Recent results from ALICE at LHC

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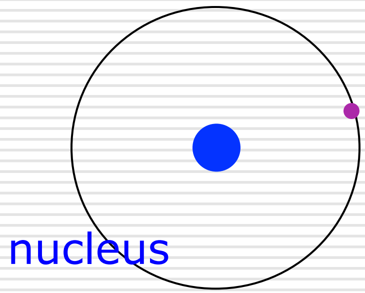
Outline:

- Introduction to heavy ion collisions
- recent Pb-Pb results: a selection
- “small systems”: pp and p-Pb results
- future
- summary

Corfù 2017

Confinement: a crucial feature of QCD



neutral atom

We can extract an electron from an atom by providing energy

But we cannot get free quarks out of hadrons: **"colour confinement"**

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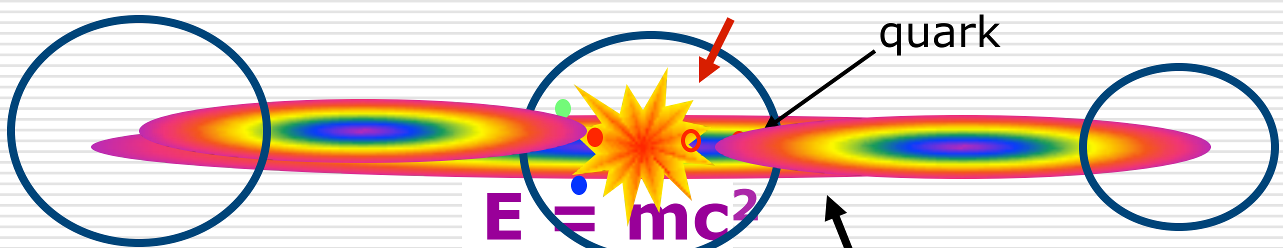
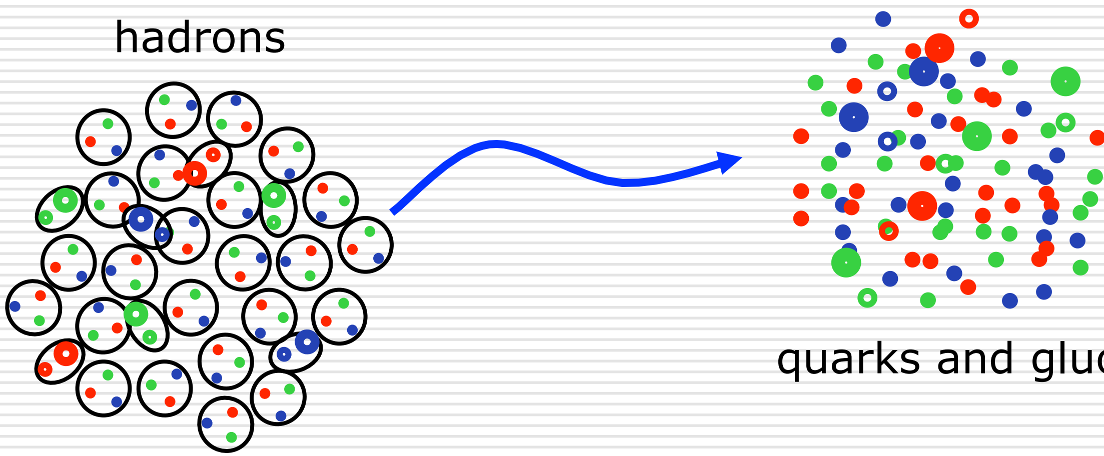
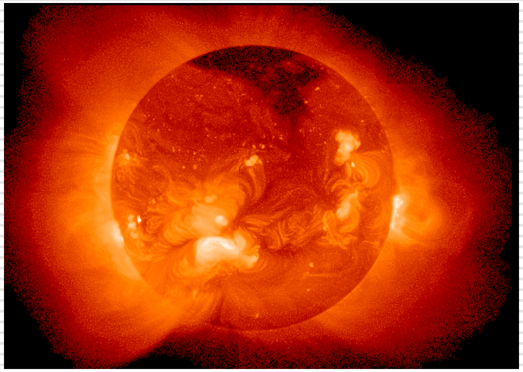


The QCD phase transition

Lattice QCD calculations indicate that, at a *critical* temperature around 160 MeV, strongly interacting matter undergoes a phase transition to a new state where the quarks and gluons are no longer confined into hadrons



How hot is a medium of T ~ 160 MeV?



15 M °K

100,000 times hotter than the Sun core

The phase diagram of QCD, in 1975

EXPONENTIAL HADRONIC SPECTRUM AND QUARK LIBERATION

N. Cabibbo and G. Parisi, Phys. Lett. B59 (1975) 67

The exponentially increasing spectrum proposed by Hagedorn is not necessarily connected with a limiting temperature, but it is present in any system which undergoes a second order phase transition. We suggest that the "observed" exponential spectrum is connected to the existence of a different phase of the vacuum in which quarks are not confined.

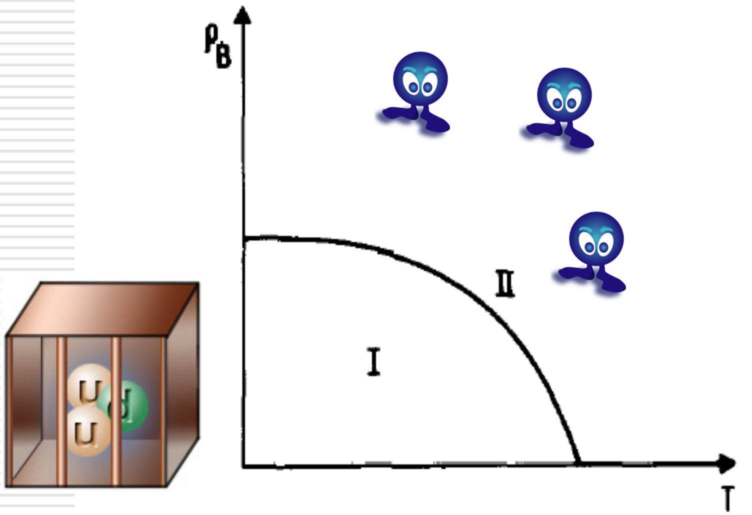
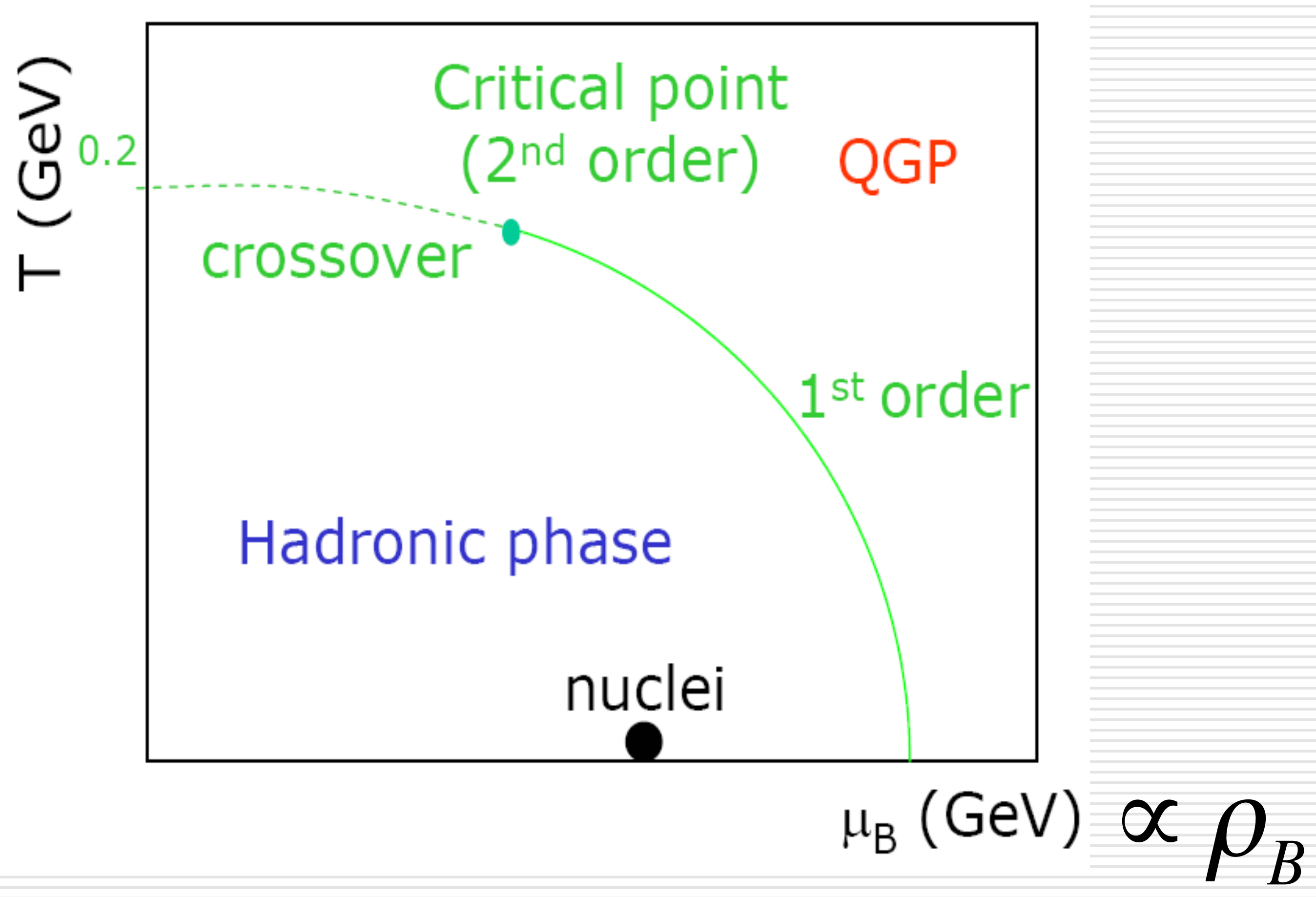


Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.

The phase diagram of QCD, today



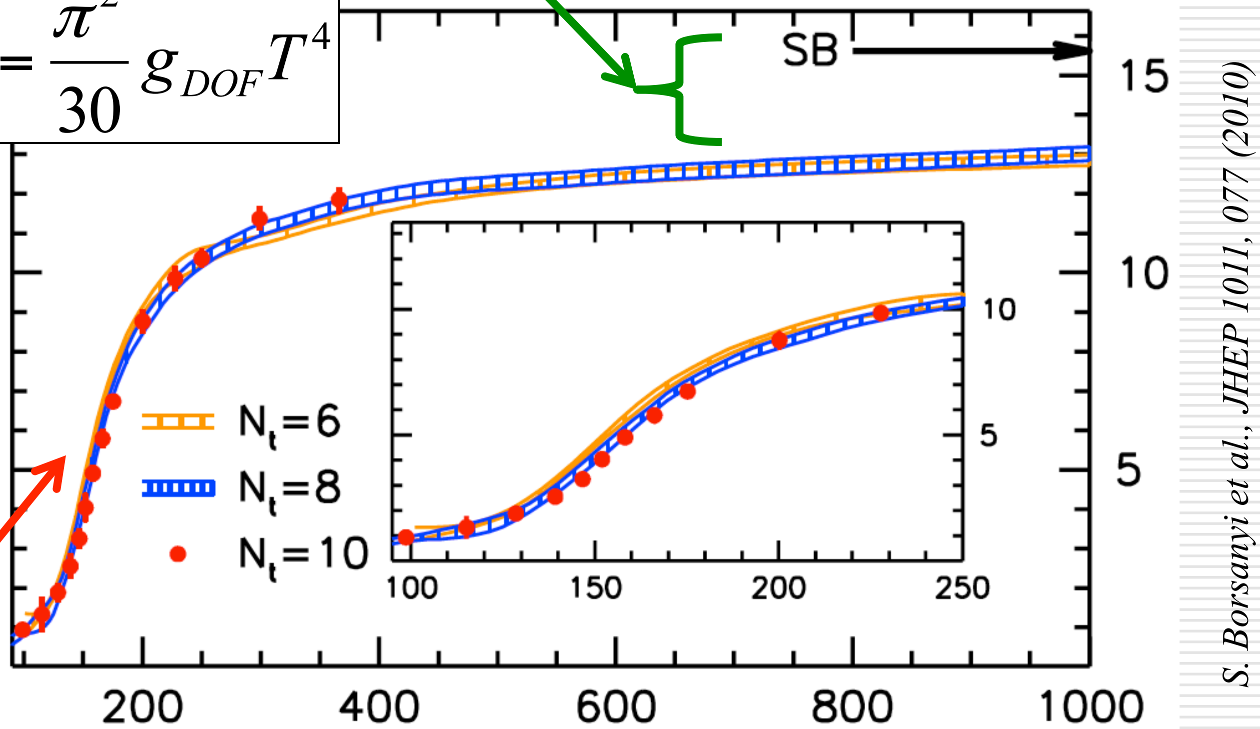
Finite Temperature QCD on the Lattice (μ_B=0)

Slow convergence to non-interacting Steffan-Boltzmann limit
What carries energy - complex bound states of q+g? "strongly-coupled" plasma?

Energy density

$$\varepsilon = \frac{\pi^2}{30} g_{DOF} T^4$$

$$\frac{\varepsilon}{T^4}$$

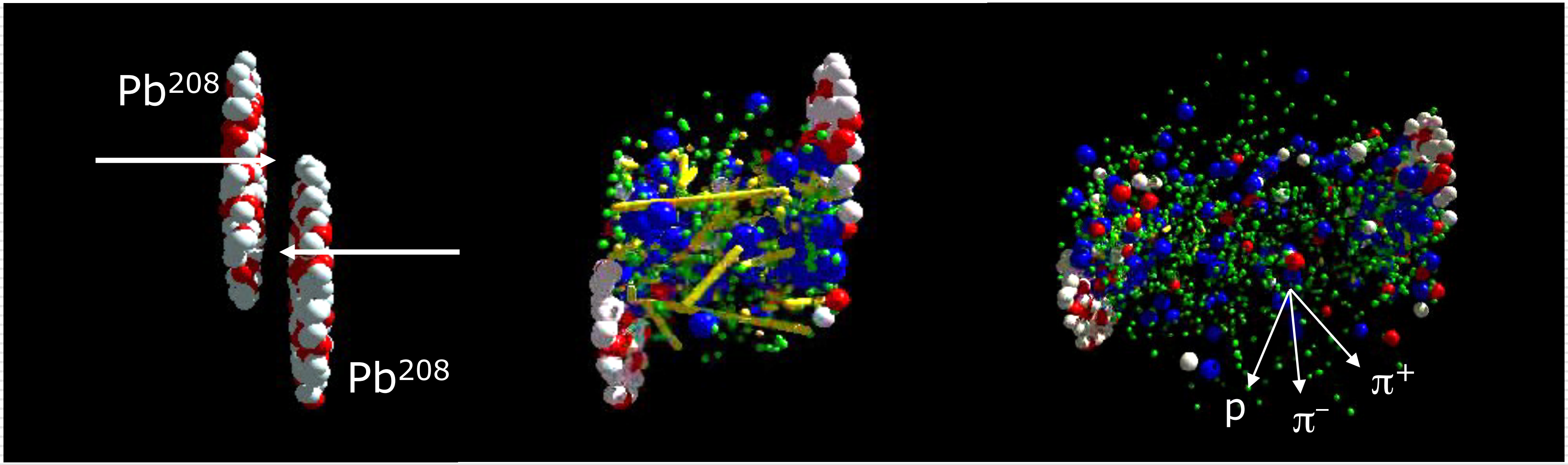


Temperature [MeV]

Cross-over, not sharp phase transition
(like ionization of atomic plasma)

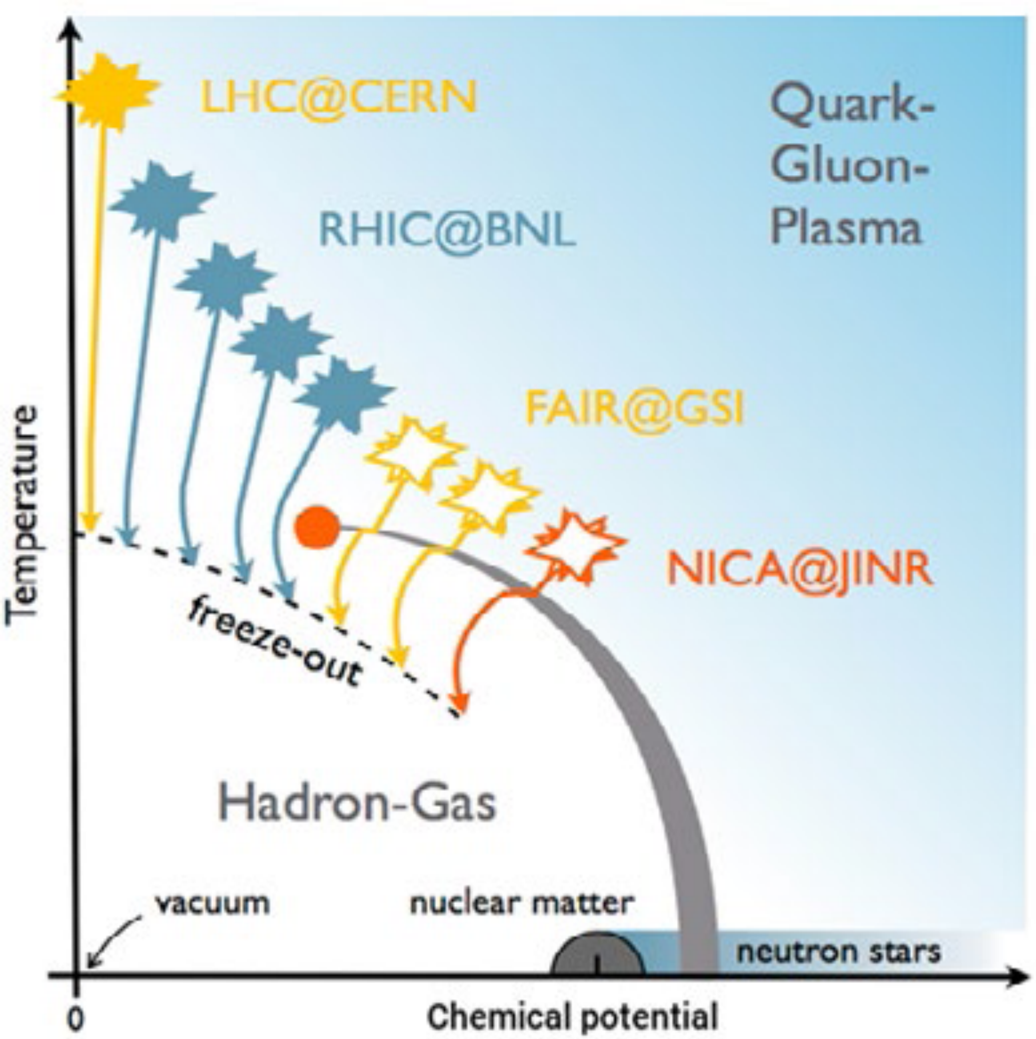
How do we study *bulk* QCD matter?

- We can heat and/or compress a large volume of QCD matter
- Done in the lab by colliding heavy nuclei at high energies

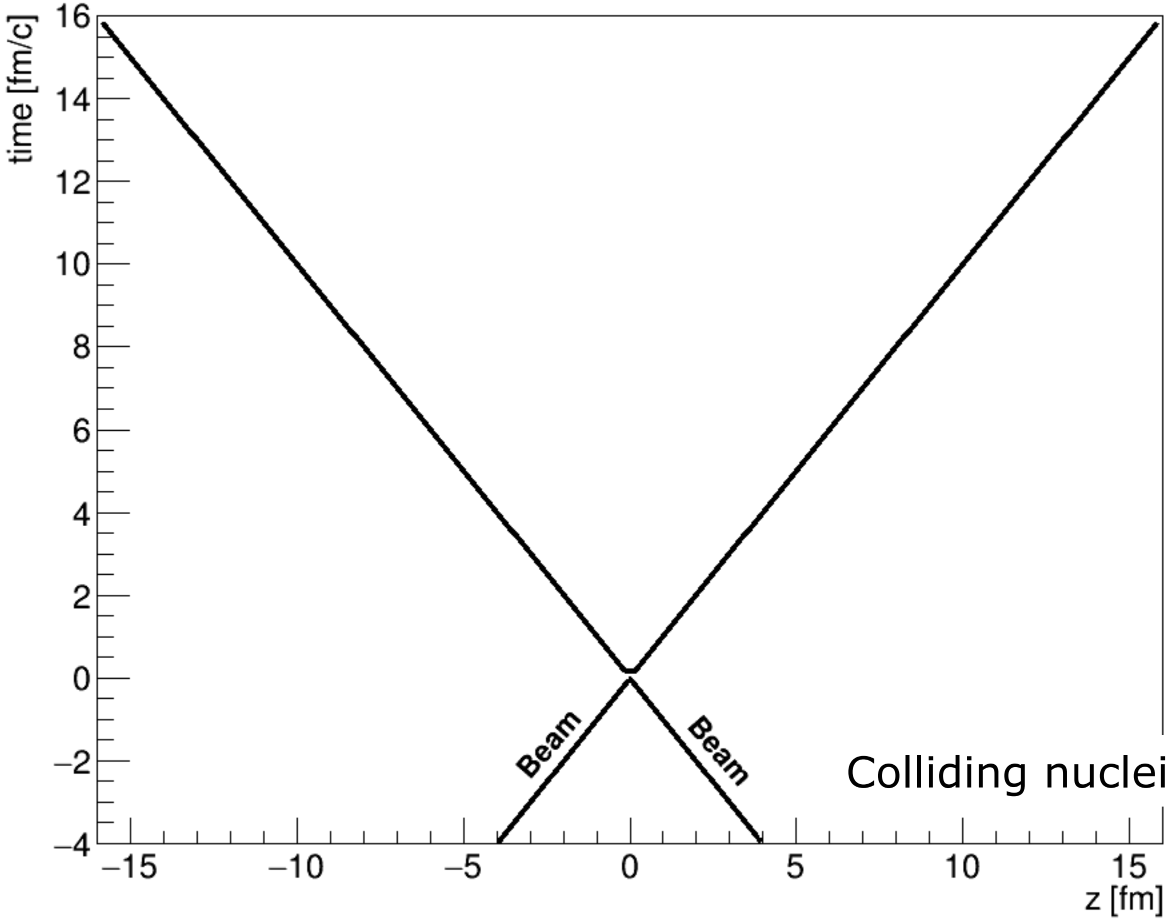


Exploring the QCD phase diagram

- regime of "transparency"
  - very high T, $\mu_b \cong 0$
  - LHC and top RHIC energy
- high density regime:
  - partial stopping of the nucleons in collisions
  - physics of FAIR@GSI and NICA@JINR



Space time evolution of A-A collision



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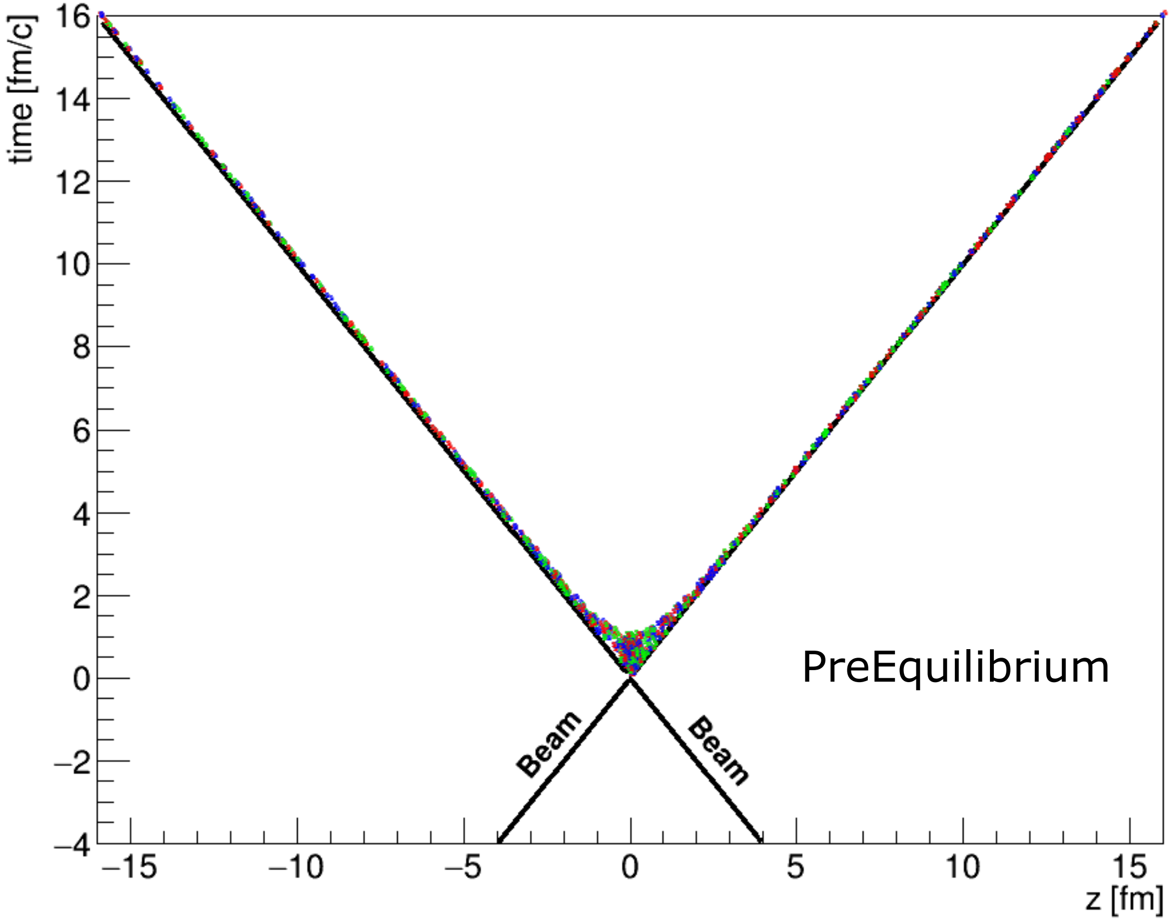

