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

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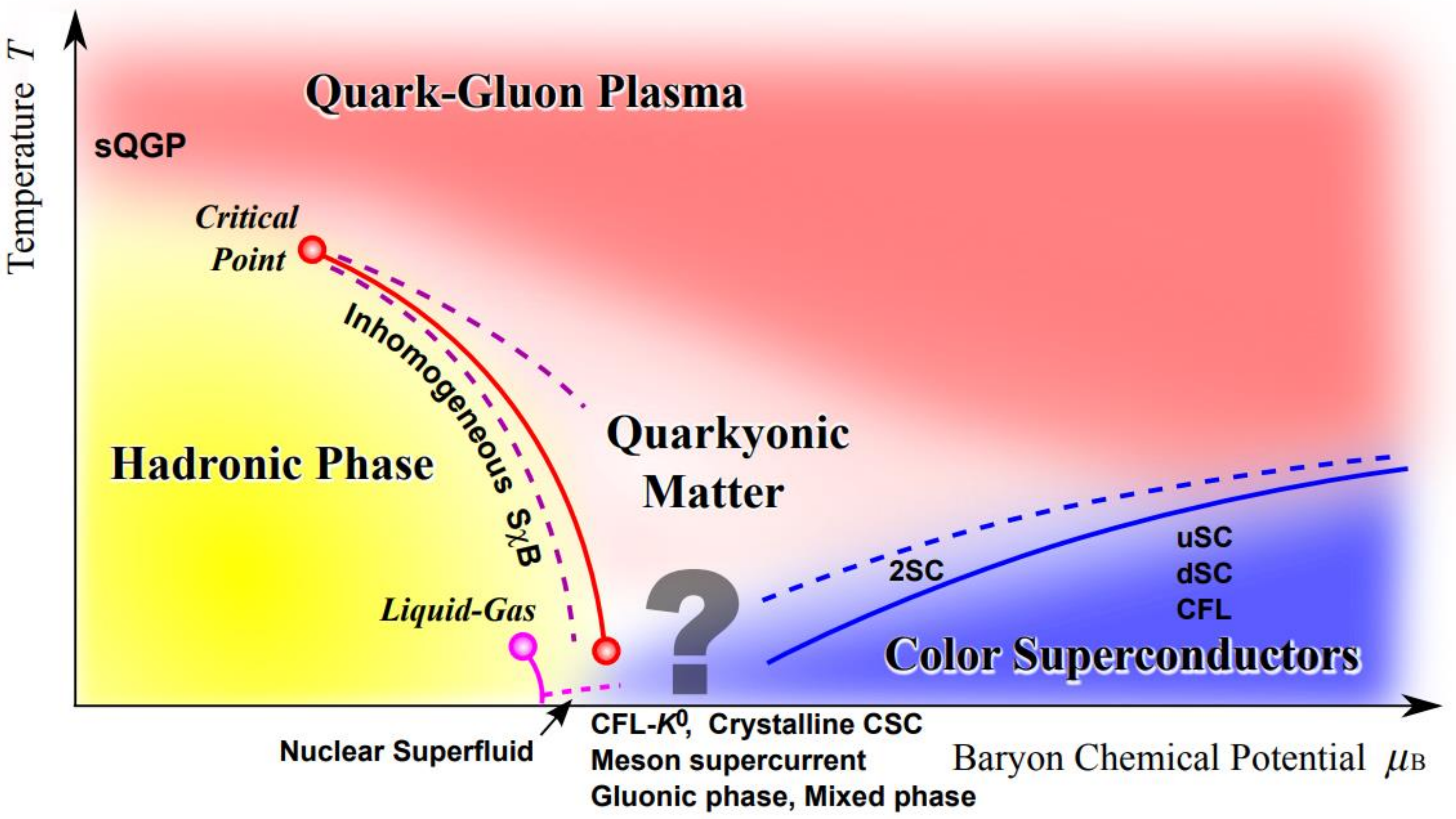
Contents

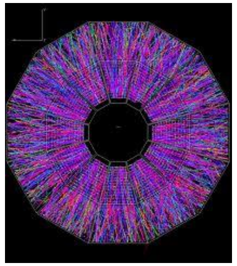
- QCD Phase diagram and evolution of heavy ion collisions
- QGP formation and properties
- Heavy quark production
- Charm hadron production in heavy ion collisions
- Polarisation measurements at high energies
- The ALICE spectrometer
- Novel methods of charm hadron reconstruction
- Summary

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

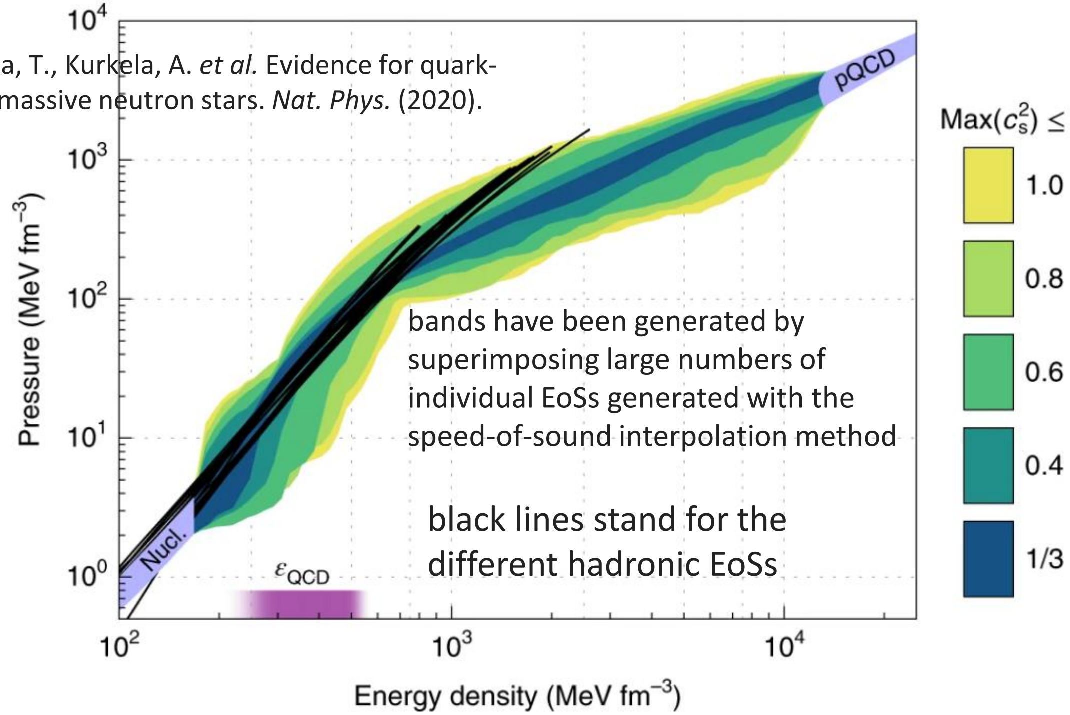
- So called critical point is a topic of extensive theoretical and experimental studies

(*) 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

- 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
- Can we expect QGP in Heavy Ion collisions or in the core of a Neutron Star ?

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



Speed of sound

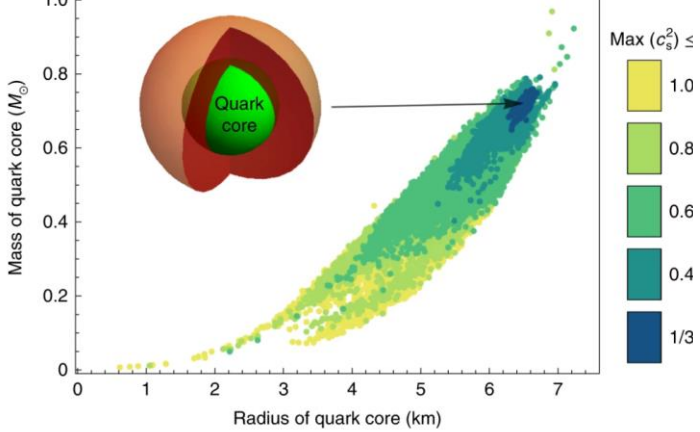
$$n(\mu) = n_{\mathrm{CET}} \exp\left[\int_{\mu_{\mathrm{CET}}}^{\mu} \frac{\mathrm{d}\mu'}{\mu' c_s^2(\mu')}\right] \qquad n_{\mathrm{CET}} < n < n_{\mathrm{pQCD}}$$

