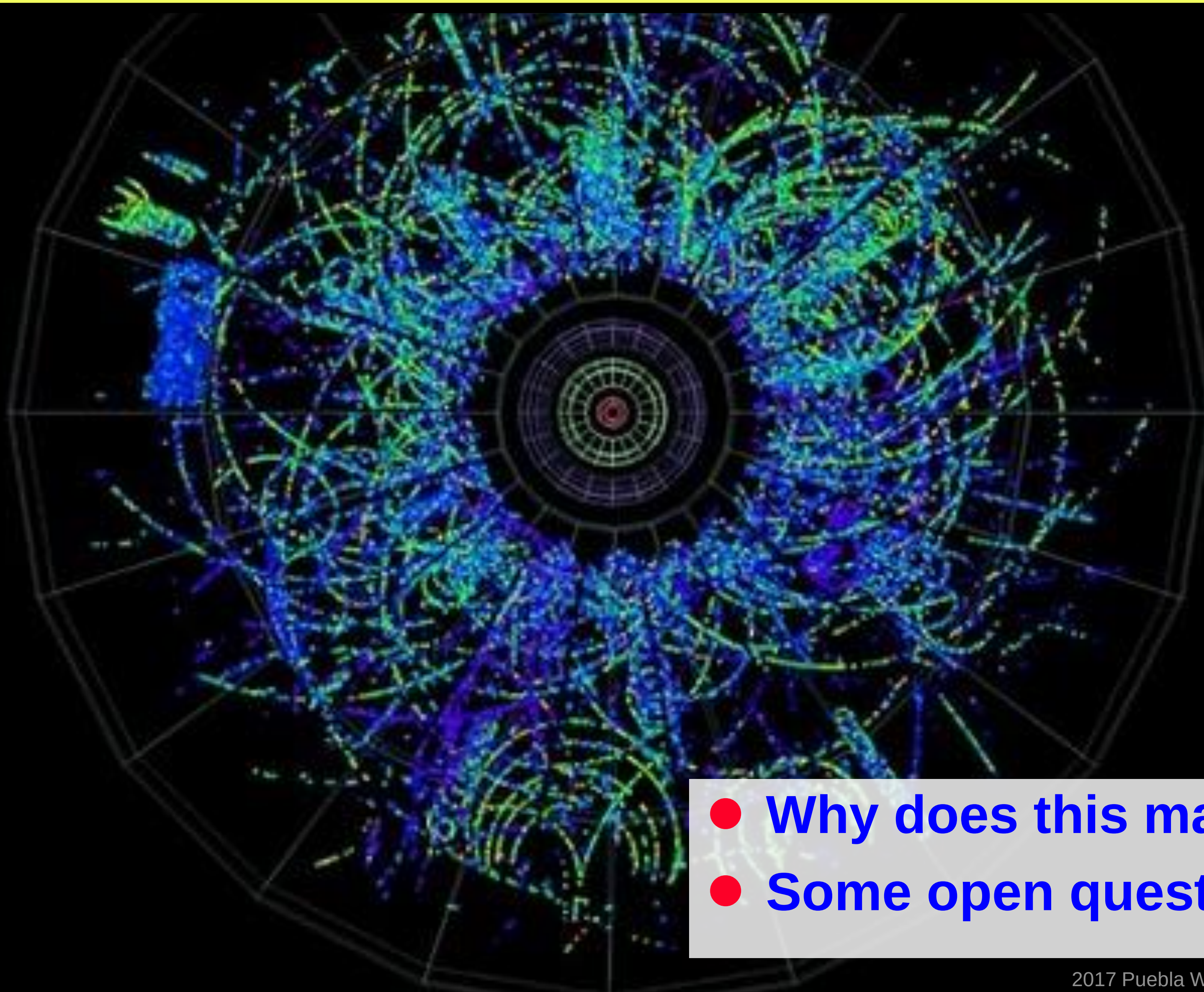
‘Collectivity’ in small systems

Some random collection of Key questions



- Why does this matter ?
- Some open questions

Answers …

How is it **!**

Macroscopic Matter properties

- What we know:
  - ⇨ increasingly precise measurements of **macroscopic properties**
    - ✪ η/S, ξ, q^, e^, D(iffusion), EoS, c_s, …
  - ⇨ good evidence for **deconfinement** (J/Ψ, Υ)
    - ✪ … **ng**
  - ⇨ s…
    - ✪ … sym ?)
  - ⇨ th…
    - ✪ **the interaction is much too strong !**

Equilibrium is part of the Problem (hides when and how achieved),

Out-of-Equilibrium may be a part of the Solution

Study out-of-equilibrium systems => test 'Dynamics at work'

=> Investigate small & dilute systems (pp/pA)

Why is it so **?**

Microscopic Dynamics

- What we don't know
  - ⇨ **What ARE the relevant dof** in the QGP ?
    - ✪ pseudoparticles, collective excitations (plasmons, ..), 'glueballs', ..
  - ⇨ **What is the dynamics ?** 'looking under the hood' of the sQGP
    - ✪ how can it happen so fast, and in very small systems (incl. pp ?)
    - ✪ what makes thermal particle ratios, why expansion seems isentropic, ..
  - ⇨ **Where is the onset (if any) ?**
    - ✪ how does collectivity & statistical behavior emerge with **size** & energy **density** ?

Why are small systems interesting ?

- 'Looking under the hood': what makes the sQGP tick ?
  - ⇨ stat. mechanics (thermo & hydro) hide very well the details: **d.o.f & dynamics**
    - ✪ **strength & limitation:** same results for different underlying 'stuff' (theories/models)
    - ✪ thermal system knows nothing about how and why it arrived in equilibrium
  - ⇨ go towards and **beyond the limits** of thermo & hydro
    - ✪ study deviations due to **finite size/finite time** (=> small systems)

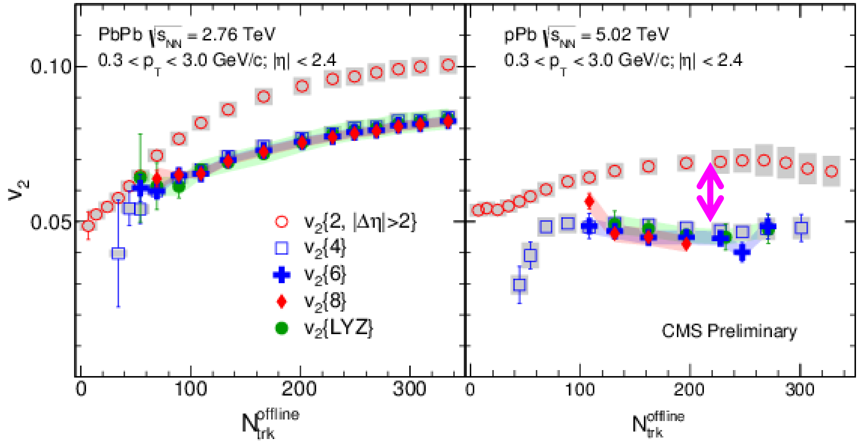
- 'Looking for the transition': how does (strong) collectivity emerge f(*r, t*) ?
  - ⇨ change size & lifetime & density (**pp -> pA -> AA**)

- 'Looking for the beginning': universal aspects of soft QCQ ?
  - ⇨ looking for connection & smooth evolution from **MB pp(e^+e^-)** to central **AA**, with **pA** the bridge in between

Collectivity

- weak (mathematical) definition:
  - ⇨ **SIMILAR** effect/probability for **ALL** particles (of some kind, say p_T/PID) in (almost) **ALL** events
    - drawn from the same inclusive single particle probability distribution (e.g. dN/dϕ)
    - probability can be arbitrarily small ! as long as it's the same for all particles/events
  - ⇨ Collectivity is **experimentally proven** in **AA** & **pA**

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



‘Collectivity’

'Standard Model' of heavy ion physics

- strong definition: {'thermo' + 'hydro'} - dynamics

⇨ **emerging-f(*t*)- strongly interacting** equilibrated matter with density/pressure **gradients**

⇨ **hydro-dynamics:**

- **LO**: radial (v_0) & elliptic (v_2) flow for > 95% of all particles (p_t < few GeV)
- **NLO**: higher harmonics v_n, PID (*m* dependence) of v_n ('mode mixing' of v_0 & v_2)
- **NNLO**: non-linear mode mixing ($v_n \neq \varepsilon_n$), factorization violation $r(p_T)$, EbE $P(v_n)$, …

⇨ **thermo-dynamics:**

- particle ratios (Statistical Model) to 10-30%
- in pp/pA: γ_s -> 1

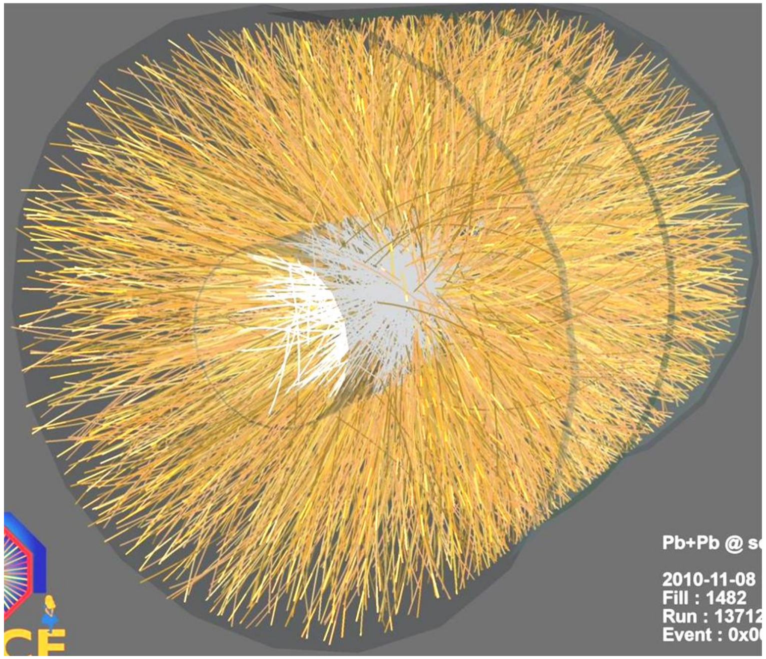
⇨ **thermo + hydro: => Space Time Evolution (STE)**

- HBT f(T, β): ($R(m_T)$, $R(N_{ch}^{1/3})$, $R_{out}/R_{side} \approx 1$)
- Charge Balance functions

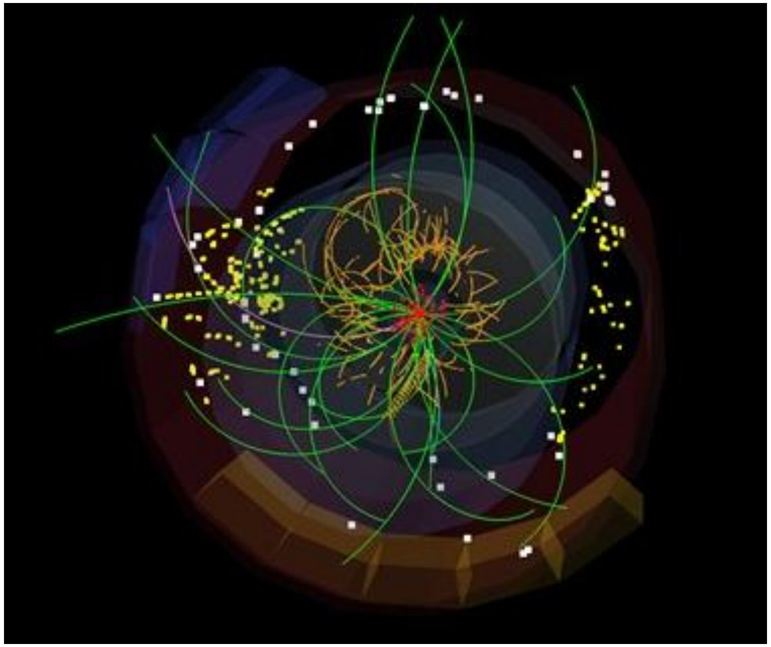
- strong Collectivity **consistent with ≈ all data in pp/pA/AA**

to (very) good accuracy, where it was measured..

1) Strong Collectivity down to dN/dy ≈ 0 ?

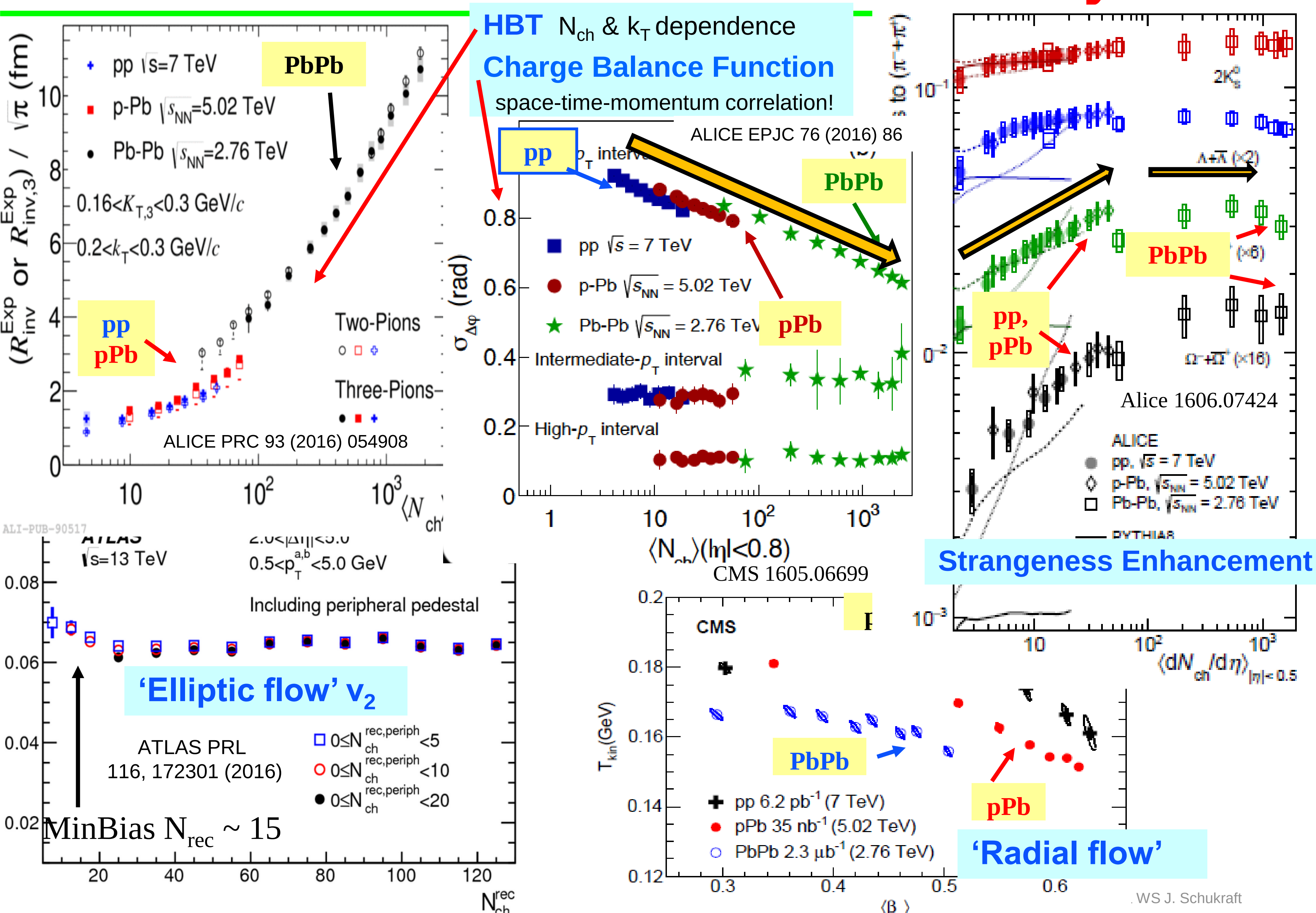


=>



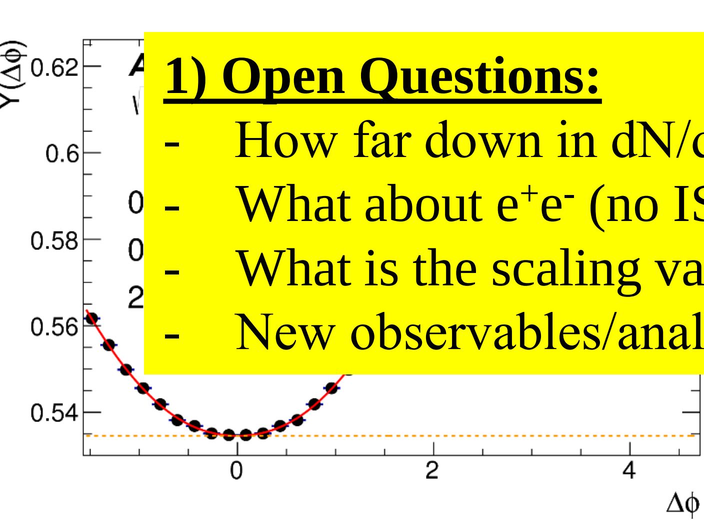
- Large&Dense (AA) <-> Small&Dense (centr. pA) <-> Small&Dilute (MB pp)
  - ⇨ TH relevance:
    - far outside applicability of statistical mechanics (thermo/hydro)
    - special property of sQGP (HIP) -> generic property of QCD (HEP)
  - ⇨ Experimental issue:
    - tiny signal, large background ('non-flow')
    - new analysis methods, new observables ?

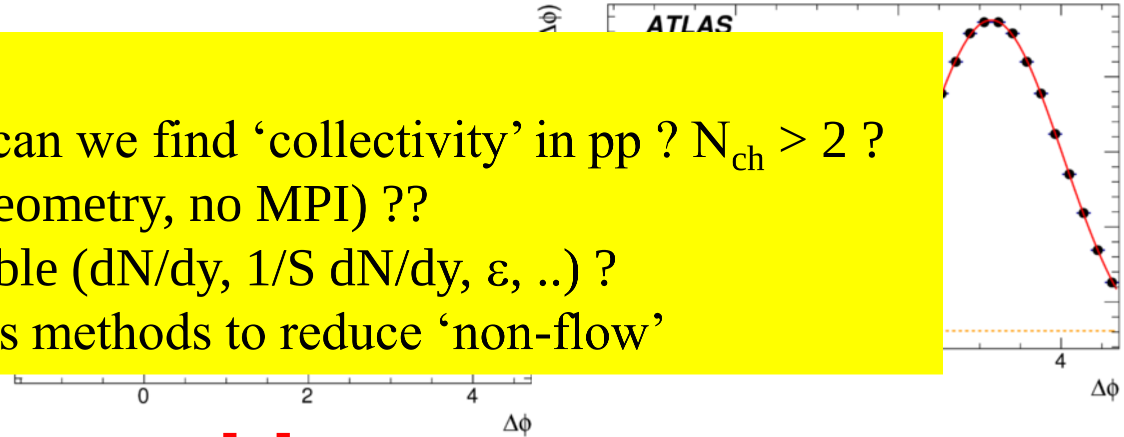
Continuous & smooth down to dN/dy ~ 0 !



