Heavy ion physics at the LHC

Elena Bruna (INFN Torino)

Incontri di Fisica delle Alte Energie, IFAE. L'Aquila, Aprile 2014

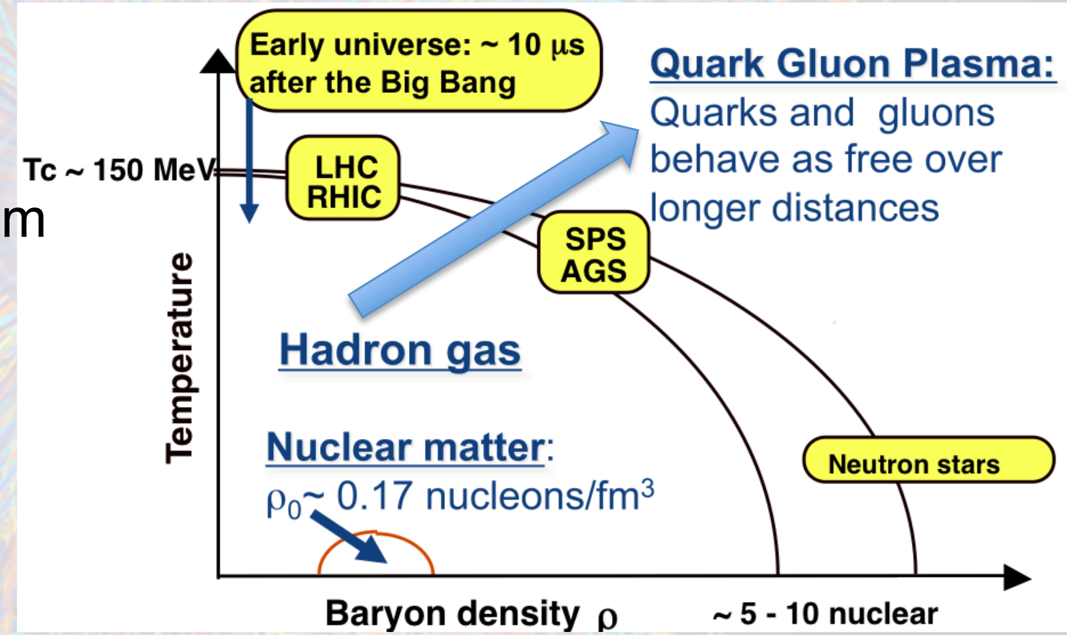
Heavy Ion Physics

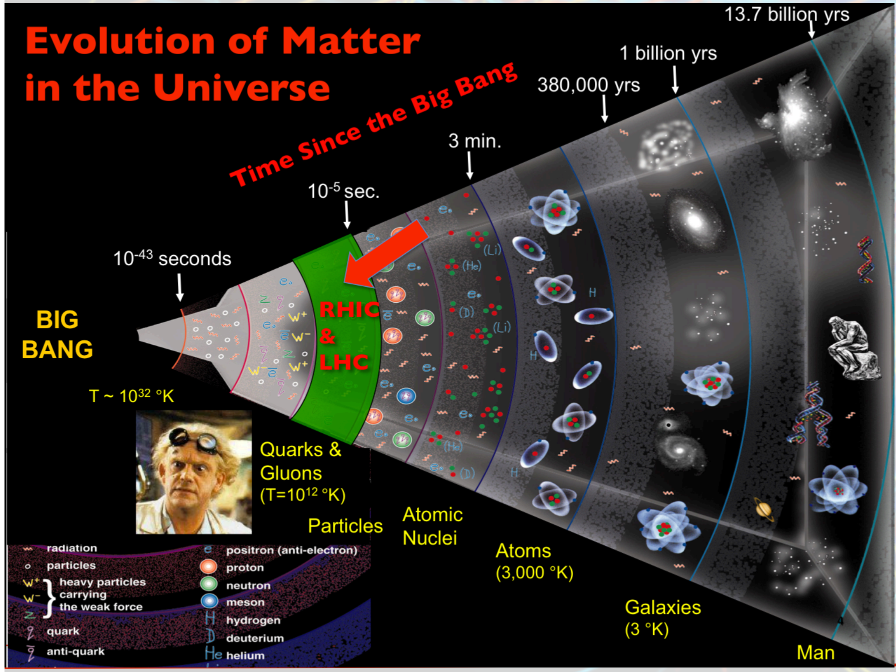
GOAL: apply Standard Model to complex and dynamically evolving systems under extreme conditions of density and temperature

→ Transition from hadronic matter to a deconfined matter:

Quark Gluon Plasma

Why **heavy ions**:
-larger volumes w.r.t pp collisions
-larger lifetime
-system with more degrees of freedom

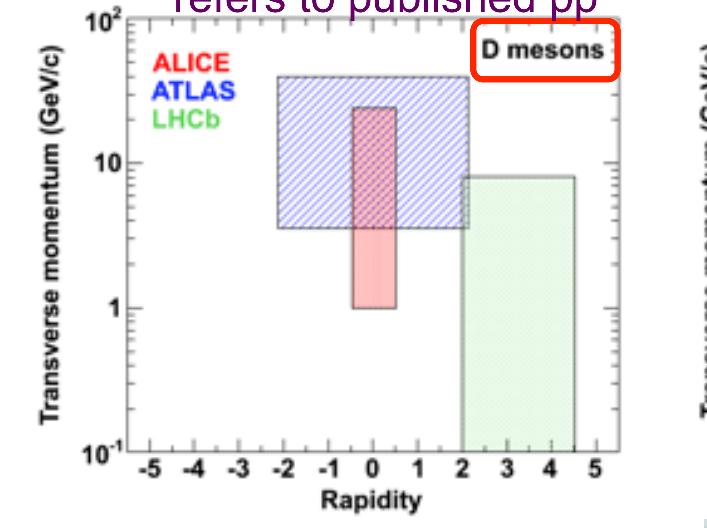




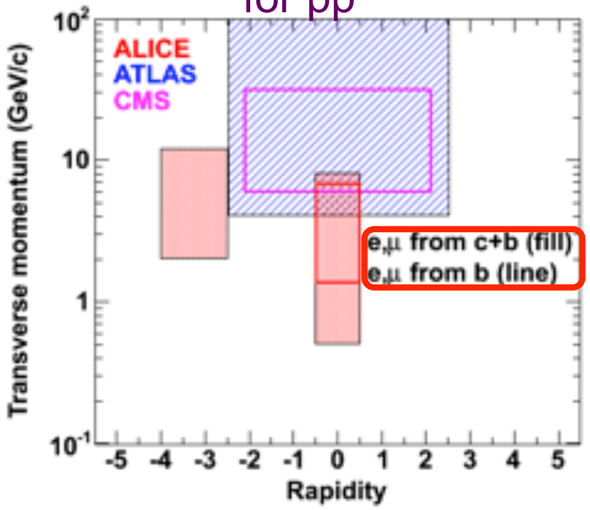
Heavy ion physics at the LHC

The LHC experiments

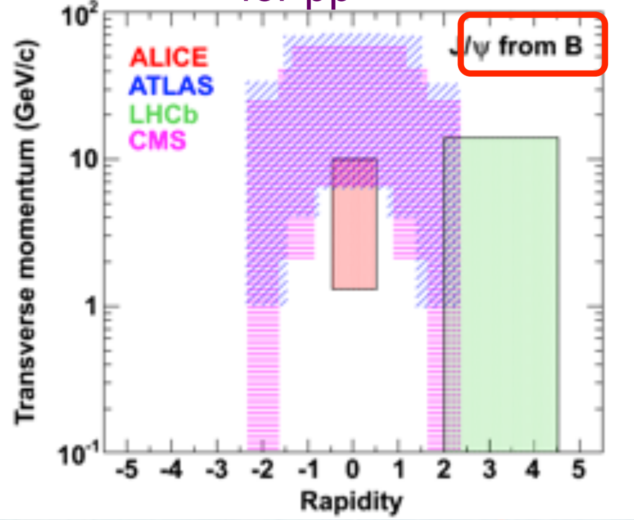
refers to published pp



for pp



for pp



ALICE uniqueness: low p_T (thanks to tracking+PID) especially at y=0

ATLAS/CMS: large rapidity acceptance, high-p_T reach

LHCb: large p_T coverage at forward rapidity

Complementary coverages and measurements

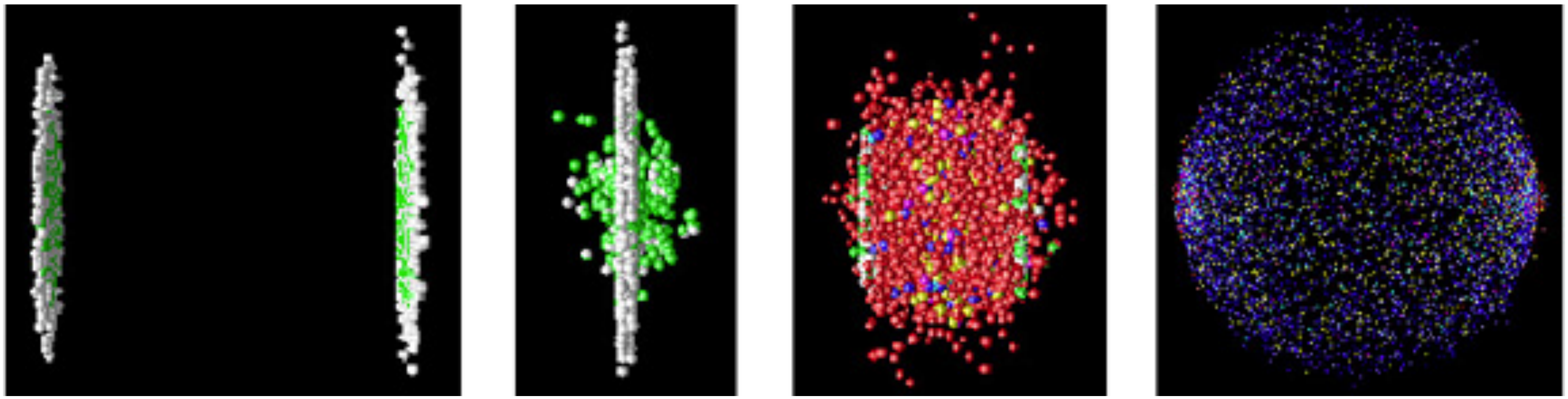
What have we learned from Pb-Pb and p-Pb collisions?

- **Soft probes:**
  - Observables: multiplicity, energy density, collective flow

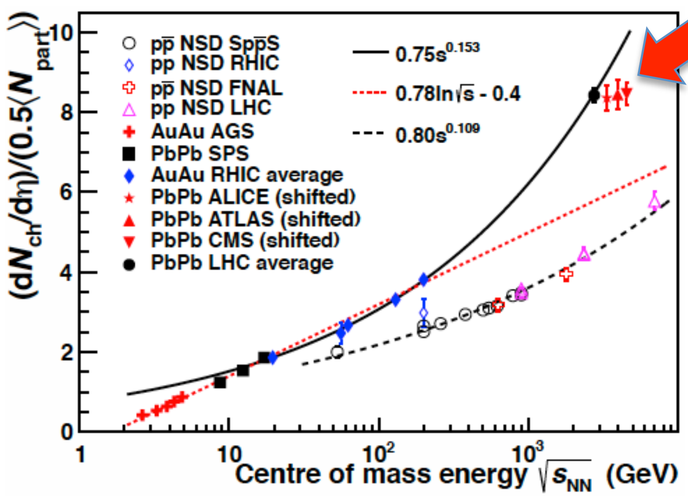
  →access to the global properties of the system

- **Hard probes:**
  - Observables: jets, EW bosons, heavy flavours, quarkonia

  →access to initial state effects (shadowing) and to final state effects (energy loss), access to transport properties

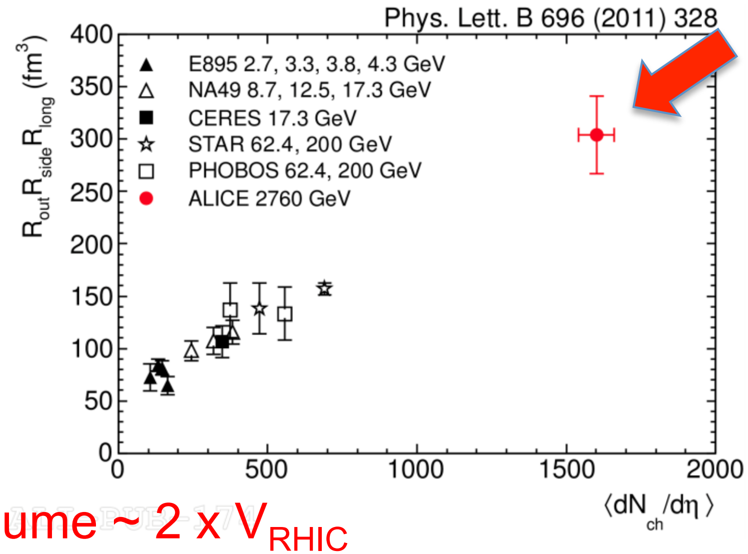


Global properties



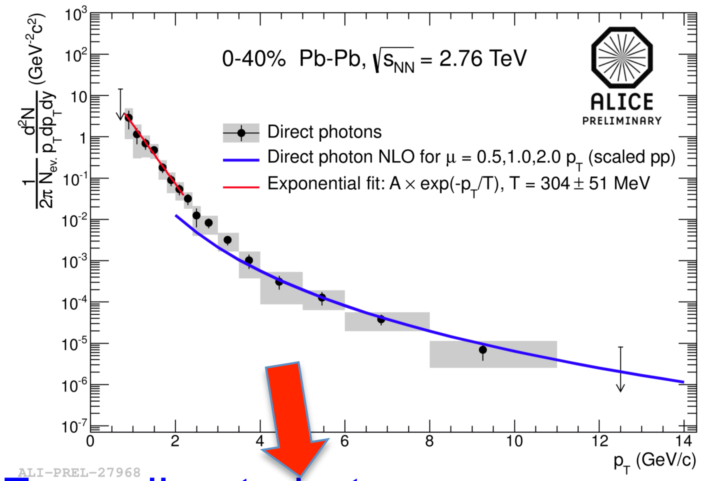
Factor of 2 rise in multiplicity at the LHC compared to RHIC

Energy density ~ 3 x RHIC



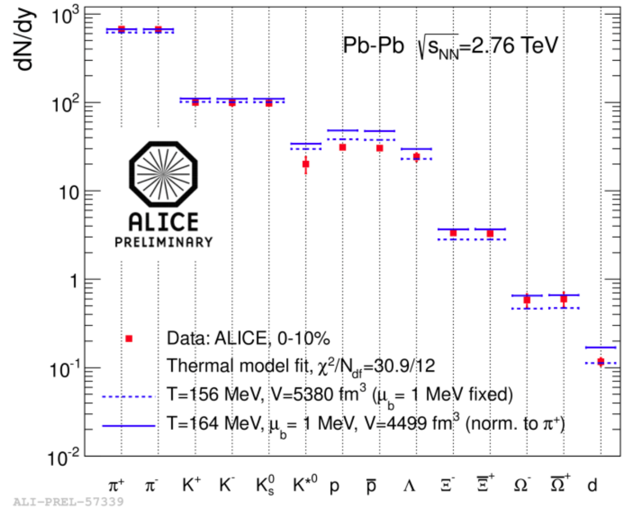
Volume ~ 2 x V_{RHIC}

Lifetime ~ 20% larger than at RHIC



From direct photon measurements

Temperature = (304±51) MeV~ 30% x RHIC

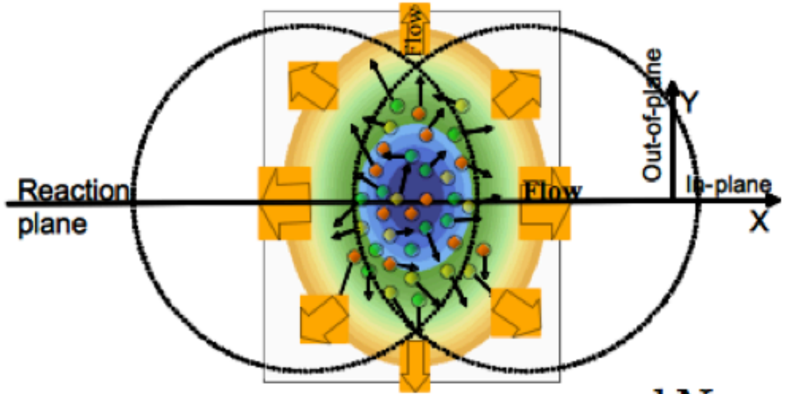


J. Phys. G 38, 124081 (2011)
model

Hadron species abundances described by thermal model, "tensions" for protons

Also other models (PhysRevLett.111.082302)

Soft probes: collective motion



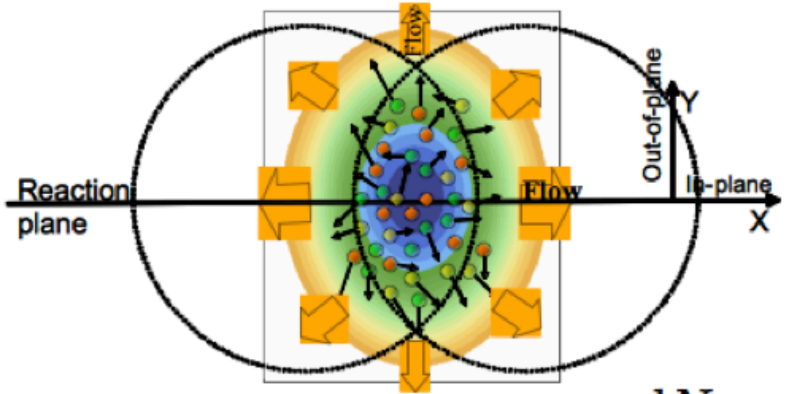
In non-central Pb-Pb collisions

→ non-isotropic azimuthal emission can originate from:

- thermalization/collective motion (low p_T)
- path-length dependence of energy loss (high-p_T)

$$\frac{dN}{d\varphi} = \frac{N_0}{2\pi}\left(1 + 2v_1\cos(\varphi - \Psi_1) + 2v_2\cos[2(\varphi - \Psi_2)] + \ldots\right)$$

Soft probes: collective motion

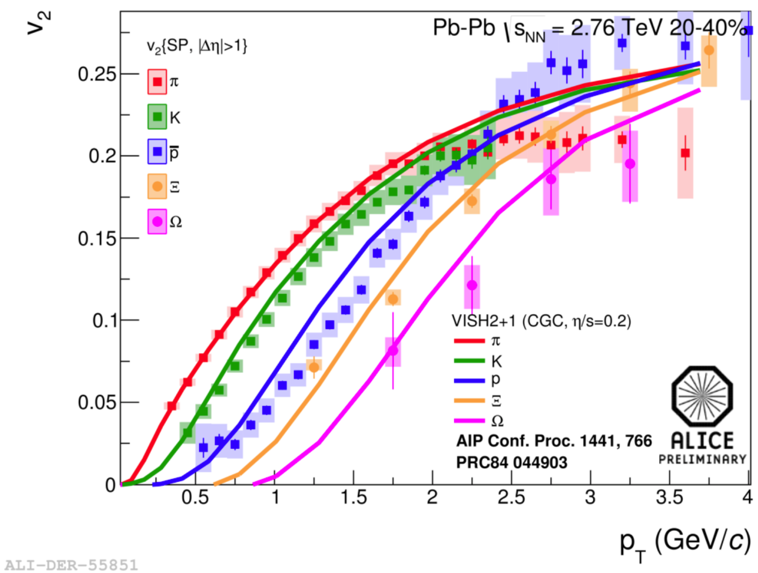


In non-central Pb-Pb collisions

→ non-isotropic azimuthal emission can originate from:

