Heavy-ion physics with ALICE detector

(a tour through selected recent results)

Dariusz Miśkowiec
GSI Darmstadt

CERN, ALICE, and (inter)nationalism

CERN's mission

- provide a unique range of particle accelerator facilities that enable research at the forefront of human knowledge.
- perform world-class research in fundamental physics.
- unite people from all over the world to push the frontiers of science and technology, for the benefit of all.

40 countries, 172 institutes, 1968 members

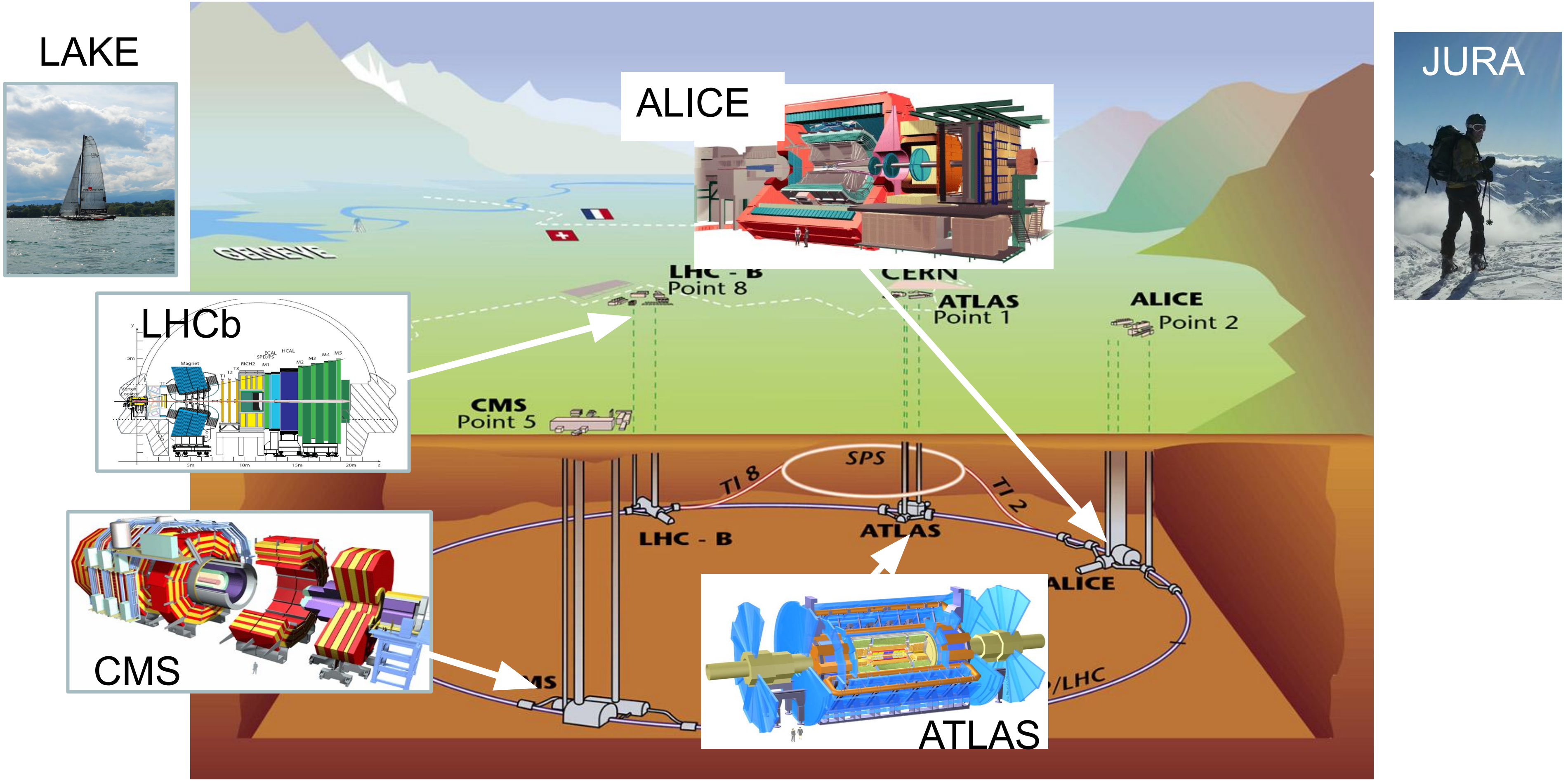
CERN, ALICE, and (inter)nationalism

CERN's mission

- provide a unique range of particle accelerator facilities that enable research at the forefront of human knowledge.
- perform world-class research in fundamental physics.
- unite people from all over the world to push the frontiers of science and technology, for the benefit of all.

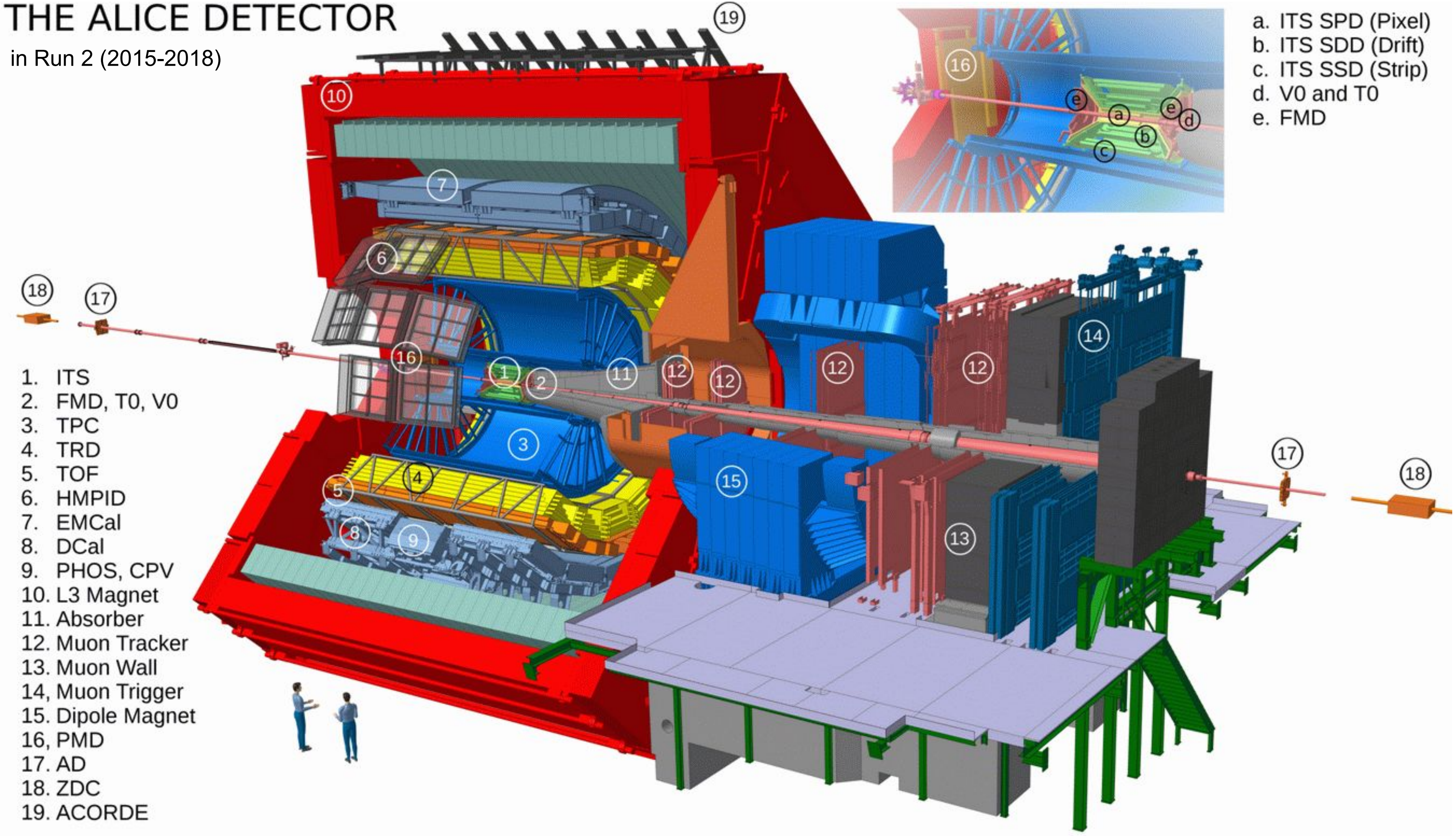
40 countries, 172 institutes, 1968 members

Large Hadron Collider at CERN



THE ALICE DETECTOR

in Run 2 (2015-2018)

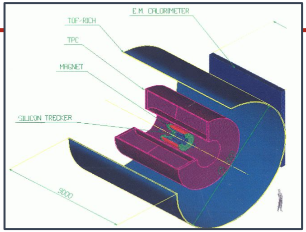


a. ITS SPD (Pixel)
b. ITS SDD (Drift)
c. ITS SSD (Strip)
d. V0 and T0
e. FMD

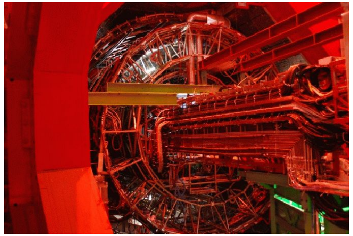
1. ITS
2. FMD, T0, V0
3. TPC
4. TRD
5. TOF
6. HMPID
7. EMCal
8. DCal
9. PHOS, CPV
10. L3 Magnet
11. Absorber
12. Muon Tracker
13. Muon Wall
14, Muon Trigger
15. Dipole Magnet
16, PMD
17. AD
18. ZDC
19. ACORDE

