Open heavy-flavour and quarkonium measurements with ALICE at the LHC

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Outline

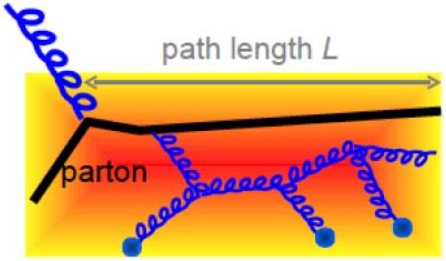
- Physics motivations
- Open-heavy flavours and quarkonia with ALICE
- Selection of results in p-Pb and Pb-Pb collisions
  - Nuclear modification factor
  - Elliptic flow
  - Model comparisons
- Conclusion

Heavy flavours as a medium probe

- Large mass (m_c ~ 1.5 GeV, m_b ~ 5 GeV) → heavy quarks are produced in initial hard scatterings with a short formation time $\tau_f \sim 1/2m_{c/b} \sim 0.1$ fm/c << τ_{QGP} ~ 5-10 fm/c
- Experience the full collision history, sensitive to the medium properties

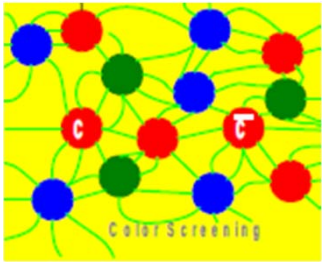
Open heavy flavours in A-A collisions

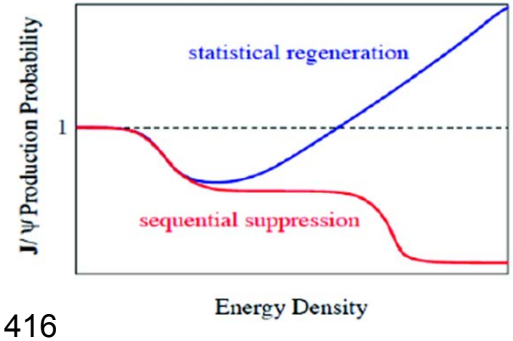
- Probe parton energy loss (high p_T)
- Participation in the collective expansion (low p_T)



Quarkonia ($c\bar{c}$, $b\bar{b}$) in A-A collisions

- Suppression by colour screening
- Regeneration via recombination of heavy quarks





Phys.Lett B 178 (1986) 416
Phys. Lett. B 490 (2000) 196; Phys. Rev. C (2001) 054905

Observables

- Nuclear modification factor: $R_{AA}(p_T) = 1/\langle N_{coll}\rangle \times \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$
- Elliptic flow, v_2: $\frac{2\pi}{N}\frac{dN}{d\varphi} = 1 + \sum_{n=1}^{\infty} 2v_n cos[n(\varphi - \Psi_n)]$ with $v_2 = \langle cos[2(\varphi - \Psi_n)]\rangle$

Heavy flavours in pp and p-A collisions

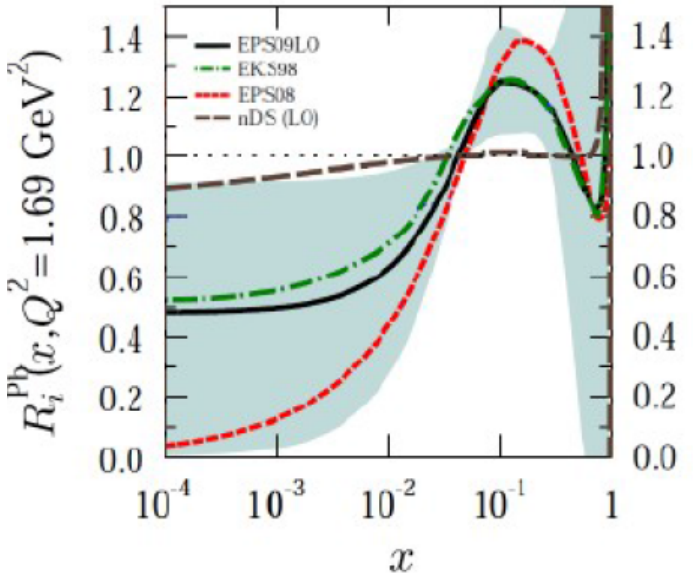
The heavy-ion physics program with heavy flavours requires also:

p-A collisions

- ❑ Control experiment for A-A collisions
- ❑ Cold nuclear matter effects
  - Nuclear modification of Parton Distribution Functions (PDF): shadowing or gluon saturation
  - Energy loss
  - k_T broadening, multiple interactions
  - Nuclear absorption of quarkonia

pp collisions

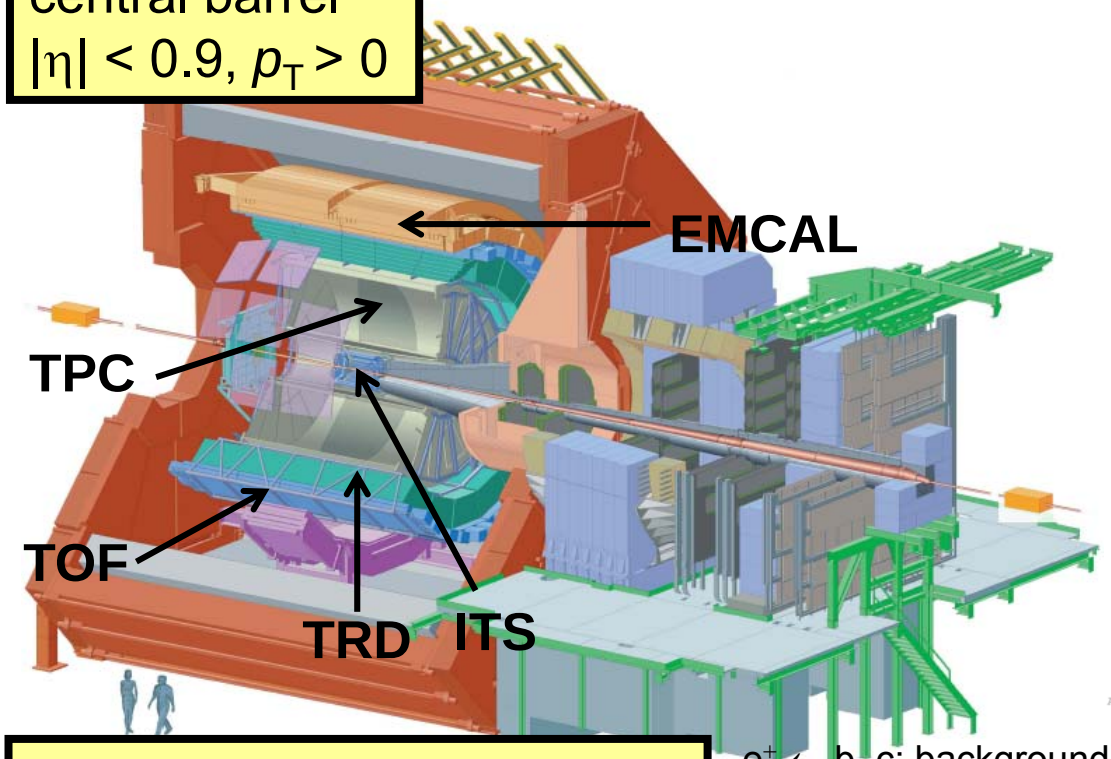
- ❑ Reference for A-A collisions
- ❑ Test of perturbative QCD calculations
- ❑ Insights into production mechanisms

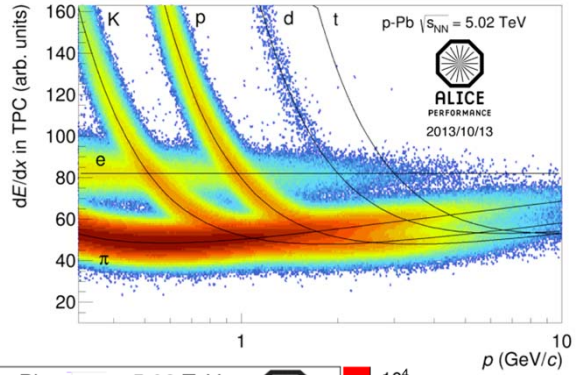


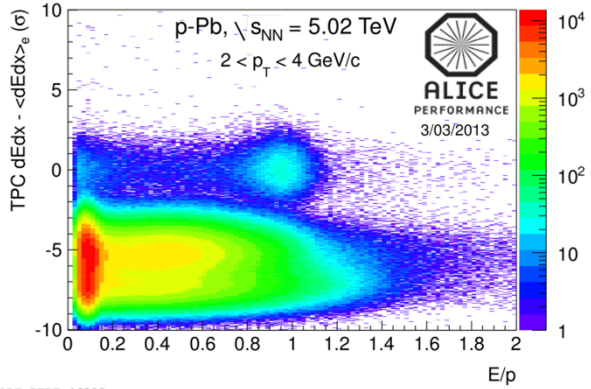
K. J. Eskola et al., JHEP 0904 (2009) 65
D.E. Kharzeev et al., arXiv:1205.1554
F. Dominguez et al., arXiv:1109.1250
R. Vogt, Phys. Rev C81 (2010) 044903
F. Arleo et al., arXiv:1204.4609
C. Lourenco et al., JHEP 0902 (2009) 014

ALICE central barrel

central barrel
$|\eta| < 0.9$, $p_T > 0$

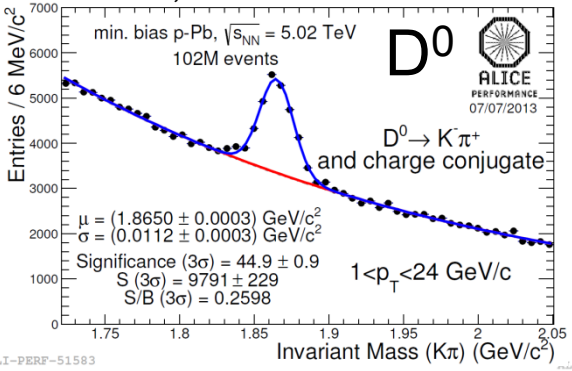


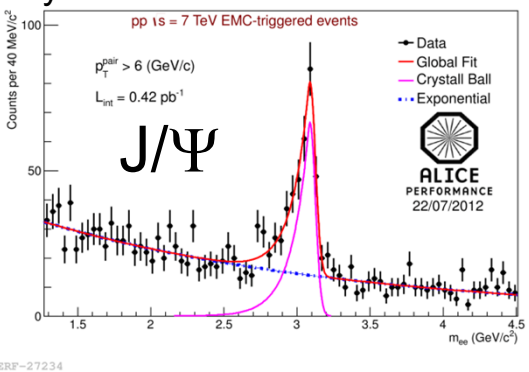




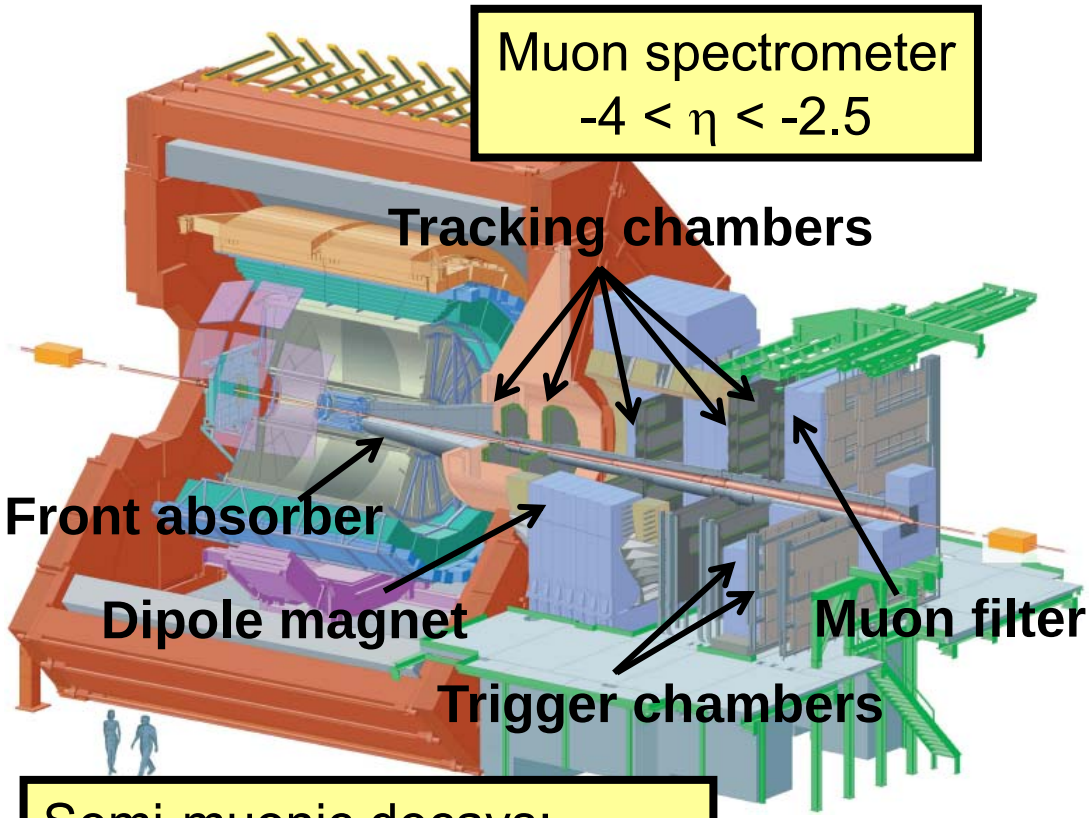
Semi-electronic decays:
D, B, Λ_c, … $\rightarrow$ e + anything
Hadronic decays:
$D^0 \rightarrow K^-\pi^+$ $D^+_s \rightarrow K^+K^-\pi^+$
$D^+ \rightarrow K^-\pi^+\pi^+$ $D^{*+} \rightarrow D^0\pi^+$
Charmonium:
$J/\Psi \rightarrow e^+e^-$

$e^{\pm} \leftarrow$ b, c: background $e^{\pm}$ via data-tuned cocktail, e^+e^- invariant mass
$e^{\pm} \leftarrow$ b via electron impact parameter
D mesons, J/Ψ via invariant mass analysis





ALICE muon spectrometer



Semi-muonic decays:

D, B, Λ_c, … $\rightarrow \mu$ + anything

Quarkonia down to $p_T = 0$

- Charmonia:
  J/Ψ, $\Psi(2S) \rightarrow \mu^+\mu^-$
- Bottomonia:
  $\Upsilon(1S)$, $\Upsilon(2S) \rightarrow \mu^+\mu^-$

Track selection

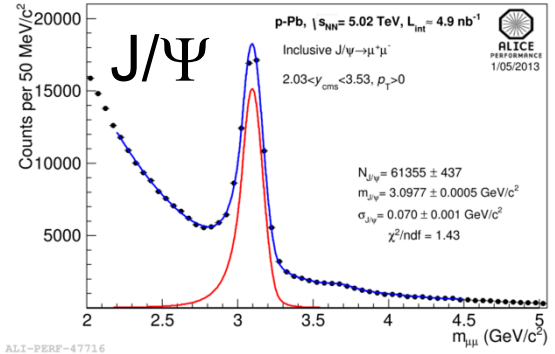
- Acceptance & geometrical cuts
- Tracks matched with trigger
- Pointing angle to the vertex

