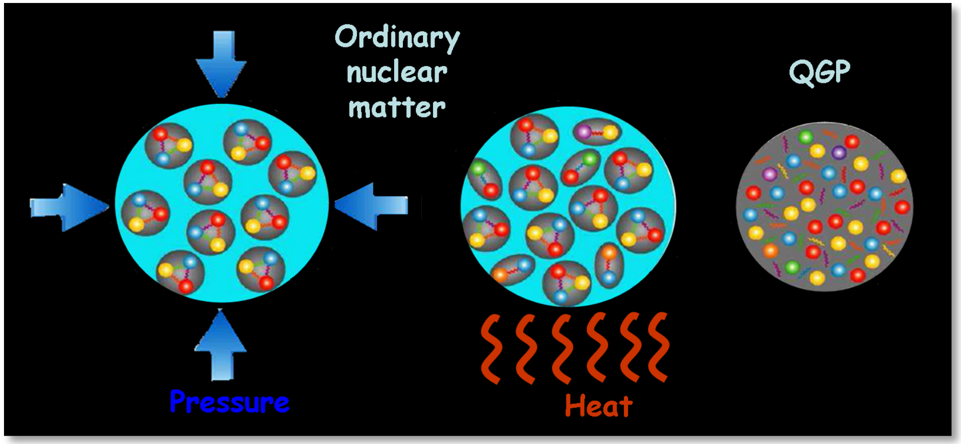
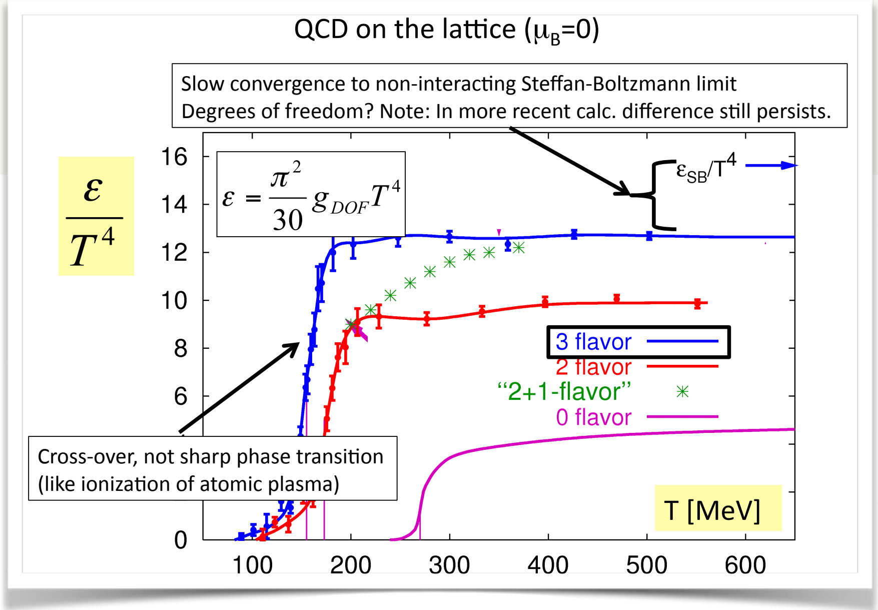
ALICE++ / Heavy-ion collisions

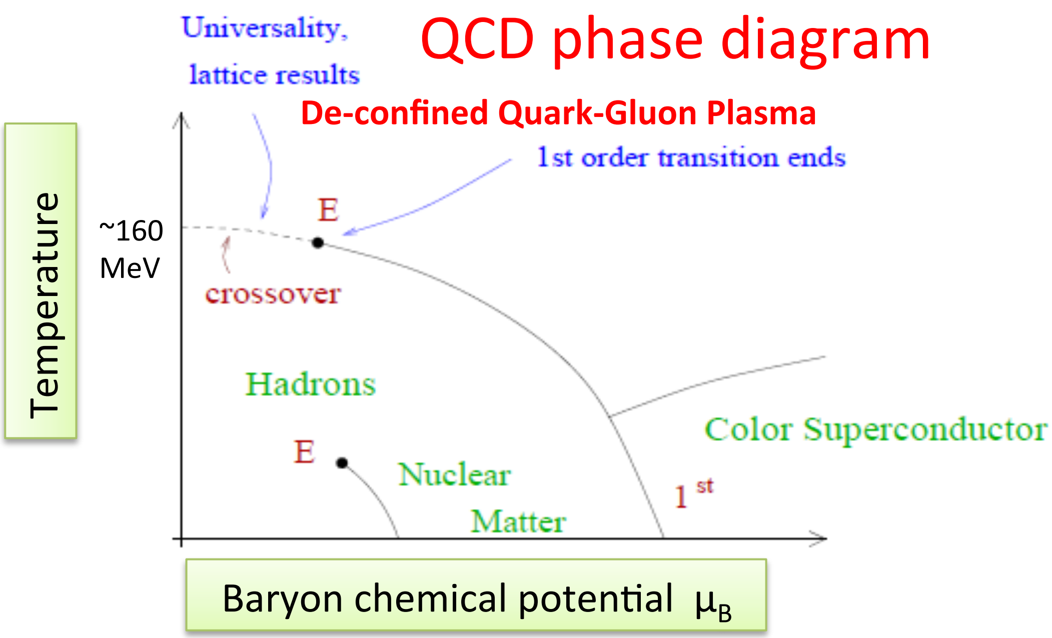
Hot QCD in laboratory



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…)





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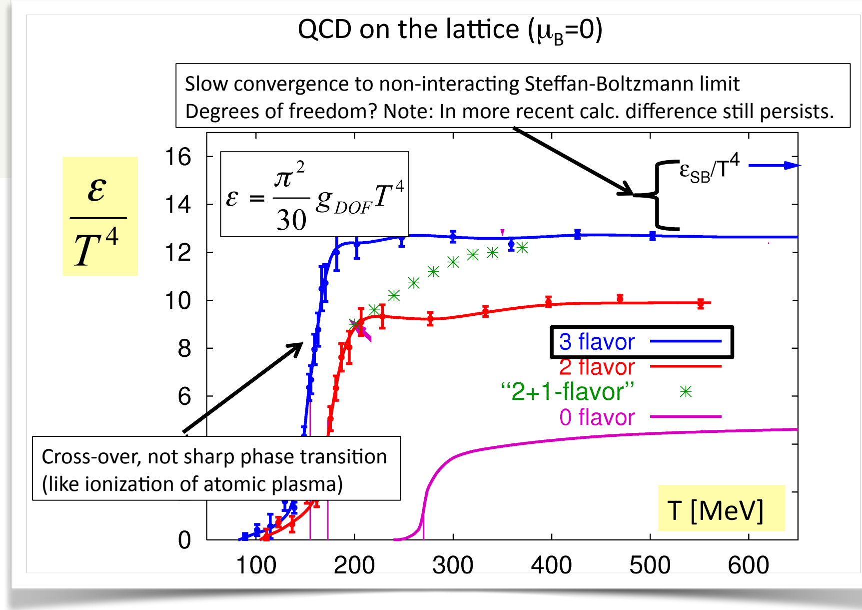
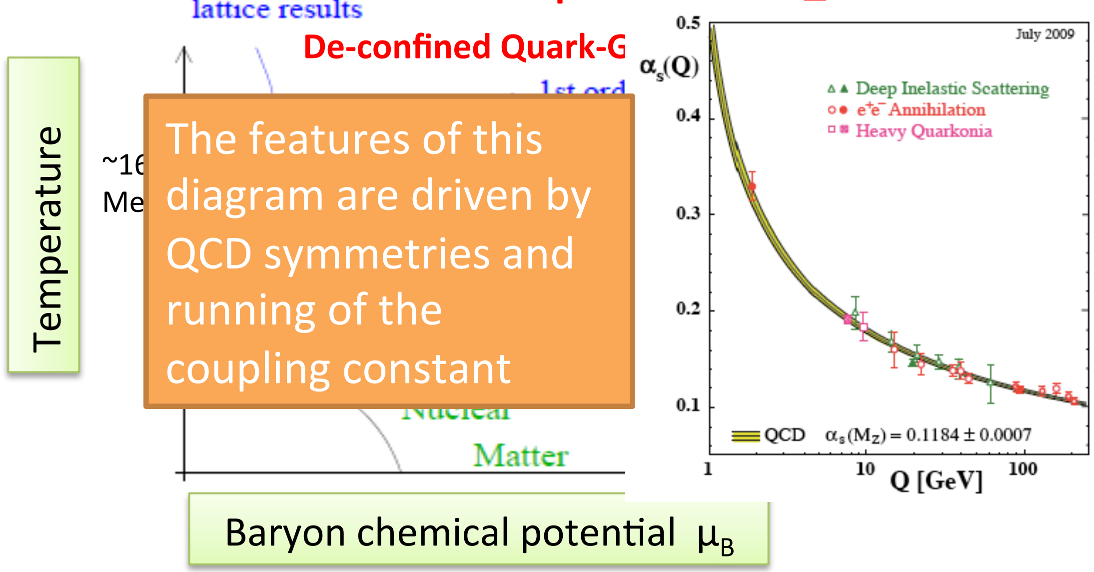


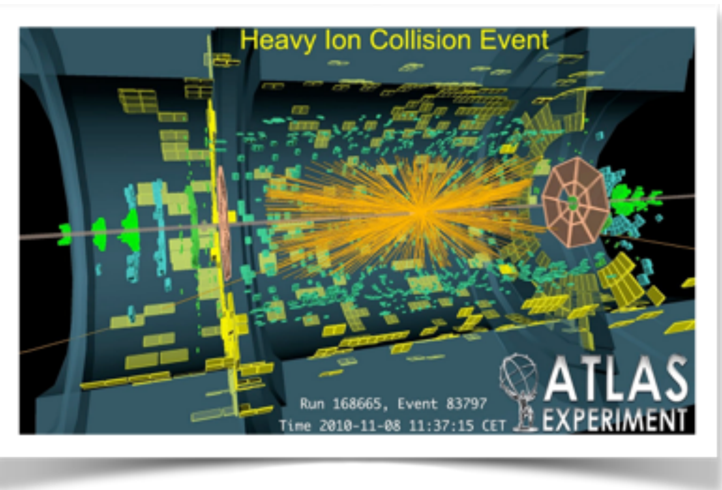
QCD phase diagram

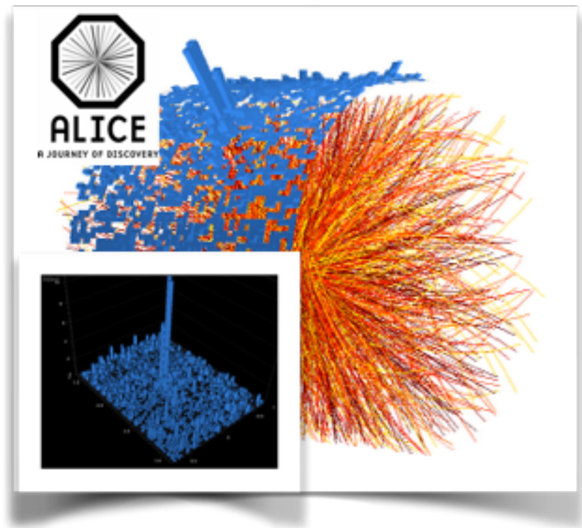


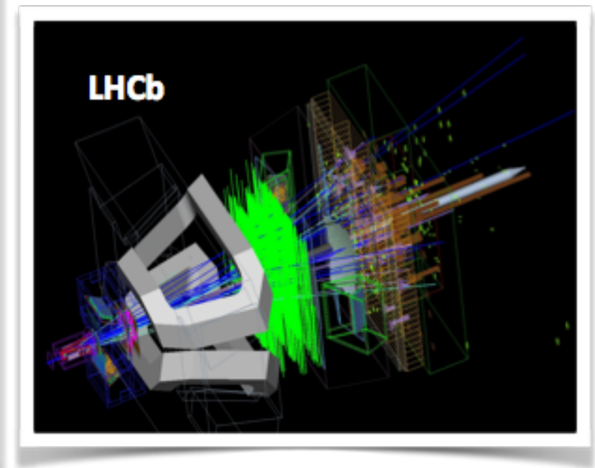
Active machines with top ion energies

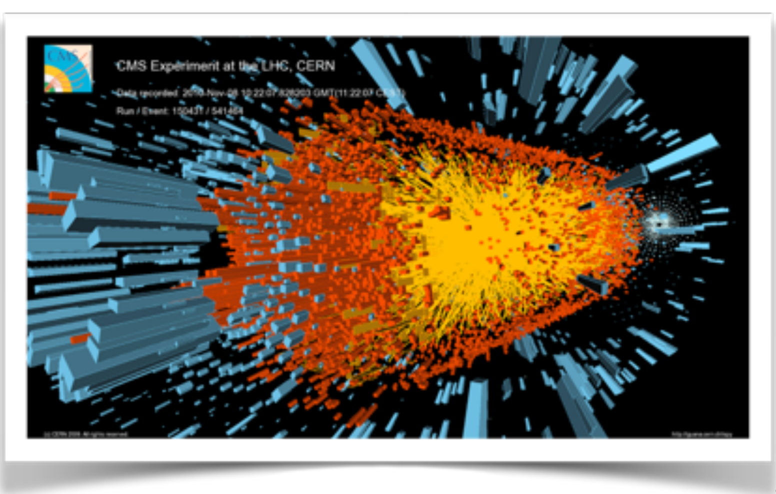
Hot QCD in laboratory - experiments

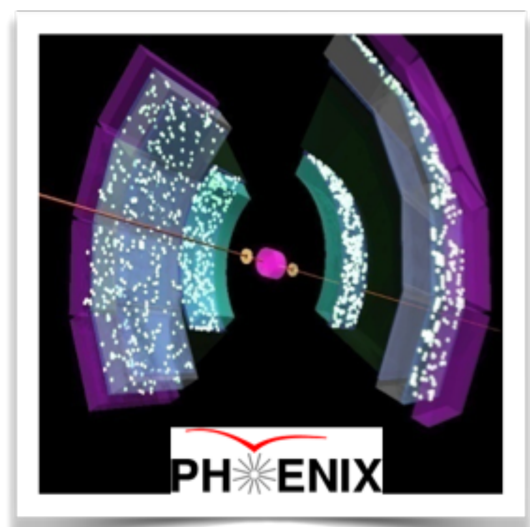
- Relativistic Heavy-Ion Collider: Au-Au collisions at 200 GeV/n)
- Large Hadron Collider: Pb-Pb collisions at 2.76 – 5 TeV (2015)



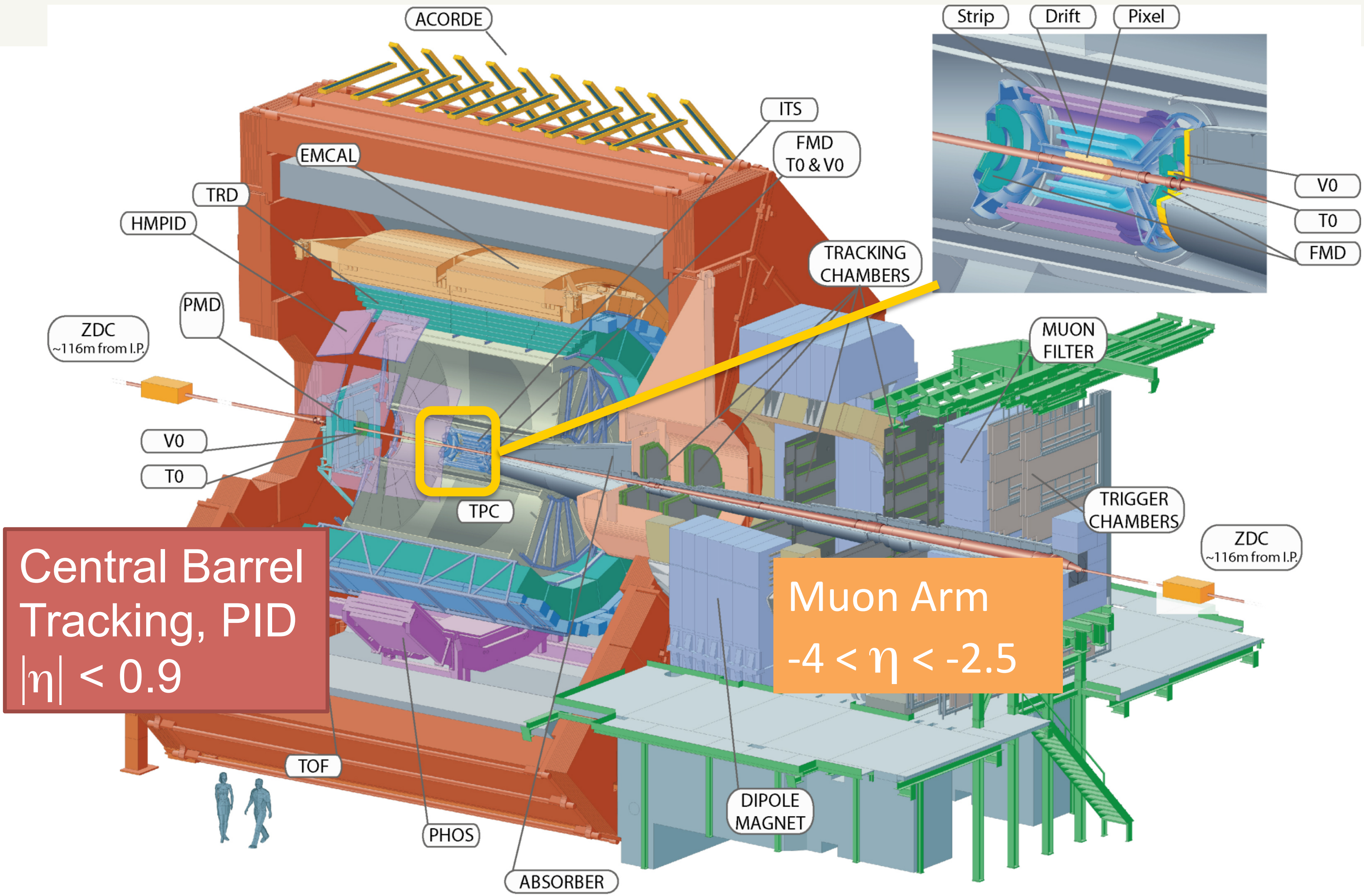








A Large Ion Collider Experiment



Outline

Systems:

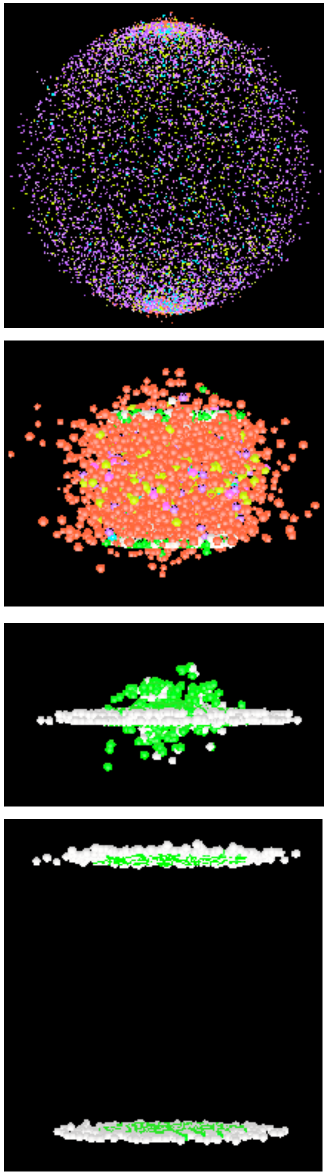
- Proton-proton
- p-Pb
- Pb-Pb

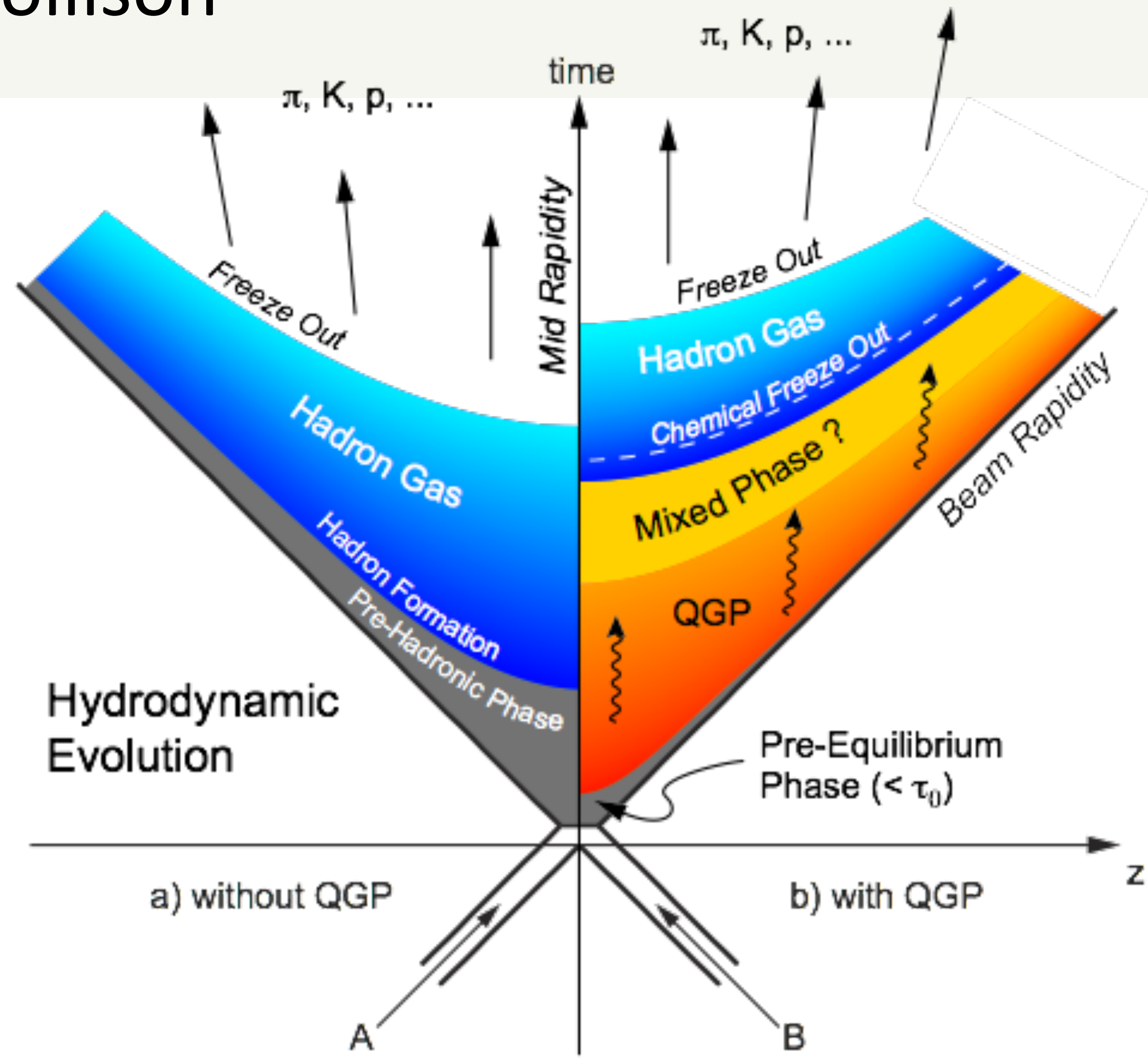
- Outline of this talk:
  - Selected subjects from soft and hard probes
  - Signatures of collective effects even in small systems – mini-QGP?
  - Summary

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)
- Jets
  - R_{AA} – inclusive production in pp and AA; jet structure; test of N_{binary} scaling in min. bias pPb
- 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

A heavy-ion collison

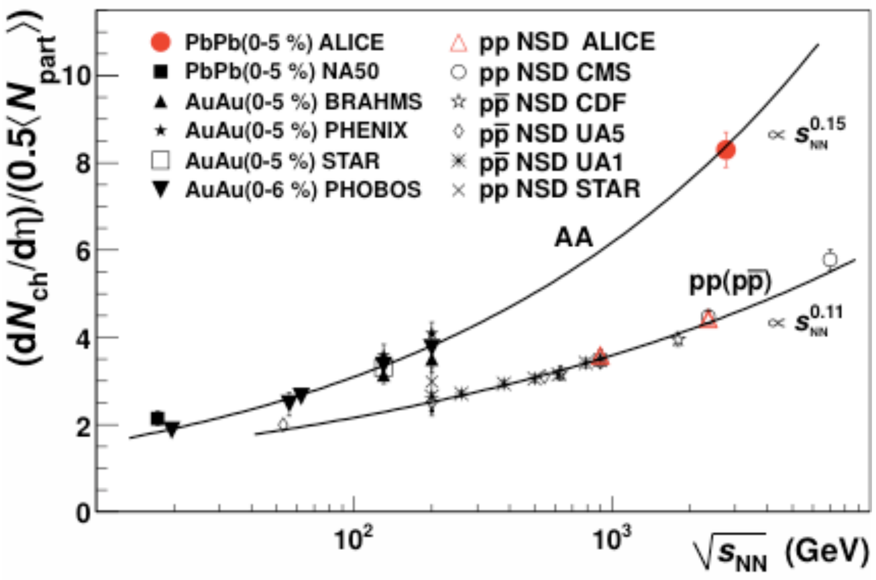




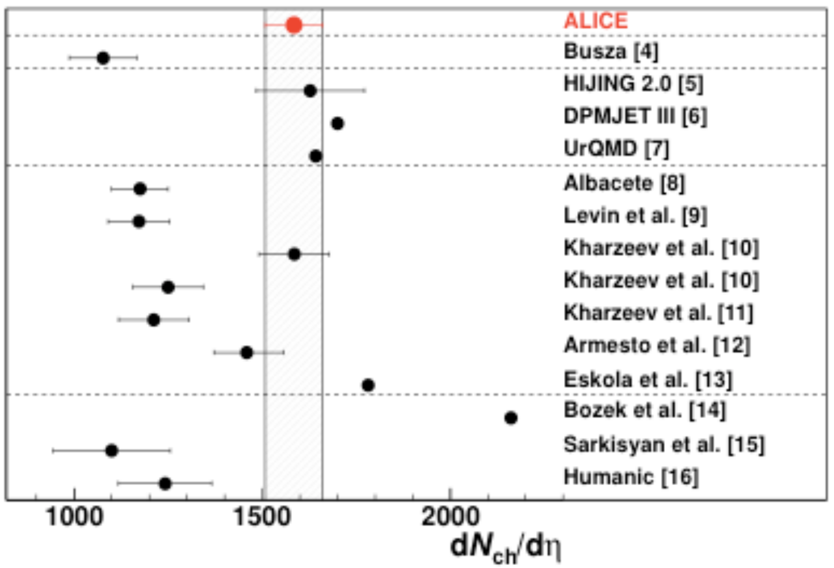
“CALIBRATION” MEASUREMENTS

Particle production in Pb-Pb

Energy dependence



Comparison to predictions



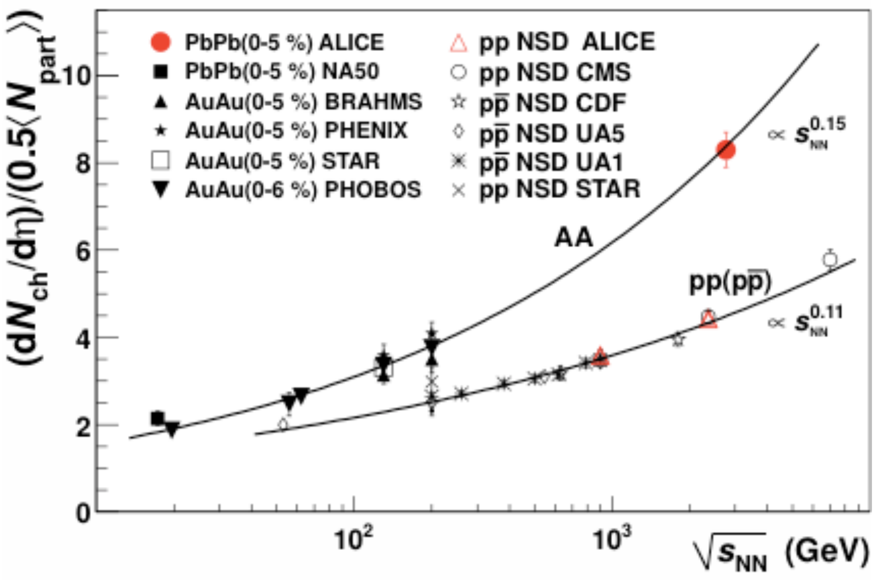
PRL 105, 252301 (2010)

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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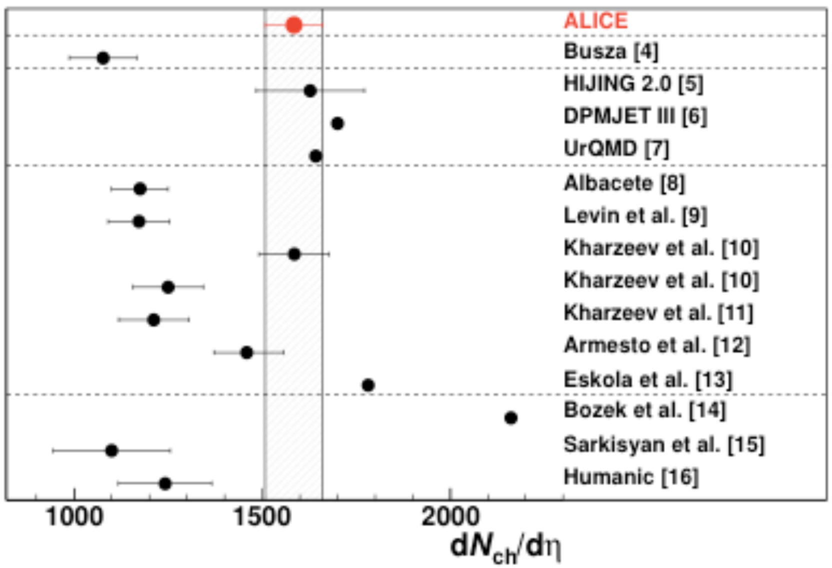
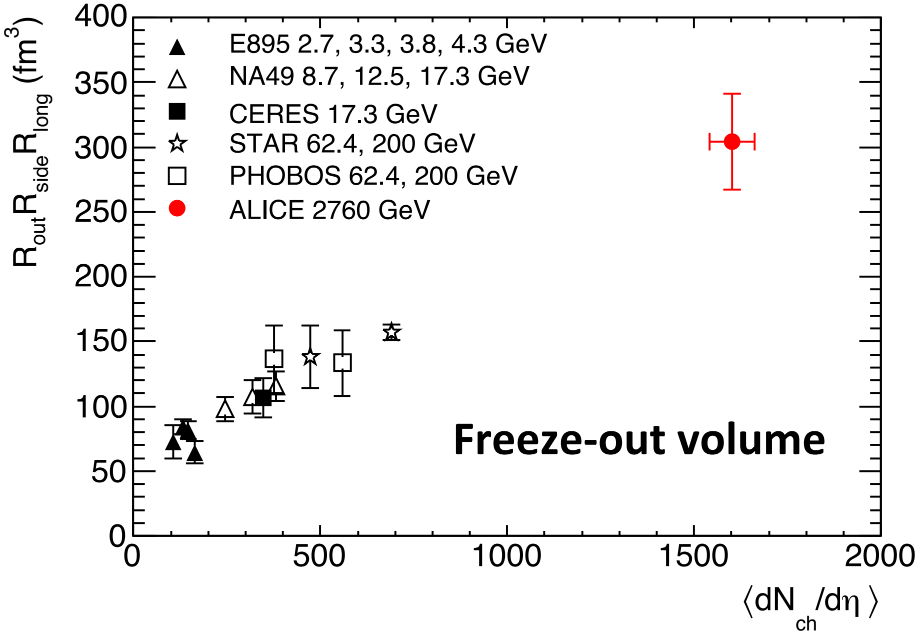
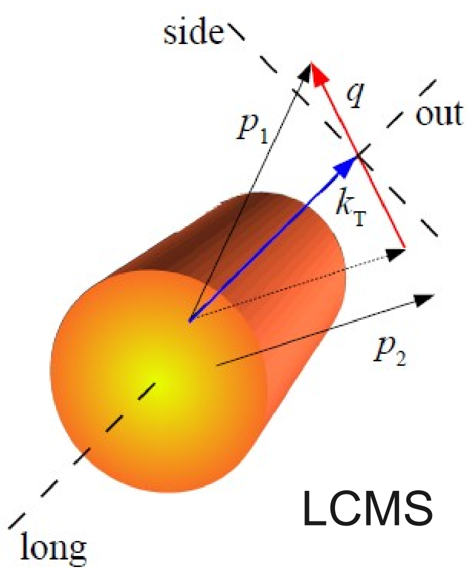


PRL 105, 252301 (2010)

- 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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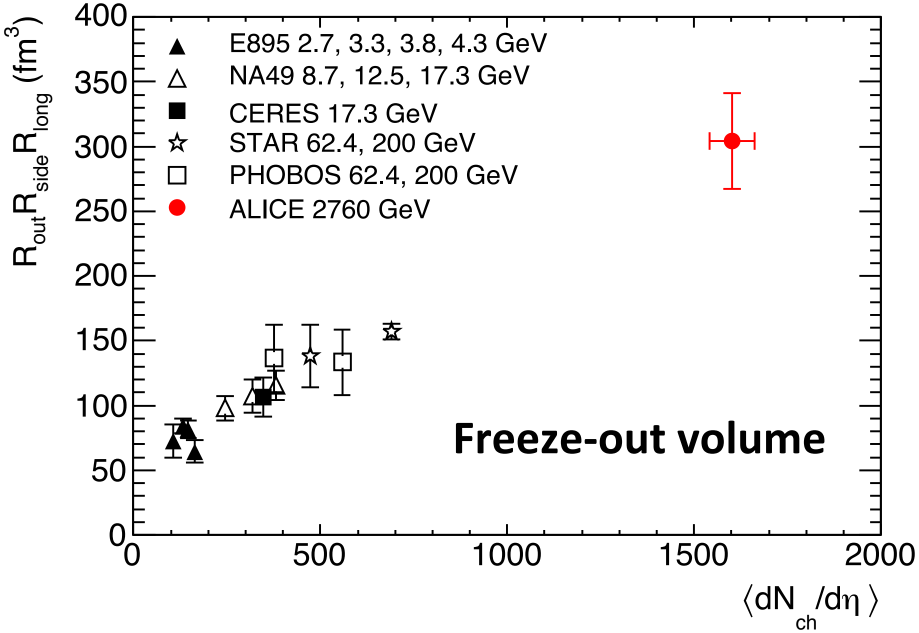

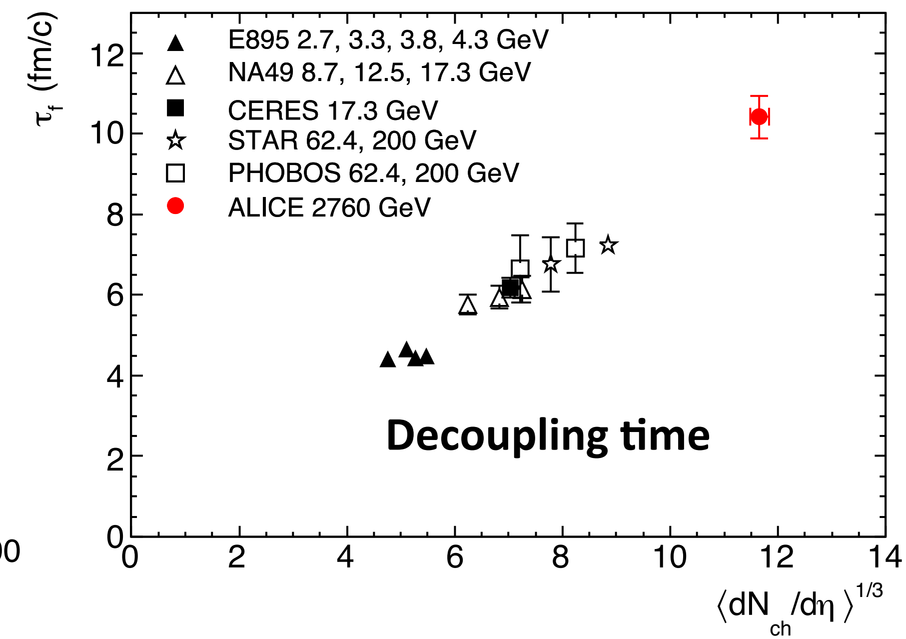

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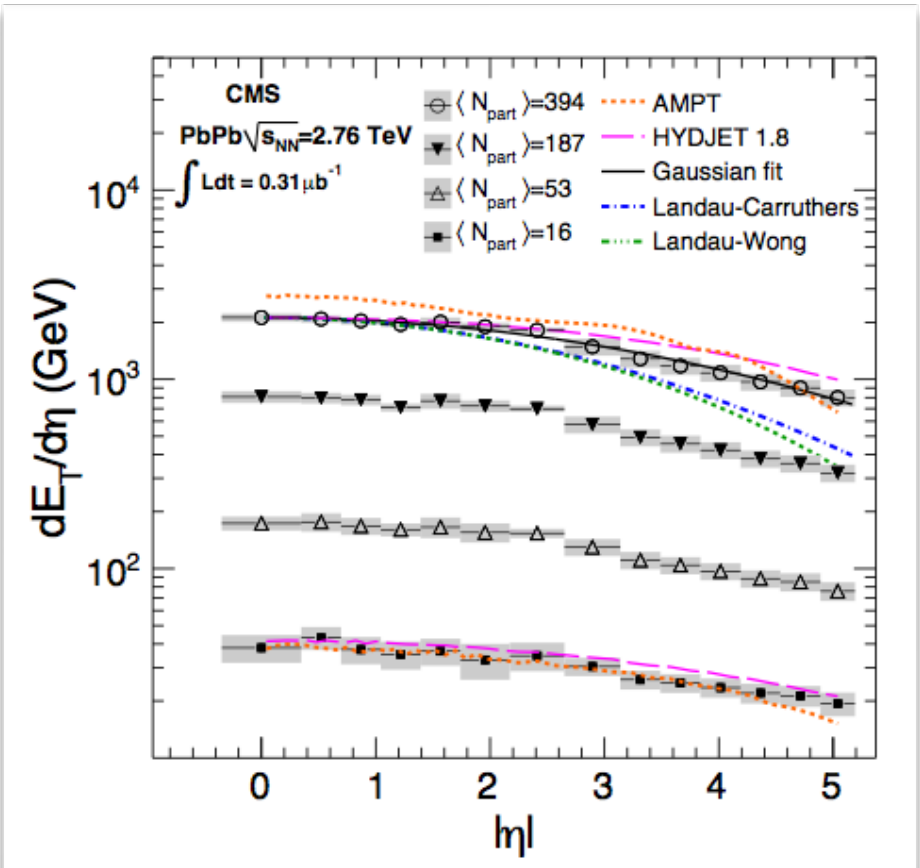
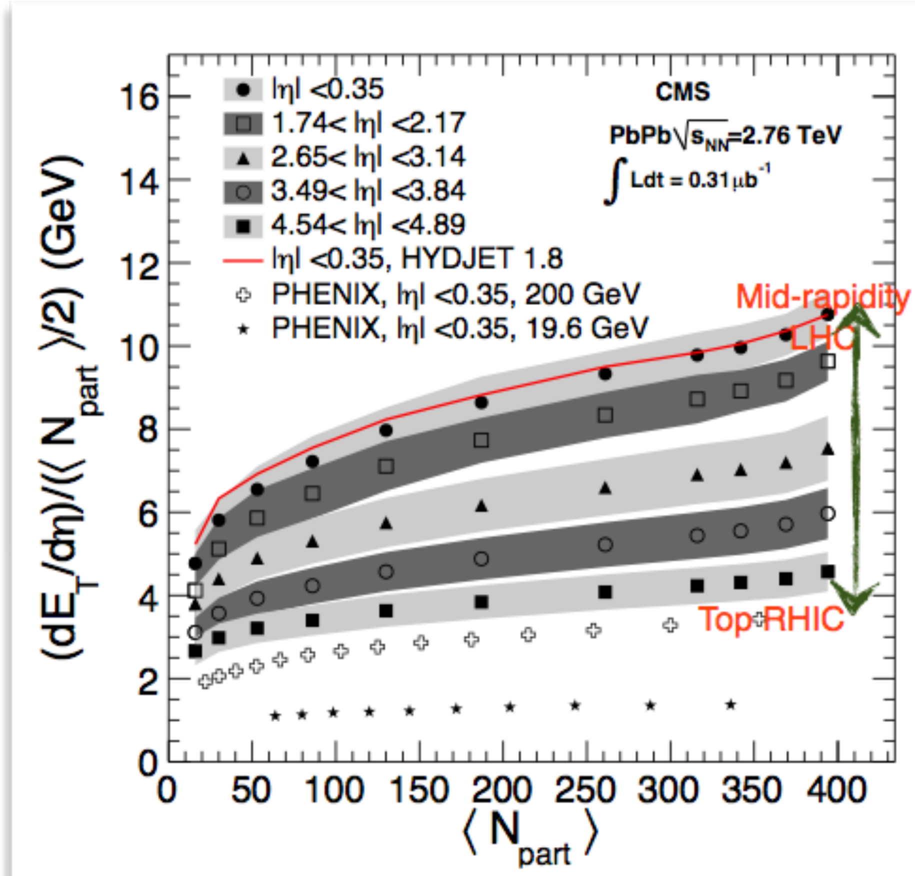
Energy density

LHC: 2.5 x RHIC



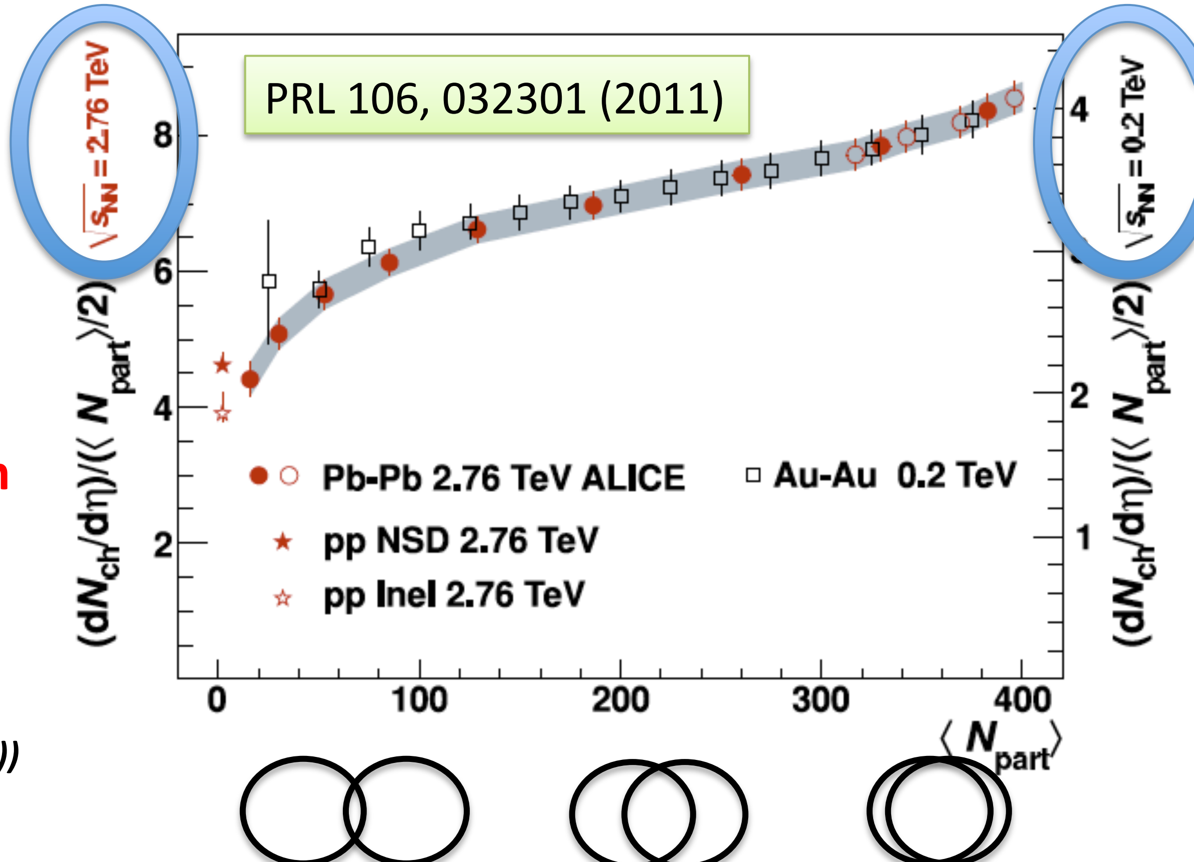
... within a volume (per nucleon)



Systematic control: compare RHIC to LHC

Centrality dependence of particle production

The same experiment under vastly different conditions!



