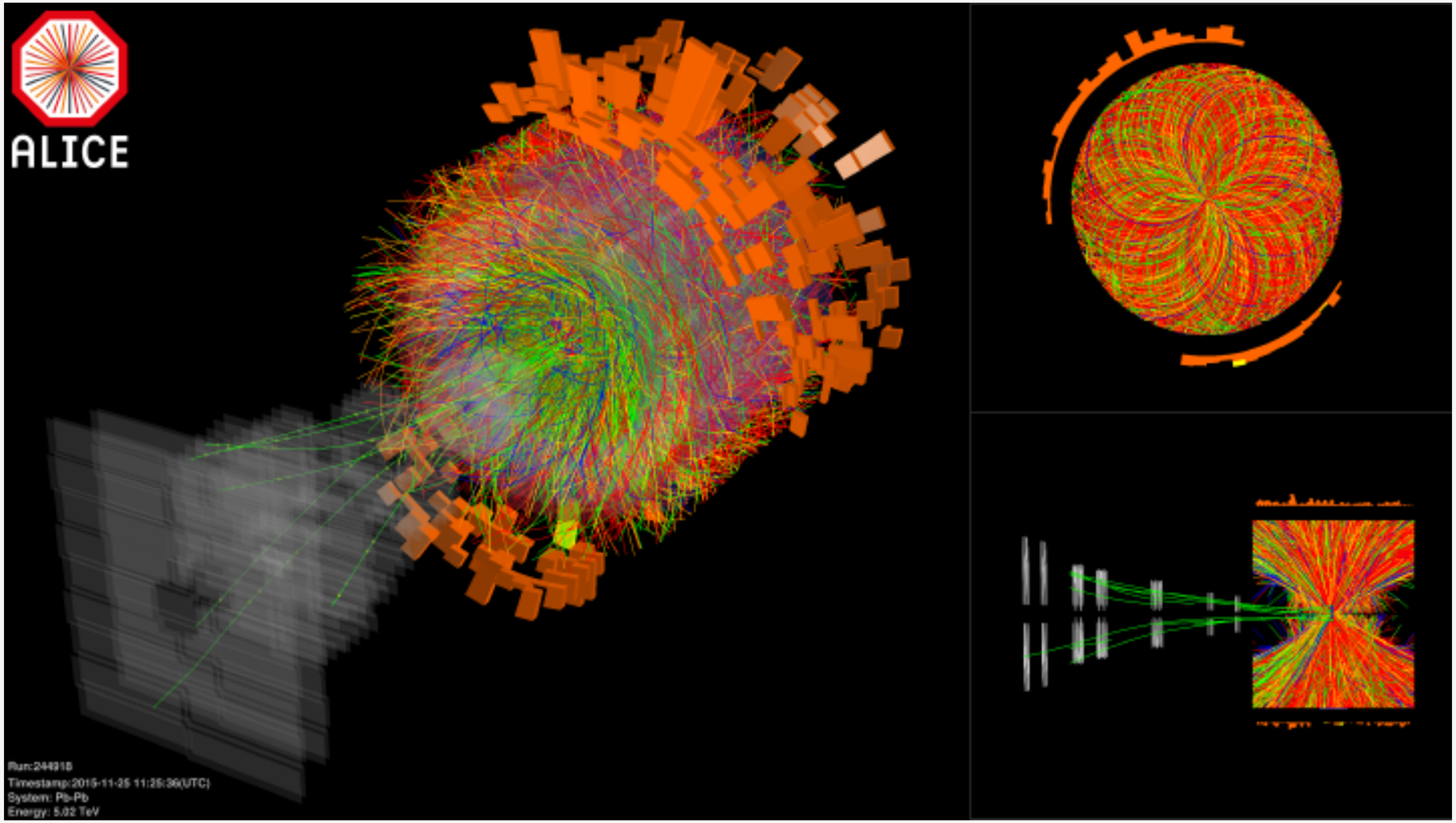
Physics with Heavy-Ion Collisions at the LHC

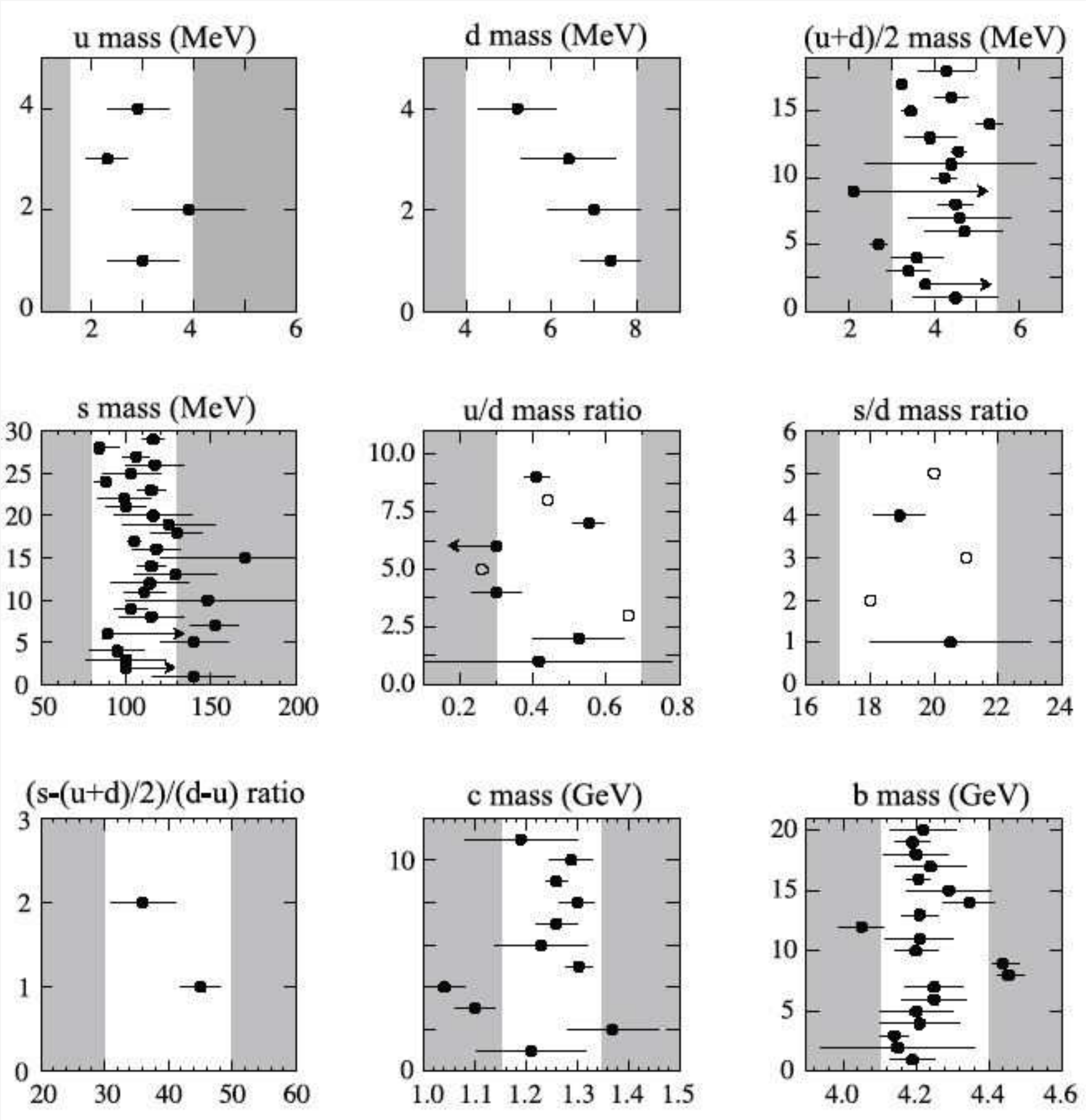


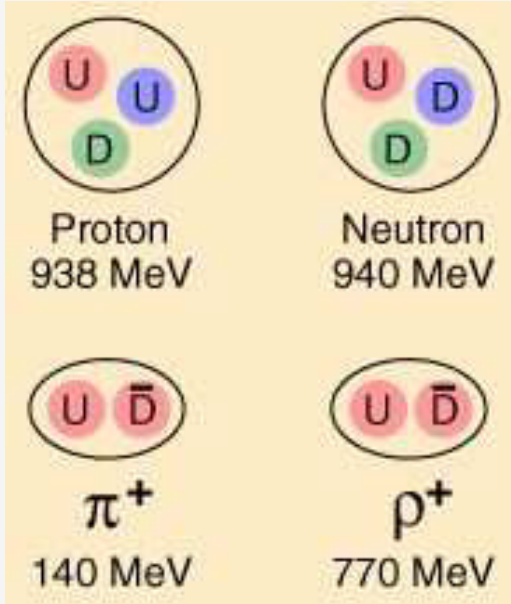
Karel Šafařík, CERN

Outlook

- **Motivation for Heavy-Ion Collisions**
  - Hadron masses
  - QCD phase transitions
- **Centrality determination**
- **Particle spectra and yields**
  - Radial flow
  - Strangeness measurement
  - Baryon anomaly
  - Statistical thermalization
- **Azimuthal anisotropy**
  - Elliptic flow
  - Higher harmonics
  - Flow in pA
- **Recent results on hard probes**
  - Heavy-flavour production
  - Direct photon production
- **Recent discussions**
  - Collectivity in small and dilute systems
  - Is there a hadronic phase in PbPb?

Hadron masses





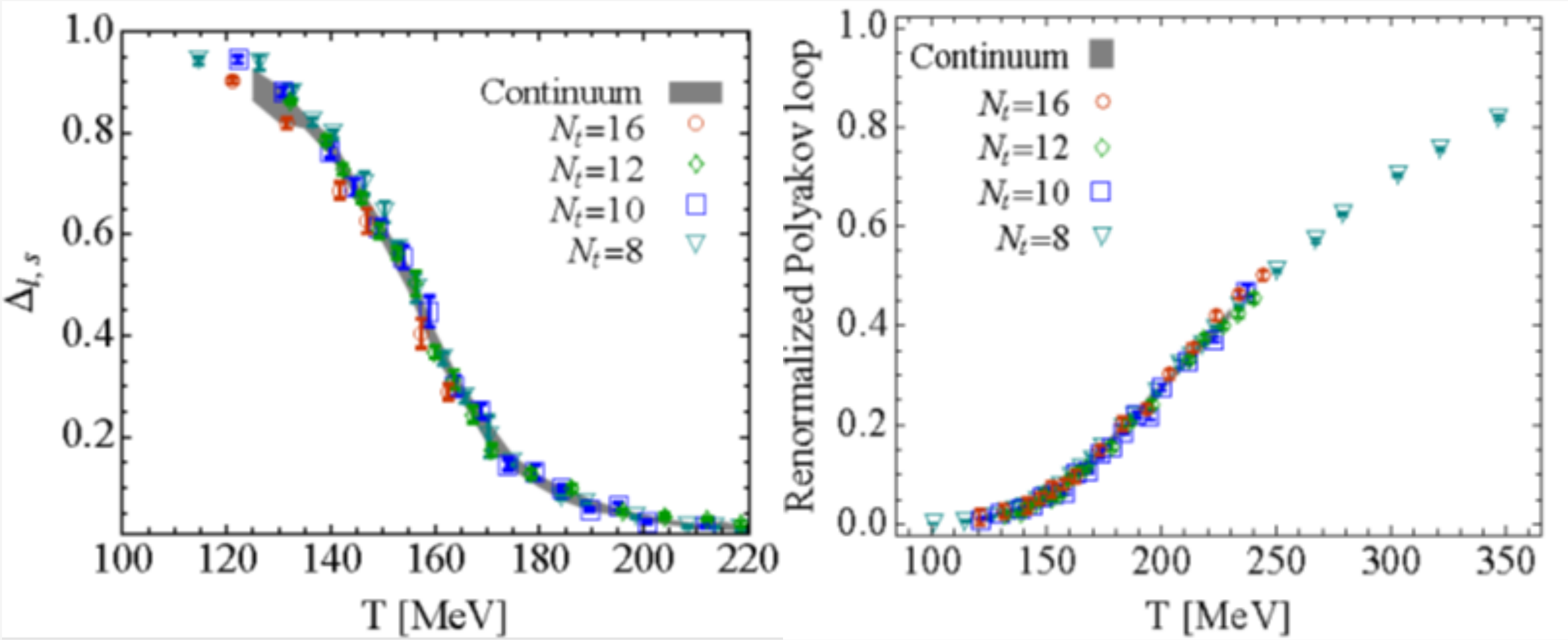
Σ quark masses ~
~ 1 % of p and n mass !

Energy of gluon field

QCD symmetries

- **QCD Lagrangian has two approximate symmetries**
  - Z_3–(centre) symmetry (for pure guage, i.e. in the limit $m_q \rightarrow \infty$)
  - chiral–symmetry (restored with vanishing masses, i.e. $m_q \rightarrow 0$)
- **At high density and temperature eventually**
  - Z_3–symmetry destroyed (confinement—deconfinement transition)
  - chiral–symmetry restored (chiral phase transition)
  - responsible: QCD vacuum condensate
- **Questions:**
  - is there one phase transition for both or two ?
  - what is the order of the phase transition(s) ?
    - is it first order (it has a latent heat) ?
    - is it second order (is just a `kink') ?
    - is just cross-over transition ?

Lattice QCD at high temperature

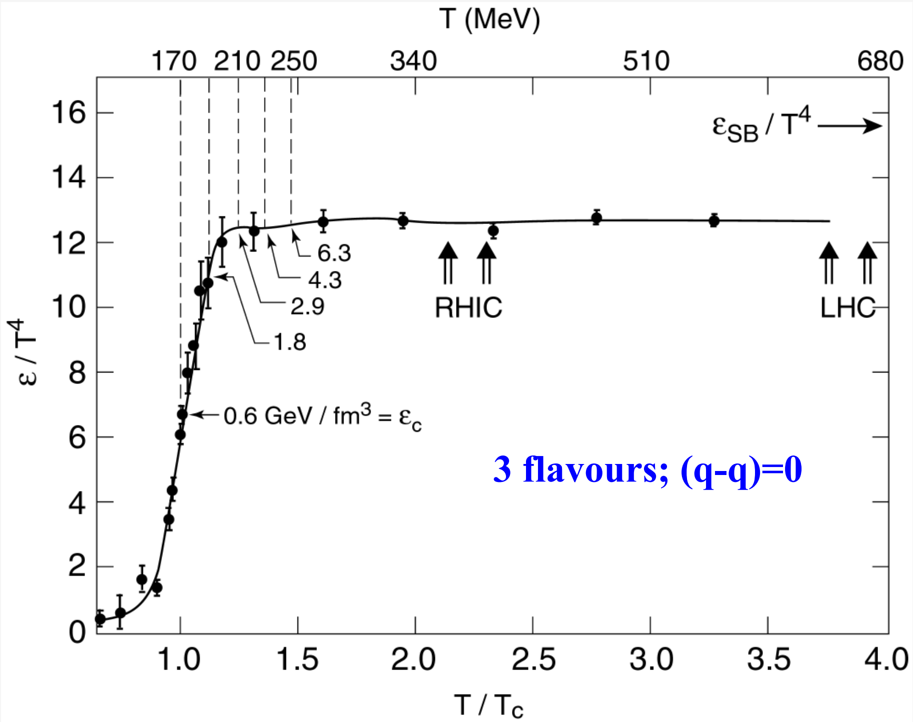


- Order parameters of QCD phase transitions:
  - quark – antiquark vacuum condensate
    - chiral phase transition in limit $m_q \to 0$
  - expectation value of Polyakov loop
    - deconfinement phase transition in limit $m_q \to \infty$

Lattice QCD

- rigorous way of doing calculations in non-perturbative regime of QCD
  - discretization on a space-time lattice

→ ultraviolet (large momentum scale) divergencies can be avoided



- **zero baryon density, 3 flavours**
- **ε changes rapidly around T_c**
- **T_c ~ 160 - 170 MeV:**
  → ε_c ~ 0.6 GeV/fm^3
- **at T ~ 1.2 T_c ε settles at about 80% of the Stefan-Boltzmann value for an ideal gas of q,q g (ε_{SB})**

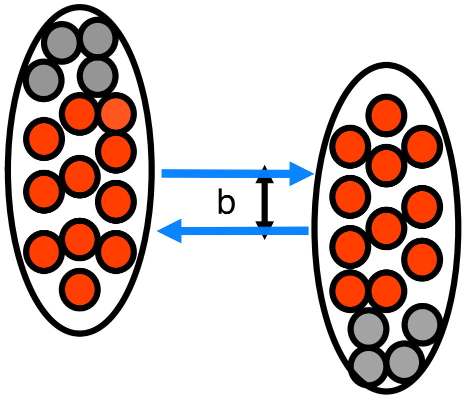
Bulk observables: multiplicity and volume

Initial conditions: collision geometry

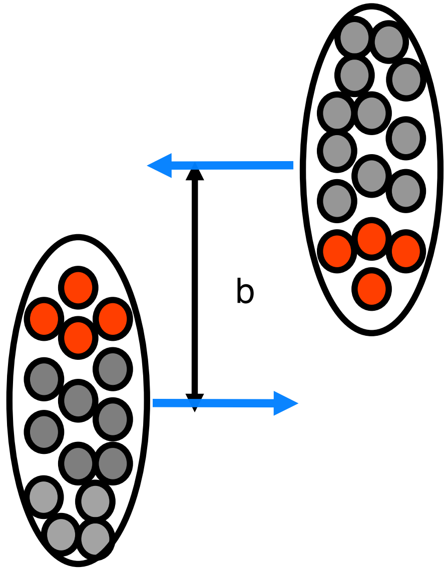
Nuclei are extended objects

Impact parameter can be estimated experimentally

Central



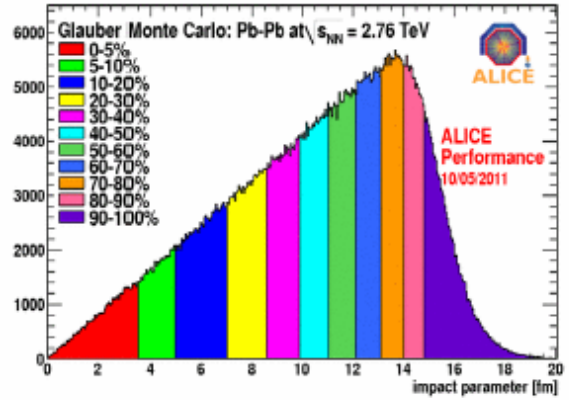
Peripheral

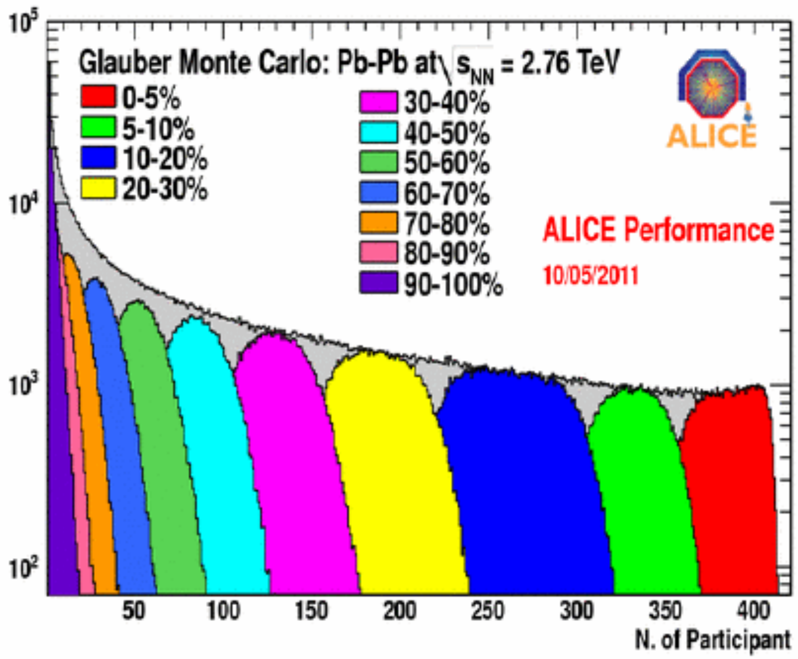


(more details on initial state later)

Glauber Monte Carlo

- Glauber model: geometrical picture of AA collision
  - Straight−line nucleon trajectories
  - N-N cross−section independent of the number of collisions the nucleons have undergone before



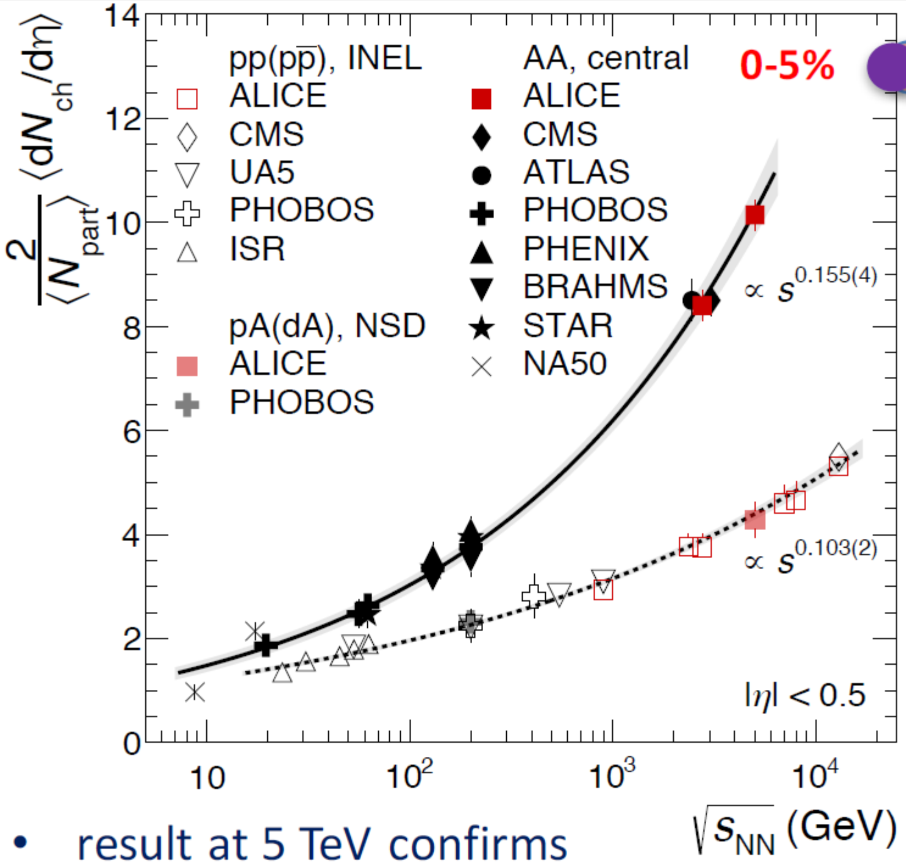


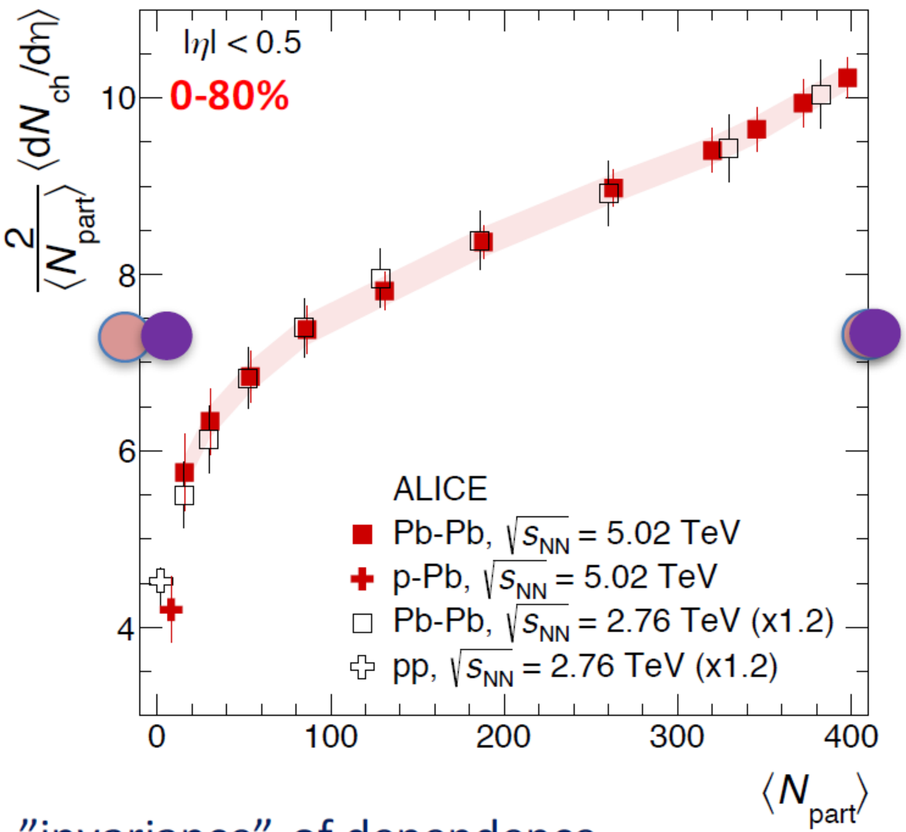
- Nuclear density profile: Woods−Saxon (2pF)

$$\rho(r) = \rho_o \cdot \frac{1}{1 + \exp\left(\frac{r - R}{d}\right)}$$

  - Radius=6.62±0.06fm
  - skin depth=0.546±0.01fm
  - Intra-nucleon distance=0.4±0.4fm
- Nucleon-Nucleon inelastic cross section σ_{NN}=64±5 mb at 2.76 TeV
- Estimate uncertainty by varying model assumptions

Particle multiplicity





- result at 5 TeV confirms trend established by lower energy data
- strong rise in Pb-Pb is not solely related to the multiple collisions

- "invariance" of dependence from centrality with respect to energy
- smooth trend towards value measured in minimum bias p-p and p-Pb collisions

~ 20% increase of multiplicity density (2.76 vs. 5.02 TeV/*NN*) as expected

Energy density

- **To evaluate the energy density reached in the collision:**

$$\varepsilon = \frac{1}{S c \tau_0} \left. \frac{dE_T}{dy} \right|_{y=0}$$

$$S = \text{transverse dimension of nucleus}$$
$$\tau_0 = \text{"formation time"} \sim 1\ \text{fm}/c$$

- **for central collisions at LHC:** $\left. \frac{dE_T}{dy} \right|_{y=o} \approx 2200\ \text{GeV}$

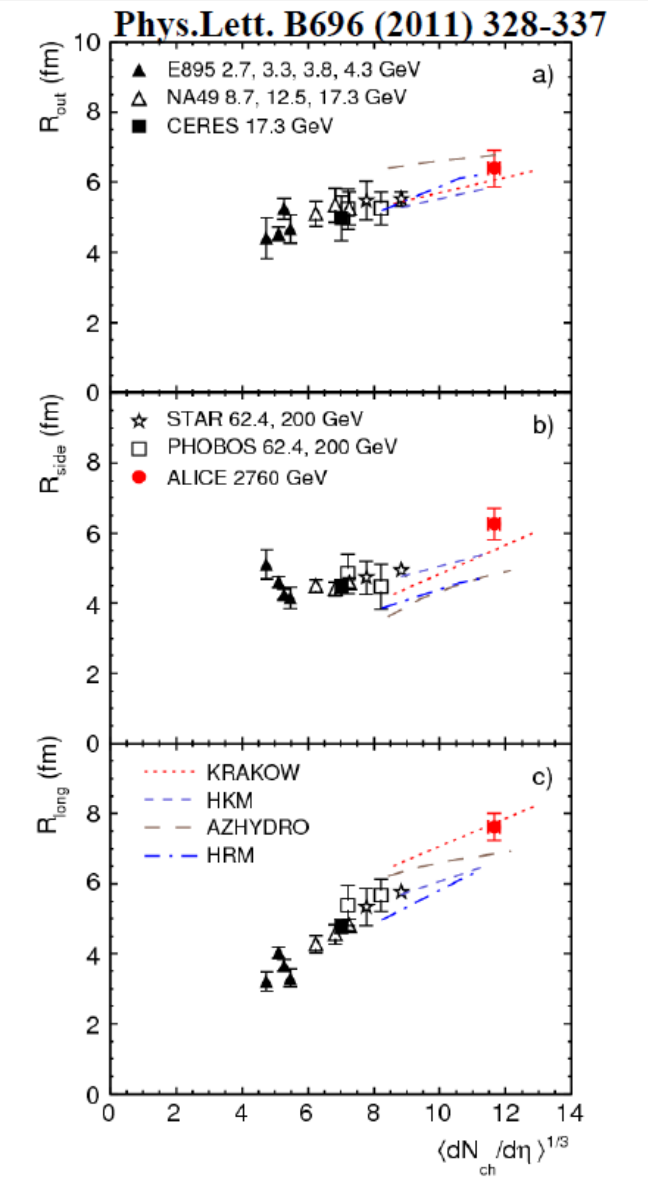
- Initial time t_0 normally taken to be ~ 1 fm/c
- i.e. equal to the "formation time": the time it takes for the energy initially stored in the field to materialize into particles

$$S \approx 160\ \text{fm}^2 \qquad (R_A \approx 1.2 A^{1/3}\ \text{fm})$$

$$\varepsilon \sim (2200/160)\ \text{GeV/fm}^3 \sim 13-14\ \text{GeV/fm}^3$$

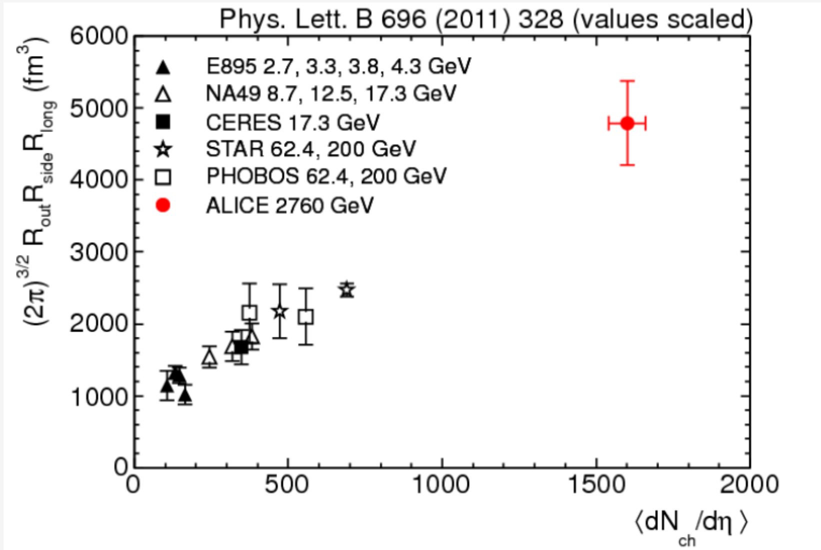
→ More than enough for deconfinement! Factor ~4 higher than on RHIC

HBT interferometry



from RHIC to LHC:

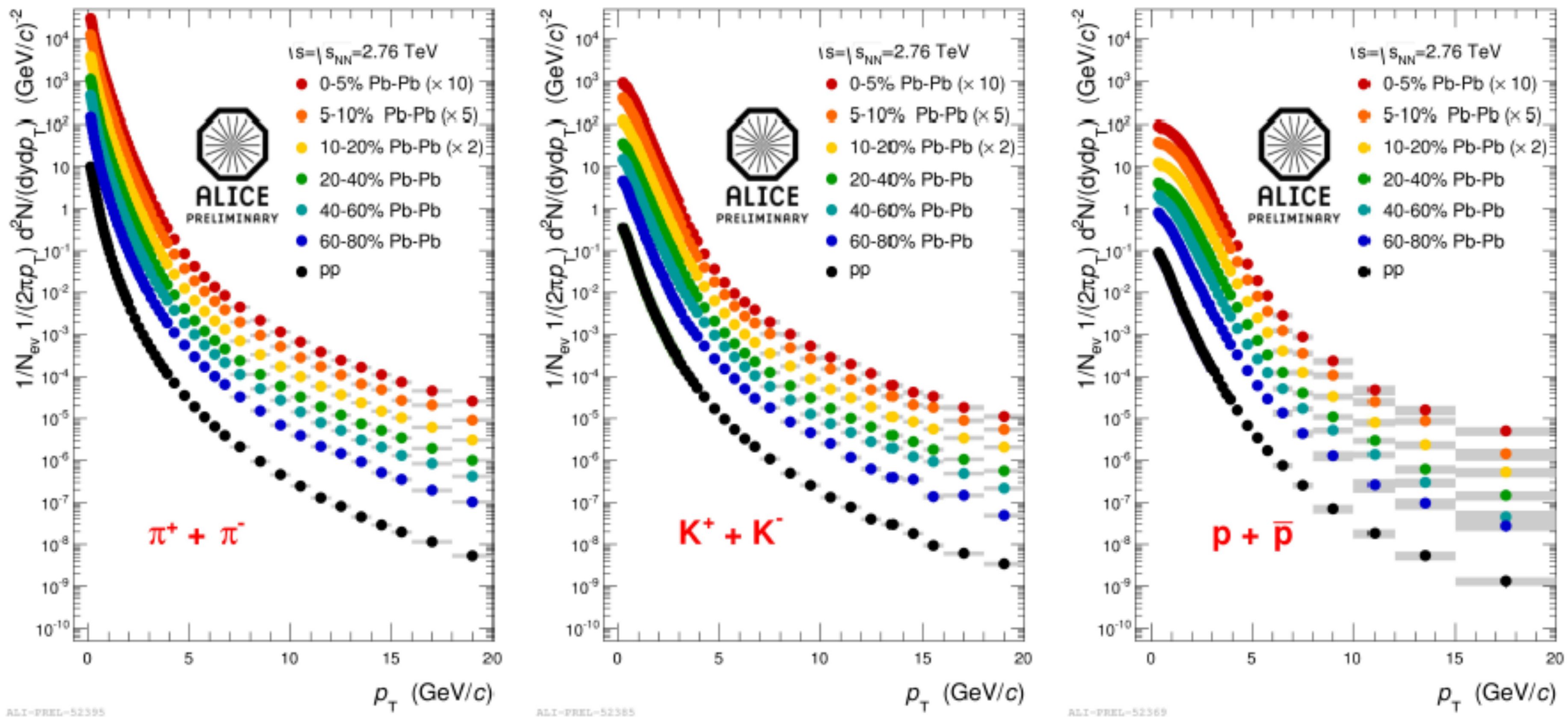
- increase of size in the 3 dimensions
  - out, long, and (finally!) side
- "homogeneity" volume ~ x 2



- for comparison: R(Pb) ~ 7 fm → V ~ 1500 fm^3

→ substantial expansion!

Transverse momentum spectra

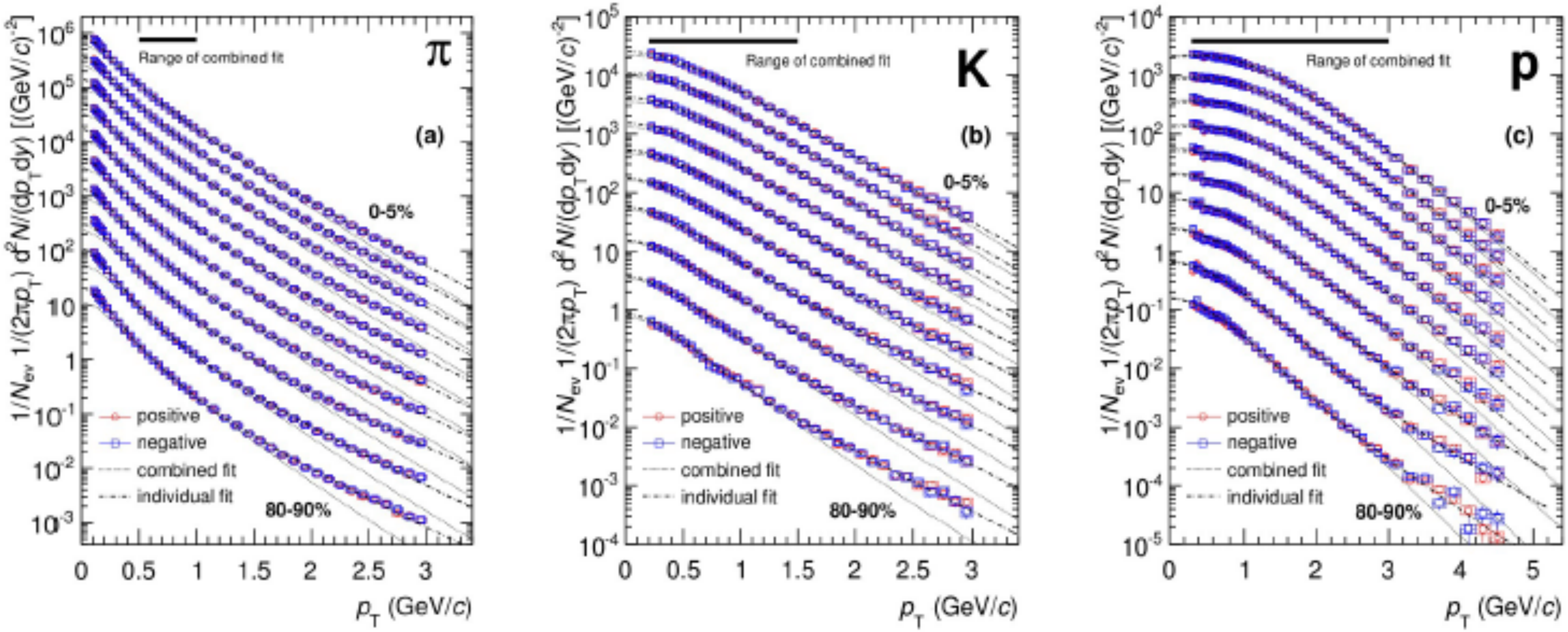


$p_T < 3$ **GeV/*c*** flow and bulk properties

3 < $p_T < 7$ **GeV/*c*** anomalous baryon enhancement and coalescence?

$p_T > 7$ **GeV/*c*** search for medium modification of fragmentation functions

Blast wave fits



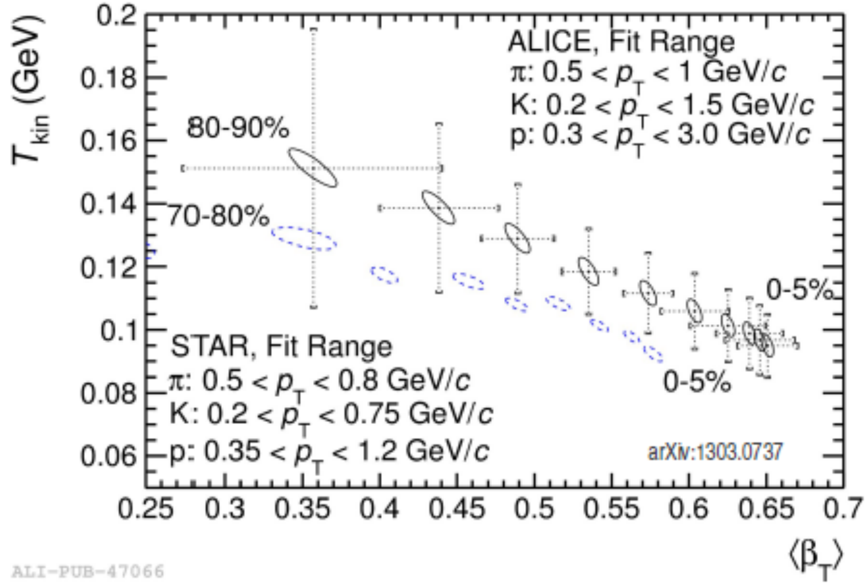
arXiv:1303.0737

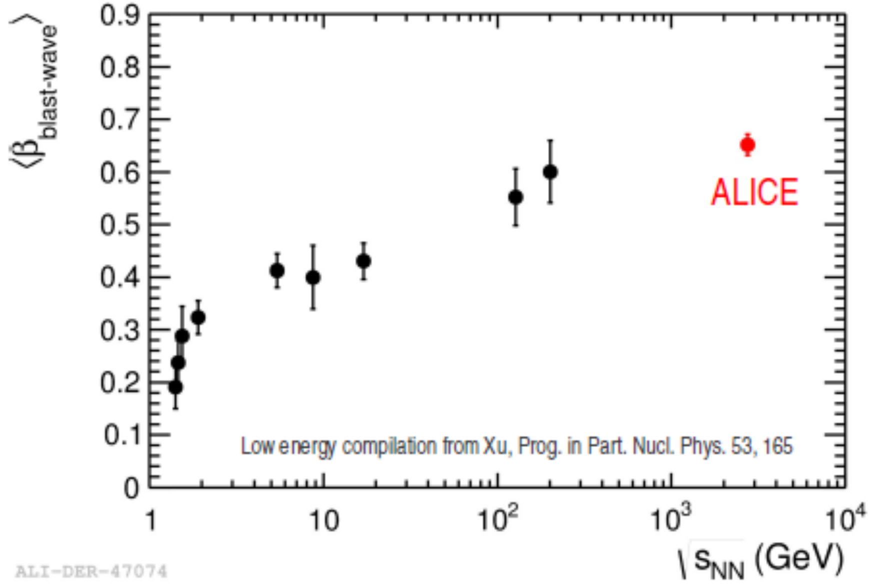
→Good description of the spectra in combined fit ranges especially for central events

→The individual fits can describe spectra over the full measured range

→Useful tool for comparison with previous results

Radial flow



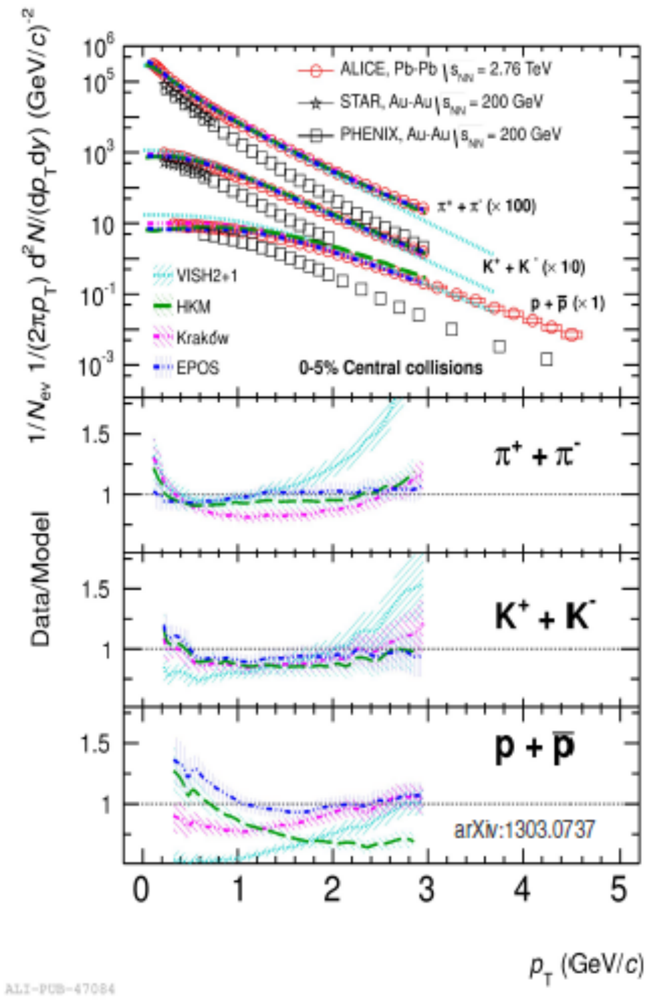


→Centrality dependence of the T_{kin}, $<\beta_T>$ similar to RHIC

→More rapid expansion with increasing centrality

Hydrodynamical models

Pb-Pb central collisions 0 – 5 % centrality



Hydro models:

VISH2+1: viscous hydrodynamics without description of hadronic phase, using thermal yields at T_{ch}=165 MeV
(Shen et al., PRC 84, 044903 (2011))

HKM: hydro+UrQMD, additional radial flow built by hadronic phase which also affects particle ratios as a result of inelastic interactions
(Karpenko et al., arXiv:1204.5351)

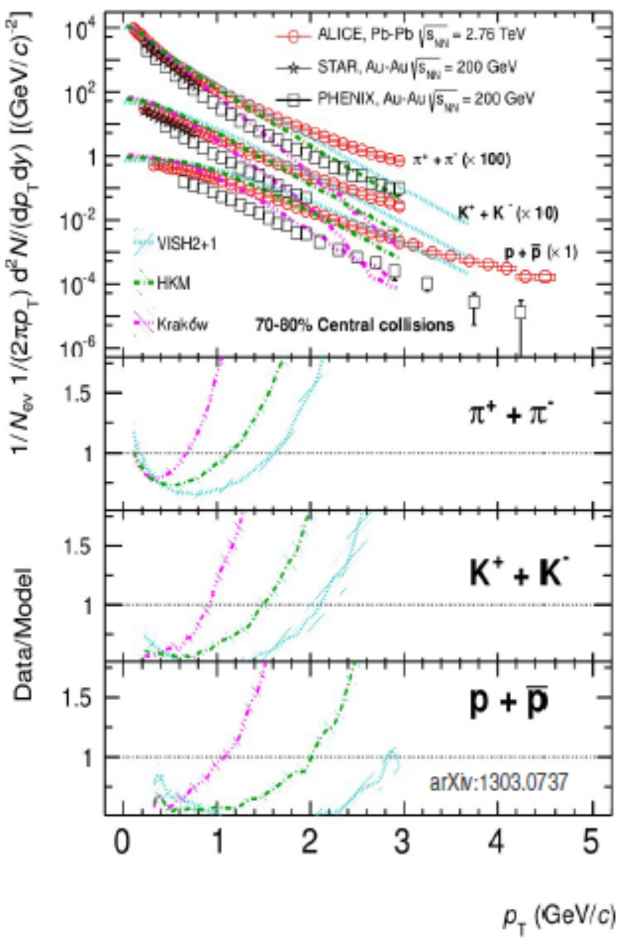
Kraków: introduces non equilibrium corrections due to the bulk viscosity at the transition from the hydrodynamic description to particles which changes the effective T_{ch}
(Bożek, PRC 85, 034901 (2012))

EPOS: uses breakup of the flux tubes created by initial hard scatterings to described the spectra shapes for all p_T
(Werner et al., Phys. Rev. C 85, 064907 (2012))

Hydro models provide a reasonable description of the measured spectra at p_T lower than 3 GeV/*c*.

Hydrodynamical models

Pb-Pb peripheral collisions 70 – 80 % centrality



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They fail in peripheral collisions.