WS J. Schukraft

Need to know what to look for..



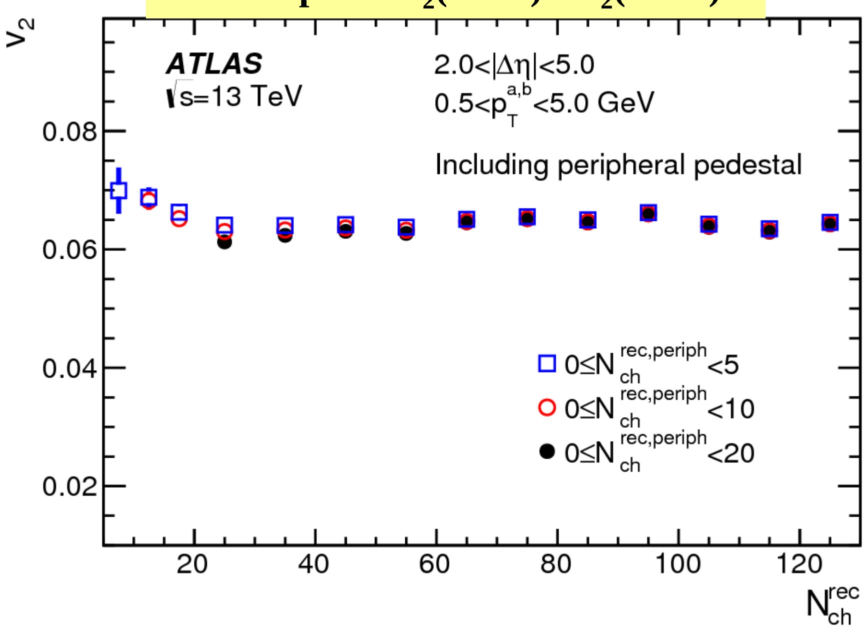


1) Open Questions:

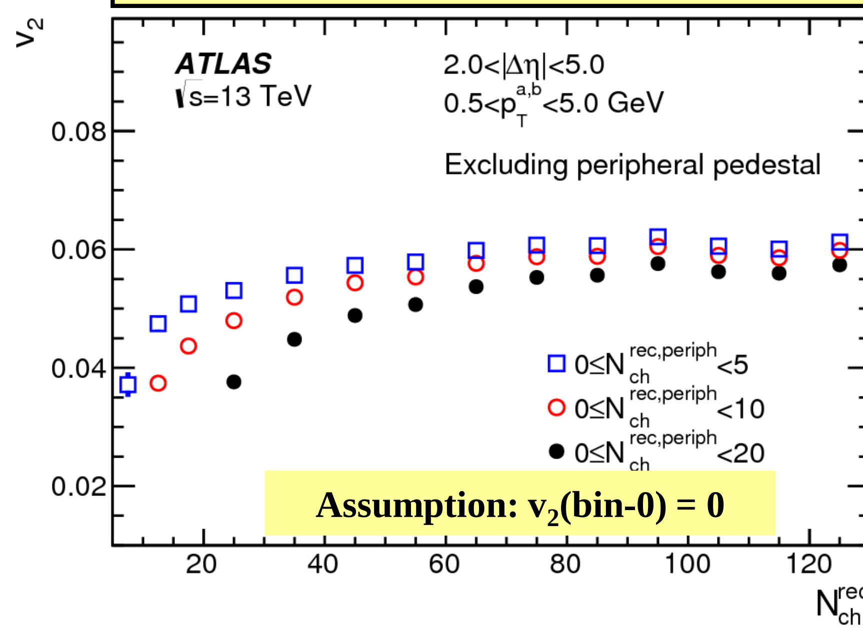
- How far down in dN/dy can we find 'collectivity' in pp ? N_{ch} > 2 ?
- What about e^+e^- (no IS geometry, no MPI) ??
- What is the scaling variable (dN/dy, 1/S dN/dy, ε, ..) ?
- New observables/analysis methods to reduce 'non-flow'

.. and how

Assumption: v_2(bin-0) = v_2(bin-1)

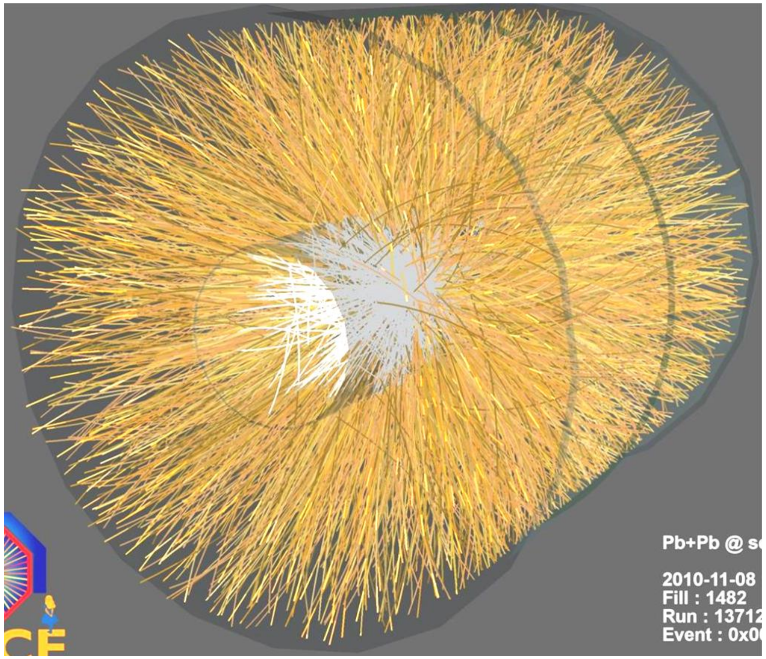


Bias could be tested with toy-model

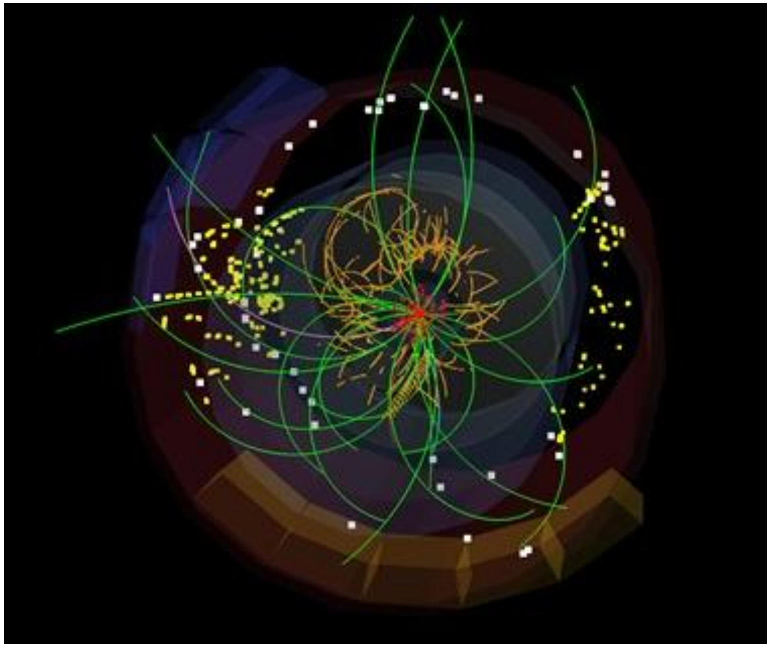


Assumption: v_2(bin-0) = 0

2) Qualitative or Quantitative Change ? (same same or different ?)



= ?



- High Density Paradigm: Hydro: K= λ/R << 1; # collisions/particle >> 1
  - ⇨ Pressure Tomography
- Low Density Paradigm: Transport + ?? # collisions/particle < 1
  - ⇨ Density Tomography

Two sides of the same coin

Or

Different physics & different observable consequences

Pressure or Density tomography ?

- sQGP Hydro model: Pressure tomography
  - ⇨ **<u>IS density homogeneities</u>** => pressure gradients => momentum anisotropy => spatial anisotropy dN/dϕ
  - ⇨ requires strong FSI, dense & large systems (small #K), low visc. 'ideal liquid'
  - ⇨ generates i) radial flow ii) azimuthal flow iii) space-time evolution STE
    - ✪ STE => HBT, CBF, but also some (small ?) part of non-linear mode mixing

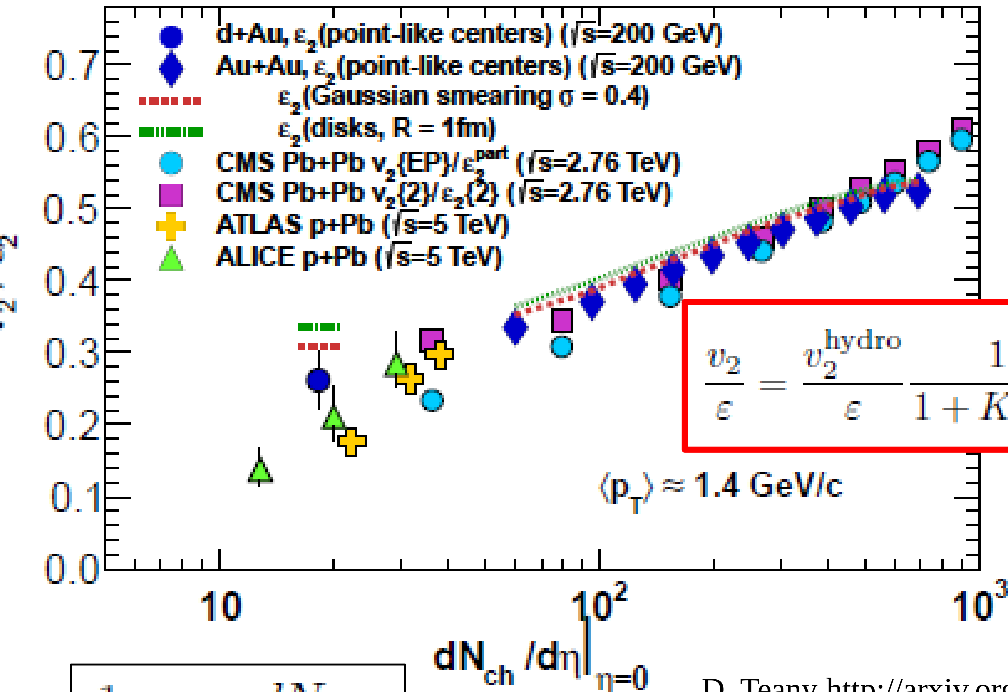
- sMOG X-ray model: Density Tomography

  sMOG=Mist Of Gray stuff
  - ⇨ **<u>IS density homogeneities</u>** => direct image by scattering
  - ⇨ requires some FSI, no problem with small or dilute systems (dilute = small contrast)
    - ✪ Density Tomography ('x-ray') => azimuthal flow
    - ✪ Color reconnection | Colour Ropes | hadronisation | ?? => radial flow AMPT 1601.05390
    - ✪ Free streaming + CF freeze-out (or ??) => space-time evolution Romatscke 1504.02529

sQGP or sMOG:
Same same or different ?

How small & dilute ?

- Change of $v_2/\varepsilon \approx$ x 5 dAu(RHIC) -> PbPb (LHC)
  - ⇨ Large systems/high $\sqrt{s}$: $v_2(p_T)$ = c, $\langle p_T \rangle$ ↑
  - ⇨ Small systems/ low dN/dy: increasing dilution K ↑



$$\frac{v_2}{\varepsilon} = \frac{v_2^{\text{hydro}}}{\varepsilon} \frac{1}{1 + K/K_0}$$

$$\frac{1}{K} = \frac{\sigma}{S} \frac{dN}{dy} c_s$$

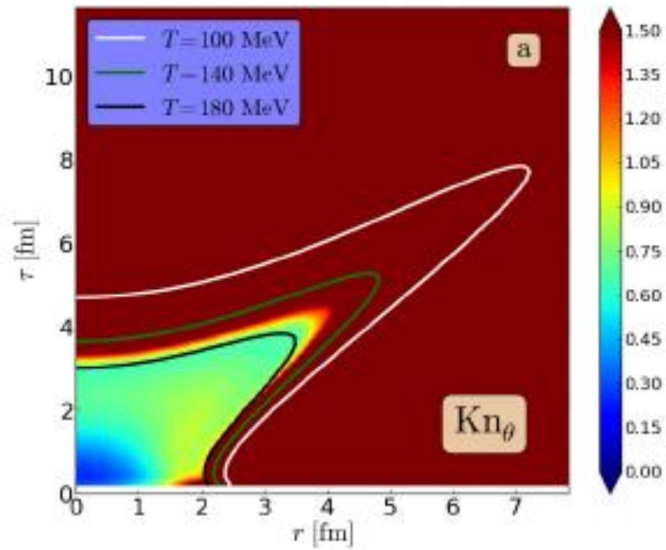
JYO: http://arxiv.org/abs/1106.4356

D. Teany http://arxiv.org/abs/1312

$$\frac{\ell_{\text{mfp}}}{L} \propto \frac{1}{T(\tau)L} \propto \frac{1}{(T_o L)^{2/3}} \propto \frac{1}{\sqrt[3]{dN/dy}}.$$

pp:pA:AA
dN/dy= 1:10:100
$dN/dy^{1/3}$= 1:2:5

H. Niemi 1404.7327



than in AA collisions: Knudsen number values at the $T = 180$ MeV hypersurface are already large enough to exceed the Kn = 0.5 limit. As a matter of fact, At the $T = 100$ MeV hypersurface the fluid dynamical description is clearly out of its applicability domain, with all Kn_θ values above 1.5. One can see that in pA collisions the fluid-dynamical description is pushed to its extreme, even with a constant $\eta/s = 0.08$ in the QGP phase. If a tem-

AMPT transport

- Dynamics is definitely oversimplified and probably wrong

  'Micky Mouse billiard balls' with tons of parameters

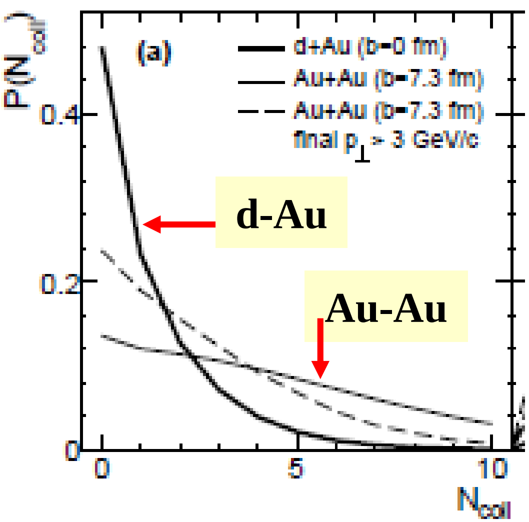
  ⇨ however, the hydrodynamics seems correct !

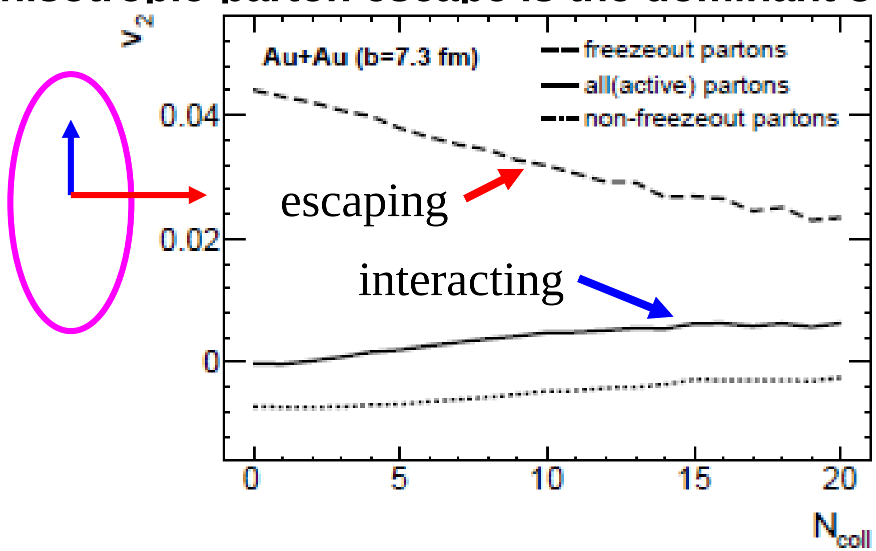
  ✪ what counts is 'lots of interacting stuff' (string melting + few mb σ)

- Common wisdom: AMPT = (a) kinetic transport underlying hydro

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

- Monkey wrench: '**Anisotropic parton escape is the dominant source' (1502.05572)**





Information is in the 'non-interacting' rays

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

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.

AMPT & Hydro in pp

- So far, both describe small & dilute systems

http://arxiv.or

<u>2) Open Questions:</u>

- Are HD hydro and LD transport **<u>observationally distinct</u>** ?
- If yes, which regime are we in pp/pA/AA
  (various indications that even AA is not in full therm+hydro equil.)
- If no, why does hydro work so well where it shouldn't ?
  (and what do we measure in pp, η/s means what ?)

