Recent studies of quark-gluon plasma and beyond from ALICE

Małgorzata Janik
for the ALICE Collaboration

XV Polish Heavy Ion Workshop

Wrocław 24-25.09.2022

The ALICE Collaboration

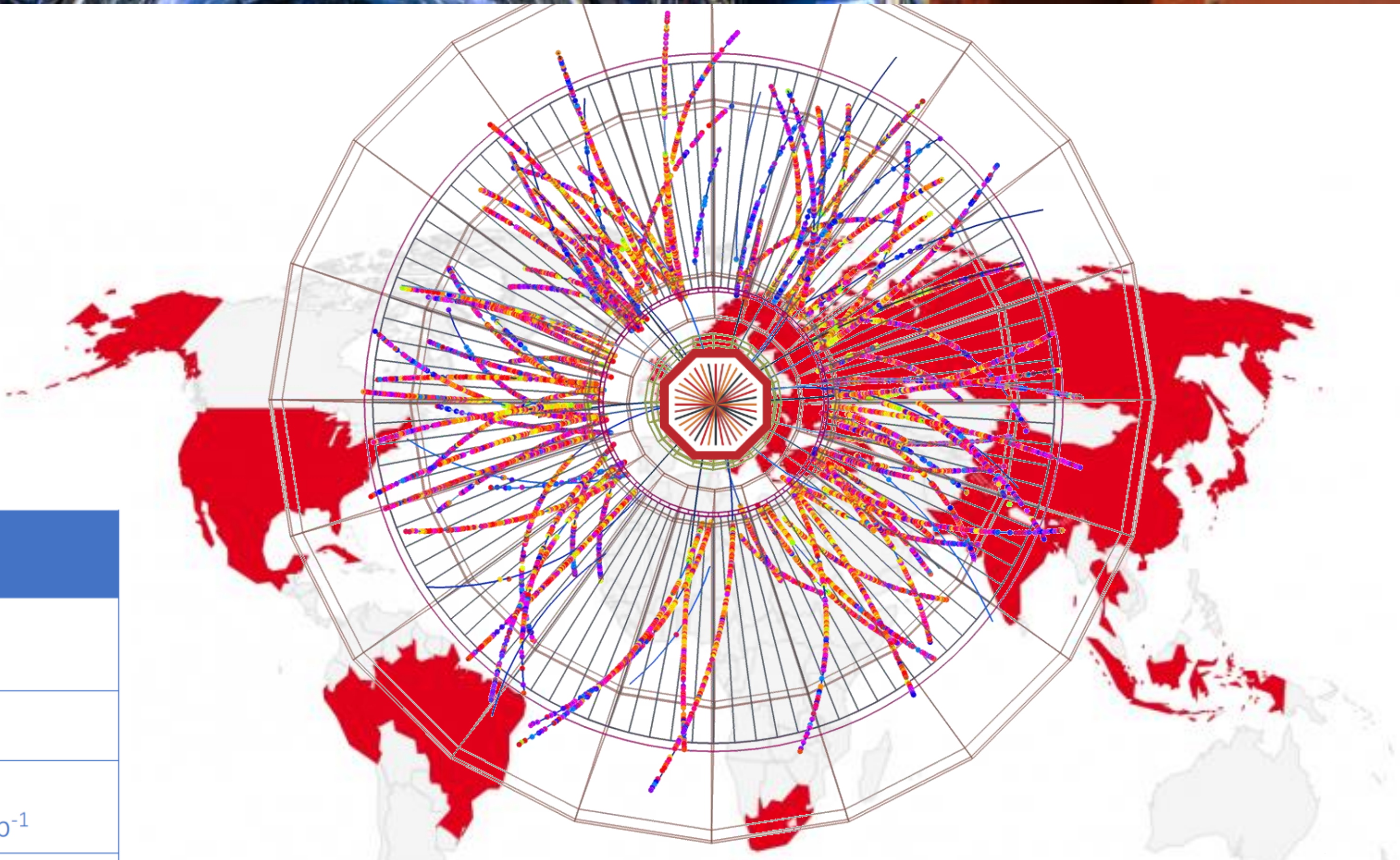
- Run 1 + Run 2 data:

398 ALICE papers on arxiv

https://alice-publications.web.cern.ch/submitted

Run 1 | Run 2

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 mb^{-1}, ~100 nb^{-1} ~1.5 pb^{-1}, ~2.5 pb^{-1} ~1.3 pb^{-1} ~36 pb^{-1}



- 40 countries
- 174 institutes
  - 4 from Poland
- 1954 members

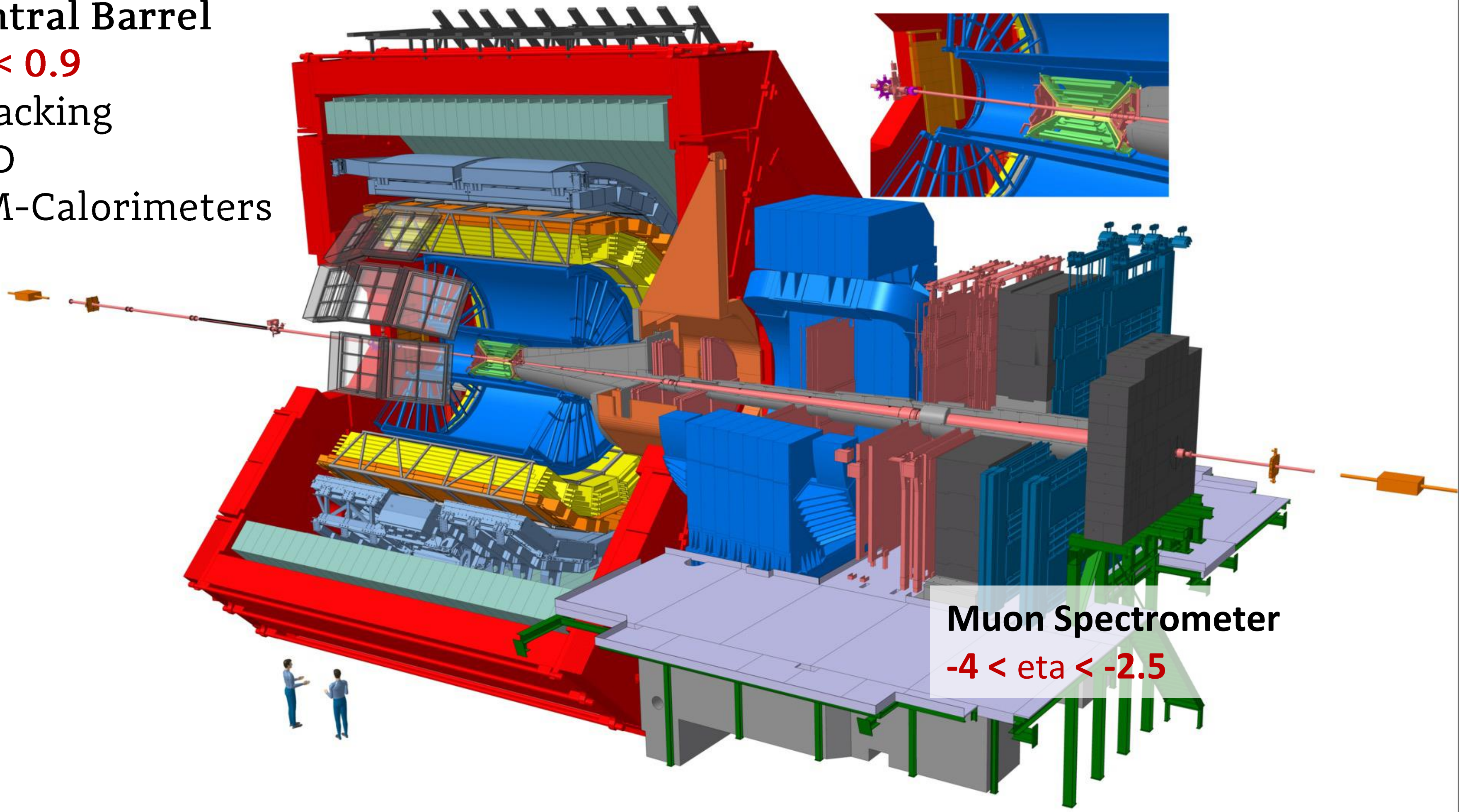
CRACOW
- The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences,
- AGH University of Science and Technology,

WARSAW
- National Centre for Nuclear Research,
- Warsaw University of Technology

ALICE detector

Run 1 + Run 2 version:

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

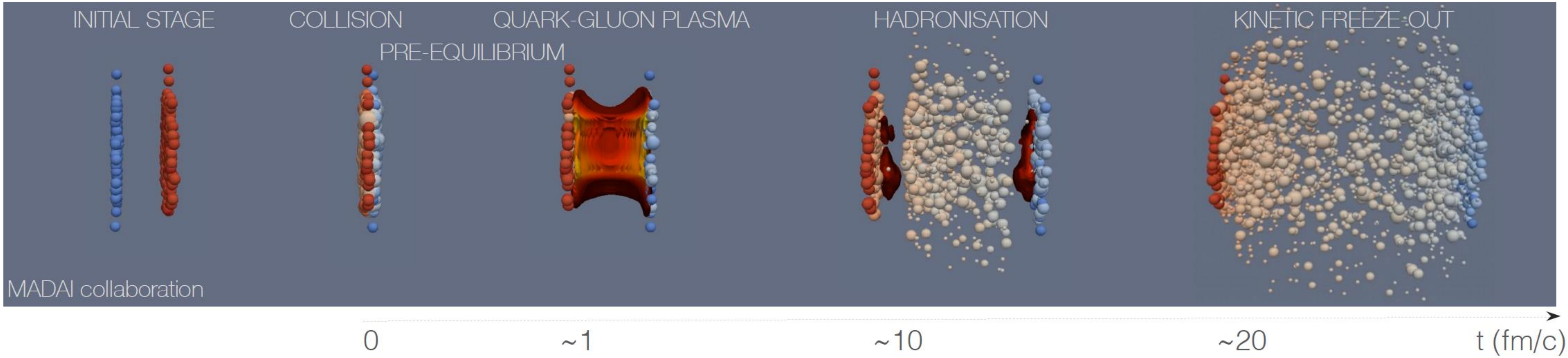


Forward detectors:
- AD (diffraction selection)
- V0 (trigger, centrality)
- T0 (timing, luminosity)
- ZDC (centrality, ev. sel.)
- FMD (N_{ch})
- PMD (N_{γ}, N_{ch})

ACORDE (cosmics)

ALICE physics

Explore the deconfined phase of QCD matter : quark-gluon plasma (QGP)



Study the properties and evolution of QGP:
→ Color deconfinement
→ Parton interactions
→ Expansion dynamics and hadronization

...and more!

→ Study QCD with small systems

→ Study hadron-hadron interactions

μ_B : Antimatter / matter imbalance

Baryochemical potential

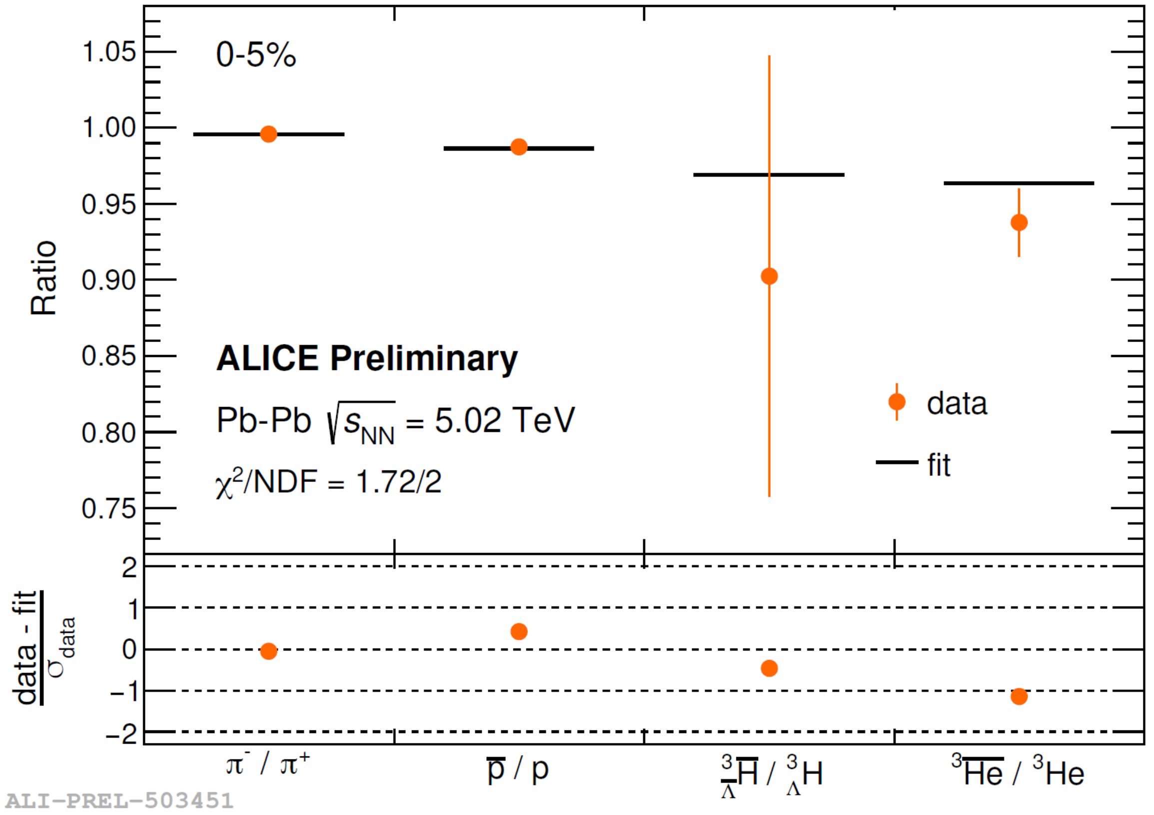
- μ_B → antimatter-matter balance in hadron systems at thermal and chemical equilibrium

Baryochemical potential μ_B can be obtained from the Statistical Hadronisation Model by fitting antihadron/hadron yield ratios :

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

where: with T = 156.2 +/- 2 MeV

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



Thanks to using ratios → cancellation of uncertainties

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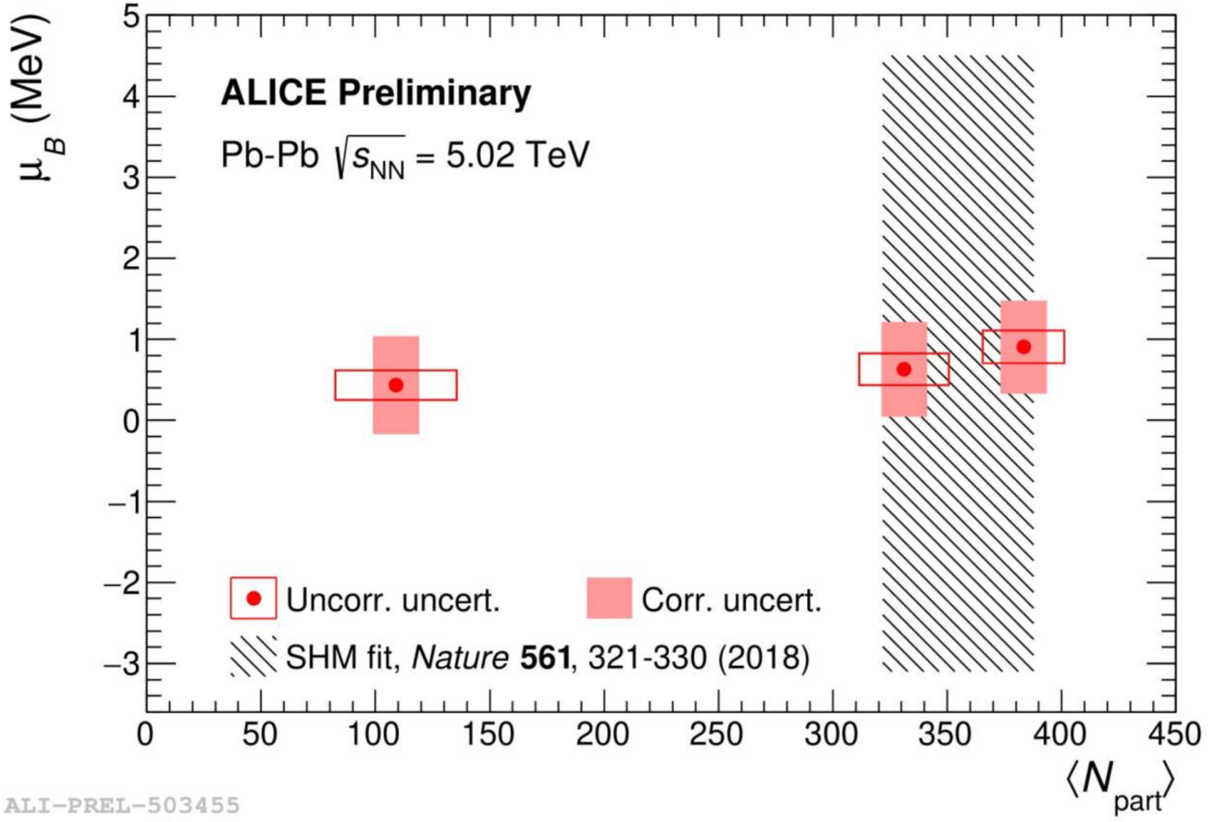
→Thanks to using ratios : cancellation of uncertainties

