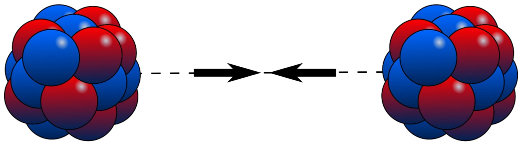
Measurements of heavy-flavour hadron production with ALICE at the LHC

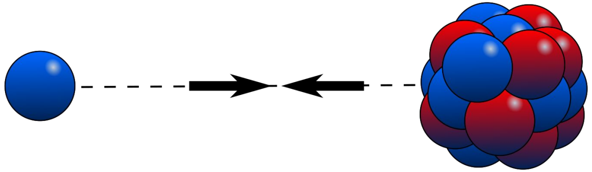
Cristiane Jahnke for the ALICE Collaboration
Universidade de São Paulo

Collision systems

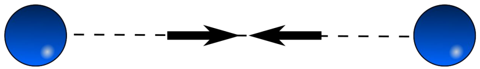


- Pb–Pb collisions:
  - In-medium energy loss
  - Colour-charge and quark-mass dependence
  - Thermalisation of heavy-quarks in the medium
  - Quarkonium dissociation and/or regeneration

- p–Pb collisions:
  - Cold nuclear matter effects can be studied:
    - Nuclear modification of parton densities
      - Collinear PDFs or saturation description
    - Propagation in nucleus and in medium
    - Secondary quarkonium interaction



- pp collisions:
  - Reference for studies with p–Pb collisions and Pb–Pb collisions
  - Test of QCD calculations



- pp and p–Pb collisions:
  - Look for possible collective behaviour in small systems

Why to study heavy quarks?

- Heavy-flavour particles contain charm or beauty quarks:
  - ✓ Quarkonium: J/ψ, ψ(2S), ϒ(1S), ϒ(2S), ϒ(3S)
  - ✓ Open heavy-flavour: B meson, D meson, Λ_c, Λ_b, $\boldsymbol{\Sigma}_c$ and $\boldsymbol{\Xi}_c$

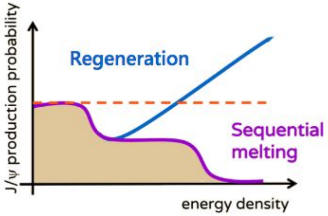
- Charm and beauty are produced (in hard scatterings) in the early stages of the collision:
  - ✓ Large mass ($m_{c,b} >> \Lambda_{QCD}$)
    → short formation time
    → hard probes, even at low p_T

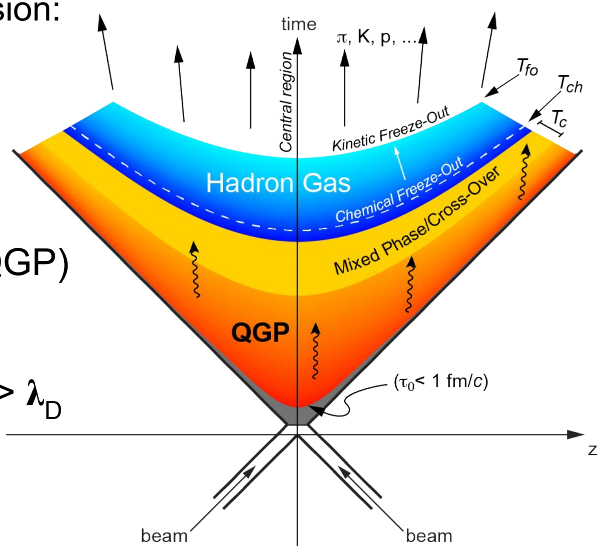
- Charm and beauty can experience the full evolution of the system:
  - ✓ They live much longer than the duration of the quark-gluon plasma (QGP)

- Quarkonium melting as a signature of QGP
  - ✓ Quarkonium destruction in a QGP by Debye screening: melted if $r > \lambda_D$

(Matsui & Satz, PLB178 (1986) 416)

- Regeneration



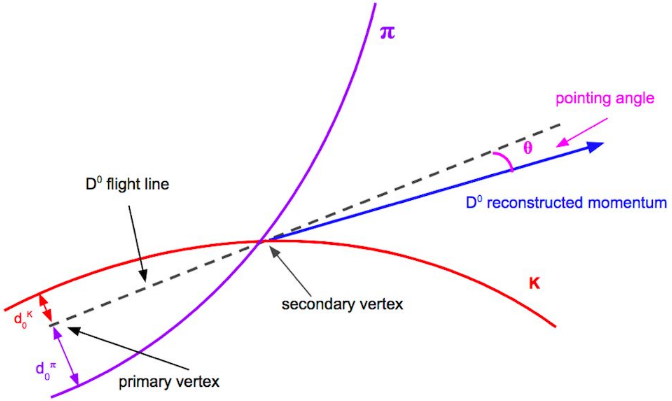


How to study heavy quarks?

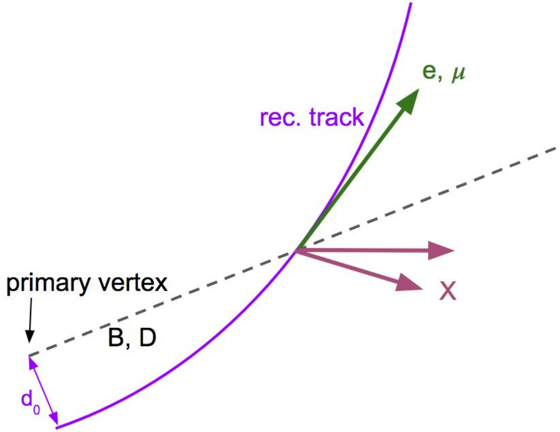
- Reconstruction via hadronic decays:
  - Prompt and non-prompt D meson reconstruction

$\Lambda_c^+ \rightarrow p\, K_s^0$

$\Lambda_c^+ \rightarrow p\, K^- \pi^+$



- Semileptonic decays (electrons and muons): branching ratio of the order of 10%:
  - B, D → l + X
  - Separation of electrons from beauty-hadron decays using the impact parameter (long life time of beauty hadrons).
    - At high p_T, it is expected that most of the leptons are from beauty-hadron decays (B).



- Quarkonium via dielectron or dimuon pairs
  - Prompt production
  - B → J/ψ (mid-rapidity)

How to study heavy quarks?

The nuclear modification factor

$$R_{\rm AA} = \frac{{\rm d}N_{\rm AA}/{\rm d}p_{\rm T}}{\langle T_{\rm AA}\rangle {\rm d}\sigma_{\rm pp}/{\rm d}p_{\rm T}}$$

- If $R_{AA} = 1$ (at high p_T): no hot medium effects and no cold nuclear matter effects.
- If $R_{AA} < 1$ (at high p_T): energy loss and/or cold nuclear matter effects.