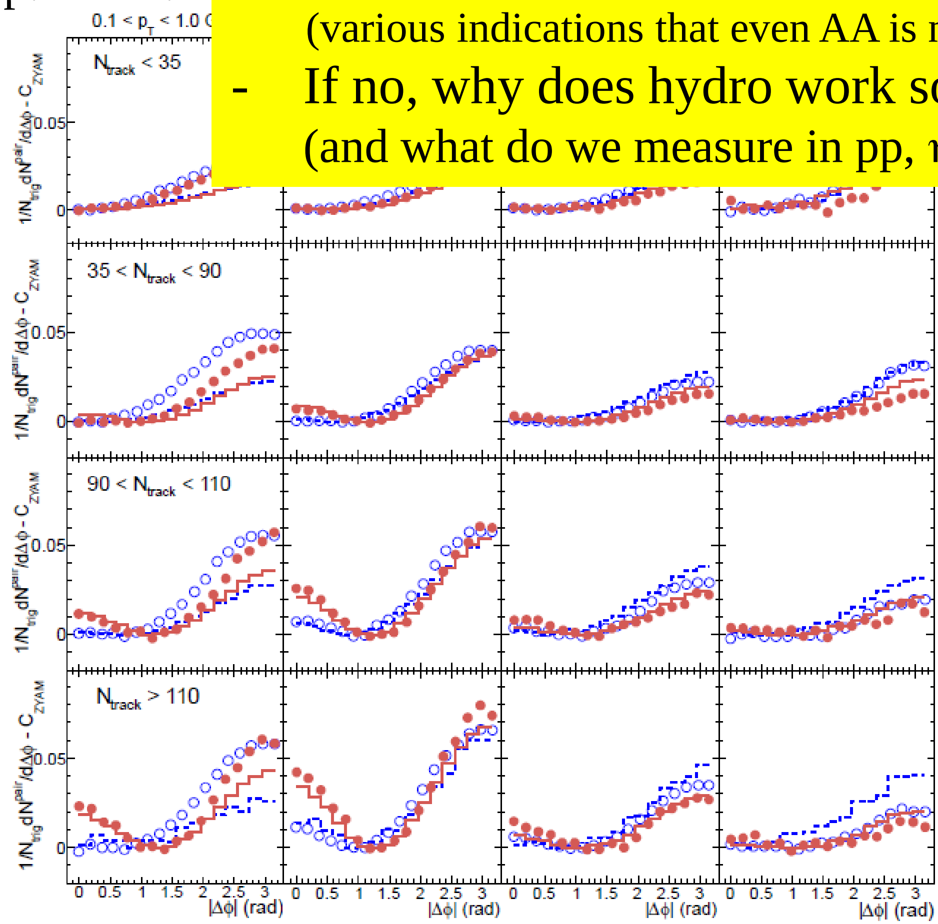
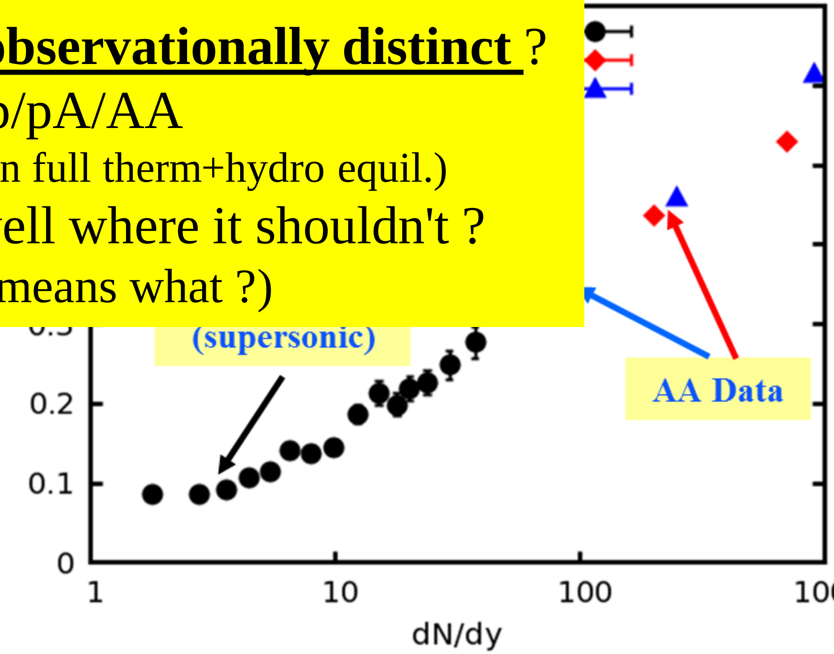


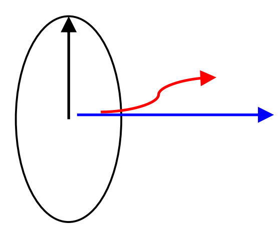
Figure 4: Distribution of pairs in p+p collisions at $\sqrt{s}$ = 7 TeV and p+Pb collisions at $\sqrt{s}$ = 5.02 TeV as a function of the relative angle $\Delta\phi$ averaged over $2 < |\Delta\eta| < 4$ in different p_T and N_{track} bins. Our results (solid and dashed curves) based on the AMPT model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



Possible differences:

- **Direct photon v_2 ?**
- **Nonlinear mode mixing ($v_4 \sim v_2^2$) ?**

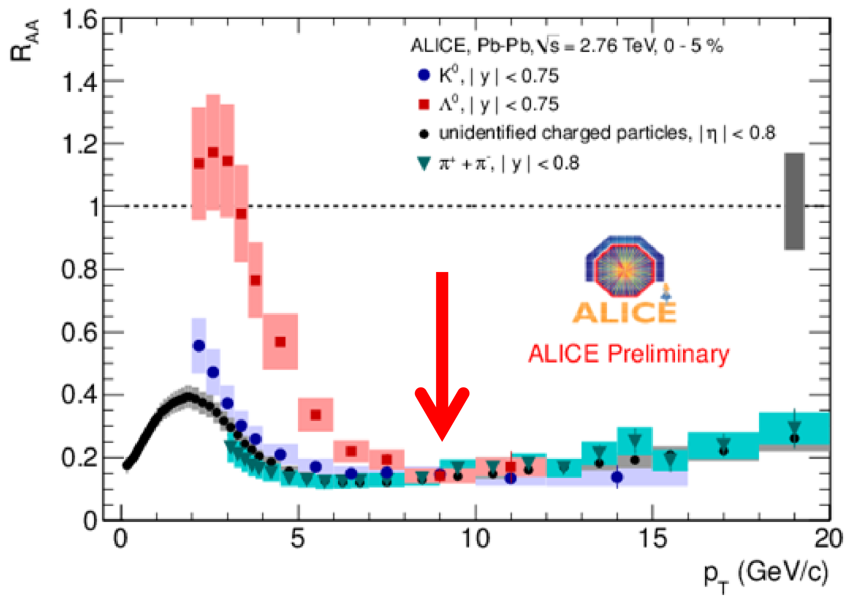
Shape evolution: pressure vs free streaming ?

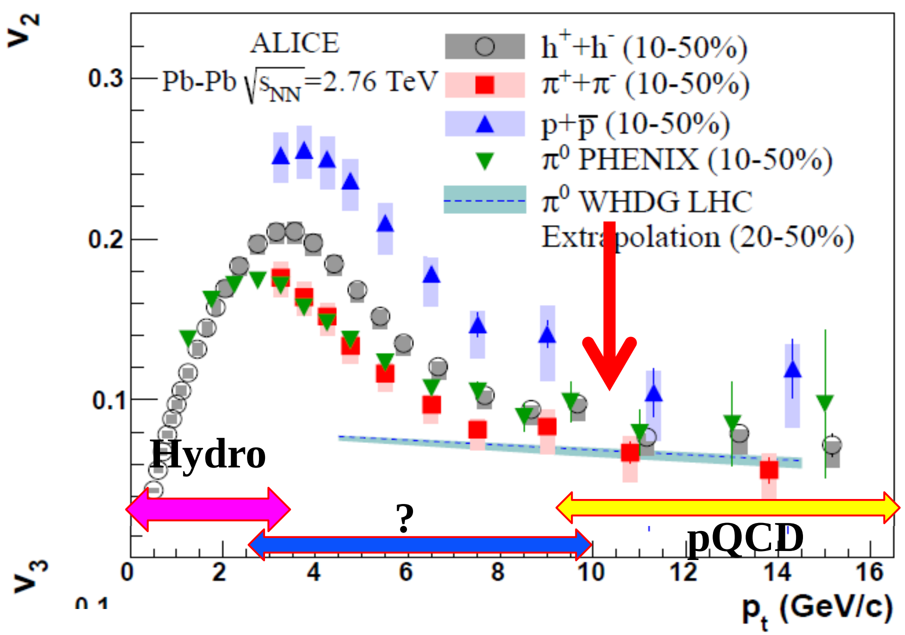


<u>Hydro:</u>	**<u>Transport:</u>**
more gradient	less matter
more flow	less scattering & BS
more N_{ch}	more N_{ch}
more γ ?	**less γ ?**

3) What happens after Hydro ?

- mass matters, up to a point (again, $p_T \approx v_2$)..
  - ⇨ presumably, 'falling out of hydro' is a smooth process (over large p_T range)
    - do we need **new physics** (eg coalescence) at intermediate p_T (4-10 GeV) ?
    - or a **smooth transition** between (hydro+thermo) and (jets+fragmentation) ?



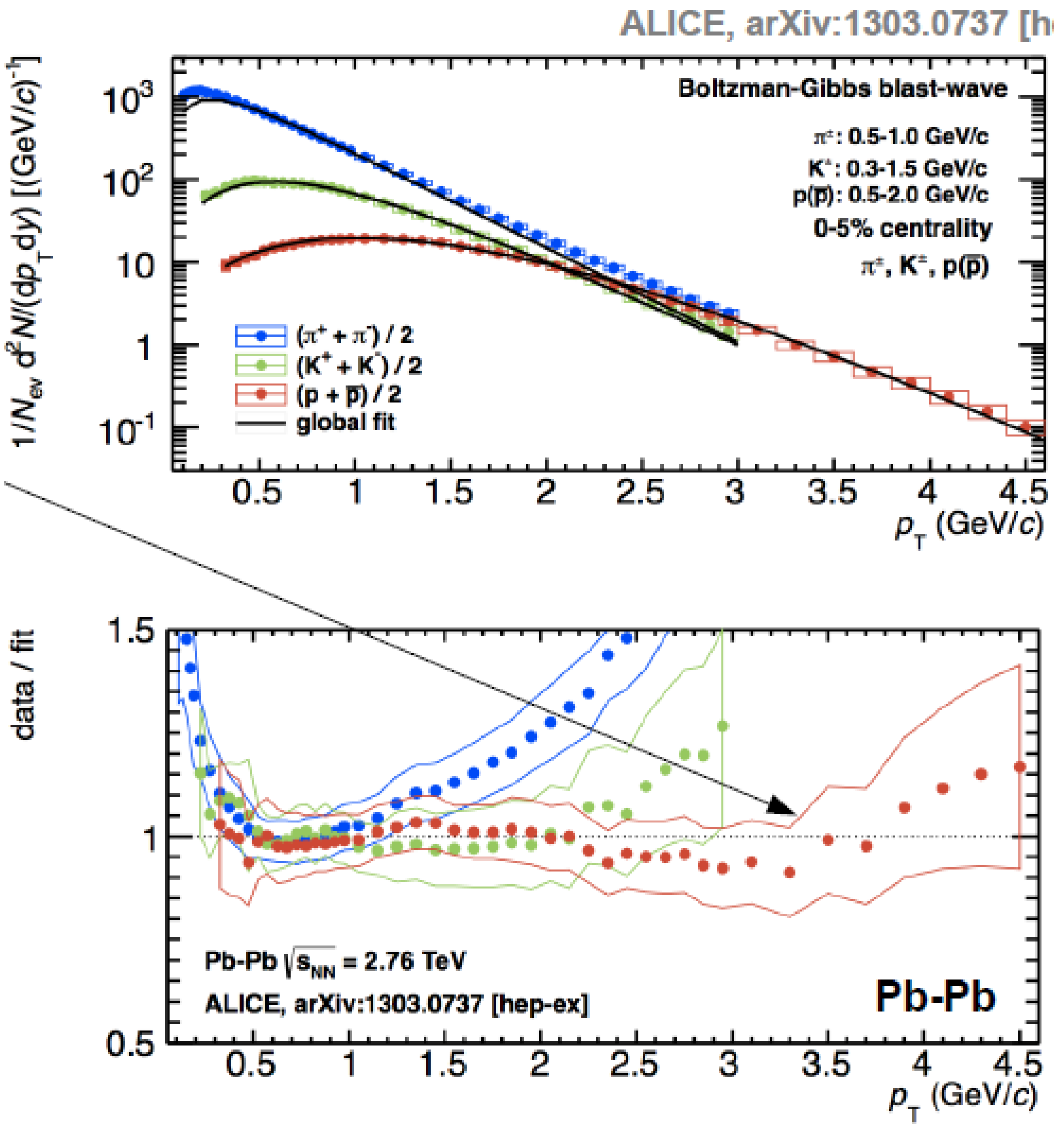


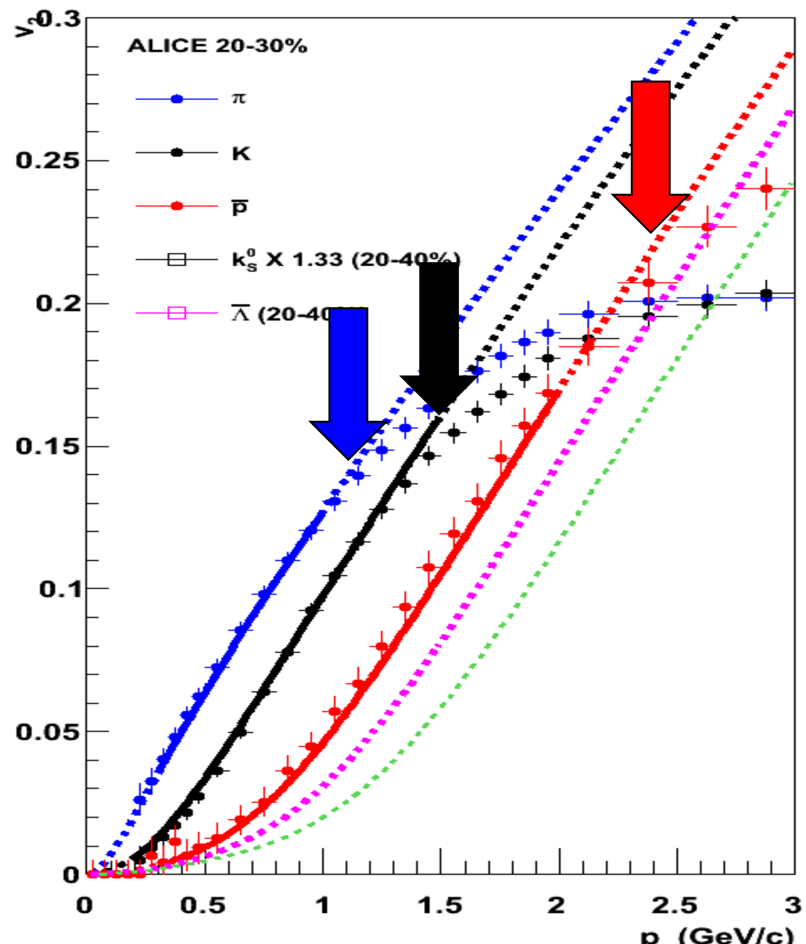
Varying size & density:
What effect in intermediate p_T ?

Hydro in PbPb

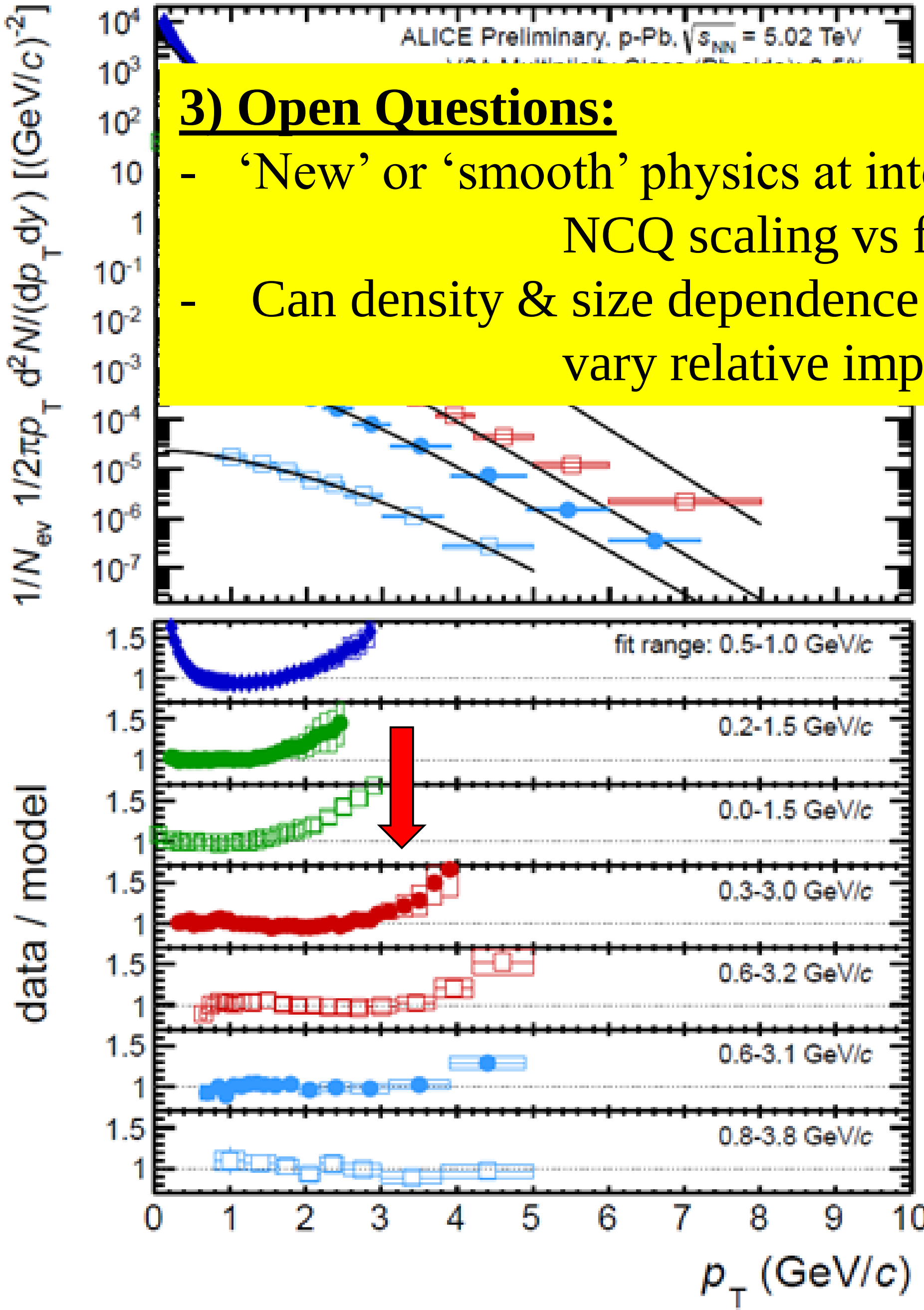
- ideal (BW) hydro ≈ ok < 1-2 GeV(p, K), > 3-4 GeV (p, Λ, ..) in both p_T and v_2
  - ⇨ deviations at high p_T: 'smooth decoupling ?'

