# Highlights from ALICE

Kai Schweda (GSI, CERN)

for the ALICE Collaboration

Workshop on the Standard Model and Beyond

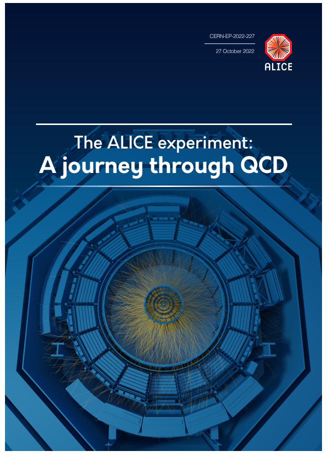
August 25 - September 4, 2024
Mon Repos, Corfu

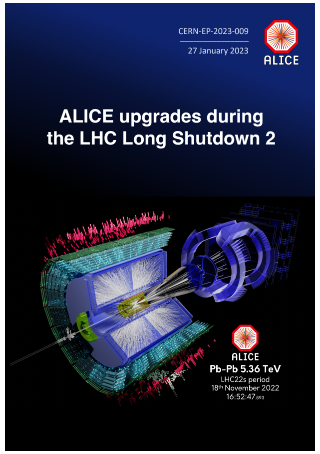
# OUTLINE

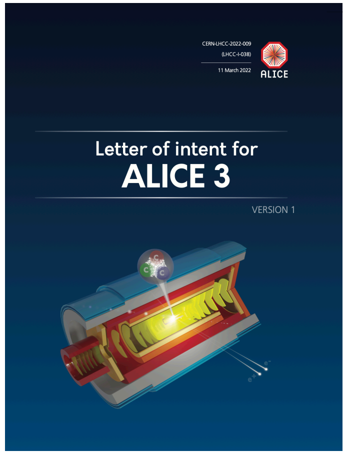
① ALICE 1 (2009 - 2018) — physics harvest

② ALICE 2 (2022 - 2032) — marvels of technology

③ ALICE 3 (2035 - 2041) — the future



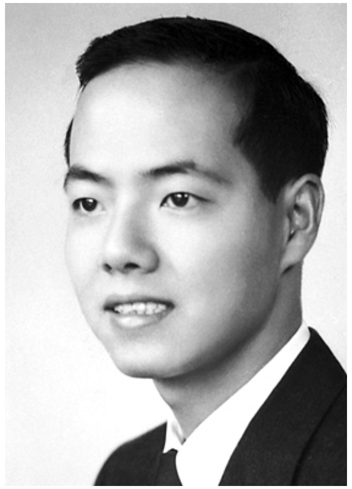
# SOME 50 YEARS AGO

ALICE

"It would be **intriguing** to explore **new phenomena** by **distributing** **high energy** or **high nuclear matter** over a relatively **large volume**."

"In this way one could temporarily **restore** broken **symmetries** of the physical vacuum and possibly **create** abnormal **states** of **nuclear matter**."

T.D. Lee (24-Nov-1926 - 04-Aug-2024), Bear Mountain, NY, 1974.



source: Nobel foundation

"Nevertheless, such speculations reminds us that the **possibility** of totally **unexpected phenomena** may be the **most compelling** reason to consider **relativistic nucleus-nucleus collisions**. It is regrettable that It is so **hard** to **estimate** the **odds** for this to happen."

J.D. Bjorken (22-Jun-1934 - 06-Aug-2024), FNAL,
Highly Relativistic Nucleus-Nucleus Collisions:
The Central Rapidity Region, FNAL, PRD 27 (1983) 140. 3673 citations

source: AIP

Quantitative results from lattice QCD: [Phys.Lett.B 795 (2019) 15]

# MOTIVATION

**Early universe** governed by **phase transitions** of fundamental **quantum fields**

**QCD quark/gluon-hadron transition** at high temperature **accessible** in **collisions** of heavy nuclei at highest energies

→ Probe **QCD** as genuine **multi-particle theory**

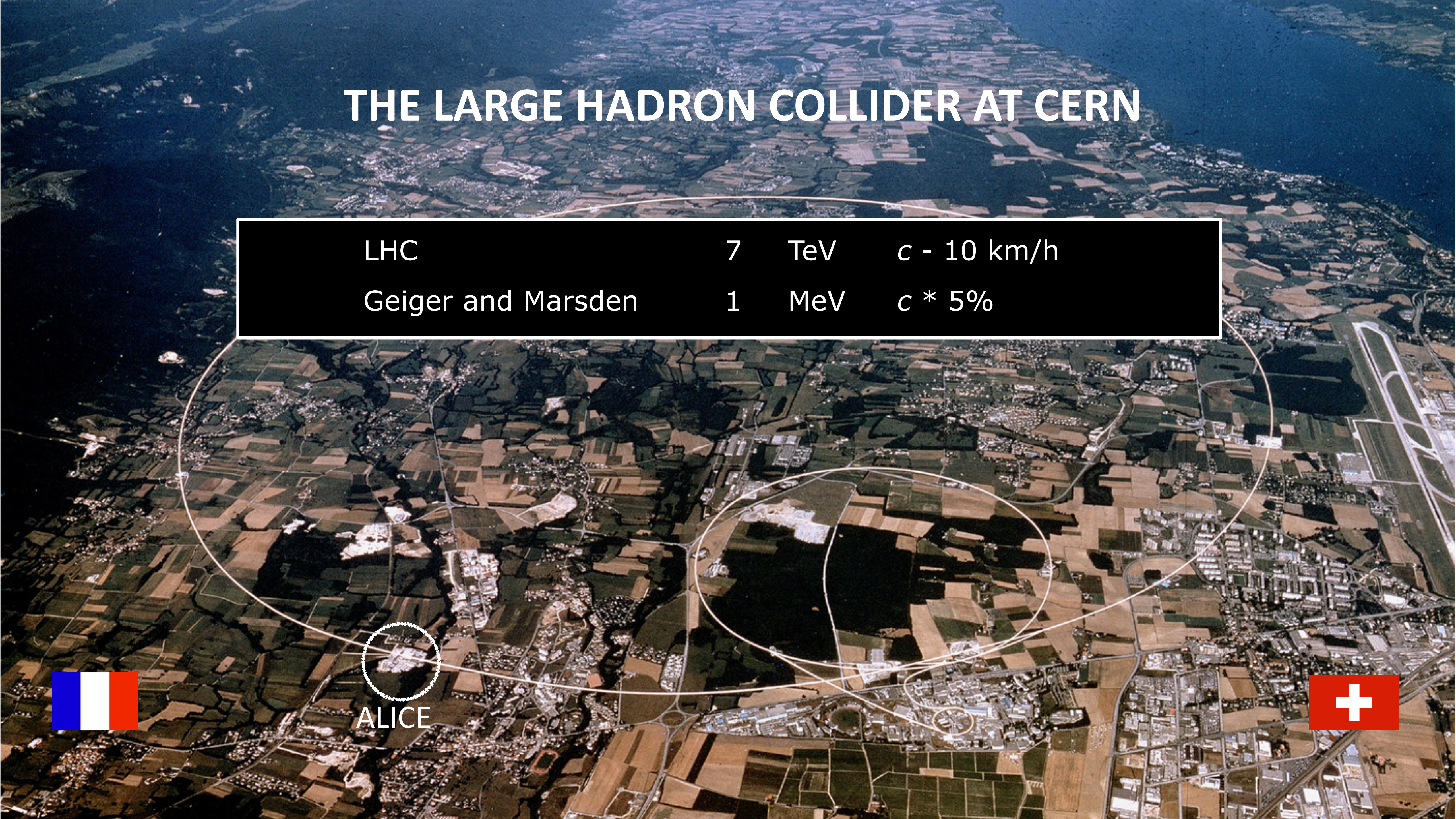
→ Relate **collective phenomena** to **fundamental interactions** in QCD

Source: Michael Turner, *National Geographic (1996)*


THE LARGE HADRON COLLIDER AT CERN
ALICE

# THE LARGE HADRON COLLIDER AT CERN

| | | | |
|---|---|---|---|
| LHC | 7 | TeV | *c* - 10 km/h |
| Geiger and Marsden | 1 | MeV | *c* * 5% |

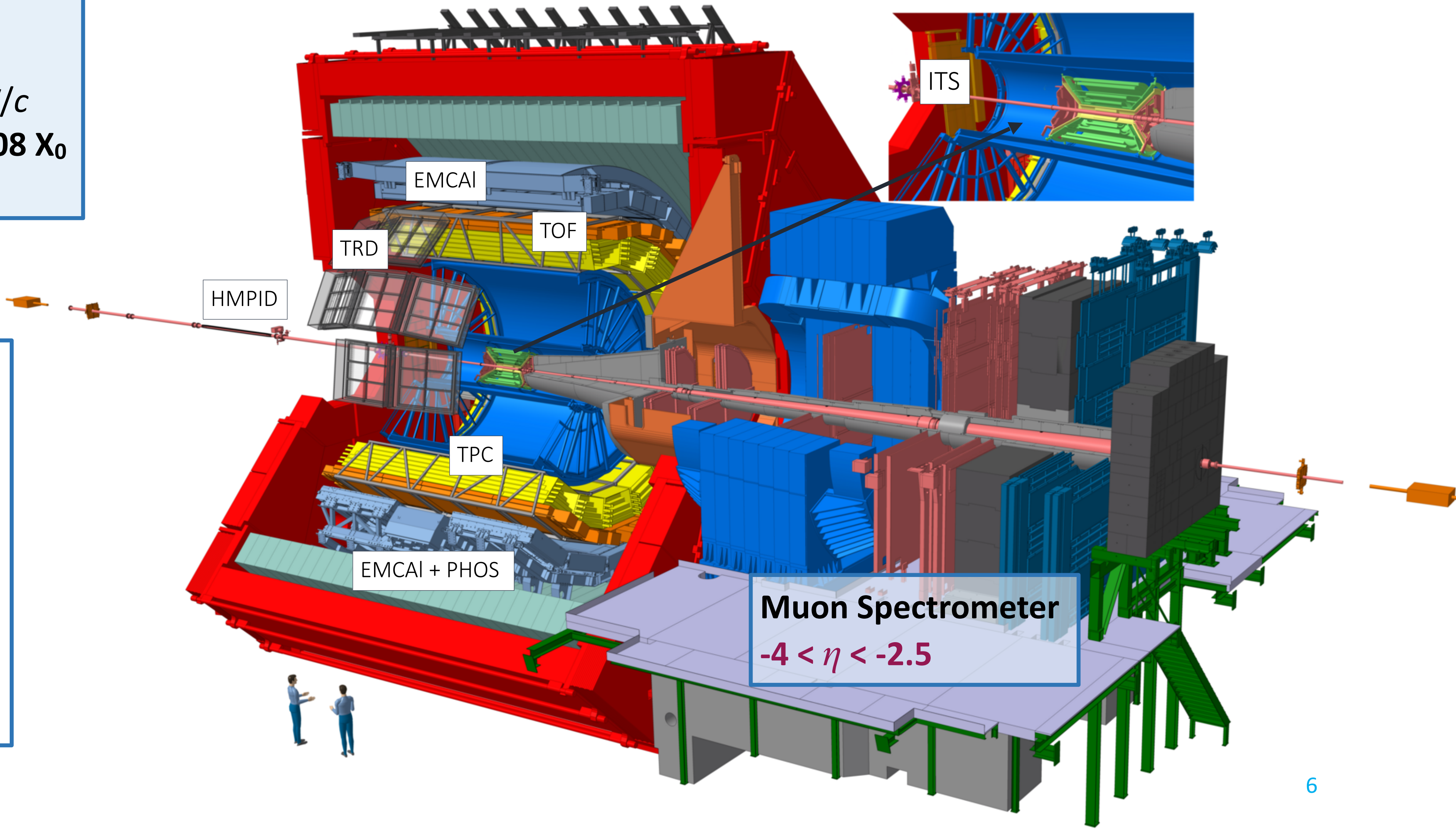


# ALICE 1 (2009 - 2018): LHC RUN 1 & 2

**Central Barrel $|\eta| < 0.9$**
- Tracking
- PID, p = 0.1 - 20 GeV/*c*
- **Material budget: 0.08 $X_0$**
- EM-Calorimeters

ACORDE (cosmics)

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




**Muon Spectrometer**
**$-4 < \eta < -2.5$**

# ALICE COLLABORATION

## **40 countries, 169 institutes**

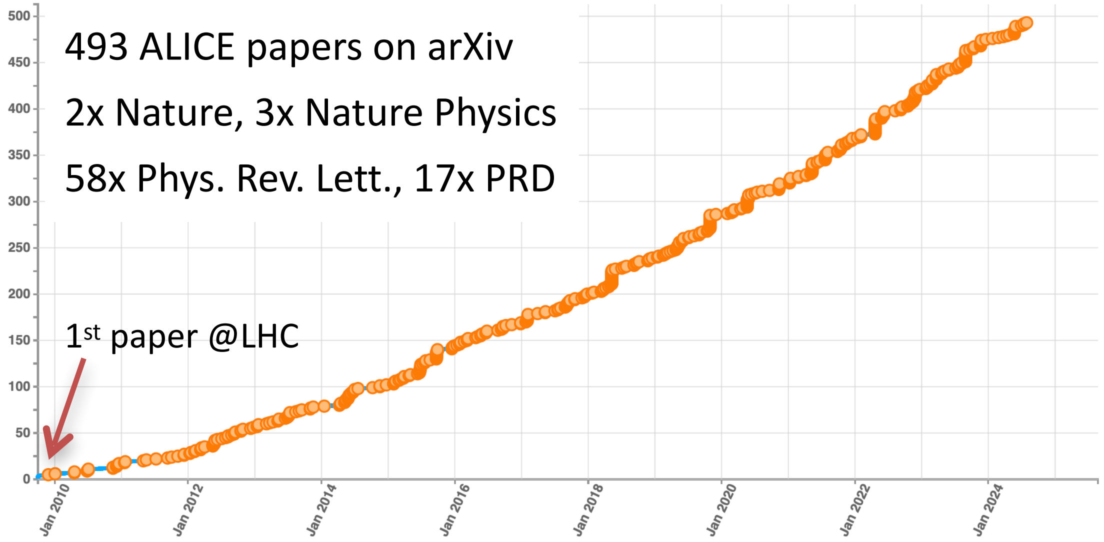
2002 members, 1034 scientific authors

377 doctoral students, 124 postdocs

Participation from **Greece:**
University of Athens
6 members, 2 PhD scientists, 1 doctoral student, 3 authors

