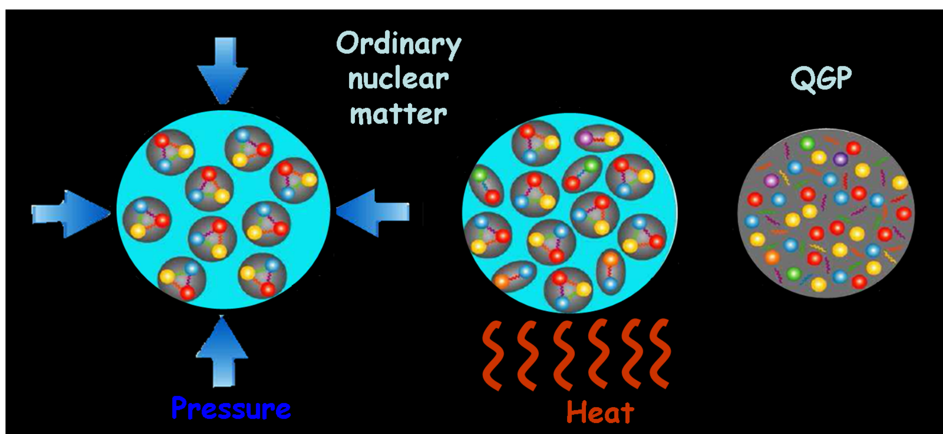
Heavy-ion collisions

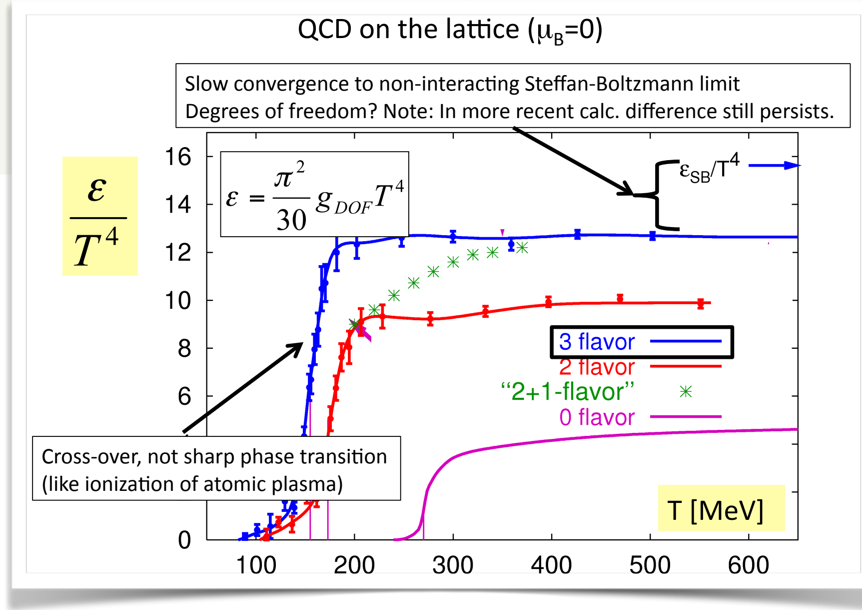
Hot QCD in laboratory

Mateusz Ploskon, Lawrence Berkeley Lab

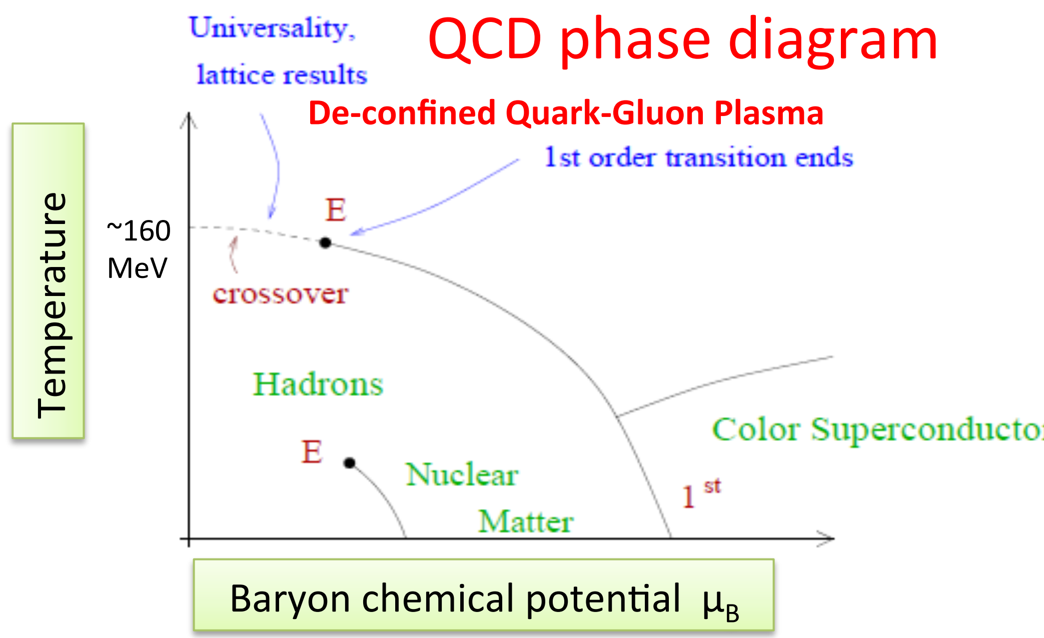


Hot QCD in laboratory - Heavy-ion collisions

- QCD (lattice) predicts a phase transition from hadronic matter to a deconfined phase at high temperatures
- QGP at μ~0 similar to early Universe (~few first μs)
- First signals of QGP from SPS and RHIC
- LHC&RHIC: detailed studies of QGP (light-flavor, multi-particle correlations, heavy-quarks, jets, quarkonia…)



QCD phase diagram



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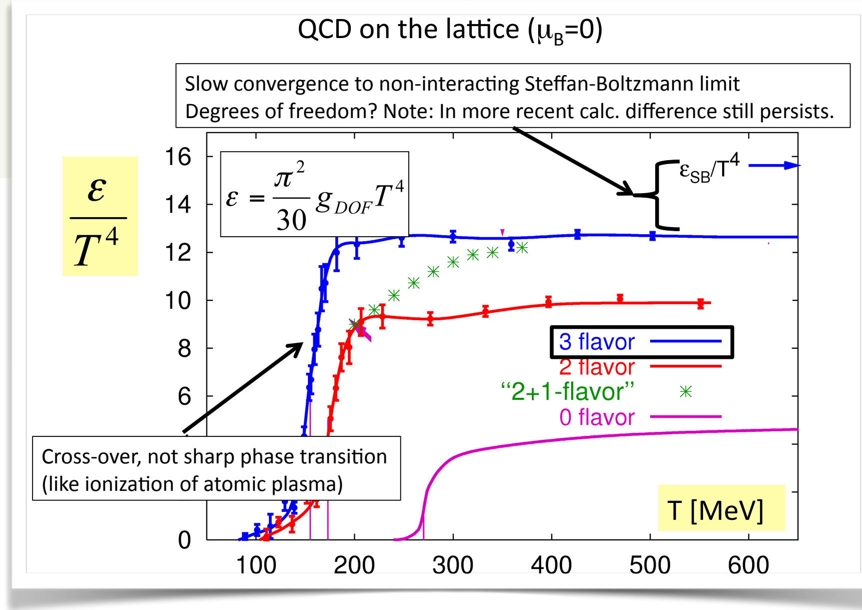
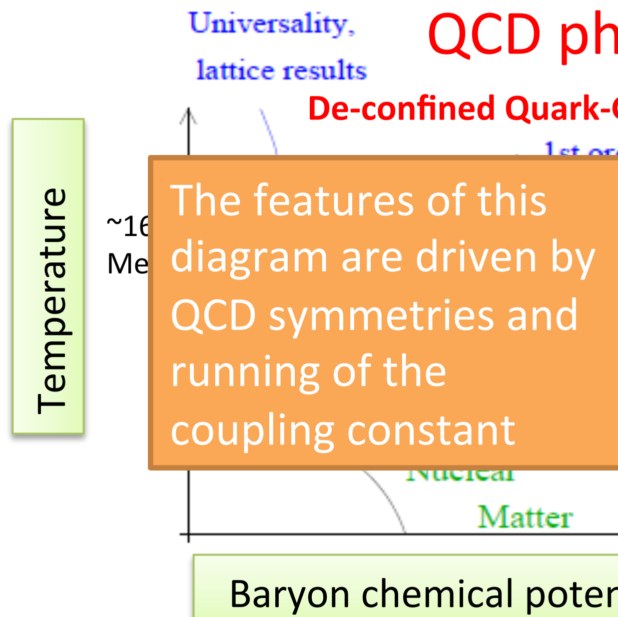
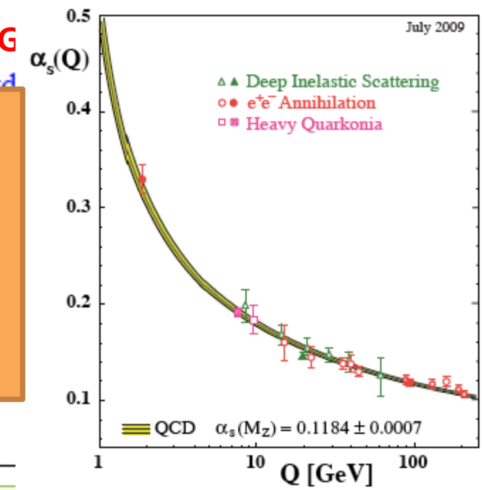


QCD phase diagram

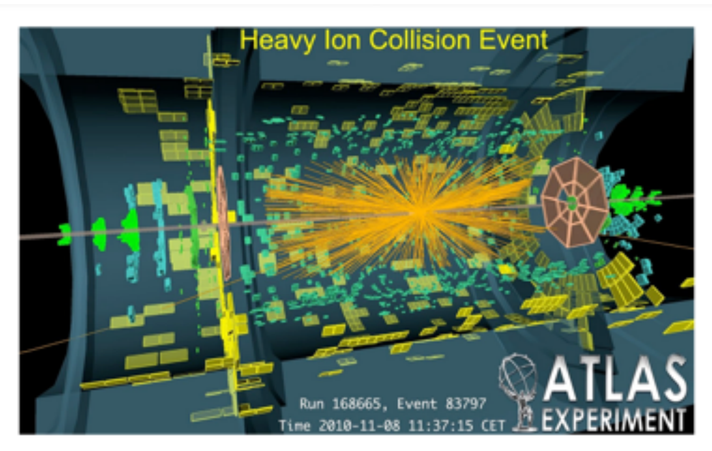


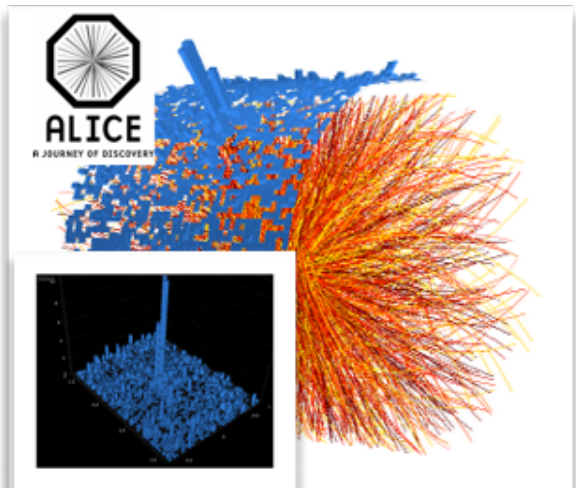
The features of this diagram are driven by QCD symmetries and running of the coupling constant

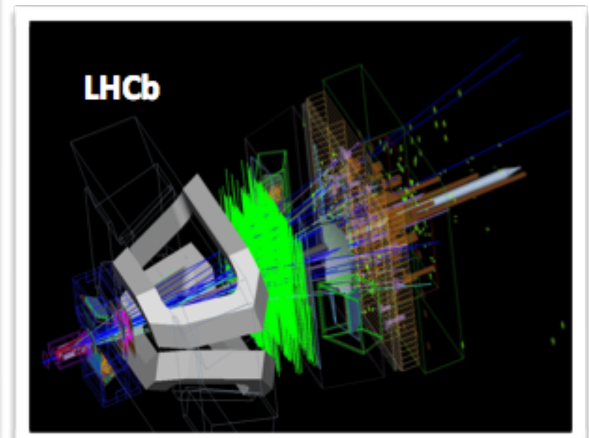


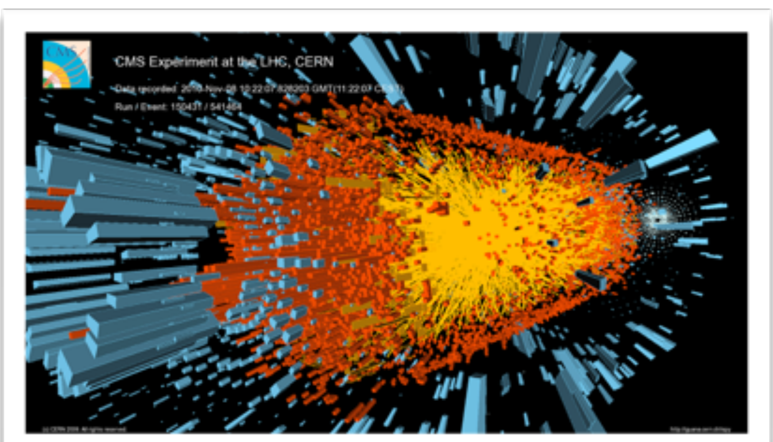
Hot QCD in laboratory - experiments

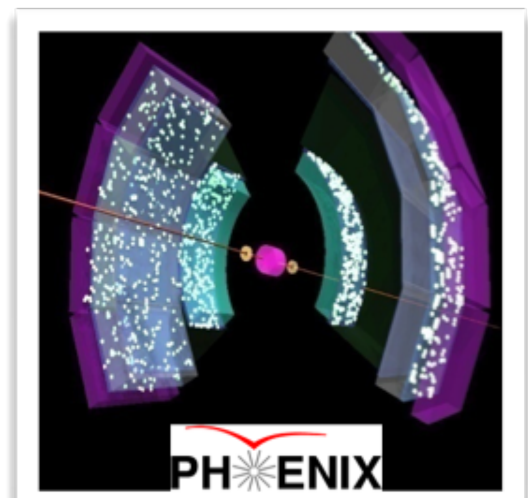
- Relativistic Heavy-Ion Collider: Au-Au collisions at 200 GeV/n)
- Large Hadron Collider: Pb-Pb collisions at 2.76 – 5 TeV (2015)











Outline

Systems:

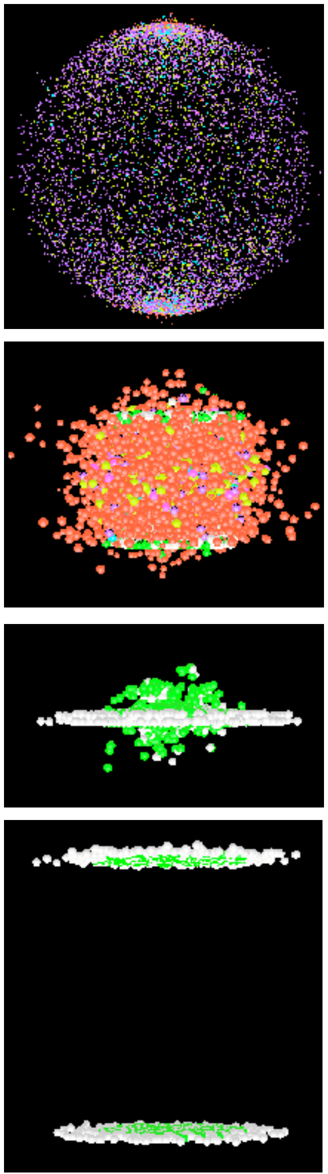
- Proton-proton
- p-Pb
- Pb-Pb

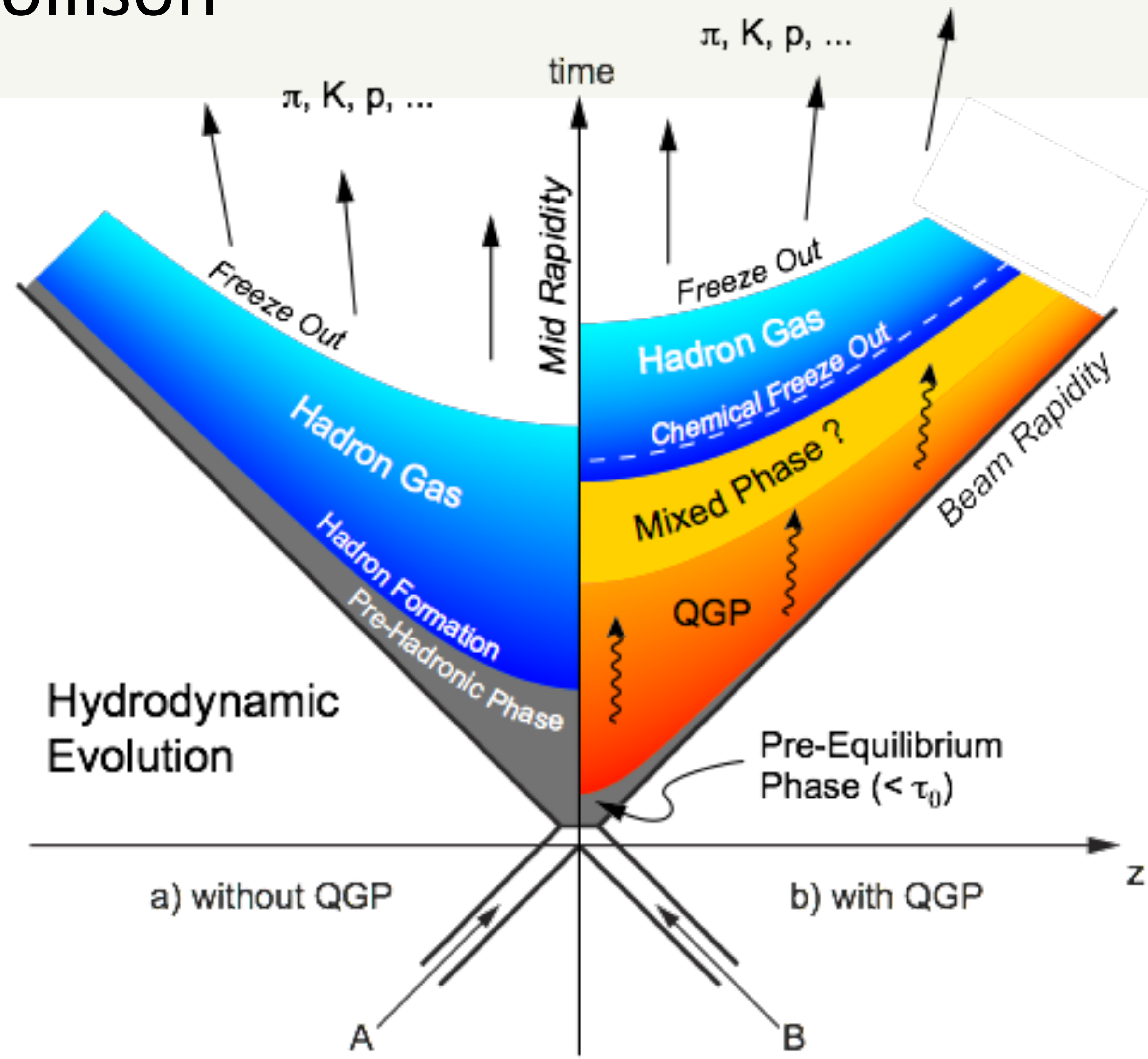
- Outline of this talk:
  - Selected subjects from soft and hard probes
  - Signatures of collective effects even in small systems – mini-QGP?
  - Summary

Properties & Tools

- Global event / system properties:
  - Inclusive spectra; Identified particles; mean p_T; "Blast-wave" fits (T, collective velocity)
- Collective effects
  - Correlations, flow coefficients, v_2, v_3 (propagation / energy dissipation)
- Heavy-flavour – energy loss and thermalization
  - Production vs. multiplicity; suppression and v_2
- Quarkonia – QGP vs. Cold Nuclear Matter
  - Production vs. multiplicity; suppression in Pb-Pb; v_2; suppression/enhancement in pA
- Jets
  - R_{AA} – inclusive production in pp and AA; jet structure; test of N_{binary} scaling in min. bias pPb

A heavy-ion collison

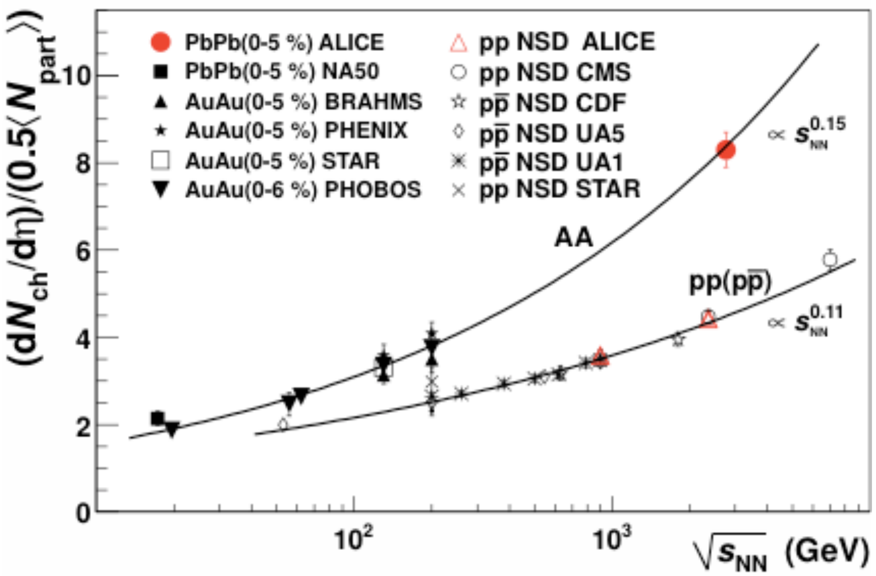




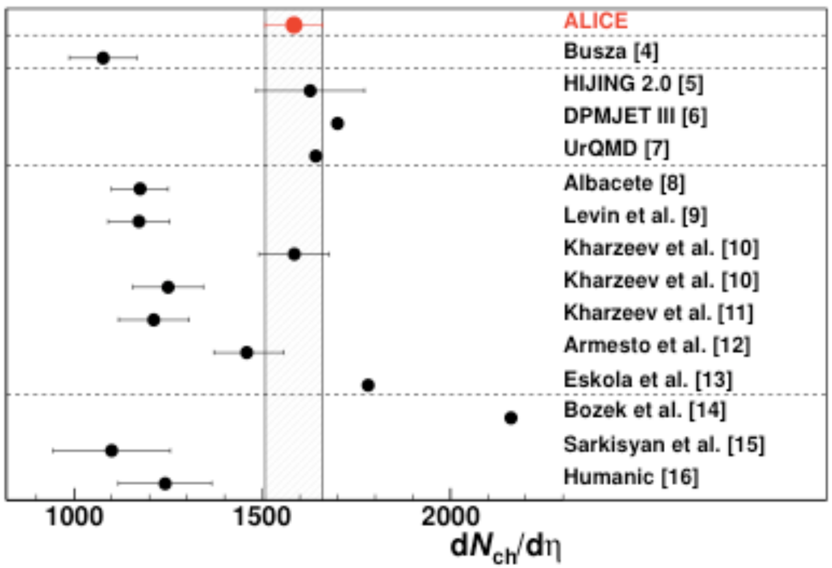
“CALIBRATION” MEASUREMENTS

Particle production in Pb-Pb

Energy dependence



Comparison to predictions



PRL 105, 252301 (2010)

Energy dependence

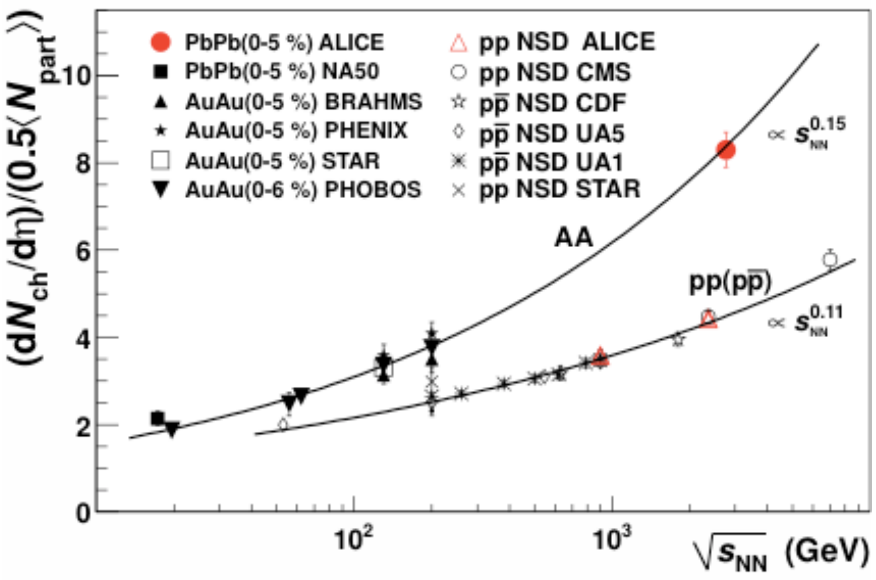
p-p ~ $s_{NN}^{0.11}$

A-A ~ $s_{NN}^{0.15}$ (most central - 2x RHIC)

– stronger rise than log extrapolation

Particle production in Pb-Pb

Energy dependence



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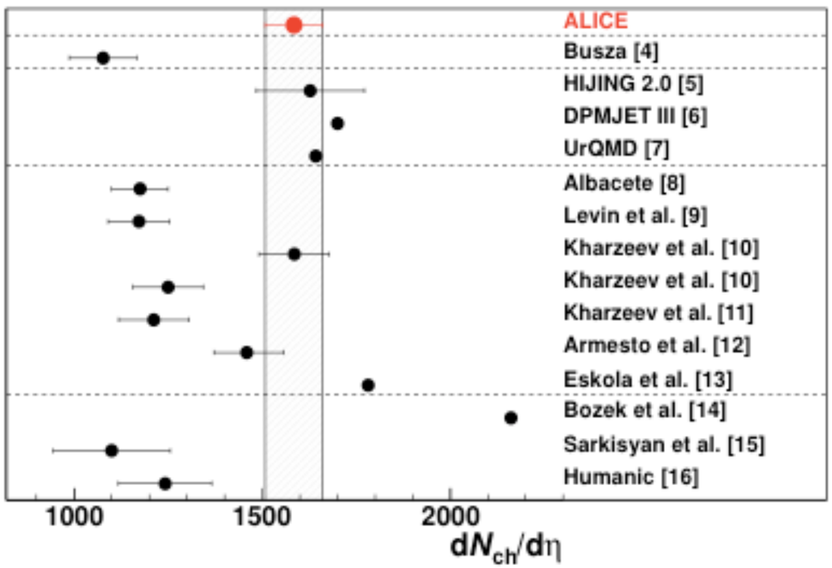
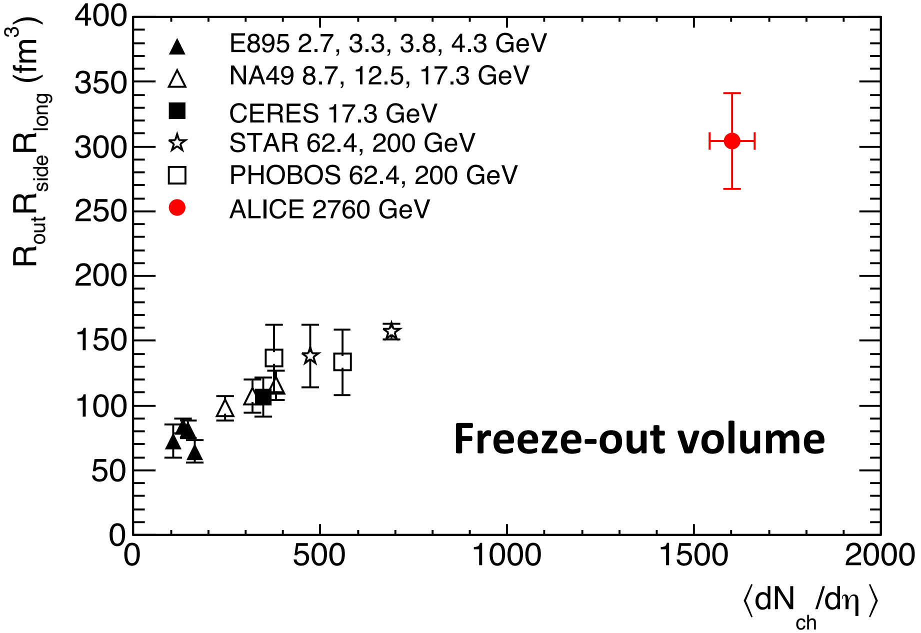
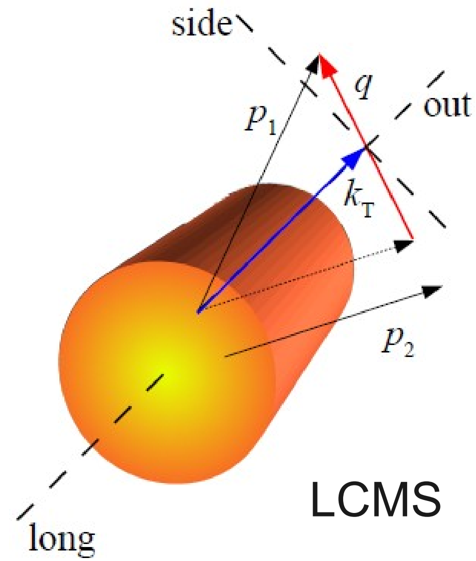


PRL 105, 252301 (2010)

- **Multiplicity is crucial [input] for modeling**
- **Saturation models tend to predict lower multiplicity**
- **Data driven extrapolations did not seem to anticipate the results**

Particle production in Pb-Pb: Measurements of source dimensions





Phys.Lett.B 696:328-337,2011

1. Energy dependence:

- **system with larger (2x) volume and (1.4x) lifetime (w.r.t RHIC); follows the trend of multiplicity; faster expansion <=> larger collective flow**

2. Pair momentum dependence:

- **larger radii, strong dependence on kT; Rout/Rside smaller than at RHIC; overall agreement with extrapolations**

