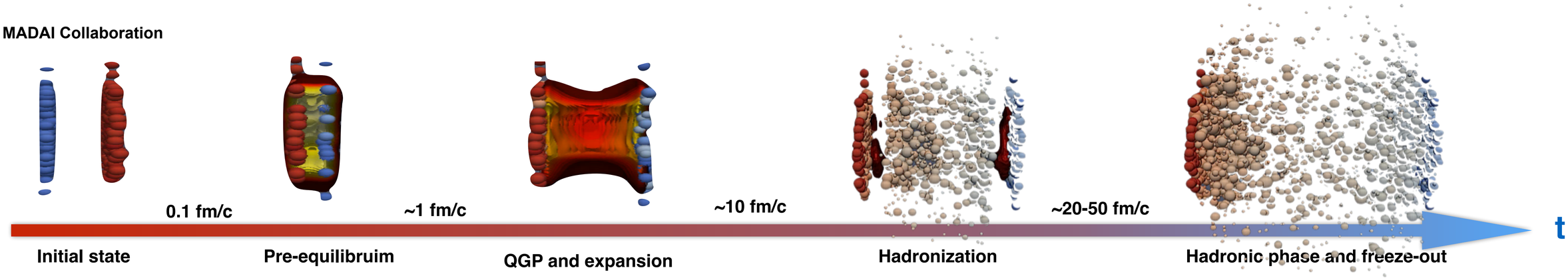
Studies of quark-gluon plasma and beyond with ALICE

Ivan Vorobyev
CERN
on behalf of the ALICE Collaboration

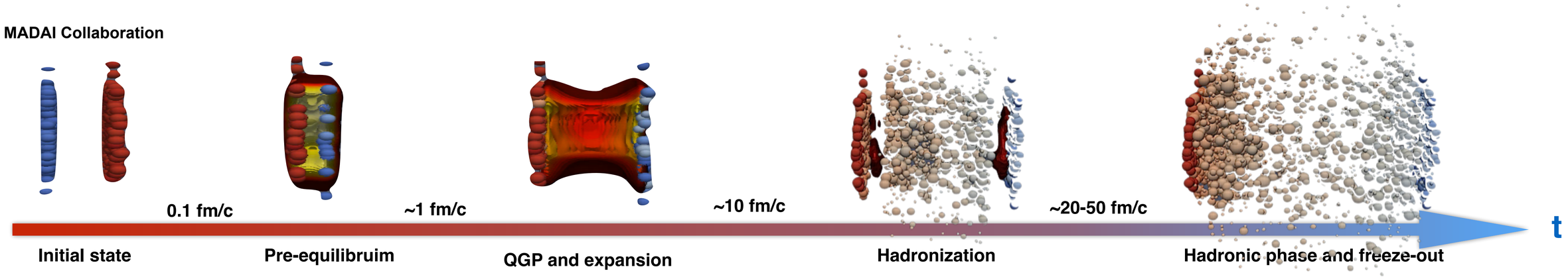
QNP2022 - The 9th International Conference on Quarks and Nuclear Physics
05.09.2022, online

Relativistic heavy-ion collisions and QGP

MADAI Collaboration

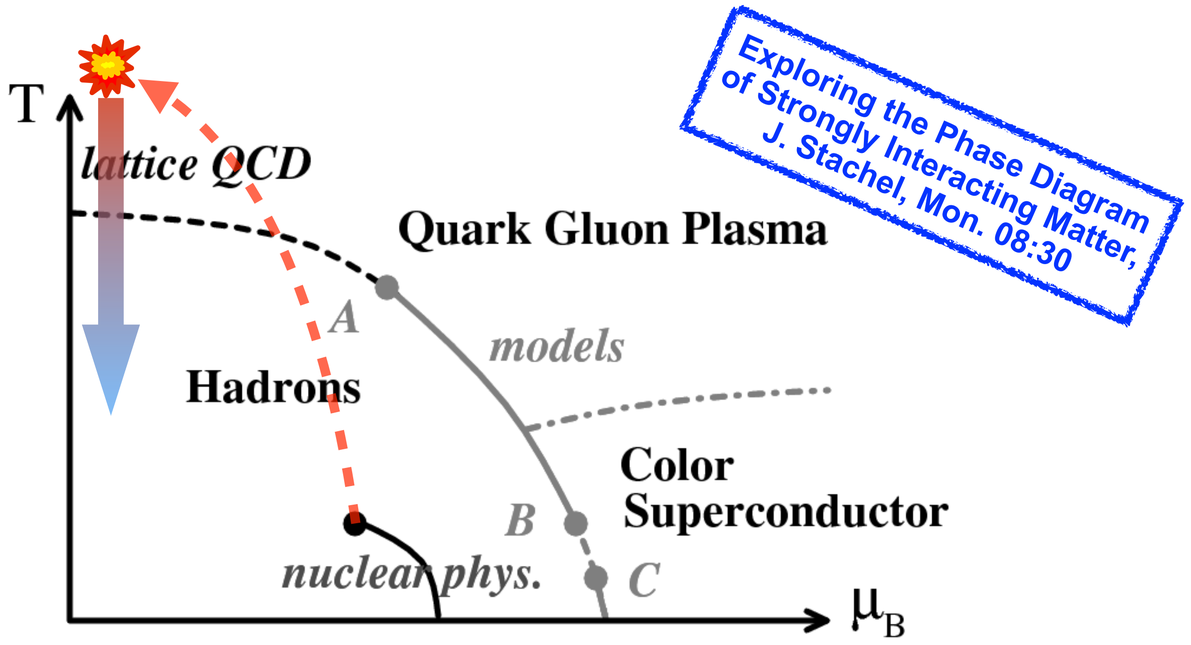


Relativistic heavy-ion collisions and QGP

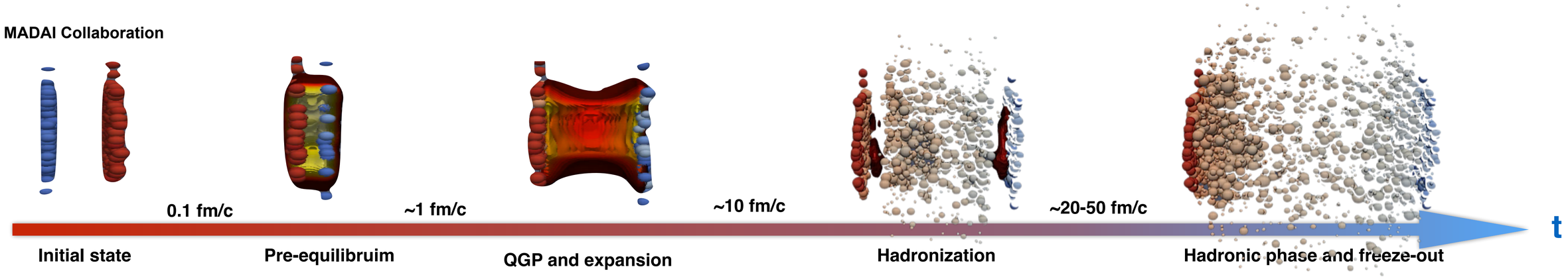


Pb−Pb collisions at LHC energies

- Hot and dense QGP with high T and ~zero μ_B



Relativistic heavy-ion collisions and QGP

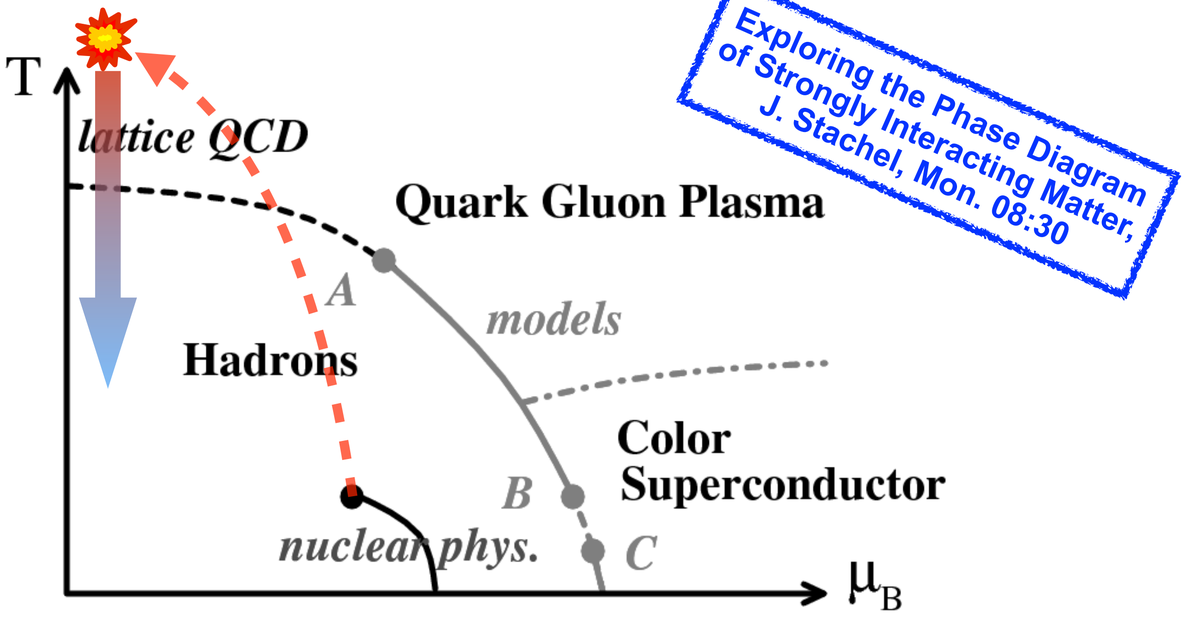


Pb−Pb collisions at LHC energies

- Hot and dense QGP with high T and ~zero μ_B

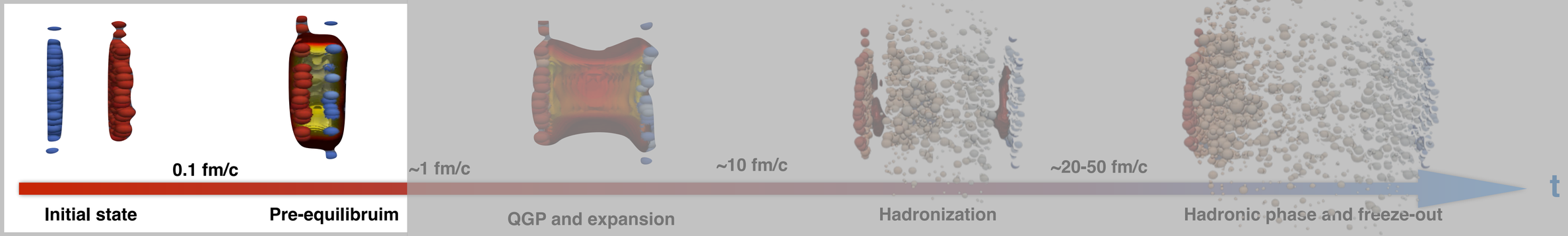
pp and p−Pb collisions

- Baseline for heavy-ion studies
- Cold nuclear matter effects
- Traces of QGP? (events with high multiplicities)



Initial stages

MADAI Collaboration



Anisotropic flow and its properties

Characterizing the initial conditions of ultra-relativistic heavy-ion collisions at the LHC, Y. Zhou, Mon. 13:45

Initial (elliptical) geometry of non-central collisions → azimuthal modulation in momentum

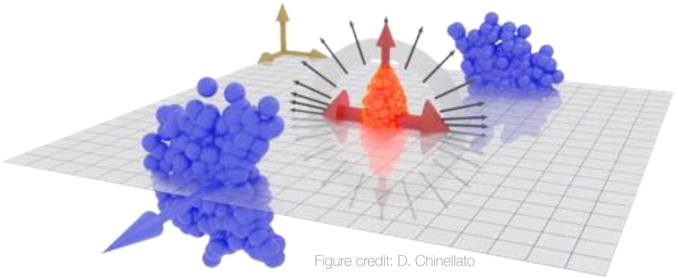


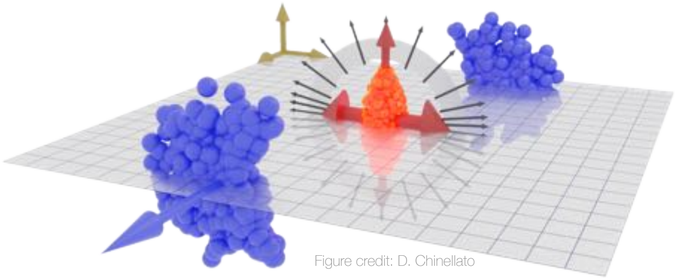
Figure credit: D. Chinellato

$$\frac{dN}{Nd\phi} = 1 + 2v_2\cos\left(2(\phi - \Psi_{RP})\right) + \textit{higher harmonics } (v_3, v_4, \ldots)$$

Anisotropic flow and its properties

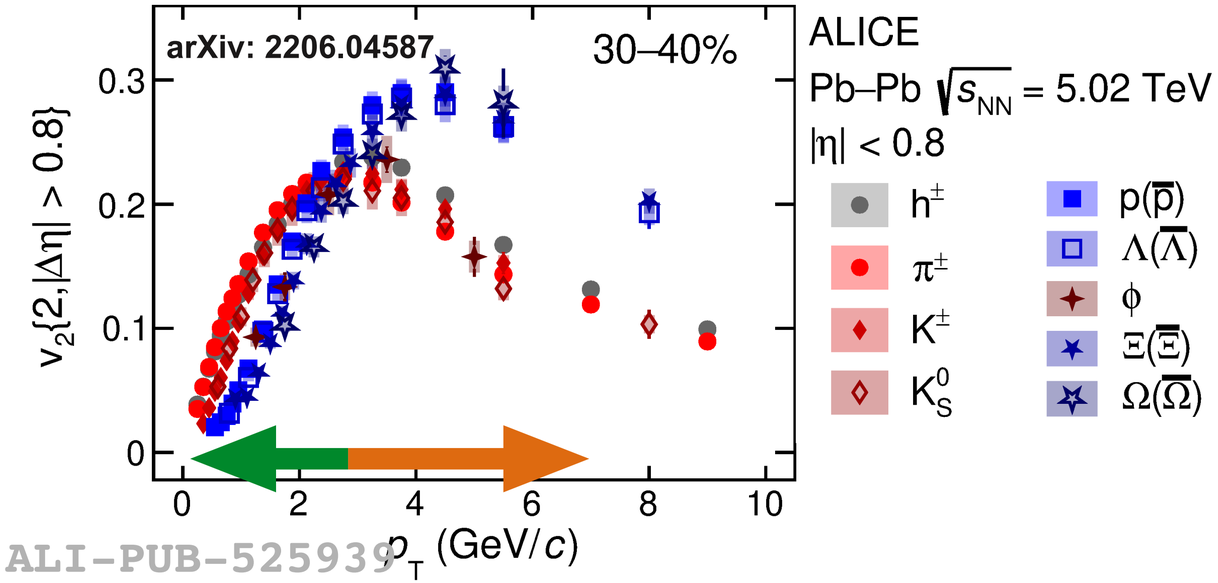
Characterizing the initial conditions of ultra-relativistic heavy-ion collisions at the LHC, Y. Zhou, Mon. 13:45

Initial (elliptical) geometry of non-central collisions → azimuthal modulation in momentum



$$\frac{dN}{Nd\phi} = 1 + 2v_2\cos\left(2(\phi - \Psi_{RP})\right) + \textit{higher harmonics } (v_3, v_4, \ldots)$$

Flow of identified hadrons



ALI-PUB-525939

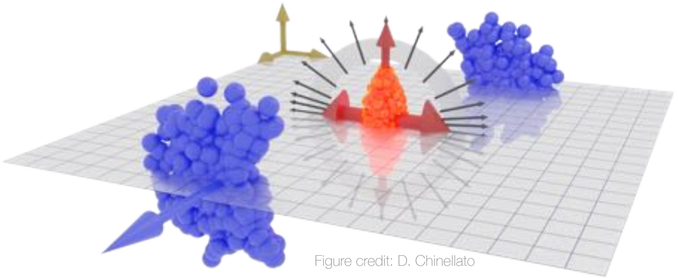
Low p_T: mass ordering described by hydro

High p_T: quark-level flow + recombination

Anisotropic flow and its properties

Characterizing the initial conditions of ultra-relativistic heavy-ion collisions at the LHC, Y. Zhou, Mon. 13:45

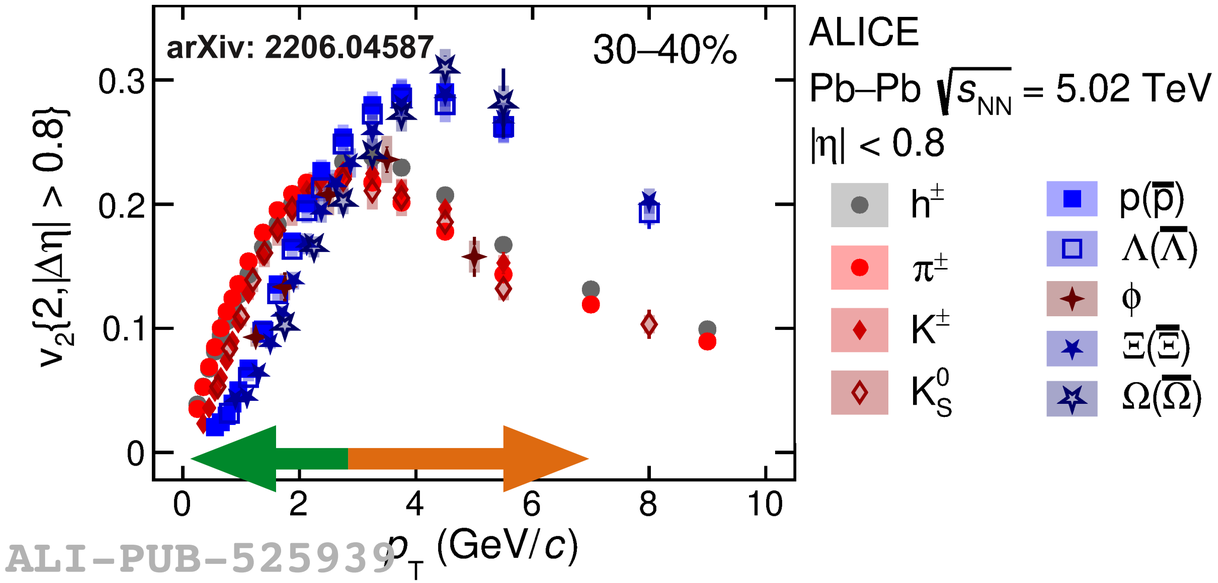
Initial (elliptical) geometry of non-central collisions → azimuthal modulation in momentum



$$\frac{dN}{Nd\phi} = 1 + 2v_2\cos\left(2(\phi - \Psi_{RP})\right) + \textit{higher harmonics } (v_3, v_4, \ldots)$$

$$\rho_n(v_n^2, [p_T]) = \frac{\mathrm{cov}(v_n^2, [p_T])}{\sqrt{\mathrm{var}(v_n^2)}\sqrt{\mathrm{var}([p_T])}}$$

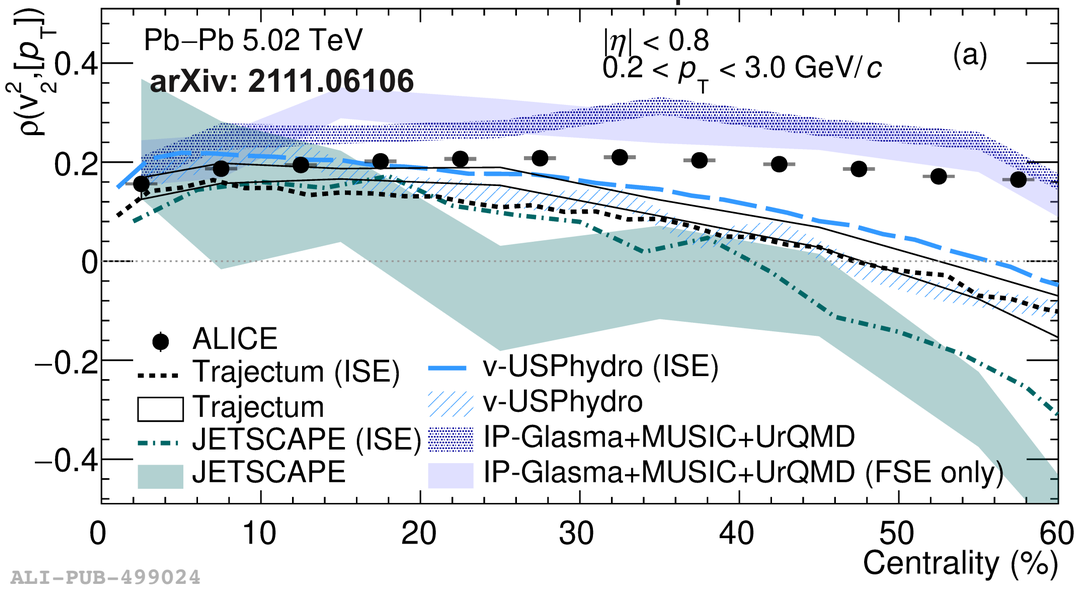
Flow of identified hadrons



Low p_T: mass ordering described by hydro

High p_T: quark-level flow + recombination

Correlation between shape and size



Access to initial conditions through bulk observables

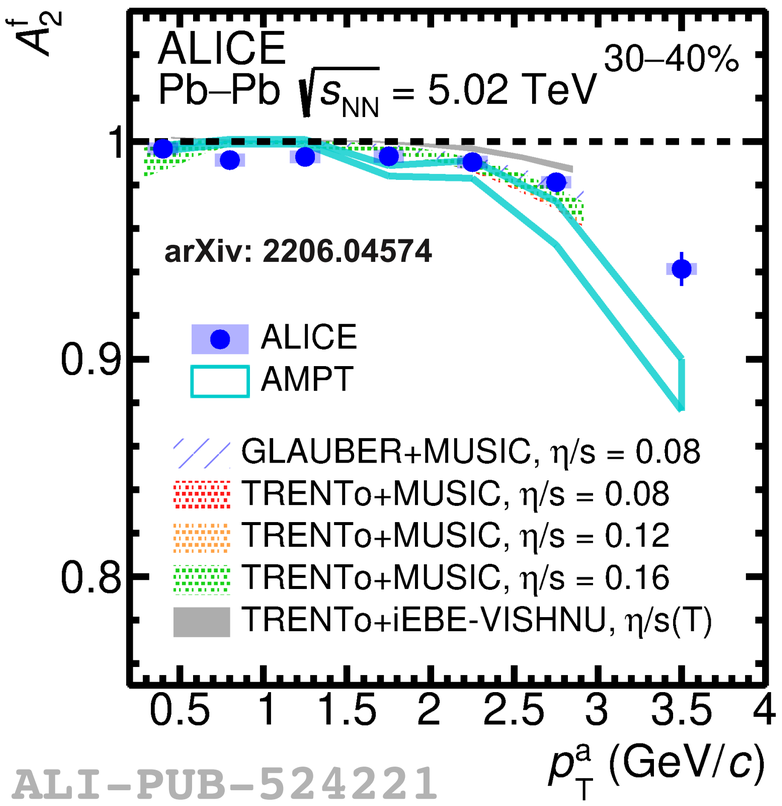
Only qualitative description of data with models