Run 1 | Run 2

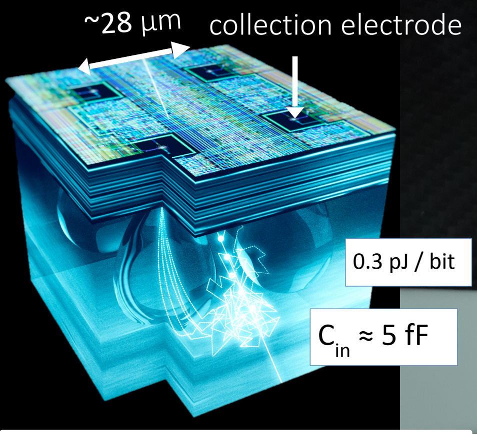
| System | Year(s) | $\sqrt{s_{NN}}$ (TeV) | $L_{int}$ |
|---|---|---|---|
| Pb-Pb | 2010, 2011<br>2015, 2018 | 2.76<br>5.02 | ~75 $\mu b^{-1}$<br>~800 $\mu b^{-1}$ |
| Xe-Xe | 2017 | 5.44 | ~0.3 $\mu b^{-1}$ |
| p-Pb | 2013<br>2016 | 5.02<br>5.02, 8.16 | ~15 $nb^{-1}$<br>~3 $nb^{-1}$, ~25 $nb^{-1}$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



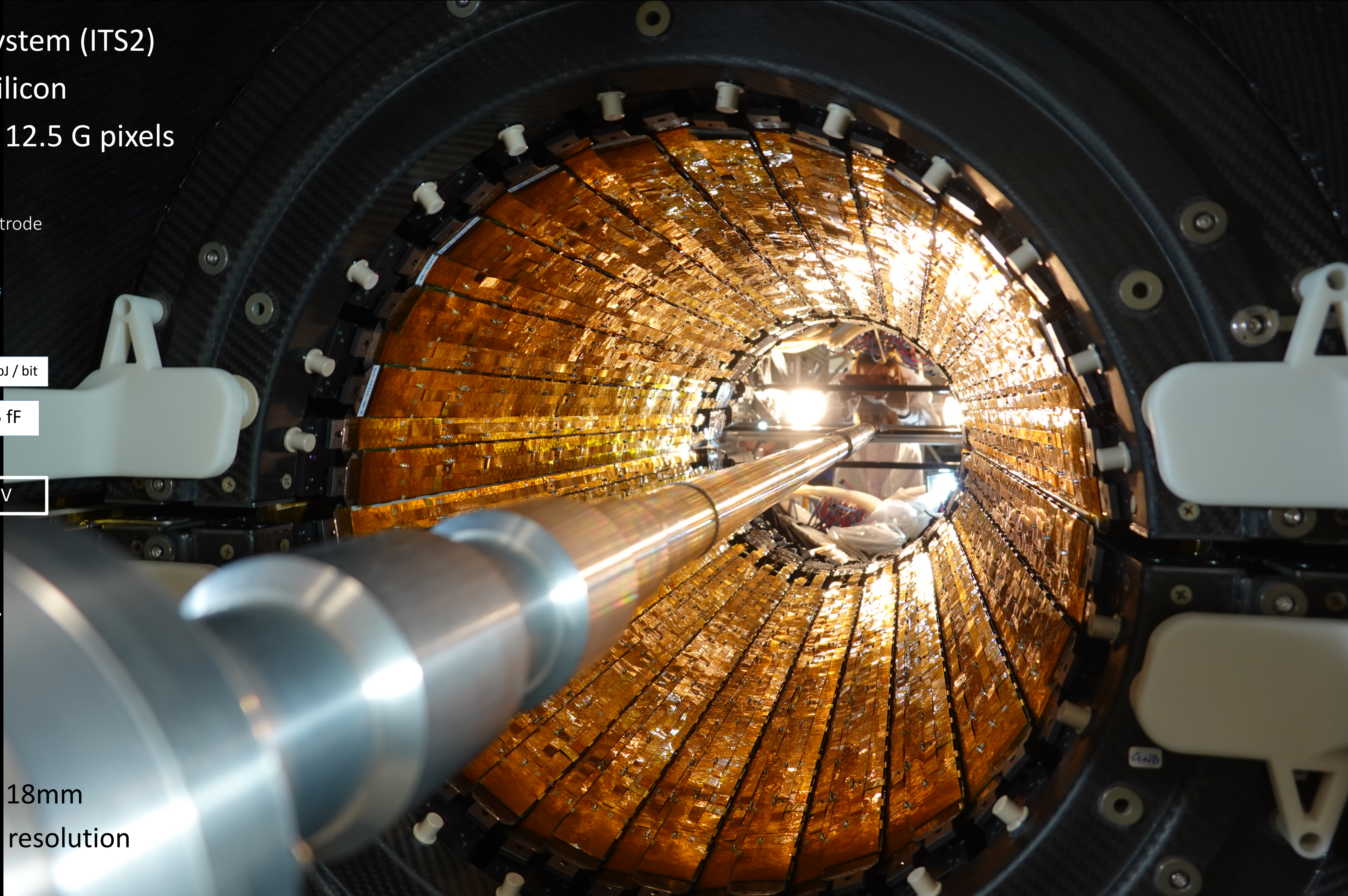
# Inner Tracking System (ITS2)

7 layers, 10 m² silicon

based on MAPS, 12.5 G pixels




$Q_{in}$ (MIP) ≈ 1300 e ⇨ V ≈ 40mV



0.36% $X_0$ per layer

pixel size:

30 x 30 μm²

beam pipe radius: 18mm

3x higher pointing resolution

Time Projection Chamber (TPC)

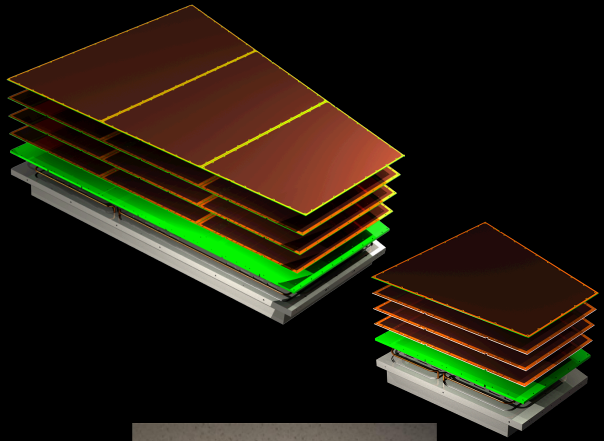
V = 88m³, $\Delta T < 0.1\ \mathrm{K}$

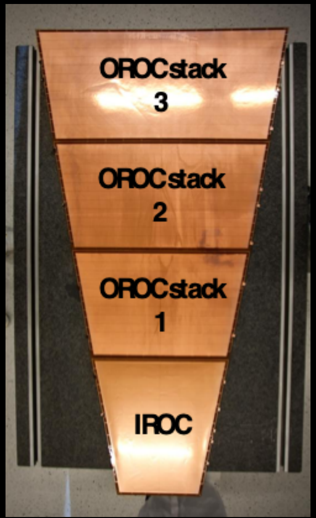
Multiwire proportional chamber

→ quadruple-GEM readout

→ continuous readout (100x faster)

