Highlights and perspectives from the ALICE experiment

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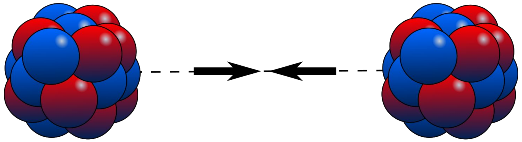
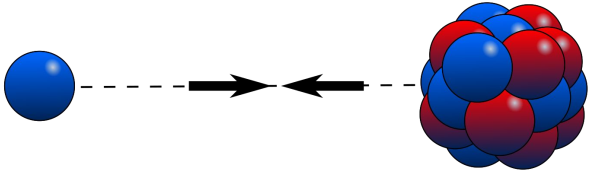
Collision systems

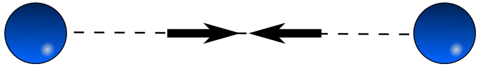


- Pb–Pb / Xe–Xe collisions:
  - Quark-gluon plasma (QGP) formation and its properties
    - Equation-of-state, transport coefficients...
  - In-medium energy loss
    - Colour-charge and quark-mass dependence
  - Thermalisation of heavy-quarks
  - Quarkonium dissociation and/or regeneration



- 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/Xe–Xe collisions
  - Studies of several aspects of QCD

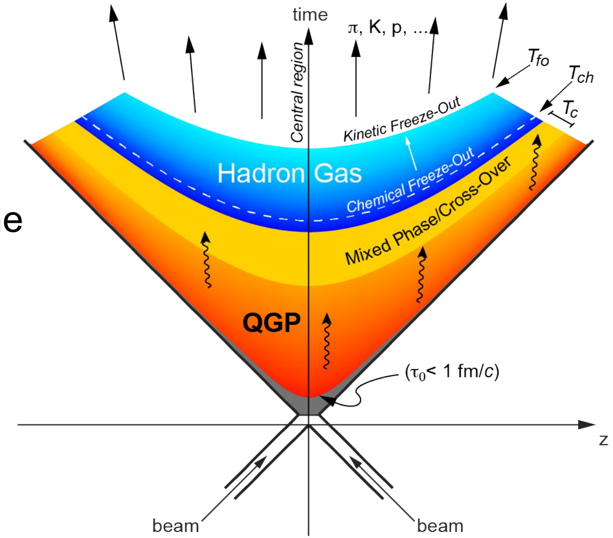


- pp and p–Pb collisions:
  - Look for possible collective behaviour in small systems

Main focus of this talk will be in heavy quarks

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, Σ_c and Ξ_c

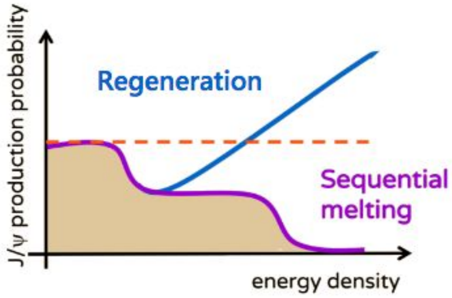


- Charm and beauty are produced (in hard scatterings) in the early stages of the collision:
  - ✓ Large mass ($m_{c,b} >> \Lambda_{QCD}$)
    → short formation time
    → hard probes, even at low p_T

- Charm and beauty can experience the full evolution of the system:
  - ✓ They live much longer than the duration of the 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 (Andronic et al, Nucl.Phys.A772:167-199,2006) (Thews et al, Phys. Rev. C63 (2001) 054905)

Why to study light quarks?

- Light-flavour particles contain up, down and strange quarks:
  - ✓ Proton, kaons, pions, deuteron, triton, ^{3}He
  - ✓ K^0_s, Λ, ϕ, Ω^-, Ξ^-

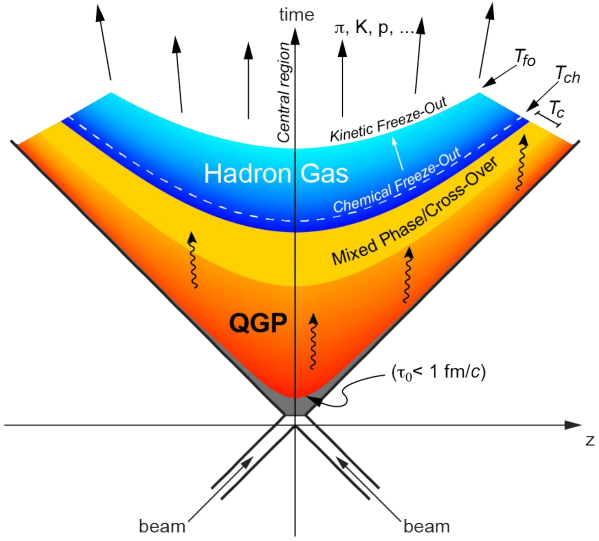
- Light-flavour particles are created in soft or hard process
  - ✓ Soft: bulk of particles produced at low transverse momenta (p_T < 2 GeV/c)
    → QCD inspired phenomenological models
  - ✓ Hard: particles with p_T > 2 GeV/c, described by pQCD.

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

- Strangeness enhancement as a signature of QGP

- Study the effective interaction between hadrons with different quark content

- Nucleosynthesis mechanisms in hadronic collisions



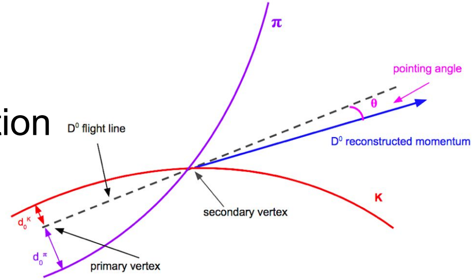
How to study heavy and light quarks?

Heavy quarks

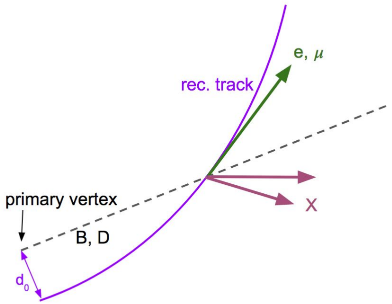
- Reconstruction via hadronic decays:
  - Prompt and non-prompt D meson reconstruction

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

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



- 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)

Light quarks

- Primary particles: Proton, kaons, pions, deuteron, triton, ^{3}He
- Reconstruction via decays:

$$K^+ \rightarrow \mu^+ \nu_\mu$$
$$K^0_S \rightarrow \pi^+ + \pi^-$$
$$K^{*0} \rightarrow \pi^- + K^+$$
$$\phi \rightarrow K^+ + K^-$$

$$\Lambda \rightarrow p + \pi^-$$
$$\Xi^- \rightarrow \Lambda + \pi^-$$
$$\Omega^- \rightarrow \Lambda + K^-$$

Observables

Spectra, particles yields, jets, correlations...

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

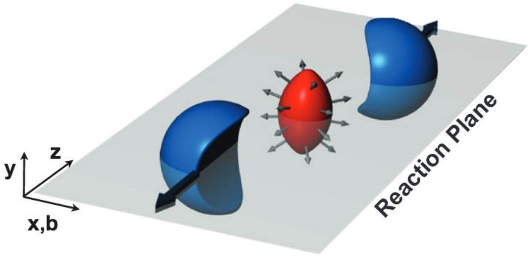
- For heavy-quarks, the energy loss is expected to depend on the parton colour-charge, parton mass and path length.

ΔE(g,u,d,s) > ΔE(c) > ΔE(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
- v_3: event-by-event fluctuations



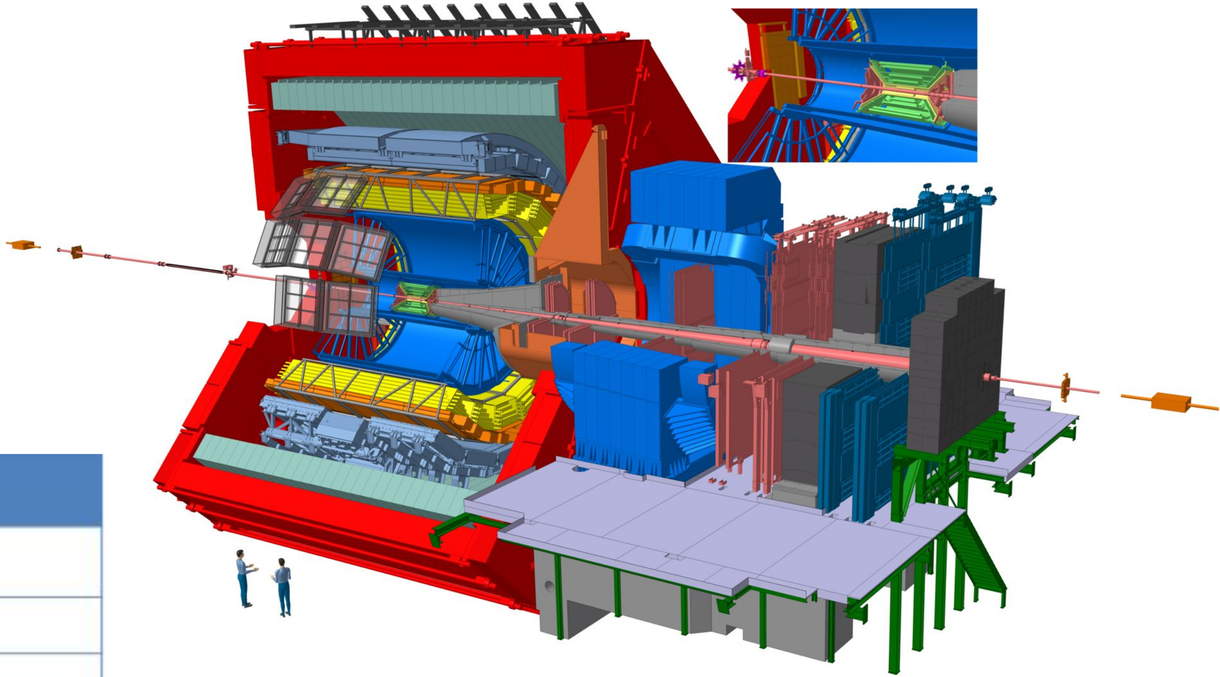
Snellings, New J.Phys. 13 (2011) 055008

ALICE detector (Run 2)

