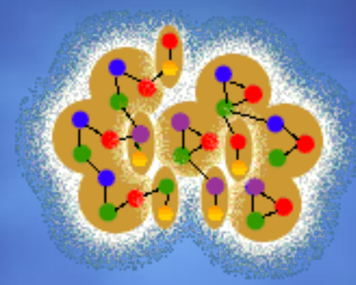


ALICE and the early universe

André Mischke (Utrecht University)
for the ALICE Collaboration

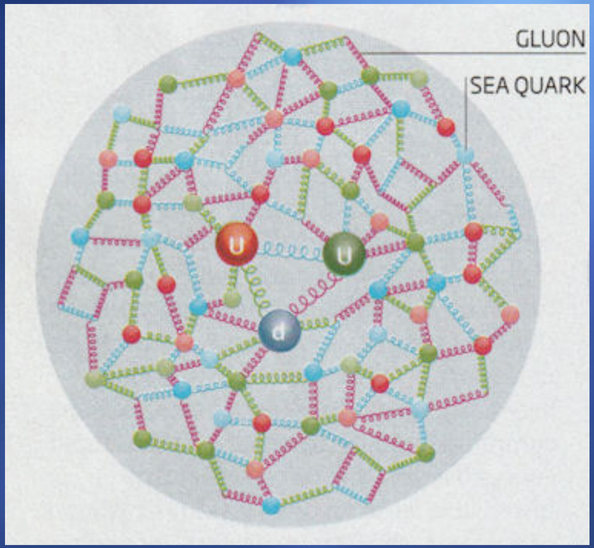
Galileo Galilei Institute Conference "Collider Physics and the Cosmos", Arcetri, Florence, Italy, 9-13 October 2017

Outline

- Strongly interacting matter in extreme conditions: the quark-gluon plasma
- Measuring apparatus and methodology
- Recent measurements
  - Global event observables
  - Hard probes and quarkonia
- Summary and outlook

Quark confinement

- Strong interaction described by Quantum Chromodynamics
- Quarks are confined into hadrons
- Asymptotic freedom



Proton and neutron are colour neutral states

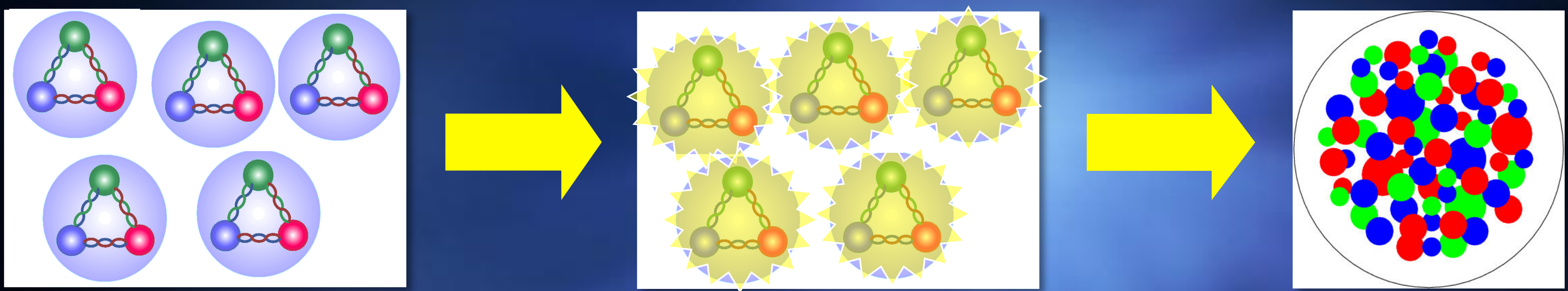
$$V(r) = -\frac{4}{3}\frac{\alpha_s(r)}{r} + kr$$

$$k = 1\ \mathrm{GeV/fm}$$

How can we liberate quarks?

Create a plasma of quarks and gluons

The quark-gluon plasma (QGP)

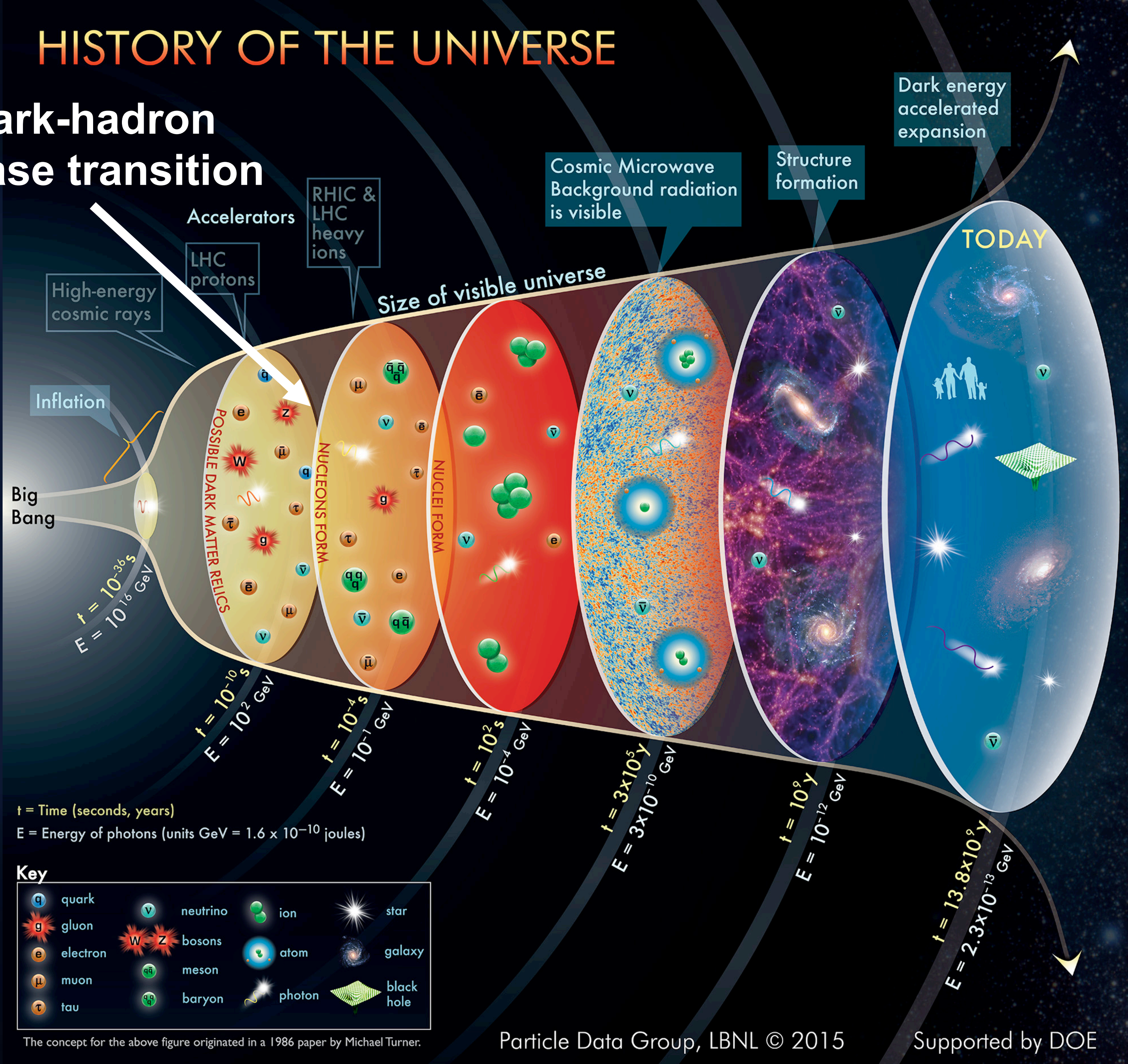


Heat and pressure

Phase transition to QGP
$T \approx 10^{12}$ K $\approx 10^5$x sun's core

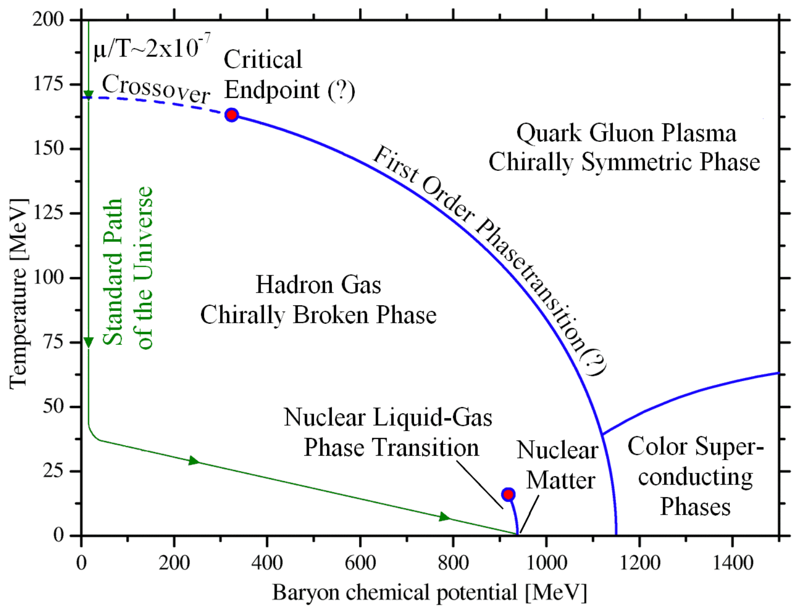
- Primordial state of matter: quarks and gluons are liberated (deconfinement)
- Evolution of the **early universe**
  - QGP may still exist in neutron stars

Quark-hadron phase transition

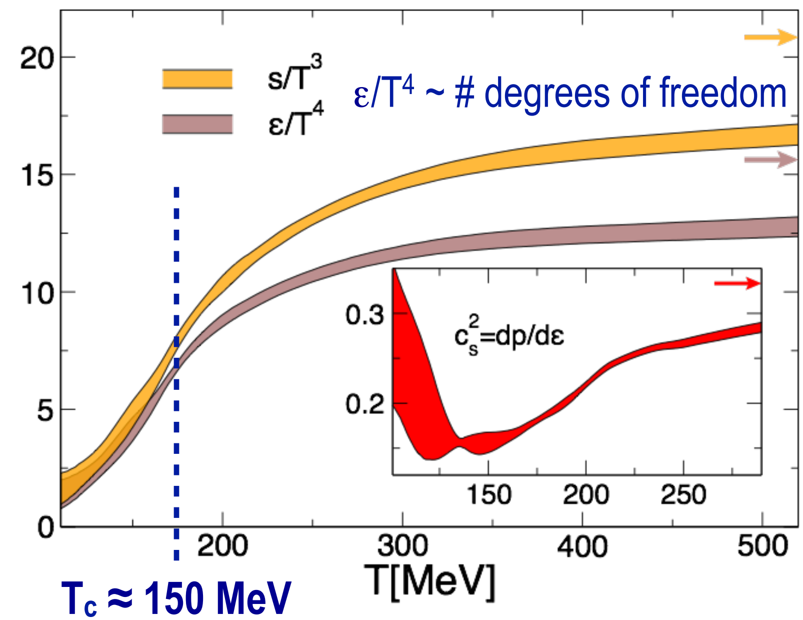


QCD phase diagram of hadronic matter

T. Boeckel, J. Schaffner-Bielich, PRD 85 (2012) 103506



A. Borsányi et al, Phys. Lett. B730, 99 (2014)

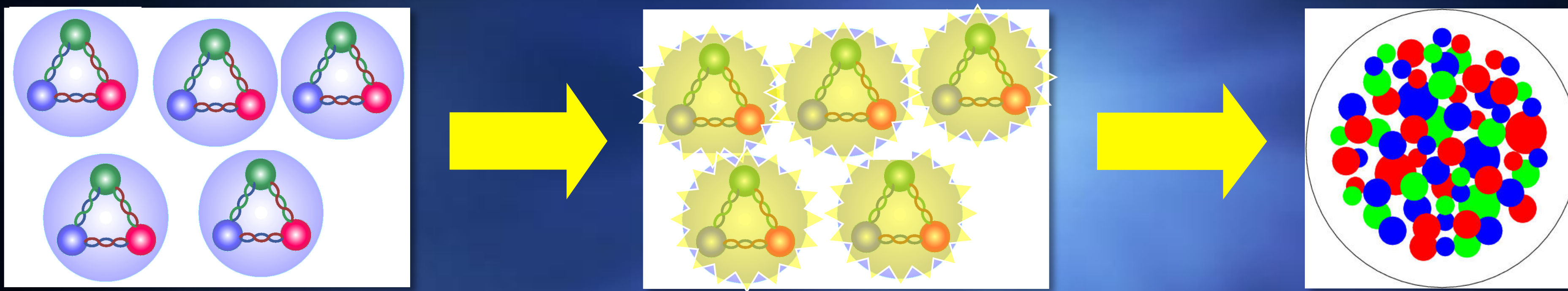


- QCD matter at extreme conditions: high temperature and/or high density
- Deconfined strongly interacting matter with color degrees of freedom
- Restoration of chiral symmetry breaking: hadrons are much heavier than their constituents

- QGP properties are in principle calculable from the QCD Lagrangian using lattice QCD
- Critical energy density $\varepsilon_C = (6 \pm 2) T_C^4$

P. Braun-Munzinger et al., Phys. Rep. 621, 76 (2016)
J. Schukraft and R. Stock, Adv. Ser. Direct. High Energy Phys. 23, 61 (2015)
N. Brambilla et al., Eur. Phys. J. C74, 2981 (2014)

The quark-gluon plasma (QGP)



