Heavy-flavour production in heavy-ion collisions

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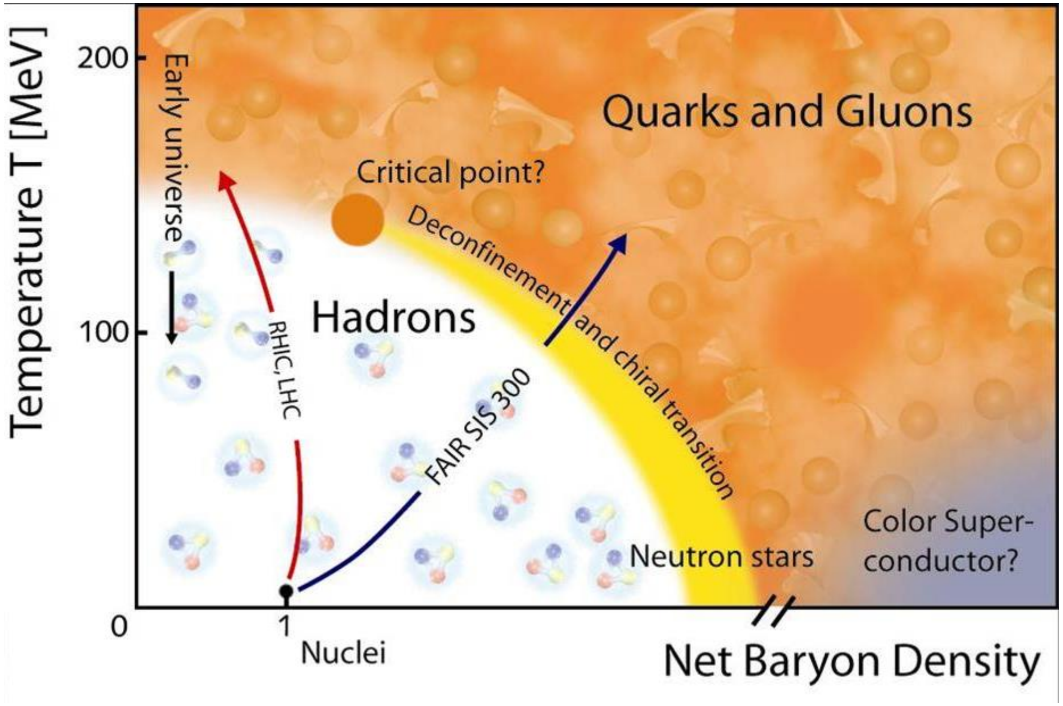
Heavy-Ion Collisions

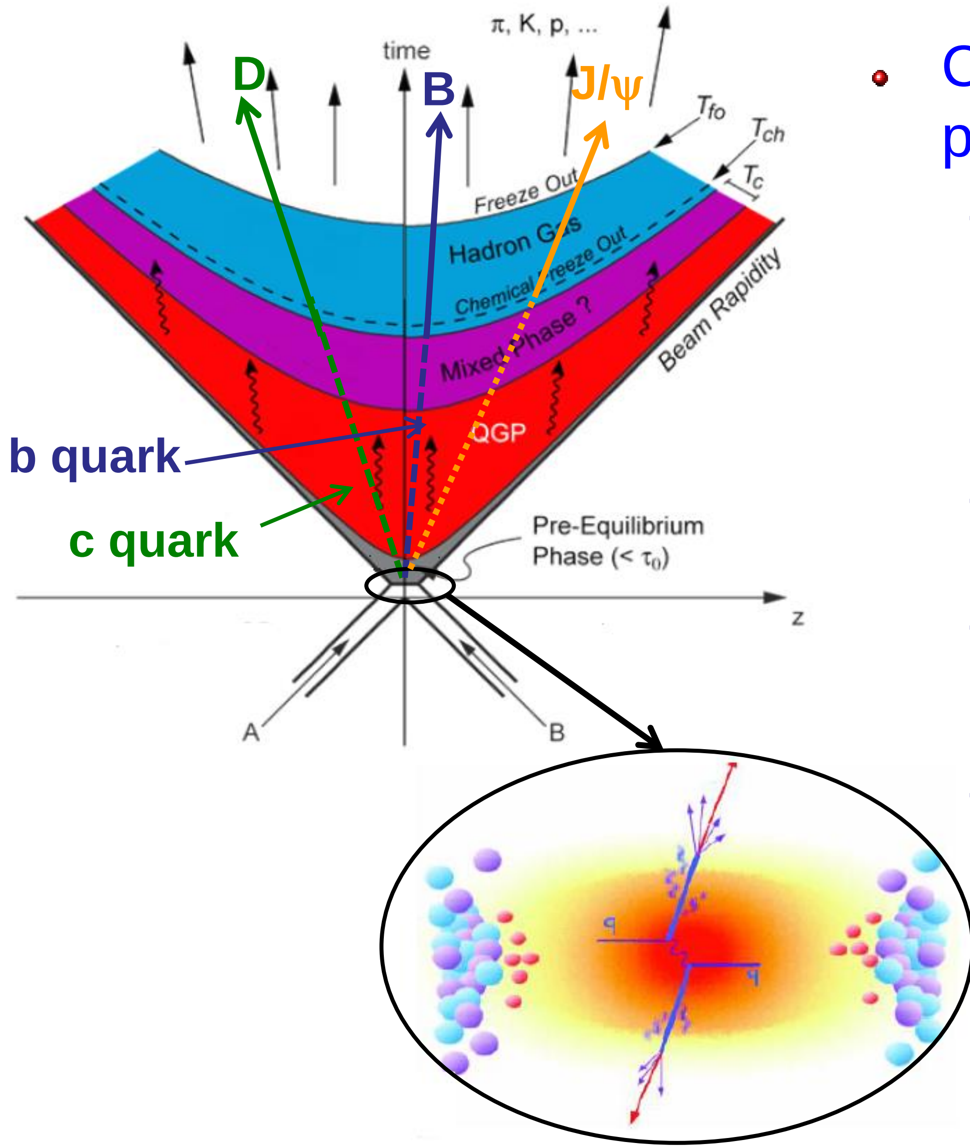
- Goal: study the properties of nuclear matter at extreme conditions of temperature and density
  - ⇨ Transition to a state where quarks and gluons are deconfined (Quark Gluon Plasma, QGP)
    - ✓ ***From lattice QCD: $T_C \approx$ 145-160 MeV $\rightarrow \varepsilon_C \approx$ 0.5 GeV/fm^3***

Bazavov et al, PRD90 (2014) 094503

Borsanyi et al, JHEP 1009 (2010) 073



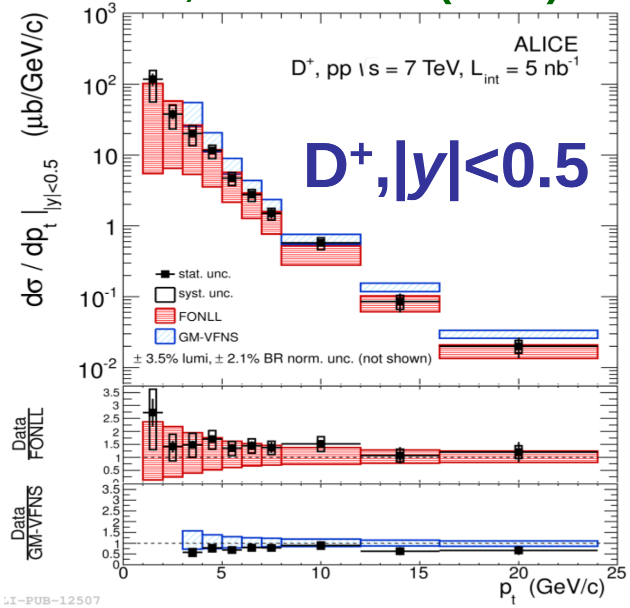
Heavy flavours (HF) in heavy-ion collisions



- Charm and beauty quarks: unique probes of the medium
  - Produced at the very early stage of the collision in partonic scattering processes with large Q^2
    - ✓ ***pQCD can be used to calculate initial cross sections***
  - Small rate of thermal production in the QGP ($m_{c,b}$>>T)
  - Large mass, short formation time
    - ✓ ***Experience the entire evolution of the medium***
  - Interactions with medium constituents don‘t change the flavor, but can modify the phase-space distribution of heavy quarks

HF in pp collisions at √s= 7 TeV

ALICE, JHEP 1201 (2012) 128

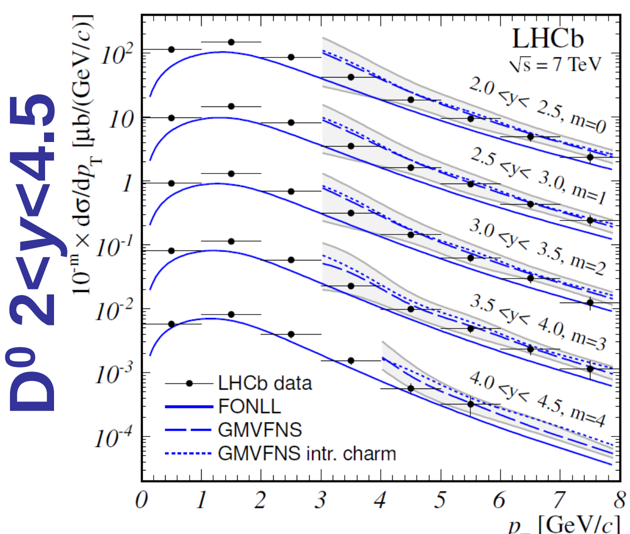


Heavy-flavour p_T-differential cross sections well described by pQCD calculations

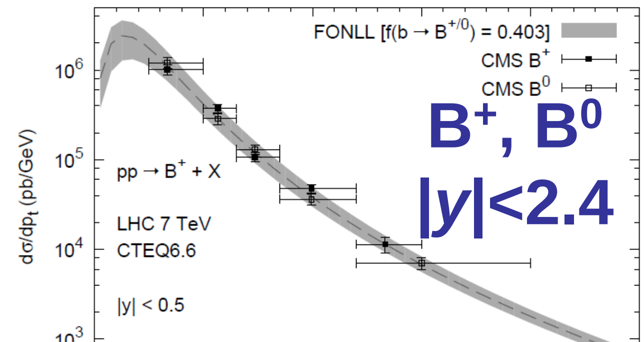
FONLL, JHEP 1210 (2012) 37

GM-VFNS, EPJ C72 (2012) 2082

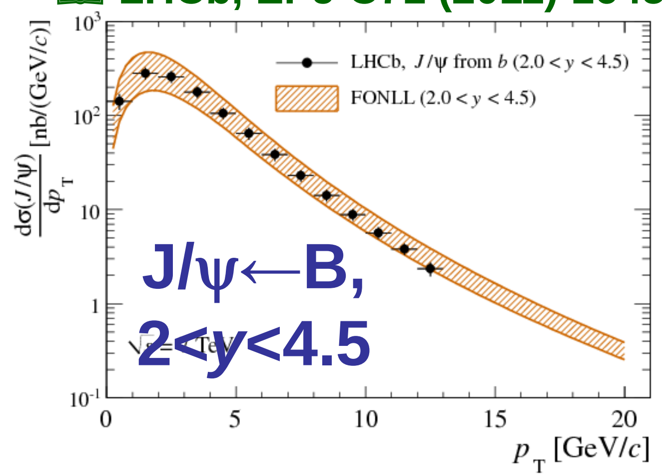
Charm cross-section on the upper side of the FONLL uncertainty band, as at lower √s (Tevatron, RHIC)



LHCb, Nucl.Phys. B871 (2013) 1



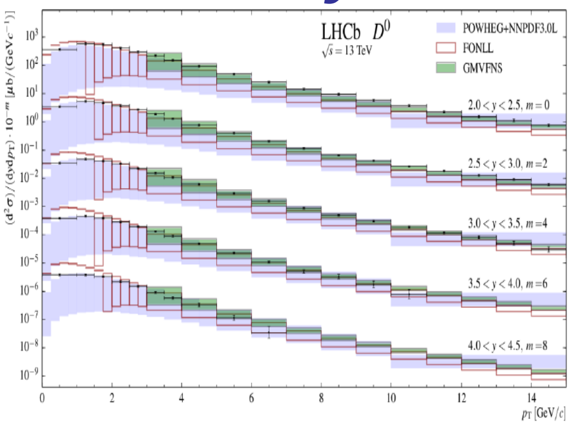
CMS, PRL 106 (2011) 112001

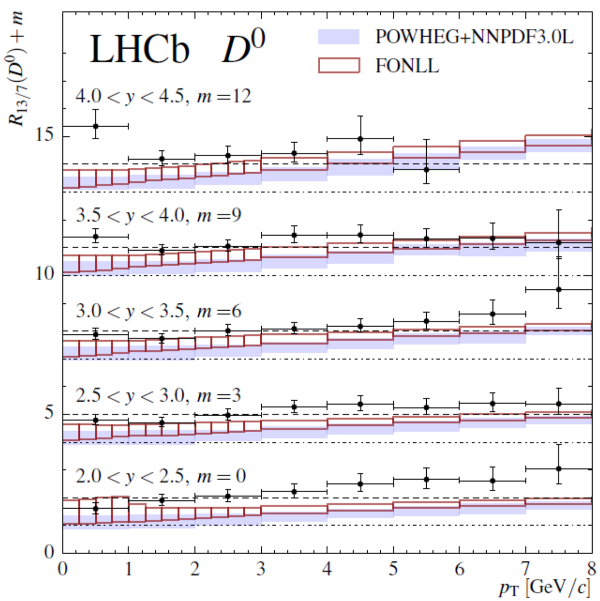


LHCb, EPJ C71 (2011) 1645

HF in pp collisions at √s= 13 TeV

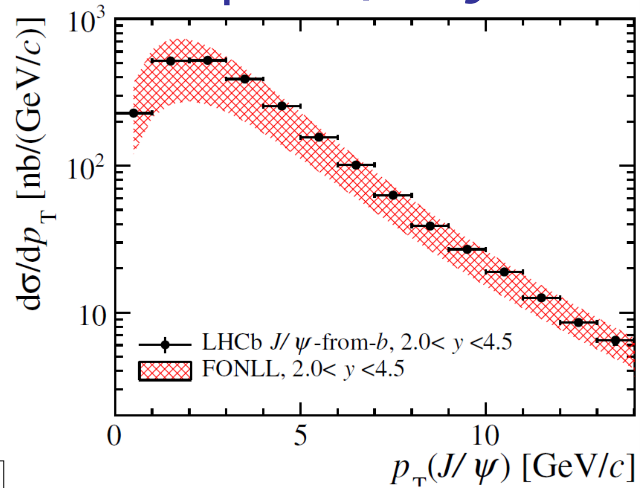
D^0 2<y<4.5

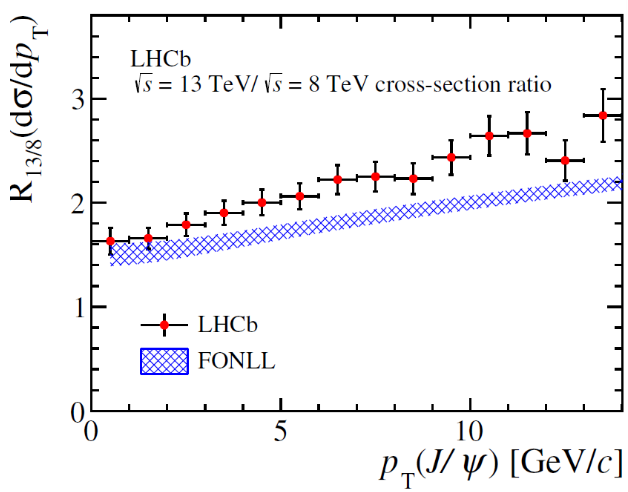




📖 **LHCb, JHEP1603 (2016) 159**

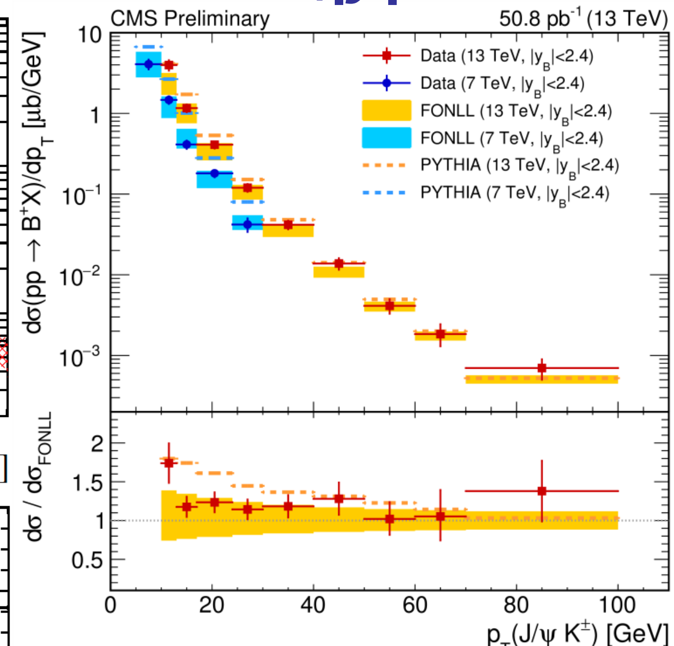
J/ψ←B, 2<y<4.5





📖 **LHCb, JHEP 1510 (2015) 172**

B$^+$,|y|<2.4



📖 **CMS-PAS-BPH-15-004**

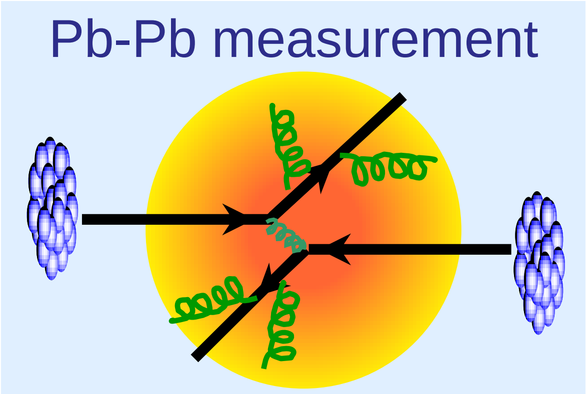
The measured ratios of the cross sections at √s=13 and 7(8) TeV lie systematically above the FONLL predictions

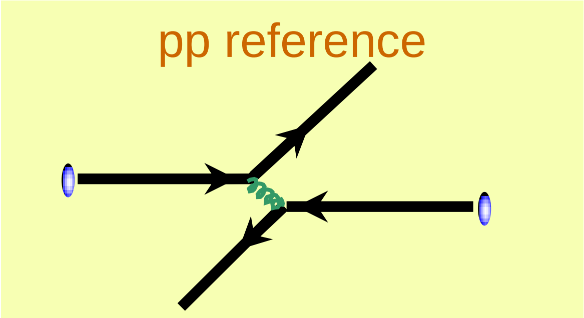
Nuclear modification factor

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

$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T} \sim \frac{QCD \text{ medium}}{QCD \text{ vacuum}}$$

- If no nuclear effects are present $\rightarrow R_{AA}=1$

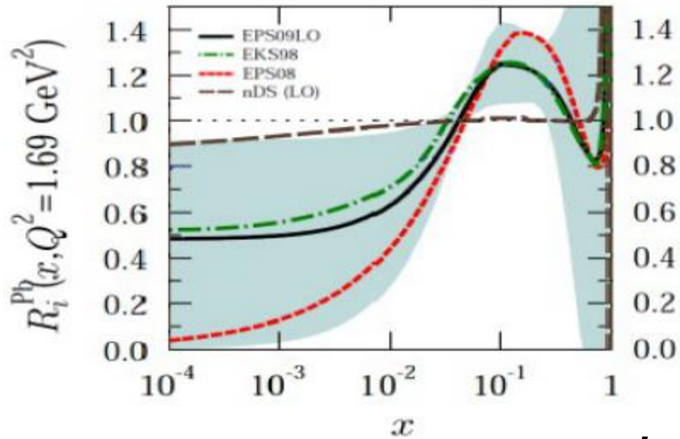


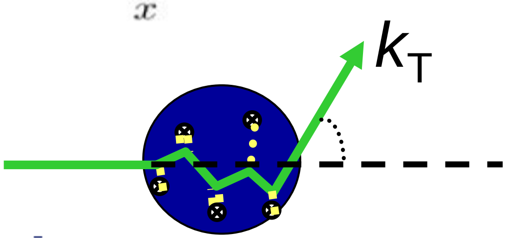


- Hot, dense and deconfined medium created in the collision can modify ($\rightarrow R_{AA}\neq 1$) the:
  - Phase space distribution of heavy quarks
    - ✓ ***In-medium parton energy loss via elastic collisions and gluon radiation, collective flow, in-medium hadronization***
  - Yield of quarkonia
    - ✓ ***Quarkonia melting in the QGP, production via $c\bar{c}$ (re)combination***

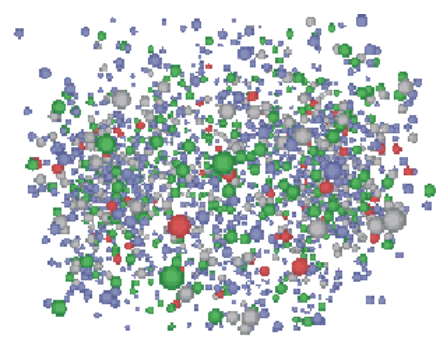
Cold nuclear matter effects: p-Pb collisions

- GOAL: assess the role of **cold nuclear matter** (CNM) **effects**
  - ⇨ **Initial-state** effects:
    - ✓ ***Nuclear modification of the PDFs***
      *→ **shadowing** at low Bjorken-x is the dominant effect at LHC energies*
    - ✓ ***Initial-state energy loss***
    - ✓ ***k_T-broadening***
      → due to multiple collisions of the parton before the hard scattering





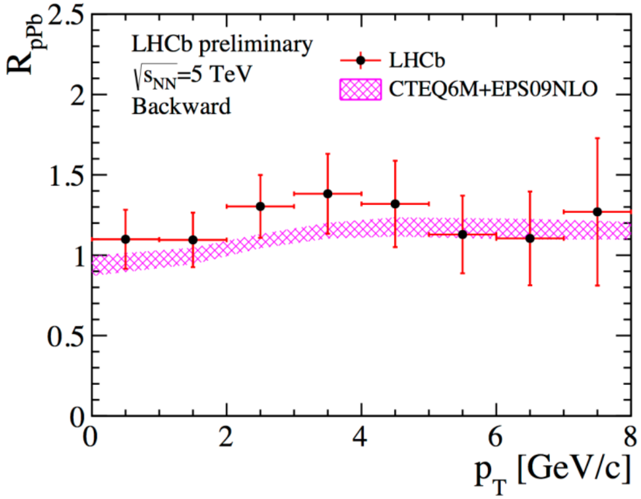
  - ⇨ **Final-state** effects
    - ✓ ***Final-state energy loss***
    - ✓ ***Interactions with the particles produced in the collision***
      → collective expansion?
      → Mini QGP?