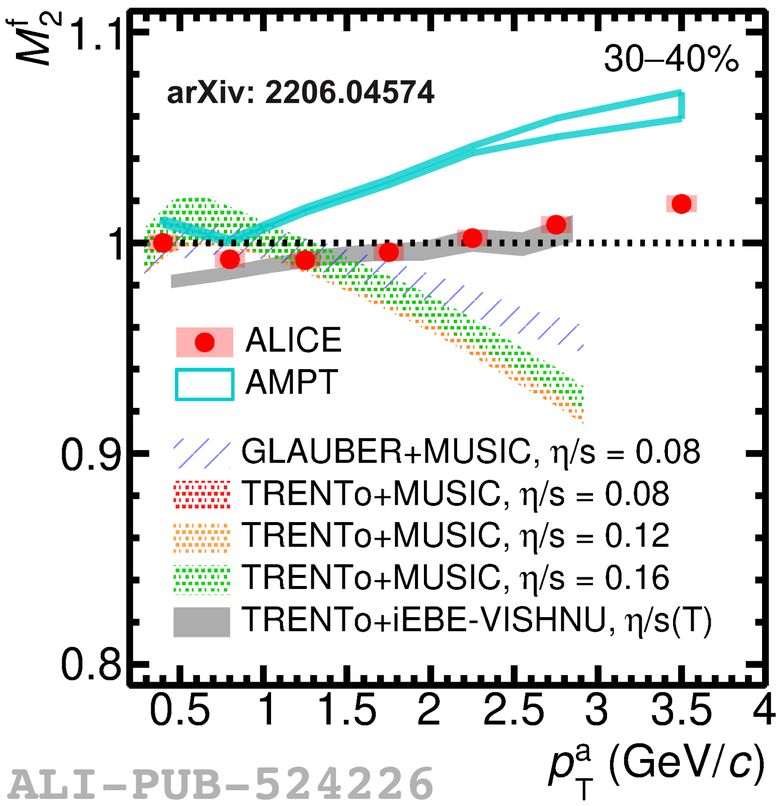
Fluctuations of flow angle and magnitude

Discovering a new flow phenomena of flow angle and flow magnitude fluctuations and its impact on QGP studies, E. Nielsen, Wed. 16:15

First measurements of flow angle and magnitude fluctuations with 4-particle correlations

- Novel insights into the initial conditions
  - *Unique sensitivity to the shear viscosity η/s, need for re-examination of existing models*

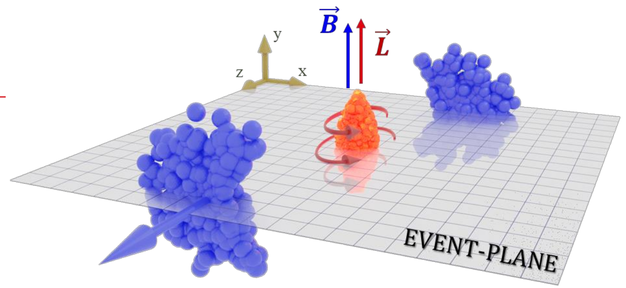




$$A_n^f = \frac{\langle v_n^2(p_T^a)\, v_n^2 \cos 2n[\Psi_n(p_T^a) - \Psi_n]\rangle}{\langle v_n^2(p_T^a) v_n^2\rangle}$$

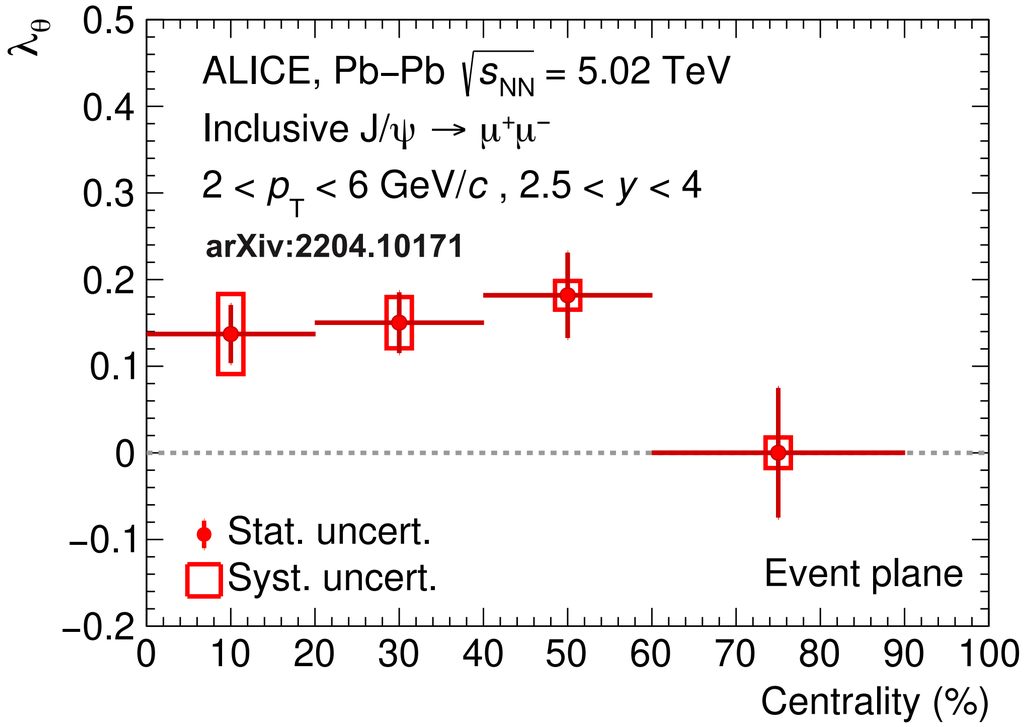
$$M_n^f = \frac{\langle v_n^2(p_T^a) v_n^2\rangle / \langle v_n^2(p_T^a)\rangle \langle v_n^2\rangle}{\langle v_n^4\rangle / \langle v_n^2\rangle^2}$$

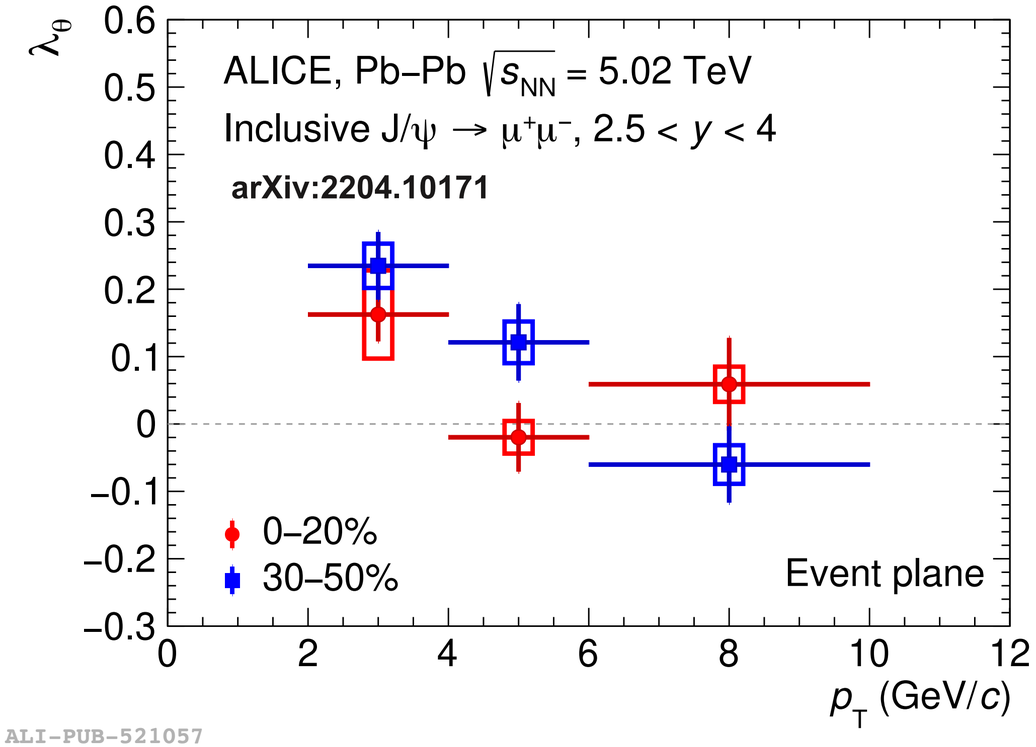
Polarisation of J/ψ in Pb−Pb collisions



Inclusive J/ψ polarisation with respect to the event plane at low p_T

Polar angular distribution of dilepton decay: $W(\theta) \propto \frac{1}{3+\lambda_\theta}(1+\lambda_\theta \cos^2\theta)$

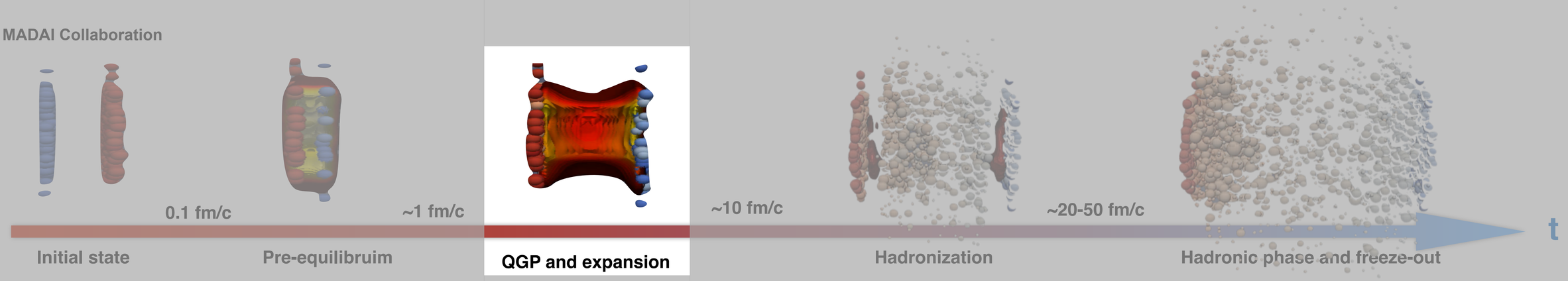




- *First evidence of J/ψ polarisation in Pb−Pb collisions!*
- *Vanishes at higher momenta: sensitive to vorticity and magnetic field?*

Properties of the medium

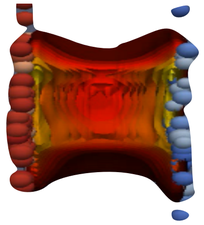
MADAI Collaboration

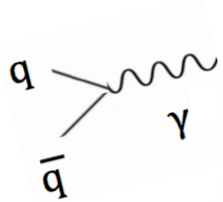


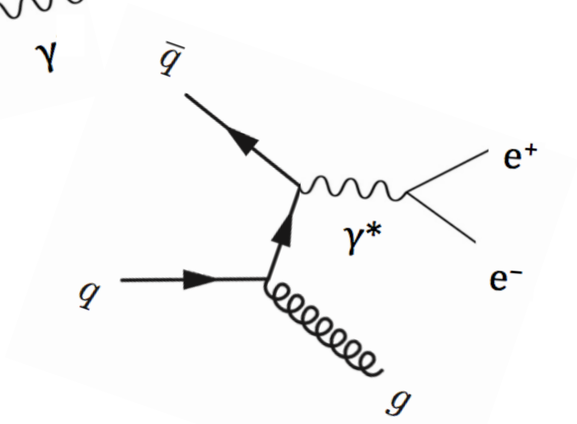
Electromagnetic probes: photons

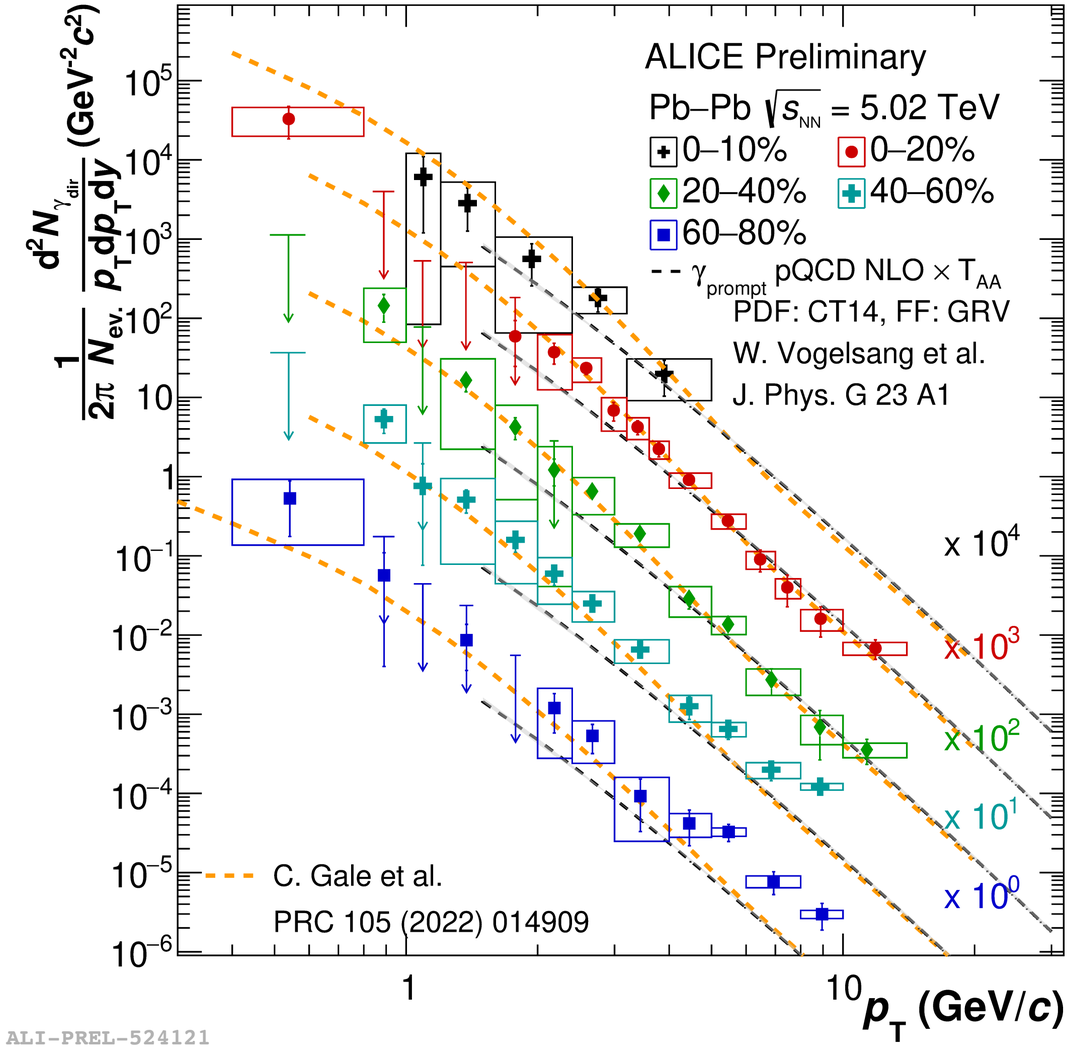
First measurement of direct photons in Pb−Pb at $\sqrt{s_{NN}}$ = 5.02 TeV
- 0−10% centrality: virtual photons via dielectrons
- Other centralities: real photons with conversion method

- High p_T: consistent with pQCD expectations
- *Low p_T: hint for an excess from thermal photons*







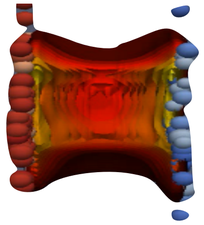


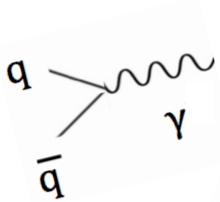
Electromagnetic probes: photons and dielectrons

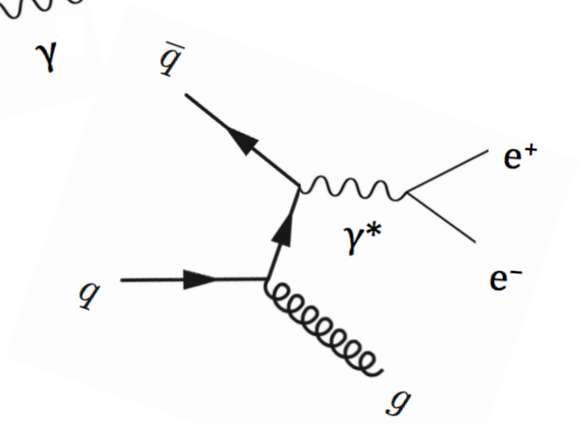
First measurement of direct photons in Pb−Pb at $\sqrt{s_{NN}}$ = 5.02 TeV
- 0−10% centrality: virtual photons via dielectrons
- Other centralities: real photons with conversion method

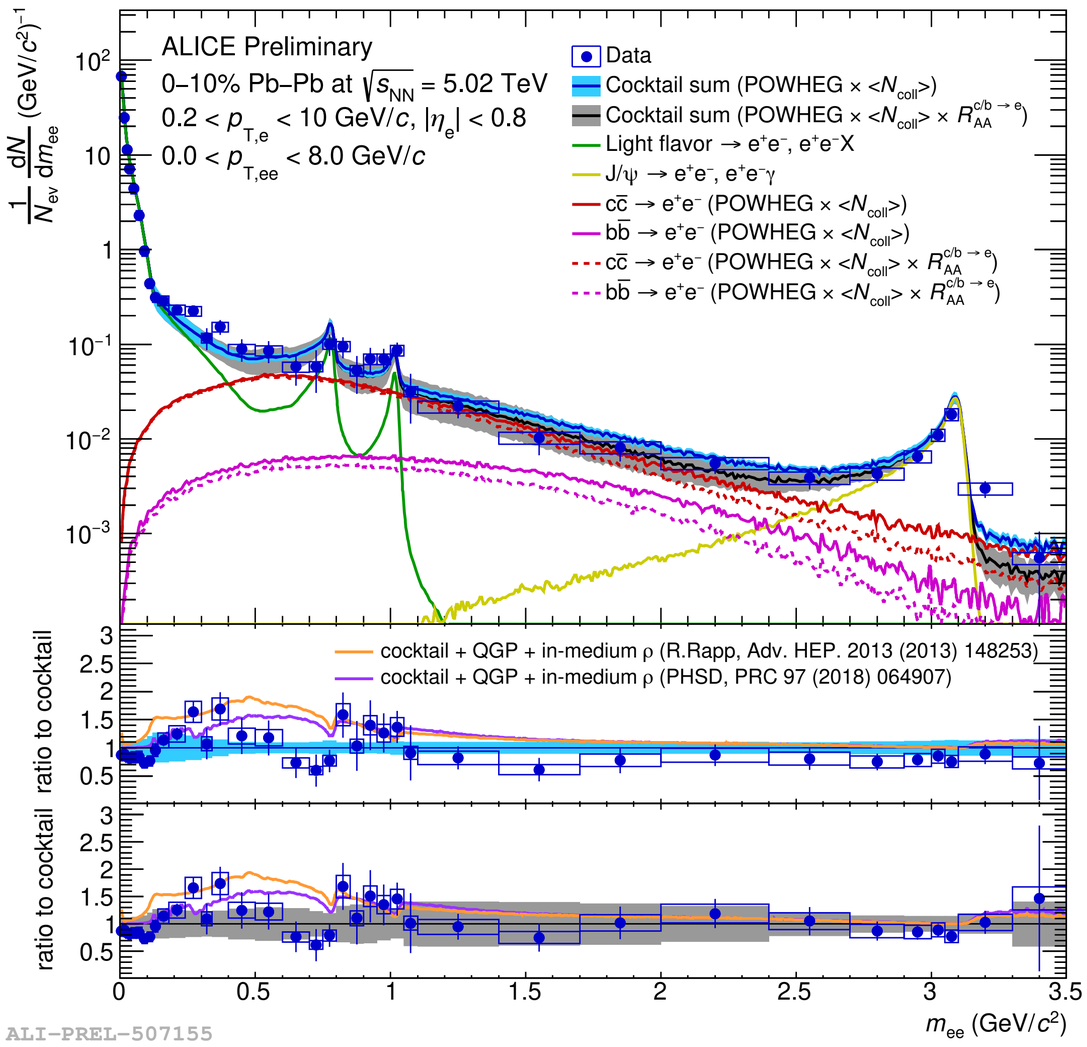
- High p_T: consistent with pQCD expectations
- *Low p_T: hint for an excess from thermal photons*