R_{AA} – definition

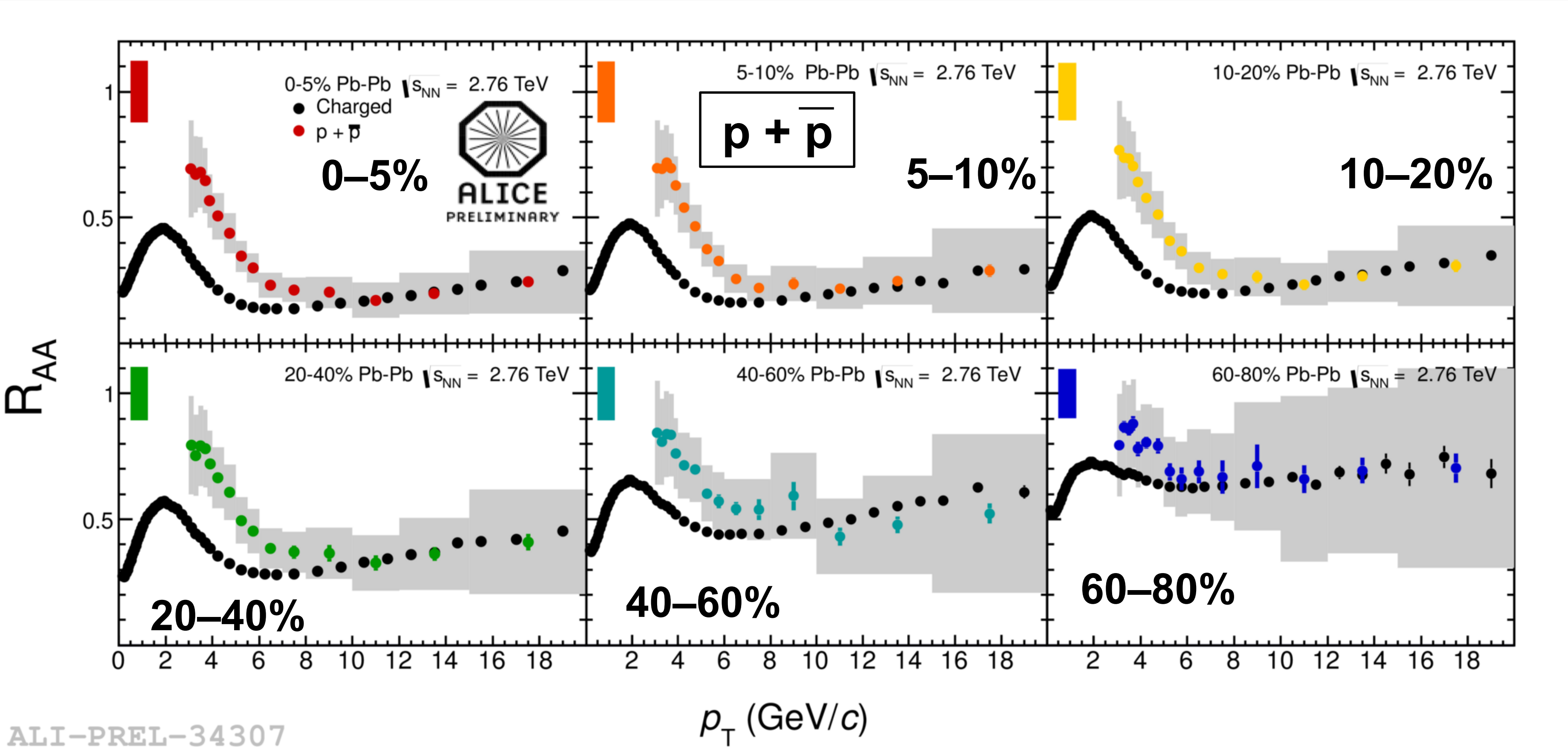
- R_{AA} – ratio of p_T spectrum in AA collisions to that in pp – properly normalized by number of binary collisions

$$R_{AA} = \frac{(\mathrm{d}\sigma/\mathrm{d}p_\mathrm{T})_\mathrm{AA}}{N_\mathrm{coll}(\mathrm{d}\sigma/\mathrm{d}p_\mathrm{T})_\mathrm{pp}} = \frac{(\mathrm{d}N/\mathrm{d}p_\mathrm{T})_\mathrm{AA}}{T_\mathrm{AA}(\mathrm{d}\sigma/\mathrm{d}p_\mathrm{T})_\mathrm{pp}} = \dots$$

if AA would be just a superposition of pp collisions R_{AA} = 1 for “hard probes” (low cross section)

Identified particles at intermediate p_T

● charged particles ●●●●●● different centralities for identified particles

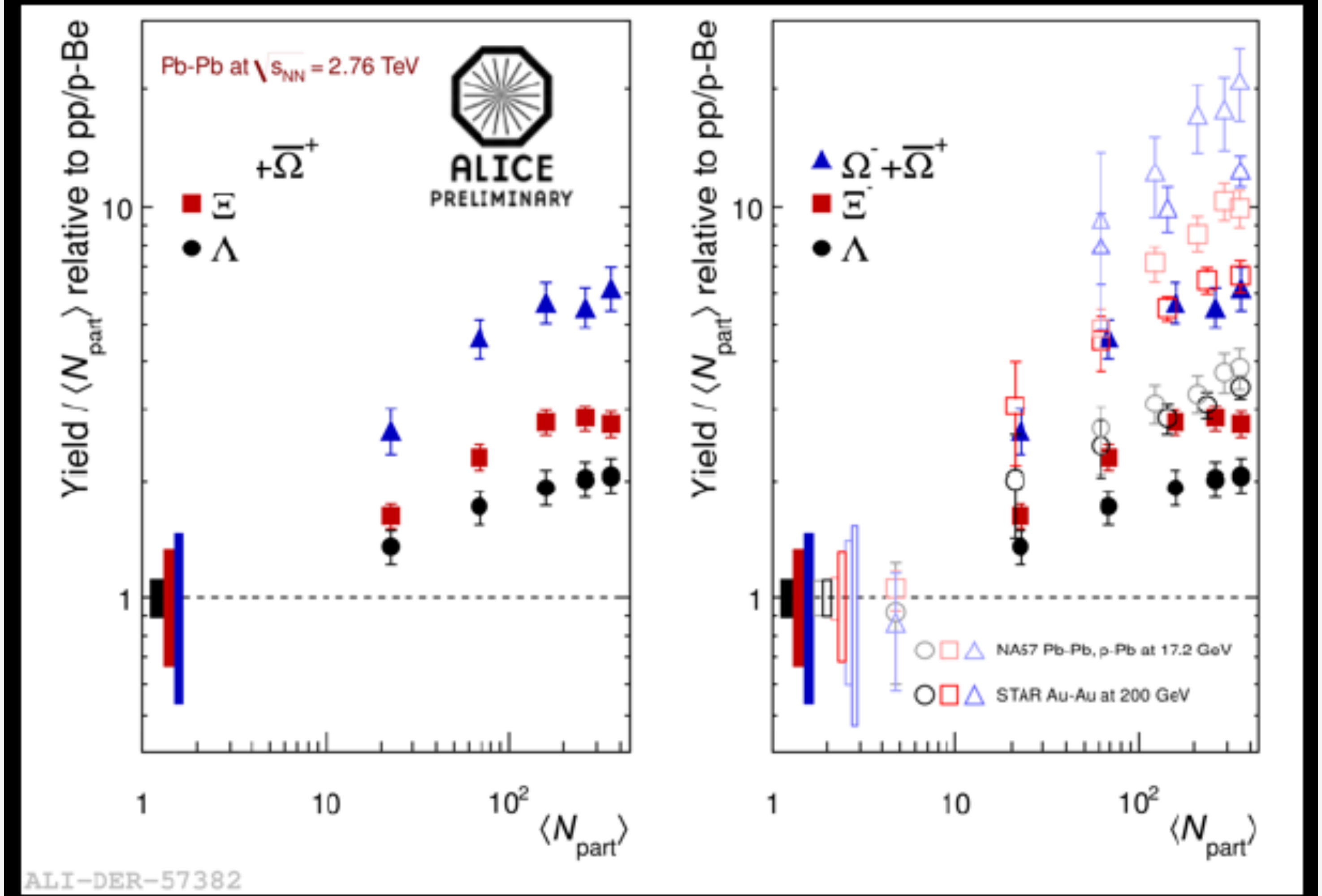


For p_T below ~ 7 GeV/c: $R_{AA}(\pi) < R_{AA}(h^{\pm})$, $R_{AA}(K) \approx R_{AA}(h^{\pm})$, $R_{AA}(p) > R_{AA}(h^{\pm})$

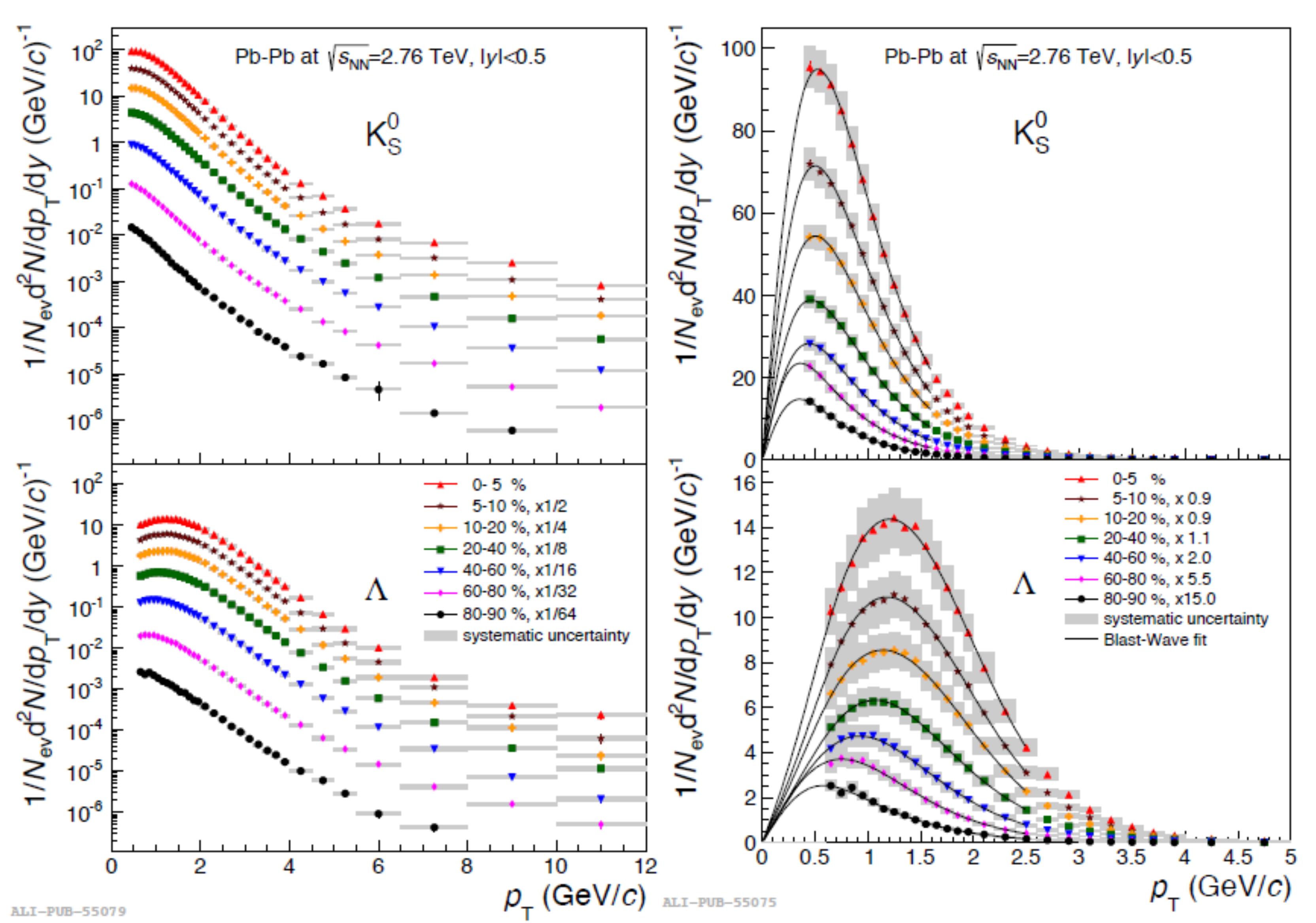
At higher p_T: R_{AA} are compatible

Strangeness enhancement

$$E = \frac{\frac{dN}{dy}_{PbPb}/N_{part}}{\frac{dN}{dy}_{pp}/2}$$



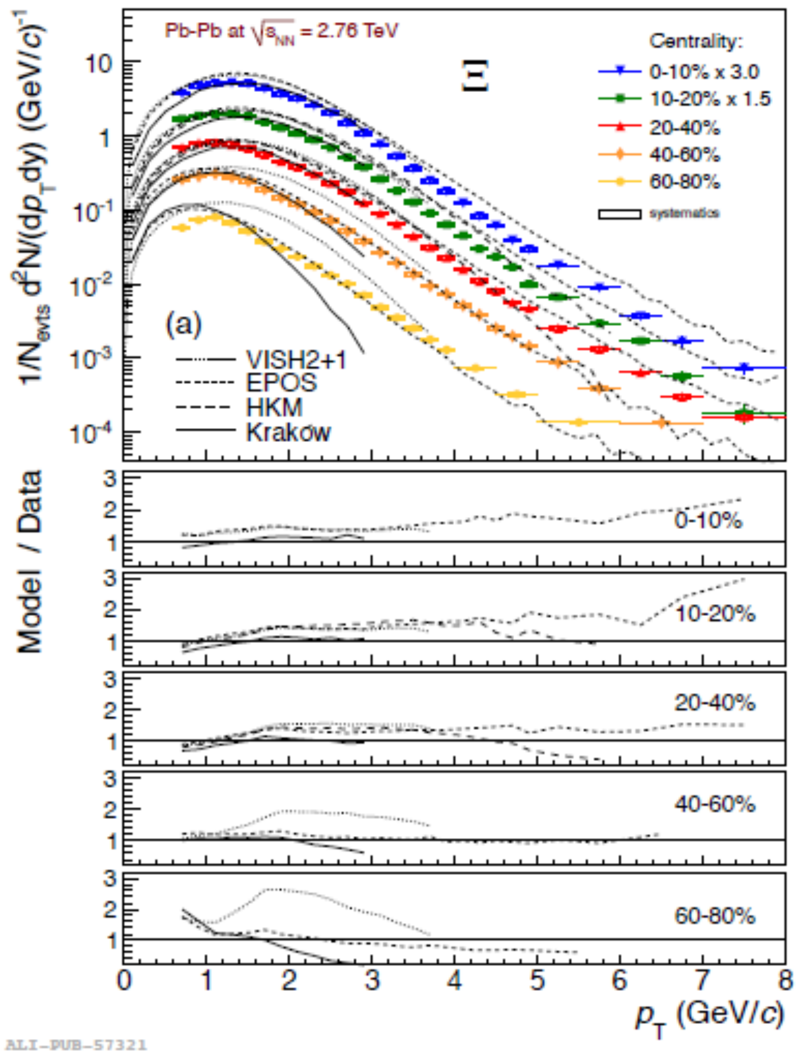
Strangeness spectra K^0_s Λ



ALICE Collaboration, (2013), arXiv:nucl-ex/1307.5530

Strangeness spectra Ξ

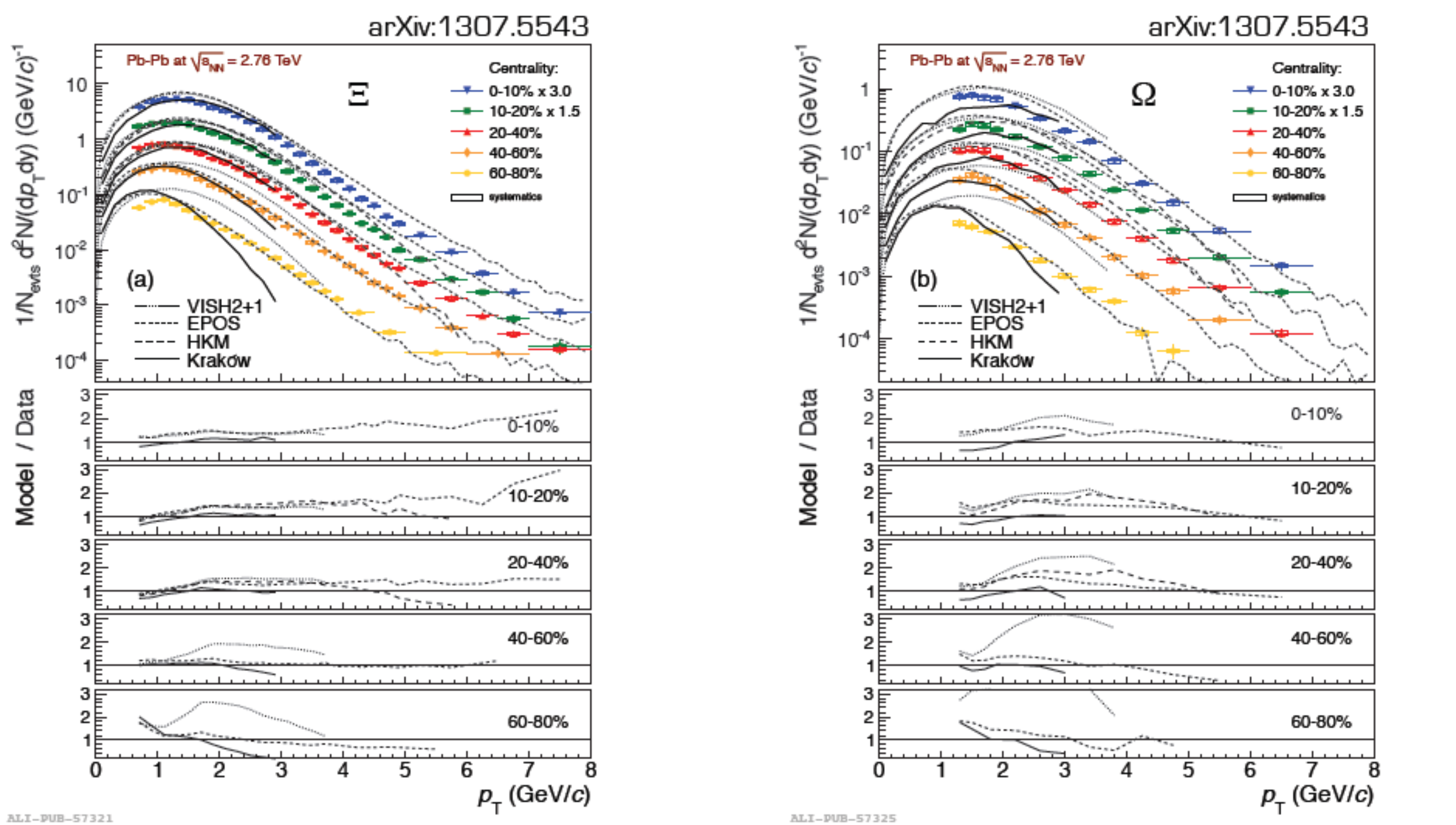
arXiv:1307.5543



- Models
  - VISH2+1[1]: viscous hydrodynamic model
  - HKM[2]: ideal hydro model, with hadron cascade (UrQMD)
  - Kraków[3]: non-equilibrium corrections due to bulk viscosity in transition from hydrodynamics to particles
  - EPOS[4]: incorporates hydrodynamics and models the interaction between high p_T hadrons and expanding fluid, also use UrQMD as hadronic cascade model
- Results
  - Kraków model provides a good description for both yields and shapes ($p_T < 3$ GeV/c)
  - EPOS gives the most successful description of spectra shape in a wider p_T range

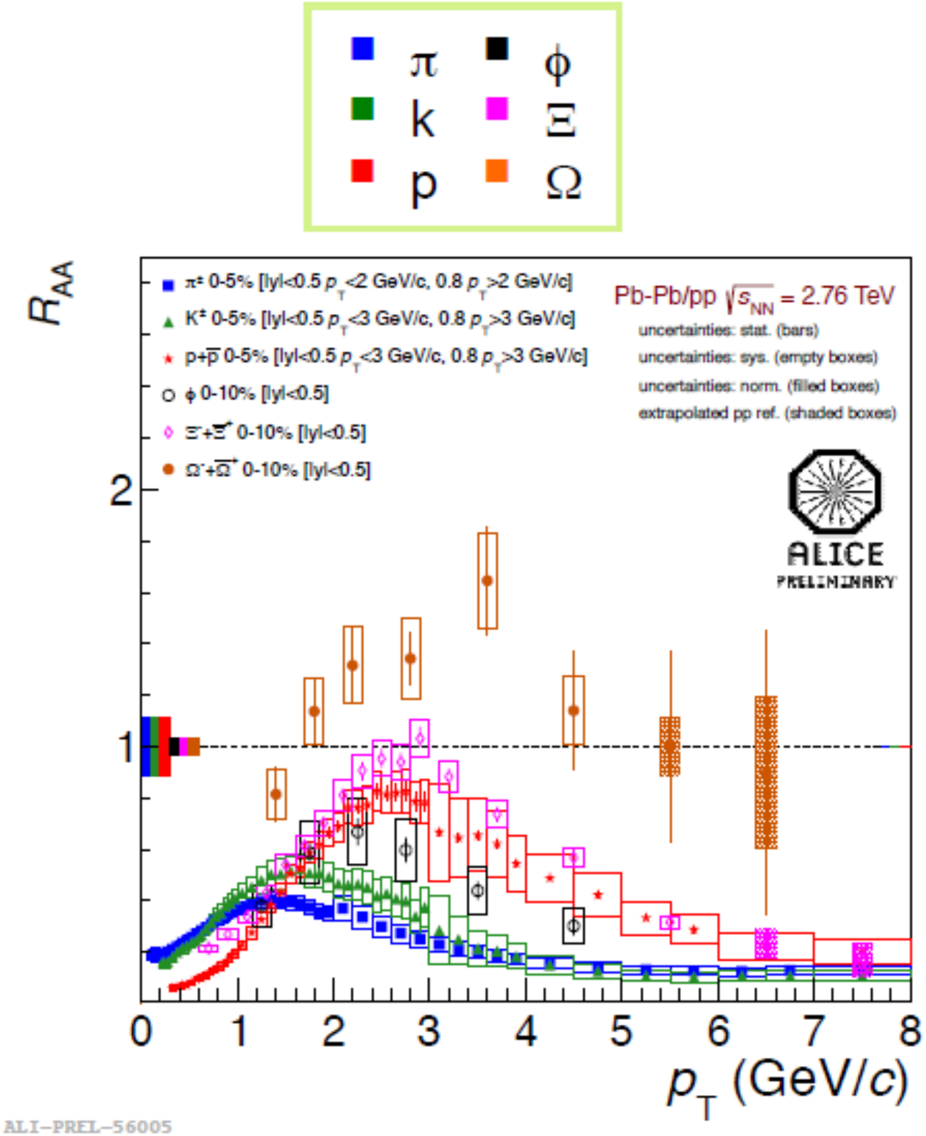
[1] Phys. Rev. C 84, 044903 (2011)
[2] J. Phys. G 38, 124059 (2011), 1204.5351 [nucl-th] (2012)
[3] Phys. Rev. C 85, 034901 (2012), Acta Phys. Pol. B 43, 4, 689 (2012)
[4] Phys. Rev. C 85, 064907 (2012), 1204.1394 [nucl-th], (2012)
1205.3379 [nucl-th] (2012)

Strangeness spectra Ξ Ω



Strangeness R_{AA}

Nuclear modification factor



$$R_{AA} = \frac{1}{\langle T_{AA} \rangle} \frac{(d^2N/dydp_T)_{A-A}}{(d^2\sigma_{INEL}/dydp_T)_{pp}}$$

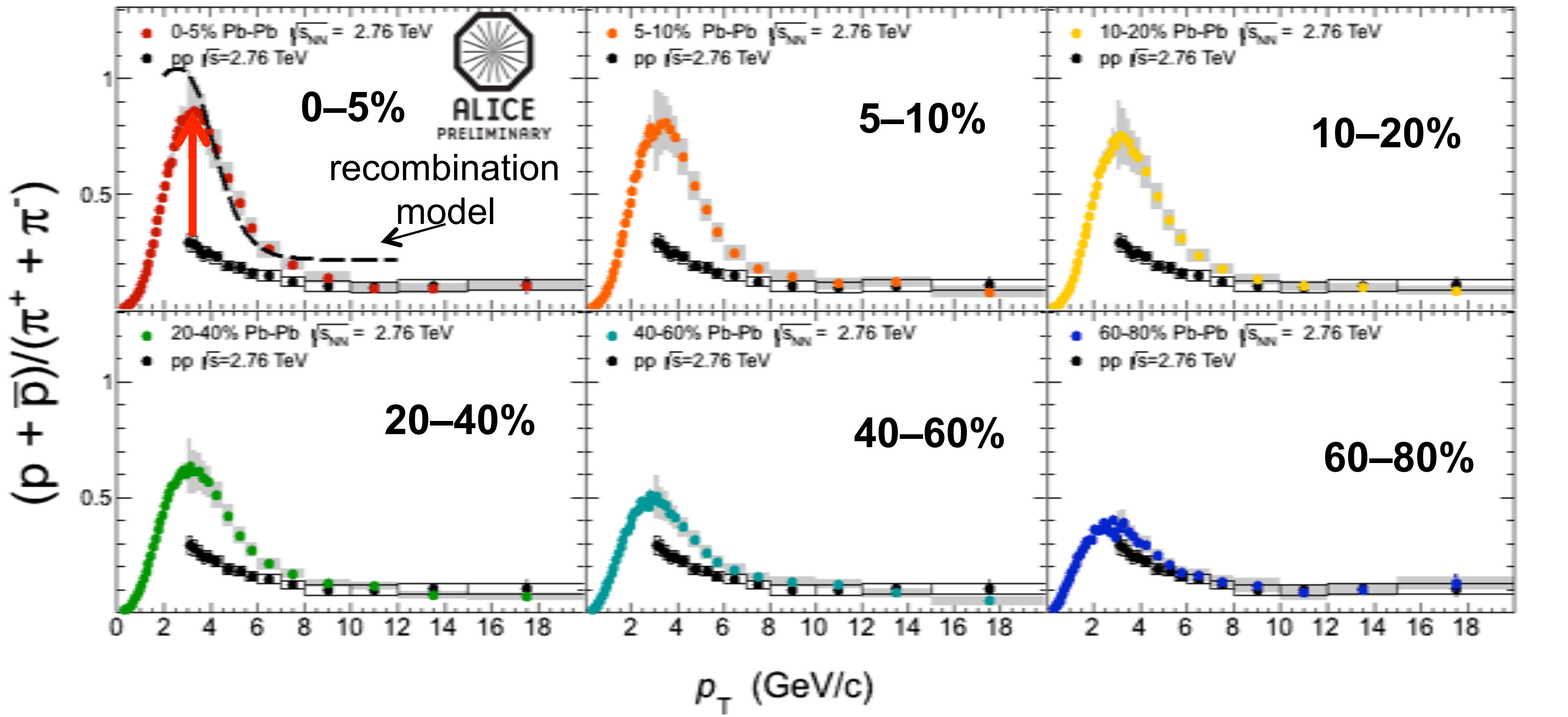
ALICE

- Compared with π, k, p at high p_T and φ
- At high p_T R_{AA} does not depend on the mass of the particle
- Mass ordering at mid-p_T
- Effect of strangeness enhancement on the Ω (and Ξ)
- Shaded points for Xi and Omega obtained with extrapolated pp ref.

INFN Istituto Nazionale di Fisica Nucleare

Baryon-to-meson ratio: p/π

● proton–proton ●●●●●● Pb–Pb different centralities



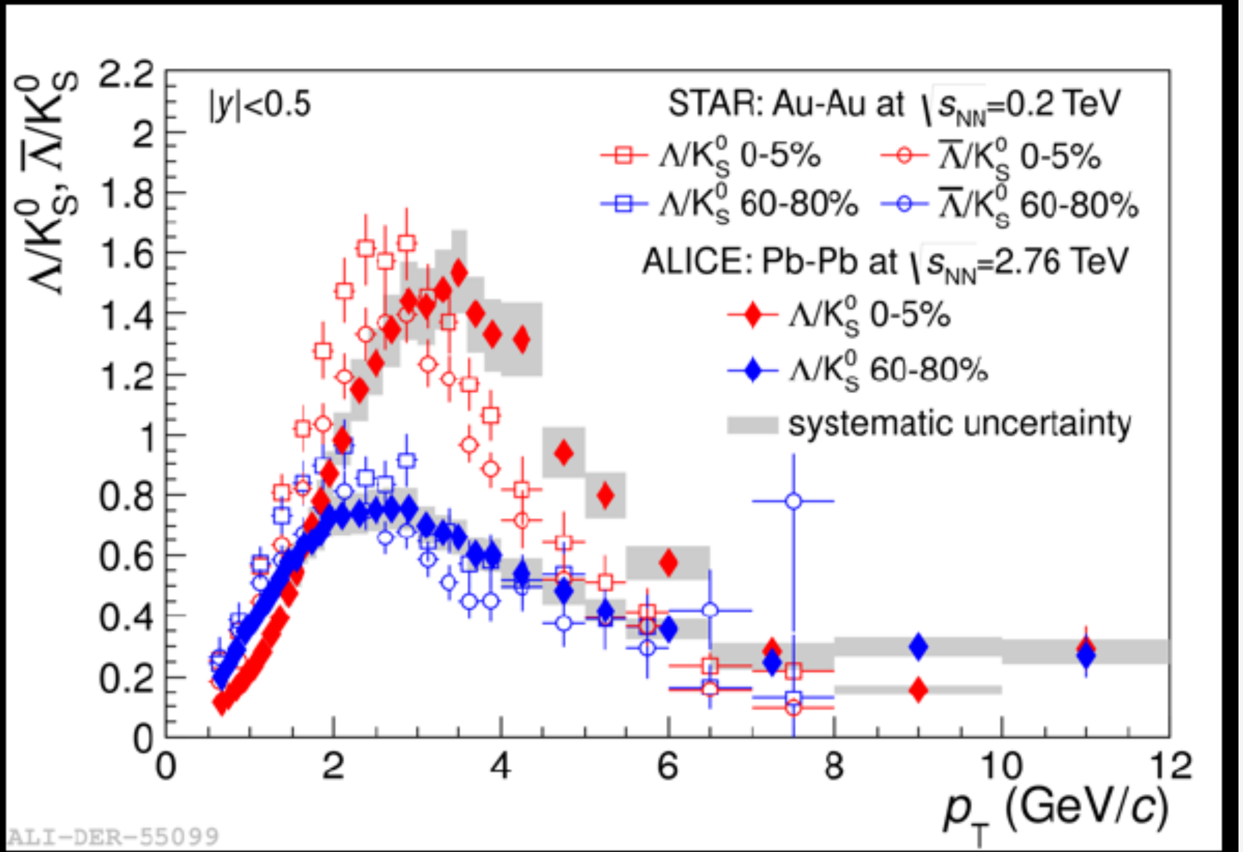
p/π ratio at $p_T \approx$ 3 GeV/*c* in 0–5% central Pb–Pb collisions factor ~ 3 higher than in pp at p_T above ~ 10 GeV/*c* back to the “normal” pp value

recombination – radial flow ?

R.J.Fries et al., PRL 90 202303; PR C68 044902

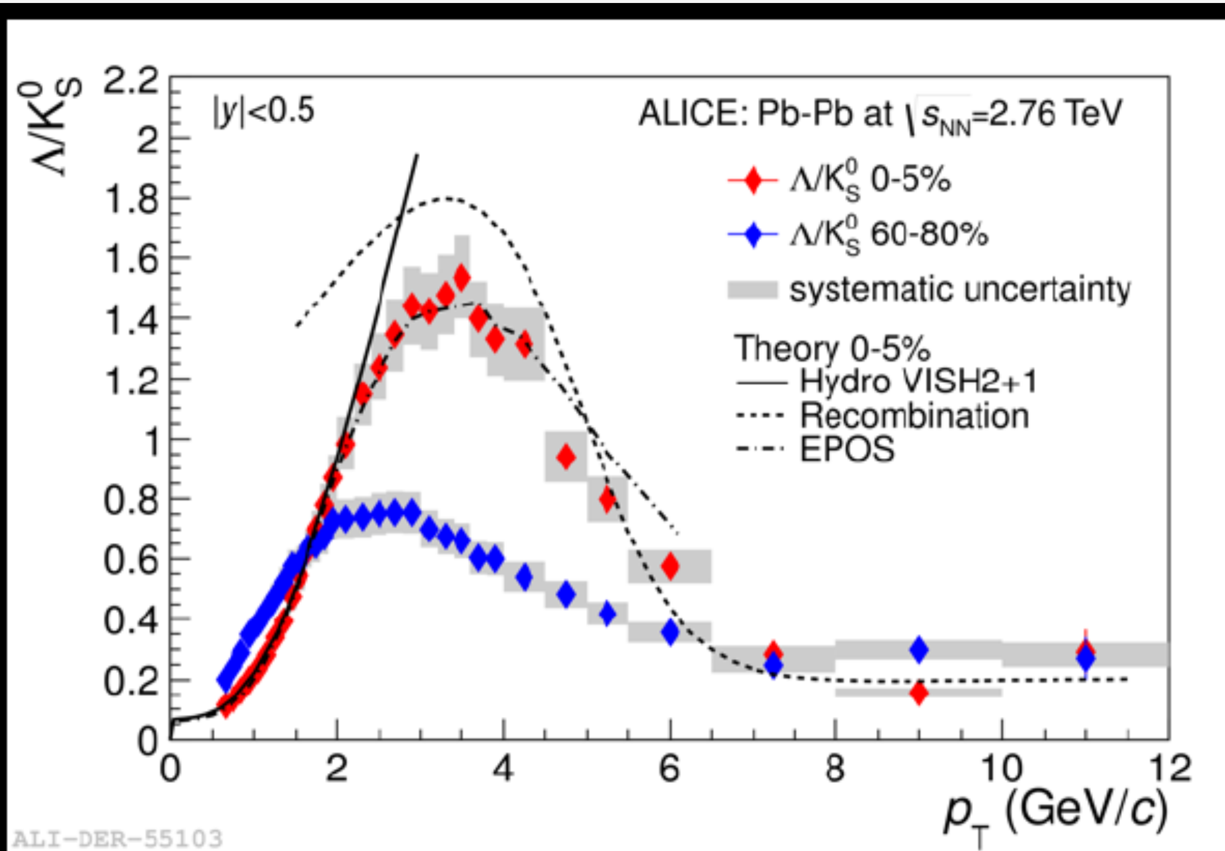
Baryon-to-meson ratio: Λ/K

- Baryon/meson ratio: Λ/K^0
- Striking maximum
  - very similar maximum value to STAR
  - occurs at larger a p_T
- Excess in central w.r.t peripheral persists to higher p_T

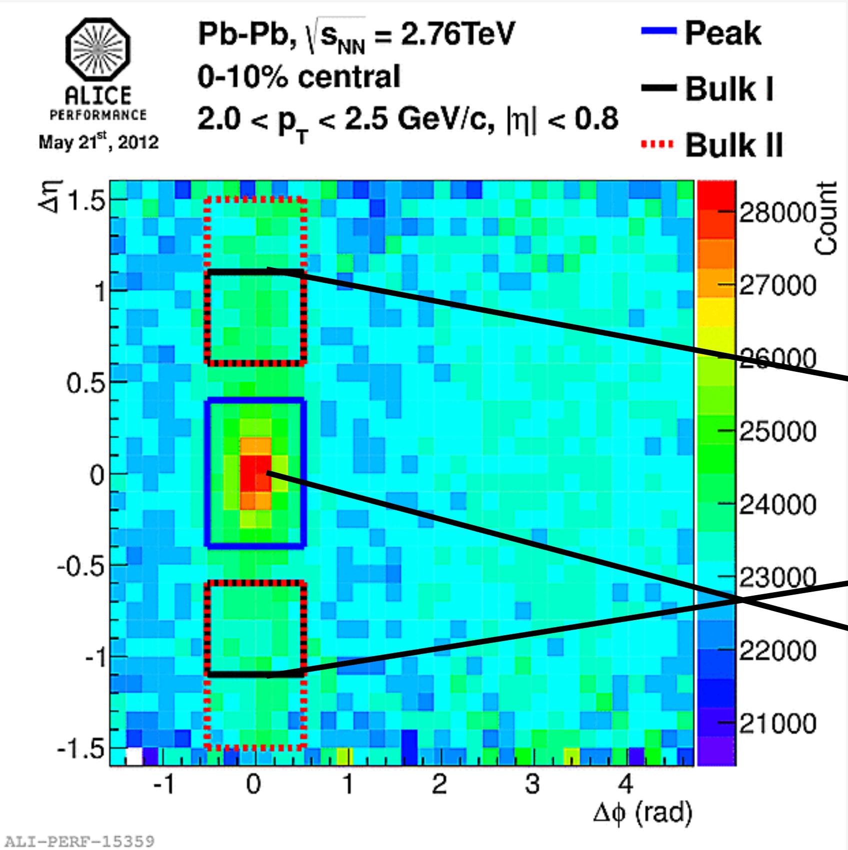


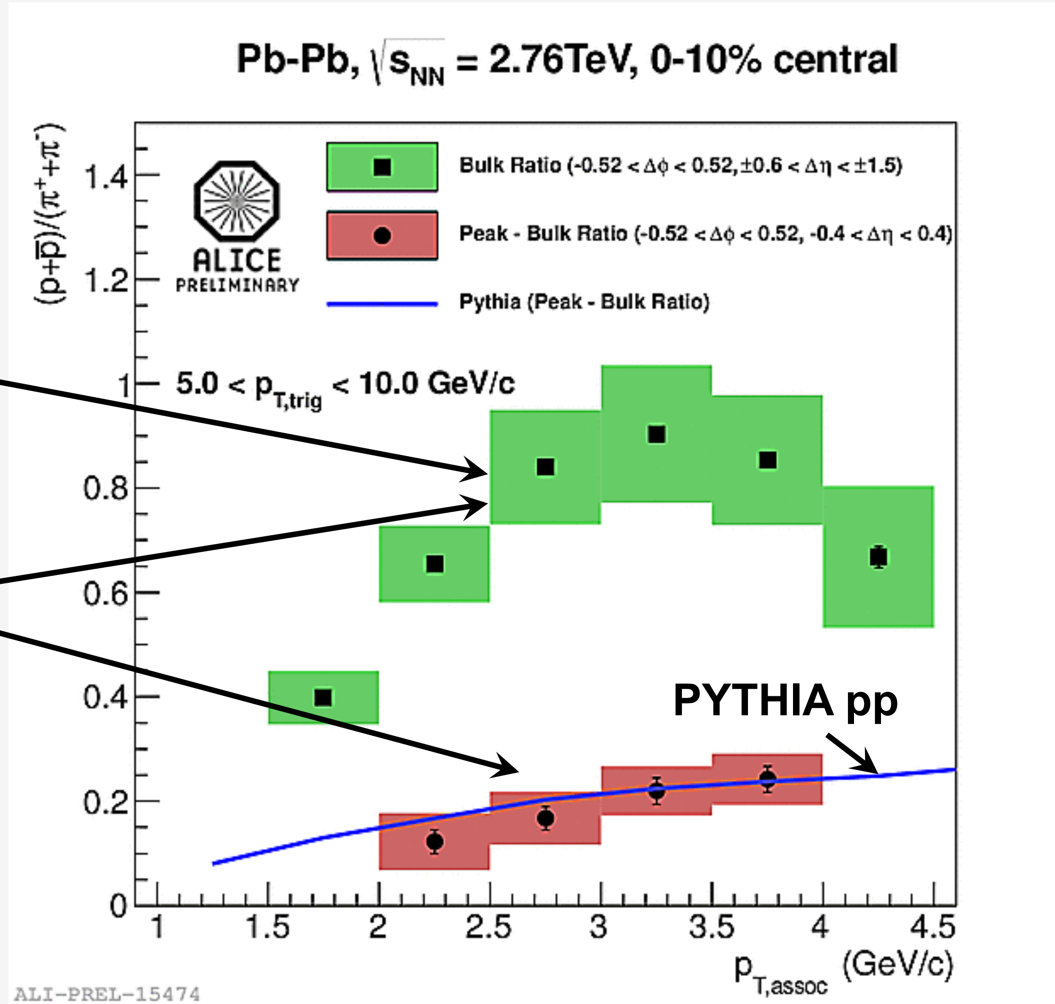
Baryon-to-meson ratio: Λ/K

- Hydro model works well at low p_T
- Recombination calculation gets correct shape
- EPOS successfully describing transition



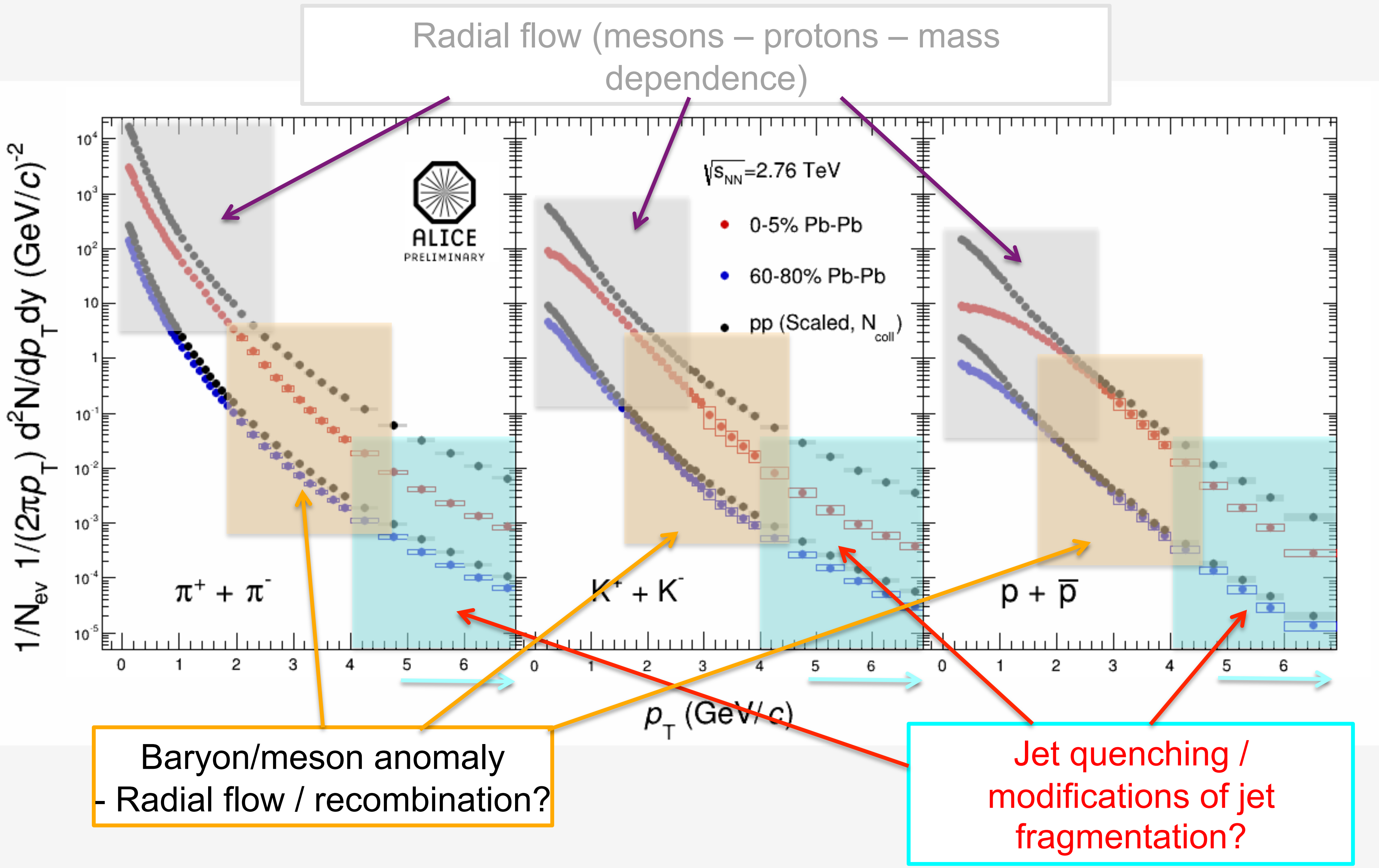
PID in jet structures





Near-side peak (after bulk subtraction): p/π ratio compatible with that of pp (PYTHIA)
Bulk region: p/π ratio strongly enhanced – compatible with overall baryon enhancement
Jet particle ratios not modified in medium? Could this still be surface bias?

