ALICE MEASURES pA COLLISIONS: COLLECTIVITY IN SMALL SYSTEMS?

Alberica Toia
Goethe University Frankfurt & GSI
on behalf of the ALICE Collaboration

WHY PROTON-NUCLEUS COLLISIONS ?

- In high-energy nucleus-nucleus collisions: large energy density over large volume
- In high-energy proton-nucleus collisions: large energy density in a small volume
  - Control experiment:
    - calibrate the initial modification of hard probes (jets, heavy quarks, quarkonia),
    - single-out final-state effects (hot medium) in Pb-Pb
  - Explore **new territory in QCD** (low-x):
    - high gluon density in the initial state (CGC, gluon-shadowing?)
- Can we separate initial state from final state?
  - Do we understand the initial state?
- What is the effect of 'cold' nuclear matter (on final state observables)?
- Can we understand multiplicity and energy dependence of p-A & A-A?
  e.g. compare high mult p-A at LHC & same mult A-A at LHC & RHIC

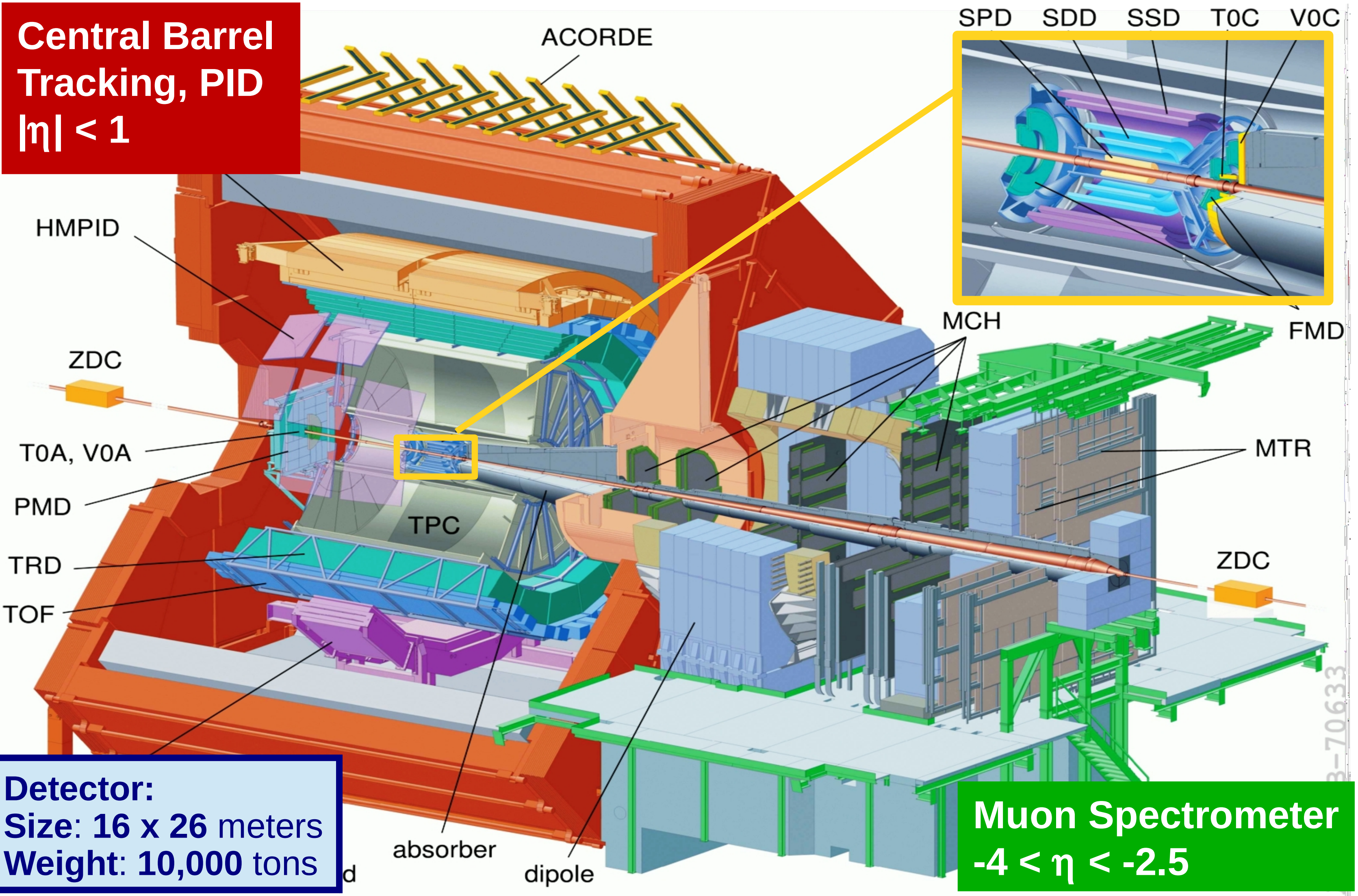
THE ALICE EXPERIMENT

ALICE

Experiment designed for Heavy Ion collision
→ comprehensive, cover all relevant observables

VERY robust tracking (0.1 - 100 GeV/*c*)
high-granularity 3D detectors
(TPC: up to **560 M pixels** → 159 space points/track)
very low material budget (**< 10%X_0** in r < 2.5 m)

Central Barrel Tracking, PID
|η| < 1



Secondary vertexing

PID large p_T range
TOF, d*E*/d*x*, RICH, TRD, topology, EM cal

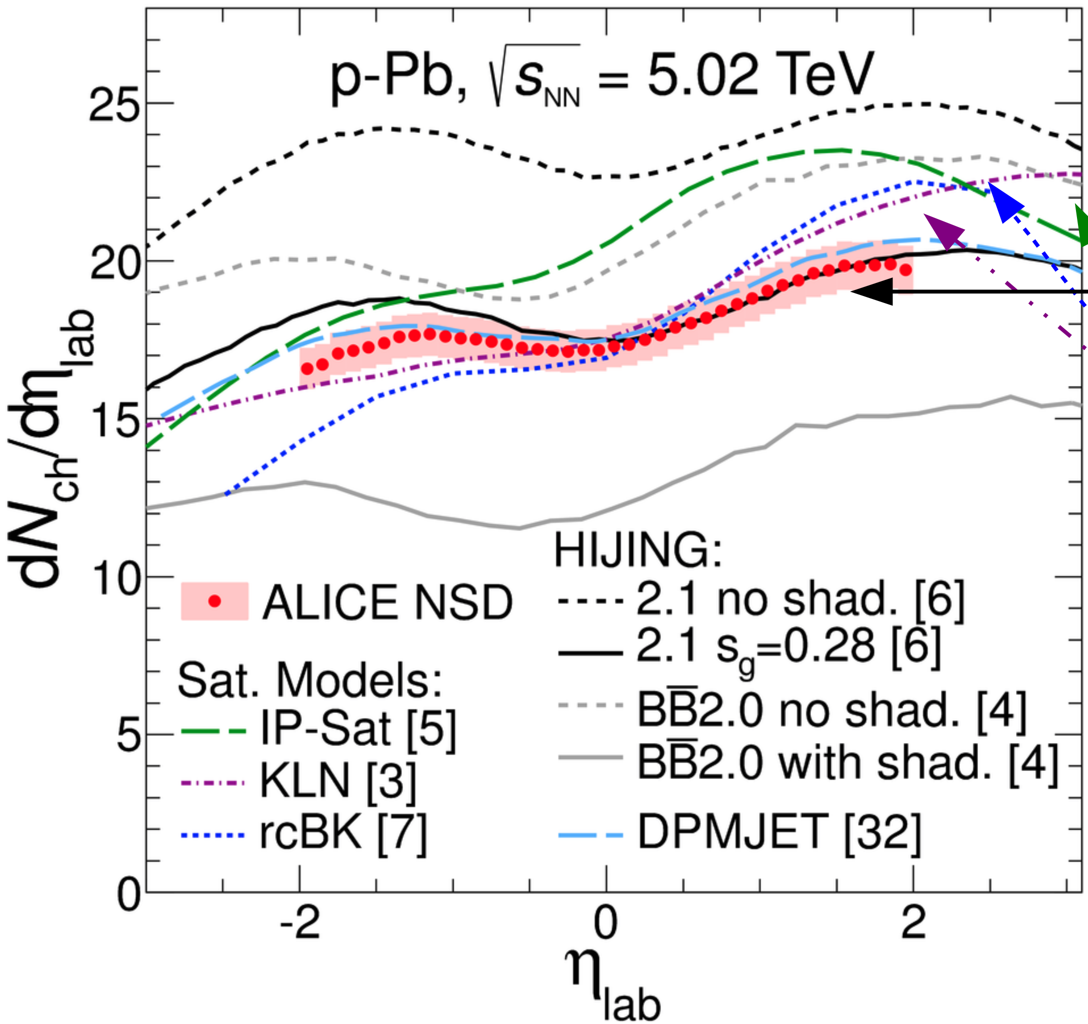
- -Hadrons
- -leptons (electrons, muons)
- -photons

Detector:
Size: **16 x 26** meters
Weight: **10,000** tons

Muon Spectrometer
-4 < η < -2.5

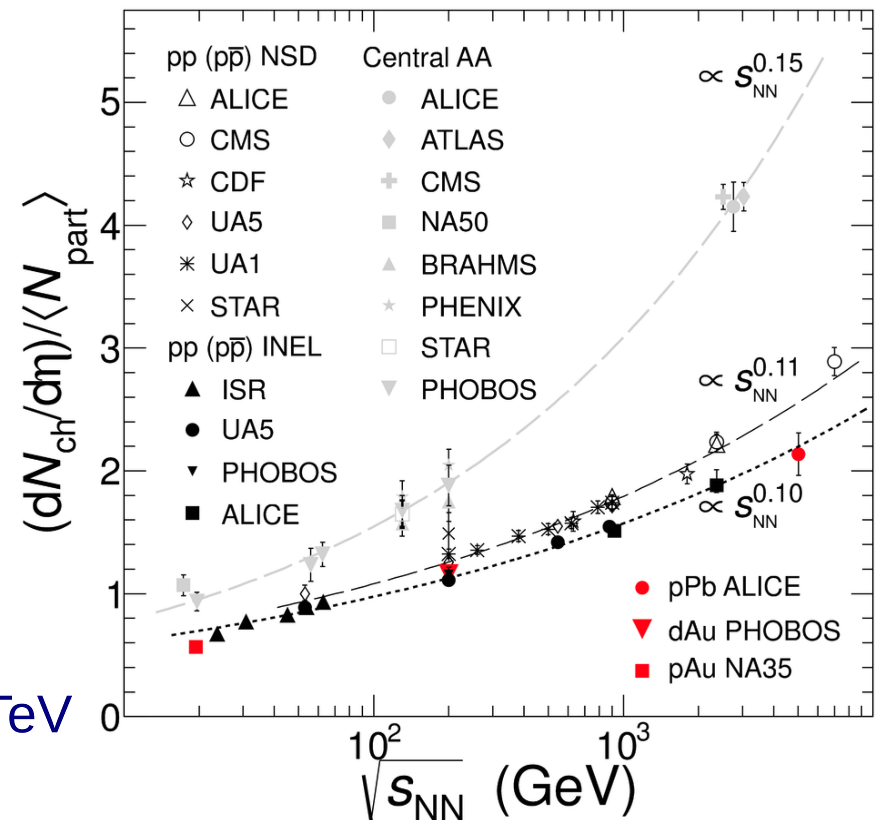
MULTIPLICITY IN pA

ALICE PRL 110 (2013) 032301



$dN_{ch}/d\eta$ DISTRIBUTION

- Most models within 20% of data
- Data favors p-QCD based models that incorporate shadowing
  - HIJING, DPMJET
- Saturation models rise too steeply with η

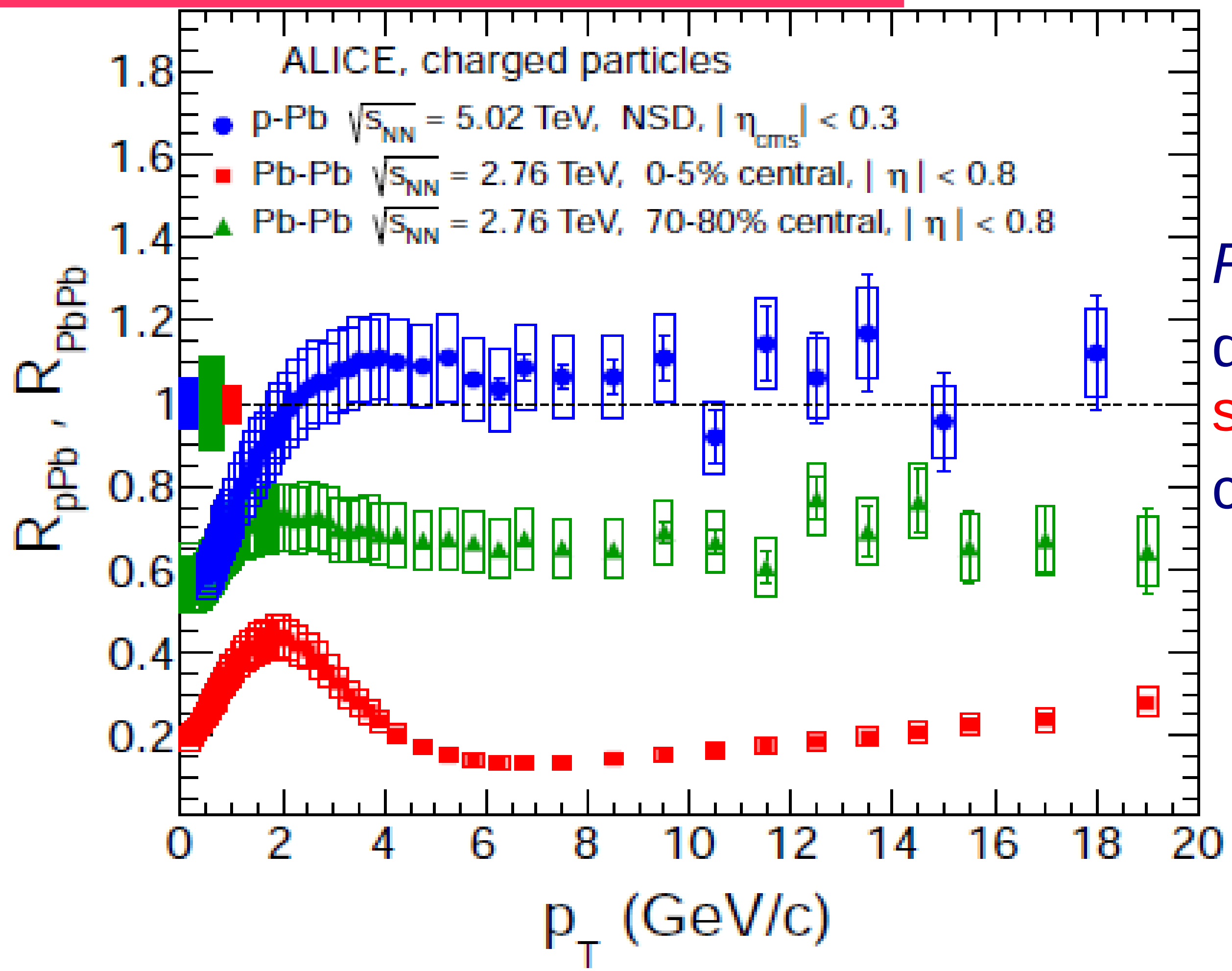


ENERGY DEPENDENCE

- ~15% below NSD pp collisions
- Similar forinelastic pp collisions
- 84% higher than in d–Au collisions at $\sqrt{s_{NN}}$ = 0.2 TeV

NUCLEAR MODIFICATION R_{pPb}

Do hard probes scale with N_{coll} in p-Pb?



$$R_{AA} = \frac{Yield\ in\ A+A}{N_{binary} \times Yield\ in\ p+p}$$

R_{AA} (R_{pA}): test if AA (pA) can be described by incoherent superposition of N_{coll} binary collisions

- R_{AA} ~ 1 → No nuclear effect
- R_{AA} < 1 → suppression
- R_{AA} > 1 → Cronin effect
  Observed at RHIC
  (Multiple initial/final state parton interactions)

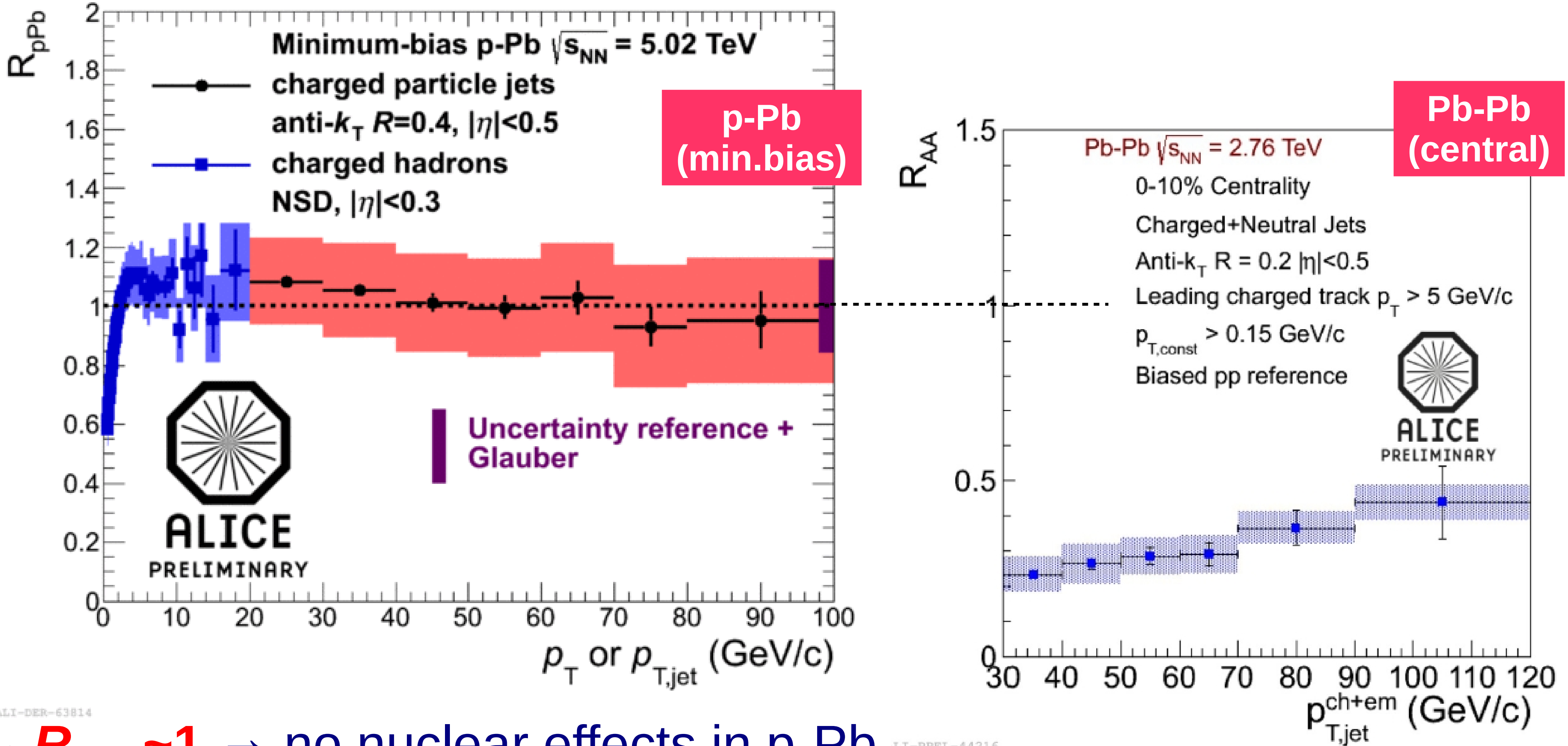
- **R_{pPb} ~1** → no nuclear effects in p-Pb

→ suppression in Pb-Pb is a final state effect

ALICE PRL 110 (2013) 082302

JETS R_{pPb}

Do hard probes scale with N_{coll} in p-Pb?