3.4 TeraBytes/second





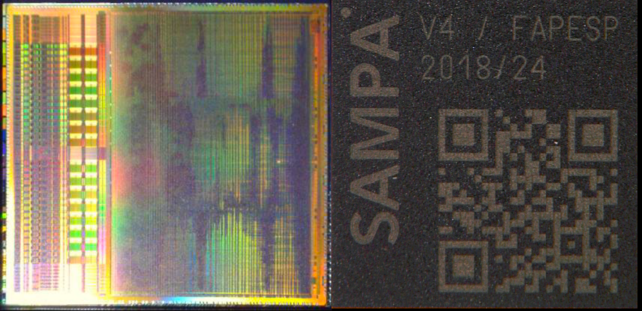

# ALICE computing: 3.6 TeraBytes/s raw data —> up to 170 GBytes/s to disk

350 EPN servers

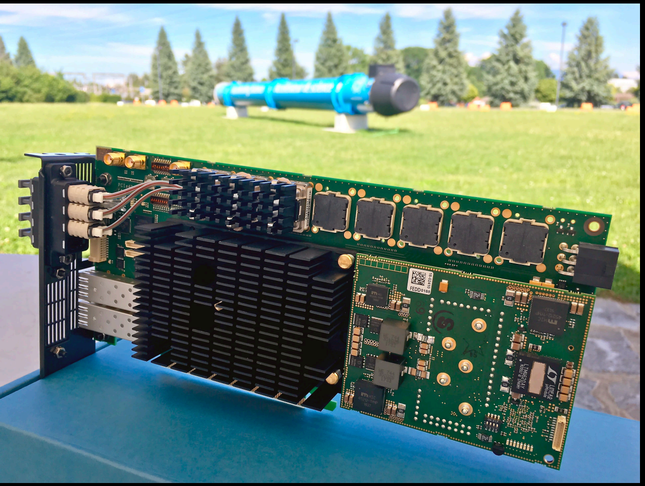
50k CPUs

2800 AMD GPUs

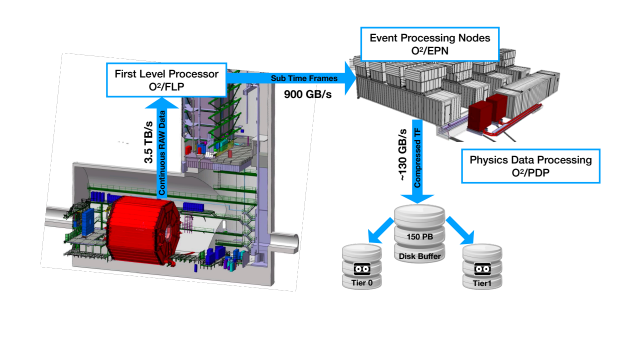
150 PetaBytes disk

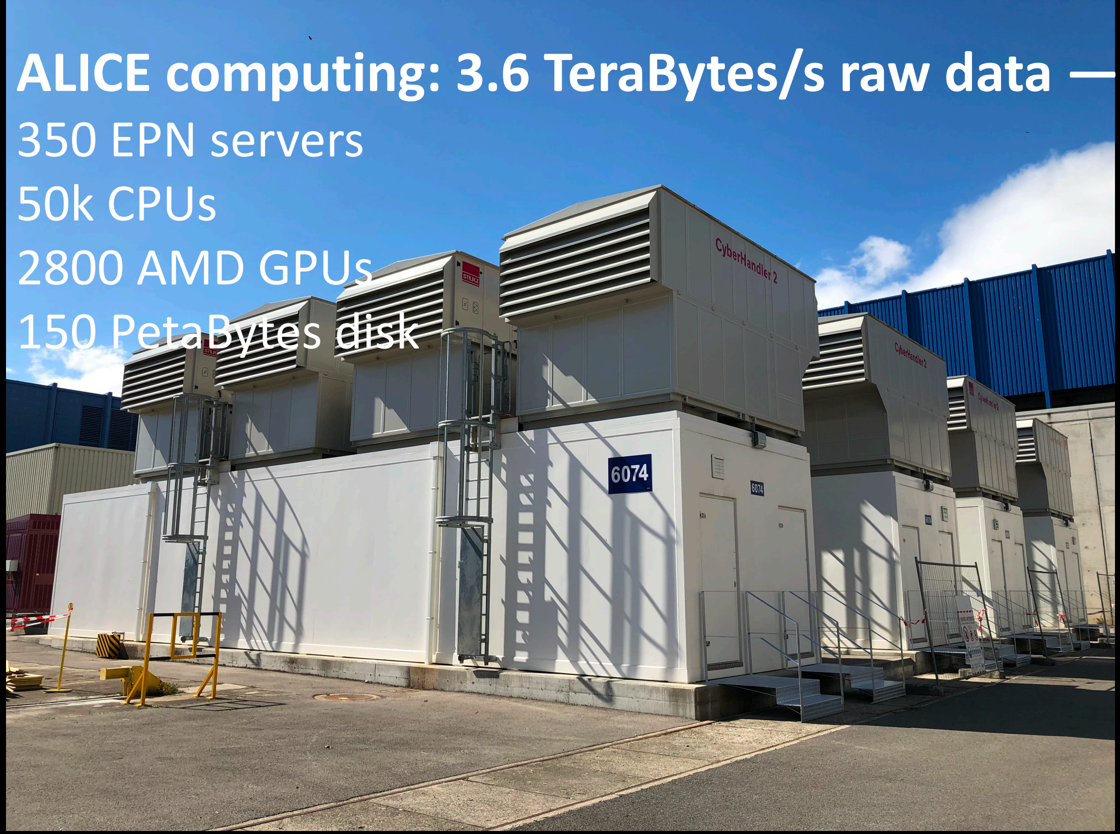


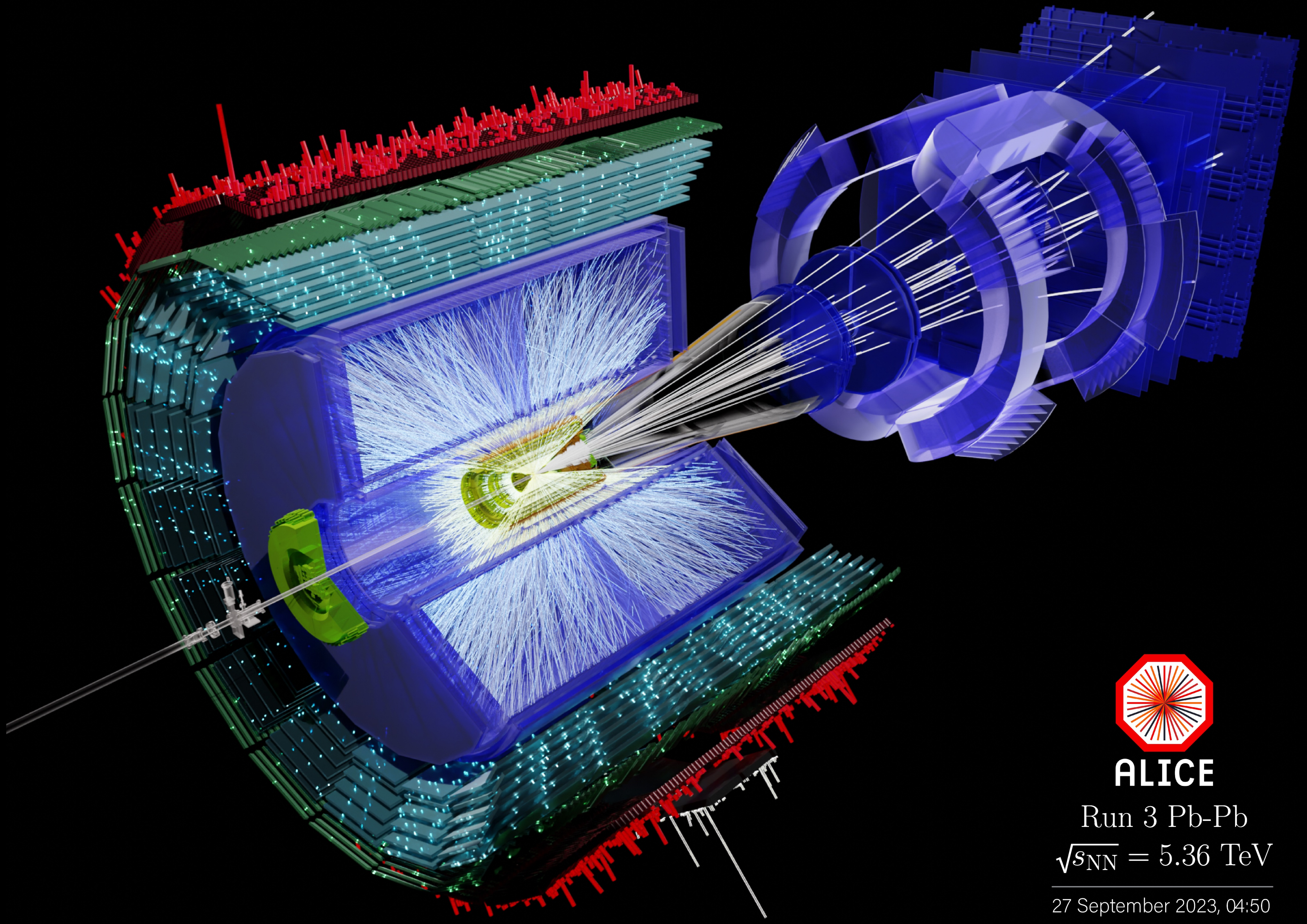

SAMPA chip



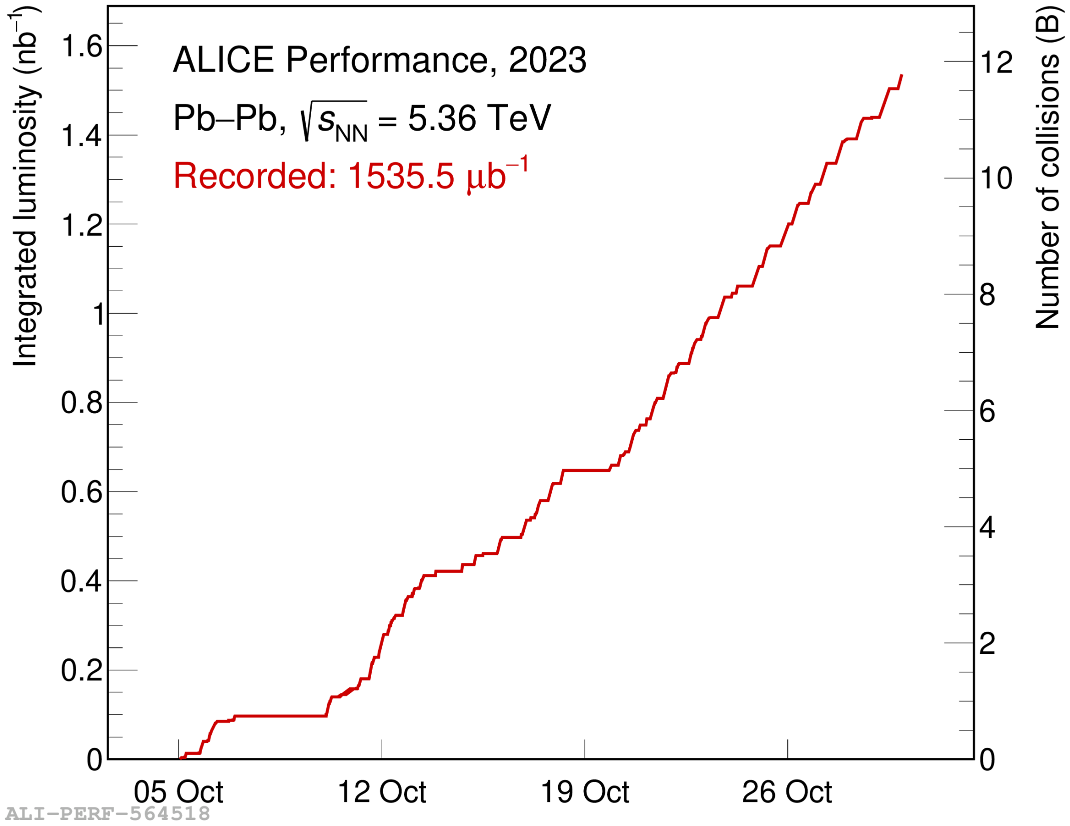
common readout unit
(world's largest FPGA)

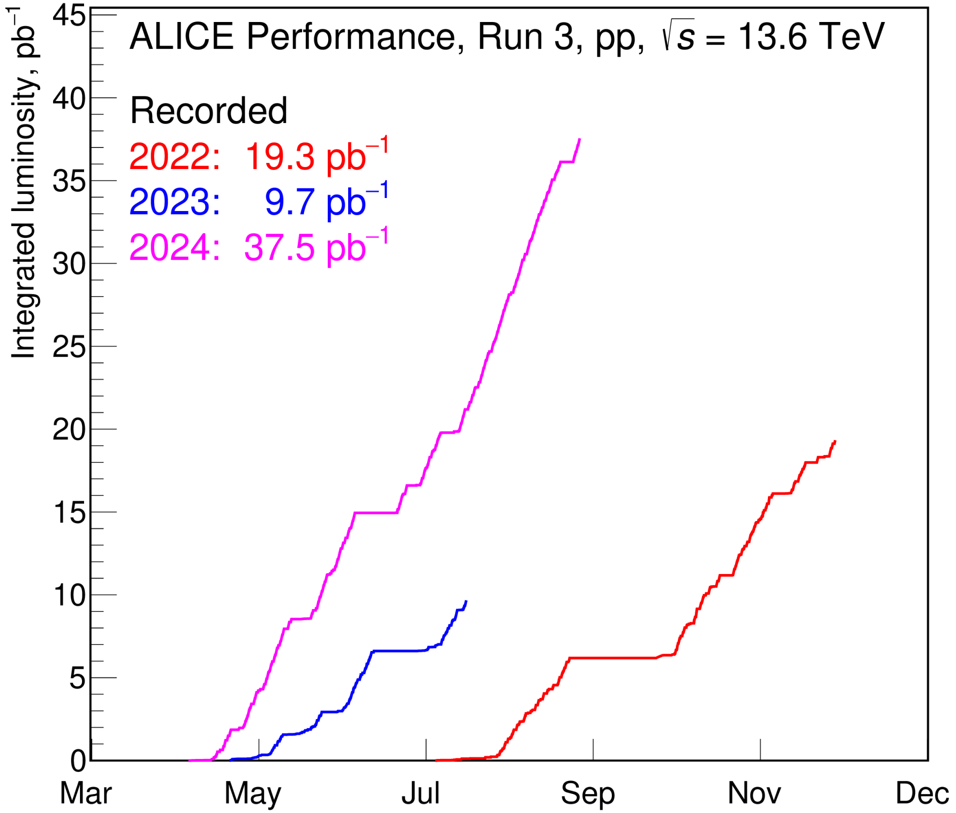




ALICE
Run 3 Pb-Pb
$\sqrt{s_{NN}} = 5.36$ TeV
27 September 2023, 04:50

# Run 3: INTEGRATED LUMINOSITY




**2023 Pb-Pb**: 12 billion minimum bias collisions
**40x minimum bias**, **6x central** wrt Run 1 + 2
expect **similar Pb-Pb data** set in **2024**

**2024 pp**: > 1.5 trillion minimum bias collisions
still counting at **95%** data recording **efficiency**
expect **about 55 pb$^{-1}$ pp** collisions in 2024

# THE HIGH-LUMINOSITY LHC (Pb-Pb)

ALICE

**instantaneous luminosity**

$$L = 6 \cdot 10^{27} \text{cm}^{-2}\text{s}^{-1}$$

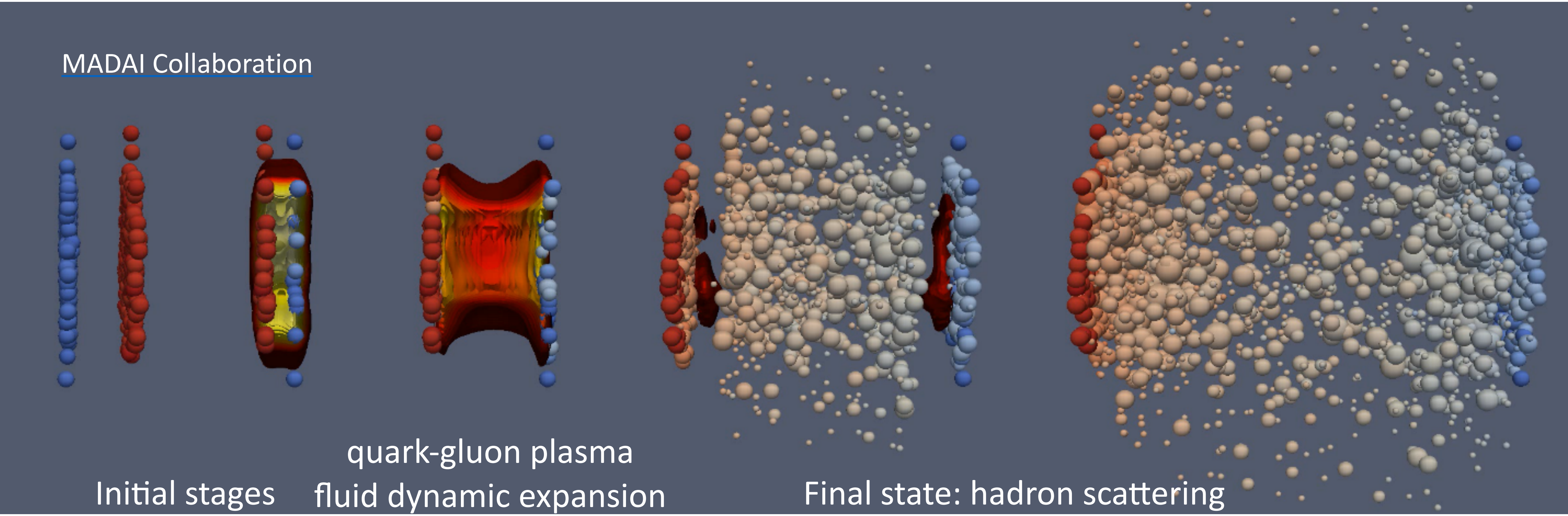
$$\text{d}N/\text{d}t = L \cdot \sigma, \quad \sigma_{\text{Pb-Pb}} = 8\text{b}, 1\text{b} = 10^{-24}\text{cm}^2$$

$$\text{d}N/\text{d}t = 6 \cdot 10^{27} \cdot 8 \cdot 10^{-24} \text{ s}^{-1} = 48000 \text{ s}^{-1}$$

**integrated luminosity** for Pb-Pb (Run 3 + 4): 2023 - 2032

$\mathscr{L}_{\text{int}} = 13\text{nb}^{-1} \rightarrow$ 100 B zero-bias Pb-Pb collisions (!) in continuous readout