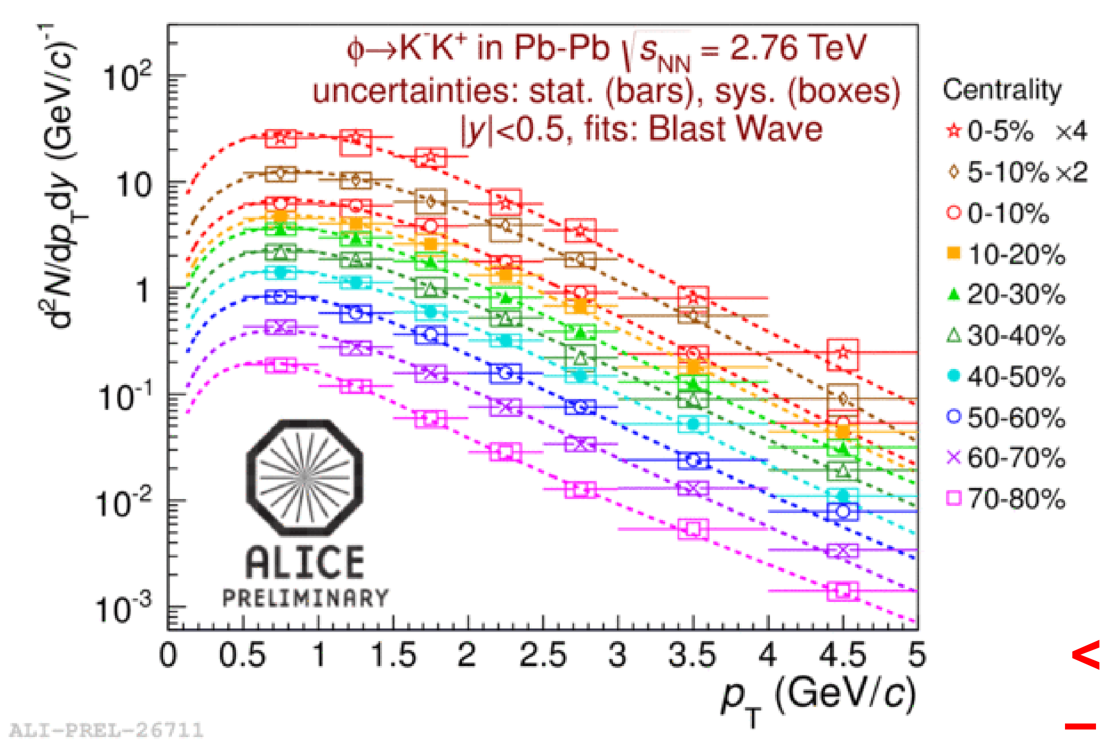
Pion/Kaon/Proton in Pb-Pb

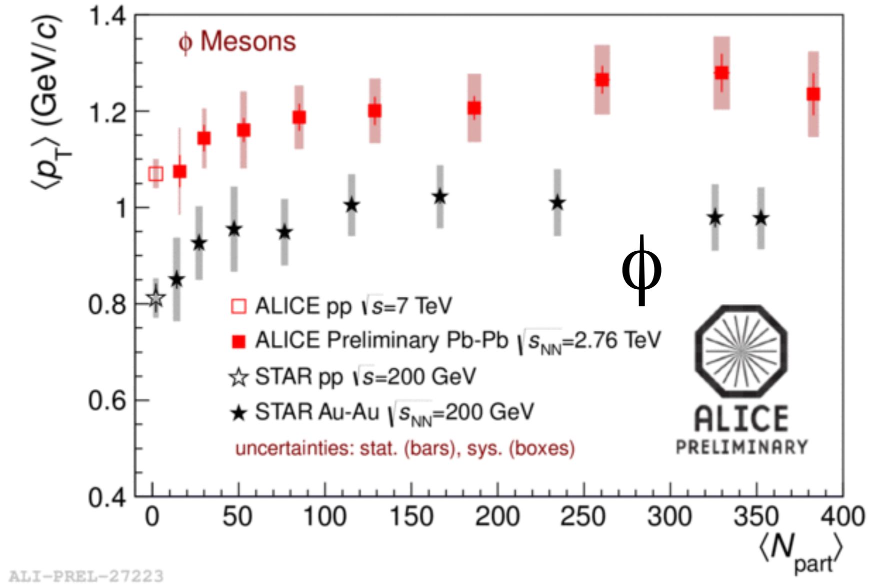


Hadronic resonances in Pb-Pb

A. Knospe

- Resonances
  - production/abundance sensitive to temperature and lifetime of fireball
    - time between chemical to kinetic freeze-out
  - Mass and width – sensitivity to chiral symmetry restoration
    - No modifications seen in the data



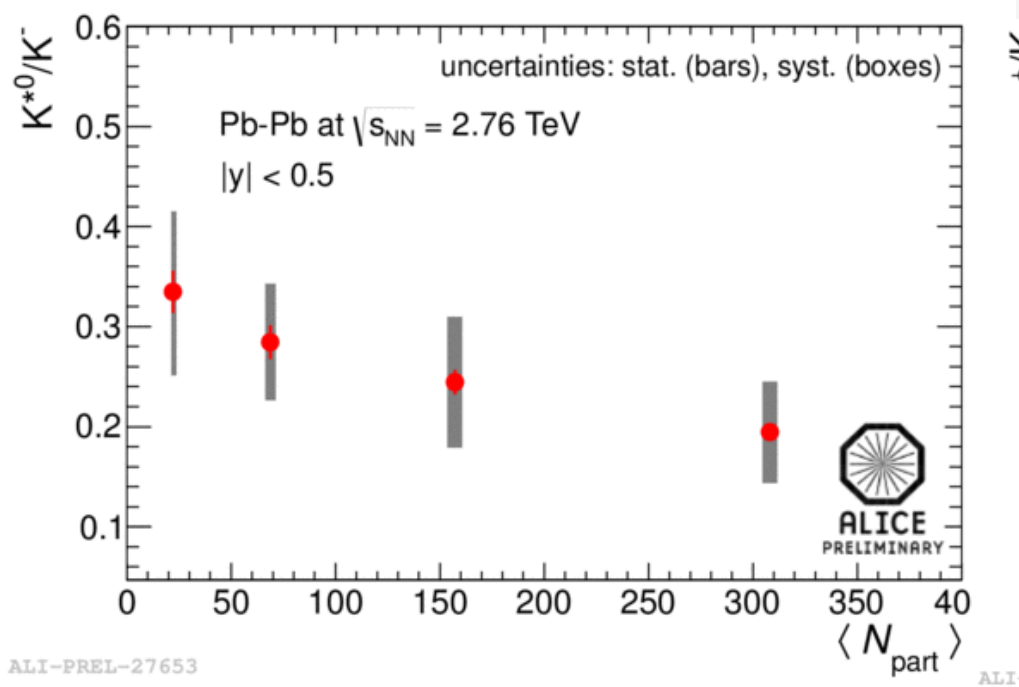


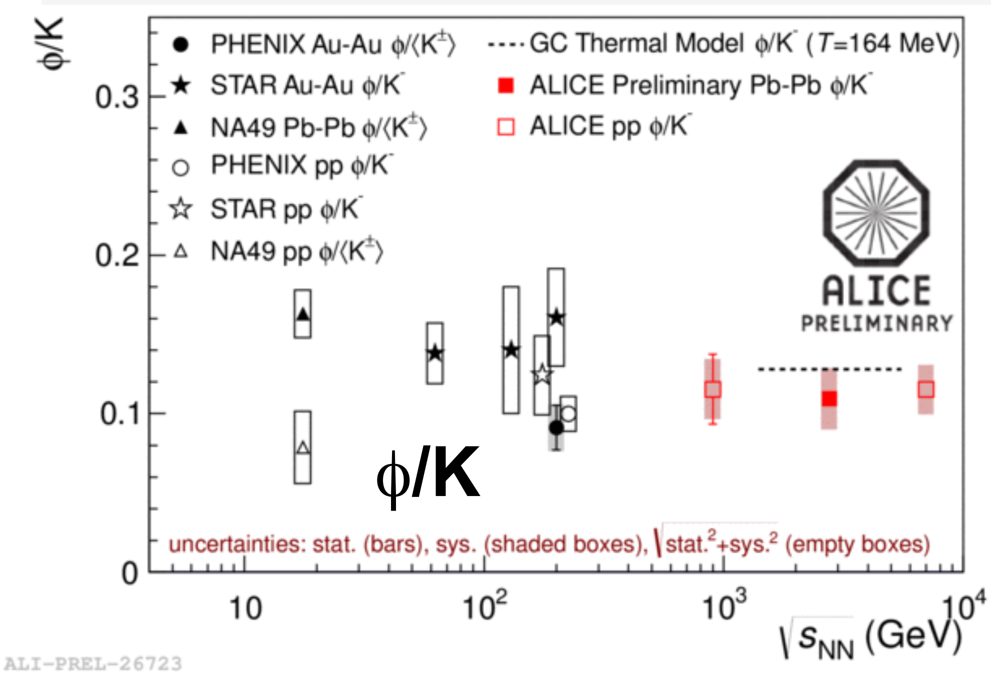
<pT> at LHC larger than at RHIC – consistent with stronger radial flow

Hadronic resonances in Pb-Pb

A. Knospe

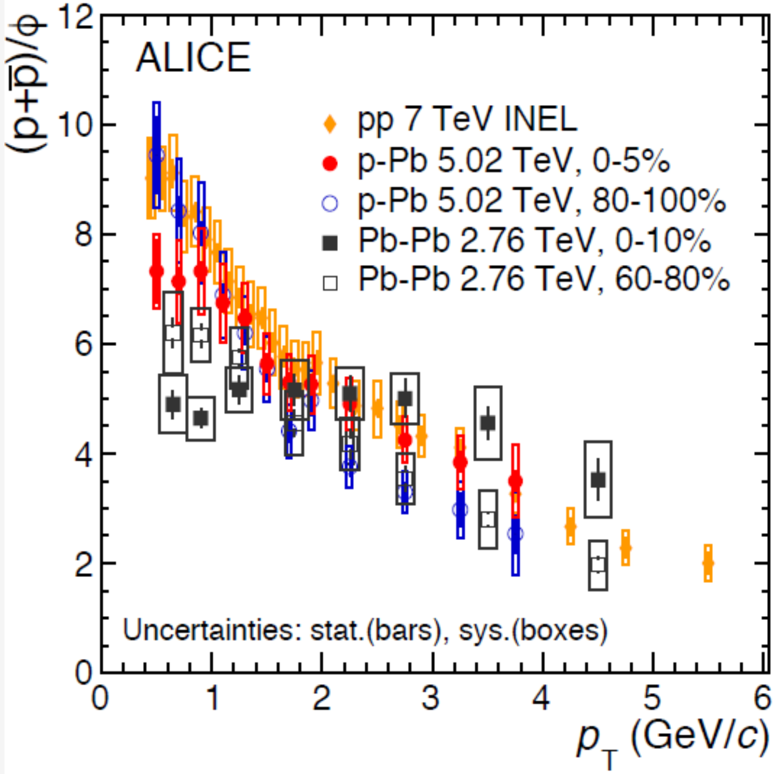
- Ratios:
  - K^{*0}/K^- decreases for central collisions – signature for re-scattering in central collisions
  - φ/K independent of energy and system from RHIC to LHC
    - Pb–Pb: consistent with Grand Canonical thermal model (Andronic *et al.*)





Production of K*(892)^0, ϕ(1020) in p-Pb 5.02 TeV

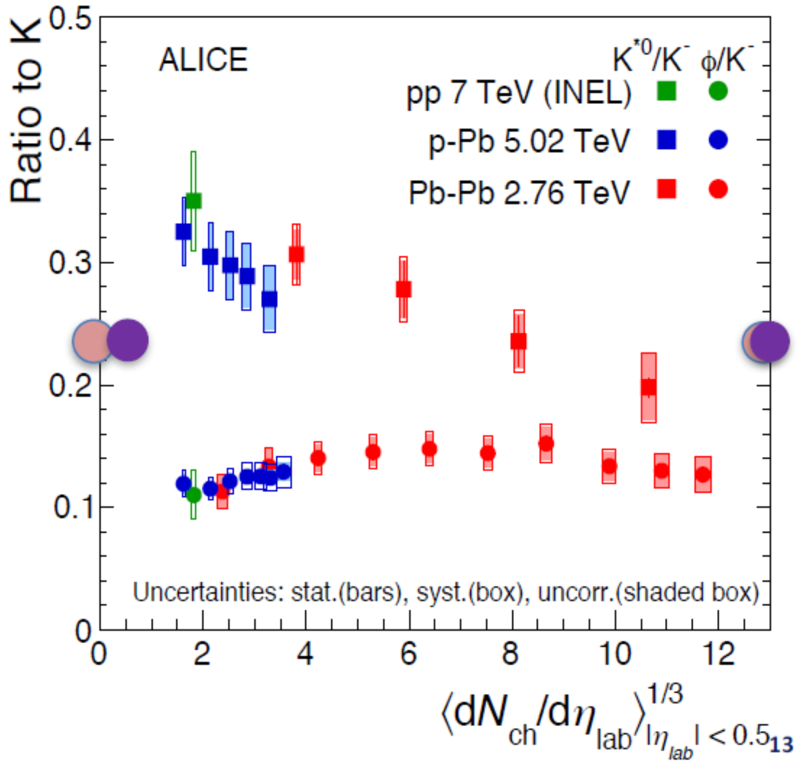
A Large Ion Collider Experiment



Production of K*(892)^0 and ϕ(1020) in p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV
→ arXiv:1601.07868 [nucl-ex]

Mass ordering observed in central Pb-Pb collisions: similar mass → similar p_T

- Hydrodynamic behavior



- ϕ/K$^-$ not suppressed in in Pb-Pb
- x10 shorter lived K^{0*} is suppressed in Pb-Pb (re-scattering of decay products)
- Hint of suppression seen also in p-Pb

F. Ronchetti - 125th LHCC

Statistical hadronization model

partition function: $\ln Z_i = \frac{V g_i}{2\pi^2} \int_0^\infty \pm p^2 dp \ln(1 \pm \exp(-(E_i - \mu_i)/T))$

particle densities: $n_i = N/V = -\frac{T}{V}\frac{\partial \ln Z_i}{\partial \mu} = \frac{g_i}{2\pi^2} \int_0^\infty \frac{p^2\,\mathrm{d}p}{\exp((E_i - \mu_i)/T) \pm 1}$

for every conserved quantum number there is a chemical potential:

$$\mu_i = \mu_B B_i + \mu_S S_i + \mu_{I_3} I_i^3$$

but can use conservation laws to constrain V, μ_S, μ_{I_3}

→ **fit at each energy provides values for T and μ_b**

- get yields of all hadrons

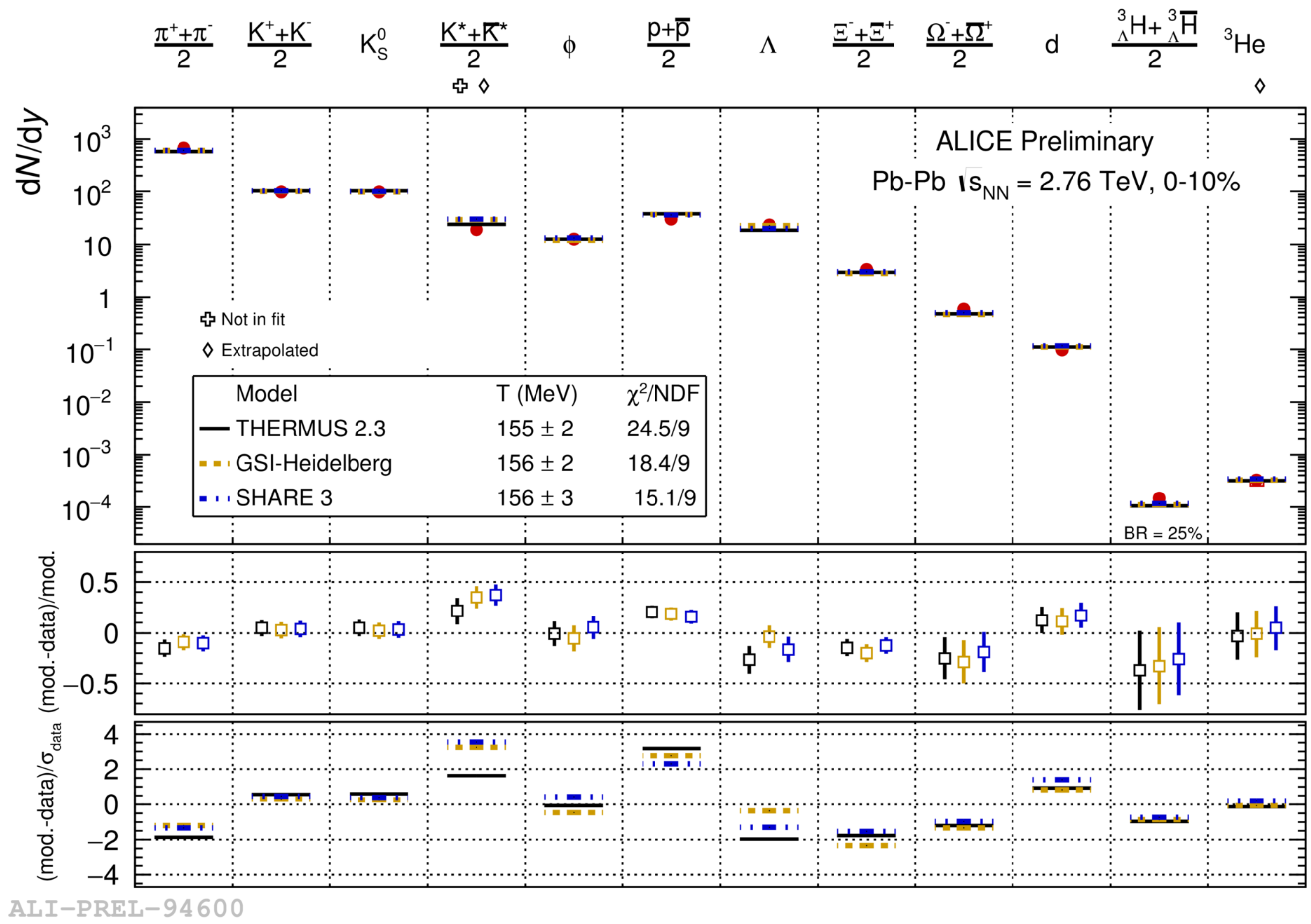
for dN/dy need in addition volume per unit y - fix to $dN_{ch}/deta$

good fit to data for central collisions of heavy nuclei at AGS, SPS, RHIC

see e.g.

A. Andronic, P. Braun-Munzinger, J.S. Nucl. Phys. A722(2006)167 nucl/th/0511071

Chemical equilibrium



Particle yields of light flavor hadrons are described over 7 orders of magnitude within 20% (except K^{*0}) with a common chemical freeze-out temperature of T_{ch} ≈ 156 MeV (prediction from RHIC extrapolation was ≈ 164 MeV).

Largest deviations observed for **protons** (incomplete hadron spectrum, baryon annihilation in hadronic phase,..?) and for **K^{*0}**.

[Wheaton et al, Comput.Phys.Commun, 180 84]
[Petran et al, arXiv:1310.5108]
[Andronic et al, PLB 673 142]

Possible explanations

- There was already this discrepancy at RHIC, but was overlooked due to misinterpretation of feed-down corrections
- At high hadron density, re-interactions after freeze-out are important, especially baryon–antibaryon annihilations, this will affect mostly protons
- Introduce non-equilibrium statistical hadronization, quark population of phase space is frozen at phase transition and may differ from thermal equilibrium, two more parameters γ_q and γ_s needed
- In statistical hadronization models, the resonance spectrum is accounted for only up to ~ 2 GeV, higher resonance would add mostly pions, thus effectively decreasing the model prediction for p/π (but also for strange baryons)
- The freeze-out temperature may be different for different flavours, some evidence from lattice QCD…

What about p-A ?

Data sample: **p-Pb collisions** collected in 2013 at the LHC **$\sqrt{s_{NN}}$ = 5.02 TeV**

- asymmetric energy/nucleon in the two beams
  - cms moves with rapidity y_{CMS} = - 0.465
  - acceptance of TPC and TOF $|\eta_{LAB}| < 0.9$

    → measurement in $0.0 < y_{CMS} < 0.5$

A-side p →   ← Pb C-side

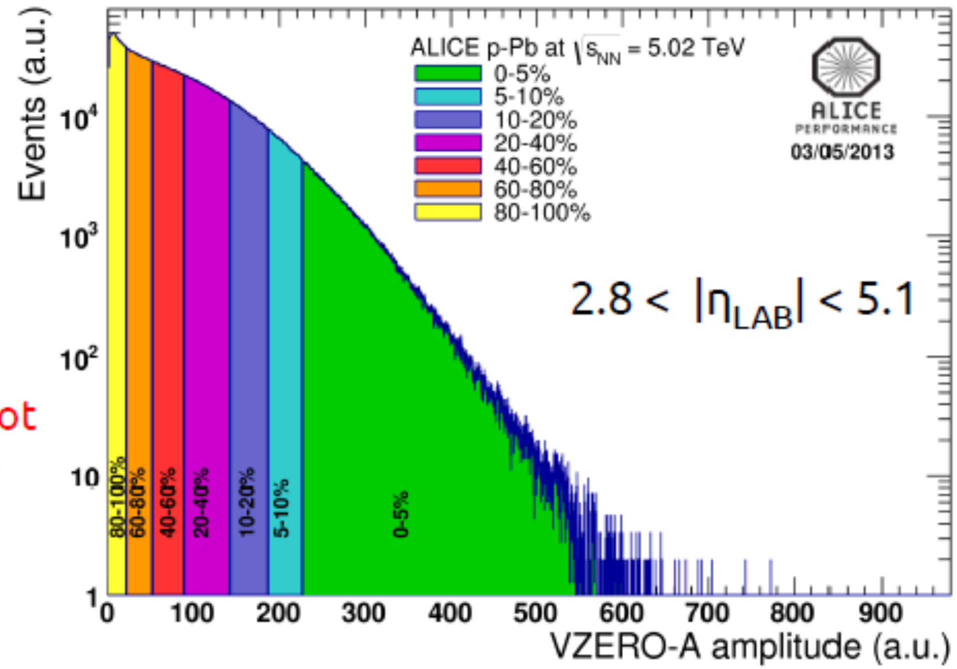
→ $y_{CMS, NN}$ = - 0.465

Definition of seven multiplicity classes:

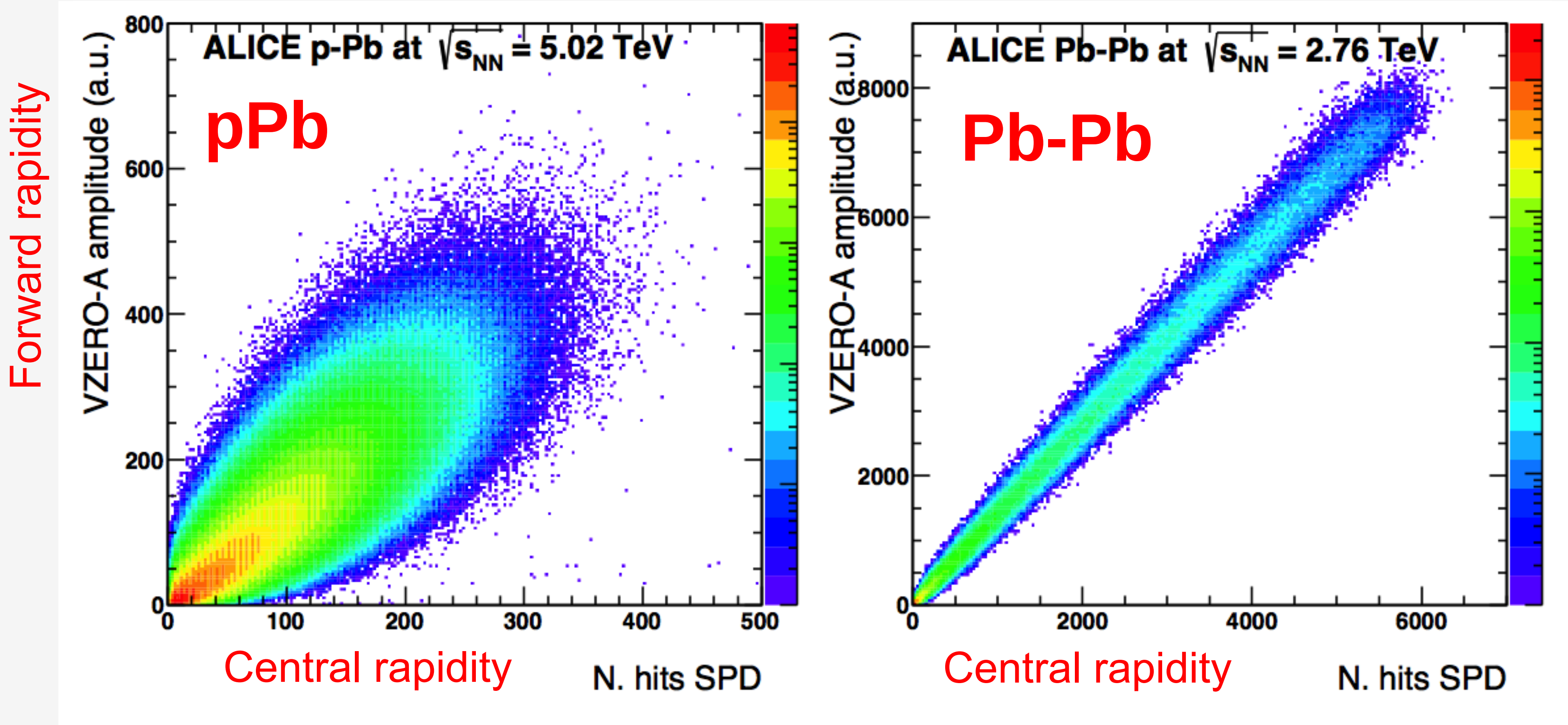
- slices in VZERO-A (V0A) amplitude

Central → Peripheral

correlation between impact parameter and multiplicity is not as straight-forward as in Pb-Pb



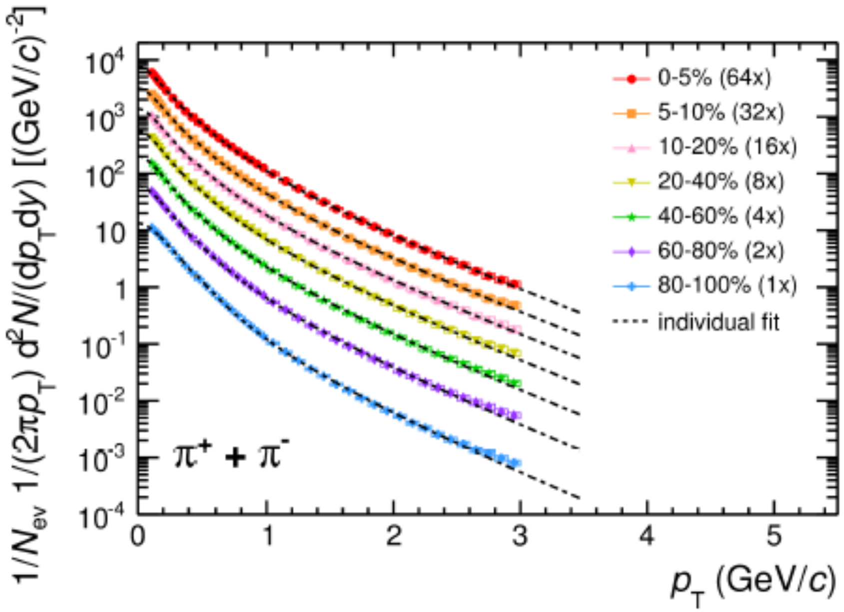
Intermezzo: p-Pb multiplicity

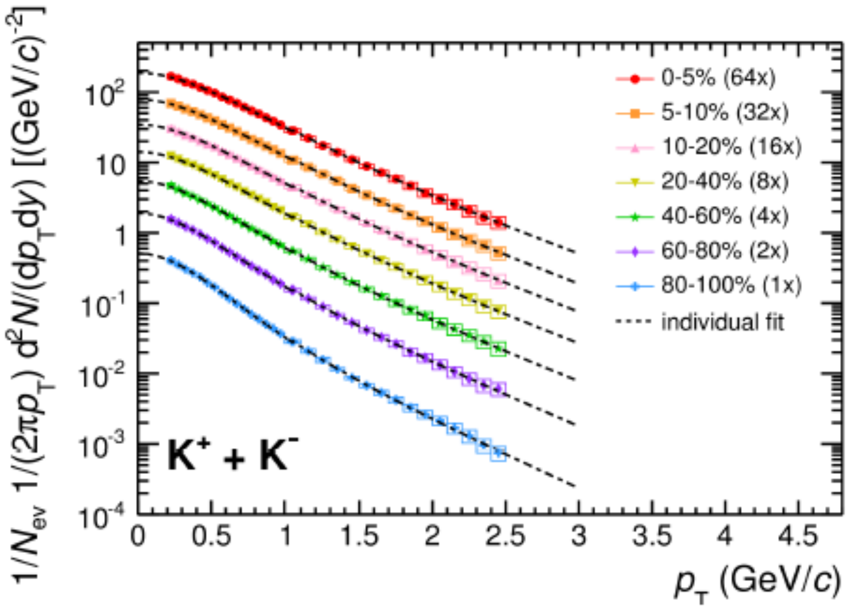


Much broader correlation between different multiplictiy (event class) estimators

$\Rightarrow$ expect different sensitivity (bias) to event geometry (Glauber! – N_{coll} scaling)

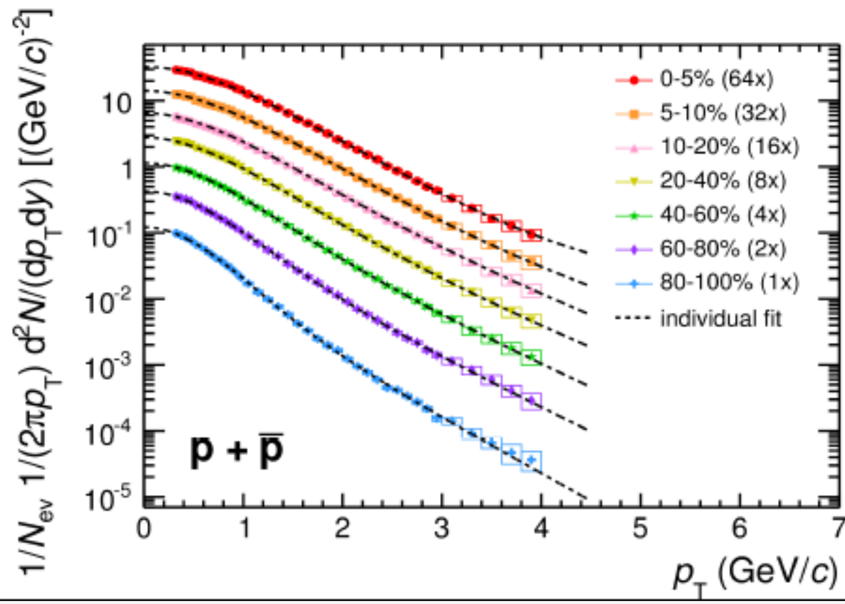
π K p spectra





Dotted lines: individual blast-wave fits for low and high p_T extrapolation

Particle	p_T range (GeV/c)
$\pi^{\pm}$	0.1 – 3.0
$K^{\pm}$	0.2 – 2.5
$p(\bar{p})$	0.3 – 4.0
K^0_s	0.0 – 8.0
$\Lambda(\bar{\Lambda})$	0.6 – 8.0



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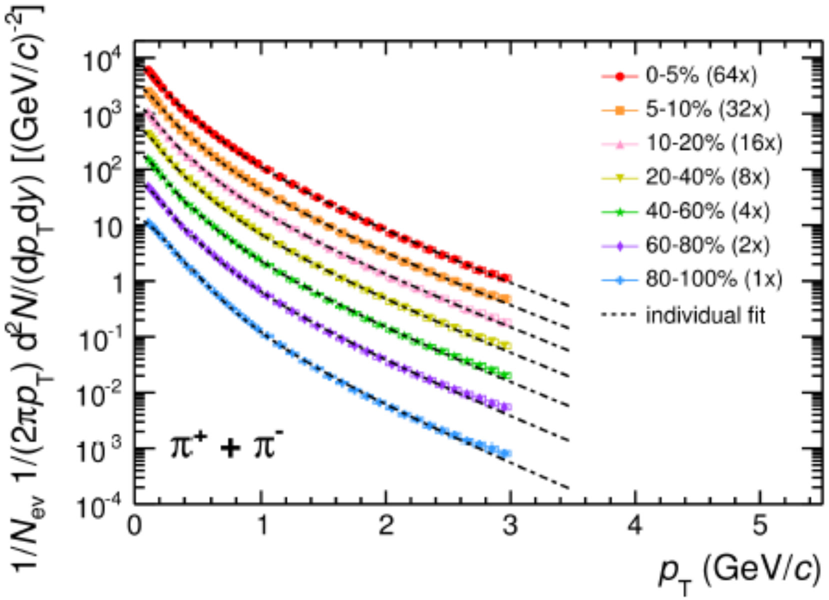
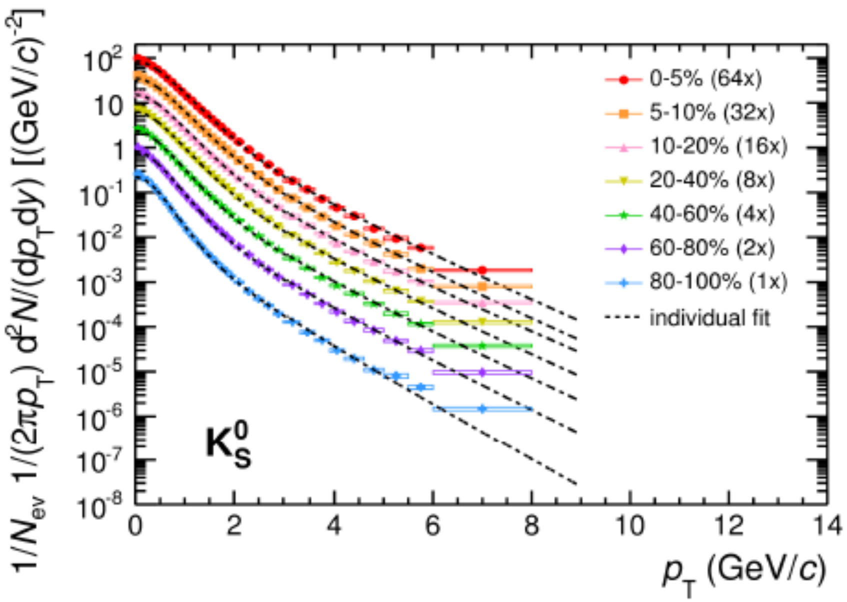
5

and K^0_s Λ spectra





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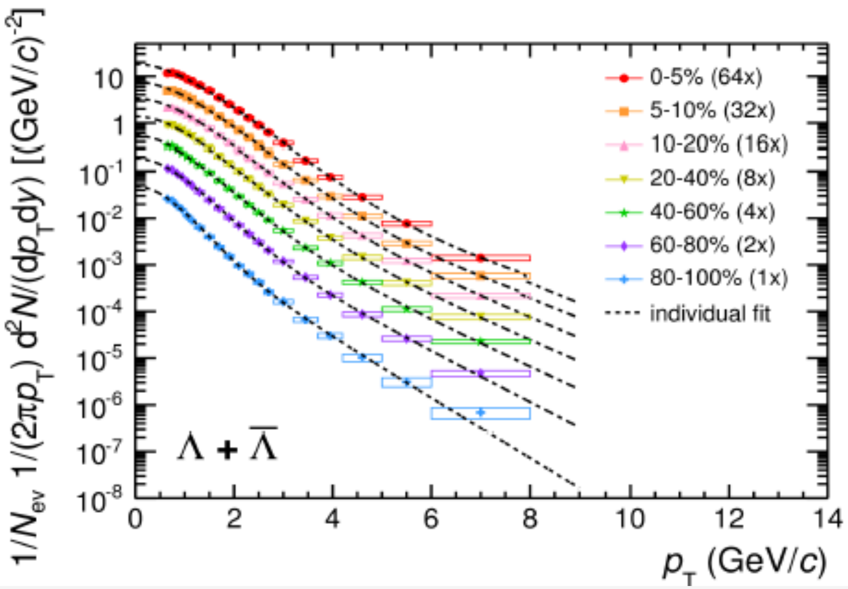

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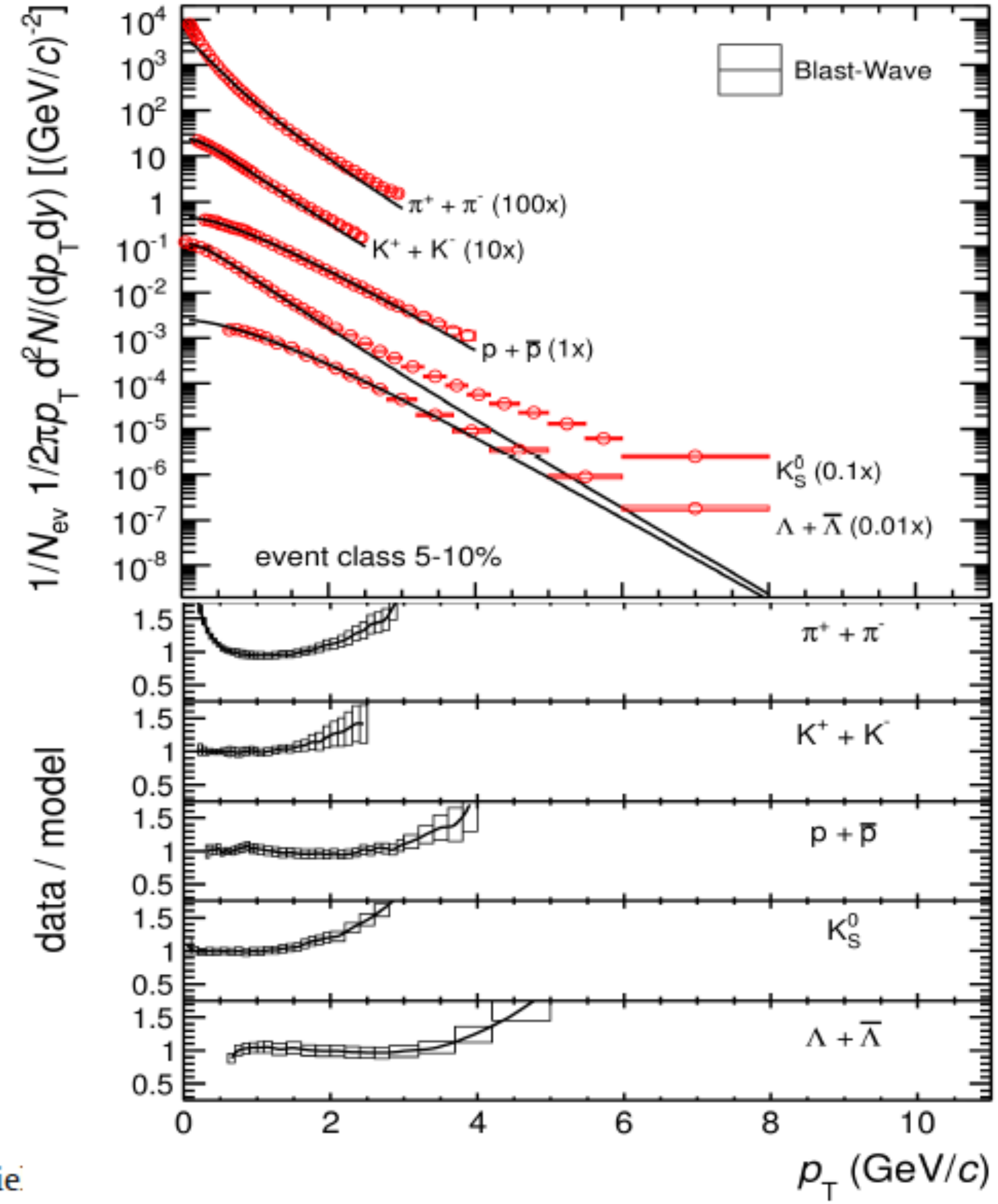
p-Pb Blast-wave analysis

п/K/p/K^0_s/L Blast-Wave analysis:

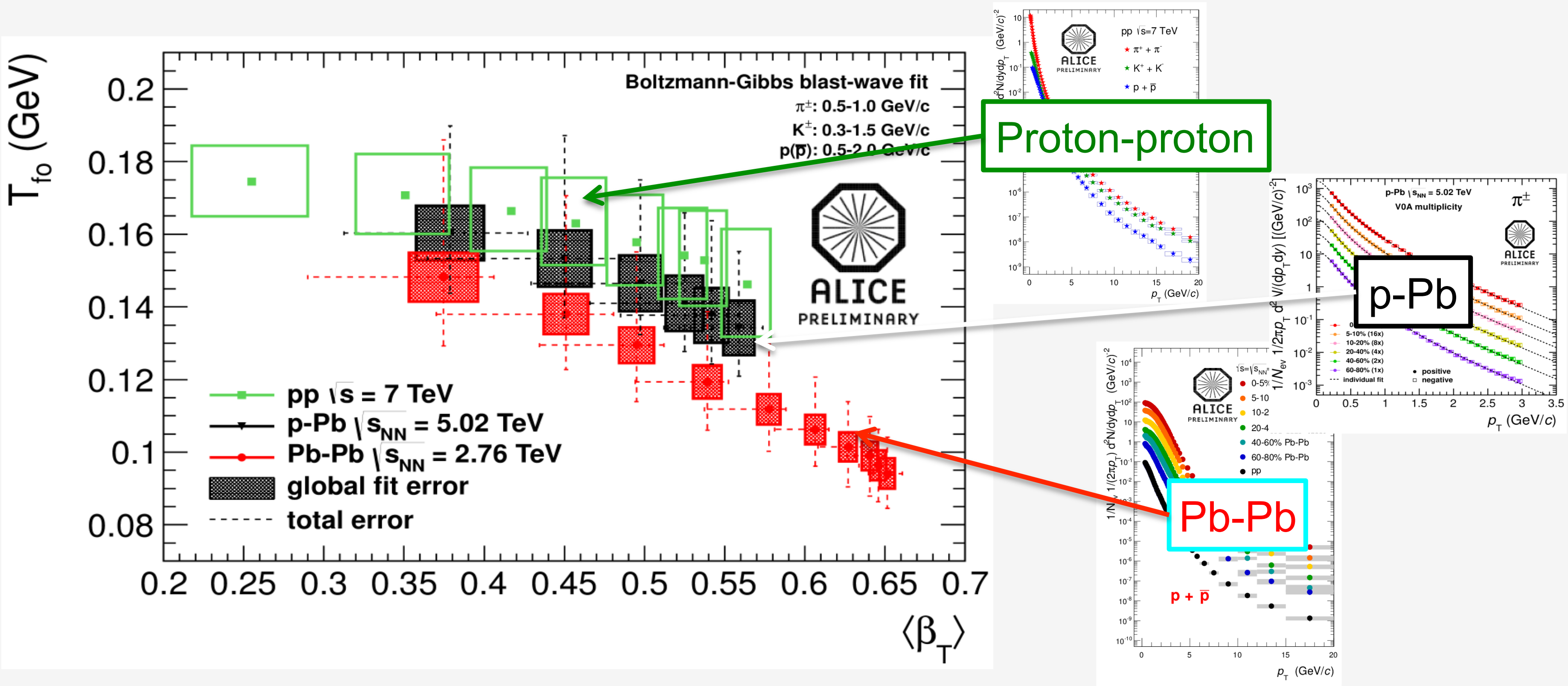
- hydro-motivated Blast-Wave model
  Schnedermann, PRC 48, 2462 (1993)

- simultaneous fit of all particles with 3 parameters:
  - $<\beta_T>$ radial flow
  - T_{fo} freeze-out temperature
  - n velocity profile

- global fit performed in the following p_T ranges:
  - п 0.5 – 1.0 GeV/c
  - K 0.2 – 1.5 GeV/c
  - p 0.3 – 3.0 GeV/c
  - K^0_s 0.0 – 1.5 GeV/c
  - Λ 0.6 – 3.0 GeV/c

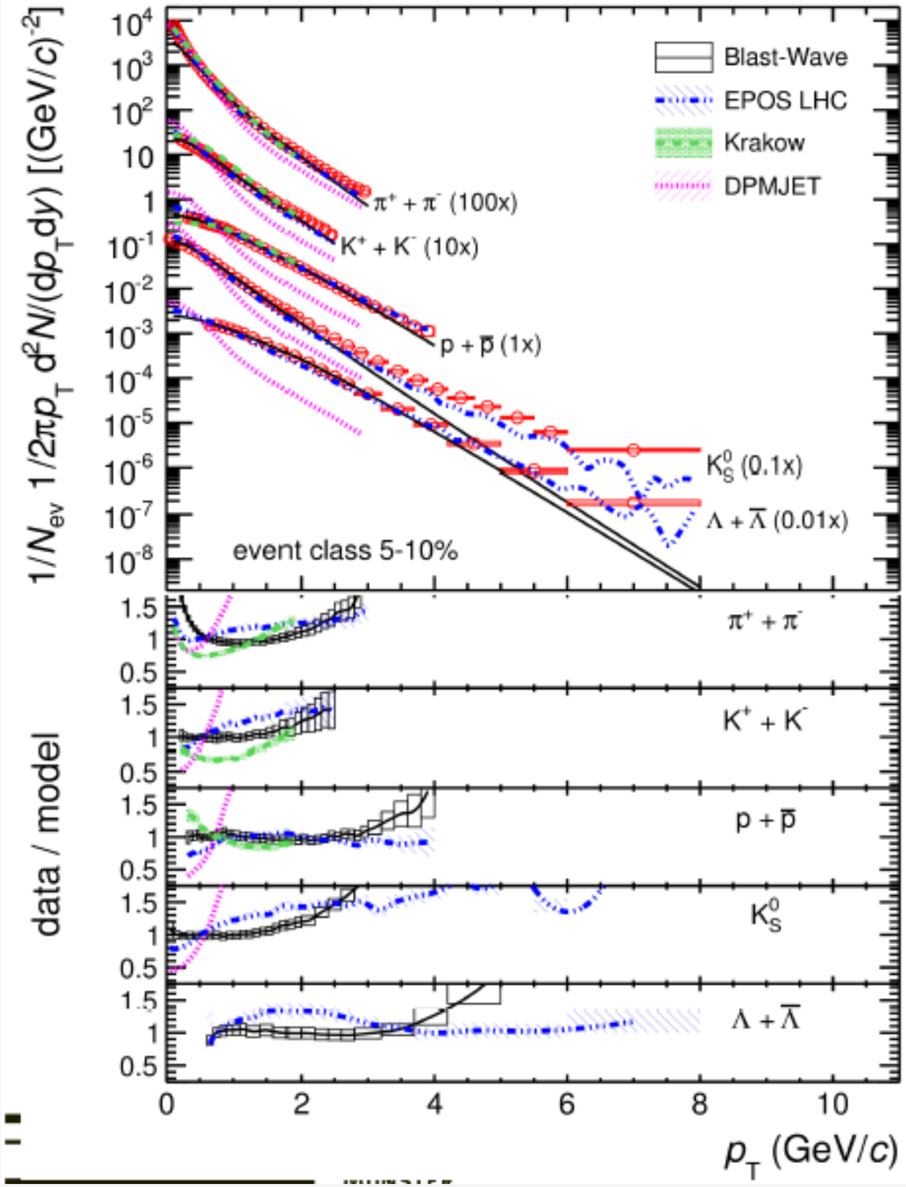


Blast-wave in pp, pPb and Pb-Pb



- Blast-wave fits: similar T vs Beta trend in p-Pb and Pb-Pb;
  - however, also in pp collisions
- Fits (spectra) sensitive not only to a collective behaviour (radial flow) but also to other sources of correlations? -> pp, pPb cases **(Colour Reconnections ?)**

Comparison with models



EPOS LHC: Pierog et al., arXiv:1306.0121 [hep-ph]

- initial hard and soft scattering create “flux tubes”, which either escape the medium and hadronize as jets, or contribute to the bulk matter, described in terms of hydrodynamics
- can reproduce the pion and proton spectra within 20%
- stronger deviations for kaons and lambdas

Kraków: Bozek, PRC85, 014911 (2012)

- hydrodynamical model
- reproduces spectra reasonably well for protons
- pion and kaons deviate for p_T >1 GeV/c
- possible onset of non-hydro effect above 1 GeV/c