3. Important constrains to [hydrodynamical] modelling

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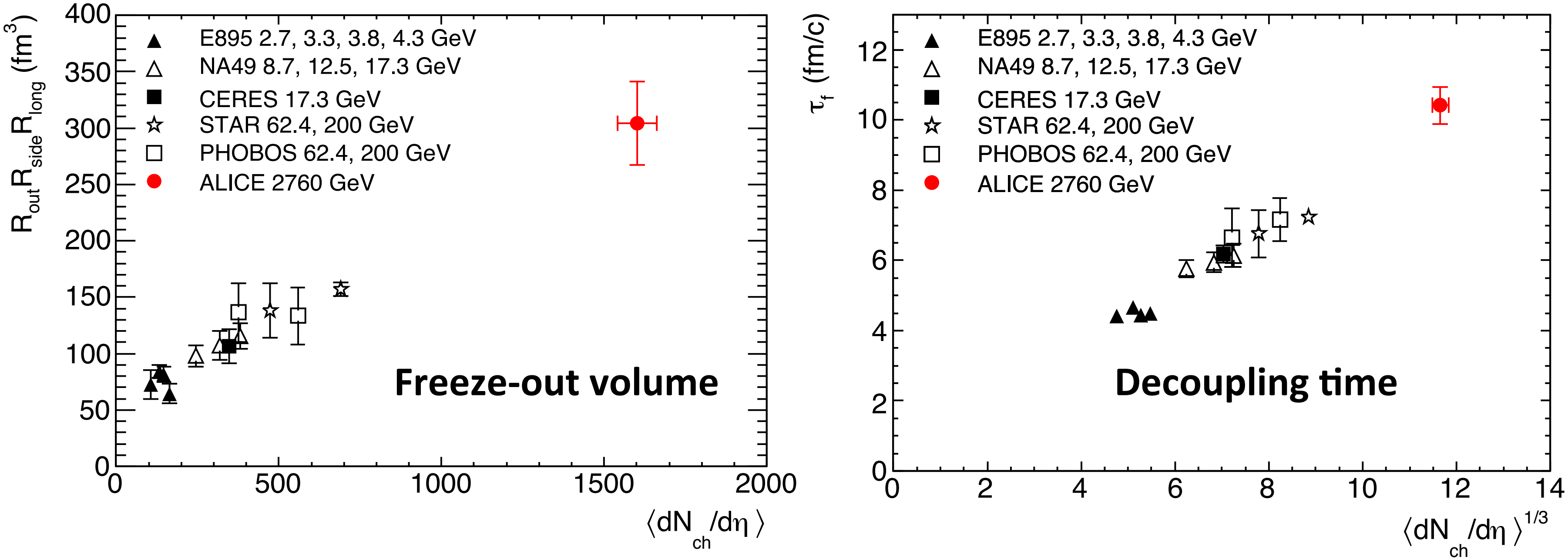

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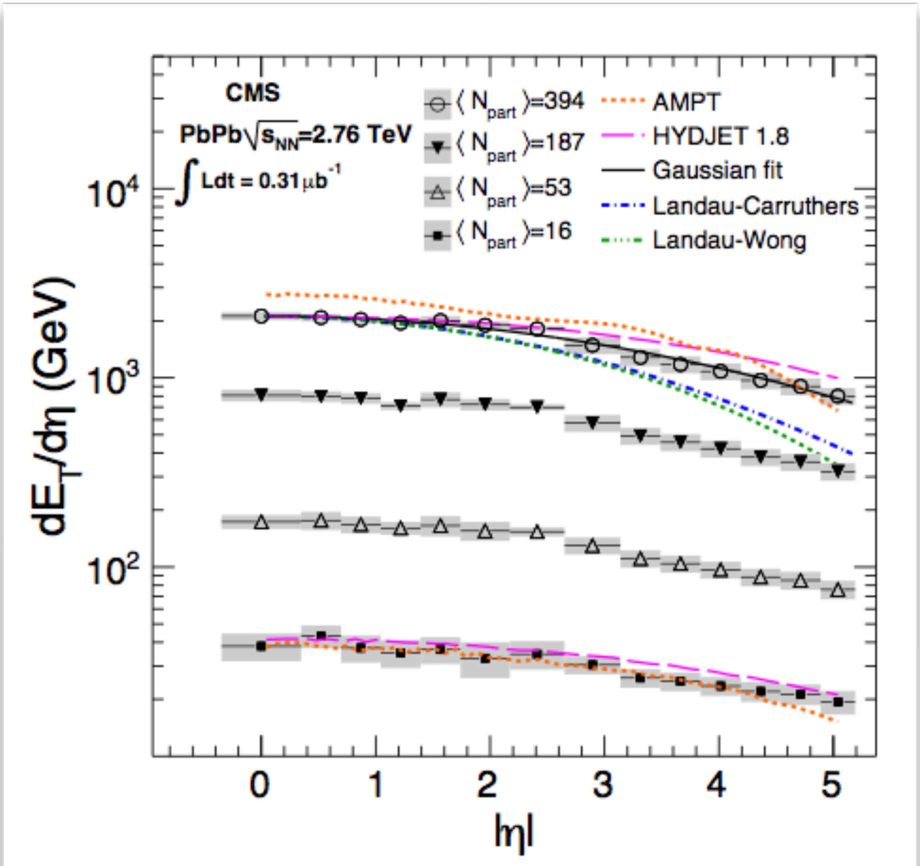
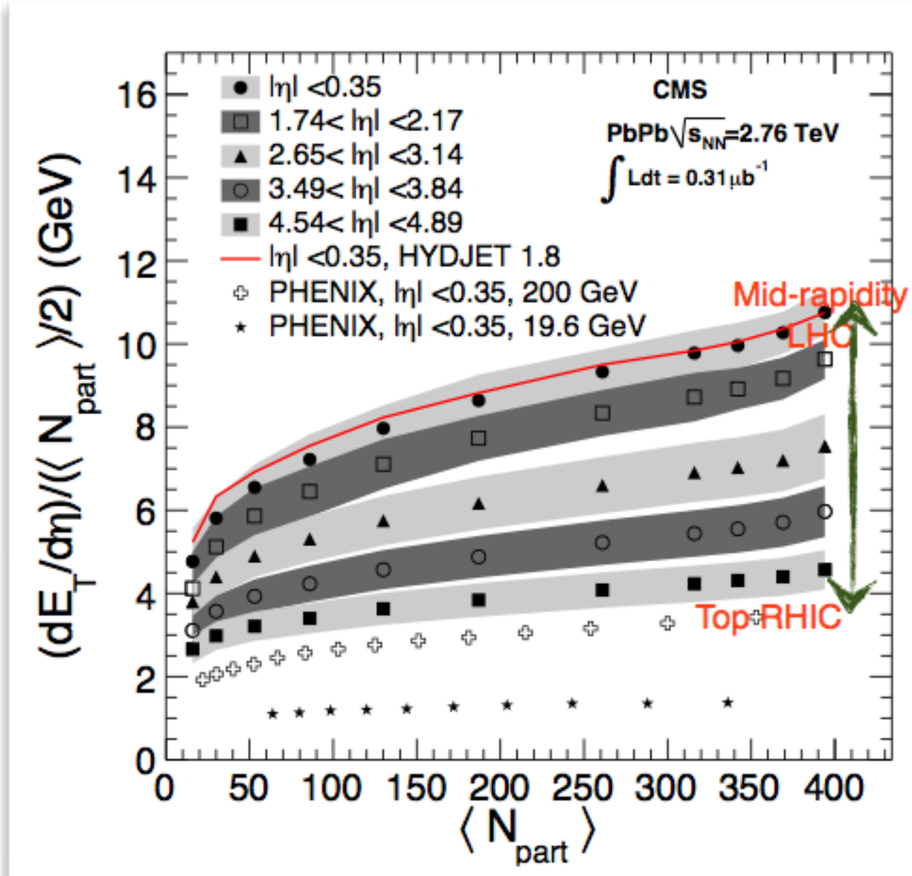
Energy density

LHC: 2.5 x RHIC



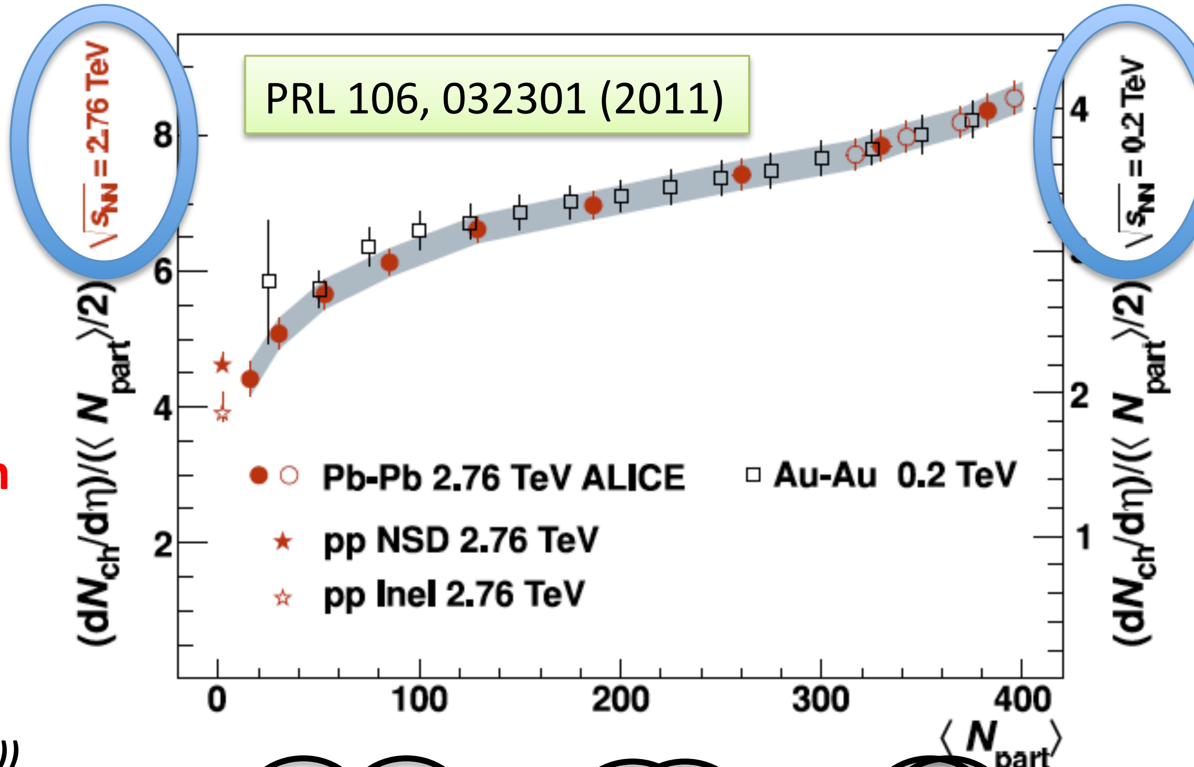
... within a volume (per nucleon)



Systematic control: compare RHIC to LHC

The same experiment under vastly different conditions!

Centrality dependence of particle production

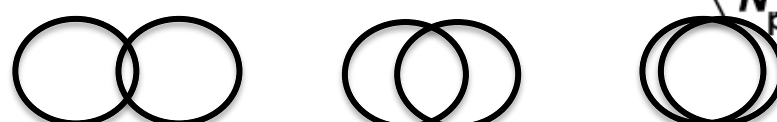


- **Identical variation of particle production with centrality (volume) at RHIC and LHC!**

⇒ Global features of the system independent on energy

⇒ Initial conditions!

More on RHIC:
*Phobos (**Phys. Rev. Lett. 102, 142301 (2009)**)*



Centrality of the collisions: peripheral semi-central central

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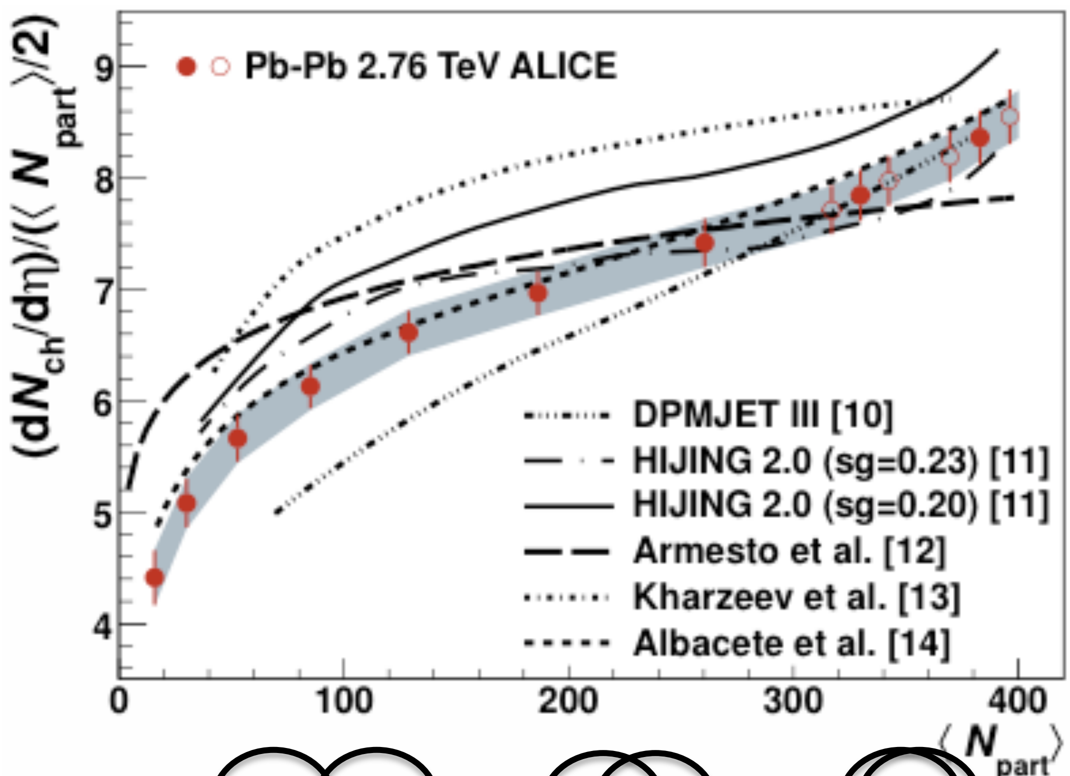

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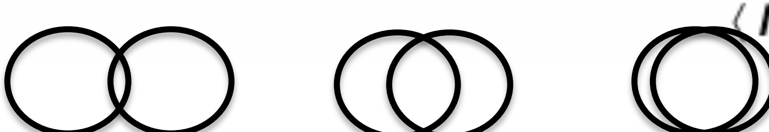
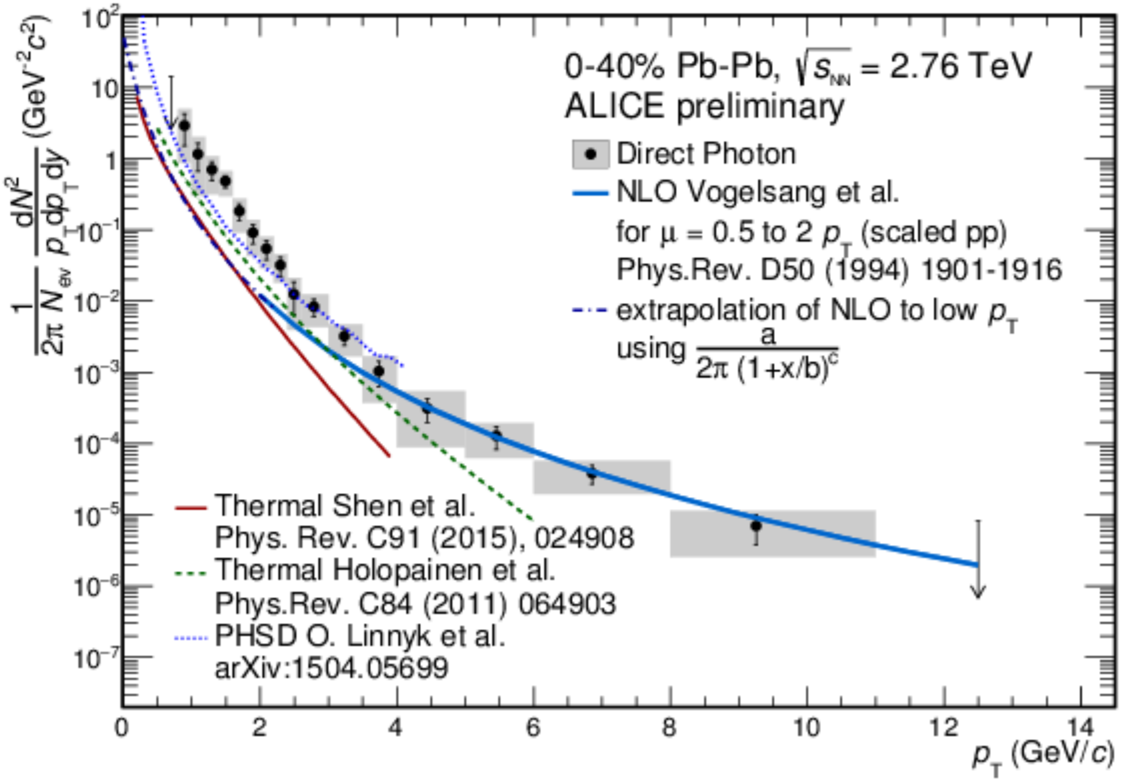


Centrality of the collisions: peripheral semi-central central

Direct photons
QGP shines



$$\gamma_{dir} = \gamma_{inc} \times (1 - \frac{\gamma_{decay}}{\gamma_{inc}})$$

Obtained from π^0 measurement and **m_T scaling** for other mesons

At p_T < 2.2 GeV/c, the spectrum is fitted with an exponential, inverse slope parameter T:

$$T = 304 \pm 51^{stat+syst} \text{ MeV}$$

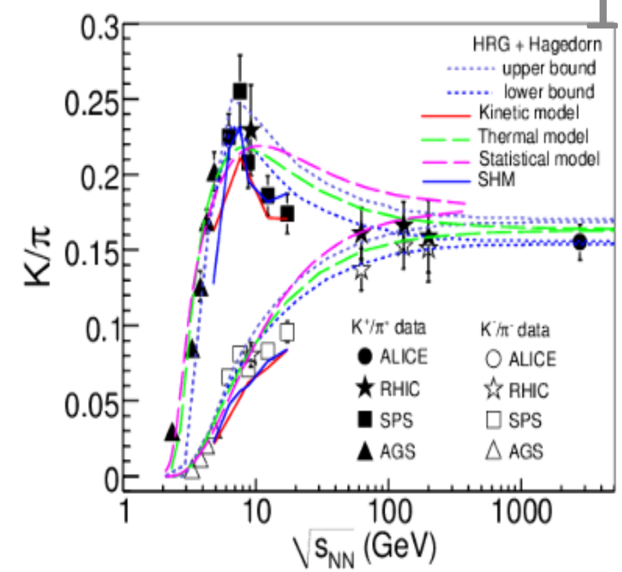
$$T = 221 \pm 19^{stat} \pm 19^{syst} \text{ MeV}$$

(Au-Au centrality 0-20%)

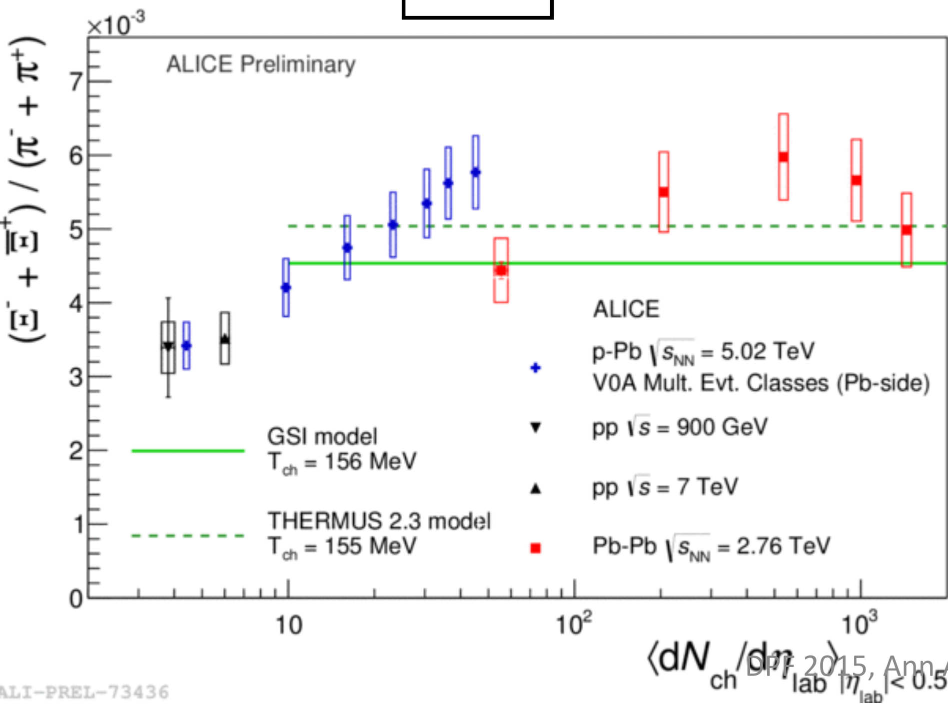
Outlook for Run-2: higher precision data (higher collision energy)

Onset of de-confined medium

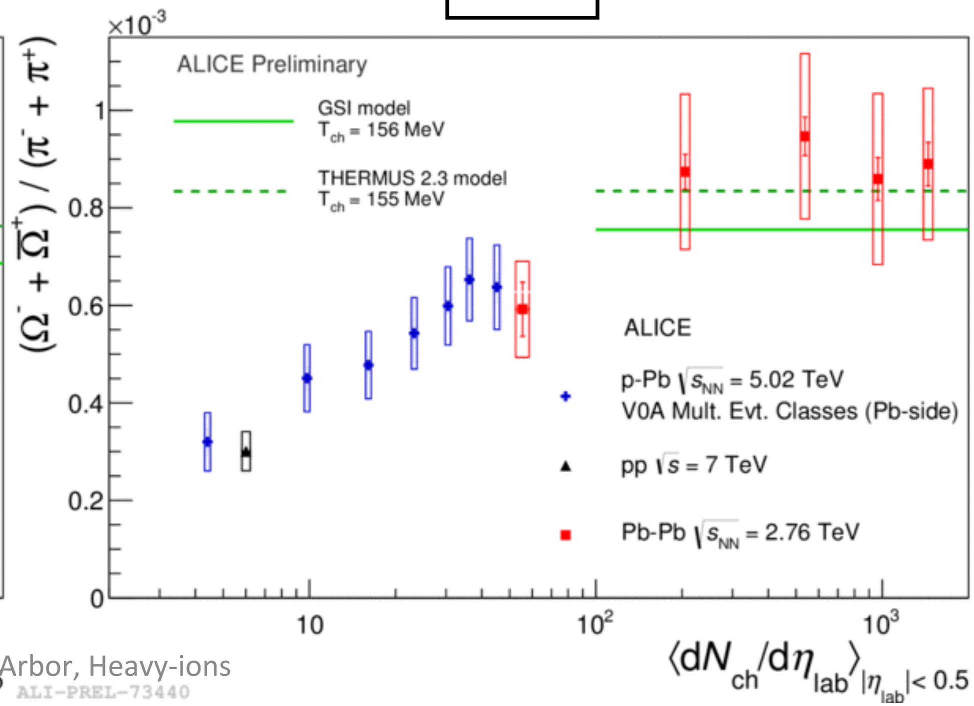
- Strangeness enhancement – especially multi-strange baryons
- Also in high-multiplicity p-Pb collisions ?
  - Xi/p reaches Pb-Pb values



Ξ/π



Ω/π



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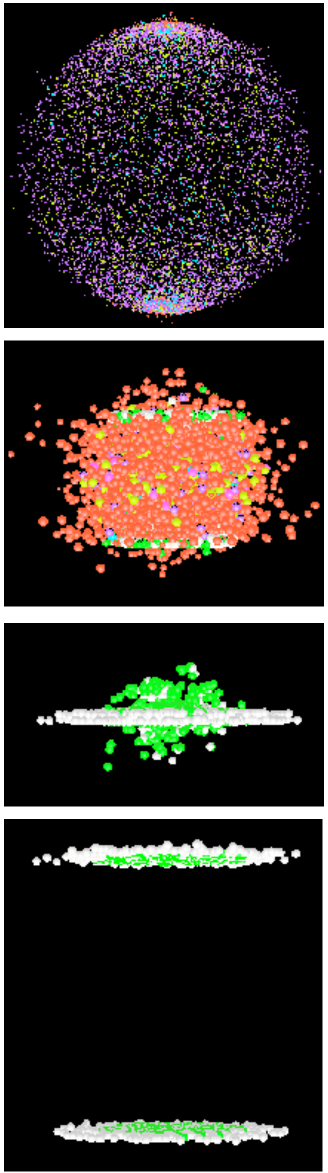
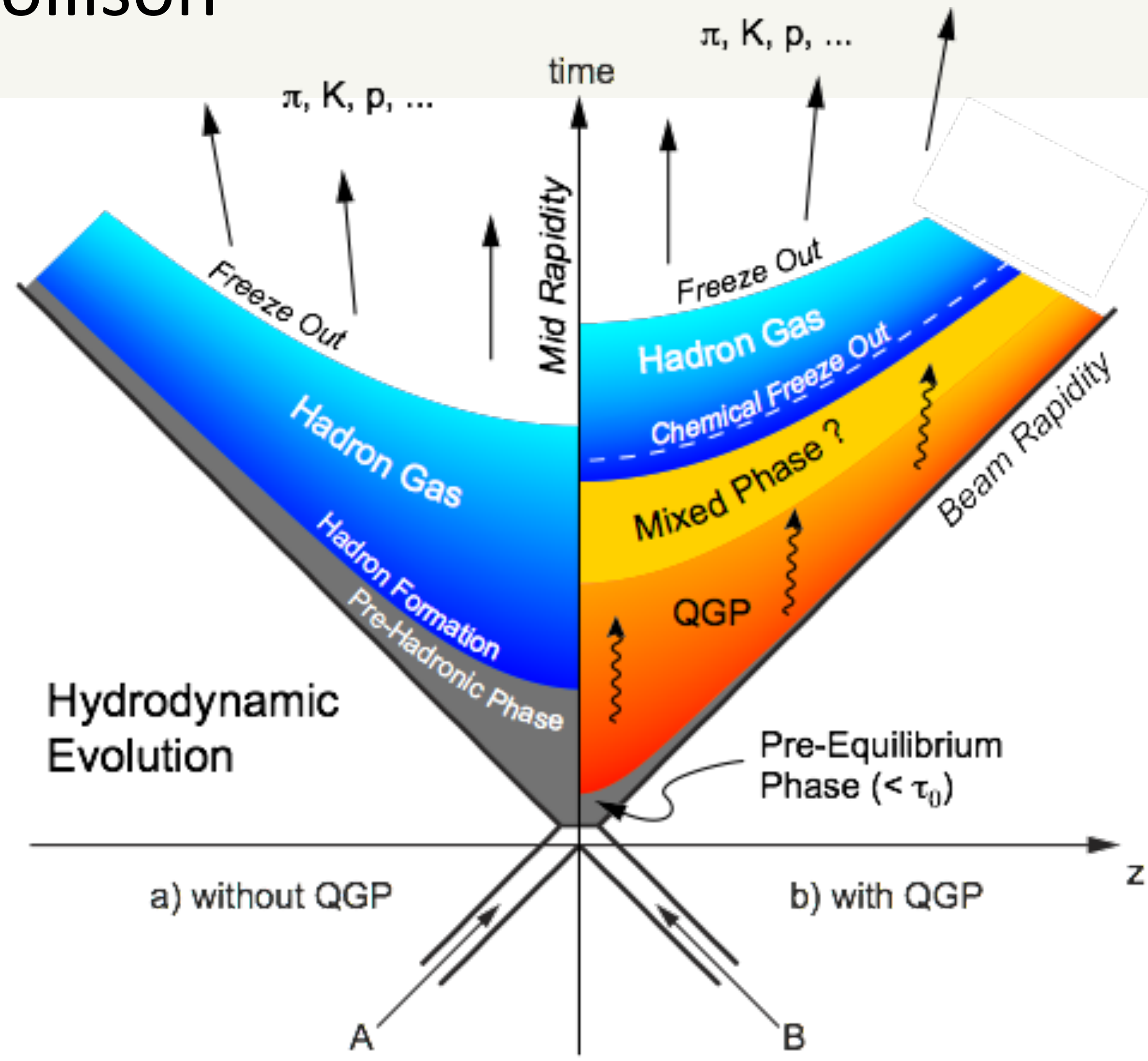




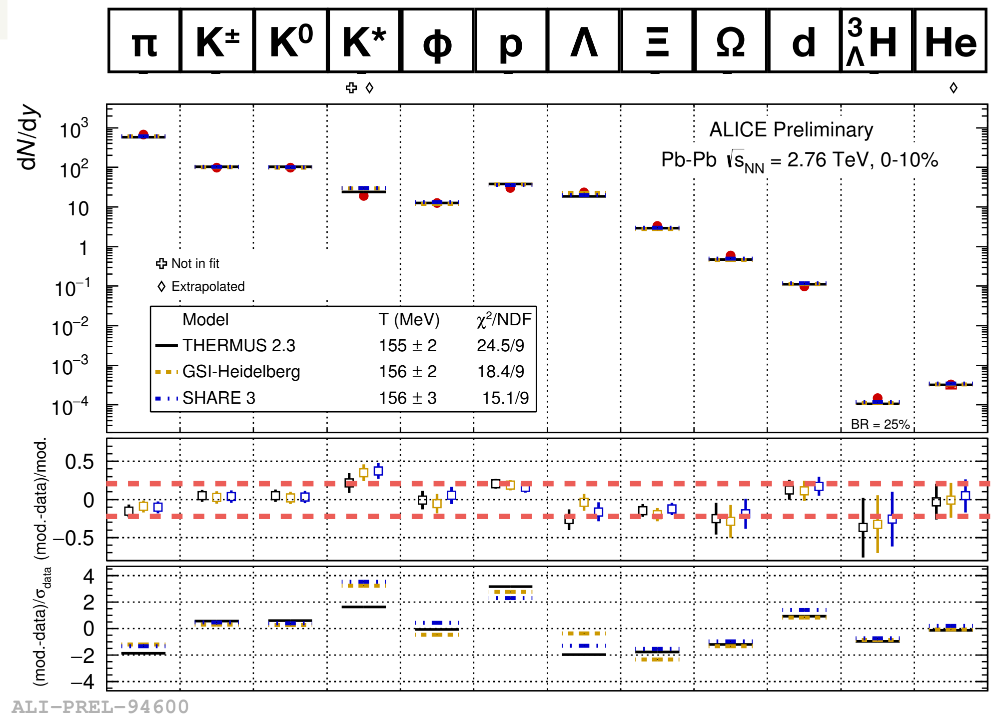
Particle production – statistical hadronization models