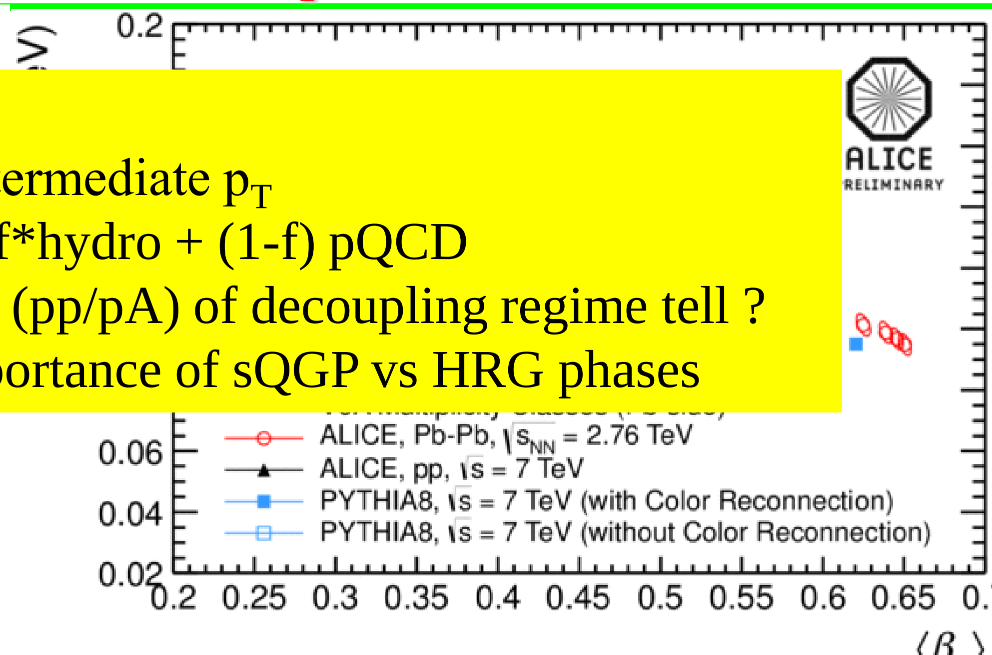
- deviation depends on mass
- ≈ same p_T in spectra and v_2





Radial Flow in pPb





3) Open Questions:

- 'New' or 'smooth' physics at intermediate p_T
  NCQ scaling vs f*hydro + (1-f) pQCD
- Can density & size dependence (pp/pA) of decoupling regime tell ?
  vary relative importance of sQGP vs HRG phases

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**

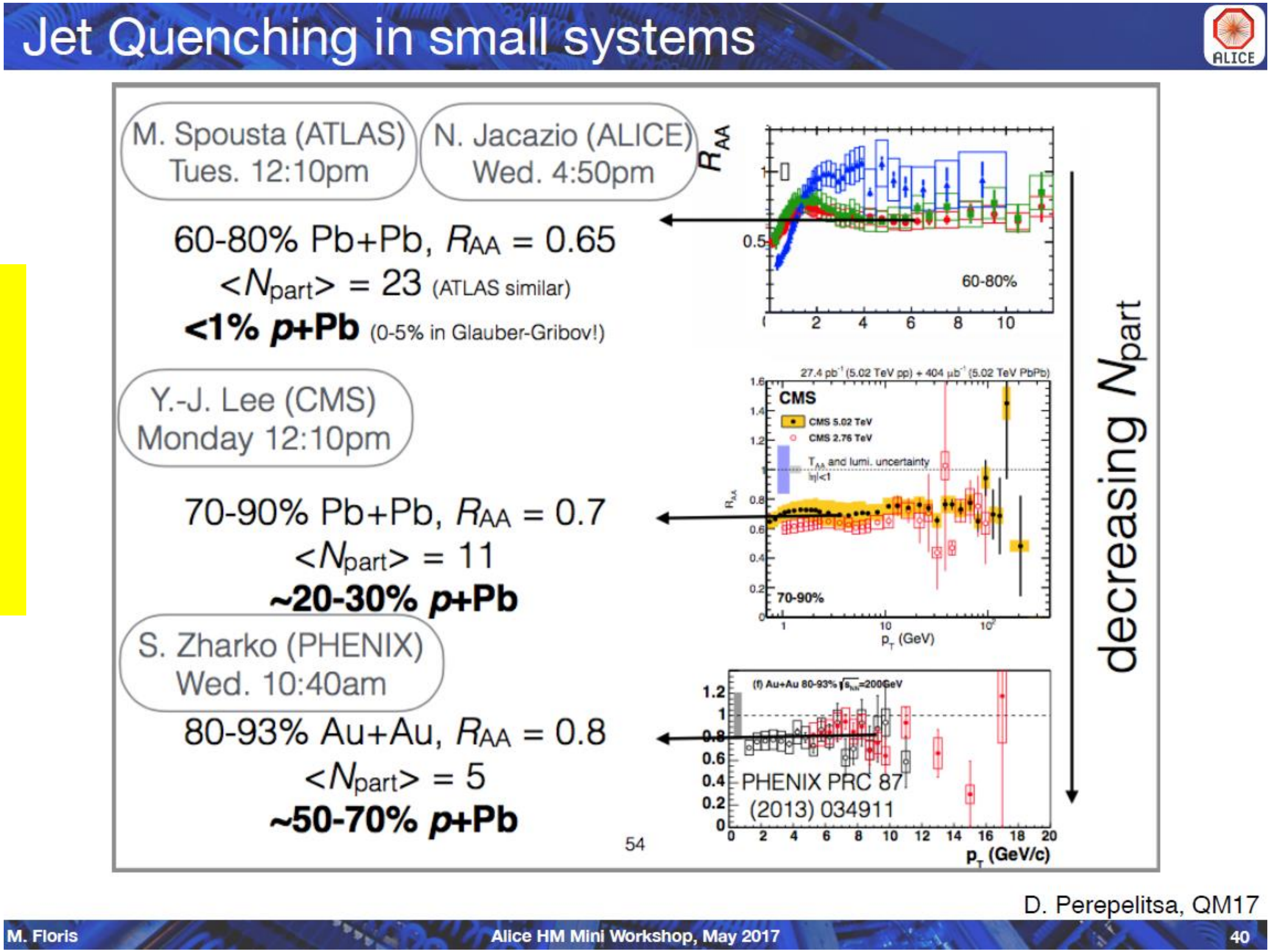
no (or little) hadronic rescattering ?

clear & direct view on the sQGP ??

4) What about 'hard Probes' ?

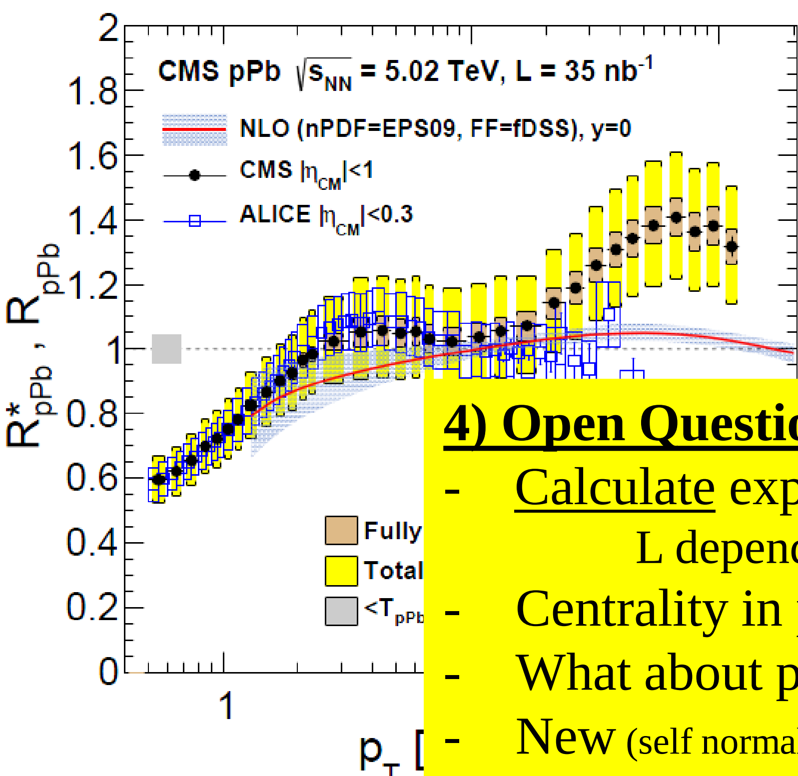
- flow and jet-quenching closely connected
  - ⇨ liquid => strong FSI => energy loss
- Naïve expectation: O(20-30% effects) for MB pA

Peripheral PbPb:
Almost certainly a 'centrality' bias rather than jet-quenching !



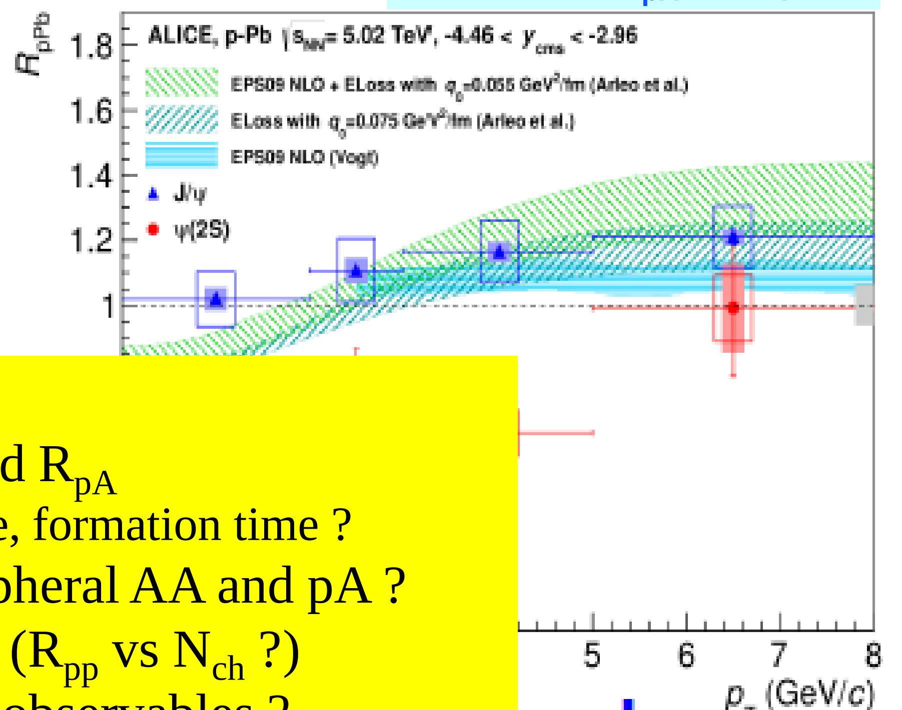
Jet Quenching & Quarkonia in pA

- Conventional Wisdom: Not (non-trivially) modified in pA
  - ⇨ beware of confounding CNM effects & limited accuracy !!
    - ✪ how to disentangle IS/CNM from sQGP in pp/pA if there is no comparison data ?
  - ⇨ only quantitative comparison between expectation(theory) and data will tell !!
    - ✪ how much jet-quenching/quarkonia melting would actually be expected ??



Syst. error in MI

J/Ψ & Ψ' R_{pA} vs p_T



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(2014) 073]

4) Open Questions:

- Calculate expected R_{pA}
  L dependence, formation time ?
- Centrality in peripheral AA and pA ?
- What about pp ?? (R_{pp} vs N_{ch} ?)
- New (self normalized) observables ?
  v2@high p_T, h+jet, γ+jet, Υ(2)/Υ(1)..

Small Systems .. wherever they lead..

- Confront and 'digest' the size/density systematics
  - ⇨ **Factorize & separate** into <u>different</u> **pp** (CR, CGC) and **AA** (QGP, hydro) physics ?
    - naturally & economically, without epicycles..
    - where to put pA ?

  - ⇨ **Incorporate** into <u>a united</u> thermo & hydro sQGP picture ?
    - **extend** 'dense matter' framework **down** to zero density, non-ec
    - **extend** 'dilute transport' framework up to central AA (AMPT like ?)

(personal) **Hypothesis: The physics underlying soft 'collectivity' signals is the same in AA, pA, and pp (e+e- ?):**
Even if dominant in AA and hardly discernable in pp
It is a <u>generic</u> property of all strongly interacting many-body (≥2?) systems.

Thermodynamical String Fragmentation
T. Sjöstrand 1610.09818

The **understanding of soft hadronic physics is changing** under the onslaught of LHC pp data …
.. we have an interesting and challenging time ahead of us, where some of the most unexpected new LHC observations may well come in the low-p_T region rather than the in high-p_T one.

backup

Heavy Ion Paradigm

1986
Commissioned
by TD Lee

AA:
‘Hot Matter’
modifications (“R_{AA}”)

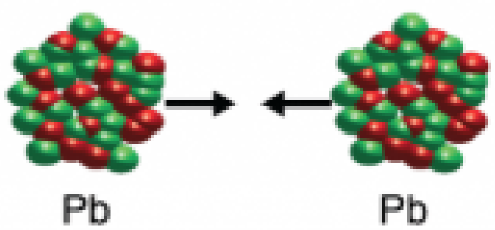
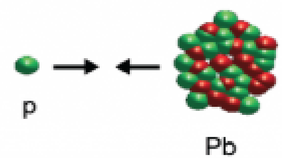
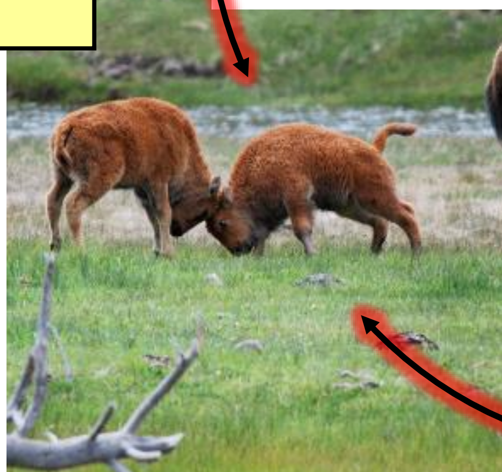


Fig. 14. Ink painting masterpiece 1986: “Nuclei as Heavy as Bulls, Through Collision Generate New States of Matter” by Li Keran, reproduced from open source works of T.D.Lee.

pA:
CNM
modifications

pp:
SEP
Somebody Elses Problem
e.g. (n)pQCD



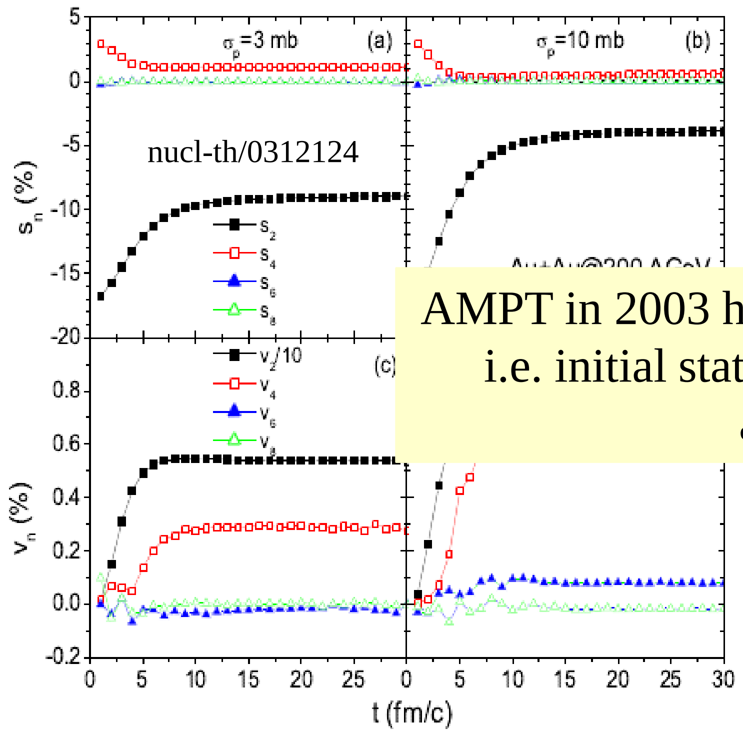


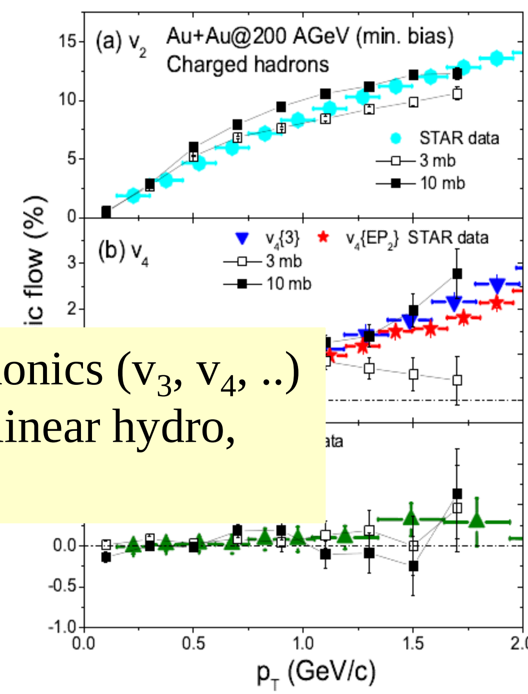
Summary **Hypothesis: The physics underlying soft 'collectivity' signals is the same in AA, pA, and pp:**
It is a <u>generic</u> property of all strongly interacting many-body (≥2?) systems.

- **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, ^{3}He), v_n(b), $v_n(p_T)$, v_2(LYZ), v_n(PID)
  - ⇨ **4)** HBT $r(N_{ch}, m_T)$
- **.. make the hypothesis increasingly more likely** (but not proven, yet !)
  - ⇨ a most 'natural' assumption, to <u>be proven wrong rather than right</u>
  - ⇨ subtle is the lord, but malicious he is not
- **What is is the 'underlying dynamical physics' ?**
  - ⇨ **sQGP: thermo + hydro** dynamics ('at the edge') ?
  - ⇨ **sMOG**: strongly **interacting FS matter** with **density gradients** (<u>1502.05572</u>)
  - ⇨ **CGC+CR+.:** weakly int. **dense IS matter** + some conspiracies (also in AA !!)
  - ⇨ ???
- **Why should we care ?**
  - ⇨ **leave the comfort zone** of infinite size equilibrium to study **dynamics**
    - ✪ from small & dilute -> large & dense: **emergence & limits of 'collectivity'**
  - ⇨ looking 'under the hood' is mandatory(and fun), whatever we may find !

The unreasonable success of AMPT

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 nonlinear hydro,
and nobody noticed !!

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.

