ALICE Highlights

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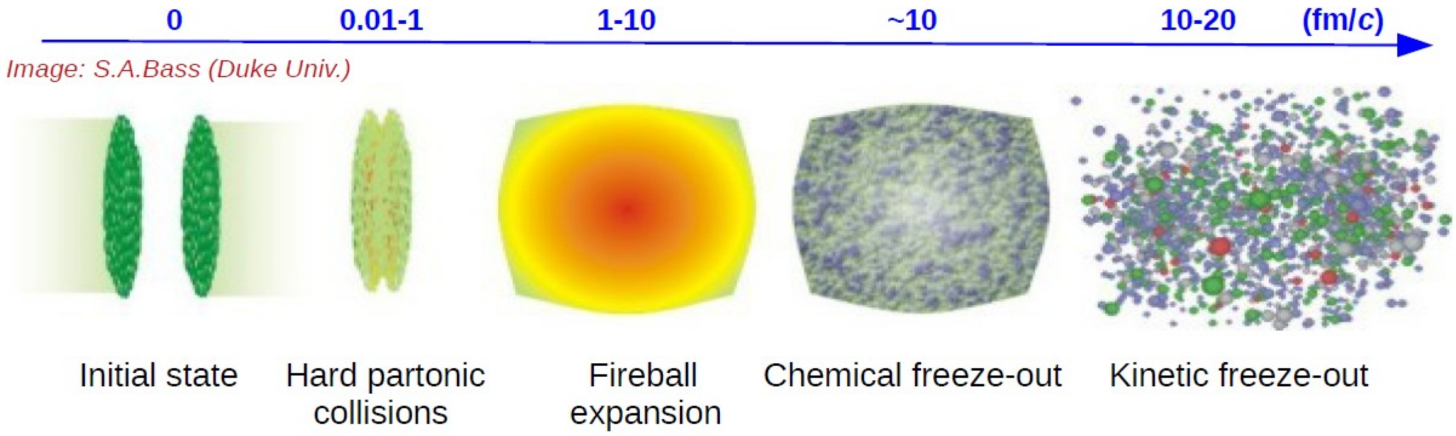
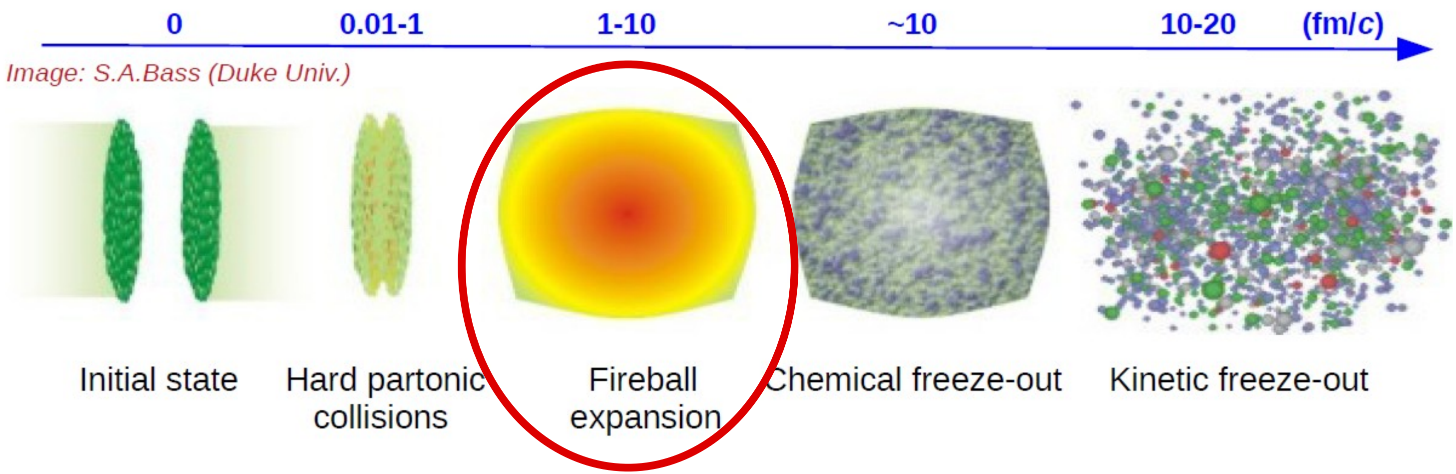
on behalf of the ALICE Collaboration
[(*)]University & INFN, Cagliari

XII International Conference on New Frontiers in Physics
July 10th-23rd, 2023 – Kolymbari, Creete, Greece

(Ultra-)Relativistic heavy-ion collisions



(Ultra-)Relativistic heavy-ion collisions

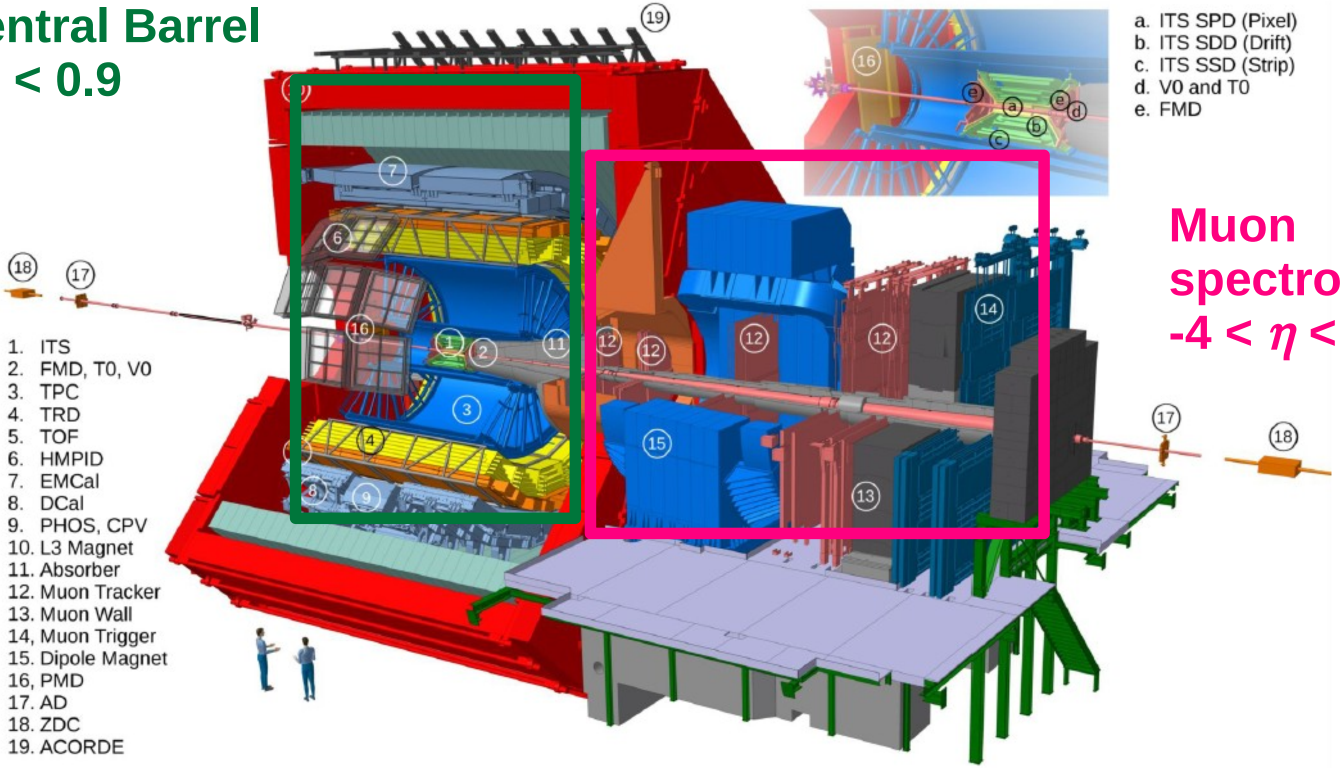


Quark-gluon plasma (QGP): deconfined state of strongly-interacting QCD matter

- ✔ Main goal of the ALICE Physics program: study the properties and the evolution of a heavy-ion collision, with a particular attention to the **QGP** state
- ✔ Rich program of measurements in **small systems**, namely **pp** and **p-Pb** collisions
  - **reference** measurements for interpreting heavy-ion results (e.g. vacuum production, Cold Nuclear Matter effects)
  - characterization of **high-multiplicity events** and search for **collectivity** in small systems

The ALICE detector in Run 1 & Run 2

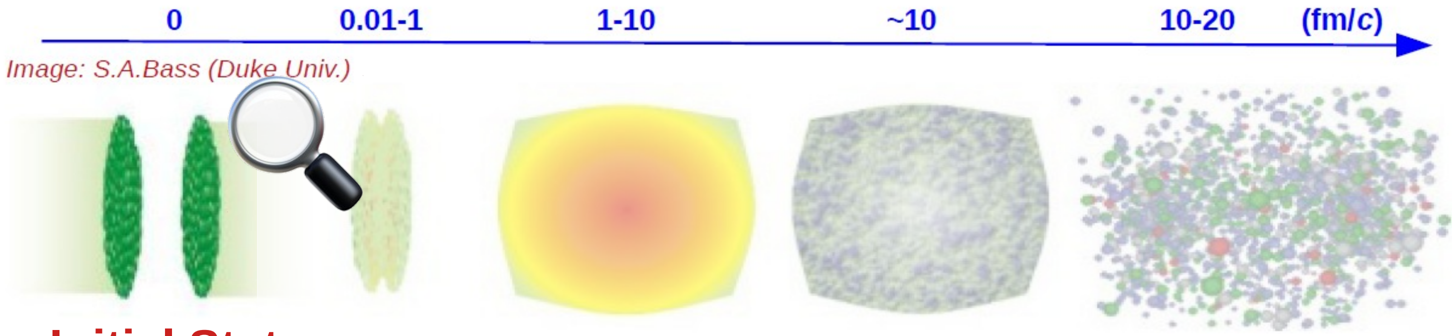
Central Barrel
$|\eta| < 0.9$



Muon spectrometer
$-4 < \eta < -2.5$

- ✔ Designed to study the QGP and heavy-ion collisions
- ✔ Excellent tracking, vertexing and PID up to very high multiplicities and low transverse momentum

The physics of ALICE



Initial State

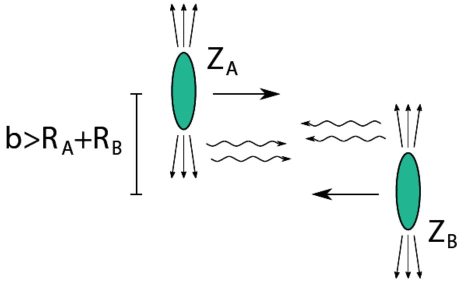
Probing gluon PDF in nuclei with ultraperipheral Pb-Pb collisions

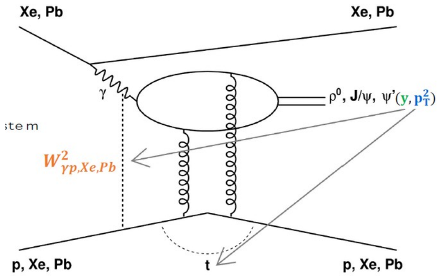
- ✓ Photon-induced reactions → Ultrarelativistic moving nuclei produce strong electromagnetic (EM) fields that can be treated as a quasi-real photons flux
- ✓ In UPC: $b > R_A + R_B$
- ✓ **Two types of processes can contribute:**

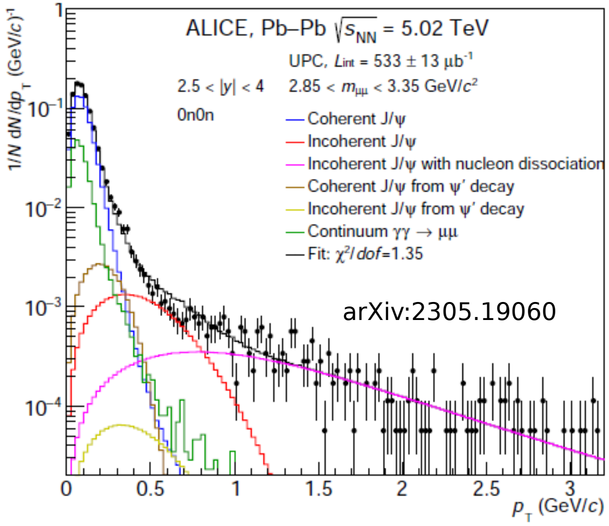
Incoherent: interaction of the photon with only one nucleon inside the nucleus