- ***R*$_{pPb}$ ~1** → no nuclear effects in p-Pb

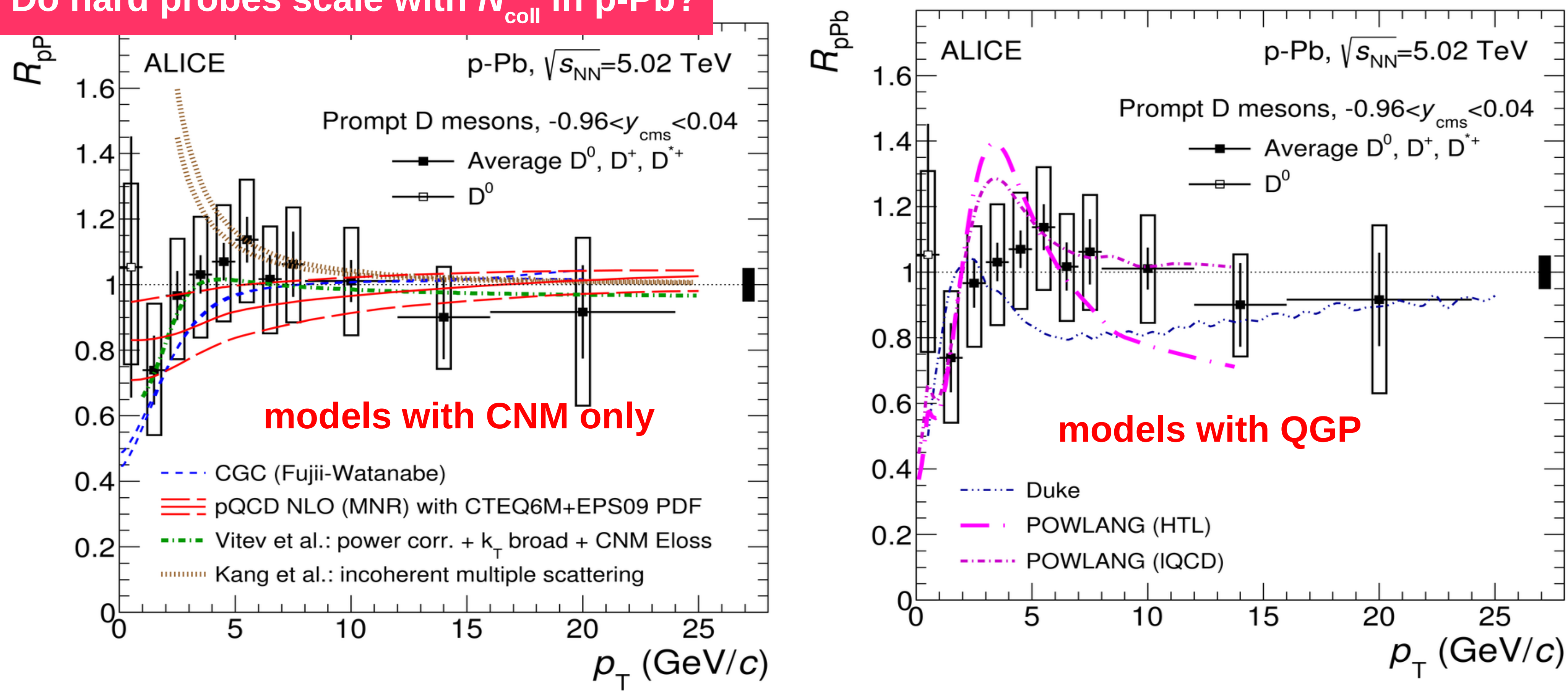
→ suppression in Pb-Pb is a final state effect

ALICE PLB 749 (2015) 68-81

HEAVY FLAVOR R_{pPb}

ALICE arXiv: 1605.07569

Do hard probes scale with N_{coll} in p-Pb?



R_{pPb} ~ 1 → no suppression at intermediate/high-p_T

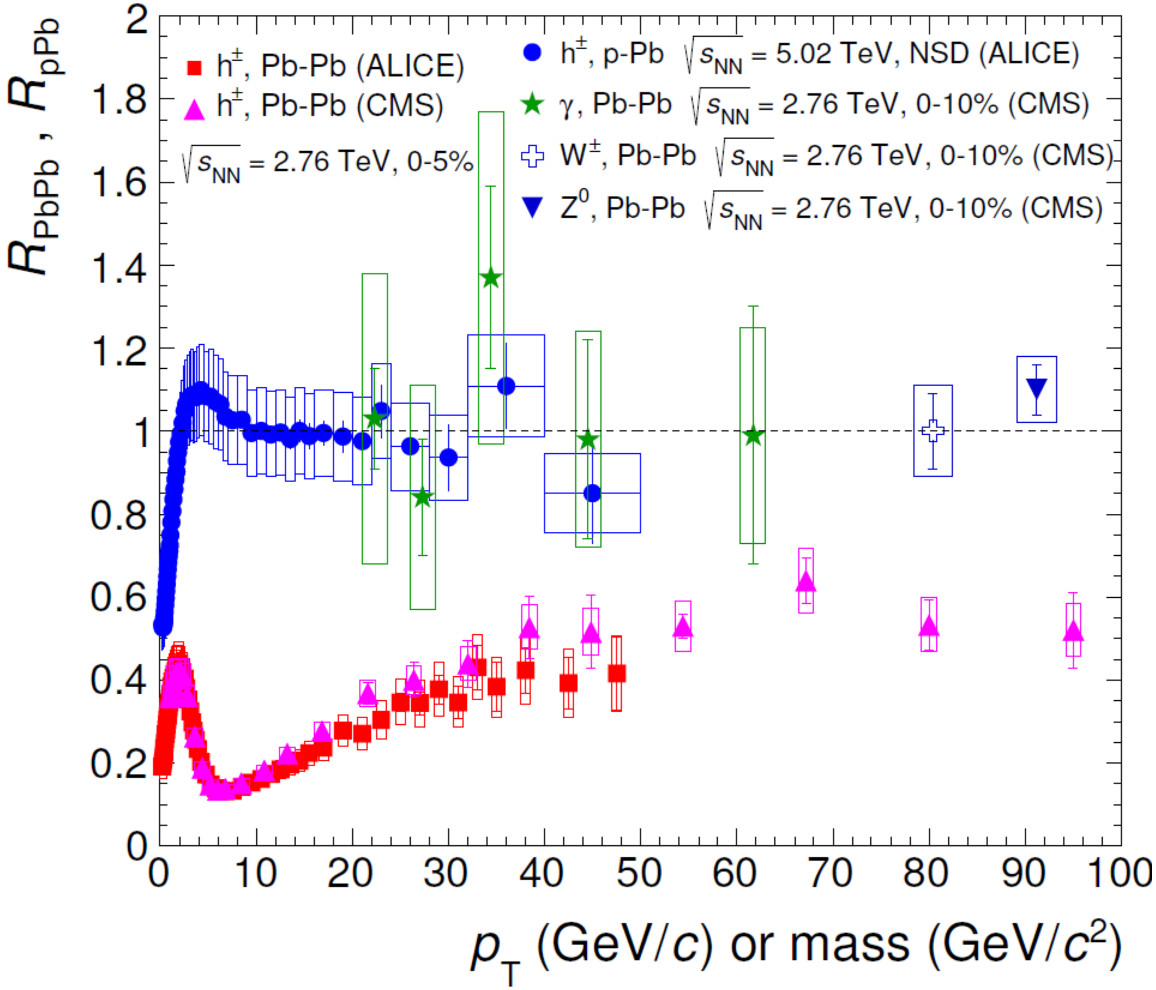
- Measurement compatible with no CNM effects
- Measurement compatible with models including initial or final state effects

→ initial and/or final state effects are small

- Experimental uncertainties are still too large to distinguish between the existing models
- A new sample of p-Pb collisions to be collected in Nov. 2016 → Constrain models

CONTROL EXPERIMENT

Is suppression of hard probes an effect of QGP?



- various observables measured in **"cold" nuclei (p–Pb):**

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- N_{ch}, EPJC 74 (2014) 3054
- heavy flavor, PRL 113 (2014) 232301
- Jets, EPJC 76 (2016) 5, 271

- **Electroweak probes**

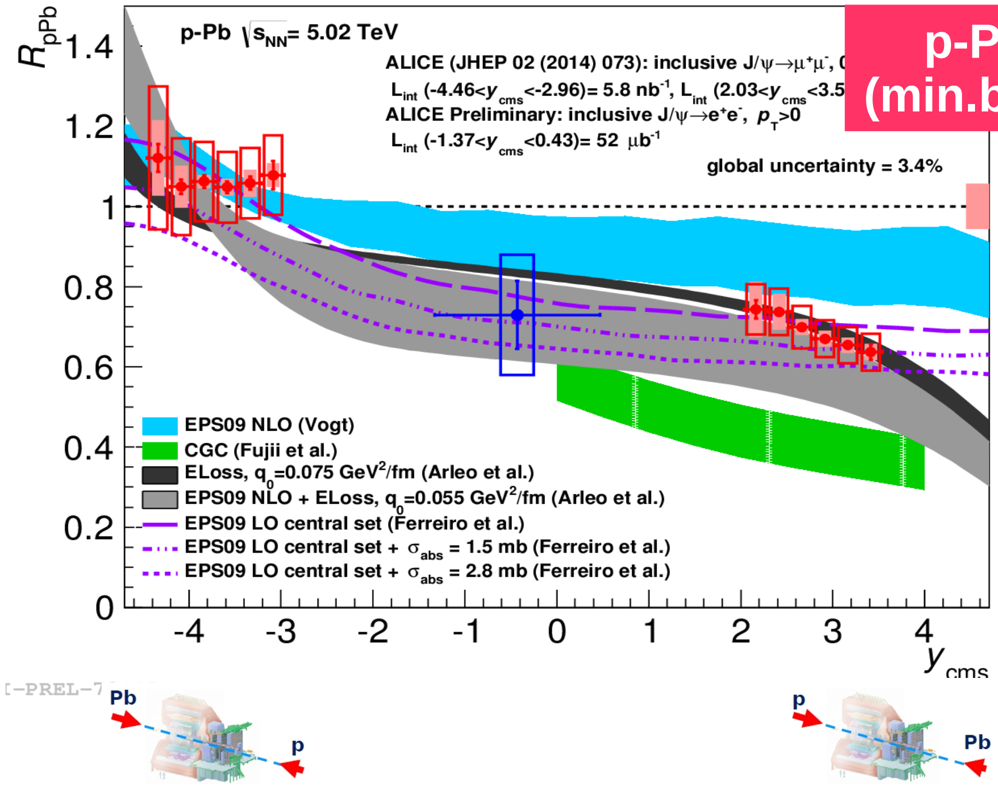
CMS

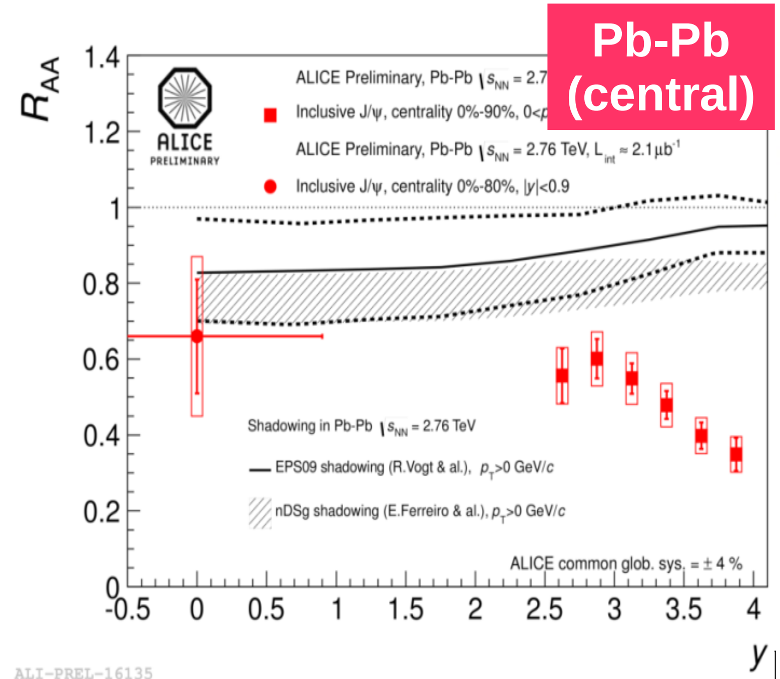
- γ, PLB 710 (2012) 256
- W±, PLB 715 (2012) 66
- Z^0, PRL 106 (2011) 212301, CMS-PAS-HIN-13-004

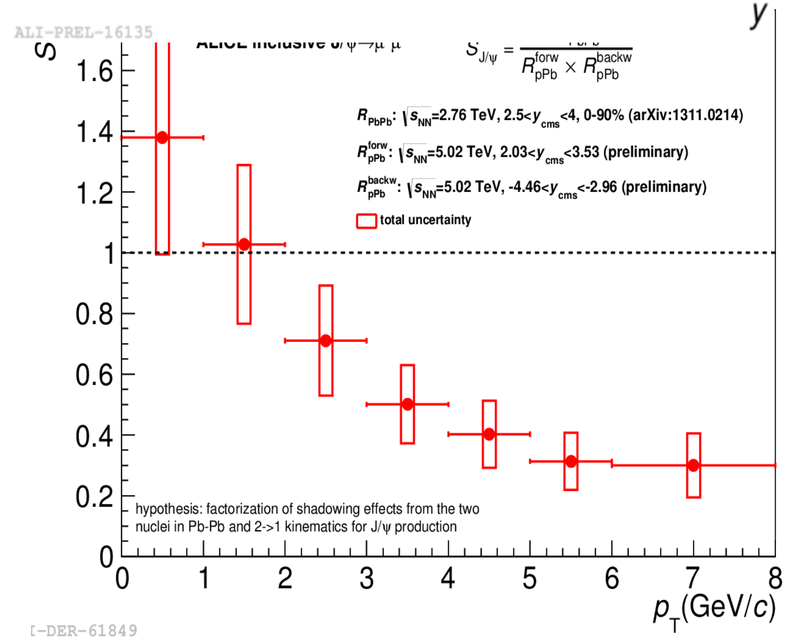
→ N_{coll} **binary scaling**

...provide experimental demonstration
that suppression in Pb-Pb is due to parton energy loss in a hot QGP

J/ψ IN pA







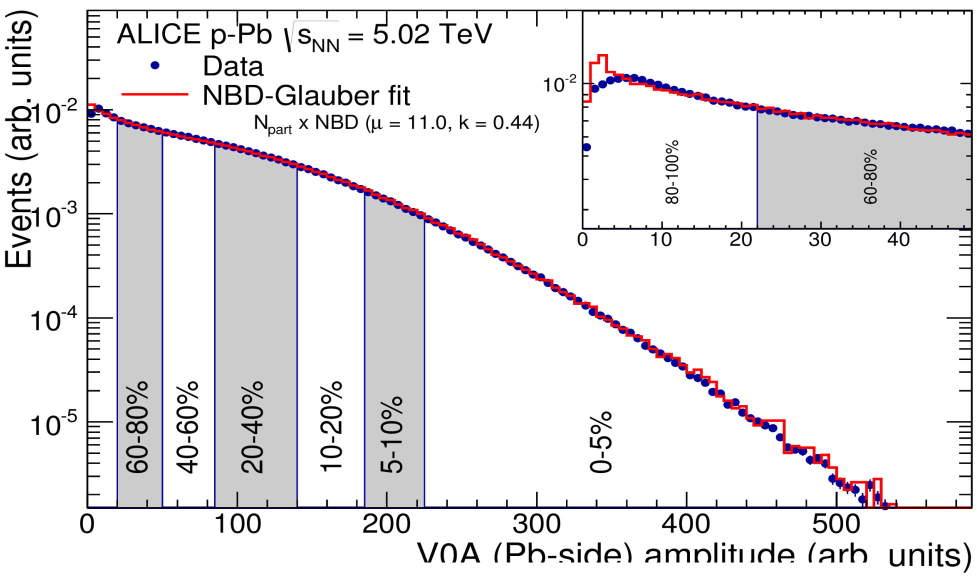
- Fair agreements with **shadowing + energy loss**
- **CGC** seems disfavoured
- Additional suppression in Pb-Pb is a medium effect → **colour-screening "melts" c-cbar**
- Pb-Pb Suppression reduced (by shadowing)
- CNM evaluated as R_{pA} x R_{Ap} (similar x-coverage as Pb-Pb): Sizable p_T-dependent suppression still visible
  - → CNM effects not enough to explain AA data at high p_T
  - → hint for enhancement at low p_T → recombination?

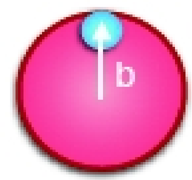
ALICE JHEP 02 (2014) 073

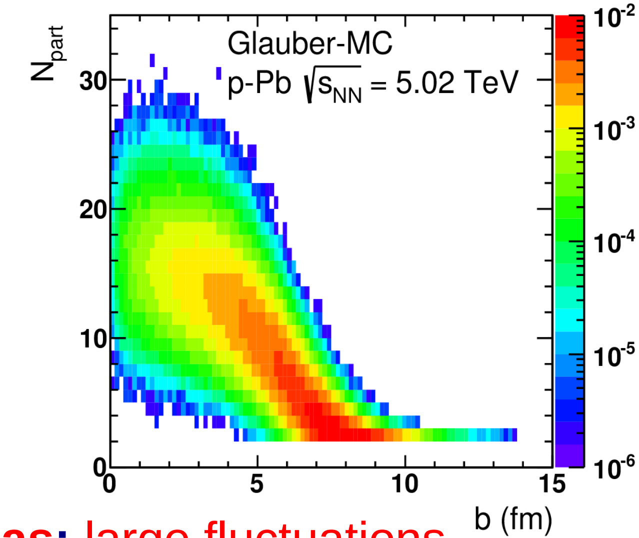
ALICE JHEP 06 (2015) 55

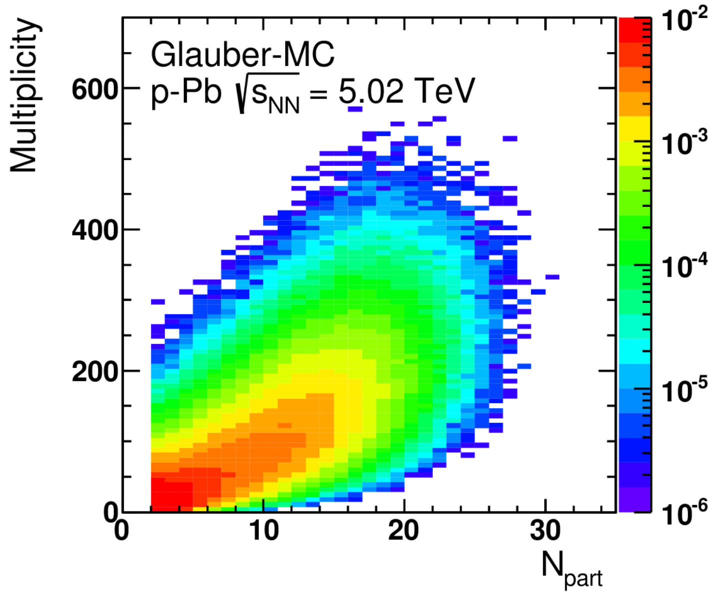
GEOMETRY DEPENDENCE: CENTRALITY

- Centrality → classification of collision geometry
  - for small systems b weakly correlated with N_{part}
- Glauber + NBD approach









- **Multiplicity bias:** large fluctuations
  →centrality selection based on multiplicity may select a sample on NN collisions biased
  high (low) mult → central (peripheral) event
  but also high (low) fluctuation
- MC generators (HIJING): multiplicity fluctuations are due to fluctuations in MPIs
  → bias in mult ~ bias in n_{hard}
- G-PYTHIA
  Incoherent superposition of N-N PYTHIA collisions coupled to Glauber MC
  → $\langle n_{hard} \rangle$ per pN collision deviates from N_{coll} scaling