ALICE timeline

~1990 inception



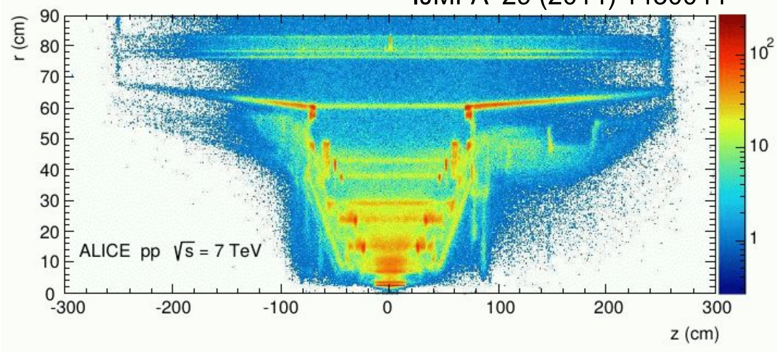
1995-2008 construction



2009-2013 LHC Run 1: Pb-Pb, p-Pb, pp at 50% energy

2015-2018 LHC Run 2: Pb-Pb, Xe-Xe, p-Pb, pp at 93% energy

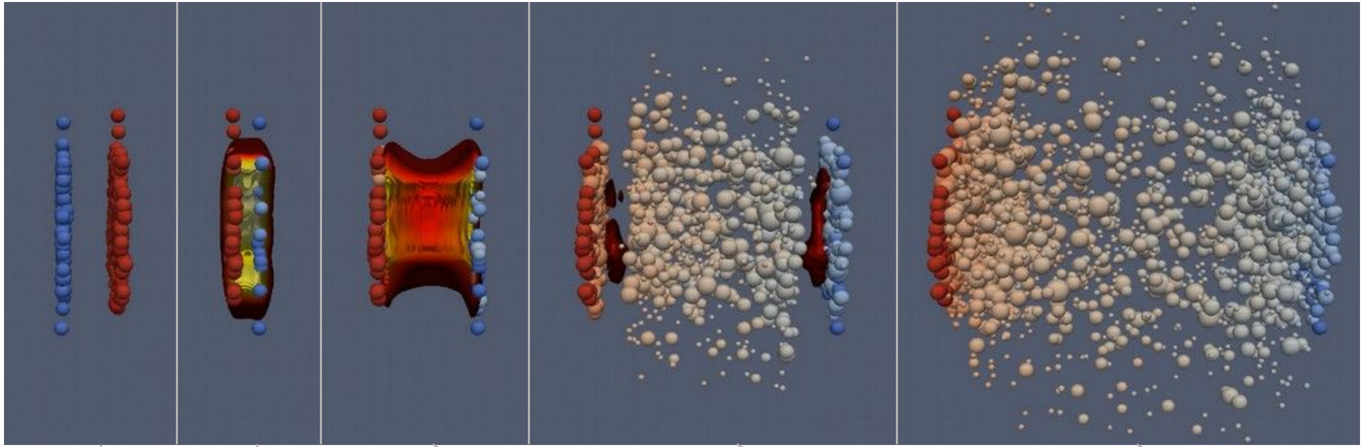
ALICE performance in Run 1
IJMPA 29 (2014) 1430044

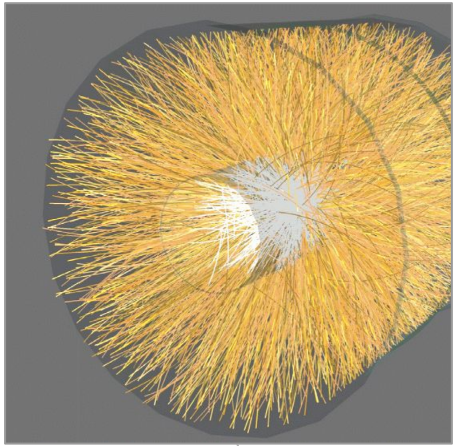


2022-2025 LHC Run 3: increased luminosity and 97% energy

phases of a relativistic nucleus-nucleus collision

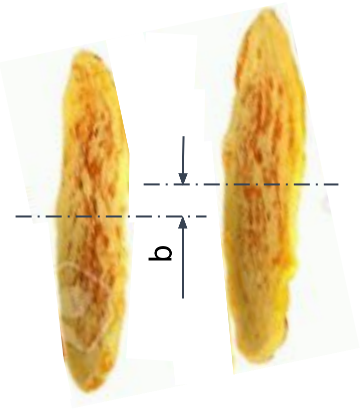
Figure: Hannah Petersen and Jonah Bernhard, MADAI collaboration





quarks gluons	hard scattering of partons	q,g energy loss	in-jet hadronization	hadron scattering	particles interact with detectors
collision geometry		bulk expansion	bulk hadronization		

phases of a relativistic nucleus-nucleus collision



impact parameter b,
density non-uniformities

viscosity, temperature,
collective flow

multiplicity, momenta, particle id

quarks gluons	hard scattering of partons	q,g energy loss	in-jet hadronization	hadron scattering	particles interact with detectors
collision geometry		bulk expansion	bulk hadronization		

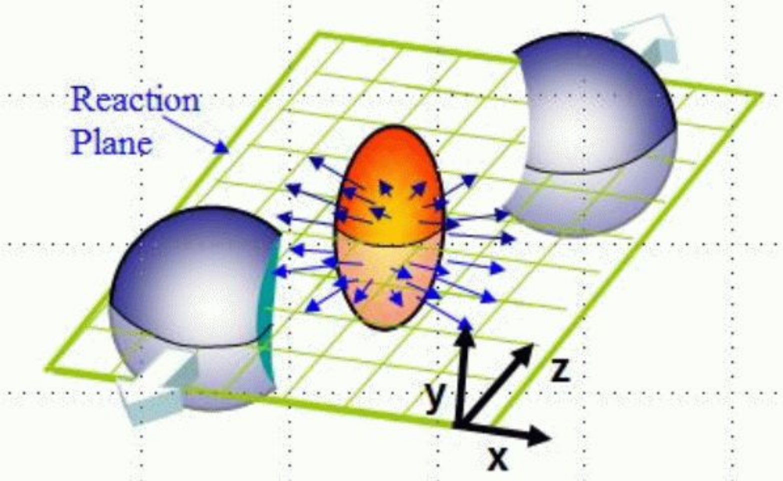
initial-state correlations

correlation between elliptic flow and mean p_T

arXiv:2111.06106

$\rho(v_2^2, \langle p_T \rangle)$

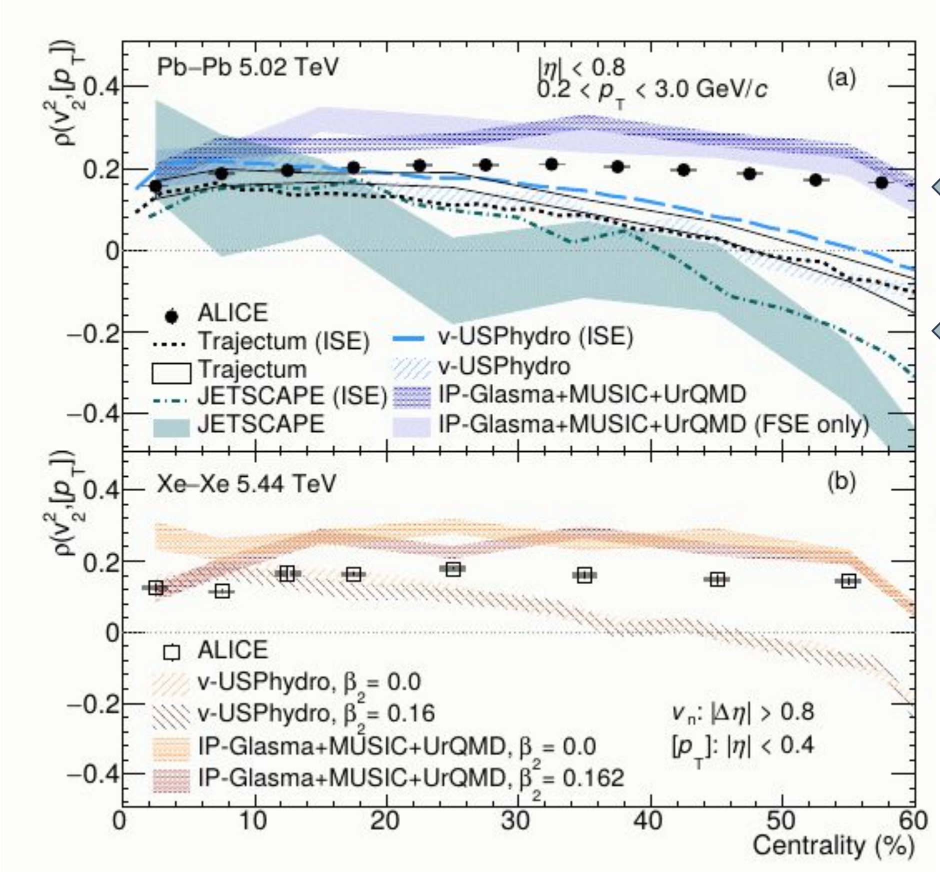
$dN/d\varphi \sim 1 + 2\, v_1 \cos(\varphi) + 2\, v_2 \cos(2\varphi) + \ldots$



p_T: average transverse momentum of particles in an event

correlation between elliptic flow and mean p_T

arXiv:2111.06106



positive correlation observed
IP-Glasma closer to the exp data than Trento

little difference between ISE and full hydro

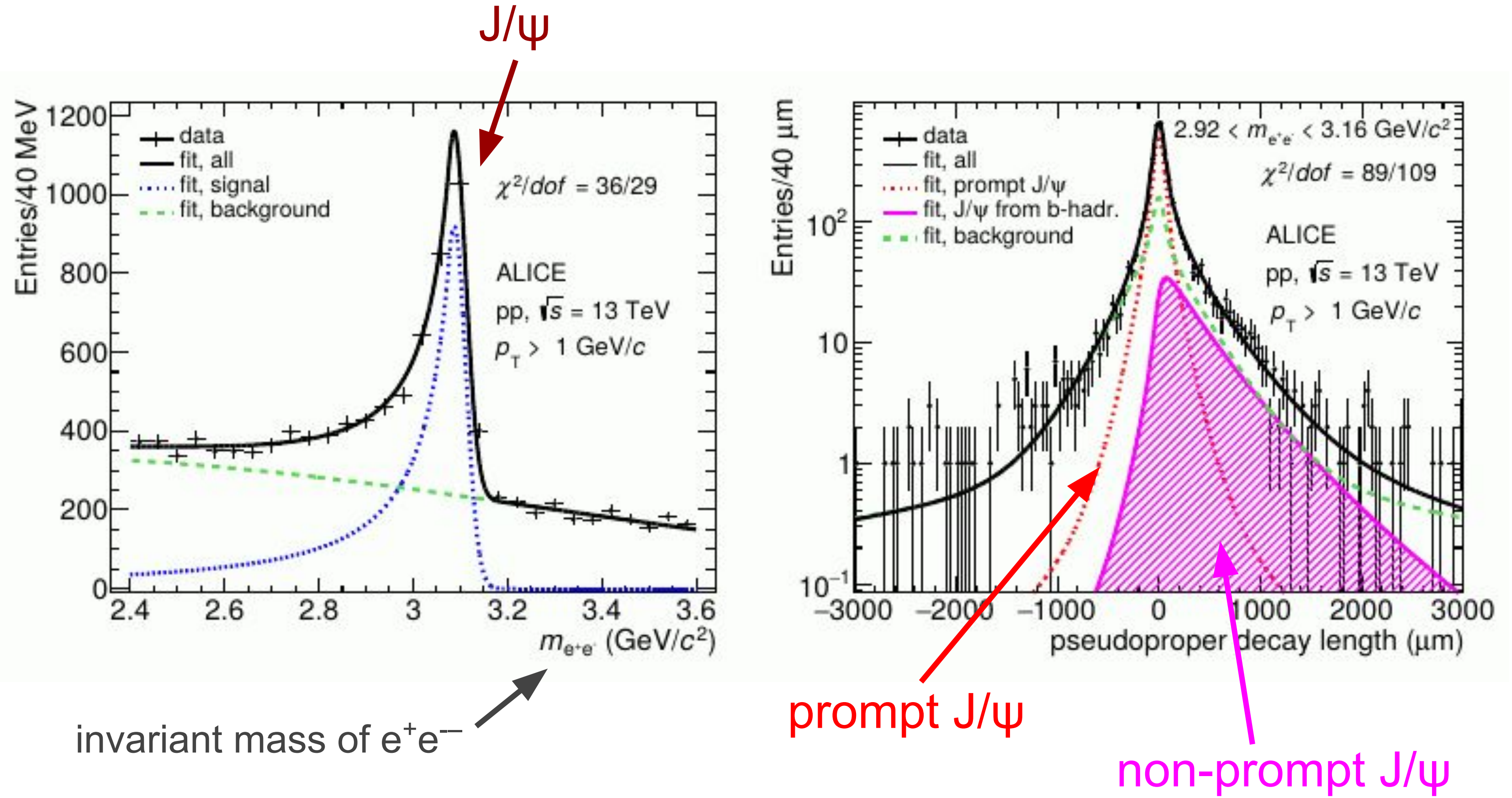
→ constraining initial conditions (prerequisite for study of QGP transport properties)