- **Elastic**: interaction with the full nucleon
- **Dissociative**: interaction with sub-nucleon sized structures inside the nucleon

Coherent: the photon interacts with the colour field of the whole nucleus

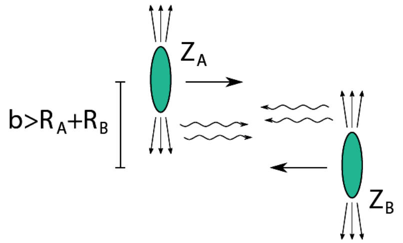




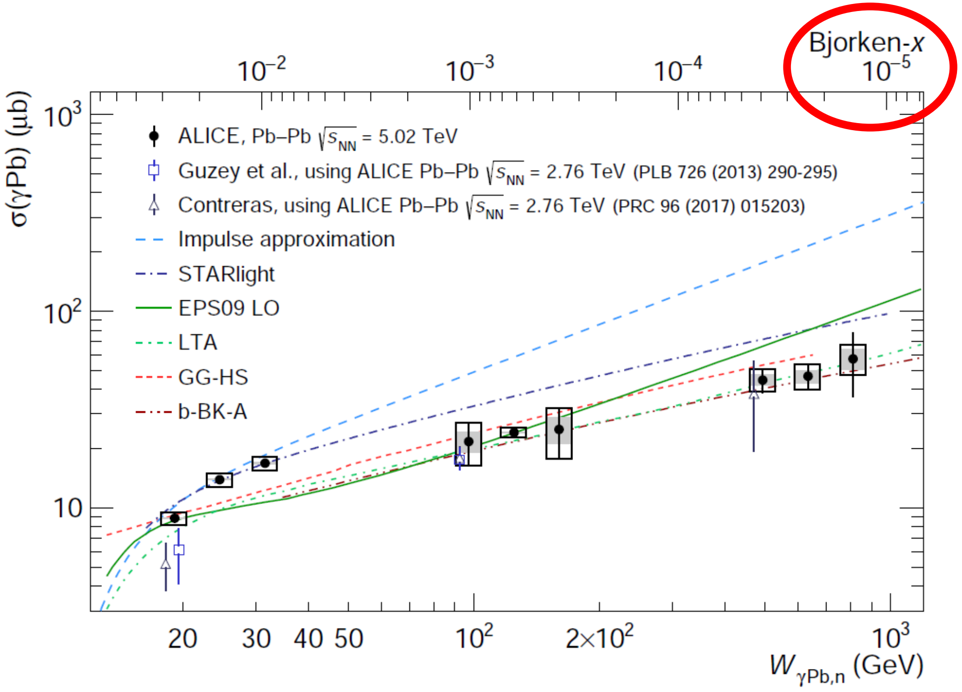


Probing gluon PDF in nuclei with ultraperipheral Pb-Pb collisions

arXiv:2305.19060



- ✓ **Coherent** photonuclear cross section γ+Pb → J/ψ+Pb:



- ✓ Cross section rises with γ-N centre-of-mass energy ($W_{\gamma Pb,n}$)
- ✓ constrain gluon PDFs in nuclei down to $x_{Bjorken}$ ~ 10^{-5}
- ✓ Impulse approximation and Starlight (no shadowing / saturation effects) systematically overpredict the cross section at intermediate / high energies
- ✓ Within uncertainties models that include either shadowing or saturation can fairly describe the data, except for the energy range 25-35 GeV

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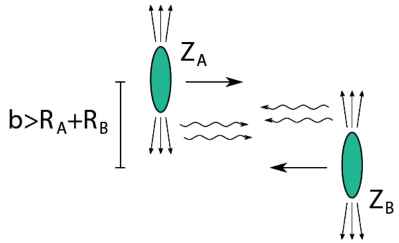
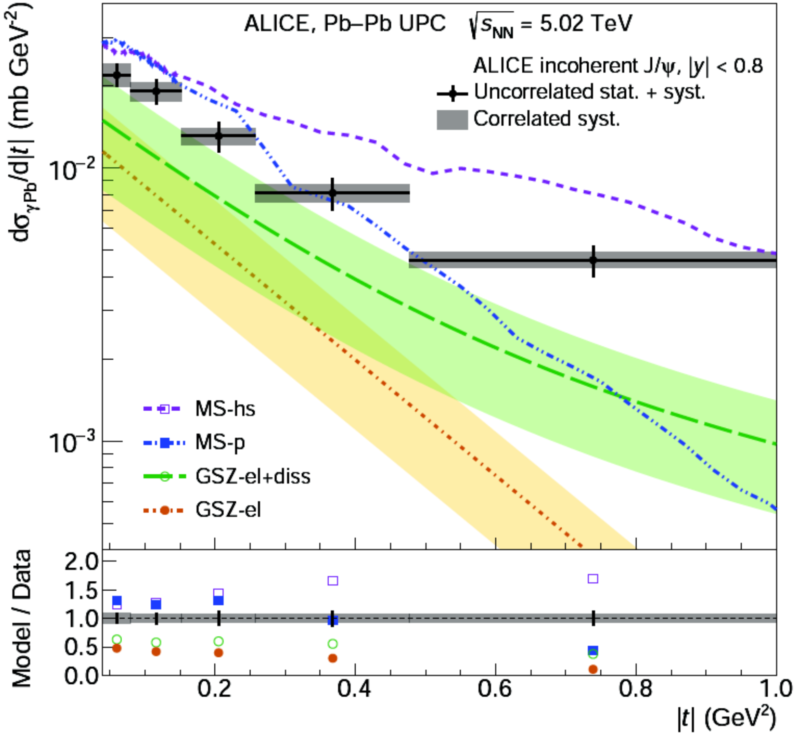
Probing gluon PDF in nuclei with ultraperipheral Pb-Pb collisions

arXiv:2305.06169



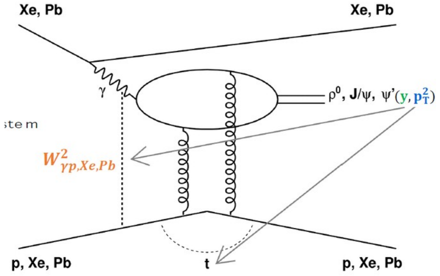
✓ **Incoherent** photonuclear cross section vs Mandelstam |*t*| variable



✓ First measurement of incoherent photonuclear production of J/ψ

✓ None of the models is able to catch normalization and |*t*| dependence simultaneously

✓ Agreement with data improves after the inclusion of scattering structures at sub-nucleon scale (i.e. dissociative-like component)



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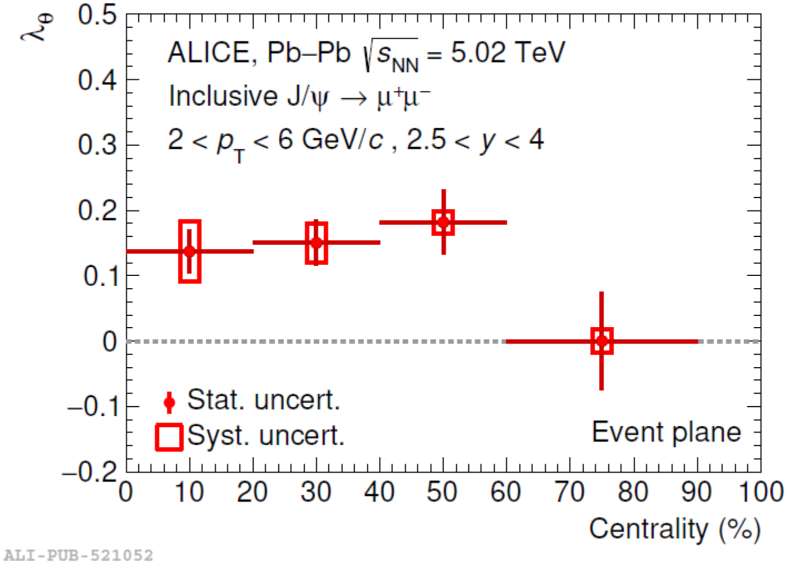
J/ψ polarization w.r.t. event plane

arXiv:2204.10171

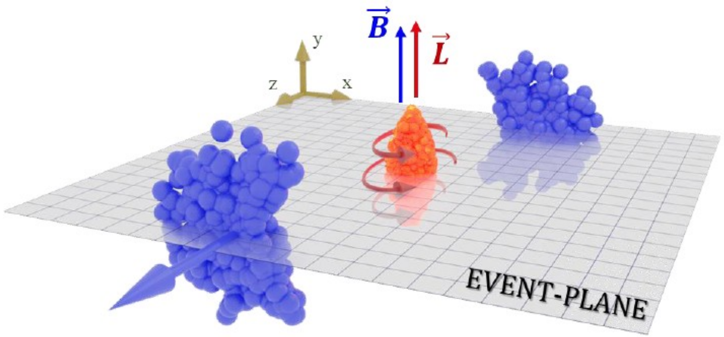


– **Polarization**: angular distributions of decay products w.r.t. a polarization axis

– **Event Plane based frame (EP)**: axis orthogonal to the event plane in the collision center of mass frame

  – Event Plane normal to ***B*** and ***L***

– **Heavy quarks produced early in the collisions can experience both *B* and *L* originated in the initial stage !**



$$W(\theta) \propto \frac{1}{3+\lambda_\theta}\left(1+\lambda_\theta \cos^2\theta\right)$$

- ✓ Significant polarization (3.5σ) in 40-60% and 2 < p_T < 6 GeV/c
- ✓ Small centrality dependence
- ✓ Theoretical description of vector meson polarization in heavy ion collisions still missing

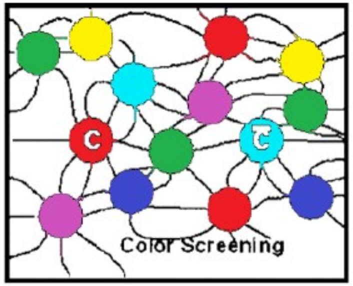
The physics of ALICE

Medium properties

Quarkonia: dissociation vs regeneration

In-medium dissociation (color Debye screening)

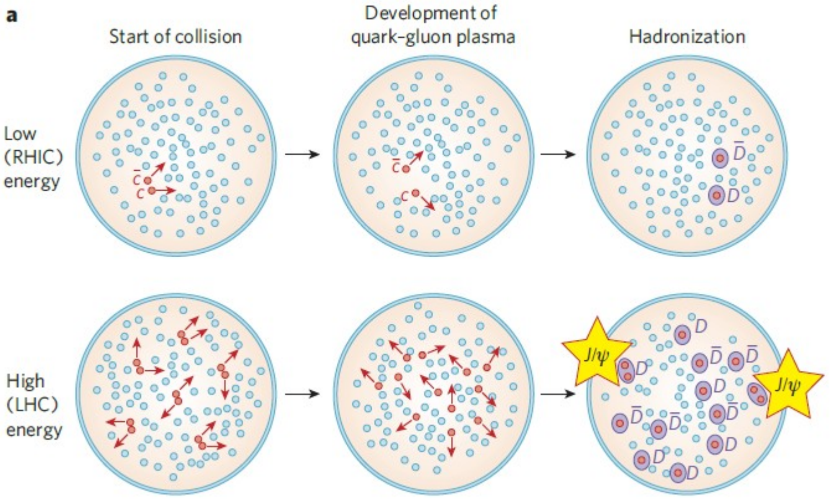
Matui & Satz, Phys.Lett. B178 (1986) 416-422



