Quarkonium and open heavy-flavour production at forward rapidity with ALICE at the LHC

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Outline

1. Physics motivations
2. Experimental setup
3. Quarkonia
4. Muons from heavy-flavour decays
5. Conclusions

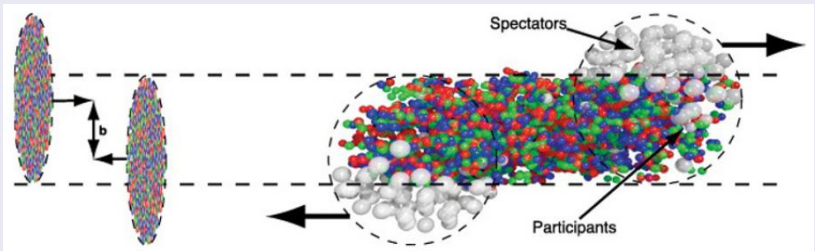
Quark-Gluon Plasma in heavy-ion collisions

Quark-Gluon Plasma

The Quark-Gluon Plasma (QGP) is a non-ordinary state of the matter in which quarks and gluons are deconfined.

It can be produced in ultrarelativistic central heavy-ion (A–A) collisions.

Centrality of the collisions



Central collision: small b and high number of colliding nucleons (participants).

Peripheral collision: high b and small number of colliding nucleons.

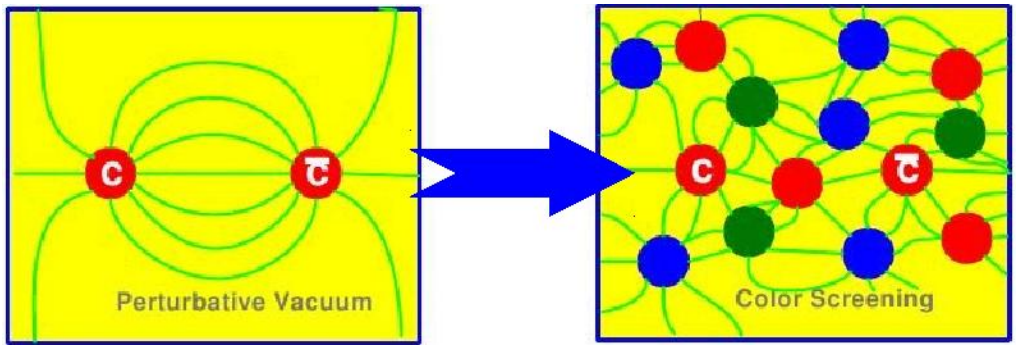
Cold nuclear matter effects

Cold nuclear matter effects (CNM) are concurrent mechanisms occurring in p–A and A–A collisions.

They can modify the particle production even in absence of QGP ($\Leftarrow$ hot effects).

Why to study quarkonium production?

- Heavy quarks (c and b) are produced in hard scatterings at the early stage of the collisions: quarkonia and open heavy flavours probe the whole evolution of the collision.
- The $Q\bar{Q}$ binding into quarkonium states is a non-perturbative process still not well understood: new data in pp collisions help to validate theoretical models.
- Colour-screening model predicts the quarkonium suppression in A–A collisions [PLB 178 (1986), PLB 490 (2000), PRC 63 (2001)].

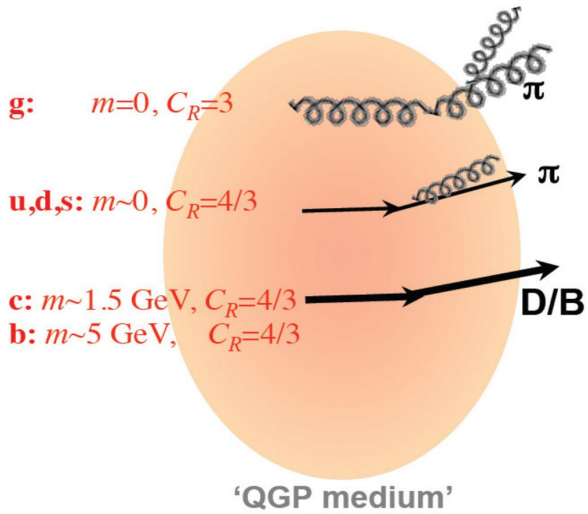


- Cold nuclear matter effects (CNM) are competing mechanisms: p–A collisions allow us to disentangle these effects from the hot ones.

...and why to study open heavy-flavour production?

- Open heavy-flavour (HF) production in pp collisions is a powerful tool to test perturbative QCD (pQCD) predictions.

- HF are sensitive probes of the properties of medium generated in A-A collisions. Heavy quarks are expected to lose less energy than light quarks and gluons
  [PLB 519 (2001)] .



- Their study in p–A collisions is necessary to disentangle the cold and hot nuclear matter effects.

Key observables

Differential cross sections

In pp collisions transverse momentum (p_T) and y-differential cross sections are used to test theoretical calculations.

Nuclear modification factor

It allows to compare the yield of a given particle in A–A or p–A collisions to that in binary-scaled pp collisions: $R_{AA(pA)} = \frac{Y_{AA(pA)}}{N_{coll} \cdot Y_{pp}}$. A value < 1 means a suppression of the particle production.

Key variables

Centrality:
expressed in number of participants N_{part}

Rapidity:
$y = \frac{1}{2} ln \frac{E+p_z}{E-p_z}$

Transverse momentum:
$p_T = \sqrt{p_x^2 + p_y^2}$

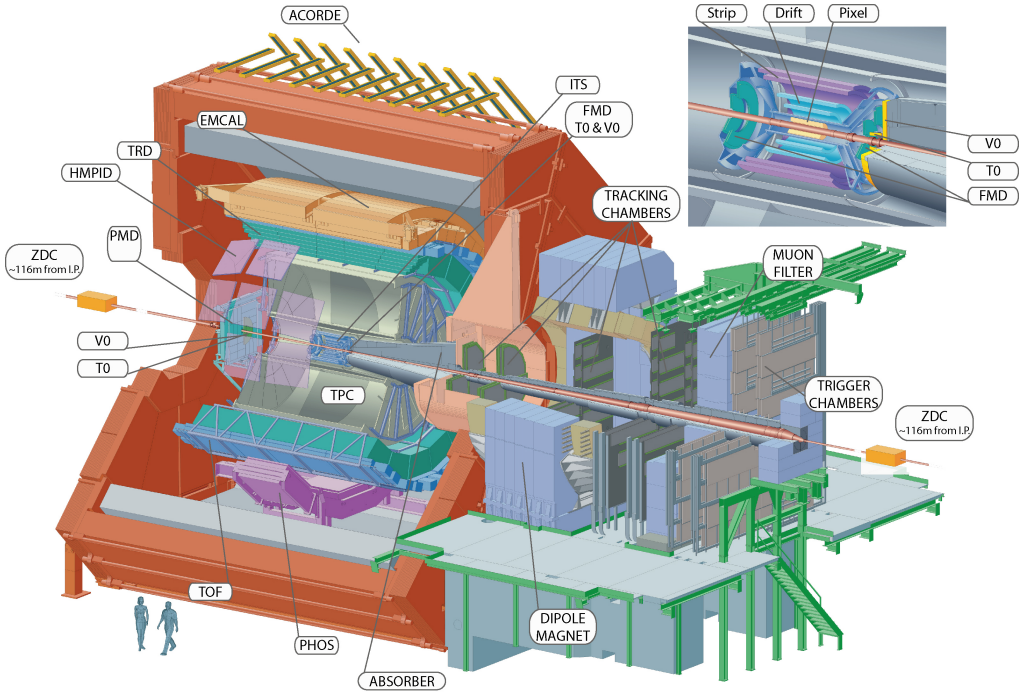
A Large Ion Collider Experiment

V0

Centrality in Pb–Pb collisions, triggering and luminosity

SPD

Primary vertex determination and triggering



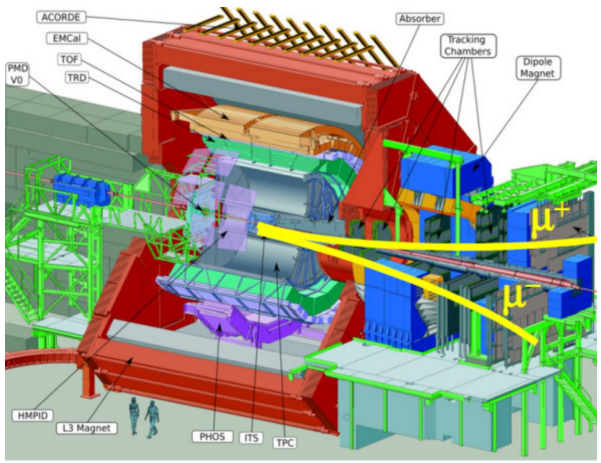
ZDC

Centrality in Pb–Pb and p–Pb collisions

Muon Spectrometer

Tracking and identificantion of muons at forward rapidity ($2.5 < y < 4$)