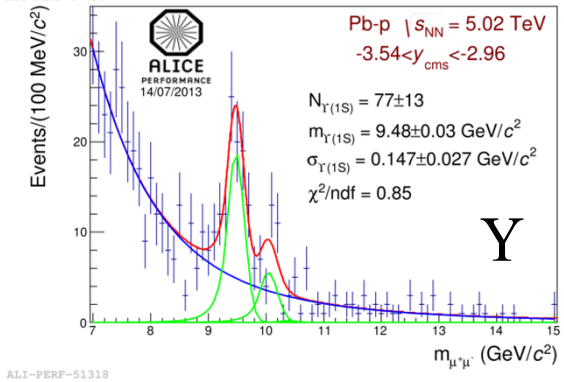
$\mu^{\pm} \leftarrow$ b, c

- Subtract remaining background
  $\mu \leftarrow$ primary π, K decays with data-tuned MC cocktail

Quarkonia

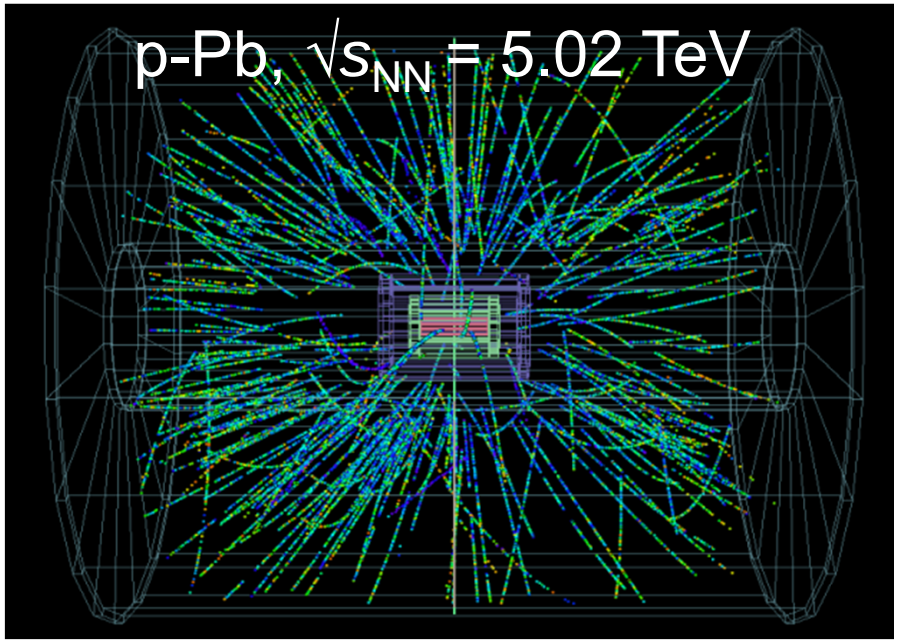
- Invariant mass analysis

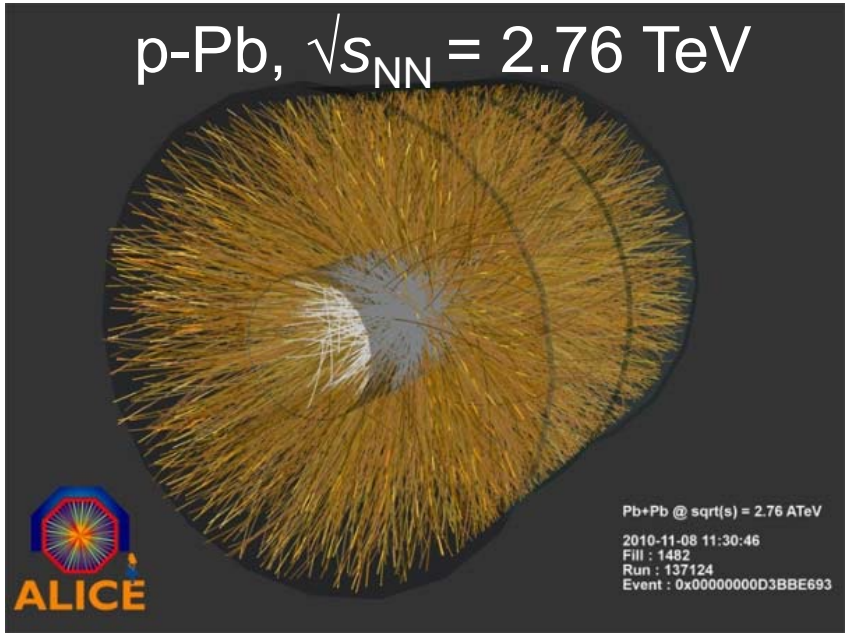




Open heavy-flavour results

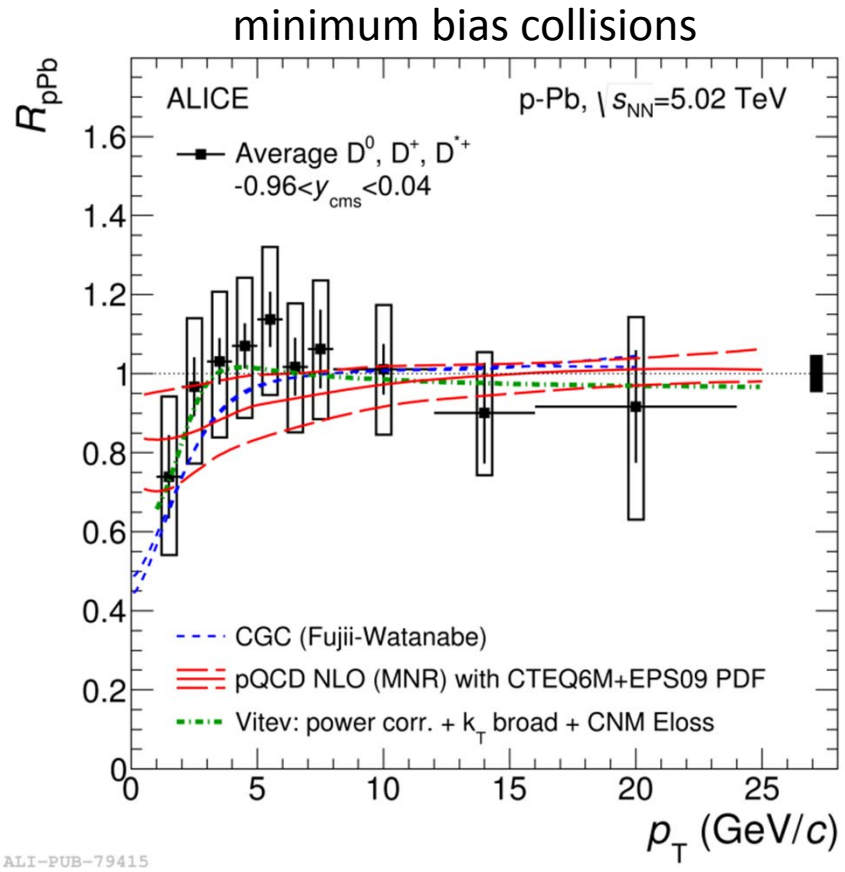
- p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV
  - ✓ Rapidity shift: $|\Delta y|$ = 0.465 in the p-beam direction (positive *y*)
  - ✓ Two configurations:
    - ➢ p-Pb , muon spectrometer in p-going direction
    - ➢ Pb-p, muon spectrometer in Pb-going direction
- Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV





D-meson results: see also M. Figueredo talk, July 22nd, 12:25

D mesons: R_{pPb} *vs* p_T

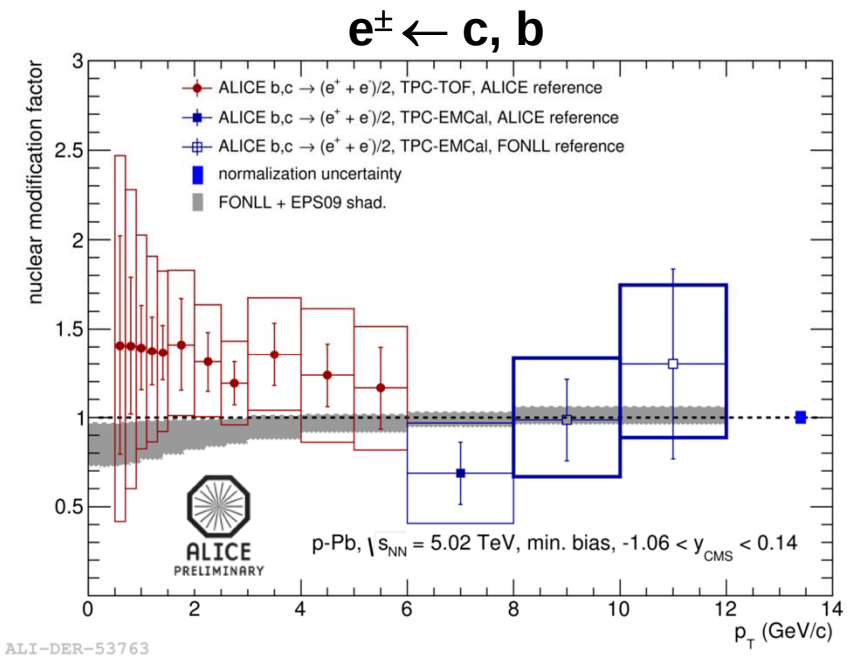


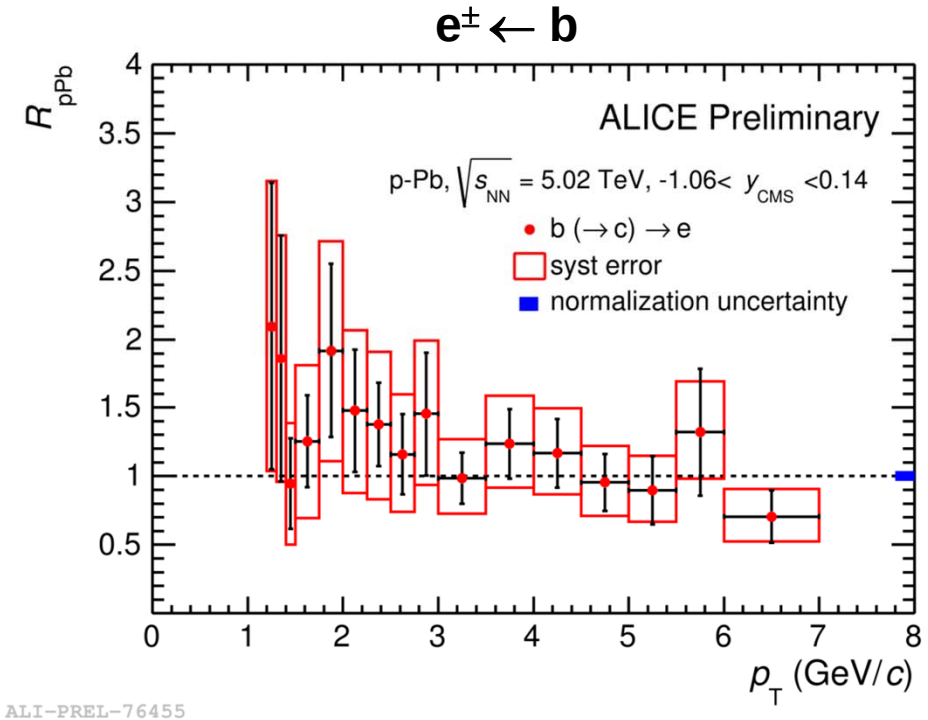
$$R_{pPb}(p_T) = 1/A \times \frac{d\sigma_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$

ALICE: arXiv:1405.3452
CGC: H.Fujii and K. Watanable, arXiv: 1308.1258
pQCD NLO (MNR): Nucl. Phys. B 373 (1992) 295, EPS09: K. J. Eskola et al., JHEP 04 (2009) 065
Vitev: Phys. Rev. C 80461 (2009) 054901

- Nuclear modification factor (R_{pPb}) consistent with unity within uncertainties in the region p_T > 2 GeV/*c*
- D-meson R_{pPb} in agreement with:
  - Perturbative QCD calculations including EPS09 parameterization of shadowing
  - Color Glass Condensate (CDG) predictions
  - Model including energy loss, shadowing and k_T broadening

Heavy-flavour decay electrons: R_{pPb} *vs* p_T

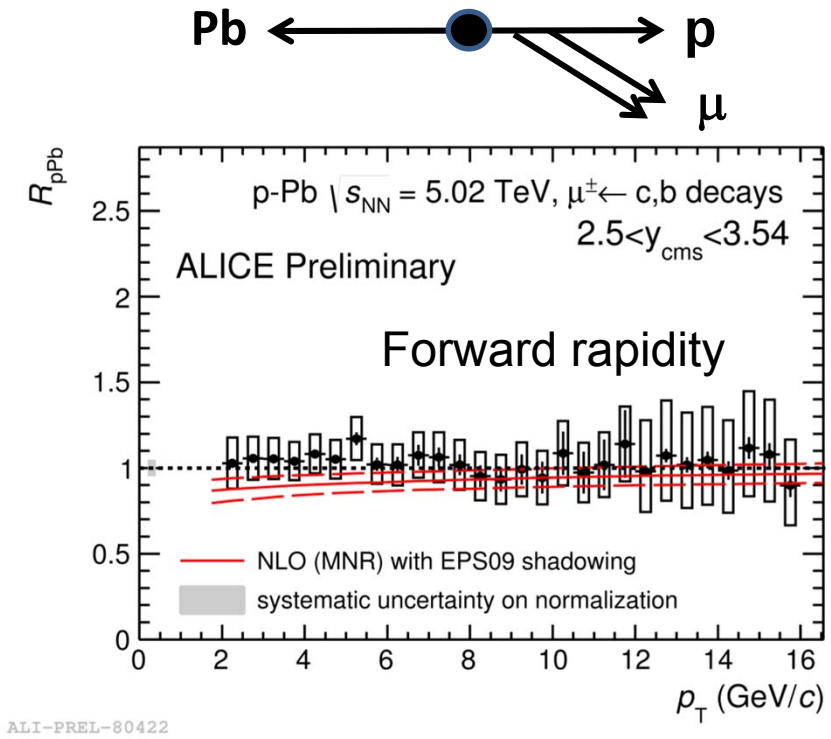


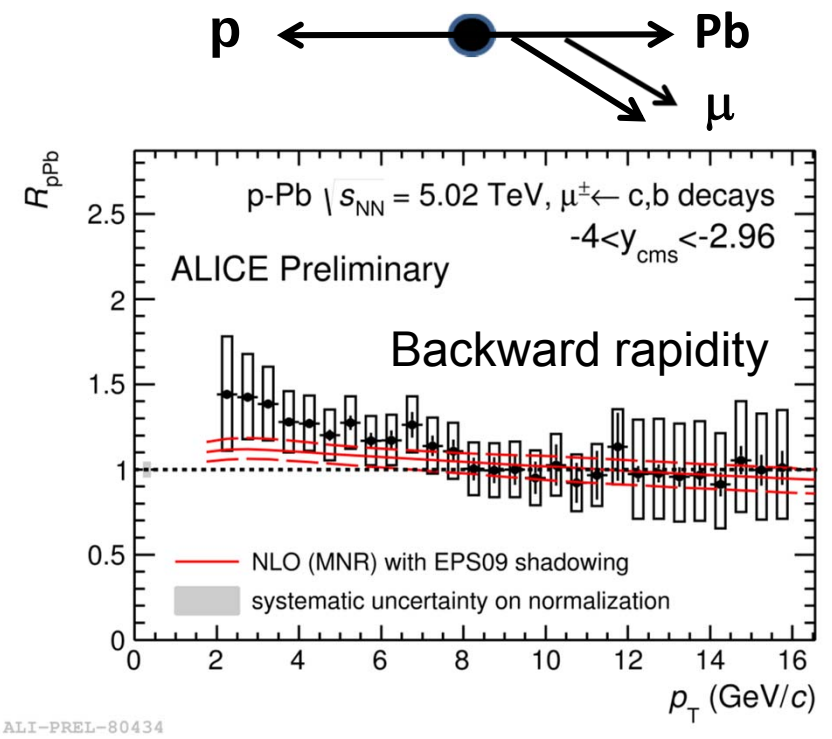


- R_{pPb} consistent with unity within uncertainties for electrons from heavy-flavour hadron decays and beauty-hadron decays
- R_{pPb} in agreement with perturbative QCD calculations including EPS09 parameterization of shadowing