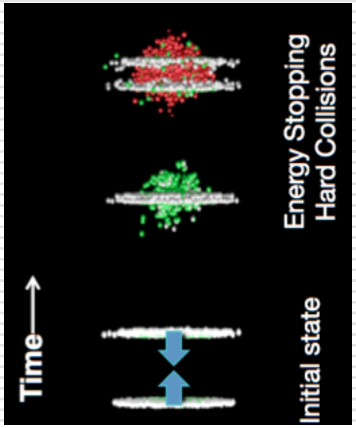

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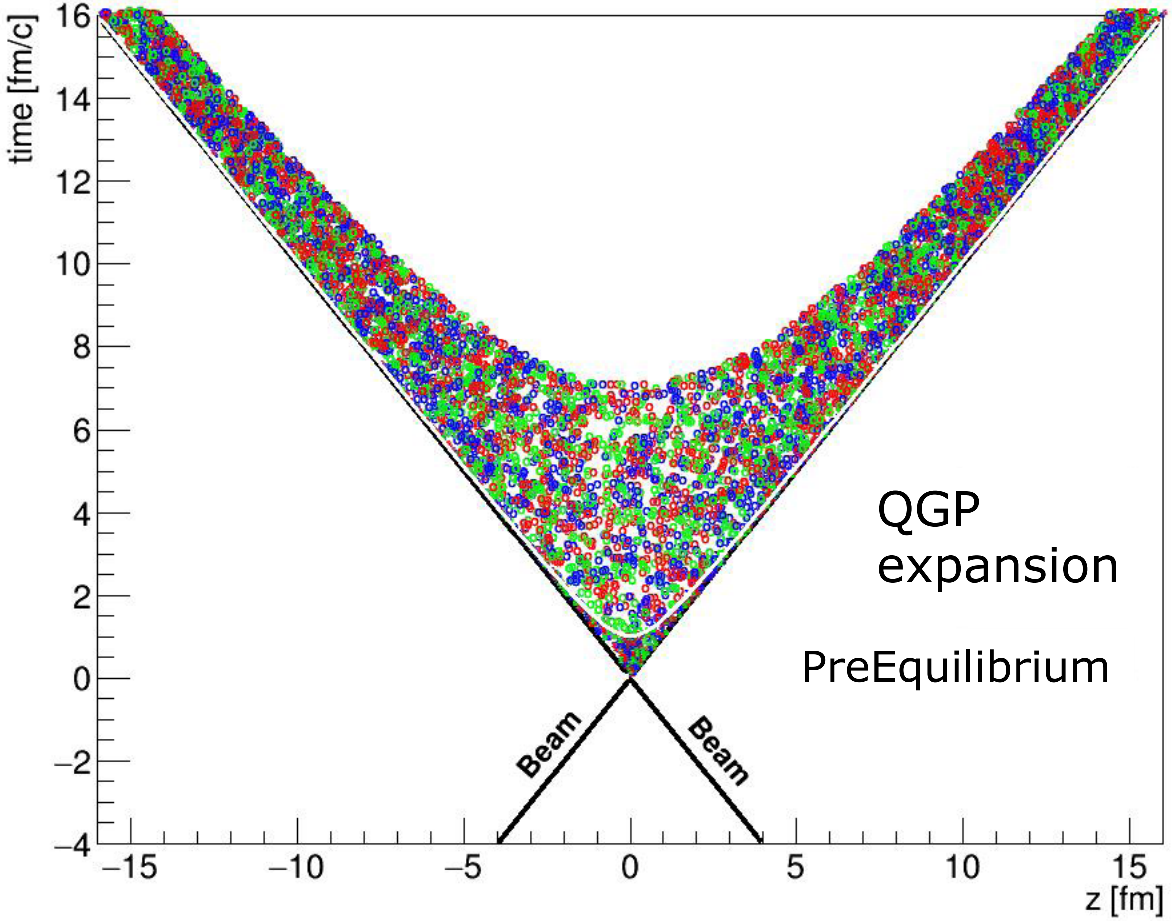

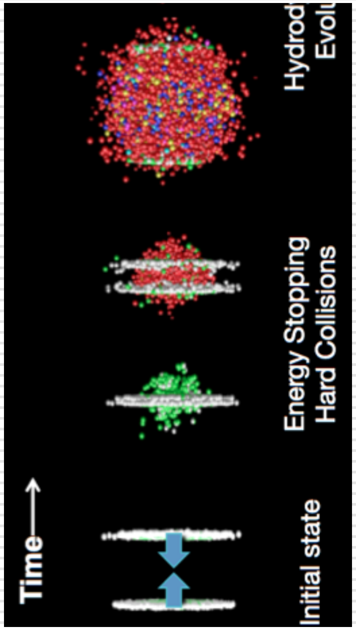

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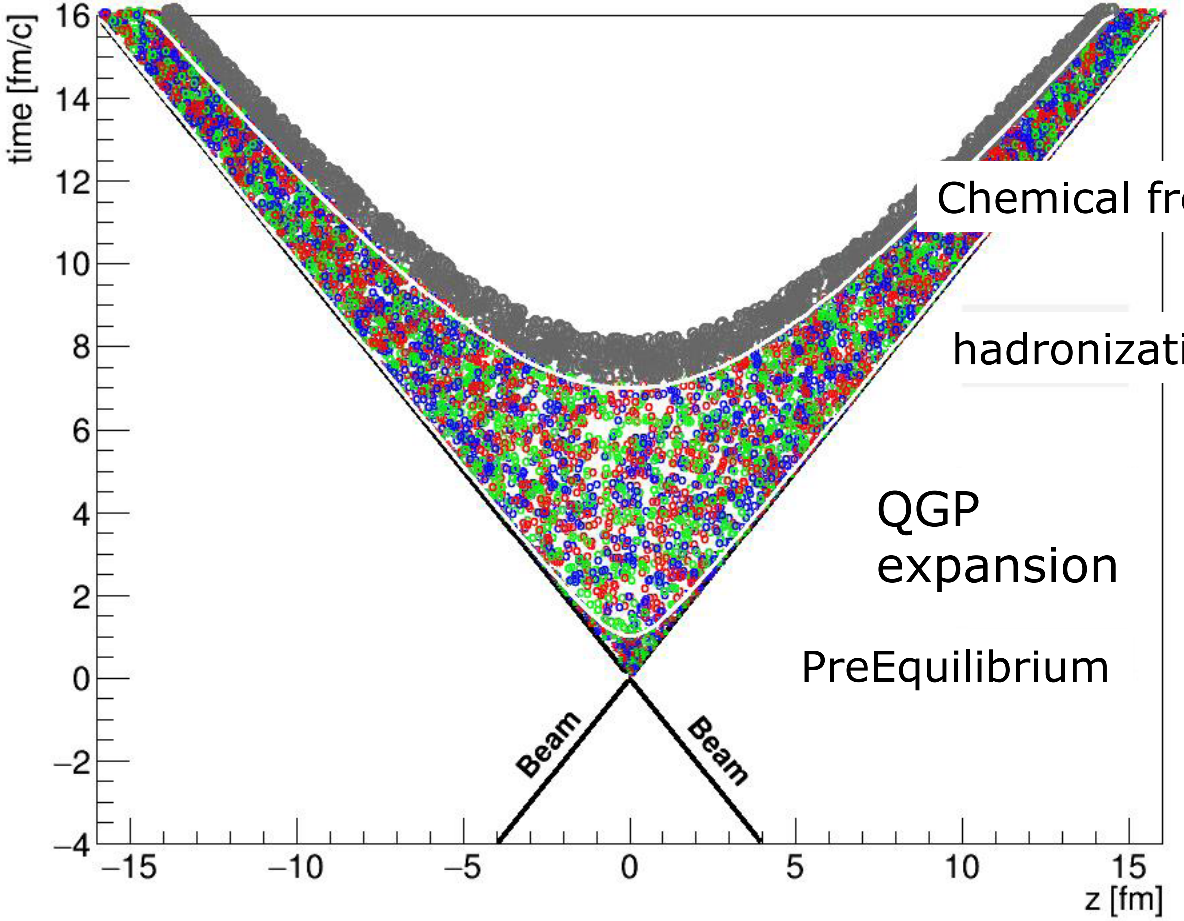

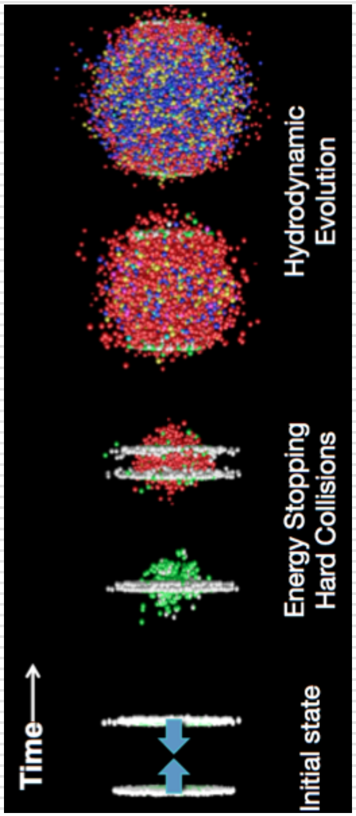

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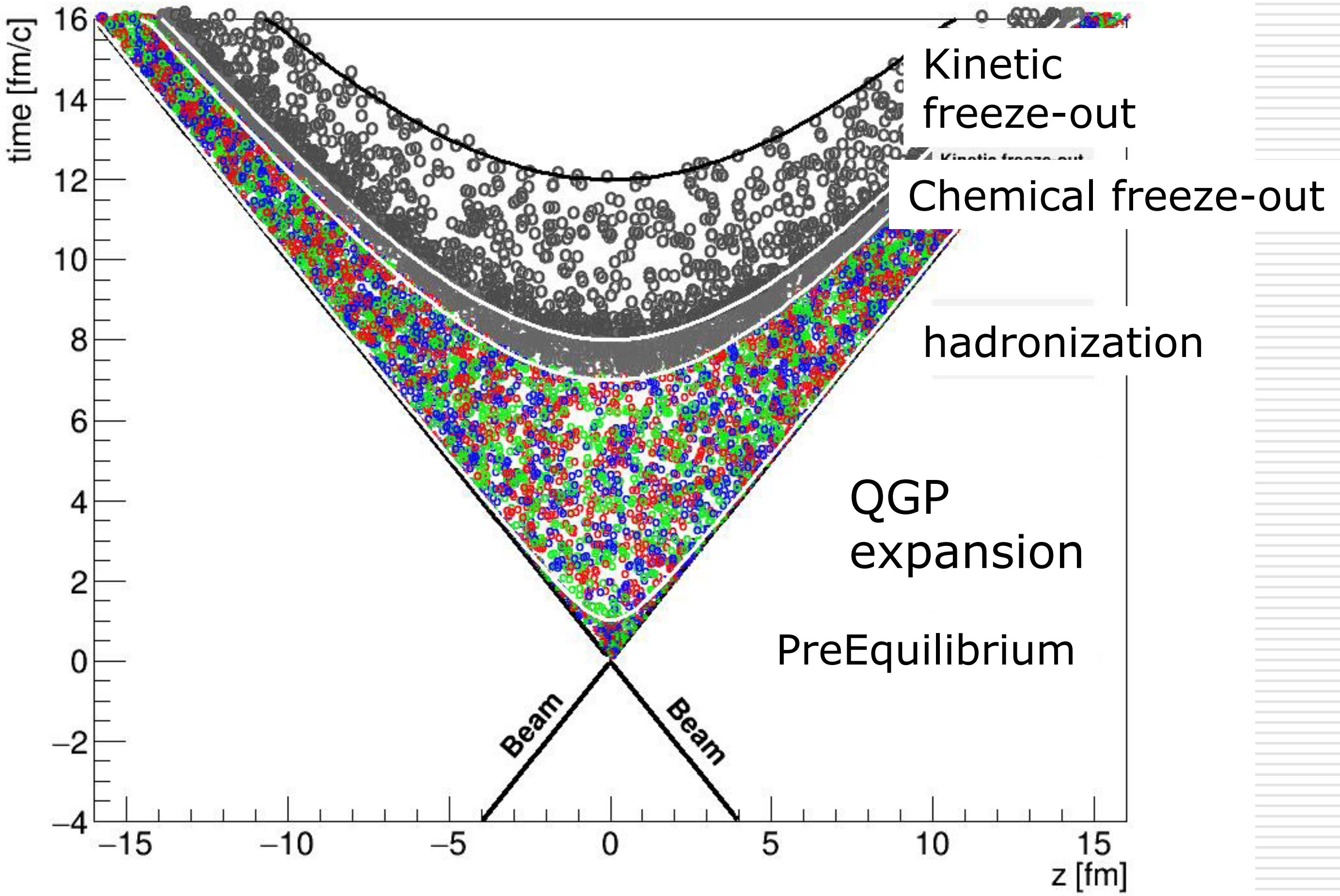

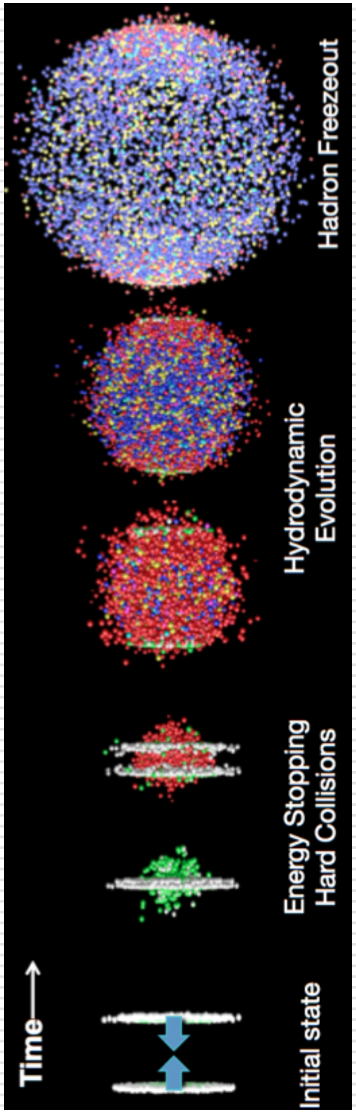

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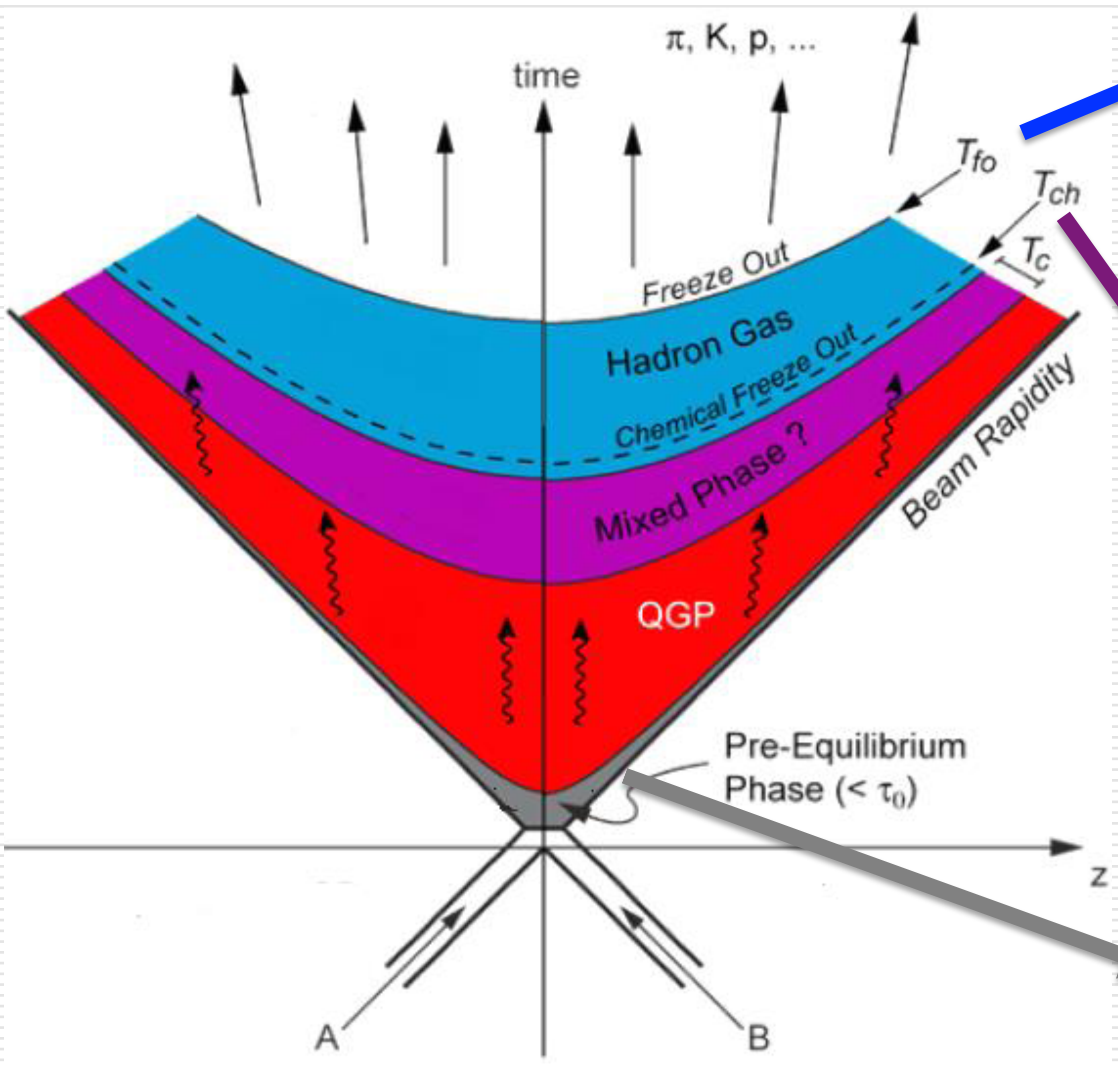
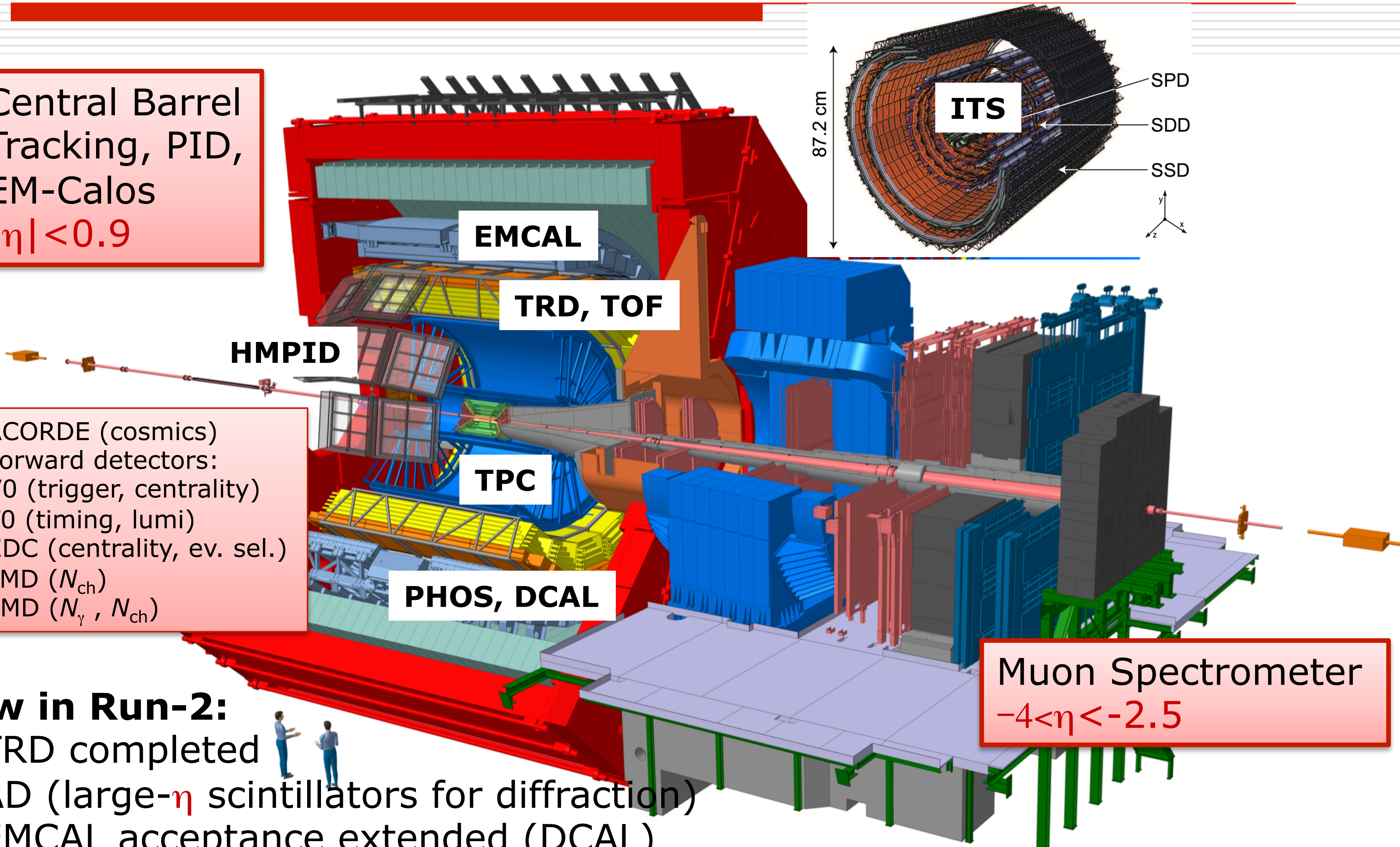


- Thermal freeze-out
  - Elastic interactions cease
  - Particle dynamics ("momentum spectra") fixed
  - T_{fo} ~ 100 MeV
- Chemical freeze-out
  - Inelastic interactions cease
  - Particle abundances ("chemical composition") are fixed
  - T_{ch} ~ 150 MeV
- Thermalization time
  - System reaches local equilibrium
  - τ_{eq} ~ 0.5 fm/c

The ALICE Detector

Central Barrel
Tracking, PID,
EM-Calos
$|\eta|<0.9$



ACORDE (cosmics)
Forward detectors:
V0 (trigger, centrality)
T0 (timing, lumi)
ZDC (centrality, ev. sel.)
FMD (N_{ch})
PMD (N_{γ} , N_{ch})

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

New in Run-2:

- TRD completed
- AD (large-η scintillators for diffraction)
- EMCAL acceptance extended (DCAL)
- PHOS (γ e.m. cal) completed, also with Charged Particle Veto

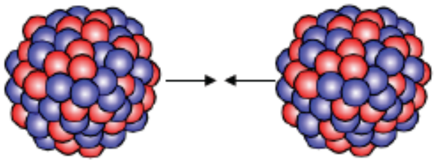
ALICE data-taking in Run-2

System	Year	$\sqrt{s_{NN}}$ (TeV)	L_{int}
pp	2015-2016	13	~14 pb^{-1}
pp	2015 (~4 days)	5.02	~100 nb^{-1}
p-Pb	2016	5.02	~3 nb^{-1}
p-Pb	2016	8.16	~20 nb^{-1}
Pb-p	2016	8.16	~20 nb^{-1}
Pb-Pb	2015	5.02	~0.4 nb^{-1}

- Goals for 2017-18:
  - Pb-Pb: reach 1/nb target
  - pp 13 TeV: reach 40/pb target
  - High statistics pp 5 TeV sample

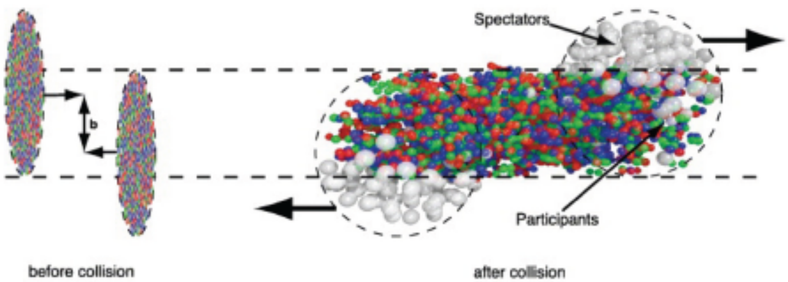
from pp to Pb-Pb collisions at LHC

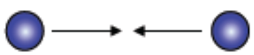
The paradigm



Pb-Pb Collisions ($\sqrt{s_{NN}}$ = 2.76, 5 TeV)

- Core business: create and characterize the QGP
- Centrality

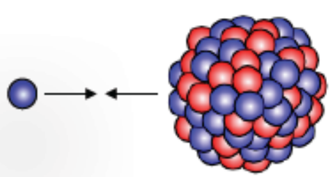




pp Collisions ($\sqrt{s}$ = 0.9 –13 TeV)

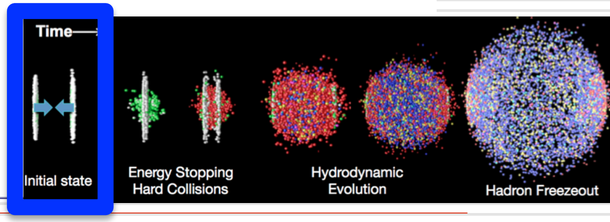
- Reference data

to be revised later on !