- thermalization/collective motion (low p_T)
- path-length dependence of energy loss (high-p_T)

$$\frac{dN}{d\varphi} = \frac{N_0}{2\pi}\left(1 + 2v_1\cos(\varphi - \Psi_1) + 2v_2\cos[2(\varphi - \Psi_2)] + \ldots\right)$$

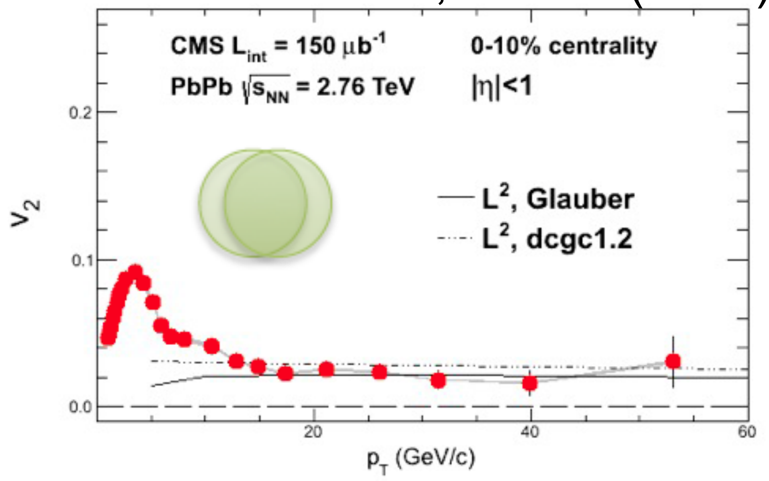


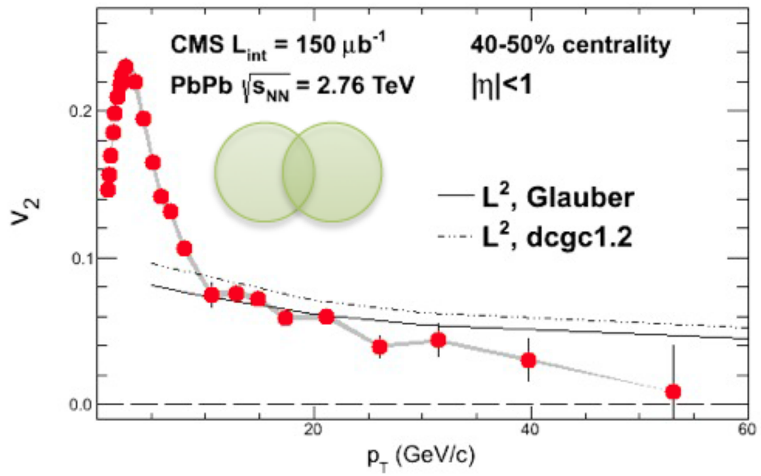
ALICE:
Elliptic flow (v_2) for identified particles

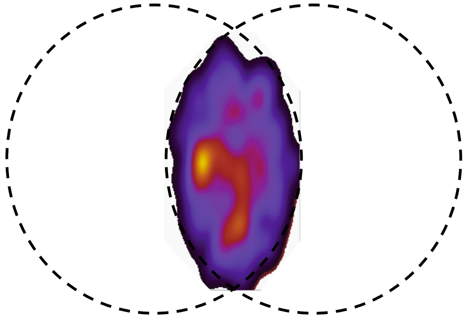
Mass ordering at low-p_T described by hydrodynamics:
$v_2(\pi)>v_2(K)>v_2(p)>v_2(\Omega)$

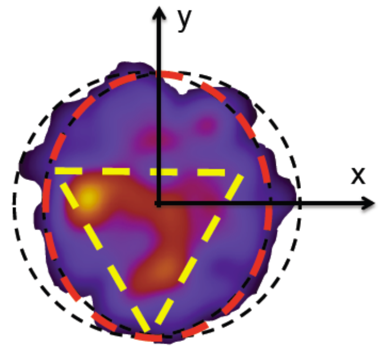
Soft probes: collective motion

PRL 109, 022301(2012)

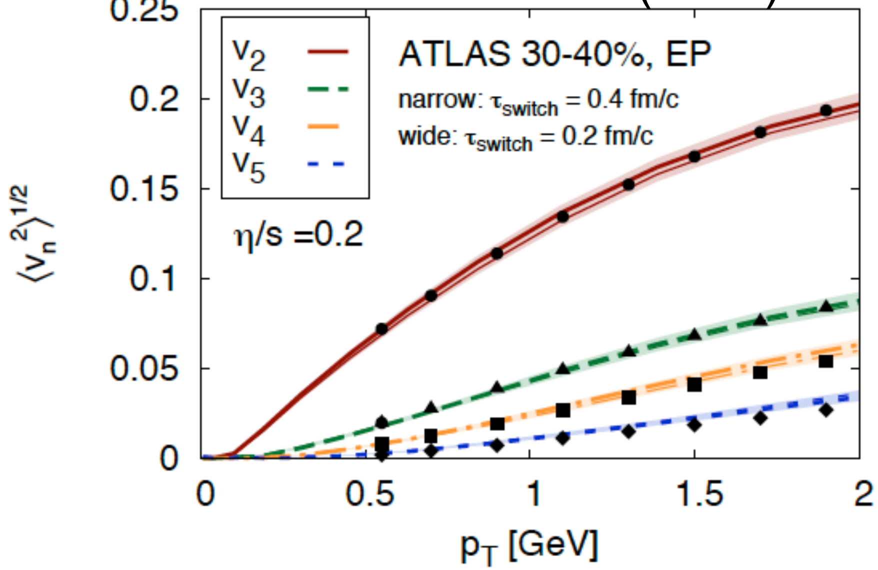








JHEP11(2013)183



CMS

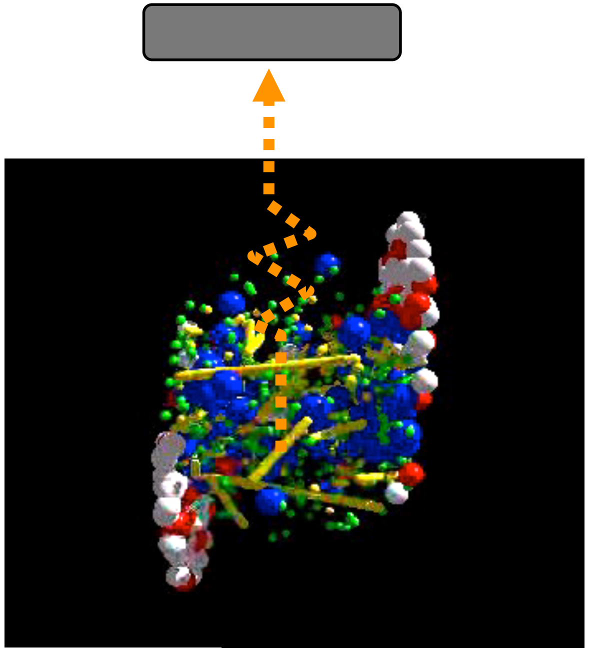
v_2 measured at very high p_T !
Can study geometry-dependence of high-p_T probes

ATLAS

More Fourier harmonic measured besides v_2.
Info on initial-state fluctuations.
Viscous hydro able to describe ATLAS v_n data.

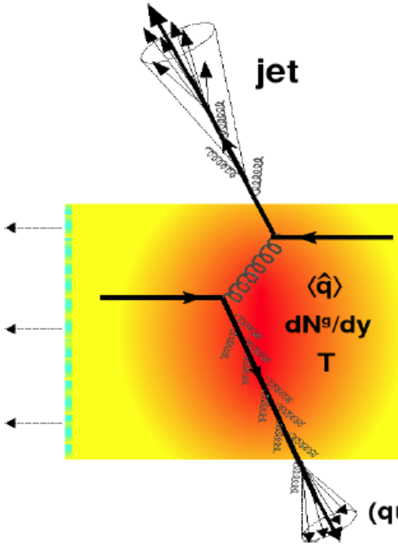
Hard probes

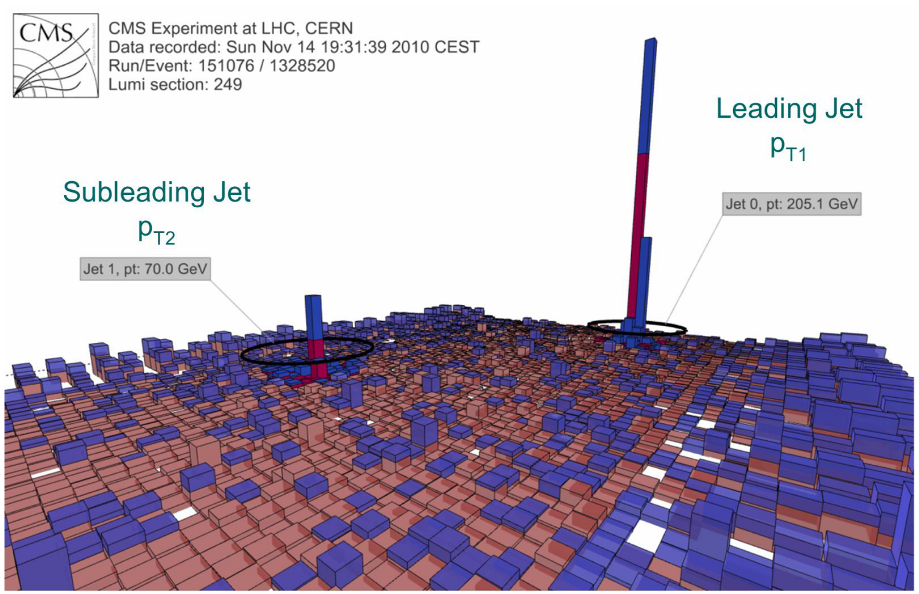
Detector



Self-generated "hard" probes

Hard processes make perturbative QCD applicable
→ high momentum transfer Q^2





Hard probes: high-p_T particles

Nuclear modification factor

$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

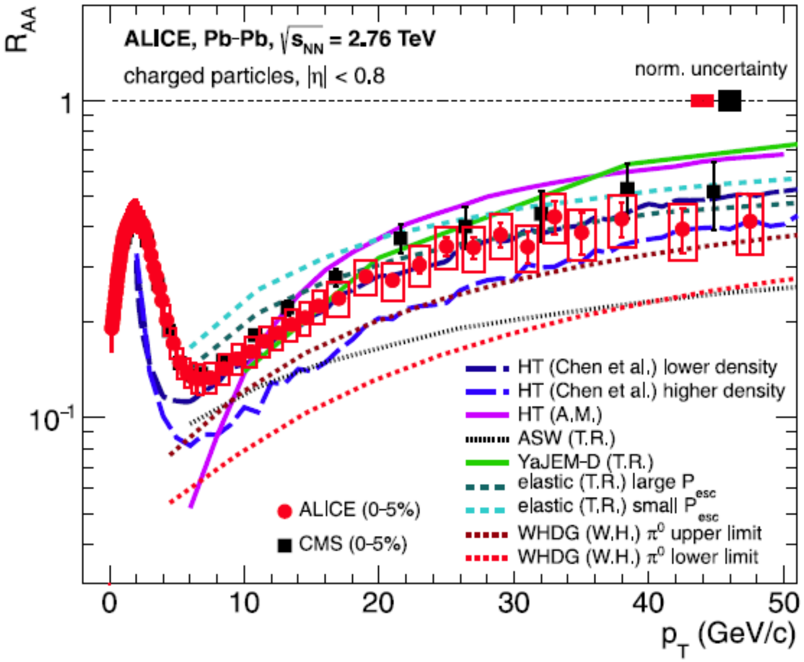
If **$R_{AA}=1$** → no nuclear effects
if **$R_{AA}\neq 1$** → binary scaling broken.
Energy loss gives rise to $R_{AA}<1$ at high p_T
→ Hot nuclear matter effect

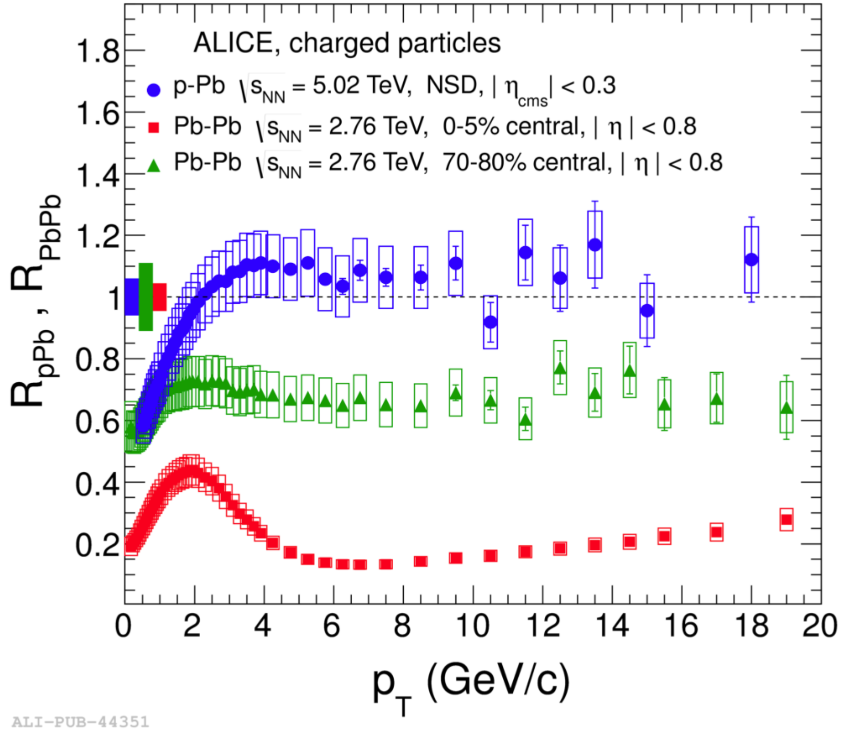
Hard probes: high-p_T particles

Nuclear modification factor

$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

If $R_{AA}=1$ → no nuclear effects
if $R_{AA}\neq 1$ → binary scaling broken.
Energy loss gives rise to $R_{AA}<1$ at high p_T
→ Hot nuclear matter effect



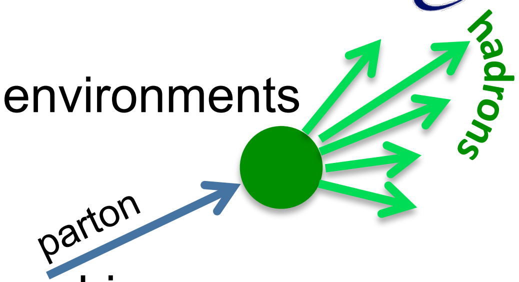


Strong suppression of charged hadrons in Pb-Pb up to very high momenta

p-Pb vs Pb-Pb: Strong suppression in Pb-Pb due to hot nuclear matter effects

Hard probes: Jets

Goal: measure the parton energy in heavy-ion collisions
How: modern jet-finding algorithms optimized for high-multiplicity environments



What to expect in A-A collisions?

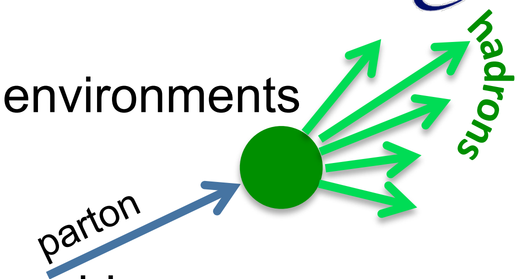
-jets are hard processes and scale as N_{bin} (n. of binary collisions)
-if the jet energy fully recovered in the jet cone even in case of quenching

$$\rightarrow \; R_{AA}^{jet} = \frac{\sigma_{AA}^{jet}}{\langle N_{bin} \rangle \sigma_{pp}^{jet}} = 1$$

Hard probes: Jets

Goal: measure the parton energy in heavy-ion collisions

How: modern jet-finding algorithms optimized for high-multiplicity environments

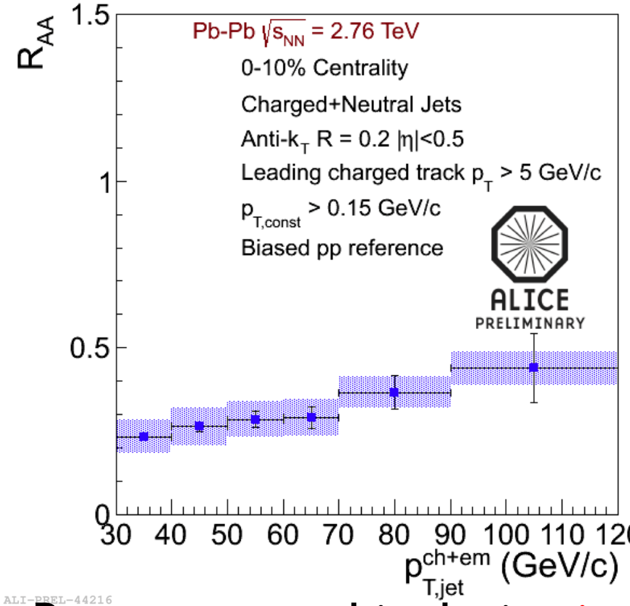


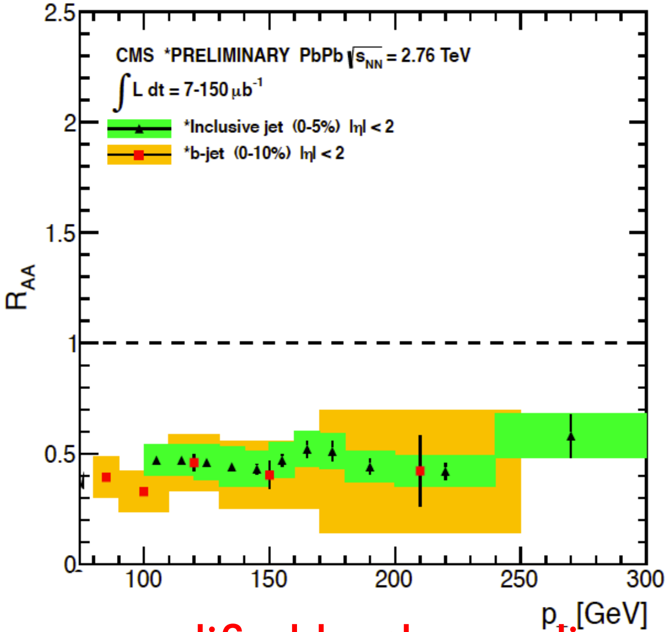
What to expect in A-A collisions?

