QCD@Work

16-19 June 2014, Giovinazzo

OVERVIEW OF RECENT ALICE RESULTS

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OUTLINE

A selection of recent ALICE Pb-Pb and p-Pb results on:

- Global observables
- Jet quenching
- Heavy-flavour production
- Quarkonia production

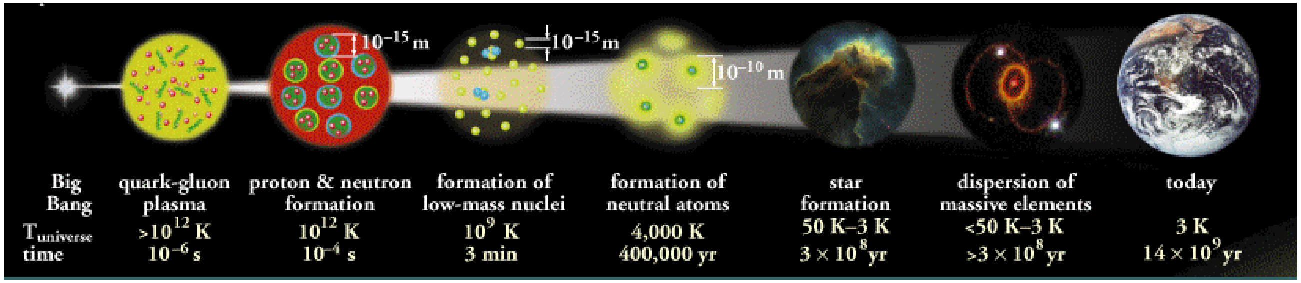
ALICE

Is p-Pb just a “control” experiment?

HEAVY-ION PHYSICS

- QCD predicts a phase transition from hadronic matter to a deconfined phase (at high temperatures)

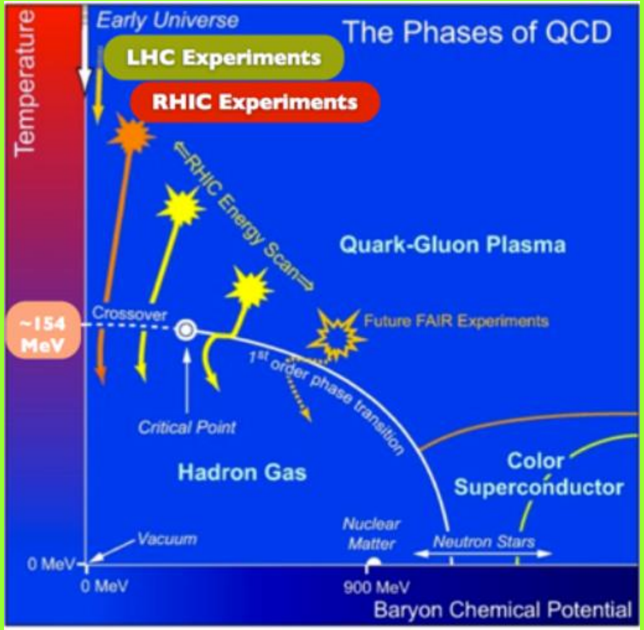
QGP at μ~0 similar to early Universe (~ few first μs)



- **Heavy-ion collisions provide experimental access to the QCD matter**

- First signal of QGP formation at SPS and RHIC

- LHC: detailed investigation of QGP properties



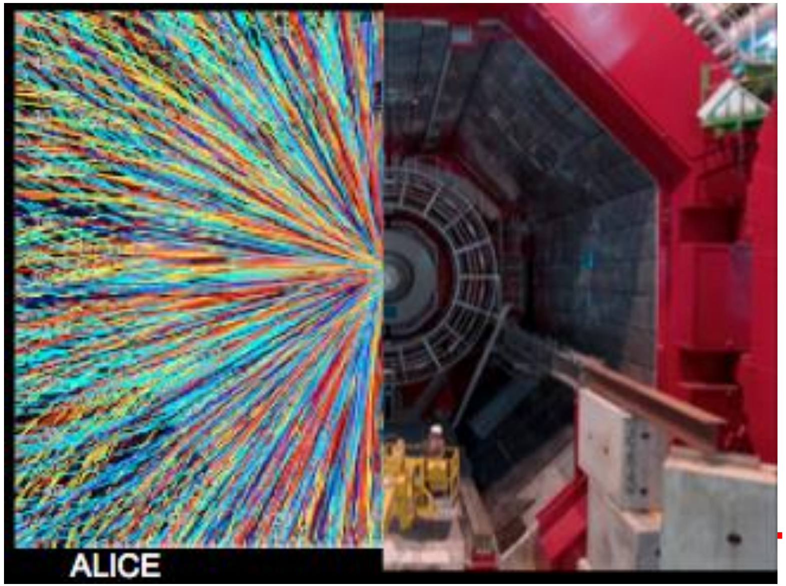
DATA SAMPLES

System	$\sqrt{s_{NN}}$ (TeV)	Year	Integrated luminosity	Physics goal
Pb-Pb	2.76	2010	~10 μb^{-1}	Study of hot and dense QGP matter
		2011	~100 μb^{-1}	
p-Pb	5.02	2012	~0.8 μb^{-1}	Investigate cold nuclear matter effects and much more…
		2013	~15 nb^{-1} p-Pb	
			~15 nb^{-1} Pb-p	

In addition (not covered in this talk)

pp collisions at $\sqrt{s}$ = 0.9, 2.76, 7, 8 TeV

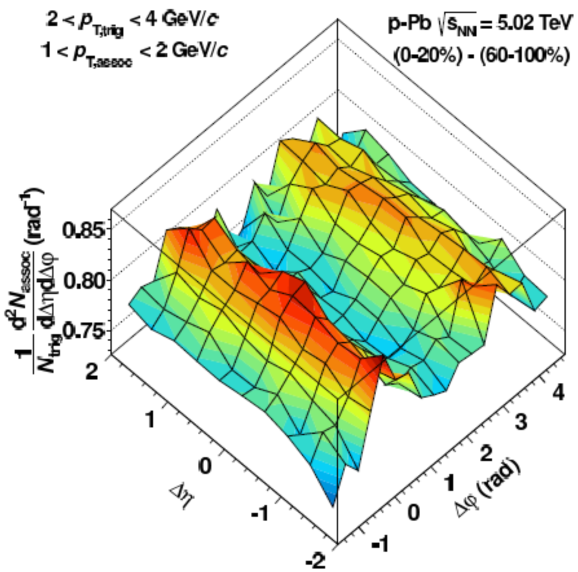
- reference for Pb-Pb and p-Pb
- genuine pp physics program



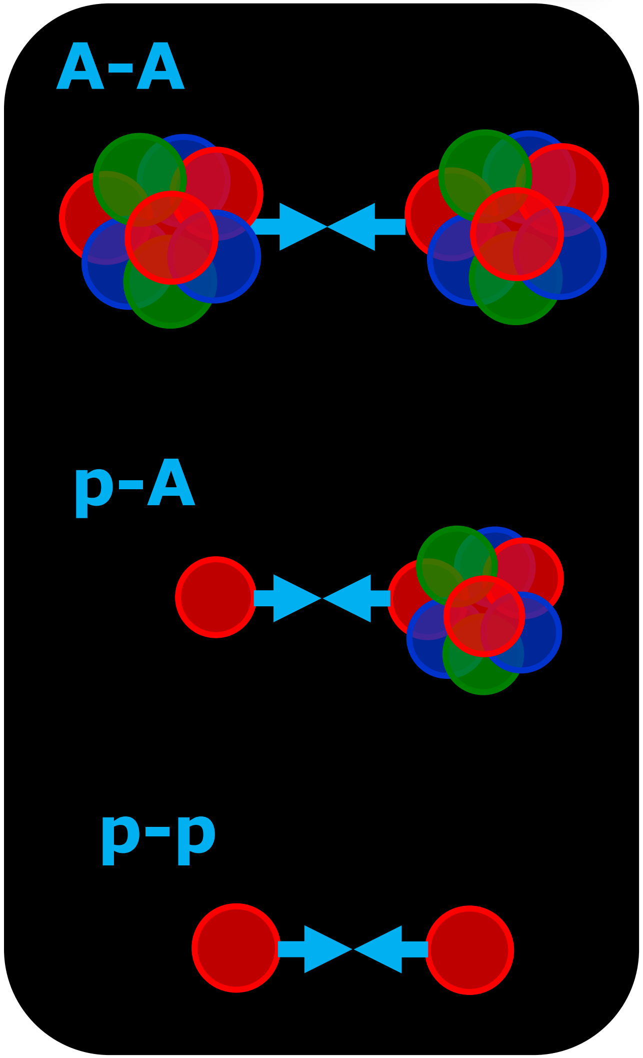
FOCUS ON p-Pb COLLISIONS!

- Tool to investigate Cold Nuclear Matter effects
  → Reference for Pb-Pb collisions

- First measurements show that in p-Pb physics there are hints of collective effects as
  - Double ridge structure
  - Non-zero v_2 + v_2 mass ordering



→ p-Pb not only a baseline for Pb-Pb



- High multiplicity p-Pb similar to Pb-Pb
  → Is there a link between p-Pb and Pb-Pb?

What can we learn from p-Pb and Pb-Pb collisions?

Soft probes

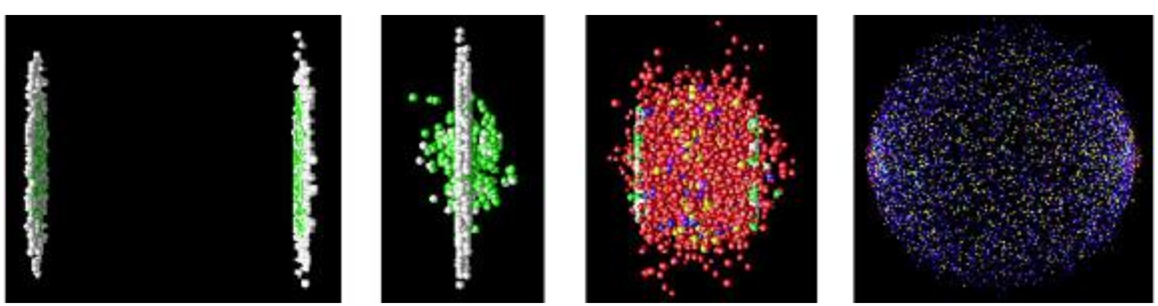
Observables: multiplicity, energy density, collective flow

→ Access to the global properties of the system

Hard probes

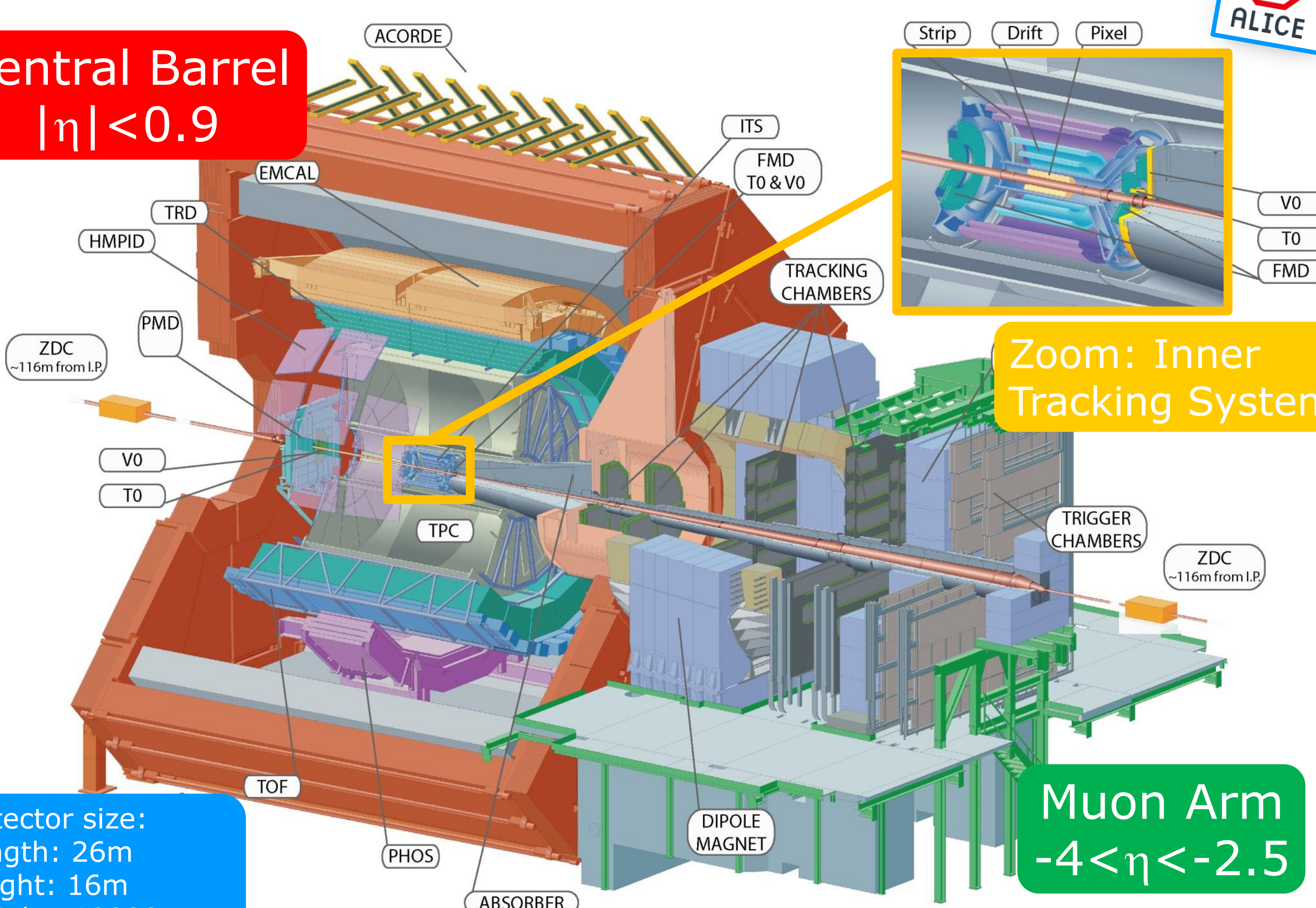
Observables: jets, EW bosons, heavy-flavour, quarkonia