- Energy loss is expected to depend on the parton colour-charge, parton mass and path length.

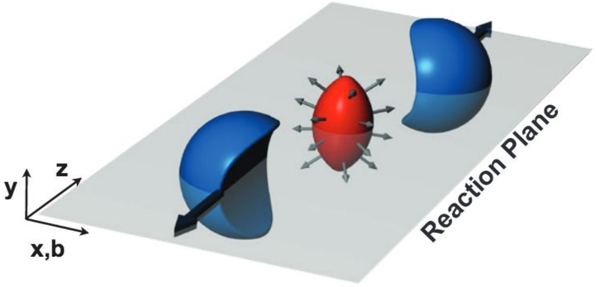
$\Delta E(\pi^{\pm}) > \Delta E(\mathrm{D}) > \Delta E(\mathrm{B})$ $\quad R_{AA}(\pi) < R_{AA}(\mathrm{D}) < R_{AA}(\mathrm{B})$ PLB 519(2001)199

Anisotropic flow

$$E\frac{d^3N}{dp_T^3} = \frac{d^3N}{p_T d\phi dp_T dy}\sum_{n=0}^{\infty} 2v_n cos[n(\phi - \Phi_R)]$$

- Anisotropic flow is caused by the initial asymmetries in the geometry of the system produced in a non-central collision.
  - Initial spatial anisotropy of the created particles is converted in momentum anisotropy due to the pressure gradients.

- v_2: indicates collective motion and thermalization
- v_3: event-by-event fluctuations

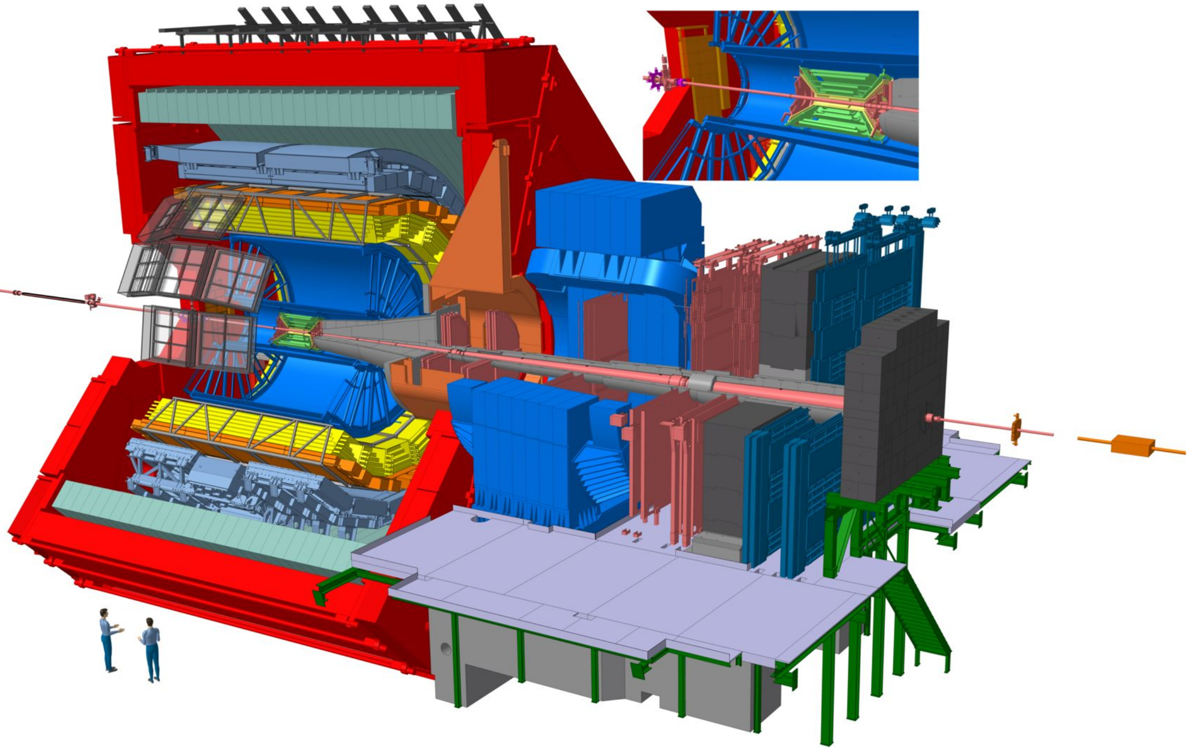


New J.Phys. 13 (2011) 055008

ALICE detector

Mid-rapidity ($|\eta| < 0.9$):

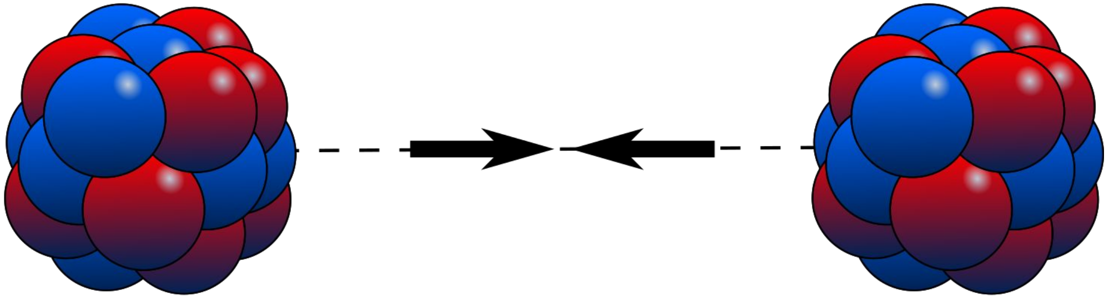
ElectroMagnetic Calorimeter
Time of Flight
Transition radiation detector
Time Projection Chamber
Inner Tracking System



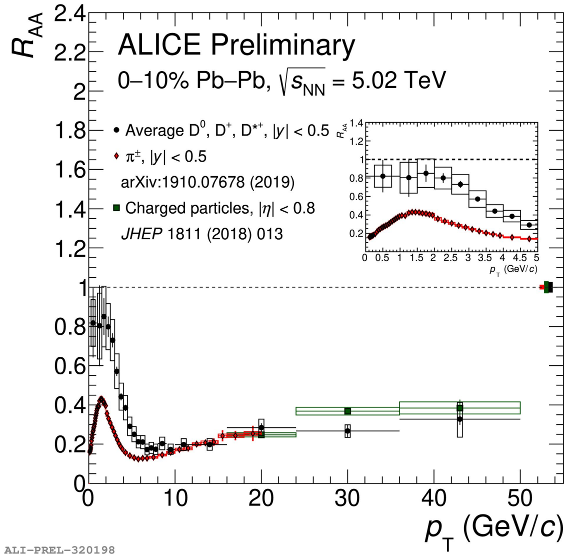
Forward rapidity ($-4 < \eta < -2.5$)
Muon tracking