vs

Regeneration of quarkonia

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



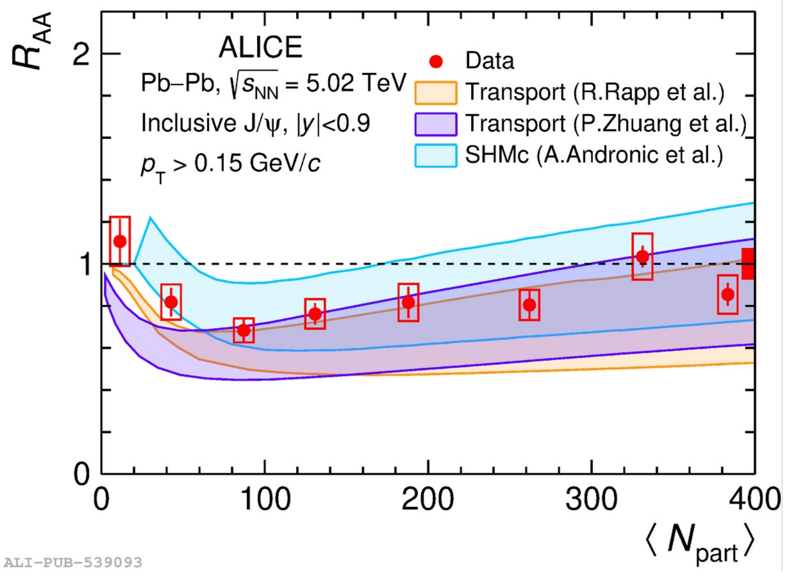
Nature 448 (2007) 302-309

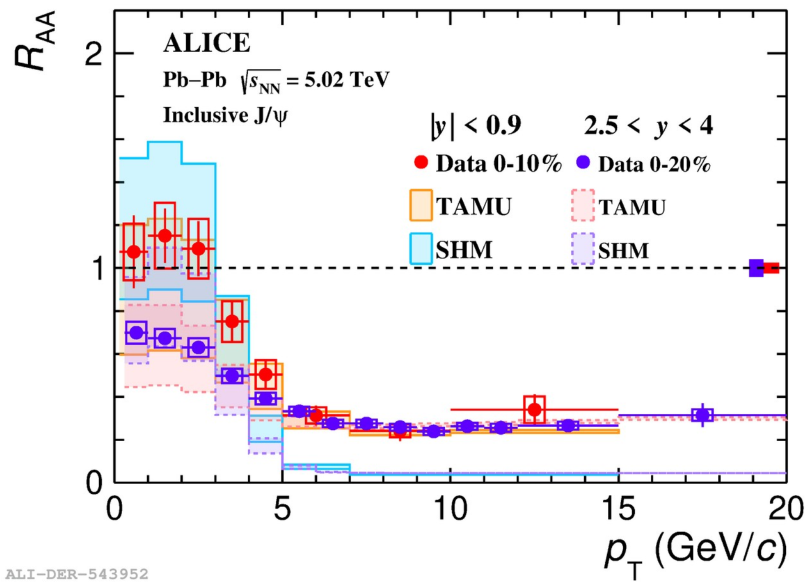
Nuclear modification factor R_{AA}

$$R_{AA} = \frac{1}{N_{coll}} \times \frac{(dN/dy)_{AA}}{(dN/dy)_{pp}}$$

Quarkonia: dissociation vs regeneration

arXiv:2303.13361





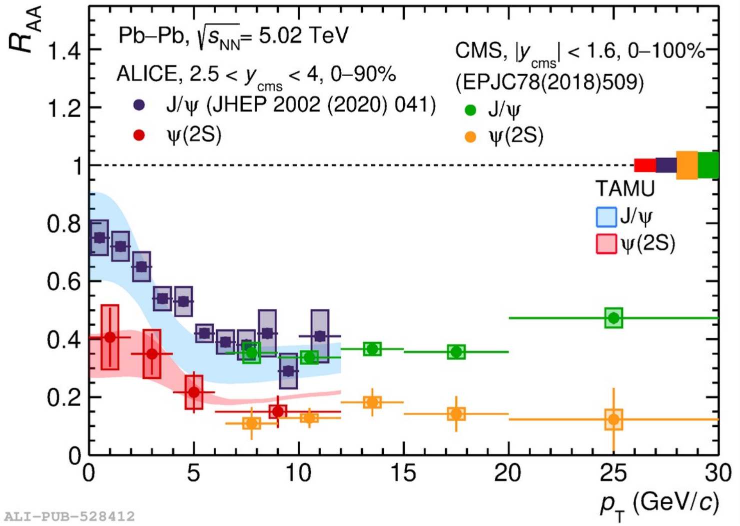
- **Models including regeneration mechanism in fair agreement with data**
  - Statistical Hadronization (SHM):all charmonia produced at the QGP phase boundary with thermal weights
  - Transport model (TAMU): solve Boltzmann equation with gain (regeneration) and loss (melting) terms

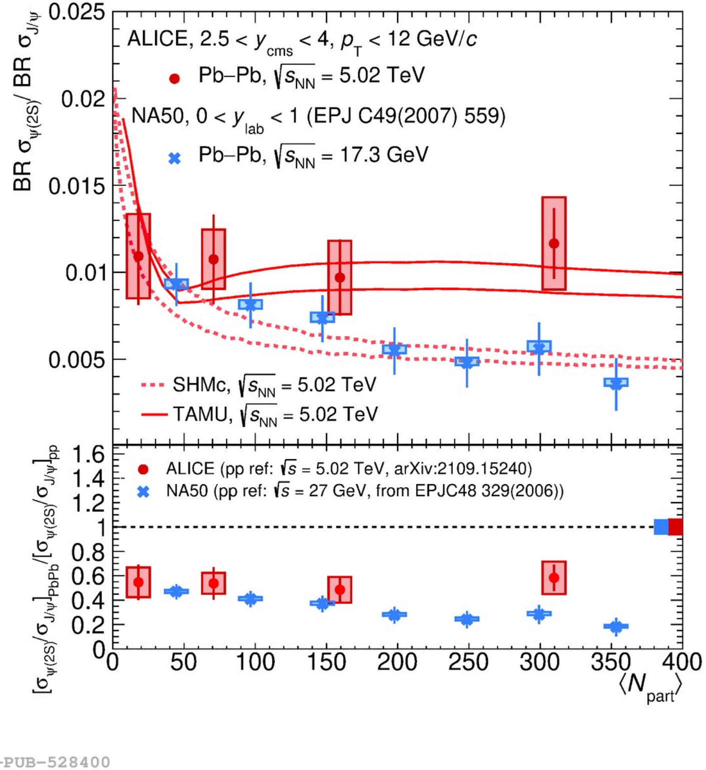
- **large uncertainties on the models arise from charm cross sections and poor constrained nuclear PDF**

Quarkonia: dissociation vs regeneration

arXiv:2210.08893

- Excited states: different binding energies are expected to change the relative contributions of suppression / regeneration

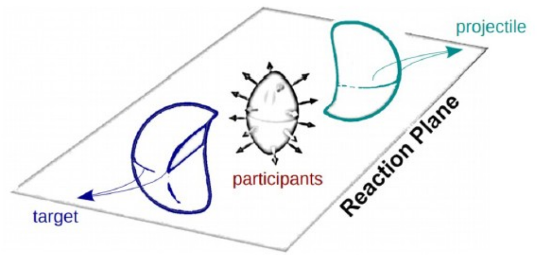


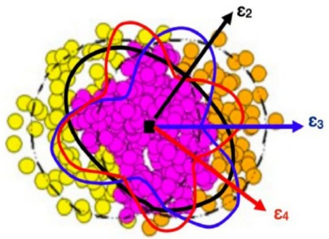


- ψ(2S) more suppressed compared to J/ψ; rise of J/ψ and ψ(2S) R_{AA} towards low p_T
- p_T dependent R_{AA} in agreement with TAMU for both charmonium states
- ψ-to-J/ψ ratio: powerful tool for disentangle among different regeneration scenarios
  - good agreement with TAMU; tensions visible with SHMc at higher centralities

Anisotropic flow of identified hadrons

$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cdot \cos[n(\varphi - \Psi_{RP})] \quad v_n = \langle \cos[n(\varphi - \Psi_{RP})] \rangle$$





Decomposed transverse projection of participant region in Fourier series

✔ **Initial spatial anisotropy:**

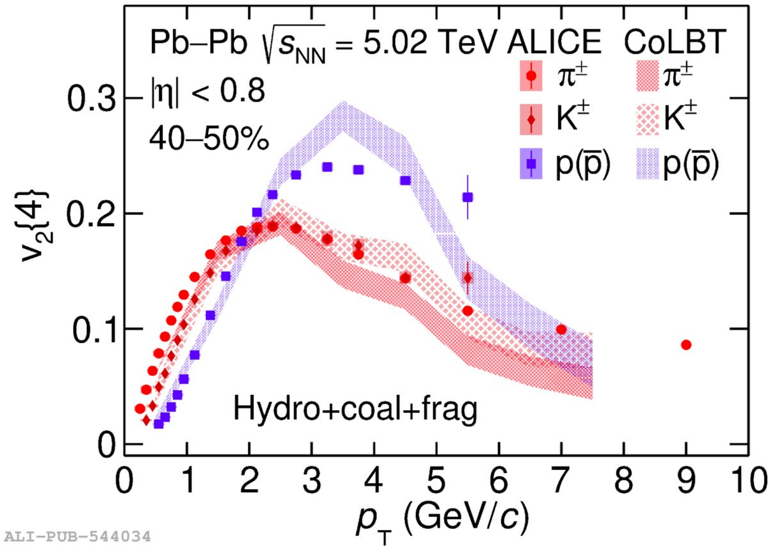
- Almond shape of the participant region → generates ellipticity (ε_2)
- Energy density fluctuations in the overlap region → generates triangularity (ε_3)
- Higher harmonics → mainly arising from the combination of the lower order components

→ **low-p_T: sensitive to bulk QGP properties**

→ **high-p_T: sensitive to the in medium energy loss (path-length dependence)**

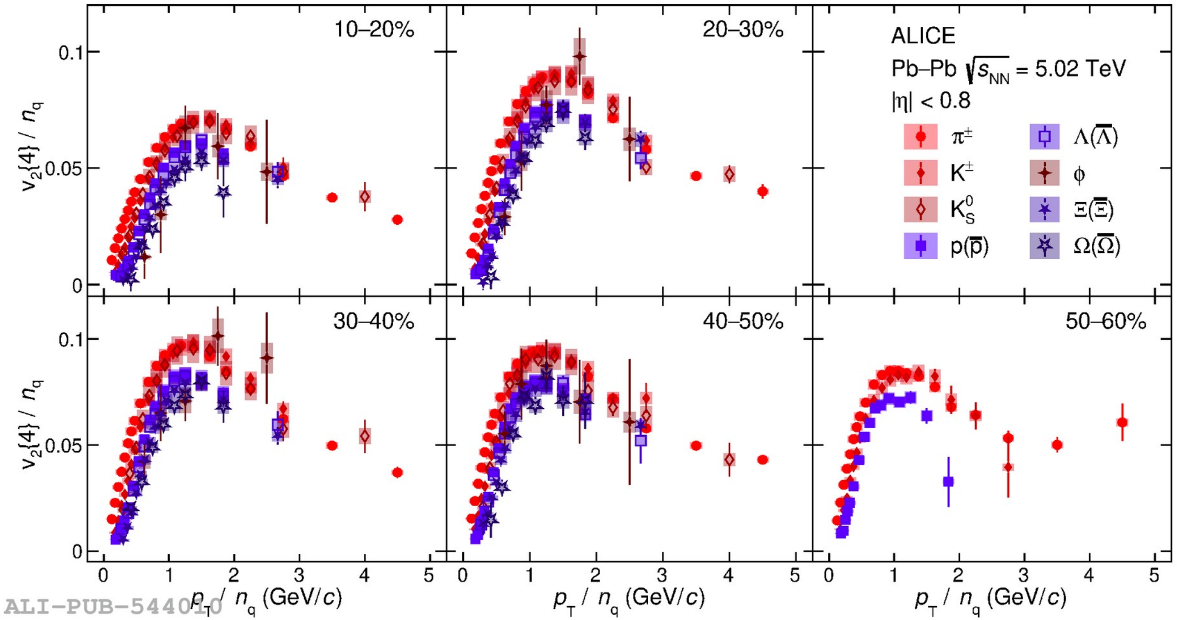
Anisotropic flow of identified hadrons

JHEP 05 (2023) 243



- ✔ Mass ordering at low p_T and meson-baryon splitting at intermediate p_T
- ✔ Overall good description provided by CoLBT model (including hydro+coalescence+fragmentation)