-jets are hard processes and scale as N_{bin}

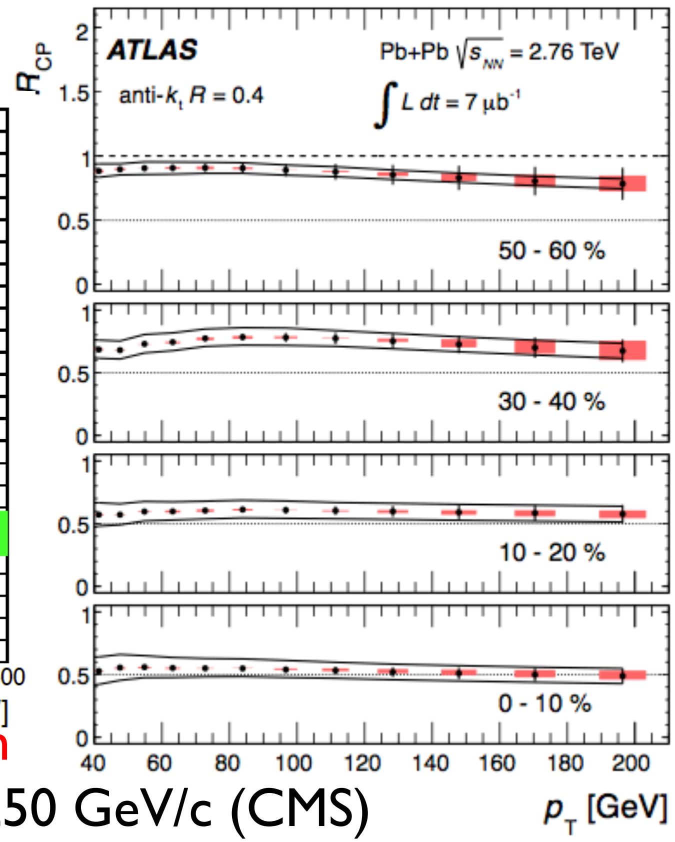
-if the jet energy fully recovered in the jet cone even in case of quenching

$$\rightarrow R_{AA}^{jet} = \frac{\sigma_{AA}^{jet}}{\langle N_{bin} \rangle \sigma_{pp}^{jet}} = 1$$





Phys. Lett. B 719 (2013) 220-241



Reconstructed inclusive jets are modified by the medium

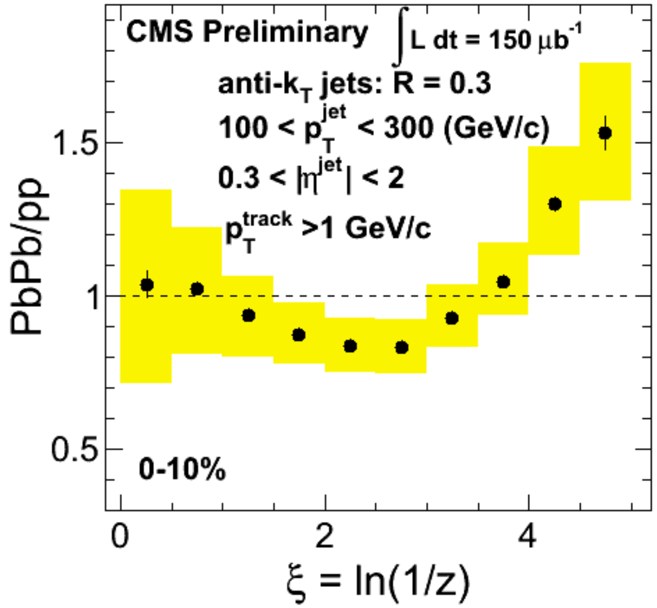
Strong suppression down to ~30 GeV/c (ALICE) up to 250 GeV/c (CMS)

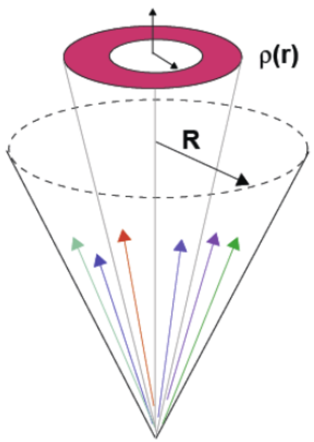
Suppression depends on collision centrality (ATLAS): stronger in central events

Hard probes: jet structures

Is the jet energy redistributed in particle p_T?
Is the jet energy redistributed in radius?

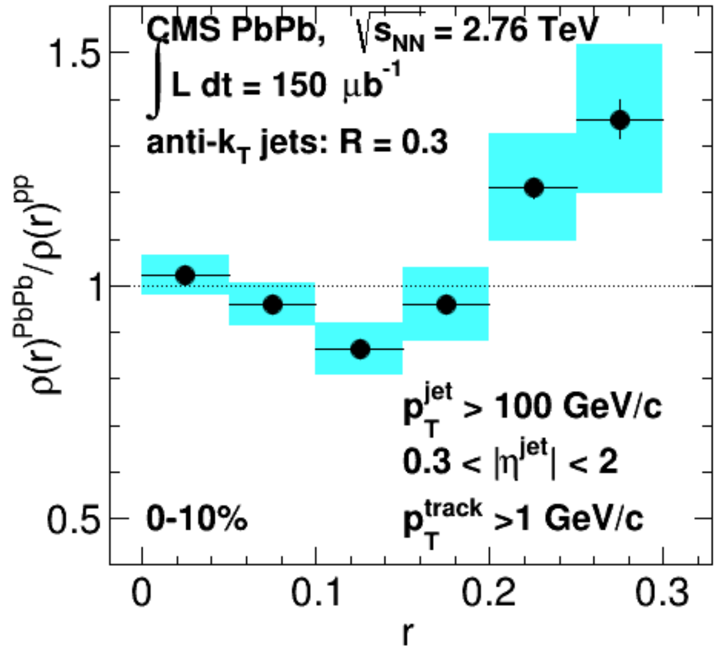
Ratio of Fragmentation Functions:
PbPb/pp





Fractional radial energy distribution

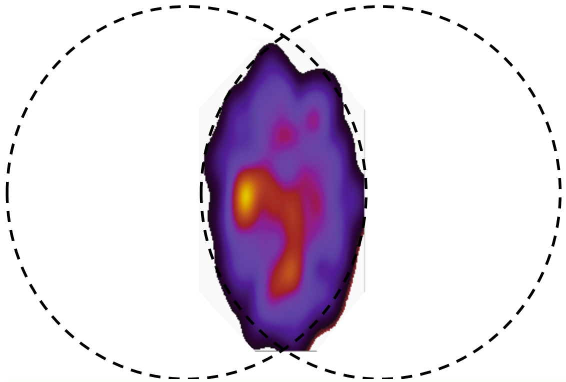
Jet Energy profile:
PbPb/pp



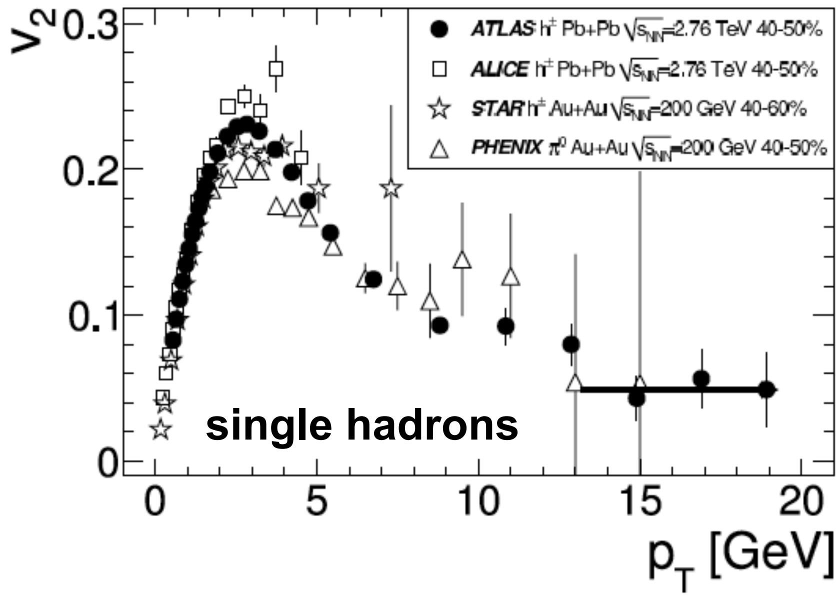
Depletion at mid p_T and radius; enhancement at low p_T and larger radius

Hard probes: Jet azimuthal anisotropy

$$\frac{dN}{d\varphi} = \frac{N_0}{2\pi}\left(1 + 2v_1\cos(\varphi - \Psi_1) + 2v_2\cos[2(\varphi - \Psi_2)] + \ldots\right)$$

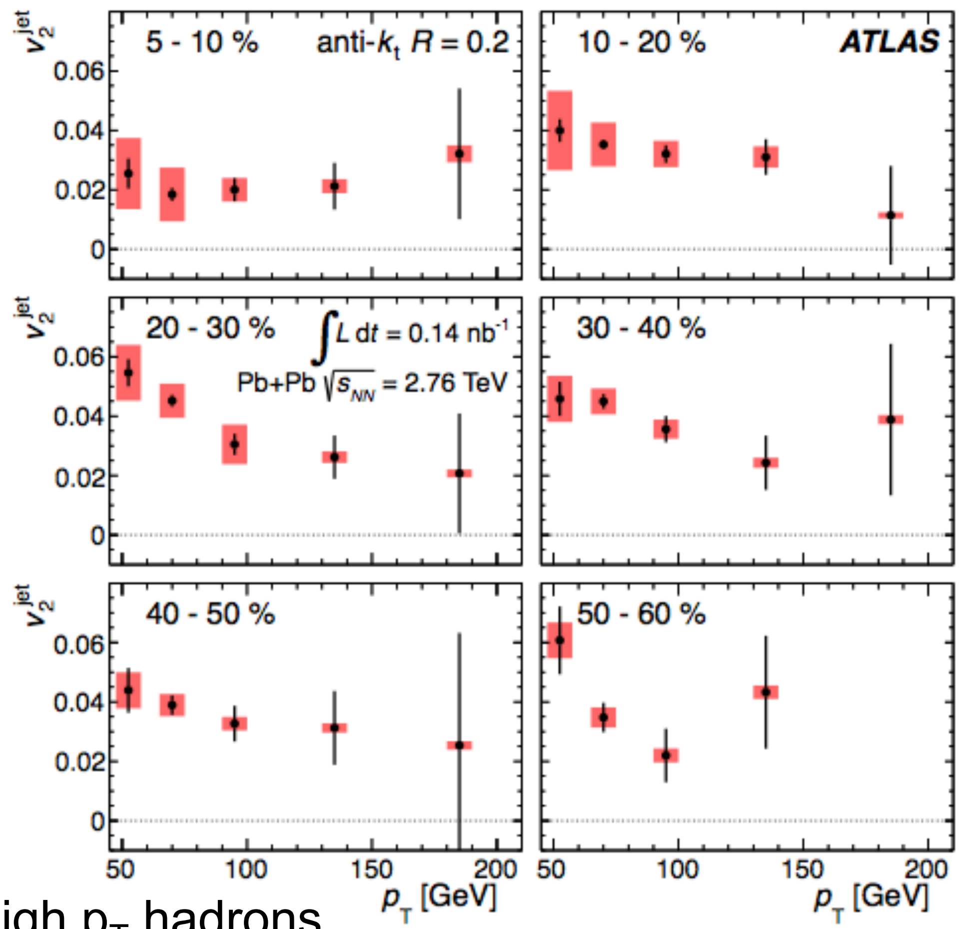


ATLAS, Phys.Lett. B707 (2012) 330-348



jets

arXiv:1306.6469



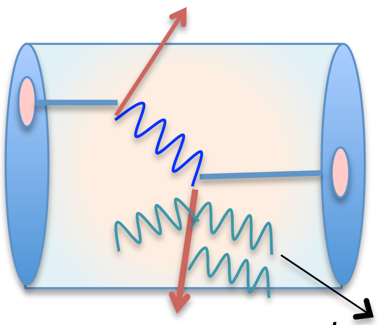
$v_{2,jet}$ is similar to magnitude seen for high p_T hadrons.

→ access path-length dependence of jet energy loss

Heavy Flavours

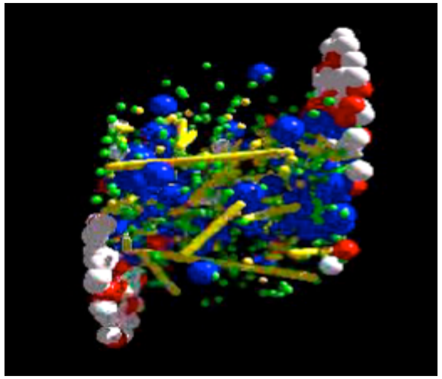
Heavy quarks are produced in high-Q^2 processes in the initial stage of the collision

→ Pb-Pb: initially-produced probes exposed to the medium evolution



How do partons interact with the medium?

- Radiative gluon emission
- Elastic collisions with the constituents



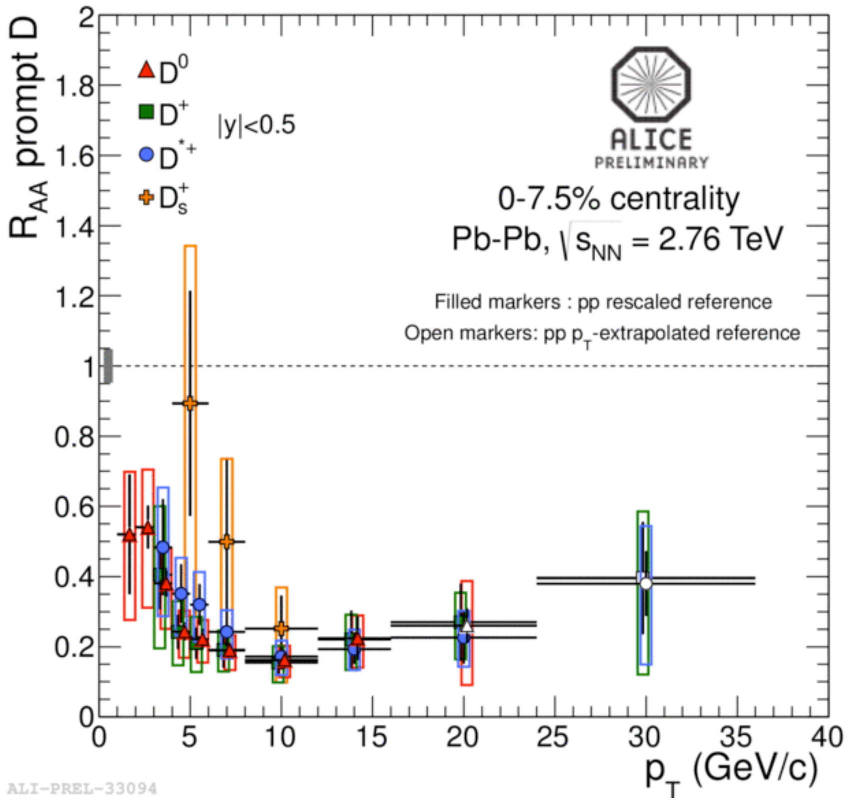
What does the radiative energy loss depend on?

- Medium density, path-length → $\langle \Delta E \rangle \propto \alpha_s C_R \hat{q} L^2$
- Colour-charge, Mass ("dead-cone") → $\Delta E_g > \Delta E_{u,d} > \Delta E_c > \Delta E_b$

Dokshitzer and Kharzeev, PLB 519 (2001) 199.

See E. Meninno's talk

D meson R_{AA}



Kuznetsova & Rafelski, EPJ C51(2007)113;
He et al., arXiv:1204.4442;
Andronic et al., arXiv:0708.1488

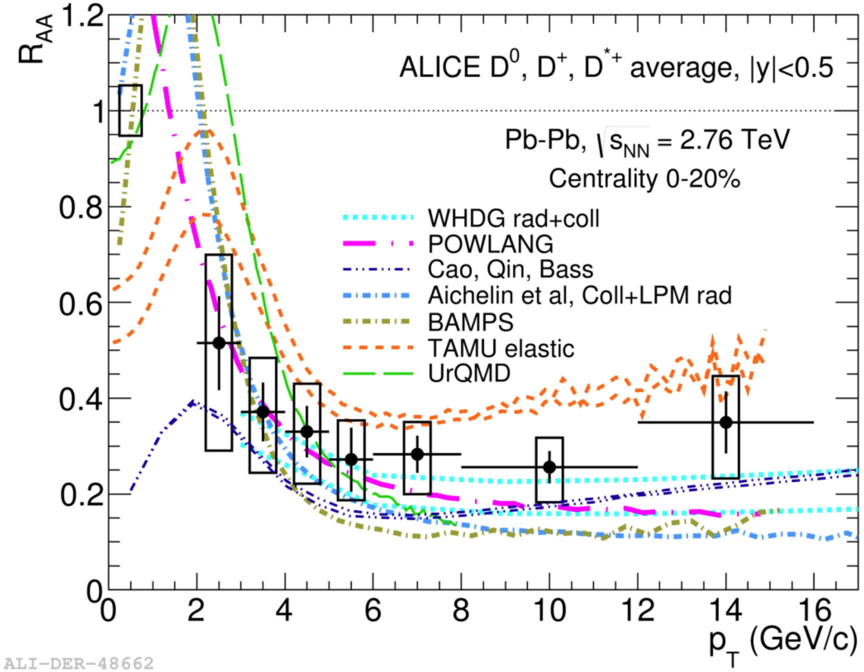
$$R_{AA}^{D}(p_T) = \frac{dN_{AA}^{D}/dp_T}{\langle T_{AA}\rangle \times d\sigma_{pp}^{D}/dp_T}$$

Large suppression in a wide p_T range:
→factor of 4-5 in $5<p_T<15$ GeV/c

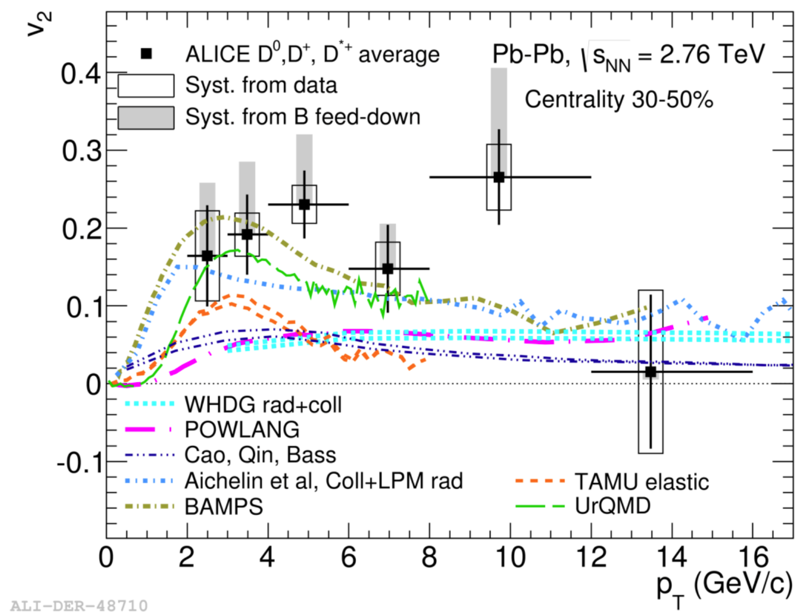
First measurement of D_s in Pb-Pb collisions with 2011 Run
→suppression of 3-5 in 8-12 GeV/c
→more statistics needed to conclude on the expected enhancement of low-p_T D_s