Selection techniques ($2.5 < y < 4$)

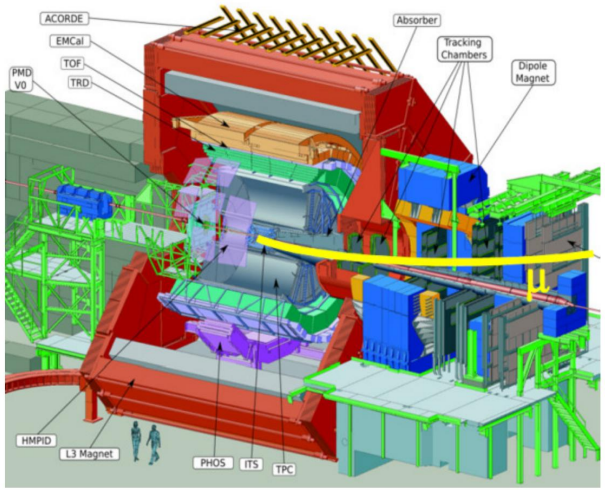


Quarkonia

- Dimuon decay $Q\bar{Q} \to \mu^+\mu^-$.
- Matching tracking-trigger tracks.
- Acceptance, geometrical and kinematic cuts.
- Fit to the invariant mass (signal+background).
- Acceptance down to $p_T = 0$.

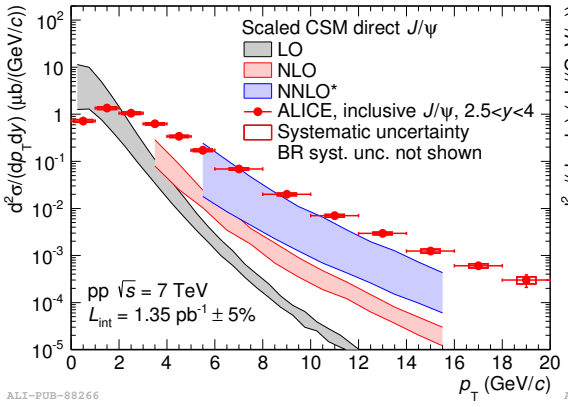
Open heavy flavours

- Semi-muonic decay $c, b \to \mu + X$.
- Tracking-trigger tracks matched.
- Acceptance, geometrical and kinematic cuts.
- Subtraction of non-HF background based on MC or data-tuned MC cocktail.

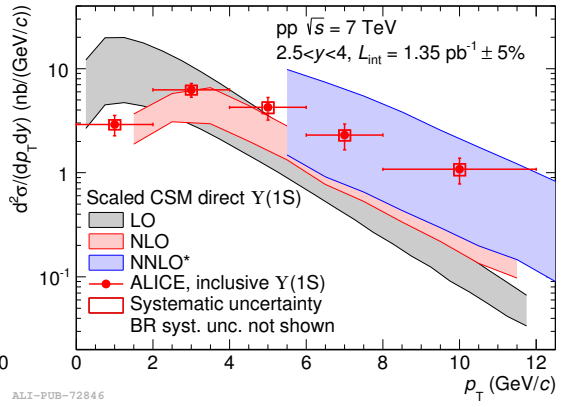


Quarkonia production in pp collisions

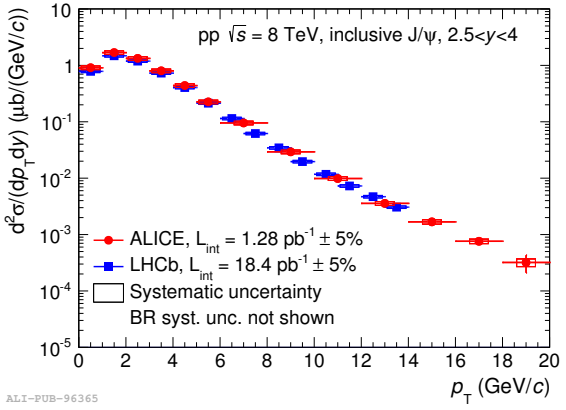
J/ψ 7 TeV



Υ(1S) 7 TeV



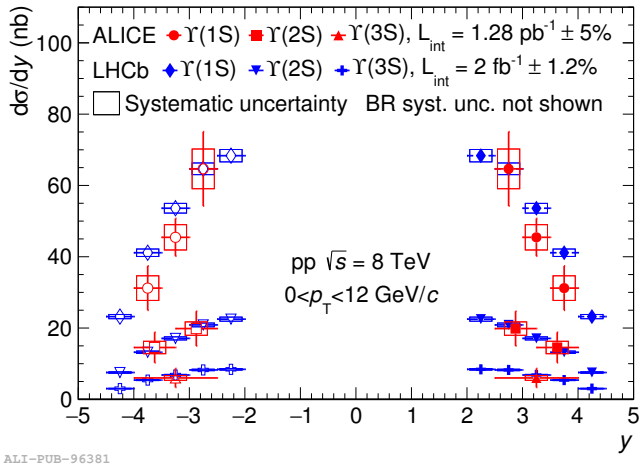
J/ψ 8 TeV



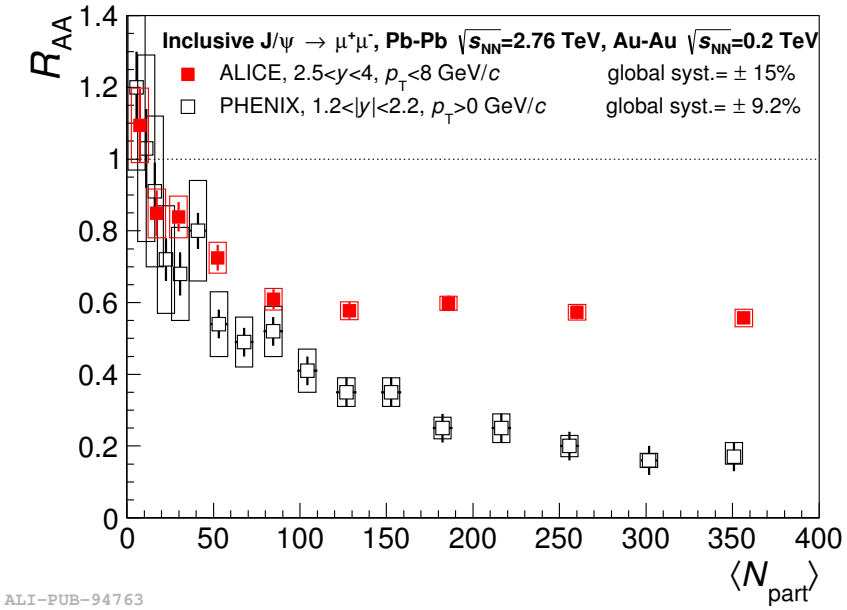
EPJC 74 (2014) 2974; arXiv:1509.08258

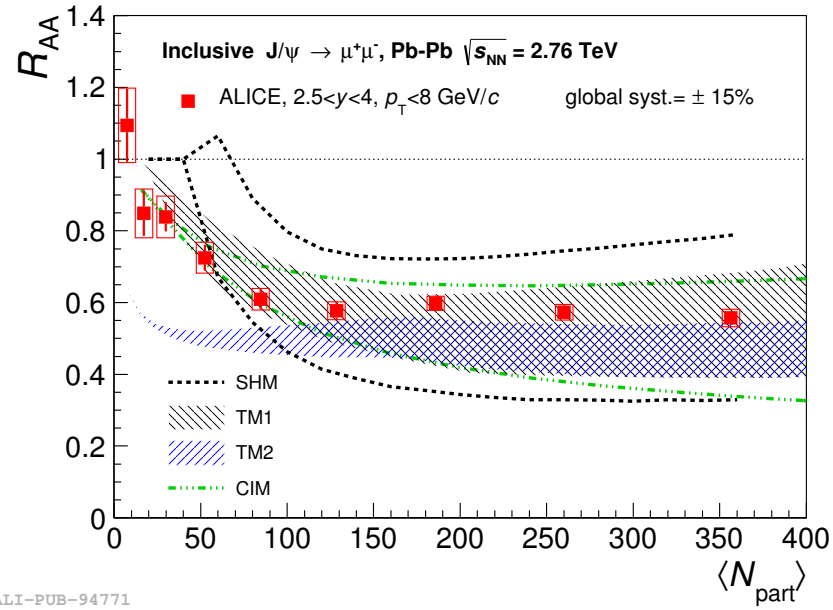
- Quarkonia differential cross sections are measured in pp collisions at different energies.
- In general model calculations have difficulties to reproduce the results
- The comparison between ALICE and LHCb results shows a good agreement.

