Soft physics in ALICE

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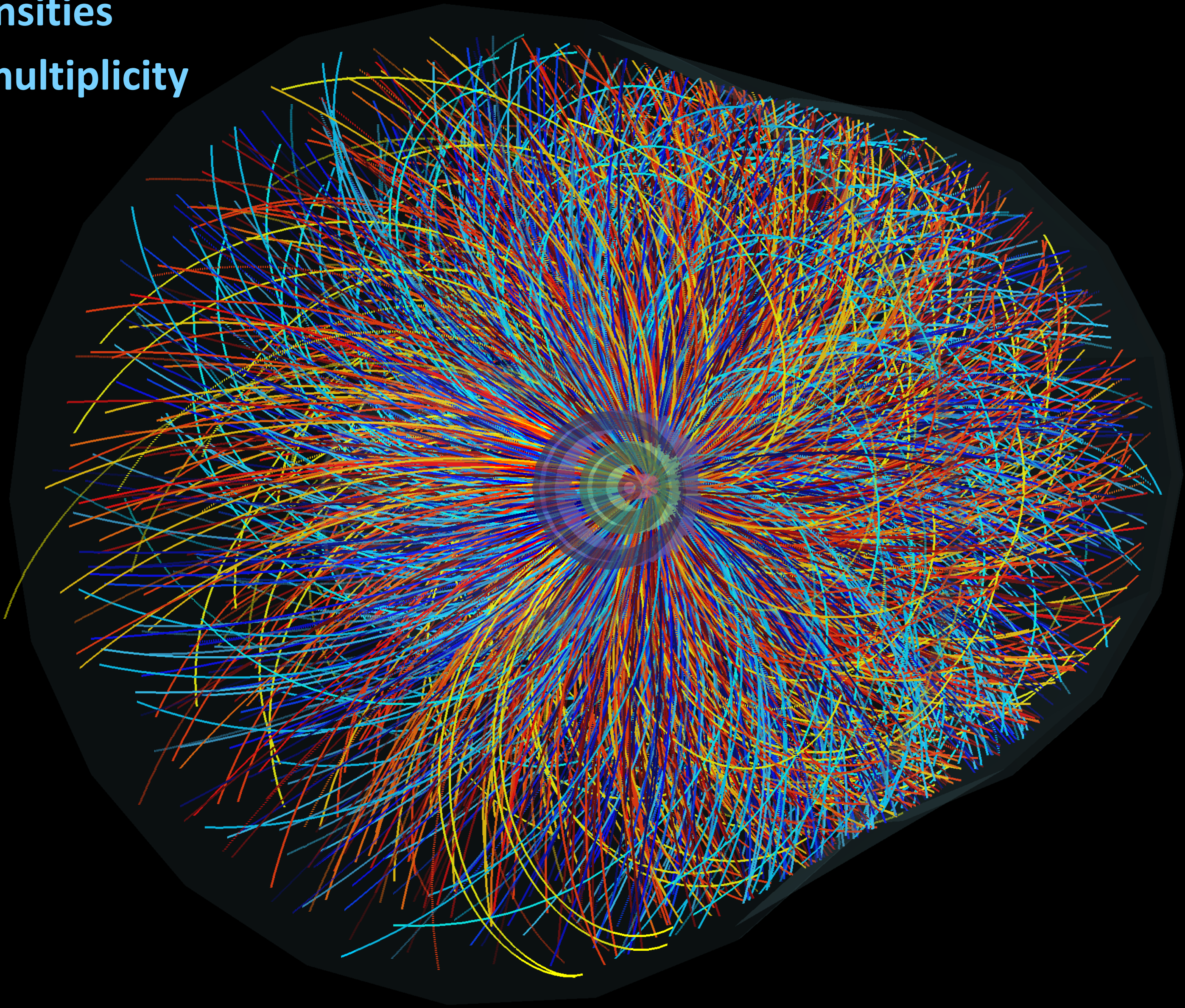
LHC Heavy-Ion running

- Two heavy-ion runs at the LHC so far:
  - in 2010 – commissioning and the first data taking
  - in 2011 – already above nominal instant luminosity!
- p–Pb run moved to beginning of 2013
  - jan-mar 2013 - 30 nb^{-1}
  - (for rare-probe statistics equivalent to ~0.15 nb^{-1} of Pb–Pb)
- Followed in 2013 by Long Shutdown–1 (LS1)

year	system	energy $\sqrt{s_{NN}}$ TeV	integrated luminosity
2010	Pb – Pb	2.76	~ 10 μb^{-1}
2011	Pb – Pb	2.76	~ 0.1 nb^{-1}
2013	p – Pb	5.02	~ 30 nb^{-1}

Pb-Pb collisions in ALICE

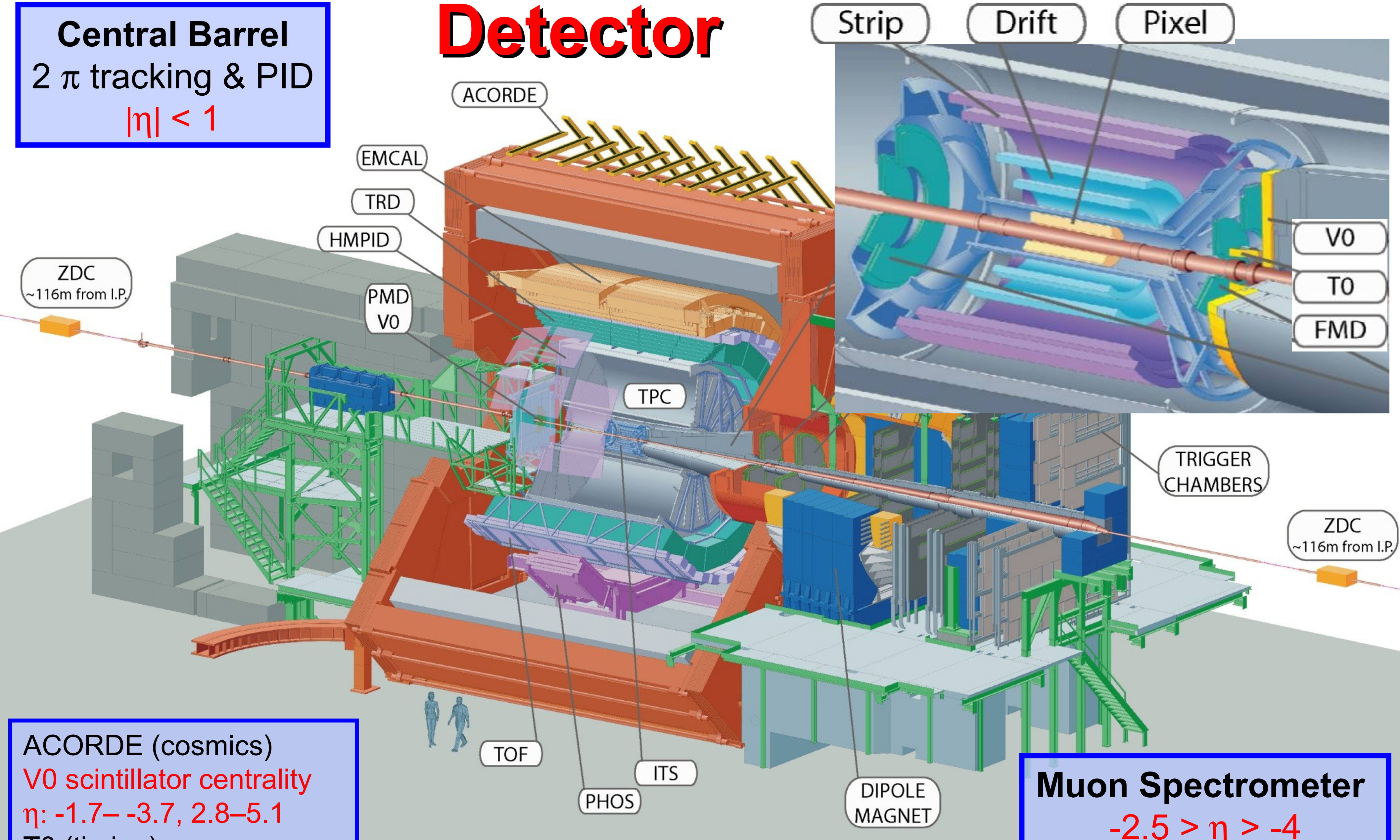
Study strongly interacting matter under extreme conditions
of temperature and energy densities
in events of extreme particle multiplicity



Fully characterize the events
Challenge for the experiment

Detector

Central Barrel
2 π tracking & PID
$|\eta| < 1$



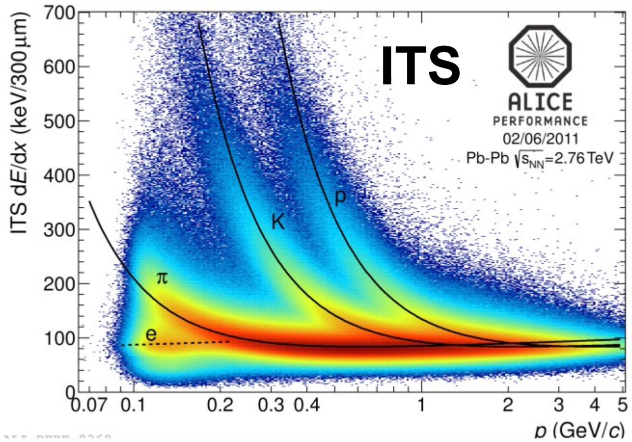
ACORDE (cosmics)
V0 scintillator centrality
η: -1.7– -3.7, 2.8–5.1
T0 (timing)
ZDC (centrality)
FMD (N_{ch} $-3.4<\eta<5$)
PMD (N_{γ}, N_{ch})

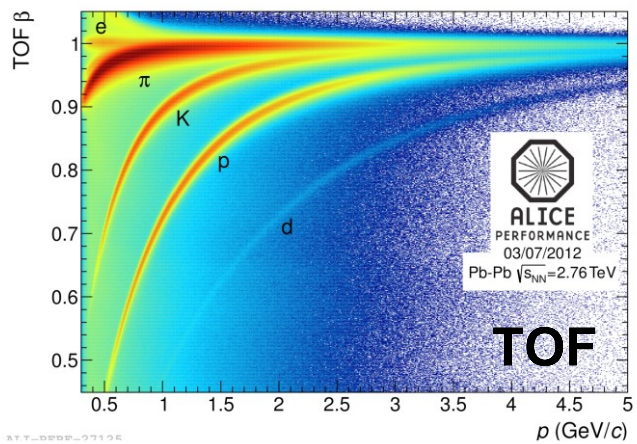
Muon Spectrometer
$-2.5 > \eta > -4$

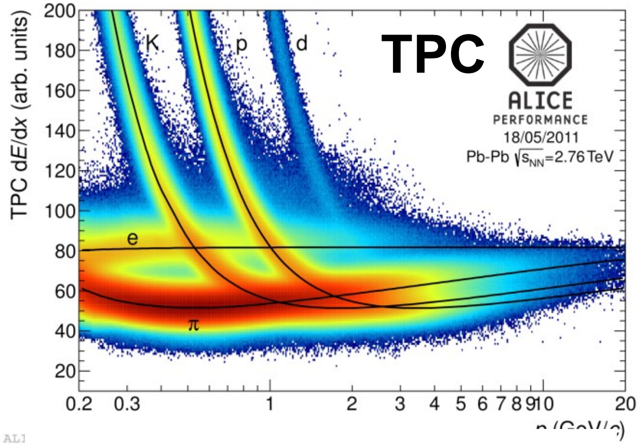
Detector:
Length: 26 meters
Height: 16 meters
Weight: 10,000 tons

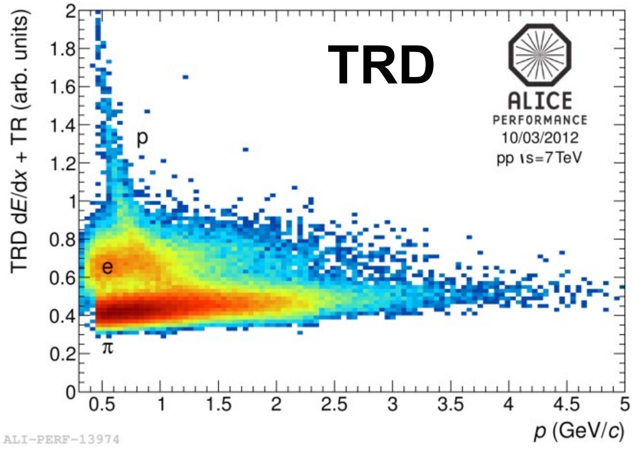
Collaboration:
> 1000 Members
> 100 Institutes
> 30 countries

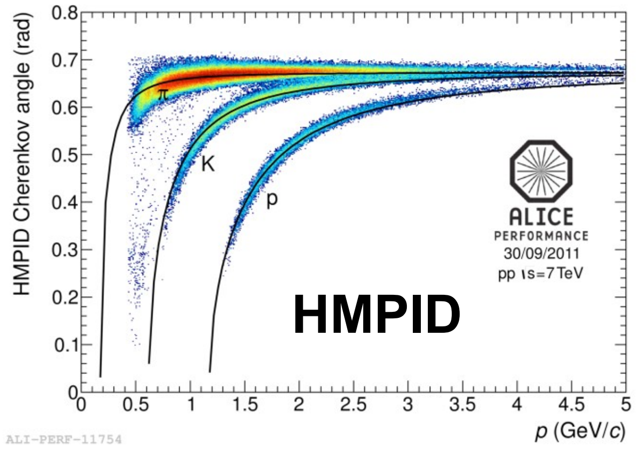
ALICE – dedicated heavy-ion experiment at the LHC