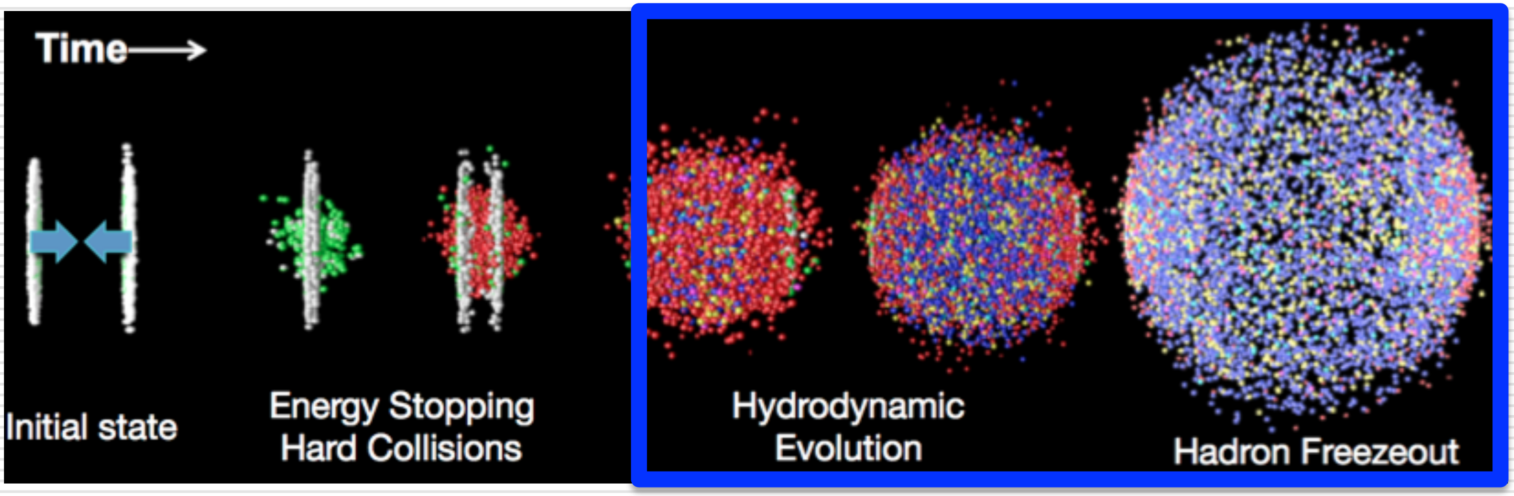
p-Pb Collisions ($\sqrt{s_{NN}}$ = 5, 8 TeV)

- Control experiment
- "Cold nuclear matter" effects (e.g. modifications to PDF)



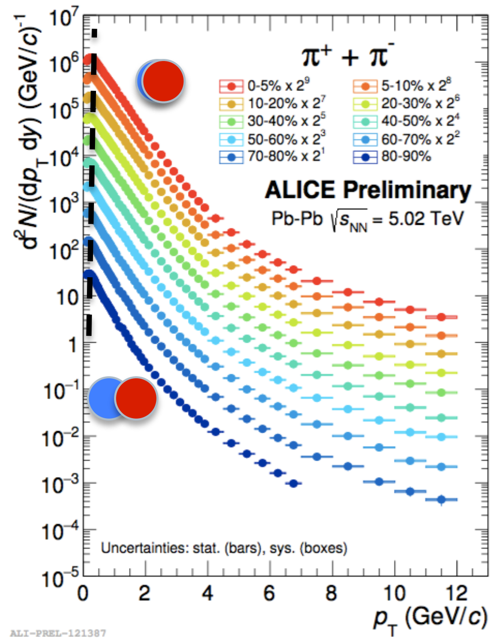
Recent Pb-Pb results

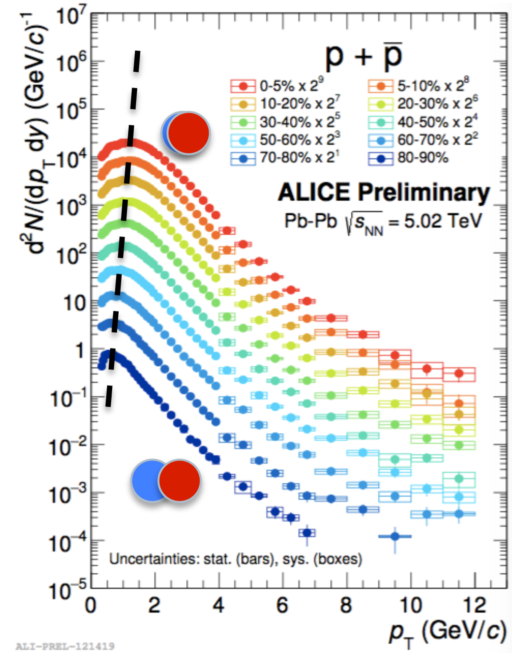
Hadron production and flow in Pb-Pb collisions at 5 TeV

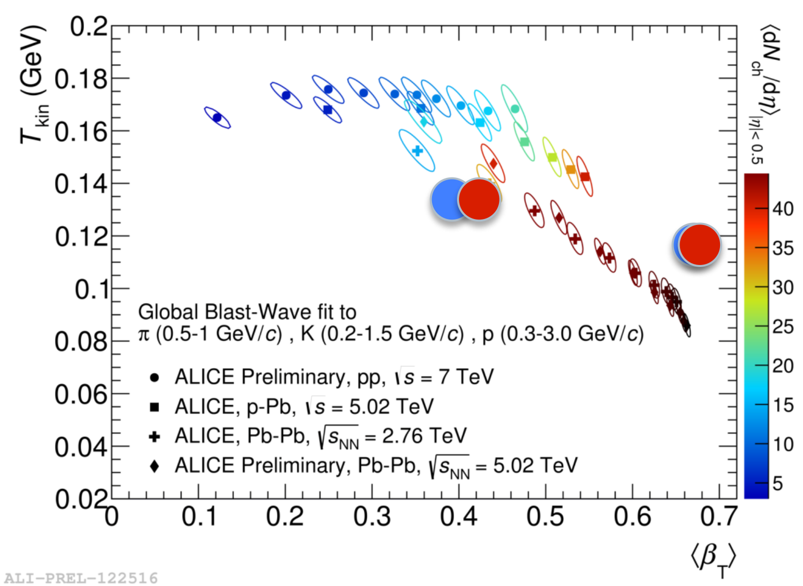


Identified hadron spectra at 5 TeV

- High-precision p_T distributions for π, K, p in 10 centrality classes
  - Measured using five different identification techniques
- Blue-shift of MPV of p_T in central collisions, more pronounced for heavier hadrons







- Fit with hydrodynamic-inspired model
  - Collective expansion with common flow velocity (β_t) superimposed to thermal motion (T ~ 100 MeV)
- Largest ever β_T ~ 0.65 in central Pb-Pb collisions at 5 TeV

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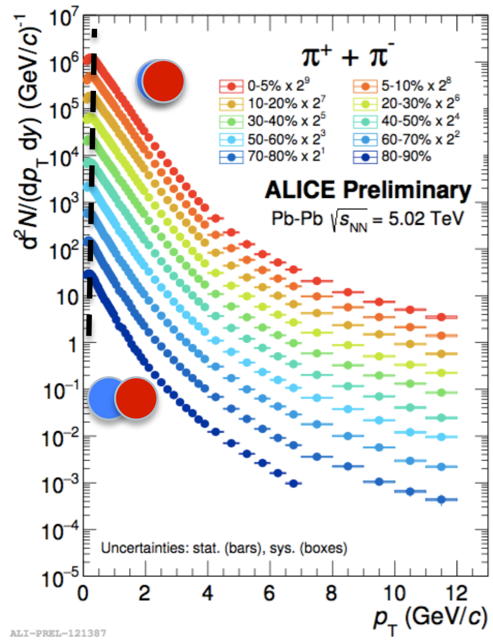
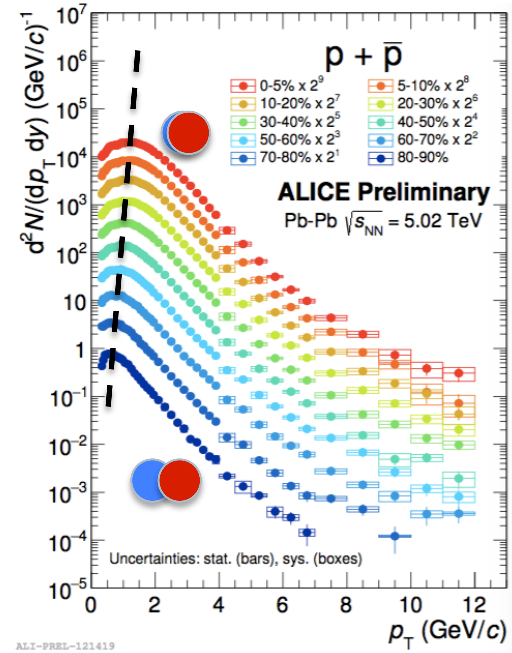
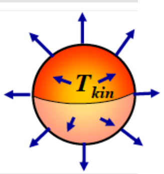
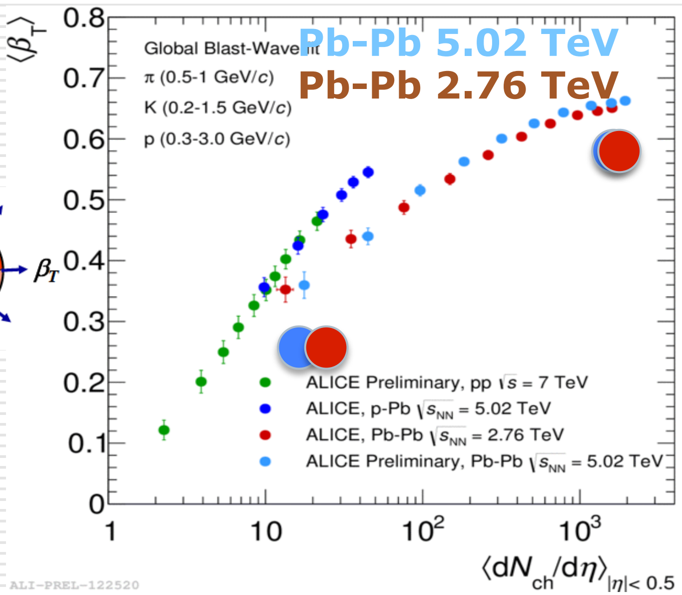


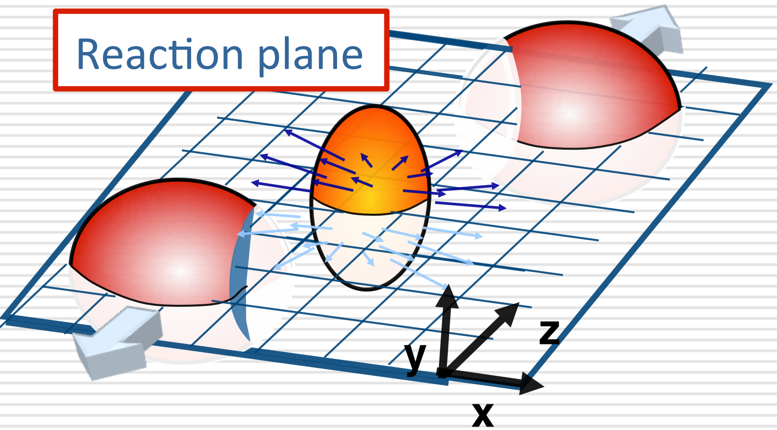


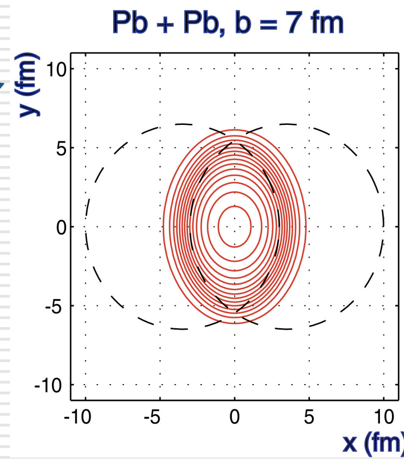


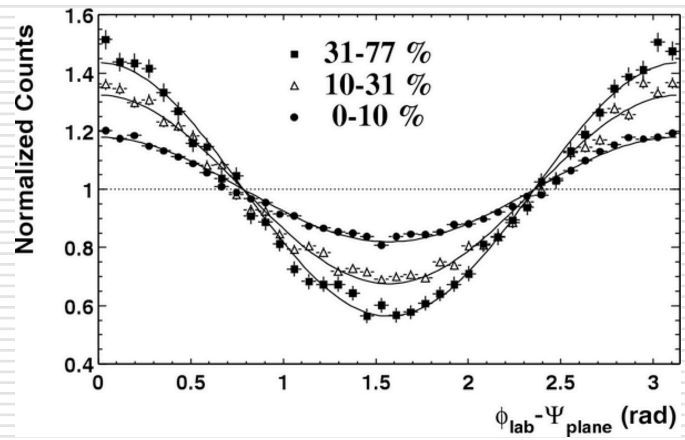


- Fit with hydrodynamic-inspired model
  - Collective expansion with common flow velocity (β_t) superimposed to thermal motion (T ~ 100 MeV)
- Largest ever $<\beta_T> \sim 0.65$ in central Pb-Pb collisions at 5 TeV

Azimuthal anisotropy



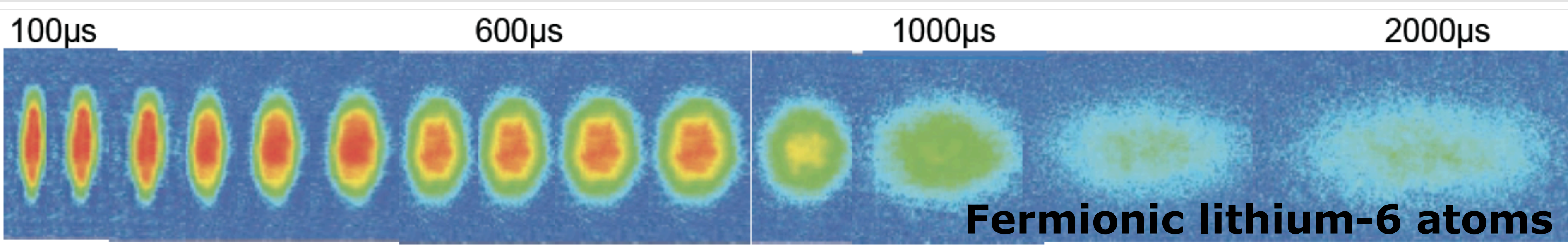




Almond shaped overlap region in geom. space → strong in-plane expansion due to pressure gradients → anisotropy in momentum space

$$\frac{dN}{d(\varphi-\psi_{RP})} \propto 1+2\sum_{n=1} v_n \cos\left(n[\varphi-\psi_{RP}]\right)$$

$$v_2 = \left\langle \cos\left[2(\varphi-\psi_{RP})\right]\right\rangle$$



M. Gehm, S. Granade, S. Hemmer, K, O'Hara, J. Thomas - **Science 298 2179 (2002)**

Elliptic flow at 5 TeV

$$\frac{dN}{d(\varphi - \psi_{RP})} \propto 1 + 2\sum_{n=1} v_n \cos\left(n[\varphi - \psi_{RP}]\right)$$

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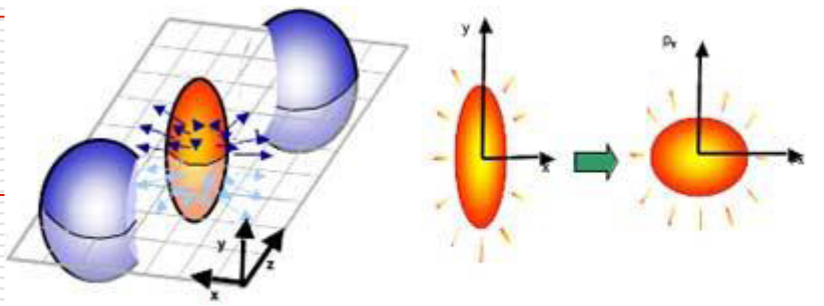
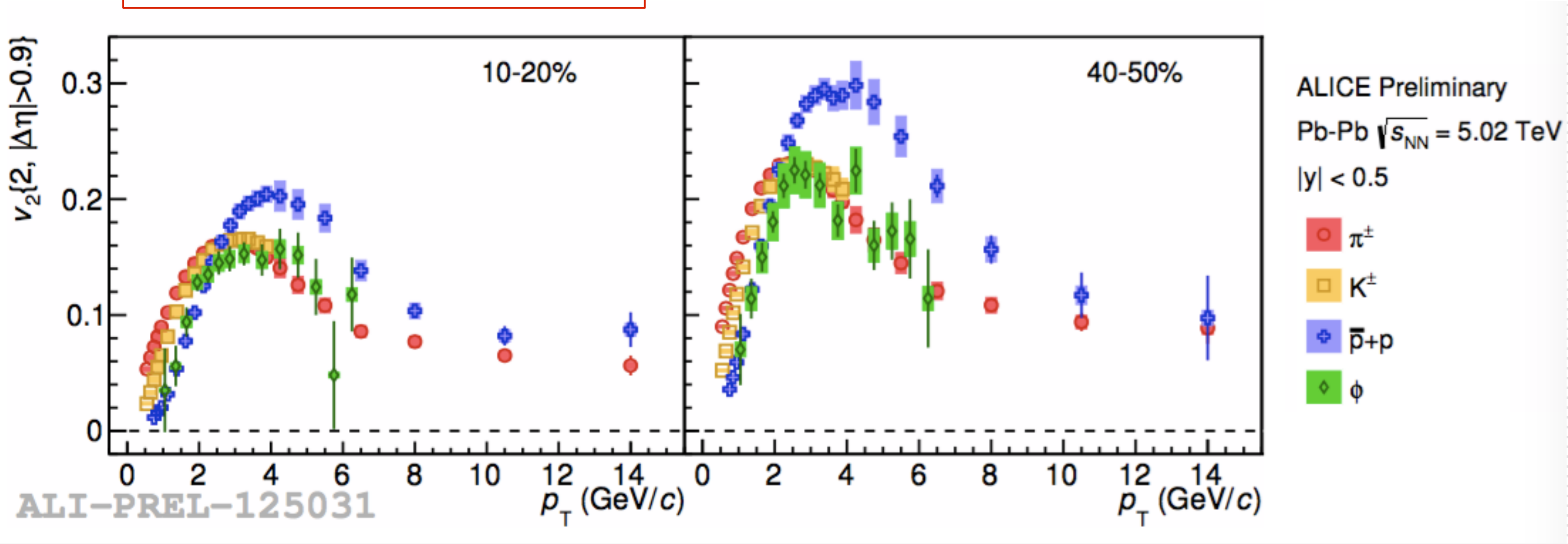
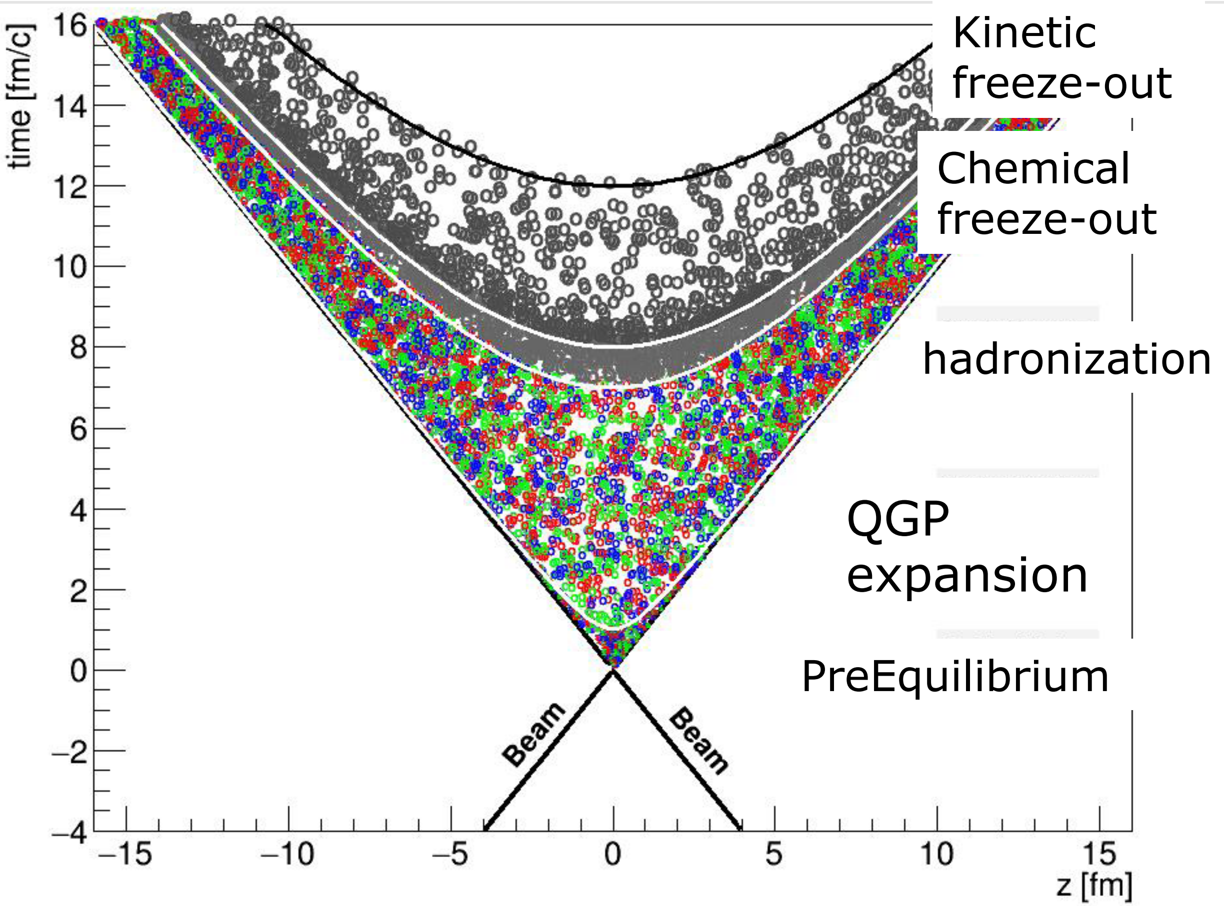




- Mass ordering at p_T<2 GeV/c → **hydro-dynamic flow, very small viscosity**
- More precise Run-2 data (esp. ϕ meson) reveal baryon vs. meson grouping at higher pT (2-6 GeV/c) → **quark-level flow + recombination?**

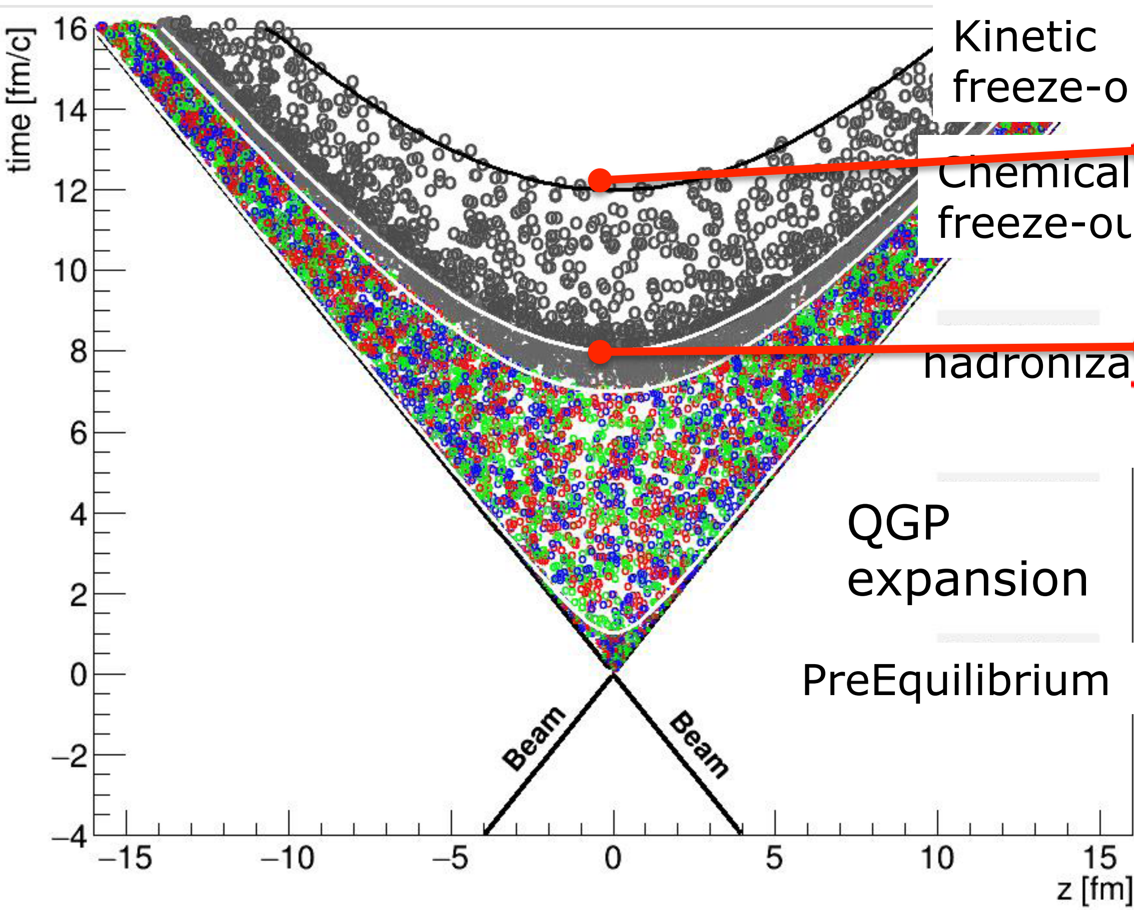
Resonances in Pb-Pb

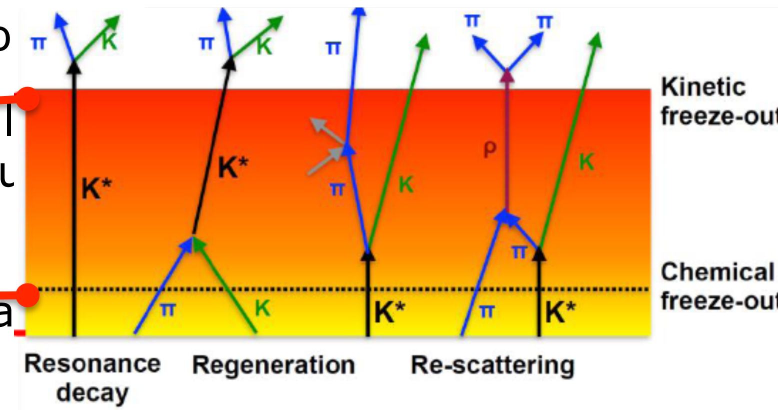
- Resonances are powerful tools to probe the hadronic phase after chemical freeze-out

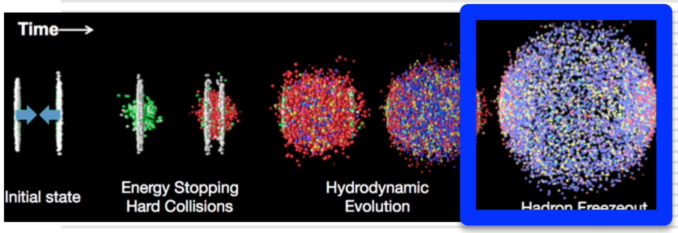


Resonances in Pb-Pb

Lifetime [fm/c] : ρ [1.3] < K^* [4.2] < Λ^* [12.6] < Ξ^{0*} [21.7] < ϕ [46.2]







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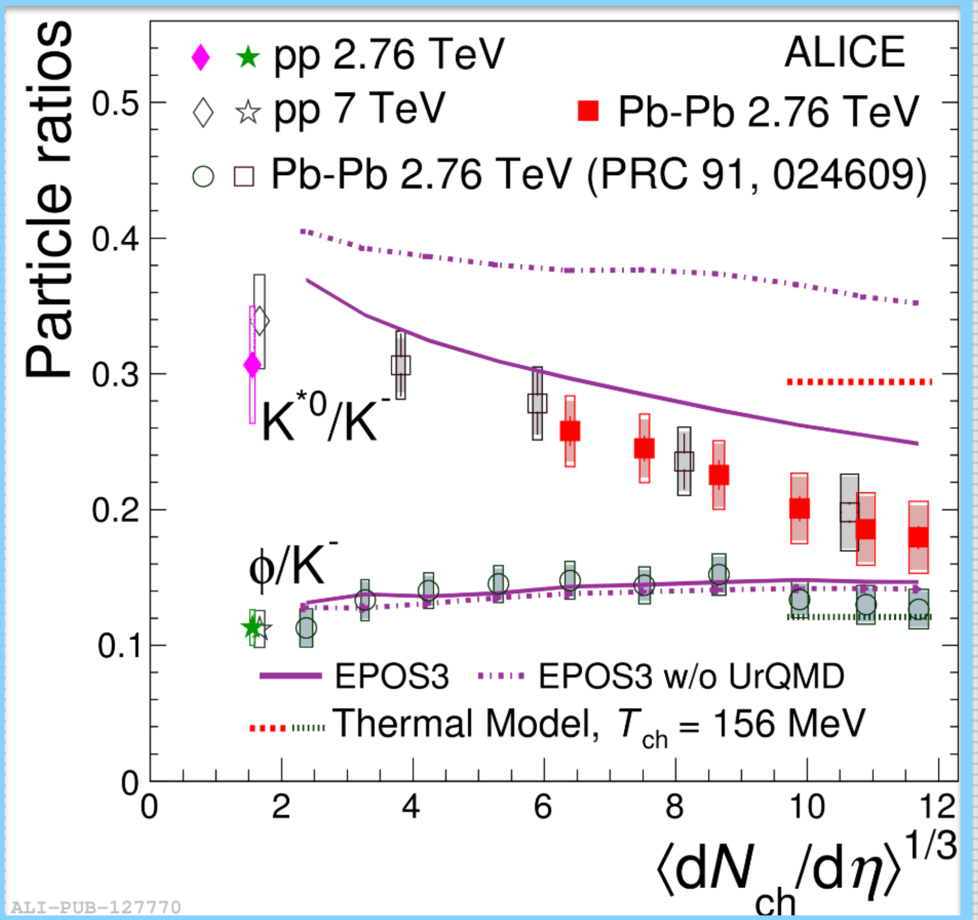