• 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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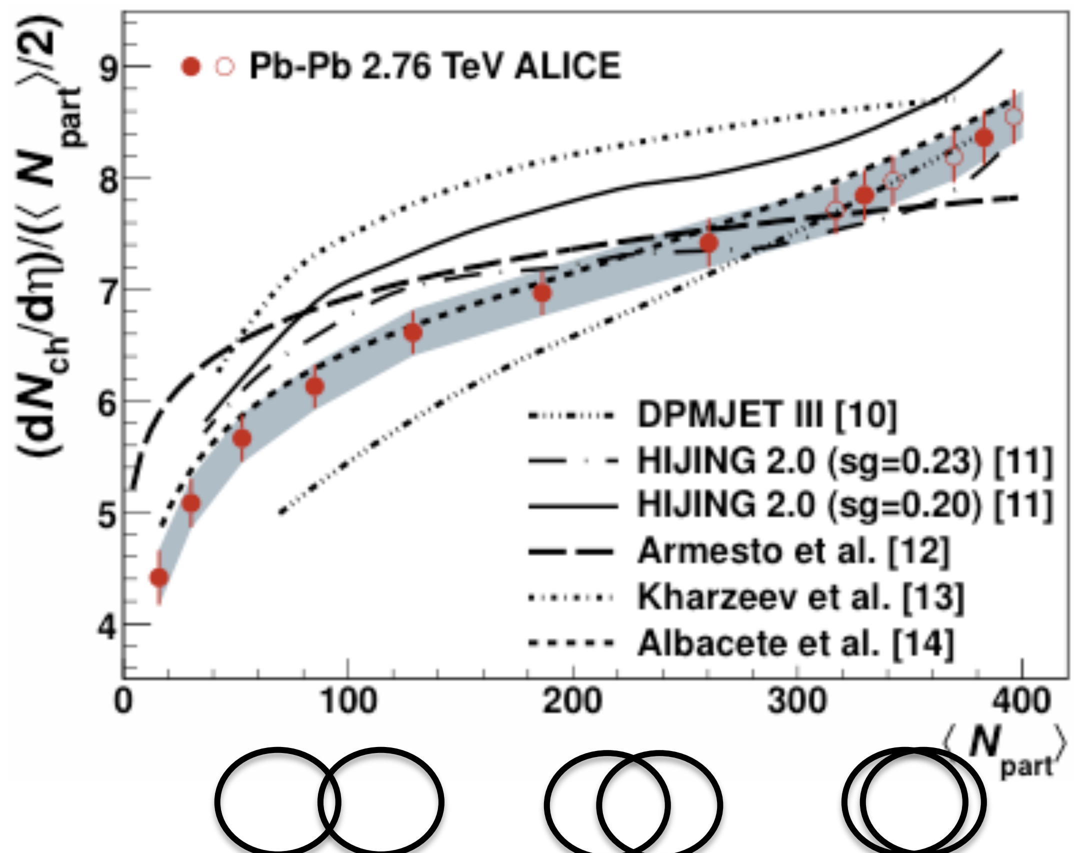
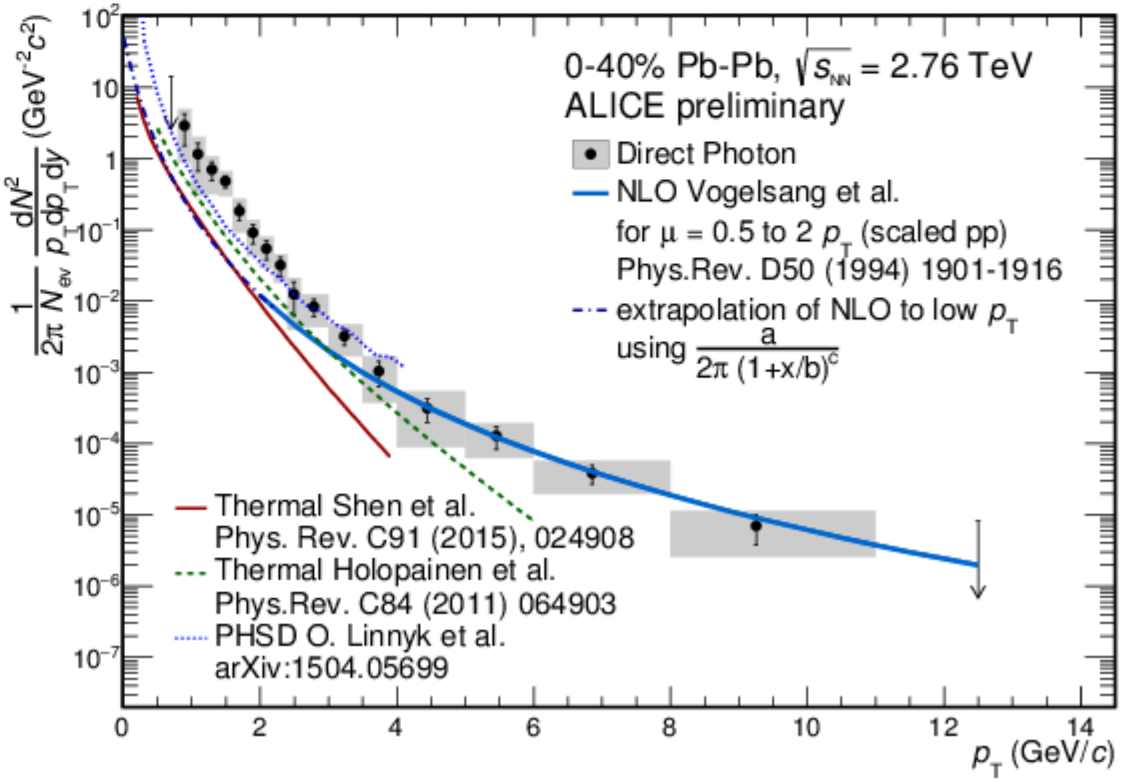


Centrality of the collisions: peripheral semi-central central

Direct photons
QGP shines



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

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:

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

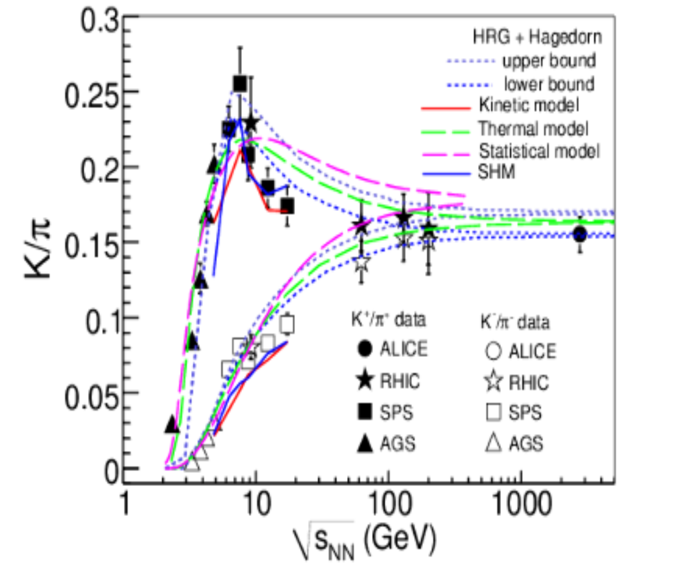
$$T = 221 \pm 19^{stat} \pm 19^{syst} \text{ MeV}$$

(Au-Au centrality 0-20%)

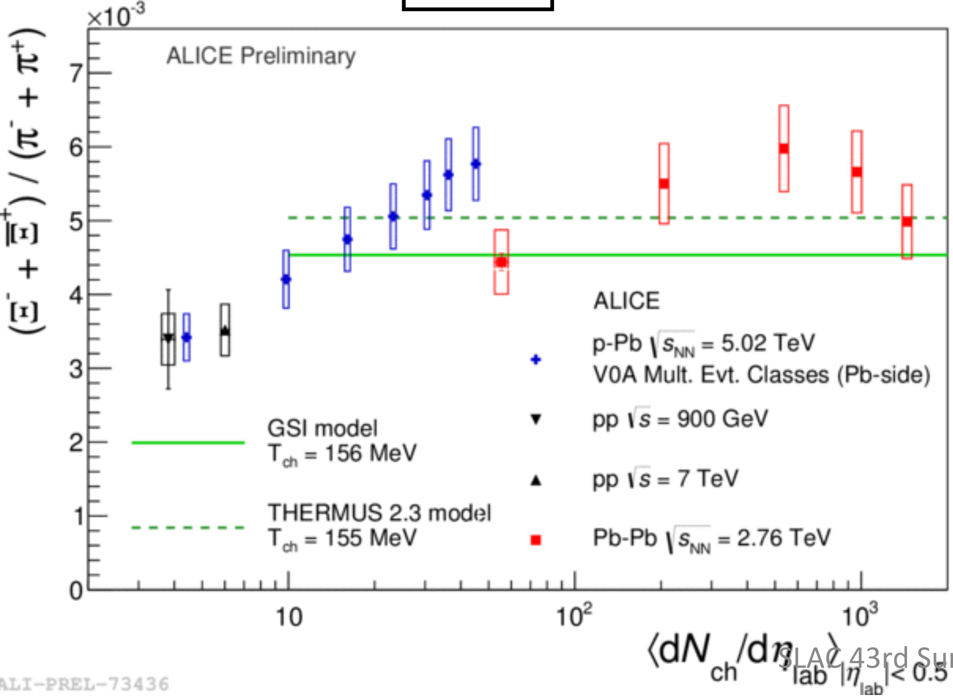
Outlook for Run-2: higher precision data (higher collision energy)

Onset of de-confined medium

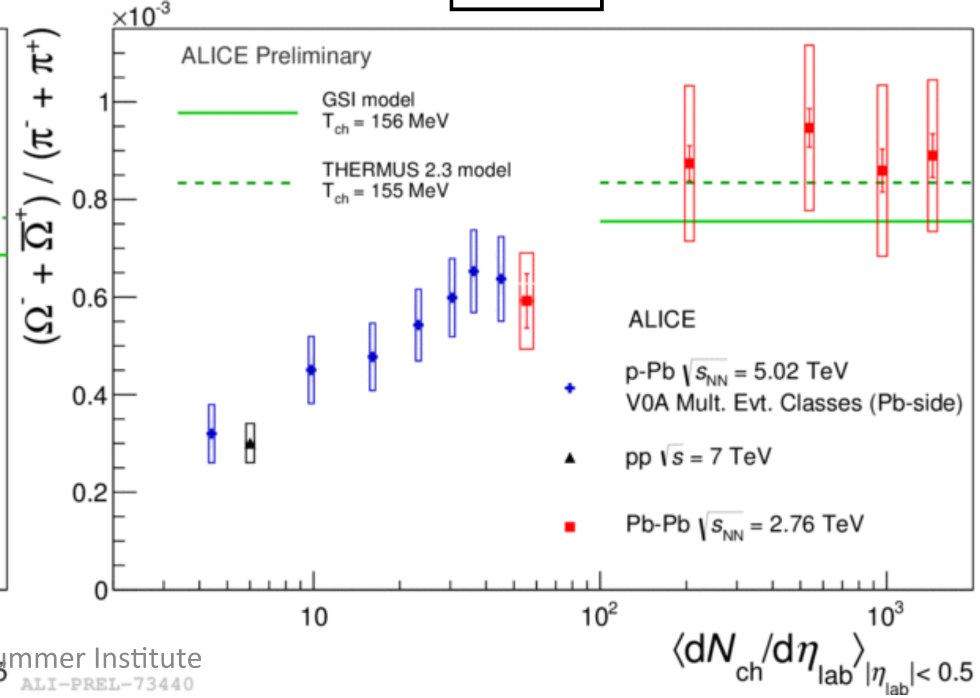
- Strangeness enhancement – especially multi-strange baryons
- Also in high-multiplicity p-Pb collisions ?
  - Xi/p reaches Pb-Pb values



Ξ/π



Ω/π



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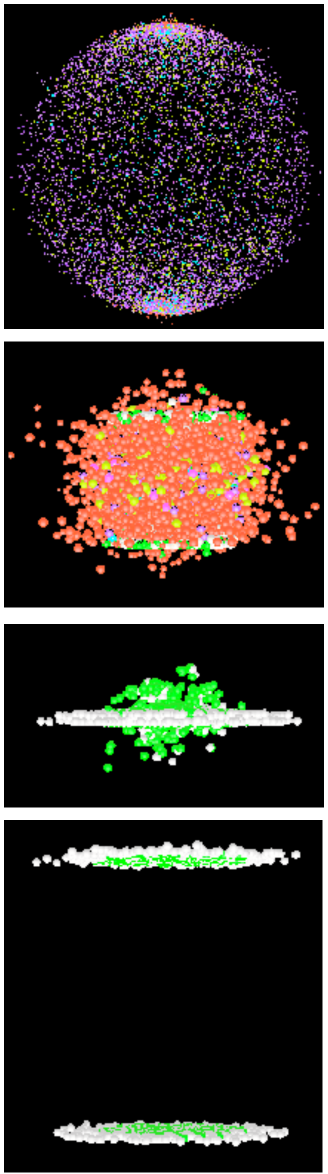
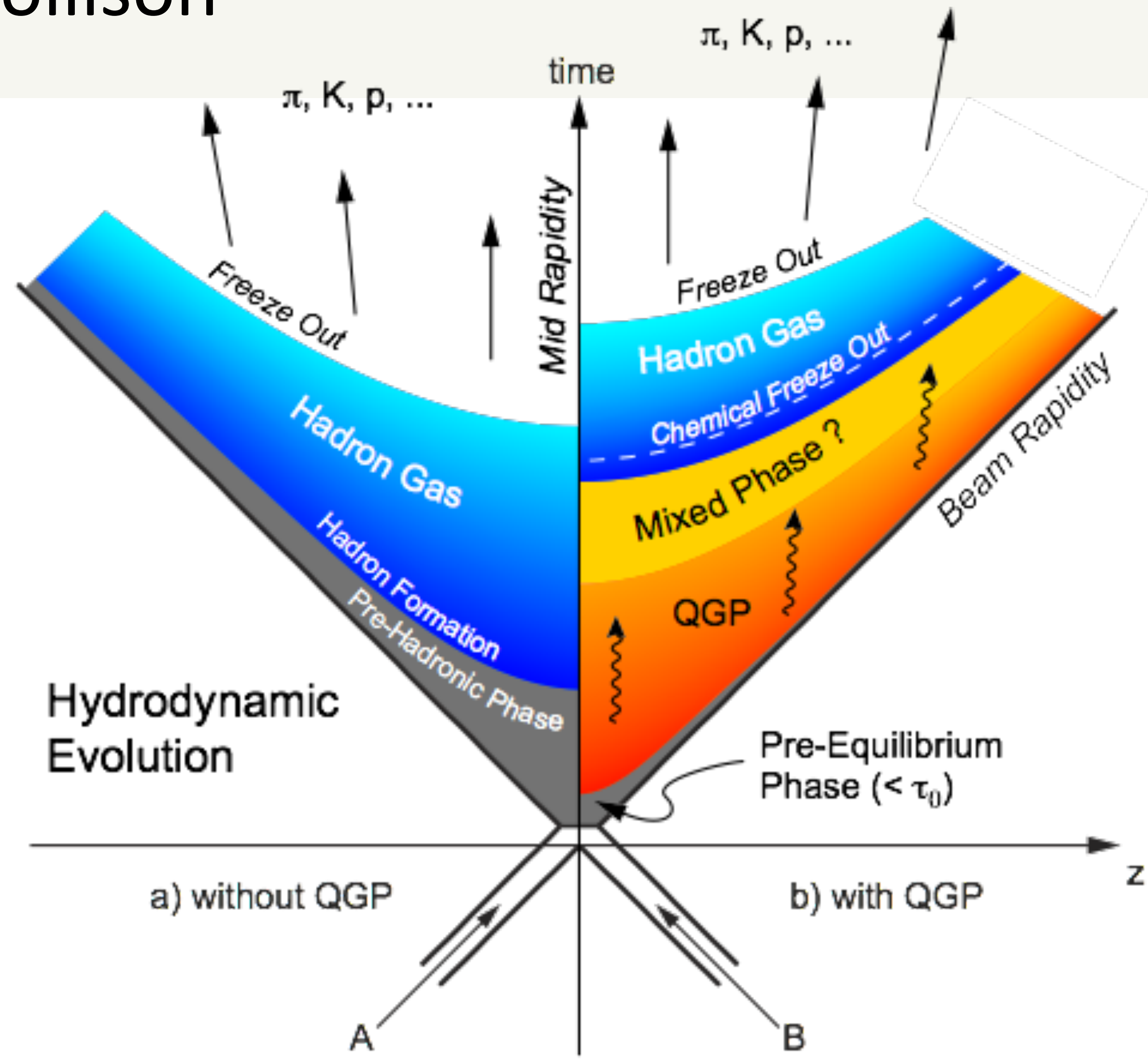




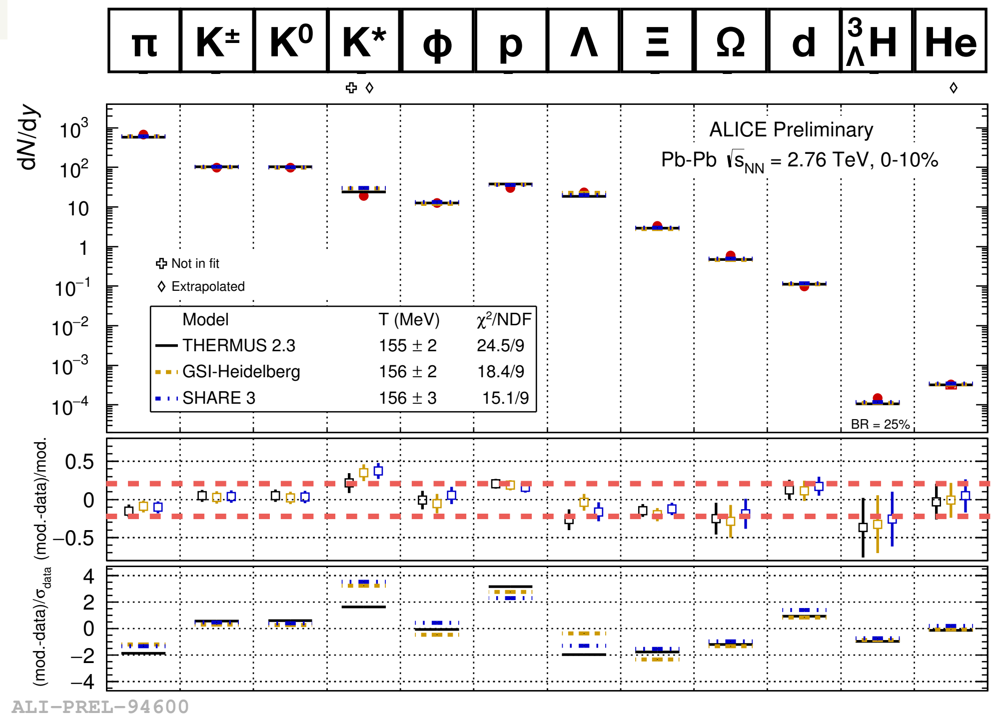
Particle production – statistical hadronization models

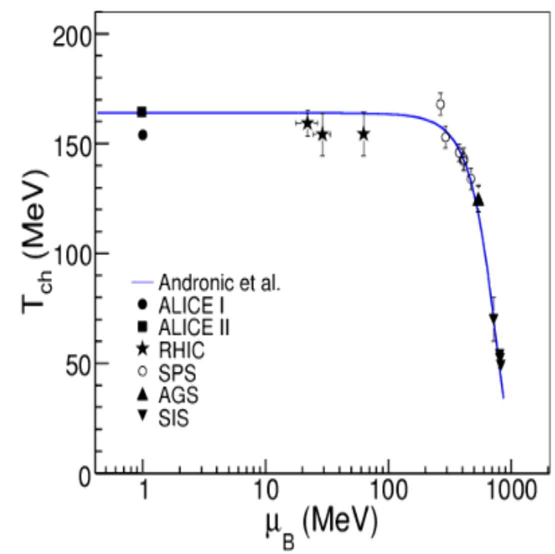
Grand-canonical ensemble analysis

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

T_{ch} Chemical freeze-out temperature

μ_B Baryochemical potential





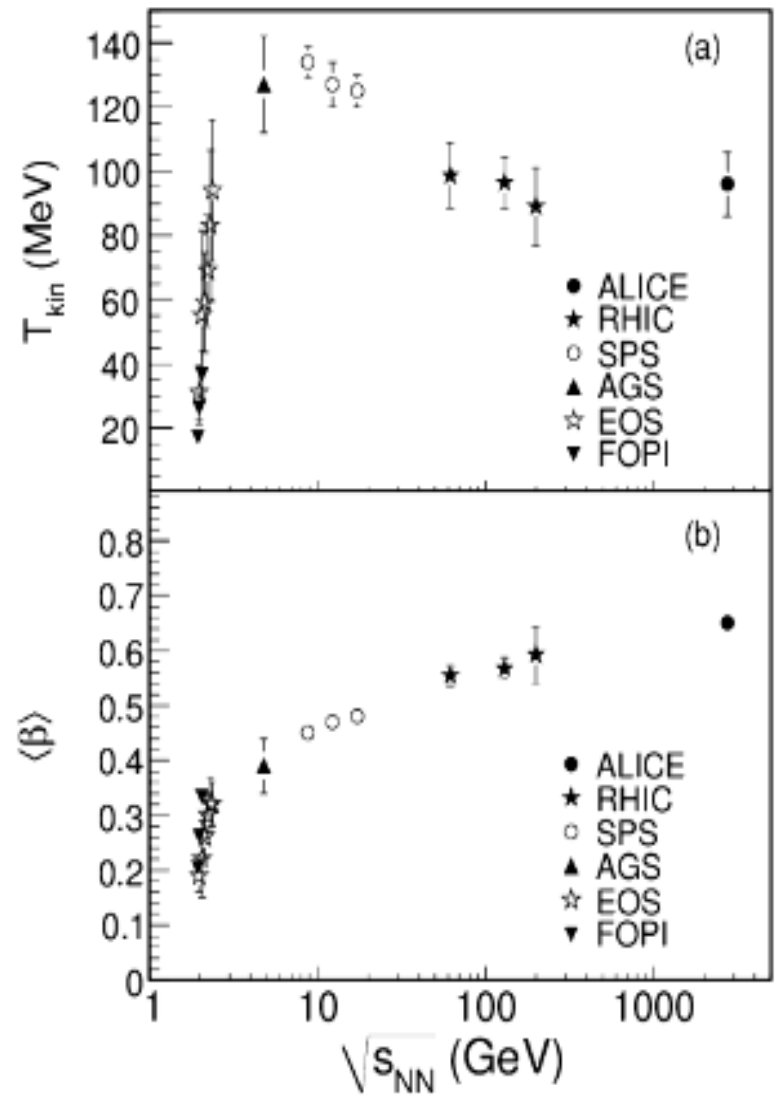
Yields described by thermal (3) models with

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

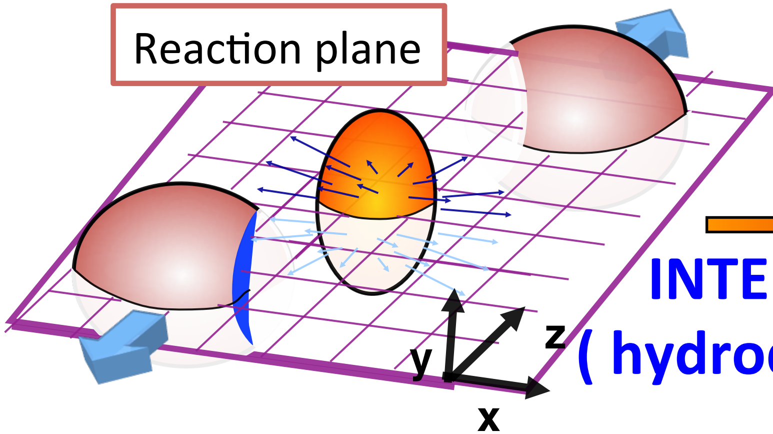
Collective expansion – particle spectra – kinetic freeze-out

- 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)

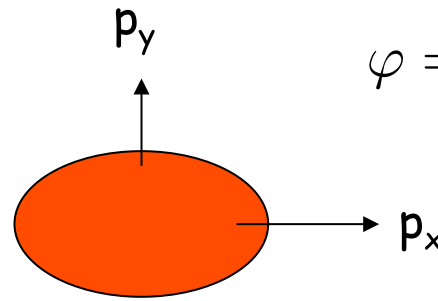


"COLLECTIVITY"

Collective Flow of QCD Matter



INTERATIONS
(hydrodynamics?)



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

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

Initial spatial anisotropy

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

Final momentum anisotropy

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

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

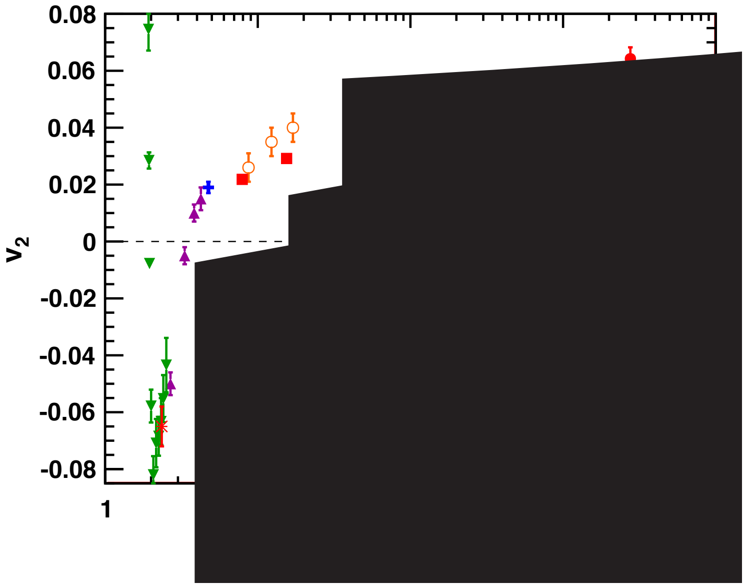
Elliptic flow

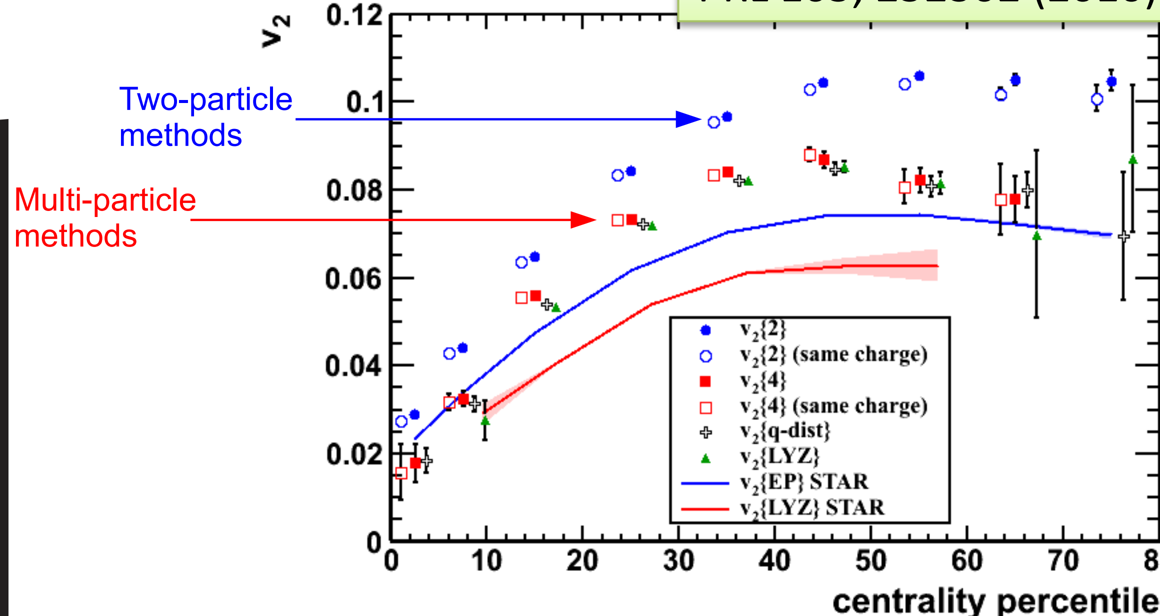
$$\frac{dN}{d\Delta\varphi} \propto 1 + 2v_2 \cos(2\Delta\varphi)$$

Azimuthal anisotropy

PRL 105, 252302 (2010)

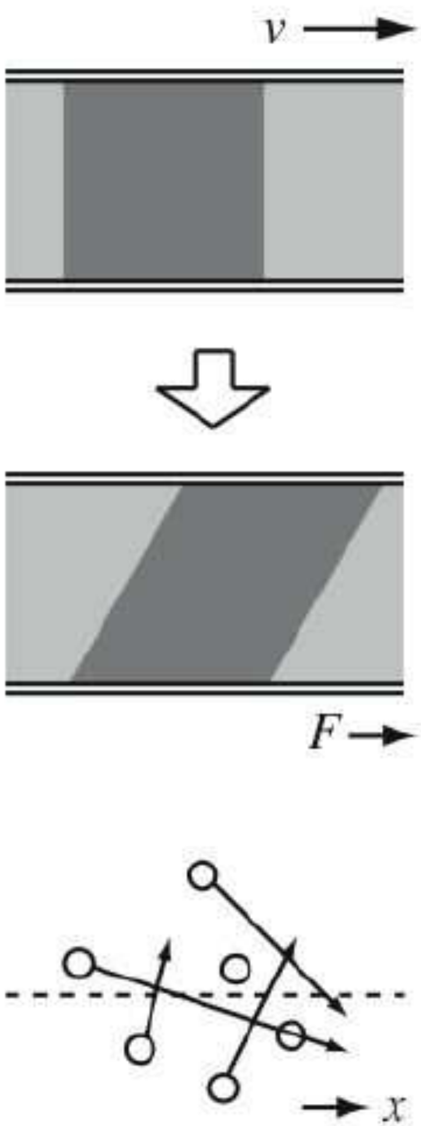
Energy dependence of v2





- **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

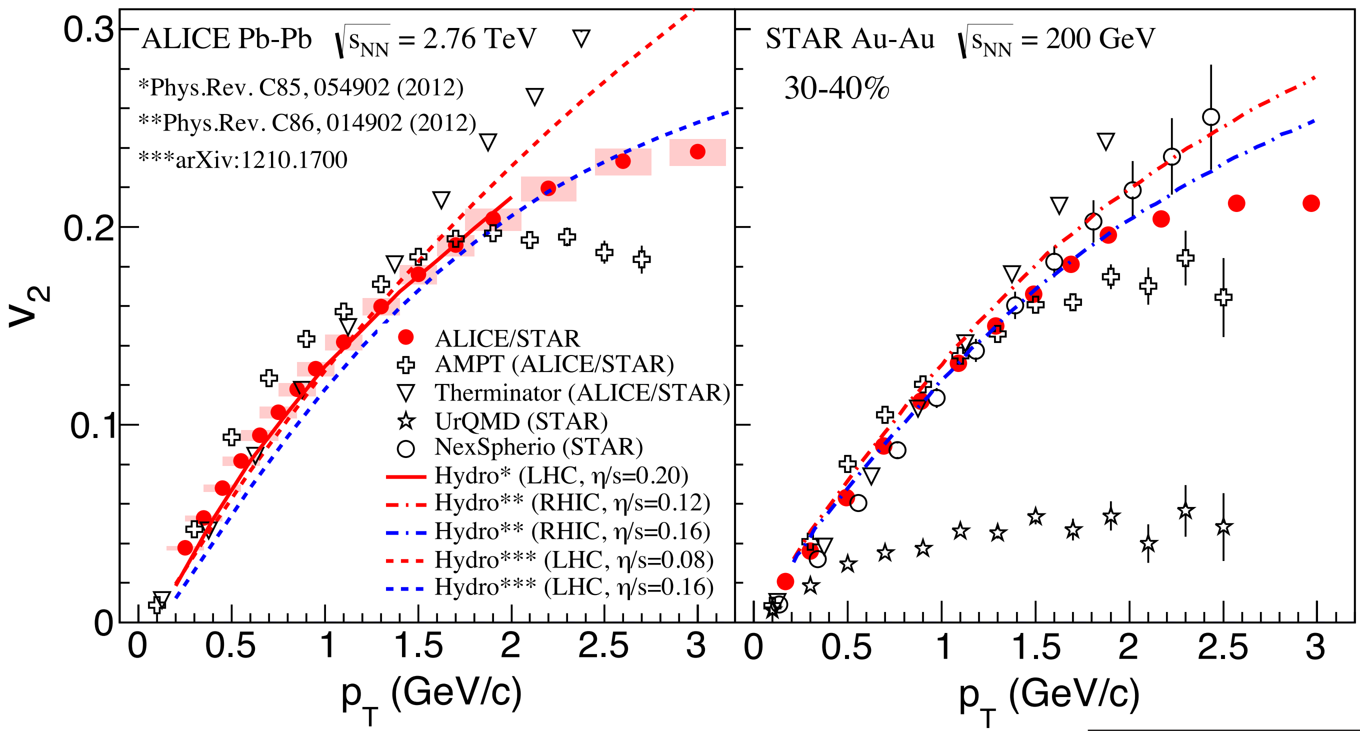
Strong coupling
- large cross section, small mean free path

$\Rightarrow$ small viscosity

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

How ideal fluid is QCD Matter?

