# ALICE heavy-ion results

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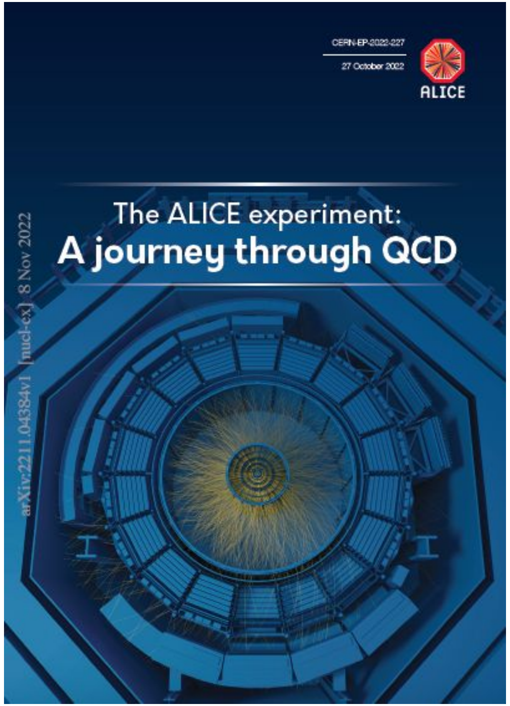
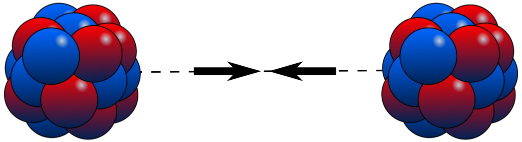


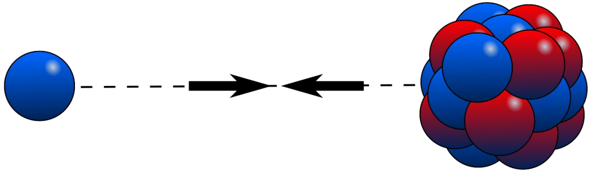

arXiv:2211.04384v1

# Collision systems

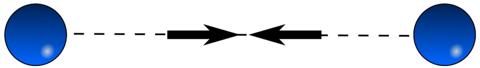




- Pb–Pb collisions:
  - Quark-gluon plasma (QGP) formation and its properties
    - Equation-of-state, transport coefficients...
  - In-medium energy loss
    - Colour-charge and quark-mass dependence
    - Jet modification
  - Thermalisation of quarks



- p–Pb collisions:
  - Cold nuclear matter effects can be studied:
    - Nuclear modification of parton densities
    - Propagation in nucleus and in medium



- pp collisions:
  - Reference for studies with p–Pb collisions and Pb–Pb collisions
  - Studies of several aspects of QCD

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

# Probes

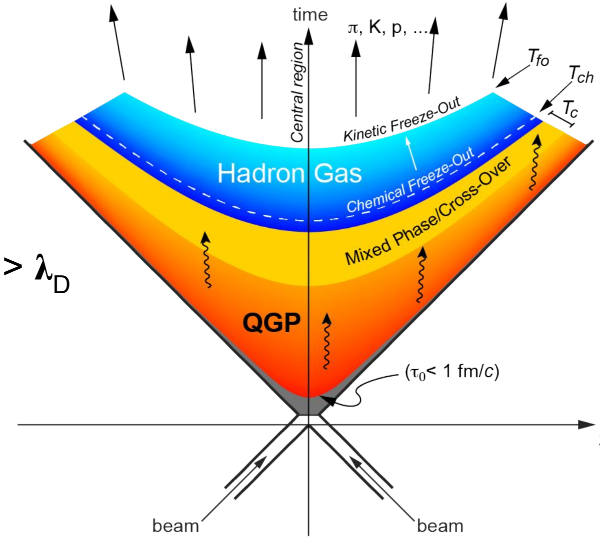
- **Charm and beauty** are produced (in hard scatterings) in the early stages of the collision:
  - ✓ Large mass ($m_{c,b} >> \Lambda_{QCD}$ )
    → short formation time
    → hard probes, even at low $p_T$

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

(Matsui & Satz, PLB178 (1986) 416)
(Andronic et al, Nucl.Phys.A772:167-199,2006) (Thews et al, Phys. Rev. C63 (2001) 054905)

- **Light-flavour particles** are created in soft or hard process
  - ✓ Soft: bulk of particles produced at low transverse momenta ($p_T$ < 2 GeV/$c$)
    → QCD inspired phenomenological models
  - ✓ Hard: particles with $p_T$ > 2 GeV/$c$, described by pQCD.

- Hydrodynamic expansion of the QGP and the mechanisms of its hadronization
  - ✓ Statistical hadronization model, coalescence...



# Observables



## The nuclear modification factor

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

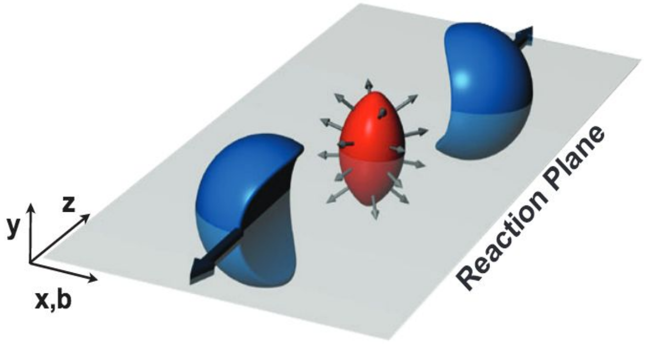
- If $R_{AA}$ = 1: no hot medium effects and no cold nuclear matter effects.
- If $R_{AA}$ < 1 : hot or cold nuclear matter effects.
- For heavy-quarks, the energy loss is expected to depend on the parton colour-charge, parton mass and path length.

$\Delta E$(g,u,d,s) > $\Delta E$(c) > $\Delta E$(b) $R_{AA}(\pi)$ < $R_{AA}$(D) < $R_{AA}$(B) Dokshitzer et al 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




Snellings, New J.Phys. 13 (2011) 055008

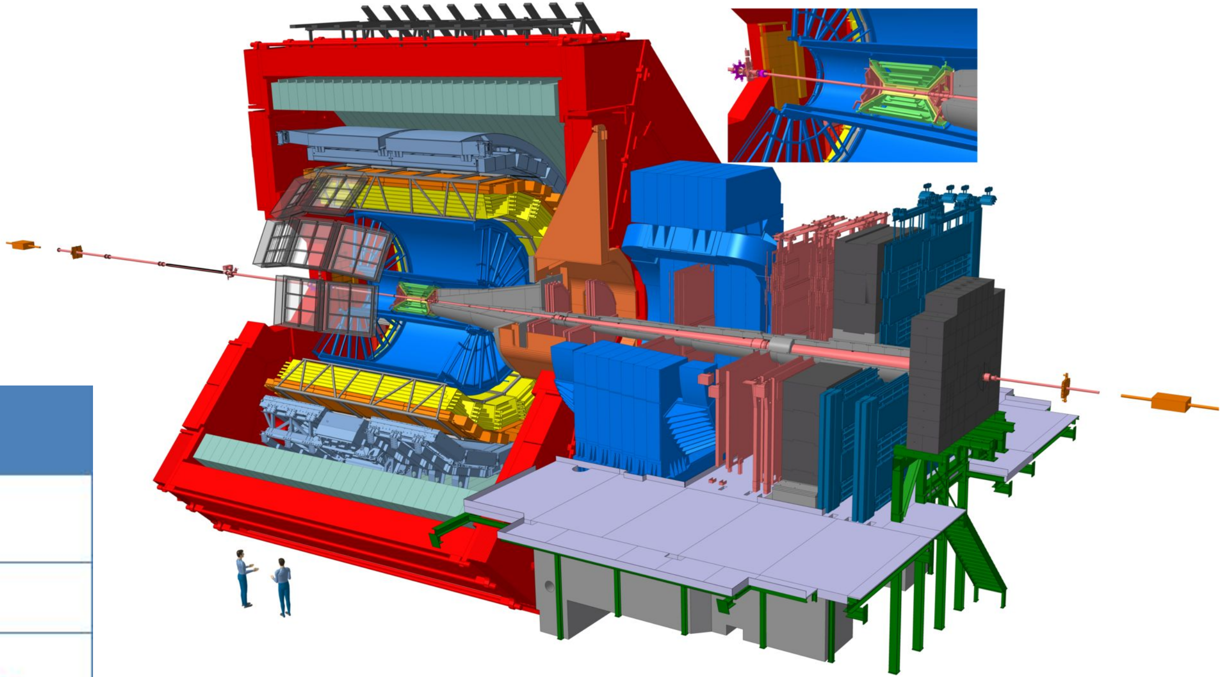
# ALICE detector (Run 2)



Midrapidity ($|\eta| < 0.9$):

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

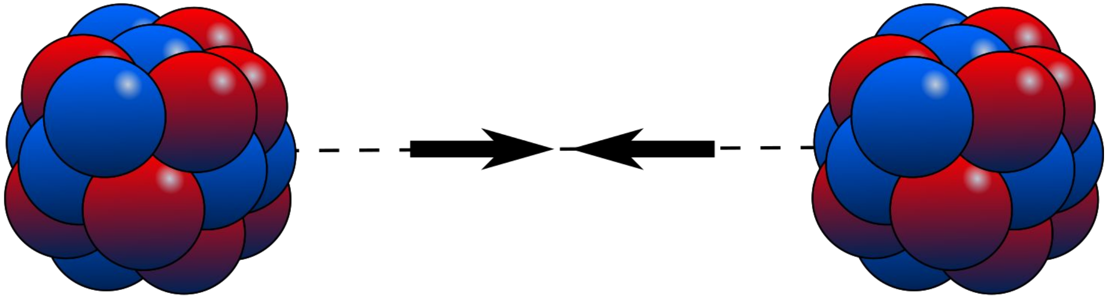
| System | Year(s) | $\sqrt{s_{NN}}$ (TeV) | $L_{int}$ |
|---|---|---|---|
| Pb-Pb | 2010, 2011<br>2015, 2018 | 2.76<br>5.02 | 75 $\mu b^{-1}$<br>800 $\mu b^{-1}$ |
| Xe-Xe | 2017 | 5.44 | 0.3 $\mu b^{-1}$ |
| p-Pb | 2013<br>2016 | 5.02<br>5.02, 8.16 | 15 $nb^{-1}$<br>3 $nb^{-1}$, 25 $nb^{-1}$ |
| pp | 2009-2013<br><br>2015, 2017<br>2015-2018 | 0.9, 2.76,<br>7, 8<br>5.02<br>13 | 200 $\mu b^{-1}$, 100 $nb^{-1}$<br>1.5 $pb^{-1}$, 2.5 $pb^{-1}$<br>1.3 $pb^{-1}$<br>36 $pb^{-1}$ |