<table>
<tr><td>quarks
gluons</td><td>hard
scattering
of partons</td><td>q,g energy loss</td><td>in-jet hadronization</td><td rowspan="2">hadron scattering</td><td rowspan="2">particles interact
with detectors</td></tr>
<tr><td>collision
geometry</td><td></td><td>bulk expansion</td><td>bulk hadronization</td></tr>
</table>

beauty production

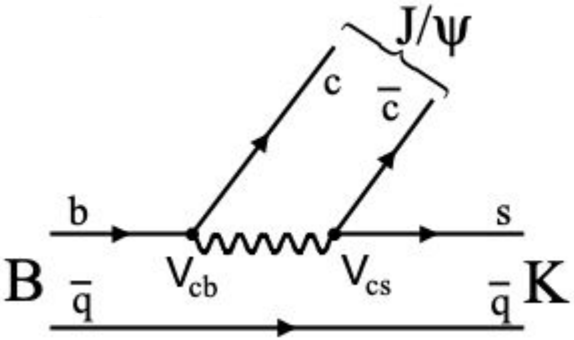
beauty production

arxiv:2108.02523



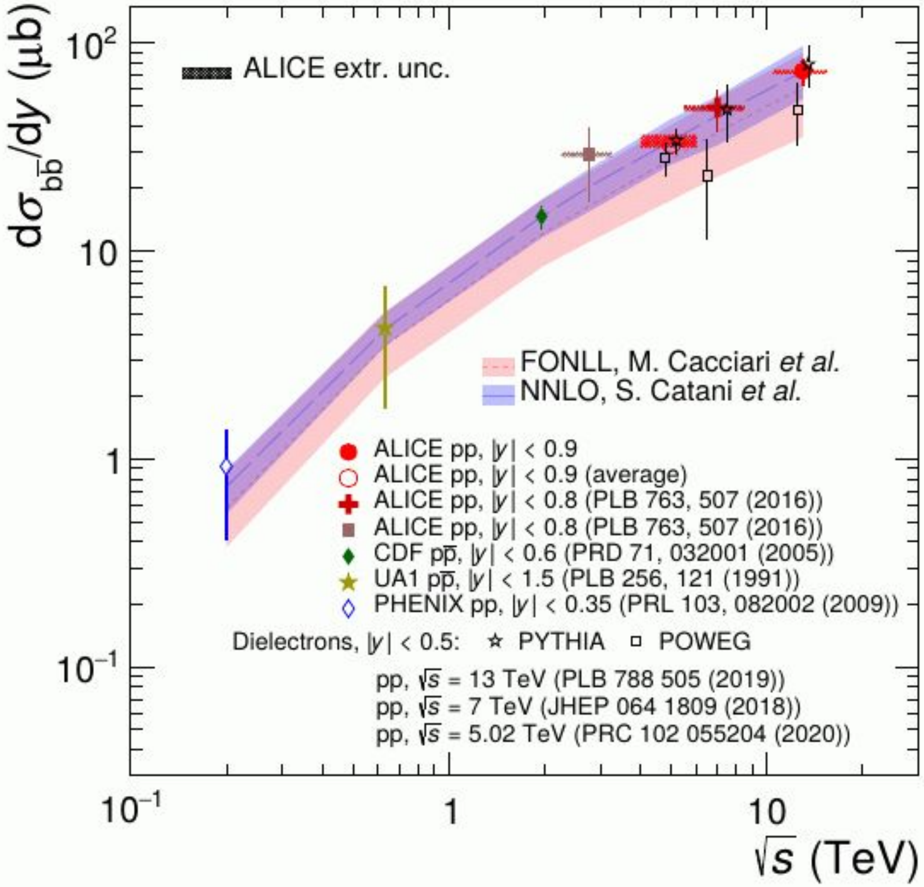
beauty production

arxiv:2108.02523



Norbert Neumeister, DELPHI, Ph.D. thesis, 1996

hadron	cτ
$B^{\pm}$	491 μm
B^0	456 μm
B^0_S	458 μm
Λ^0_b	440 μm

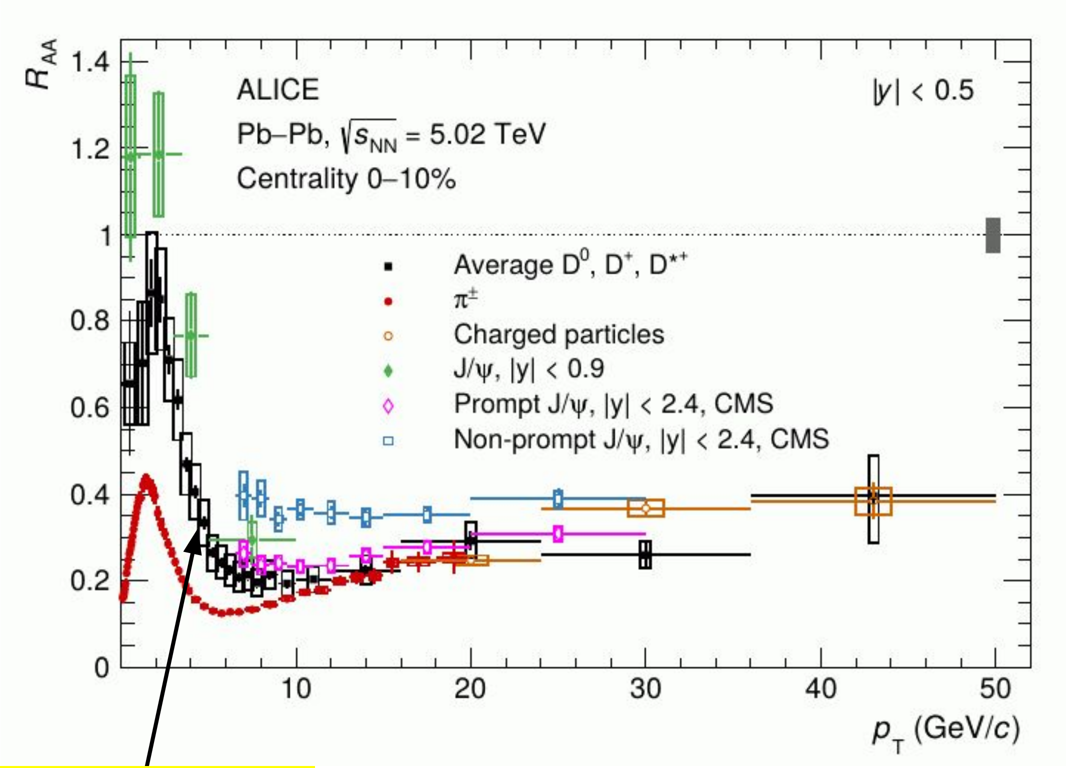


quarks gluons	hard scattering of partons	q,g energy loss	in-jet hadronization	hadron scattering	particles interact with detectors
collision geometry		bulk expansion	bulk hadronization		

parton energy loss

c quark in medium - energy loss

arxiv:2110.09420



c quark energy loss

$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

$R_{AA} < 1$ basic signature of energy loss

$D^0 = c\,\bar{u}$

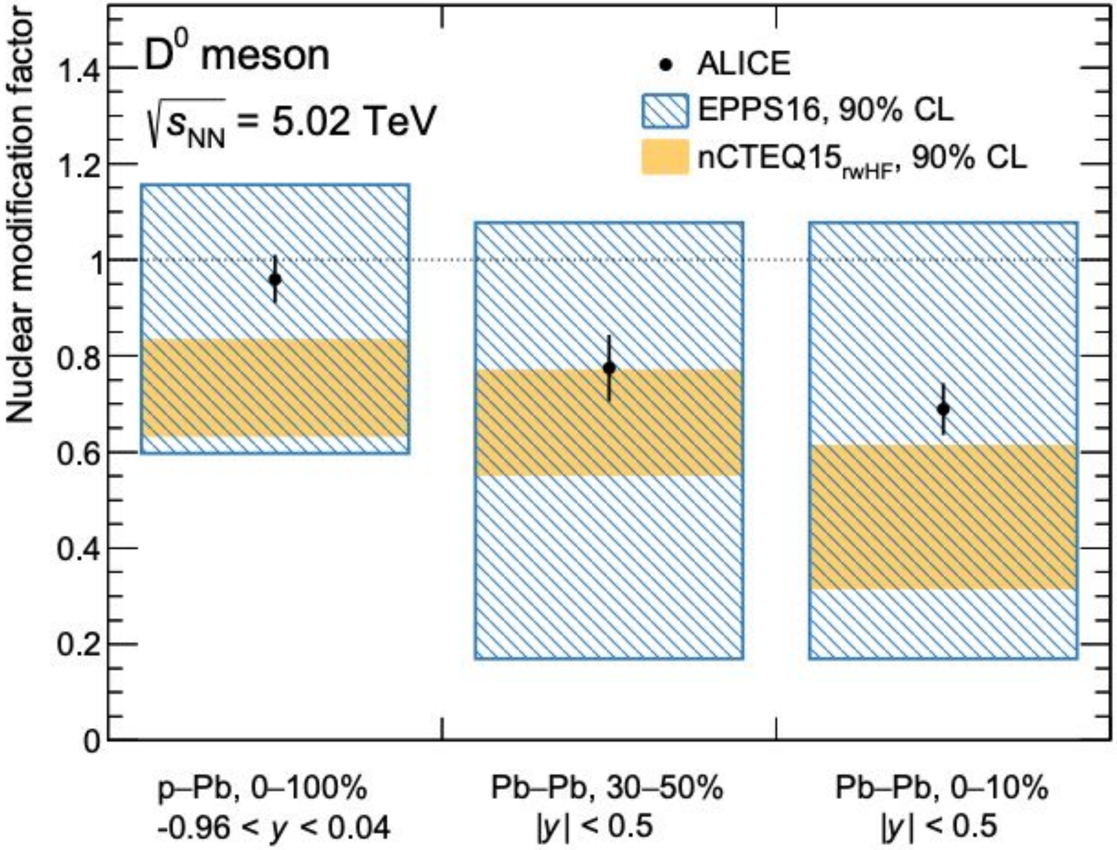
BR ($D^0 \rightarrow K^- \pi^+$) = 4%

D^0 measured down to p_T=0

R_{AA} at p_T>8 GeV agrees with calculation of collisional and radiative energy loss