Heat and pressure

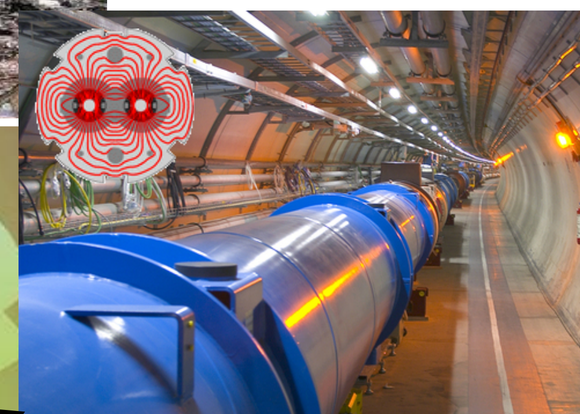
Phase transition to QGP
T ≈ 10^{12} K ≈ 10^{5}x sun's core

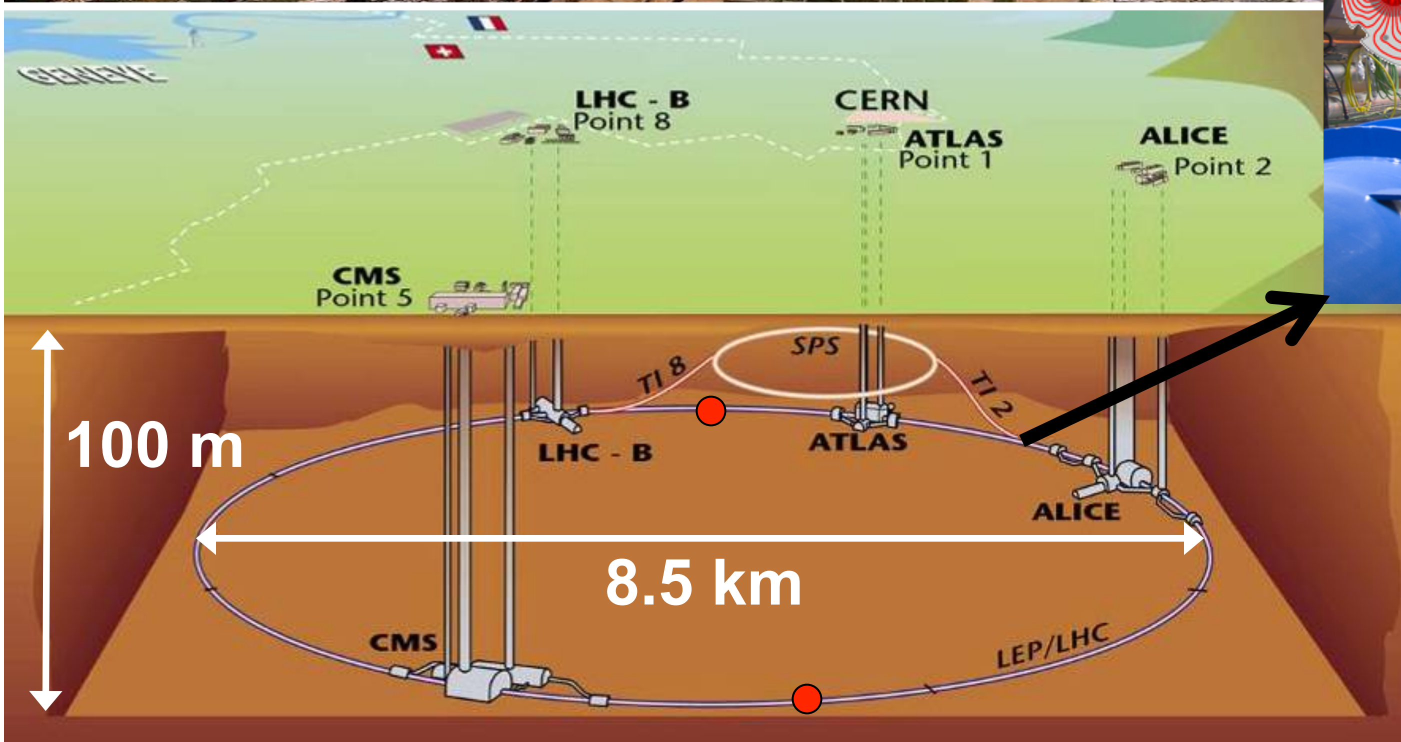
- Primordial state of matter: quarks and gluons are liberated (deconfinement)
- Evolution of the early universe
- Produce and study QGP in the laboratory
  - high density and temperature
  - sufficient large reaction volume

→ Collisions of heavy atomic nuclei, e.g. Pb^{208} and Au^{197}

Large Hadron Collider (LHC) at CERN

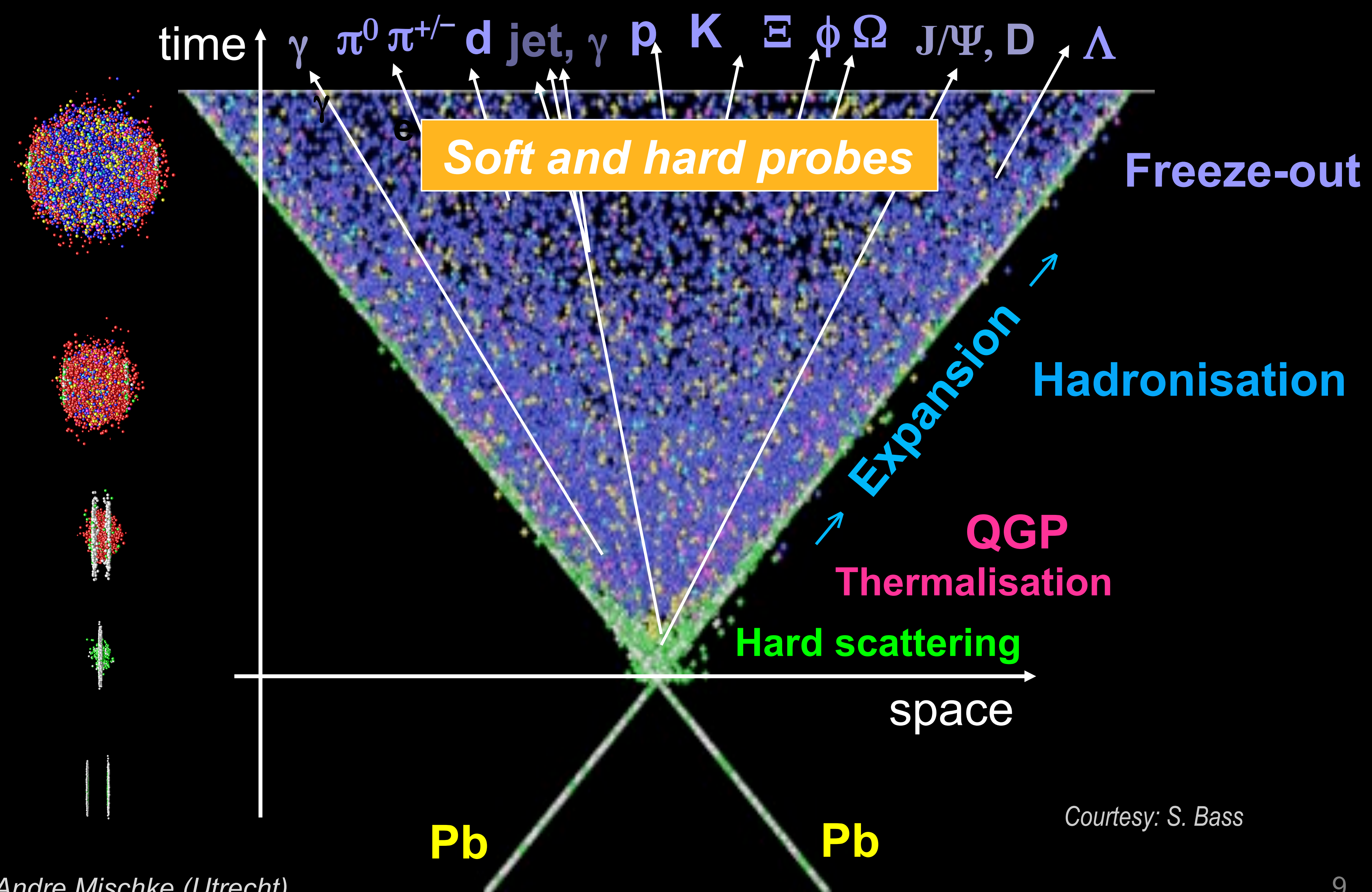
- 1232 dipole magnets
- Two counter-rotating beams
- Operation with super-fluid helium at 1.9K (~120t)
- 8 Tesla bending field



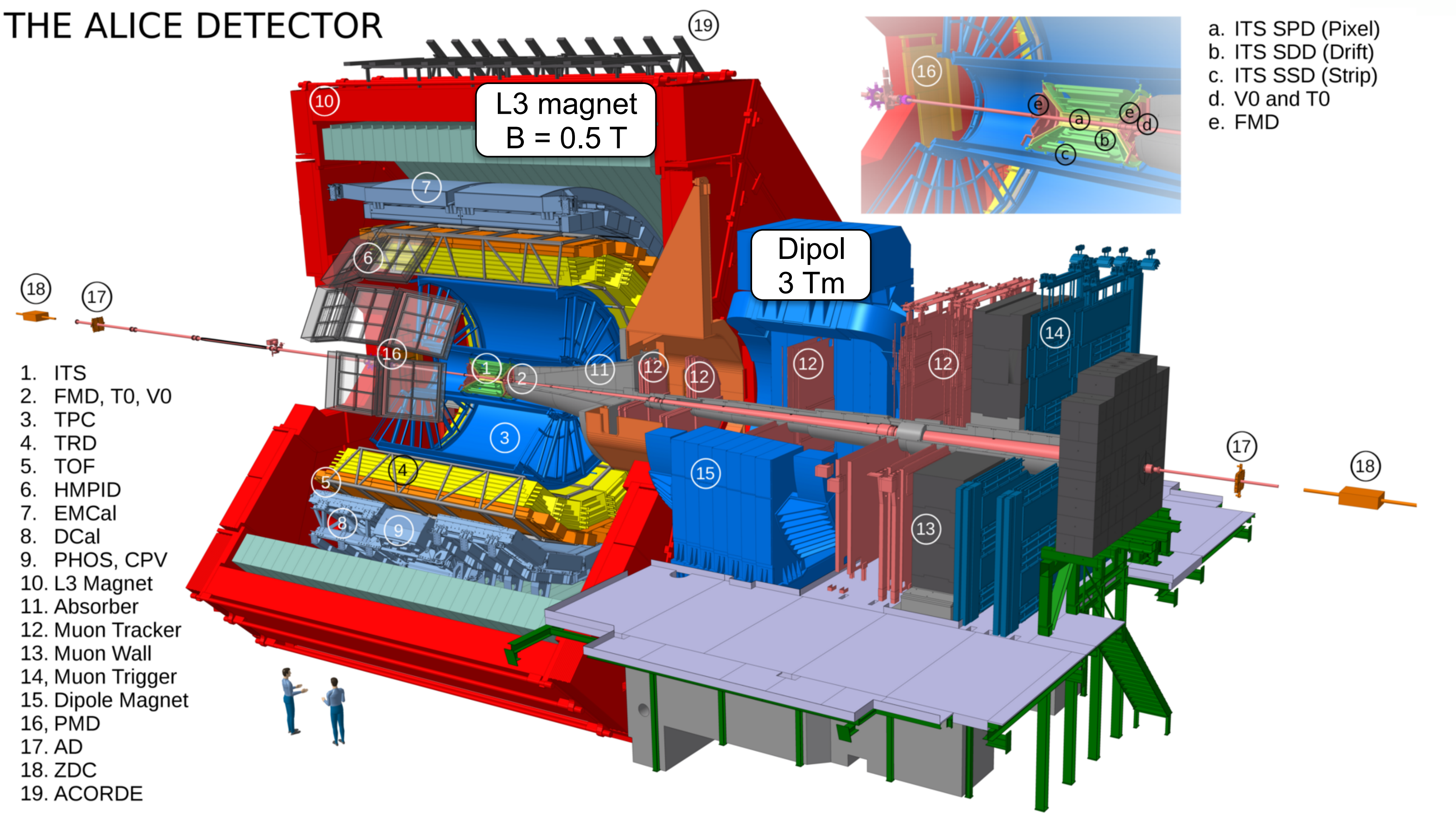


- Data taking since November 2010
- Systems and energies
  - Pb-Pb, $\sqrt{s_{NN}}$ = 2.76, 5.02 TeV
  - pp, $\sqrt{s}$ = 0.9, 2.36, 2.76, 5, 7, 8, 13 TeV
  - p-Pb, $\sqrt{s_{NN}}$ = 5.02, 8.16 TeV