FONLL: M. Cacciari et al., JHEP 007 (1998) 9805, JHEP 006 (2001) 0103
pQCD NLO (MNR): Nucl. Phys. B 373 (1992) 295, EPS09: K. J. Eskola et al., JHEP 04 (2009) 065

Heavy-flavour decay muons: R_{pPb} *vs* p_T



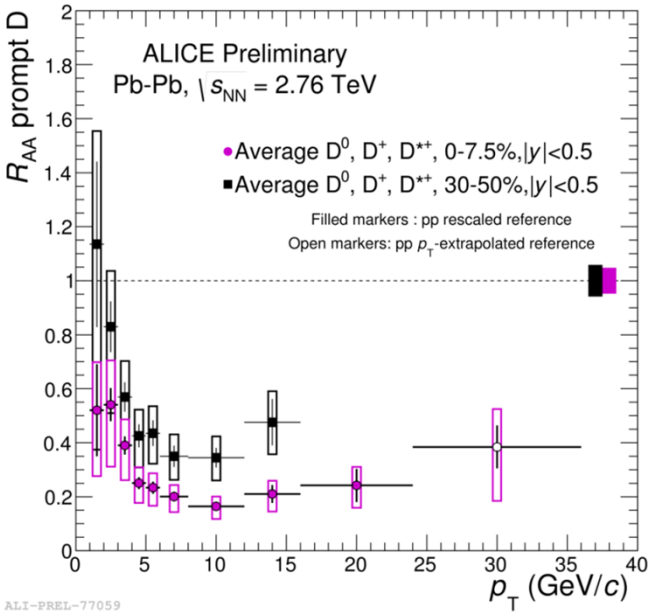


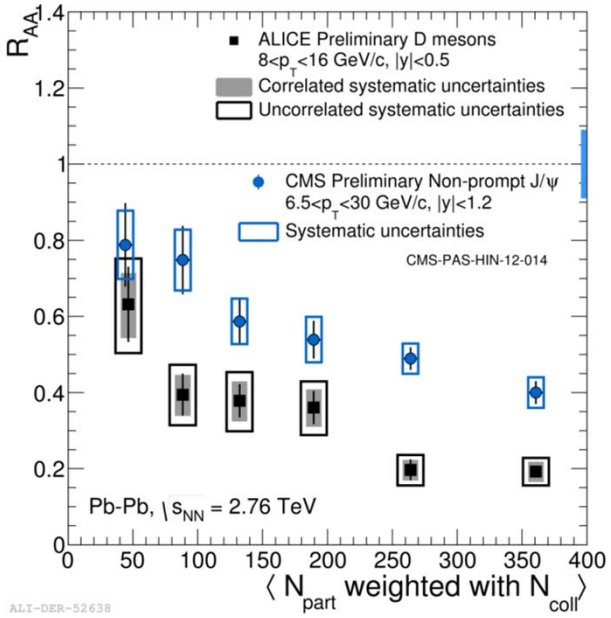
- R_{pPb} at forward rapidity consistent with unity within uncertainties over the whole measured p_T region
- R_{pPb} at backward rapidity slightly larger than unity in $2 < p_T < 4$ GeV/c and close to unity at higher p_T
- R_{pPb} in agreement with perturbative QCD calculations including EPS09 parameterization

pQCD NLO (MNR): Nucl. Phys. B 373 (1992) 295, EPS09: K. J. Eskola et al., JHEP 04 (2009) 065

D mesons: R_{AA} vs p_T and centrality

$$R_{AA}(p_T) = 1/\langle N_{coll}\rangle \times \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

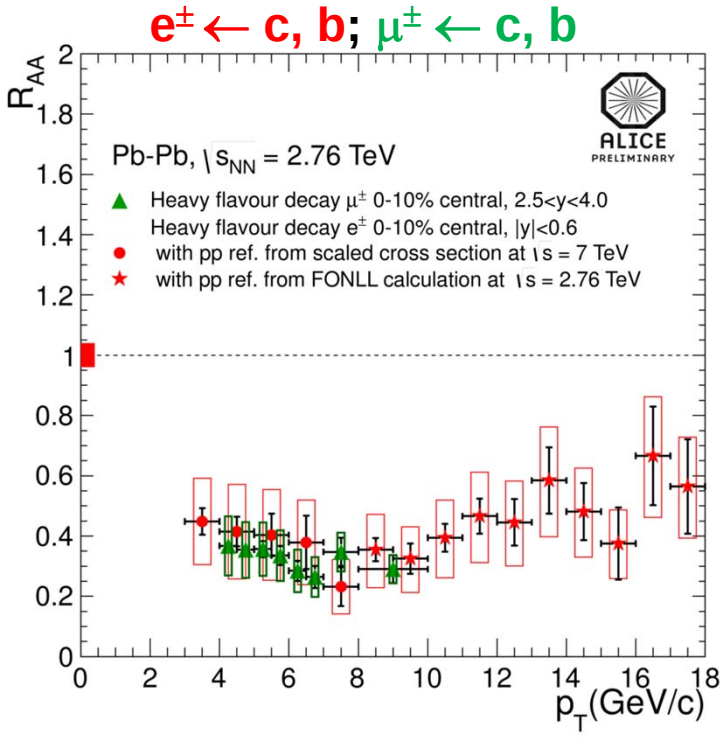


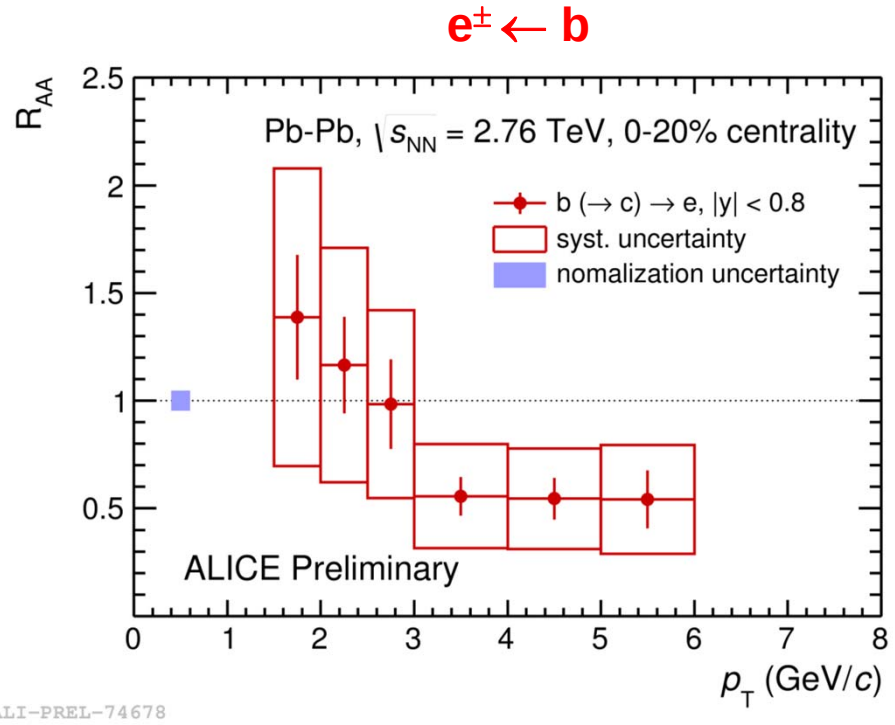


- Strong suppression at high p_T in central Pb-Pb collisions relative to the binary scaled pp reference (a factor of about 4 at p_T = 5 GeV/c in 0-7.5%)
- Measured suppression is a final-state effect (R_{pPb} close to unity)
- Non-prompt J/Ψ (i.e from B decays) measured by CMS more suppressed than D mesons in central collisions: consistent with the expectation $\Delta E_c > \Delta E_b$ (due to the dead cone effect, Phys. Lett. B 519 (2001) 1999)

[Similar <p_T> (~10 GeV/c) for D and B $\rightarrow$ J/Ψ, rapidity range slightly different]

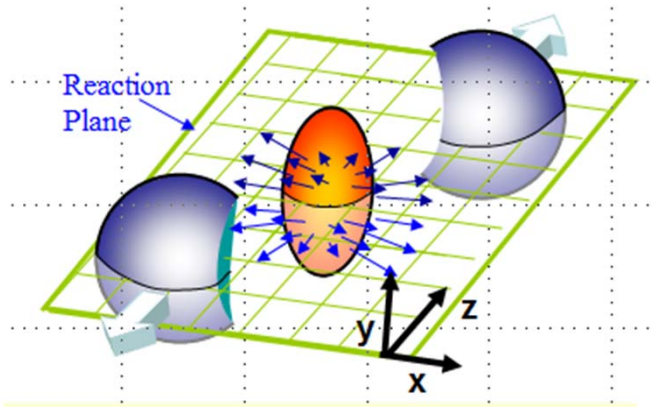
Heavy-flavour decay leptons: R_{AA} *vs* p_T





- Strong suppression measured at high p_T in the most central Pb-Pb collisions (a factor 3-4 in $4 < p_T < 10$ GeV/c) for both heavy-flavour decay electrons ($|y| < 0.6$) and muons ($2.5 < y < 4$)
- Measured suppression is a final-state effect (R_{pPb} close to unity)
- Hint for a suppression of electrons from beauty-hadron decays in Pb-Pb: $R_{AA} < 1$ for $p_T > 3$ GeV/c

Heavy-flavour decay lepton v_2 in Pb-Pb

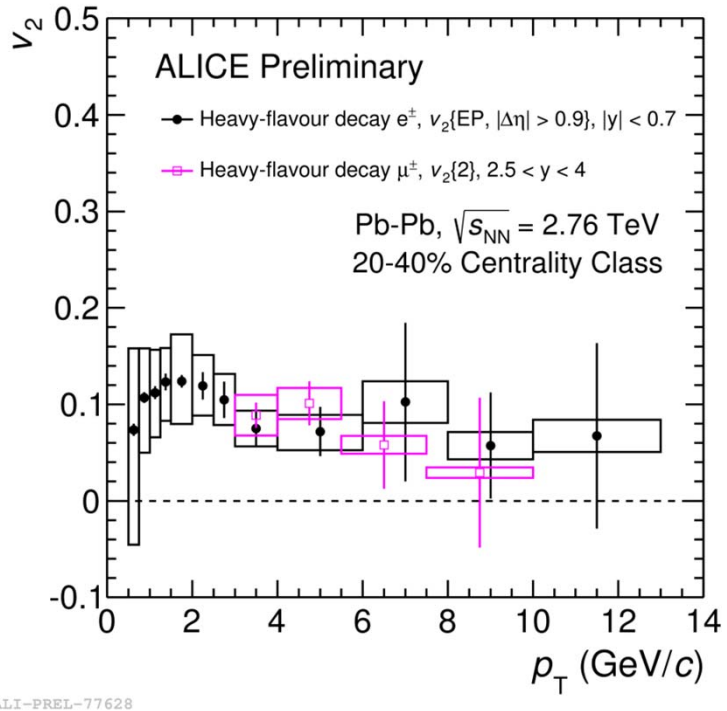


initial spatial anisotropy → momentum anisotropy

$$\frac{2\pi}{N}\frac{\mathrm{dN}}{\mathrm{d}\varphi} = 1 + \sum_{n=1}^{\infty} 2v_n cos[n(\varphi - \Psi_n)]$$

$$\text{with } v_2 = \langle cos[2(\varphi - \Psi_n)]\rangle$$

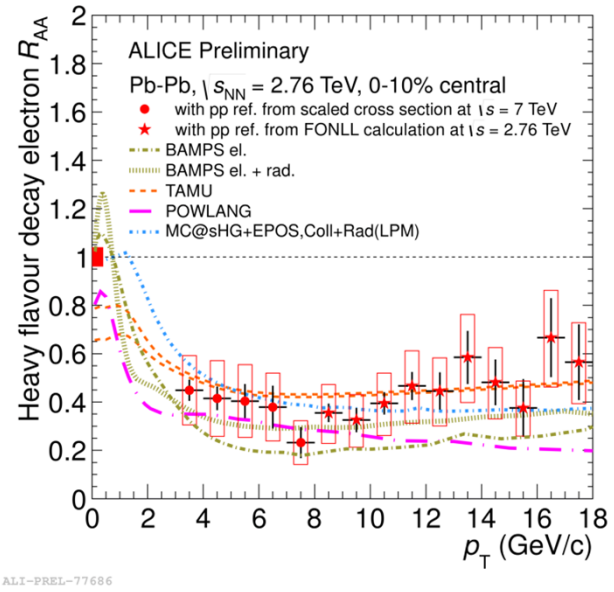
$e^{\pm}$ ← c, b; μ± ← c, b

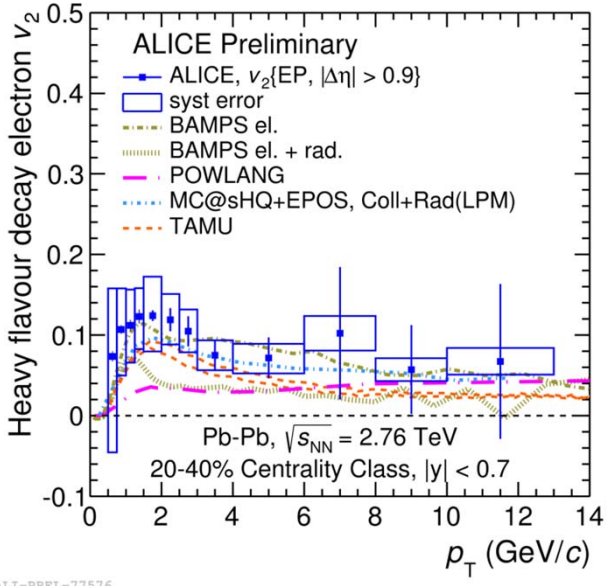


- Positive heavy-flavour lepton v_2 measured (> 3σ effect) in semi-central collisions and at intermediate p_T
  - Significant interaction of heavy quarks with the medium
  - Suggest collective motion of low p_T heavy quarks (mainly charm) in the expanding fireball
- Positive v_2 also measured for D mesons (ALICE, Phys. Rev. Lett. 111 (2013) 102301)