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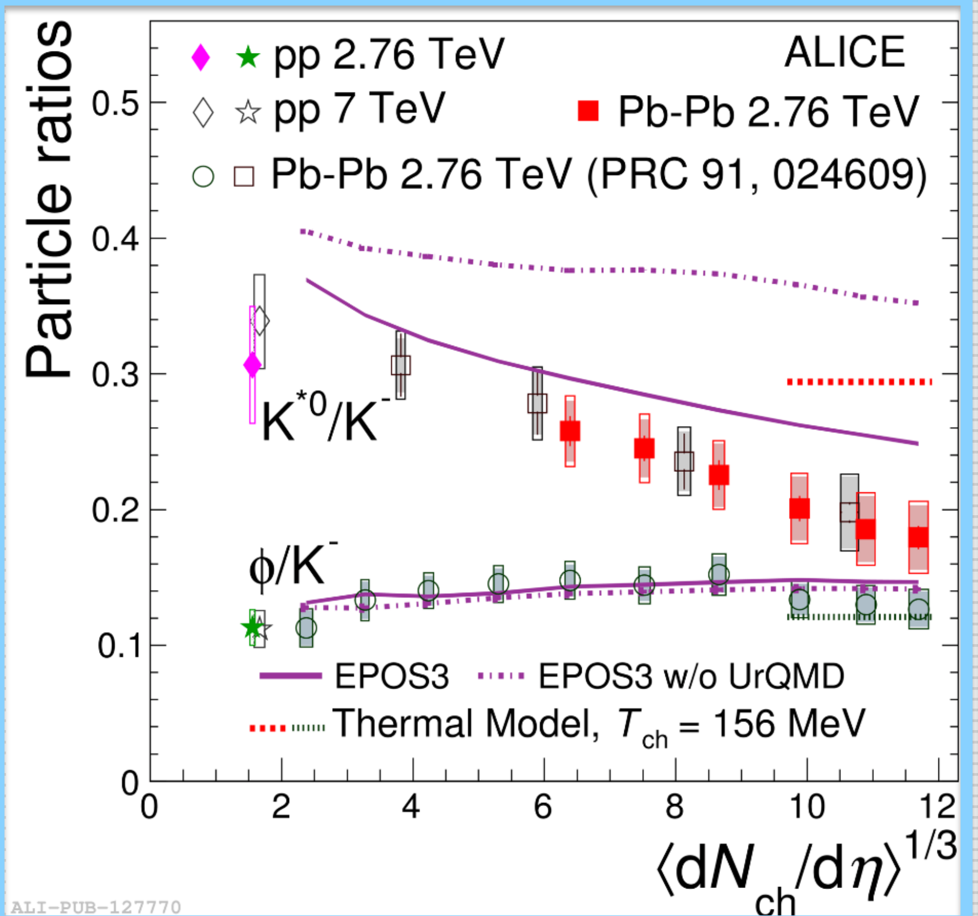

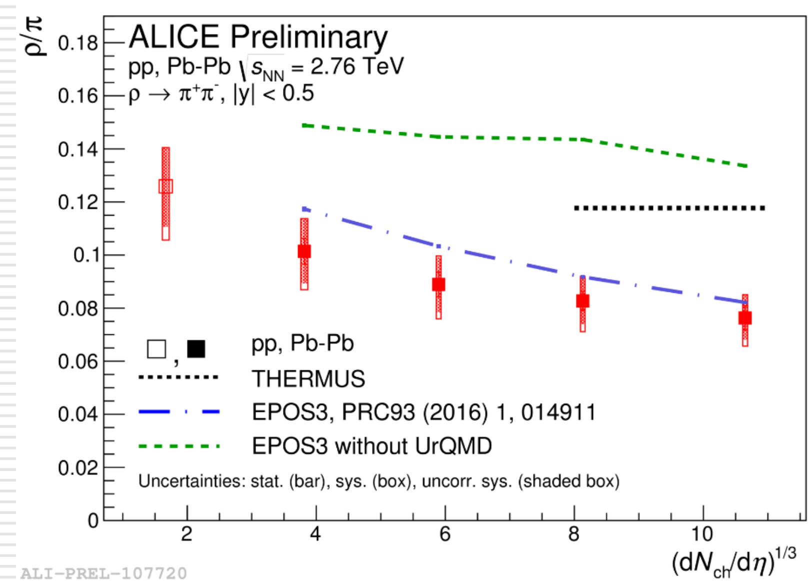

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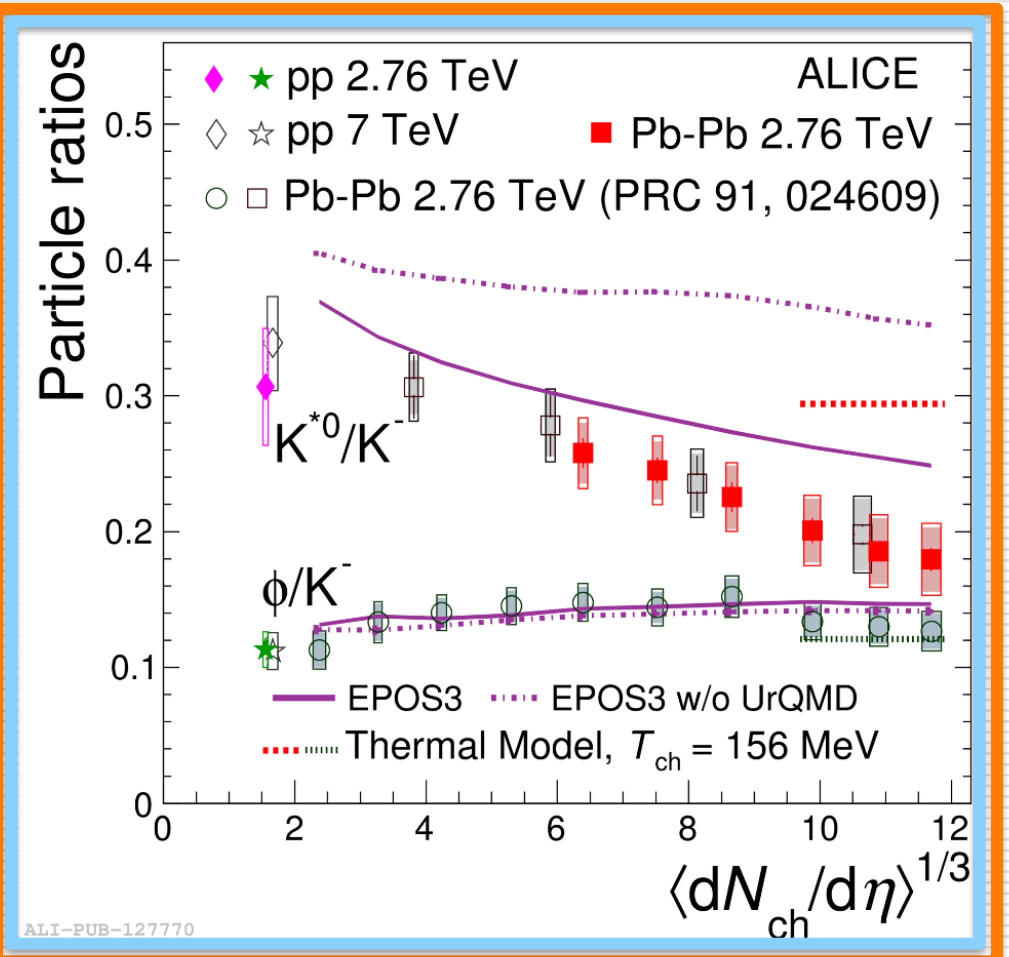

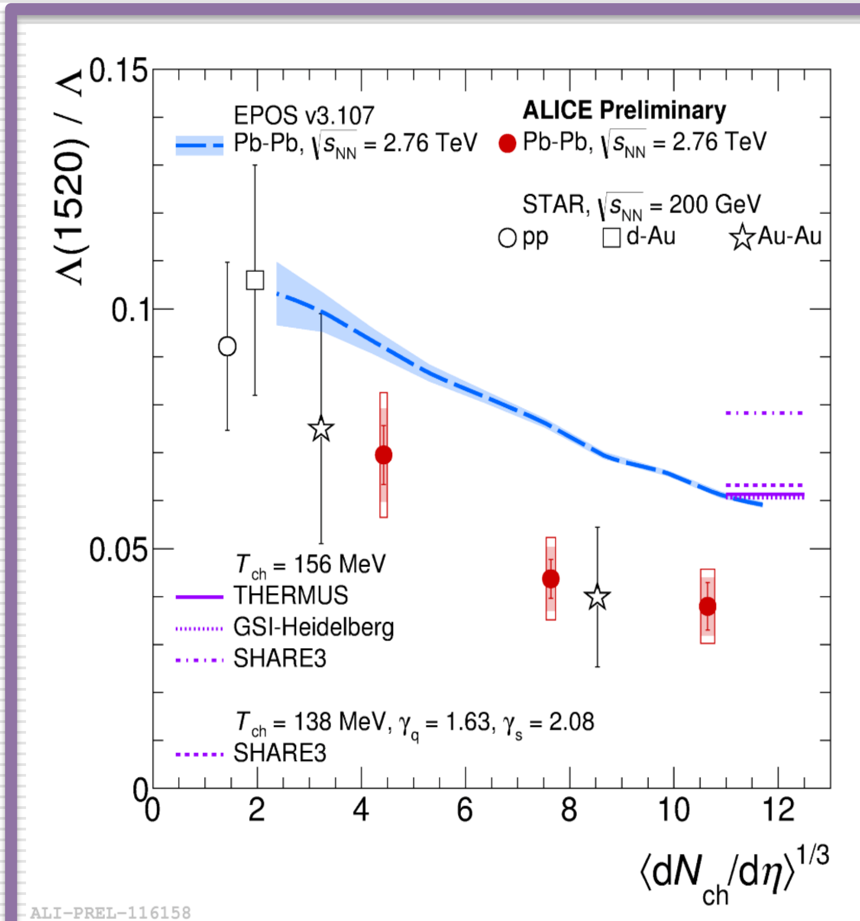

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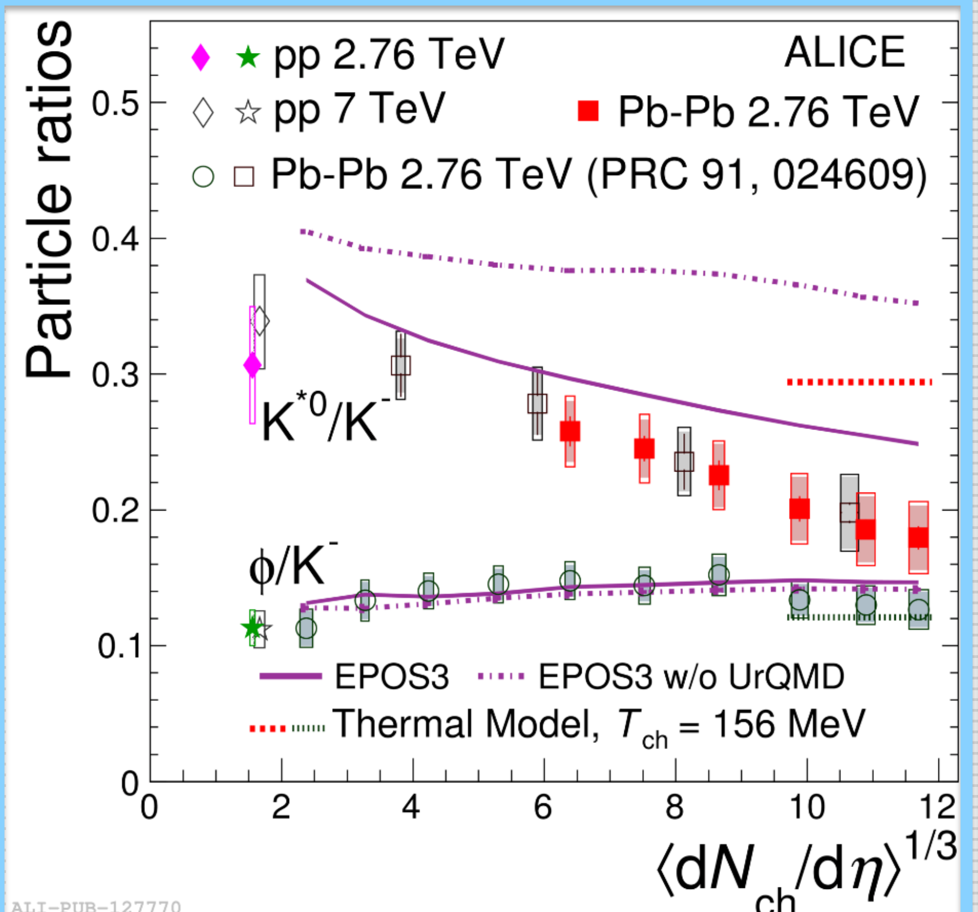
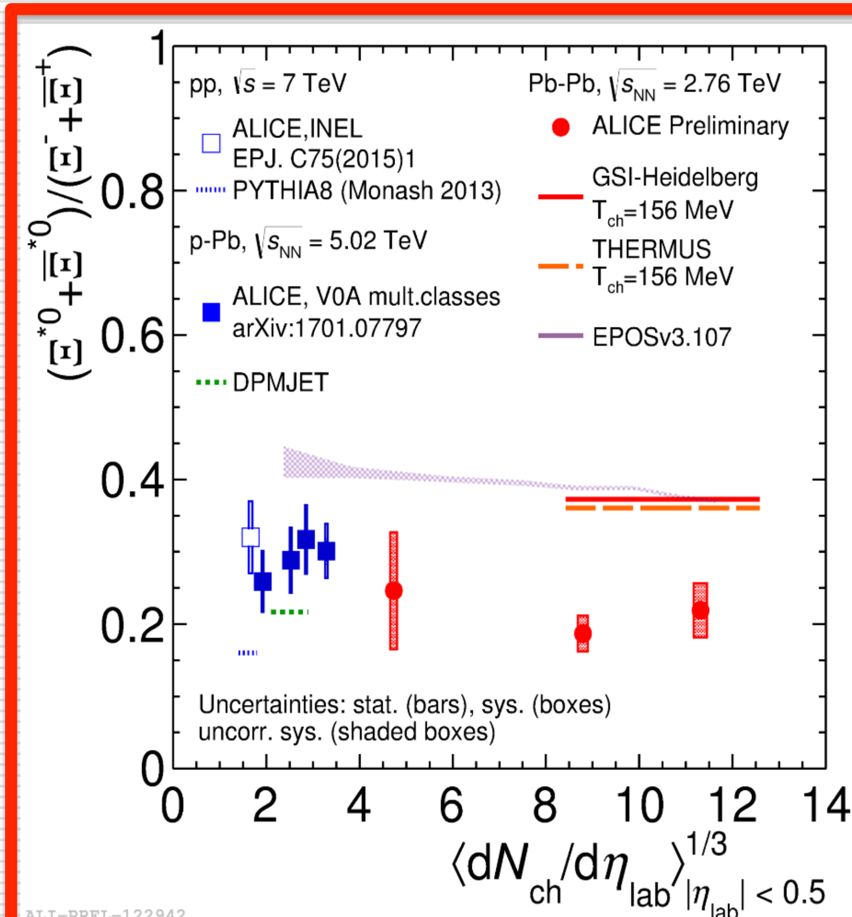
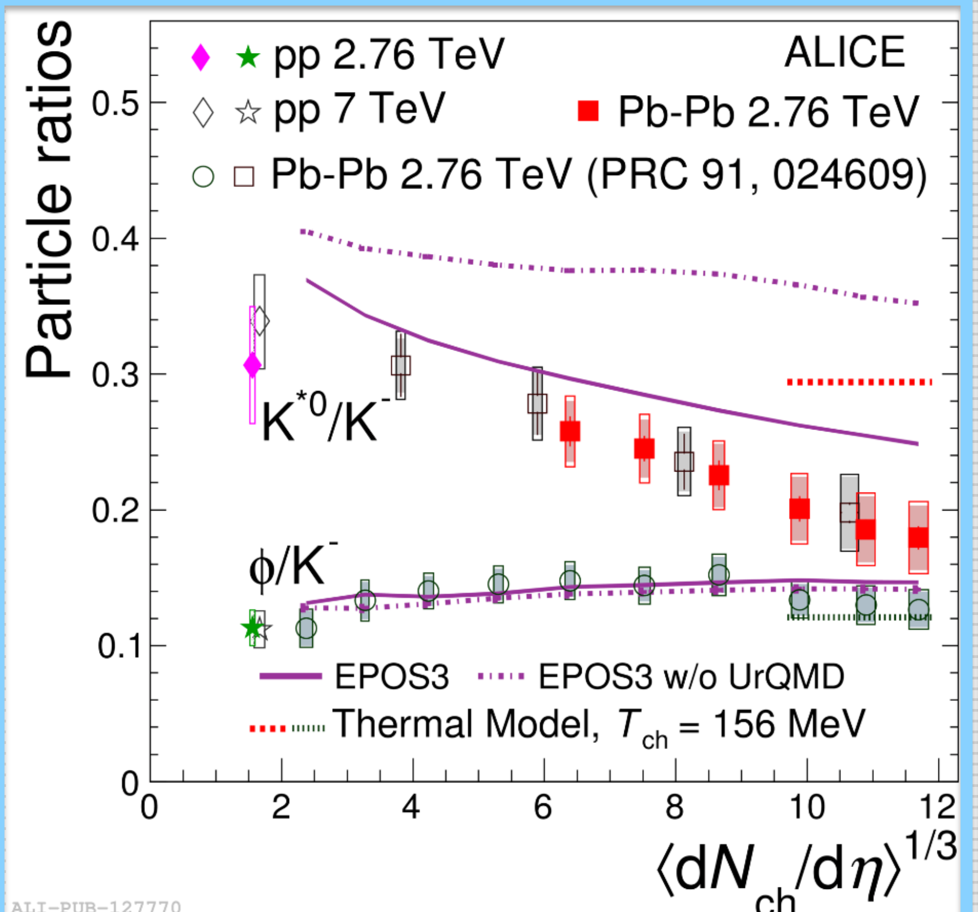
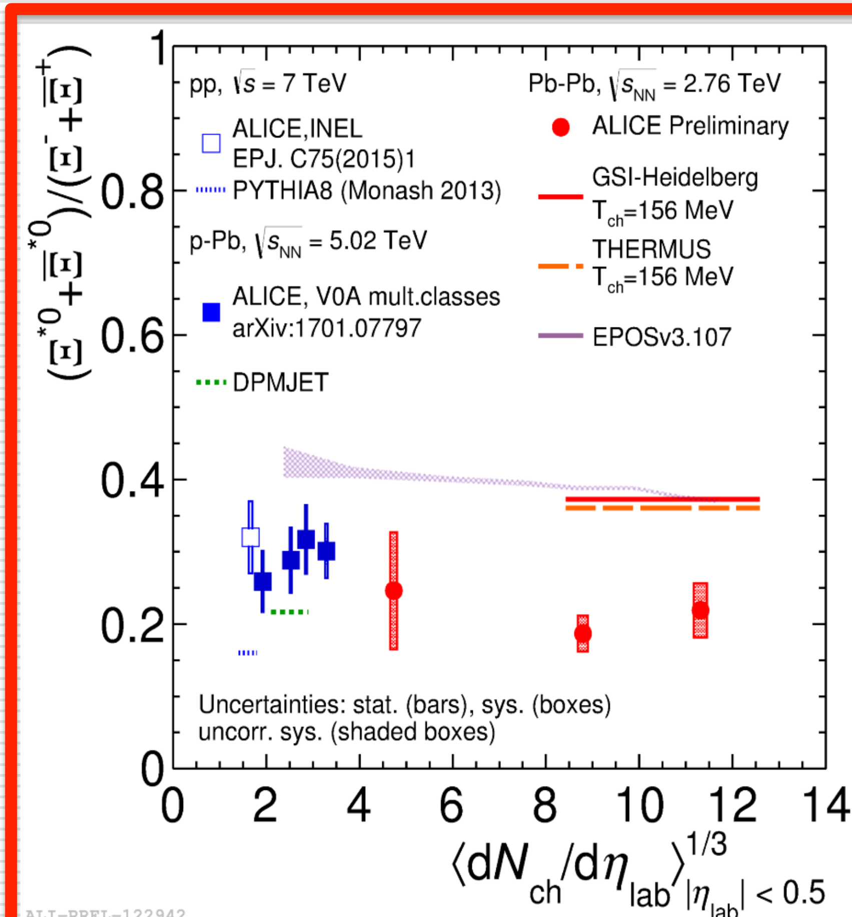




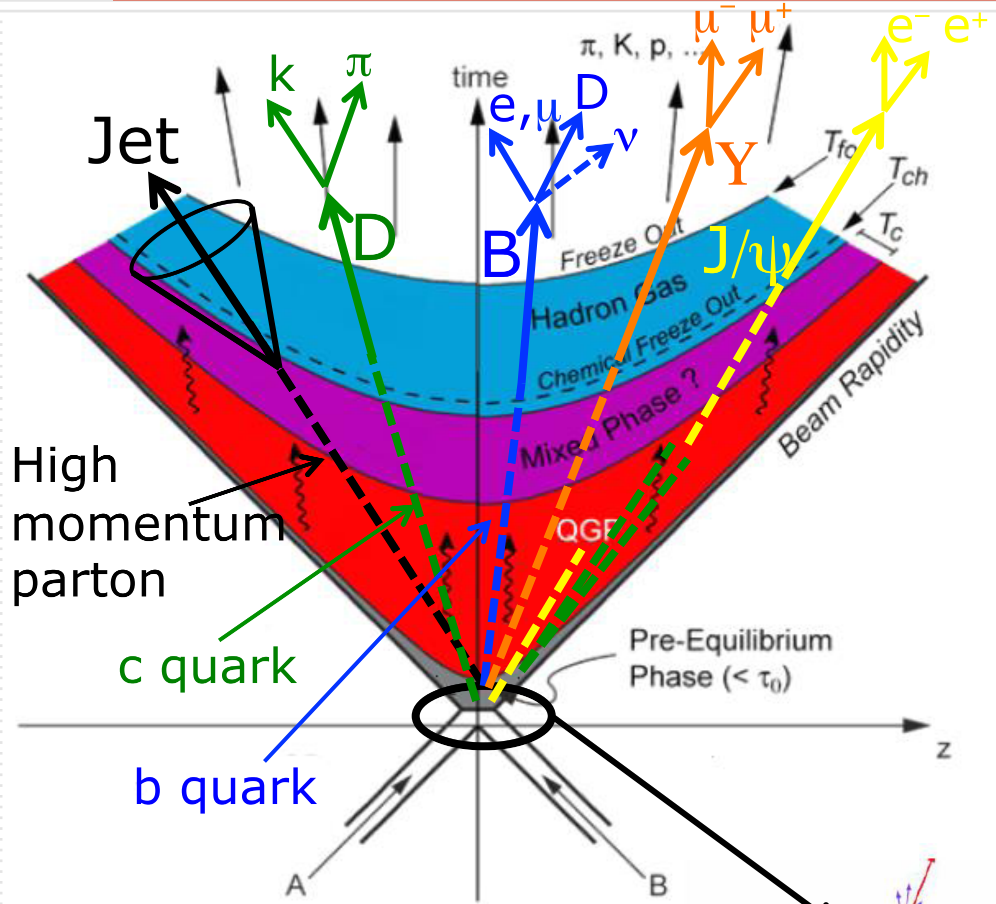
Resonances in Pb-Pb

Short-lived resonances exhibit suppression
→ suggests elastic scattering as dominant mechanism



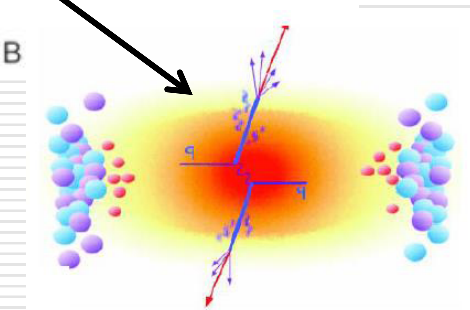


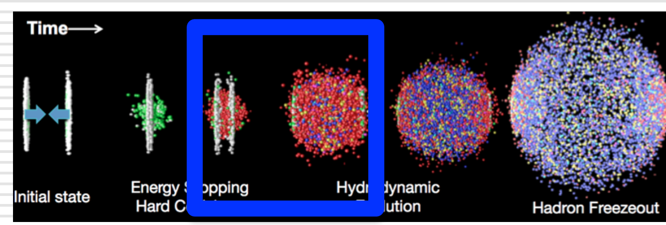
Hard probes of A-A collision



- Hard probes in nucleus-nucleus collisions:
  - produced at the very early stage of the collisions in partonic processes with large Q^2
  - pQCD can be used to calculate initial cross sections
  - traverse the hot and dense medium
  - can be used to probe the properties of the medium

$$\tau_f = \frac{\hbar}{m_T}$$

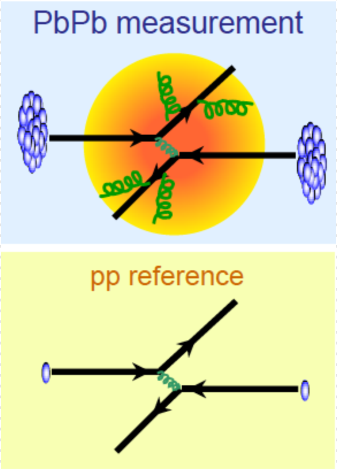




Nuclear modification factor

- Without nuclear effects, the production of hard probes in A-A is expected to scale with the number of nucleon-nucleon collisions N_{coll} (**binary scaling**)
- Observable: **nuclear modification factor**

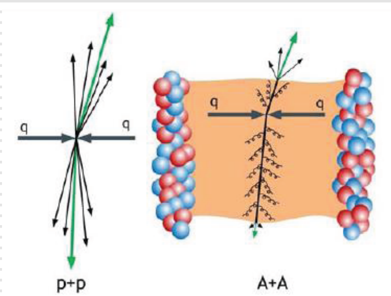
$$R_{AA} = \frac{1}{N_{coll}} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T} = \frac{1}{T_{AA}} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T} \sim \frac{\text{QCD medium}}{\text{QCD vacuum}}$$