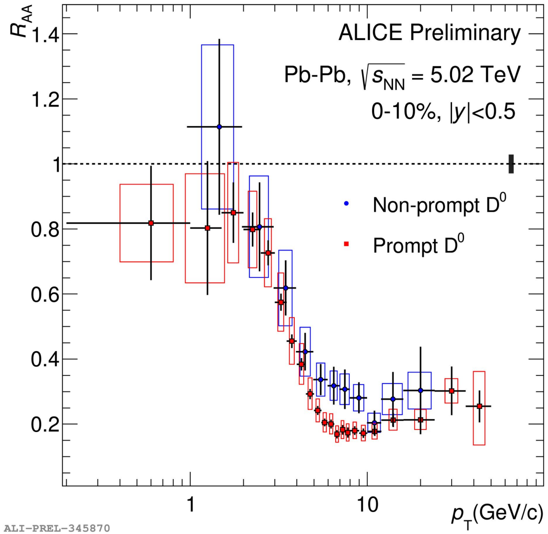
Int. J. Mod. Phys. A 29 (2014) 1430044
JINST3 S08002

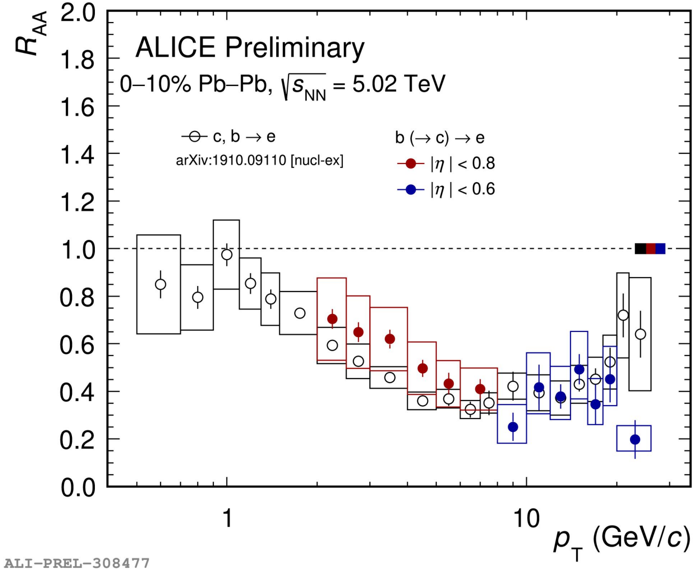
Results in Pb–Pb collisions



Open heavy-flavour R_{AA}





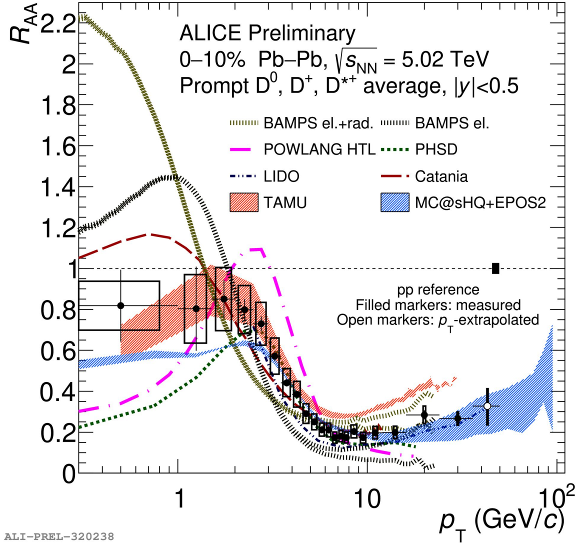


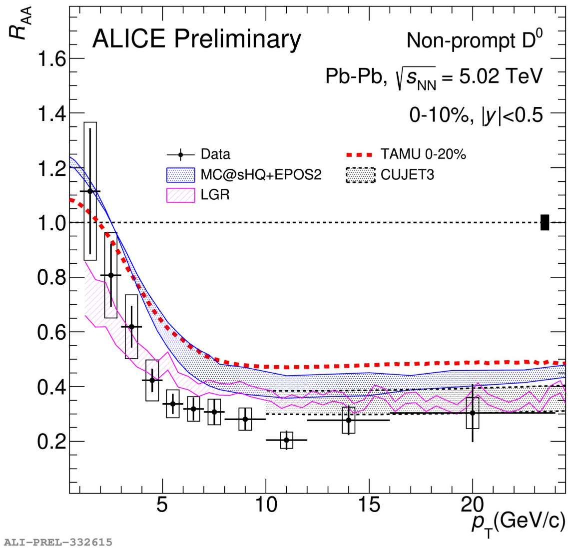
- Strong suppression of open heavy-flavour particles in Pb–Pb collisions
- Mass ordering:
  - $R_{AA}(\pi)$ < **R_{AA}(D)** (p_T < 10 GeV/c)
  - R_{AA}(c→D) < R_{AA}(b→D) (4 < p_T < 10 GeV/c)
  - Hint of **R_{AA}(c,b→e)** < R_{AA}(b→e) at low p_T

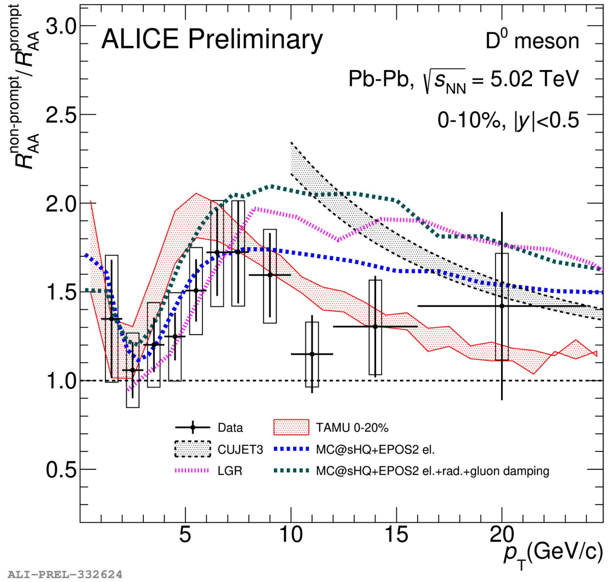
$R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$