- Crucial for interpretation of Pb-Pb results

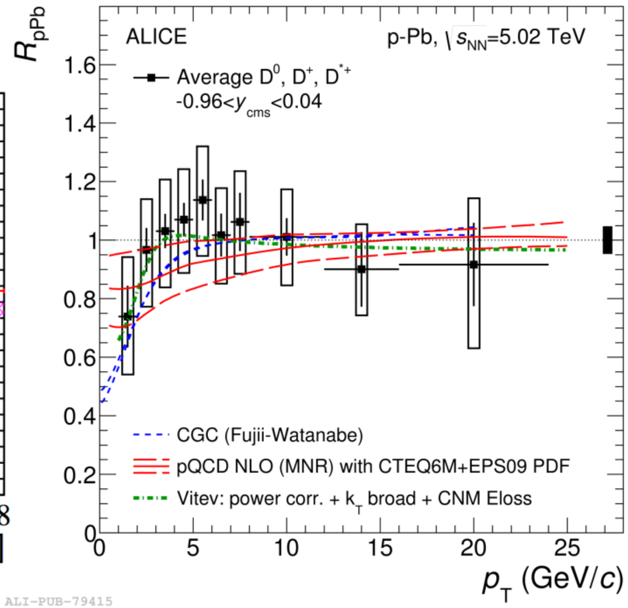
D mesons in p-Pb collisions

Backward rapidity (Pb-going side)



📖 LHCb-CONF-2016-003

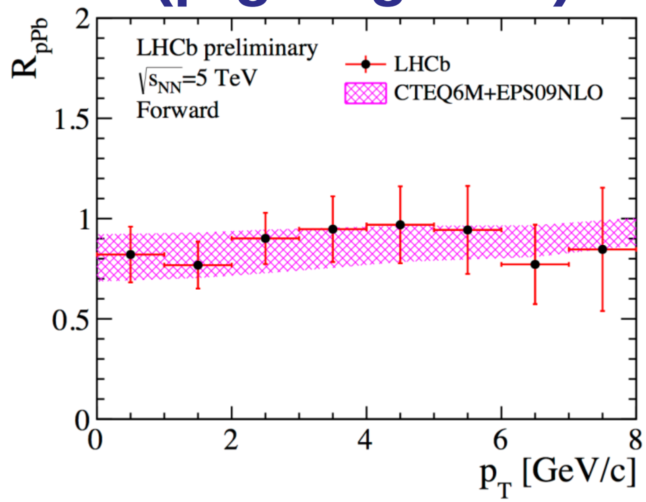
Mid-rapidity



ALI-PUB-79415

📖 ALICE, PRL113 (2014), 232301

Forward rapidity (p-going side)



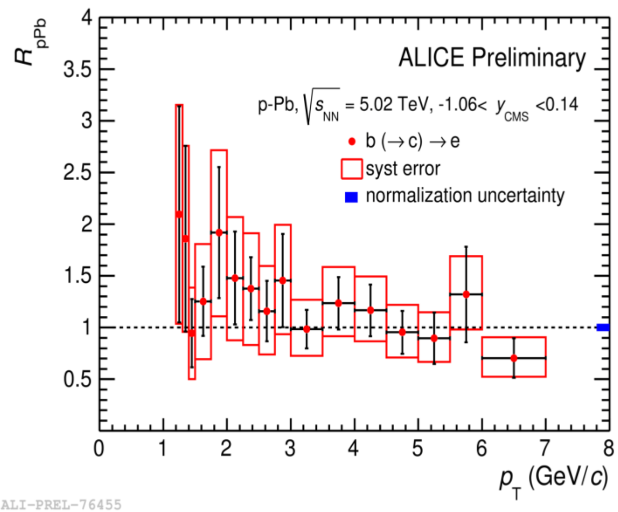
📖 LHCb-CONF-2016-003

- Charm production in p-Pb collisions described by pQCD calculations including nuclear PDFs and other CNM effects
  - ⇨ Also forward-backward asymmetry described by pQCD+nuclear PDFs

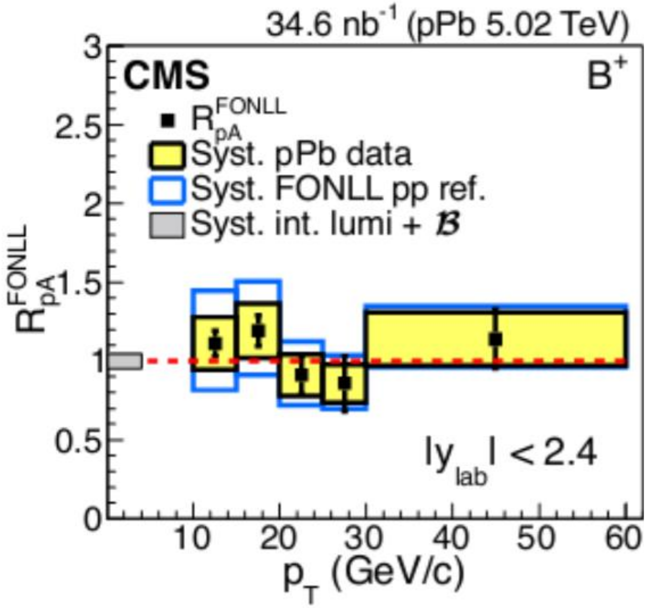
-> No indication of significant cold nuclear matter effects on charm production

Beauty in p-Pb collisions

Beauty-decay electrons

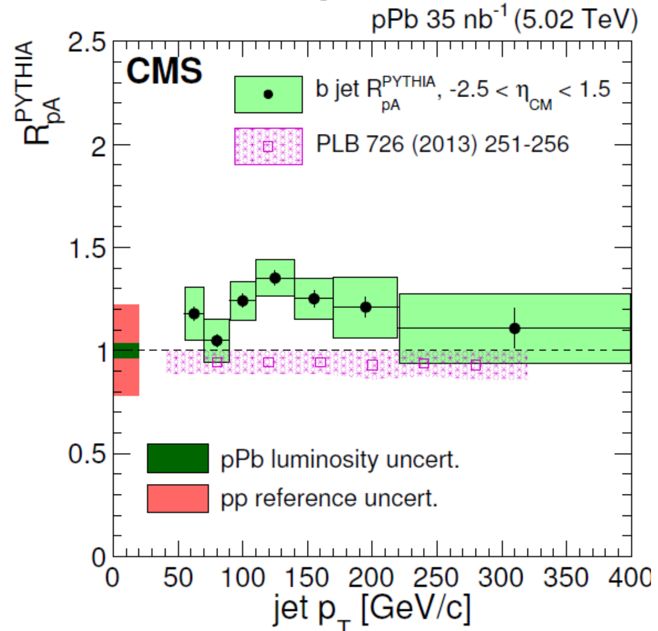


B mesons



📖 CMS, PRL 116 (2016) 032301

b-jets



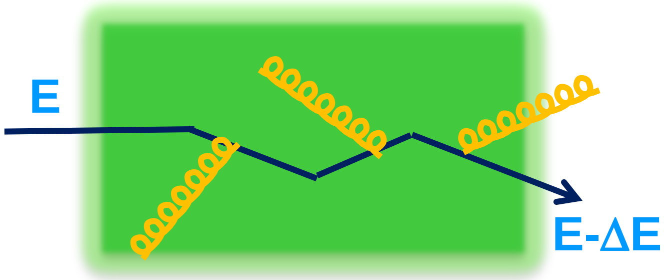
📖 CMS, PLB 754 (2016) 59

- R_{pPb} of beauty-decay electrons (low p_T), B mesons ($10<p_T<60$ GeV/c) and b-jets (high p_T) consistent with unity

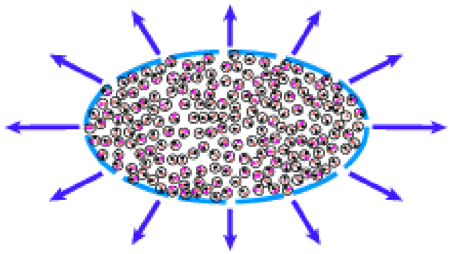
-> No indication of significant cold nuclear matter effects on beauty production

Hot and dense medium effects: Pb-Pb collisions

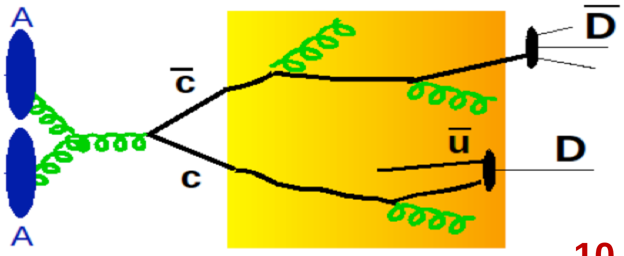
- Interaction of heavy quarks with the QCD medium constituents
  - Energy loss:
    - ✓ *Elastic collisions with the medium constituents (-> collisional energy loss)*
    - ✓ *Gluon radiation*



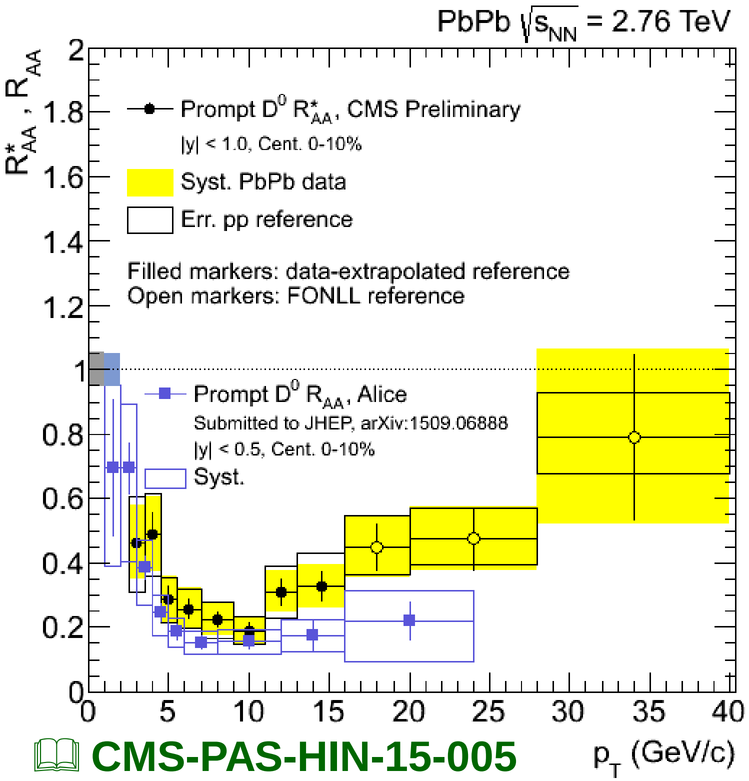
  - Momentum gain due to the "push" from medium collective expansion
    - ✓ *Do low-p_T heavy quarks thermalize in the medium?*



  - In-medium hadronization
    - ✓ *Hadronization via (re)combination of the charm quark with a (light) quark from the medium ?*



D mesons in Pb-Pb collisions

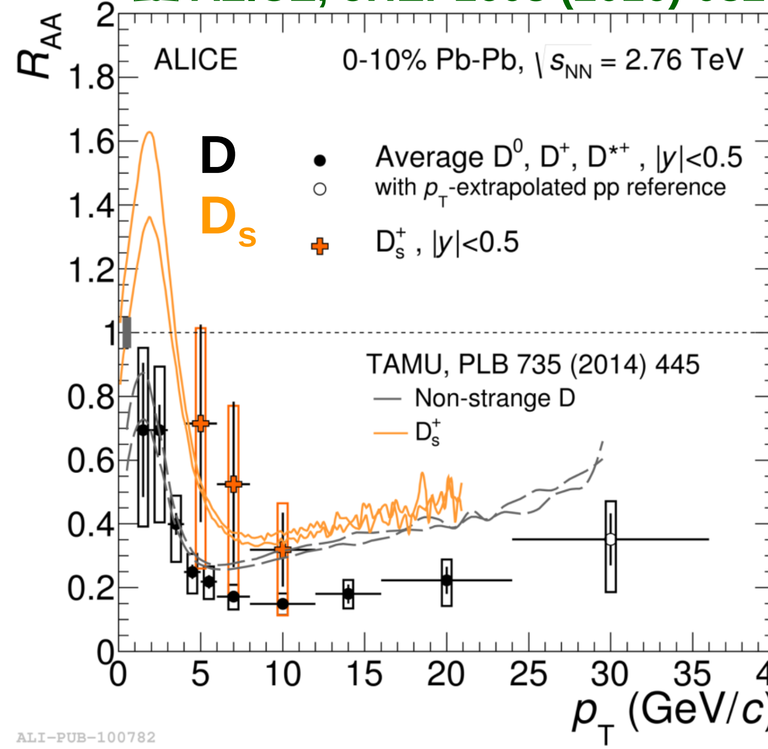


📖 **CMS-PAS-HIN-15-005**

📖 **ALICE, JHEP1603 (2016) 081**

- Strong suppression of prompt D-meson yield in central Pb-Pb collisions
  - ⇨ up to a factor of 5 at p_T≈10 GeV/c

📖 **ALICE, JHEP1603 (2016) 082**



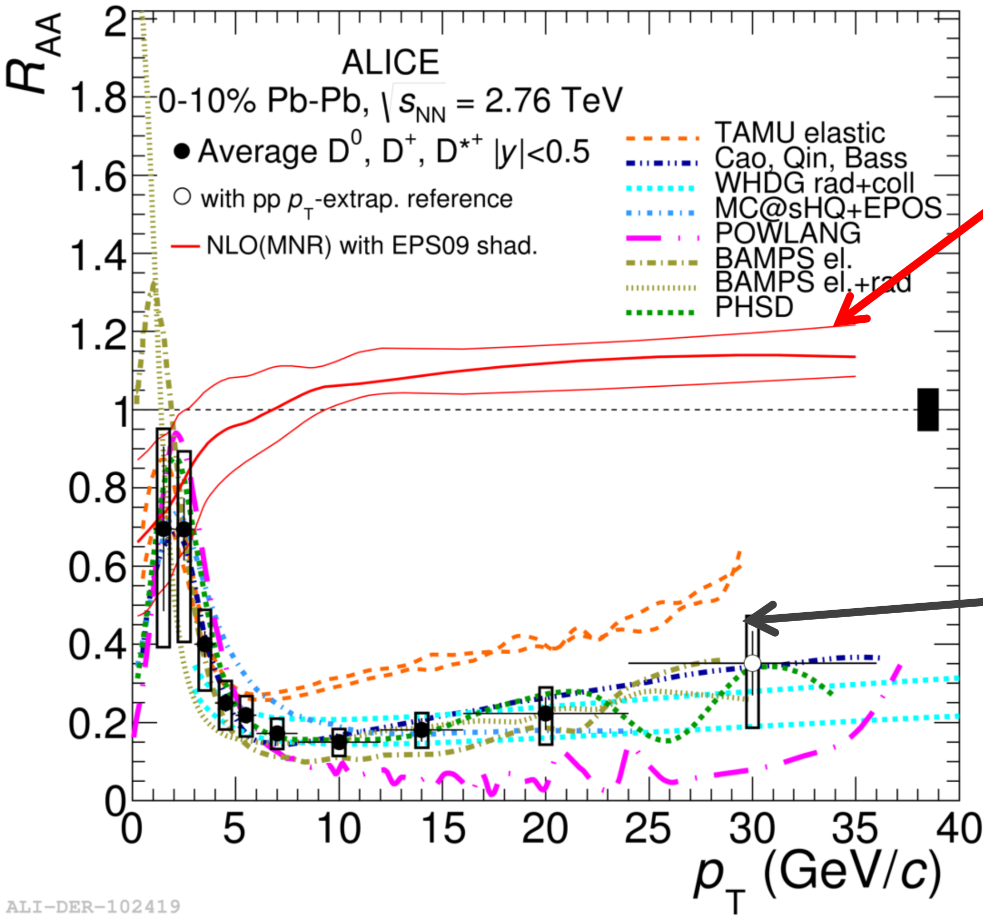
- Hint for less suppression of D_s^+ than non-strange D at low p_T
  - ⇨ Expected if recombination plays a role in charm hadronization

📖 **Kuznetsova, Rafelski, EPJ C 51 (2007) 113**

📖 **He, Fries, Rapp, PLB 735 (2014) 445**

D-meson R_{AA} vs. models

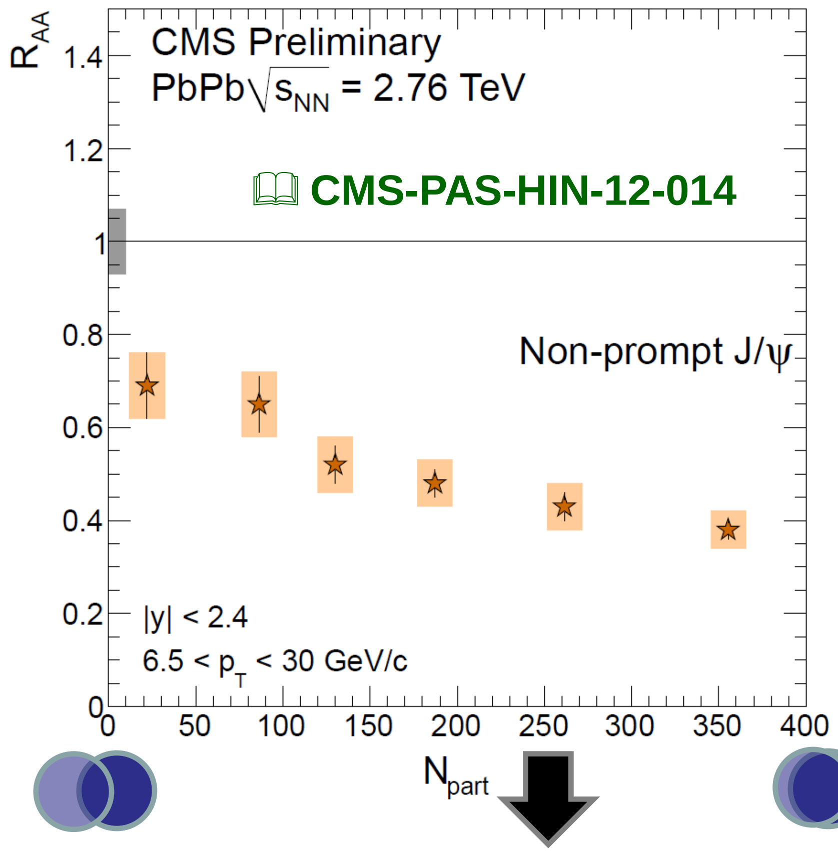
📖 ALICE, JHEP1603 (2016) 081



- Expectation from pQCD+nuclear PDFs (no QGP medium)
  - ⇨ Fails in describing the Pb-Pb data
- Models including interactions of charm quarks with medium constituents
  - ⇨ describe qualitatively (and in some cases quantitatively) the data