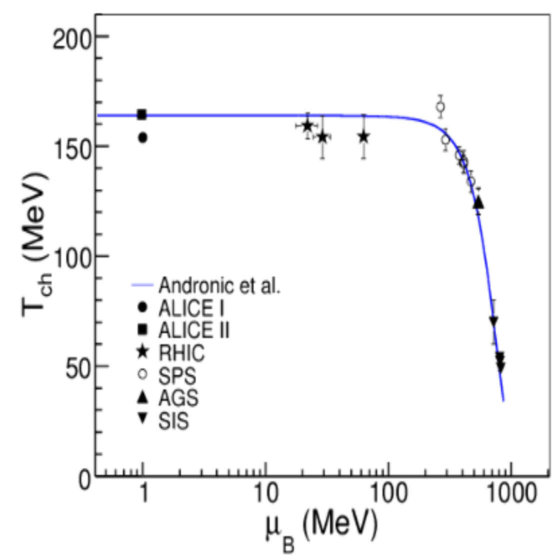
Grand-canonical ensemble analysis

$$N_i \propto V \int \frac{d^3p}{2\pi^3} \frac{1}{e^{(E_i - \mu_B B_i)/T_{ch}} \pm 1}$$

T_{ch} Chemical freeze-out temperature

μ_B Baryochemical potential





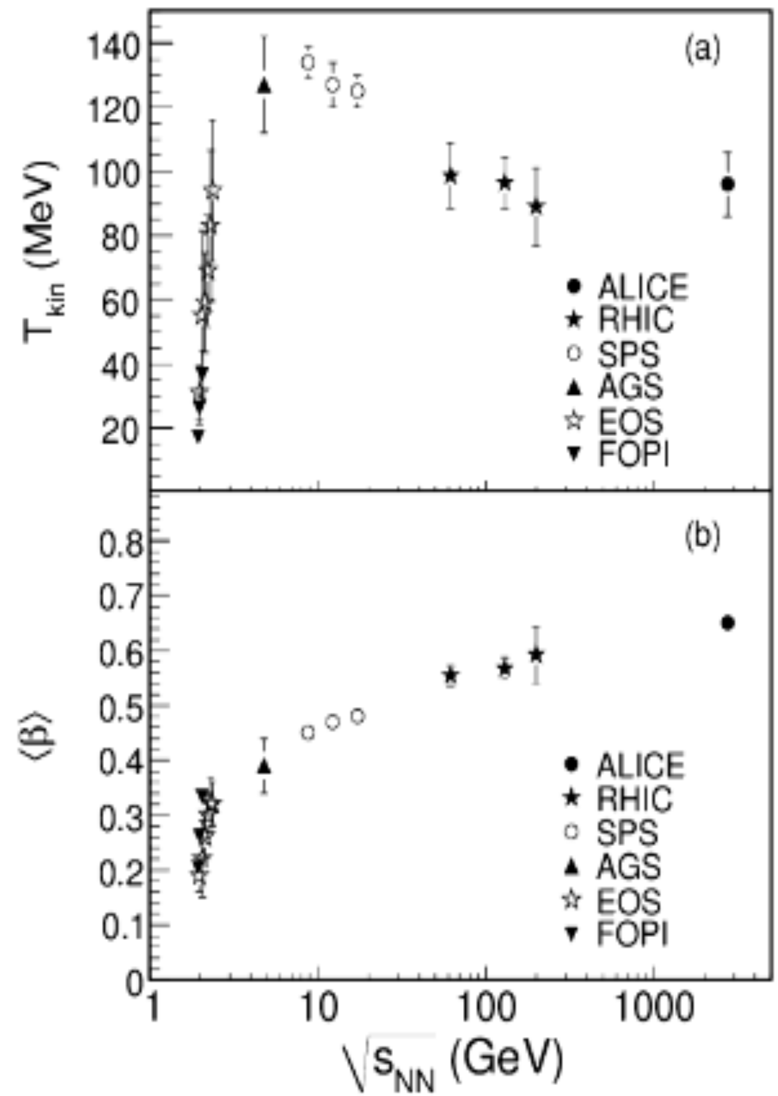
Yields described by thermal (3) models with

T_{ch}=155-156 MeV

- Similar temperature as at RHIC, however proton/pion below the fit – the tension already present at RHIC
- Strange particles constrain the fit

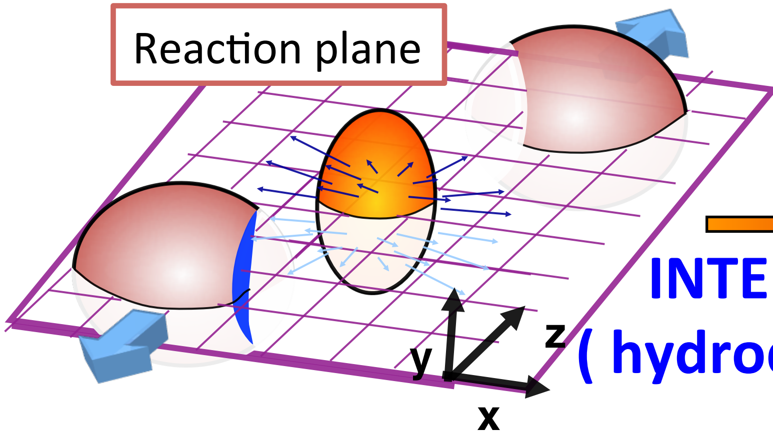
Collective expansion – particle spectra – kinetic freeze-out

- Collective expansion modifies particle spectra – mass dependence
- Kinetic freeze-out and radial flow:
  - interacting system expands into vacuum
  - => radial flow is a natural consequence
  - Cascade process => an ordering of particles with the highest common underlying velocity at the outer edge
- Hadrons are released in the final stage and therefore measure "FREEZE-OUT" Temperature
  - => simple parametrization - radially boosted source with velocity β (y=0)

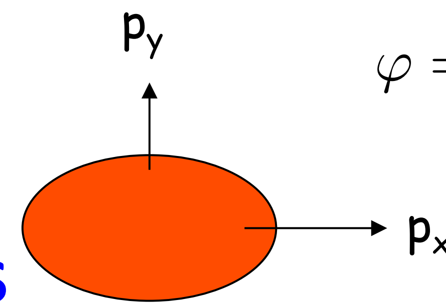


“COLLECTIVITY”

Collective Flow of QCD Matter



INTERATIONS
(hydrodynamics?)



$$\varphi = \arctan \frac{p_y}{px}$$

$$v_2 = \frac{\langle p_x^2 \rangle - \langle p_y^2 \rangle}{\langle p_x^2 \rangle + \langle p_y^2 \rangle}$$

Final momentum anisotropy

$$\varepsilon = \frac{\langle y^2 \rangle - \langle x^2 \rangle}{\langle y^2 \rangle + \langle x^2 \rangle}$$

Initial spatial anisotropy

Reaction plane defined by "soft" (low p_T) particles

$$\Delta\varphi = \varphi - \varphi^{Reaction\ \ Plane}$$

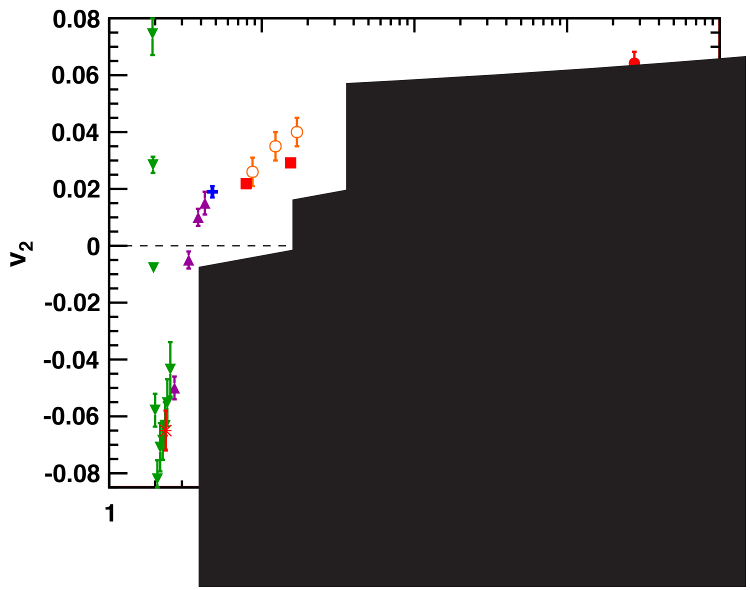
Elliptic flow

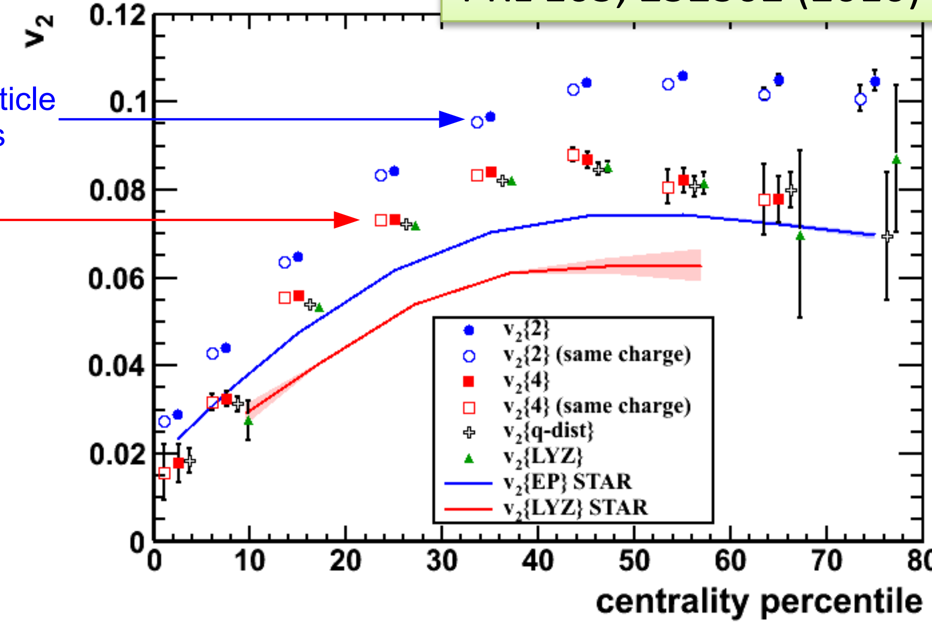
$$\frac{dN}{d\Delta\varphi} \propto 1 + 2v_2 \cos(2\Delta\varphi)$$

Azimuthal anisotropy

PRL 105, 252302 (2010)

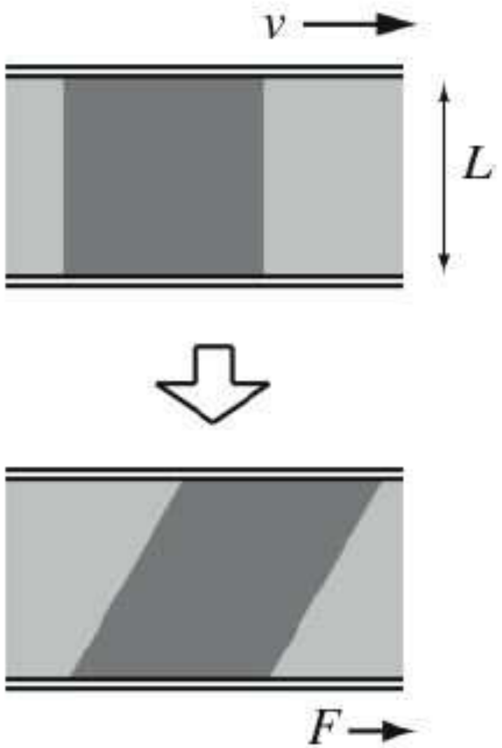
Energy dependence of v2

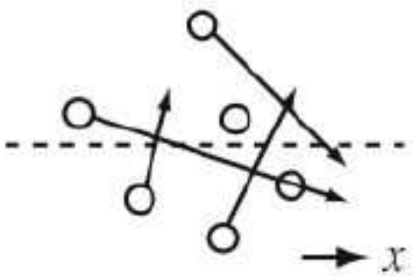




- **Collective behavior observed in Pb-Pb collisions at LHC (integrated: +0.3 v_2^{RHIC} – consequence of larger <p_T>) -> $v_2(p_T)$ similar to RHIC – almost ideal fluid at LHC ? Similar observation down to ~20 GeV!**
- **New input to the energy dependence of collective flow**
- **Additional constraints on Eq-Of-State and transport properties**

Shear viscosity in fluids





$$\frac{F}{A} = \eta \frac{\mathrm{v}}{L}; \quad \eta \sim \rho \langle \mathrm{v} \rangle \lambda_{mfp}$$

Weak coupling
- small cross section, long mean free path

$\Rightarrow$ large viscosity

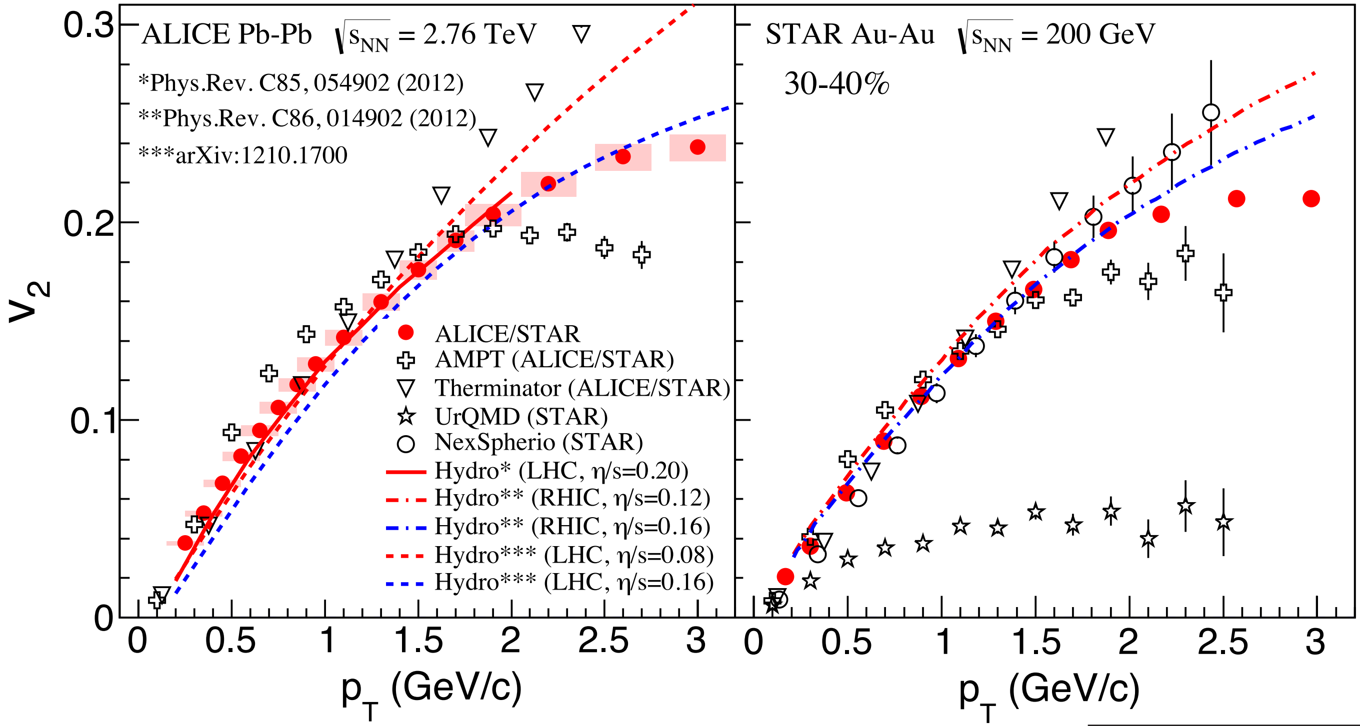
Strong coupling
- large cross section, small mean free path

$\Rightarrow$ small viscosity

$\eta \rightarrow 0$: strongly coupled (perfect) fluid
$\eta \rightarrow \infty$: weakly coupled (ideal) gas

How ideal fluid is QCD Matter?

Viscous hydrodynamics needed to explain the data



$T_{LHC} > T_{RHIC}$

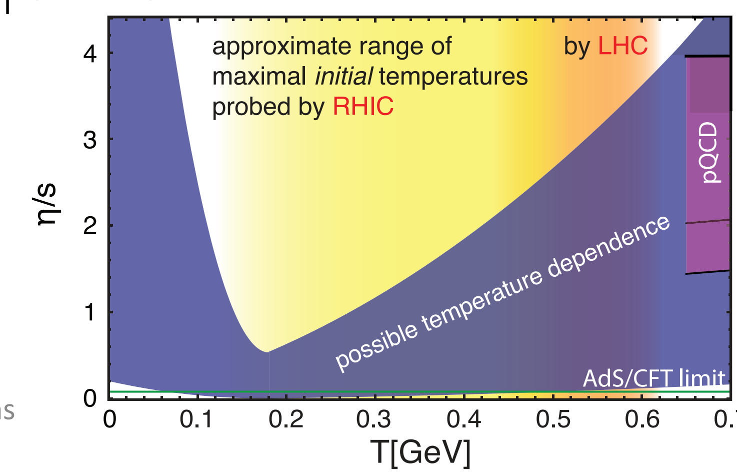
$[\eta/s]_{LHC} > [\eta/s]_{RHIC}$

Shear viscosity – lower limit:

$$\frac{\eta}{s} > \frac{1}{4\pi}$$

KSS (string theory); Gyullassy-Danielewicz (quantum mechanics + ballistic theory)

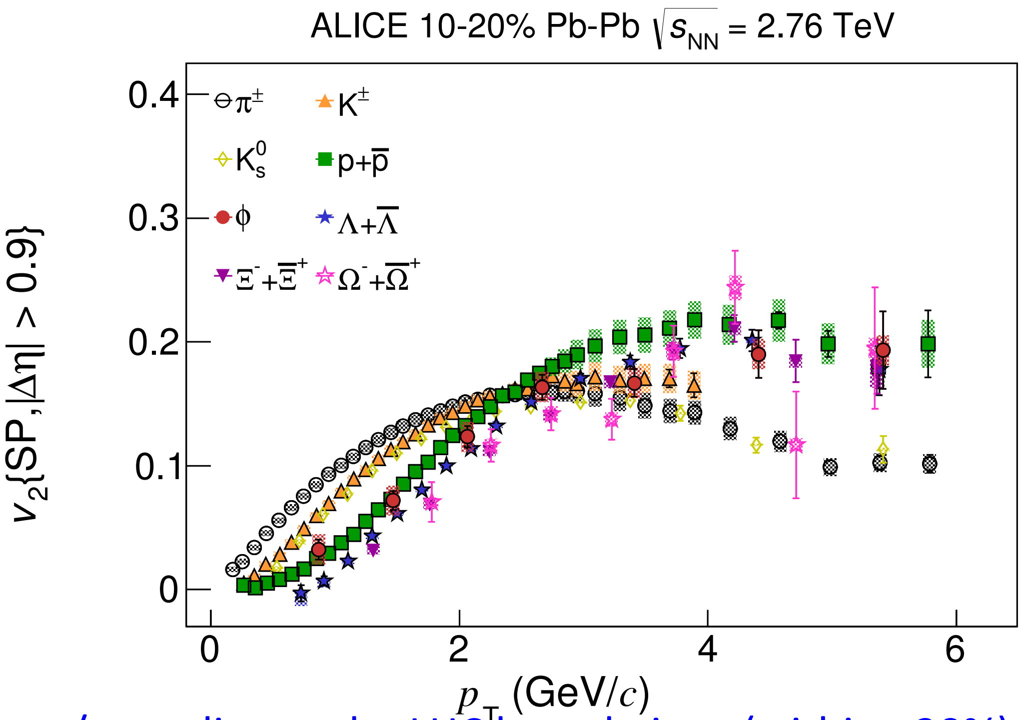
Hot, deconfined QCD matter flows as an almost perfect liquid



v_2 of identified particles

arXiv: 1405.4632

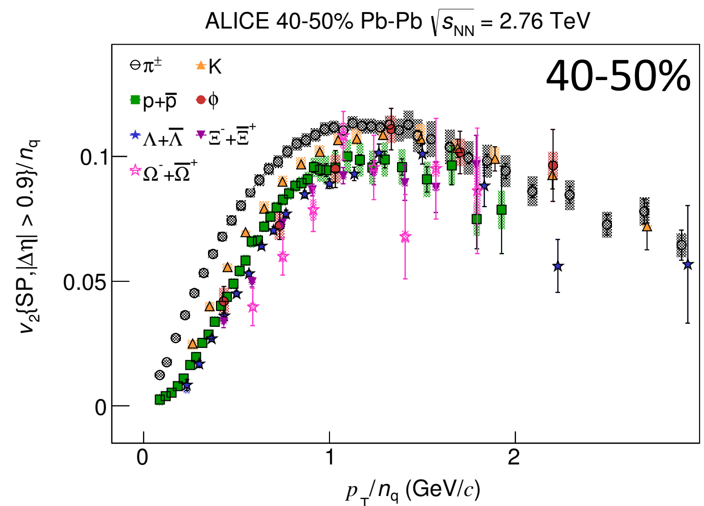
Viscous hydro predictions are able to describe the data
Hydrodynamic flow: Pronounced mass dependence



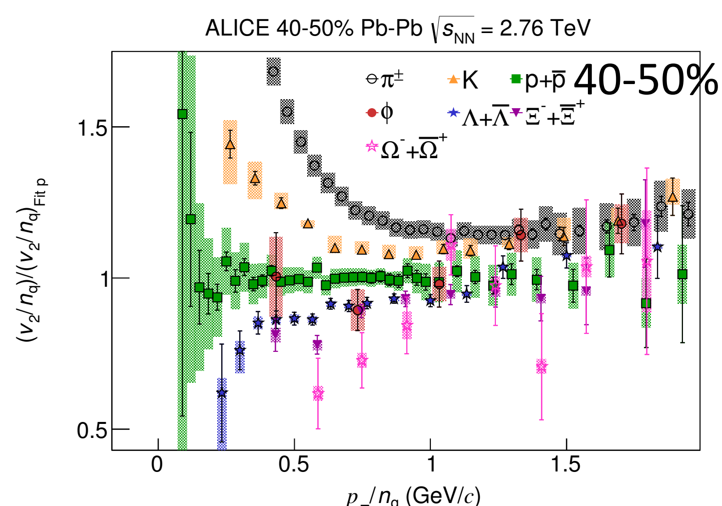
- v_2/n_q scaling at the LHC less obvious (within ~20%)

ALI-PUB-82653

Not shown: v_2 and $v_3(p_T)$ – mass ordering reproduced by hydrodynamic calculations with very small viscosity to entropy ratio: η/s ~ 0.2



ALI-PUB-82731



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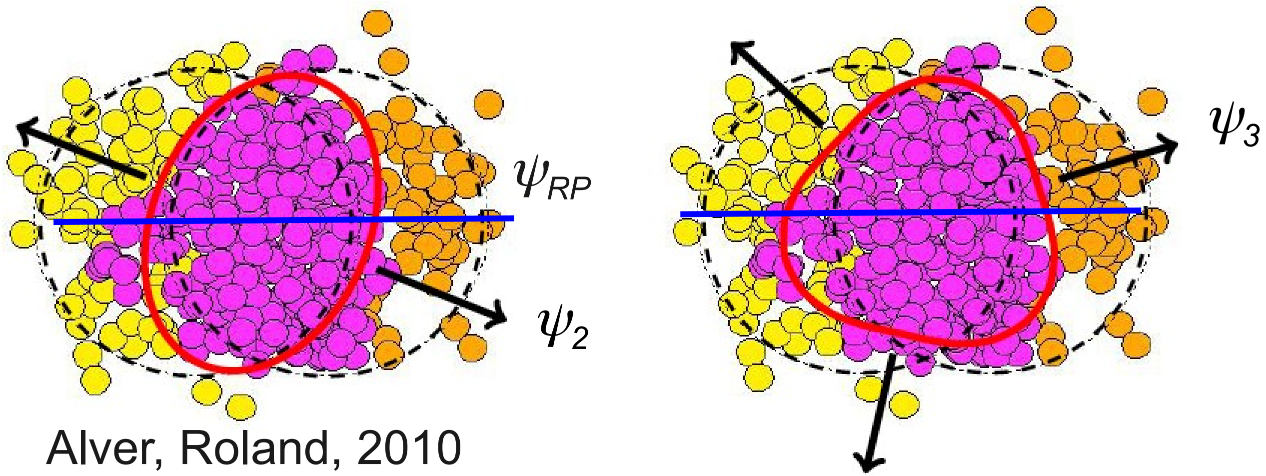
Higher harmonics in azimuthal decomposition

$$\frac{dN}{d\Delta\varphi} \sim 1 + 2v_2\cos(2\Delta\varphi) + \ldots$$

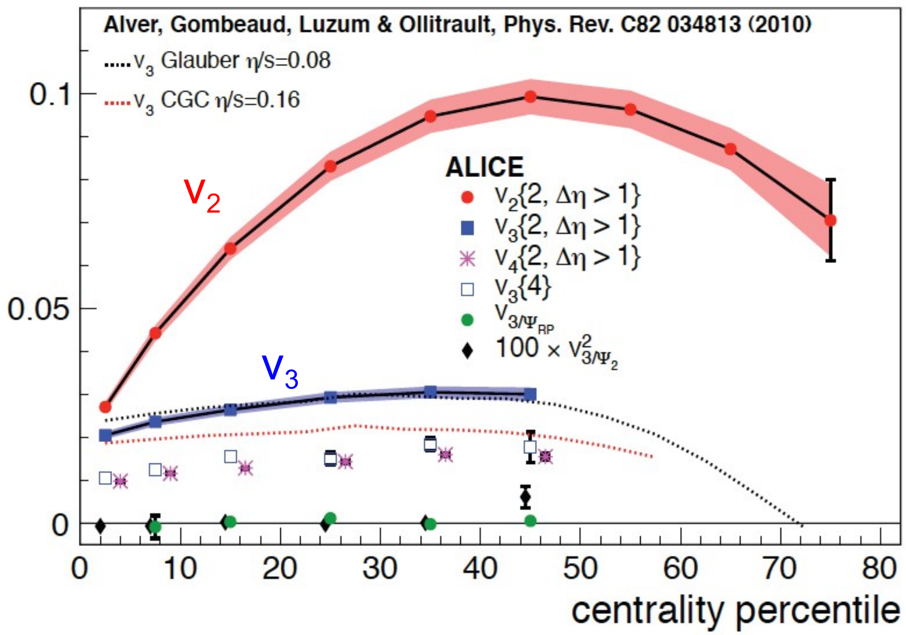


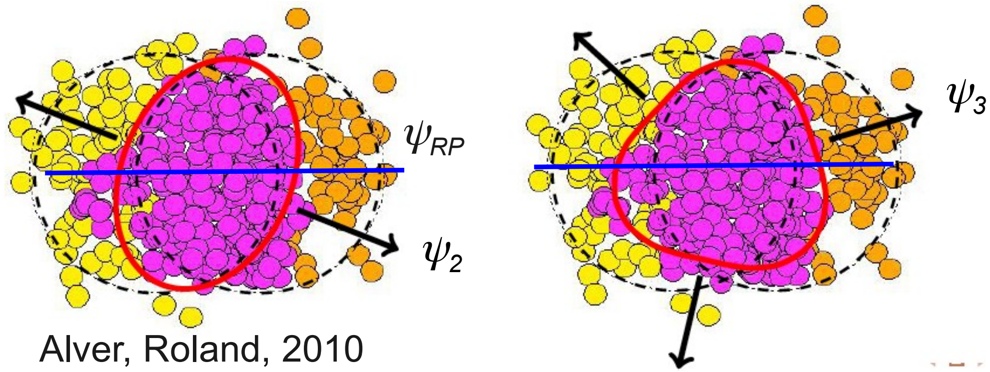
Alver, Roland, 2010

Fluctuations in initial state lead to e-by-e fluctuating symmetry planes

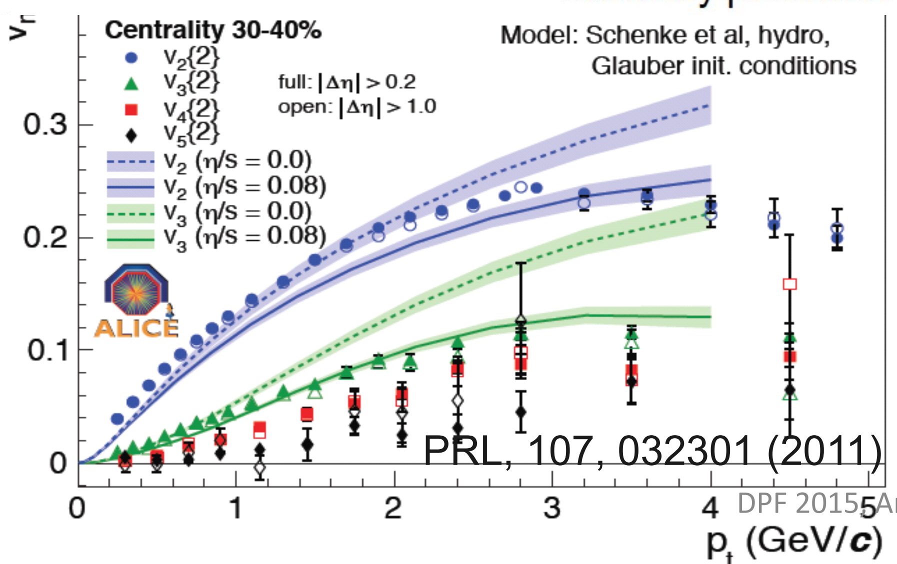
=> Odd harmonics are not zero

Higher harmonics – the measurements





Alver, Roland, 2010



PRL, 107, 032301 (2011)

v_3 - triangular flow :
- weak centrality dependence
- vanishes as expected when measured w.r.t. reaction plane