Open heavy-flavour R_{AA}

Model comparisons



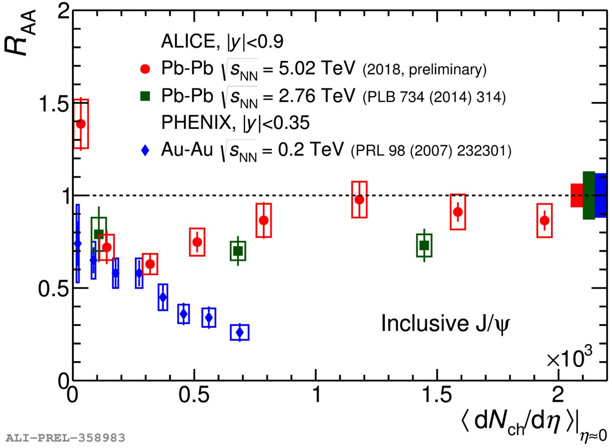


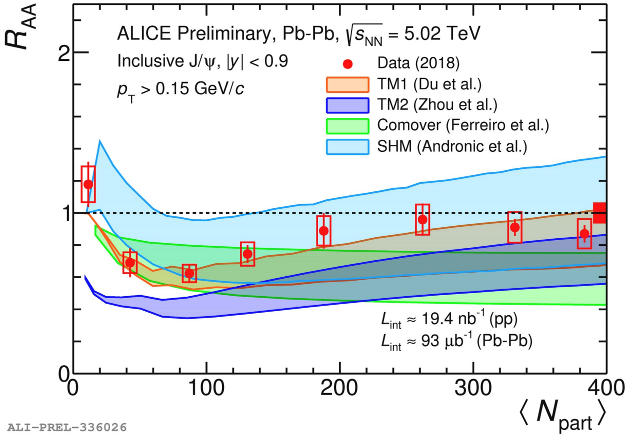


- Models including collisional (POWLANG, BAMPS el., TAMU) and collisional+radiative energy loss (BAMPS el.+rad., LIDO, PHSD, Catania, MC@sHQ+EPOS2, Djordjevic) can describe the suppression at high p_T (at least qualitatively)
- Models: TAMU, POWLANG, PHSD, MC@sHQ, LIDO and Catania include quark recombination

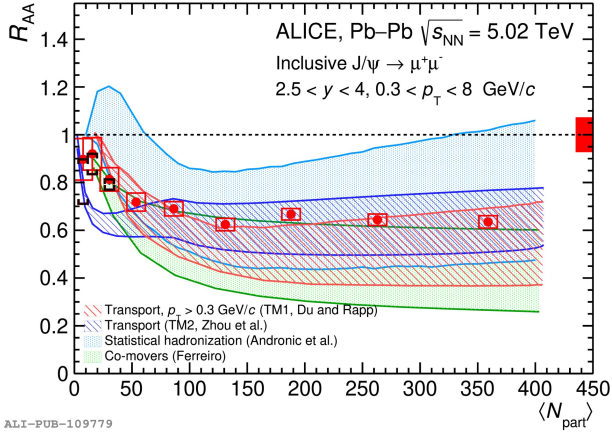
J/ψ R_{AA}

Centrality dependence





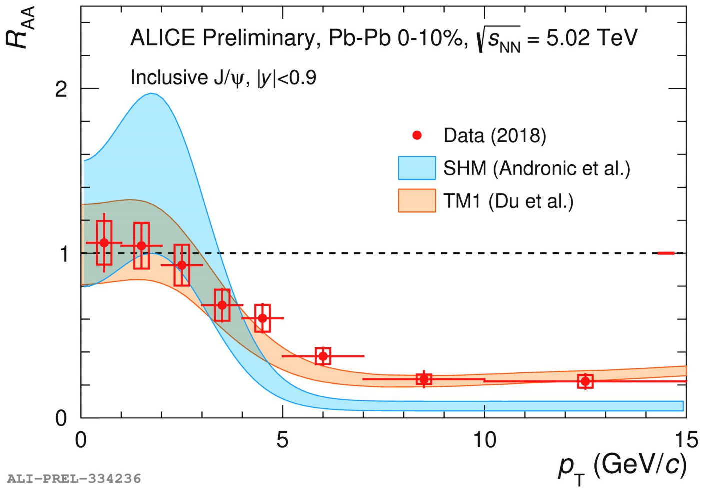
PLB 766 (2017) 212

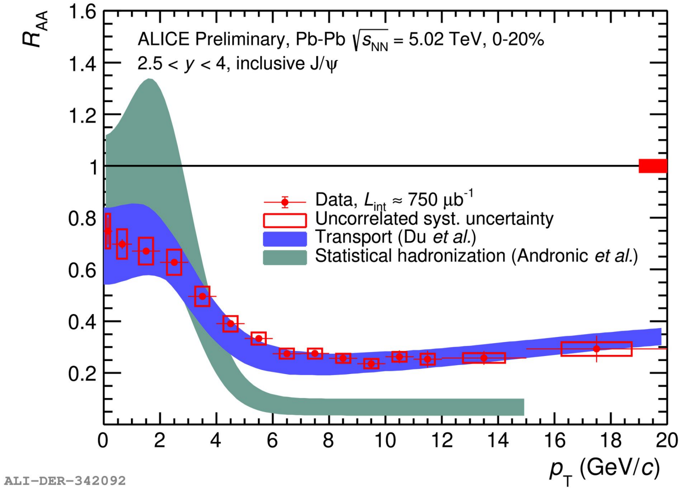


- Weaker suppression at higher collision energy
  - Effect predicted by regeneration models
- Models including charm-quark regeneration are in good agreement with the data in both mid- and forward-rapidity
  - TM1 and TM2: includes dissociation and regeneration in QGP and hadronic phase
  - Comovers: suppression via comovers interactions and includes regeneration
  - SHM: charmed particles are generated at chemical freeze-out