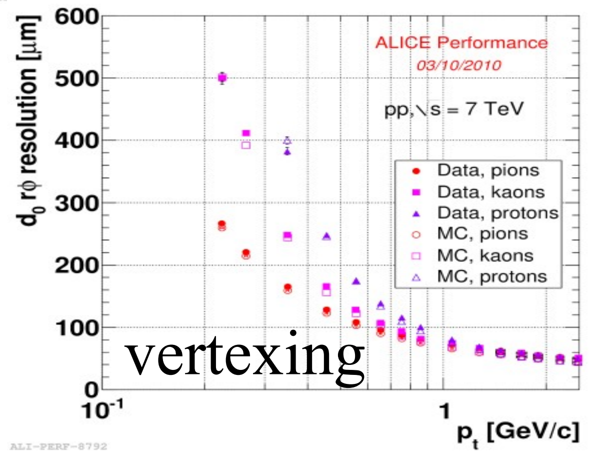








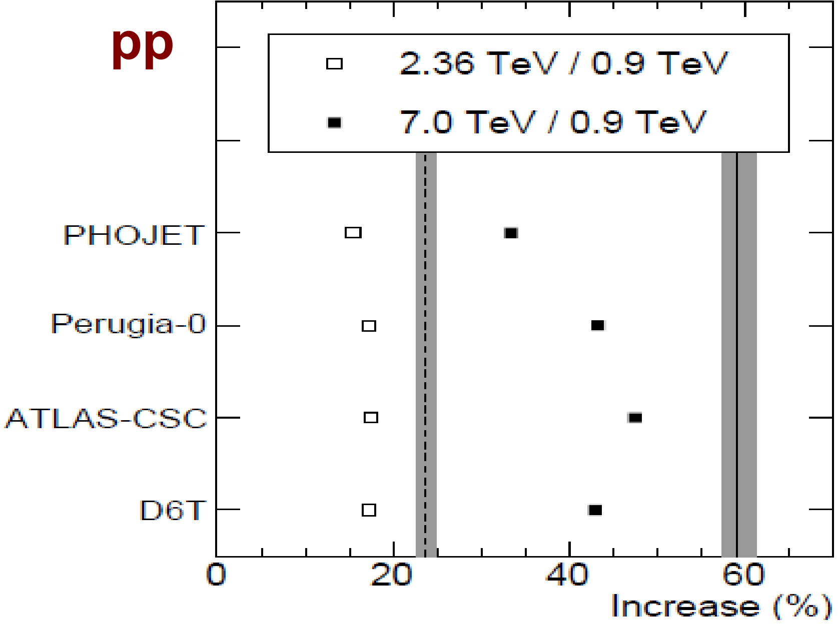




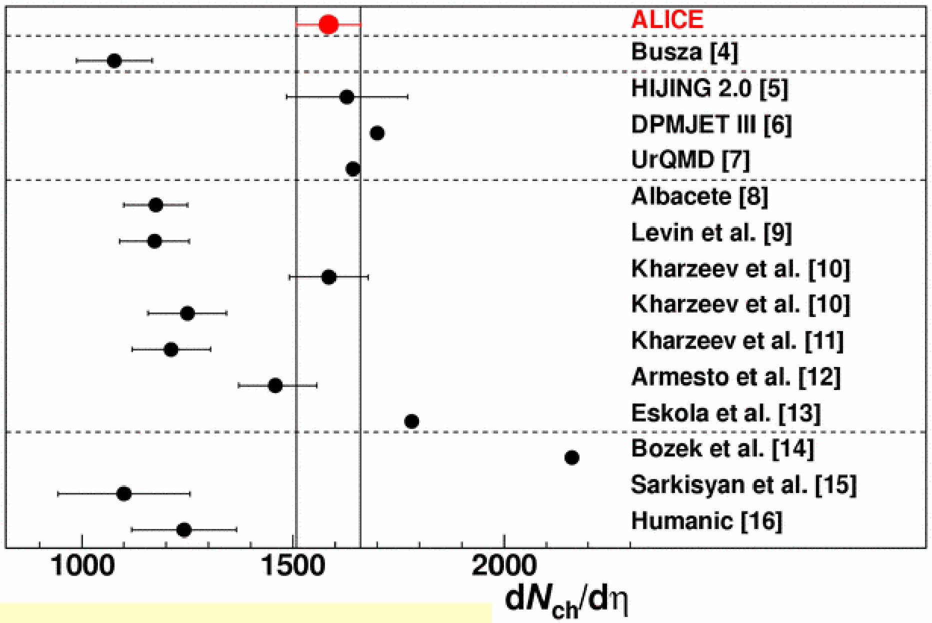
- particle identification (practically all known techniques)
- extremely low-mass tracker ~ 10% of X_0
- excellent vertexing capability
- efficient low-momentum tracking – down to ~ 100 MeV/*c*

Charged particle multiplicity

pp

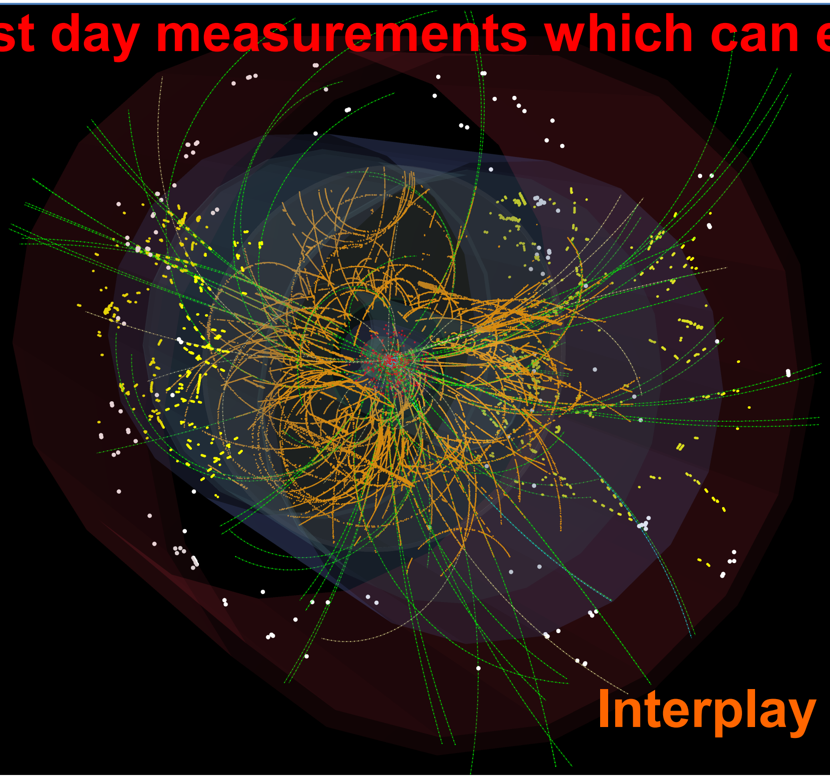


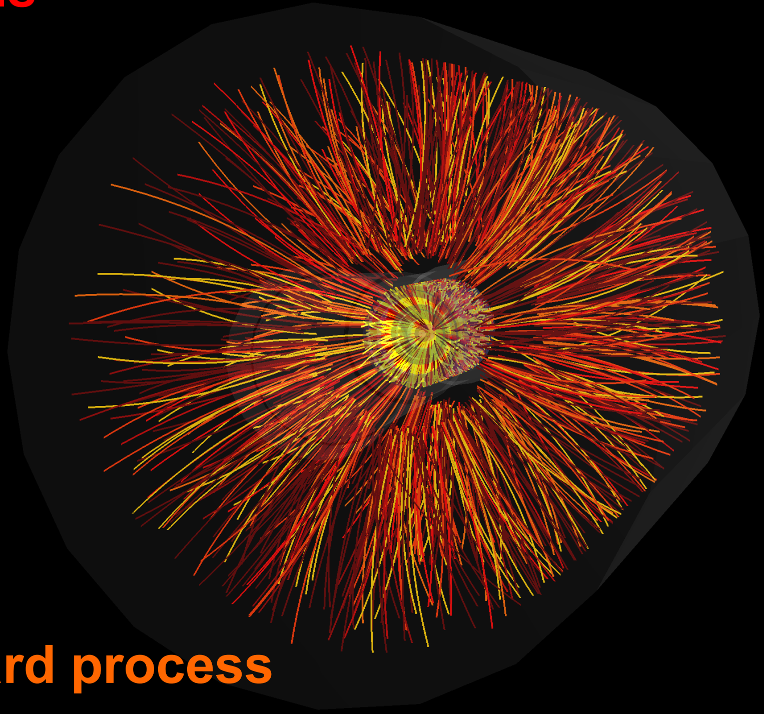
PbPb



Phys. Rev. Lett. 105, 252301 (2010)

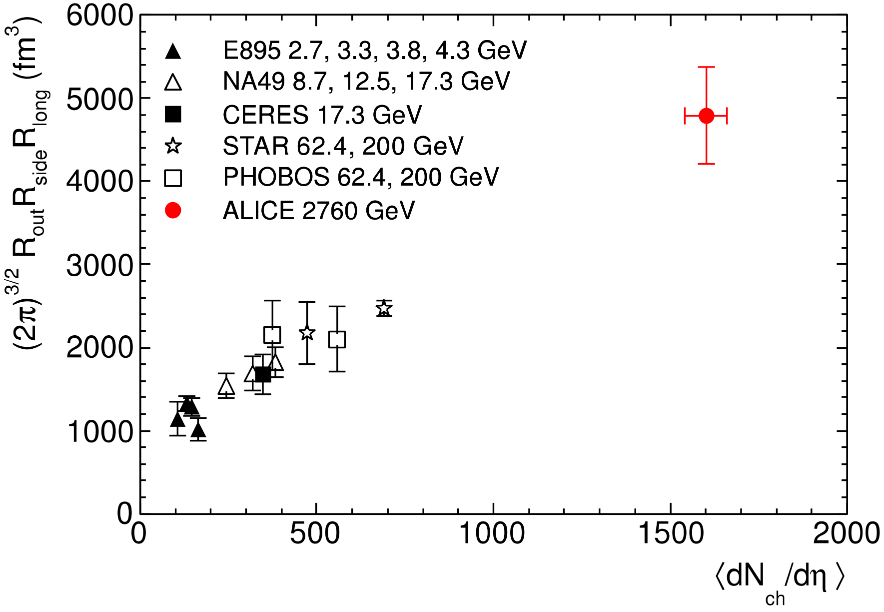
First day measurements which can exclude models

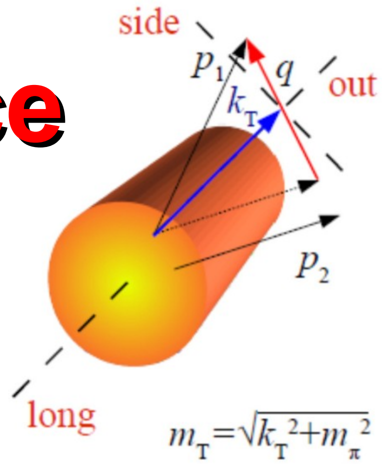




Interplay of soft and hard process

Volume and lifetime of the source



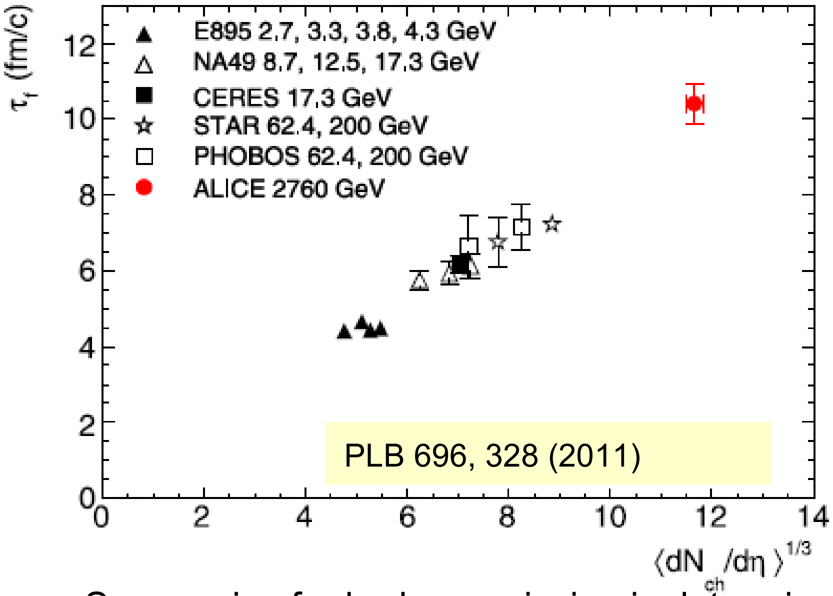


$m_T = \sqrt{k_T^2 + m_\pi^2}$

Volume at freeze out: ~ 5000 fm^3

x2 of RHIC

Initial volume ~ 800 fm^3



PLB 696, 328 (2011)

Lifetime from collision to freeze out

~ 10 fm/c

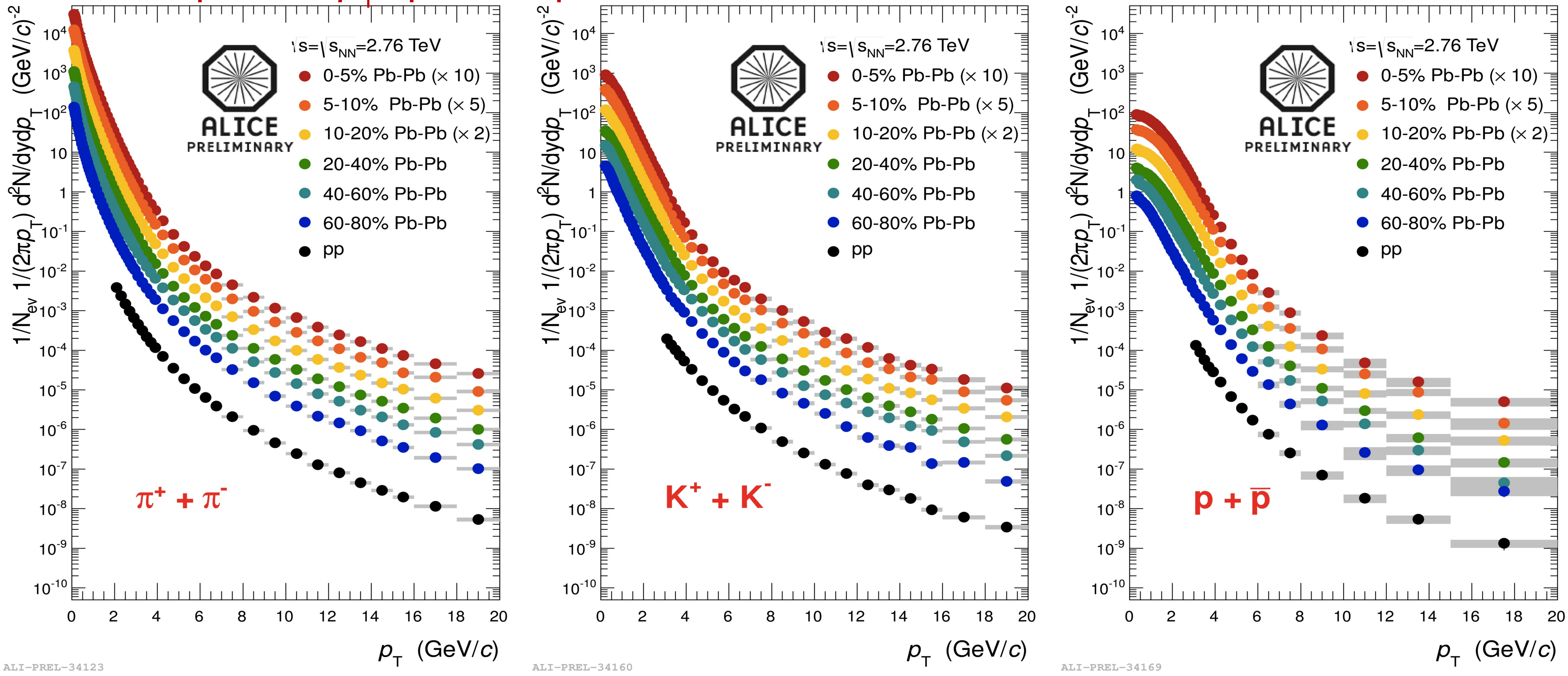
30% longer

Hotter, bigger and longer-lived

Source size for hadron emission is determined by two-pion correlations methods: Hanbury-Brown Twiss (HBT)

p_T domains

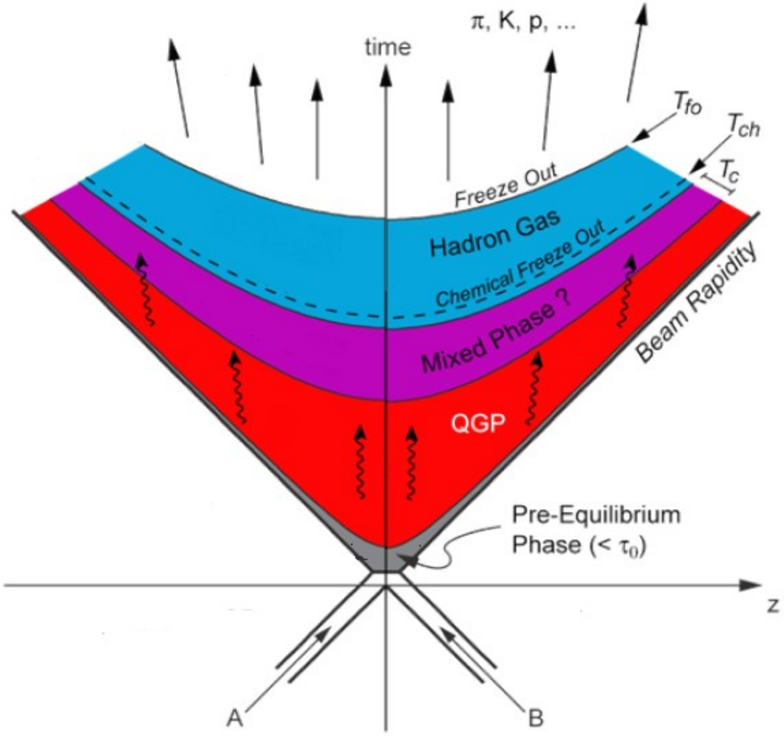
Identified-particle p_T spectra up to 20 GeV/c