Density – n
Baryon chemical potential – μ
speed of sound - c_s^2
matter resides in the hadronic-matter phase - n_{cet}

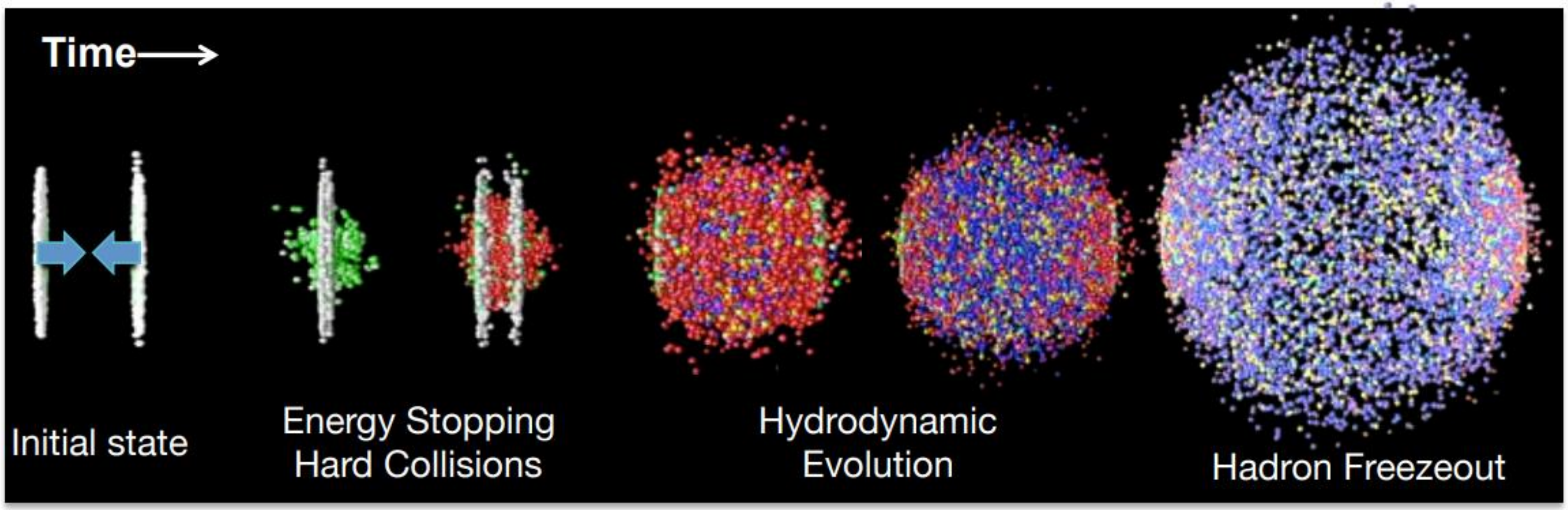
$$p(\mu) = p_{\mathrm{CET}} + n_{\mathrm{CET}} \int_{\mu_{\mathrm{CET}}}^{\mu} \mathrm{d}\mu' \exp\left[\int_{\mu_{\mathrm{CET}}}^{\mu'} \frac{\mathrm{d}\mu''}{\mu'' c_s^2(\mu'')}\right]$$

where $p_{\mathrm{CET}} \equiv p(\mu_{\mathrm{CET}})$.

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

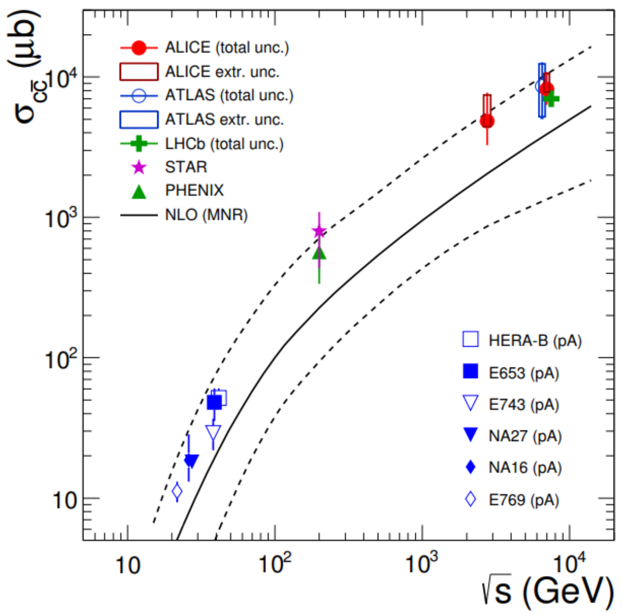
The production of hadrons from a "QGP" fireball occurs mainly by way of quark coalescence and gluon fragmentation, and there can be quark fragmentation as well

Heavy quark production

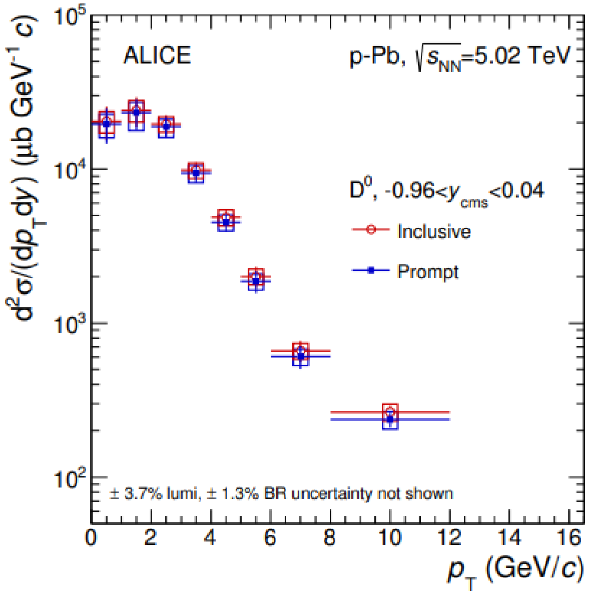
- Heavy quarks can be a probe of QGP
- Produced in high energy hard partonic scattering process in the early stage of the collision

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 (forward rapidity measurement)

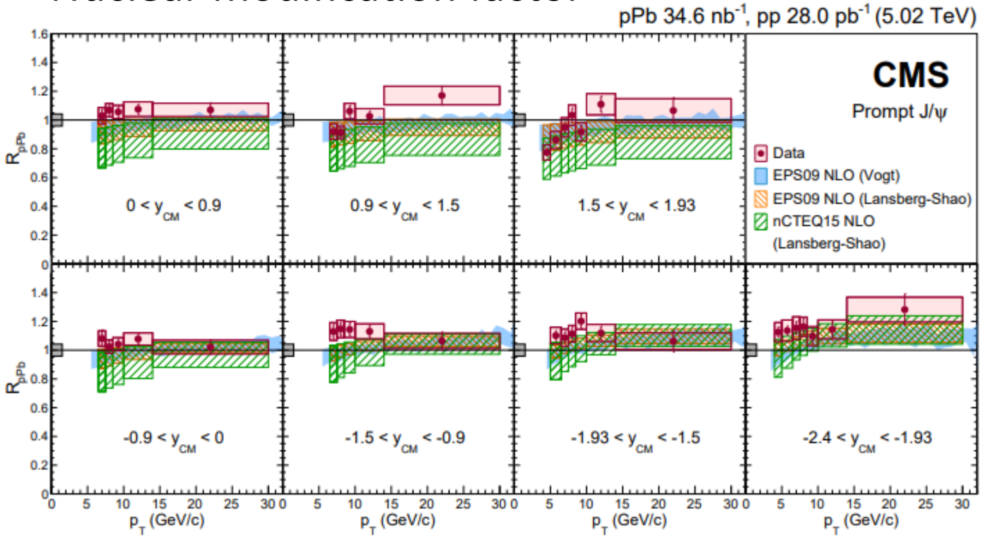


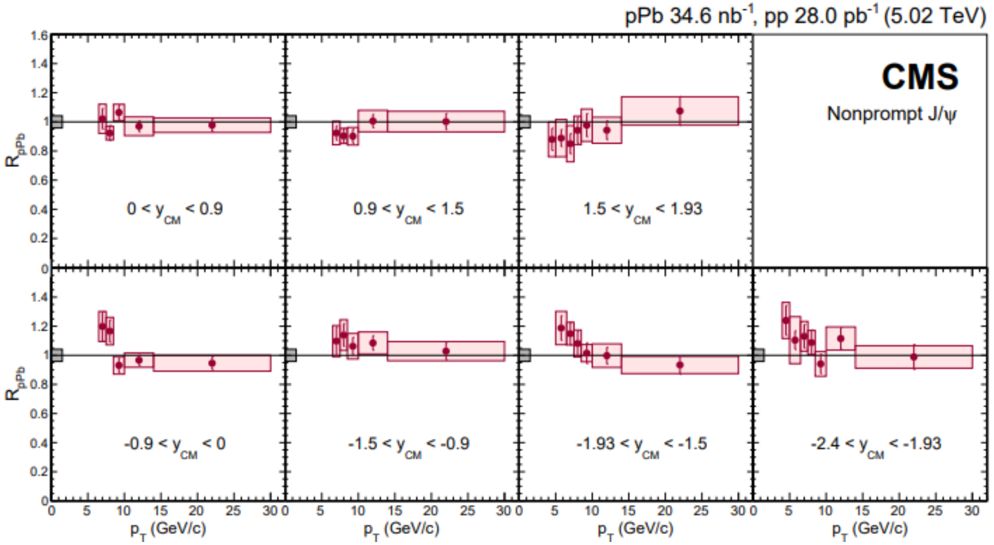
Strong p_t dependence of D-meson production cross section