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

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

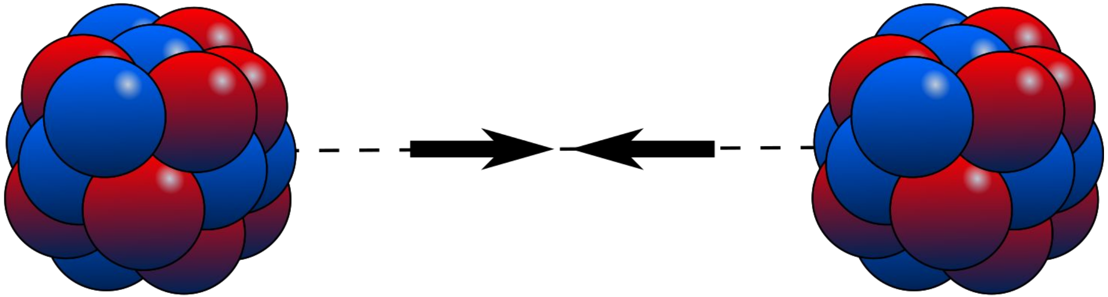
System	Year(s)	$\sqrt{s_{NN}}$ (TeV)	L_{int}
Pb-Pb	2010, 2011 2015, 2018	2.76 5.02	75 μb^{-1} 800 μb^{-1}
Xe-Xe	2017	5.44	0.3 μb^{-1}
p-Pb	2013 2016	5.02 5.02, 8.16	15 nb^{-1} 3 nb^{-1}, 25 nb^{-1}
pp	2009-2013 2015, 2017 2015-2018	0.9, 2.76, 7, 8 5.02 13	200 μb^{-1}, 100 nb^{-1} 1.5 pb^{-1}, 2.5 pb^{-1}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



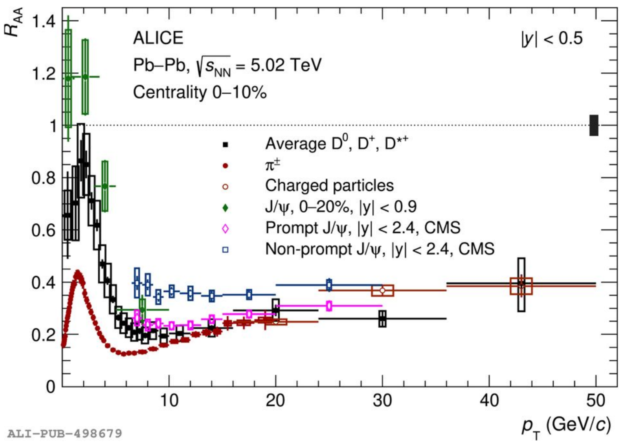
Forward rapidity ($-4 < \eta < -2.5$)
Muon tracking and trigger

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

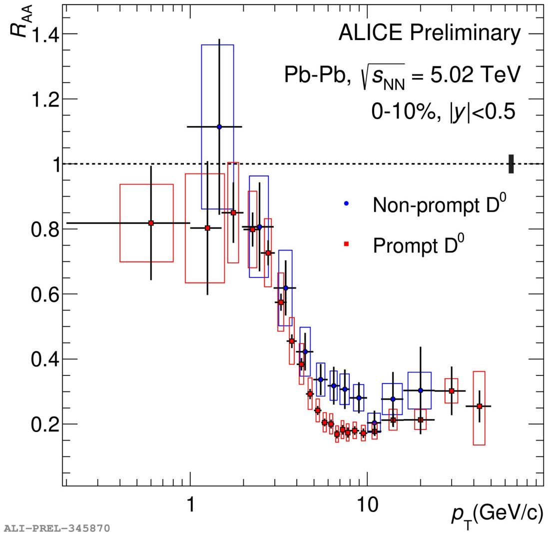
Results in Pb–Pb/ Xe–Xe collisions

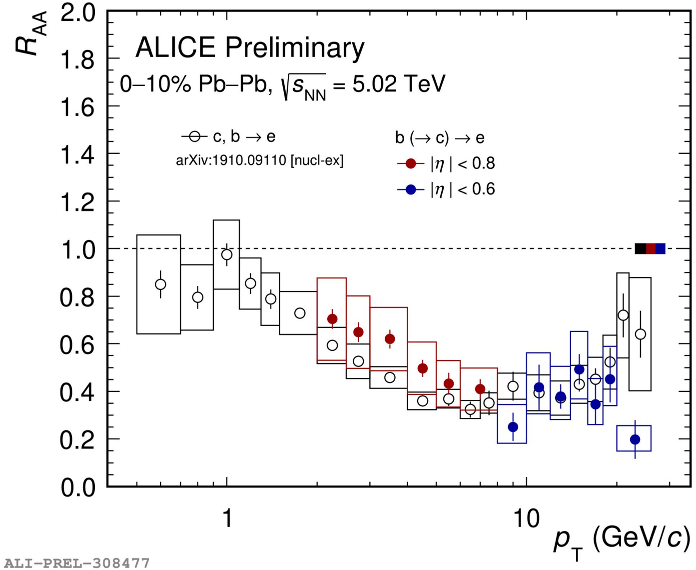


Open heavy-flavour R_{AA}



arXiv:2110.09420



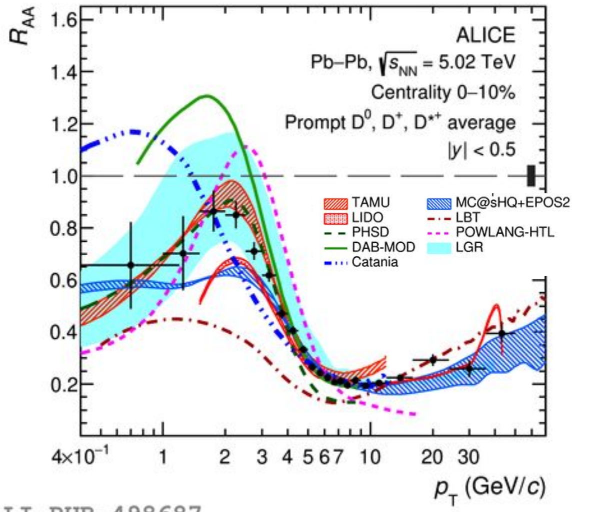


- Strong suppression of open heavy-flavour particles in Pb–Pb collisions
- Mass ordering:
  - $R_{AA}(\pi)$ < $\mathbf{R_{AA}(D)}$ (p_T < 10 GeV/c)
  - R_{AA}(c→D) < R_{AA}(b→D) (4 < p_T < 10 GeV/c)
  - Hint of $\mathbf{R_{AA}(c,b\to e)}$ < R_{AA}(b→e) at low p_T

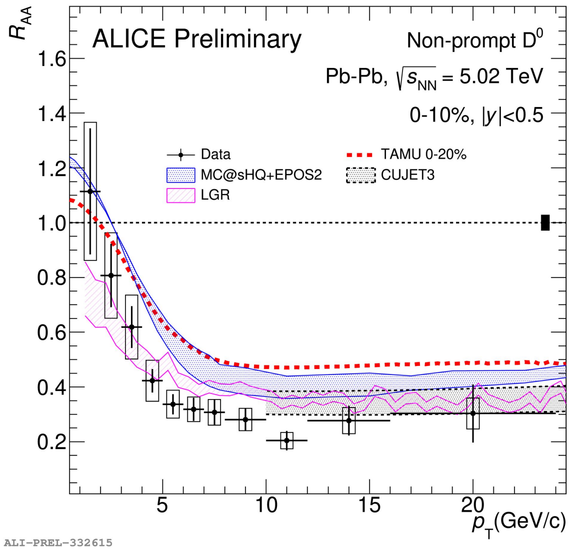
$R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$

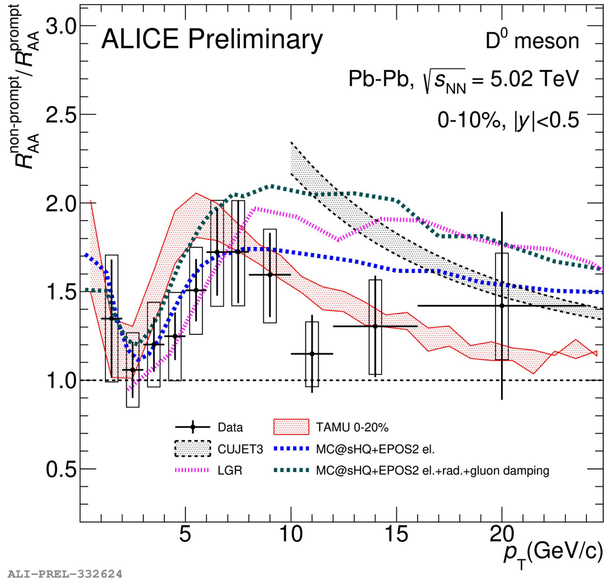
Open heavy-flavour R_{AA}

Model comparisons



arXiv:2110.09420

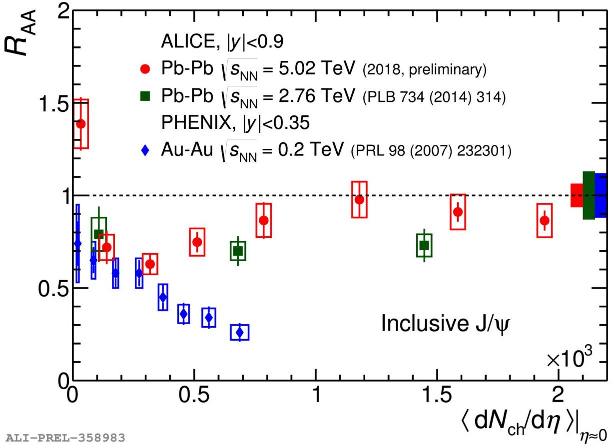


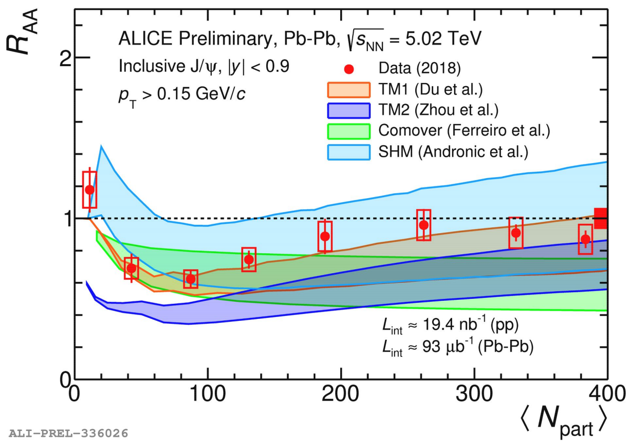


- Models including collisional (POWLANG, BAMPS el., TAMU) and collisional+radiative energy loss (BAMPS el.+rad., LIDO, PHSD, Catania, MC@sHQ+EPOS2, Djordjevic) can describe the suppression at high p_T (at least qualitatively)
- Models: TAMU, POWLANG, PHSD, MC@sHQ, LIDO and Catania include quark recombination