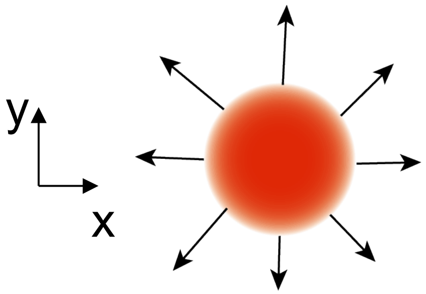
95 % of all particles below 1.5 GeV/*c* : particle production a non-perturbative process

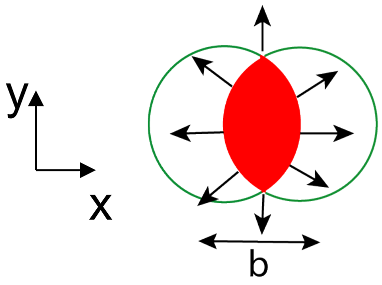
- **Low-p_T < 2 GeV/*c* :** dynamics of bulk matter described by **R**elativistic **H**ydro**D**ynamic **M**odels **(RHDM)**
- **High-p_T > 8 GeV/*c* :** spectra reflect interaction of partons from hard scatterings with the medium
- **Intermediate p_T 2 < p_T < 8 GeV/*c* :** interplay of soft and hard processes

Collective expansion



p_T spectra and azimuthal corerlations (v_n)





In a thermalized system the radial expansion is driven by the pressure gradient from inside to outside resulting in boosted p_T spectra and decrease in HBT size

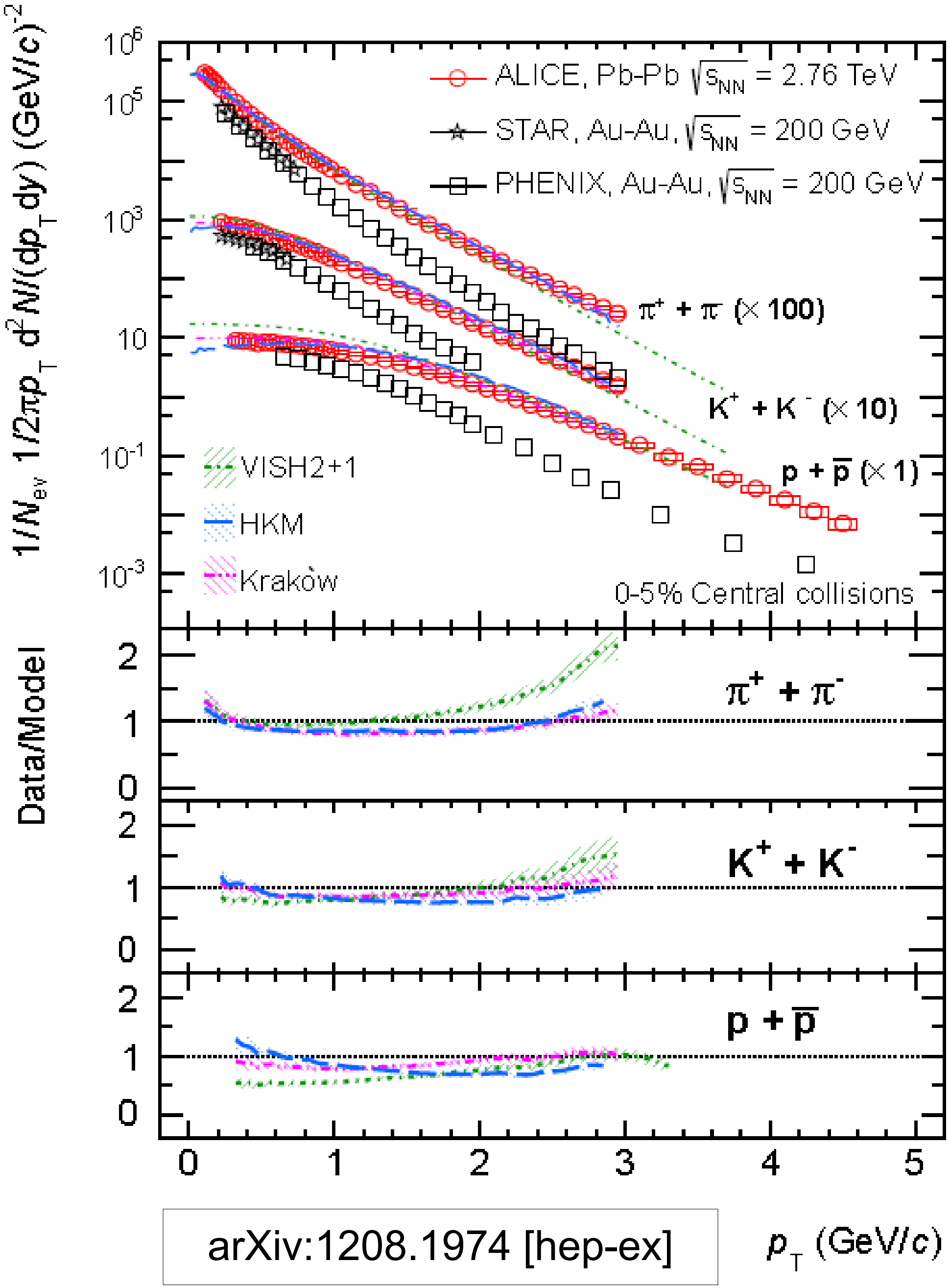
If the system is asymmetric in spatial coordinates the expansion will lead to anisotropy in momentum space (v_2 - azimuthal correlations)

The final state anisotropy at low p_T is calculated using hydrodynamics, taking as input:

- initial conditions (eccentricity, volume, energy density,..)
- properties of produced matter (viscosity, ...)

- **v_2 at low p_T :** collective bulk phenomena, degree of thermalization
- **v_2 at high p_T :** path - length dependence of energy loss

Low p_T particle production

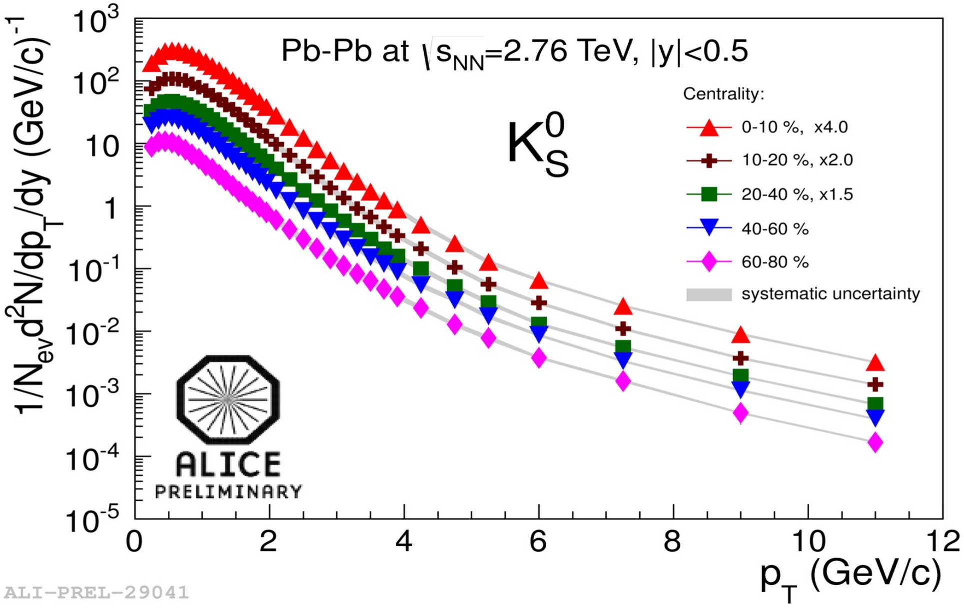


arXiv:1208.1974 [hep-ex]

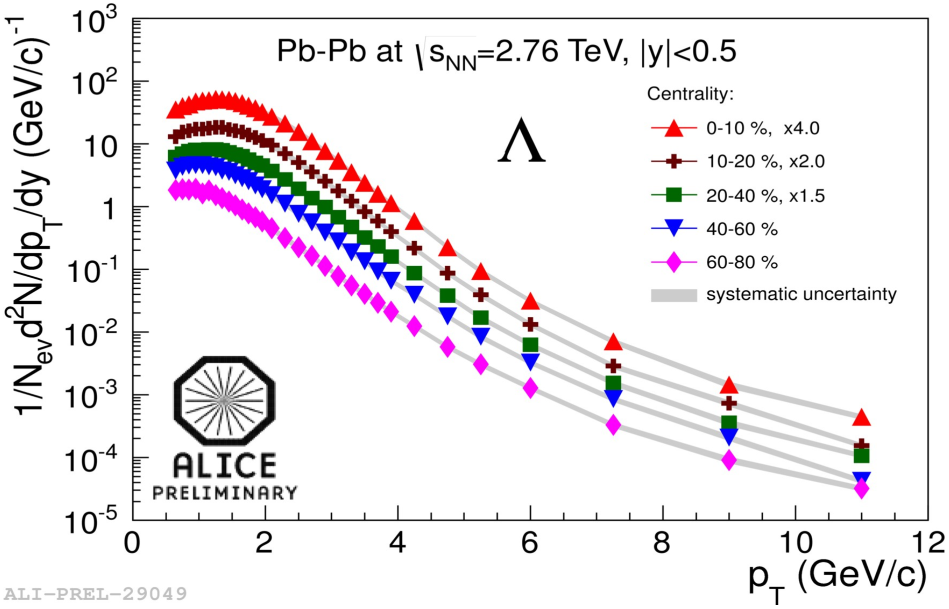
Shape of the low-p_T spectra well described by modern hydrodynamic models (3D, with viscosity, resonances included, sometimes coupled to hadronic cascade codes), similarly to collisions at lower energies

Overall normalization of each spectrum can be modified independently in simple “blast-wave” models, but in full hydrodynamics they are tied by the “statistical” temperature

Strange particle spectra



ALI-PREL-29041



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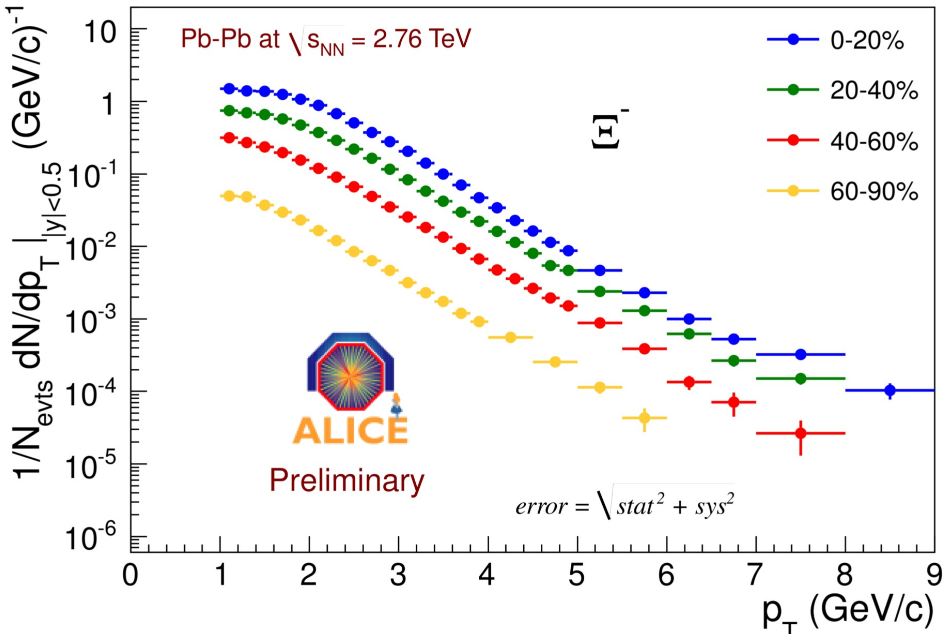

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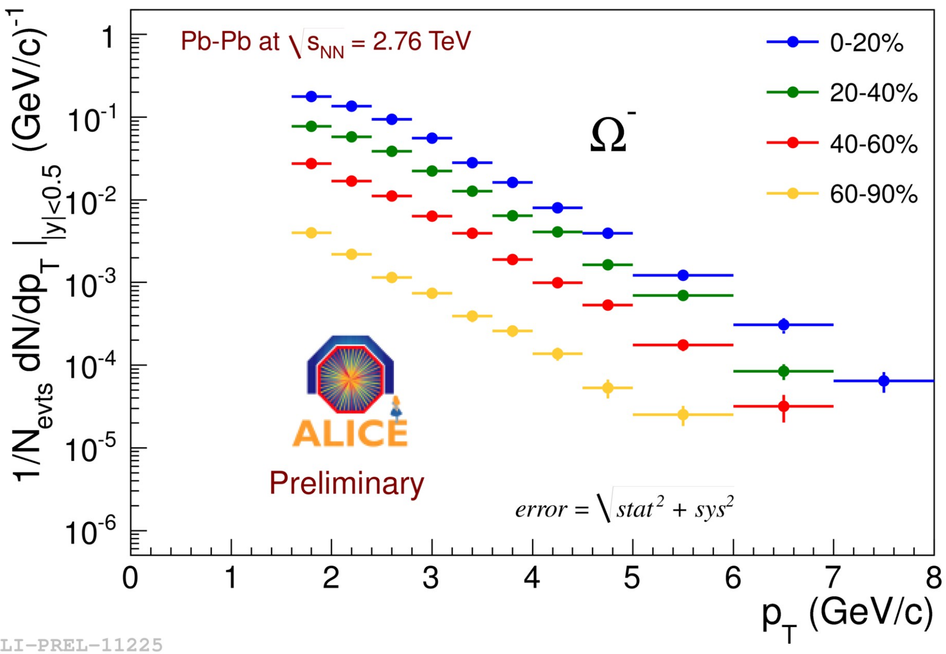
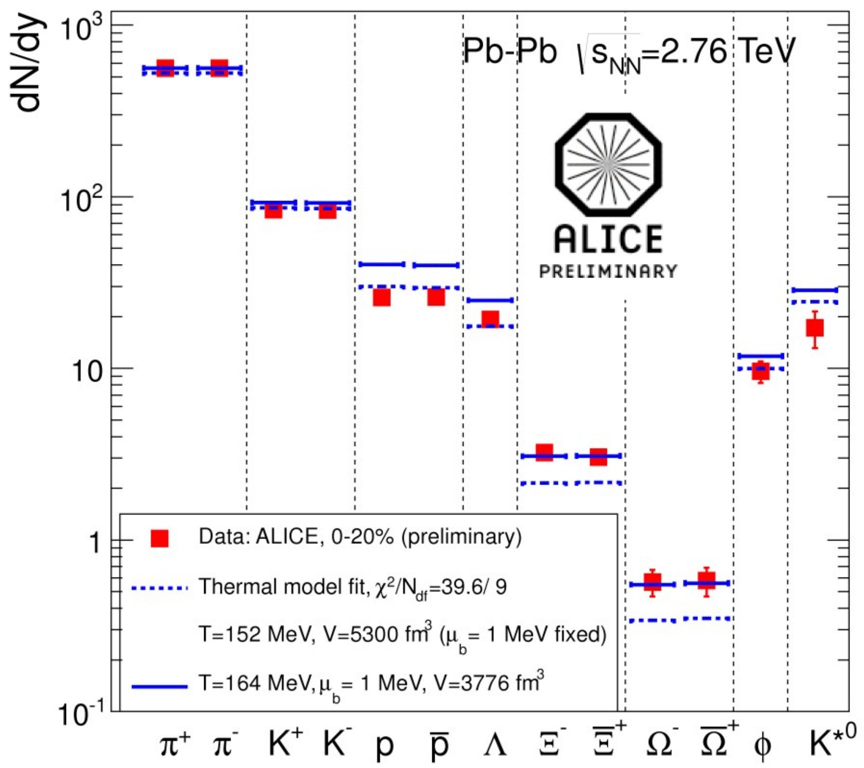
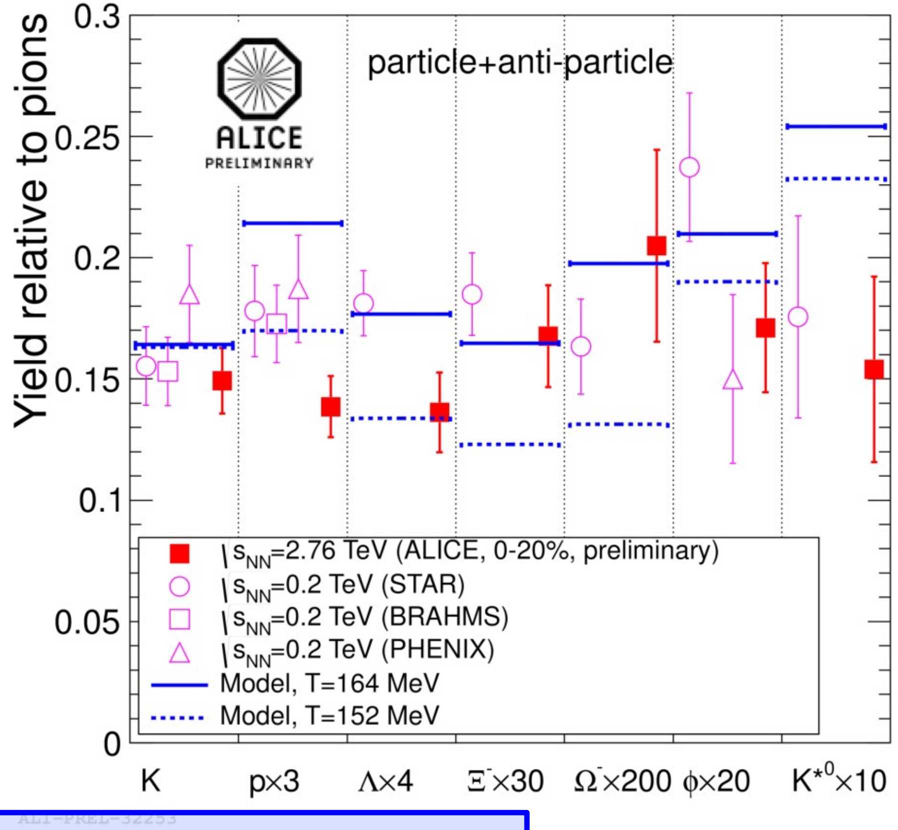


