Heavy flavour physics in heavy ions collisions at LHC

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La Biodola, May the 9th 2018

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Outline:

- Introduction to heavy ion collisions
  - Heavy Flavour probes of the QGP
- Recent Pb-Pb results: a selection
- The intriguing "small systems"
- Summary and outlook

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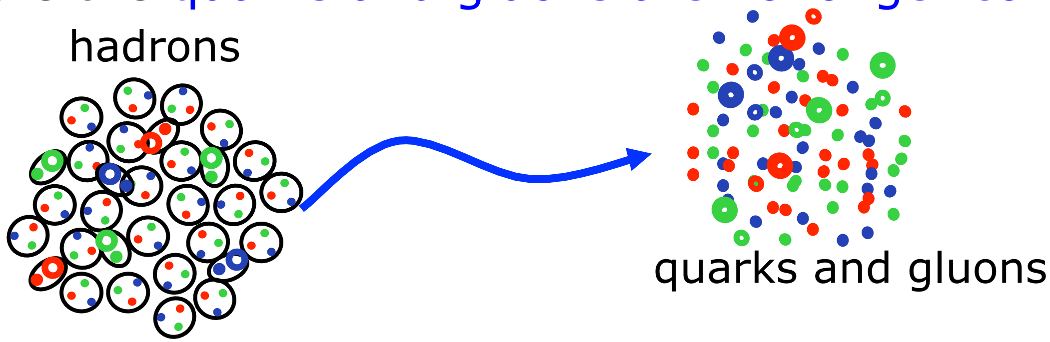
The QCD phase transition

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



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.

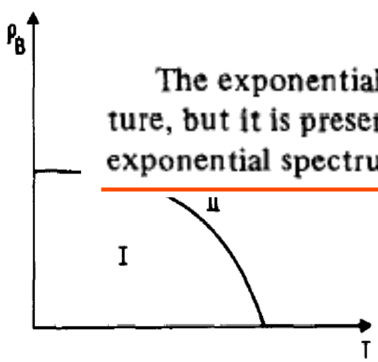
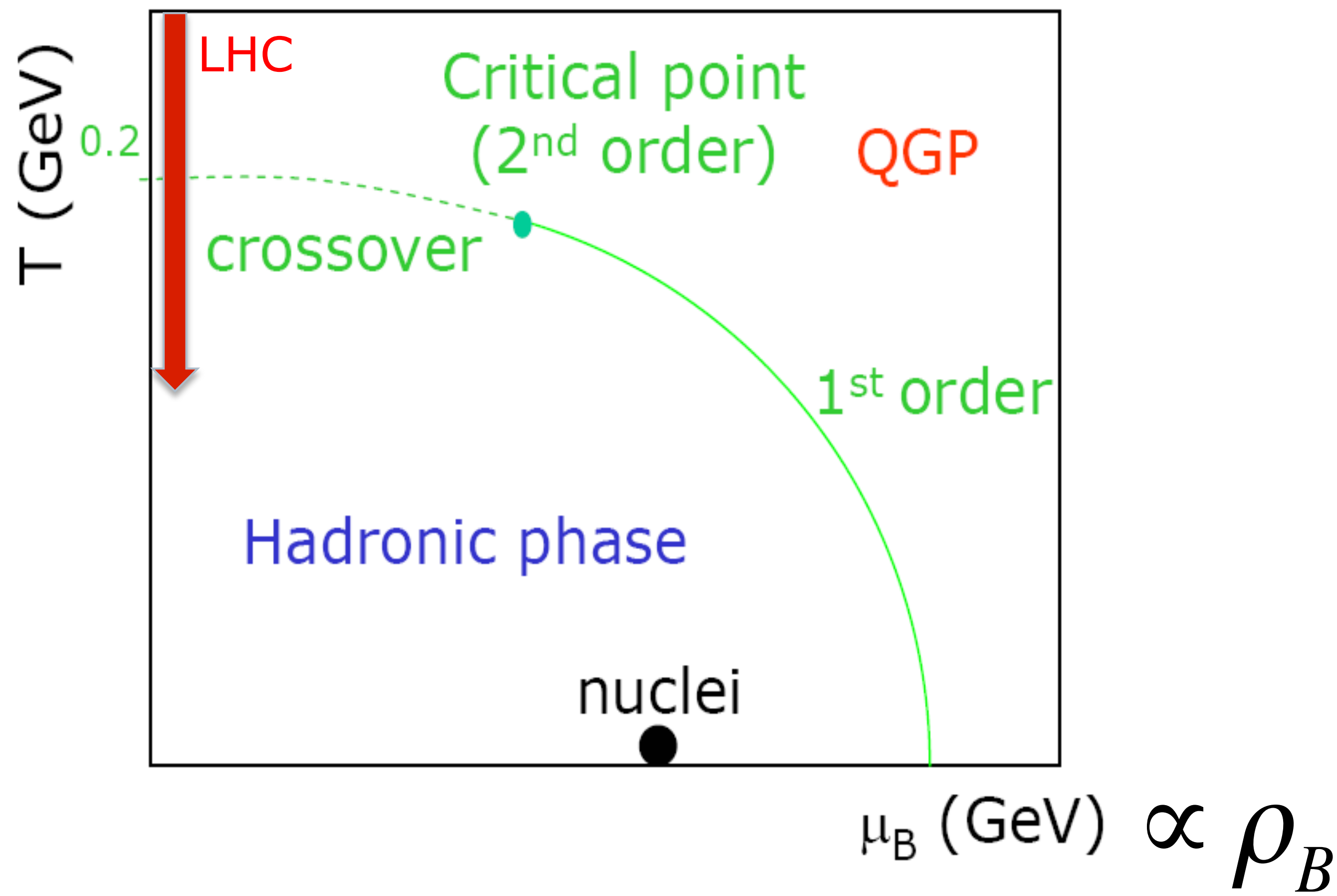


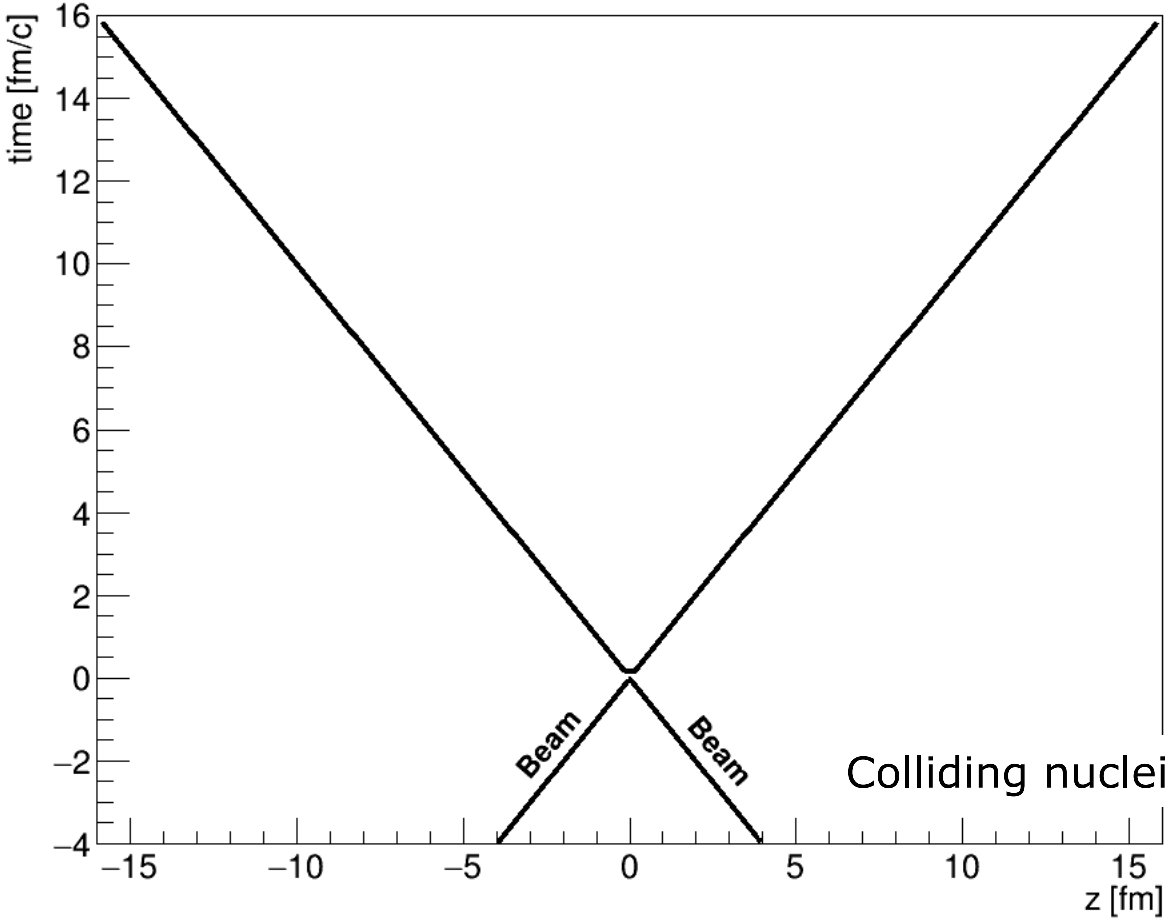
Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.