Analysis of dielectron (e^+e^-) invariant mass spectrum
- *Hint for an excess at low m_{ee} from thermal source*
- Need to better control heavy-flavour background







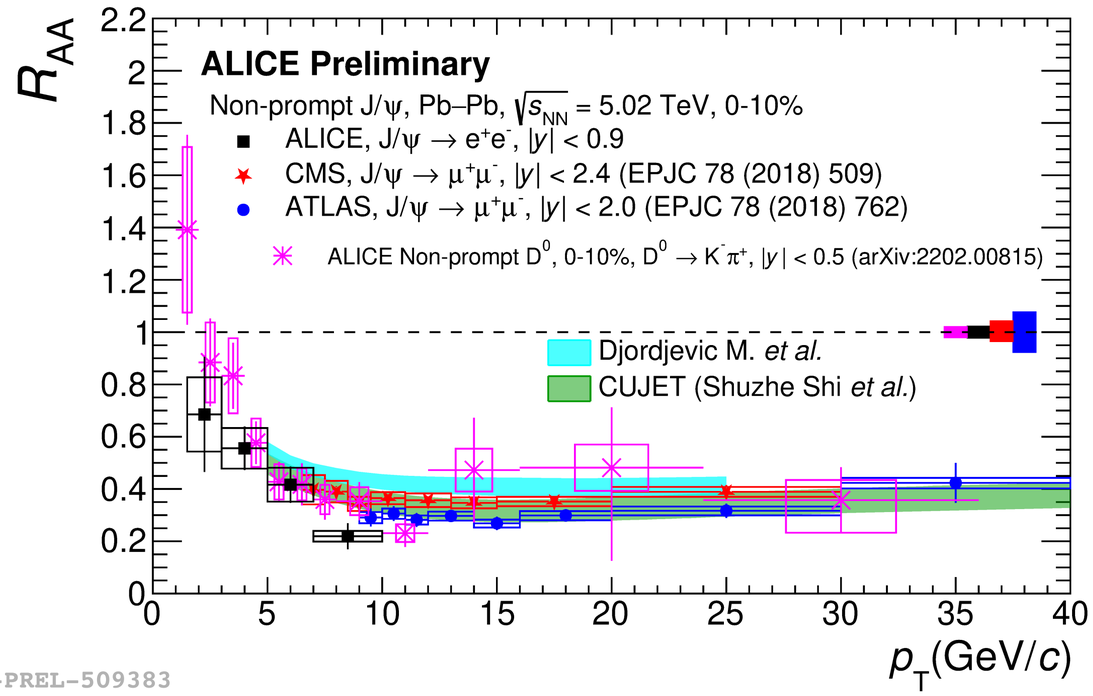


R_{AA} of J/ψ and D meson from beauty

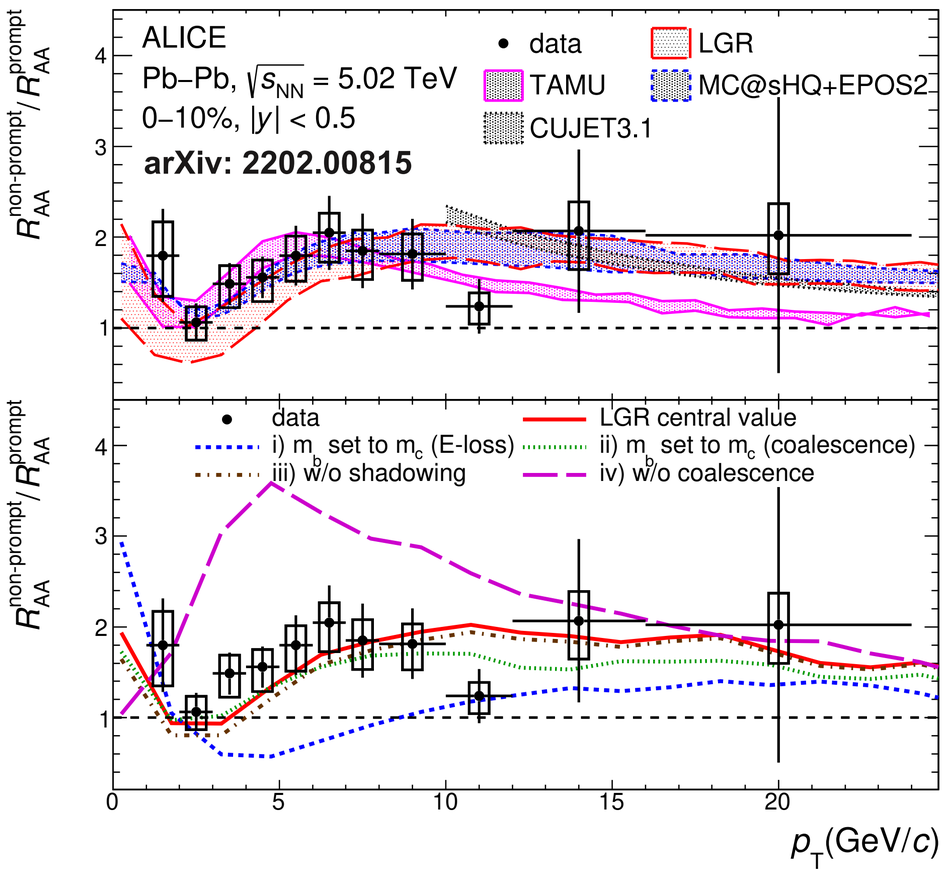
Unprecedented measurement of beauty hadron R_{AA} down to low p_T via non-prompt J/ψ and D

- R_{AA}(non-prompt)/R_{AA}(prompt) > 1 for p_T > 5 GeV/*c*
- *Model description requires mass-dependent energy loss and coalescence*

J/ψ production in pp, p–Pb and Pb–Pb collisions with ALICE, C. Cot, Wed. 16:40



ALI-PREL-509383



$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{dN/dp_T|_{PbPb}}{dN/dp_T|_{pp}}$$

ALI-PUB-501659

ψ(2S) production in Pb–Pb

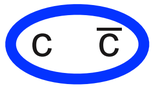
Extending the ψ(2S) measurement down to zero p_T

Clear hierarchy of suppression over all the p_T and for all centralities

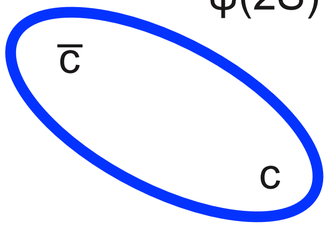
Hint for regeneration of ψ(2S) at low momentum

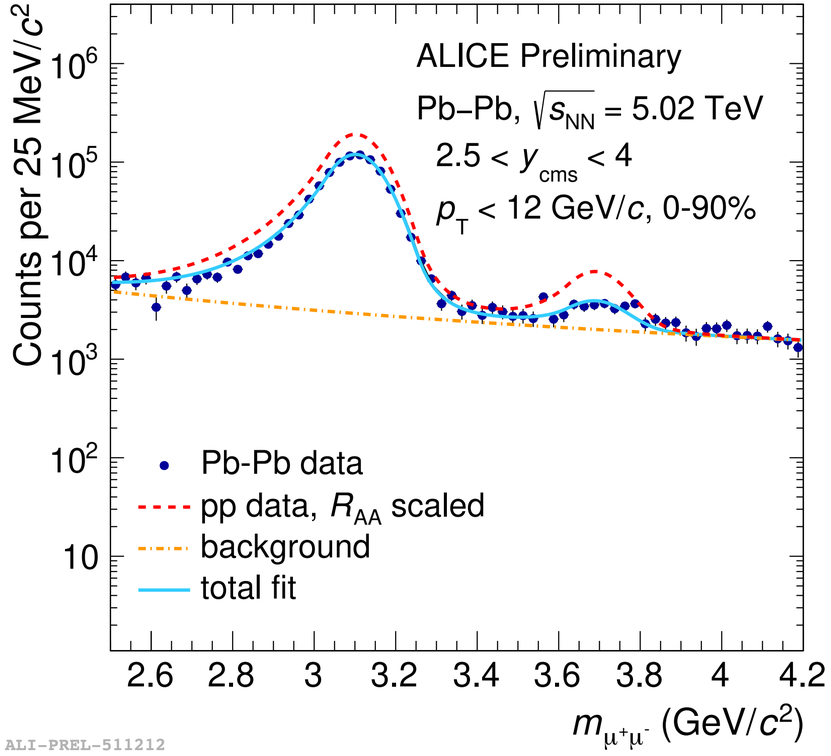
	J/ψ	ψ(2S)
Mass	3.07 GeV/c^2	3.68 GeV/c^2
Binding energy	0.64 GeV	0.05 GeV

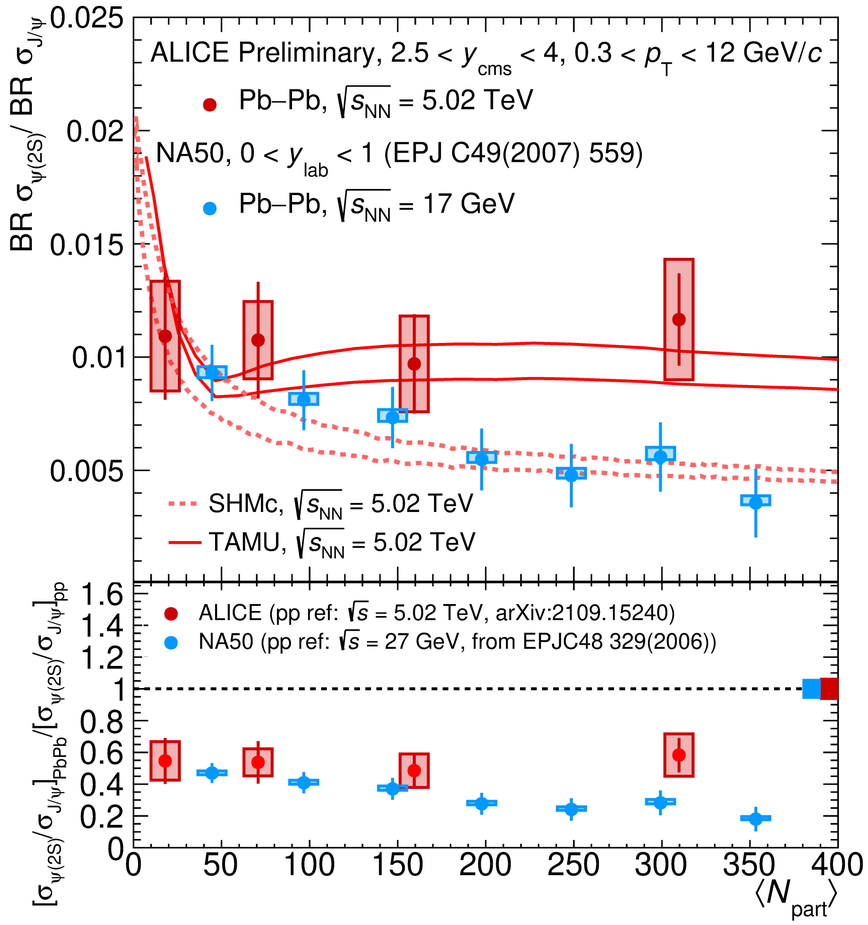
J/ψ



ψ(2S)







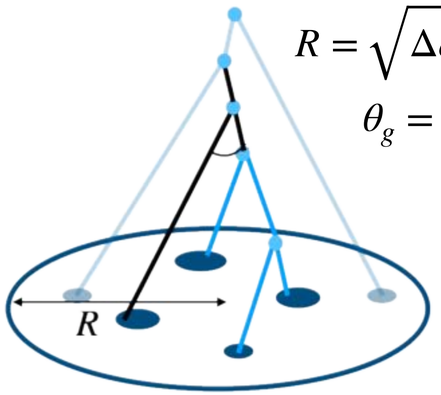
Medium-induced jet modifications

Jet studies with grooming: find first hard splitting

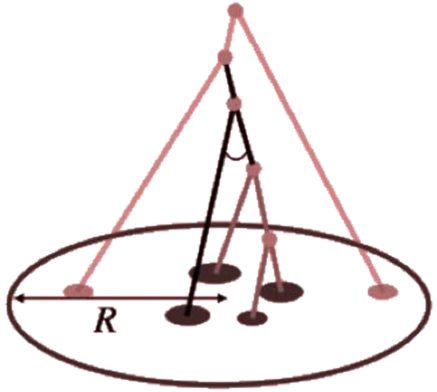
- Model comparisons indicate QGP resolves individual hard prongs that interact incoherently
- *Jet core is more collimated in Pb−Pb than in pp*

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

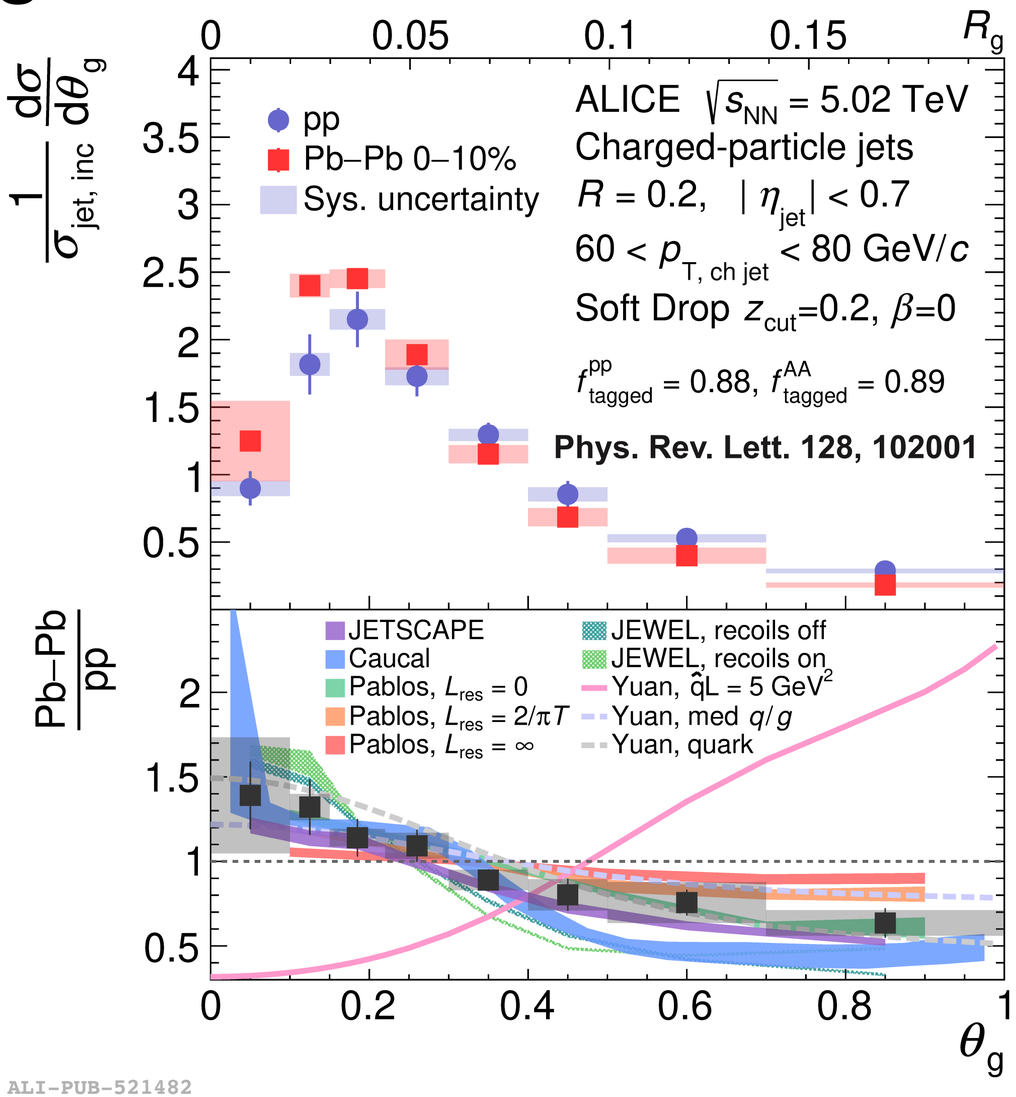
$$\theta_g = R_g / R$$



pp



Pb-Pb



ALI-PUB-521482

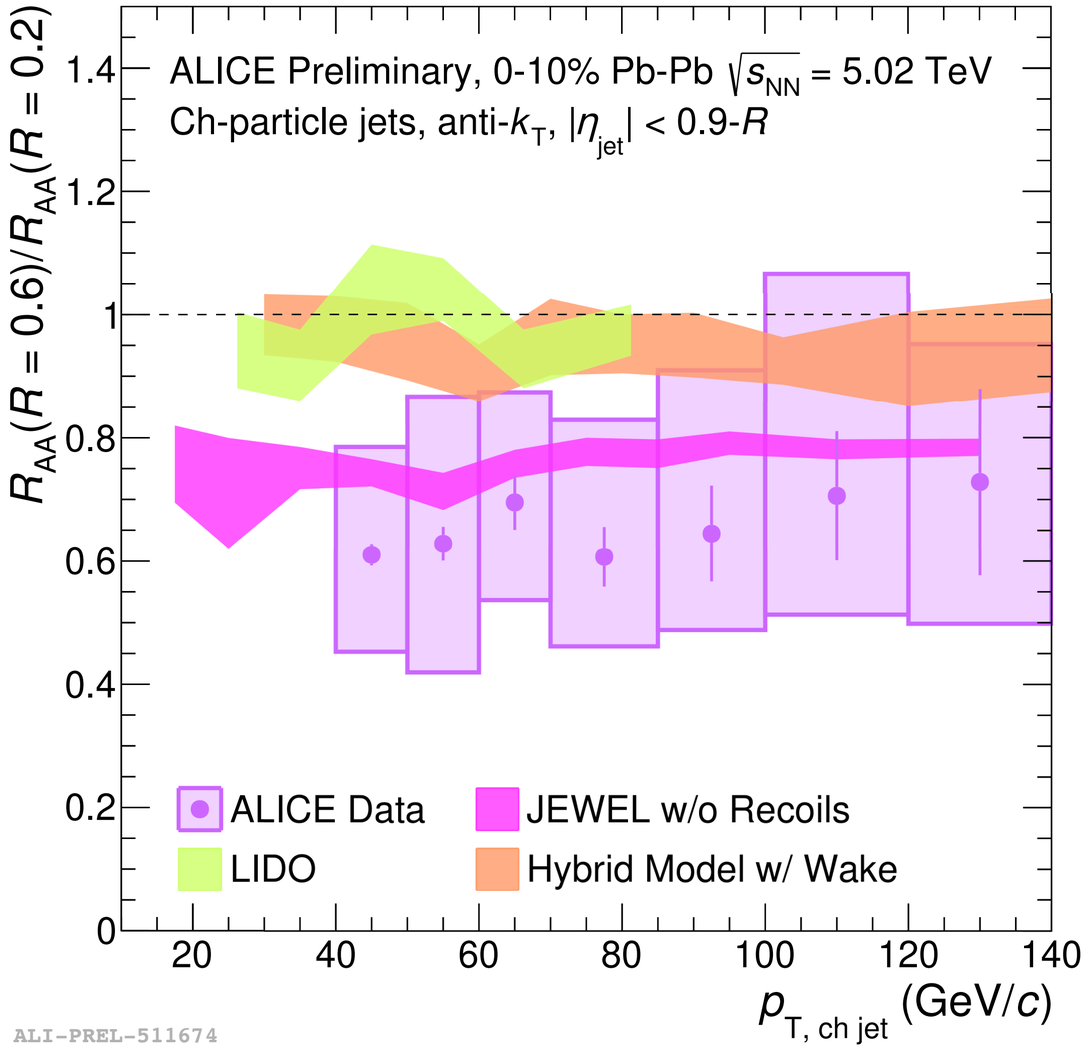
Jet modifications in PbPb

Jet studies with grooming: find first hard splitting

- Model comparisons indicate QGP resolves individual hard prongs that interact incoherently
- *Jet core is more collimated in Pb−Pb than in pp*

Jets with larger R are more suppressed in Pb−Pb collisions

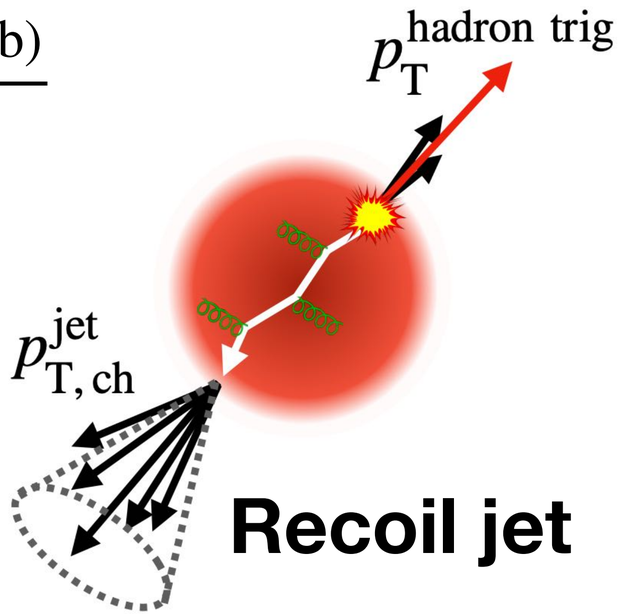
- Hint of R-dependent suppression, not seen up to R = 0.4
- Consistent with narrower jet population

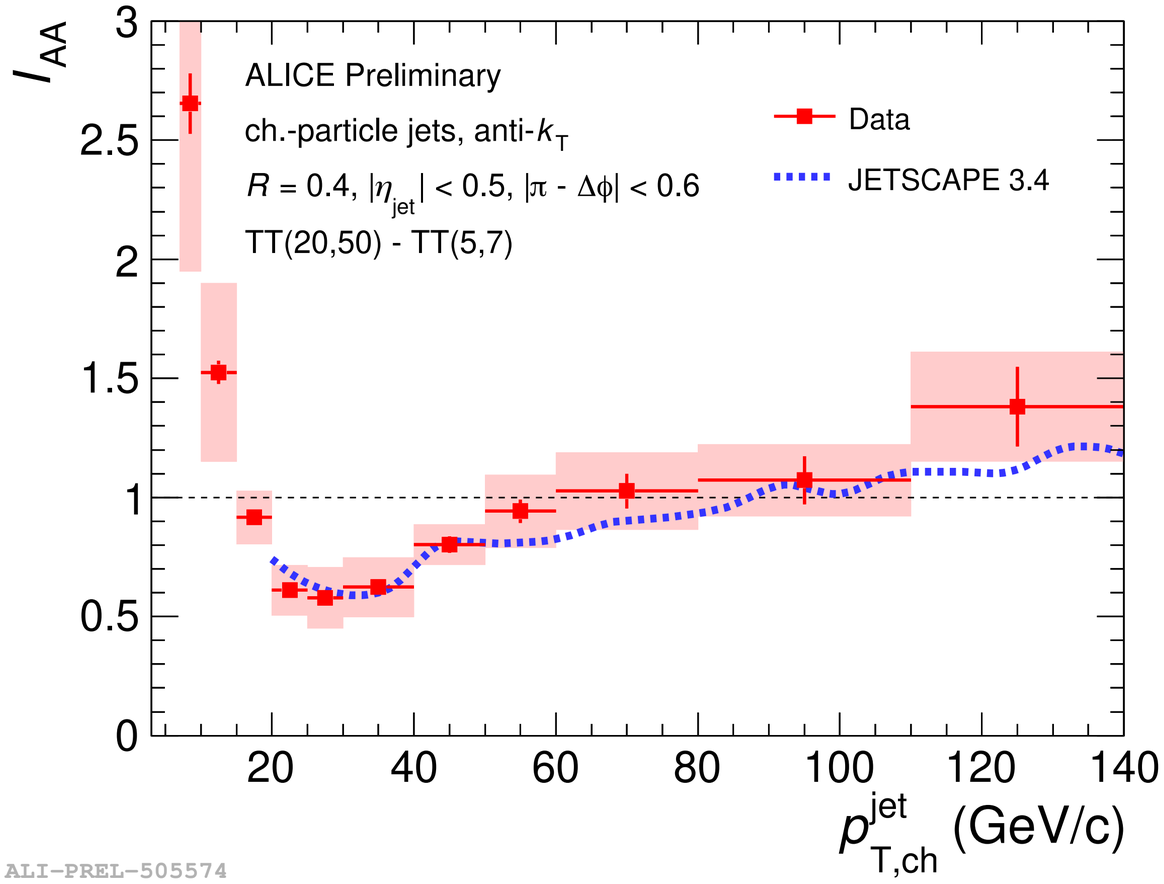


Where does the energy go?