→ Access to initial and final state effects, access to transport properties



ALICE @ THE LHC

Central Barrel
$|\eta|<0.9$



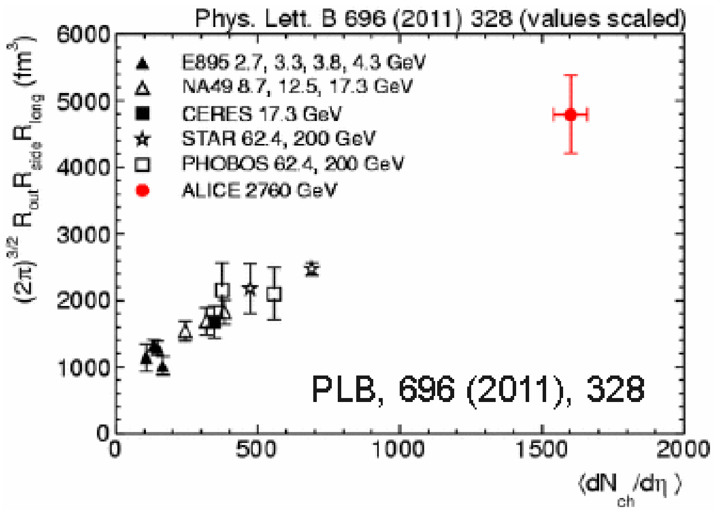
Zoom: Inner Tracking System

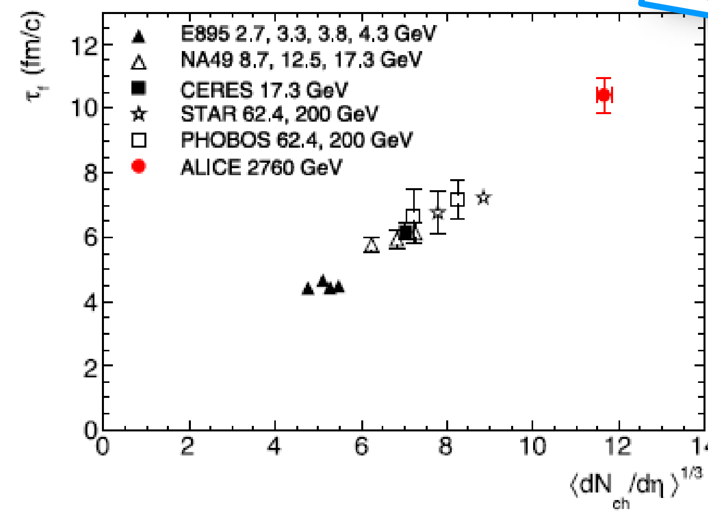
Muon Arm
$-4<\eta<-2.5$

Detector size:
Length: 26m
Height: 16m
Weight: 10000 tons

GLOBAL PROPERTIES

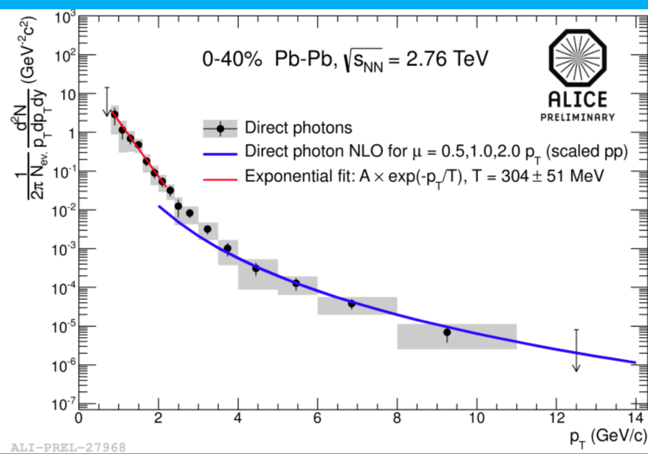
Pb-Pb GLOBAL PROPERTIES

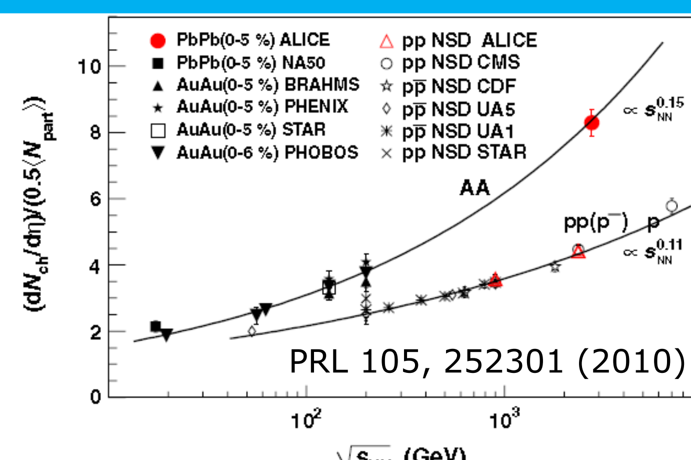




From identical boson interferometry:

Freeze-out volume ~ 2 x V_{RHIC} Lifetime ~ 40% larger than RHIC





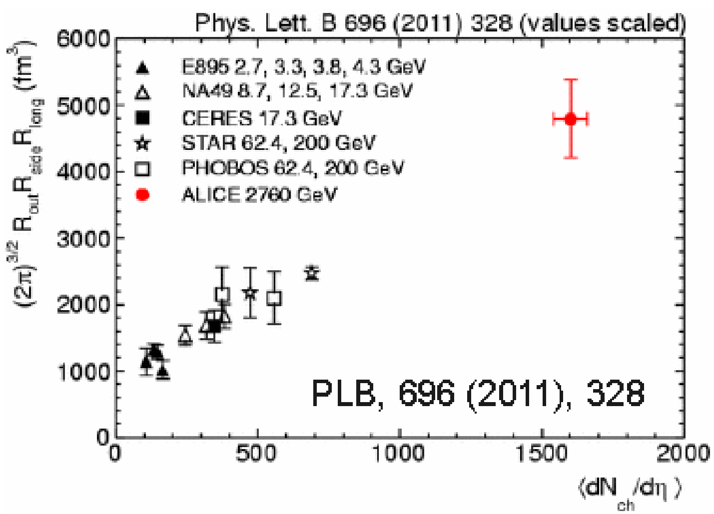
From direct photon measurements:

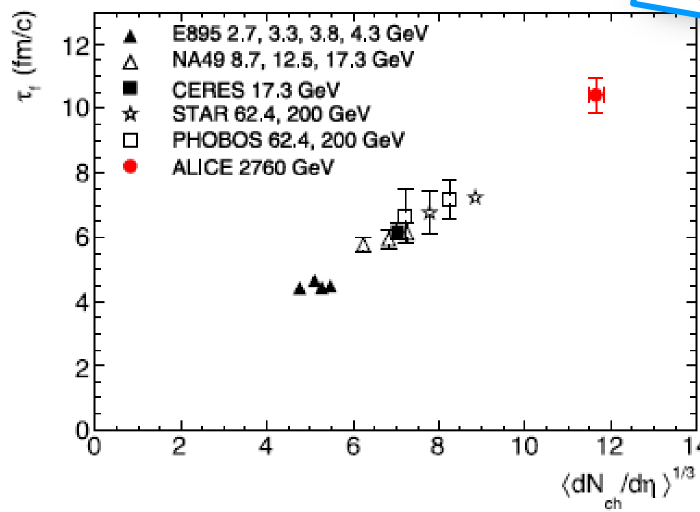
T = 304 ± 51MeV ~ 1.4 x T_{RHIC}

Multiplicity ~ 2 x N_{RHIC}

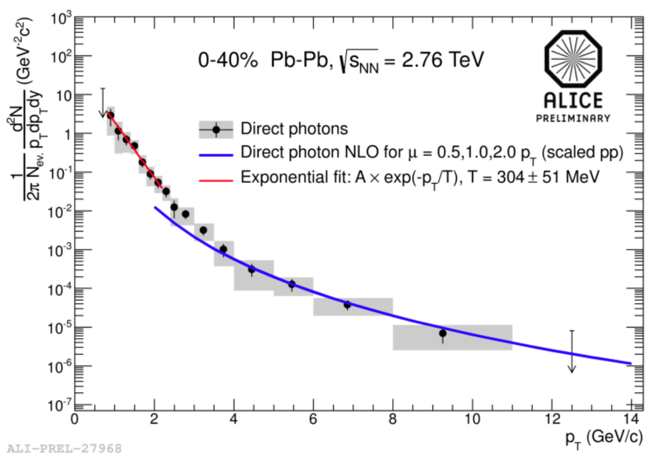
Energy density ~ 3 x ε_{RHIC}

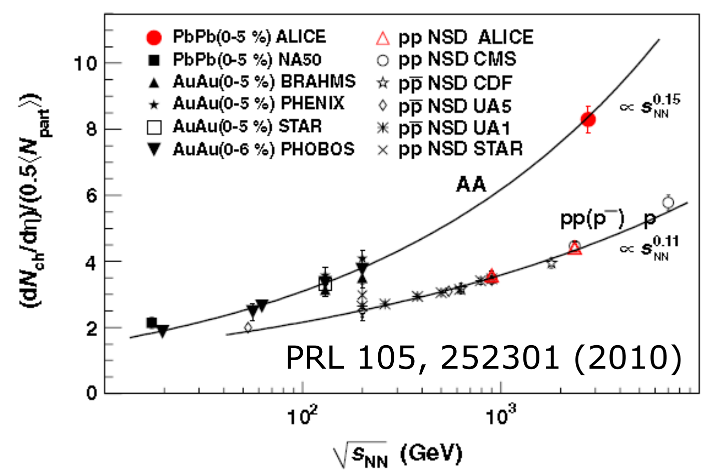
Pb-Pb GLOBAL PROPERTIES





Fireball has larger volume and it’s longer lived





Denser and hotter system!

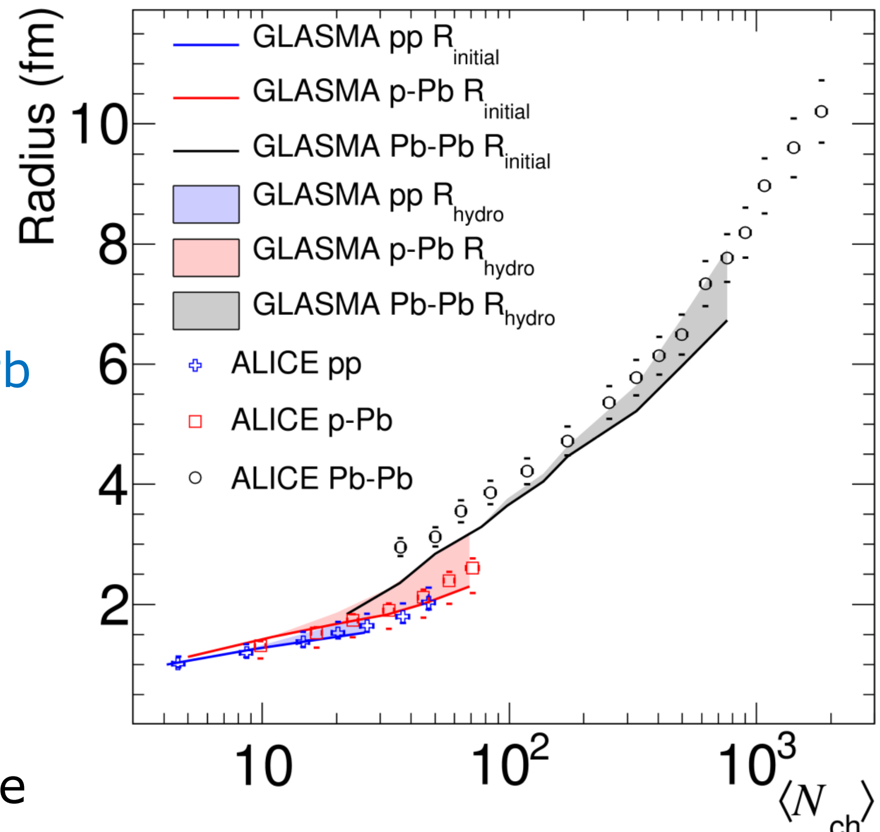
p-Pb SOURCE RADIUS

Comparison of source radii in pp, p-Pb and Pb-Pb can provide infos on the role of

initial conditions	**vs**	**hydrodynamical evolution**
→ similar freeze-out radius in p-Pb and pp		→ larger freeze-out radius, p-Pb more similar to Pb-Pb

- First extraction of femtoscopic radii with 3 π cumulants
- For a given multiplicity:
  - p-Pb radii 5-15% larger than in pp
  - Pb-Pb radii 35-45% larger than in p-Pb
- p-Pb and pp can be reproduced by initial conditions from saturation (GLASMA) (p-Pb may accommodate also hydro)

  Pb-Pb requires hydro-dynamical phase

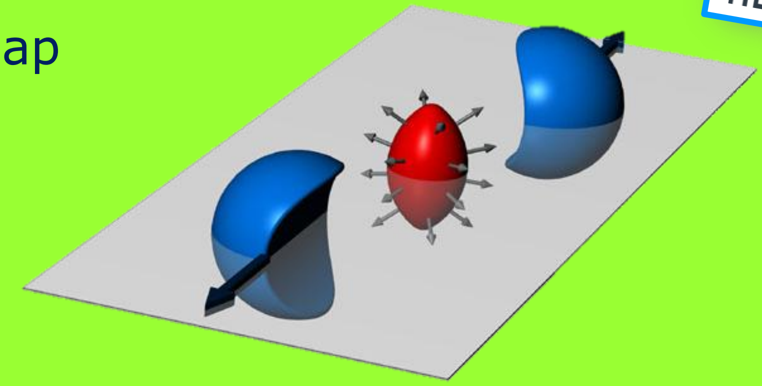


arXiv:1404.1194

COLLECTIVE FLOW

- Initial spatial anisotropy of the overlap region of colliding nuclei

  → anisotropy in momentum space through interactions of produced particles



- Measured by the elliptic flow parameter (v_2) extracted from the Fourier decomposition of particle azimuthal distributions relative to the reaction plane

$$\frac{dN}{Nd\phi} \sim 1 + 2v_2 \cos\left(2(\phi - \Psi_{RP})\right) + \textit{higher harmonics } (v_3, v_4, \ldots)$$

- v_2 provides a measurement of collectivity
  → constraints the properties of deconfined medium

- Large mean free path → particles stream out isotropically, no memory of initial asymmetry (ideal gas)
- Small mean free path → large density and pressure gradients, larger momentum anisotropy (ideal liquid)

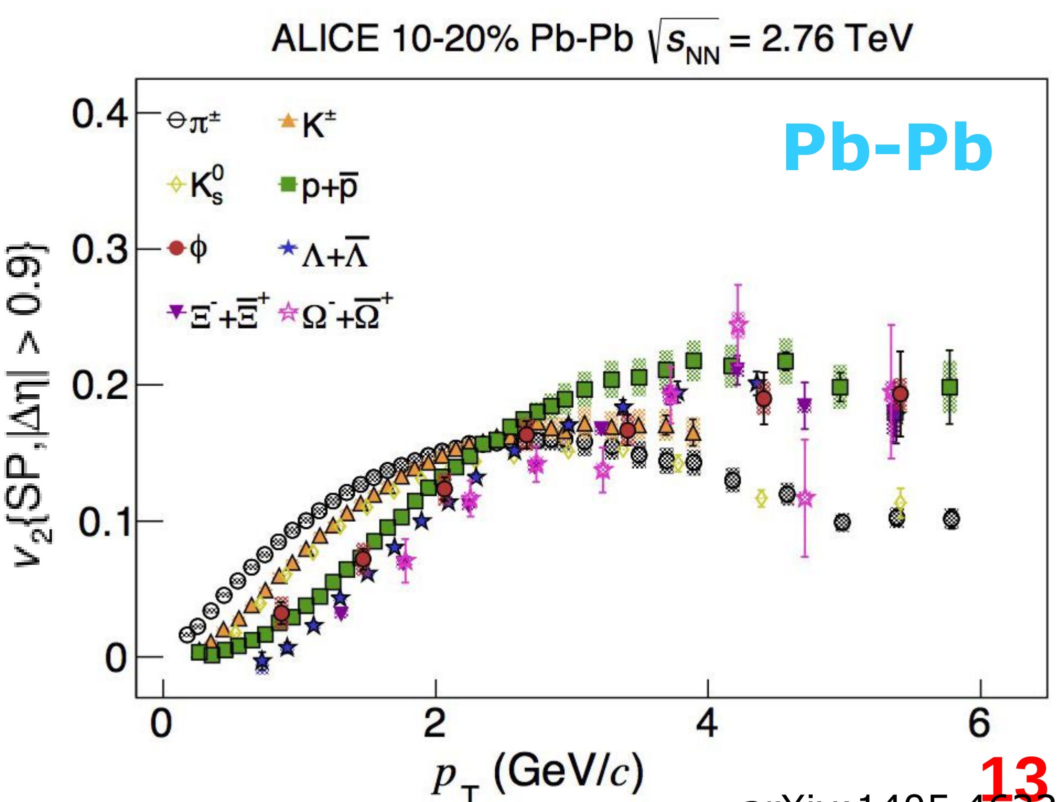
v_2 OF IDENTIFIED PARTICLES

- Identified particle $v_2\{SP\}$ (π^{+-}, K^{+-}, K^0, p, ϕ, Λ, Ξ, Ω)
  - → allows for precision measurements
    - add constraints to initial conditions, particle production mechanisms
    - probes the freeze-out conditions of the system
    - checks the number of constituents quarks scaling