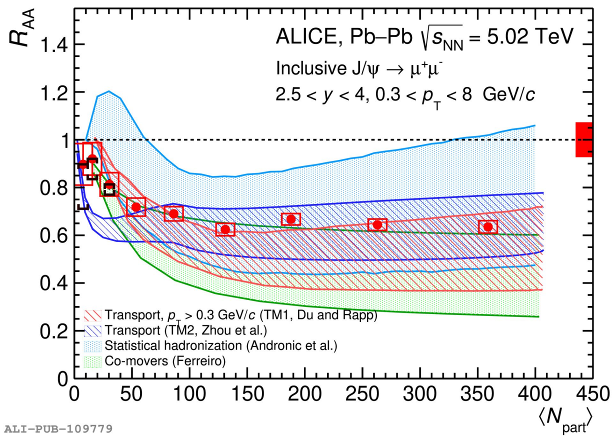
J/ψ R_{AA}

Centrality dependence





PLB 766 (2017) 212



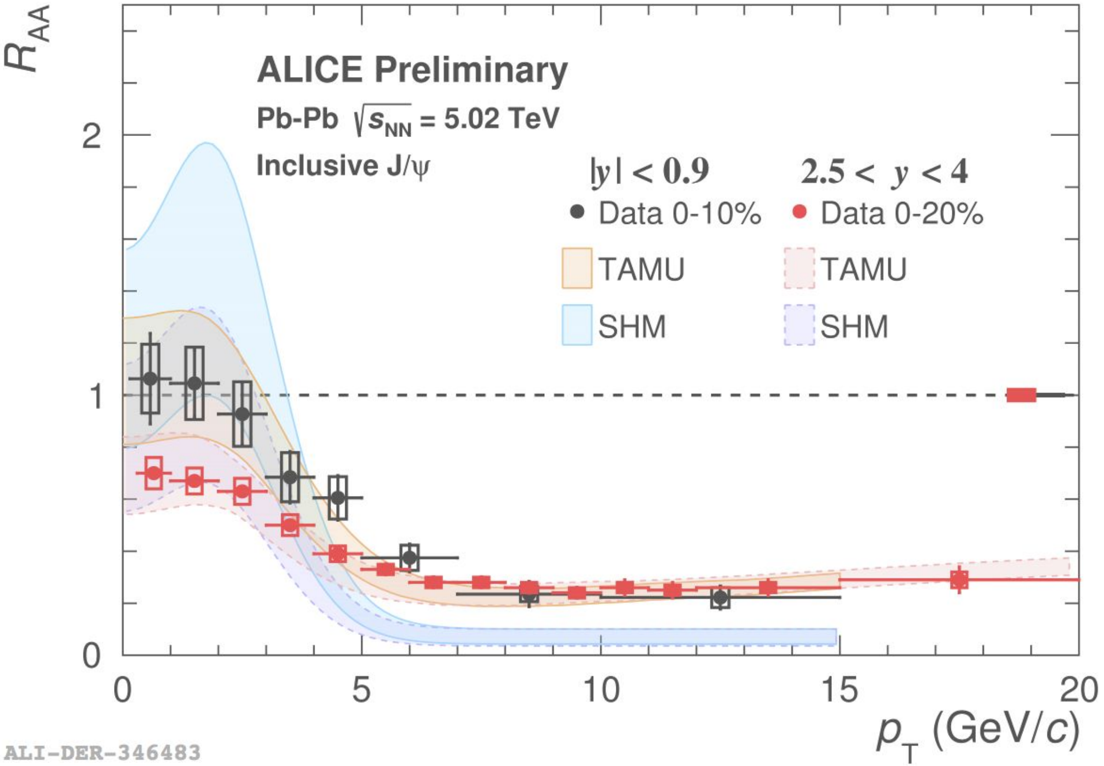
- Weaker suppression at higher collision energy
  - Effect predicted by regeneration models
- Models including charm-quark regeneration are in good agreement with the data in both mid- and forward-rapidity
  - TM1 and TM2: includes dissociation and regeneration in QGP and hadronic phase
  - Comovers: 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

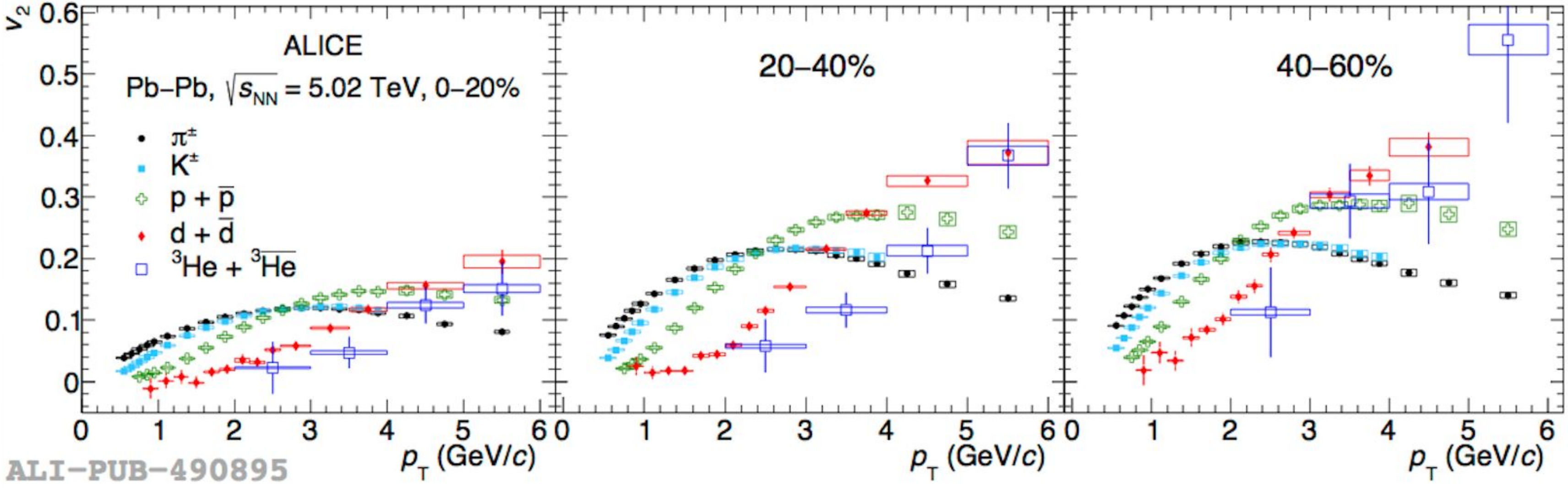
- p_T < 5 GeV/c: stronger suppression at forward rapidity.
- p_T > 5 GeV/c: similar suppression for mid- and forward-rapidity.

- 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 (light flavour)

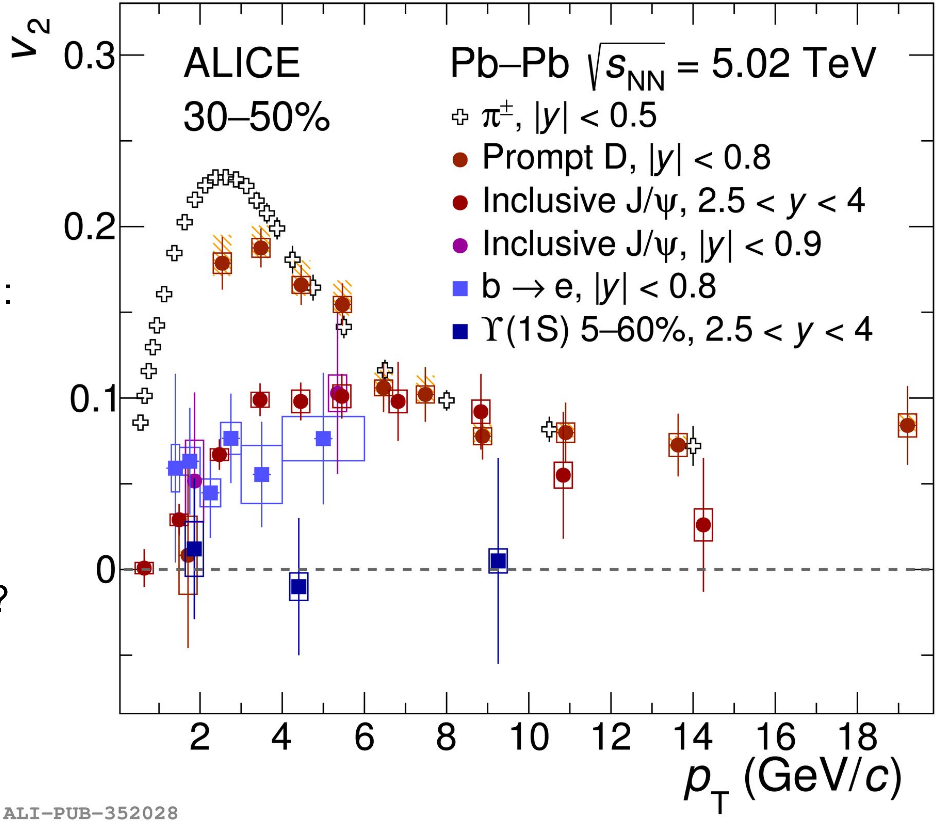
- Light-flavour particles flows in Pb–Pb:
  - A clear mass ordering of v_2 is observed at low p_T, as expected for a system expansion driven by the pressure gradient as described by relativistic hydrodynamics