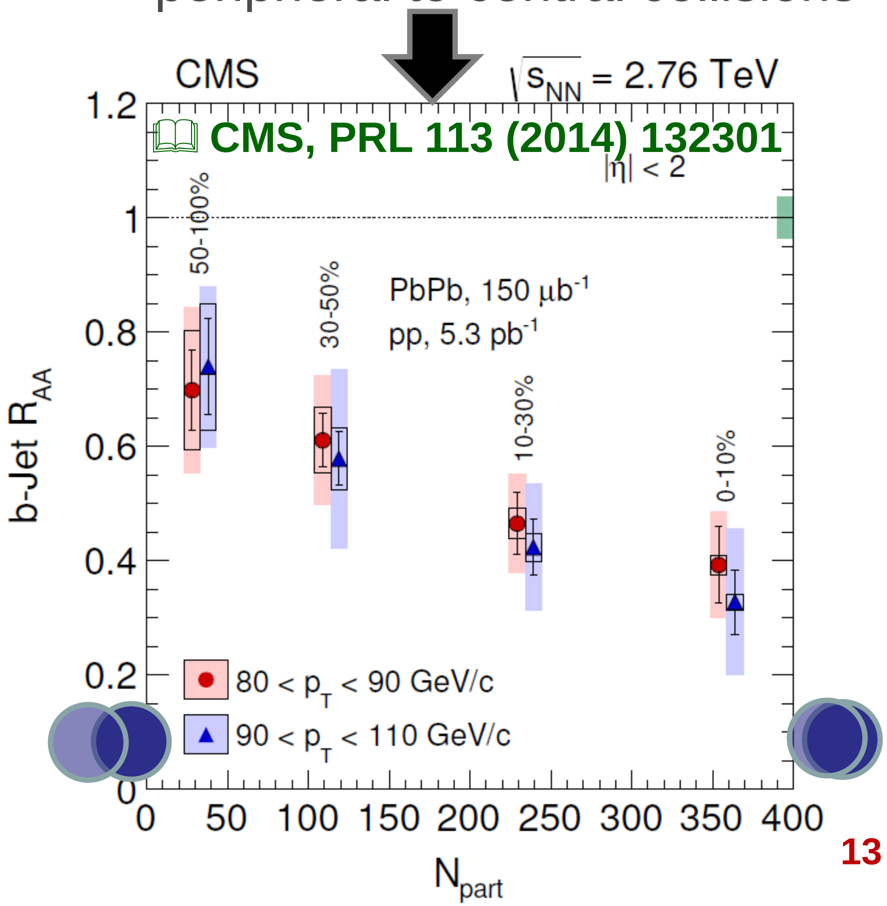
The suppression is a final-state effect
-> due to interactions with the hot and dense medium

Beauty in Pb-Pb collisions



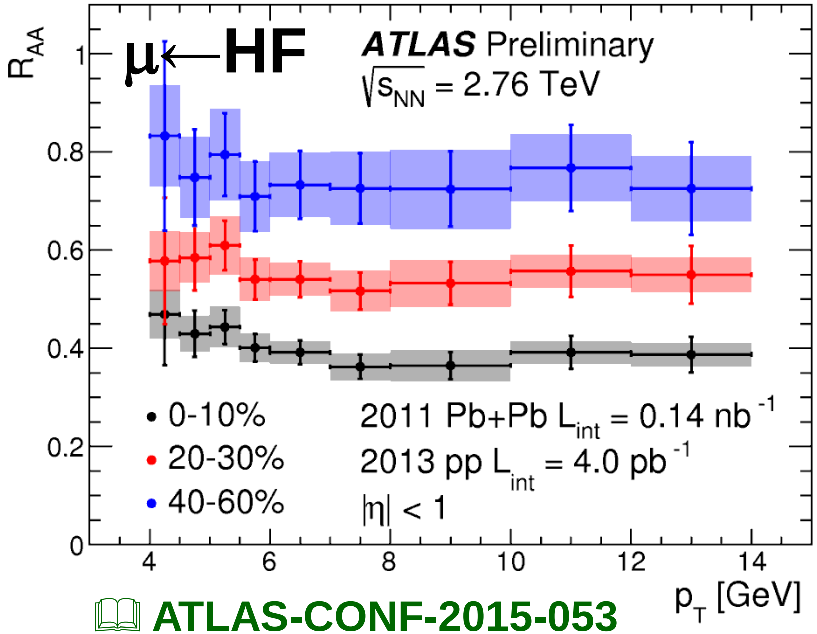
- Production of non-prompt J/ψ with p_T>6.5 GeV/*c* suppressed in Pb-Pb collisions
  - ⇨ Suppression up to a factor of 2.5 for central collisions

- Production of b-jets suppressed in Pb-Pb collisions for p_T>80 GeV/*c*
  - ⇨ Suppression increases from peripheral to central collisions



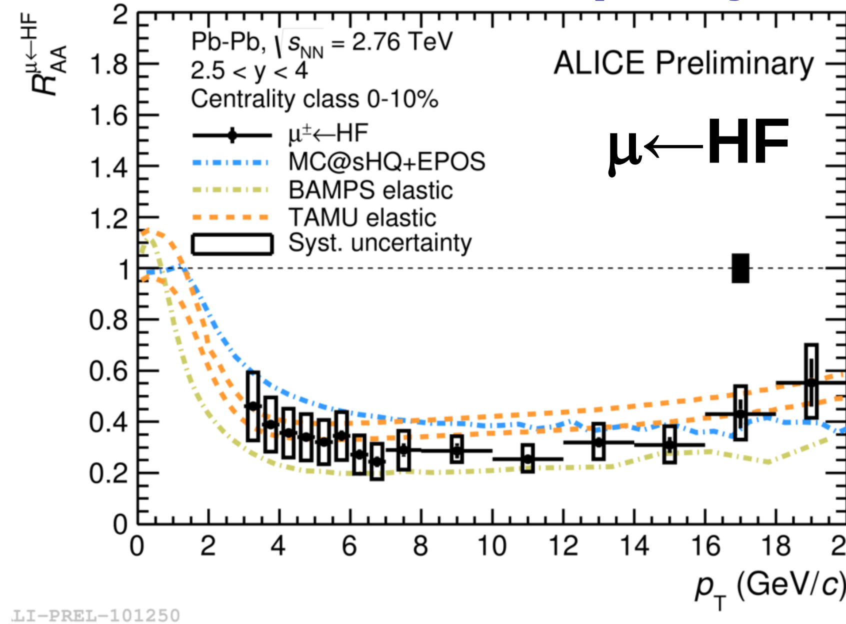
More beauty in Pb-Pb collisions

Mid-rapidity



ATLAS-CONF-2015-053

Forward rapidity

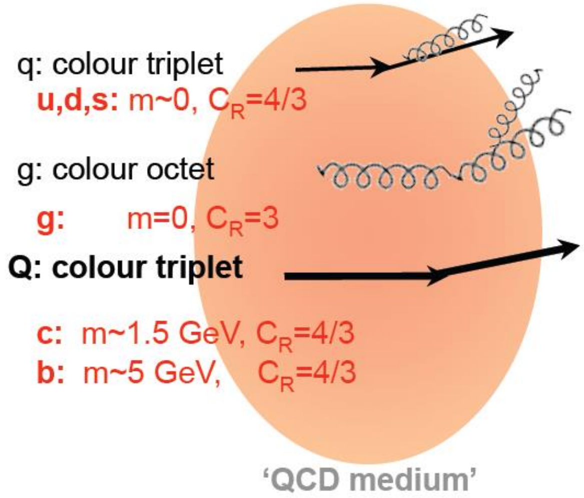


- Production of heavy-flavour decay muons (dominated by beauty for p_T>4-5 GeV/c) suppressed in Pb-Pb collisions
  - ⇨ Suppressed by a factor of 2.5-3 for central collisions
  - ⇨ Similar R_{AA} at mid-rapidity and at forward rapidity
  - ⇨ Suppression described by models including energy loss in QGP

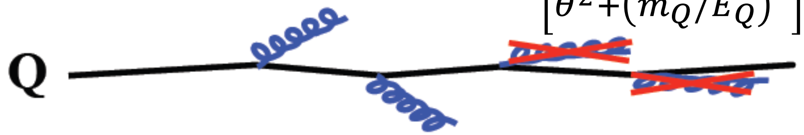
-> substantial energy loss of beauty quarks in the medium

Heavy-quark energy loss

- In-medium energy loss ΔE depends on:
  - ⇨ Properties of the medium (density, temperature, mean free path, …)
    -> **transport coefficients**
  - ⇨ Path length in the medium (L)
  - ⇨ Properties of the parton (**colour charge, mass**) traversing the medium:
    - ✓ ***Casimir coupling factor***
      -> C_R = 3 for gluons
      -> C_R = 4/3 for quarks
    - ✓ ***Mass of the quark***
      -> dead cone effect



Gluonstrahlung probability $\propto \frac{1}{\left[\theta^2+\left(m_Q/E_Q\right)^2\right]^2}$

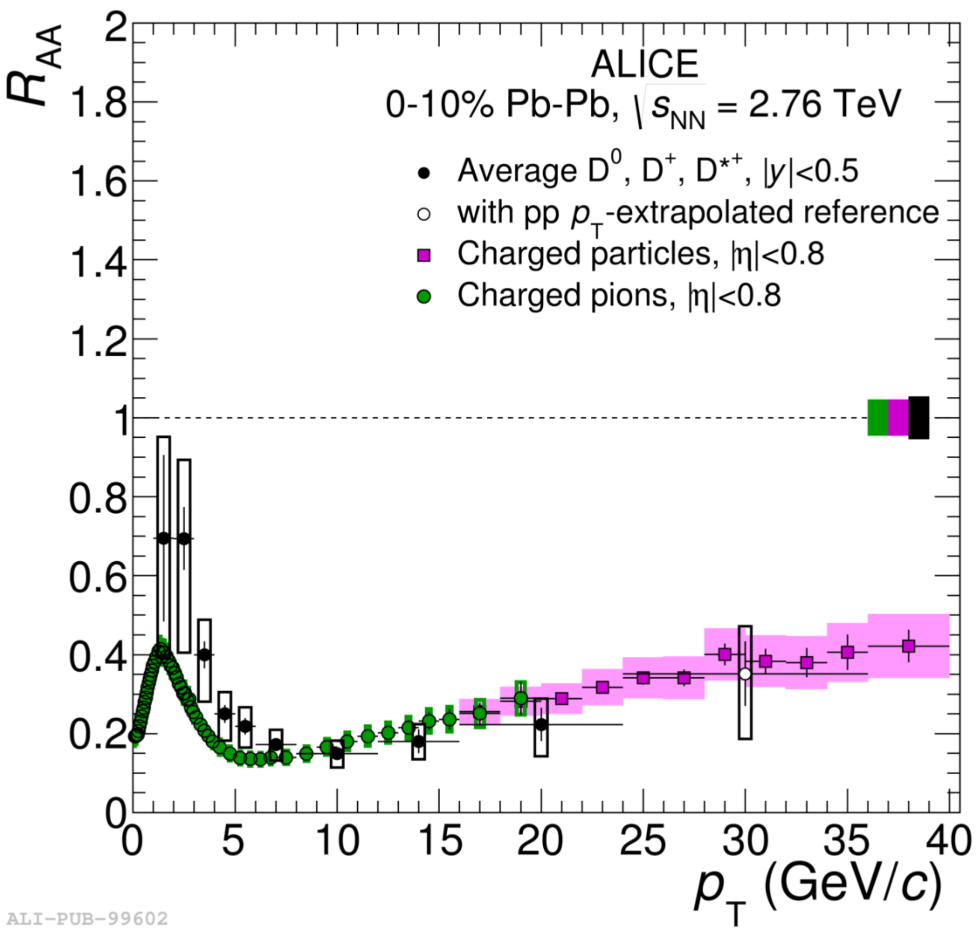


📖 Dokshitzer, Kharzeev, PLB 519 (2001) 199

- Expectation: $\boxed{\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b}$
- Is this reflected in a R_{AA} hierarchy: $\boxed{R_{AA}(\pi) < R_{AA}\,(D) < R_{AA}(B)}$?

R_{AA}: D mesons vs. pions

- Expectation: $\boxed{\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b}$
- Is this reflected in a R_{AA} hierarchy: $\boxed{R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)}$?

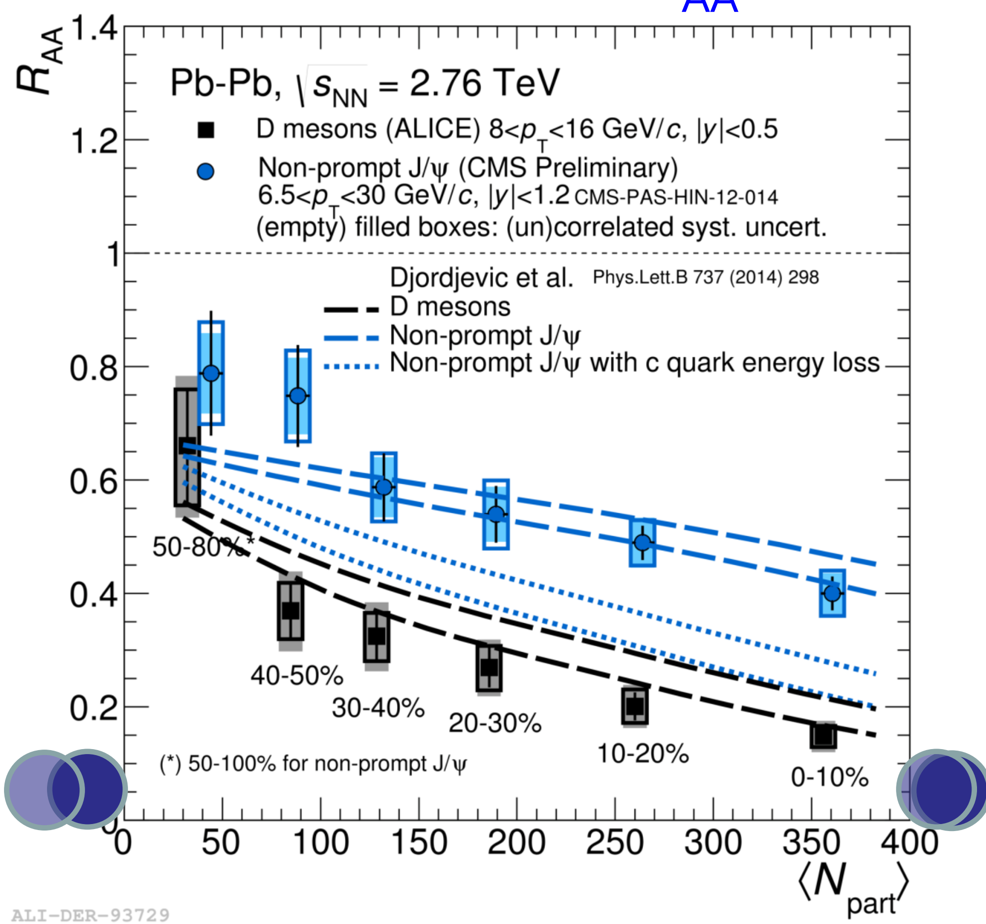


📖 **ALICE, JHEP1603 (2016) 081**

- D-meson and pion R_{AA} compatible within uncertainties
- Described by models including
  - ⇨ energy loss hierarchy ($\Delta E_g > \Delta E_{u,d,s} > \Delta E_c$)
  - ⇨ different p_T shapes of produced partons
  - ⇨ different fragmentation functions of gluons, light and charm quarks

R_{AA}: D mesons vs. J/ψ from B

- Expectation: $\boxed{\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b}$
- Is this reflected in a R_{AA} hierarchy: $\boxed{R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)}$?



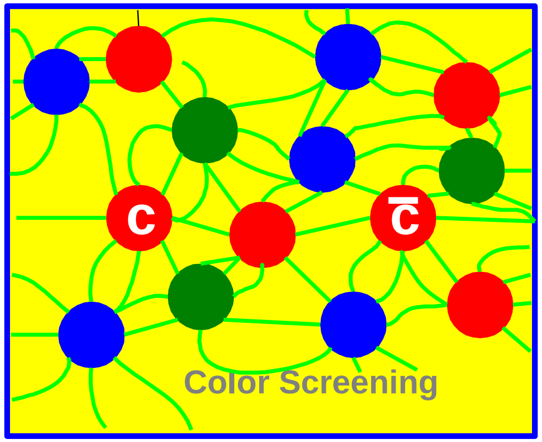
ALICE, JHEP 1511 (2015) 205
CMS-PAS-HIN-12-014
CMS-PAS-HIN-15-005

- Clear indication for $R_{AA}(B)>R_{AA}(D)$
  - Consistent with the expectation $\Delta E_c > \Delta E_b$
  - Described by models including quark-mass dependent energy loss

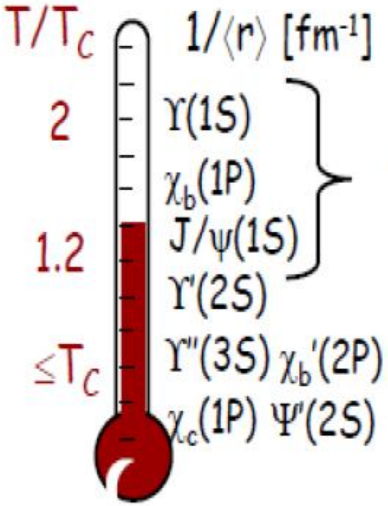
-> consistent with prediction of quark-mass dependent energy loss

Quarkonium: in-medium dissociation

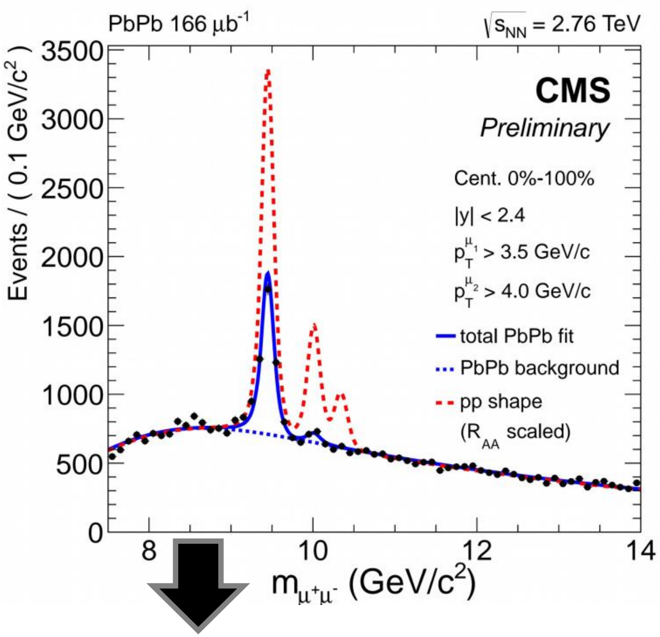
- In the QGP, quarkonium states with radius larger than Debye screening length are expected to **melt** due to colour screening of the $q\bar{q}$ potential.
  - ⇨ Quarkonium production **suppressed** in A-A collisions due to colour screening in the QGP
  - 🕮 **Matsui, Satz, PLB178 (1986) 416**



- Different quarkonium states melt at different temperatures, depending on their binding energy
  - ⇨ **Sequential suppression pattern**
- Melting sequence of quarkonia as a **QGP thermometer**
  - ⇨ Relevant for the interpretation of experimental results: **feed-down** from higher quarkonium states and (for charmonia) from B decays
  - 🕮 **Digal et al., PRD64 (2001) 094015**



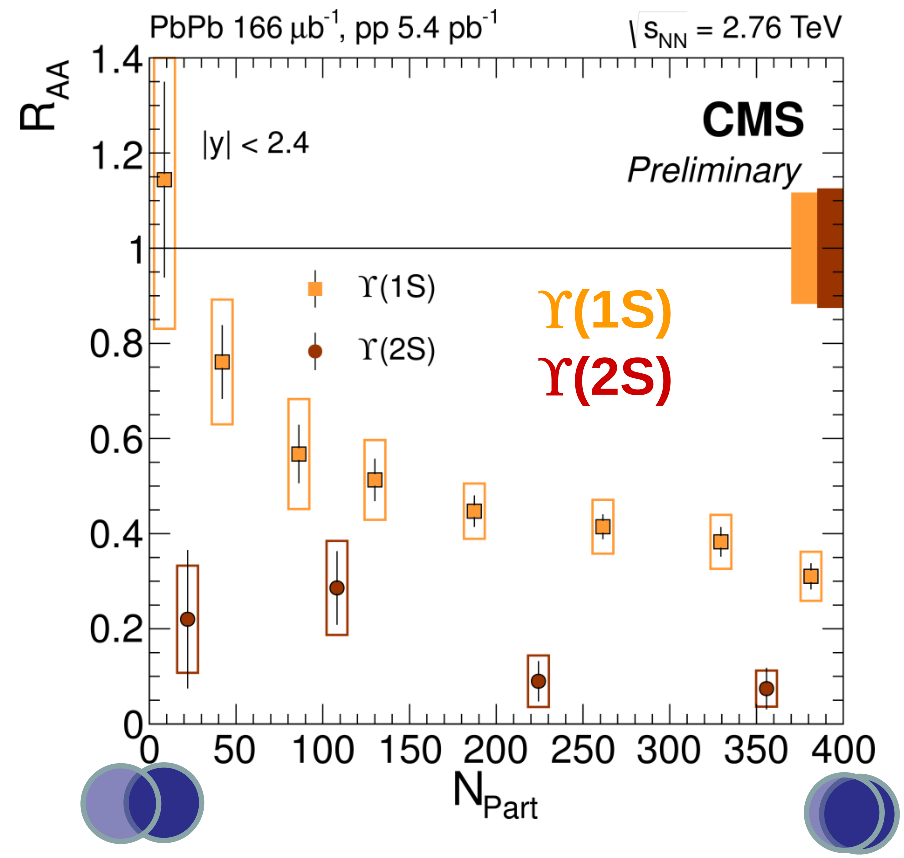
Bottomonium thermometer



$$R_{AA}^{\Upsilon(1S)} = 0.425 \pm 0.029 \pm 0.070$$

$$R_{AA}^{\Upsilon(2S)} = 0.116 \pm 0.028 \pm 0.022$$

$$R_{AA}^{\Upsilon(3S)} < 0.14 \text{ at } 95\% \text{ CL}$$

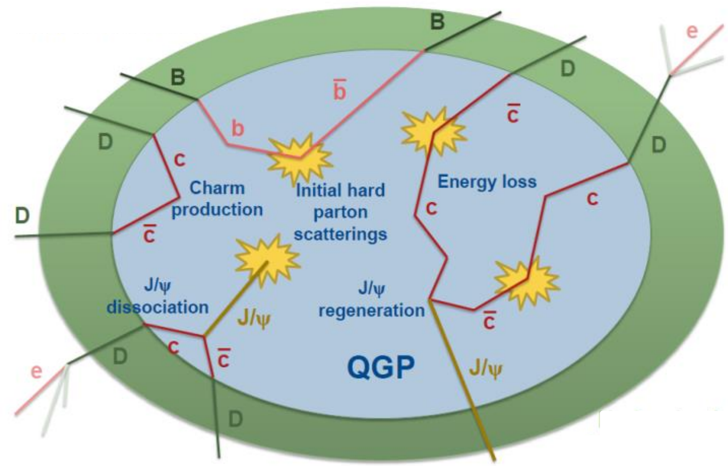


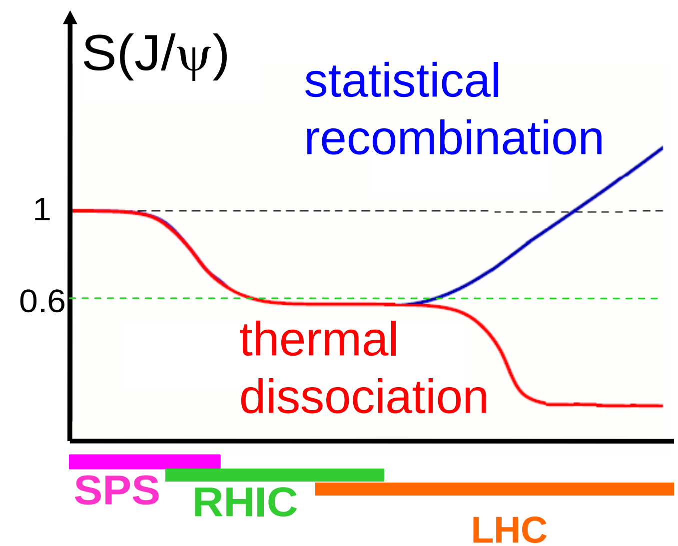
- Sequential suppression observed: $R_{AA}^{\Upsilon(3S)} < R_{AA}^{\Upsilon(2S)} < R_{AA}^{\Upsilon(1S)}$
- Suppression of Υ(1S) and Υ(2S) increases with centrality
- Feed-down from excited states seems not enough to explain the observed Υ(1S) suppression