Almost as good as hydro

http://arxiv.org/abs/1210.0512

LO: v_2

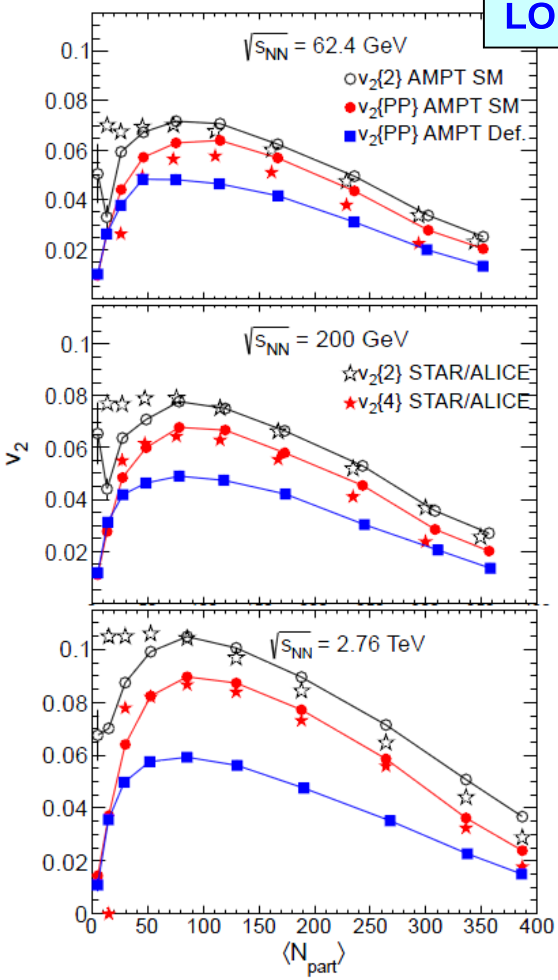


Figure 2: Elliptic flow data from AMPT and experiments at $\sqrt{s_{NN}}$=62.4 GeV, 200 GeV [STAR], and 2.76 TeV [ALICE]. For the String Melting calculation we show v_2 calculated relative to the participant plane $v_2\{PP\}$ defined by the positions of the nucleons and using the two particle cumulant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

NNLO: mode mixing in EP correlations

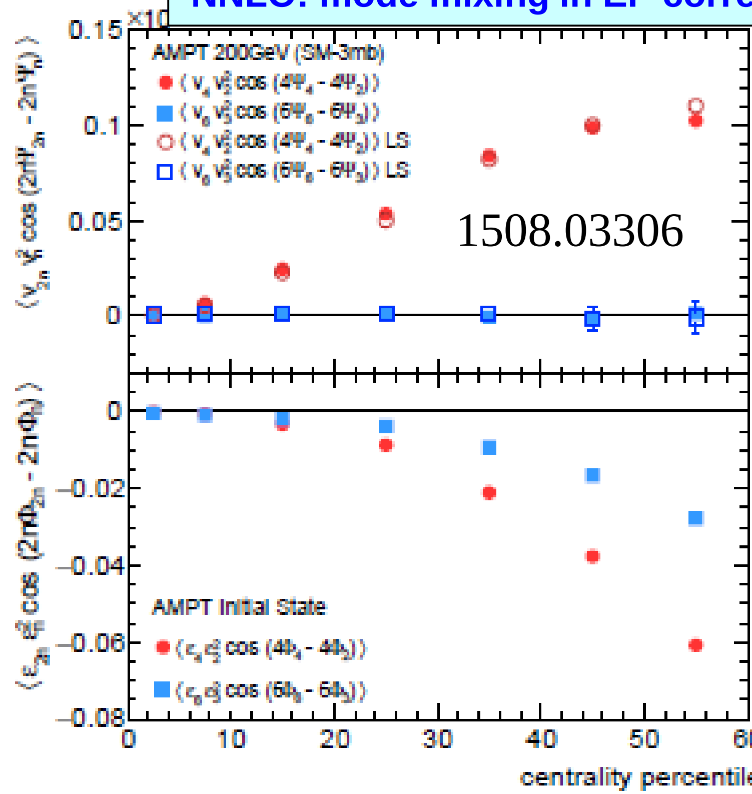


FIG. 7: (Color online) Centrality dependence of the final state QC{3}(top) and the 2-plane correlations in the initial state (bottom) in Au+Au collisions at 200 GeV by AMPT String-Melting.

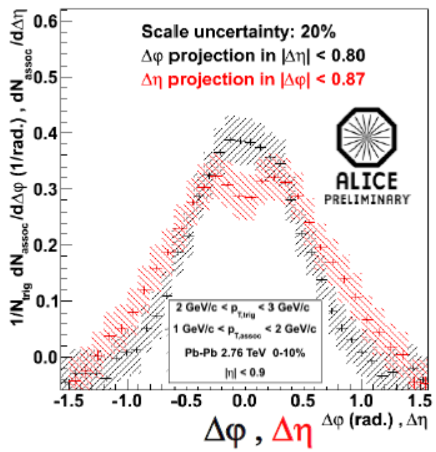
4 (bottom). The negative initial (Φ_4, Φ_2) correlation and positive final (Ψ_4, Ψ_2) correlation observed in the AMPT model are in qualitative agreement with viscous hydrodynamic calculations [17]. There is a clear sign change of the 4th-order and 2nd-order plane correlation during the collision system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

Double humped near side peak shape

Departure from Gaussian

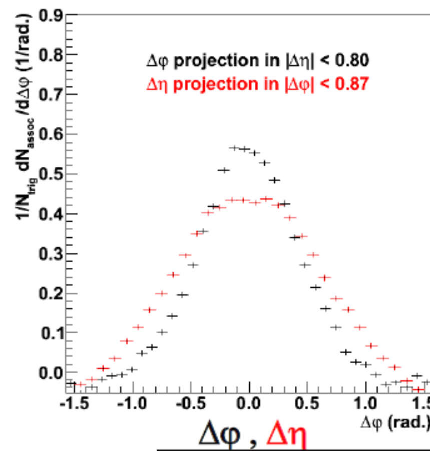
- The lowest p_T bin shows a structure with a flat top in $\Delta\eta$
- This feature is reproduced by AMPT

Data



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

AMPT



http://arxiv.org/abs/1507.06194

- Qualitative and quantitative agreement of with AMPT compatible with hypothesis of with the flowing bulk

Paper Proposal - Jan Fiete Grosse-Oetringhaus

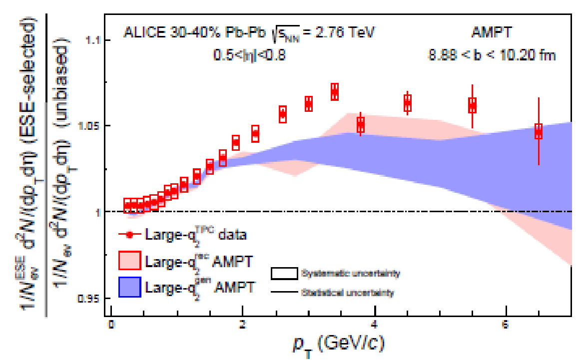
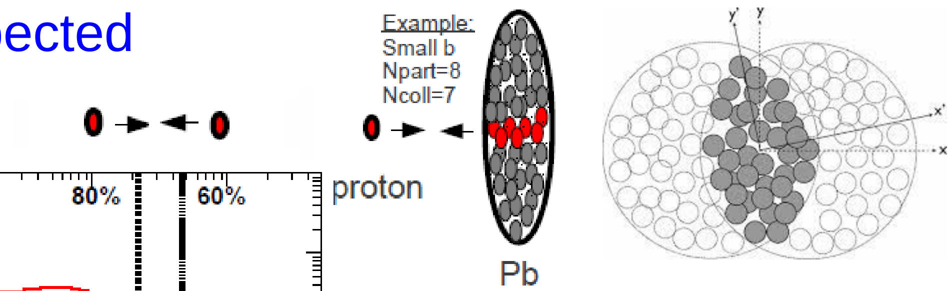
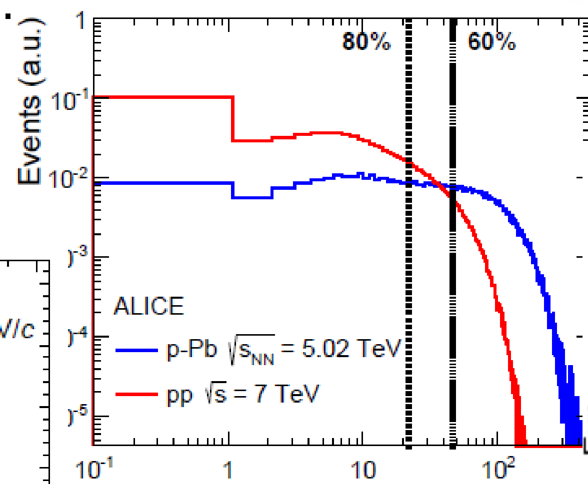


Fig. 15: Ratio of the p_T distribution of charged hadrons in the large$-q_2$ sample to the unbiased sample for the q_2^{TPC} selection. Data points (full markers) are compared with AMPT Monte Carlo model (bands).

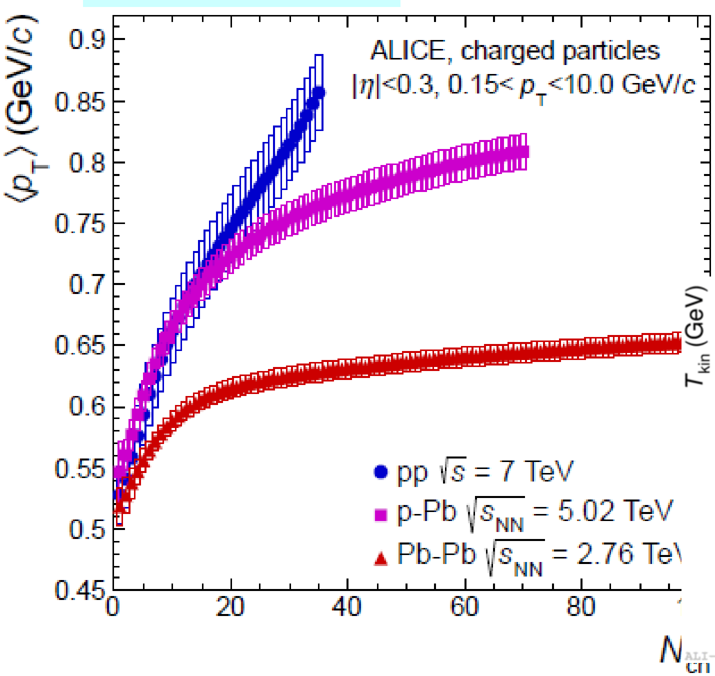
A priori: pp ≈ pA @ same dN/dy

- LO pp = pA: N_{ch}, transverse size & shape => Initial State $\varepsilon(x,y)$ similar:
  - ⇨ **experimentally verified**: final state R(pp) ≈ R(pA) < R(AA) @ same N_{ch} (≈ N_{part})
  - ⇨ IF there is collectivity in central pA, THEN there is no reason why not in 'central' pp
- NLO pp ≠ pA: some differences expected
  - ⇨ MPI vs N_{coll}, transverse ε-profile, $d\sigma/dN$ => bias, jet fraction, ..

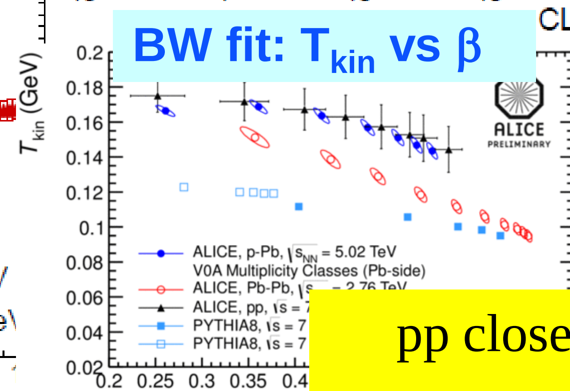




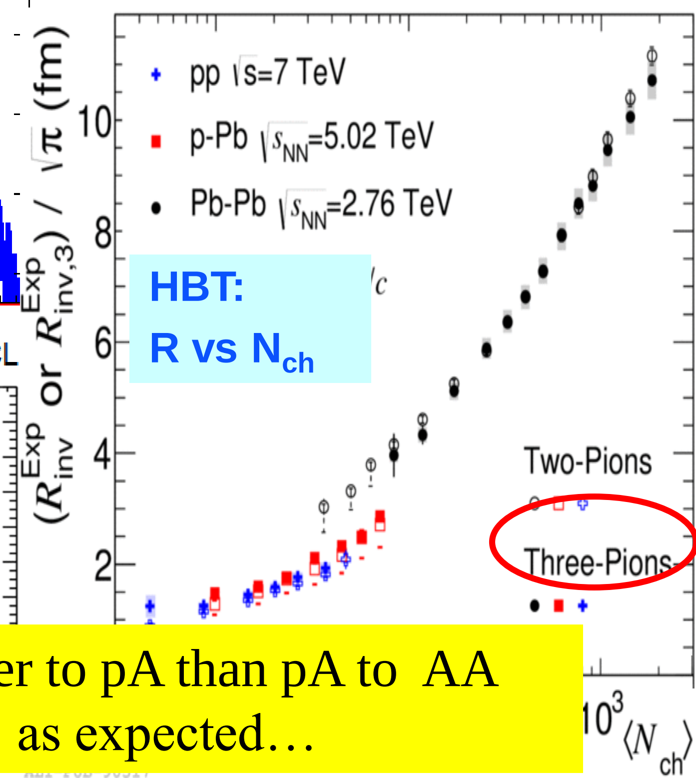
<p_T> vs N_{ch}



BW fit: T_{kin} vs β



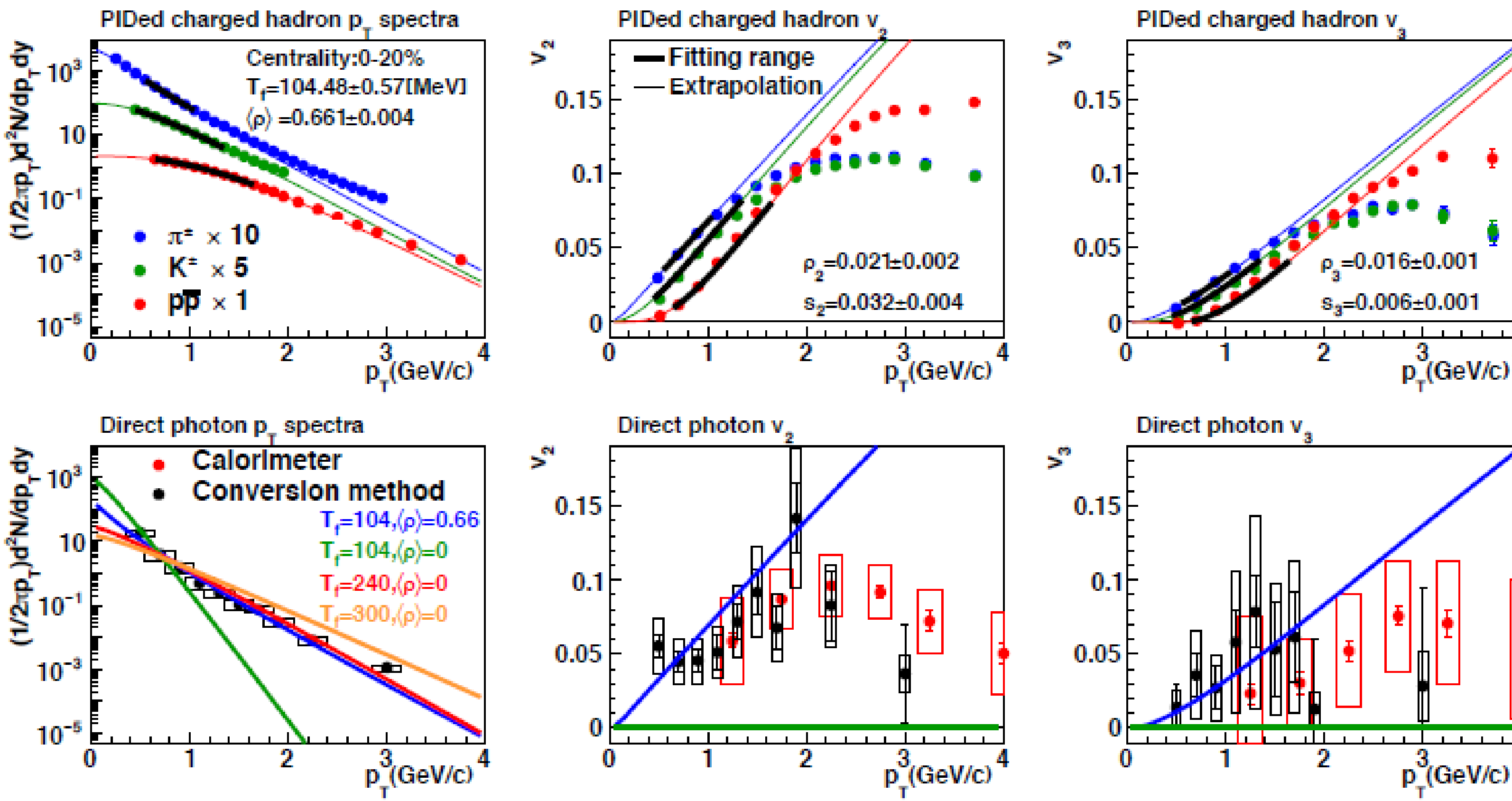
HBT: R vs N_{ch}



pp closer to pA than pA to AA as expected…

Blast-wave fit

Sanshiro Mizuno, D-thesis



- Blast wave fit to direct photon p_T spectra & v_n
  - p_T spectra can be fitted with the same T for hadrons
  - Reasonable description for v_2 & v_3

'Decoupling' at RHIC at somewhat lower p_T

Facts & 'Fiction'

- Experimental facts:
  - ⇨ **weak collectivity** proven in **AA**, essentially proven in **pA**, less well known in **pp**
    - ✪ **'all particles in all events'** must be part of any physics model
  - ⇨ strong coll. **(thermo & hydro**) compatible with vast 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}**

- Hypothesis: There **IS*** collectivity in small systems at high N_{ch} !
  - ⇨ 1) **pA ≈ AA**: mostly based on measurements (@same N_{ch})
    - ✪ many similar phenomena <=> similar underlying physics
  - ⇨ 2) **pp ≈ pA**: based on a priori expectations, increasingly on measurements
    - ✪ similar IS & FS in pp and pA @ same dN/dy => similar collective physics
    - ✪ mind the jet-bias in pp !
  - ⇨ 3) **≈ ≠ =**: differences are interesting and important to study !
    - ✪ finite size/finite time/non-equilibrium effects teach us about dynamics