The phase diagram of QCD, in 1975

The phase diagram of QCD, today

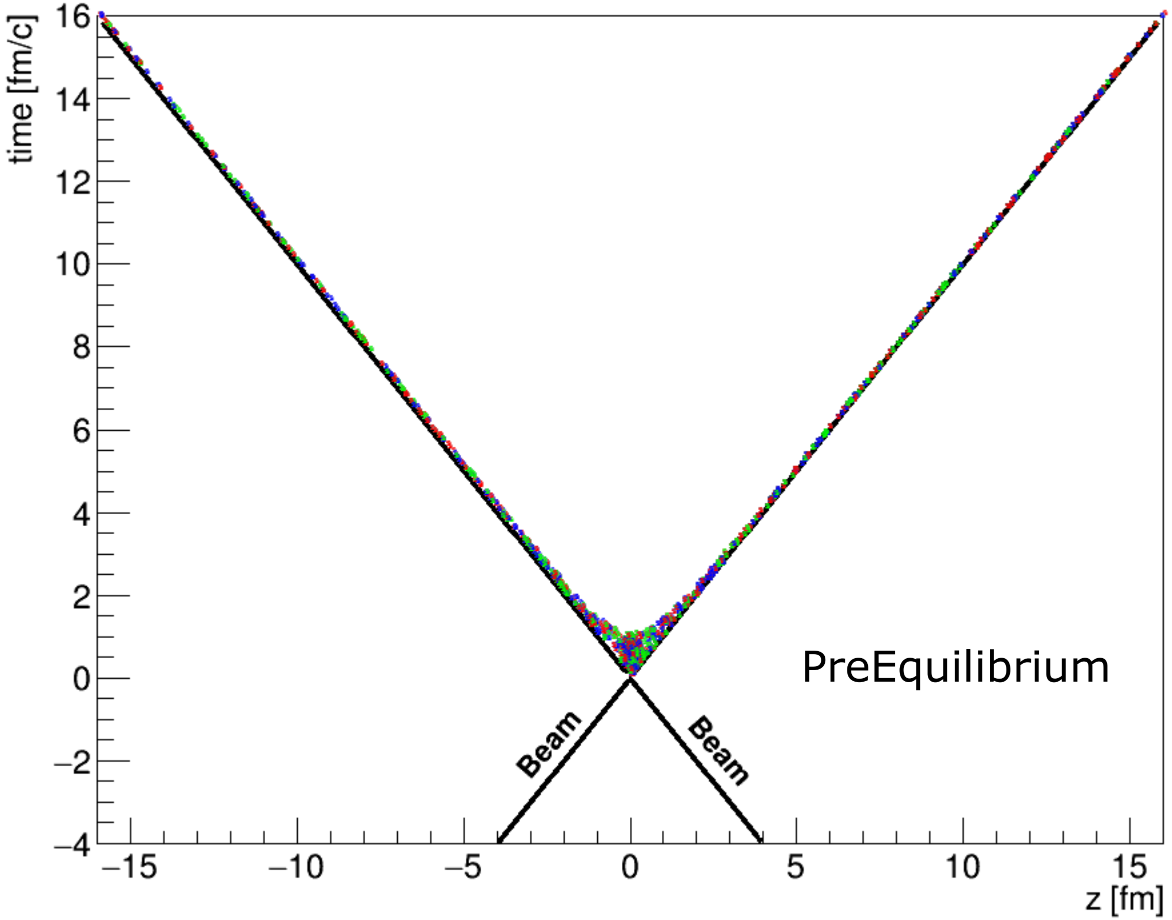


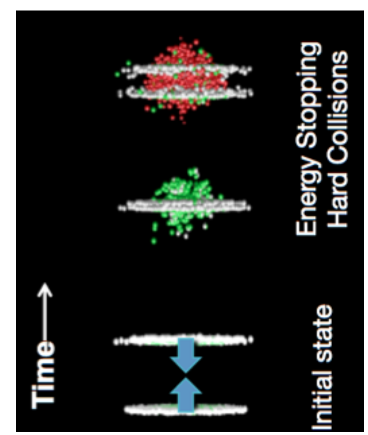
Space time evolution of A-A collision



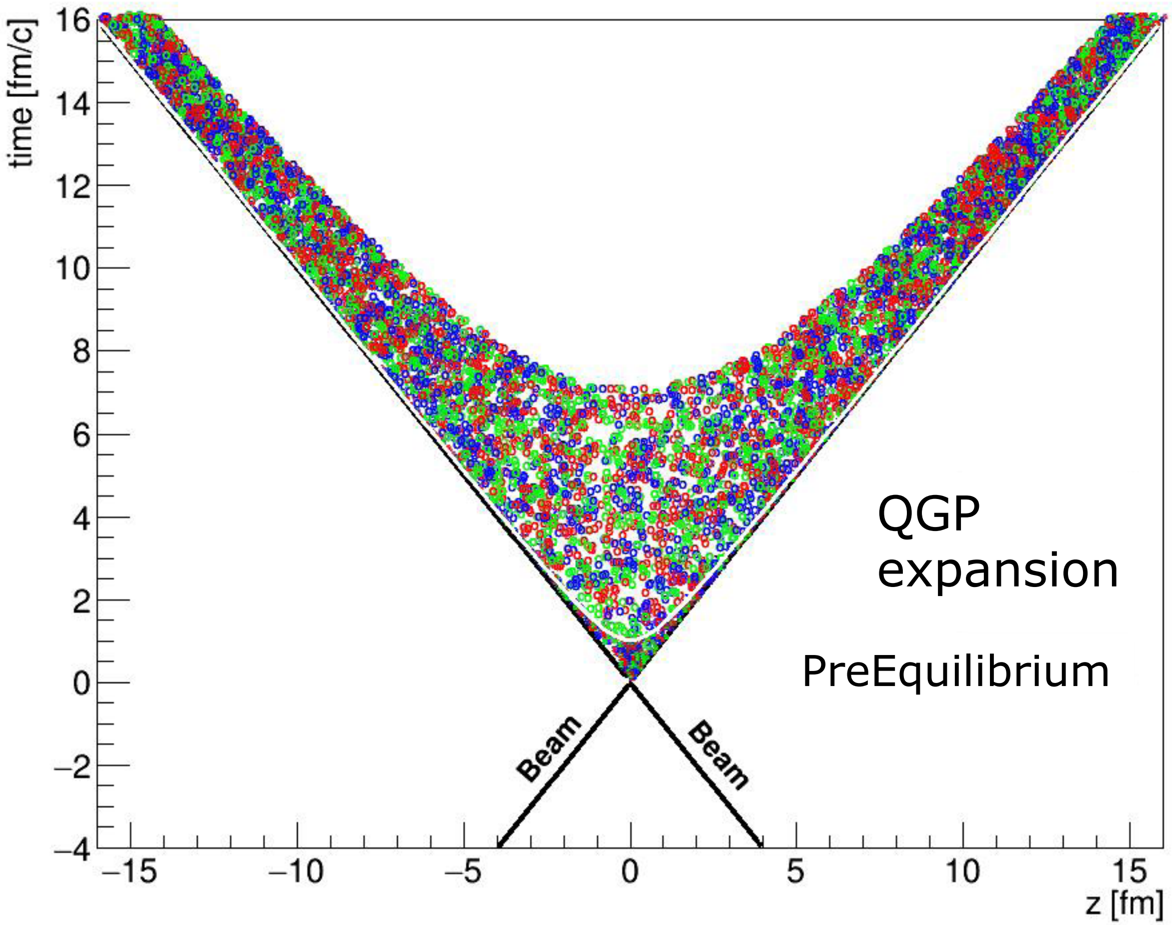
Colliding nuclei

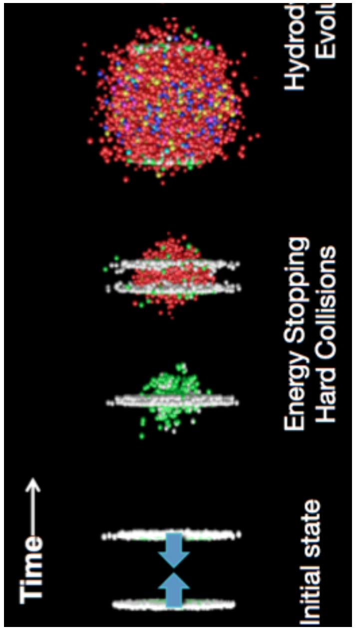
Space time evolution of A-A collision



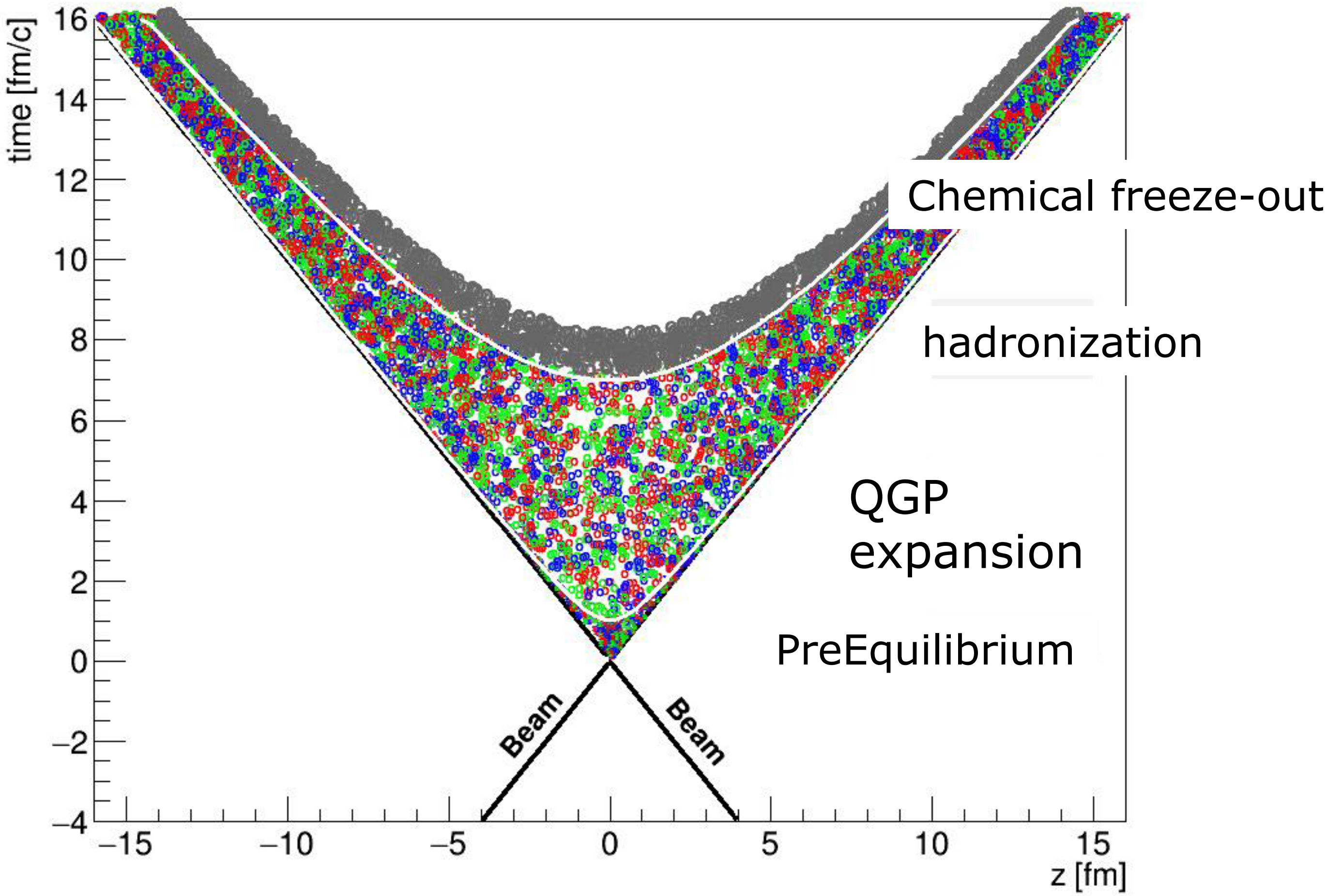


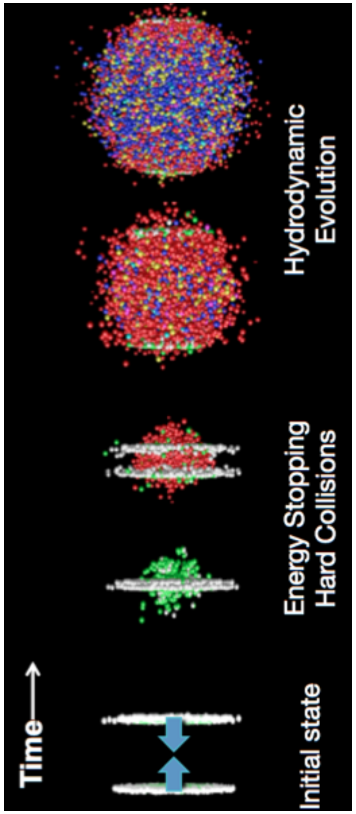
Space time evolution of A-A collision



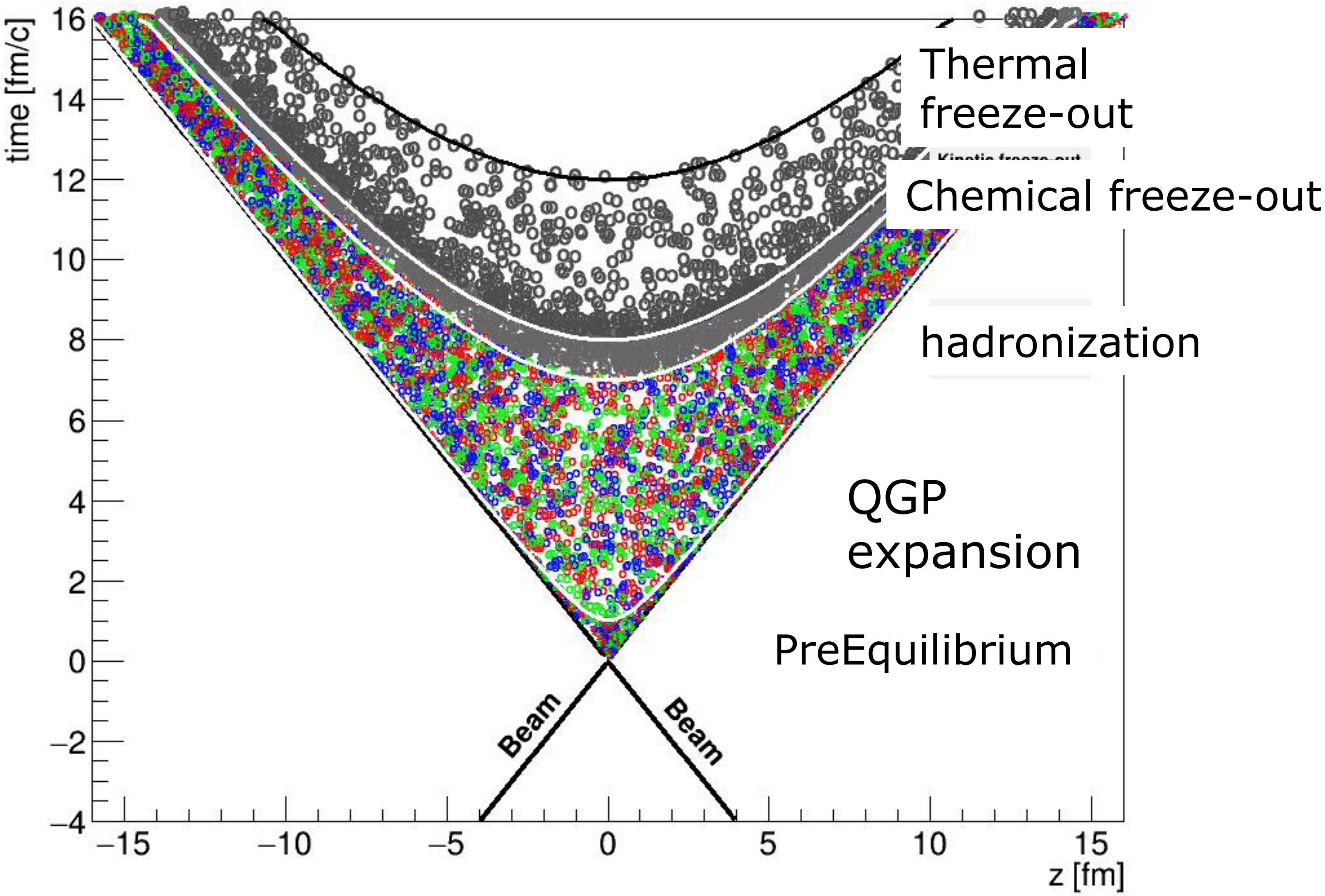


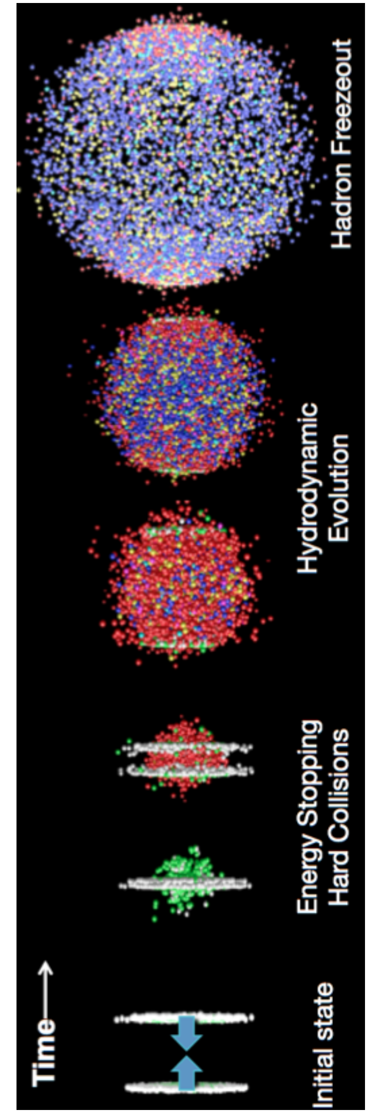
Space time evolution of A-A collision



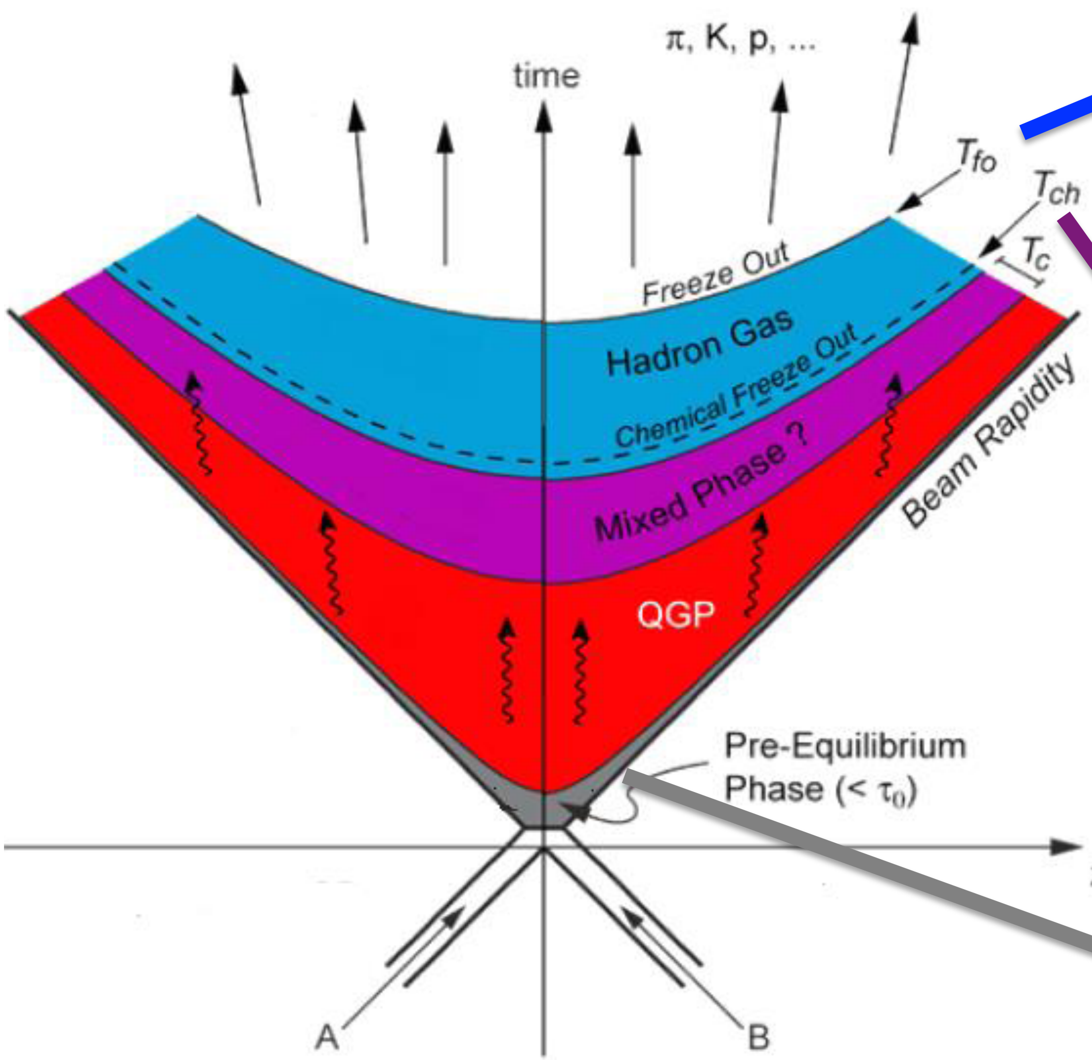


Space time evolution of A-A collision



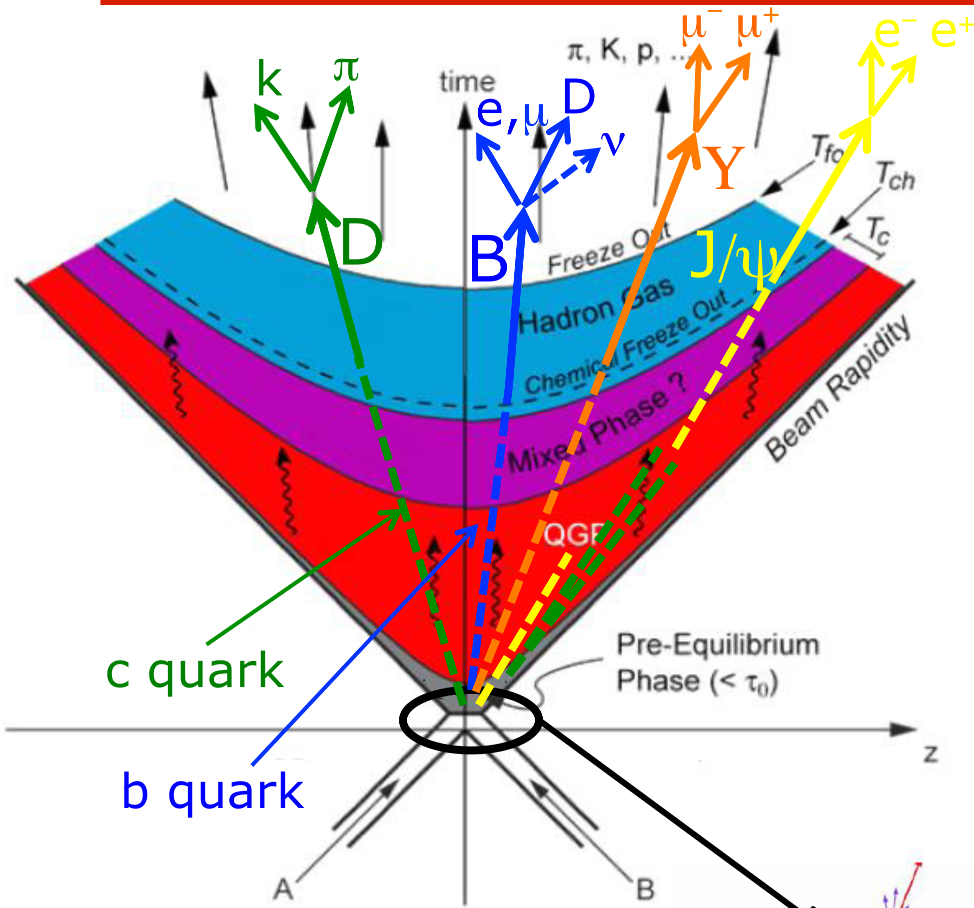


Space time evolution of A-A collision



- 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

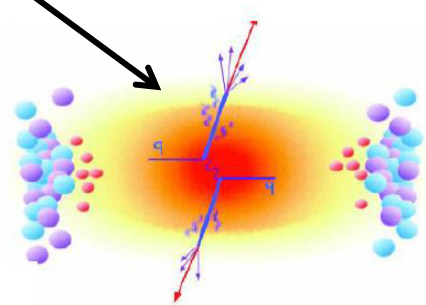
Heavy flavours: hard probes of QGP

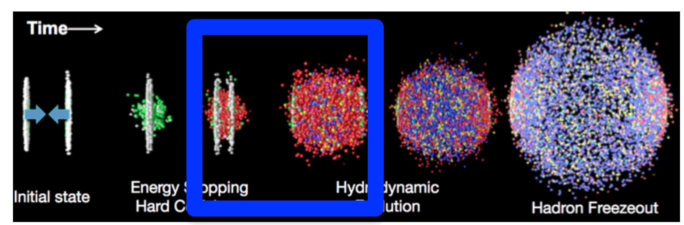


- Hard probes in nucleus-nucleus collisions:
  - produced at the very early stage of the collisions in partonic processes with large Q^2
  - pQCD can be used to calculate initial cross sections
  - traverse the hot and dense medium
  - can be used to probe the properties of the medium

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

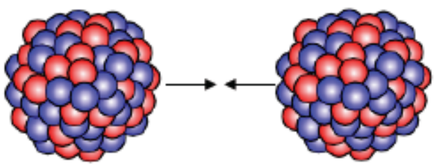
$$m_T = \sqrt{m_Q^2 + p_T^2}$$





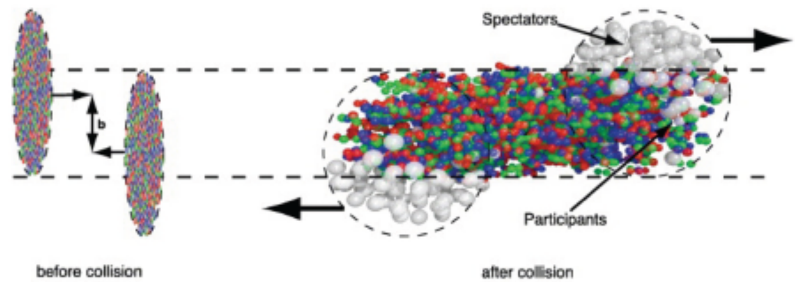
from pp to Pb-Pb collisions at LHC

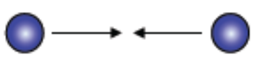
The paradigm



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

- Core business: create and characterize the QGP
- Centrality

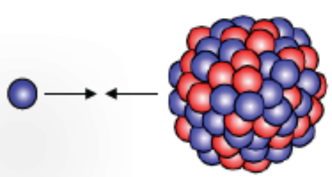




pp Collisions ($\sqrt{s}$ = 0.9 –13 TeV)

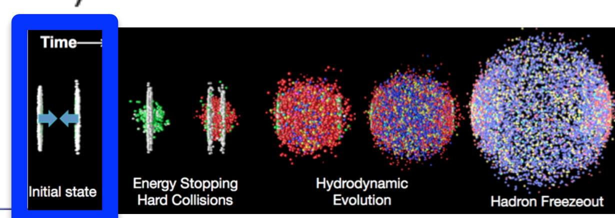
- Reference data

to be revised later on !