J/ψ R_{AA}

p_T dependence, mid vs. forward rapidity

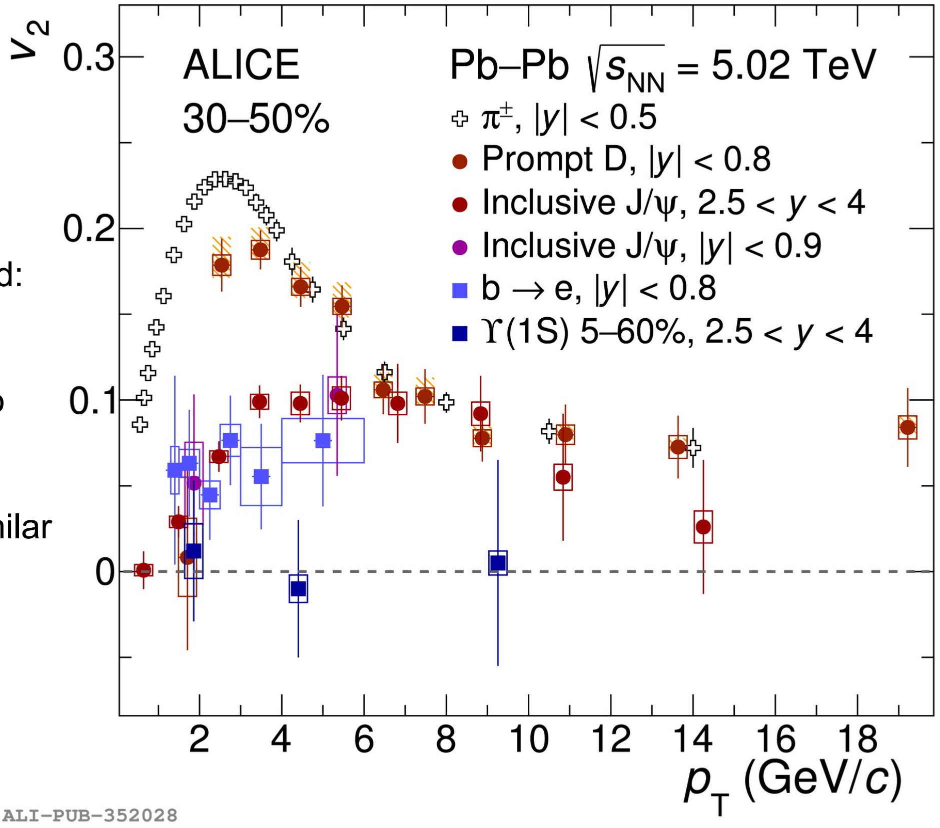




- p_T < 5 GeV/c: stronger suppression at forward rapidity.
- p_T > 5 GeV/c: similar suppression for mid- and forward-rapidity.
- Model uncertainties dominated by total ccbar cross section uncertainty
  - TM1 can describe the data over the whole p_T range for both mid- and forward-rapidities.
  - SHM describes the data qualitatively.

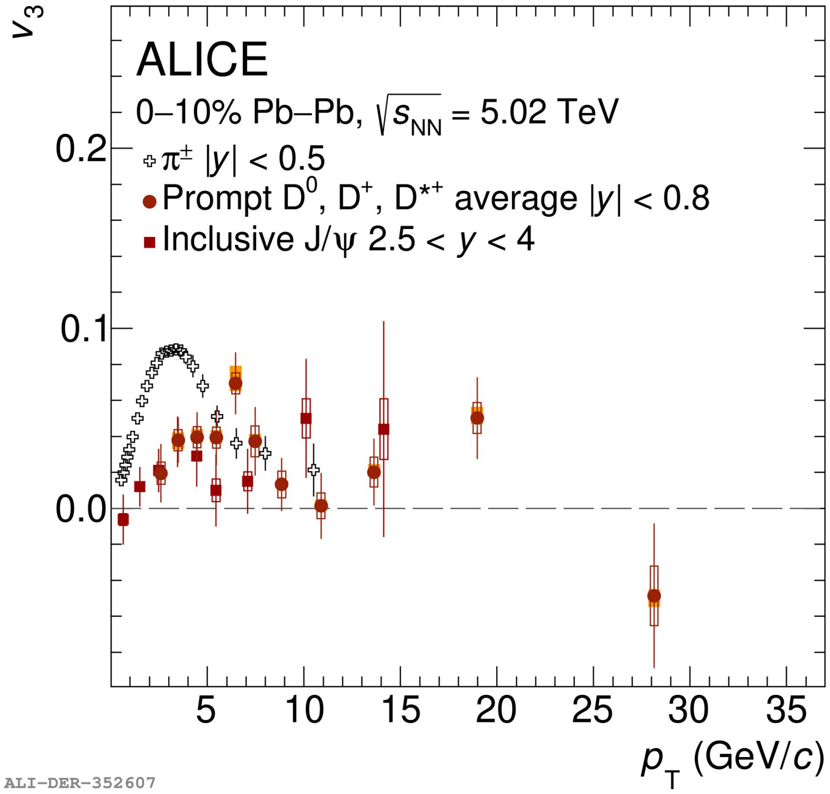
Elliptic flow

- Positive v_2 for prompt D mesons, J/ψ, b→e
- Υ(1S) v_2 compatible with zero
- For p_T < 3 GeV/c, a mass ordering can be observed: $v_2(\Upsilon(1S)) \lesssim v_2(b\to e) \sim v_2(J/\psi) < v_2(D) < v_2(\pi)$
- For 3 < p_T < 6 GeV/c: $v_2(J/\psi) < v_2(D) \sim v_2(\pi)$ due to charm quark thermalization
- For p_T > 6 GeV/c: $v_2(J/\psi) \sim v_2(D) \sim v_2(\pi)$ due to similar path-length dependence of the energy loss



JHEP 09 (2018) 006
arXiv:2005.11131
arXiv:2005.14518
arXiv:2005.11130
PRL 123 (2019)192301

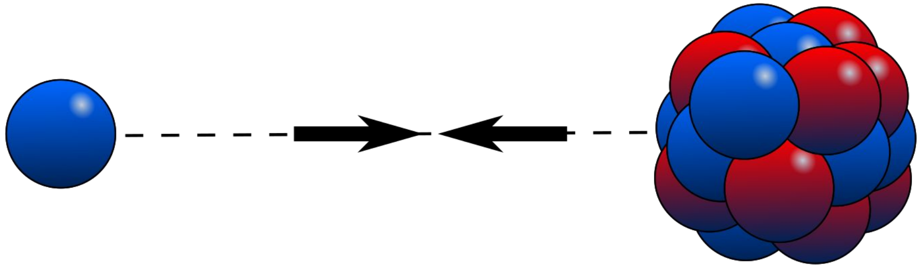
Triangular flow



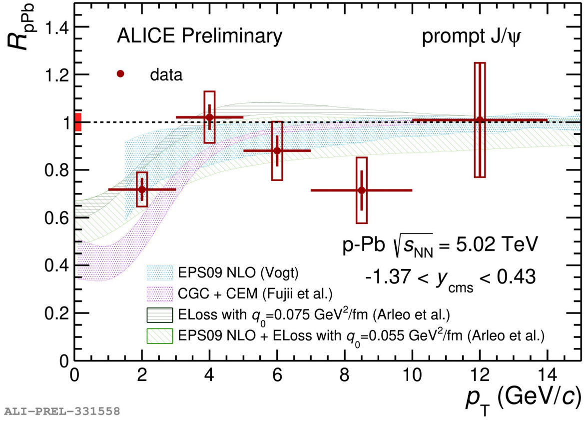
- v_3 of prompt D mesons, J/ψ and $\pi^{\pm}$
- For p_T < 5 GeV/c:
  - 0 < v_3(J/ψ) ~ v_3(D) < $v_3(\pi^{\pm})$
  - Indication that charm quarks are sensitive to initial state fluctuations

