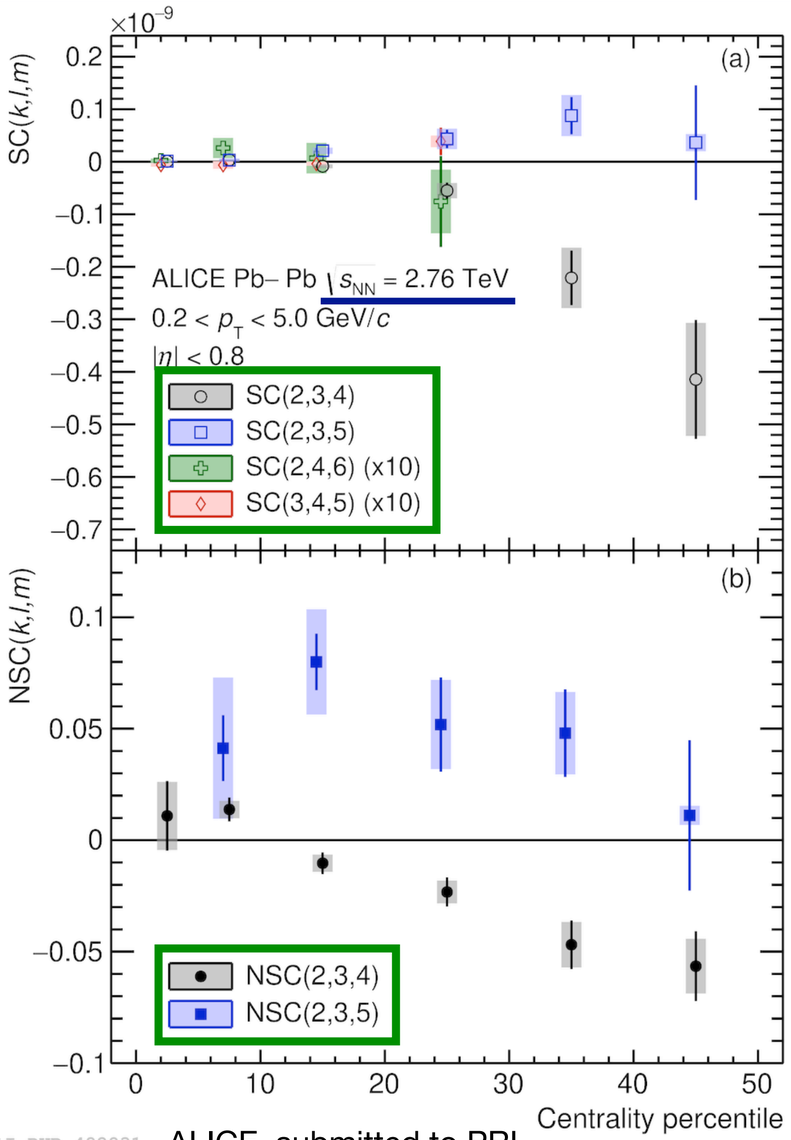
Beyond v_n: flow correlations

- Correlations between flow harmonics of different orders
  - sensitive to initial conditions and final state interactions
  - measurements now extended to correlations between three harmonics, and eight-particle correlations



ALICE, PLB 818 (2021) 136354, arXiv:2102.12180 [nucl-ex]

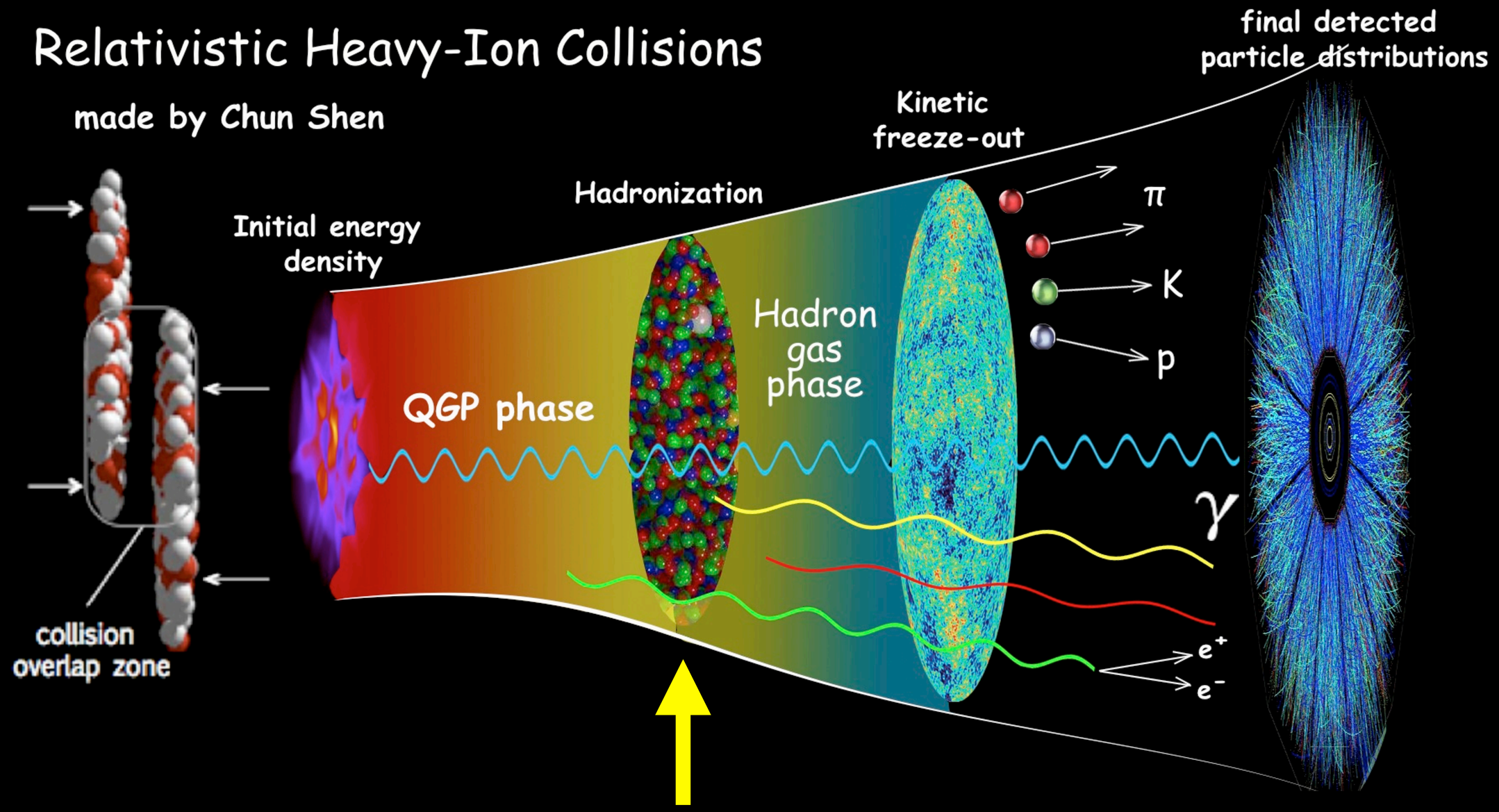




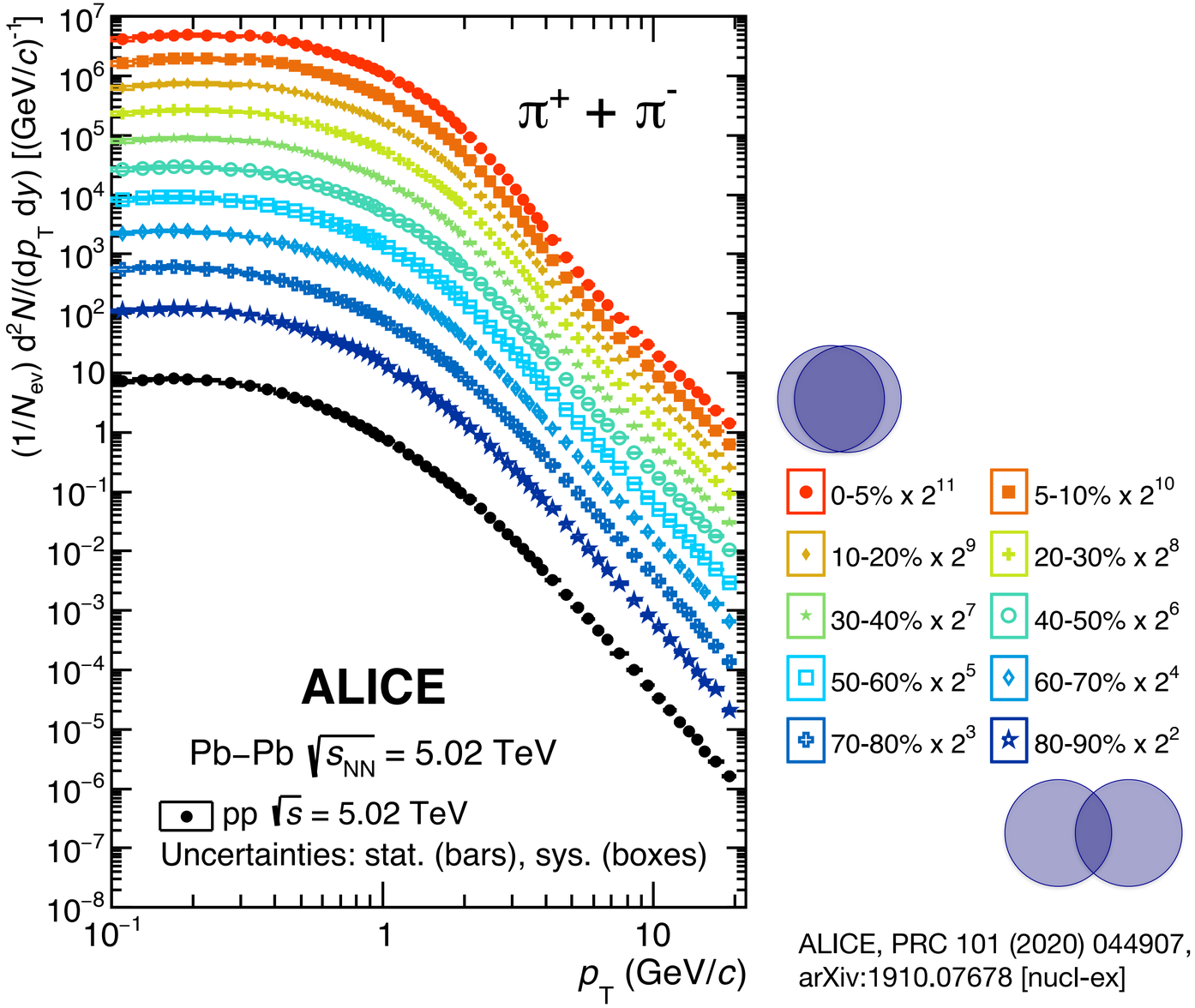
ALICE, submitted to PRL, arXiv:2101.02579 [nucl-ex]