I_{AA} measurement: how the jet energy is redistributed in heavy-ion collisions

$$I_{AA} = \frac{\Delta_{recoil}(Pb - Pb)}{\Delta_{recoil}(pp)}$$



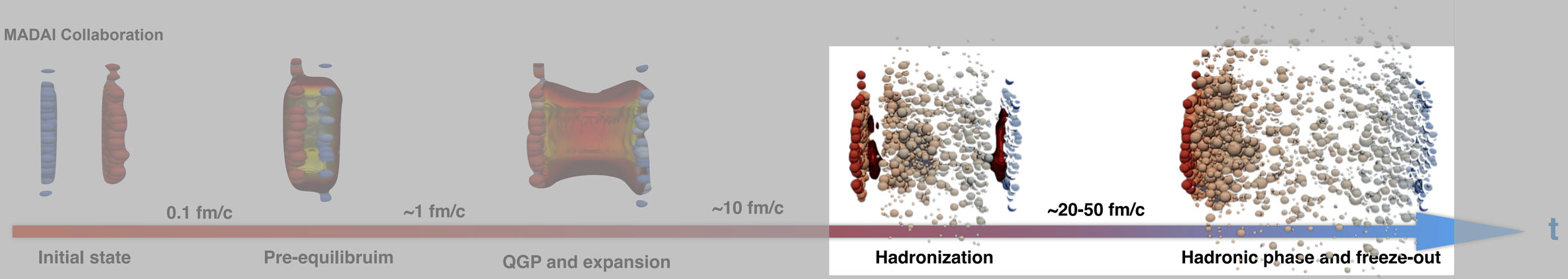


Hint for an energy recovery at low jet momentum
- In association with azimuthal broadening

Good description of results with JETSCAPE

Hadronization and hadronic phase

MADAI Collaboration



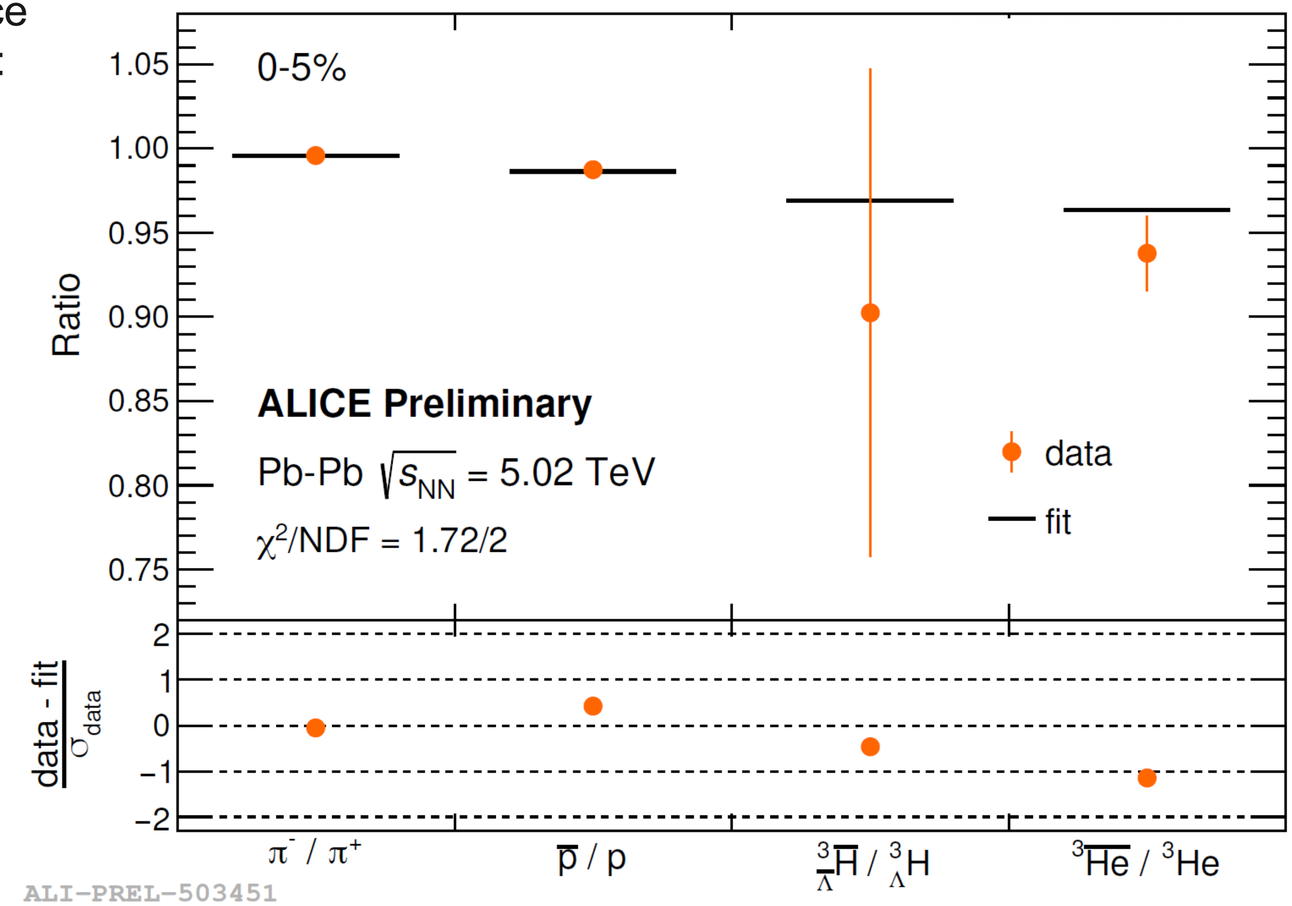
Antimatter/matter imbalance and μ_B

Baryochemical potential $\mu_B \rightarrow$ antimatter/matter imbalance
Can be obtained from the statistical hadronisation model:

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

where T = 156.2 ± 2 MeV and

	π^+	p	^{3}He	$_\Lambda^3$H
B + S/3	0	1	3	8/9
I_3	1	1/2	1/2	0



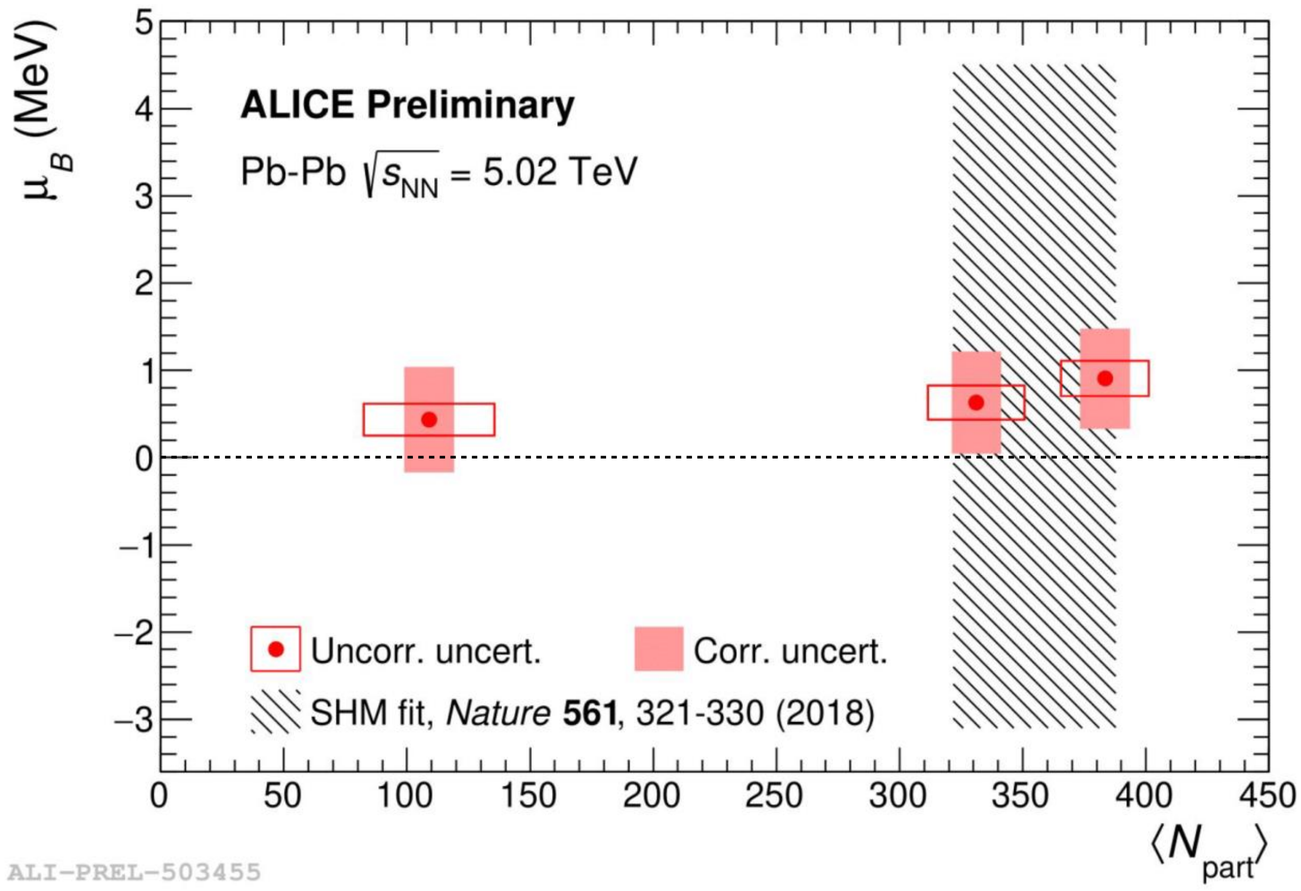
Antimatter/matter imbalance and μ_B

Baryochemical potential $\mu_B \rightarrow$ antimatter/matter imbalance
Can be obtained from the statistical hadronisation model:

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

where T = 156.2 ± 2 MeV and

	π^+	p	^{3}He	$_\Lambda^3$H
B + S/3	0	1	3	8/9
I_3	1	1/2	1/2	0



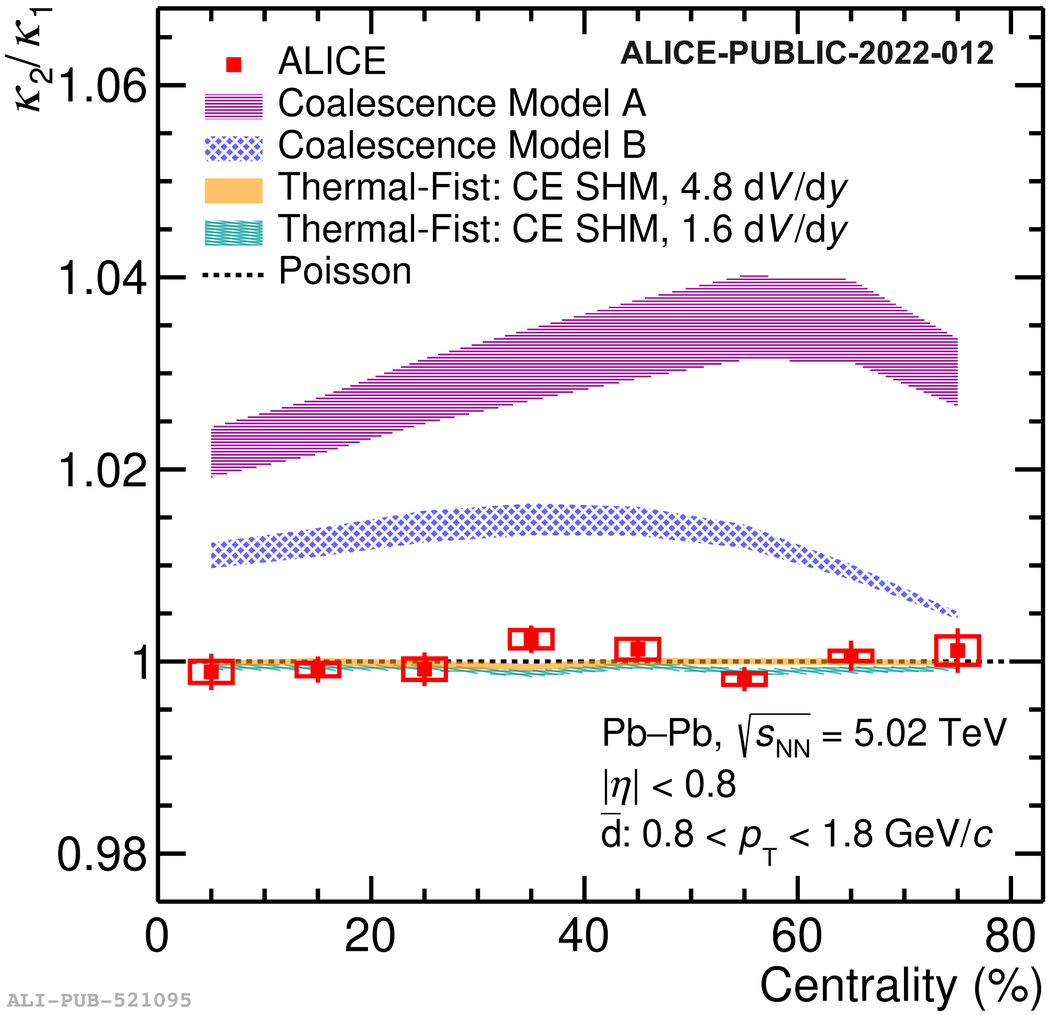
Most precise measurement of μ_B at TeV scale!
- Cancellation of uncertainties in the ratio
- Consistent with previous results, but with x6 smaller errors

Antinucleosynthesis beyond the average

New observable based on event-by-event fluctuations to distinguish between hadron coalescence and statistical hadronisation [1]:

$$\frac{\kappa_2}{\kappa_1} = \frac{\langle (n - \langle n \rangle)^2 \rangle}{\langle n \rangle}$$

- *SHM is clearly favoured by the cumulant ratio*



[1] A. Andronic, P. Braun-Munzinger, J. Stachel, and H. Stoecker, Phys. Lett. B 697 (2011) 203-207

Antinucleosynthesis beyond the average

New observable based on event-by-event fluctuations to distinguish between hadron coalescence and statistical hadronisation [1]:

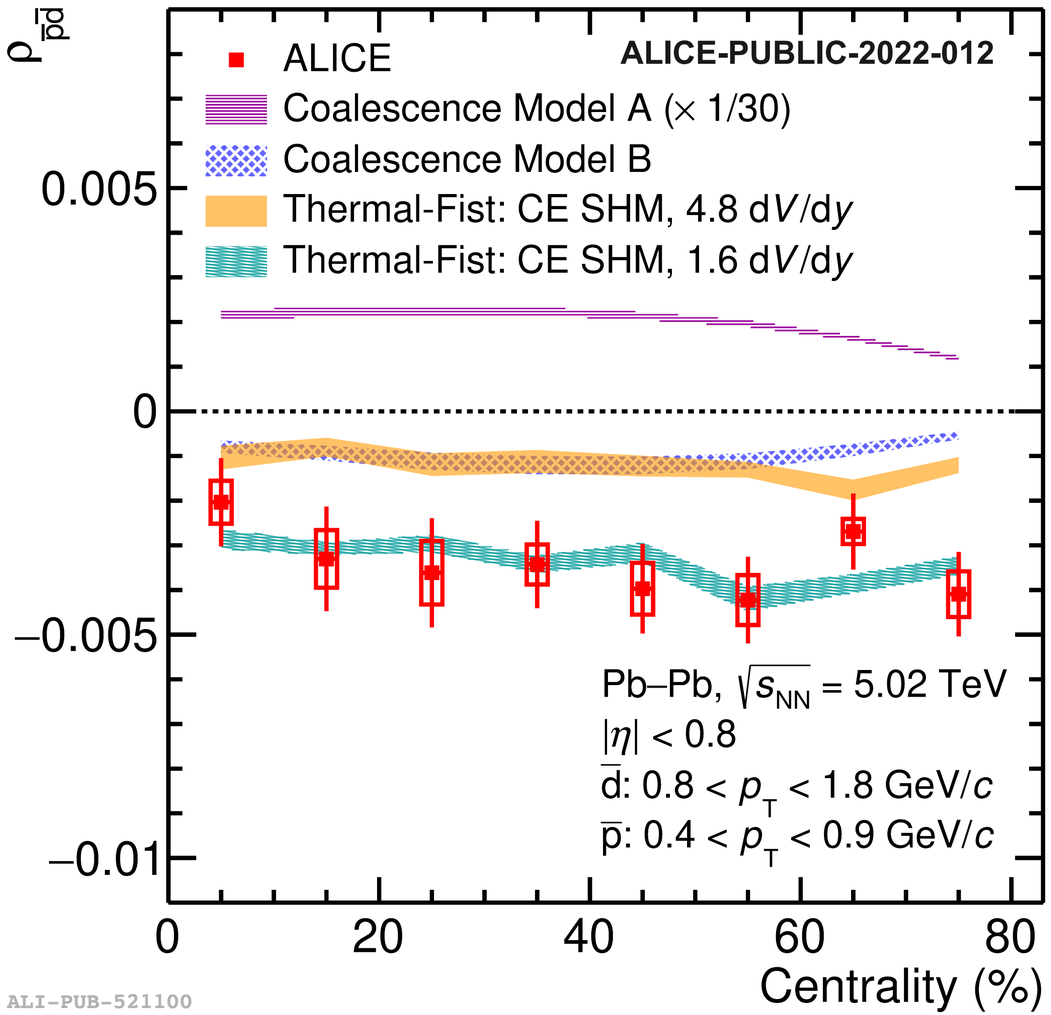
$$\frac{\kappa_2}{\kappa_1} = \frac{\langle (n - \langle n \rangle)^2 \rangle}{\langle n \rangle}$$

- *SHM is clearly favoured by the cumulant ratio*

Pearson correlation to constrain the correlation volume for baryon number:

$$\rho_{\bar{\mathrm{p}}\bar{\mathrm{d}}} = \frac{\langle (n_{\bar{\mathrm{d}}} - \langle n_{\bar{\mathrm{d}}} \rangle)(n_{\bar{\mathrm{p}}} - \langle n_{\bar{\mathrm{p}}} \rangle) \rangle}{\sqrt{\kappa_{2\bar{\mathrm{d}}} \kappa_{2\bar{\mathrm{p}}}}}$$

- Coalescence model A: full correlation among p and n
- Coalescence model B: independent p and n production



[1] A. Andronic, P. Braun-Munzinger, J. Stachel, and H. Stoecker, Phys. Lett. B 697 (2011) 203-207

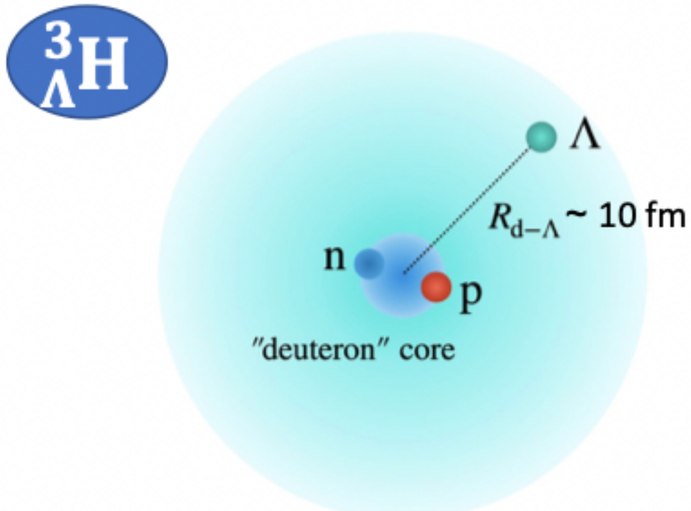
Production of (anti)(hyper)nuclei

(Anti)(hyper)nuclei production in small systems is of particular interest

- System size smaller or compatible to the one of the nucleus
- Allows for the study of coalescence since nucleons are created close to each other
- Very different model predictions, ideal environment to constrain production mechanism