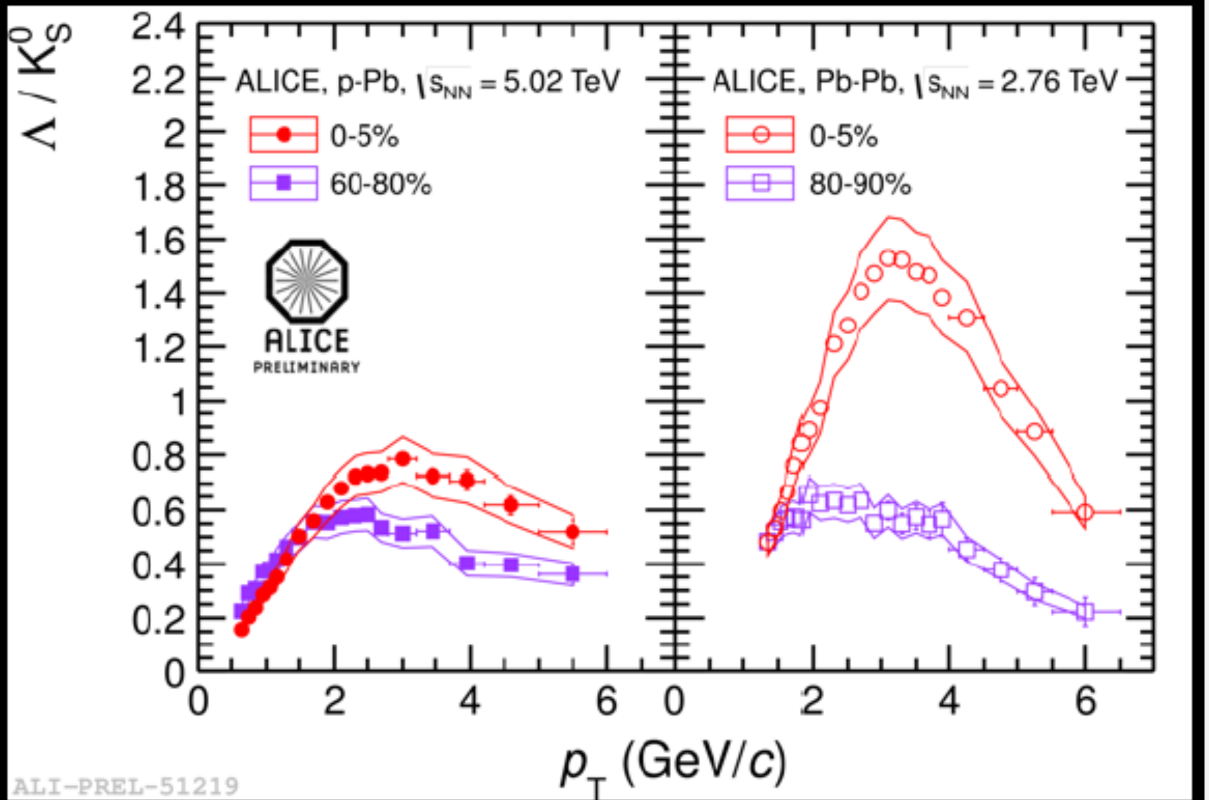
DPMJET:

- QCD- inspired – based on the Gribov-Glauber approach and treats soft and hard scattering processes in an unified way
- can reproduce dN_{ch}/dη
- fails to describe p_T distributions of identified particles

i - Identified spectra in pPb - SQM 2013 18

Baryon-to-meson ratio in p-Pb

- Show similar centrality dependence to Pb-Pb
- Try to relate increase in Λ/K ratio to increase in dN/dη



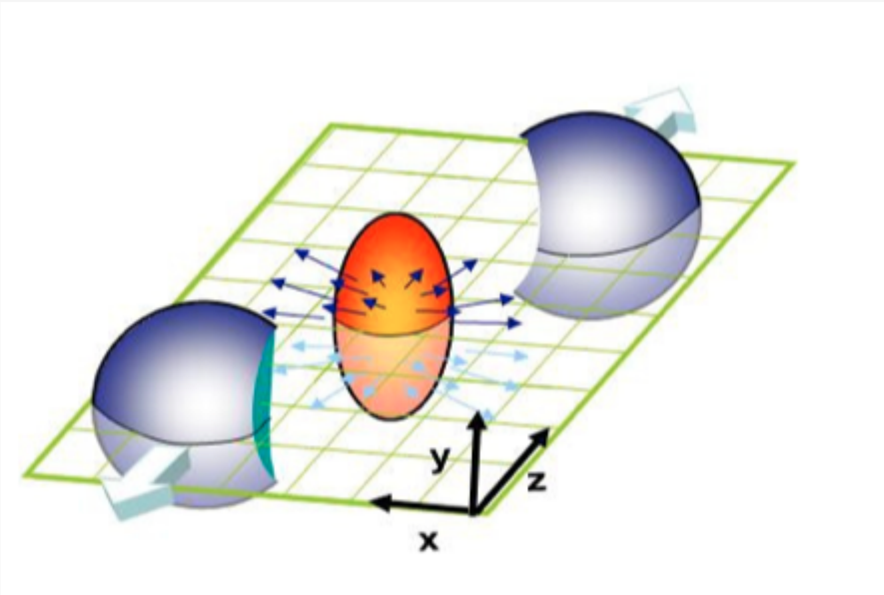
Azimuthal anisotropies

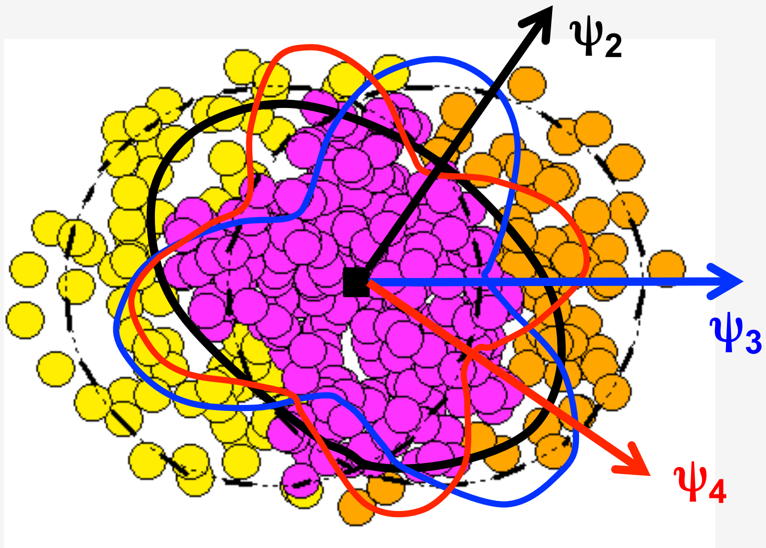
v_n – definition

- v_n – Fourier coefficients of particle distributions in azimuthal angle φ with respect to n-th reaction plane

$$\frac{dN}{d\varphi}(\ldots) \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos n(\varphi - \psi_n)$$

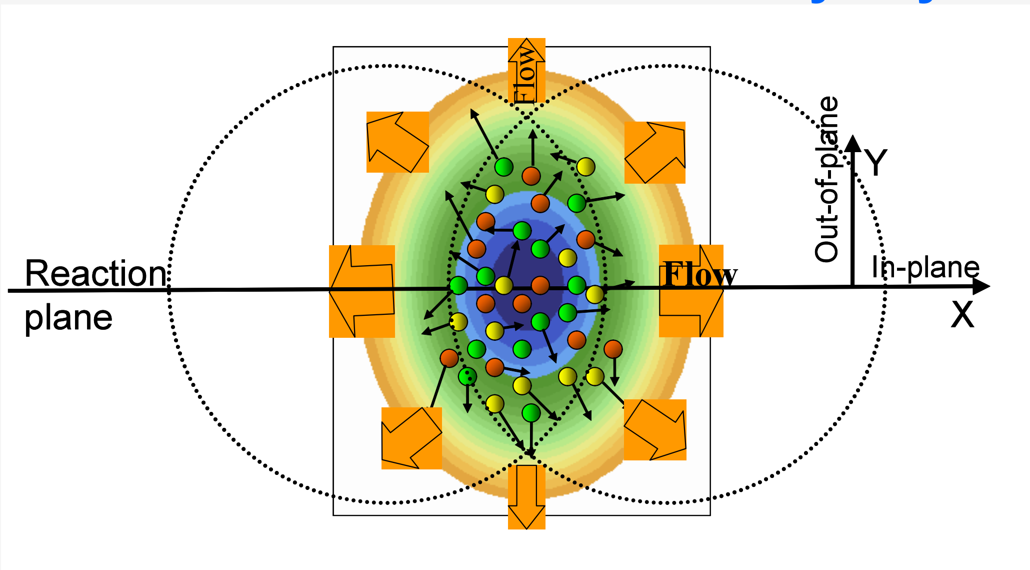
$v_n = 0$ would mean azimuthally symmetric distribution





Elliptic Flow

- **Non-central collisions are azimuthally asymmetric**



→ **The transfer of this asymmetry to momentum space provides a measure of the strength of collective phenomena**

- **Large mean free path**
  - ⇨ **particles stream out isotropically, no memory of the asymmetry**
  - ⇨ **extreme: ideal gas (infinite mean free path)**
- **Small mean free path**
  - ⇨ **larger density gradient -> larger pressure gradient -> larger momentum**
  - ⇨ **extreme: ideal liquid (zero mean free path, ideal hydrodynamic limit)**

Azimuthal Asymmetry

- Fourier expansion of azimuthal distribution:

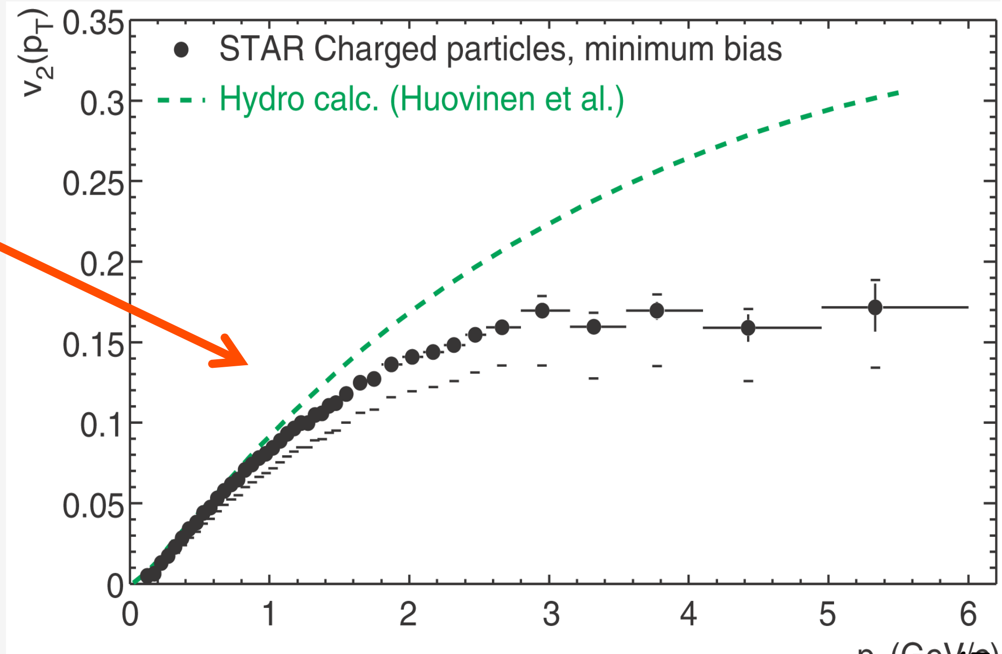
$$\frac{dN}{p_T dp_T dy d\varphi} = \frac{1}{2\pi}\frac{dN}{p_T dp_T dy}\left(1 + 2v_1\cos(\varphi) + 2v_2\cos(2\varphi) + \ldots\right)$$

$$v_1 = \langle \cos\varphi \rangle \quad \text{"directed flow"}$$

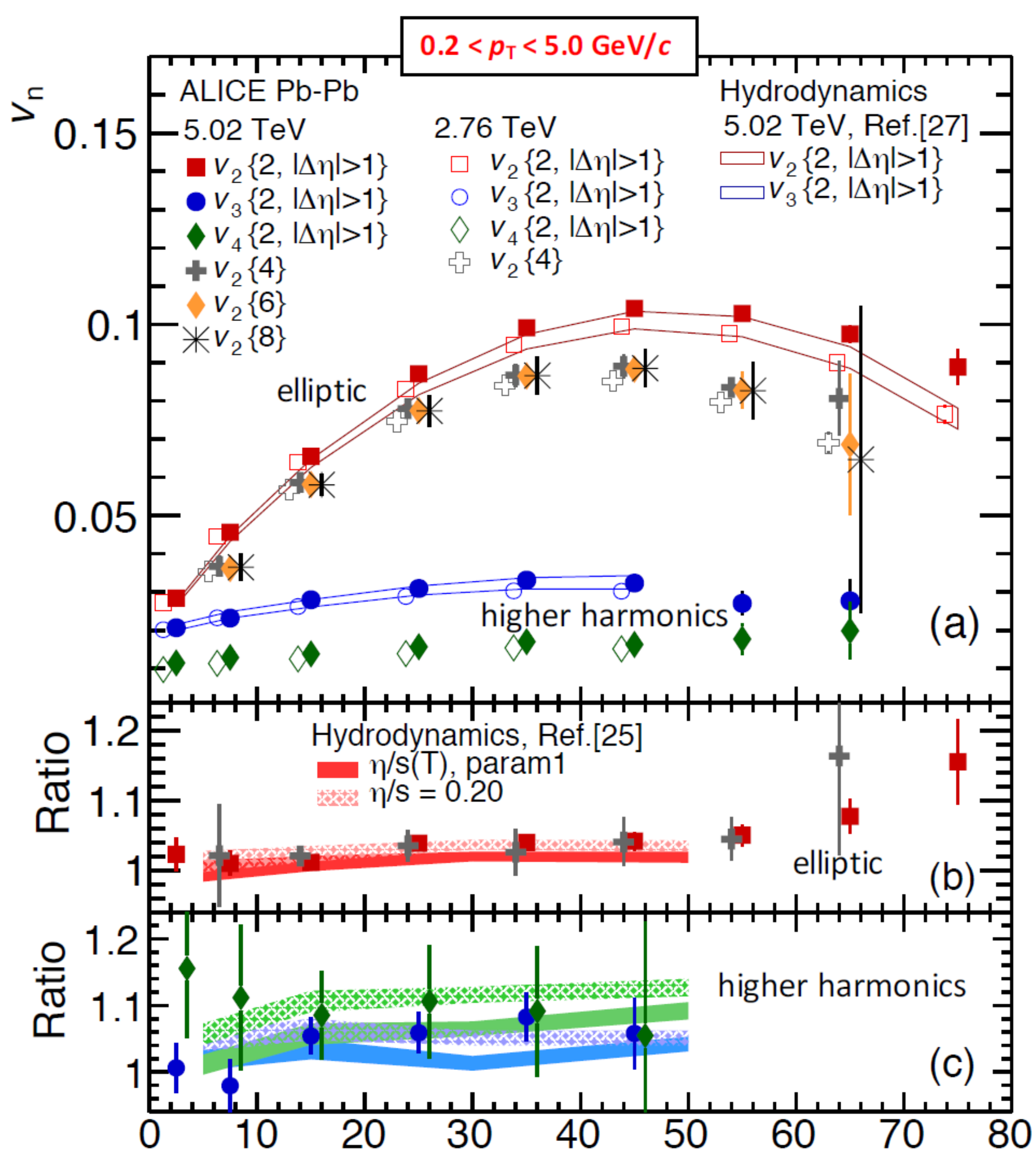
$$v_2 = \langle \cos 2\varphi \rangle \quad \text{"elliptic flow"}$$

@RHIC:

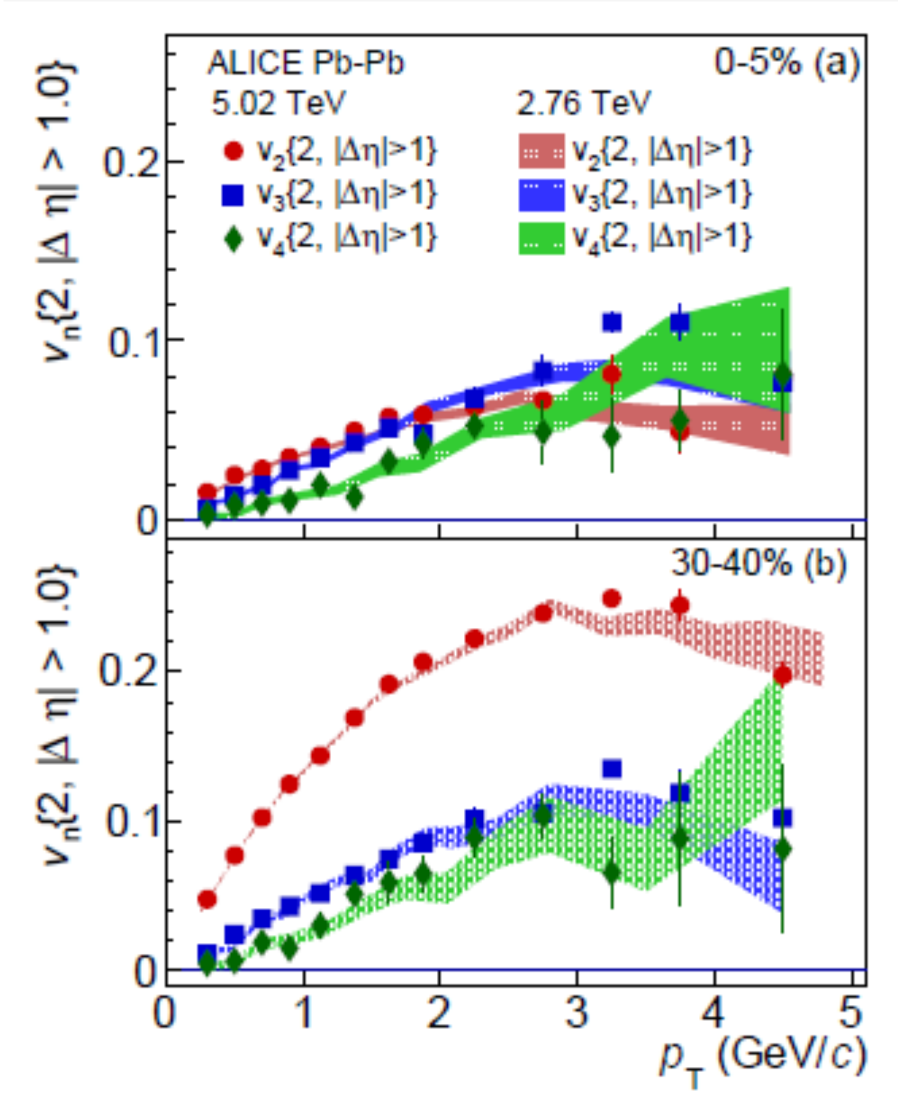
- **at low p_T: azimuthal asymmetry almost as large as expected at hydro limit!**
  - ⇨ **"perfect liquid"?**
- **very far from "ideal gas" picture of plasma**



v_n at the LHC



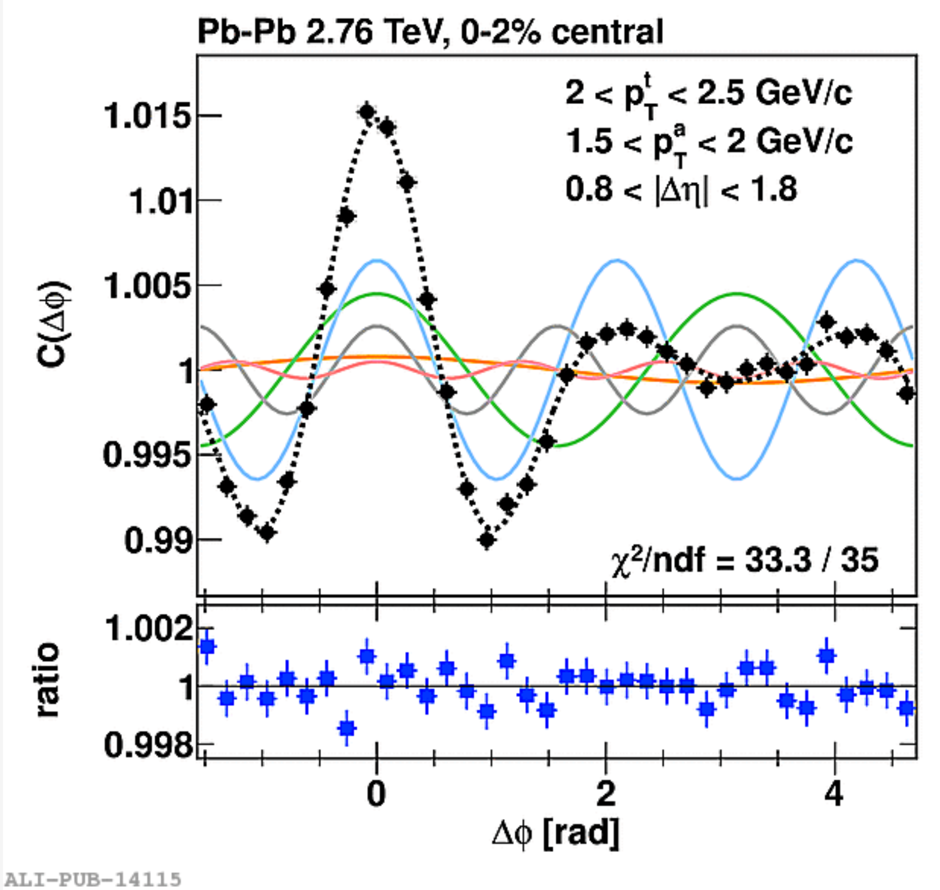
0.2 < p_T < 5.0 GeV/c
v_n
ALICE Pb-Pb
5.02 TeV
$v_2\{2, |\Delta\eta|>1\}$
$v_3\{2, |\Delta\eta|>1\}$
$v_4\{2, |\Delta\eta|>1\}$
$v_2\{4\}$
$v_2\{6\}$
$v_2\{8\}$
2.76 TeV
$v_2\{2, |\Delta\eta|>1\}$
$v_3\{2, |\Delta\eta|>1\}$
$v_4\{2, |\Delta\eta|>1\}$
$v_2\{4\}$
Hydrodynamics
5.02 TeV, Ref.[27]
$v_2\{2, |\Delta\eta|>1\}$
$v_3\{2, |\Delta\eta|>1\}$
elliptic
higher harmonics
(a)
Ratio
Hydrodynamics, Ref.[25]
$\eta/s(T)$, param1
$\eta/s = 0.20$
elliptic
(b)
Ratio
higher harmonics
(c)



ALICE Pb-Pb
5.02 TeV
2.76 TeV
0-5% (a)
$v_2\{2, |\Delta\eta|>1\}$
$v_3\{2, |\Delta\eta|>1\}$
$v_4\{2, |\Delta\eta|>1\}$
$v_n\{2, |\Delta\eta| > 1.0\}$
30-40% (b)
p_T (GeV/c)

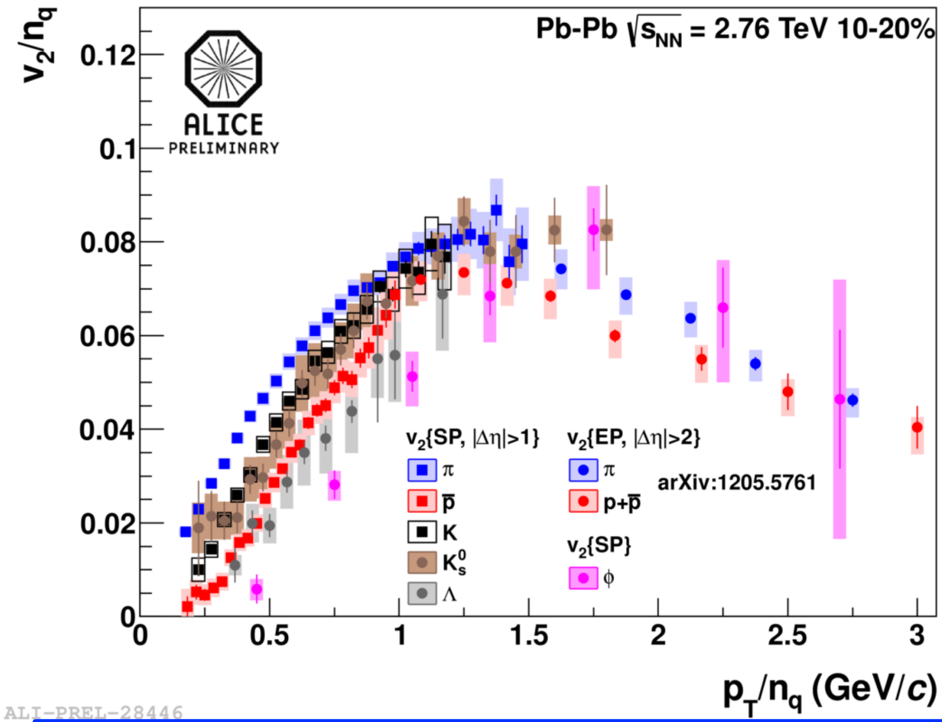
Long-η-range correlations

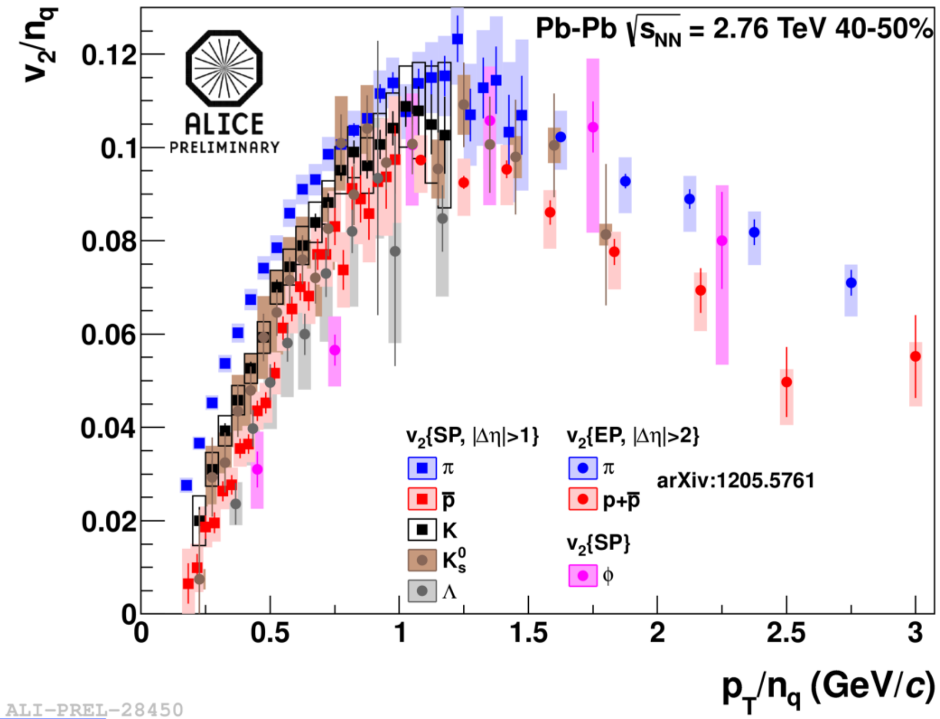
- “ultra-central” events: dramatic shape evolution in a very narrow centrality range
- double hump structure on away-side appears on 1% most central
  - ⇨ visible without any need for v_2 subtraction!
- first five harmonics describe shape at 10^{-3} level
  - ⇨ explanations based on medium response to propagating partons were proposed at RHIC
  - ⇨ Fourier analysis of new data suggests very natural alternative explanation in terms of hydrodynamic response to initial state fluctuations



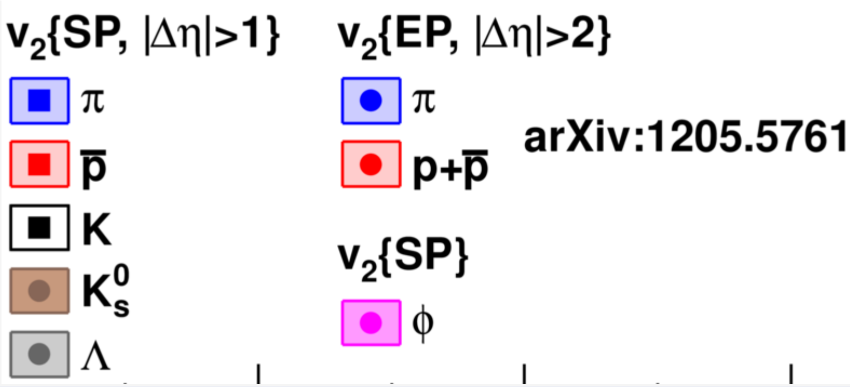
ALICE: Phys. Lett. B 708 (2012) 249

Identified-particle v_2





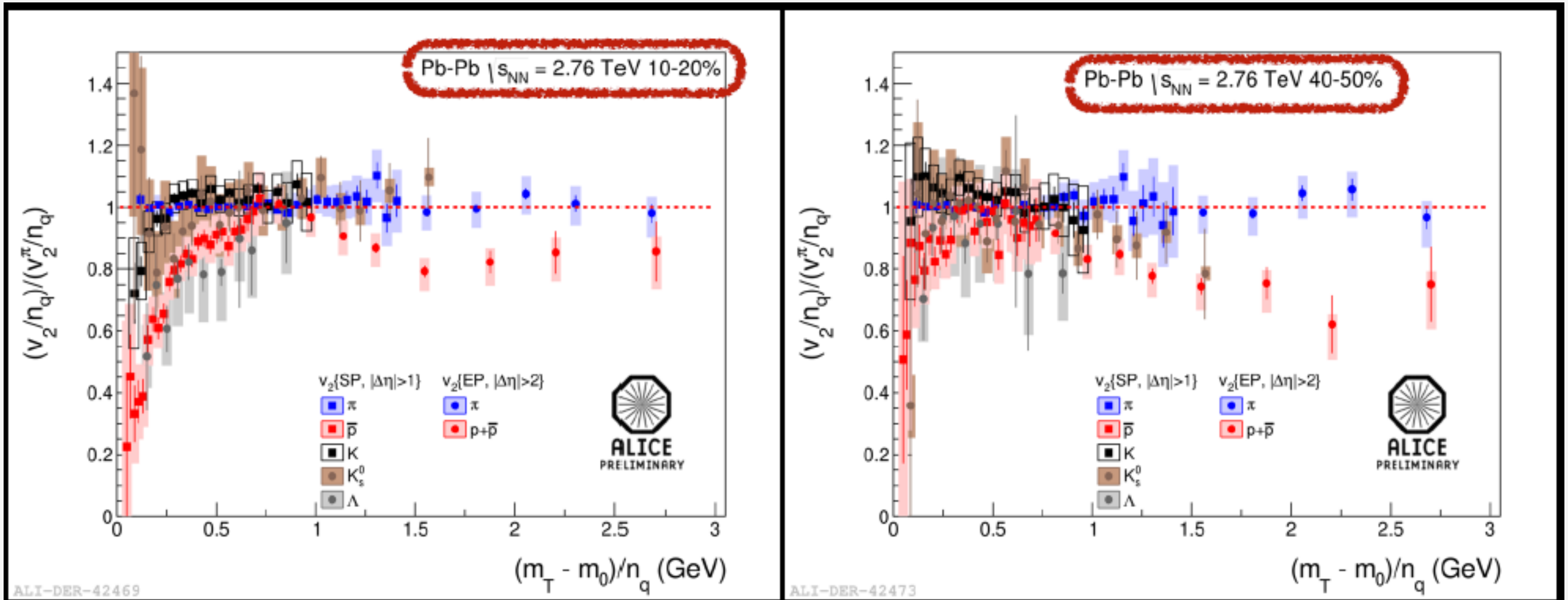
v_2 for π, p, $K^{\pm}$, K^0_s, Λ, ϕ (not shown for Ξ, Ω)
ϕ at low p_T (<3 GeV/c) follows mass hierarchy – at higher p_T joins mesons
overall qualitative agreement with hydro up to p_T 1.5–3 GeV/c (π–p); quantitative precision needs improvements – hadronic afterburner



$n_q(m_T)$-scaling worse than at RHIC

$n_q(p_T)$-scaling at p_T > 1.2 GeV/c violation 10–20%

$n_q(m_T)$ scaling violation

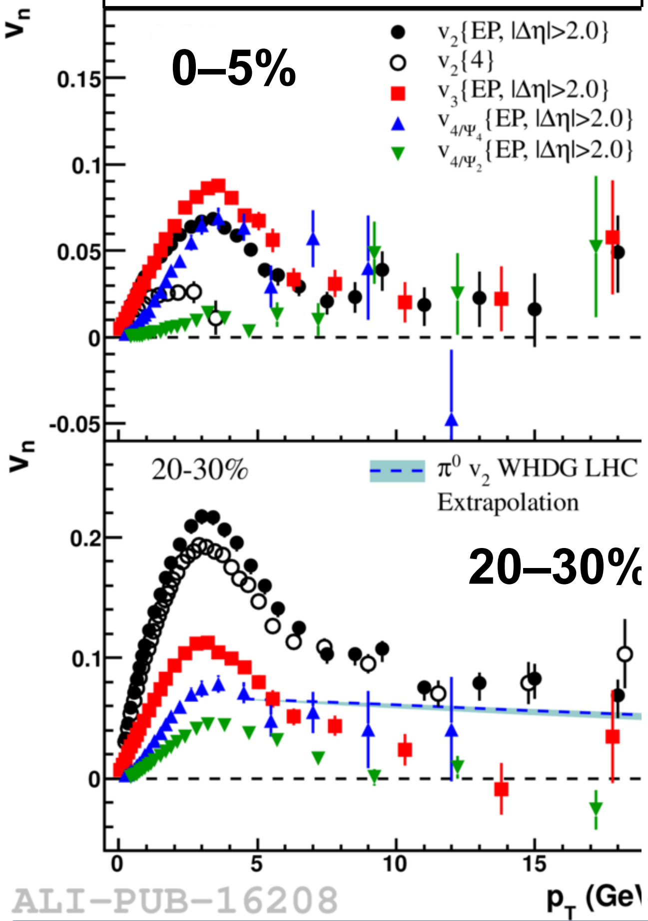


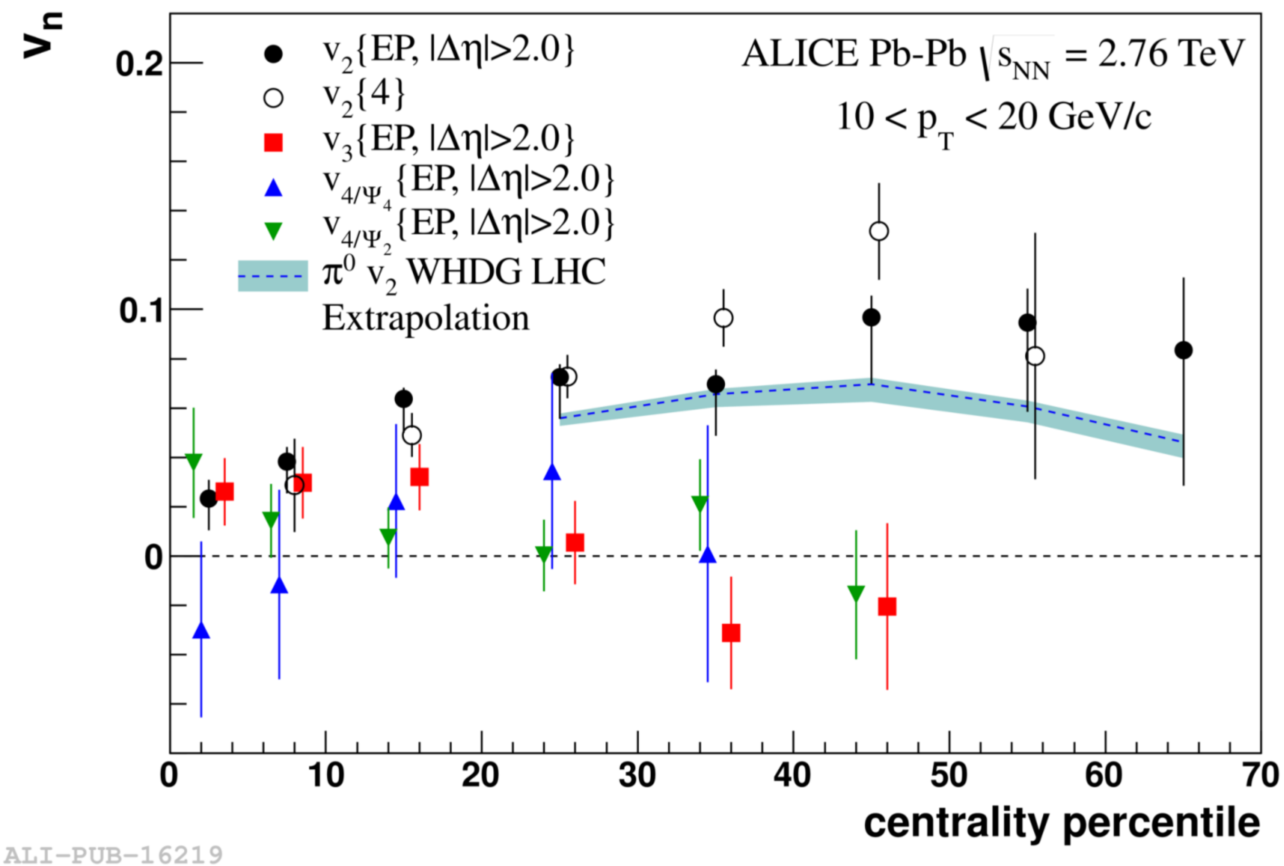
- Low $(m_T-m_0)/n_q$: scaling is broken at the LHC
- Intermediate $(m_T-m_0)/n_q$: scaling holds at the level of ~20%

v_2 , v_3, v_4 versus p_T

arXiv:1205.5761 [hep-ex]

----- *W.Horowitz,M.Gyulassy, J.Phys. G38 124114*



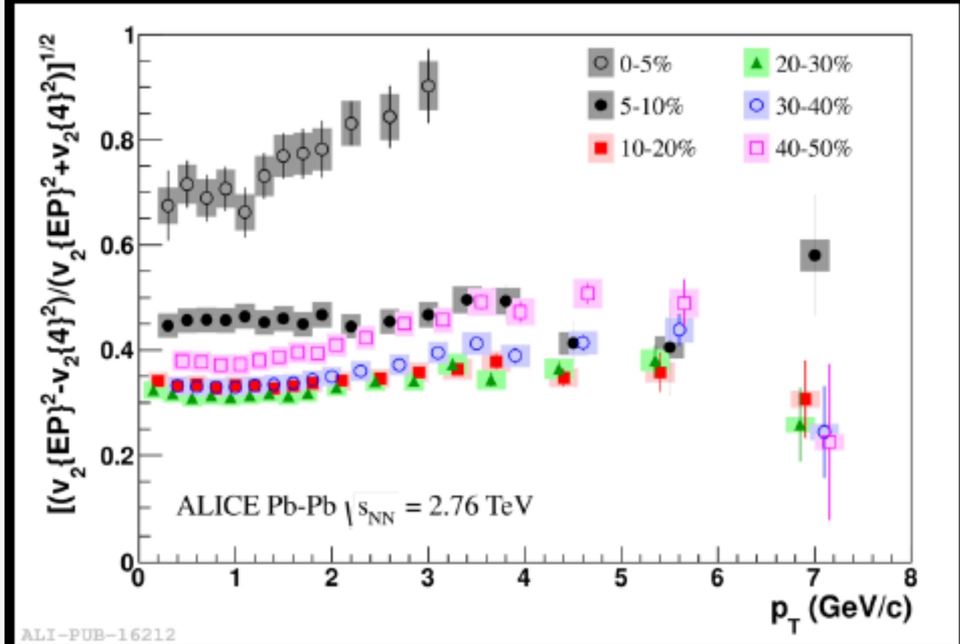


v_n measurements up to 20 GeV/*c* – where dominated by jet quenching
Non-flow effects suppressed by rapidity gap or using higher cumulants
Non-zero value of v_2 at high p_T both for $\Delta\eta > 2$ and 4-particle cumulant

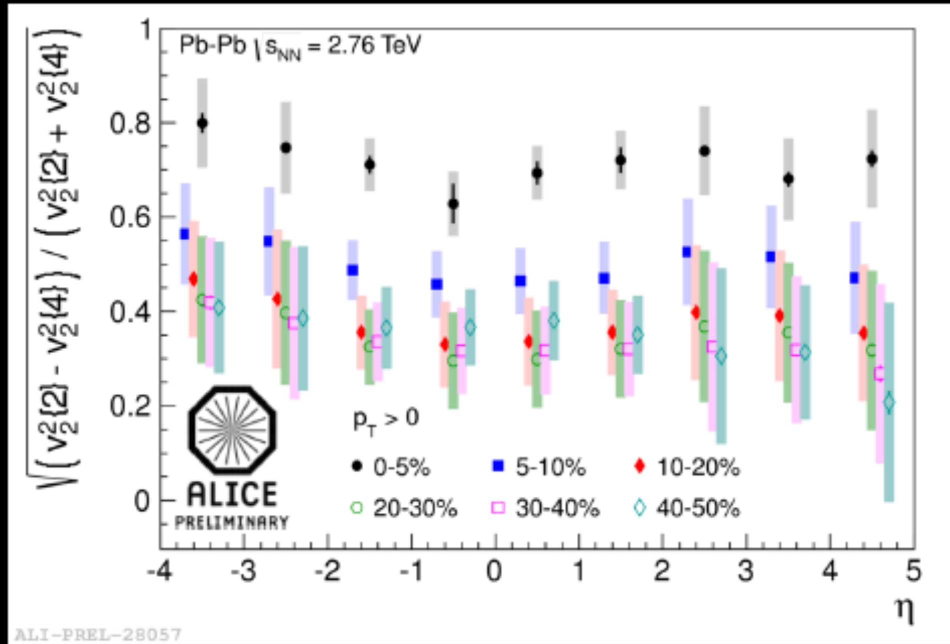
v_3 and v_4 diminish above 10 GeV/*c* – indication of disappearance of fluctuations at high p_T

Elliptic flow fluctuations

ALICE Collaboration: Phys. Lett. **B719**, (2013) 18

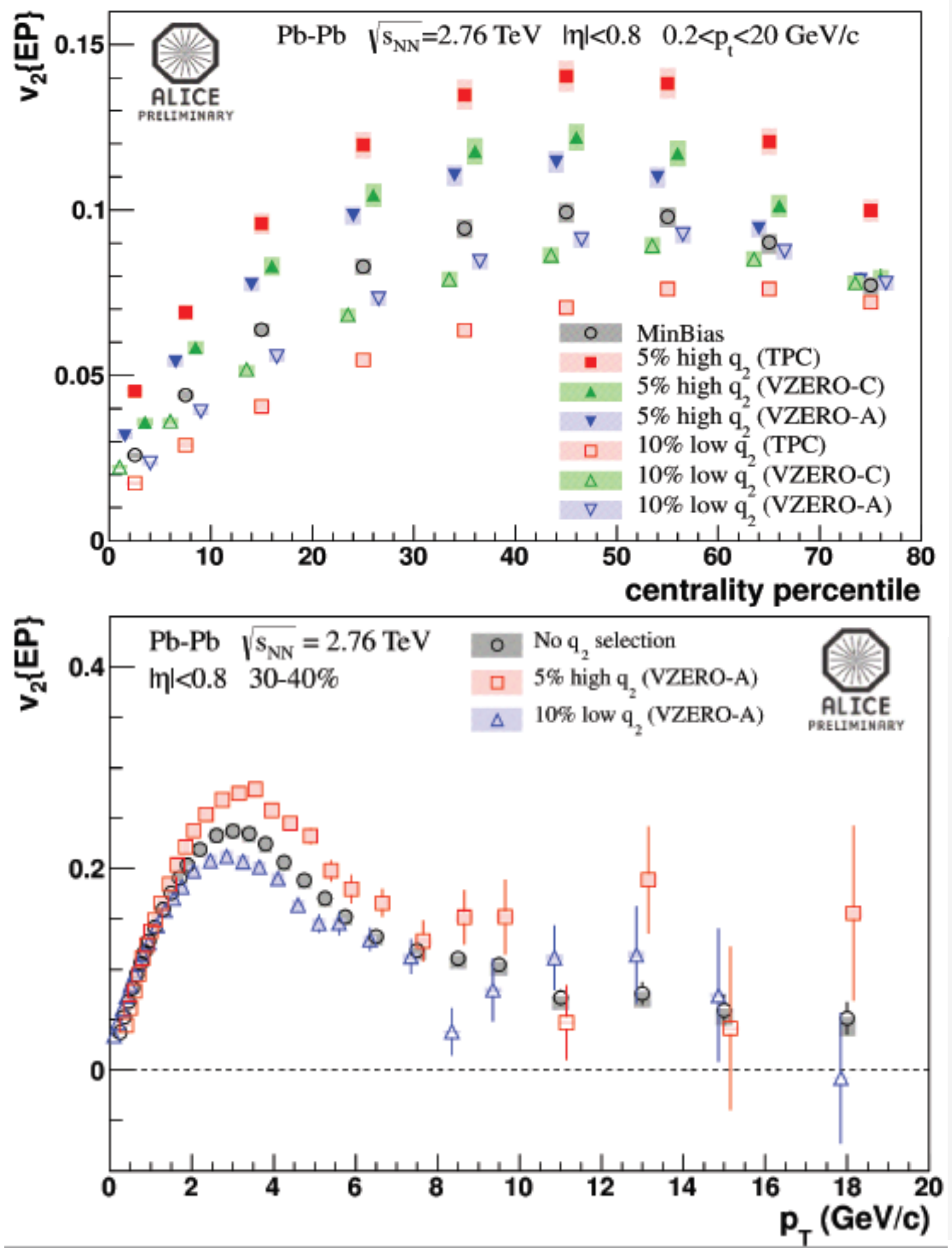


A. Hansen (ALICE Collaboration) @ QM2012



- No strong transverse momentum dependence except
  - the most central events (i.e. 0-5%)
  - the 40-50% class
- Little pseudorapidity dependence

Event Shape Engineering



$$Q_{n,x} = \sum_{i=1}^{M} \cos n\varphi_i$$

$$Q_{n,y} = \sum_{i=1}^{M} \sin n\varphi_i$$

$$q_n = Q_n/\sqrt{M}$$

At fixed centrality large flow fluctuations: Select events of given v_2 by means of q_2-vector length in a subevent and study another region (subevent)

v_2 splits by factor of two for semi-central events (30–50%)