→ Consistent with previous measurement but **with x6 better precision**

→ **Most precise μ_B measurement at TeV scale!**



(in 2018: μ_B = 0.7 ± 3.8 MeV)

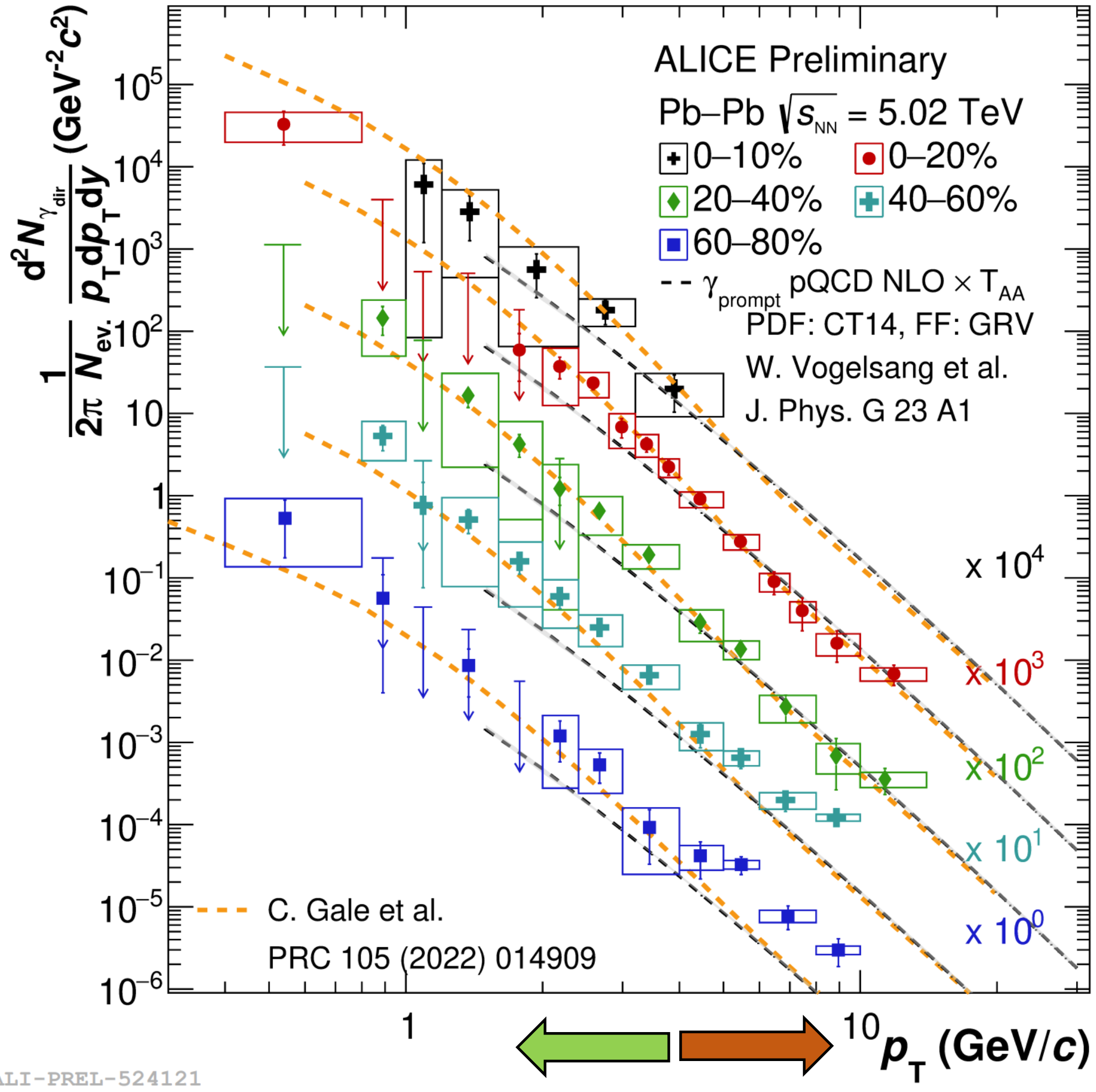
Direct (real and virtual) photons

Direct photons are well suited to study the whole space-time evolution of QGP since they are produced during all stages of the collision with negligible final-state interactions

New measurement of direct γ in Pb-Pb at 5.02 TeV
- Virtual γ (M_{ee} method), 0-10% centrality ■
- Real γ (conversion method), other centralities ■ ■ ■ ■

High p_T ($p_T \gtrsim 5$ GeV/c) – prompt photons
- consistent with pQCD expectations

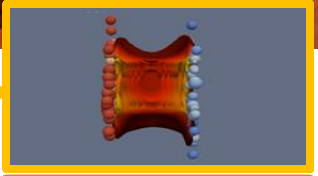
Low p_T ($p_T \lesssim 4$ GeV/c) – "thermal" photons
- described by model with prompt + pre-equilibrium + thermal photons

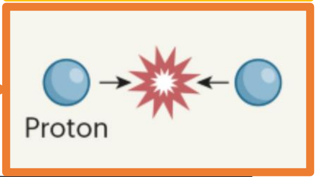


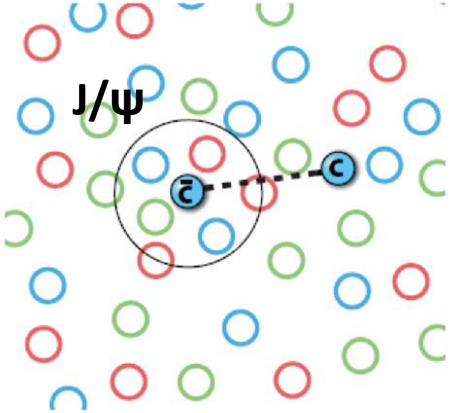
Quarkonia

- J/ψ suppression due to color screening in QGP

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

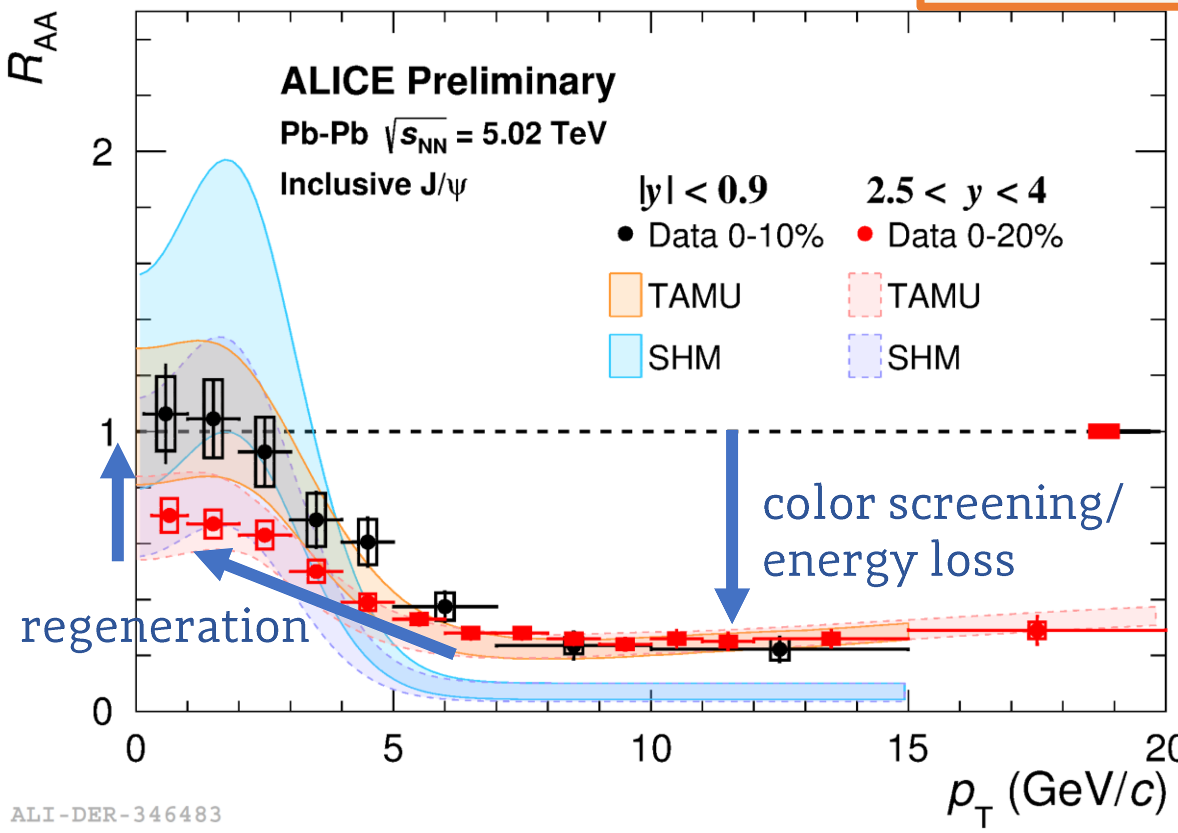






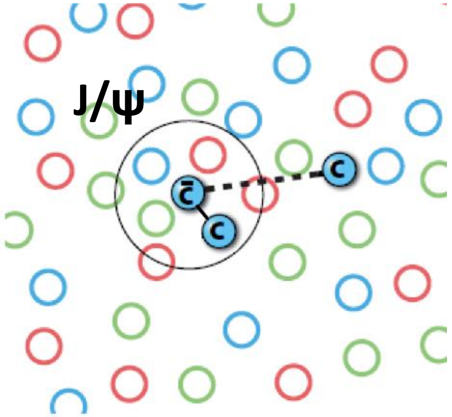
J/ψ dissociation and (re)combination at the LHC

~100 $c\bar{c}$ pairs in central Pb-Pb at LHC



Quarkonia

- J/ψ suppression due to color screening in QGP
  + interplay with $c\bar{c}$ recombination
  (in low p_T and large centrality)



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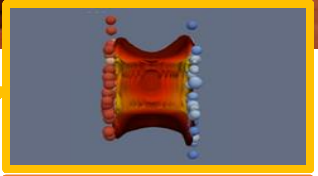