Phys. Rev. C 102 (2020) 055203

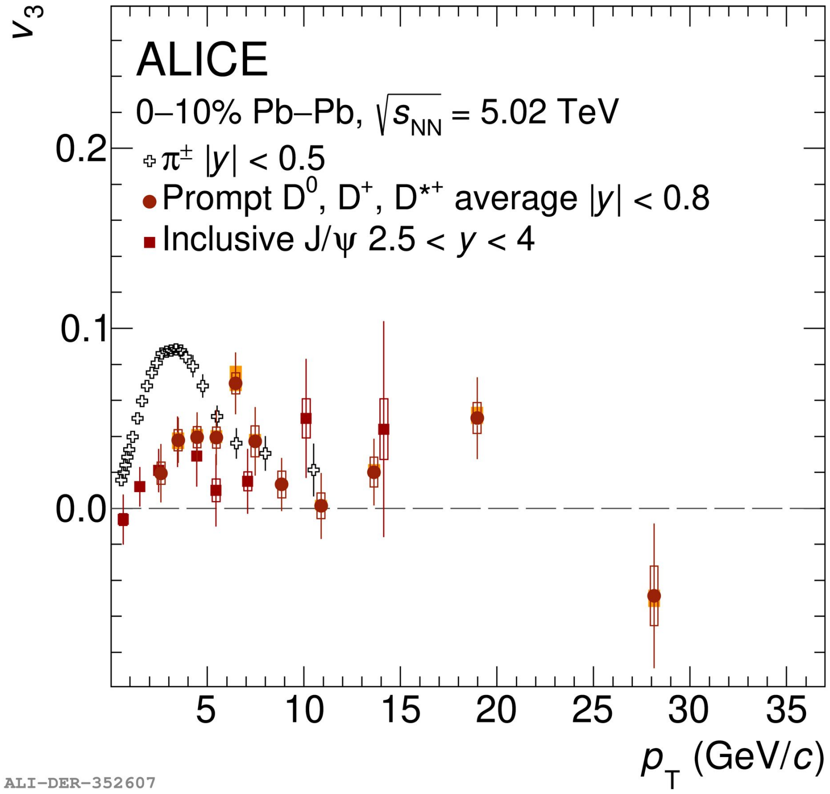
Elliptic flow (heavy flavour)

- 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: $v_2(\Upsilon(1S)) \lesssim v_2(b\rightarrow e) \sim v_2(J/\psi) < v_2(D) < v_2(\pi)$
- 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

Triangular flow

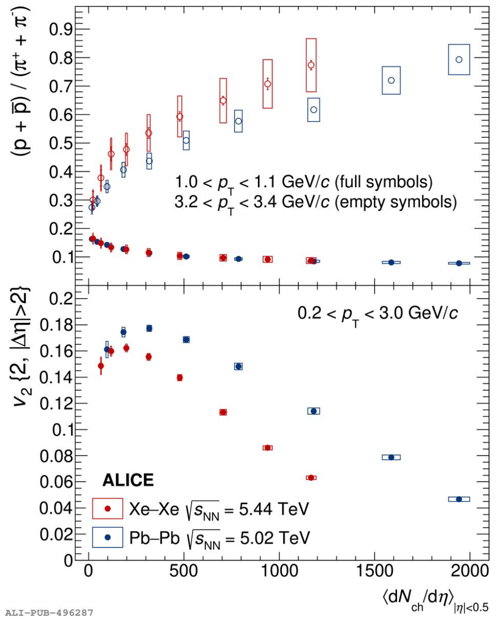


- v_3 of prompt D mesons, J/ψ and $\pi^{\pm}$
- For $p_T < 5$ GeV/c:
  - $0 < v_3(\mathrm{J}/\psi) \sim v_3(\mathrm{D}) < v_3(\pi^{\pm})$
  - Indication that charm quarks are sensitive to initial state fluctuations

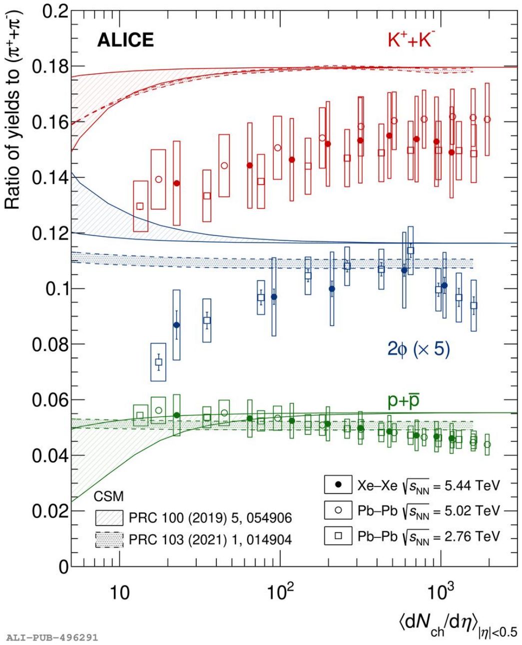
JHEP 09 (2018) 006
PLB 813 (2021) 136054
JHEP 10 (2020) 141

Xe–Xe vs Pb–Pb

System dependence of radial and elliptic flow:
Comparison at similar charged-particle multiplicities but with different initial geometrical eccentricities



Opposite behaviour for radial and elliptic flow: radial flow depends exclusively on the multiplicity, while elliptic flow depends also on the initial eccentricities of the collision region.

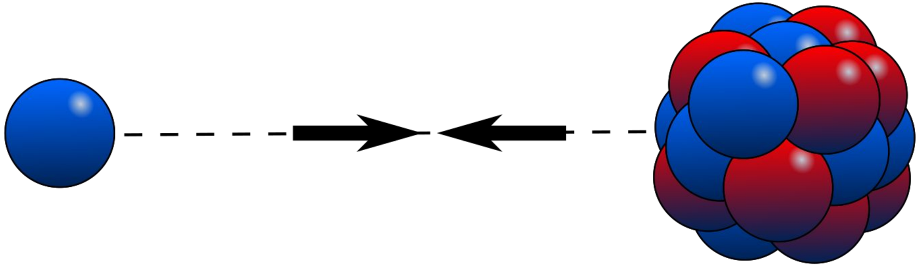


Features of the particle production:

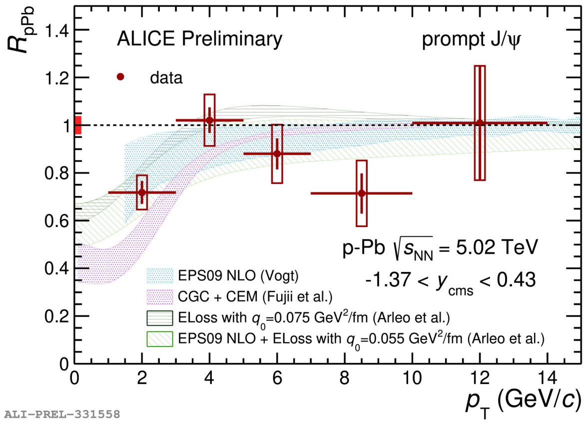
- Lower proton-to-pion ratio with respect to the thermal model expectations
- Increase of the phi-to-pion ratio with increasing final-state multiplicity

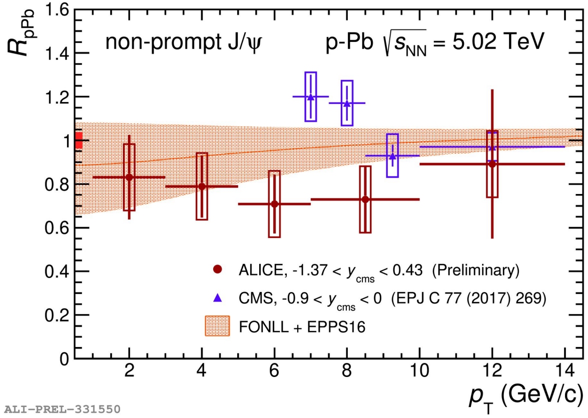
Eur. Phys. J. C 81(2021) 584

Results in p–Pb collisions

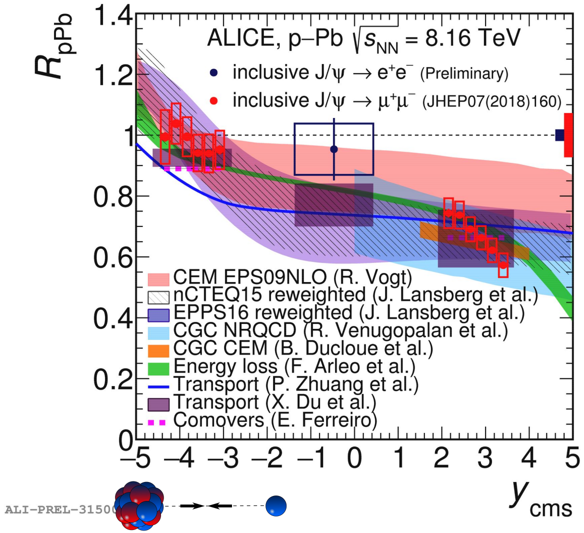


J/ψ R_{pPb}





- 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

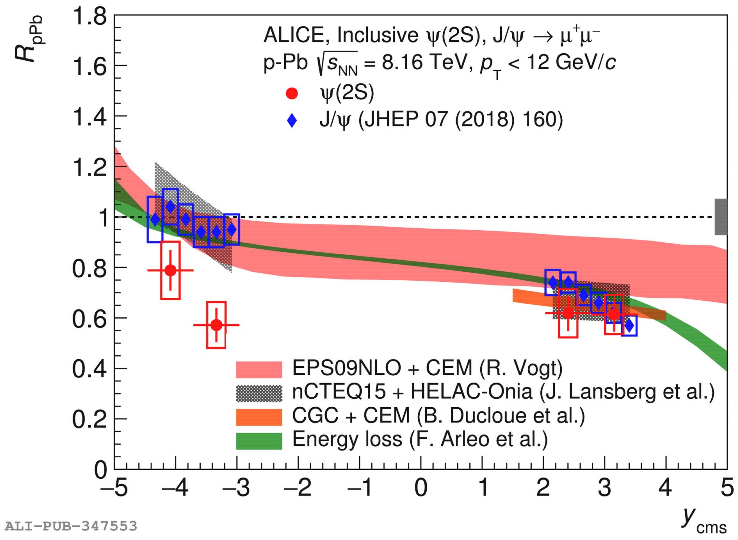


Theoretical models in good agreement with inclusive J/ψ, despite the very different approaches:

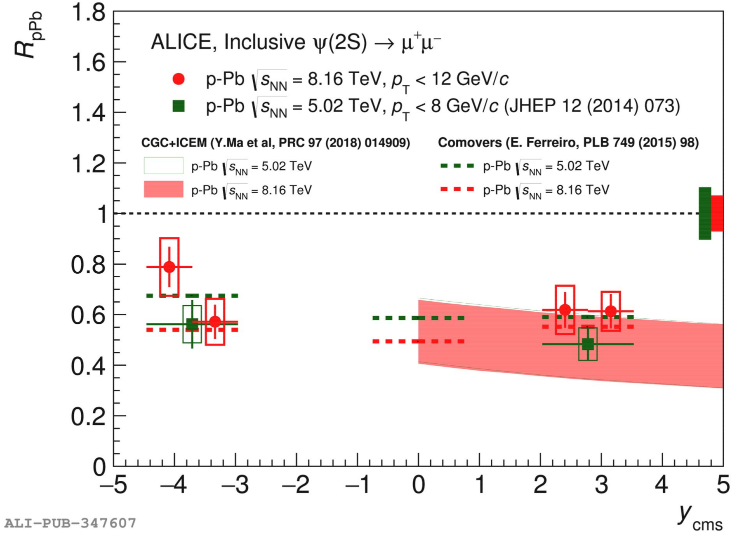
- Shadowing (EP09NLO, nCTEQ15, EPPS16)
- CGC (NRQCD, CEM)
- Energy loss
- Final state effects (Transport, comovers)

J/ψ vs. ψ(2S) R_{pPb}

backwards vs. forward rapidity



JHEP 07 (2020) 237

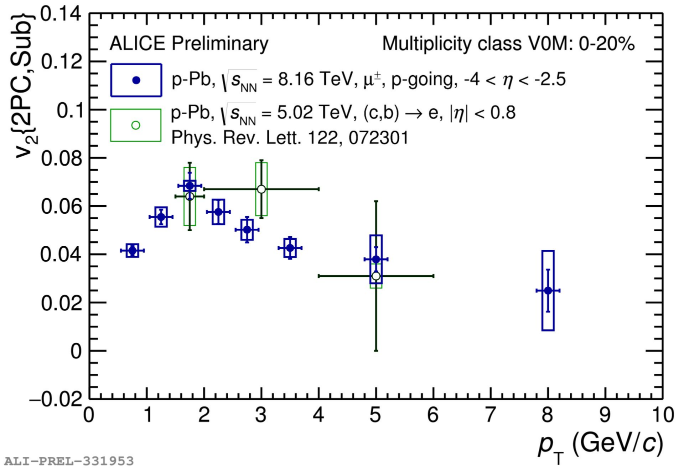


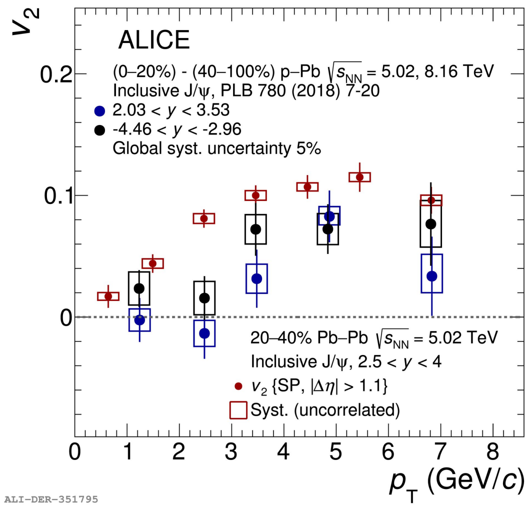
- ψ(2S): suppression compatible at forward and backward rapidities.
  - Stronger suppression than J/ψ at backward rapidity, whereas compatible at forward rapidity.
  - Hint for hot matter effects on ψ(2S).

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?



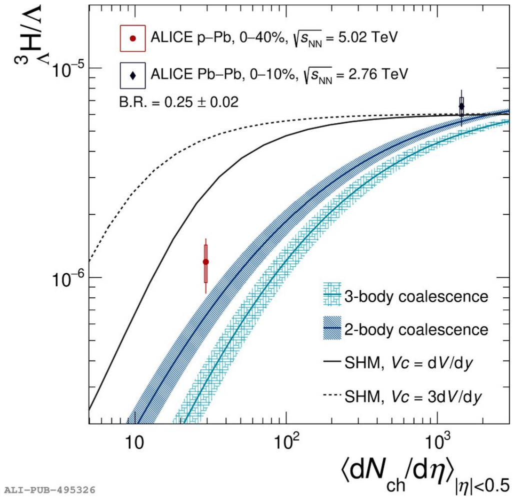


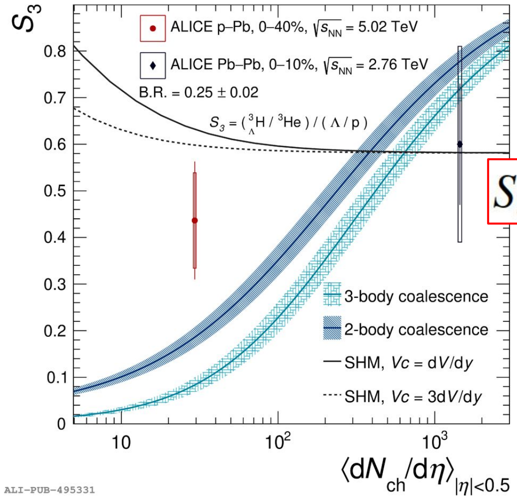
- Non-zero v_2 for electrons and muons from heavy-flavour lepton decays
- v_2 of J/ψ
  - Consistent with zero for p_T < 3 GeV/c
  - v_2 > 0 for p_T > 3 GeV/c with similar amplitude as measured in semi-central Pb–Pb collisions
- Possible final states effects and collective motion

Light flavour in p–Pb

Hypertriton:

arXiv: 2107.10627v1

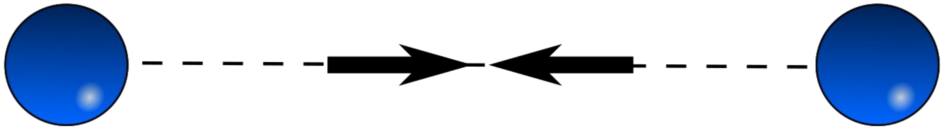




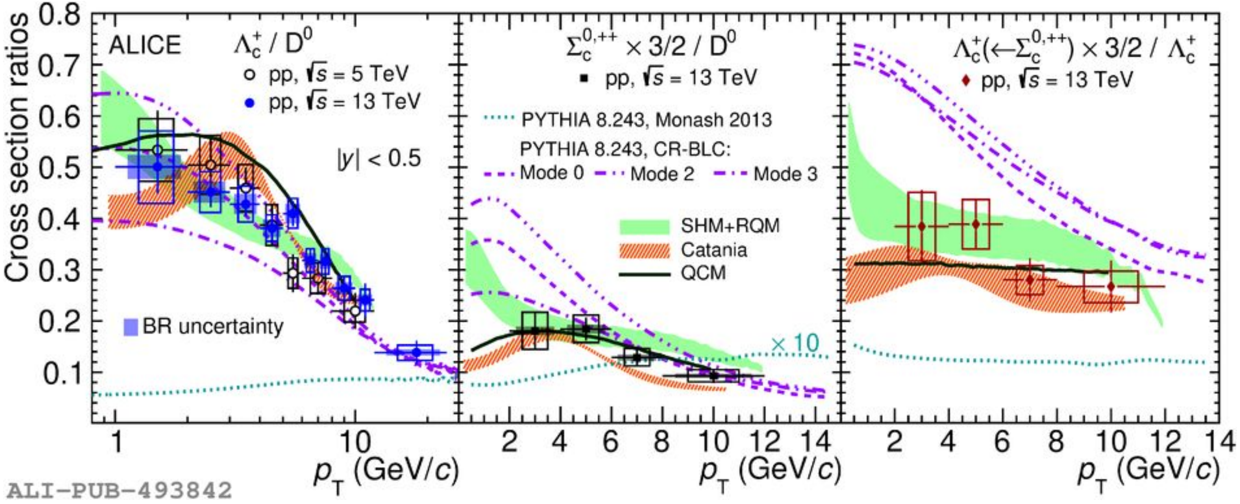
$$\boxed{S_3 = ({}^{3}_{\Lambda}\mathrm{H}/{}^{3}\mathrm{He})/(\Lambda/\mathrm{p})}$$

- Ability to discriminate between nucleosynthesis mechanisms in hadronic collisions.
- The measured p_T integrated yield is better described by coalescence than by statistical hadronization models
- The ${}^{3}_{\Lambda}$H/Λ ratio is well described by the 2-body coalescence prediction while the 3-body formulation is disfavoured by our measurement.