c quark in medium - total number conserved

arxiv:2110.09420



integrating the yields over p_T → overall nuclear modification factor

deviation from unity caused by
- **shadowing**
- **hadronization in medium**

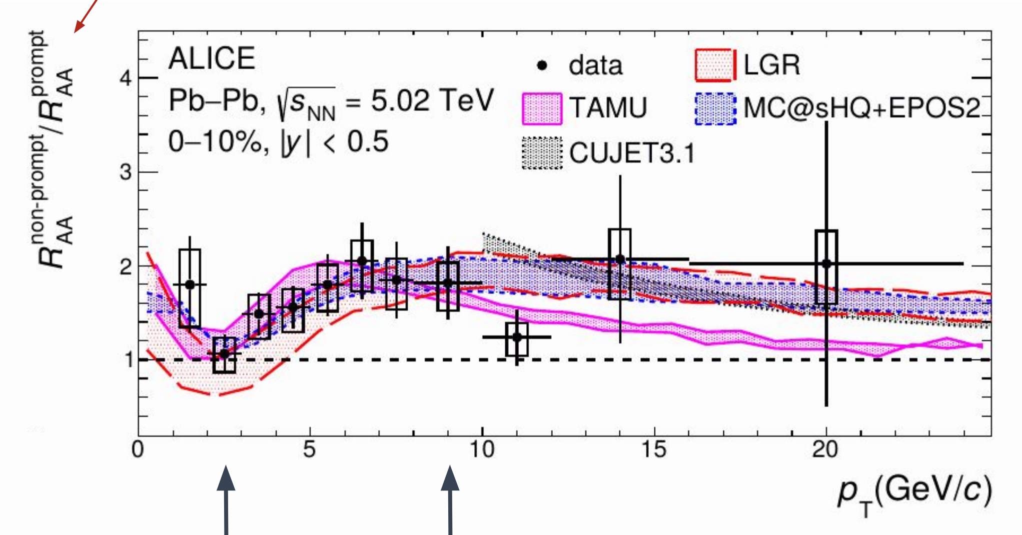
b quark in medium - energy loss

arxiv:2202.00815

$$\frac{\text{beauty in Pb-Pb / beauty in pp}}{\text{charm in Pb-Pb / charm in pp}}$$

non-prompt D^0

prompt D^0



at low p_T collisional energy loss: comparable for c and b

at high p_T radiative energy loss: less for b than c

<table>
<tr><td>quarks gluons</td><td>hard scattering of partons</td><td>q,g energy loss</td><td>in-jet hadronization</td><td rowspan="2">hadron scattering</td><td rowspan="2">particles interact with detectors</td></tr>
<tr><td>collision geometry</td><td></td><td>bulk expansion</td><td>bulk hadronization</td></tr>
</table>