Charmonium production

- Charmonium <u>production</u> and <u>polarisation</u> is still a puzzle
- Due to there <u>long life time</u> (in comparison to Δ and N resonances) they can probe all of the stages of medium evolution interacting with the constituents via energy loss (gluon radiation and elastic collision)
- J/Ψ (charm) production can occur directly (prompt) and via B-feed down (non-prompt)
- depletion of nuclear gluon density at small values of the momentum fraction (x) , “shadowing” can suppress J/Ψ at forward y

Nuclear modification factor





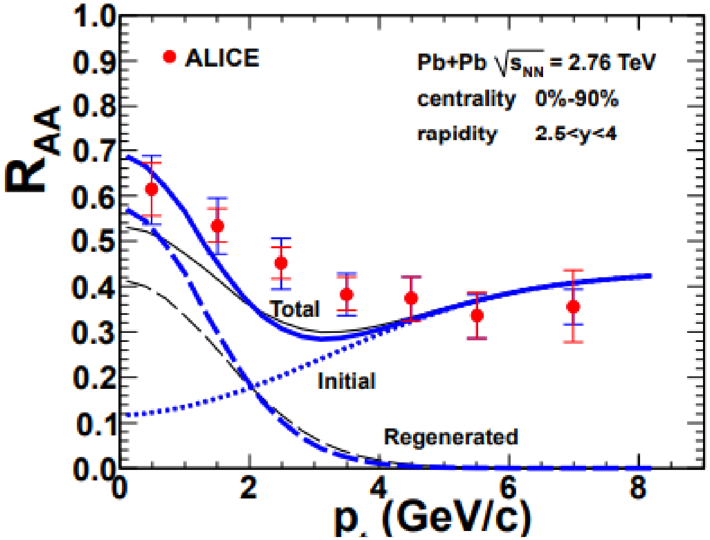
Eur. Phys. J. C 77 (2017) 269

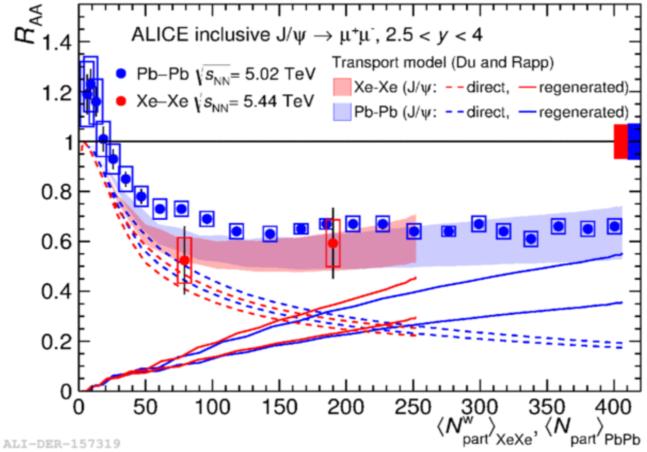
Charmonium production in heavy ion collisions

- In HI collisions charmonium production can be modified by regeneration (*) and dissociation (@) 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

Phys.Rev.C 86 (2012) 034906





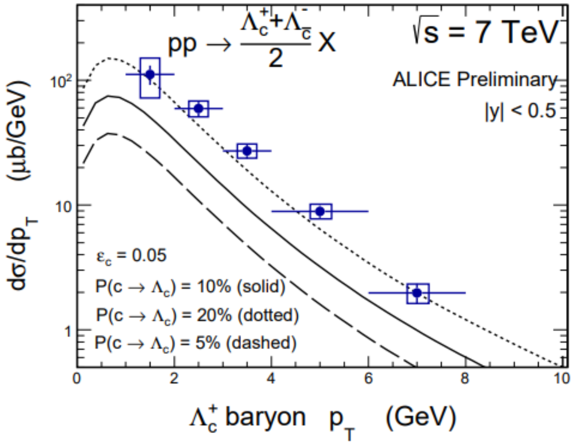
@T. Matsui and H. Satz, "J/ψ Suppression by Quark-Gluon Plasma Formation" Phys. Lett. B168 (1986) 415

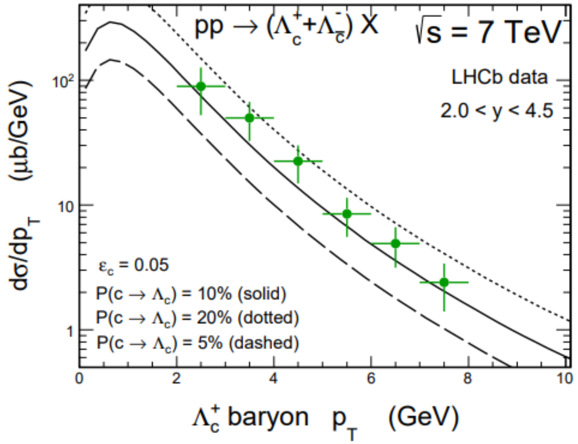
*P. Braun-Munzinger and J. Stachel, "(Non)Thermal Aspects of Charmonium Production and a New Look at J/ψ Suppression", Phys. Lett. B490 (2000) 196

Charm hadron production in heavy ion collisions

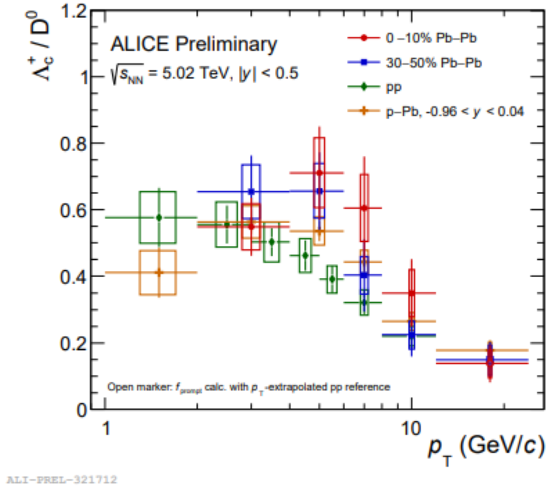
- What abut baryons (Λ_c) ?
- The models are based on independent parton fragmentation approach
- Strong enchantment in pp observed due to coalescence mechanism (formation in QGP)?
- Flow affects Λ_c p_t distributions, shifting them to higher values?
- Results for PbPb collisions seem to hint to the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