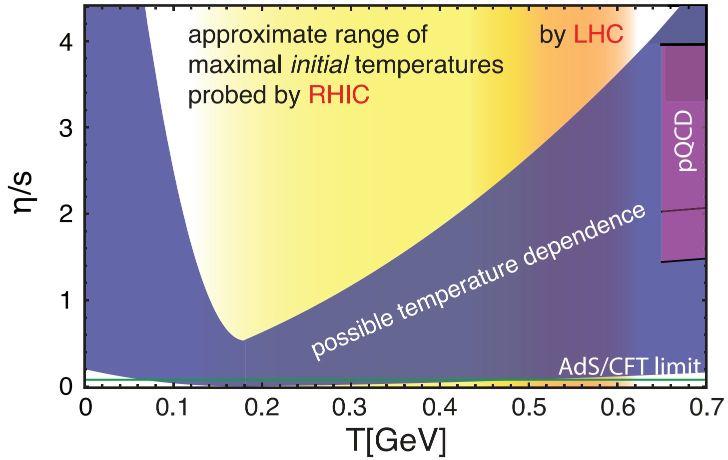
Viscous hydrodynamics needed to explain the data



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

Shear viscosity – lower limit: $$\frac{\eta}{s} > \frac{1}{4\pi}$$

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

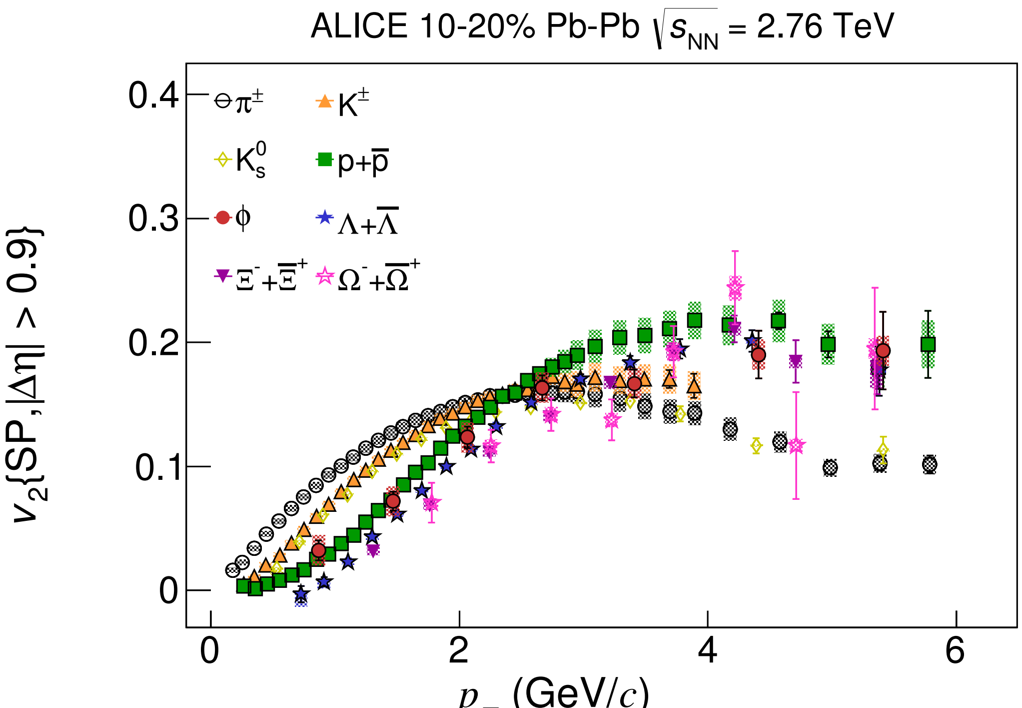


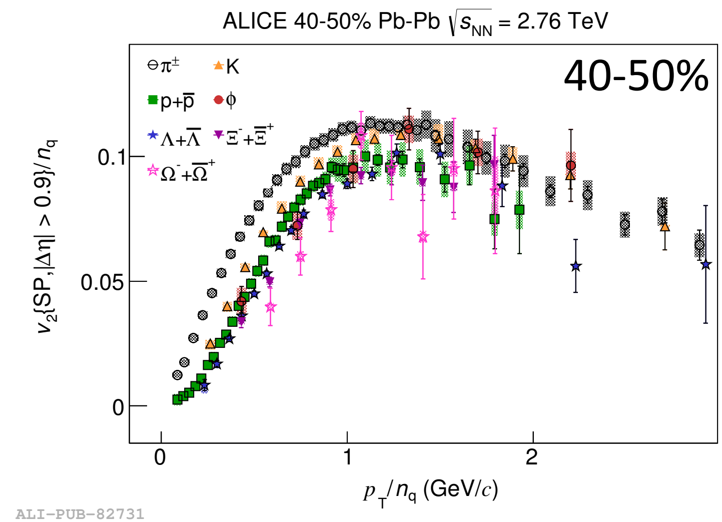
Hot, deconfined QCD matter flows as an almost perfect liquid

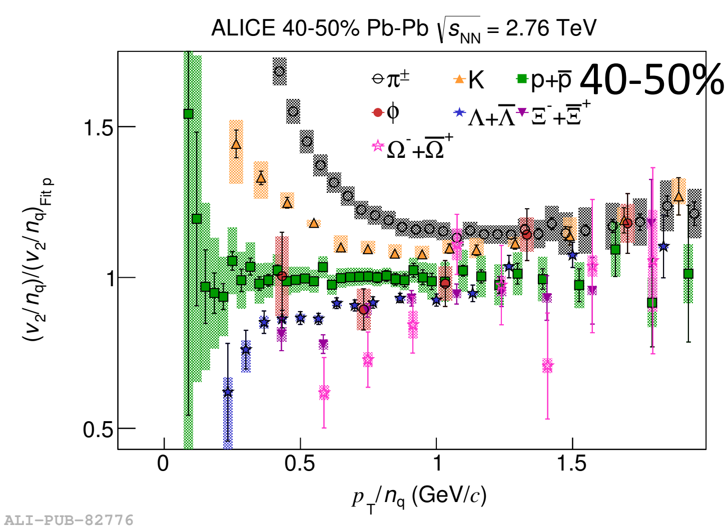
v_2 of identified particles

arXiv: 1405.4632

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







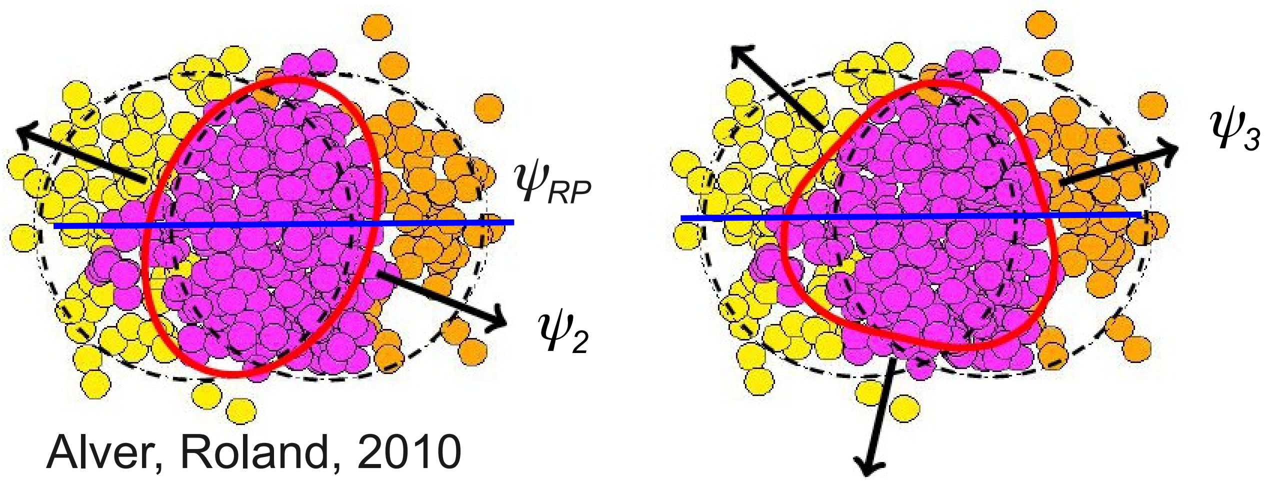
- v_2/n_q scaling at the LHC less obvious (within ~20%)

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

Higher harmonics in azimuthal decomposition

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

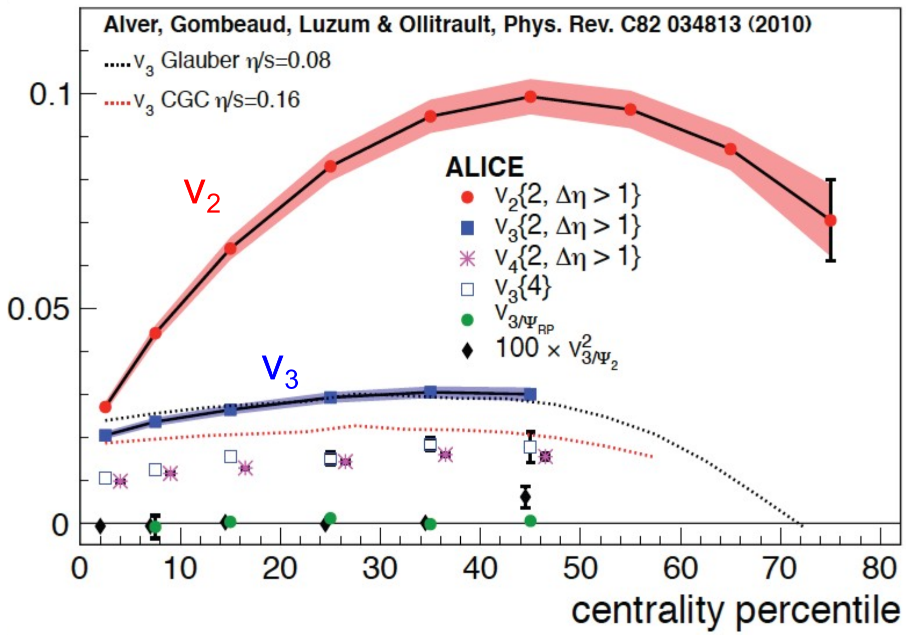


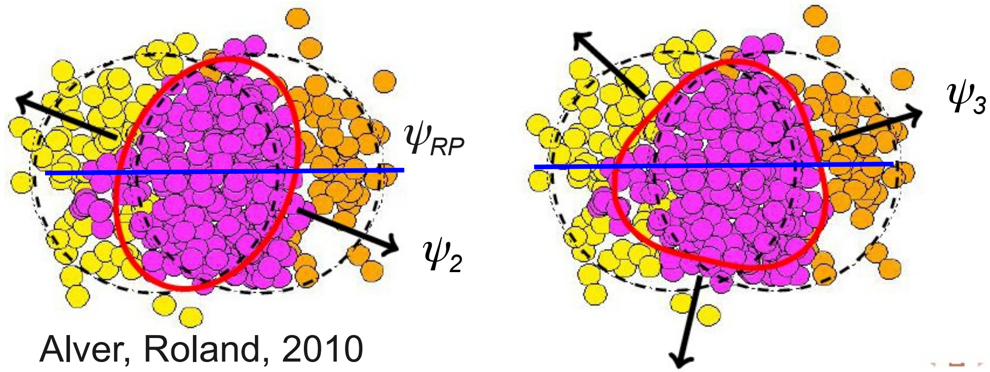
Alver, Roland, 2010

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

=> Odd harmonics are not zero

Higher harmonics – the measurements





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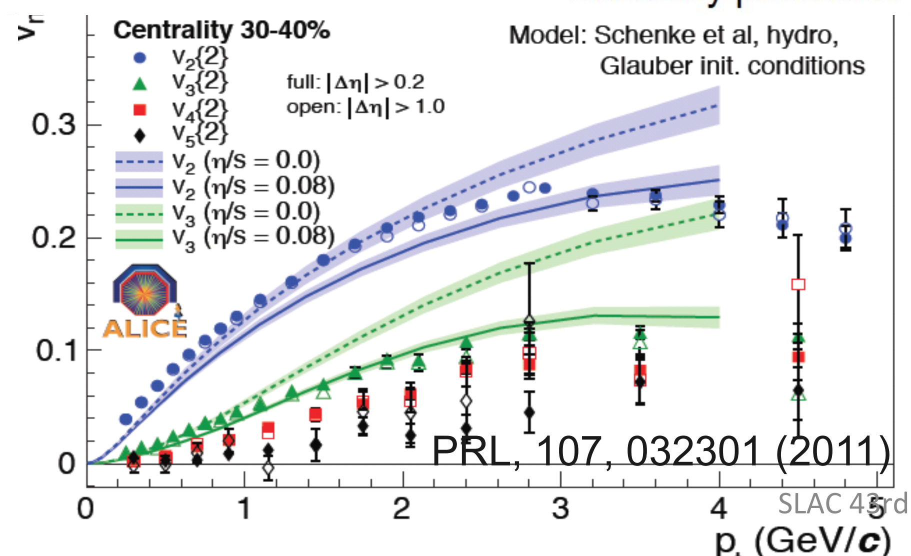


PRL, 107, 032301 (2011)

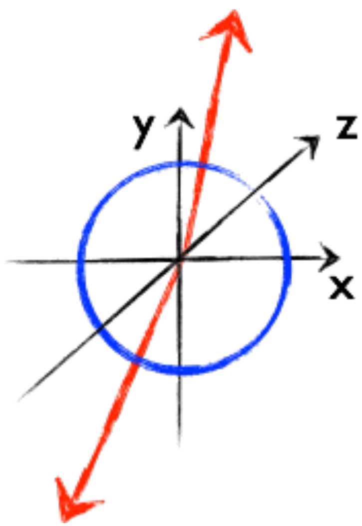
v_3 - triangular flow :
- weak centrality dependence
- vanishes as expected when measured w.r.t. reaction plane

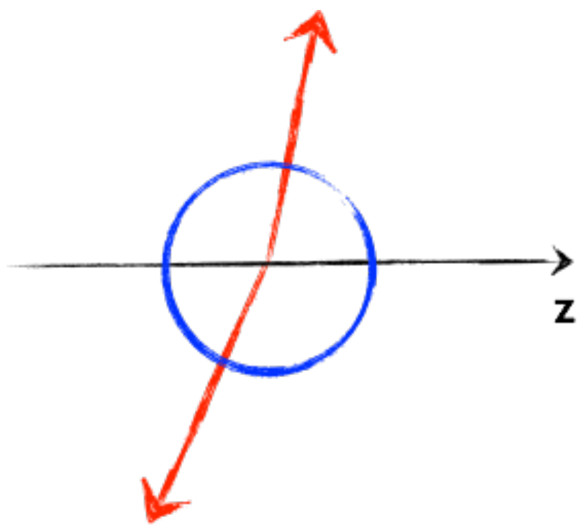
Similar p_T dependence for all v_n
Also similar to RHIC

Higher harmonics - additional constraints on η/s

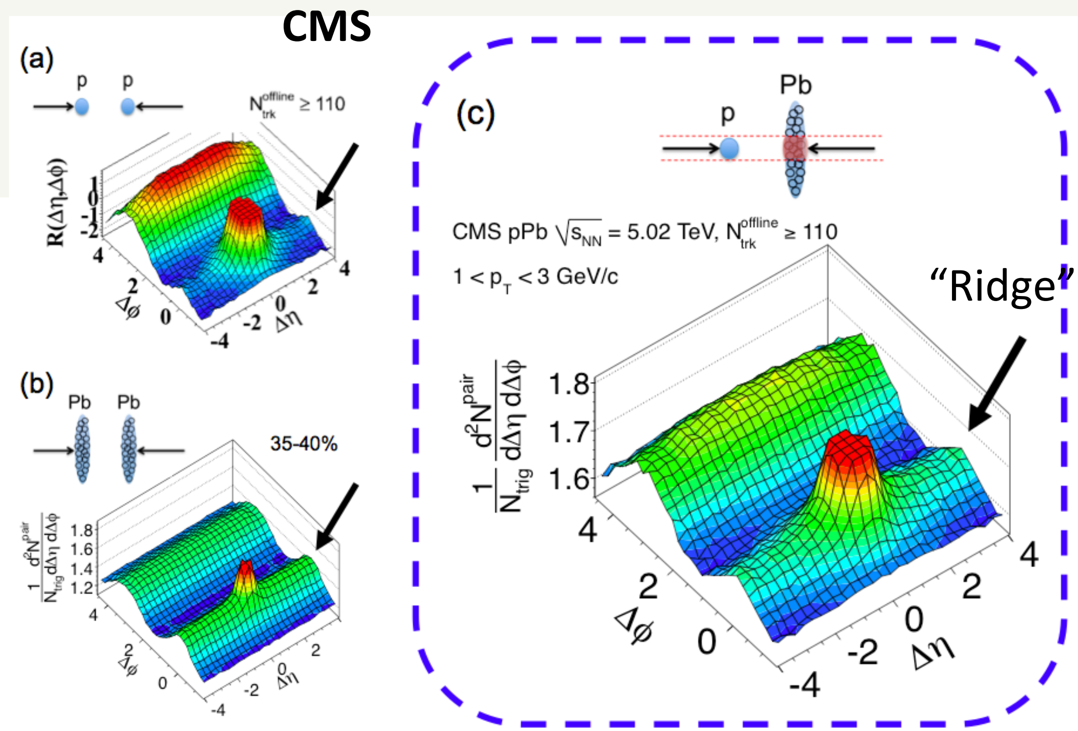
2-particle correlations

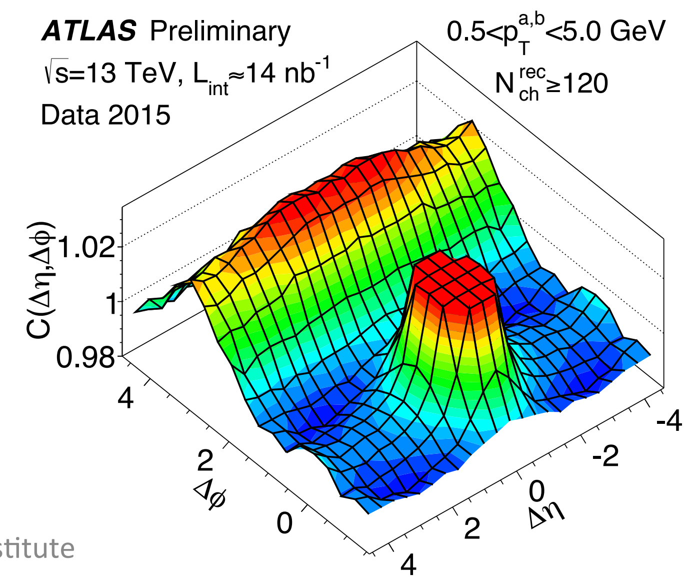
$\Delta\varphi$ azimuthal angle difference
- angle in the transverse plane



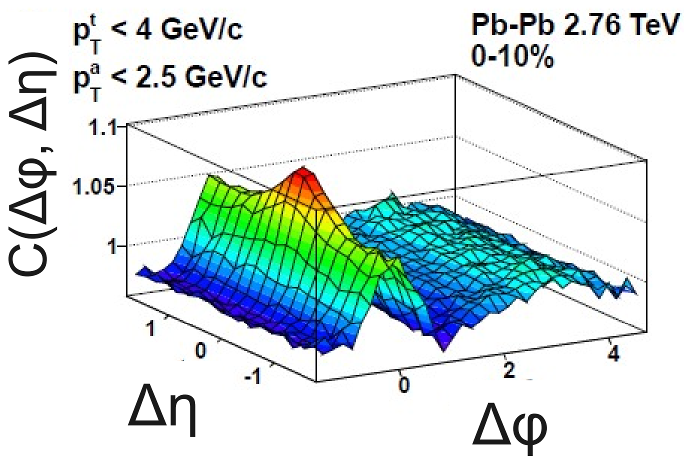


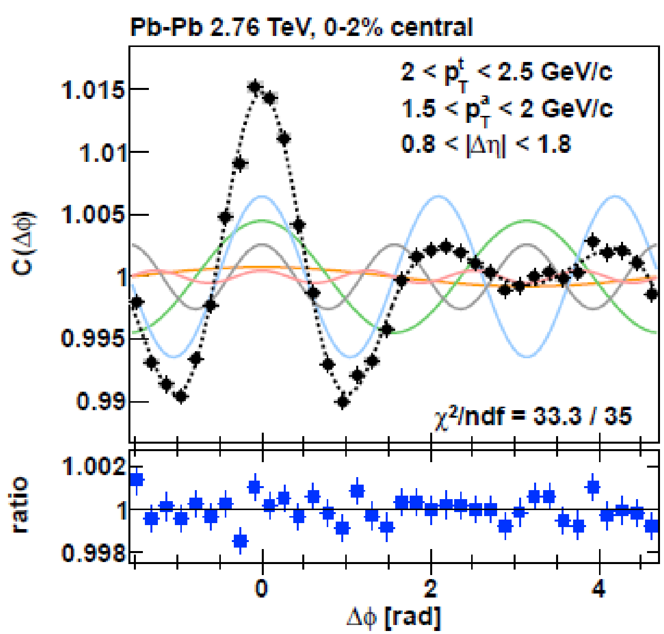
Δη - longitudinal - pseudo-rapidity distance





Two particle correlations – Fourier decomposition – long range correlations



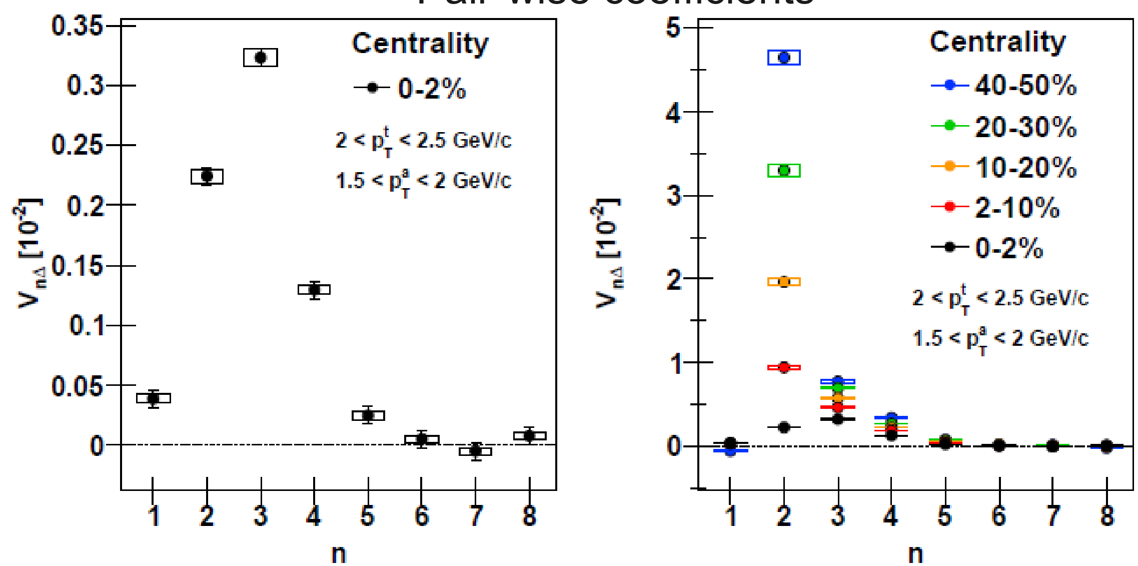


Integration of the correlation function in 0.8 < |Δη| < 1.8 (long) and Fourier decomposition

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



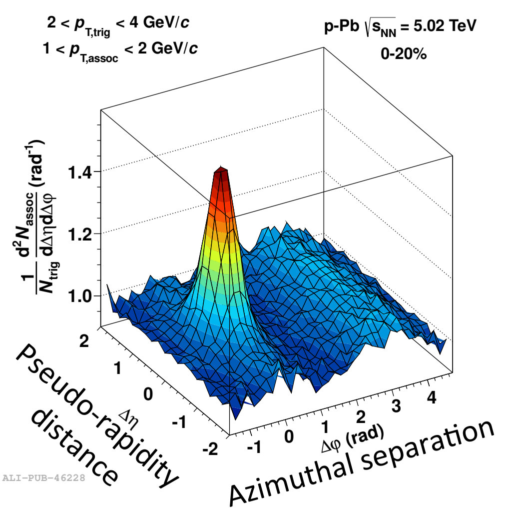
Few components describe the low-pT correlations

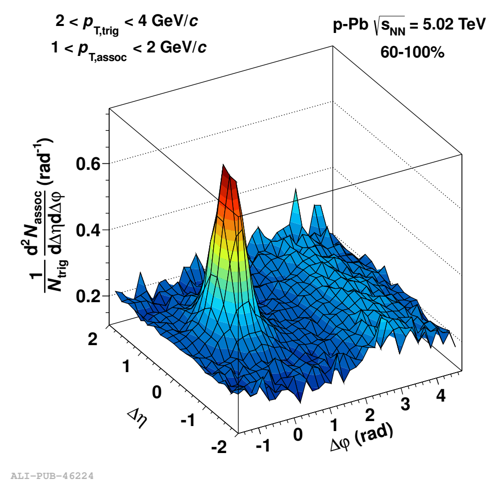
⇔ Strong near side ridge and double-peak on the away

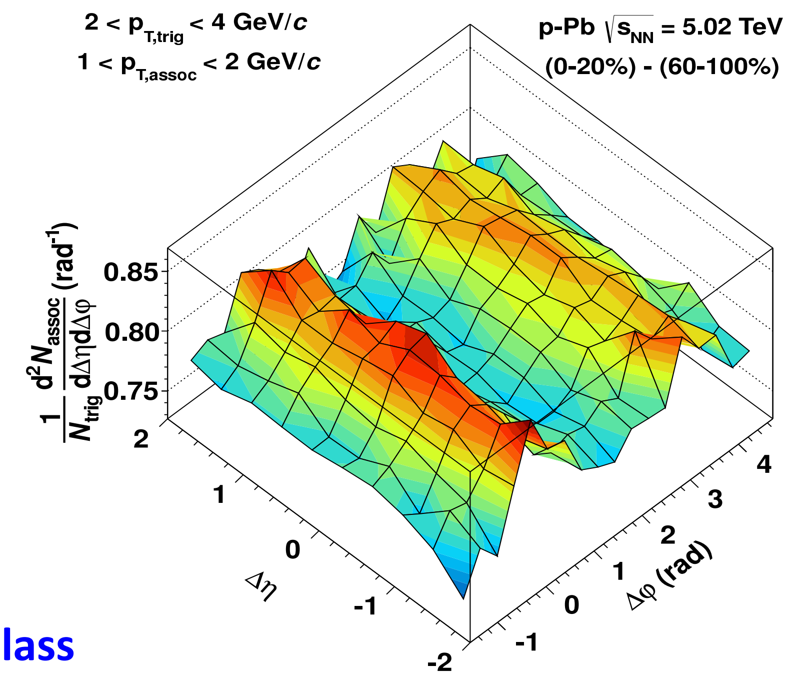
⇔ Also recoil jet up to p_T^{trig}>8 & p_T^{assoc} 6-8 in central

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

$\langle dN_{ch}/d\eta \rangle \sim 35$

Low multiplicity event class

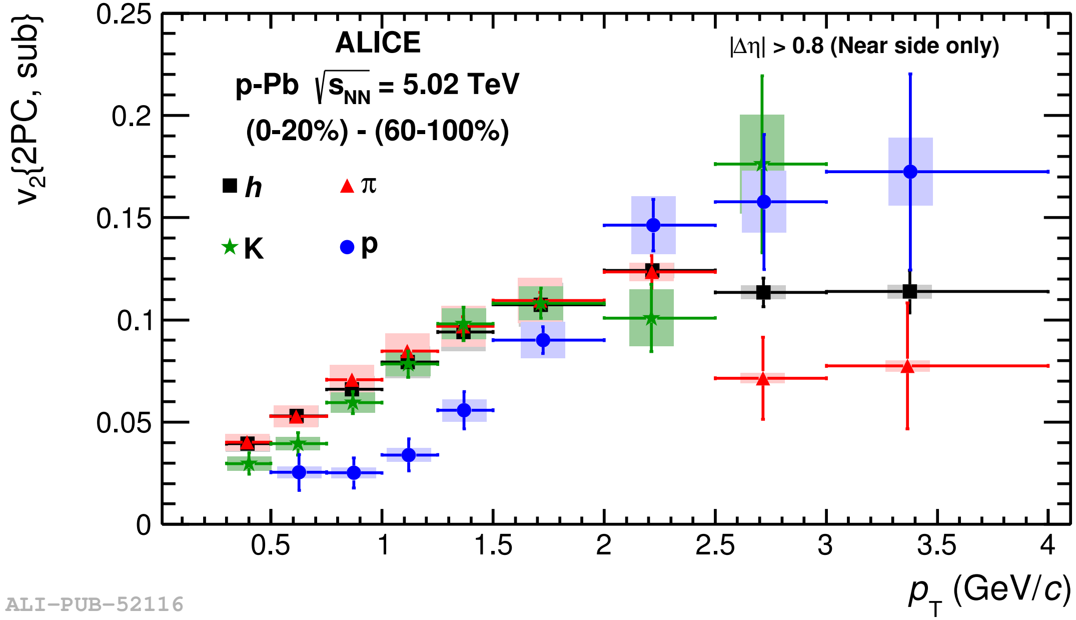
$\langle dN_{ch}/d\eta \rangle \sim 7$

Remaining correlation: two twin long range structures

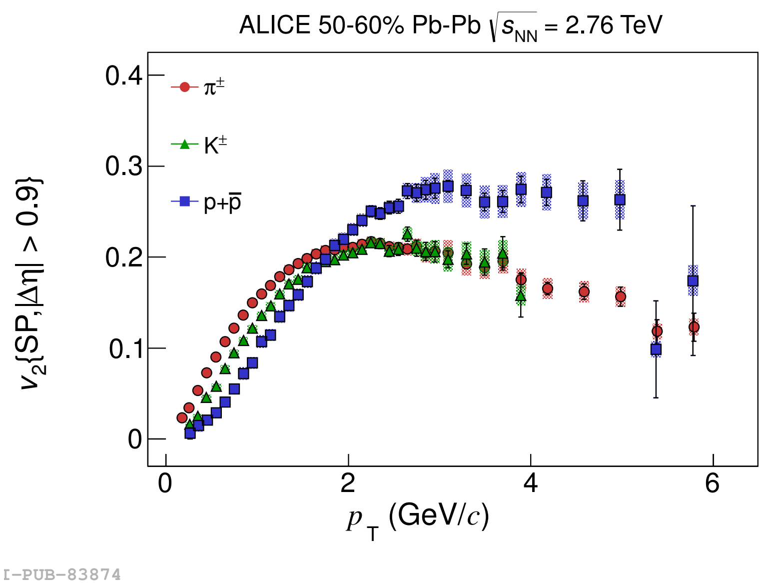
Analysis in multiplicity classes defined by the total charge in VZERO detector (away from the central region)

Comparison of v_2 in Pb-Pb and p-Pb

High-multiplicity p-Pb collisions



50-60% Pb-Pb

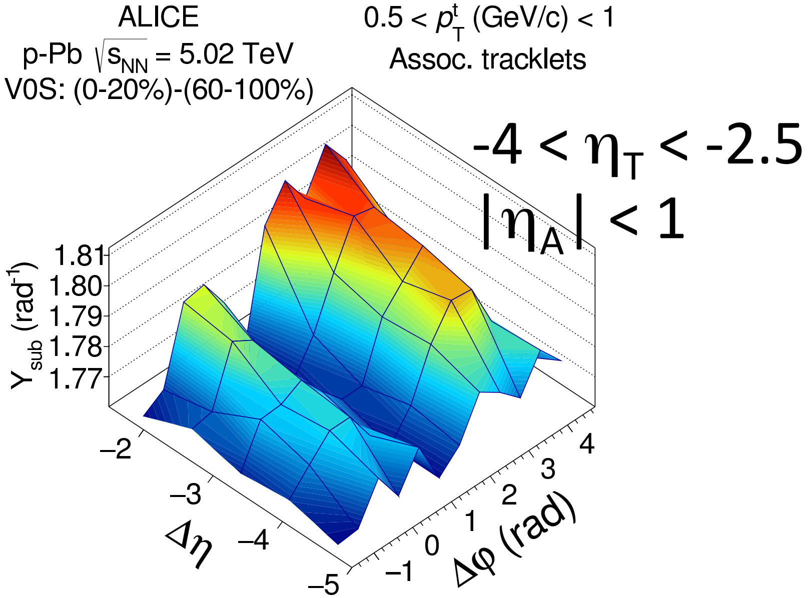


Similar features in p-Pb and Pb-Pb: mass ordering at low-p_T in Pb-Pb ascribed to hydrodynamics

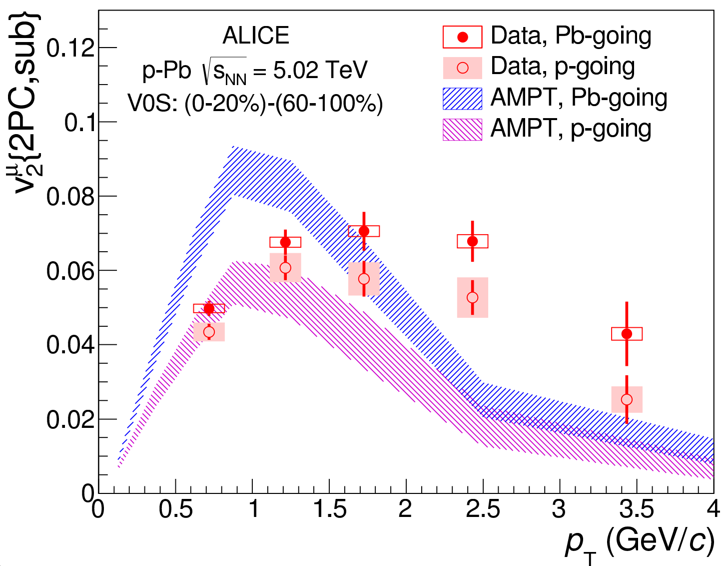
- Not shown: more signatures for collectivity from cumulant analysis

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

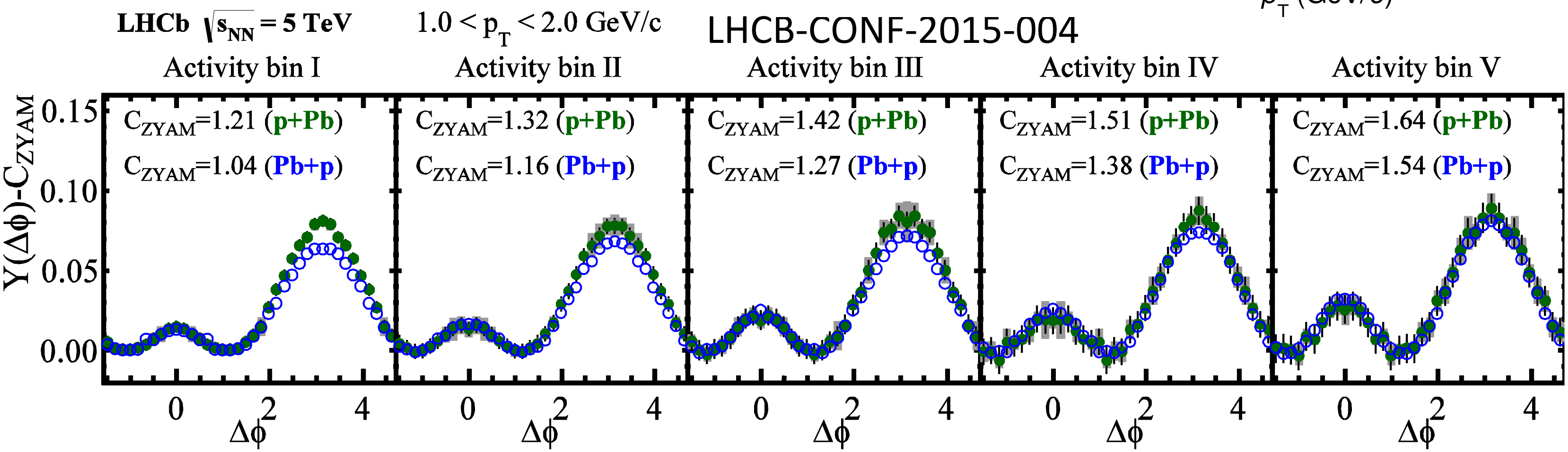
ALICE arXiv:1506.08032



v$_2$(Pb-going) > v$_2$(p-going) and independent of p$_T$



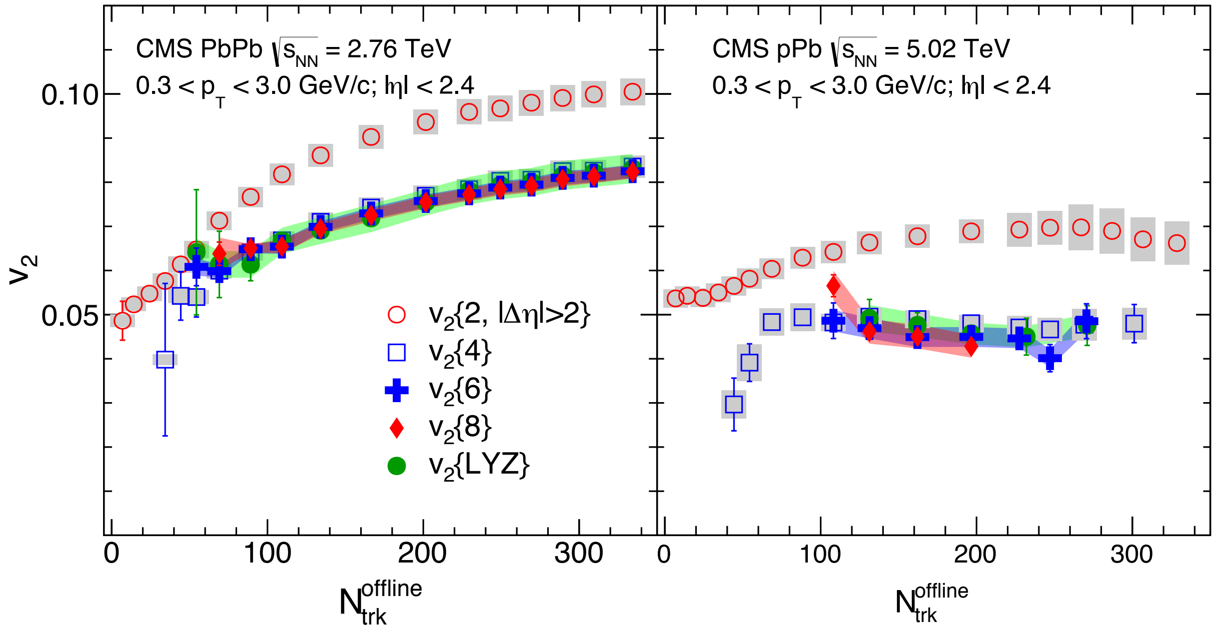
LHCB-CONF-2015-004



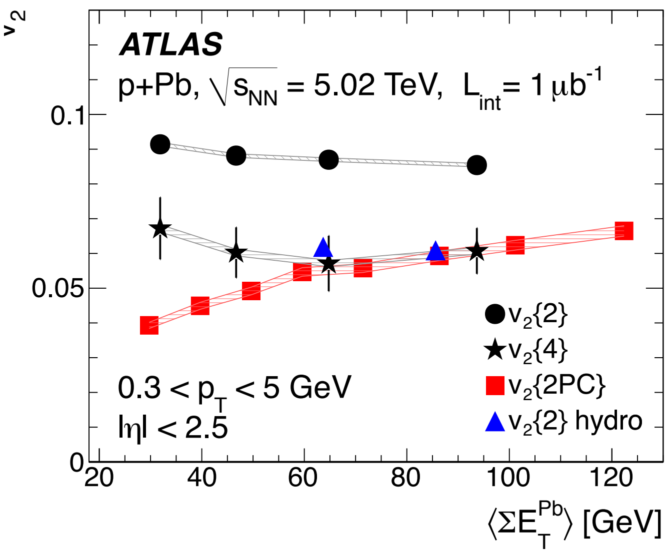
Collective particle production in p-Pb

Multiple-particle correlations

PhysRevLett.115.012301



Phys.Lett. B725 2013 (60-78)



Multiple particle (up to N=8) correlations

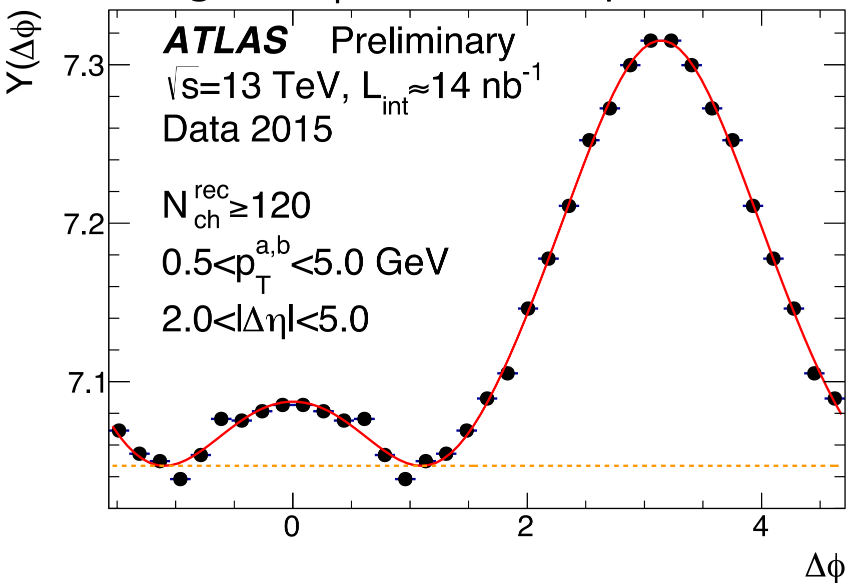
– **very clear signal of collective particle production**

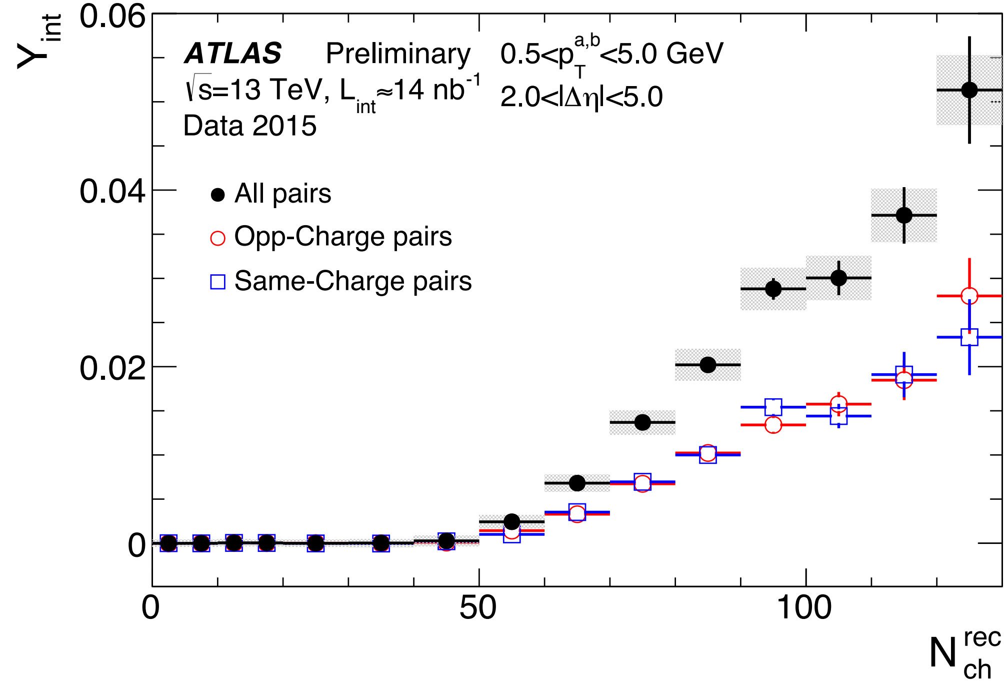
Droplets of QGP in pA collisions? Other "initial-state" effects?