Υ 8 TeV



J/ψ production in Pb–Pb collisions vs centrality



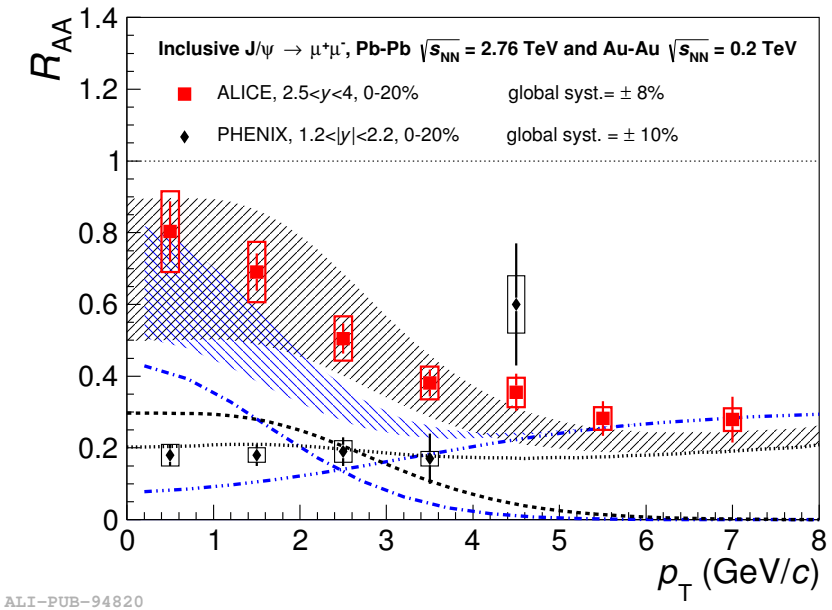


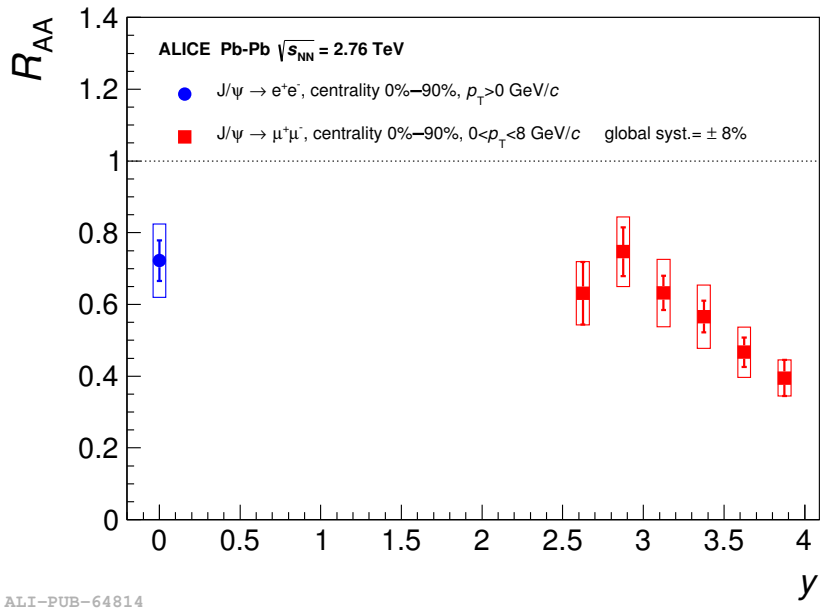
ALICE: PLB 734 (2012) 314; PHENIX: PRC 84 (2011) 054912

Models: PLB 731 (2014) 57; PRC 89 (2014) 054911; NPA 859 (2011) 114; JPG 38 (2011) 12

- The J/ψ production measured by ALICE in central and semi-central Pb–Pb collisions is much less suppressed than that measured by PHENIX in Au–Au collisions at 200 GeV.
- The results are compared to models which include recombination: the agreement is satisfactory within the model uncertainties.

J/ψ in Pb–Pb collisions vs p_T and y



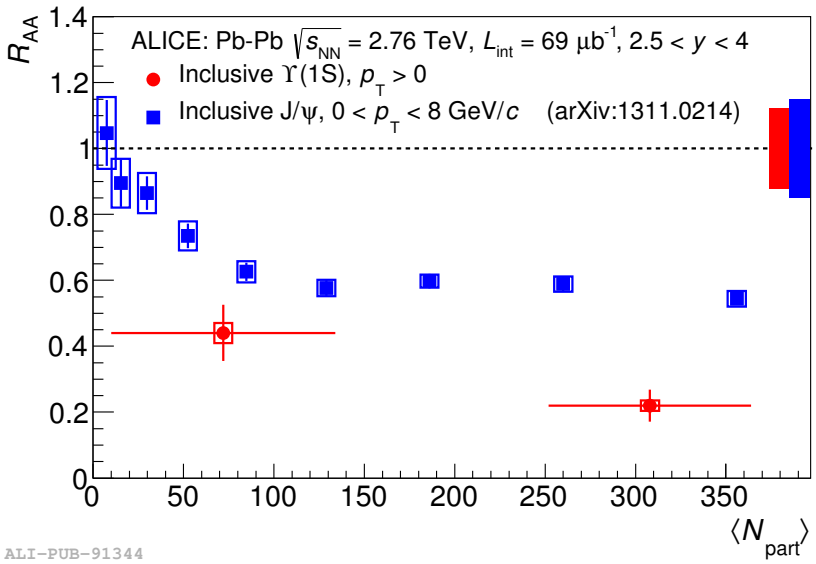


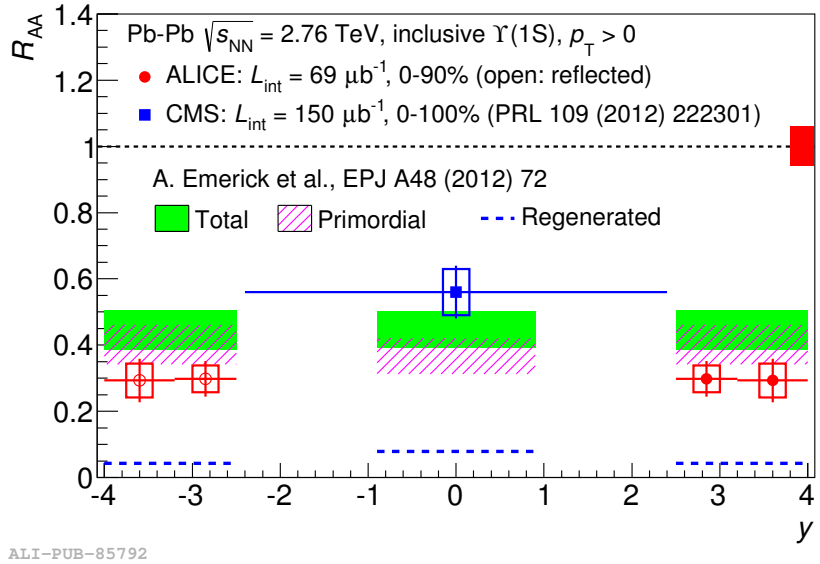
ALICE: PLB 734 (2012) 314; PHENIX: PRC 84 (2011) 054912

Models: PLB 731 (2014) 57; PRC 89 (2014) 054911; NPA 859 (2011) 114; JPG 38 (2011) 12

- The comparison between ALICE and PHENIX results shows a smaller suppression at LHC energies at low p_T where models point to an important quarkonium regeneration.
- Furthermore, the suppression is increasing from mid- to forward rapidity.