Initial shape fluctuation effect very similar up to p_T ~ 6–8 GeV/c

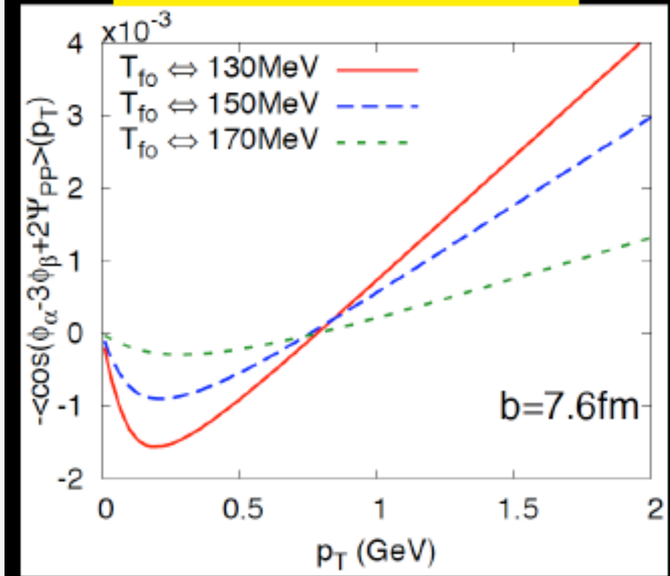
Symmetry plane correlations

R.S. Bhalerao, M. Luzum, J.-Y. Ollitrault, Phys. Rev. **C84** , (2011) 034910

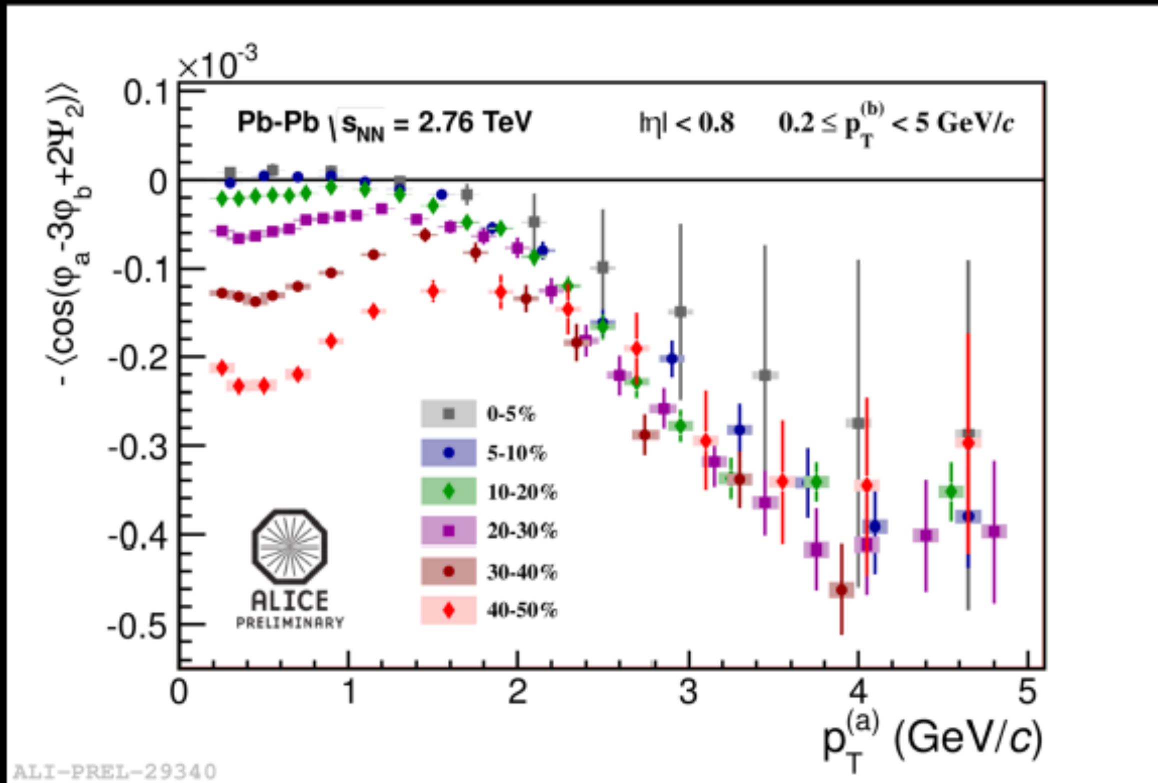
$$\langle \cos(n_1\varphi_1+n_2\varphi_2+\ldots+n_k\varphi_k) \rangle = v_{n_1} v_{n_2} \ldots v_{n_k} \langle \cos(n_1\Psi_1+n_2\Psi_2+\ldots+n_k\Psi_k) \rangle$$

$$\langle \cos(\varphi_1-3\varphi_2+2\varphi_3) \rangle = v_1 v_2 v_3 \langle \cos(\Psi_1-3\Psi_3+2\Psi_2) \rangle$$

D. Teaney and L. Yan, Phys. Rev. **C83**, (2011) 064904



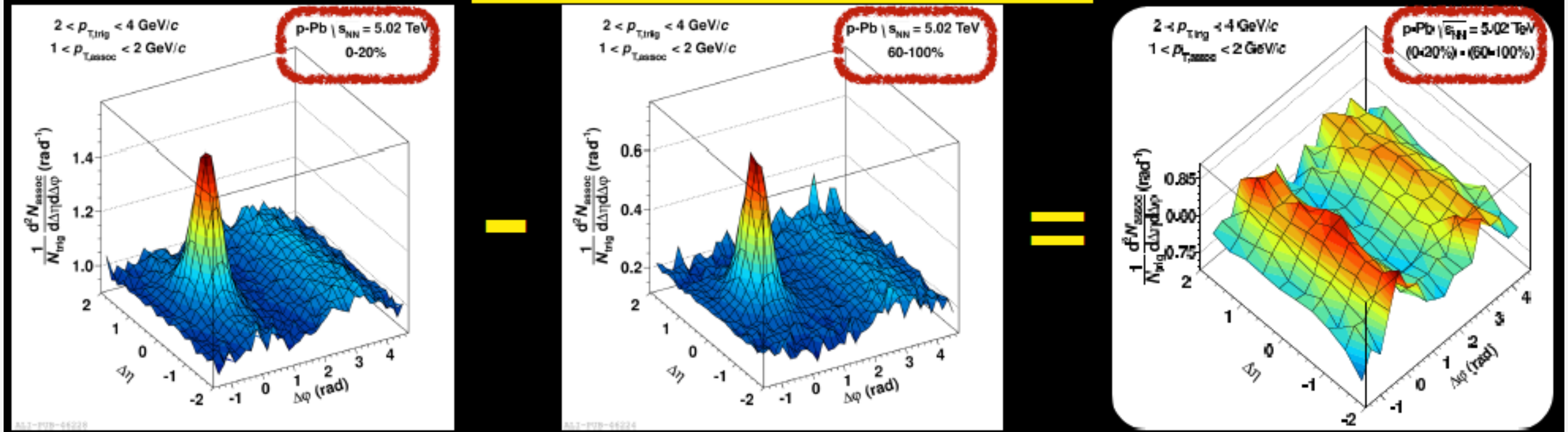
Glauber MC + ideal hydro



- Observation of a 3-plane correlation
- In qualitative agreement with MC Glauber+ideal hydro calculations at low p_T but hydro curves do not follow data at high p_T

Double ridge in p-Pb

ALICE Collaboration: Phys. Lett. **B719**, (2013) 29



$$\frac{1}{N_{trig}}\frac{d^2N_{assoc}}{d\Delta\eta d\Delta\varphi}\frac{S(\Delta\eta,\Delta\varphi)}{B(\Delta\eta,\Delta\varphi)}$$

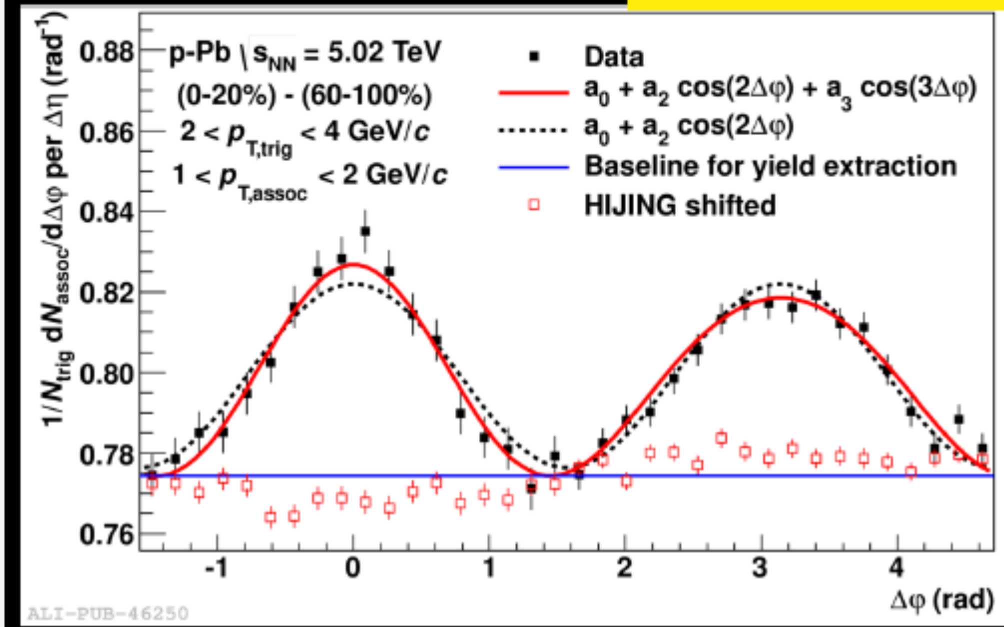
$$S(\Delta\eta,\Delta\varphi)=\left(\frac{1}{N_{trig}}\frac{d^2N_{assoc}}{d\Delta\eta d\Delta\varphi}\right)_{same}$$

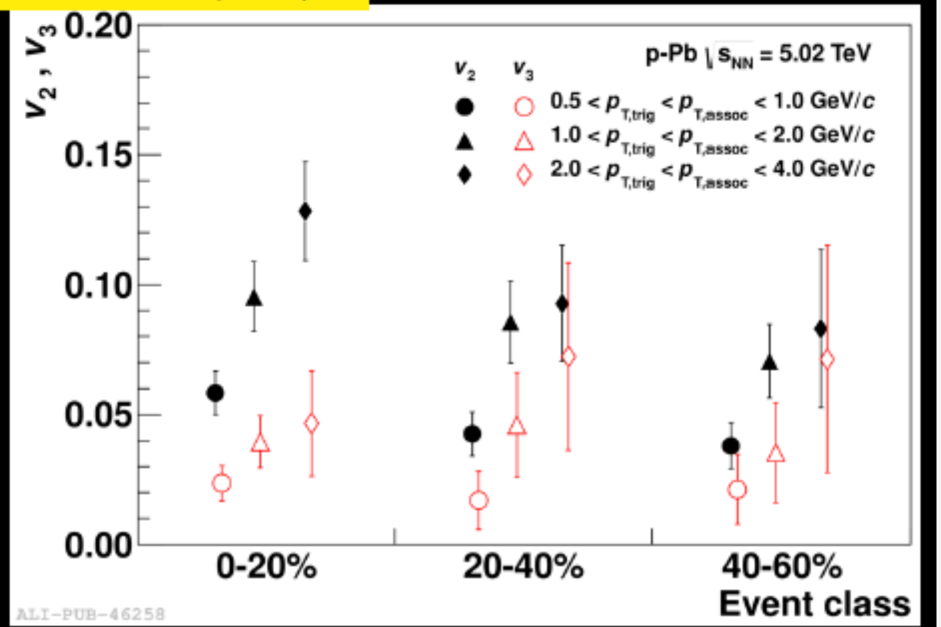
$$B(\Delta\eta,\Delta\varphi)=a\left(\frac{d^2N_{assoc}}{d\Delta\eta d\Delta\varphi}\right)_{mixed}$$

- Near side ridge is observed in central p-Pb collisions
- Subtraction of the jet component i.e. as measured in the 60-100% centrality class reveals
  - ★ a double symmetric ridge on the near and the away side!

Double ridge in p-Pb: v_2 v_3

ALICE Collaboration: Phys. Lett. **B719**, (2013) 29



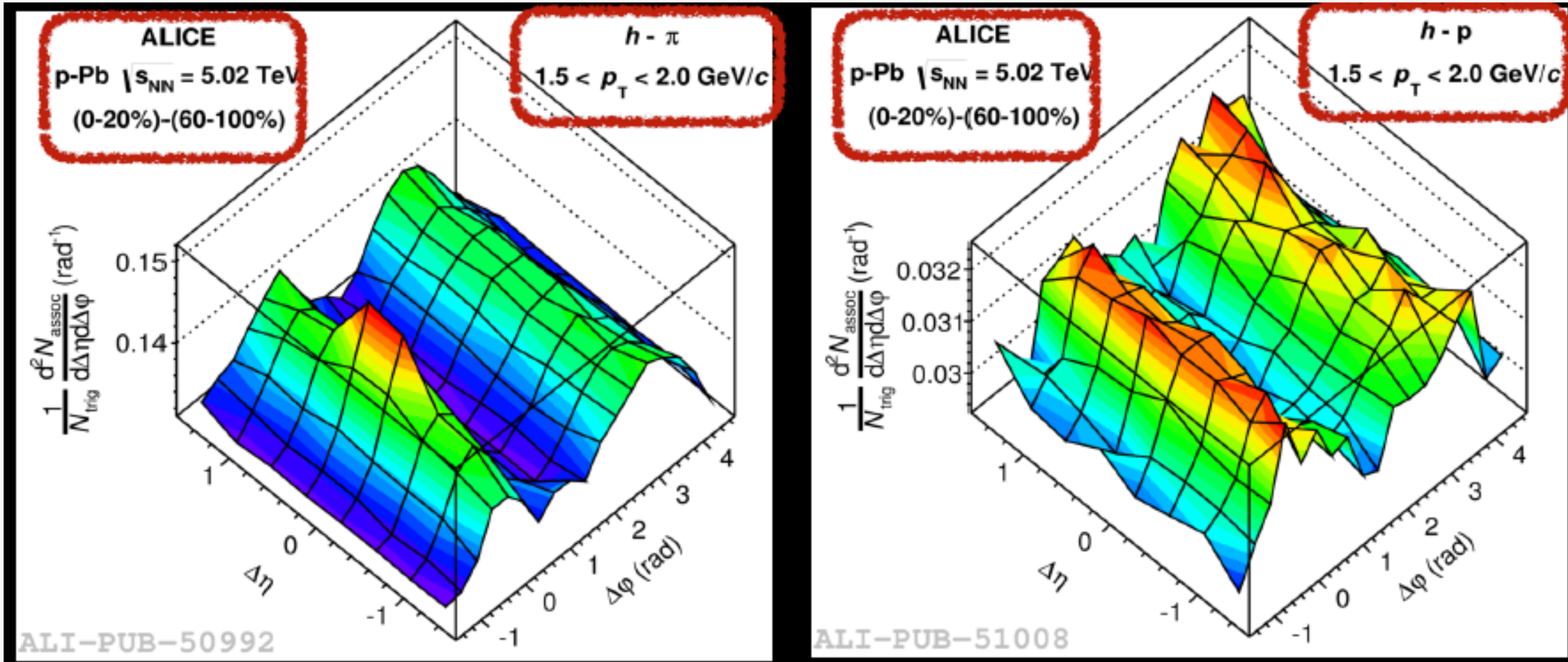


$$\frac{1}{N_{trig}}\frac{dN_{assoc}}{d\Delta\varphi} = a_0 + a_2\cos(2\Delta\varphi) + a_3\cos(3\Delta\varphi)$$

- Fourier decomposition using the 2nd and the 3rd harmonic
- v_2 and v_3 increase with increasing p_T, while exhibiting a mild multiplicity dependence
- In qualitative agreement with hydro and CGC calculations

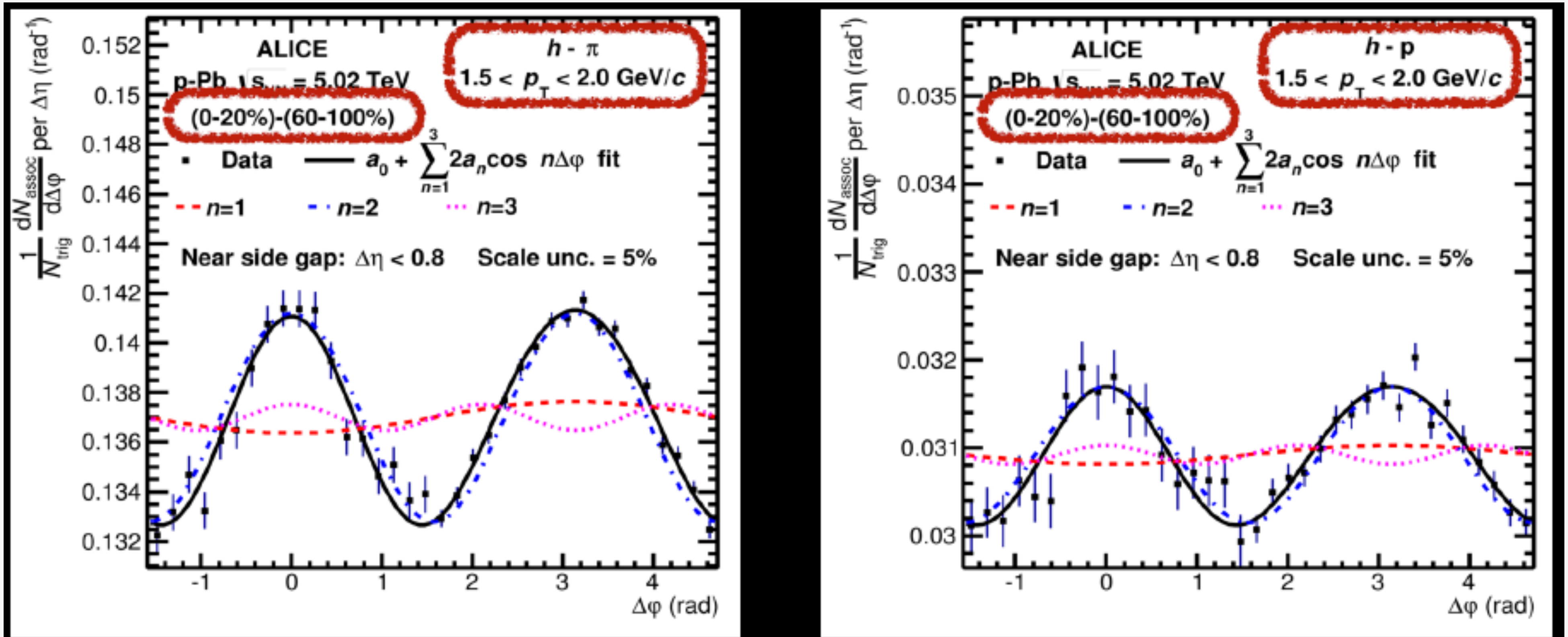
K.Dusling and R. Venugopalan, arXiv:1302.7018
P. Bozek and W. Broniowski, arXiv:1211.0845

p-Pb correlations with PID



- Similar analysis: charged particle ⇒ "trigger", (π,K,p) ⇒ "associated"
- Jet component reduction: (0-20)% - (60-100)%
- Symmetric ridges in all cases i.e. π-h, K-h, p-h
  - ★ Residual near side jet peak for π-h and to a smaller extent K-h

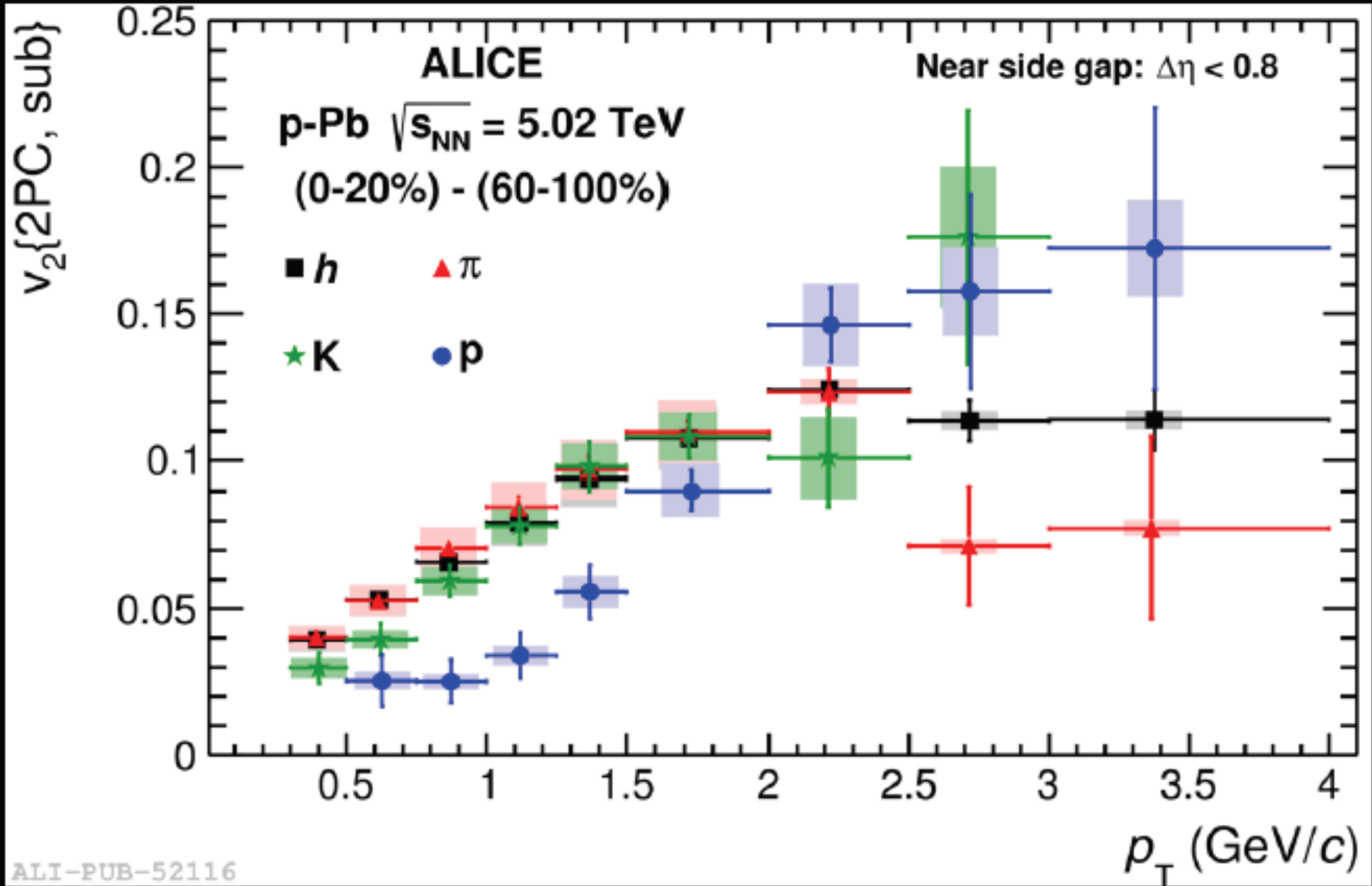
p-Pb v_2 v_3 with PID



$$\frac{1}{N_{trig}} \frac{dN_{assoc}}{d\Delta\varphi} = a_0 + a_1 \cos(\Delta\varphi) + a_2 \cos(2\Delta\varphi) + a_3 \cos(3\Delta\varphi)$$

- After subtraction: symmetric double ridges for h-π, h-K, h-p
- Small contribution from the odd coefficients

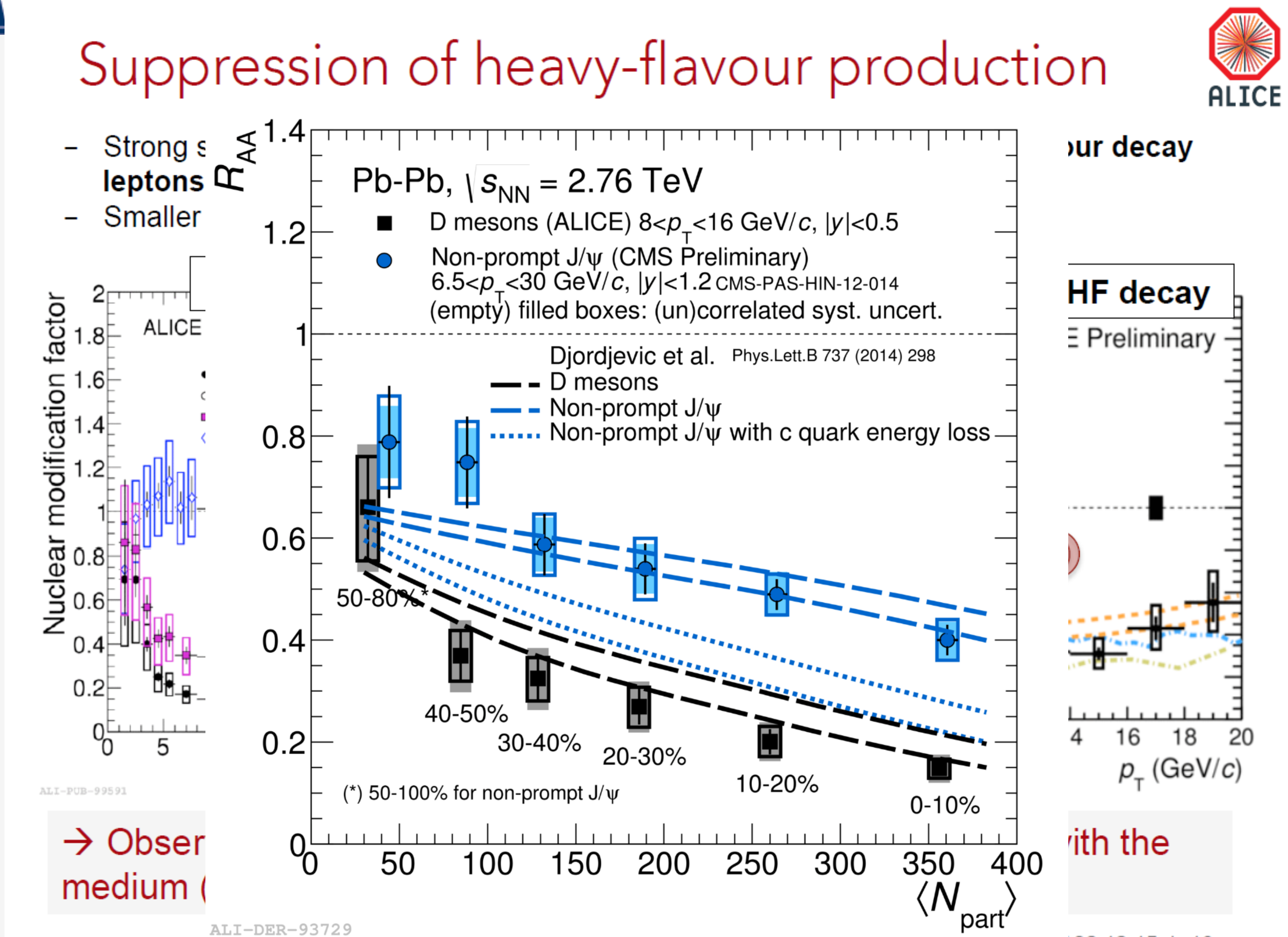
v_2 mass splitting in p-Pb



- Mass splitting observed in p-Pb collisions!
- Qualitatively similar picture as in Pb-Pb
  - ★ Qualitatively consistent with a system that develops some degree of collective behavior

Heavy flavours

c and b suppression

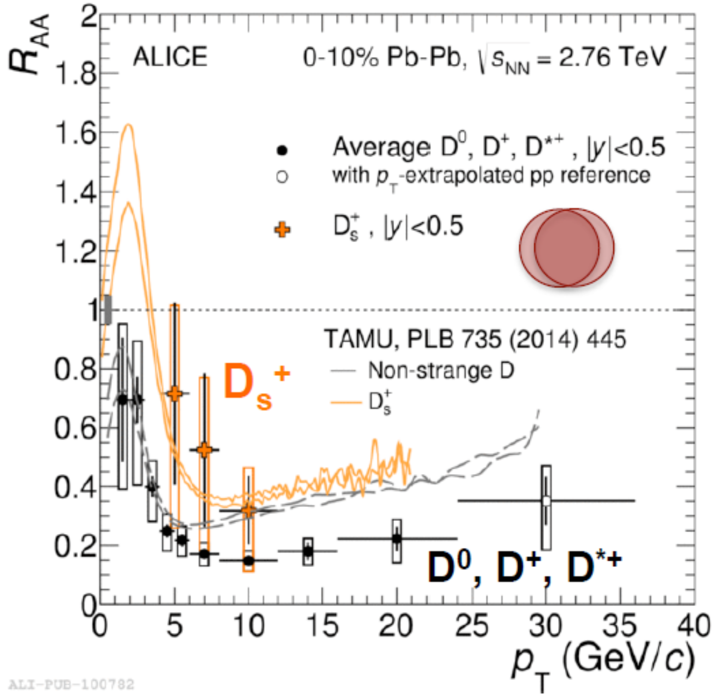


arXiv:1509.06888

Suppression of D_s^+ production

ALICE

Suppression of D_s^+ meson observed at high p_T in central Pb-Pb collisions
– Hints for less suppression than non-strange D mesons



Measurement compatible with TAMU model [Phys. Lett. B735 (2014) 445–450], implementing recombination of c with s quarks, enhanced in the medium

→ Uncertainties substantially reduced with expected Run 2 statistics

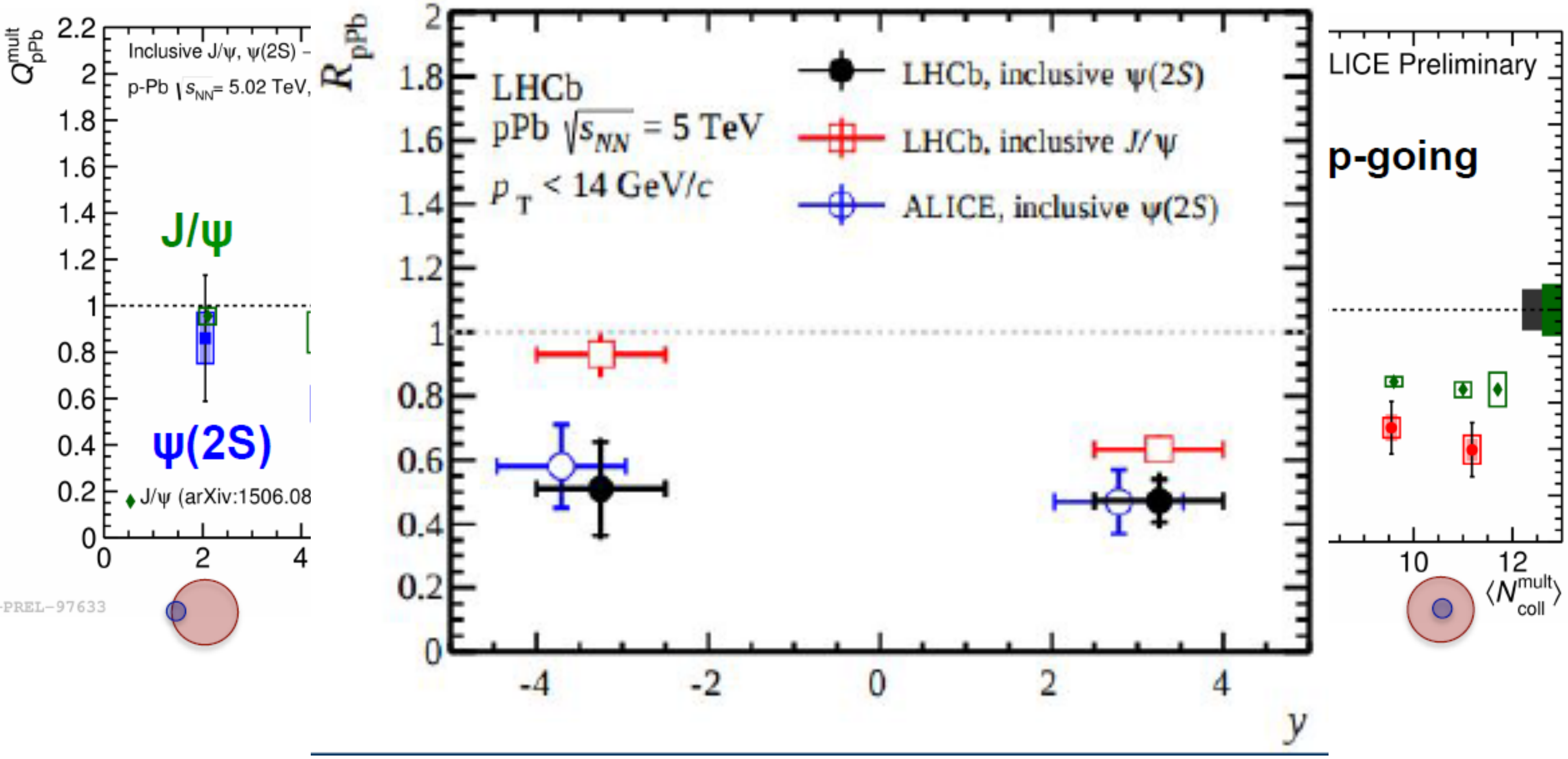
D_s^+ sensitive to coalescence of charm and strange quarks

arXiv:1509.07287

Charmonium suppression in pPb

ψ (2S) suppression in p-Pb

- Observed suppression of J/ψ in p-going direction
- ψ(2S) more suppressed than J/ψ
  - Increase of suppression with event activity



ALICE, 124th LHCC meeting |02.12.15 | 8

QGP radiation

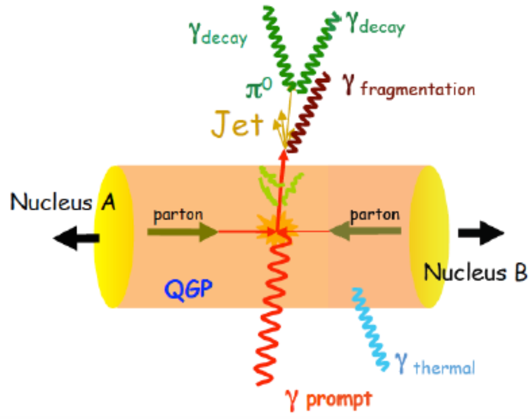
Direct photons

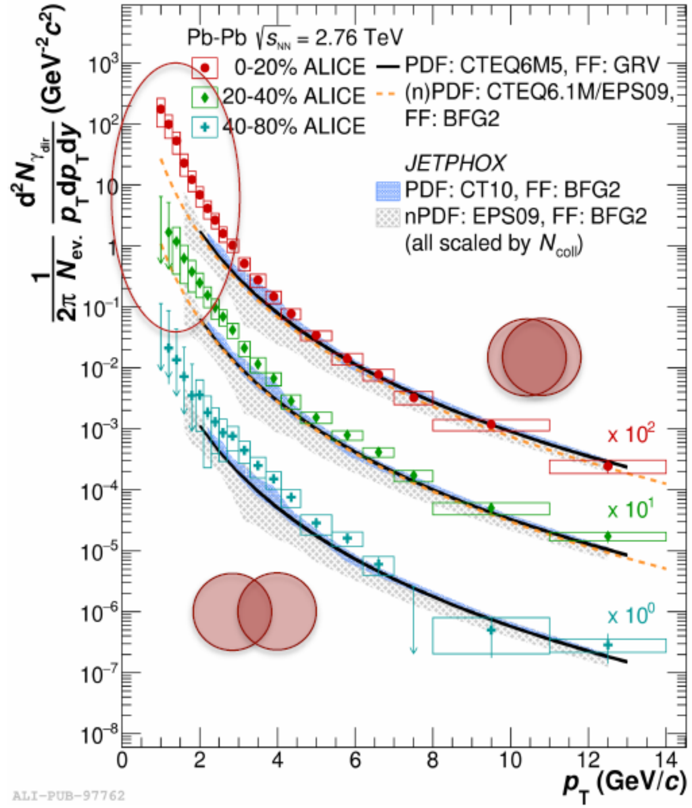
Direct photons = not coming from particle decays
Largest background from π^0 and η decay

Observed a 2.6σ excess above pQCD expectations at low p_T in 0-20% Pb-Pb

Exponential shape = thermal spectrum
→ inverse slope interpreted as temperature
T_{eff} = 304 ± 11 ± 40 MeV, 30% larger than at RHIC

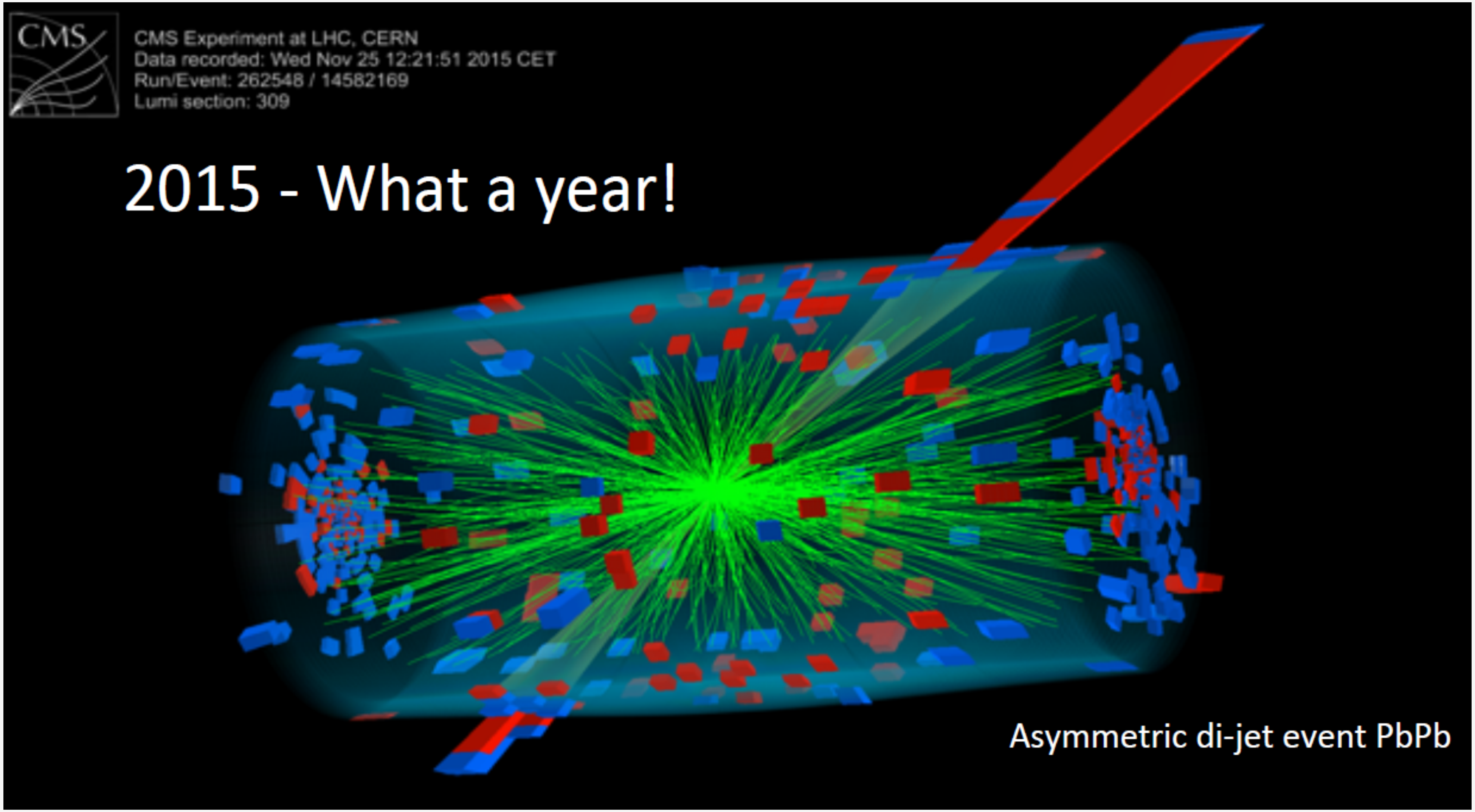
Expected higher T_{eff} due to higher initial temperature and larger blue-shift by stronger radial flow





arXiv:1509.07324

Jet quenching

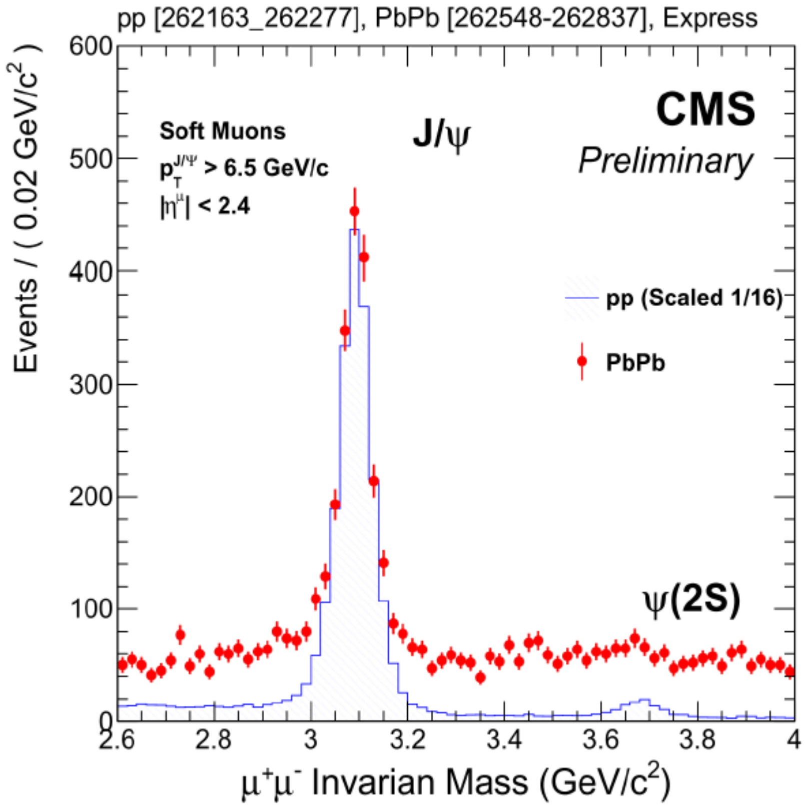


Today's Peak activity Pb-Pb @ 5.02 TeV/nucleon

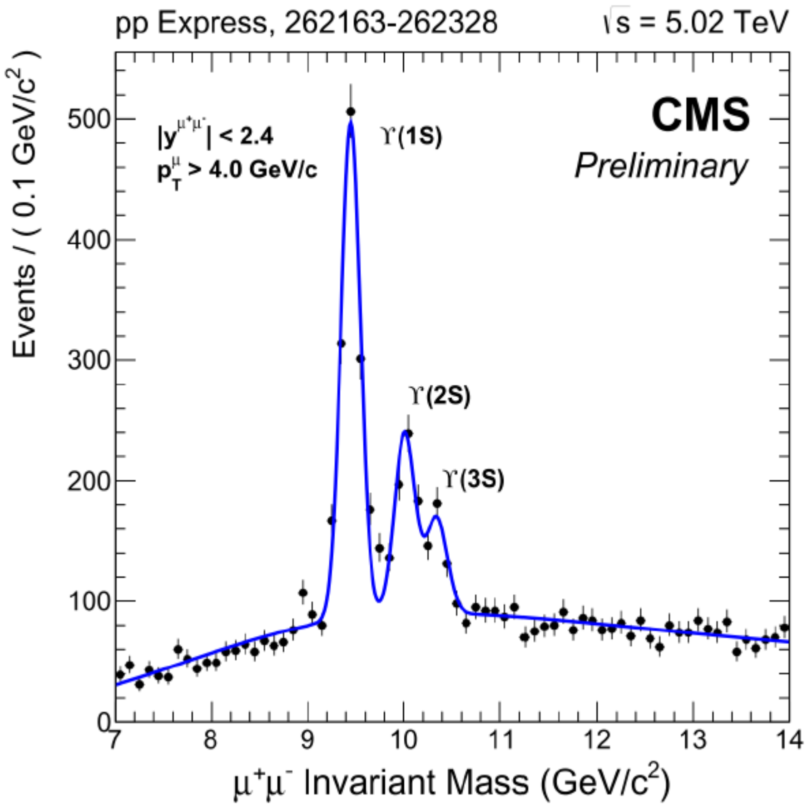
LHC Page1 Fill: 4664 E: 6369 Z GeV t(SB): 03:20:17 26-11-15 20:53:56

ION PHYSICS: STABLE BEAMS

Charmonia



Bottomonia



02-12-2015 CMS Status Report 8

Collectivity in small systems ?