R_{AA} and v_2

ALICE, JHEP 1209 (2012) 112



ALICE, PRL 111 (2013) 102301



Theoretical models reproduce reasonably well open charm R_{AA} but are challenged by simultaneously reproducing results from heavy-flavour R_{AA} and v_2

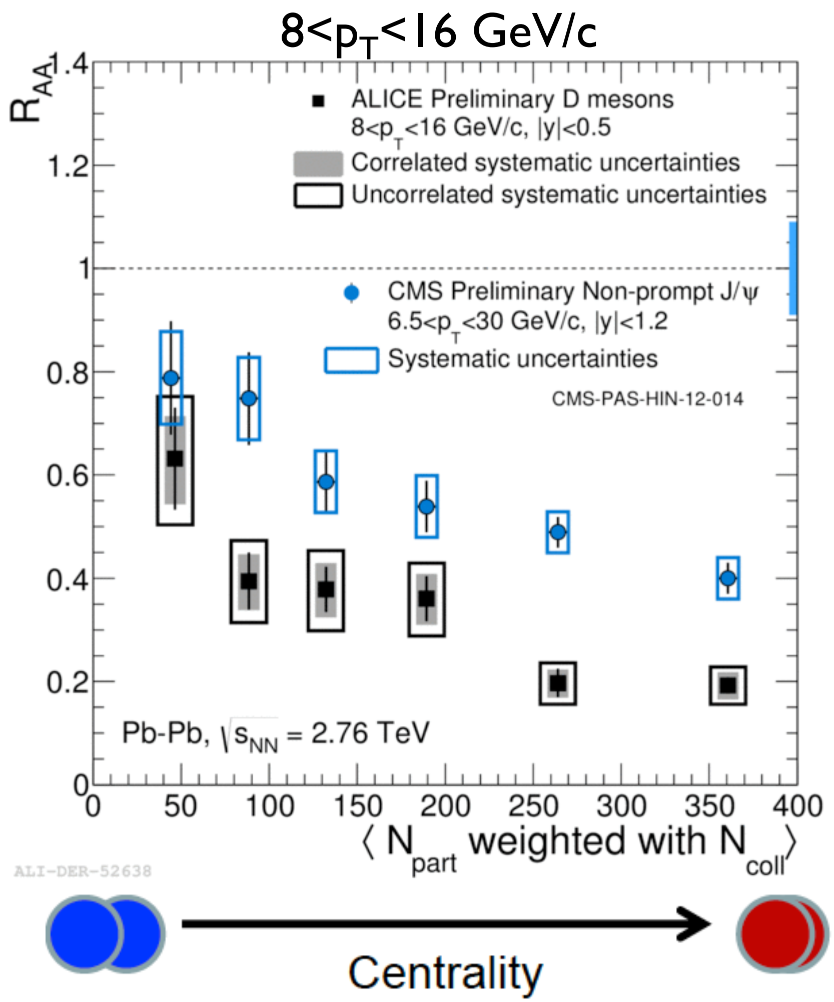
Reducing statistical and systematic errors and introducing new differential observables will help to disentangle among different models

BAMPS: Fochler et al., J. Phys. G38 (2011) 124152
POWLANG: Alberico et al., Eur.Phys.J C71 (2011) 1666
UrQMD: T. Lang et al, arXiv:1211.6912 [hep-ph];
T. Lang et al., arXiv:1212.0696 [hep-ph].
TAMU: Rapp, He et al., Phys. Rev. C 86 (2012) 014903
WHDG: Horowitz et al., JPhys G38 (2011) 124114
Aichelin et al.: Phys. Rev. C79 (2009) 044906
J. Phys. G37 (2010) 094019

Charm vs beauty suppression

Charm: prompt D mesons (ALICE)

Beauty non-prompt J/ψ (CMS)



Indication of a difference between charm and beauty suppression in central collisions, expected from hierarchy in energy loss:

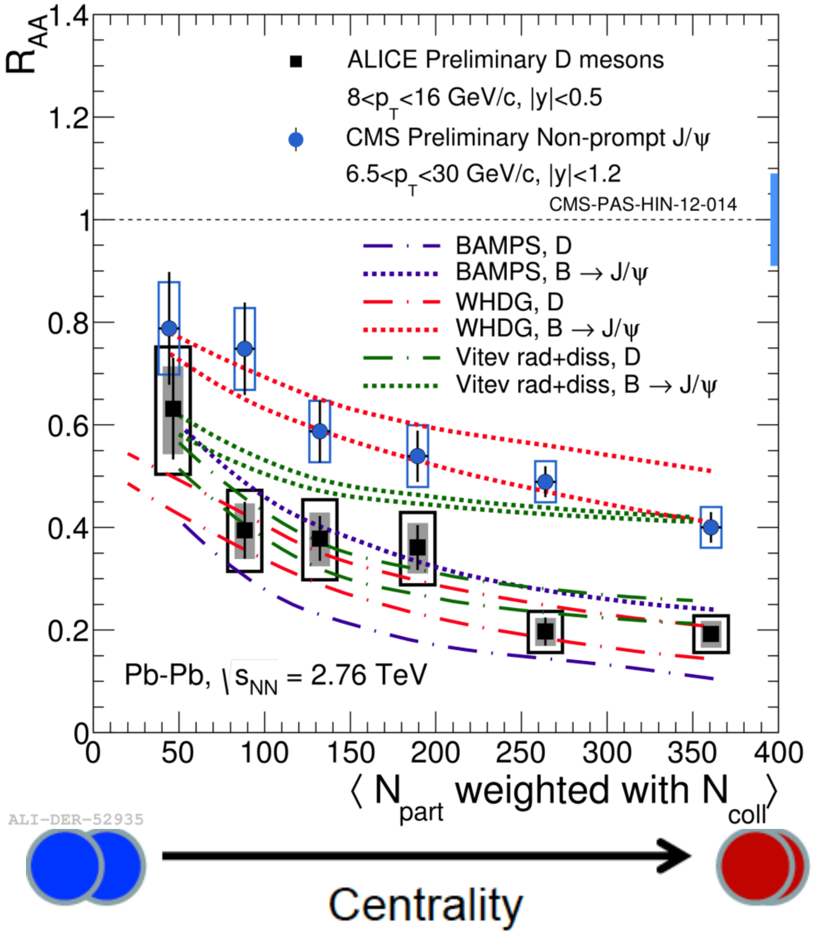
$\Delta E_g > \Delta E_{uds} > \Delta E_c > \Delta E_b \quad \rightarrow \quad R_{AA}(B) > R_{AA}(D) > R_{AA}(\pi)$

Charm vs beauty suppression

8<p_T<16 GeV/c

Charm: prompt D mesons (ALICE)

Beauty non-prompt J/ψ (CMS)



Indication of a difference between charm and beauty suppression in central collisions, expected from hierarchy in energy loss:

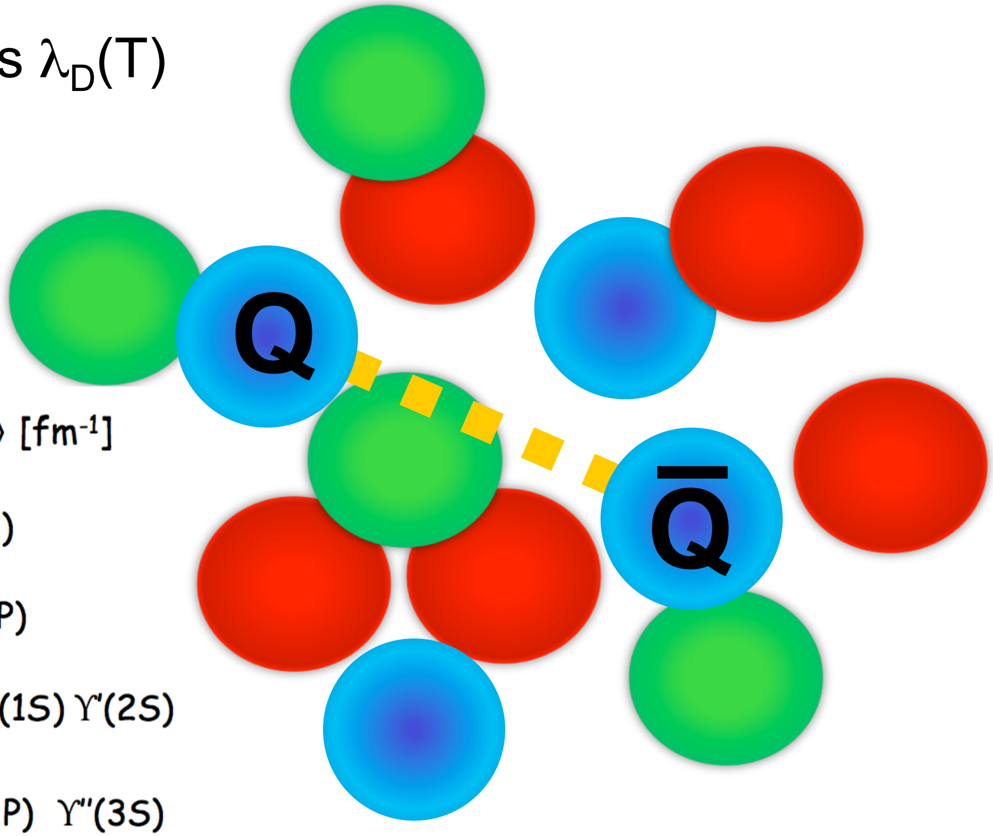
$\Delta E_g > \Delta E_{uds} > \Delta E_c > \Delta E_b \rightarrow R_{AA}(B) > R_{AA}(D) > R_{AA}(\pi)$

Hard Probes: Quarkonia

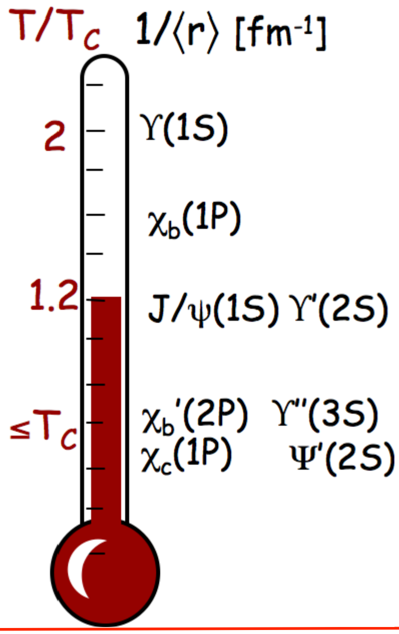
What happens to a $q\bar{q}$ pair in the Quark Gluon Plasma?

The binding of the $q\bar{q}$ pair is subject to the effects of the colour screening

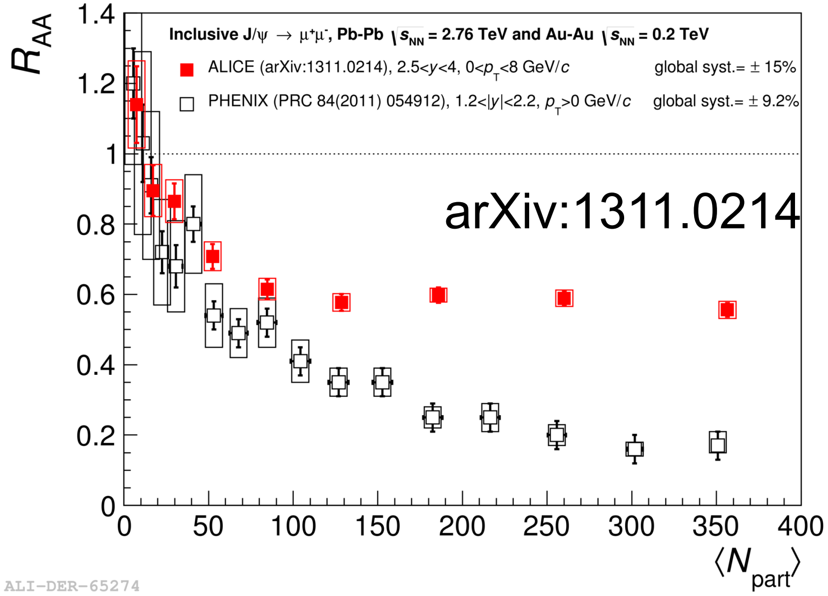
If resonance radius > screening radius $\lambda_D(T)$
→no resonance can be formed
→suppression of J/ψ as a signature for the QGP (Matsui, Satz, 1986)



Differences in the binding energies of $q\bar{q}$ states
→ sequential melting of the states with increasing temperature



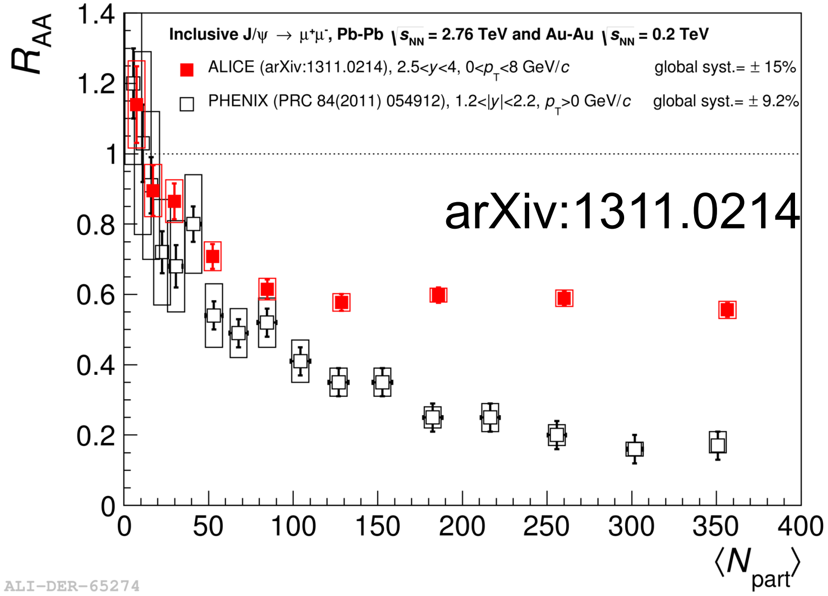
Hard Probes: Quarkonia



Difference in J/ψ suppression ALICE(LHC) - PHENIX (RHIC).

Could it be recombination at LHC energies?
-i.e. quarkonium formed by statistical recombination of $c\bar{c}$ quarks close in momentum
-if so, it should be at low p_T

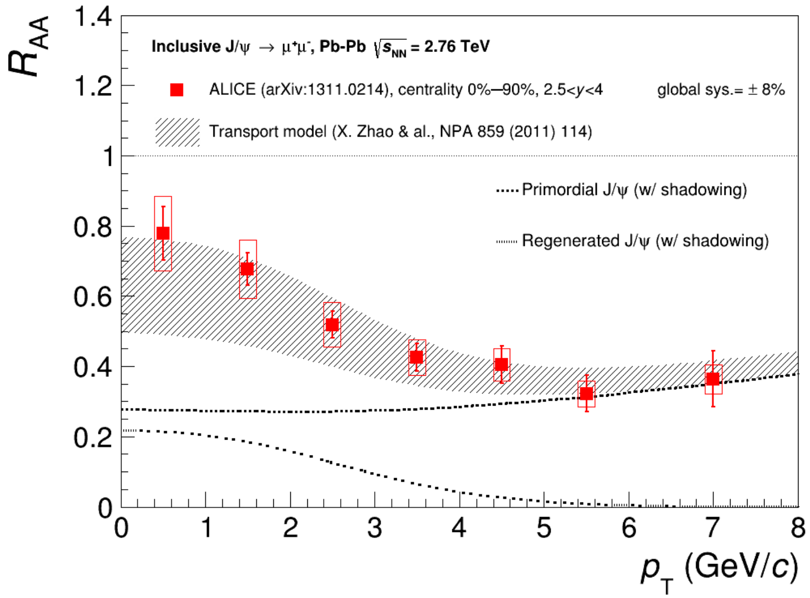
Hard Probes: Quarkonia



J/ψ suppression smaller at ALICE (LHC) then at PHENIX (RHIC).

Could it be recombination at LHC energies?
-i.e. quarkonium formed by statistical recombination of $c\bar{c}$ quarks close in momentum
-if so, it should be at low p_T

arXiv:1311.0214



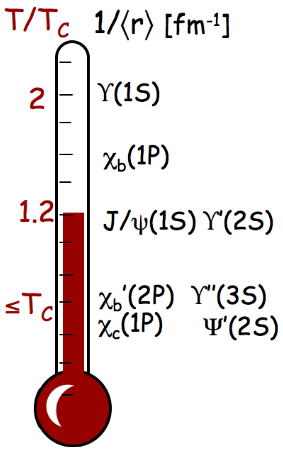
Strong dependence of J/ψ suppression vs p_T!