Low p_T:
mass ordering
→ attributed to interplay between radial and elliptic flow

Qualitative description with hydrodynamical calculations + hadronic cascade model
→ small η/s favoured

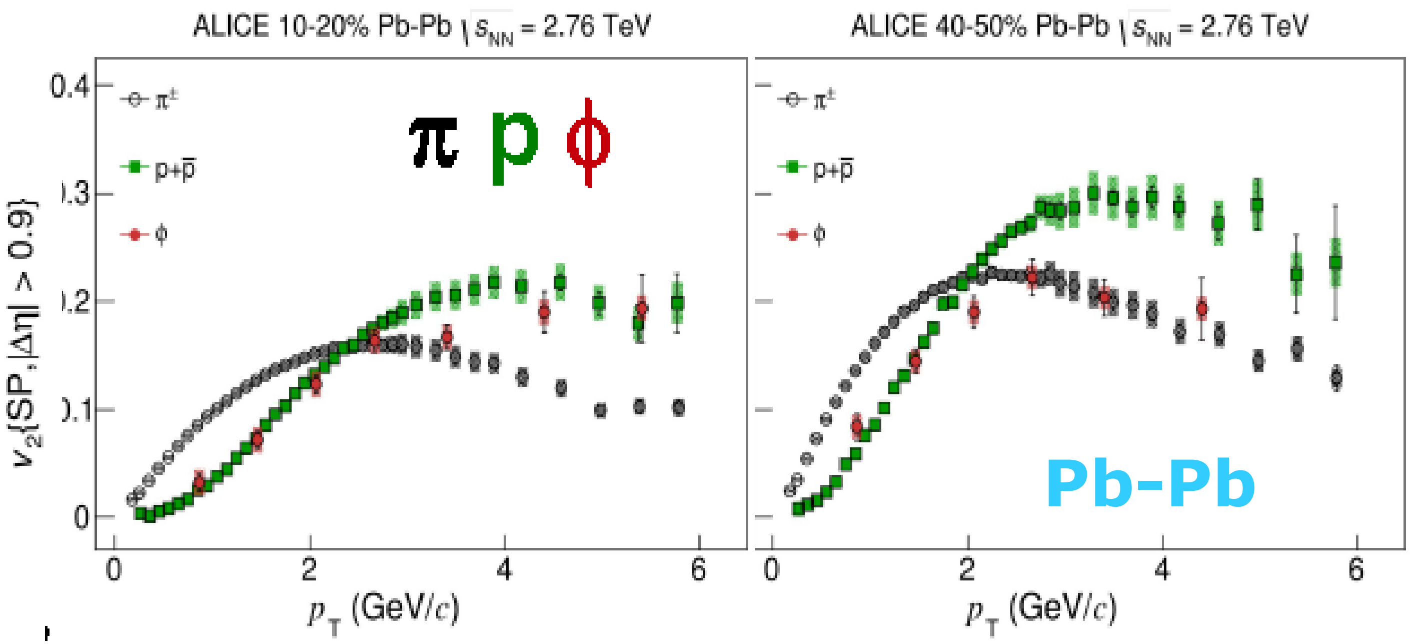
High p_T:
particles tend to group into mesons and baryons



arXiv:1405.4632

v_2 OF IDENTIFIED PARTICLES: ϕ

ϕ (heavy meson) is of particular interest as testing ground for mass ordering and baryon-meson grouping



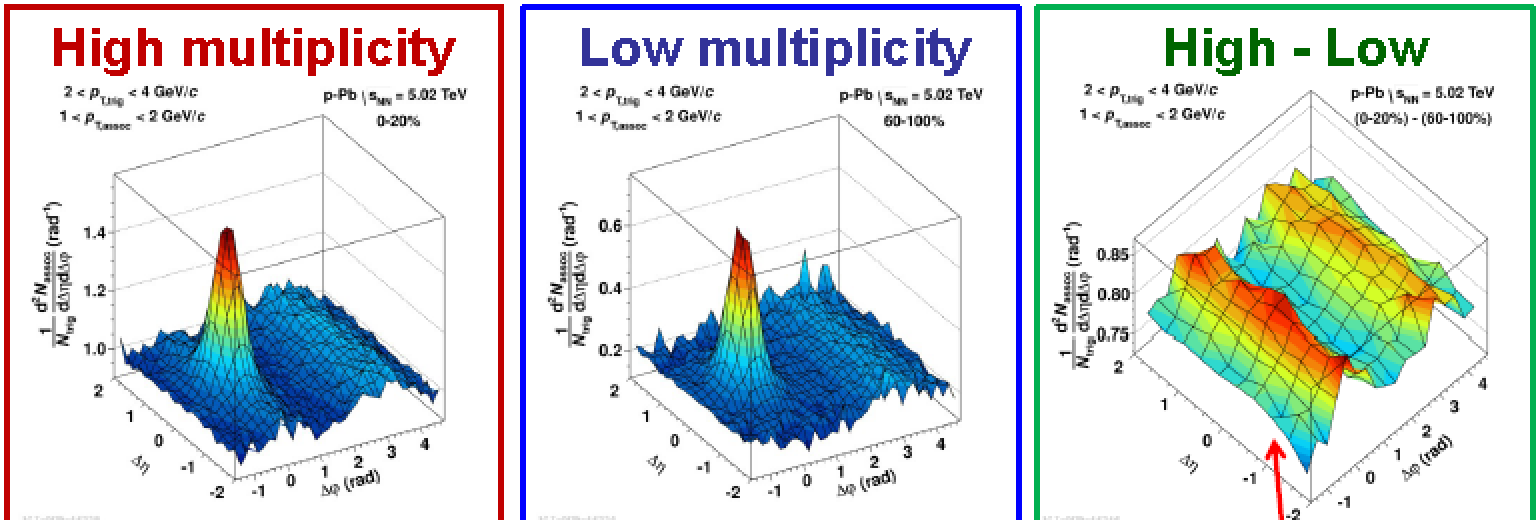
- Low p_T: v_2 follows mass ordering
- High p_T: v_2 close to p in central collisions and close to π in mid-central

Mass (and not number of constituent quarks) is main driver for v_2 in central Pb-Pb → consistent with hydrodynamic picture

Scaling with number of quark constituents violated by 20%, in particular in central collisions

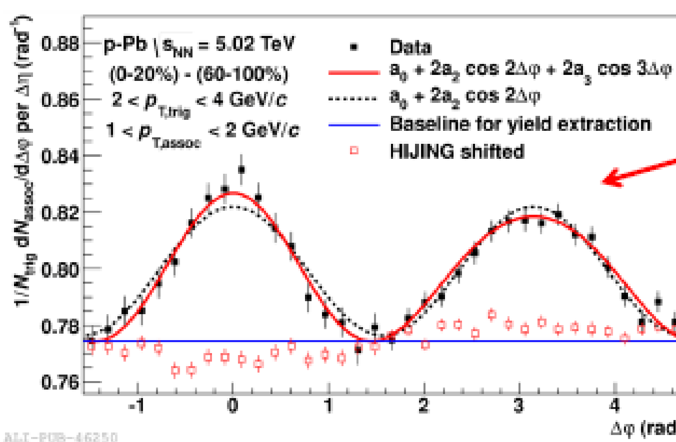
HADRON-HADRON CORRELATIONS IN p-Pb

- Two particles ($\Delta\eta$, $\Delta\phi$) correlations are a tool to explore particle production mechanisms: unexpected observation of an underlying azimuthal anisotropy in high-multiplicity p-Pb collisions



Double ridge structure

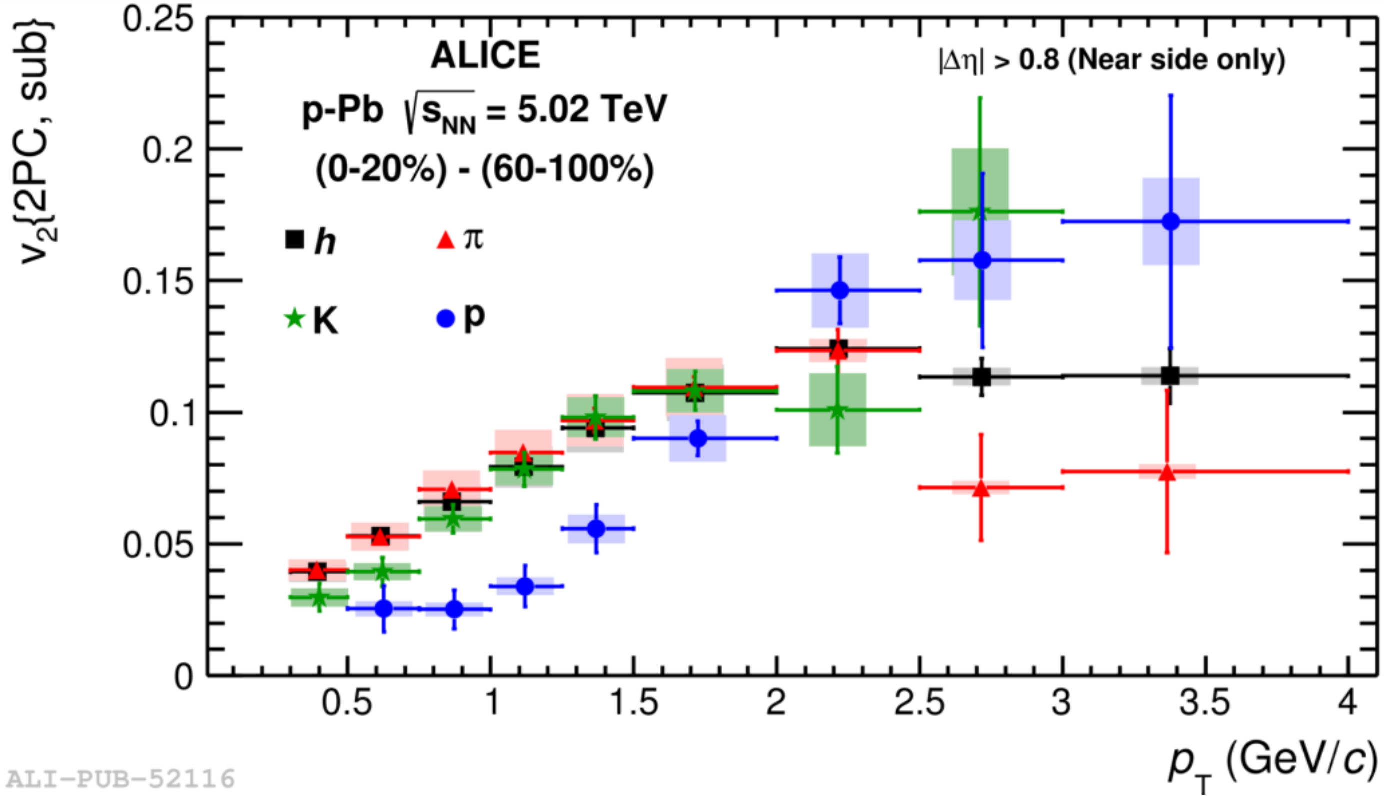
- Double ridge described by both color glass condensate (initial state effect) or hydro (final state effect) (PLB719 (2013) 29)



Remaining correlation: two twin long-range structures (double ridge)

HADRON-HADRON CORRELATIONS IN p-Pb

h - π, K, p correlations



v_2 extracted from two-particles correlations

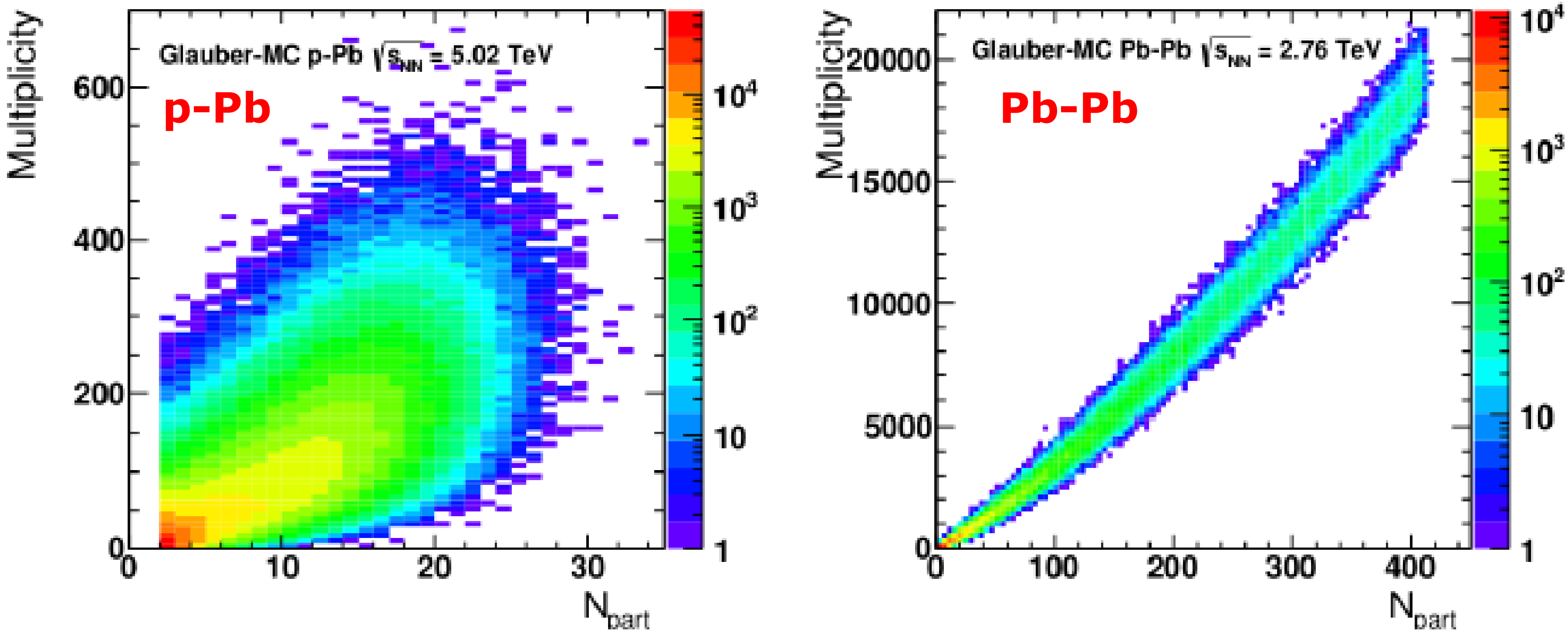
- Mass ordering at low p_T
- Crossing at p_T~2GeV/c

Qualitatively similar to Pb-Pb and consistent with hydro-predictions

CENTRALITY IN p-Pb

Centrality determination in p-Pb is challenging!