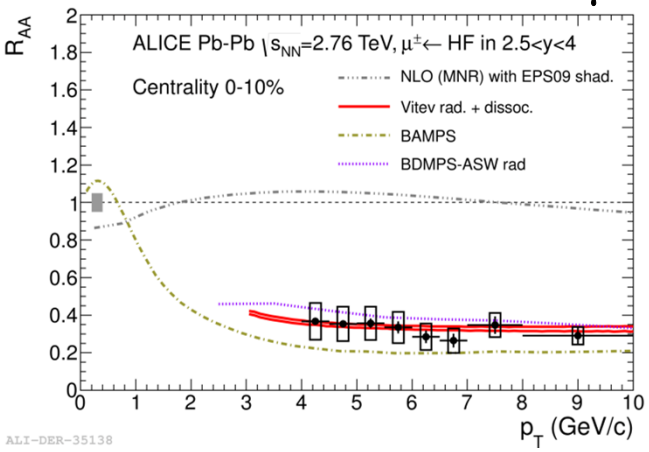
Model comparisons: R_{AA} and v_2

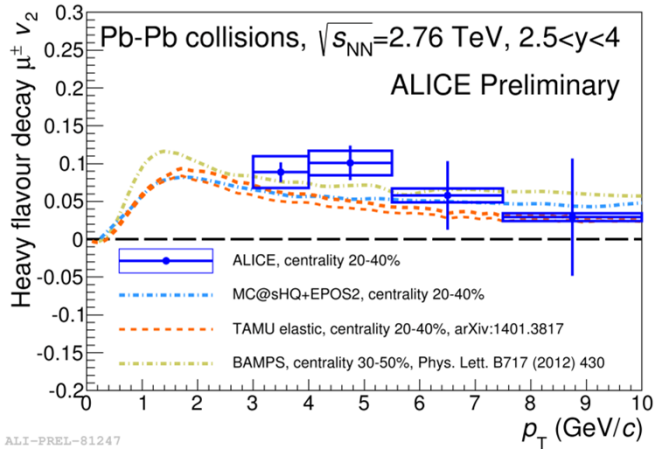
$e^{\pm} \leftarrow$ c, b





$\mu^{\pm} \leftarrow$ c, b



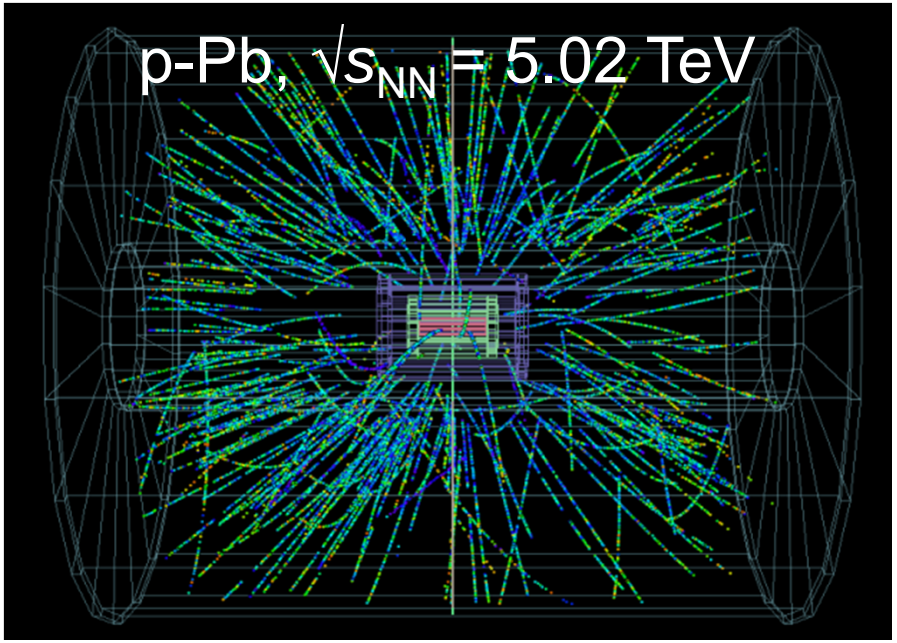


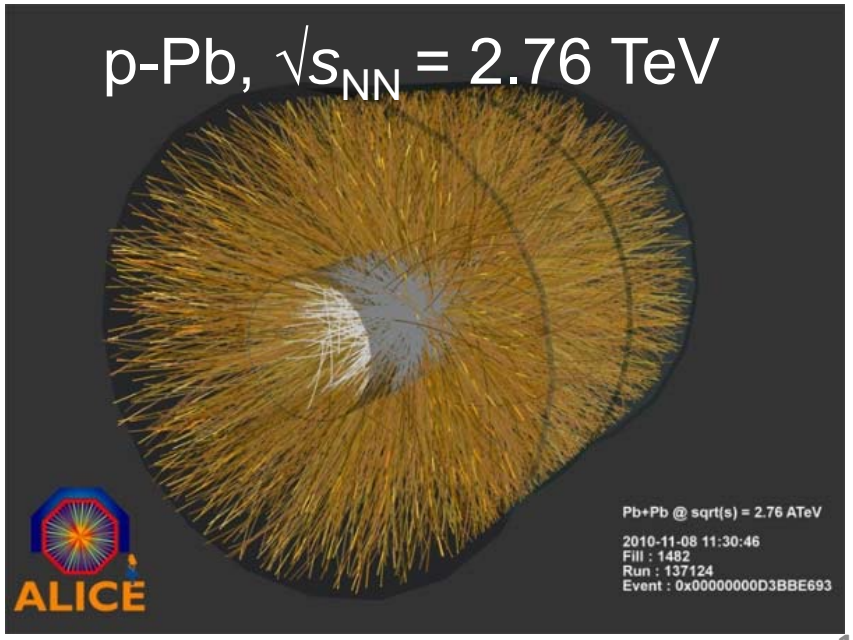
BAMPS: Phys. Lett. B 717 (2012) 430, arXiv: 1401.3817
POWLANG, Eur. Phys. J. C 71 (2011) 1666, J. Phys. G 38 (2011) 124144
TAMU: arXiv:1401.3817
MC@ Shq+EPOS: Phys. Rev. C 89 (2014) 014905

- Reasonable agreement with models including in-medium energy loss
- Simultaneous measurement of R_{AA} and v_2 allows one to constrain models

Quarkonium results

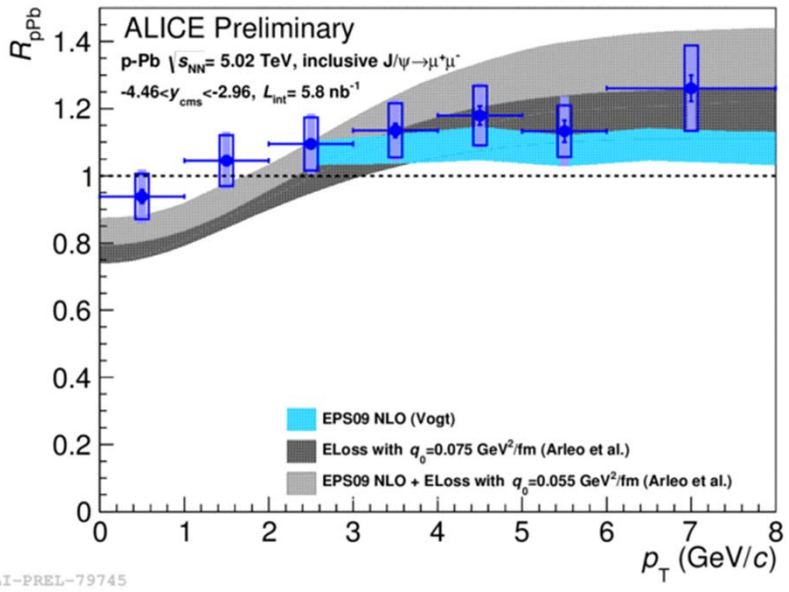
- p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV
  - ✓ Rapidity shift: $|\Delta y|$ = 0.465 in the p-beam direction (positive *y*)
  - ✓ Two configurations:
    - ➢ p-Pb , muon spectrometer in p-going direction
    - ➢ Pb-p, muon spectrometer in Pb-going direction
- Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV





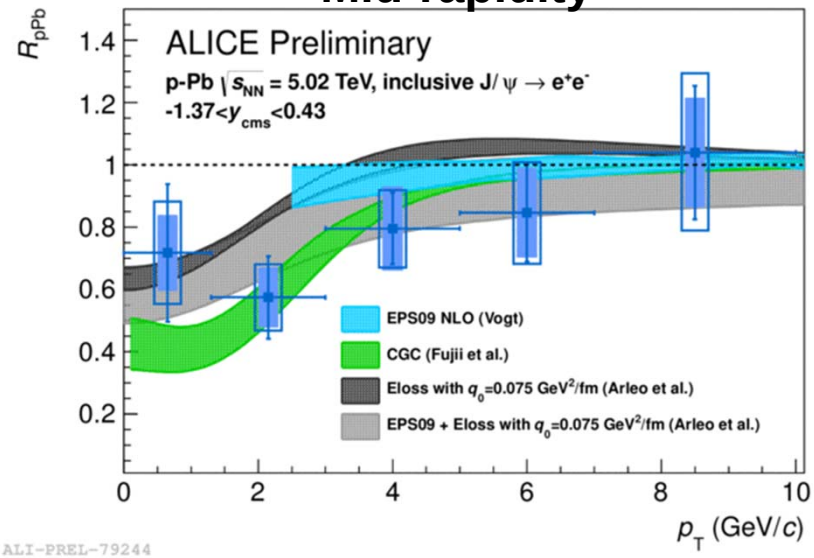
J/Ψ : R_{pPb} *vs* rapidity and p_T

Backward



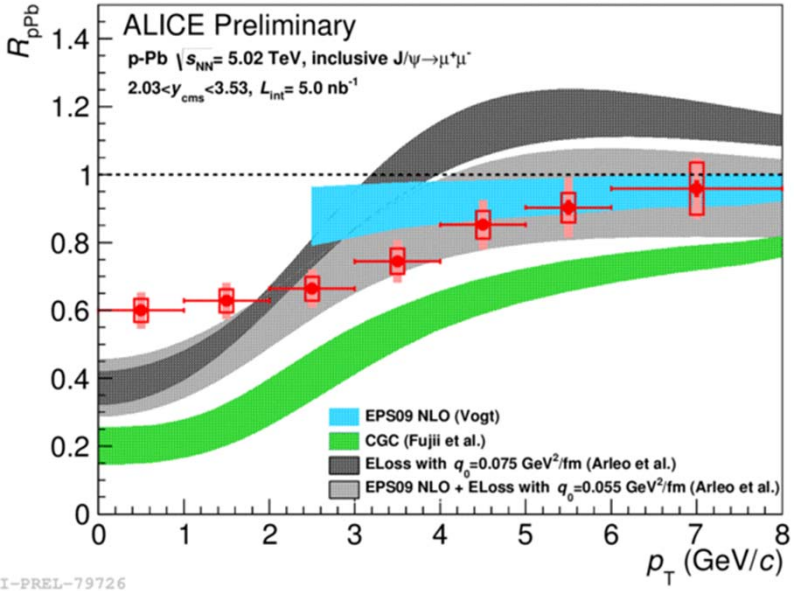
ALI-PREL-79745

Mid-rapidity



ALI-PREL-79244

Forward



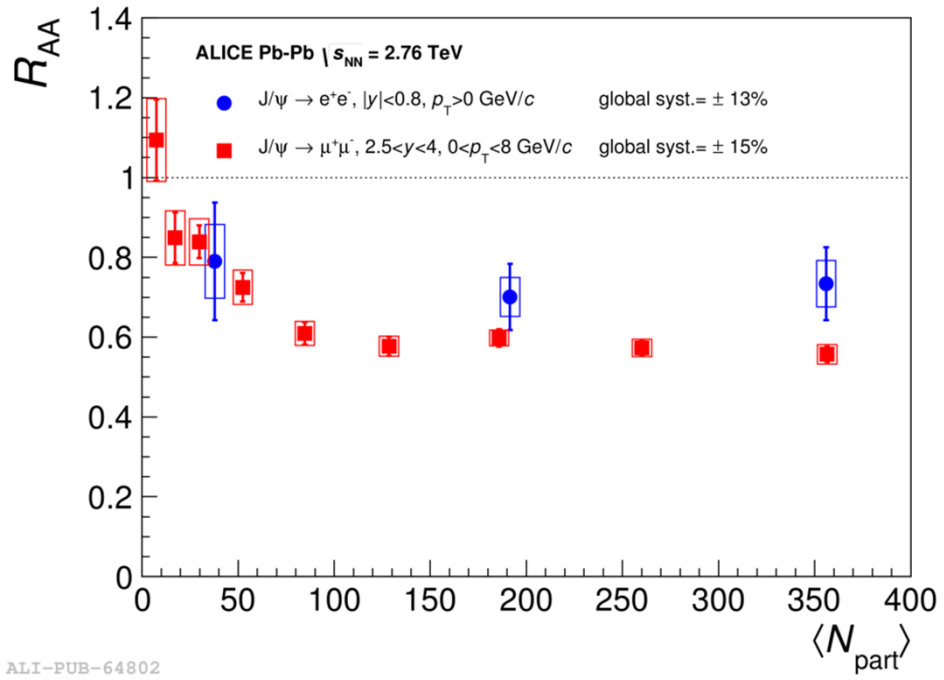
ALI-PREL-79726

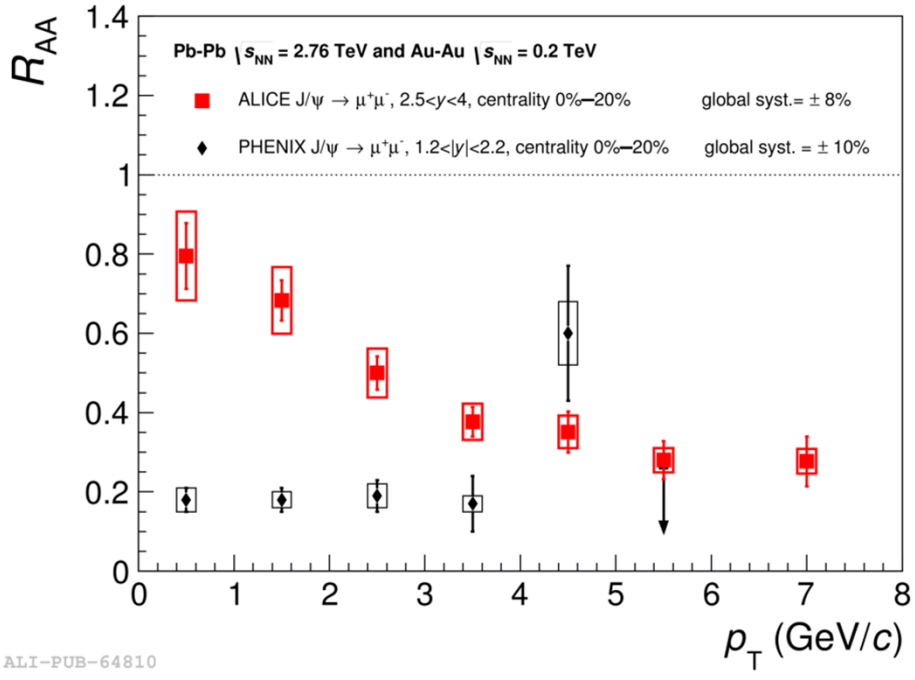
- Data in reasonable agreement with NLO calculations including EPS09 shadowing
- Coherent energy loss model overestimates the suppression at forward rapidity and low p_T
- CGC model overestimates suppression at forward rapidity

JMP E22 (2013) 1330007; K.Eskola et al., JHEP 04467 (2009) 065; F. Arleo et al., JHEP 1303 (2013) 122; H. Fujii et al., Nucl. Phys. A 915 (2013) 1