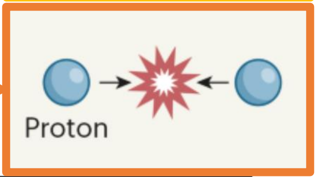

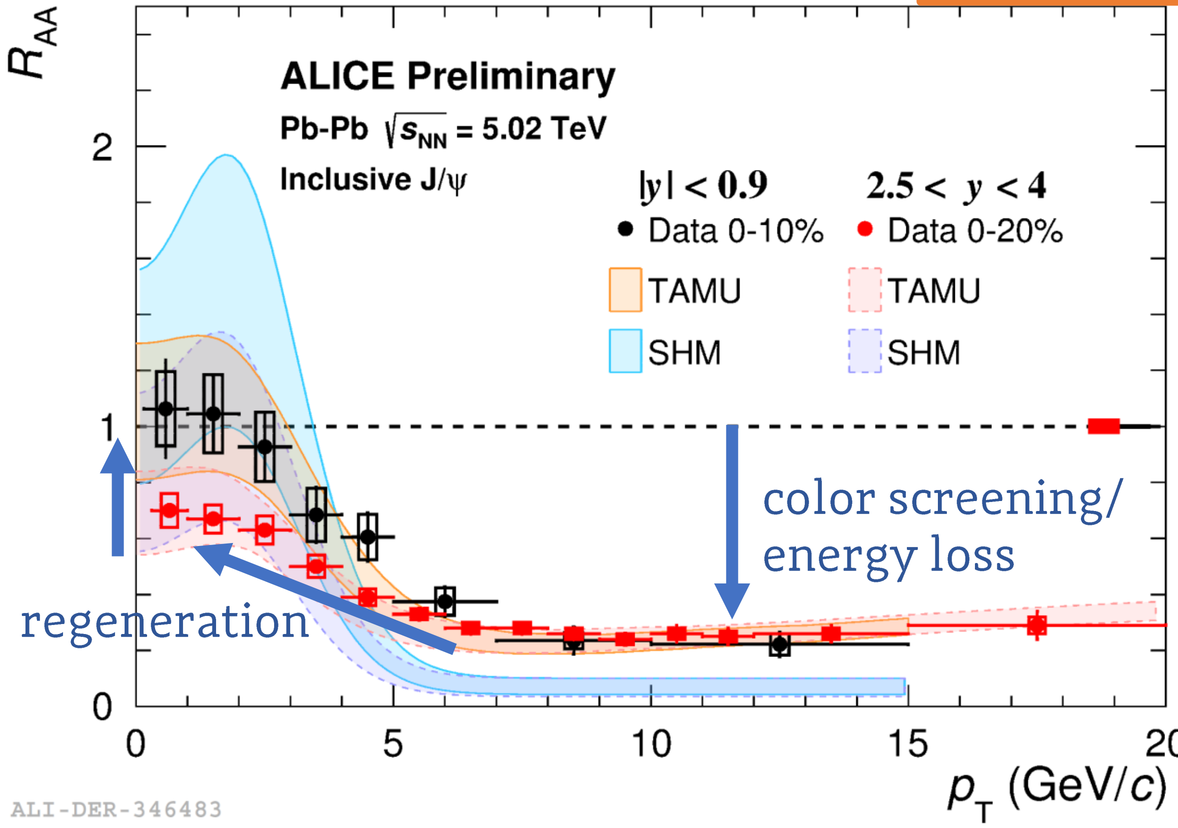

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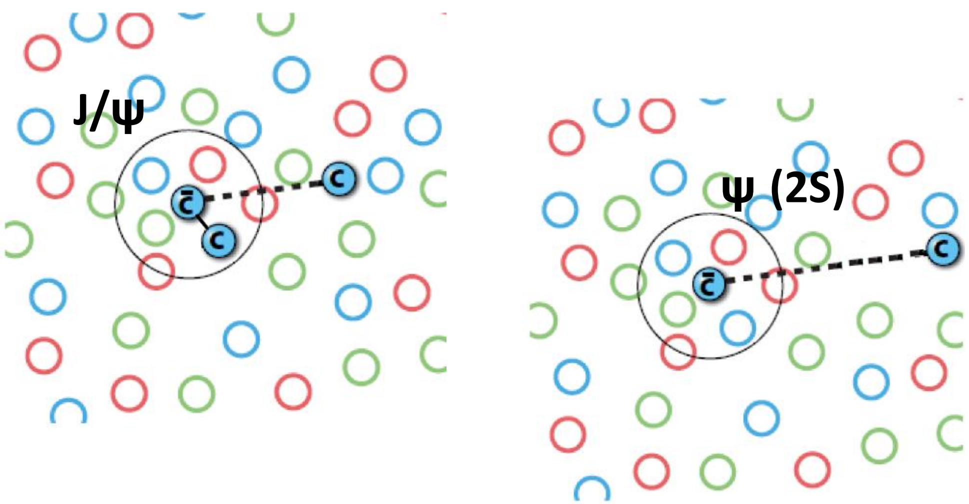
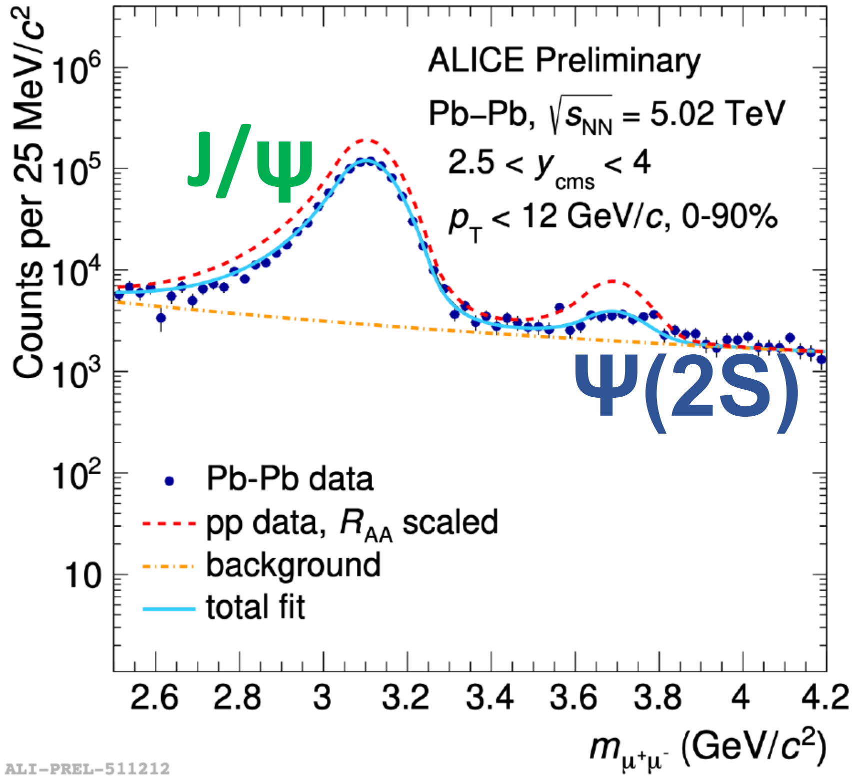
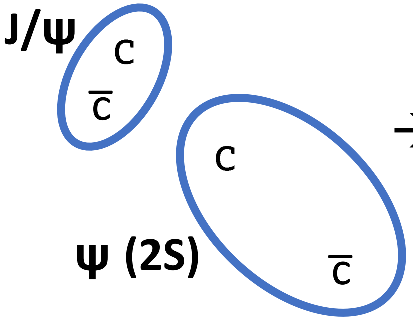




New result:
measured ψ(2S) – 10x lower binding energy!

State	J/ ψ,	ψ(2S)
Mass	3.07	3.68
Binding	0.64	0.05



→ expected higher suppression for the ψ(2S) compared to the J/ψ

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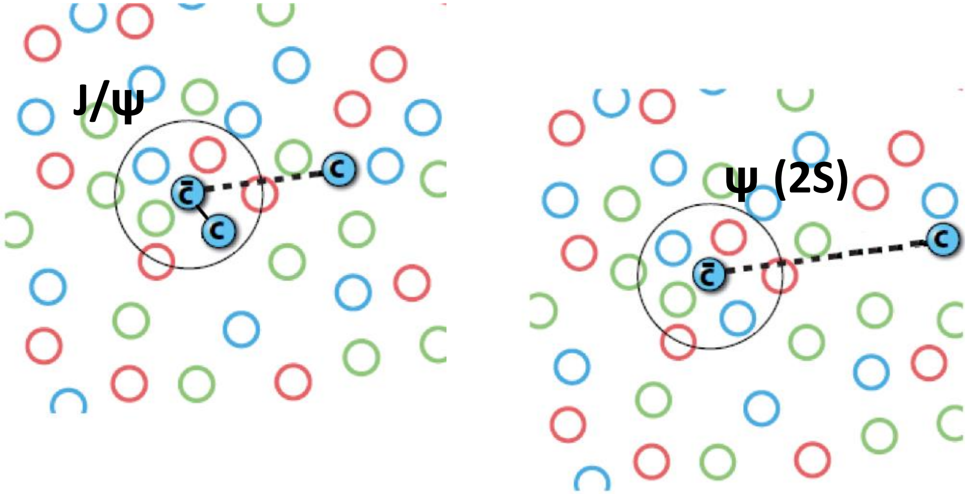

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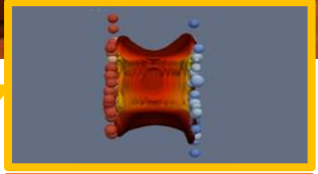
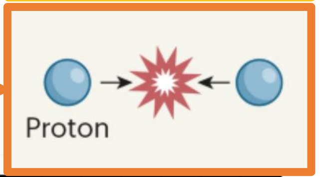
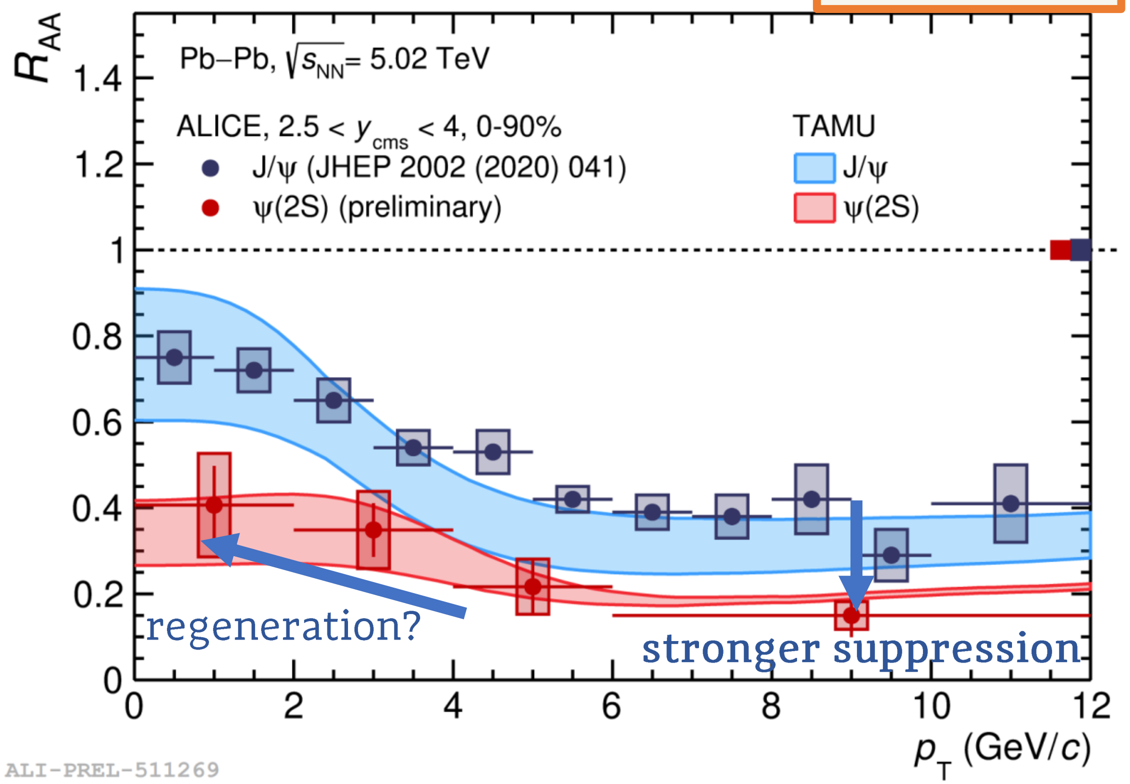






Extension of the ψ(2S) measurement down to 0 p_T

<u>New result:</u>
measured ψ(2S) – 10x lower binding energy!

→ 2 x stronger suppression of ψ(2S) than J/ψ
→ hints of regeneration of ψ(2S)

Elliptic flow in Pb-Pb

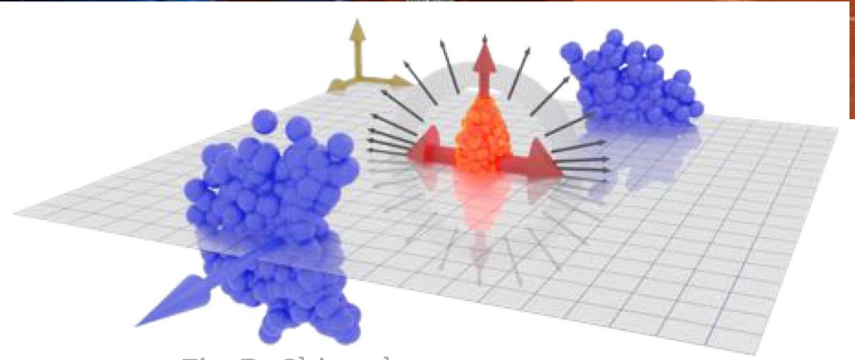


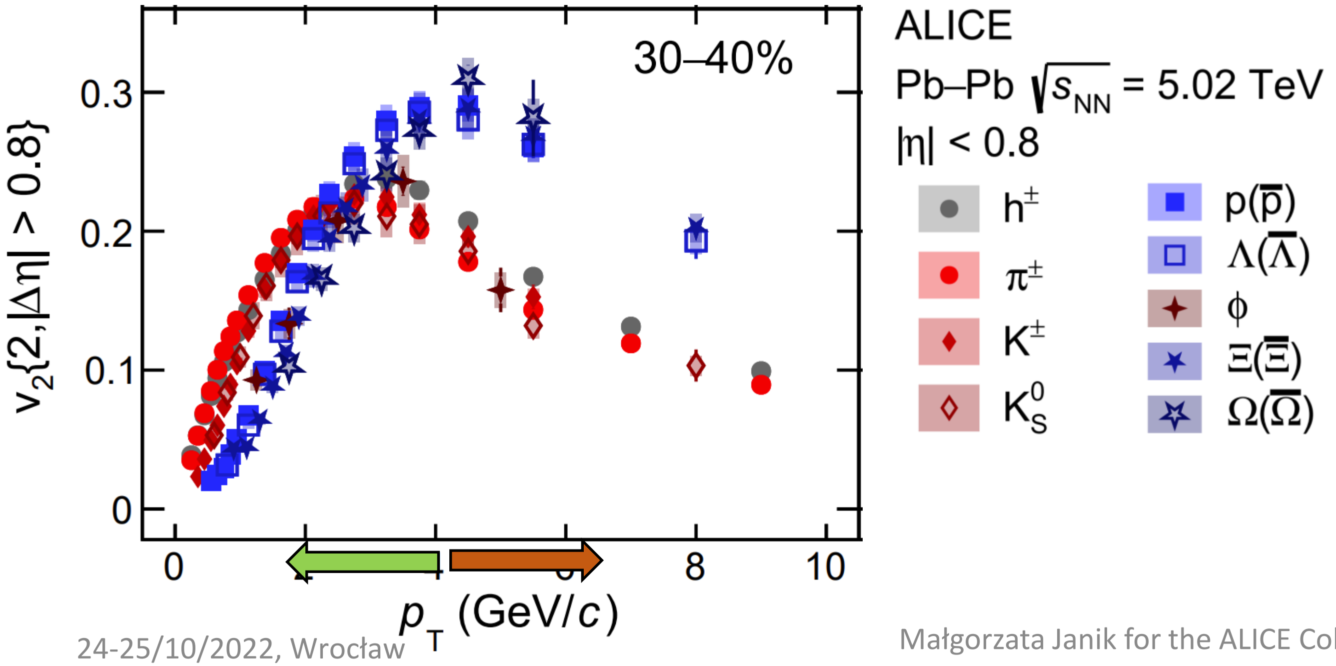
Fig. D. Chinnelato

v_2 – tool to study the flow of produced particles

- non-central collisions : elliptical geometry
- expansion (flow) → azimuthal modulation in momentum
- azimuthal mom. distribution → **decomposed into a Fourier expansion**, with anisotropic flow coefficients:

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

arXiv: 2206.04587



Mass ordering at low p_T:
described by hydrodynamics

Baryon vs meson splitting at high p_T:
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Elliptic flow in small systems

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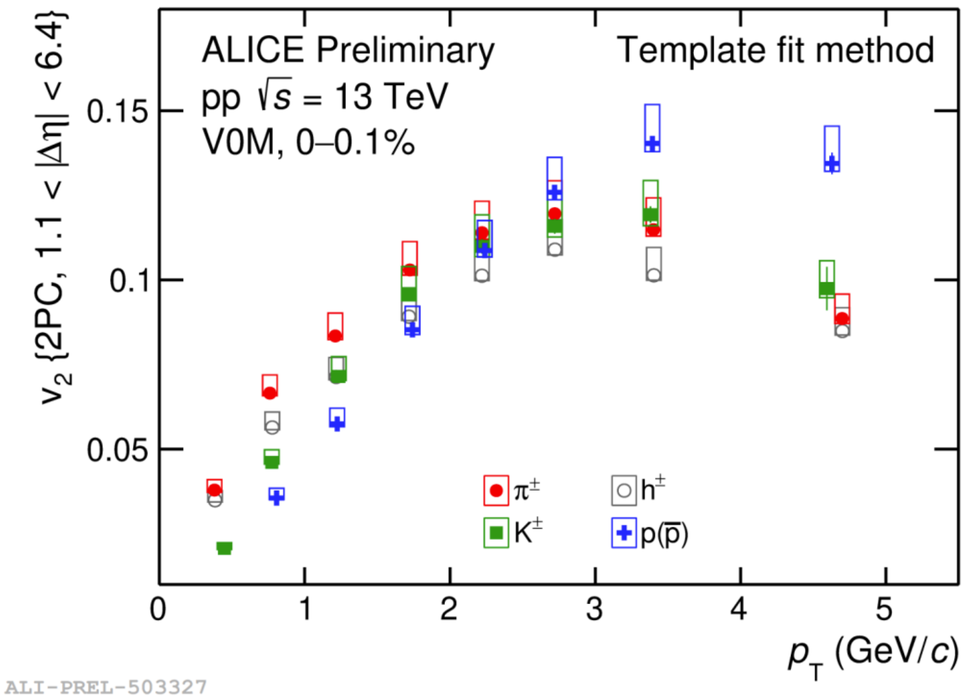
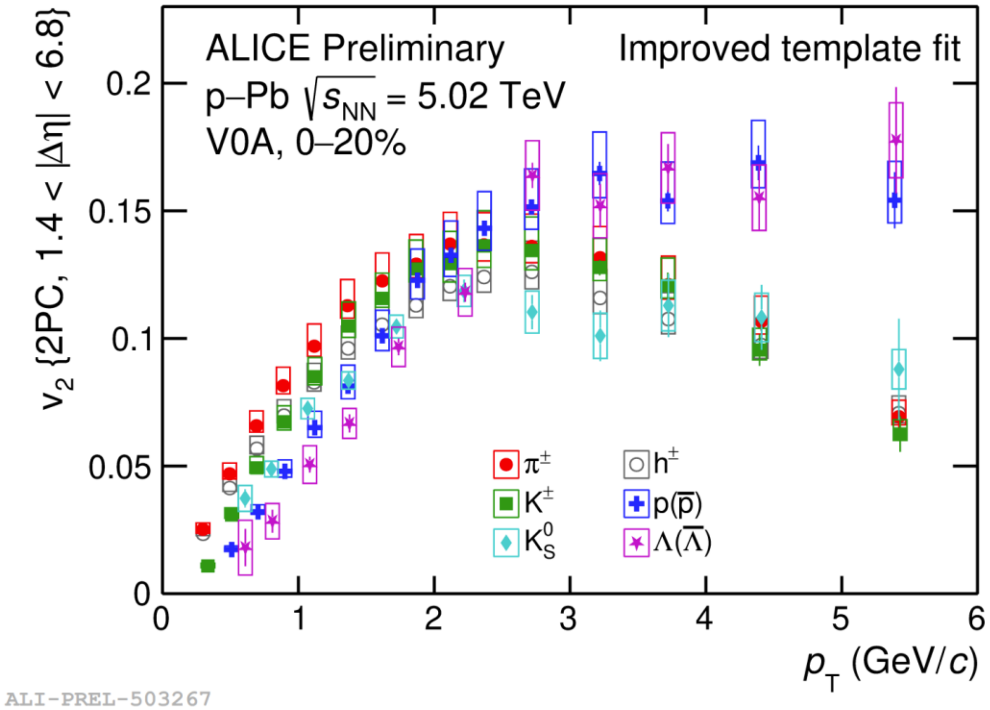
- Baryon vs meson splitting at high p_T: quark-level flow + recombination