ALI-PREL-11225

Hadron yields vs. statistical model

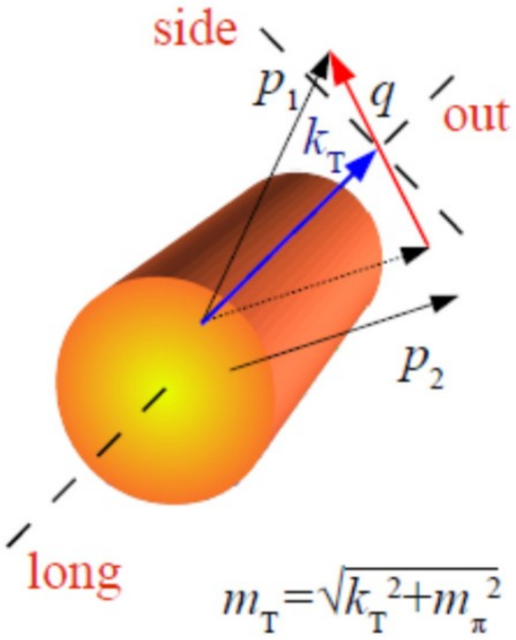




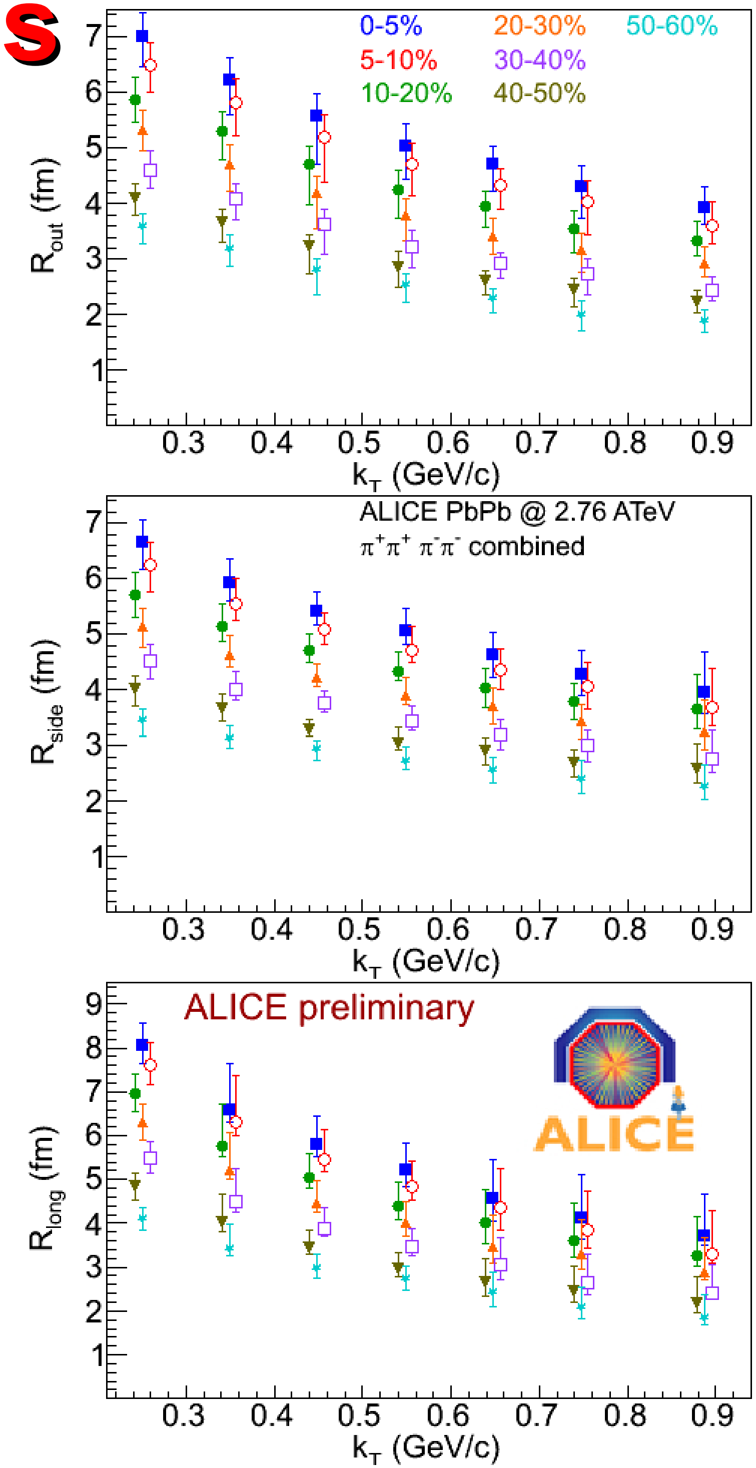
Predicted temperature T=164 MeV
A.Andronic, P.Braun-Munzinger, J.Stachel NP A772 167
Thermal fit (w/o res.): T=152 MeV (χ^2/ndf = 40/9)
Ξ and Ω significantly higher than 152, agree with 164

p/π and Λ/π ratios at LHC lower than at RHIC
Hadronic re-interactions ?
F.Becattini et al. 1201.6349 J.Steinheimer et al. 1203.5302

Femtoscopic correlations



$$m_T=\sqrt{k_T^2+m_\pi^2}$$



Quantum statistics leads to enhancement of identical bosons emitted close-by in phase space which modifies the 2-particle correlation function.
CF relates via Fourier transformation to the space-time distribution of the source. Used in particle physics to measure source space-time size with pions (Goldhaber, Kopylov&Podgoretsky)

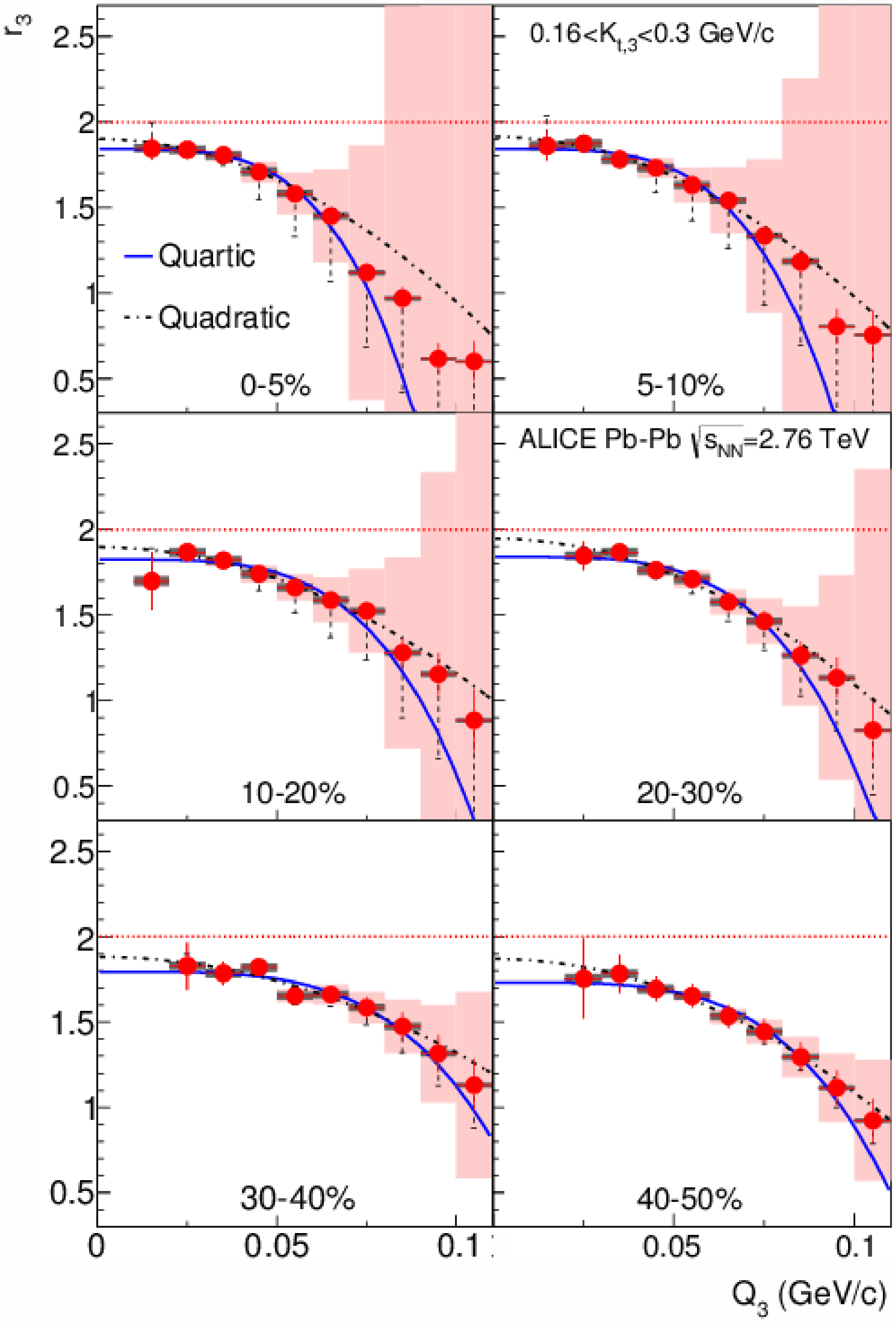
Transverse radii show decrease of apparent size with increasing transverse momentum. Qualitatively consistent with hydrodynamic predictions.

Radii increase with final-state multiplicity

Coherence in pion emission

- **3-pion correlations sensitive to "chaoticity" of pion emission**
- **The r_3 cumulant should approach 2 for the "fully chaotic" limit**

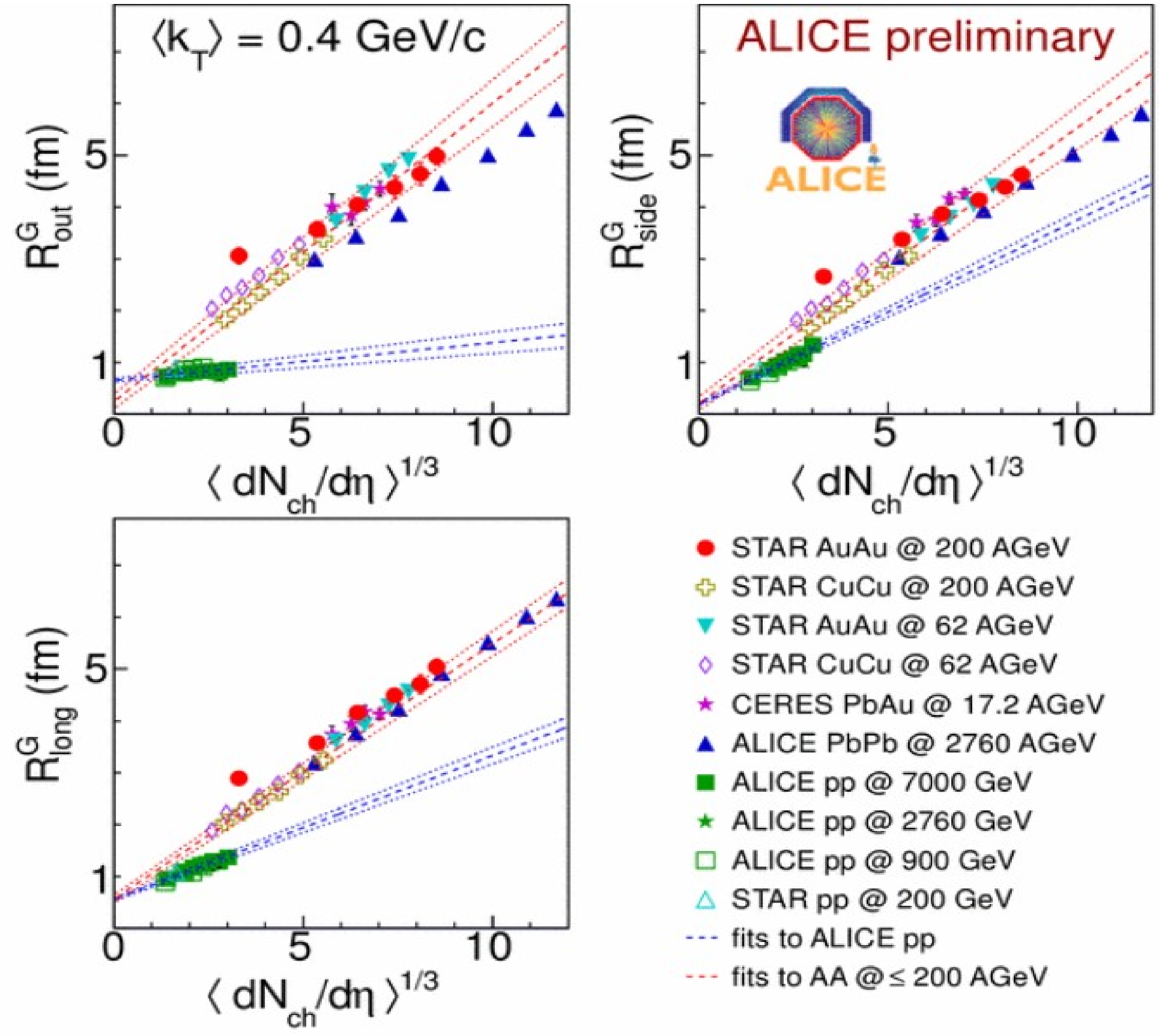
- **At low momentum limit not reached. Possible interpretation: 10-20% coherent pion emission**
- **At high momentum "fully chaotic" limit reached**



arXiv:1310.7808 [hep-ex]