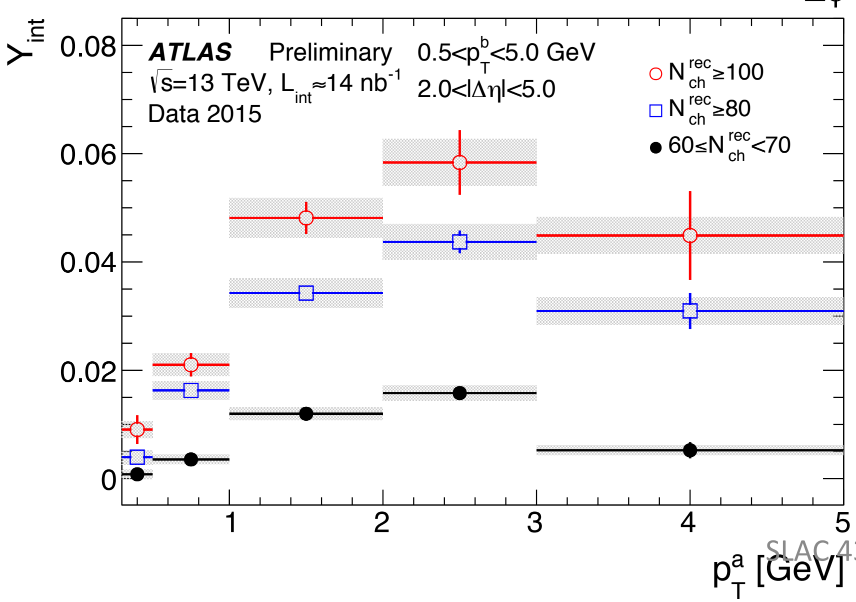
Long-range correlations also in pp collisions at 13 TeV

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)

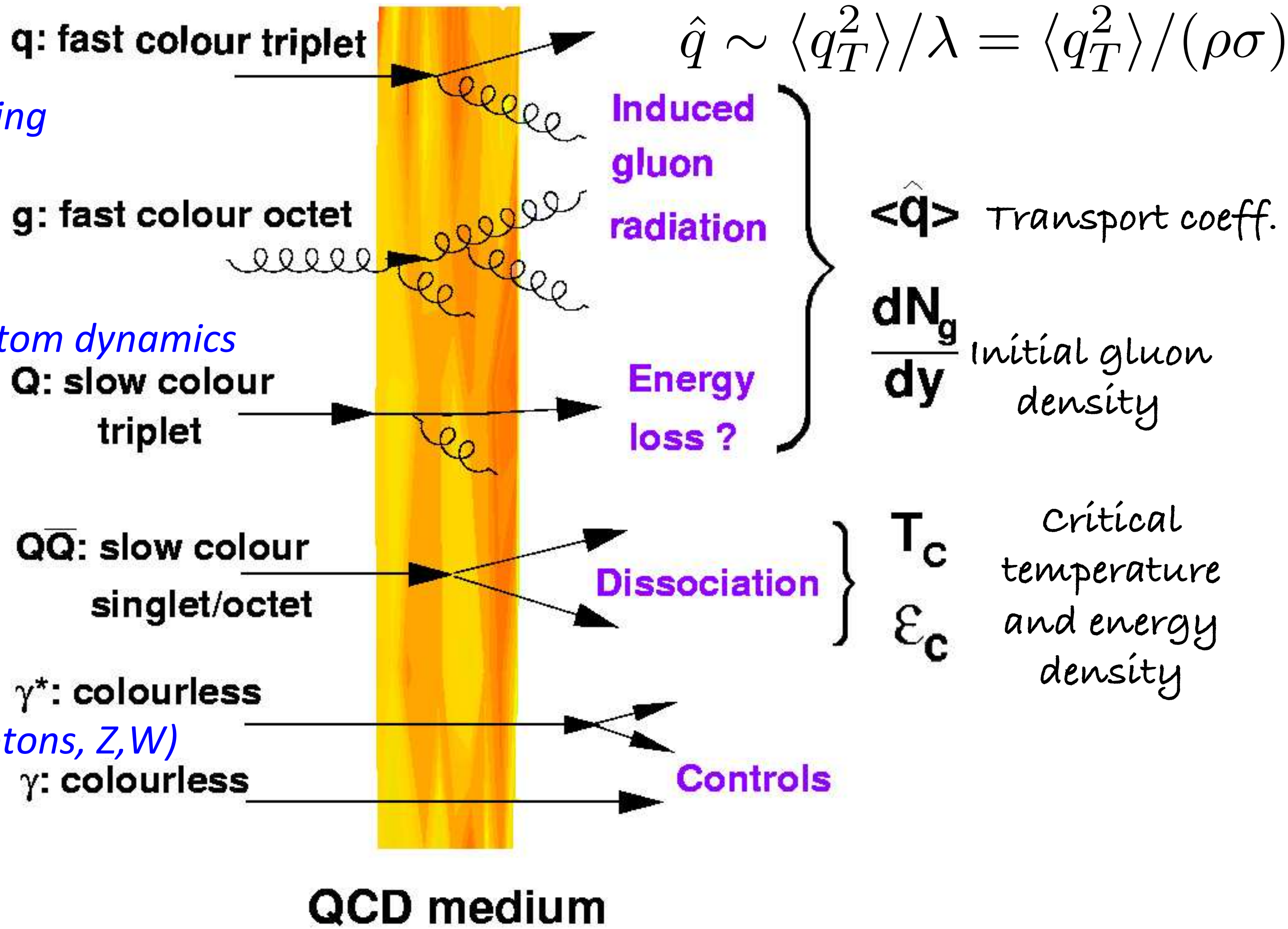
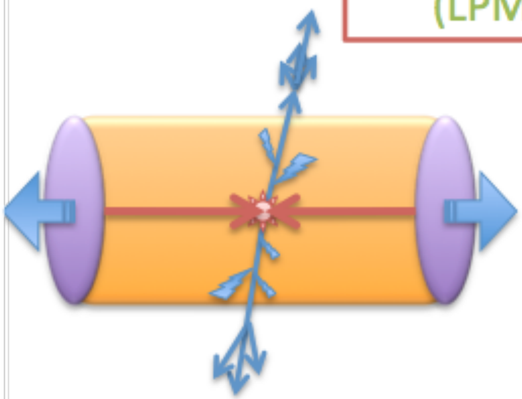


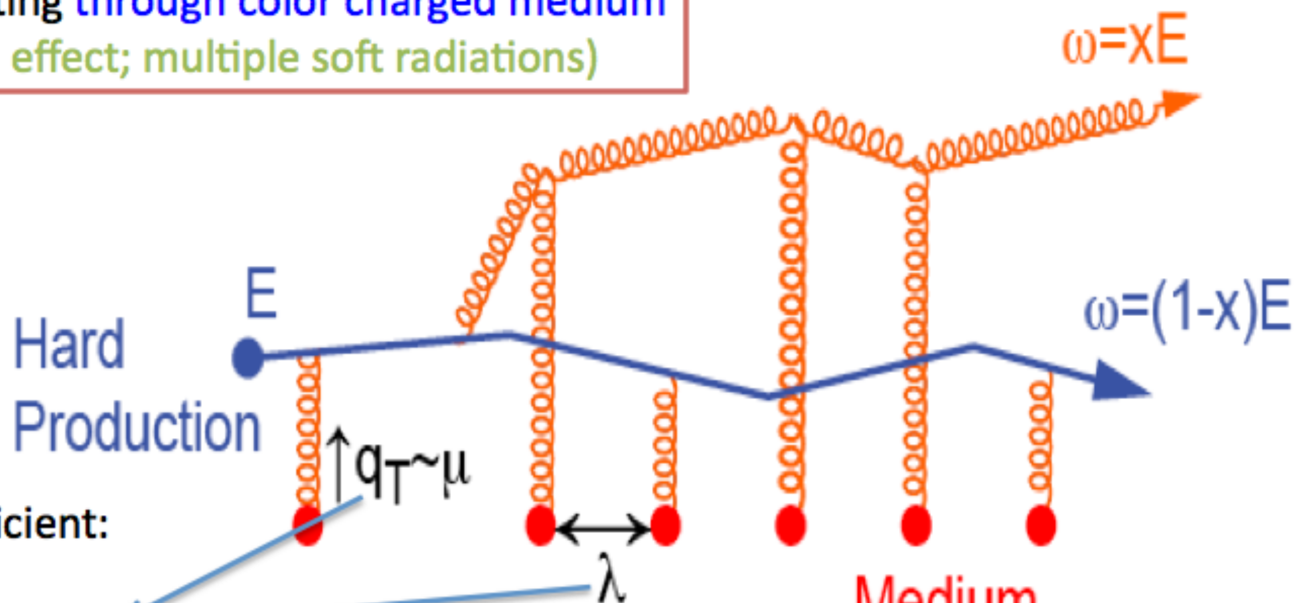
Figure: d'Enterria arXiv:0902.2011

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:

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

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

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

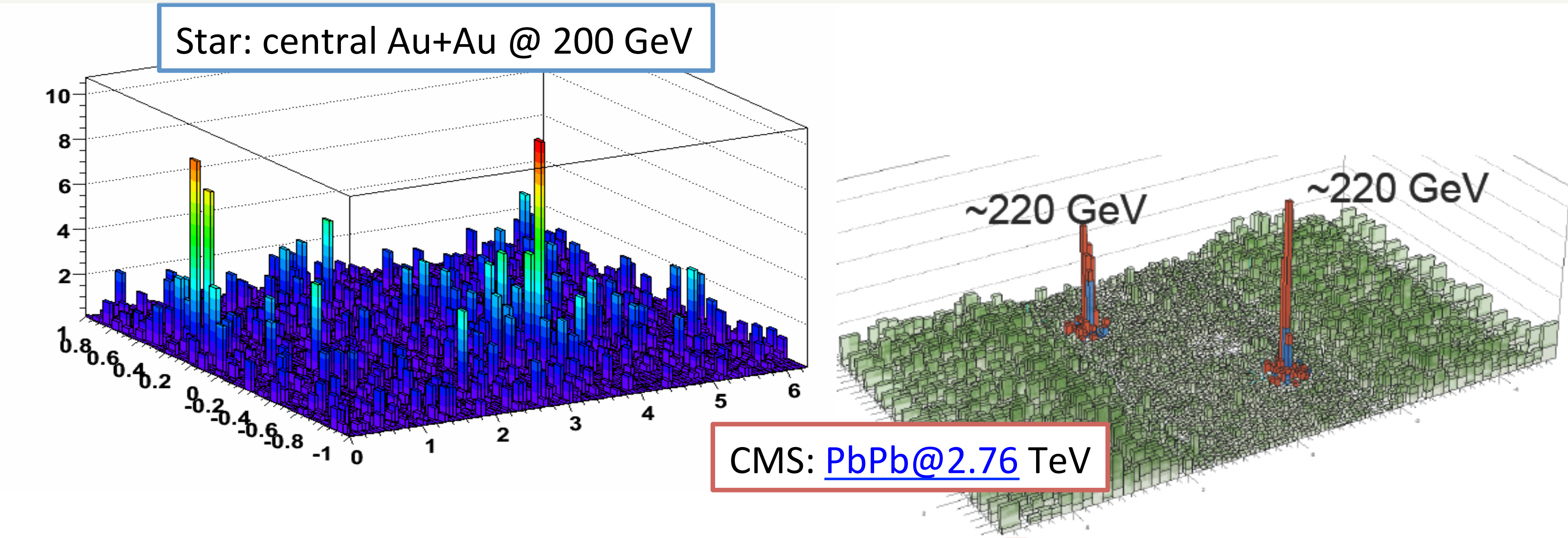
Partonic energy loss in QCD medium is proportional:

- 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

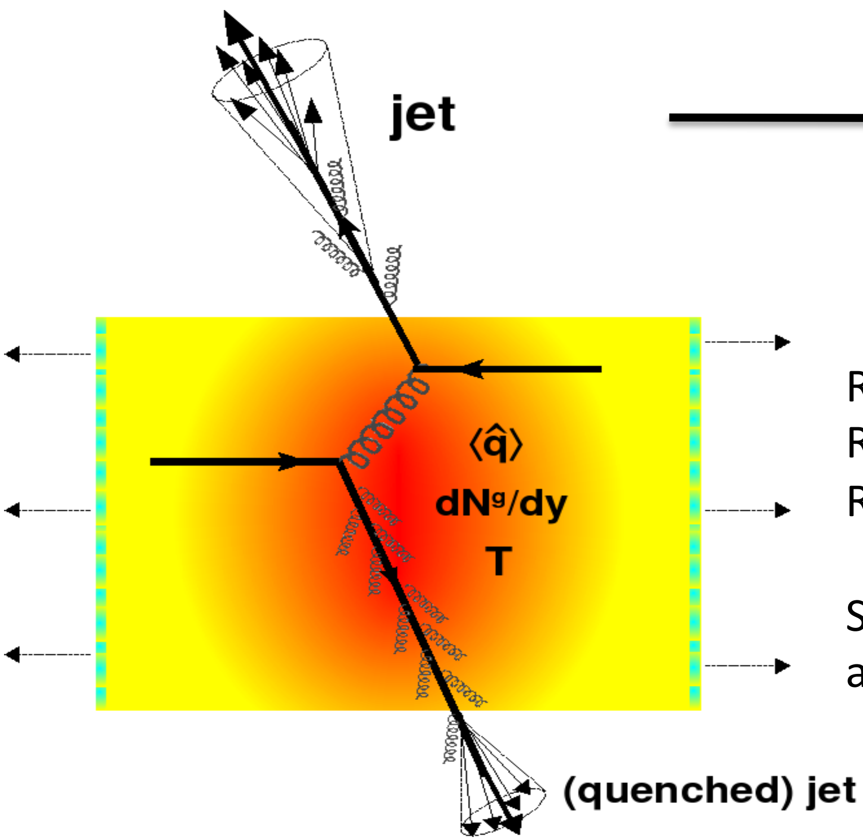
⇒ LHC: Vary the scale with which QGP is probed (a la **DIS**)

⇒ Compare and contrast RHIC and LHC

Quantifying nuclear effects: R_{AB}

$$R = \frac{\text{"QCD medium"}}{\text{"QCD vacuum"}}$$

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



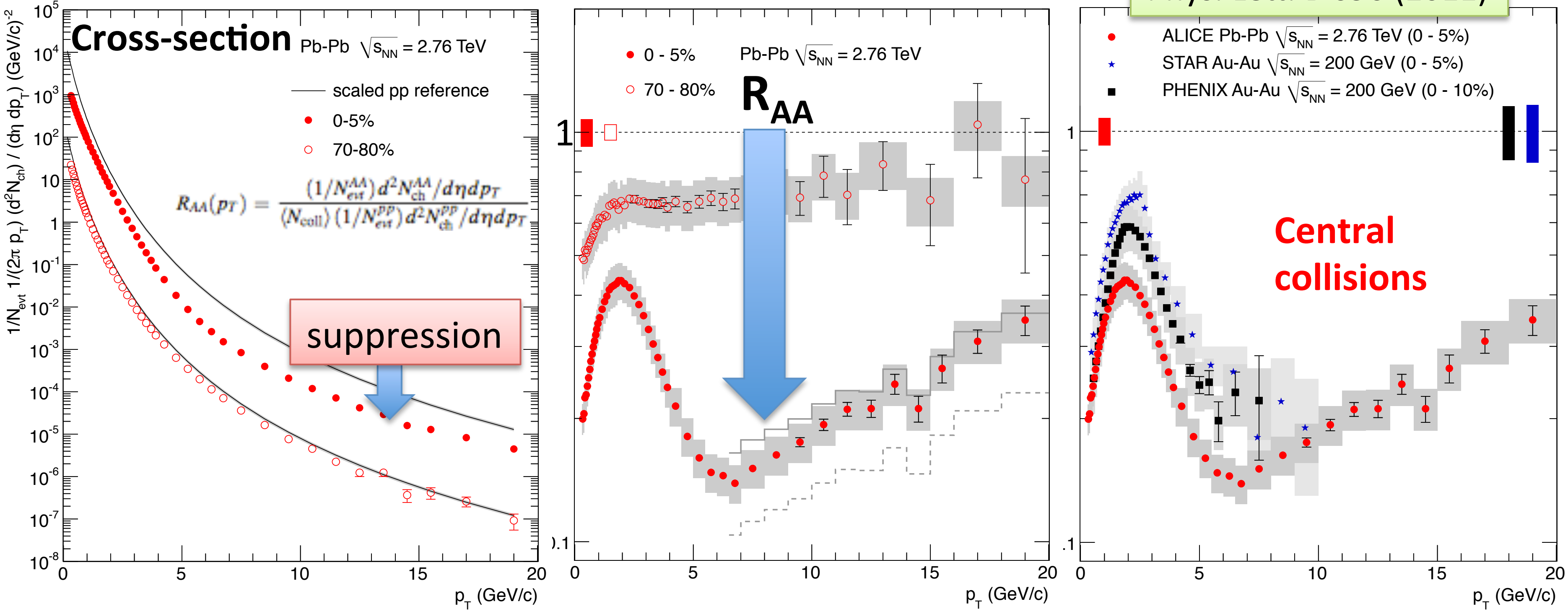
R > 1 – enhanced particle production
R = 1 – no nuclear effects
R < 1 – suppression

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

Jet quenching via hadron suppression

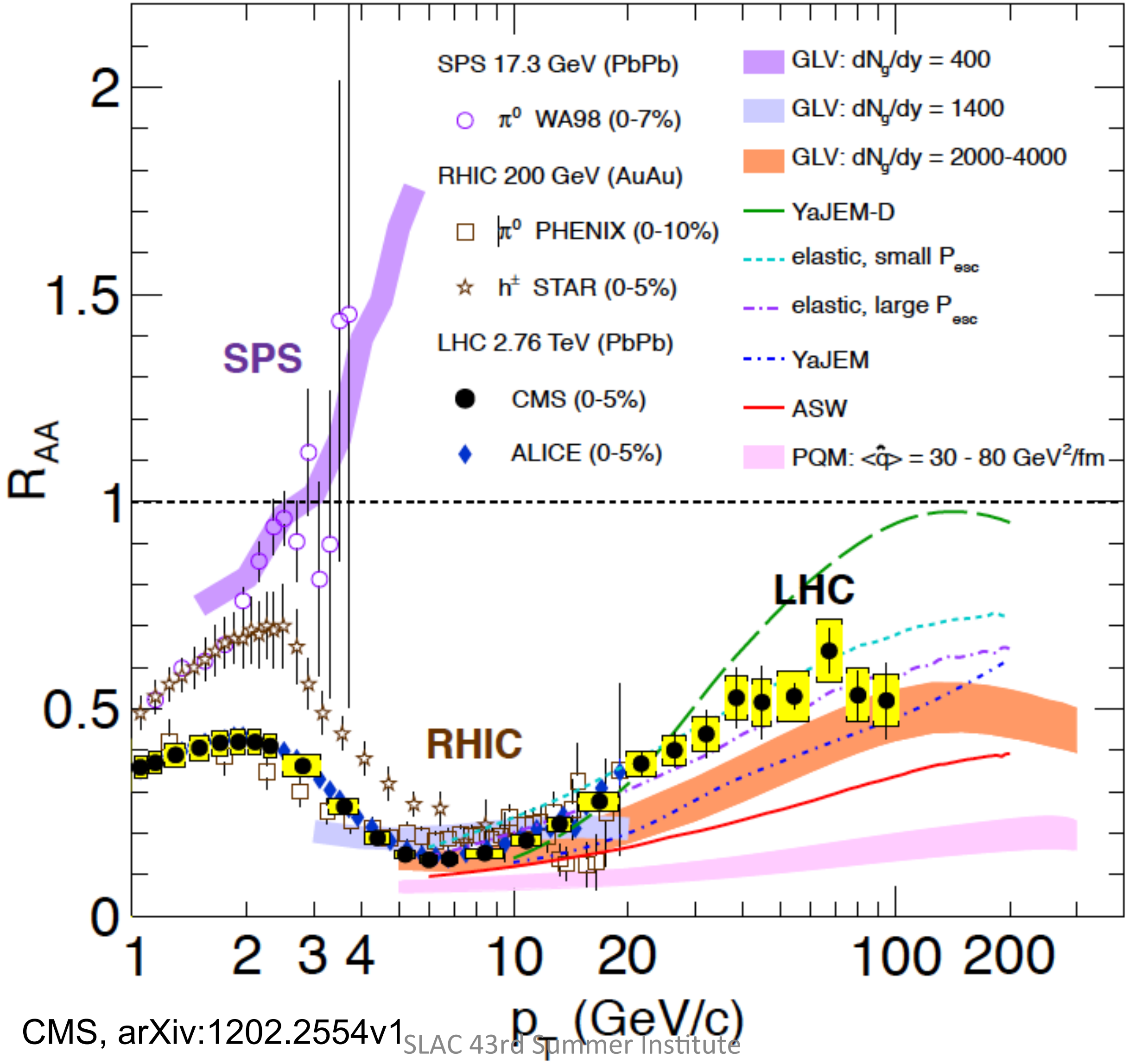
$$\text{Ratio} = \frac{\#(\text{particles observed in AA collision per N-N (binary) collision})}{\#(\text{particles observed per p-p collision})}$$

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

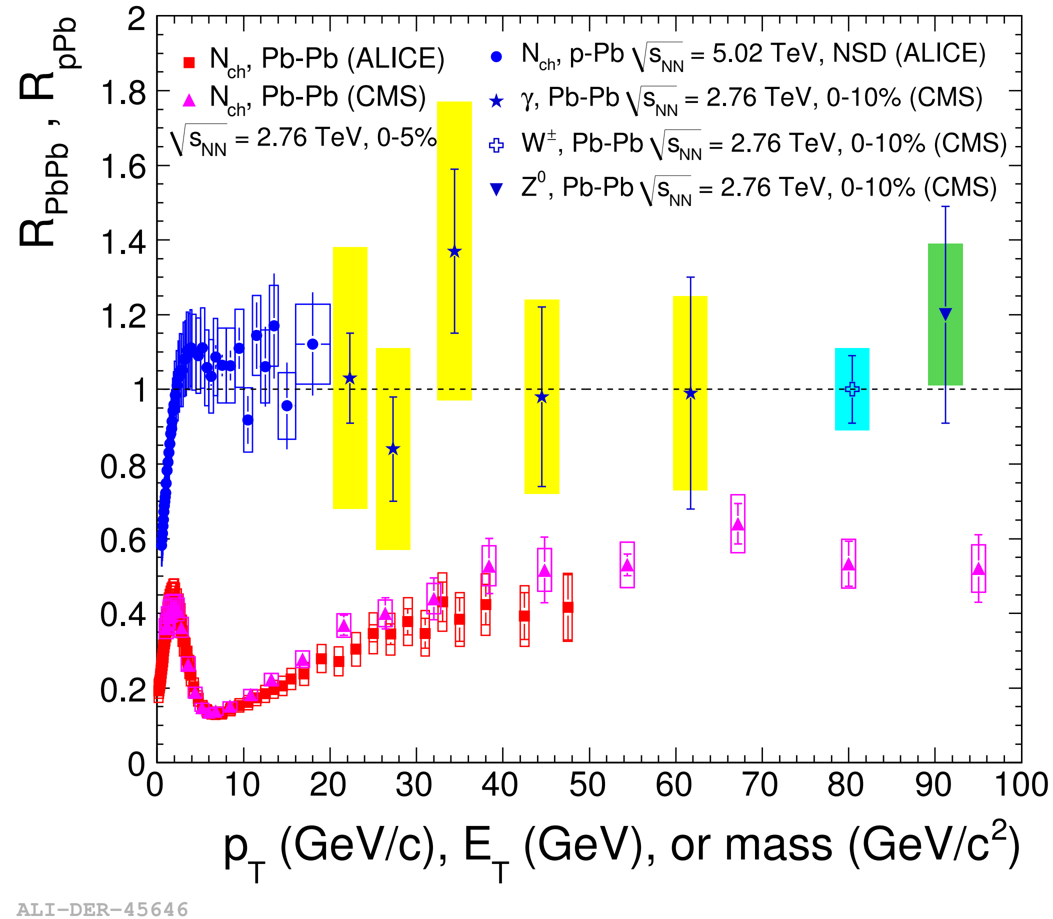
RAA from SPS, RHIC & LHC



CMS, arXiv:1202.2554v1

Hadron suppression

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

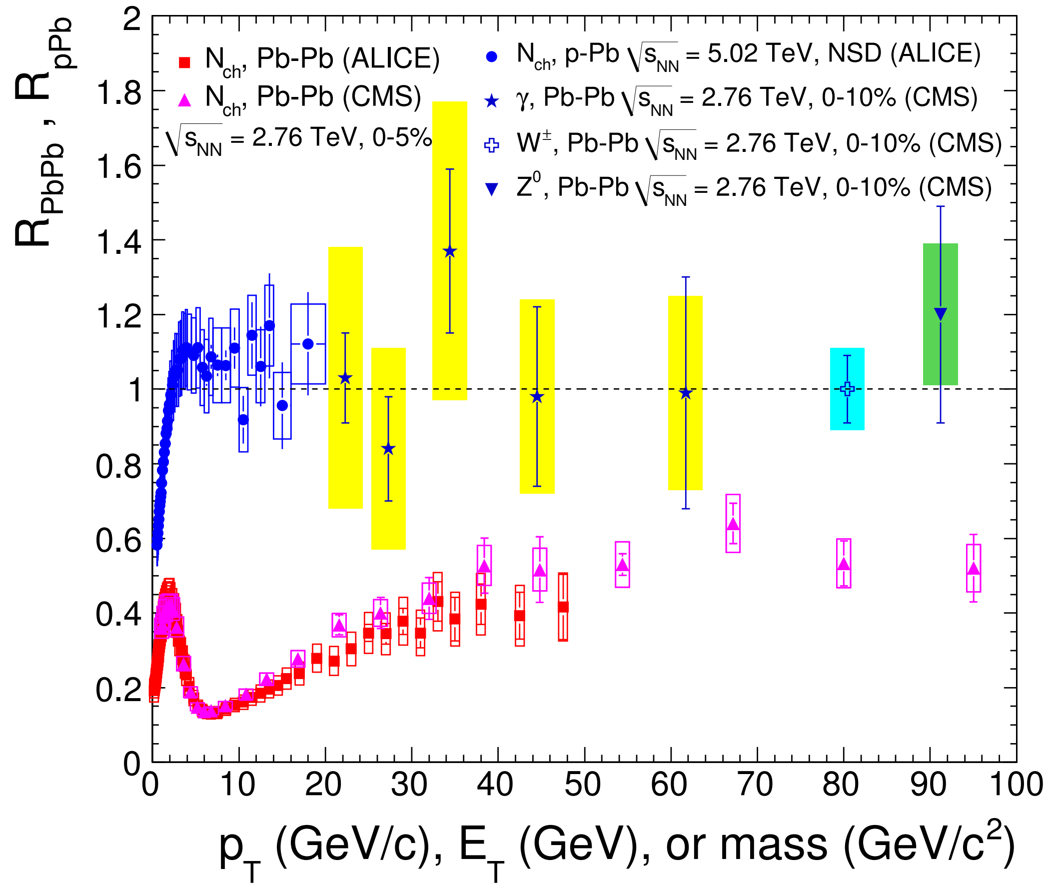


ALICE: Phys.Lett. B 720 (2013) 52-62; Phys.Rev.Lett. 110 (2013) 082302
CMS: Eur.Phys.J. C72 (2012) 1945; Phys.Lett. B710 (2012) 256-277; Phys. Lett. B 715 (2012) 66-87; PAS HIN-13-004

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 and jets consistent with unity



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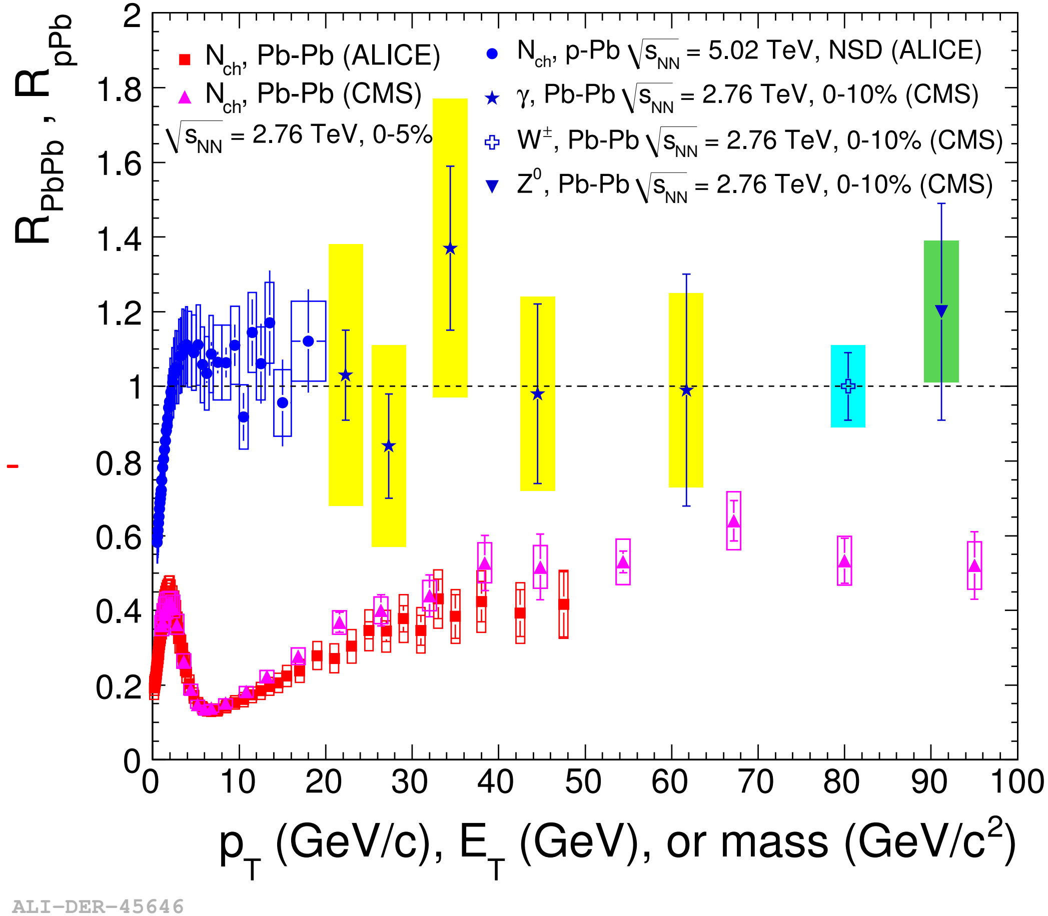
Strong suppression of hadron yield in most central Pb-Pb collisions => final state effect
R_{AA} rising up to 0.4 and flattening at high-p_T - reproduced by (most) models



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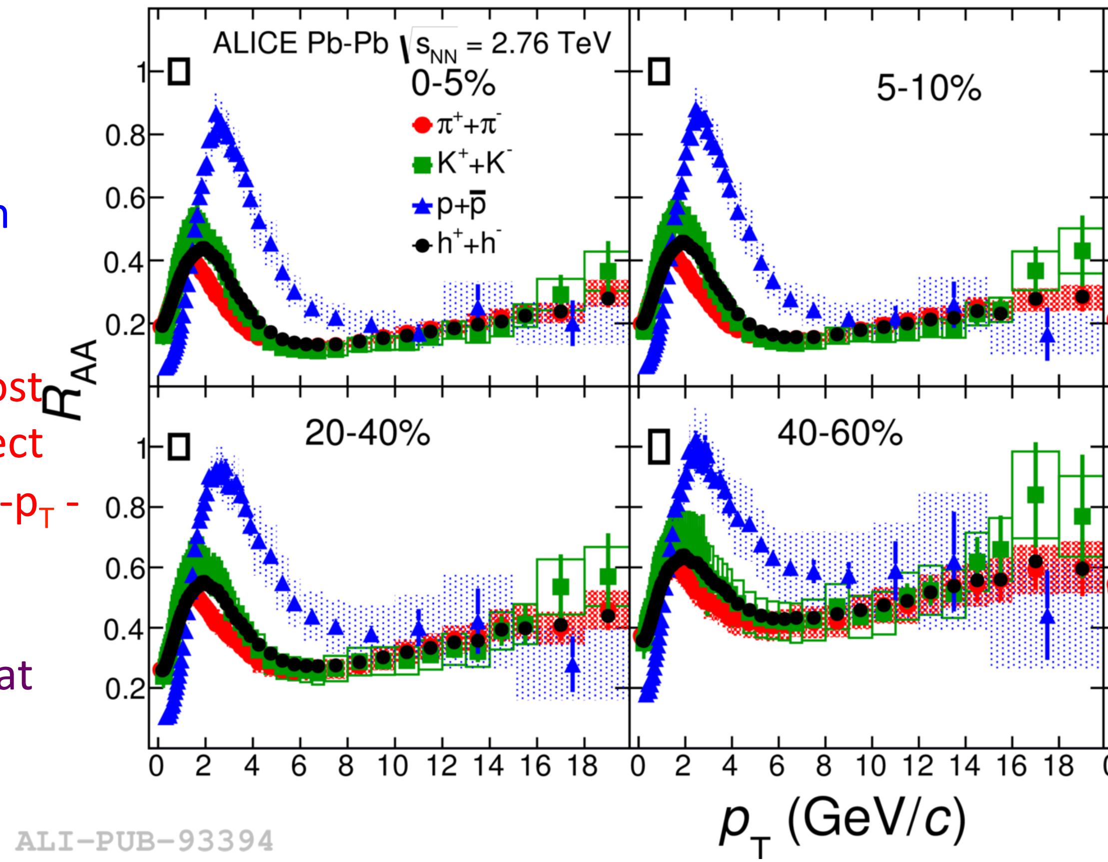
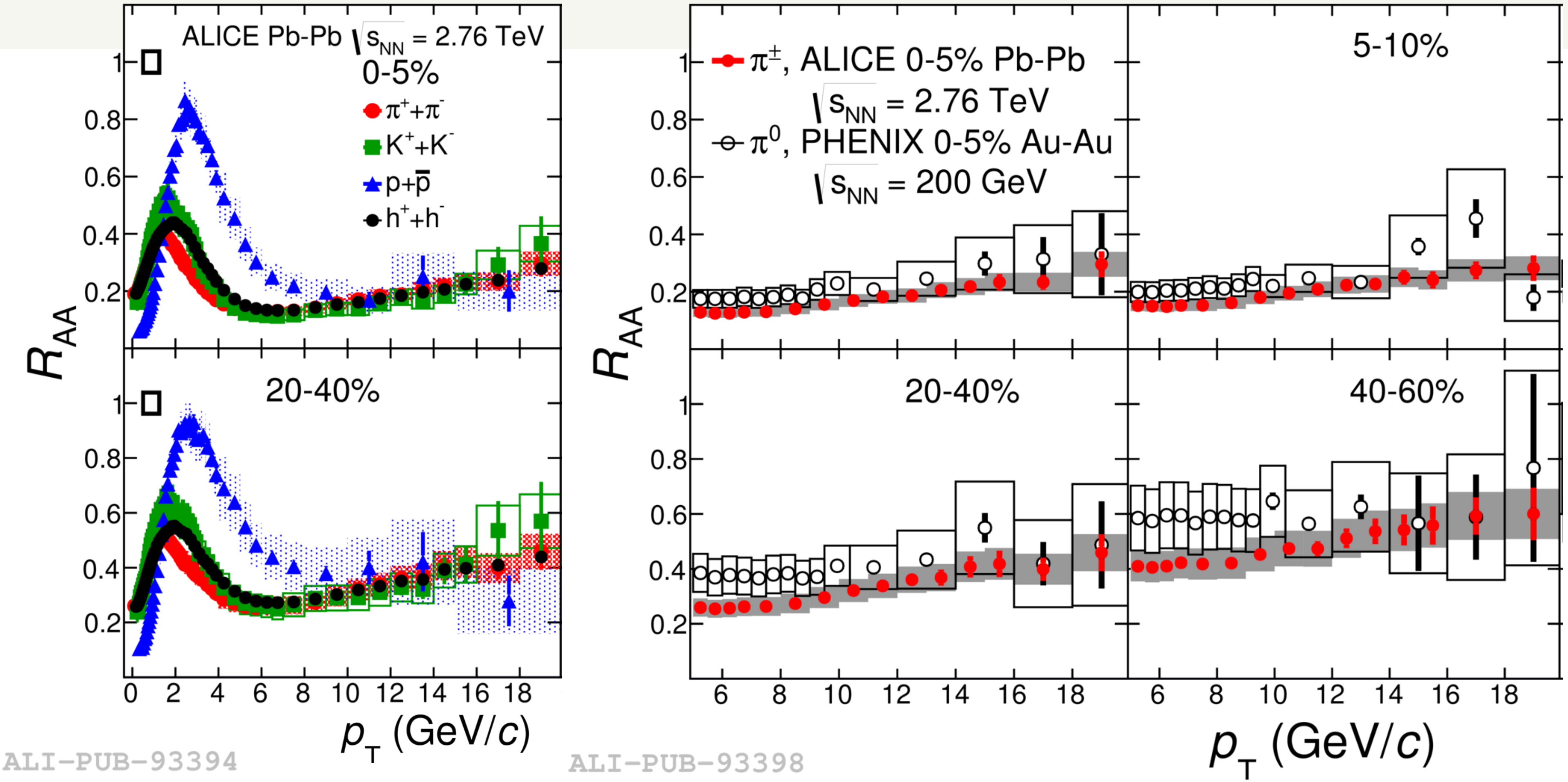
Similar R_{AA} for pions, kaons and protons at high-p_T



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

Hadron suppression LHC and RHIC

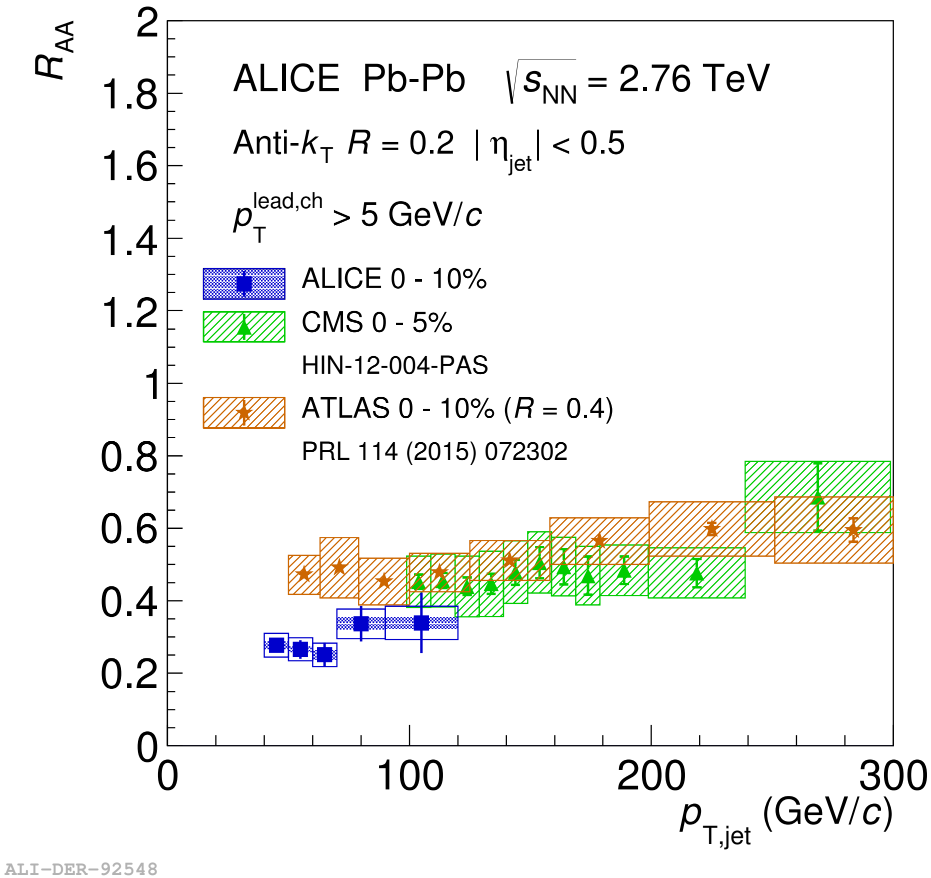


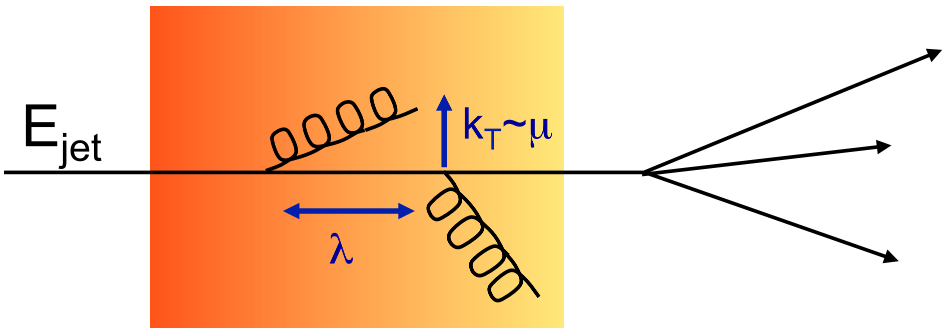
- High-p_T: Similar suppression for all particles ⇔ leading particle jet structure umodified
- Similar suppression for identified pions at RHIC and the LHC (all centralities)