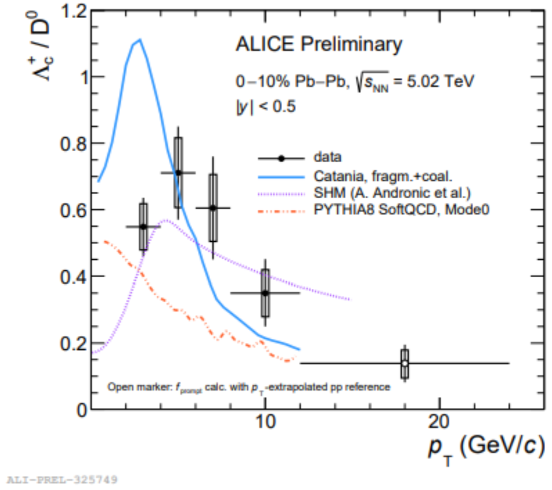
PoS DIS2019 (2019) 158





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





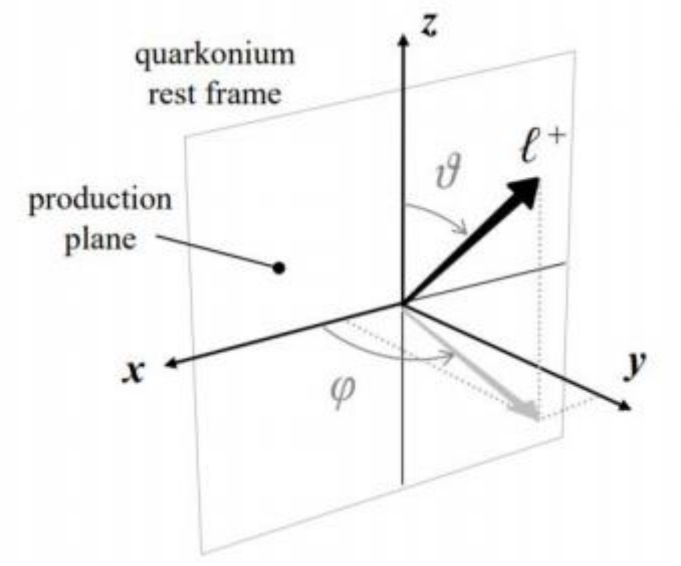
Polarisation measurements at high energies

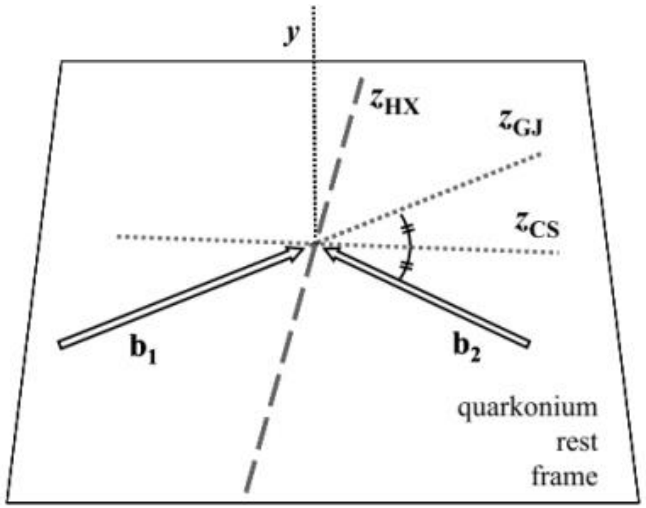
- Measurements of quarkonium polarisation preformed at ALICE in PbPb
- $(c\bar{c}$ & $b\bar{b}) \rightarrow \mu\mu$
- There is no model describing the polarisation !

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

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



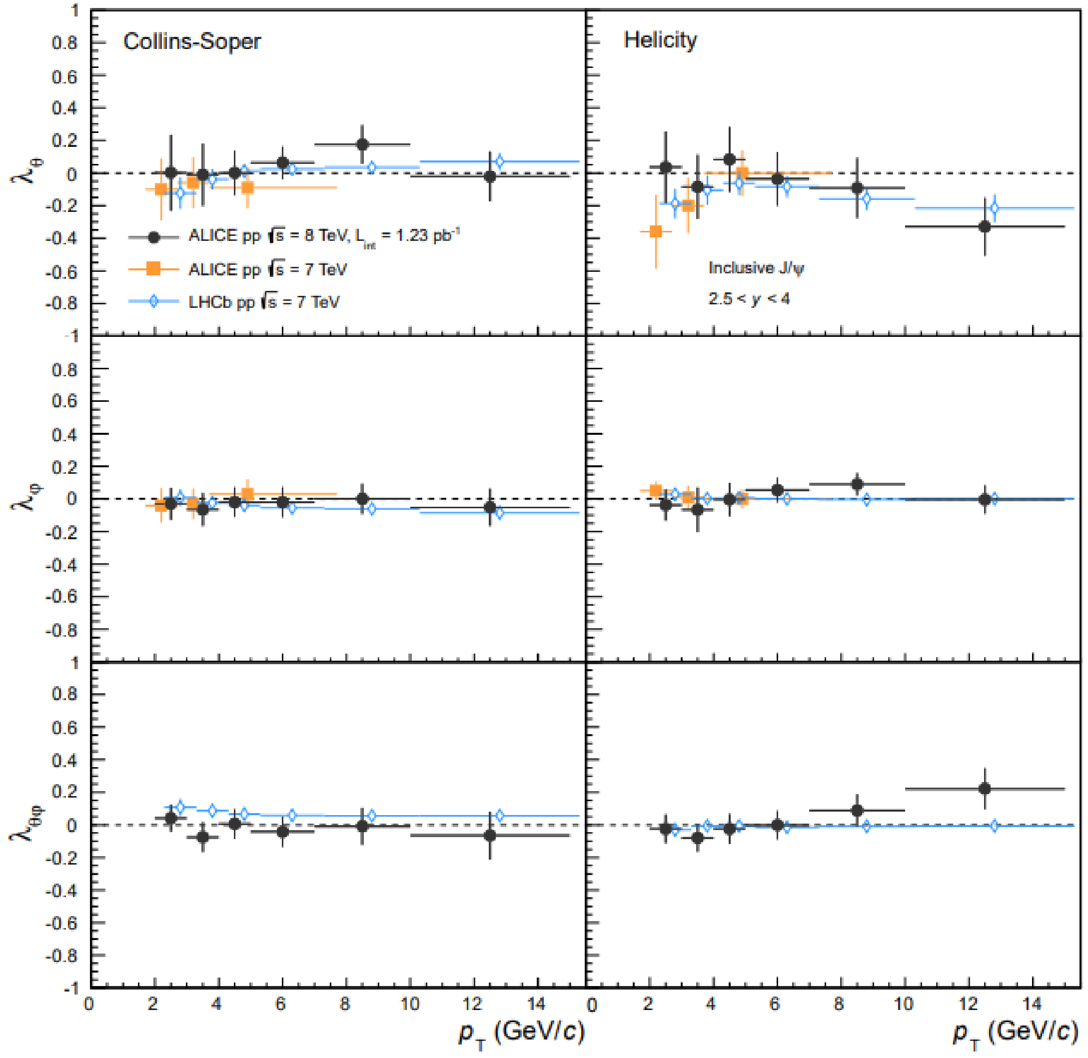


$\lambda_\Theta, \lambda_\varphi, \lambda_{\theta\varphi} \rightarrow (0,0,0)$ no polarisation ☹
$\lambda_\Theta, \lambda_\varphi, \lambda_{\theta\varphi} \rightarrow (-1,0,0)$ longitudinal polarisation
$\lambda_\Theta, \lambda_\varphi, \lambda_{\theta\varphi} \rightarrow (+1,0,0)$ Transvers polarisation

Polarisation measurements at high energies

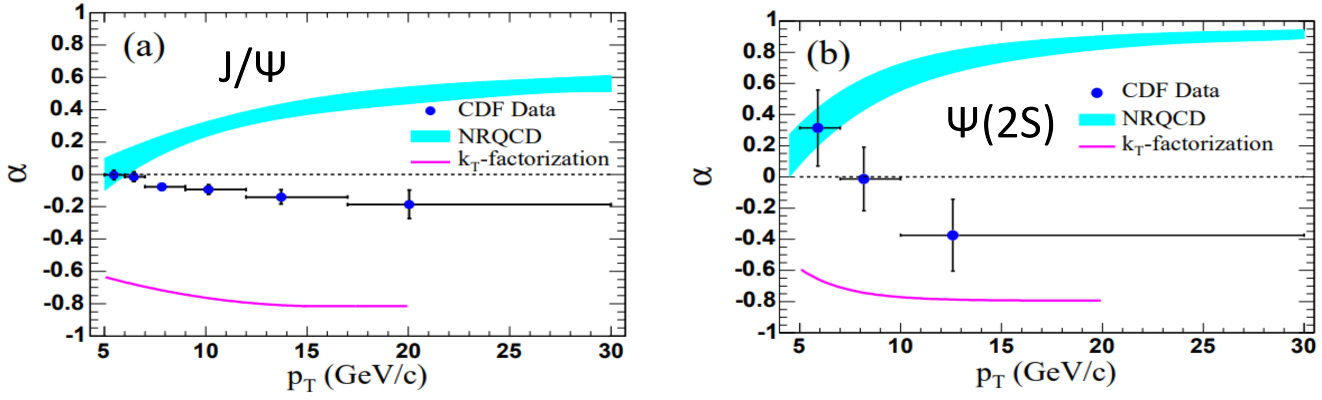
- J/Ψ Inclusive polarisation measurements in pp collisions in the forward rapidity bins
- Calculations done in two reference frames, Colin Soper and Helicity
- LHCb and ALICE follow the same trend in CS frame
- Discrepancies can bee observed in HX frame, the polarization is non zero in high p_t bins (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 ?