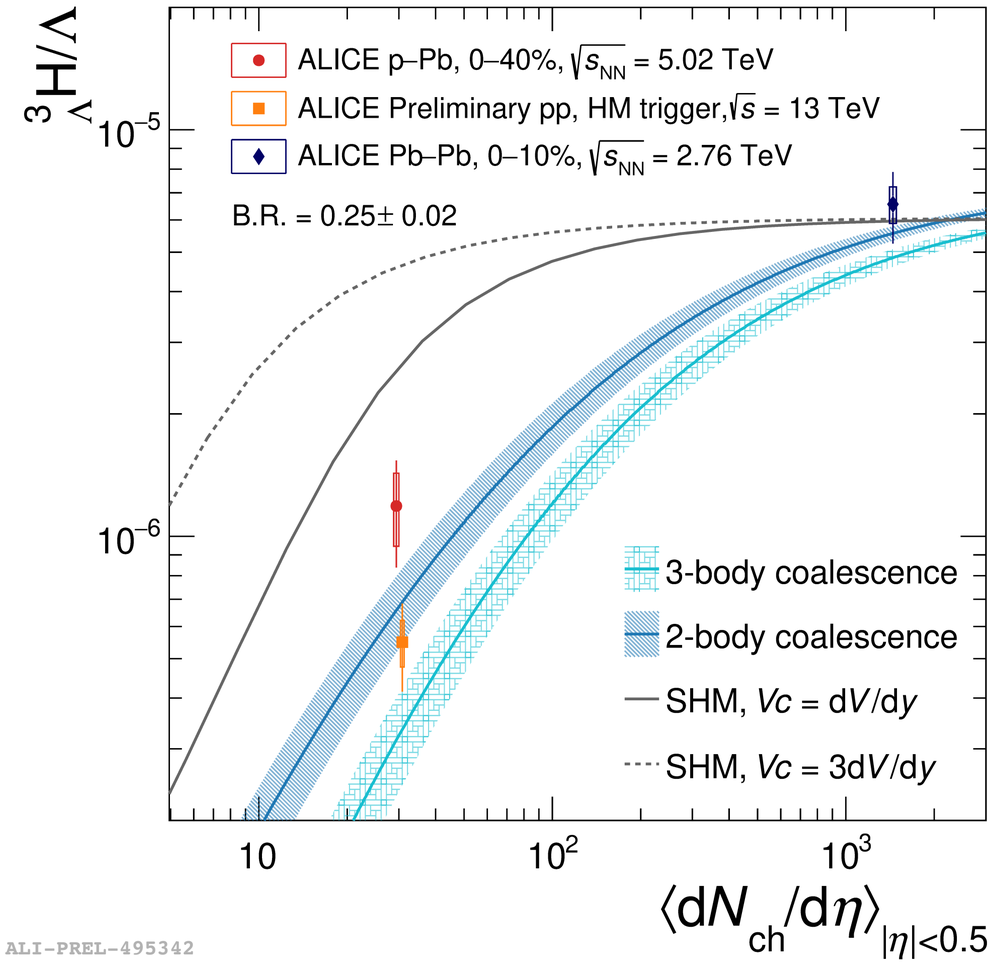
Measurements in pp and p−Pb collisions:

- *In good agreement with 2-body coalescence*
- *Tension with SHM at low charged-particle multiplicities*

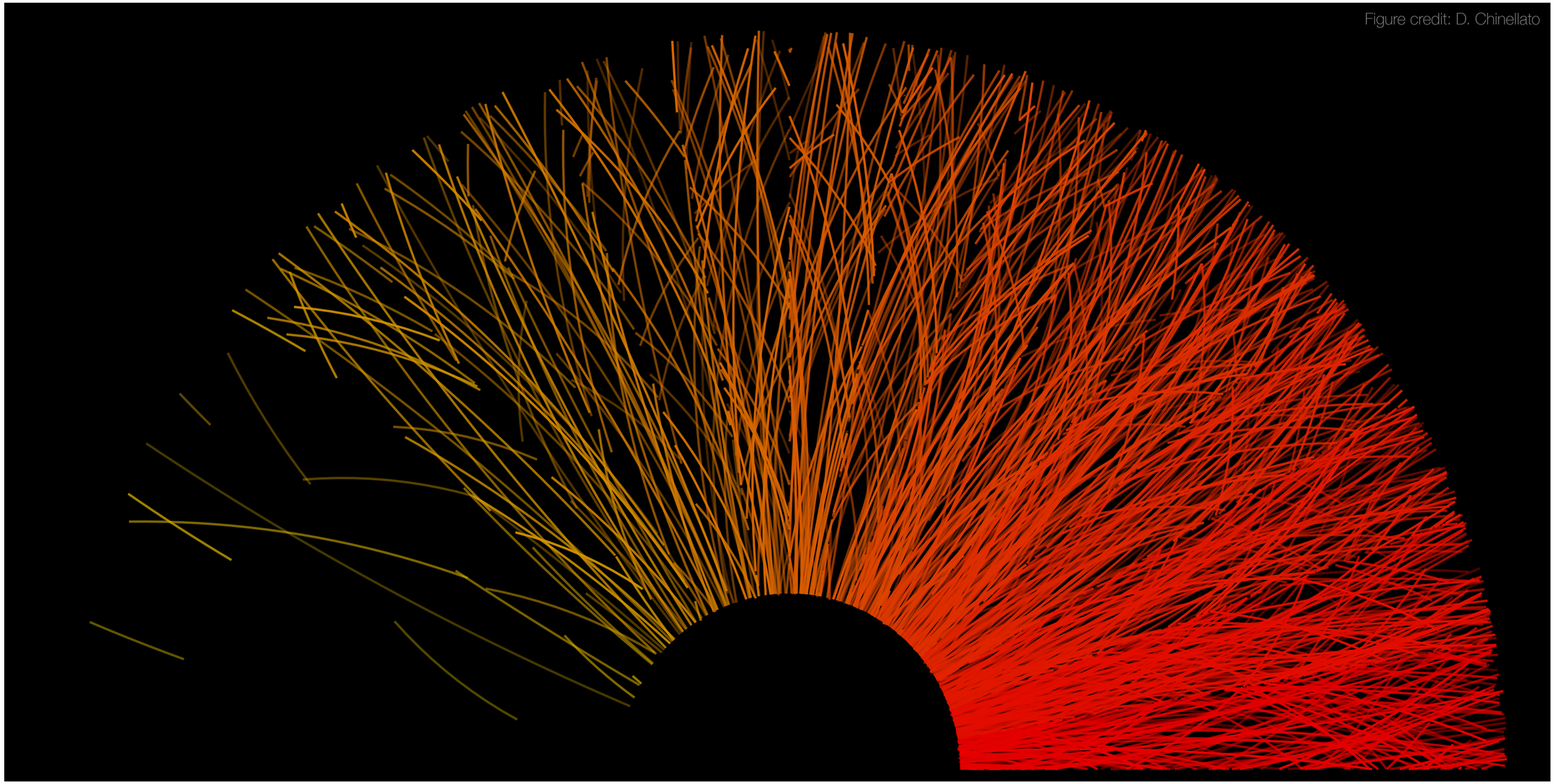


Hypetriton lifetime and binding energy measurement with ALICE, S. Bufalino, Thu. 12:30

p−Pb: PRL 128 (2022) 25, 252003
Pb−Pb: PLB 754 (2016) 360-372



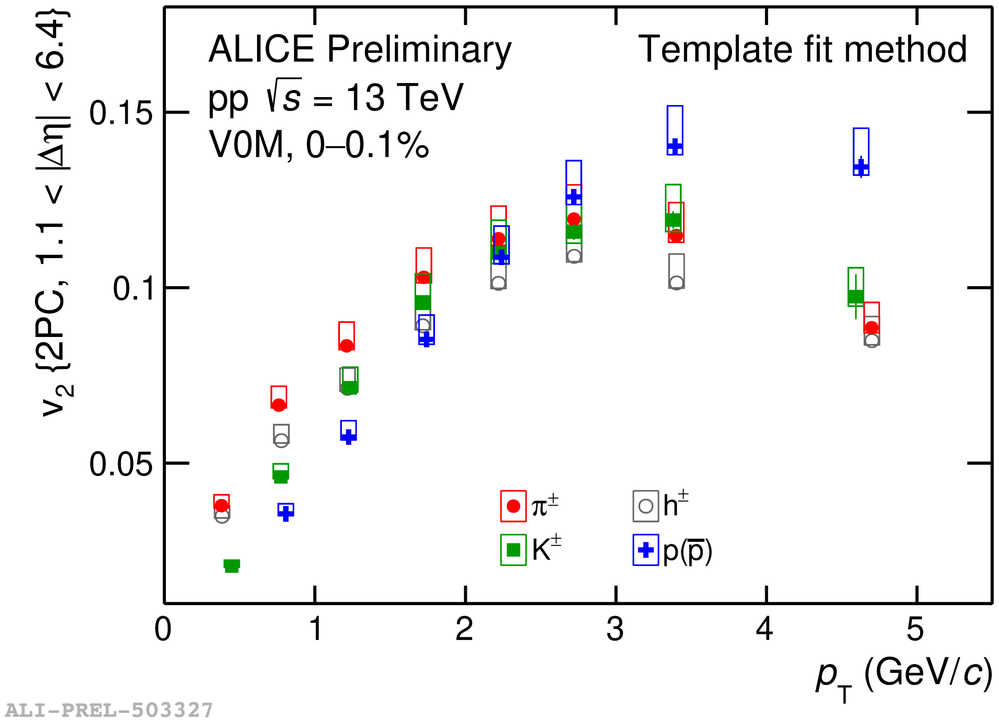
Collisions of small systems: pp, p−Pb

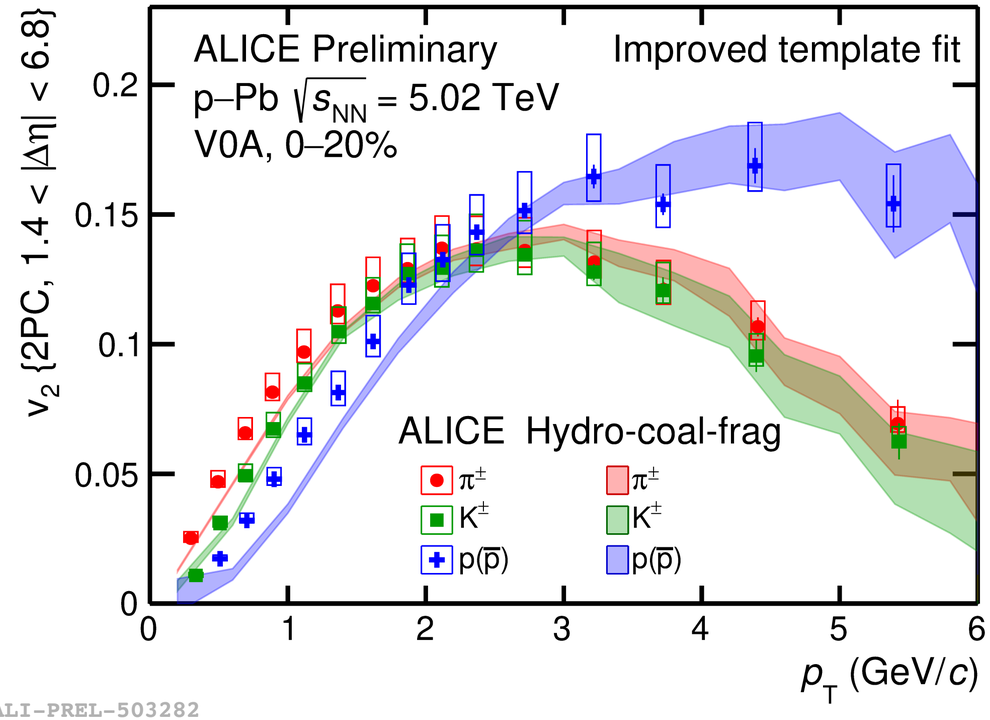


Flow of identified particles in small systems

Big questions on small systems, D. Das, Fri. 09:40

Baryon-meson splitting at intermediate p_T in both pp and p−Pb collisions
Comparison of p−Pb results with models indicates partonic flow + coalescence
(No J/ψ flow within uncertainties in high-multiplicity pp collisions)



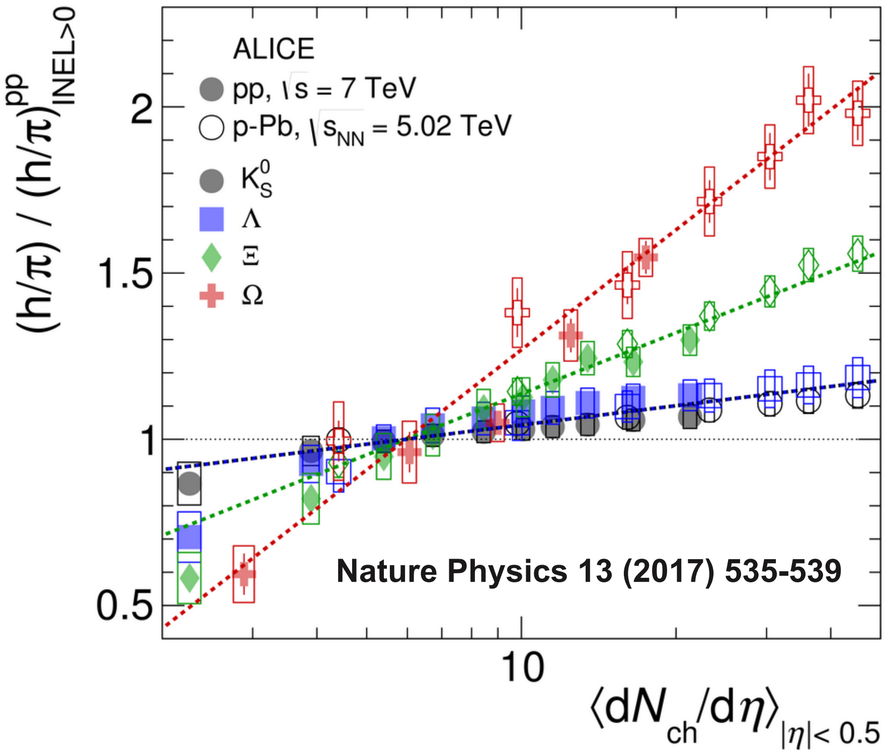


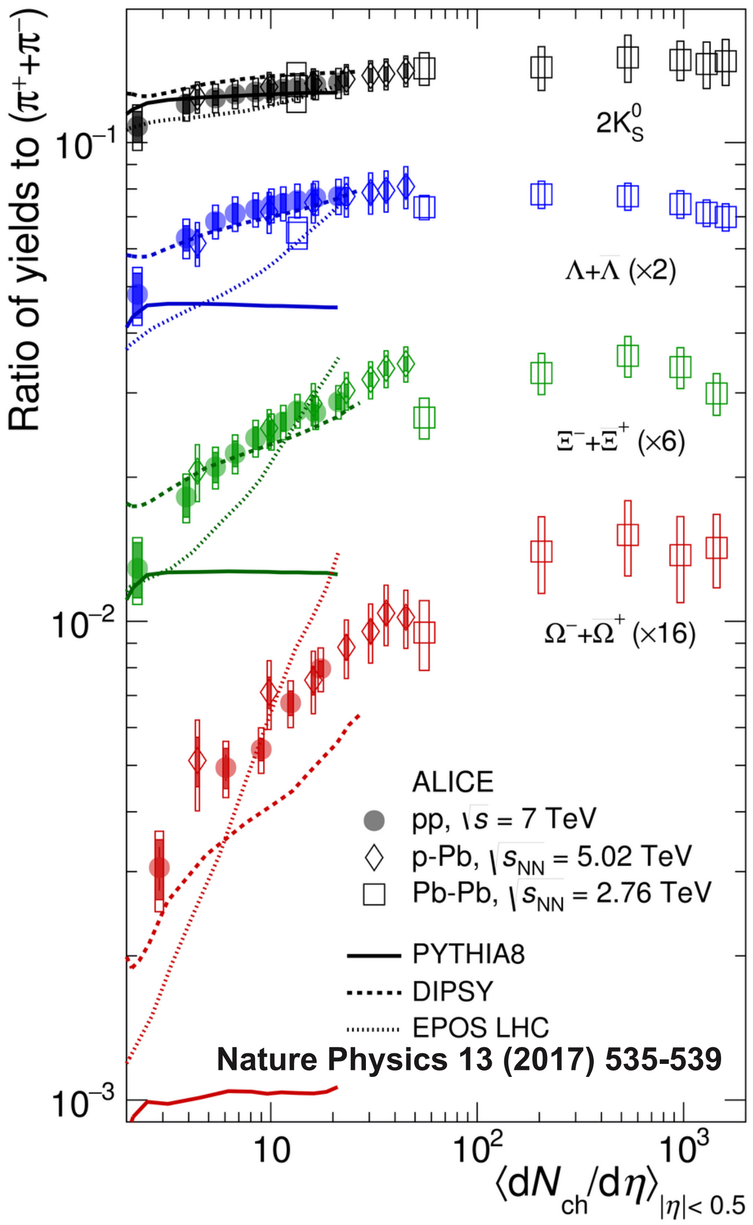
Strangeness enhancement in pp collisions

Large enhancement of (multi-)strange particle production in high-multiplicity pp collisions at $\sqrt{s}$ = 7 TeV

- In remarkable agreement with results from p−Pb collisions
- In high-multiplicity events strangeness production reaches values similar to those observed in Pb–Pb collisions!

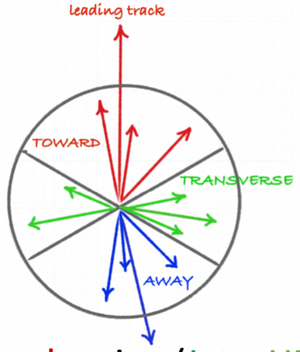
How are these multi-strange particles produced, and in which direction?





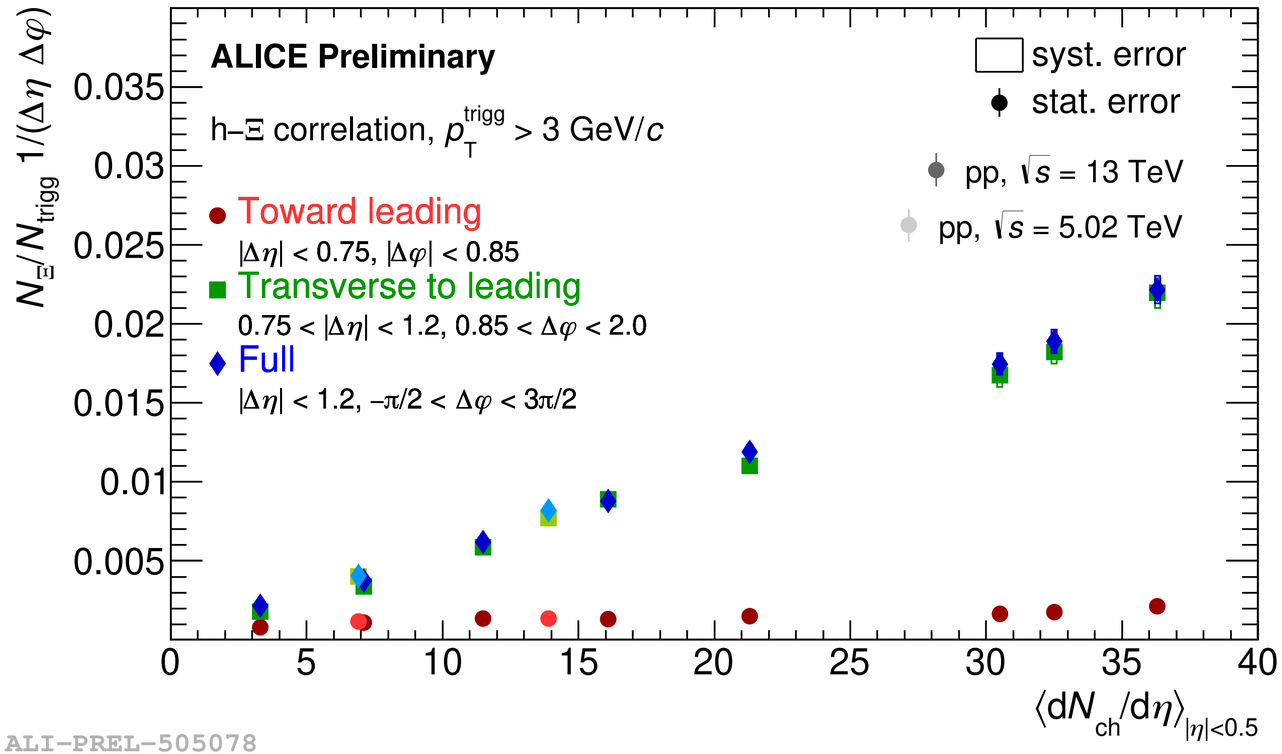
Investigating the enhancement in more details