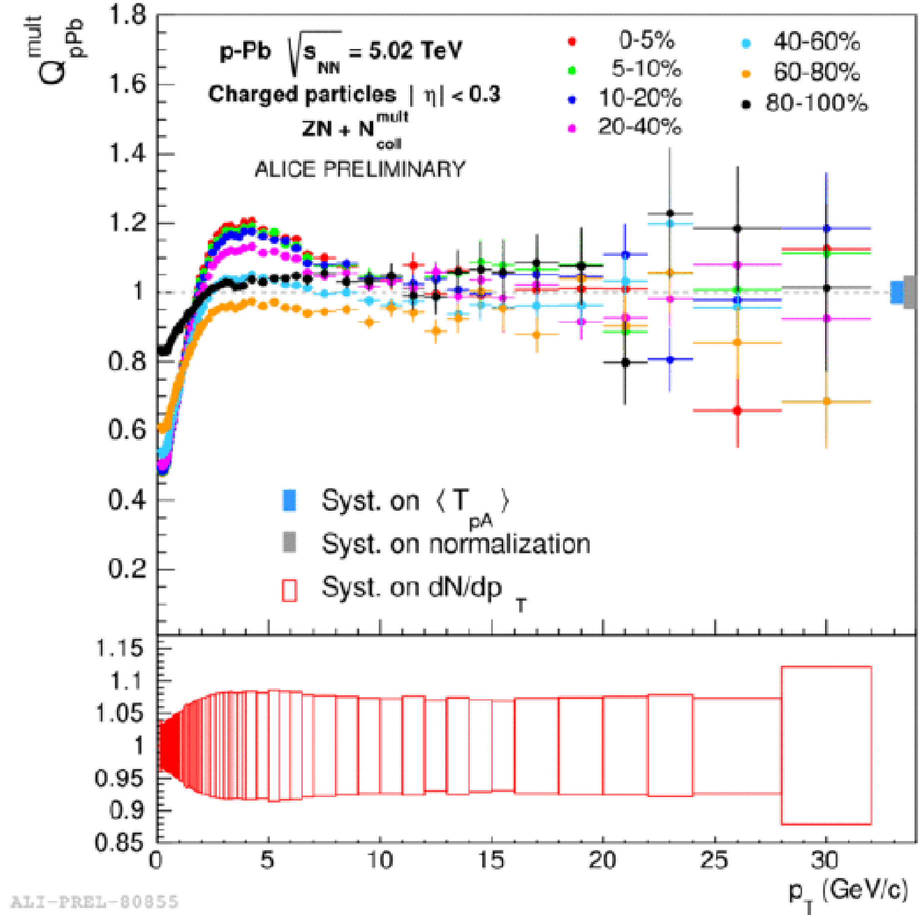
- looser correlation between N_{part} and impact parameter
- looser correlation between N_{part} and multiplicity



Fluctuations might induce a bias in the centrality determination

CENTRALITY IN p-Pb

- Event selection based on Pb-going neutron energy released in ZDC → minimizes the bias
- N_{part} and N_{coll} obtained assuming one out of:
  - forward $dN_{ch}/d\eta \sim N_{part}^{Pb} = N_{part} - 1$
  - mid-rapidity $dN_{ch}/d\eta \sim N_{part}$
  - high-p_T yields $\sim N_{Coll}$



- Q_{pA} instead of R_{pA} due to potential bias from the centrality estimator, not related to nuclear effects

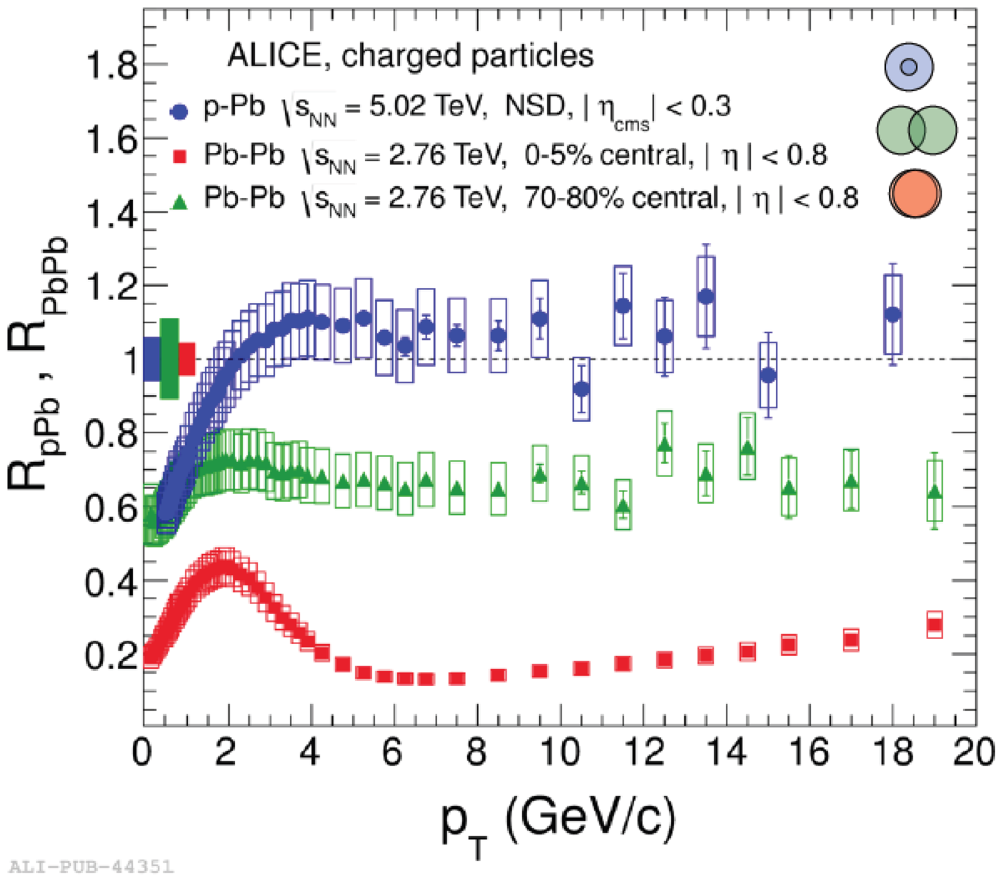
$$Q_{pA}^{i} = \frac{dN_{pA}/dp_T}{\langle N_{coll} \rangle_i \, dN_{pp}/dp_T}$$

- Flat Q_{pPb} at high p_T for all event activity classes

HARD PROBES

HARD PROBES: HIGH P_T PARTICLES

- High p_T particles originate from hard parton scattering:
  - early formation time
  - interaction with the medium
- Tool to probe the dense medium formed in A-A collisions



PRL110 (2013)082302

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

- if $R_{AA} = 1$ → no nuclear effects
- if $R_{AA} \neq 1$ → (hot or cold) medium effects

- Strong suppression of charged hadrons in Pb-Pb, wrt pp, up to very high momenta
- p-Pb results confirm that strong suppression in Pb-Pb is due to hot nuclear matter effects

HARD PROBES: HIGH P_T PARTICLES

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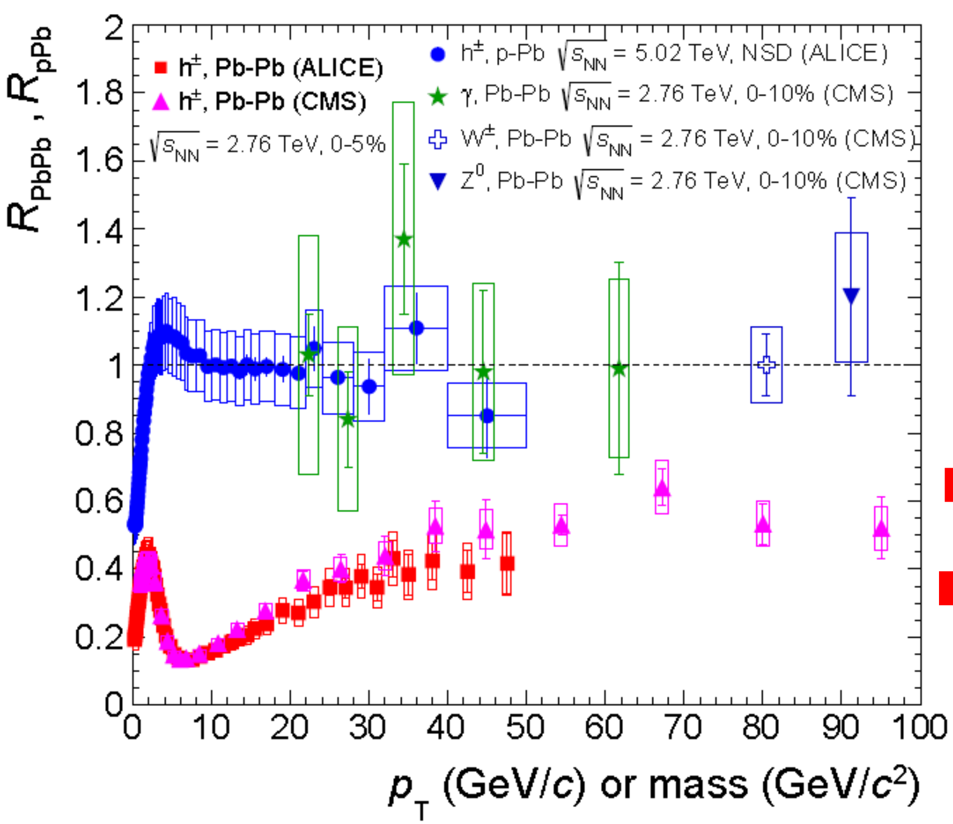

arXiv:1405.2737

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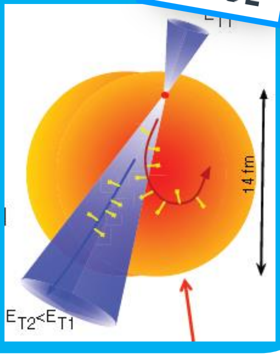
if $R_{AA} \neq 1$ → (hot or cold) medium effects

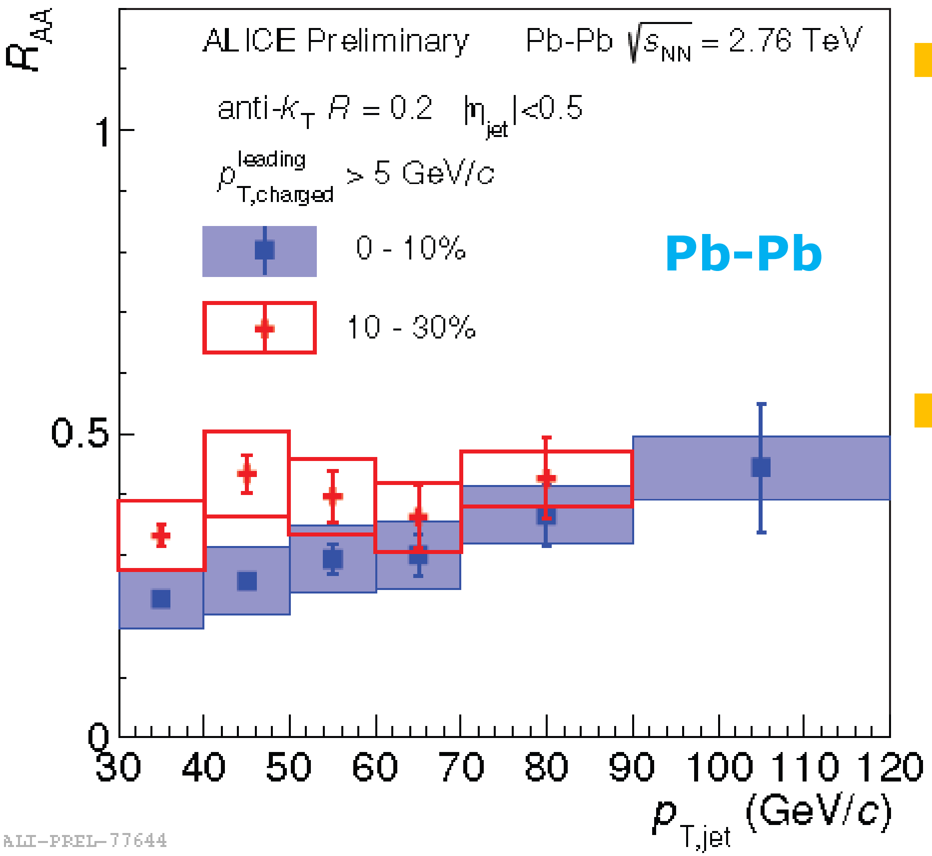
- R_{pA} consistent with 1 up to 50 GeV/c
- p-Pb results consistent with binary scaling (in Pb-Pb collisions, binary scaling is observed only for observables not affected by QCD matter, as direct photons and vector bosons)

HARD PROBES: JETS

Jets are spray of particles created in collisions by hard scattering followed by hadronization. Jet fragmentation is modified by the medium → jet quenching:

- Suppression of jet yield
- Broadening of jet shape
- di-jet imbalance





Strong suppression of jet yields in most central Pb-Pb collisions (down to 30 GeV/c)

→ Moderate increase of R_{AA} with increasing p_T

Dependence on centrality class

Jet energy is moved from high to low p_T and from small to large angles (with respect to the jet axis)

ALICE low-p_T reach allows to recover most of jet fragments

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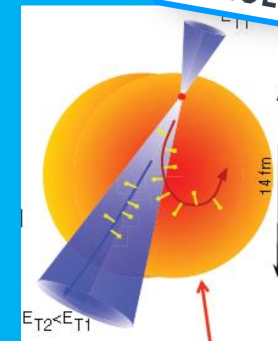
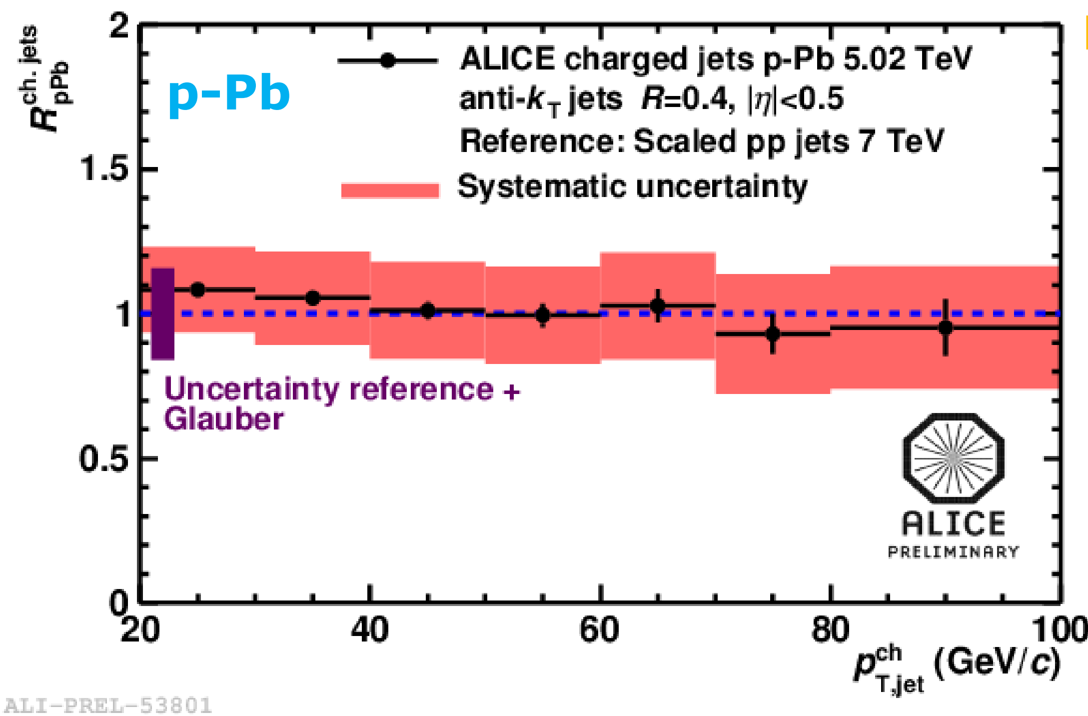




