Probing QGP in Heavy Ion collisions with charm hadrons at ultra relativistic energies with ALICE

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ALICE

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Contents

- QCD Phase diagram and evolution of heavy ion collisions
- QGP formation and properties
- Heavy quark production
- Charm hadron production in heavy ion collisions
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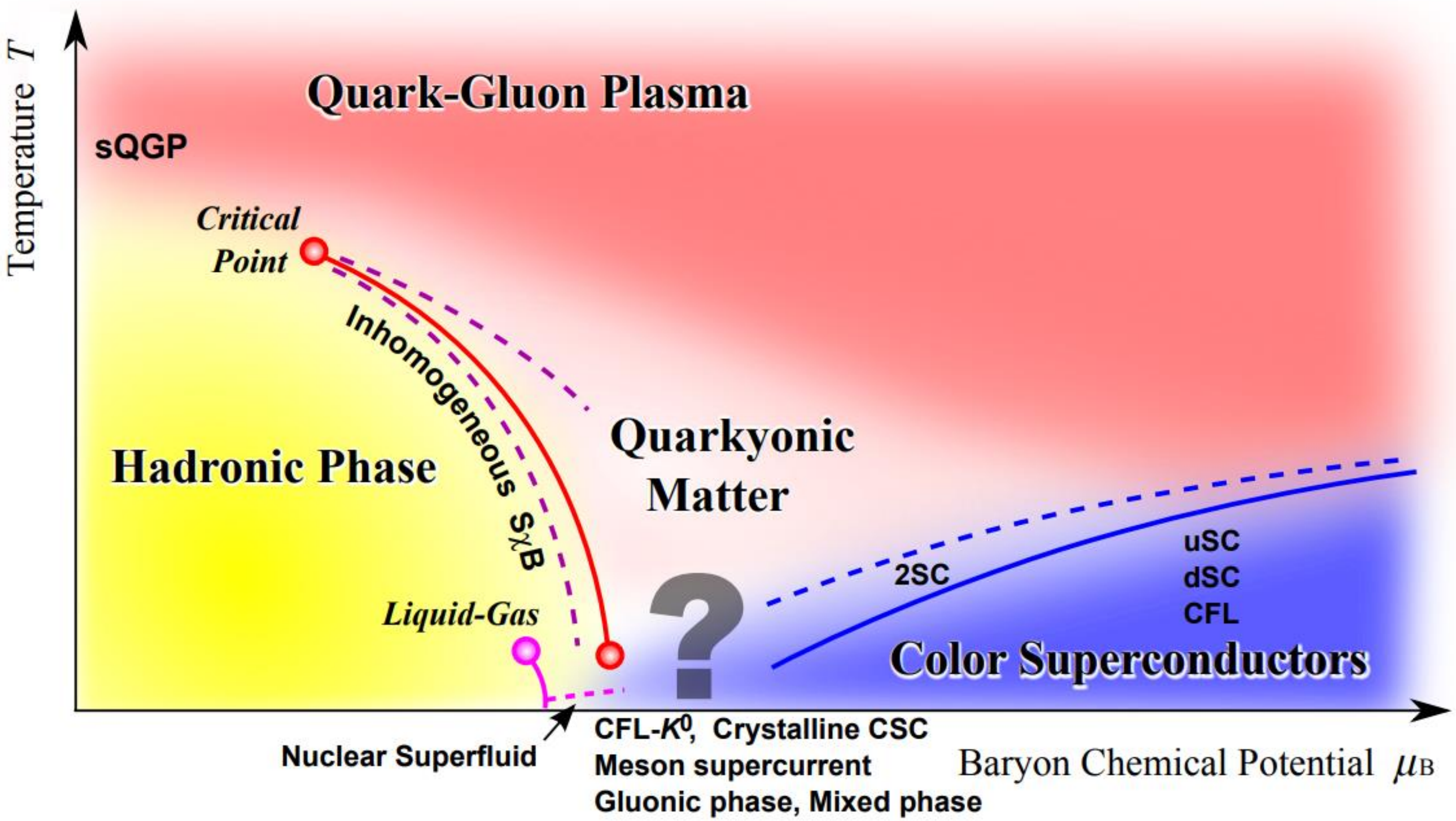
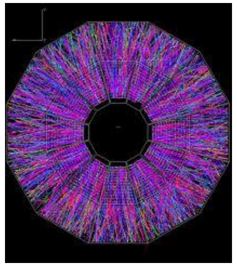
- Novel methods of charm hadron reconstruction
- Summary

QCD Phase diagram



LHC measurements are taken at μ_b= 0

- The diagram shows a rich structure
- QCD phase boundaries have not been established experimentally
- Quark- Gluon Plasma (QGP) expected at high temperatures and densities (*)



- first-order phase transition is expected up to a certain temperature and above it the phase boundary is supposed to be a smooth cross-over

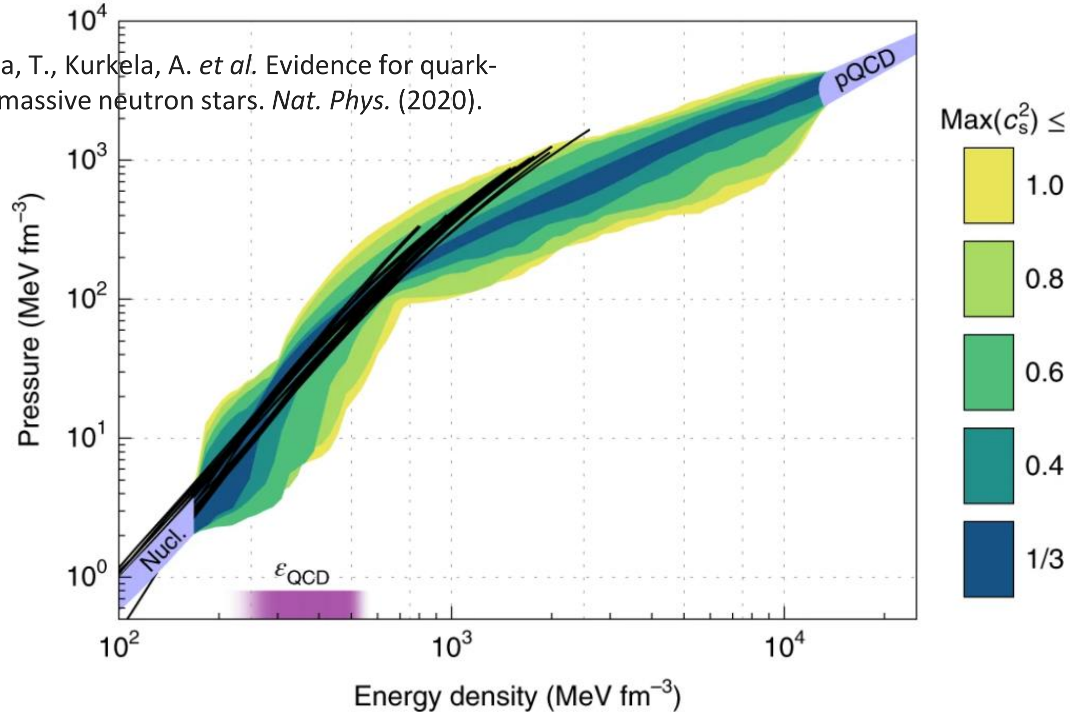
- So called critical point is a topic of extensive theoretical and experimental studies

(*) È. V. Shuryak, "Theory of hadron plasma", Sov. Phys. JETP 47 (1978) 212- 219 Zh. Eksp. Teor. Fiz. 74 (1978) 408-412.