# HISTORY OF A LEAD-LEAD COLLISION



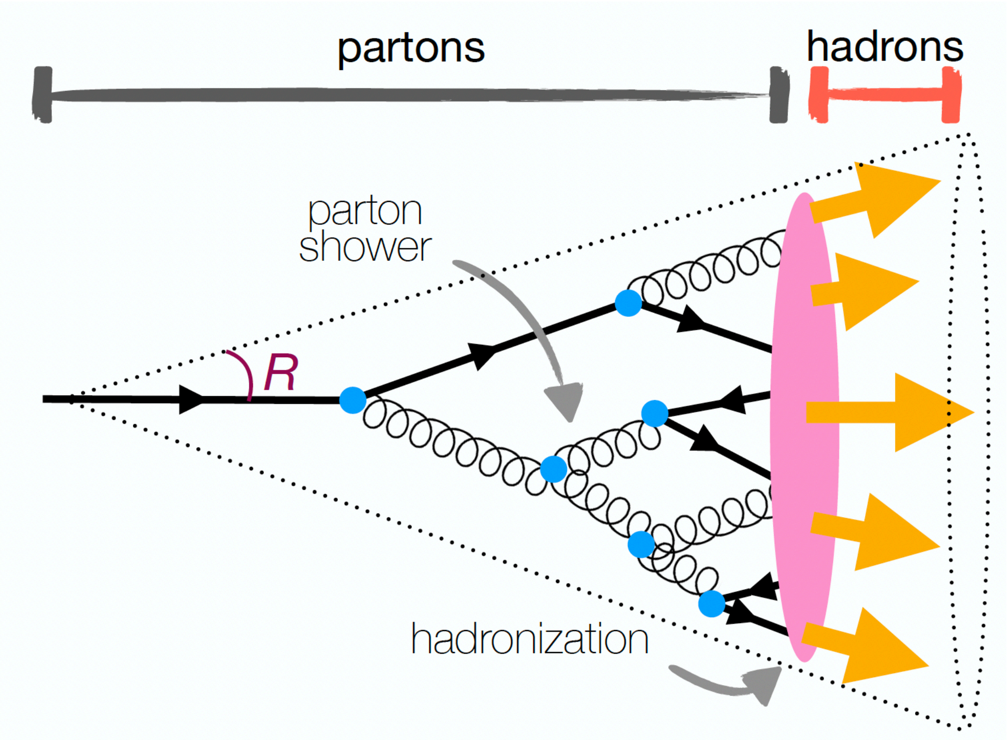

**Emission of thermal radiation** $\propto T^2$

| Initial stages | quark-gluon plasma / fluid dynamic expansion | Final state: hadron scattering |
|---|---|---|
| geometry<br>gluon density<br>saturation ? | parton energy loss, collectivity<br>transport coefficients, temperature | scattering lengths<br>hypernuclei, exotica |

# Probing QGP with jets

## Vacuum fragmentation (e.g. pp collisions)

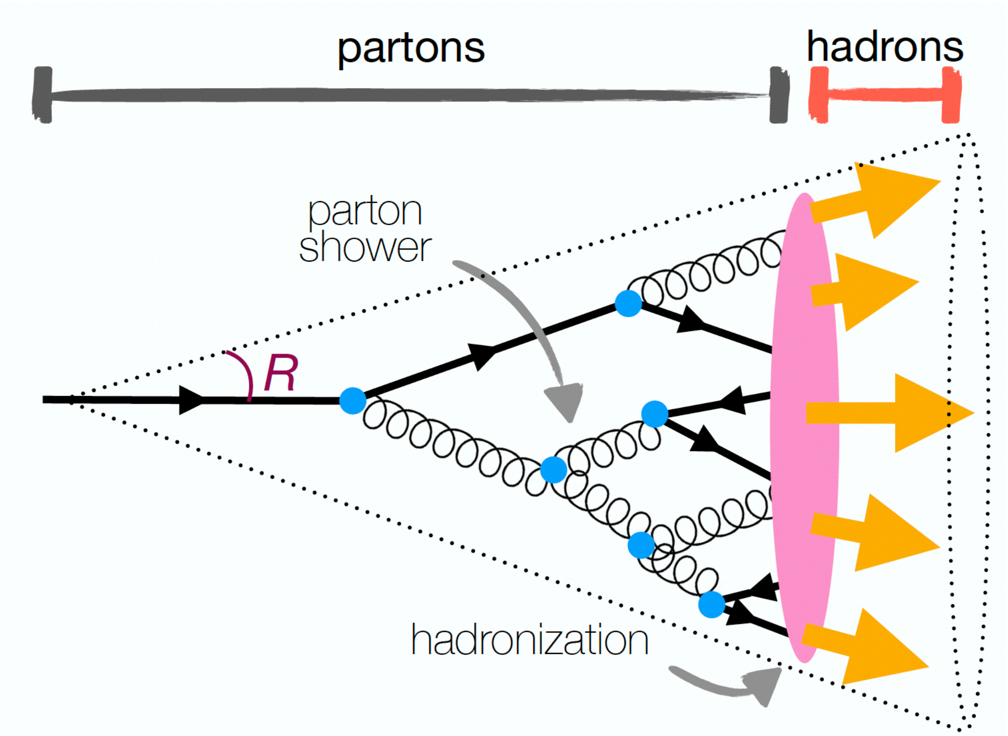
Collimated sprays of hadrons resulting from fragmentation and subsequent hadronization of “high-energy” partons (quarks&gluons)



# Probing QGP with jets

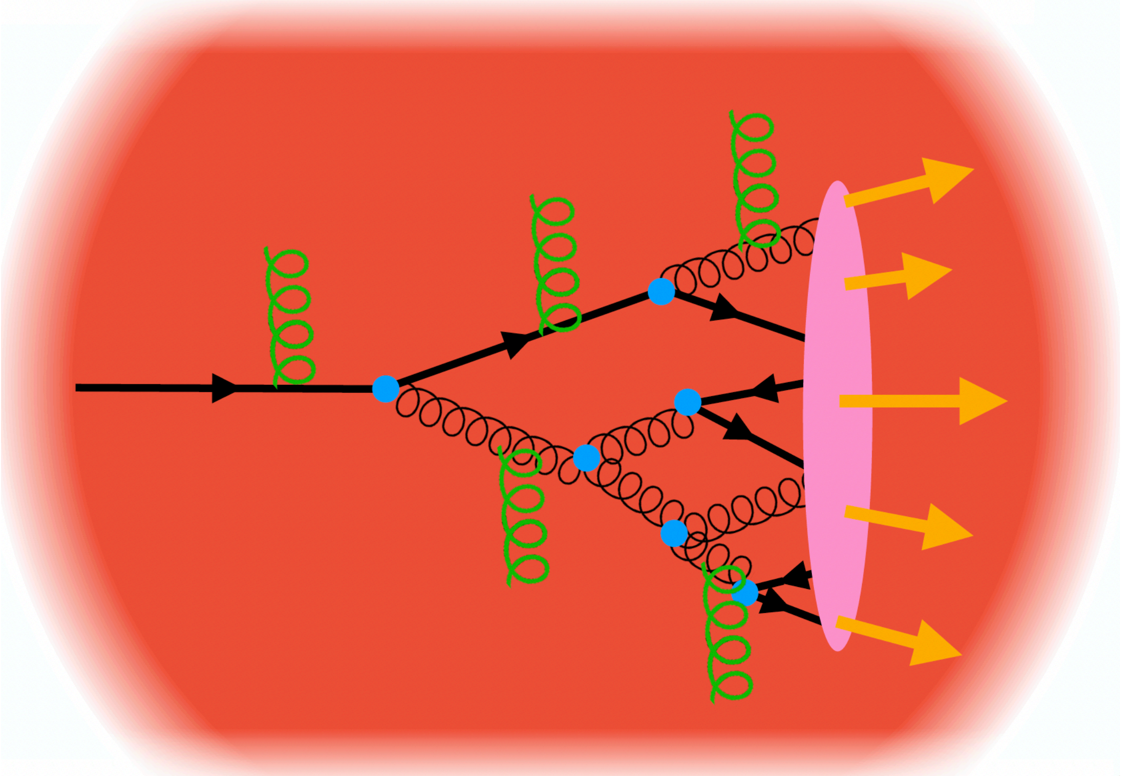
## Vacuum fragmentation (e.g. pp collisions)

Collimated sprays of hadrons resulting from fragmentation and subsequent hadronization of "high-energy" partons (quarks&gluons)



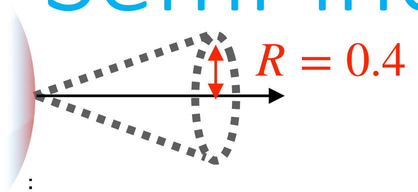

## In-medium fragmentation (e.g. Pb-Pb collisions)

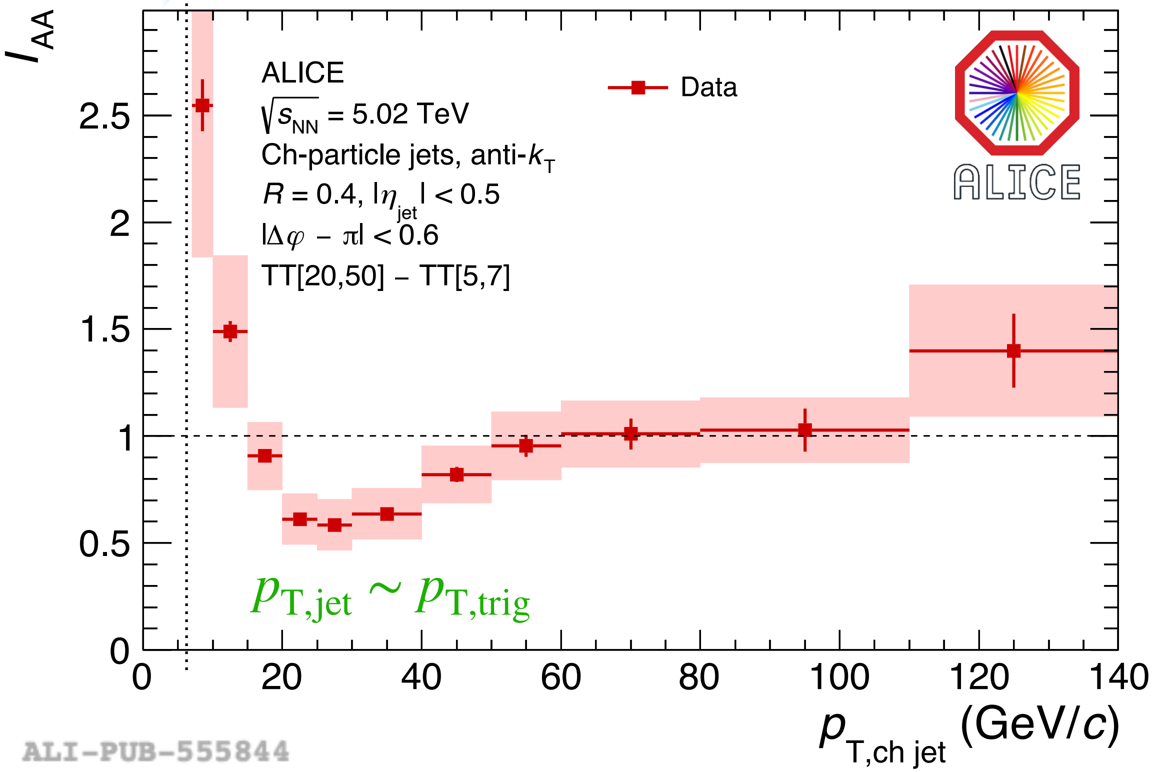
Quenching→parton lose energy through medium-induced gluon radiations and collisions with medium constituents



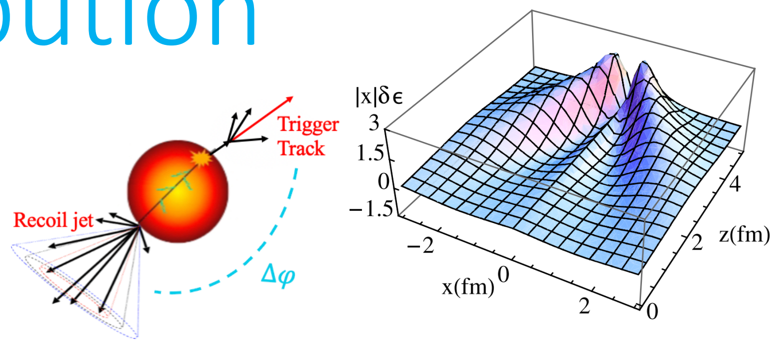
G-Y. Qin, et. al, PRL 103 (2009) 152303

# Semi-inclusive jet energy redistribution




$$I_{AA} \equiv \frac{\Delta_{recoil}\ (p_T)_{AA}}{\Delta_{recoil}\ (p_T)_{pp}}$$




First measurements of semi-inclusive recoil jet yields down to very low $p_T$ (7 GeV/$c$) with ALICE

Jet yield enhancement at low $p_T$

→ hint of energy recovery in low $p_T$ jets?