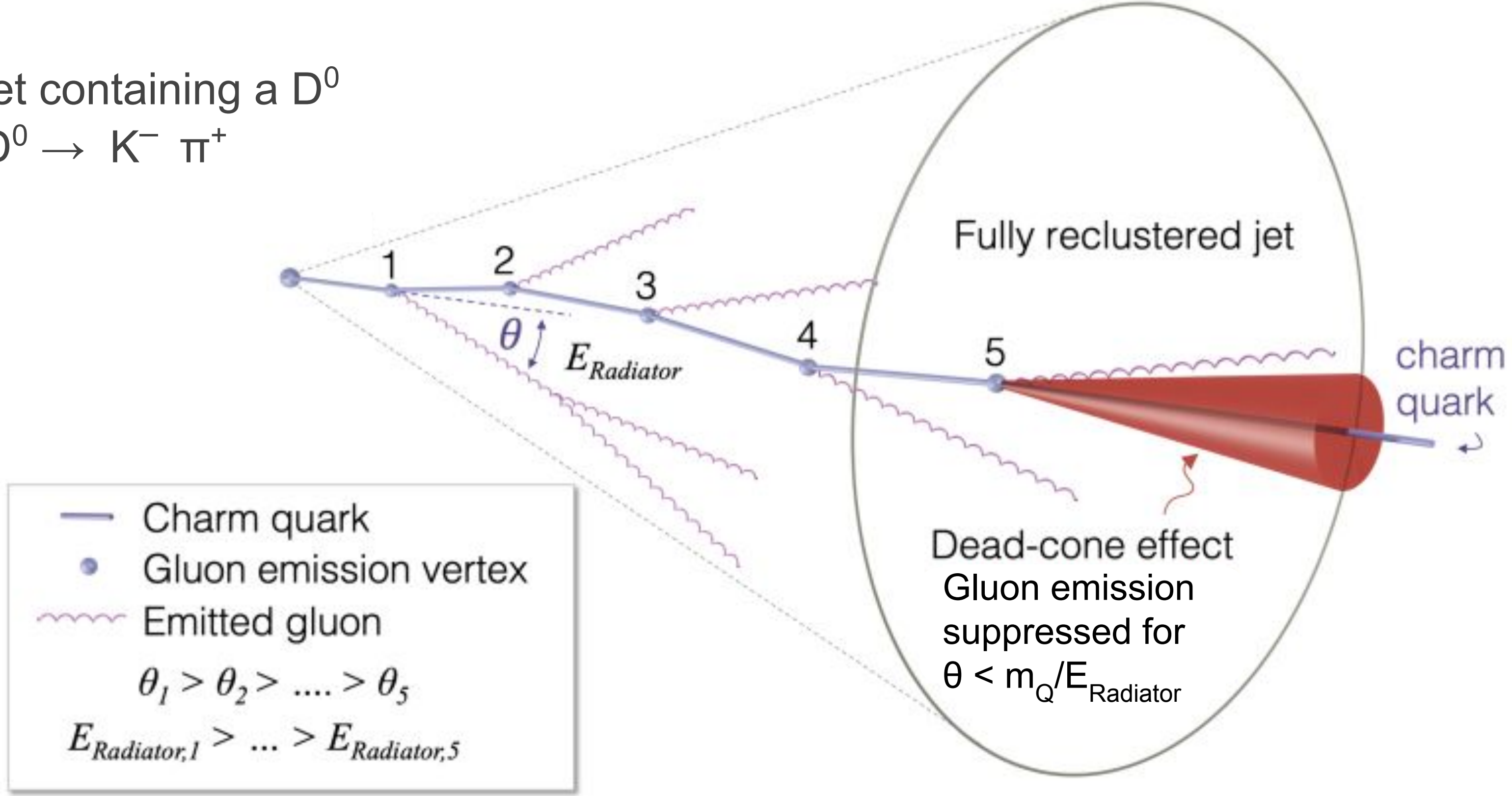
dead cone

dead cone in the radiation of gluons by c quark

arxiv:2106.05713

jet containing a D^0

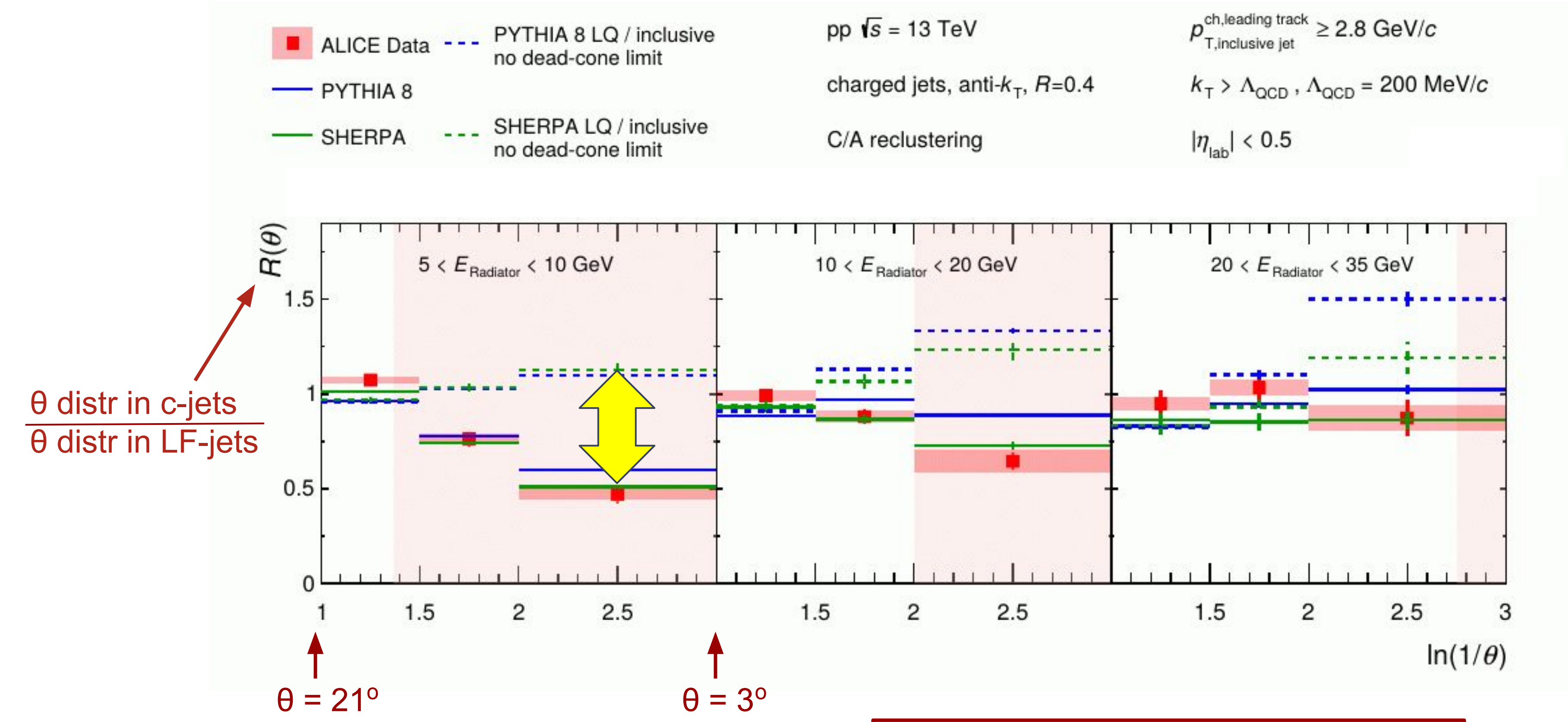
$D^0 \rightarrow K^- \pi^+$



Gluon emission suppressed for $\theta < m_Q/E_{Radiator}$

dead cone in the radiation of gluons by c quark

arxiv:2106.05713



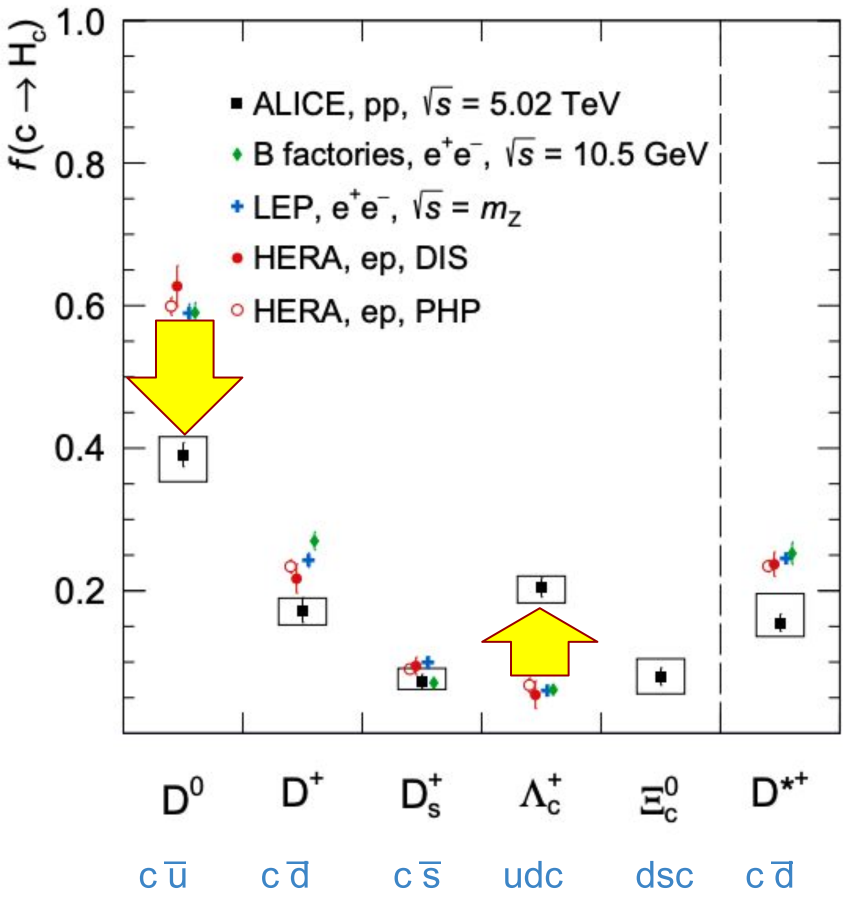
first direct observation of dead cone

quarks gluons	hard scattering of partons	q,g energy loss	in-jet hadronization	hadron scattering	particles interact with detectors
collision geometry		bulk expansion	bulk hadronization		

in-medium hadronization

charmed baryon/meson enhancement

arxiv:2105.06335



first measurement of charm fragmentation fractions including baryons at the LHC

first measurement of fragmentation fraction to Ξ_c

Λ_c fraction enhanced
D^0 fraction reduced
compared to ee and ep

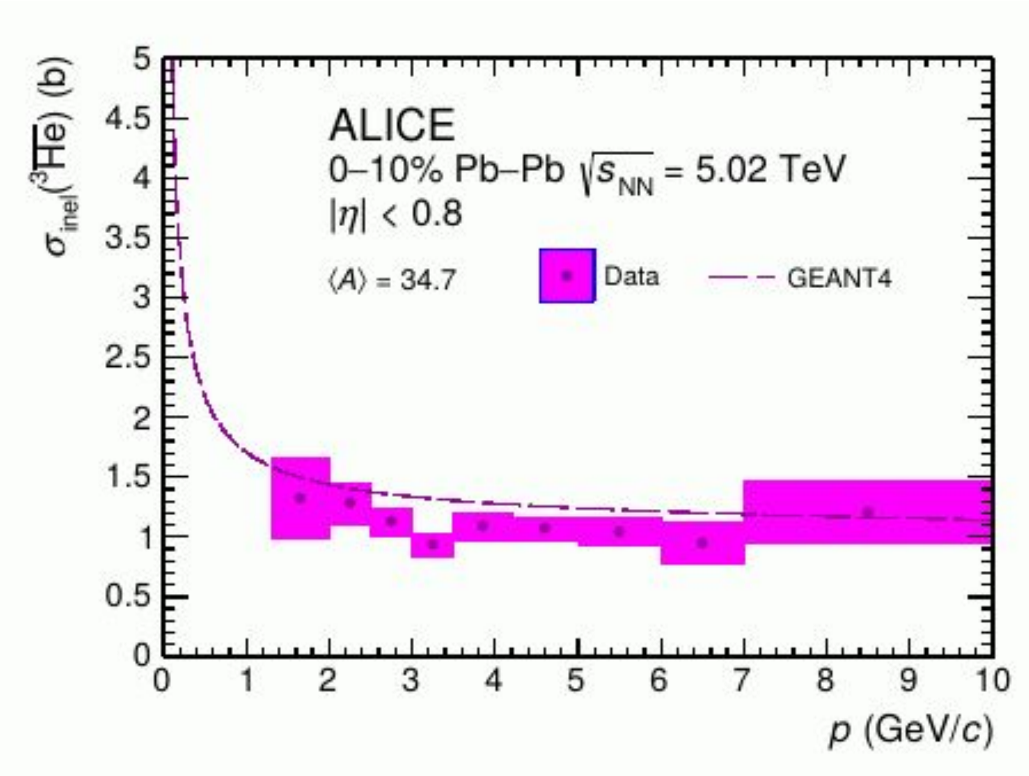
hadronization depends on environment

<table>
<tr><td>quarks
gluons</td><td rowspan="2">hard
scattering
of partons</td><td>q,g energy loss</td><td>in-jet hadronization</td><td rowspan="2">hadron scattering</td><td rowspan="2">particles interact
with detectors</td></tr>
<tr><td>collision
geometry</td><td>bulk expansion</td><td>bulk hadronization</td></tr>
</table>

interaction of anti-^{3}He with matter

absorption of anti-^{3}He by matter

arxiv:2202.01549

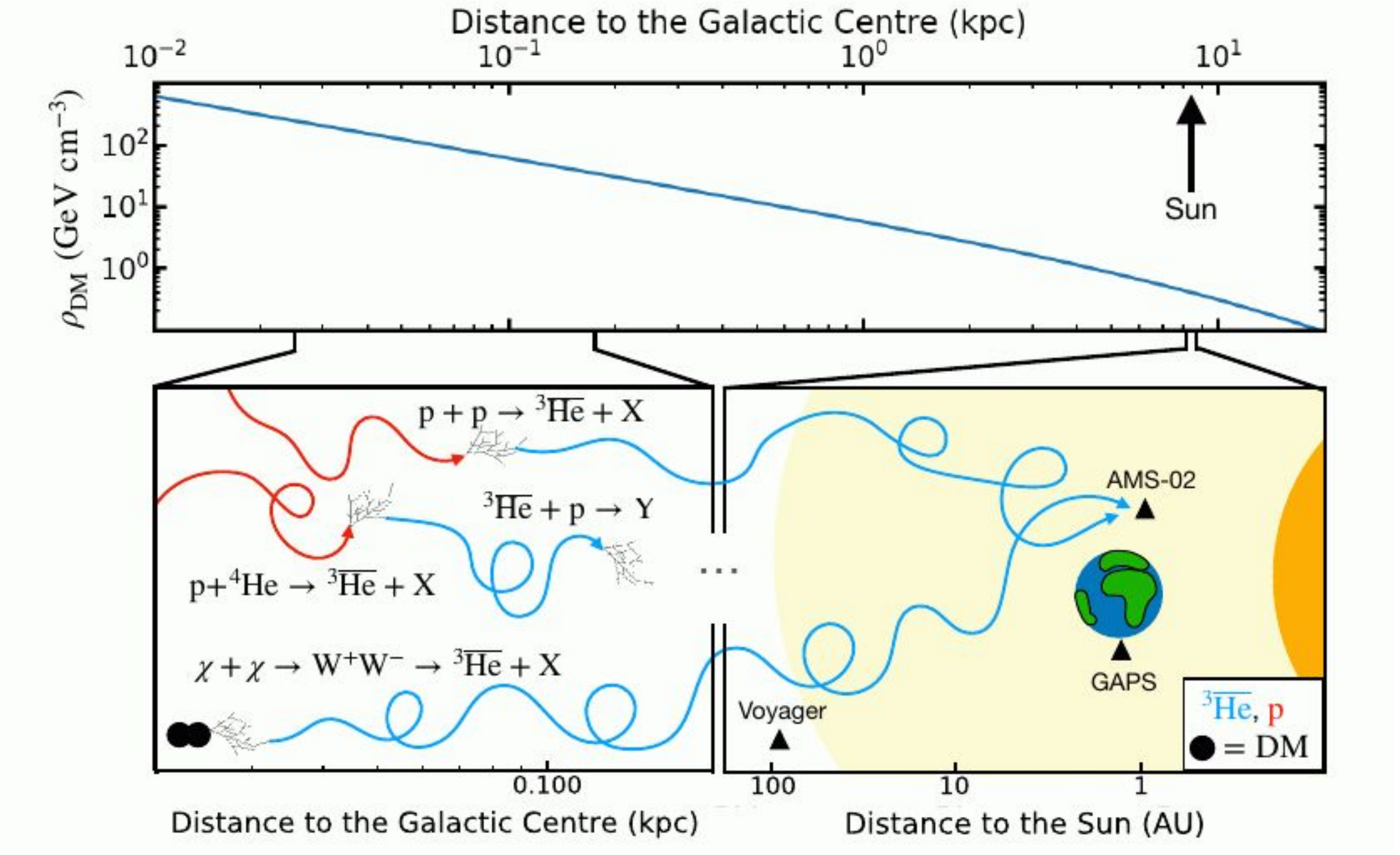


first measurement of inelastic interaction cross section of anti-^{3}He with matter