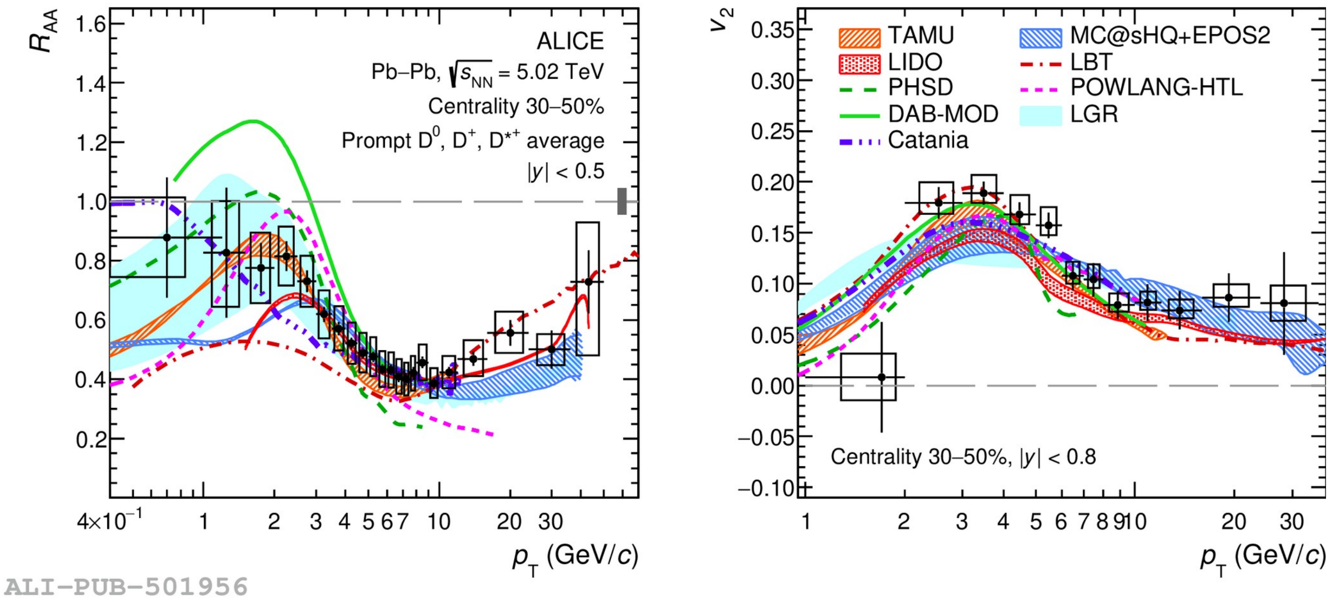
- ✔ Approximate scaling with number of constituent quarks observed (accuracy 20%)
  - Coalescence contribution needed for describing data at intermediate p_T (but not the only mechanism at play)



R_{AA} and flow of prompt D mesons

JHEP 01 (2022) 174

- First measurement of D^0 meson R_{AA} in Pb-Pb collisions down to $p_T = 0$
- The simultaneous description of R_{AA} and v_2 in central and semicentral collissions is a challenge for theoretical models



ALI-PUB-501956

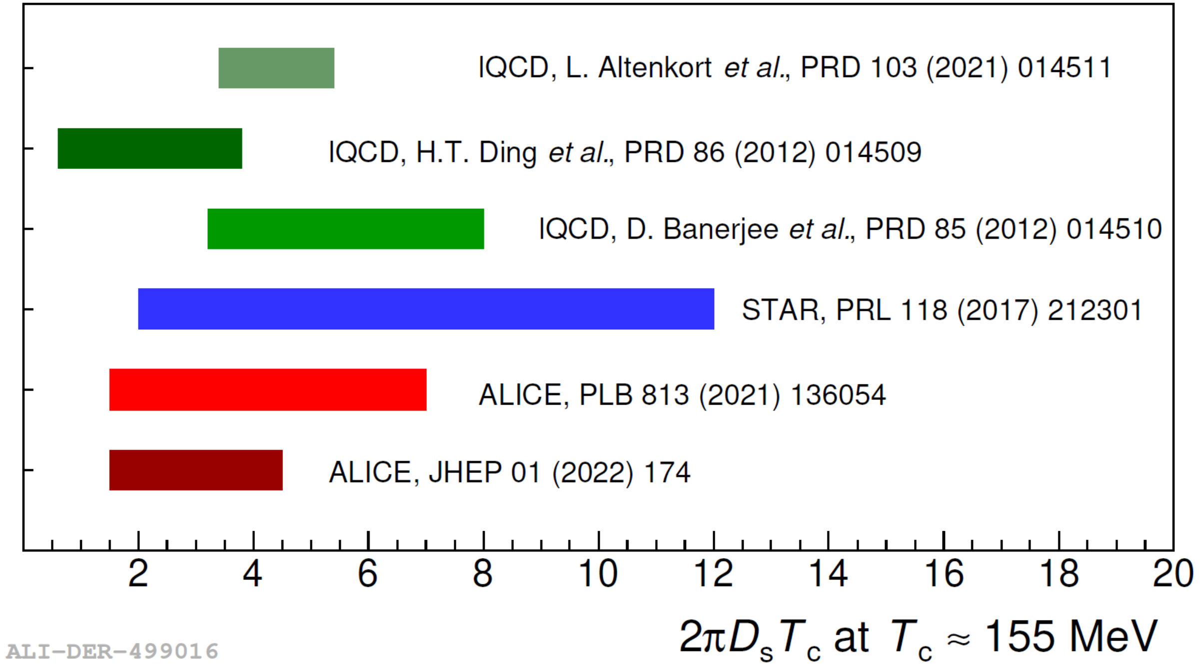
R_{AA} and flow of prompt D mesons

JHEP 01 (2022) 174

- First measurement of D^0 meson R_{AA} in Pb-Pb collisions down to $p_T = 0$
- The simultaneous description of R_{AA} and v_2 in central and semicentral collissions is a challenge for theoretical models
- Few models that are in fair agreement with both observables used to constrain the heavy-quark spatial diffusion coefficient:

$$1.5 < 2\pi D_s T_c < 4.5$$

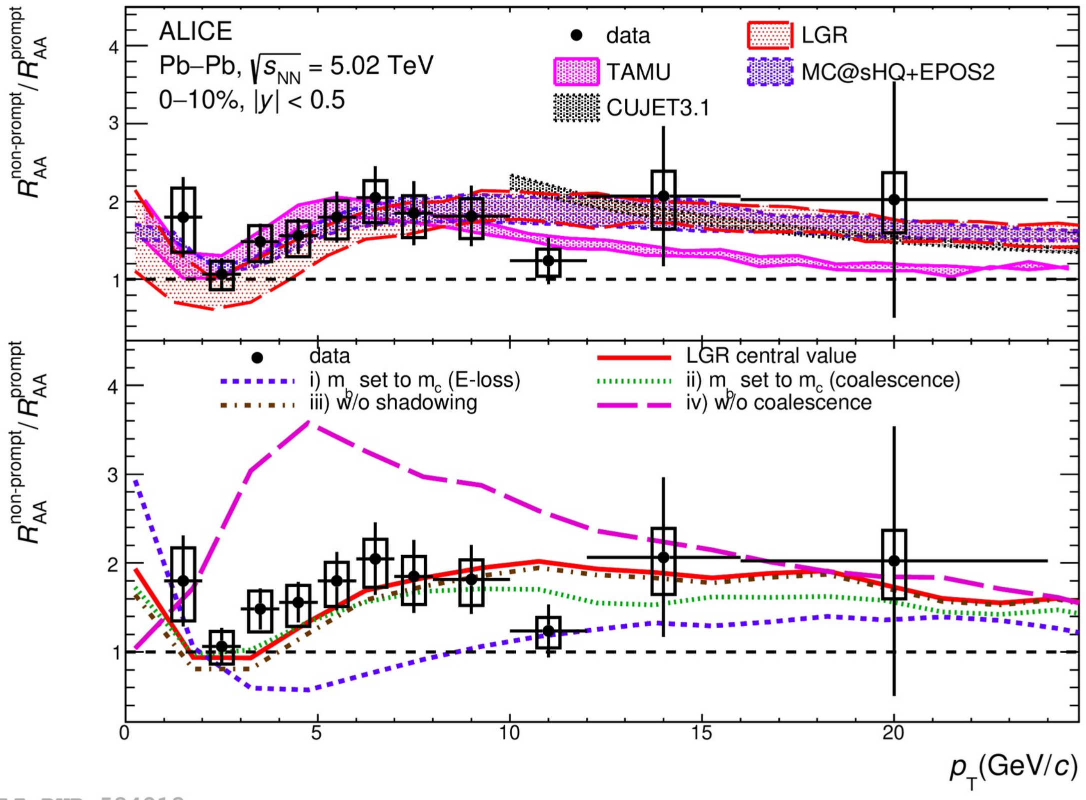
→ narrower interval w.r.t. previous estimations based on D-meson measurements at LHC energies



b-quark energy loss in QGP

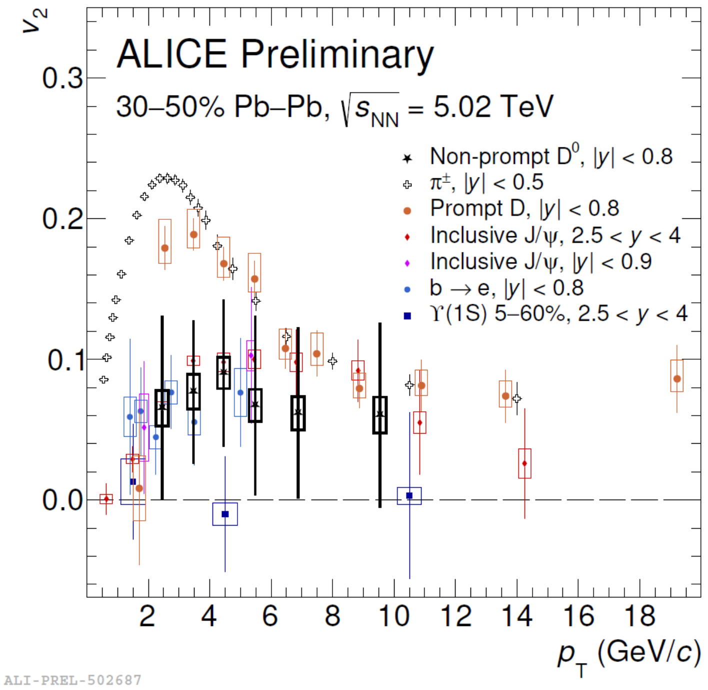
JHEP 12 (2022) 126

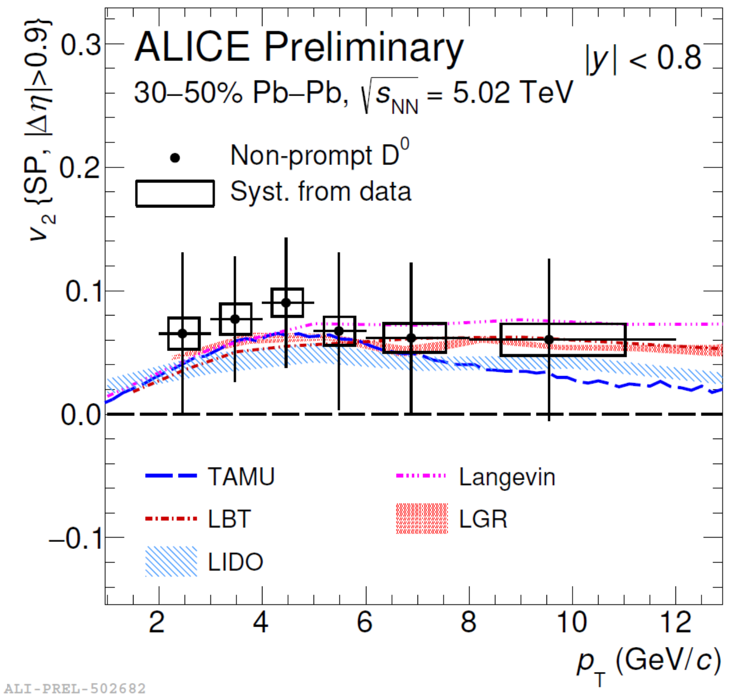
- ✔ Accessed via non-prompt D^0 measurements
- ✔ Larger suppression observed for prompt compared to non-prompt D^0 above 5 GeV/c
- ✔ Well described within uncertainties by TAMU, CUJET3.1, LGR and MC@sHQ +EPOS2 → all, but TAMU, include both radiative and collisional energy loss mechanisms
- ✔ Coalescence can explain the minimum observed at low p_T in the non-prompt to prompt D^0 R_{AA} ratio
- ✔ Radiative energy loss contribution needed at intermediate / high p_T