Jet yield suppression at $20 < p_{T,jet} < 60$ GeV/$c$

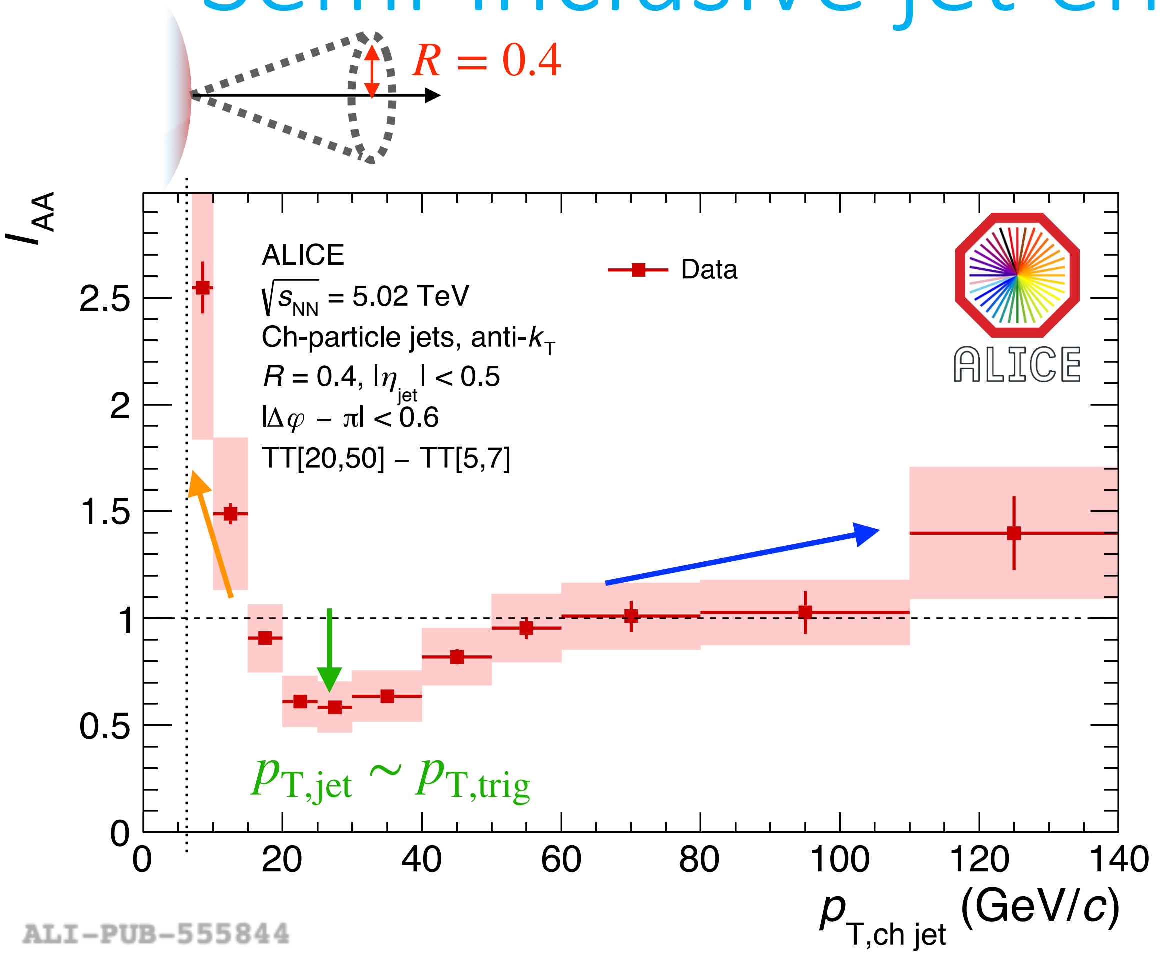
→ Jet energy loss

Rising trend with increasing jet $p_T$

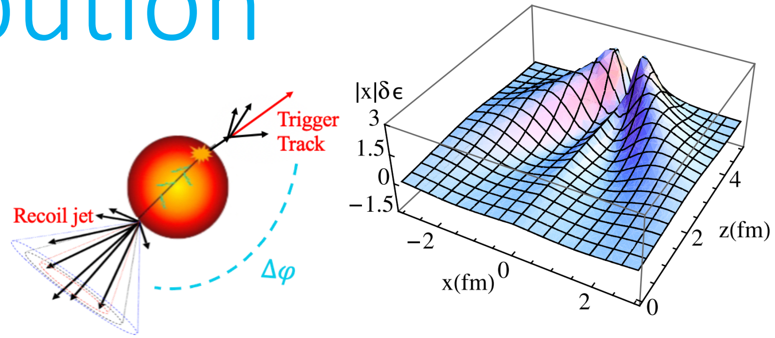
→ Interplay of jet quenching and jet production

G-Y. Qin, et. al, PRL 103 (2009) 152303

# Semi-inclusive jet energy redistribution




$$I_{AA} \equiv \frac{\Delta_{recoil}\,(p_T)_{AA}}{\Delta_{recoil}\,(p_T)_{pp}}$$




First measurements of semi-inclusive recoil jet yields down to very low $p_T$ (7 GeV/$c$) with ALICE

Jet yield enhancement at low $p_T$

→ hint of energy recovery in low $p_T$ jets?

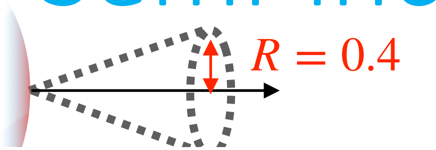
Jet yield suppression at $20 < p_{T,jet} < 60$ GeV/$c$

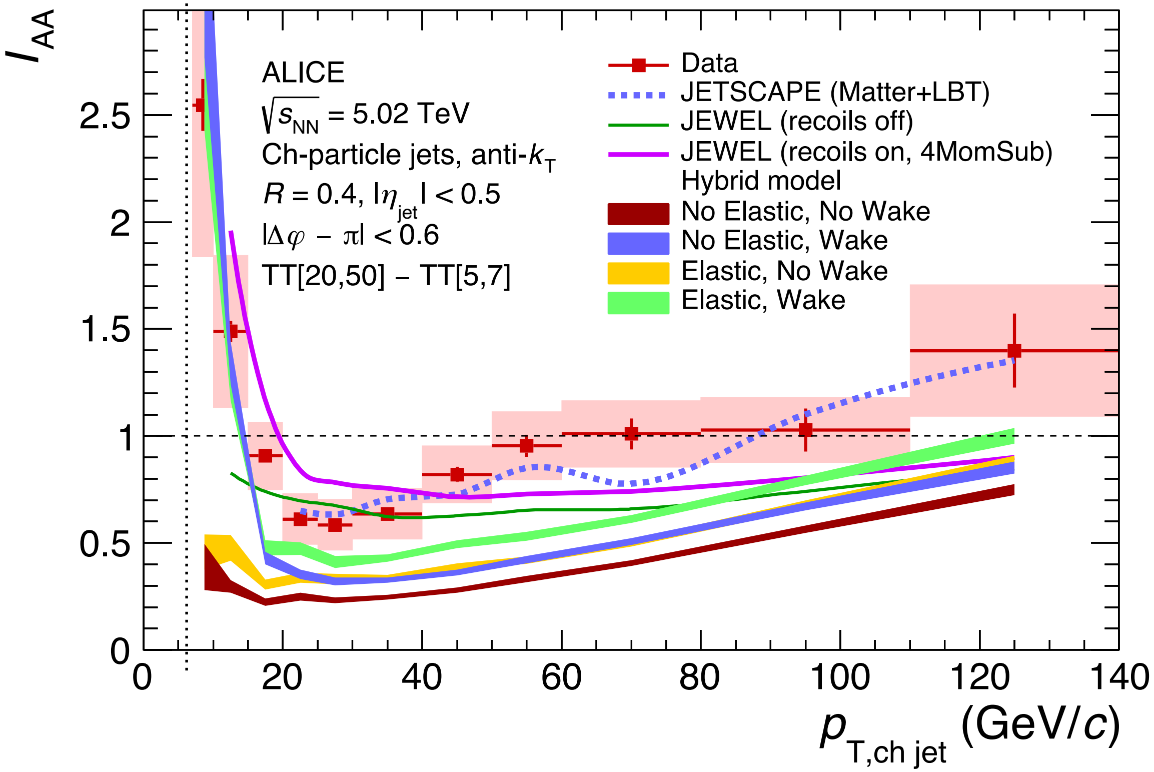
→ Jet energy loss

Rising trend with increasing jet $p_T$

→ Interplay of jet quenching and jet production

# Semi-inclusive jet energy redistribution

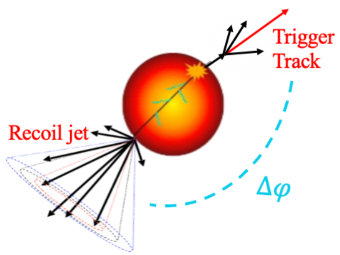


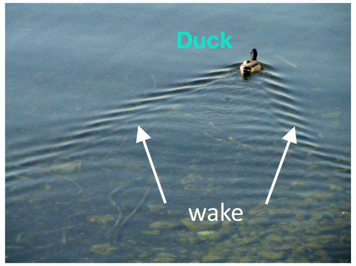




PRL 133 (2024) 022301

PRC 110 (2024) 014906

$$I_{AA} \equiv \frac{\Delta_{recoil}\ (p_T)_{AA}}{\Delta_{recoil}\ (p_T)_{pp}}$$



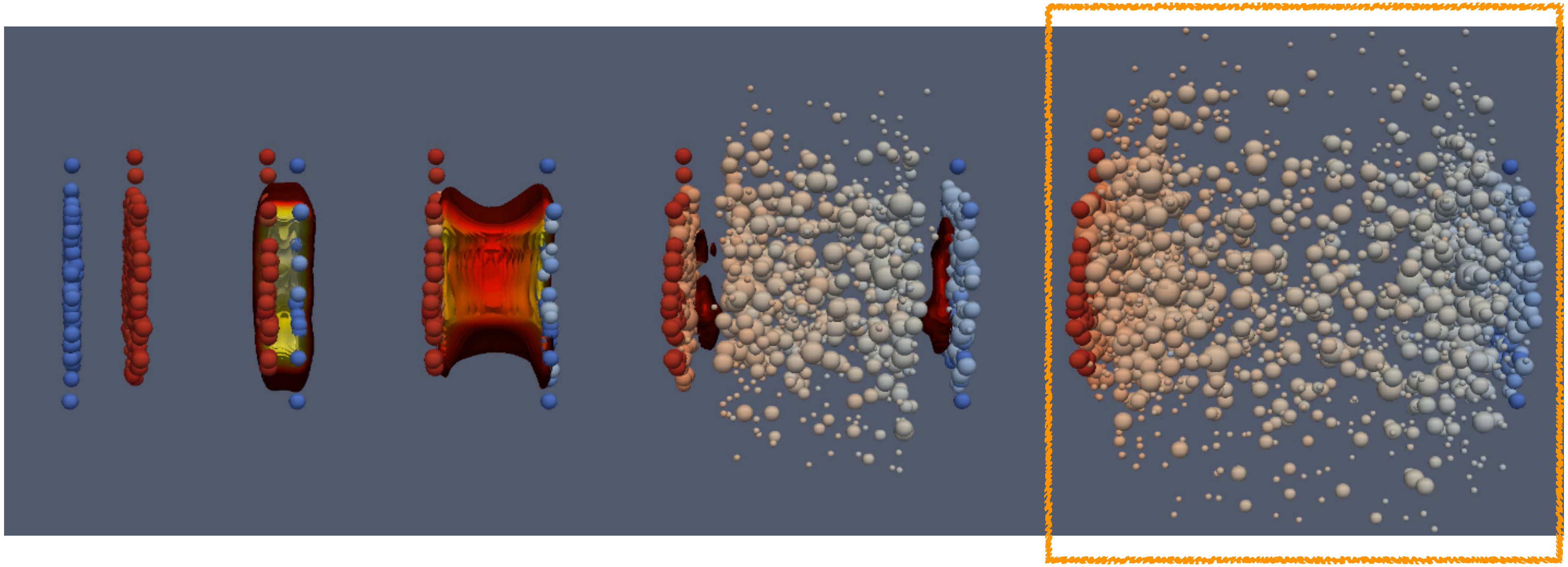

First measurements of semi-inclusive recoil jet yields down to very low $p_T$ (7 GeV/$c$) with ALICE

The rising trend is qualitatively described by all predictions

Hybrid model and JEWEL predictions overestimate the suppression at high $p_T$

Hybrid model with wake effect and JEWEL with recoils on capture the yield enhancement at low $p_T$ → Medium response could be responsible for enhancement

# FINAL STATE: HADRON PRODUCTION

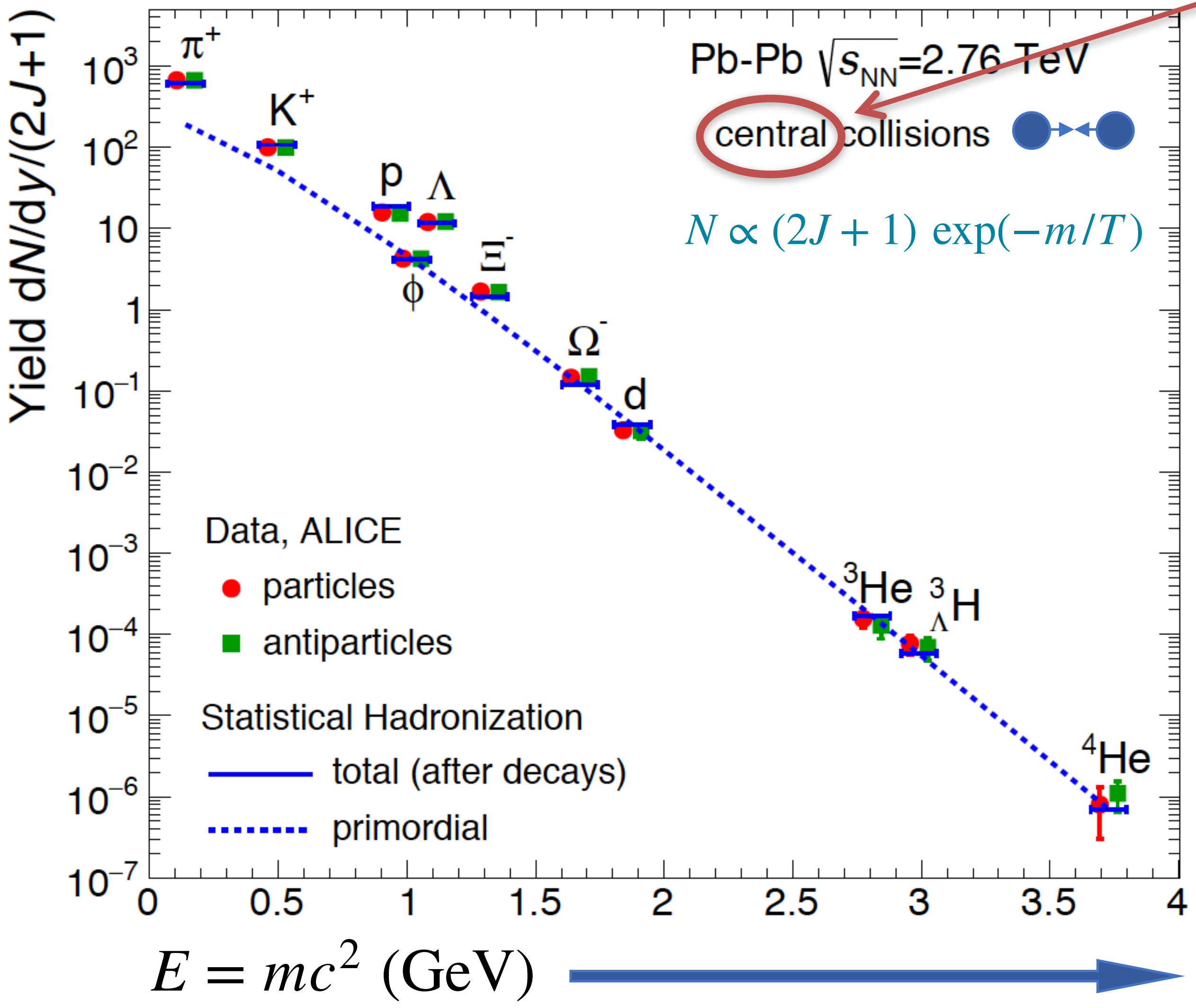


**Hadronic Stage**

particle production, resonances, scattering lengths, …

# Thermal particle production

ALICE




Highest multiplicity

**QCD**-analog of **Planck spectrum**

T = 156.2 ± 2 MeV

[Nature 561, 321 (2018)]