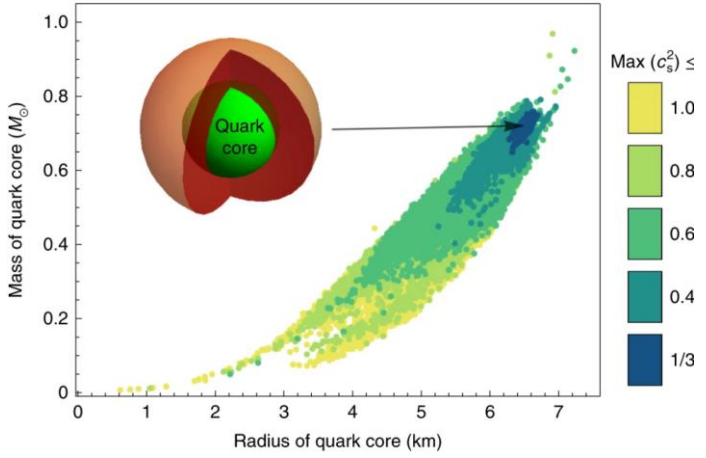
Quark Gluon Plasma

Annala, E., Gorda, T., Kurkela, A. *et al.* Evidence for quark-matter cores in massive neutron stars. *Nat. Phys.* (2020).

- QCD predicts that matter under high pressure and temperature can exist as QGP
- In such conditions the quarks and the gluons are not confined in to hadrons
- It is expected that such conditions existed shortly after the BIG BANG in the formation of the early Universe
- Can we expect QGP in Heavy Ion collisions or in the core of a Neutron Star ?

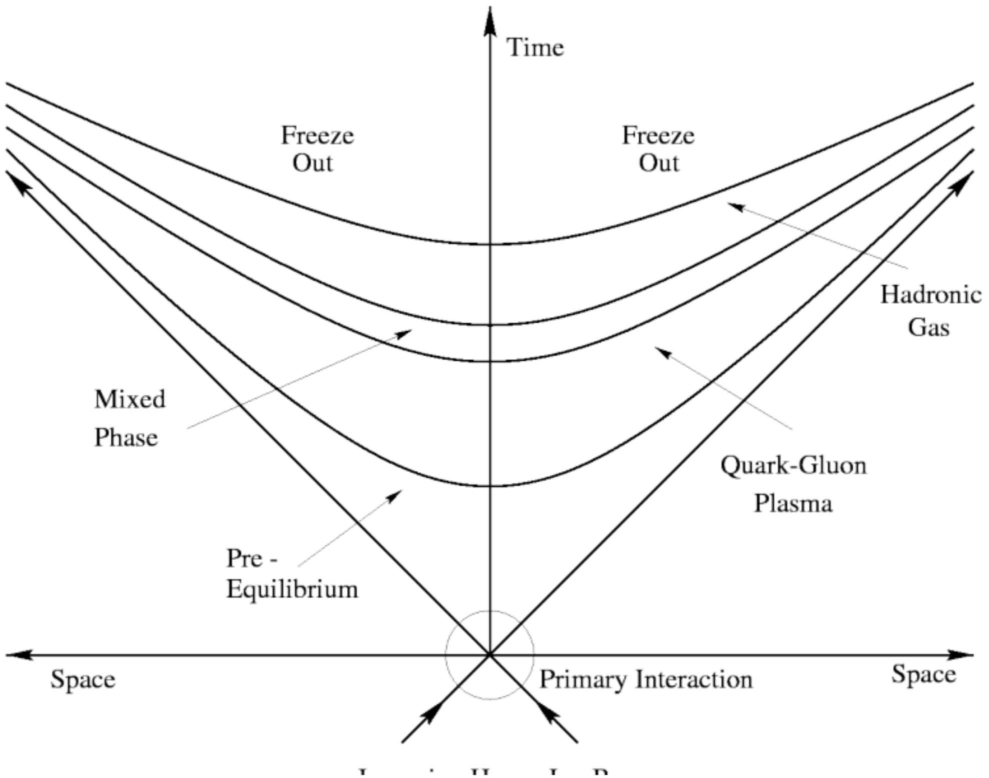


Speed of sound calculation for different equation of state, ε – rough transition point in to QGP

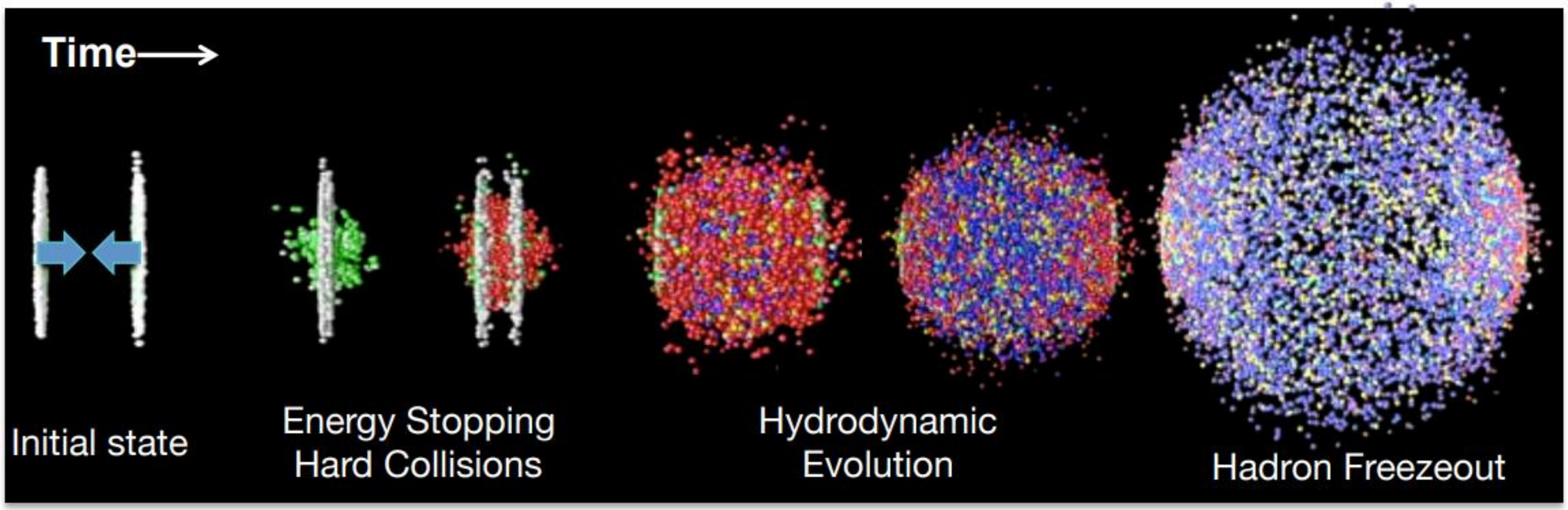


Quark Gluon Plasma (Dynamic Model)

- Systems consisting of deconfined quarks and gluons, the fundamental constituents of matter and the mediators of the strong force
- It is expected that QGP can be the outcome of the thermalization process
- QGP is expanding while the temperature (energy) of the system drops (hydrodynamic models (ref))
- The system undergoes rapid thermalization, possible explanation is a rapid transition form CGC(ref) to the thermalized QGP?