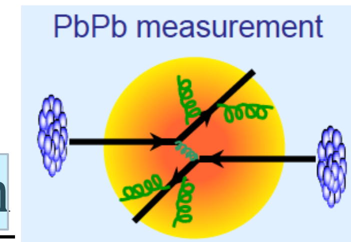
p-Pb Collisions ($\sqrt{s_{NN}}$ = 5, 8 TeV)

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

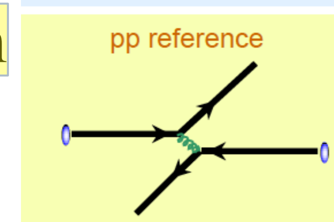


Nuclear modification factor

- Production of hard probes in A-A expected to scale with the number of nucleon-nucleon collisions N_{coll} (**binary scaling**)
- Observable: **nuclear modification factor**



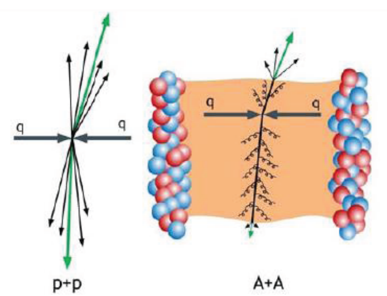
$$R_{AA} = \frac{1}{N_{coll}} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T} = \frac{1}{T_{AA}} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T} \sim \frac{\text{QCD medium}}{\text{QCD vacuum}}$$



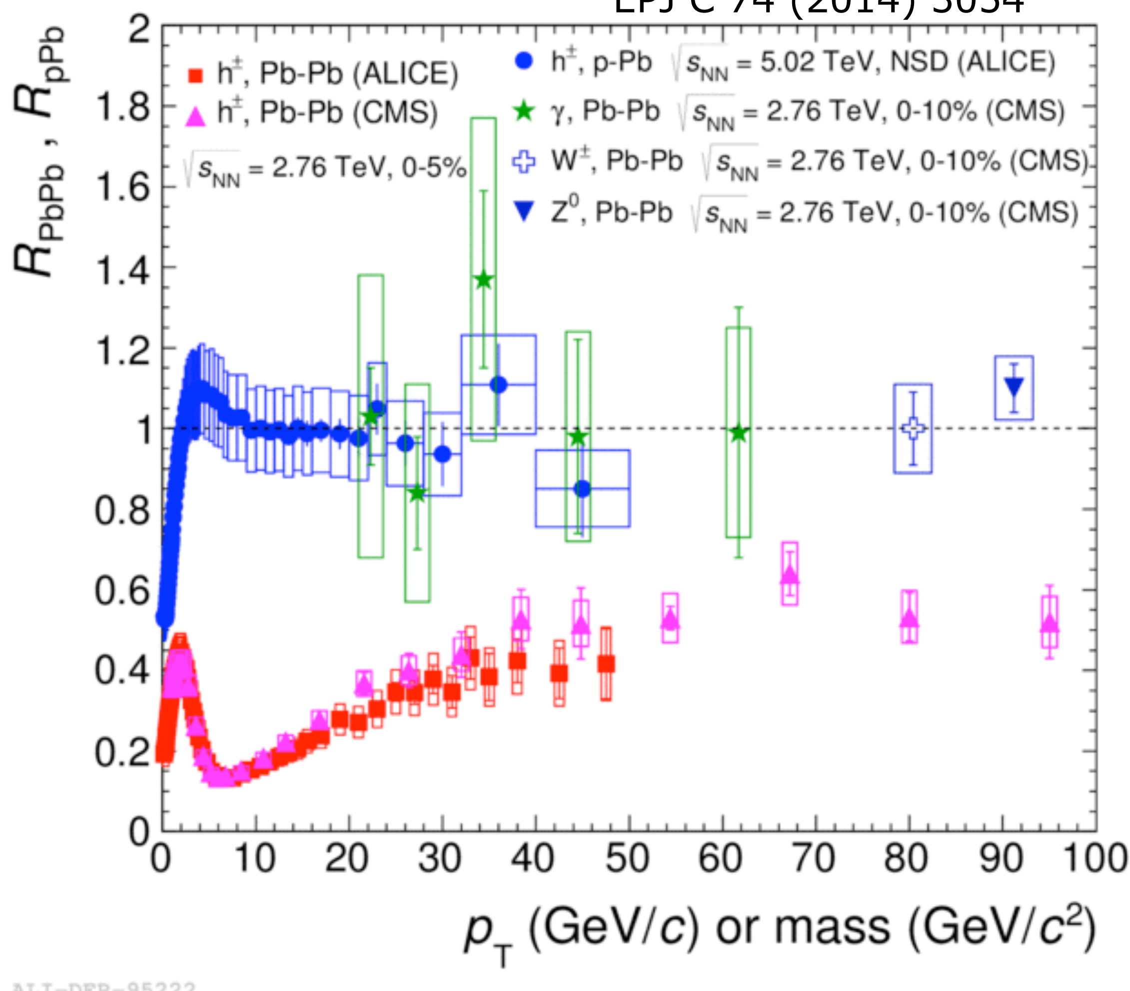
- If no nuclear effects are present → $R_{AA}=1$
- Effects from the hot and deconfined medium created in the collision → breaking of binary scaling → $R_{AA}\neq 1$
  - **Parton energy loss** via gluon radiation and collisions in the medium
  - **Quarkonium melting** in the QGP
- But also initial state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

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)



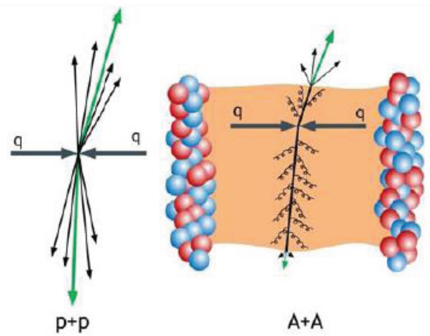
EPJ C 74 (2014) 3054



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**

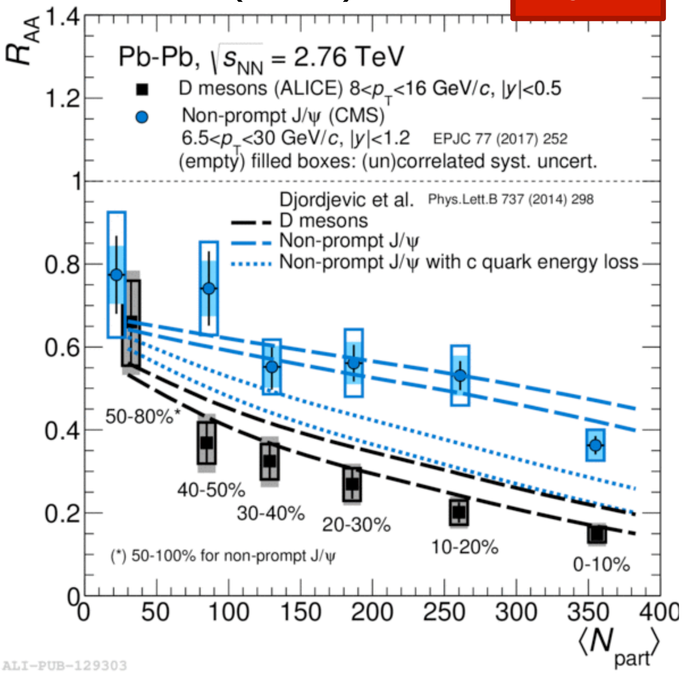
- Expectations: $\Delta E_g > \Delta E_q > \Delta E_c > \Delta E_b \rightarrow$
  naively: $R_{AA}^{h} < R_{AA}^{D} < R_{AA}^{B}$
  considering different p_t distributions and fragmentations:

  $$\boldsymbol{R_{AA}^{h} \approx R_{AA}^{D} < R_{AA}^{B}}$$

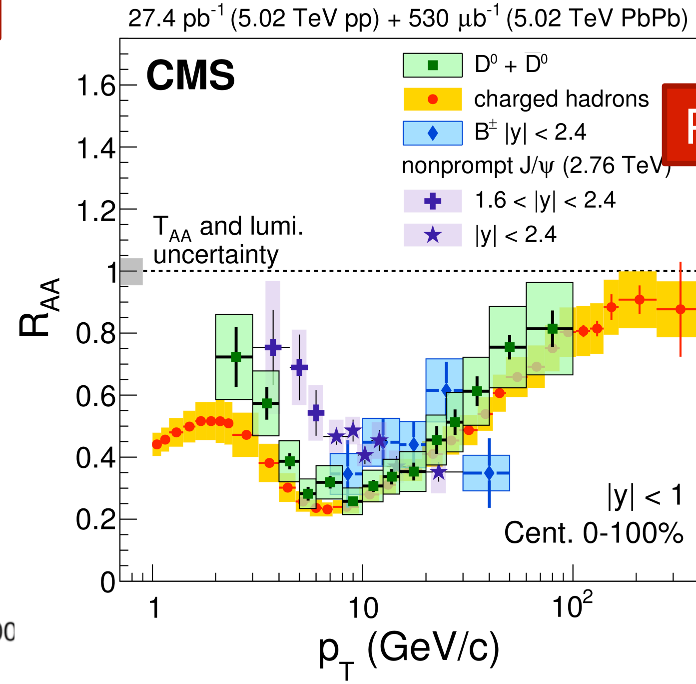
Mass effect of energy loss

JHEP 11 (2015) 205

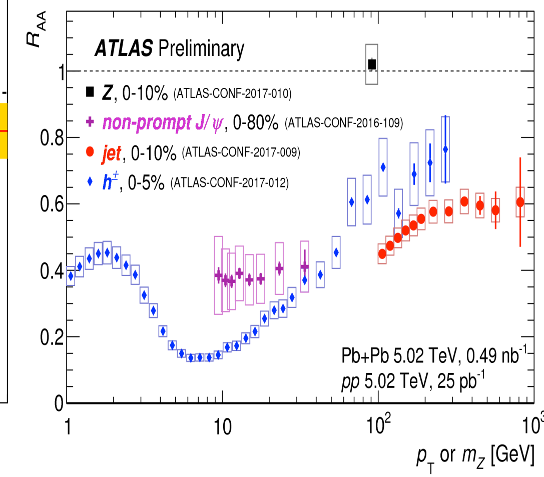
Run1



arXiv:1708.04962

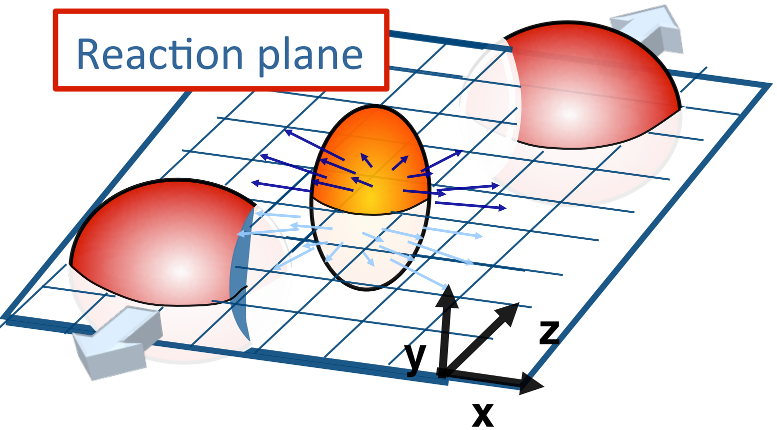


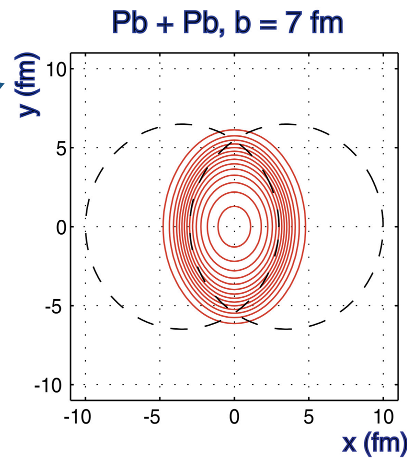
Run2

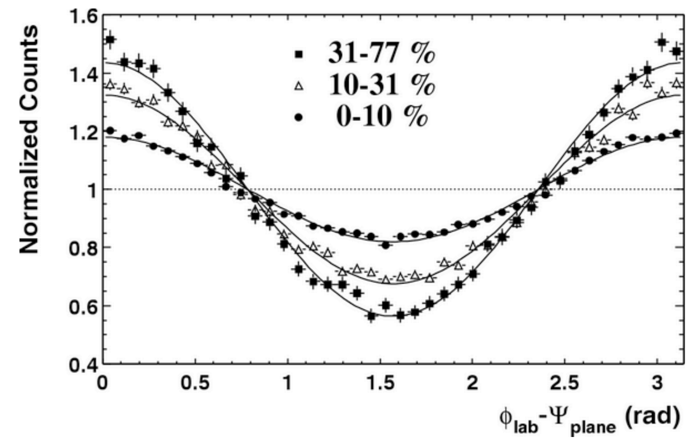


- Indication of mass dependent suppression $R_{AA}(b)>R_{AA}(c)$
  - D-meson R_{AA} (ALICE) significantly smaller than the RAA of non-prompt J/ψ (CMS)
  - confirmed by more precise Run2 data by ALICE, CMS and ATLAS

Azimuthal anisotropy



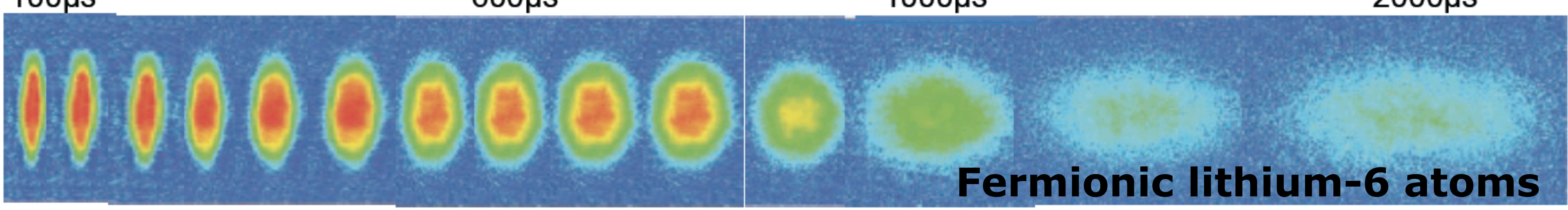




Almond shaped overlap region in geom. space → strong in-plane expansion due to pressure gradients → anisotropy in momentum space

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

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

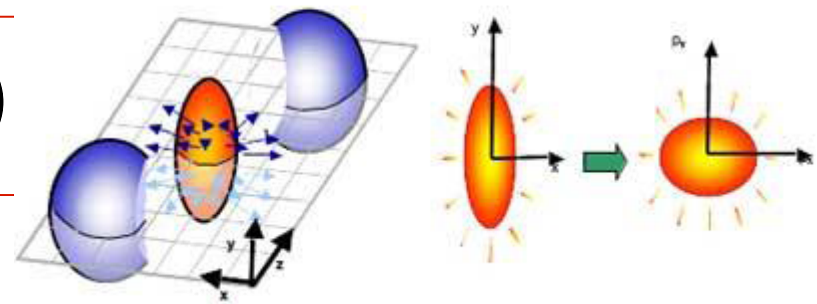


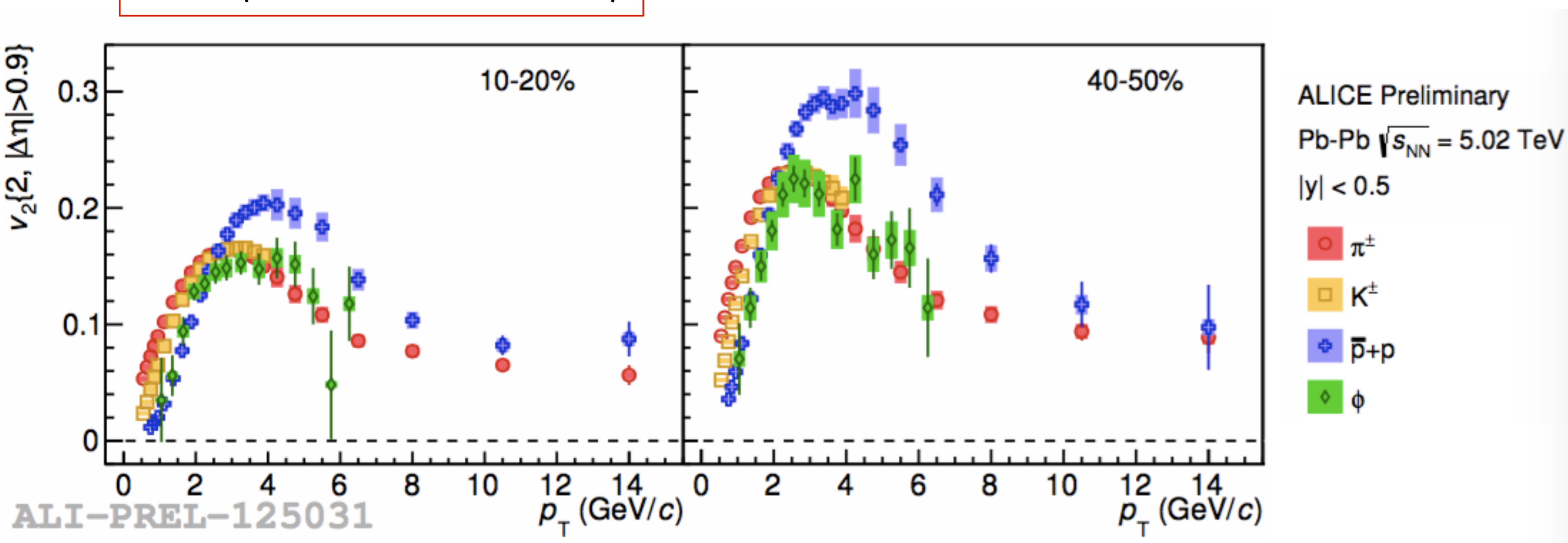
M. Gehm, S. Granade, S. Hemmer, K, O'Hara, J. Thomas - **Science** 298 **2179 (2002)**

Elliptic flow at 5 TeV: light flavour

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

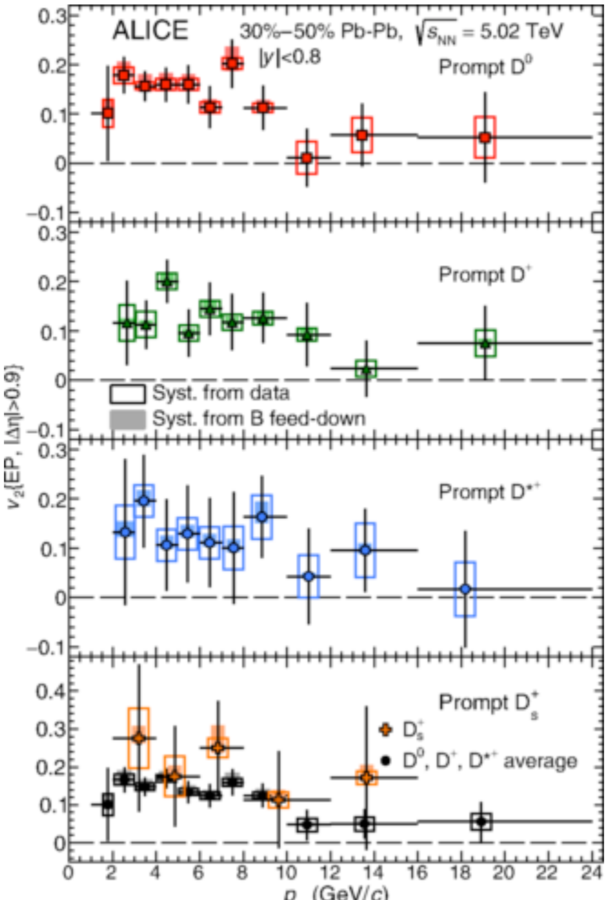
$$v_2 = \left\langle \cos\left[2(\varphi-\psi_{RP})\right]\right\rangle$$