Similar p_T dependence for all v_n
Also similar to RHIC

Higher harmonics - additional constraints on η/s

Flow and particle mass…
Focus on the ϕ meson

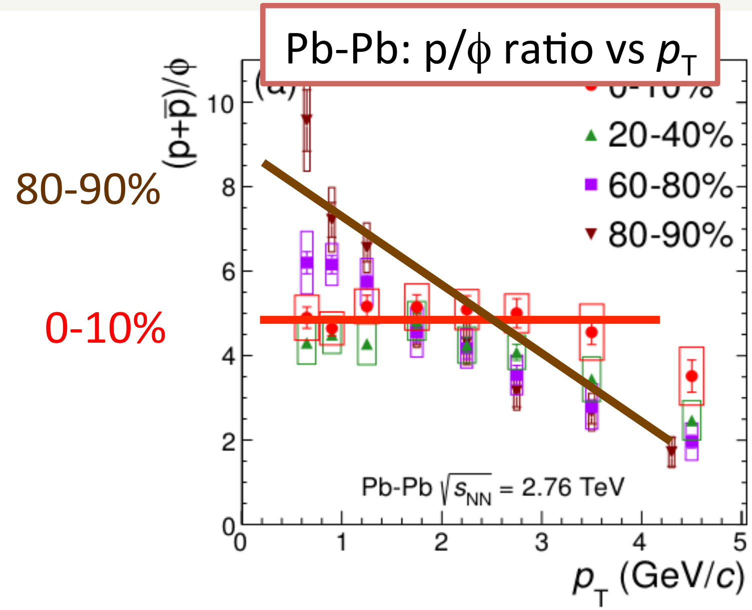
arXiv: 1404.0495

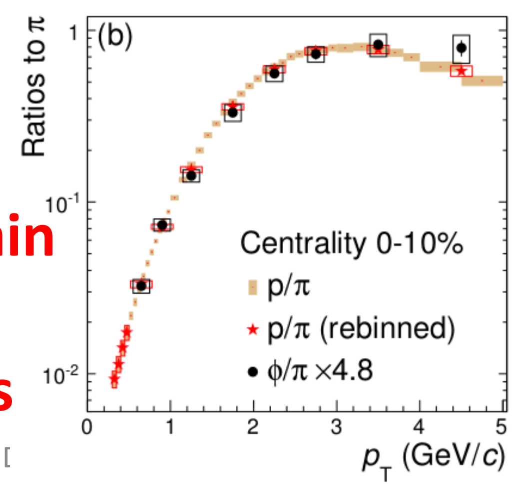
- Pb-Pb: Hydrodynamics + hadronic rescattering model struggles with v_2

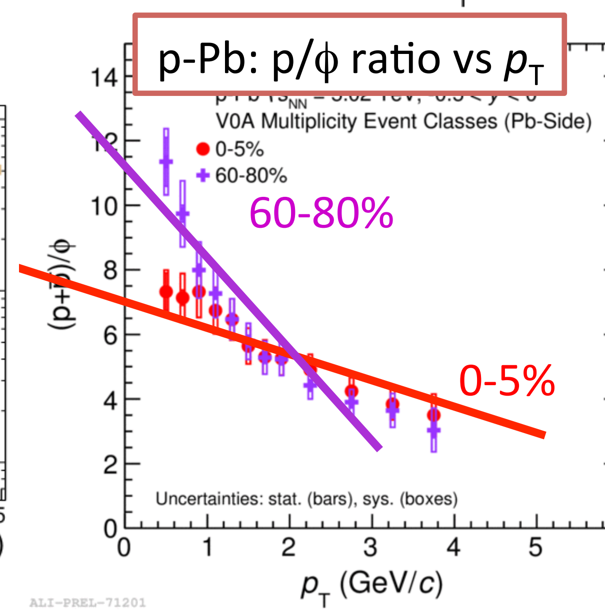
- v_2 at low p_T follows mass ordering
- v_2 at high p_T close to p in central and close to π in mid-central

- **In central collisions p and ϕ p_T spectra: similar shape up to ~4 GeV/c**
  - **As expected from radial flow**
  - **Similar in p-Pb?**

- **Mass (not number of constituent quarks) is main driver of v_2 and spectra in central Pb-Pb collisions**

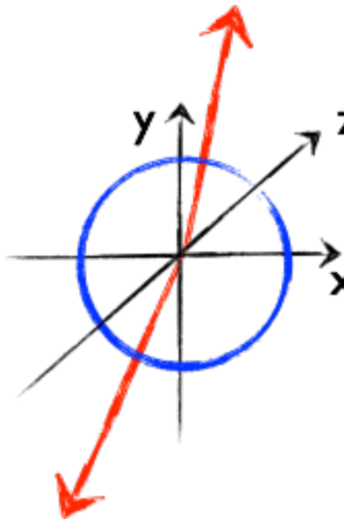


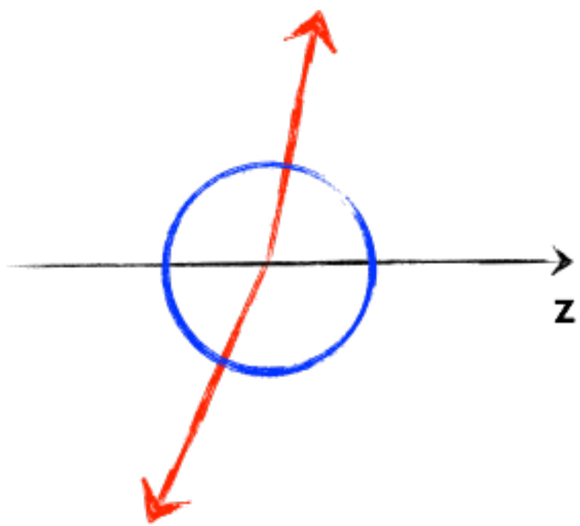




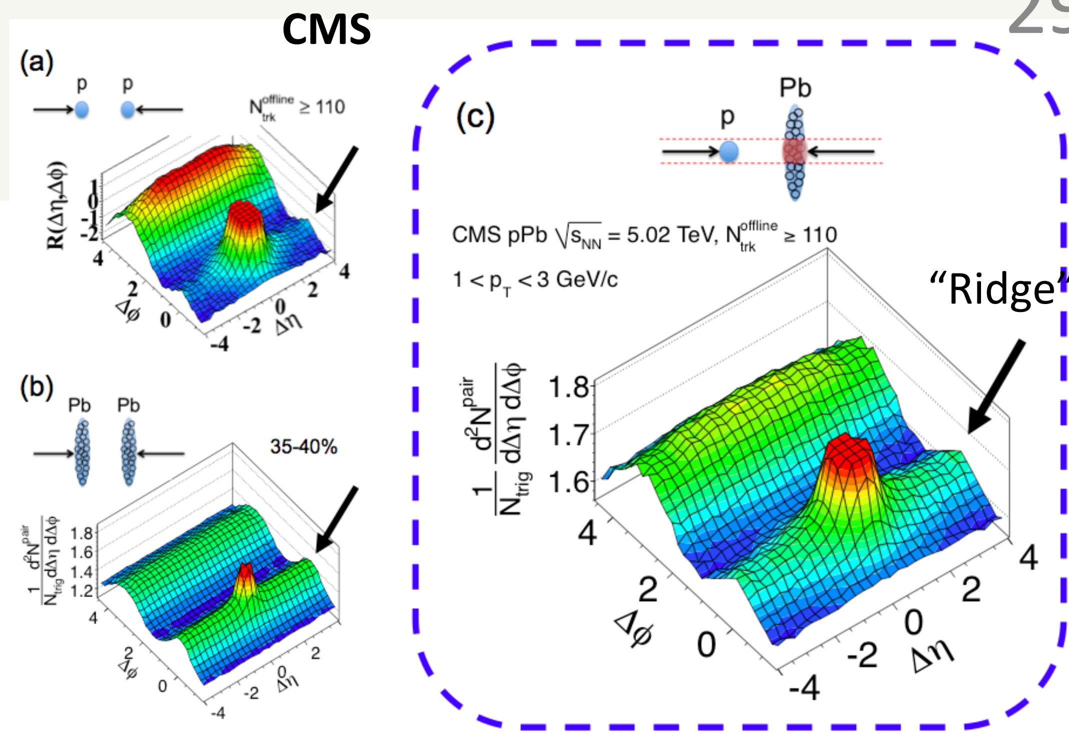
2-particle correlations

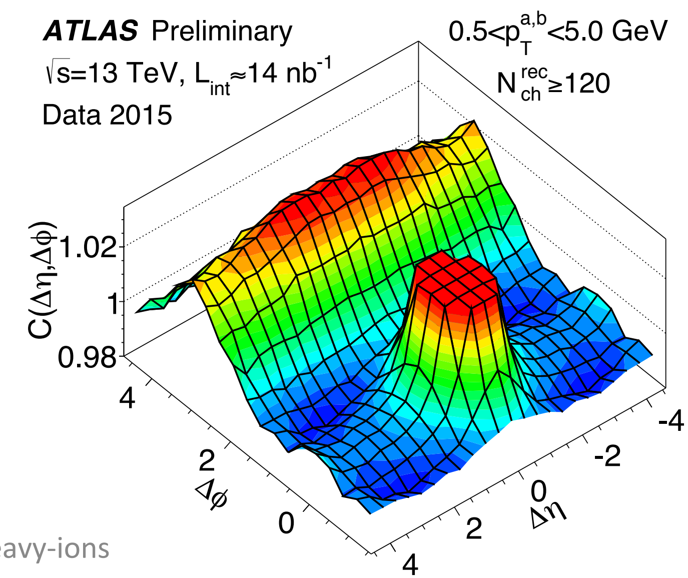
$\Delta\varphi$ azimuthal angle difference
- angle in the transverse plane



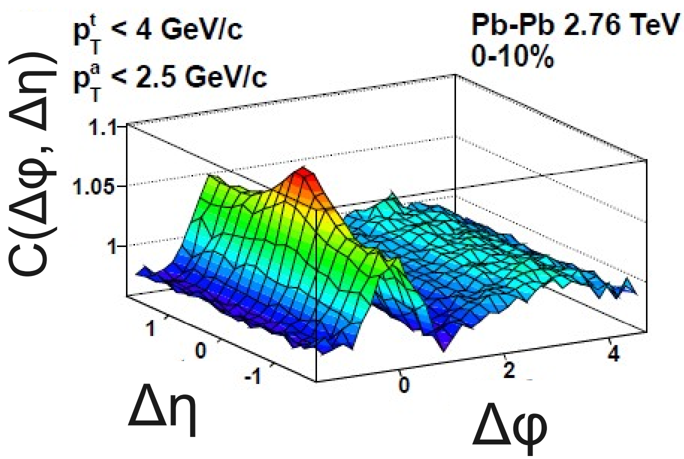


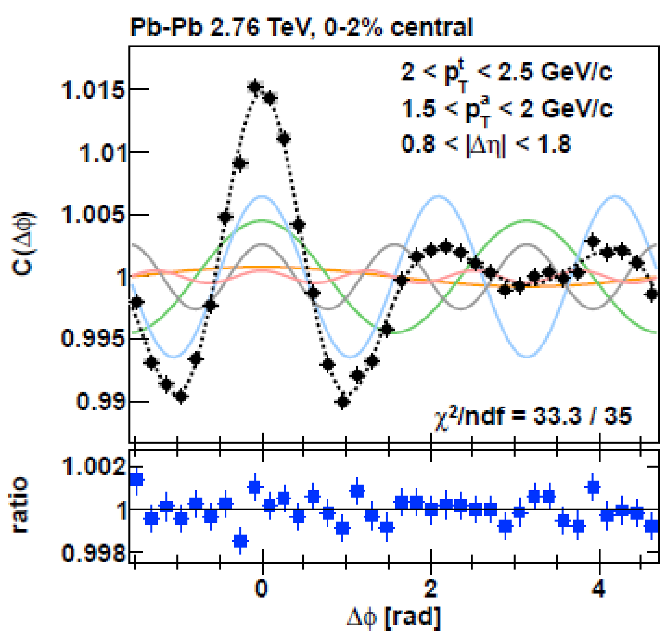
Δη - longitudinal - pseudo-rapidity distance





Two particle correlations – Fourier decomposition – long range correlations



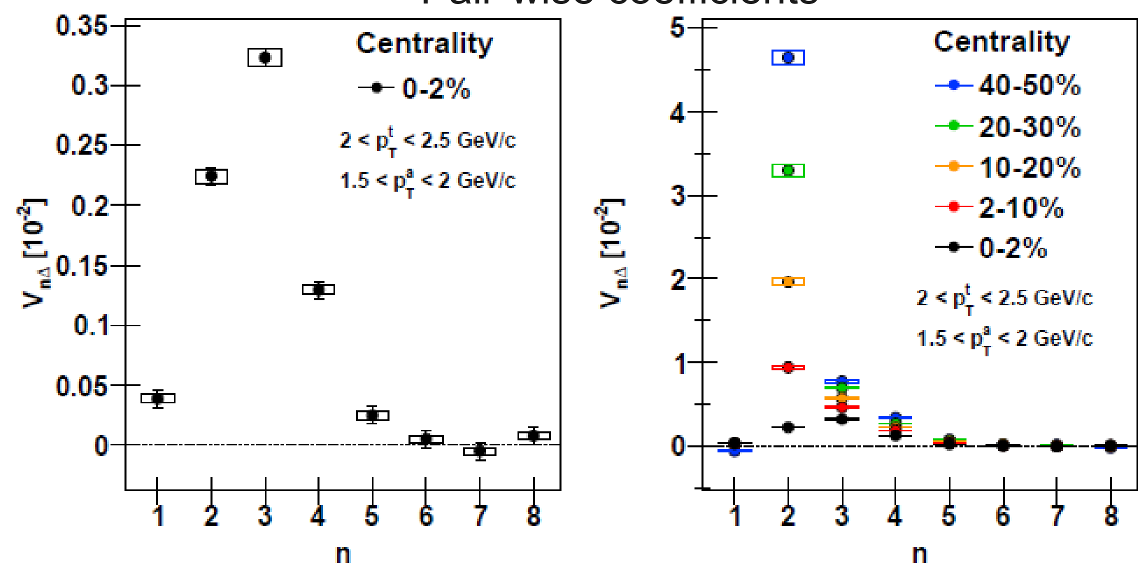


Integration of the correlation function in 0.8 < |Δη| < 1.8 (long) and Fourier decomposition

Collective flow: the coefficients factorize $V_{n\Delta}=v_n(p_T^T)v_n(p_T^A)$

$$C(\Delta\phi)=\frac{1}{\Delta\eta_{max}-\Delta\eta_{min}}\int_{\Delta\eta_{min}}^{\Delta\eta_{max}} C(\Delta\eta,\Delta\phi)\sim 1+2\sum_{n=1} V_{n\Delta}\cos(n\Delta\phi)$$

Pair-wise coefficients



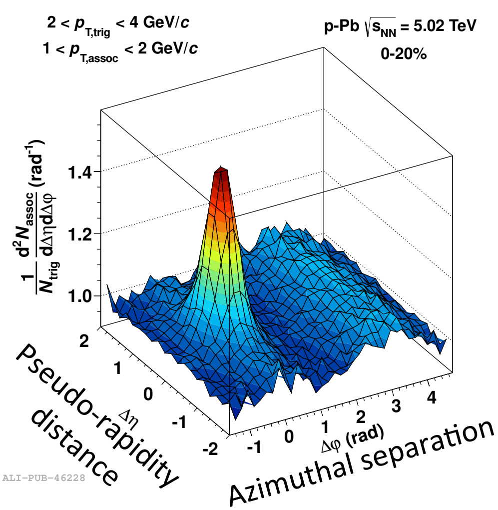
Few components describe the low-pT correlations

⇔ Strong near side ridge and double-peak on the away

⇔ Also recoil jet up to p_T^{trig}>8 & p_T^{assoc} 6-8 in central

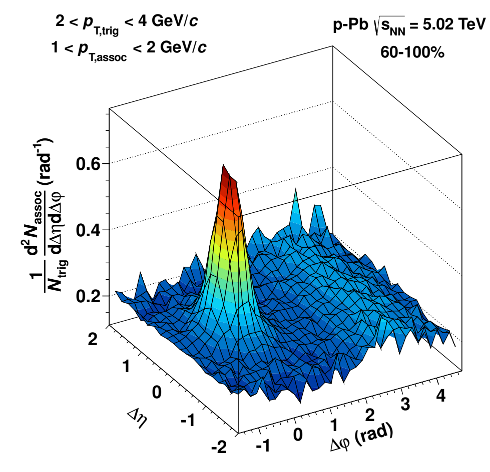
Two-particle correlations in p-Pb

The method: from the high-multiplicity yield subtract the jet yield in low-multiplicity events (no ridge)



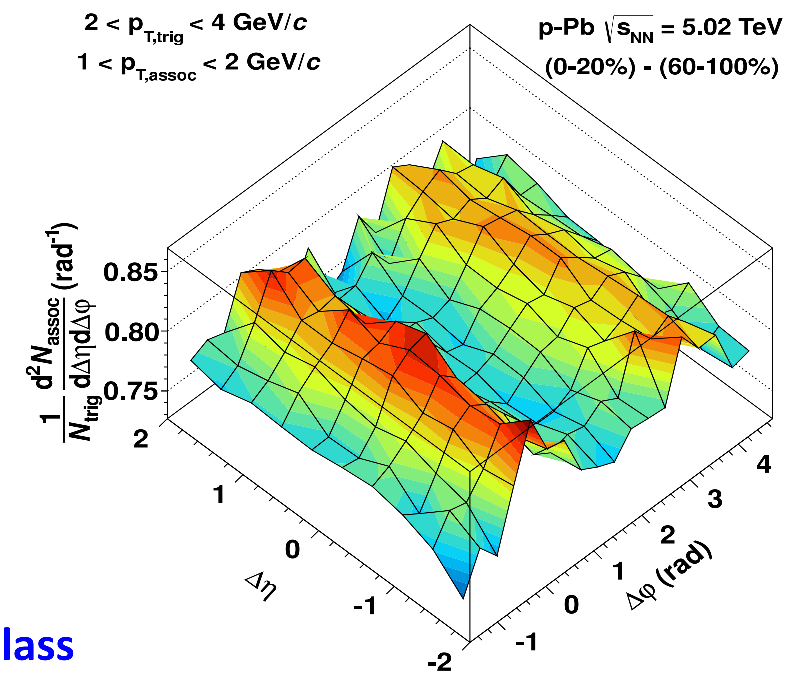
High multiplicity event class

$<dN_{ch}/d\eta>$ ~ 35



Low multiplicity event class

$<dN_{ch}/d\eta>$ ~ 7

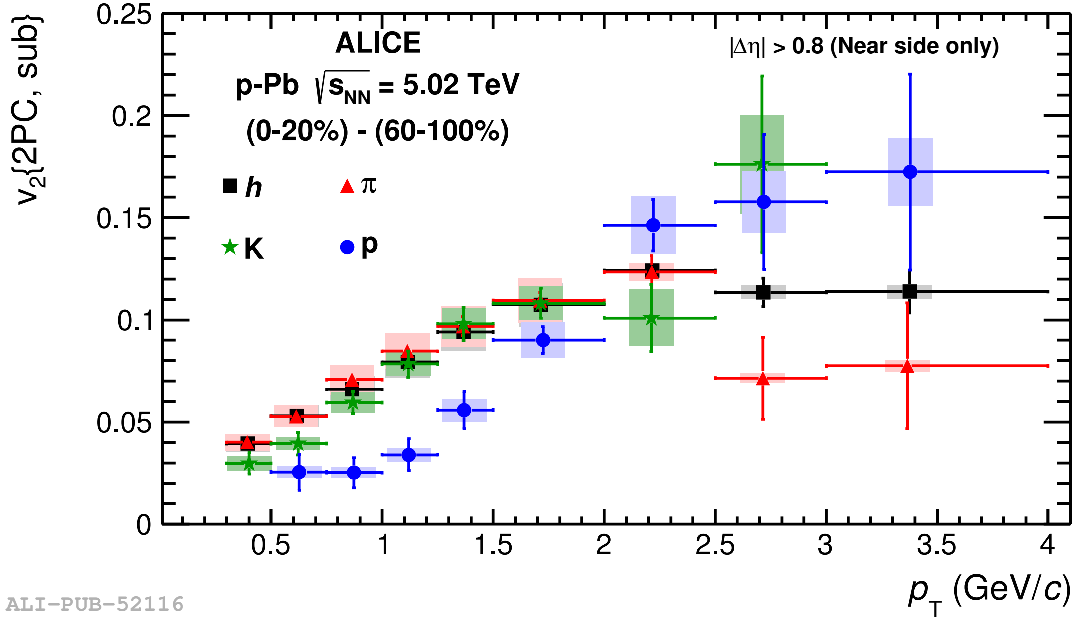


Remaining correlation: two twin long range structures

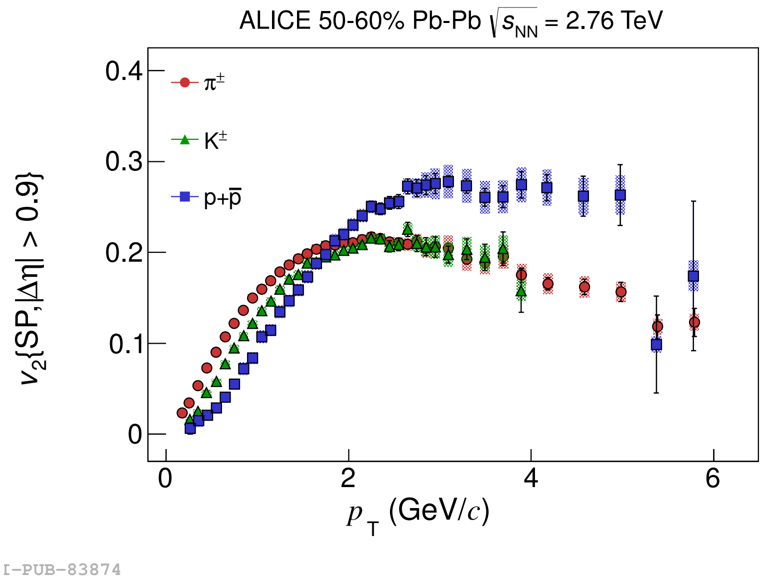
Analysis in multiplicity classes defined by the total charge in VZERO detector (away from the central region)

Comparison of v_2 in Pb-Pb and p-Pb

High-multiplicity p-Pb collisions



50-60% Pb-Pb

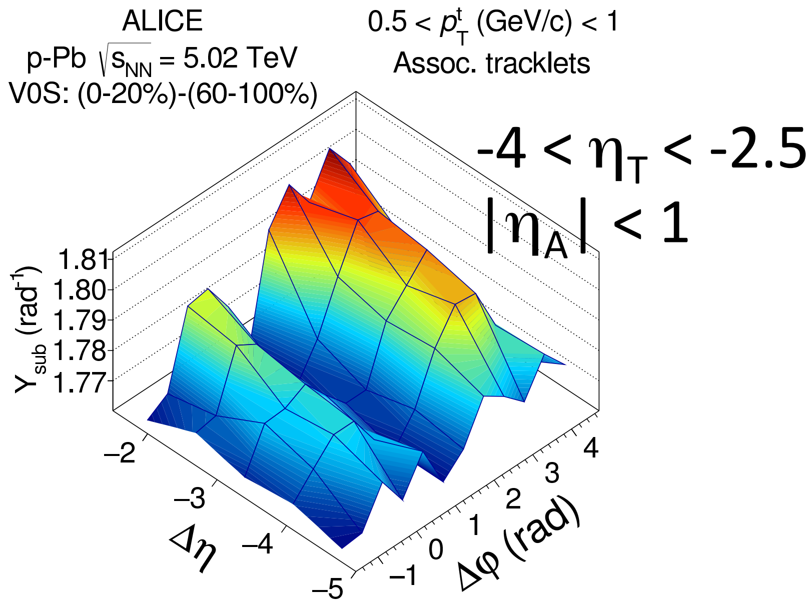


Similar features in p-Pb and Pb-Pb: mass ordering at low-p_T in Pb-Pb ascribed to hydrodynamics

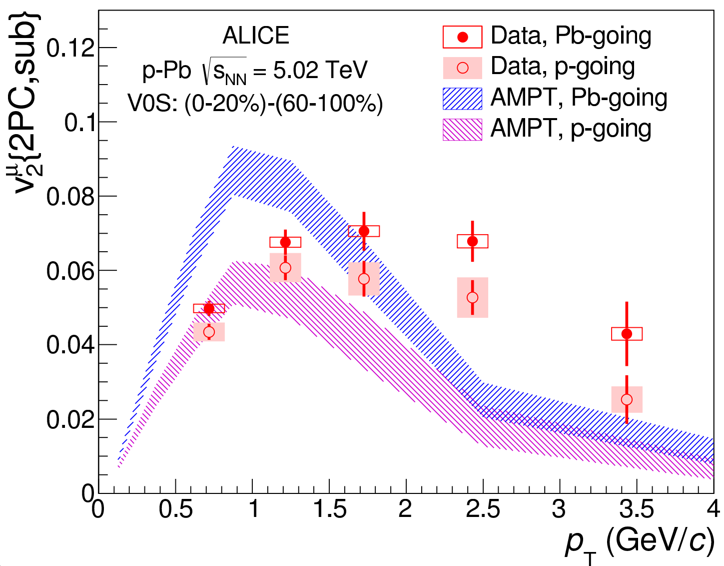
- Not shown: more signatures for collectivity from cumulant analysis

Double ridge structure in p-Pb Extends to very large rapidities

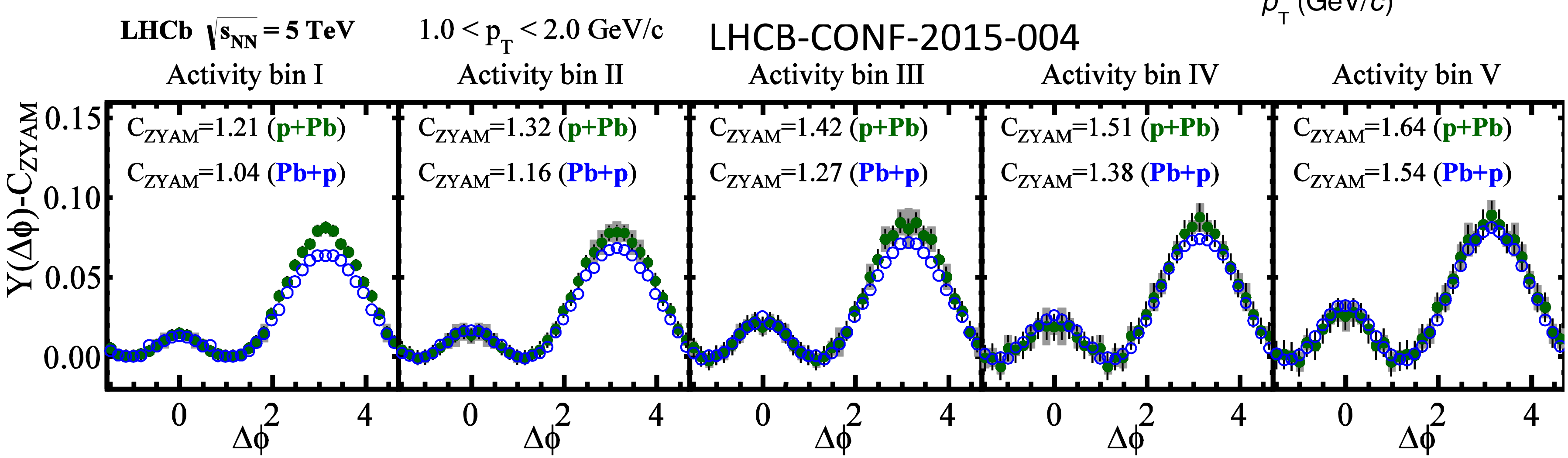
ALICE arXiv:1506.08032



v_2(Pb-going) > v_2(p-going) and independent of p_T



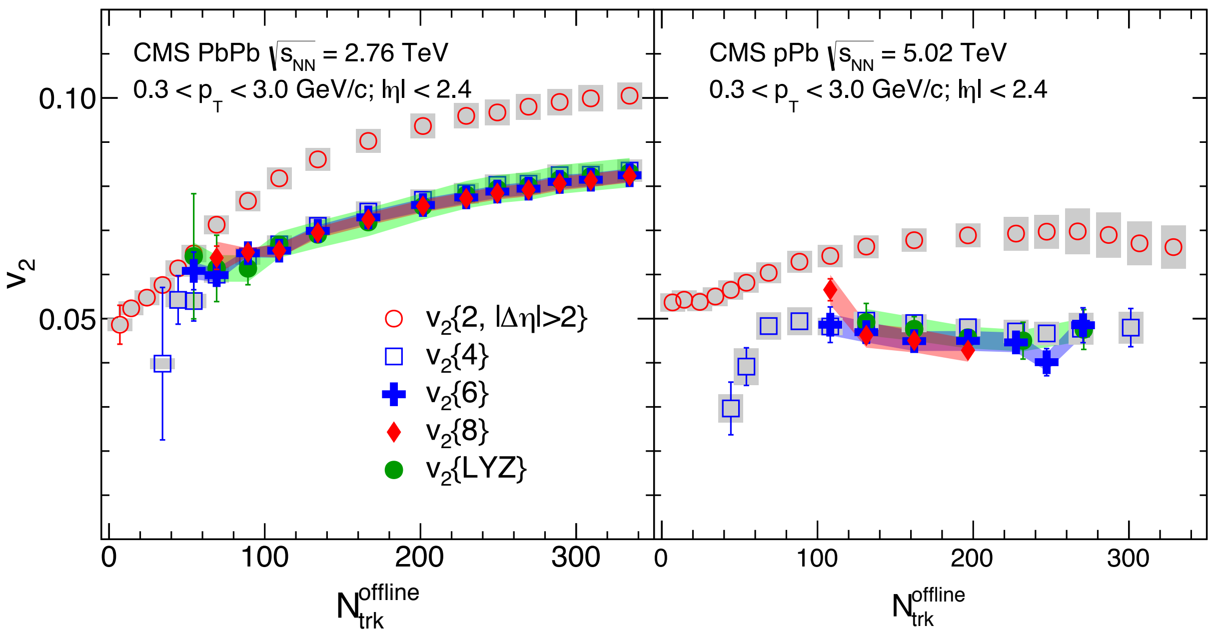
LHCB-CONF-2015-004



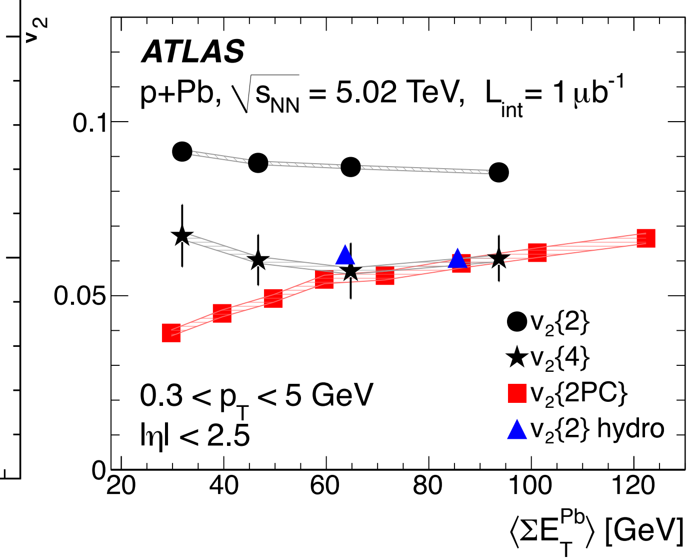
Collective particle production in p-Pb

Multiple-particle correlations

PhysRevLett.115.012301



Phys.Lett. B725 2013 (60-78)