J/Ψ R_{AA}: differential measurements in Pb-Pb

ALICE rapidity regions: |y| <0.8, 2.5 < y < 4



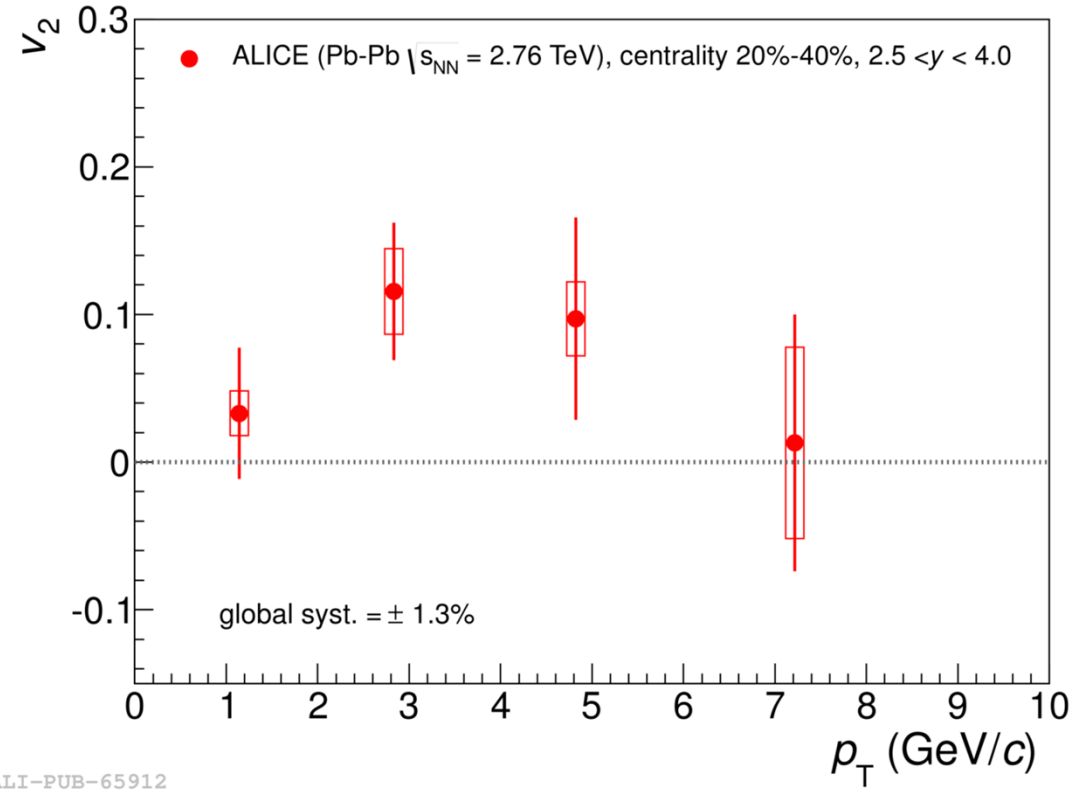


ALICE, Phys. Lett. B 734 (2014) 314

- Clear suppression at forward rapidity, slightly larger than measured at mid-rapidity in central collisions
- Suppression measured at the LHC increases with increasing p_T and is smaller than that observed at RHIC

- Results consistent with a significant fraction of J/Ψ from recombination at low p_T

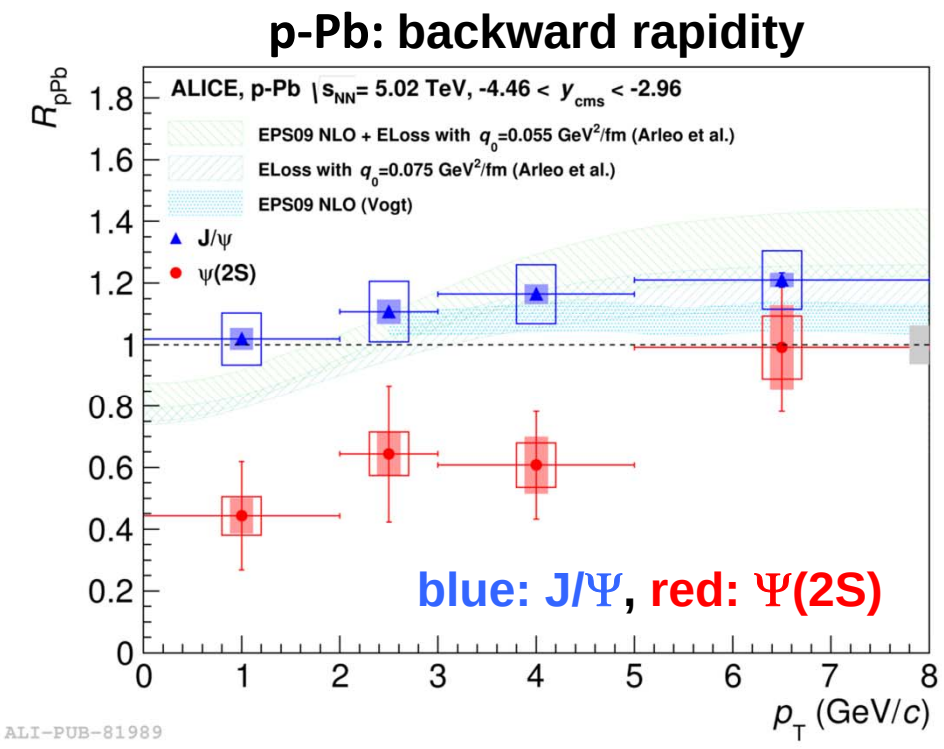
J/Ψ elliptic flow in Pb-Pb

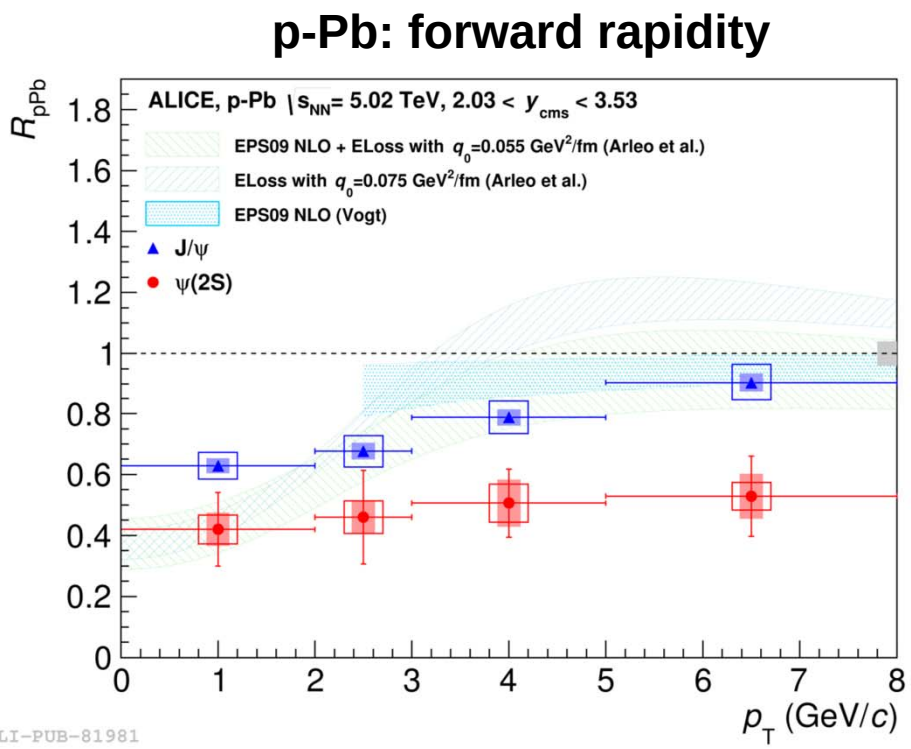


ALICE, Phys. Rev. Lett. 111 (2014) 162301

- Positive v_2 in semi-central collisions (20-40% centrality) at intermediate p_T (2.7σ effect)
- Consistent with a significant fraction of J/Ψ from the recombination of charm quarks in a flowing medium

$\Psi(2S)$: R_{pPb} *vs* p_T with comparisons to J/Ψ results and models

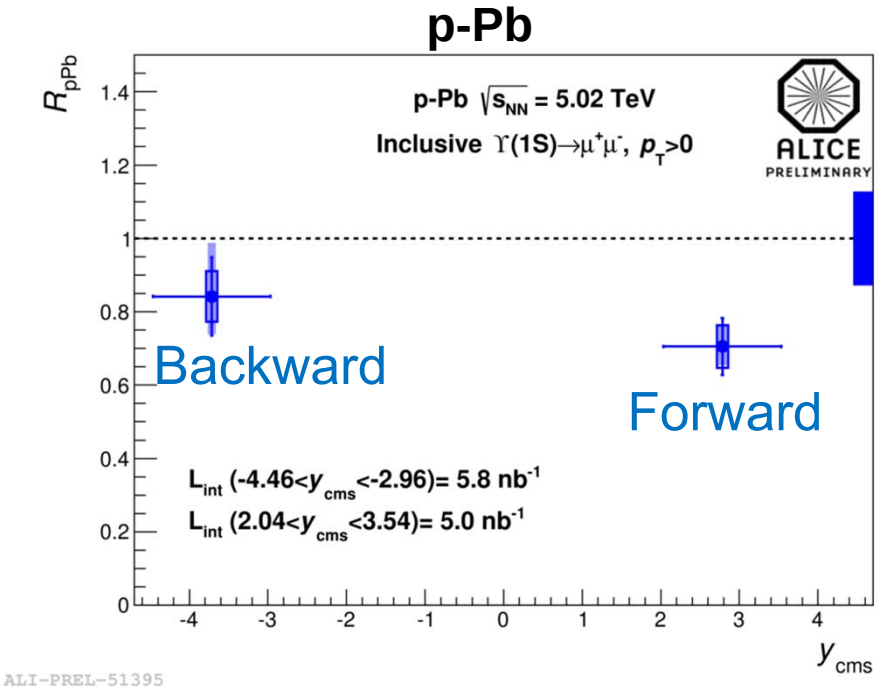


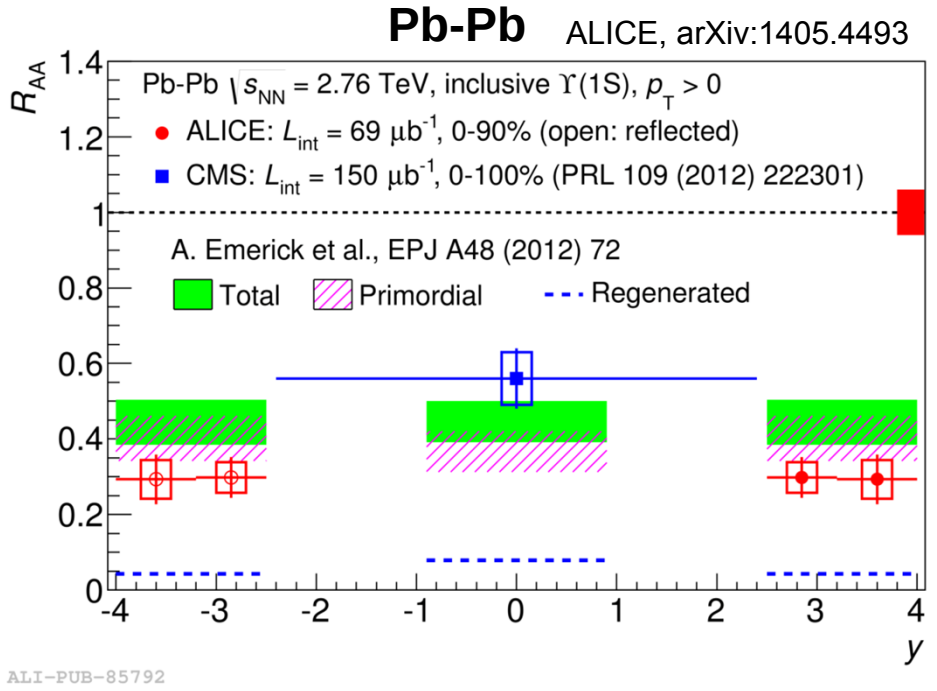


ALICE, arXiv: 1405.3796

- $\Psi(2S)$ more suppressed than J/Ψ at forward and backward rapidity
- $\Psi(2S)$ suppression not described by model predictions including only initial-state effects
- Indication for sizeable final-state effects on $\Psi(2S)$ production such as the interaction of the $c\bar{c}$ pair with the final state hadronic system formed in p-Pb collisions

Υ: R_{pPb} and R_{AA} vs rapidity





- p-Pb: indication of a suppression at forward rapidity and consistent with no suppression at backward rapidity
- Pb-Pb: strong suppression at forward rapidity that cannot be ascribed to only cold nuclear matter effects
  - Larger at forward rapidity than at mid-rapidity
- Pb-Pb: transport model does not reproduce the R_{AA} rapidity dependence and underestimates the measured suppression

Conclusion

Open heavy-flavour measurements

- Open heavy-flavour production in p-Pb collisions is well described by pQCD calculations including shadowing predictions
- The measured suppression of open heavy-flavour production at high p_T in central Pb-Pb collisions is a medium effect (R_{pPb} close to unity at high p_T) related to in-medium parton energy loss
- Heavy quarks participate in the collective expansion of the system

Quarkonium measurements

- J/Ψ suppression in p-Pb collisions is in reasonable agreement with shadowing and coherent energy loss models
- Final-state effects on the $\Psi(2S)$ production in p-Pb collisions
- The measured J/Ψ suppression in Pb-Pb collisions is consistent with a significant fraction of J/Ψ from regeneration (low p_T)
- The Υ suppression in Pb-Pb collisions is not reproduced by models

More measurements to come with the LHC run II and ALICE upgrades


Thank you for
your attention

Backup

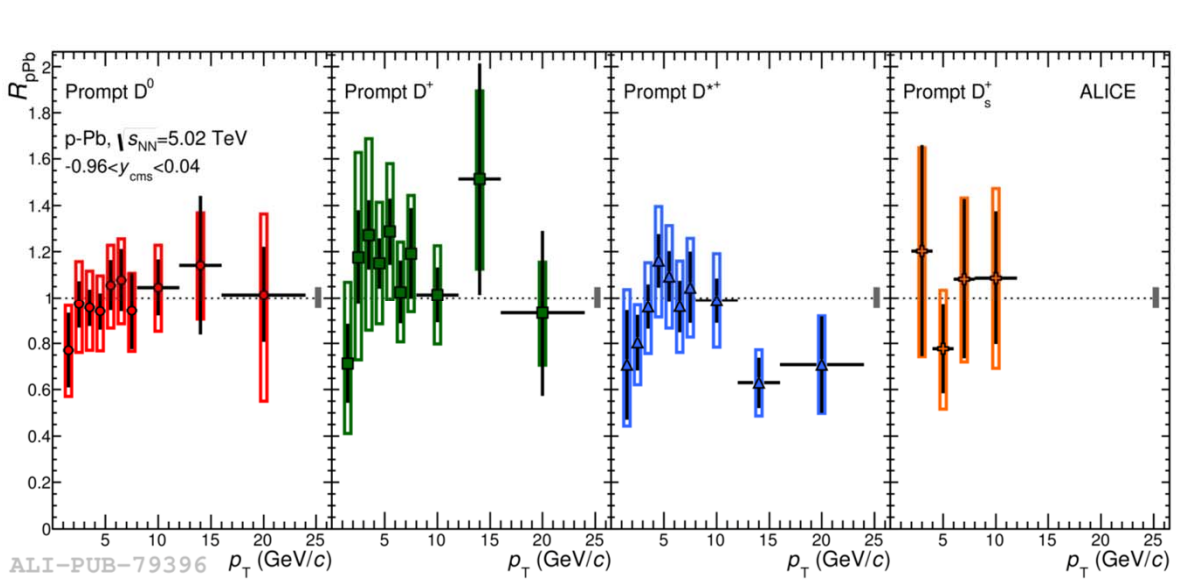
Data samples: p-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV

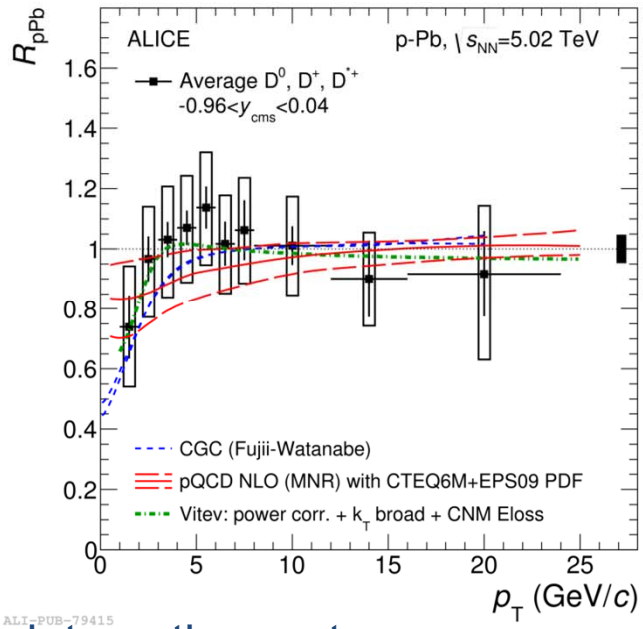
Observable	Integrated luminosity
D mesons	48.6 μb^{-1} (MB trigger, mid-rapidity)
$e^{\pm} \leftarrow$ c, b	48.6 μb^{-1} (MB trigger, mid-rapidity)
$\mu^{\pm} \leftarrow$ c, b	196 μb^{-1} (low p_T μ trigger, forward rapidity) 4.9×10^3 μb^{-1} (high p_T μ trigger, forward rapidity)
	254 μb^{-1} (low p_T μ trigger, backward rapidity) 5.8×10^3 μb^{-1} (high p_T μ trigger, backward rapidity)
$J/\Psi \rightarrow e^+e^-$	48.6 μb^{-1} (MB trigger, mid-rapidity)
J/Ψ, $\Psi(2S)$, $\Upsilon \rightarrow \mu^+\mu^-$	5.0 nb^{-1} (unlike-sign μ trigger, forward rapidity) 5.8 nb^{-1} (unlike-sign μ trigger, backward rapidity)

Data samples: Pb-Pb, $\sqrt{s_{NN}}$ = 2.76 TeV

Observable	Integrated luminosity
D mesons	2010: 2.12 μb^{-1} (0-80%) 2011: 23 μb^{-1} (0-10%), 6.2 μb^{-1} (10-30%), 6.2 μb^{-1} (30-50%)
$e^{\pm} \leftarrow$ c, b	2010: 2.0 μb^{-1} (0-80%) 2011: 22 (37) μb^{-1} in 0-10% and 6 (34) μb^{-1} in 20-40% with MB (EMCAL) triggers
$\mu^{\pm} \leftarrow$ c, b	2010: 2.7 μb^{-1} (0-80%) 2011: 11.3 μb^{-1} (0-10%) and 3.5 μb^{-1} in 10-40%
$J/\Psi \rightarrow e^+e^-$	2010 & 2011:: 27.7 μb^{-1} in 0-90%
J/Ψ, $\Psi(2S)$, $\Upsilon \rightarrow \mu^+\mu^-$	69 μb^{-1} in 0-90% with unlike-sign μ trigger

D-mesons: R_{pPb} *vs* p_T

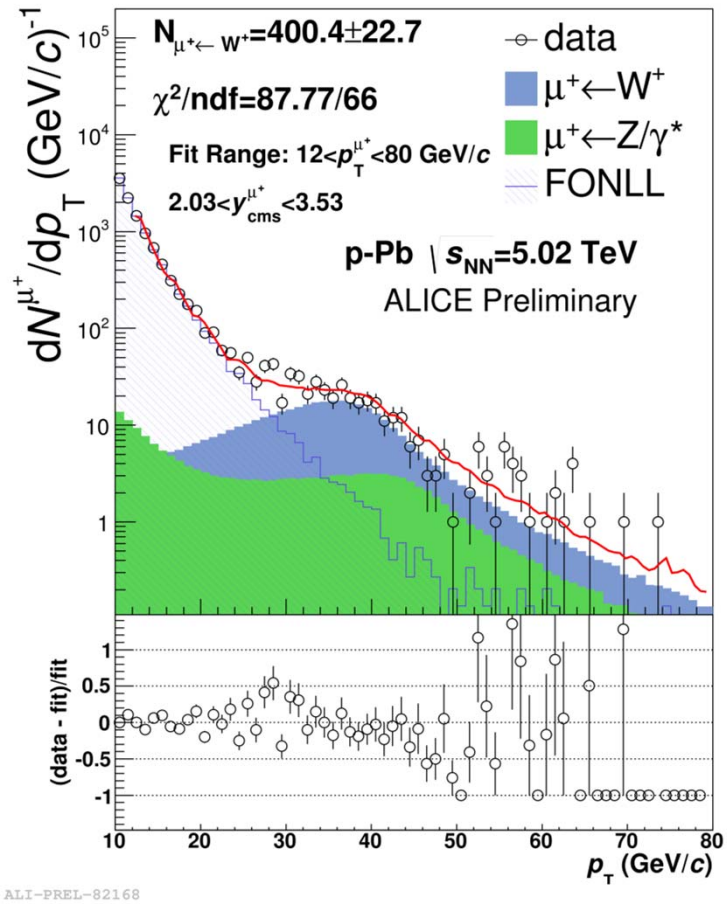


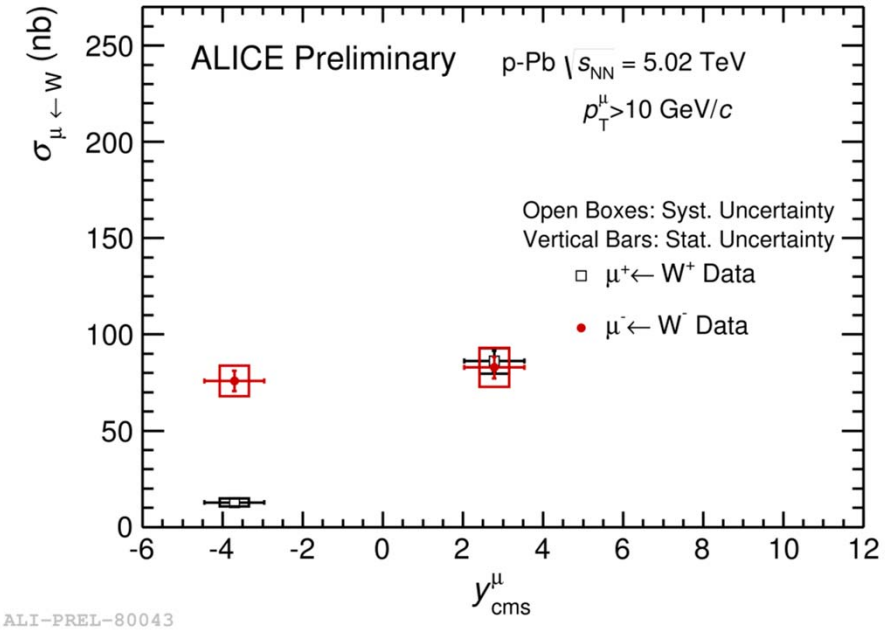


- ➢ Reconstruction of hadronic decays displaced from the interaction vertex
- ❑ Nuclear modification factor (R_{pPb}) consistent with unity within uncertainties for all D-meson species with no significant p_T dependence
- ❑ D-meson R_{pPb} in agreement with:
  - Perturbative QCD calculations with EPS09 shadowing
  - Color Glass Condensate (CDG) predictions
  - Model including energy loss, shadowing and k_T broadening

ALICE: arXiv:1405.3452
CGC: H.Fujii and K. Watanable, arXiv: 1308.1258
pQCD NLO (MNR): Nucl. Phys. B 373 (1992) 295, EPS09: K. J. Eskola et al., JHEP 04 (2009) 065
Vitev: Phys. Rev. C 80461 (2009) 054901

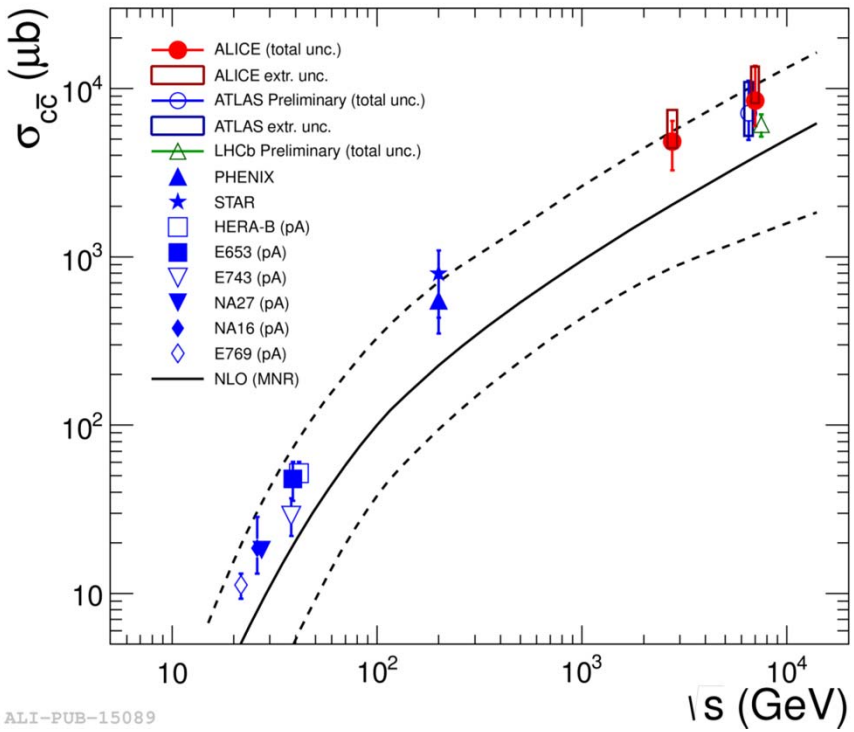
W-boson production in p-Pb



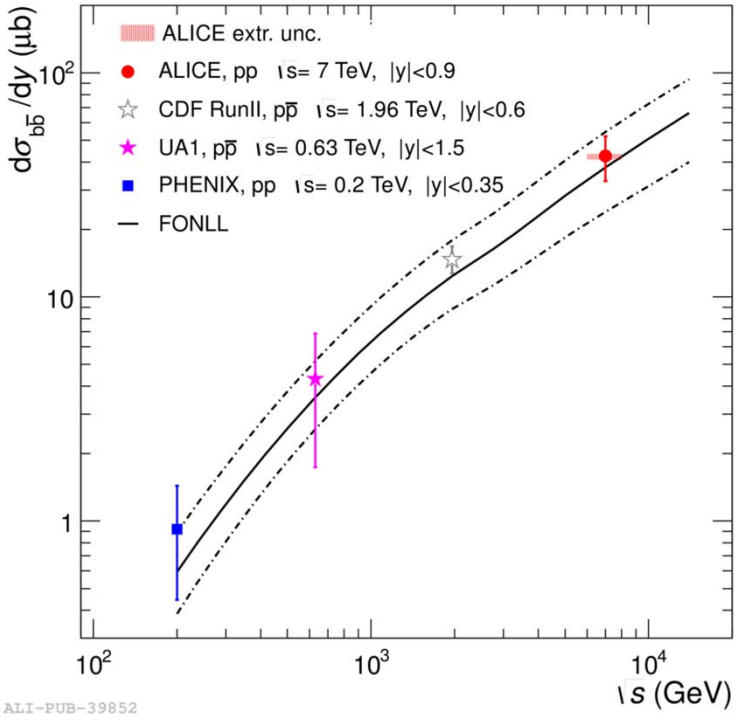


- Production cross sections of muons from W-boson decays measured at forward and backward rapidity

The LHC: a heavy-flavour factory



JHEP 1207 (2012) 191



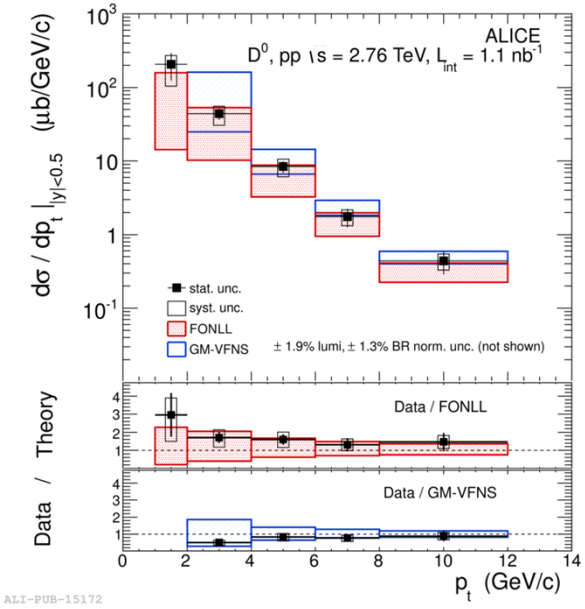
PLB 721 (2013) 13 & arXiv:1405.4144

- Abundant heavy-flavour production rates at the LHC, have been measured in pp collisions
  - σ_c(LHC) = σ_c(RHIC) x 10
  - σ_b(LHC) = σ_b(RHIC) x 50
- Central (5%) Pb-Pb (LHC, 2.76TeV) : ~60 $c\bar{c}$ & ~2 $b\bar{b}$

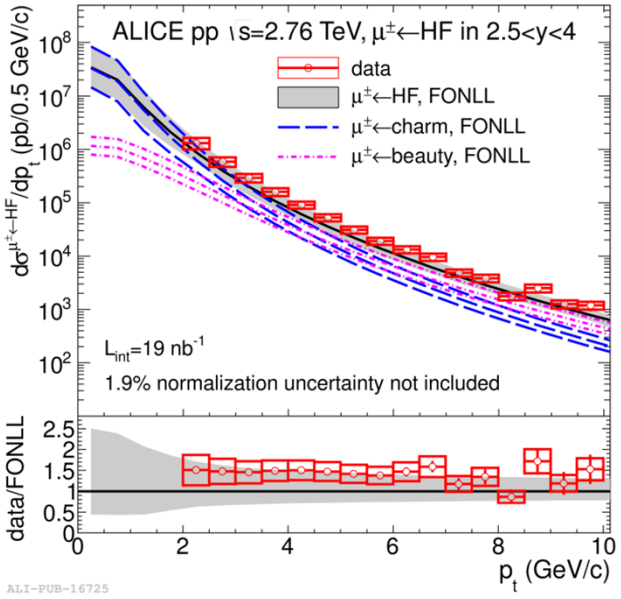
(MNR code: Nucl. Phys. B 373 (1992) 295; EKS98, EPS08: EPJ C9 (1999) 61, JHEP07 (2008) 102)