Relativistic Heavy-Ion Collisions

made by Chun Shen

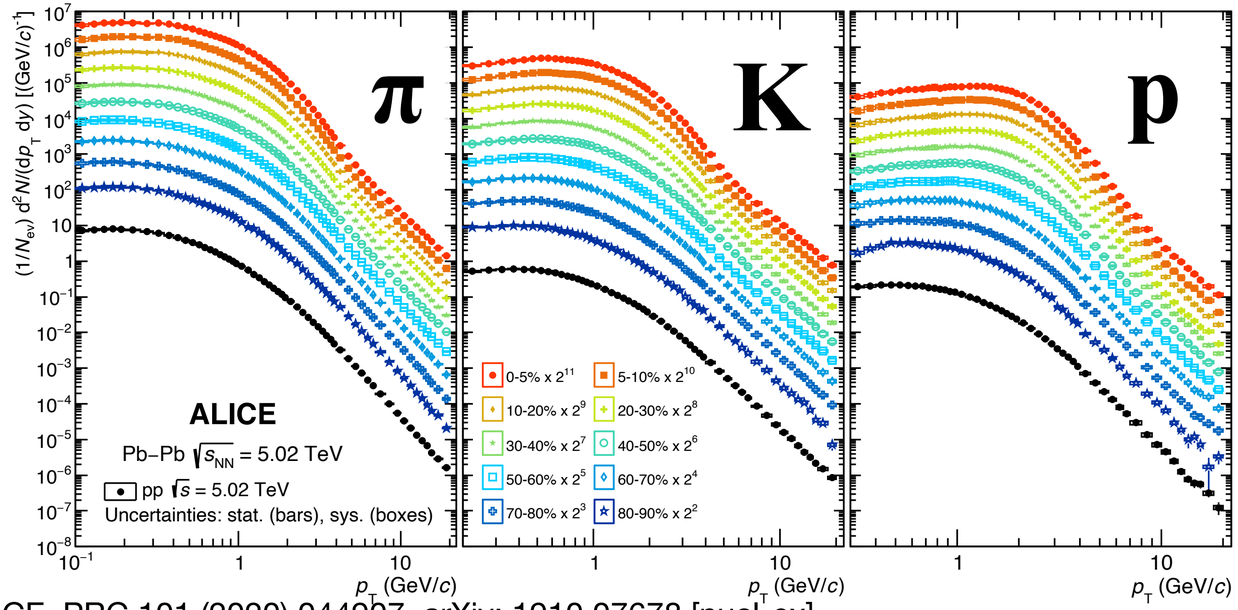


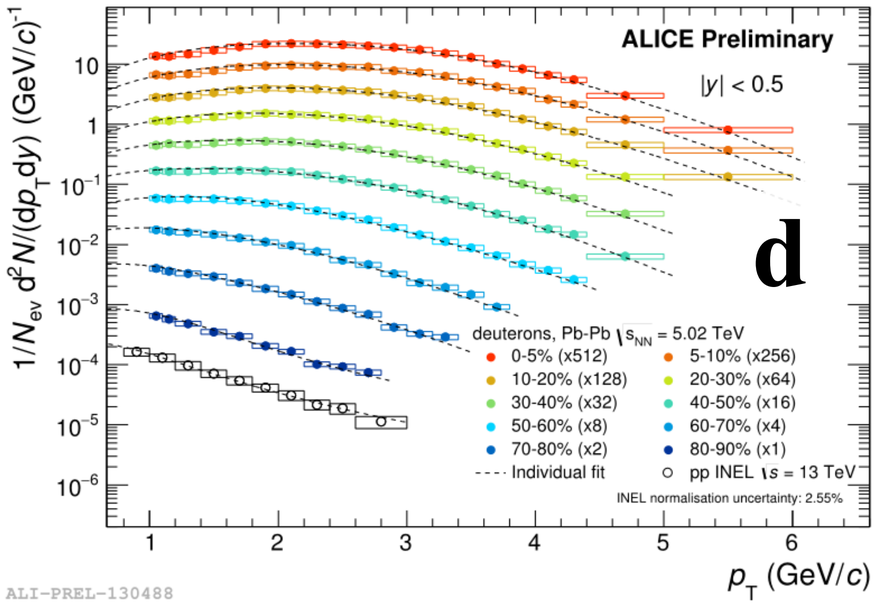
Identified particle spectra



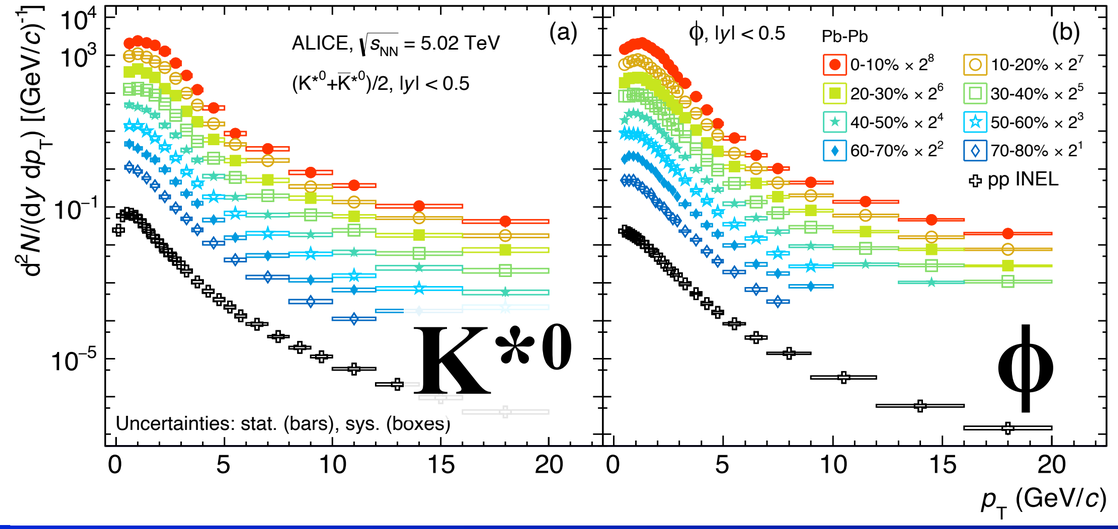
ALICE, PRC 101 (2020) 044907,
arXiv:1910.07678 [nucl-ex]

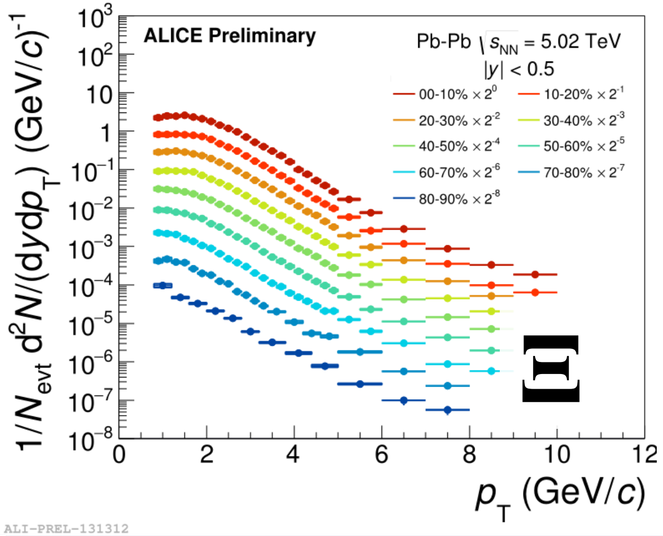
Hadrochemistry at chemical freeze-out

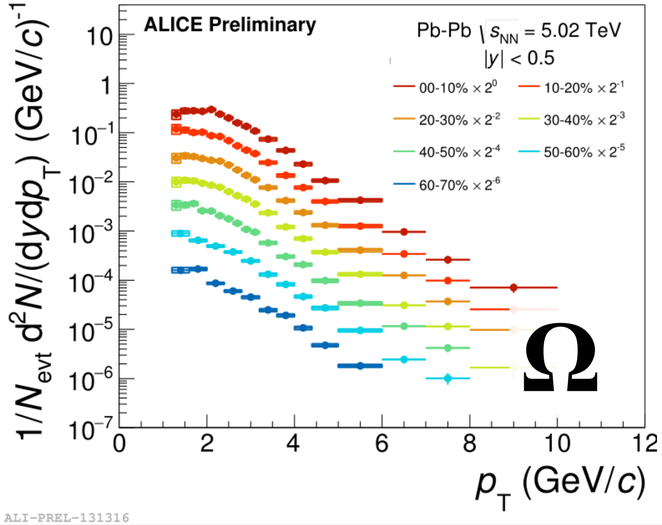




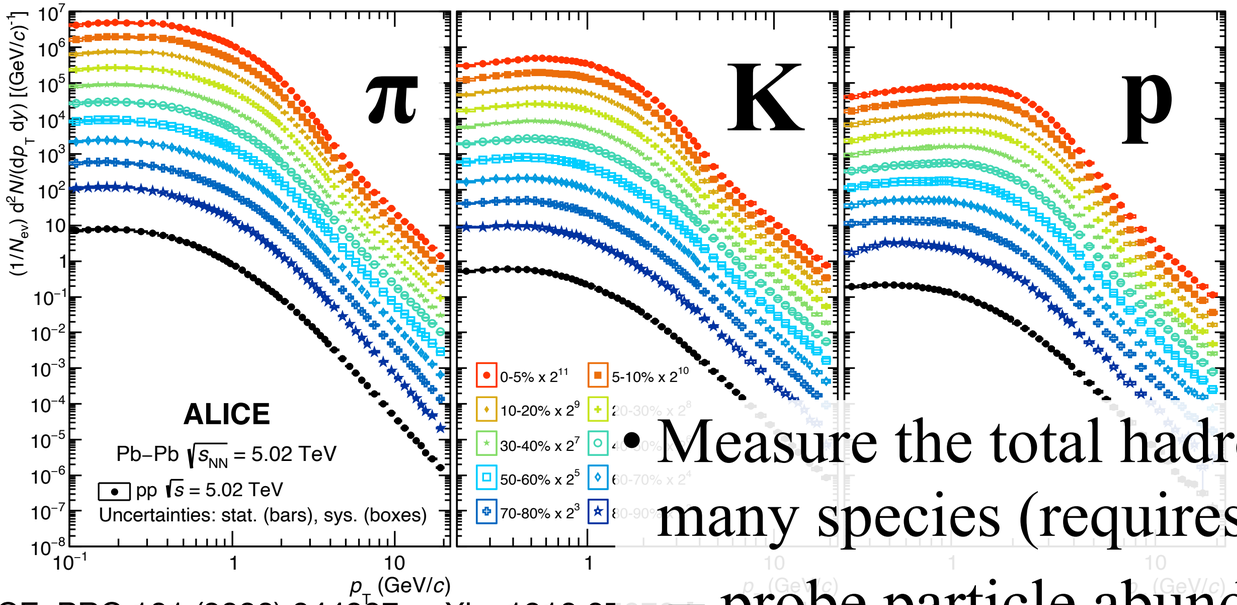
ALICE, PRC 101 (2020) 044907, arXiv: 1910.07678 [nucl-ex]
ALICE, PLB 802 (2020) 135225, arXiv: 1910.14419 [nucl-ex]

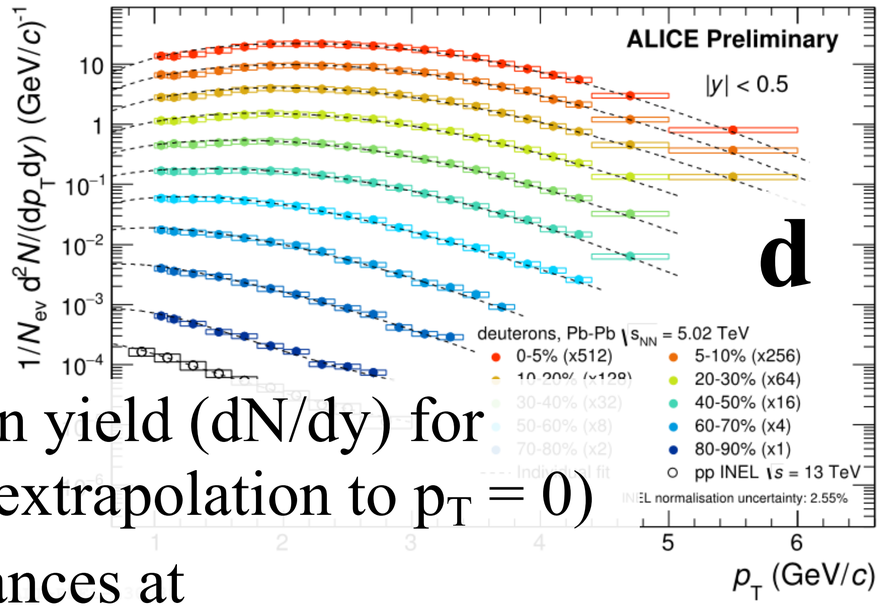






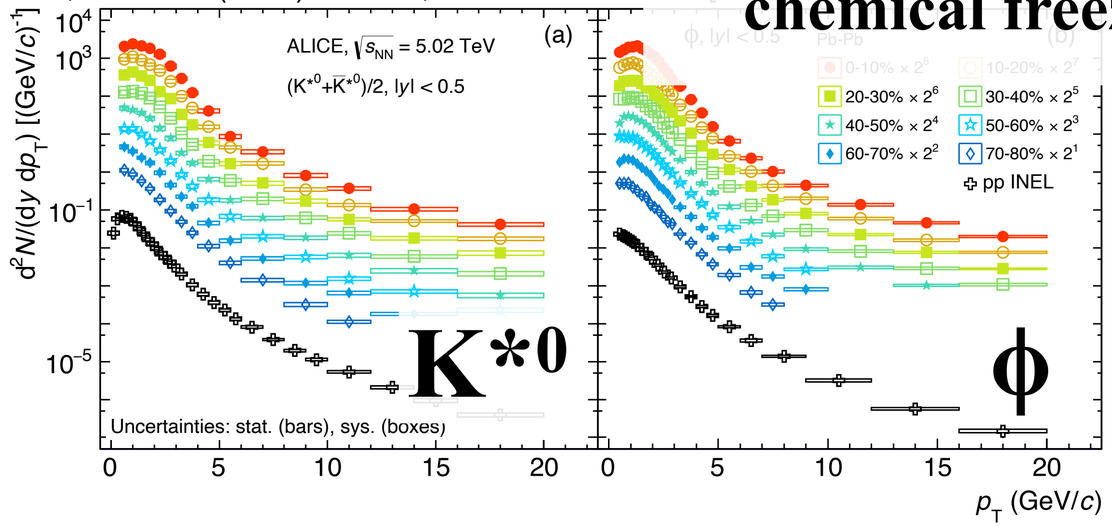
Hadrochemistry at chemical freeze-out

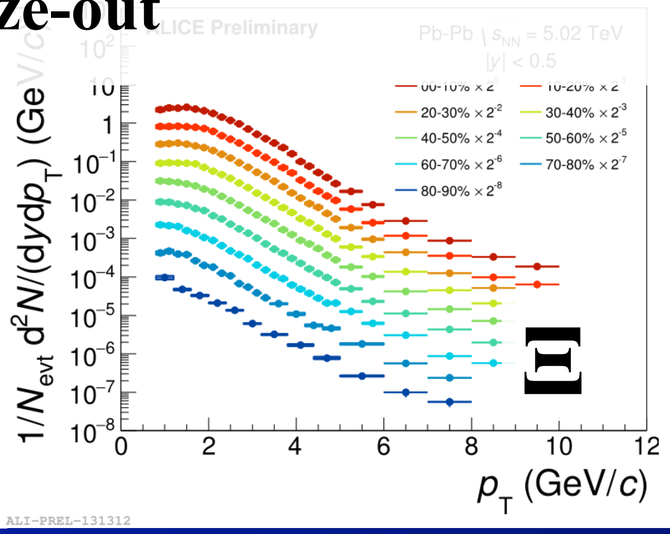


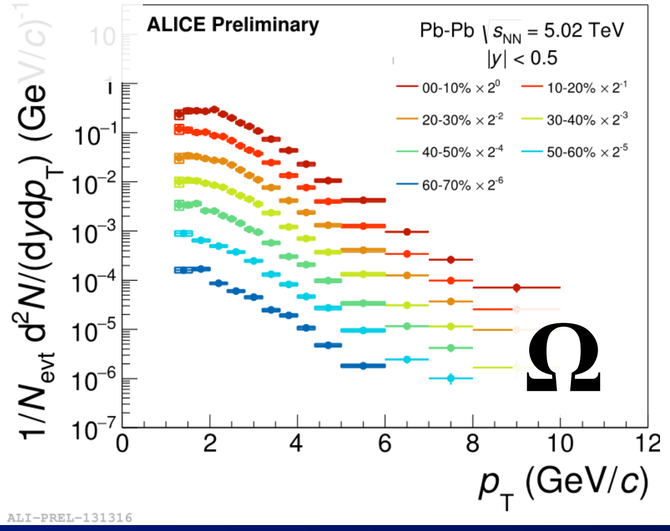


- Measure the total hadron yield (dN/dy) for many species (requires extrapolation to $p_T = 0$)
  - probe particle abundances at **chemical freeze-out**