Baryo-chemical potential

$$\mu_B = 0.71 \pm 0.45 \text{ MeV}$$

**Particle** and **antiparticles** created at almost **identical yields**

[arXiv:2311.13332]

**Lattice-QCD** results **agree**

$T_{pc}$ = 156.5 ±1.5 MeV

A. Bazavov et al. (Hot QCD) [arXiv:1812.08235]

# Chemical Freeze-out Model

ALICE

## Hadron resonance ideal gas

P. Braun-Munzinger et al., nucl-th/0304013

Density of particle *i*

$$\rho_i = \frac{N_i}{V} = \frac{g_i}{2\pi^2} T_{\mathrm{ch}}{}^3 \left(\frac{m_i}{T_{\mathrm{ch}}}\right)^2 K_2(m_i/T_{\mathrm{ch}})\, \lambda_q^{Q_i}\, \lambda_s^{s_i}$$

$$\lambda_q = \exp(\mu_q/T_{ch}), \quad \lambda_s = \exp(\mu_s/T_{ch})$$

$q_i$ : 1 for u and d, -1 for ū and d̄

$s_i$ : 1 for s, -1 for s̄

$g_i$ : spin-isospin freedom

$m_i$ : particle mass

$T_{ch}$ : Chemical freeze-out temperature

$\mu_q$ : light-quark chemical potential

$\mu_s$ : strange-quark chemical potential

V : volume term, drops out for ratios!

$\mu_B = 3\mu_q$

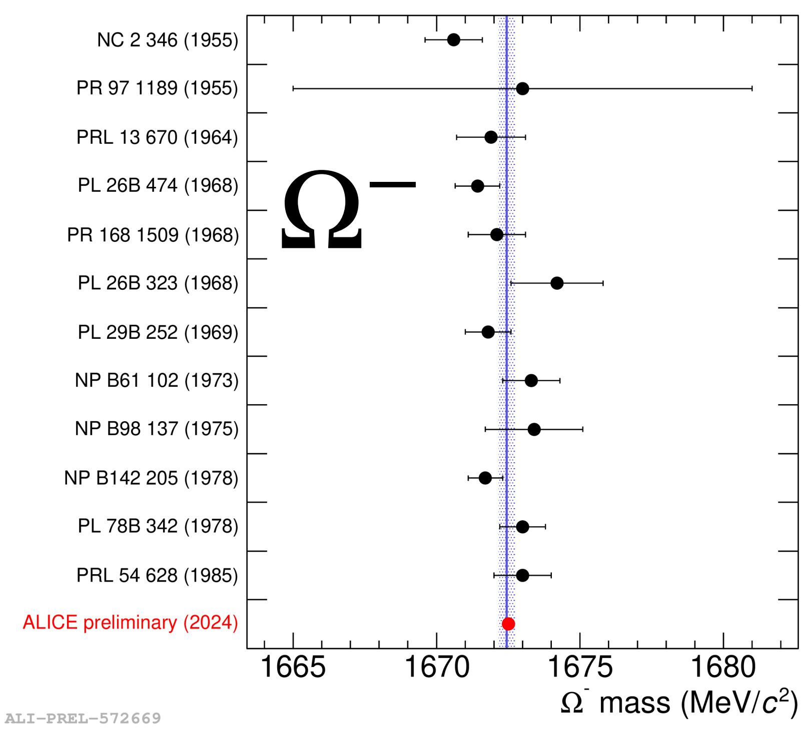
$\mu_S = \mu_q - \mu_s$

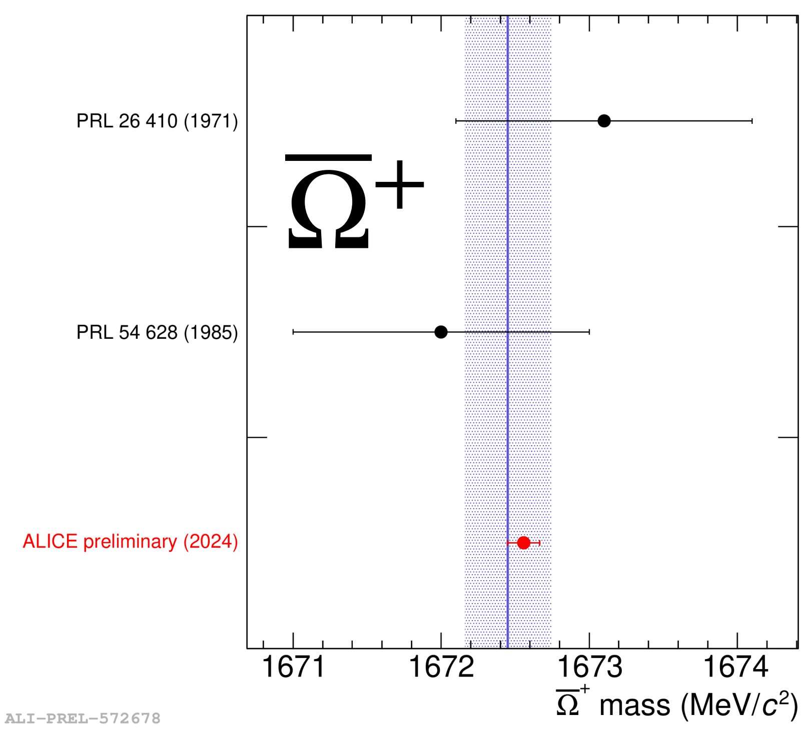
All resonances and unstable particles are decayed

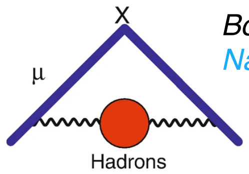
↓

Compare particle ratios to experimental data

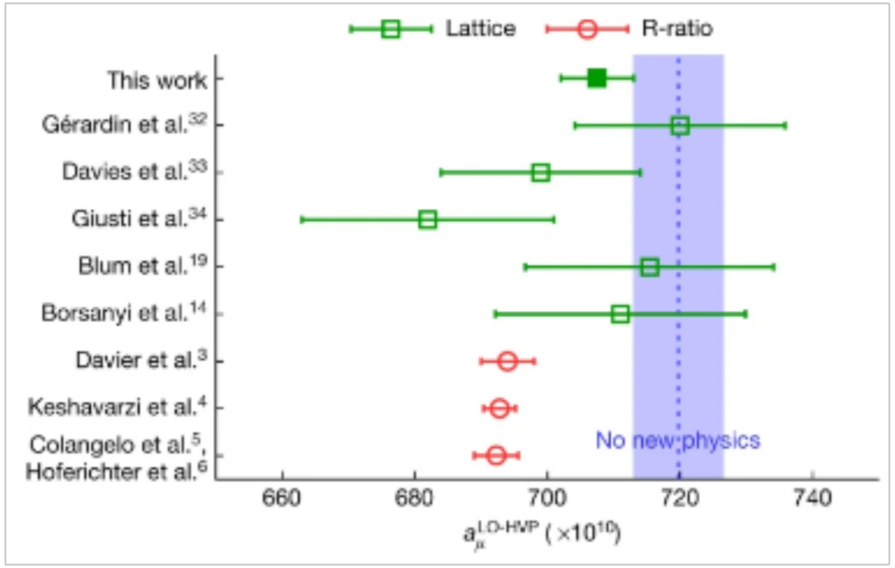
# $\Omega^-$ AND $\overline{\Omega}^+$ MASS - MUON G-2




*Borsanyi, Fodor, Guenther, et al.*
*Nature 593, 51–55 (2021)*




**high-precision** measurement of $\Omega^-$and $\overline{\Omega}^+$ **mass**

**3x** more precise than **world average** $\Omega^-$and $\overline{\Omega}^+$

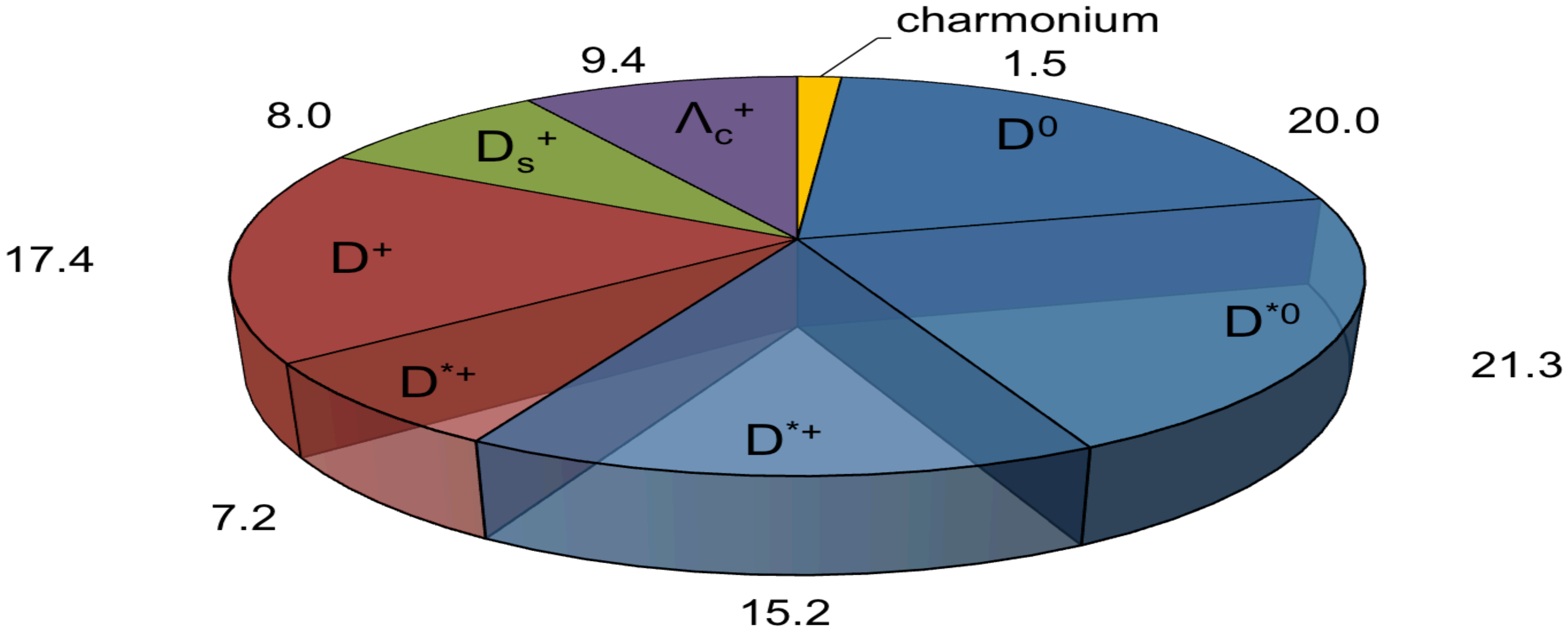
(**world** average **based** on **257 counts**)

$\Omega^-$and $\overline{\Omega}^+$ used to set **physical scale** in **lattice QCD**

**muon g-2**, $4\sigma$ **discrepancy** between **theory** and **experiment** might be due to **hadron vacuum polarization (HVP)**