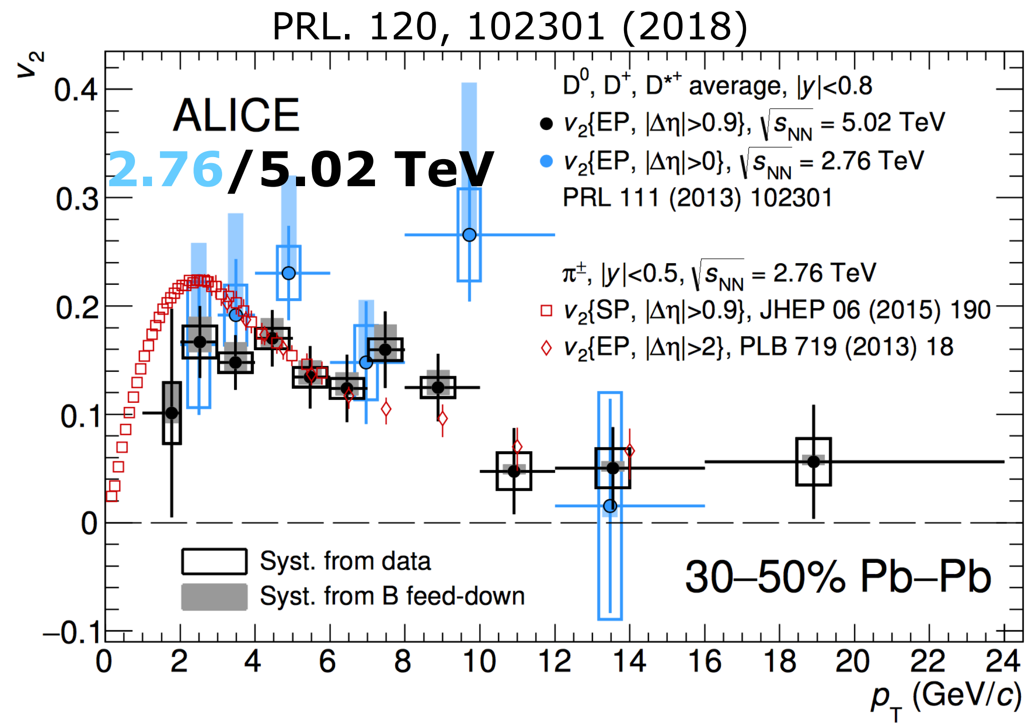




- Mass ordering at p_T<2 GeV/c → **hydro-dynamic flow, very small viscosity**
- More precise Run-2 data (esp. ϕ meson) reveal baryon vs. meson grouping at higher p_T (2-6 GeV/c) → **quark-level flow + recombination?**

Evidence of charm flowing with the medium at LHC



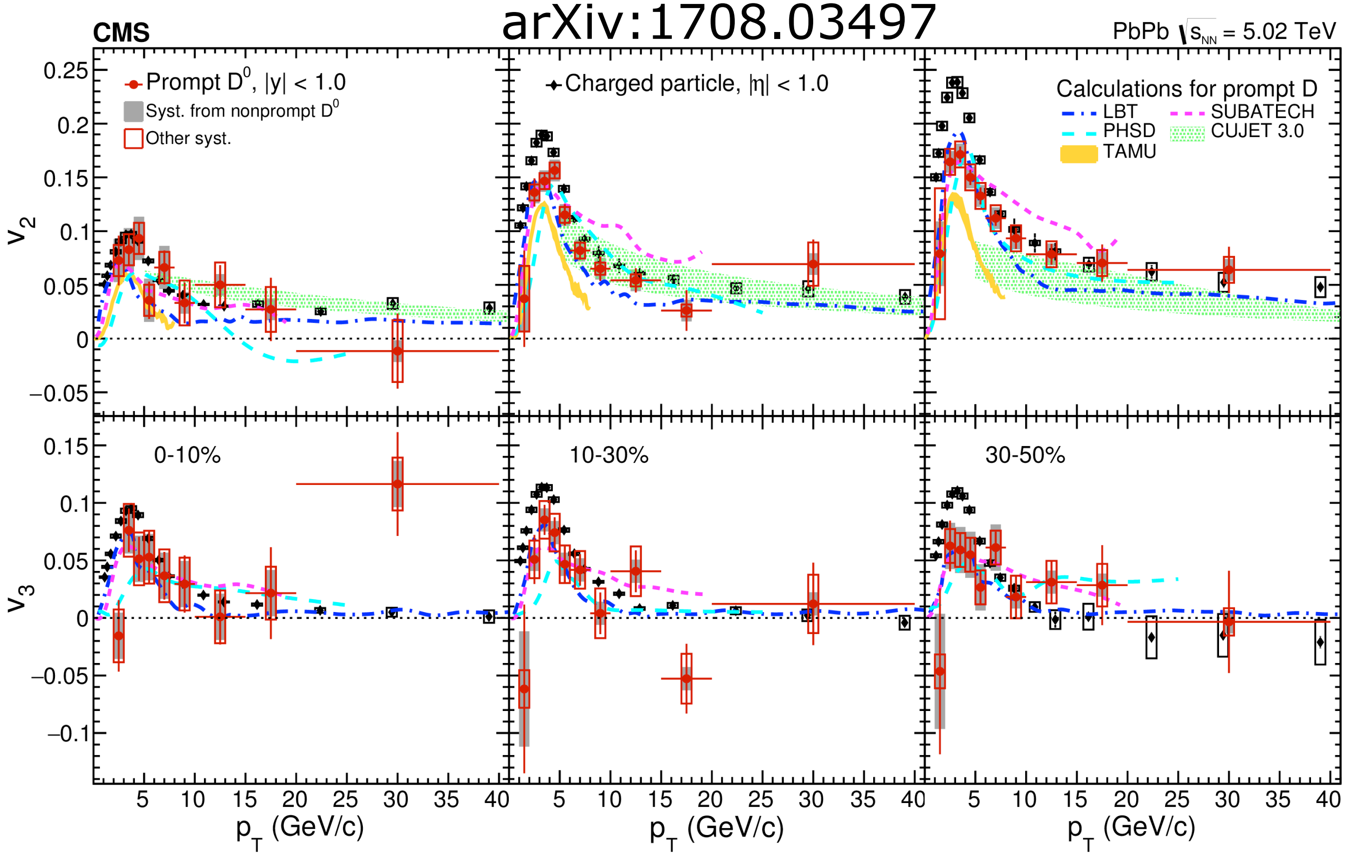


- D^0 v_2 < pion/charged particle v_2 (see also next slide)
- in agreement with CMS results (next slide)
- ALICE: also first ever measurement of D_s flow (large uncertainties)

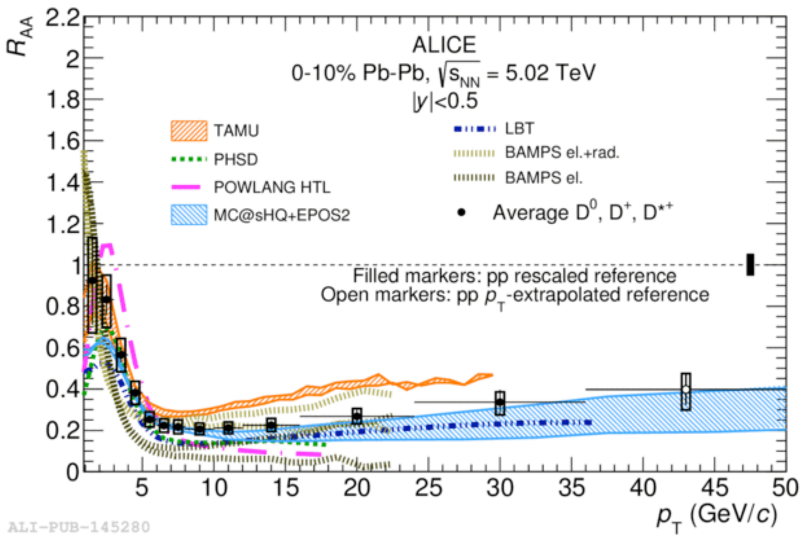
Evidence of charm flowing with the medium at LHC

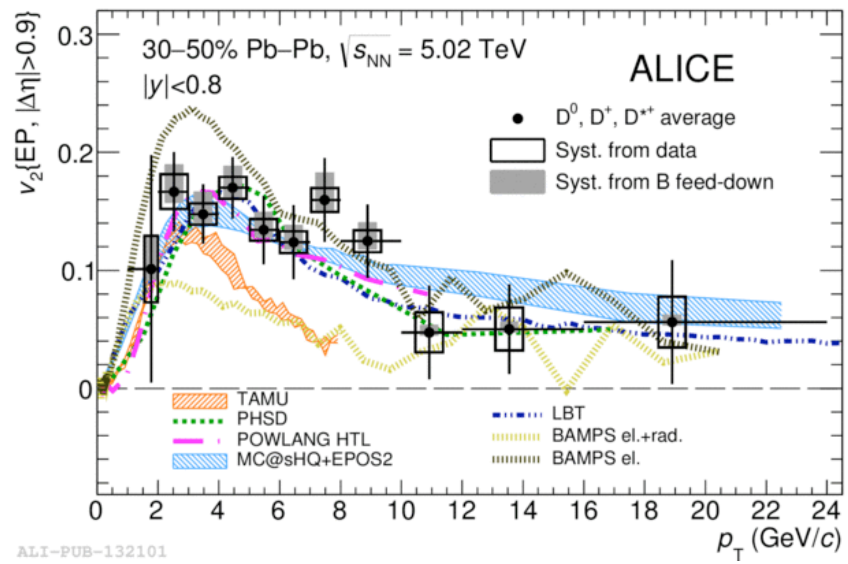
- CMS has also measured the 3rd harmonic (v_3)
  - sensitive to the initial geometry fluctuations and to the interaction strength between charm quarks and the medium

arXiv:1708.03497



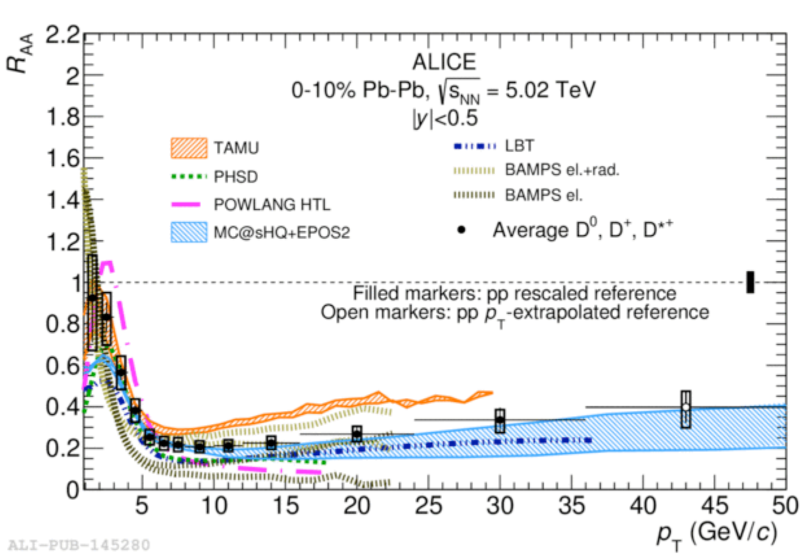
Constraining models with charm

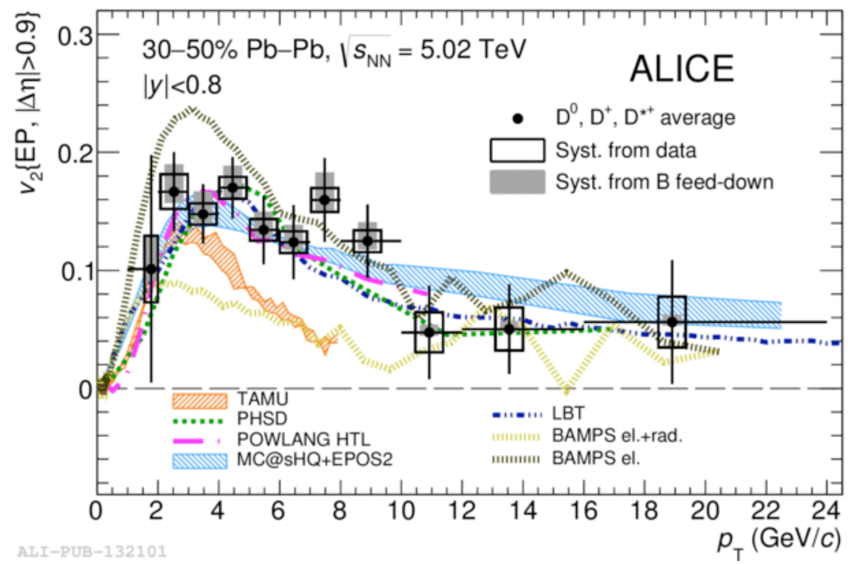




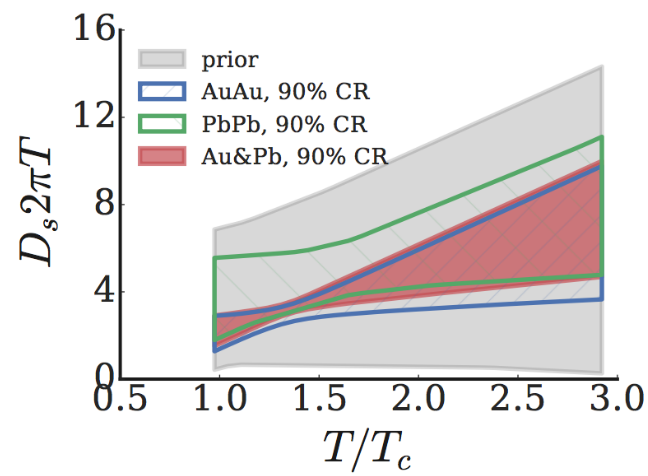
- Models where charm quarks pick up collective flow via recombination and/or subsequent elastic collisions in expanding hydrodynamic medium do better at describing both R_{AA} and v_2 at low p_T (BAMPS elastic, LBT, MC@sHQ +EPOS, TAMU, POWLANG, PHSD)
- Models that describe that data use:
  - Diffusion coefficient $2\pi T D_s(T)$ ≈ 1.5–7 at critical temperature T_c
  - Charm thermalization time τ_{charm}~3-10 fm/c

Constraining models with charm





- **Ongoing**: theoretical effort through Bayesian analysis to calibrate model parameters via model-data comparison
  - Find the optimal parameters that describe R_{AA} and v_2

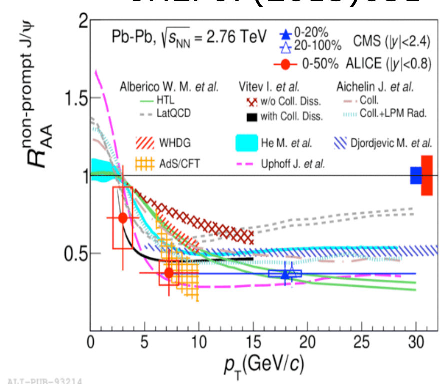


S. Bass et al. NP A 967 (2017) 67

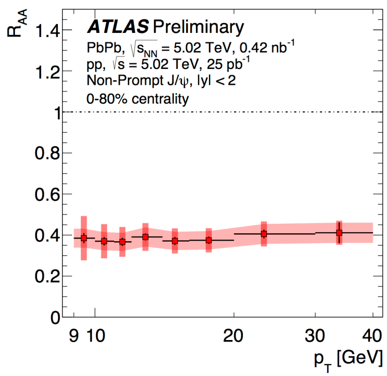
What about Beauty ?

- Energy loss measured well at high p_T
  - non prompt J/ψ, B meson, B jets, B → e+X

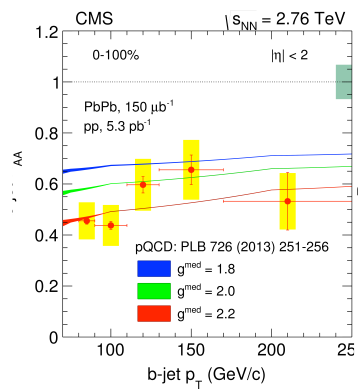
JHEP07(2015)051



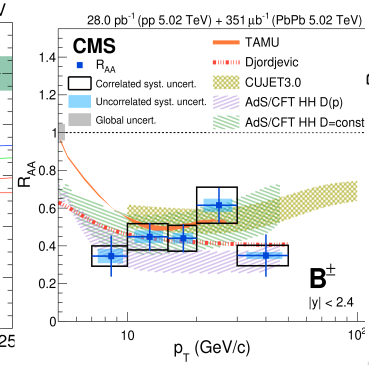
ATLAS-CONF-2016-109



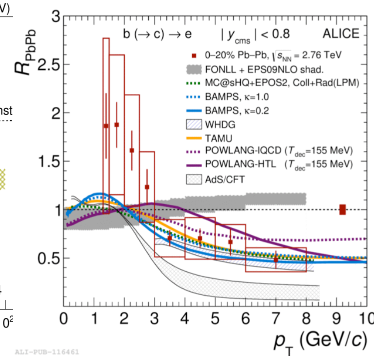
PRL 113 (2014) 132301



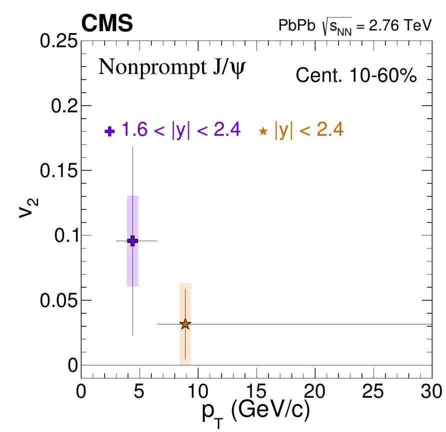
PRL 119 (2017) 152301



HEP 07 (2017) 052



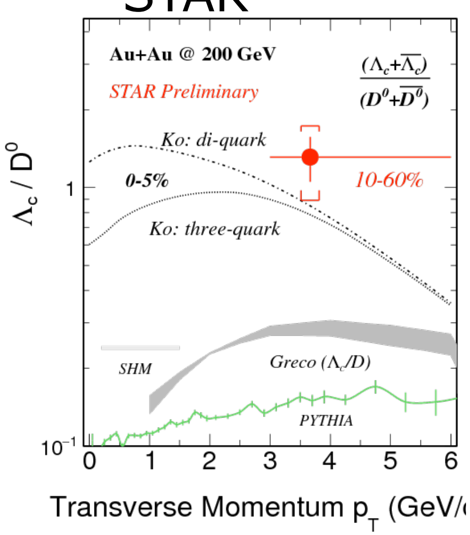
- Collectivity of beauty ?
  - likely answer only with LHC run3
  - more statistics and low p_t

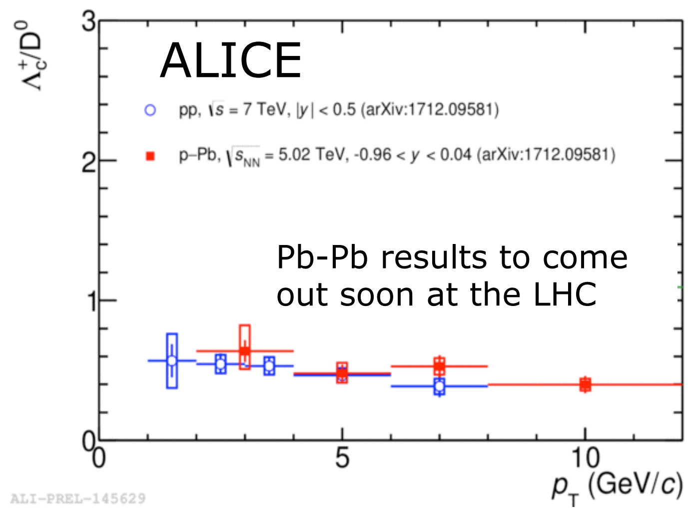


Hadronisation by quark coalescence ?