CMS-PAS-HIN-15-001

Charmonium production via (re)combination

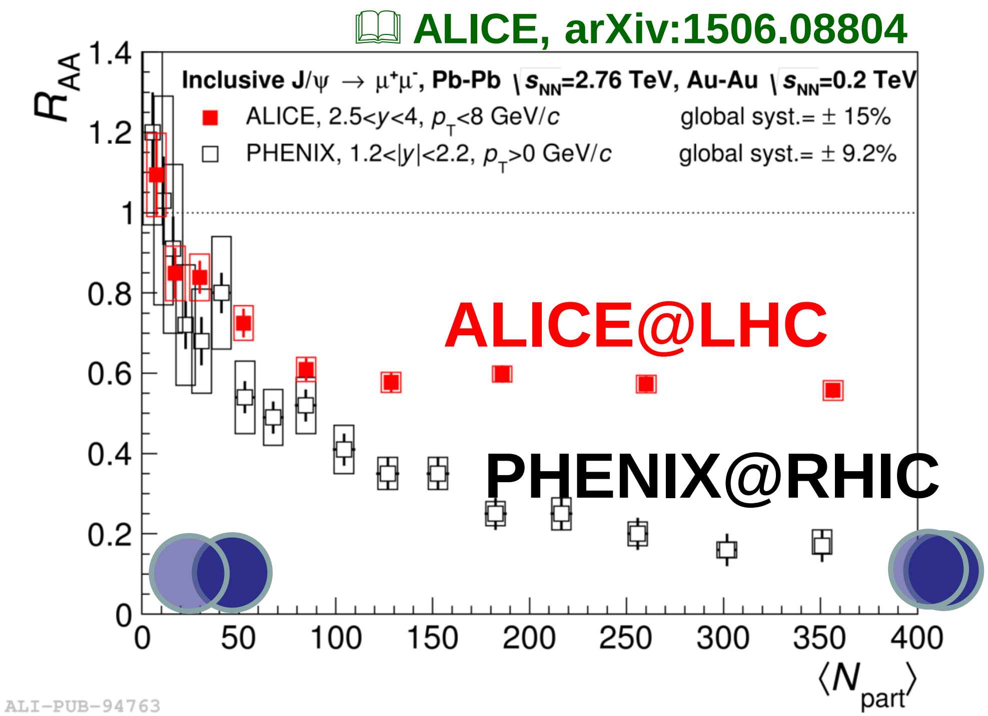
- Charmonium production in A-A collisions expected to occur also via **$c\bar{c}$ (re)combination** in the QGP or at the phase boundary
  - ⇨ J/ψ from (re)combination mainly produced with **low momentum**
  - ⇨ (Re)combination expected to be less relevant for bottomonium
- Charm production cross section increases with increasing √s
  - ⇨ (Re)combination increases with √s
  - ⇨ Quarkonium production **enhanced** in A-A collisions at higher √s

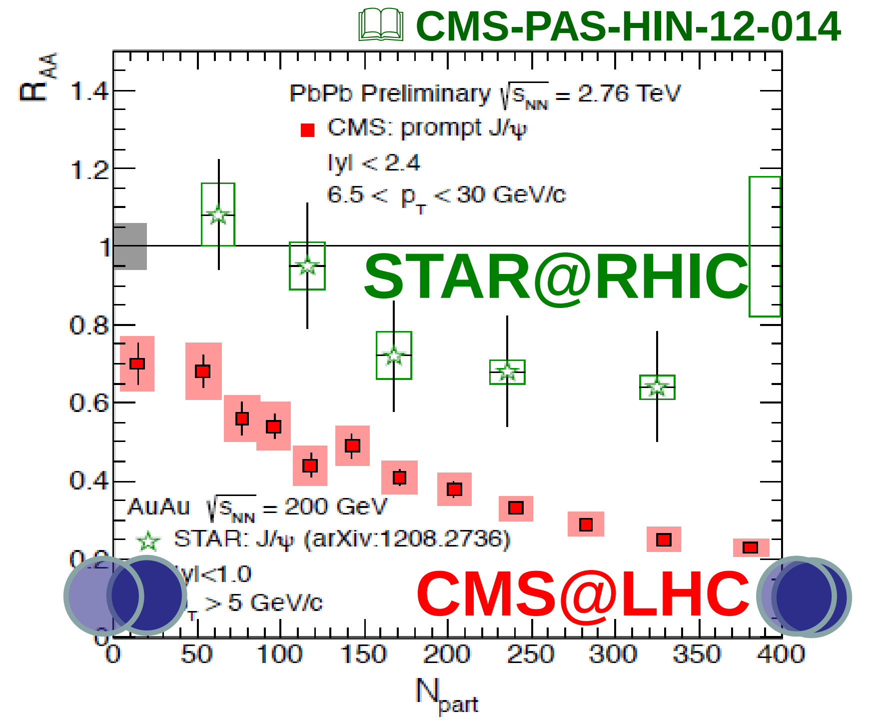




📖 **Braun-Munzinger, Stachel, PLB 490 (2000) 196**
📖 **Thews et al., PRC 63 (2001) 054905**

J/ψ R_{AA} at RHIC and LHC

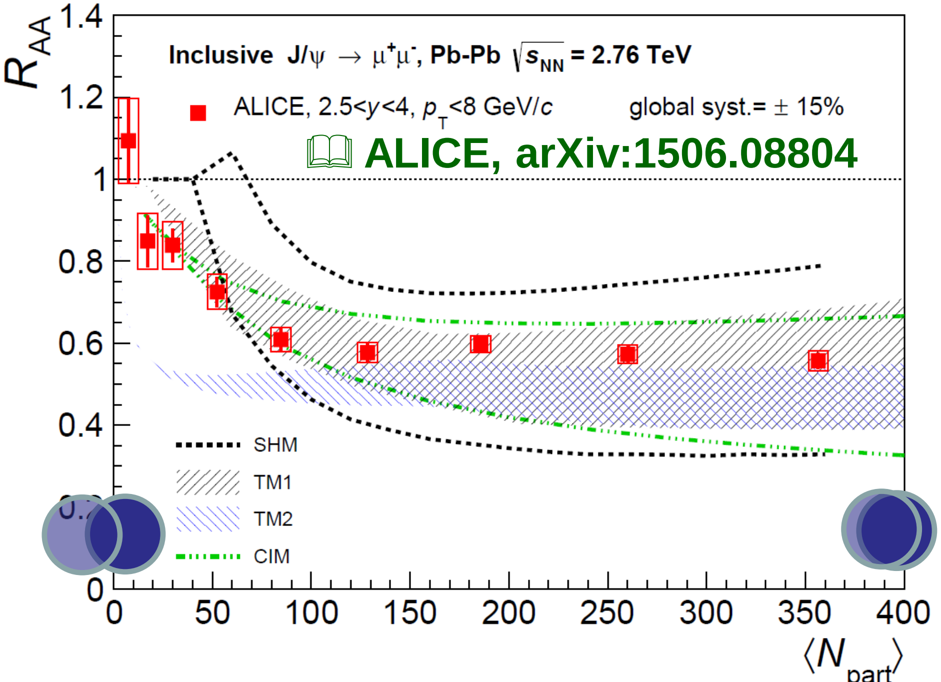


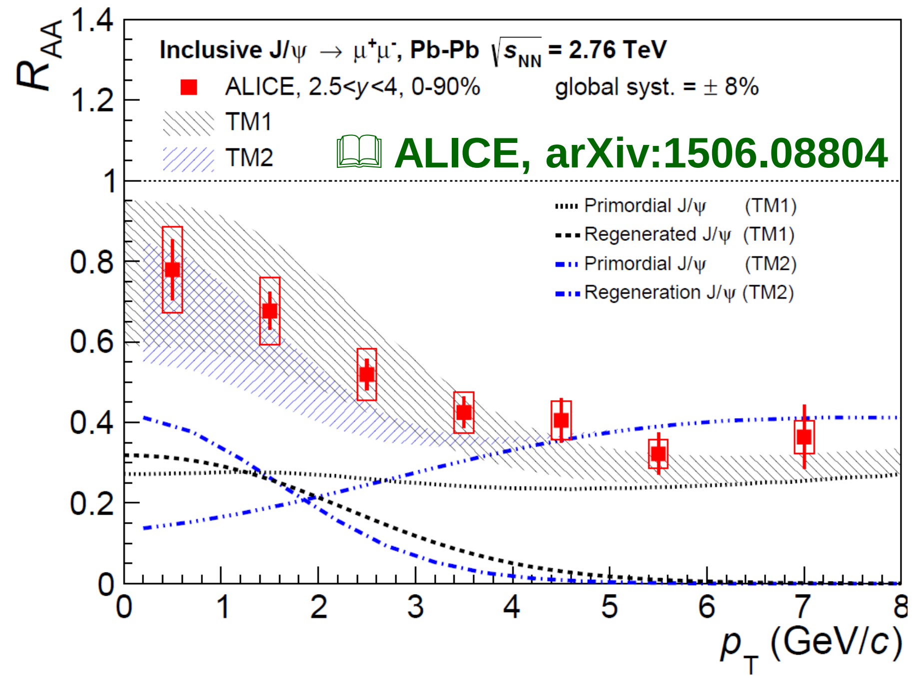


- Low p_T J/ψ
  - ⇨ **Less suppression at LHC** (√*s*=2.76 TeV) than at RHIC (√*s*=200 GeV)
- High p_T J/ψ
  - ⇨ **More suppression at LHC** (√*s*=2.76 TeV) than at RHIC (√*s*=200 GeV)

-> qualitatively as expected in a scenario with J/ψ (re)combination

J/ψ R_{AA} vs. models



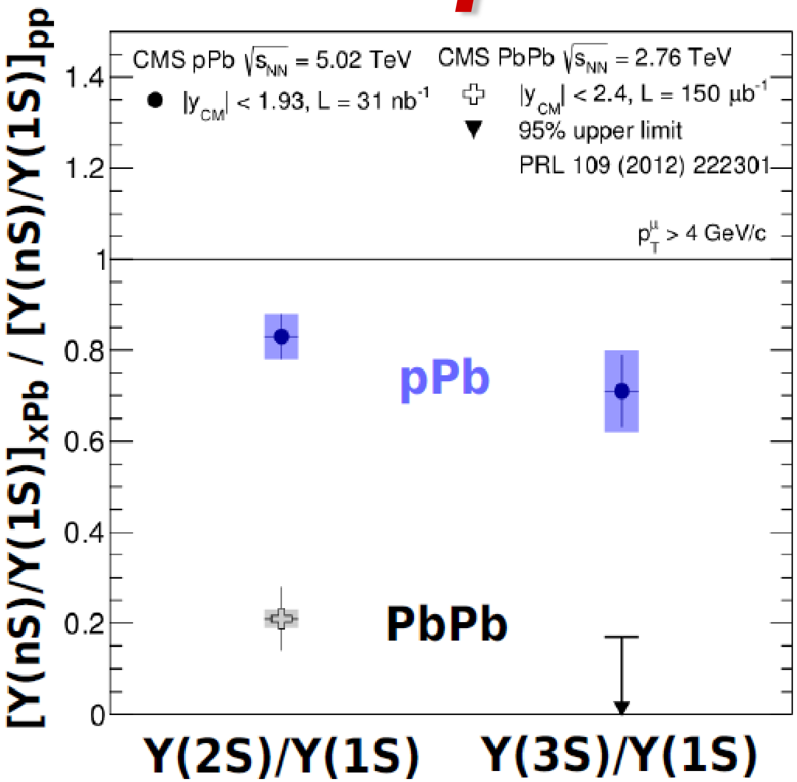


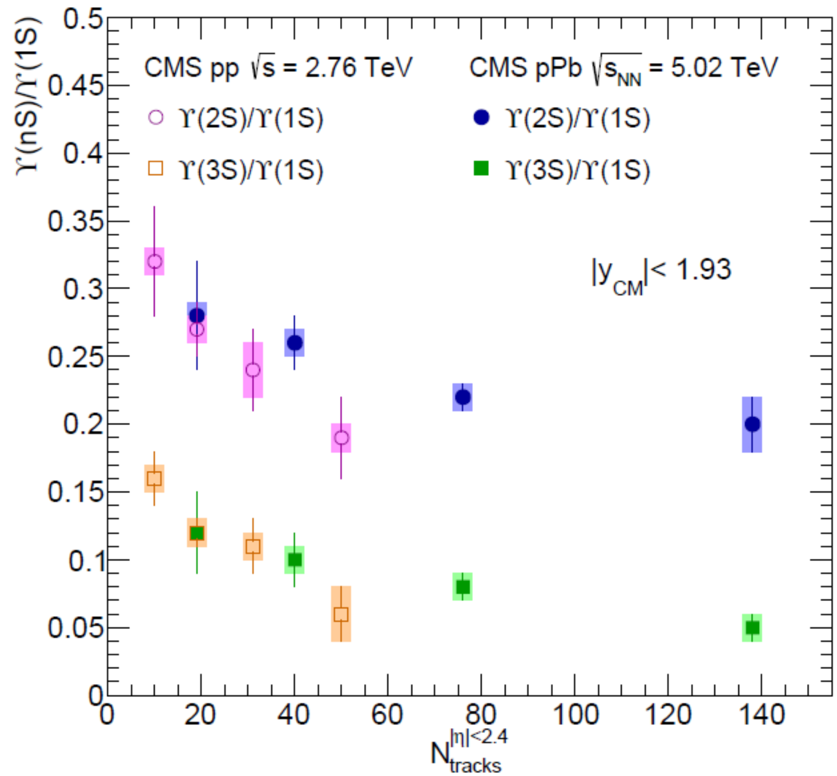
SHM: Andronic et al., JPG38 (2011) 124081
CIM: Ferreiro, PLB731 (2014) 57

TM1: Zhao, Rapp, NPA859 (2011) 114
TM2: Zhou et al., PRC89 (2014) 054911

- Models including (re)combination can describe the data
  - ⇨ In Statistical Hadronization Model all J/ψ produced at hadronization
  - ⇨ In Transport Models (TM)
    - ✓ ***~50% of low-p_T J/ψ produced via recombination***
    - ✓ ***Recombination contribution negligible at high p_T***

Back to p-Pb collisions: ϒ(nS)



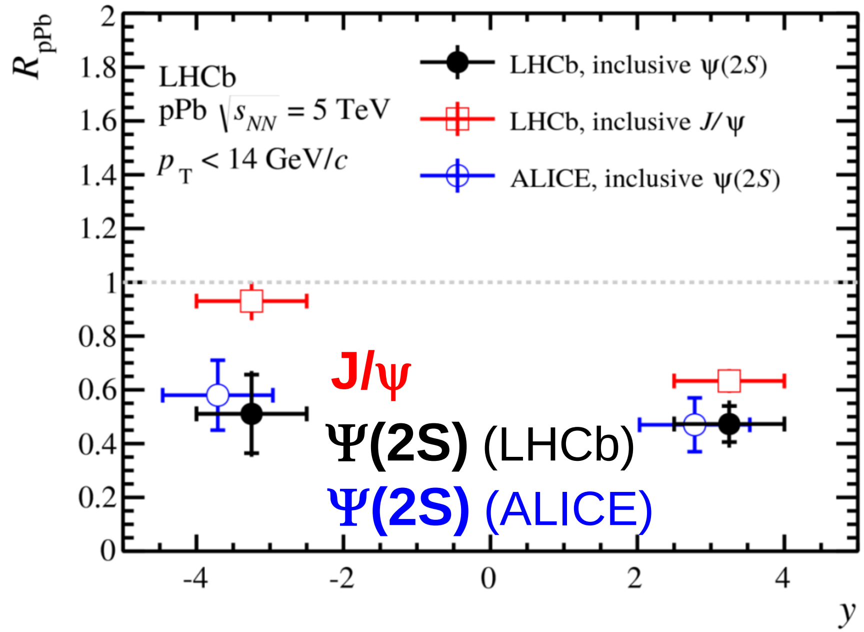


- Double ratio of ϒ(nS) to ϒ(1S) yields
  - ⇨ Binding energy ordering also in p-Pb collisions
  - ⇨ Excited states suffer more CNM effects than ground state
- ϒ(nS) production ratios depend on multiplicity
  - ⇨ Ground state systematically produced with more particles?
  - ⇨ Excited states more easily dissociated by interactions with other particles?