ALICE, PRC 101 (2020) 044907, arXiv: 1910.07
ALICE, PLB 802 (2020) 135225, arXiv: 1910.14

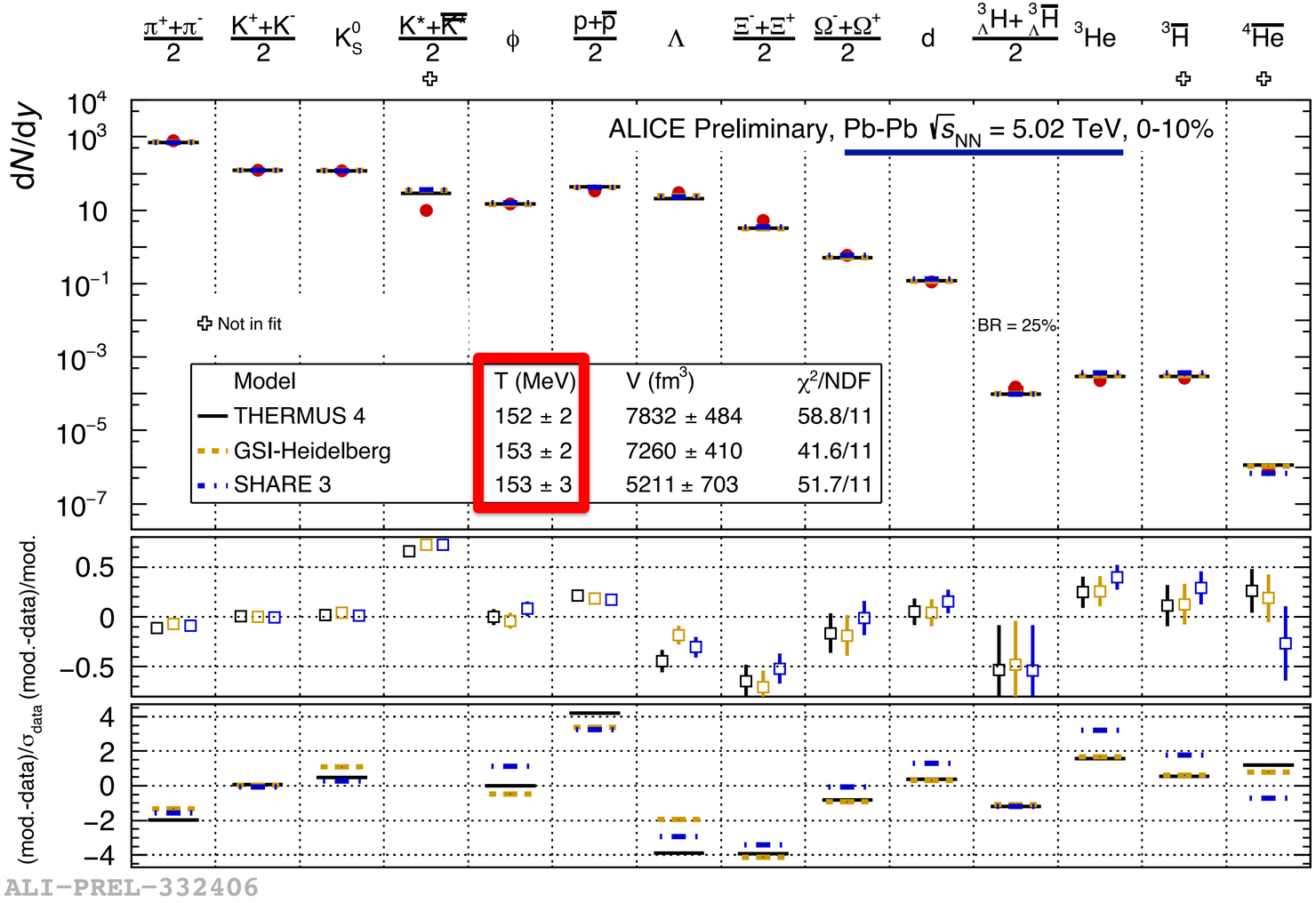






Statistical model of particle production

- Calculation of particle yields in thermal equilibrium with a common chemical freeze-out temperature (T_{chem}) shows excellent agreement with the data over seven orders of magnitude

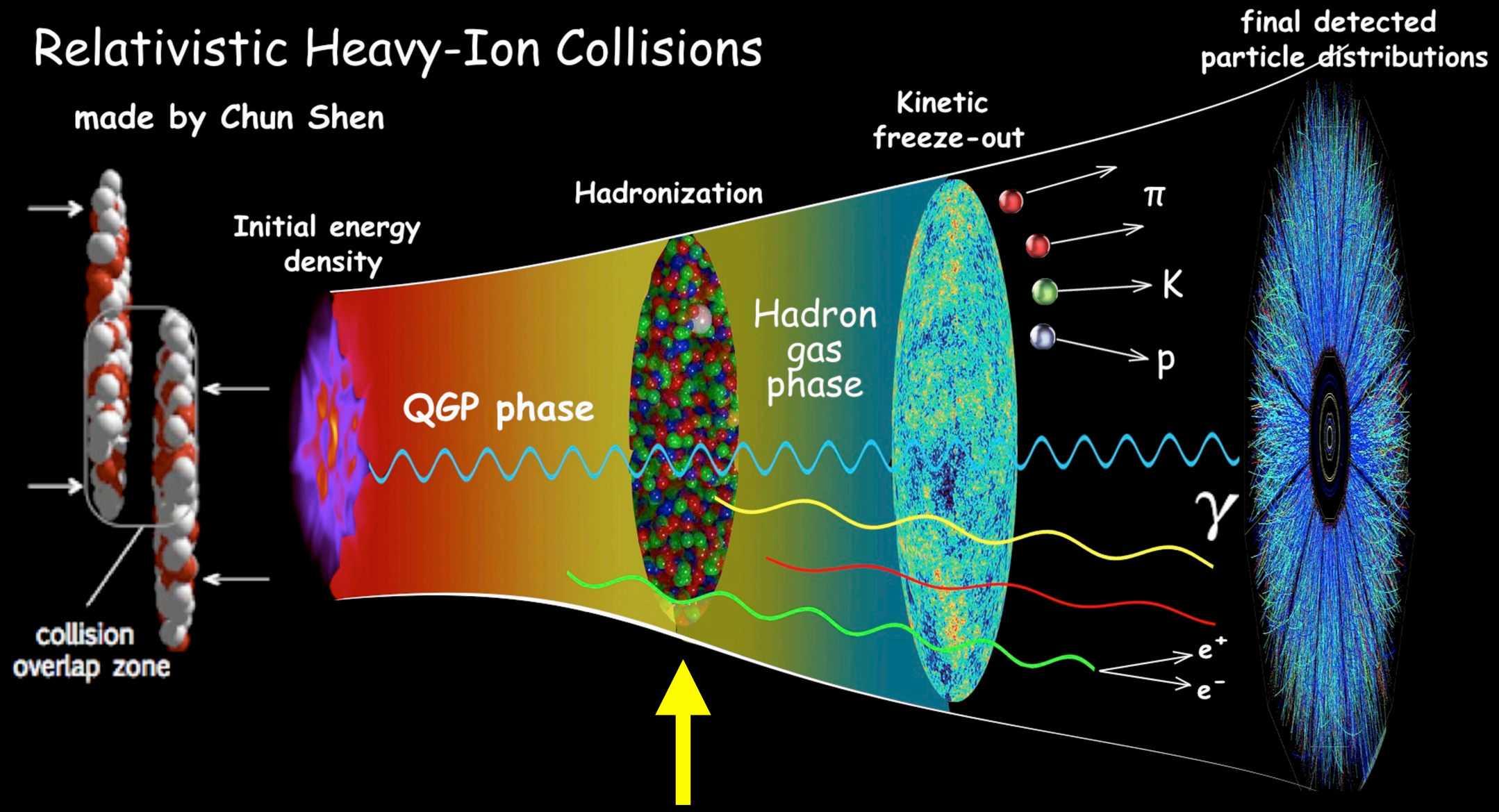


L. Barioglio
Heavy ion parallel session
Monday 18:15

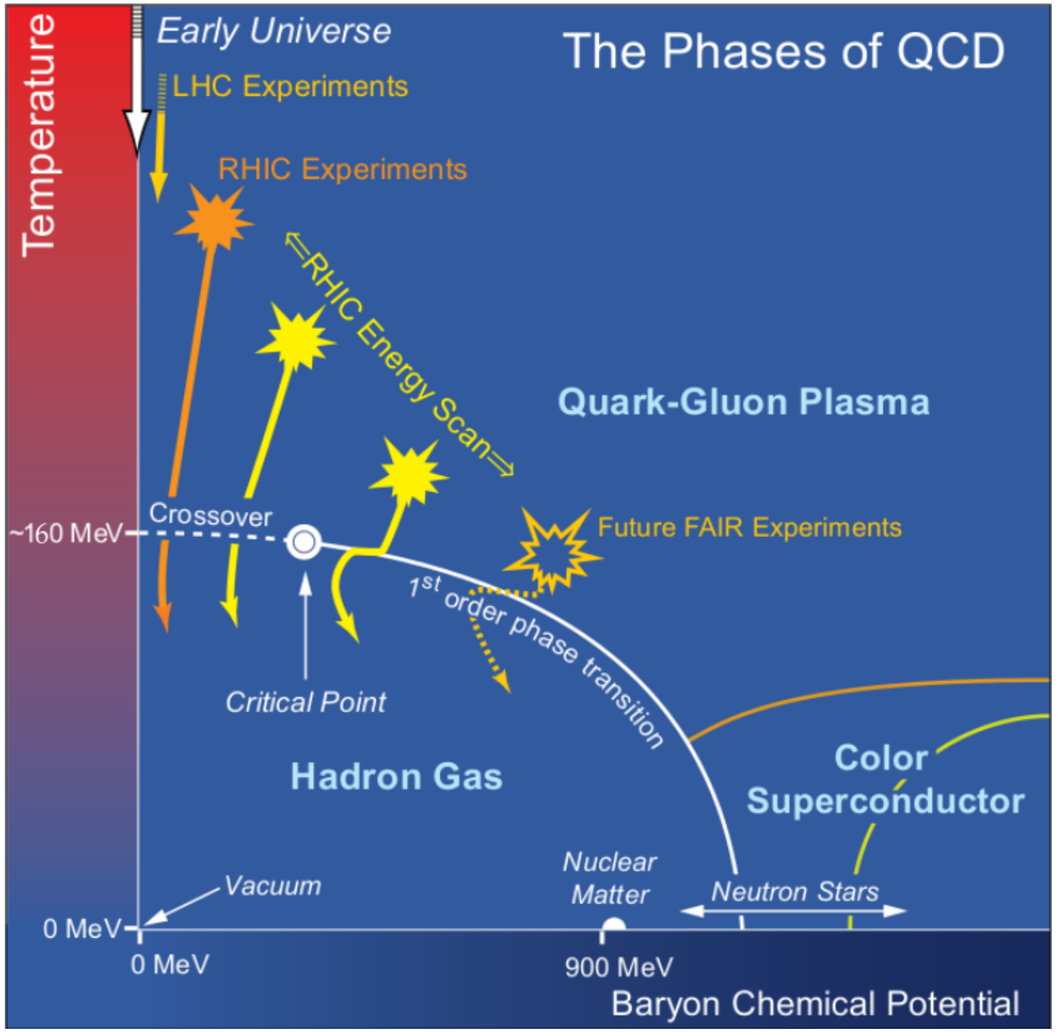
Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV:
ALICE, Nucl. Phys. A 971 (2018) 1, arXiv:1710.07531 [nucl-ex]

Relativistic Heavy-Ion Collisions

made by Chun Shen



Phase structure of nuclear matter



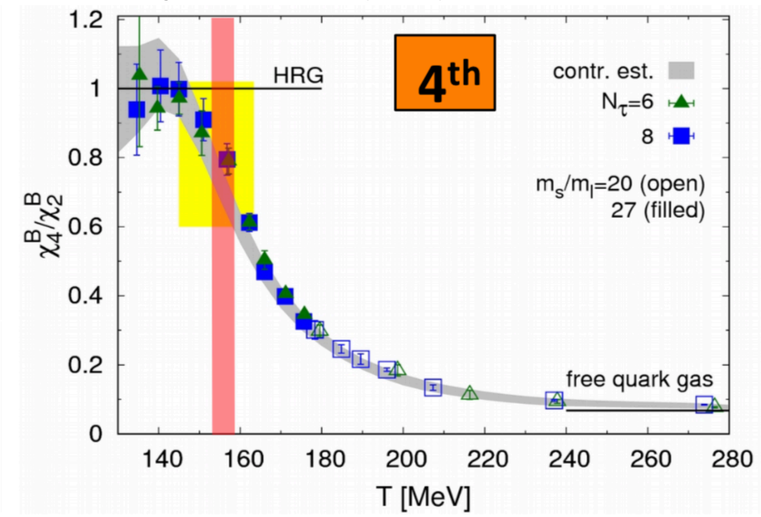
- Event-by-event fluctuations of net particle multiplicities are used to study properties and phase structure of strongly-interacting matter
  - Fluctuations grow in the region near a phase transition and/or critical point
    → Can we observe signs of criticality?
  - Fluctuations of conserved charges can be related to susceptibilities calculable in lattice QCD
    → Precision test of LQCD at $\mu_B \approx 0$

$$\chi_n^B = \frac{\partial^n \left(P/T^4\right)}{\partial\left(\mu_B/T\right)^n}$$