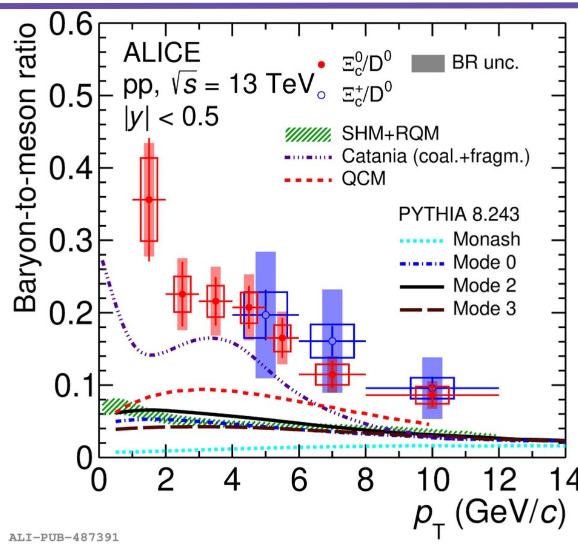
Results in pp collisions



Open heavy-flavour production



arXiv:2106.08278

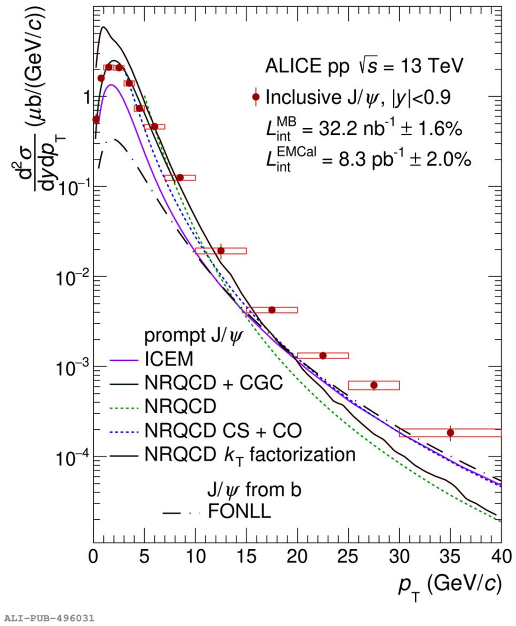


arXiv:2105.05187v1

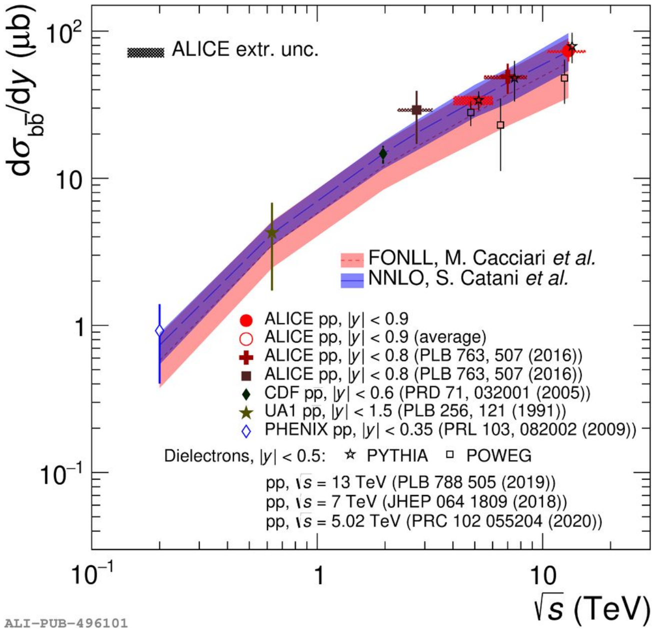
- Λ_c^+/D^0, $\mathbf{\Sigma}_c/D^0$ and Ξ_c/D^0
  - Shows a higher value than in e^+e^- collisions
  - Modification not captured by standard hadronization models
- No hadronization universality between e^+e^- and pp
- PYTHIA 8 with Color Reconnection: reasonable reproduction for Λ_c^+/D^0 and $\mathbf{\Sigma}_c/D^0$ but not Ξ_c/D^0

J/ψ production

arXiv:2108.01906

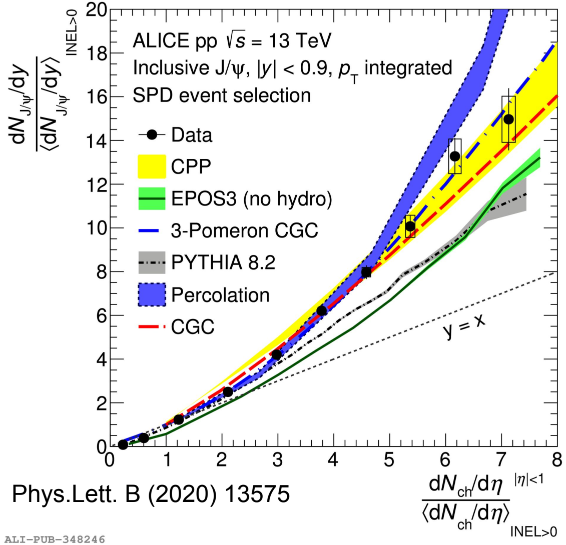


arXiv:2108.02523

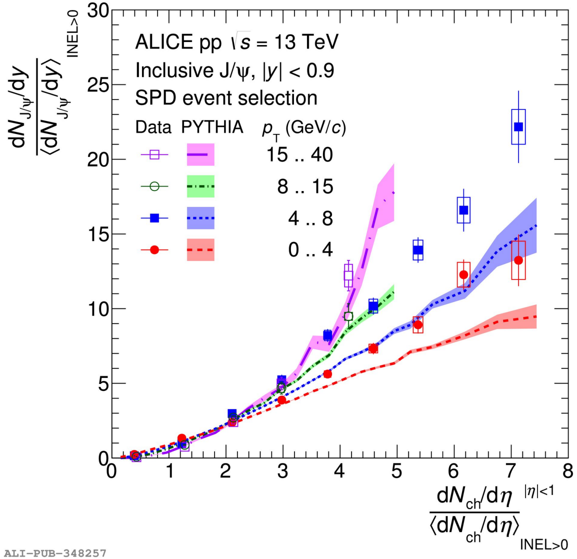


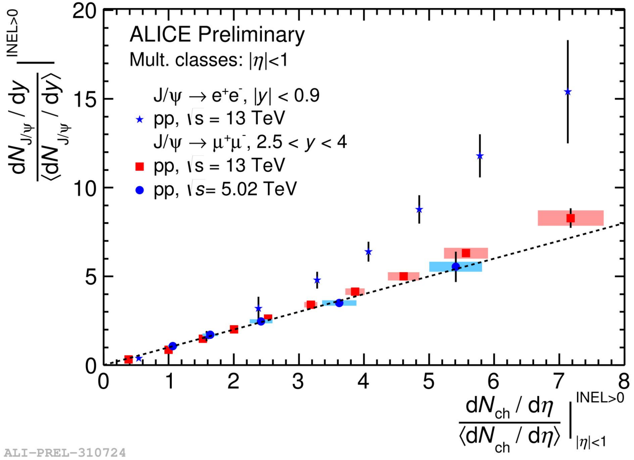
- The p_T-differential inclusive J/ψ production cross sections are measured in the p_T range $0 < p_T < 40$ GeV/c.
    - High momentum reach was achieved thanks to the ALICE electromagnetic calorimeter trigger
- From the non-prompt J/ψ cross section measurements, the beauty quark production cross sections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

J/ψ production vs. multiplicity



Phys.Lett. B (2020) 13575



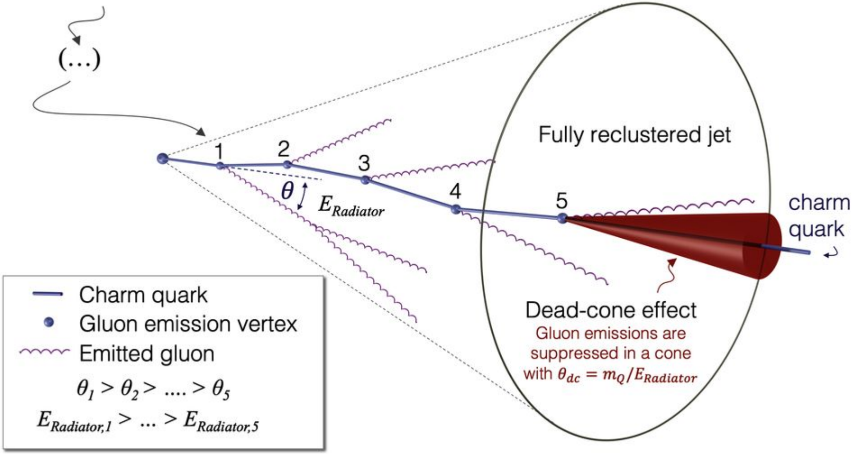


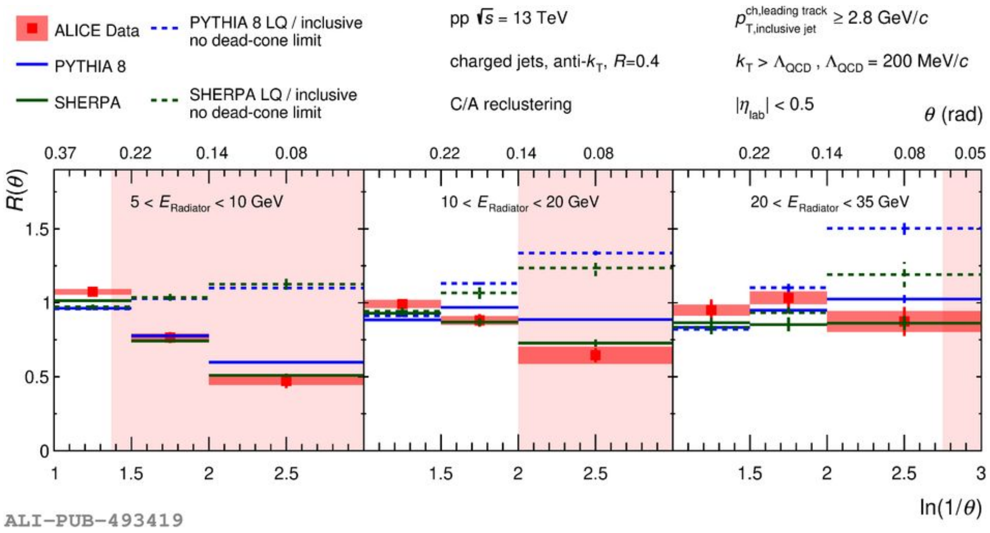
- J/ψ self normalized yield
  - Midrapidity: increase faster than linear
    - Enhancement qualitatively described by several model calculations
      - PYTHIA8 which includes multi-parton interactions describes qualitatively the p_T dependence
    - Higher enhancement for higher p_T
  - Forward-rapidity: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