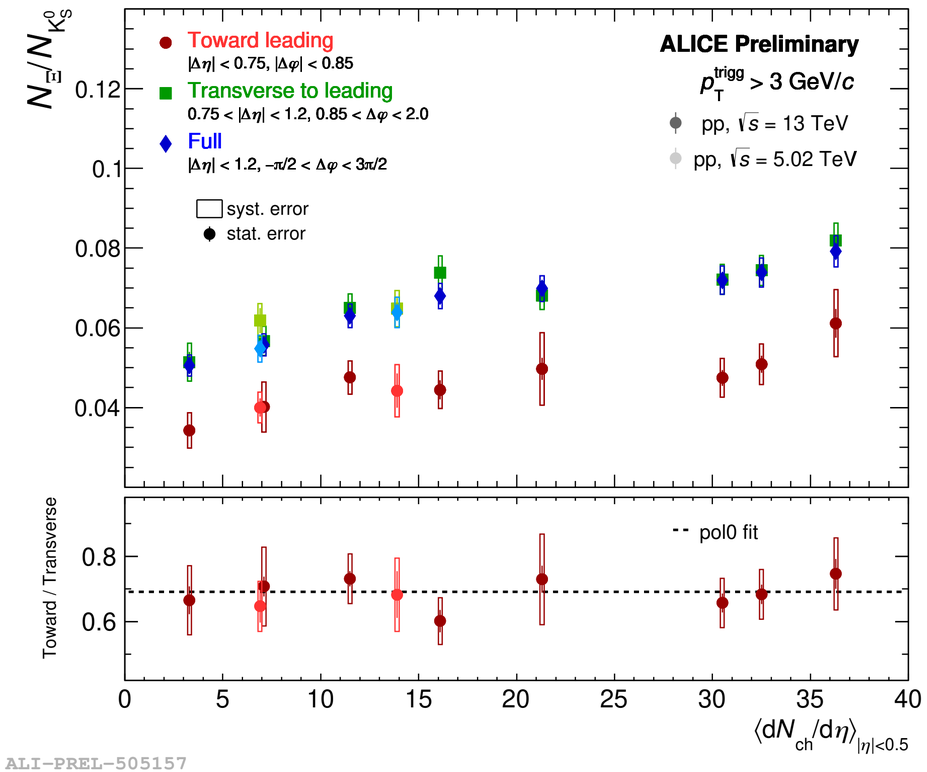
- Both Full and Transverse to leading particle yields increase with multiplicity
- Toward leading particle yield shows almost flat dependence with multiplicity
- No collision energy dependence



Toward region (Jet + UE)

Transverse region (UE)



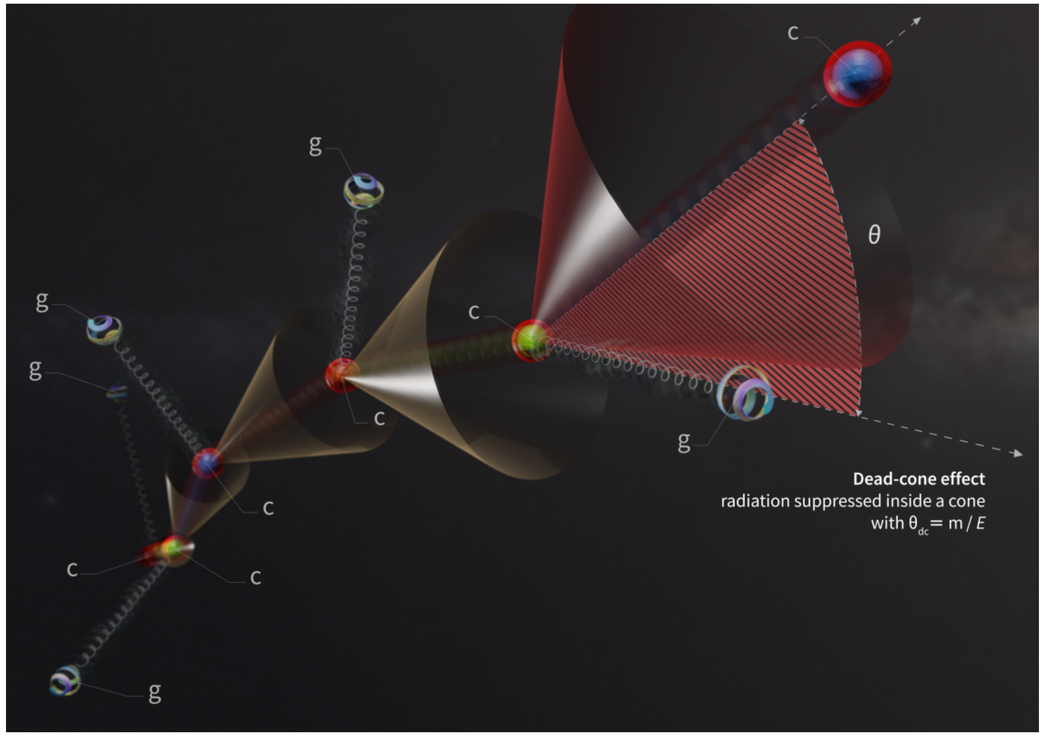


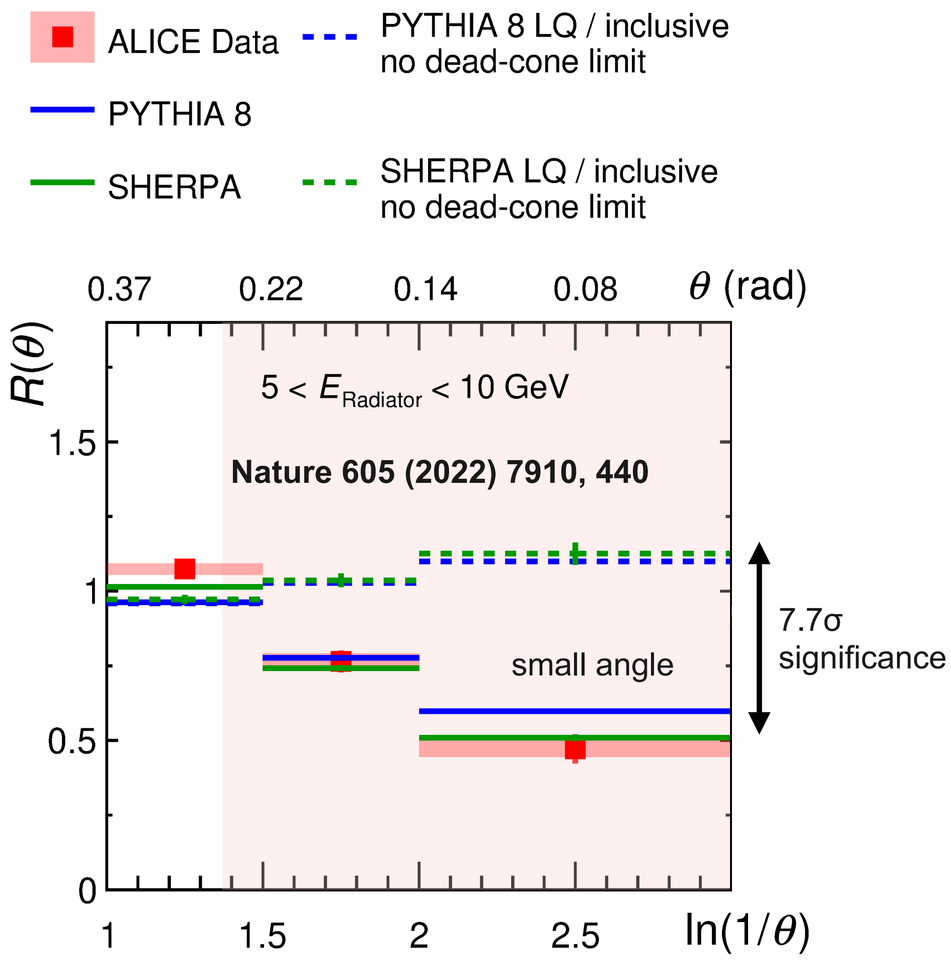
Strange hadrons in pp collisions are dominantly produced in the transverse direction to the leading particles

Dead-cone effect exposed by ALICE

Suppression of gluon radiation from heavy quarks at small angles [1]

$$R(\theta) = \frac{1}{N^{\mathrm{D}^0\,\mathrm{jets}}} \frac{\mathrm{d}n^{\mathrm{D}^0\,\mathrm{jets}}}{\mathrm{d}\ln(1/\theta)} \Big/ \frac{1}{N^{\mathrm{inclusive\,jets}}} \frac{\mathrm{d}n^{\mathrm{inclusive\,jets}}}{\mathrm{d}\ln(1/\theta)} \Bigg|_{k_{\mathrm{T}},\,E_{\mathrm{Radiator}}}$$



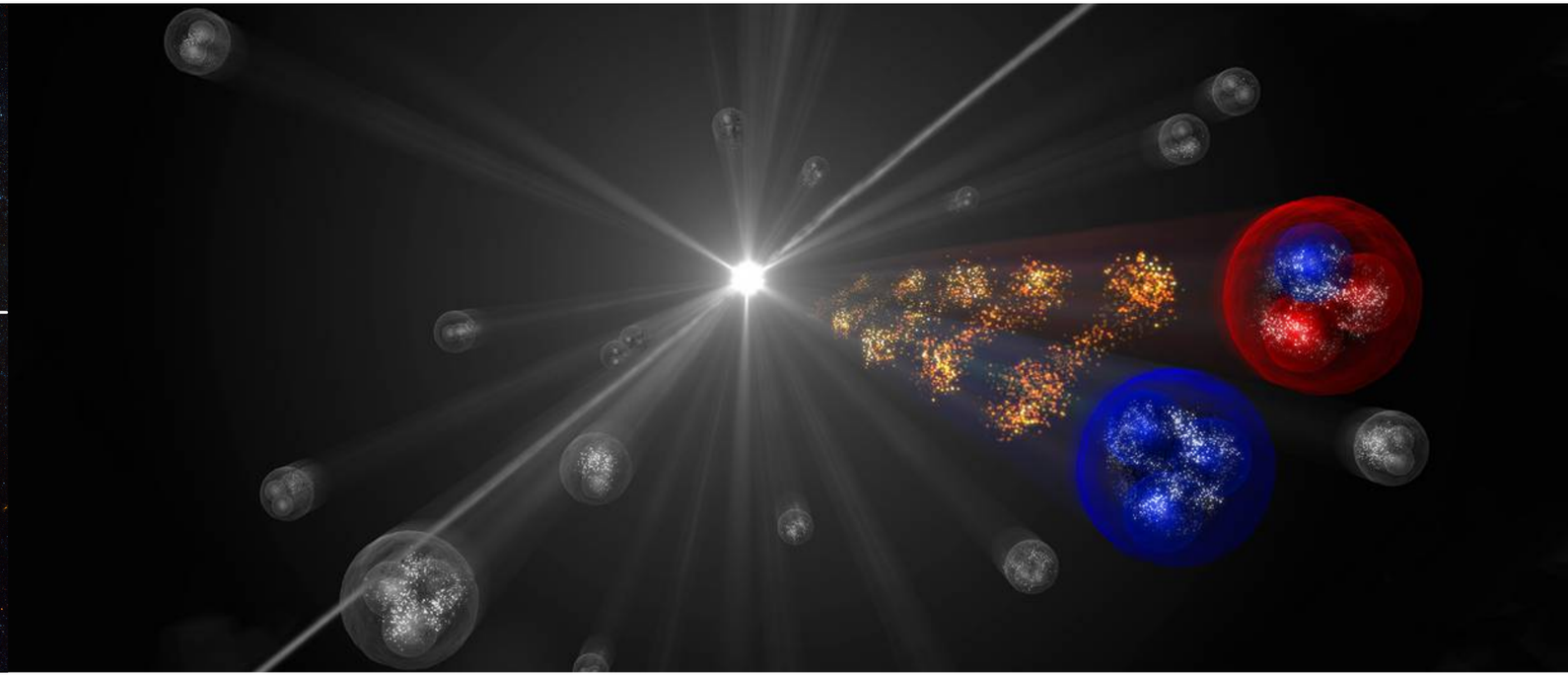


ALI-PUB-493419

First direct observation using iterative jet declustering and Lund plane analysis of jets with a soft D^0 meson

[1] Dokshitzer, Khoze, Troian, J. Phys. G 17 (1991) 1602

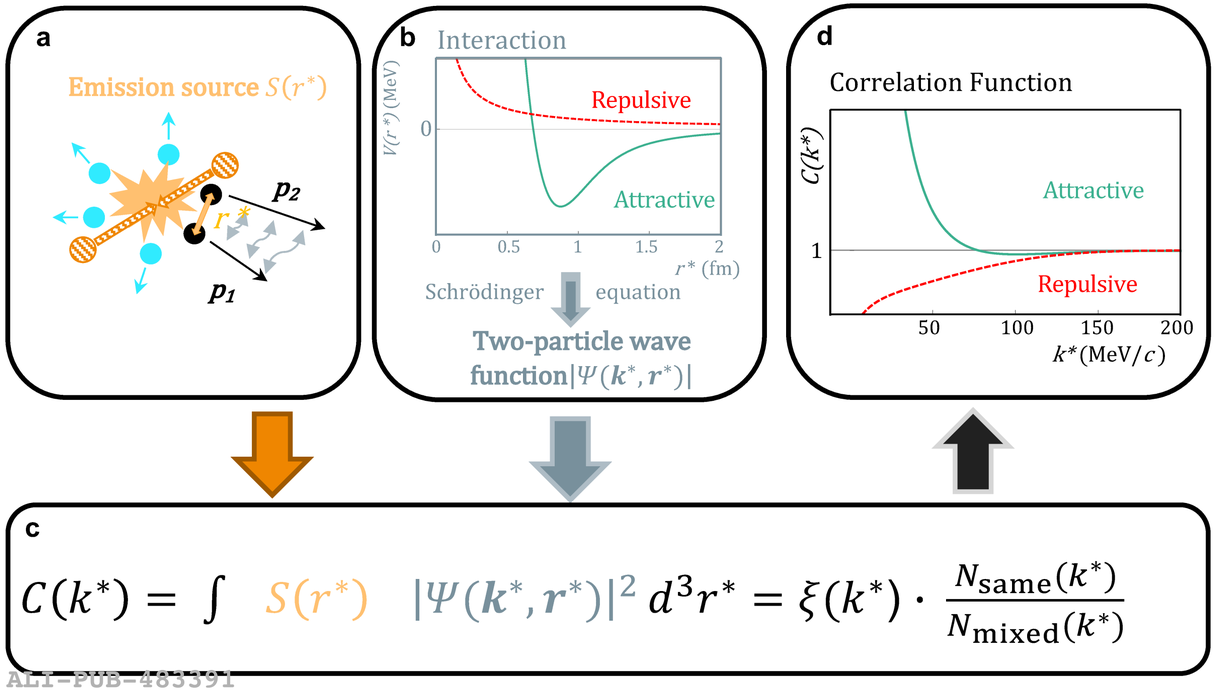
Beyond the QGP studies



Hadron-hadron interactions

ALICE is pioneering the study of strong interactions using femtoscopic correlations

New experimental frontiers in the study of the hadronic interactions with ALICE at the LHC, R. Del Grande, Tue. 16:15

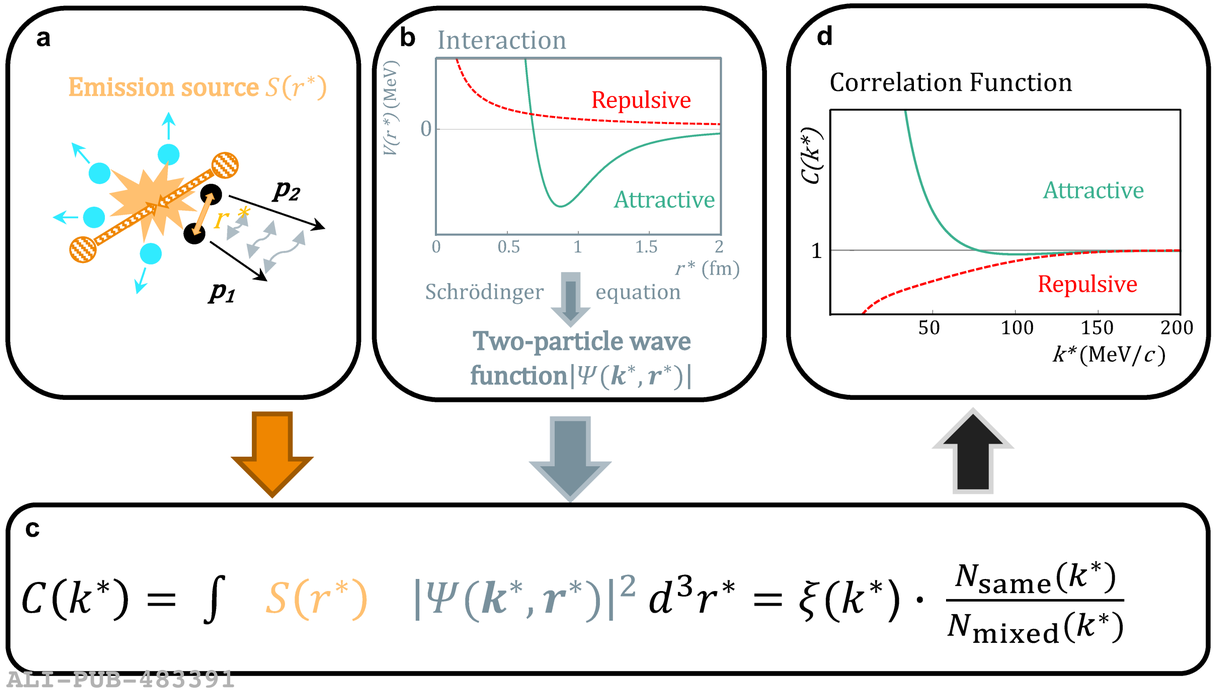


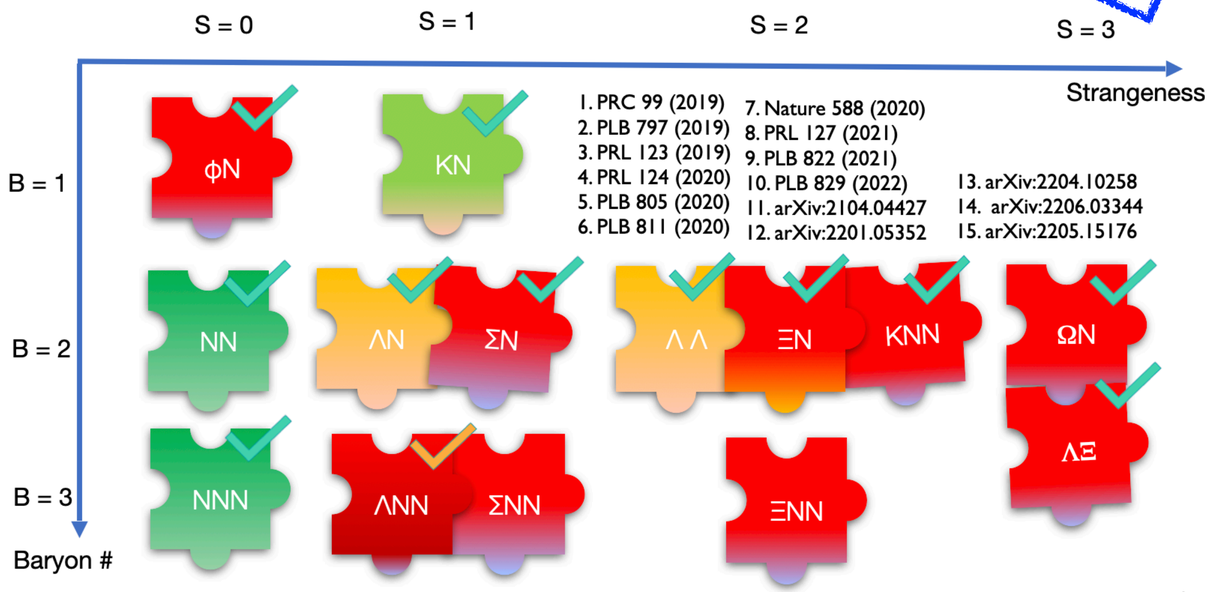
- Emission source is constrained from pairs for which the interaction is well-known
- → by measuring correlation function we can study the interactions among hadron pairs!

Hadron-hadron interactions

ALICE is pioneering the study of strong interactions using femtoscopic correlations

New experimental frontiers in the study of the hadronic interactions with ALICE at the LHC, R. Del Grande, Tue. 16:15



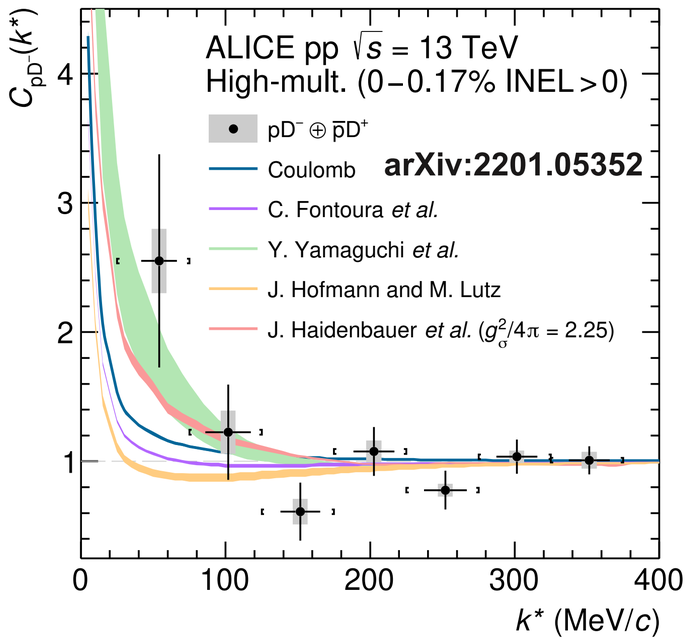


- Emission source is constrained from pairs for which the interaction is well-known
- → by measuring correlation function we can study the interactions among hadron pairs!