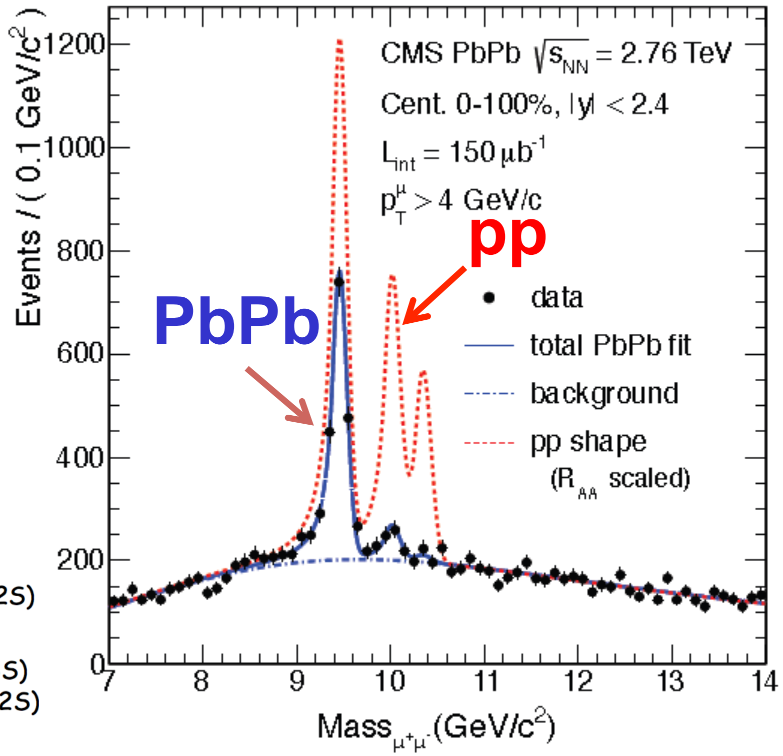
Models: ~50% of low-p_T J/ψ are produced via (re)combination, while at high p_T the contribution is negligible

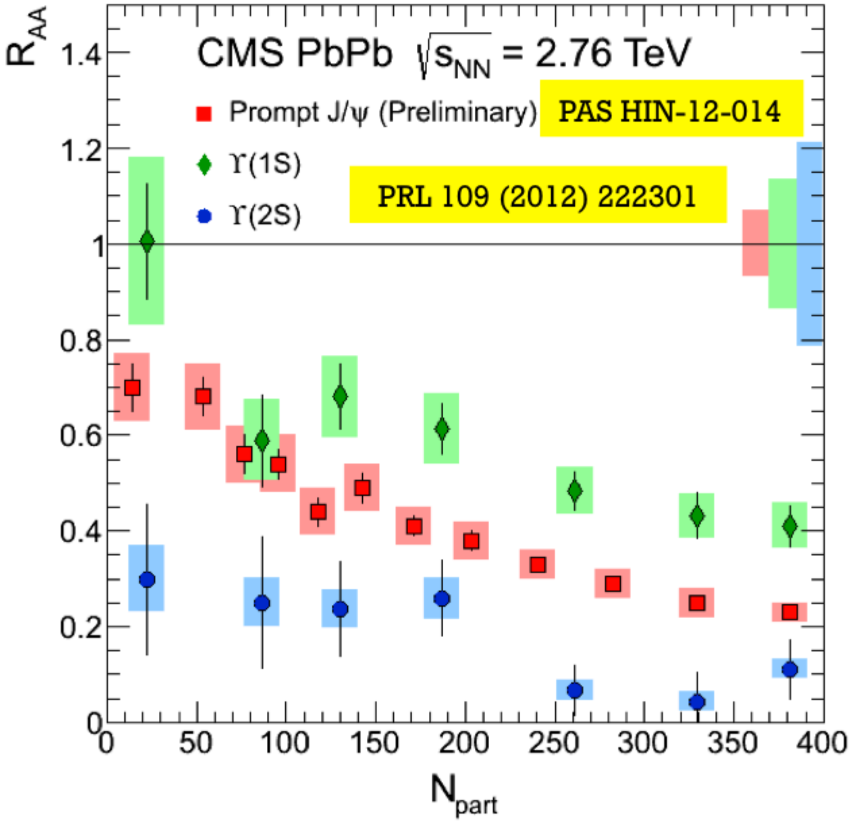
See M. Leoncino's talk

Hard Probes: Quarkonia

PRL 109, 222301 (2012)







$$R_{AA}^{\Upsilon(3S)} < R_{AA}^{\Upsilon(2S)} < R_{AA}^{\Upsilon(1S)}$$

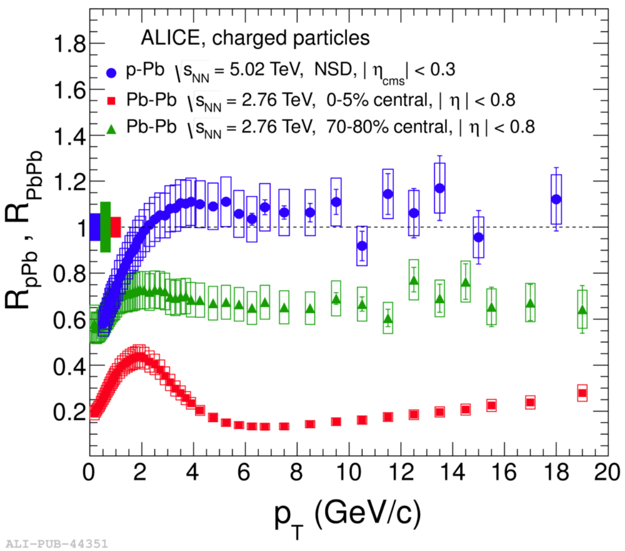
Υ(1S) suppression might be compatible with feed-down suppression (50%).

Possibly Υ(1S) dissociation threshold still beyond LHC reach

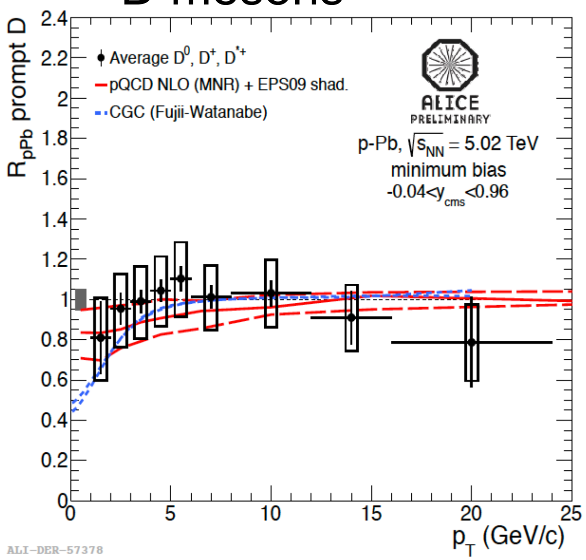
→ wait for LHC full energy!

p-Pb collisions: just a control experiment?

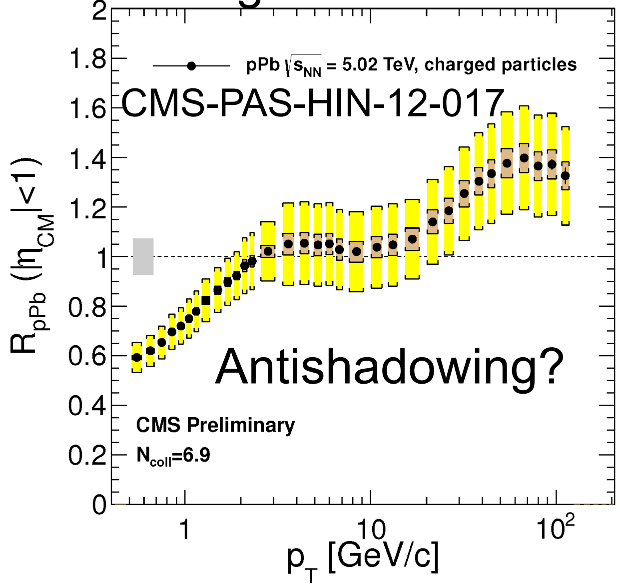
Charged hadrons



D mesons

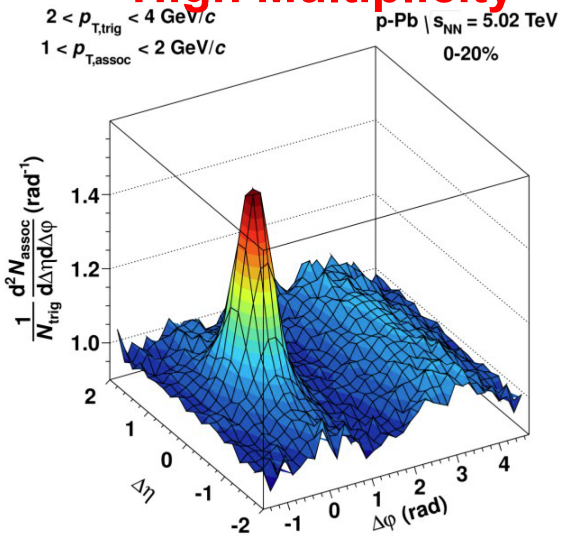


Charged hadrons

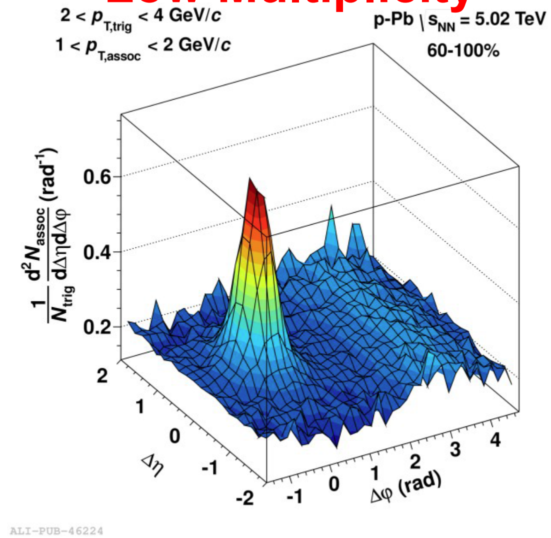


p-Pb: two-particle Δη-Δφ correlations

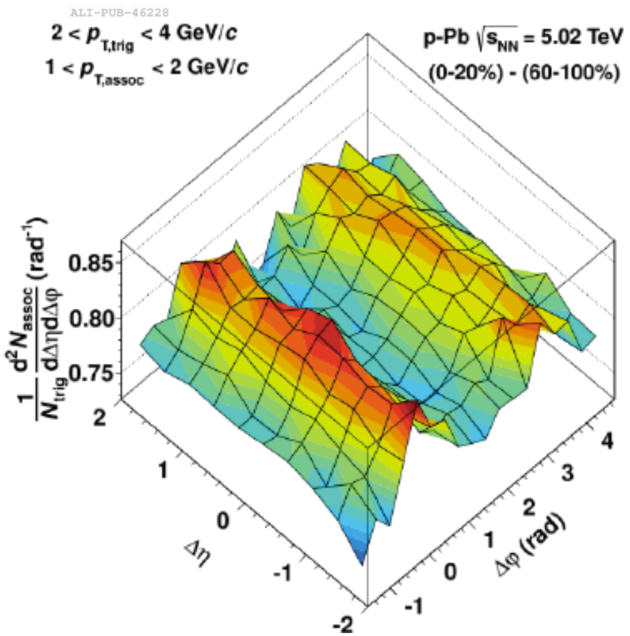
High Multiplicity



Low Multiplicity



High - Low Multiplicity



Remaining Δη-Δφ after subtracting the jet component

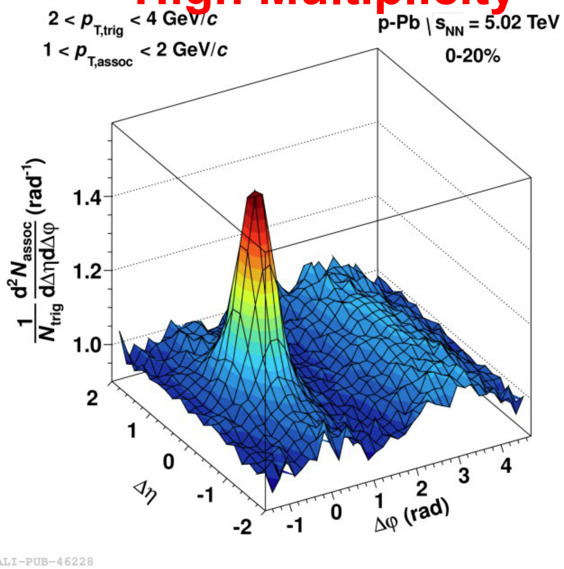
→two long range structures (double ridge)

..flow in pPb !?

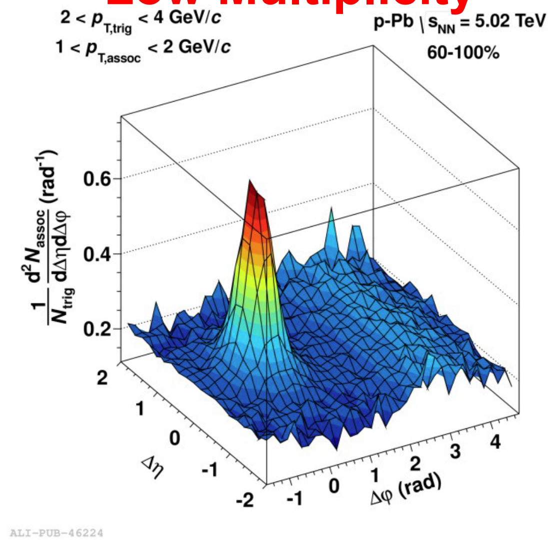
...or other initial/final state effects?

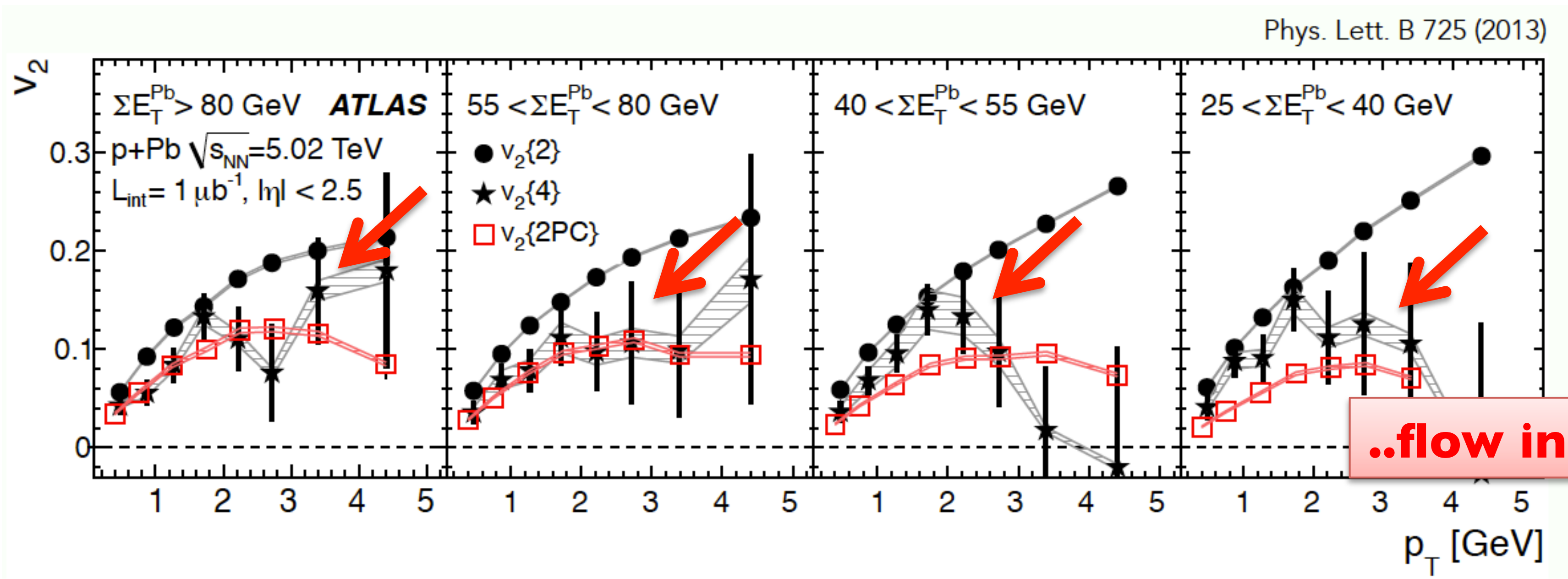
p-Pb: two-particle Δη-Δφ correlations

High Multiplicity



Low Multiplicity

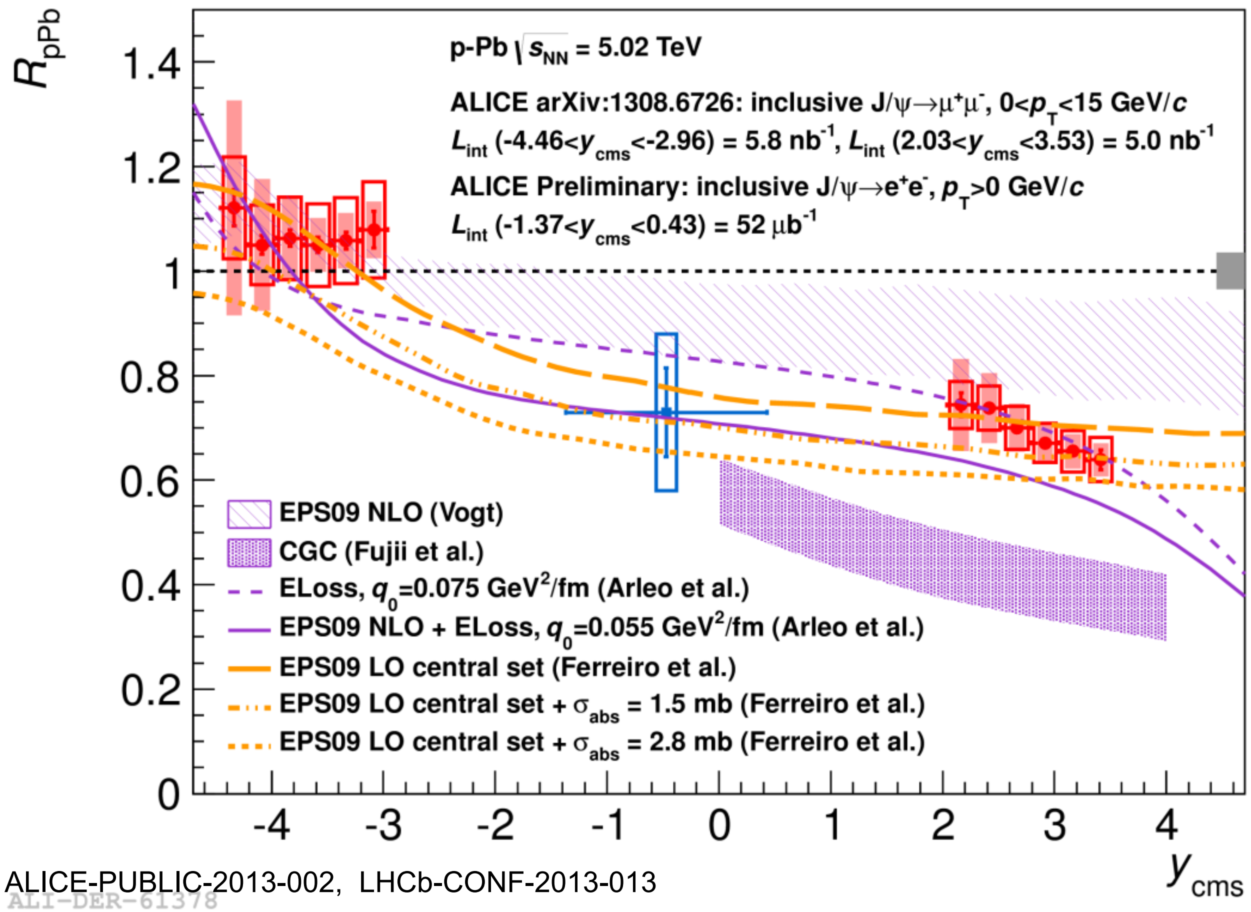




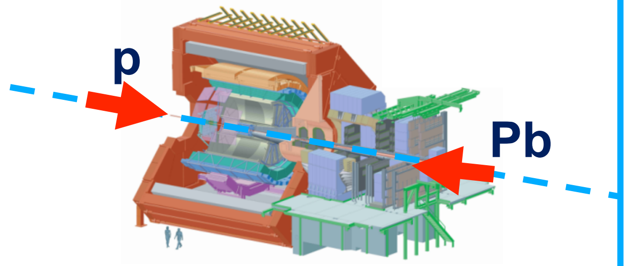
..flow in pPb !?