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

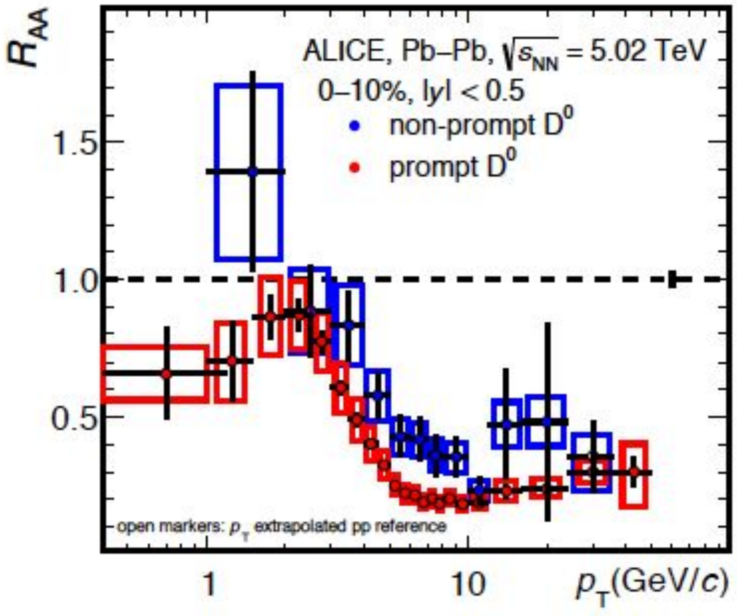
Int. J. Mod. Phys. A 29 (2014) 1430044
JINST3 S08002

# Results in Pb–Pb collisions

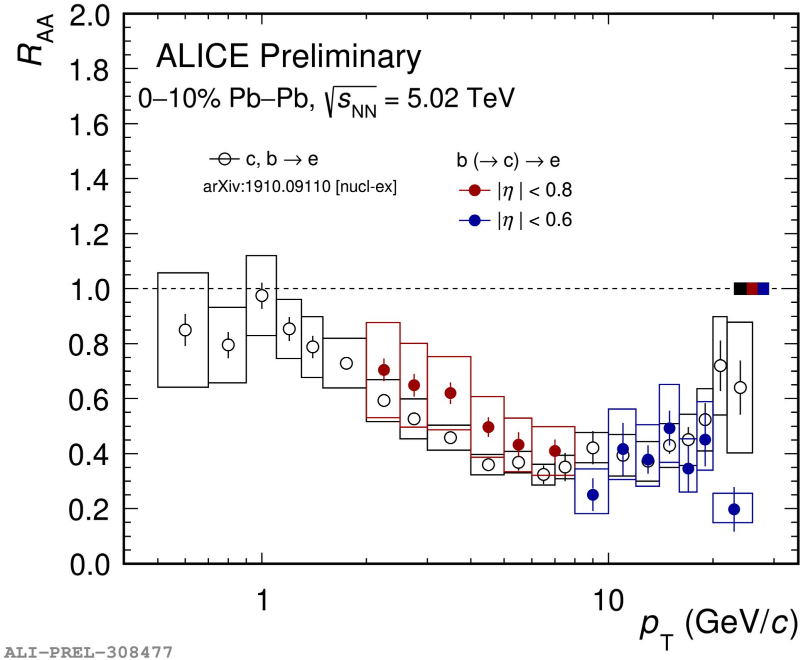


# Open heavy-flavour $R_{AA}$





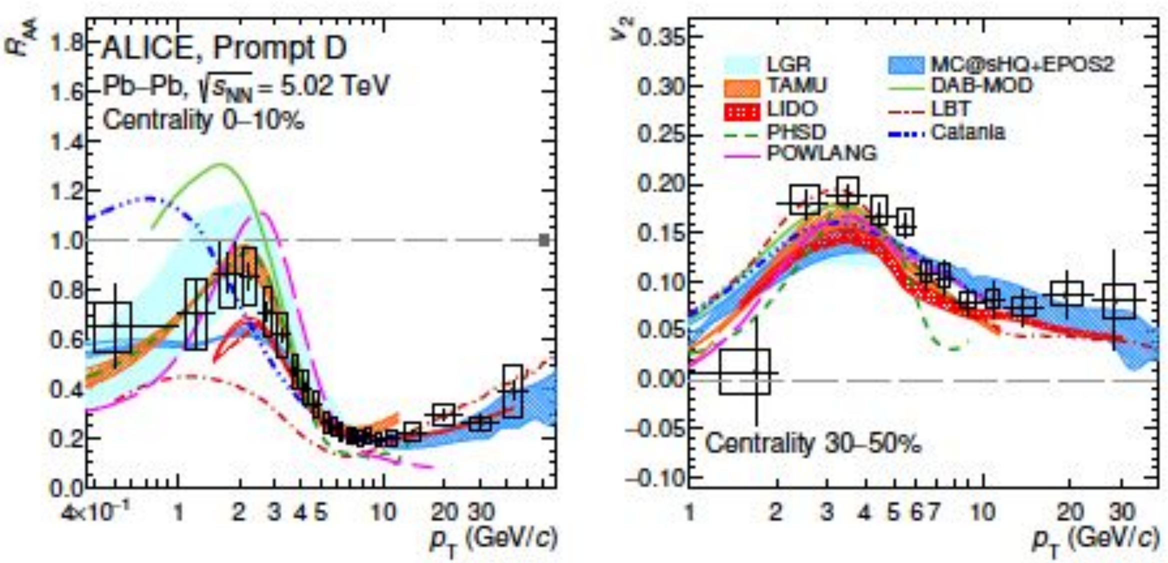

arXiv:2202.00815




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

# Open heavy-flavour $R_{AA}$





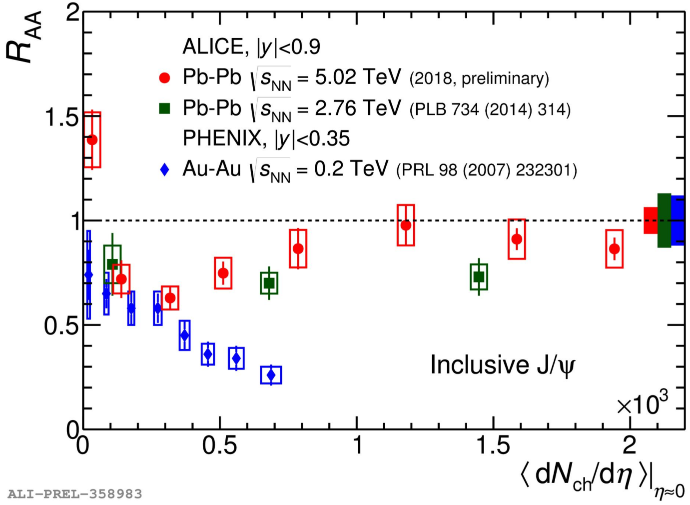

arXiv:2211.04384v1

- Models including collisional (POWLANG, TAMU) and collisional+radiative energy loss (LIDO, PHSD, Catania, MC@sHQ+EPOS2) can describe the suppression at high $p_T$ (at least qualitatively)
- Models: TAMU, POWLANG, PHSD, MC@sHQ, LIDO and Catania include quark recombination
- Non zero elliptic flow described by model calculations