ALICE PRC 91 (2015) 064905

NUCLEAR MODIFICATION VS CENTRALITY

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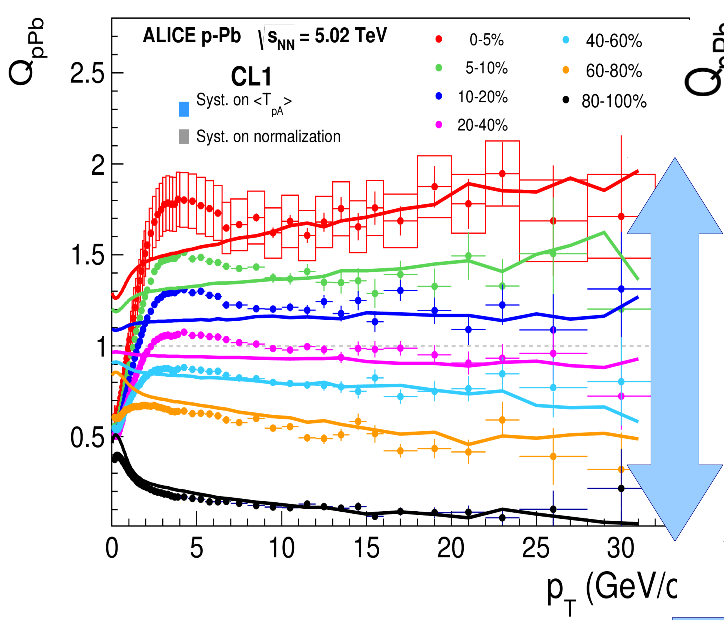
ALICE PRC 91 (2015) 064905

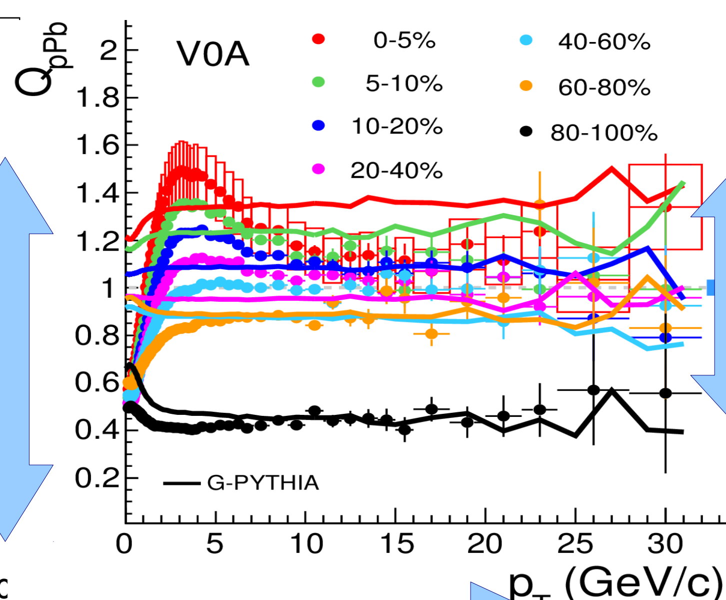
Selecting events according to **multiplicity leads to a dynamical bias**:
→ large spread **NOT** related to nuclear effects!
- G-PYTHIA incoherent superposition of NN collisions reproduces the biases!
- the bias reduced increasing $\Delta\eta$ between the tracking region and the estimator

Selecting events according to **zero-degree energy**: NO bias
- no departure from unity at high-p_T in all centrality classes
- intermediate-p_T enhancement increases with centrality

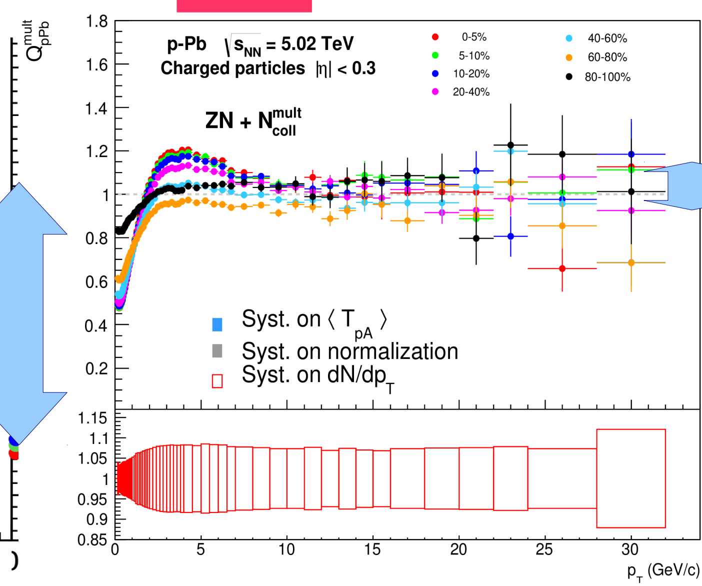
CL1



V0A

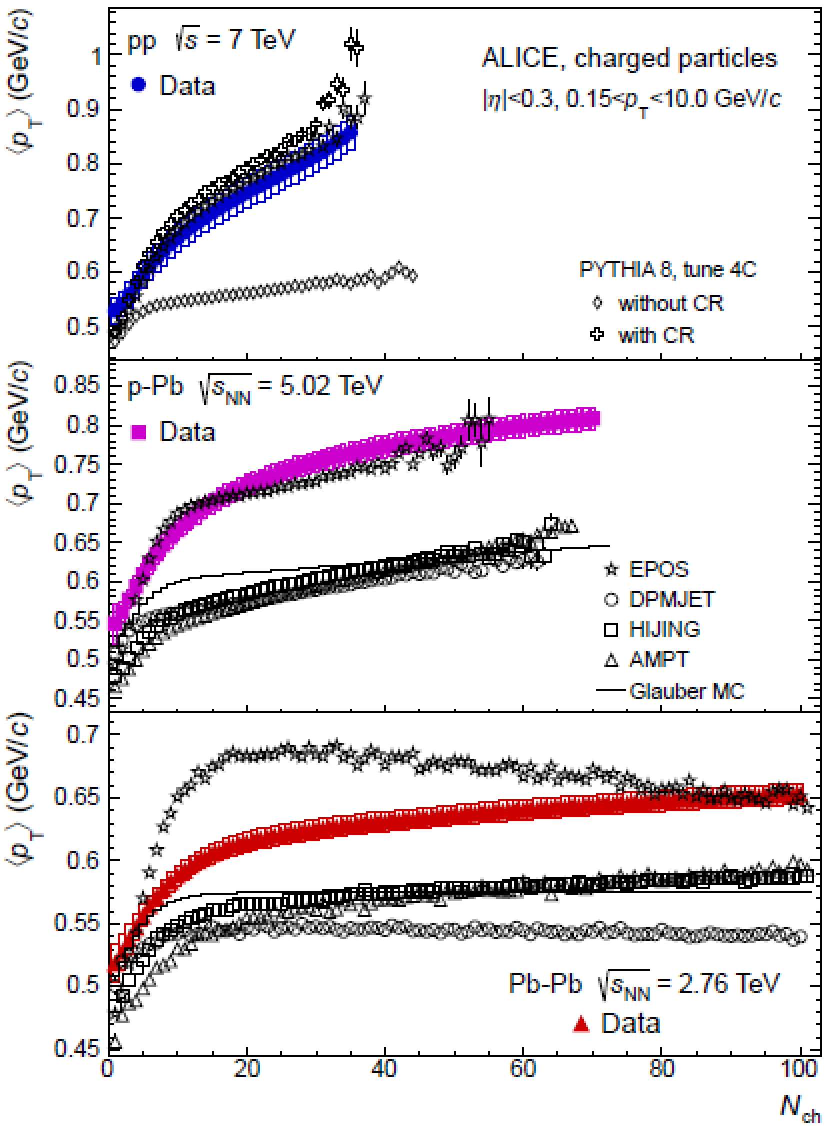


ZNA



PSEUDORAPIDITY

MEAN p_T



ALICE PLB 727 (2013) 371

pp: high-mult through multiple parton interactions BUT incoherent production → same $<p_T>$

→ Color reconnection: strings from independent parton interactions do not independently produce hadrons, but fuse before hadronization

→ fewer, but more energetic, hadrons

Sign of collectivity?

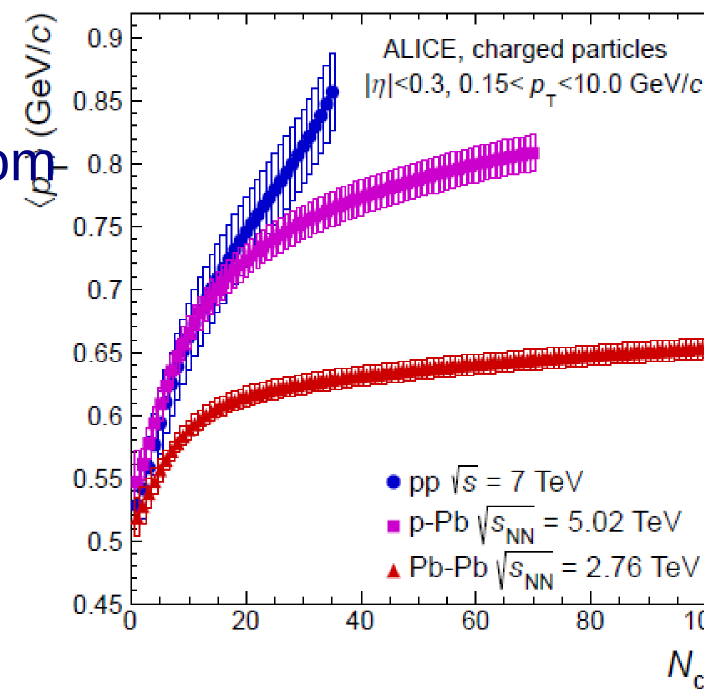
p-Pb: features of both

less saturation than in Pb-Pb → higher $<p_T>$

Sign of collectivity?

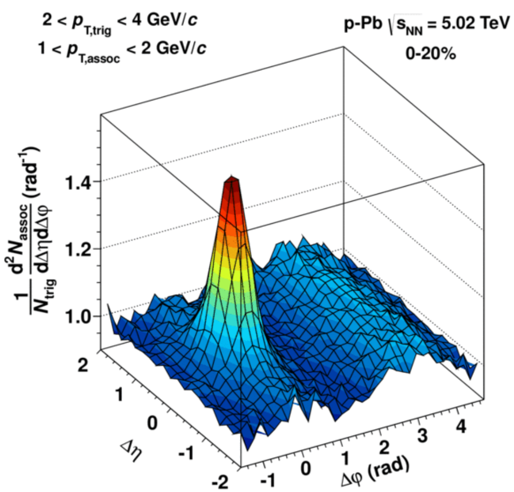
Pb-Pb: high-mult from superposition of parton interactions, collective flow

→ moderate increase of $<p_T>$



DOUBLE RIDGE

0-20%



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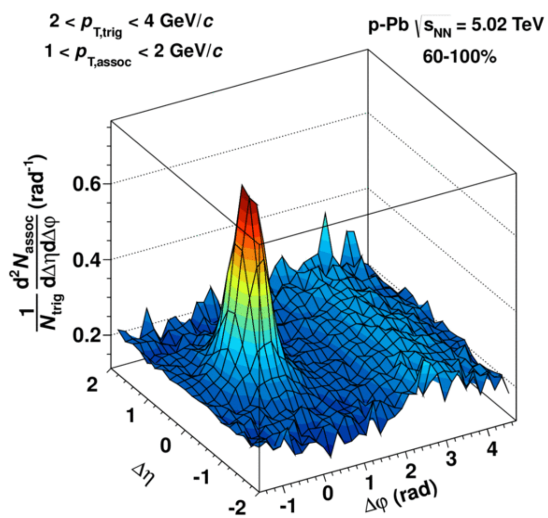
60-100%



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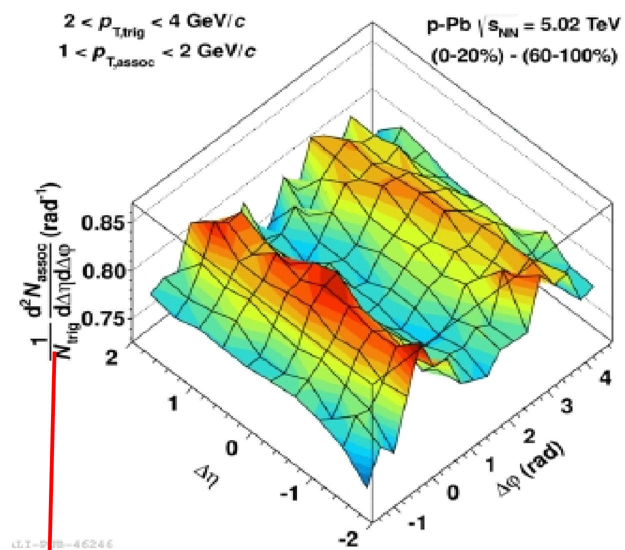
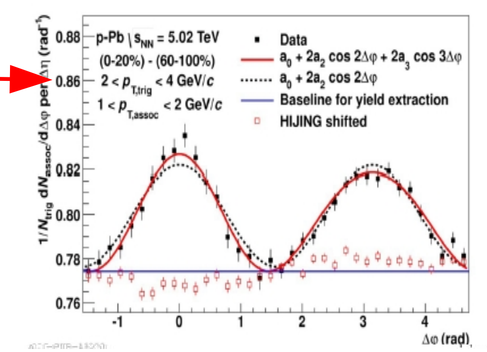


ALICE PLB 719 (2013) 29-41

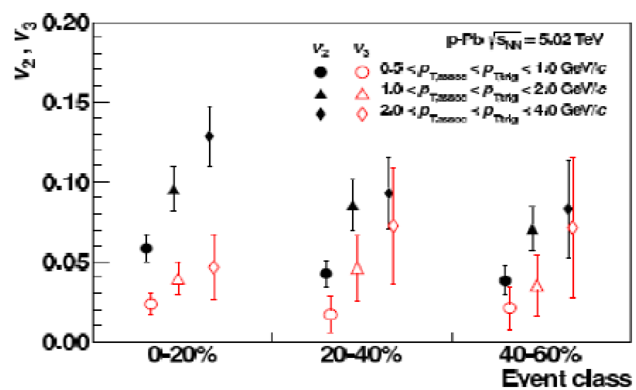


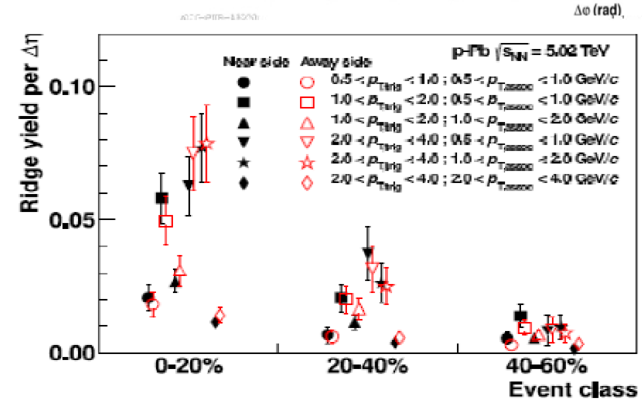
long range correlation:

Double (near+away side) **ridge structure** emerging when subtracting per-trigger yield of low (60-100%) from high-multiplicity (0-20%) events.

Near and away side
- nearly identical
- independent of multiplicity

→ common underlying physics?

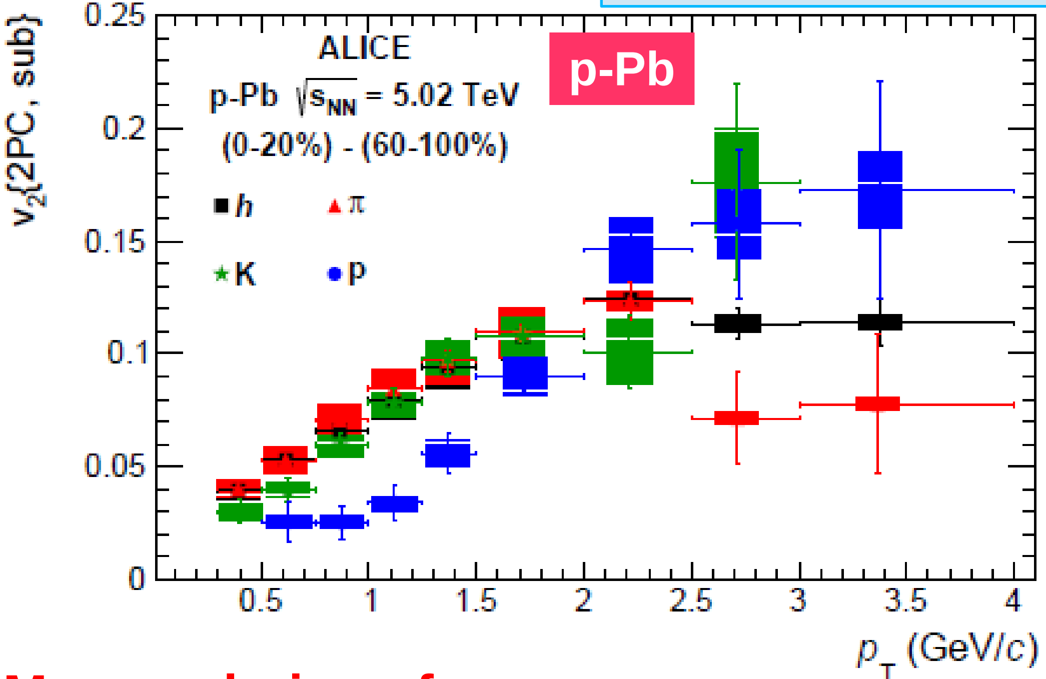


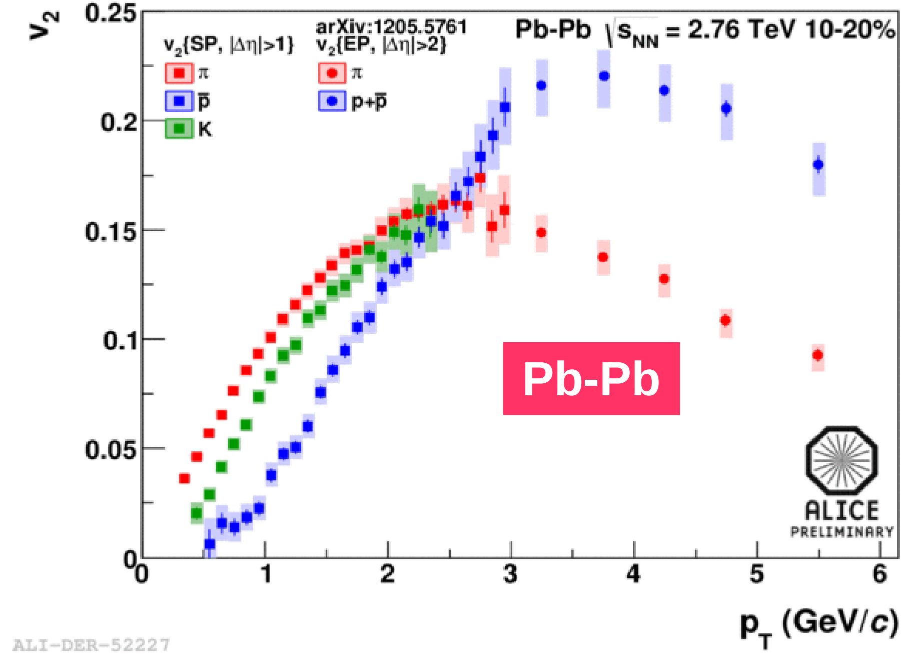


FLOW OF PARTICLES

Quantify the azimuthal modulation in terms of second order Fourier harmonics v_2

ALICE PLB 726 (2013) 164





Mass ordering of v_2

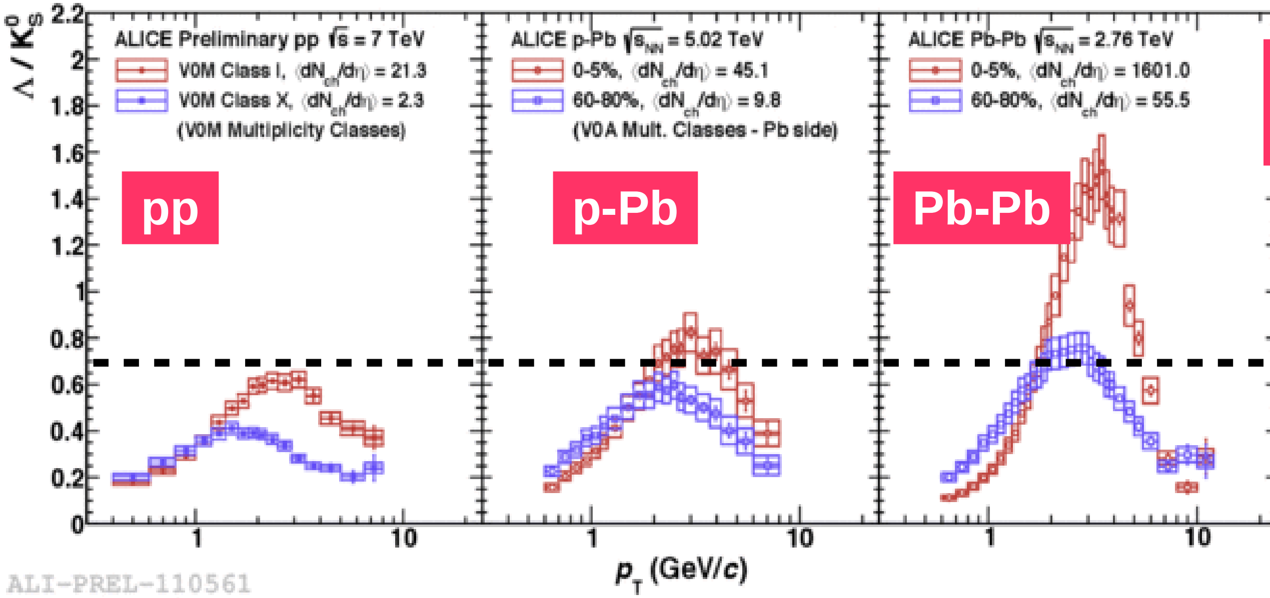
Pb-Pb interpretation:

hydrodynamic model assuming a collectively expanding system

- v_2 arises from initial anisotropy of local energy density
- Mass ordering arises from the interactions with the medium and their dependence on the mass of the hadrons

→ signs of collectivity?