Quarkonia in p-Pb

JHEP02(2014)073

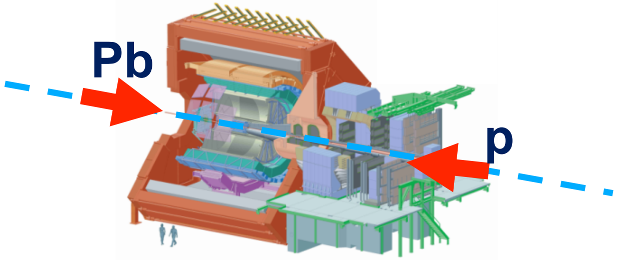


ALICE-PUBLIC-2013-002, LHCb-CONF-2013-013



$2.03<y_{CMS}<3.53$

$10^{-5}<x<8\cdot10^{-5}$



$-4.46<y_{CMS}<-2.96$

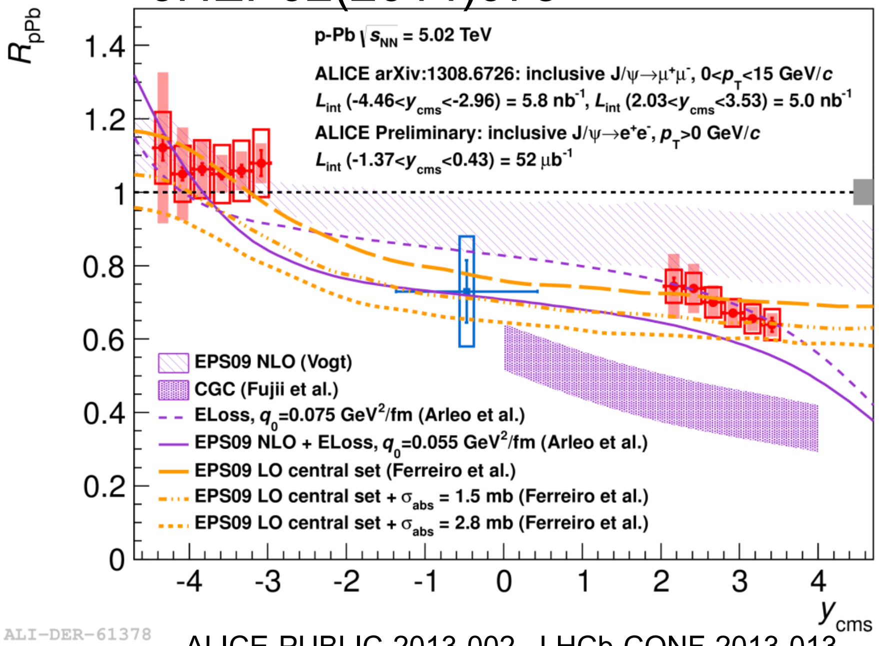
$10^{-2}<x<5\cdot10^{-2}$

J/ψ production is modified also in pA because of Cold Nuclear Matter effects: R_{pA} decreases towards forward *y*.

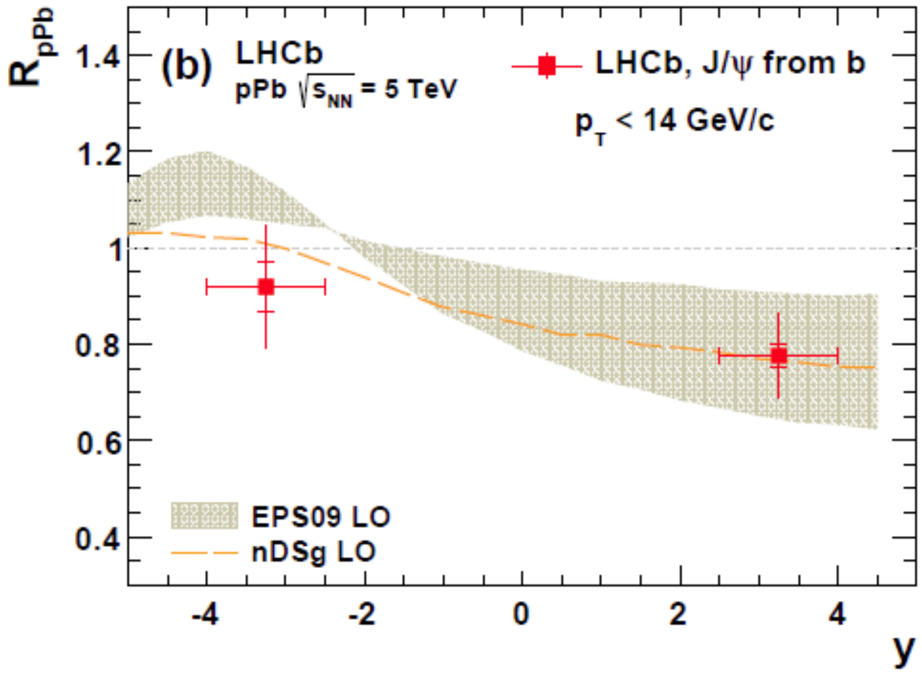
Reasonable agreement with theoretical predictions (shadowing depends on y)

Quarkonia in p-Pb

JHEP02(2014)073



ALICE-PUBLIC-2013-002, LHCb-CONF-2013-013



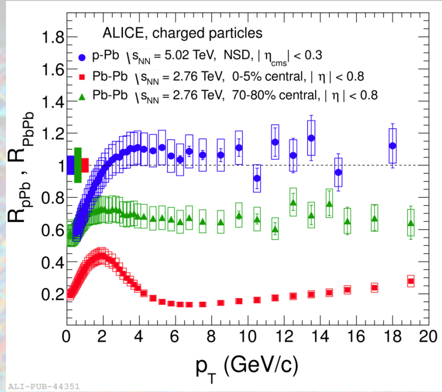
Similar dependence found by LHCb, also for non-prompt J/ψ from B decays

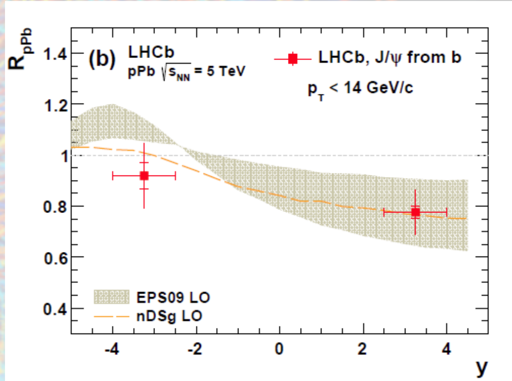
→B hadrons less affected by cold nuclear effects?

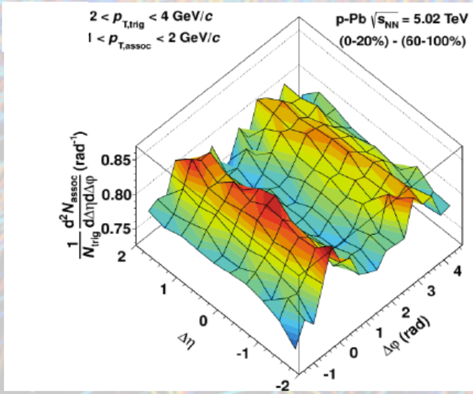
Conclusions

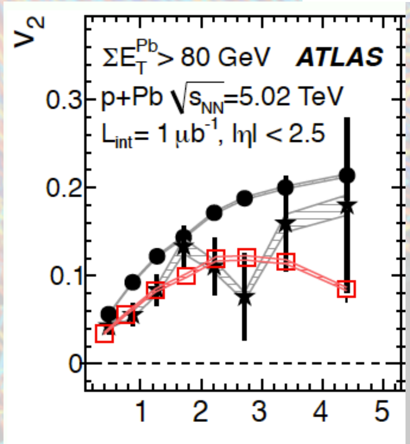
p-Pb:

- Not only a control experiment to compare to Pb-Pb!
- Investigate Cold Nuclear Matter Effects, study shadowing and saturation at low x
- Collective effects at high multiplicities in small systems like pp and pPb!





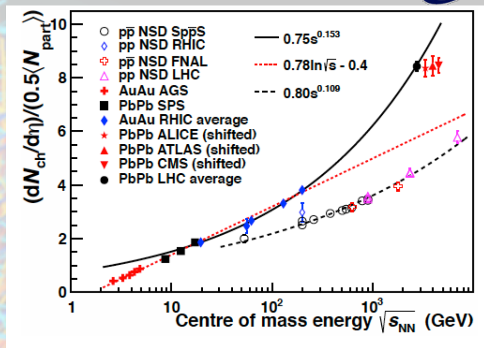


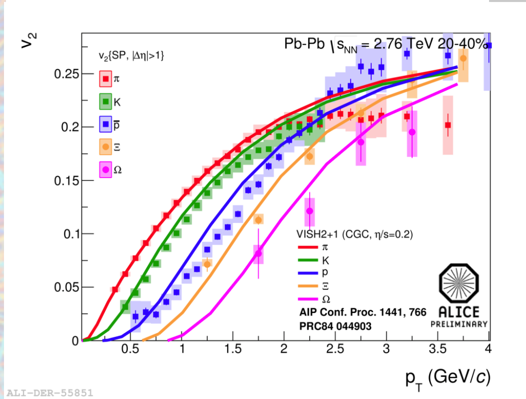


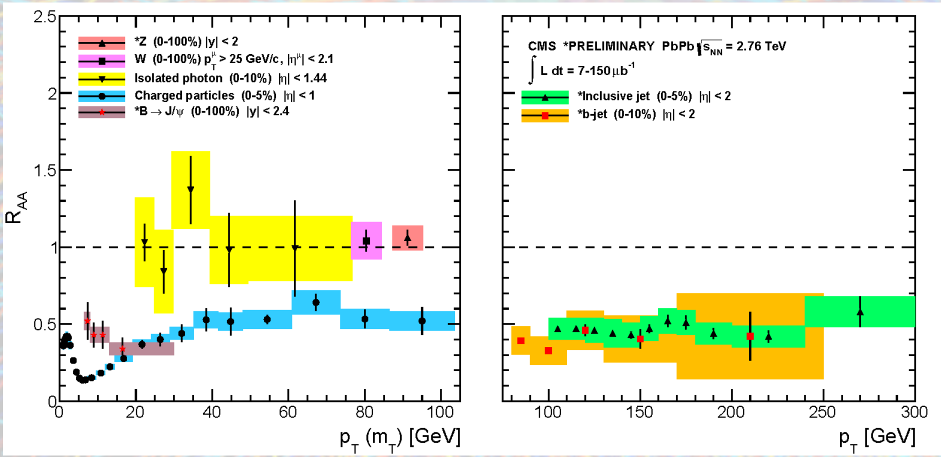
Conclusions

Pb-Pb:

- strong coupling liquid created in PbPb collisions at the LHC
- Different probes (soft, hard) enable the access to the medium properties (temperature, density, transport properties)







See S. Siddhanta's poster

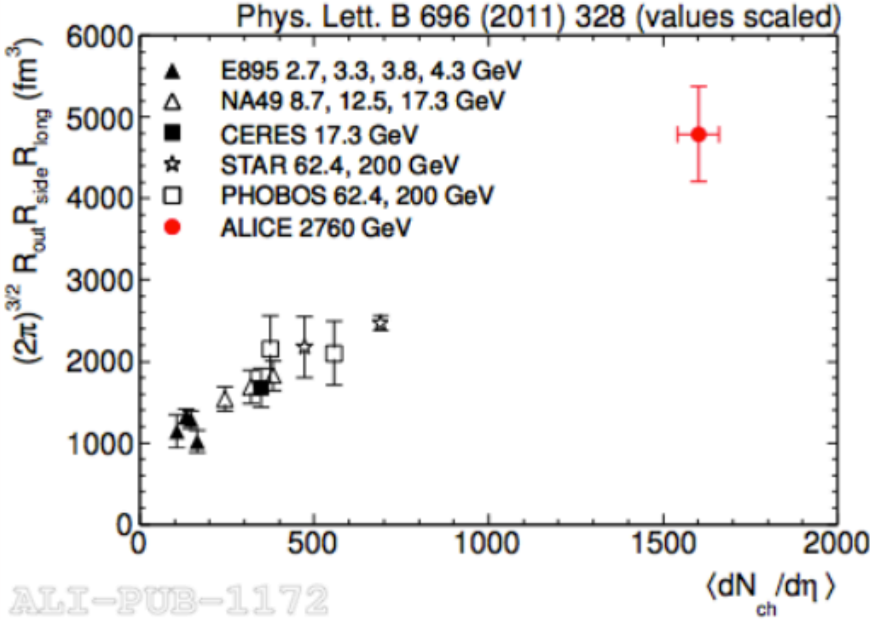
With future data **(Run 2 and Run 3 with LHC and detector upgrades)**, smaller statistical and systematic uncertainties and new differential measurements will help to further constrain theory.

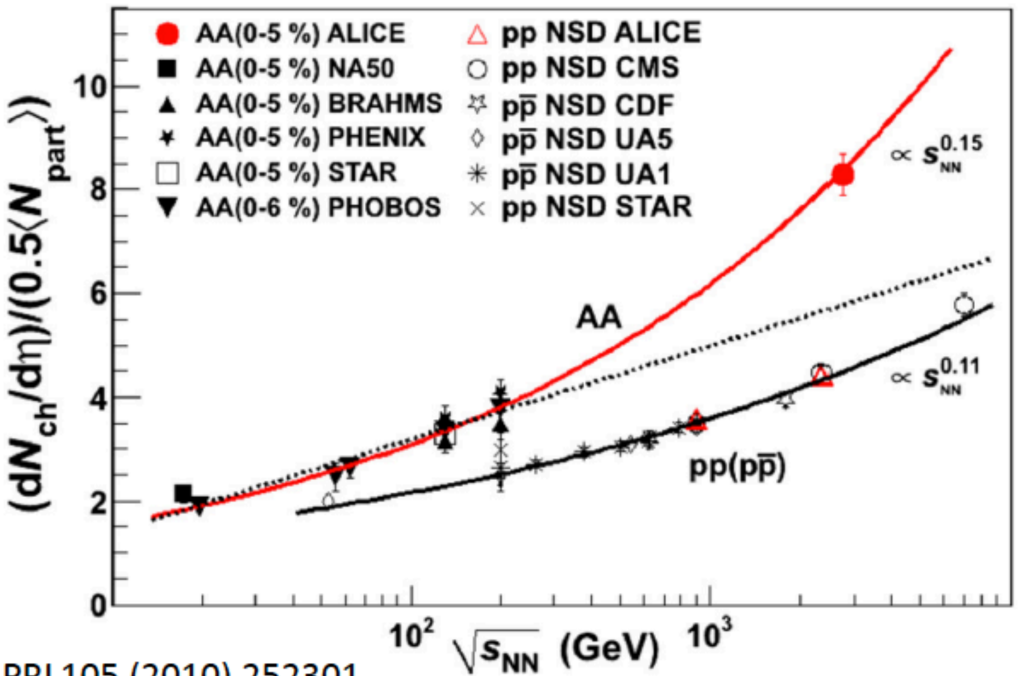
Thank you!

Backup

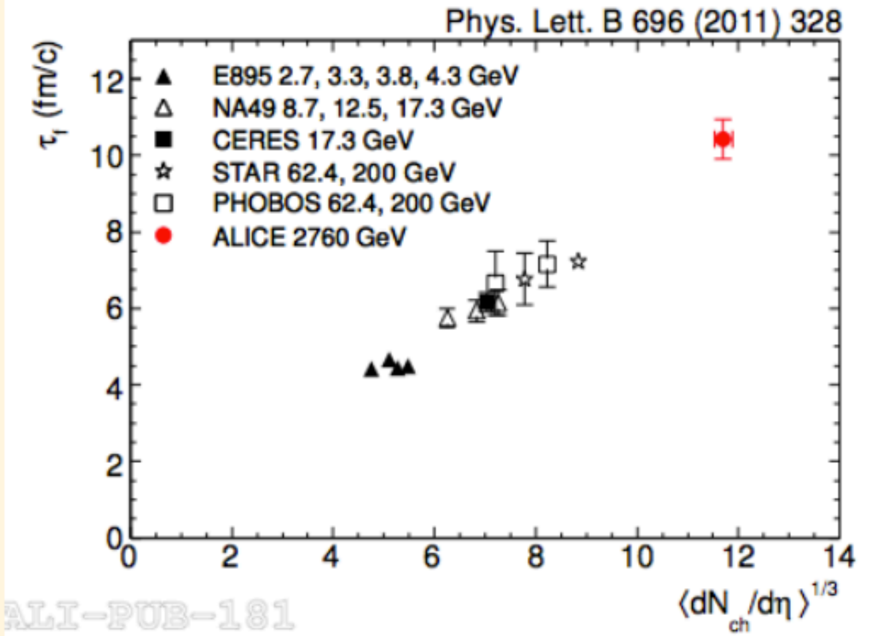
Medium properties

- **Significant difference to RHIC**
  - $dN_{ch}/d\eta$ ~ 1600 ± 76 (syst)
    - on the high side of expectations
    - growth with √s faster in AA than pp
  - Energy density ≈ 3 x RHIC
  - Size: twice w.r.t. RHIC
  - Lifetime: 40% larger w.r.t. RHIC