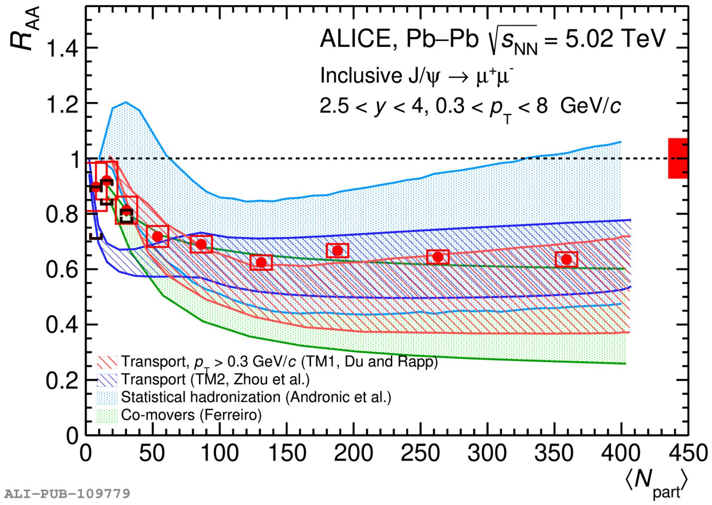
# J/ψ $R_{AA}$



## 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
  - 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

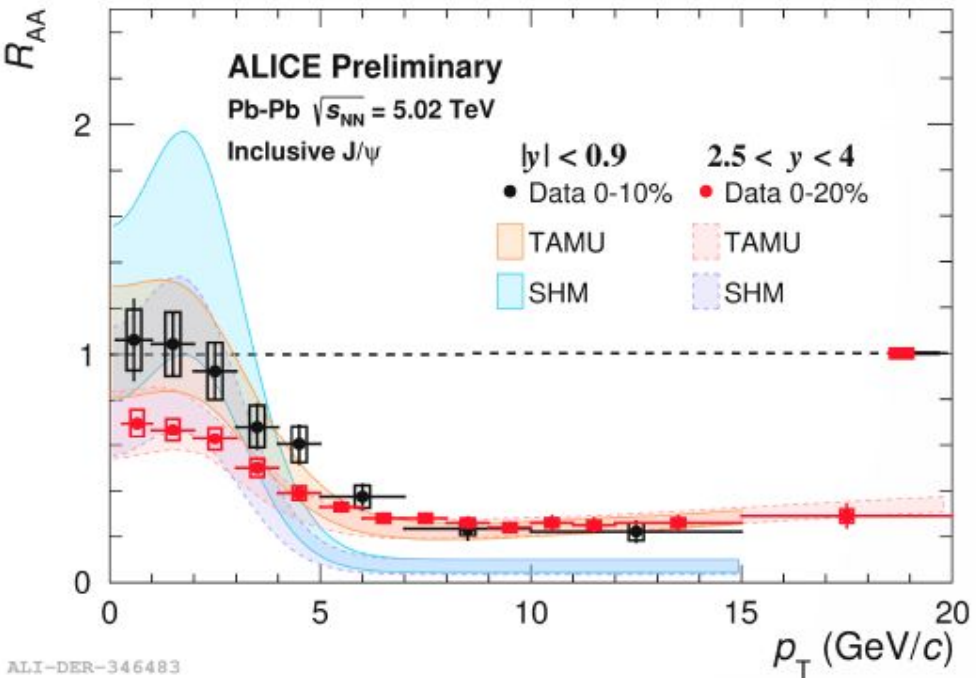
# J/ψ $R_{AA}$



## $p_T$ dependence, mid vs. forward rapidity

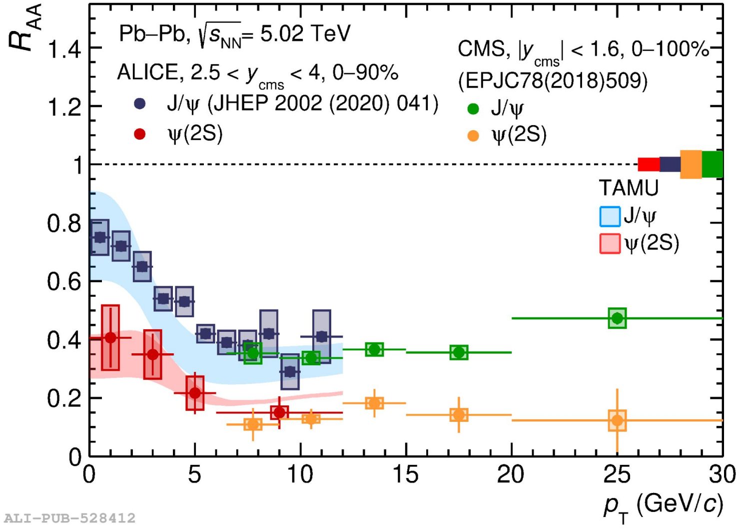
- $p_T$ < 5 GeV/$c$: stronger suppression at forward rapidity.
- $p_T$ > 5 GeV/$c$: similar suppression for midrapidity and forward rapidity.

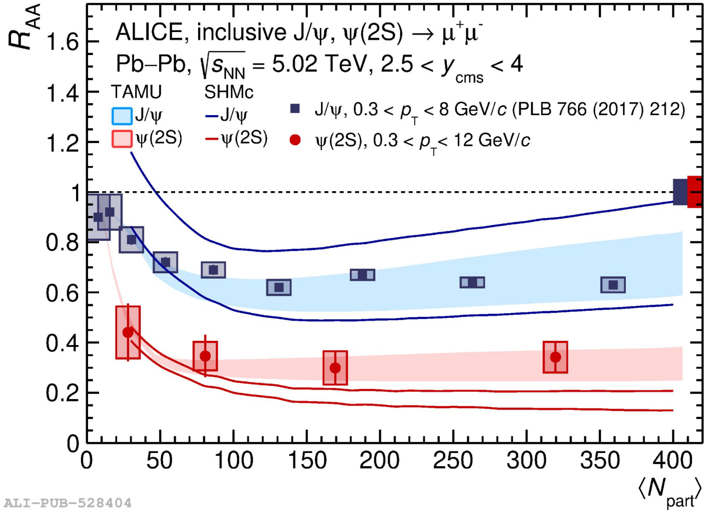
- Model uncertainties dominated by total ccbar cross section uncertainty
  - **TAMU** can describe the data over the whole $p_T$ range for both mid and forward rapidities.
  - **SHM** describes the data qualitatively.



# $\psi(2S)$ $R_{AA}$





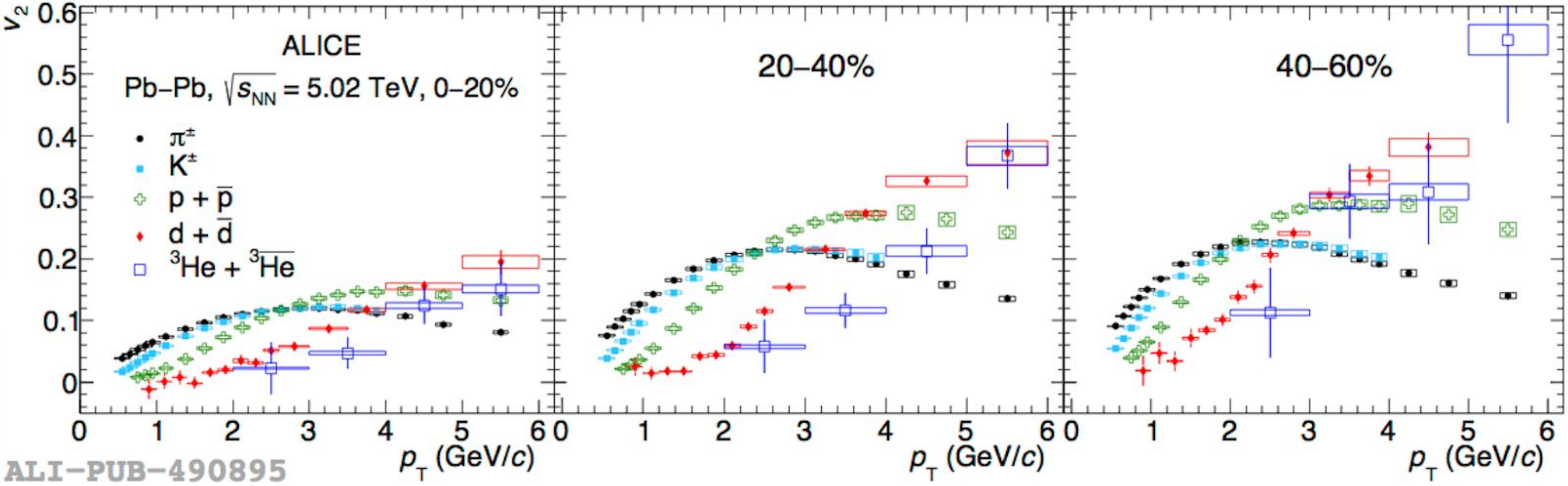

arXiv:2210.08893v2

- $\psi(2S)$ $R_{AA}$ show a hint for a decrease as a function of $p_T$
  → also observed for the J/ψ (charm quark recombination processes)
- $\psi(2S)$ $R_{AA}$ ~ 0.4 independent of centrality.
- The transport model, slightly better reproduces the results for central events.
- A relative suppression by a factor 2 of the $\psi(2S)$ with respect to the J/ψ is observed, with no significant $p_T$ or centrality dependence within the uncertainties

# Elliptic flow (light flavour)



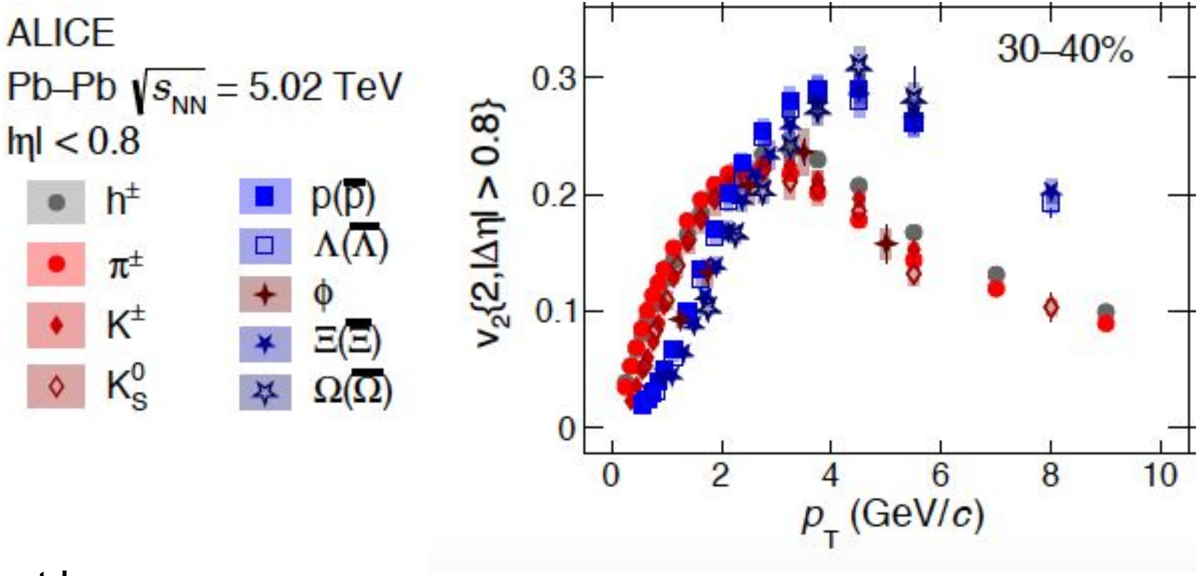
- Light-flavour particles flows in Pb–Pb:
  - A clear mass ordering of $v_2$ is observed at low $p_T$, as expected for a system expansion driven by the pressure gradient as described by relativistic hydrodynamics