Radii scaling with multiplicity

- **HBT radii scale roughly linearly with multiplicity$^{1/3}$ with different slopes in pp and Pb-Pb**
- **HBT radii in Pb-Pb vs. trend from lower energy AA:**
  - Rlong: perfectly agree
  - Rside: reasonably agree
  - Rout: clearly below the trend
- **Behaviour of all 3 radii in qualitative agreement with hydro expectations**
  - Rout/Rside decreases with √s due to change of the freeze-out shape



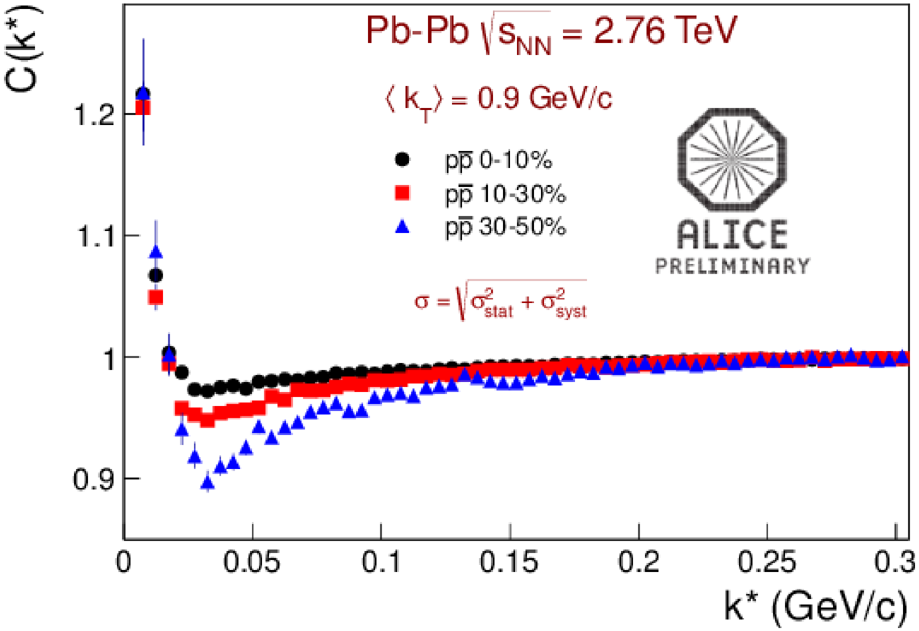
Baryon-antibaryon interactions

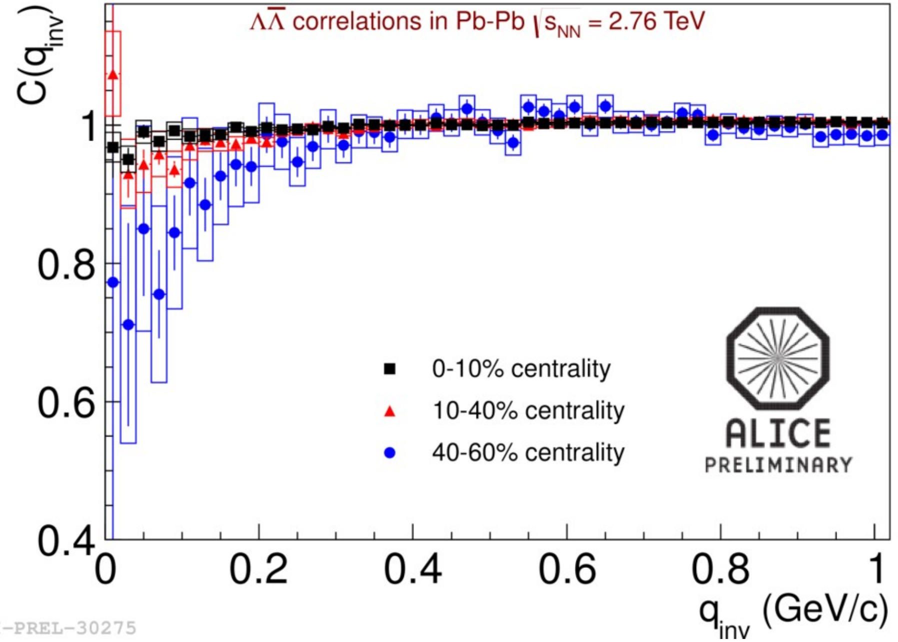
In baryon-antibaryon systems the dominating source of correlation is the strong Final State Interaction.
The FSI has contribution from annihilation.

Strong FSI (with annihilation) can be considered in two regimes:
- low relative momentum – leads to femtoscopic (anti-)correlation
- large relative momentum – leads to yield decrease via annihilation

If annihilation is responsible for lower proton yield – it should also be seen in correlations

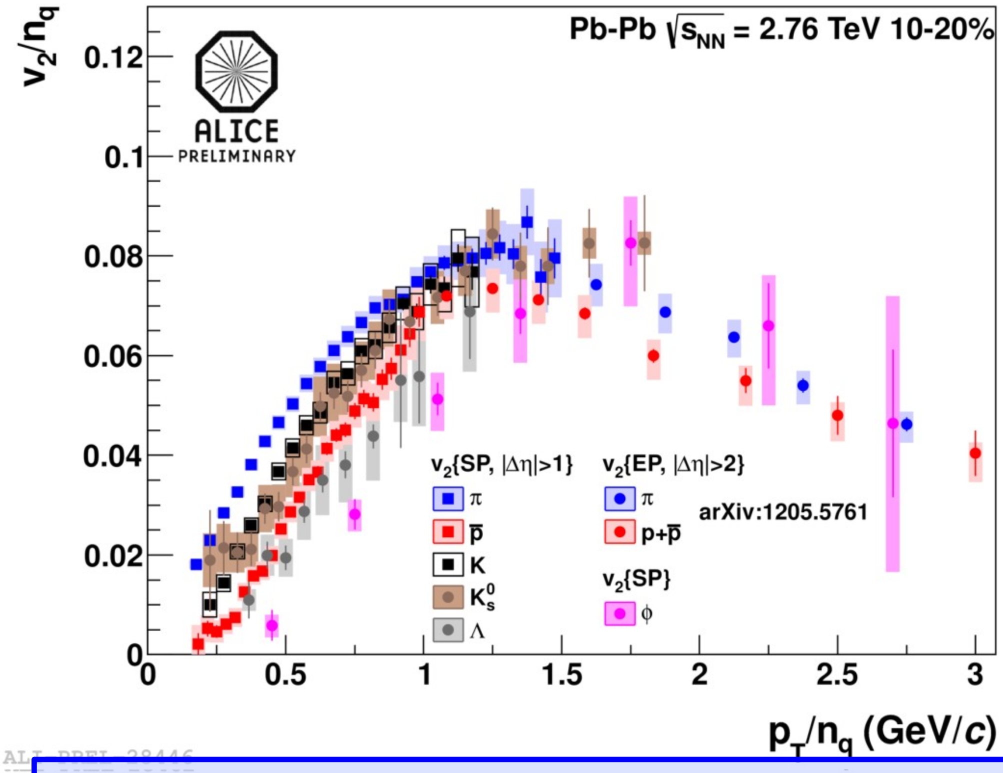
Wide anti-correlation, consistent with annihilation effects, is observed for all baryon-antibaryon systems

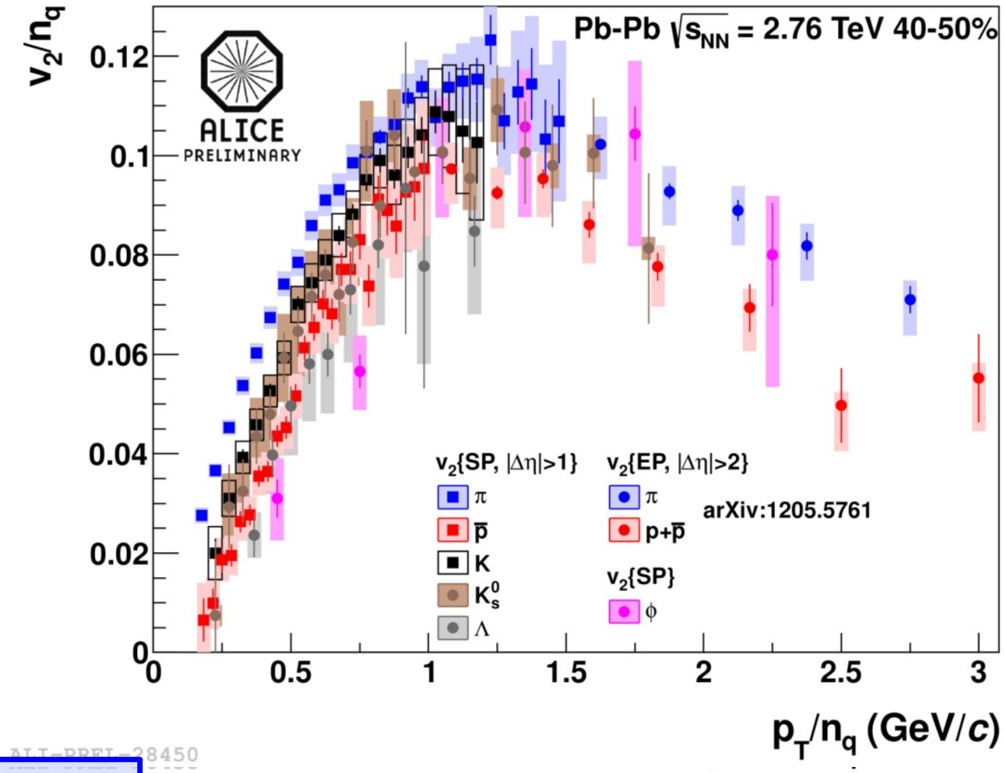




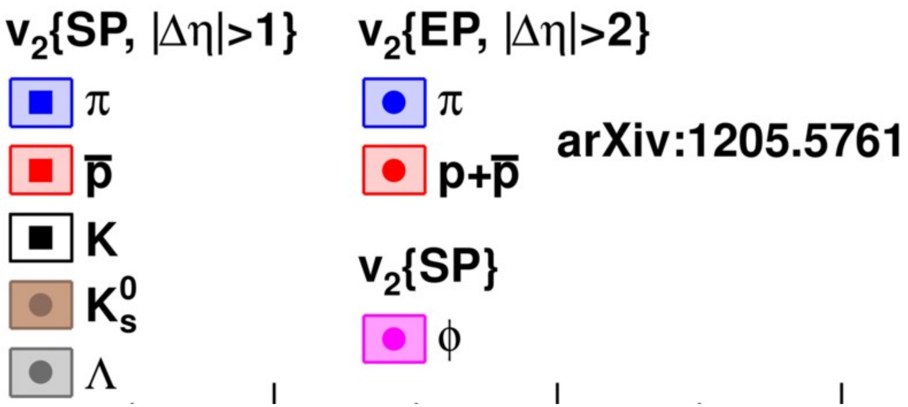
ALI-PREL-30275

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



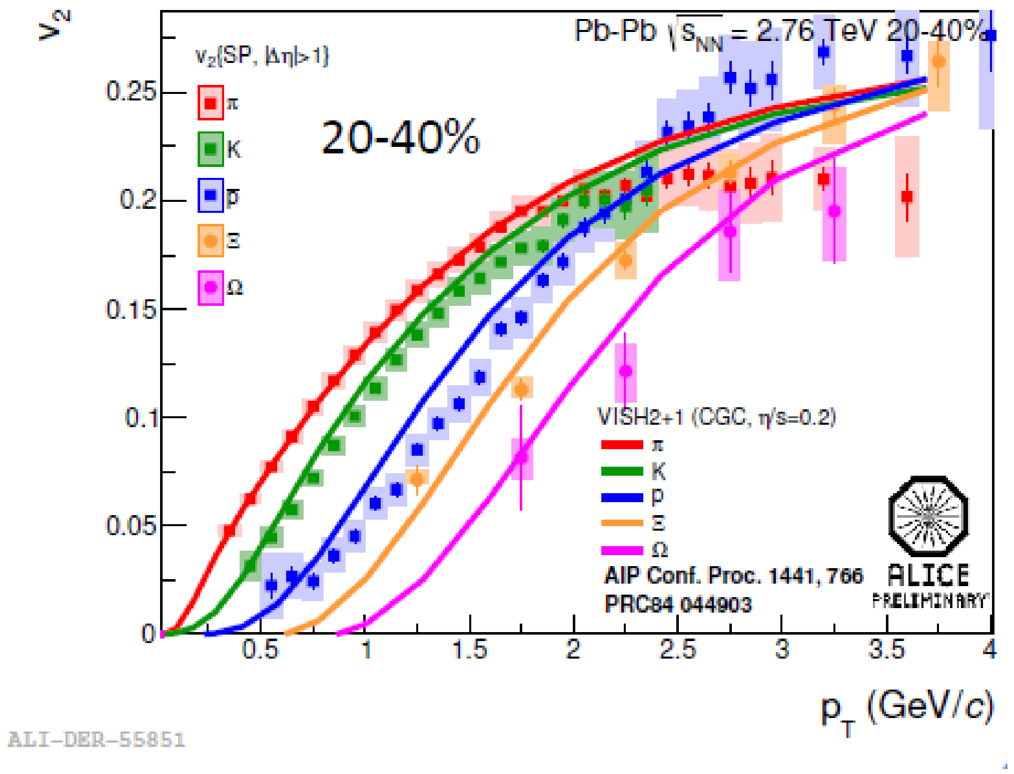
$n_q(m_T)$-scaling worse than at RHIC

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

Models vs. identified-particle v_2

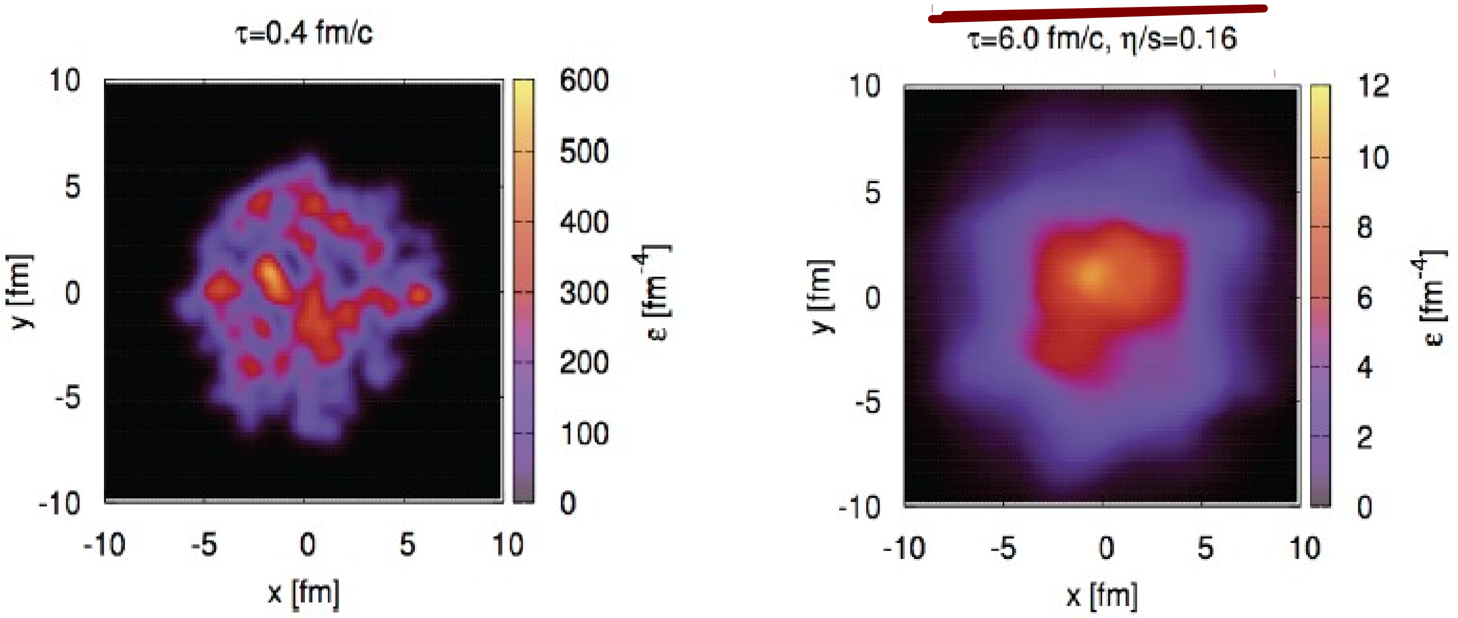
v_2 shows mass ordering up to multi-strange baryons

v_2 vs. p_T described by hydrodynamical models



Higher harmonics and initial state

- **Initial geometry not described by the ideal almond shape**
  - Fluctuations of initial energy/pressure distributions lead to “irregular” shapes that fluctuate event-by-event
  - Higher (odd) harmonics each one having its own symmetry plane
- **Higher harmonics more sensitive to the value of shear viscosity**