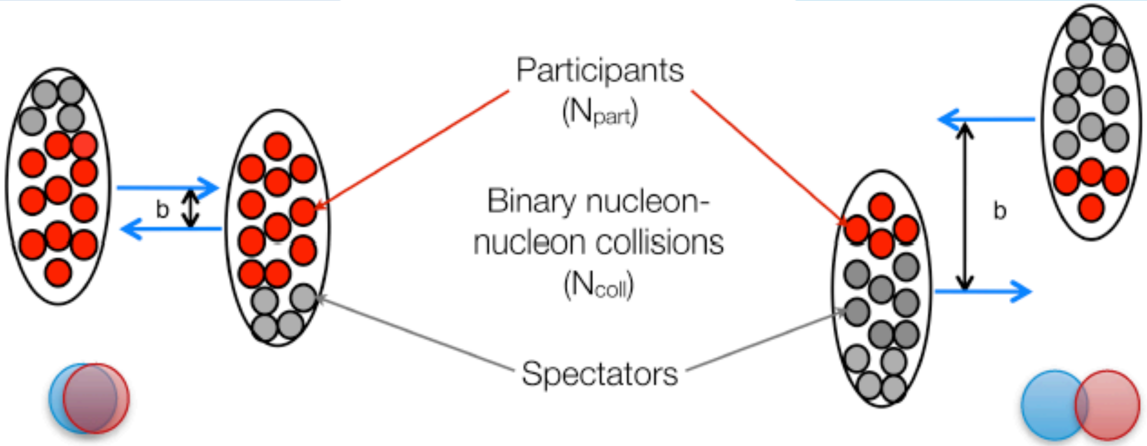
PRL105 (2010) 252301

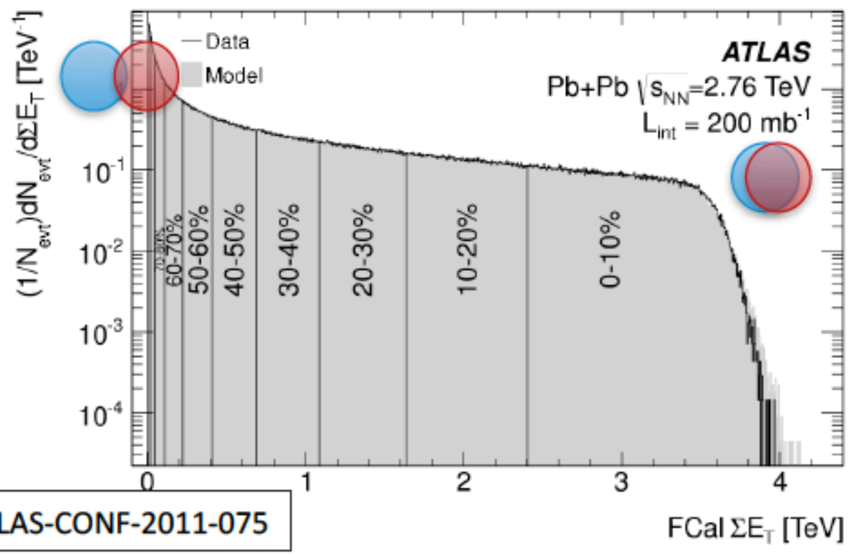


Collision centrality

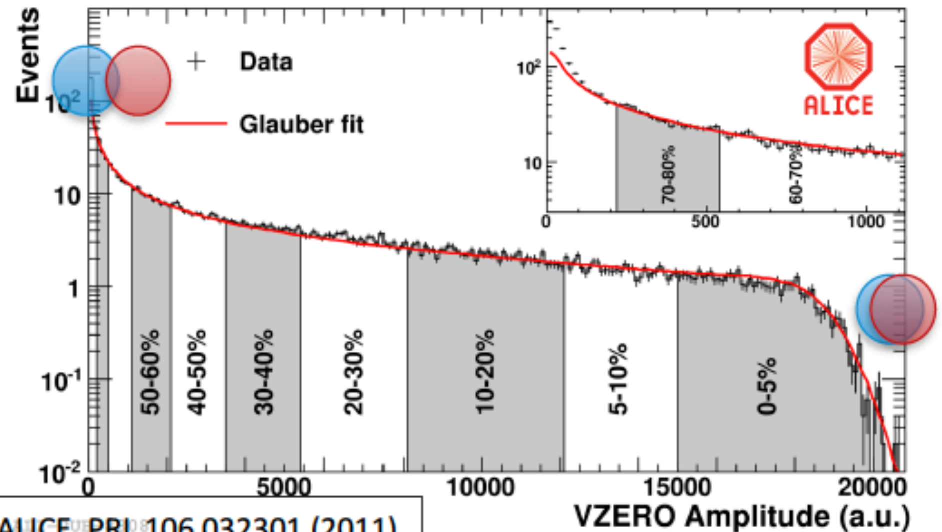
Central collisions

Peripheral collisions



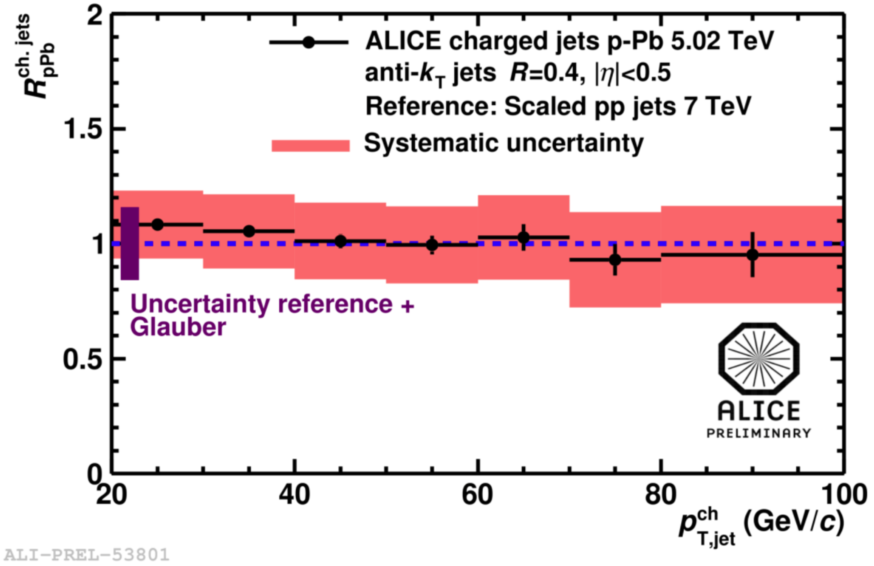


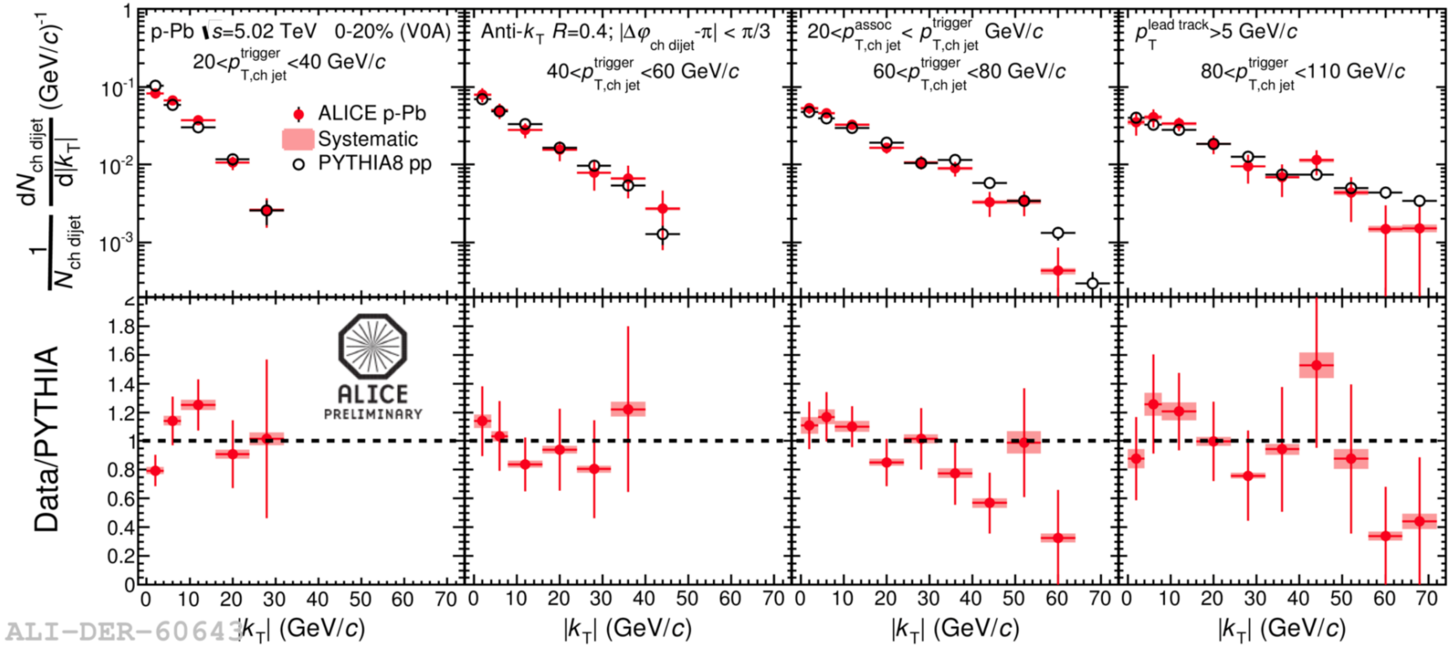
ATLAS-CONF-2011-075



ALICE, PRL 106 032301 (2011)

p-Pb: the control experiment



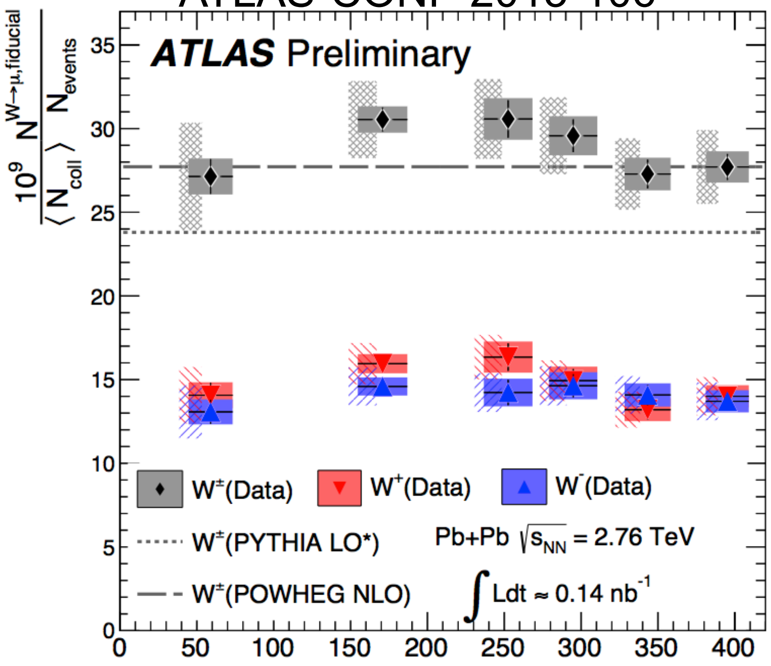


Hard probes: EW Bosons

Electro-weak bosons are medium blind

- References for modified processes
- Ultimately can help to constrain initial state

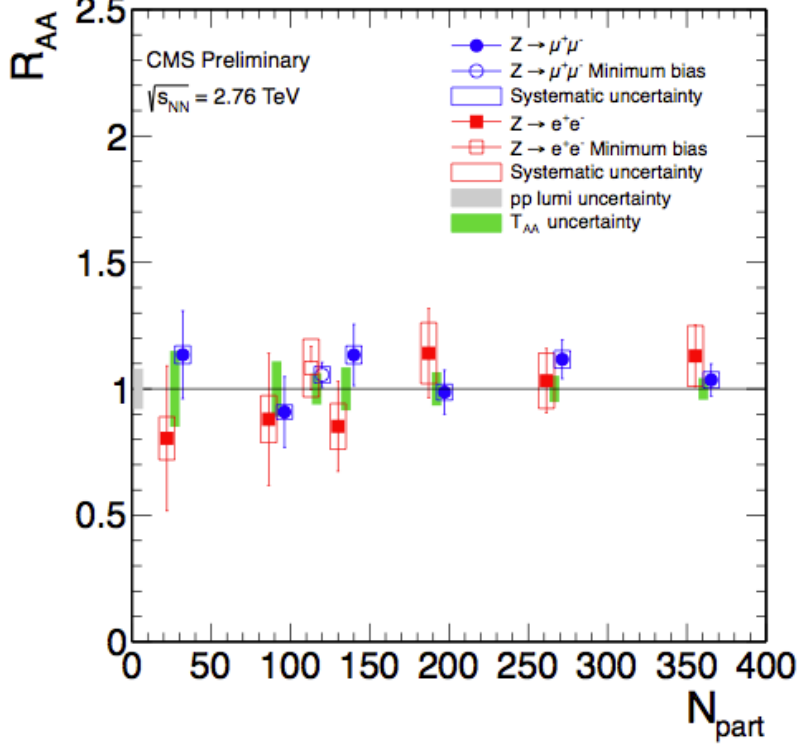
ATLAS-CONF-2013-106



W yield per binary collision approximately constant over 0-80% centrality range.

Data better described by NLO

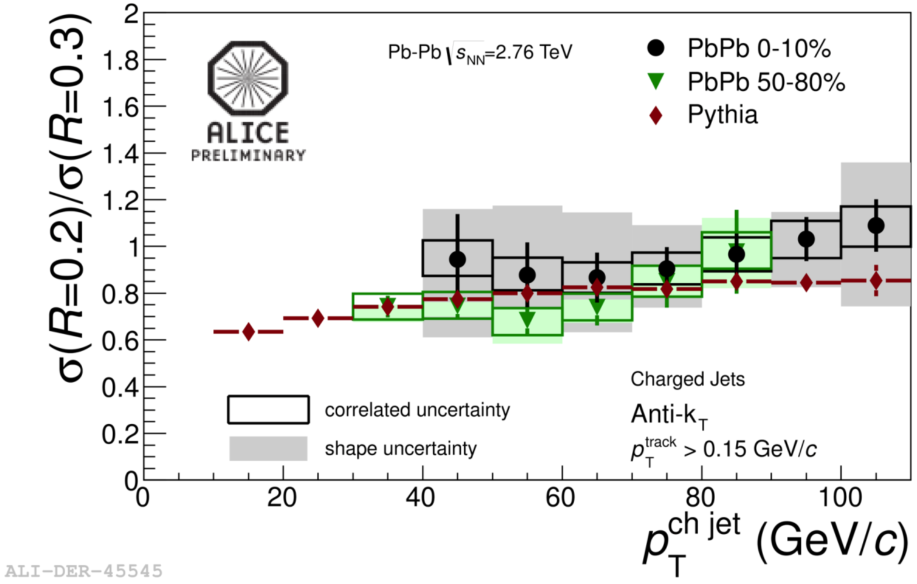
CMS-PAS-HIN-13-004

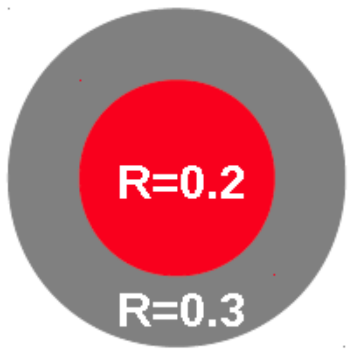


R_{AA} independent of centrality and compatible with 1 for Z (and W, not shown)

Reference for other processes!

Hard probes: jet structures

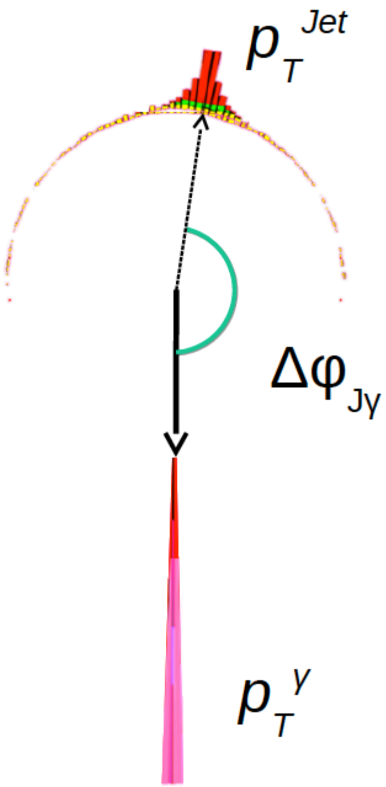




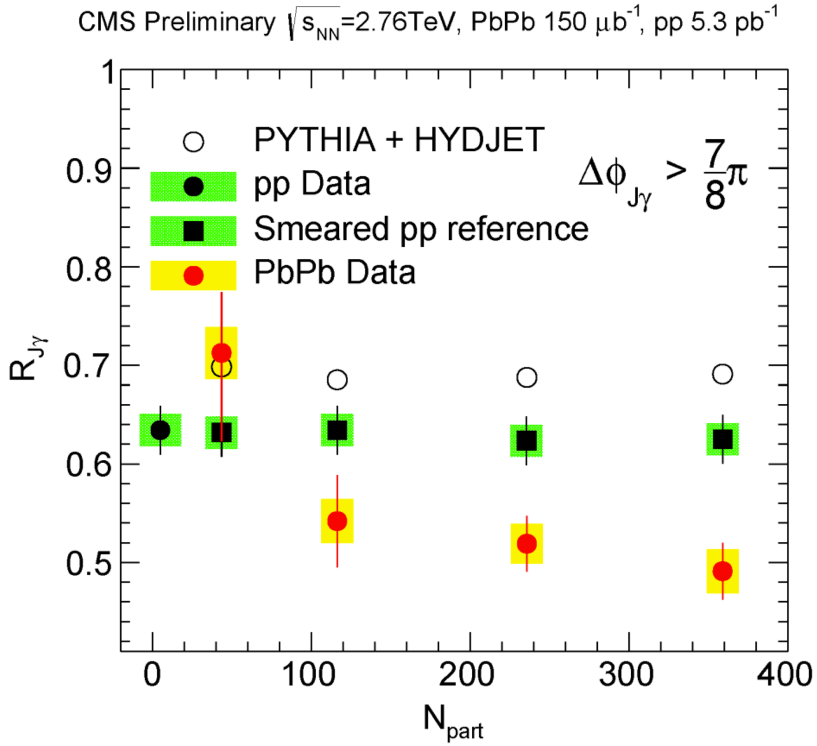
Ratio σ(R=0.2)/σ(R=0.3) of jet cross sections in Pb-Pb compatible with fragmentation in vacuum (PYTHIA)

Is the jet energy redistributed in particle p_T?
Is the jet energy redistributed in radius?