THE BARYON ANOMALY

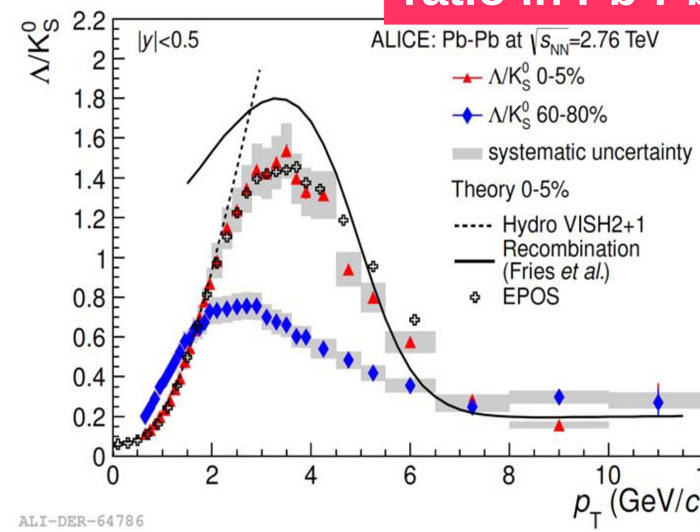


Collective flow or recombination in small systems?

where $10<dN_{ch}/d\eta<20$

pp: 0-1%
pA: 60-80%
AA: 80-90%

ratio in Pb-Pb



Clear evolution with multiplicity

Quantitatively **similar in p-Pb and Pb-Pb** when comparing event classes with **similar N_{ch}**

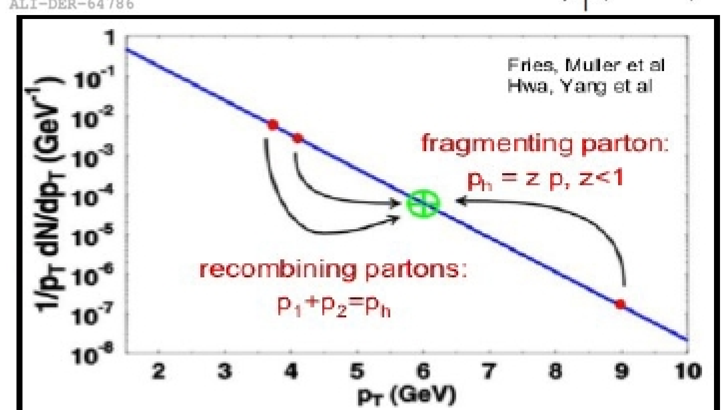
Mid-p_T: ratio increases

Low-p_T: corresponding depletion

Reminiscent of Pb-Pb phenomenology

...generally understood in terms of

- collective flow
- recombination

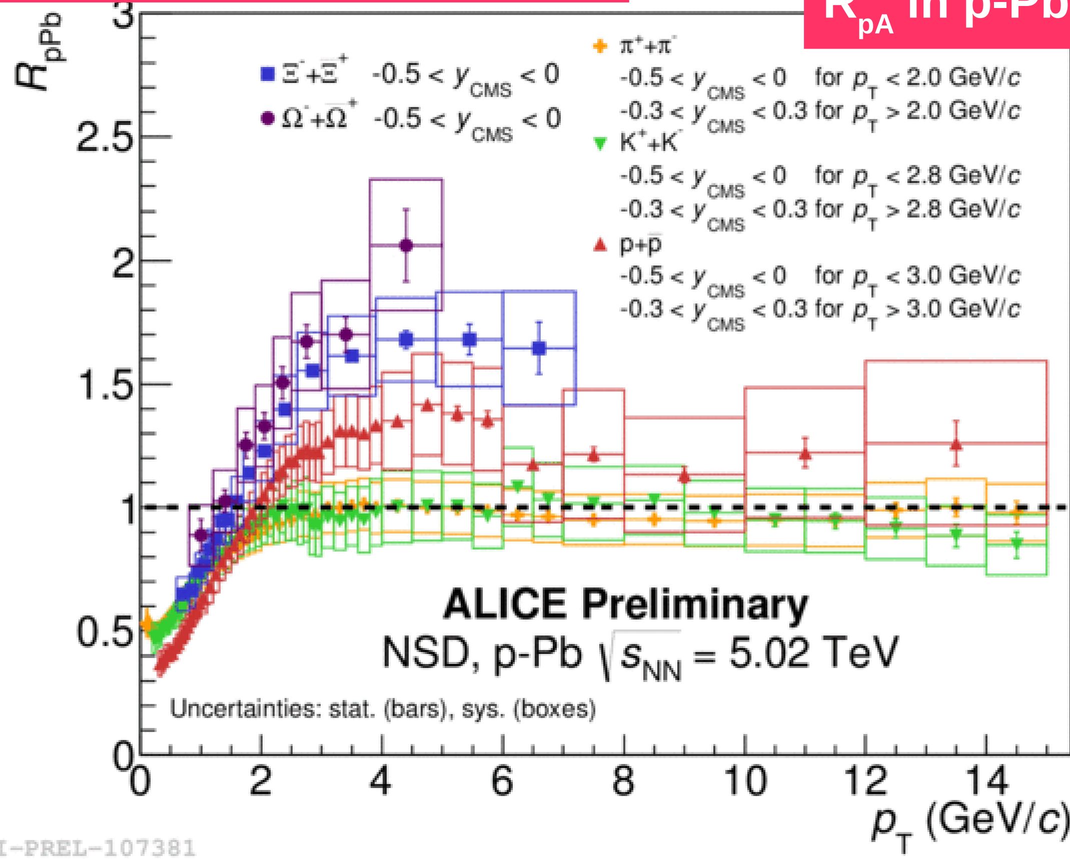


ALICE arXiv: 1307.6796

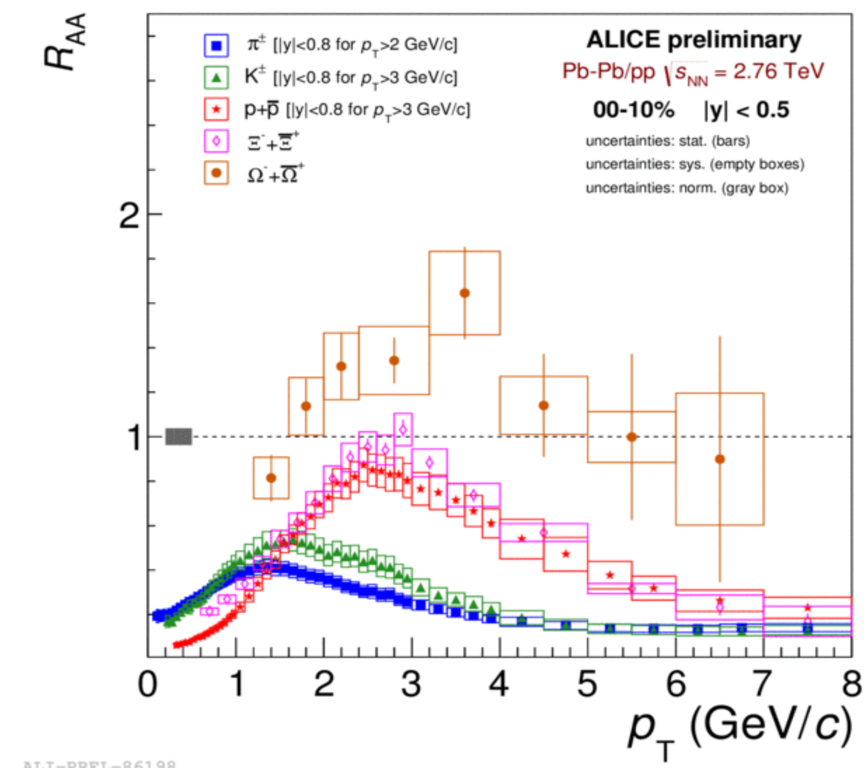
NUCLEAR MODIFICATION VS PARTICLE SPECIES

Effects of the hadro-chemistry

R_{pA} in p-Pb



R_{AA} in Pb-Pb



- R_{pPb} is consistent with 1 at high p_T for all species.
- Mass ordering at intermediate p_T (Cronin region)
    - **Strong enhancement for p, Ξ and Ω**
    - Similar enhancement observed at RHIC.
    - Similar enhancement observed in Pb-Pb.

→ **signs of collectivity or change in paradigm?**

STRANGENESS ENHANCEMENT

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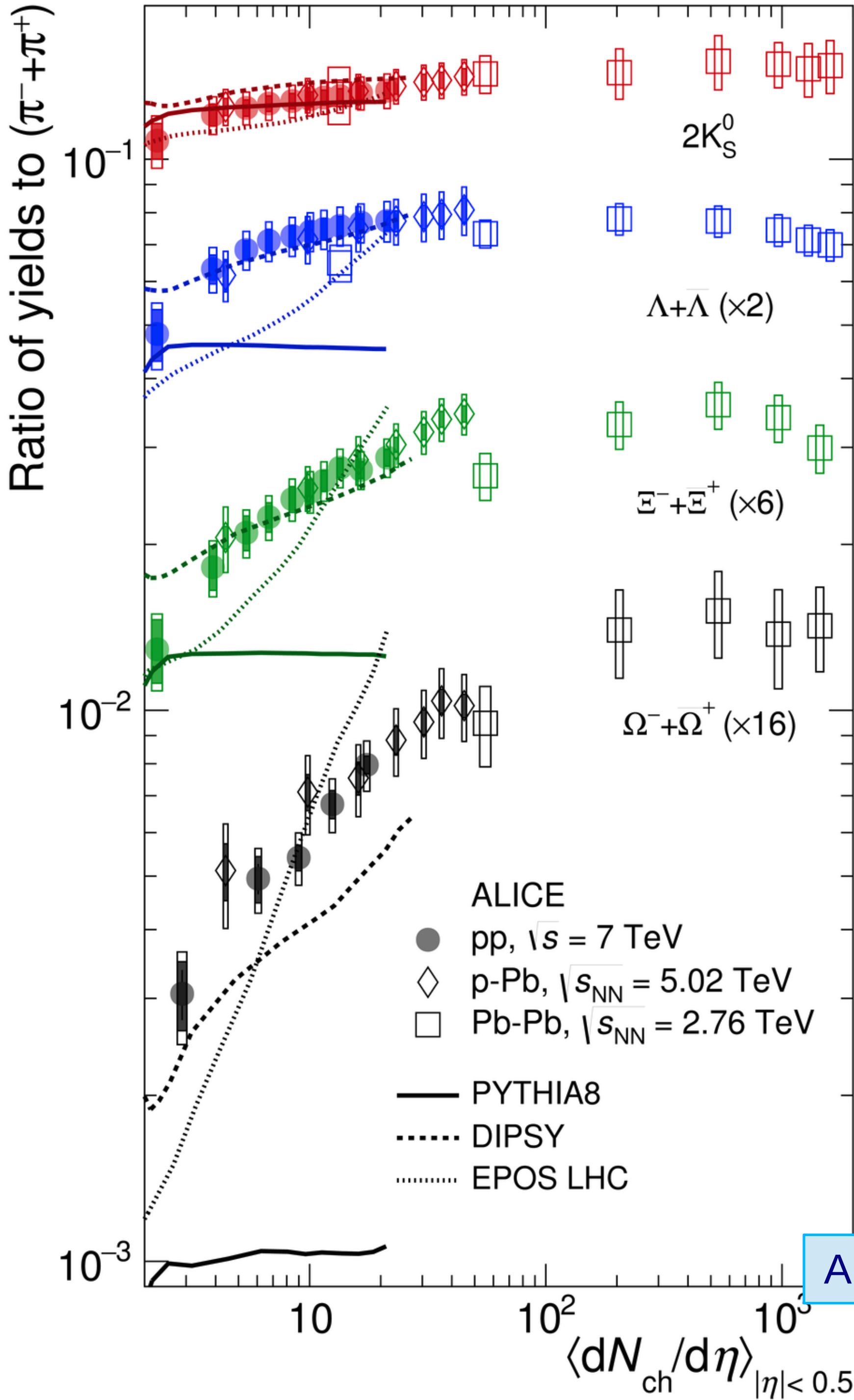
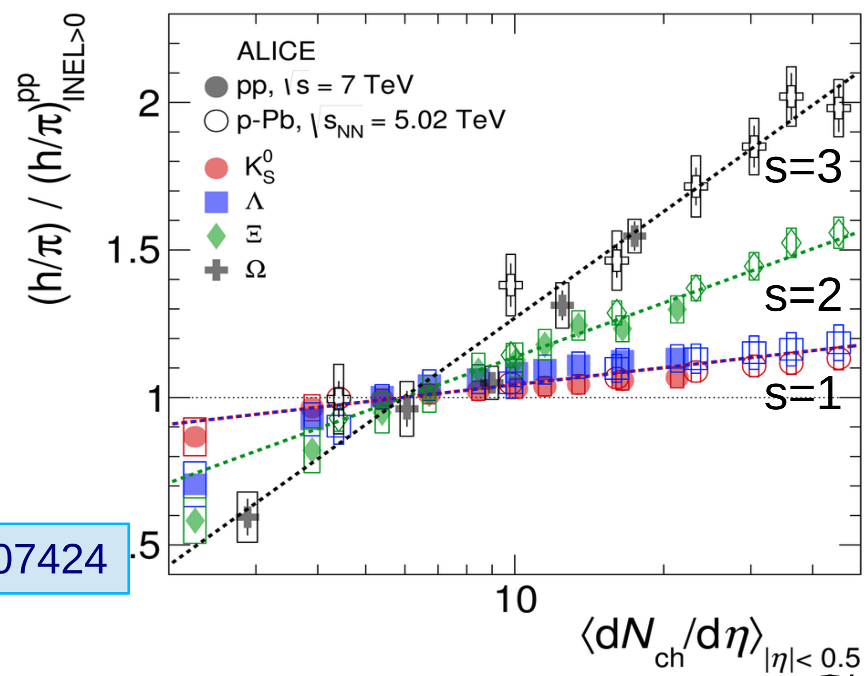


Which scaling for strangeness?

Study Yields Ratios evolution across systems

- For the **first time in pp and p-Pb collisions**: Significant **enhancement of strange** to non-strange hadron production is observed
- The observed enhancement follows a **hierarchy with the number of strange valence quarks**
  - smooth evolution with multiplicity
  - Reach equilibrium limit (Pb-Pb)?
- MC model predictions do not describe satisfactorily the behavior of the data

ALICE arXiv: 1606.07424



SUMMARY: CONTROL EXPERIMENT OR MORE ?