- No modification of jet cross section in p-Pb relative to pp

→ no significant cold nuclear matter effects observed in jet measurements in p-Pb

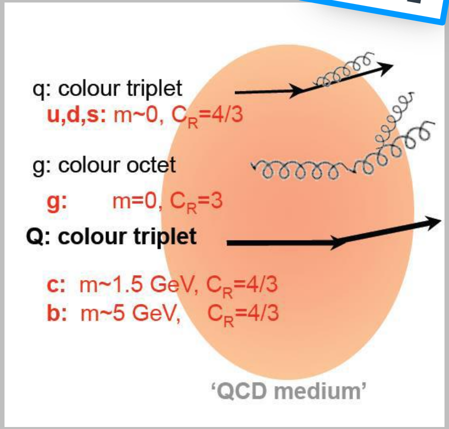
(pp reference for R_{pPb} at $\sqrt{s_{NN}}$ = 5.02TeV obtained scaling the 7TeV pp spectrum with PYTHIA)

HEAVY FLAVOUR: ENERGY LOSS

Heavy quarks are produced in initial hard scattering and experience the full system evolution

Uniqueness of heavy quarks: cannot be destroyed/created in the medium

→ **tool to characterize the properties of the parton-medium**



Partons energy loss by:
- Medium-induced gluon radiation
- Elastic collisions with medium partons

Energy loss ΔE in the medium depends on:
- Properties of the medium
- Path length
- Parton properties

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

Casimir factor (color-charge dependence)
→ 3 for g, 4/3 for q interactions
Dead cone effect (mass dependence)
→ Gluon radiation is suppressed for angles $\vartheta < M_Q/E_Q$

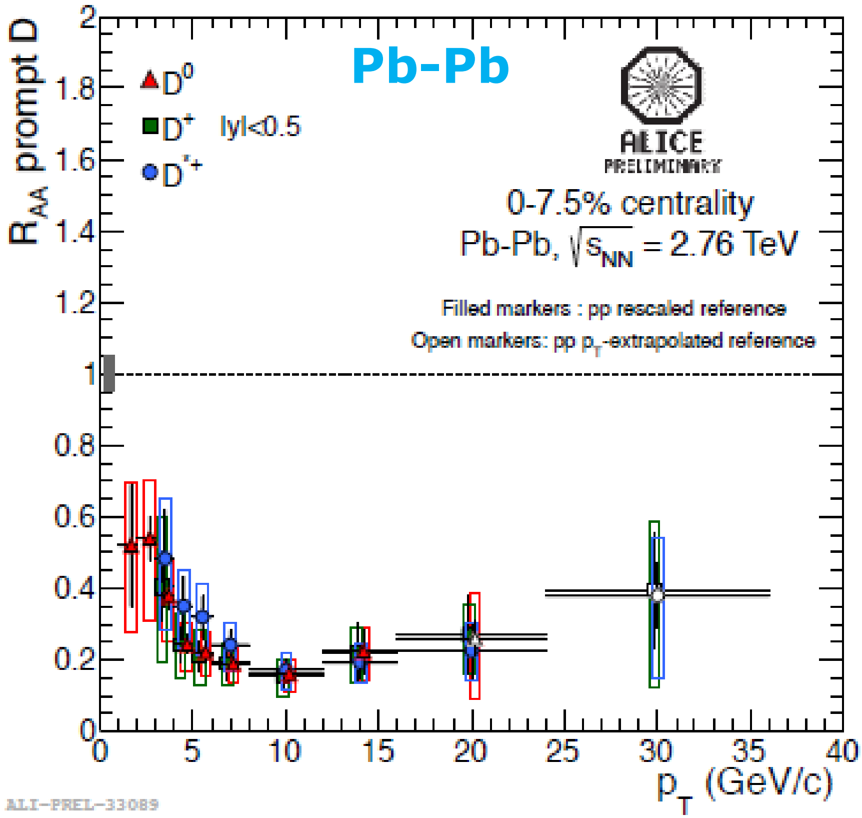
$\Delta E_g > \Delta E_{charm} > \Delta E_{beauty}$

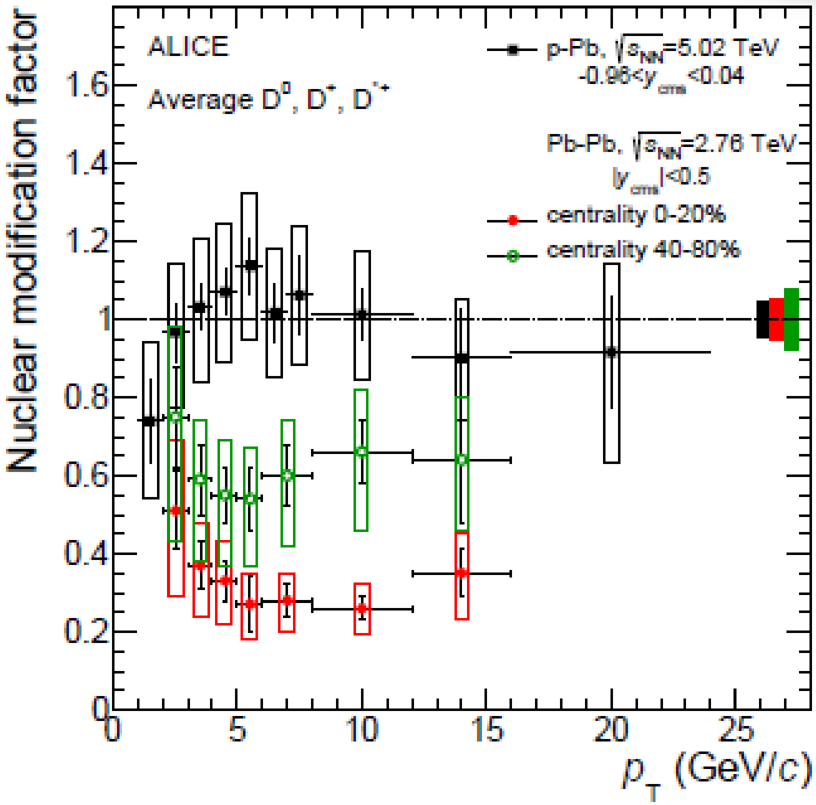
which might lead to

R_{AA} (light hadrons) < R_{AA} (D) < R_{AA} (B)

Heavy flavor abundantly produced at LHC → allow precision measurements

D MESON R_{AA} AND R_{PA}





Pb-Pb:

D^0, D^+ and D^{*+} R_{AA} agree within uncertainties

Strong suppression of prompt D mesons in central collisions
→ up to a factor of 5 for p_T ~10GeV

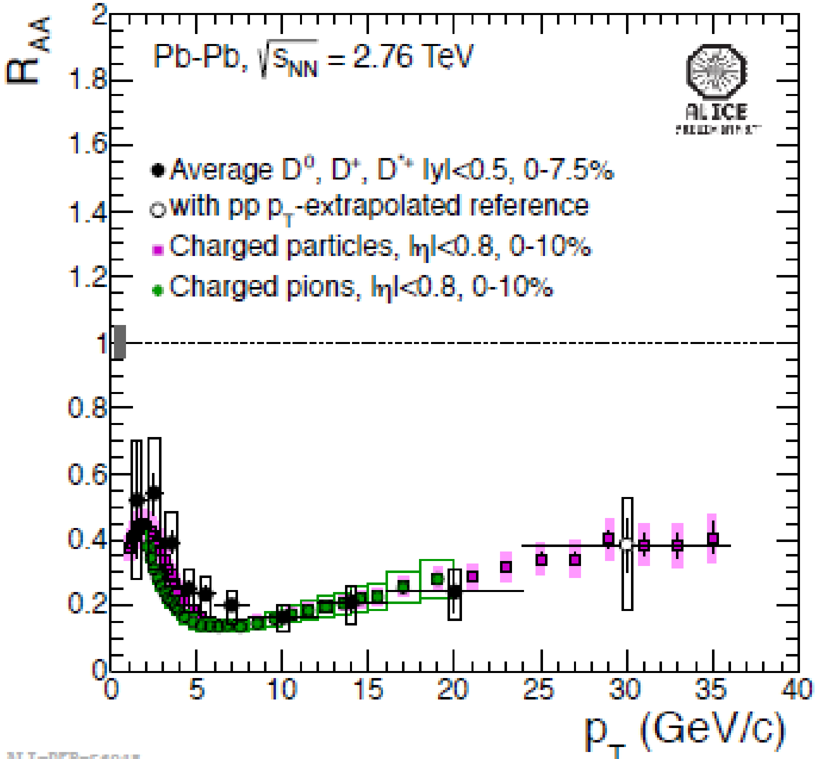
p-Pb vs Pb-Pb

Suppression observed in central Pb-Pb due to strong final state effects induced by hot partonic matter

MASS ORDERING OF ENERGY LOSS

D vs light hadrons

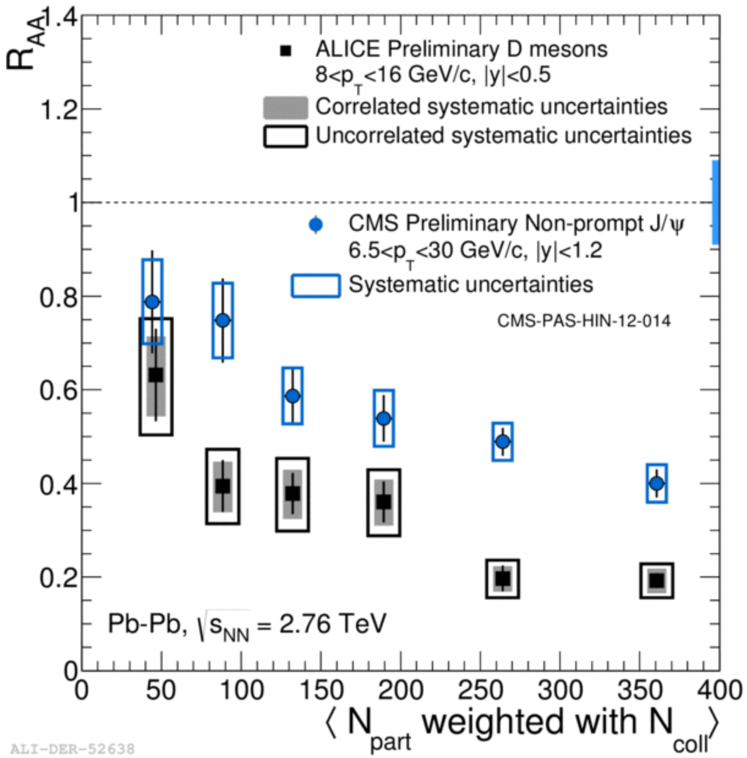
$\Delta E(g) > \Delta E(c)$?



D consistent with π within errors but improved accuracy needed to conclude (consistency described by theory taking into account different p_T shapes and fragmentation functions)

Charm vs beauty

$\Delta E(c) > \Delta E(b)$?

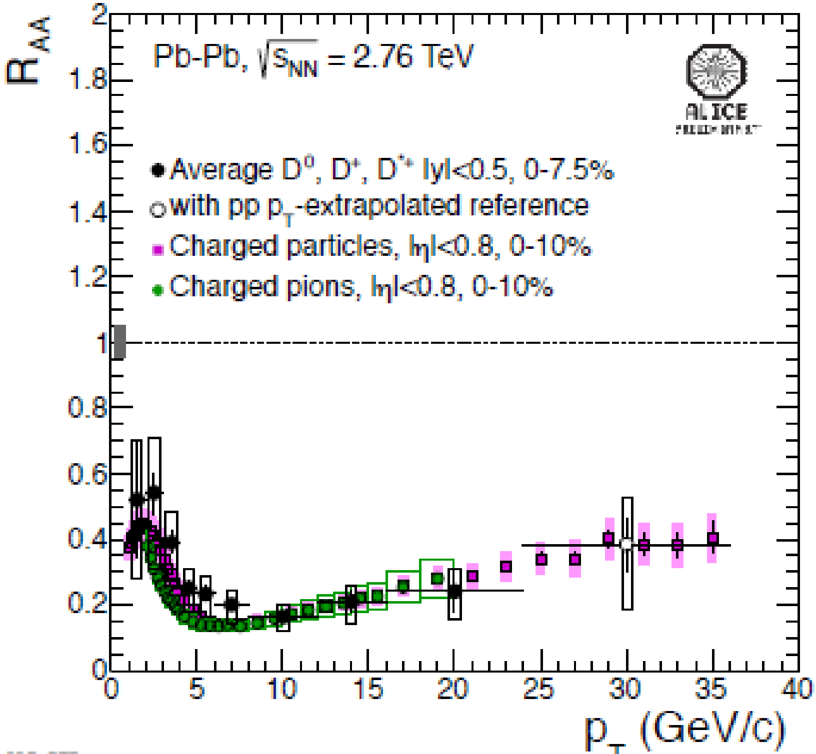


- Comparing D with (non prompt) J/ψ from B decay [p_T range (~10GeV/c) tuned to have $<p_T(D)>\sim<p_T(B)>$]
- In agreement with expectations: $R_{AA}(B) > R_{AA}(D)$

MASS ORDERING OF ENERGY LOSS

D vs light hadrons

$\Delta E(q,g) > \Delta E(c)$?