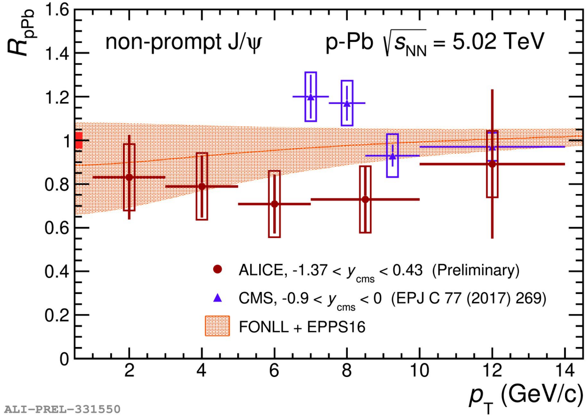
JHEP 09 (2018) 006
arXiv:2005.11131
arXiv:2005.14518

Results in p–Pb collisions

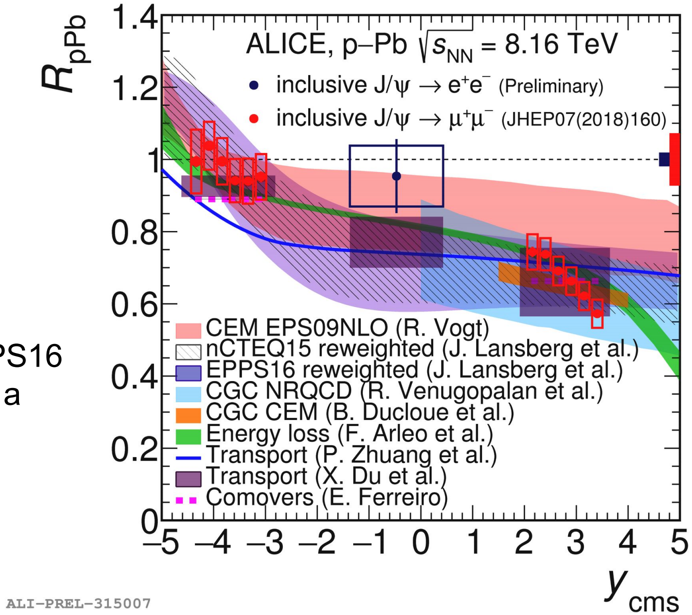


J/ψ R_{pPb}





- Prompt J/ψ is consistent with several model predictions: (EPS09-NLO, CGC+CEM, Energy loss and EPS09 NLO + energy loss)
- Non-prompt J/ψ: FONLL + EPPS16 agrees with data and suggests a small shadowing at low p_T



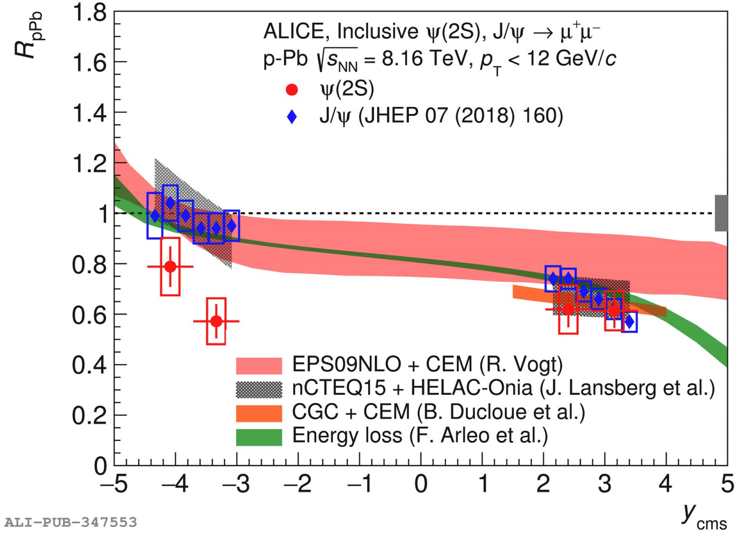
Theoretical models in good agreement with inclusive J/ψ, despite the very different approaches:

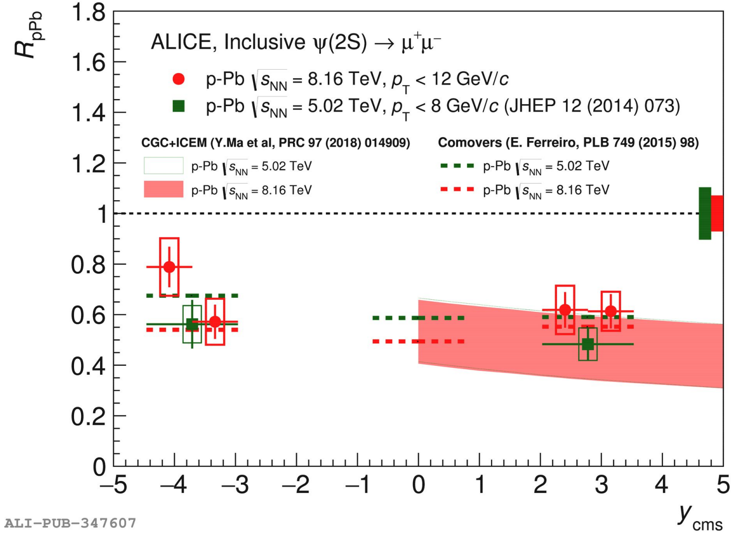
- Shadowing (EP09NLO, nCTEQ15, EPPS16)
- CGC (NRQCD, CEM)
- Energy loss
- Final state effects (Transport, comovers)