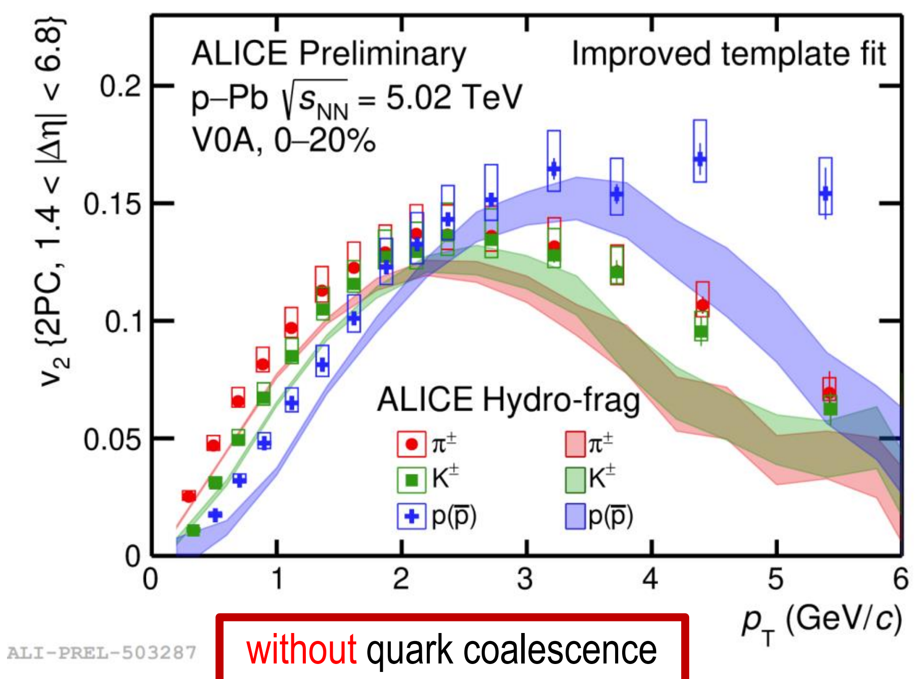




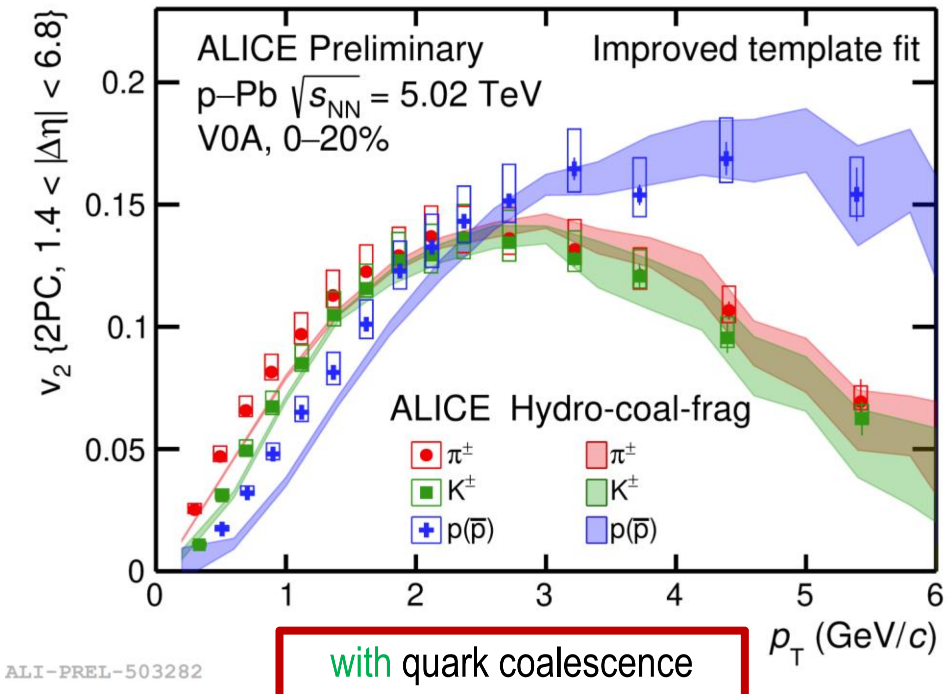
- Characteristic flow behaviors of Pb-Pb have been observed in pp and p-Pb!

Flow of partons in small systems

- Mass ordering at low p_T: described by hydrodynamics
- Baryon vs meson splitting at high p_T: quark-level flow + recombination



without quark coalescence



with quark coalescence

- Model without quark coalescence cannot qualitatively describe trends seen in data
- Indication of partonic flow in small systems

Dead-cone effect

"Dead cone" effect reduces small-angle gluon radiation for high-mass quarks.

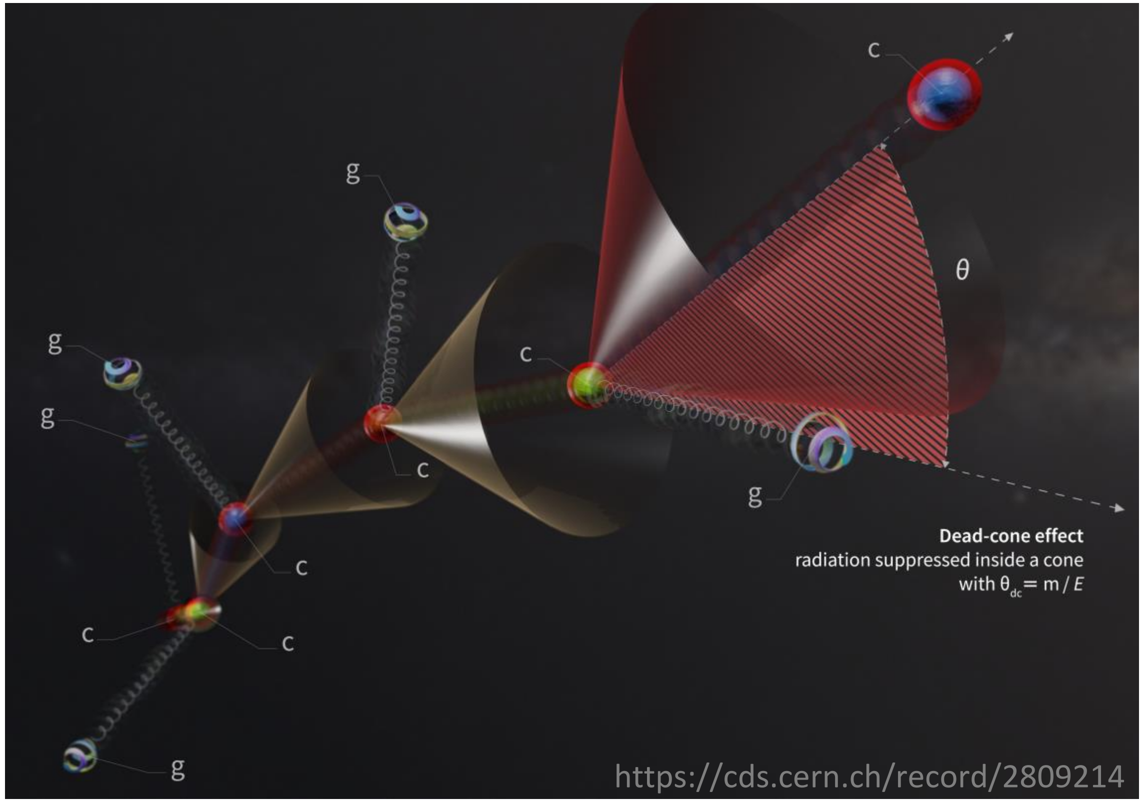
Dokshitzer, Khoze, Troian, J.Phys.G 17 (1991) 1602

- **First direct observation** using jet iterative declustering and **Lund plane** analysis of jets that contain a D^0 meson
- **The dead cone is uncovered through a direct measurement of the emission angle:**

R(θ) – comparison of the angular distribution of charm-quark emissions to those of light quarks and gluons

$$R(\theta) = \frac{1}{N^{D^0 \text{jets}}} \frac{dn^{D^0 \text{jets}}}{d\ln(1/\theta)} \Bigg/ \frac{1}{N^{\text{inclusive jets}}} \frac{dn^{\text{inclusive jets}}}{d\ln(1/\theta)} \Bigg|_{k_T, E_{\text{Radiator}}}$$

Nature 605 (2022) 7910, 440



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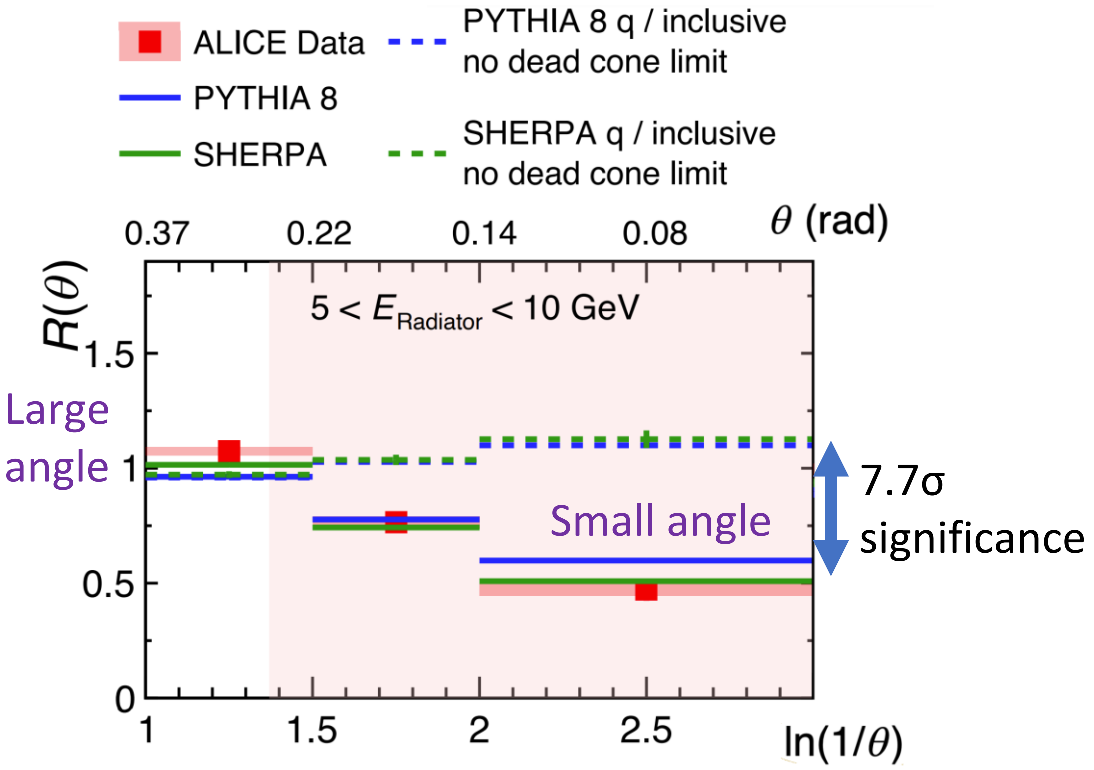
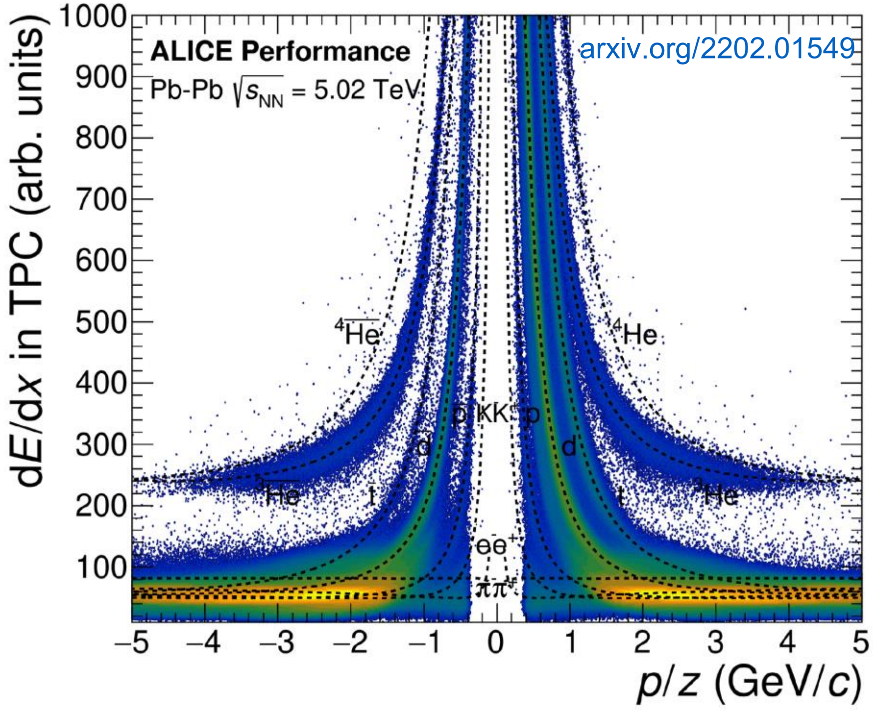


Small angle emissions suppressed for charm quarks compared to light quarks and gluons

Light antinuclei absorption in ALICE and Galaxy

LHC – (anti)nuclei factory

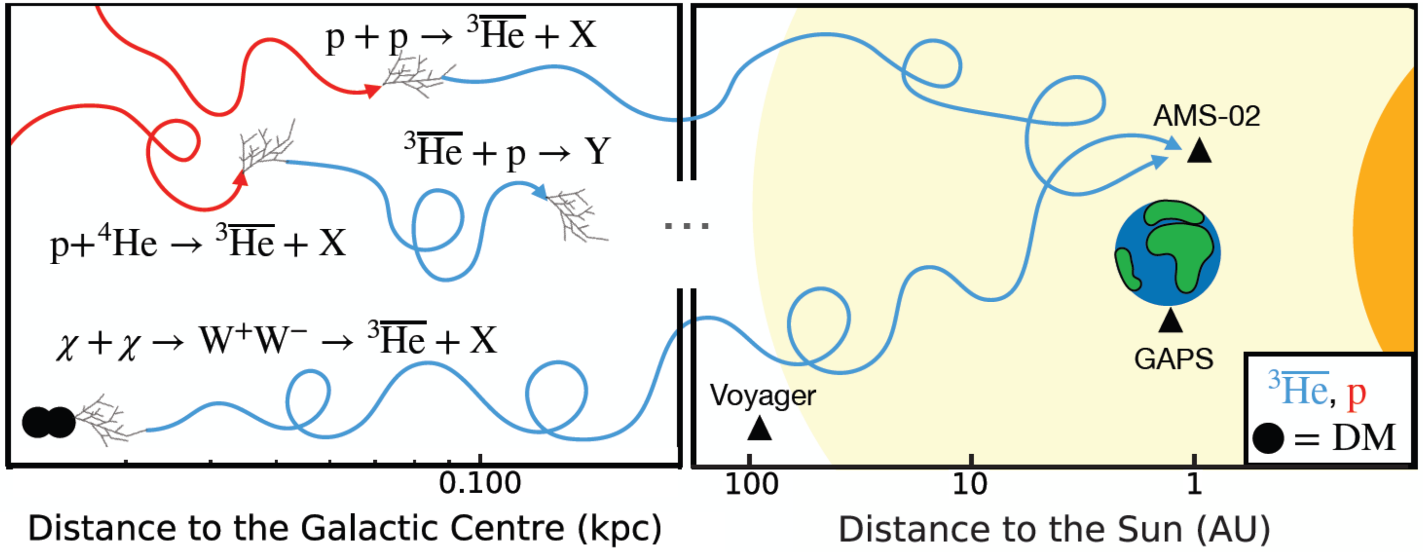
Nuclei accessible in Run 2:
d, t, ${}_{\Lambda}^{3}H$, ${}^{3}He$, ${}^{4}He$