Space-time evolution of a heavy-ion collision

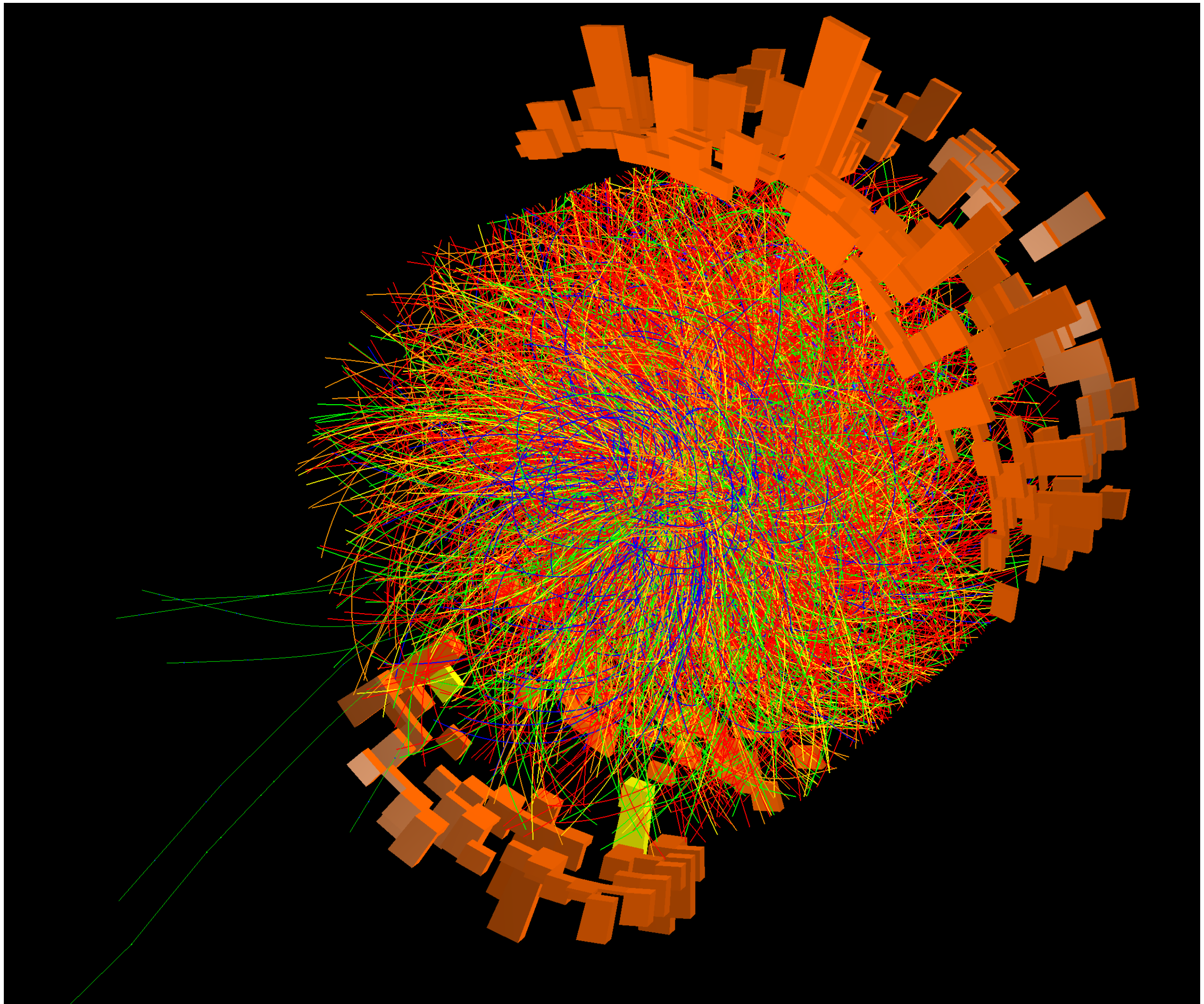


A Large Ion Collider Experiment



- PID over a very broad momentum range (> ~100 MeV/c)
- Large acceptance in azimuth
- Mid-rapidity coverage ($|\eta| < 0.9$) and $-4 < \eta < -2.5$ in forward region

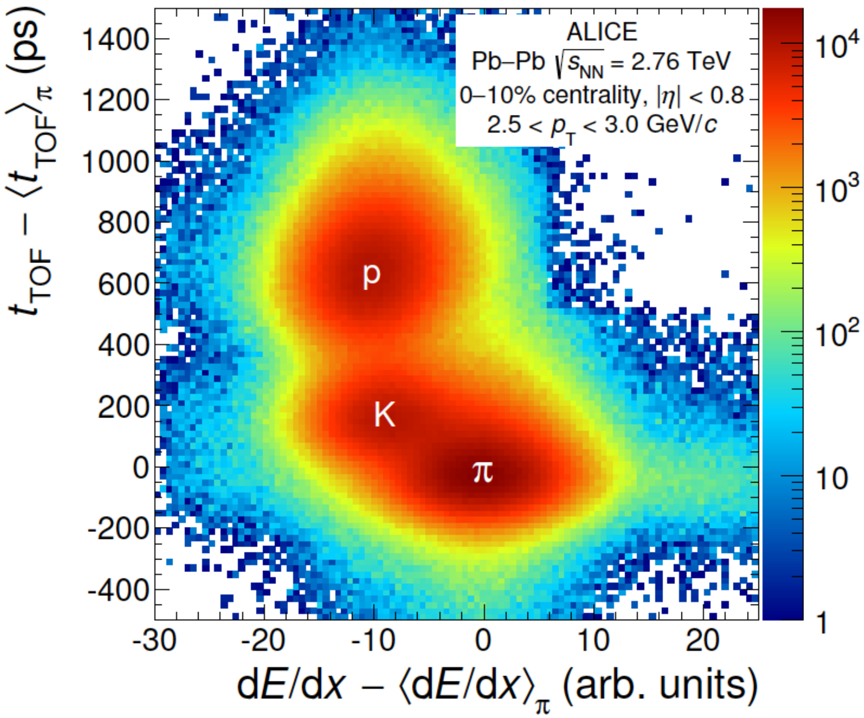
Typical event display



Tracks of particles recorded with the Time Projection Chamber and clusters in the calorimeter for a Pb-Pb collision at $\sqrt{s_{NN}}$ = 5.02 TeV

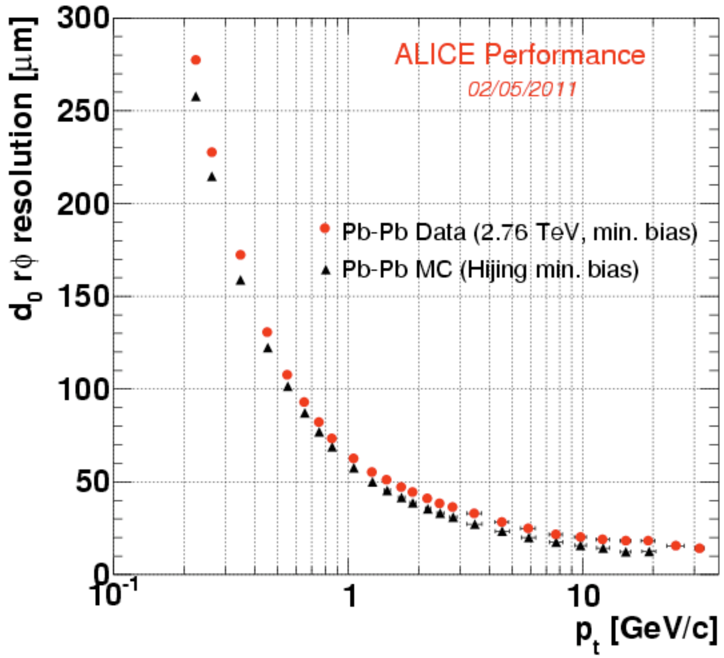
Experimental methodology

Particle identification



- Bayesian particle identification
  - Generalized approach for usage of full PID information in ALICE

Impact parameter resolution



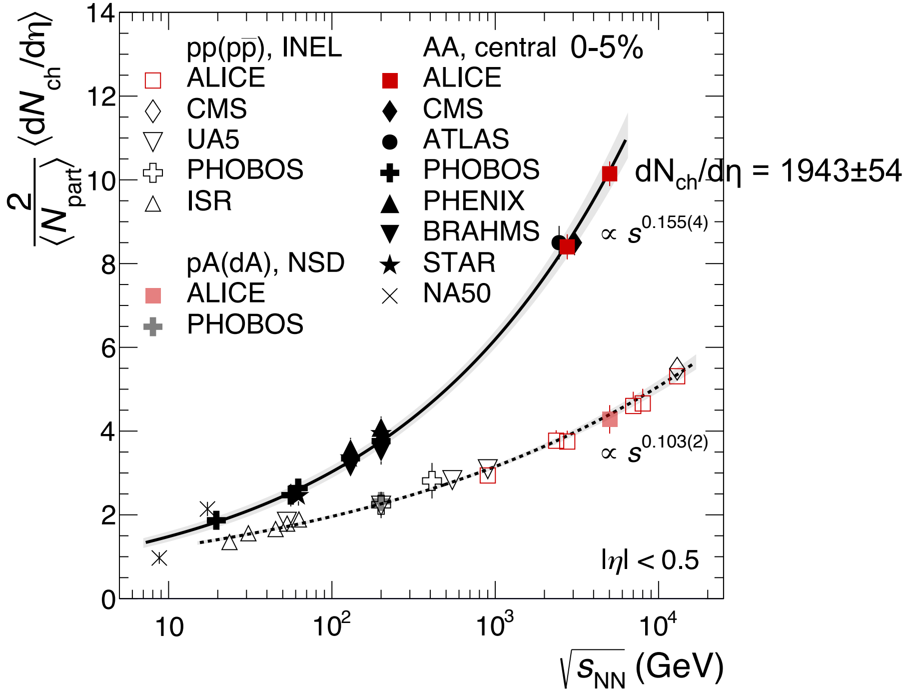
- Capabilities to measure open charm down to p_T=0 in pp and p-Pb (1 GeV/c in Pb-Pb)
- High precision tracking, better than 65 μm for p_T > 1 GeV/c

Global event observables

Charged particle multiplicity

vs. cms energy

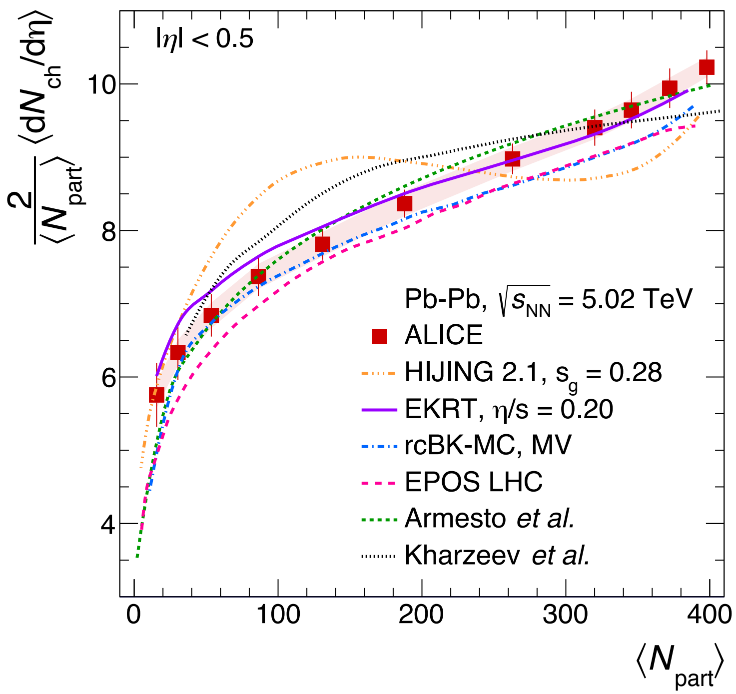
Phys. Rev. Lett. 116, 222302 (2016), Phys. Rev. Lett. 105, 252301 (2010)



- Power law dependence fits well and faster in Pb-Pb $\sim s^{0.155}$ than in pp $\sim s^{0.103}$

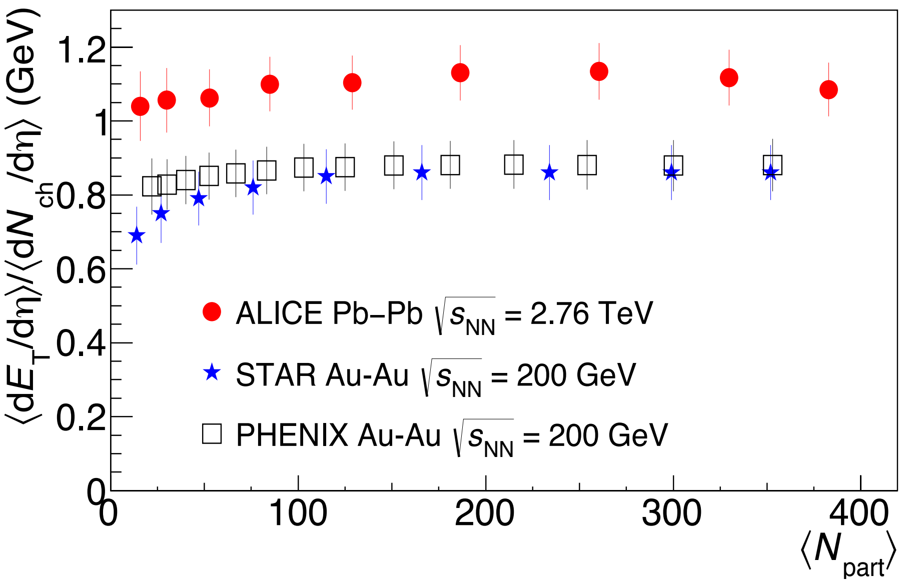
vs. number of participants

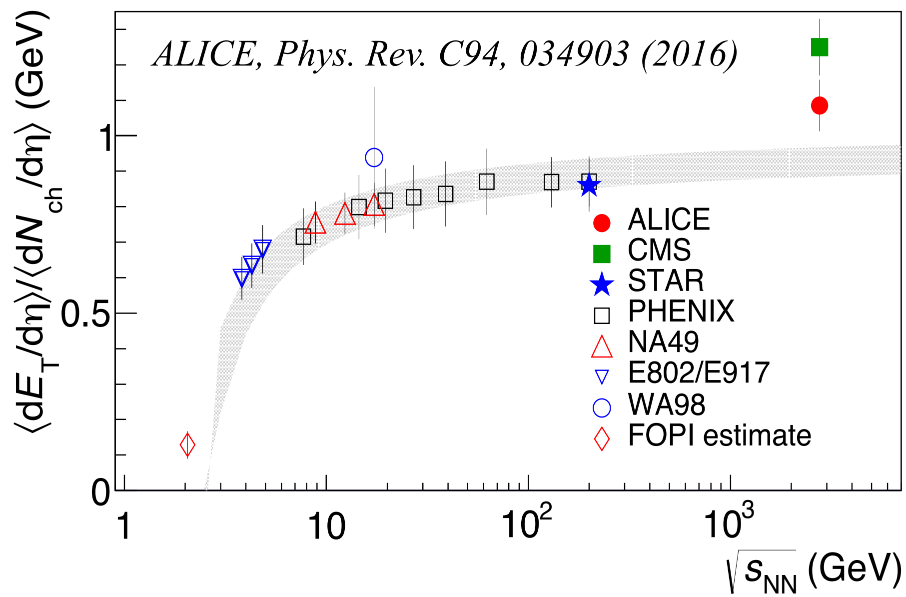
Phys. Rev. Lett. 106, 032301 (2011)