J/ψ vs. ψ(2S) R_{pPb}

mid vs. forward rapidity

JHEP 07 (2020) 237

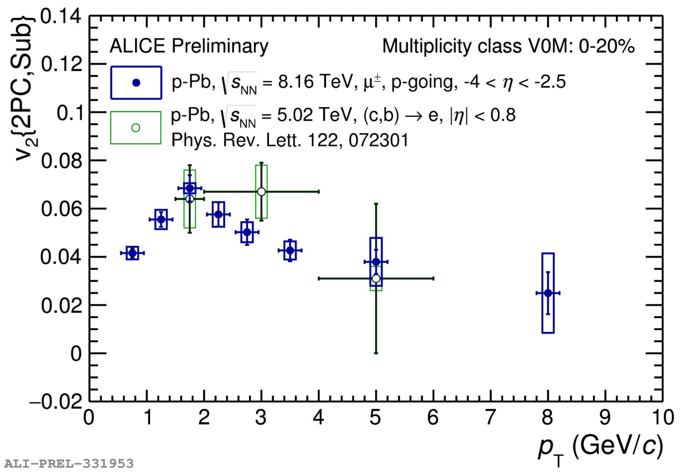


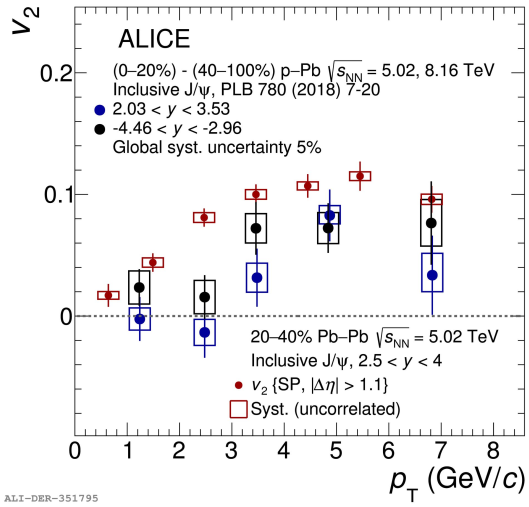


- ψ(2S): suppression compatible at forward and backward rapidities.
  - Stronger suppression than J/ψ at backward rapidity, whereas compatible at forward rapidity.
  - Secondary interactions proposed as mechanism to explain this effect

Elliptic flow in p–Pb

- Light-flavour particles flows in p–Pb following a mass ordering → collective behaviour in small systems
- What about heavy-flavour?



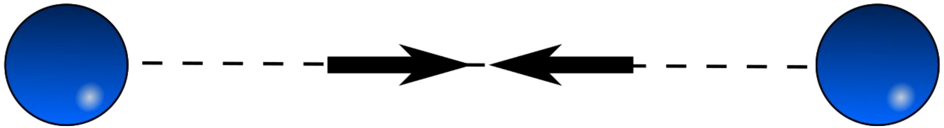


- Non-zero v_2 for electrons and muons from heavy-flavour lepton decays

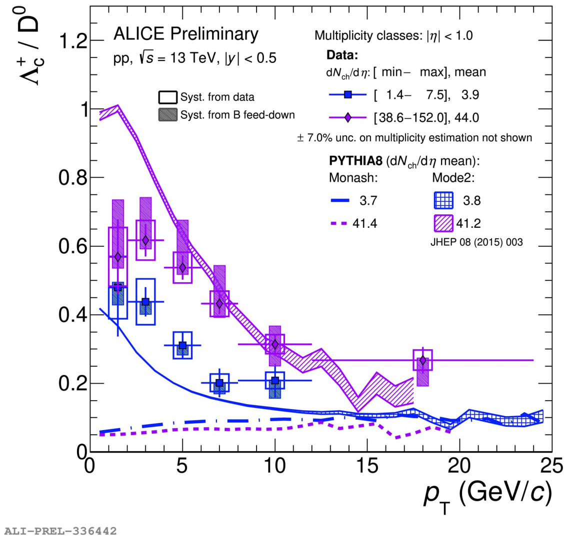
- v_2 of J/ψ
  - Consistent with zero for p_T < 3 GeV/c
  - v_2 > 0 for p_T > 3 GeV/c with similar amplitude as measured in semi-central Pb–Pb collisions

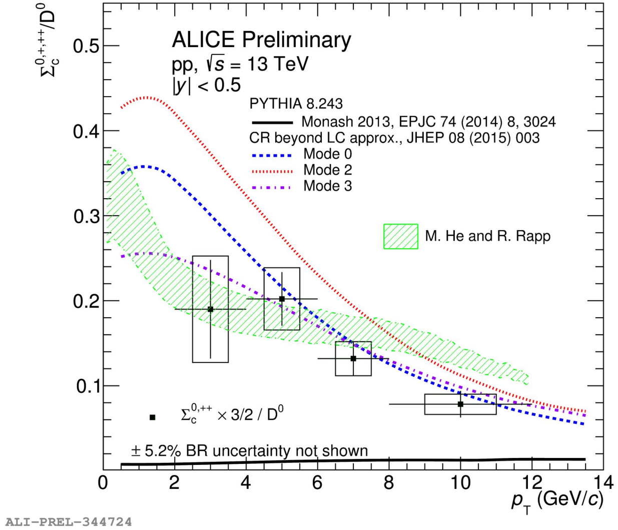
- Possible final states effects and collective motion