Multiple particle (up to N=8) correlations

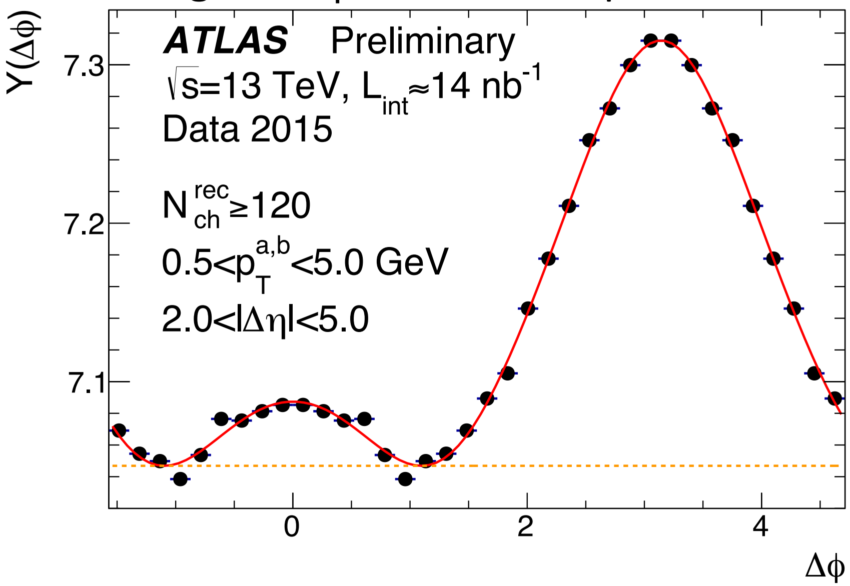
– **very clear signal of collective particle production**

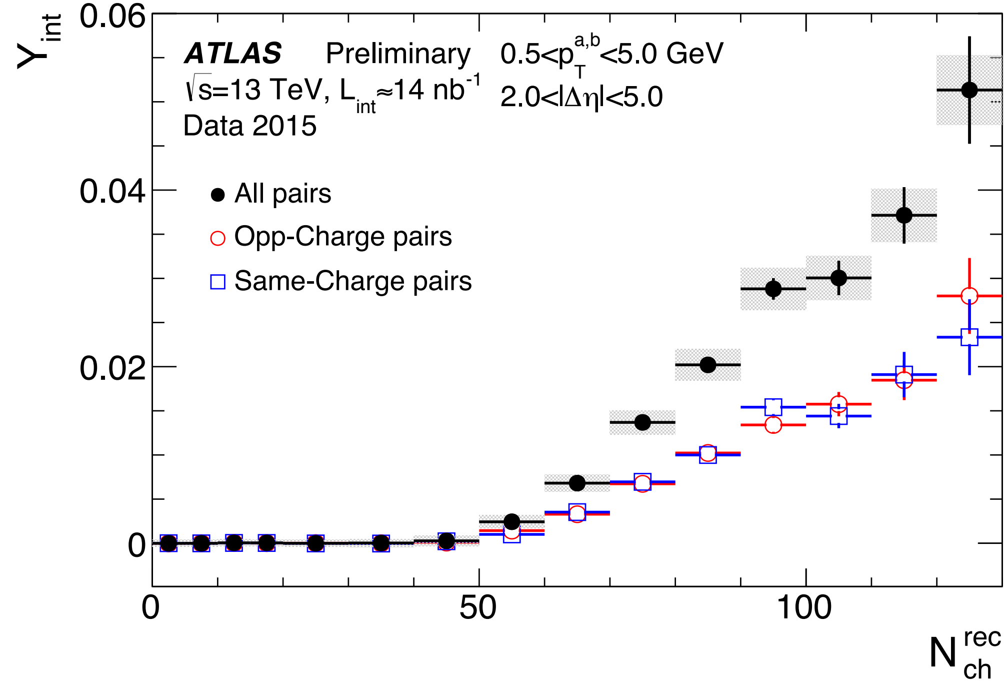
Droplets of QGP in pA collisions? Other "initial-state" effects?

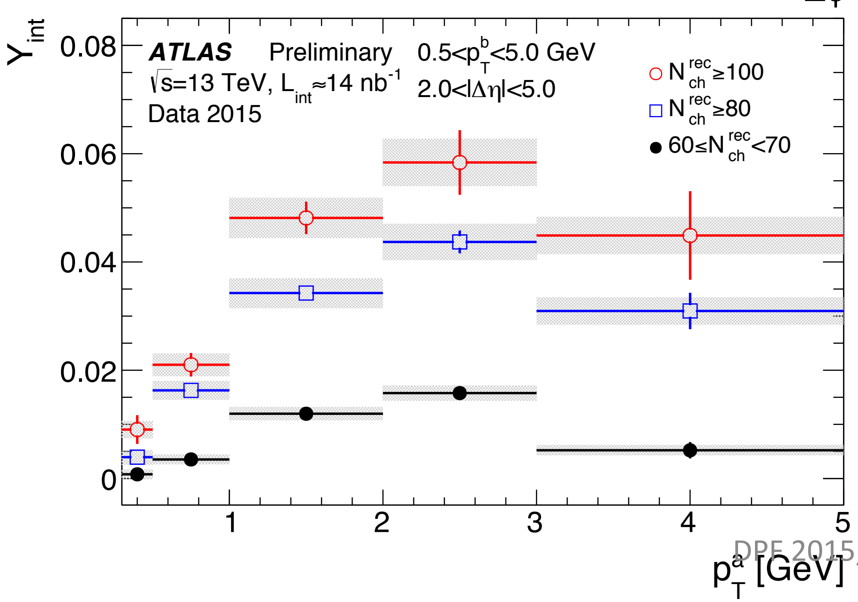
Long-range correlations also in pp collisions at 13 TeV

Ridge at Δϕ~0 over all rapidities

ATLAS-CONF-2015-027







Finite yield for high-multiplicity events N>50

- Same yield in like-sign and unlike-sign pairs
  – this is not a jet effect

Yield increases up to 2.5 GeV then drops

Similar trend as in Pb-Pb and p-Pb collisions

Consistent with 7 TeV observation by CMS

“Hard probes” of the medium

$$\hat{q} \sim \langle q_T^2 \rangle / \lambda = \langle q_T^2 \rangle / (\rho\sigma)$$

jet quenching

charm/bottom dynamics

J/ψ & Υ

Colorless (photons, Z,W)

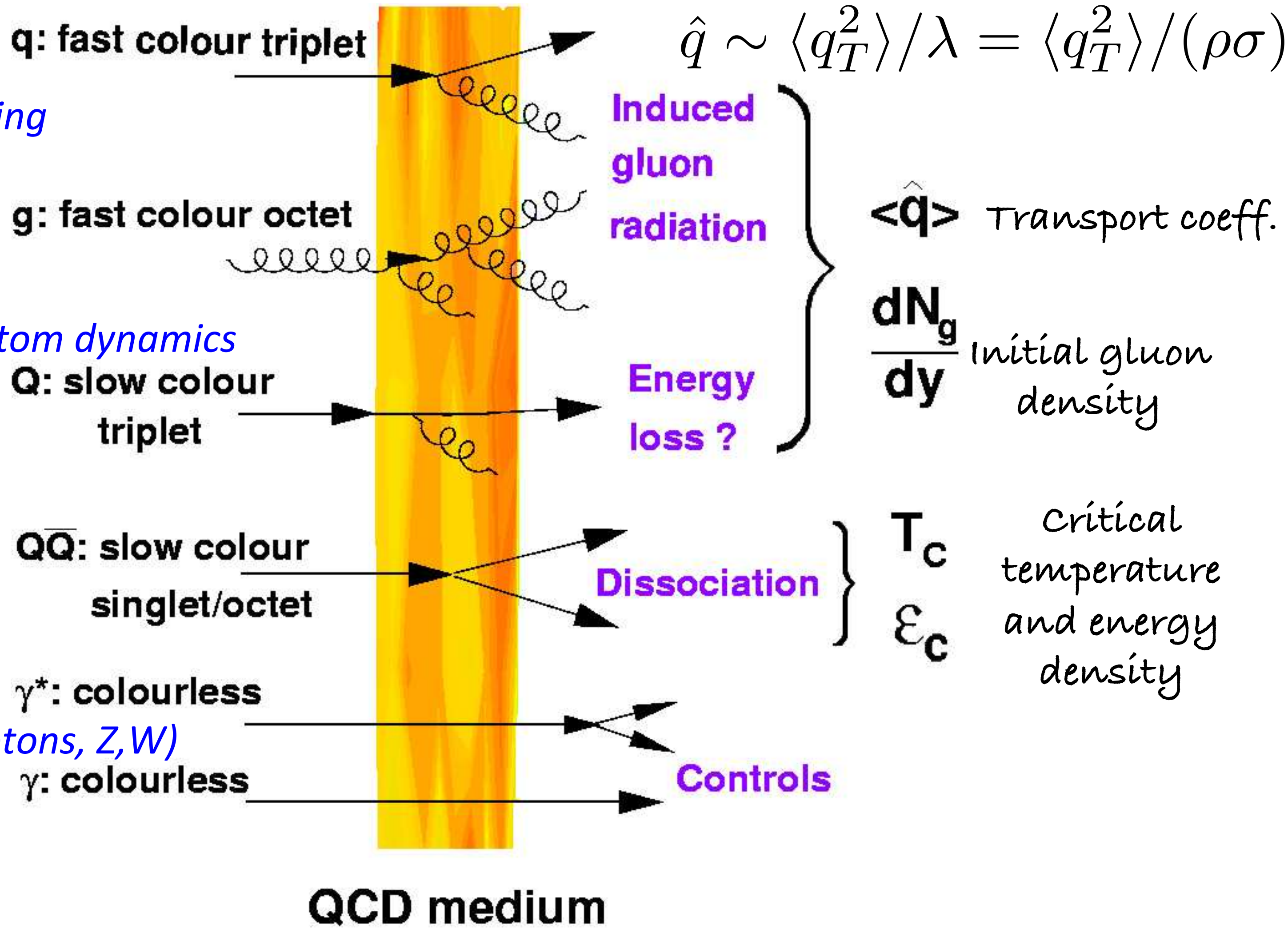
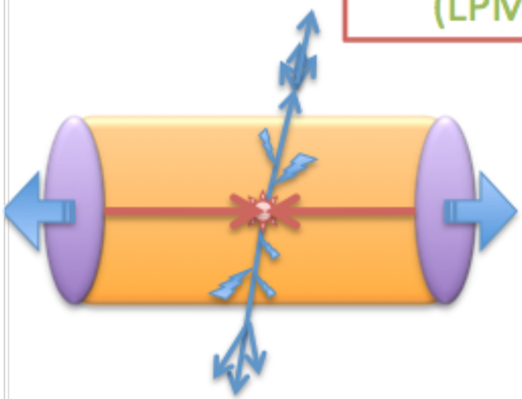


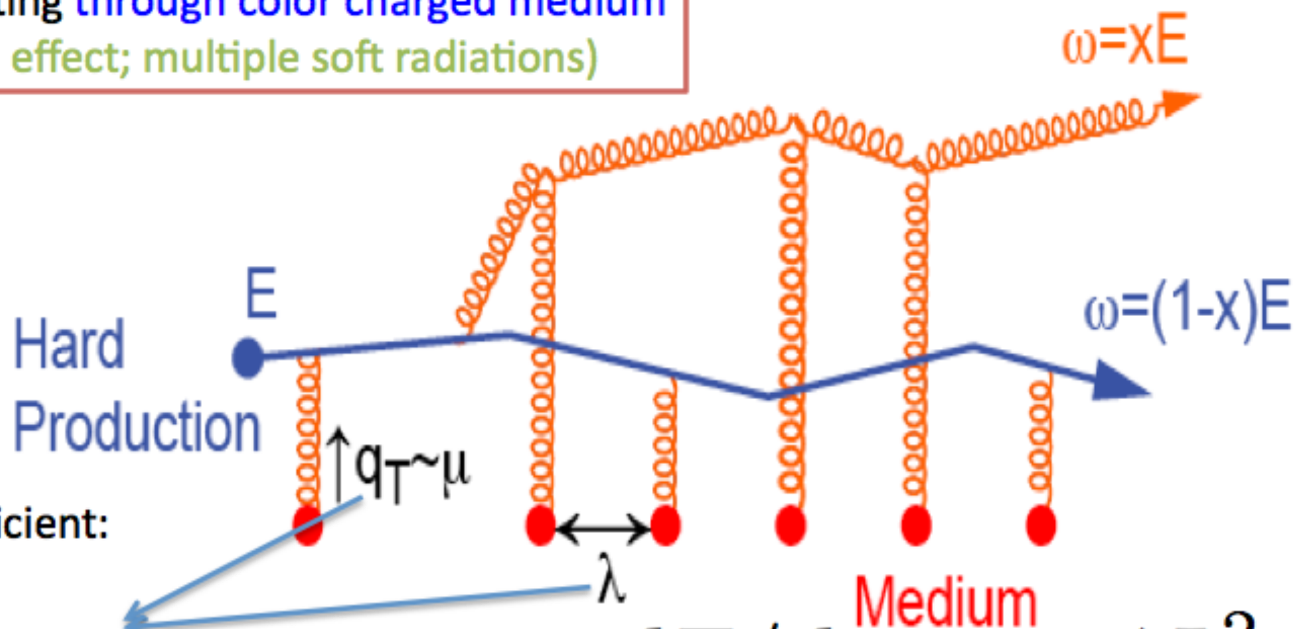
Figure: d'Enterria arXiv:0902.2011

Jet quenching at high-energy QCD Bremsstrahlung

High energy **color charged probe**
propagating **through color charged medium**
(LPM effect; multiple soft radiations)

$$t_{formation} < L \Leftrightarrow \omega < \omega_c$$





Define a transport coefficient:

$$\hat{q} \sim \mu^2/\lambda$$

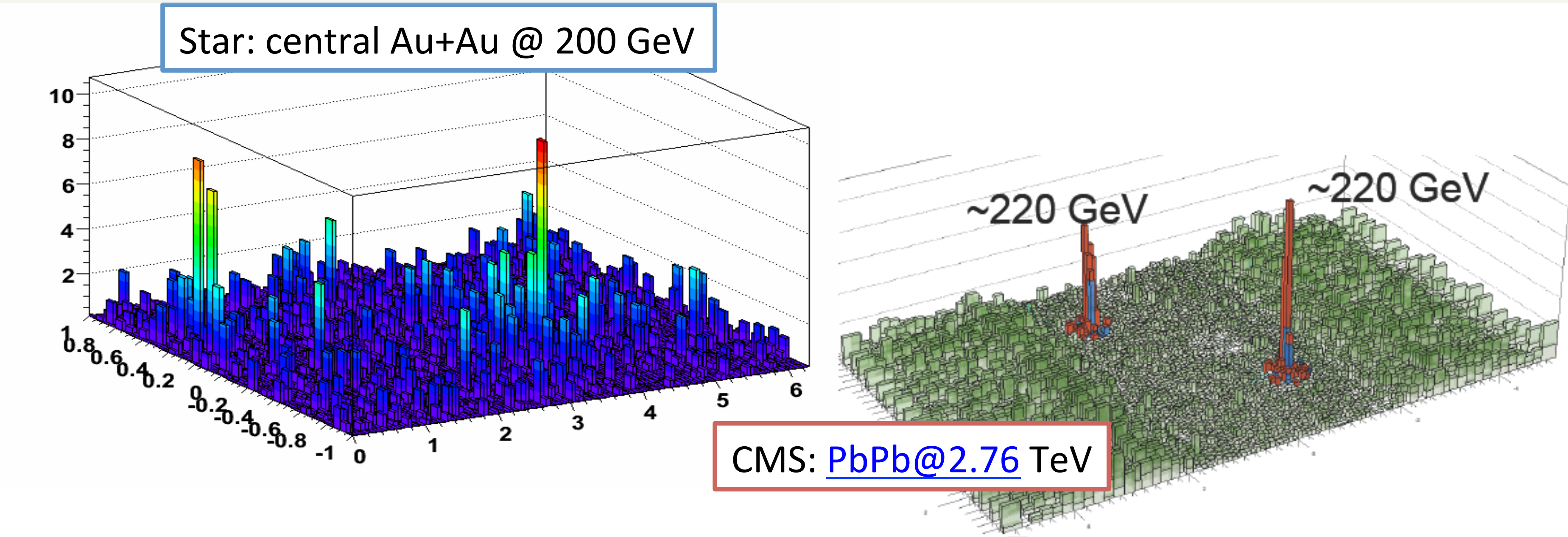
$$-dE/dx \sim \alpha_s \hat{q} L^2$$

$$\lambda \propto \frac{1}{\rho}$$

Partonic energy loss in QCD medium is proportional:
- to squared average path length (Note: QED ~ linear)
- to density of the medium

⇒ energy flow (parton+radiation) modified as compared to jet in vacuum
⇒ jet "quenched" ("softened" fragmentation)

Jets: LHC vs RHIC



LHC + RHIC: **QCD evolution of jet quenching ?**

Vary energy of the jet

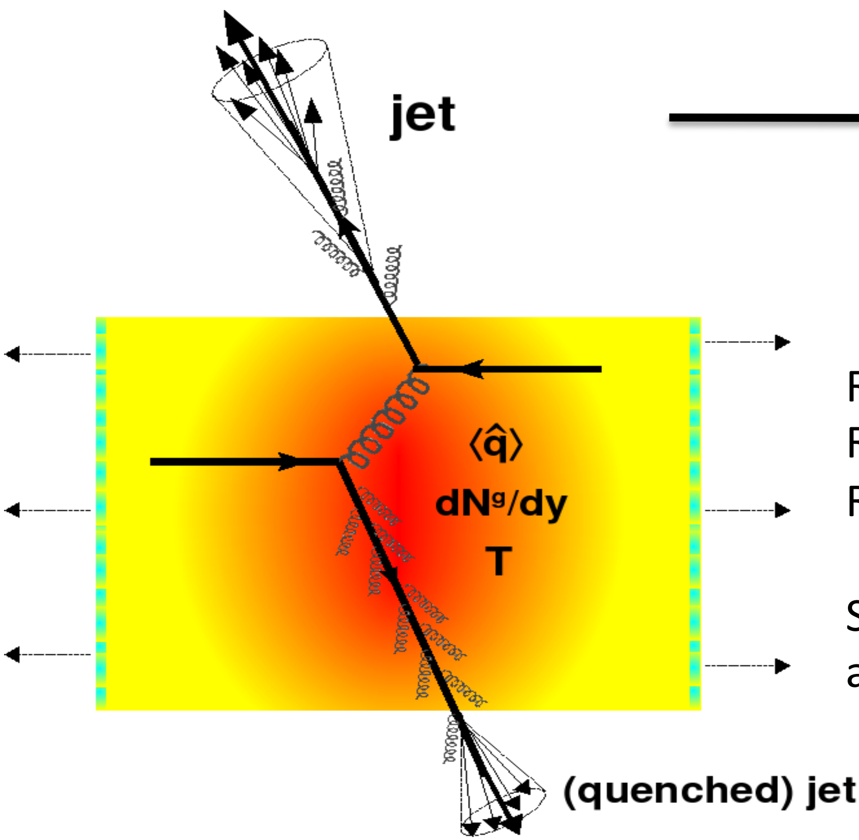
⇒ LHC: Vary the scale with which QGP is probed (a la **DIS**)

⇒ Compare and contrast RHIC and LHC

Quantifying nuclear effects: R_{AB}

$$R = \frac{\text{“QCD medium”}}{\text{“QCD vacuum”}}$$

$$\frac{\text{Yields measured in AA (or pA) per binary N-N collision}}{\text{Yields measured in pp collisions}}$$



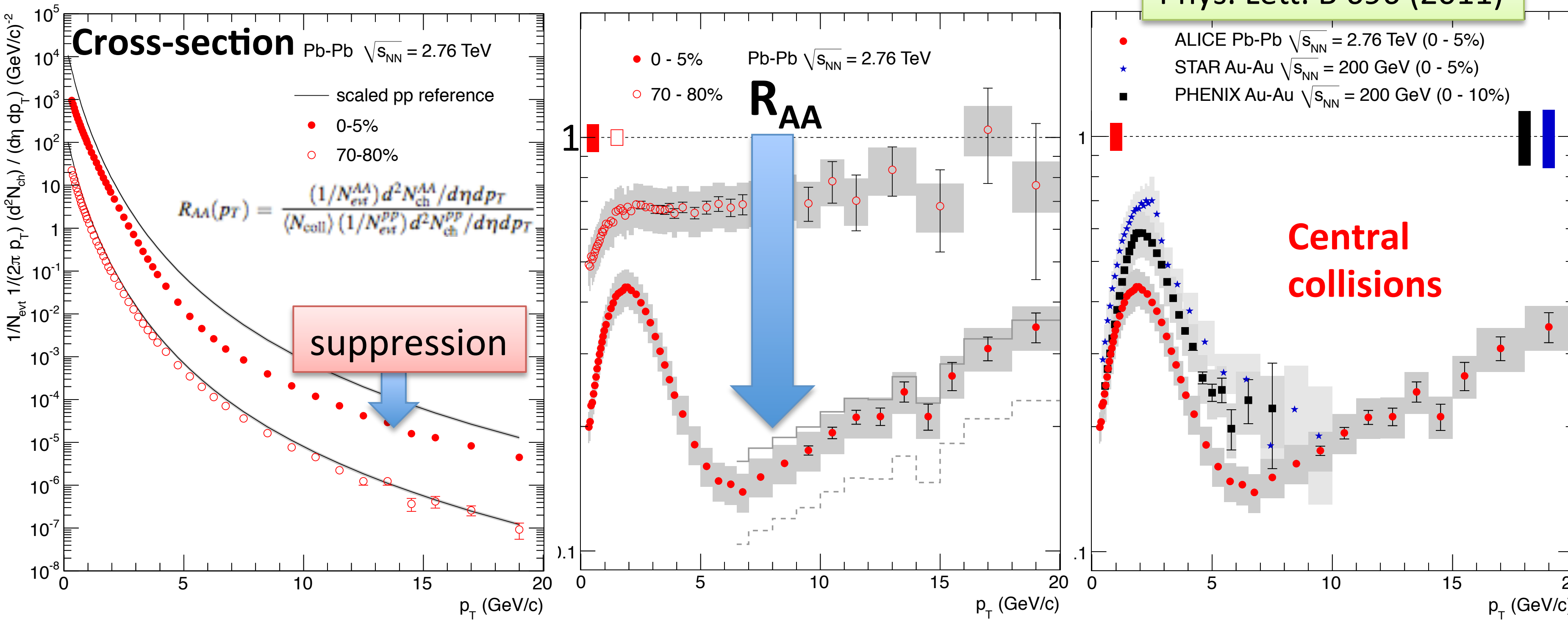
R > 1 – enhanced particle production
R = 1 – no nuclear effects
R < 1 – suppression

Sometimes useful to take the “vacuum” reference as yields in peripheral events – defined as R_{CP}

Jet quenching via hadron suppression

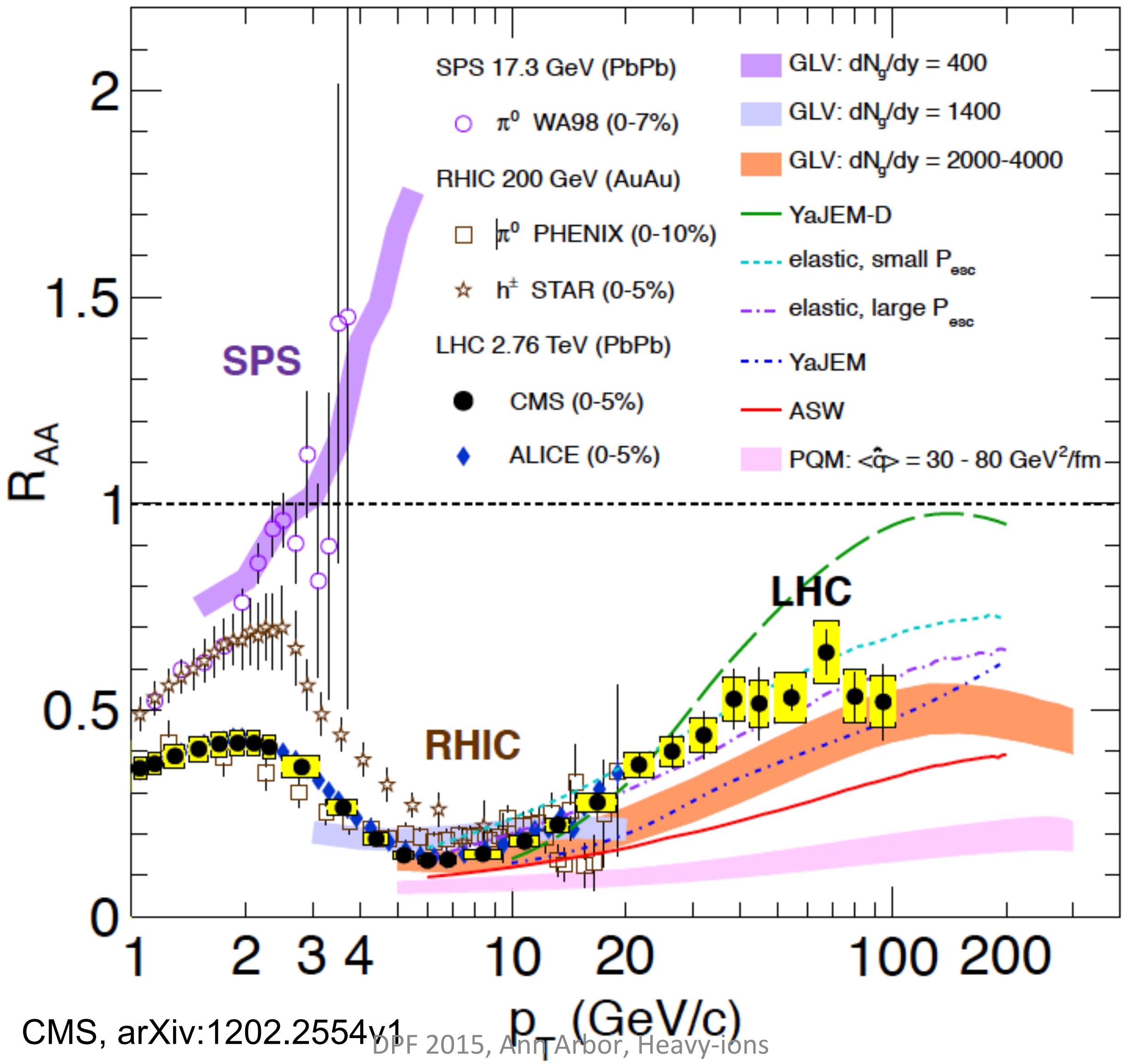
Ratio = $\dfrac{\text{\#(particles observed in AA collision per N-N (binary) collision)}}{\text{\#(particles observed per p-p collision)}}$

Phys. Lett. B 696 (2011)



1. **Strong depletion of high-pT hadrons in A-A collisions – consistent with parton energy loss (jet quenching)**
2. **Qualitatively new feature : evolution of R_{AA} as a function of p_T**
3. **New, much anticipated constraint for parton energy-loss models**