J/Ψ -> μ μ



arXiv:1805.04374v2 [hep-ex]

Prompt



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

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

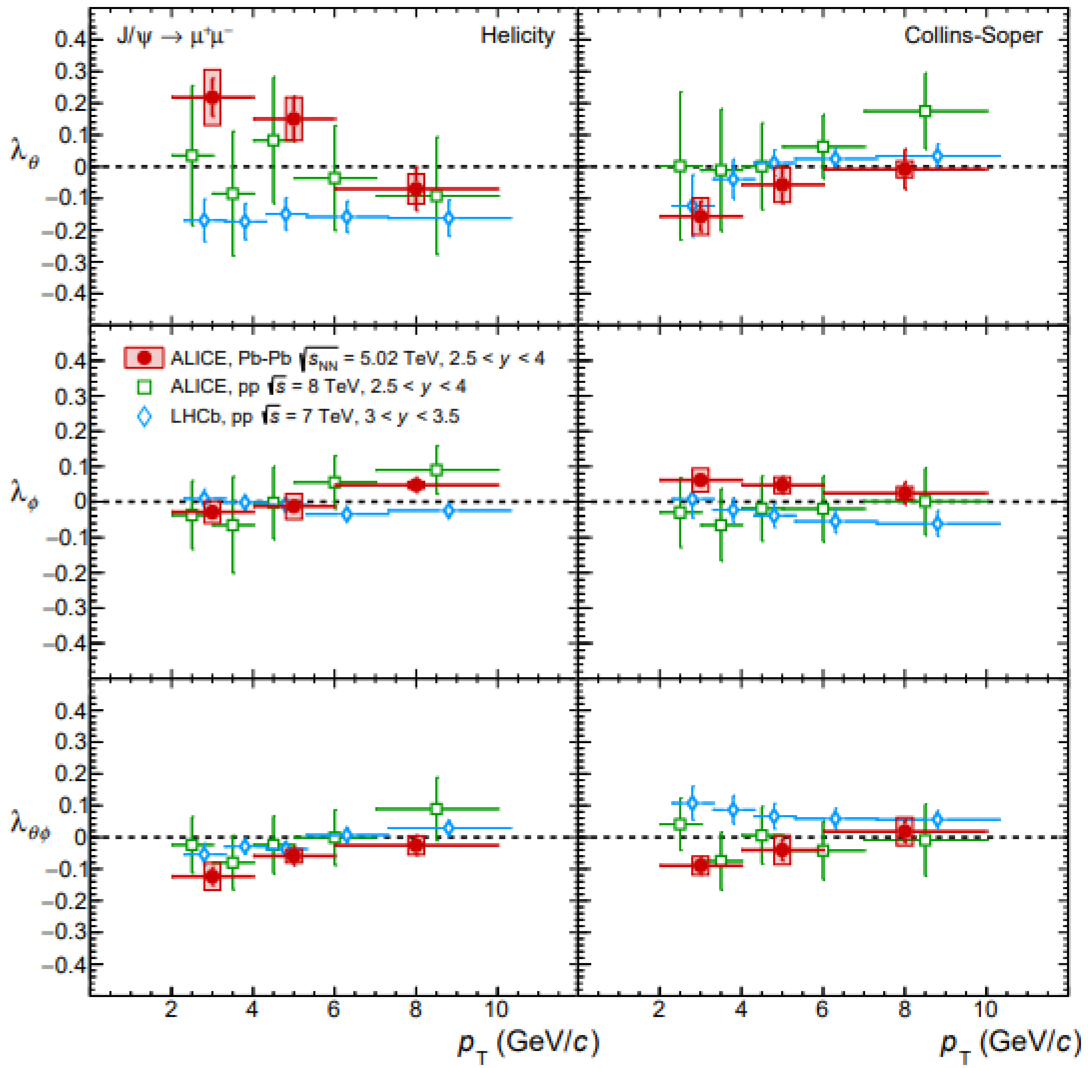
α = 1 Transvers polarization

α = 0 No polarization ☹

α = -1 Longitudinal polarization

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 except λ_θ both in CS and HX 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

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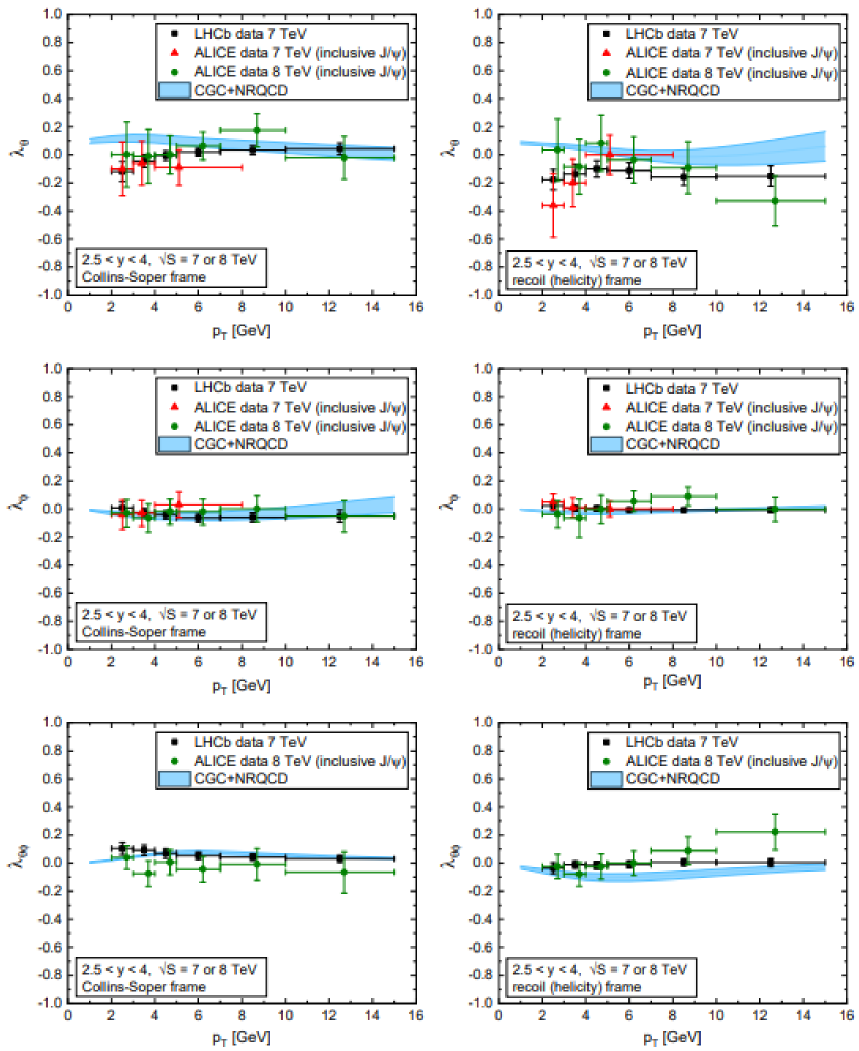
- Parameter values are close to zero both in the HX and CS frames except λ_θ both in CS and HX frames
- It is expected that HI collisions have a different prompt / non prompt ratio in comparison to pp or $p\bar{p}$ data sets
- The model fails to provide a satisfying description of the data (blue band)