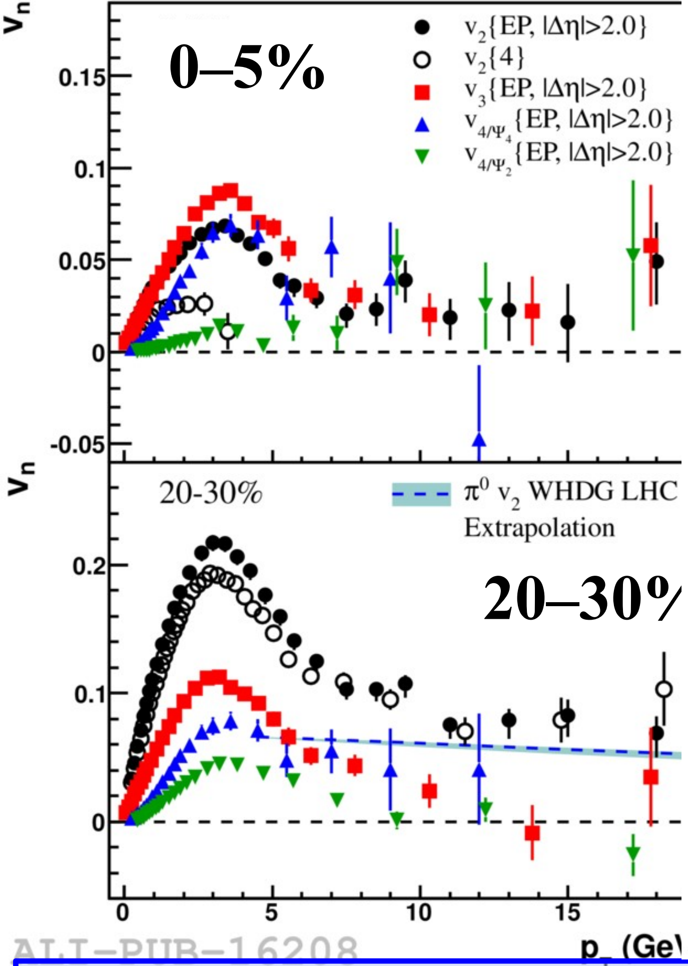
Hydro simulation of initial state (ideal and viscous hydro):
fluctuations of initial state are damped by viscosity

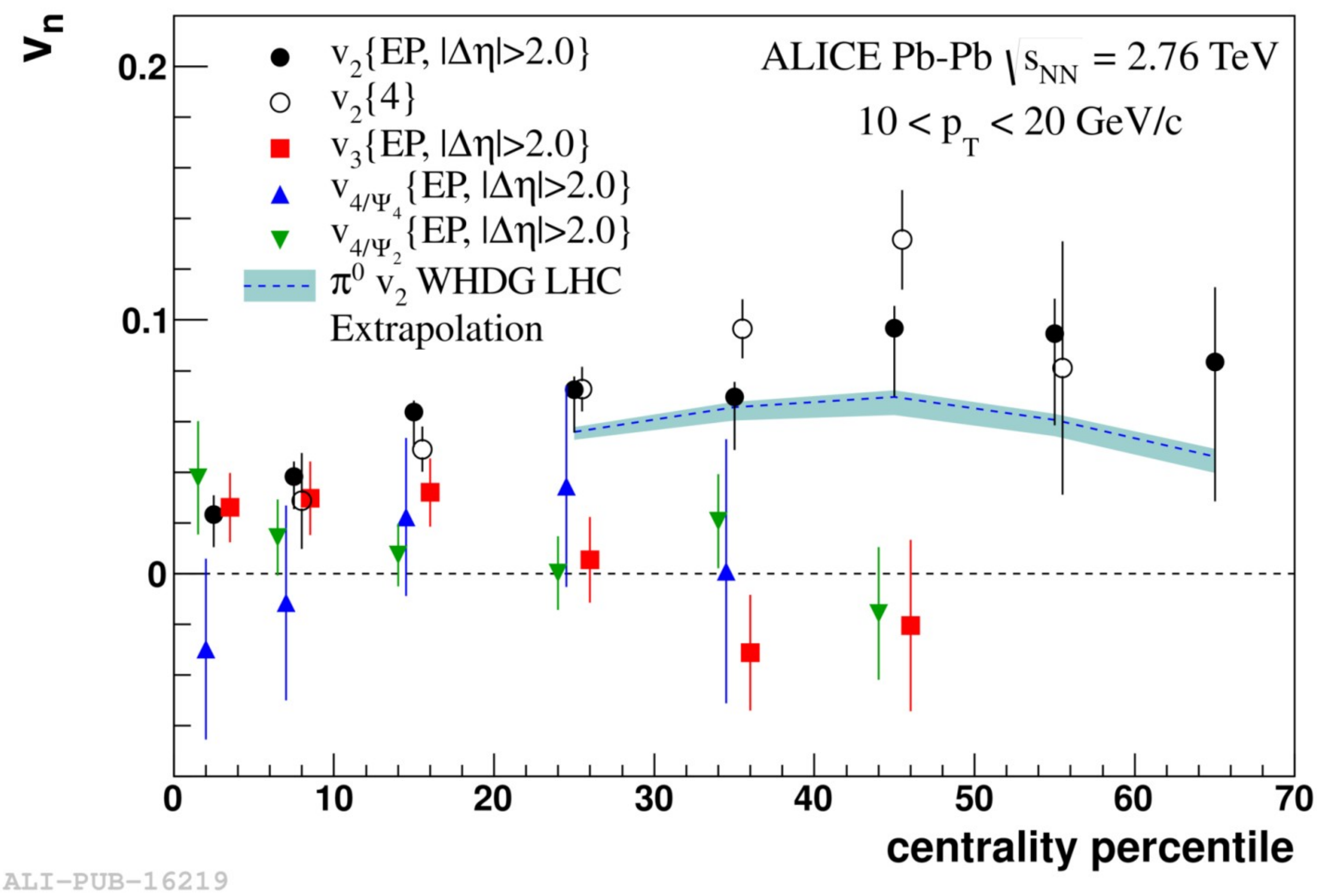
ALICE coll., PRL 107, 032301 (2011)

v_2 , v_3, v_4 versus p_T

arXiv:1205.5761 [hep-ex]

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





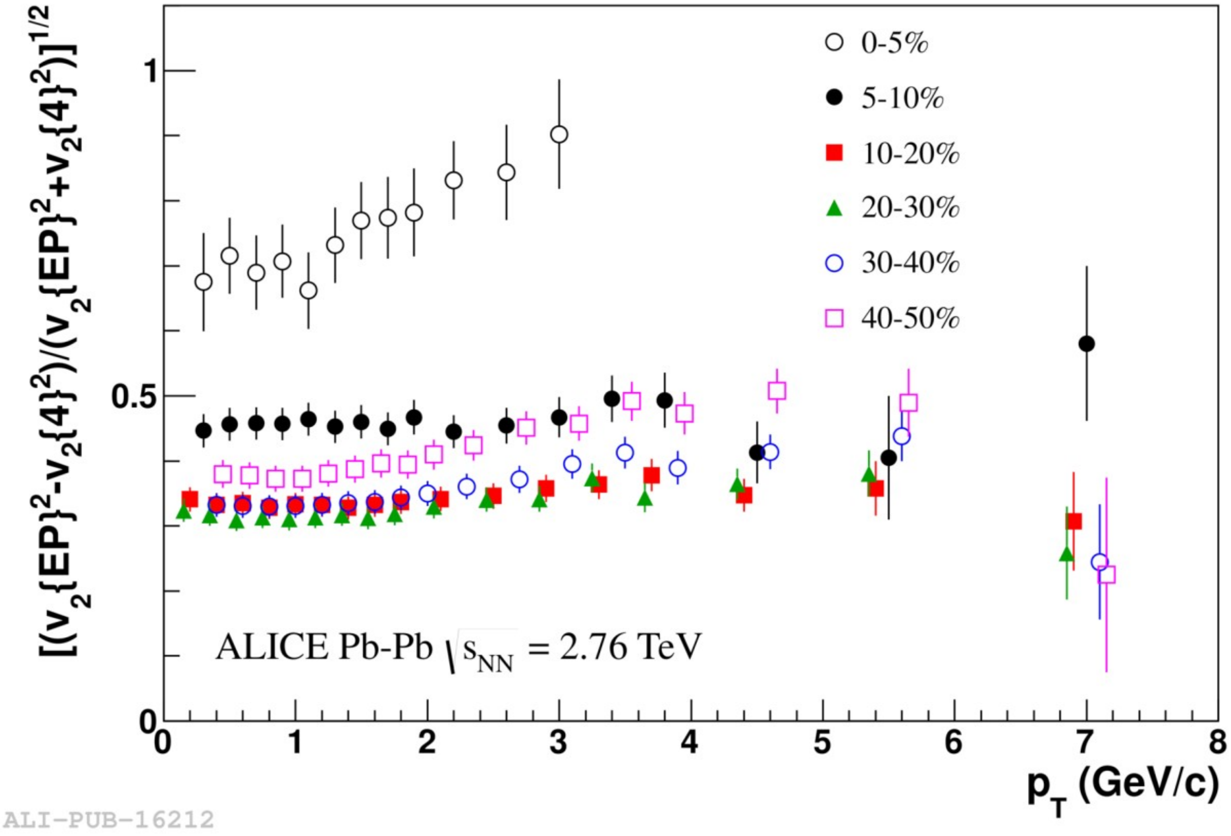
v_n measurements up to 20 GeV/*c* – where dominated by jet quenching

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 decrease of fluctuations at high p_T

Fluctuations contribution to v_2

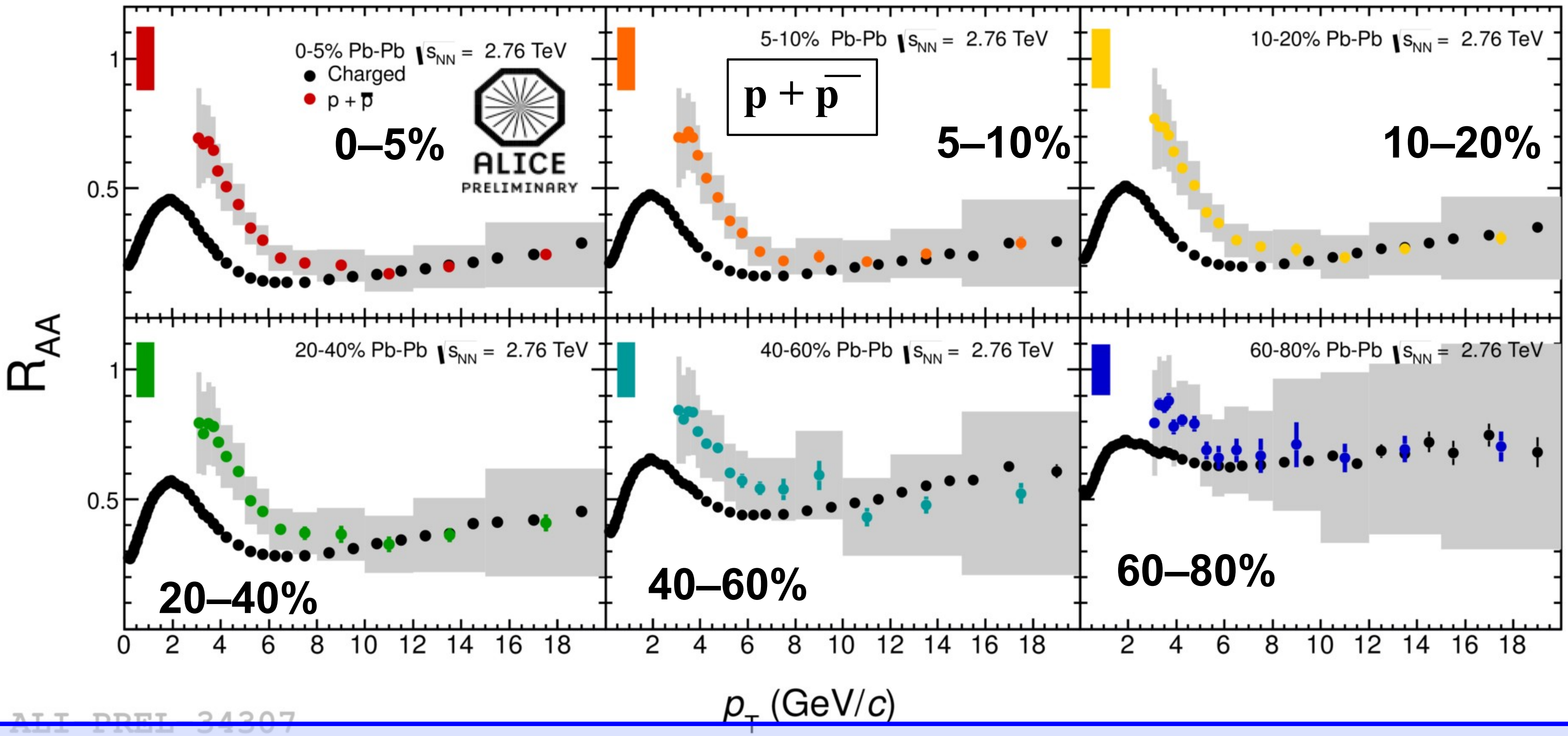


v_2 dominated by fluctuations at small eccentricity

Fluctuations independent of p_T

Identified particles at intermediate p_T

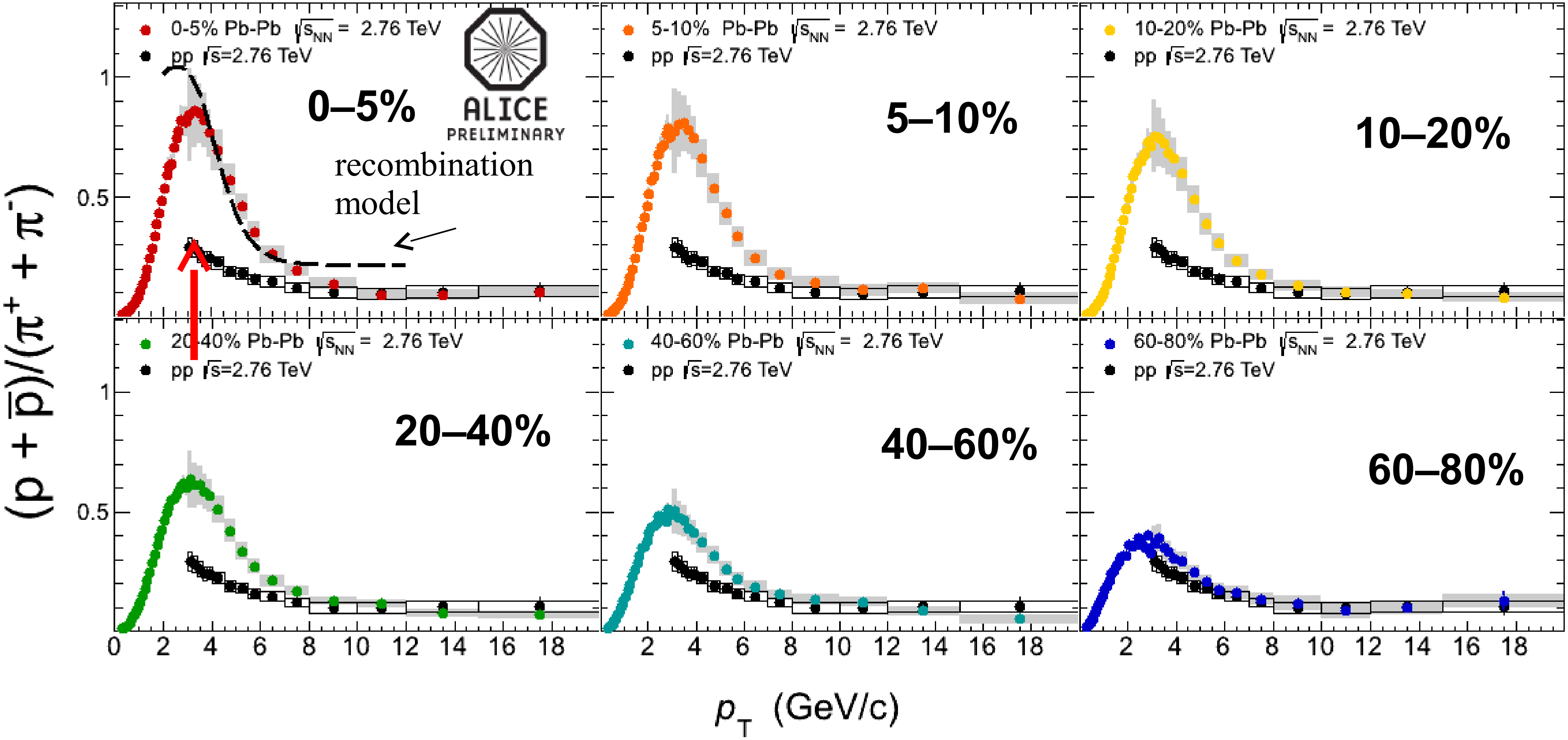
● charged particles ●●●●●● different centralities for identified particles