ALI-PUB-534213

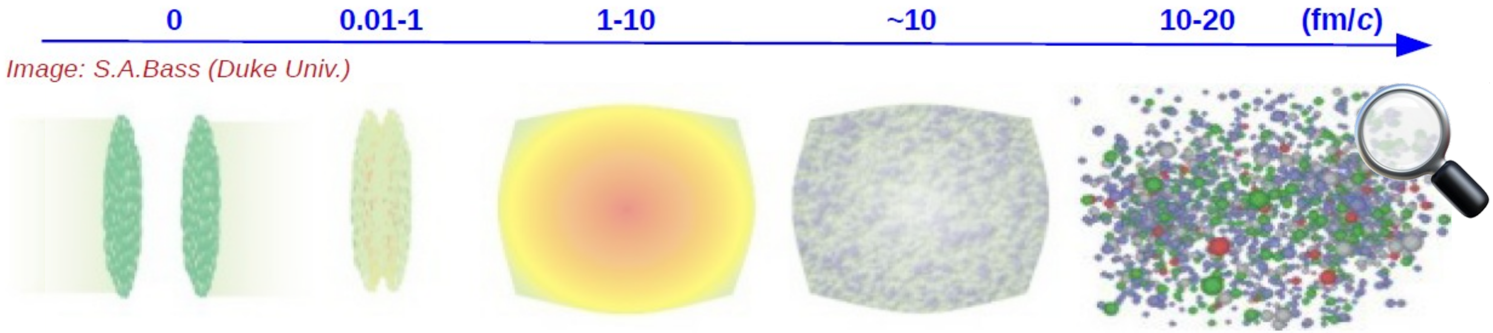
b-quark thermalisation in QGP





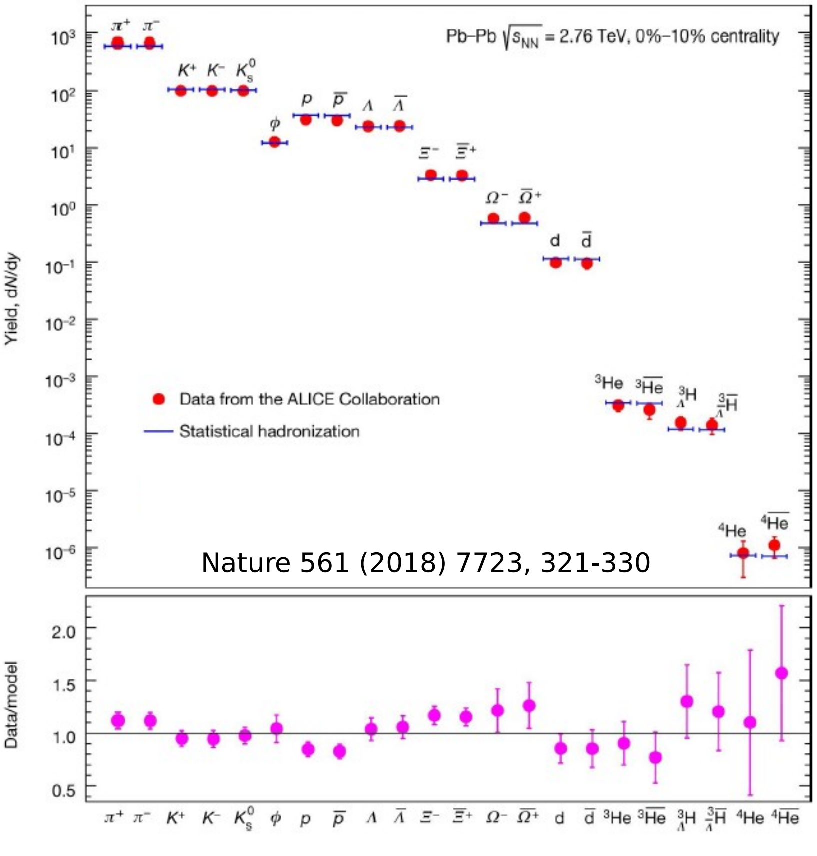
- Positive non-prompt D^0 v_2 observed in 2 < p_T < 12 GeV/c in semicentral collisions
  - Compatible with elliptic flow of b → e
- Described by models including hadronization via coalescence and fragmentation

The physics of ALICE



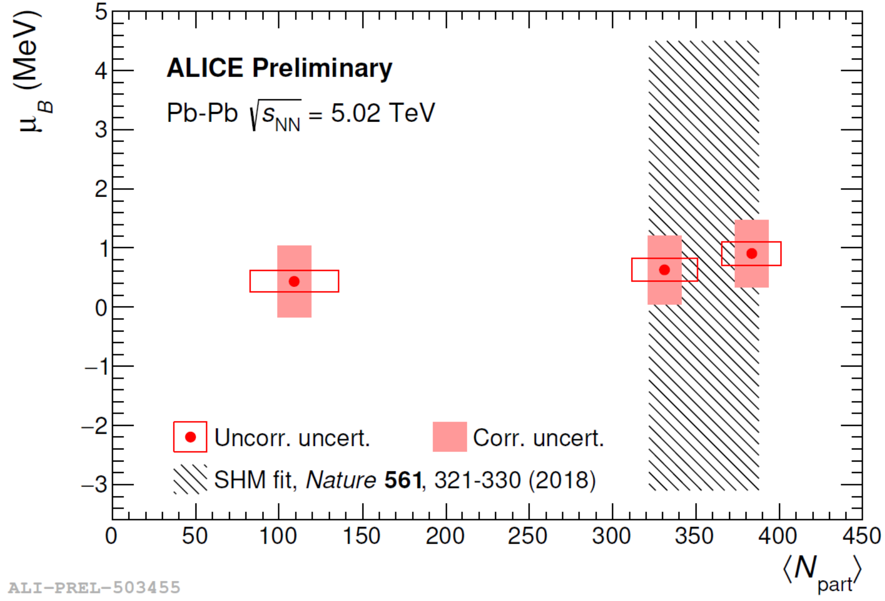
Freeze-out and rescattering

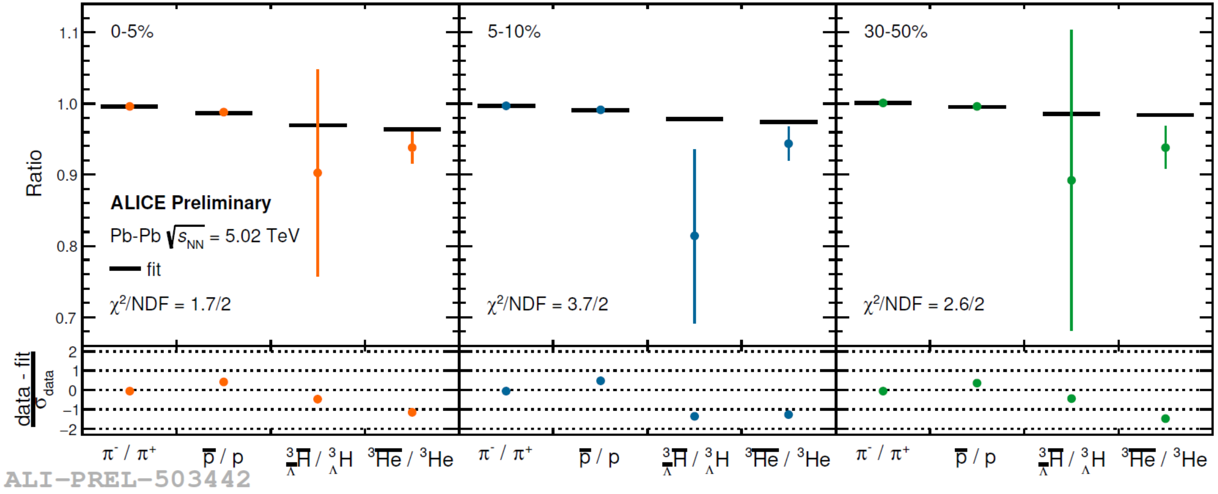
Light-flavour hadron abundances at the freeze-out



- ✔ Production of light-flavour hadrons well described by Statistical Hadronization Model (SHM) fit over 9 orders of magnitude (Grand Canonical ensemble forumulation)
- ✔ Hadron yields can be described as emerging from a hot Hadron-Resonance Gas in thermal equilibrium
  - **At LHC: $\mu_B \sim 0$, $T_{ch} \sim 156$ MeV**
- ✔ Precise determination of the parameters thanks to the wide variety of particle yields available with good experimental precision

Antimatter / matter imbalance at the LHC





- ✔ Precise determination of μ_B from antimatter / matter imbalance within the SHM model by fitting:

$$\bar{h}/h \propto \exp\left[-2\left(B+\frac{S}{3}\right)\frac{\mu_B}{T} - 2I_3\frac{\mu_{I_3}}{T}\right]$$

with $T = 156.2 \pm 2$ MeV

- ✔ Reduced uncertainties on μ_B w.r.t. global SHM fit thanks to the cancellation of correlated uncertainties in the ratio

The physics of ALICE

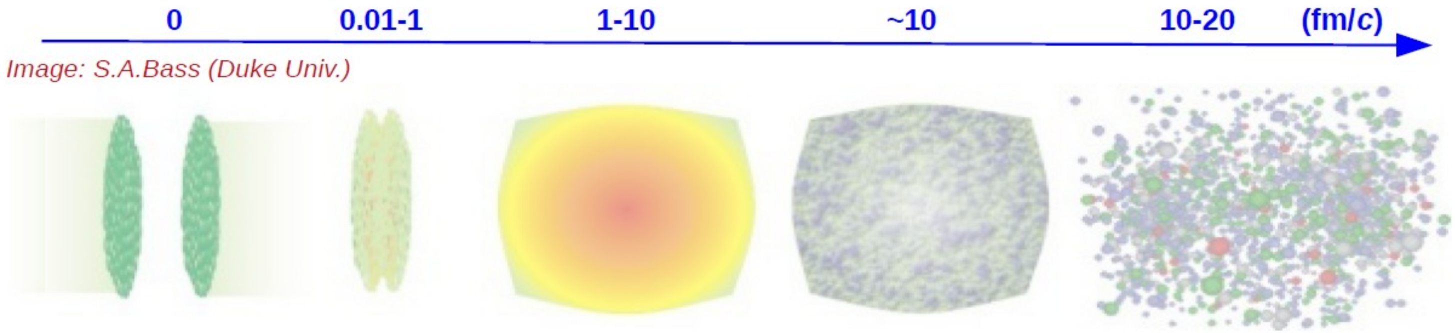
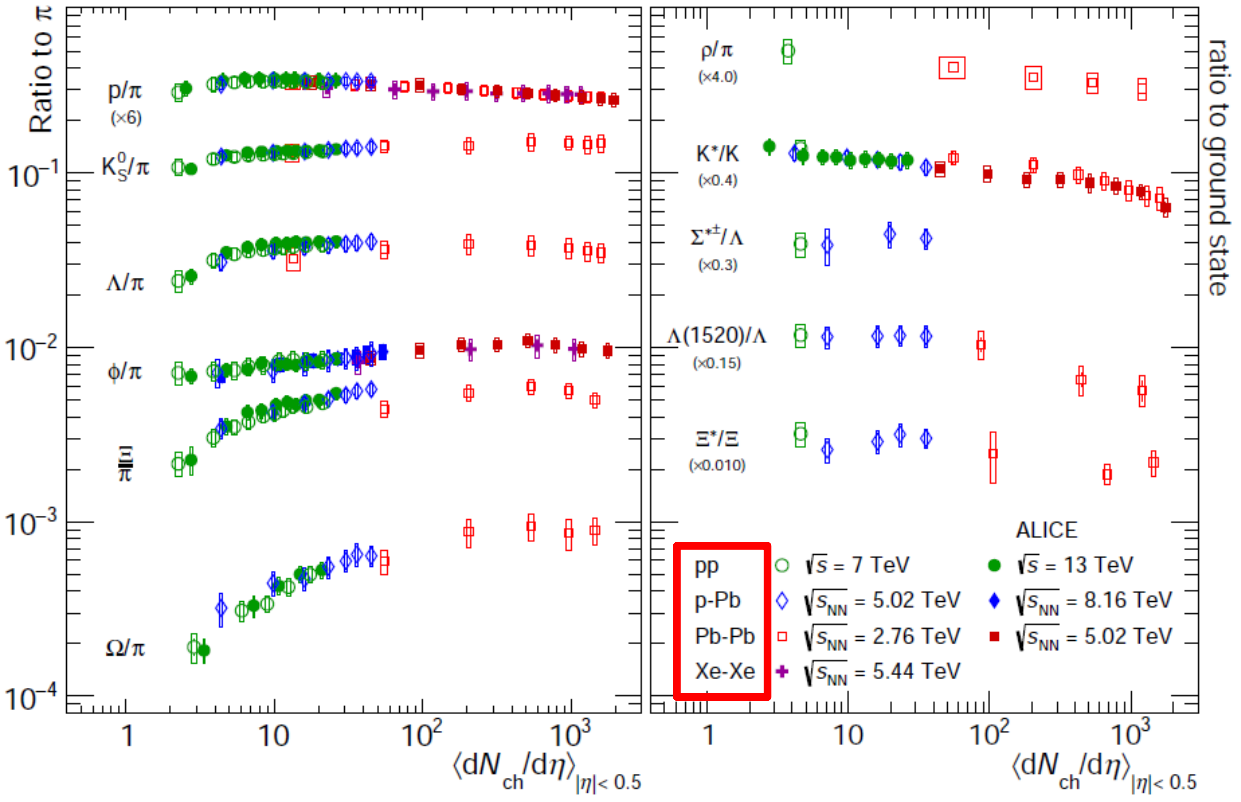


Image: S.A.Bass (Duke Univ.)