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

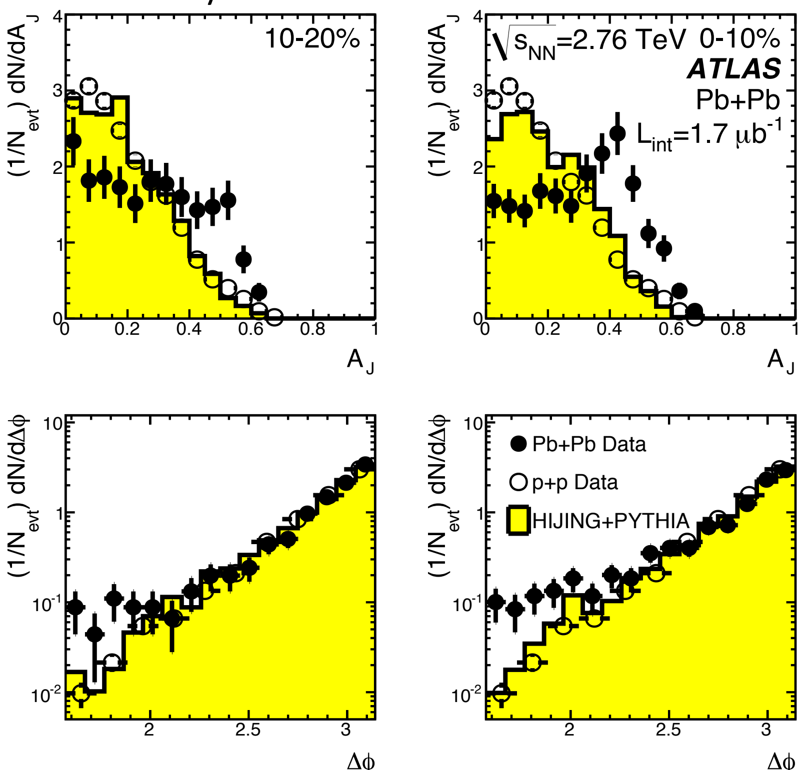
- out-of-cone: increase acoplanarity kT
- in-cone: broadening of jet-profile

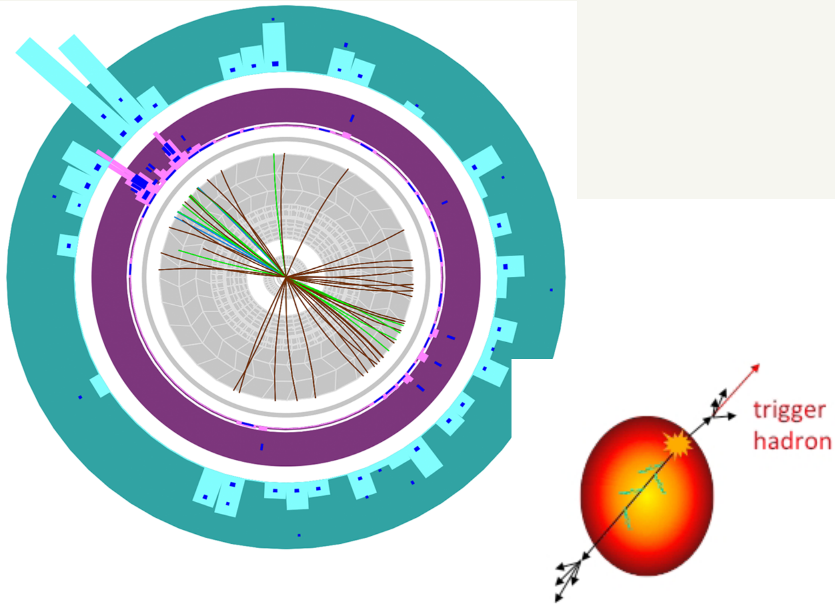
LHC: Estimates (on average) of about 10-20 GeV radiated – similar preliminary result at RHIC

Di-jet asymmetry

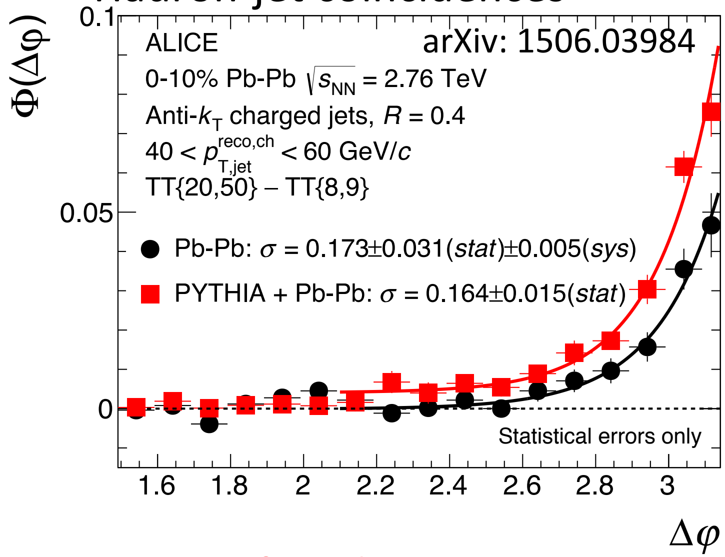
$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}, \Delta\phi > \frac{\pi}{2}$$

PhysRevLett.105.252303





Hadron-jet coincidences



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

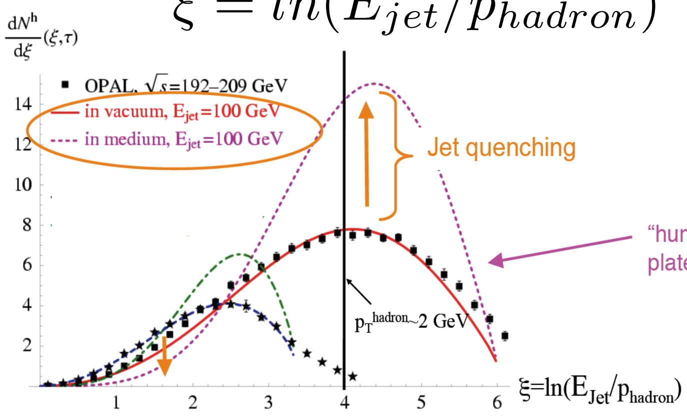
No sign of Moliere scattering
- Sensitivity to medium homogenity

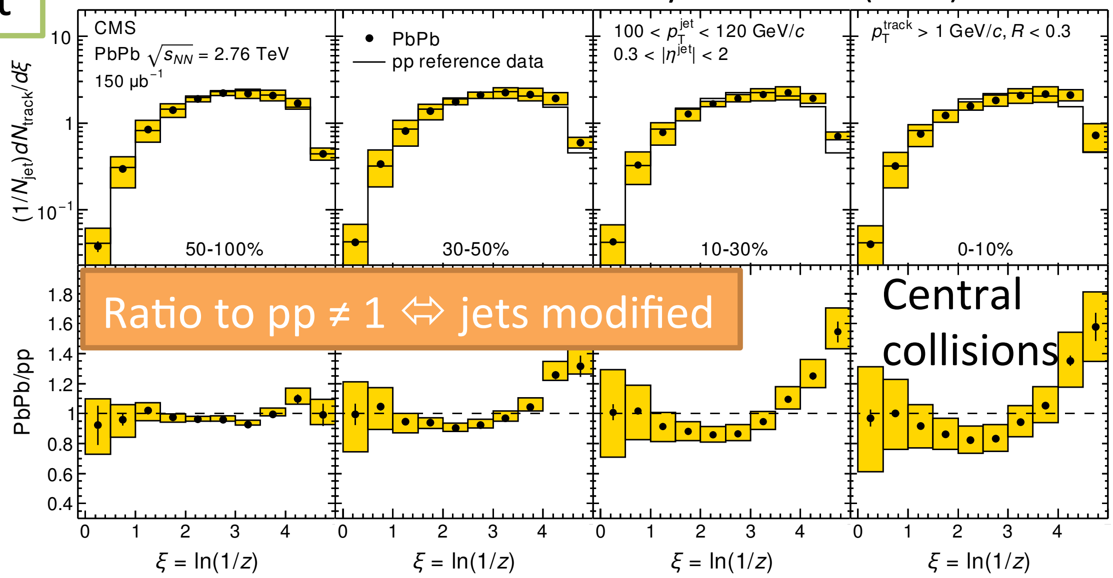
In-medium jet modifications – jet quenching

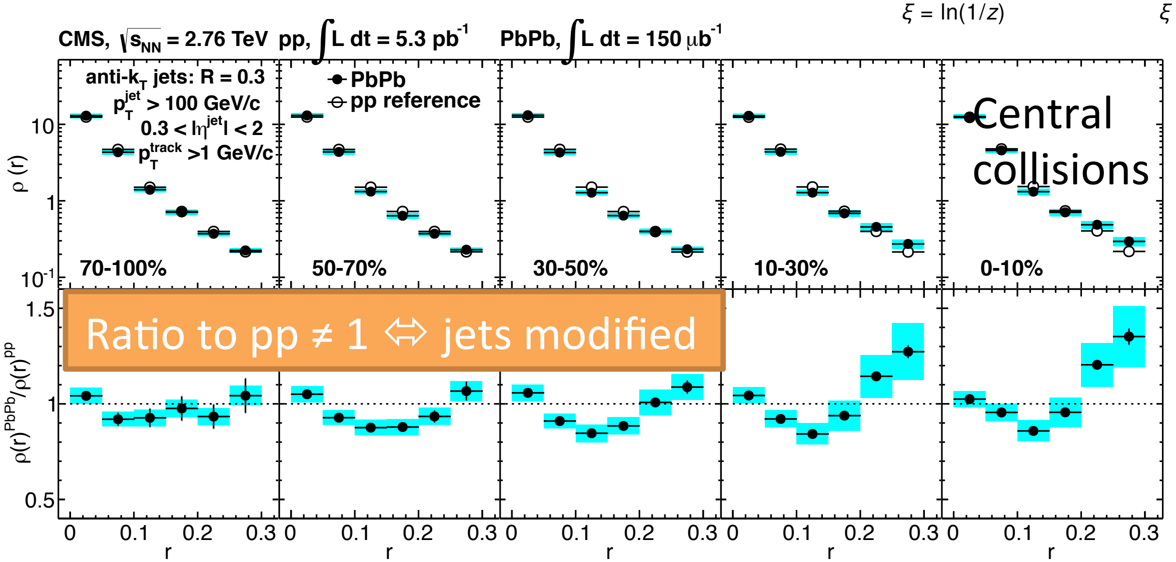
Momentum distribution within a jet

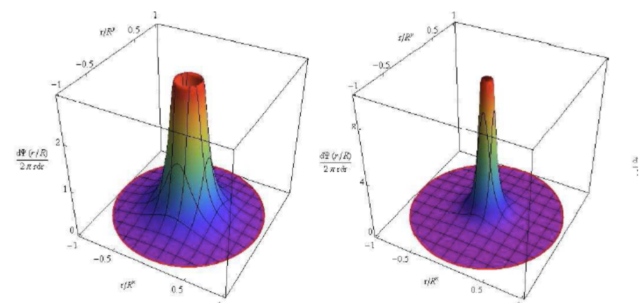
Phys. Rev. C 90 (2014) 024908

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









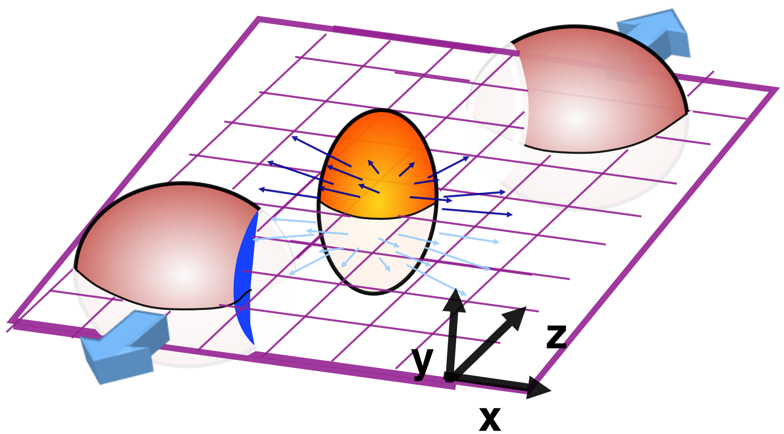
$$\rho(r) = \frac{1}{\delta r}\frac{1}{N_{\rm jet}}\sum_{\rm jets}\frac{\sum_{{\rm tracks}\in[r_a,\,r_b)} p_{\rm T}^{\rm track}}{p_{\rm T}^{\rm jet}}$$

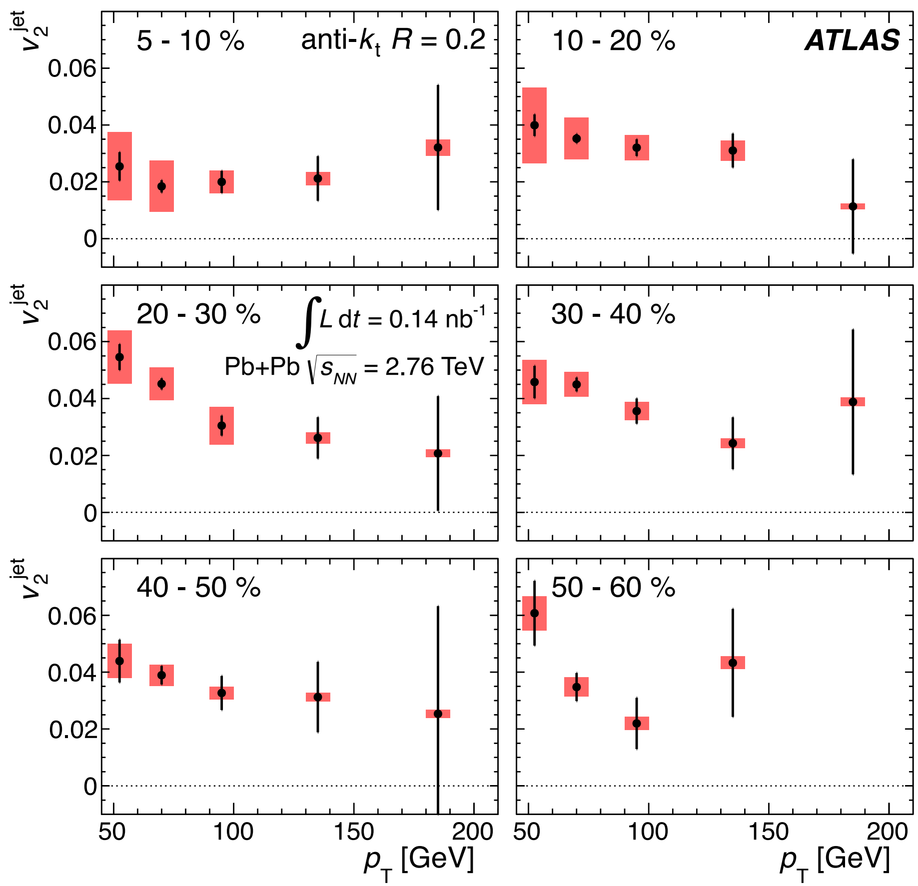
$$r = \sqrt{(\eta_{\rm track}-\eta_{\rm jet})^2+(\phi_{\rm track}-\phi_{\rm jet})^2} \leq 0.3$$

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

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

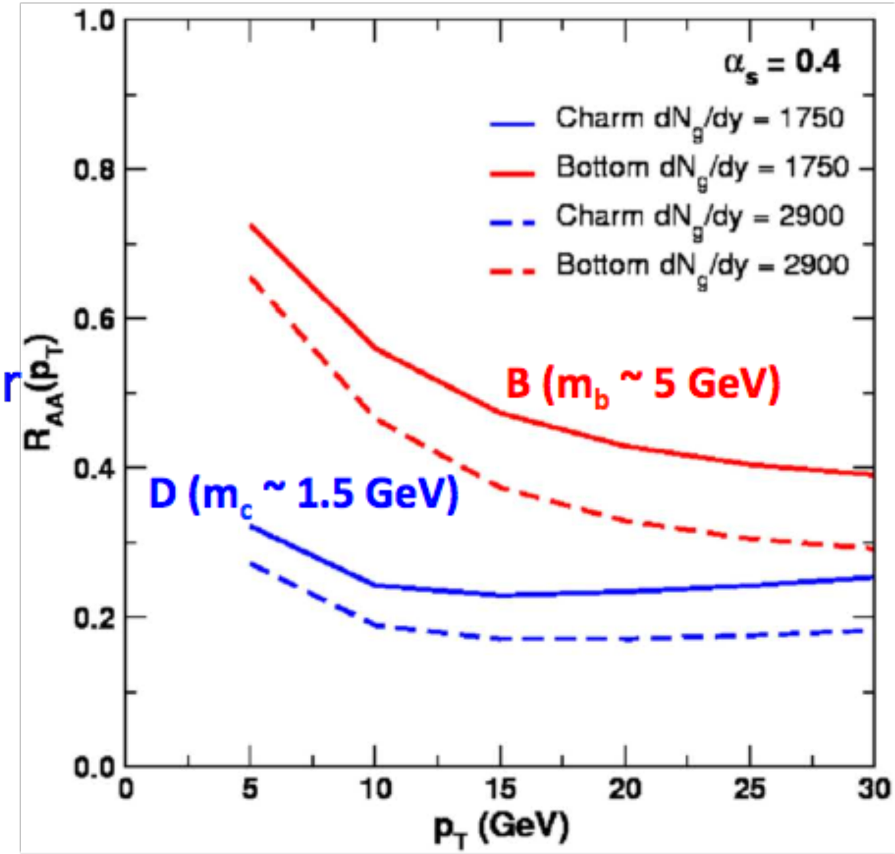
- Energy loss depends on parton:
  - Casimir factor (C_R=3 for gluons and 4/3 for quarks)
  - Mass of the quark (**dead cone** effect): radiation suppressed for angles $\theta < m/E$

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

- Does it persist at low-p_T as:

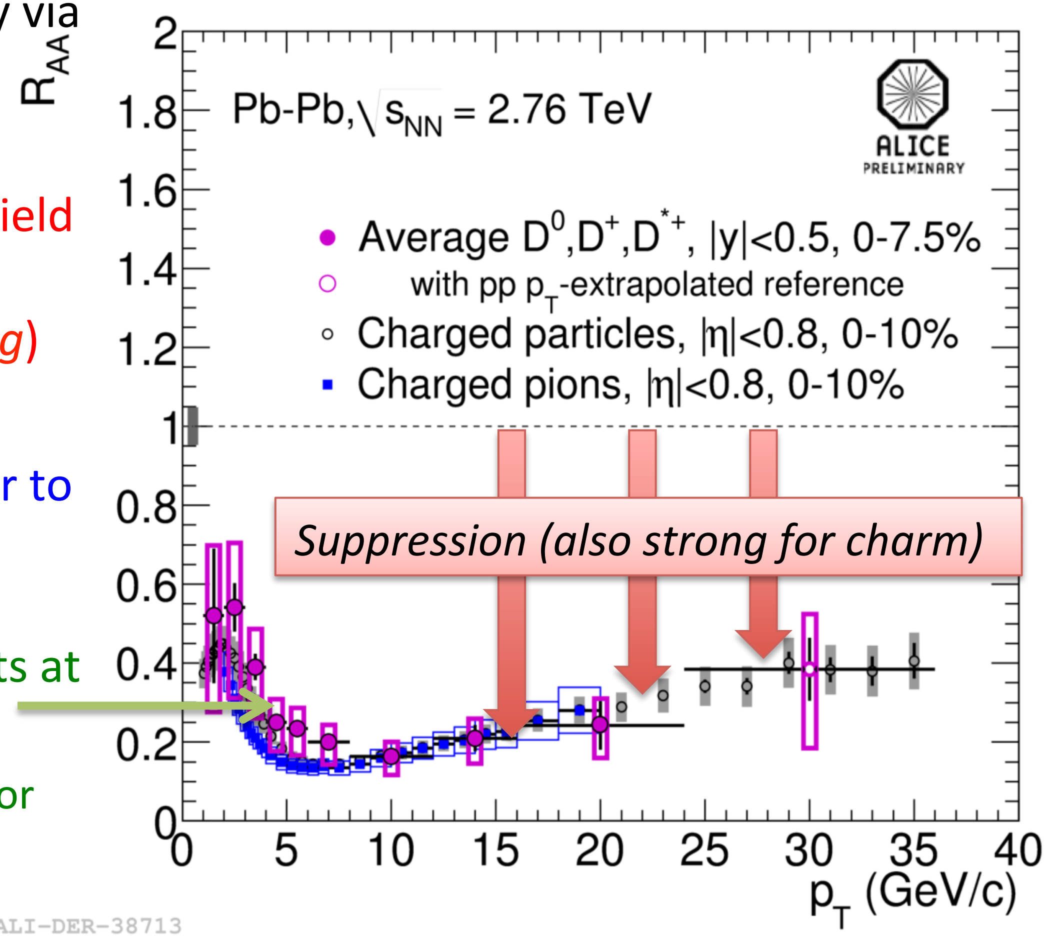
$$R^{\pi}_{AA} < R^{D}_{AA} < R^{B}_{AA}$$

Wicks, Gyulassy, Last Call for LHC predictions

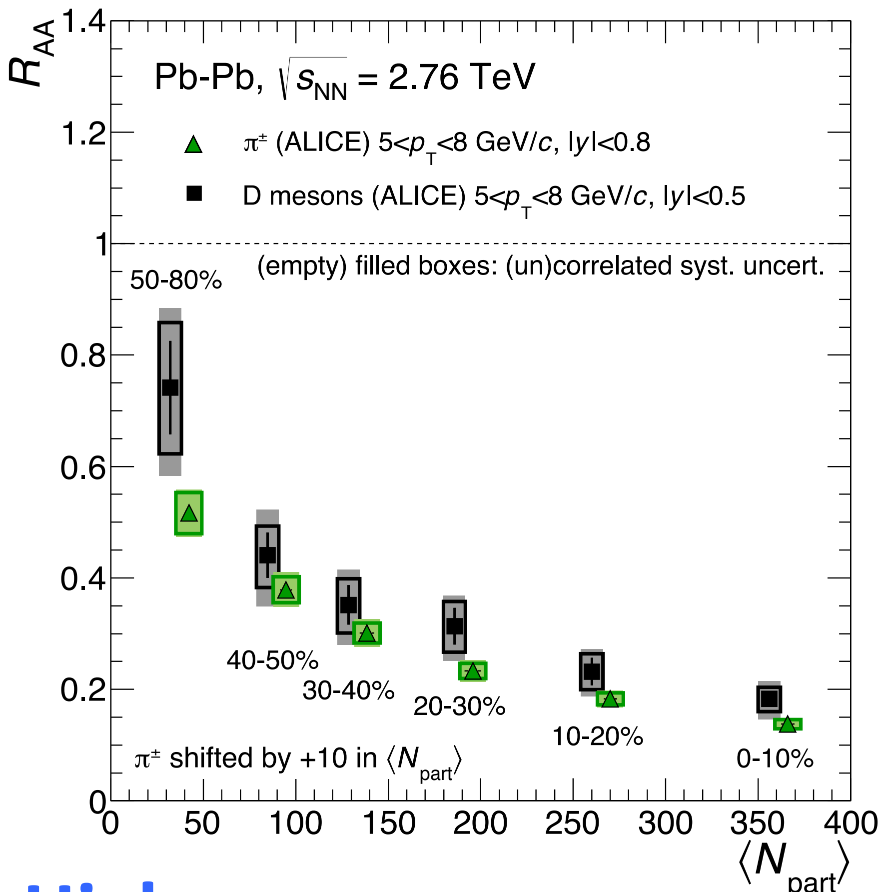


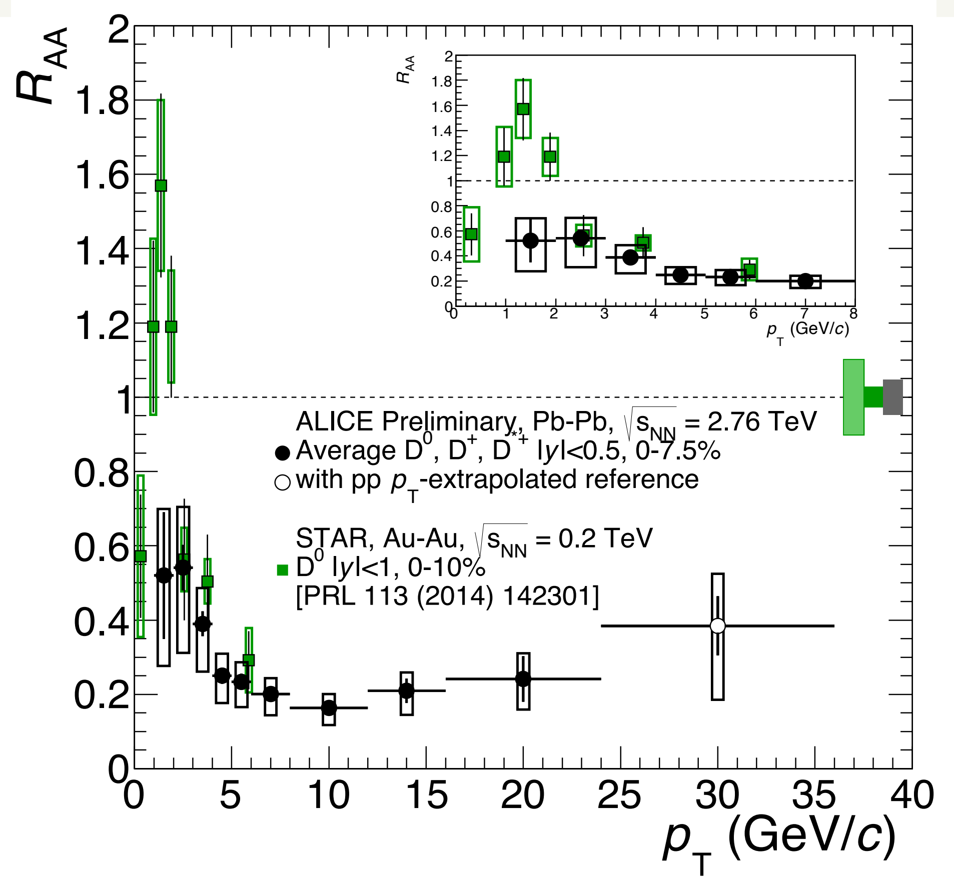
Charm suppression ⇔ Jet quenching

- 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





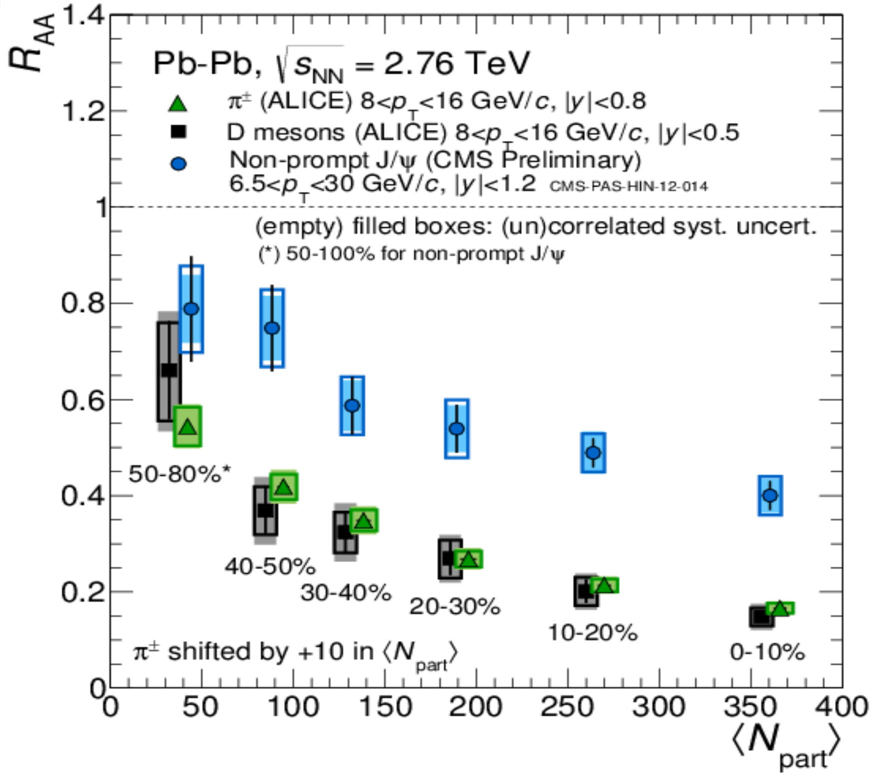
High-p_T: R_{AA} for D-mesons compatible with R_{AA} of pions

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

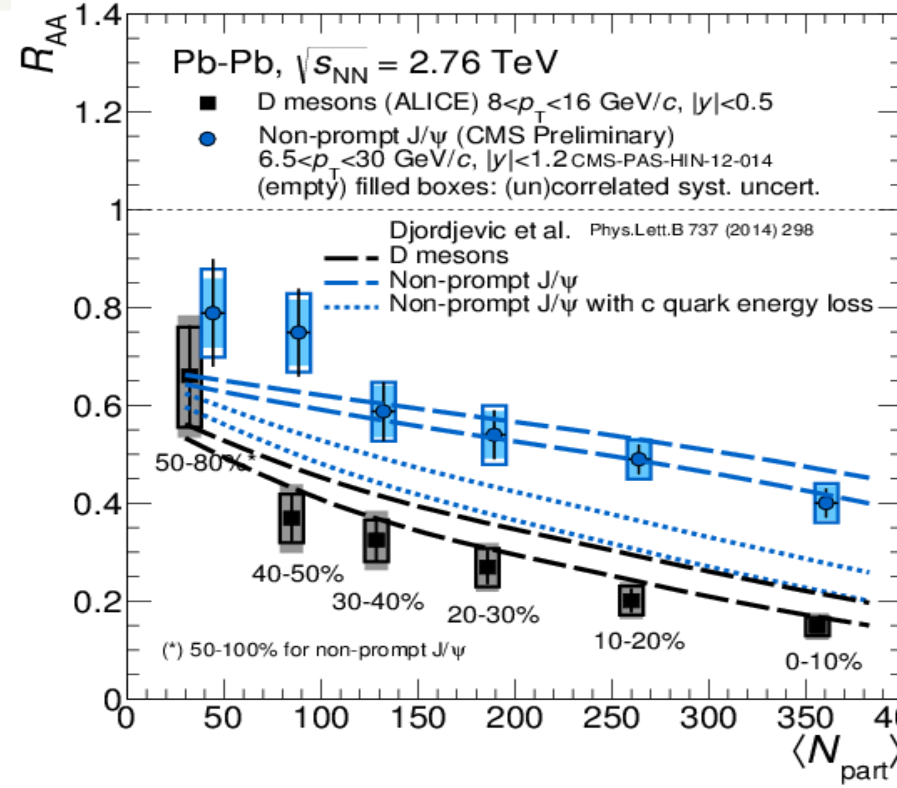
Despite different $d\sigma/dp_T$ R_{AA}^{RHIC} compatible with R_{AA}^{LHC}

Mass dependence of in-medium E-loss

arXiv:1506.06604



ALICE & CMS data

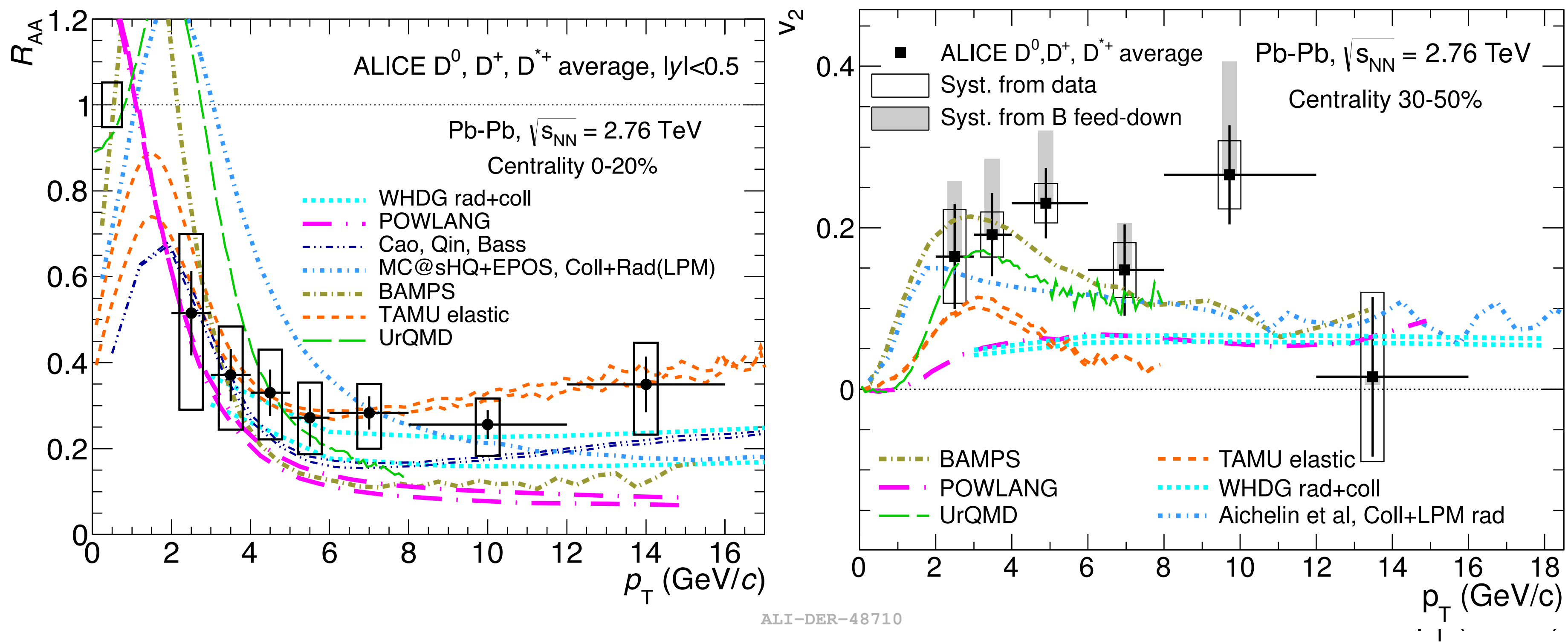


Indication of $R_{AA}^{D} < R_{AA}^{\text{non-prompt } J/\psi}$

Consistent with mass dependent energy loss

Open charm: R_{AA} and v_2

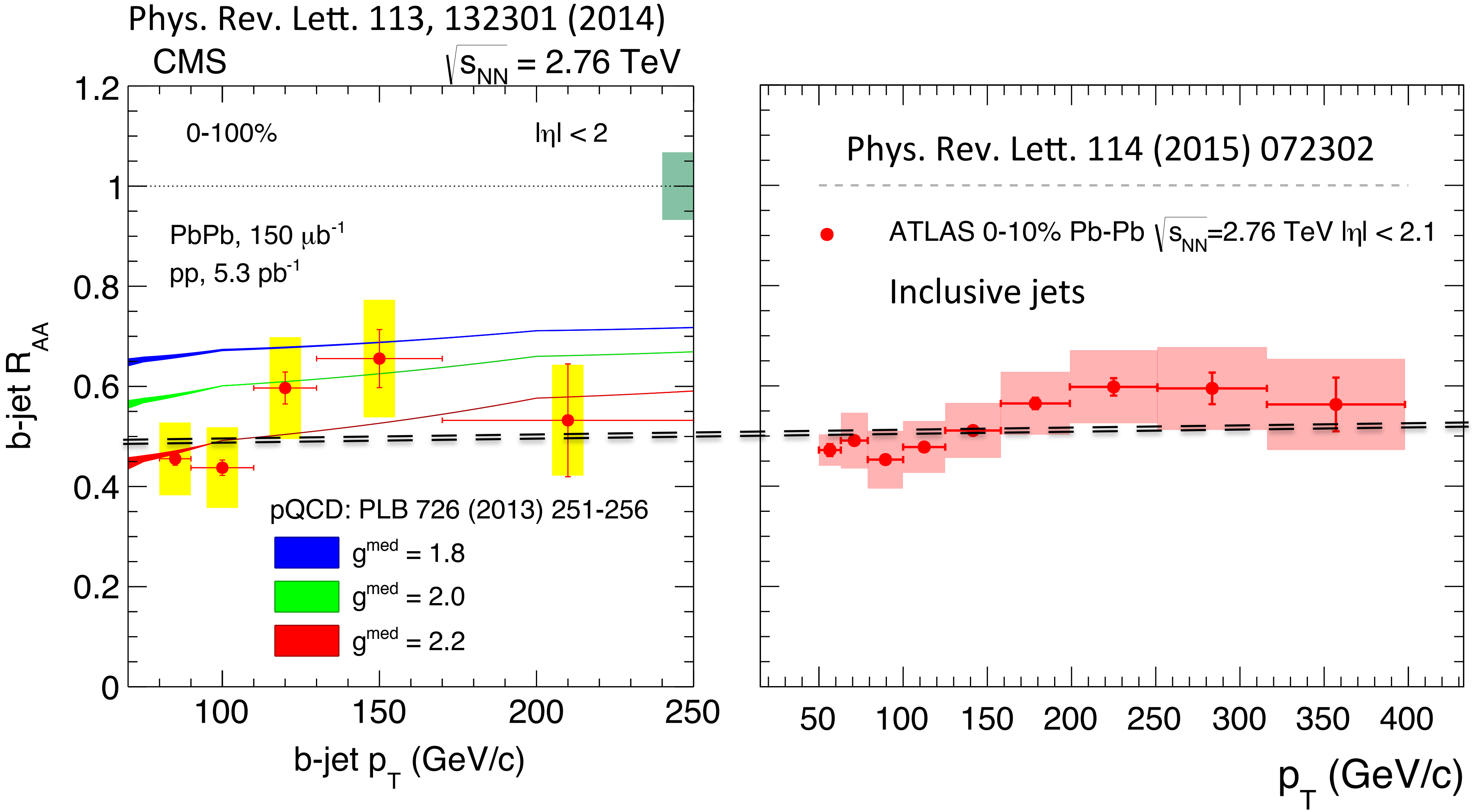
D-meson R_{AA} arXiv: 1203.2160 (JHEP 1209)



- 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

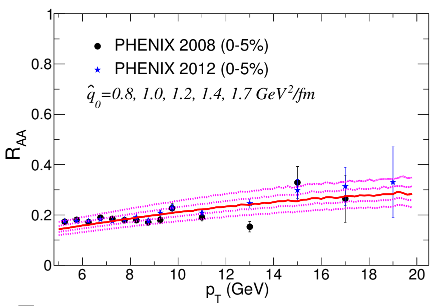
Consistent with the expectation – e-loss independent of mass at high-p_T

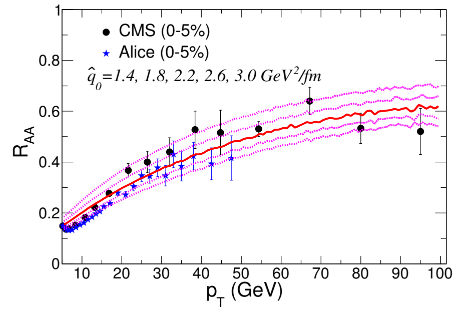
Extracting jet transport coefficient from jet quenching at RHIC and LHC

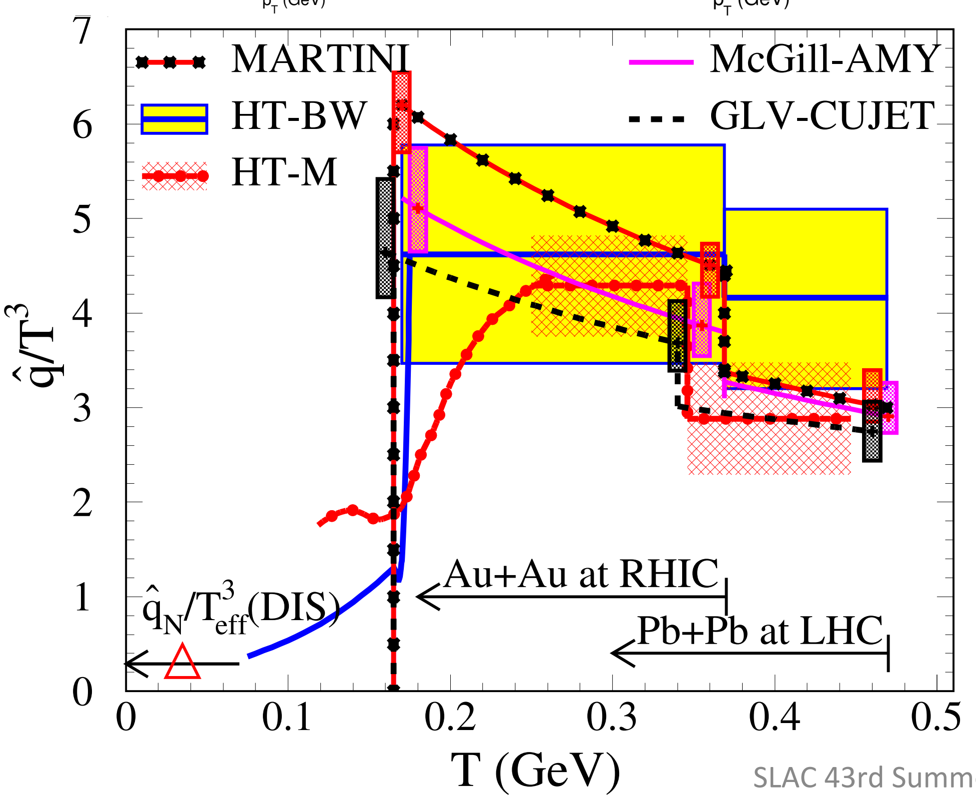
arXiv:1312.5003

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,

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

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

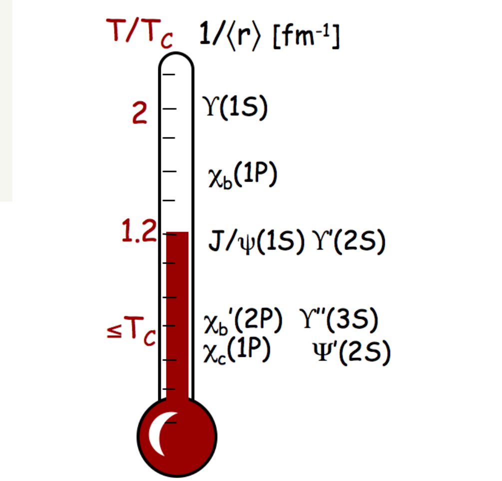
RHIC ~ 25% uncert. LHC~ 37% uncert.