Evolution of heavy ion collisions



Initial state:

- Dominated by N-N interaction
- Bremsstrahlung (low energies)
- Drell- Yan processes at high energies

The system temperature increases and its density rises rapidly, possibly forming <u>QGP</u>

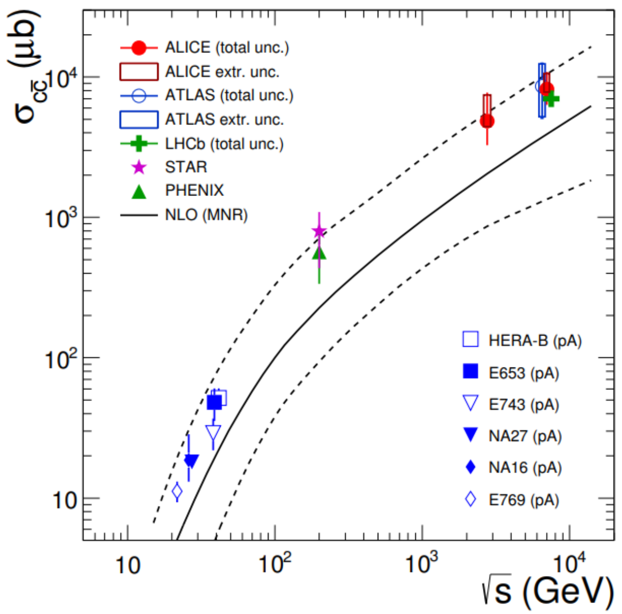
The production of hadrons from a "QGP" fireball occurs mainly by way of quark coalescence and gluon fragmentation, and there can be quark fragmentation as well

Heavy quark production

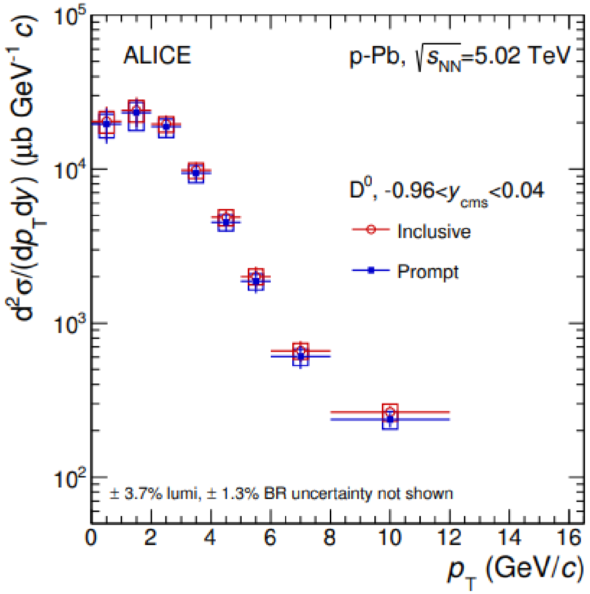
- Heavy quarks can be a probe of QGP
- Produced in high energy hard partonic scattering process in the early stage of the collision
- Due to there long life time (in comparison to Δ and N resonances) they can probe all of the stegs of medium evolution interacting with the constituents via energy loss (gluon radiation and elastic collision)

Data are from pA collisions for √ s < 100 GeV and from pp collisions for √ s > 100 GeV. Data from pA collisions were scaled by 1/A

ALICE, PRC 94 (2016) 054908



Charmed quark production
Cross section increases with the system energy

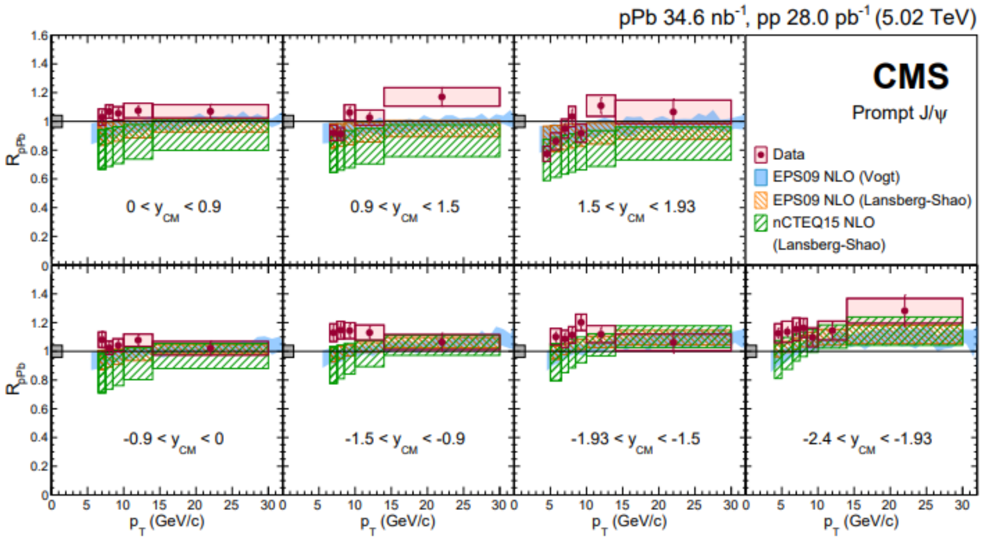


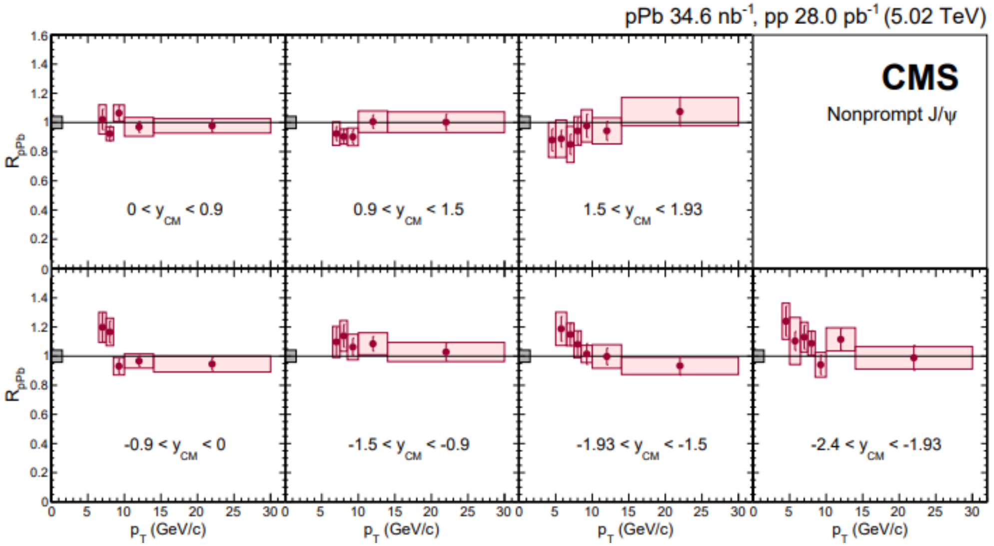
Strong p_t dependence of D-meson production cross section

Heavy quark production

- Quarkonium production and polarisation is still a puzzle
- J/Ψ (charm) production can occur directly (prompt) and via B-feed down (non-prompt)
- Suppression of J/Ψ production by Debye screening (QGP formation ?) in pPb vs pp collisions
- depletion of nuclear gluon density at small values of the momentum fraction (x) , “shadowing” can suppress J/Ψ at forward y