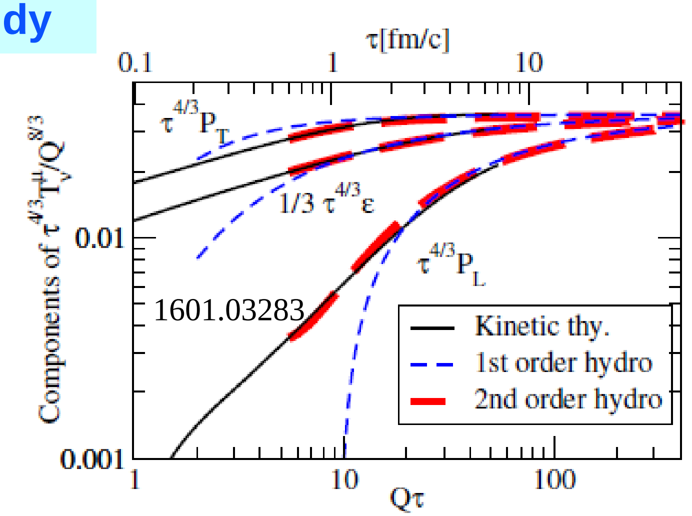
* of the same type as in large systems, i.e. AA

pA ≈ AA: Objections

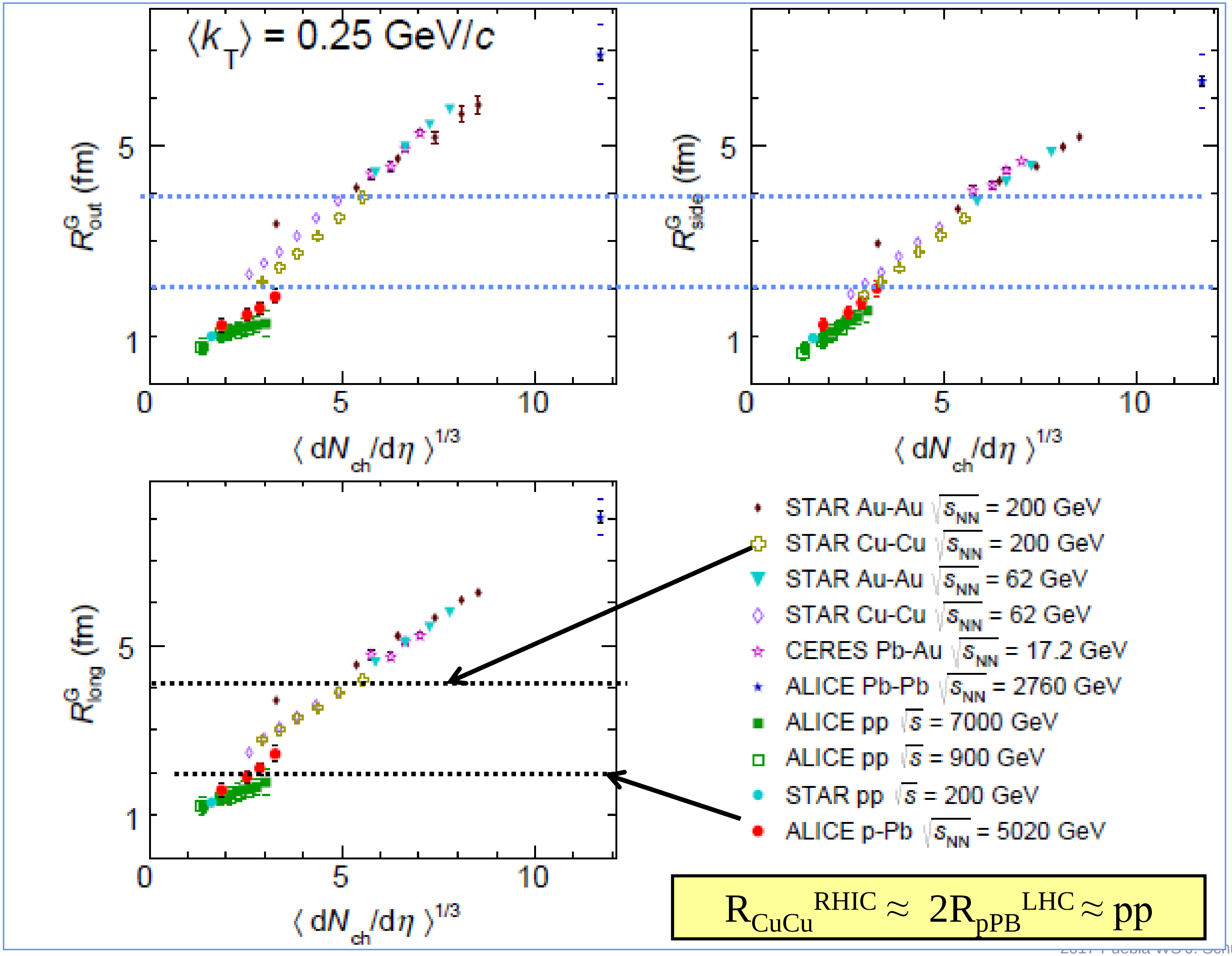
- sQGP: no ideal liquid w/o jet-quenching (energy loss) (conformal scaling ?)
  - ⇨ hydro is dimensionless **($K_n = \lambda/R << 1$)**,
    - ✪ R = 1-2 fm may be big: τ_0(<0.2 fm/c?), $\eta/S \approx 0 \Rightarrow \lambda \approx 0$; $1/\langle p_t \rangle \approx 0.3$ fm
  - ⇨ energy loss has dimension: **$\Delta E \sim (\Delta x\text{-}a)^n$**, Δx = path length, a = formation length
    - ✪ $\Delta E_{pA} > 1/5 \times \Delta E_{AA}$ (n = 1, a = 0), and possibly much more
    - ✪ is measured **R_{pPb} (in)compatible** with <u>quantitative</u> expectations for ΔE ?
- hydro not applicable (large K_n, large gradient/viscosity corrections, ..)
  - ⇨ Why then does it still give a ‘correct’ answer ??
  - ⇨ we may need different TH tools, not necessarily different physics ?
    - ✪ 'hydro' : physics driven by gradients in SI matter
    - ✪ smoothly extends into 'partial hydro/decoupling/non-equilibrium' regime ?

Thermalisation study

- difference is size is significant, but not huge !
  - ⇨ made up (largely ?) by higher density ?



HBT radii pp, pA, AA



$R_{CuCu}{}^{RHIC} \approx 2R_{pPB}{}^{LHC} \approx pp$

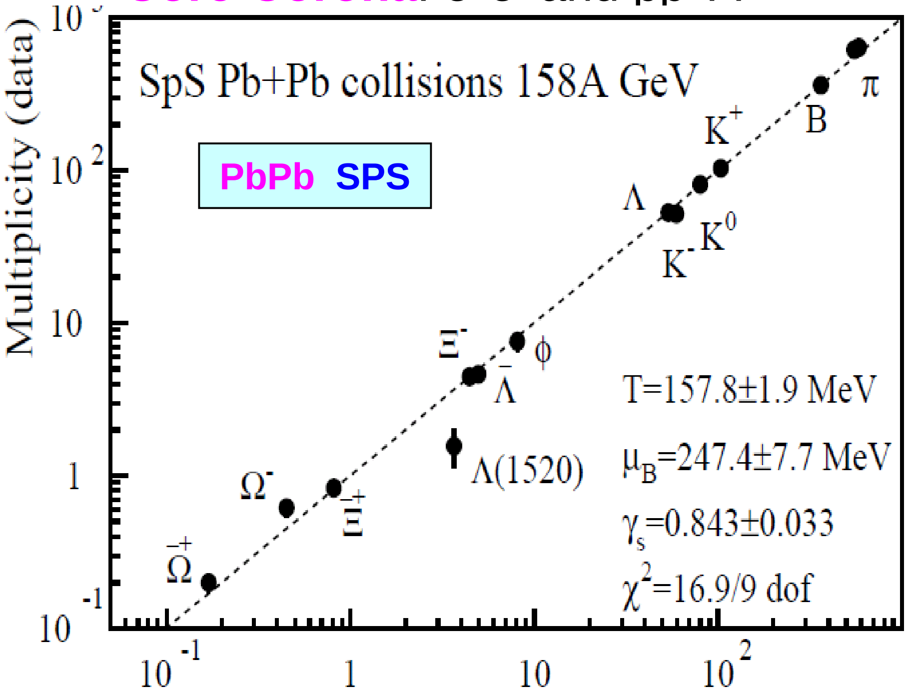
pA ≈ AA: Objections

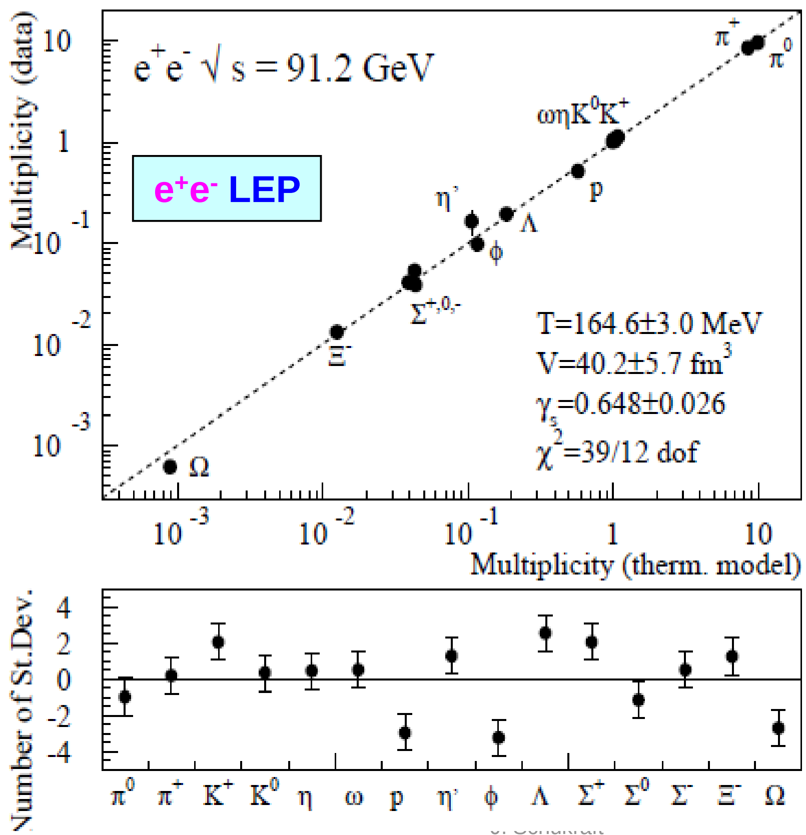
- similar phenomena ≠> same physics
  - ⇨ <u>counter examples:</u>
    - elliptic flow: v_2(< 2 GeV) = **hydro** ($\Delta\rho/\Delta x$), v_2(> 10 GeV) **quenching** (ρ)
      linked by geometry and SI matter, but driven by distinct physics
    - radial flow: AA **hydro**, pp: **Color Reconnection** ?
      'hydrodynamics' similar (emission from boosted system T, β), dynamics different
  - ⇨ **likelihood** argument: better if <u>many independent phenomena</u> are involved
    - 'razor': **What looks more natural & simple:** different or similar physics ?
  - ⇨ we should not jump to conclusions, either way, but …

pp-pA-AA: Similarities & Differences

- Similar Particle Production
  - ⇨ Striking & very non-trivial similarities between pp(e+e-) and AA
  - ⇨ Striking & very non-trivial difference ('strangeness enhancement):

- Different Explanations & no connection (in general):
  - ⇨ **Born** (pp) <-> **Evolving** (AA) into equilibrium
  - ⇨ γ_s(GC) or r_c (SC) are fudge factors , i.e. not predicted/calculable as f(√(s),dn/dy, ..)
  - ⇨ **Core-Corona**: e^+e^- and pp ??





Particle Production:
Data versus Thermal Model

Known, but often ignored

- No quantitative interpretation which smoothly describes small & large
  - ⇨ despite evident relevance for understanding HOW we reach thermal ratios..

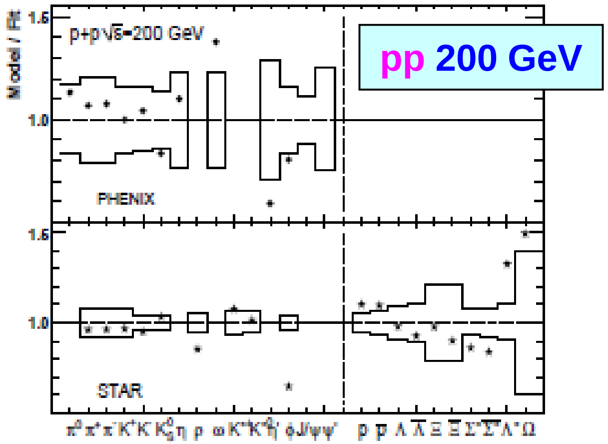


FIG. 18: Ratio of integrated yields predicted by the statistical model [40] to those of the constrained Tsallis fits for various particles. Results for fits to PHENIX data are shown in the upper panel and STAR data in the lower panel. The band reflects the uncertainty of the Tsallis fit results and includes ... rediction was ... IX. There are ... l dashed line

Particle production:
Data /Thermal Model

Although statistical models are not commonly used to describe $p+p$ data the agreement of the statistical model calculation with the STAR results was found to be accurate for most particles except for the ρ, ϕ, and Λ^* [40]. Leaving aside baryons, for which the calcula-

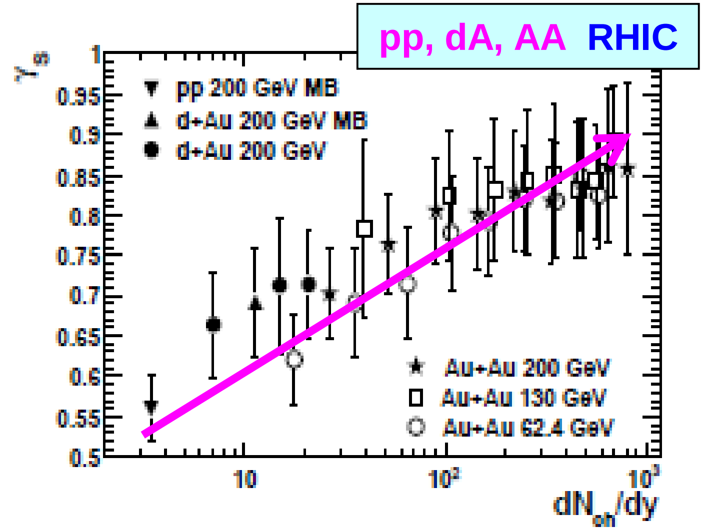


FIG. 35: Strangeness suppression factor extracted from chemical equilibrium model fit to pp and d+Au data at 200 GeV, and Au+Au data at 62.4 GeV, 130 GeV, and 200 GeV. Errors shown are the total statistic... ties. The 200 GeV pp and Au+... Ref. [17].

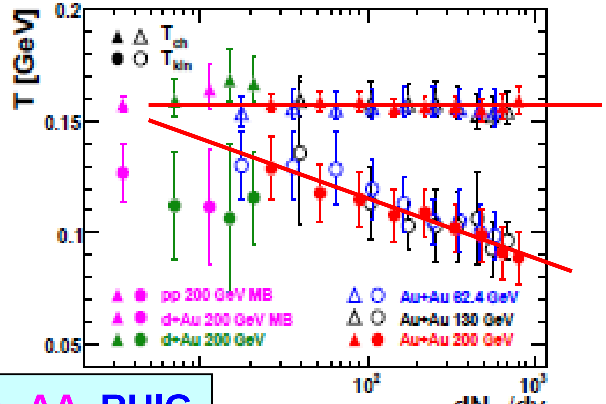
Particle production:
γ_s vs dN_{ch}/dy

nificantly suppressed in these collisions. The strangeness suppression factor in medium-central to central Au+Au collisions is not much below unity; the strangeness and light flavor are nearly equilibrated, which may suggest a fundamental change from peripheral to central collisions.

Star http://arxiv.org/abs/0808.2041 Phenix http://arxiv.org/abs/1005.3674 STAR http://arxiv.org/abs/nucl-ex/0607033

Momentum Spectra

- Known, but not really understood

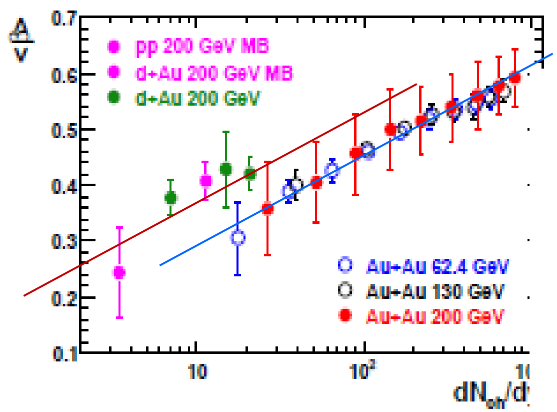


pp, dA, AA RHIC

Radial Flow fit (BW):
T & <β> vs dN_{ch}/dy

FIG. 36: (color online) Che... peratures as a function of ... Errors shown are the total ... tainties. The 200 GeV *pp* and Au+Au data are taken from Ref. [17].

The interpretation of the fit parameters is difficult in the context of a $p+p$ collision where the system is not expected to thermalize and the volume is small. It is important to note that in a pure thermal model, all emitted particles would be expected to reflect the same temperature. Non-thermal effects such as flow would modify this result. In $p+p$ collisions, the particle spectra clearly show different slopes and those slopes are not in agreement with the T parameter that results from the statistical model fit to the particle ratios. As no flow is thought to be present in the $p+p$ system and the results of Section IV B support that conclusion, this result is a further indication of contributions to the particle spectra from non-thermal processes like mini-jets.



pp 200 GeV

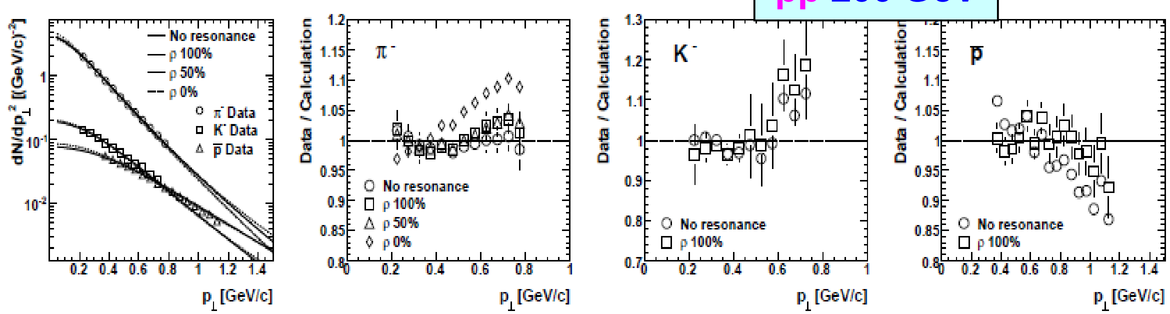


FIG. 37: (color online) Average transverse radial flow v... ity extracted from blast-wave model fit to pp and d+A... 200 GeV, and to Au+Au collisions at 62.4 GeV, 130 ... and 200 GeV as a function of the charged hadron multipl... Errors shown are the total statistical and systematic u... tainties. The 200 GeV *pp* and Au+Au data are taken ... Ref. [17].