Needed: high precision & higher moments

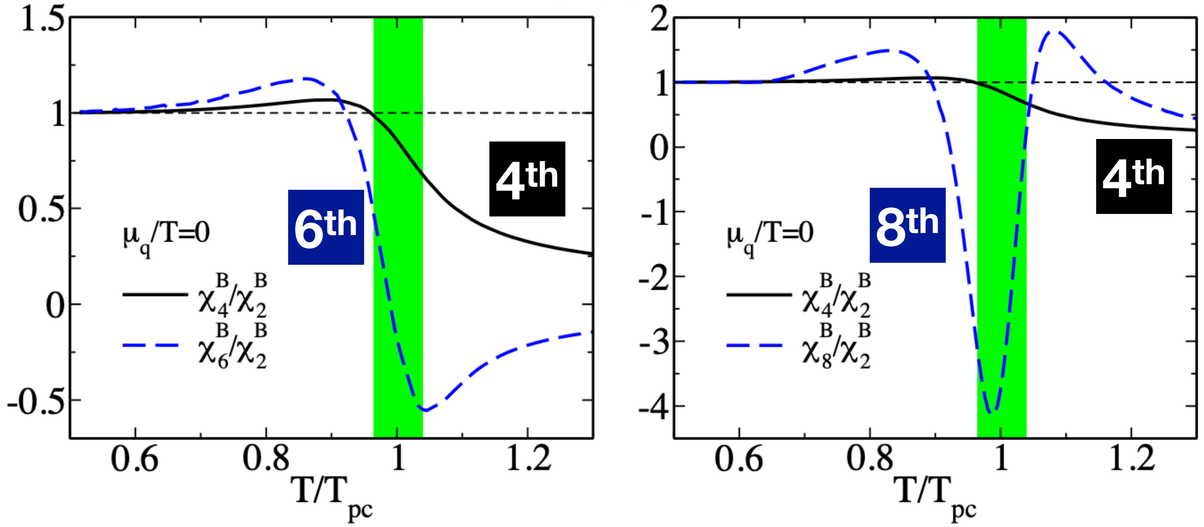
- 2nd order moments → no deviation between hadron gas and LQCD expectations
- 4th order → 30% deviation from unity expected from LQCD

A. Bazavov et al. (HotQCD Collaboration), Phys. Rev. D 95 (2017) 054504



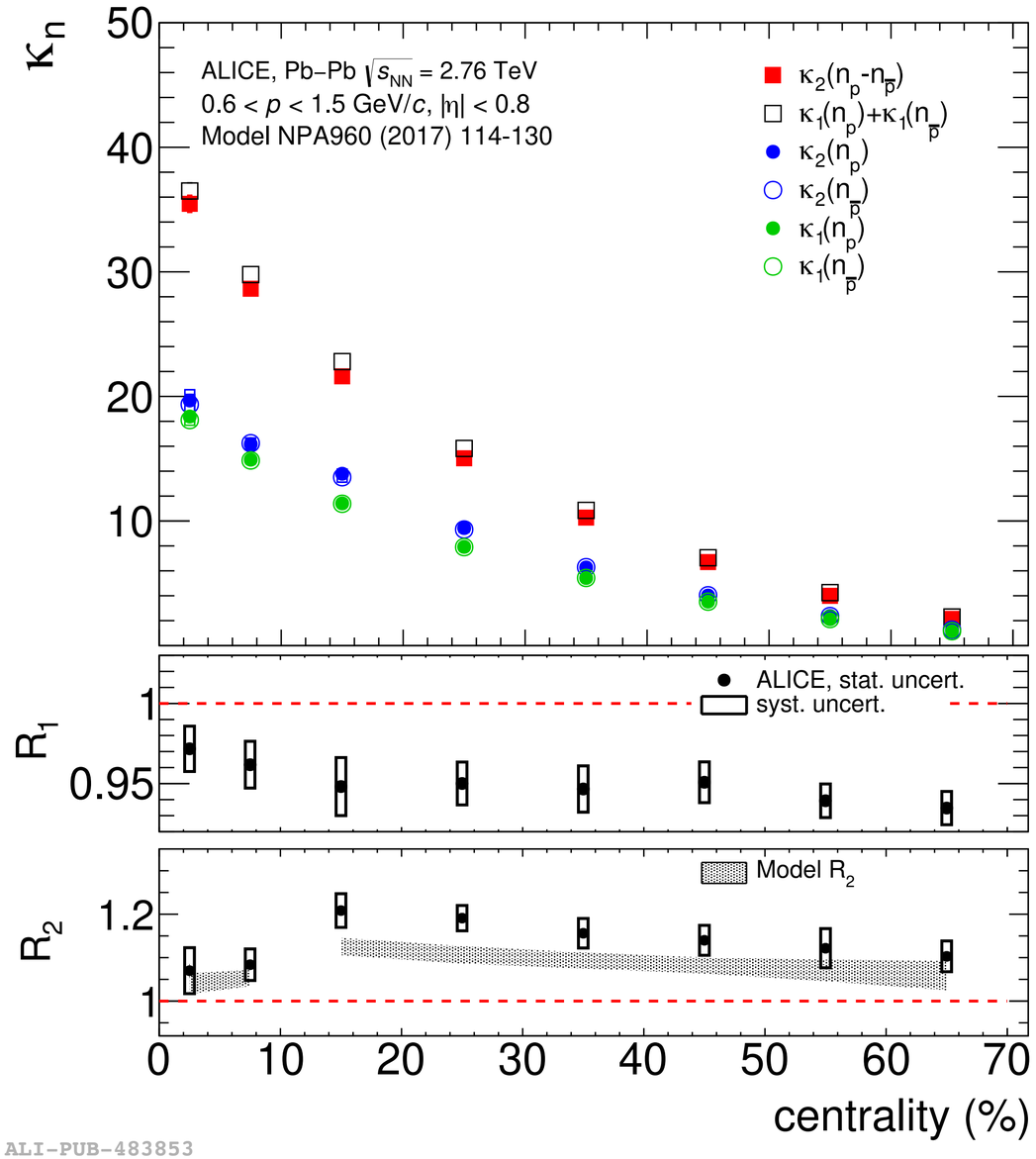
- Deviations from unity and signs of criticality are greatly enhanced for the higher moments (4th, 6th, 8th,…)

Friman, B., et al. Eur. Phys. J. C 71 (2011) 1694, arXiv:1103.3511 [hep-ph]



- But huge statistics are needed and experimental effects must be carefully controlled!

Net proton second moments



- If multiplicity distributions of protons and antiprotons are Poissonian and uncorrelated → Skellam distribution for net protons

$$\kappa_2(Skellam) = \kappa_1(p) + \kappa_1(\bar{p})$$

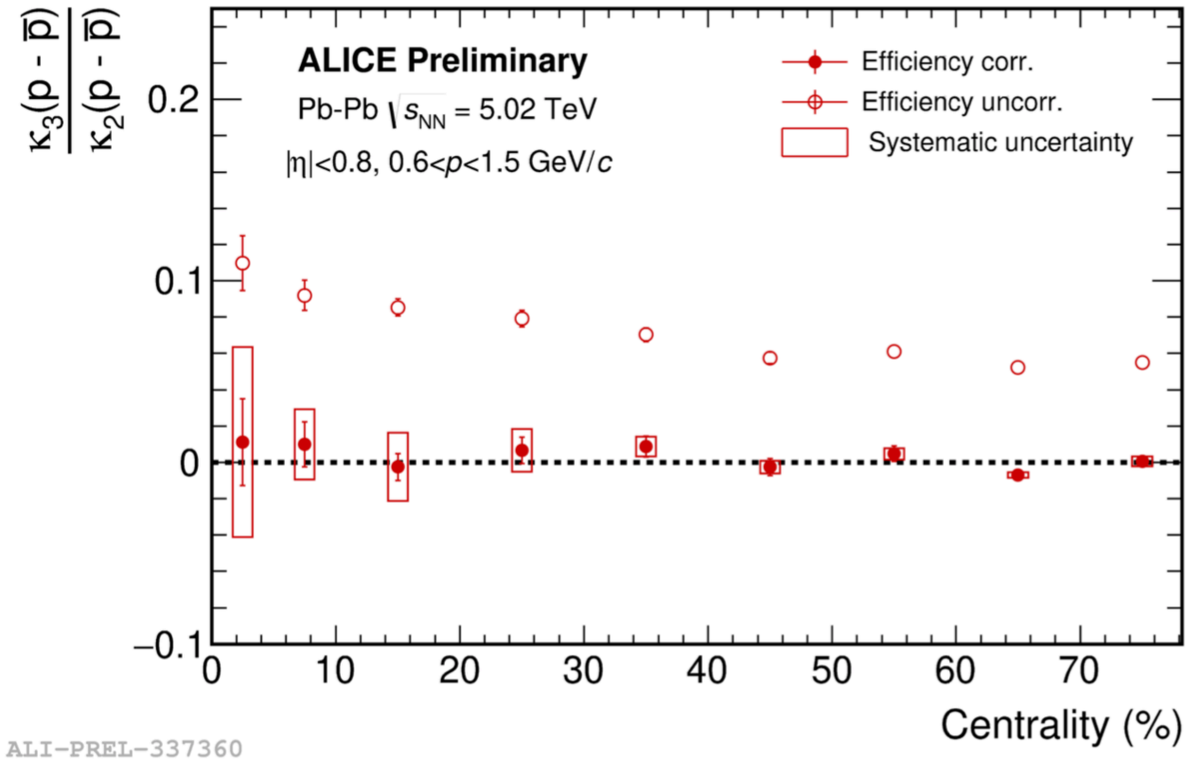
$$R_2 = \kappa_2(p - \bar{p})/(\kappa_1(p) + \kappa_1(\bar{p})) \rightarrow 1$$

- Deviations from Poissonian/Skellam baseline can be fully explained by global baryon number and volume fluctuations, without need of correlations or critical fluctuations

P. Braun-Munzinger et al., NPA 960 (2017) 114, arXiv:1612.00702 [nucl-th]

ALICE, PLB 807 (2020) 135564, arXiv:1910.14396

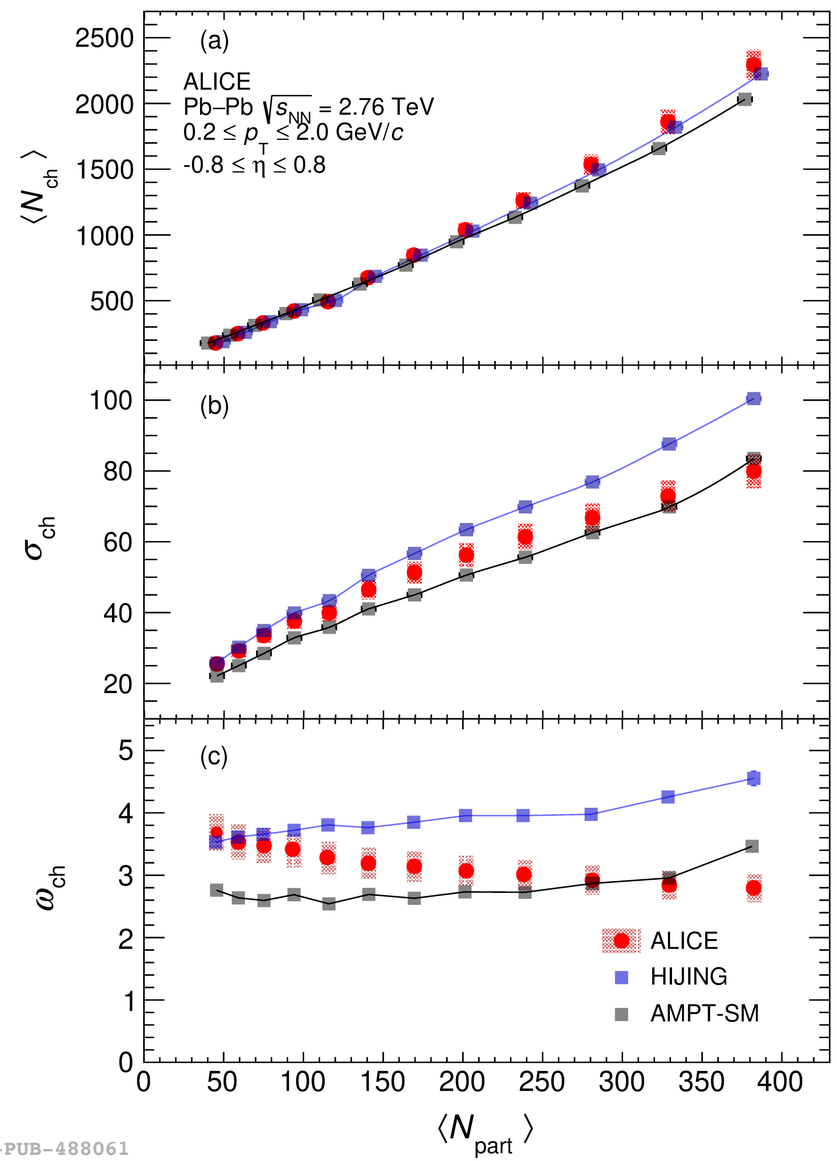
Net proton third moments



- Third moments agree with Skellam expectation of zero, precision on the order of 5%
- Very sensitive measurements, requires great experimental control over efficiencies, etc
- Runs 3+4 at the LHC will allow us to measure the fourth and sixth moments of the net proton distribution with unprecedented precision