Phys. Rev. C 102 (2020) 055203

# Elliptic flow (light flavour)






arXiv:2206.04587

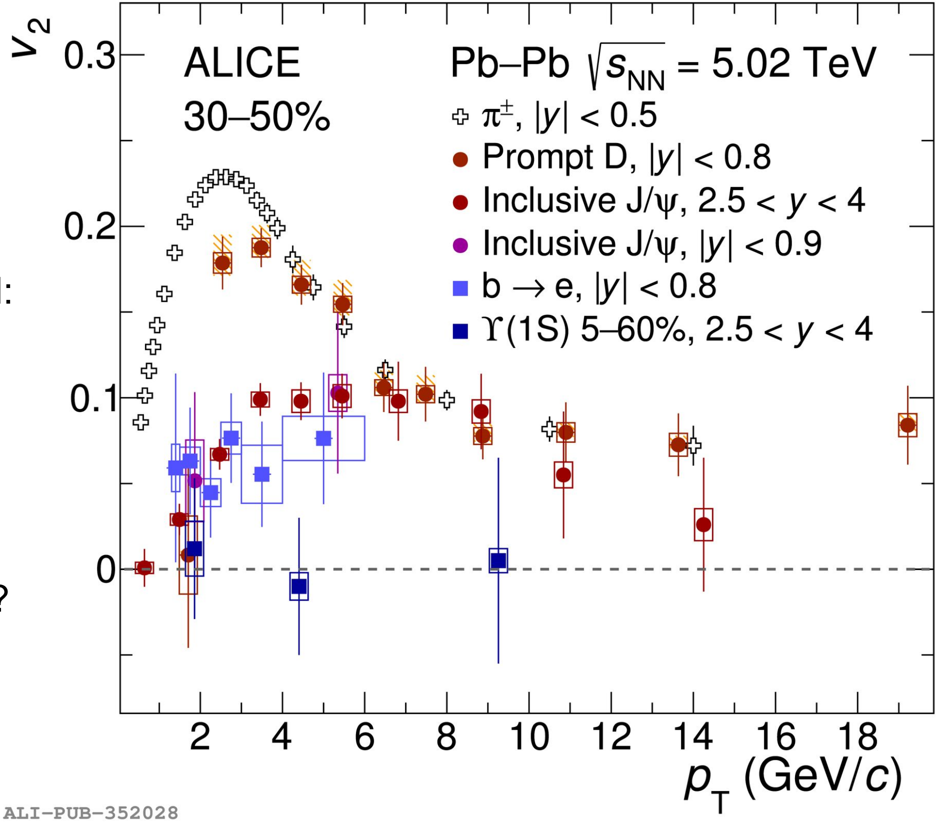
- Mass ordering at low $p_T$
  → due to hydrodynamic flow

- Grouping of baryons and mesons at intermediate $p_T$
  → quark level flow + recombination

# Elliptic flow (heavy flavour)



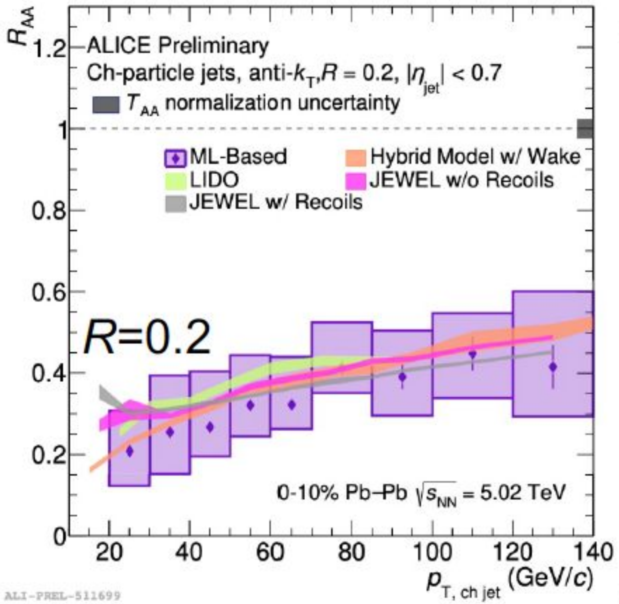
- Positive $v_2$ for prompt D mesons, J/ψ, b→e
- $\Upsilon$(1S) $v_2$ compatible with zero
- For $p_T < 3$ GeV/$c$, a mass ordering can be observed: $v_2(\Upsilon(1S)) \lesssim v_2(b\rightarrow e) \sim v_2(J/\psi) < v_2(D) < v_2(\pi)$
- For $3 < p_T < 6$ GeV/$c$: $v_2(J/\psi) < v_2(D) \sim v_2(\pi)$ 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 ?

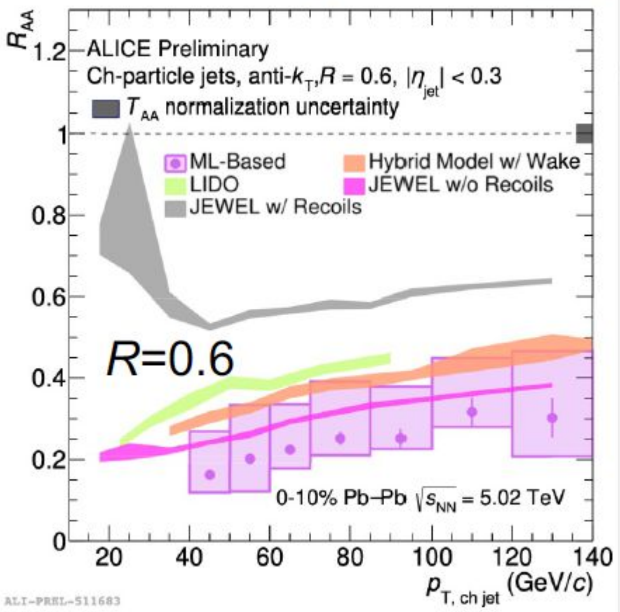



JHEP 09 (2018) 006
PLB 813 (2021) 136054
JHEP 10 (2020) 141
PRL 126, 162001 (2021)
PRL 123 (2019)192301

# Jet quenching

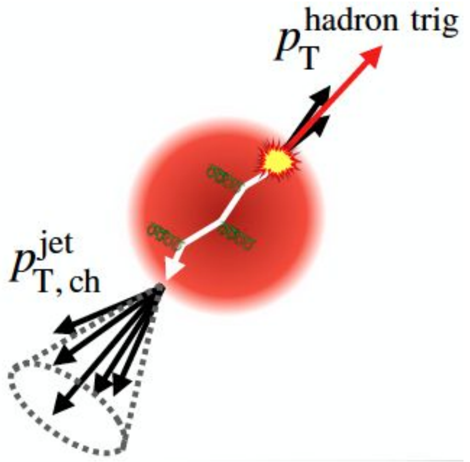
- Charged-particle jets obtained using Machine Learning to subtract the background
  - Measurement extended to lower jet $p_T$ and large R
  - Large suppression of jets



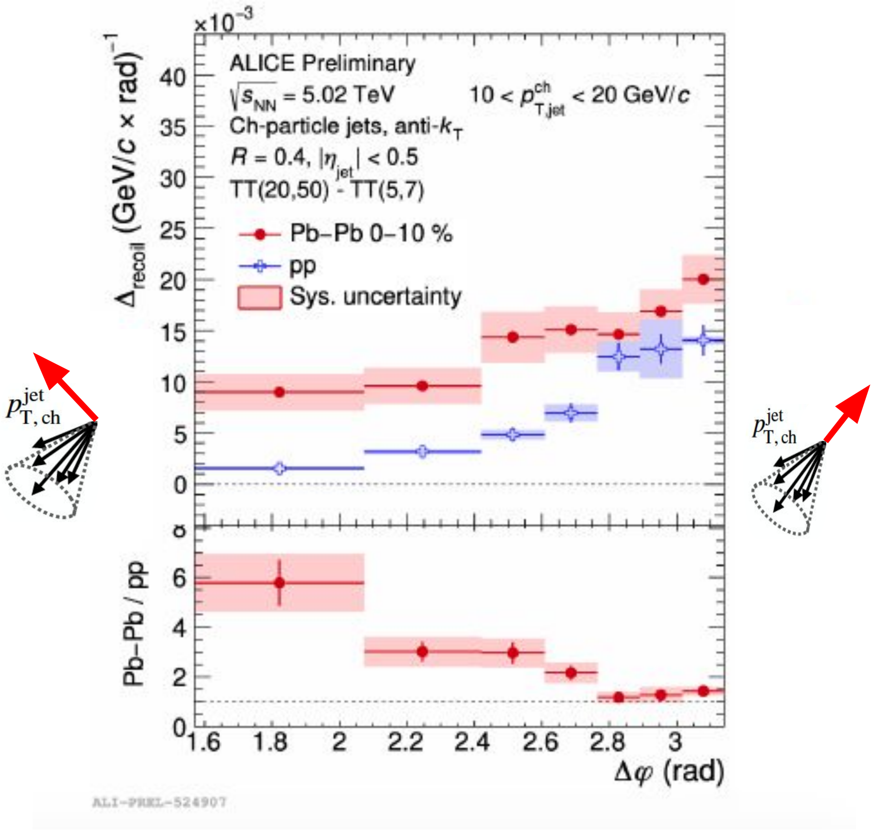



# Jet-hadron correlations



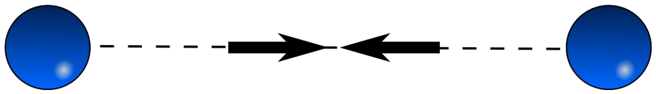


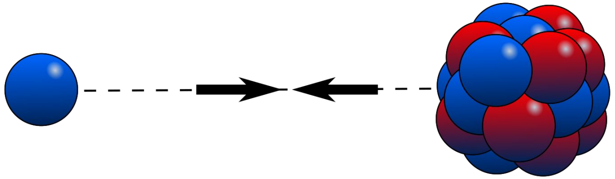

- Semi-inclusive soft jets are deflected
- Jets recoiling from high $p_T$ hadrons
- $\Delta_{recoil}$ vs $\Delta\varphi$ is broader in Pb-Pb than in pp
- **Scattering on medium?**
- **Multiple soft scattering?**