$\Upsilon(1S)$ production in Pb–Pb collisions



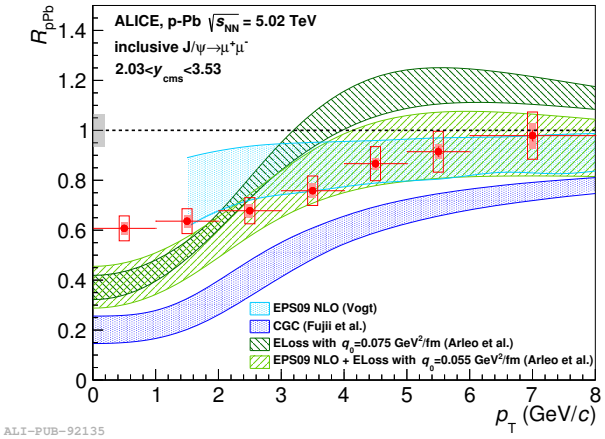


PLB 738 (2014) 361

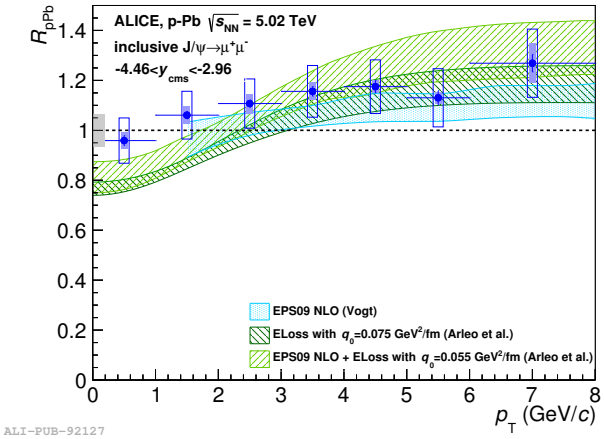
- The suppression of the $\Upsilon(1S)$ increases with the centrality of the collisions and it is stronger than that of the J/ψ: $c\bar{c}$ recombination and feed-down from higher states can play an important role.
- The comparison to CMS mid-rapidity results suggests a rapidity dependence of the $\Upsilon(1S)$ suppression *[caveat: recently CMS reported on a slightly stronger suppression]*.
- Models accounting for suppression, CNM effects and regeneration can barely reproduce the measurements.

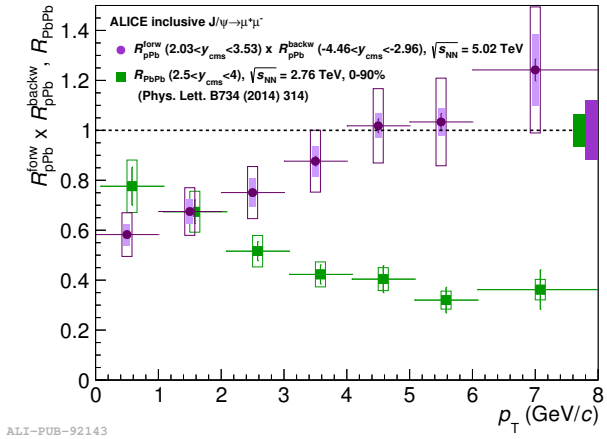
J/ψ production in p–Pb collisions vs p_{T}

p-going



Pb-going



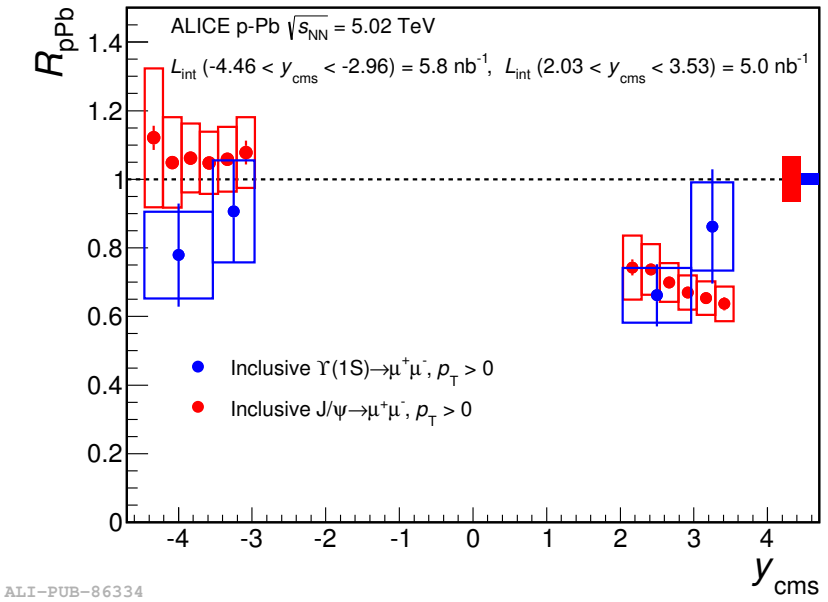


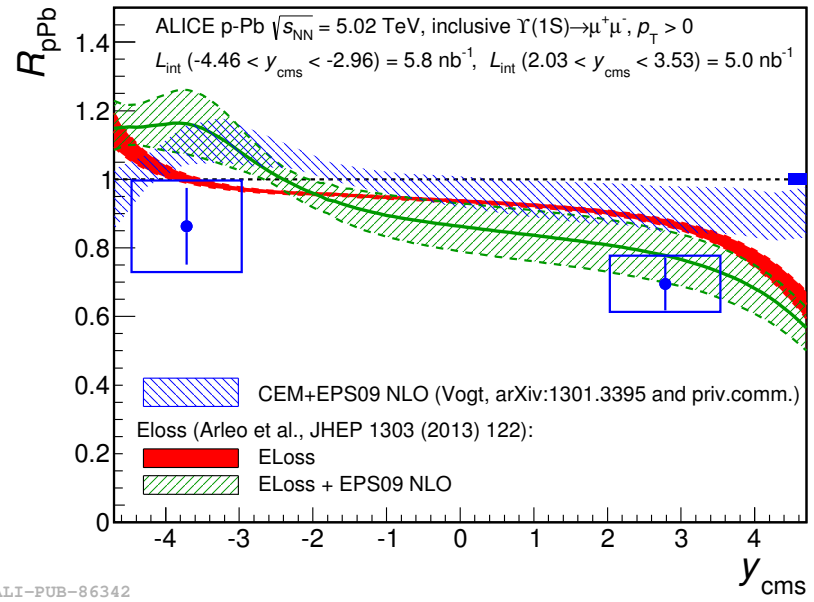
JHEP 06 (2015) 55

- J/ψ is suppressed at forward rapidity (left), except for the highest-p_{T} region, while no suppression is measured in the backward region (right).
- The results are consistent with the expectations from shadowing and energy loss calculations.
- The R_{PbPb} is compared to $R^{\mathrm{forw}}_{\mathrm{pPb}} \times R^{\mathrm{backw}}_{\mathrm{pPb}}$: cold nuclear matter effects alone are not enough to explain the suppression at high p_{T} in Pb–Pb collisions.

Υ production in p–Pb collisions

J/ψ $\Upsilon(1S)$

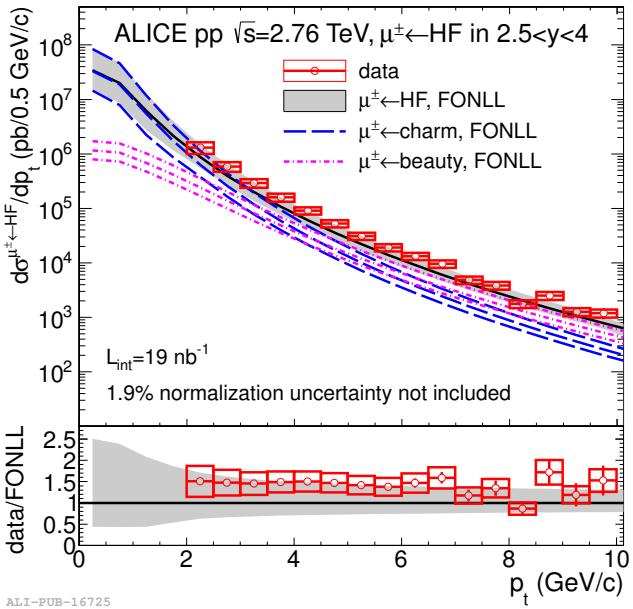


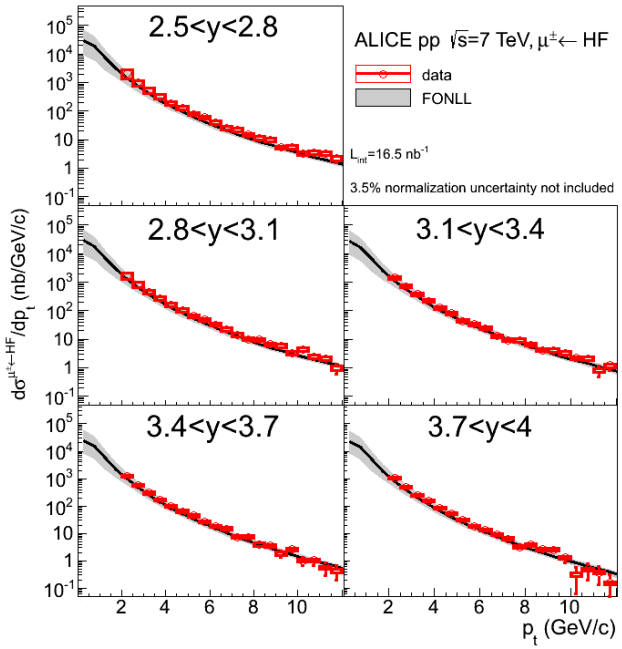


PLB 740 (2015) 105

- The $\Upsilon(1S)$ suppression is compatible with the J/ψ one within uncertainties especially at forward rapidity (p-going direction).
- NLO Colour Evaporation Model (CEM) calculation with EPS09 overpredicts the measured R_{pPb}.
- The parton energy loss with EPS09 calculation reproduces well the data at forward rapidity, while data at backward rapidity are in a better agreement with parton energy loss only calculation.