LHC Yellow Report: arXiv:1812.06772 [hep-ph]

Multiplicity fluctuations



ALICE, submitted to EPJC
arXiv:2105.05745 [nucl-ex]

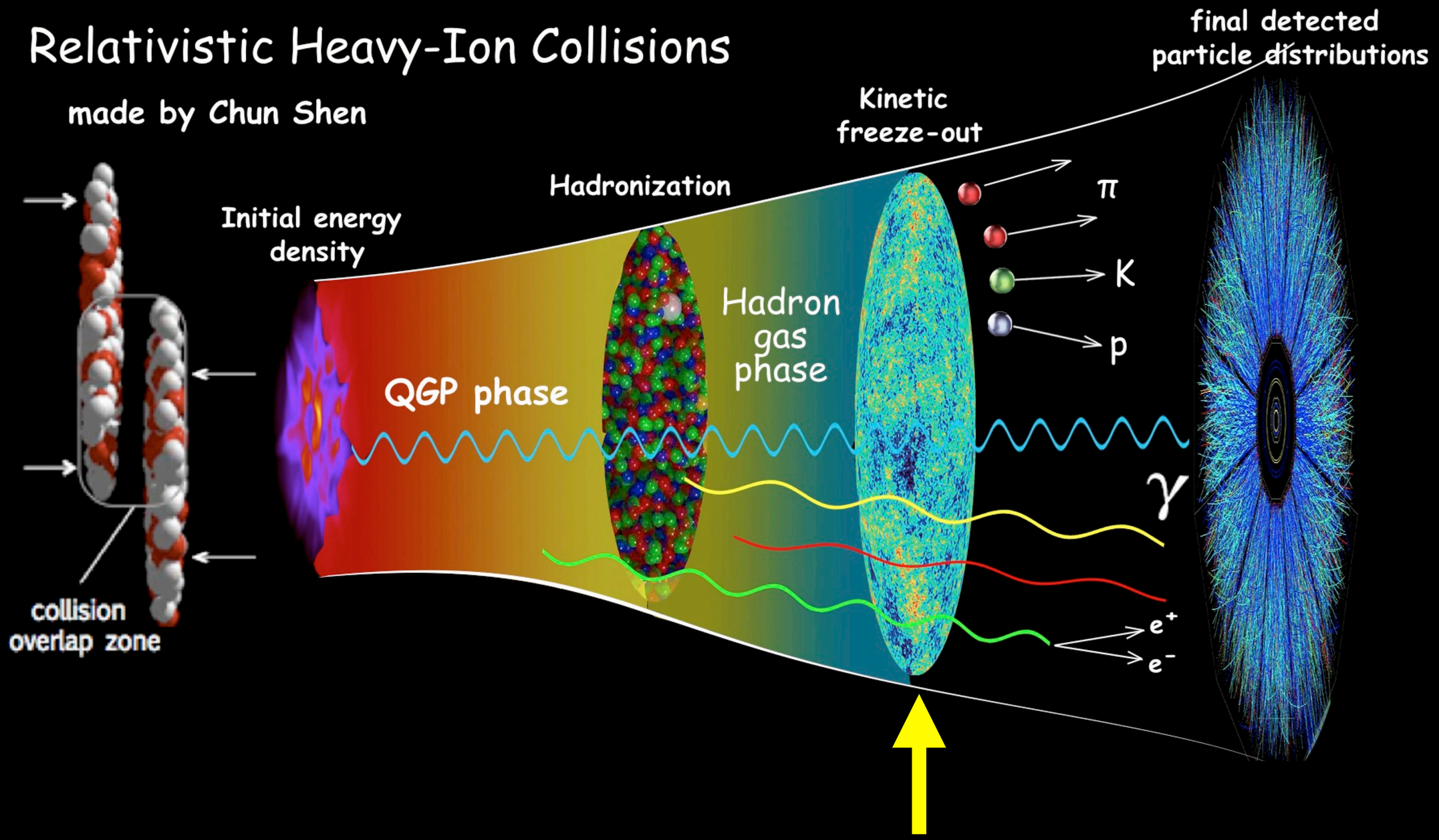
- Measure moments of charge multiplicity distribution
  - mean N_{ch}, standard deviation σ_{ch}, and scaled variance $\omega_{ch} = \sigma_{ch}^2/\langle N_{ch}\rangle$
- Scaled variance ω_{ch} is related to the isothermal compressibility

$$k_T = -\frac{1}{V}\left(\frac{\partial V}{\partial P}\right)\Big|_T \qquad \omega_{ch} = \frac{k_B T \langle N_{ch}\rangle}{V} k_T$$

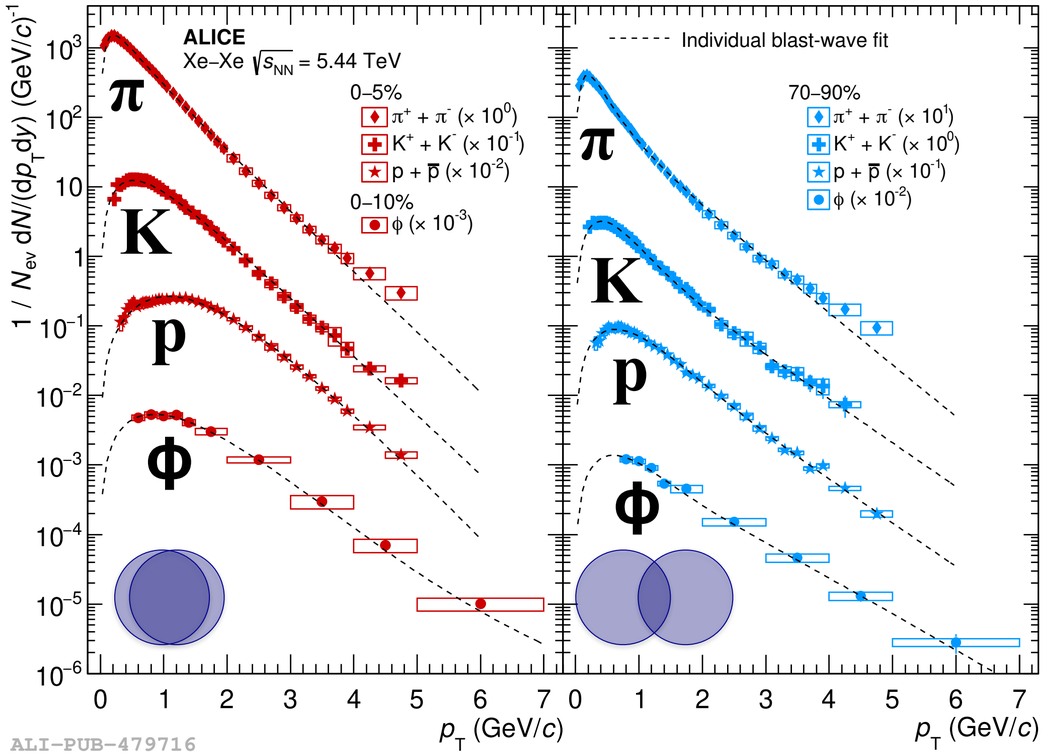
- After estimations of background contributions, place upper limit on isothermal compressibility of the QGP → $k_T < 27.9 \pm 3.18$ fm^3/GeV
  → 10x lower than normal nuclear matter

Relativistic Heavy-Ion Collisions

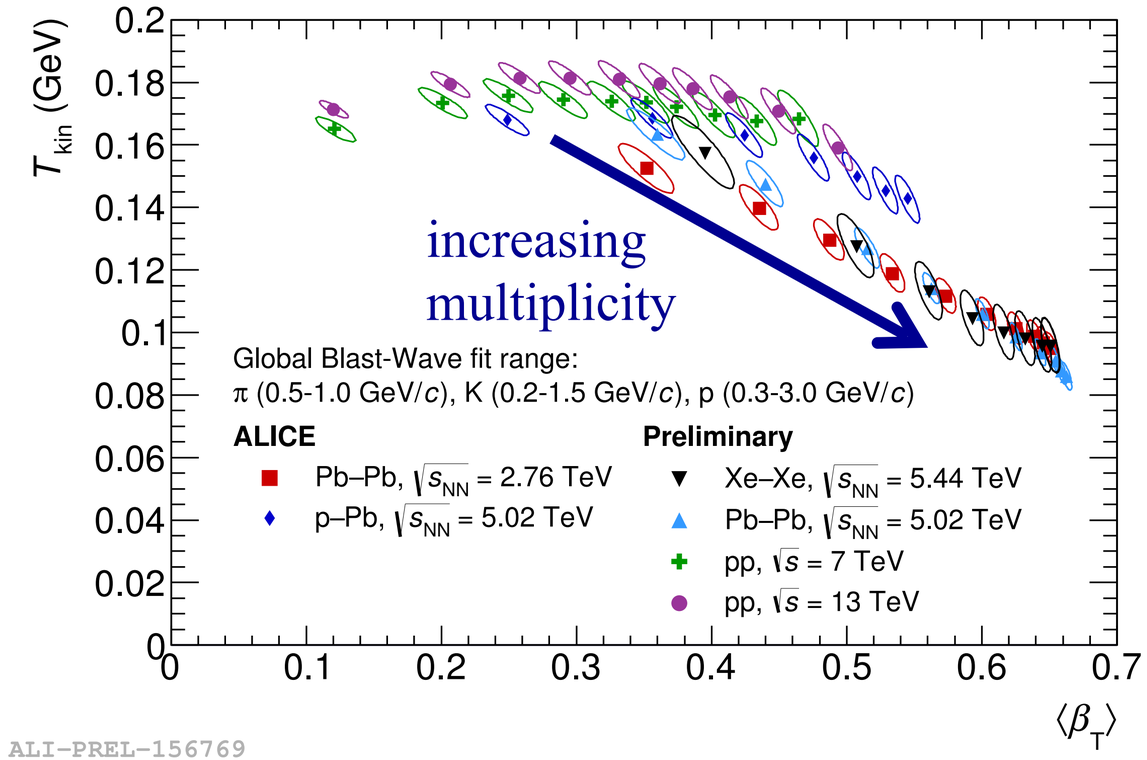
made by Chun Shen



Kinematics at kinetic freeze-out

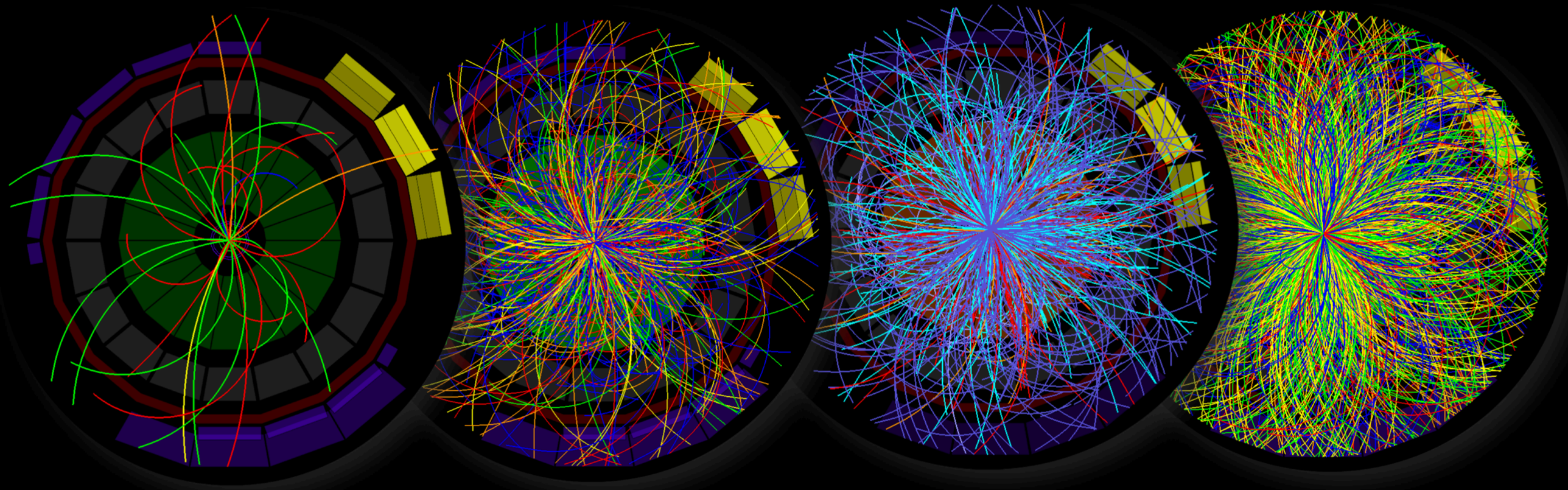


ALICE, submitted to EPJC, arXiv: 2101.03100 [nucl-ex]



- Fit shape of p_T spectrum → probe final hadron kinematics at **kinetic freeze-out**
- Boltzmann-Gibbs Blast-Wave model: a simplified hydrodynamic model