Cold nuclear medium



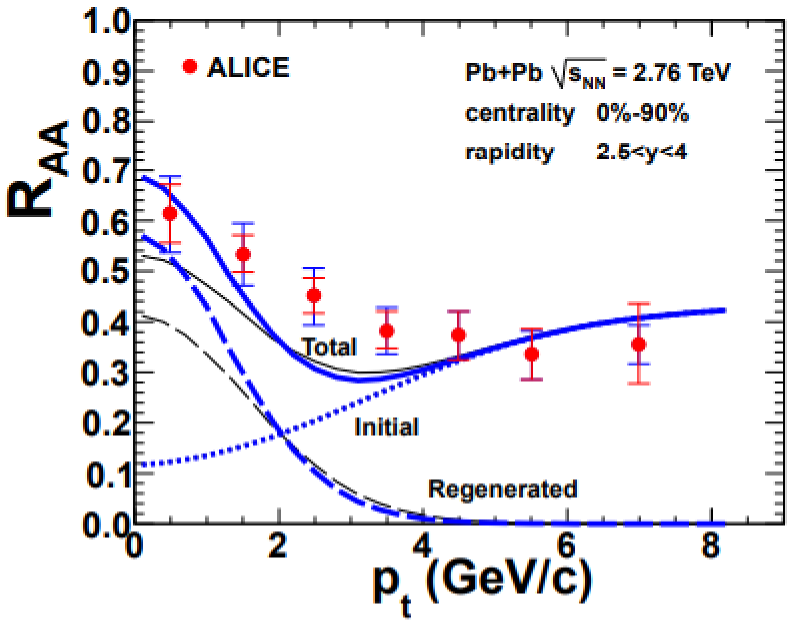


Eur. Phys. J. C 77 (2017) 269

Charm hadron production in heavy ion collisions

Phys.Rev.C 86 (2012) 034906

- In HI collisions charmonium production can be modified by regeneration (*) and distortive (@) processes
- Shadowing reduces the regeneration process
- The initial production is not affected by the QGP formation in contrast to the regeneration process (?)
- High p_t region is mostly unaffected and dominated by non prompt J/Ψ



The initial production, the regeneration, and the total are shown by dotted, dashed and solid lines, and the thick and thin lines are the calculations with and without considering the mean field effect

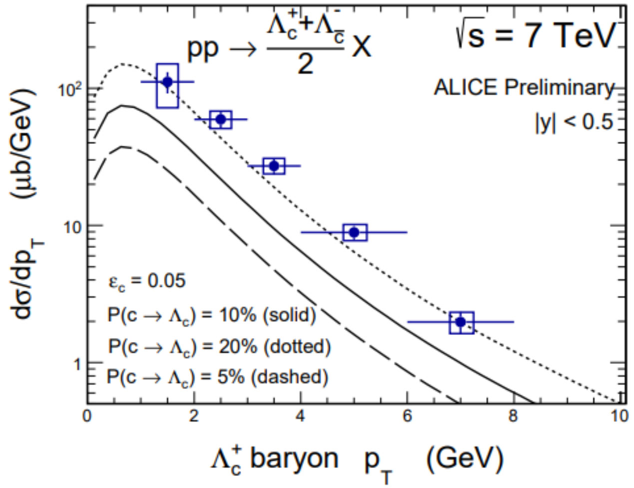
@T. Matsui and H. Satz, "J/ψ Suppression by Quark-Gluon Plasma Formation" Phys. Lett. B168 (1986) 415

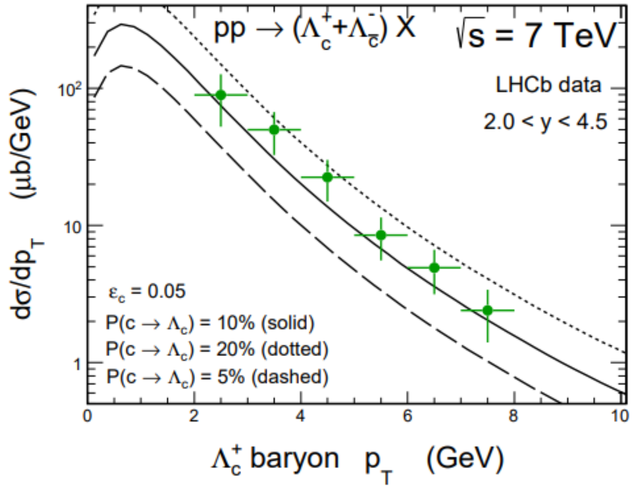
*P. Braun-Munzinger and J. Stachel, "(Non)Thermal Aspects of Charmonium Production and a New Look at J/ψ Suppression", Phys. Lett. B490 (2000) 196

Charm hadron production in heavy ion collisions

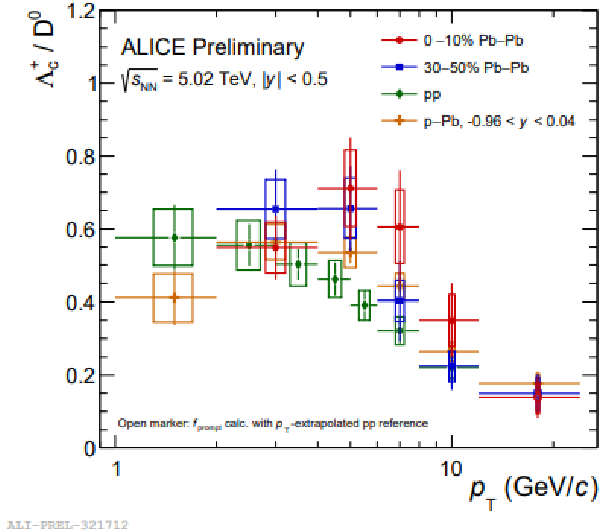
- What abut baryons (Λ_c) ?
- The models are based on independent parton fragmentation approach
- Strong enchantment in pp observed due to coalescence mechanism (formation in QGP)?
- Results for PbPb collisions seem to hint to the similar production mechanism as in pp

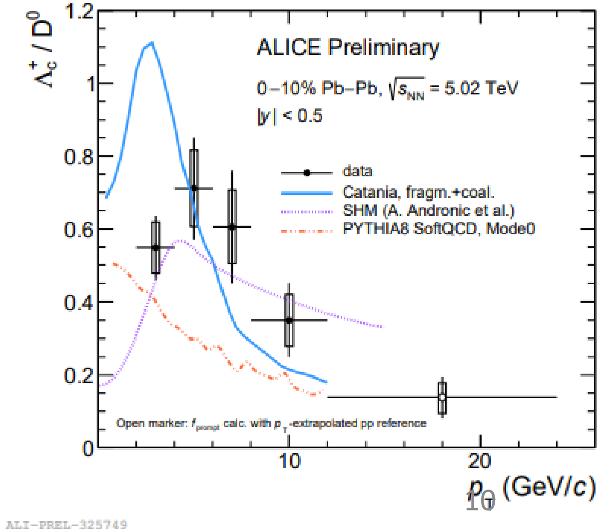
PoS DIS2019 (2019) 158





arXiv:1910.11738 **[nucl-ex]**





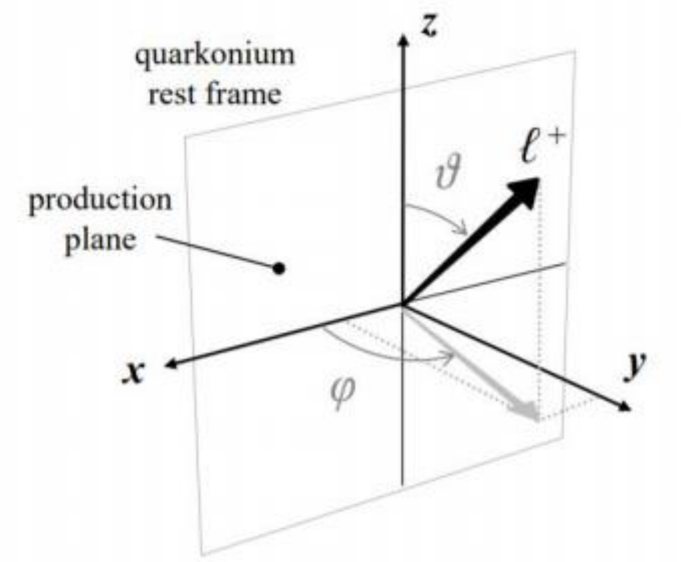
Polarisation measurements at high energies