JHEP 12 (2018) 057

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}***

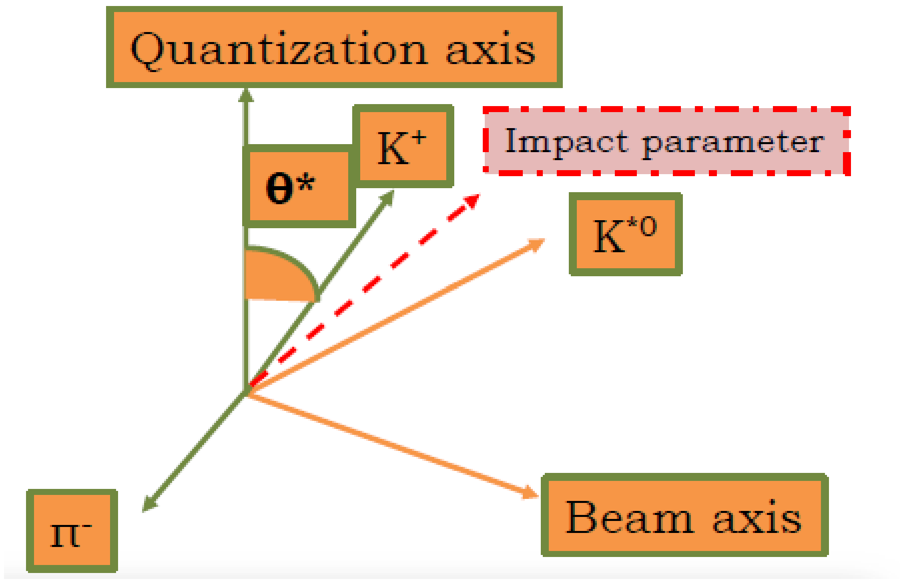
Spin alignment of vector mesons measured in Pb-Pb collisions with ALICE
Bedanga Mohanty

Polarisation measurements at high energies (Angular momentum)

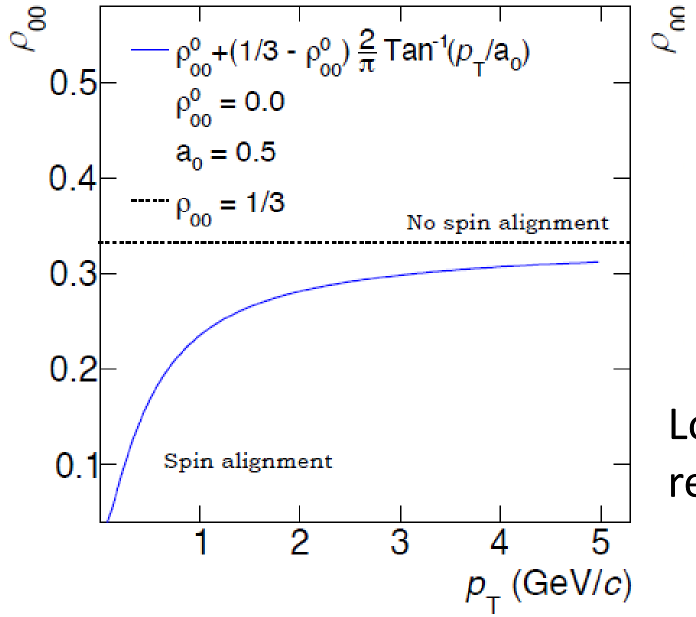
K. Schilling et al., Nucl. Phys. B 15 (1970) 397

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

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



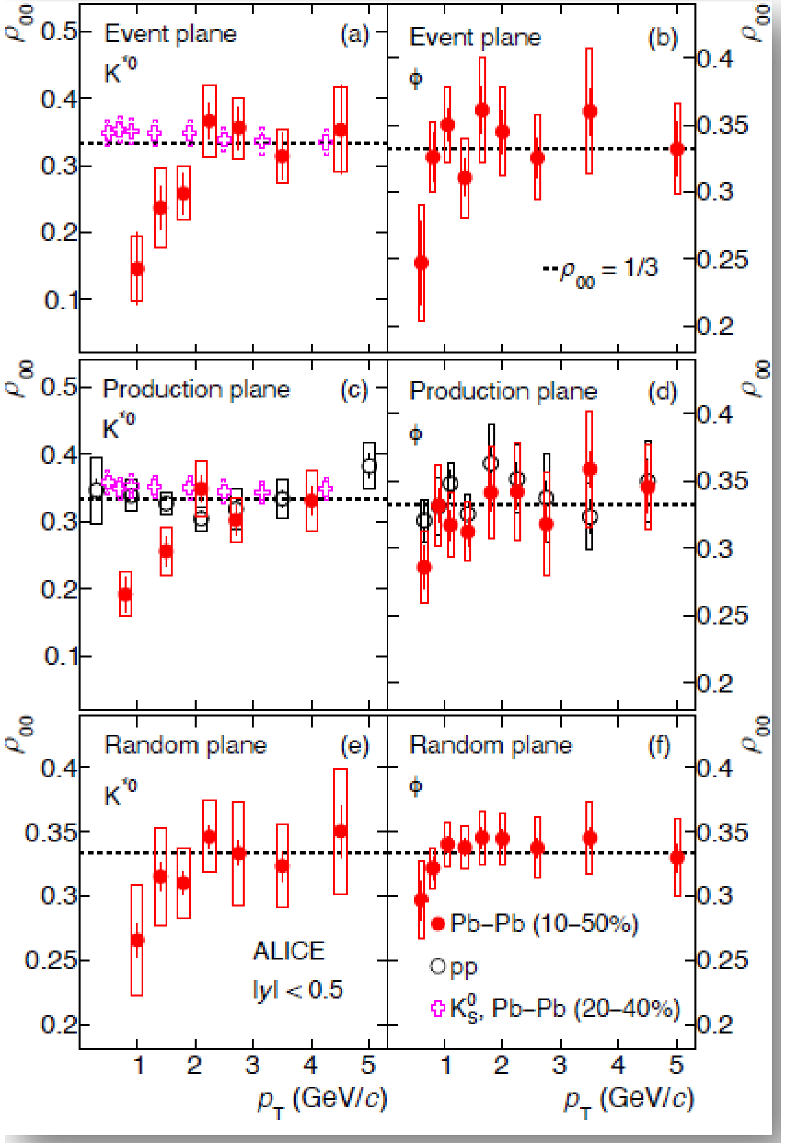
λ = Helicities
ρ = spin density matrix
M = Decay amplitude



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

Low p_t dominated by recombination effects

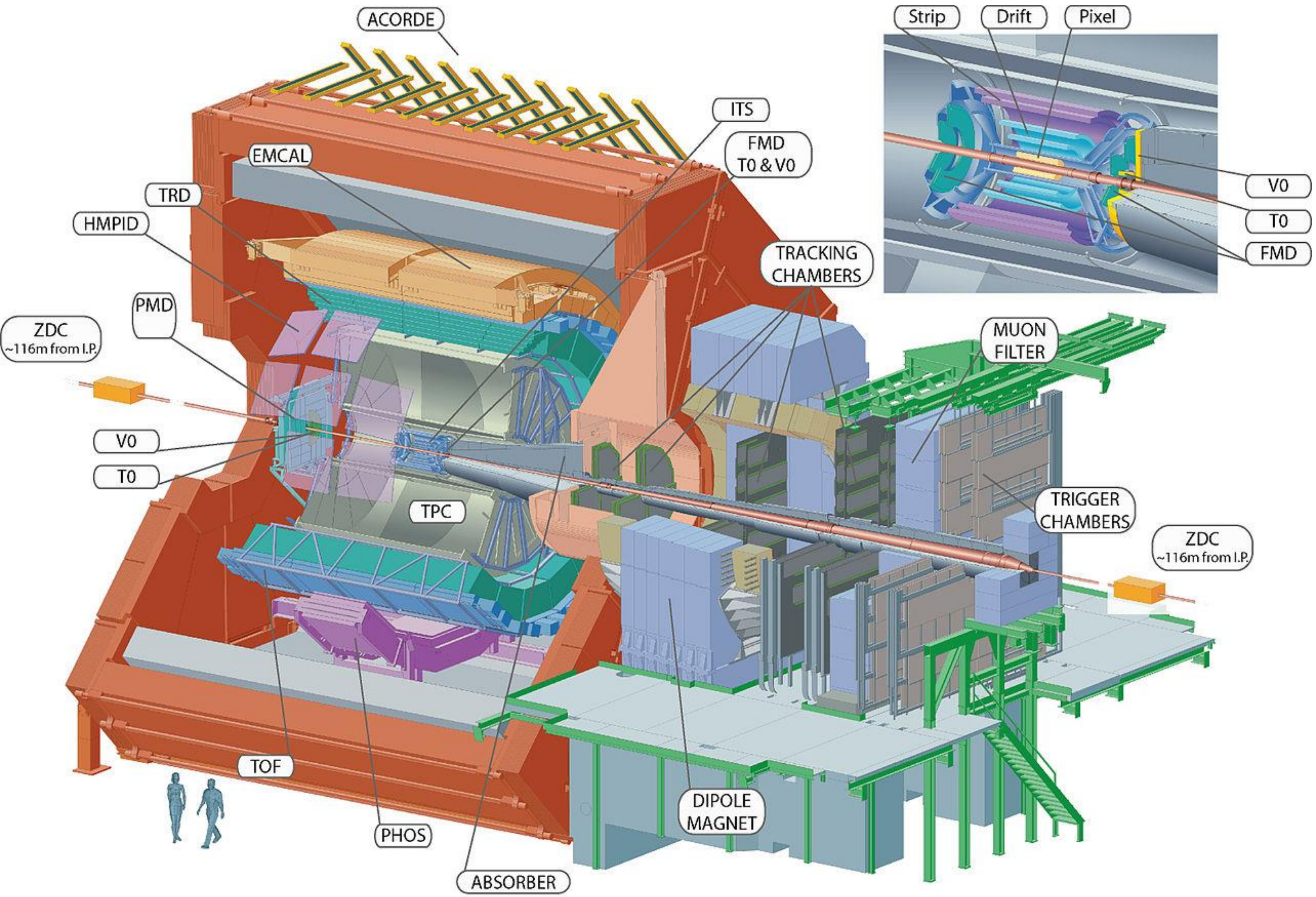
Polarisation measurements at high energies (Spin alignment of vector mesons)