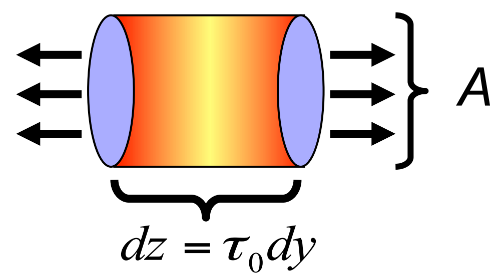
- Very similar centrality dependence at LHC and RHIC (not shown)
  Once corrected for difference in absolute values
- Shape almost energy independent

Transverse energy density E_T





- $\langle dE_T/d\eta\rangle/\langle dN_{ch}/d\eta\rangle$ rises much stronger than expected from extrapolation from low energies



- Bjørken estimate for volume averaged energy density assuming τ_0 = 1 fm/c as formation time

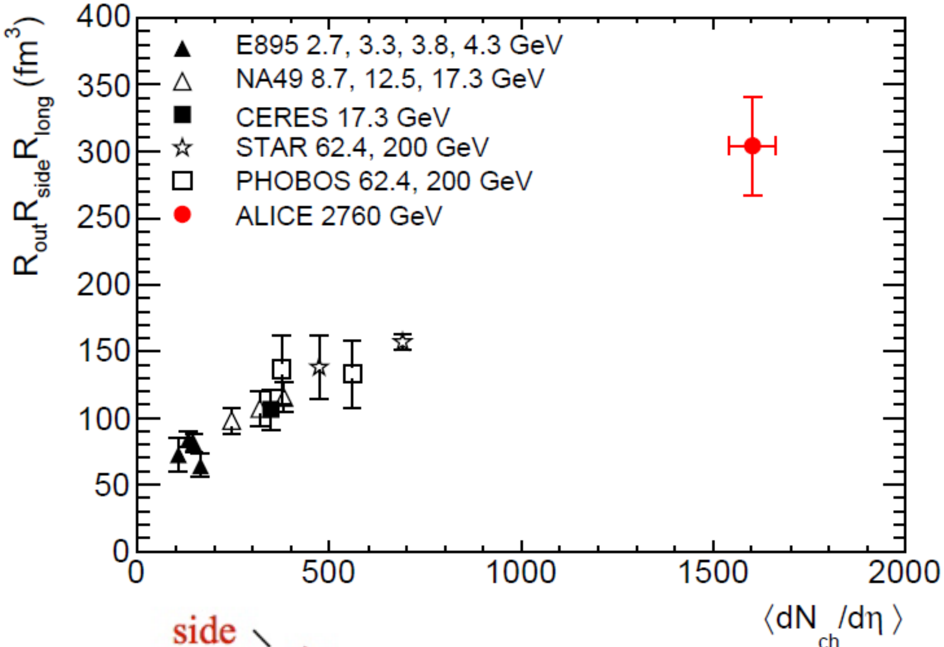
→ **12.3±1.0 GeV/fm³** for 5% most central Pb-Pb

$$\epsilon\tau_0 = \frac{1}{Ac} J \left\langle \frac{dE_T}{d\eta} \right\rangle$$

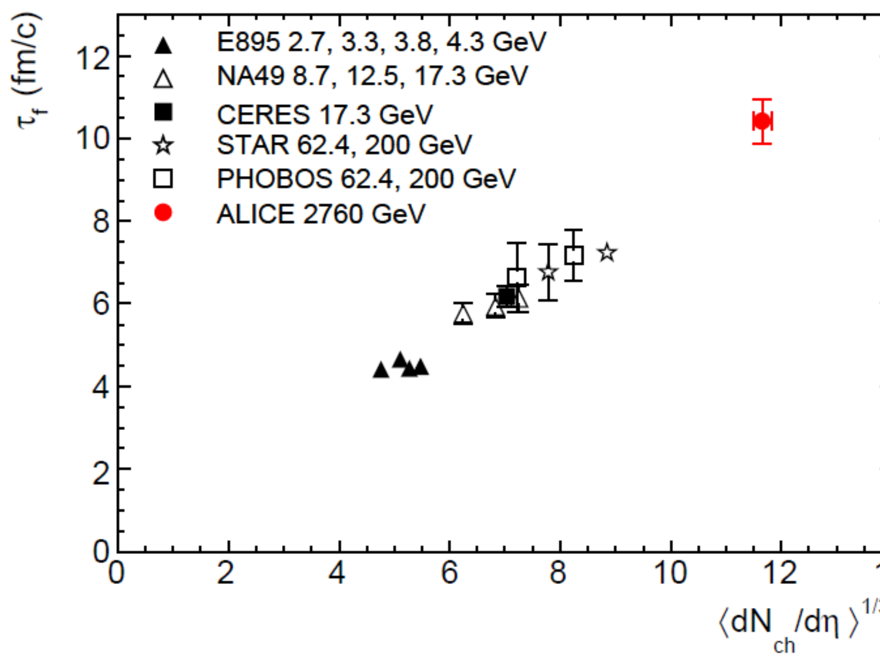
System size and lifetime of the fireball

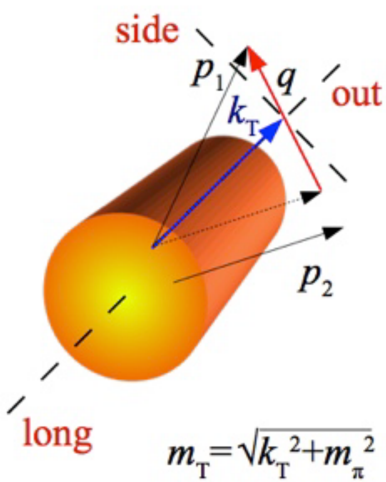
System size

Phys. Lett. B 696, 328 (2011)



Lifetime

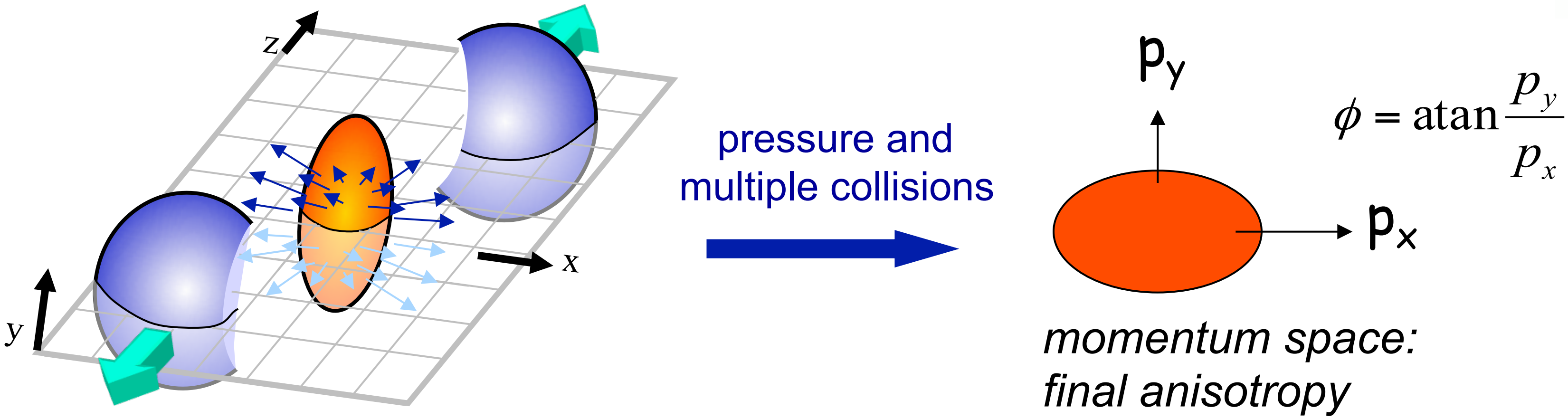




τ_f(central 2.76 TeV Pb-Pb) ~ 10-11 fm/c

- From Bose-Einstein Correlations analysis (HBT)
- Fireball at LHC has larger volume and longer lifetime

Azimuthal anisotropy (elliptic flow)



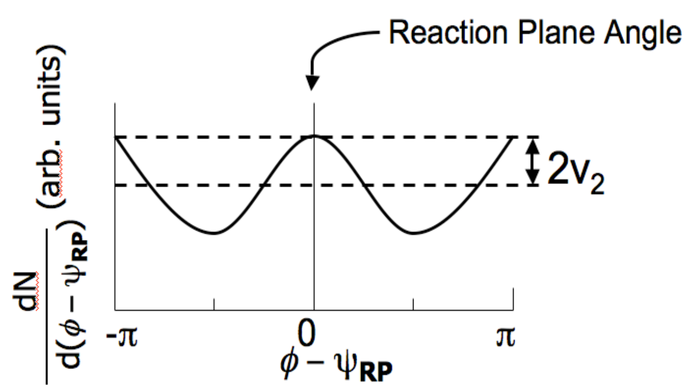
coordinate space: initial anisotropy

momentum space: final anisotropy

- Multiple interactions lead to thermalisation → hydrodynamic behaviour of the system
- Pressure gradient generates collective flow → anisotropy in momentum space
- Fourier decomposition:

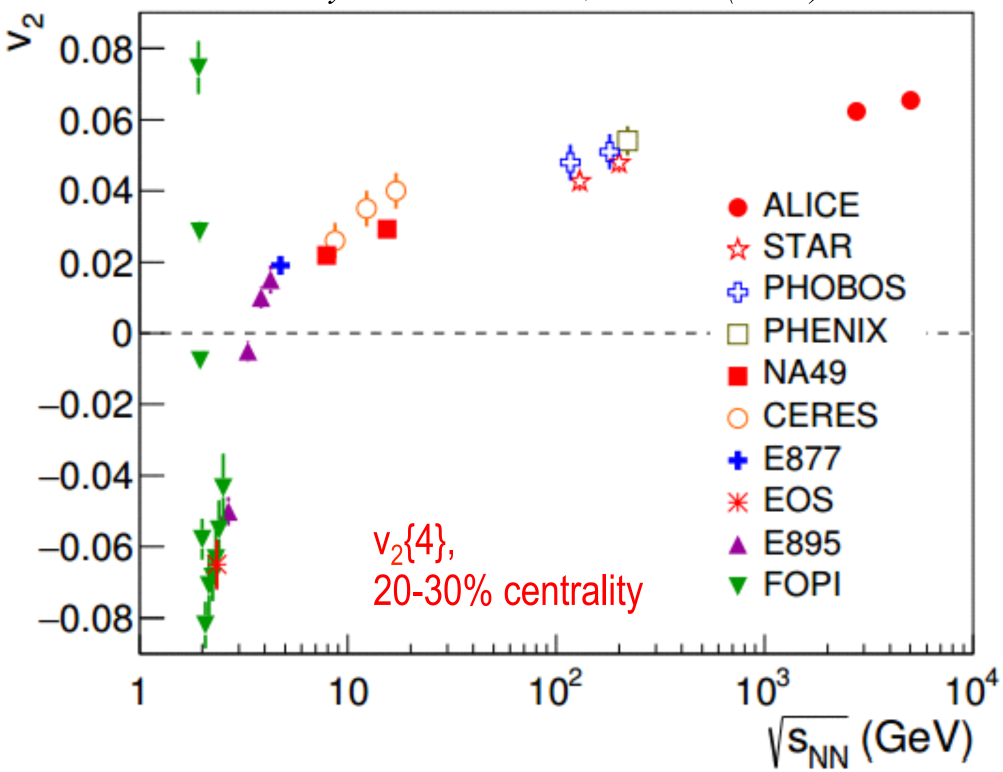
$$\frac{dN}{d(\phi-\psi_n)} \propto 1 + 2\sum_{n=1} v_n \cos(n[\phi-\psi_n])$$

$$v_n = \langle \cos(n[\phi-\psi_n]) \rangle$$



Energy dependence of elliptic flow parameter

Phys. Rev. Lett. 116, 132302 (2016)
Phys. Rev. Lett .105, 252302 (2010)



Described by hydro-dynamic models with:

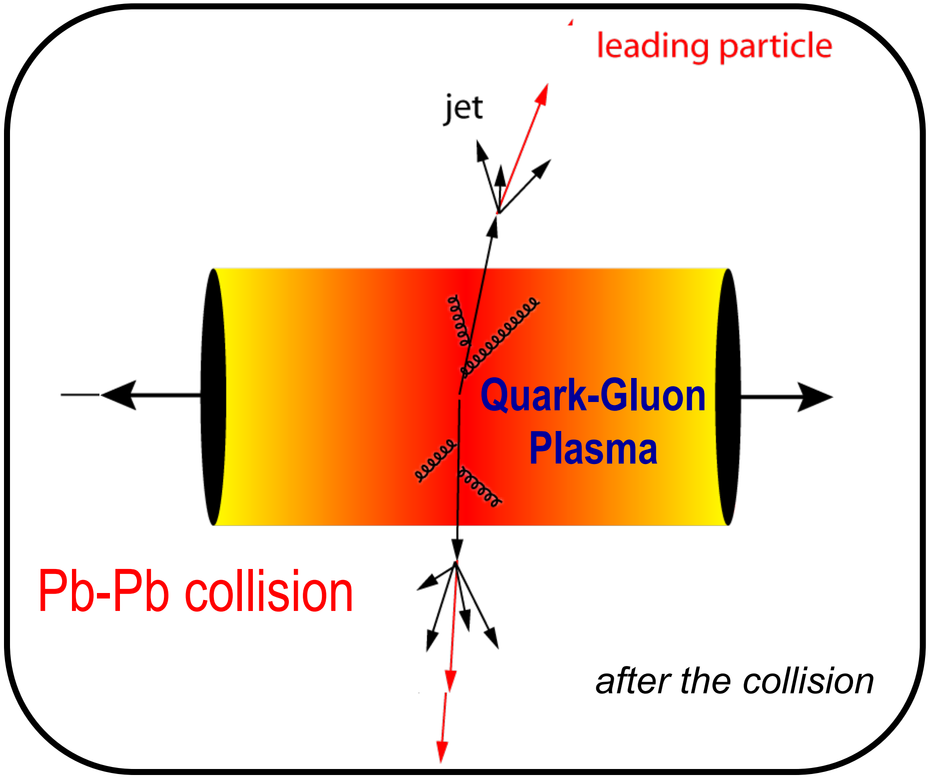
- Glauber geometry
- viscous corrections η/s still small (~0.1-0.2)
- changes expected in space-time evolution