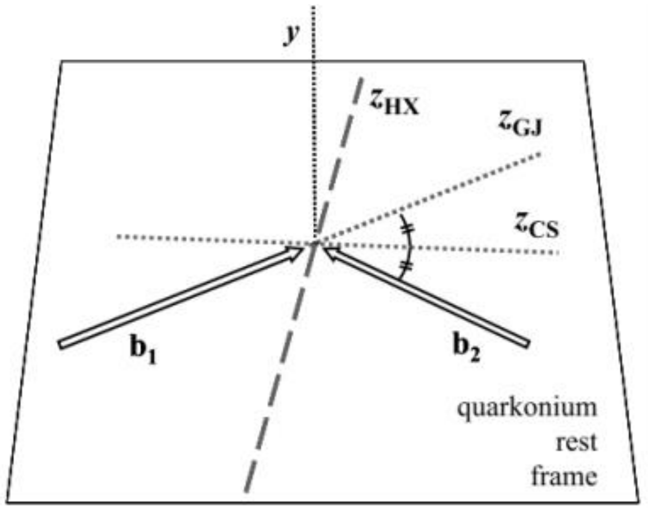
- Measurements of quarkonia polarisation preformed at ALICE in PbPb
- ($c\bar{c}$ & $b\bar{b}$) →μμ
- There is no model describing the polarisation !

$$W(\theta,\phi) \propto \frac{1}{3+\lambda_\theta}\left(1+\lambda_\theta\cos^2\theta+\lambda_\phi\sin^2\theta\cos 2\phi+\lambda_{\theta\phi}\sin 2\theta\cos\phi\right),$$

Two body decay angular parametrization where:

θ – polar production angle in the quarkonium rest frame
Φ – azimuthal production angle in the quarkonium rest frame
λ – represents various polarization parameters depended on the quarkonium production spin density matrix elements



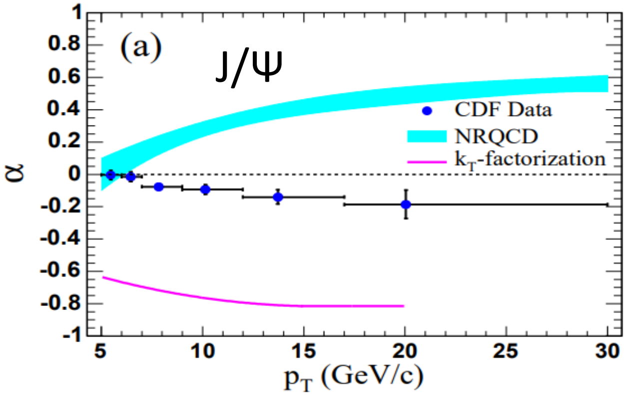


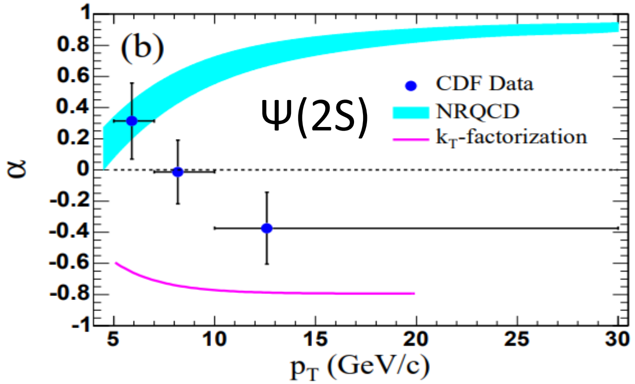
$\lambda_\Theta, \lambda_\varphi, \lambda_{\theta\varphi} \rightarrow$ $(0,0,0)$ no polarisation ☹
$\lambda_\Theta, \lambda_\varphi, \lambda_{\theta\varphi} \rightarrow$ $(-1,0,0)$ longitudinal polarisation
$\lambda_\Theta, \lambda_\varphi, \lambda_{\theta\varphi} \rightarrow$ $(+1,0,0)$ Transvers polarisation

Polarisation measurements at high energies

- J/Ψ Inclusive polarisation measurements in pp collisions in the forward rapidity bins
- Calculations done in two reference frames, Colin Soper and Helicity
- LHCb and ALICE follow the same trend in CS frame
- Discrepancies can bee observed in HX frame, the polarization is non zero in high p_t bins (dominated by non-prompt J/Ψ)
- Measurements obtained by CDF form $p\bar{p}$ show a different pattern
- High p_t J/Ψ may come form jets ?

Prompt



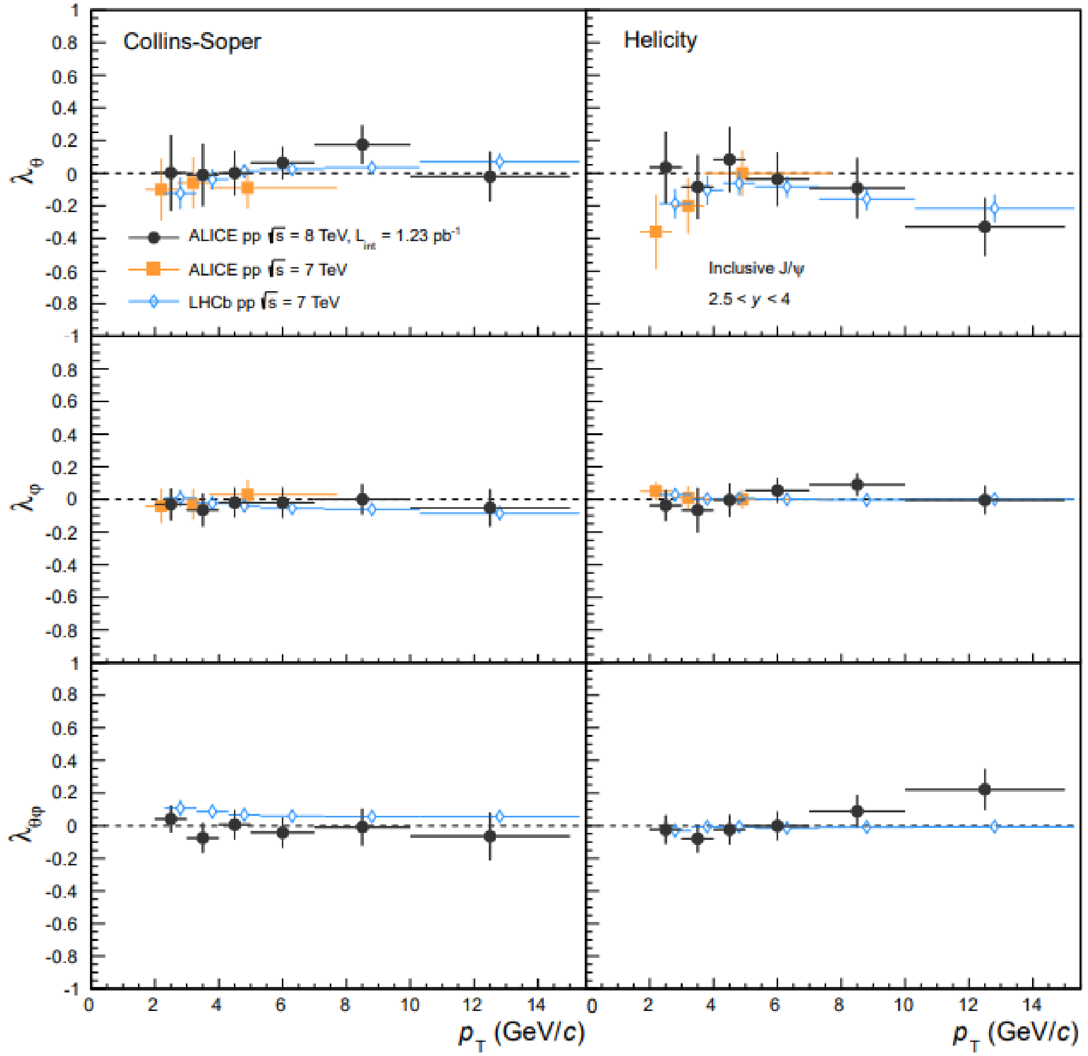


$$I(\cos\theta^*) = \frac{3}{2(\alpha+3)}(1+\alpha\ \cos^2\theta^*)$$

Phys.Rev.Lett.85:2886-2891,2000

α = 1 Transvers polarization
α = 0 No polarization ☹
α = -1 Longitudinal polarization