# Results in small systems

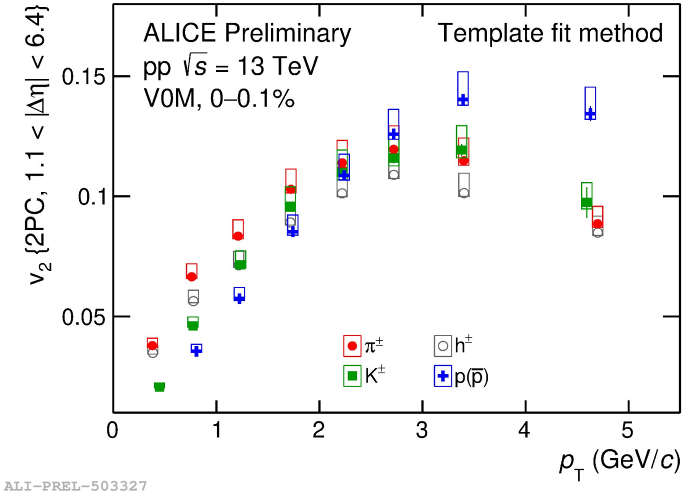


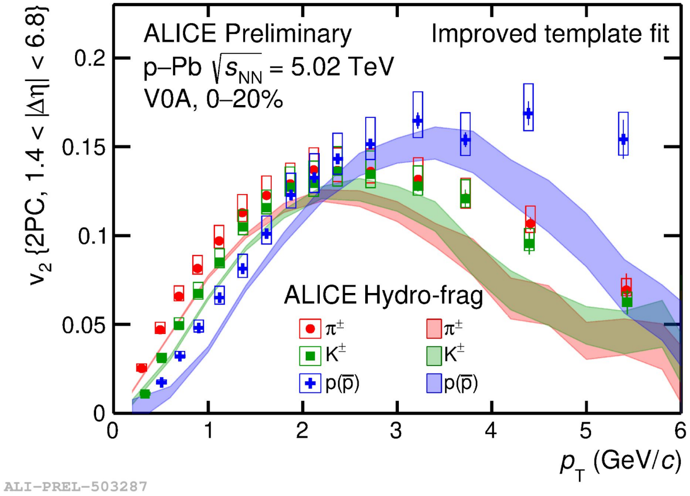




# Elliptic flow in small systems

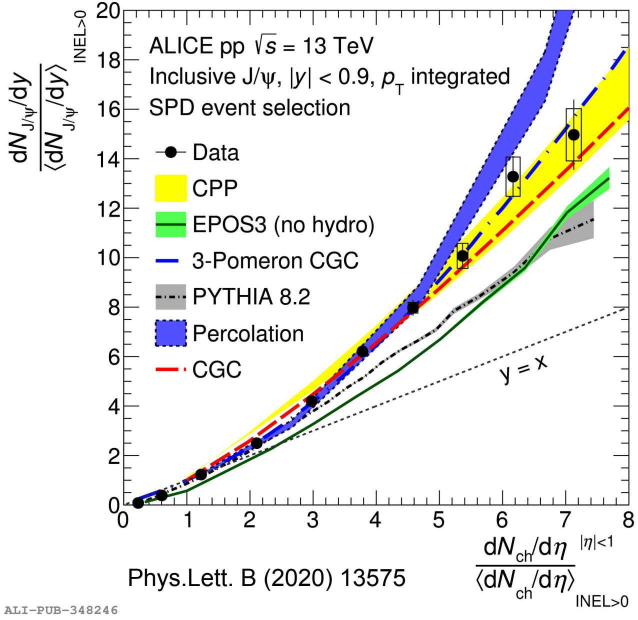


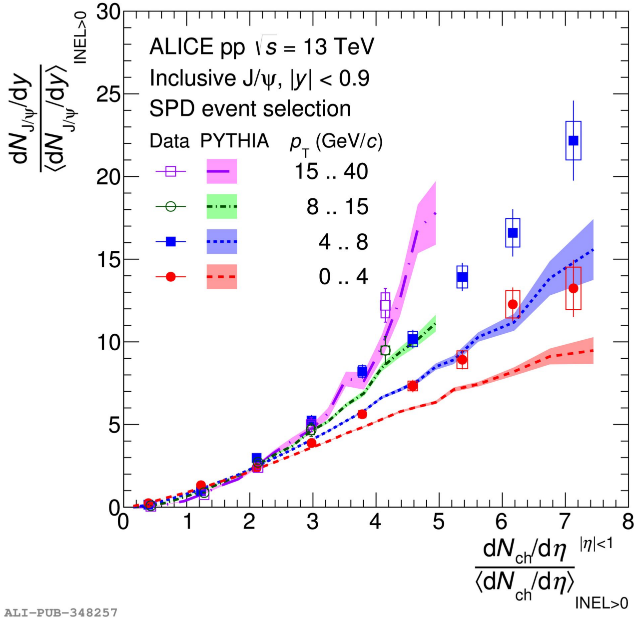



- Grouping of baryons and mesons at intermediate $p_T$ for high multiplicity pp and p-Pb collisions
  - Similar behaviour as in Pb-Pb collisions
- Model comparison for p-Pb results indicates quark level flow + recombination

# J/ψ production vs. multiplicity




**See F. Colamaria talk on small systems: Thursday, 12:30**

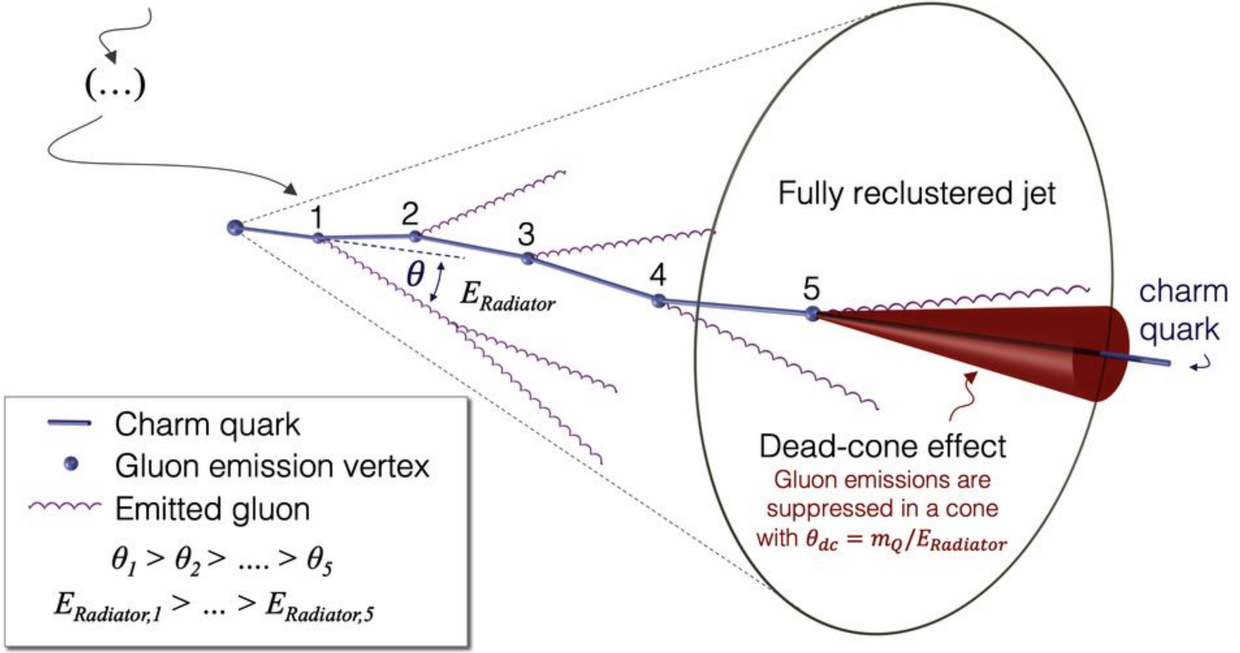
- J/ψ self normalized yield
  - Midrapidity: increase faster than linear
    - Enhancement qualitatively described by several model calculations
      - PYTHIA8 which includes multi-parton interactions describes qualitatively the $p_T$ dependence
    - Higher enhancement for higher $p_T$

# First direct observation of dead cone effect



- Suppression of the gluon spectrum emitted by a heavy quark of mass *m* and energy *E*:
  - Cone of angular size *m*/*E* around the emitter