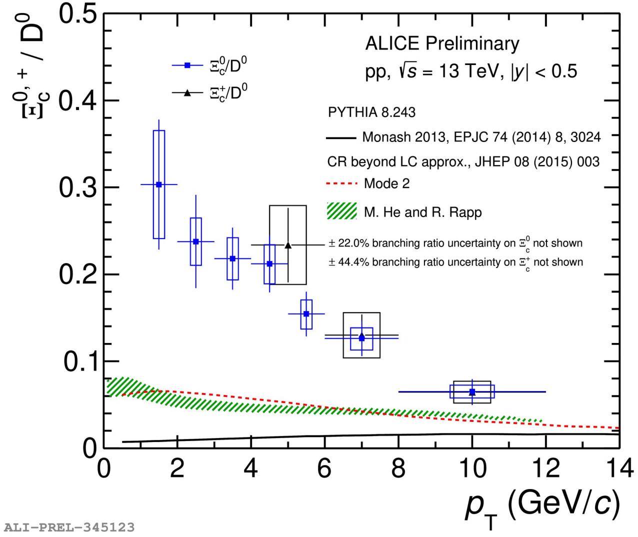
Results in pp collisions



Open heavy-flavour production vs. multiplicity



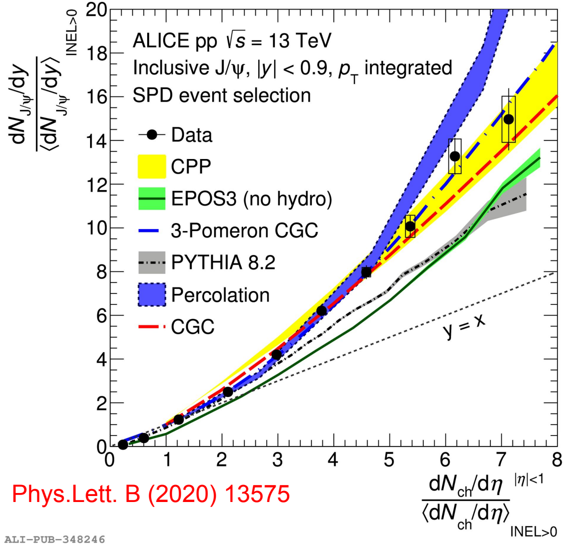




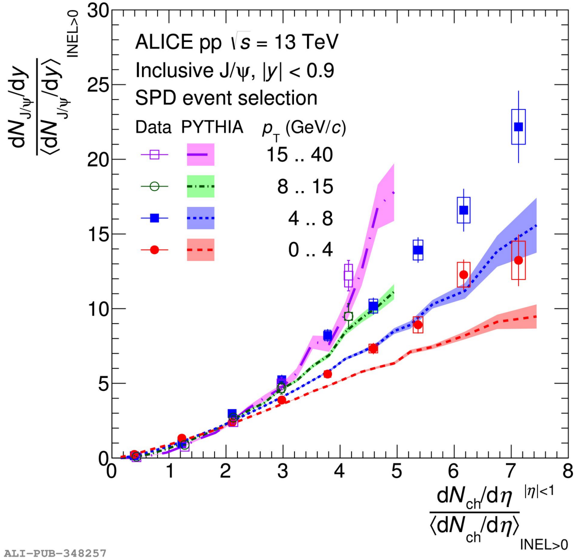
- Λ_c^+/D^0, $\boldsymbol{\Sigma}_c/D^0$ and $\boldsymbol{\Xi}_c/D^0$
  - Shows a higher value than in e^+e^- collisions
  - Increases from low to high multiplicity (Λ_c^+/D^0)
  - Modification not captured by standard hadronization models
- No hadronization universality between e^+e^- and pp
- PYTHIA 8 with Color Reconnection: reasonable reproduction for Λ_c^+/D^0 and $\boldsymbol{\Sigma}_c/D^0$ but not $\boldsymbol{\Xi}_c/D^0$
- Violation of universal hadronization fractions

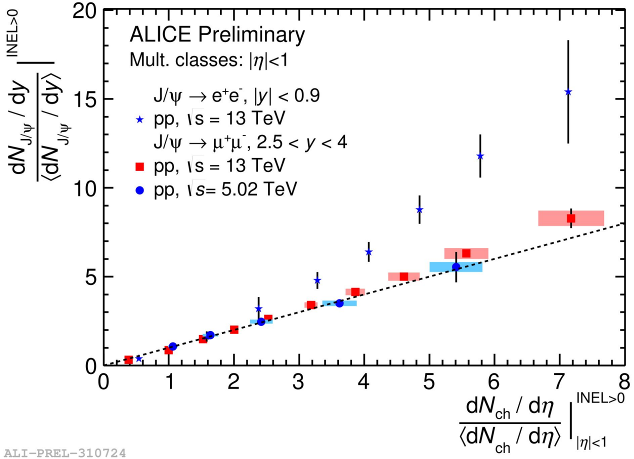
J/ψ production vs. multiplicity

Looking for collective behaviour in small systems



Phys.Lett. B (2020) 13575





- J/ψ self normalized yield
  - Mid-rapidity: increase faster than linear
    - Enhancement qualitatively described by several model calculations
      - PYTHIA8 which includes multi-parton interactions describes qualitatively the p_T dependence
    - Higher enhancement for higher p_T
  - Forward-rapidity: shows a linear increase

Conclusions

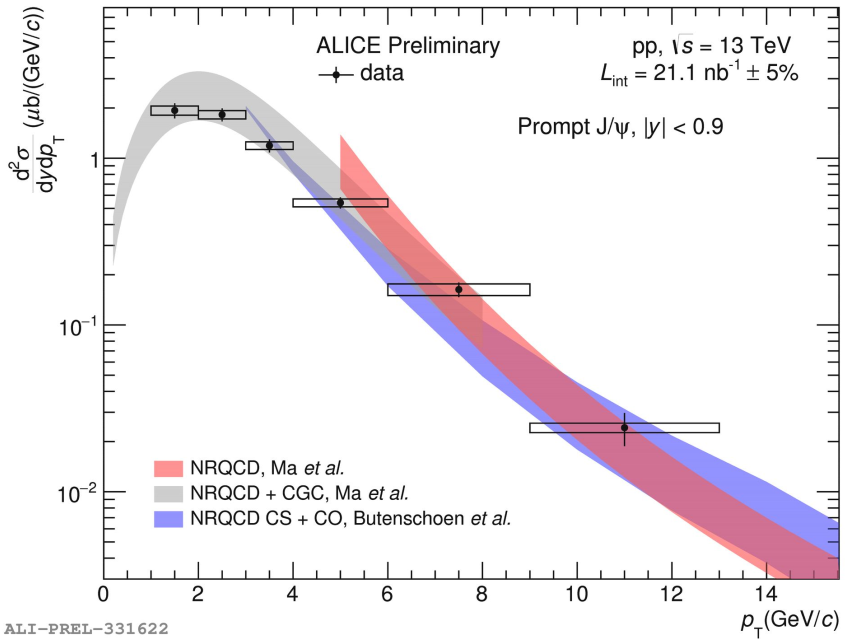
- **Pb–Pb collisions:**
    - Charm diffusion and energy loss constrained by azimuthal anisotropies and nuclear modification factor of heavy-flavour hadrons
    - Beauty measurements indicate partial thermalisation and weaker energy loss
    - Quarkonium indicating strong regenerated component at late stage

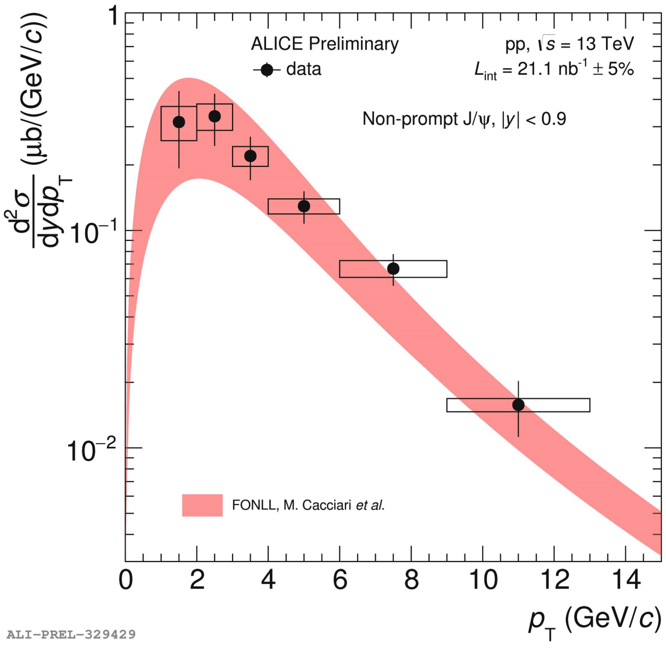
- **pp and p–Pb collisions:**
    - Similar behaviour as in Pb–Pb collisions for hadronization and azimuthal anisotropies;
    - Hint of multi-parton interactions affecting the J/ψ yield.

Thank you for your attention!

Backup slides

Heavy-flavour production in pp collisions





- Prompt J/ψ described by NRQCD calculations
- Non-prompt J/ψ described by FONLL calculations