- Continuous increase in v_2 at high collision energy
- **Strongly-coupled medium** with very low shear viscosity ($\rightarrow \eta/s = 1/4\pi$; perfect liquid)

Hard probes

- *High-p_T particle production and jets*
- *Heavy quarks (charm and beauty)*

Probing hot QCD matter with hard probes



Heavy-ion collision

- hard processes serve as calibrated probe (pQCD)
- traverse through the medium and interact strongly
- suppression pattern provides density measurement
- General picture: parton energy loss through medium-induced gluon radiation and collisions with medium constituents

Quantify medium effects with nuclear modification factor

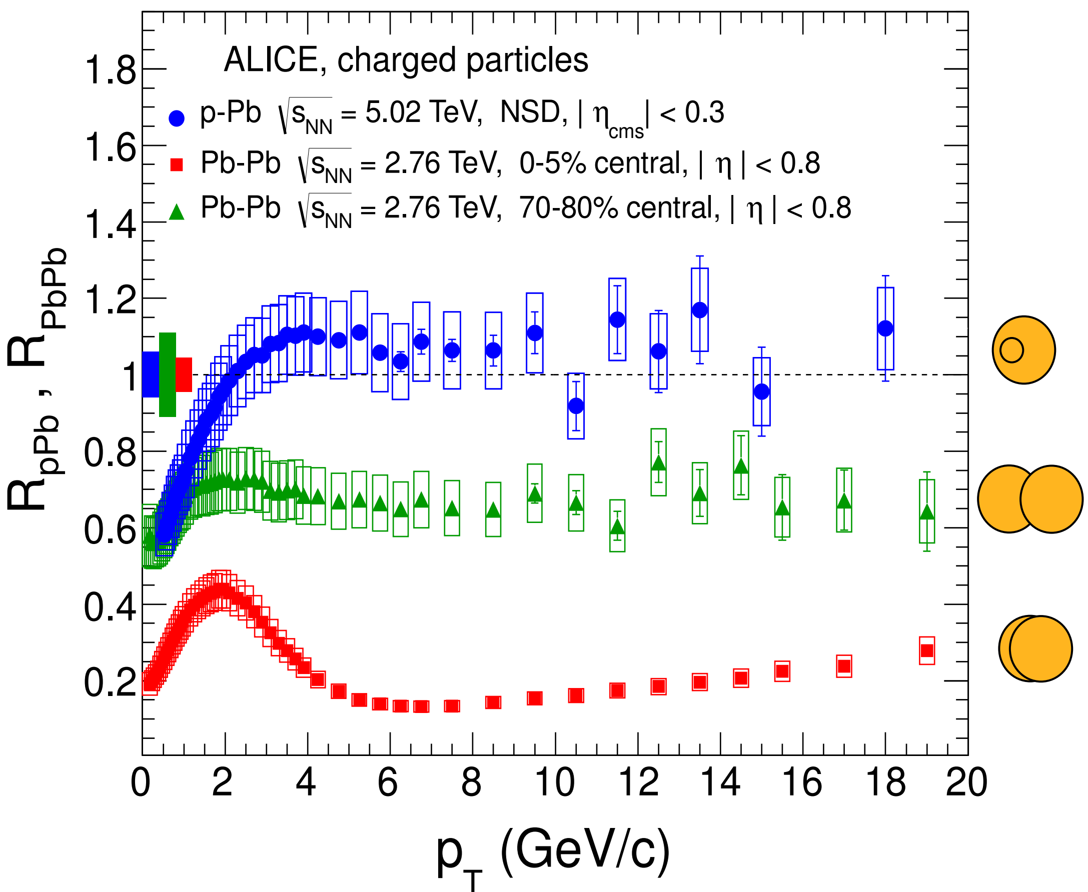
$$R_{AA}(p_T) = \frac{\mathrm{Yield}_{AA}(p_T)}{\langle N_{bin} \rangle_{AA} \mathrm{Yield}_{pp}(p_T)}$$

if $R_{AA} = 1$ → no nuclear effects

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

High-p_T particle production

Phys. Rev. Lett. 110, 082302 (2013)

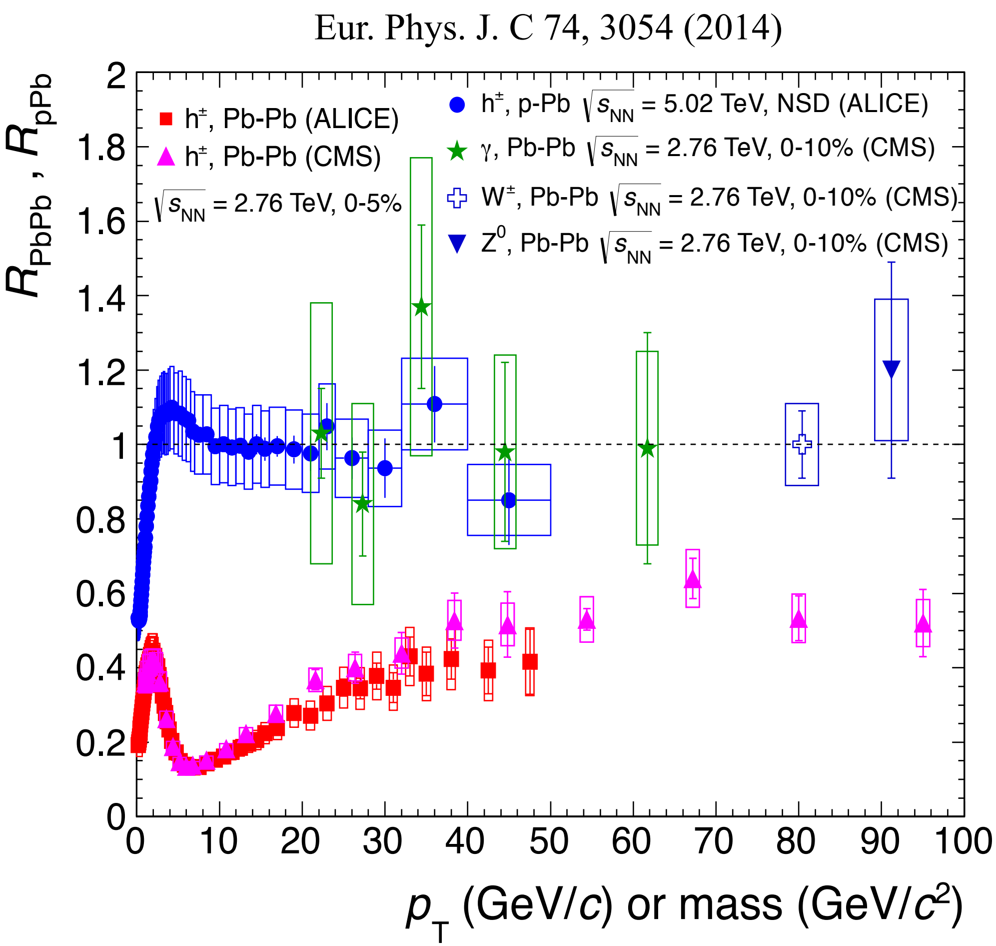


ALI-PUB-44351

p-Pb (p_T > 2 GeV/c)
- Binary scaling (R_{pPb} ~ 1)
- Absence of nuclear modification
- Initial state effects small

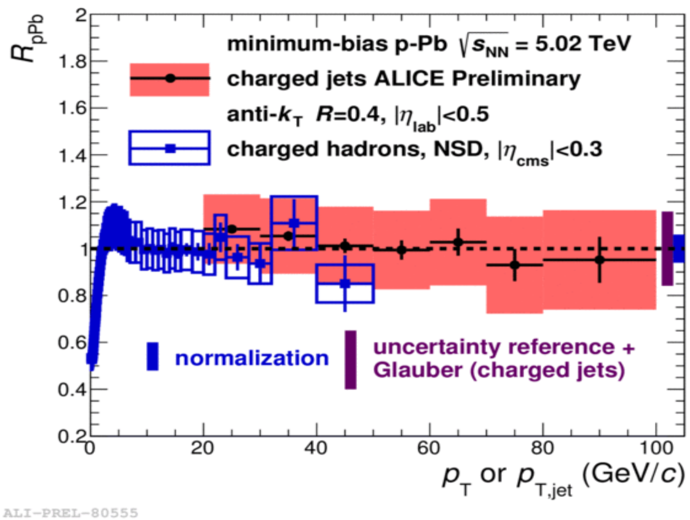
Pb-Pb – suppression
- Increases with centrality
- Not initial state
- Final state effect; due to hot and dense QCD matter

High-p_T particle production (cont'd)



$Z^0 \rightarrow \mu^+\mu^-$
$W \rightarrow \mu\nu$ using single muon recoil against missing p_T

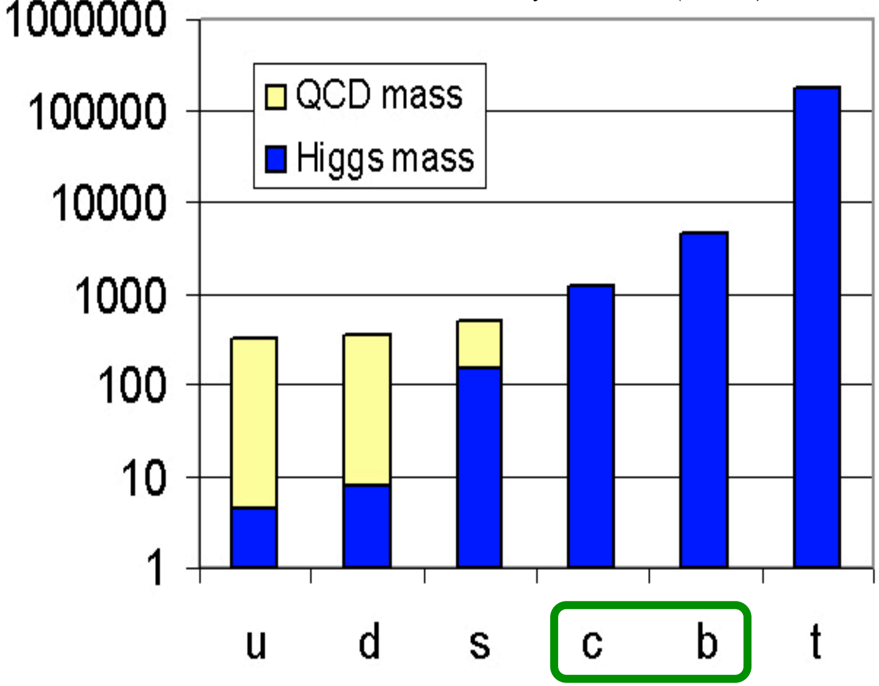
Z, W and γ production in Pb-Pb consistent with N_{coll} scaling ($R_{AA} \approx 1$)
→ not sensitive to the medium as expected
→ geometry (N_{coll}) under control



No modifications observed for **charged jets** up to 100 GeV/c

Heavy quarks are ideal probes

B. Müller, Nucl. Phys. A750 (2005) 84



Formation time:

$\tau \sim 1/2m_Q \sim 0.1\text{fm} \ll \tau_{QGP} \sim 5\text{-}10$ fm

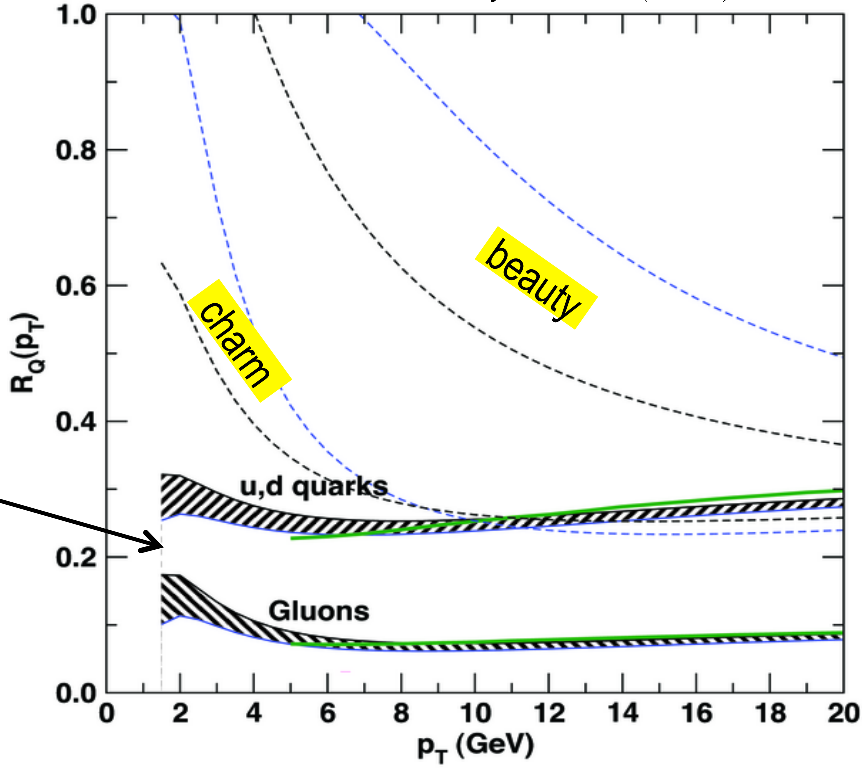
- Symmetry breaking
  - Higgs mass: electro-weak symmetry breaking → current quark mass
  - QCD mass: chiral symmetry breaking → constituent quark mass
- Charm and beauty quark masses are not affected by QCD vacuum → ideal probes to study QGP
- Test QCD at transition from perturbative to non-perturbative regime: Charm and beauty quarks provide hard scale for QCD calculations