From large to small systems...

Particle production across systems

arXiv:2211.04384



- ✔ Smooth trend of multiplicity dependent particle production ratios from pp to Pb-Pb multiplicities
- ✔ Is charged particle multiplicity the relevant parameter to explain strangeness enhancement or other “QGP-like” effects in small systems ?

F. Fionda, ICNFP 2023

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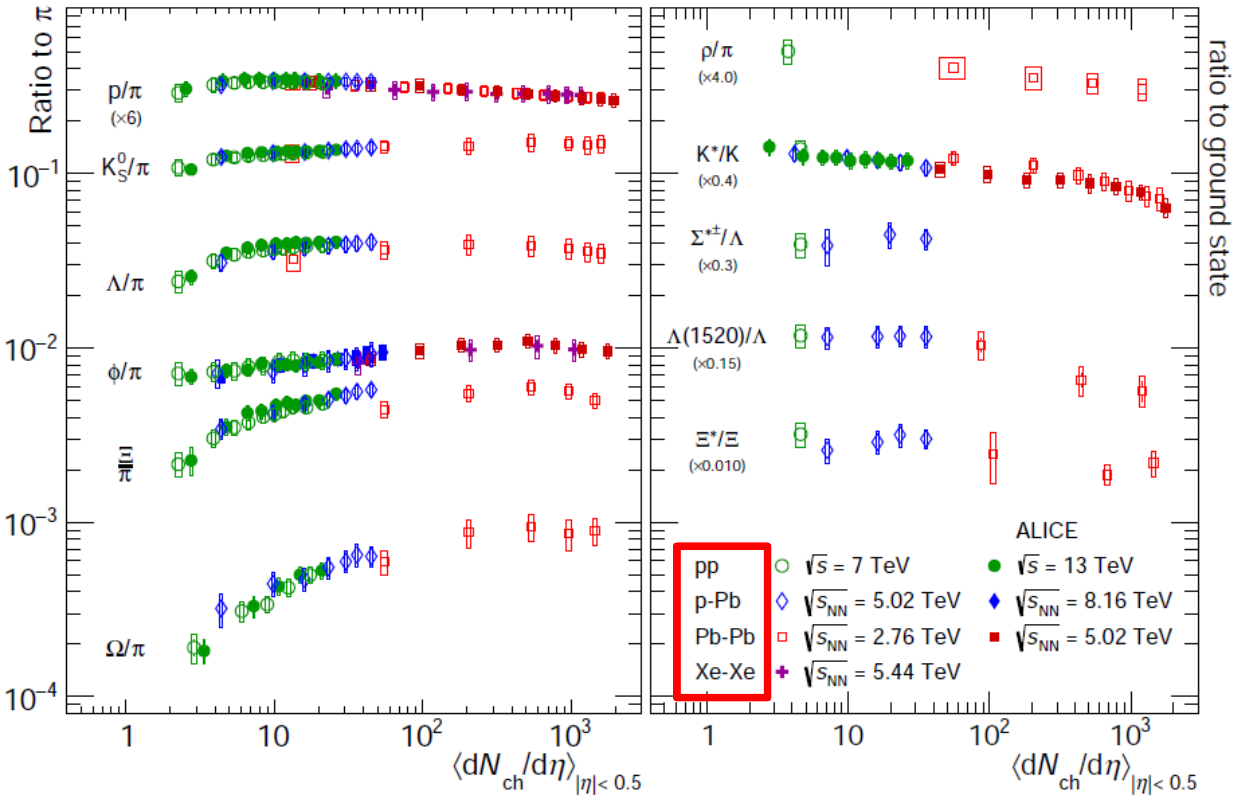

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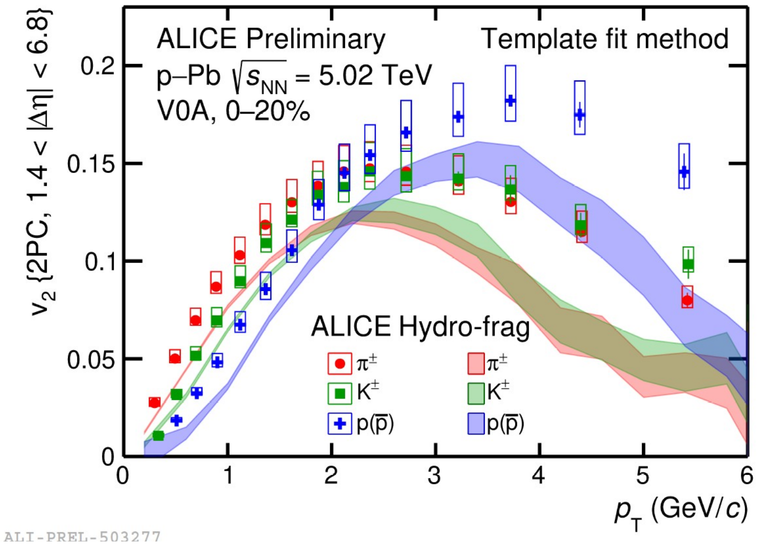
→ See more in Maria Barlou’s talk

Collectivity in small systems ?



✔ Similar mass ordering and meson-baryon splitting in p-Pb collisions as observed in Pb-Pb collisions

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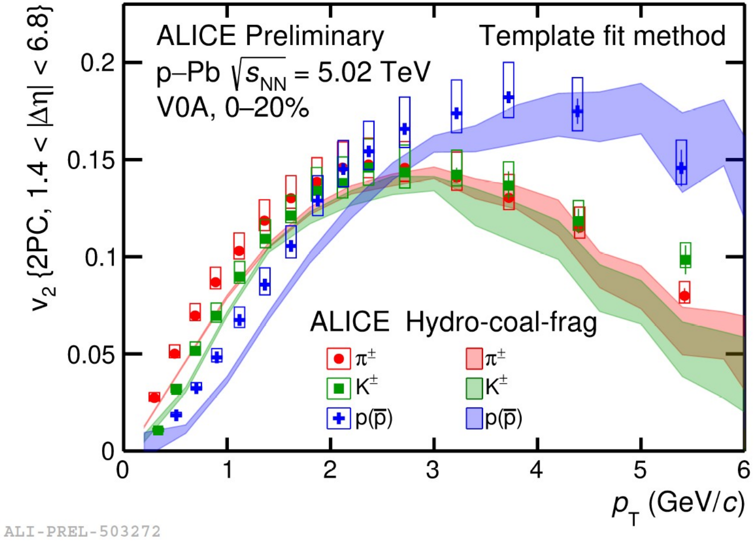
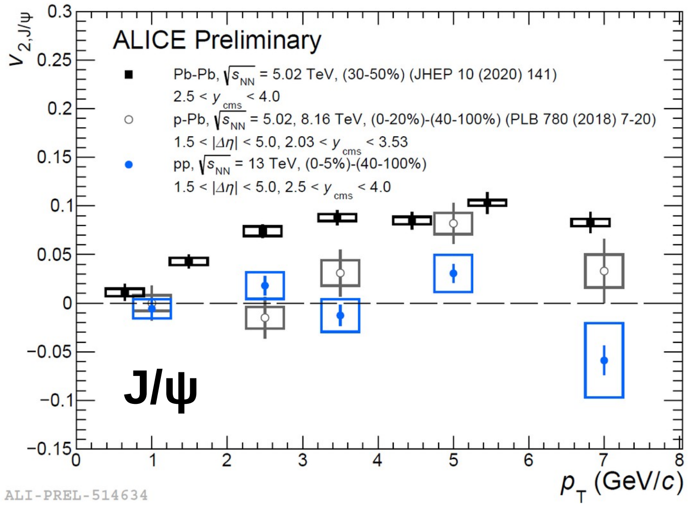
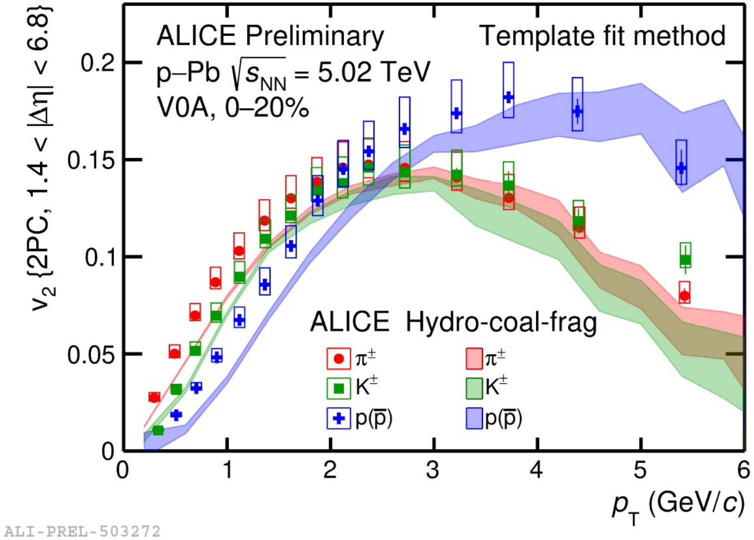
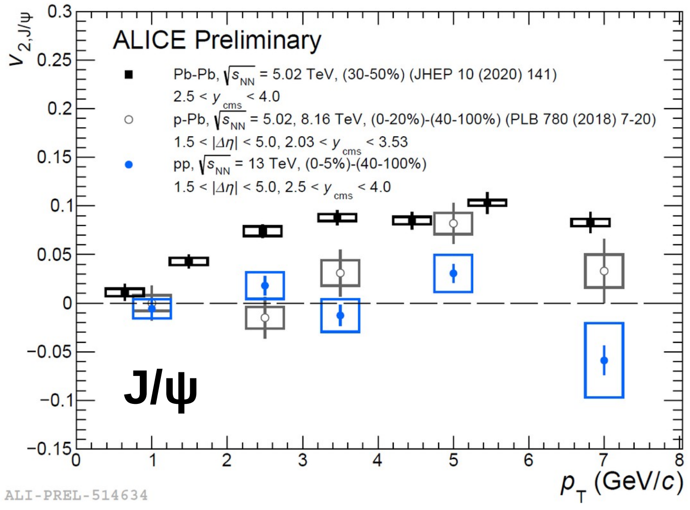




- ✔ Similar mass ordering and meson-baryon splitting in p-Pb collisions as observed in Pb-Pb collisions
- ✔ Comparison with models indicate that coalescence is needed to describe the flow at intermediate p_T
- ✔ Collective behaviour observed in p-Pb collisions also for J/ψ, but only at high p_T

Collectivity in small systems ?





→ Common mechanism at the origin of the flow in large and small systems ?