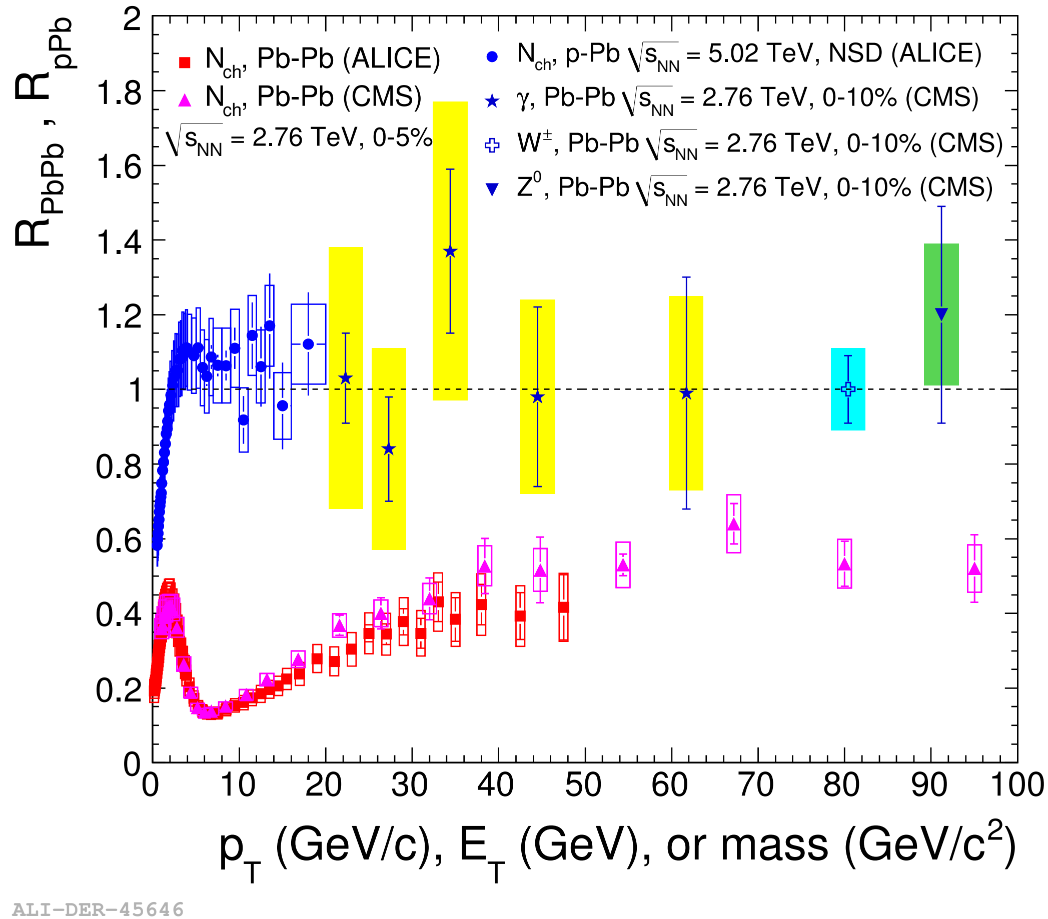
RAA from SPS, RHIC & LHC



CMS, arXiv:1202.2554v1

Hadron suppression

Pb-Pb: QGP transparent to color neutral probes – R_{AA}~1

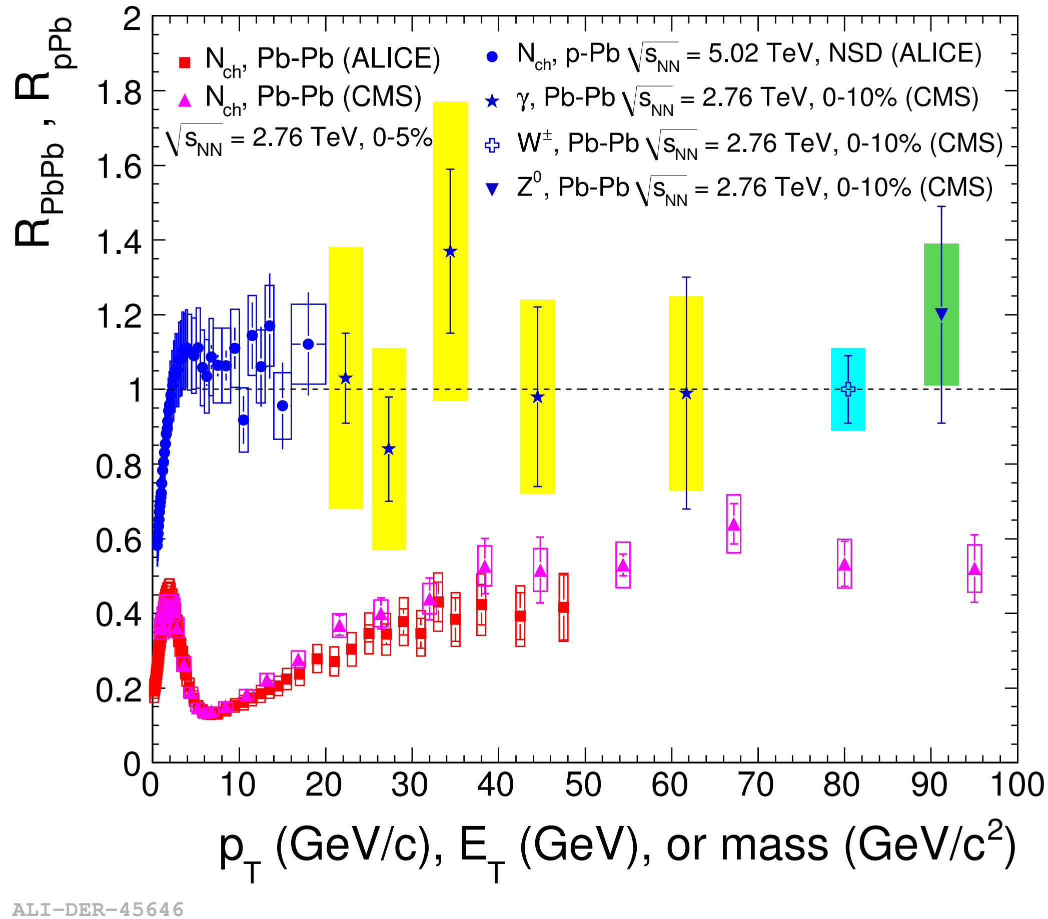


ALICE: Phys.Lett. B 720 (2013) 52-62; Phys.Rev.Lett. 110 (2013) 082302
CMS: Eur.Phys.J. C72 (2012) 1945; Phys.Lett. B710 (2012) 256-277; Phys. Lett. B 715 (2012) 66-87; PAS HIN-13-004

Hadron suppression

Pb-Pb: QGP transparent to color neutral probes – R_{AA}~1

p-Pb: R_{pPb} (min. bias) for hadrons with p_T> 4 GeV/c consistent with unity



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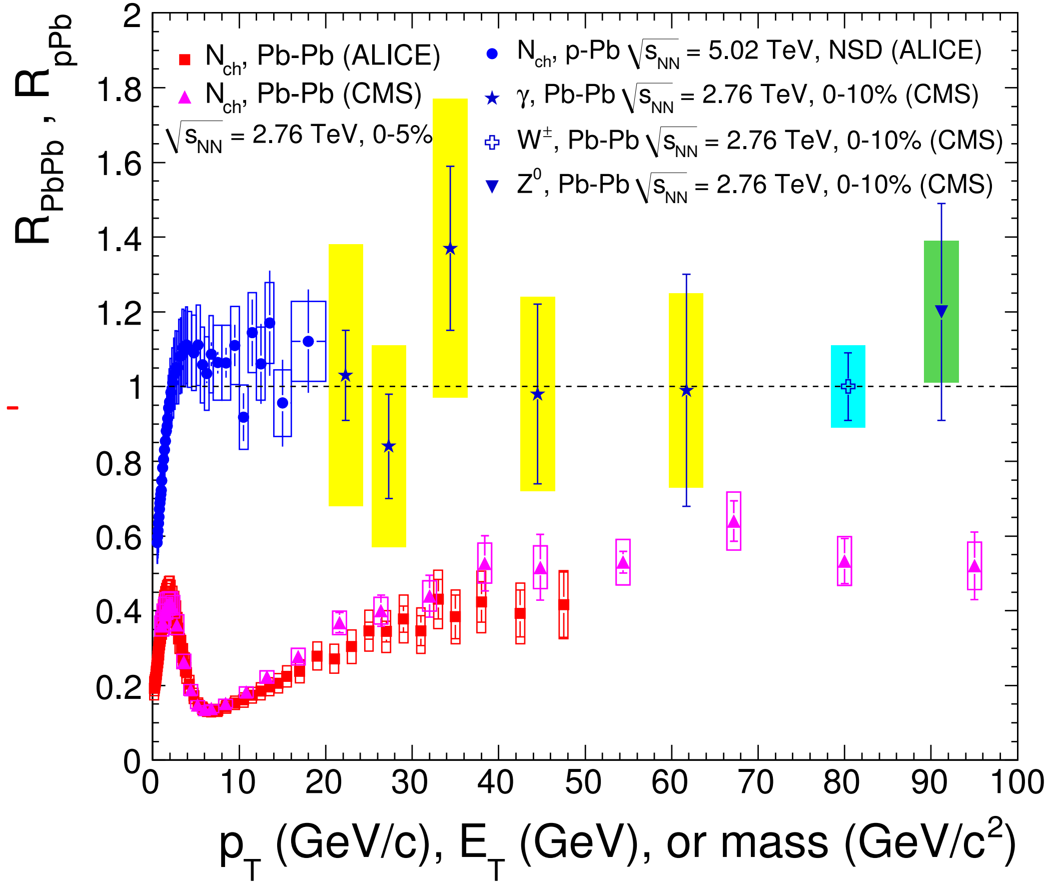
Strong suppression of hadron yield in most central Pb-Pb collisions => final state effect R_{AA} rising up to 0.4 and flattening at high-p_T - reproduced by (most) models



ALI-DER-45646

ALICE: Phys.Lett. B 720 (2013) 52-62; Phys.Rev.Lett. 110 (2013) 082302
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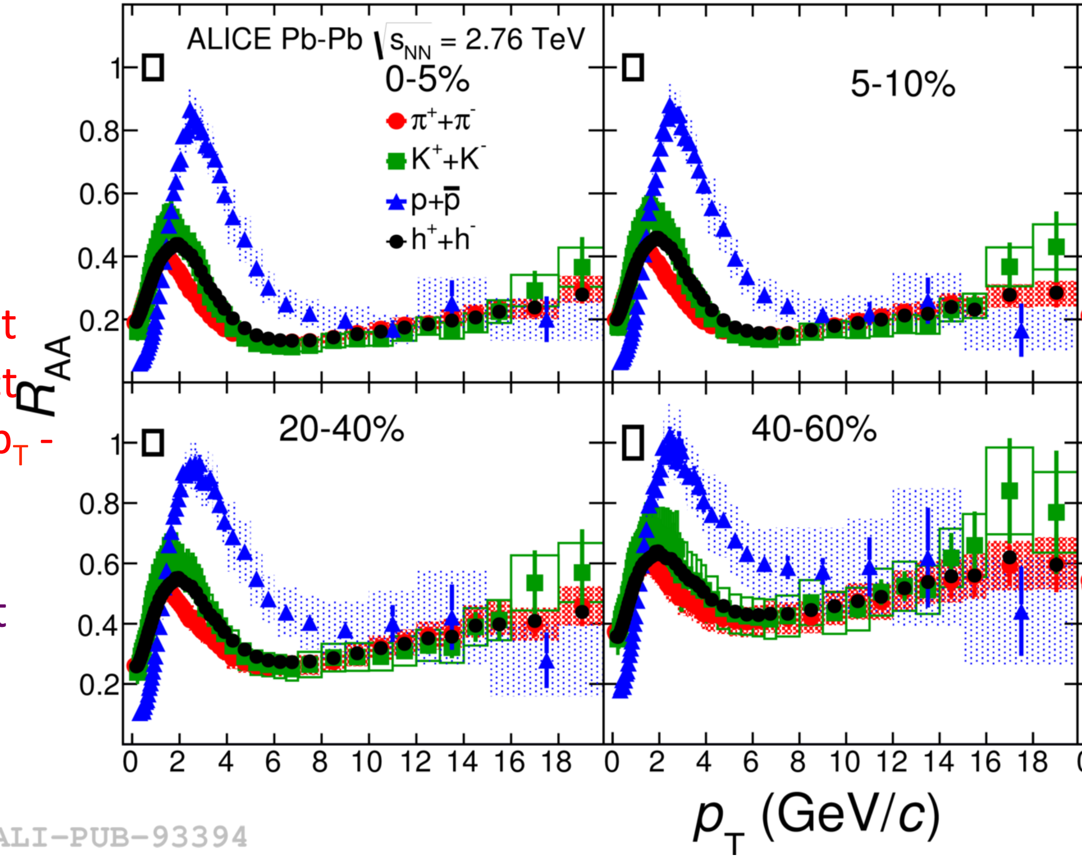
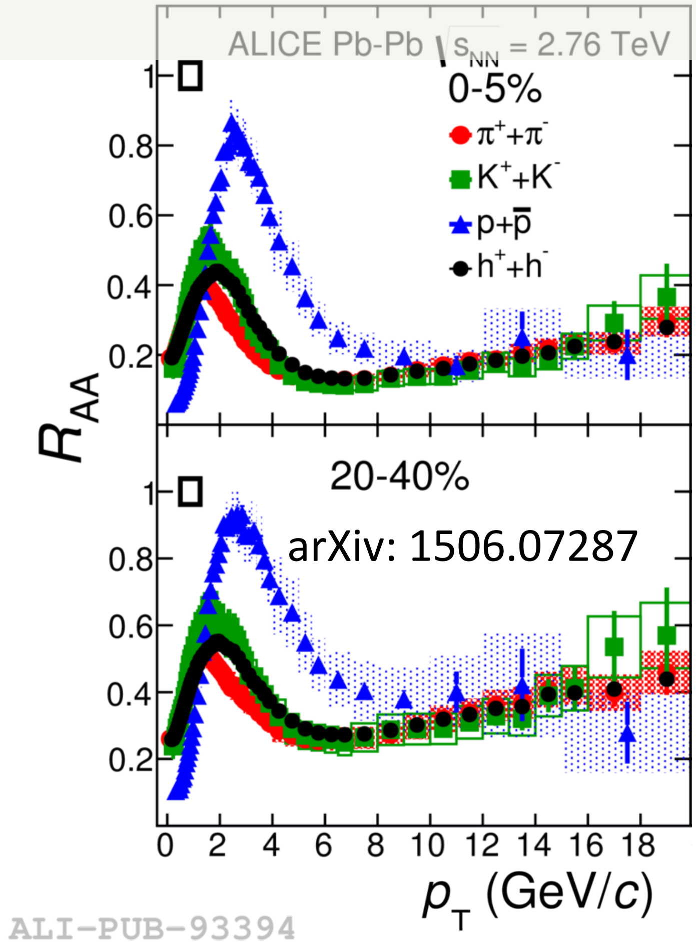
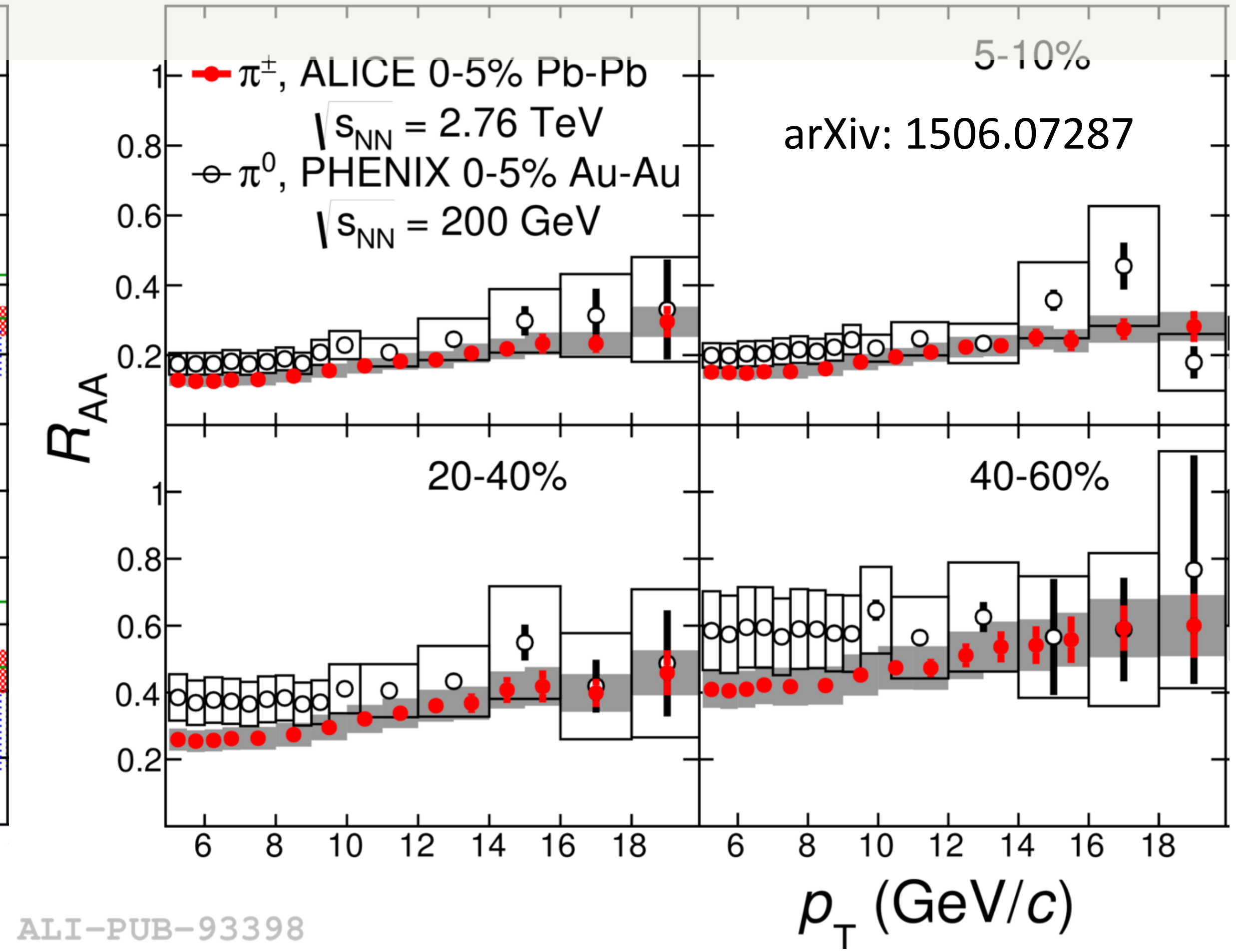
Similar R_{AA} for pions, kaons and protons at high-p_T



ALICE: Phys. Rev. Lett. 109, 252301 (2012)
arXiv:1303.0737;
Preliminary SQM 2013

Hadron suppression LHC and RHIC



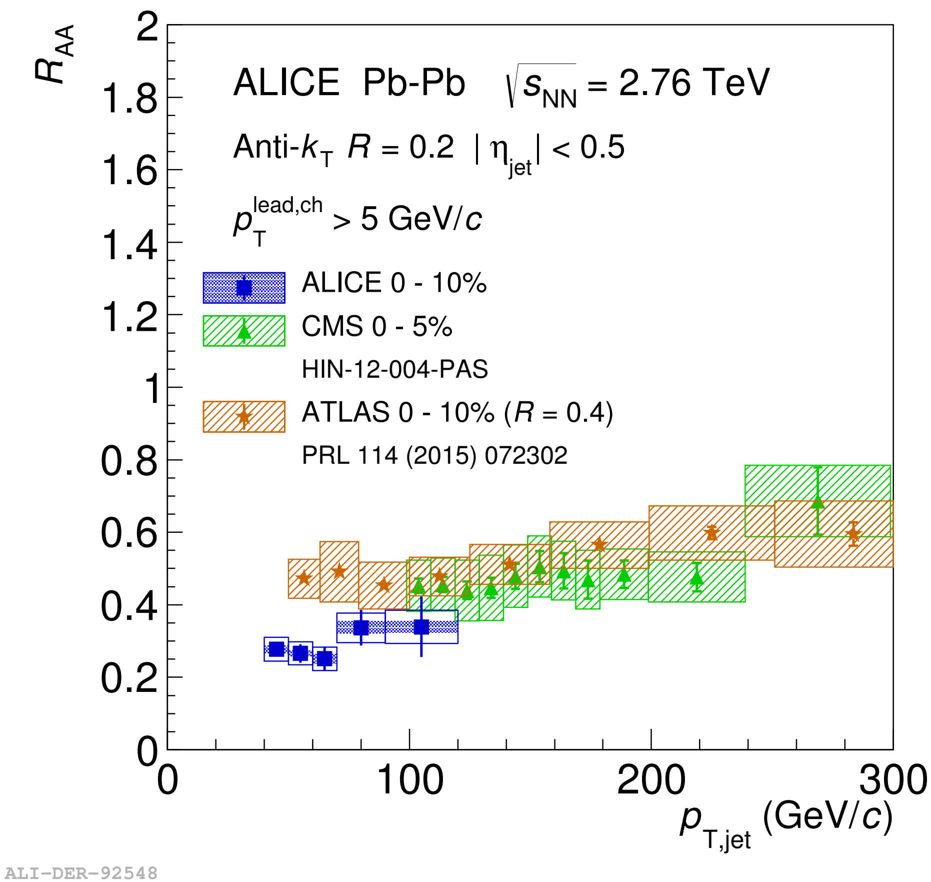


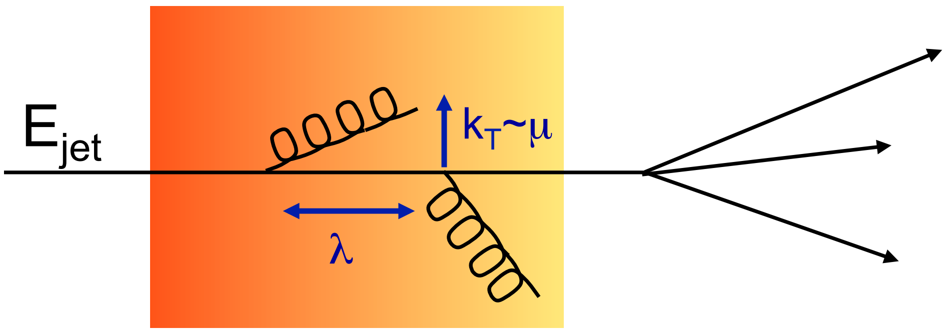
- High-p_T: Similar suppression for all particles ⇔ leading particle jet structure umodified
- Similar suppression for identified pions at RHIC and the LHC (all centralities)

Despite different $d\sigma/dp_T$ R_{AA}^{RHIC} compatible with R_{AA}^{LHC}

Jet suppression

R_{AA} < 1: medium induced out-of-cone radiation





Longitudinal modification:

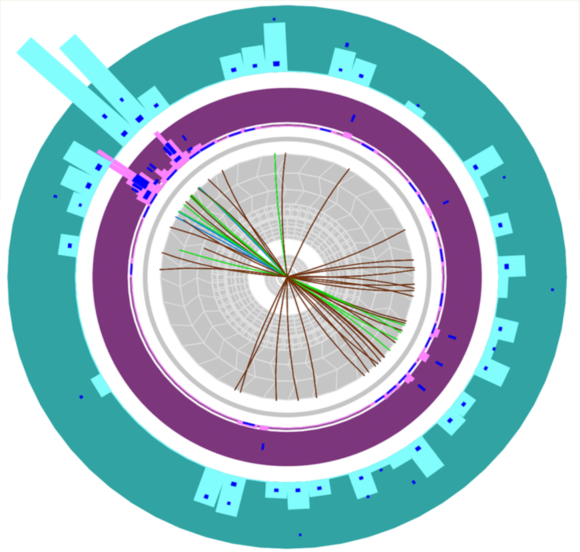
- out-of-cone: energy lost, loss of yield, di-jet energy imbalance
- in-cone: softening of fragmentation

Transverse modification

- out-of-cone: increase acoplanarity kT
- in-cone: broadening of jet-profile

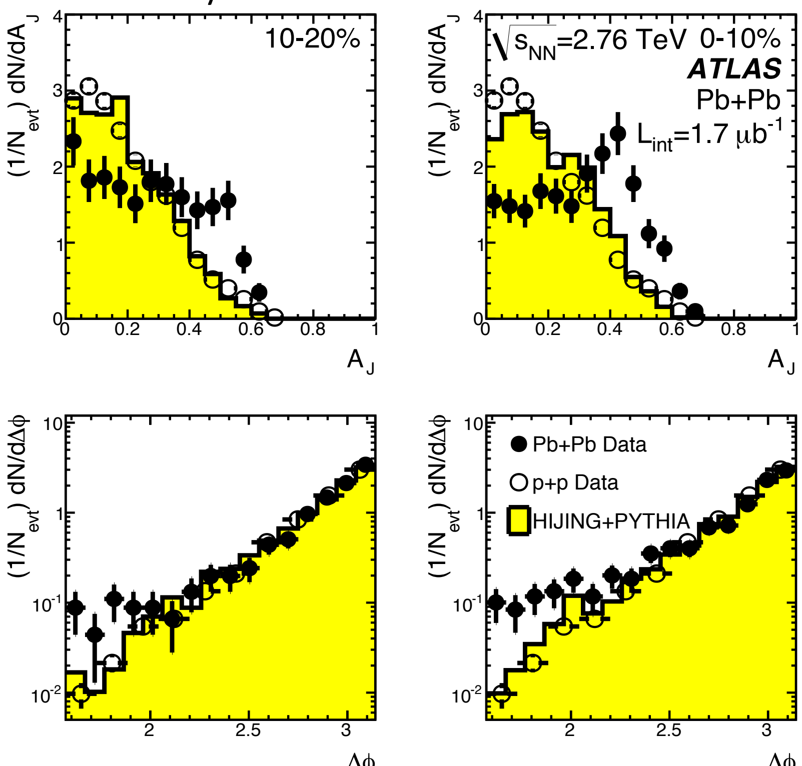
LHC: Estimates (on average) of about 10-20 GeV radiated – similar preliminary result at RHIC

Di-jet asymmetry



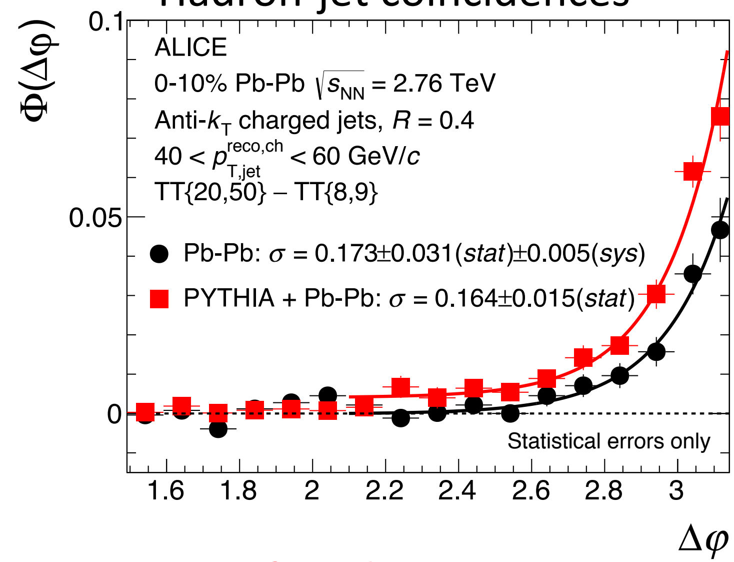
$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}, \Delta\phi > \frac{\pi}{2}$$

PhysRevLett.105.252303



A$_j$ is modified
but no medium-induced accoplanarity
(angular distribution as in pp collisions)

Hadron-jet coincidences

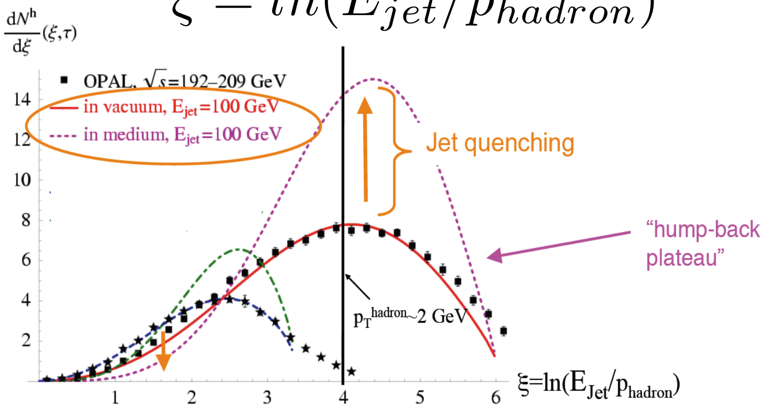


No sign of Moliere scattering
- Sensitivity to medium homogenity

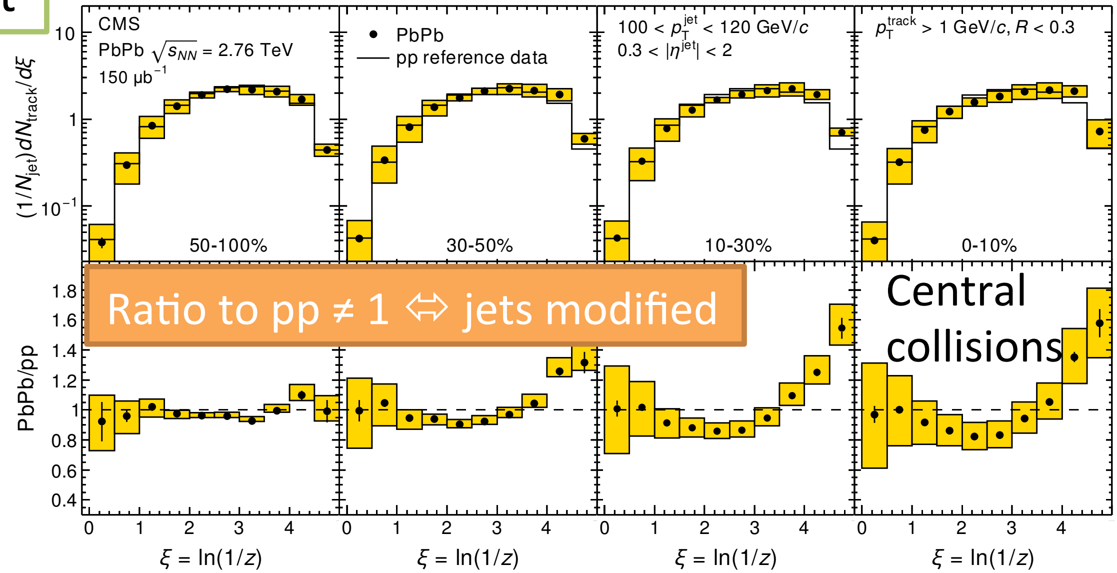
In-medium jet modifications – jet quenching