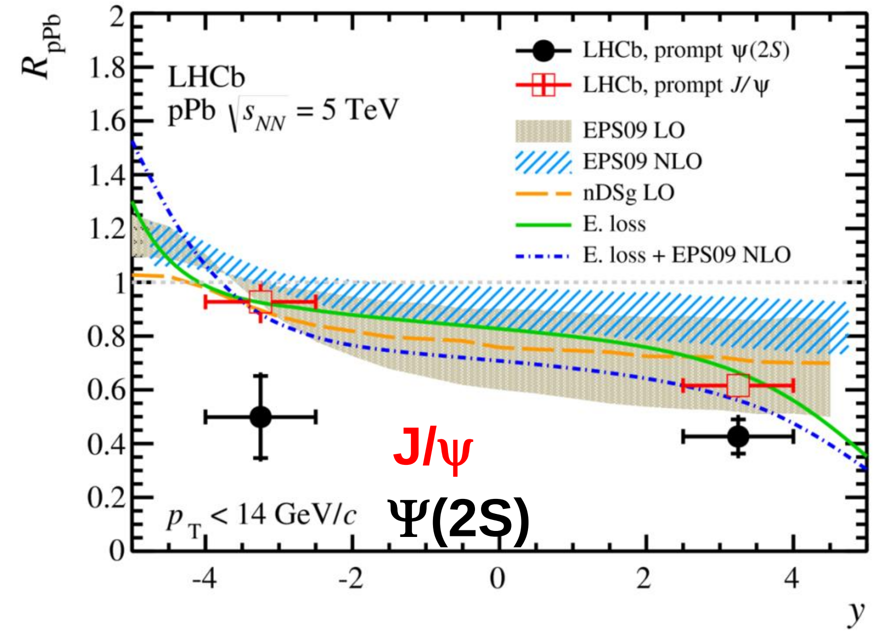
📖 CMS, JHEP 1404 (2014) 103

p-Pb collisions: J/ψ and Ψ(2S)

Inclusive



Prompt

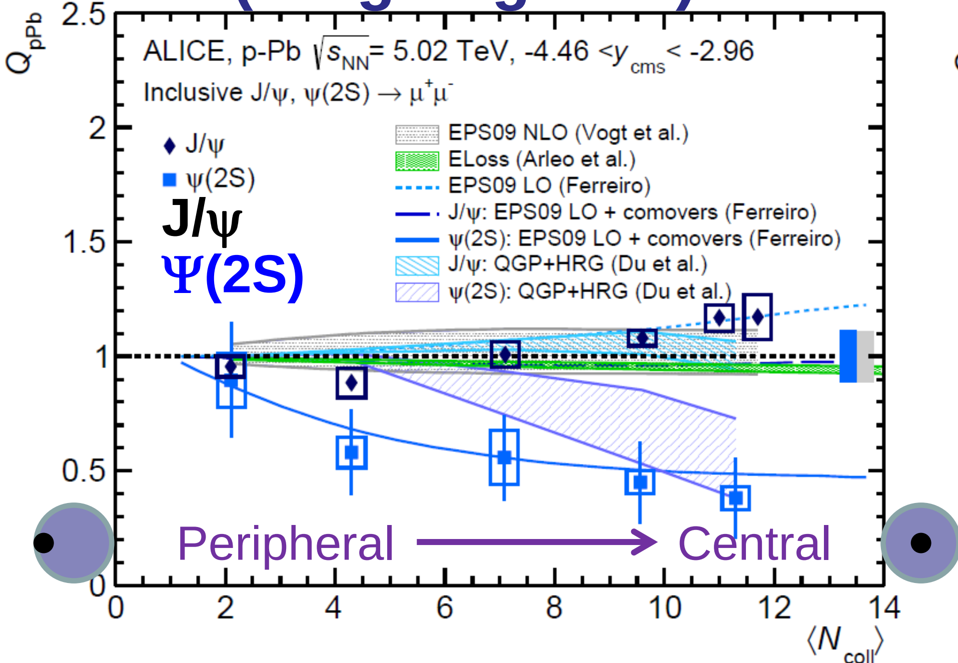


- J/ψ R_{pPb} described reasonably well by CNM effects
- Ψ(2S) production suppressed relative to J/ψ at both backward and forward rapidity
  - ⇨ Shadowing and energy loss, expected to be the same for J/ψ and Ψ(2S), cannot describe the different suppression

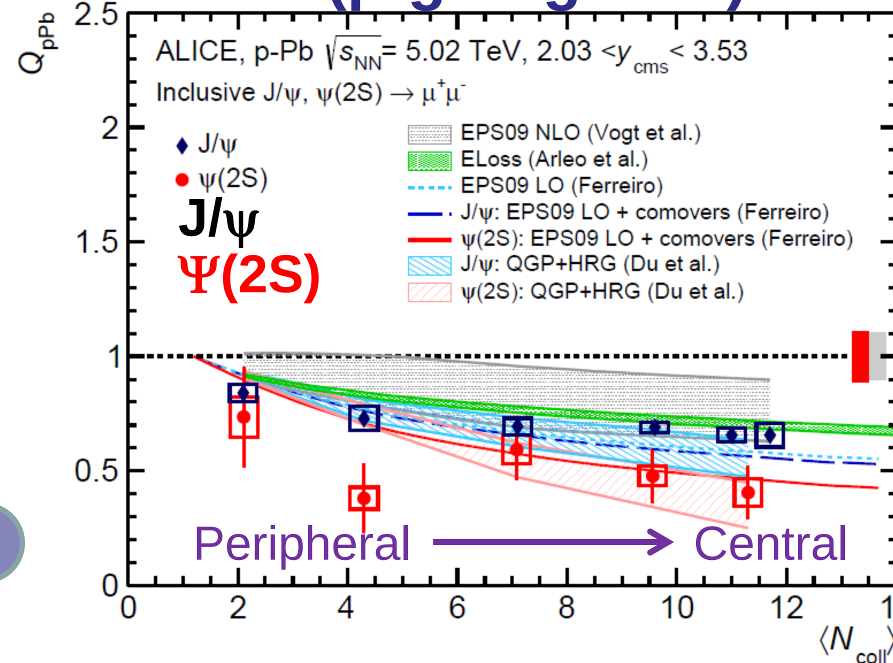
📖 ALICE, JHEP 1402 (2014) 073
📖 ALICE, JHEP 1412 (2014) 073
📖 LHCb, JHEP 1402 (2014) 072
📖 LHCb, JHEP 1603 (2016) 133

p-Pb: J/ψ and Ψ(2S) vs. centrality

Backward rapidity (Pb-going side)



Forward rapidity (p-going side)



- At backward rapidity, different trend for J/ψ and Ψ(2S)
  - ⇨ Ψ(2S) suppression increases from peripheral to central p-Pb collisions
  - ⇨ Not described by (anti)shadowing and energy loss
- Indication for additional final-state effects
  - ⇨ Interactions with co-moving hadrons (and QGP?) + dissociation of fully-formed resonance in nuclear matter ?

📖 **ALICE, JHEP 1511 (2015) 127**

📖 **ALICE, arXiv:1603.02816**

Where we are…

- Pb-Pb collisions
  - ⇨ Substantial **modification of D and B meson p_T spectra**
    - ✓ ***Potential to constrain energy loss mechanisms and medium transport coefficients***
  - ⇨ Indication for $R_{AA}^{beauty} > R_{AA}^{charm}$
    - ✓ ***Consistent with the predicted quark-mass dependent energy loss***
  - ⇨ Interplay of suppression and recombination on the yield of quarkonium states
    - ✓ ***Bottomonium as medium thermometer ?***
    - ✓ ***Charmonium states sensitive to hadronization of a deconfined medium***

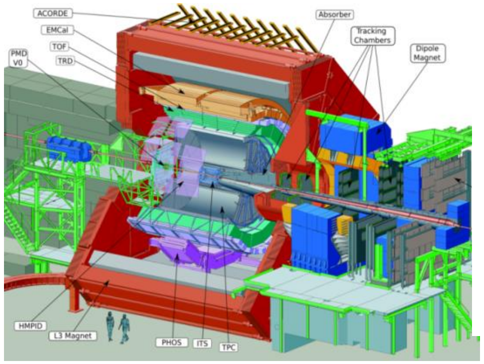
- p-Pb collisions
  - ⇨ Original motivation: a control experiment
    - ✓ ***Confirm that D and B meson suppression in Pb-Pb at high p_T is a final-state effect***
  - ⇨ Indication for final-state effects on charmonium and bottomonium yield in p-Pb collisions

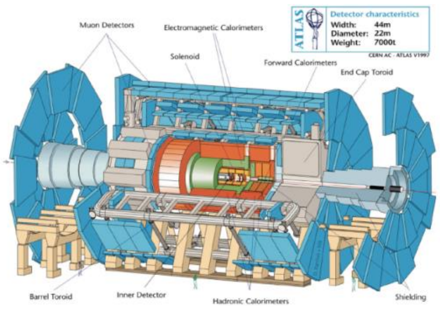
… and what next

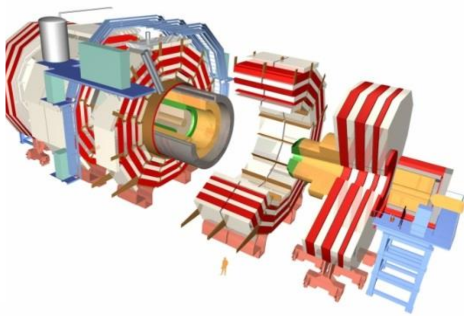
- Pb-Pb: larger samples at higher energy
  - ⇨ Improved precision + extended p_T coverage + full reconstruction of B-meson decays …
    - ✓ ***Precise assessment of suppression and recombination contributions in quarkonium production (including excited charmonium states)***
    - ✓ ***Quantitatively constrain energy loss models***
    - ✓ ***Study whether charm and beauty quarks thermalize in the medium***
  - ⇨ HF hadrochemistry: D_s and baryon-to-meson ratios
    - ✓ ***Constrain the hadronization mechanism (recombination/fragmentation)***
- p-Pb and pp
  - ⇨ Improved precision on pp reference and assessment of CNM effects
    - ✓ ***Crucial role in the interpretation of Pb-Pb results***
  - ⇨ Production vs. multiplicity/centrality
  - ⇨ Collectivity in high multiplicity pp and p-Pb collisions in the HF sector?
- Major step towards high-precision measurements in the HF sector with the LHC detector upgrades after Run2

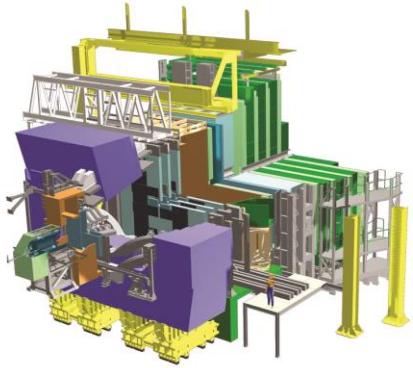
Backup

Heavy-flavours at the LHC

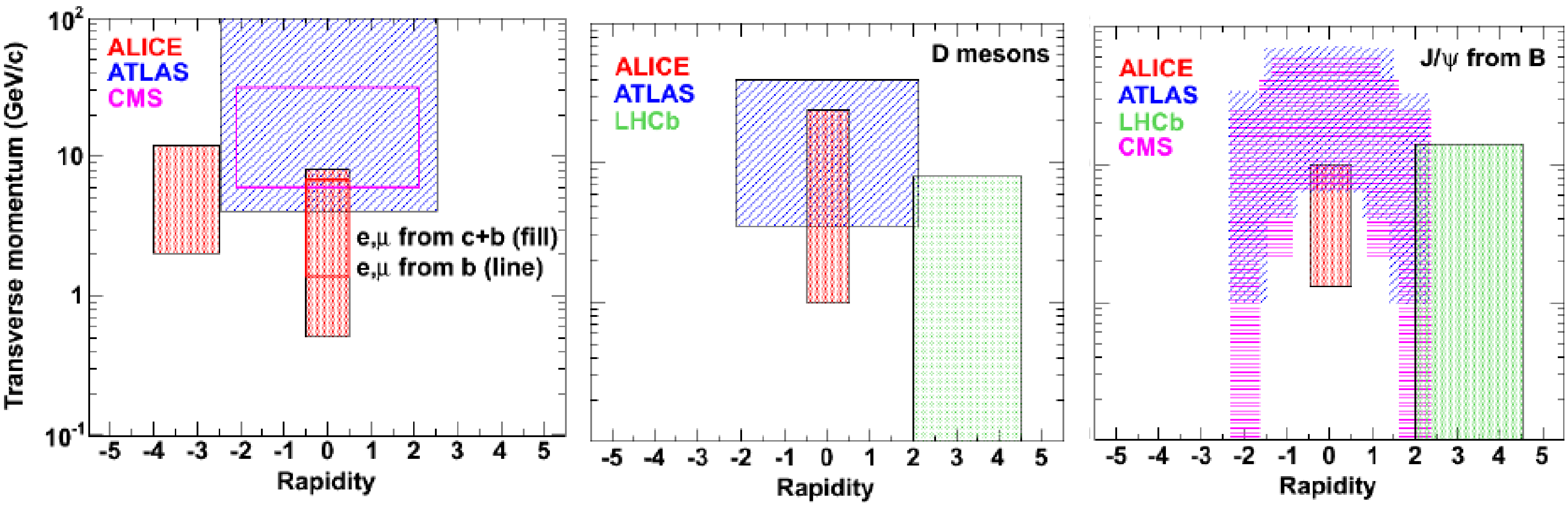








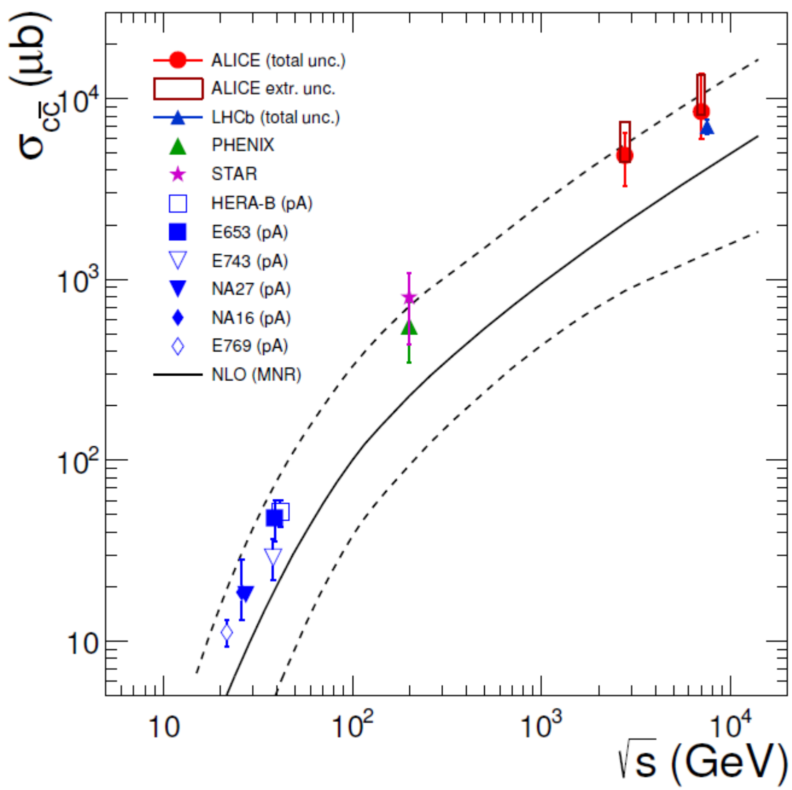
- Complementary rapidity and p_T coverage



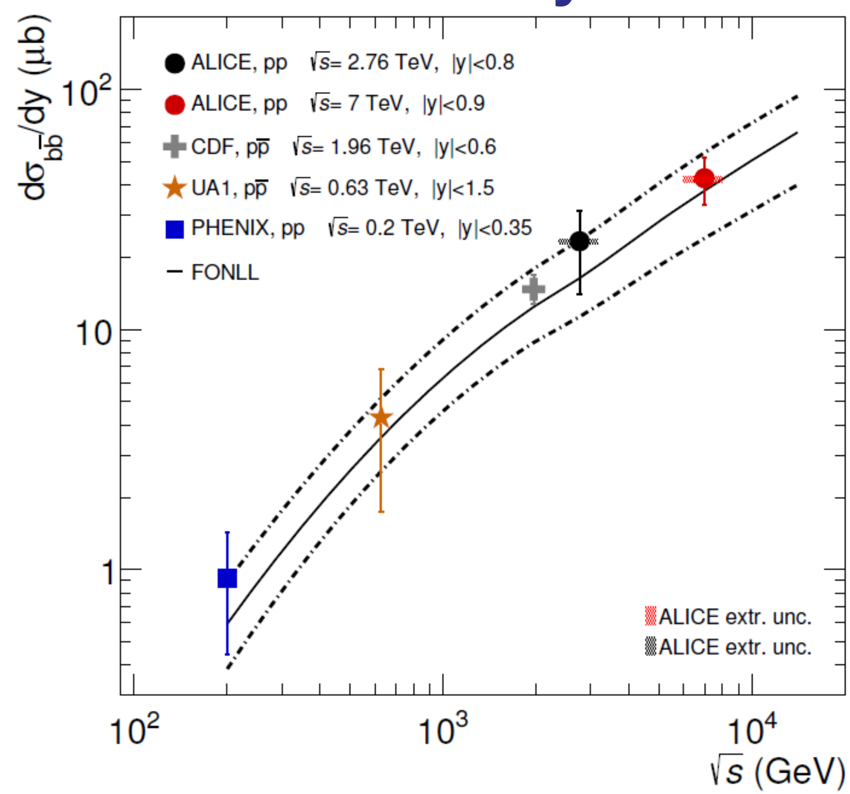
DISCLAIMER: acceptance plots refer to published measurements in pp

HF production cross section

Charm



Beauty

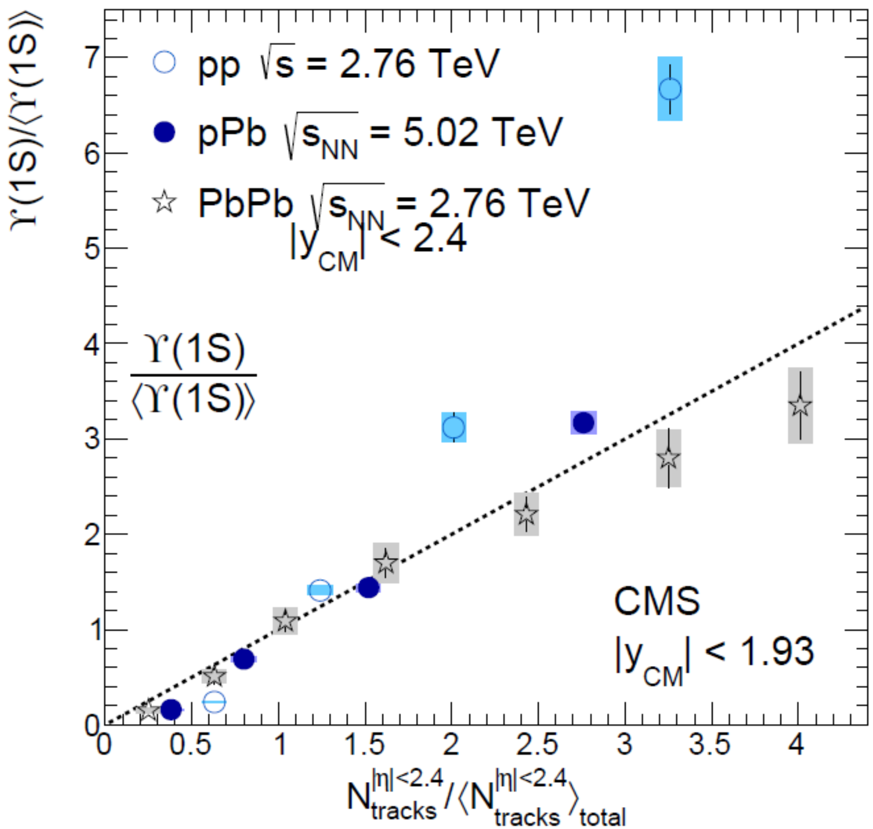


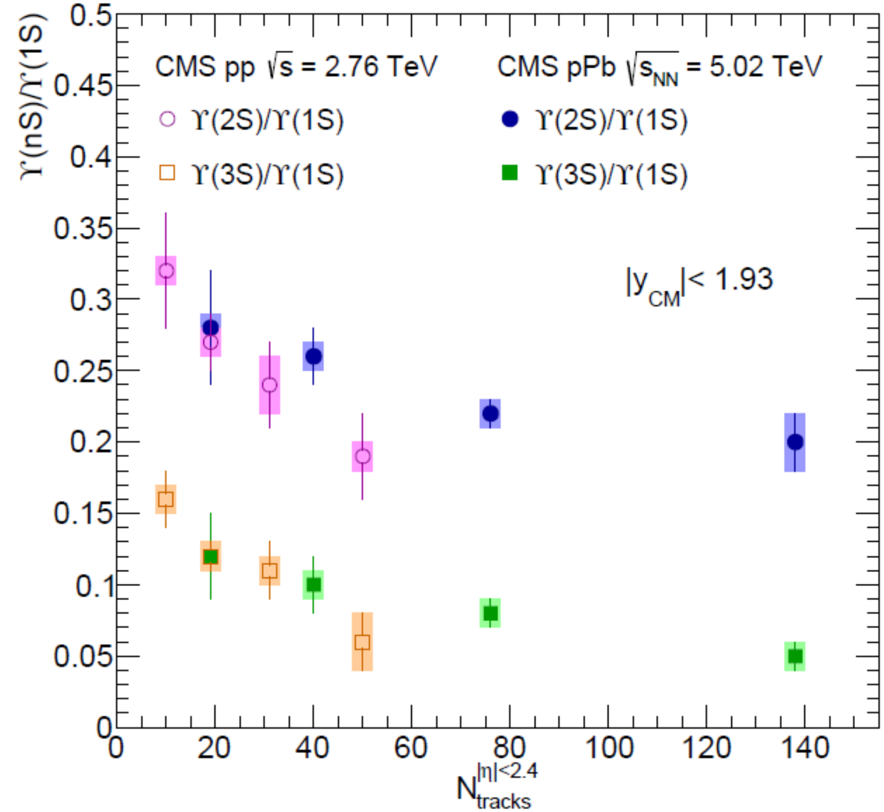
Andronic et al., EPJ C76 (2016) 107

ALICE, PLB 738 (2014) 97

- Total charm and beauty production cross section described by pQCD calculations within uncertainties
  - ⇨ Charm on the upper edge of the theoretical uncertainty band at all collision energies