Information about antinuclei has **strong impact on dark matter searches** in Space, e.g. $\chi_0\chi_0 \rightarrow$ anti-d, anti-${}^{3}He$+X (AMS-02, GAPS, BESS)

- $^{3}\overline{He}$ can be produced via high-energy cosmic-ray collisions with the interstellar medium or could originate from the annihilation of dark-matter.
- **Antinuclei absorption** in space poorly known.

arxiv.org/2202.01549



Light antinuclei absorption in ALICE and Galaxy

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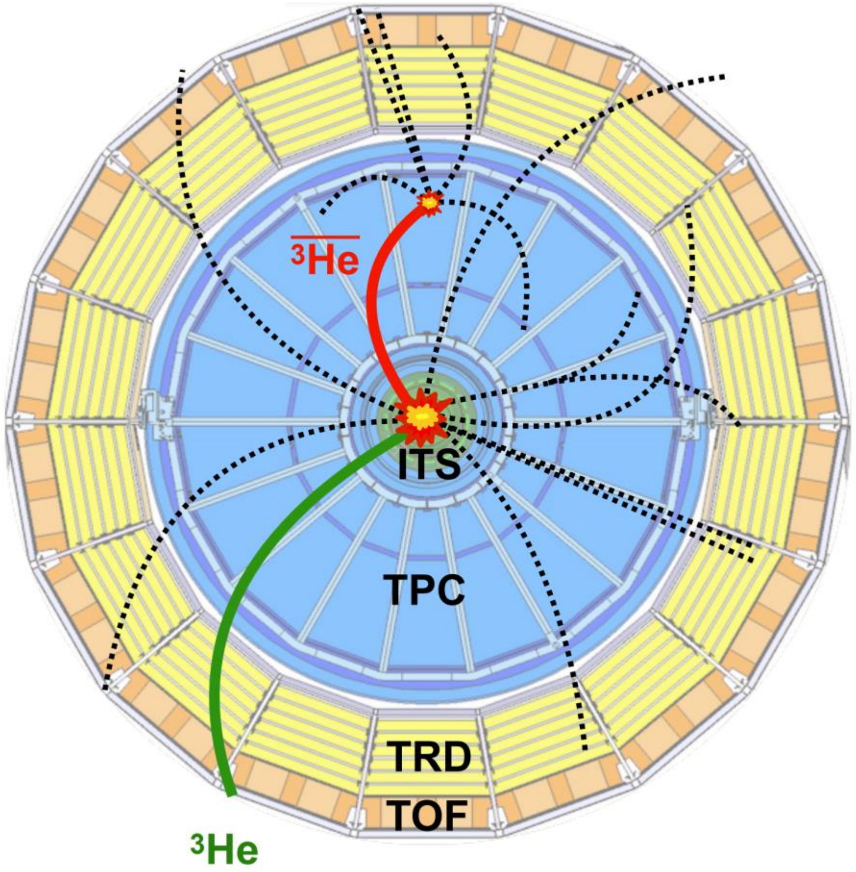

- Novel technique to use detector as an antiparticle absorber
- First experimental measurement of $\sigma_{inel}(^3\overline{He})$

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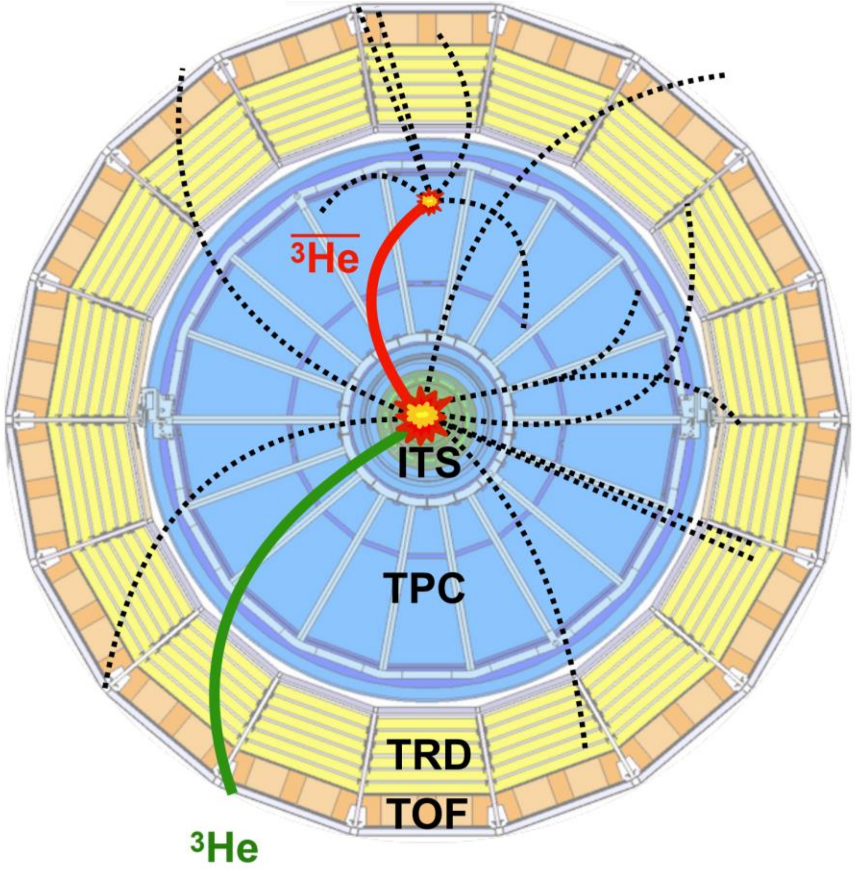

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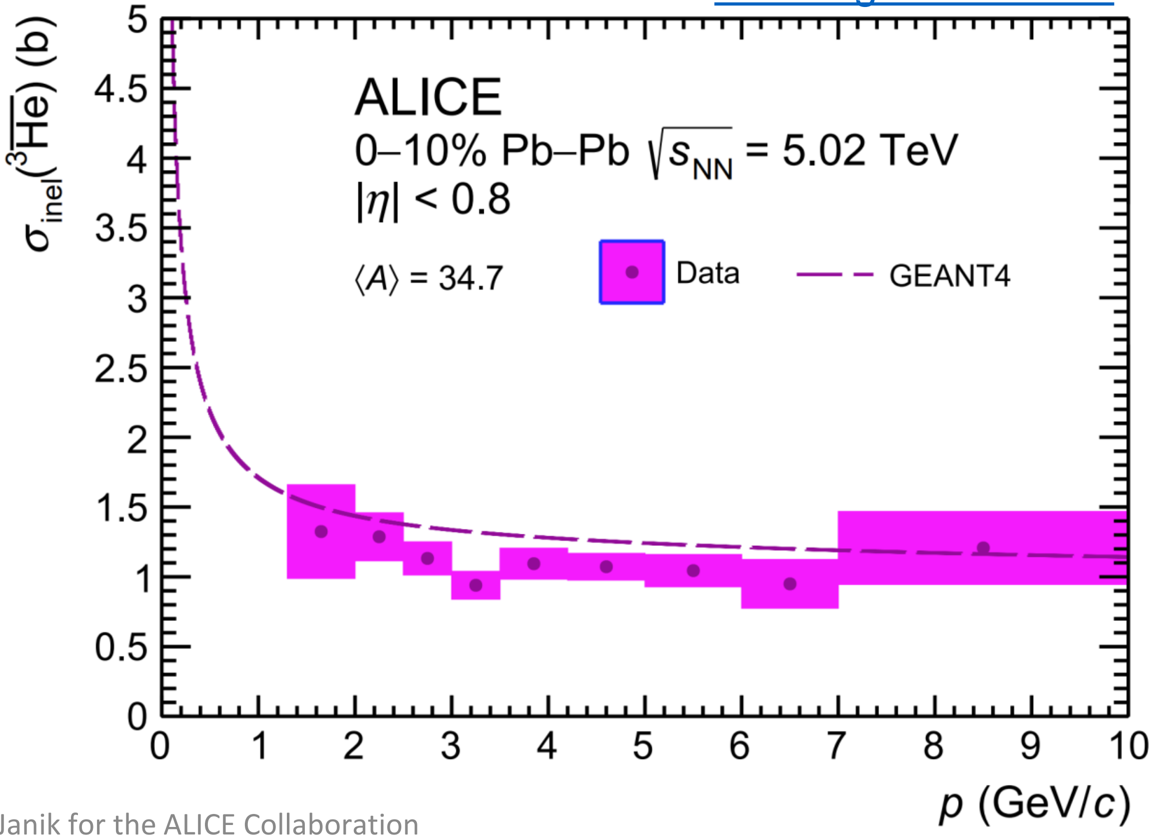

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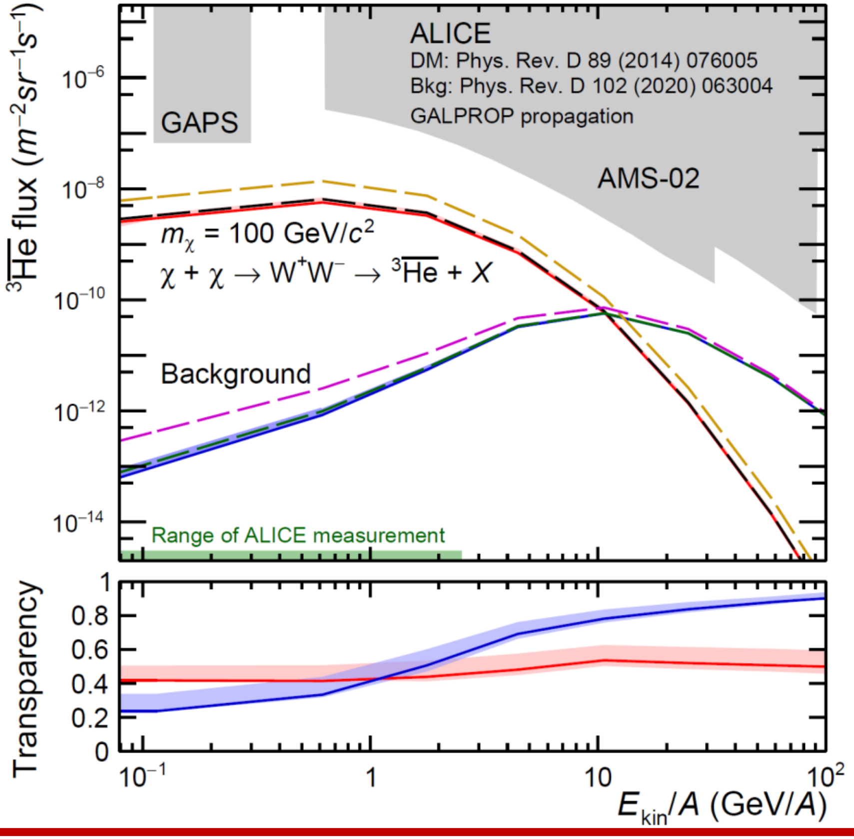

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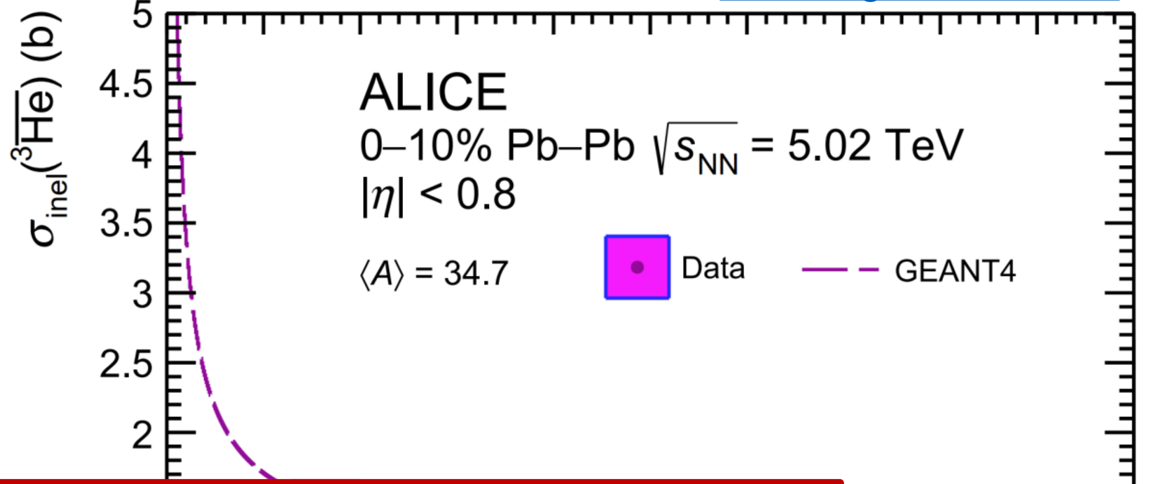
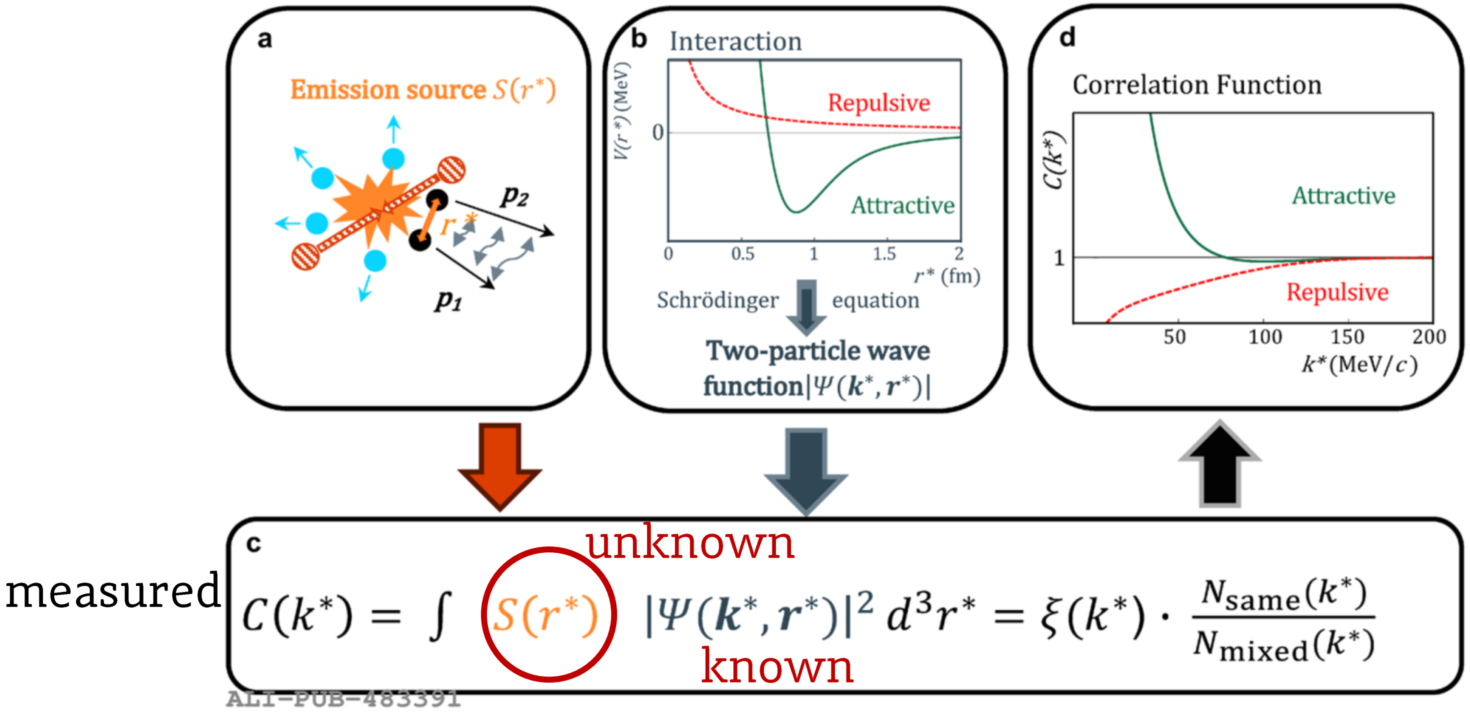


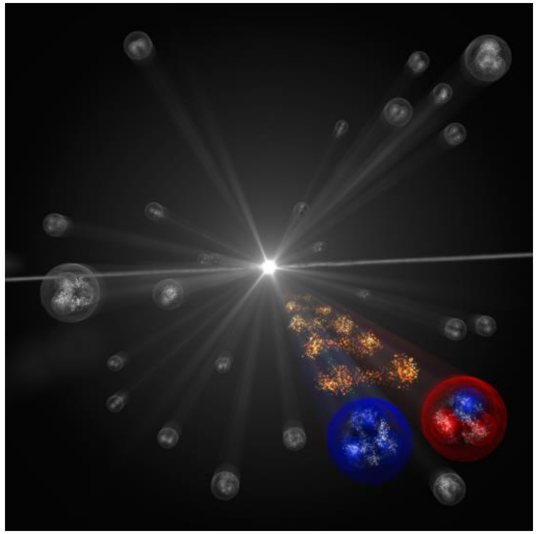
→ measured $\sigma_{inel}({}^3\overline{\mathrm{He}})$ was employed to carry out the propagation of ³He using GALROP
- can be used by for any dark-matter or cosmic-ray interaction modelling

→ ${}^3\overline{\mathrm{He}}$ nuclei can travel distances of several kpc in our galaxy without being absorbed
- excellent probe for new physics that awaits discovery

Source size – femtoscopy measurement

Femtoscopic correlation function carry information about the particle source $S(r^*)$ from which pairs emerge, as well as the interaction potential via the two-particle wave function $\psi(k^*,r^*)$.