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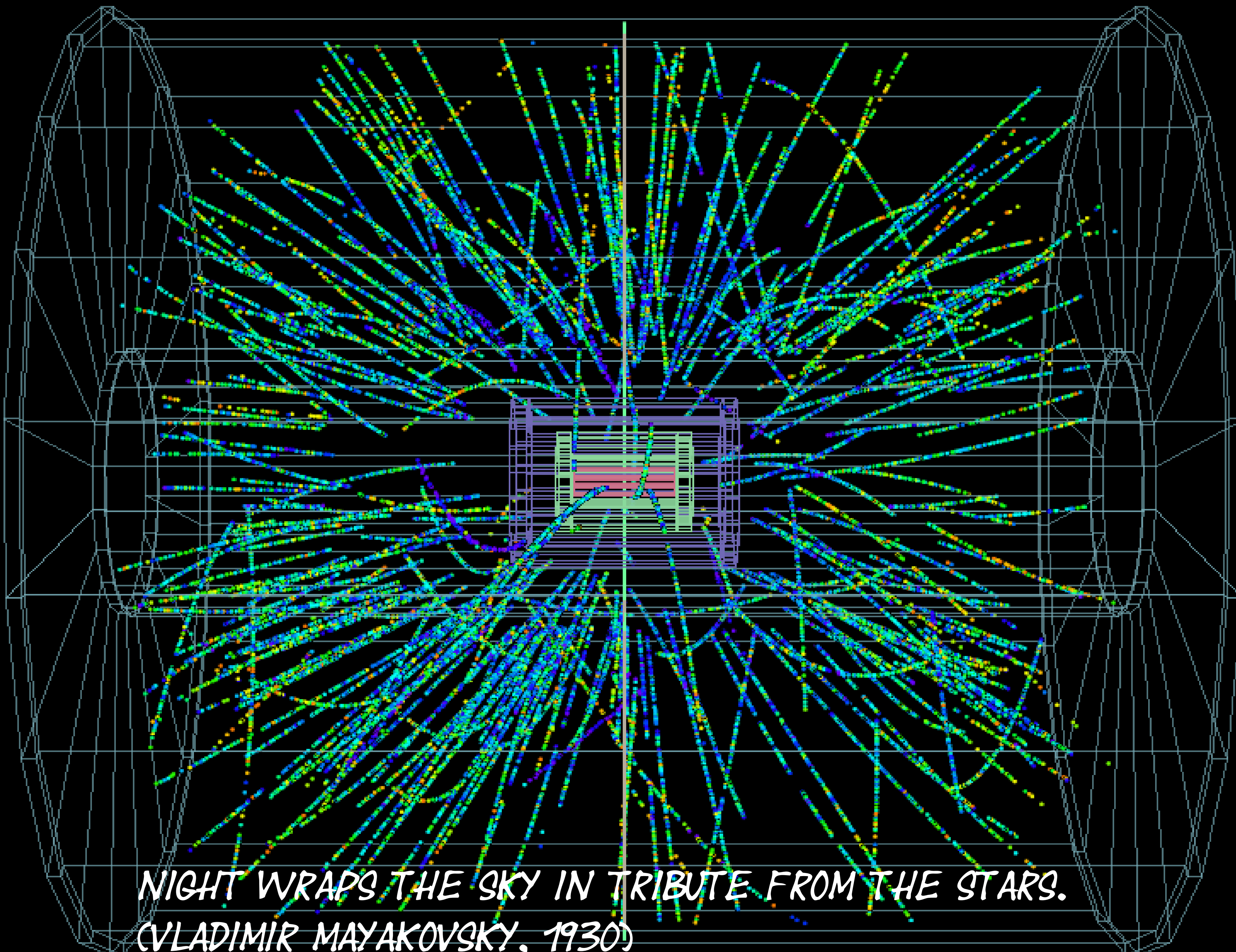
- As control experiment:
  - $dN_{ch}/d\eta$ described by pQCD + shadowing
  - R_{pA} ~1 for N-charged, D-mesons, jets
    → no or small initial/final state effects
  - R_{pA} < 1 for J/ψ at forward rapidity
    described by shadowing + energy loss

  → effects in Pb–Pb collisions are genuine hot deconfined QGP effects
- Many surprises:
  - $\langle p_T \rangle$ increases with multiplicity, and exhibits mass ordering
  - Double ridge structure in two particle correlations
  - Patter of baryon/meson ratios with multiplicity
  - Strangeness enhancement

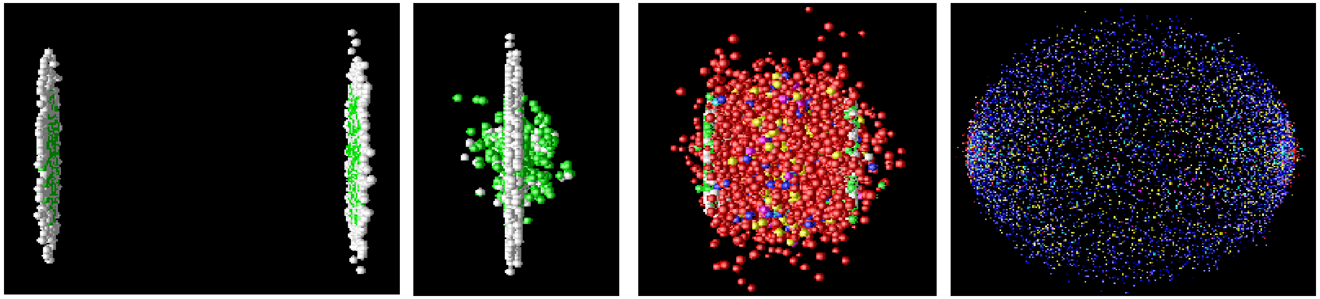
  → existence of collective effects at high multiplicities also in small systems
    - The conventional hydrodynamic models rather successful → QGP in pA?
    - Initial energy density in p-Pb comparable to Pb-Pb
    - p-Pb small and short-lived system: able to thermalize on such short time scale?
    - Jet quenching would need larger path length and longer time
- ALICE has collected an excellent set of data for pp, p-Pb and Pb-Pb collisions in Run1 and Run2



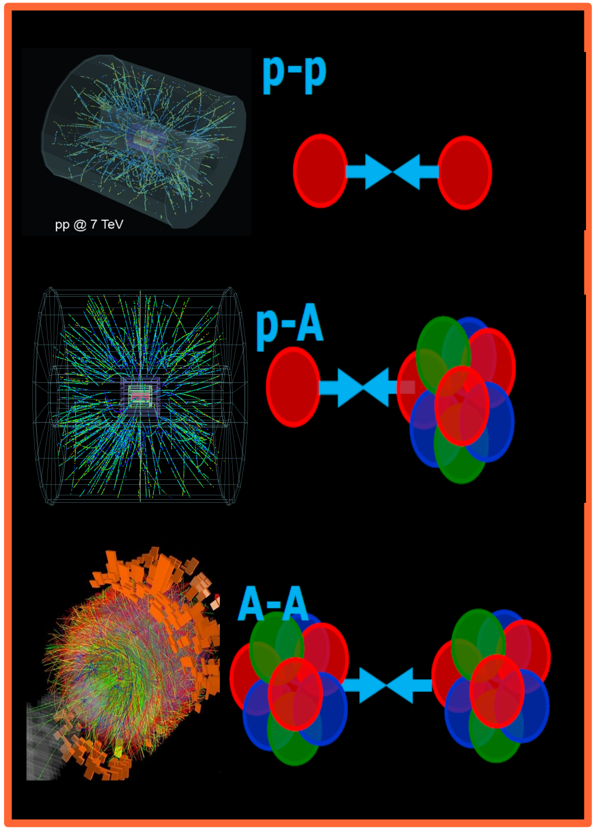
NIGHT WRAPS THE SKY IN TRIBUTE FROM THE STARS.
(VLADIMIR MAYAKOVSKY, 1930)

BACKUP

THE ALICE PHYSICS PROGRAM

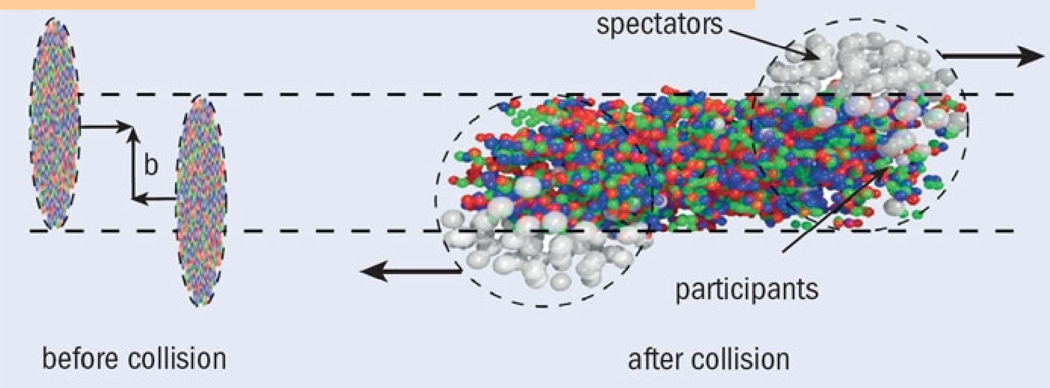


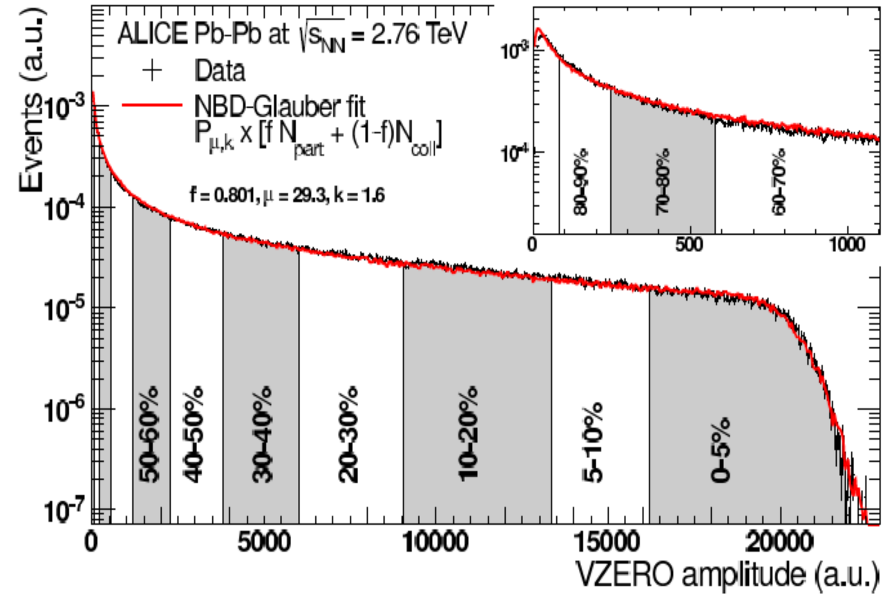
- **pp**
  - **collect 'reference data' for heavy ion program**
  - **comprehensive study of MB@LHC** (MC tuning)
    soft & semi-hard QCD
  - **very high multiplicity pp events** → mini-QGP?
- **p-Pb**
  - **Control experiment for Pb-Pb**
  - **Important measurements in their own right**
    nucleus structure in low-x (gluon saturation, shadowing…)
- **Pb-Pb**
  - **Study the properties of strongly interacting matter under extreme conditions of temperature and density.**
    - Confinement → deconfined QGP
      analogous to the early Universe evolution
- **Run II: new higher energy pp@13 TeV, Pb-Pb@5TeV**
  - New frontiers in physics
    → study the evolution of the basic event properties



Collision Geometry & Event Activity

Global properties of the system
Multiplicity ~ energy density





Centrality Determination

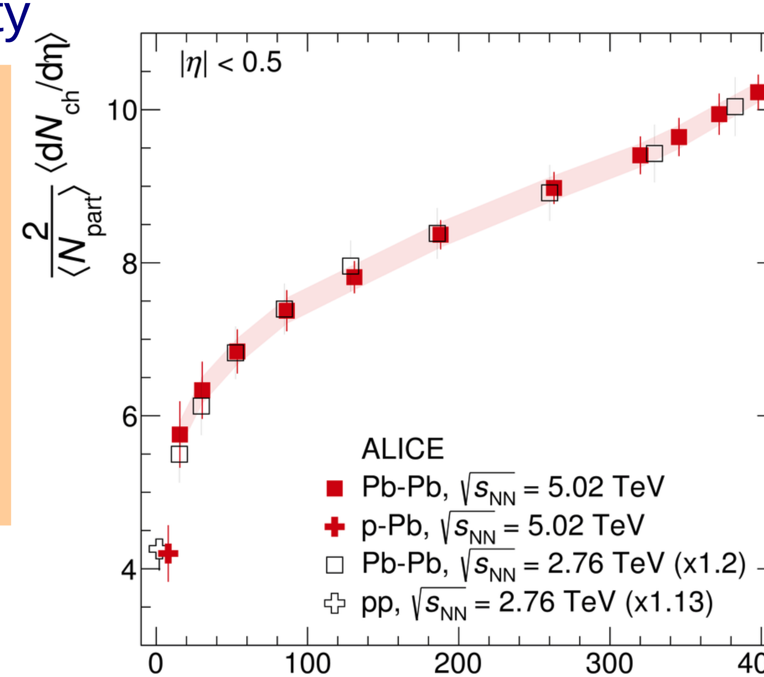
- Glauber model
- Charged particle multiplicity at central/forward rapidity

The average yield per participant pair is strongly dependent on collision centrality

- Similar trend seen at $\sqrt{s_{NN}}$=2.76 and 5.02 TeV

→ Energy- (and system-) scaling

- Yield in peripheral collisions close to the one measured in pp collisions
- Most of the models fairly describe the data (except HIJING).

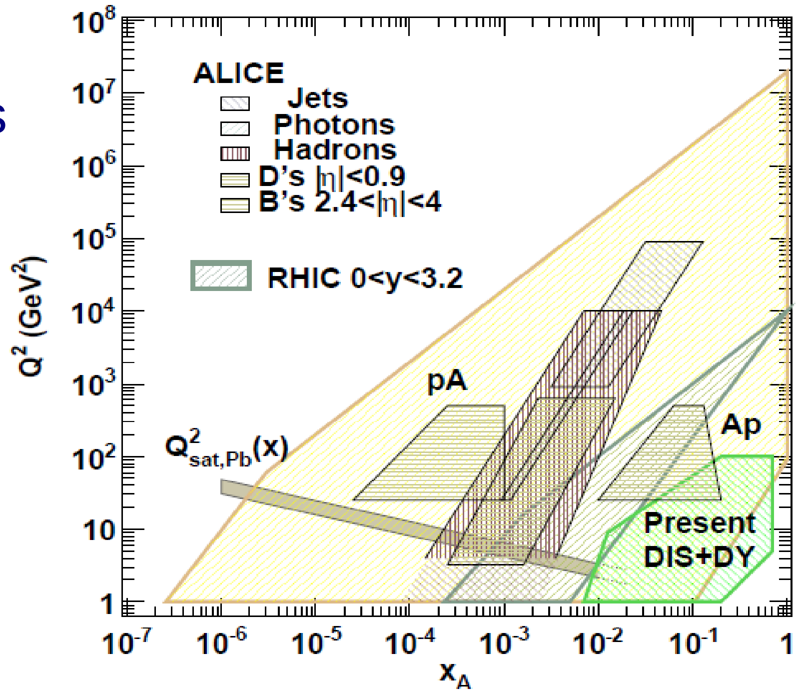


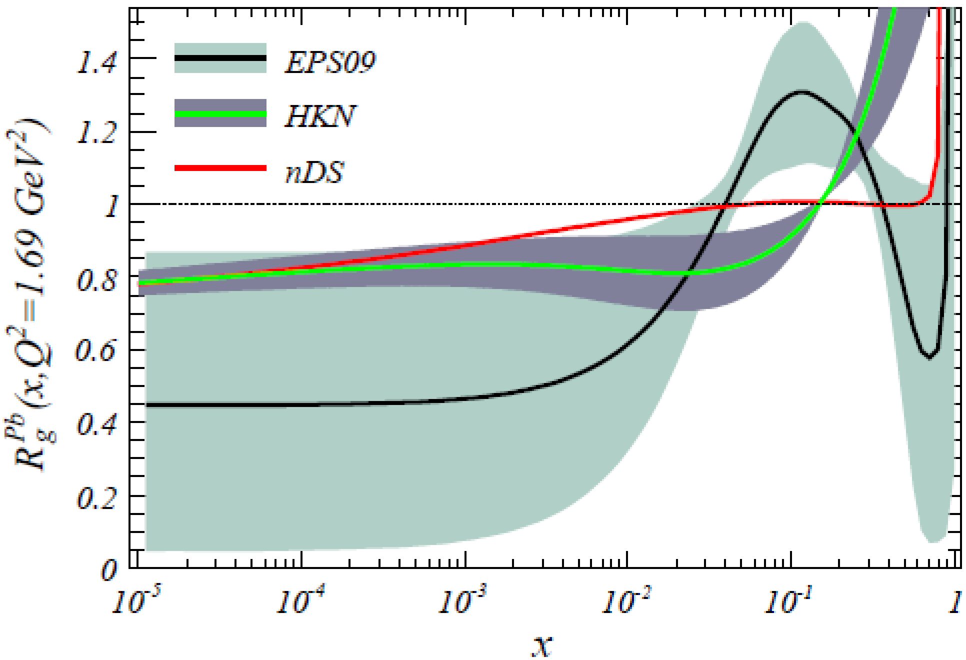
N_{part} ~ collision geometry
N_{ch} ~ energy density

ALICE PRL 116 (2016) 222302

INITIAL STATE

Explore new territory in QCD (low-x):
- No data in the (x,Q^2) region of LHC
→ Parton Distribution Functions: large uncertainties
- Large gluon density for p and even more for Pb
GLUON SHADOWING
Ratio nuclear-nucleon PDF:
shadowing/anti-shadowing from constructively/destructively interference of the amplitudes due to multiple scattering





Gluon Shadowing
increases with decreasing x and Q^2
some of the partons are obscured by others in front of them
→ decrease of the scattering amplitude relative to what is expected from incoherent independent scattering

Salgado et al, arxiv: 1105.3919
Helenius et al., JHEP 1207 (2012) 073

INITIAL STATE

Explore new territory in QCD (low-x):
- No data in the (x,Q2) region of LHC
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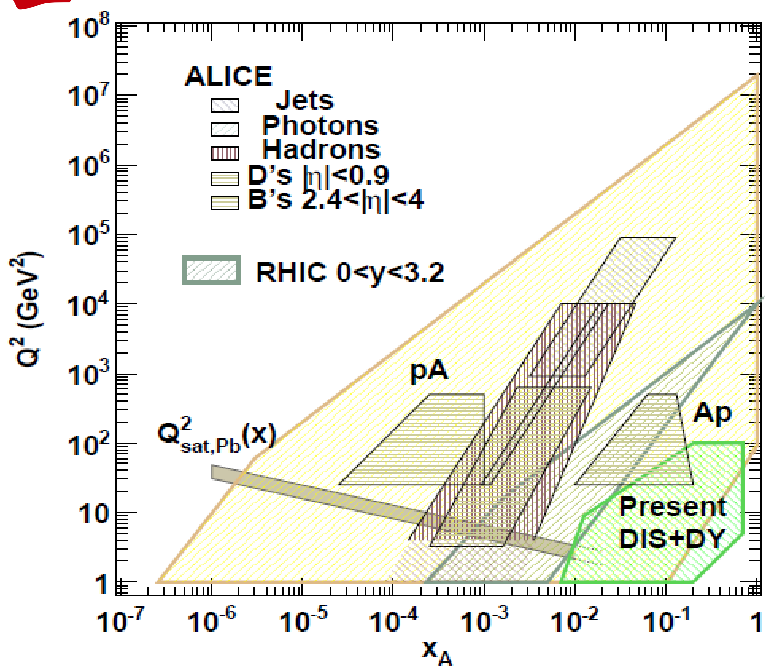
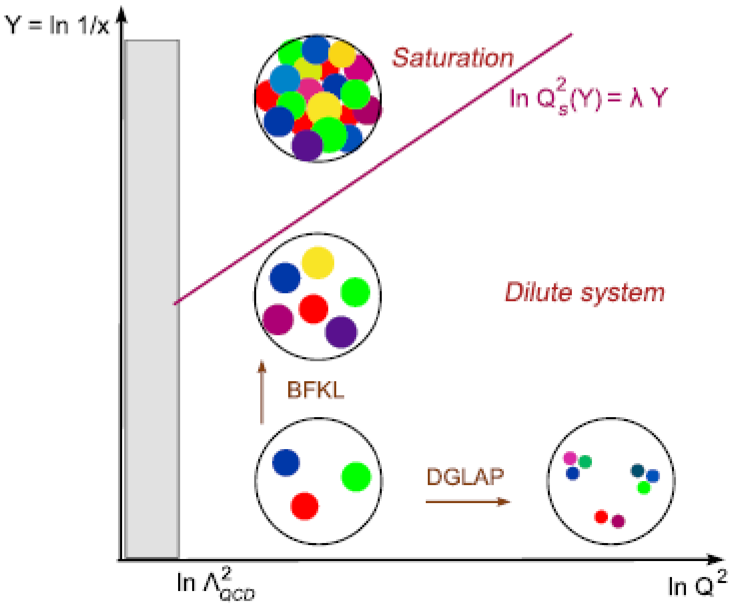
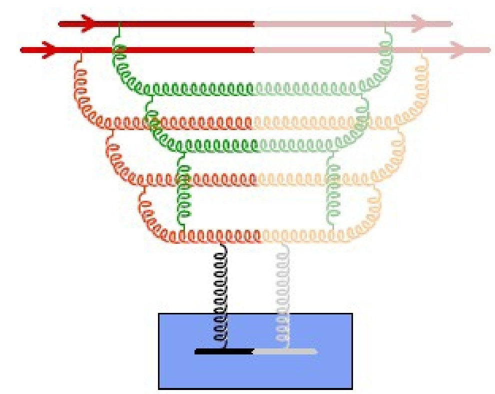
- Large gluon density for p and even more for Pb
COLOR GLASS CONDENSATE
parton evolution proceeds via soft collinear gluon emission





At a characteristic momentum scale (saturation scale) gluon density is large enough that parton evolution becomes non-linear → parton recombination.
Gluons act as frozen color sources (CGC)
Scale depends on x and A
→ geometric scaling



$$Q_s^2 \sim \frac{\alpha_s x G_A(x, Q_s^2)}{\pi R_A^2} \sim A^{1/3}\frac{1}{x^{0.3}}$$

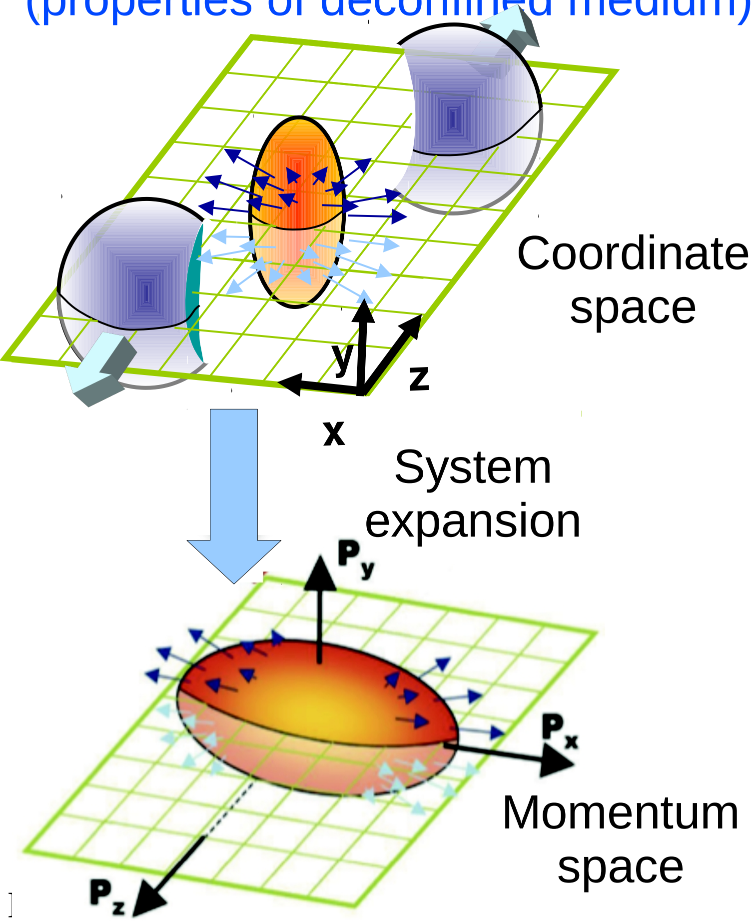
ANISOTROPIC FLOW

Collectivity of the system?