Muons from heavy-flavour decays in pp collisions

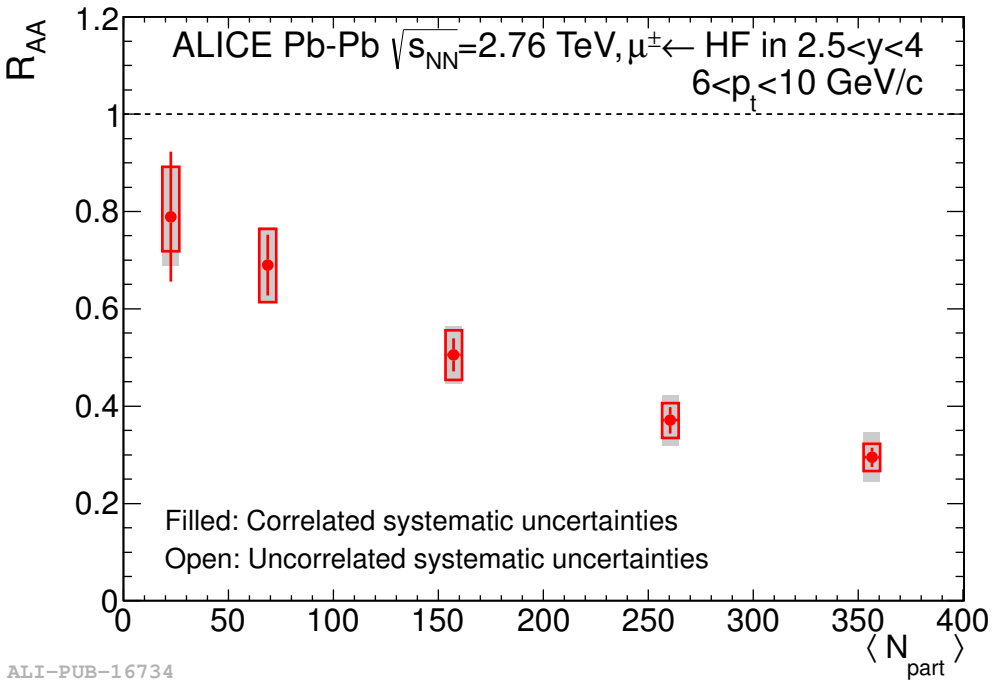




PLB 708 (2012) 265; PRL 109 (2012) 112301

- ALICE studied the differential cross sections of muons from heavy flavours in pp collisions at $\sqrt{s} = 2.76$ and 7 TeV vs p_{T} and in bins of rapidity.
- pQCD calculations based on fixed-order approach (α_s^3) with next-to-leading logarithmic terms (FONLL) are in agreement with the measured cross sections.

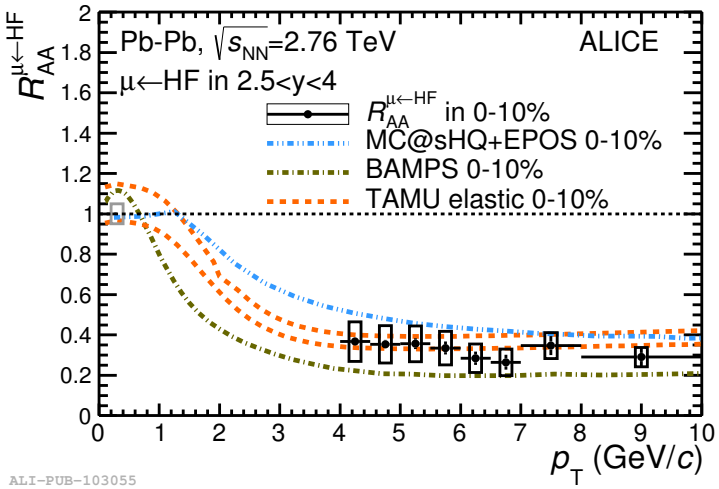
Muon from HF decays in Pb–Pb collisions vs centrality



PRL 109 (2012) 112301

- A strong suppression of the muons from heavy-flavour hadron decays at high p_T is well visible in central collisions.
- According to FONLL in this kinematic range the beauty contribution dominates (pp collisions).

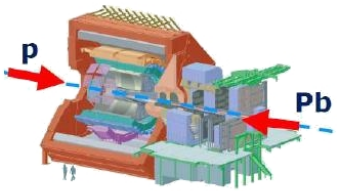
Muon from HF decays in Pb–Pb collisions vs p_T

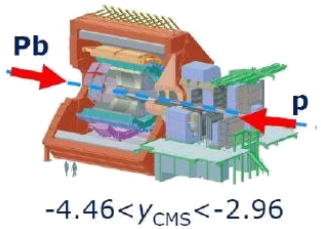


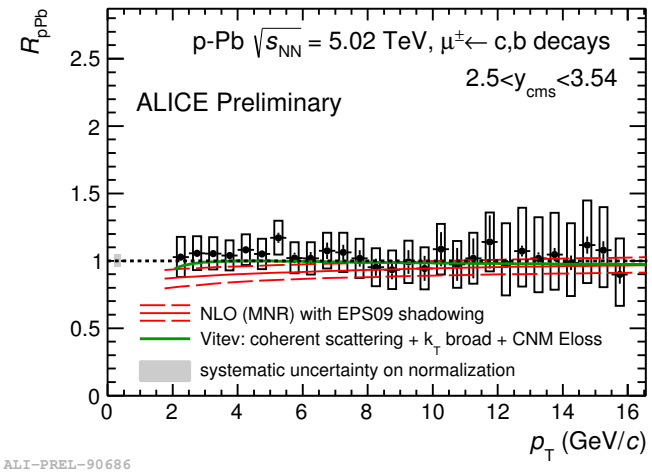
PLB 753 (2016) 41; PRL 109 (2012) 112301

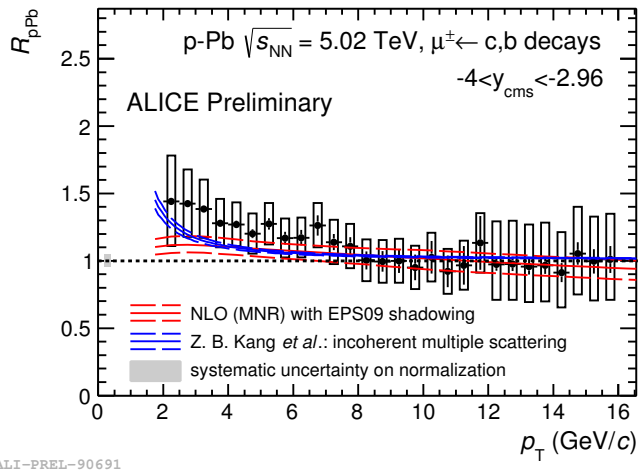
- The yield of muons from heavy-flavour decays is strongly suppressed at high p_T in central Pb–Pb collisions w.r.t. binary scaled pp collisions.
- Several theoretical predictions are able to describe the suppression. With these uncertainties it is not possible to exclude any of them.
- Shadowing can not explain such a suppression: it is a hot and dense matter effect.

Muons from heavy-flavour decays in p–Pb collisions









- HF-decay muon R_{pPb} is close to unity. The suppression measured at high p_{T} in Pb–Pb collisions is due to the hot and dense medium.
- A slight enhancement is measured at backward rapidity in $2 < p_{\mathrm{T}} < 4$ GeV/c.
- Models implementing cold nuclear matter effects (shadowing, multiple scattering and energy loss) describe the data within uncertainties.

Conclusions

Quarkonia:

- ALICE is able to measure quarkonia down to a zero transverse momentum. The results in pp collisions are in agreement with those of LHCb in the same rapidity interval. Models still have difficulties to reproduce the data.
- At the LHC energy an important pair recombination predicted by transport models explains the limited suppression of the J/ψ in Pb–Pb, especially at low p_{T}.
- Moreover, cold nuclear matter effects cannot explain the J/ψ suppression at high p_{T}.
- Models have some difficulties to predict the $\Upsilon(1S)$ suppression pattern in both Pb–Pb and p–Pb collisions: the feed-down from higher states could play an important role.