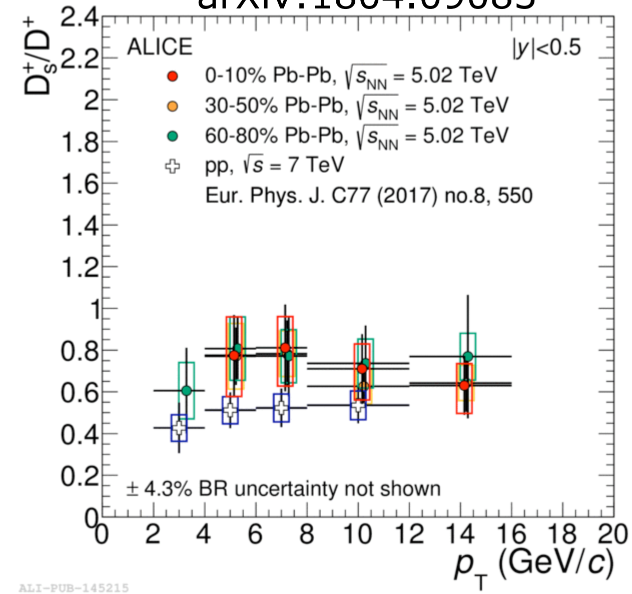
- hadrons can be formed by coalescence of quarks from the QGP
  - in the light sector: observation of baryon/meson enhancement
  - enhancement of strange particles
- D_s and Λ_c production relative to D^0 sensitive to this mechanism
  - Λ_c: preliminary results from STAR in Au-Au at 200 GeV

STAR



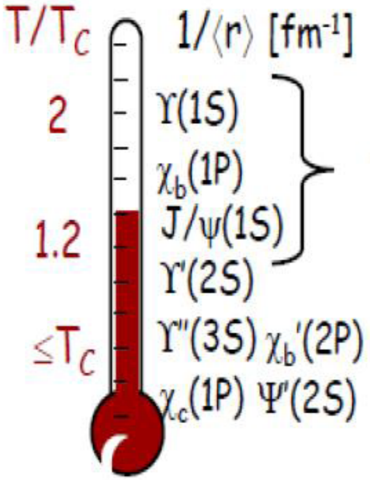


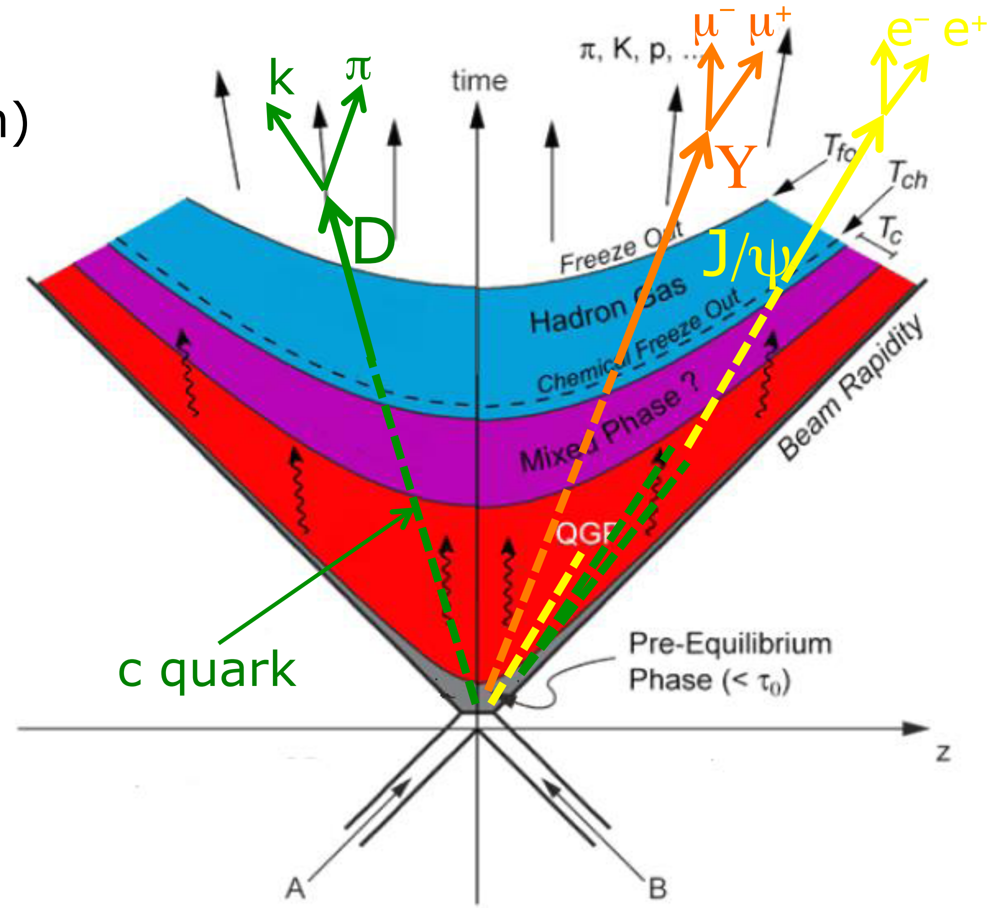
arXiv:1804.09083



Quarkonia

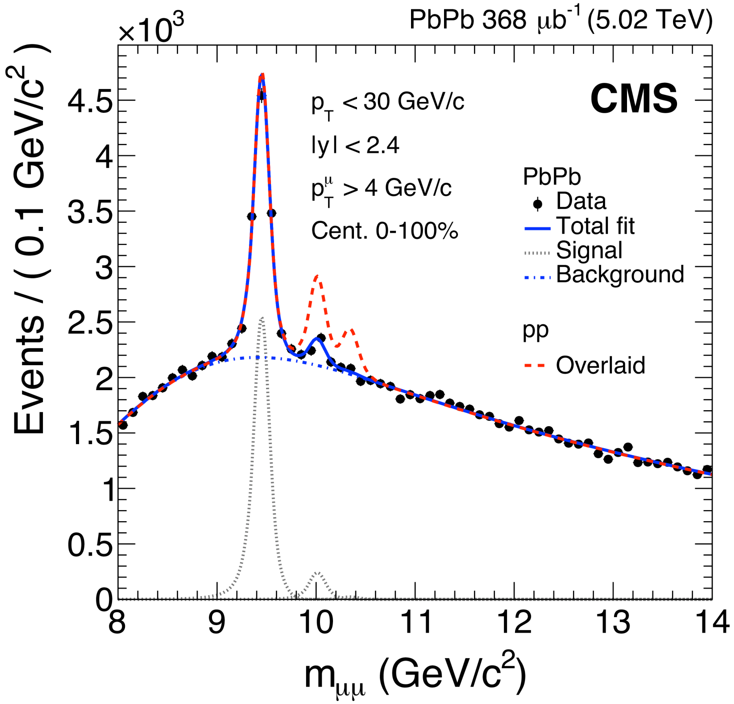
colour (Debye) screening in QGP
and $\bar{c}c$ recombination (charmonium)

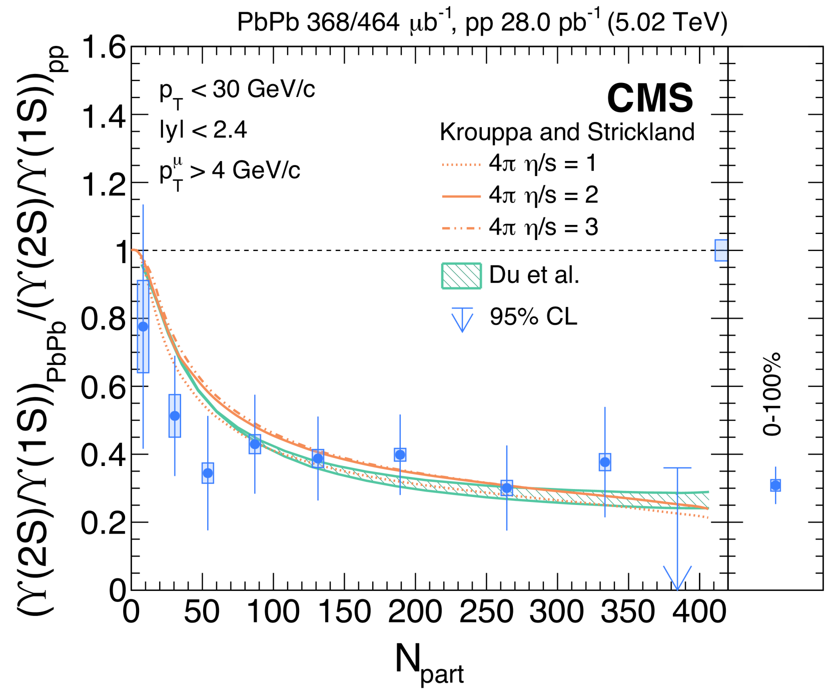




Upsilon sequential dissociation

PRL 120 (2018) 142301

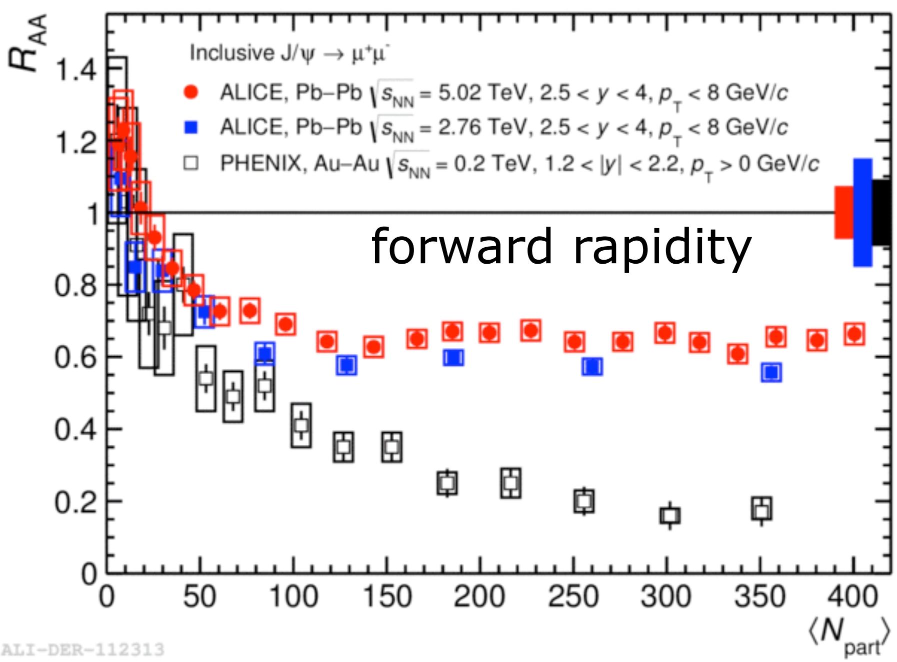


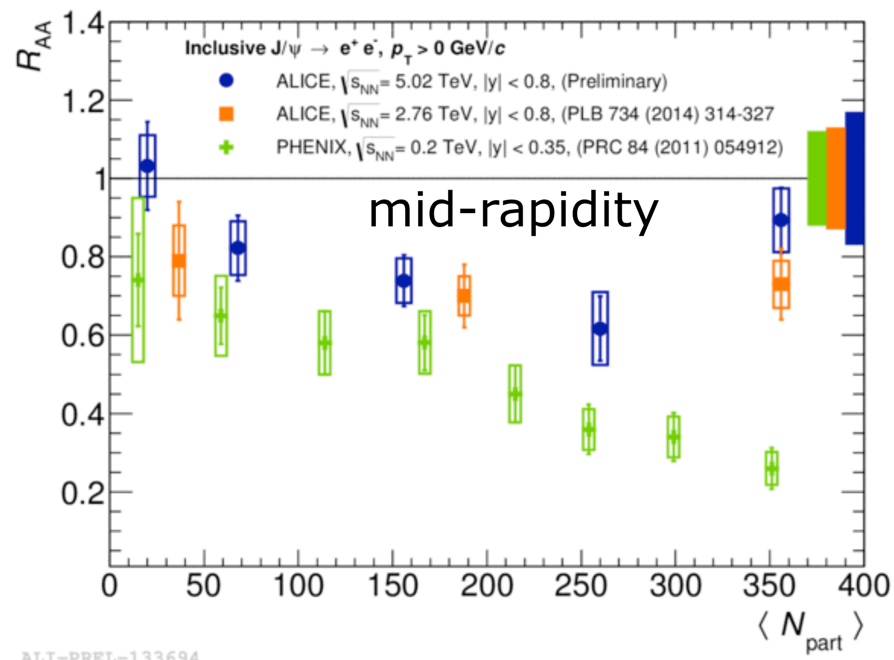


- double ratio measured to be less than 0.26 at 95% CL for the Υ(3S)
- no p_T dependence for the Υ(2S) double ratio

- Krouppa and Strickland: model with color-screening effects and feed-down contributions from decays of heavy quarkonia, plus hydro description (initial T of about 630 MeV) well describe data
- Du et al.: kinetic rate equation (regeneration important for 2S state)

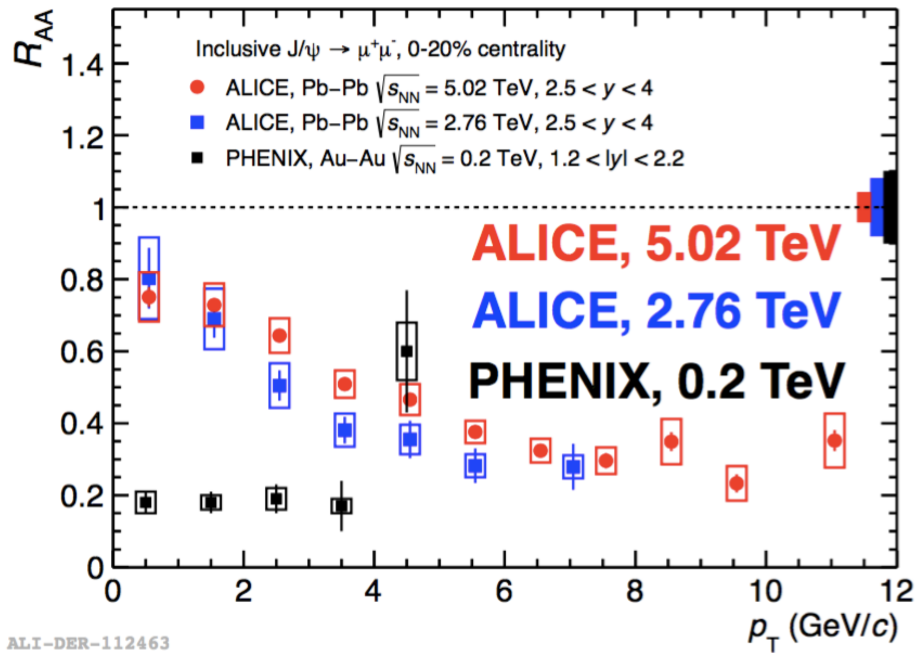
J/ψ production at $\sqrt{s_{NN}}$ = 5.02 TeV

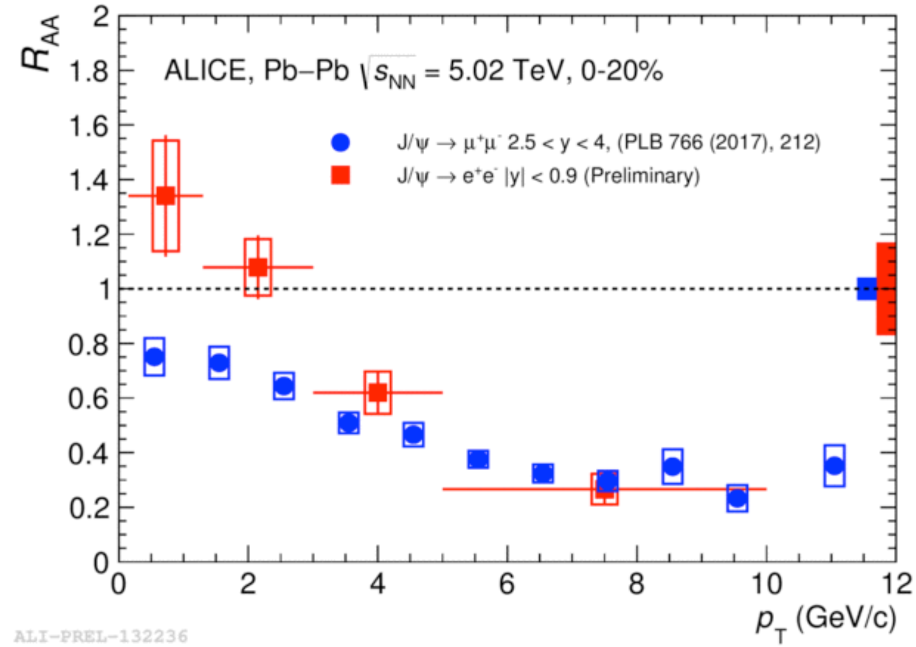




- At **2.76 TeV** a significant suppression w.r.t. pp was measured: expected as an effect of **colour screening** (melting of the charmonium state)
- The suppression is smaller than at **0.2 TeV**, in central collisions and low p_T: described by models with **re-generation from c quarks in the QGP**
- **New results at 5.02 TeV**: similar R_{AA} as at **2.76 TeV**
  - significantly increased precision at 5.02 TeV