- **confirms GEANT 4 parametrization**
- **quantifies absorption uncertainties**

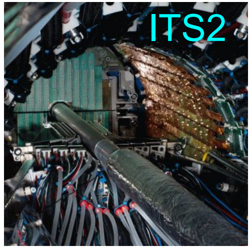
absorption of anti-^{3}He by matter

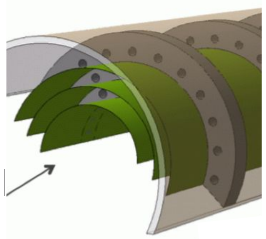
arxiv:2202.01549

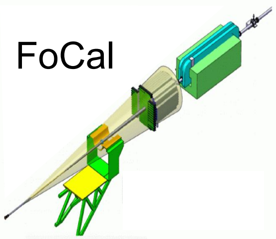


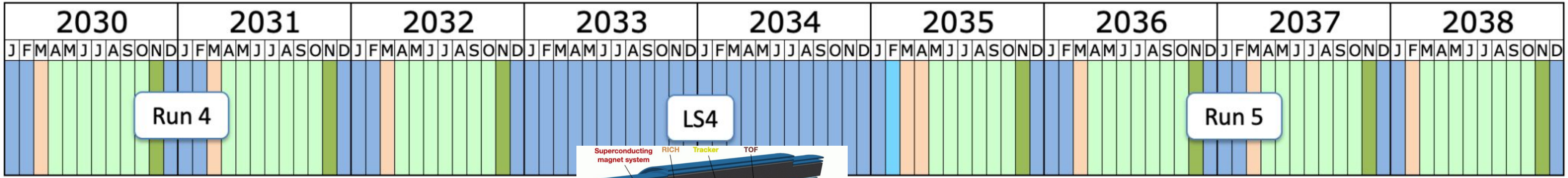
THE END

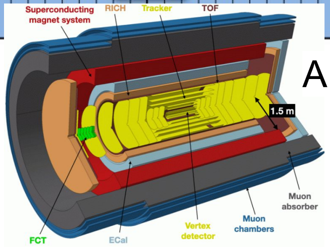
LHC and ALICE schedule









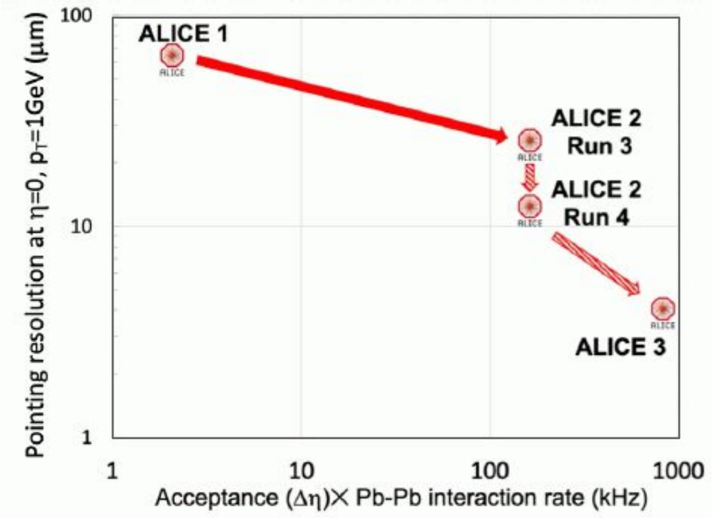


ALICE 3

Last updated: January 2022

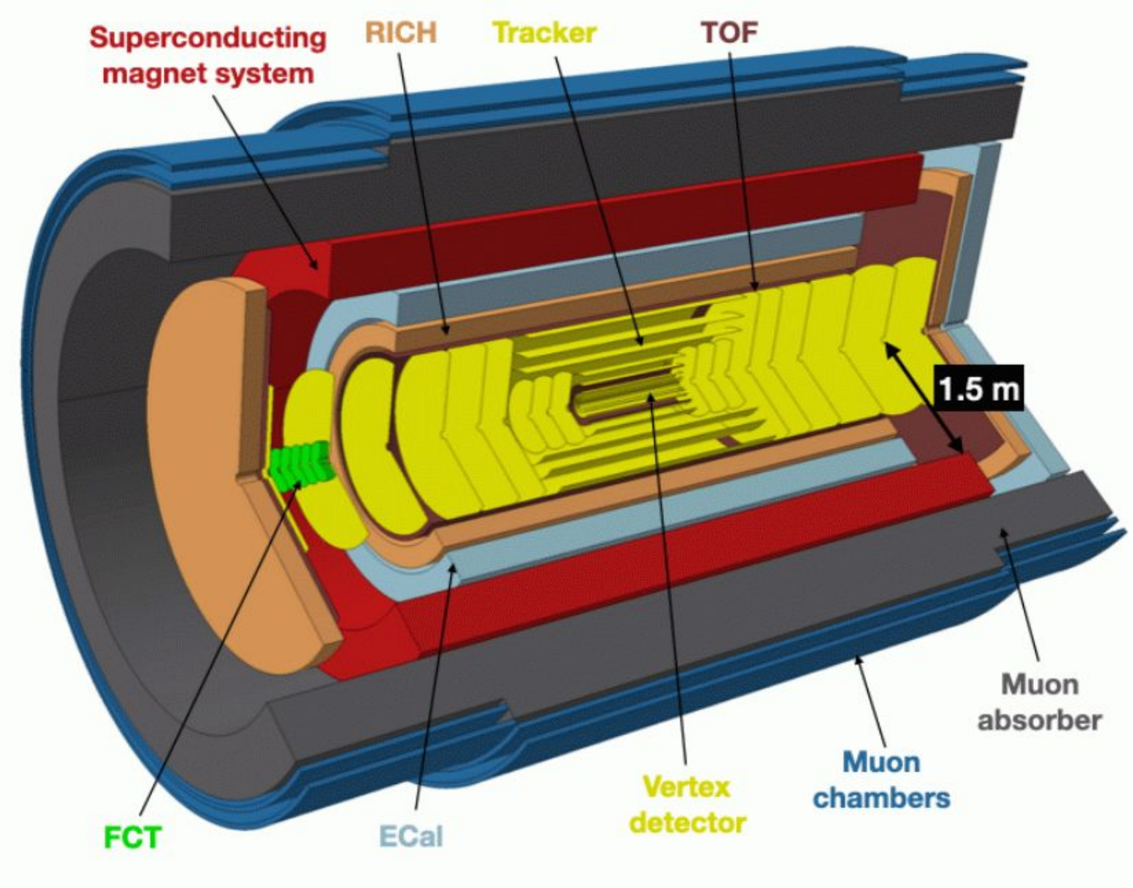
- Shutdown/Technical stop
- Protons physics
- Ions
- Commissioning with beam
- Hardware commissioning/magnet training

ALICE 3



ALICE 3: compact low-mass all-silicon tracker with excellent PID capabilities over wide acceptance

LoI to be published by end of March

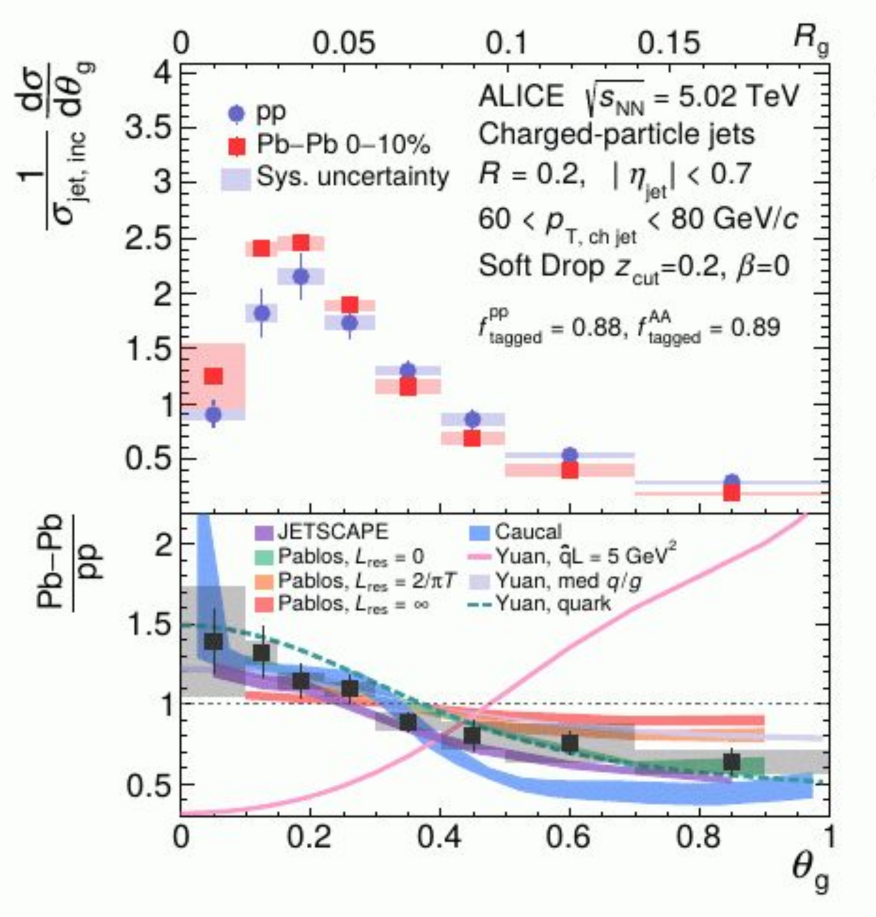


quarks gluons	hard scattering of partons	q,g energy loss	in-jet hadronization	hadron scattering	particles interact with detectors
collision geometry		bulk expansion	bulk hadronization		

parton energy loss

jet modification by medium in Pb-Pb collisions

arxiv:2107.12984



$$\theta_g \equiv \frac{\sqrt{\Delta y^2 + \Delta\varphi^2}}{R}$$

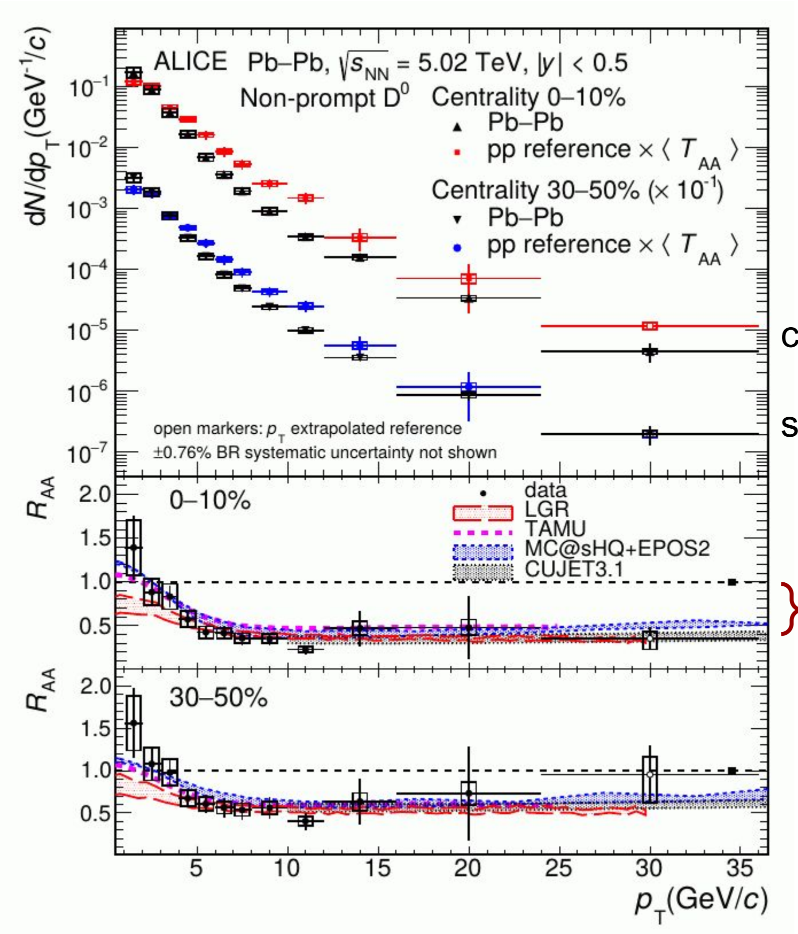
θ_g - relative opening angle of a hard splitting in jet

hard → calculable by pQCD

- **first measurement of θ_g in nuclear collisions**
- **θ_g in central Pb-Pb collisions is smaller then in pp collisions**