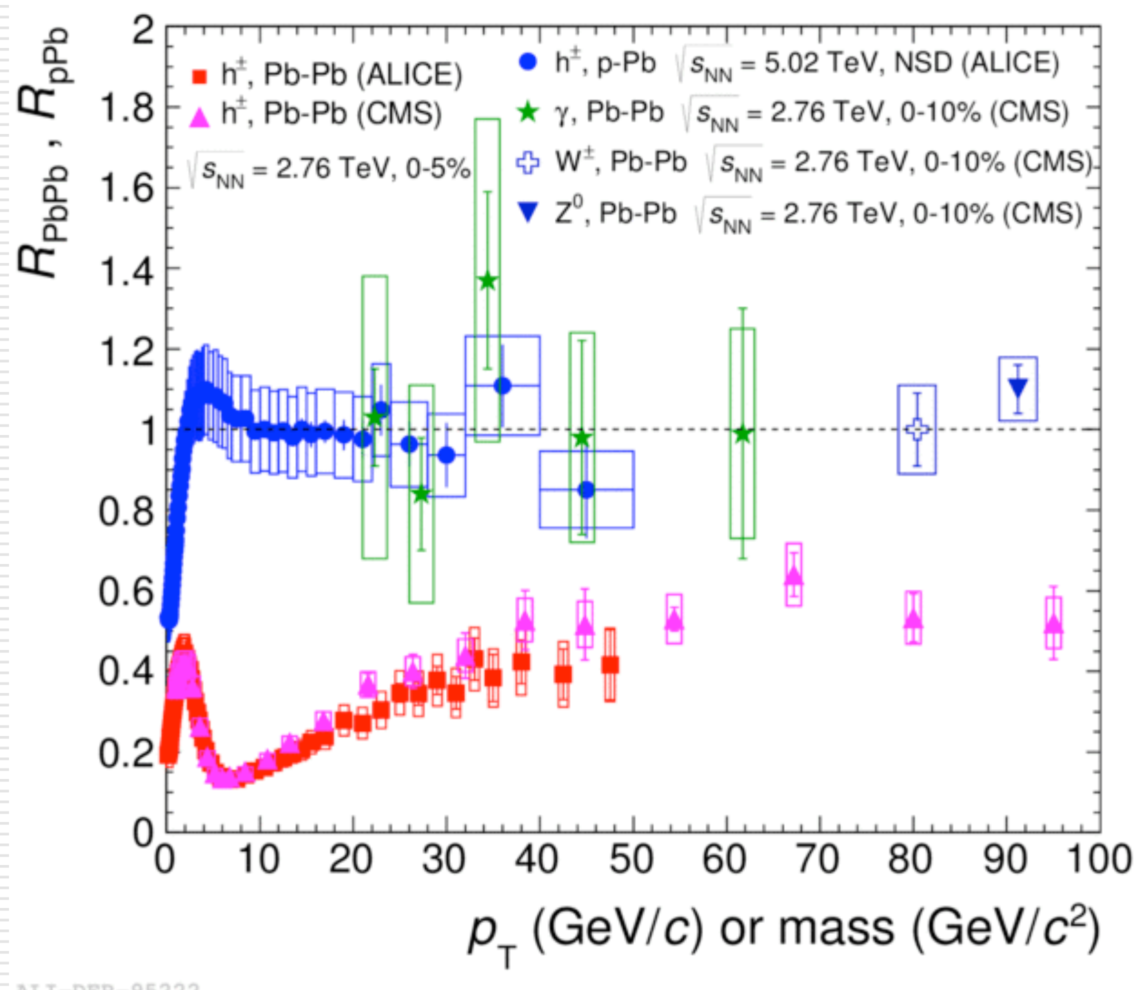


- If no nuclear effects are present → $R_{AA}=1$
- Effects from the hot and deconfined medium created in the collision → breakup of binary scaling → $R_{AA}\neq 1$
  - **Parton energy loss** via gluon radiation and collisions in the medium
- But also initial state effects (e.g. nuclear modification of PDFs) may lead to $R_{AA}\neq 1$
  - Need control experiments: p-A collisions + medium-blind probes (photons, W, Z)

Nuclear modification of unidentified particles

- The easiest way to study “jet quenching”
- physics interpretation:
  - scattered parton (high p_t) looses energy while traversing the medium
    - collisional energy loss
    - radiative energy loss (gluonstrahlung)

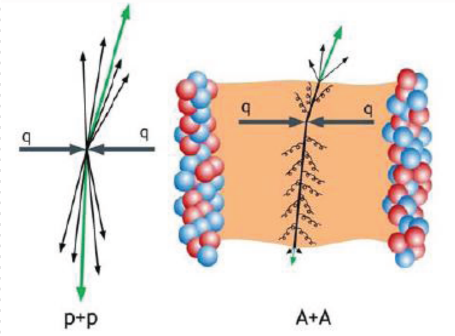




Nuclear modification of identified particles

light flavour vs. charm vs. beauty hadrons (or jets)

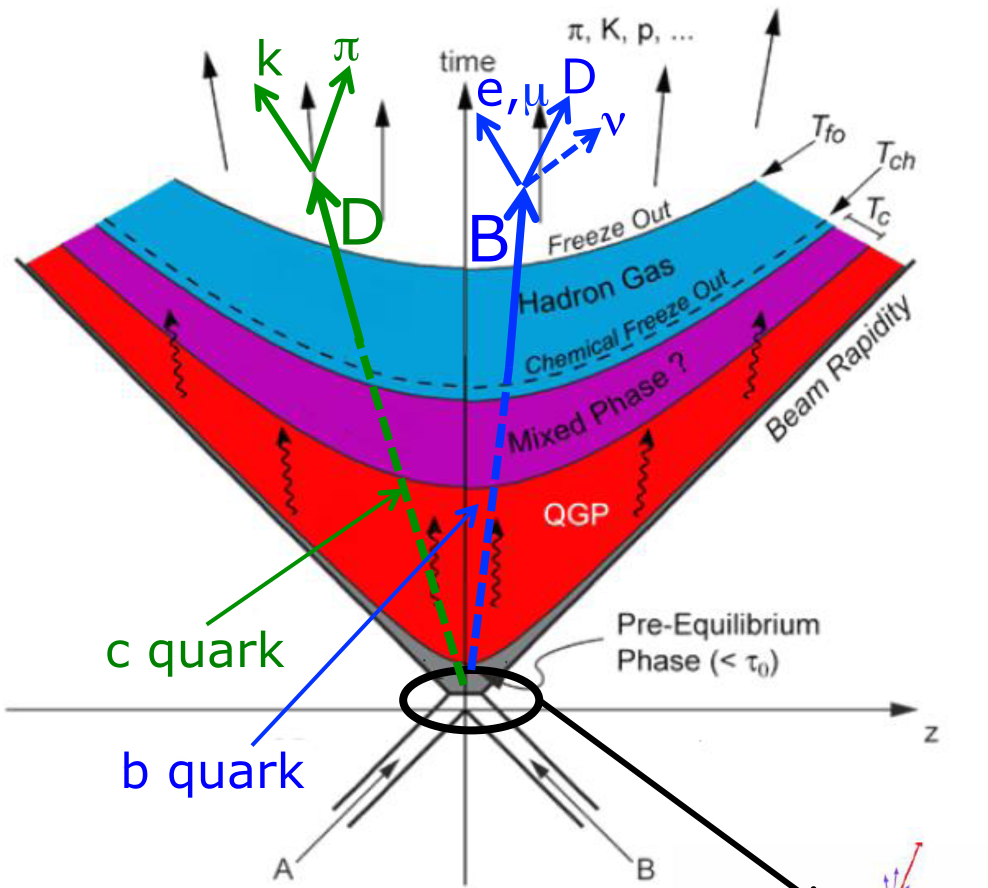
- quenching vs. colour charge of partons
  - heavy flavour hadron comes from quark (C_R = 4/3)
  - light flavour from (p_T-dep) mix of quark and gluon (C_R = 3) jets



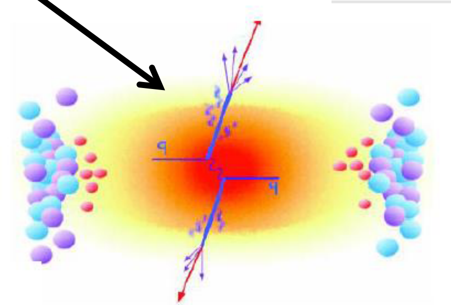
- quenching vs. mass of partons
  - heavy flavour predicted to suffer less energy loss
    - gluonstrahlung (dead cone effect)
    - collisional loss
  - **beauty vs charm**

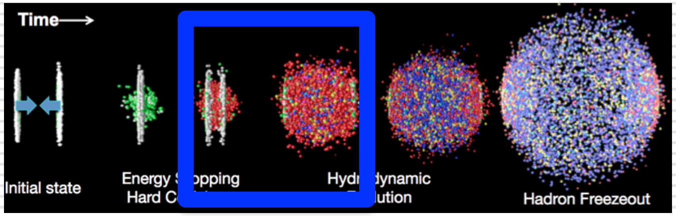
- Expectations: $\Delta E_g > \Delta E_q > \Delta E_c > \Delta E_b$ →
  naively: $R_{AA}^h < R_{AA}^D < R_{AA}^B$
  considering different p_t distributions and fragmentations:
  $$\boldsymbol{R_{AA}^h \approx R_{AA}^D < R_{AA}^B}$$

Open heavy Flavour



$$\tau_f = \frac{\hbar}{m_T}$$

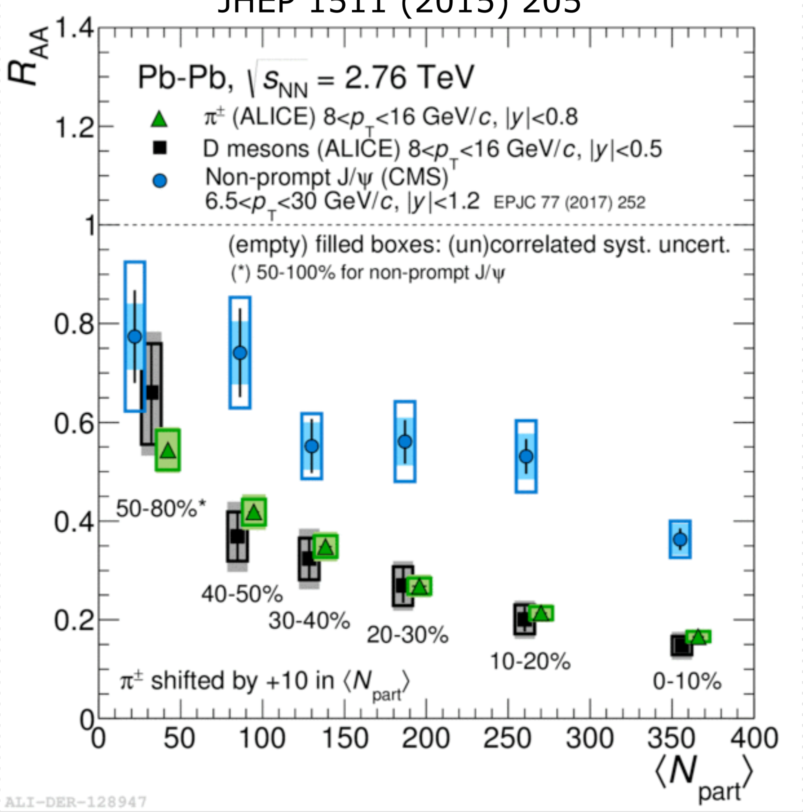




Run-1 main results

- Indication of mass dependent suppression R_{AA}(b) > R_{AA}(c)
  - D-meson R_{AA} significantly smaller than the R_{AA} of non-prompt J/ψ (CMS) in central collisions

JHEP 1511 (2015) 205



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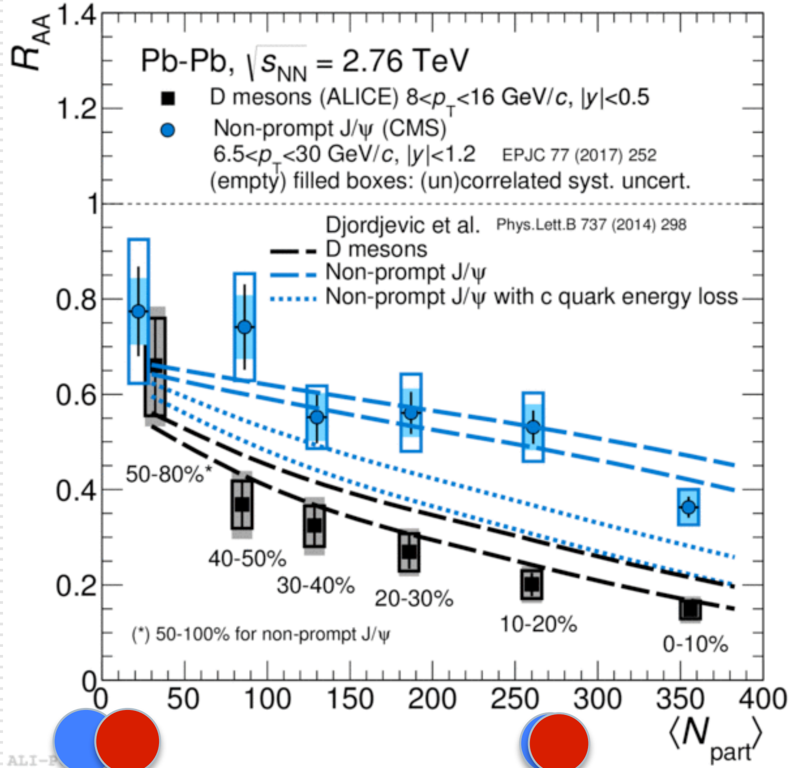
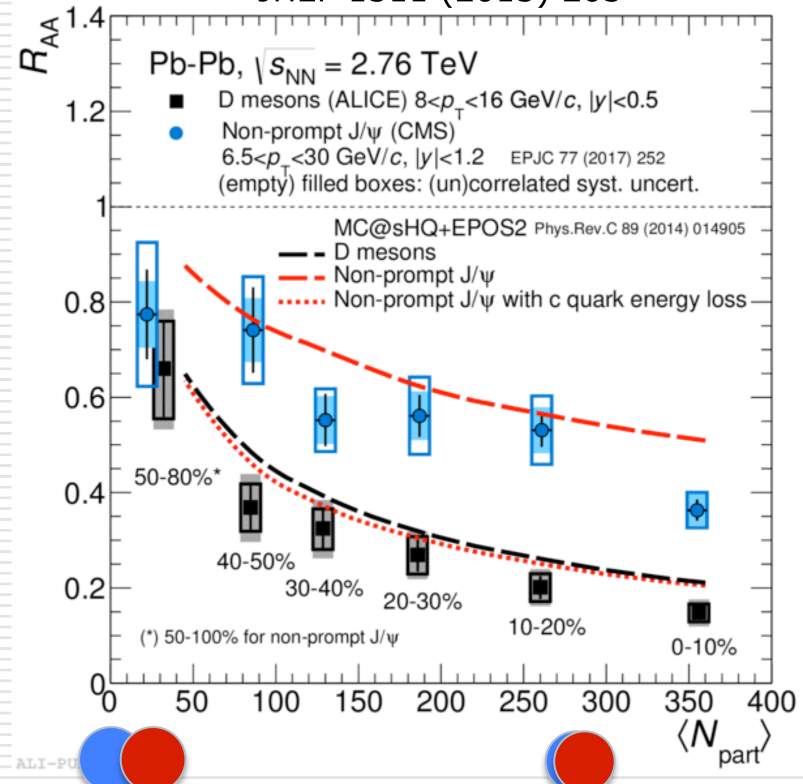
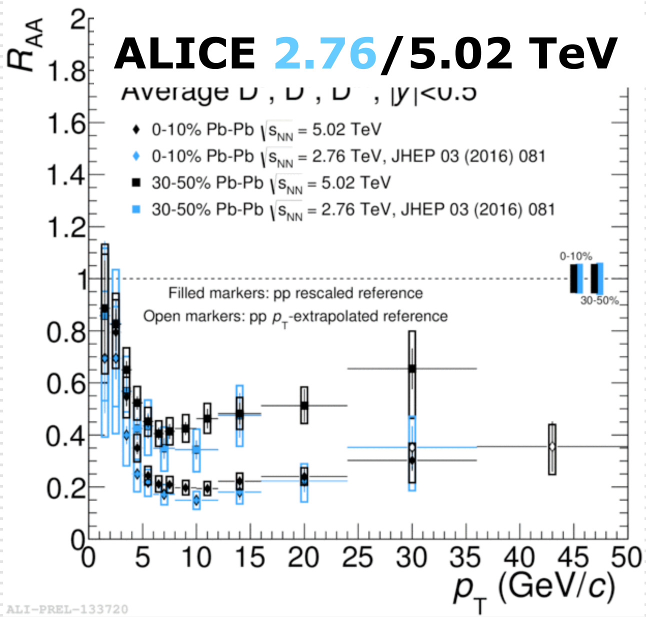
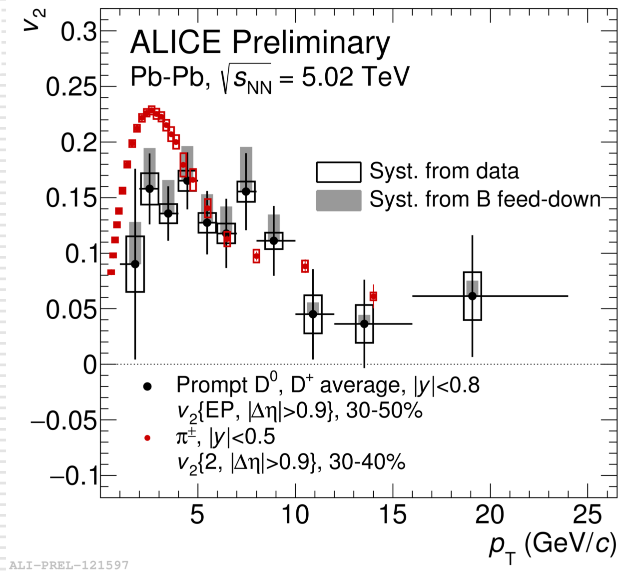


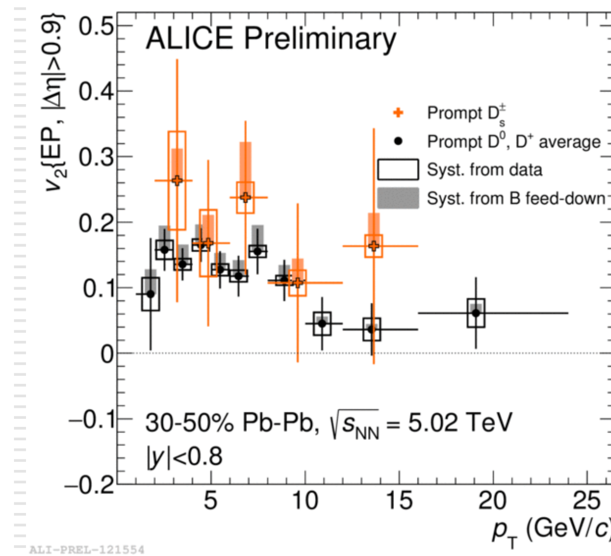


- Examples of 2 models describing the mass dependence of the energy loss in the QGP

Run-2 results

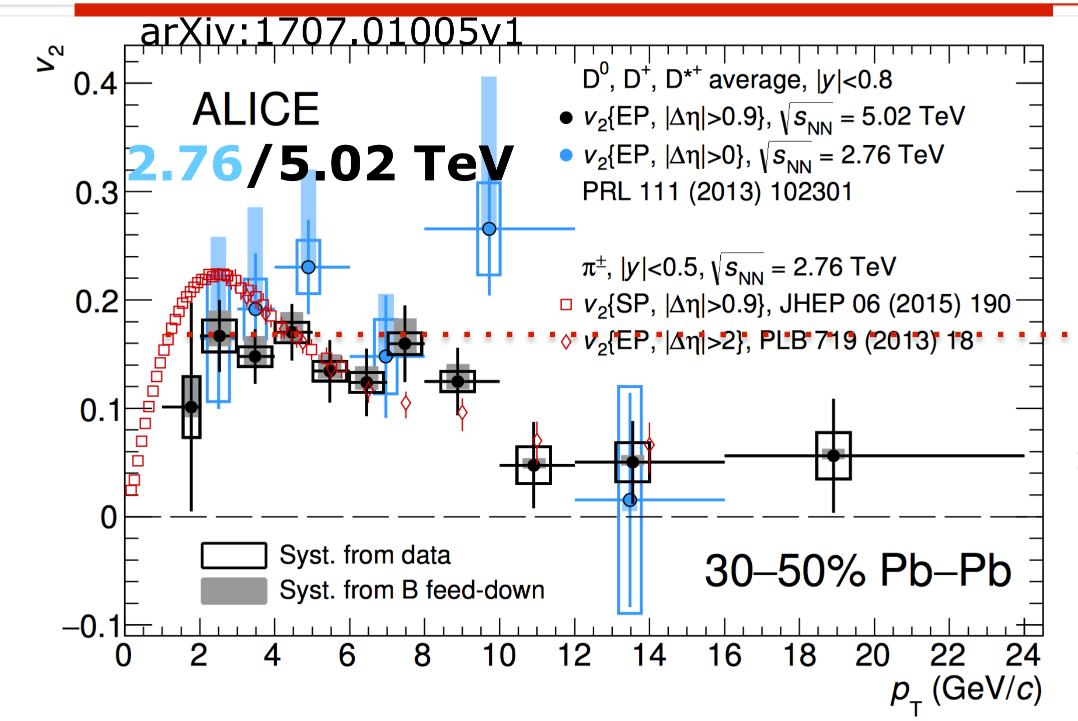


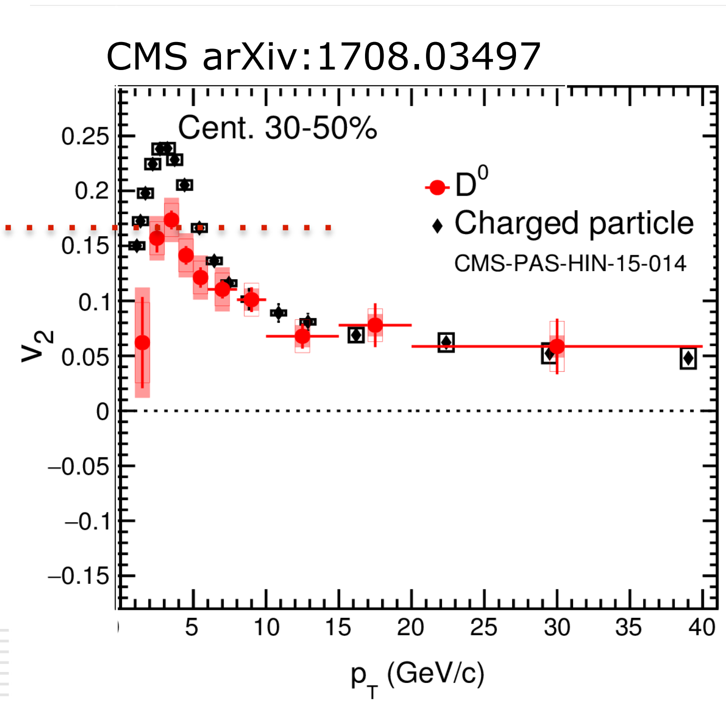




- D meson nuclear modification factor R_{AA} at 5 TeV
  - Uncertainties reduced by a factor ~2 (in 30-50%)
  - Similar R_{AA} as at 2.76 TeV: consistent with higher QGP opacity, given the harder dN/dp_T
- **Charm flows → models describe data with thermalisation time ~3-8 fm/c**
- First ever measurement of D_s flow (large uncertainties)

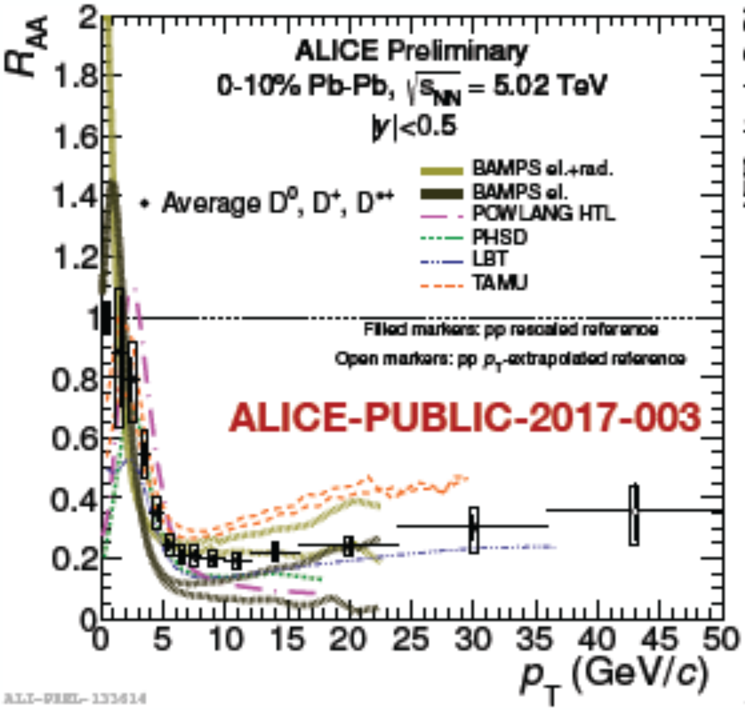
Evidence of charm flowing with the medium at LHC

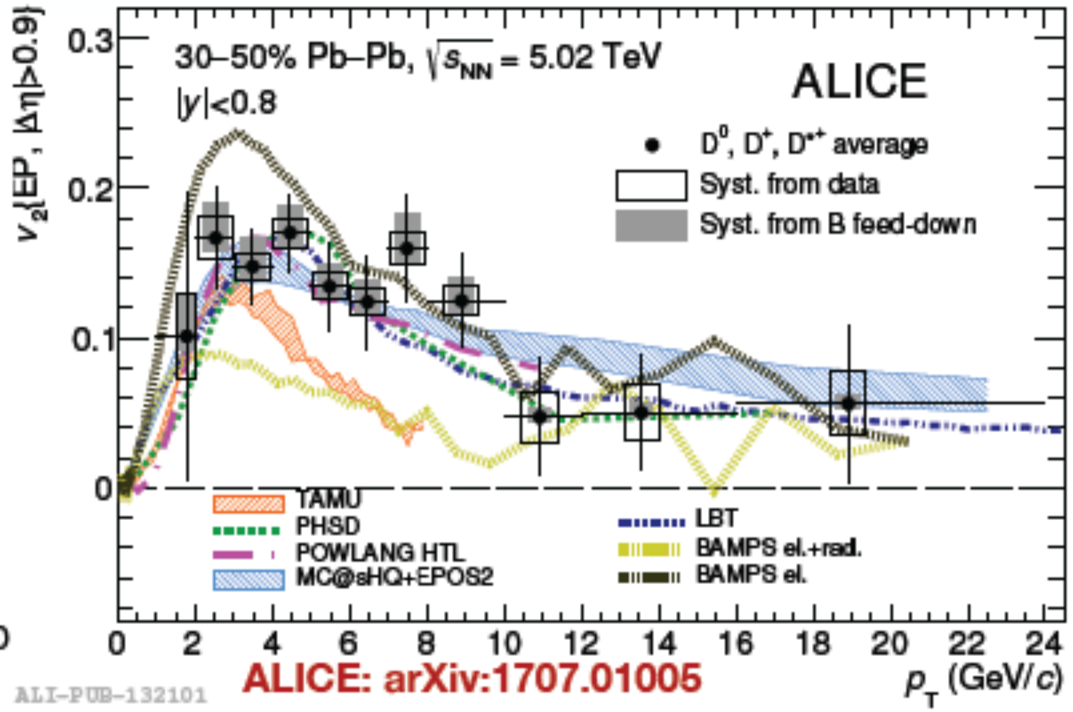




- final results from ALICE
  - much improved with respect to RUN2 data
- in agreement with CMS results (covering higher p_t range)
- D^0 v_2 < charged particle v_2