- **Is there collectivity in small dense systems (central pA) ?**
- **What about small dilute systems (MinBias pp) ??**

Collectivity

⇨ Collectivity is **experimentally proven** in **AA** & **pA**

- weak definition:

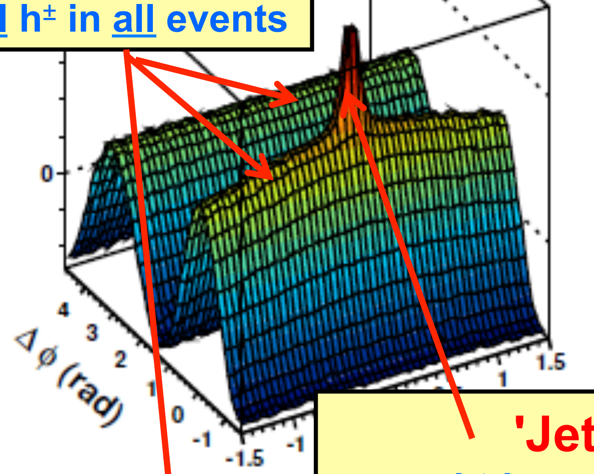
⇨ **SIMILAR** effect for **ALL** particles (of some kind, say p_T/PID) in (almost) **ALL** events

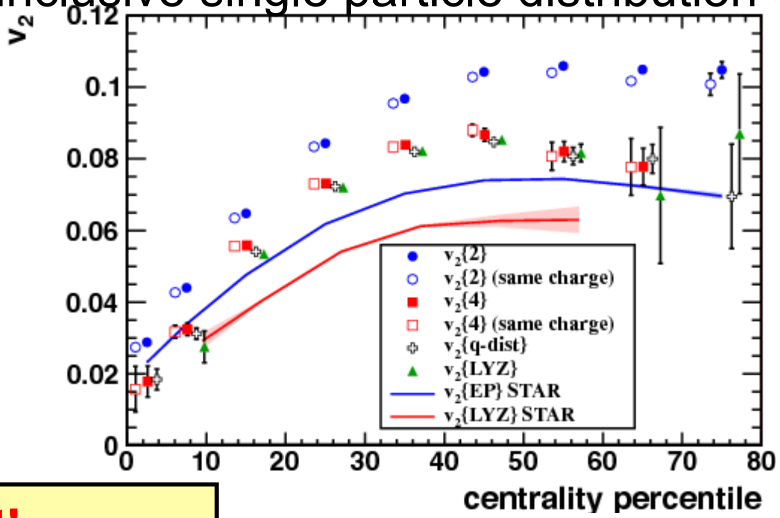
✪ drawn from the same inclusive single particle distribution

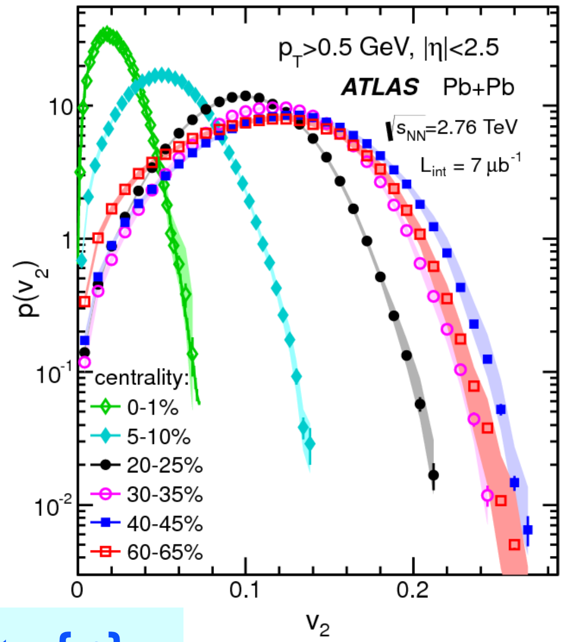
EbE P(v_2)

'Ridge'
all h± in all events

PbPb 10-20%



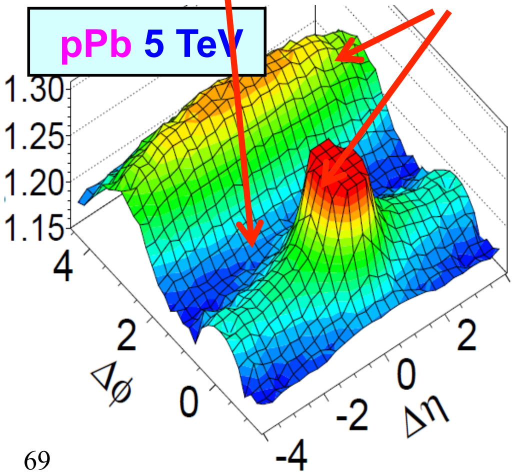


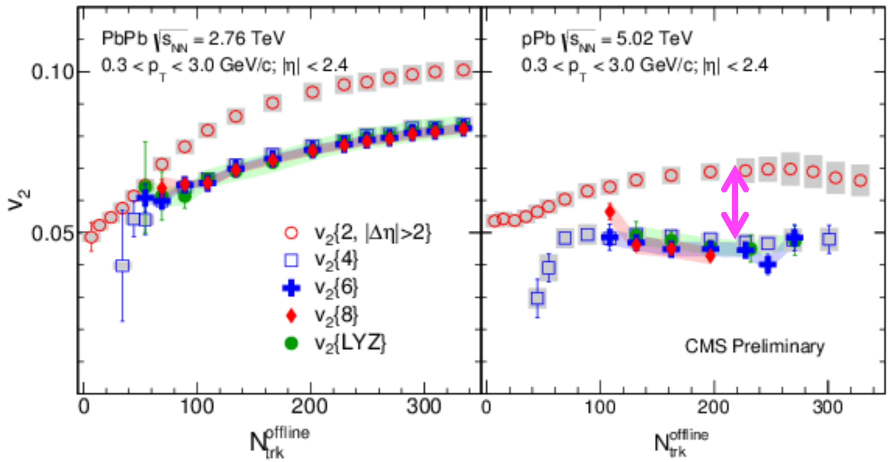


'Jet'
some h± in some events

$v_2\{2\}< v_2\{4\}\approx v_2\{6\}\approx \dots \approx v_2\{\infty\}$

pPb 5 TeV





pA, AA definitely 'weakly' collective

Collectivity in large systems: AA

- strong definition: {'thermo' + 'hydro'} - dynamics
  - ⇨ **emerging-f(*t*)-** in **strongly interacting** matter with density/pressure **gradients**

- strong Collectivity **consistent with ≈ all data in AA** to (very) good accuracy

  - ⇨ **thermo-dynamics:**
    - particle ratios (Statistical Model) to 10-30%

  - ⇨ **hydro-dynamics:**
    - radial (v_0) & elliptic (v_2) flow for > 95% of all particles (p_t < few GeV)
    - higher harmonics v_n, PID (*m* dependence) of v_n ('mode mixing' of v_0 & v_2)

  - ⇨ **thermo + hydro:**
    - HBT f(T, β): ($R(m_T)$, $R(N_{ch}^{1/3})$, $R_{out}/R_{side} \approx 1$)

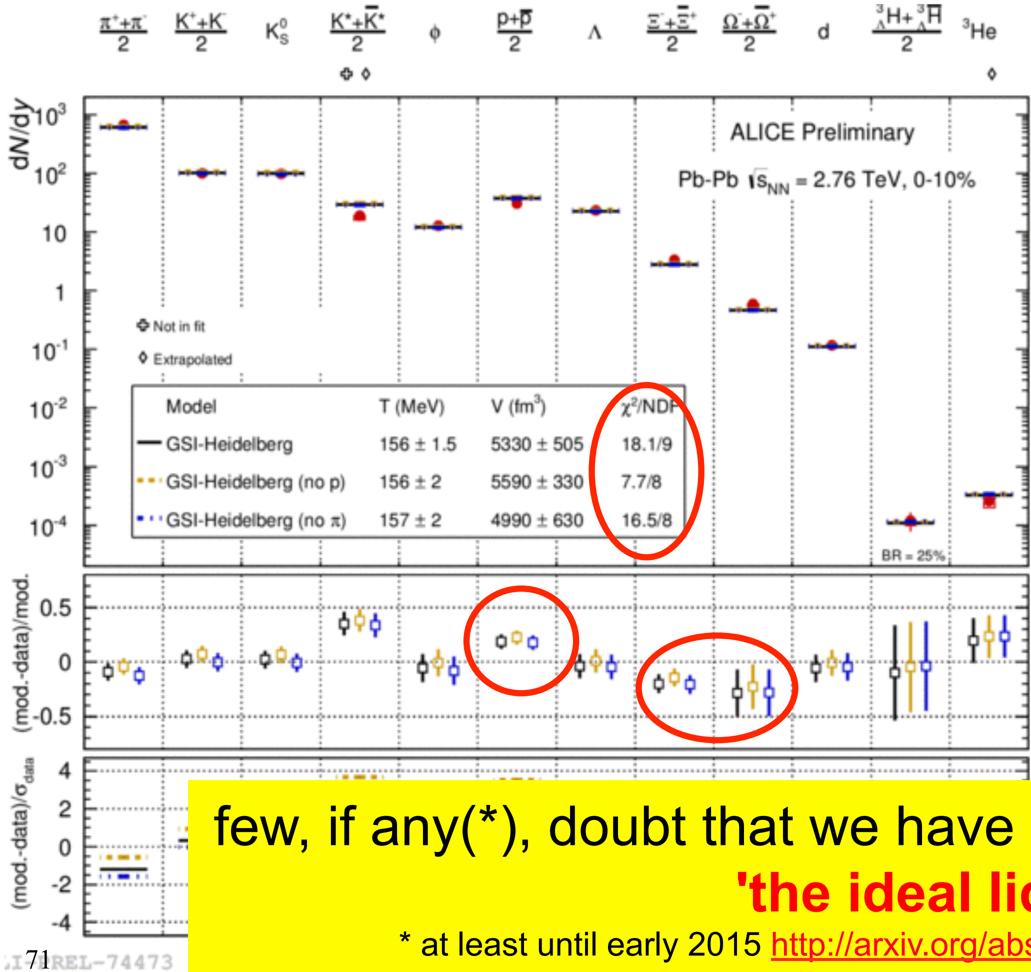
'Standard Model' of heavy ion physics

Some tensions…

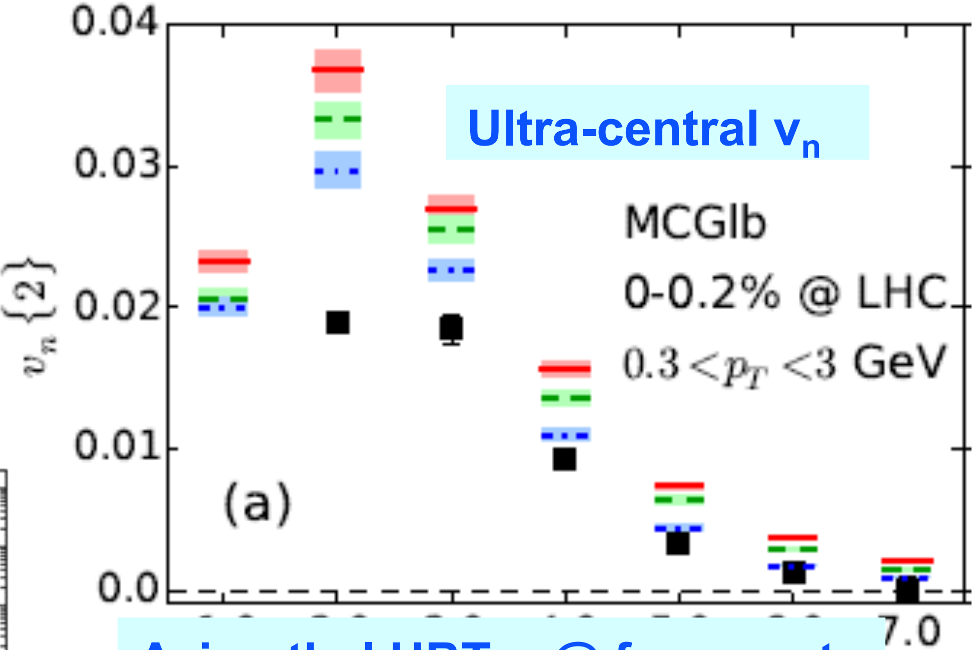
- p/π ratio, v_n, HBT ε_f, …

rather work in progress

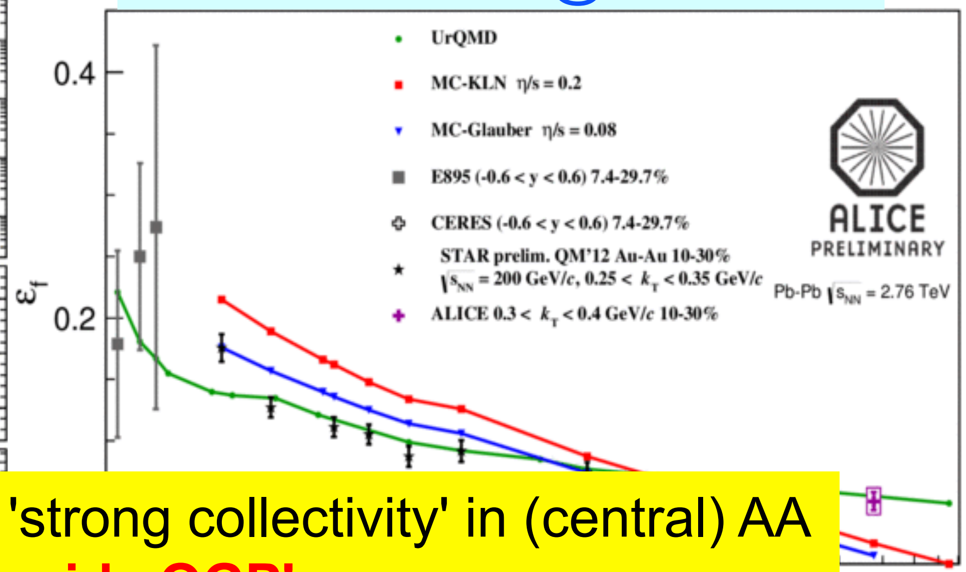
SM fits to particle ratios



Ultra-central v_n



Azimuthal HBT: ε @ freezeout



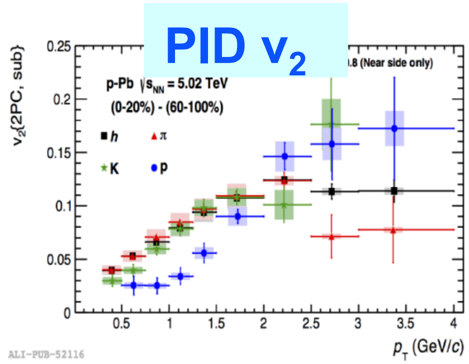
few, if any(*), doubt that we have 'strong collectivity' in (central) AA

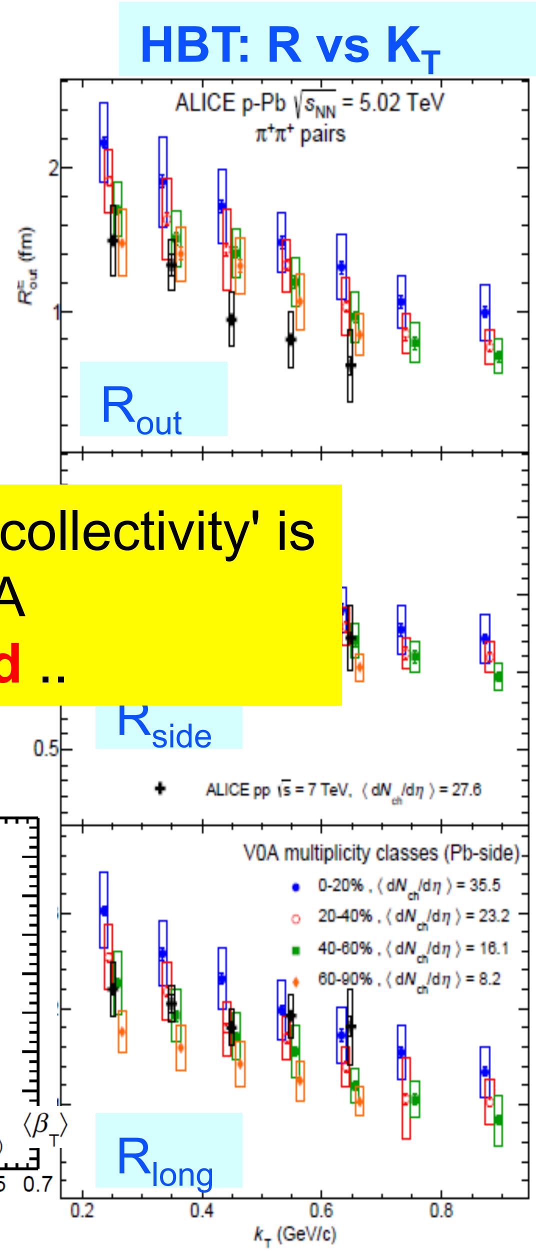
'the ideal liquid sQGP'

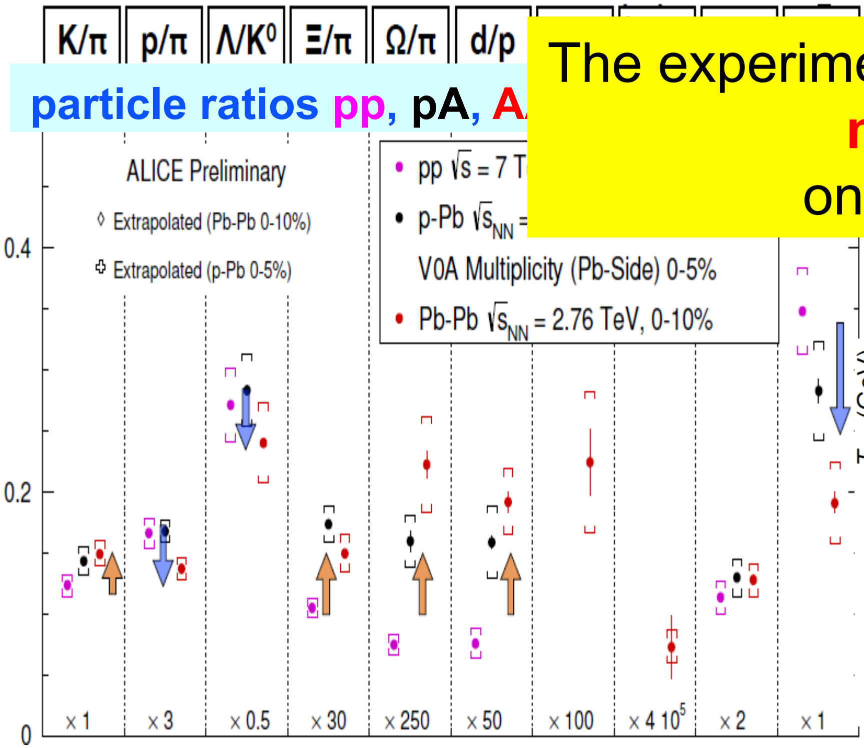
* at least until early 2015 http://arxiv.org/abs/1502.05572 .(AMPT 'escape' hypothesis)

Collectivity in small dense systems: 'central' pA

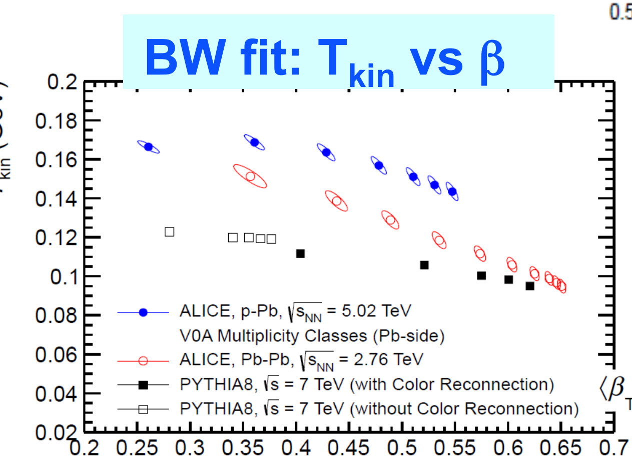
- Collectivity **consistent with ≈ all data in central pA** to reasonable accuracy
  - ⇨ **thermo-dynamics:** particle ratios (SM, γ_s=1!) to ≈ 20-30%
  - ⇨ **hydro-dynamics:** pA, dA, ^{3}He-A
    - ✪ radial & elliptic flow
    - ✪ higher harmonics v_3, PID v_2
  - ⇨ **thermo + hydro:**
    - ✪ HBT ($R(m_T)$, $R(N_{ch}^{1/3})$, R_{out}/R_{side} ≈ 1





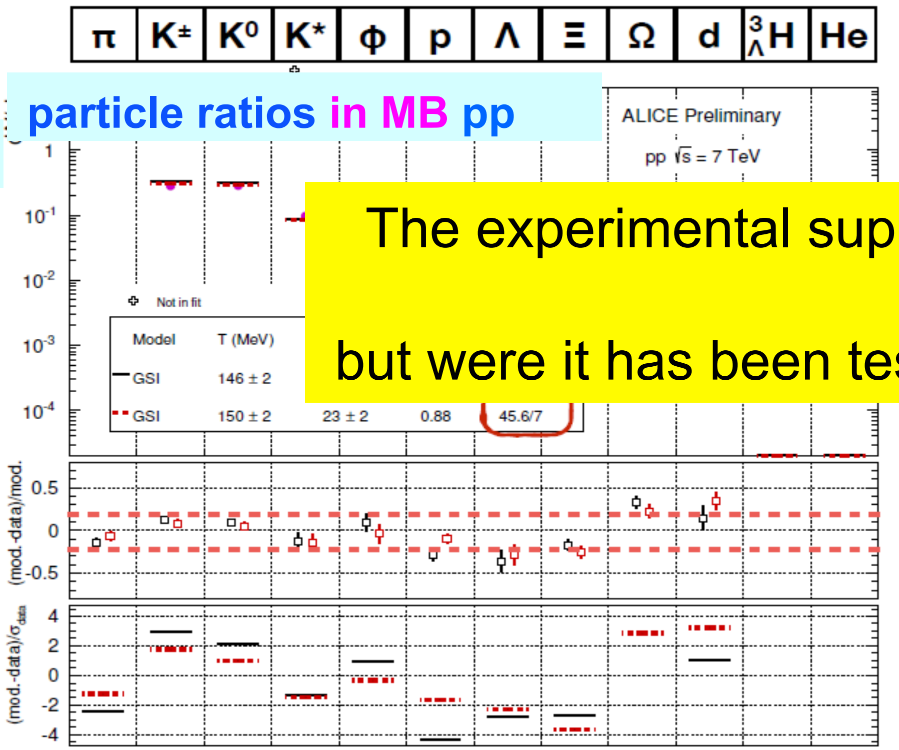


The experimental support for 'strong collectivity' is **not really worse** than AA
only <u>somewhat</u> **less tested** ..

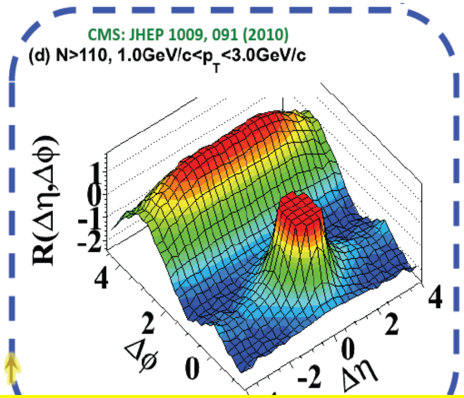


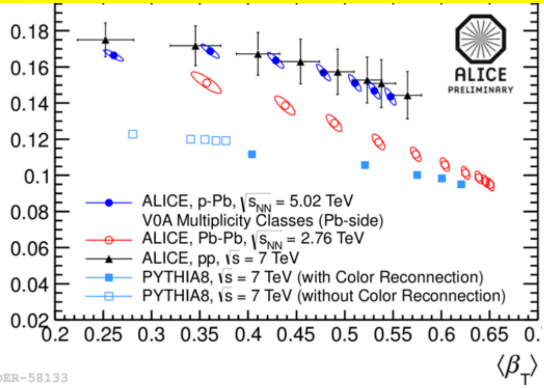
Collectivity in small dense systems: 'central' pp

- Collectivity ≈ consistent with data in <u>high N_{ch}</u> pp
  - ⇨ **thermo-dynamics: MB particle ratios to ≈20-40% γ_s < 1!**
  - ⇨ **hydro-dynamics:**
    - ✪ radial & elliptic flow
    - ✪ v_3, PID v_2 (CMS PAS HIN-15-009)
  - ⇨ **thermo + hydro:**
    - ✪ HBT ($R(m_T)$, $R(N_{ch}^{1/3})$, $R_{out}/R_{side} \leq 1$)

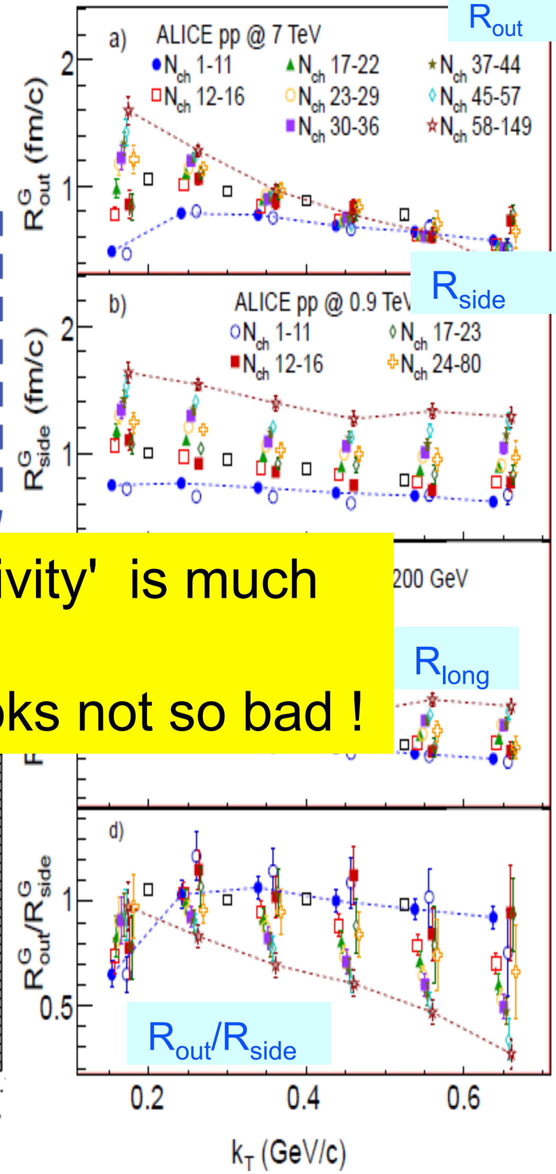


The Ridge





HBT: R vs K_T



The experimental support for 'strong collectivity' is much **less tested** ..
but were it has been tested, at high N_{ch}, it looks not so bad !

Facts

- Experimental facts:

  ⇨ **weak collectivity** proven in pA & **AA**, not measured in **pp**

  - **'a priori'** pp ≈ pA at same N_{ch} (both IS and FS are known to be similar)
  - **'all particles in all events'** must be part of any physics model (led to a significant modification in physics origin of CGC ridge !!)

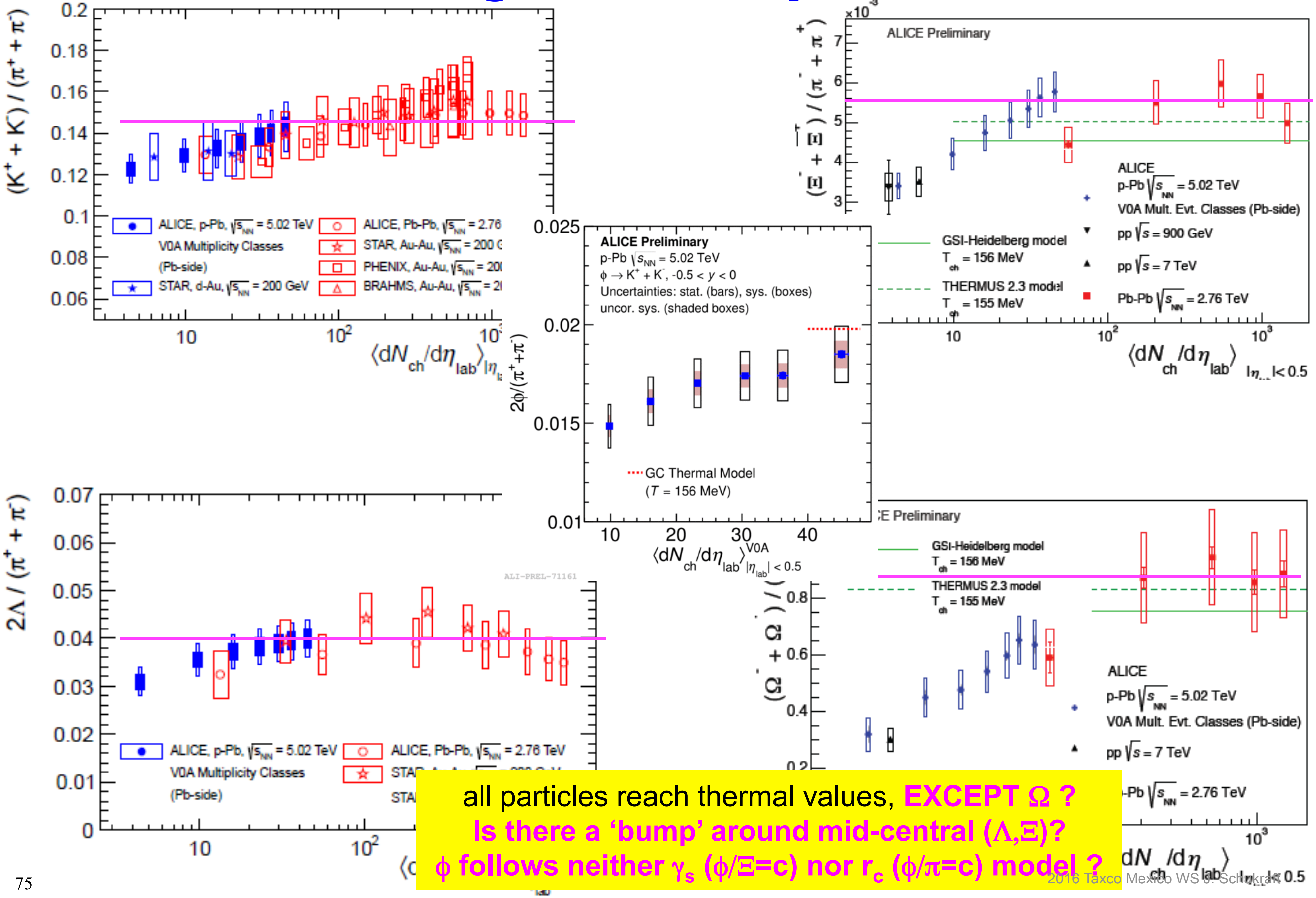
  ⇨ strong coll. **(thermo & hydro)** compatible with majority of data in **AA & pA**

  - some areas need work, some tests missing in pA

  ⇨ limited data in **pp** at high N_{ch}, but compatible with SC !

  - final state (HBT, p_T-spectra (v_0), ridge (PID v_2), part. ratios): **pp ≈ pA @ same N_{ch}**

Strange Developments



all particles reach thermal values, **EXCEPT Ω ?**

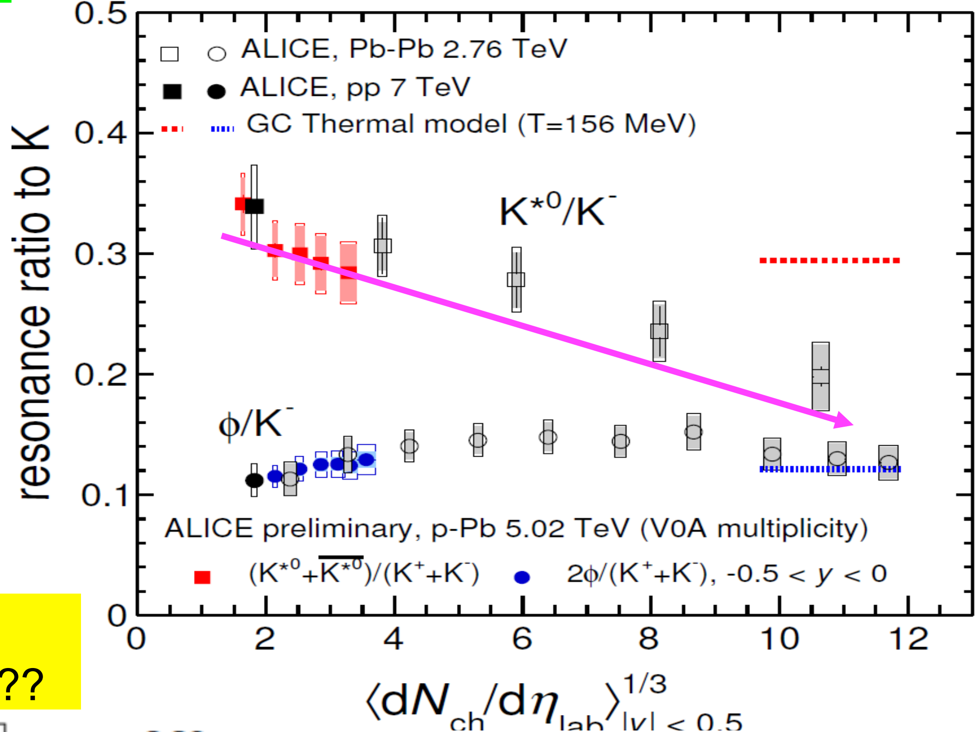
Is there a 'bump' around mid-central (Λ,Ξ)?

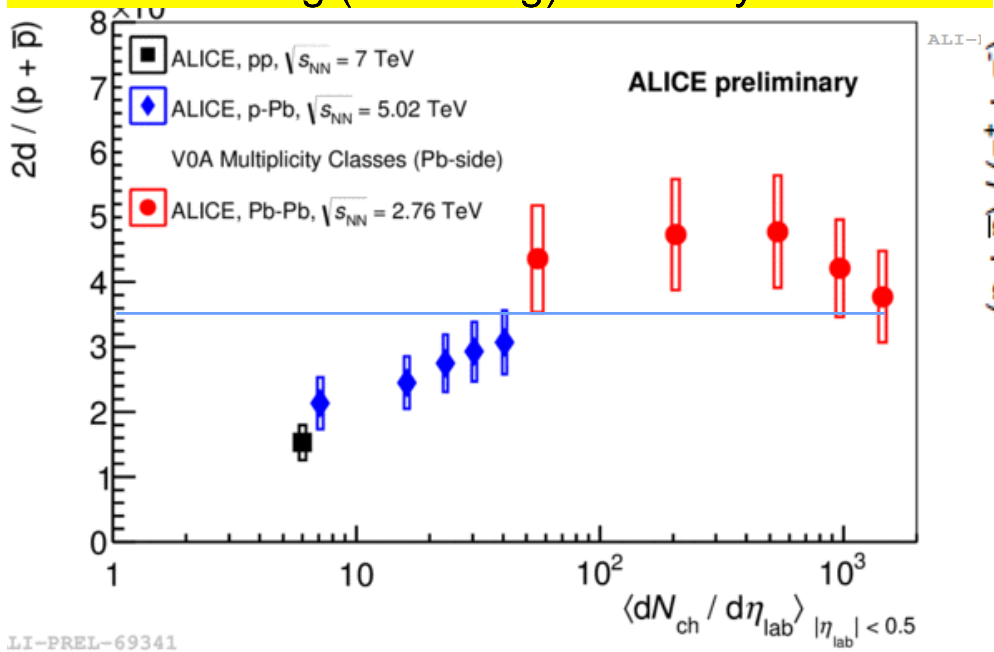
φ follows neither γ_s (φ/Ξ=c) nor r_c (φ/π=c) model ?

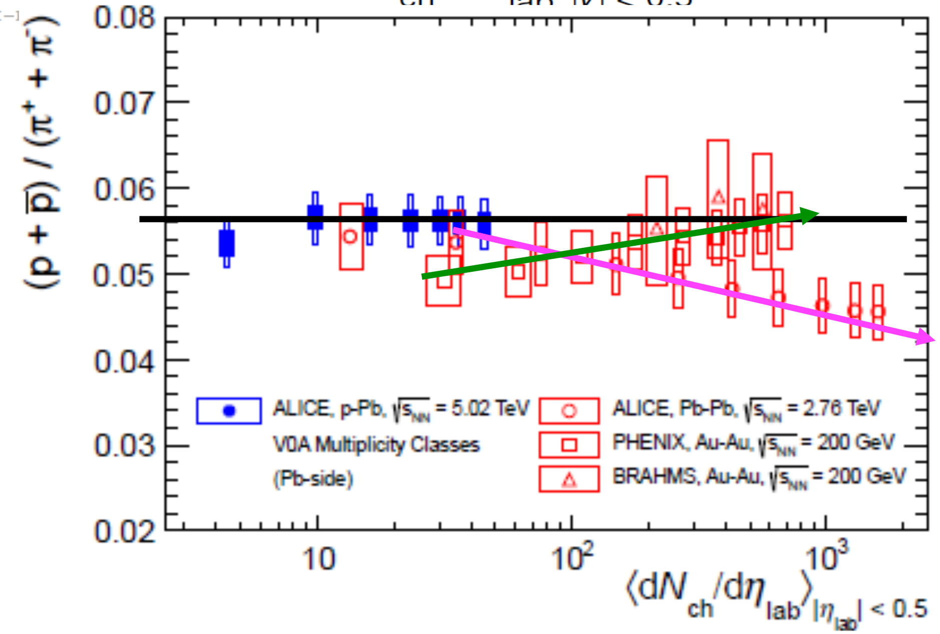
Other 'Developments'

- Final state chemistry ?
  - ⇨ K* : decay + scattering
    - ✪ or sequential freeze-out (lower T_{chem})
  - ⇨ p/π: B annihilation (= seq. freezeout)
- light nuclei d,(^{3}He)
  - ⇨ pp x 2, reaches ≈ SM value
  - ⇨ canonical suppression ?
  - ⇨ Coalescence ? (but ... ≠ c ?)

do we see dynamics at work
while reaching (or leaving) thermodynamics ??

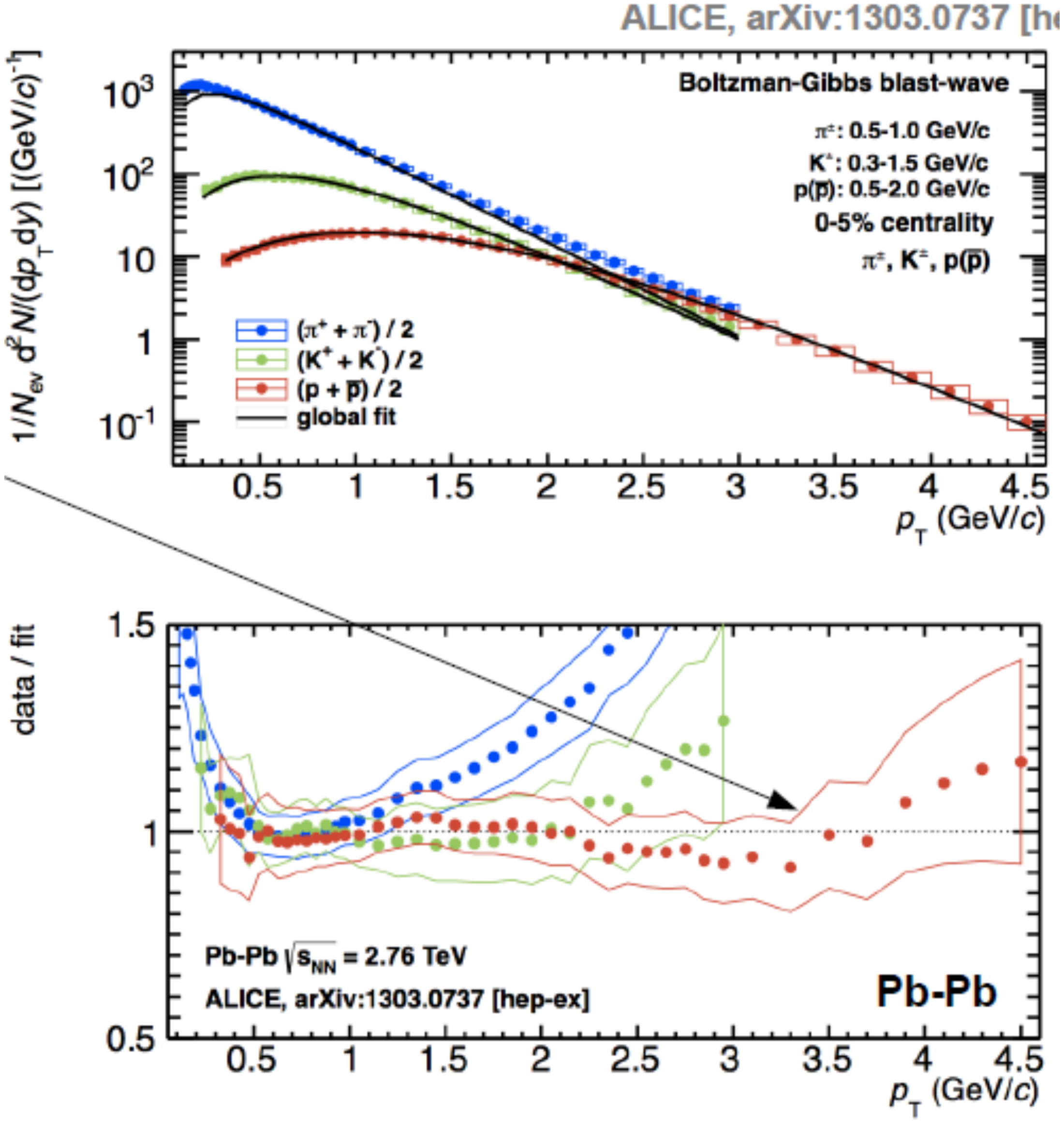


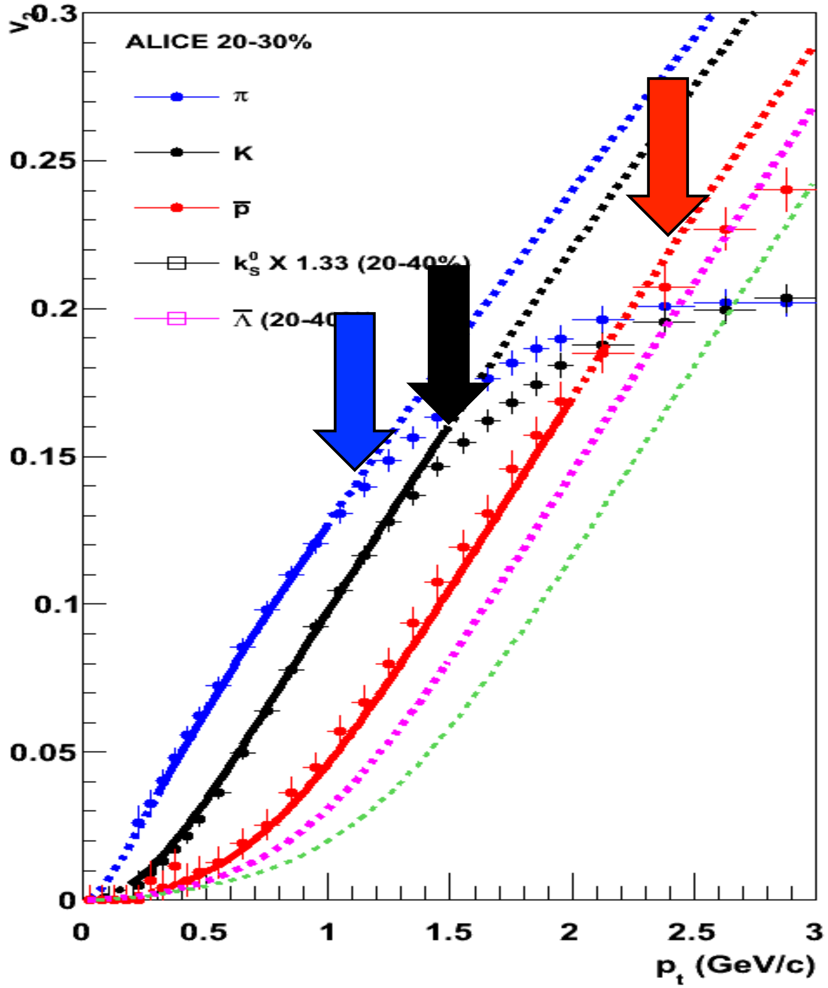




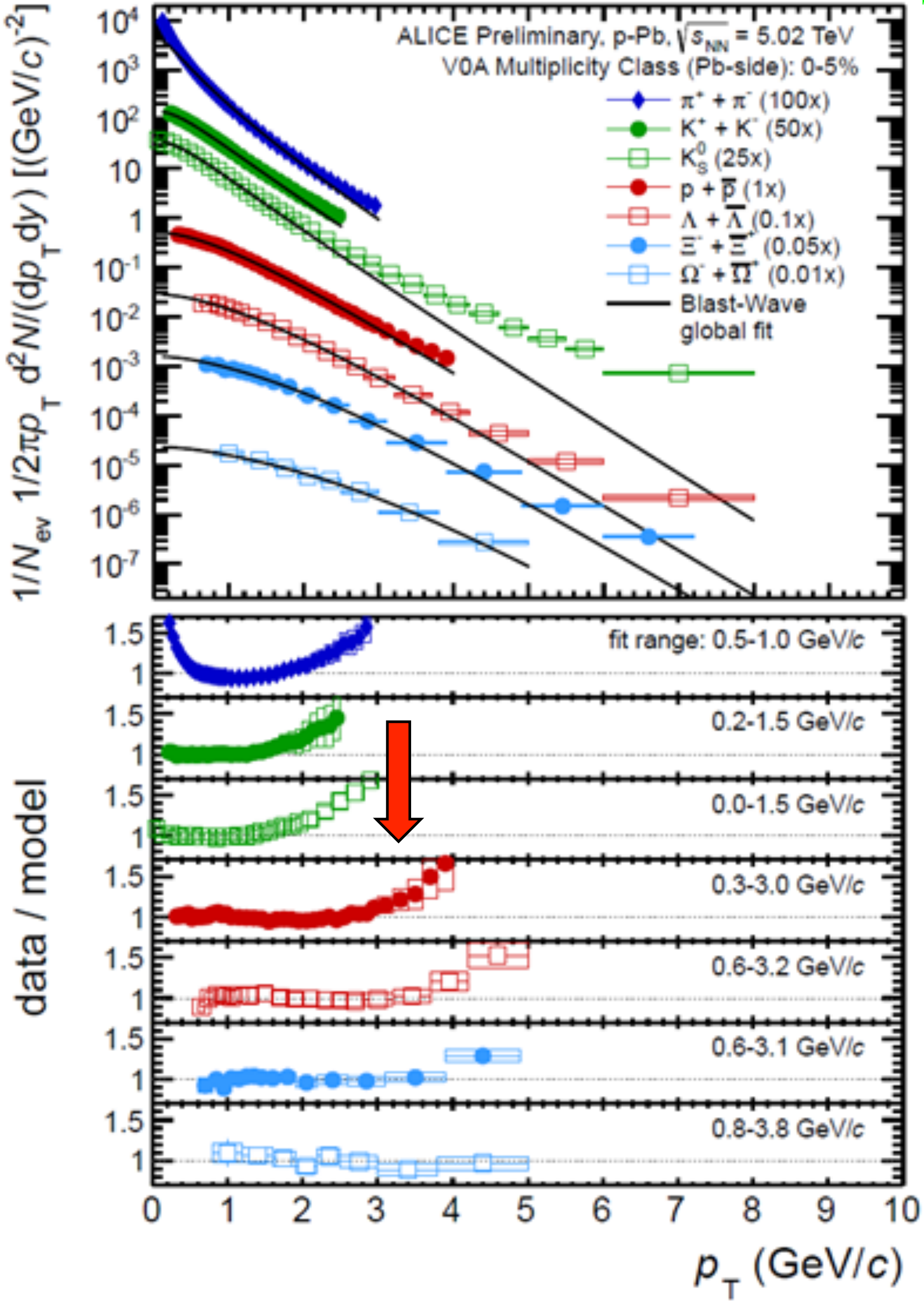
Hydro in PbPb

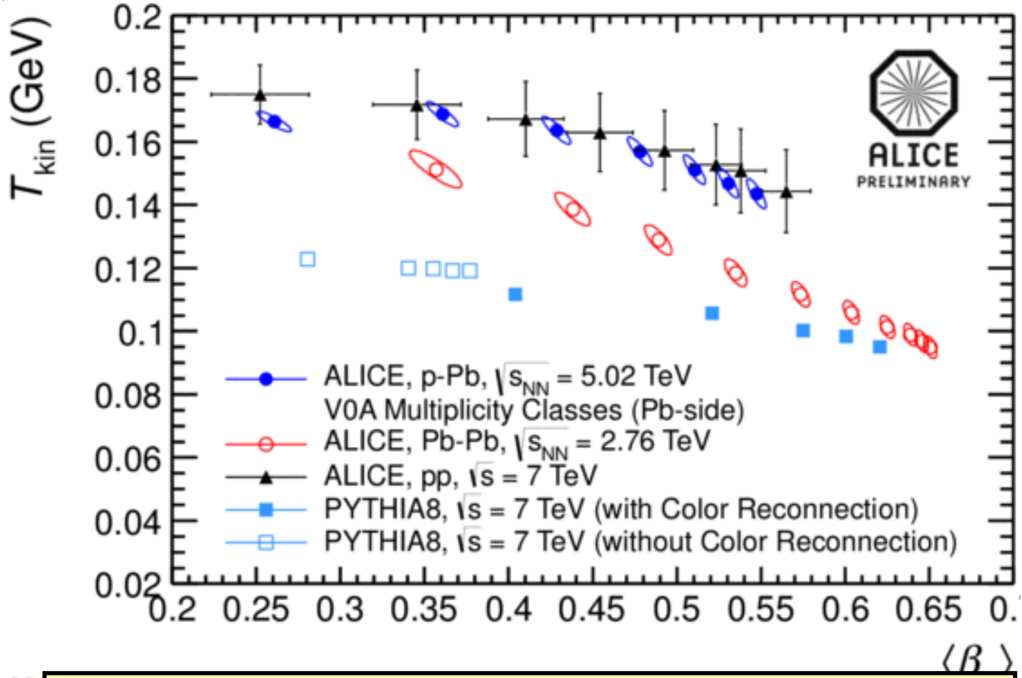
- ideal (BW) hydro ≈ ok < 1-2 GeV(p, K), > 3-4 GeV (p, Λ, ..) in both p_T and v_2
  - ⇨ deviations at high p_T: 'smooth decoupling ?'