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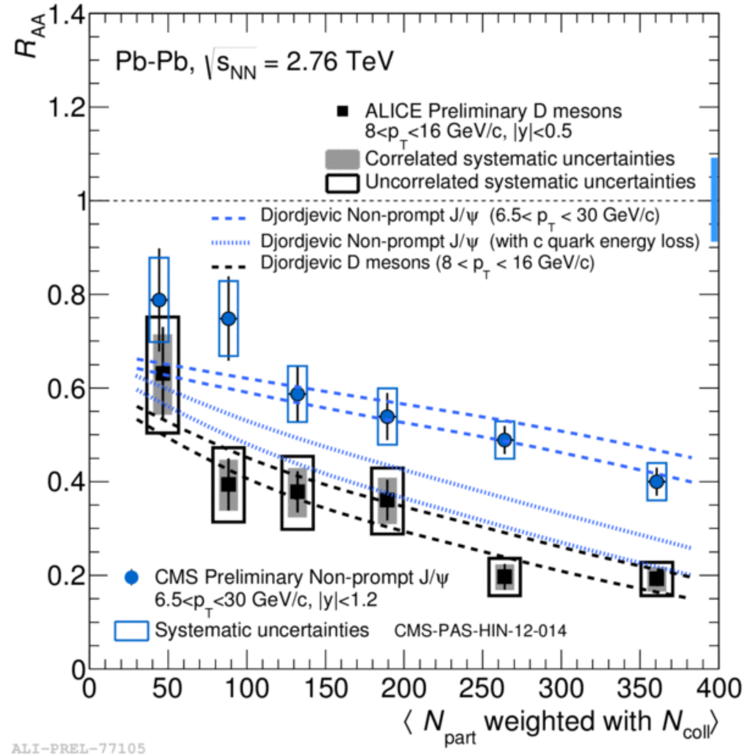
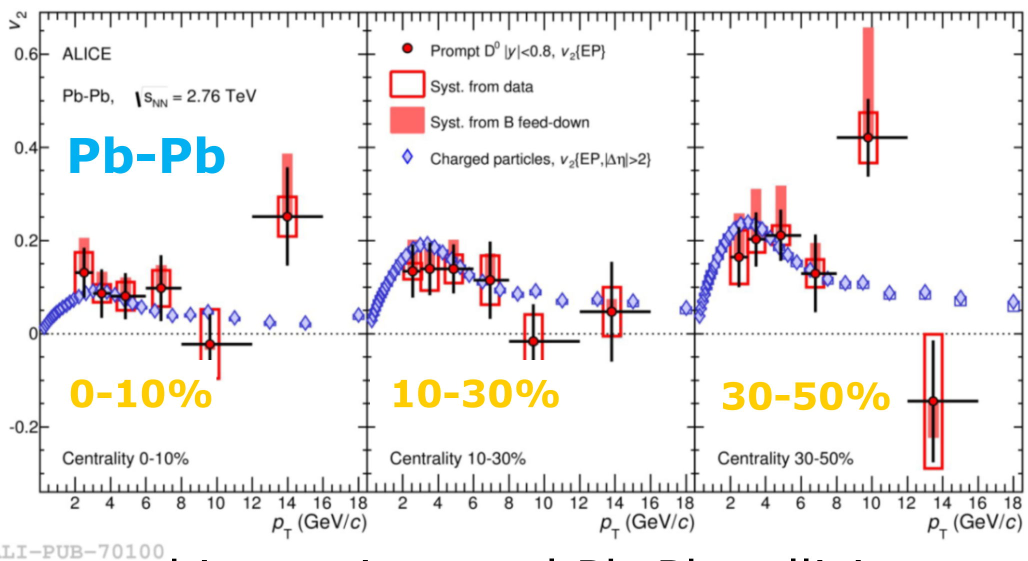


pQCD models including mass dependent radiative and collisional en. loss predicts a difference similar to the one observed in data

Heavy Flavor: Elliptic Flow

- Due to the large mass, b and c quarks should take longer time to be influenced by the collective expansion of the medium ($\rightarrow v_2^b < v_2^c$)

  Heavy-flavor v_2 measurements probe:
  - Low p_T: collective motion, thermalization of heavy-quarks
  - High p_T: path-length dependence of heavy-quark energy loss



- Non-zero v_2 observed in semi-central Pb-Pb collisions (hint of increase from central to semi-central collisions)
- v_2 (D) ~ charged particle v_2
- Confirm significant interaction of charm quarks with the medium $\rightarrow$ suggest collective motion of low p_T charm quarks in the expanding fireball

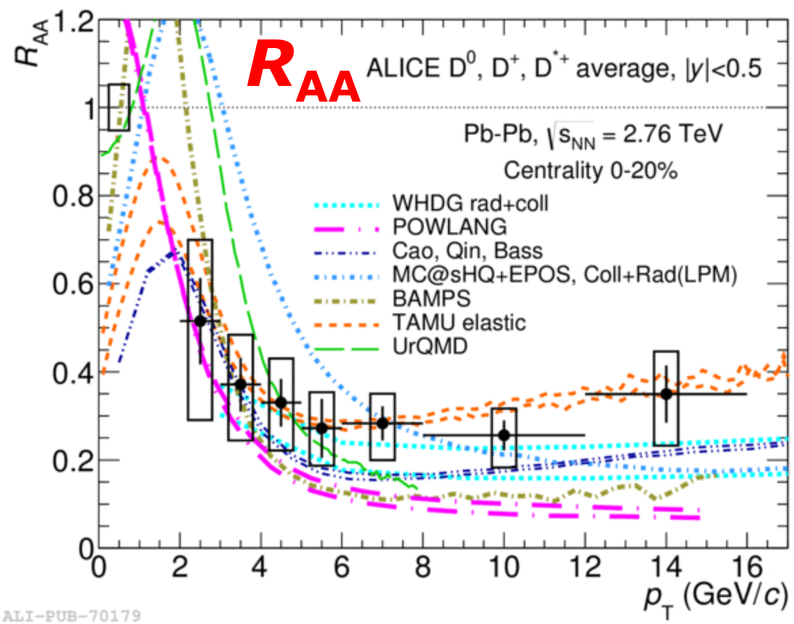
HEAVY FLAVOR: ELLIPTIC FLOW

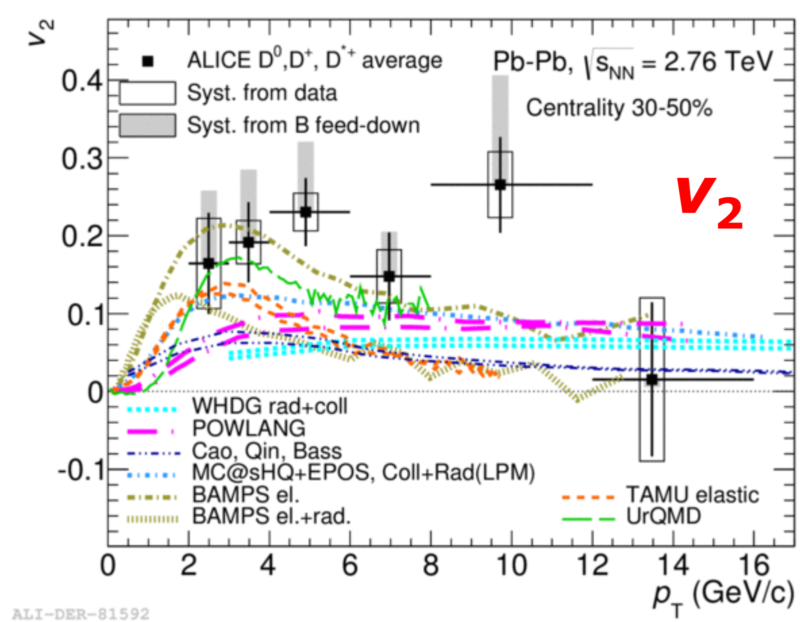
Due to the large mass, b and c quarks should take longer time to be influenced by the collective expansion of the medium → $v_2^b < v_2^c$

Heavy-flavor v_2 measurements probe:

- Low p_T: collective motion, thermalization of heavy-quarks
- High p_T: path-length dependence of heavy-quark energy loss

Challenging description, for theory, of nuclear modification and charm flow measurements together





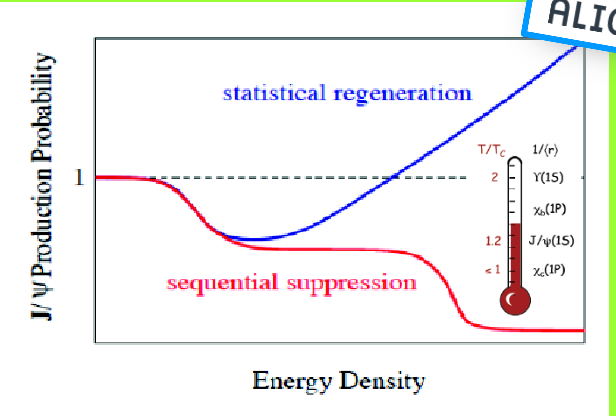
QUARKONIA

QUARKONIA IN p-Pb AND Pb-Pb

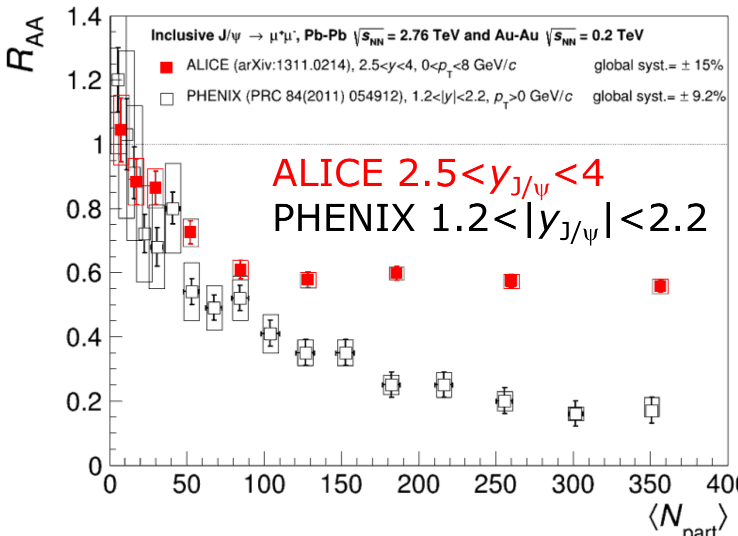
- Quarkonium is one of the main signatures for QGP formation

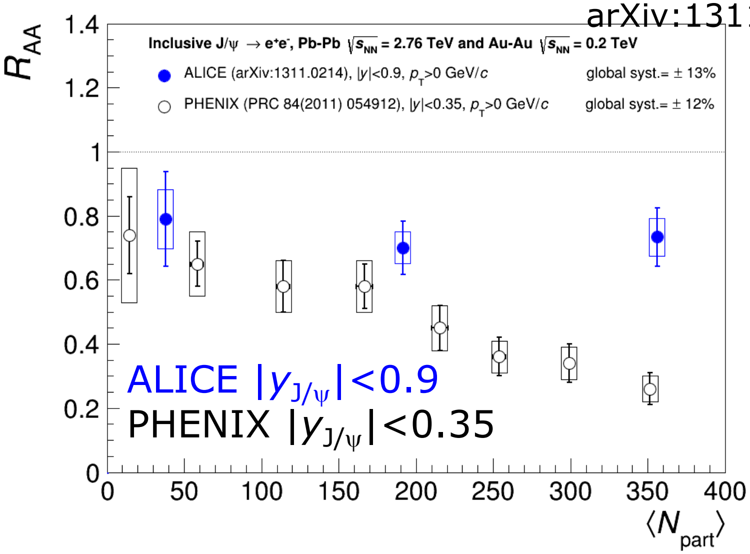
  → strongly affected by the hot medium: suppression vs. recombination

See Indranil Das's talk



arXiv:1311.0214





- **Pb-Pb**: clear J/ψ suppression with almost no centrality dependence above N_{part}~100. Less suppression at mid-*y* wrt forward *y* for central events

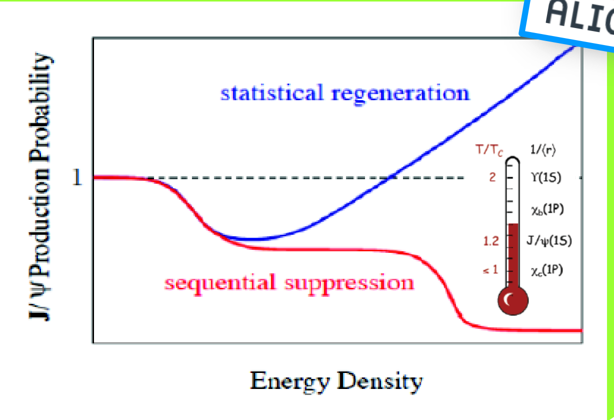
- Comparison with PHENIX: ALICE results show weaker centrality dependence and smaller suppression for central events

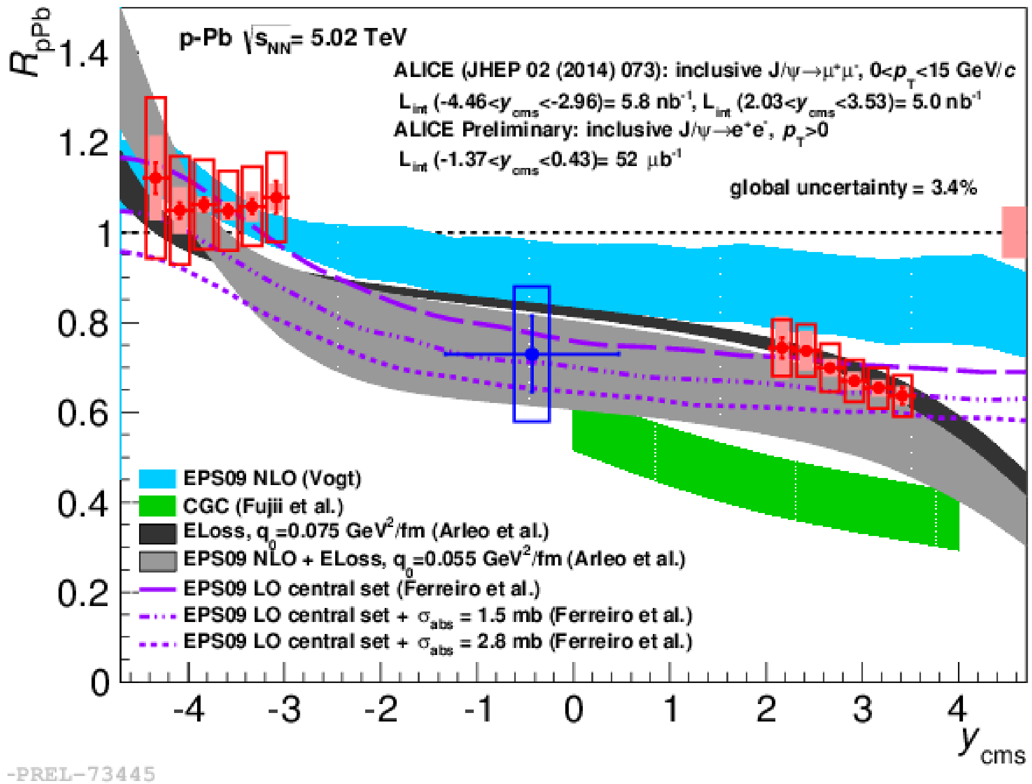
QUARKONIA IN p-Pb AND Pb-Pb

- Quarkonium is one of the main signatures for QGP formation

  → strongly affected by the hot medium: suppression vs. recombination

See Indranil Das's talk





- **p-Pb**:

  J/ψ production is strongly modified also in p-Pb because of cold nuclear matter effects

  → R_{pA} decreases towards forward *y* in agreement with shadowing and coherent energy-loss models

QUARKONIA IN p-Pb AND Pb-Pb

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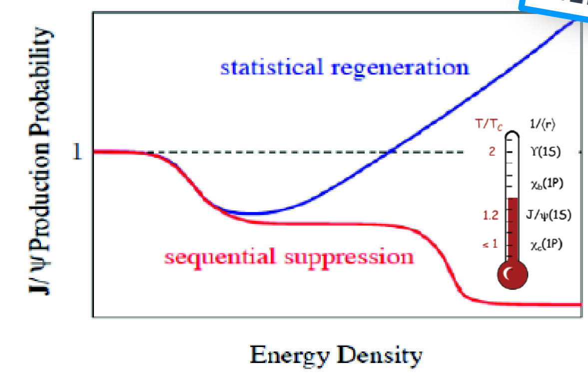
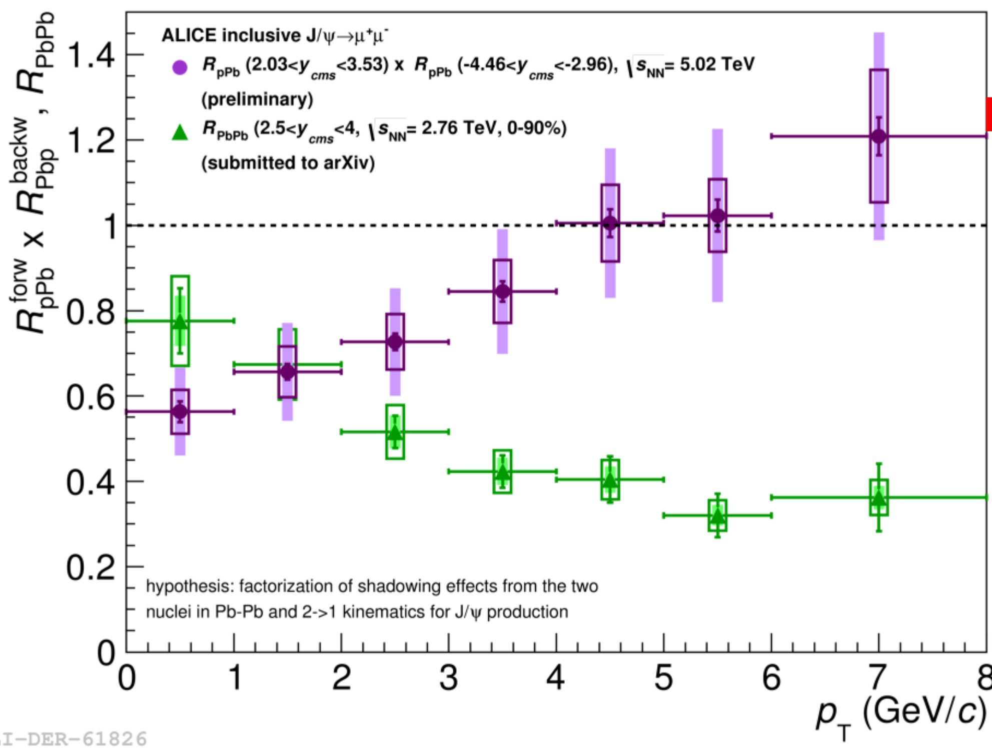




- **p-Pb vs Pb-Pb**:

(Rough) extrapolation of CNM effects, evaluated in p-Pb, to Pb-Pb

→ evidence of hot matter effects in Pb-Pb!