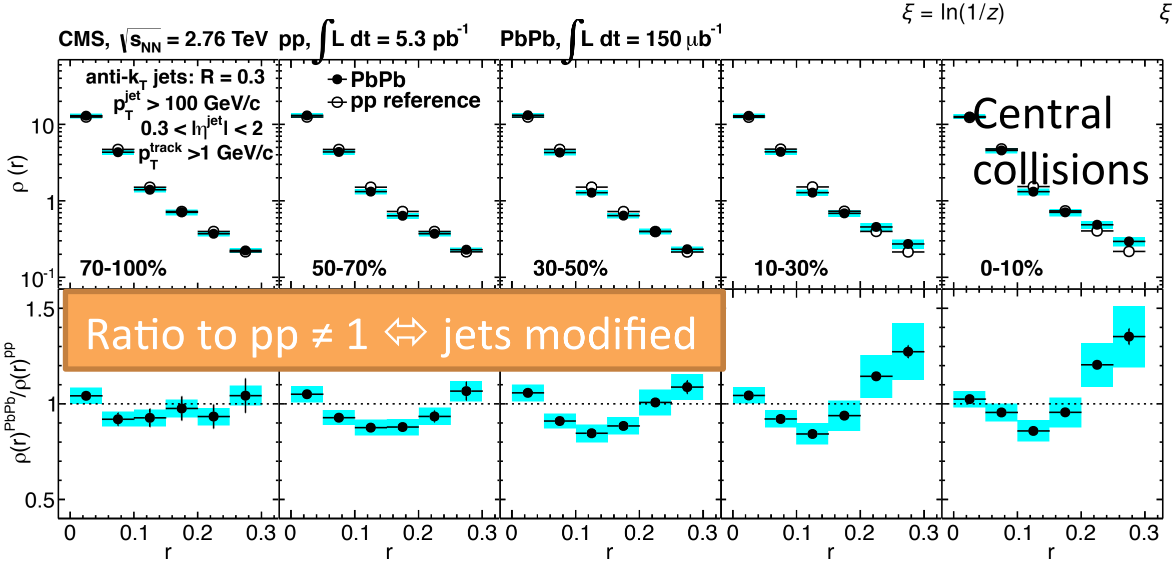
Momentum distribution within a jet

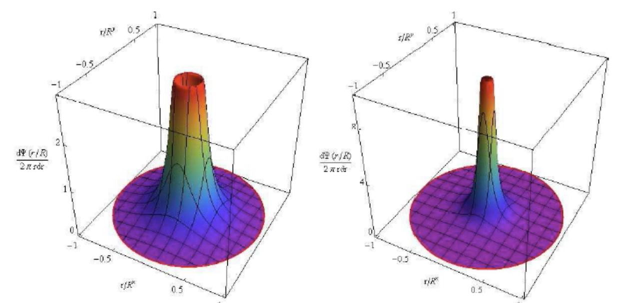
$$\xi = ln(E_{jet}/p_{hadron})$$



Phys. Rev. C 90 (2014) 024908







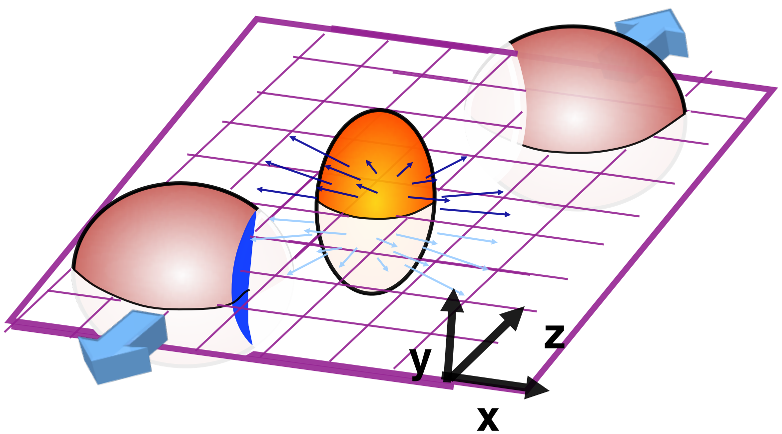
$$\rho(r) = \frac{1}{\delta r} \frac{1}{N_{jet}} \sum_{jets} \frac{\sum_{tracks \in [r_a, r_b)} p_T^{track}}{p_T^{jet}}$$

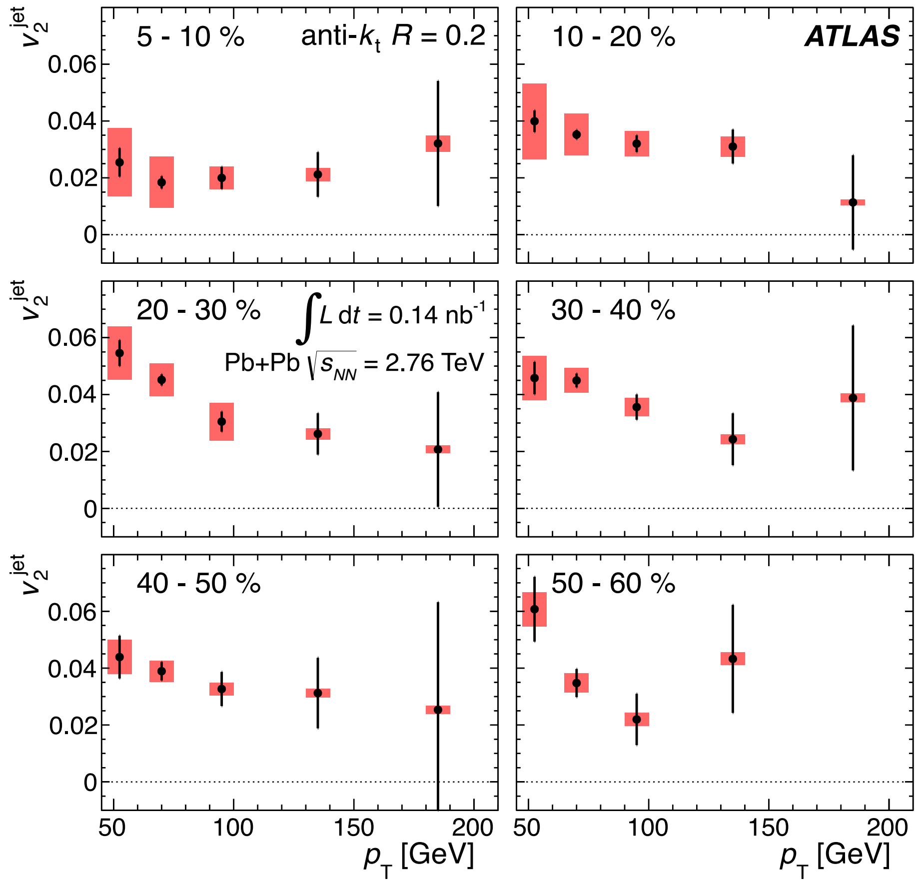
$$r = \sqrt{(\eta_{track} - \eta_{jet})^2 + (\phi_{track} - \phi_{jet})^2} \leq 0.3$$

Phys. Lett. B 730 (2014)

Jet v_2 (azimuthal asymmetry)

Sensitivity to path length dependence of parton energy loss





Jets studied in-plane and out-of-plane – traversing different path length

=> v_2 of jets – finite value expected; its magnitude important input for jet quenching models

PhysRevLett.111.152301

Parton type/mass dependence of energy loss

$$\Delta E \propto \alpha_s C_R \hat{q} L^2$$

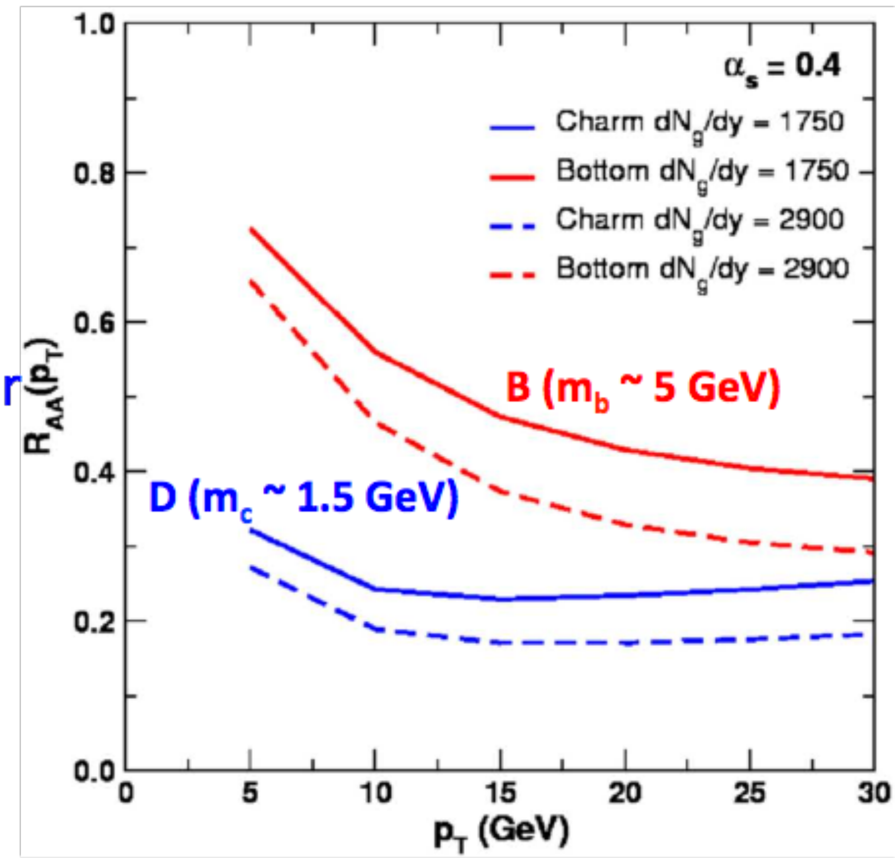
- Energy loss depends on parton:
  - Casimir factor (C_R=3 for gluons and 4/3 for quarks)
  - Mass of the quark (**dead cone** effect): radiation suppressed for angles $\theta < m/E$

$$\Delta E_{gluon} > \Delta E_{quark}$$
$$\Delta E_{light-q} > \Delta E_{heavy-q}$$

- Does it persist at low-p_T as:

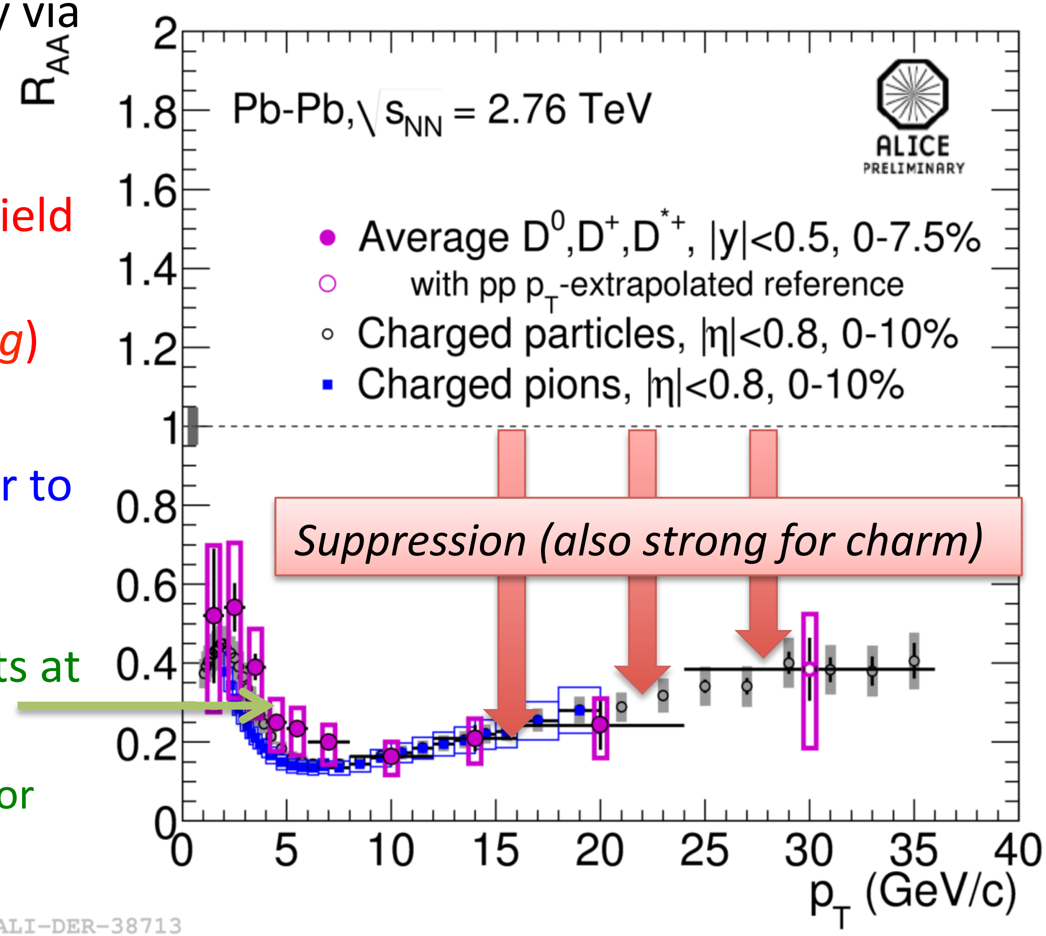
$$R^{\pi}_{AA} < R^{D}_{AA} < R^{B}_{AA}$$

Wicks, Gyulassy, Last Call for LHC predictions

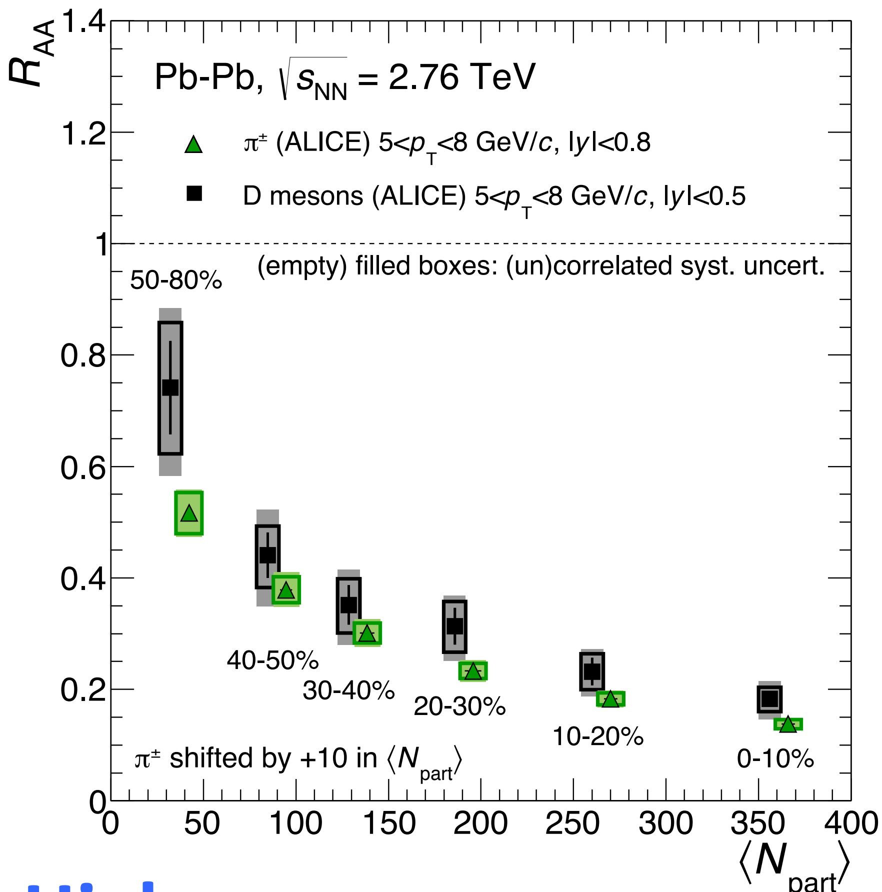


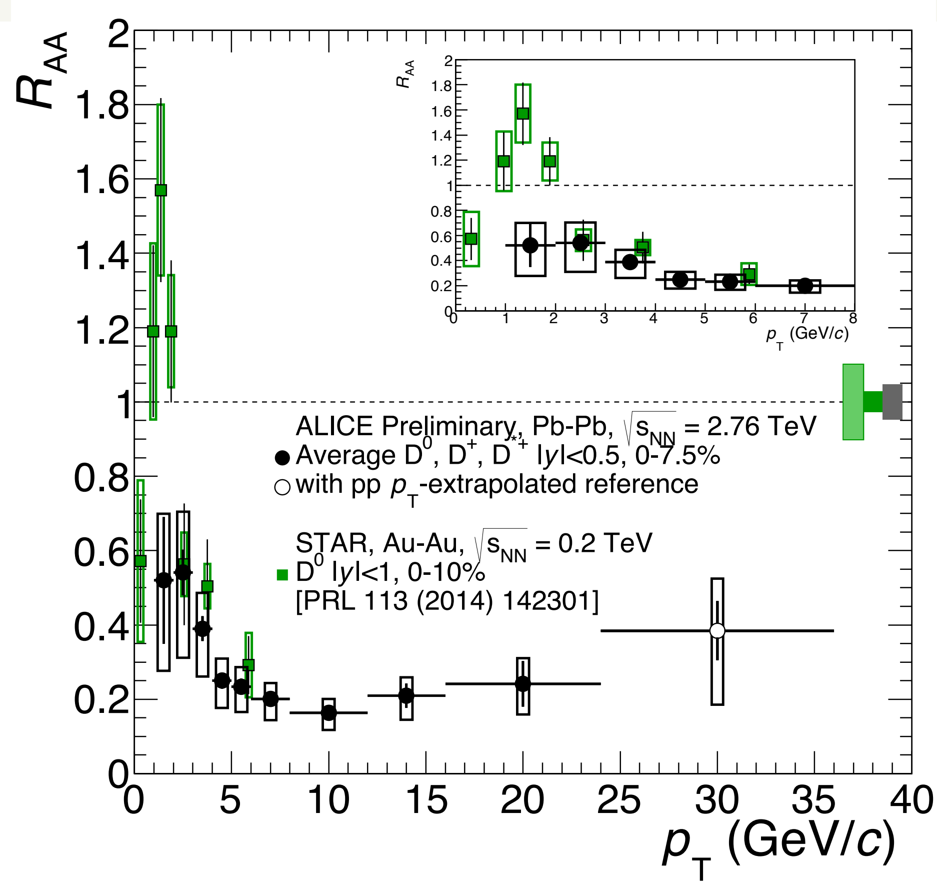
Charm suppression ⇔ Jet quenching

- D-mesons measured at mid-rapidity via hadronic decays
- R_{AA} - suppression pattern (ratio of yield in Pb-Pb to yield in proton-proton) shows a strong deficit (*jet quenching*)
- Quenching: charm at high-pT similar to light flavor
- Possible hint of colour charge effects at low-p_T (below 10 GeV/c)
  - => need better precision (outlook for next years and upgraded detector)



Charm suppression





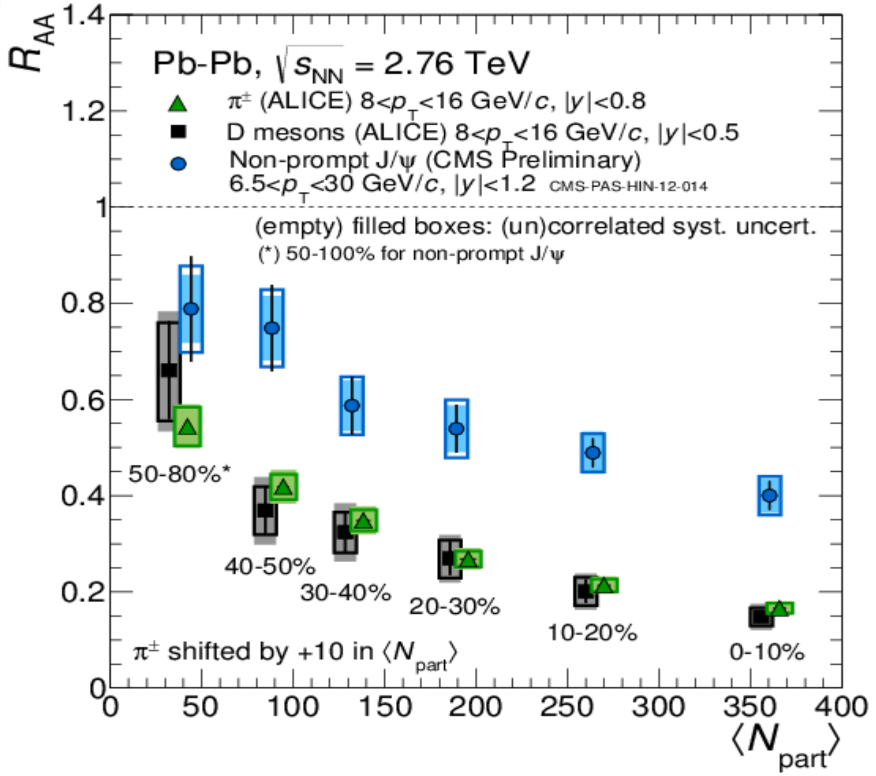
High-p_T: R_{AA} for D-mesons compatible with R_{AA} of pions

=> Similar E-loss for glue/light- and charm quarks

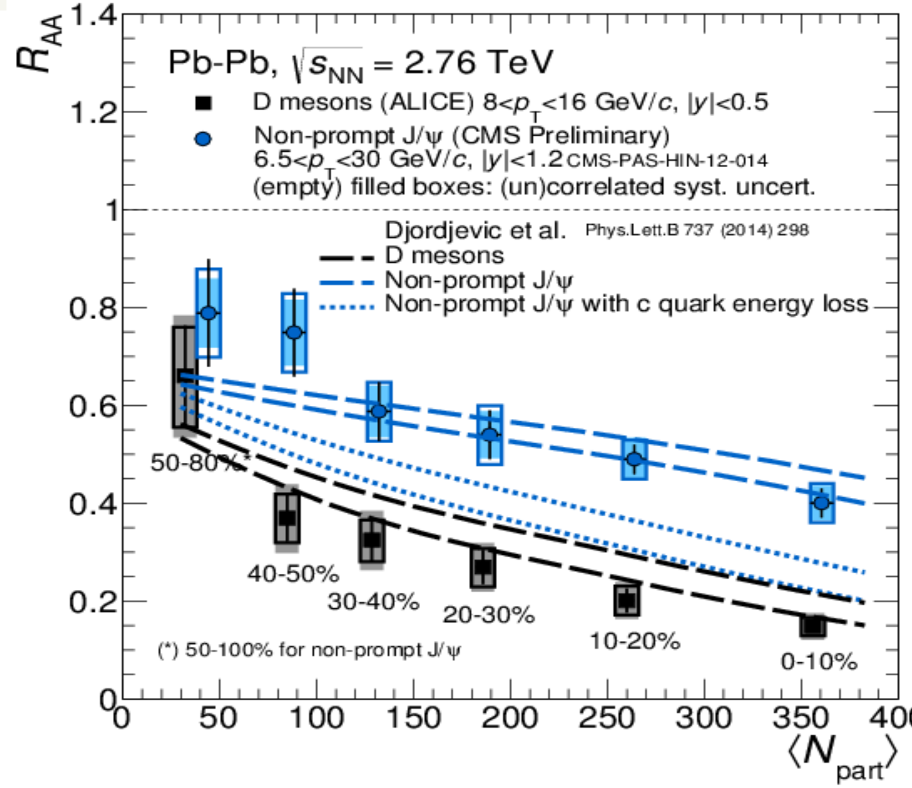
Despite different $d\sigma/dp_T$ R_{AA}^{RHIC} compatible with R_{AA}^{LHC}

Mass dependence of in-medium E-loss

arXiv:1506.06604



ALICE & CMS data

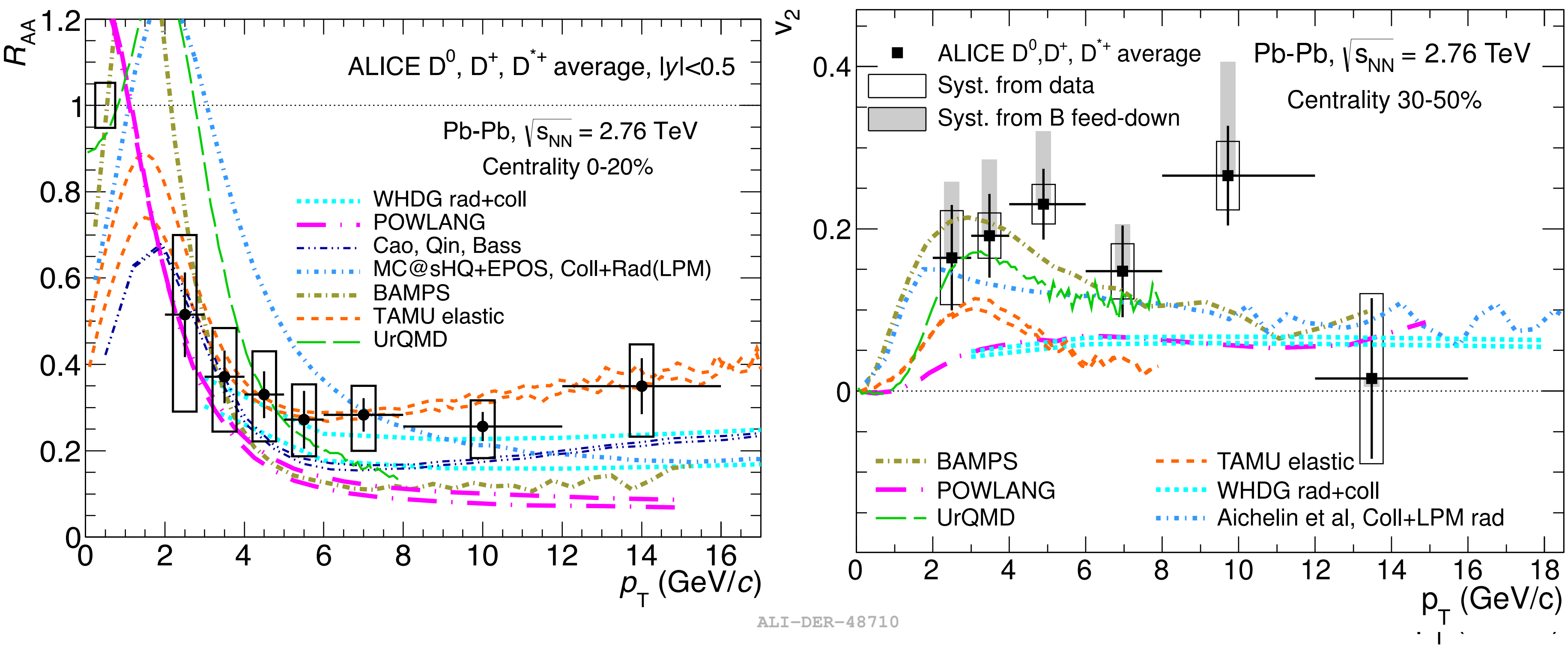


Indication of $R_{AA}^{D} < R_{AA}^{\text{non-prompt } J/\psi}$

Consistent with mass dependent energy loss

Open charm: R_{AA} and v_2

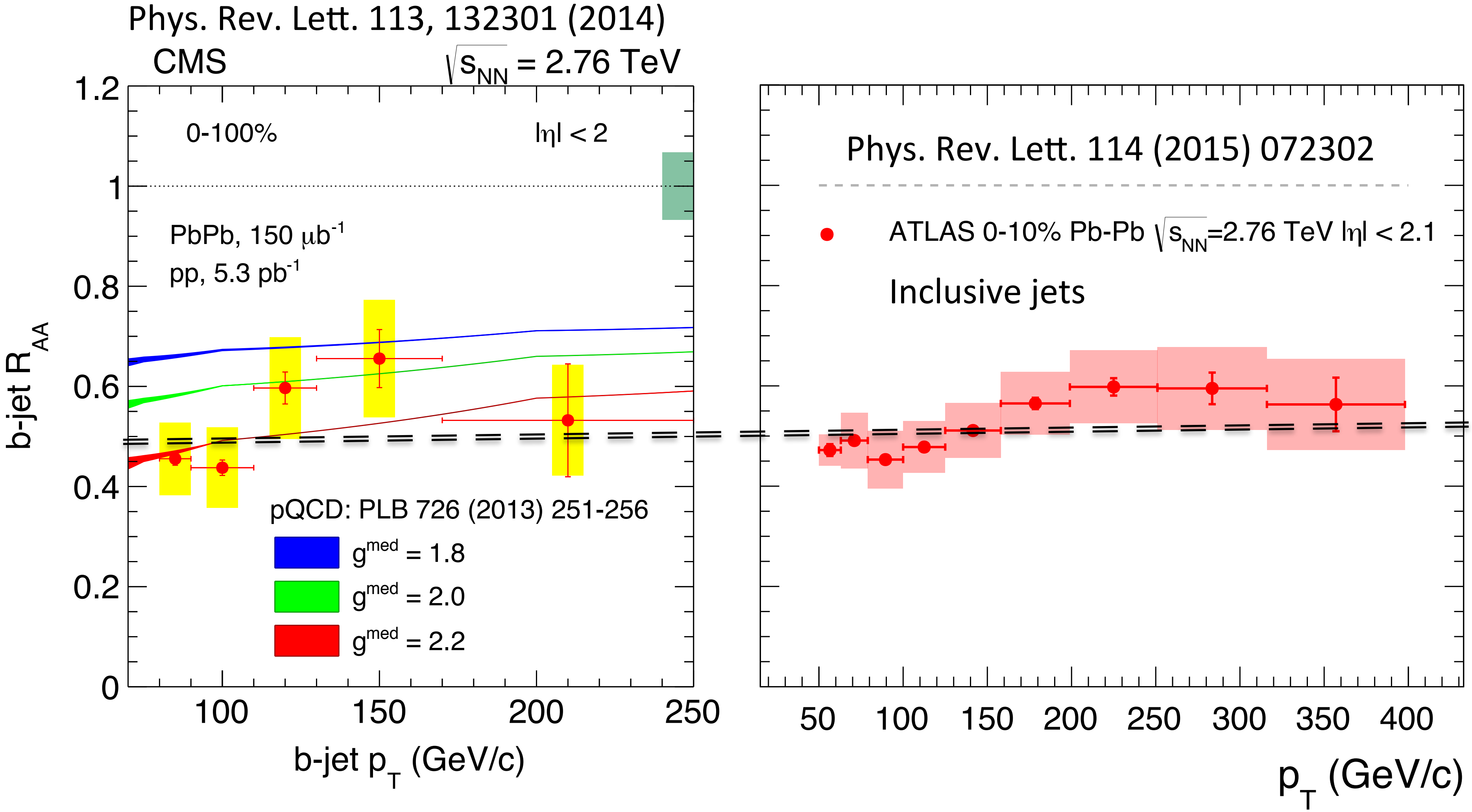
D-meson R_{AA} arXiv: 1203.2160 (JHEP 1209)



- RAA of D – similar suppression as light flavor
- **Non-zero D v_2 – interactions of the c-quark withing thermal bulk (TBC)**
- **The simultaneous description of D meson R_{AA} and v_2 needed**

Does B flow?

b-jet suppression



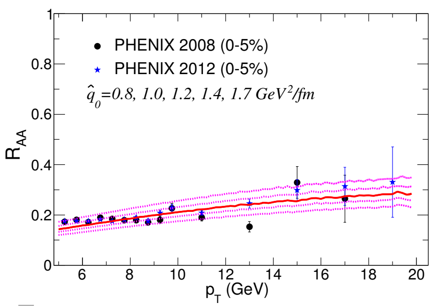
Similar suppression for b-jets as compared to inclusive jets