- Simultaneous fit to π, K, p spectra to obtain
  - radial expansion velocity β_T
  - kinetic freeze-out temperature T_{kin}
- More central (higher multiplicity) events have lower T_{kin} and higher expansion rate



pp
13 TeV

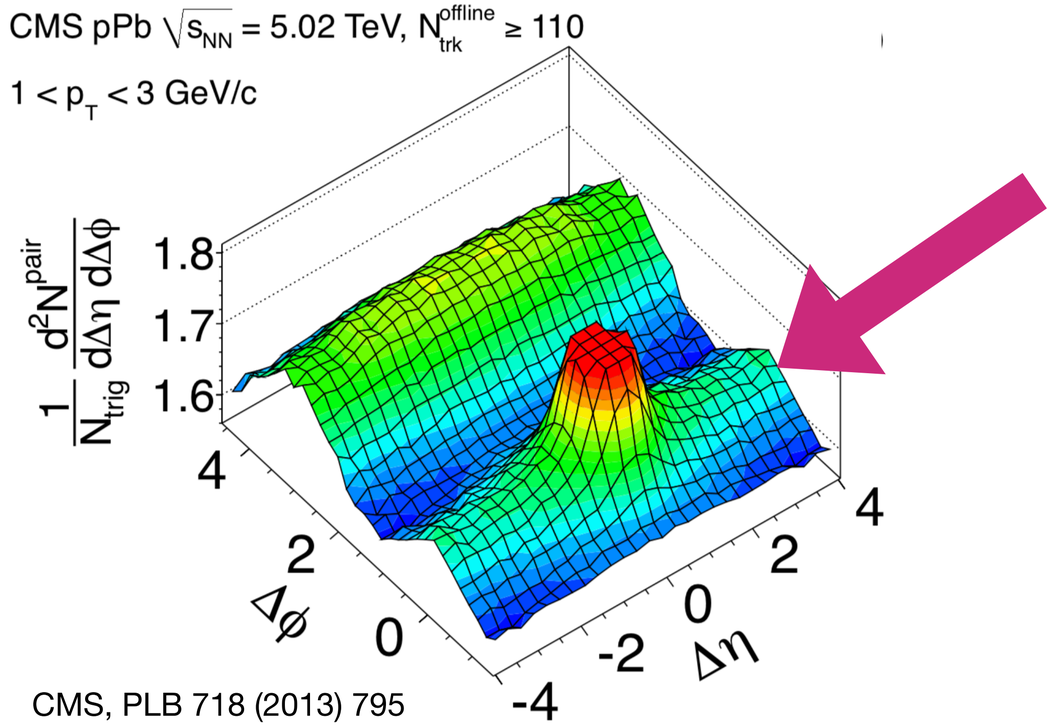
p-Pb
5.02 TeV

Xe-Xe
5.44 TeV

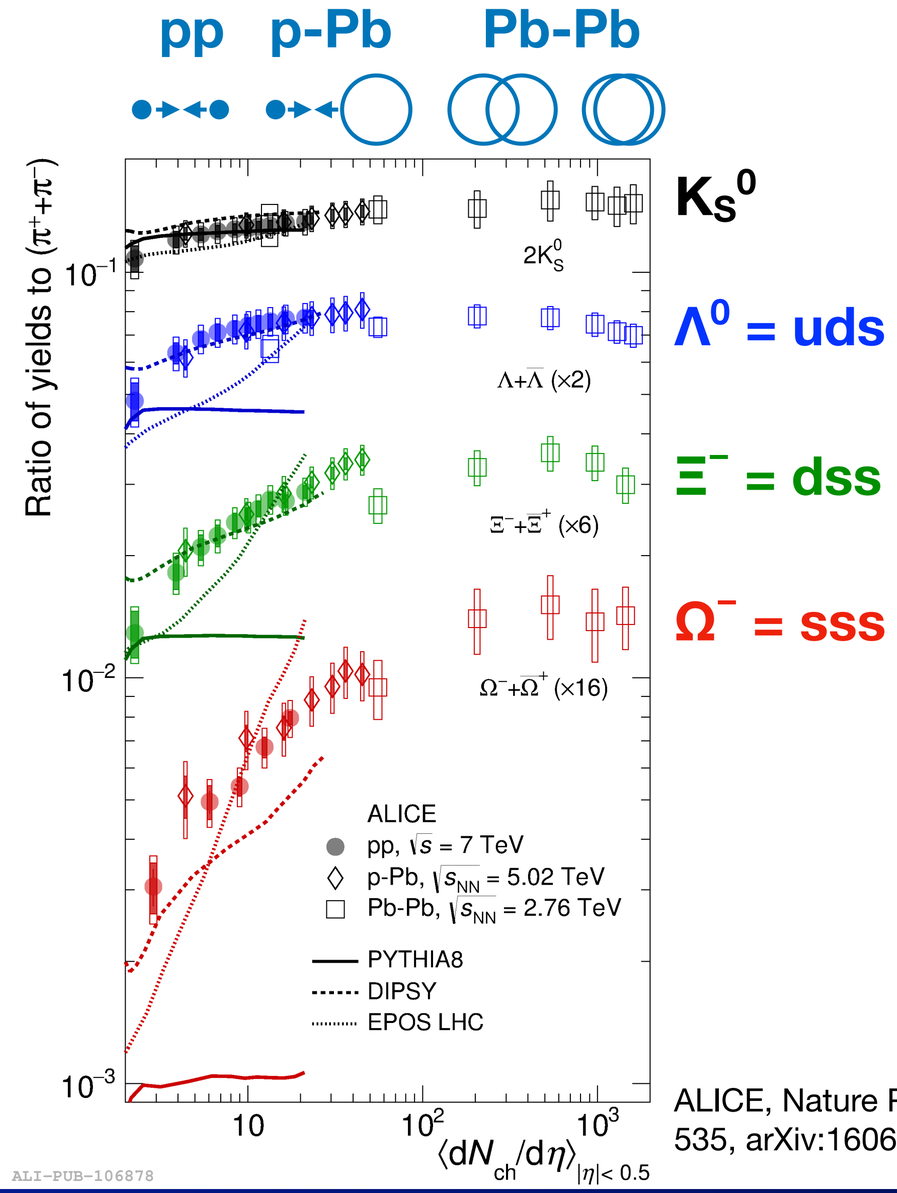
Pb-Pb
5.02 TeV

Small systems: pp and p-Pb collisions

- Similar v_n signals observed in pp and p-Pb collisions as well!
- Ratio of strange to non-strange hadrons increases smoothly with multiplicity in pp and p-Pb, towards Pb-Pb limit



CMS, PLB 718 (2013) 795



K_S^0

Λ^0 = uds

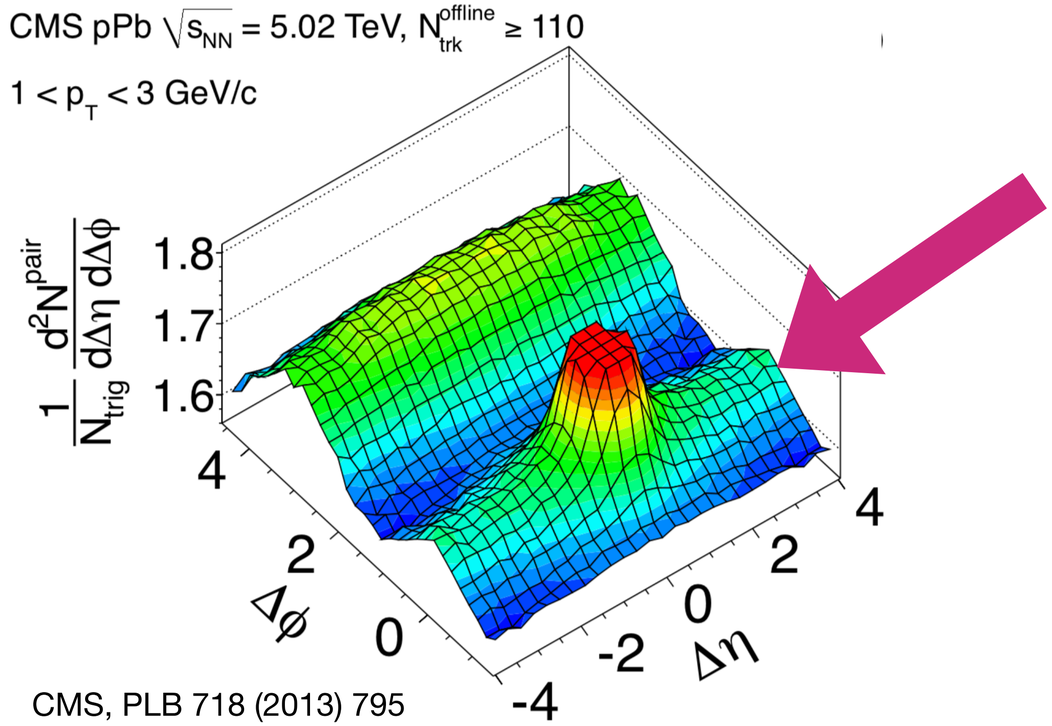
Ξ^- = dss

Ω^- = sss

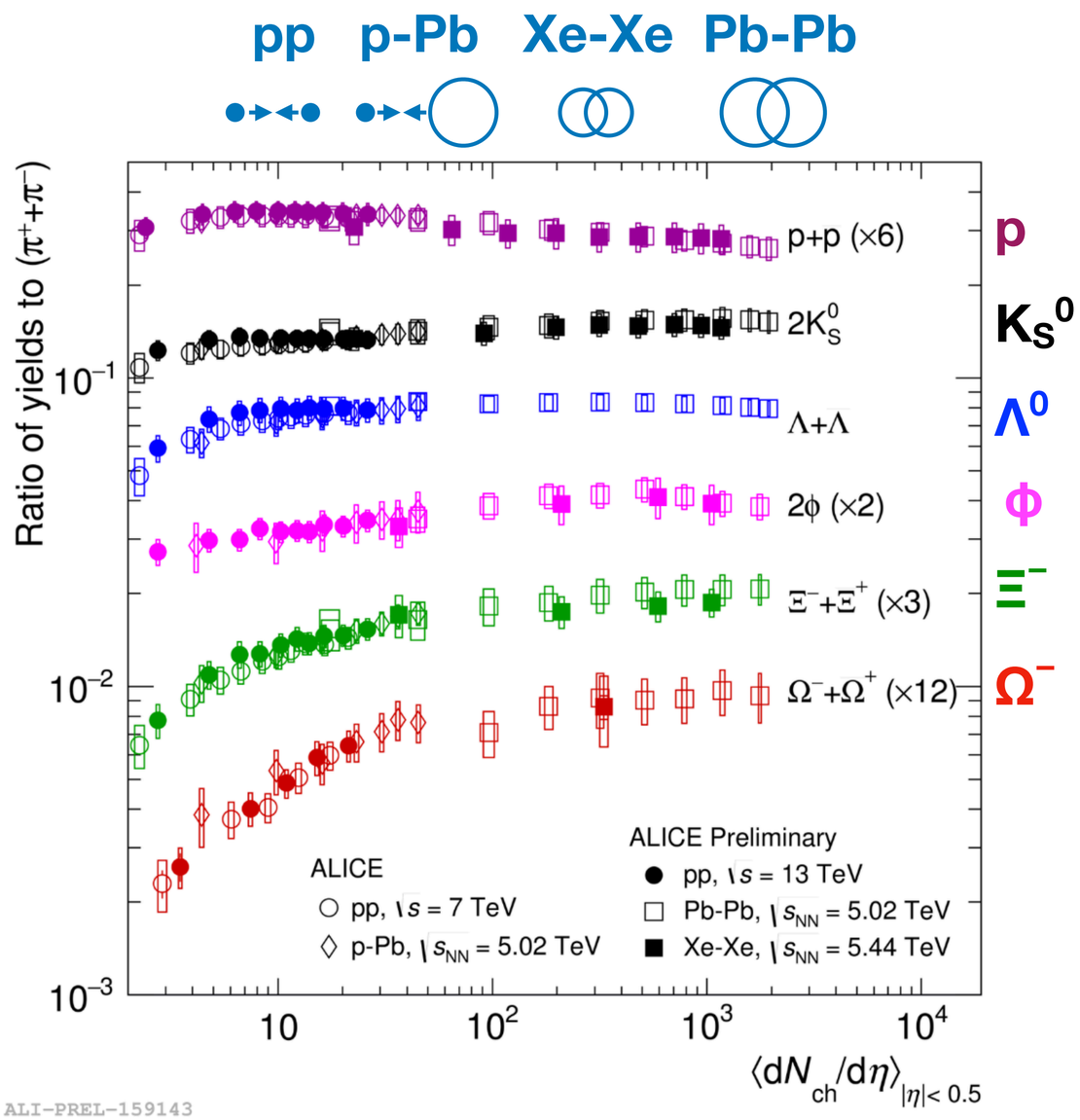
ALICE, Nature Physics 13 (2017) 535, arXiv:1606.07424 [nucl-ex]

Small systems: pp and p-Pb collisions

- Similar v_n signals observed in pp and p-Pb collisions as well!
- Ratio of strange to non-strange hadrons increases smoothly with multiplicity in pp and p-Pb, towards Pb-Pb limit