Conclusions

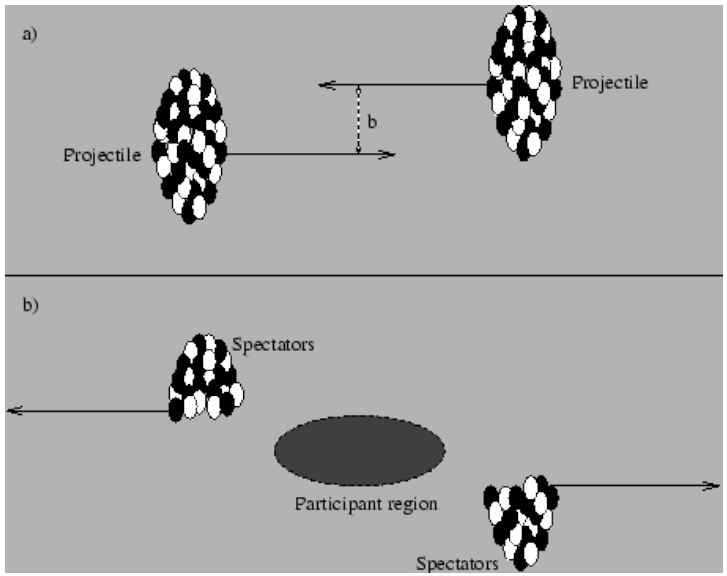
Muons from heavy-flavour hadron decays:

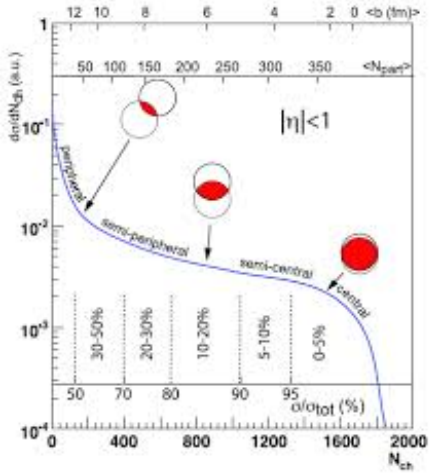
- ALICE measures the muon production from open heavy-flavour hadron decays at forward rapidity at intermediate and high p_{T} in all colliding systems.
- Models reproduce reasonably well the cross sections in pp collisions at different energies.
- Several models predict the strong suppression measured in central Pb–Pb collisions at high p_{T}: this is not a CNM effect.
- The production of muons from HF decays is similar in p–Pb and binary-scaled pp collisions. Only a slight enhancement is measured at backward rapidity, in agreement with models including CNM effects.

Backup

Centrality of the collisions

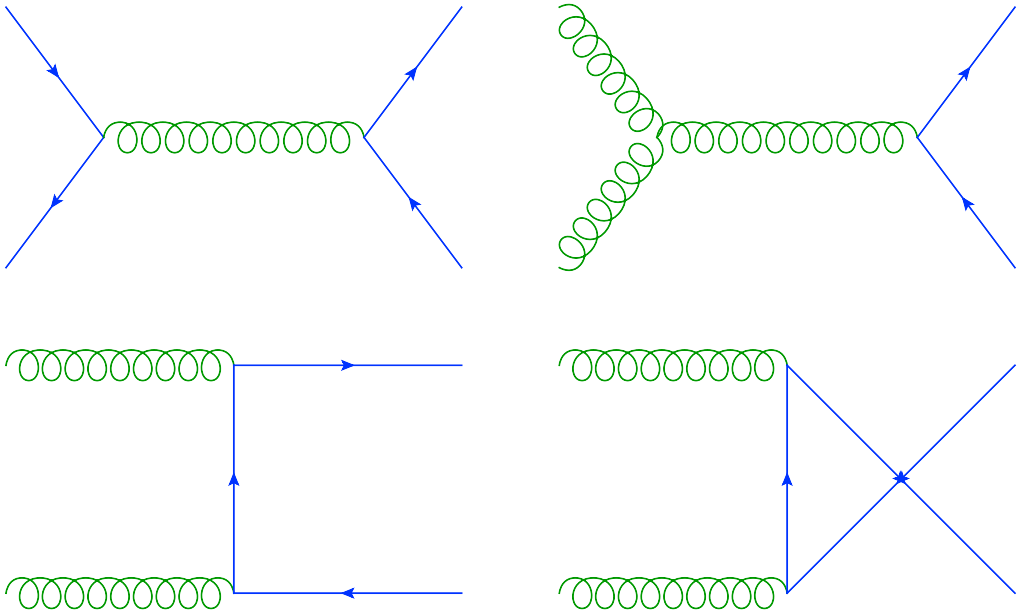
- Impact parameter: distance of the centers of the two colliding nuclei in the transverse plane
- Central collisions: small impact paramenter and high number of colliding nuclei (participants)
- Peripheral collisions: large impact paramenter and small number of colliding nuclei (participants)





Quarkonium production mechanisms /1

In hadron collisions the dominant processes involved in the quarkonium production are gluon fusion and gluon fragmentation.



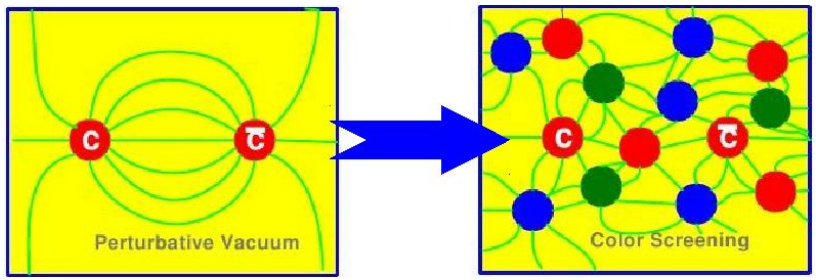
The creation of a pair $q\bar{q}$ pair can be calculated with a perturbative approach. This is not valid for the transition to the quarkonium state.

Quarkonium production mechanisms /2

- Color Singlet Model: the $q\bar{q}$ pair evolving in a quarkonium state is in a colour singlet state and the quantum numbers are conserved after the formation of the meson.
- Color Evaporation Model: the production rate for the quarkonium state is a certain fraction of the cross section for producing $q\bar{q}$ pairs. There are not constraints on the quantum numbers of the final state. The $q\bar{q}$ pair neutralizes its colour by interaction with the collision-induced colour field.
- Non-Relativistic QCD: the production cross section of a quarkonium state is written as a sum of terms taking into account a short distance partonic cross section and a long distance matrix element: $d\sigma(H) = \sum_n d\hat{\sigma}\,(q\bar{q}_n)\,\langle 0|\mathcal{O}_n^H|0\rangle$.

Quarkonium in heavy-ion collisions

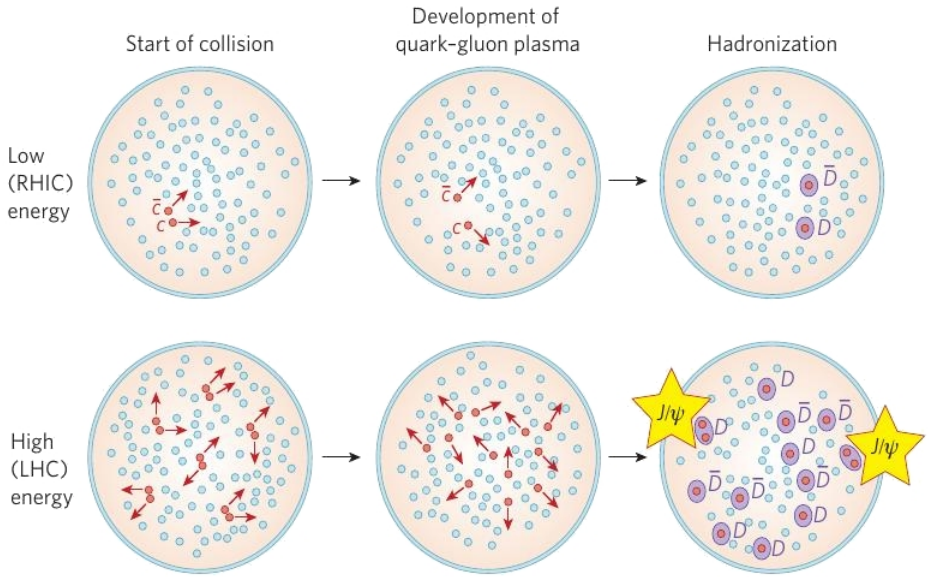
- Quarkonia play an important role in the study of Quark-Gluon Plasma (a deconfined phase of quarks and gluons) because:
  - they are created in the early stage of the collision;
  - the production is expected to be modified by the QGP (PLB, 178 (1986) 416);



  - having different radii (i.e. different binding energies) a sequential suppression is expected (PRD, 64 (2001) 094015).
- Concurrent mechanisms:
  - an important $c\bar{c}$ recombination is expected at LHC energy;
  - cold nuclear matter (CNM) effects can modify quarkonium production even in absence of hot and dense matter.