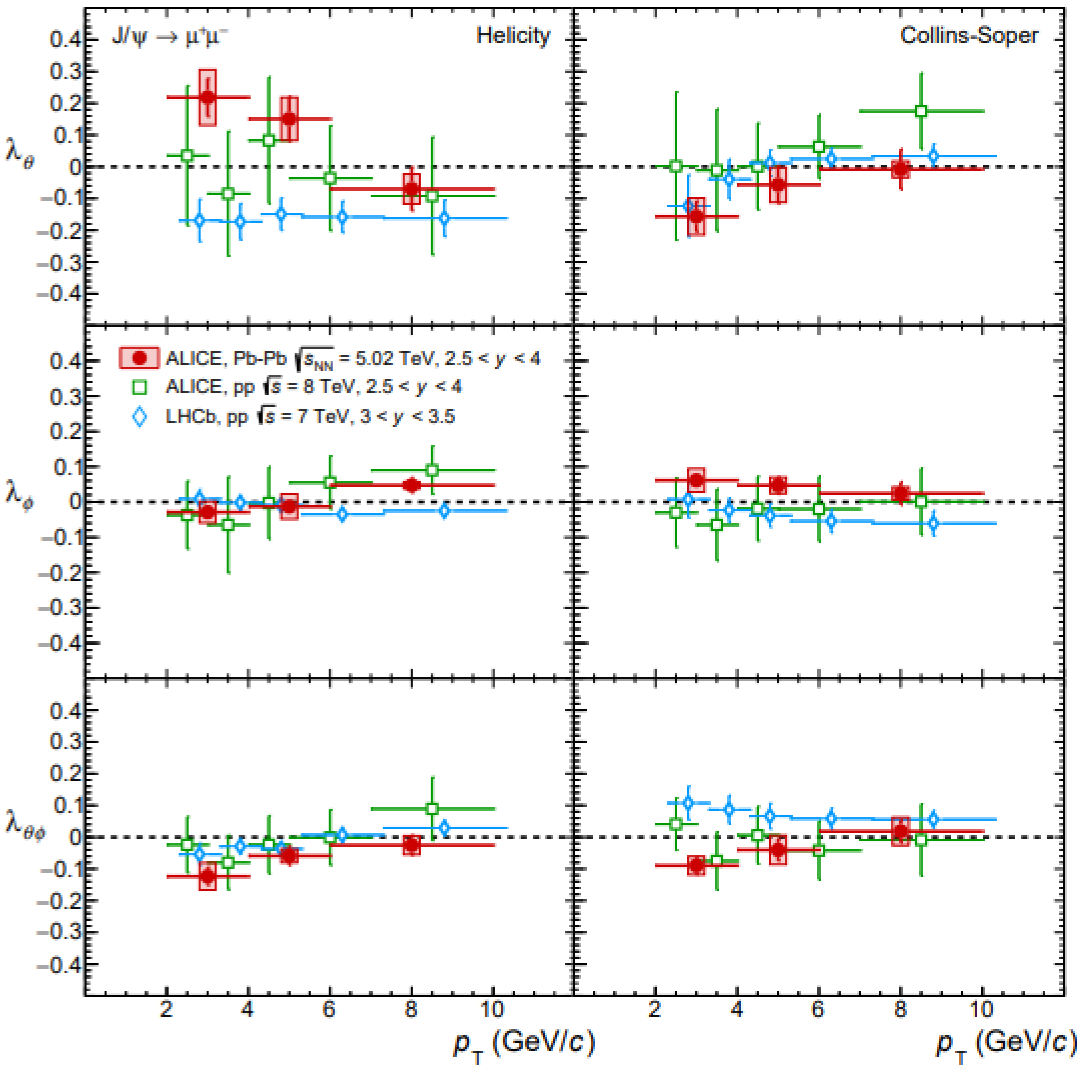
J/Ψ -> μ μ



arXiv:1805.04374v2 [hep-ex]

Polarisation measurements at high energies

- First polarization measurement of inclusive J/Ψ in Heavy Ion Collisions (PbPb)
- Parameter values are close to zero both in the HX and CS frames
- It is expected that HI collisions have a different prompt / non prompt ratio in comparison to pp or $p\bar{p}$ data sets



Polarisation measurements at high energies

- The polarization is somewhat sensitive to the production mechanism when one compares pp, PbPb and $p\bar{p}$?
- Is polarization sensitive to the formation of QGP ?
- Is there a difference between prompt and non prompt J/Ψ polarisation ?
- What abut the data for low p_t ex. J/Ψ -> $e^+ e^-$?
- Is there a magnetic filed influence ?

System	Magnetic Field in Tesla
Human brain	10^{-12}
Earth's magnetic field	10^{-5}
Refrigerator magnet	10^{-3}
Loudspeaker magnet	1
Strongest field in lab	10^{3}
Neutron star	10^{6}
Heavy-ion collisions	***10^{15} - 10^{16}***

Spin alignment of vector mesons measured in Pb-Pb collisions with ALICE

Bedanga Mohanty

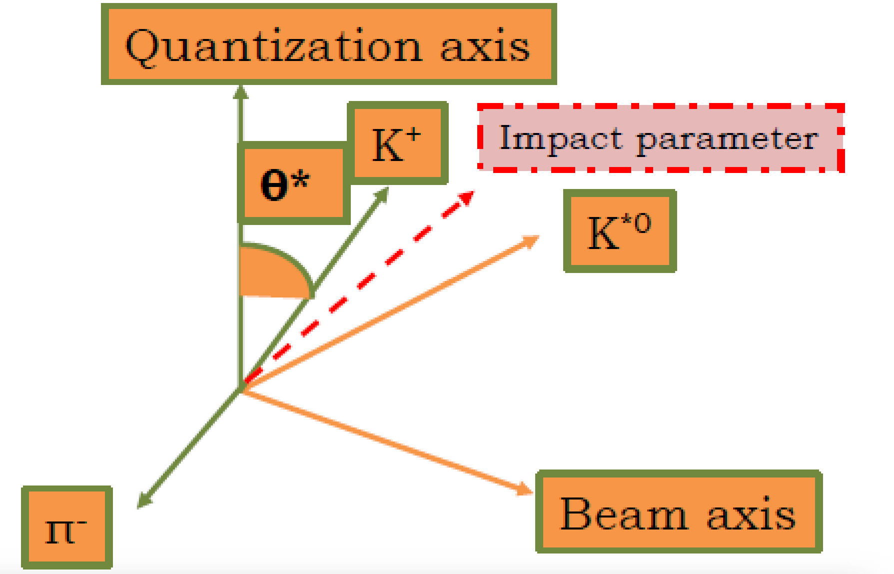
Polarisation measurements at high energies (Angular momentum)