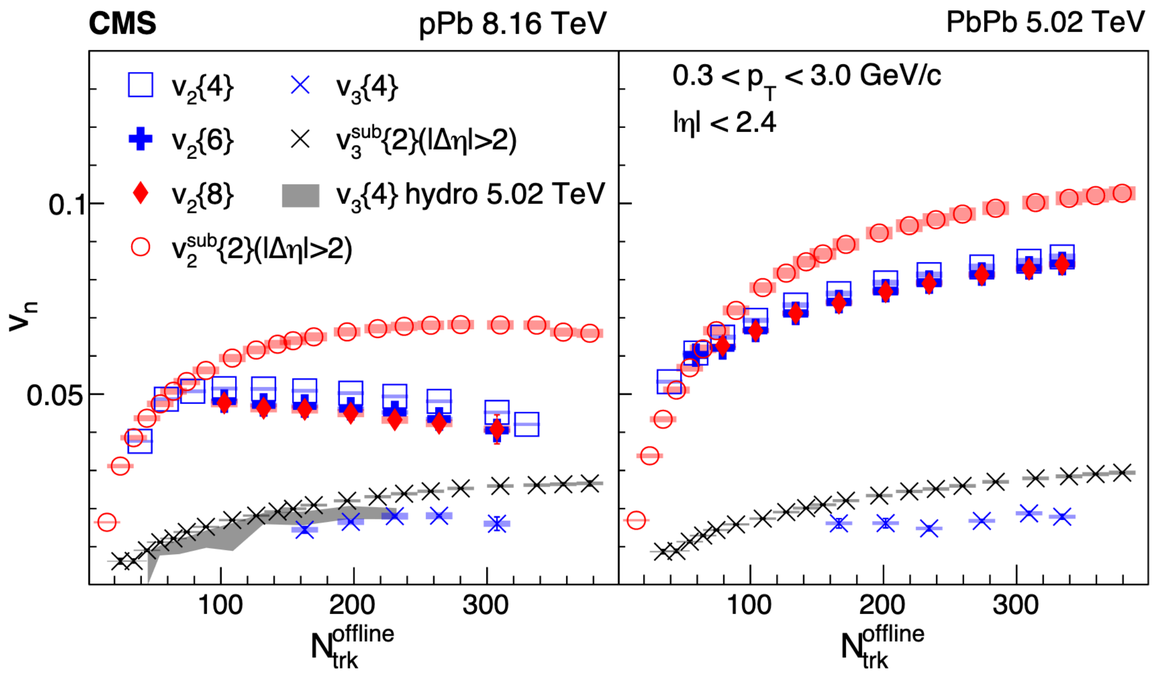


CMS, PLB 718 (2013) 795

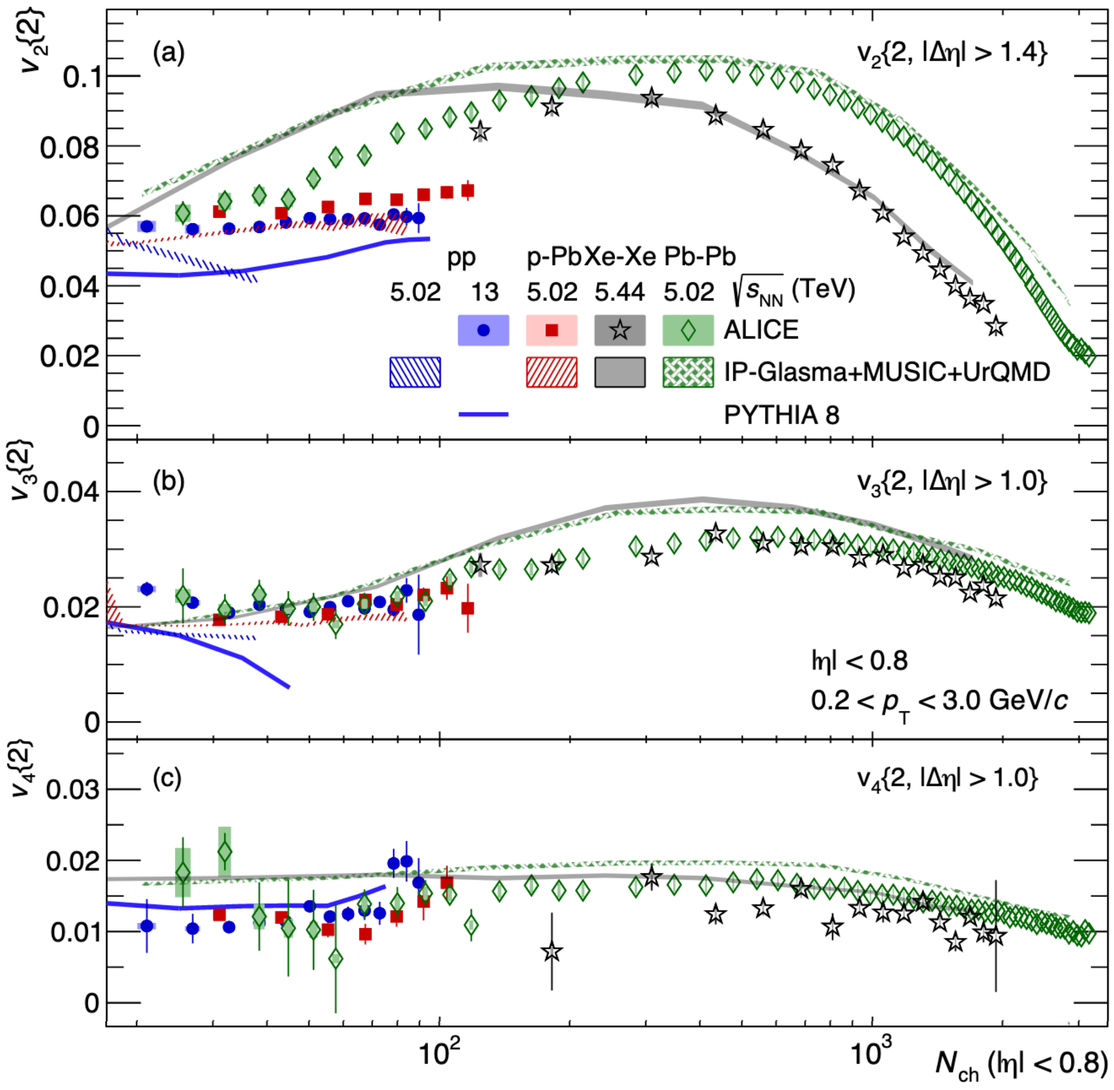


v_n in small systems

- Multi-particle cumulants → collectivity
- Smooth transition from pp to Pb-Pb



CMS, PRC 101 (2020) 014902, arXiv: 1904.11519 [hep-ex]

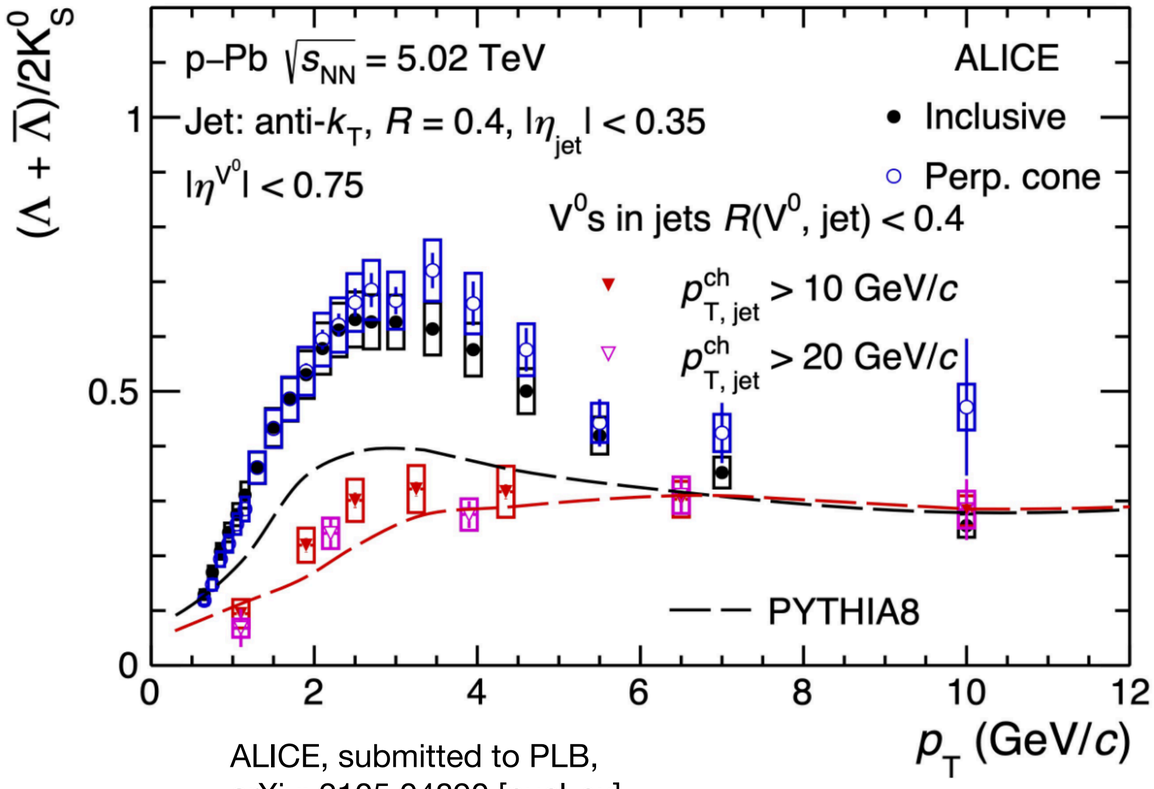


ALICE, PRL 123 (2019) 142301, arXiv: 1903.01790 [nucl-ex]

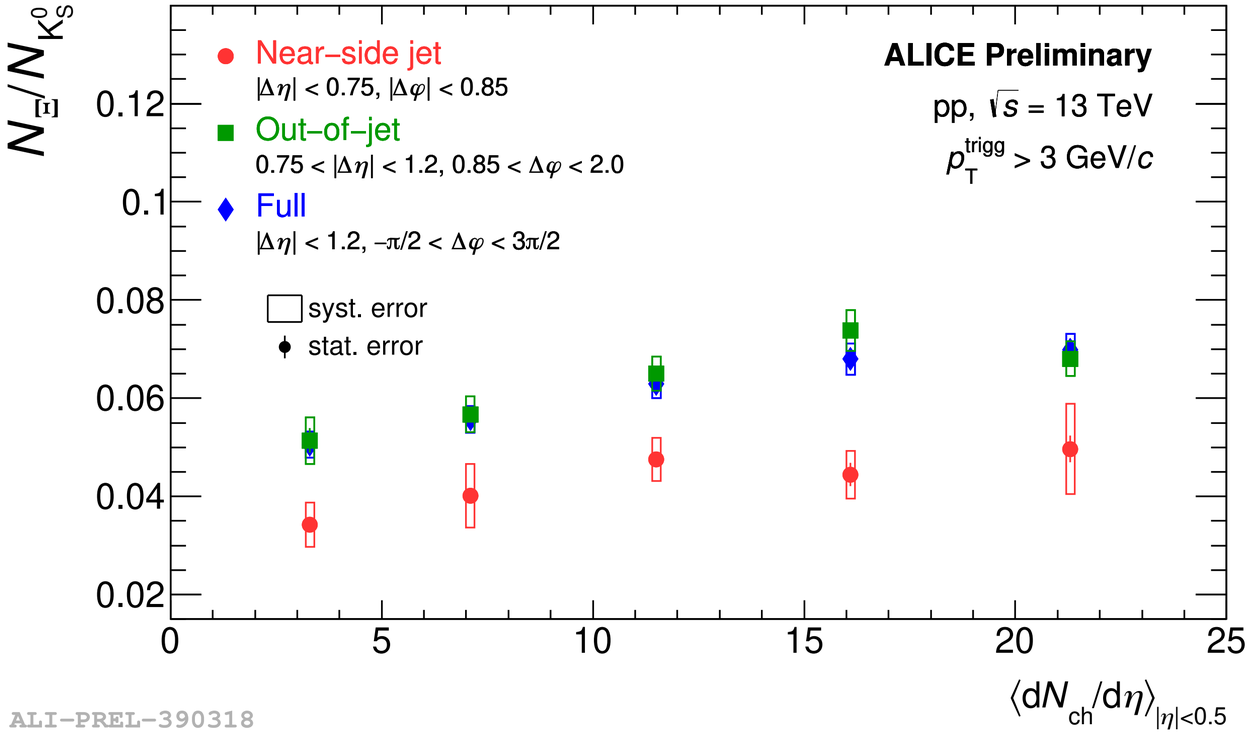
T. Bold
Heavy ion parallel session
Wednesday 15:45

Strangeness in small systems

- Does strangeness enhancement come from the bulk medium or from jet fragmentation?