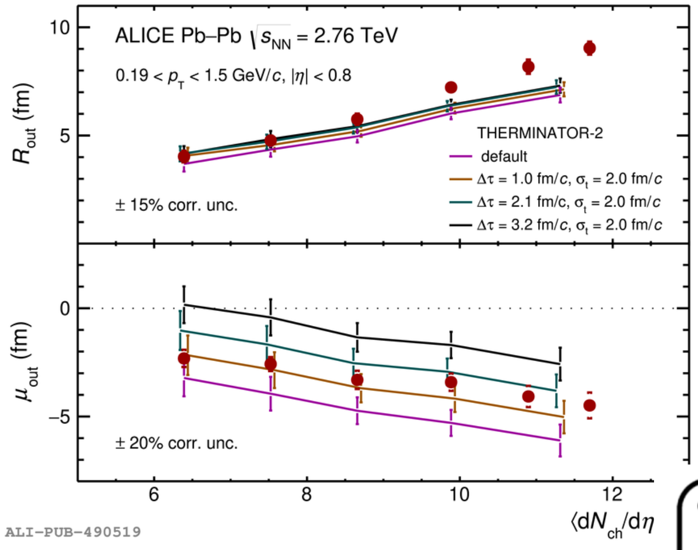




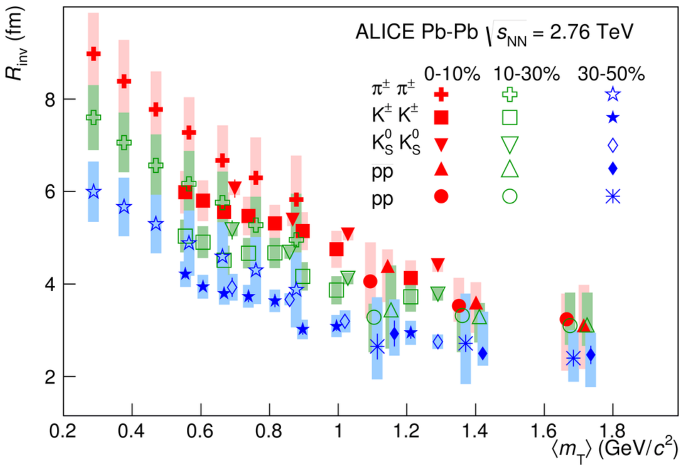
If the interaction is well known we can study the source $S(r^*)$ by measuring correlation function C(k*)

Source size – femtoscopy measurement

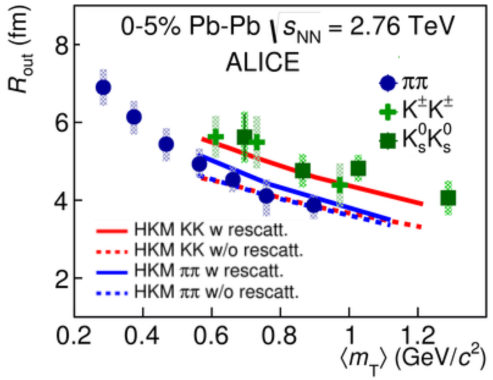
PLB 813 (2021) 136030

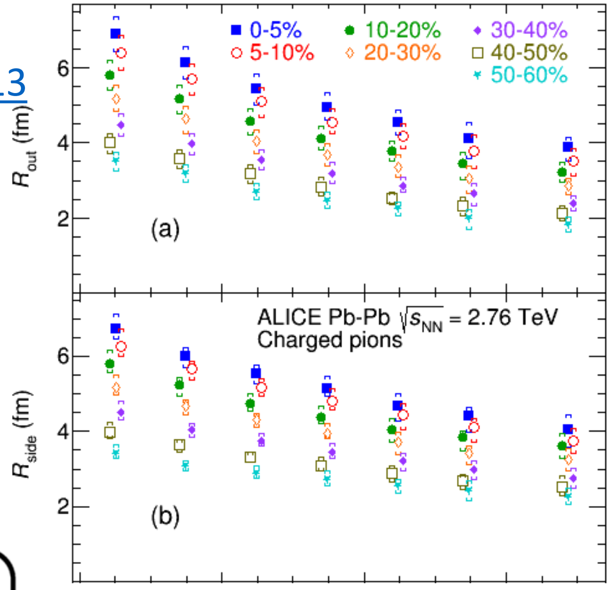


Phys. Rev. C 92 (2015) 054908



Phys. Rev. C96 (2017) 064613





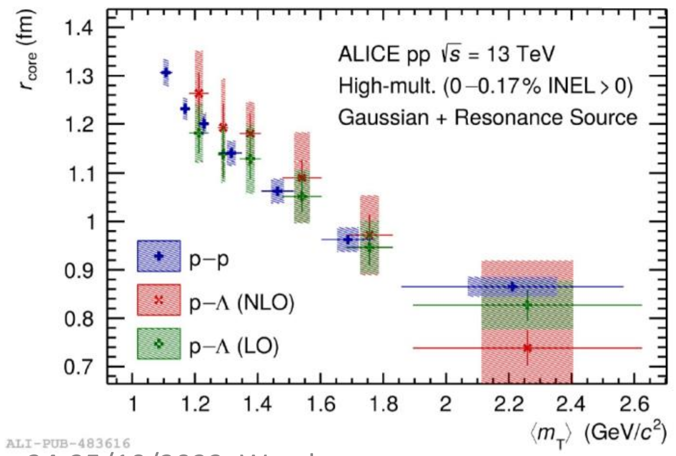
Phys. Rev. C93 (2016) 024905

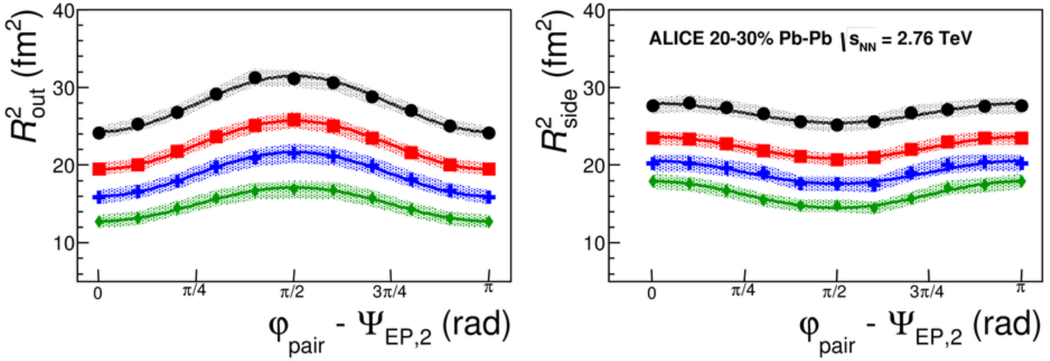
c

$$C(k^*) = \int S(r^*)\ |\Psi(\boldsymbol{k}^*, \boldsymbol{r}^*)|^2\, d^3r^* = \xi(k^*) \cdot \frac{N_{\mathrm{same}}(k^*)}{N_{\mathrm{mixed}}(k^*)}$$

ALI-PUB-483391

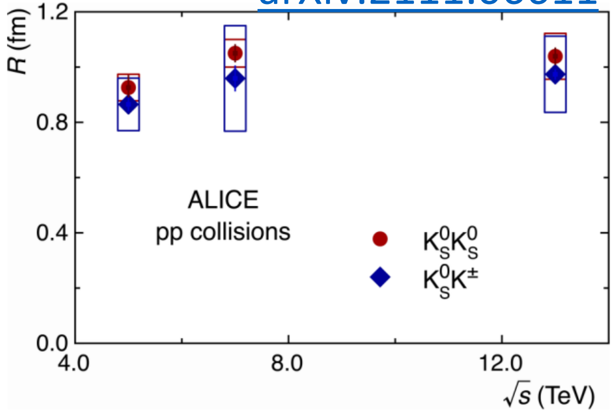
Phys. Lett. B 811 (2020) 135849
arXiv:2004.08018





Phys. Rev. Lett. 118 (2017) 222301

arXiv:2111.06611



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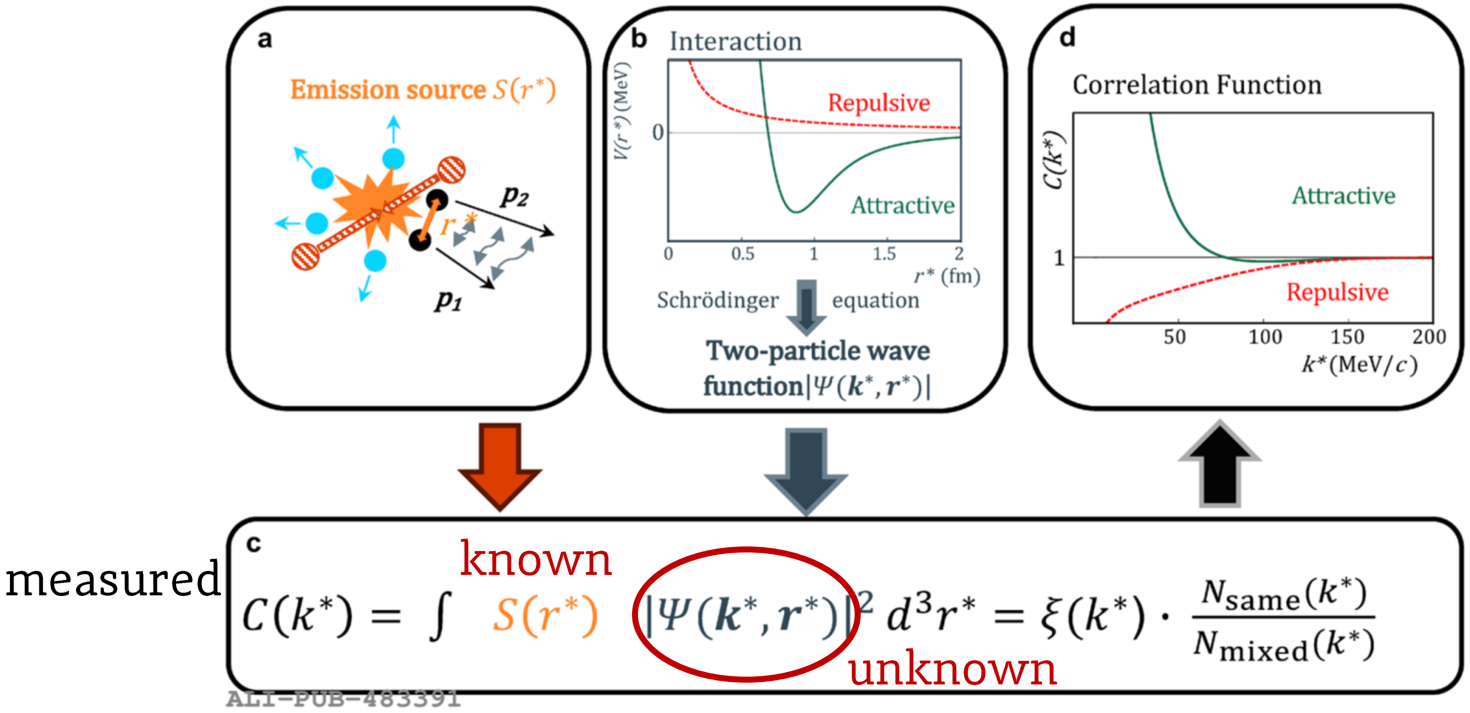
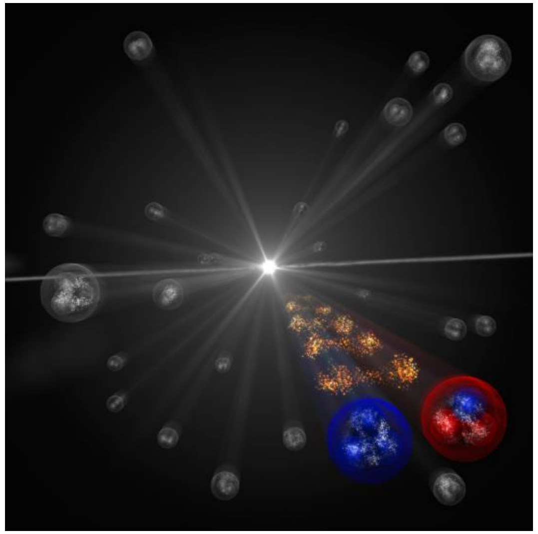


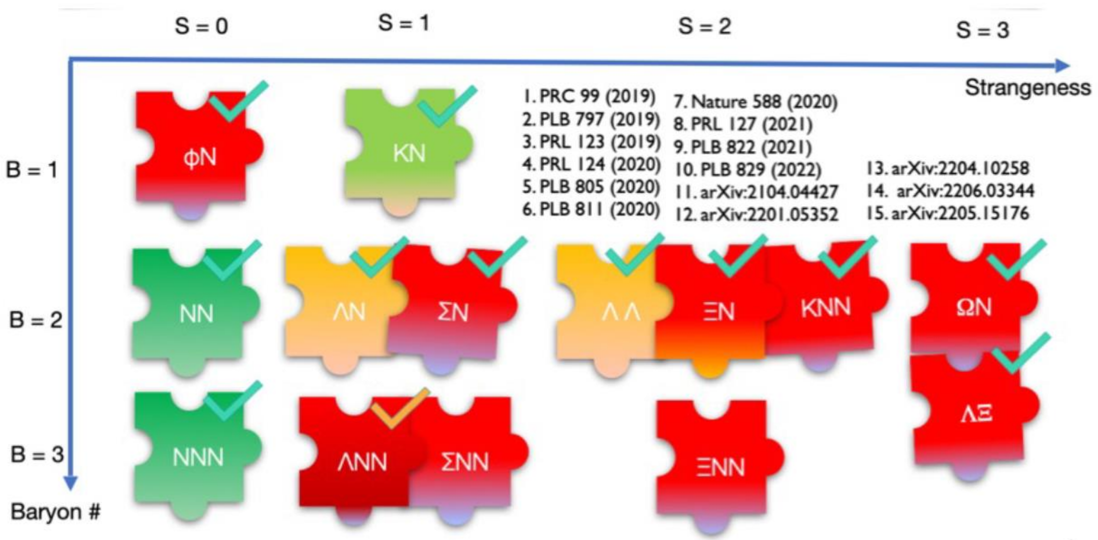


- We constrain the source $S(r^*)$ from pairs where interaction is known
- We can use femtoscopy to measure the interactions ***ψ*** between other particle species