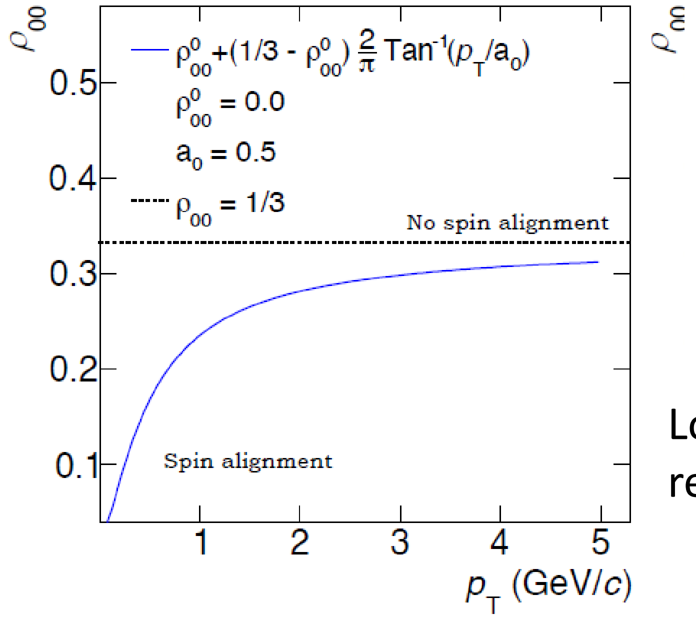
K. Schilling et al., Nucl. Phys. B 15 (1970) 397

$$\frac{dN}{dcos\theta d\phi} = \langle \theta, \phi, \lambda_1, \lambda_2 | M \rho M^\dagger | \theta, \phi, \lambda_1, \lambda_2 \rangle$$

$$= \sum_{\lambda_V} \sum_{\lambda_{V'}} \langle \theta, \phi, \lambda_1, \lambda_2 | M | \lambda_V \rangle \langle \lambda_V | \rho | \lambda_{V'} \rangle \langle \lambda_{V'} | M^\dagger | \theta, \phi, \lambda_1, \lambda_2 \rangle$$

λ = Helicities
ρ = spin density matrix
M = Decay amplitude

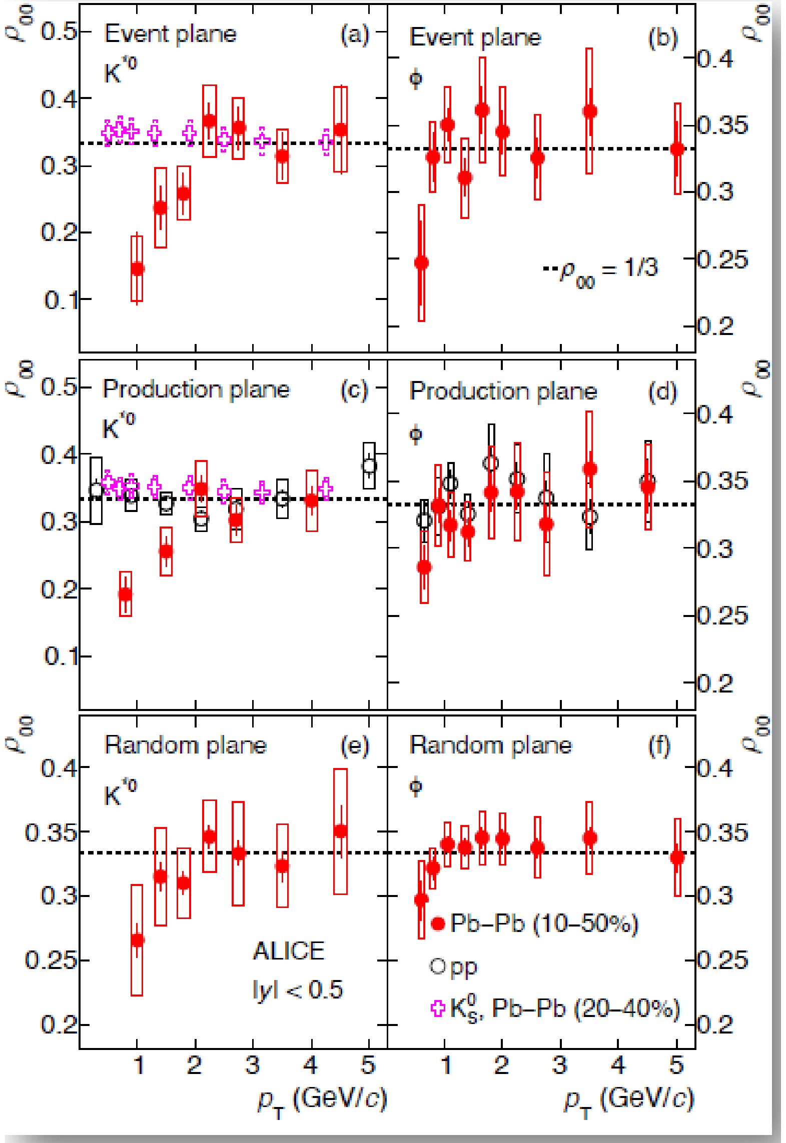




Z. Liang et. al., Phys. Lett. B629, 20 (2005)

Low p_t dominated by recombination effects

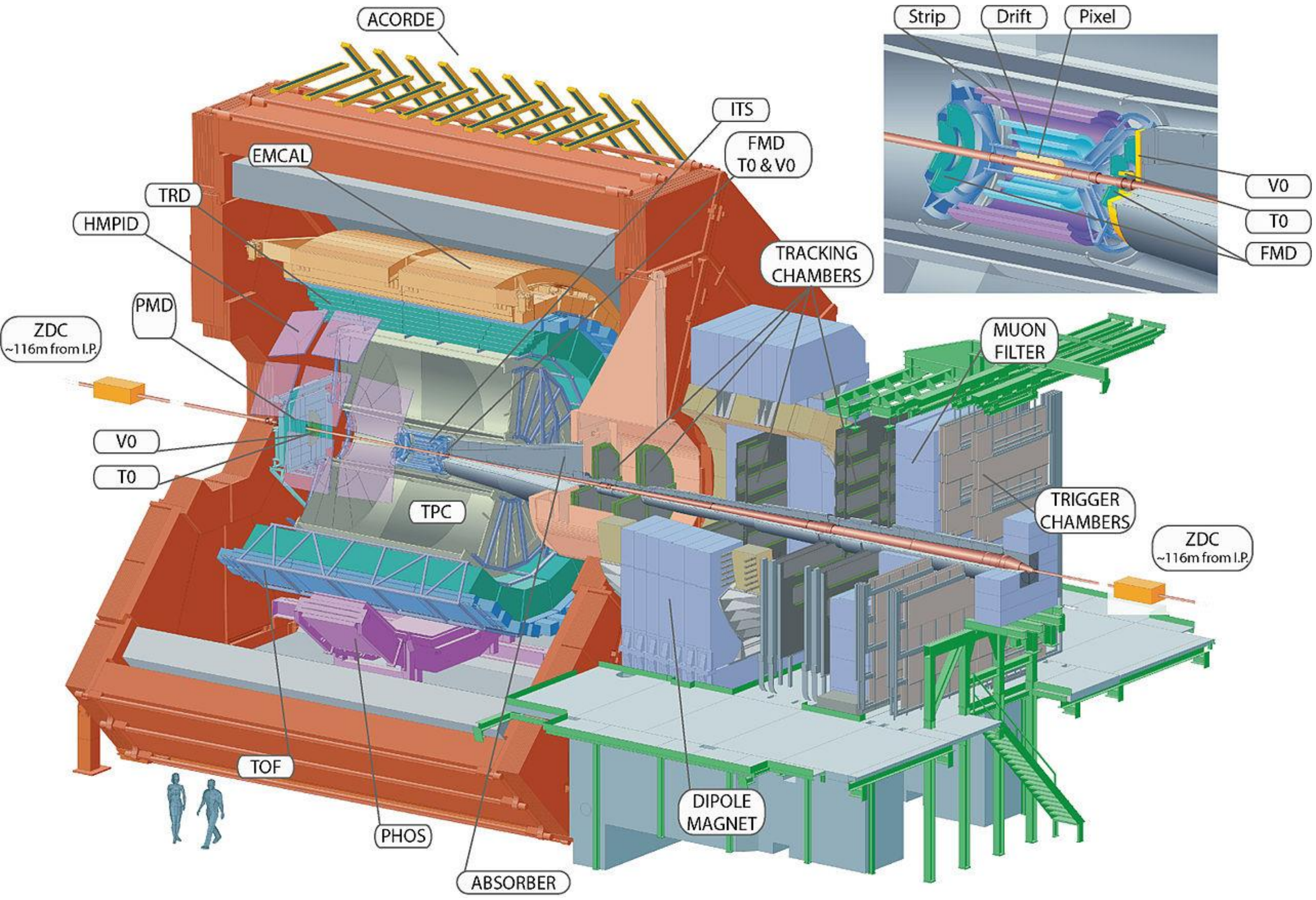
Polarisation measurements at high energies (Spin alignment of vector mesons)