J/ψ production at $\sqrt{s_{NN}}$ = 5.02 TeV





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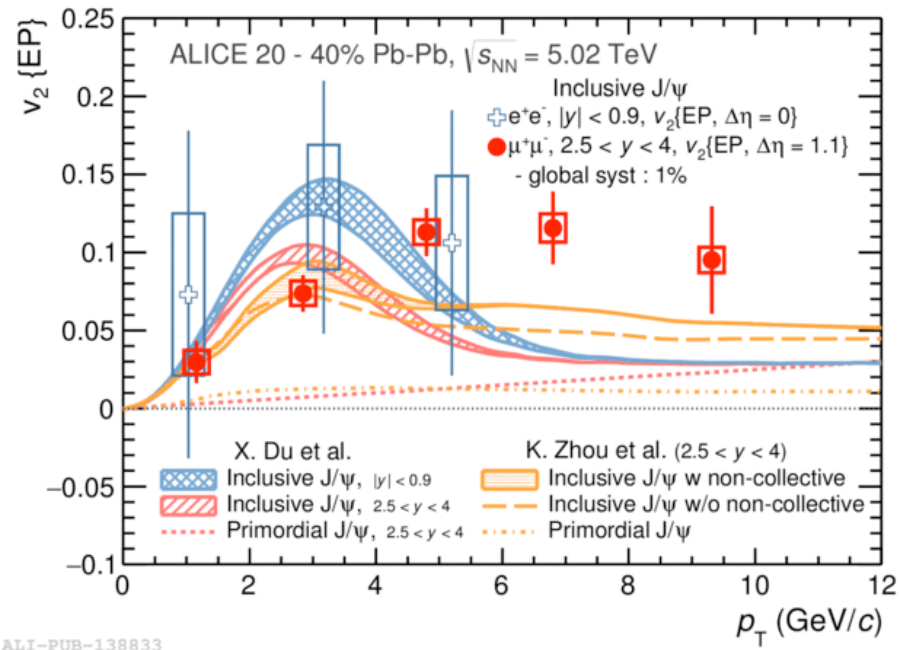
- **New results at 5.02 TeV**: similar R_{AA} as at **2.76 TeV**
  - R_{AA} at low p_t much larger than at RHIC energies
  - at low p_T lower reduction (or even enhancement) at mid- than forward rapidity → consistent **with regeneration scenario**

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 5.02 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*

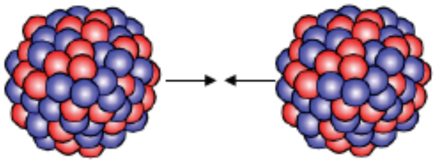


PRL 119 (2017) 242301

- Possible explanation: the large v_2 values measured can 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 …

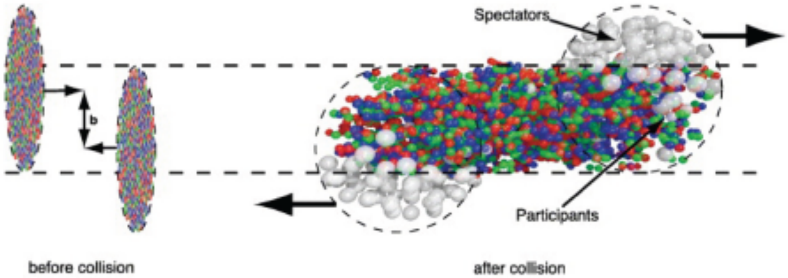
Small systems: pp and pPb

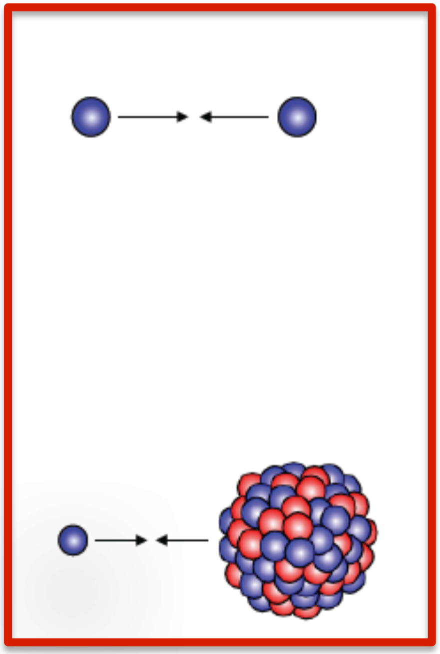
The paradigm



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

- Core business: create and characterize the QGP
- Centrality



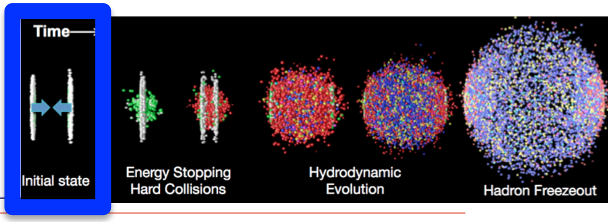


pp Collisions ($\sqrt{s}$ = 0.9 –13 TeV)

- Reference data

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

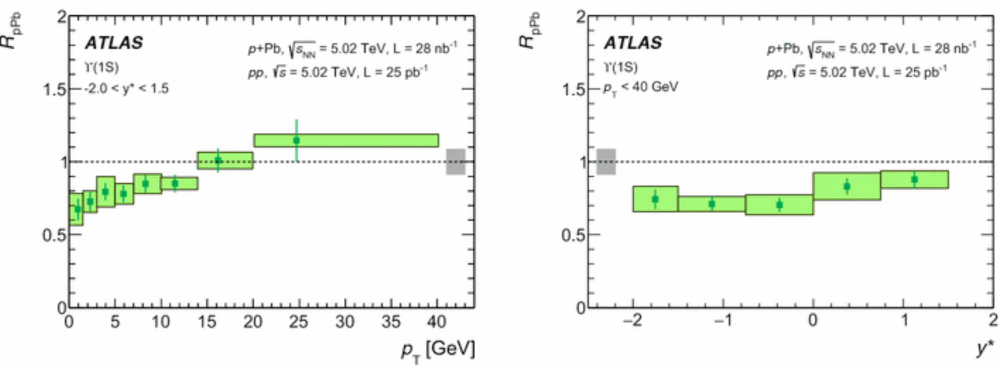
- Control experiment
- "Cold nuclear matter" effects (e.g. modifications to PDF)



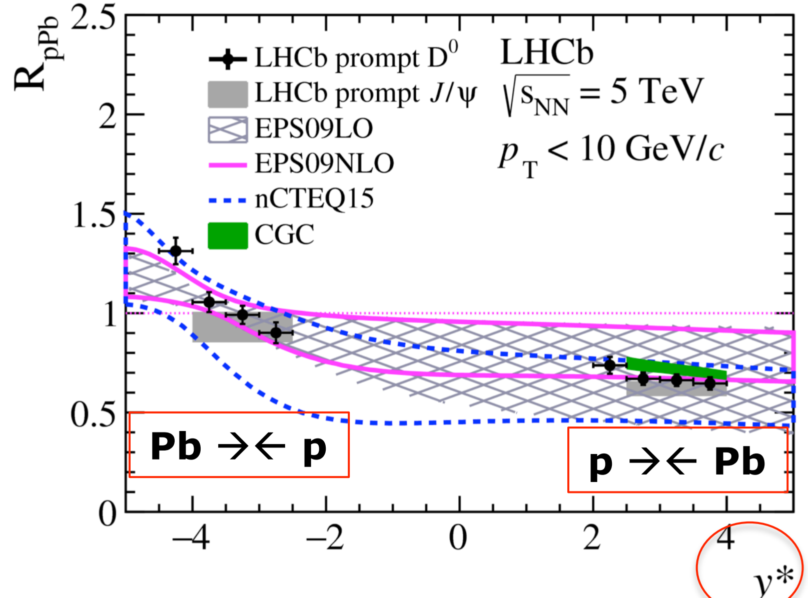
Two examples within the paradigm

- Upsilon production in p-Pb by ATLAS
- Prompt D^0 and prompt J/ψ at forward and backward rapidity with p-Pb and Pb-p by LHCb

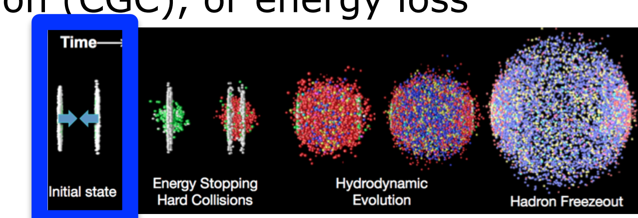
EPJ C (2018) 78 171



JHEP 10 090



- 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



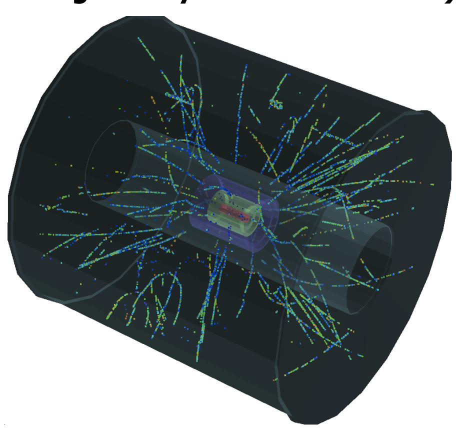
Small systems: pp and pPb

Revisiting the paradigm

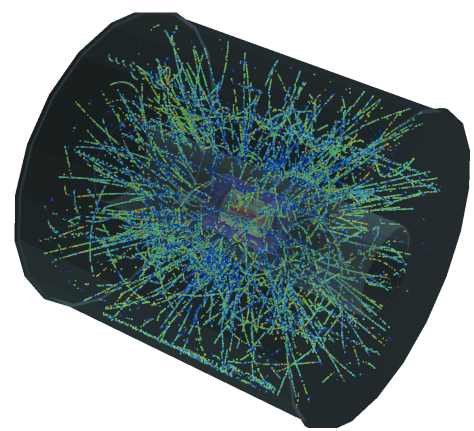
- striking properties observed in very high multiplicity p-Pb and pp collisions at LHC, which resemble those due to collectivity/ QGP-like properties of the Pb-Pb systems

one of the major surprise at the LHC so far

low multiplicity pp
(majority of events)

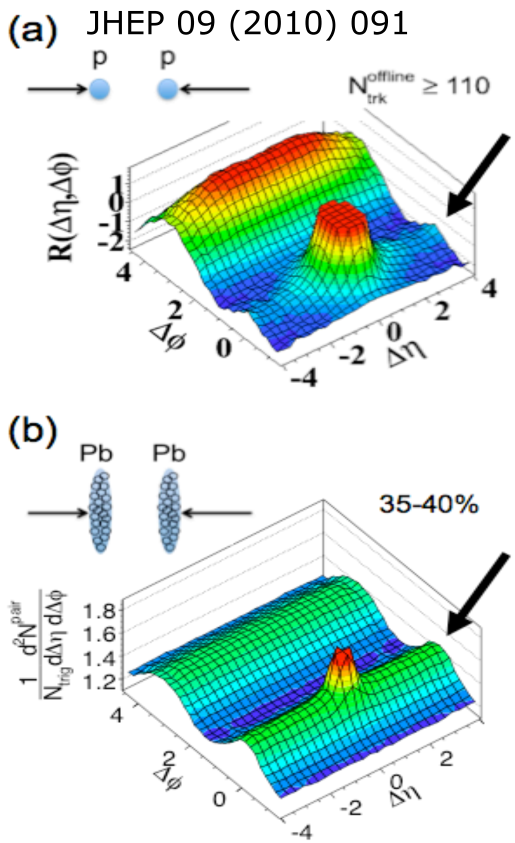


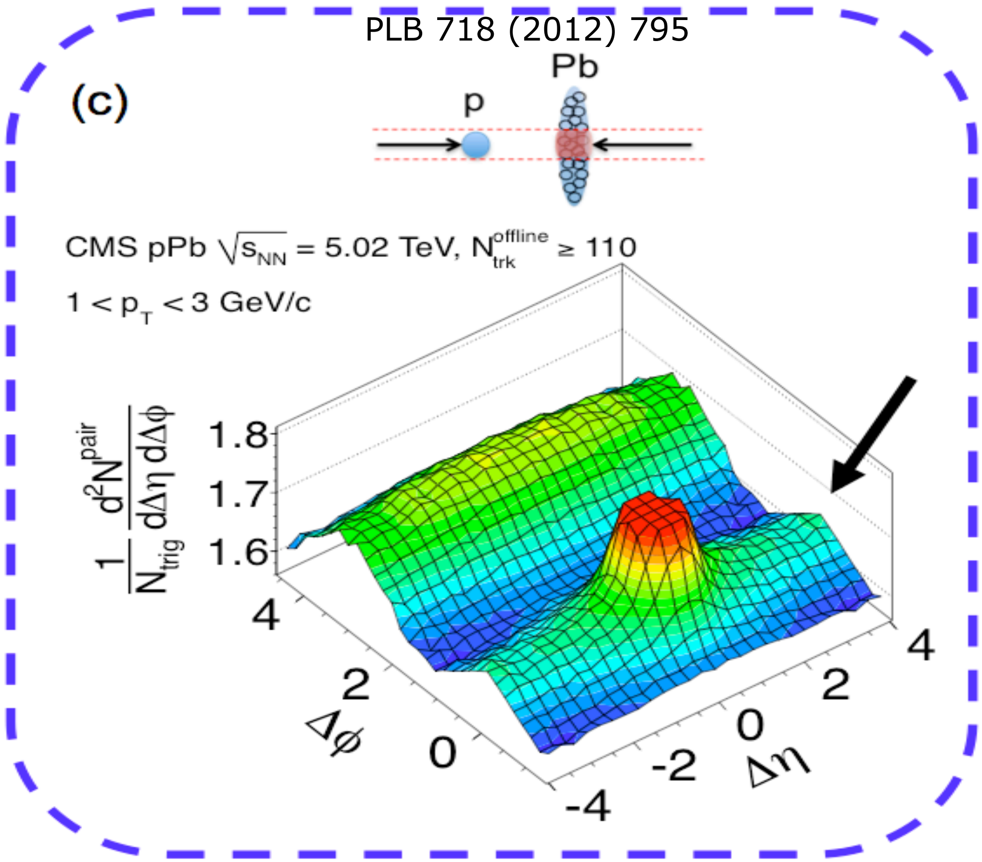
high multiplicity pp
(very rare events)



for instance

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

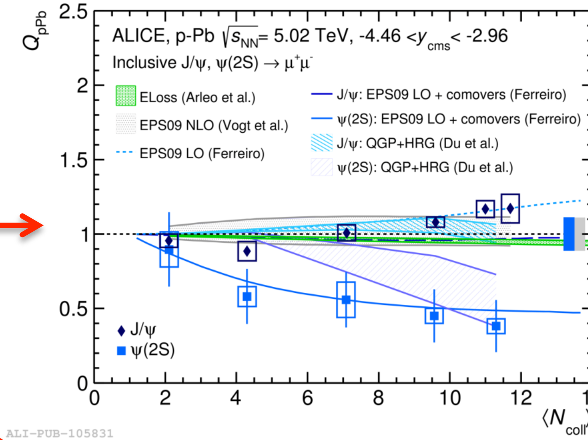


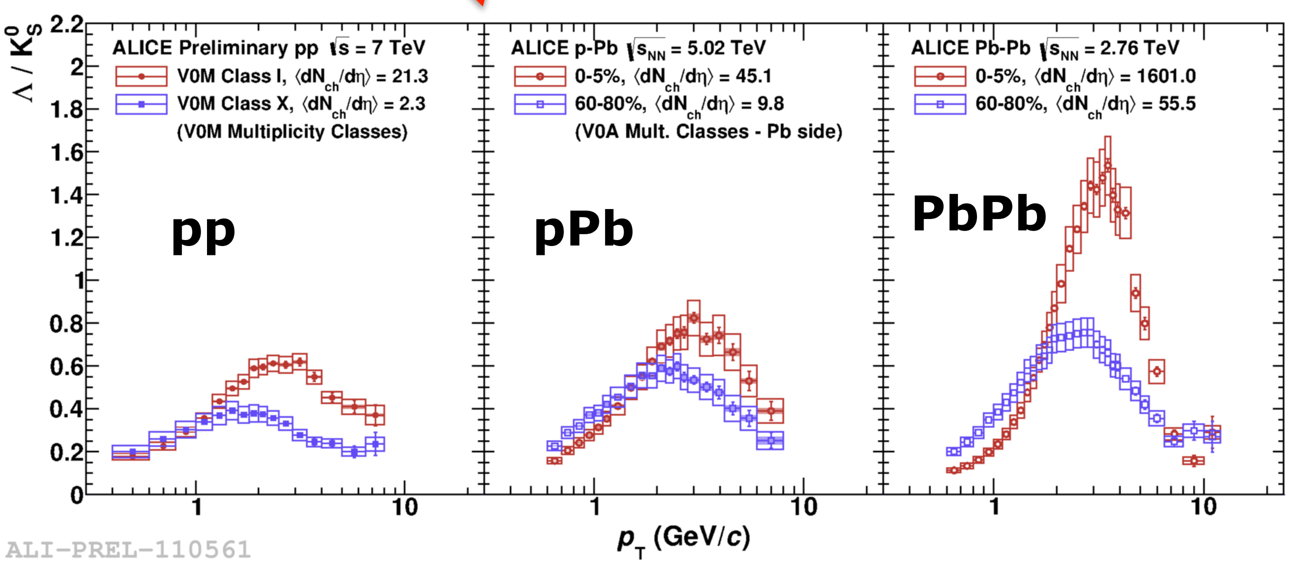


long range in $\Delta\eta$ indicates early time origin

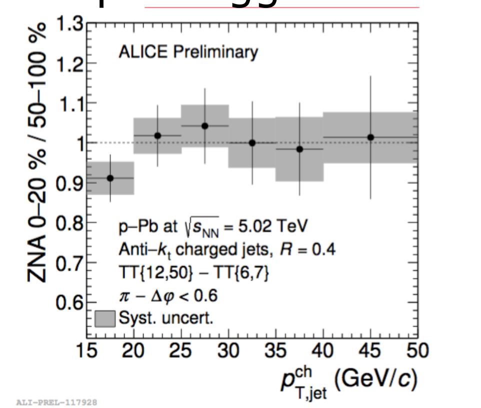
The intriguing small systems

- 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
- strangeness enhancement (next slide)
- but no sign of parton energy loss in a small QGP