Differential cross sections in pp, √s = 2.76 TeV

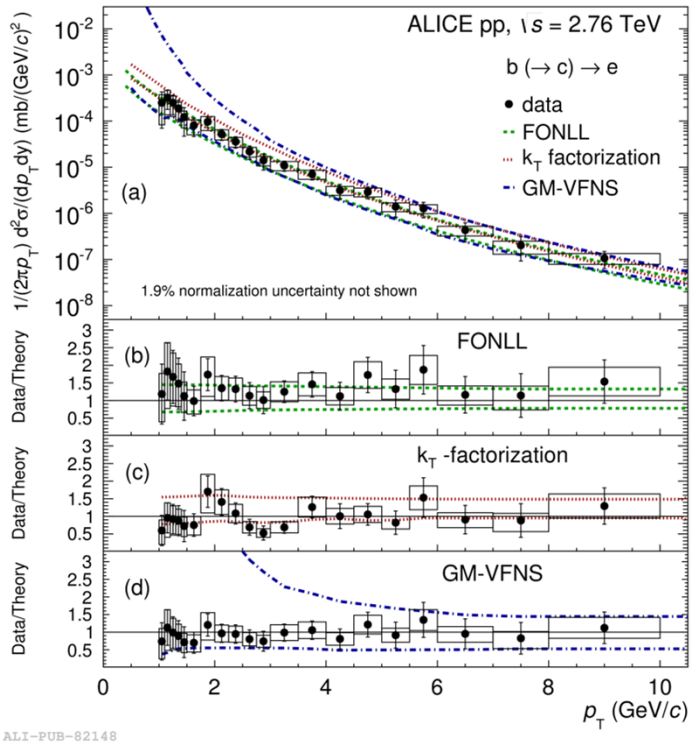
D mesons



$\mu^{\pm} \leftarrow$ b, c

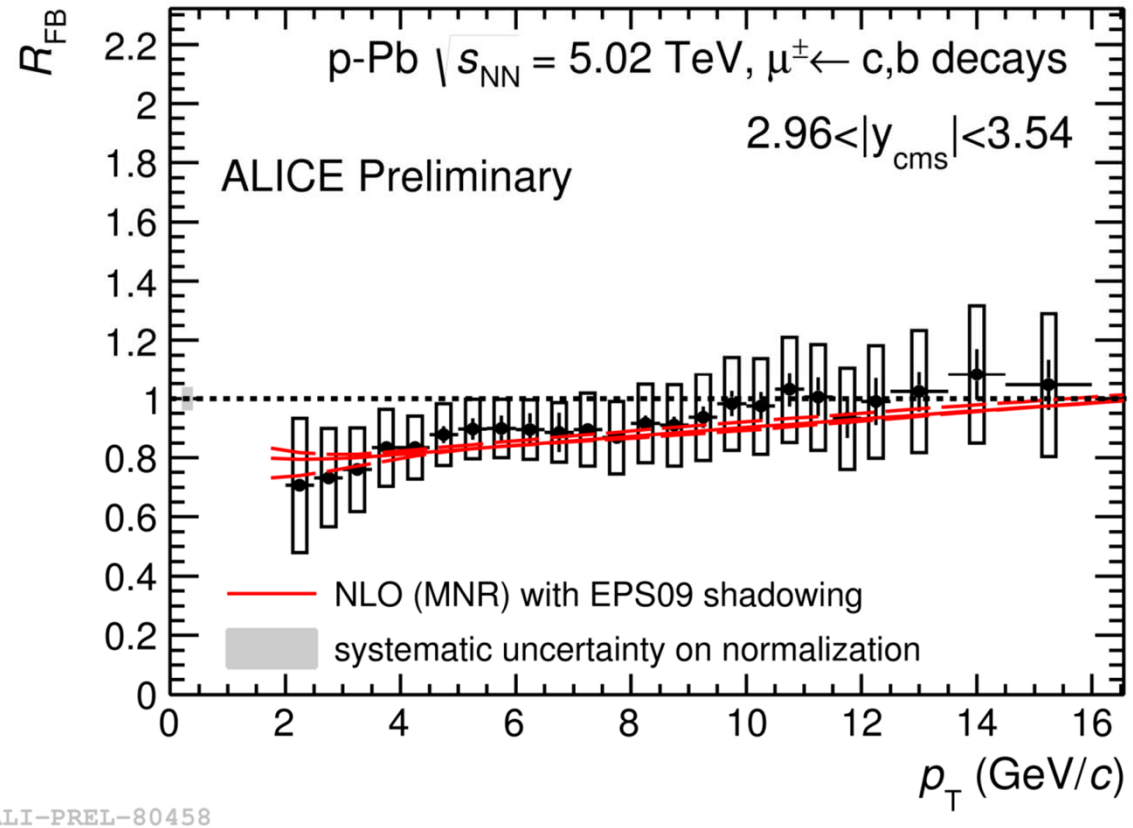


$e^{\pm} \leftarrow$ b

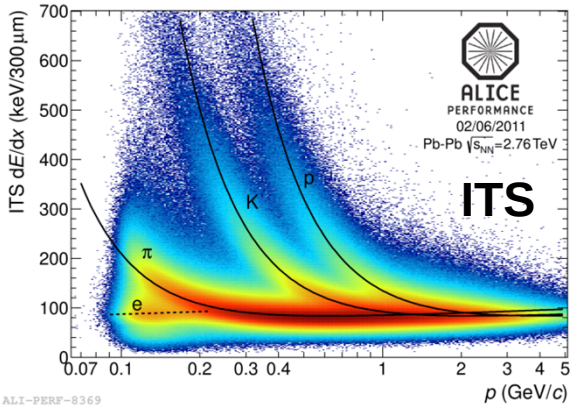


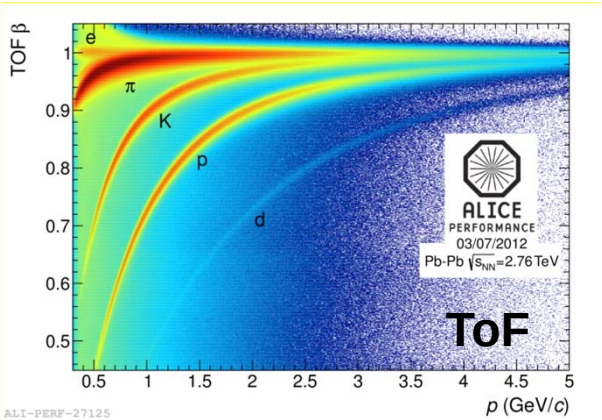
- Good agreement within uncertainties with Pqcd calculations

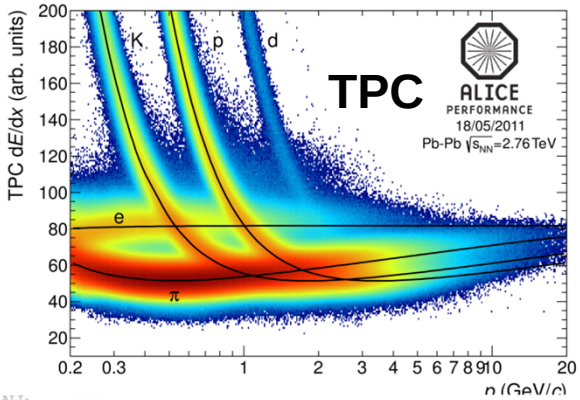
Heavy-flavour decay muons in p-Pb forward-to-backward ratio

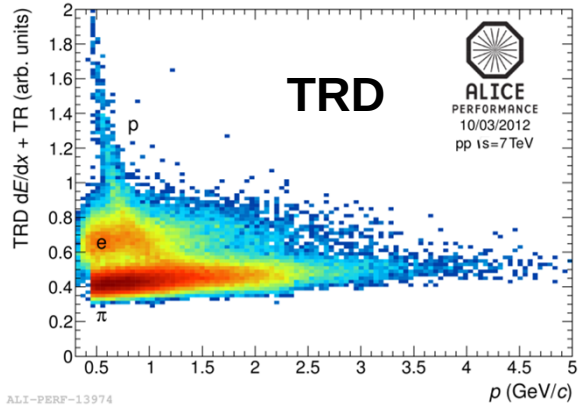


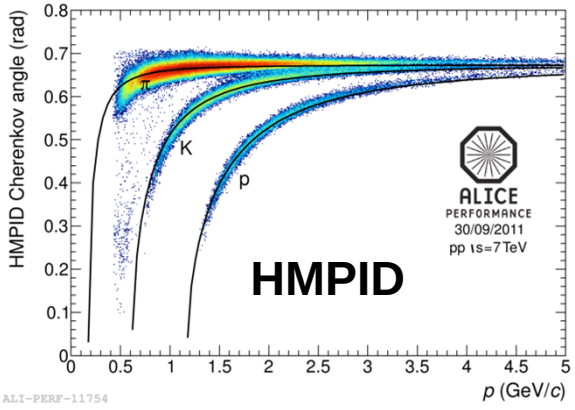
Particle IDentification (PID) in ALICE

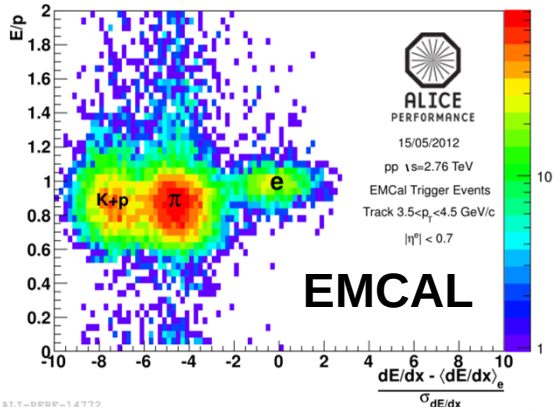


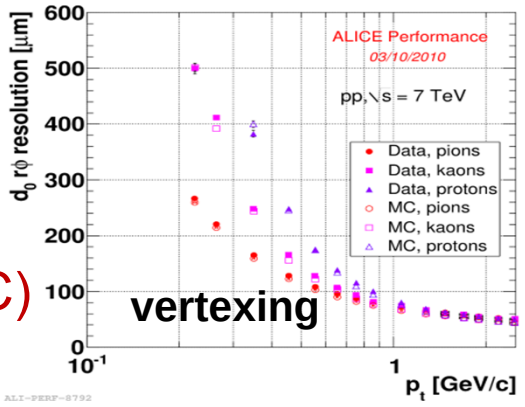






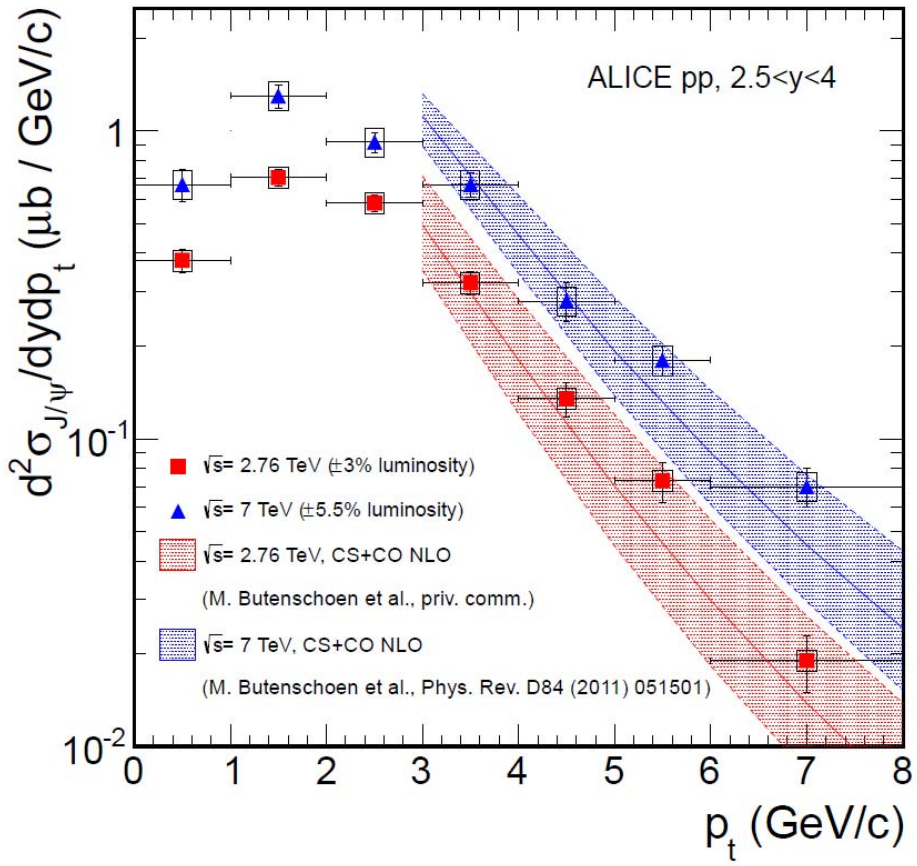






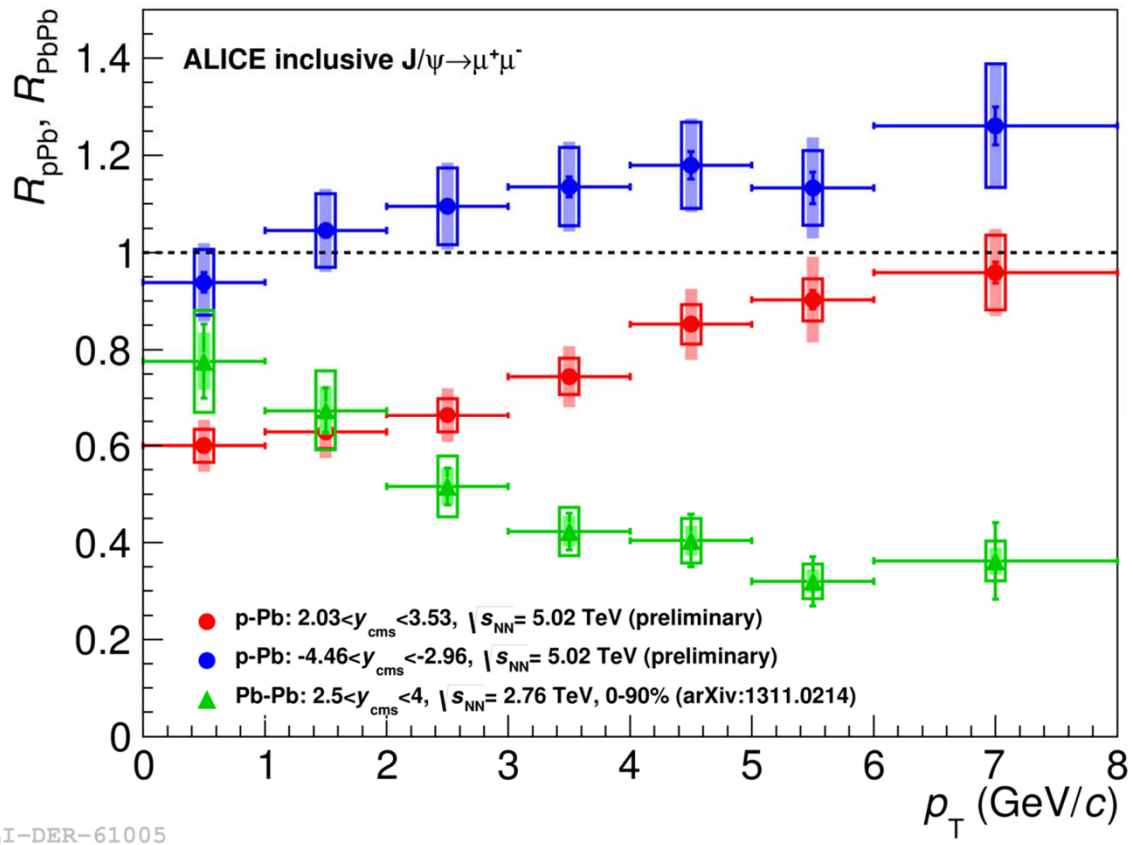
- particle identification over a large rapidity range (almost all known techniques)
- excellent tracking down to ~ 100 MeV/c & vertexing
- quarkonium detection down to $p_T = 0$ (unique at LHC)