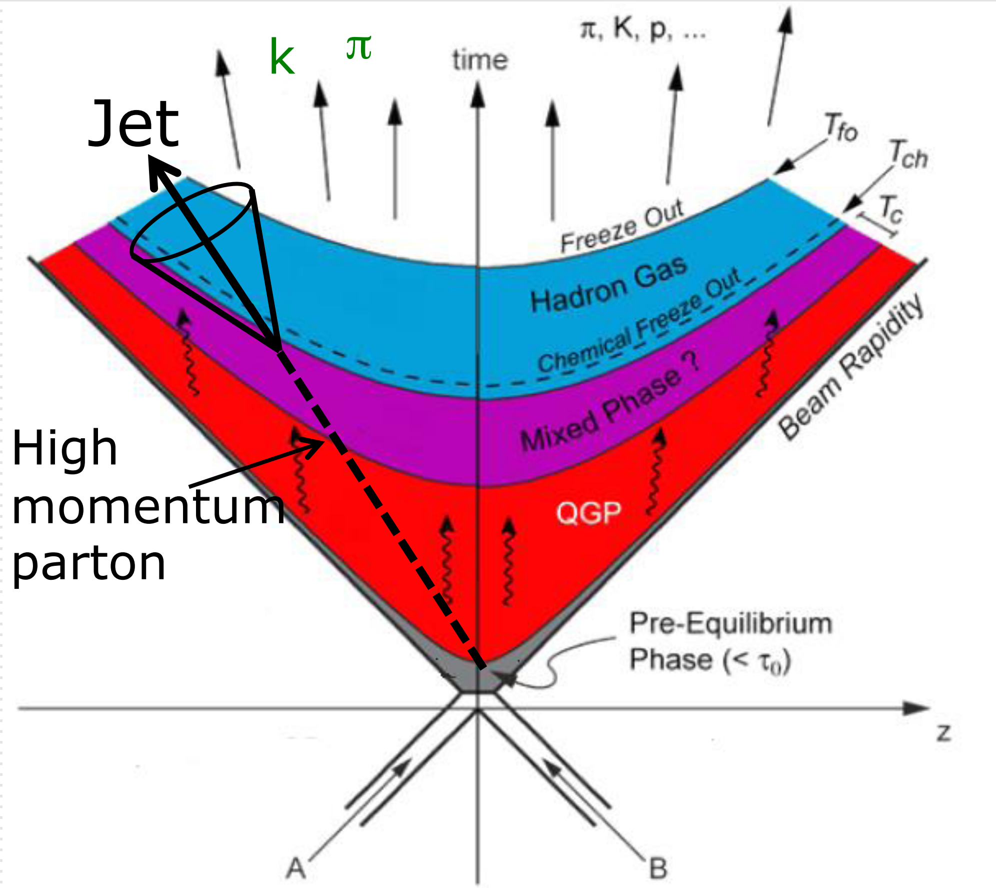
Constraining the models in the charm sector



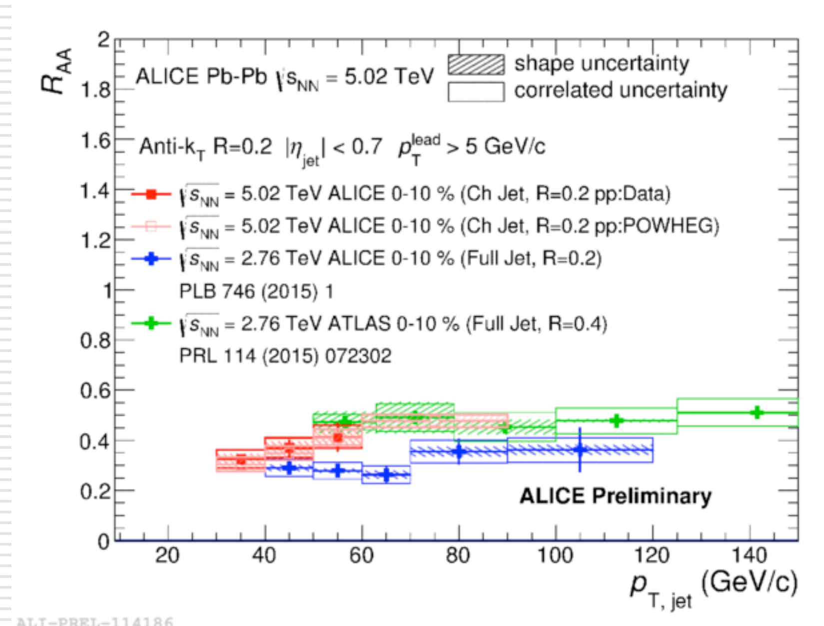


- stringent constraint to models aiming at describing both R_{AA} and v_2
  - both radiative energy loss (e.g., needed to describe the high p_T region) and collisional one necessary to match the results

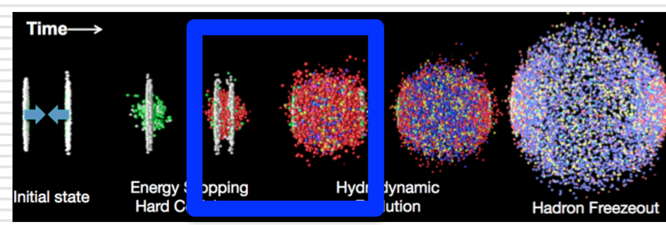
JETS



Jet
k
π
time
π, K, p, ...
T_{fo}
T_{ch}
T_c
Freeze Out
Hadron Gas
Chemical Freeze Out
Mixed Phase ?
Beam Rapidity
QGP
High
momentum
parton
Pre-Equilibrium
Phase (< τ_0)
z
A
B



R_{AA}
ALICE Pb-Pb $\sqrt{s_{NN}}$ = 5.02 TeV
shape uncertainty
correlated uncertainty
Anti-k_T R=0.2 $|\eta_{jet}|$ < 0.7 p_T^{lead} > 5 GeV/c
$\sqrt{s_{NN}}$ = 5.02 TeV ALICE 0-10 % (Ch Jet, R=0.2 pp:Data)
$\sqrt{s_{NN}}$ = 5.02 TeV ALICE 0-10 % (Ch Jet, R=0.2 pp:POWHEG)
$\sqrt{s_{NN}}$ = 2.76 TeV ALICE 0-10 % (Full Jet, R=0.2)
PLB 746 (2015) 1
$\sqrt{s_{NN}}$ = 2.76 TeV ATLAS 0-10 % (Full Jet, R=0.4)
PRL 114 (2015) 072302
ALICE Preliminary
$p_{T, jet}$ (GeV/c)
ALI-PREL-114186



Time
Initial state
Hadron Freezeout

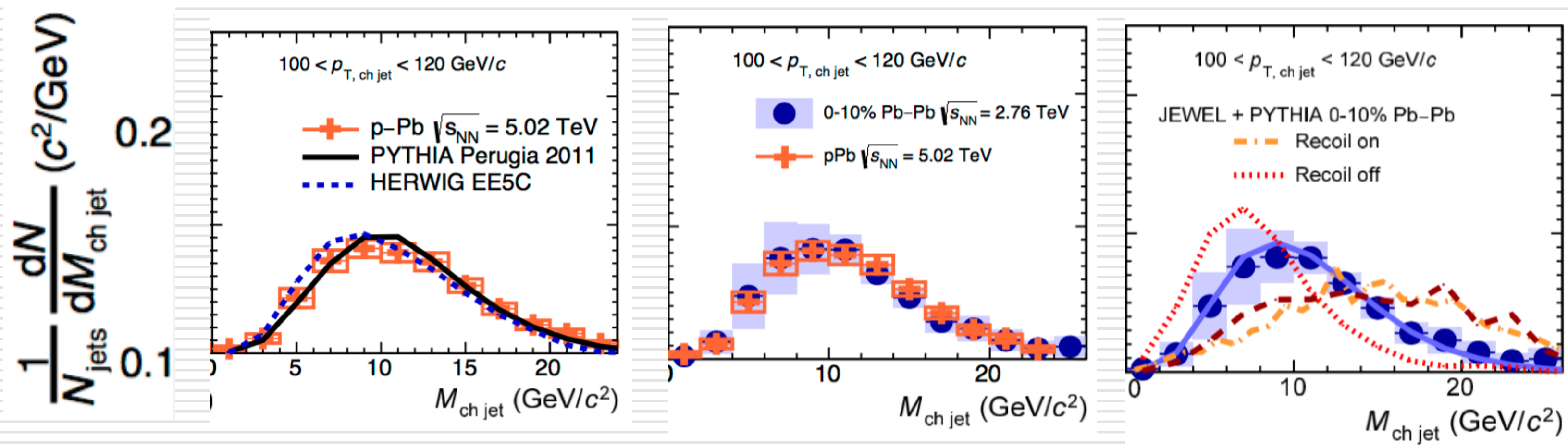
Jet-structure modifications

- First measurement of jet mass in Pb-Pb (and in p-Pb):

$$M = \sqrt{p^2 - p_T^2 - p_z^2}.$$

$$p_z = \sum_{i=1}^{n} p_{T_i} \sinh \eta_i, \quad p = \sum_{i=1}^{n} p_{T_i} \cosh \eta_i$$

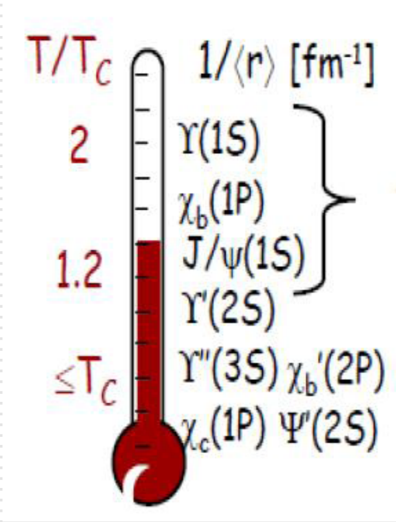
- Large M: soft constituents far from jet axis
- Small M: few hard constituents close to axis
- $\langle M_{\text{quark jet}} \rangle < \langle M_{\text{gluon jet}} \rangle$

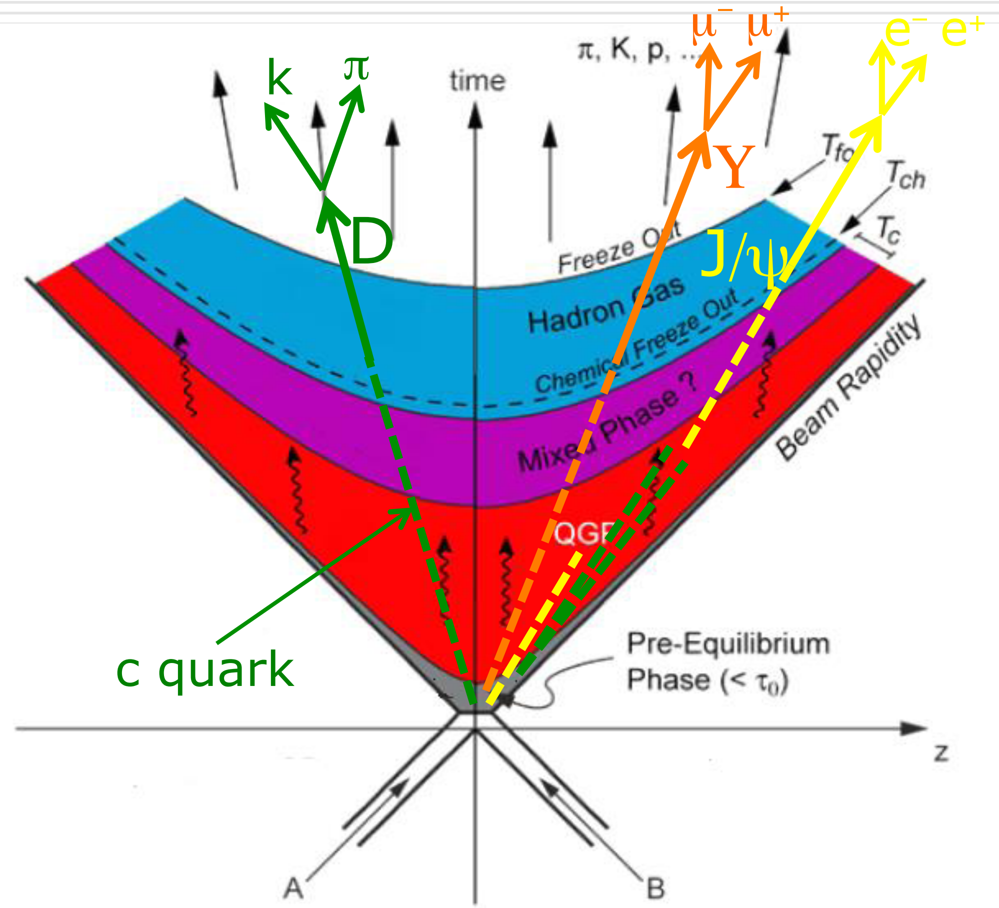


- p-Pb baseline described by PYTHIA and HERWIG
- **No significant modification of jet structure in central Pb-Pb wrt p-Pb**
- Pb-Pb better described by PYTHIA than by generators with gluon radiation in a QGP

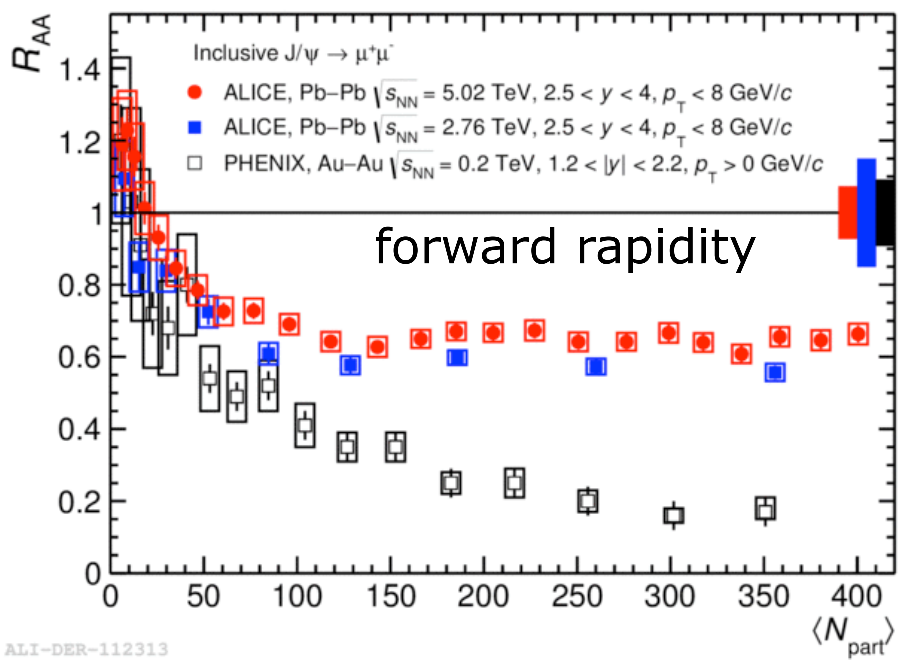
Heavy Flavour: quarkonia

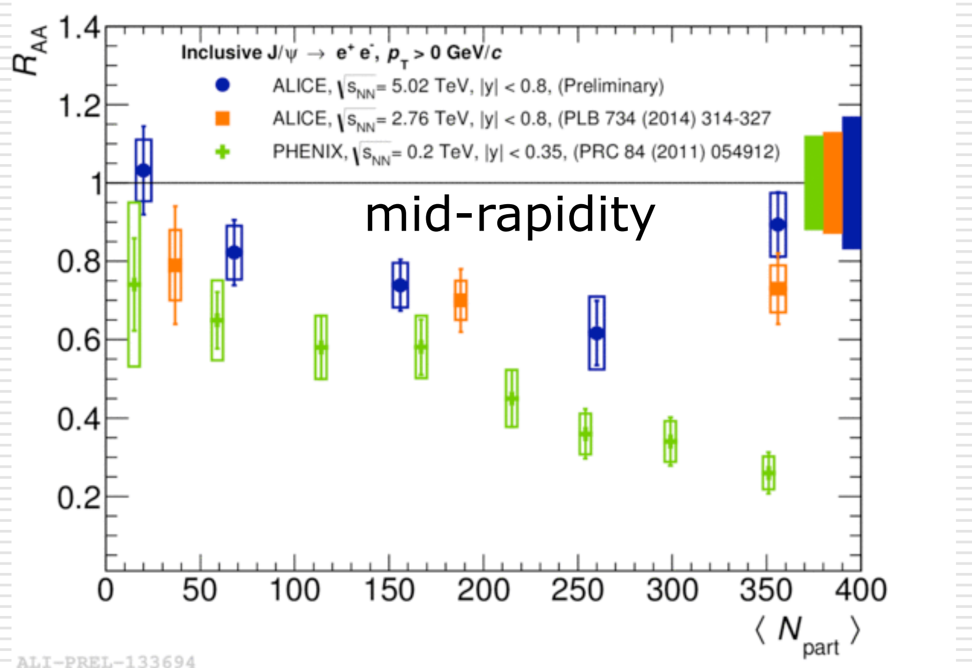
colour screening in QGP and $c\bar{c}$ recombination (charmonium)





J/ψ production at $\sqrt{s_{NN}}$ = 5 TeV





- At **2.76 TeV** a significant suppression wrt pp was measured: expected as an effect of **colour screening** (melting of the charmonium state)
- The suppression is smaller than at **0.2 TeV**, in central collisions and low p_T: described by models with **re-generation from c quarks in the QGP**
- **New results at 5 TeV**: similar R_{AA} as at **2.76 TeV**

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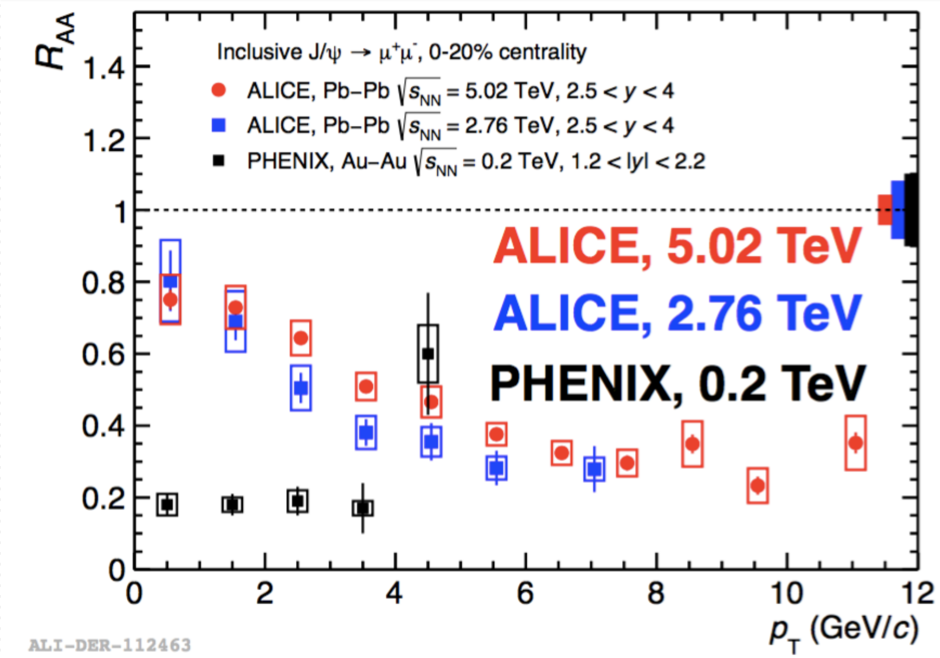

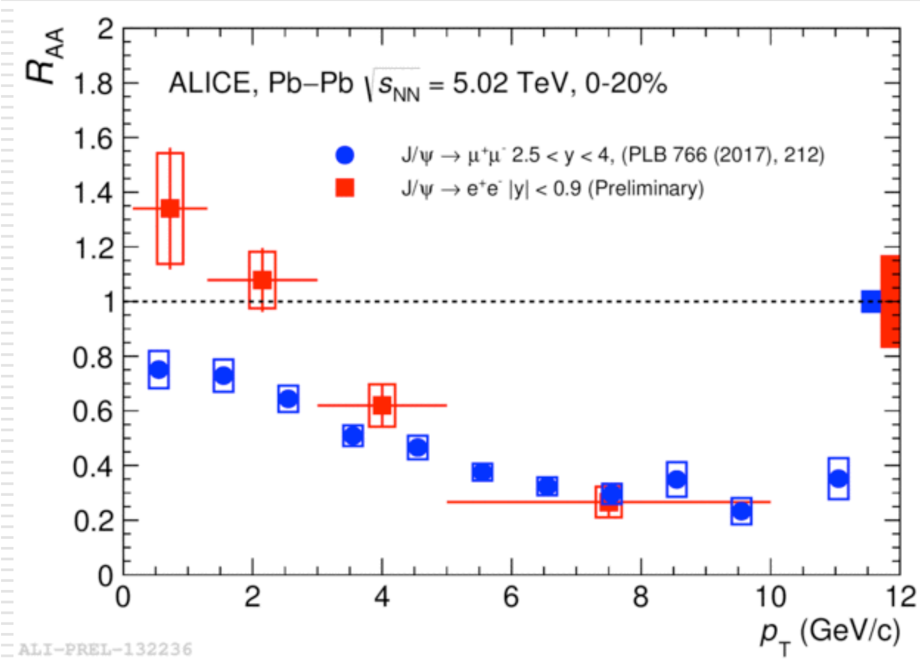

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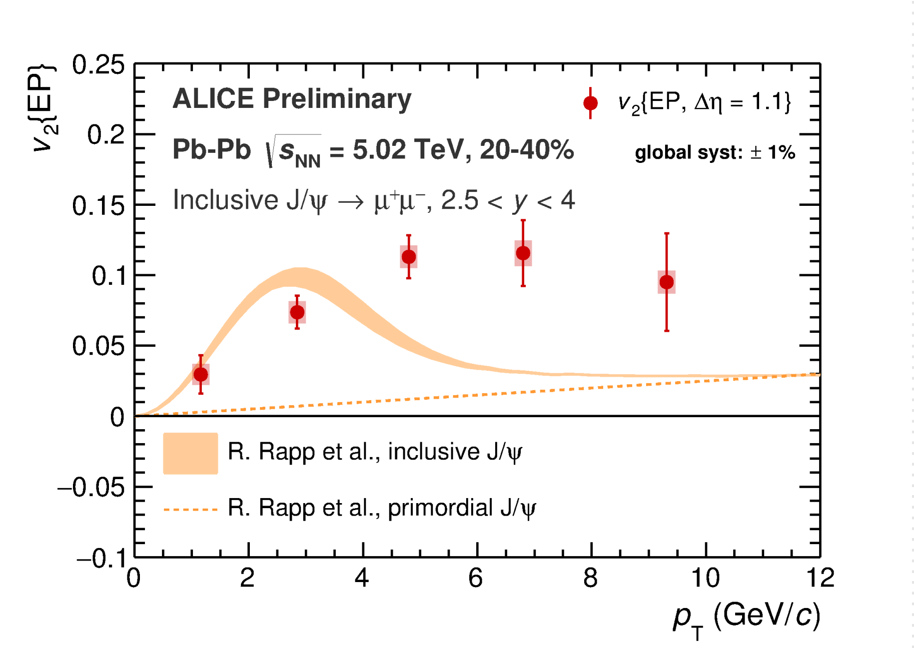
- **New results at 5 TeV**: similar R_{AA} as at **2.76 TeV**
  - hint of lower reduction at p_T 2-6 GeV/*c* at forward rapidity
  - at low p_T lower reduction at mid- than forward rapidity
    → consistent **with regeneration scenario**

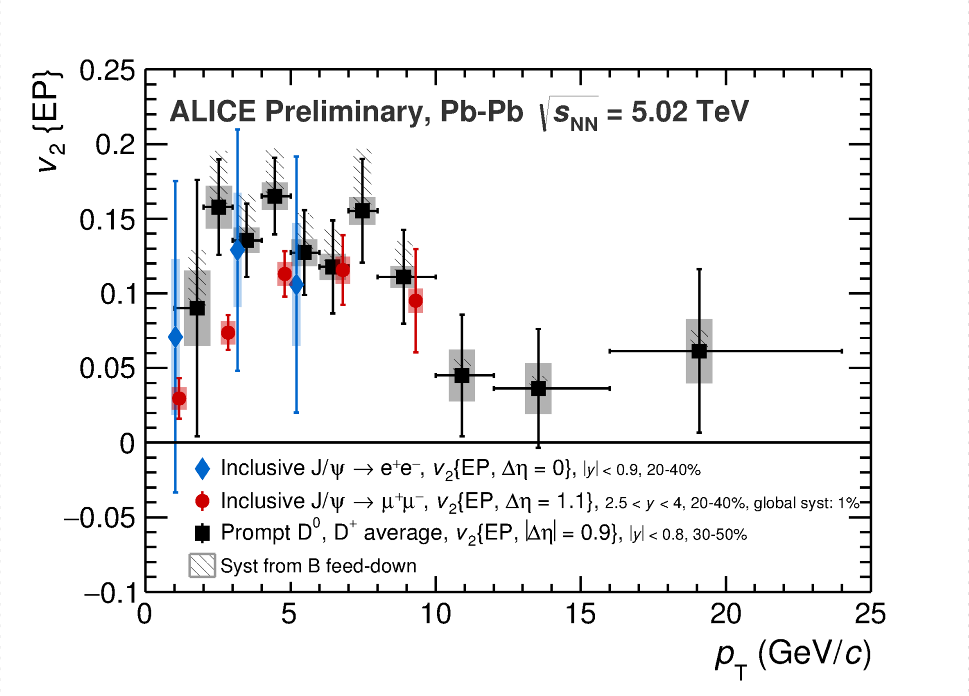
J/ψ elliptic flow at 5 TeV

- Unambiguous observation of non-zero J/ψ v_2 in semi-central (20-40%) Pb-Pb collisions at 5 TeV for J/ψ with $0 < p_T < 12$ GeV/c
- J/ψ $v_2(p_T)$ increases with p_T up to about 0.11 at $4 < p_T < 6$ GeV/c



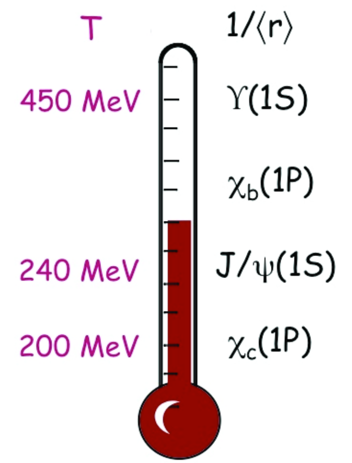
- In the framework of transport models, the large v_2 values measured can only be achieved by including a strong J/ψ regeneration component from recombination of thermalized charm quarks in the QGP
  - Dominant at low p_T (< 4 GeV/c), dying out at high p_T
- The large values of the J/ψ v_2 at high p_T are a challenge to models …

Hidden versus Open charm v2

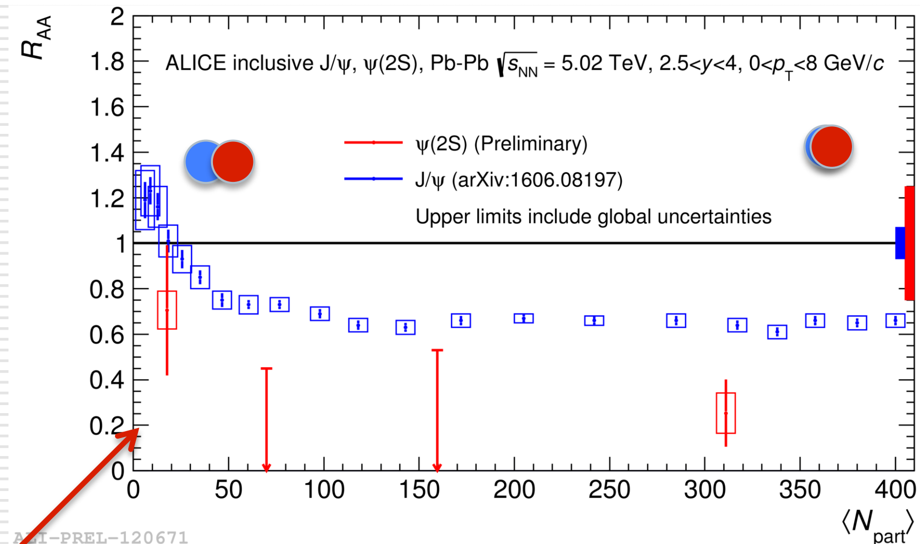


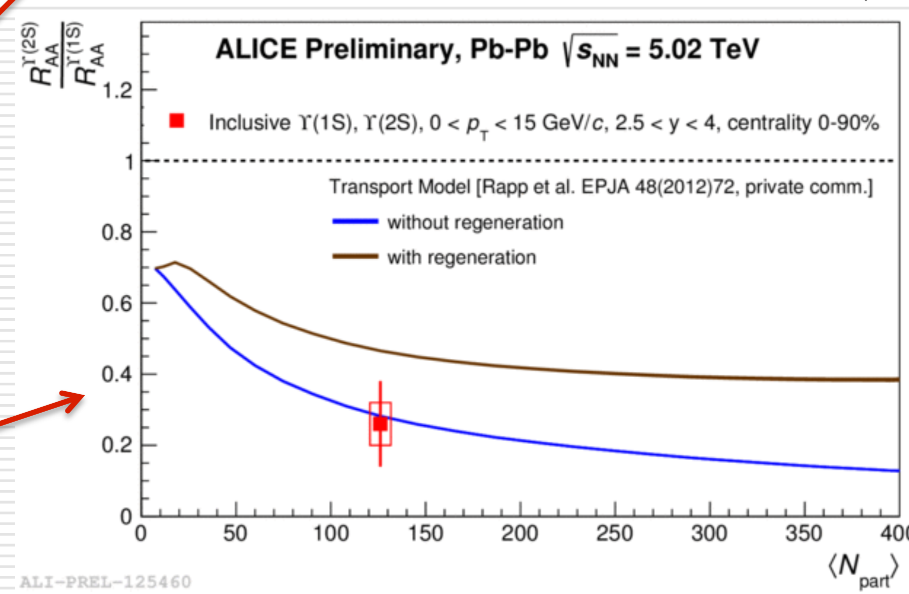
- Similar magnitude
- Consistently suggesting that charm quark flows!