Quarkonium regeneration

Quarkonium regeneration is due to the statistical recombination of the heavy quarks emerging from the medium. It is more and more important when the center-of-mass energy of the collision increases.



Accelerator and center-of-mass energy	SPS 20 GeV	RHIC 200 GeV	LHC 2.76 TeV
$N_{c\bar{c}}$/**event**	~ 0.2	~ 10	~ 60
$N_{b\bar{b}}$/**event**	–	~ 0.05	~ 6

Open heavy flavour production

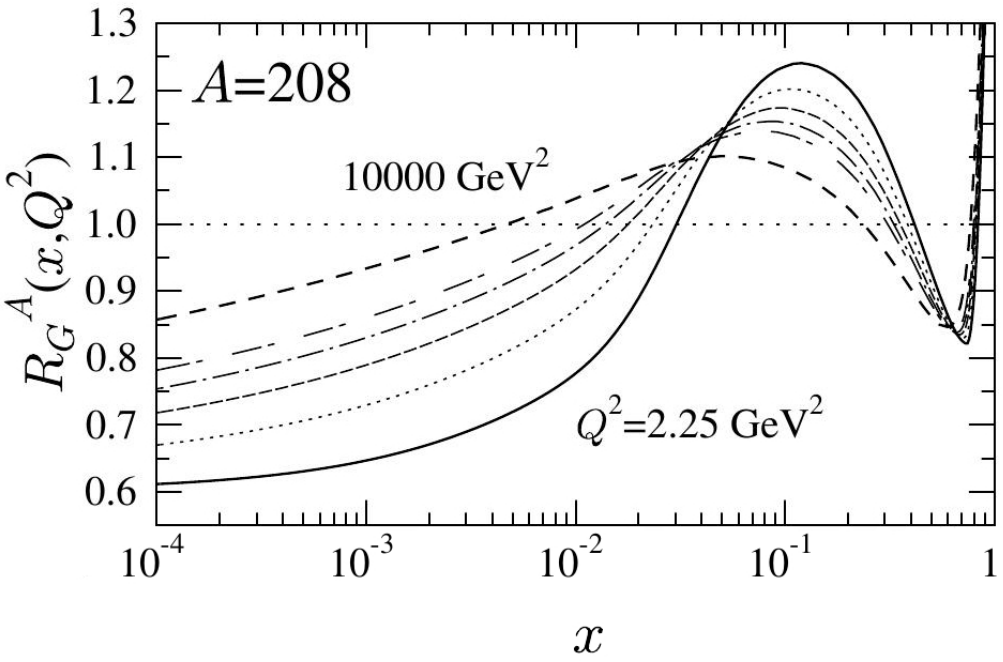
- heavy flavours produced in initial hard scattering
- with short formation time sensitivity to the medium properties
- expected to lose less energy than light particles in the medium (dead cone effect, Y.L. Dokshitzer and D.E. Kharzeev, Phys. Lett. B 519 (2001) 199)

$$\Delta E_g > \Delta E_{q \approx c} > \Delta E_b$$

- The probability to lose energy in the hot and dense medium decreases at high parton mass $\rightarrow$ mostly gluon radiation.
- The energy loss depends on the square of the path length of the parton in the medium.
- $\langle \Delta E \rangle \propto \alpha_s C_R L^2$

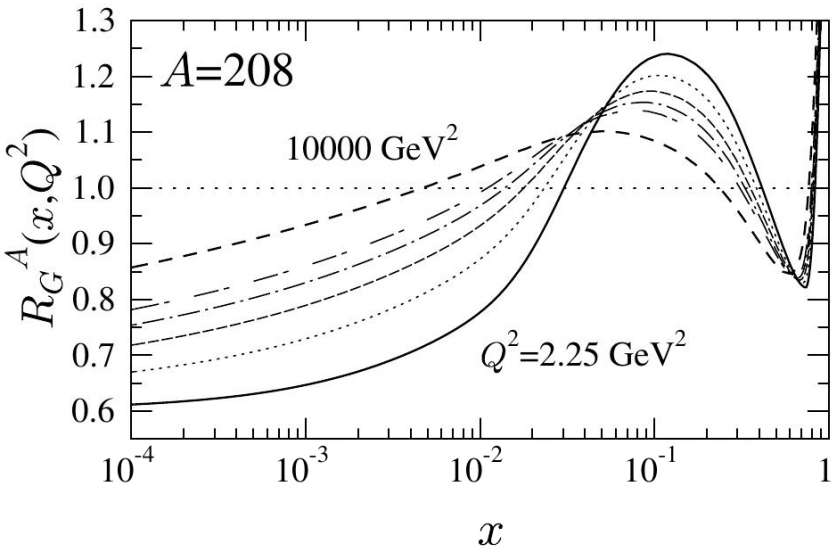
CNM effects: shadowing

PDF of a nucleon in a nucleus $\neq$ PDF of a free nucleon.



Plot shows the ratio between the gluon PDF in a nucleon of a Pb nucleus and in a free proton as a function of the Bjorken-x (from EPS09 model). The quarkonium cross sections ($\Rightarrow$ the yields) depend on PDF. Therefore their modifications influence the comparison of the different collision systems even in absence of QGP.

Shadowing and Bjorken region



Shadowing: $x_{\mathrm{Bj}} < 0.01$, anti-shadowing: $0.01 < x_{\mathrm{Bj}} < 0.3$; EMC effect: $0.3 < x_{\mathrm{Bj}} < 0.7$; Fermi motion: $x_{\mathrm{Bj}} > 0.7$.
Under the assumption of the $gg \rightarrow \Upsilon$ production process, the sampled Bjorken-x are:

- $5.5 \cdot 10^{-5} < x_{\mathrm{Bj}} < 2.5 \cdot 10^{-4}$ (shadowing region) at forward rapidity;
- $3.6 \cdot 10^{-2} < x_{\mathrm{Bj}} < 1.6 \cdot 10^{-1}$ (anti-shadowing region) at backward rapidity.

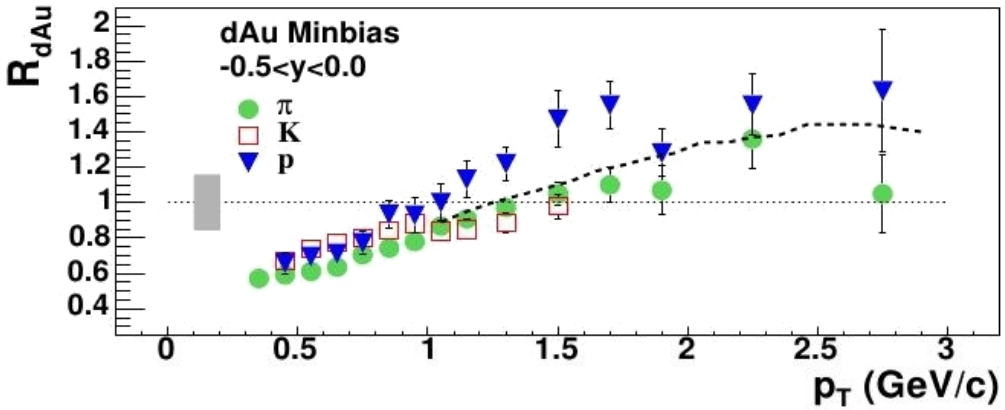
Bjorken-x range

- Assuming a $2 \rightarrow 1$ production process the tested Bjorken-x ranges are
  - Backward: $3.6 \cdot 10^{-2} < x < 1.6 \cdot 10^{-1}$ (Υ) and $1.2 \cdot 10^{-2} < x < 5.3 \cdot 10^{-2}$ (J/ψ)
  - Forward: $5.5 \cdot 10^{-5} < x < 2.5 \cdot 10^{-4}$ (Υ) and $1.8 \cdot 10^{-5} < x < 8.1 \cdot 10^{-5}$ (J/ψ)

$$x_{1,2} = \frac{m_T}{\sqrt{s}} \cdot e^{\pm y}$$

CNM effects: coherent parton energy loss and Cronin effect

- Coherent parton energy loss: a parton moving through the nucleus can scatter elastically and lose energy before the hard scattering. The effect is responsible of an hadrons suppression in pA collisions.
- Cronin effect: a parton can undergo a multiple scattering process in the nucleus before to hadronize. It acquires an extra transverse momentum which modifies the p_T spectrum of the hadrons with respect to pp collisions. This effect is responsible of an enhanced hadron production in pA collisions.