p_T < 7 GeV/c: $R_{AA}(\pi) < R_{AA}(h\pm) \sim R_{AA}(K) < R_{AA}(p)$; p_T > 7 GeV/c: all same

Baryon-to-meson ratio: p/π

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



p/π ratio at p_T ≈ 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^0_S

Baryon enhancement at LHC

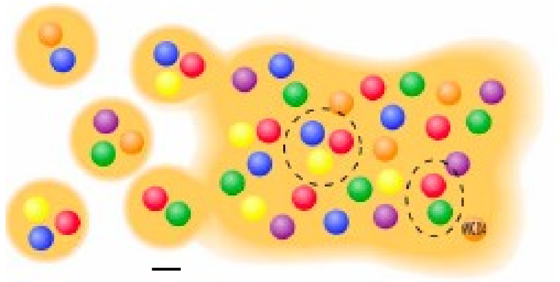
- larger than at RHIC
- extending to higher p_T
- well described by models like EPOS

Effect of radial flow?

extends farther than expected from radial flow

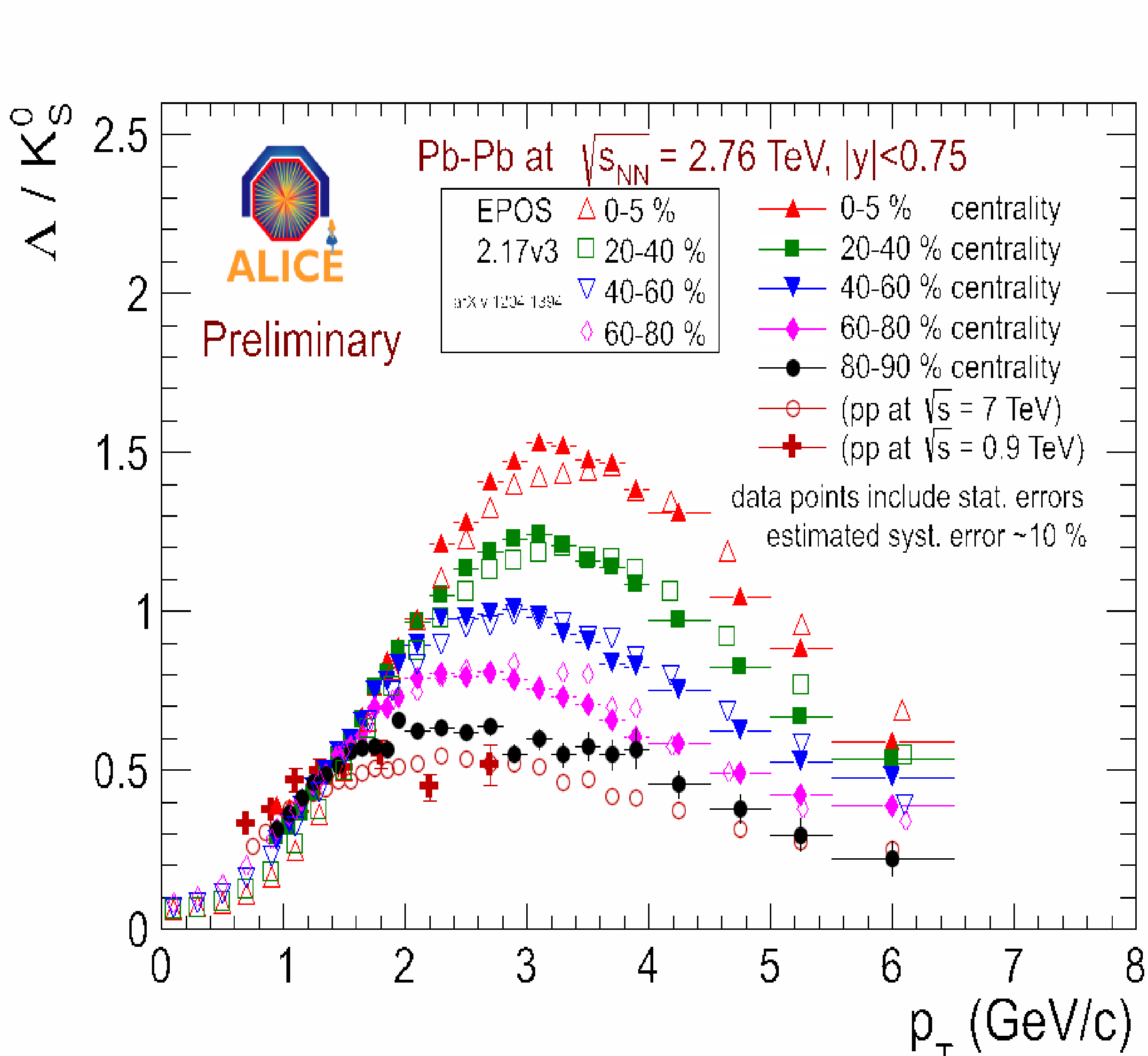
OR

Recombination of quarks?



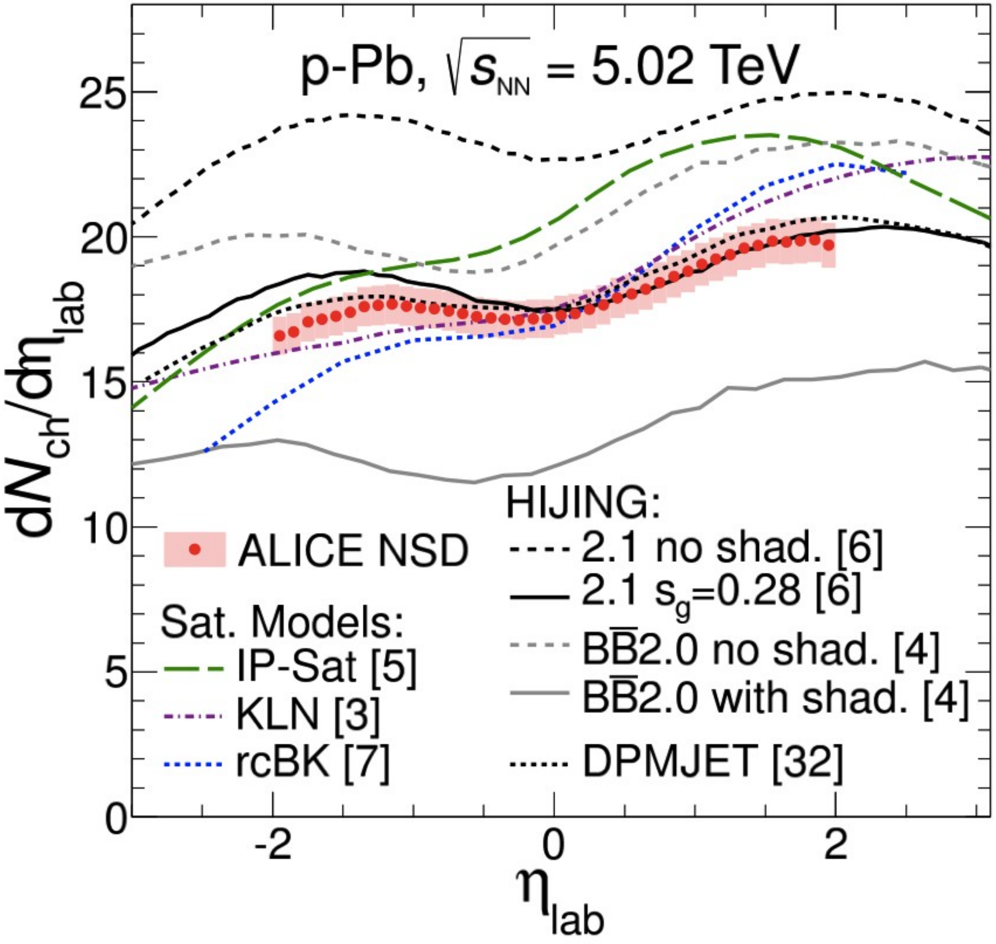
$$p_T(q\bar{q}) \approx 2 \times p_T(q)$$

$$p_T(qqq) \approx 3 \times p_T(q)$$



RHDM Recombination? Parton energy loss

dN_{ch}/dη in p-Pb collisions



NSD p-Pb at 5.02 TeV $|\eta| < 2$

dN_{ch}/dη : 16.95 ± 0.75

Disentangle

- final state effects : hot QCD matter

- initial state effects: cold nuclear matter

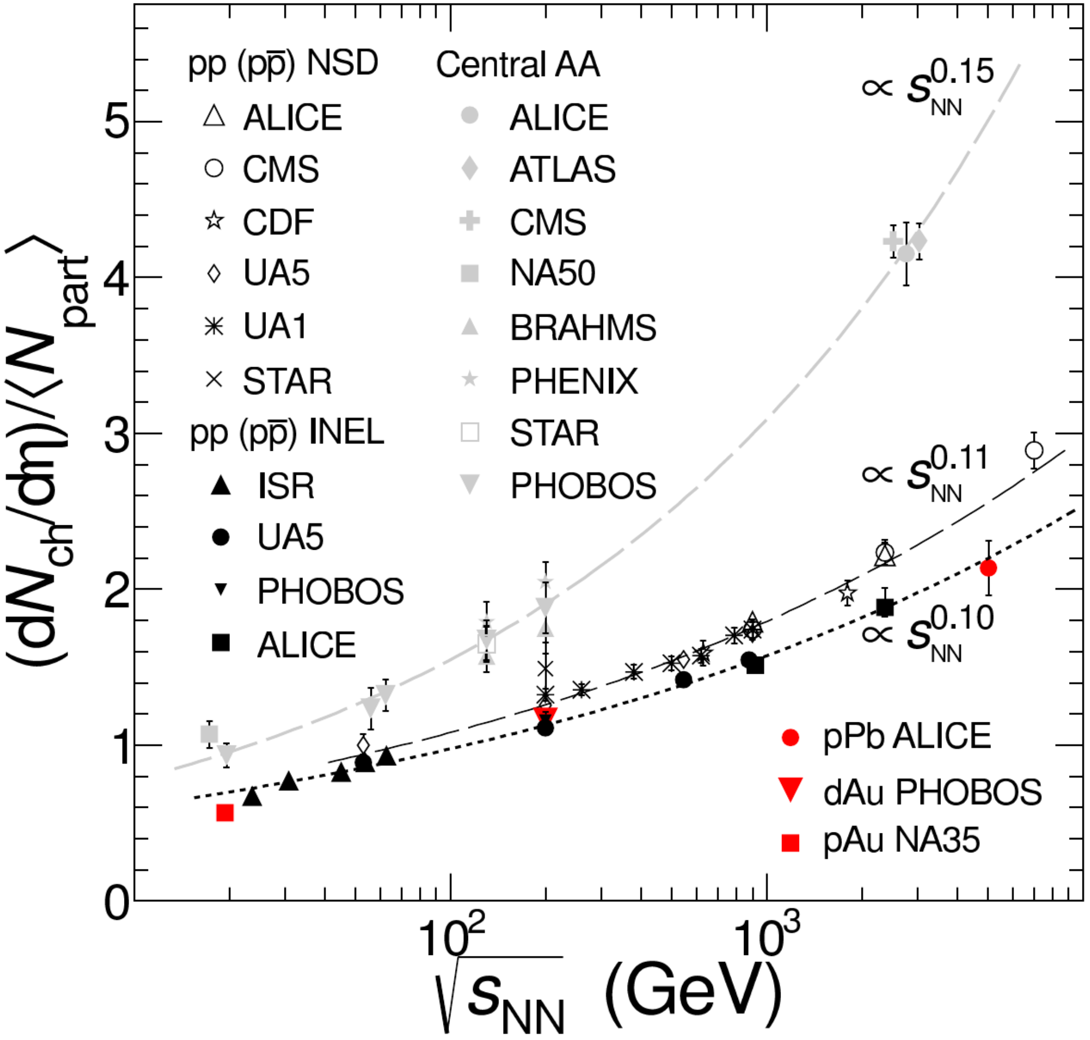
Probe nuclear wave-function at small x

QCD at high gluon density:
parton shadowing, gluon saturation?

- **Models that include shadowing or saturation approximately get right value**

arXiv:1210.3615 [nucl-ex], Phys Rev Lett 110, 032301 (2013)

dN_{ch}/dη energy dependence



p-Pb : ~ $\sqrt{s_{NN}}^{0.10}$

dN_{ch}/dη : 16.95 ± 0.75

pp : ~ $\sqrt{s_{NN}}^{0.11}$

dN_{ch}/dη : 6.01 ± 0.01 (stat.) + 0.2 – 0.12

Pb-Pb : ~ $\sqrt{s_{NN}}^{0.15}$ (most central)

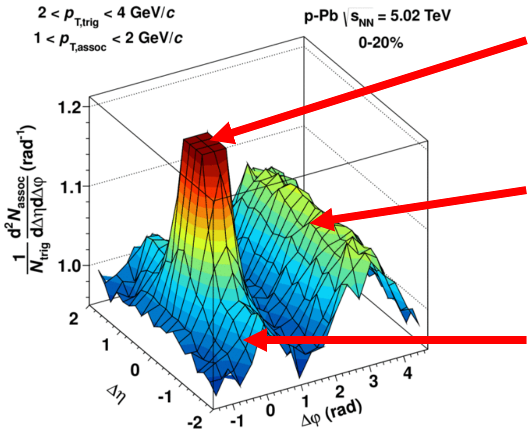
dN_{ch}/dη : 1584 ± 4 (stat.) ± 76 (syst.)

p-Pb

- 20% lower than pp, same energy
- 80% higher than dAu, 200 GeV/c

Long range correlations in p-Pb

Correlations between a trigger and an associated particle



Near-side jet
(Δφ ~ 0, Δη ~ 0)

Away-side jet
(Δφ ~ π, elongated in Δη)

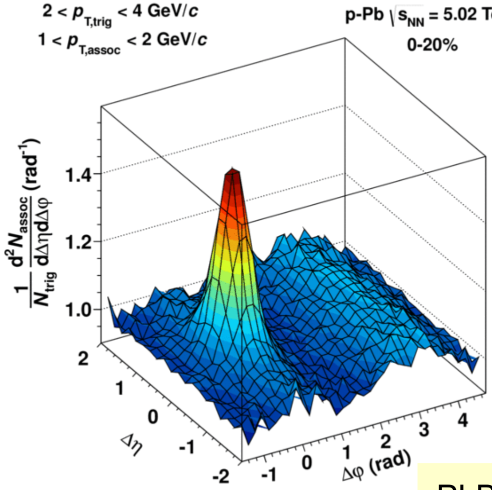
Near-side ridge
(Δφ ~ 0, elongated in Δη)

$2 < p_T$,trig < 4 GeV/c
$1 < p_T$,assoc < 2 GeV/c
20% highest multiplicity class

Can we separate the jet and ridge components ?