Quarkonium production



Binding energy (GeV)	
Υ(1S)	1.1
J/ψ	0.65
Υ(2S)	0.55
ψ(2S)	0.05

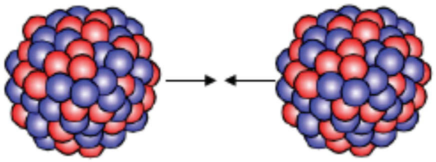




- Indication that ψ(2S) is more suppressed than J/ψ
  - role of regeneration to be understood
- Υ(2S) is 4 times more suppressed than Υ(1S)

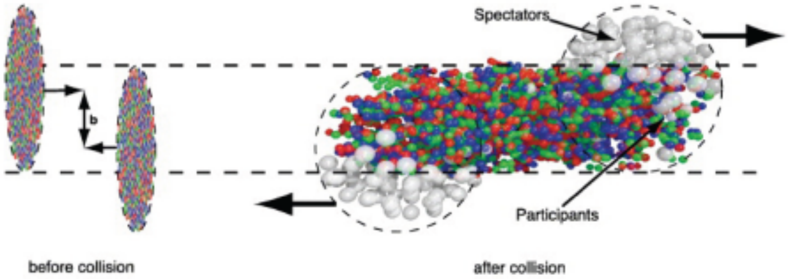
Small systems: pp and pPb

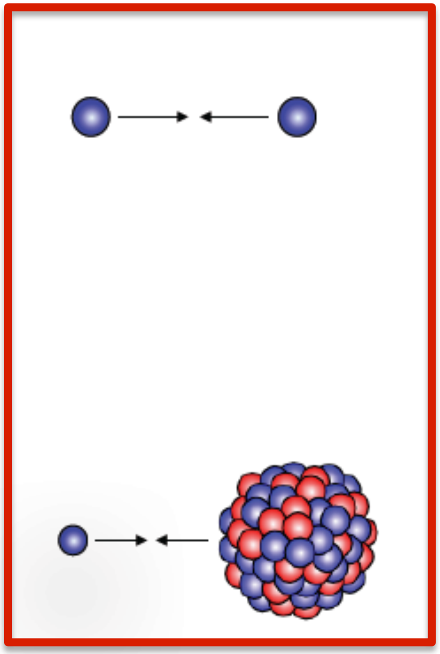
The paradigm



Pb-Pb Collisions ($\sqrt{s_{NN}}$ = 2.76, 5 TeV)

- Core business: create and characterize the QGP
- Centrality





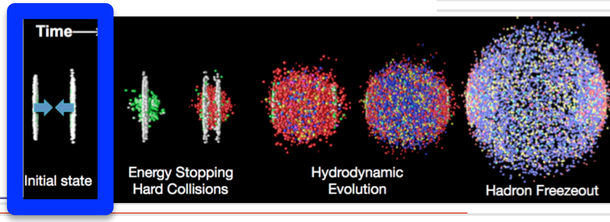
pp Collisions ($\sqrt{s}$ = 0.9 –13 TeV)

- Reference data

to be revised later on !

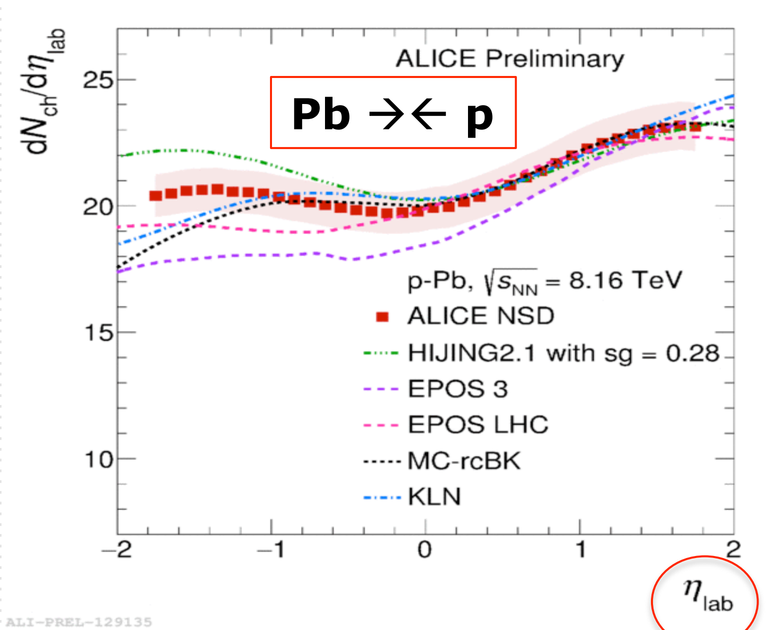
p-Pb Collisions ($\sqrt{s_{NN}}$ = 5, 8 TeV)

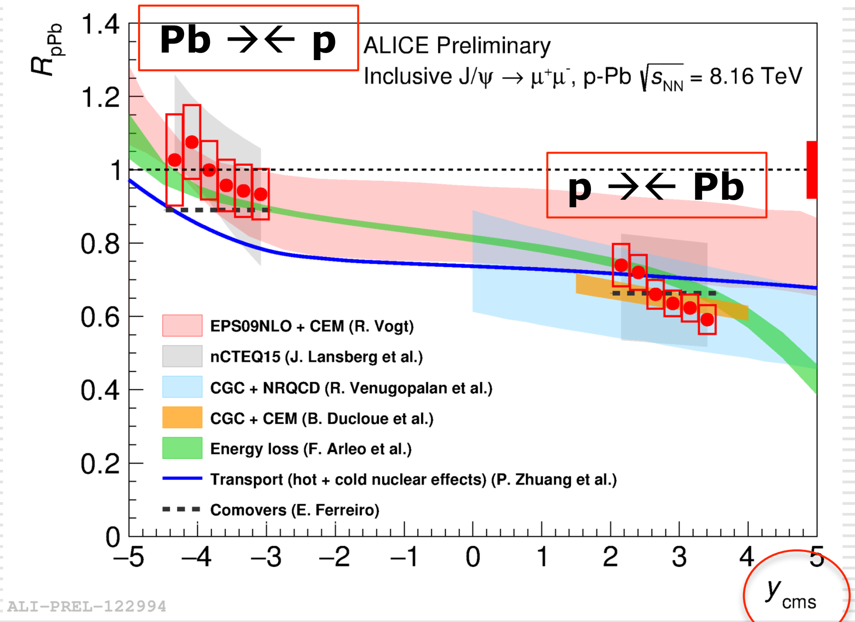
- Control experiment
- "Cold nuclear matter" effects (e.g. modifications to PDF)



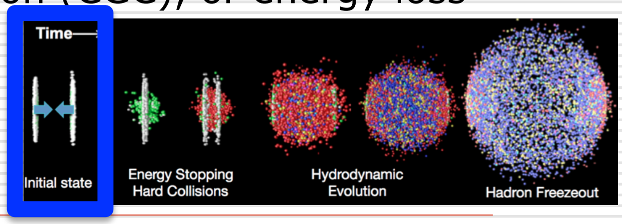
Two recent examples within the paradigm: p-Pb at 8 TeV

- Charged-particle multiplicity distribution, dN_{ch}/dη, measured using tracklets in the pixel detector
- Inclusive J/ψ at forward and backward rapidity with p-Pb and Pb-p





- Reduction of particle production in the "p-going" direction, where small-*x* gluons in the Pb nucleus are probed
  - Described by models with nuclear-PDFs or gluon saturation (CGC), or energy loss
- Essential reference for the role of these effects in Pb-Pb



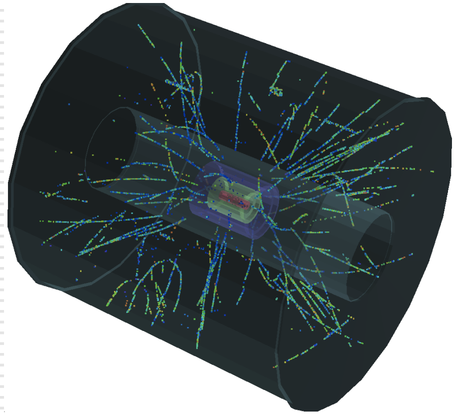
Small systems: pp and pPb

Revisiting the paradigm

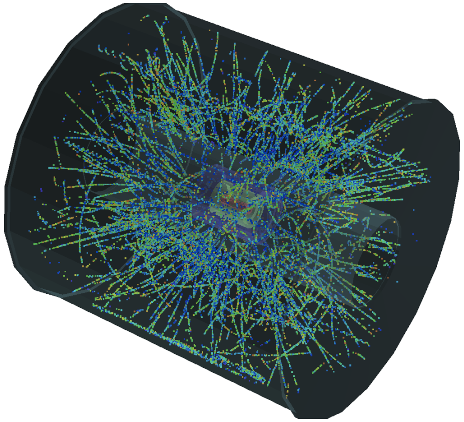
- striking properties observed in very high multiplicity p-Pb and pp collisions at LHC, which resemble those due to collectivity/ QGP-like properties of the Pb-Pb systems

one of the major surprise at the LHC so far

low multiplicity pp
(majority of events)

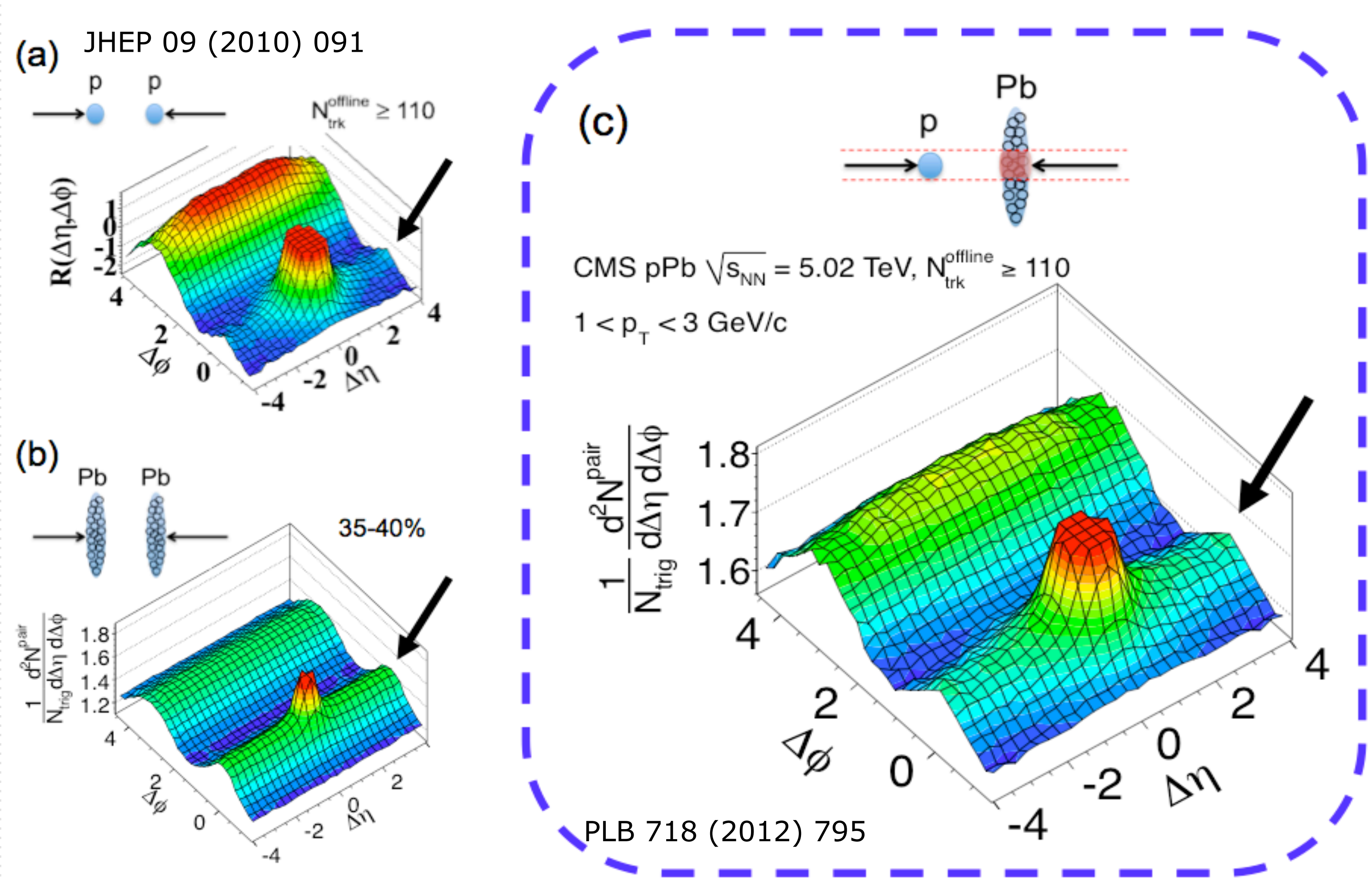


high multiplicity pp
(very rare events)



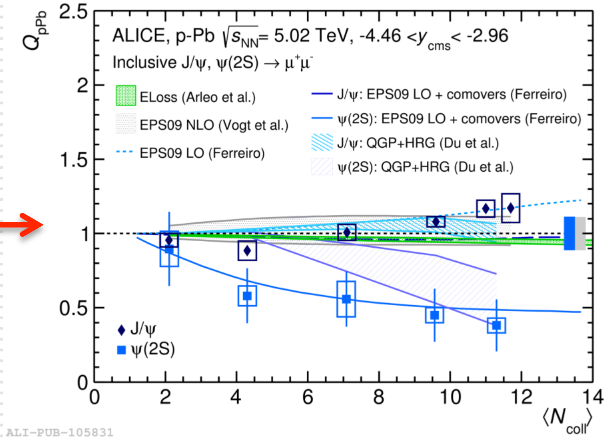
… not only ALICE

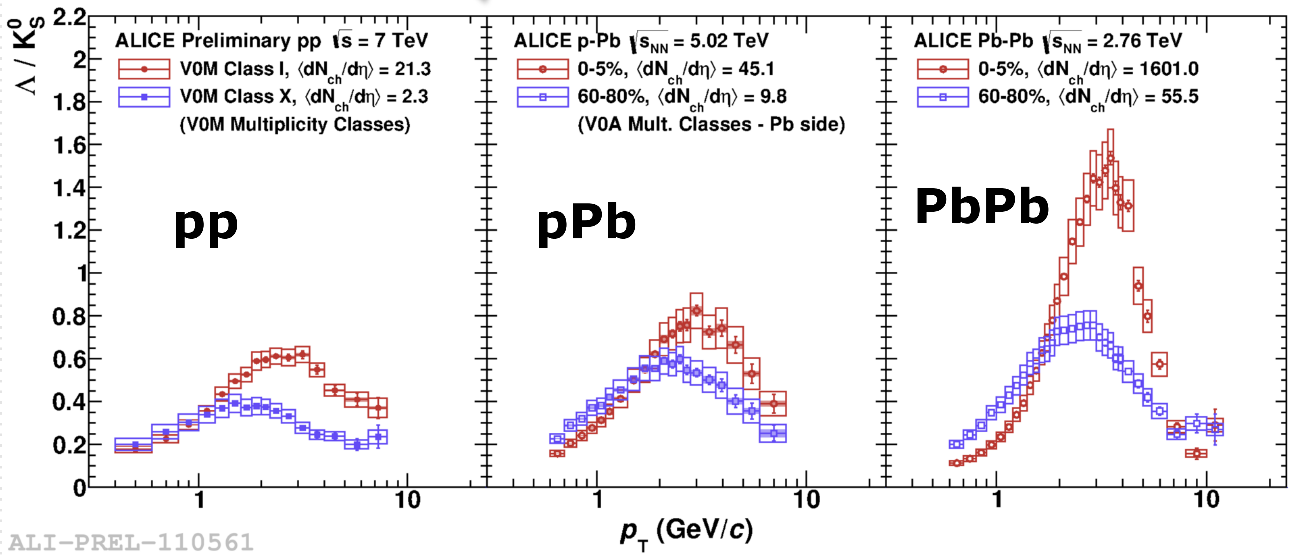
- CMS famous papers of 2010 (pp) and 2012 (pPb)



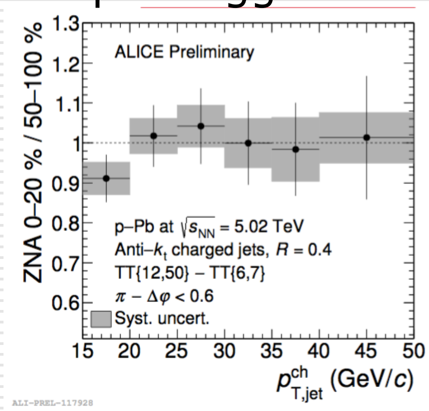
The intriguing small systems

- Azimuthal modulation of particle production, that could signal onset of collective expansion (previous slide)
- Baryon/meson ratio increases with multiplicity
- Reduction of relative yields of excited/ground quarkonium states
- but no sign of parton energy loss in a small QGP





Jets per trigger hadron

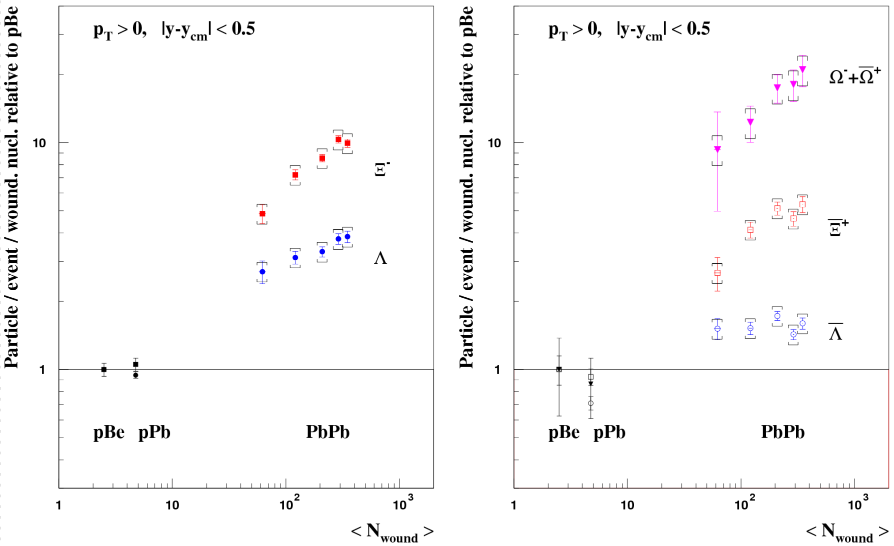


Strangeness enhancement

- Among first proposed signatures of the QGP
  - Rafelski, Müller, PRL48(1982)1066
- Observed in A-A at SPS, then at RHIC and LHC

WA97/NA57, SPS

JPG 32, 427 (2006)



Strangeness enhancement in pp!

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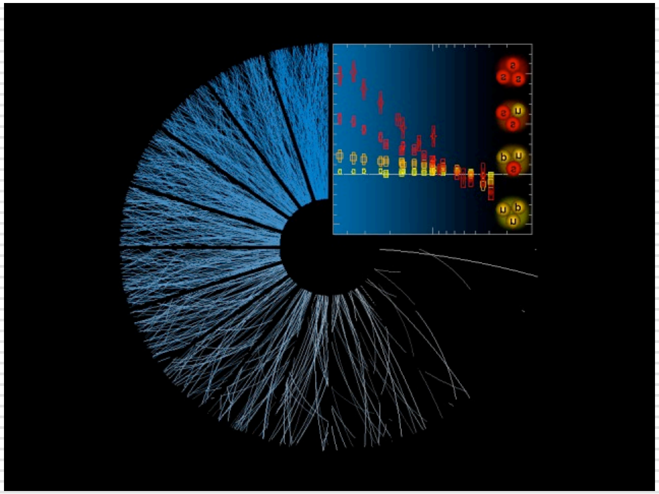
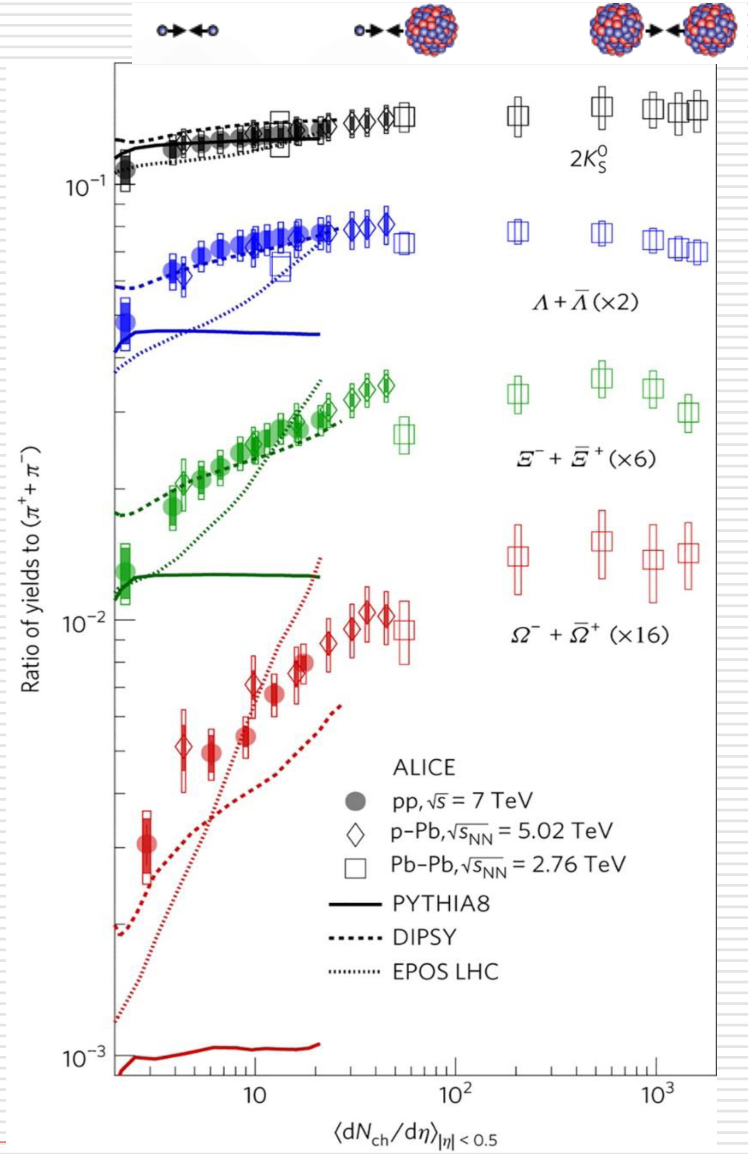
Nature Phys. 13 (2017) 535-539