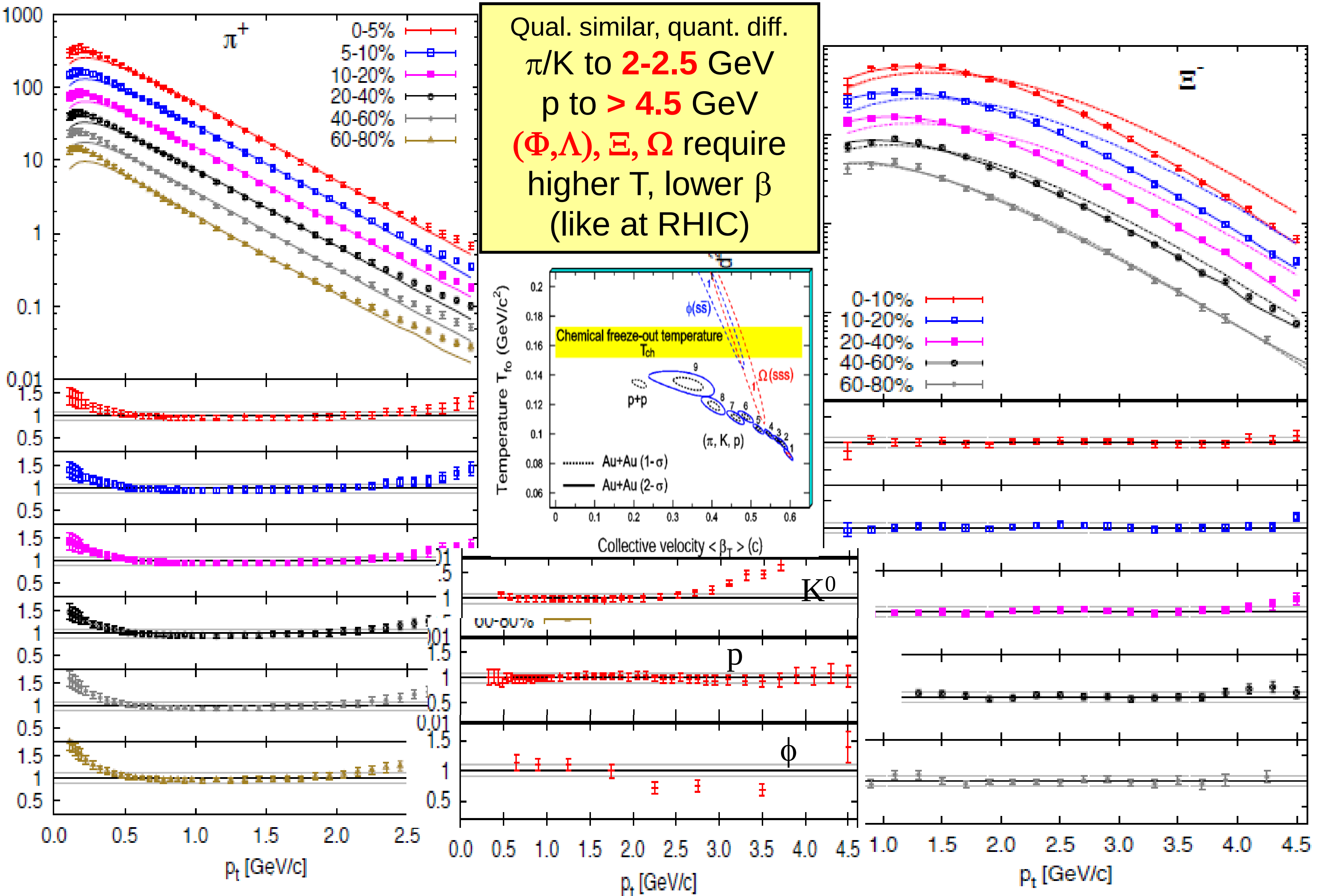
FIG. 45: Left panel: Fit of the calculated spectra (curves) to the measured ones (data points) in *pp* collisions at 200 GeV [17]. Four calculated spectra are shown for π^- (upper curves): including resonances with three different ρ contributions and excluding resonances. Only two calculated curves are shown for K^- (middle curves) and $\bar{p}$ (lower curves): including resonances with ...nels: Ratios of data spectrum to calculations. Two calculations are shown for ... for π^-. Error bars a... point-to-point ... for two sets of the data points for π^- and only one set for K^- and $\bar{p}$.

Radial Flow fit (BW):
Data/Fit (π,K,p)

Star http://arxiv.org/abs/0808.2041

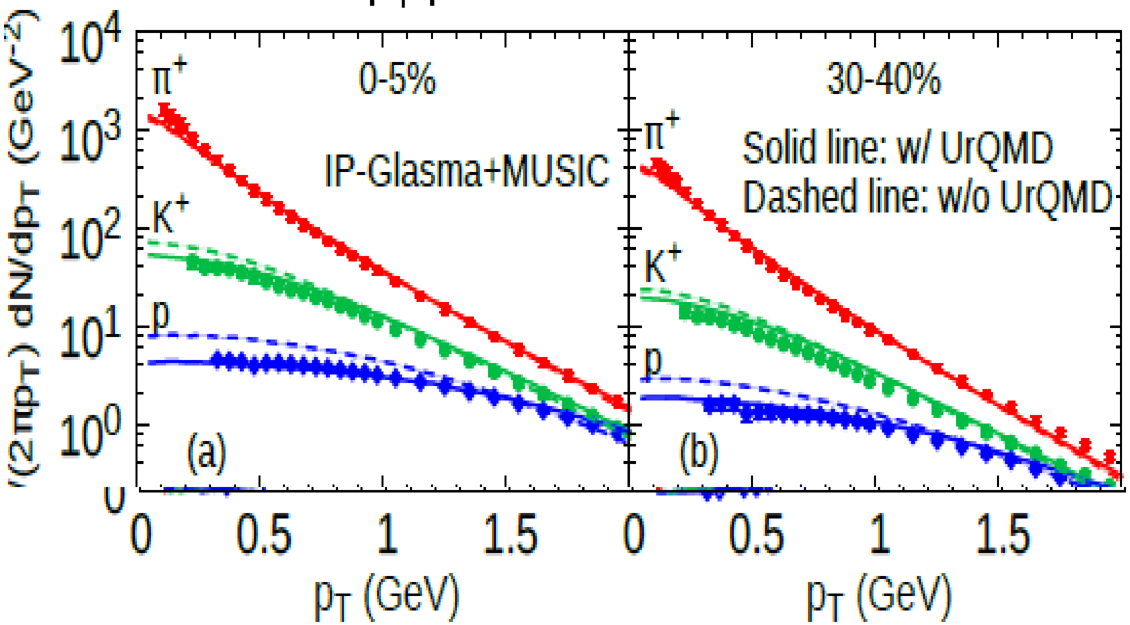
BW + Resonances (DRAGON 1502.01247)

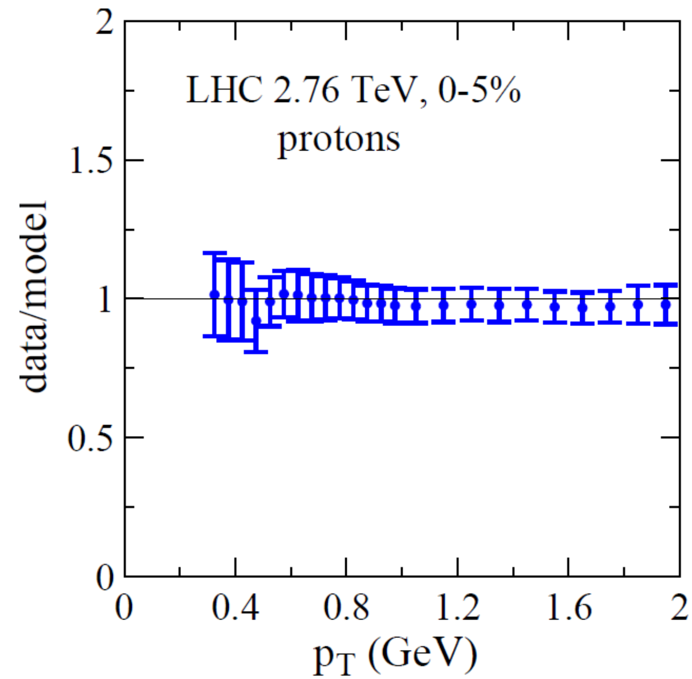
Qual. similar, quant. diff.
π/K to **2-2.5** GeV
p to **> 4.5** GeV
(Φ,Λ), Ξ, Ω require higher T, lower β
(like at RHIC)

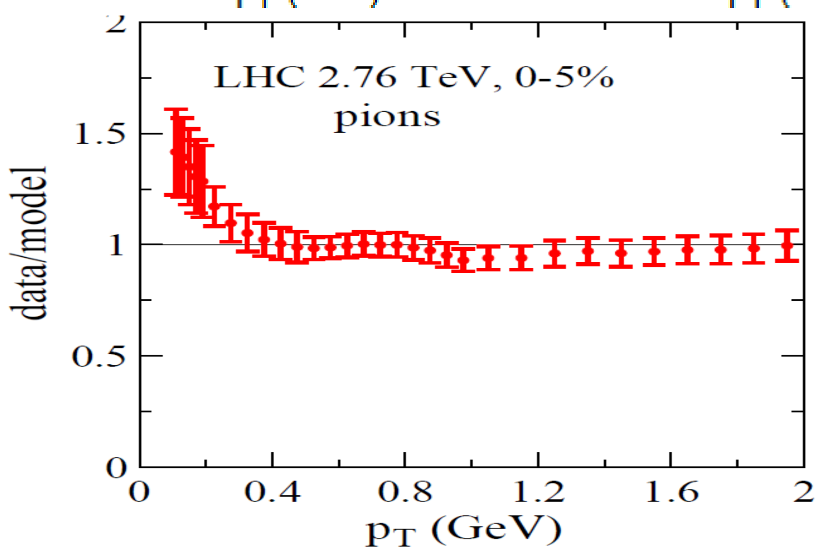


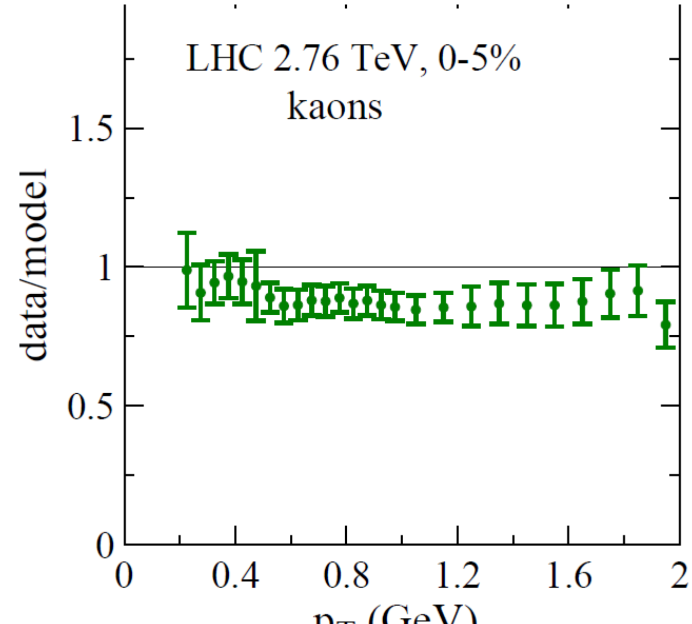
Real Hydro: IP-Glasma + Music (1502.016750)

- Data/Model (almost too perfect !)
  - ⇨ note that low p_T pion excess !!









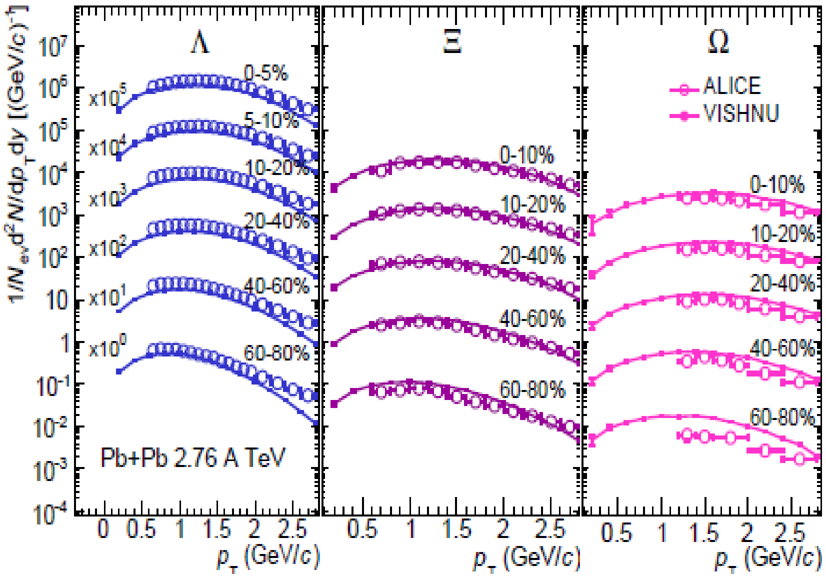
Hydro + AB does very well
(T, β, v_n)

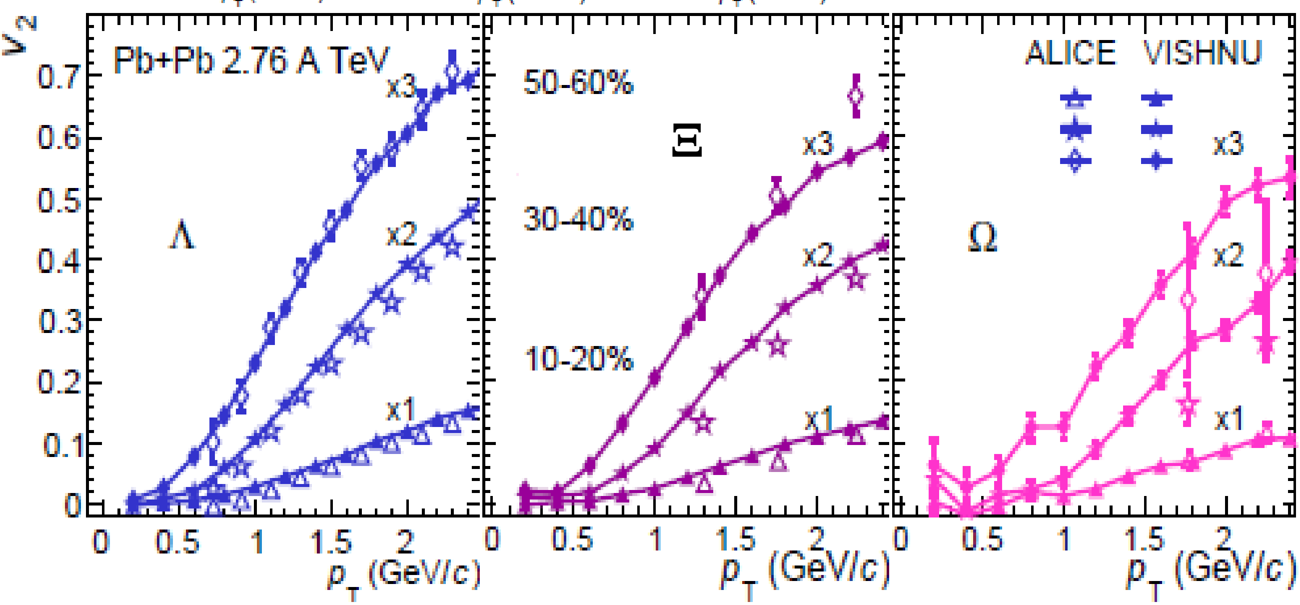
Real Hydro Comparison

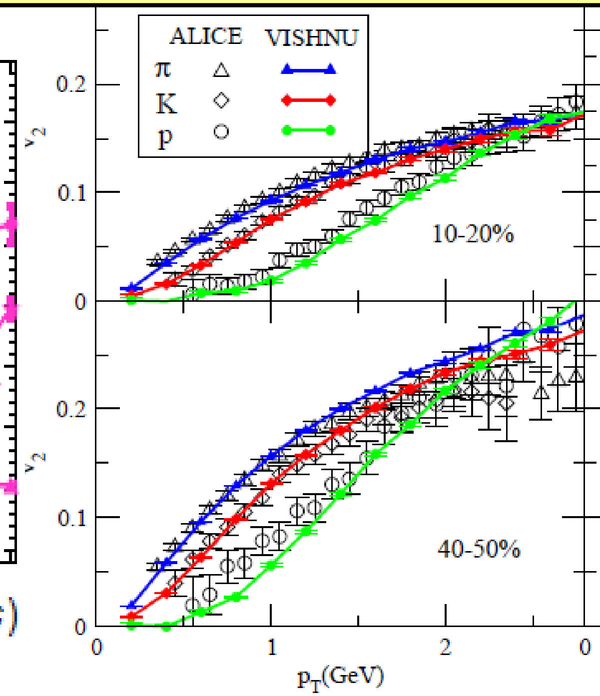
- VISHNU(Hydro + URQMD)1501.03286

AfterBurner important:
incr. radial flow in hadron phase
=> explain differential freeze-out T_{kin} ?
=> meson-baryon crossing in v_2 ?

Would be interesting to see where data & (hydro + AB) deviate:
- Does it coincide in p_T & v_n
- Higher decoupling p_T for large mass ?

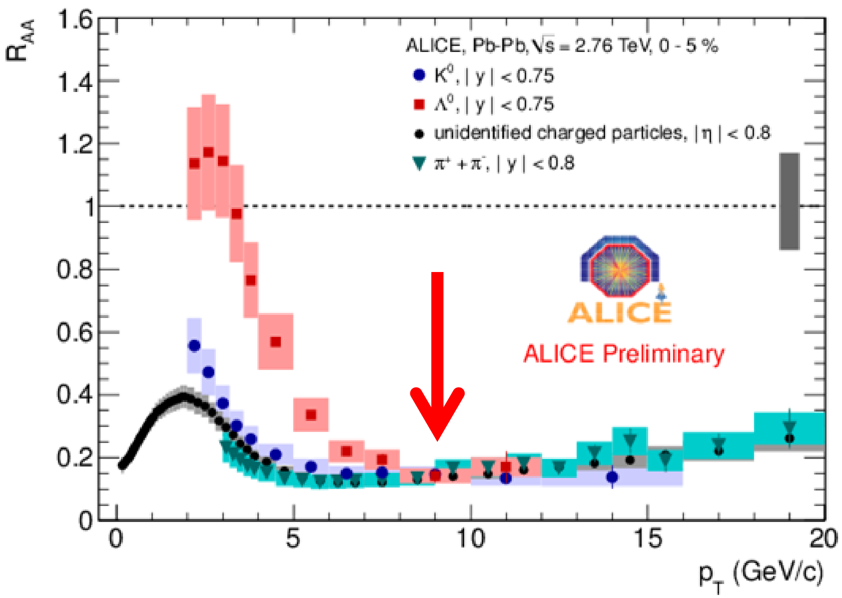


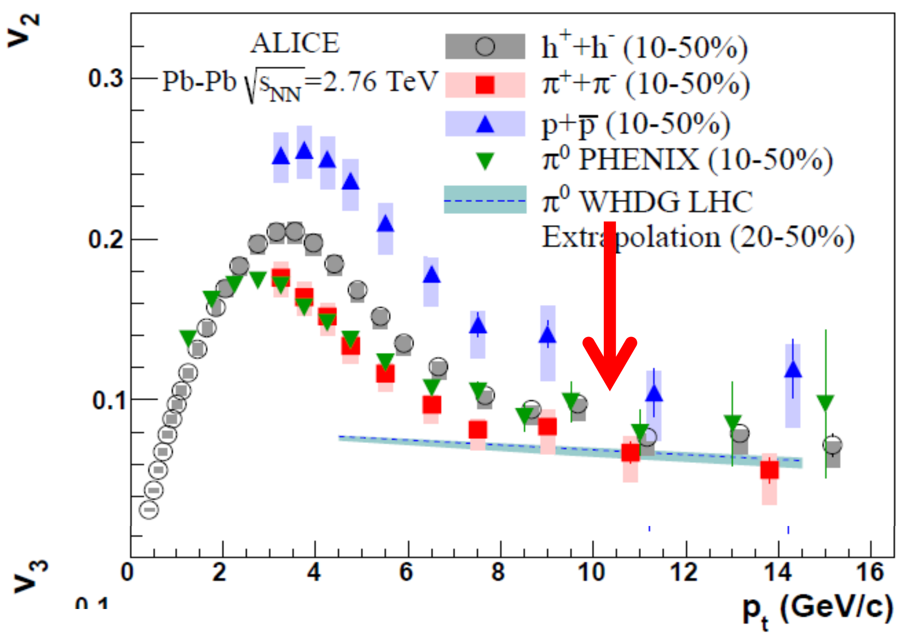




What happens after Hydro ?