Nature 605 (2022) 440-446

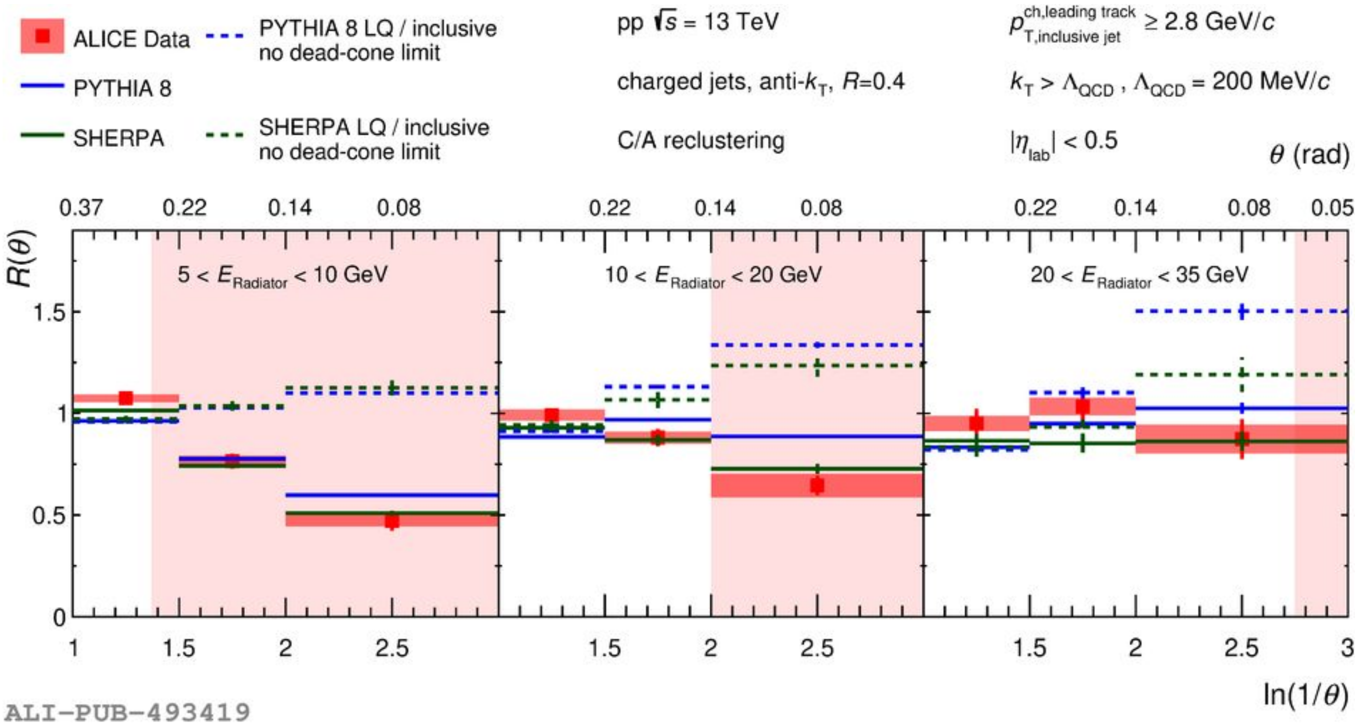



- Reclustering the jet constituents according to the Cambridge-Aachen algorithm:
  - Angular distance from one another

# First direct observation of dead cone effect



- Ratio of the splitting angle distributions for $D^0$-meson tagged jets and inclusive jets, in bins of $E_{Radiator}$
- Radiation suppressed in the expected areas (shaded)




Nature 605 (2022) 440-446

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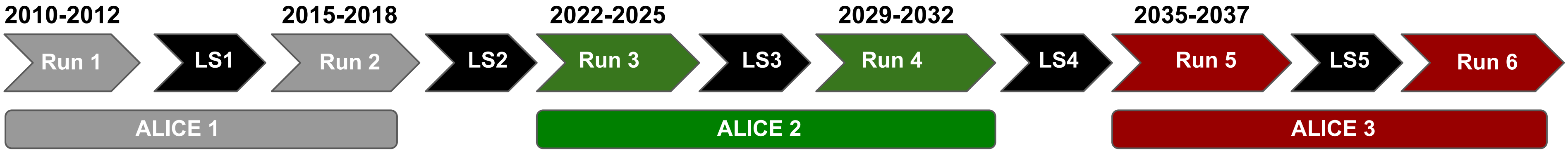
# ALICE future perspectives

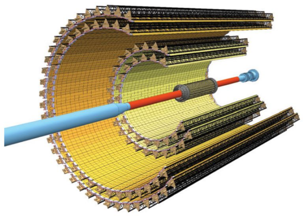


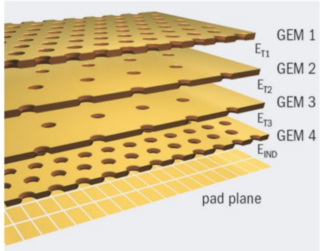
# ALICE future perspectives

| 2010-2012 | | 2015-2018 | | 2022-2025 | | 2029-2032 | | 2035-2037 | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Run 1 | LS1 | Run 2 | LS2 | Run 3 | LS3 | Run 4 | LS4 | Run 5 | LS5 | Run 6 |
| ALICE 1 | | | | ALICE 2 | | | | ALICE 3 | | |

## Run 3:

- new readout for all detectors
- new TPC readout (GEMs)
- new Fast Interaction Trigger (FIT)
- new silicon trackers (MFT & ITS2)
- new online/offline system ($O^2$)



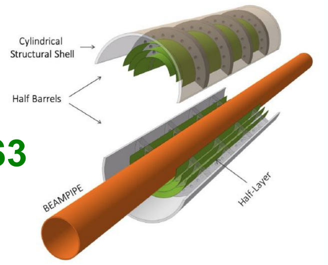



*J. Phys. G* 41 (2014) 087002    JINST 16 (2021) P03022

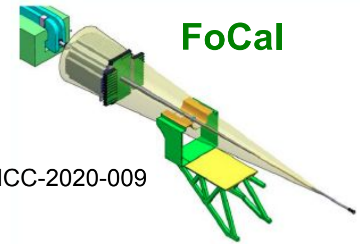
## LS3:

ALICE-PUBLIC-2018-013

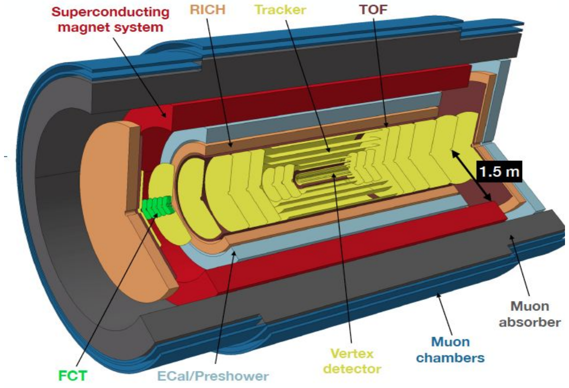
**ITS3**




**FoCal**



CERN-LHCC-2020-009




arXiv:2211.02491

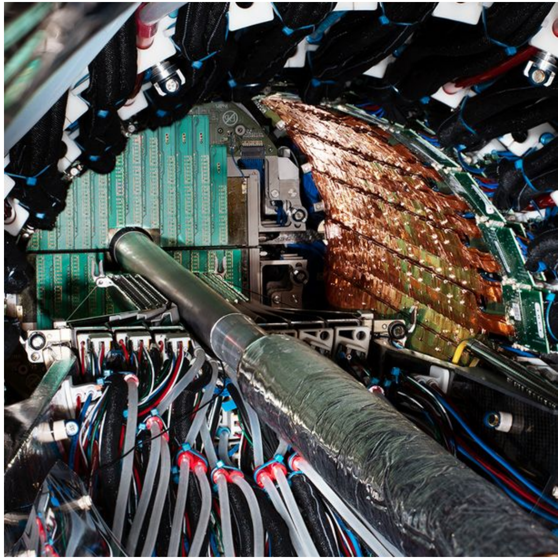
# ALICE future perspectives (Run 3 - now)



ITS2: Consists of seven layers of CMOS MAPS*

- Improved pointing resolution
- Inner barrel with 0.35% $X_0$ per layer
- Smaller beam pipe with first layer closer to the interaction point (22 mm)

(*) Complementary Metal-Oxide-Silicon (CMOS) Monolithic Active Pixel Sensors (MAPS) technology



MFT: muon forward tracker

- New tracker based on CMOS MAPS
- Improved muon pointing: tracking before the absorber

TPC with GEMs: Continuous readout at 50 kHz Pb-Pb interaction rate possible due to GEMs

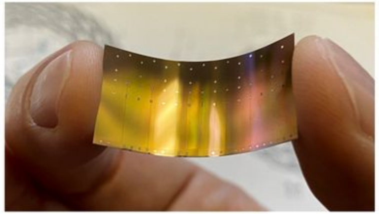
- 50 kHz and luminosity of 13 $nb^{-1}$ in Pb–Pb collisions in Run 3 + Run 4
- 0.6 $pb^{-1}$ in p–Pb collisions
- 200 $pb^{-1}$ in pp collisions

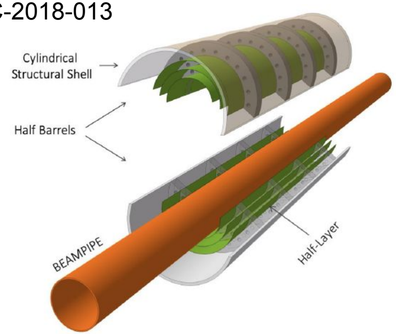
# ALICE future perspectives (Run 4 - 2029)

ITS3: the three innermost layers of ITS2 will be replaced with three truly cylindrical layers of wafer-scale ultra-thin silicon detectors.