Spin alignment for vector mesons (spin 1) in PbPb

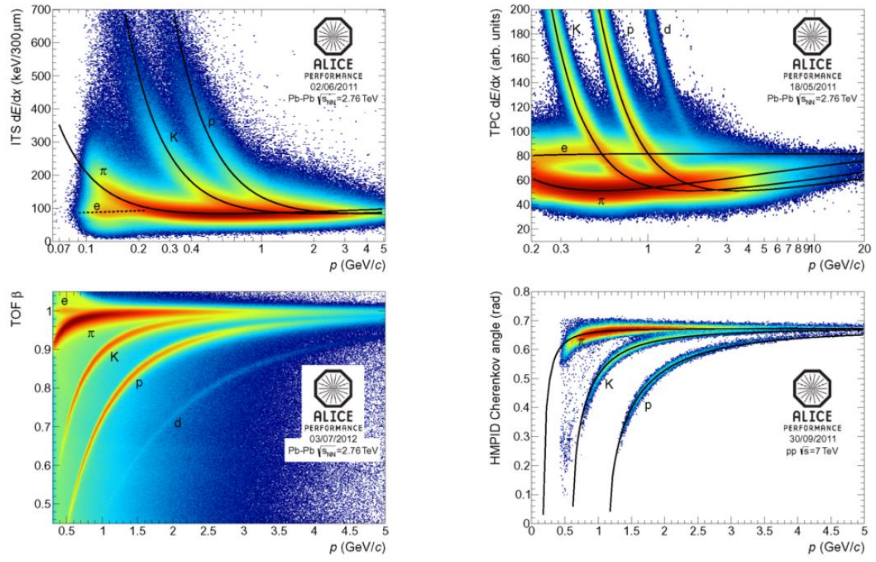
arXiv:1910.14408 (ALICE)

The ALICE experiment

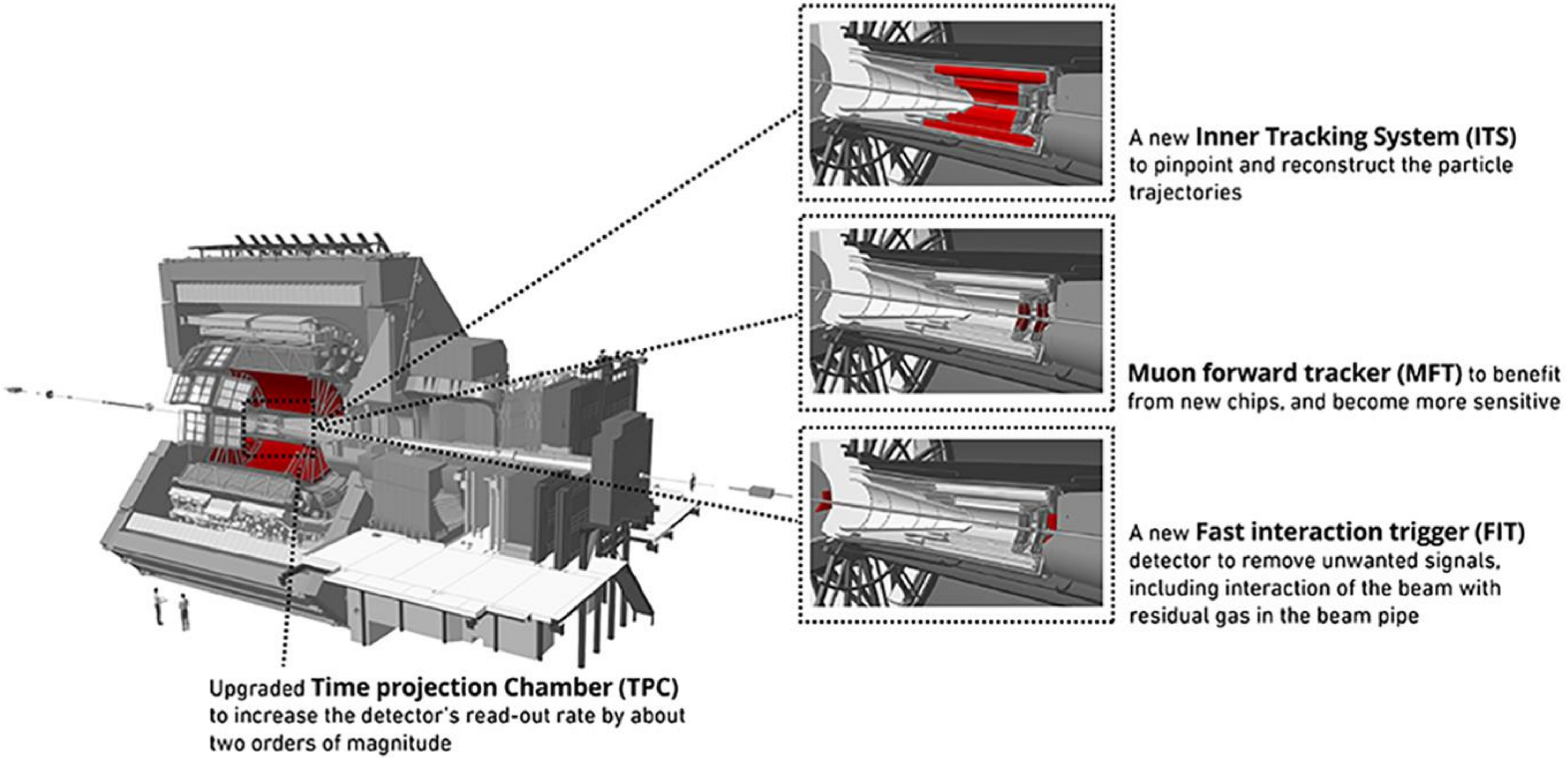


Key features:

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



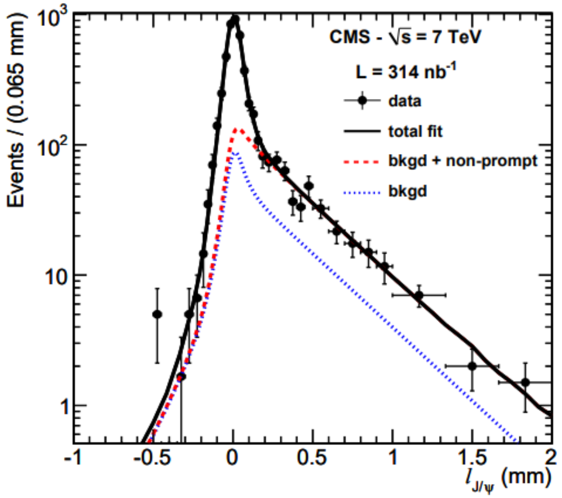
Upgrade

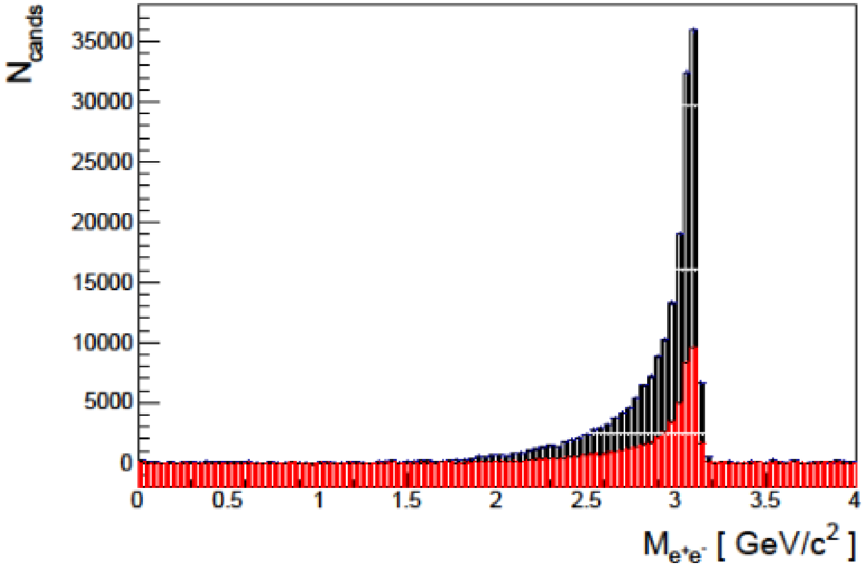

A new **Inner Tracking System (ITS)** to pinpoint and reconstruct the particle trajectories
Muon forward tracker (MFT) to benefit from new chips, and become more sensitive
A new **Fast interaction trigger (FIT)** detector to remove unwanted signals, including interaction of the beam with residual gas in the beam pipe
Upgraded **Time projection Chamber (TPC)** to increase the detector's read-out rate by about two orders of magnitude

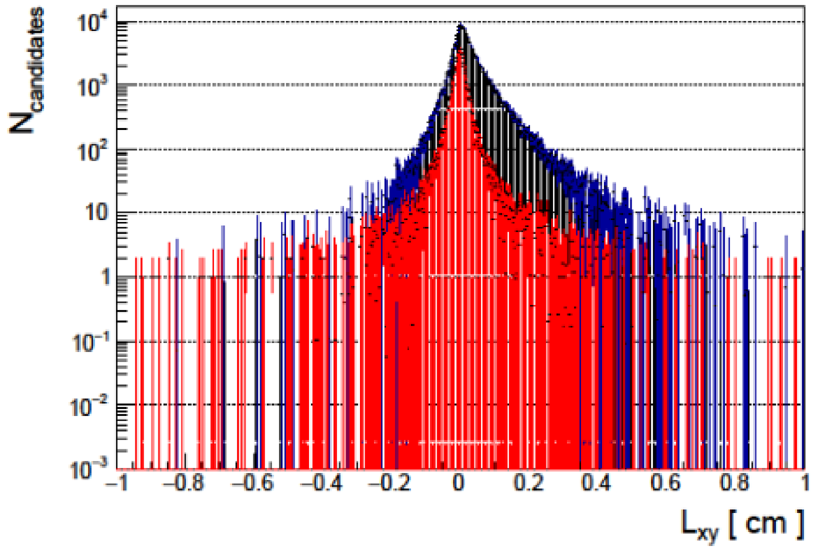
Novel methods

- PbPb collisions are expected to have slightly different ratio of prompt to non prompt J/Ψ production in comparison to pp
- Due to smaller number of non prompt events and higher background the tagging will be based on Bayesian Neural Network interfaces exploiting the so called of vertex J/Ψ coming form B-baryon feed down
- The algorithm is relatively fast, the training phase is 1 min on a user grade GPU of RTX 2060

Eur.Phys.J.C71:1575,2011







Based on ALICE data like MC, prompt to non prompt ratio is 7/3

Pseudo proper decay length one of the “sensitive” observables

Novel methods

Tensorflow and Keras

- Keras simplifies construction of NN-models
- in combination with Python: Quick way to test your model
- Additional Tensorflow Libraries for Bayesian Approach

A project by my two students
http://www.it.uu.se/edu/course/homepage/projektTDB/ht18/project09/Project09_report.pdf

Summary

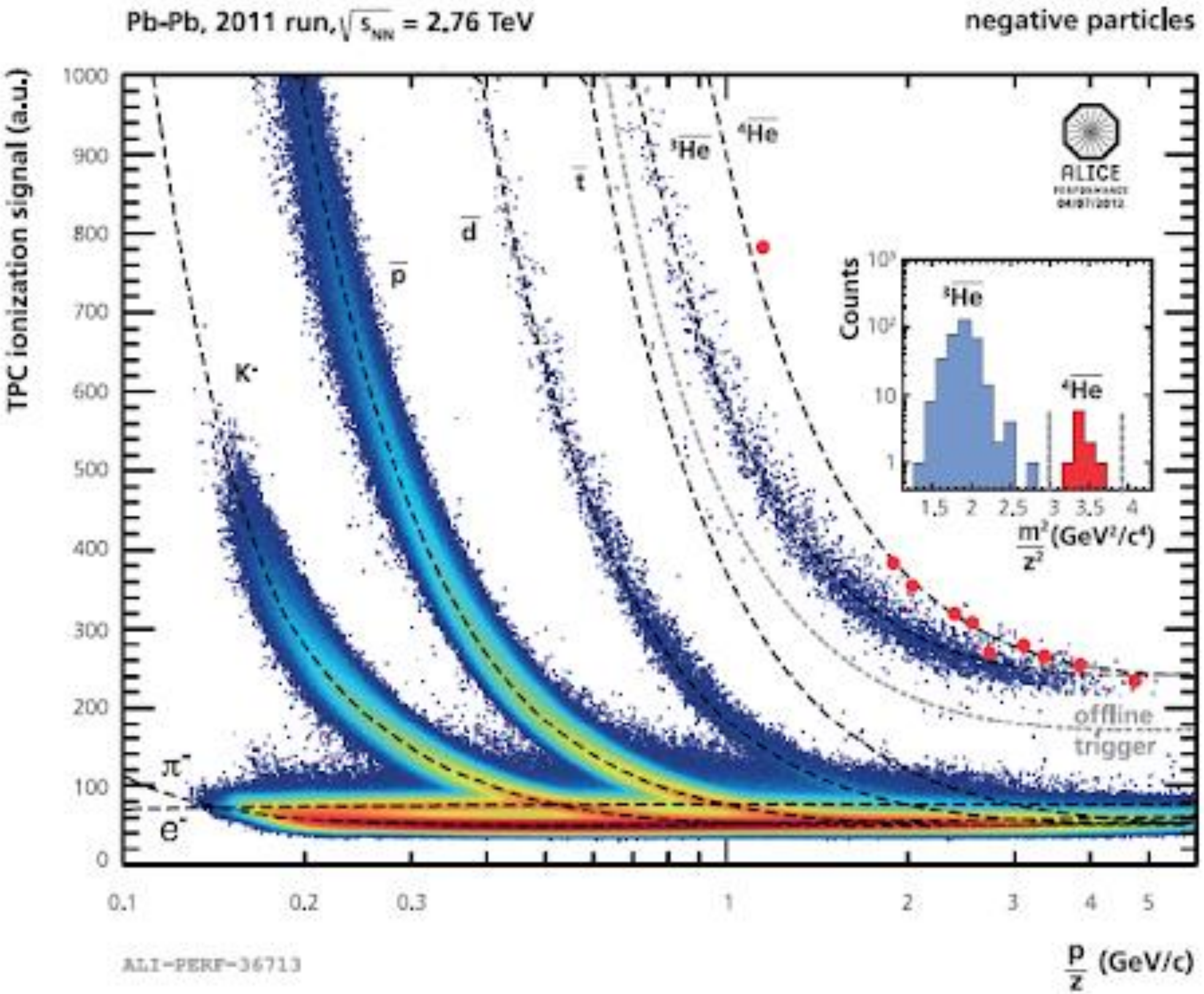
- The search for the QGP signature is a big challenge
- The quarkonium production mechanisms are complex so far non of the models describe the data very well
- The polarisation measurements give interesting patterns (pp vs ppbar vs PbPb) and hint a sensitivity to the production mechanisms, therefore is it sensitive to QGP (^)?
- Low p_t data are scares or missing (below 2 GeV)
- It will be interesting to compare the polarisation for prompt and non prompt J/Ψ taking in to account recent BES III results (*)

*Complete Measurement of the Λ Electromagnetic Form Factors

Phys.Rev.Lett. 123 (2019) 12

^Phys.Part.Nucl.35:S98-S101,2004


Bac



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

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?