- mass matters, up to a point (again, $p_T \approx v_2$)..
  - ⇨ presumably, 'falling out of hydro' is a smooth process (over large p_T range)
    - do we need **new physics** (eg coalescence) at intermediate p_T (4-10 GeV) ?
    - or a **smooth transition** between hydro and jets ?

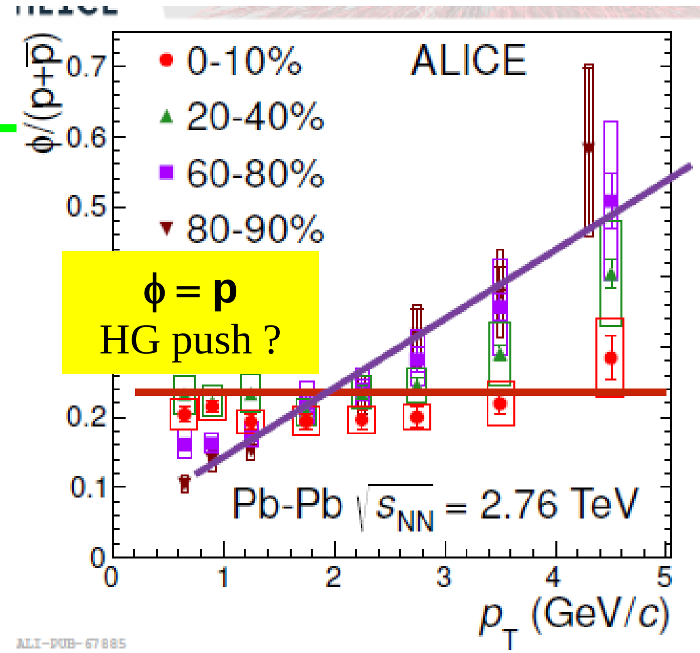


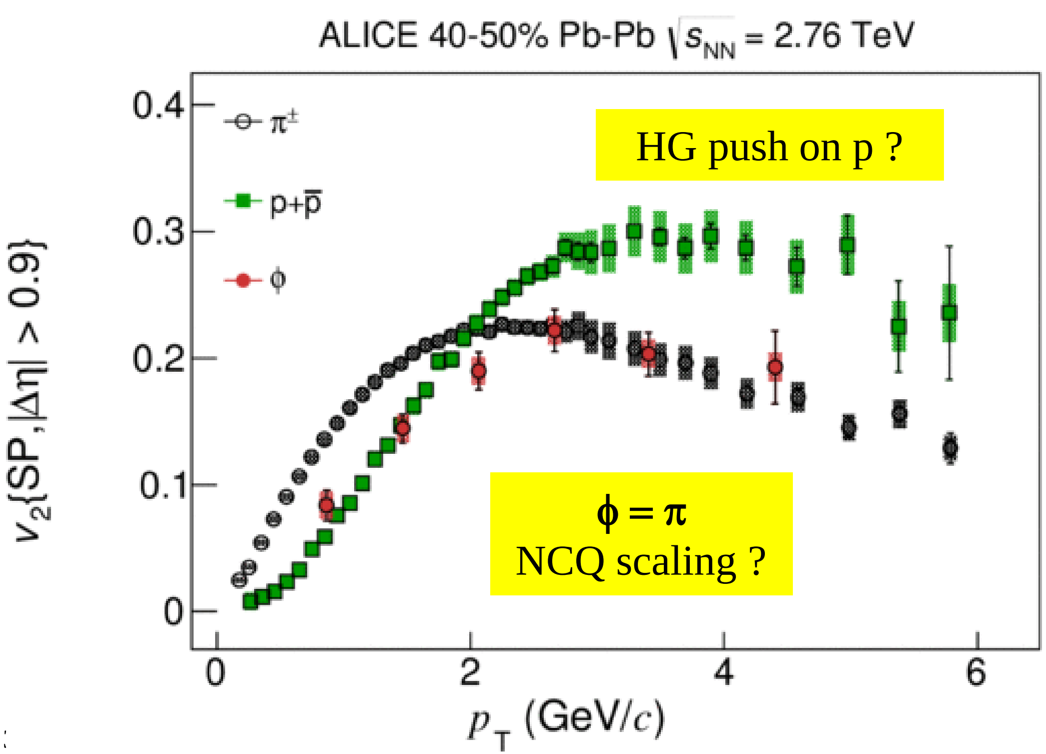


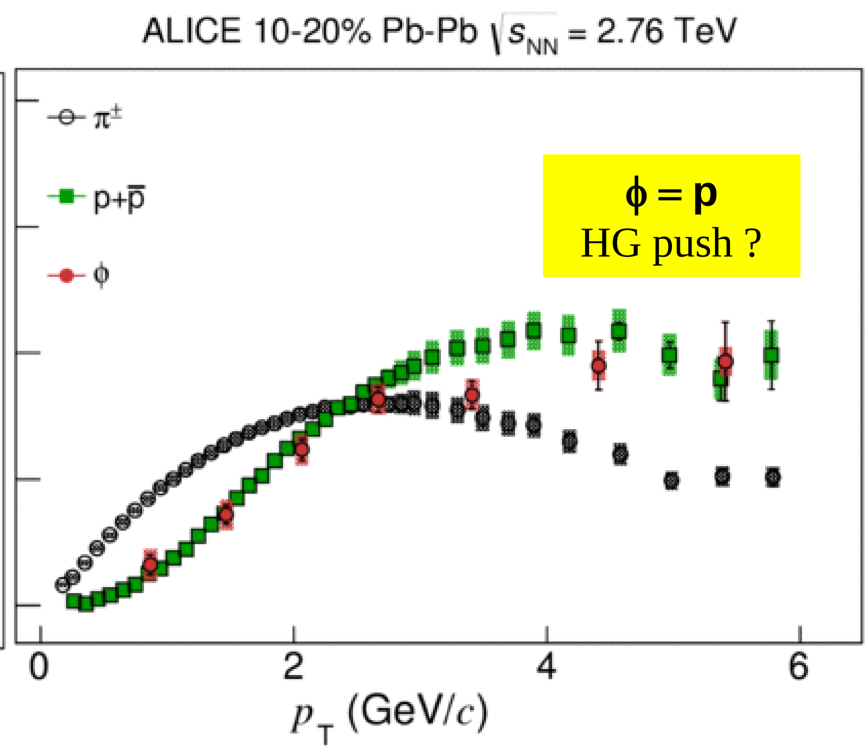
Will the ϕ tell ?

NCQ scaling in 40-50%
or
it's breaking in 10-20%
could be a (m, σ) effect in the HG !

If only we could switch off the HG..



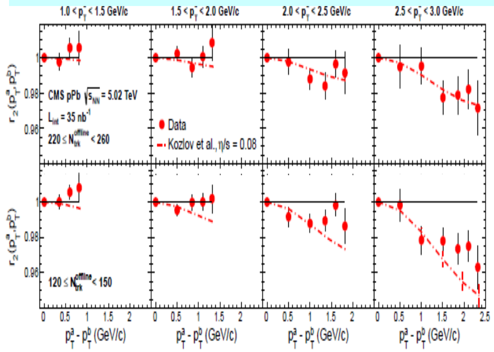




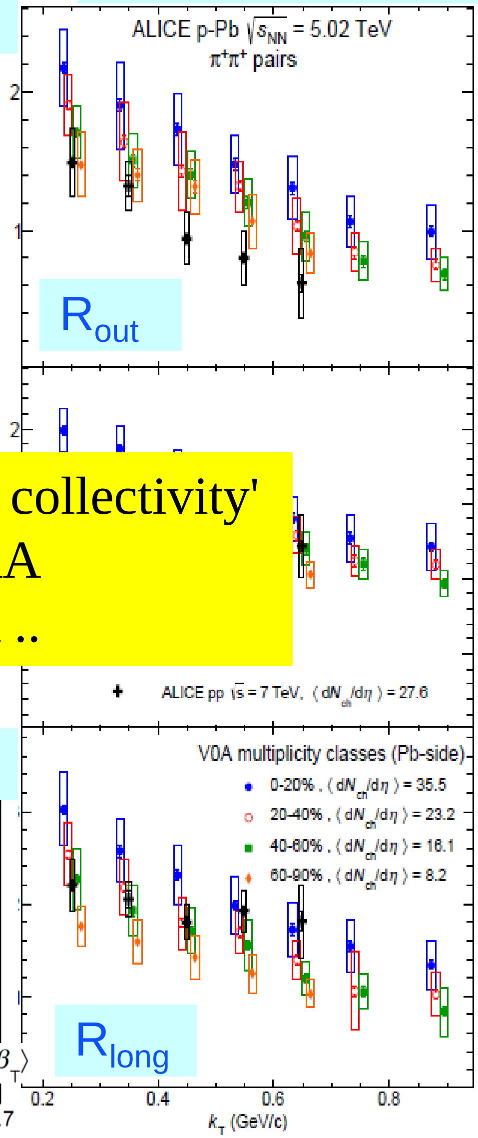
Collectivity in small dense systems: 'central' pA

- 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
    - ✪ **LO**: radial & elliptic flow
    - ✪ **NLO**: higher harmonics v_3, PID v_2
    - ✪ **NNLO**: factorization violation $r(p_T)$
  - ⇨ **thermo + hydro:**
    - ✪ HBT ($R(m_T)$, $R(N_{ch}^{1/3})$, R_{out}/R_{side} ≈ 1

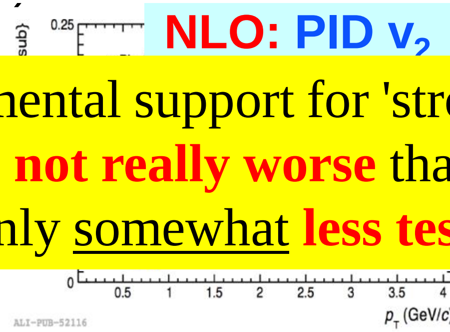
NNLO: Factorization test



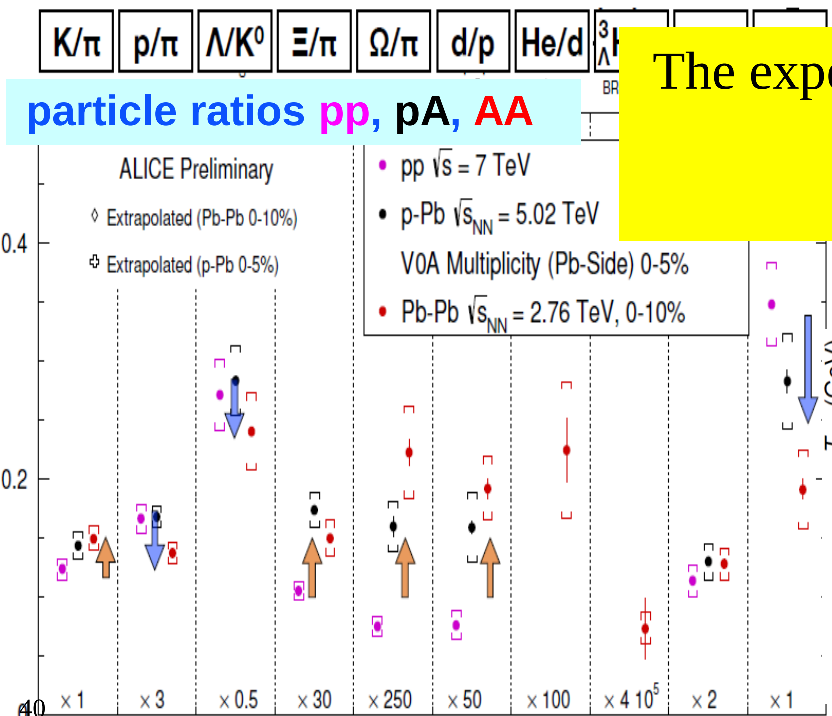
HBT: R vs K_T



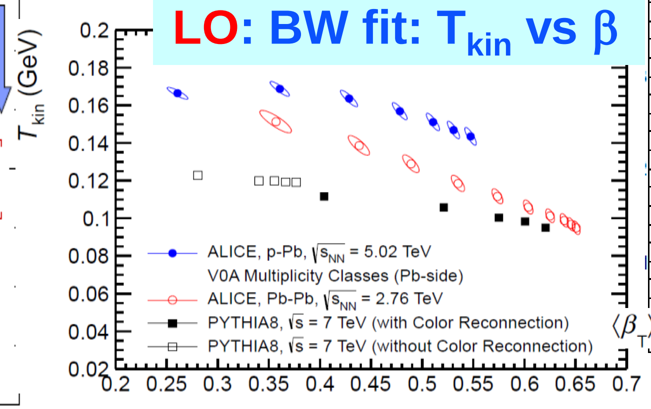
NLO: PID v_2



particle ratios pp, pA, AA



LO: BW fit: T_{kin} vs β



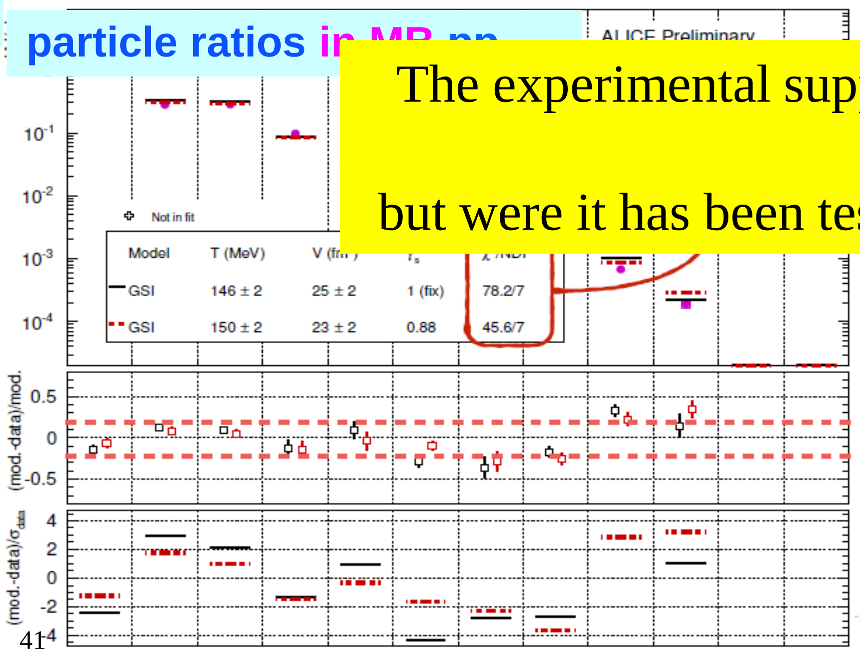
The experimental support for 'strong collectivity'
is **not really worse** than AA
only <u>somewhat</u> **less tested** ..

Collectivity in small dense systems: 'central' pp

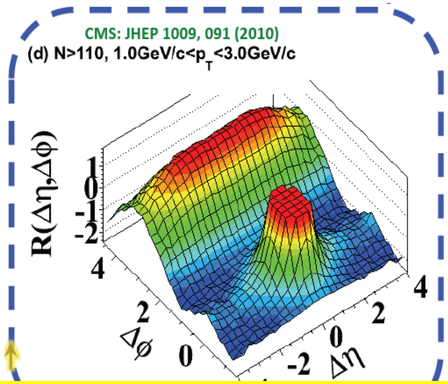
- Collectivity ≈ consistent with data in high N_{ch} pp
  - ⇨ **thermo-dynamics: MB** particle ratios to ≈20-40% $\gamma_s < 1$!
  - ⇨ **hydro-dynamics:**
    - ✪ **LO**: radial & elliptic flow
    - ✪ **NLO**: v_3, PID v_2 (CMS PAS HIN-15-009)
    - ✪ **NNLO**: not yet tested
  - ⇨ **thermo + hydro:**
    - ✪ HBT ($R(m_T)$, $R(N_{ch}^{1/3})$, $R_{out}/R_{side} \leq 1$)

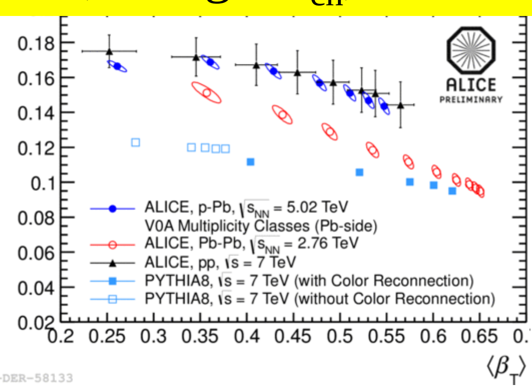
π	K±	K⁰	K*	φ	p	Λ	Ξ	Ω	d	${}^{3}_{\Lambda}H$	He

particle ratios in MB pp

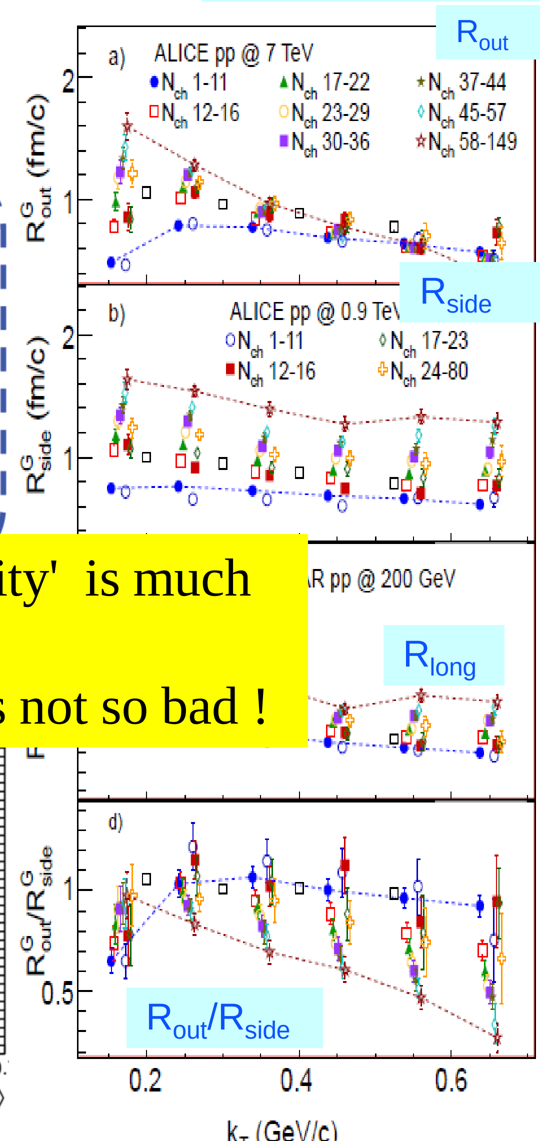


The Ridge





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 !