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

arXiv:2106.05713



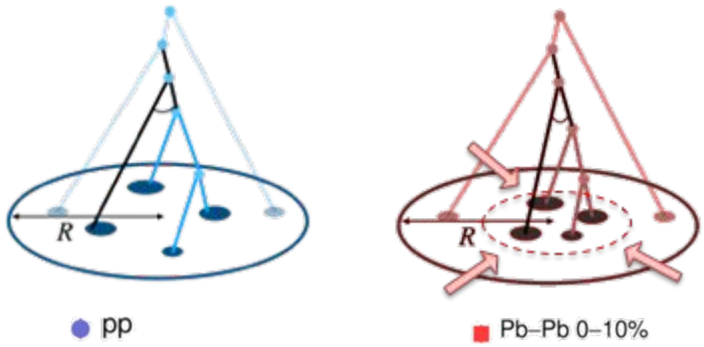


- Reclustering the jet constituents according to the Cambridge-Aachen algorithm:
  - Angular distance from one another

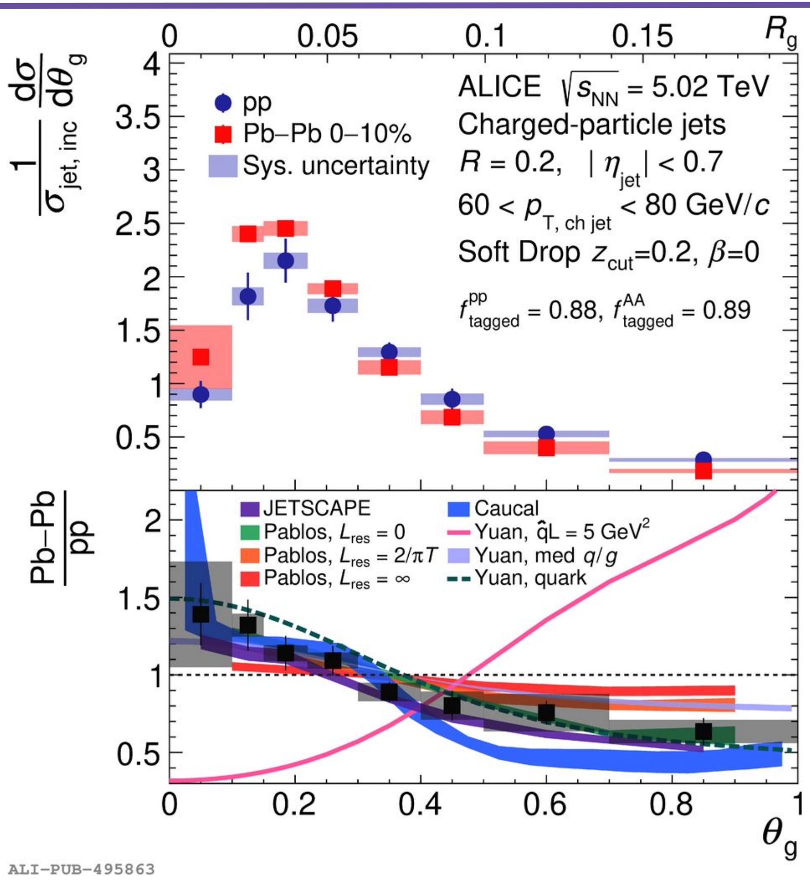
- Ratio of the splitting angle distributions for D^0-meson tagged jets and inclusive jets, in bins of $E_{Radiator}$
- Radiation suppressed in the expected areas (shaded)

Groomed jets

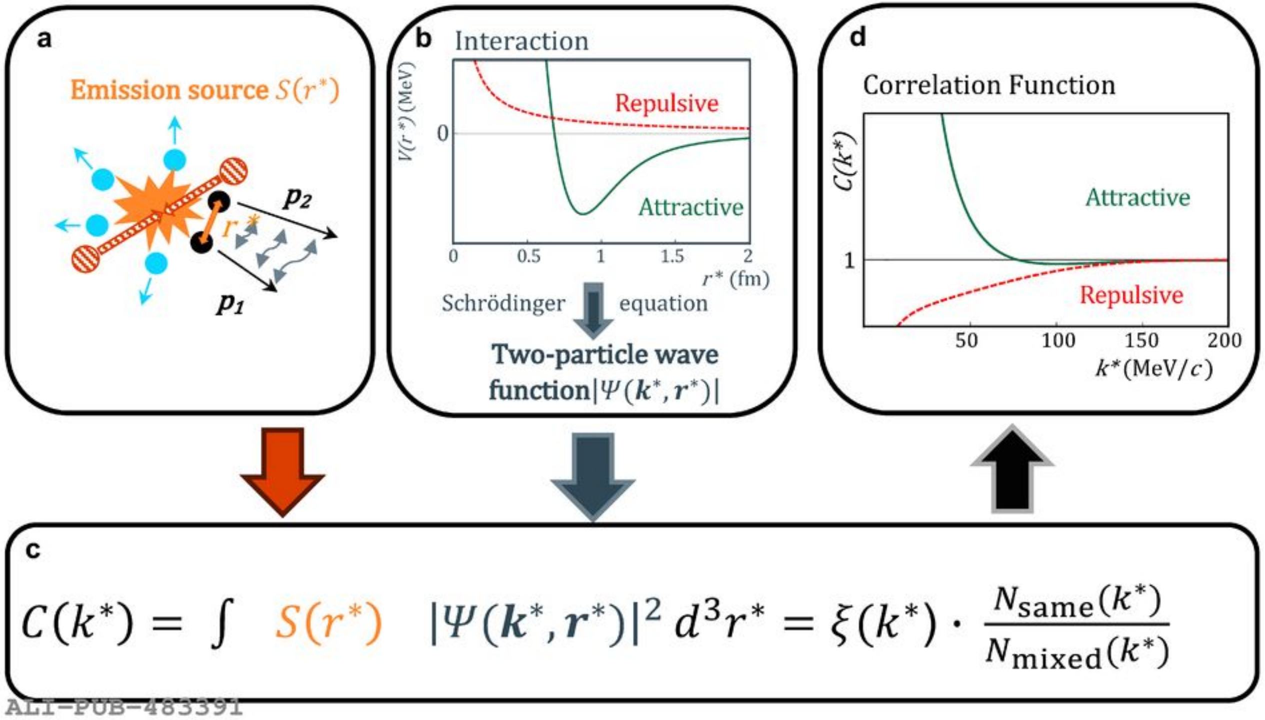
- The cores of jets are narrower in Pb–Pb compared to pp collisions
- First direct experimental evidence for the modification of the angular scale of groomed jets in heavy-ion collisions



arXiv:2107.12984



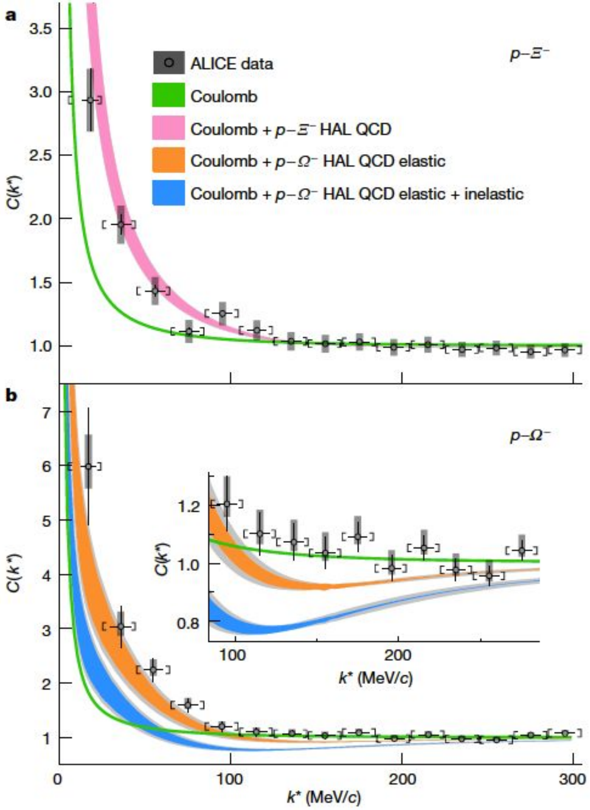
Strong hadron-hadron interactions via femtoscopy



To understand the effective interaction between hadrons with different quark content

- Measuring correlations in the momentum space

Strong hadron-hadron interactions via femtoscopy



Nature 588, 232 (2020)

- Correlations above unity: implies the presence of an attractive interaction for p-Ω^- and p-Ξ^- pairs
    - Coulomb interaction + Gaussian distribution for the source shape
        - Underestimate the strength of the measured correlation
    - **An attractive interaction exists and exceeds the strength of the Coulomb interaction**

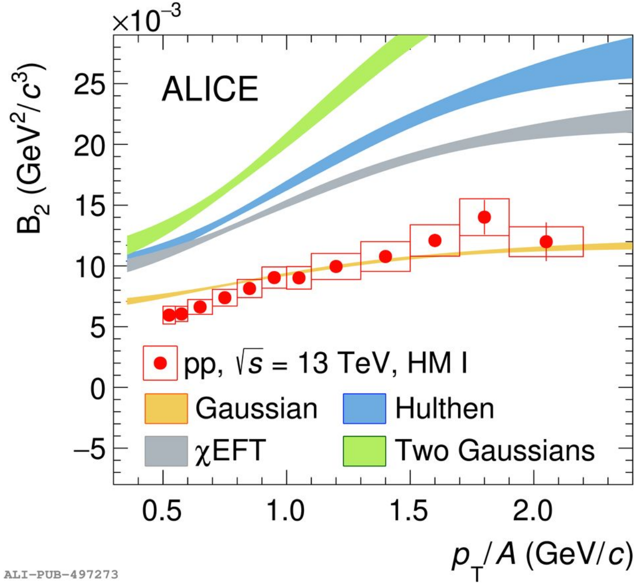
- Test for lattice QCD calculation

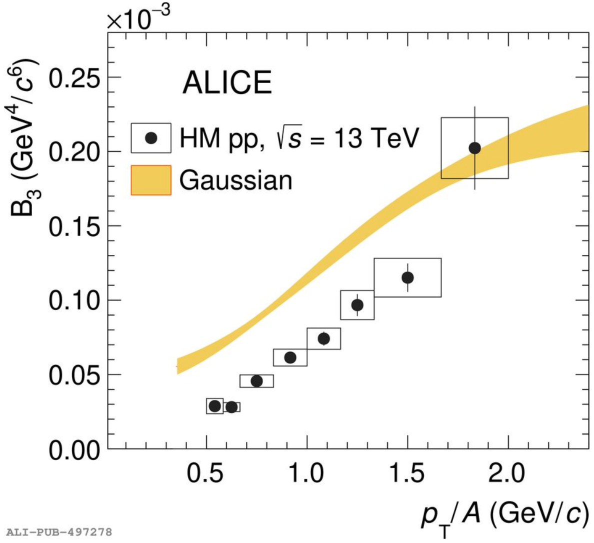
- Input for the equation-of-state of neutron stars which contain hyperons