Hadron-hadron interactions: few highlights

First studies of residual strong interaction between charm and light-flavour hadrons

- Results compatible with Coulomb interaction and with shallow attractive strong interaction



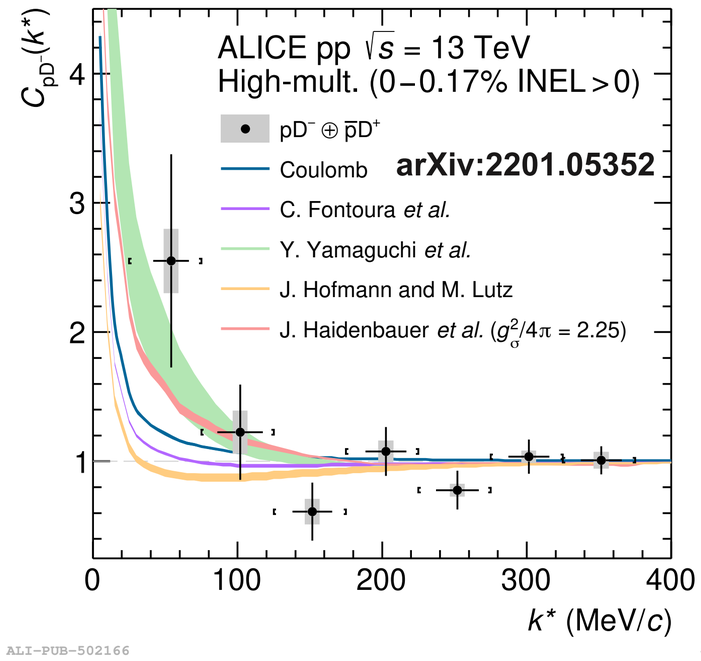
Hadron-hadron interactions: few highlights

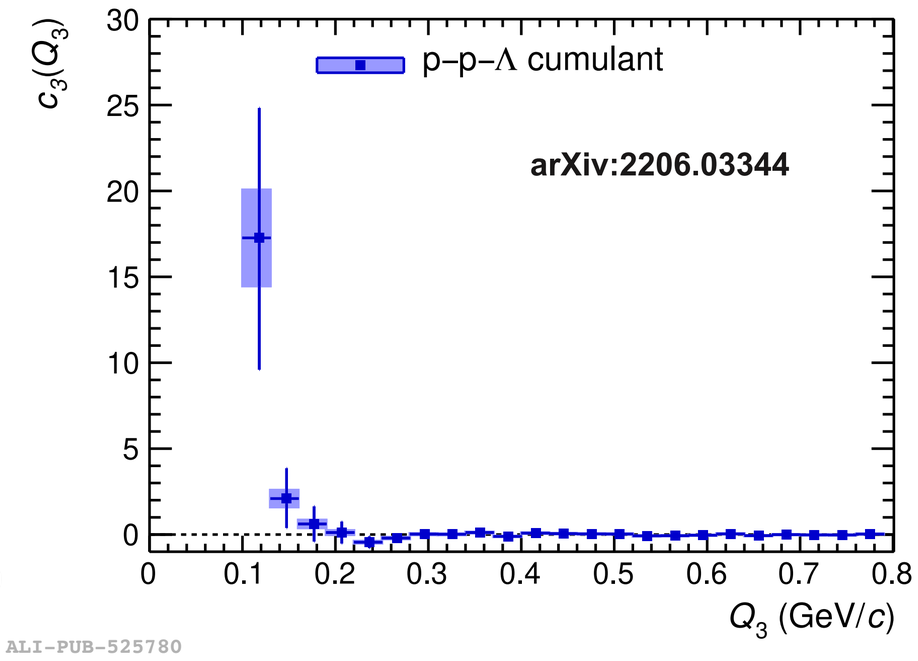
First studies of residual strong interaction between charm and light-flavour hadrons

- Results compatible with Coulomb interaction and with shallow attractive strong interaction

First studies of three-body interactions

- Important role in the structure of (hyper)nuclei and in models to describe dense baryonic matter (e.g. neutron stars)



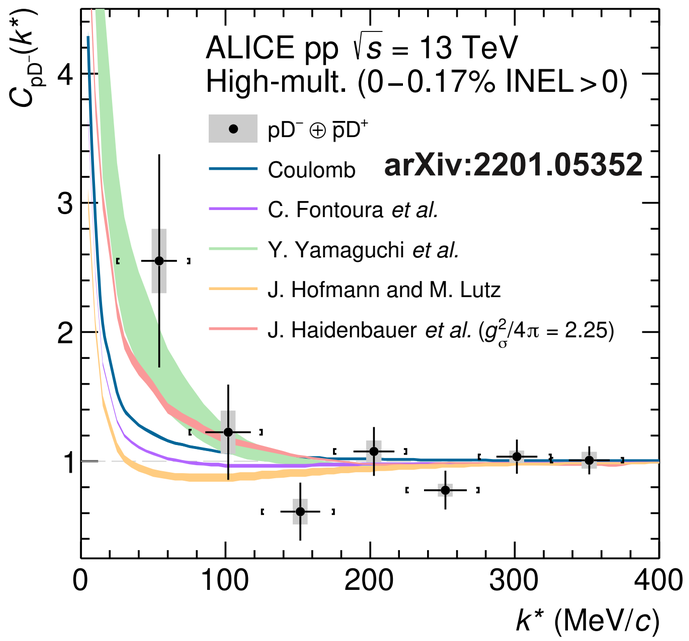


Hadron-hadron interactions: few highlights

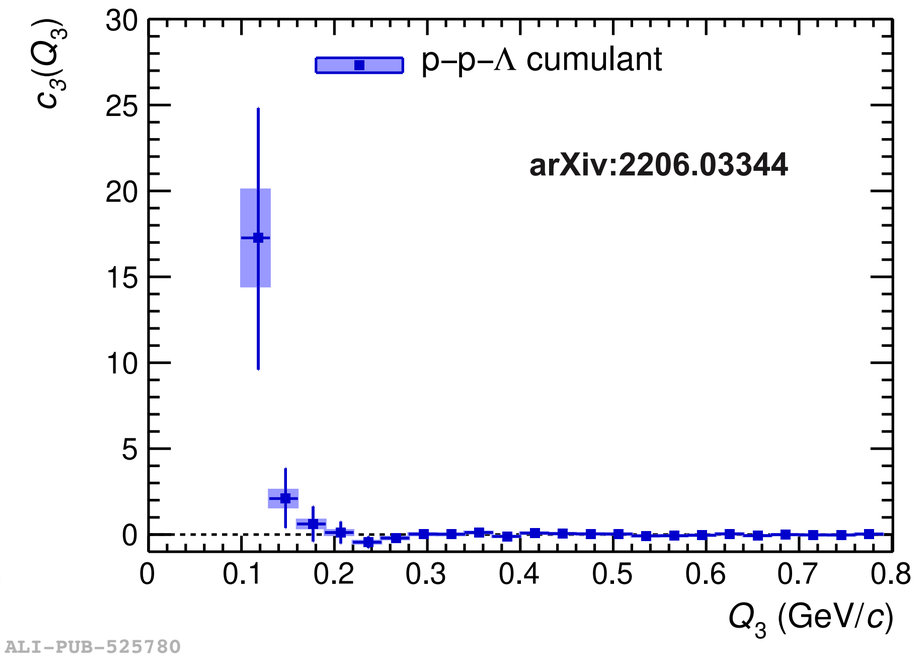
First studies of residual strong interaction between charm and light-flavour hadrons
- Results compatible with Coulomb interaction and with shallow attractive strong interaction

First studies of three-body interactions
- Important role in the structure of (hyper)nuclei and in models to describe dense baryonic matter (e.g. neutron stars)

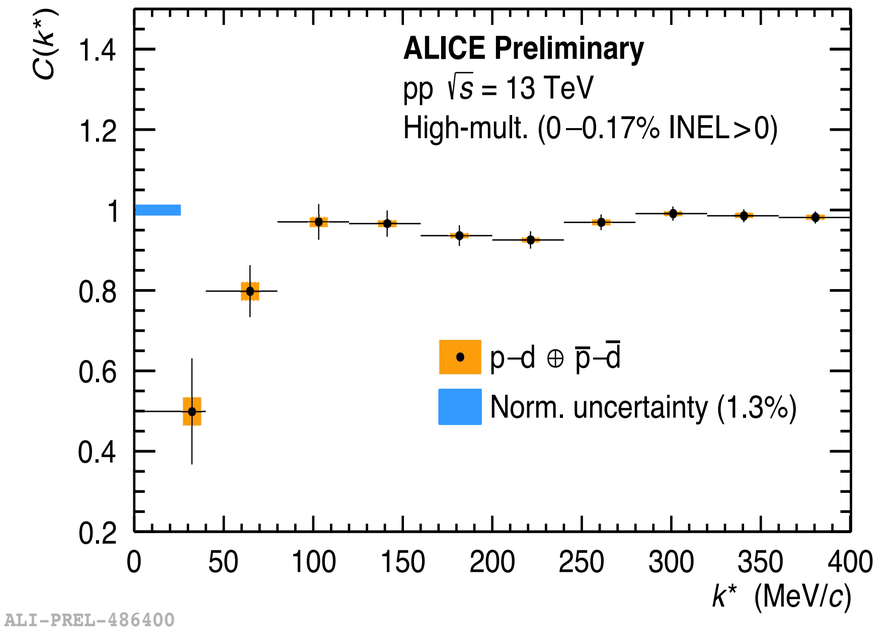
First measurement of proton-deuteron interaction at the LHC
- Valuable input for models, insight into light nuclei formation



ALI-PUB-502166



ALI-PUB-525780

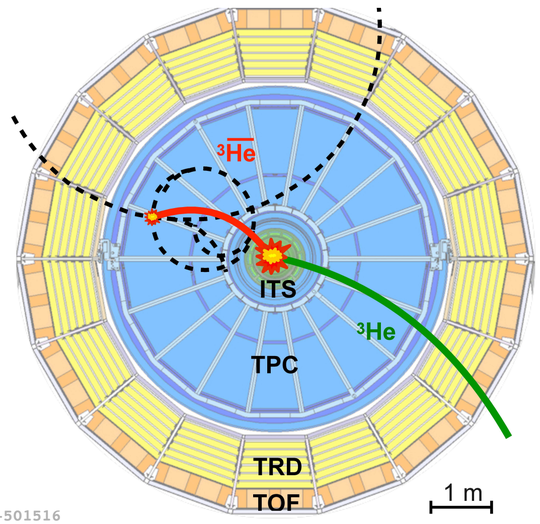


ALI-PREL-486400

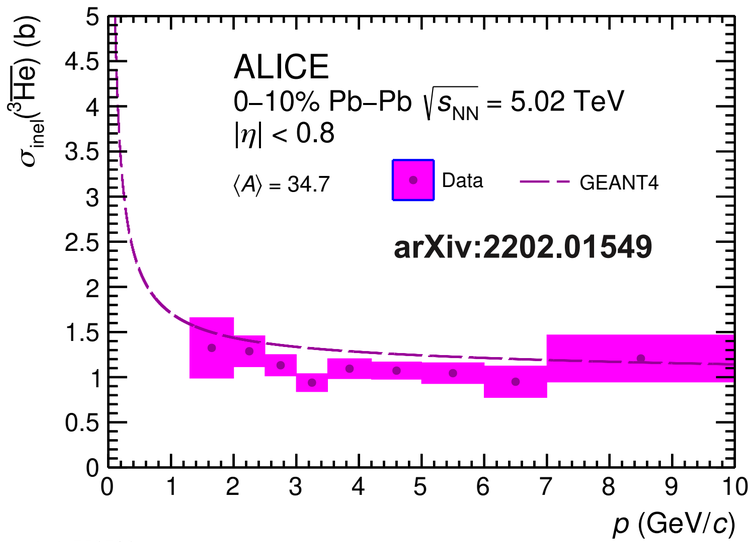
On the transparency of our Galaxy to $^{3}\overline{He}$ nuclei

Pioneering studies of antinuclei inelastic interactions with matter at low kinetic energies

- Fixed-target experiment within ALICE: LHC as an antimatter factory, ALICE detector material as a target



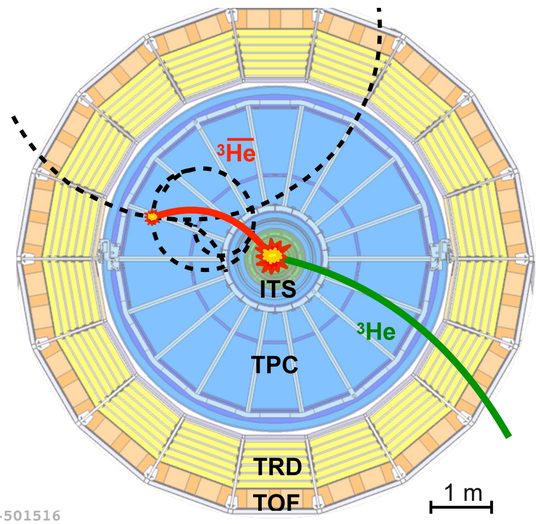
ALI-PUB-501516



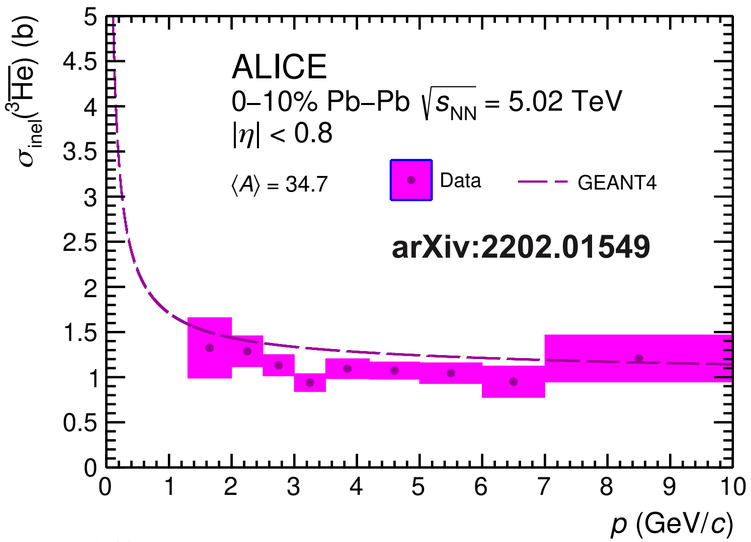
ALI-PUB-501531

On the transparency of our Galaxy to $^{3}\overline{\mathrm{He}}$ nuclei

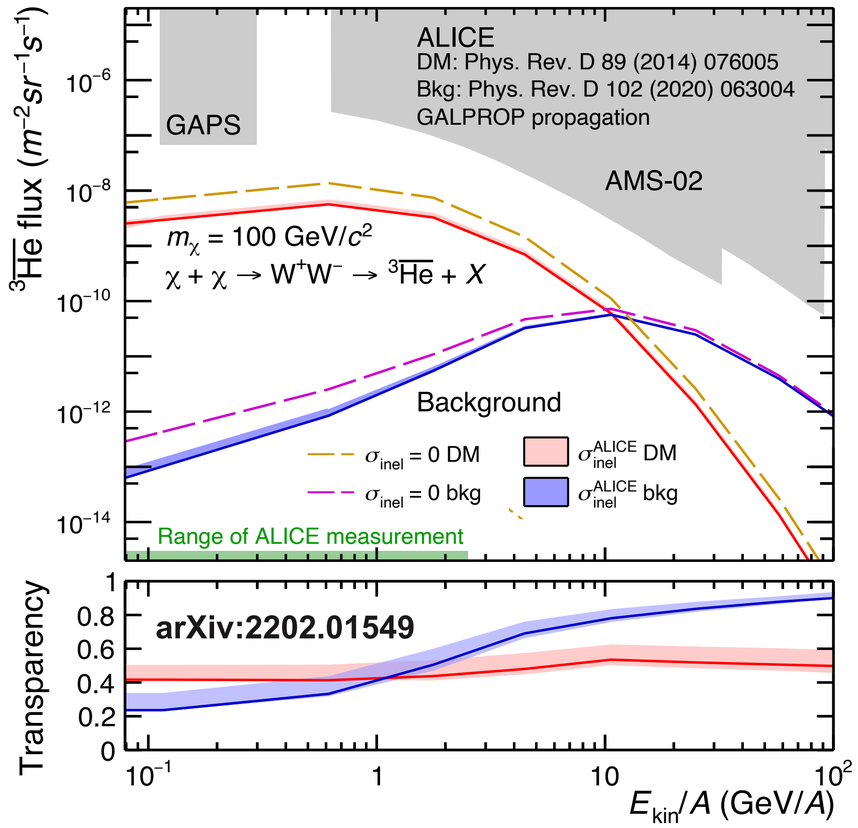
Pioneering studies of antinuclei inelastic interactions with matter at low kinetic energies
- Fixed-target experiment within ALICE: LHC as an antimatter factory, ALICE detector material as a target



ALI-PUB-501516



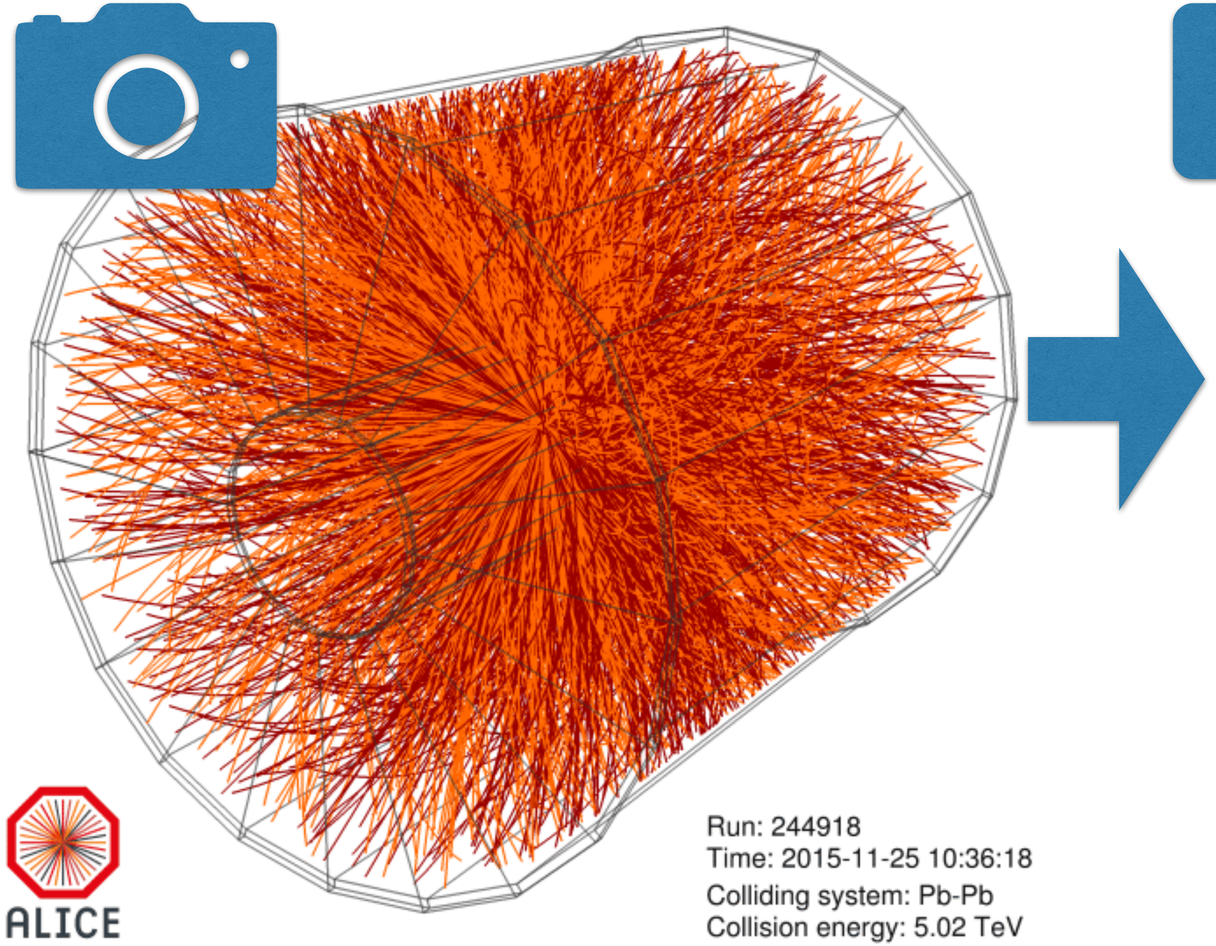
ALI-PUB-501531

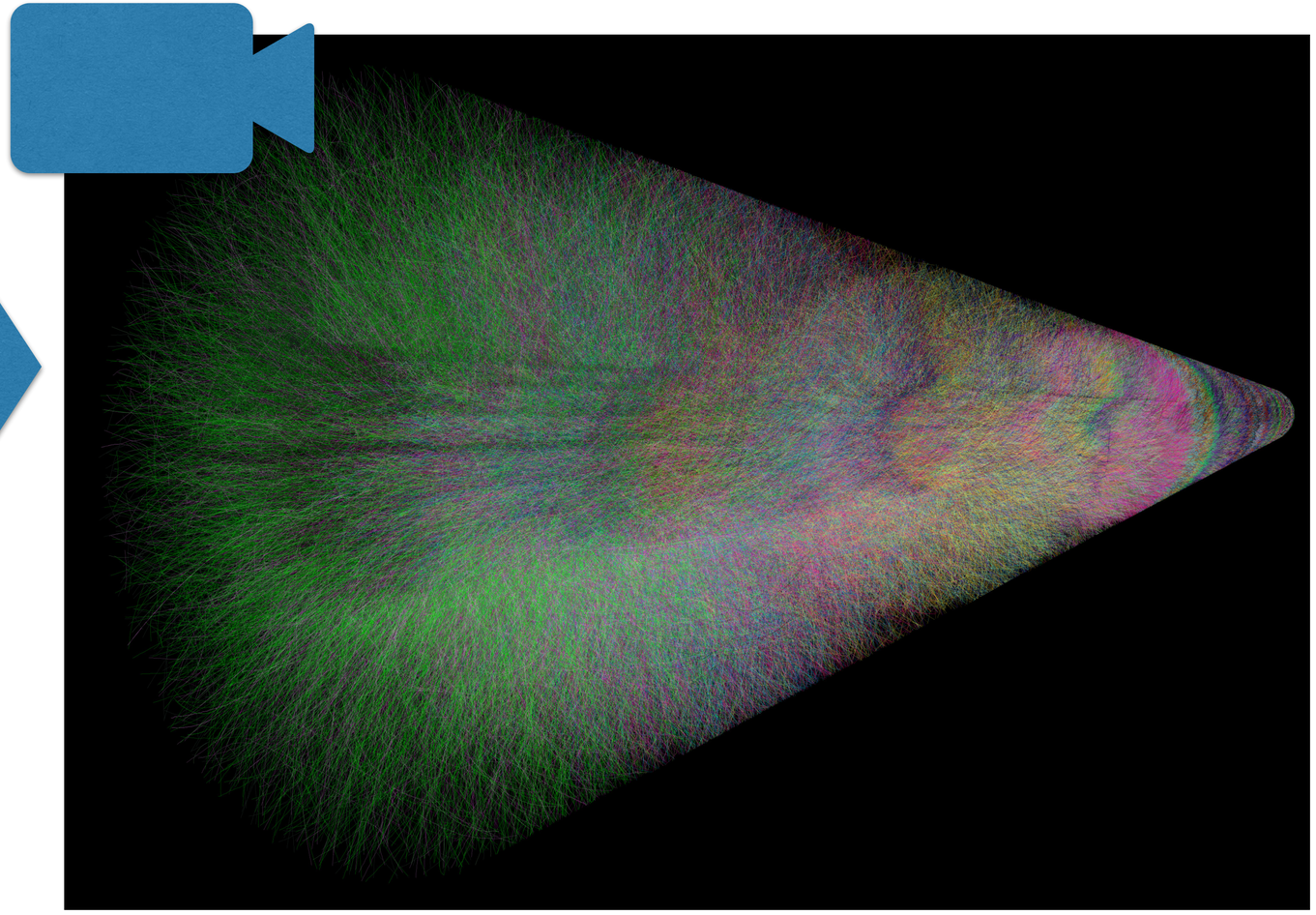


ALI-PUB-501546

Essential input for indirect searches of dark matter in space with antinuclei!
- High transparency of our Galaxy to $^{3}\overline{\mathrm{He}}$ nuclei from a DM source