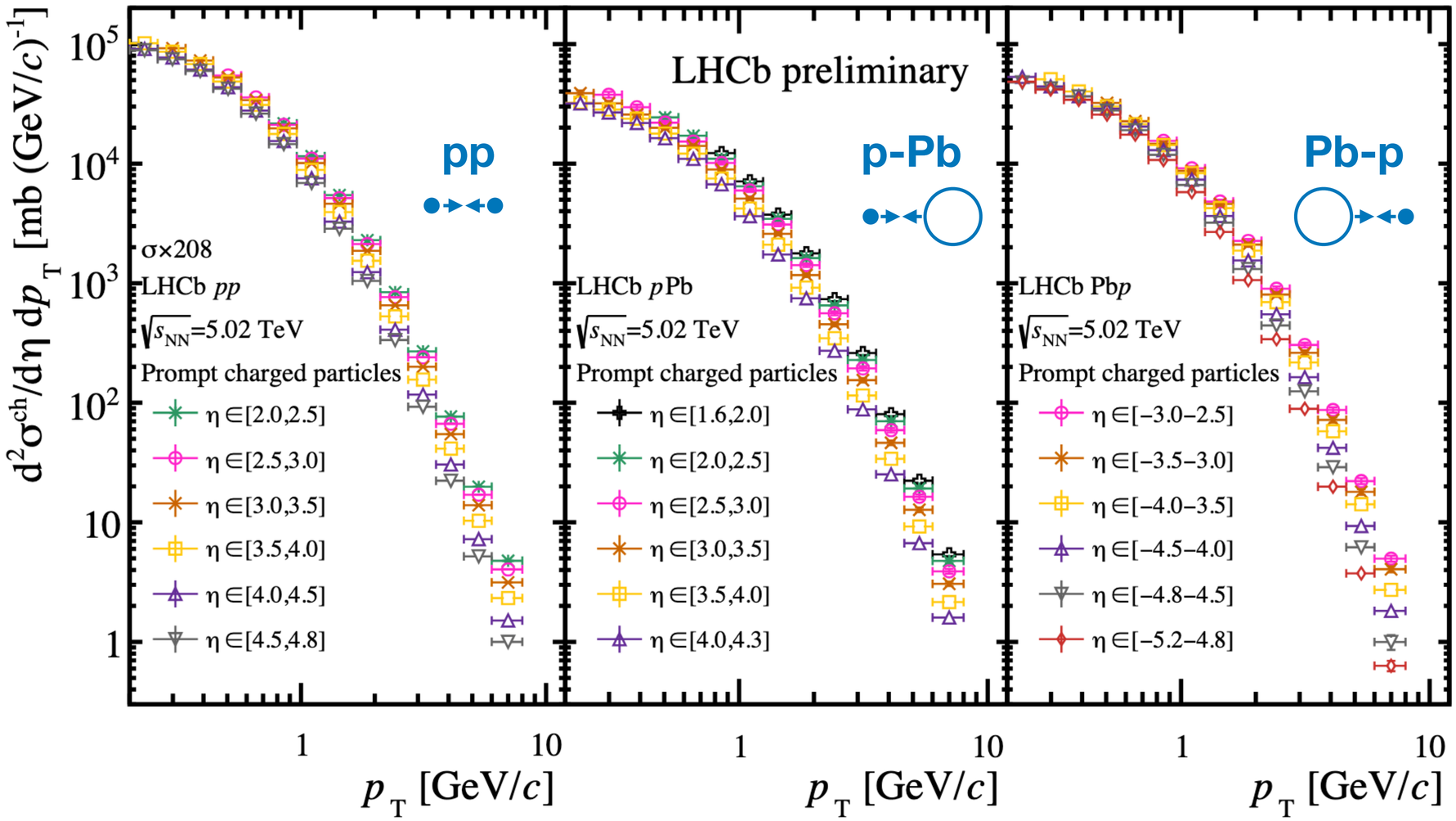
ALICE, submitted to PLB,
arXiv: 2105.04890 [nucl-ex]



- Enhancement of (multi-)strange baryons relative to kaons is a bulk effect in pp and p-Pb

Particle spectra vs pseudorapidity

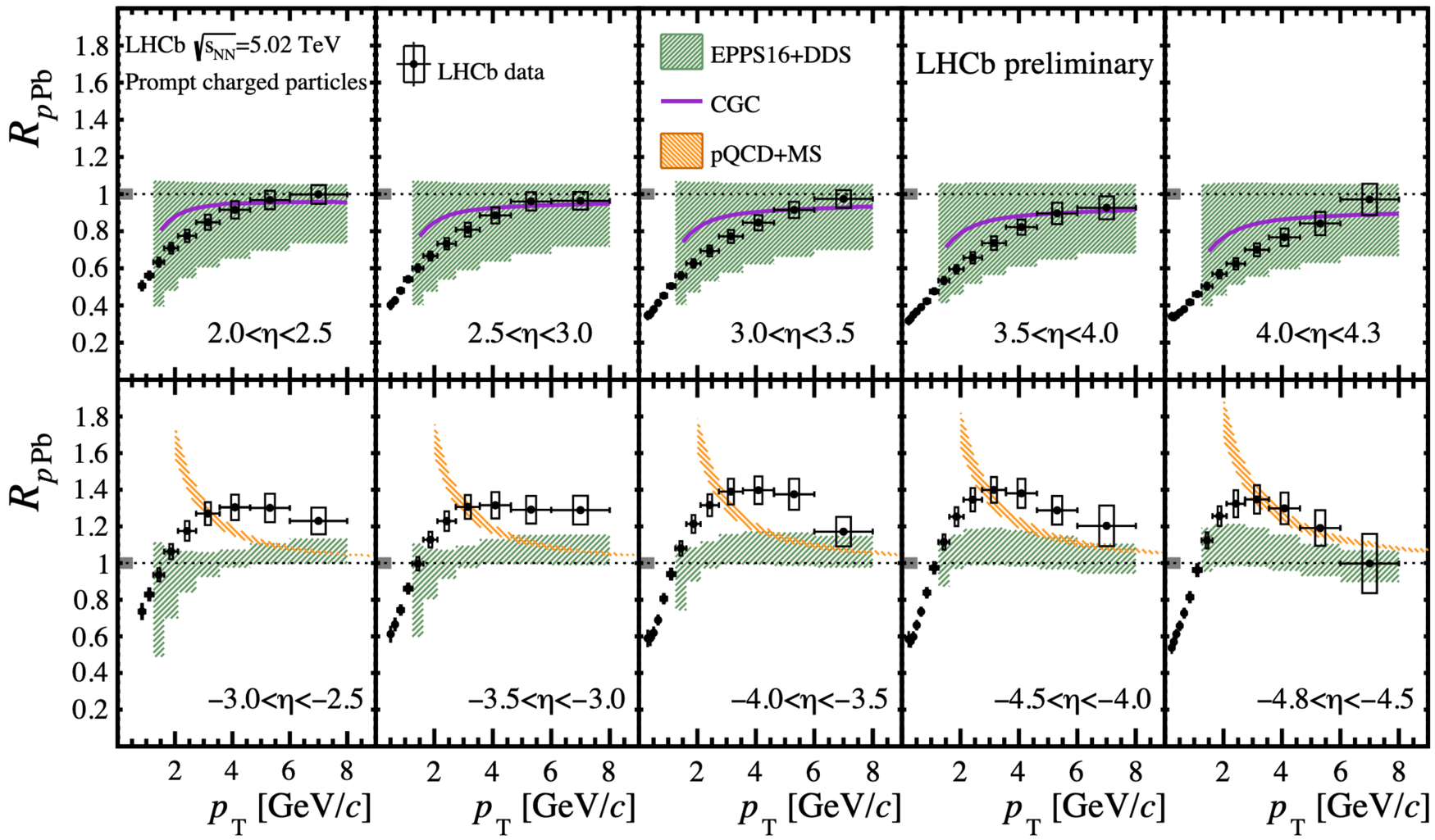
- Precision test of initial state and final state effects in small systems



LHCb-PAPER-2021-015, in preparation

Particle spectra vs pseudorapidity

- Precision test of initial state and final state effects in small systems



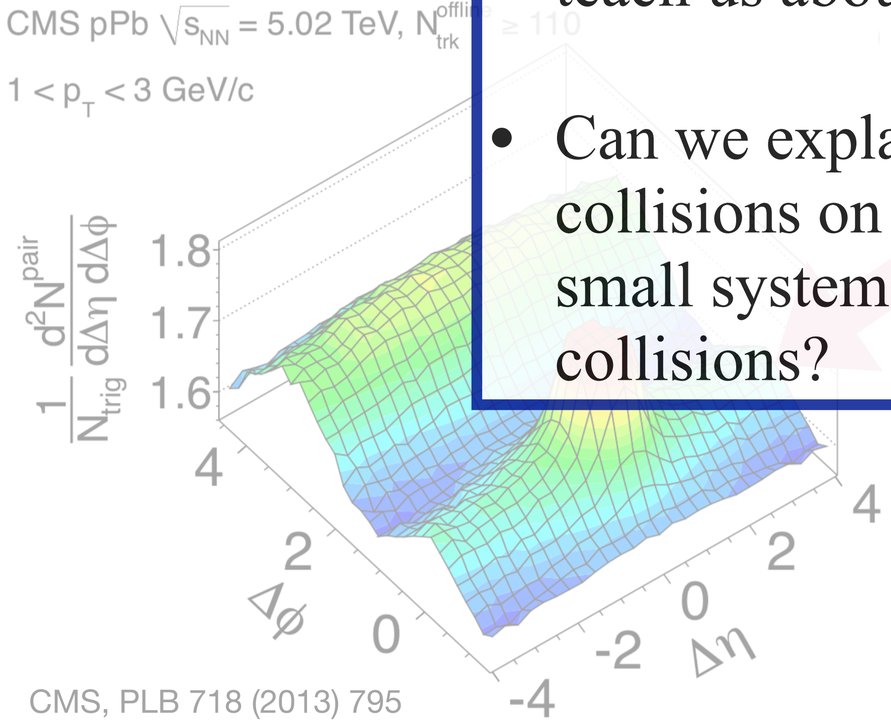
$$R_{pPb} = \frac{1}{A}\frac{d^2\sigma_{pPb}/d\eta dp_T}{d^2\sigma_{pp}/d\eta dp_T}$$

LHCb-PAPER-2021-015, in preparation

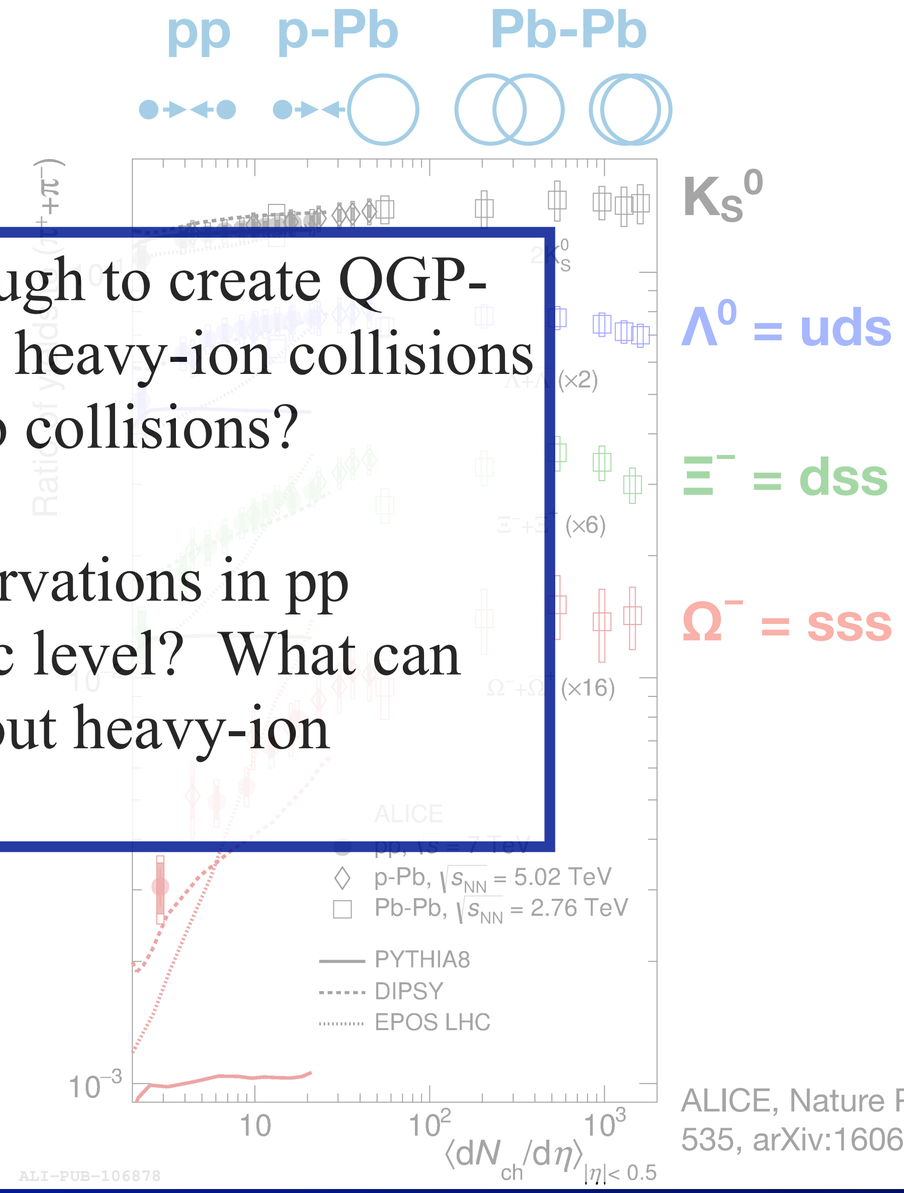
Small systems: pp and p-Pb collisions

- Similar v_n signals observed in pp and p-Pb collisions as well!
- Ratio of strange to non-strange hadrons increases smoothly with multiplicity in pp and p-Pb, towards Pb-Pb limit

- Are pp and p-Pb large enough to create QGP-like conditions? What can heavy-ion collisions teach us about pp and p-Pb collisions?
- Can we explain these observations in pp collisions on a microscopic level? What can small systems teach us about heavy-ion collisions?



CMS, PLB 718 (2013) 795



ALICE, Nature Physics 13 (2017) 535, arXiv:1606.07424 [nucl-ex]

Conclusions

- All stages of the evolution of heavy-ion collisions are reflected in the production and dynamics of soft final-state particles
  - QGP phase, phase transition, chemical freeze-out, hadron gas phase, kinetic freezeout
- Precision measurements of soft particle production and kinematics give us information about the properties of the QGP and its evolution
  - viscosities η/s and ζ/s, susceptibilities χ, compressibility k_T, temperatures T_{ch} and T_{kin}
- Similar signals are observed in small collision systems (pp and p-Pb)
  - We are using heavy-ion measurements to better understand pp collisions, and applying our knowledge of particle production mechanisms in pp to heavy-ion collisions