CNM effects: nuclear and comovers absorption

This final state effect is responsible of the break-up of the quarkonium state. It occurs when the $q\bar{q}$ pair is formed and passes through the nucleus and is parametrized using a phenomenological production cross section:

$$\sigma(AB \rightarrow J/\psi) \propto ABe^{-\rho\sigma_{abs}L}$$

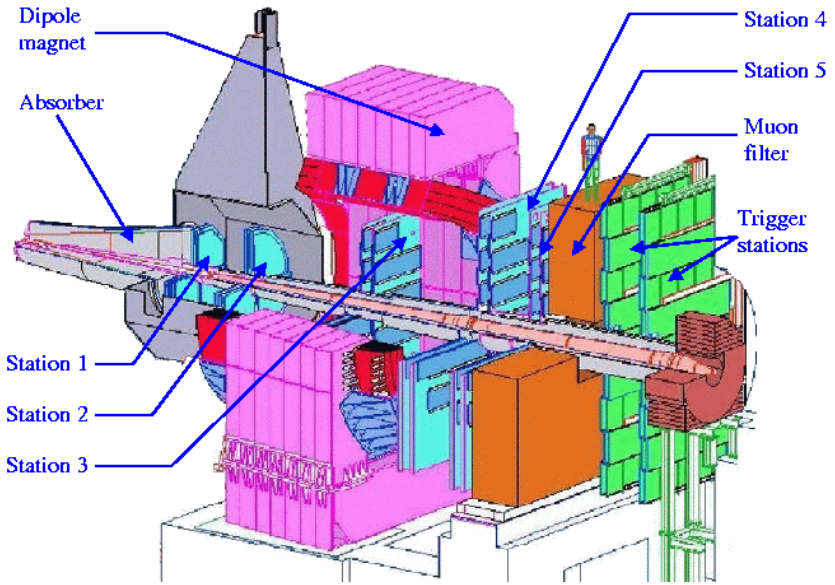
A and B are the mass numbers of the nuclei, ρ is the nuclear density, L is the path length of the pair through the nuclear matter and σ_{abs} is the absorption cross section which decreases increasing the collision energy.

Similarly, in a dense gas system formed by conventional hadrons like pions and kaons, the quarkonium could be suppressed by processes like $J/\psi + \pi \rightarrow D + \bar{D} + X$, called suppression by hadronic comovers.

The ALICE Muon Spectrometer

The Muon Spectrometer is composed of:

- front absorber;
- beam shield;
- iron wall;
- dipole (integrated field = 3 T·m);
- muon tracking chambers (10 planes of MWPC with a spatial resolution in the bending coordinate better than 100 μm);
- muon trigger chambers (4 planes of RPC with a time resolution of some ns and the possibility to deliver single and dimuon triggers above two p_T cuts).



Dynamical model

- The prediction is based on a complex potential approach in an evolving QGP described by an hydrodynamics formalism. The imaginary part is related to the in medium decay.
- The boost invariant plateau describing the spatial temperature profiles corresponds to a Bjorken picture (transparency in collisions), a Gaussian profile corresponds to a Landau picture (colliding nuclei lose all their energy).
- The plasma shear viscosities $4\pi\eta/s = \{1, 2, 3\}$ corresponds to different initial temperatures $T_0 = \{520, 504, 494\}$ MeV in central collisions, in order to keep $dN_{ch}/dy = 1400$ fixed.
- The suppression of direct $\Upsilon(1S)$ is $\sim 50\%$ of the total R_{AA}.
- Since CNM effects are not included in the model, the predictions should be considered as an upper limit.
- This model describes successfully the elliptic flow of charged particles measured by ALICE in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.

Transport model

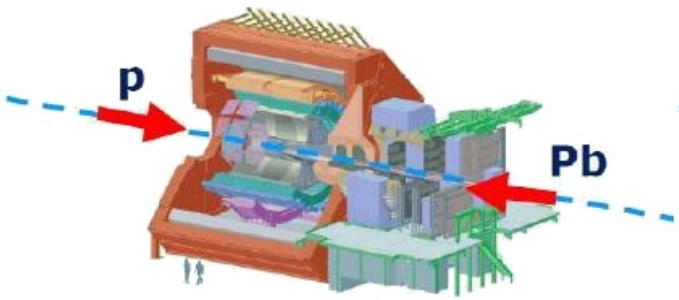
- Model relies on a strongly binding scenario $\rightarrow$ the suppression of the $\Upsilon(1S)$ is small, while that of higher states is substantial.
- The suppression and regeneration contributions are balanced by means of a rate equation: $\boxed{\frac{dN_\Upsilon}{dt} = -\Gamma_\Upsilon^{diss}(N_\Upsilon - N_\Upsilon^{eq})}$.
- The spatio-temporal evolution of the medium is described by an expanding fire cylinder whose initial dimension are tuned according to the recent LHC measurements.
- The initial condition for the number of bottomonia at the QGP formation time and the implemented regeneration component requires the knowledge of the beauty quark cross-section.
- The CNM considered (shadowing, Cronin effect and energy loss) are approximated by a suppression factor: $e^{-\rho\sigma_{abs}L}$, from Glauber model and previous measurements.

Models for single muons

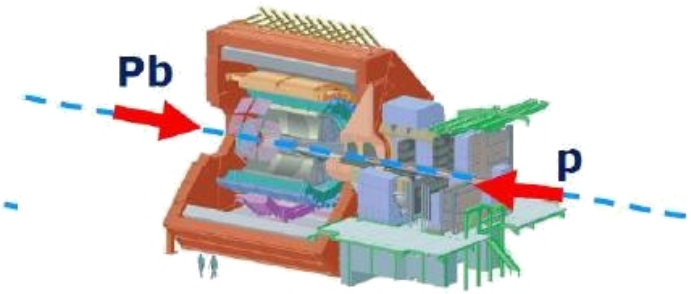
- MC@sHQ+EPOS transport model: the propagation of heavy quarks including collisional and radiative energy loss treated within a 3+1 dimensional fluid dynamical expansion. Hadronization of heavy quarks takes place at the transition temperature via recombination at low p_T and fragmentation at intermediate and high p_T.
- TAMU transport model: only collisional processes via the Langevin equation. The hydrodynamical expansion is constrained by p_T spectra and elliptic flow data of light-flavour hadrons.
- BAMPS transport model: based on the Boltzmann approach to multi-parton scatterings. It includes collisional processes with a running strong coupling constant.

p–Pb and Pb–p collisions: energy and rapidity

- $\sqrt{s_{NN}} = 5.02$ TeV in nucleon-nucleon center of mass
  - p beam energy: 4 TeV
  - Pb beam energy: 1.58 TeV/A
  - $\Rightarrow \Delta y_{NN} = 0.465$ in p beam direction
- p–Pb collisions: $2.03 < y_{cms} < 3.53 \Rightarrow 3.43 < y_{lab} < 4$
- Pb–p collisions: $-4.46 < y_{cms} < -2.96 \Rightarrow 2.5 < y_{lab} < 3.07$
- Rapidity overlap region: $2.96 < |y_{cms}| < 3.53$



$2.03 < y_{CMS} < 3.53$



$-4.46 < y_{CMS} < -2.96$

Inputs for theoretical models

Statistical Hadronization Model

- Thermal model with T=164 MeV and $\mu = 1$ MeV (from particles ratio fit).
- All charm are produced in the initial hard scatterings and at phase boundary.

Transport Model by Zhao et al.

- Boltzmann transport equation for J/ψ.
- $\sigma_{c\bar{c}}|_{y=3.25} \cong 0.5$ mb.
- Shadowing: 30% suppression in the most central collisions.
- No Croning effect and $\sigma_{abs} = 0$.
- 10% of J/$\psi \leftarrow B$ and no quenching.

Transport Model by Liu et al.

- Boltzmann transport equation for J/ψ.
- $\sigma_{c\bar{c}}|_{y=3.25} \cong 0.38$ mb.
- EKS98 shadowing and $\sigma_{abs} = 0$.
- 10% of J/$\psi \leftarrow B$ and $R_{AA}^{B} = 0.4$ for all p_T range.