New ALICE experiment results show novel phenomena in proton collisions





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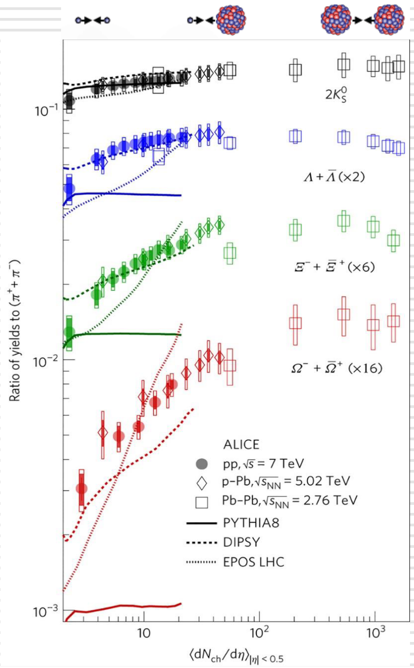
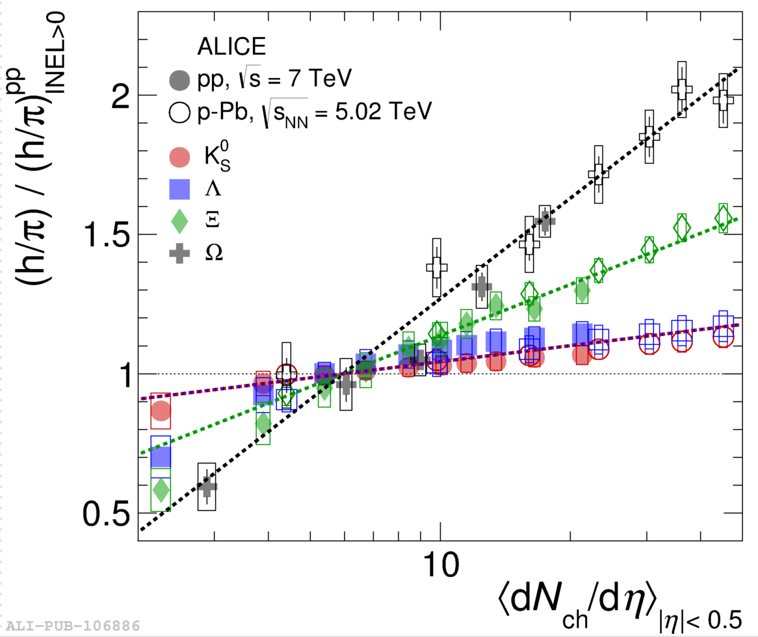
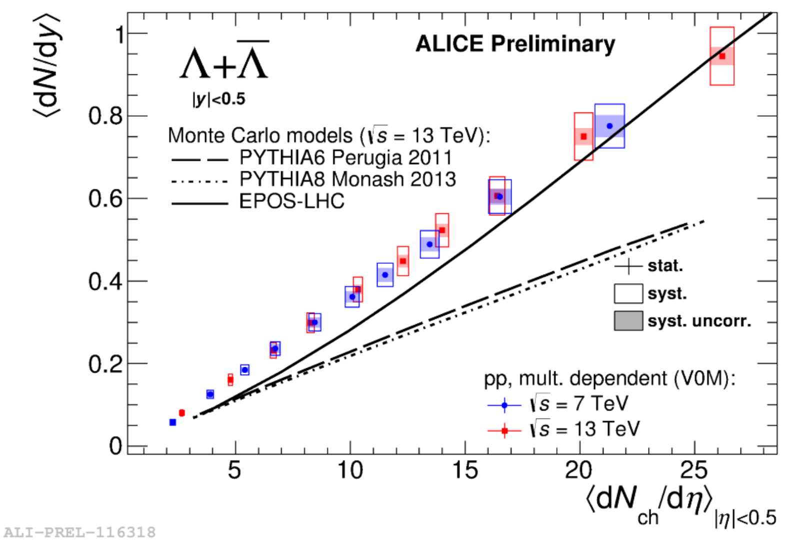


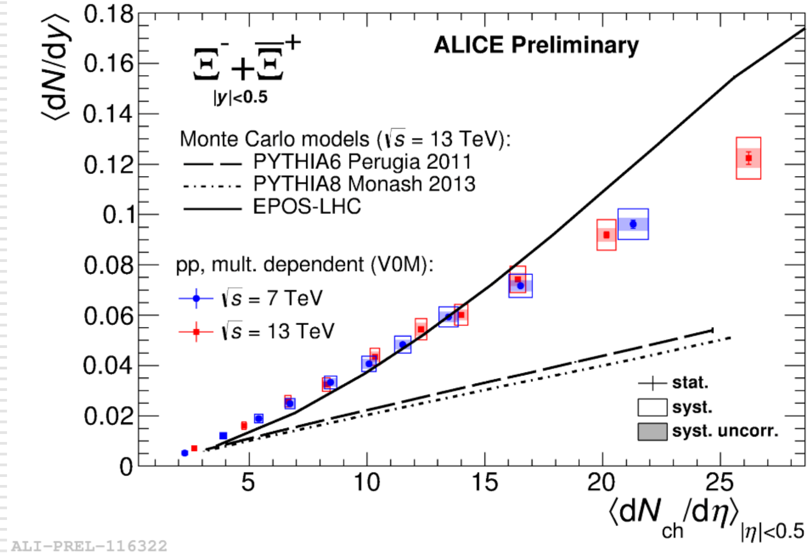


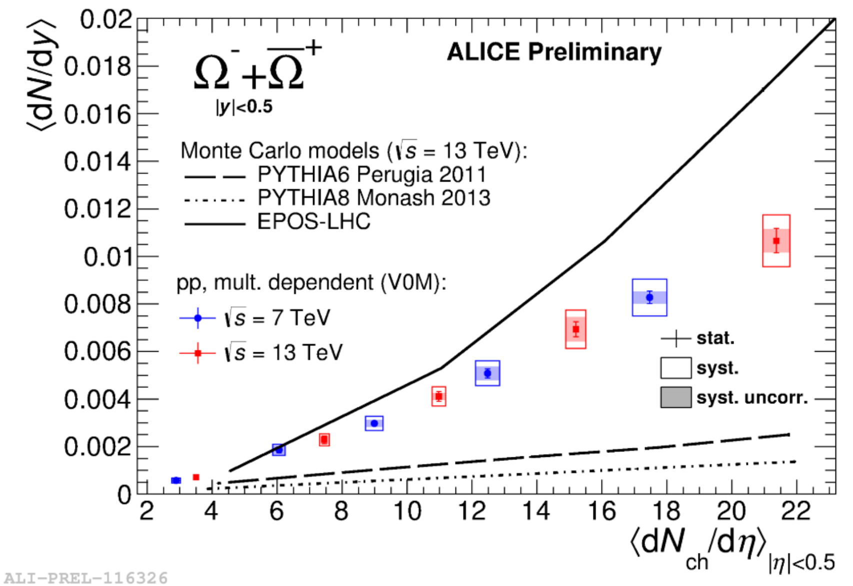
- Now in high-multiplicity pp (and p-Pb)!
- Adds to other similarities, also seen by the other experiments, e.g. collectivity
- QGP in high-mult. pp?
- New directions for research!

Nature Phys. 13 (2017) 535-539

Strangeness enhancement: energy dependence?







- Strangeness enhancement does not depend on √s
- next: data with high multiplicity triggers at 13 TeV(should reach ~dN_{ch}/dη= 50)

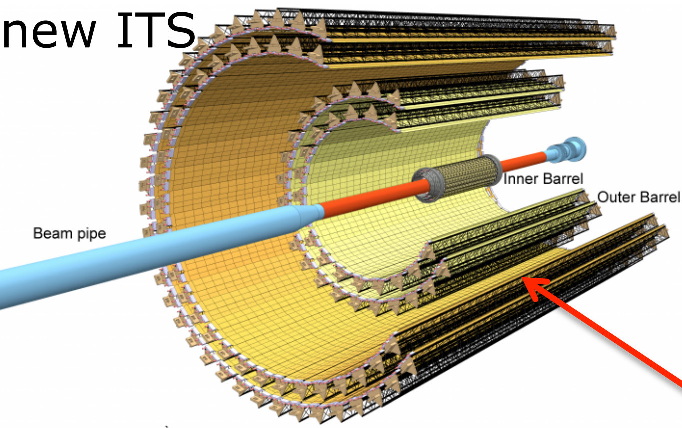
ALICE after Run-2

- Major upgrade during LS2
- Strategy driven by these main physics goals:
  - HF mesons and baryons
  - Charmonium states
  - Di-leptons from QGP radiation and low-mass vector mesons
  - Light nuclei and Hyper-nuclei
- Improve tracking resolution at low p_T
  - increase granularity, reduce material thickness
- Large minimum-bias statistics (no dedicated trigger possible)
  - write all Pb-Pb interactions at 50 kHz (x50 faster)

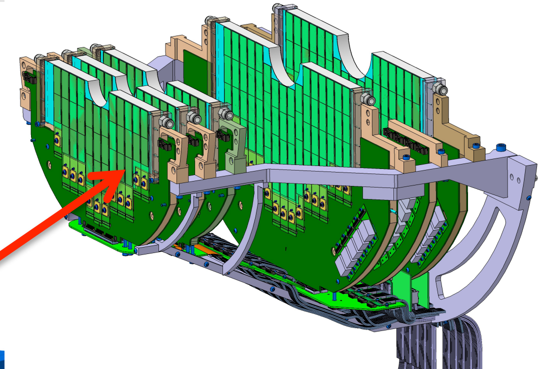
Run 3+4: increase of MB sample x100 wrt Run2

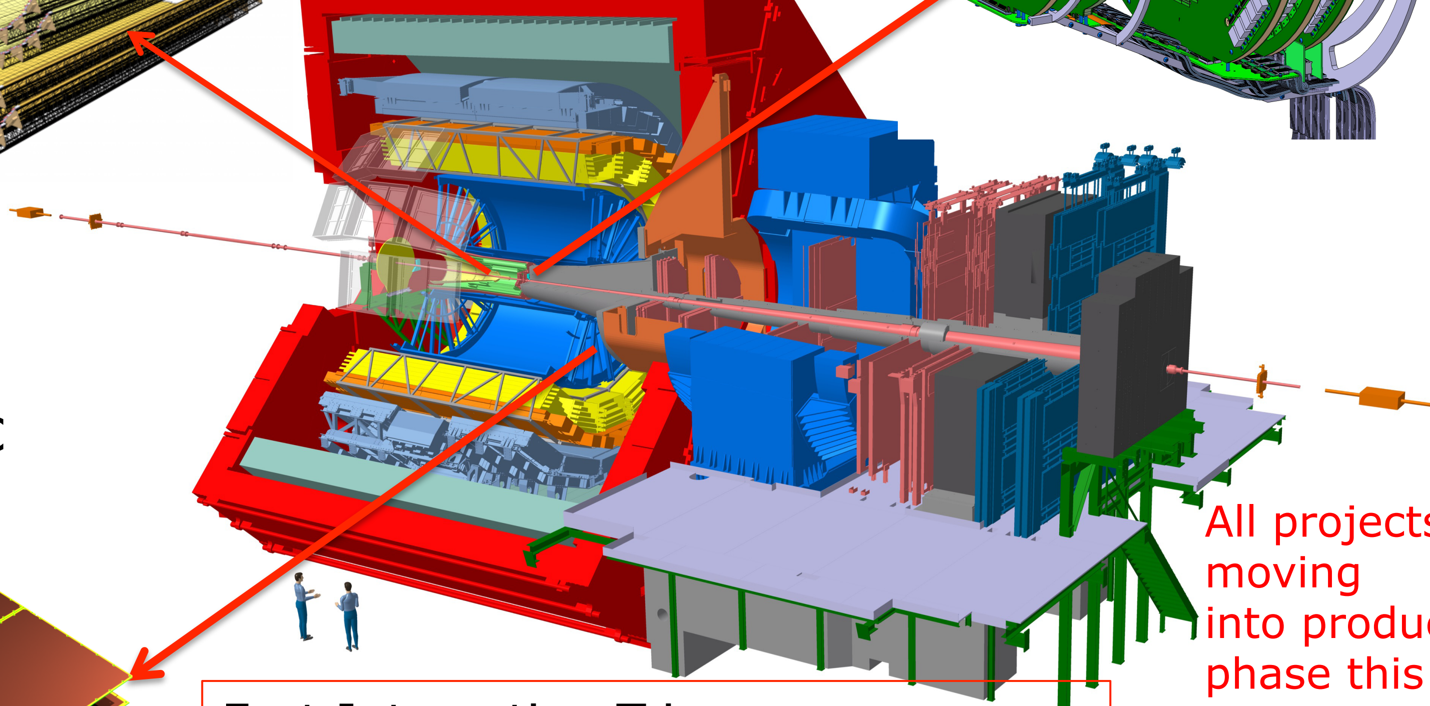
ALICE after Run-2

new ITS

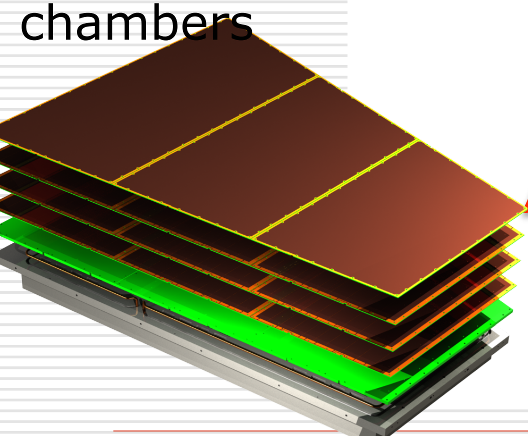


Pixel muon forward tracker





GEM-based TPC chambers

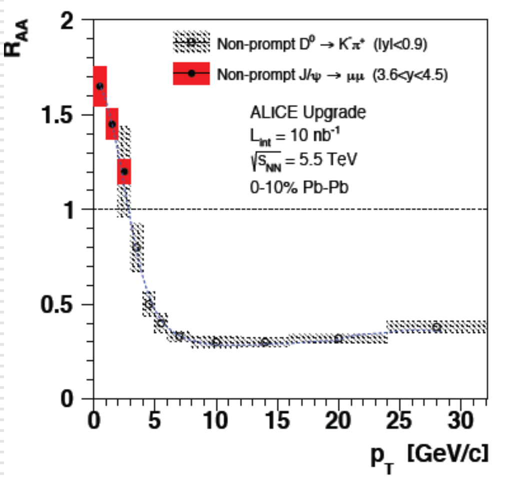


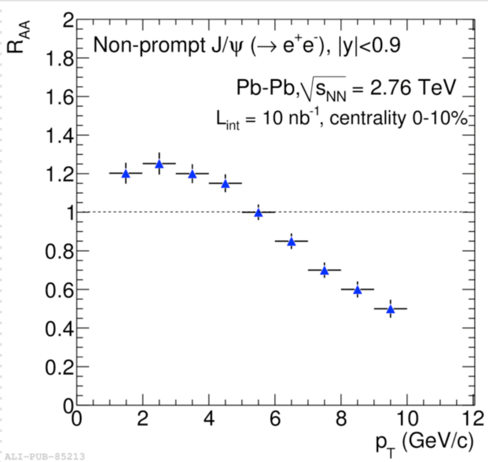
Fast Interaction Trigger
New Online-Offline system
Readout upgrade of other detectors

All projects moving into production phase this year

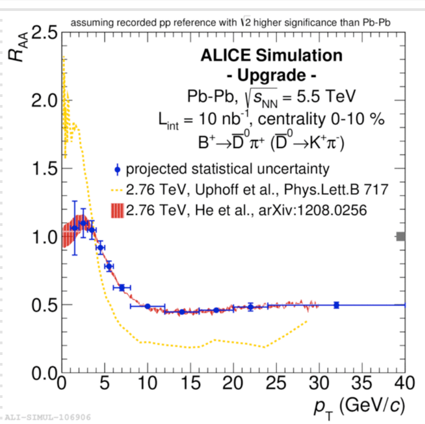
bechmark studies: B mesons

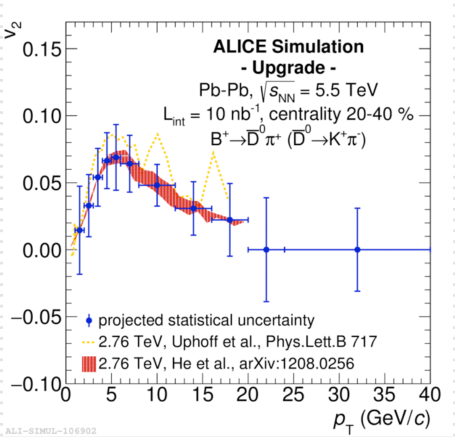
- B→D^0+X (barrel) and B→ J/ψ+X (barrel & MFT)





- fully reconstructed beauty mesons ($B^- \to D^0\pi^+$)

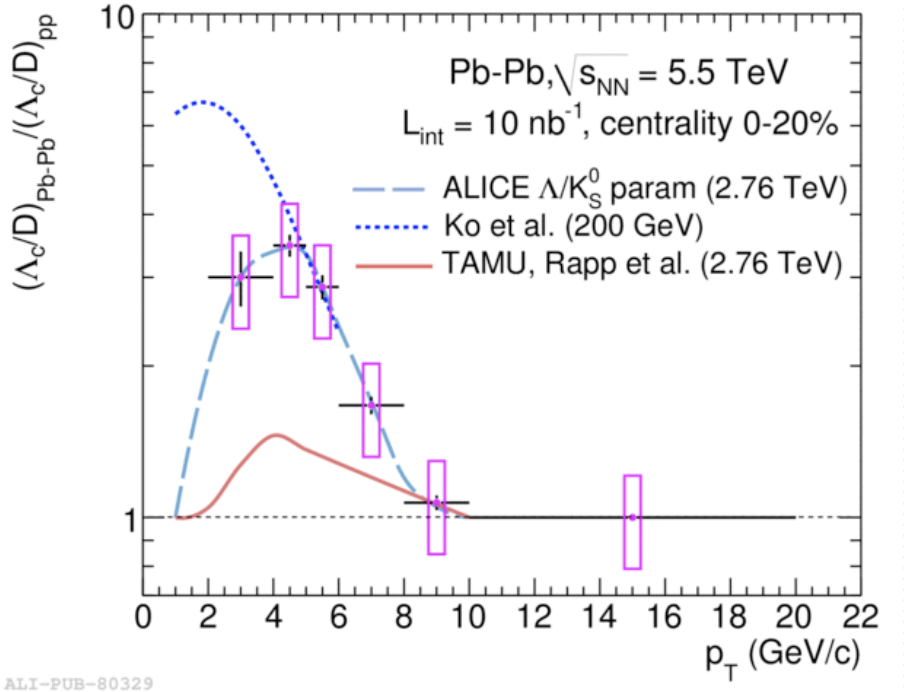




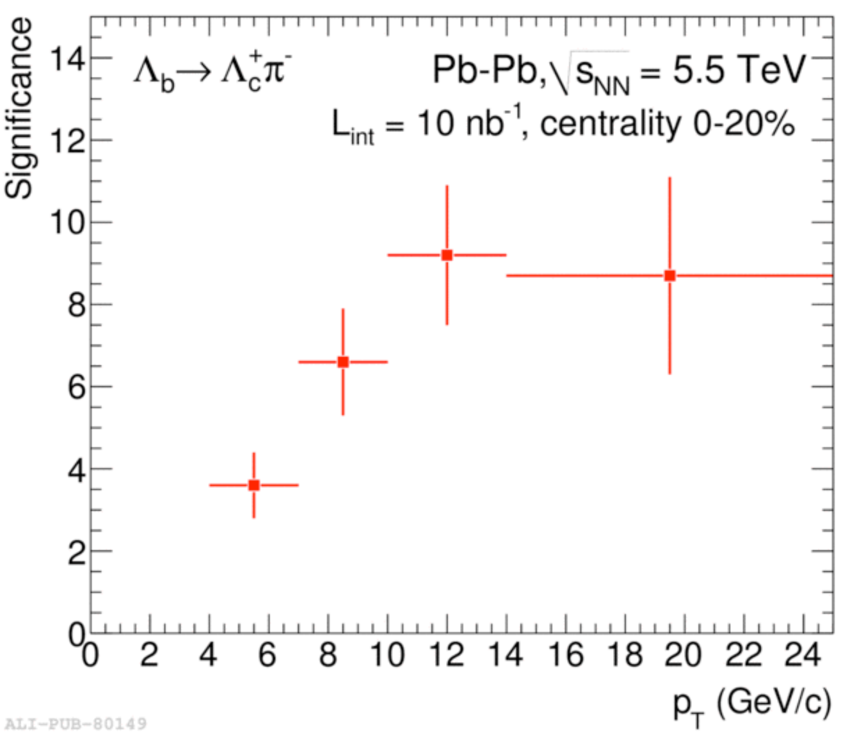
bechmark studies: HF baryons

- Λ_c and Λ_b

charm



beauty



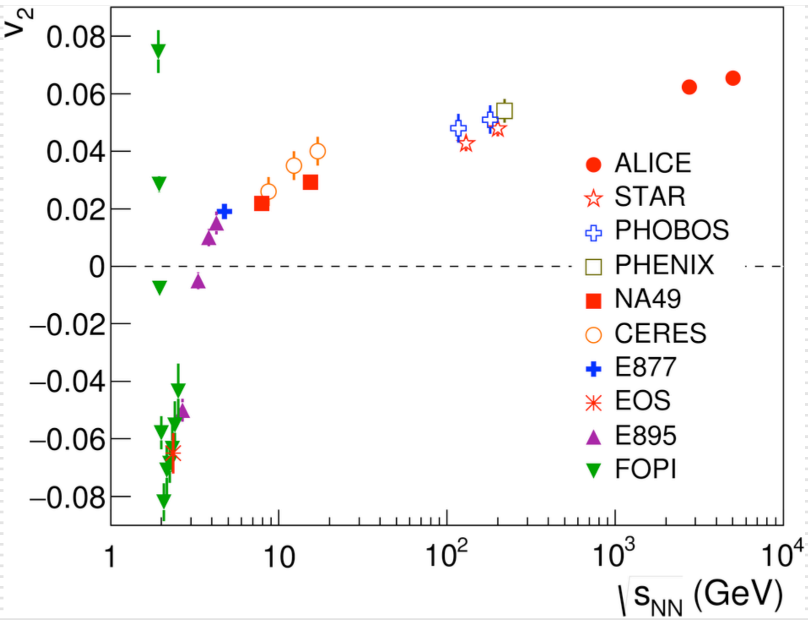
Summary

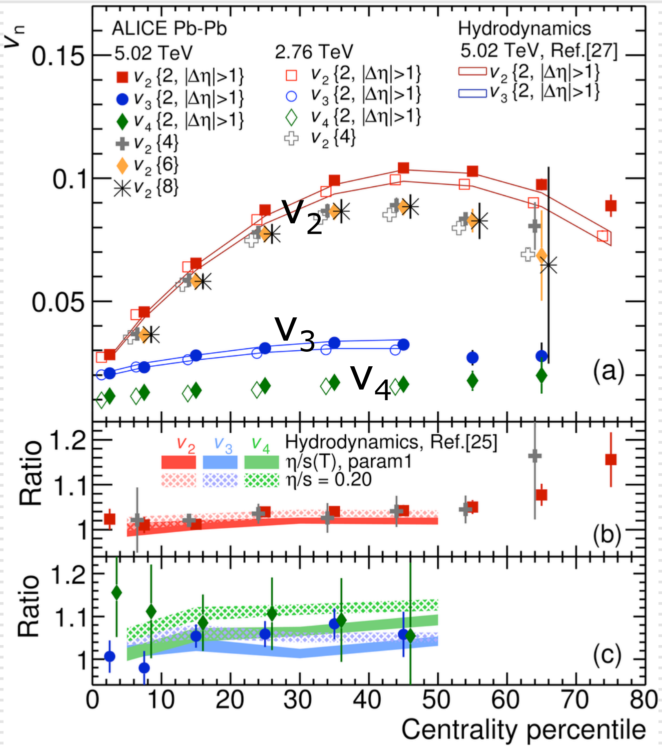
- ALICE is producing a large number of results from Run-2
- Measurements in Pb-Pb collisions with improved precision are providing a more detailed insight on the QGP workings
- Small systems (pp and p-Pb) continue to reveal unexpected results that open the search for the smallest droplet of QGP
- The ALICE Upgrade is gearing up in view of installation in the next LS

SPARES

Flow of unidentified charged particles

PRL 105 25230 (2010) ; PRL 116, 132302 (2016)

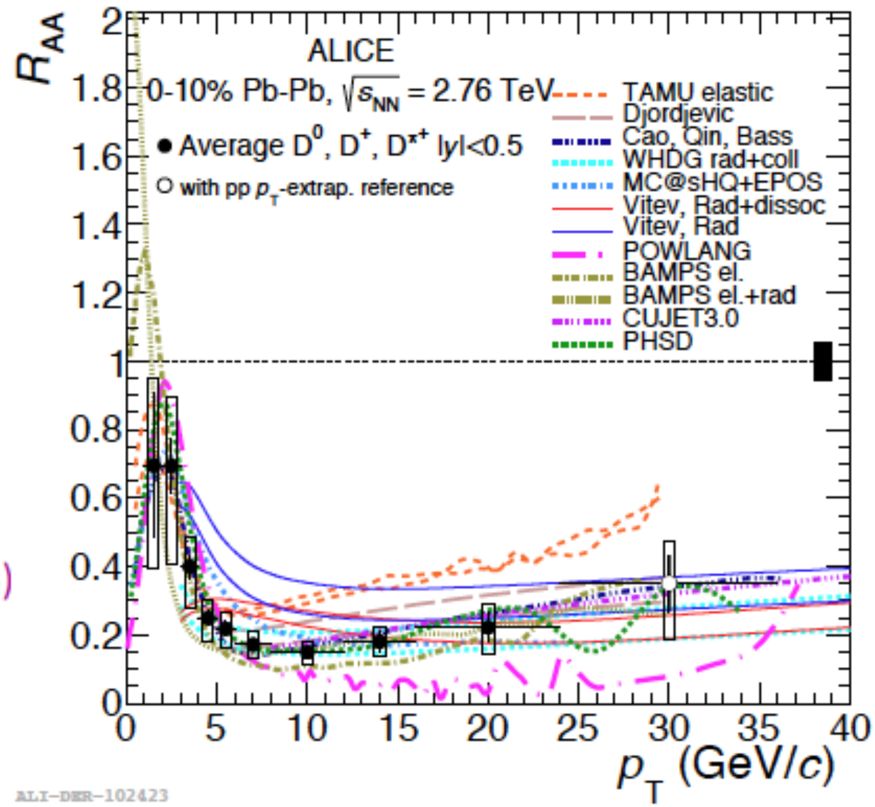




- The flow increases by about 30% w.r.t. RHIC. The system produced at the LHC behaves as a very low viscosity fluid (a perfect fluid)
  - constraints dependence of η/s versus temperature

Model references

– POWLANG: EPJ C 75 (2015) 121;
– TAMU: arXiv:1401.3817;
– MC@HQ+EPOS: PRC 89 (2014) 014905;
– WHDG: Nucl. Phys. A 872 (2011) 256;
– BAMPS: PLB 717 (2012) 430;
arXiv:1310.3597v1[hep-ph];
– Cao,Quin, Bass: PRC 88 (2013);
– Vitev:: PRC 80 (2009) 054902;
– Djordjevic: PRL 737 (2014) 298
– CUJET 3.0: Chin. Phys. Lett. 32 no. 9, (2015)
arXiv:1411.3673 [hep-ph].
– PHSD: arXiv:1512.00891



J/ψ in p-Pb at 8 TeV