Spin alignment for vector mesons (spin 1) in PbPb

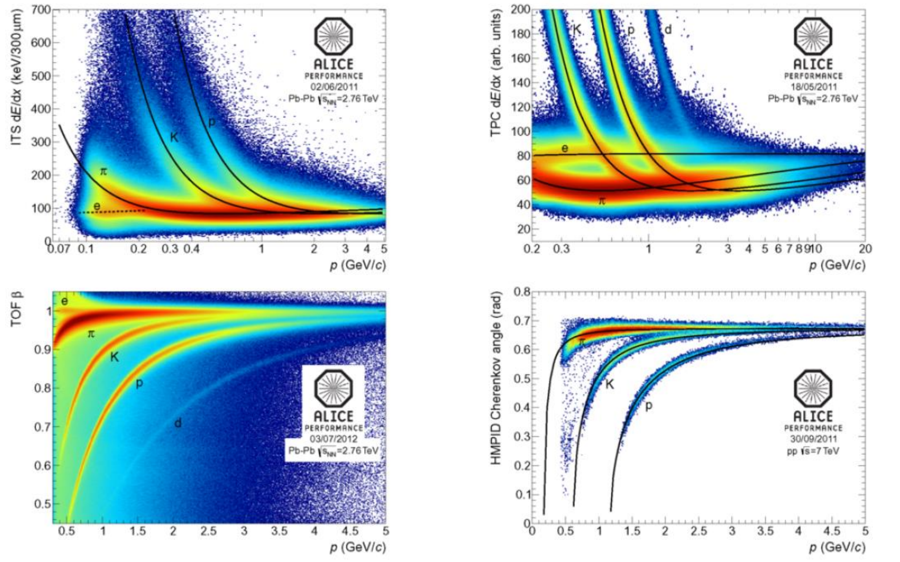
arXiv:1910.14408 (ALICE)

The ALICE experiment



Key features:

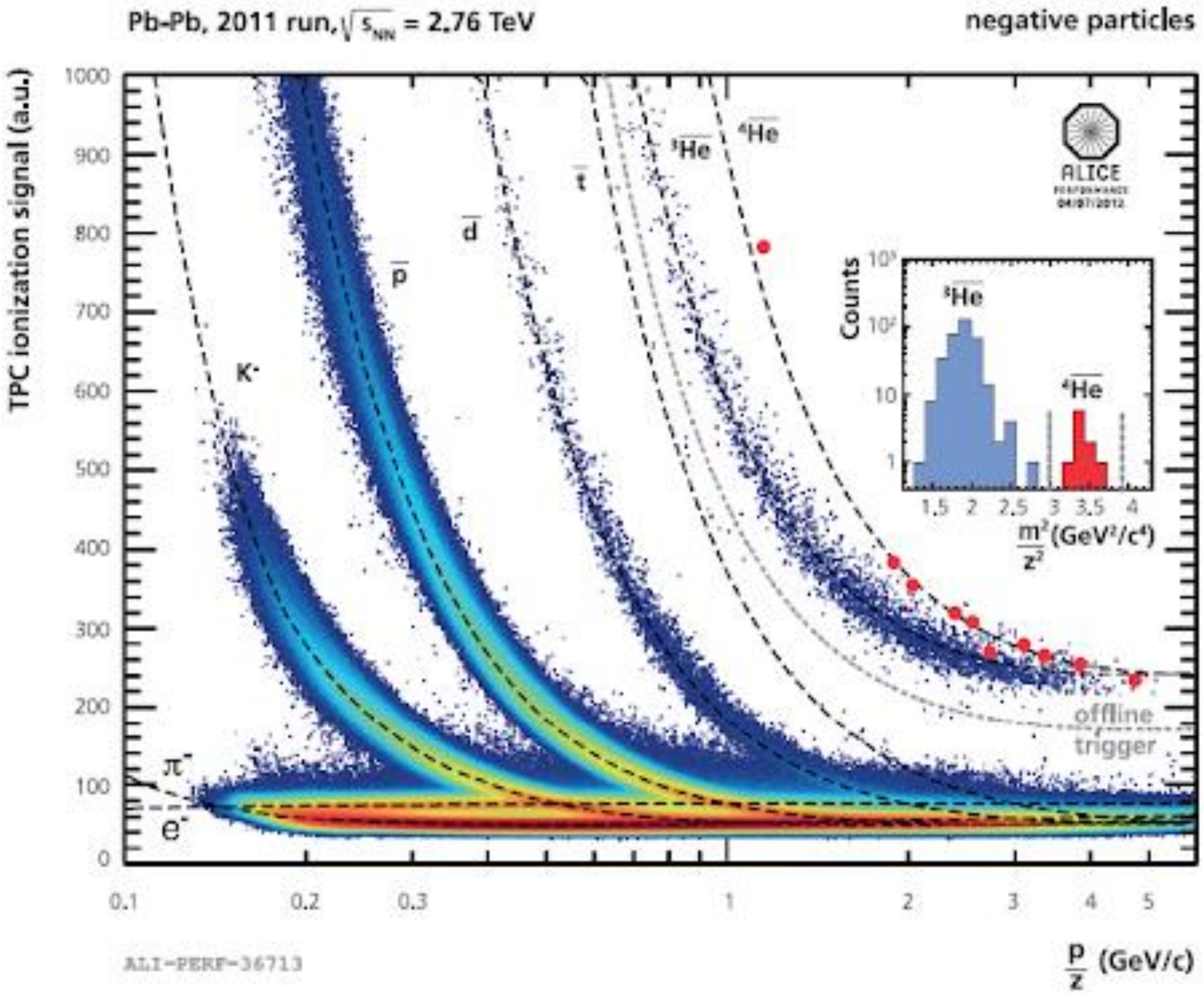
- Excellent PID capabilities
- High resolution tracking for low p_t tracks
- Low magnetic field (only 0.5 T)



Novel methods

- TBA

Bac


Pb-Pb, 2011 run, $\sqrt{s_{NN}}$ = 2.76 TeV
negative particles
TPC ionization signal (a.u.)
ALICE
$\overline{p}$
$\overline{d}$
$\overline{t}$
$^{3}\overline{He}$
$^{4}\overline{He}$
K^-
π^-
e^-
offline
trigger
Counts
$\frac{m^2}{z^2}$ (GeV²/c⁴)
ALI-PERF-36713
$\frac{p}{z}$ (GeV/c)