ALICE PAST & FUTURE

Heavy-ion data from RUN1:

System	$\sqrt{s_{NN}}$ (TeV)	Year	Integrated luminosity
Pb-Pb	2.76	2010	~10 μb^{-1}
		2011	~100 μb^{-1}
p-Pb	5.02	2013	~30nb^{-1}

Future:

RUN2 (2015-2017): complete the heavy-ion program:

- improved detectors, readout and trigger
- higher LHC energy ($\sqrt{s}$ = 13TeV for pp, 5.1TeV for PbPb)
- pp, p-Pb, Pb-Pb runs with much larger statistics!

RUN3+4 (~2020): major detectors upgrade

- operate ALICE at high rate (increased by a factor 100!), preserving unique tracking and PID
- improvements in vertexing capability and low p_T tracking (new ITS and TPC readout)
- focus on rare probes (heavy flavor,quarkonia,low-mass dileptons,jets…)

CONCLUSIONS

- Large wealth of results both in Pb-Pb and in p-Pb collisions from Run-1 !

Pb-Pb:

- Different probes (soft, hard) allow to access to the medium properties (temperature, density, transport properties…)
- Significant progress in precision: v_2 of identified particles, heavy-flavour, quarkonium…

p-Pb:

- Not only a “control” experiment to compare to Pb-Pb!
- Tool to investigate cold nuclear matter effects
- Existence of collective effects at high multiplicities also in small systems (like pp and p-Pb)!

- Many results would benefit from more data to sharpen the conclusions: Waiting for Run-2 and future ALICE upgrade!

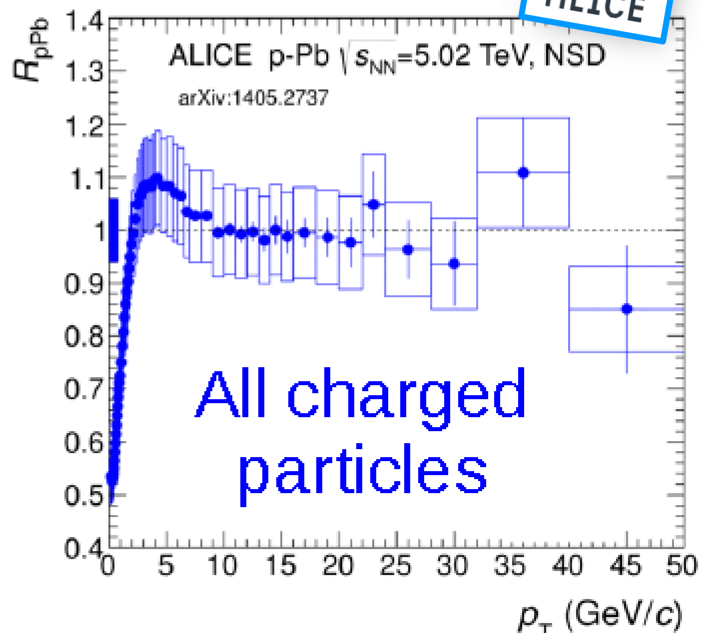
BACKUP SLIDES

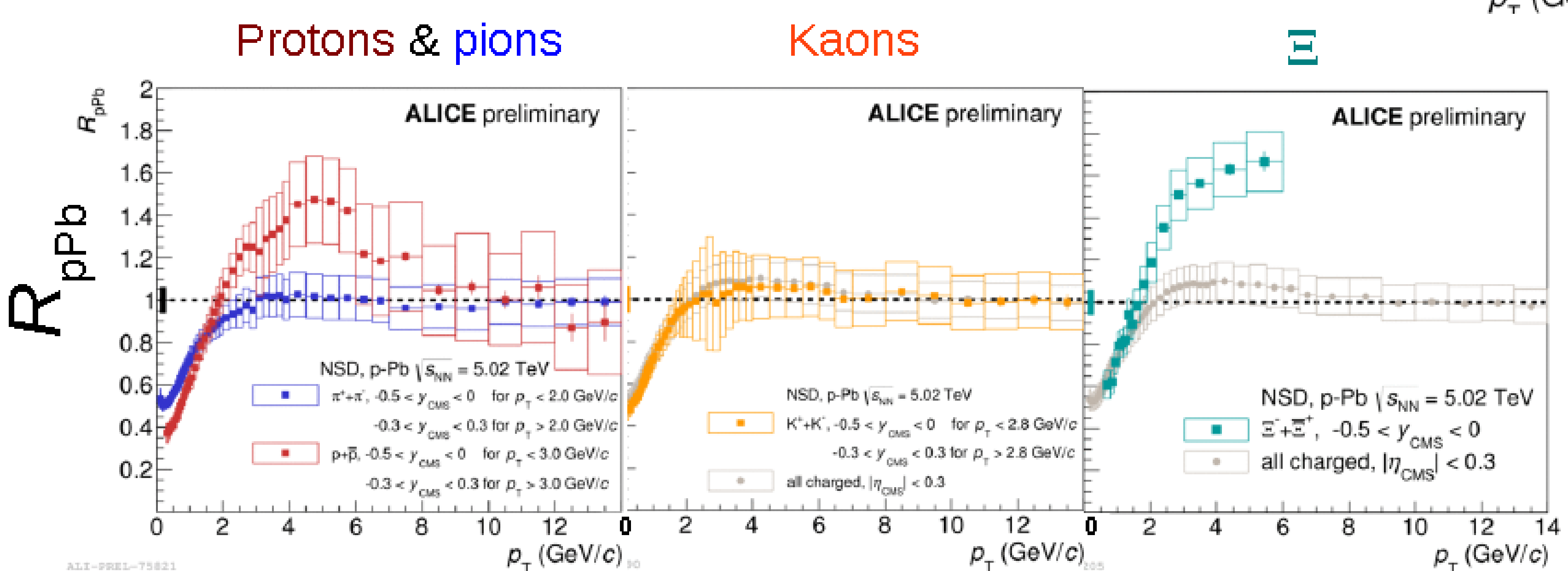
NUCLEAR MODIFICATION FACTOR:PID

- Comparison of particle spectra in p-Pb and pp

$$R_{\mathrm{pA}} = \frac{\mathrm{d}N_{\mathrm{pA}}/\mathrm{d}p_{\mathrm{T}}}{\langle N_{\mathrm{coll}}\rangle \mathrm{d}N_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

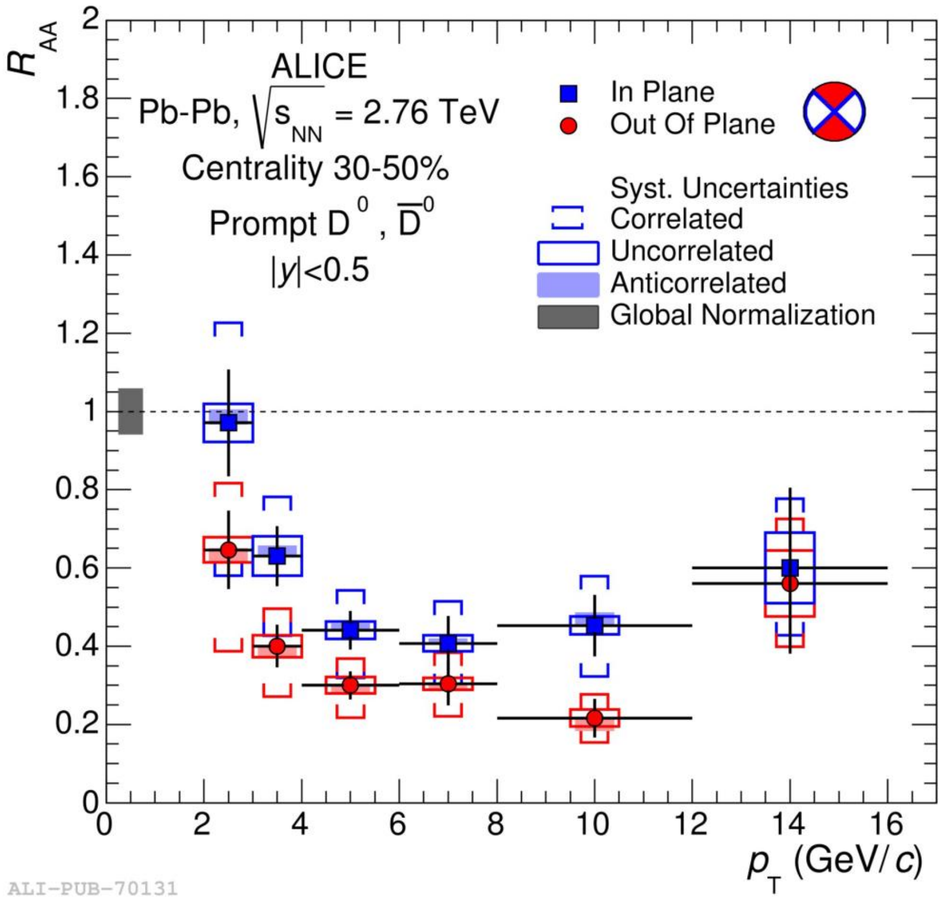
- R_{pA} shows dependence on particle mass, being enhanced, at intermediate p_{T}, for heavier particles as p, Ξ
- Enhancement is flow-like





HEAVY FLAVOR: IN & OUT OF PLANE

- $D\ R_{AA}$ measured in and out of plane (in 30-50% centrality class) is sensitive to
  - path-length dependence of parton energy loss at high p_T
  - collectivity at low p_T

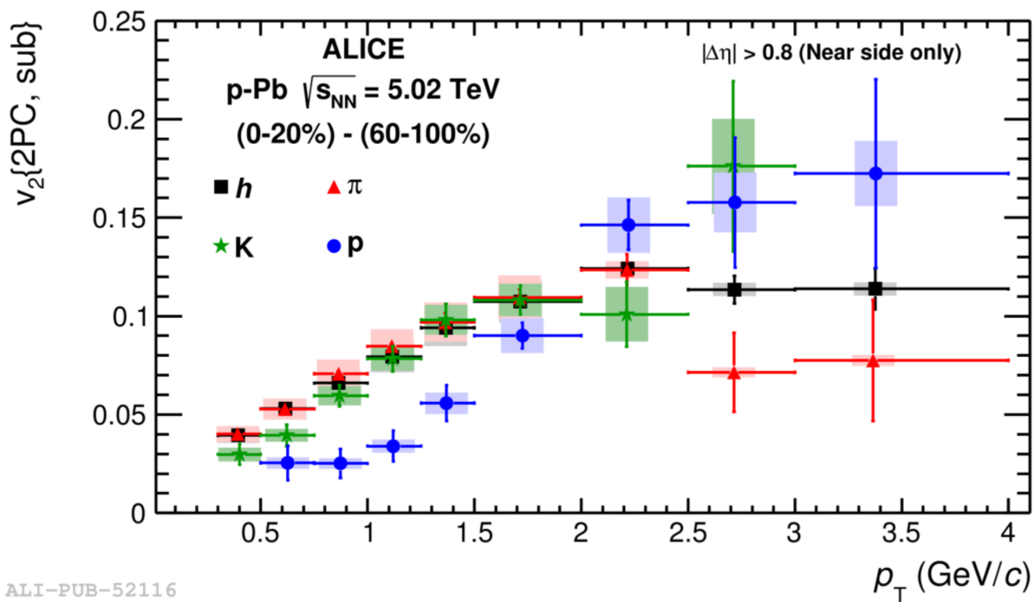


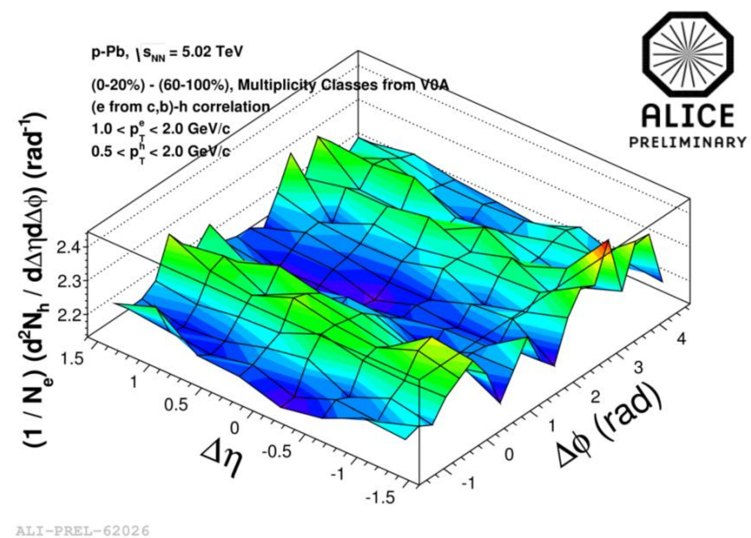
- Out-of-plane:
  longer path length
  → more suppression

HADRON-HADRON CORRELATIONS IN p-Pb

h - π, K, p correlations

HF decay e± - h correlations





v_2 extracted from two-particles correlations

- Mass ordering at low p_T
- Crossing at p_T~2GeV/c
- Qualitatively similar to Pb-Pb

Double ridge seen also in the correlation of heavy-flavour decay electrons with hadrons

Suggesting that the mechanism generating the double ridge is at work also for heavy-flavor