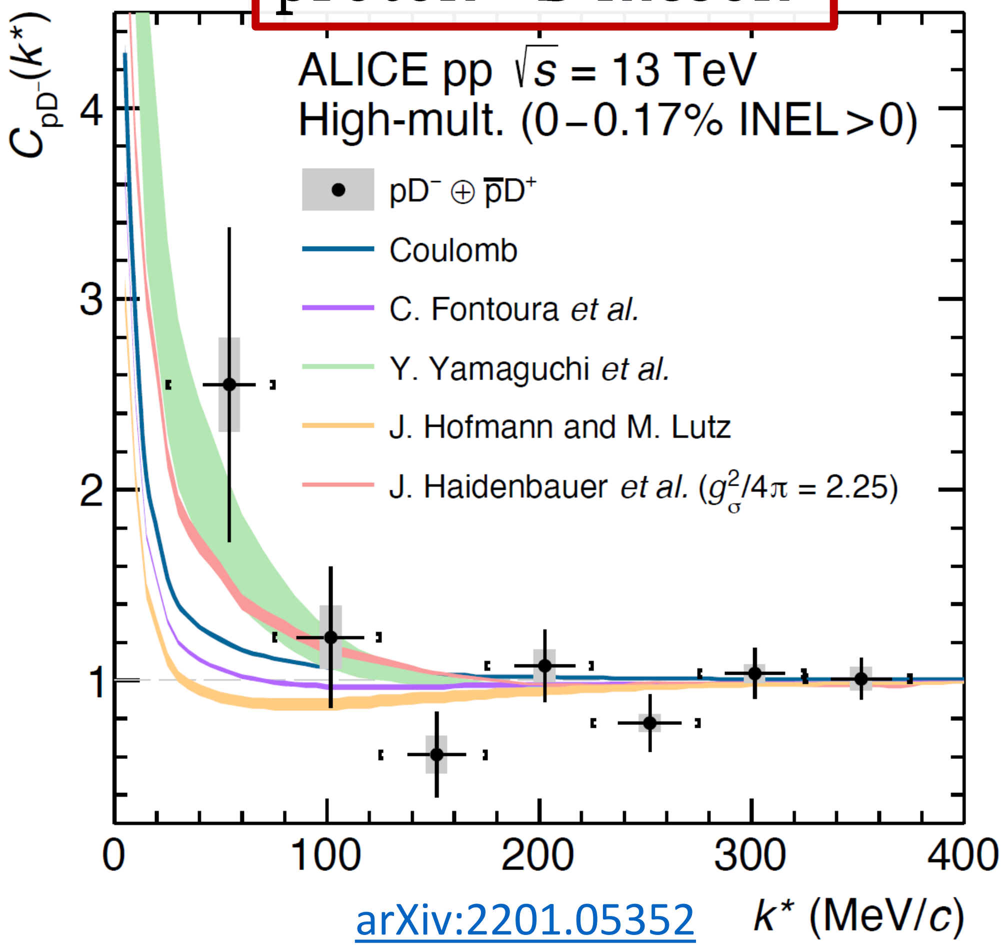
Hadron-hadron interaction

Hadron-hadron interaction:

- Poorly known for strange baryons
  → Relevant for neutron star modeling
- Unknown for charm hadrons and 3-body



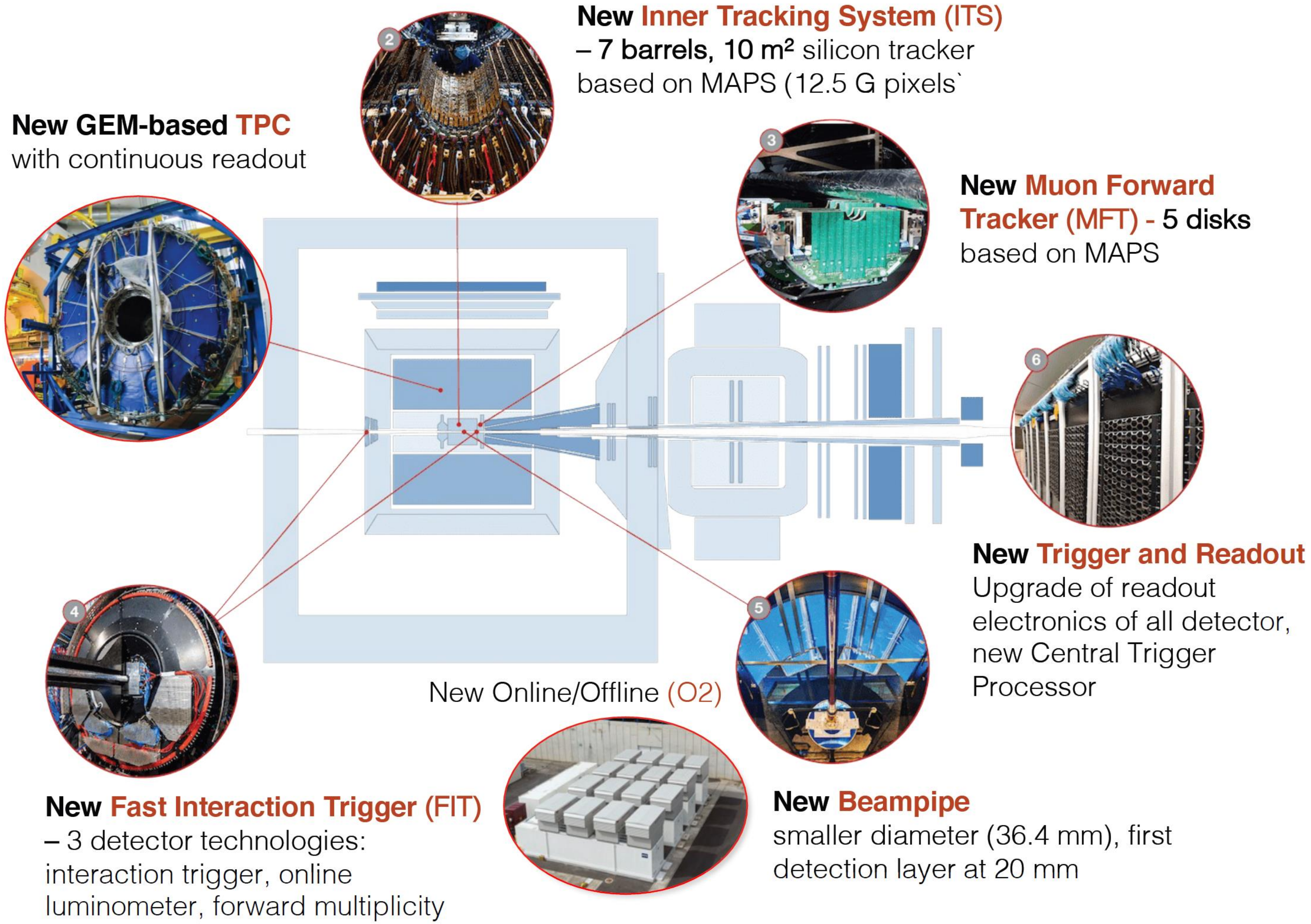
proton – D meson



arXiv:2201.05352

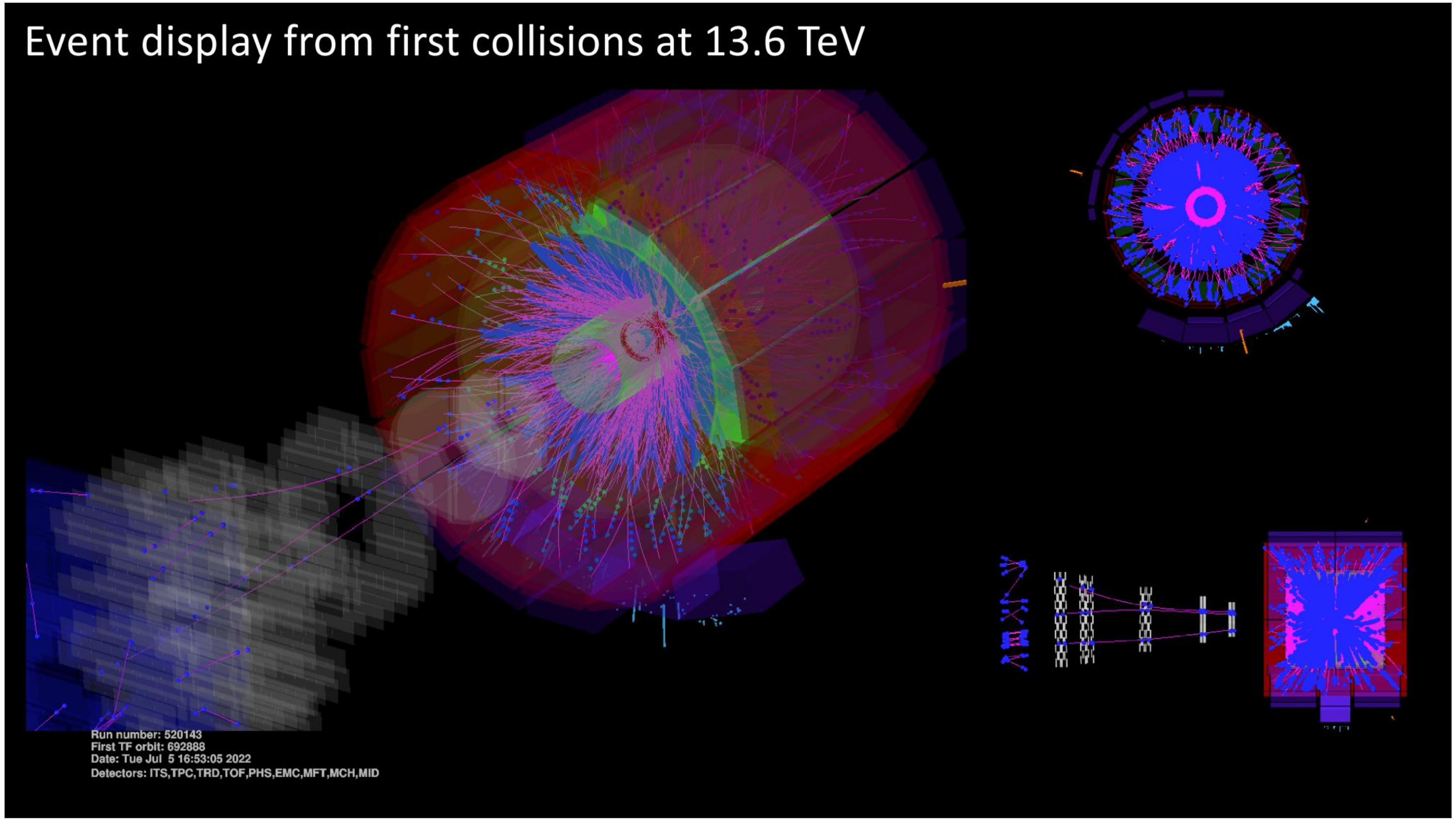
ALICE upgrade for Run 3

- Tracking resolution **x3**
  (especially low p_T!)
- Pb-Pb rate **x50**
  (50 times more statistics for most observables!)
- New analysis software
  (O2 framework)



First results from Run 3

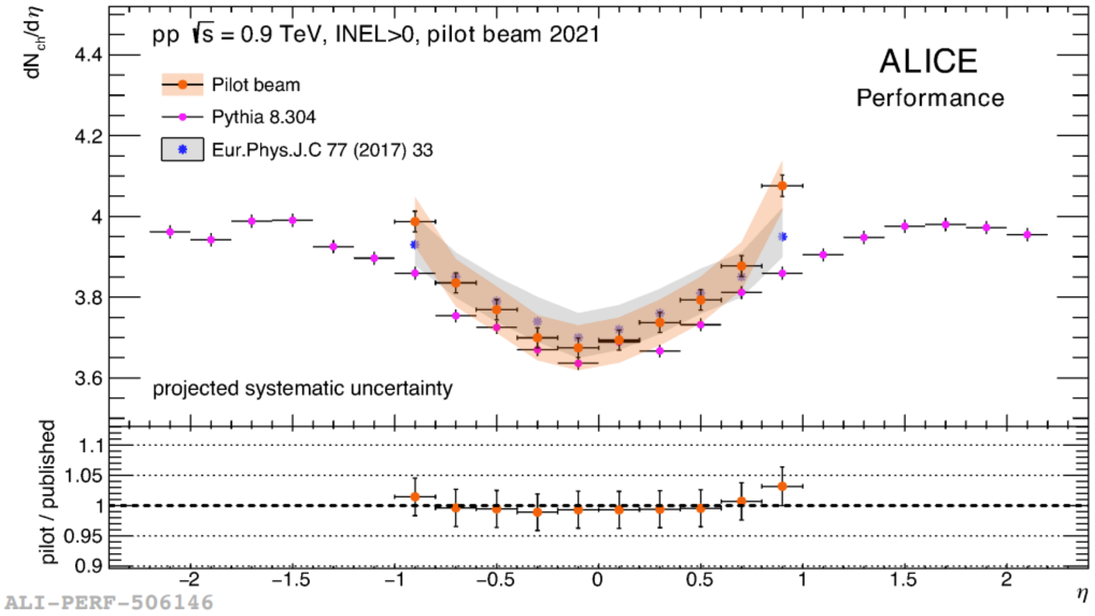
- First collisions from Run 3: data-taking on the way!



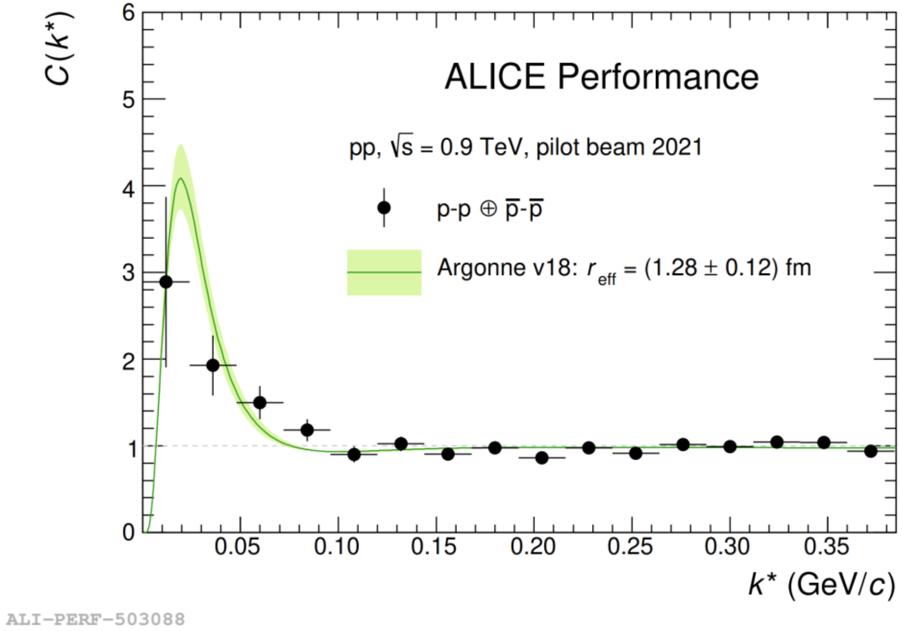
First results from Run 3

- First collisions from Run 3: data-taking on the way!