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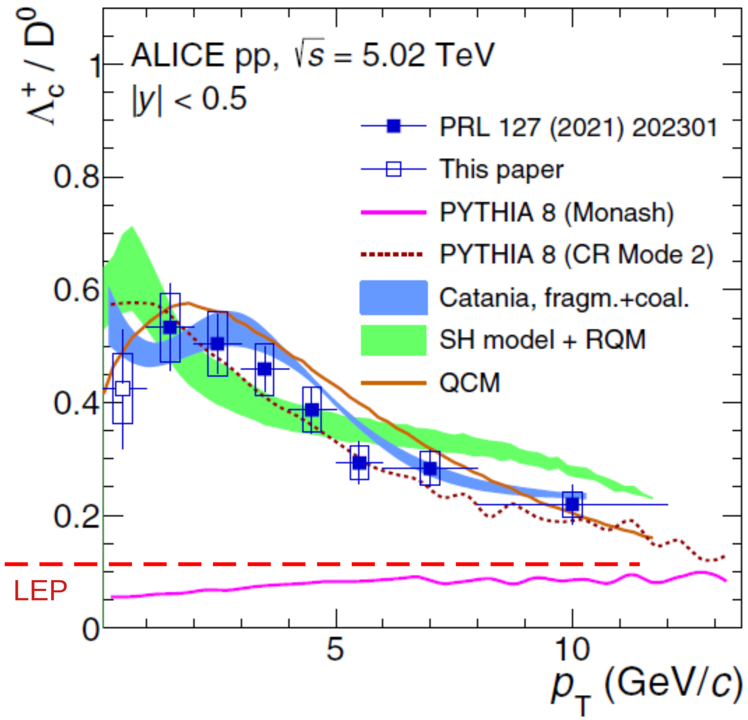
The "baryon anomaly" in the HF sector

Phys. Rev. C 107 (2023) 064901



- ✔ First measurement of Λ_c production down to p_T = 0 in small systems !
- ✔ Enhancement of $\mathbf{\Lambda_c/D^0}$ ratio at low and intermediate momentum w.r.t. e^+e^- results (LEP average: 0.113 ± 0.013 ± 0.006 [EPJC 75 (2015) 19])
  - Significantly underestimated by PYTHIA8 Monash tune (which incorporates fragmentation parameters from e^+e^- data)
- ✔ Data qualitatively reproduced by models implementing baryon to meson ratio enhancement via various mechanisms (color reconnection, feed-down from unobserved resonant charm baryon states, quark coalescence)

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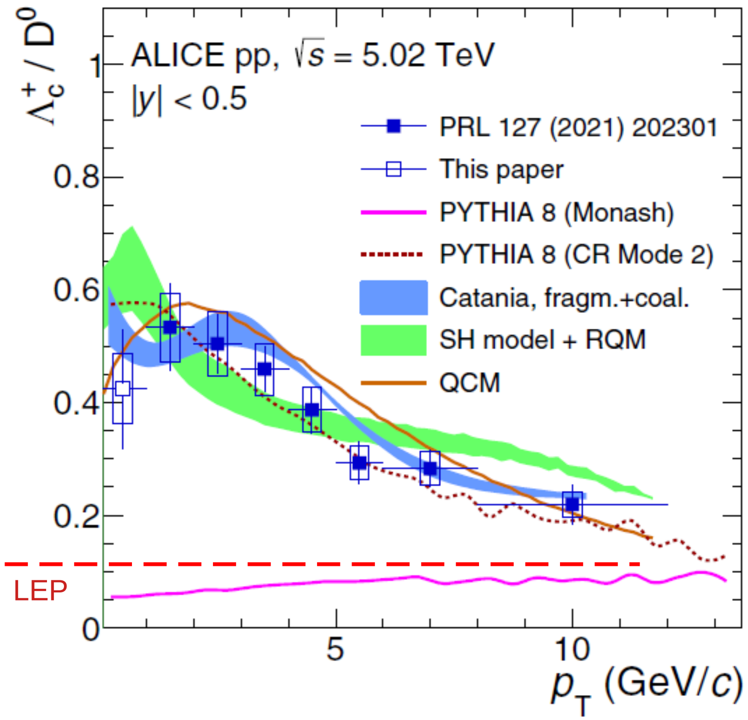

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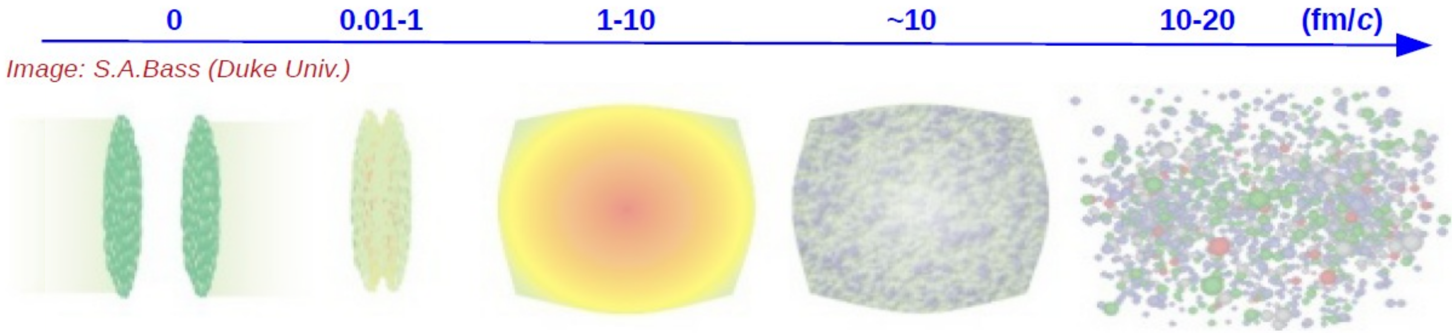
→ **See more in Syaefudin Jaelani's talk**

The physics of ALICE

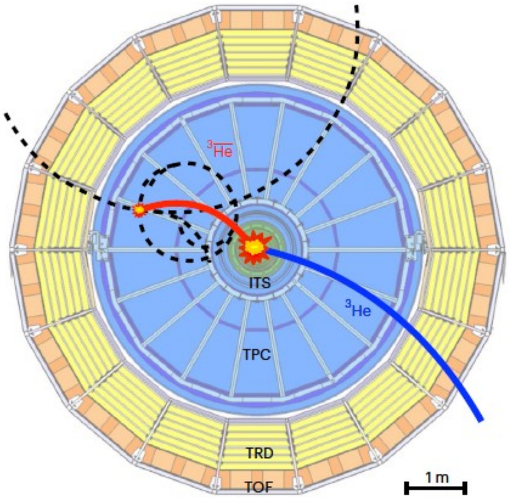


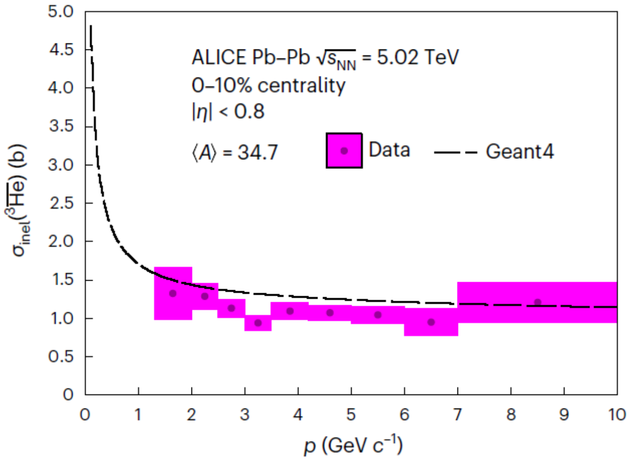
From large to small systems...

… and beyond

Contributing to dark matter research

Nature Phys. 19 (2023), 61





- ALICE detector used as anti-particle absorber → novel technique
- First experimental measurement of σ_{inel}(anti-^{3}He) !

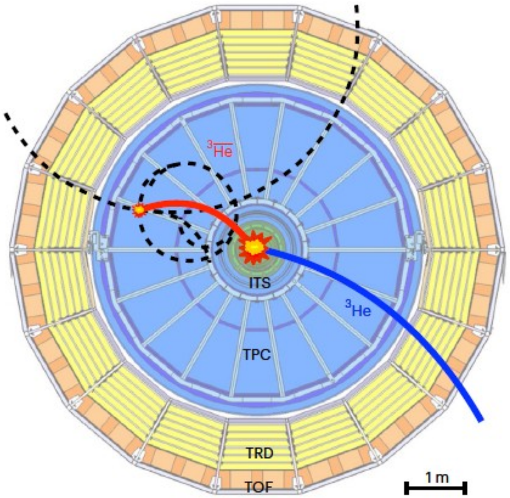
- DM annihilation – possible production source of anti-^{3}He
- Disappearance probability of anti-^{3}He (quantified by the anti-^{3}He absorption cross section σ_{inel}) is crucial for studying the galaxy transparency(*)

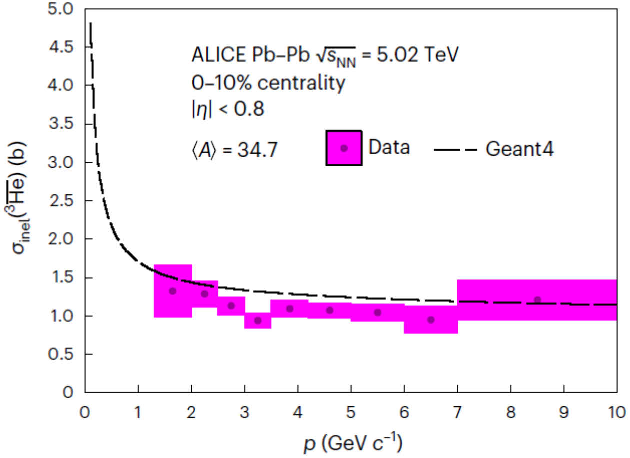
(*)galaxy transparency: the ratio of the flux obtained with and without the inelastic processes in GALPROP (https://galprop.stanford.edu).

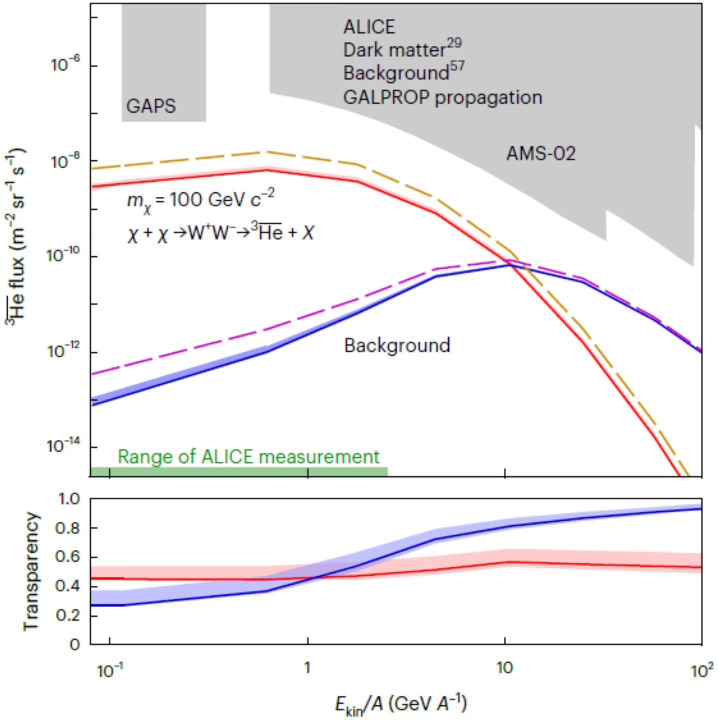
ALICE

Contributing to dark matter research

Nature Phys. 19 (2023), 61







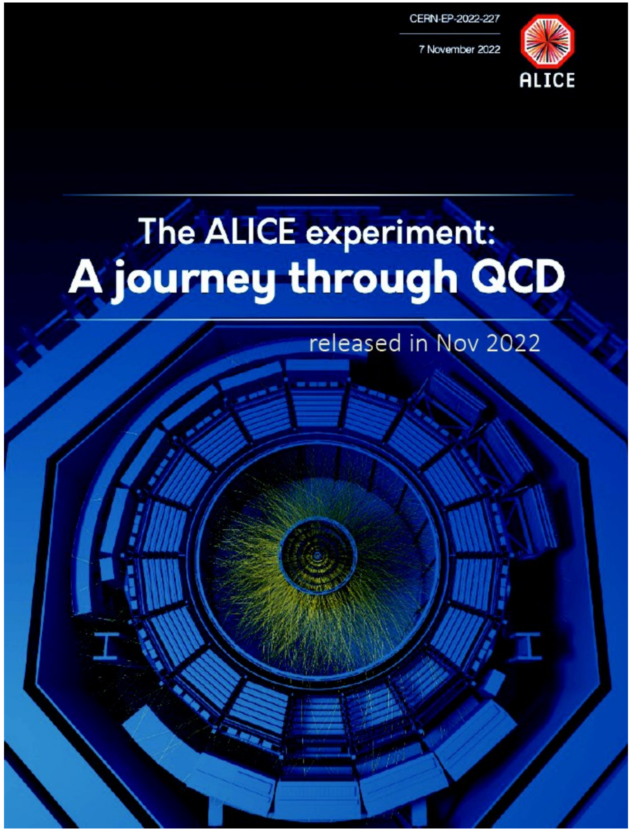
- DM annihilation – possible production source of anti-^{3}He
- Disappearance probability of anti-^{3}He (quantified by the anti-^{3}He absorption cross section σ_{inel}) is crucial for studying the galaxy transparency$^{(*)}$