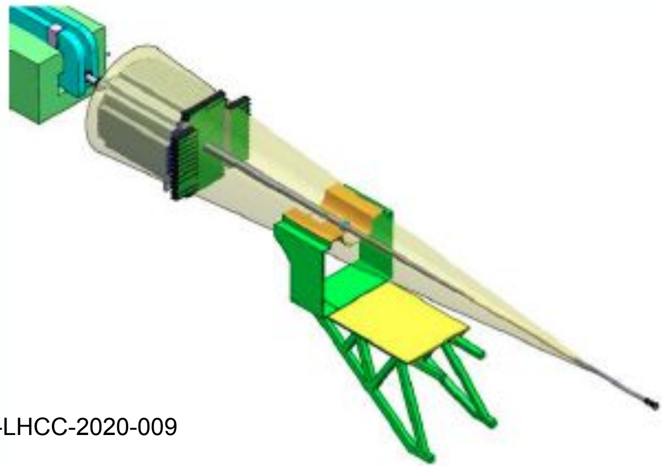
- Material budget of only 0.05% $X_0$ per layer
- Significant improvement at low momentum

ALICE-PUBLIC-2018-013









CERN-LHCC-2020-009

FoCal: Si+W electromagnetic calorimeter combined with a sampling hadronic calorimeter

- Pseudorapidity: $3.4 < \eta < 5.8$
- Unique capabilities to measure small-x gluon distributions
- Explore the dynamics of hadronic matter at small x down to $\sim 10^{-6}$

# ALICE future perspectives (Run 5 and 6)



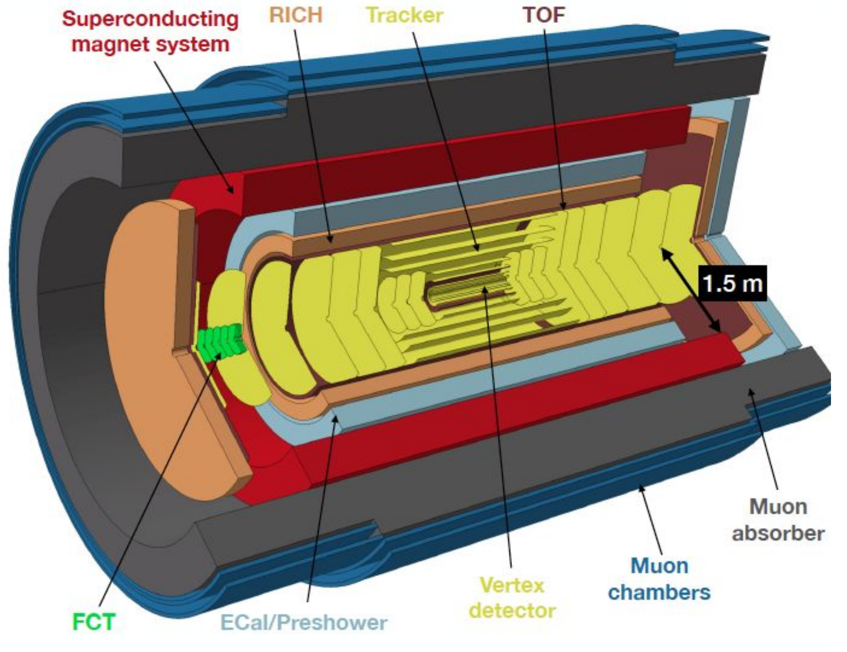
ALICE 3:

- ➔ Compact all-silicon tracker with high-resolution vertex detector
- ➔ Superconducting magnet system
- ➔ Fast readout and online processing

- Studies of A–A collisions at luminosities a factor of 5-10 times higher than possible now.

- The excellent timing resolution (≈ 20 ps)

- Ultrasoft region of phase space
  - Production of very low transverse momentum lepton pairs, photons and hadrons.
  - Heavy-flavour, quarkonia, multi-charm hadrons and heavy-flavour correlations
  - Low-mass dileptons
  - Soft and ultra-soft photons




arXiv:2211.02491

# Conclusions

- **Pb–Pb collisions:**
  - Charm diffusion and energy loss
    - constrained by $v_2$ and $R_{AA}$ of heavy-flavour hadrons
  - Beauty measurements indicate partial thermalisation and weaker energy loss compared to charm
  - Quarkonium indicating strong regeneration component at late stage
  - Jet modification in medium
  - Elliptic flow shows a mass ordering

- **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.

- **Future perspectives:**
  - High precision data coming soon! Stay tuned!

- **The ALICE review paper is already available in arXiv:2211.04384v1**

# More ALICE talks



Two-particle transverse momentum correlations as a tool to assess viscous effects in pp, p–Pb, and Pb–Pb systems with the ALICE detector
→ Victor Luis Gonzalez Sebastian (Thursday, 15:00)

Flow of identified hadrons in p--Pb and pp collisions with ALICE
→ Zuzana Moravcova (Thursday, 16:30)

Heavy-flavour production in small systems with ALICE
→ Fabio Filippo Colamaria (Thursday, 12:30)

Recent ALICE results on photon-induced interactions
→ Evgeny Kryshen (Tuesday, 14:30)

Particle production as a function of the UE activity in small and large systems and search for jet-like modifications
→ Omar Vazquez Rueda (Monday, 10:20)

**Thank you for your attention!**

# Backup slides

# How to study heavy quarks?

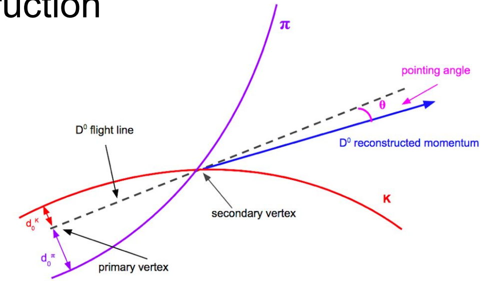


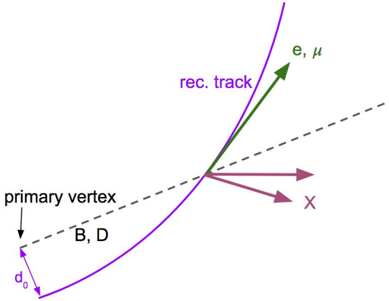
Heavy quarks

- 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).

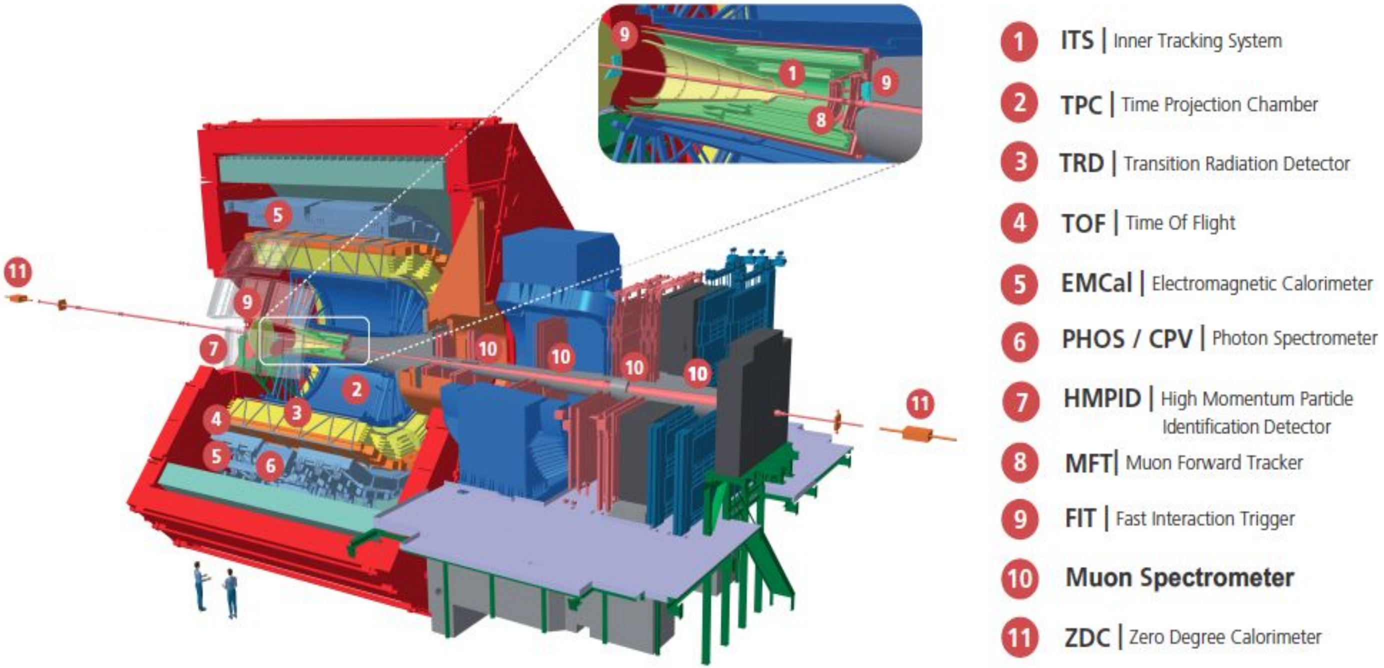
- Quarkonium via dielectron or dimuon pairs (Prompt production or B → J/ψ)

# ALICE 2 detector (Run 3 & Run 4)



**LS2 upgrade**

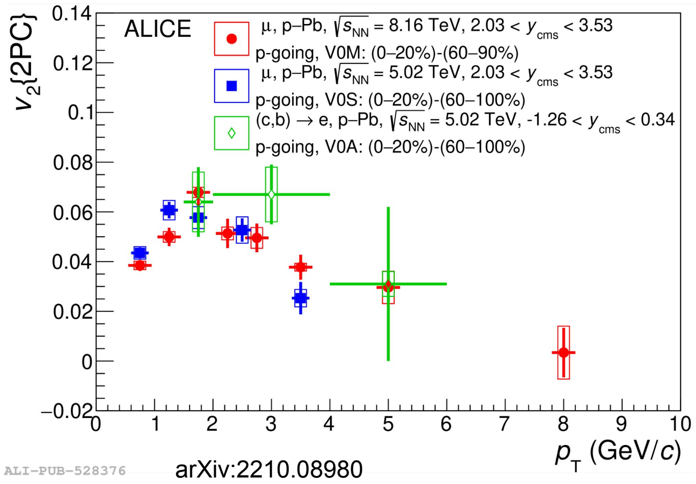
- new TPC detectors (GEMs)
- new silicon trackers (MFT & ITS2)
- new Fast Interaction Trigger (FIT)
- new online/offline system ($O^2$)
- new readout for all detectors