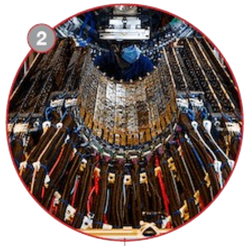
“ALICE 1” (2010’s) → “ALICE 2” (2020’s)



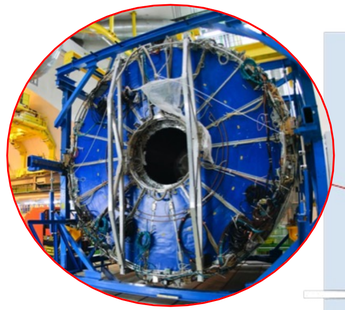


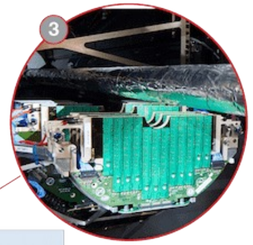
Detector and software upgrades for Run 3

New Inner Tracking System (ITS)
– 7 barrels, 10 m² silicon tracker based on MAPS (12.5 G pixels`



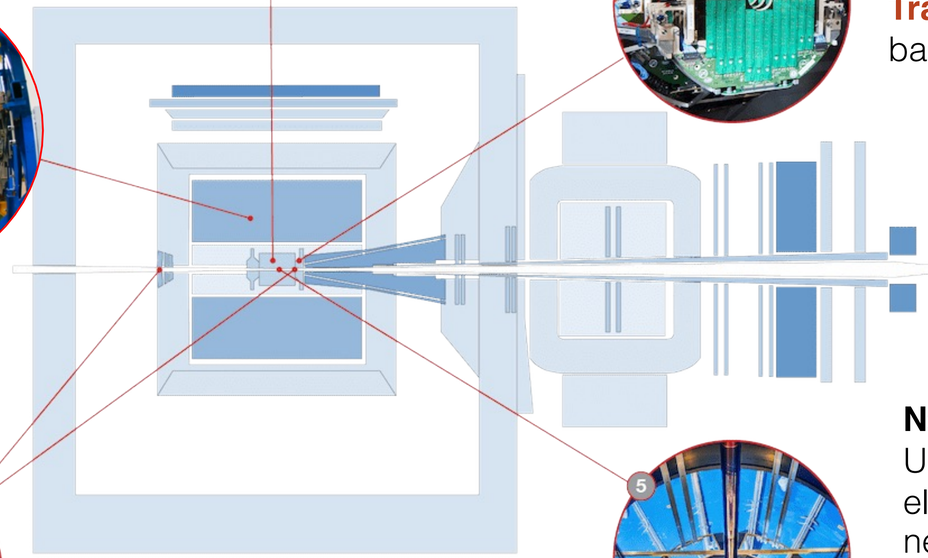
New GEM-based TPC
with continuous readout



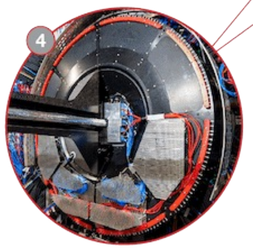


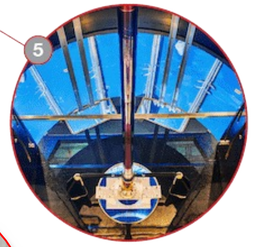
New Muon Forward Tracker (MFT) - 5 disks
based on MAPS

About x3 better tracking precision
Pb−Pb collisions rate x50 higher



New Trigger and Readout
Upgrade of readout electronics of all detector, new Central Trigger Processor





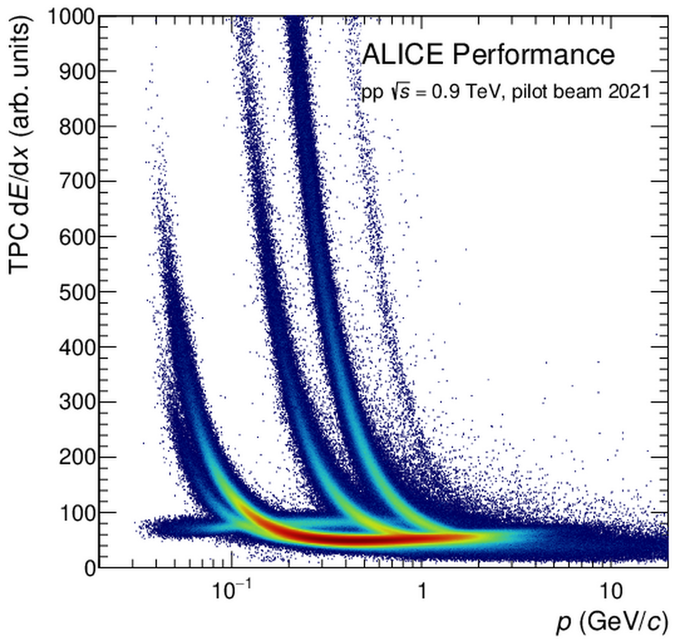
New Online/Offline (O2)

New Fast Interaction Trigger (FIT)
– 3 detector technologies: interaction trigger, online luminometer, forward multiplicity

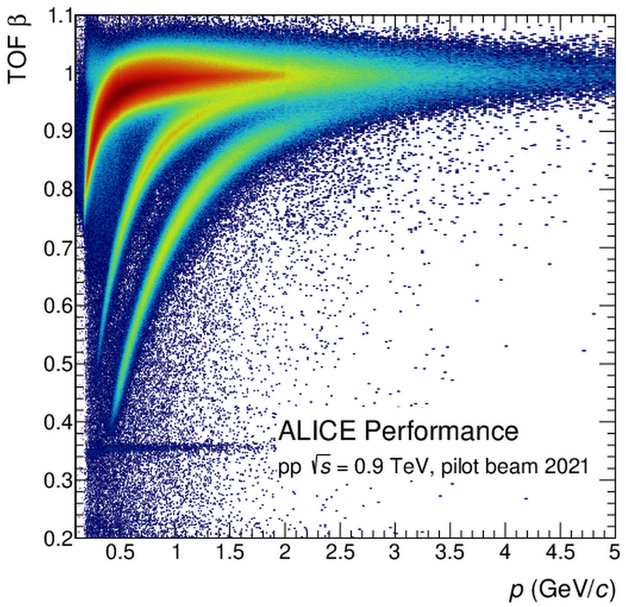
New Beampipe
smaller diameter (36.4 mm), first detection layer at 20 mm

Results from first collisions (pilot beam 2021)

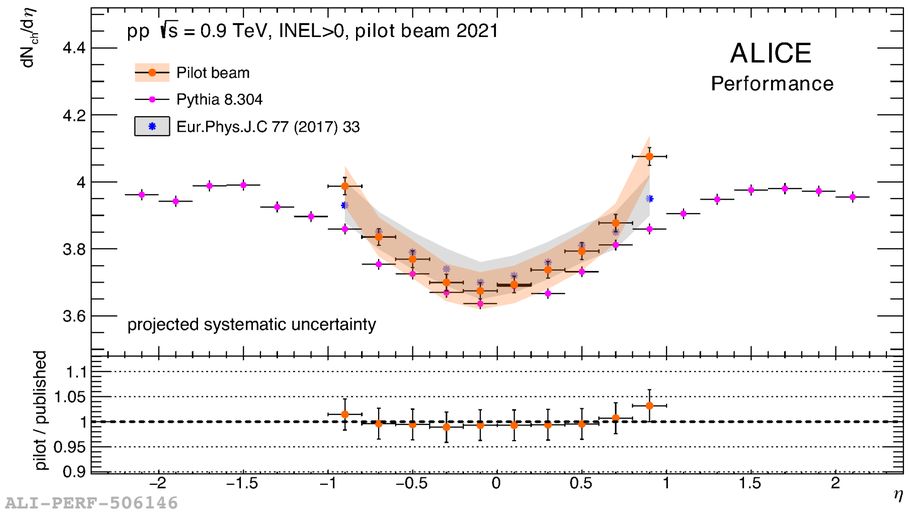
Full PID capabilities from TPC and TOF are available
First look at the charged-particle multiplicity and pp correlation function



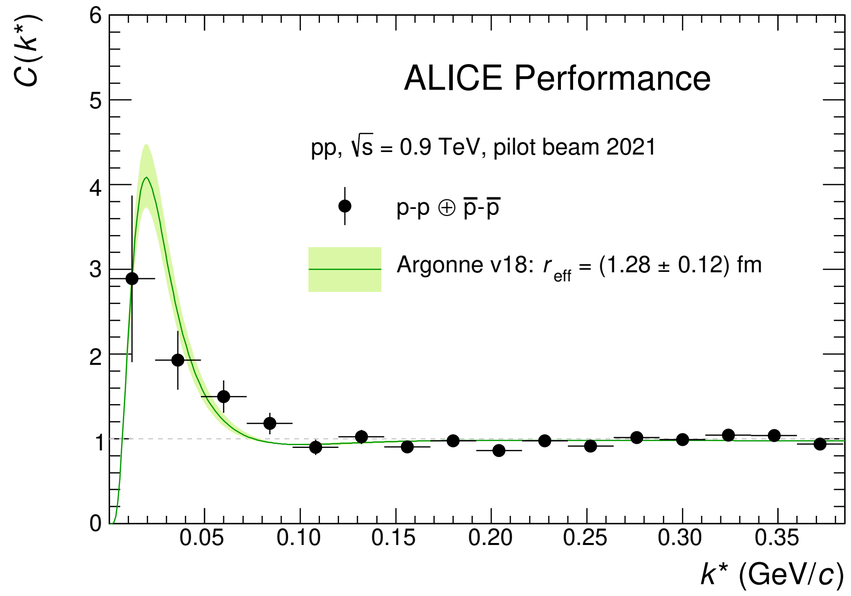
ALI-PERF-500457



ALI-PERF-500446



ALI-PERF-506146

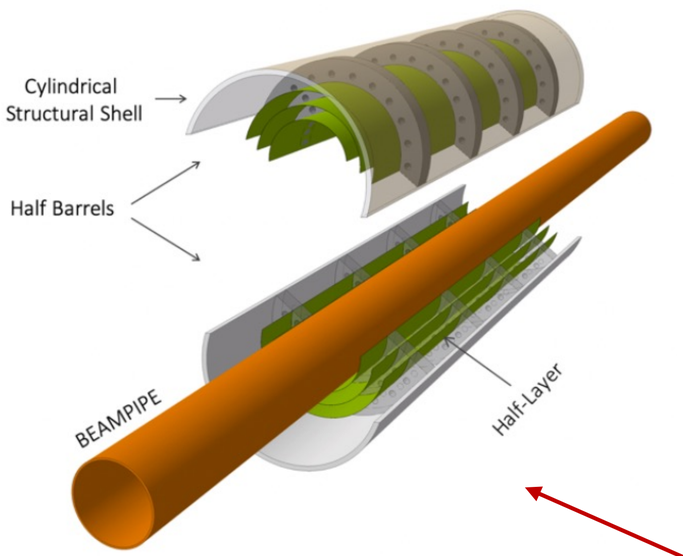


ALI-PERF-503088

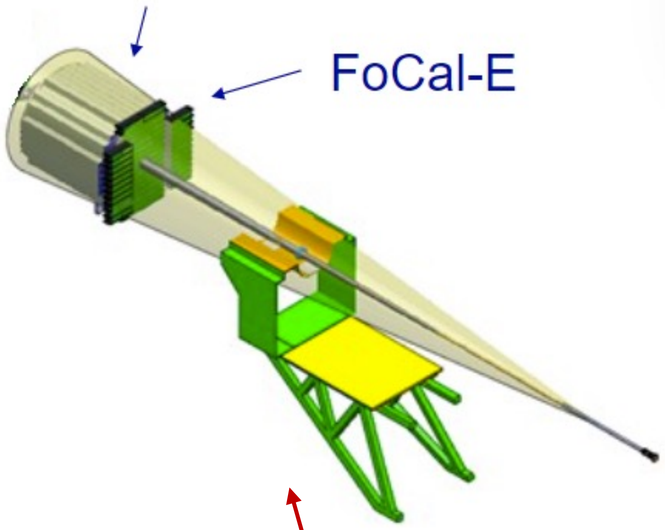
Detector, simulation, reconstruction and analysis software are ready for physics! ✅

Already preparing for Run 4 and beyond!

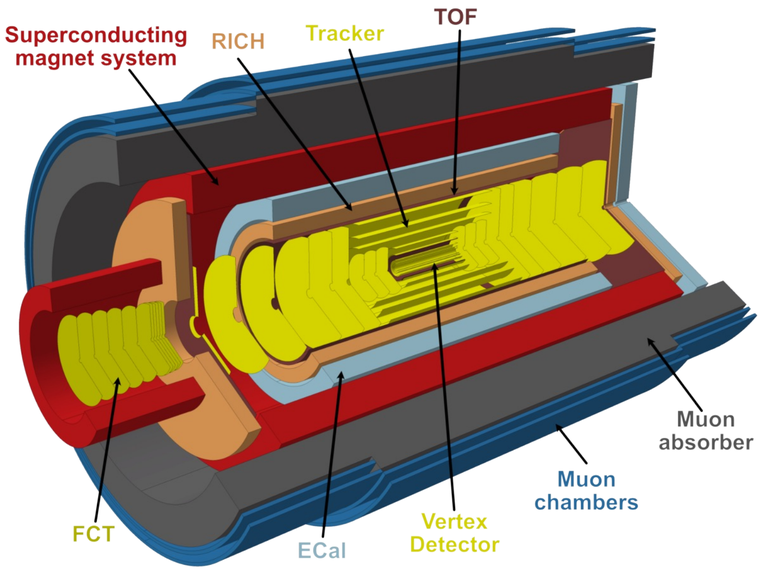
ITS3

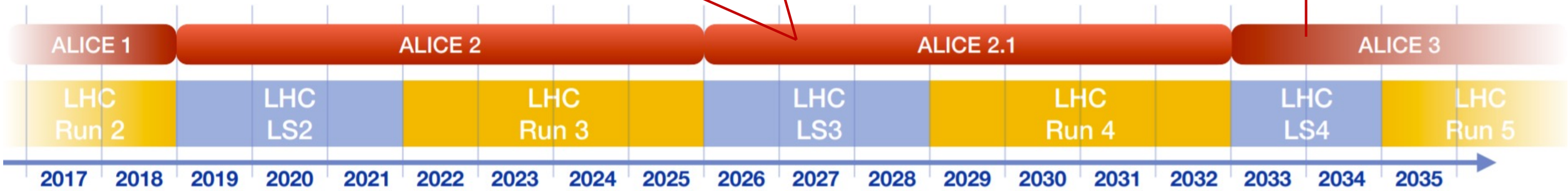


FoCal-H



ALICE 3





Summary

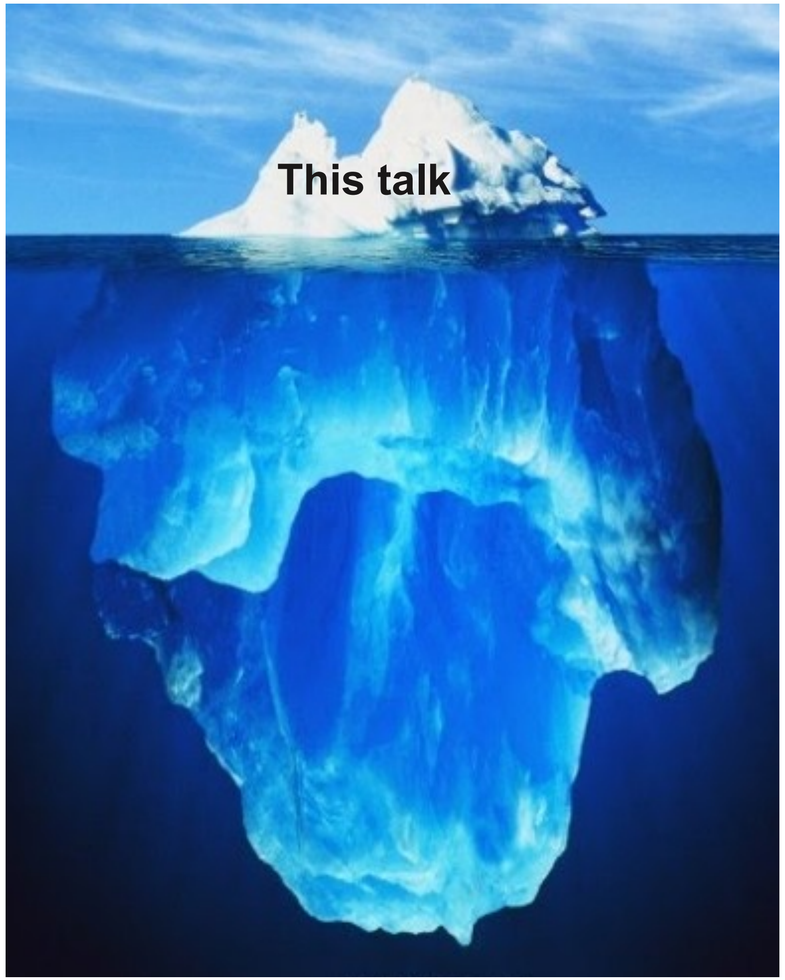
Fruitful harvest of ALICE results from Run 1 and Run 2 campaigns

- Detailed insights into the QGP properties
- Broad programme of the studies in pp and p−Pb collisions
- Unique and novel studies beyond the QGP physics

ALICE completed the Phase I upgrade and is ready for Run 3

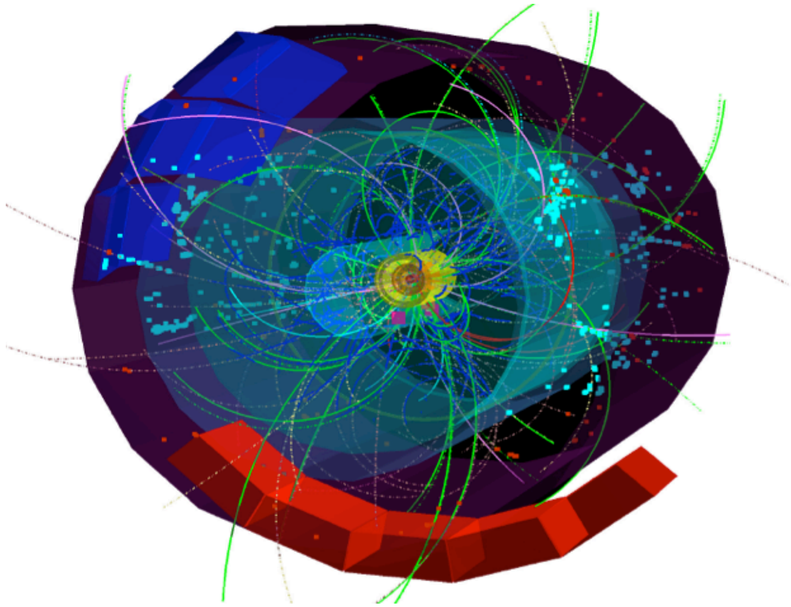
- Significantly enhanced capabilities

In preparation for Run 4 and beyond



Thank you for your attention!

Back-up slides



The ALICE Detector during Run1 and Run2

Central Barrel $|\eta| < 0.9$
- Tracking
- PID
- EM-Calorimeters

ACORDE (cosmics)

Forward detectors:
- AD (diffraction selection)
- V0 (trigger, centrality)
- T0 (timing, luminosity)
- ZDC (centrality, ev. sel.)
- FMD (N_{ch})
- PMD ($N\gamma$, Nch)