b quark in medium - energy loss

arxiv:2202.00815



central Pb-Pb

semicentral Pb-Pb

} energy loss of b quarks

$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

non-prompt D^0 = proxy for beauty hadrons

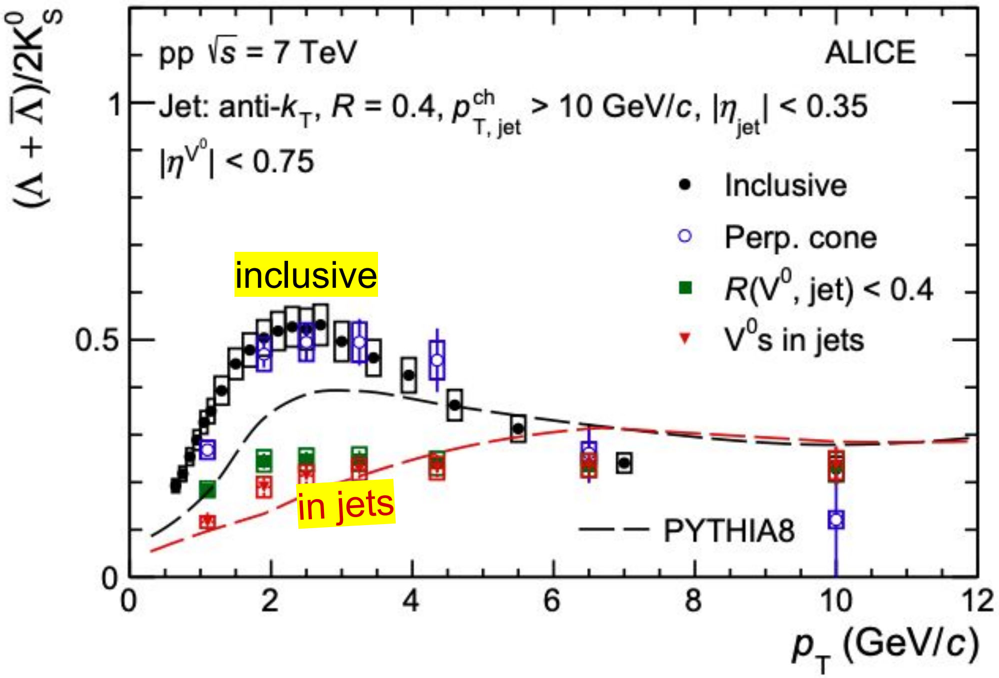
integrating the yields over p_T → overall nuclear modification factor consistent with unity

quarks gluons	hard scattering of partons	q,g energy loss	in-jet hadronization	hadron scattering	particles interact with detectors
collision geometry		bulk expansion	bulk hadronization		

transverse expansion

baryon/meson enhancement in pp

arxiv:2105.04890

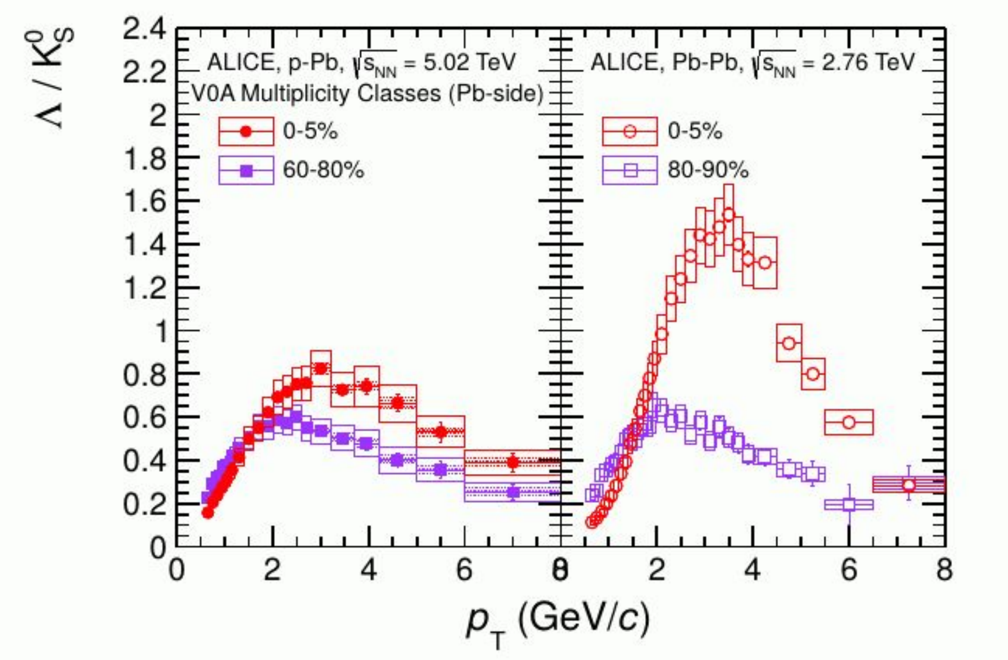


- peak in baryon/meson ratio
- in central Pb-Pb, attributed to radial flow
- origin in light collision systems?

the peak does not originate from jets

baryon/meson enhancement in p-Pb and Pb-Pb

PLB 728(2014)25



déjà vu back in 2012-2014

transverse flow:
outward push by Δv
Δv (Λ) = Δv (K)
Δp_T (Λ) > Δp_T (K)

signatures of collectivity in small collision systems

- spectra: transverse flow
- long-range two particles correlations: ridge (elliptic flow)
- HBT analysis: p dependence of HBT radii
- …

big surprise!

signatures of collectivity in small collision systems

- spectra: transverse flow
- long-range two particles correlations: ridge (elliptic flow)
- HBT analysis: p dependence of HBT radii
- …

big surprise!

…Really?

QM2008, panel discussion
Jurgen Schukraft said:

- even protons get obese these days
  - ⇨ p@LHC ~ small (but very dense) nucleus@SPS

	SPS	RHIC	LHC
# of partons in proton 3 + $\int g(x > 2\text{GeV})$	4	10	**30**

- 'QGP' physics with protons
  - ⇨ at least: onset of hadronic FS interactions
  - ⇨ maybe: collective hadronic/partonic dynamics
  - ⇨ why not: the QGP, mini serving

quarks gluons	hard scattering of partons	q,g energy loss	in-jet hadronization	hadron scattering	particles interact with detectors
collision geometry		bulk expansion	bulk hadronization		

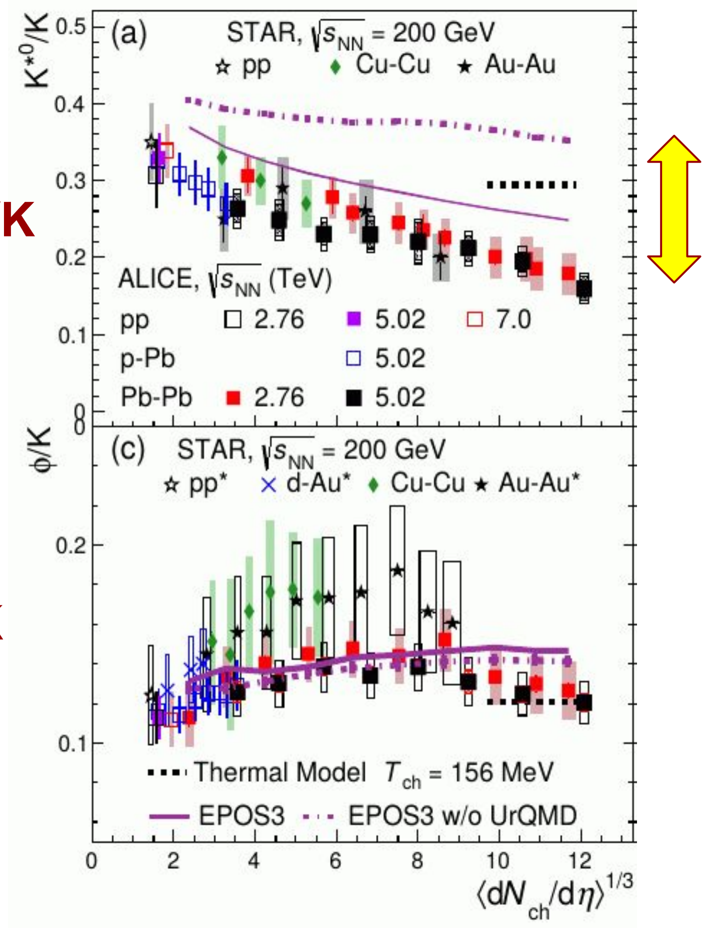
rescattering

rescattering of K^{*0} daughters

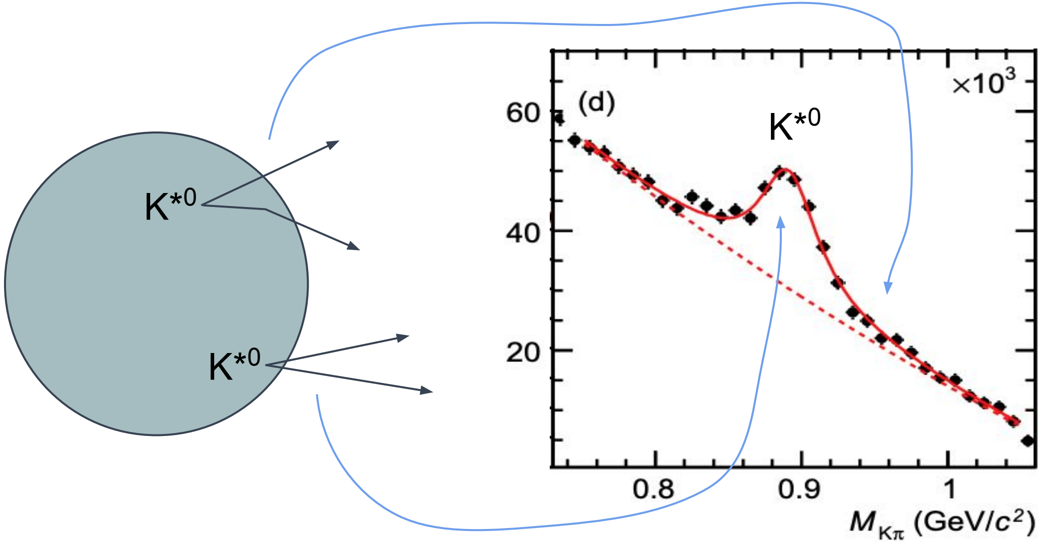
arxiv:2106.13113

K^{*0}/K

Φ/K



	$c\tau$	decay
$K^*(892)^0$	4.2 fm	$\rightarrow K^{\pm}\pi^{\mp}$
$\Phi(1020)$	46 fm	$\rightarrow K^{+}K^{-}$