Initial spatial anisotropy of the overlap region of colliding nuclei
→ anisotropy in momentum space via interactions of produced particles.

Sensitive to:
- initial collision geometry
- transport mechanism

→ provides a measurement of collectivity (properties of deconfined medium)

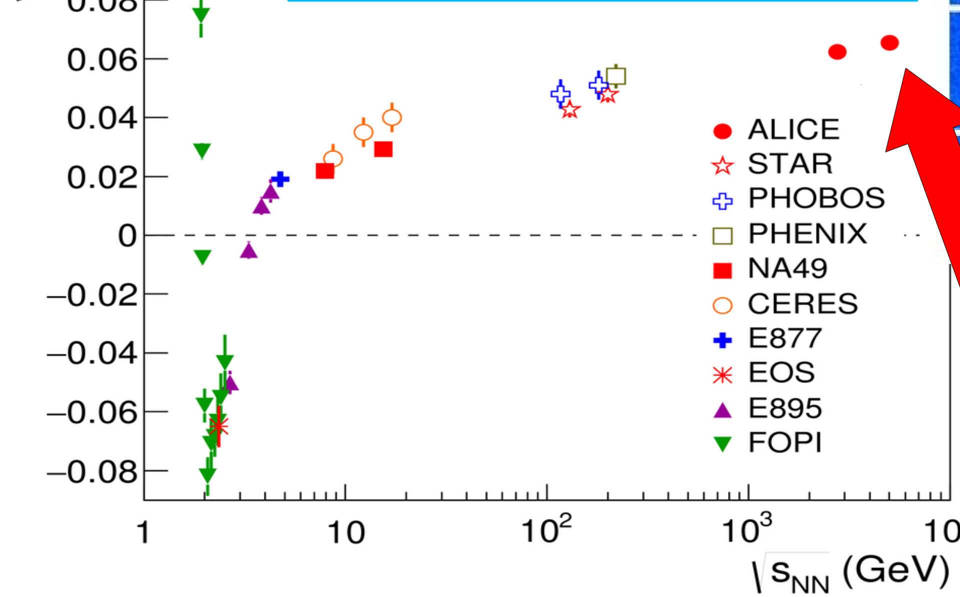


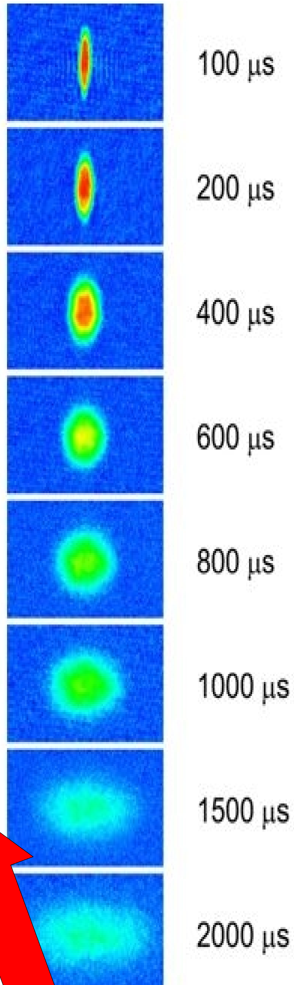
Quantified by the Fourier decomposition

$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\varphi - \Psi_n)]$$

v1: directed flow
v2: elliptic flow
v3: triangular flow
...

ALICE PRL 116 (2016) 132302



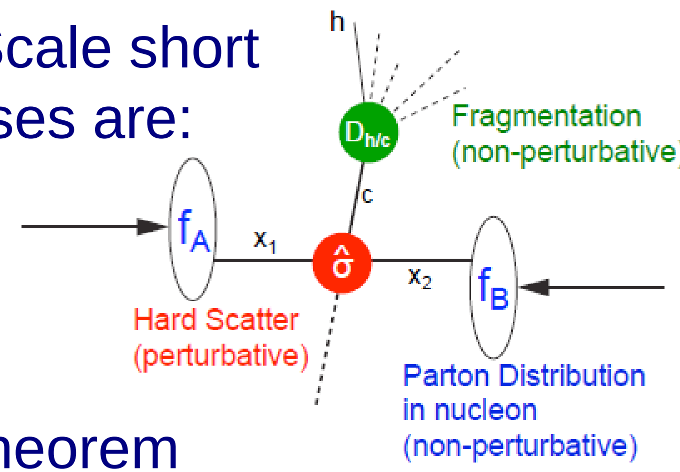


SCIENCE Vol: 298 2179 (2002)

Ultra-cold Li explode into vacuum

HARD PROBES

•Hard processes are those processes with high momentum transfer → short distances → Time Scale short



•Experimental observables connected to hard processes are:

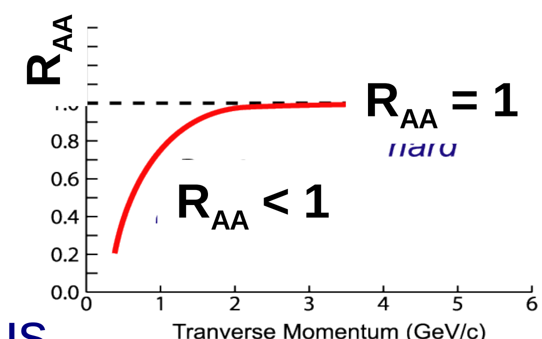
- Hadrons with high p_T → Jets
- Hadrons from open heavy flavour (charm and beauty)
- Quarkonia (J/Ψ, Ψ', ϒ, ϒ', ϒ'')

•In pp collisions calculable with pQCD techniques using universality (of PDF and FF) and factorization theorem

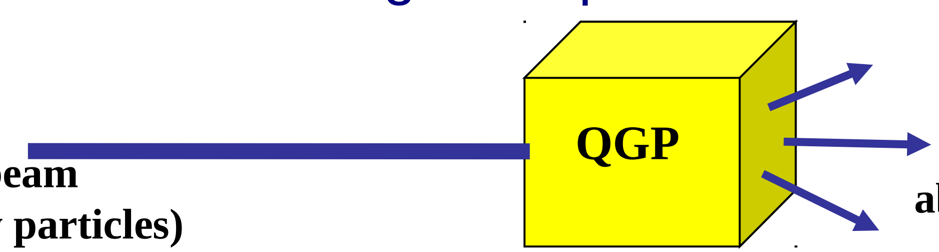
•In AA collisions hard processes are expected to **scale with the number of elementary nucleon-nucleon collisions**

•The nuclear modification factor is defined as:

$$R_{AA}(p_T) = \frac{1}{N_{coll}} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T} = \frac{1}{T_{AA}} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$



•Rutherford experiment α → atom discovery of nucleus
SLAC electron scattering e → proton discovery of quarks



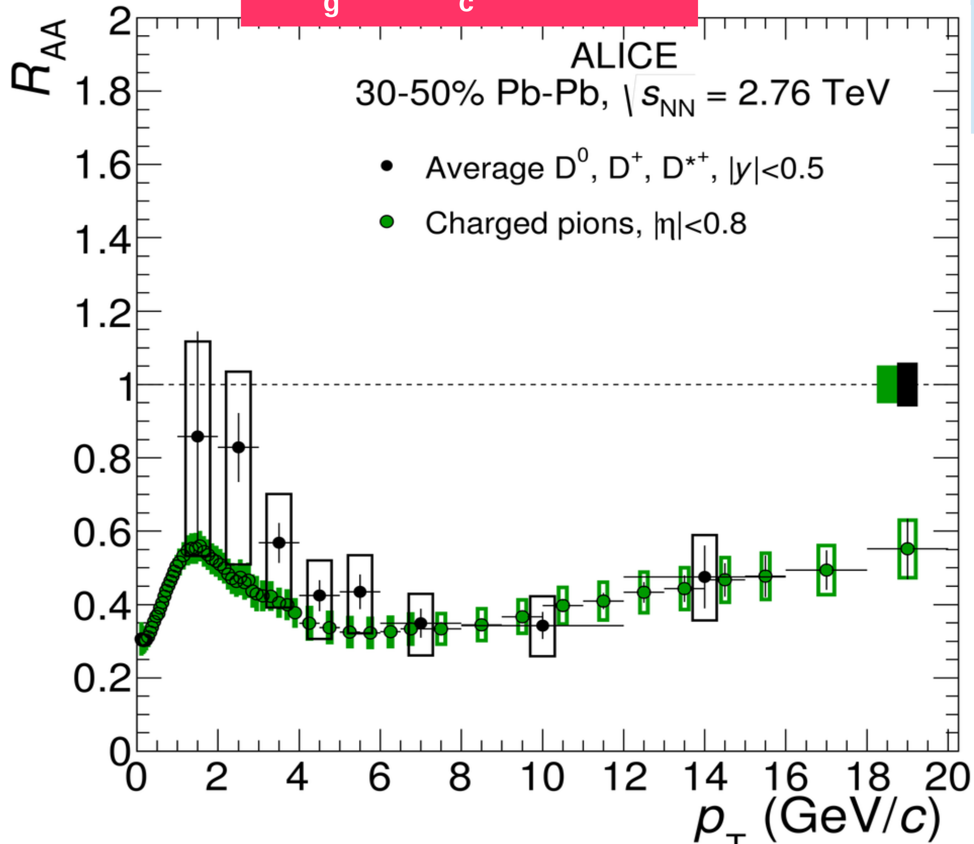
penetrating beam (jets or heavy particles)

absorption or scattering pattern

HEAVY FLAVOR: PB-PB

ALICE JHEP 03 (2016) 081

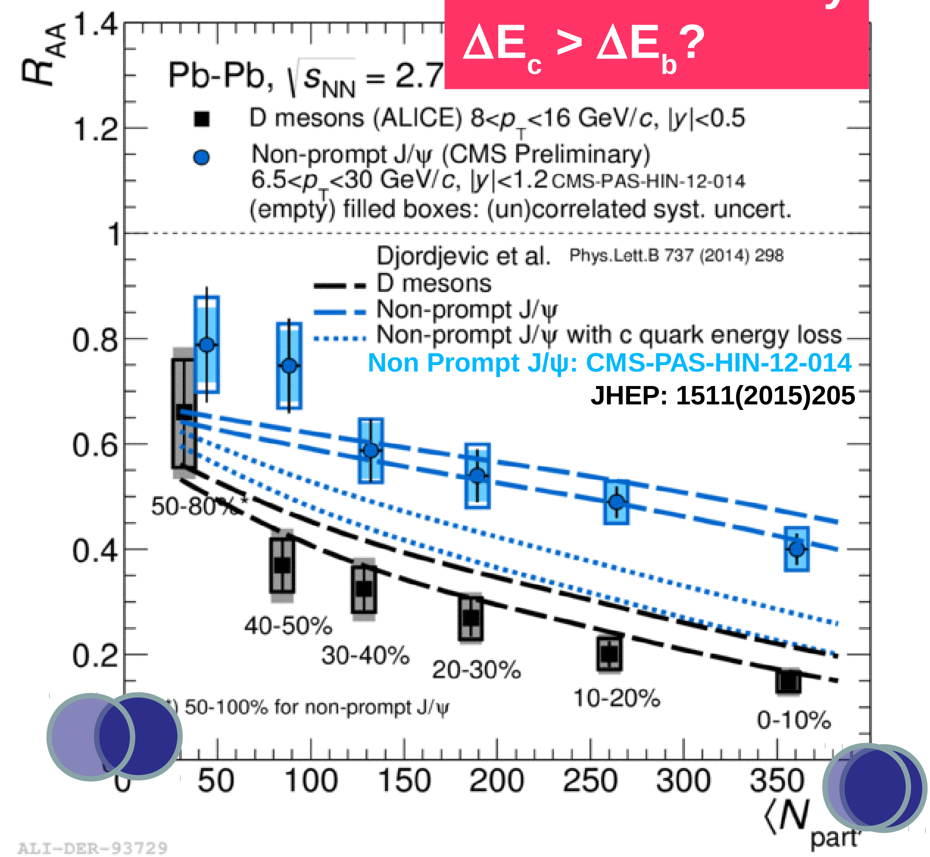
D vs light hadrons
$\Delta E_g > \Delta E_c$?



Expectations of **Hierarchy**
Radiative Energy loss decreases wrt light quarks
(Casimir factor and dead cone effect)
$\Delta E^{rad}_{g} > \Delta E^{rad}_{charm} > \Delta E^{rad}_{beauty}$
$\rightarrow R_{AA}$ (U,D) $< R_{AA}$ (D) $< R_{AA}$ (B)

- Comparison between D and secondary J/ψ (from B decays) for central collisions
- $R_{AA}^{charm} < R_{AA}^{beauty}$ → **expected hierarchy**

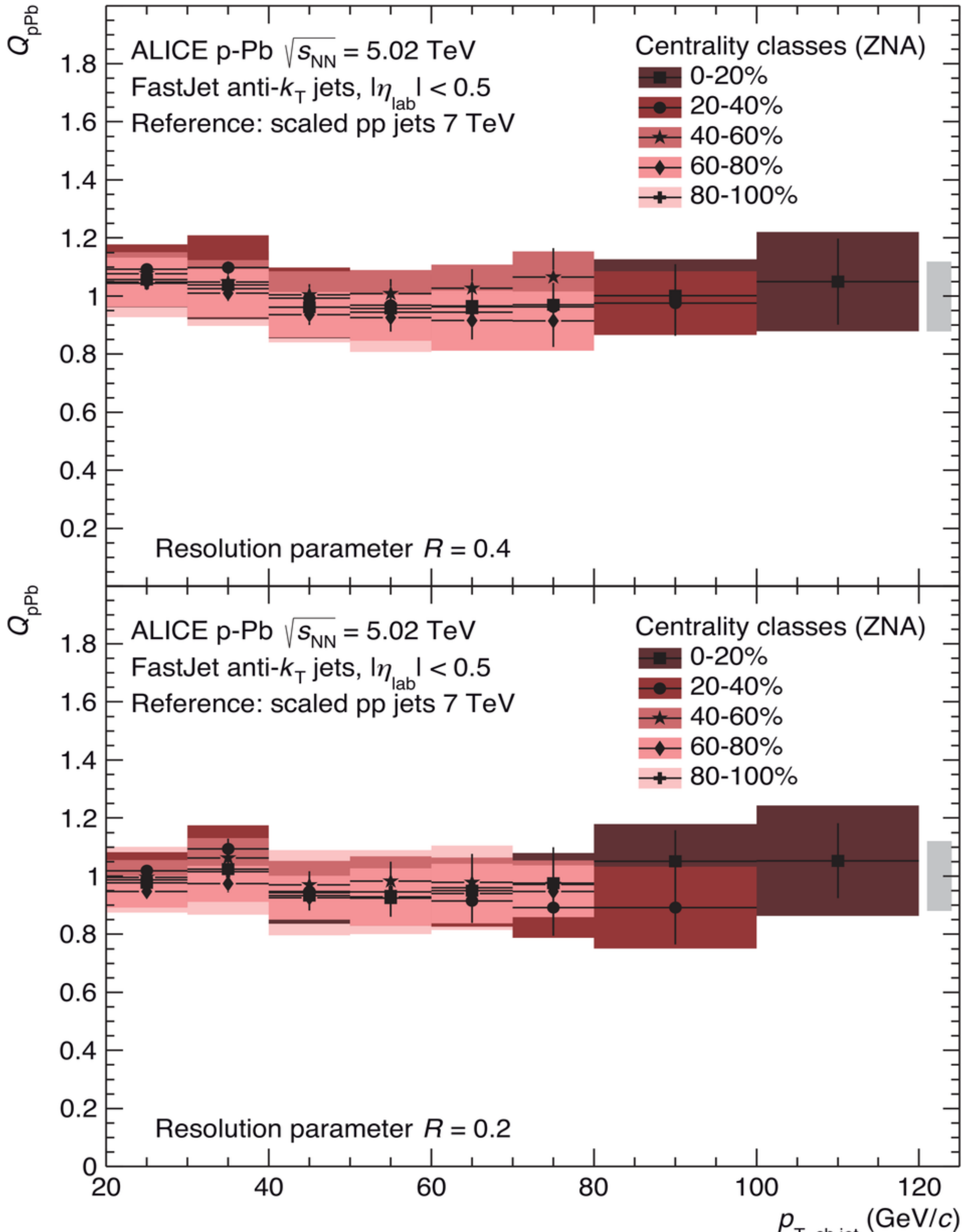
Charm vs beauty
$\Delta E_c > \Delta E_b$?



- Suppression of D mesons in central collisions
  - High p_T: the suppression for D and π is similar → explained by softer fragmentation and p_T spectrum of gluons w.r.t. c-quarks
  - Low p_T: indications of $R_{AA}^{D} > R_{AA}^{\pi}$

JETS R_{PA}

Do hard probes scale with N_{coll} in p-Pb?