Radial Flow in pPb





earlier 'decoupling'

$T_{kin} \approx T_{chem}$

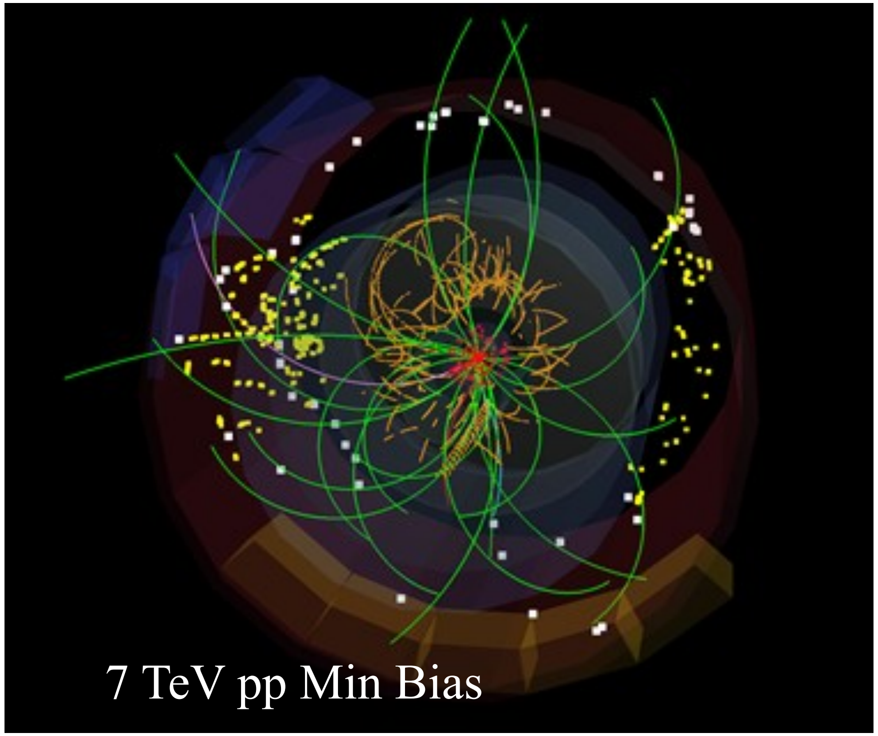
$\beta, T_{kin}(\pi, K, p) \approx \beta, T_{kin}(\Xi, \Omega)$

(**d, 3He**) in PbPb compatible with **flow**
d in pPb compatible with **coalescence**

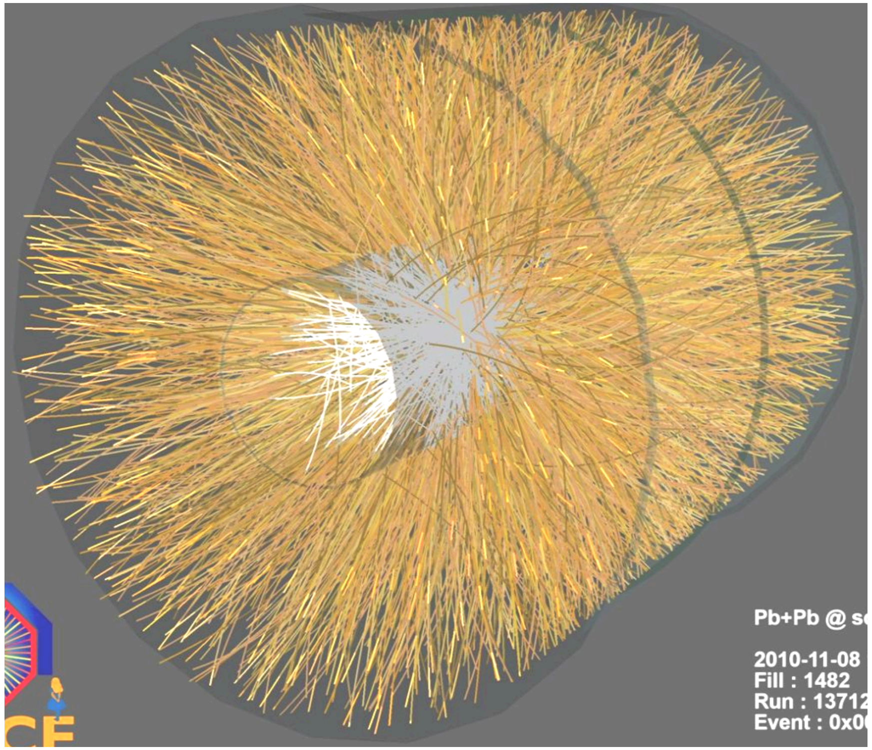
no (or little) hadronic rescattering ?

clear & direct view on the sQGP ??

What about small dilute (pp) ?



? =



- **> 2013: central pA ~ peripheral AA**

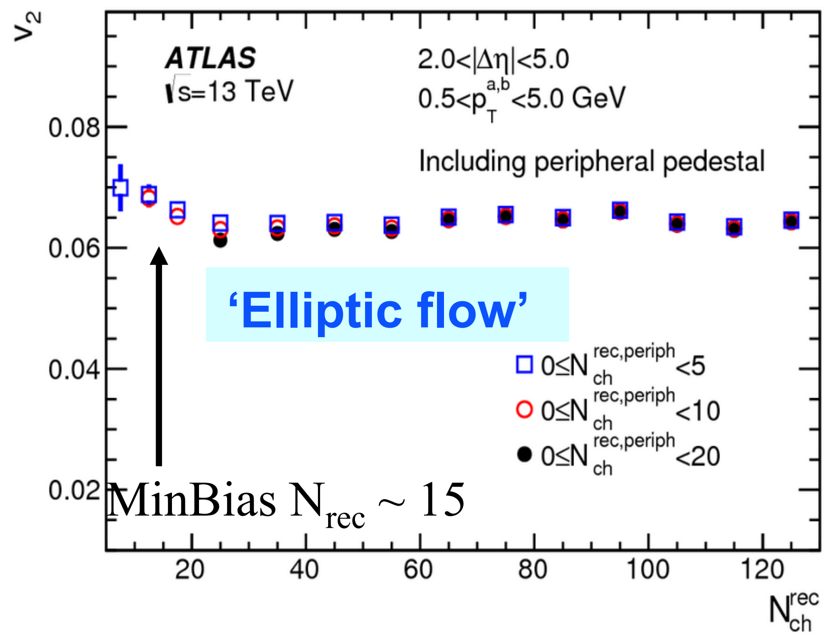
  (largely) accepted & assimilated : small droplet of sQGP (-like) stuff

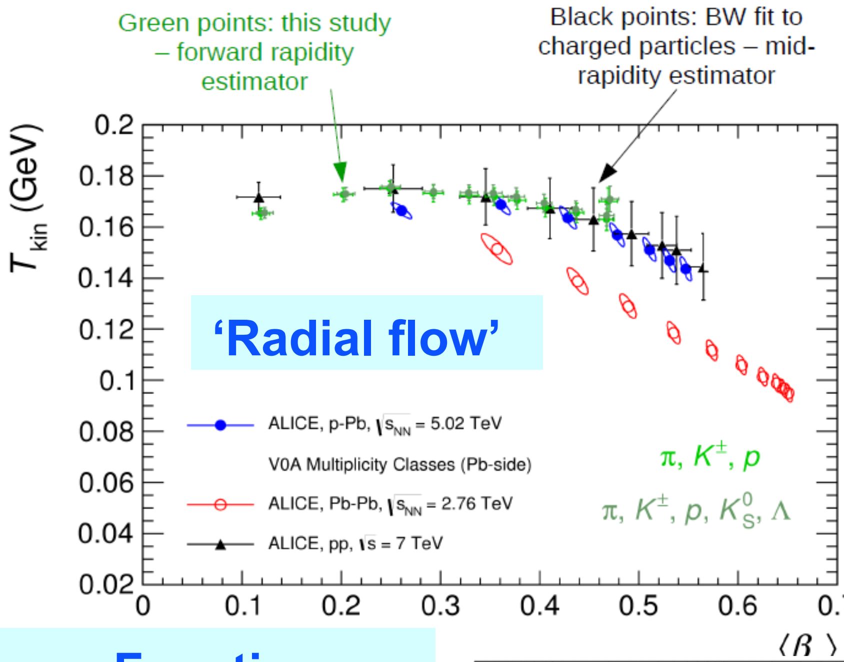
  conformal invariance, hydro & thermo 'at its limits'

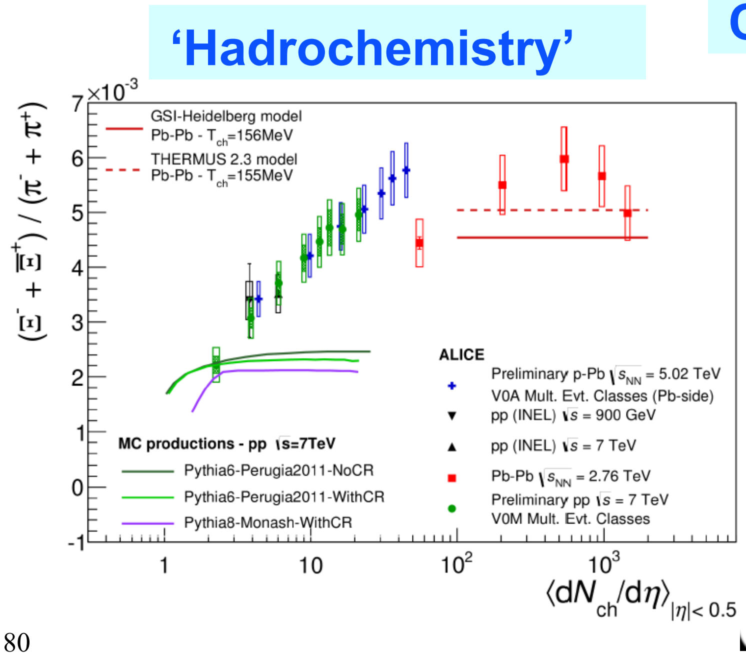
- **> QM 2015: no end in sight ?**

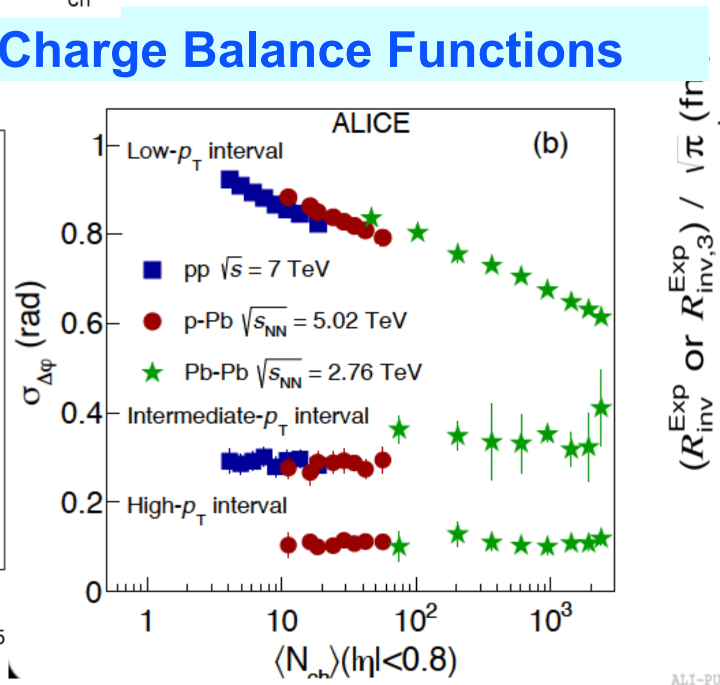
  Thermo & hydro in MinBias pp ??

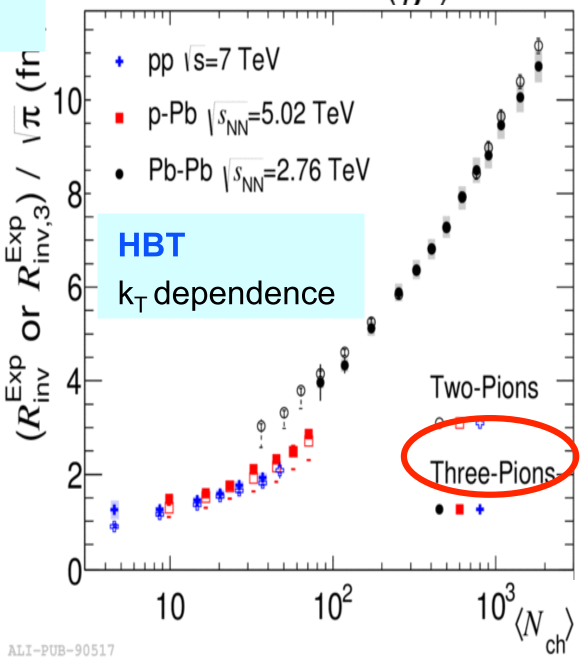
Continuous & smooth down to dN/dy ~ 0 (pp)



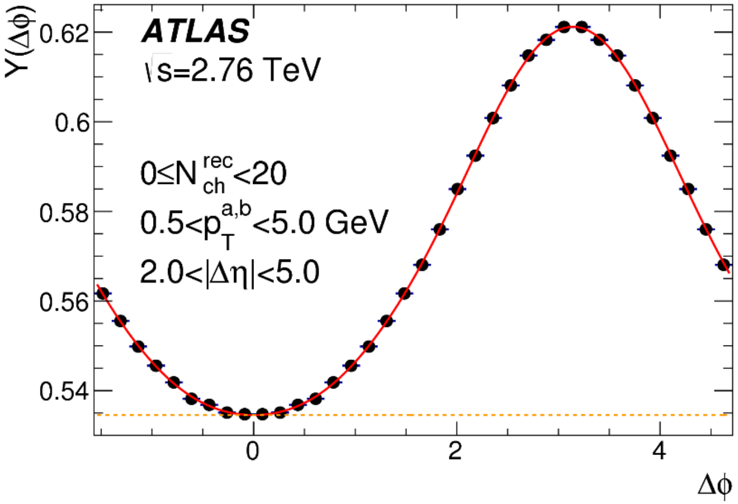


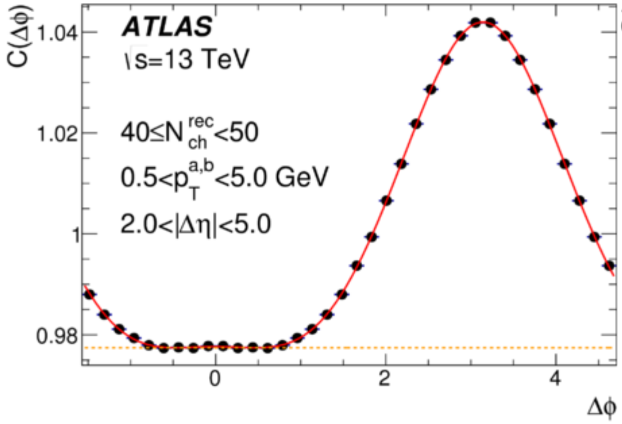


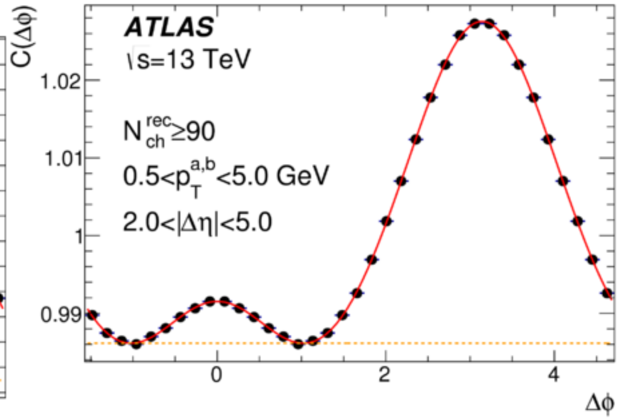


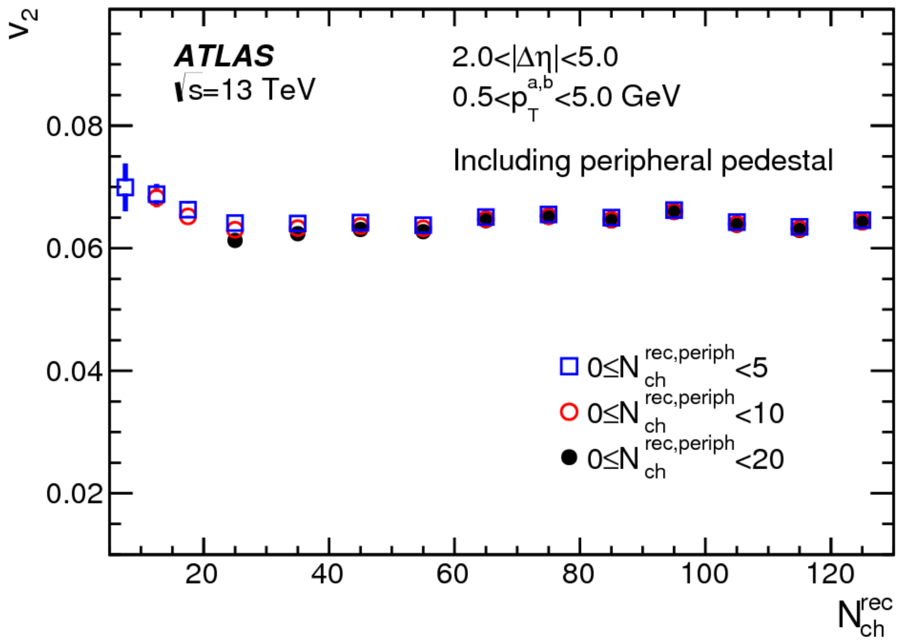


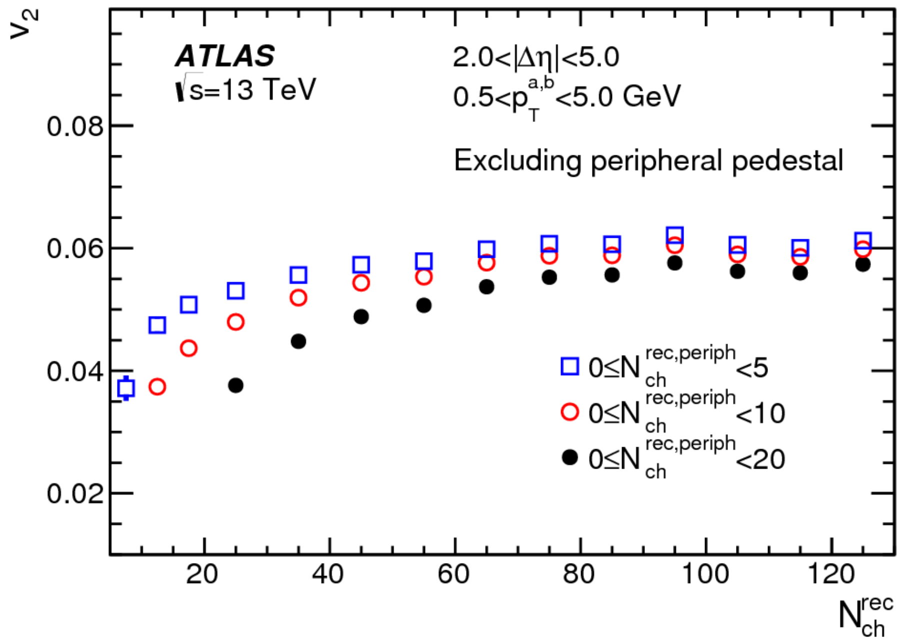
Need to know what to look for…







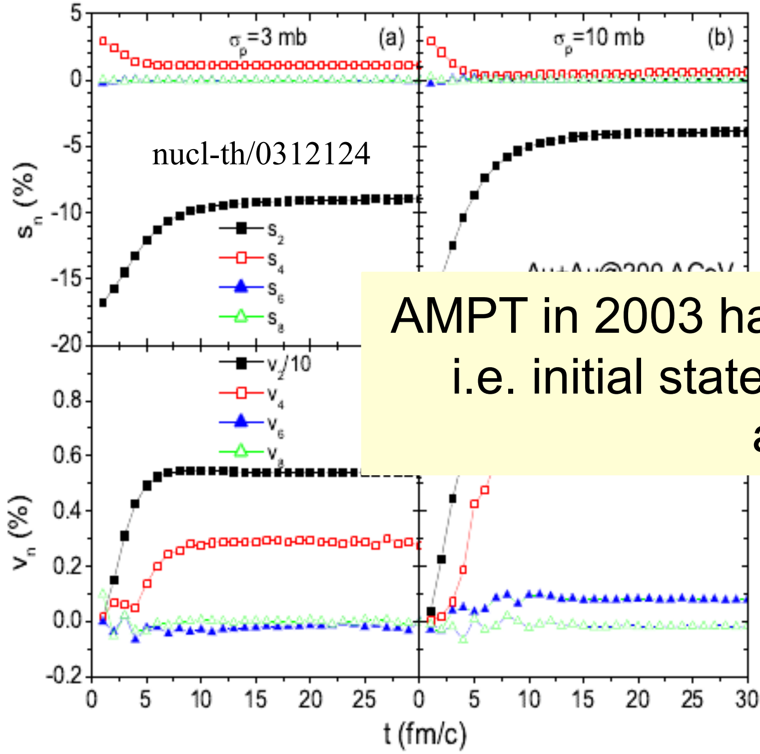


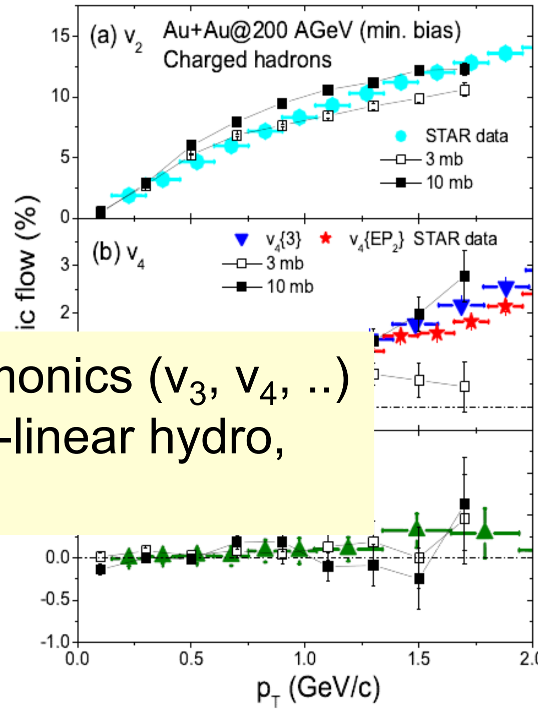


Immorally successful AMPT

A Multi-Phase Transport

anisotropic flows of odd orders vanish as a result of the symmetry $\phi \leftrightarrow \phi + \pi$. The anisotropic flows generally de-





AMPT in 2003 had correct higher harmonics (v_3, v_4, ..)
i.e. initial state fluctuations and non-linear hydro,
and went unnoticed !

FIG. 1: (Color online) Time evolutions of spatial anisotropic coefficients s_n and anisotropic flows v_n of partons in midrapidity from Au + Au collisions at $\sqrt{s} = 200$ AGeV and $b = 8$ fm for parton scattering cross sections $\sigma_p = 3$ mb (left panels) and $\sigma_p = 10$ mb (right panels).

FIG. 2: (Color online) Anisotropic flows v_2 (a), v_4 (b), and v_6 (c) of charged hadrons in the pseudorapidity range $|\eta| < 1.2$ from minimum bias Au + Au collisions at $\sqrt{s} = 200$ AGeV as functions of transverse momentum p_T for parton scattering cross sections $\sigma_p = 3$ (open squares) and 10 (solid squares) mb. The experimental data are from STAR Collaboration [14]

The experimental data indicate that there is a scaling relation among hadron anisotropic flows, i.e., $v_n(p_T) \sim v_2^{n/2}(p_T)$ [14]. It has been shown by Kolb [35] that such scaling relation follows naturally from a naive quark coalescence model [36] that only allows quarks with equal

The resulting hadron scaling factors of 3/4 and 1/2 are, however, smaller than the one extracted from measured anisotropic flows of charged hadrons. Since the naive quark coalescence model does not allow hadron formation from quarks with different momenta as in more realistic quark coalescence models [26, 27, 28?], it is not expected to give a quantitative description of the experimental observation. Such effects are, nevertheless, included in the AMPT model, which have been shown in Fig. 2 to reproduce the measured hadron anisotropic flows.

ft

Almost as good as hydro

http://arxiv.org/abs/1210.0512

v_2

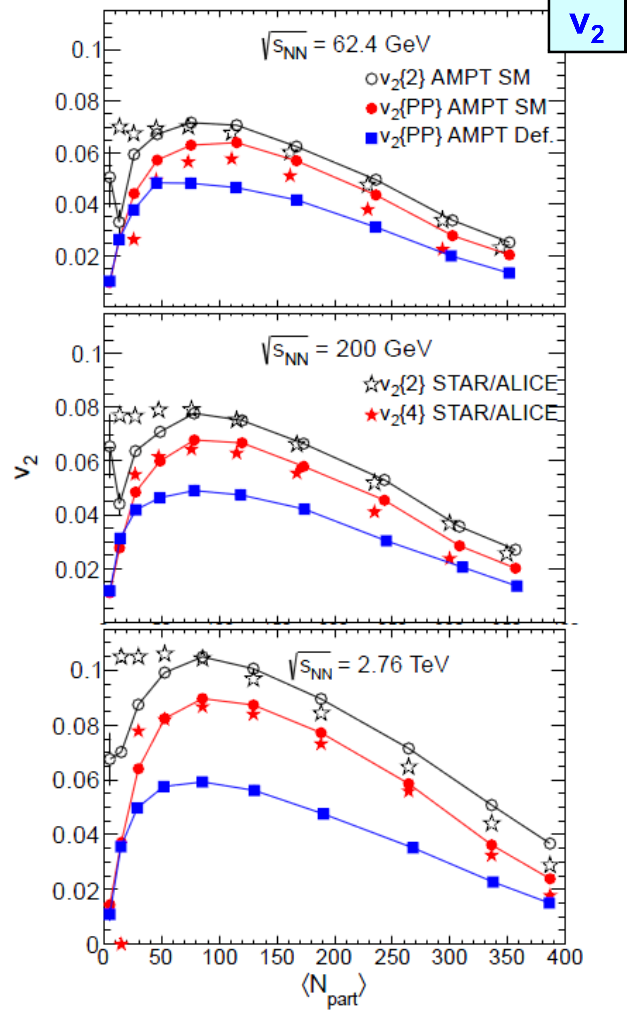


Figure 2: Elliptic flow data from AMPT and experiments at $\sqrt{s_{NN}}$=62.4 GeV, 200 GeV [STAR], and 2.76 TeV [ALICE]. For the String Melting calculation we show v_2 calculated relative to the participant plane $v_2\{PP\}$ defined by the positions of the nucleons and using the two particle cumulant $v_2\{2\} = \langle \cos 2(\phi_i - \phi_j) \rangle$. Experimental results are shown for the two-particle $v_2\{2\}$ and four-particle $v_2\{4\}$ cumulants.

mode mixing in EP correlations

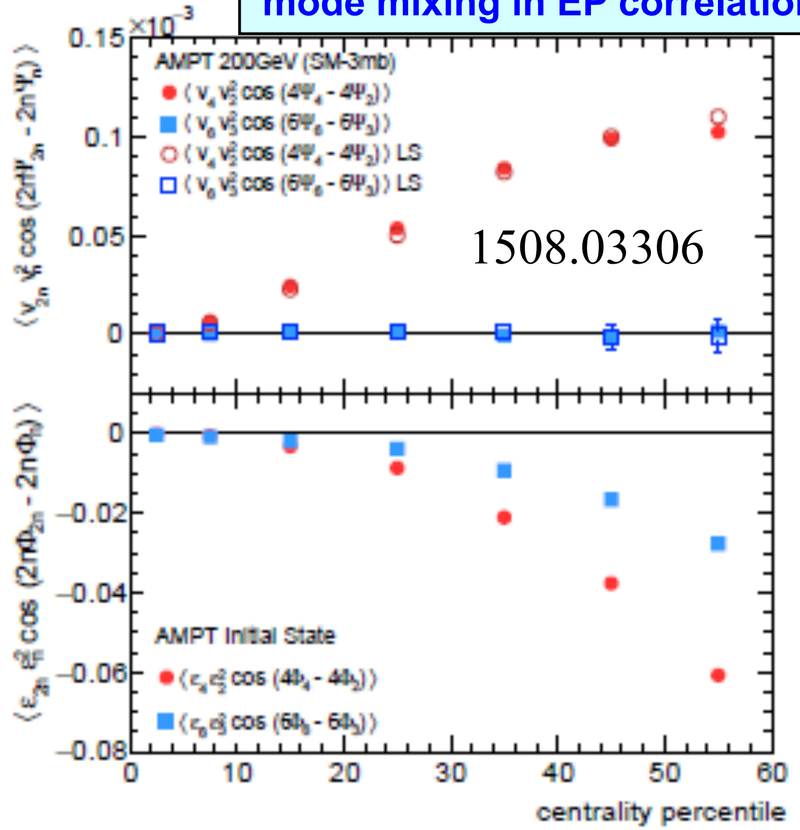


FIG. 7: (Color online) Centrality dependence of the final state QC{3}(top) and the 2-plane correlations in the initial state (bottom) in Au+Au collisions at 200 GeV by AMPT String-Melting.

4 (bottom). The negative initial (Φ_4, Φ_2) correlation and positive final (Ψ_4, Ψ_2) correlation observed in the AMPT model are in qualitative agreement with viscous hydrodynamic calculations [17]. There is a clear sign change of the 4th-order and 2nd-order plane correlation during the collision system evolution, both in the transport model and in the hydrodynamic calculations [17]. On the other

No problem with small systems

http://arxiv.org/abs/1404.4129

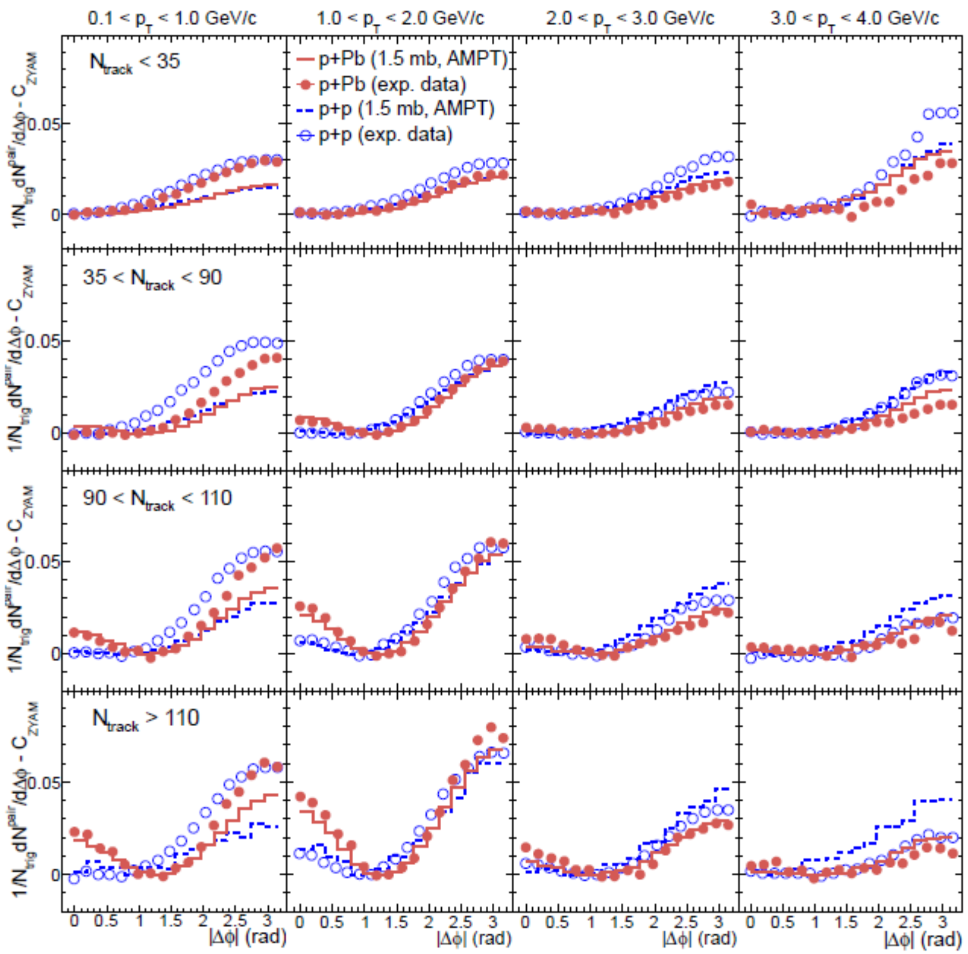


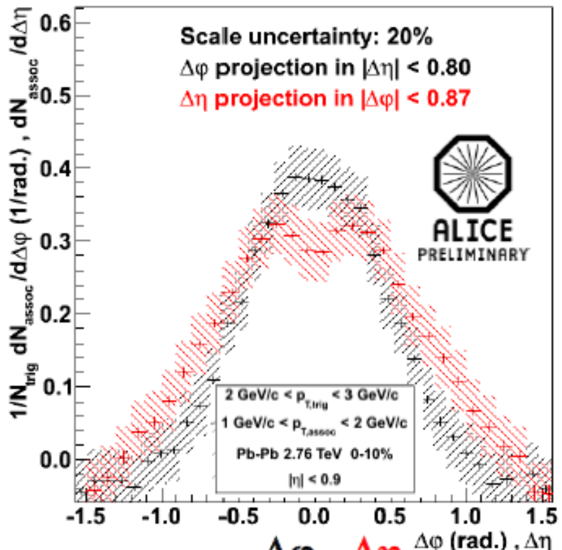
Figure 4: Distribution of pairs in p+p collisions at $\sqrt{s}$ = 7 TeV and p+Pb collisions at $\sqrt{s}$ = 5.02 TeV as a function of the relative azimuthal angle $\Delta\phi$ averaged over $2 < |\Delta\eta| < 4$ in different p_T and N_{track} bins. Our results (solid and dashed curves) based on the AMPT model (with string melting, σ = 1.5 mb) are compared to the CMS data (full and open circles).

Double humped near side peak

Departure from Gaussian

- The lowest p_T bin shows a structure with a flat top in $\Delta\eta$
- This feature is reproduced by AMPT

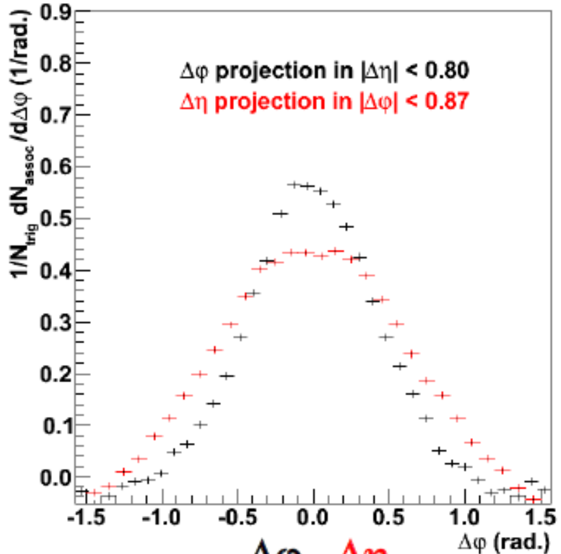
Data



Δφ , Δη

0-10%
$2 < p_{T,t} < 3$ GeV/c
$1 < p_{T,a} < 2$ GeV/c

AMPT



Δφ , Δη

- Qualitative and quantitative agreement of peak shapes with AMPT compatible with hypothesis of interplay of jets with the flowing bulk

What makes AMPT work ?

- Dynamics is very simple, probably oversimplified

  (‘Micky Mouse billiard balls’ with thousands of parameters)

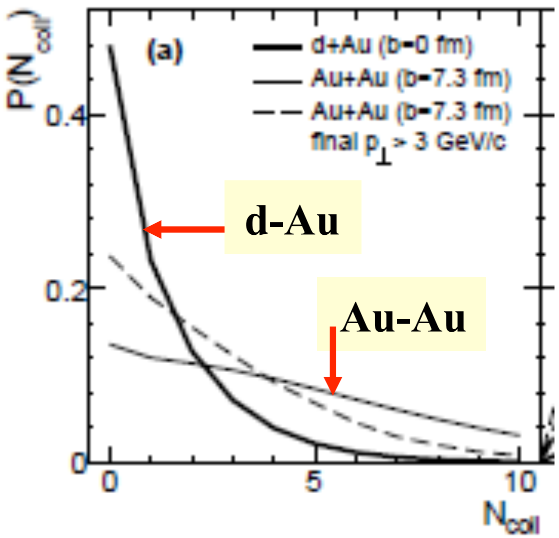
  ⇨ however, the hydrodynamics seems correct !

  ✪ what counts is ‘lots of interacting stuff’ (string melting + few mb σ)

- Common wisdom: AMPT = kinetic transport underlying hydro

  ⇨ and as such smoothly extrapolates to dilute & small systems with large K

- ‘**Anisotropic parton escape i**



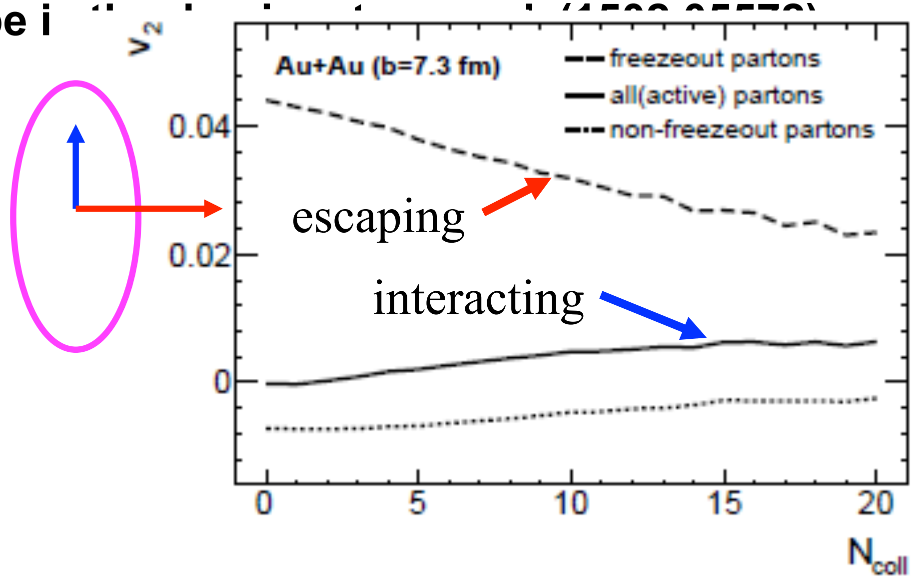


FIG. 2: Parton v_2 in Au+Au collisions as a function of the number of collisions N_{coll} that a parton has suffered. The solid curve is the v_2 of all(active) partons after suffering N_{coll} collisions, the dashed curve freezeout partons, and the dotted curve non-freezeout partons.

Information is in the ‘non-interacting’ rays !

$<N_{col}>$ = 5 (1) in AuAu(dAu)

Pressure or Density tomography ?

- sQGP Hydro model:
  - ⇨ IS density homogeneities => pressure gradients => momentum anisotropy => spatial anisotropy dN/dϕ
  - ⇨ requires strong FSI, dense & large systems (small #K), low visc. 'ideal liquid'

- sMOG X-ray model:

sMOG=Mist Of Gray stuff

  - ⇨ IS density homogeneities => direct image by scattering
  - ⇨ requires some FSI
    - ✪ no problem with small or dilute systems (dilute = small contrast)

- Open questions for X-ray model:
  - ⇨ is a) and b) actually really different ?
  - ⇨ radial flow ? mass dependence of v_2 (1601.05390)? HBT Space-time correlation ?
    - ✪ 'free streaming + late Cooper-Frye' = radial flow + HBT (1504.02529)

sQGP or sMOG:
Crucial question in our field, which (to my taste) is not sufficiently seriously discussed..

Questions from small & dilute systems

- Confront and 'explain' the size/density systematics
  - ⇨ **Factorize and separate** into different pp and AA physics (eg CR , hydro) ?
    - ✪ naturally & economically, without epicycles..
    - ✪ where to put pA ?
  - ⇨ **Incorporate** into the current thermo & hydro sQGP 'ideal liquid' picture ?
    - ✪ **extend** the 'dense matter' framework **down** to zero density ?
    - ✪ **extend** the 'dilute transport' framework up to central AA ? (AMPT like ?)
    - ✪ 'probabilistic' hydro (#coll/particle << 1) ? Ok for thermo (< 1 Omega/evt even in 4π at SPS)
  - ⇨ Require **paradigm shift** ?
    - ✪ different but unified view(model/interpretation, ..) of soft multi-particle QCD

Summary **Hypothesis:**

The physics underlying soft 'collectivity' signals is the same in AA, pA, and pp:

It is a generic property of all strongly interacting many-body (≥2?) systems

- **MANY similar/identical observations**(@ similar N_{ch}), **no inconsistency** (?), ..
  - ⇨ **1)** particle ratios (γ_s -> 1)
  - ⇨ **2)** p_T-spectra (radial flow),
  - ⇨ **3)** anisotropic flow: $v_n \sim \varepsilon_n$, $v_n(p, d, {}^3He)$, $v_n(b)$, $v_n(p_T)$, $v_2(LYZ)$, $v_n(PID)$
  - ⇨ **4)** HBT $r(N_{ch}, m_T)$

- **What is is the 'underlying dynamical physics' ?**
  - ⇨ **sQGP: thermo + hydro** dynamics ('at the edge') ?
  - ⇨ **sMOG**: strongly **interacting FS matter** with **density gradients** (1502.05572)
  - ⇨ **CGC+CR+.:** weakly int. **dense IS matter** + some conspiracies (also in AA !)
  - ⇨ ???