Hard probes: γ-jets



Fraction of photons with associated jets

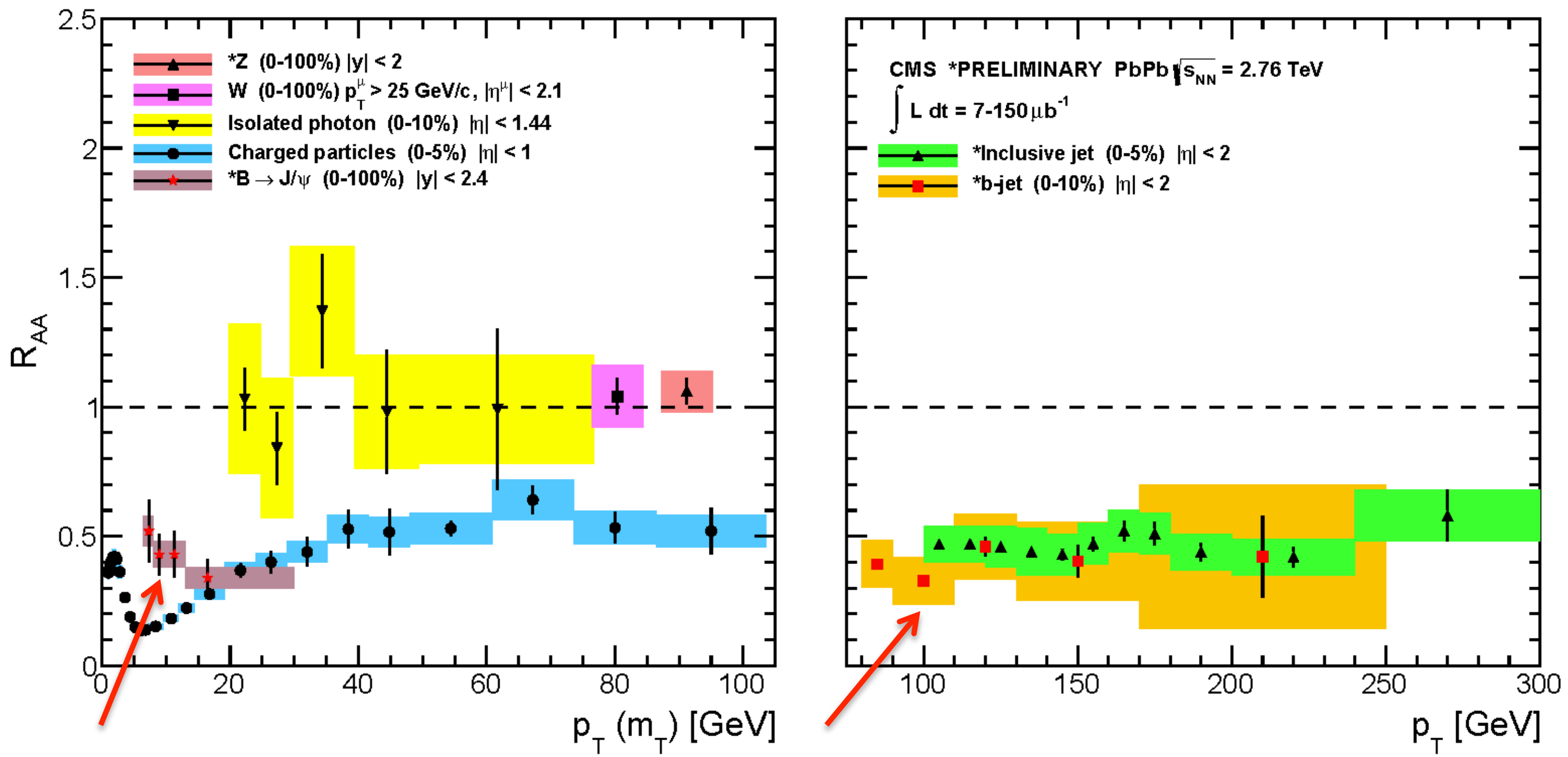


γ-jet correlations

The fraction of jets associated to photons decreases from pp to PbPb collisions

Beauty: B hadrons and b-jets

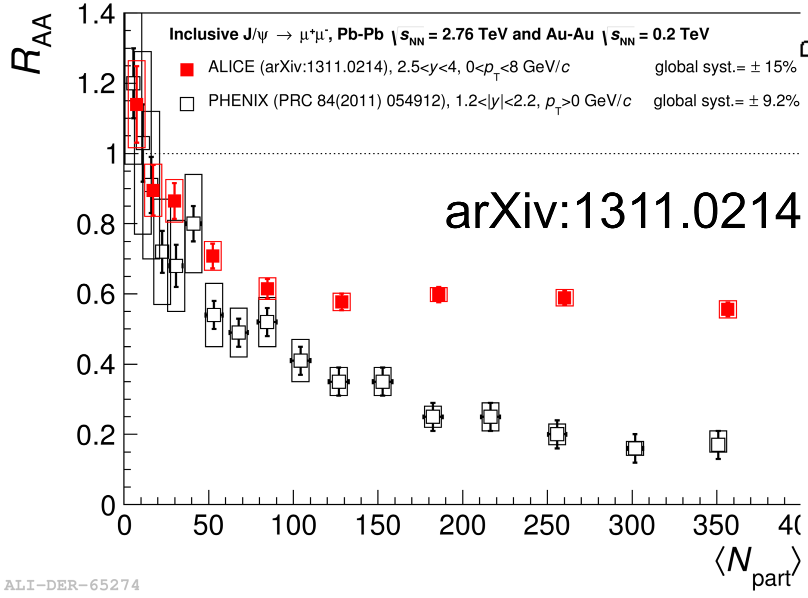
First measurement of fully reconstructed beauty jets in heavy-ion collisions by CMS
Tagging method based on reconstruction of displaced secondary vertices in the jets.

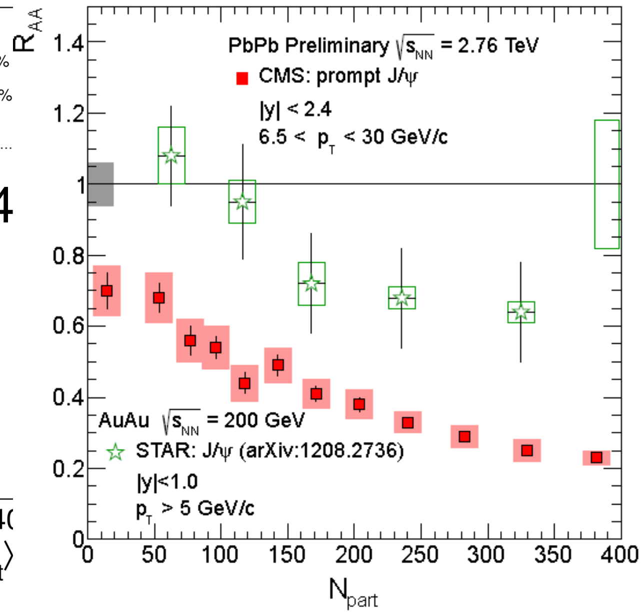


Indication of less suppression of B mesons compared to charged hadrons in Pb-Pb collisions. Compatible with mass hierarchy expectations.

At high p_T, b-jets as suppressed as inclusive jets: mass effects only at lower jet p_T!

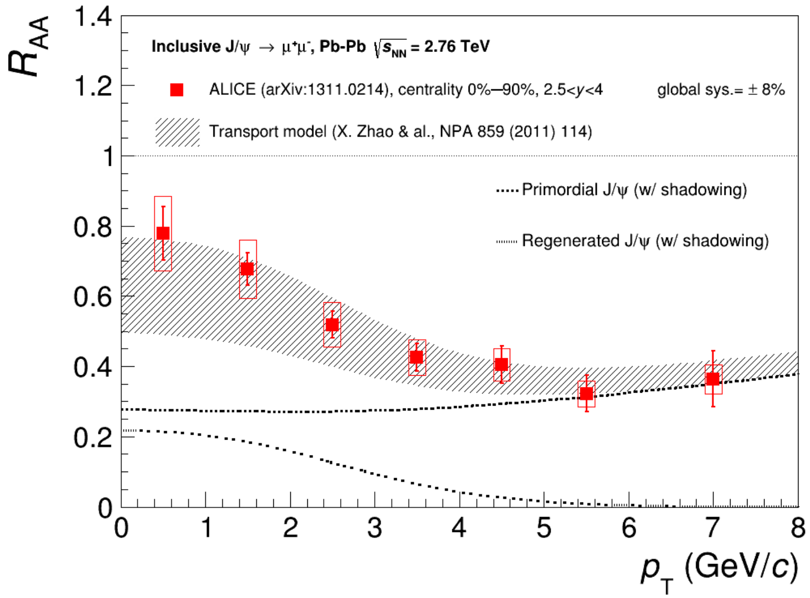
Hard Probes: Quarkonia

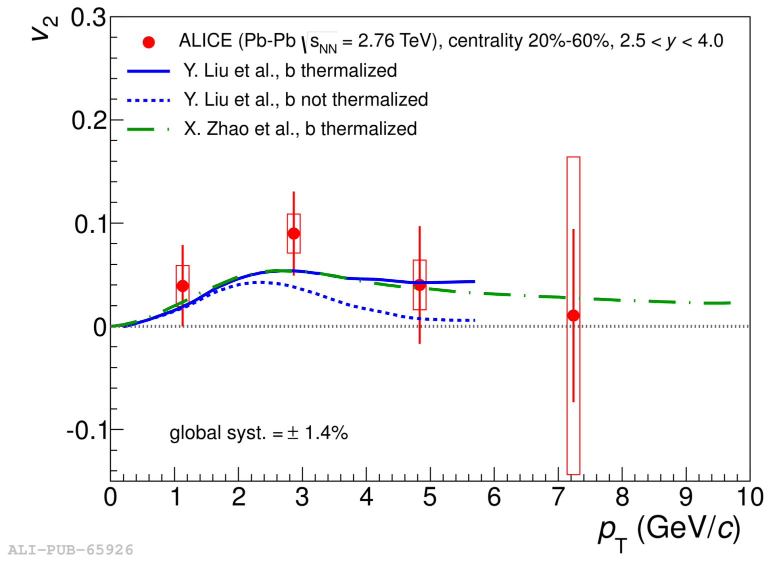




CMS PAS
HIN-12-014

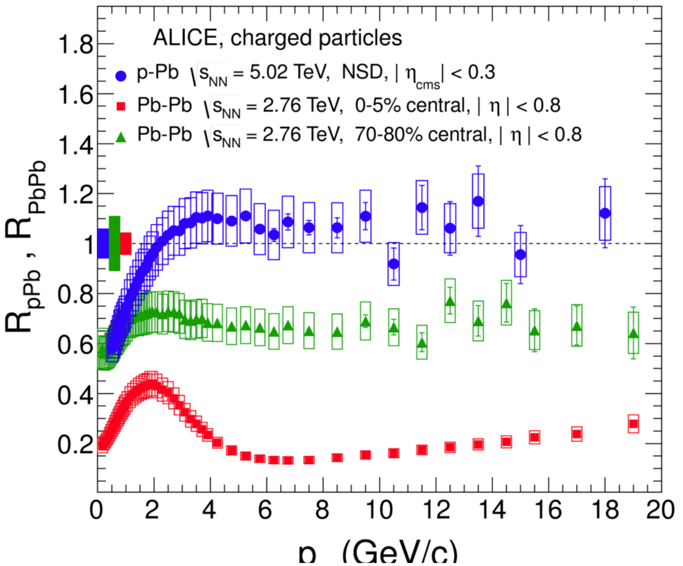
arXiv:1311.0214



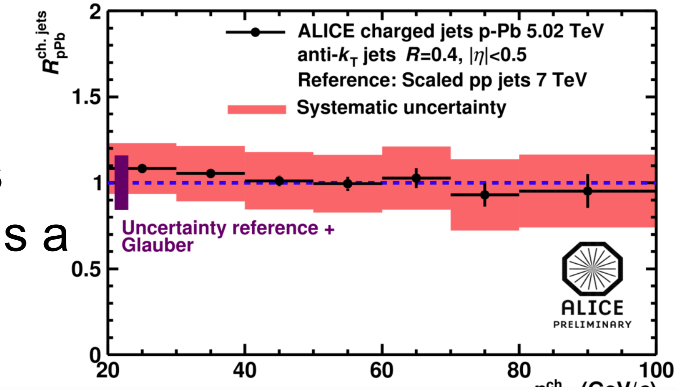


J/ψ v_2 at LHC!

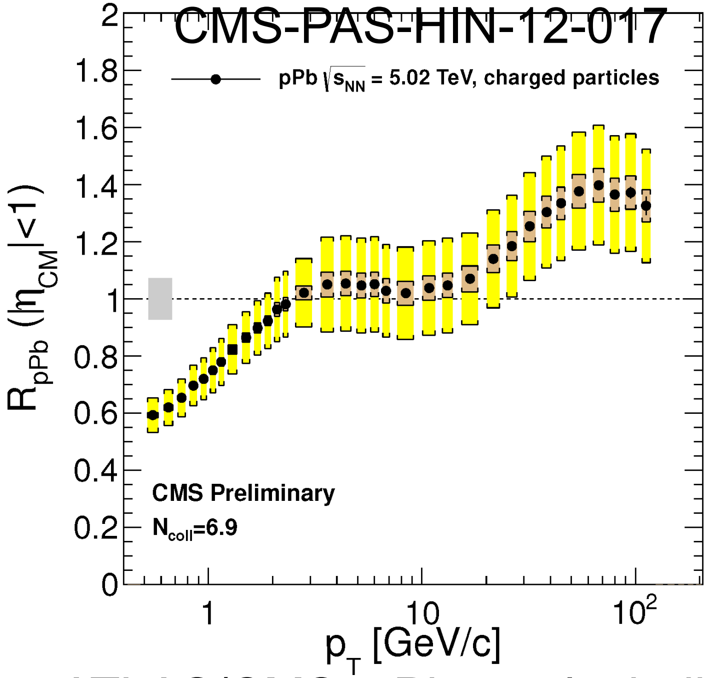
R_{pA}



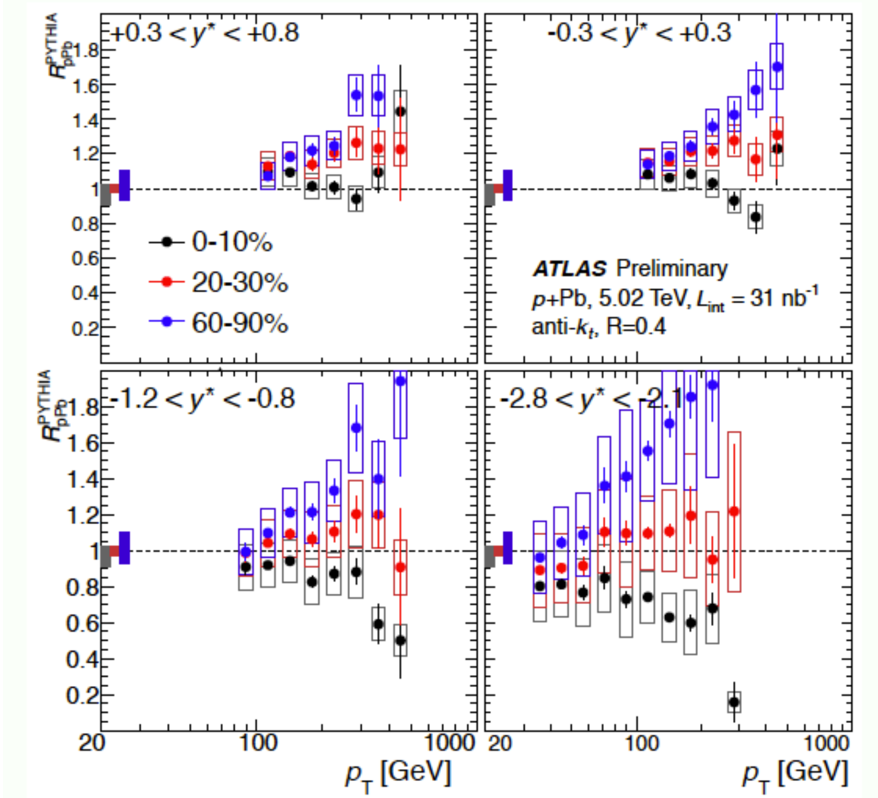
ALICE: pPb results confirm that PbPb is a final state effect



CMS-PAS-HIN-12-017



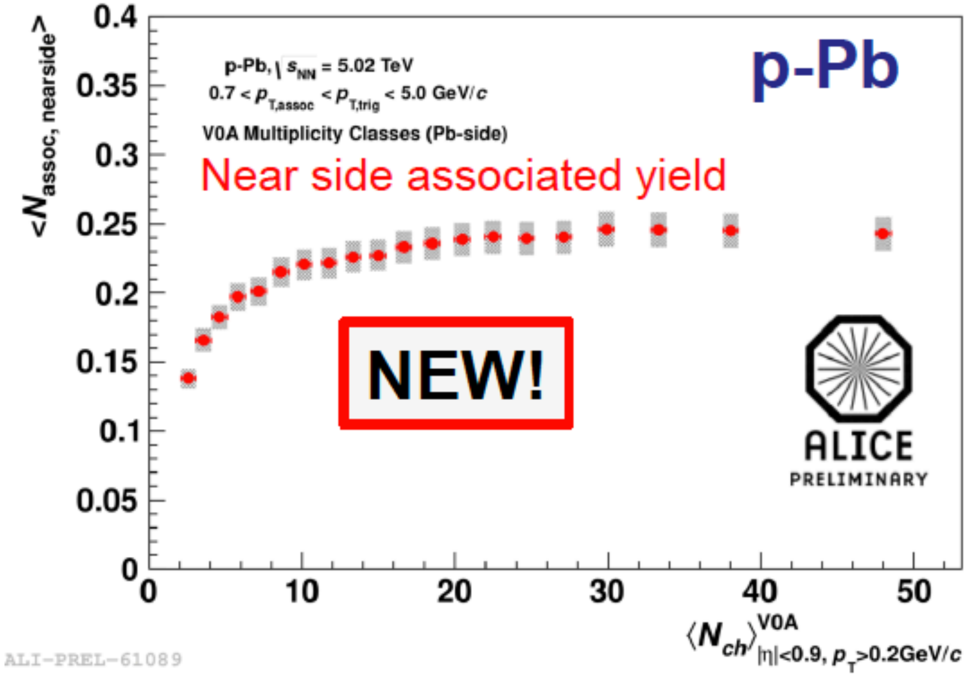
ATLAS-CONF-2013-105

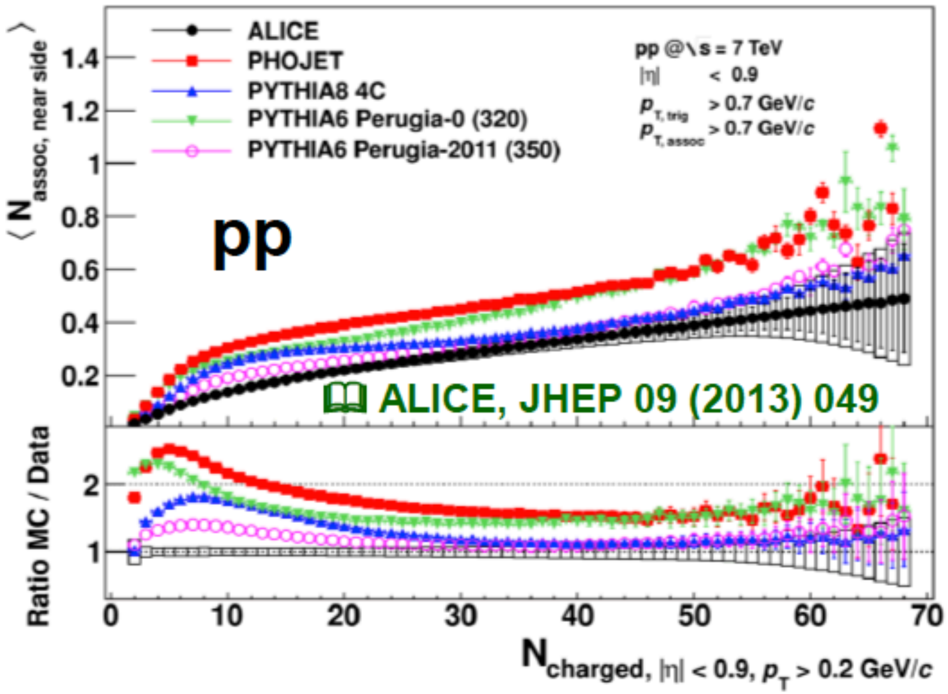


ATLAS/CMS: pPb results indicate $R_{AA} \neq 1$. antishadowing?

More on p-Pb

- High-multiplicity p-Pb events do not have as many associate particles in the jet peak as in pp





Goals for Run 2

- currently all LHC experiments are consolidating their detectors
- complete the approved heavy ion program, i.e. collection of at least 1/nb in Pb-Pb collisions at top energy (13 TeV p equivalent (5.1 TeV)) until LS 2 (mid-2018 for 18 months)
- some pp reference running at corresponding top Pb-Pb energy
- likely another p-Pb run

Run 3

LHC luminosity upgrade – target 50 kHz minimum-bias rate for Pb-Pb

Peak rate of Pb-Pb collisions will be 50 kHz in 2020, i.e. two orders of magnitude more than the currently achieved 500 Hz ALICE detector readout rate.

ALICE: expects to collect $O(10)$ nb^{-1} Pb-Pb (net gain factor 100)

ALICE Upgrades:
- new, smaller radius,beam pipe
- new inner tracker
- upgrade of TPC woth GEM readout chambers
- upgrades of the online and computing concepts to cope with much higher rates.

Target for installation and commissioning: Long Shutdown 2 (2018)

Other experiments/facilities

Towards the exploration of the QCD phase diagram