Measured $dN_{ch}/d\eta$ compatible with previous results



First look into pp femto correlations

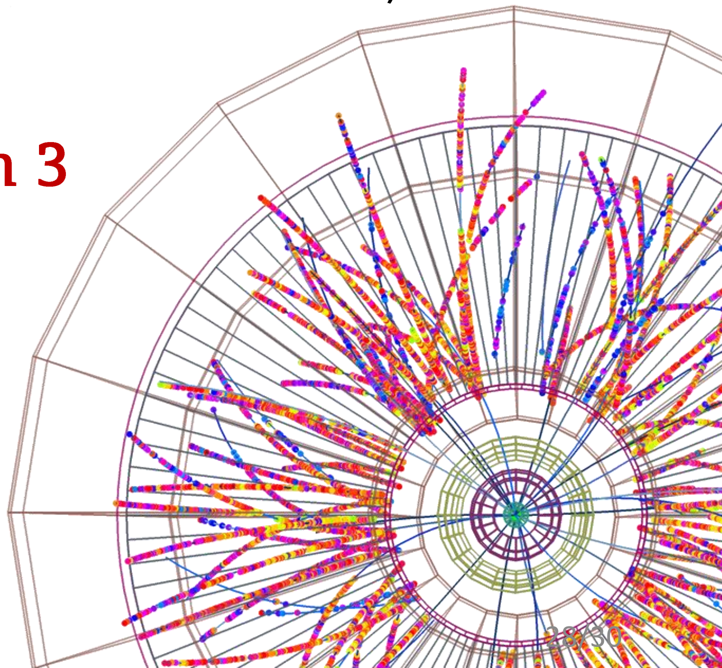


Summary

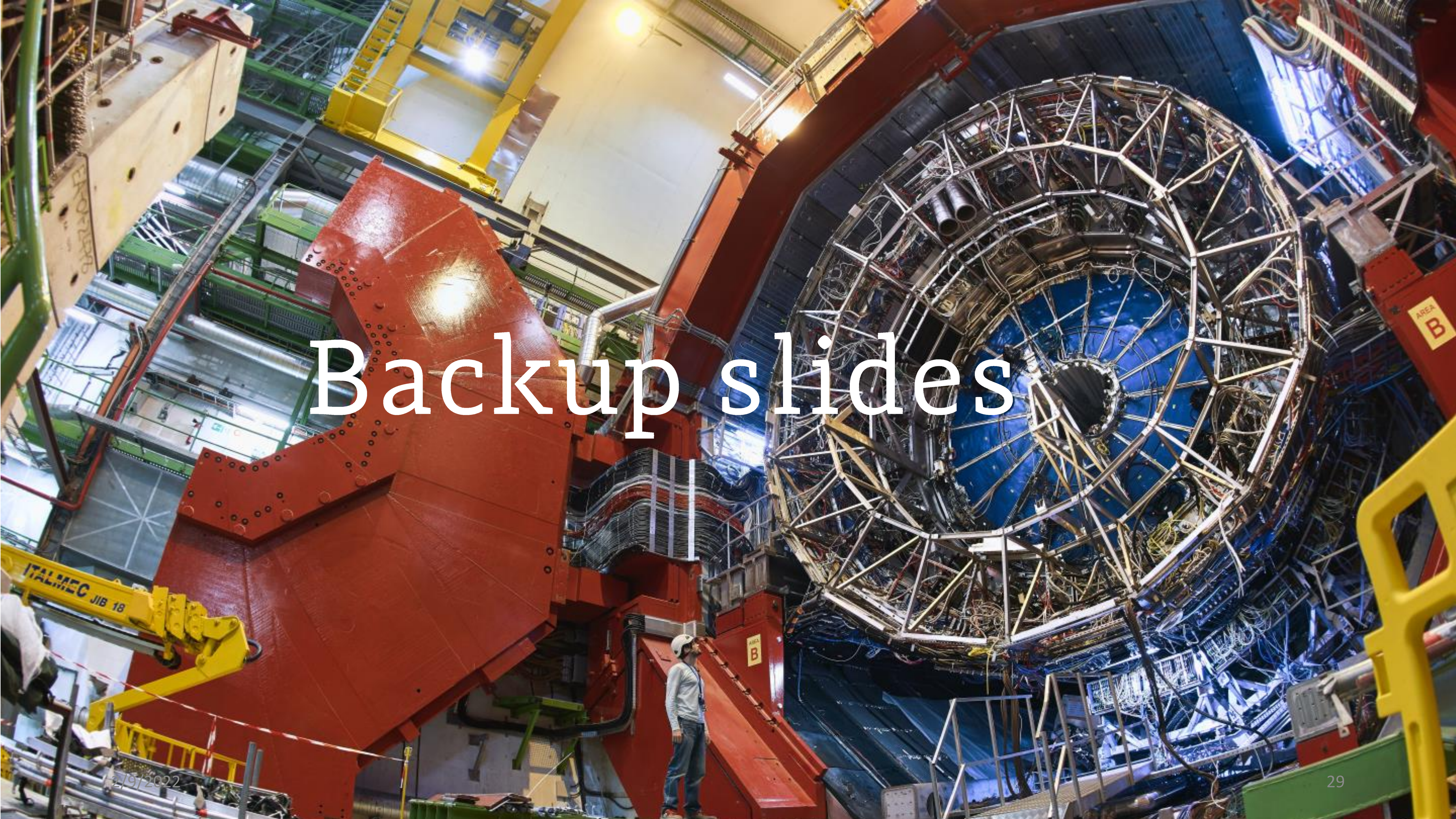
The ALICE results from Run 1 and 2 offer

- detailed description of the **QGP properties**
  - including fluid-dynamic properties, heavy quark interactions, jet modification
- as well as an **insights into QCD**:
  - formation and annihilation of nuclei, hadron-hadron interactions, ...

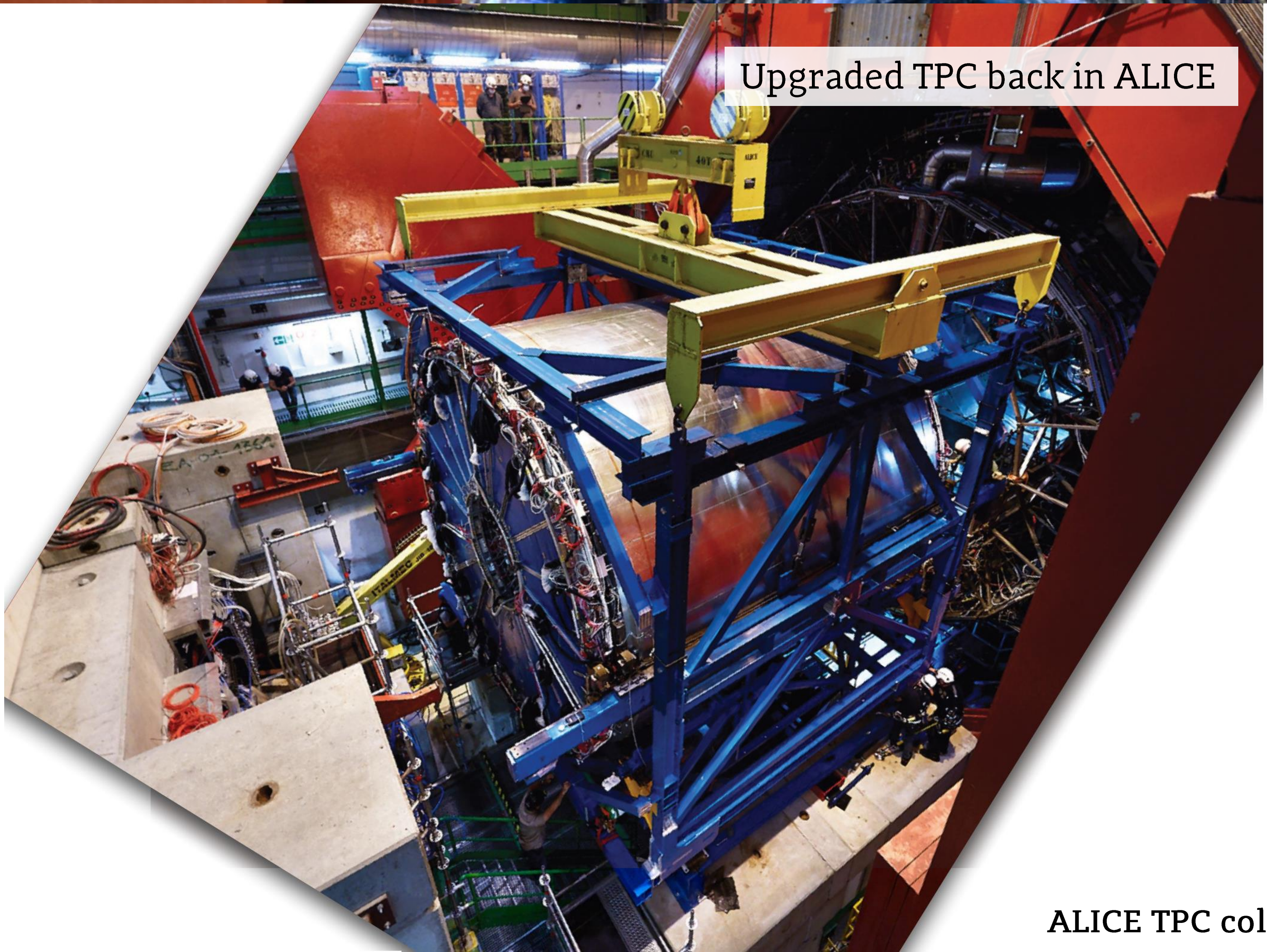
ALICE **completed the upgrade** and is now **collecting Run 3 data** with significantly enhanced capabilities,
and **first results already on the way.**



Backup slides

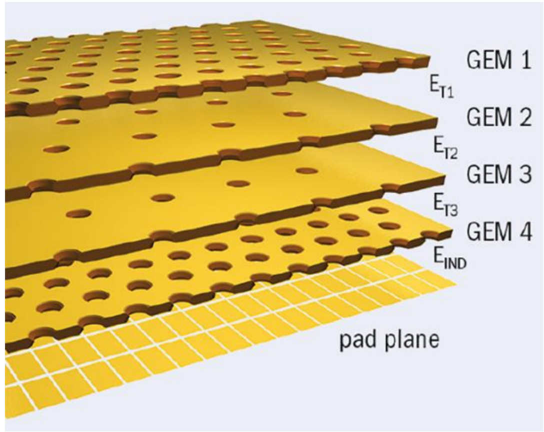


ALICE upgrade for Run 3: TPC



New TPC:

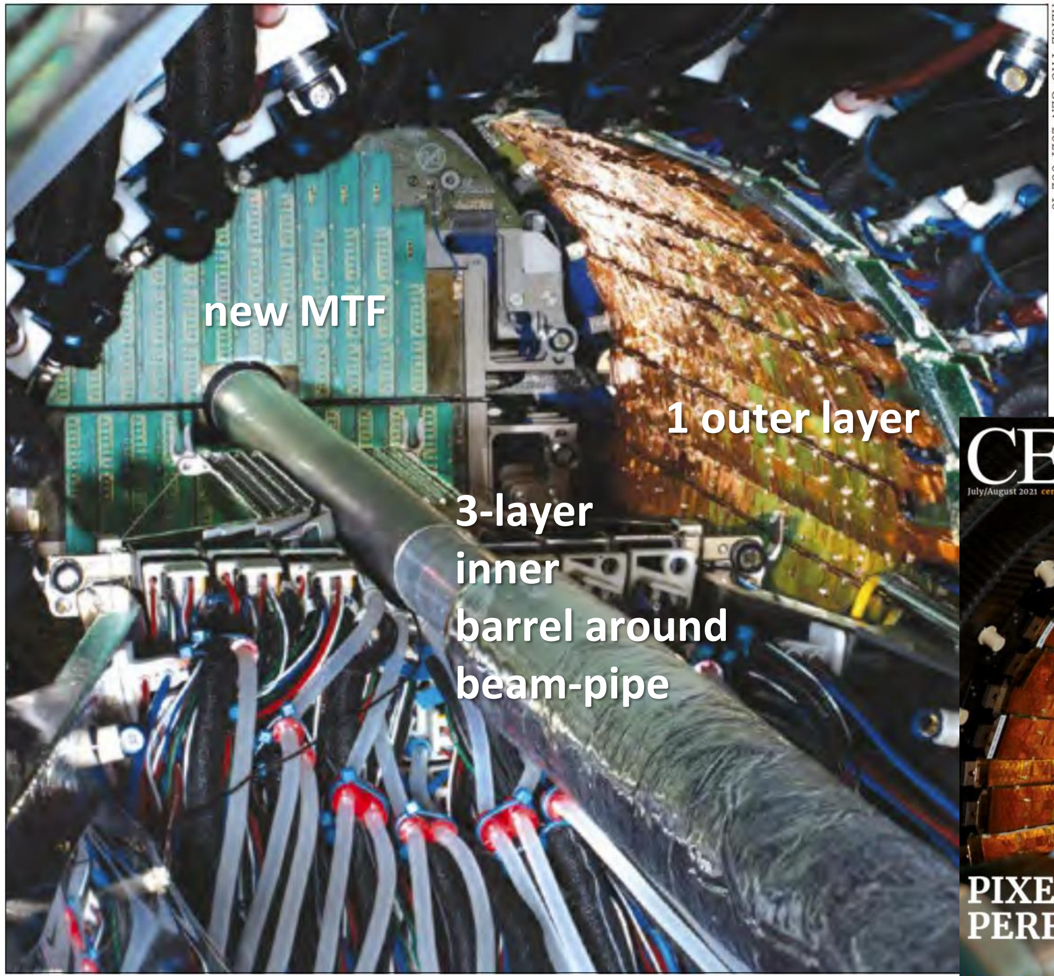
- MWPCs replaced with GEMs
- Enabling continuous readout @50 kHz Pb-Pb interaction rate
- Fully installed in August 2020



ALICE TPC coll., JINST 16 (2021) 03, P03022

ALICE upgrade for Run 3: ITS

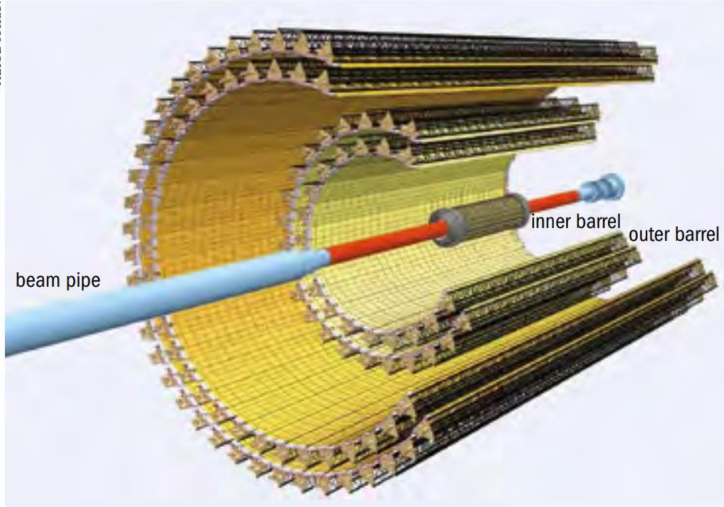
ALICE inner tracking system is the largest pixel detector ever built



New ITS:

- Inner tracking with 7 barrels (3 inner and 4 outer)
- Improved pointing resolution (× 3)
- Smaller beam pipe, 1st layer closer (22 mm)

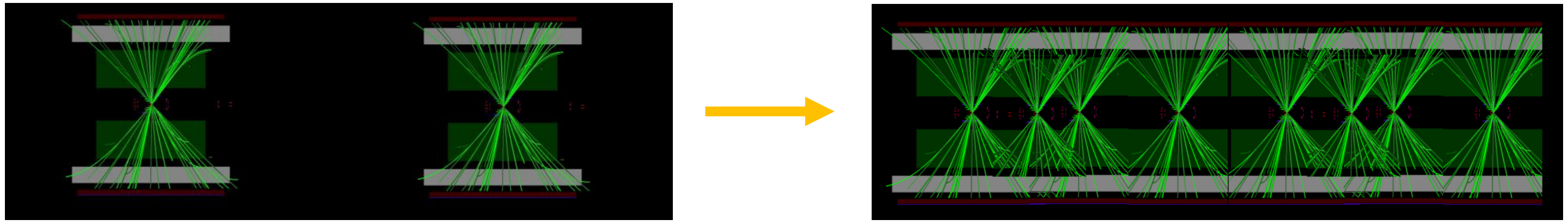
ALICE collab.



O²: new ALICE software framework

After upgrade:

- The ALICE experiment in the LHC Run 3 is expected to process 100 x more data with just 4 times the resources with respect to the LHC Run 2,
- data will be collected with continuous readout (many events will be registered in one timeframe of 20 ms).



New ALICE software framework:

- redefines both the data format and the analysis flow
- modern data structures and modern programming languages
- execution of the code is parallelized
- still under development
- open source

First results from Run 3

- First collisions from Run 3: data-taking on the way!

PID capabilities fully available!