Charmonium production in pp



- J/Ψ measured in pp collisions at 2.76 TeV and 7 TeV
- Good agreement between data and theory
- Reference data for p-Pb and Pb-Pb

J/Ψ production in p-Pb collisions



ALI-DER-61005

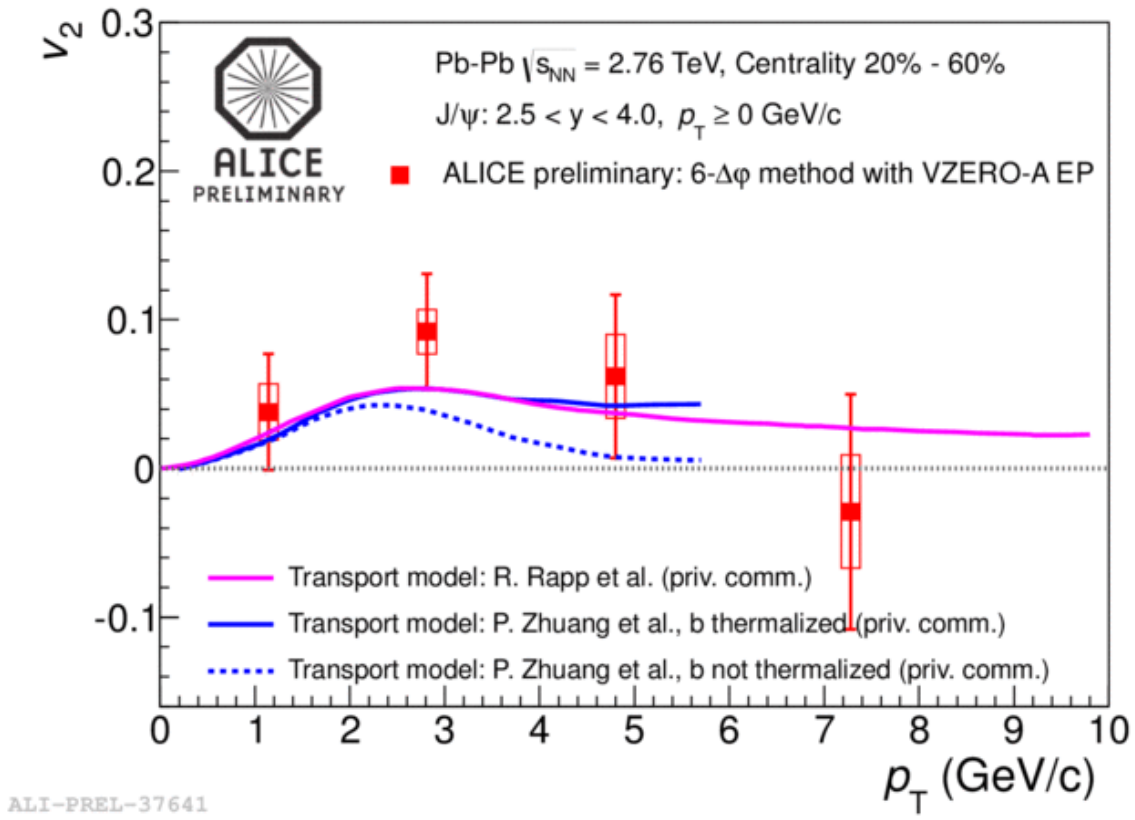
p-Pb, backward

p-Pb, forward

Pb-Pb, forward

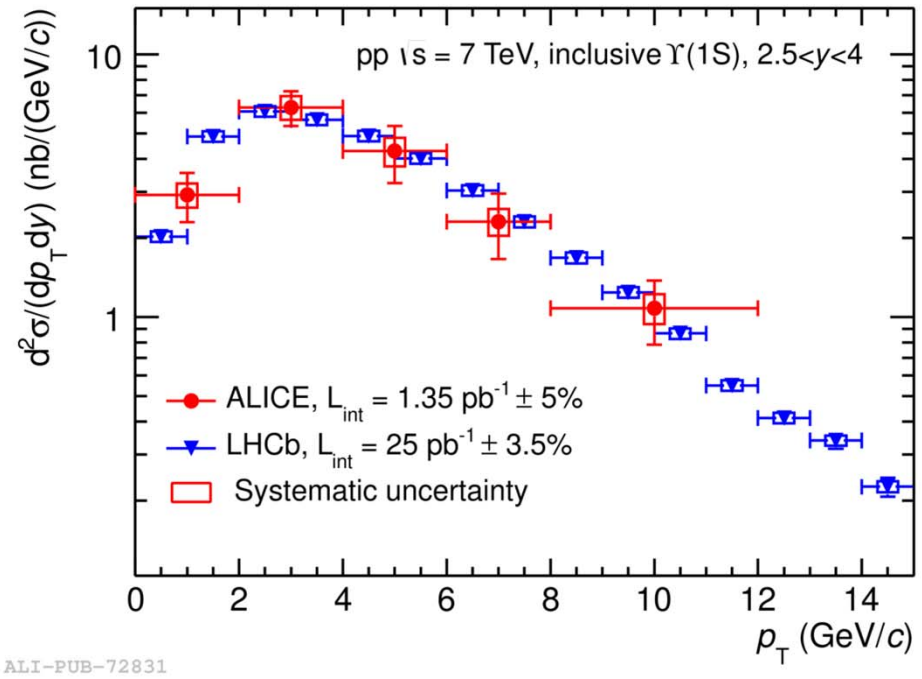
- Cold nuclear matter effects are not negligible, in particular at forward rapidity
- Different p_T dependencies of the nuclear modification factor in p-Pb and Pb-Pb collisions
- Hint for enhancement at low p_T in Pb-Pb relative to p-Pb and the suppression at high p_T is a hot matter effect

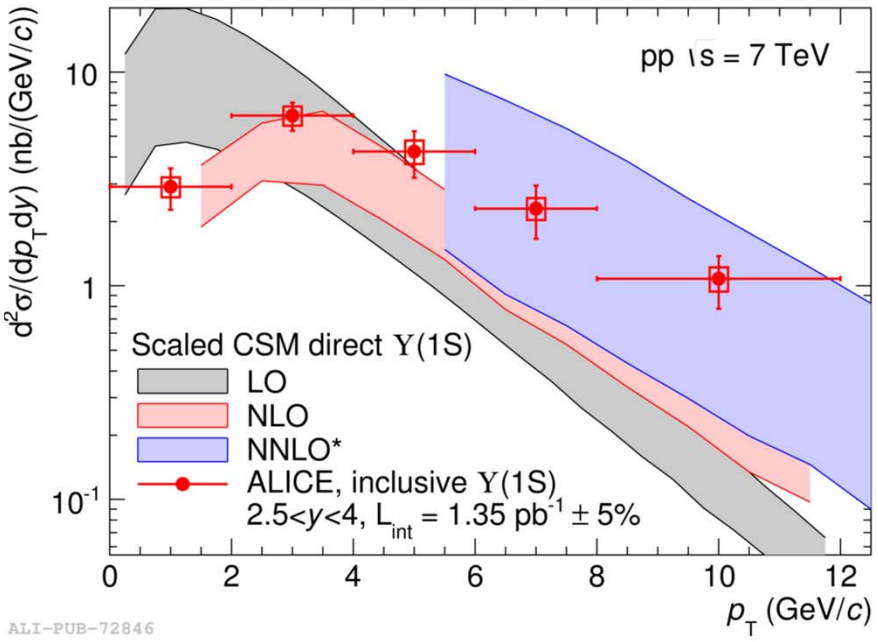
J/Ψ elliptic flow



- Indication of a non-zero v_2 at the LHC
- In favour of production in the QGP i.e. from charm quarks (regeneration)
- In contrast to this observation, STAR experiment at RHIC measures $v_2 = 0$

Υ production in pp collisions

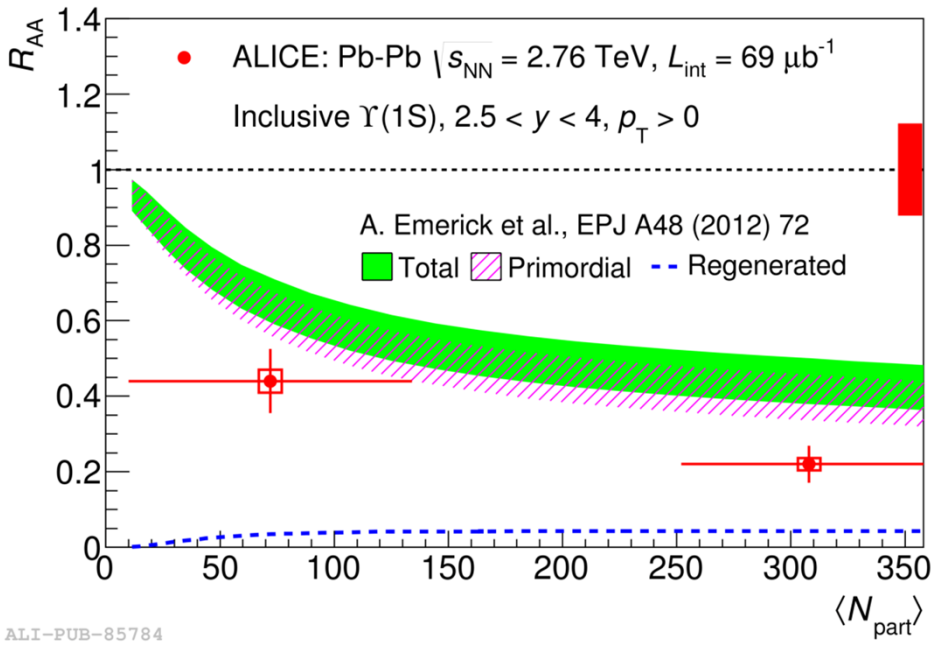


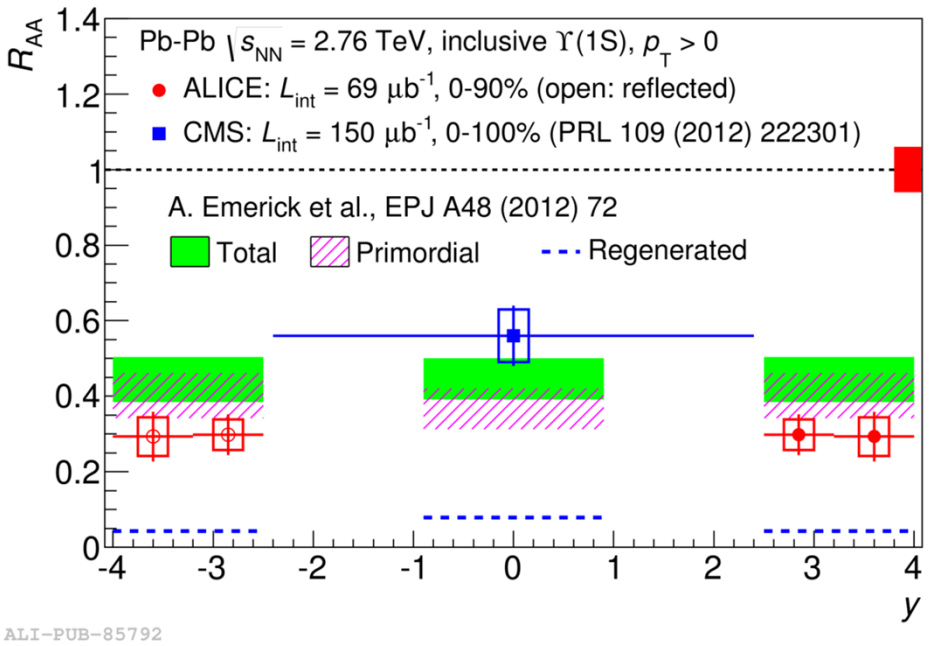


- Nice agreement between the ALICE and LHCb experiments
- pp results: understanding production mechanisms

Υ: R_{AA} & model comparisons

ALICE, arXiv:1405.4493

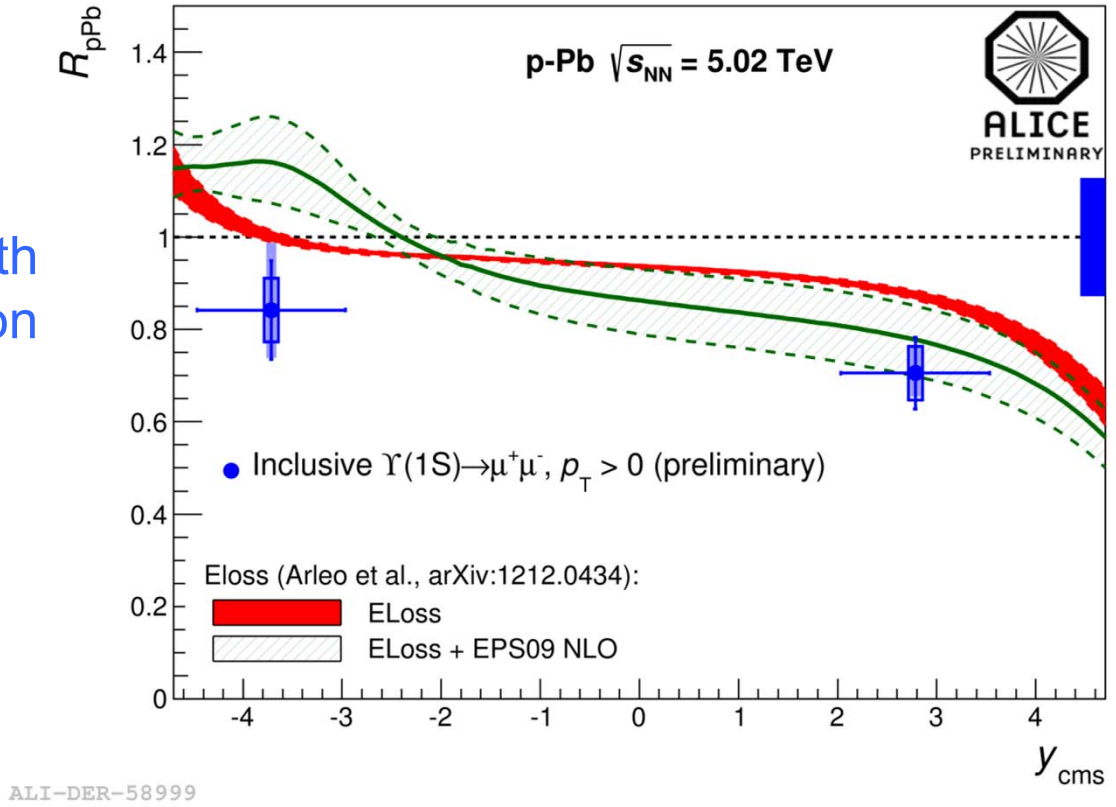




- Strong Υ suppression at forward rapidity in Pb-Pb collisions that cannot be ascribed to only cold nuclear matter effects
  - Increases with increasing centrality
  - Larger at forward rapidity than at mid-rapidity
- Transport model does not reproduce the R_{AA} rapidity dependence and underestimates the measured suppression at forward rapidity

Υ measurements in p-Pb collisions

Consistent with no suppression at backward



Consistent with suppression at forward

- Forward: better agreement with energy loss and shadowing
- Backward: better agreement with energy loss