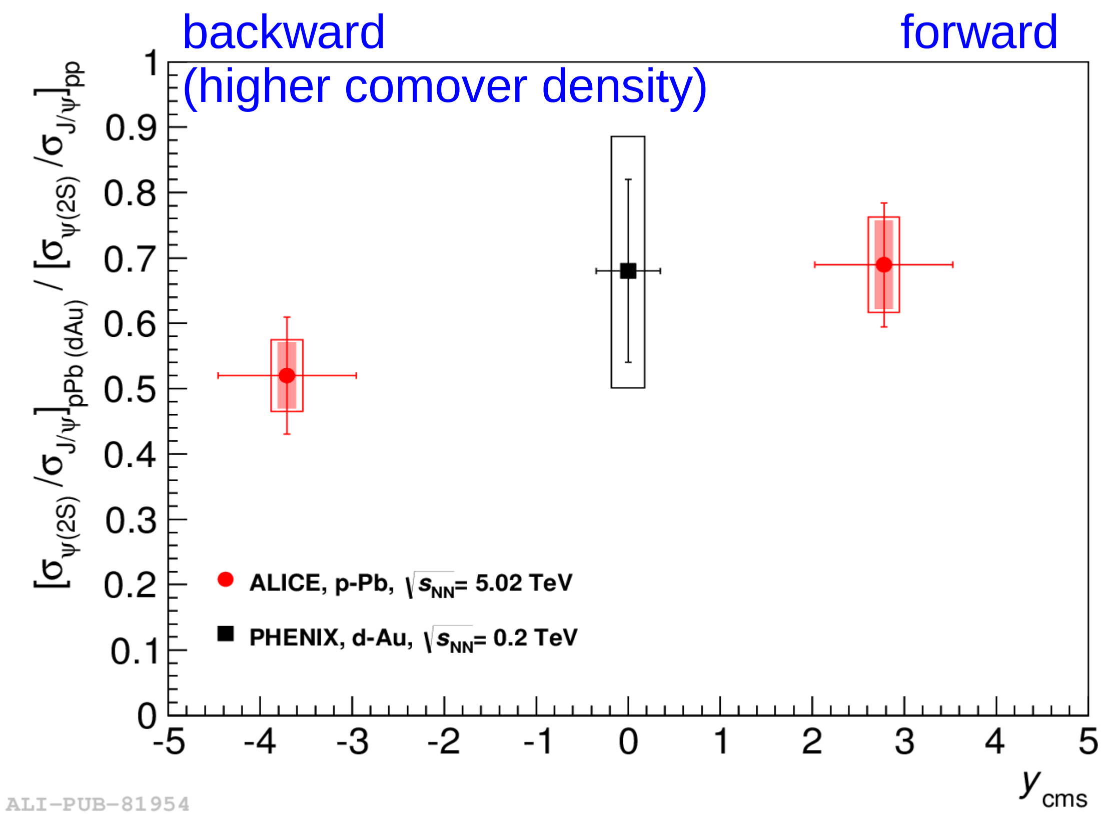


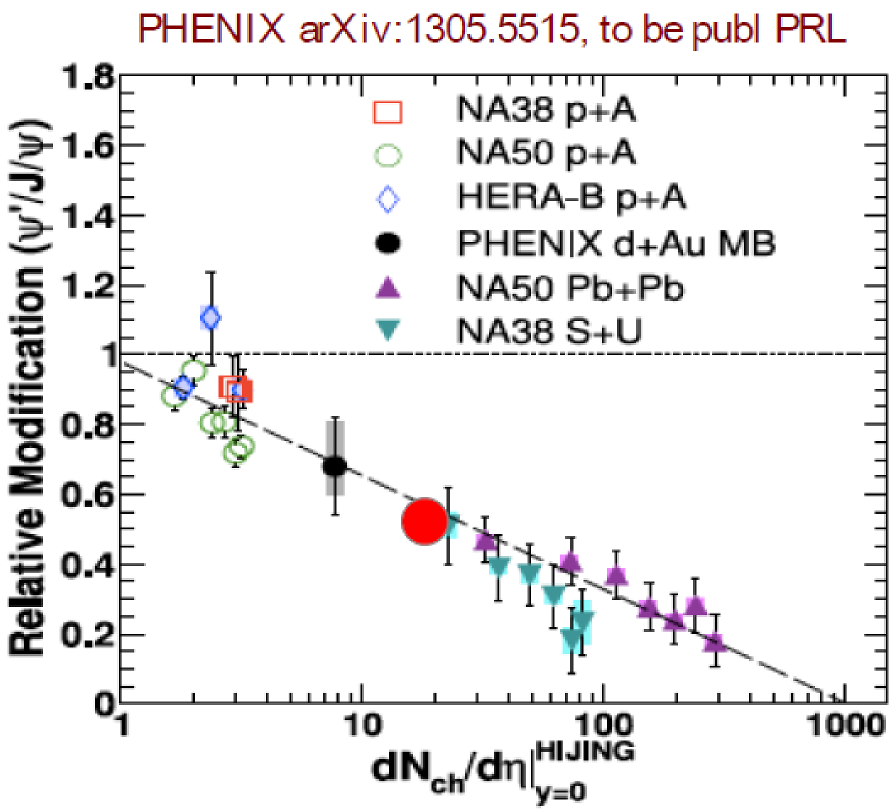
Charged jets production in p-Pb collisions measured as a function of centrality

- Q_{pPb}~1 for all centrality classes and independent on the resolution parameter R and jet p_T
- No or very small CNM effects in this kinematic range

ALICE EPJC 76 (2016) 5, 271

ψ': Stronger suppression

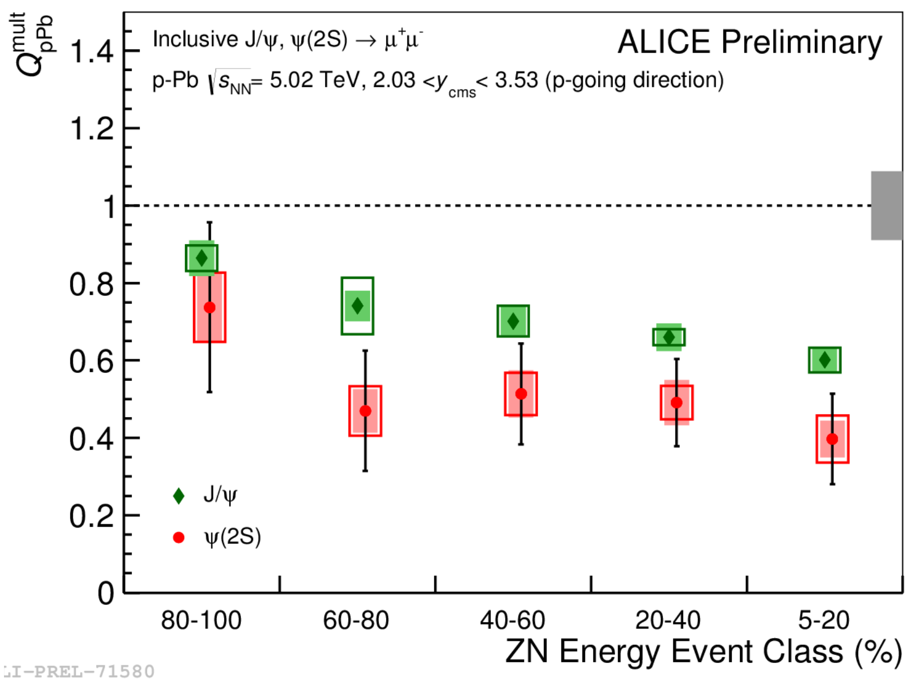


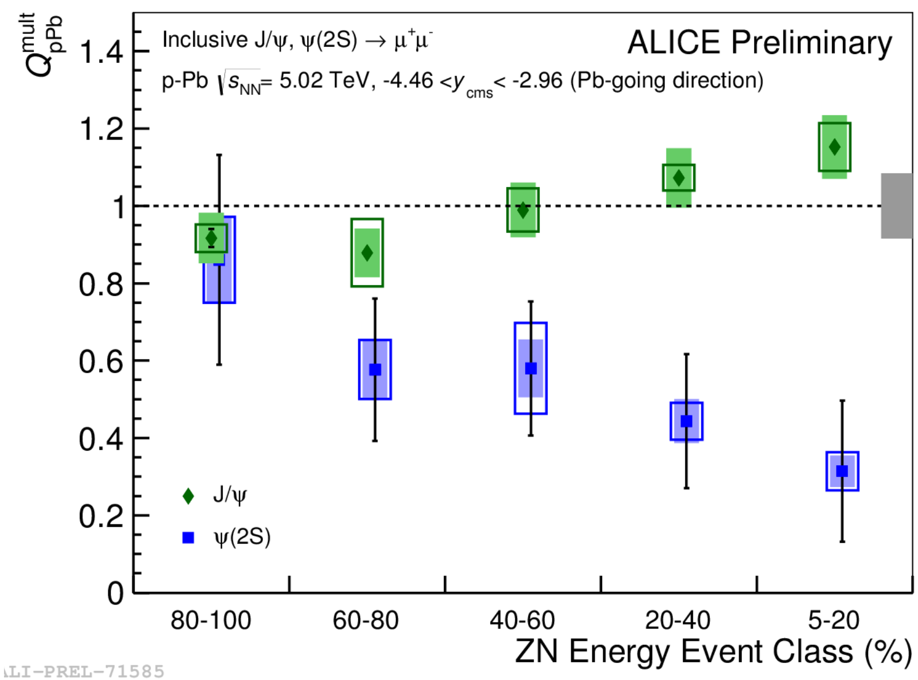


- **Anomalous suppression of heavier and less bound ψ(2S) wrt J/ψ**
- **In Pb-Pb**: sequential melting depending on binding energy and T(QGP)
  → Qualitatively consistent with break-up by co-moving medium
- **In trend with multiplicity dependence** observed p(d)-A and A-A at lower √s
  → **Important to check rapidity and centrality dependence.**

J/ψ and ψ' vs centrality

J/ψ and ψ(2S) Q_{pA} are compared vs centrality



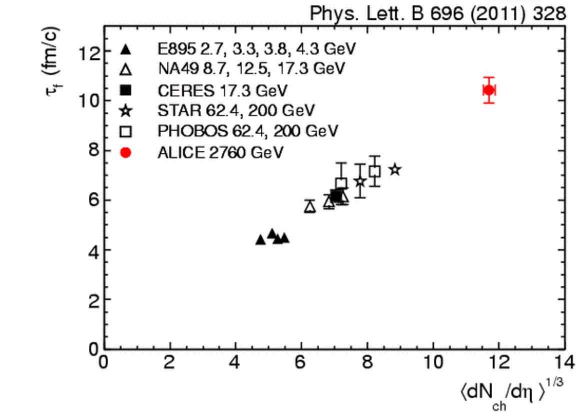


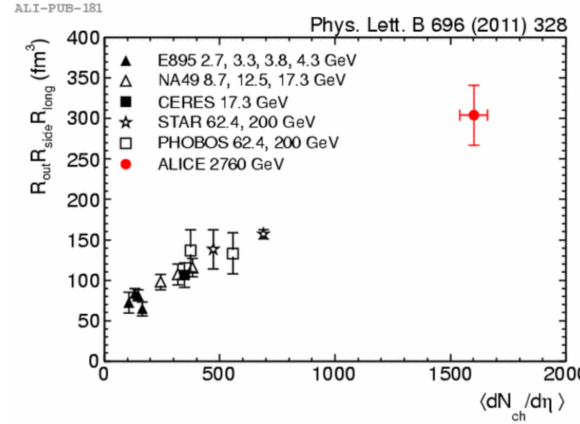
forward-*y*: J/ψ and ψ(2S) show a similar decreasing pattern vs centrality

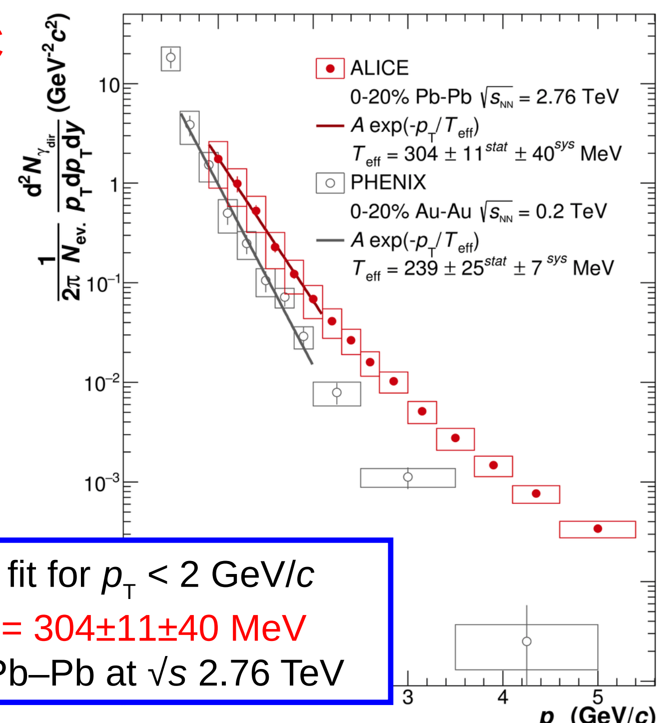
backward-*y*: the J/ψ and ψ(2S) behaviour is different, with the ψ(2S) significantly more suppressed for largest centrality classes
→ Qualitatively consistent with break-up by co-moving medium

PB-PB: GLOBAL PROPERTIES

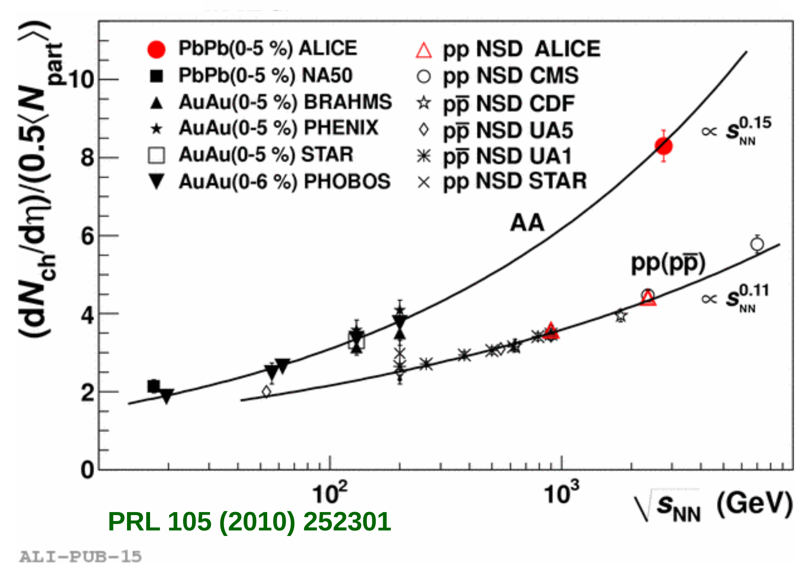
- From the very first analyses, fireball at the LHC densest, largest, hottest and longest lived ever produced in lab
  - **Multiplicity ≈ 2 x RHIC**
  - **Energy density ≈ 3 x RHIC** (p_T is larger)
  - **Volume ≈ 2 x RHIC**
  - **Lifetime ≈ +20%** **(≈ 10 fm/c)**
  - **T ≈ 1.4 x RHIC**



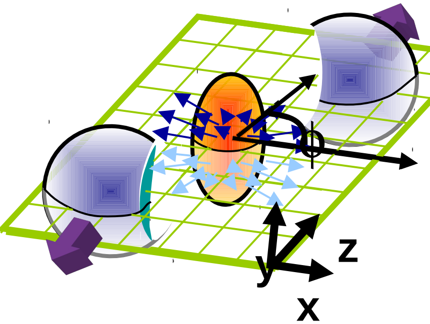




Exponential fit for p_T < 2 GeV/c
inv. slope T = 304±11±40 MeV
for 0–20% Pb–Pb at √s 2.76 TeV

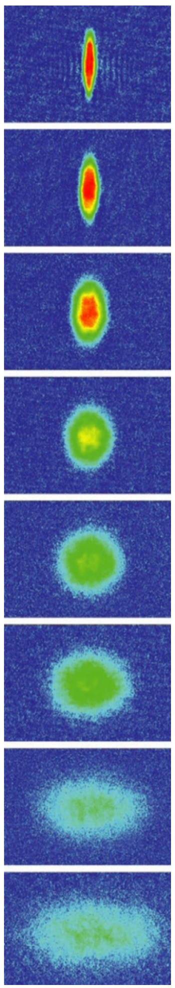


Pb-Pb: Signs of collectivity

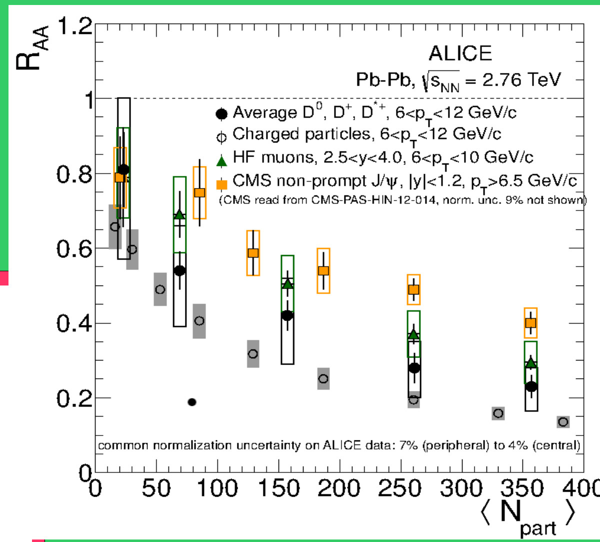


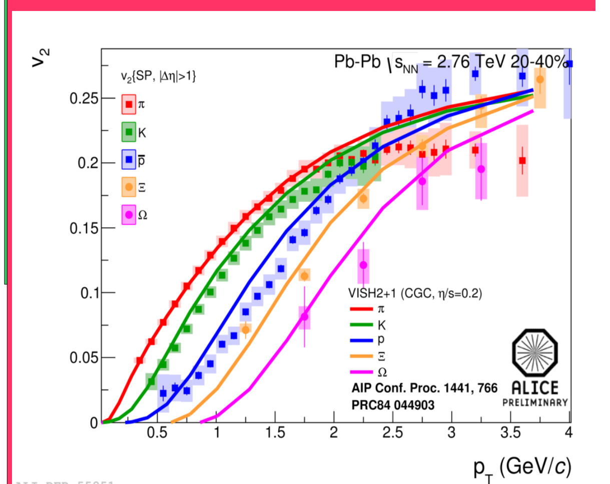
Search for medium effects with
- nuclear modification factors
- strength of collective phenomena *(mean free path)*

$$R_{AA} = \frac{Yield\ in\ A+A}{N_{binary} \times Yield\ in\ p+p}$$



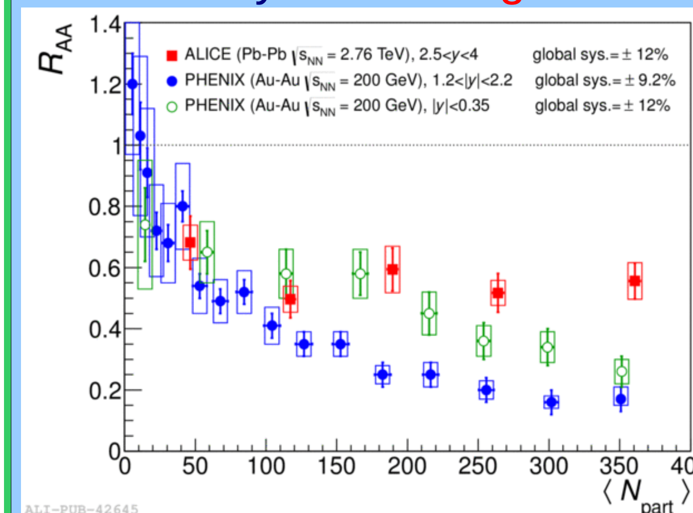
Large radiative energy loss in the medium
Hints of mass hierarchy



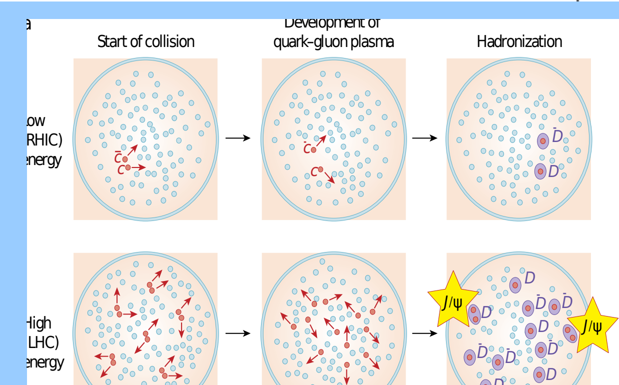


Collective behavior close to ideal fluid behavior described by hydrodynamics

Suppression of quarkonia
→ Debye screening ...