Bottomonia vs. multiplicity



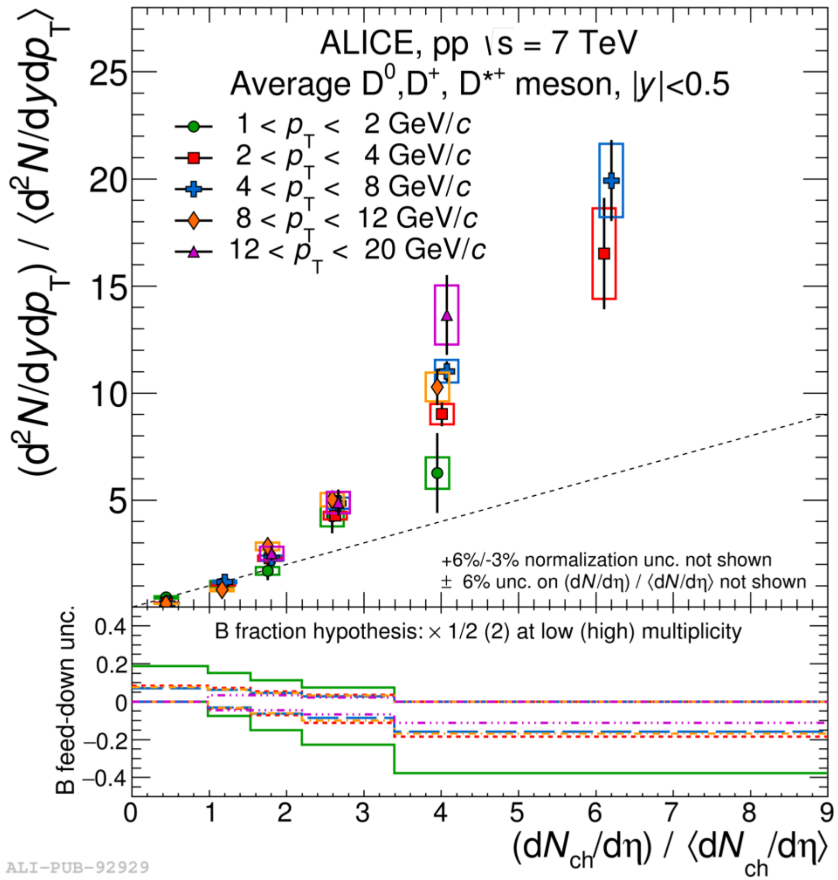


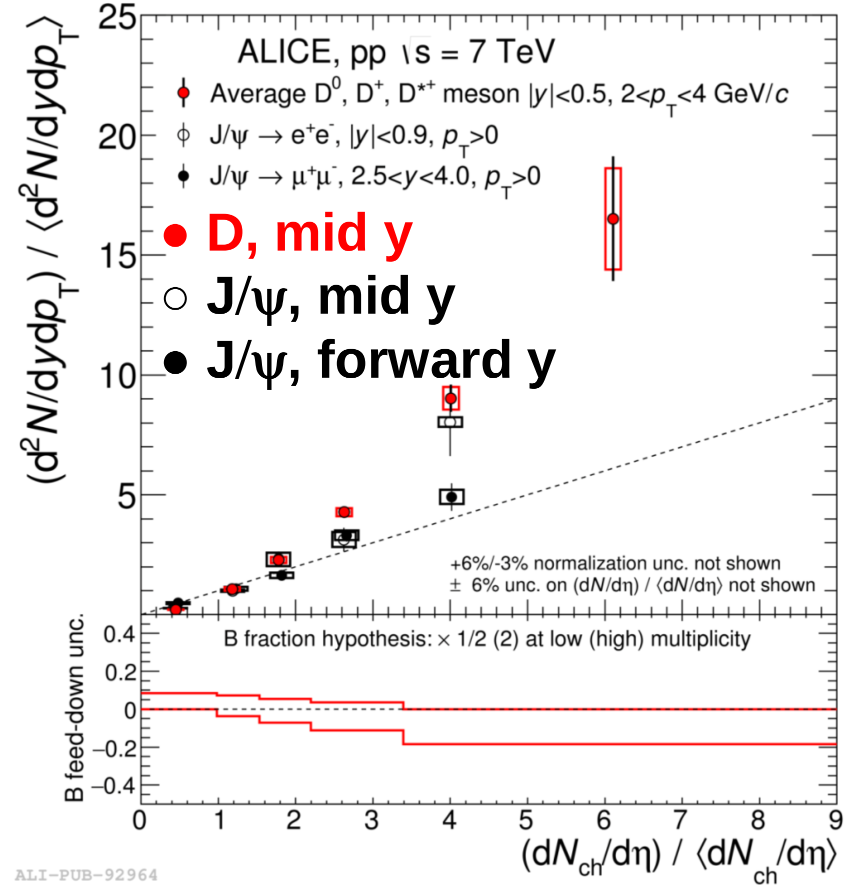
- Yield of Υ increases with multiplicity
  - ⇨ Similar in pp, p-Pb and Pb-Pb
  - ⇨ In Pb-Pb (and p-Pb) number of nucleon-nucleon collisions increases with multiplicity

- Υ(nS) production ratios depend on multiplicity
  - ⇨ Ground state Υ(1S) systematically produced with more particles?
  - ⇨ Excited states more easily dissociated by interactions with other particles?

📖 **CMS, JHEP 1404 (2014) 103**

D mesons and J/ψ vs. multiplicity

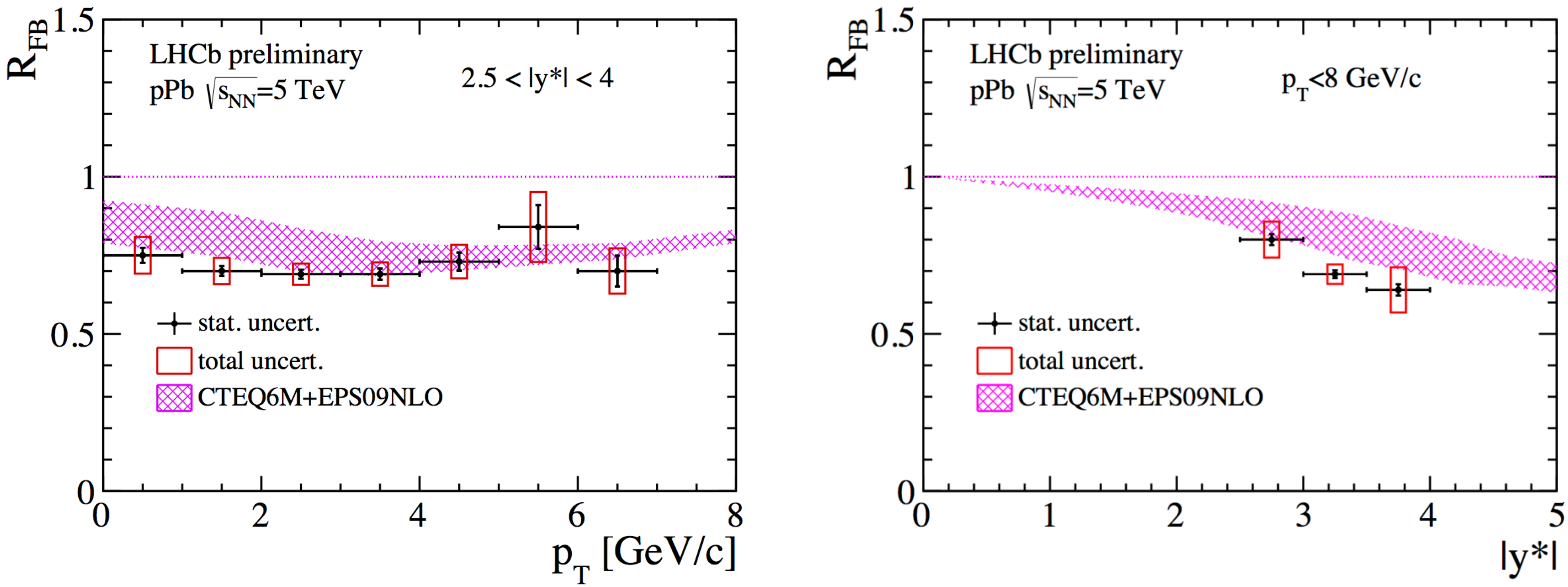




- Per-event yield of D mesons and J/ψ increases with increasing charged-particle multiplicity
  - ⇨ Similar trend in different D meson pT bins
  - ⇨ Described by models including MPIs

📖 **ALICE, PLB 712 (2012) 165** 📖 **ALICE, JHEP 1509 (2015) 148**

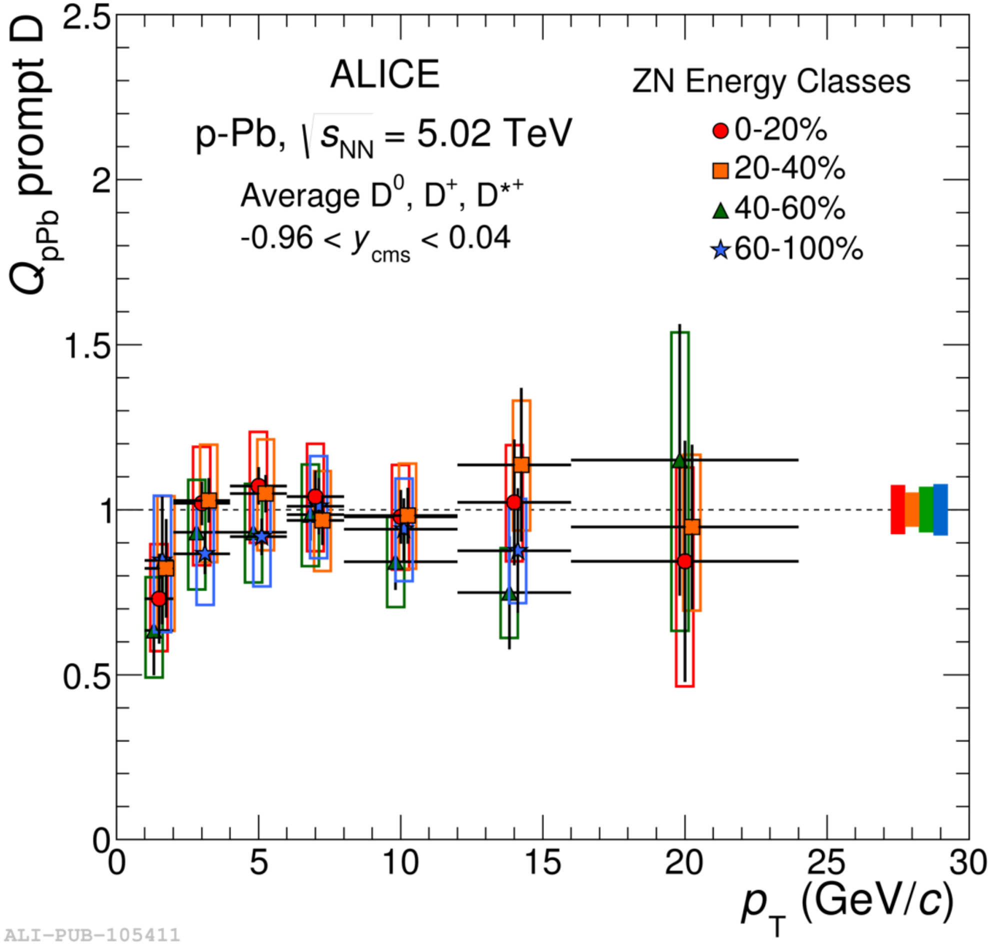
D mesons in p-Pb collisions forward-backward ratios



- Forward-backward asymmetry in D-meson production in p-Pb collisions described by pQCD calculations including nuclear PDFs

LHCb-CONF-2016-003

D-meson R_{pPb} vs. centrality

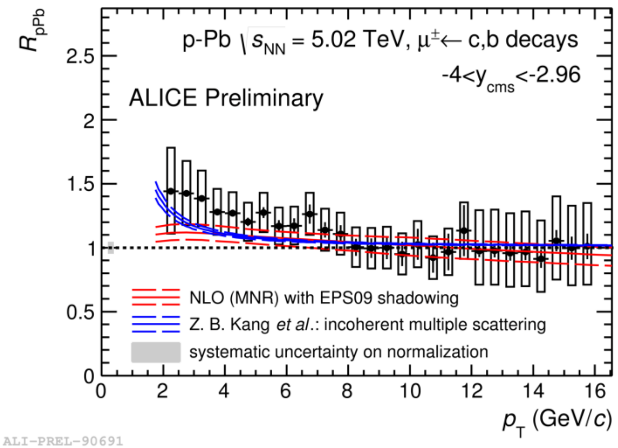


- D-meson nuclear modification factor in four bins of centrality
  - ⇨ Energy deposited in neutron ZDC (ZN) provides an (almost) unbiased estimation of collision centrality
- R_{pPb} compatible with unity also for the 20% most central p-Pb collisions

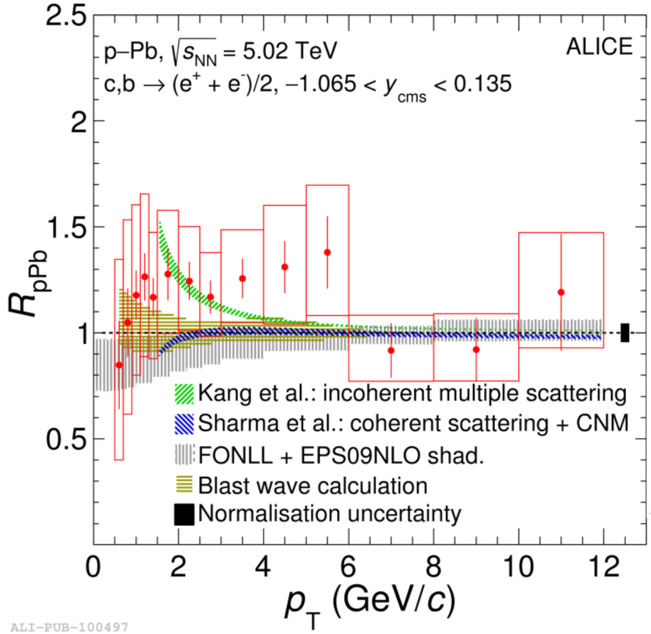
📖 **ALICE, arXiv:1602.07240**

HF decay lepton R_{pPb} at the LHC

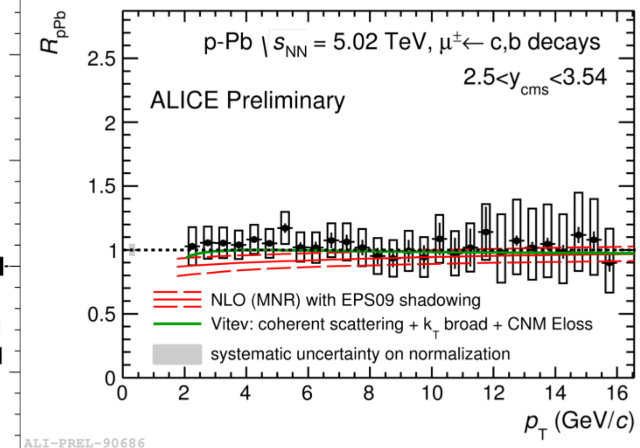
Backward rapidity (Pb-going side)



Mid-rapidity



Forward rapidity (p-going side)

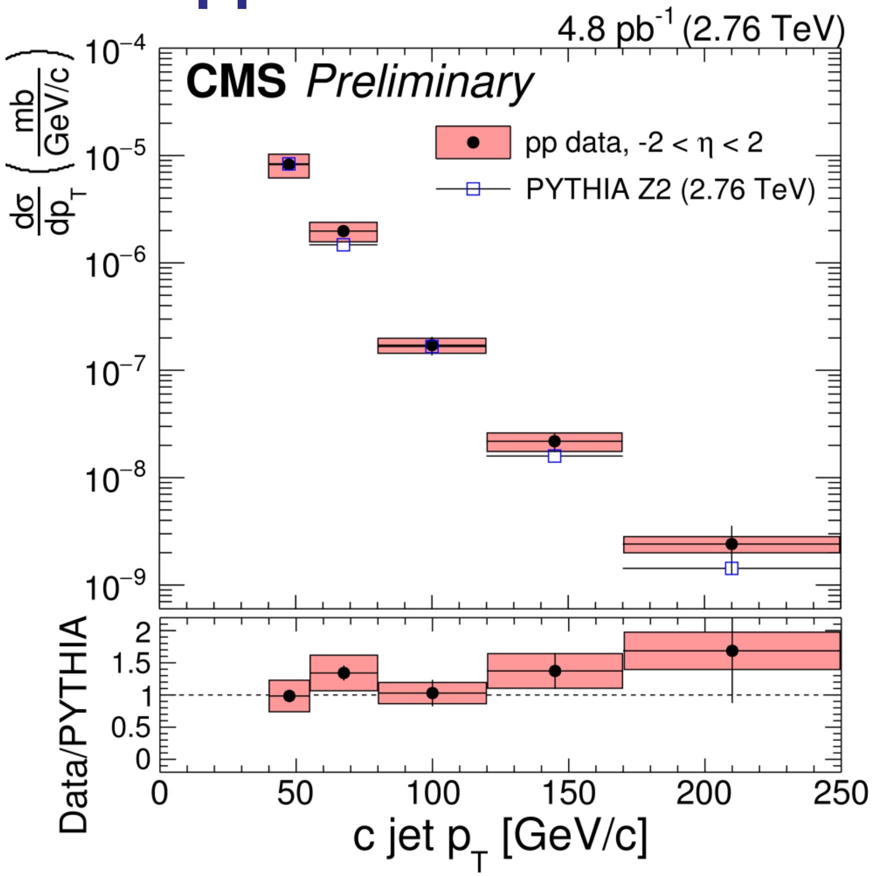


ALICE, PLB754 (2016) 81

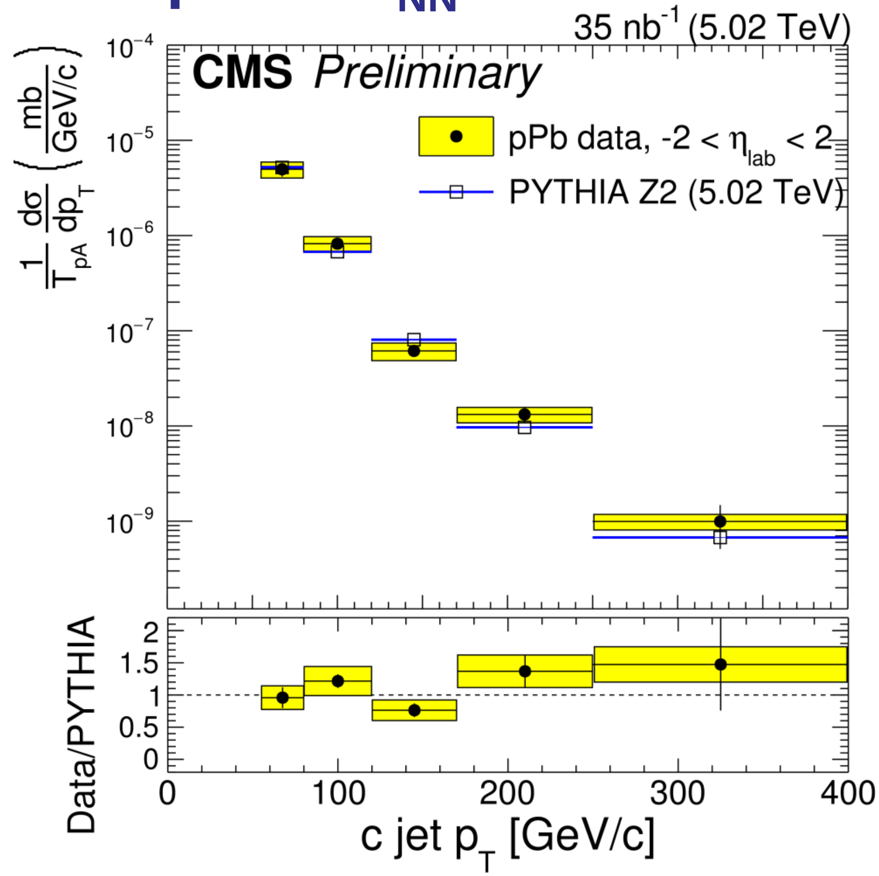
- R_{pPb} of HF decay leptons:
  - ⇨ consistent with unity at mid- and forward rapidity
  - ⇨ slightly larger than unity at backward rapidity for $2< p_T< 4$ GeV/c
- Described within uncertainties by models including cold nuclear matter effects

Charm jets in pp and p-Pb

pp $\sqrt{s}$=2.76 TeV



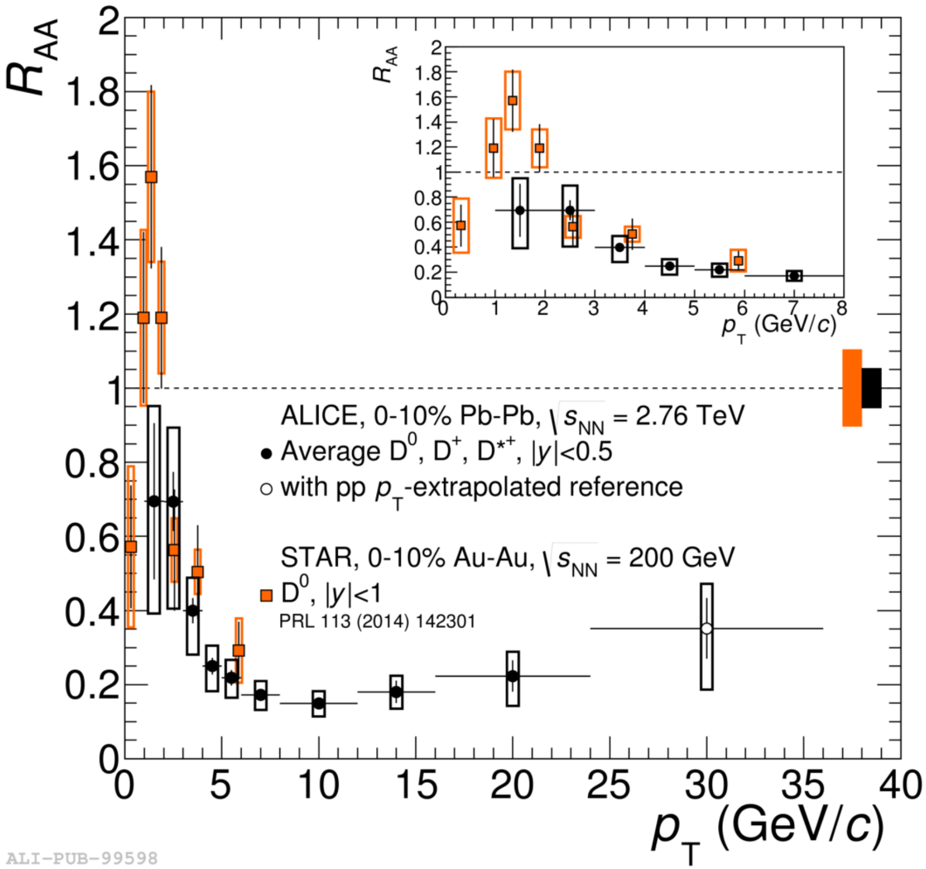
p-Pb $\sqrt{s_{NN}}$=5.02 TeV



- Charm-jet p_T differential cross section consistent with PYTHIA in pp and p-Pb collisions
  - ⇨ No significant CNM effects on charm production at high p_T