Radiative parton energy loss

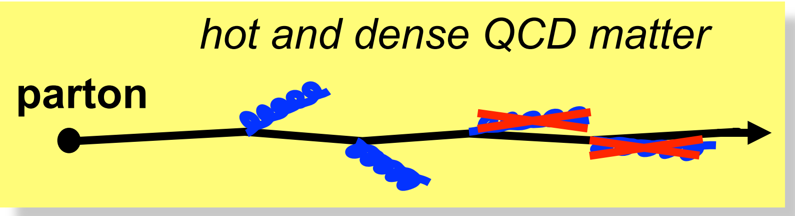
- …depends on
  - Medium properties (e.g. density, temperature, mean free path)
    → transport coefficients ($\hat{q}$)
  - Path length in the medium (L)
  - Parton properties (colour charge and mass) traversing the medium → Casimir coupling factor (C_R):
    C_R = 4/3 for quarks and 3 for gluons
    R. Baier et al., Nucl. Phys. B483 (1997) 291 (BDMPS)

$$\left\langle \Delta E_{medium} \right\rangle \propto \alpha_S C_R \hat{q} L^2$$

S. Wicks et al., Nucl. Phys. A 784 (2007) 426



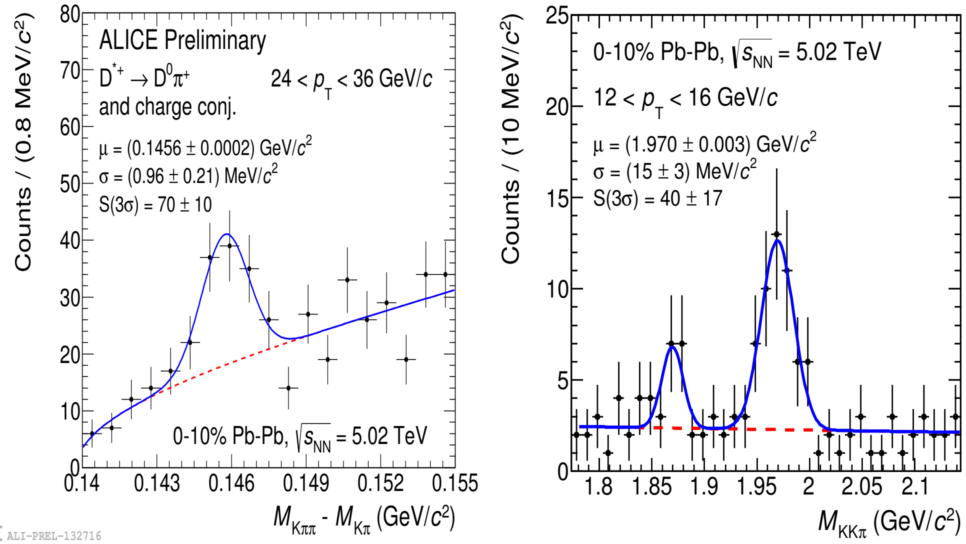
- Dead-cone effect: gluon radiation suppressed at small angles ($\theta < m_Q/E_Q$)
  Y. Dokshitzer, D. Kharzeev, PLB 519 (2001) 199, hep-ph/0106202

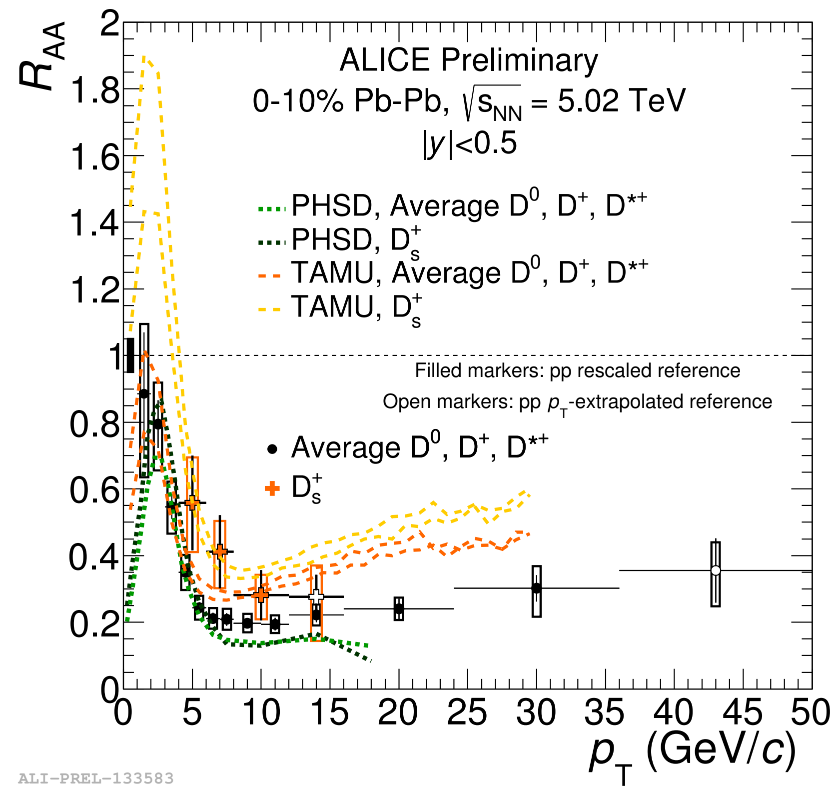


- *Expectation:* $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$
  $R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$

Prompt D-meson R_{AA} in Pb-Pb

ALICE, JHEP 03 (2016) 081 and JHEP 03 (2016) 082

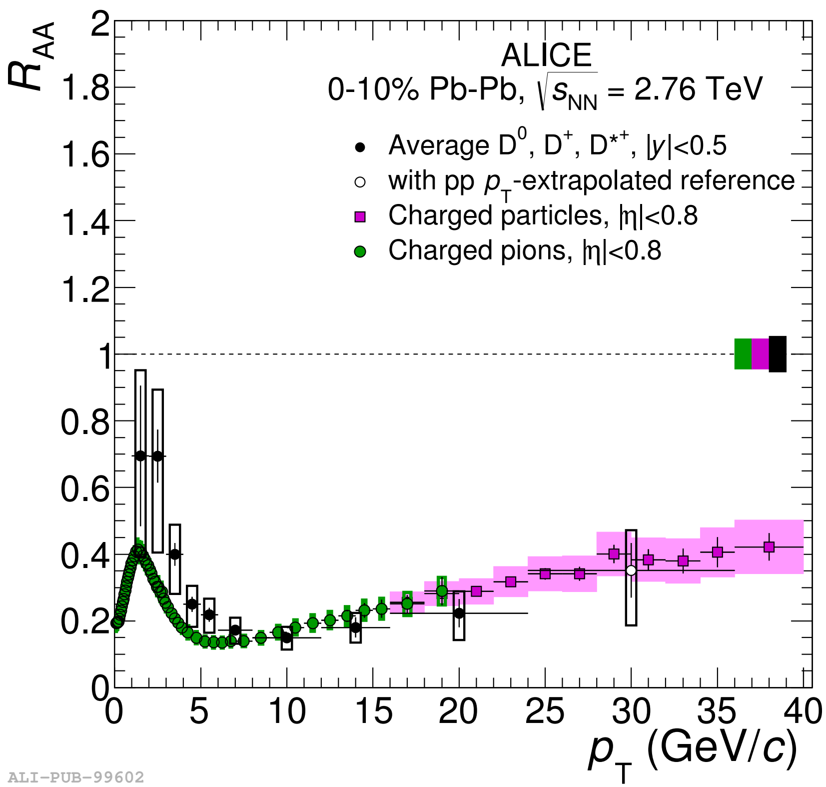




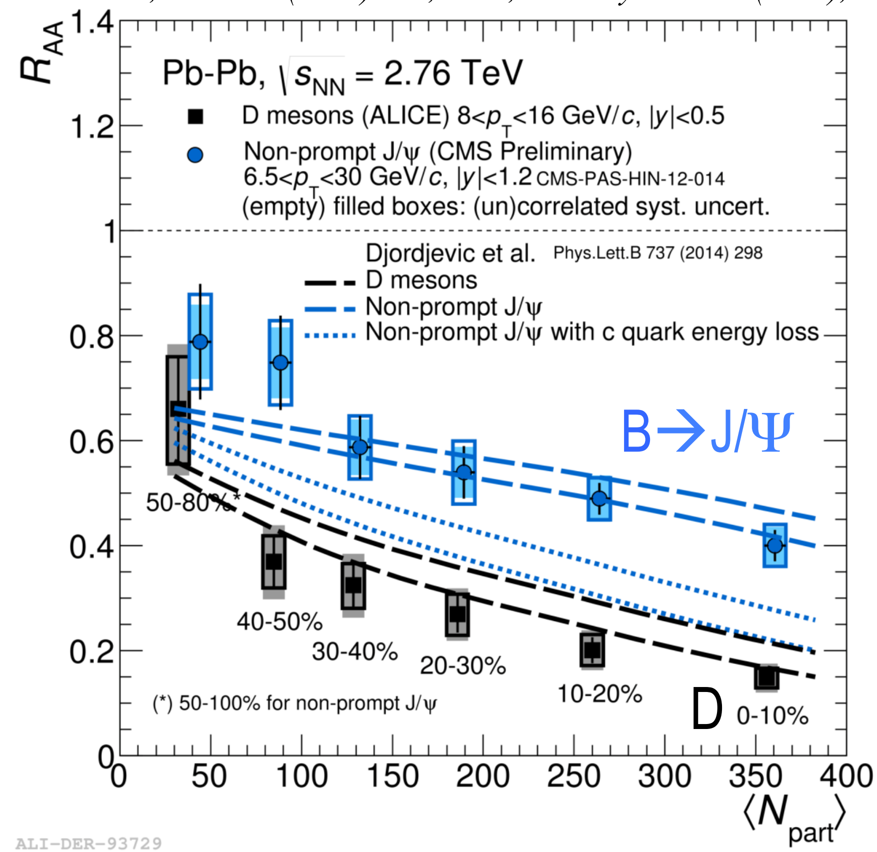
- Above 5 GeV/c strong suppression (factor 4-5) of D-meson yield in central Pb-Pb, compared to binary scaling from pp
- First $D_s^+(c\bar{s})$ measurement in heavy-ion collisions
- Expectation: enhancement of strange D-meson yield at intermediate p_T if charm hadronises via recombination in the medium

Probe flavour and mass dependence

JHEP 1603 (2016) 081



ALICE, JHEP 11 (2015) 205, CMS, Eur. Phys. J. C77 (2017), 252



- Slight enhancement of D at low p_T for 10% most central collisions
- Indication for rising R_{AA}

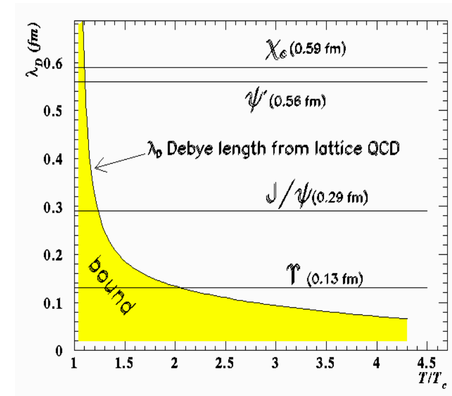
- D and B meson $\langle p_T \rangle$ ~10 GeV/c
- Described by theoretical calculations including quark-mass dependent energy loss ($R_{AA}^D < R_{AA}^B$) in the studied p_T range

Quarkonia production in hot QCD matter

- Colour screening length λ_D in the deconfined medium decreases with temperature

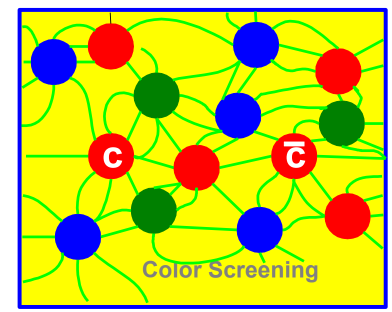
- Quarkonia "melt" when their binding distance becomes bigger than screening length → yields suppressed (one of the first QGP signatures)

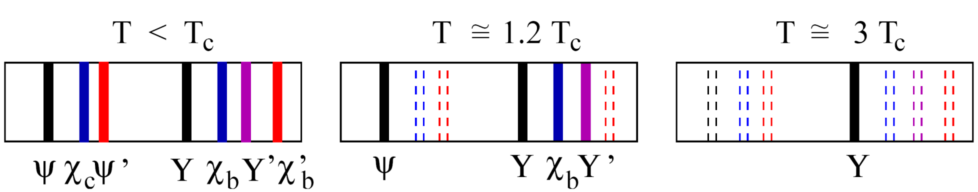
T. Matsui and H. Satz, Phys. Lett. B 178 (1986) 416



- Screening at different temperature for different states (binding energy) → sequential suppression of the quarkonium states → QCD thermometer