rescattering in hadronic phase

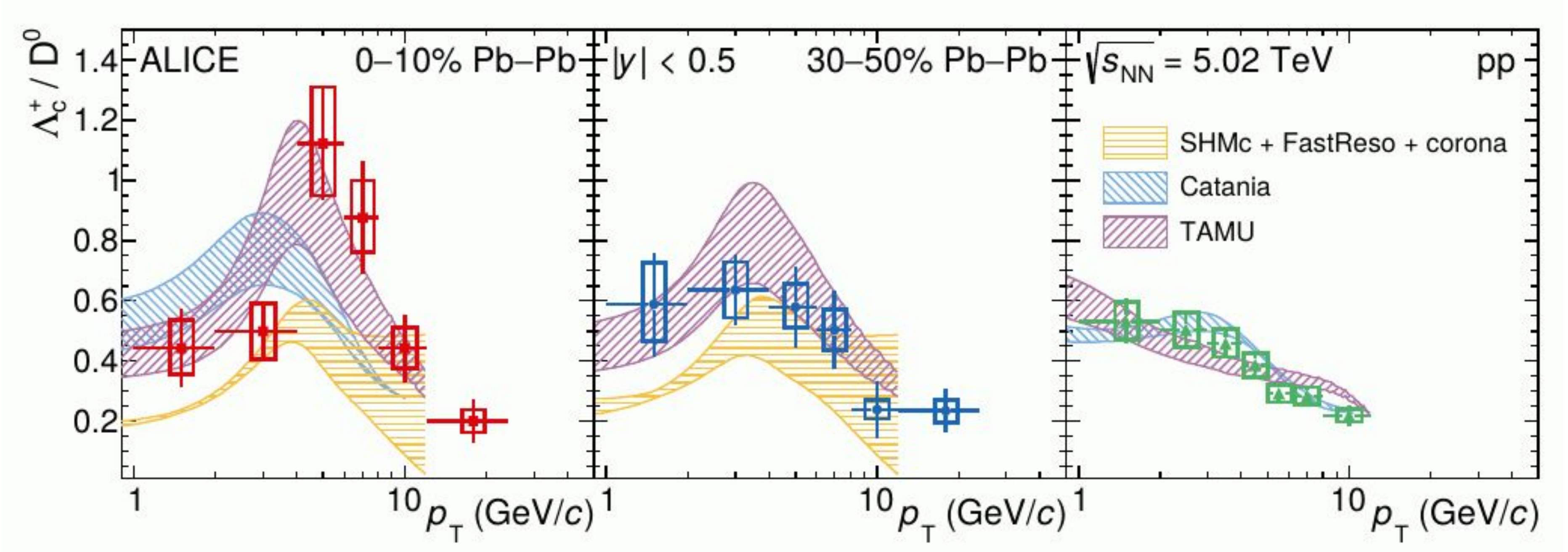
<table>
<tr><td>quarks gluons</td><td>hard scattering of partons</td><td>q,g energy loss</td><td>in-jet hadronization</td><td rowspan="2">hadron scattering</td><td rowspan="2">particles interact with detectors</td></tr>
<tr><td>collision geometry</td><td></td><td>bulk expansion</td><td>bulk hadronization</td></tr>
</table>

in-medium hadronization

charmed baryon/meson enhancement

arxiv:2112.08156

see also arxiv:2105.05187, arxiv:2105.05616, arxiv:2106.08278, arxiv:2111.11948



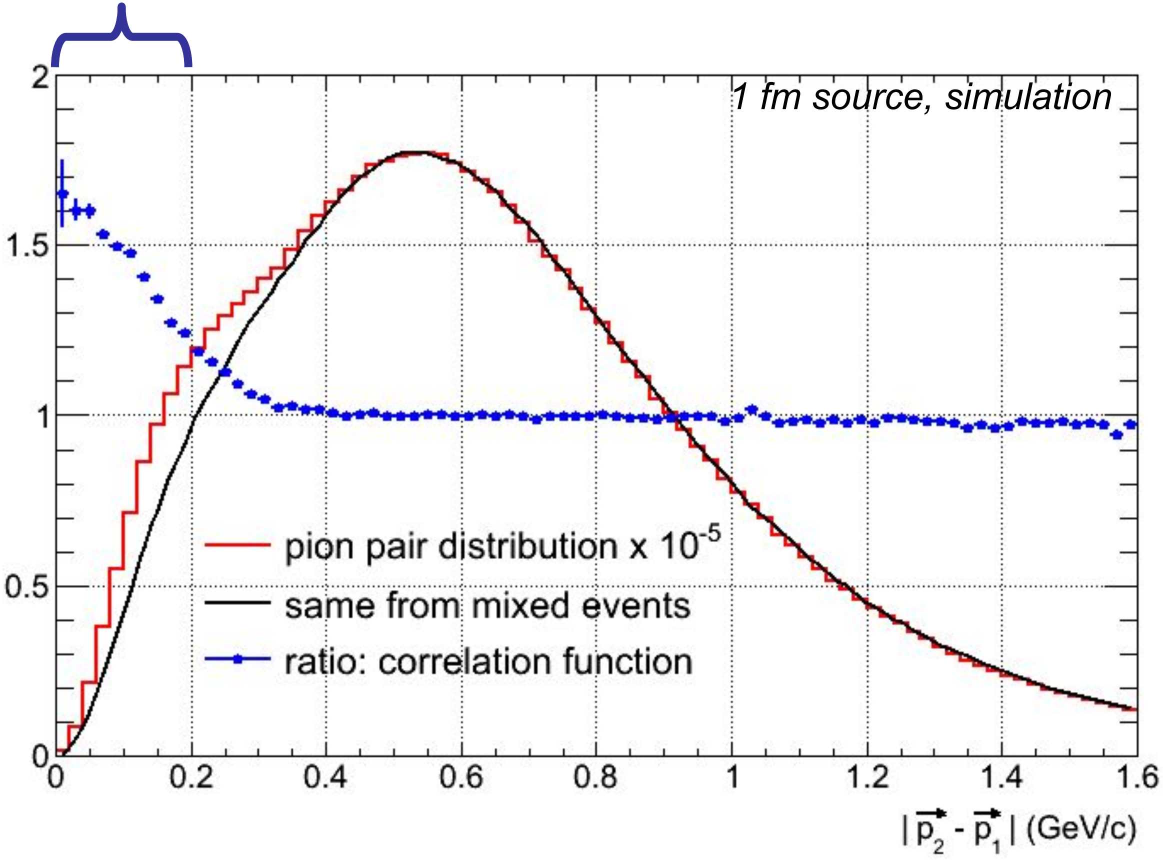
hadronization by coalescence! (and fragmentation)

<table>
<tr><td>quarks gluons</td><td>hard scattering of partons</td><td>q,g energy loss</td><td>in-jet hadronization</td><td rowspan="2">hadron scattering</td><td rowspan="2">particles interact with detectors</td></tr>
<tr><td>collision geometry</td><td></td><td>bulk expansion</td><td>bulk hadronization</td></tr>
</table>

correlation measurement of the strong interaction

two-pion Hanbury Brown and Twiss correlation analysis

peak width ~ 1 / source size



correlation measurement of two-particle interaction

$$C(\vec{k}^*) = \int S(\vec{r}^*) \left|\Psi(\vec{k}^*, \vec{r}^*)\right|^2 \mathrm{d}^3 r^*$$

measured two-particle correlation function

particle source distribution

mutual interaction (BE or FD, Coulomb, strong)

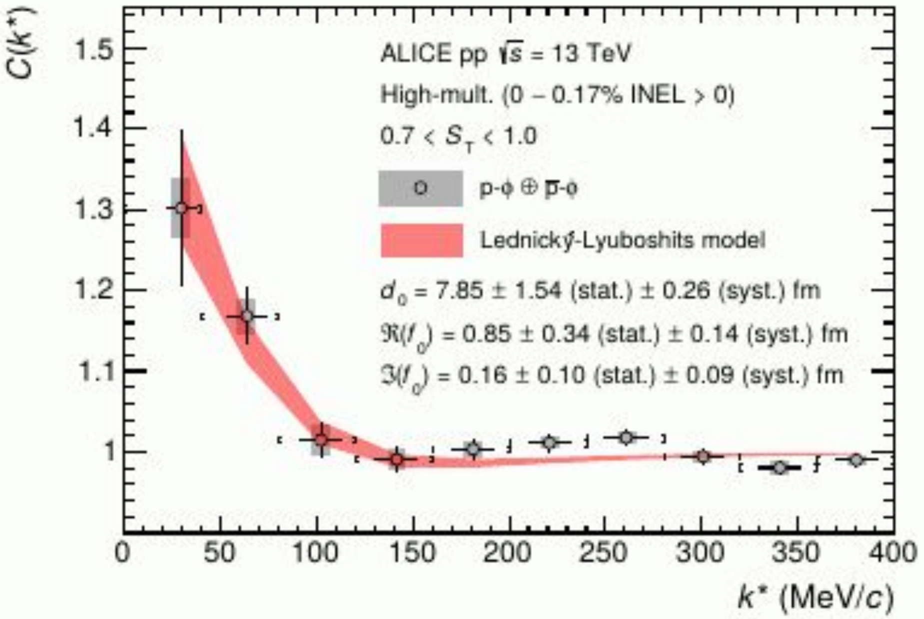
strategy:

1) measure source with (abundant) species with known interaction
2) invert formula to learn about mutual interactions between rare species

correlation measurement of two-particle interaction

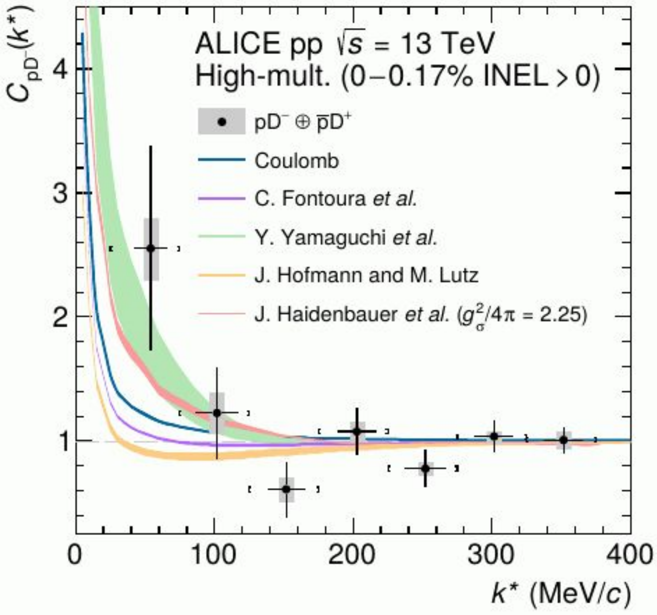
p-ϕ

arxiv:2105.05578



p-D⁻

arxiv:2201.05352



other recent combinations of species:

arxiv:2105.05190	p-p̄, p-Λ̄, Λ-Λ̄
arxiv:2104.04427	p-Λ
arxiv:2105.05683	p-K^-
arxiv:2111.06611	K^0_S-K^0_S, K^0_S-$K^\pm$

…as well as 10 earlier ALICE papers further covering p-p, p-K, p-Λ, Λ-Λ, p-Σ^0, p-Ξ^-, Λ-$K^\pm$, Λ-K^0_S, and p-Ω^- (Nature 588(2020)232)