CMS-PAS-HIN-15-012

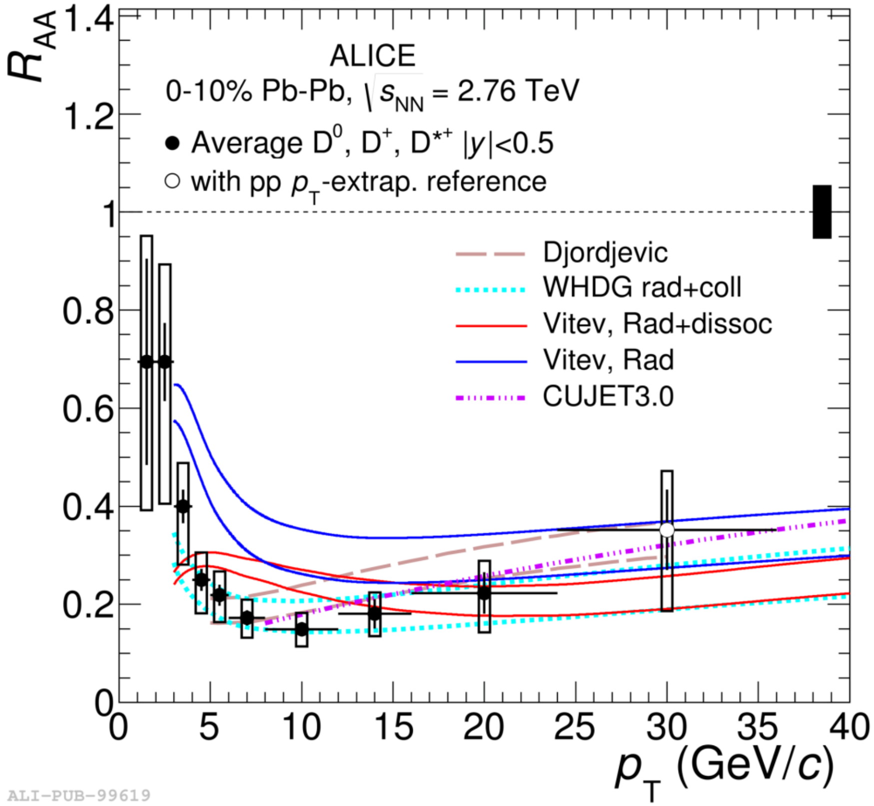
D-meson R_{AA}: LHC vs. RHIC

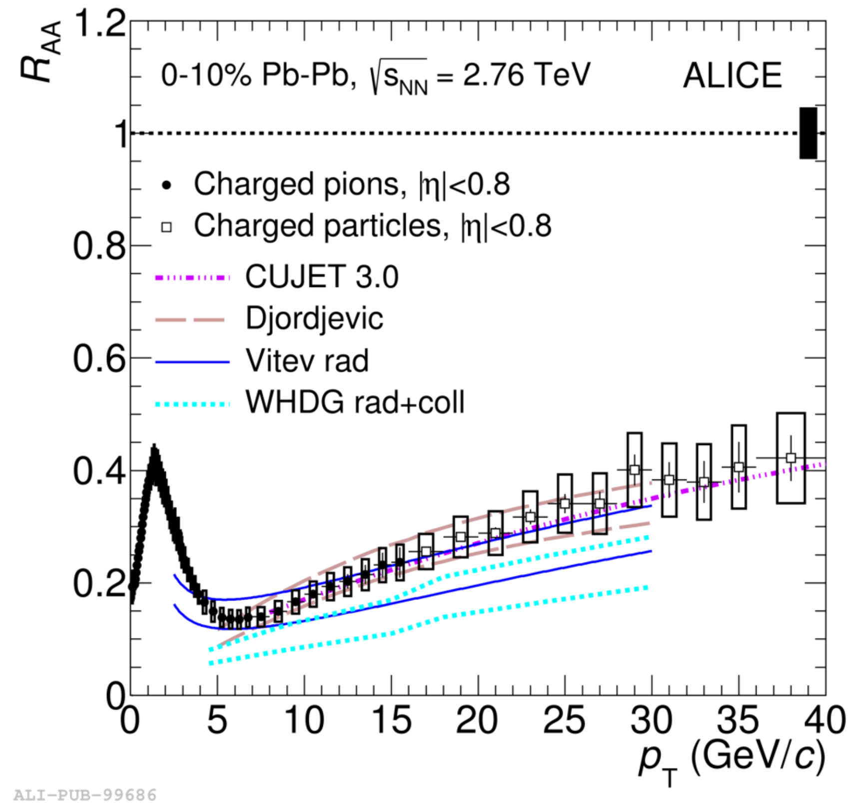


📖 **ALICE, JHEP1603 (2016) 081**
📖 **STAR, PRL 113 (2014) 142301**

- D-meson R_{AA} factor at $\sqrt{s_{NN}}$=0.2 and 2.76 TeV
  - ⇨ Similar R_{AA} for p_T >3 GeV/c
  - ⇨ Maybe different trend at lower p_T
- Many effects are different at different collision energies:
  - ⇨ Different p_T shape of produced charm quarks / pp reference
  - ⇨ Different shadowing
  - ⇨ Different radial flow
  - ⇨ Different medium density and energy loss
- Some theoretical models can describe both measurements reasonably well

R_{AA}: D mesons vs. pions

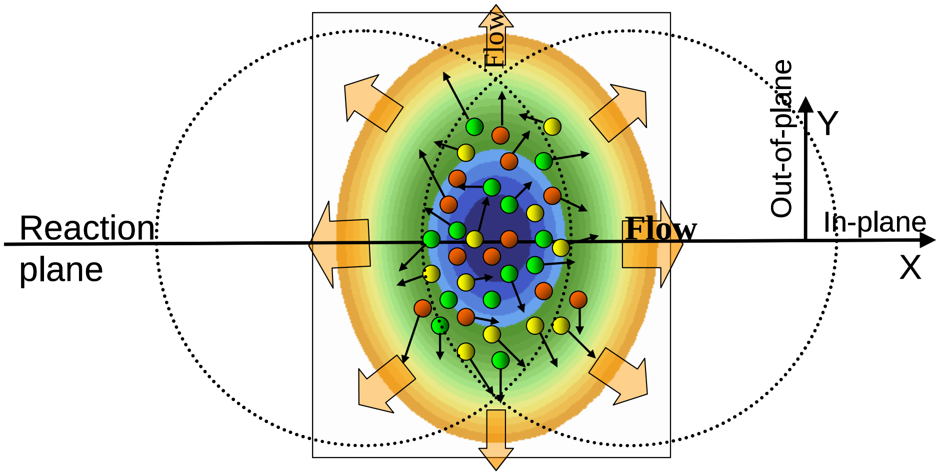




- D-meson and pion R_{AA} compatible within uncertainties
- Described by models including
  - ⇨ energy loss hierarchy ($\Delta E_g > \Delta E_{u,d,s} > \Delta E_c$)
  - ⇨ different p_T shapes of produced partons
  - ⇨ different fragmentation functions of gluons, light and charm quarks

ALICE, JHEP1603 (2016) 081

Azimuthal anisotropy



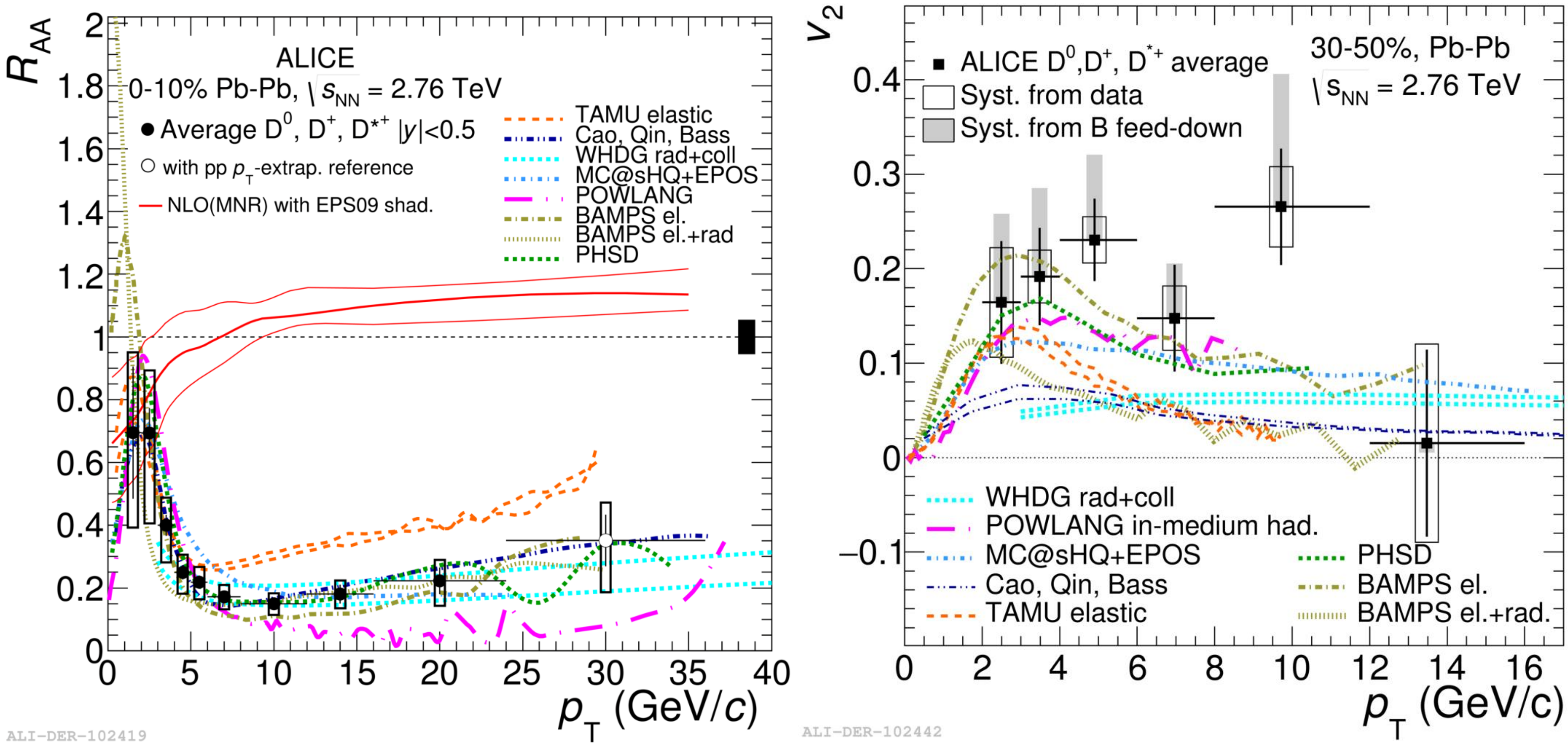
- Initial geometrical anisotropy in non-central heavy-ion collisions
  - ⇨ The impact parameter selects a preferred direction in the transverse plane

- Re-scatterings among produced particles convert the initial geometrical anisotropy into an observable momentum anisotropy
  - ⇨ Collective motion (flow) of the "bulk" (low p_T)
- In addition, path-length dependent energy loss in an almond-shaped medium induces an asymmetry in momentum space
  - ⇨ Longer path length -> larger energy loss for particles exiting out-of-plane
- Observable: Fourier coefficients of the particle azimuthal distribution, in particular 2nd harmonic v_2, called **elliptic flow**

$$\frac{dN}{d\varphi} = \frac{N_0}{2\pi}\left\{1 + 2v_2\cos\left[2\left(\varphi - \Psi_{RP}\right)\right] + \ldots\right\}$$

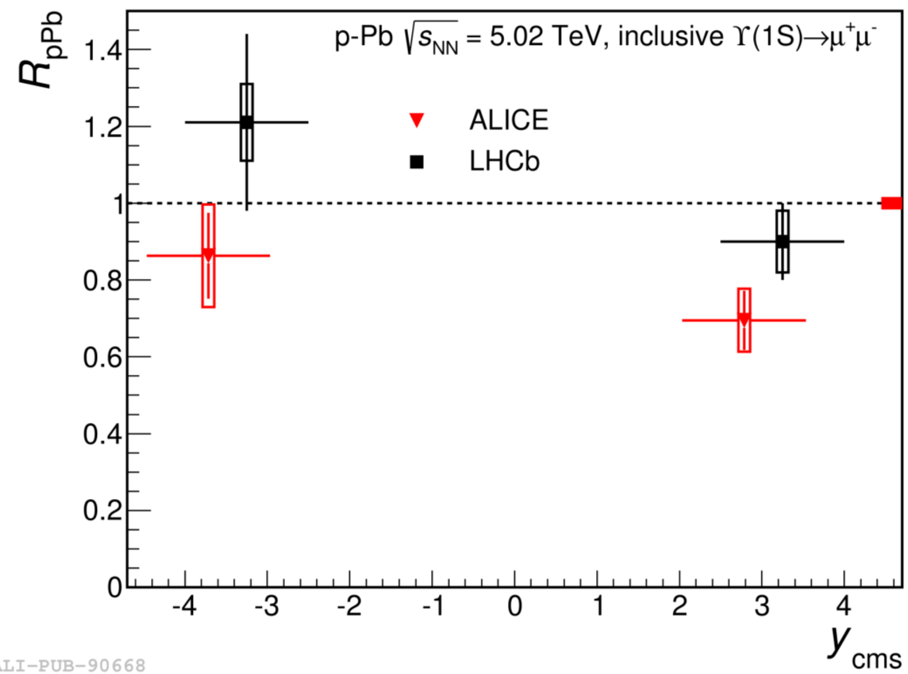
$$v_2 = \left\langle \cos\left[2\left(\varphi - \Psi_{RP}\right)\right]\right\rangle$$

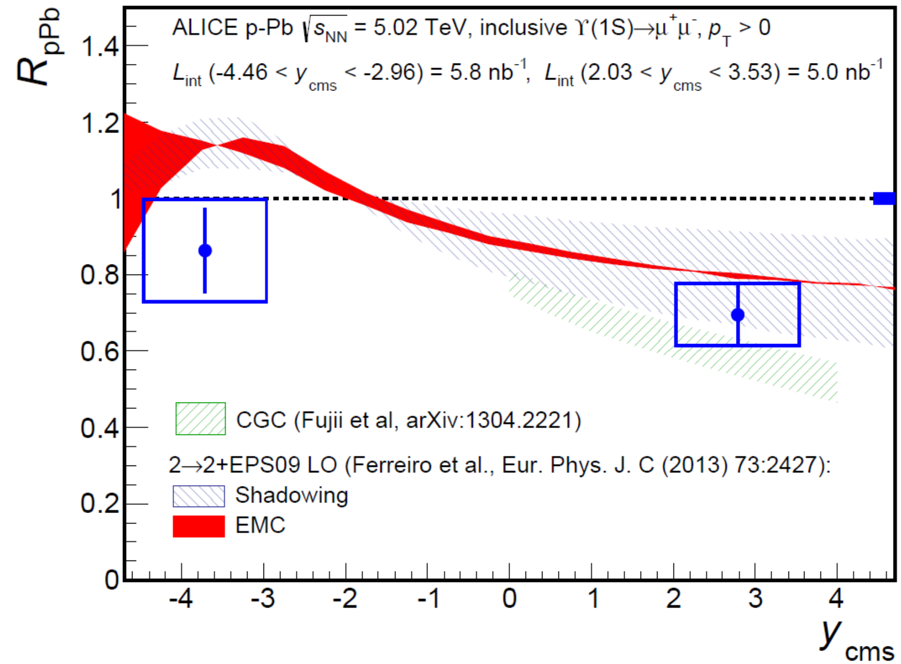
D meson R_{AA} and v_2 vs. models



- The simultaneous description of D meson R_{AA} and v_2 is a challenge for theoretical models
  - ⇨ Data have the potential to constrain the models
    - ✓ ***Description of the energy loss mechanisms, medium transport coefficients***

$\Upsilon(1S)$ R_{pPb}

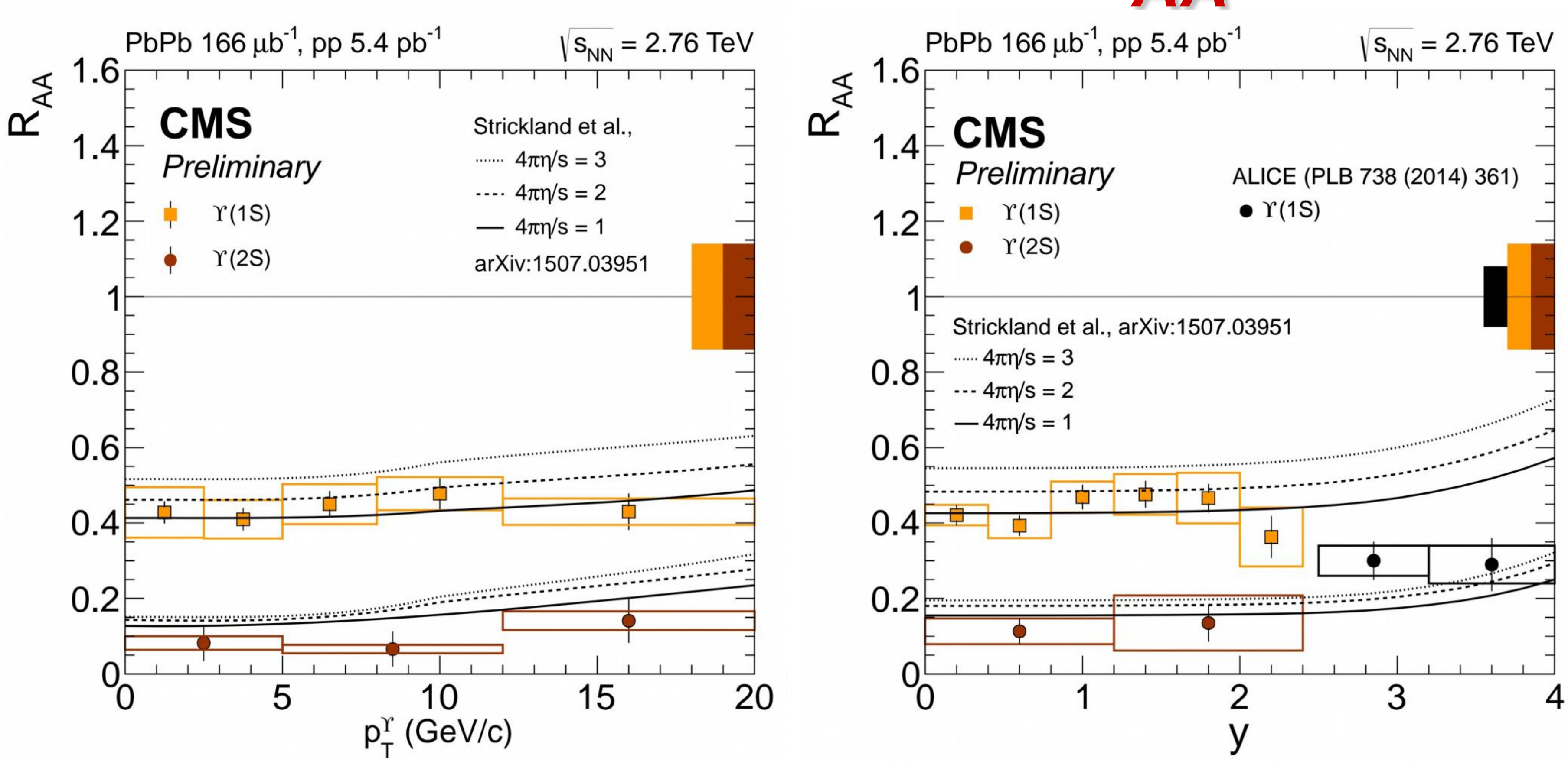




- Suppression of $\Upsilon(1S)$ production at forward rapidity
  - ⇨ Consistent with expectations from nuclear shadowing
- Backward rapidity: R_{pPb} compatible with unity
  - ⇨ Not conclusive on the size of anti-shadowing
- More data needed for a precise investigation of CNM effects