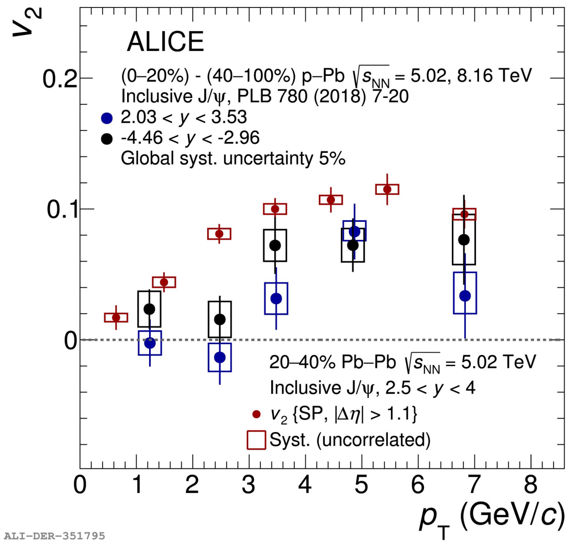


# Elliptic flow in p–Pb

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

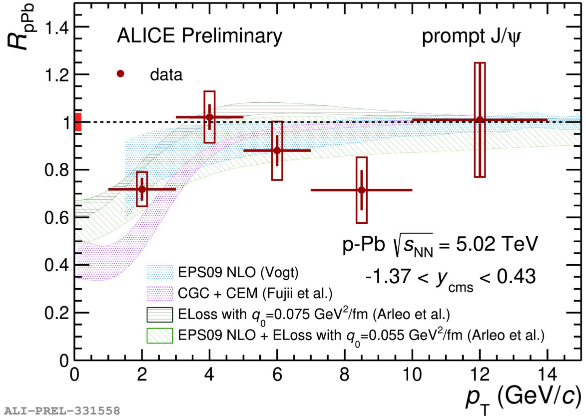
- What about heavy-flavour?

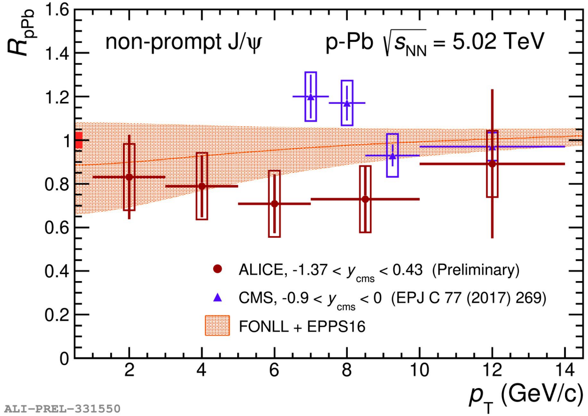



- Non-zero $v_2$ for electrons and muons from heavy-flavour lepton decays
- $v_2$ of J/ψ
  - Consistent with zero for $p_T$ < 3 GeV/$c$
  - $v_2$ > 0 for $p_T$ > 3 GeV/$c$ with similar amplitude as measured in semi-central Pb–Pb collisions
- Possible final states effects and collective motion

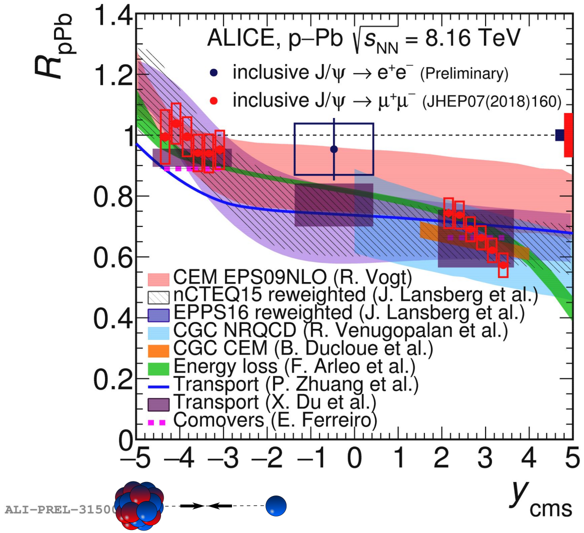
# J/ψ $R_{pPb}$




- 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 $p_T$



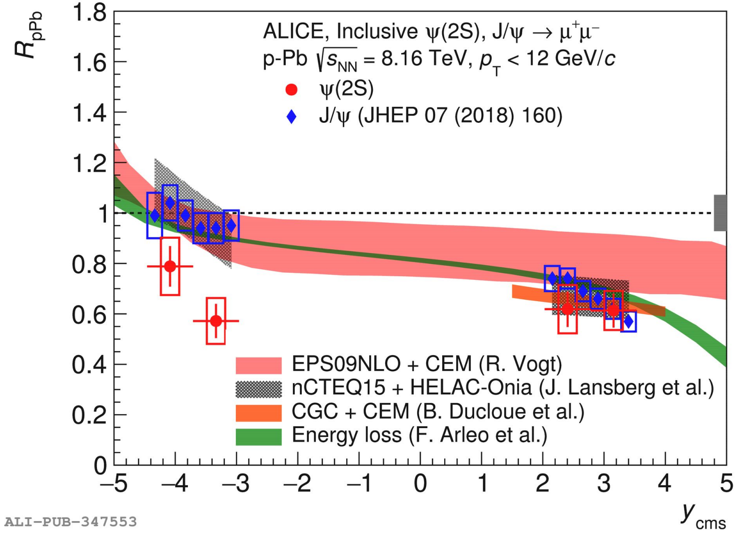

Theoretical models in good agreement with inclusive J/ψ, despite the very different approaches:

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

# J/ψ vs. ψ(2S) $R_{pPb}$



backwards vs. forward rapidity

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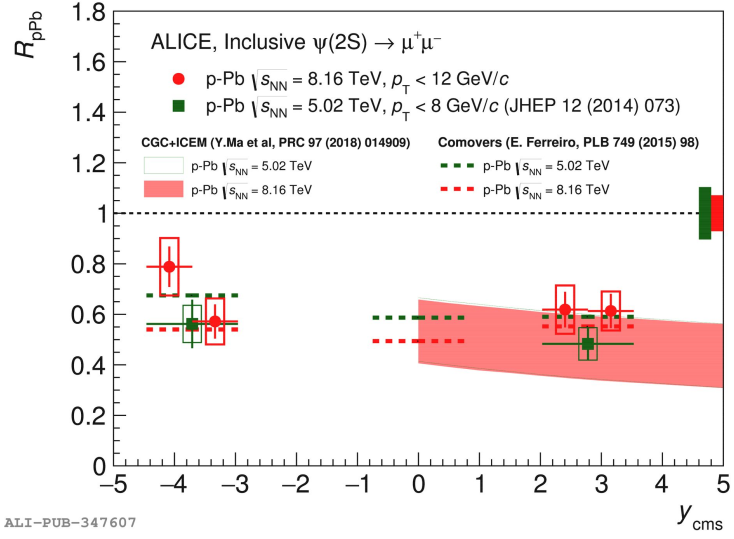


- ψ(2S): suppression compatible at forward and backward rapidities.
  - Stronger suppression than J/ψ at backward rapidity, whereas compatible at forward rapidity.
  - Hint for hot matter effects on ψ(2S).

# J/ψ production

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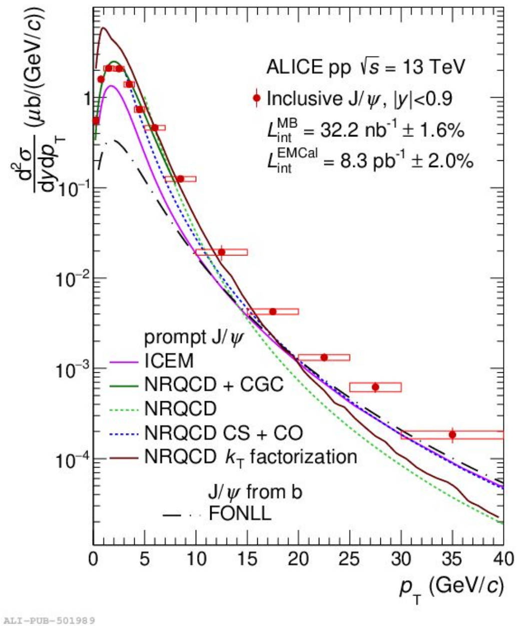


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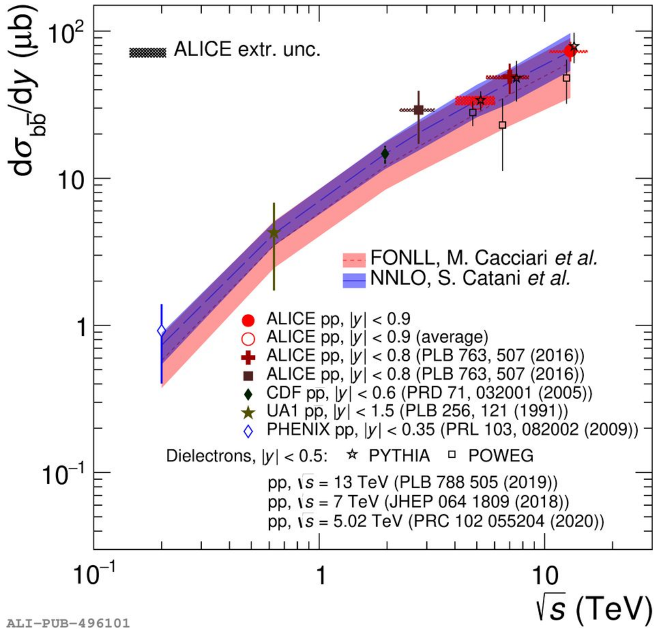


- The $p_T$-differential inclusive J/ψ production cross sections are measured in the $p_T$ range $0 < p_T < 40$ GeV/c.
  - High momentum reach was achieved thanks to the ALICE electromagnetic calorimeter trigger
- From the non-prompt J/ψ cross section measurements, the beauty quark production cross sections at midrapidity can be extrapolated.