Excellent progress within the last few years.

Next steps: use full jets, jet structure, …

Extraction of ehat with (new) HF data

Quarkonia in QGP

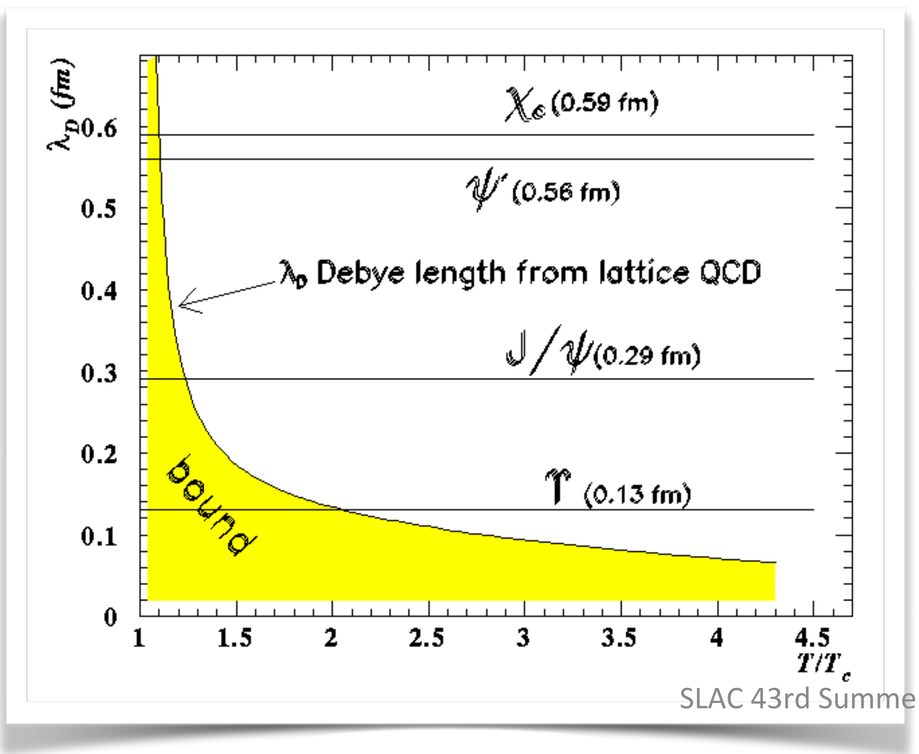


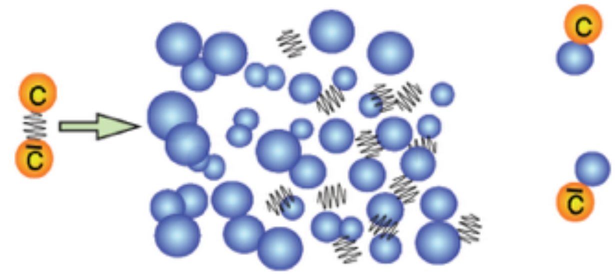
Mocsy, EPJ C 61 (2009) 705

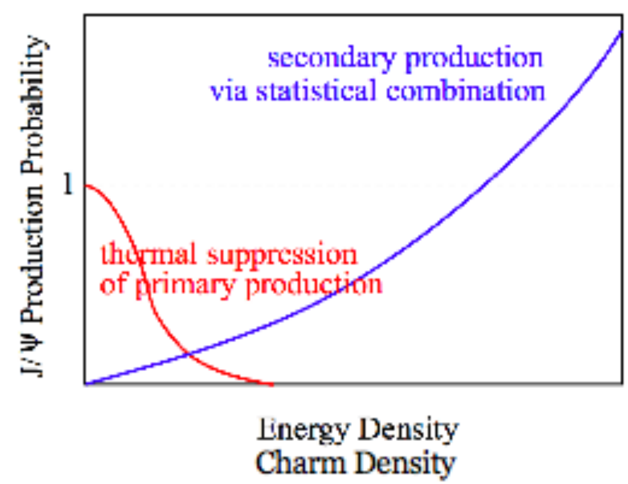
QGP signature proposed by Matsui and Satz, 1986

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")

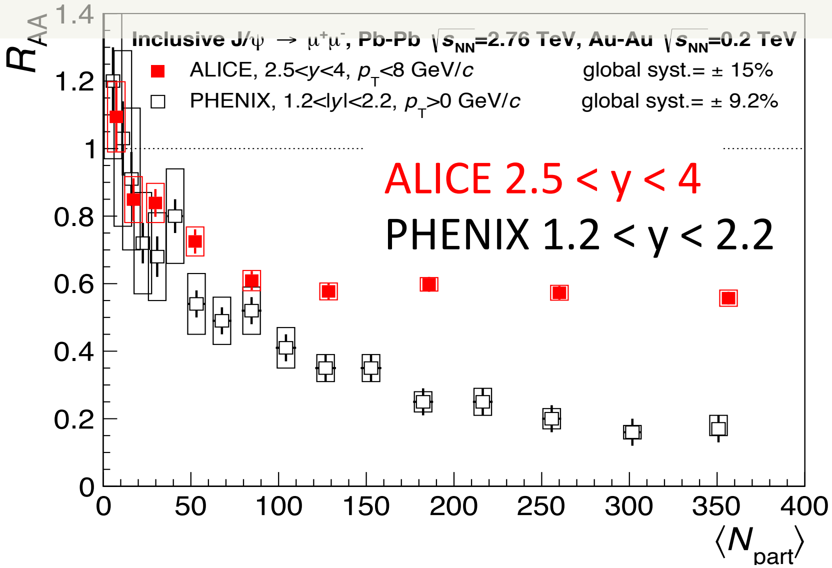


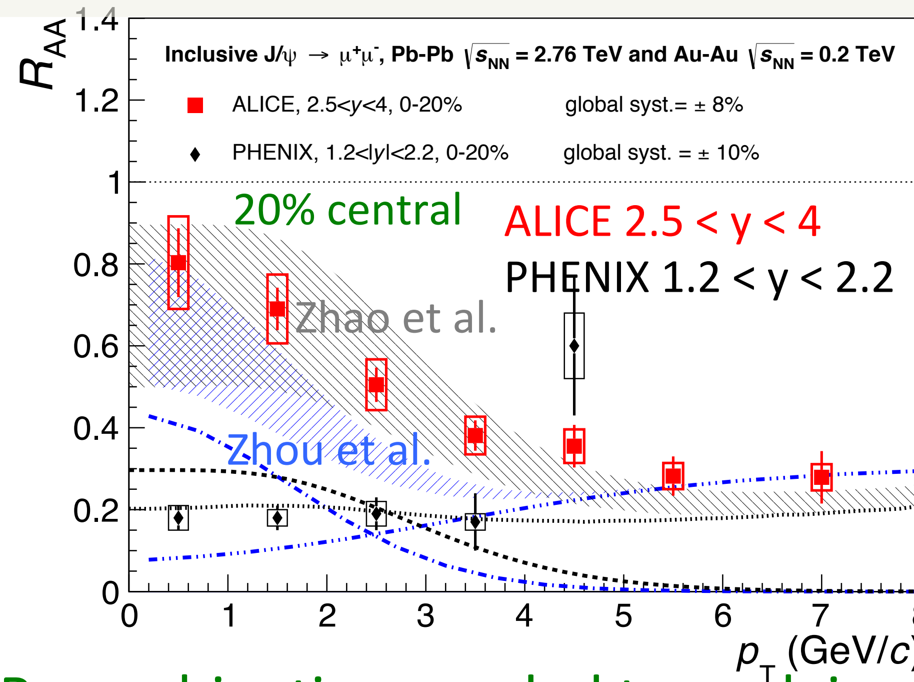


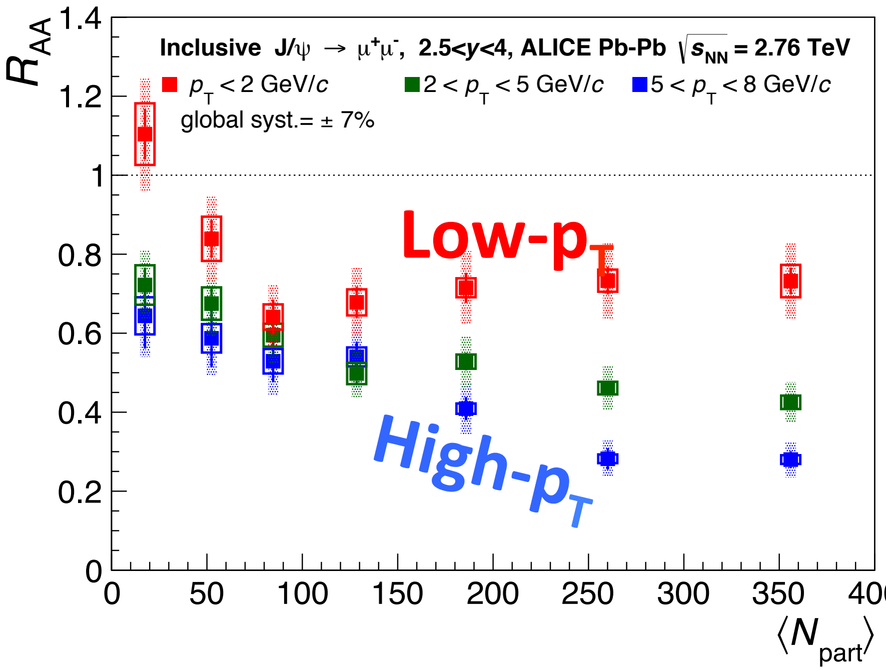


J/ψ Suppression

ALICE Coll. PLB 734 (2014) 314







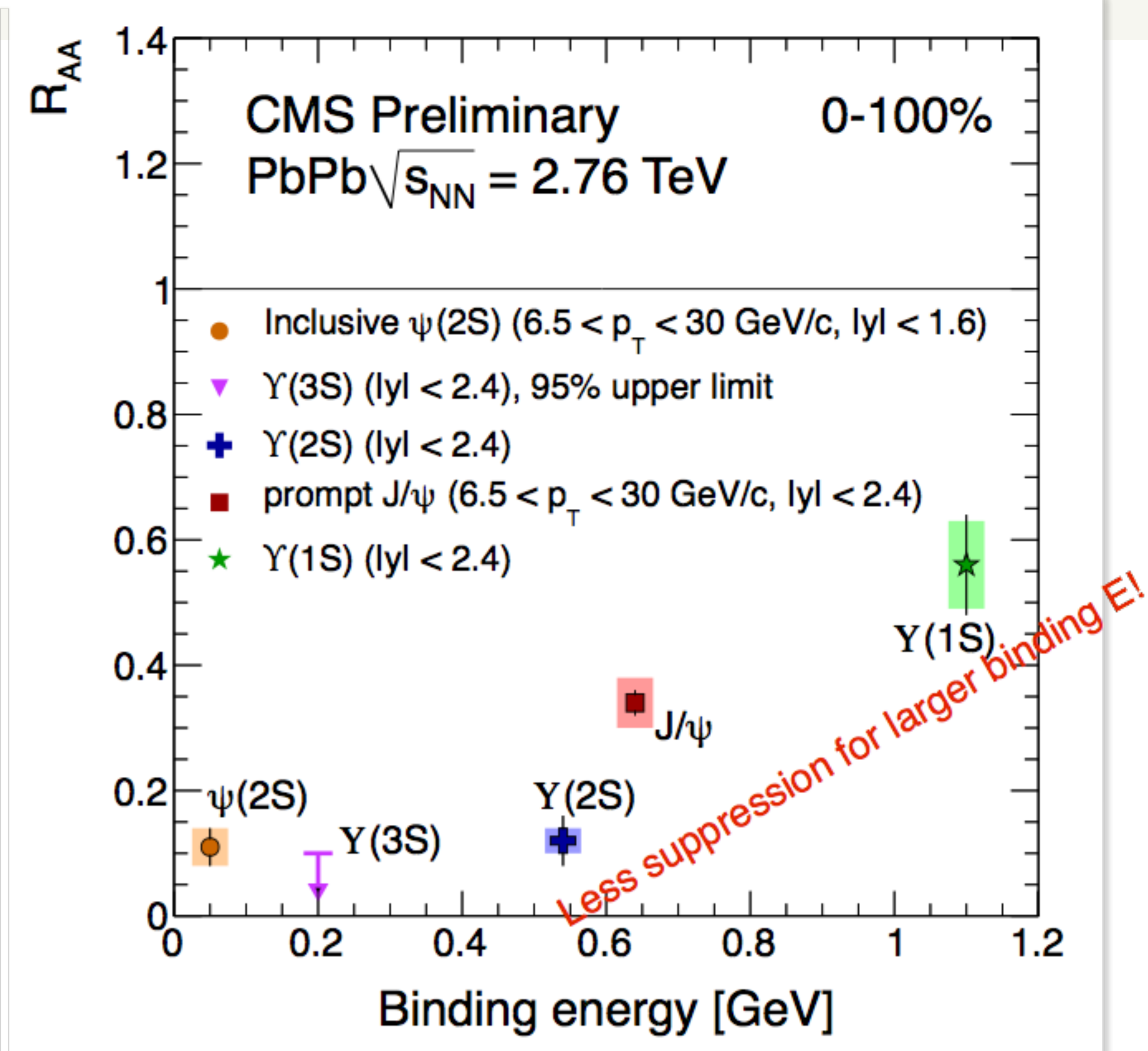
Recombination needed to explain R_{AA} at the LHC

J/ψ re-generated at low-p_T

High-p_T J/ψ suppressed (LHC & RHIC)

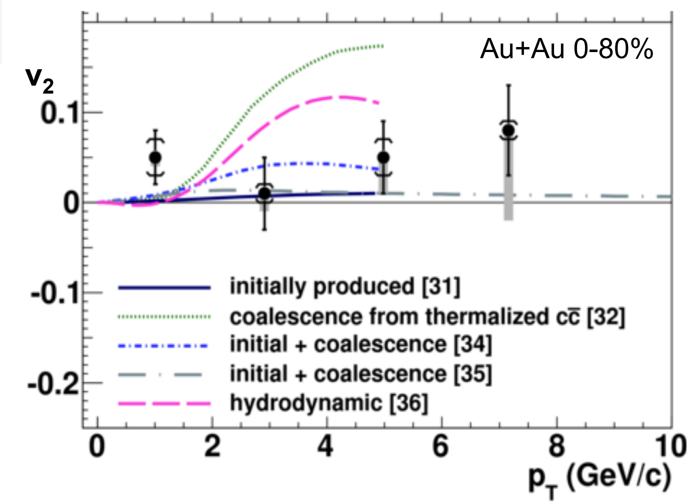
Strong suppression in central as compared to peripheral collisions

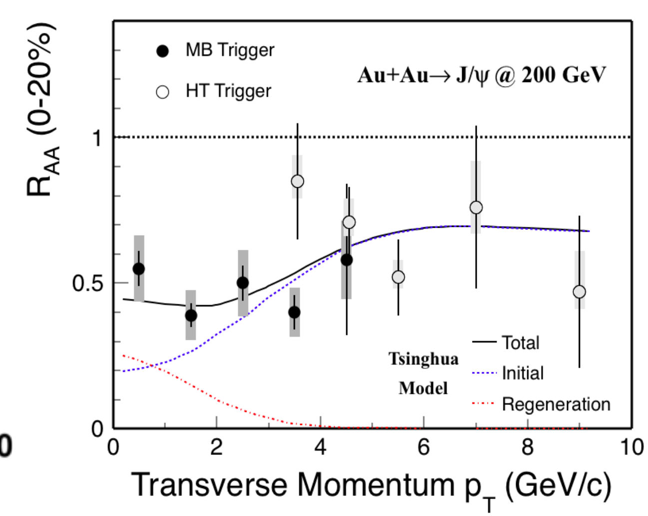
Suppression vs. binding energy of quarkonia



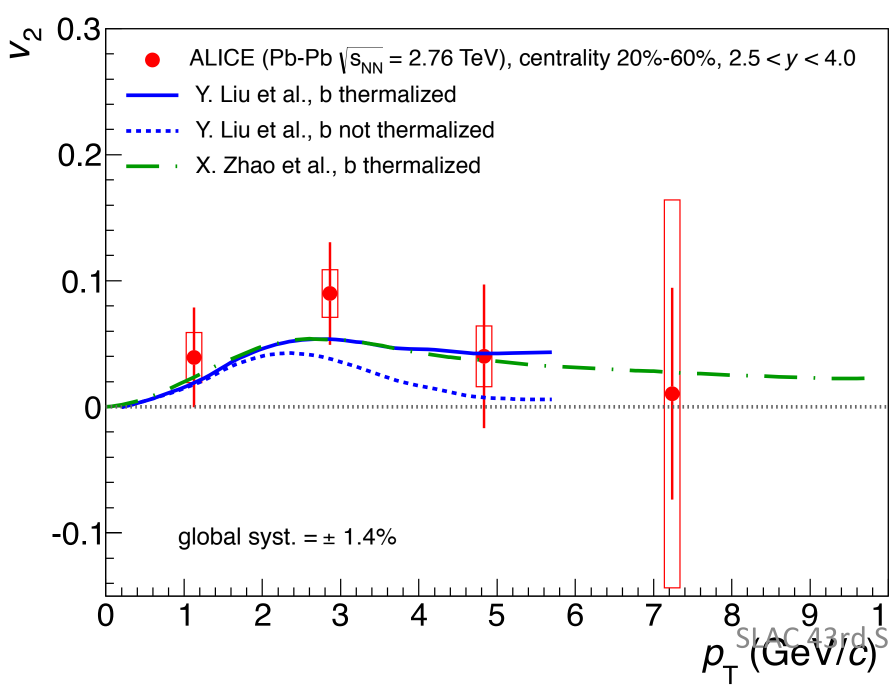
Regeneration ⇔ J/ψ flow?

RHIC v_2





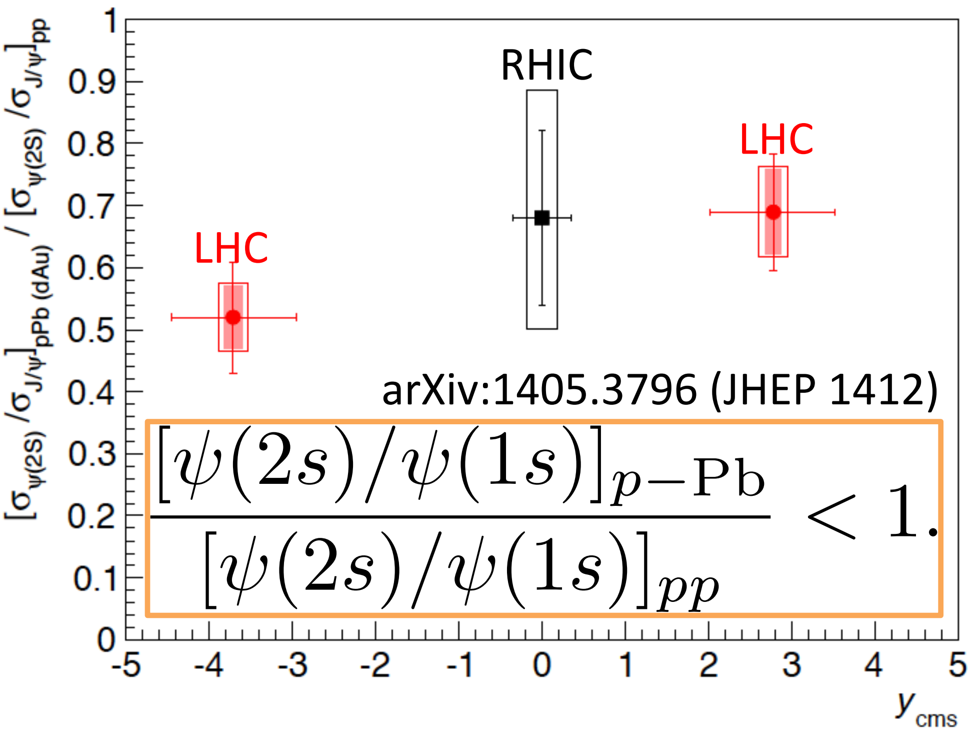
STAR, PRL 111 (2013) 052301, PLB 722 (2013) 55, PRC 90 (2014) 024906



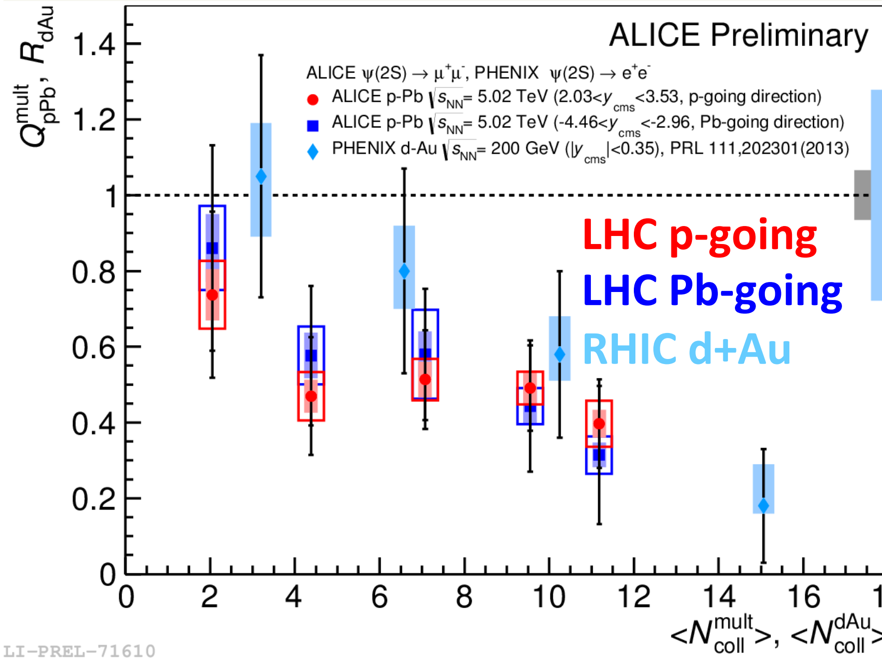
- Expect J/ψ from regeneration to exhibit similar elliptic flow as D mesons
- STAR at RHIC:
  - no significant elliptic flow
- ALICE at LHC:
  - hint at 3 GeV/c
  - local significance 2.2 σ
- Does one point really make the difference?
  - More data will bring the answer

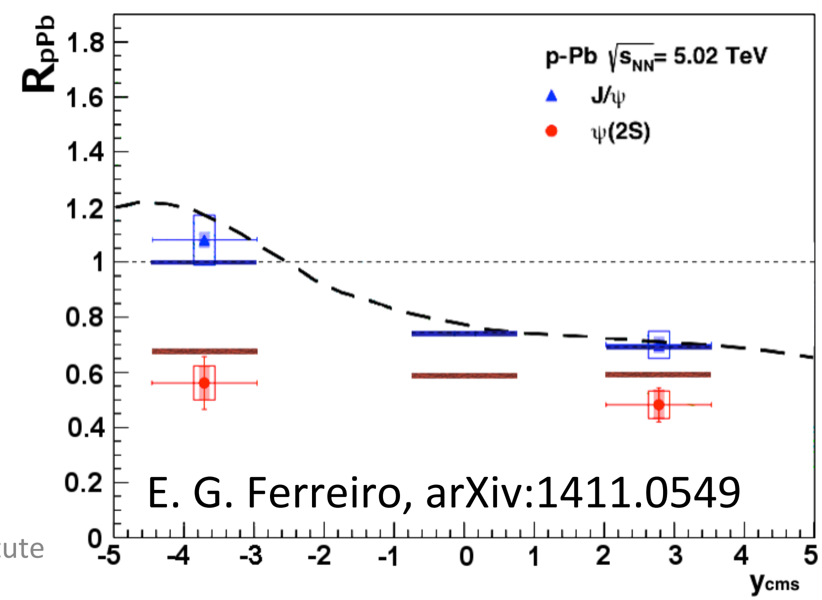
sqrt(s) grows

J/ψ and ψ(2s) in p-Pb (and d–Au at RHIC)



$$\frac{[\psi(2s)/\psi(1s)]_{p-\mathrm{Pb}}}{[\psi(2s)/\psi(1s)]_{pp}} < 1.$$





- **Suppression pattern of ψ(2S) in p-Pb and d-Au puzzling**
- Model w/ **co-mover interactions** + EPS09 agrees with ALICE and PHENIX

a final state effect for ψ(2s) (?)

Summary

- *Note: not all the topics where covered*

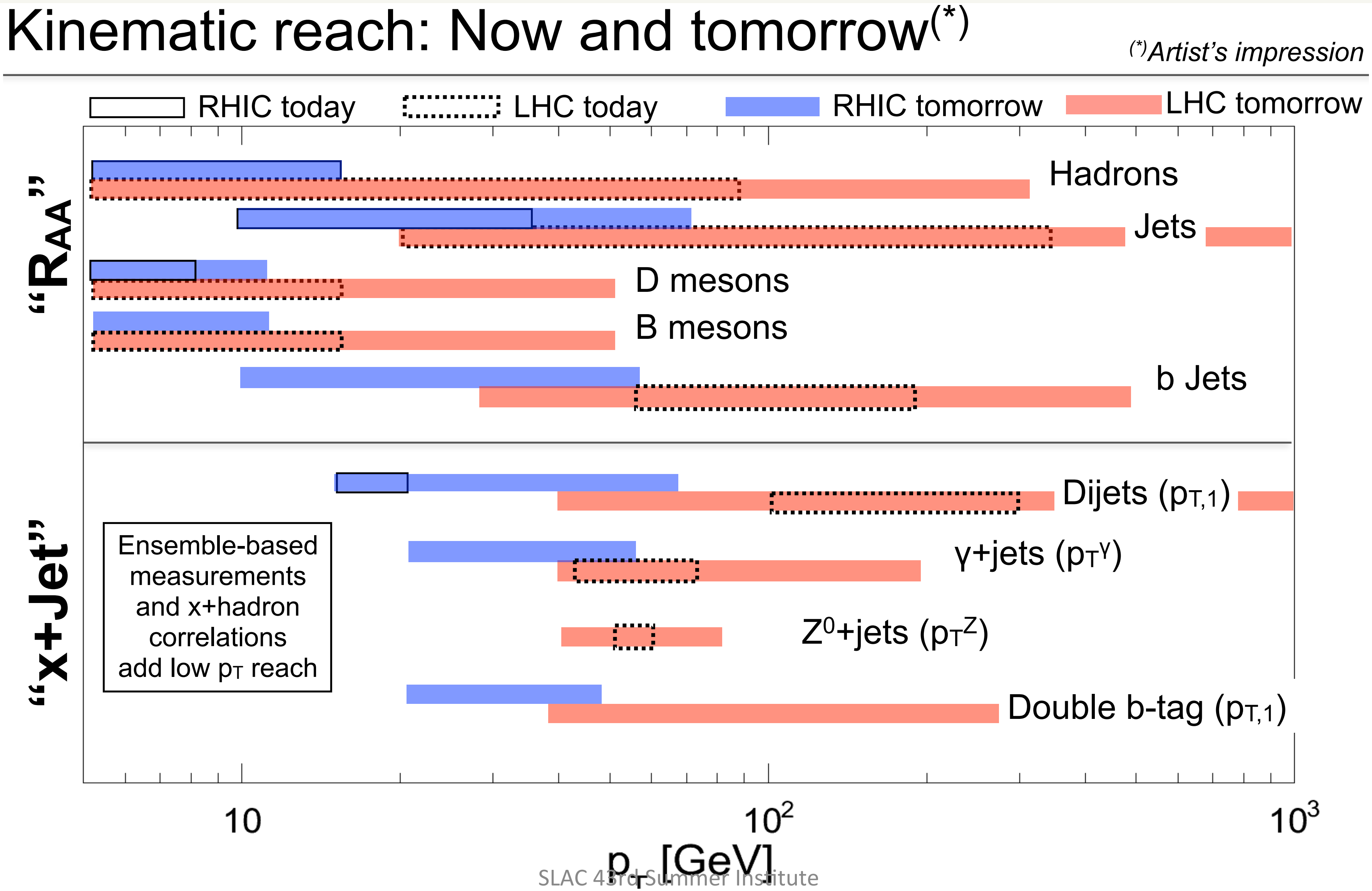
- QGP is a strongly coupled; almost perfect fluid with the smallest η/s of all known materials
- It is hot – it dissolves quarkonia states – according to their binding energy
- It is dense – it is opaque to high-energy partons and modifies their structure transporting the radiated energy to large angles; 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



ADDITIONAL SLIDES

Key physics Run1+Run2+Run3 light/heavy-quarks within the medium

Physics problems

- **Dynamics of jet quenching:** detailed features of radiated spectrum depends on properties (density) of the medium and type of the probe
- **Thermalization mechanism:** dynamics of soft quarks interactions with the bulk (via multiple scatterings) depends on quark-medium coupling, transport properties (temperature, viscosity) of the medium

Investigations/sensitivity

Flavor in jets - complete-z spectrum:

- parton dependent energy loss;
- energy dependence of e-loss – jet collimation
- flavor & color in fragmentation – dynamics – formation time – (de-)coherence in modified parton shower
- gluon splitting vs. in-medium modifications of angular ordering

Flow of quarks:

- collective behavior / flow vs. L/H flavor energy loss
- more differential studies – initial conditions (fluctuations)

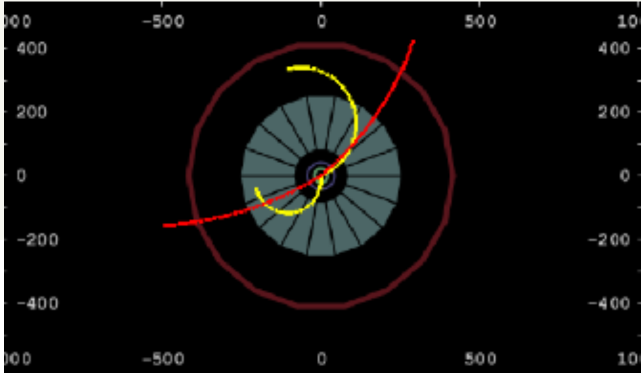
Baryon to meson ratio:

- collective radial expansion of the medium (L/HF-bulk coupling)
- recombination/coalescence; in/out-medium hadronization (?)

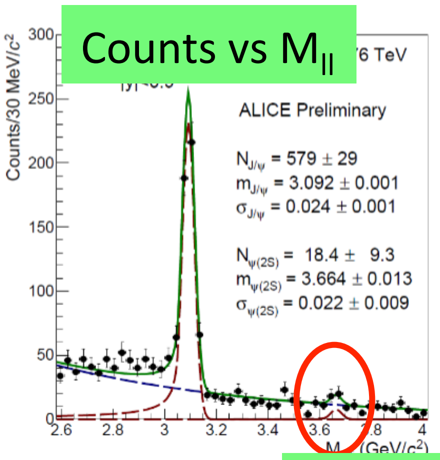
The factorized picture is an oversimplification – separation of scales is wrong or approximate at best – the **measured interplay** carries profound impact on theory – an ultimate reason to make these measurements

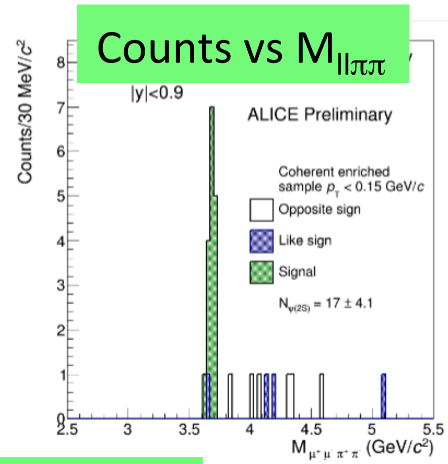
The window of opportunity for L is run-2; for H is run-3

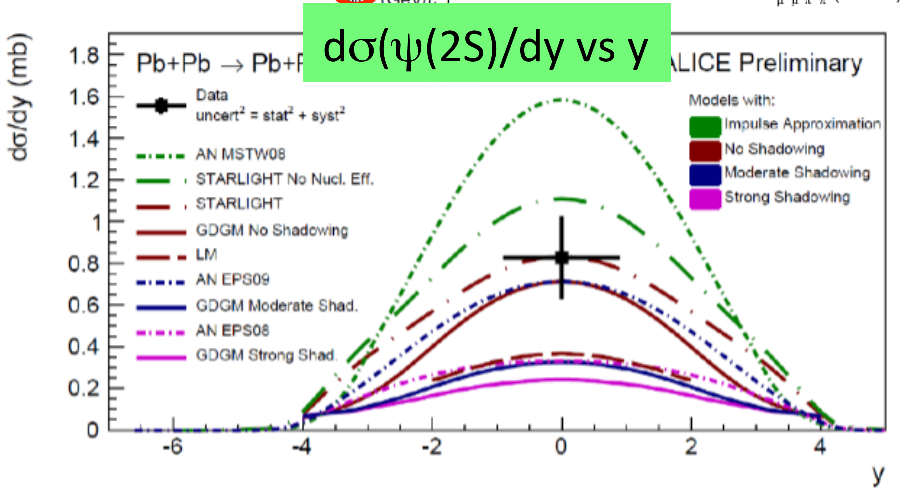
More from ALICE! Ultra-Peripheral Collisions



- Coherent J/ψ photo-production (PLB718 (2013) 1273, EPJC 73 (2013) 2617)
- **First measurement of exclusive ρ^0**
- First measurement of ψ(2S) photoproduction in a nuclear target
  - ψ(2S) → l^+l^-
  - ψ(2S) → l^+l^- + $\pi^+\pi^-$
- Strong model constraints
  - Strong shadowing disfavored
  - No nuclear effects disfavored

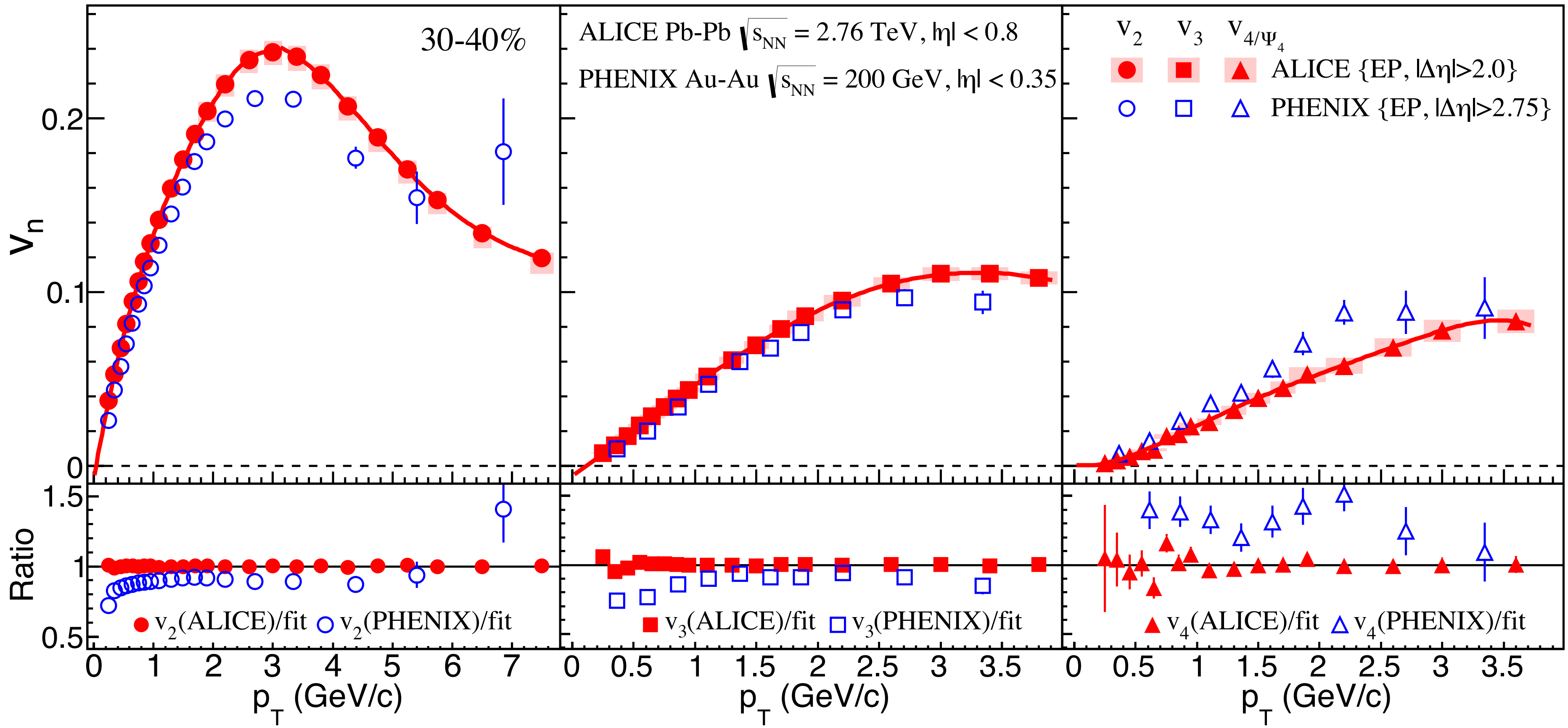






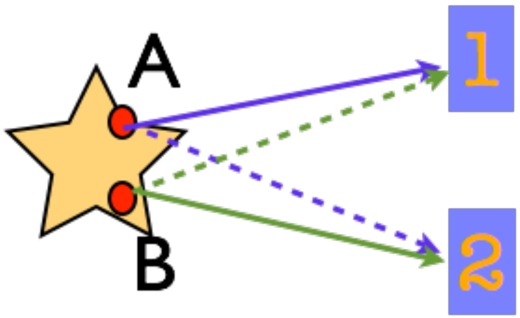
Talk by Christoph Mayer

Flow – Higher order terms – RHIC and LHC



Similar magnitude of vn at RHIC and LHC

How to measure the dimensions of a source... - interferometry



quantum phenomenon: enhancement of correlation function for identical bosons from Heisenberg's uncertainty principle

Two particles emitted from two locations (A,B) within a single source.
These two are detected by detector elements (1,2).

$$A = \frac{1}{\sqrt{2}}\left(e^{ik_1^\mu (r_1 - r_a)^\mu} e^{ik_2^\mu (r_2 - r_b)^\mu} + e^{ik_1^\mu (r_1 - r_b)^\mu} e^{ik_2^\mu (r_2 - r_a)^\mu}\right)$$