No ridge seen in 60-100% and similar to pp
→ **what remains if we subtract 60-100%?**

0-20%



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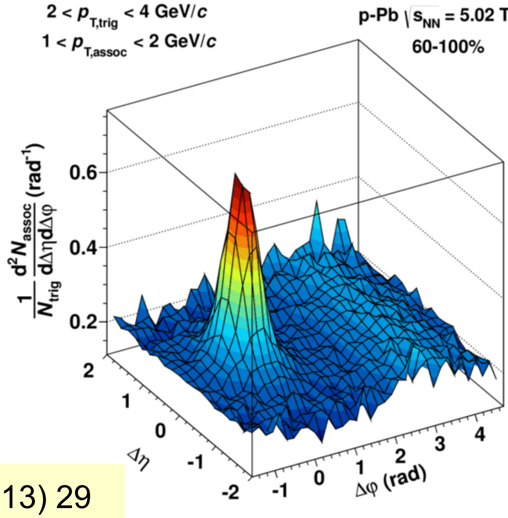
60-100%



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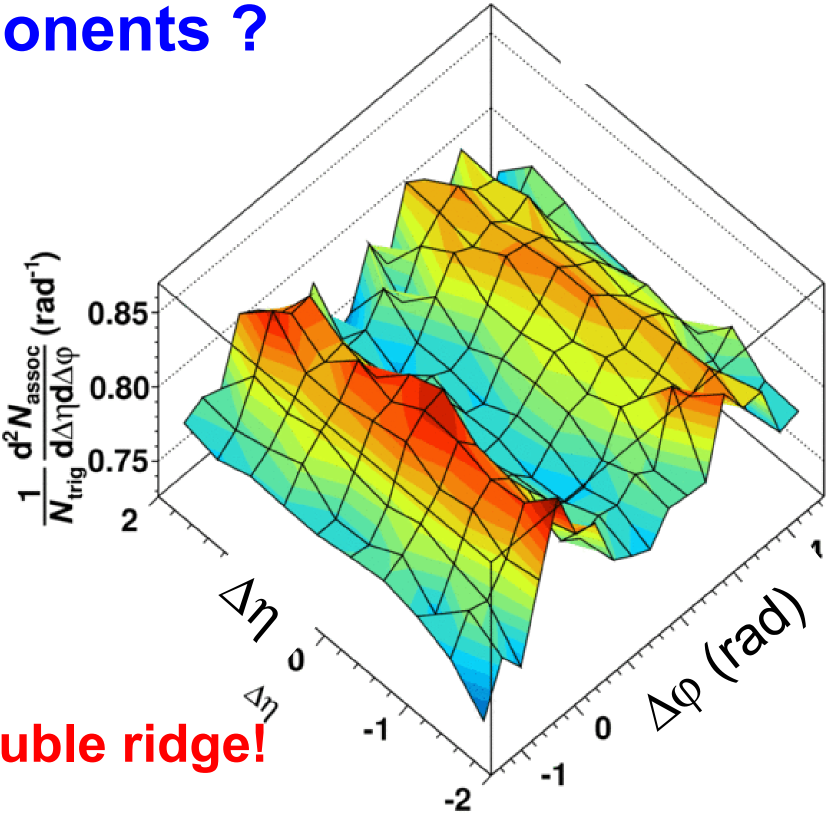
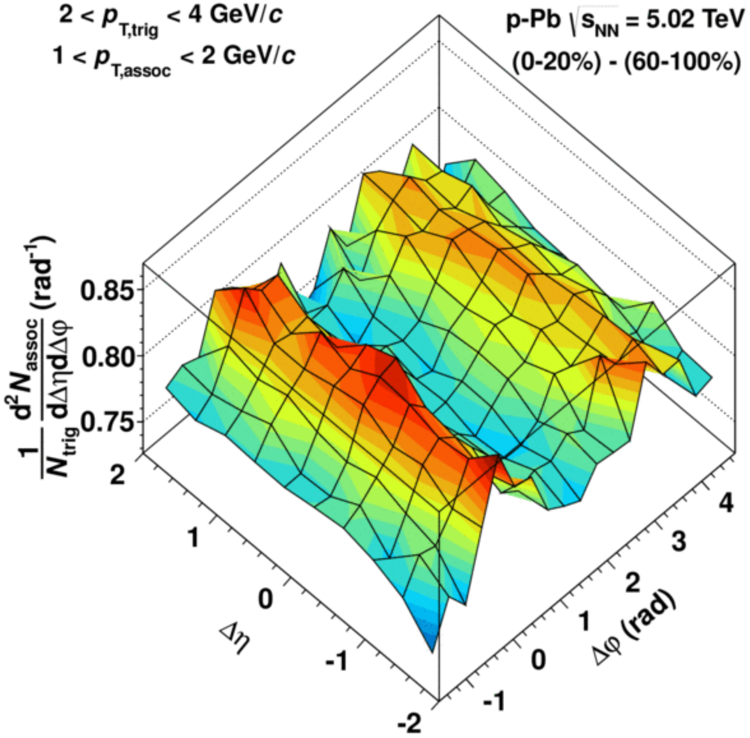


A double ridge!

PLB719 (2013) 29

The double ridge

Excess in the correlation yield between the two multiplicity event classes



$|\Delta\varphi| < \pi/3$

$|\Delta\varphi - \pi| < \pi/3$

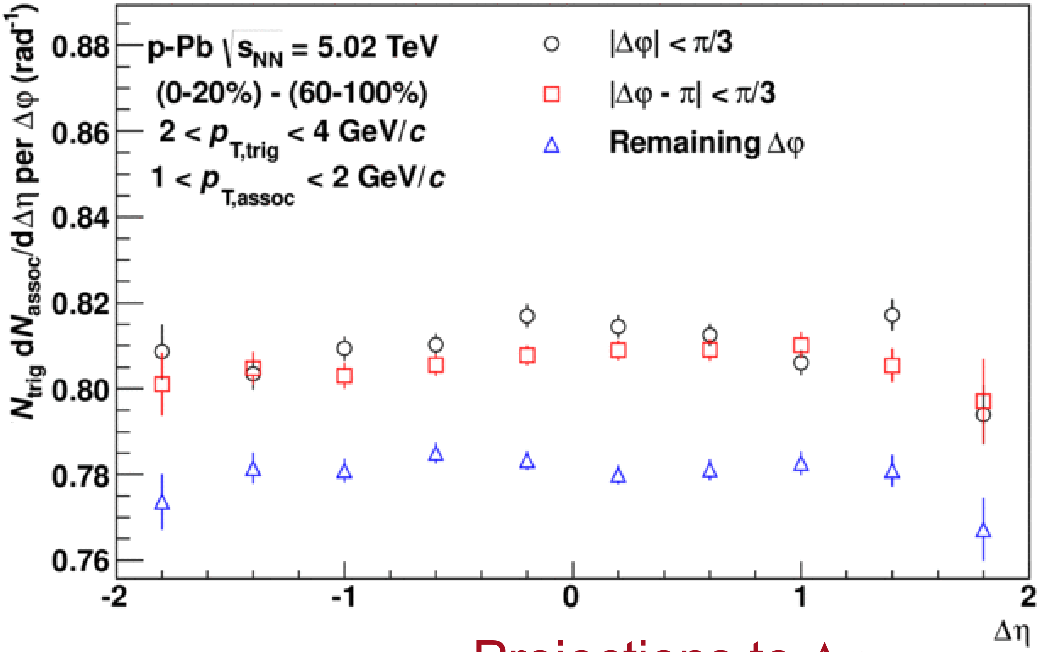
Remaining $\Delta\varphi$

Two ridges:
Magnitude the same
and fairly flat in $\Delta\eta$

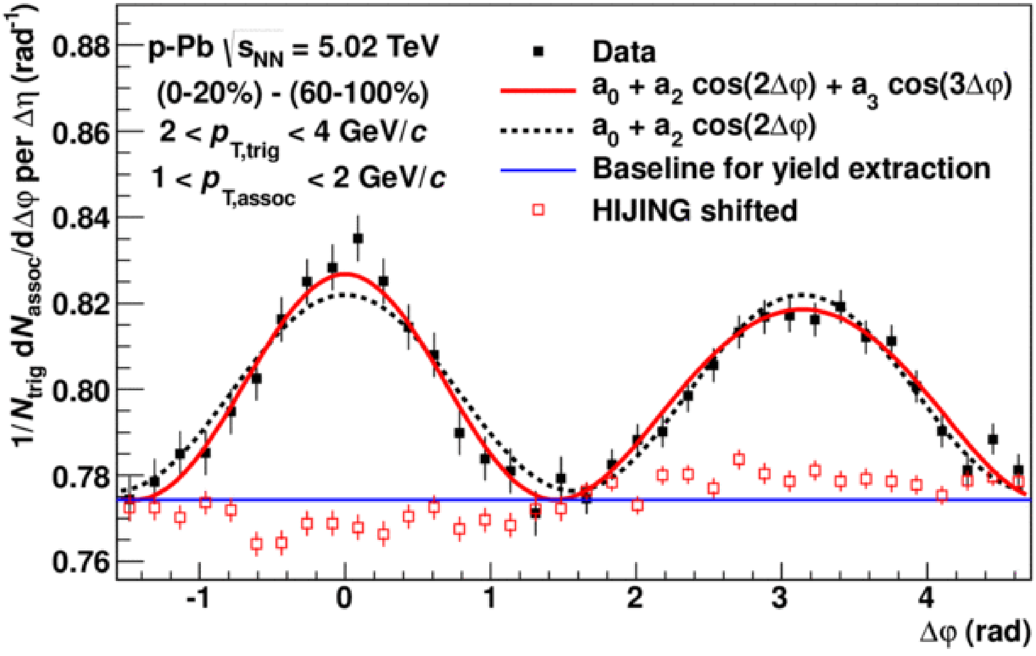
Fit allows to extract v_n coefficient

$$v_n = \sqrt{a_n / b}$$

Projections to $\Delta\eta$



Projections to $\Delta\varphi$

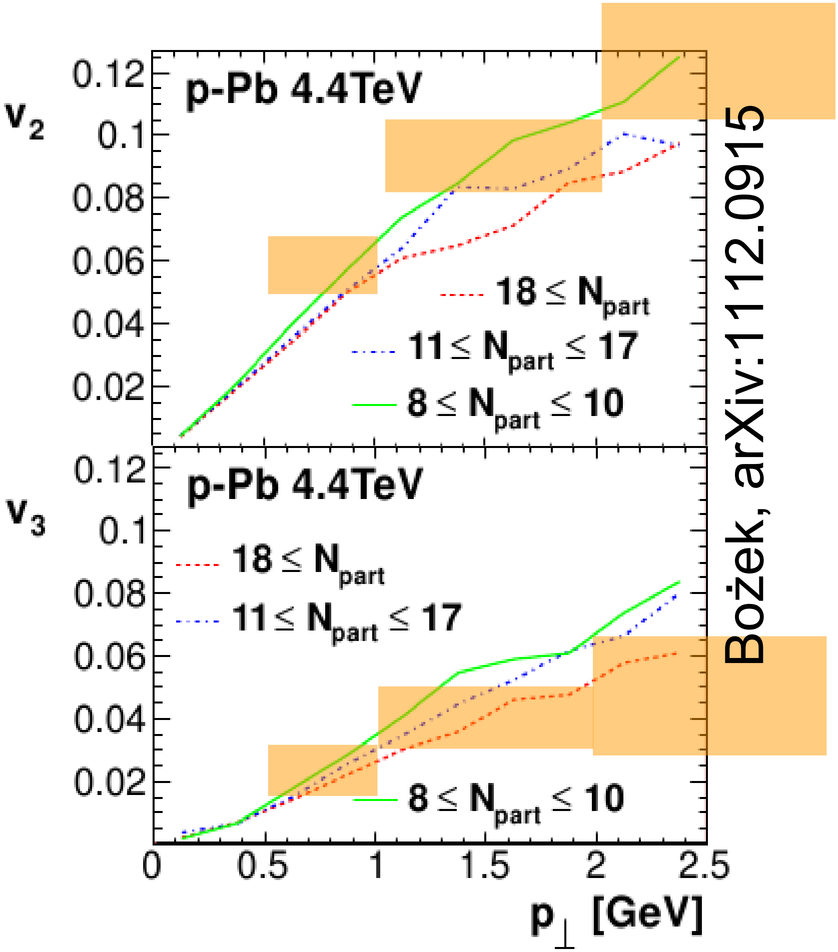


PLB719 (2013) 29

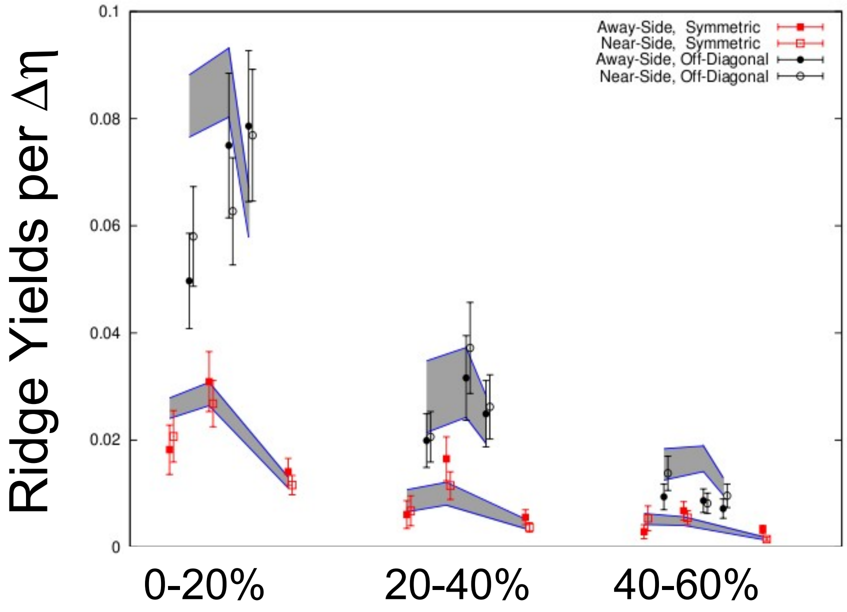
Comparison to models

3+1 viscous hydro in p-Pb collisions

Boxes: ALICE data for 0-20%



Bożek, arXiv:1112.0915



arXiv:1302.7018

Near and away side yields:

- **vary over a large range**
- **agree for each p_T and event class**

Common underlying processes?

Summary

- ALICE is obtaining a wealth of physics results from the first two LHC heavy-ion runs:
  - bulk, soft probes:
    - spectra, yields and particle chemistry
    - elliptic flow of identified particles
    - higher harmonics momentum anisotropy
    - femtoscopy

- Entering the precision measurement era

- Important new findings from the p-Pb run
  - Total particle multiplicity discriminates models
  - The “double-ridge” structure appears