📖 **LHCb, JHEP 1407 (2014) 094** 📖 **ALICE, PLB 740 (2015) 105**

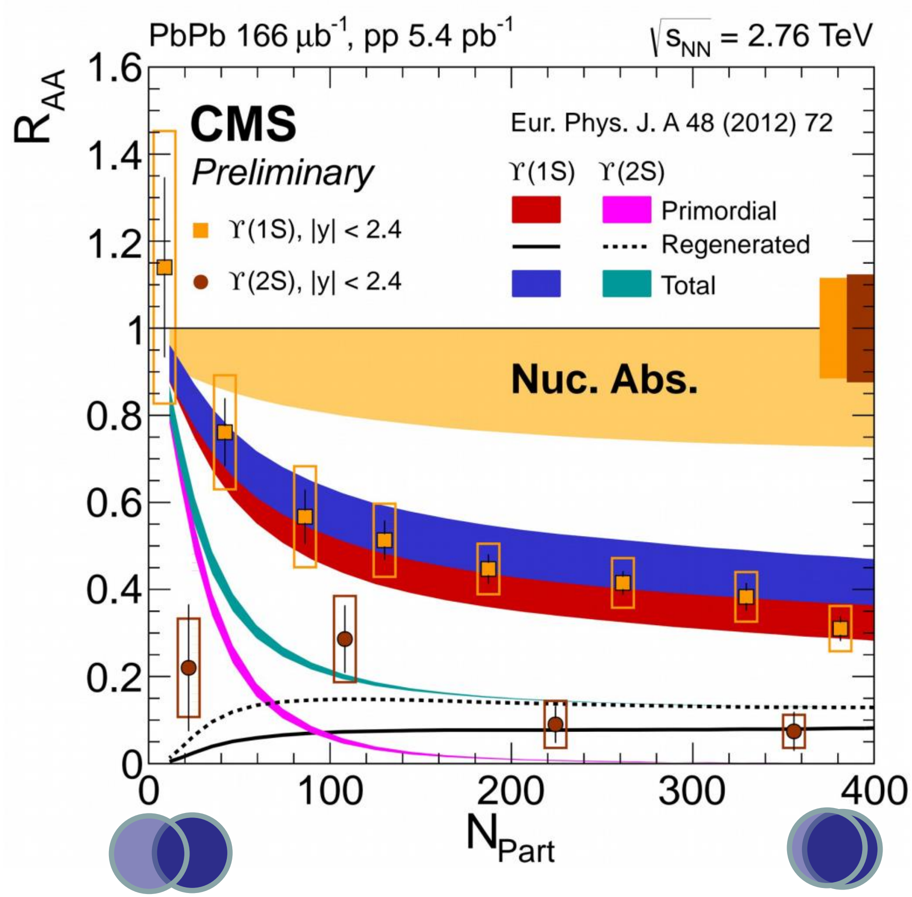
Bottomonium R_{AA}

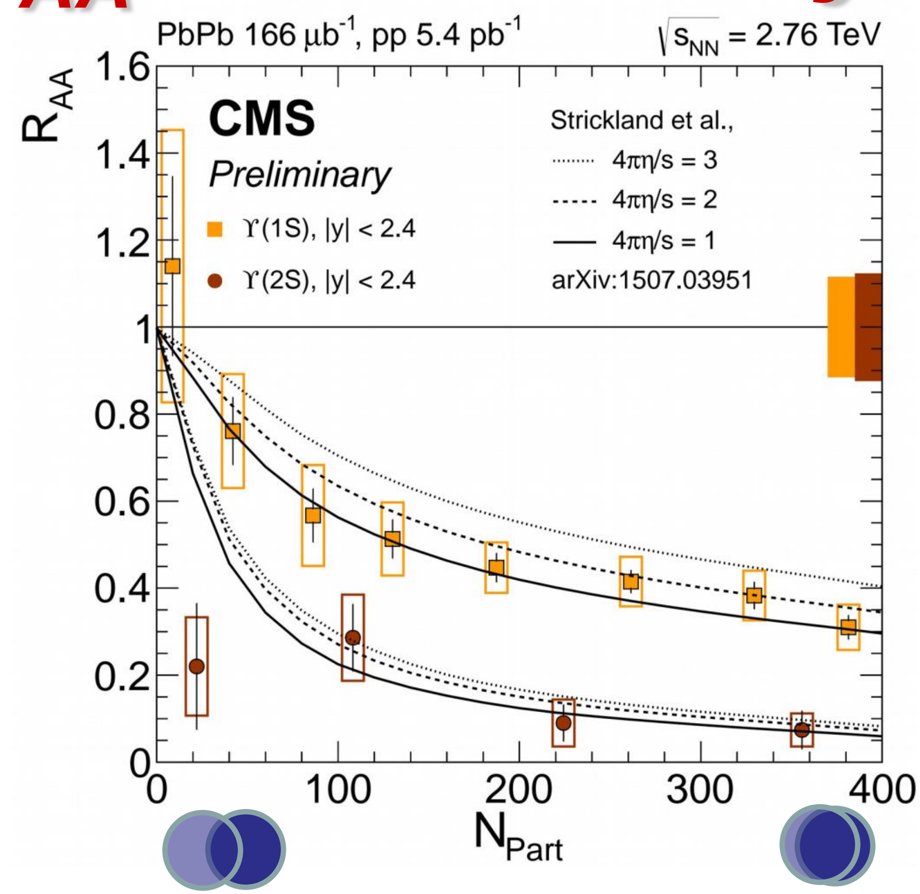


- No significant p_T and rapidity dependence of Υ yield suppression observed in the measured intervals
  - ⇨ Described by models including thermal suppression in the QGP (even though rapidity dependence needs some more tuning)

📖 CMS-PAS-HIN-15-001 📖 ALICE, PLB 738 (2014) 361

Bottomonium R_{AA} vs. centrality





📖 **CMS-PAS-HIN-15-001**

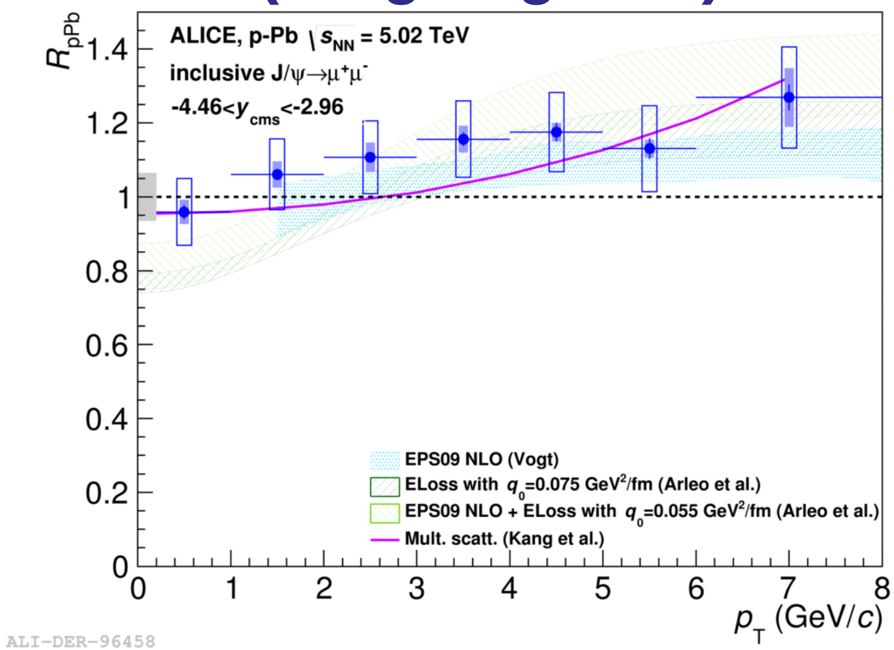
- Data vs. transport model with dissociation in QGP, regeneration and shadowing
- Data vs. model including thermal suppression of bottomonium in QGP

📖 **Emerick at al., EPJ A48 (2012) 72**

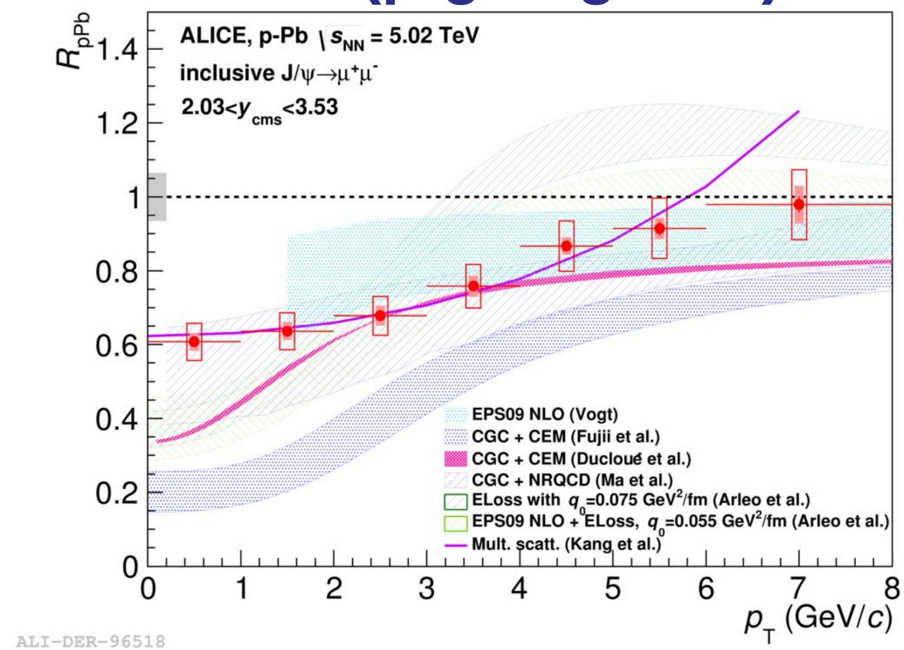
📖 **Krouppa at al., PRC92 (2015) 061901**

Back to p-Pb collisions: J/ψ

Backward rapidity (Pb-going side)



Forward rapidity (p-going side)

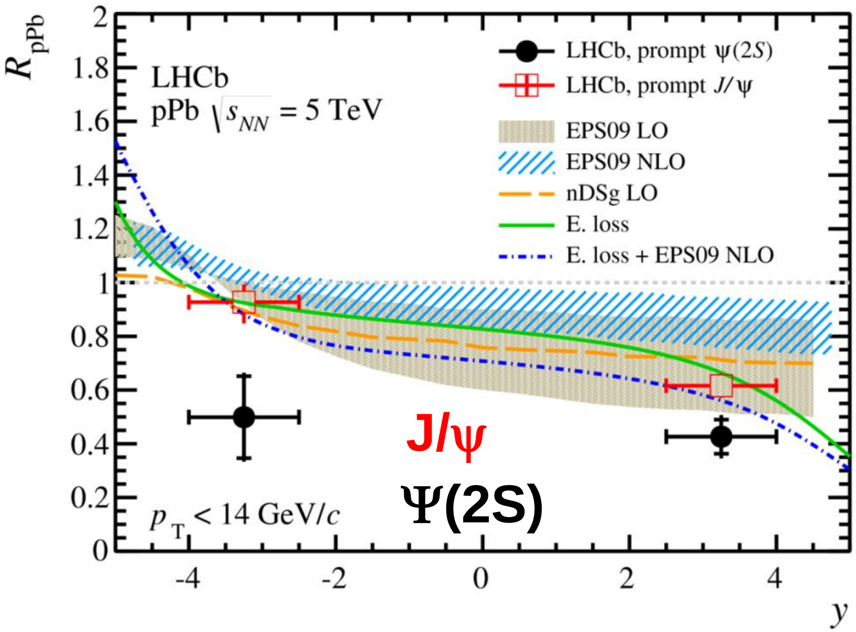


📖 **ALICE, JHEP 1506 (2015) 055**

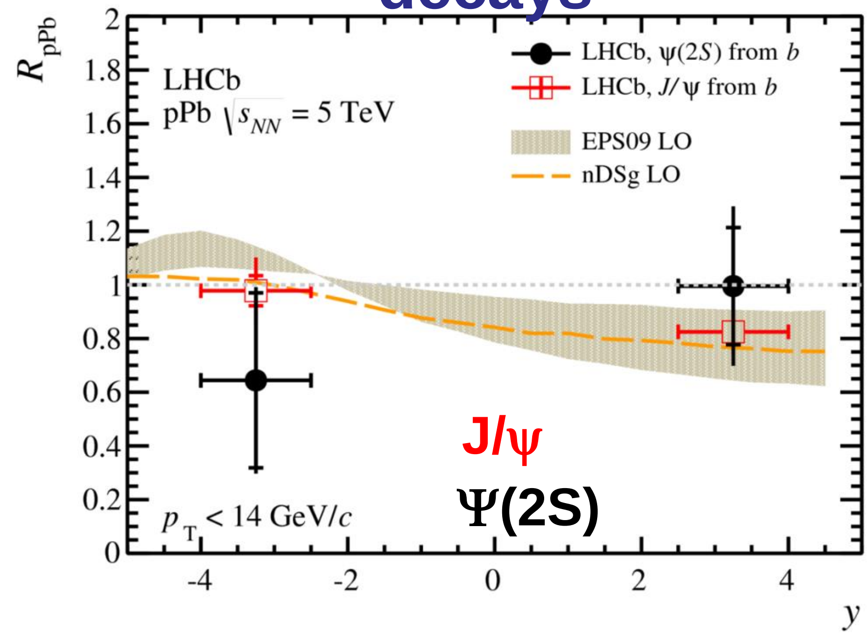
- Backward rapidity (Pb-going side):
  - ⇨ R_{pPb} close to unity, small p_T dependence
- Forward rapidity (p-going side)
  - ⇨ More significant p_T dependence, R_{pPb} lower than unity at low p_T
- Described reasonably well by models including CNM effects

p-Pb collisions: J/ψ and Ψ(2S)

Prompt



From beauty-hadron decays

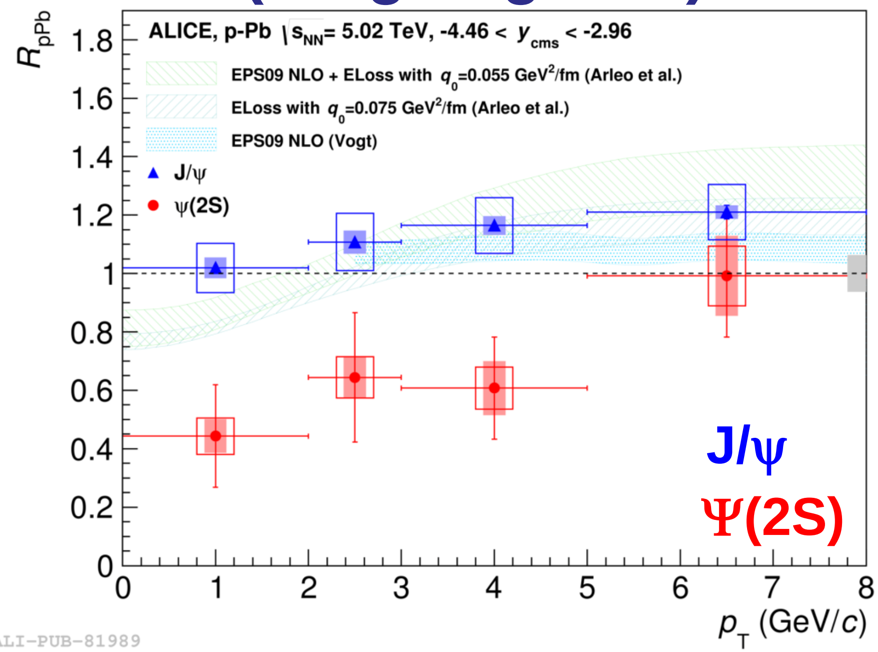


- Prompt J/ψ R_{pPb} described reasonably well by CNM effects
- Prompt Ψ(2S) production suppressed relative to J/ψ at both backward and forward rapidity
  - ⇨ Shadowing and energy loss, expected to be almost identical for J/ψ and Ψ(2S), cannot describe the different suppression

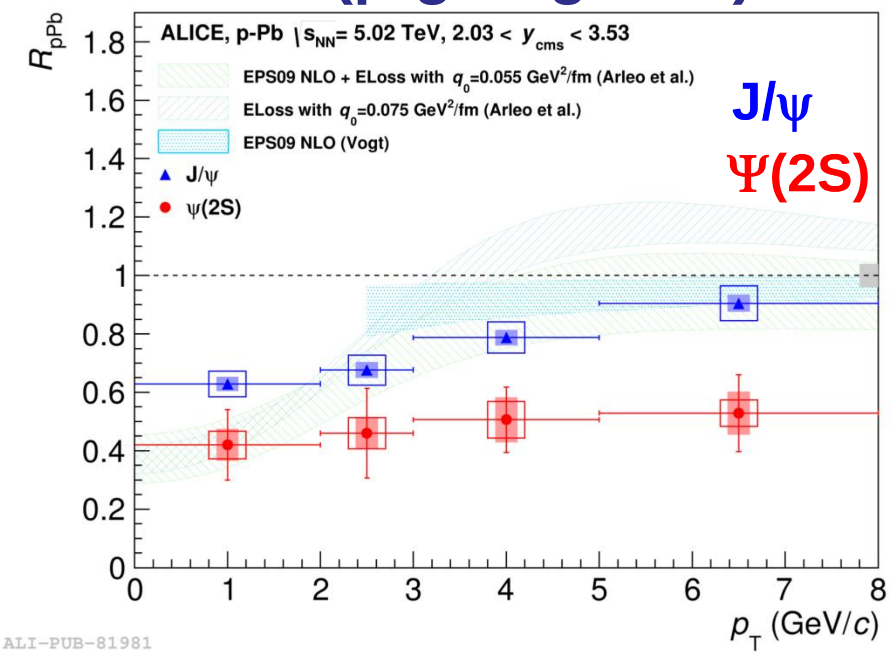
📖 **LHCb, JHEP 1603 (2016) 133**

p-Pb collisions: J/ψ, Ψ(2S) vs. pT

Backward rapidity (Pb-going side)



Forward rapidity (p-going side)

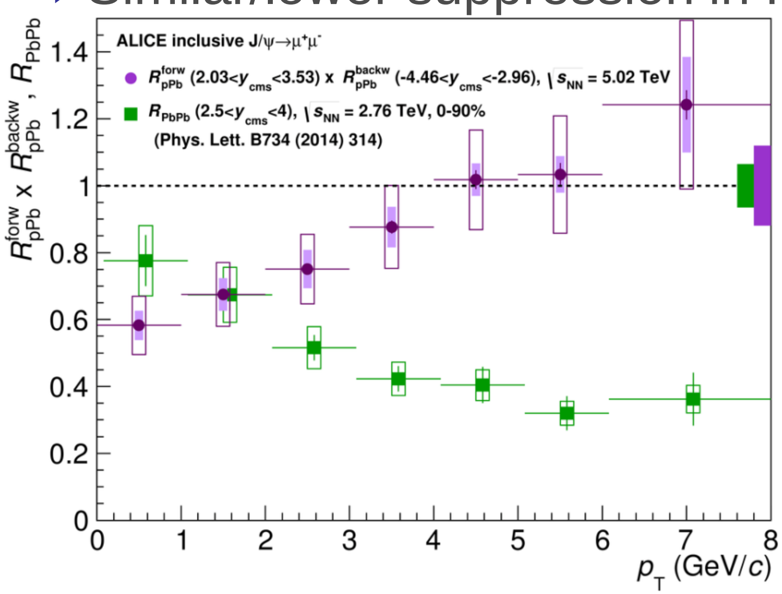


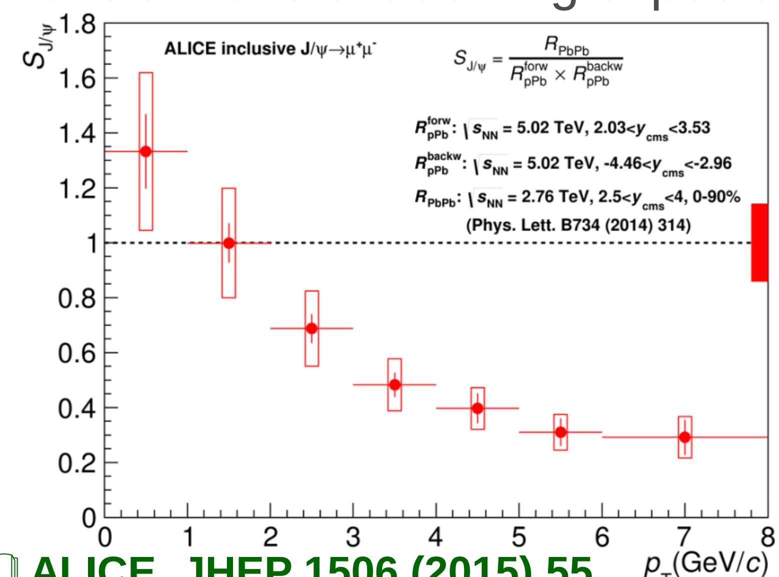
- J/ψ R_{pPb} described reasonably well by CNM effects
- Ψ(2S) production suppressed relative to J/ψ at both backward and forward rapidity
  - ⇨ Shadowing and energy loss, expected to be almost identical for J/ψ and Ψ(2S), cannot describe the different suppression

📖 ALICE, JHEP 1412 (2014) 073   📖 ALICE, JHEP 1506 (2015) 055

J/ψ from p-Pb to Pb-Pb

- Estimate CNM effects on J/ψ production in Pb-Pb collisions from the measured R_{pPb} at forward and backward rapidity
  - ⇨ Hypotheses: 2→1 kinematics + shadowing factorization
  - ⇨ Compare R_{AA} with $R_{pPb}(y>0) \times R_{pPb}(y<0)$
- At high p_T (> 4 GeV/c): small CNM effects
  - ⇨ Not enough to explain the high-p_T J/ψ suppression in Pb-Pb
- At low p_T (<2 GeV/c): large CNM effects
  - ⇨ Similar/lower suppression in Pb-Pb relative to shadowing expectation





📖 **ALICE, JHEP 1506 (2015) 55**