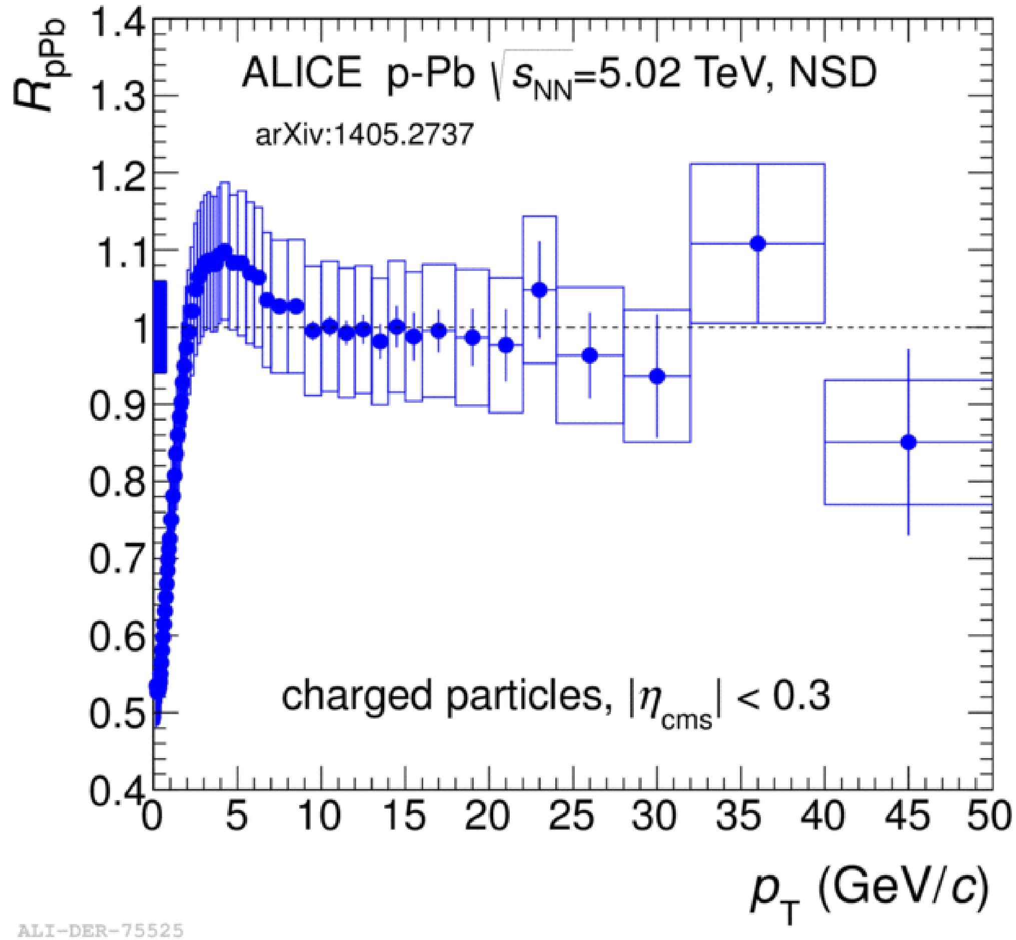
HARD PROBES R_{pPb}

To summarize: do hard probes scale with the number of binary collisions (N_{coll}) in p-Pb?

$$R_{pA} = \frac{dN_{pA}/dp_T}{\langle N_{coll}\rangle dN_{pp}/dp_T}$$

R_{pA} consistent with unity for:

- **High p_T charged particles (above 10GeV/c)**



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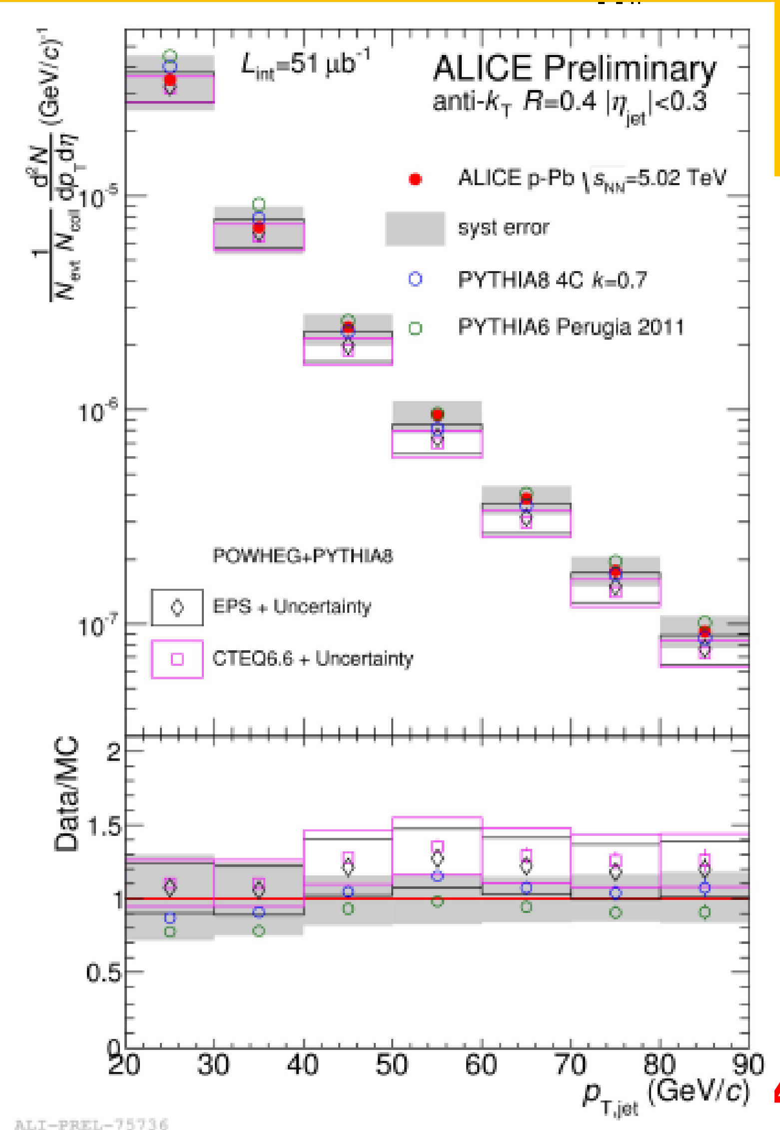

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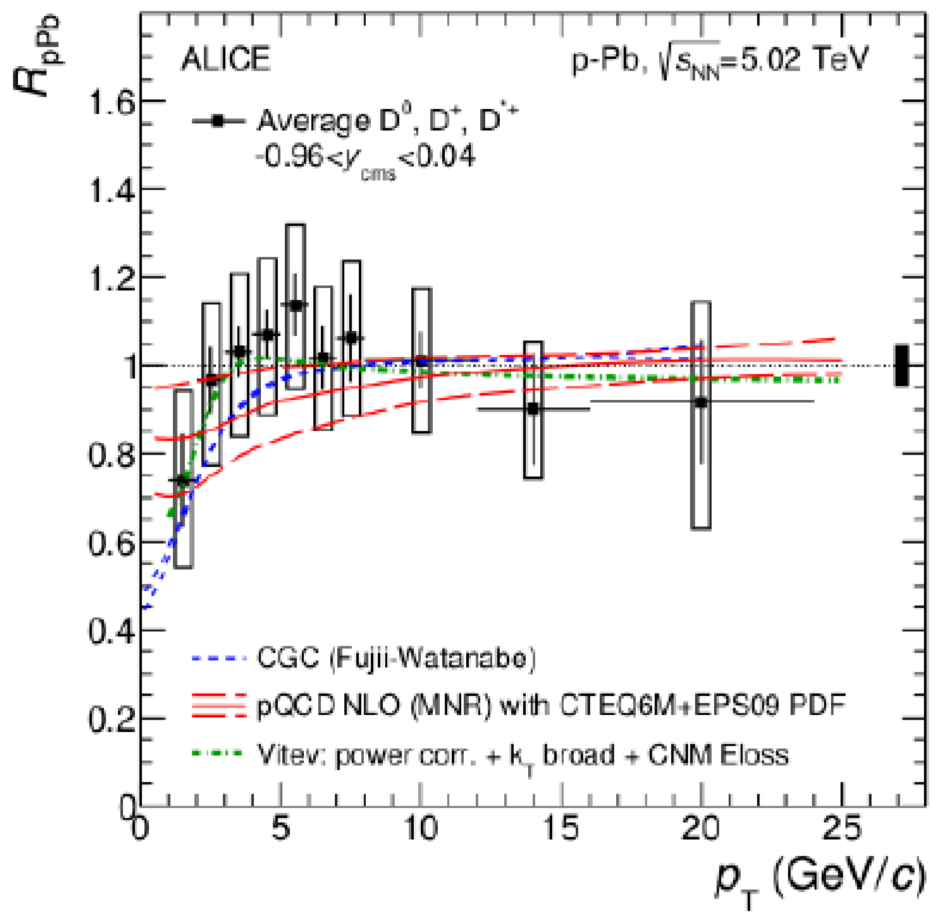

arXiv:1405.3452

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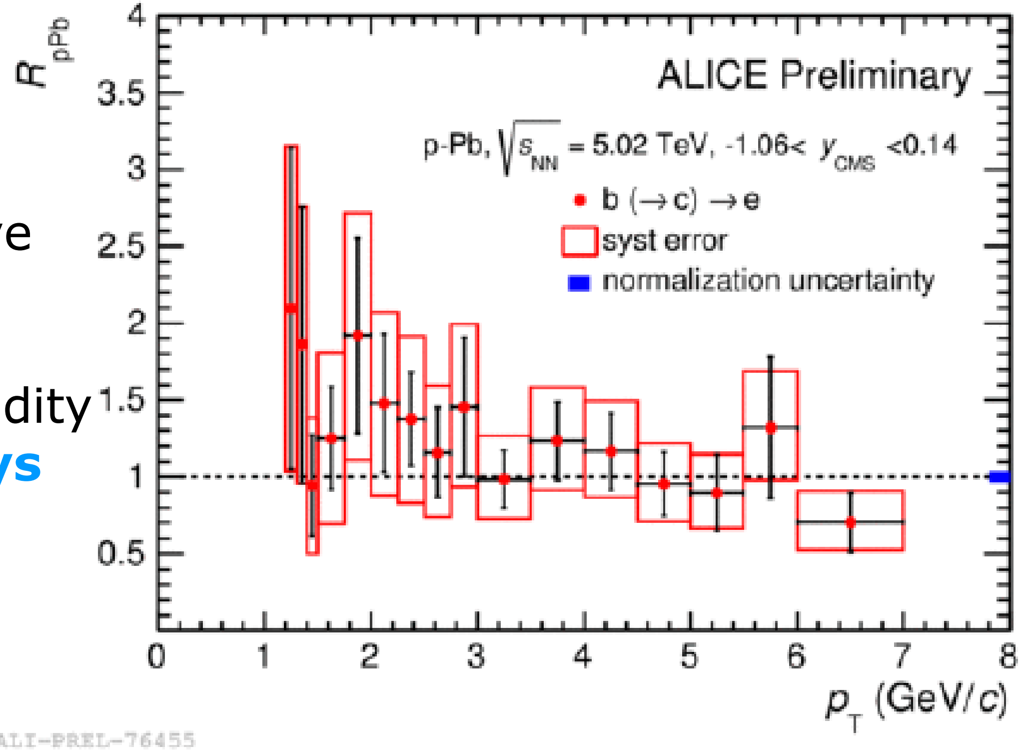

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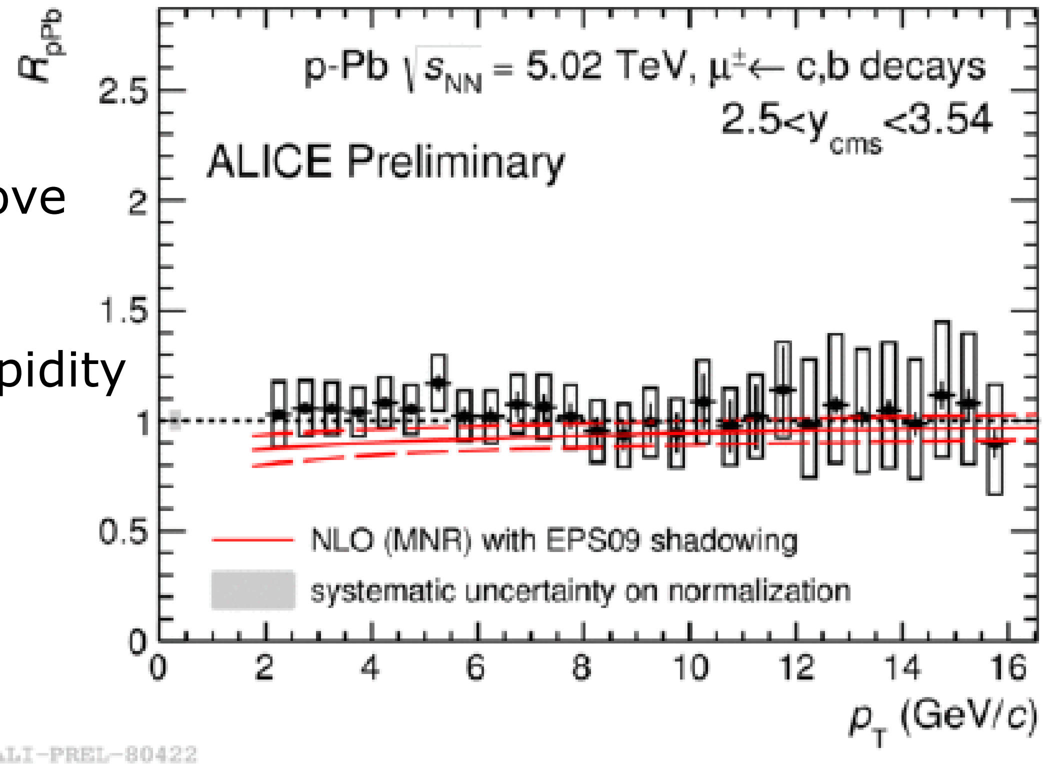

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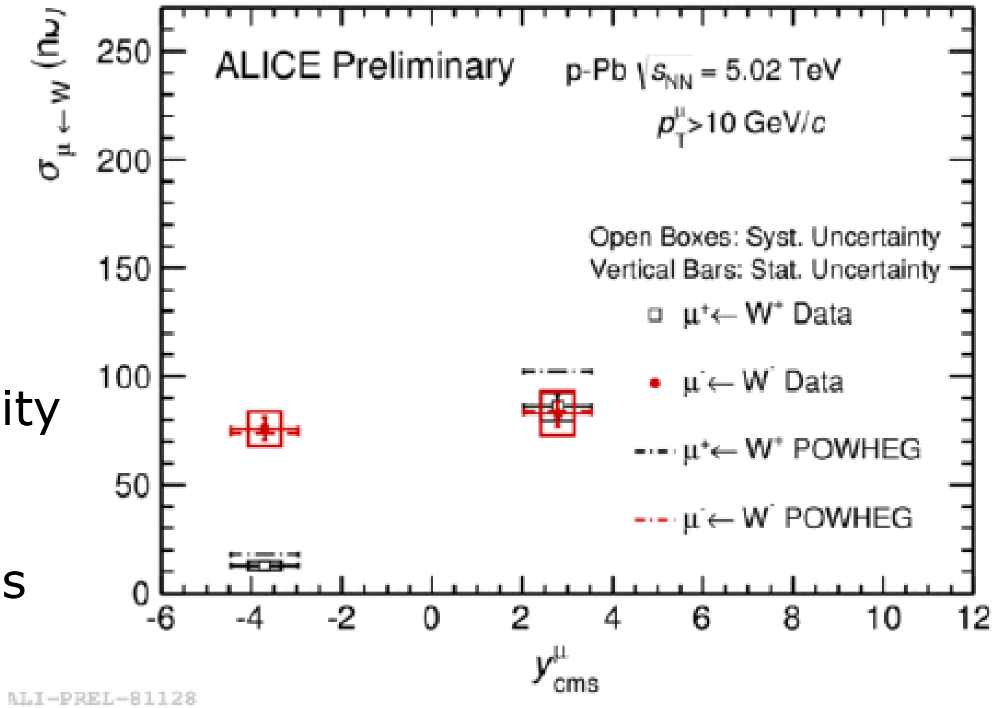
- Muons from heavy-flavour decays (forward-y)
- **W→μ decay**



For several hard probes binary scaling is observed in pA:
→ suppression in Pb-Pb is a final state effect!