Light (anti)nuclei

- Production mechanism of light (anti)nuclei is one of the key challenges of nuclear physics
- Provides an input for indirect dark matter searches in space

arXiv:2109.13026v1





The production probability of a nucleus with mass number A is proportional to B_A:

$$B_A\left(p_T^p\right) = \frac{1}{2\pi p_T^A}\frac{d^2N_A}{dydp_T^A} \Big/ \left(\frac{1}{2\pi p_T^p}\frac{d^2N_p}{dydp_T^p}\right)^A$$

- The coalescence parameters B_2 for deuterons and B_3 for helions are compared with parameter-free theoretical predictions.
- A Gaussian wave function describes the deuteron results (left) and overestimates the helion results (right).

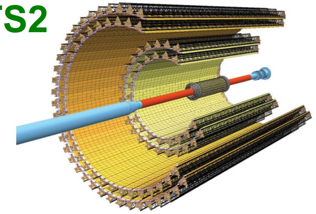
ALICE future perspectives

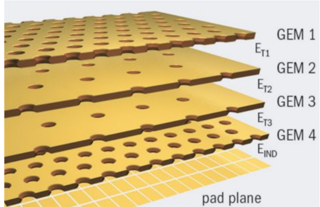
2021	LS2
2022	Run 3
2023	Run 3
2024	Run 3
2025	LS3
2026	LS3
2027	LS3 / Run 4
2028	Run 4
2029	Run 4
2030	Run 4
2031	LS4
2032	LS4 / Run 5
2033	Run 5

ALICE 2:
- 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

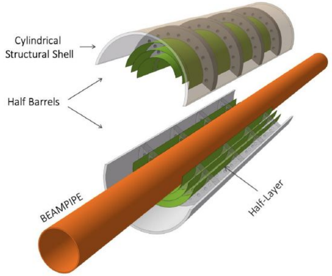
ITS2





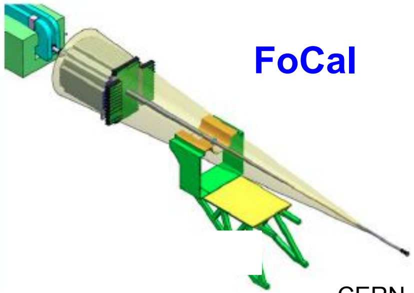
JINST 16 (2021) P03022

GEMs



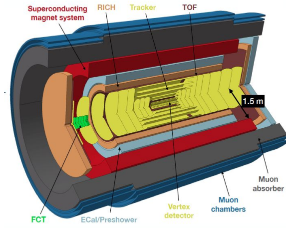
ITS3

ALICE-PUBLIC-2018-013



FoCal

CERN-LHCC-2020-009



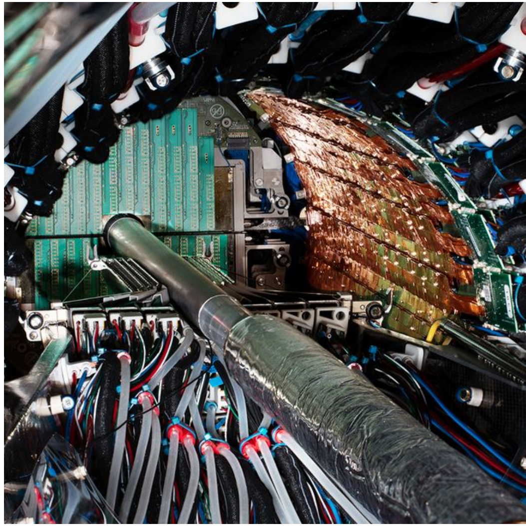
ALICE 3

arXiv:1902.01211v2

ALICE future perspectives (Run 3 - now)

ITS2: Consists of seven layers of CMOS MAPS: Complementary Metal-Oxide-Silicon (CMOS) Monolithic Active Pixel Sensors (MAPS) technology.

- 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)



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

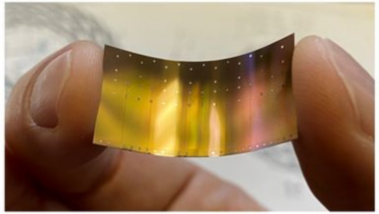
- 50 kHz and luminosity of 13 nb^{-1} in Pb–Pb collisions in Run 3 + Run 4 (x 50 min. bias in Run 1 and 2)
- 0.6 pb^{-1} in p–Pb collisions (x 1000 min. bias in Run 2)
- 200 pb^{-1} in pp collisions

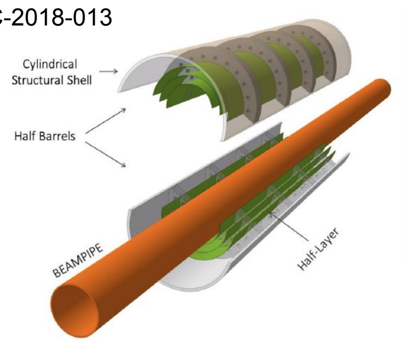
ALICE future perspectives (Run 4 - 2027)

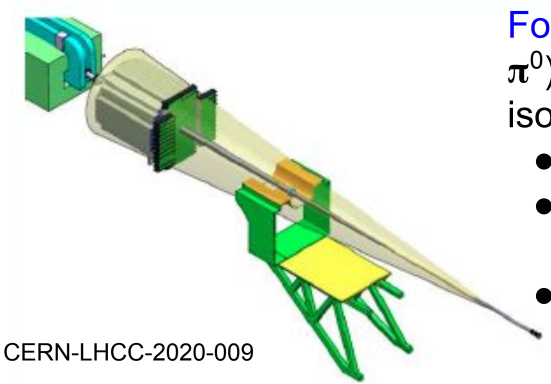
ITS3: the three innermost layers of ITS2 will be replaced with three truly cylindrical layers of wafer-scale ultra-thin silicon detectors.

- Material budget of only 0.05% X_0 per layer
- Significant improvement in the measurement of low momentum charm and beauty hadrons and low-mass dielectrons.

ALICE-PUBLIC-2018-013







CERN-LHCC-2020-009

FoCal: a highly granular Si+W electromagnetic calorimeter (FoCal-E: photons and π^0) combined with a conventional sampling hadronic calorimeter (FoCal-H : photon isolation)

- Pseudorapidity: $3.4 < \eta < 5.8$
- Unique capabilities to measure small-x gluon distributions via prompt photon production
- Measurements with mesons, photons, and jets to explore the dynamics of hadronic matter at small x down to $\sim 10^{-6}$

ALICE future perspectives (Run 5 - 2032)

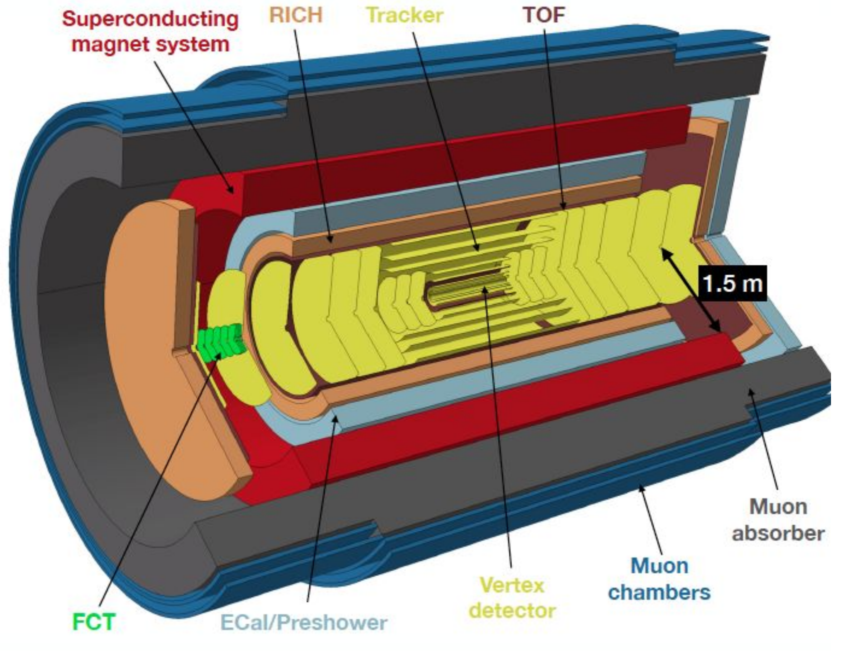
ALICE3:

➔ Compact all-silicon tracker with high-resolution vertex detector
➔ Superconducting magnet system
➔ Particle identification over large acceptance
➔ 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) will provide particle identification information.

- 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:1902.01211v2
https://indico.cern.ch/event/1063724/

Conclusions

- **Pb–Pb/Xe–Xe 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 regeneration component at late stage
    - Radial flow depends exclusively on the multiplicity (not collision system dependent)
    - Elliptic flow depends also on the initial eccentricities of the collision region

- **pp and p–Pb collisions:**
    - Similar behaviour as in Pb–Pb collisions for hadronization and azimuthal anisotropies;
    - Hypertriton explained by 2-body coalescence models
    - Dead cone effect was experimentally measured
    - Indication of an attractive interaction for p-Ω^- and p-Ξ^- pairs that exceeds the Coulomb force
    - Hint of multi-parton interactions affecting the J/ψ yield.

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

Thank you for your attention!

Backup slides

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