Light (anti-)(hyper-)nuclei

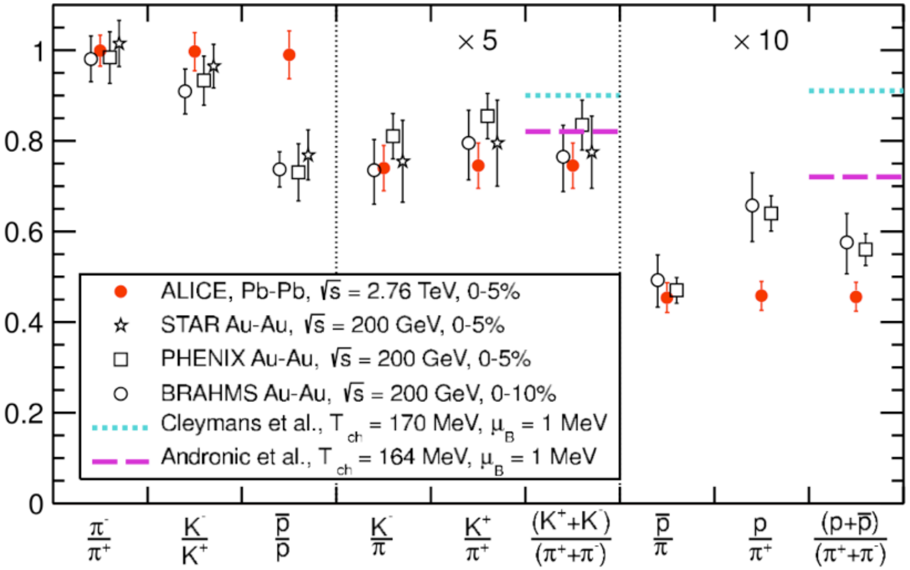
From A.Kalweit
talk at CERN

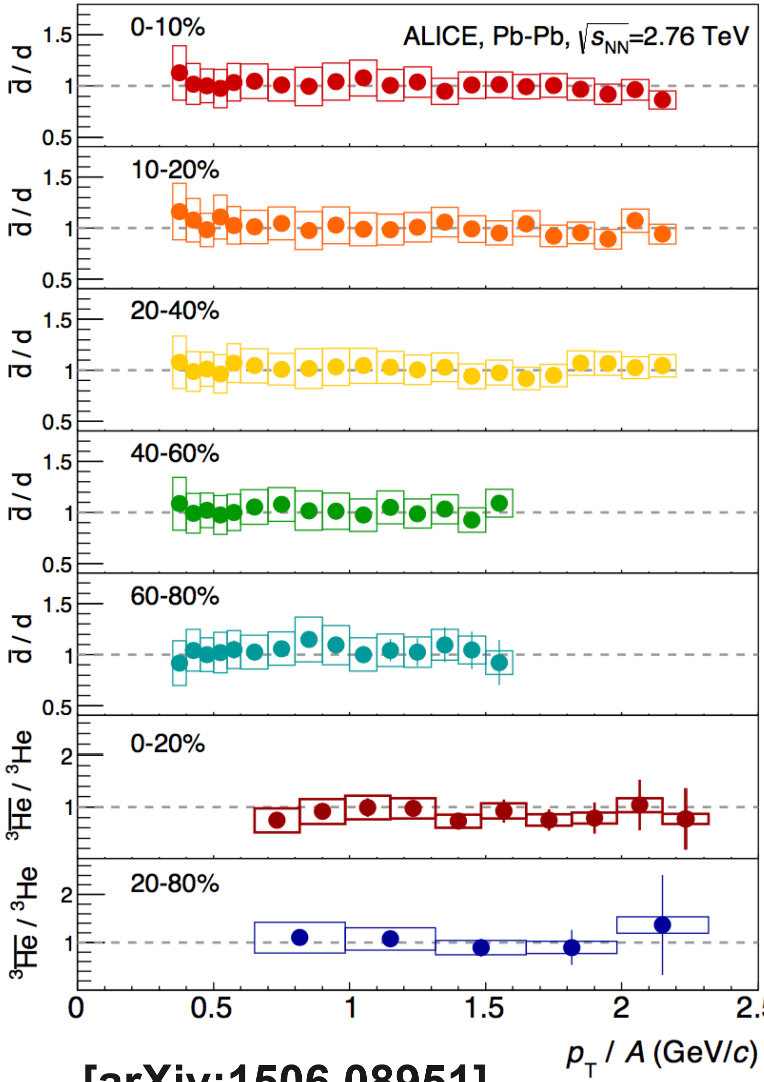
Matter and anti-matter

Particle production in pp, p-Pb, and Pb-Pb collisions shows an equal abundance of matter and anti-matter in the central rapidity region: $\mu_B \approx 1$ MeV.

$$\frac{n_{\bar{p}}}{n_p} = e^{-(2\mu_B)/T} \qquad \frac{n_{^3\overline{He}}}{n_{^3He}} = e^{-(6\mu_B)/T}$$

[PRL 109, 252301 (2012)]



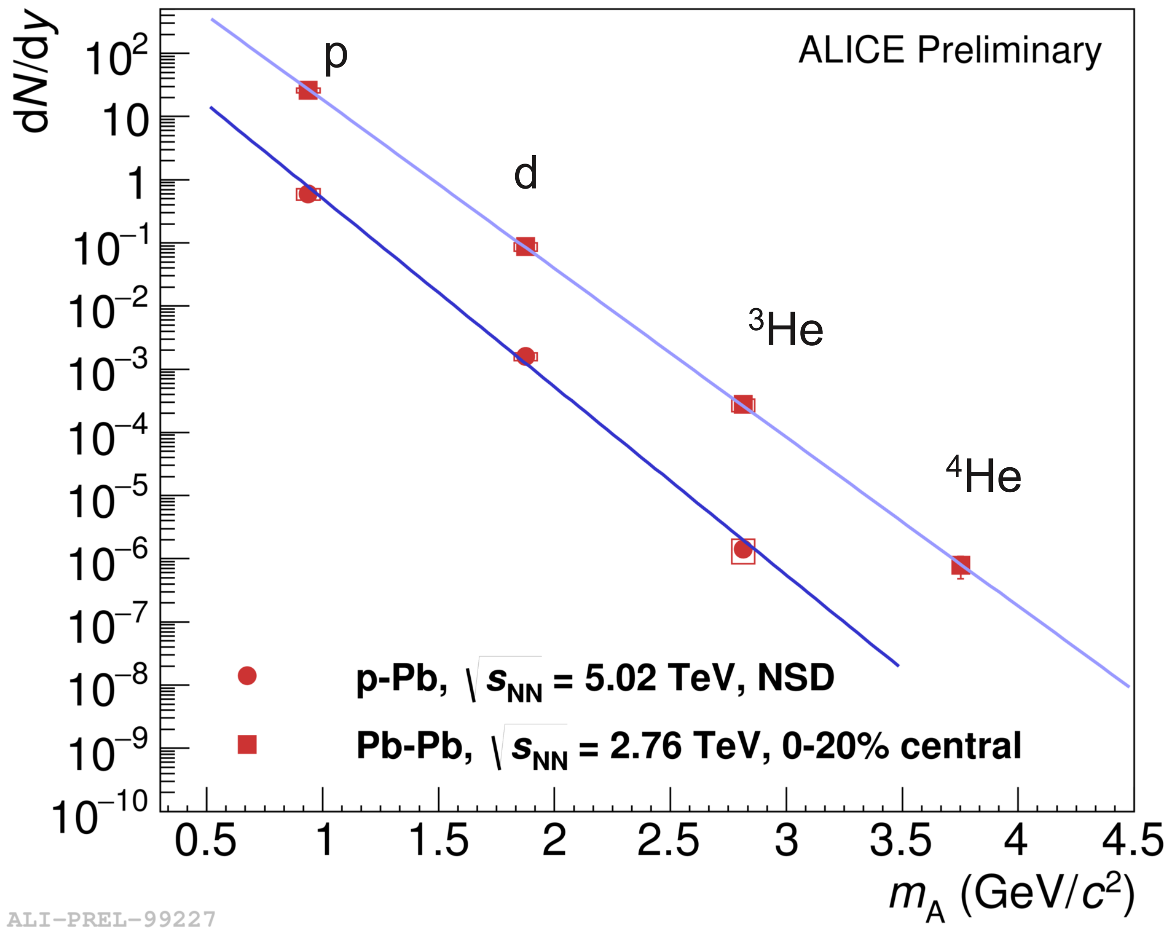


[arXiv:1506.08951]

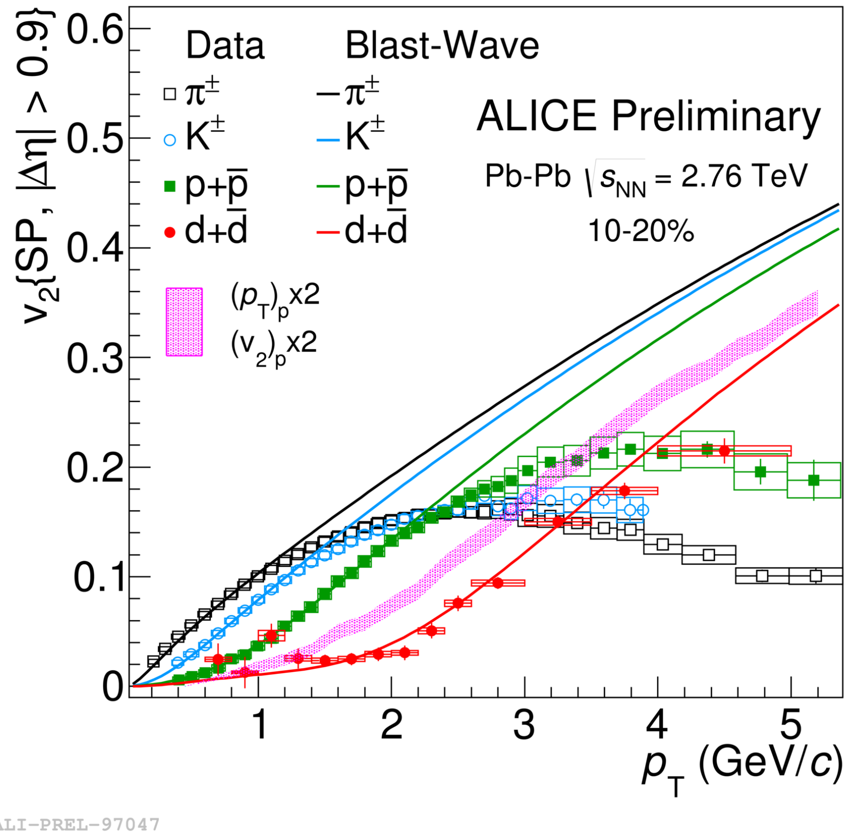
Mass ordering

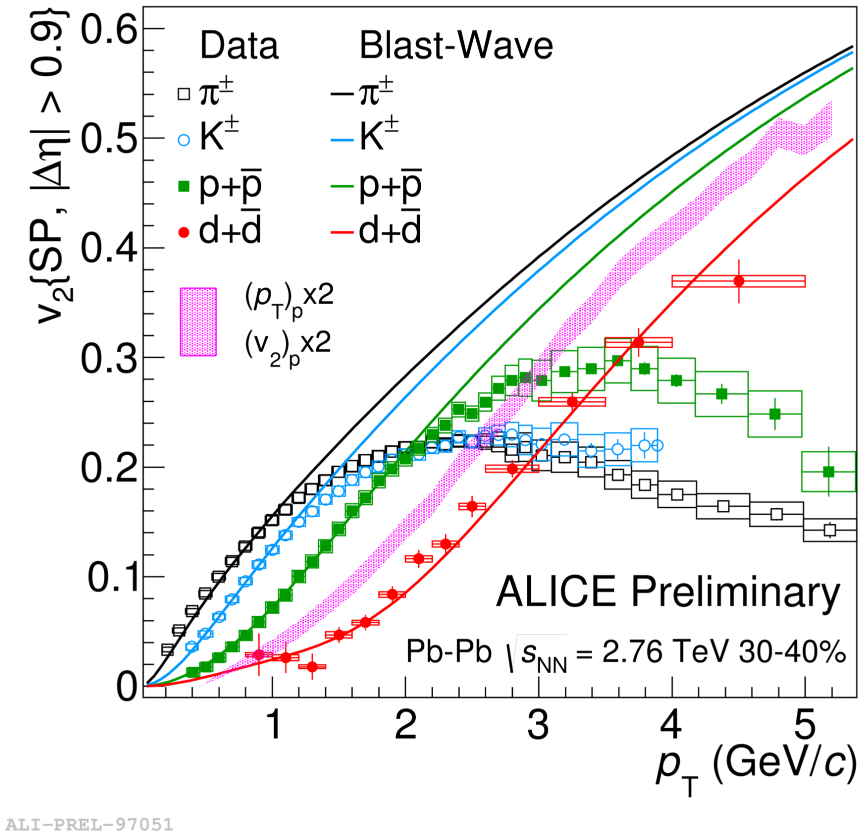
For each additional nucleon the production yield decreases by a factor of about 300!

Such a behaviour can be directly derived from the thermal model which predicts in first order
dN/dy ~ exp(-m/T)



Elliptic flow of (anti-)deuterons

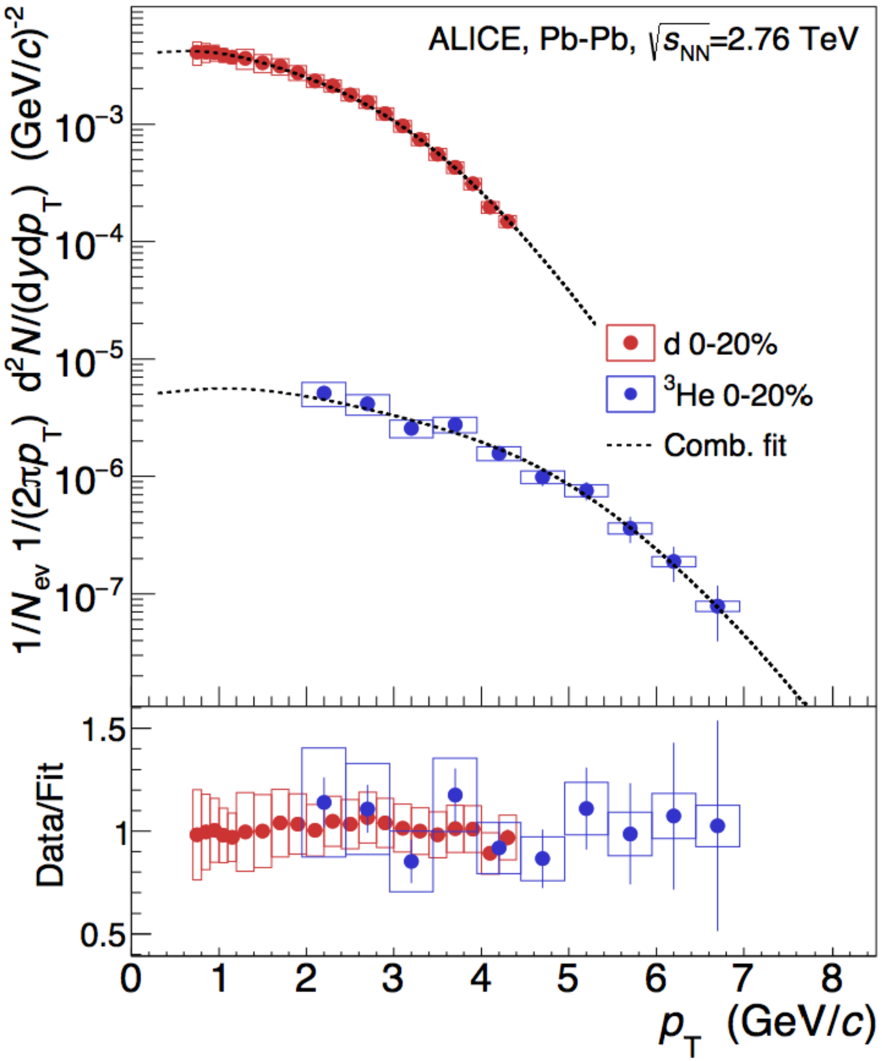




Deuteron v_2 is well described by the blast-wave fit which describes π, K, p.

A simple coalescence approach estimated by the proton v_2 ($=2v_2(2p_T)$) does not describe the data.

Radial flow of (anti-)d and (anti-)^{3}He



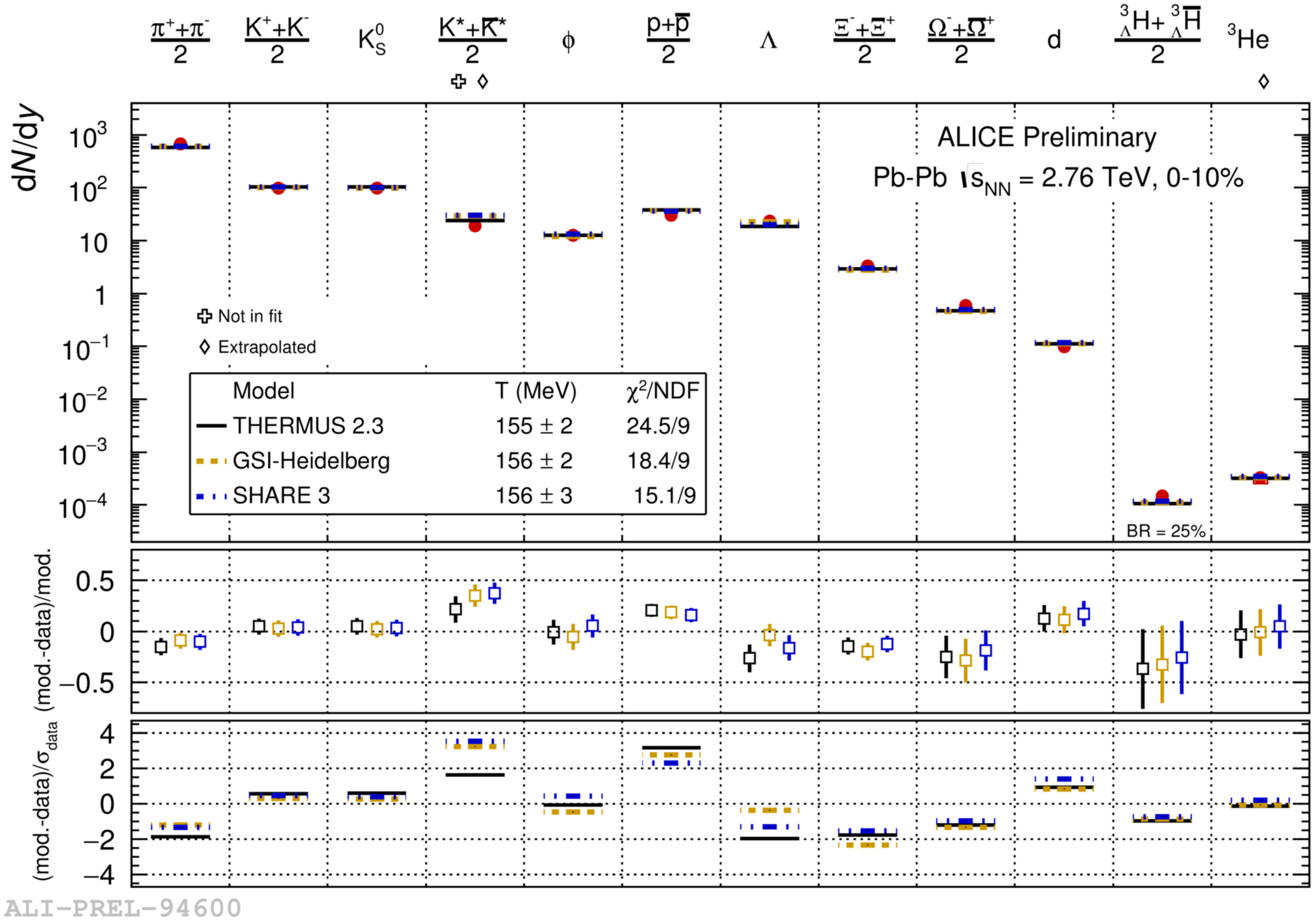
[arXiv:1506.08951]

Also the p_T-spectra of deuteron and ^{3}He are well described by the blast-wave fit which describes to π, K, p.

Also the p_T-integrated particle yields are described by the same thermal fit which describes all other light flavour hadrons.

This behaviour is unique to heavy-ion collisions! In pp collisions, the d/p-ratio is a factor 2.2 lower and thus inconsistent with thermal model estimates.

Chemical equilibrium



Particle yields of light flavor hadrons are described over 7 orders of magnitude within 20% (except K^{*0}) with a common chemical freeze-out temperature of $T_{ch} \approx 156$ MeV (prediction from RHIC extrapolation was ≈ 164 MeV).

Largest deviations observed for **protons** (incomplete hadron spectrum, baryon annihilation in hadronic phase,..?) and for **K^{*0}**.

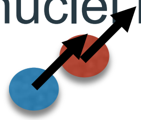
Despite their low binding energy (E_B = 2.2 MeV << T_C = 156 MeV), light (anti)nuclei behave like all other **non-composite** particles! → Thermal model yield and shape of the spectrum according to radial flow.

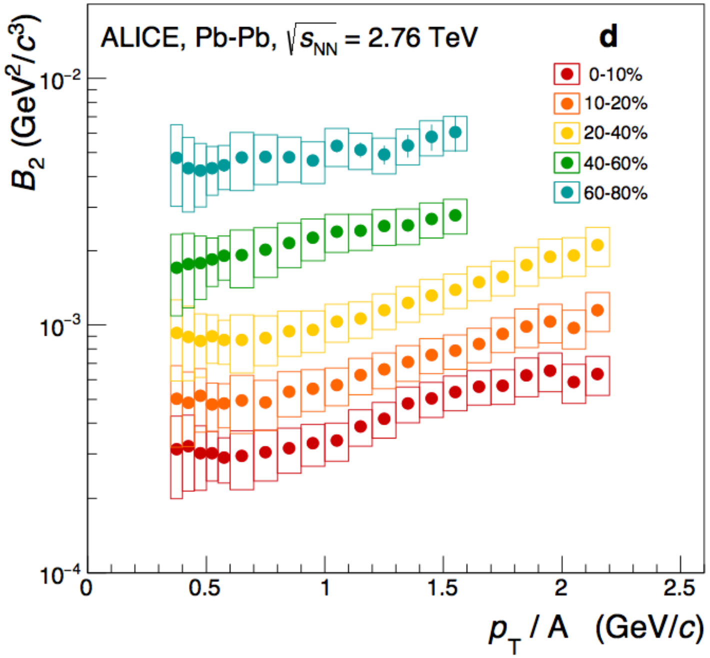
[Wheaton et al, Comput.Phys.Commun, 180 84]
[Petran et al, arXiv:1310.5108]
[Andronic et al, PLB 673 142]

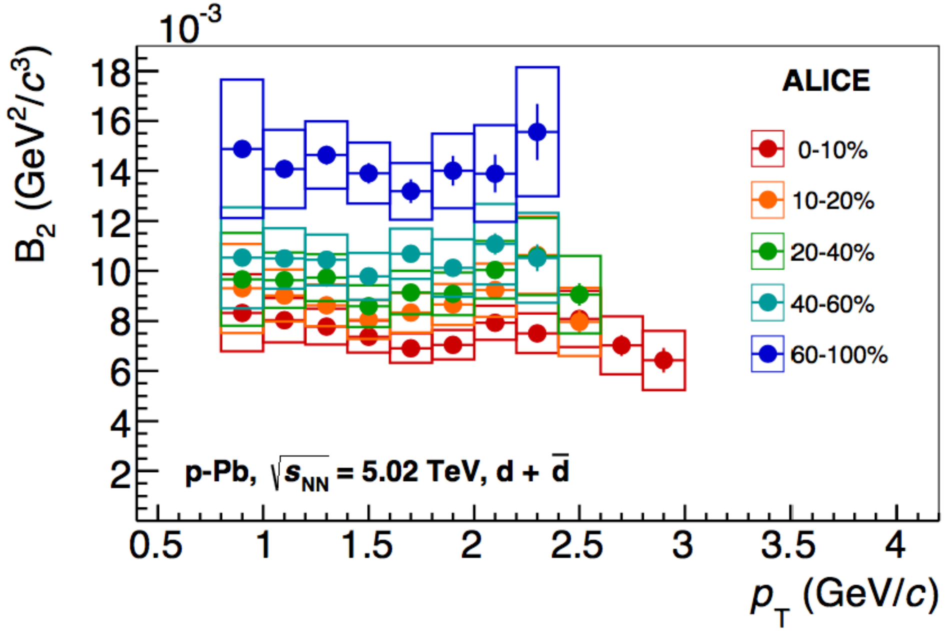
Possible scenarios

Coalescence (1)

- Production of nuclei by coalescence of nucleons which are close in phase space:







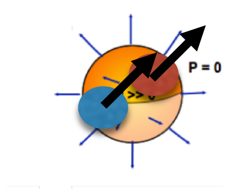
$$B_A = \frac{E_A \frac{d^3 N_A}{dp_A^3}}{\left(E_p \frac{d^3 N_p}{dp_p^3}\right)^A}$$

B_2 is flat vs. p_T in p-Pb collisions and in peripheral Pb-Pb collisions.

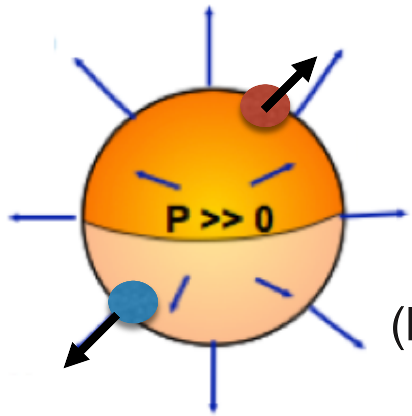
B_2 is strongly decreasing with centrality in Pb-Pb collisions. d/p ratio shows no significant dependence with centrality.
→ **physics beyond a *simple* coalescence model.**

Coalescence (2)

- As a matter of fact, the size of the emitting volume has to be taken into account.



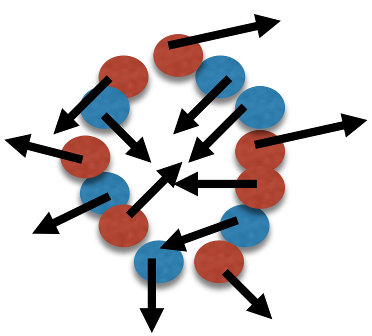
(small fireball)

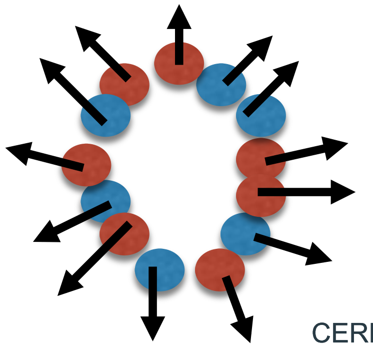


(large fireball)

- The strong decrease of B_2 with centrality in Pb-Pb collisions can be naturally explained as an increase in the emitting volume: Particle densities are relevant and not absolute multiplicities.
- The increase with transverse momentum can be explained by space-momentum correlations which correspond to the radial flow.

purely thermal source: position and momentum of particles completely uncorrelated





collective radial expansion: momentum and position are partially linked

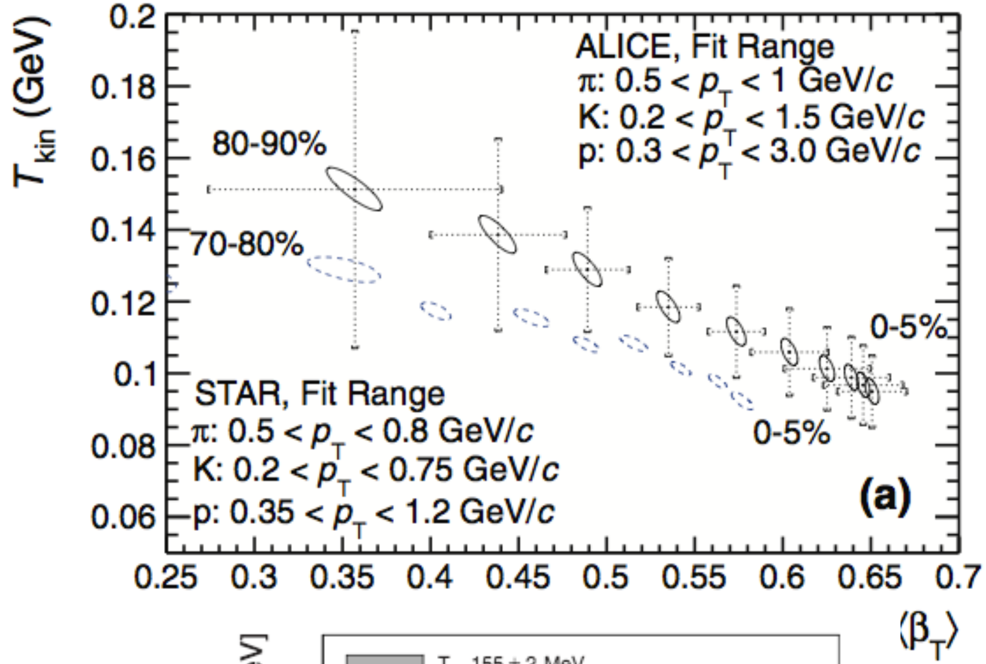
[A. Polleri *et al.*, PLB 419 (1998) 19-24]

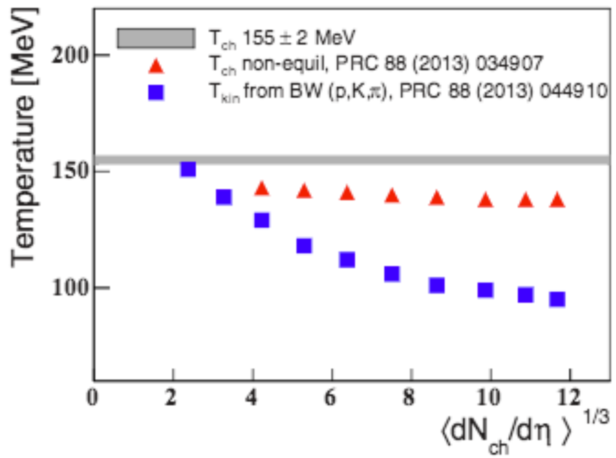
Possible scenarios

- Scenario A: there is no hadronic phase after the chemical freeze-out.
  - Then (anti-)nuclei are not destroyed by re-scattering.
  - This explains why their yield agrees with the thermal model.
  - They show the same flow pattern as all other non-composite particles. → A very simple solution!
  - Problem: there are other indications for a hadronic phase.
- Scenario B: (anti-)nuclei are formed after the hadronic phase by final-state coalescence.
  - Then it does not matter what happens at chemical freeze-out and during the hadronic phase. The agreement of the yields with the thermal model for d, ^{3}He, ^{4}He, and hyper-triton would be a coincidence.
  - Problem 1: The agreement with the thermal model is not explained.
  - Problem 2: We are still missing a full space-time coalescence calculation based on a hydro model which describes the data.
- Another idea: fix entropy per baryon after chemical freeze-out (works at low energies…)

Is there a hadronic phase?

- Most often, it is argued that the kinetic freeze-out temperature is lower than the chemical freeze-out temperature.
- But this is model dependent and might be less striking than the survival of the deuteron in the fireball!
- The combined blast-wave fit proves that different particles have *identical* freeze-out conditions, but the kinetic freeze-out temperature is not constrained and depends strongly on the pion fit range.
- Fine, but what about re-scattering of resonances?





[PRC 93 (2016) 014911]

Resonances

Re-scattering of resonances: K* and ϕ (1)

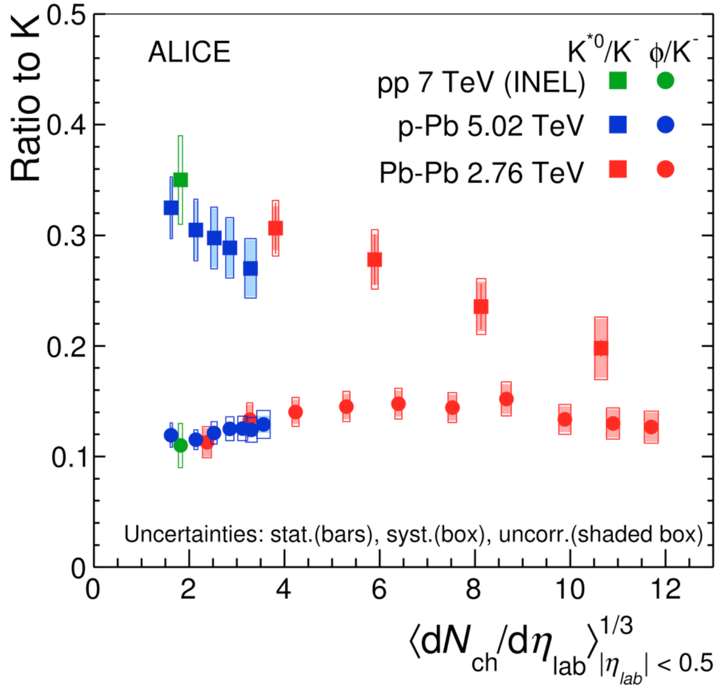
- For short-lived resonances, it is a priori not clear that they can be described in a thermal picture..

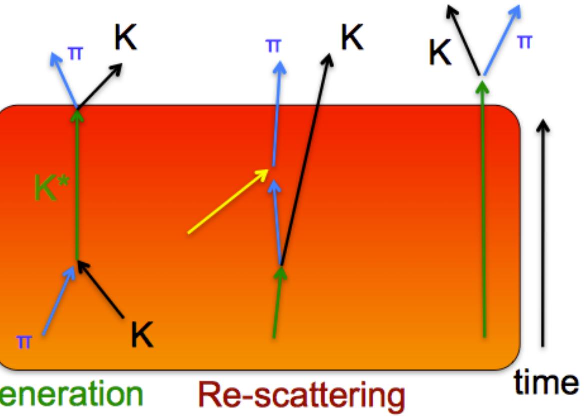
- A deviation of the K^{*0} yield can be explained by *hadronic re-scattering* of the daughter tracks if the decay happens in the medium.
  - The life-time of the particle is similar to the life-time of the fireball (≈ 10 fm/*c*):

    $K^* \rightarrow c\tau = 4.0$ fm

  - In contrast to the Φ-meson:

    $\phi \rightarrow c\tau = 45$ fm

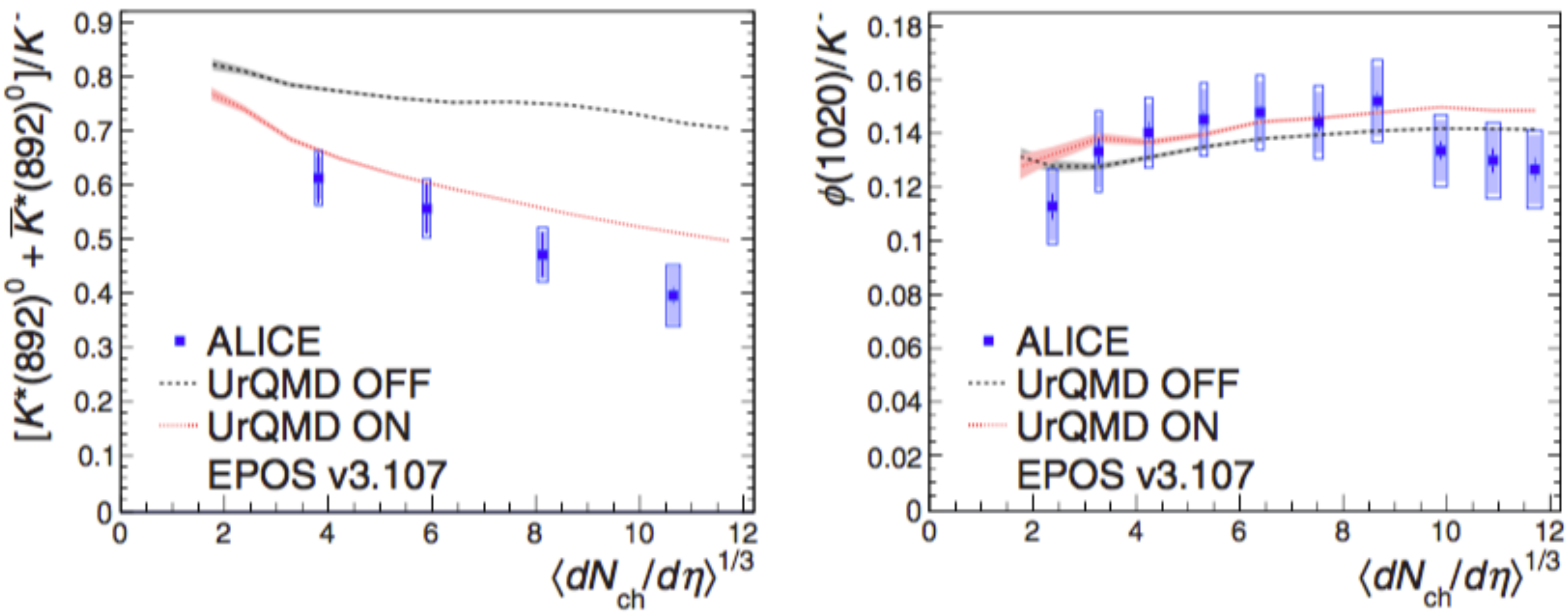




(Figure: M. Floris)

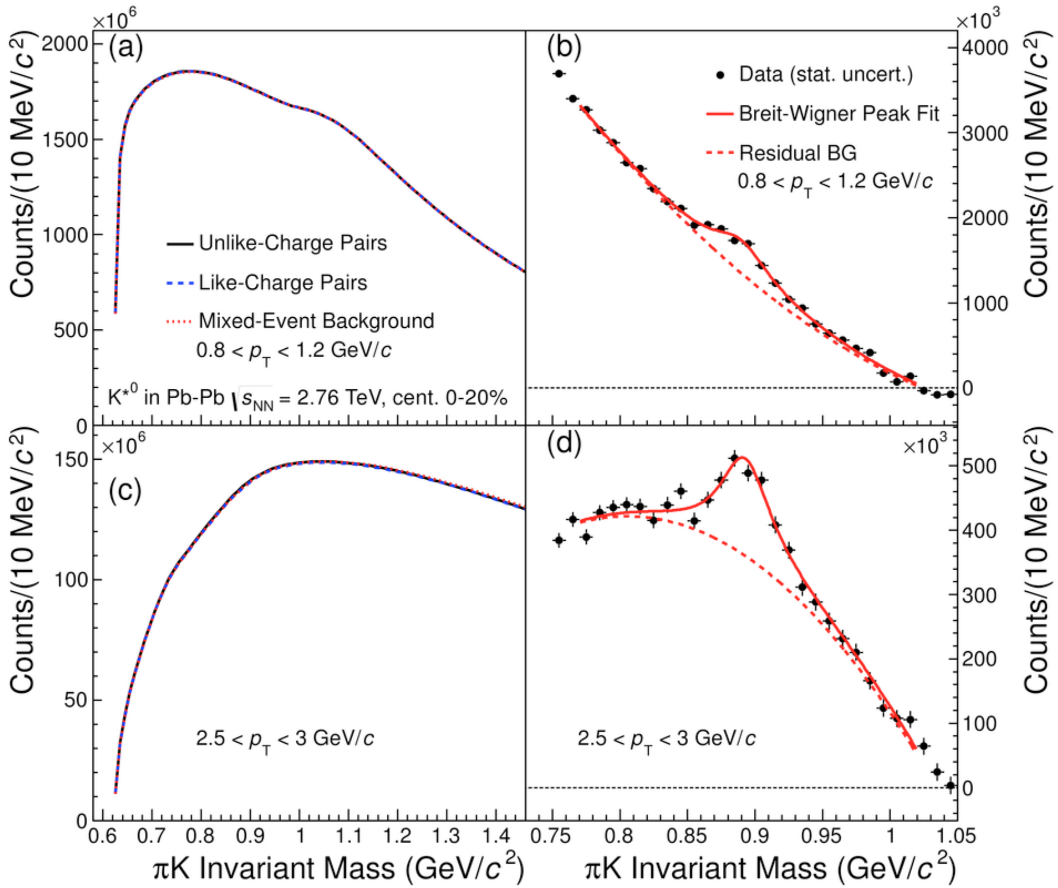
Re-scattering of resonances: K* and ϕ (2)

- The effect can be semi-quantitatively described by EPOS with an UrQMD afterburner for the hadronic phase.
- See details in: **[A. G. Knospe *et al.*, PRC 93 (2016) 014911]**.



Resonances and the hadronic phase

- However, there are some open questions…
  - Why don't we see a broadening of the line-shape of the resonances in the invariant mass spectrum? Are we not sensitive to this?
  - By how much does one need to deflect a daughter particle so that the resonance cannot be reconstructed anymore? N.B. the K* and *ρ* are relatively wide.
  - In EPOS+UrQMD a resonance is not reconstructed anymore independent of the deflection angle!



Summary and conclusions

- Results for light (anti-)(hyper-)nuclei production and for short-lived resonances seem to point in different directions:
  - nuclei: non-existence of a hadronic phase
  - resonances: existence of a dense and long lived hadronic phase.
- More data and more studies are needed in order to establish a scenario which seamlessly describes all observations.
- The physics of light flavour hadrons remains exciting even in the LHC era after Run 1 and we are looking forward to more interesting results from Run 2.

Summary

- LHC heavy-ion programme is obtaining a wealth of physics results from the first two LHC heavy-ion runs:
  - bulk, soft probes:
    - spectra and flow of identified particles, thermal photons
  - high-p_T probes:
    - jet quenching and fragmentation, particle-type dependent
  - heavy-flavour physics:
    - suppression and flow of D mesons, leptons, J/ψ
- Entering the precision measurement era – charmed era of the QGP
  - before LS2 (2018): p–Pb and Pb–Pb, higher energy and complete approved ALICE detector
- Long-term upgrade for high-luminosity LHC based on:
  - ambitious physics programme
  - clear detector upgrade plan for improved vertexing and tracking
  - high-rate capability of all subdetectors

Future

Future plans

Precision measurement of the QGP parameters at $\mu_b = 0$ to fully exploit scientific potential of the LHC – unique in:

- large cross sections for hard probes
- high initial temperature

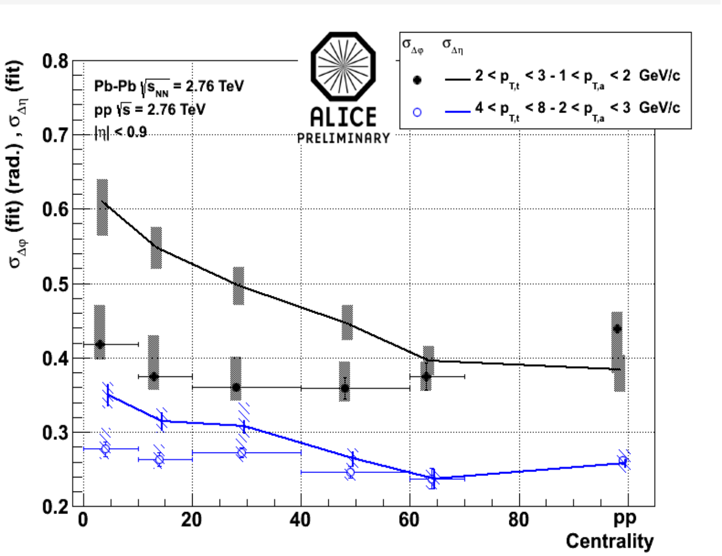
Main physics topics, uniquely accessible with the ALICE detector:

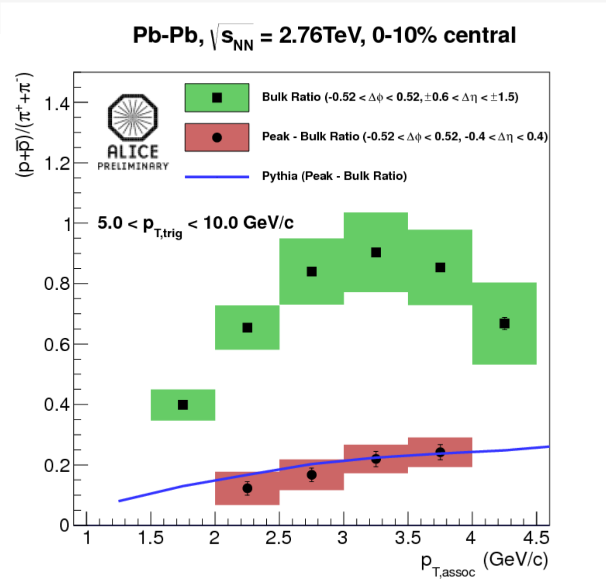
- measurement of heavy-flavour transport parameters
  - study of QGP properties via transport coefficients (η/s, $\hat{q}$)
- J/ψ , ψ', and χ_c states down to zero p_T in wide rapidity range
  - statistical hadronization versus dissociation/recombination
- measurement of low-mass and low-p_T di-leptons
  - study of chiral-symmetry restoration
  - space-time evolution and equation of state of the QGP

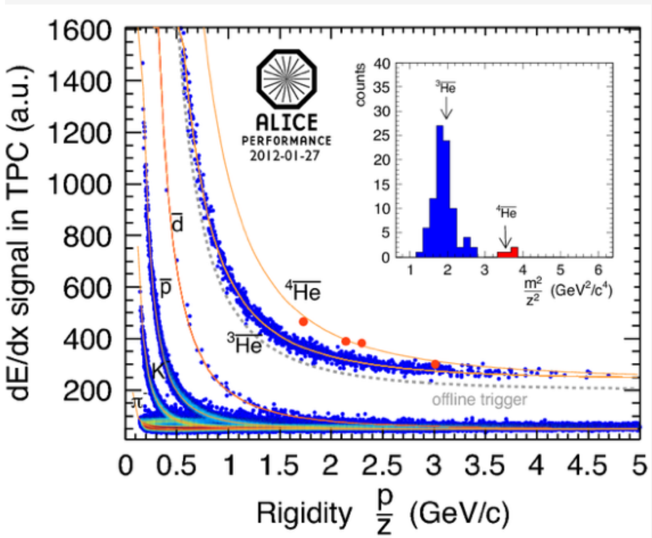
- for main physics programme factor > 100 increase in statistics (maximum readout with present ALICE ~ 500 Hz) for triggered probes increase in statistics by factor > 10

… and more

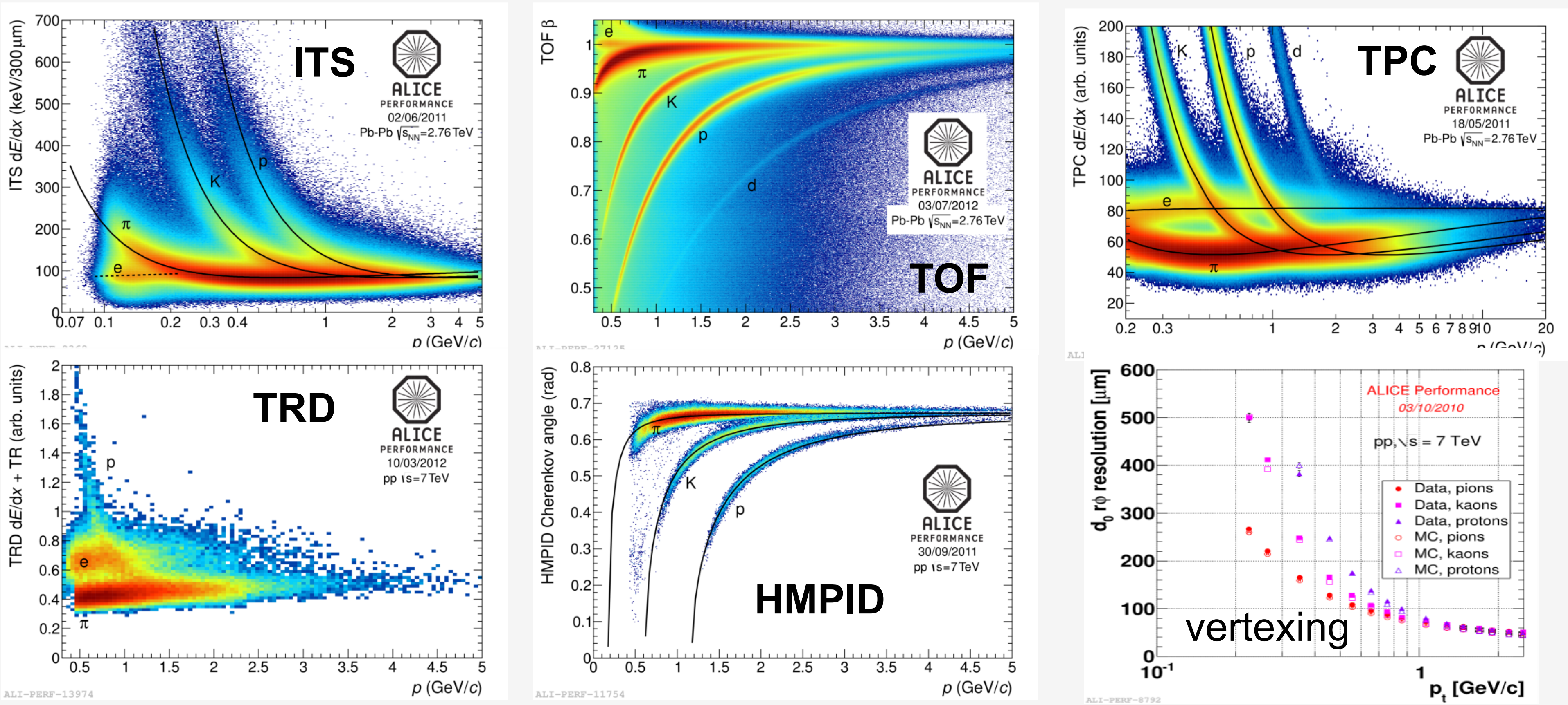
- **Jet quenching and fragmentation**
  - jet energy recuperation at very low p_T
  - heavy-flavour tagged jets, gluon vs. quark induced jets
  - heavy-flavour produced in fragmentation
  - particle identified fragmentation functions
- **Heavy nuclear states**
  - high statistics mass-4 and -5 (anti-)hypernuclei
  - search for H-dibaryon, Λn bound state, etc.







ALICE Upgrade – build on demonstrated strengths…



- particle identification (practically all known techniques)
- extremely low-mass tracker ~ 10% of X_0
- excellent vertexing capability
- efficient low-momentum tracking – down to ~ 100 MeV/*c*

ALICE Upgrade strategy

Luminosity upgrade – target 50 kHz minimum bias rate for Pb–Pb
run ALICE at this high rate, inspecting all events
corresponds to Pb–Pb luminosity 6×10^{27} $cm^{-2}s^{-1}$ – achievable at LHC

Upgrade heavy-ion programme already after LS2 (2018)
collect more than 10 nb^{-1} of integrated luminosity
– increase by factor 10 compared to initially approved programme
implies running with heavy ions few years after LS3 (until 2026-7)

- Improved vertexing and tracking at low p_T
- Preserve particle-identification capability
- High-luminosity operation without dead-time

- New, smaller radius, beam pipe
- New inner tracker (ITS) (performance and rate upgrade)
- High-rate upgrade for the readout of the TPC, TRD, TOF, CALs, DAQ-HLT, Muon-Arm and Trigger detectors

Additional proposal to be submitted: Muon Forward Tracker (MFT)
postponed: Forward Calorimeter (FoCal)