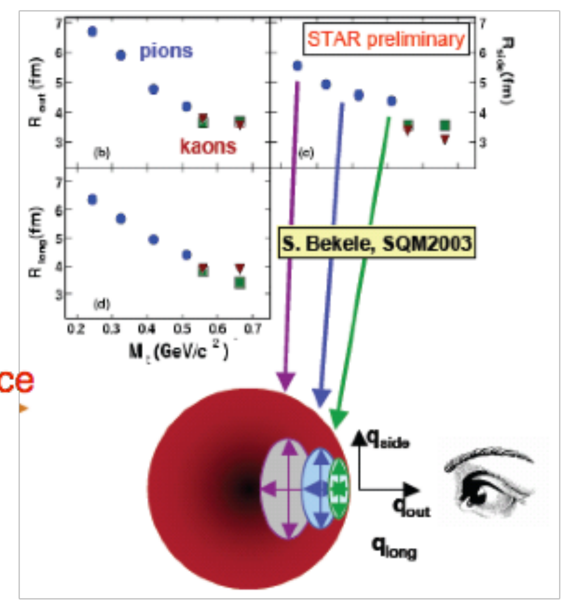
$$I = |A|^2 = 1 + \left\{e^{i(k_2 - k_1)^\mu (r_a - r_b)^\mu} + c.c.\right\}$$

The intensity interference between the two point sources is an oscillator depending upon the relative momentum $q = k_2 - k_1$, and the relative emission position!

$$C(p_1, p_2) = \frac{E_1 E_2 dN/(d^3p_1 d^3p_2)}{(E_1 dN/d^3p_1)(E_2 dN/d^3p_2)} \cdot \qquad E_p \frac{dN}{d^3p} = \int d^4x\, S(x,p)$$

Correlation function summed incoherently (integration over all pairs of source points) in a function of 4-momentum sums and differences (q,k) - extract source dimensions:

$$C(q,K) = 1 \pm \lambda(K) \exp\left(-R_s^2(K) q_s^2 - R_o^2(K) q_o^2 - R_l^2(K) q_l^2\right)$$



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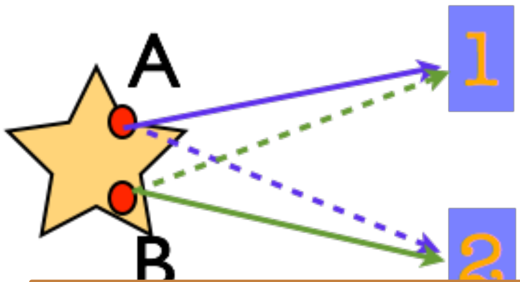

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quantu
correlat
from H

First used with photons in the 1950s by astronomers Hanbury Brown and Twiss - hence HBT measurements in heavy-ion collisions...
=> measured size of star Sirius by aiming at it two photomultipliers separated by a few metres

The inte
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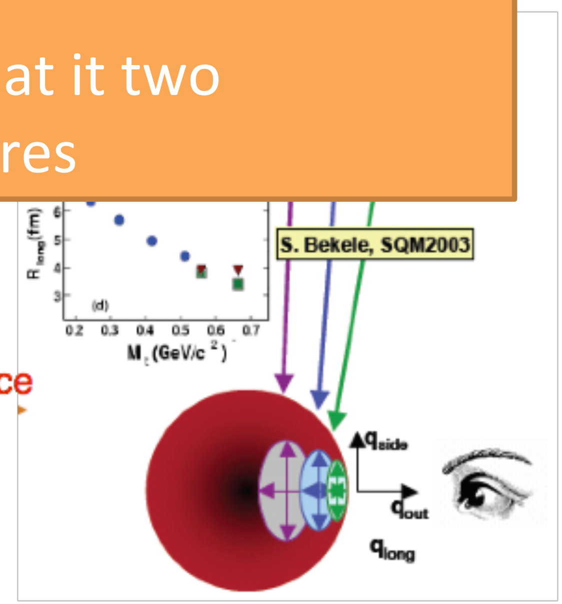
$$C(p_1, p_2) = \frac{E_1 E_2 dN/(d^3p_1 d^3p_2)}{(E_1 dN/d^3p_1)(E_2 dN/d^3p_2)}.$$

$$E_p \frac{dN}{d^3p} = \int d^4x\, S(x,p)$$



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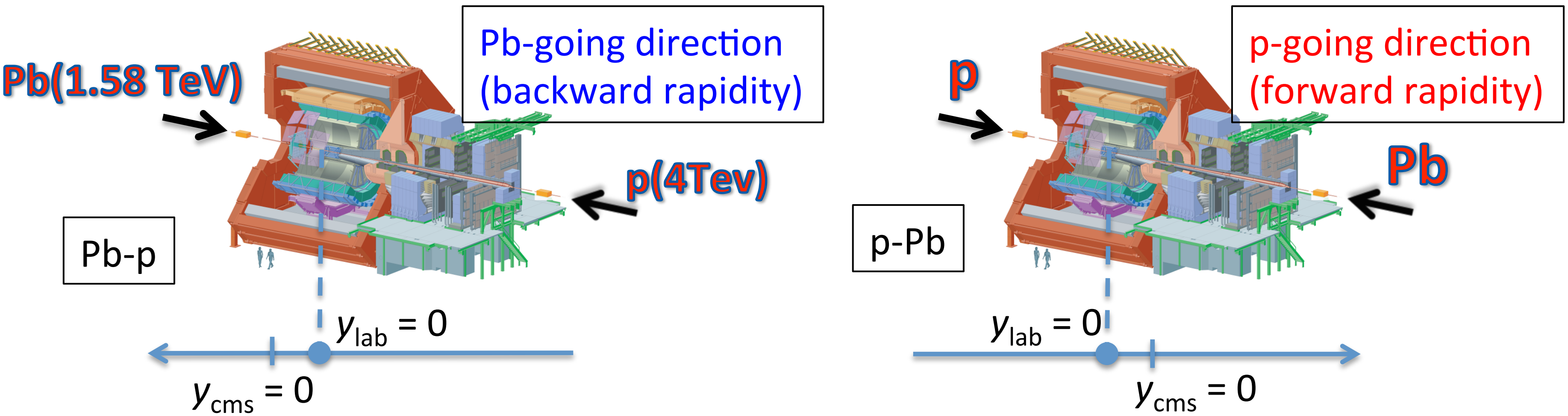
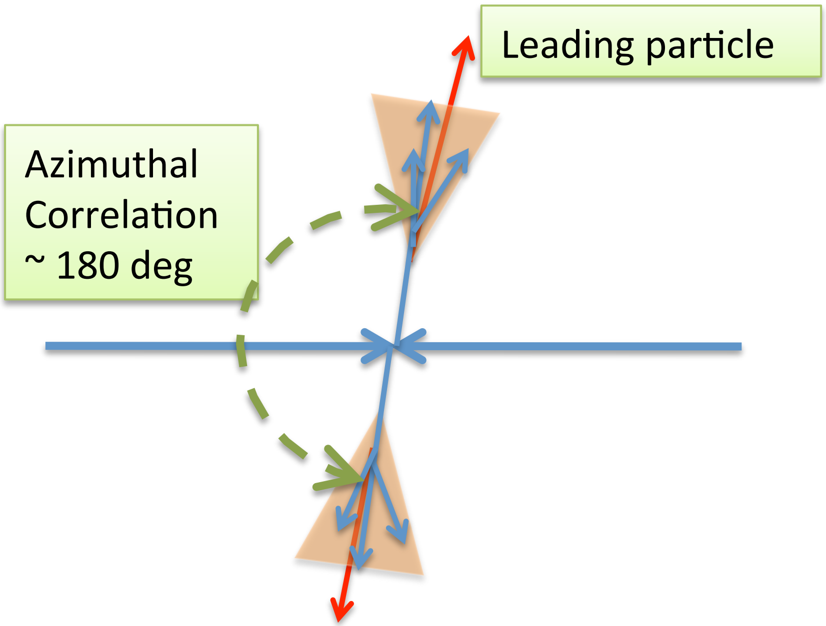
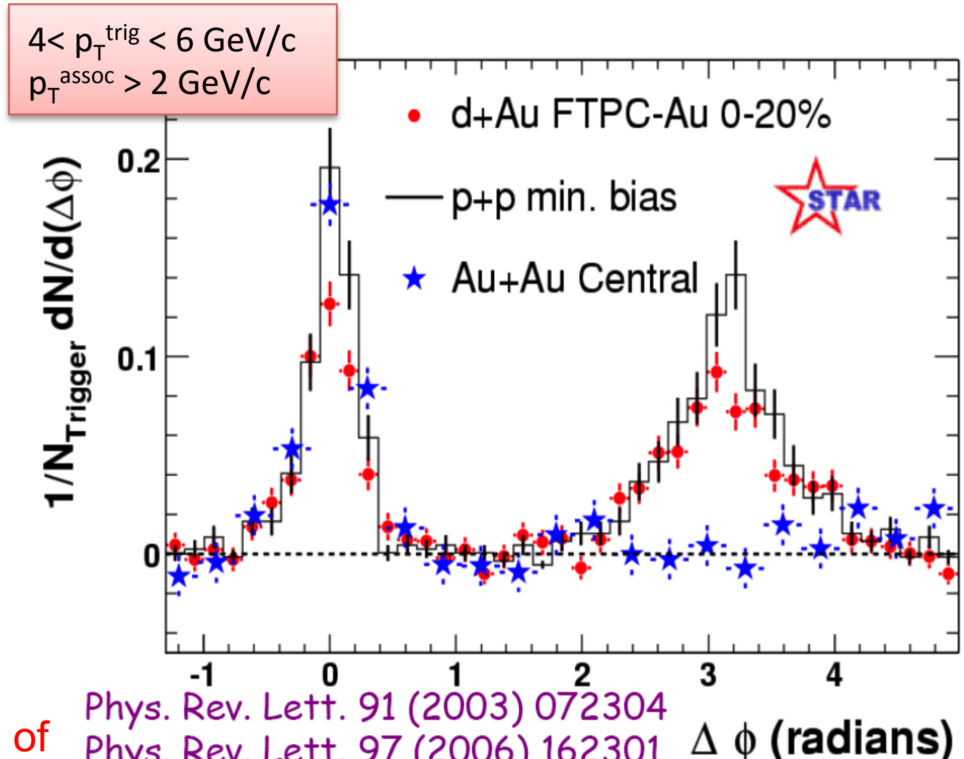
LHC beam asymmetry (E_{Pb}=1.58•A TeV, E_p=4 TeV)

$\Rightarrow$ $|\Delta y|_{cms}$ = 0.5 Log($Z_{Pb}A_p/Z_pA_{Pb}$) = 0.465 in the p-beam direction



Jet quenching: recoil jet suppression via leading hadron azimuthal correlations

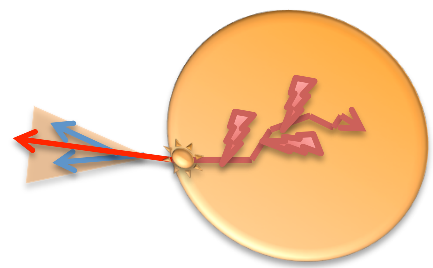




Phys. Rev. Lett. 91 (2003) 072304
Phys. Rev. Lett. 97 (2006) 162301

Intermediate pT di-hadrons: Strong modification of the recoil-jet indicates **substantial partonic interaction within the medium -> quenching**

High-pT di-hadrons: Selection of non-interacting jets



=> Limited sensitivity to quenching details

Flow and particle mass…
Focus on the ϕ meson

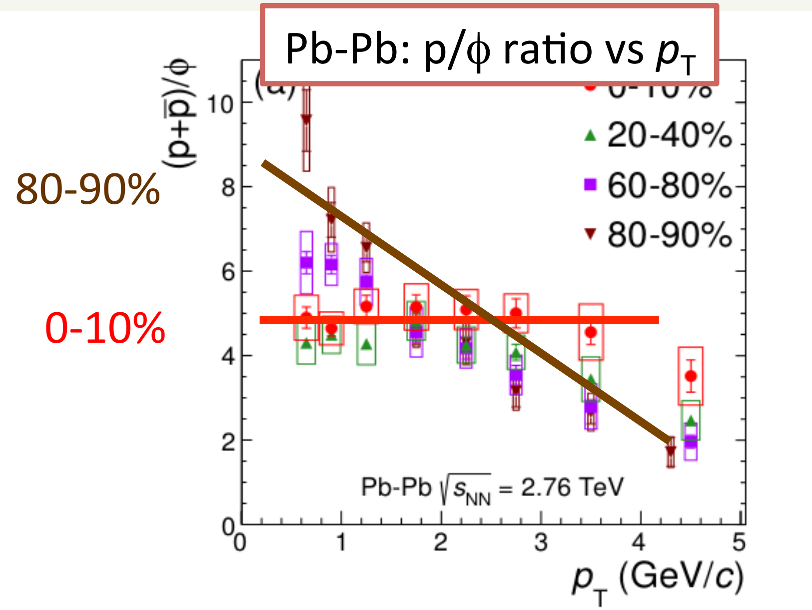
arXiv: 1404.0495

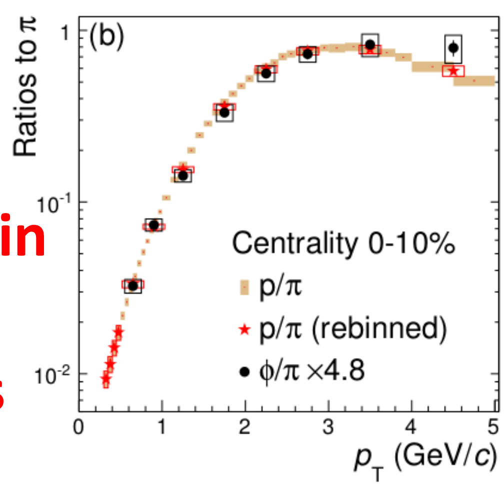
- Pb-Pb: Hydrodynamics + hadronic rescattering ⇔ v_2

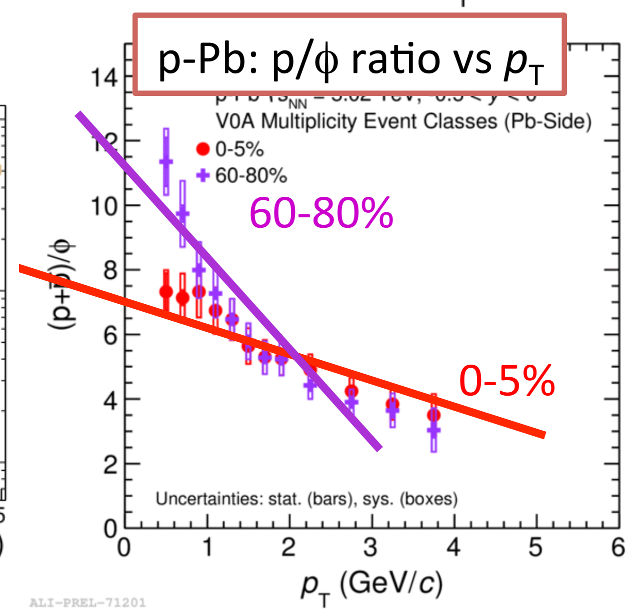
- v_2 at low p_T follows mass ordering
- v_2 at high p_T close to p in central and close to π in mid-central

- **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**

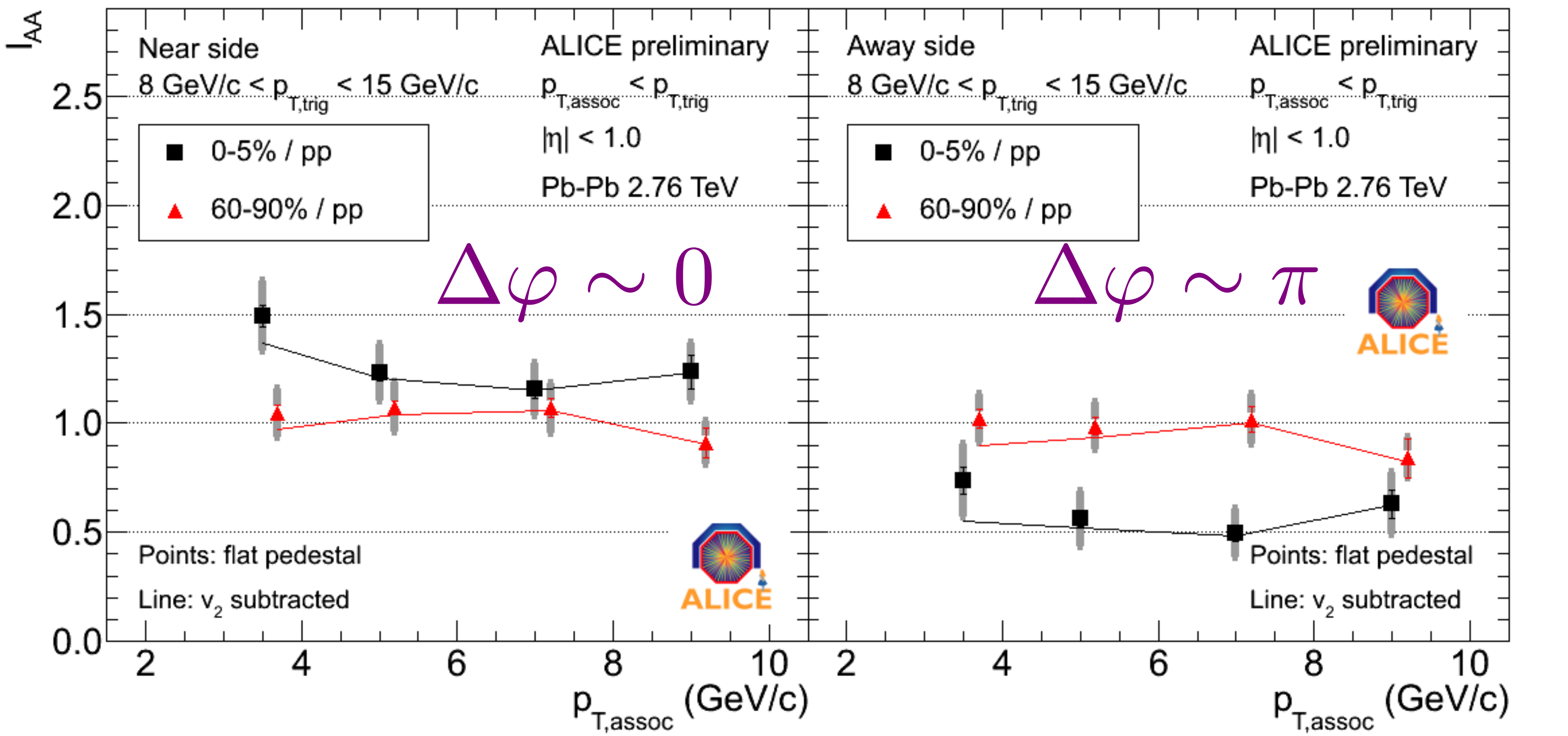






Ratio of conditional yields: I_{AA}

Conditional yields in AA divided by yields in p-p



Central events

Near side slightly enhanced I_{AA} ~ 1.2

Away side suppressed I_{AA} ~ 0.5 – 0.7

Peripheral events

I_{AA} consistent with 1

v2 contribution small except the lowest bin, therein v3 of same order

LHC pA: no nuclear effects at high-p_T

- **R_{pPb} (or Q_{pPb}) consistent with unity** for
  - Jets and charged hadrons
  - D-mesons and HF-decay leptons
- Measurements **consistent with pp**:
  - di-jet k_T
  - Jet structure (cross-section ratios with different R) and baryon/meson ratio in jets (indep. of event multiplicity)
  - D-meson – hadron correlations

arXiv: 1503.00681
arXiv: 1503.03050 PLB 746
arXiv: 1405.3452 PRL 113
arXiv: 1405.2737 EPJ C74
arXiv: 1210.4520 PRL 110

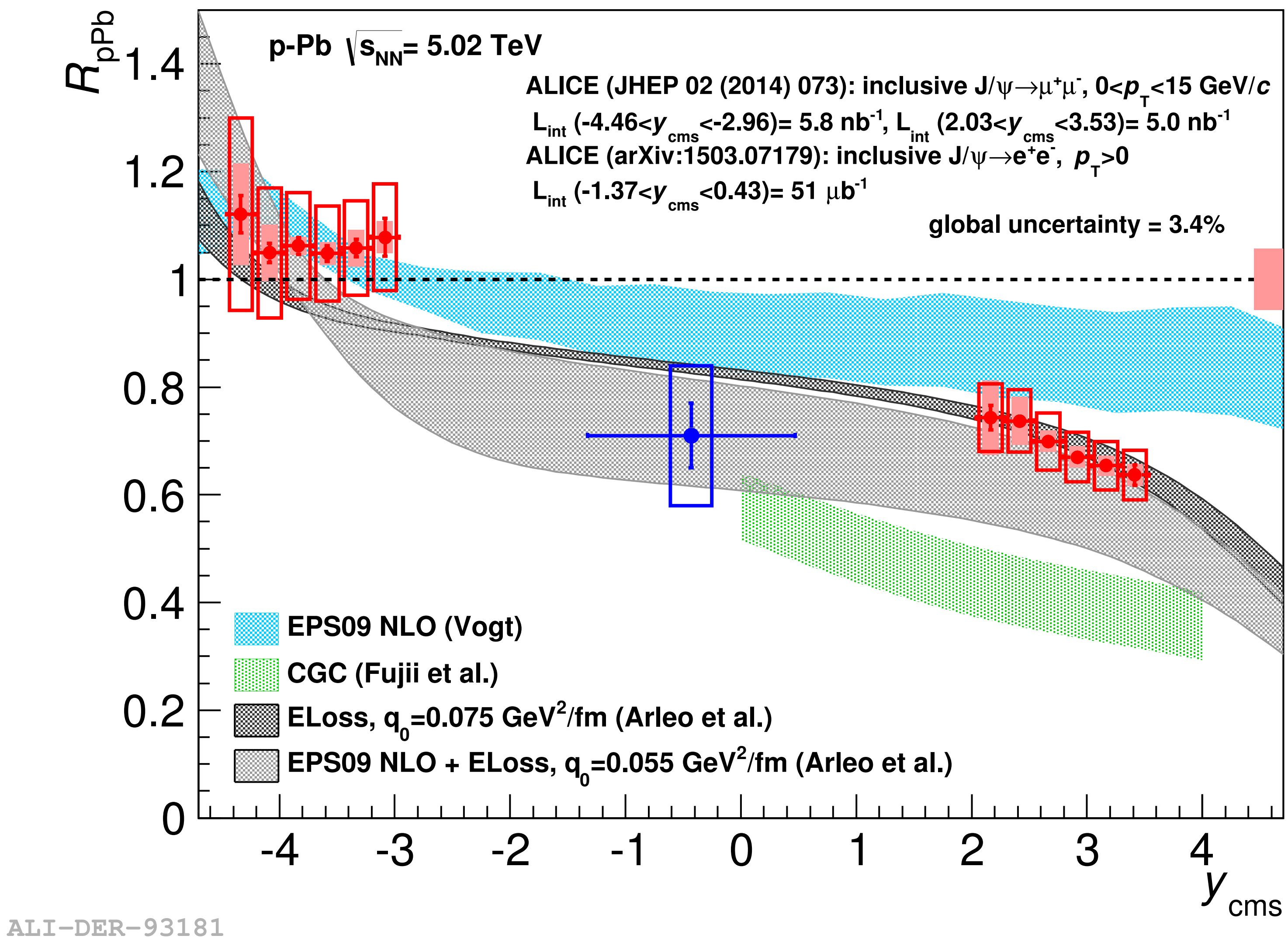
Jets: Megan Connors, Wednesday 11:50
L/K^0 in jets : Vit Kucera, Tuesday 11:10
D-mesons: Cristina Bedda, Tuesday 14:10
D-hadron correlations: Jitendra Kumar, Wednesday 9:20

Next: news on selected pA results…

J/ψ in pA collisions

R_{pPb} close to unity at backward (Pb-going) rapidity

CNM effects at mid- and forward (p-going) rapidity



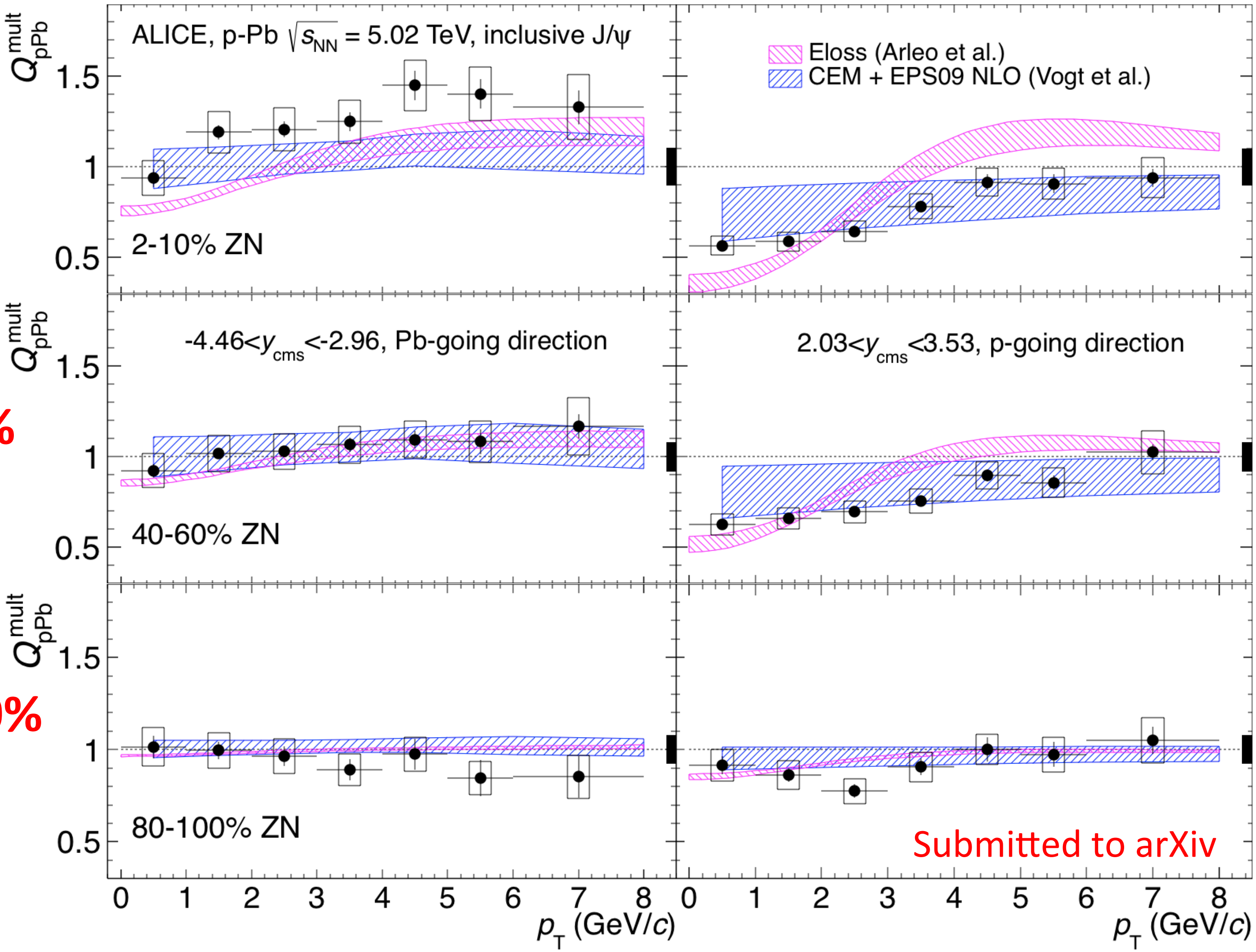
J/ψ vs. p_T and event activity

Pb-going **p-going**

2-10%

40-60%

80-100%



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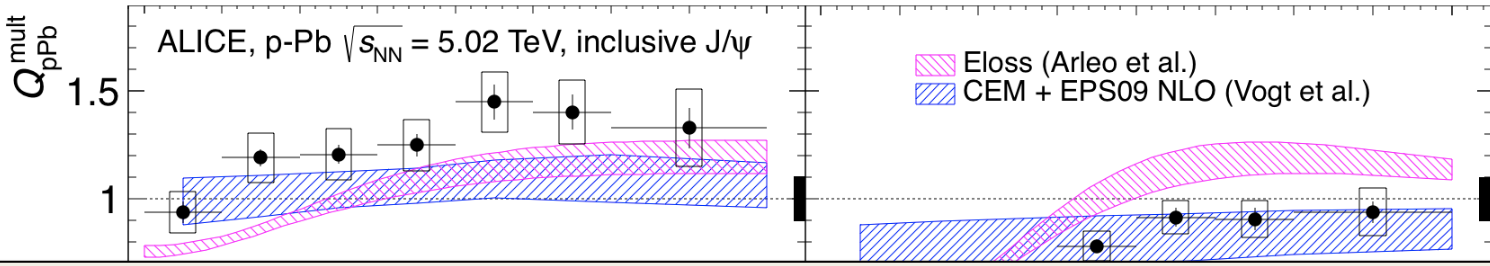
Pb-going **p-going**

2-10%



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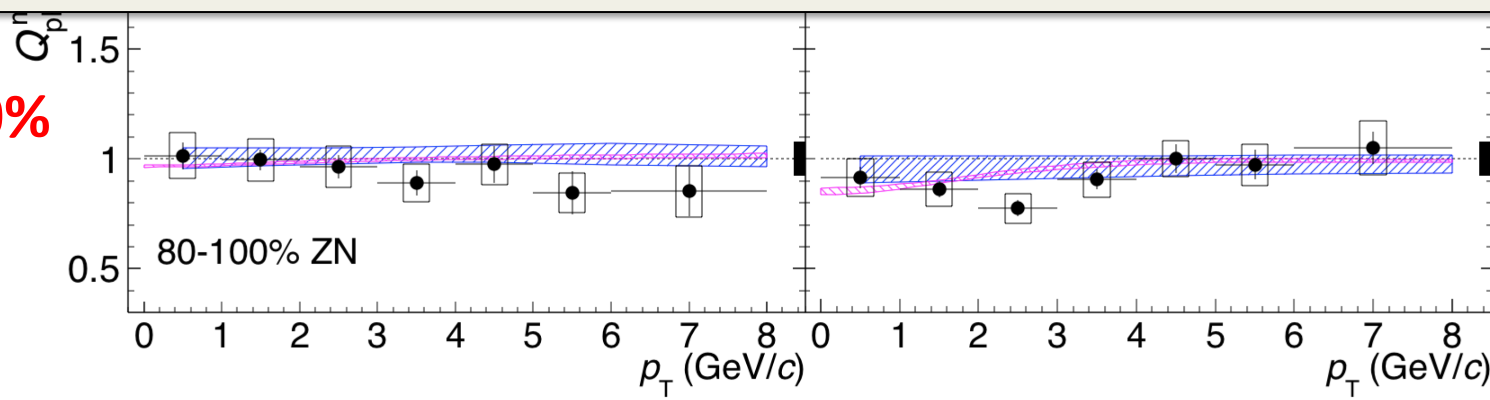
Large CNM effects in most "central" events

No effects when event activity small ("peripheral")

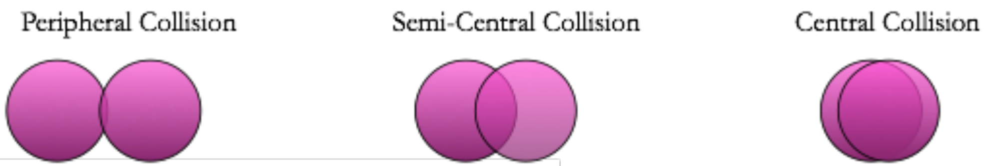
p_T-broadening due to CNM ?

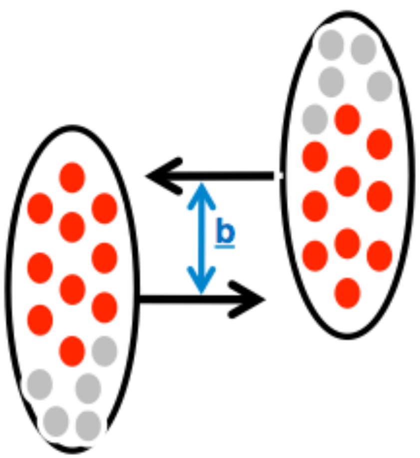
Indication of harder p_T at forward rapidity [not shown]

80-100%



Classification of HI collisions – centrality





Spectators

Participants
aka wounded nucleons

central collisions:
- small impact parameter b
- high number of participants
- high energy density
- large volume
- -> large number of produced particles

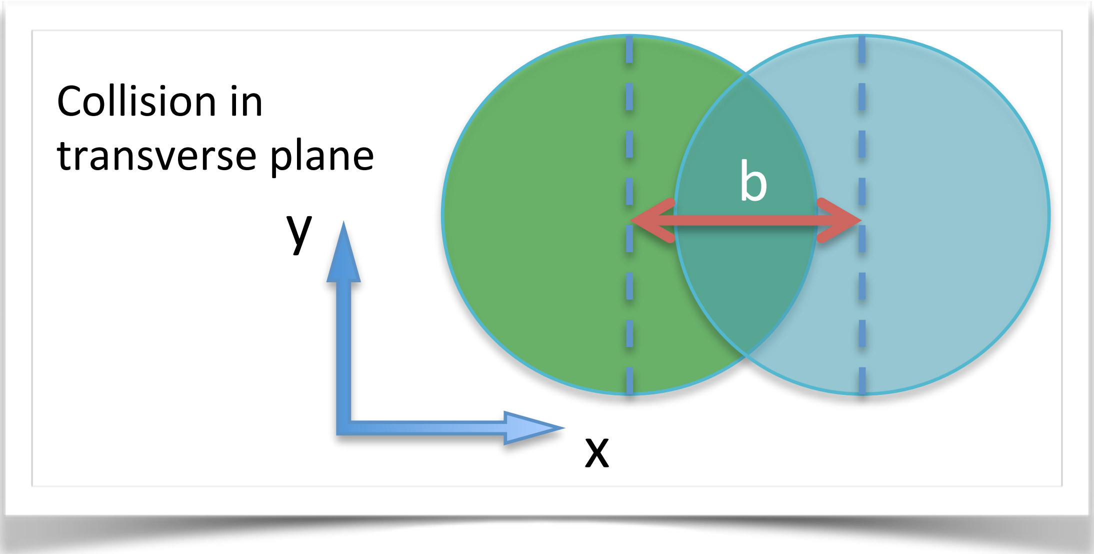
peripheral collisions:
- large impact parameter b
- low number of participants
- -> low multiplicity

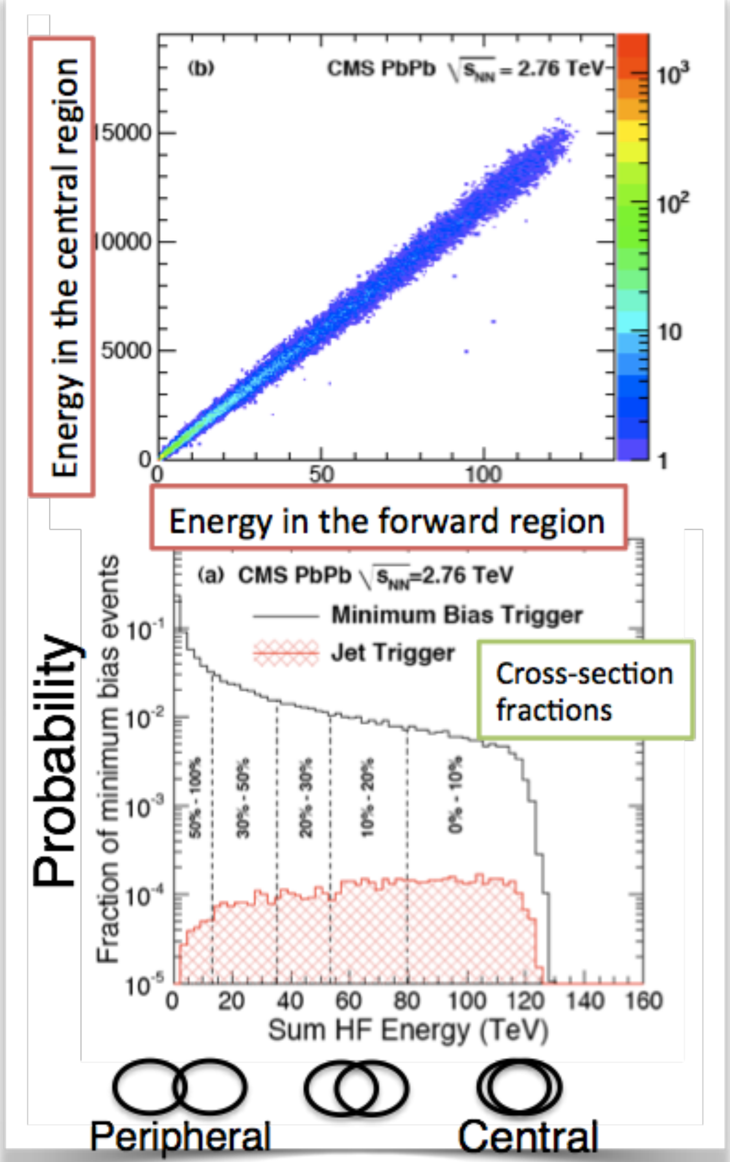
Impact parameter b is measured as:
- Fraction of cross section "centrality"
- Number of participants
- Number of nucleon-nucleon collisions

"Centrality" – experimental control of collision geometry

How can we measure impact parameter in heavy-ion collisions?