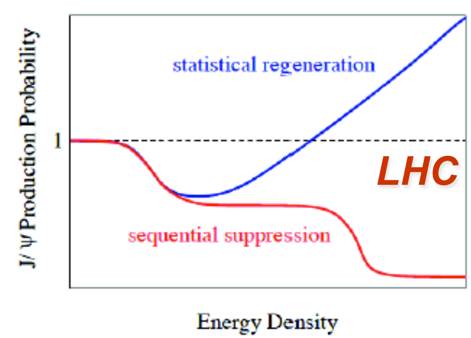
S. Digal, P. Petreczky and H. Satz, Phys. Rev. D 64 (2001) 0940150



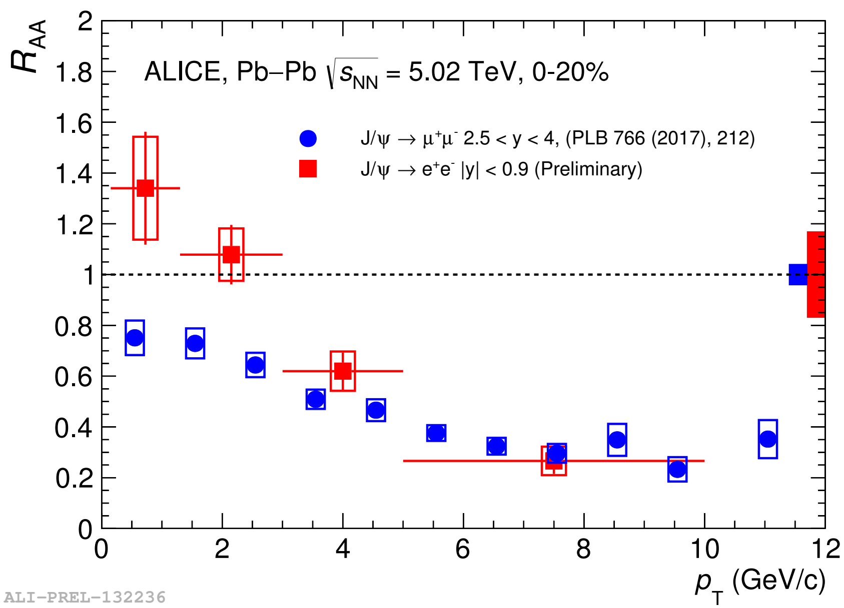


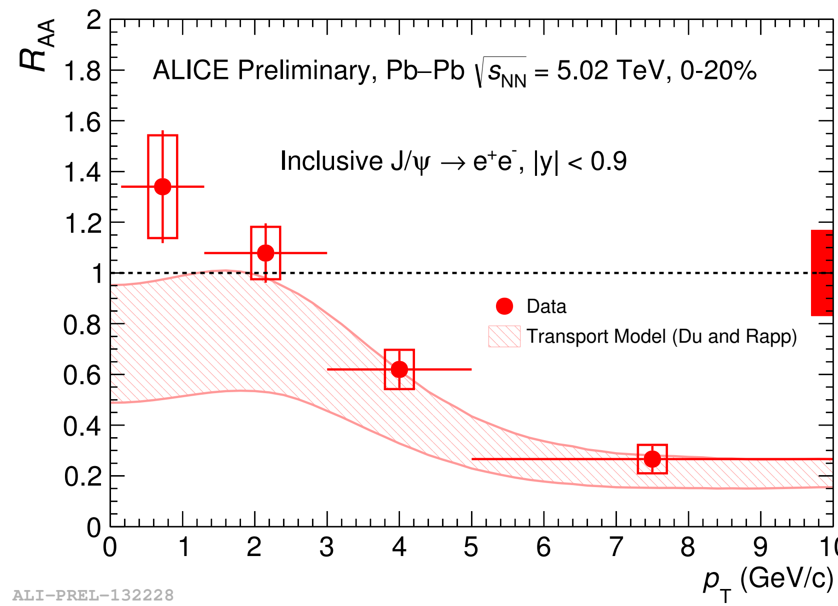
- Enhancement via (re-)generation of quarkonium states due to large heavy quark multiplicity

A. Andronic, P. Braun-Munzinger, K. Redlich and J. Stachel, Phys. Lett. B 571(2003) 36



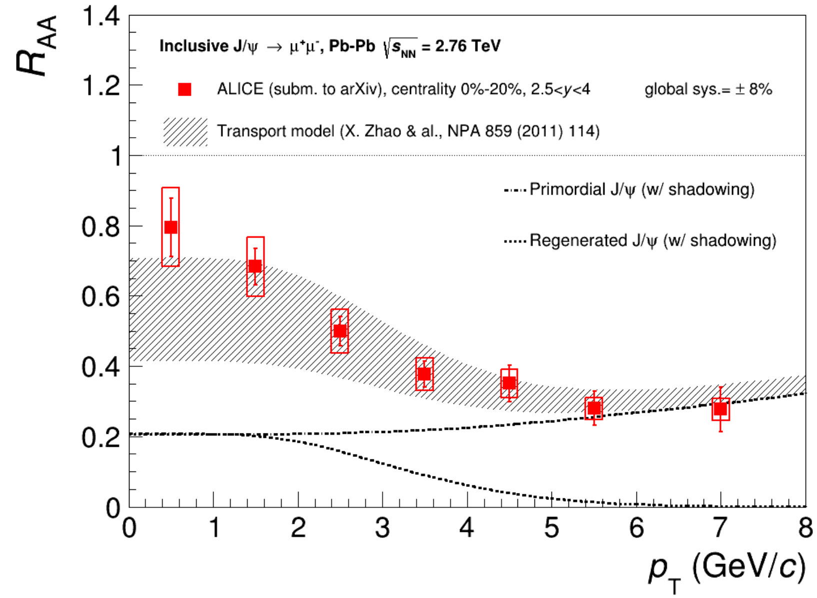
J/ψ production in 5.02 TeV Pb-Pb





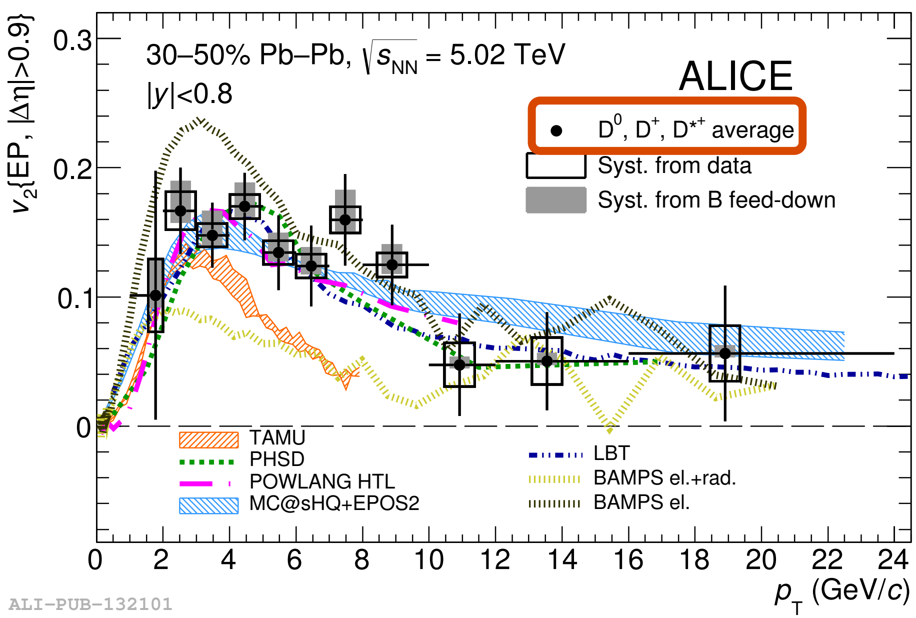
- Data indicate a smaller suppression at mid-rapidity than at forward rapidity in central collisions and low p_T

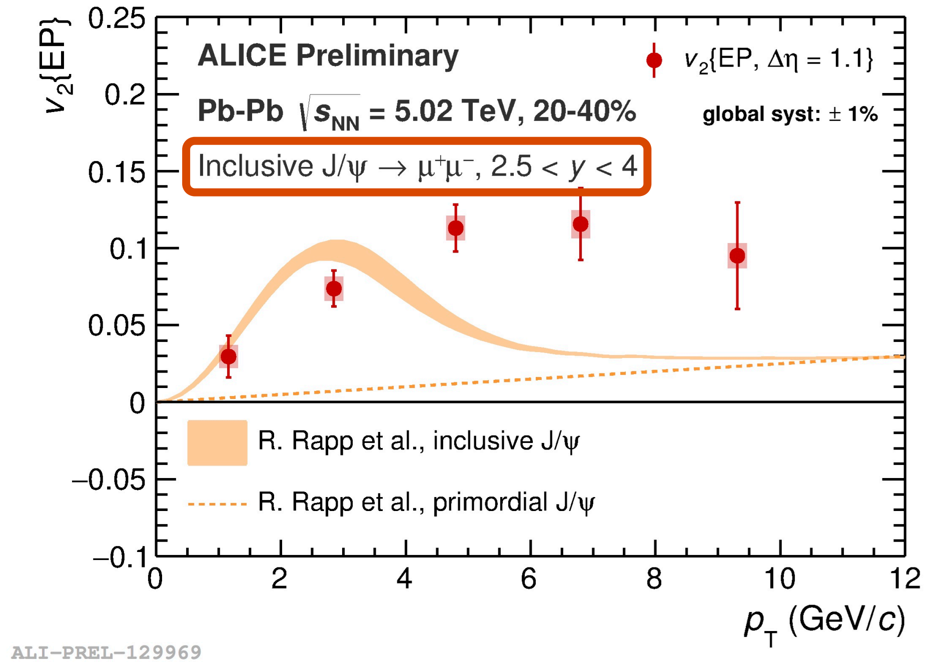
- Transport model with sizeable QGP regeneration component describes data within uncertainties; data on the upper side of the theory band



Azimuthal anisotropy of D and J/Ψ

Submitted to PRL (arXiv:1707.01005)





- Due to the large mass, long thermalisation process is expected for heavy quarks → less influenced by collective expansion

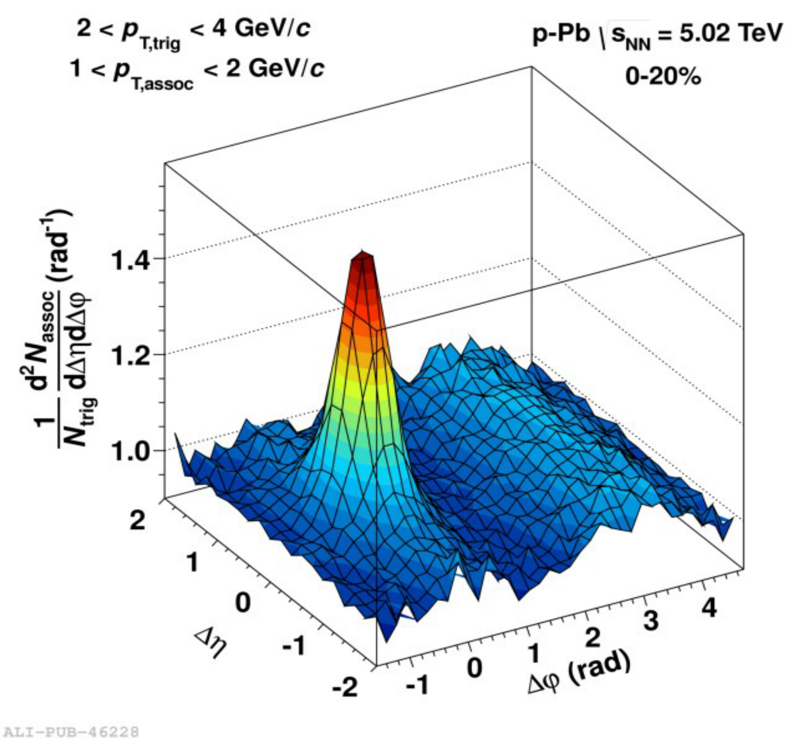
→ Significant interaction of charm quarks with the medium

→ The observed v_2 suggests that D mesons and J/ψ are formed by “flowing” charm quarks

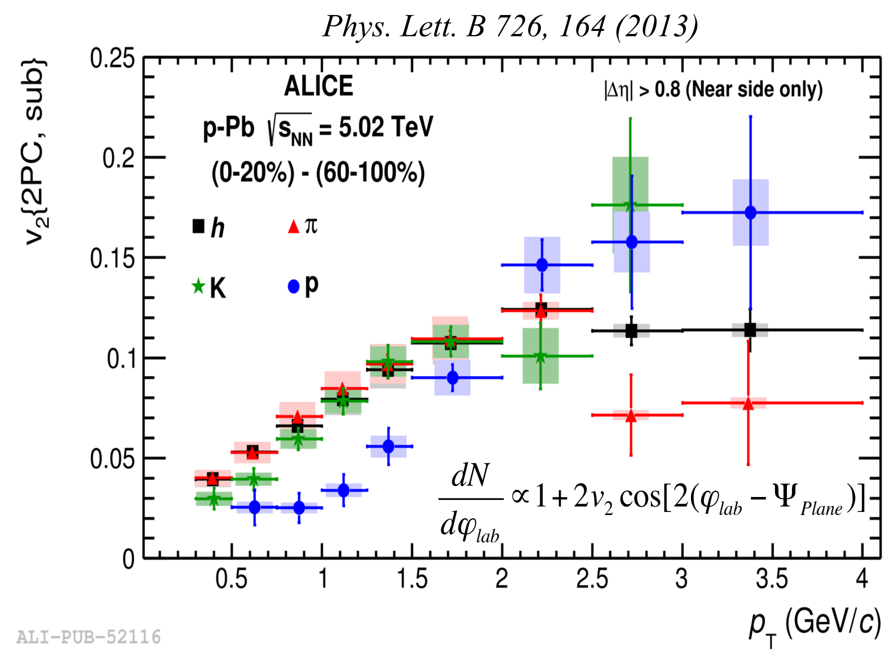
•

Small systems –
How small can a droplet of early-Universe matter be?