Jets per trigger hadron

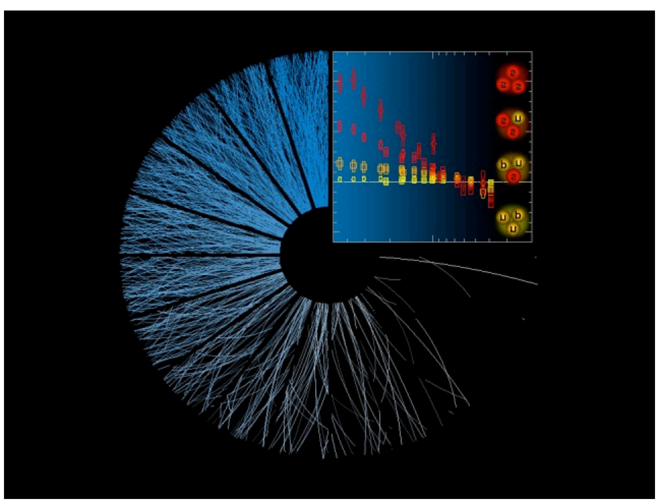


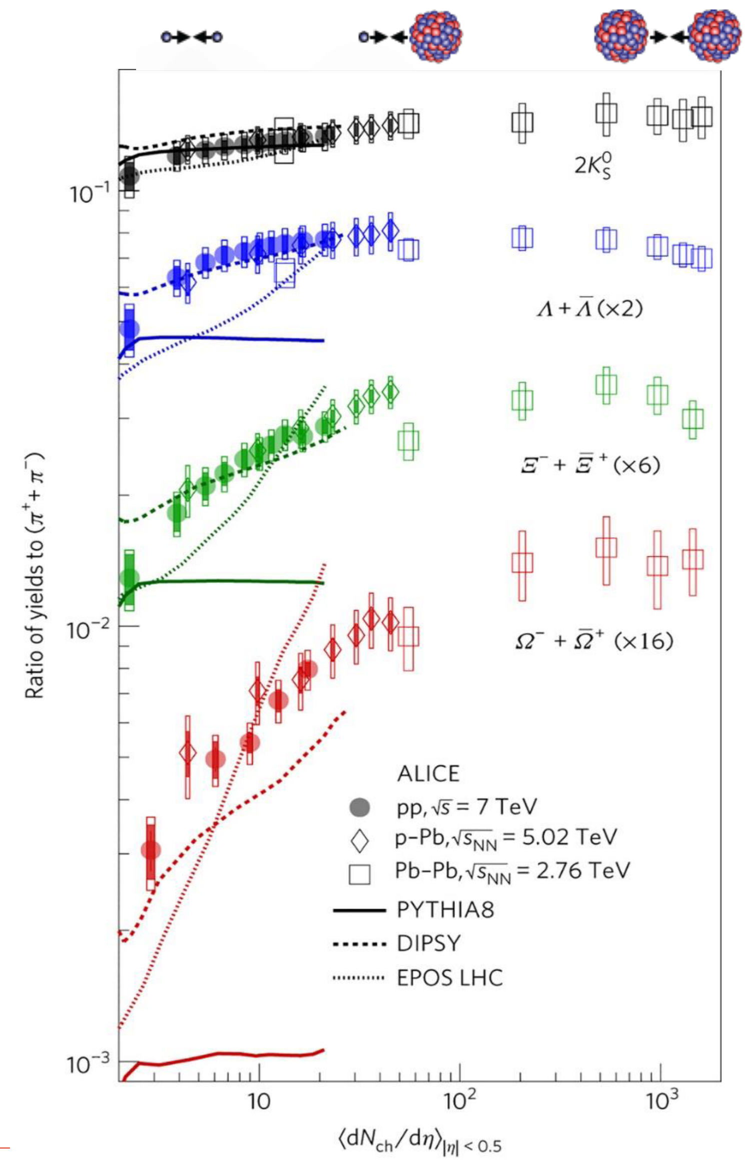
Strangeness enhancement in pp!

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

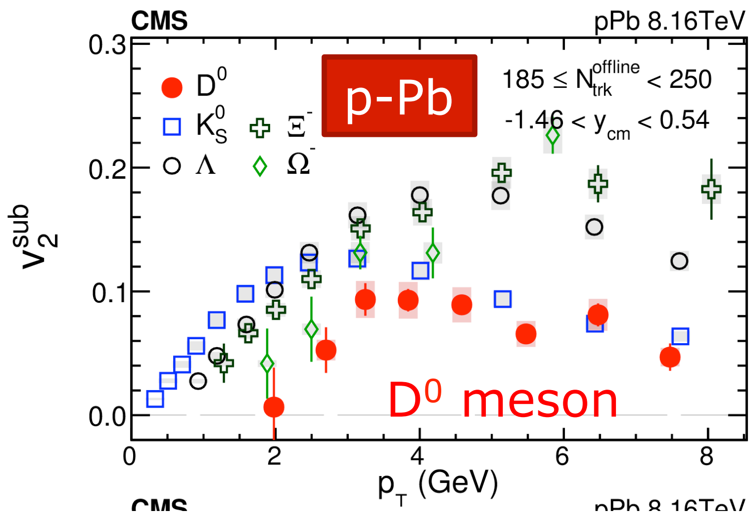
Nature Phys. 13 (2017) 535-539

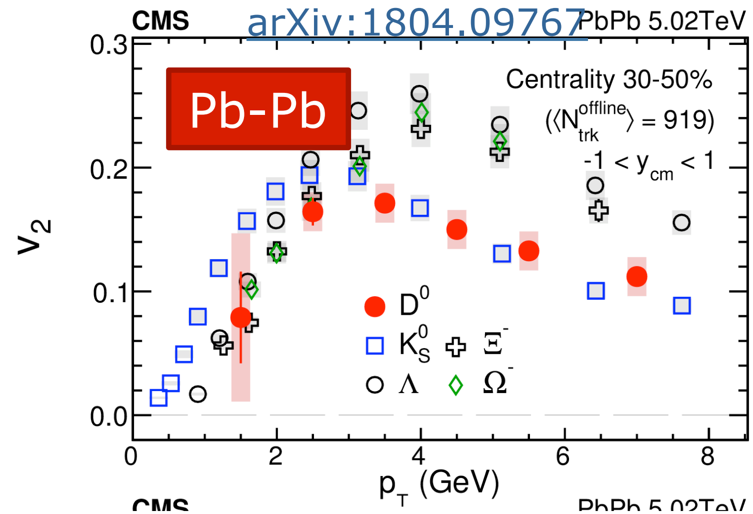
New ALICE experiment results show novel phenomena in proton collisions

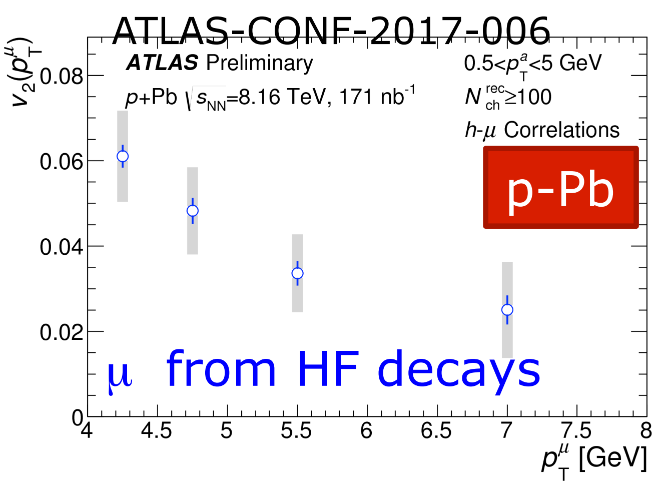


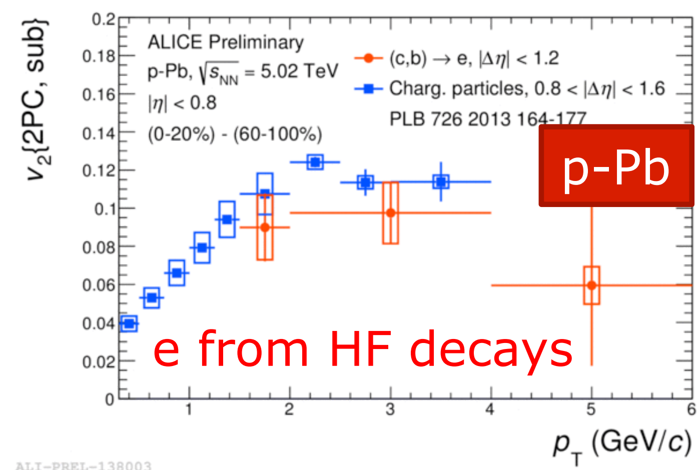


v_2 of HF hadrons in high multiplicity p-Pb events





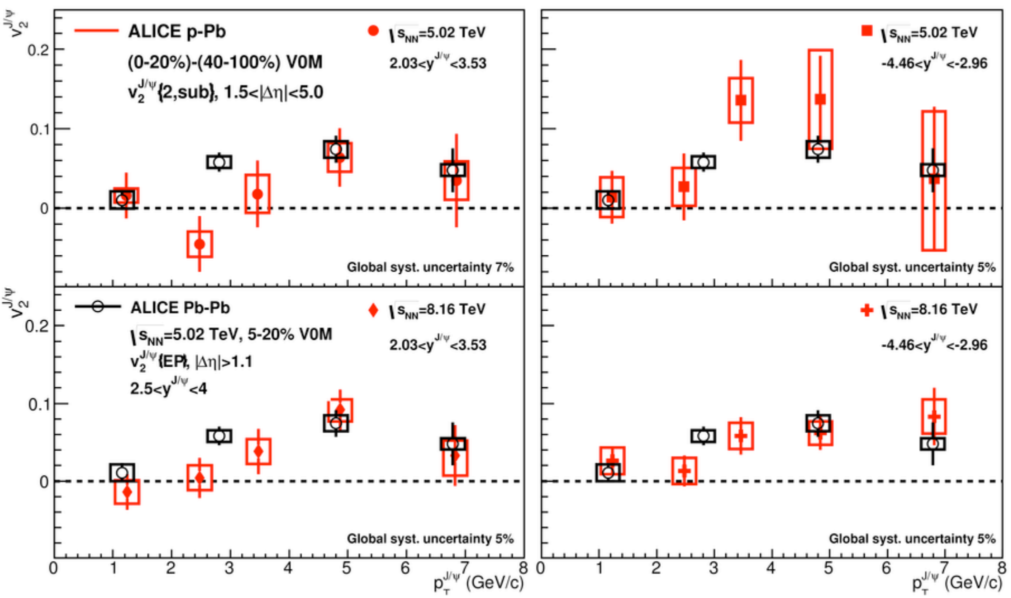


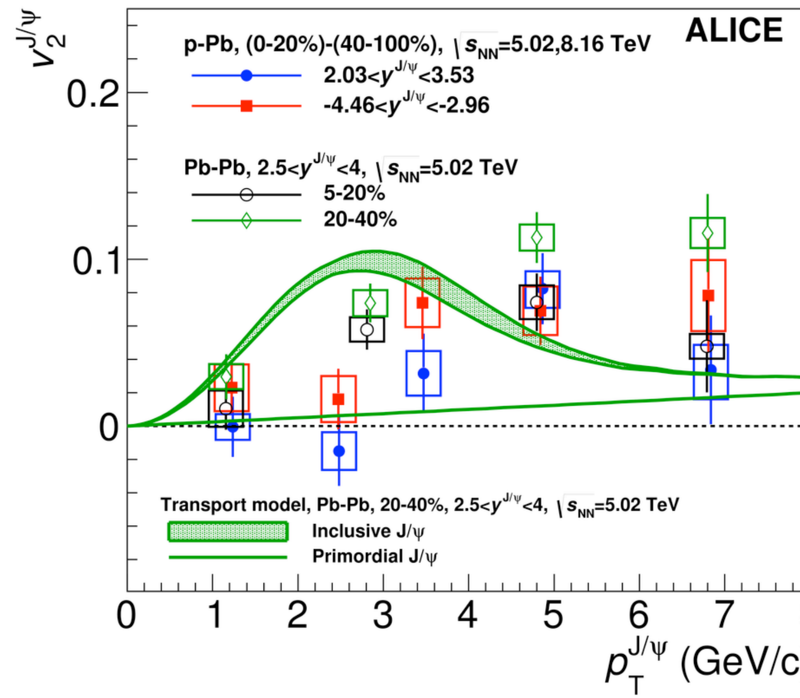


- open HF hadrons show collectivity in small systems
  - hints of smaller v_2 for charm quarks than lighter quarks

Collectivity also for J/ψ in pPb!

PLB 780 (2018) 7-20





- similar J/ψ v_2 coefficients as measured in Pb–Pb collisions
  - suggesting a common mechanism at the origin of the J/ψ v_2.

Summary, open questions and outlook

- LHC is already providing precise measurements in the HF sector
  - stringent constraints on the models describing the properties of the system (e.g., transport coefficients, η/s) and its dynamical evolution
  - Open questions:
    - are charm quarks fully thermalized ?
    - do also beauty quarks take part to collective dynamics?
    - how relevant is recombination/coalescence for beauty ?
- Small systems:
  - a new laboratory to study QCD in extreme conditions
    - how small can be a droplet of QGP and what are its properties ?
    - HF are key probes due to their short formation time
- Outlook: how to answer to open questions?
  - with next LHC runs and thanks to detector upgrades

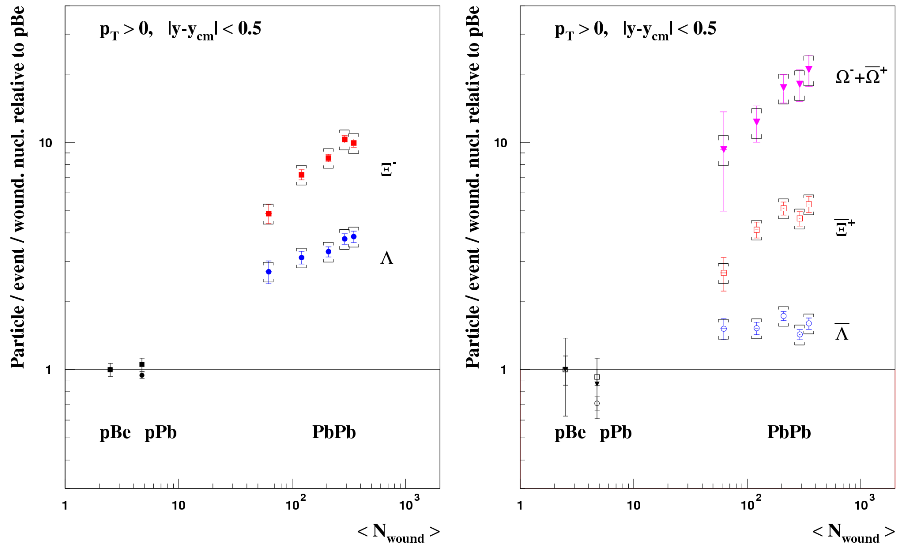
SPARES

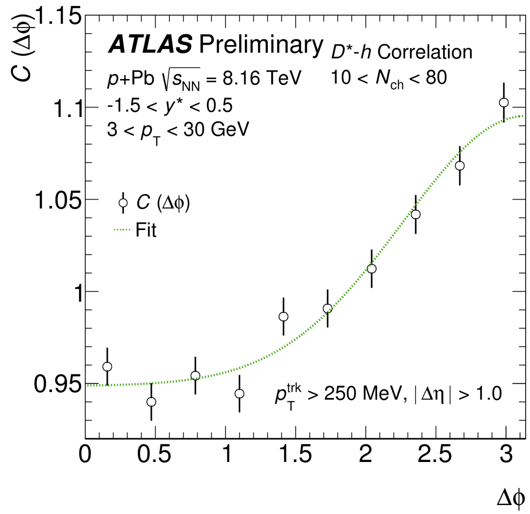
Strangeness enhancement

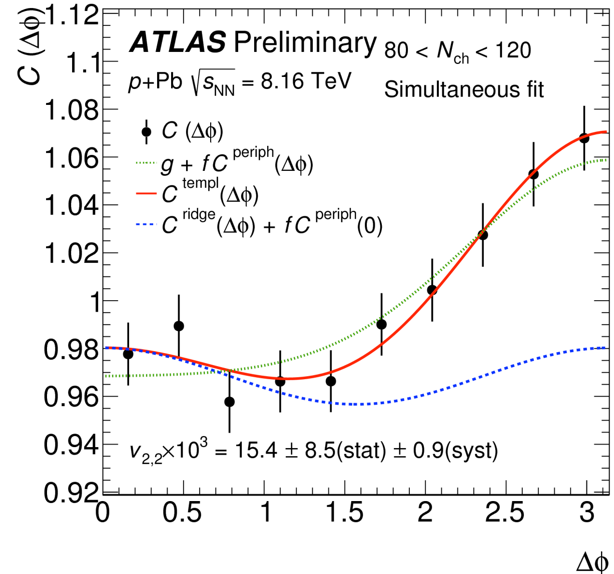
- Among first proposed signatures of the QGP
  - Rafelski, Müller, PRL48(1982)1066
- Observed in A-A at SPS, then at RHIC and LHC

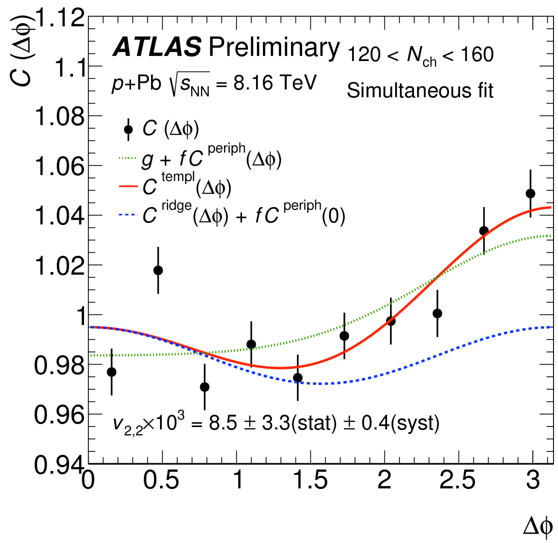
WA97/NA57, SPS

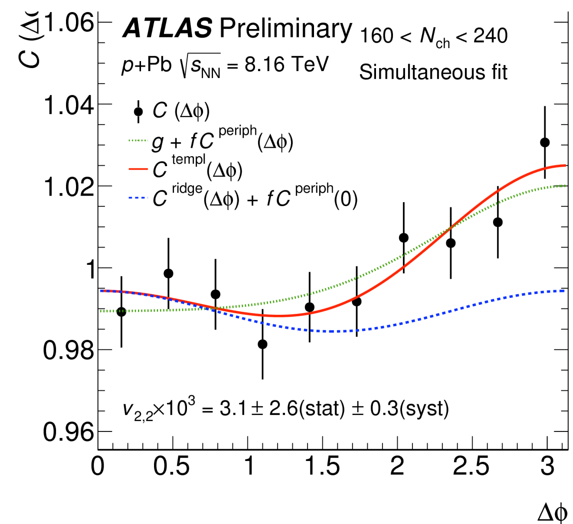
JPG 32, 427 (2006)