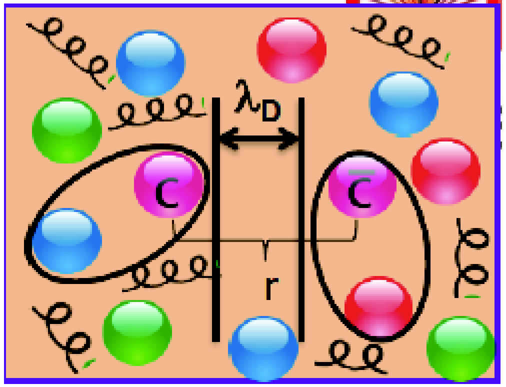
… however less suppressed than at RHIC
Agreement with models of statistical generation
→ quarkonia regenerated in deconfined medium?



Braun-Munzinger & Stachel, Nature Vol. 448 (2007)

QUARKONIA

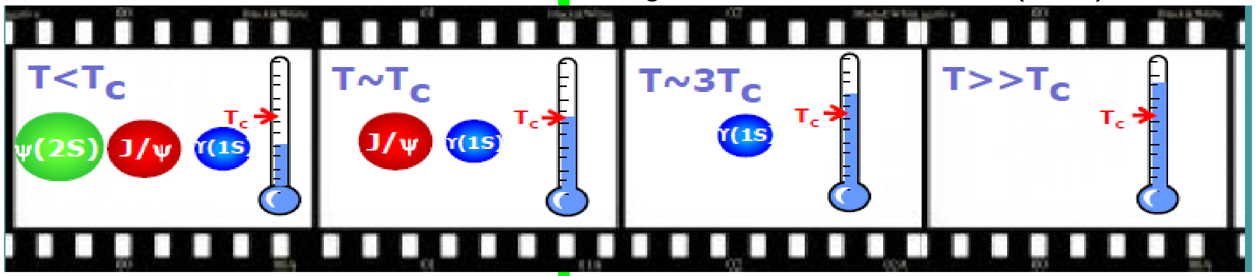
Bound states of charm or beauty quark and its anti-quark
Heavy and tightly bound
Heavy quark pairs produced in the initial hard partonic collisions.



Digal,Petrecki,Satz PRD 64(2001) 0940150

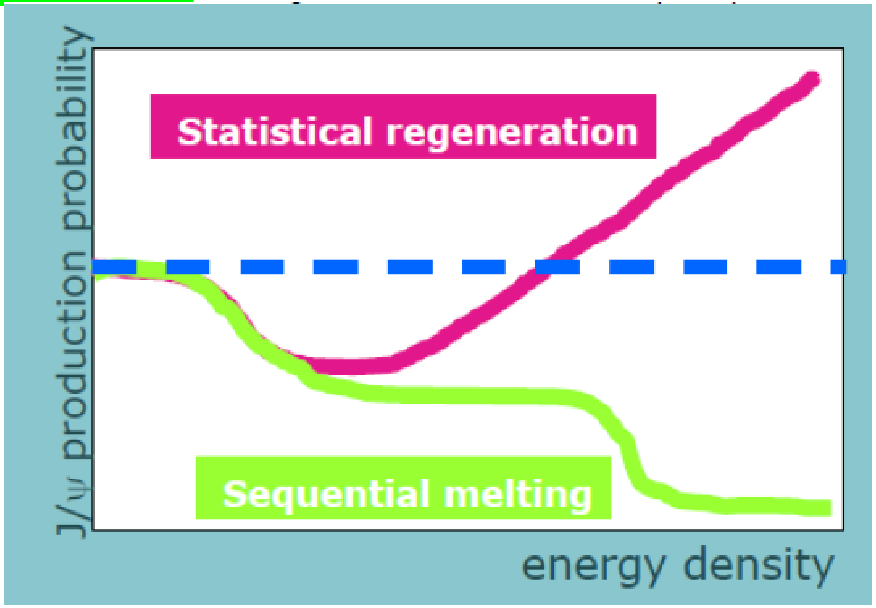
Suppression (Debye screening) → Sequential melting

Color charge of one quark masked by surrounding quarks.
Prevents qq binding in the QGP.
Debye screening radius (λ_D) vs quarkonium radius (r).
λ_D < r the quarks are effectively masked from each other.
→ depending on the binding energies of the quarkonium states

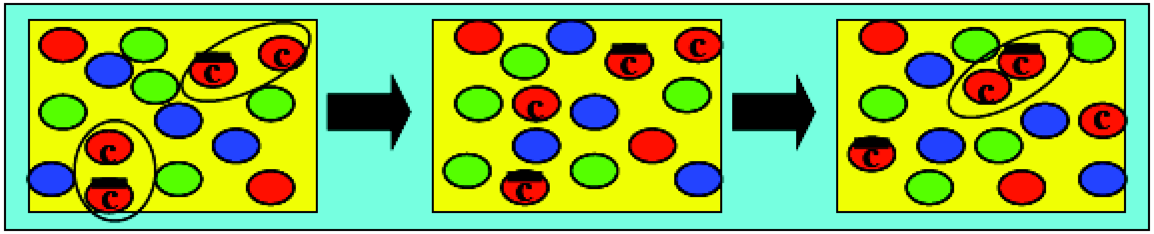


Recombination

Increasing the collision energy the cc pair multiplicity increases (RHIC: ~10; LHC: ~100).
Regeneration of J/ψ pairs from independently cc.
Leads to an enhancement of J/ψ (or less suppression).
No/small regeneration is expected for bottomonia.

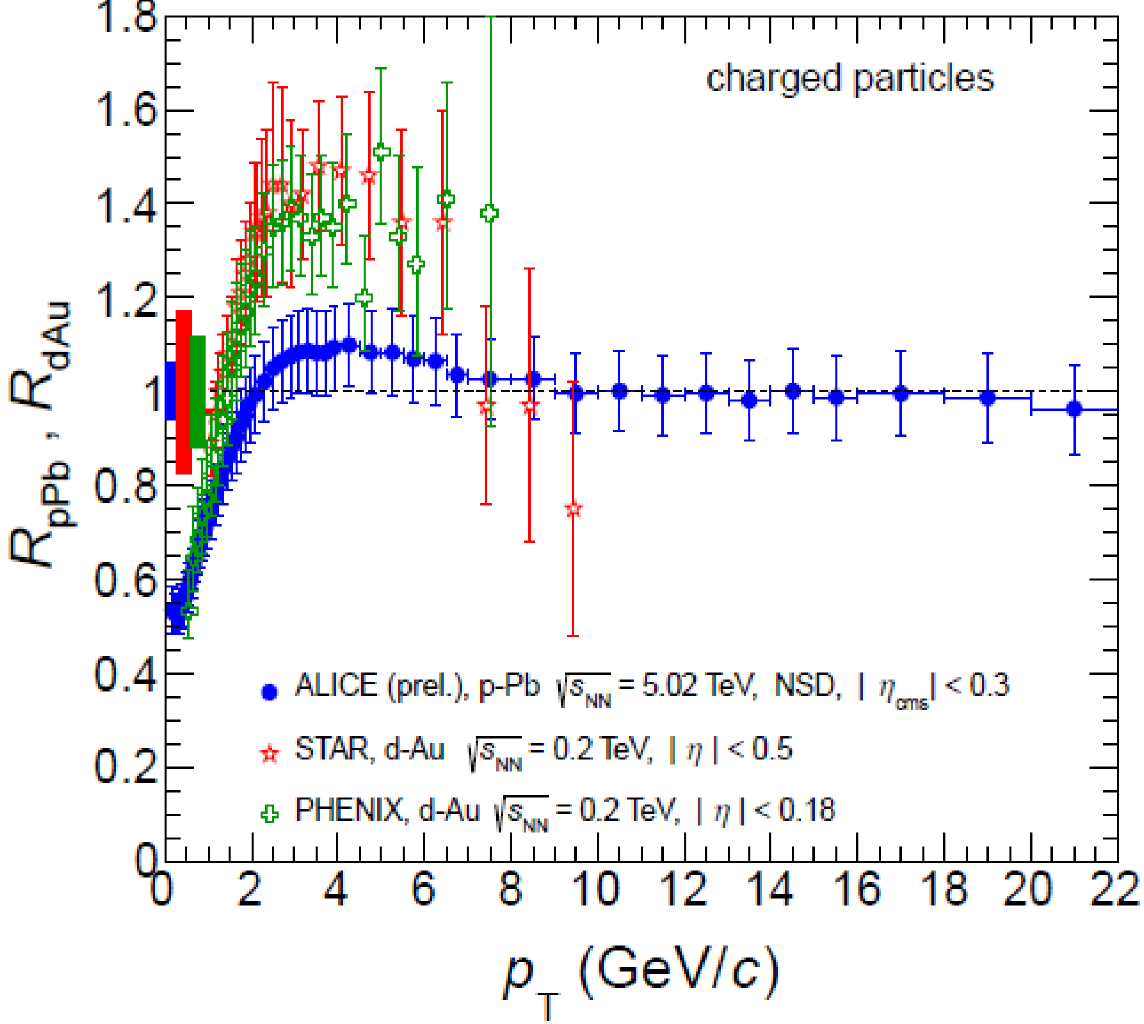


P. Braun-Munzinger,J. Stachel, PLB 490(2000) 196
R. Thews et al, Phys.Rev.C63:054905(2001)



FLOW, CRONIN OR SATURATION?

Any initial or final state effects?



LHC vs. RHIC data

- Cronin effect: “re-distribution” of low-p_T hadrons at higher p_T due to multiple (parton) scattering larger at RHIC
First observed by Cronin in PRD 11 (1975) 3105
→ Multiple soft scatterings in IS prior to hard scatter (arXiv:hep-ph/0212148)

- flow: blue-shift of spectra larger at LHC

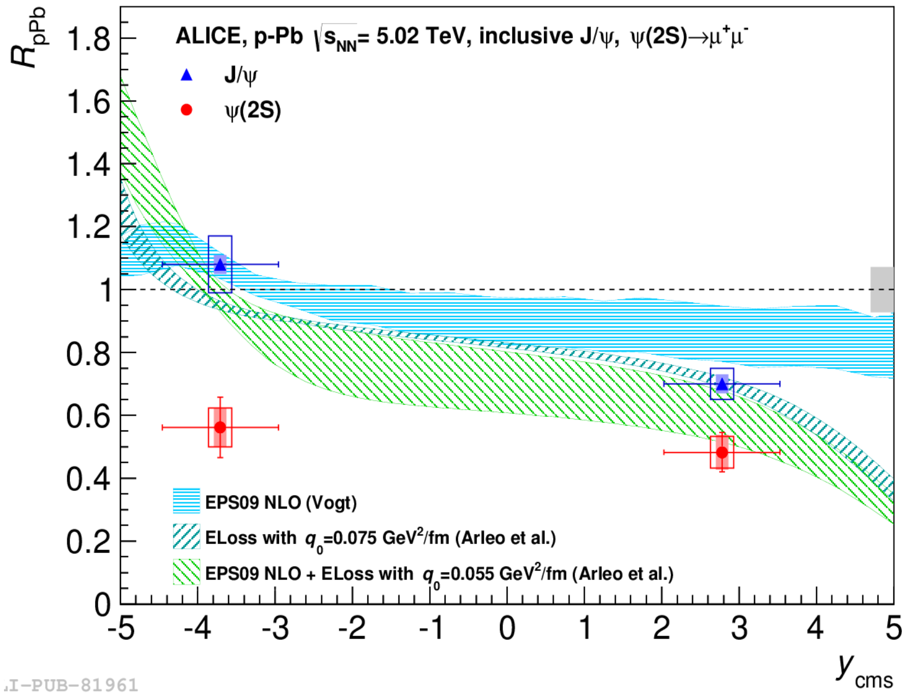
- saturation: depletion of spectra at low p_T
larger at LHC

To distinguish scenarios look differentially!

ψ': Stronger suppression

ALICE

- **Anomalous suppression of heavier and less bound ψ(2S) wrt J/ψ**
- In Pb-Pb: sequential melting depending on binding energy and T(QGP)
- In trend with multiplicity dependence observed p(d)-A and A-A at lower √s
- Qualitatively consistent with break-up by co-moving medium



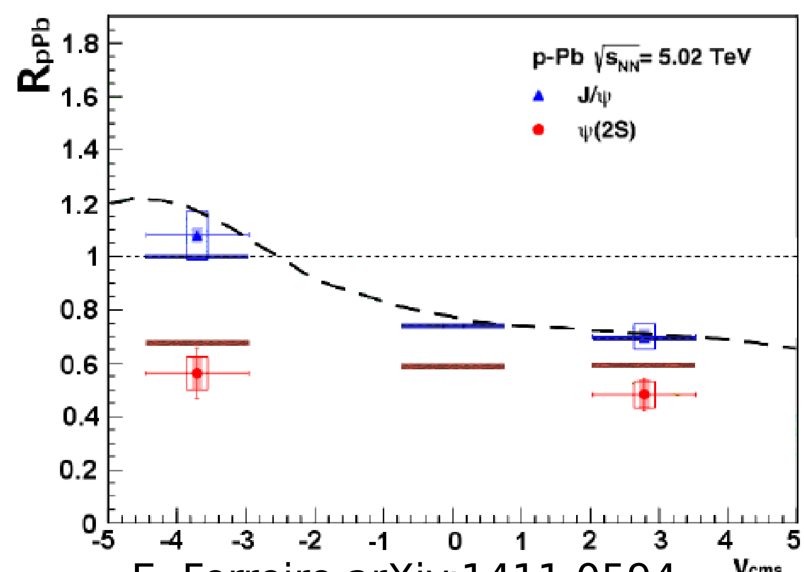
- Shadowing and coherent energy loss: same for for both J/ψ and ψ(2S)
- Break-up of the fully formed resonance in CNM possible if formation (τ_f) < crossing time (τ_c)

(τ_f ~0.05-0.15fm/c)

forward-*y*: $\tau_c \sim 10^{-4}$ fm/c → break-up effects excluded

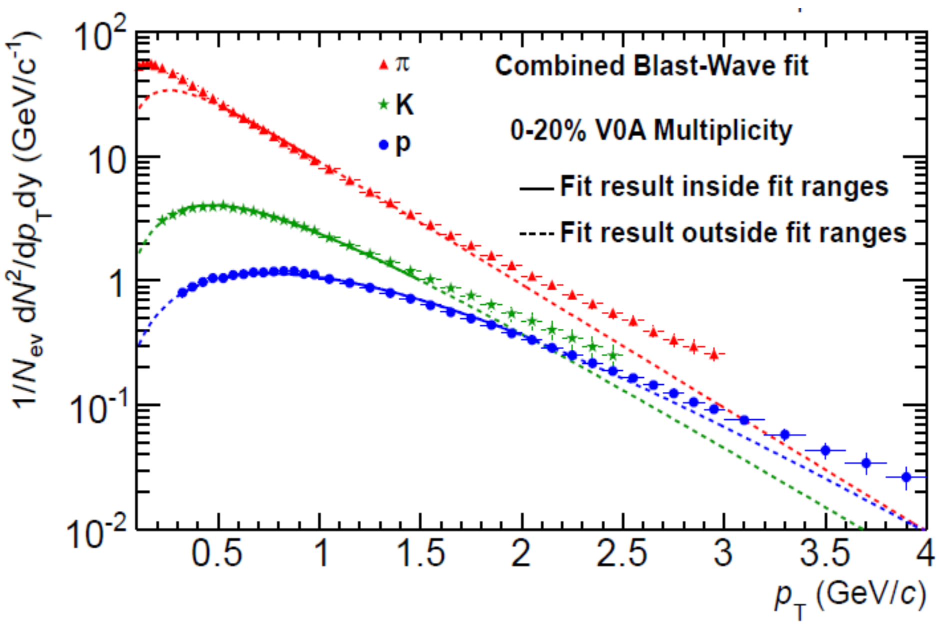
backward-*y*: $\tau_c \sim 10^{-1}$ fm/c → $\tau_f \sim \tau_c$, break-up quasi excluded

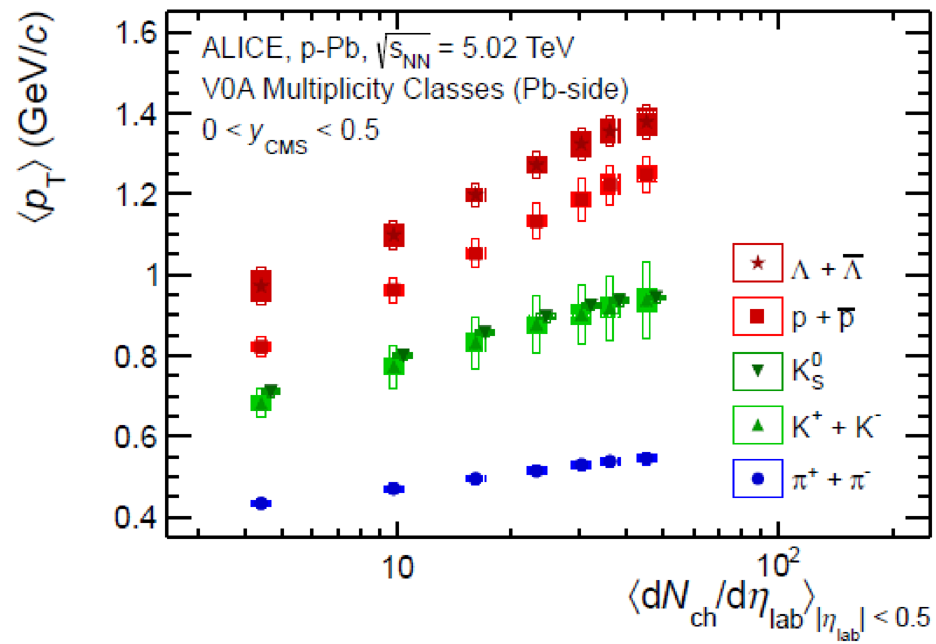
Charmonium interaction with comoving particles:
- Comovers dissociation affects more strongly the loosely bound ψ(2S) than the J/ψ
- Comovers density larger at backward rapidity

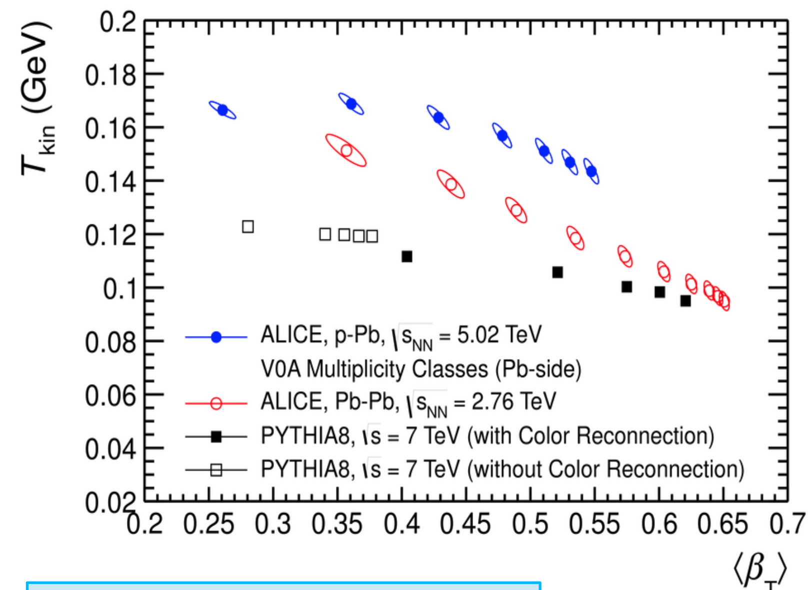


E. Ferreiro arXiv:1411.0594

IDENTIFIED PARTICLE SPECTRA







- Hardening of the spectra with increasing multiplicity
- Hardening is stronger for heavier particles
- Pb-Pb interpretation: common radial boost (radial flow)
- Blast Wave fits → kinetic freeze-out temperature and mean transverse-expansion velocity
  - Similar in p-Pb and Pb-Pb
- Hydro-evolution or color reconnection?

ALICE arXiv: 1307.6796