Di-hadron correlations in p-Pb



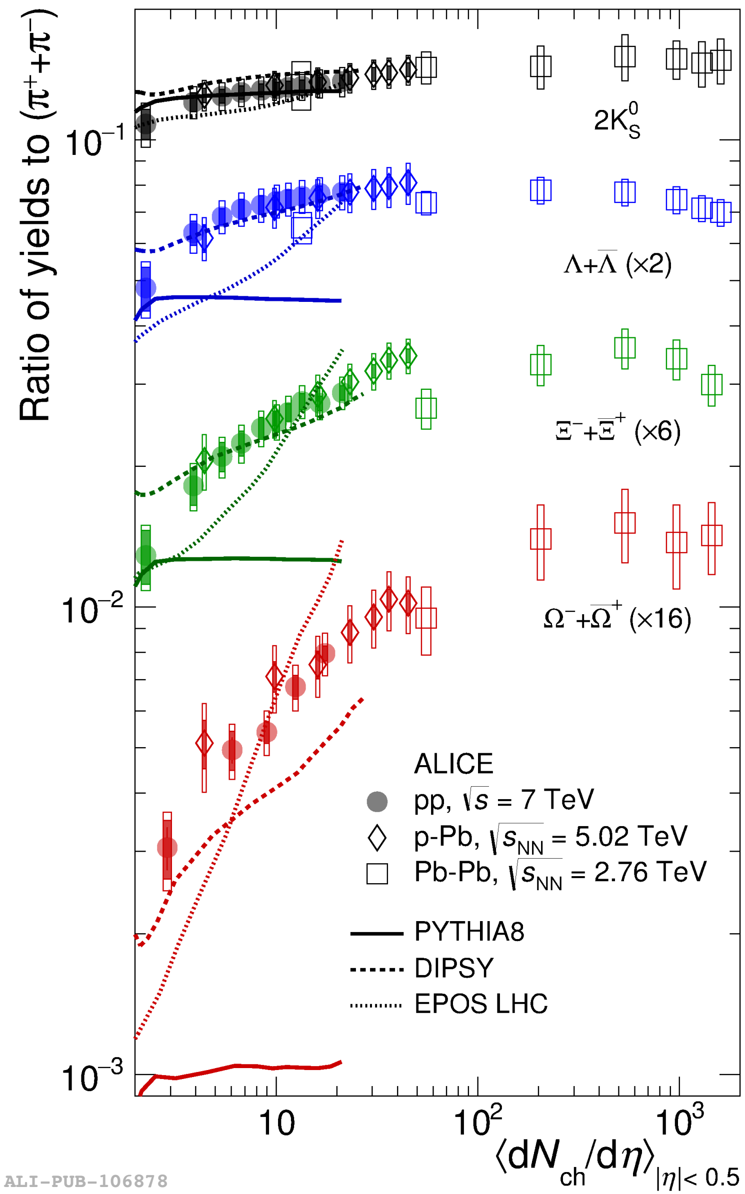
hadron – (π, K, p) correlations



- v_2 obtained from two-particles correlations
  - mass ordering at low p_T
  - crossing at $p_T \sim 2$ GeV/c
- Qualitatively similar to Pb-Pb and consistent with hydrodynamic calculations

→ Suggests similar physics (collectivity?) at place?

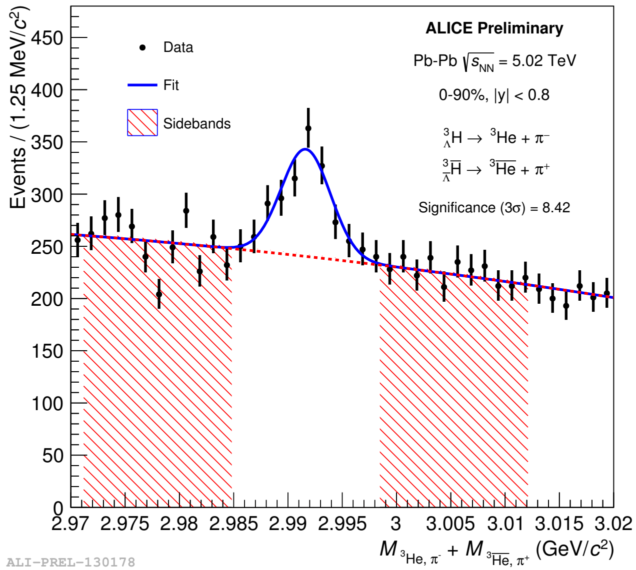
Hyperon production in pp, p-Pb and Pb-Pb

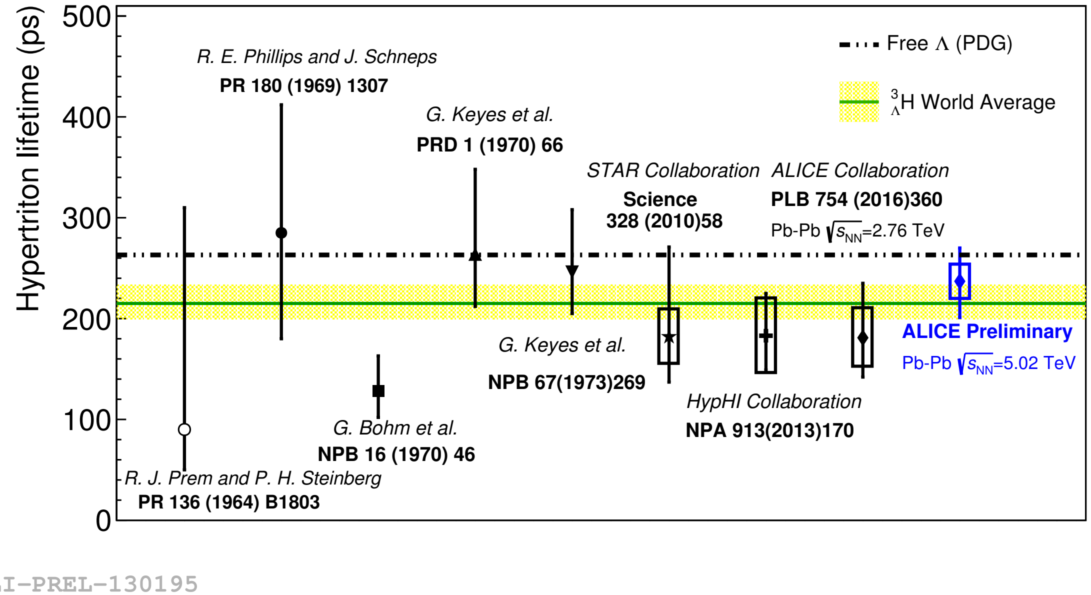


Nature Physics 13 (2017) 535

- Significant enhancement of strangeness production
- At high multiplicities, pp ratio reaches values similar to the one in Pb-Pb
- No evident dependence on cms energy: strangeness production apparently driven by final state rather than collision system or energy
- **Same mechanism in smaller system?**
- String hadronisation models do not describe the data; only DIPSY gives a qualitative description

(Anti-)hypertriton lifetime in Pb-Pb





- $^{3}_{\Lambda}H$ reconstructed in the ^{3}He-π decay channel
- Result fully compatible with the world-average and with the free Λ lifetime
- Significantly improved uncertainties wrt Run-1 (and one of the most precise available measurements)

Conclusions

- LHC ideal for the study of the properties of the matter of the early Universe, the quark-gluon plasma

- Lots of exciting measurements from Pb-Pb collisions
  - High degree of collectivity → perfect liquid
  - Parton-medium interaction → parton energy loss
  - $R_{AA}(\pi) \sim R_{AA}(\mathrm{D, single\ leptons}) < R_{AA}(\mathrm{B \rightarrow J/\psi})$ at low p_T
  - Quarkonia melting and regeneration

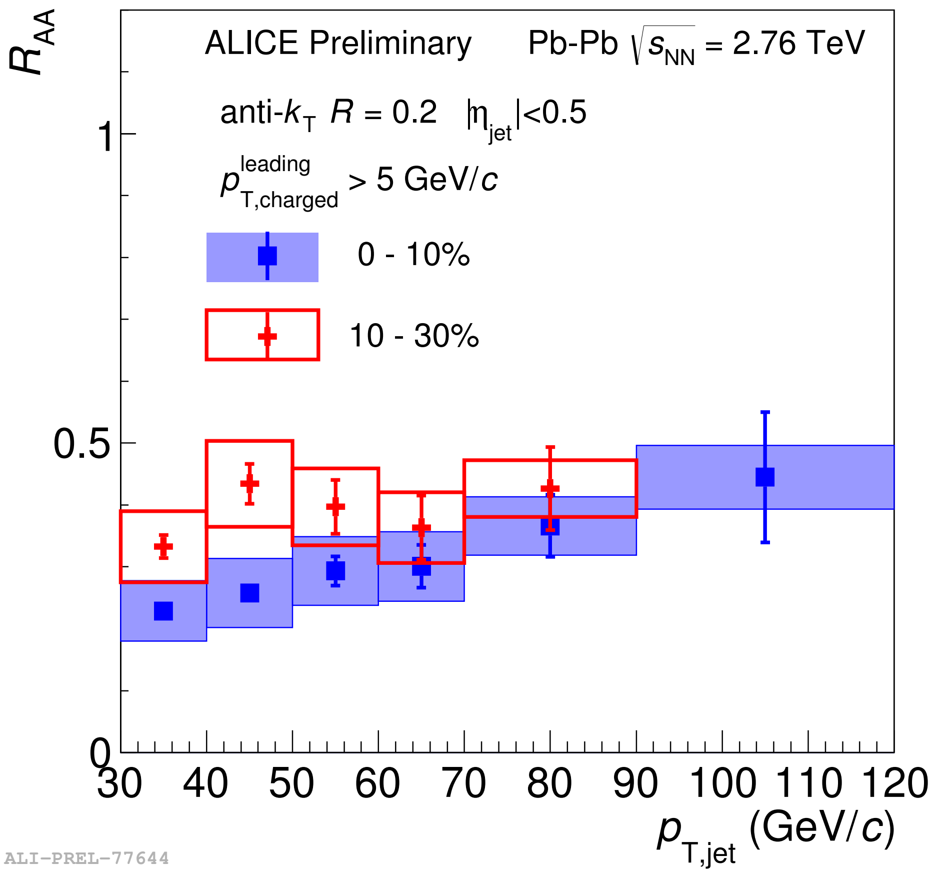
- p-Pb (and also pp) data: More than control measurements; mechanisms at work not fully understood
  - Indication for collective-like behaviour in small systems, reminiscent of that observed in Pb-Pb collisions

- Many more exciting results ahead of us
  - After detector upgrades in 2019/20

Thank you

Back-up

Jets in Pb-Pb



Expectation:
Jet fragmentation is modified by the medium
- suppression of jet yield
- broadening of jet shape
- di-jet imbalance

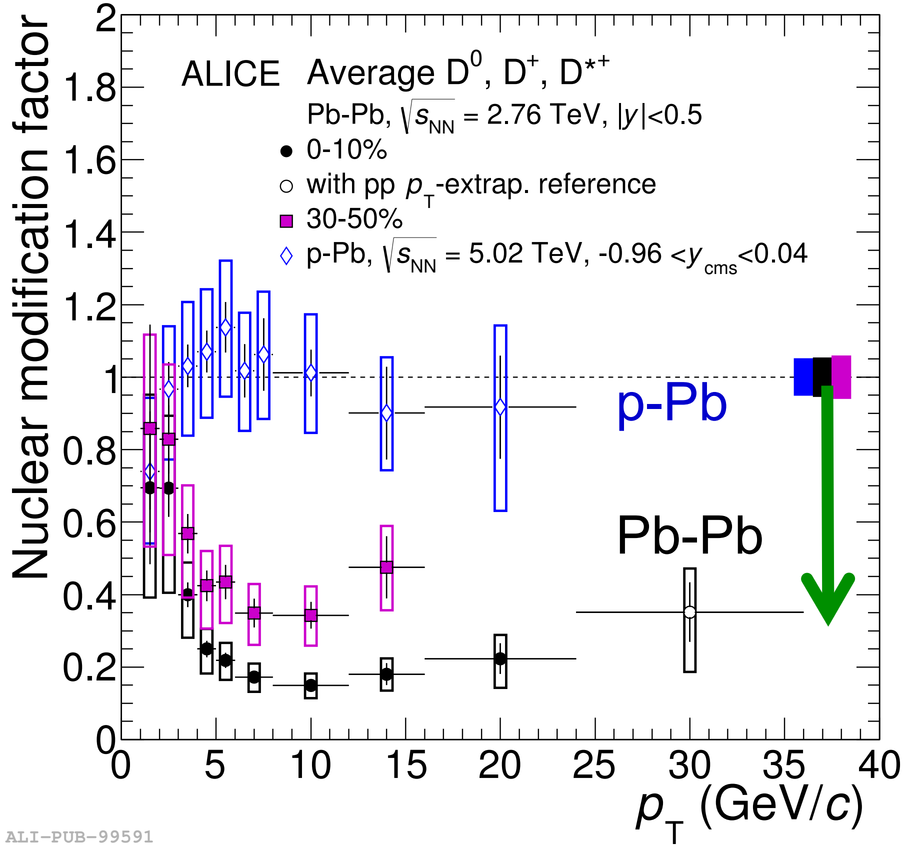
Findings:

- Strong suppression of jet yields in most central Pb-Pb collisions
→ Moderate increase of R_{AA} with increasing p_T

- Dependence on centrality class → Jet energy is moved from high to low p_T and from small to large angles (with respect to the jet axis)

Prompt D-meson R_{pPb} at 5.02 TeV

ALICE, Phys. Rev. C 94, 054908 (2016) and Phys. Rev. Lett. 113 (2014) 232301



- D-meson R_{pA} shows consistency with unity
- High-p_T suppression of production yield in Pb-Pb is a **final-state effect**

→ Due to interactions of charm quarks with the medium