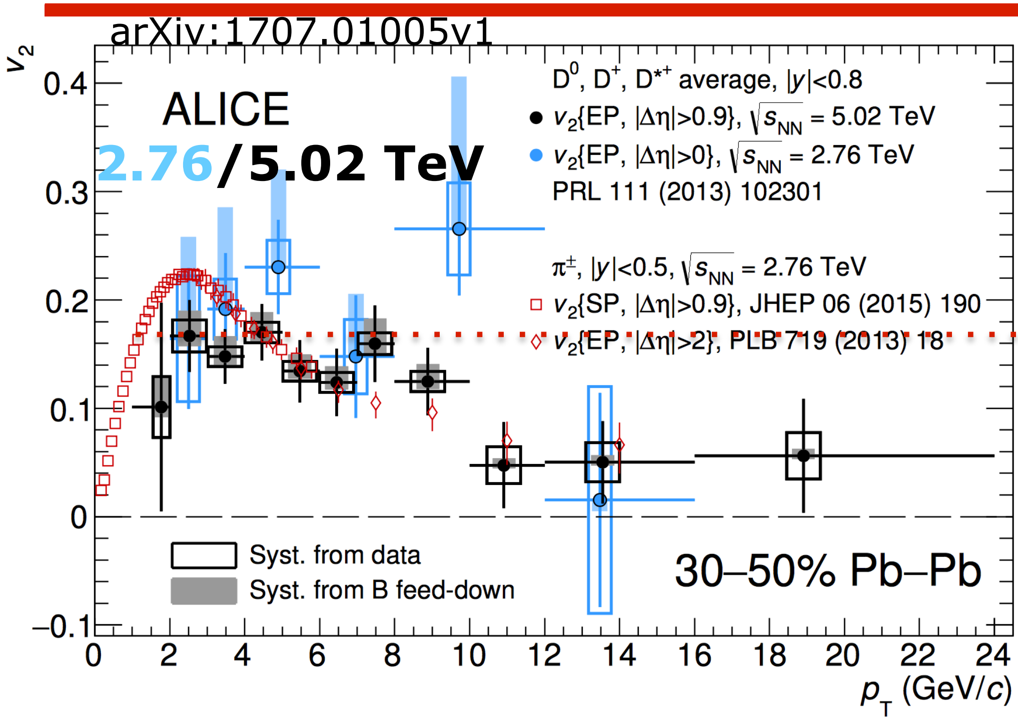

ATLAS Preliminary
D*-h Correlation
p+Pb √sNN = 8.16 TeV
10 < Nch < 80
-1.5 < y* < 0.5
3 < pT < 30 GeV
C (Δφ)
Fit
pTtrk > 250 MeV, |Δη| > 1.0
Δφ

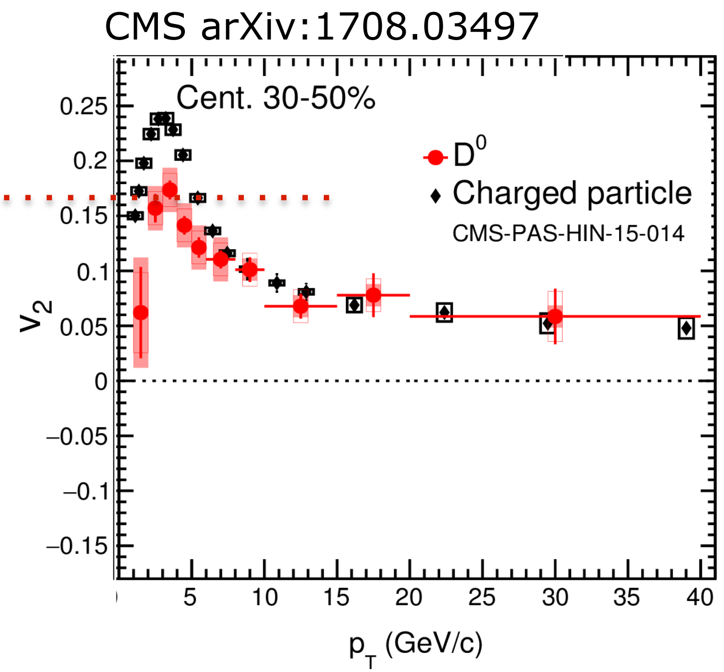

ATLAS Preliminary
80 < Nch < 120
p+Pb √sNN = 8.16 TeV
Simultaneous fit
C (Δφ)
g + f C periph(Δφ)
C templ(Δφ)
C ridge(Δφ) + f C periph(0)
v2,2×10^3 = 15.4 ± 8.5(stat) ± 0.9(syst)
Δφ


ATLAS Preliminary
120 < Nch < 160
p+Pb √sNN = 8.16 TeV
Simultaneous fit
C (Δφ)
g + f C periph(Δφ)
C templ(Δφ)
C ridge(Δφ) + f C periph(0)
v2,2×10^3 = 8.5 ± 3.3(stat) ± 0.4(syst)
Δφ


ATLAS Preliminary
160 < Nch < 240
p+Pb √sNN = 8.16 TeV
Simultaneous fit
C (Δφ)
g + f C periph(Δφ)
C templ(Δφ)
C ridge(Δφ) + f C periph(0)
v2,2×10^3 = 3.1 ± 2.6(stat) ± 0.3(syst)
Δφ

Evidence of charm flowing with the medium at LHC



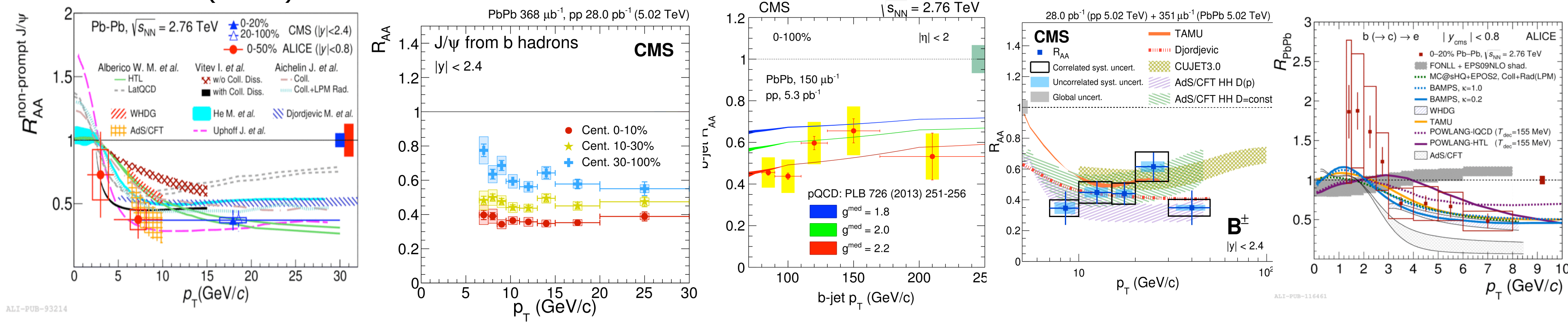


- final results from ALICE
  - much improved with respect to RUN2 data
- in agreement with CMS results (covering higher p_t range)
- D^0 v_2 < charged particle v_2

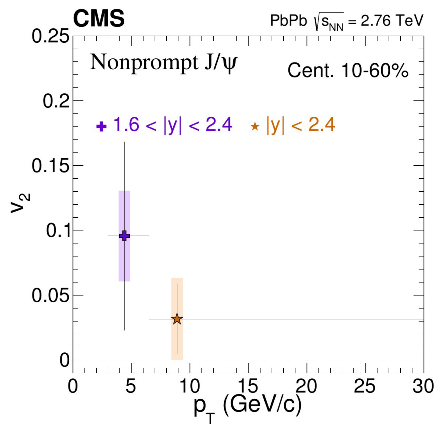
What about Beauty ?

- Energy loss measured well at high p_T
  - non prompt J/ψ, B meson, B jets, B → e+X

JHEP07(2015)051 arXiv:1712.08959 PRL 113 (2014) 132301 PRL 119 (2017) 152301 HEP 07 (2017) 052

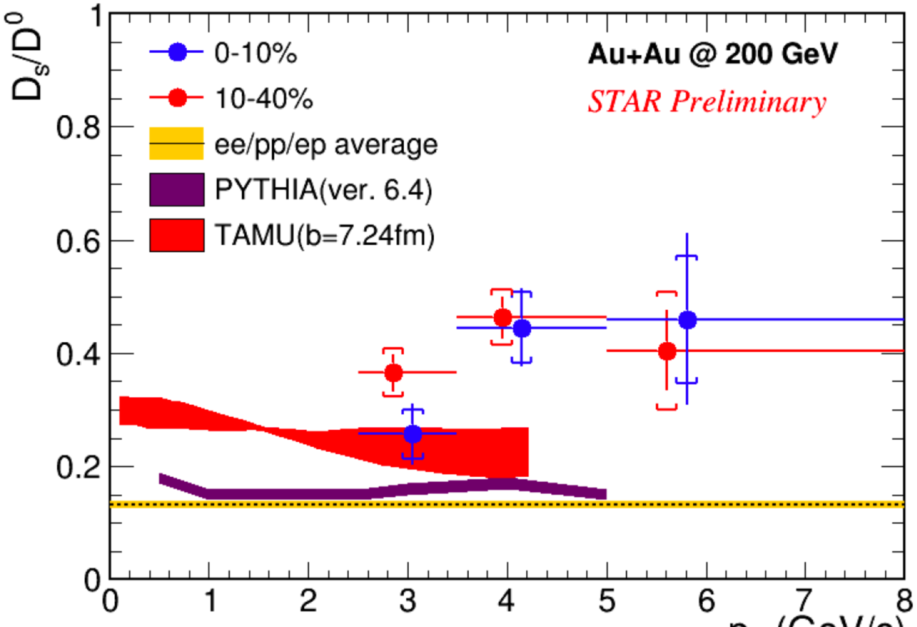


- Collectivity of beauty ?
  - likely answer only with LHC run3
  - more statistics and low p_t

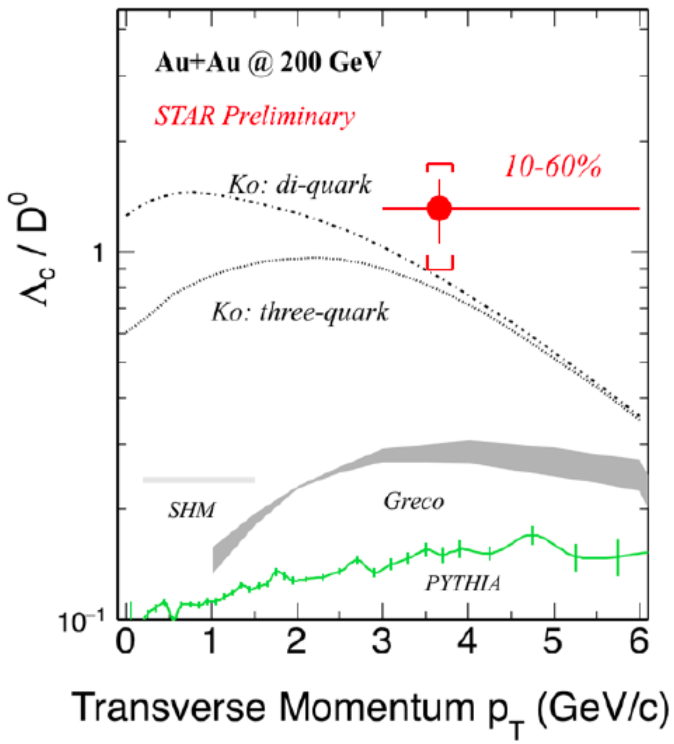


D_s and Λ_c at RHIC

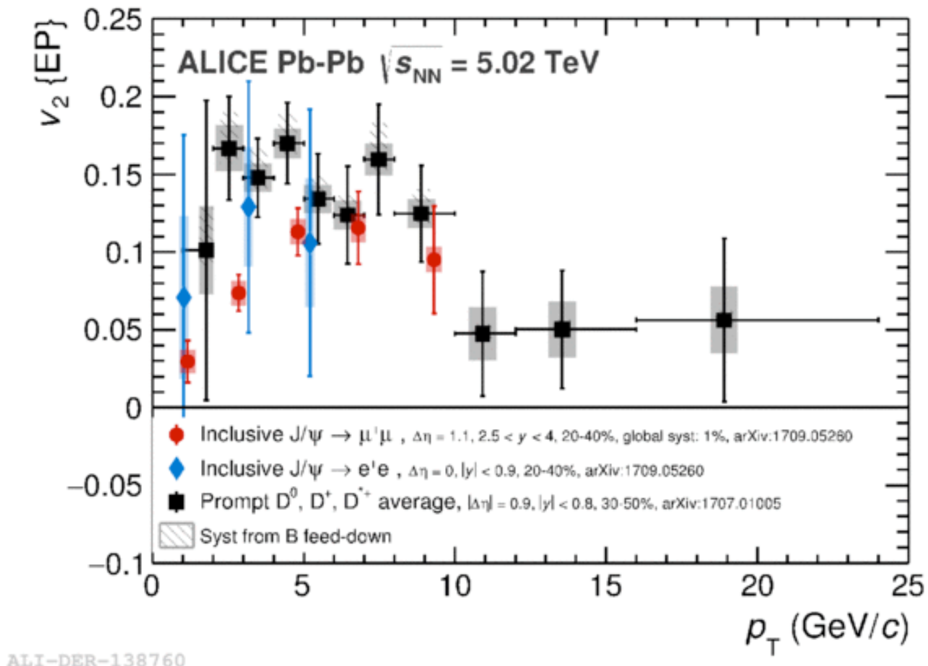
- similar results as at the LHC



TAMU: H. Min et al. PRL 110, 112301 (2013)



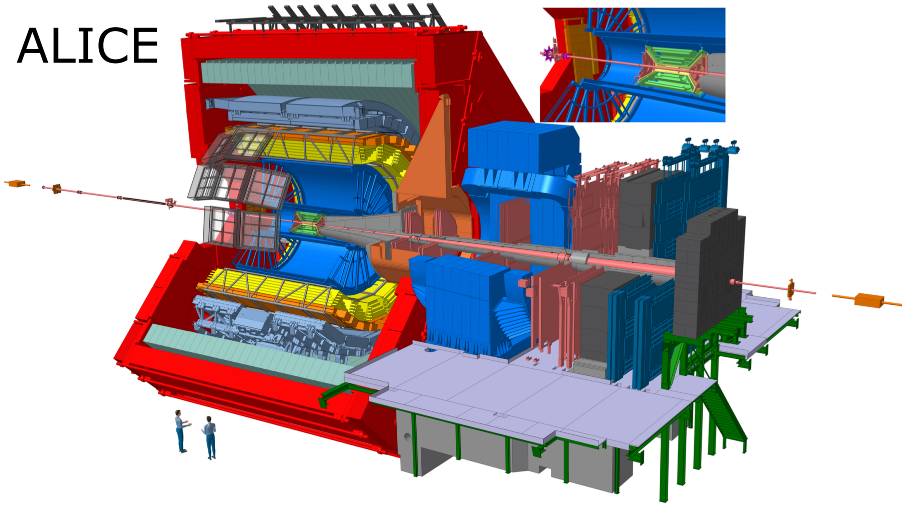
Hidden versus Open charm v2



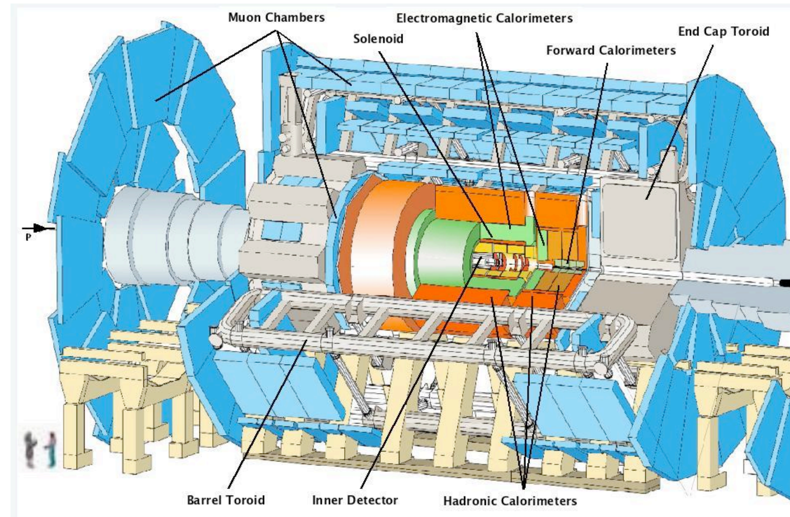
- Similar magnitude
- Consistently suggesting that charm quark flows!

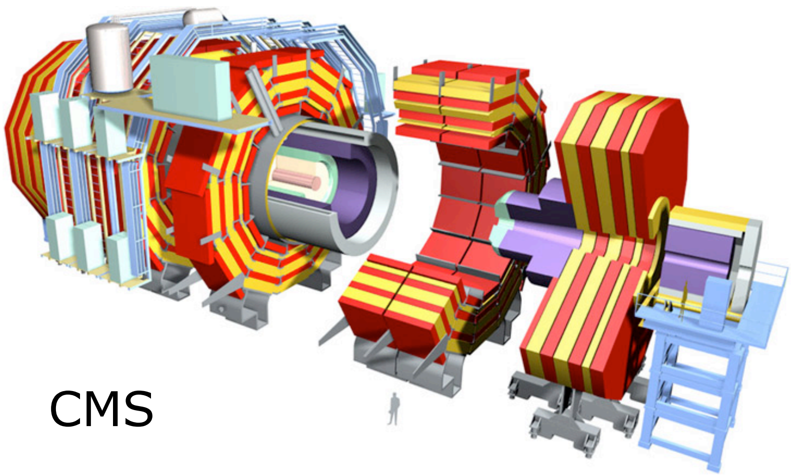
The LHC experiments with HI program

ALICE



ATLAS





CMS

LHCb