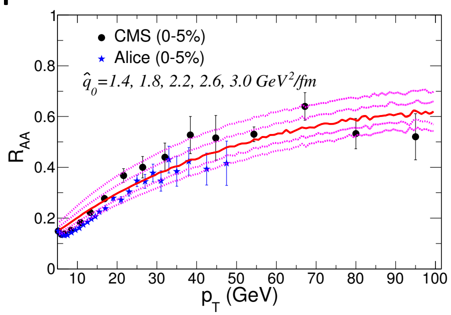
Consistent with the expectation – e-loss independent of mass at high-p_T

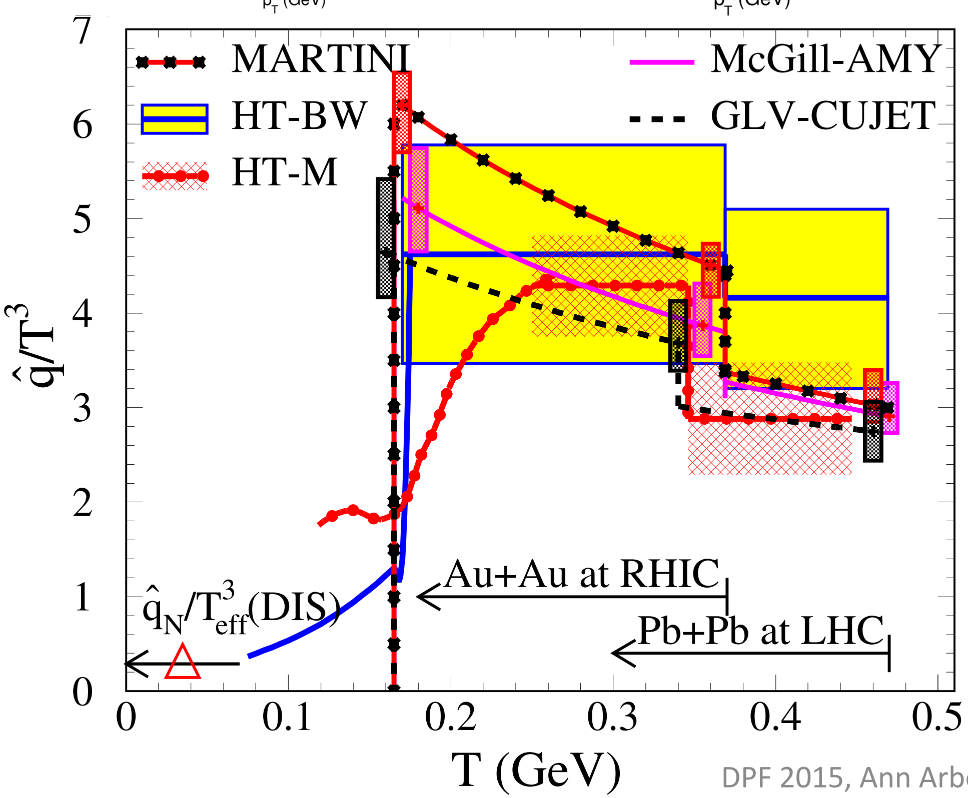
Extracting jet transport coefficient from jet quenching at RHIC and LHC

arXiv:1312.5003
Phys.Rev. C90 (2014) 014909

Evaluation of qhat in a perturbative framework based on inclusive hadron RAA







Considering the variation of the $\hat{q}$ values between the five different models studied here as theoretical uncertainties, one can extract its range of values as constrained by the measured suppression factors of single hadron spectra at RHIC and LHC as follows:

$$\frac{\hat{q}}{T^3} \approx \begin{cases} 4.6 \pm 1.2 & \text{at RHIC,} \\ 3.7 \pm 1.4 & \text{at LHC,} \end{cases}$$

at the highest temperatures reached in the most central Au+Au collisions at RHIC and Pb+Pb collisions at LHC. The corresponding absolute values for $\hat{q}$ for a 10 GeV quark jet are,

$$\hat{q} \approx \begin{cases} 1.2 \pm 0.3 \\ 1.9 \pm 0.7 \end{cases} \text{GeV}^2/\text{fm} \;\; \text{at} \;\; \begin{matrix} \text{T=370 MeV,} \\ \text{T=470 MeV,} \end{matrix}$$

at an initial time $\tau_0 = 0.6$ fm/c. These values are very close to an early estimate [6] and are consistent with LO pQCD estimates, albeit with a somewhat surprisingly small value of the strong coupling constant as obtained in CUJET, MARTINI and McGill-AMY model. The HT

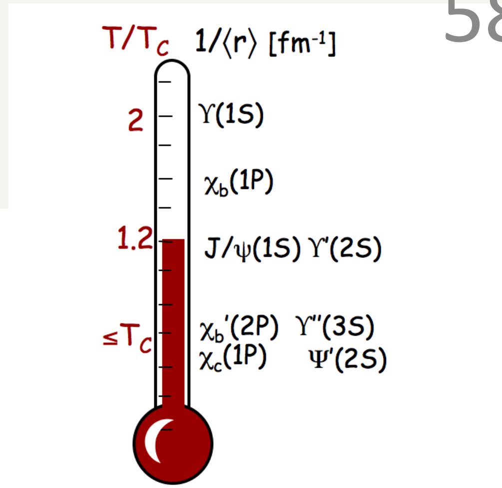
RHIC ~ 25% uncert. LHC~ 37% uncert.

Excellent progress within the last few years.

Next steps: use full jets, jet structure, …

Extraction of ehat with (new) HF data

Quarkonia in QGP

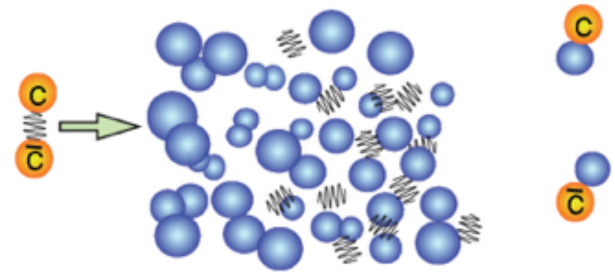


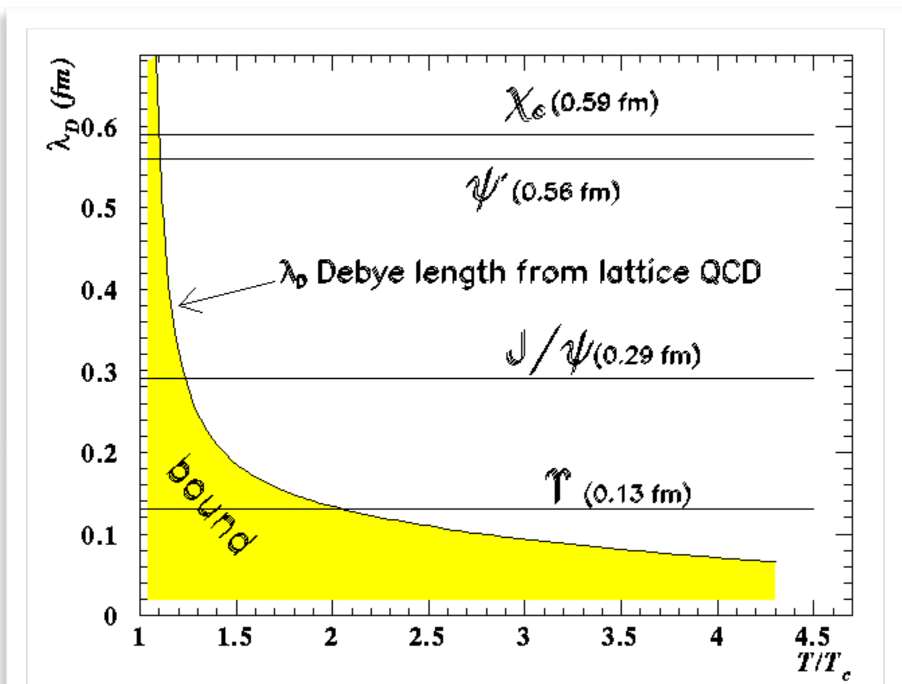
QGP signature proposed by Matsui and Satz, 1986

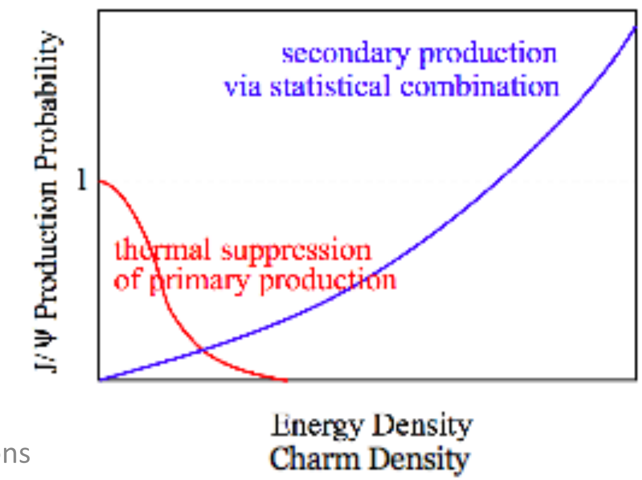
In the plasma phase the interaction potential is expected to be screened beyond the Debye length λD (analogous to e.m. Debye screening):

Charmonium(cc) and bottonium(bb) states with r > λD will not bind; their production will be suppressed (qqbar states will "melt")

Mocsy, EPJ C 61 (2009) 705

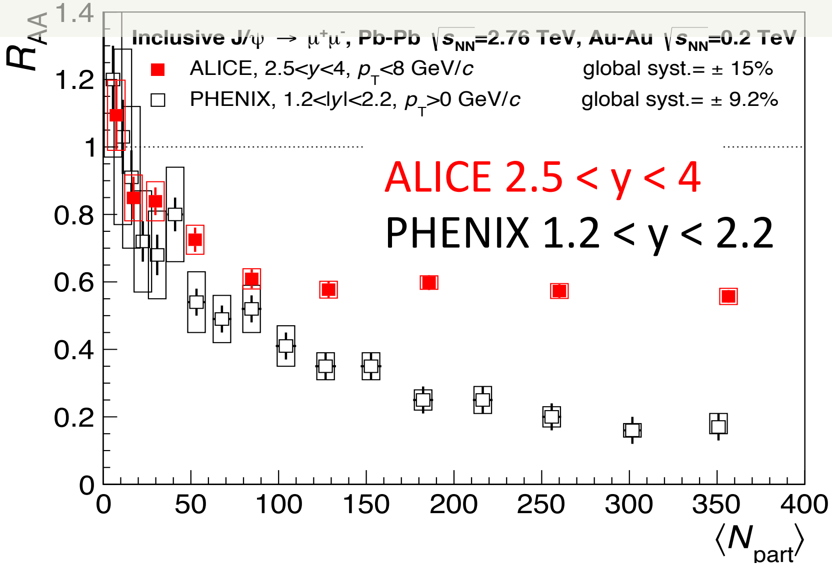


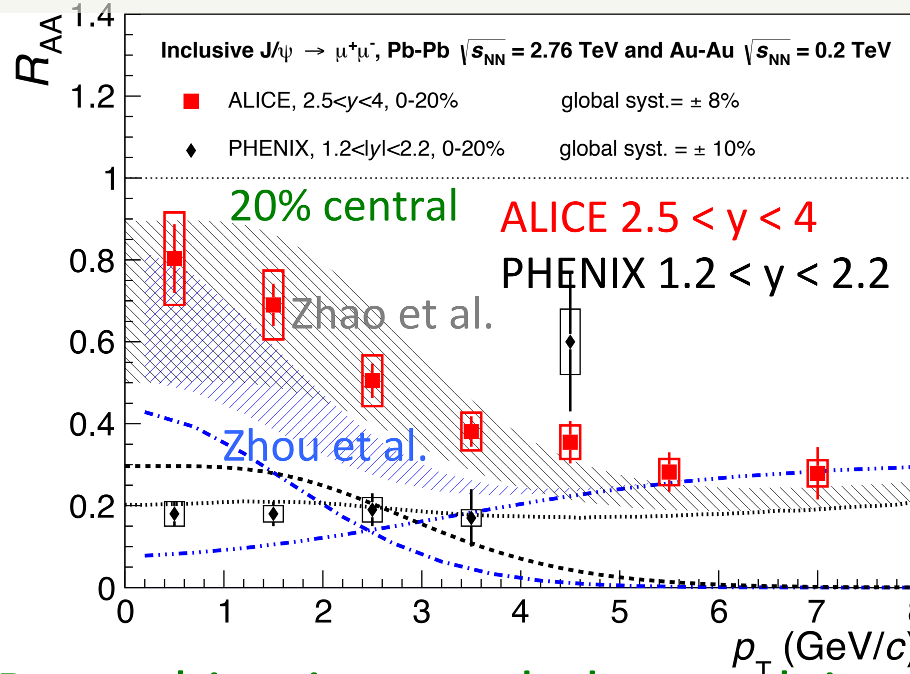


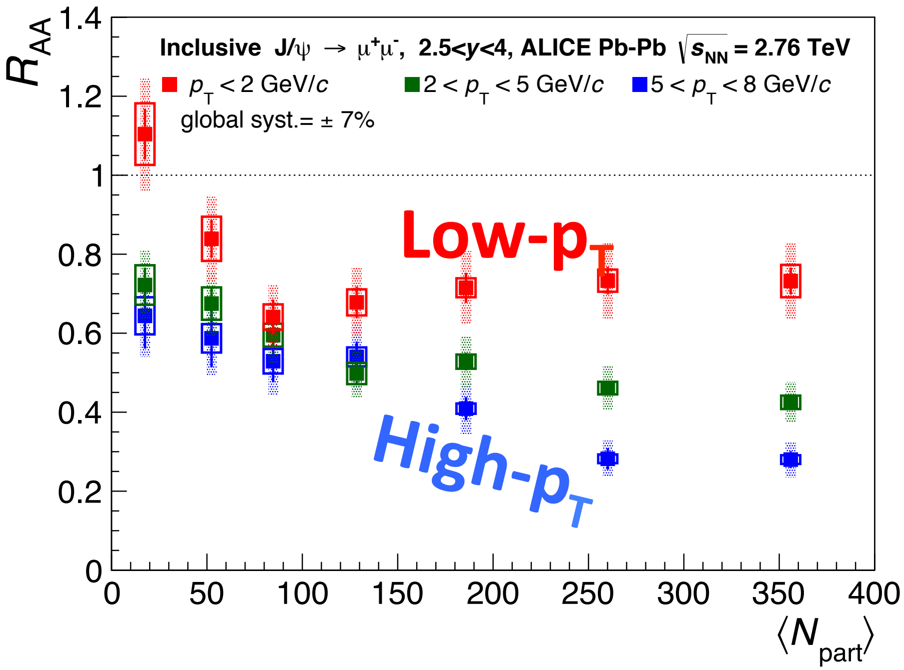


J/ψ Suppression

ALICE Coll. PLB 734 (2014) 314







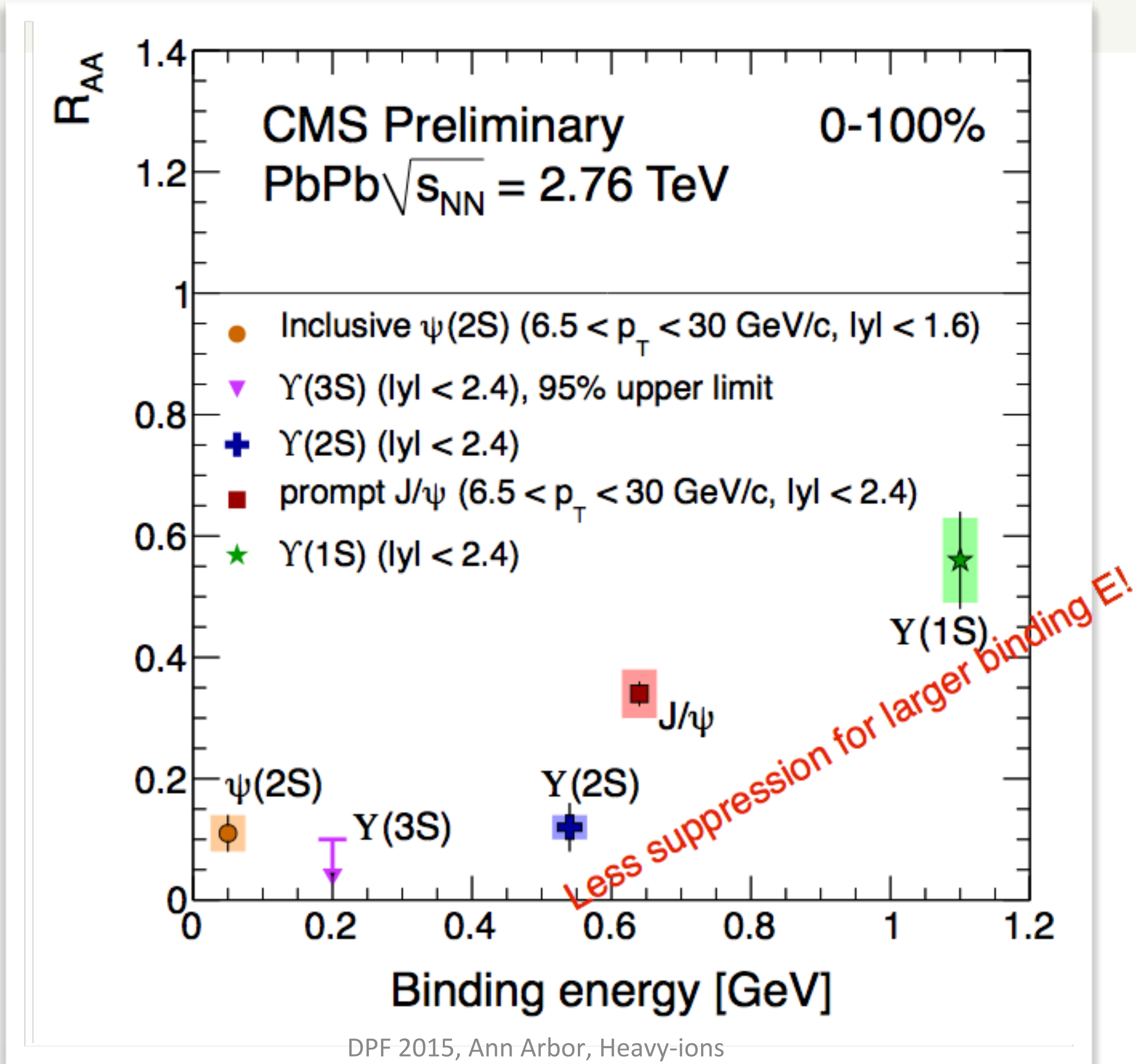
Recombination needed to explain R_{AA} at the LHC

J/ψ re-generated at low-p_T

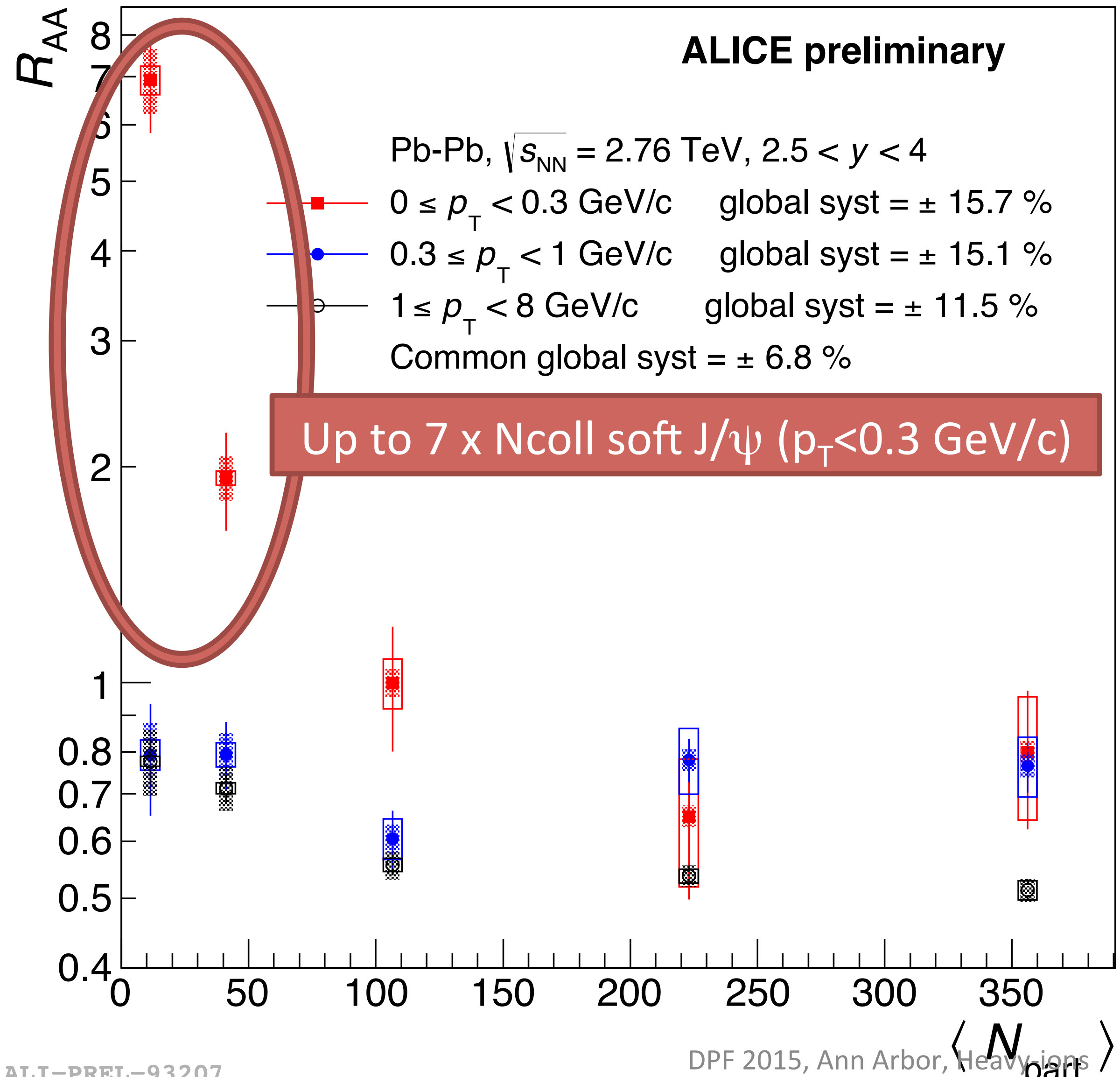
High-p_T J/ψ suppressed (LHC & RHIC)

Strong suppression in central as compared to peripheral collisions

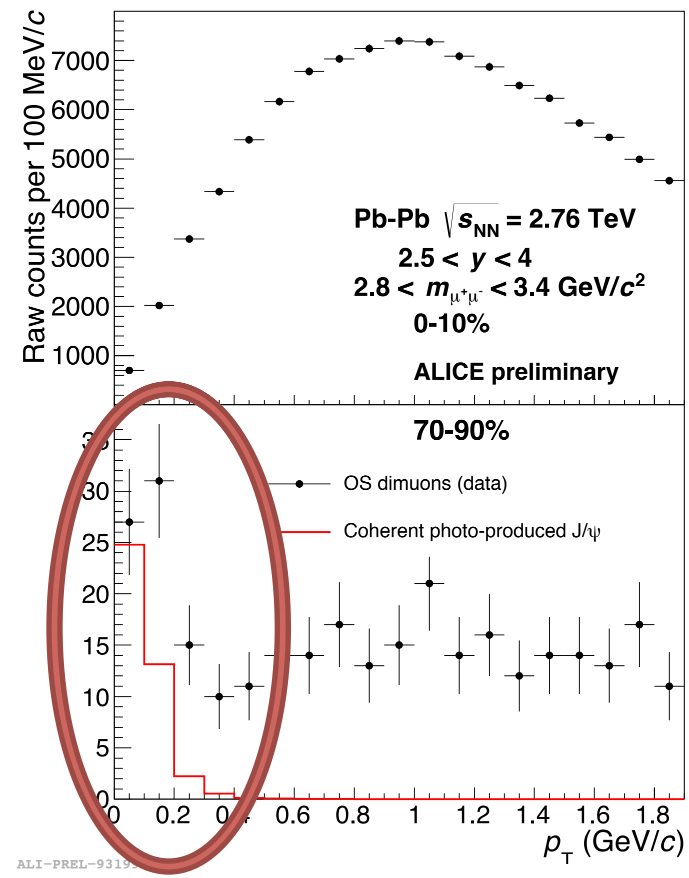
Suppression vs. binding energy of quarkonia



J/ψ R_{AA} – closer look at low-pT



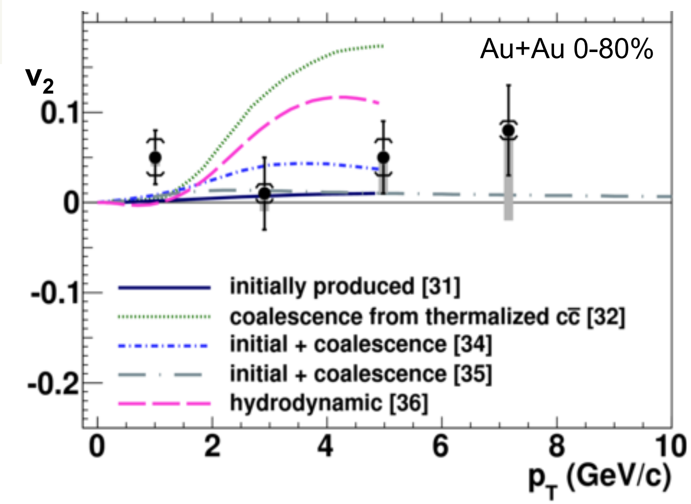
Up to 7 x Ncoll soft J/ψ (p_T<0.3 GeV/c)

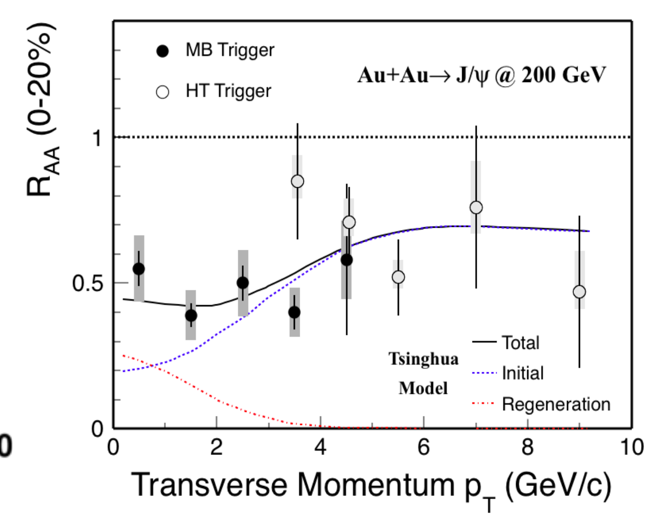


p_T spectrum similar to **photo-production** known in collisions with b > 2R

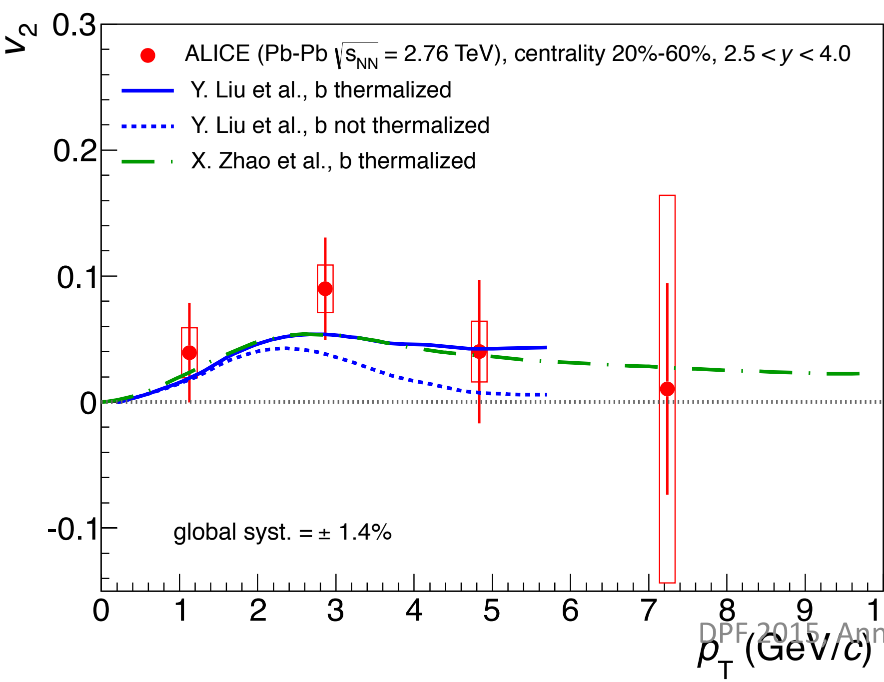
Regeneration ⇔ J/ψ flow?

RHIC v_2





STAR, PRL 111 (2013) 052301, PLB 722 (2013) 55, PRC 90 (2014) 024906



- Expect J/ψ from regeneration to exhibit similar elliptic flow as D mesons
- STAR at RHIC:
  - no significant elliptic flow
- ALICE at LHC:
  - hint at 3 GeV/c
  - local significance 2.2 σ
- Does one point really make the difference?
  - More data will bring the answer

sqrt(s) grows

Summary

- *Note: not all the topics where covered*

- QGP is a strongly coupled; almost perfect fluid with the smallest η/s of all known materials
- It is hot – it dissolves quarkonia states – according to their binding energy
- It is dense – it is opaque to high-energy partons and modifies their structure transporting the radiated energy to large angles; lost energy depends on the traversed path length (jet v_2>0)

- Charm quarks flow within the medium (strong input for understanding of medium transport properties – thermalization and elastic processes)
- First indications that charm quark looses more energy than bottom quark – a predicted mass dependence of energy loss

- Signals of collective phenomena seen in AA also present in high-multiplicity pA collisions – signal also in pp collision - unexpected; however, droplets of plasma where mean-free path is much smaller than the system size are possible

RHIC and LHC outlook

Figure by G. Roland