- High transparency of **50%** for typical **DM scenario** and **25-90%** for **background** processes

ALICE: a journey through QCD

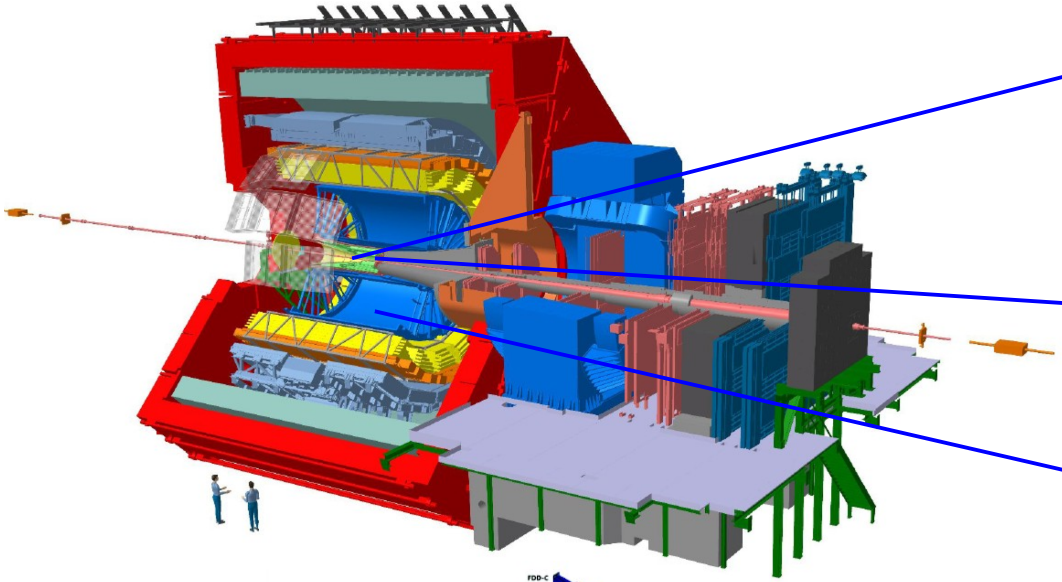
arXiv:2211.04384

- ✔ Bulk properties and thermodynamics of the QGP
- ✔ QGP dynamics and evolution
- ✔ Interactions of partons with QGP medium
- ✔ Hadronization mechanisms in the QGP medium
- ✔ Electromagnetic properties and phenomena
- ✔ Initial state
- ✔ QGP-like effects in small systems
- ✔ Many other aspects of QCD and beyond…

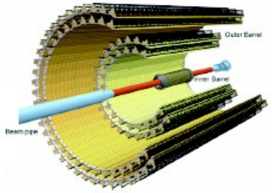


The ALICE detector in Run 3

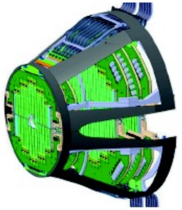
ALICE upgrades during LS2 (arXiv:2302.01238)



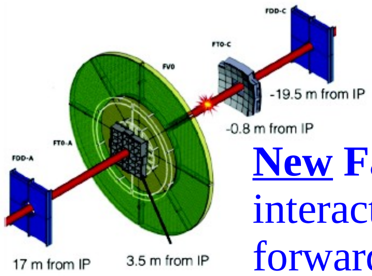
Upgraded Inner tracking system:
7 layers ($10m^2$ silicon tracker) based on MAPS.
First detection layer at 20mm (thanks to new beampipe)



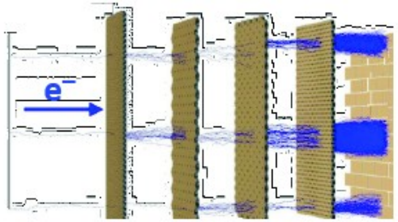
New Forward Muon Tracker:
5 planes of MAPS at forward rapidity, forward vertexing and tracking for muons



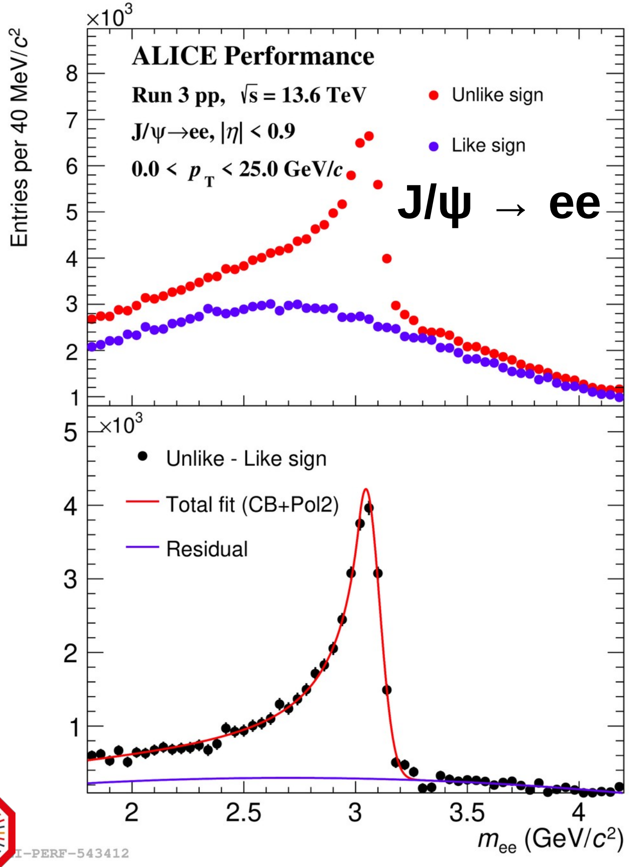
Upgraded Time Projection Chamber:
new readout chambers with Gas Electron Multipliers (GEM)



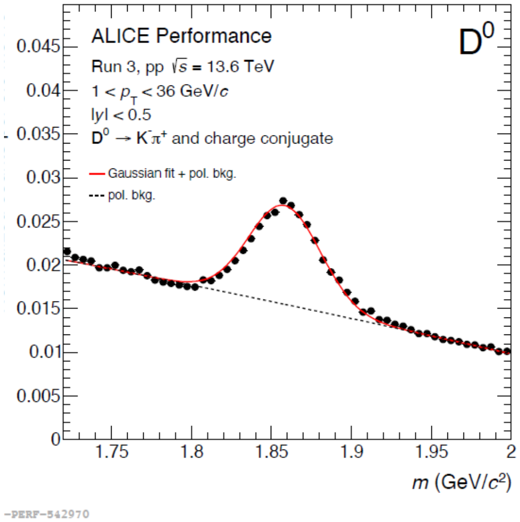
New Fast Interaction Trigger:
interaction trigger, online luminometer, forward multiplicity

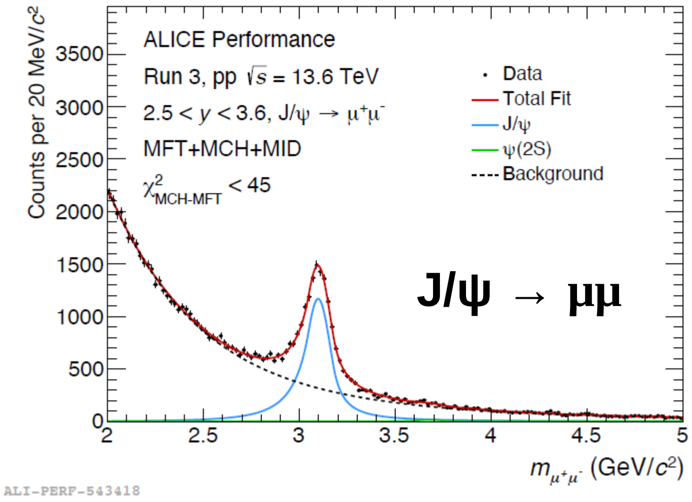


Operations and performance with the upgraded detector



- ✔ Continuous readout
  - 500 kHz in pp (software trigger for selecting rare events)
  - goal: 50 kHz in Pb-Pb (x 50 compared to Run 2)
- ✔ Target luminosities in Run 3/Run 4
  - 200 pb^{-1} in pp
  - 10 nb^{-1} in Pb-Pb





F. Fionda, ICNFP 2023

Summary & Outlook

- ✔ Impressive collection of physics results produced by ALICE from Run 1 and Run 2
- ✔ Detailed insight into initial and final states of heavy-ion collisions at the LHC
- ✔ Intriguing results in small collisions systems
- ✔ Efficiently Run 3 data taking ongoing with upgraded ALICE detector

  → many Run 3 data results coming soon: stay tuned !

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Thank you for your attention!

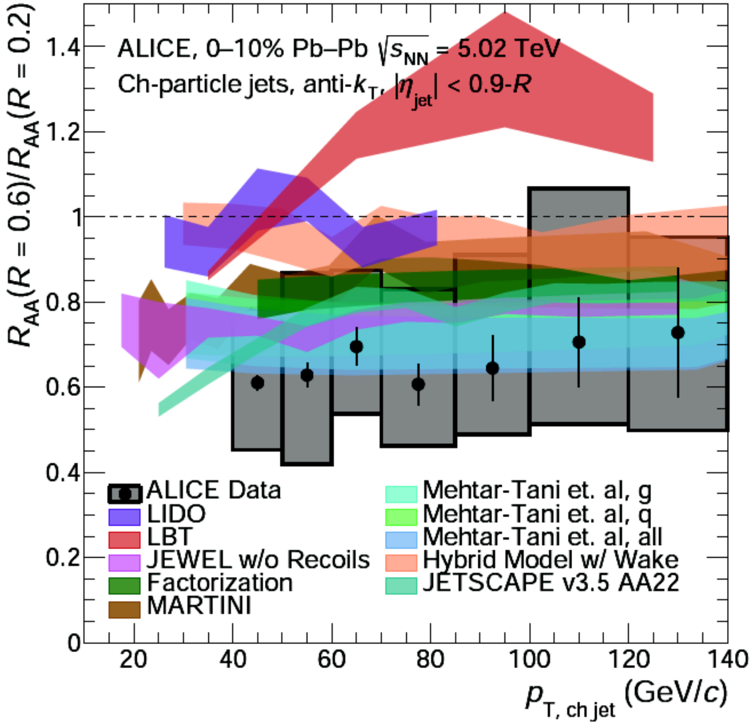
ALICE

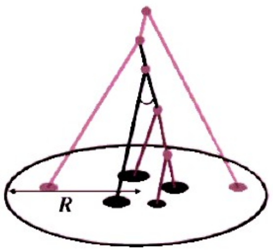
BACK-UP

Jet modifications in Pb-Pb

arXiv:2303.00592

- ML technique for background subtraction allows for inclusive charged-particle jets measurements up to $R = 0.6$ in Pb–Pb collisions down 40 GeV/c and in central collisions
- Jet suppression increases with increasing R, most significantly for jets with $R = 0.6$ (not observed up to $R = 0.4$) → **wider jets lose more energy**
- Results consistent with a variety of theoretical descriptions within uncertainties





$$R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$$

$$\theta_g = R_g/R$$

suppression factor:

$$R_{AA} = \frac{AA}{\langle T_{AA}\rangle\, pp}$$