=> Correlate observables connected **only** by geometry





Characterize events via percentile (fraction) of inelastic cross section (jargon: "N% most central")

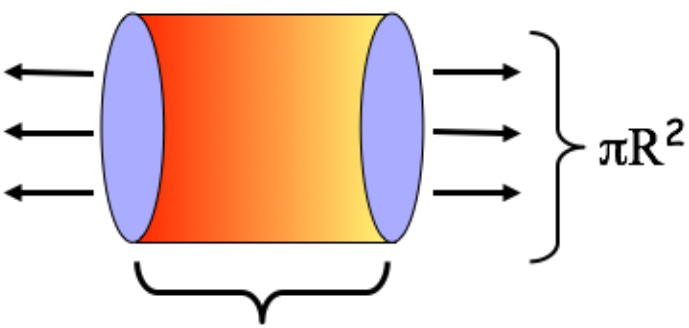
"Calibration" measurements

Bjorken energy density:

$$\varepsilon_{Bj} = \frac{\Delta E_T}{\Delta V} = \frac{1}{\pi R^2}\frac{1}{\tau_0}\frac{dE_T}{dy}$$

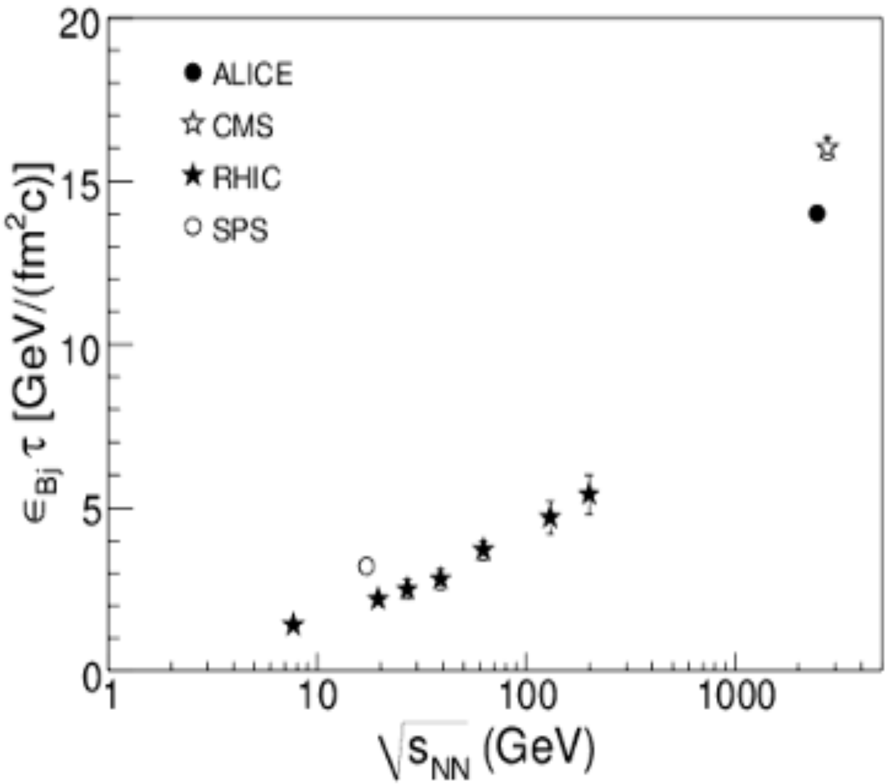
R~6.5 fm

Time it takes to thermalize system ($t_0 \sim$ 1 fm/c)

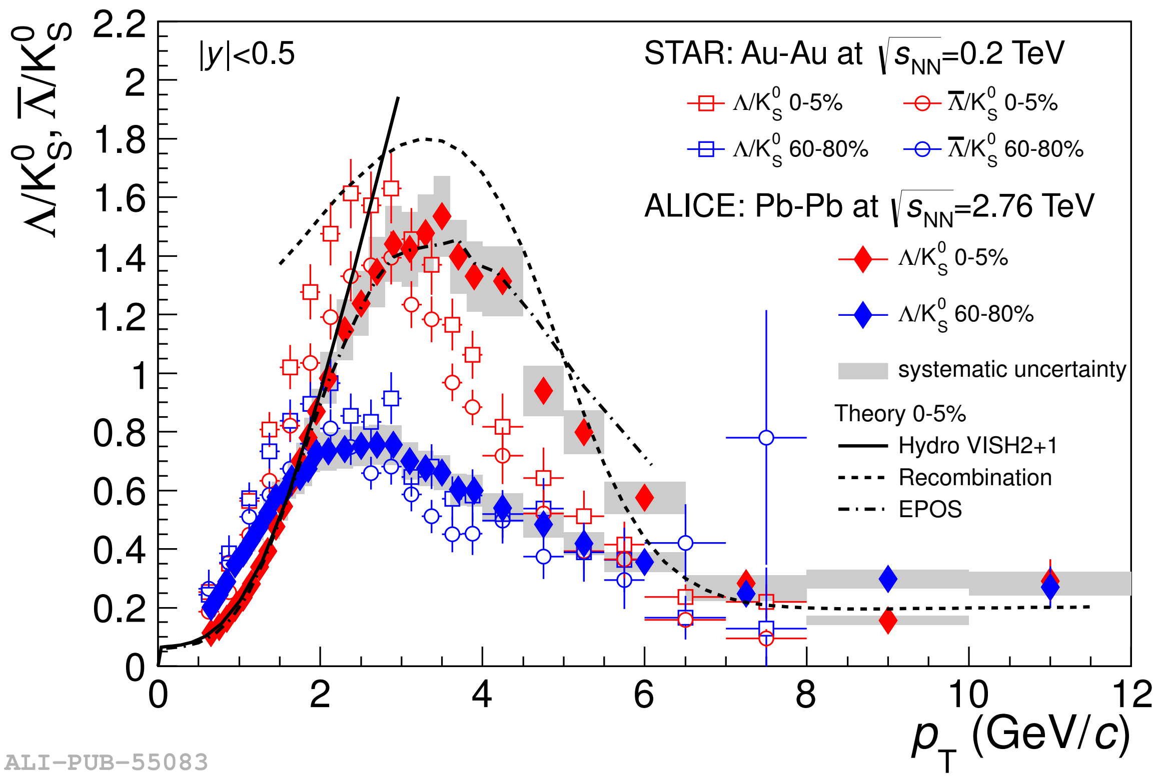


$$dz = \tau_0 dy$$

Bjorken energy density x formation time



Baryon/meson "anomaly"

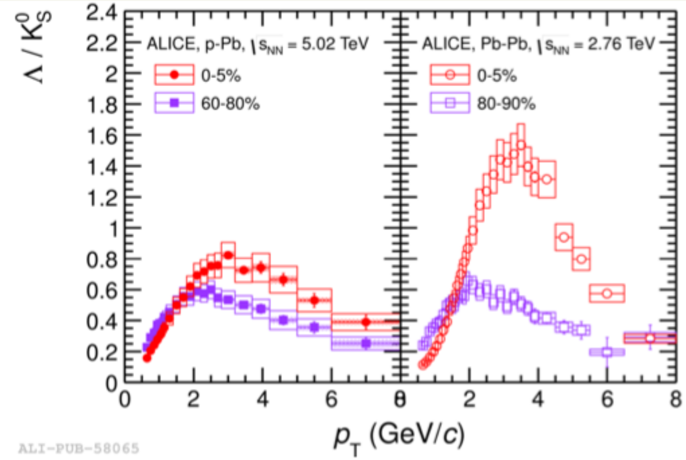


- Integrated ratio independent of centrality (L/K^0_s ~ 0.25)
- Intermediate p_T: Λ/K^0_s ratio enhanced in central Pb-Pb
  - consistent with radial flow
- High-p_T: ratio consistent with vacuum-like fragmentation.

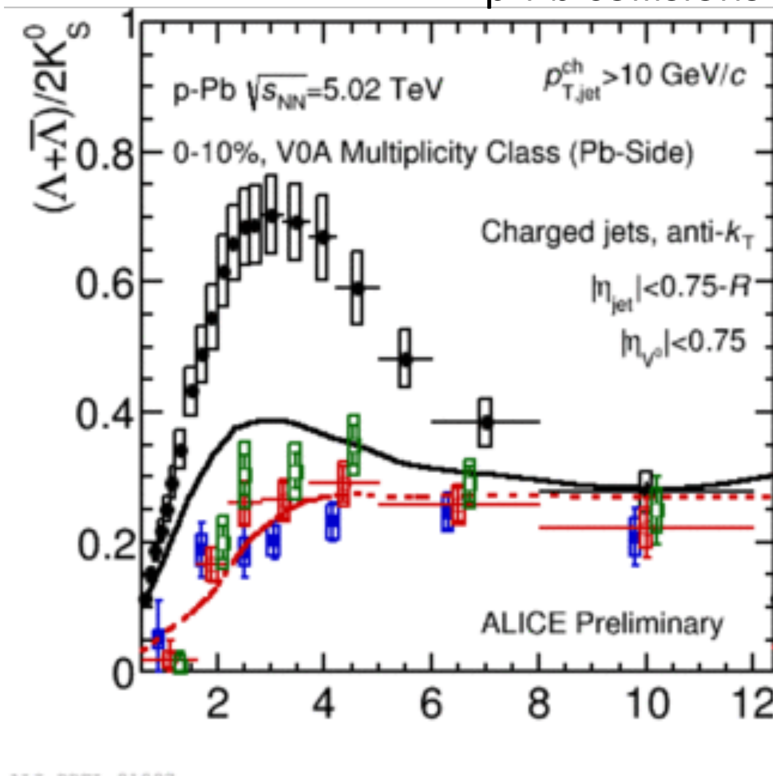
Λ/K^0 in jets and underlying event

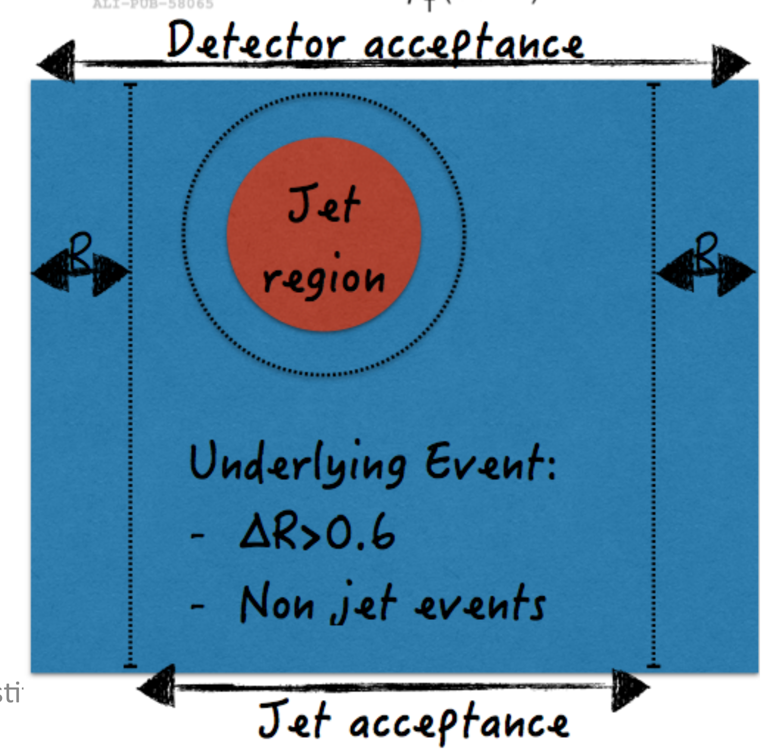
Λ/K in jets and UE separately consistent with vacuum

Baryon/meson enhancement is not associated to jets => feature of underlying event



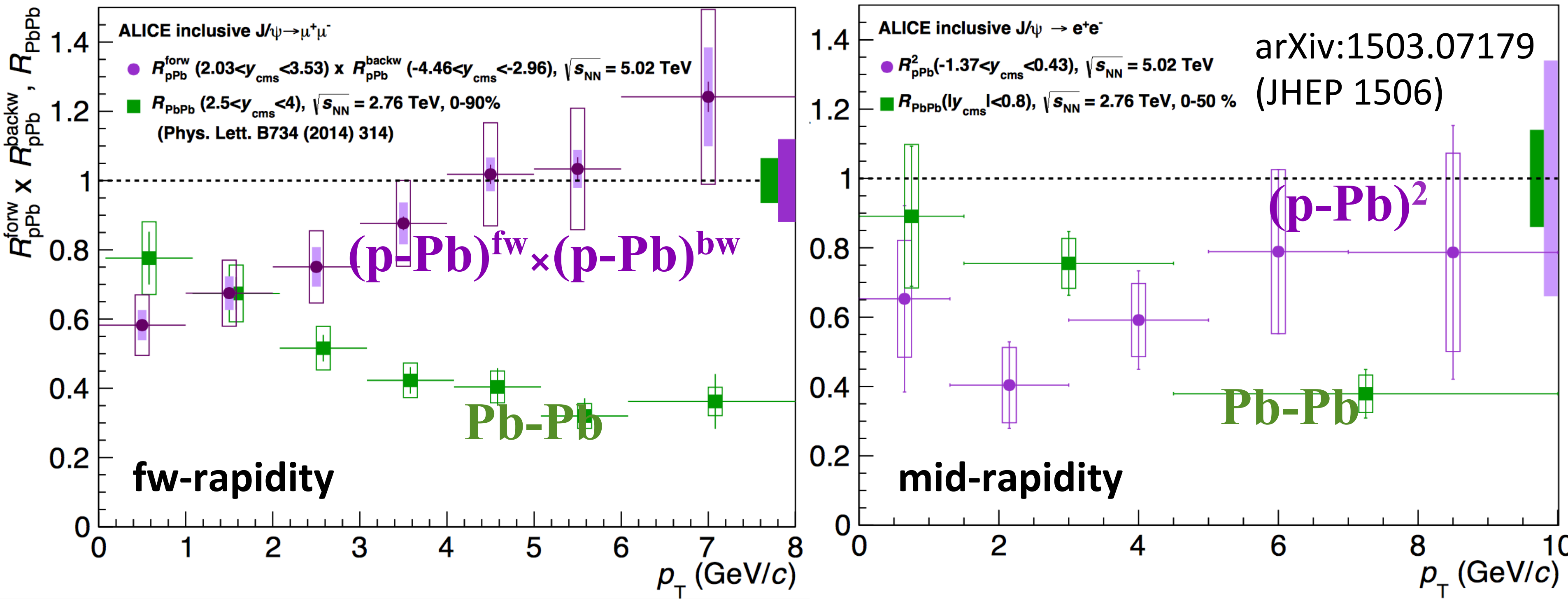
p-Pb collisions





J/ψ R_{AA} from R_{pA} and R_{Ap}

Hypothesis: 'x' similar in Pb for Pb-Pb@$\sqrt{s_{NN}}$=2.76 TeV and in p-Pb@$\sqrt{s_{NN}}$=5.02 TeV; factorized shadowing

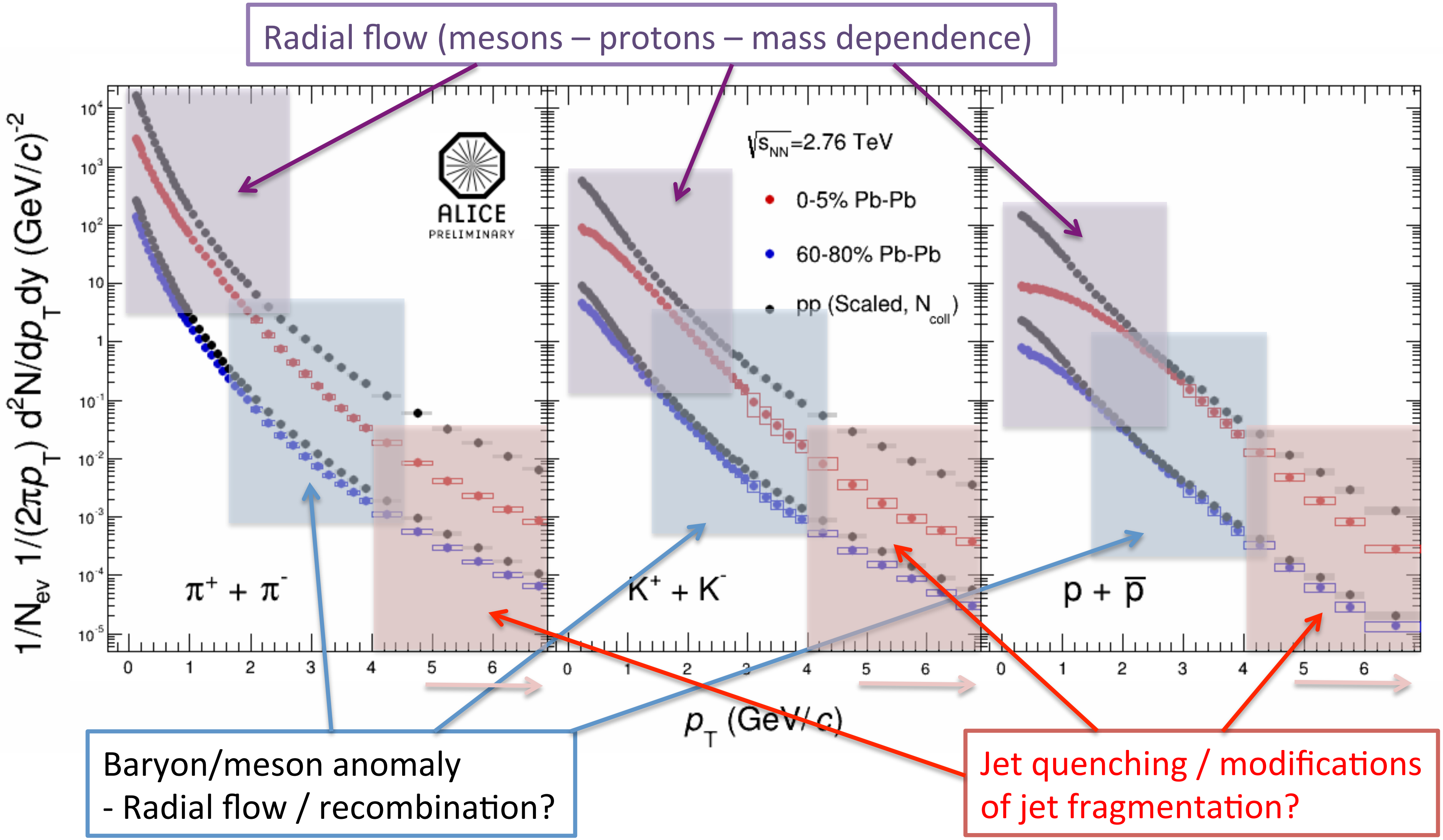


CNM R_{AA} constructed with $R_{pPb}(y>0)$ x $R_{pPb}(y<0)$

Pb-Pb R_{AA} dominated by final state (QGP) effects

Talk by Igor Lakomov, Tuesday 16:00

Pion/Kaon/Proton p_T spectra in pp and Pb-Pb



Thermal equilibrium… Chemical and kinetic freeze-out

Chemical equilibrium:

- correct relative particle abundances?
- large system -> Grand Canonical ensemble: many particles; conservation laws on average - chemical potentials
- small system -> conservation laws E-by-E -> "canonical suppression" (strangeness)

$$n_i^0 = \frac{g_i}{2\pi^2}\int \frac{p^2 dp}{e^{\left(E-\mu_B B_i-\mu_s S_i-\mu_3 I^3\right)/T} \pm 1}$$

The ratios of produced particle yields between various species can be fitted to determine T, μ.

Kinetic equilibrium - radial flow:

- for any interacting system of particles expanding into vacuum, radial flow is a natural consequence.

During the cascade process, an ordering of particles with the highest common underlying velocity at the outer edge develops naturally

Hadrons are released in the final stage and therefore measure "FREEZE-OUT" Temp. - instructive simple parametrization - radially boosted source with velocity β and at y=0:

$$\frac{d^3N}{dp^3} \propto e^{-E/T}; E\frac{d^3N}{dp^3} = \frac{d^3N}{m_T dm_T d\phi dy} \propto E e^{-E/T} = m_T \cosh(y) e^{-m_T \cosh(y)/T}$$

$$\frac{1}{m_T}\frac{dN}{dm_T} \propto m_T I_0\left(\frac{p_T \sinh(\rho)}{T}\right) K_1\left(\frac{m_T \cosh(\rho)}{T}\right)$$

$$\rho = \tanh^{-1}(\beta_{boost})$$

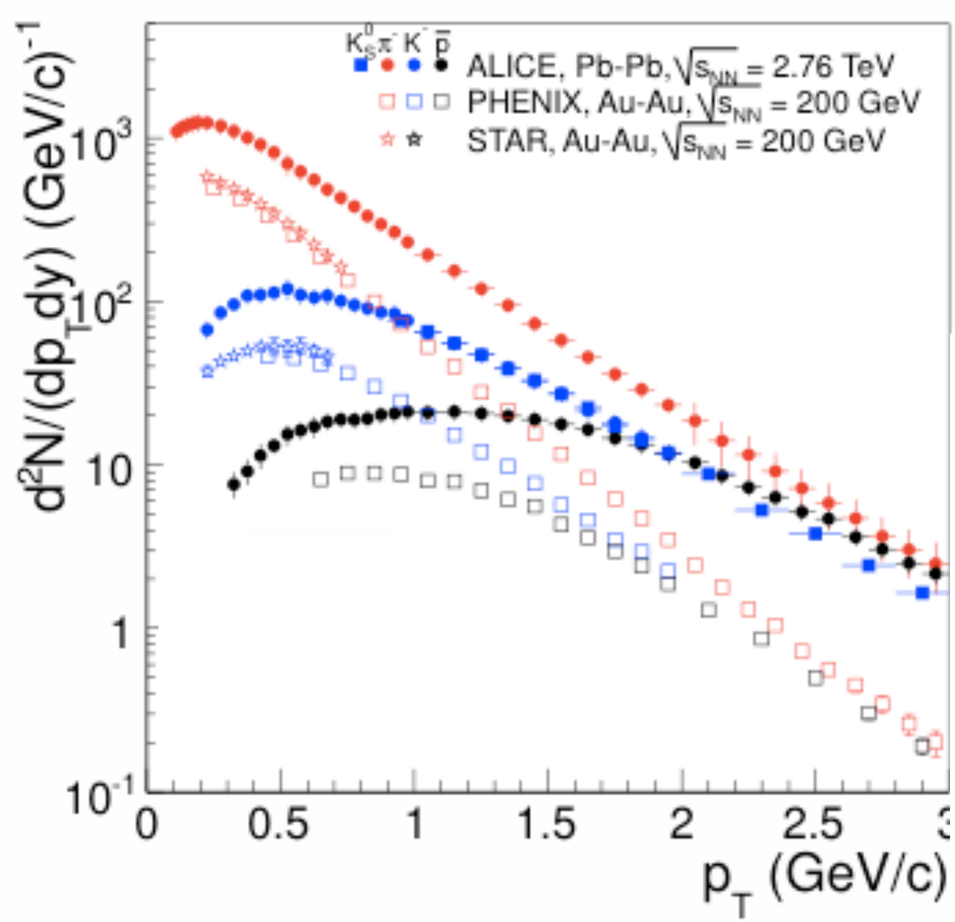
Simple assumption: uniform sphere of radius R and boost velocity varies linearly w/ r:

$$\frac{1}{m_T}\frac{dN}{dm_T} \propto \int_0^R r^2 dr m_T I_0\left(\frac{p_T \sinh(\rho)}{T}\right) K_1\left(\frac{m_T \cosh(\rho)}{T}\right)$$

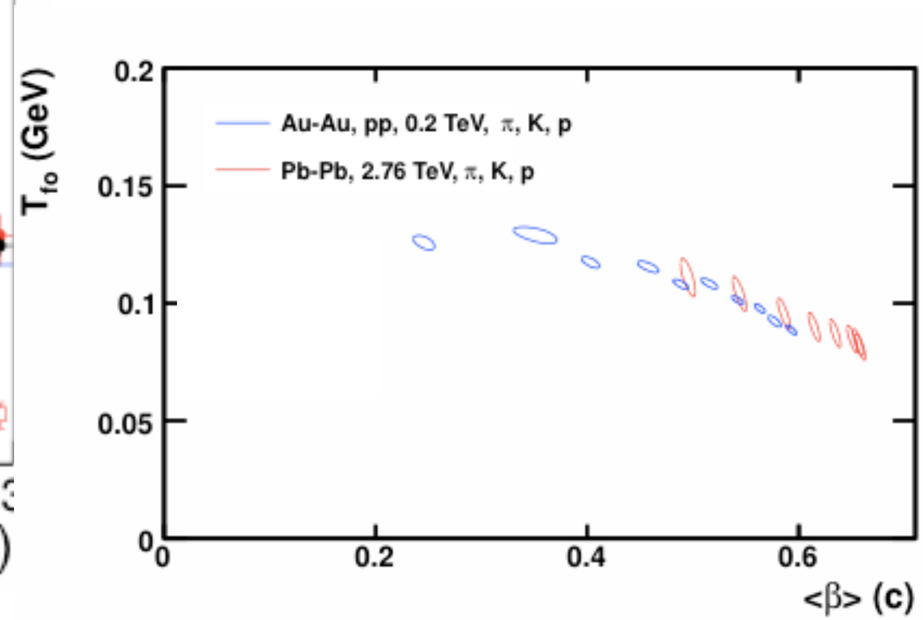
$$\rho(r) = \tanh^{-1}\left(\beta_T^{MAX} \frac{r}{R}\right)$$

Blast Wave model => common T and β

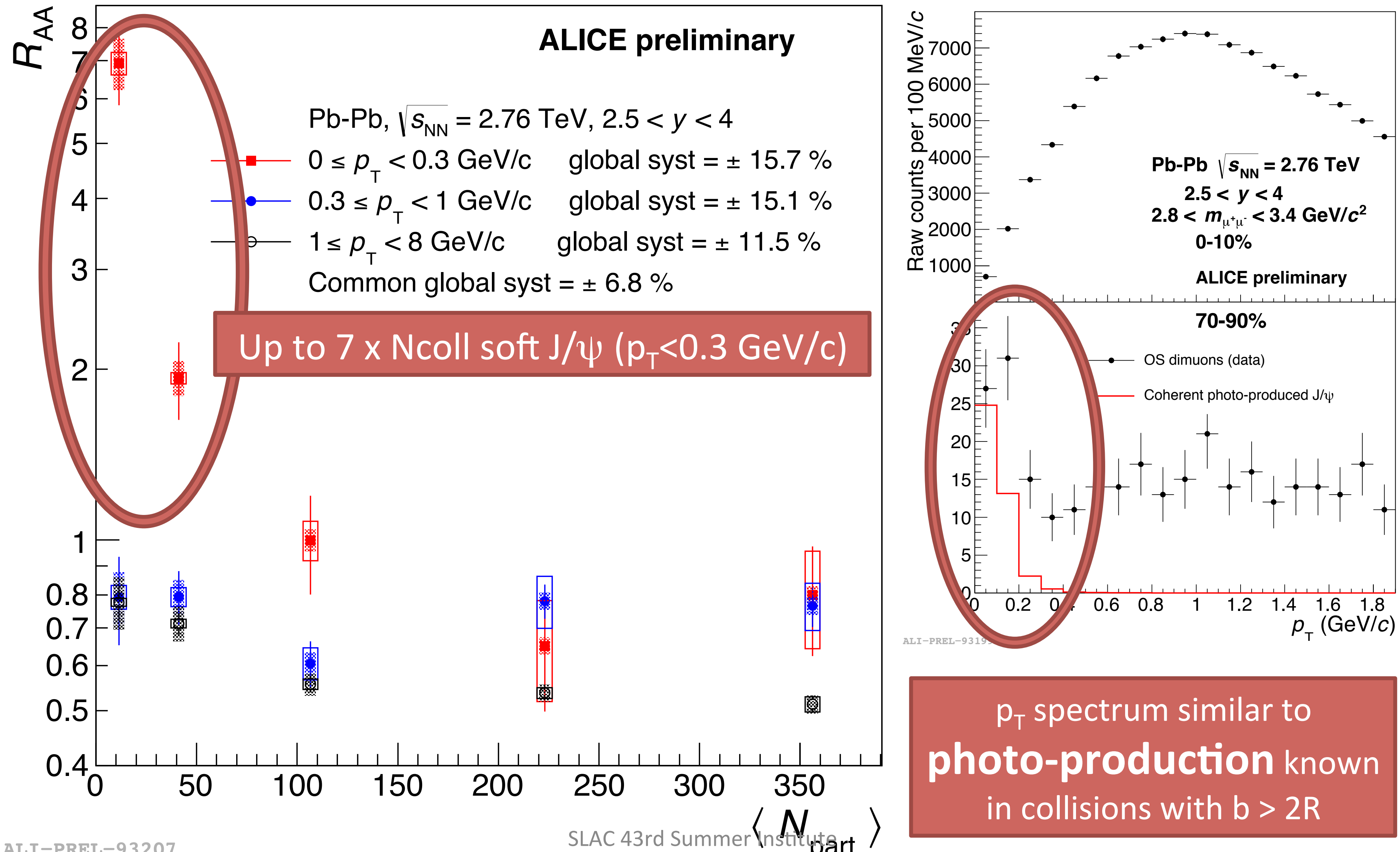
Identified particle spectra and radial flow



Stronger radial flow at the LHC.
"Blast wave" fits to spectra indicate an **increase of the average radial boost velocity** up to (2/3)c and a decrease in the kinetic freeze-out temperature at about 100 MeV



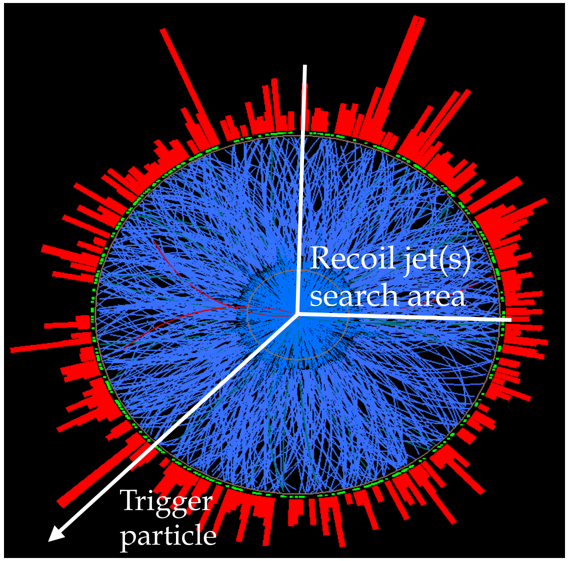
J/ψ R_{AA} – closer look at low-pT



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

Jet measurements - new observable: hadron-jet coincidences

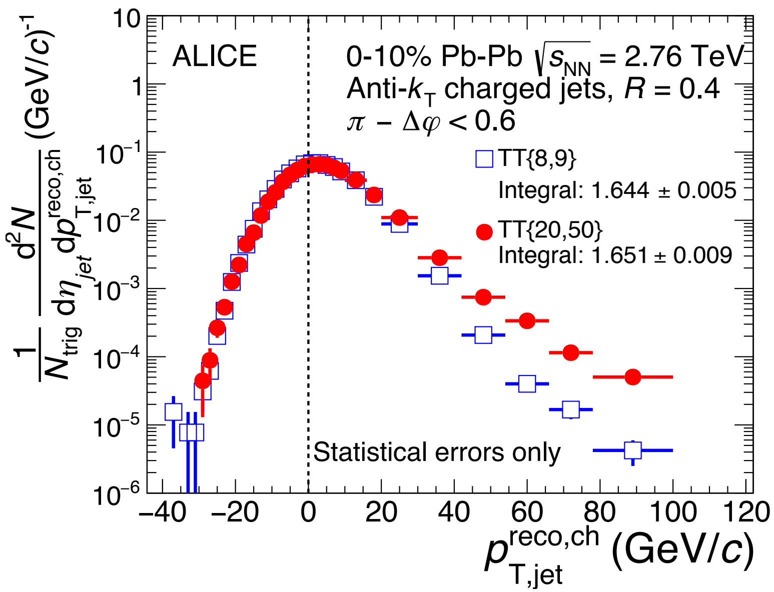
- Observable: hadron-triggered semi-inclusive recoil jet distribution
  - Calculable in fixed order pQCD
  - Recoil jets unbiased
  - Removal of uncorrelated jet background on ensemble-averaged basis via difference of triggered distributions: Δ_{recoil}
  - No selection bias due to bkgd removal; jets measurable over broad range of R and p_T
  - Systematically different measurements as compared to other experiments/methodologies

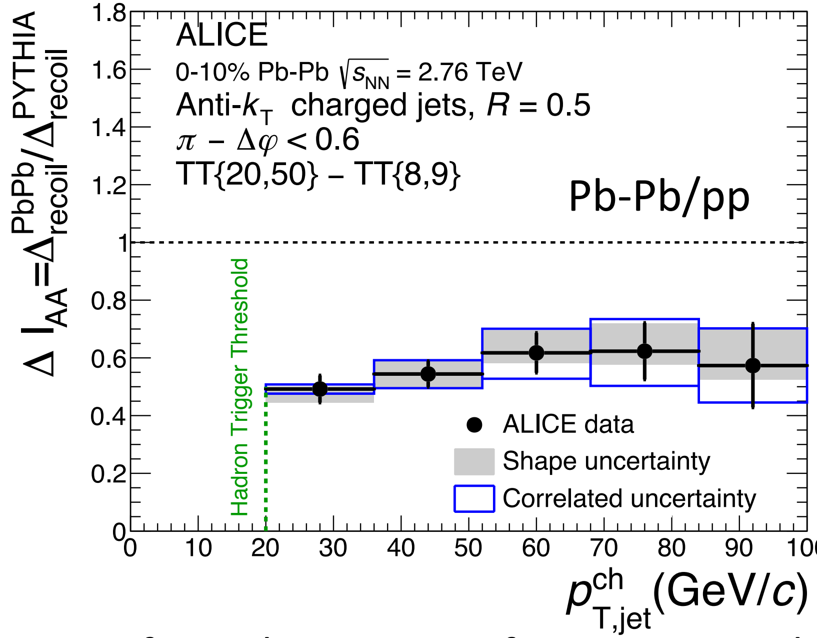


$$\Delta_{\text{recoil}}(p_T, jet) = \frac{1}{N_{\text{trig}}} \frac{dN_{\text{jet}}^{\text{h-signal}}}{dp_{T,\text{jet}}} - \frac{1}{N_{\text{trig}}} \frac{dN_{\text{jet}}^{\text{h-ref}}}{dp_{T,\text{jet}}}$$

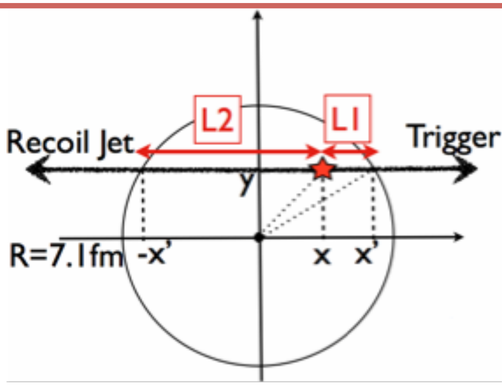
h-jet at the LHC: Recoil jet spectrum

arXiv:1506.03984





TT{20,50} : 20 < $p_T^{\text{trigger hadron}}$ < 50 GeV/c
TT{8,9} : 8 < $p_T^{\text{trigger hadron}}$ < 9 GeV/c

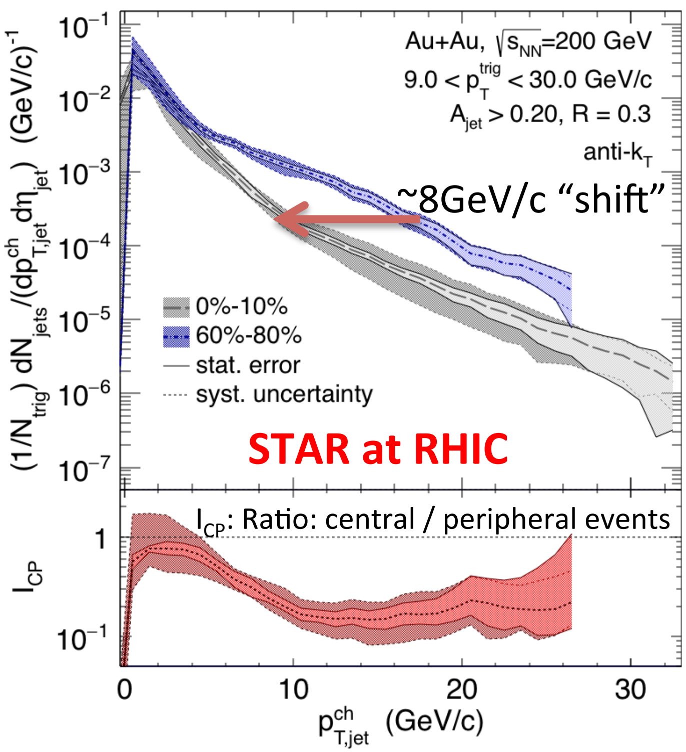


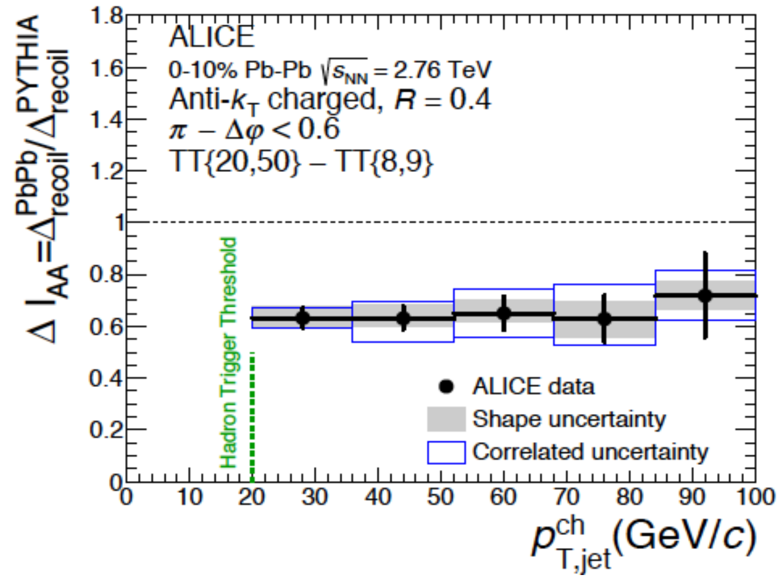
- Δ_{recoil} = difference of recoil jet spectra for two intervals of trigger hadron p_T

$$\Delta_{recoil} = \left(\frac{1}{N_{trig}} \frac{dN}{dp_{T,trigger}}\right)_{TT[20-50]} - \left(\frac{1}{N_{trig}} \frac{dN}{dp_{T,trigger}}\right)_{TT[8-9]}$$

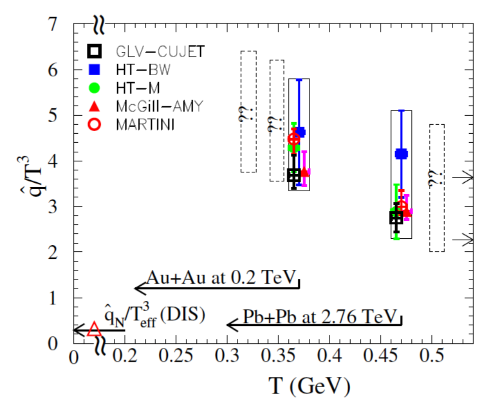
- Δ_{recoil} suppressed as compared to pp (PYTHIA)
  - Consistent with parton energy loss and out-of-cone radiation
  - Radiation out-of-cone is 8 (±2) GeV on average
  - and independent of jet p_T

Jet quenching via hadron-jet coincidences at RHIC and LHC



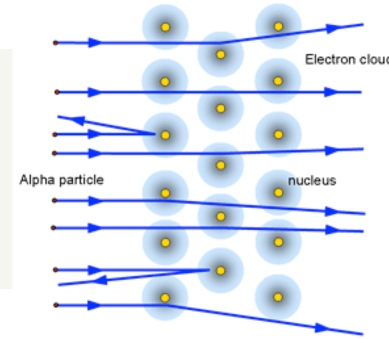


- Larger suppression at RHIC as compared to LHC
  - but similar out-of-cone radiation: 8 ± 2 GeV

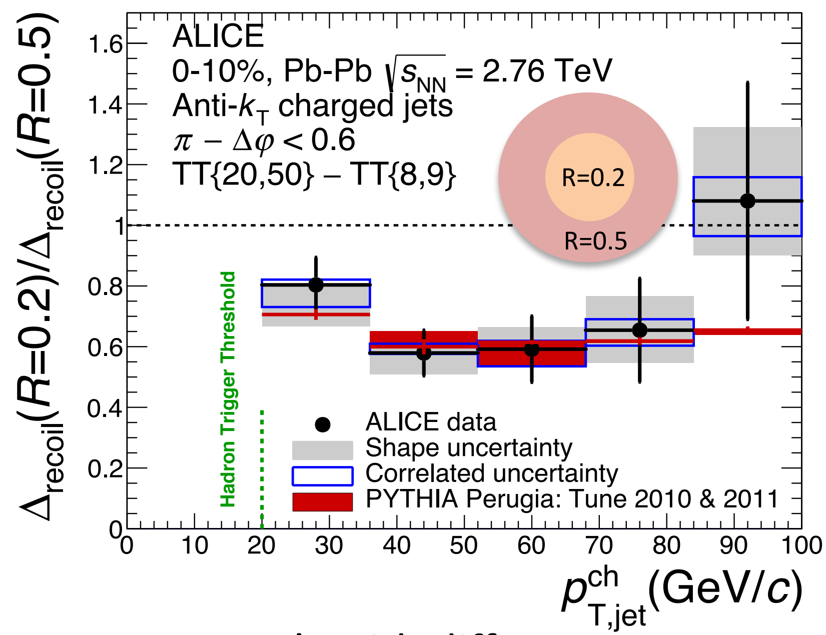


- Out-of-cone radiation at RHIC and LHC
- Similar average jet energy-loss at RHIC and LHC?
  ⇔ weak temperature dependence?

Jet quenching via hadron-jet coincidences and LHC



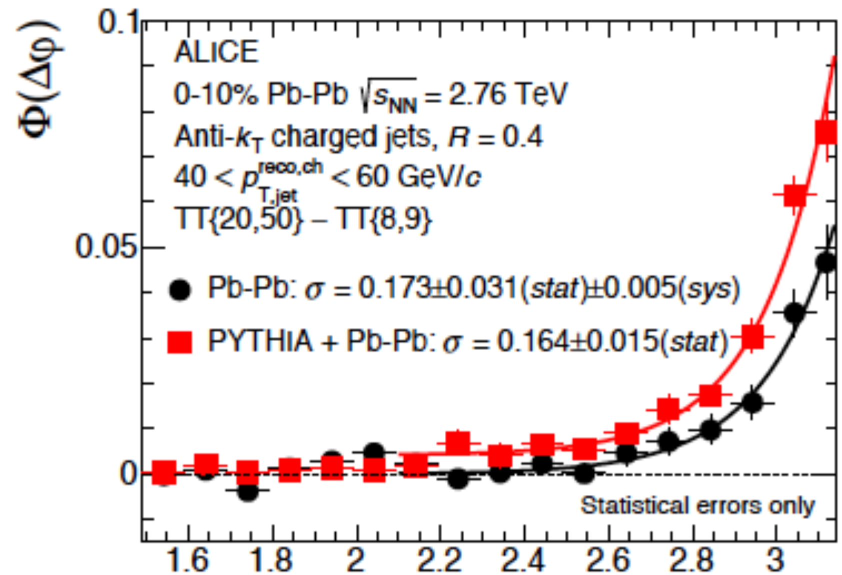
Ratio of Δ_{recoil} with different R's allows to study modifications of internal jet structure



Measurement's with different R:

- Consistent with pp reference
- No jet structure modifications within uncertainties

Ratio of azimuthal correlations is sensitive to medium induced accoplanarity and large angle parton-medium scatterings



Azimuthal correlations:

- No medium induced accoplanarity (consistent with CMS and ATLAS)
- Unique limit on rate of Moliere scatterings – sensitivity to medium homogenity (ongoing discussion with theorists)