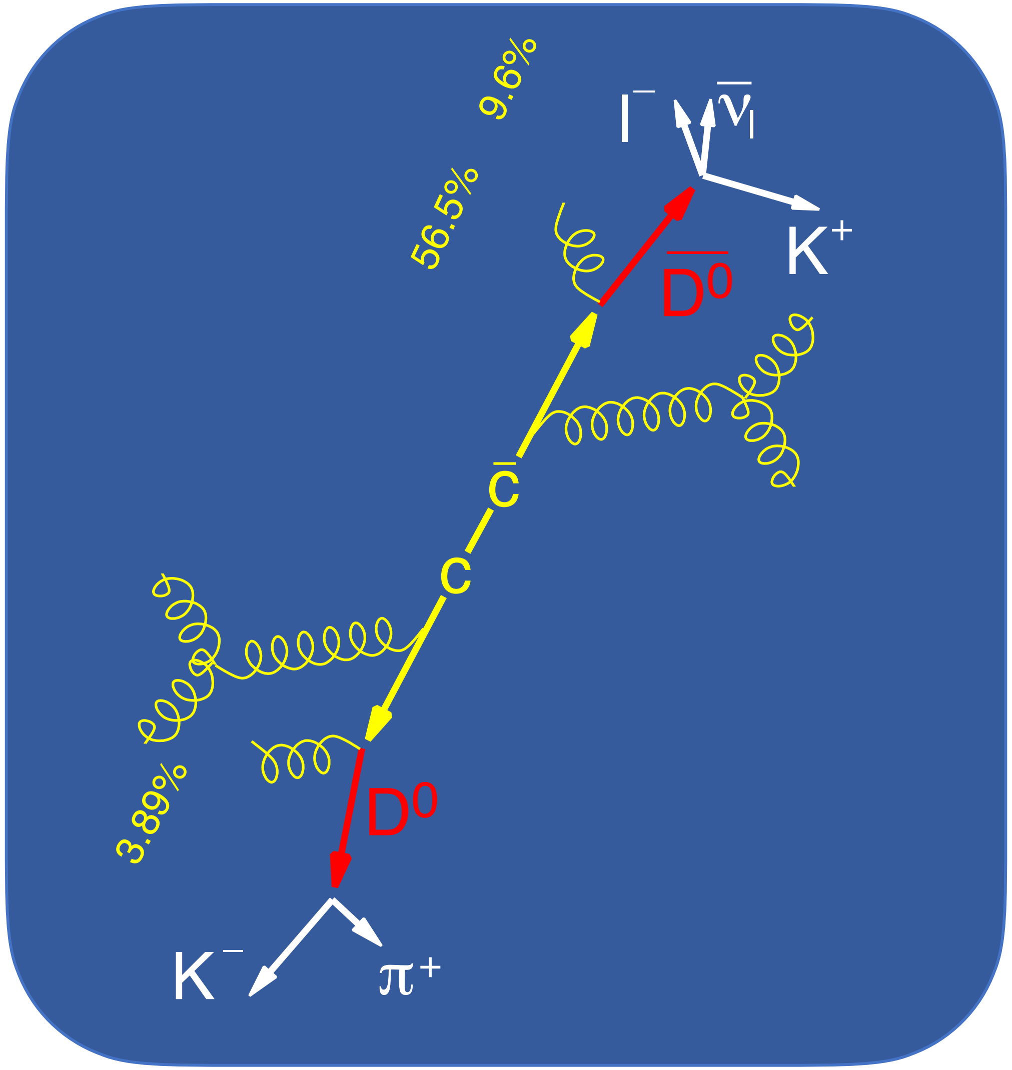
**calculate** HVP in lattice **QCD**

# Where does all the charm go ?




**in vacuo** ($e^+e^-$ collisions): about **56%** of all **charm quarks** fragment into **$D^0$** mesons

# heavy-quark detection




e.g., $D^0$ ($c\overline{u}$)→ $K^-$ + $\pi^+$ , cτ = 123 μm

displaced decay vertex is signature of heavy-quark decay

→ need sub-millimeter pointing precision to collision vertex

separation of time scales:

charm quark creation - 0.08 fm/c

hadronization - 1 fm/c

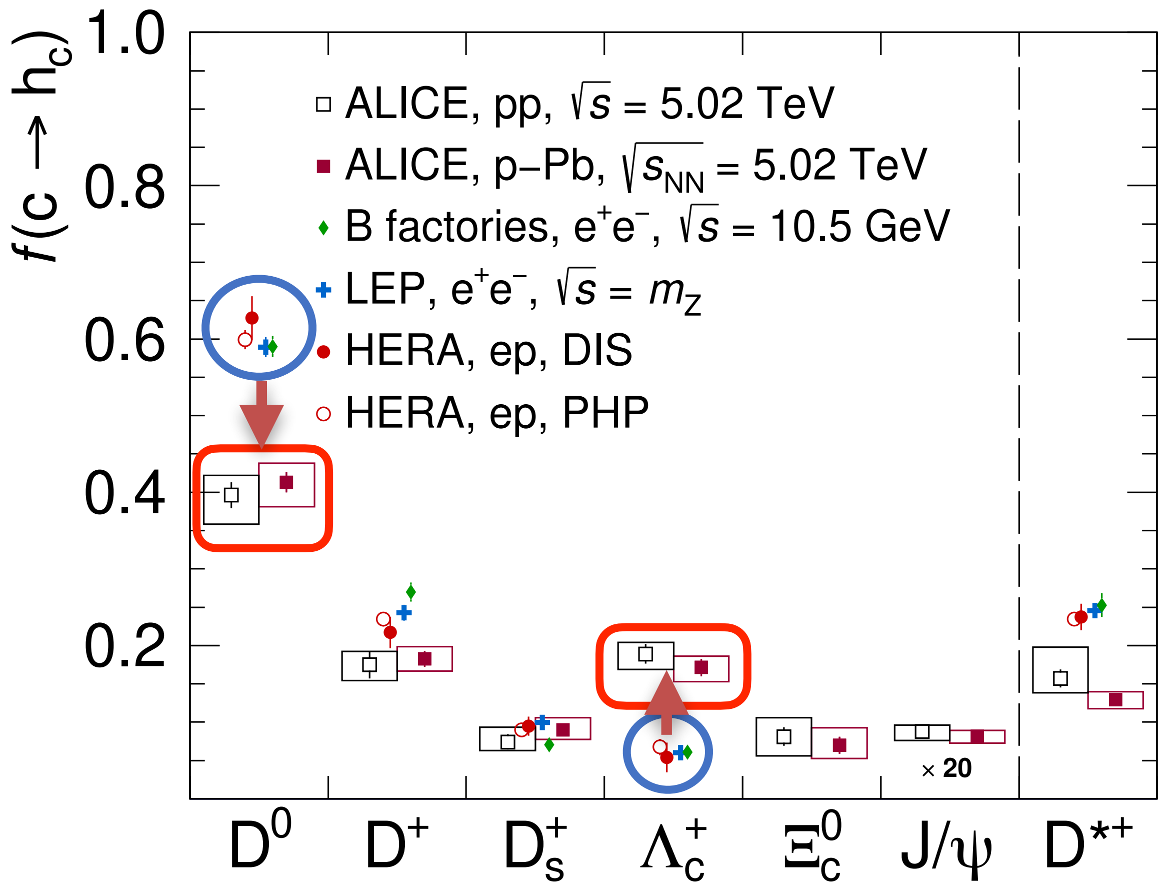
$D^0$ decay - $10^{10}$ fm/c

plot: courtesy of D. Tlusty

# CHARM PRODUCTION AND FRAGMENTATION

ALICE

Charm fragmentation fraction




ALI-PUB-570972

**Charmed baryon** production **larger** in **pp** and also **p-Pb** than in **$e^+e^-$**

$\Lambda_c$, $\Xi_c$ measured

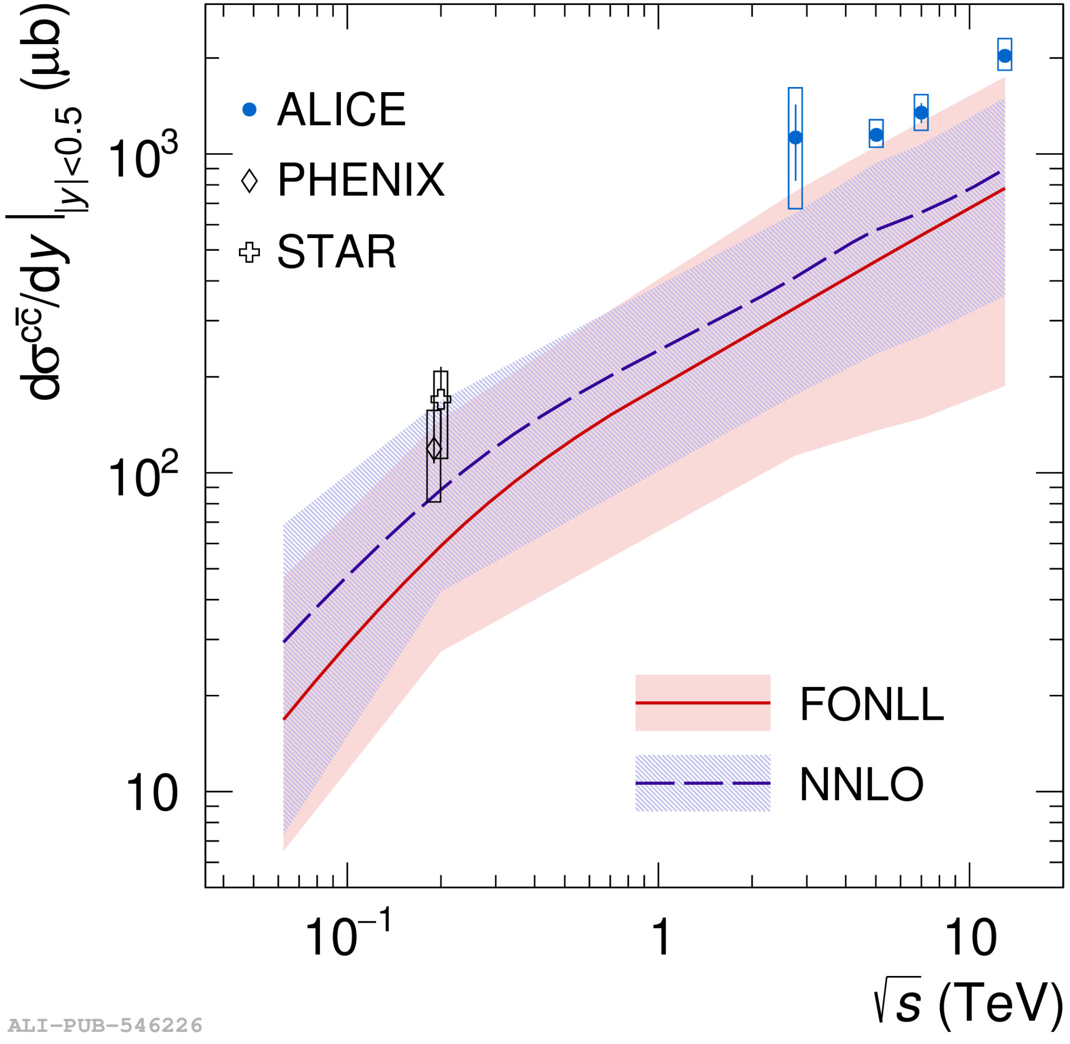
**charm hadronization not universal**

$\sigma_{c\bar{c}}$ **experimental precision** much **better** than **theory**

→ calls for $N^3LO$ calculations

arXiv:2405.14571
arXiv:2308.04877

# CHARM PRODUCTION AND FRAGMENTATION




**Charmed baryon** production **larger** in **pp** and also **p-Pb** than in **$e^+e^-$**

$\Lambda_c$, $\Xi_c$ measured

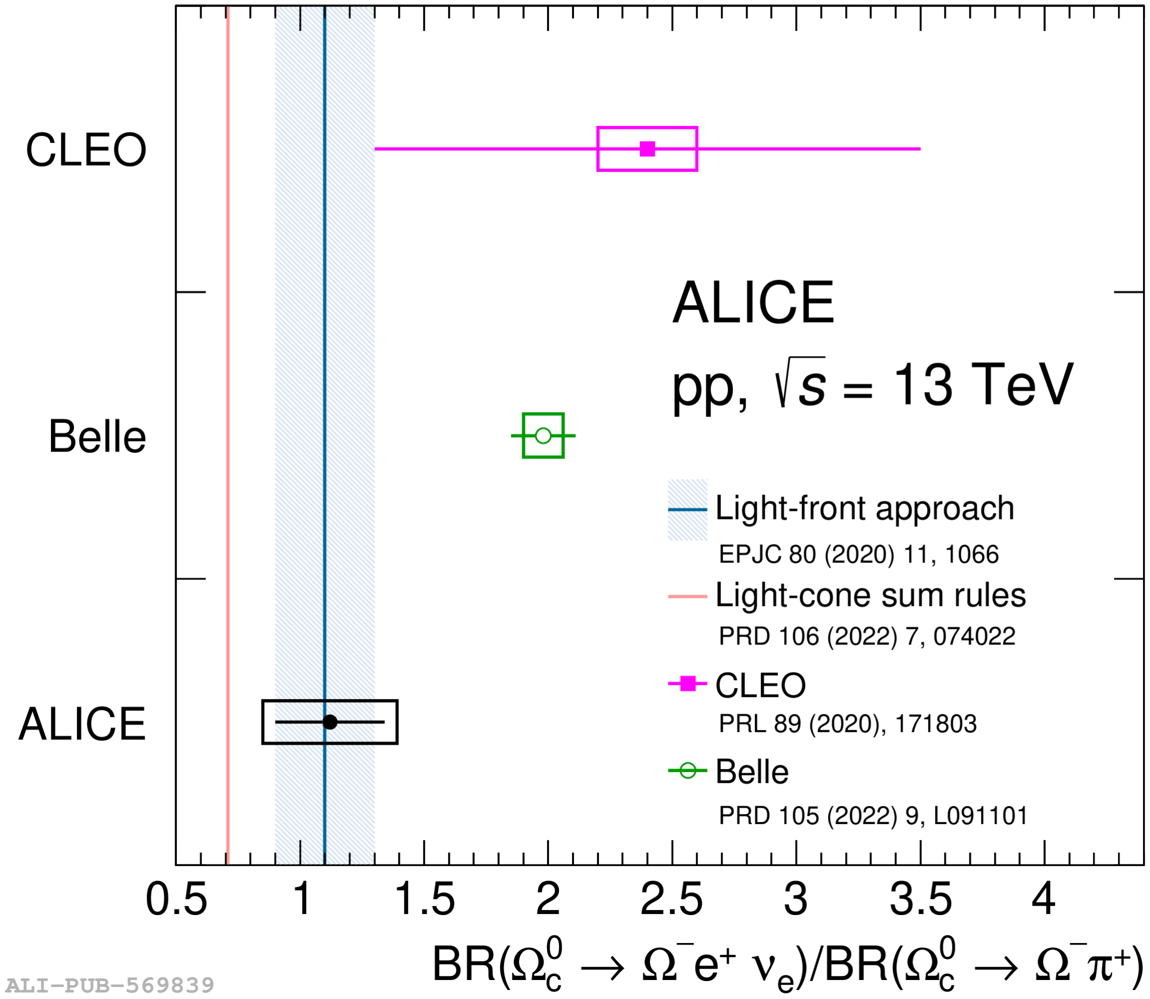
**charm hadronization not universal**

$\sigma_{c\bar{c}}$ **experimental precision** much **better** than **theory**

→ calls for $N^3LO$ calculations

arXiv:2405.14571
arXiv:2308.04877

# branching ratios - $\Omega_c\,,\,|css\rangle$



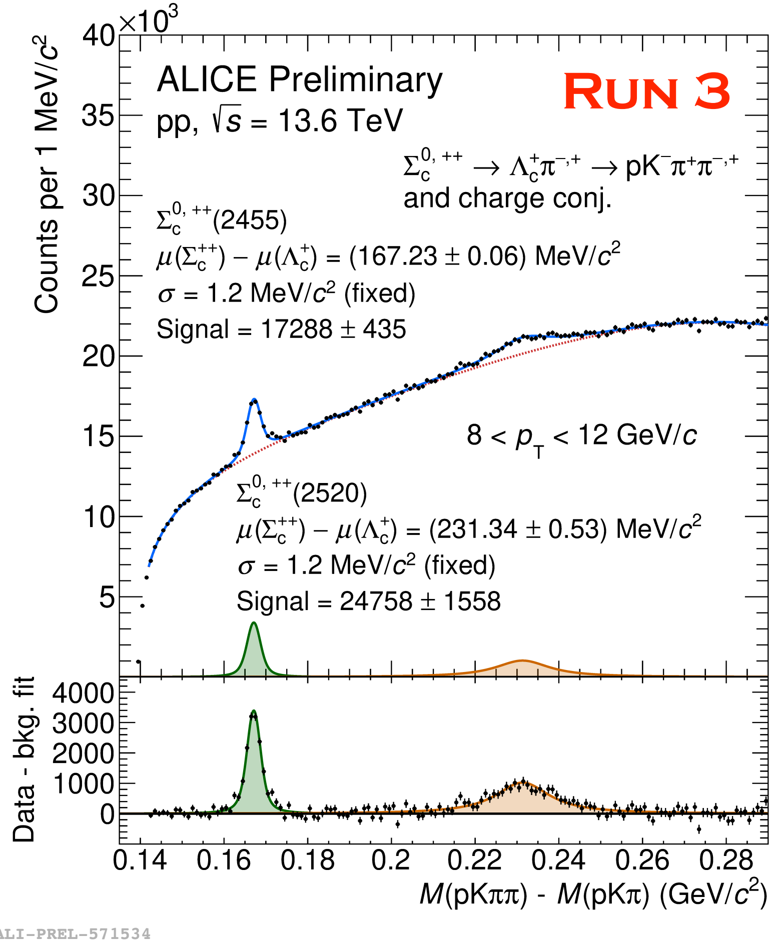

**branching ratios**

- essential for determining total charm production

- challenge to theory

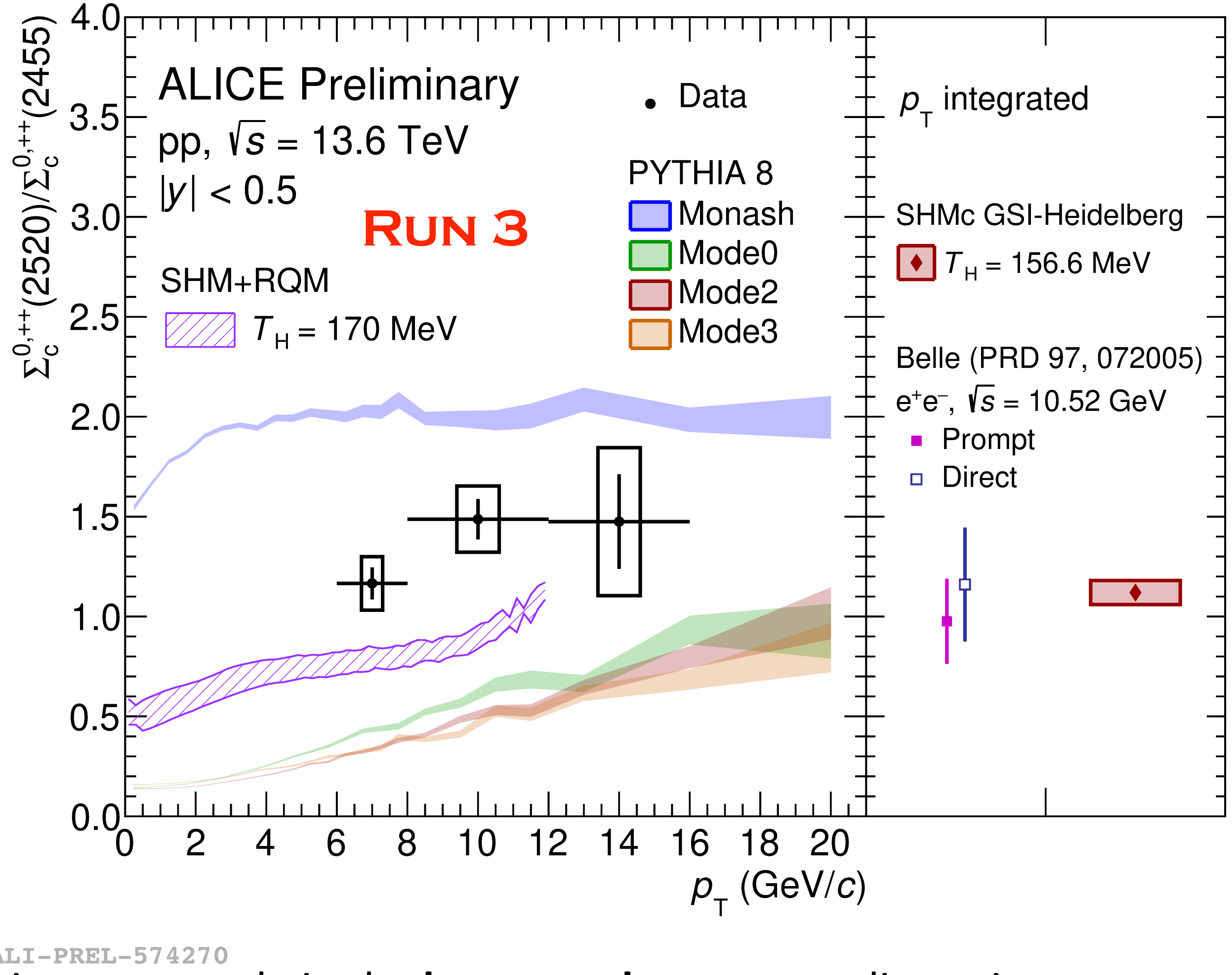
arXiv:2404.17272

# $\Sigma_c^{0,++}(2520)/\Sigma_c^{0,++}(2455)$ in pp @ 13.6 TeV




$|uuc\rangle,\ s = 1/2$

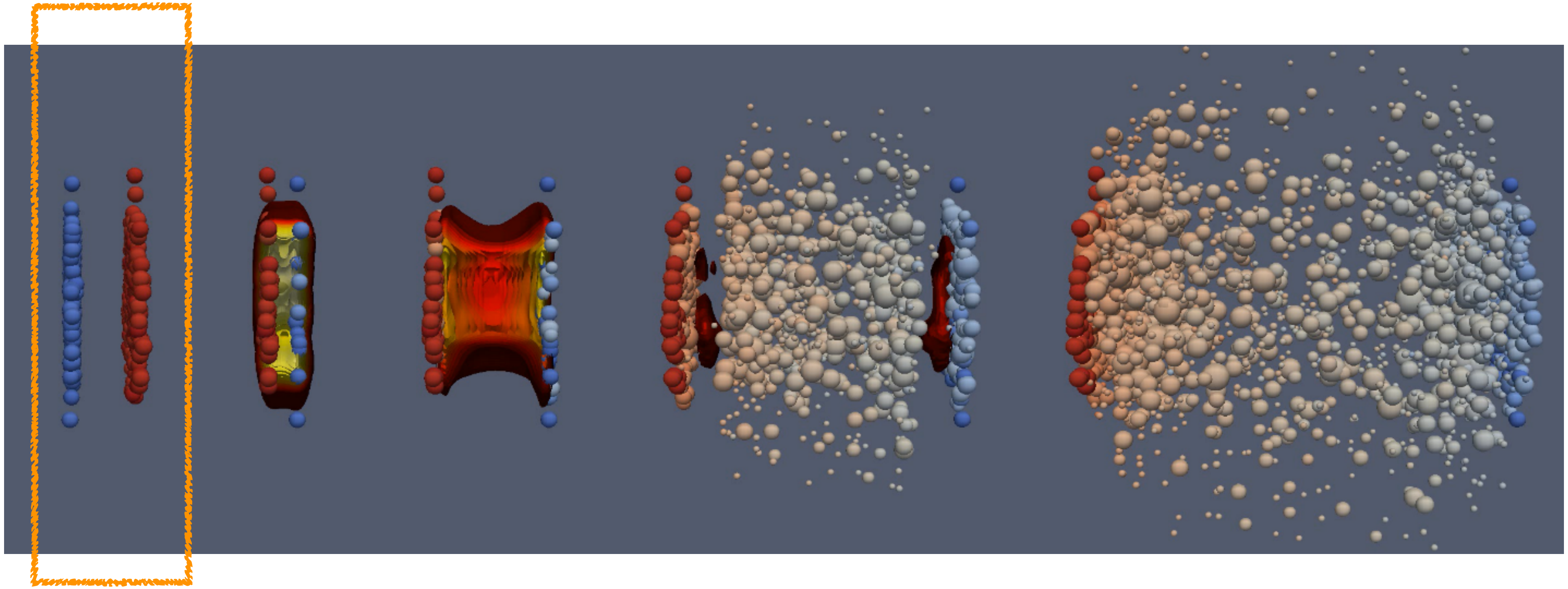
$|uuc\rangle,\ s = 3/2$




→ **Resonances** of **charmed baryons** might play an important role in the **baryon enhancement** discussion

→ **Run 3: Large pp dataset** now allows to address this. **PYTHIA does not** describe the data in **contrast** to **SHM**.

# CAN WE PROBE THE INITIAL STATE OF Pb?



**Probing the initial stage**

Gluon-dominated

Color Glass Condensate?

# Ultra-peripheral collisions - QED processes

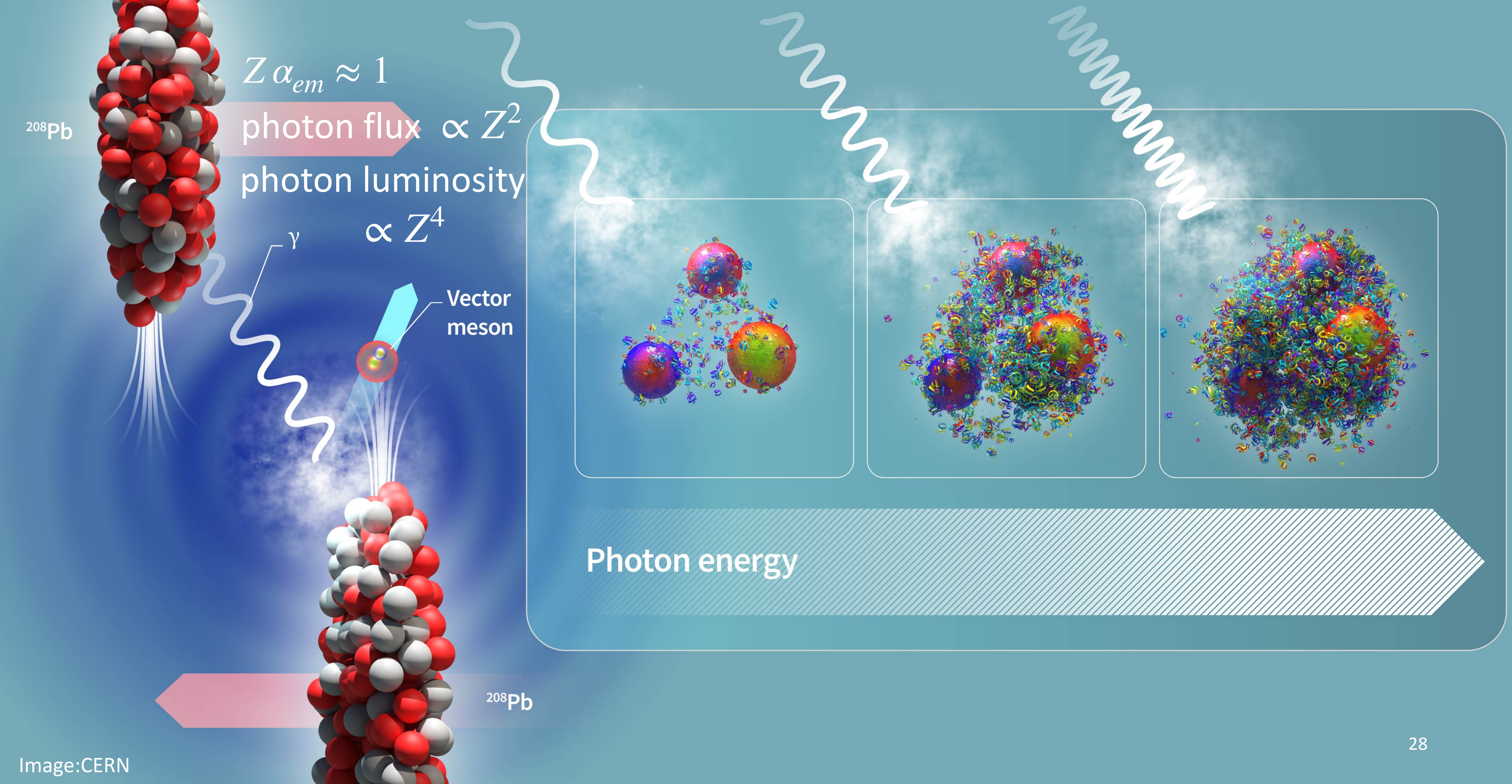
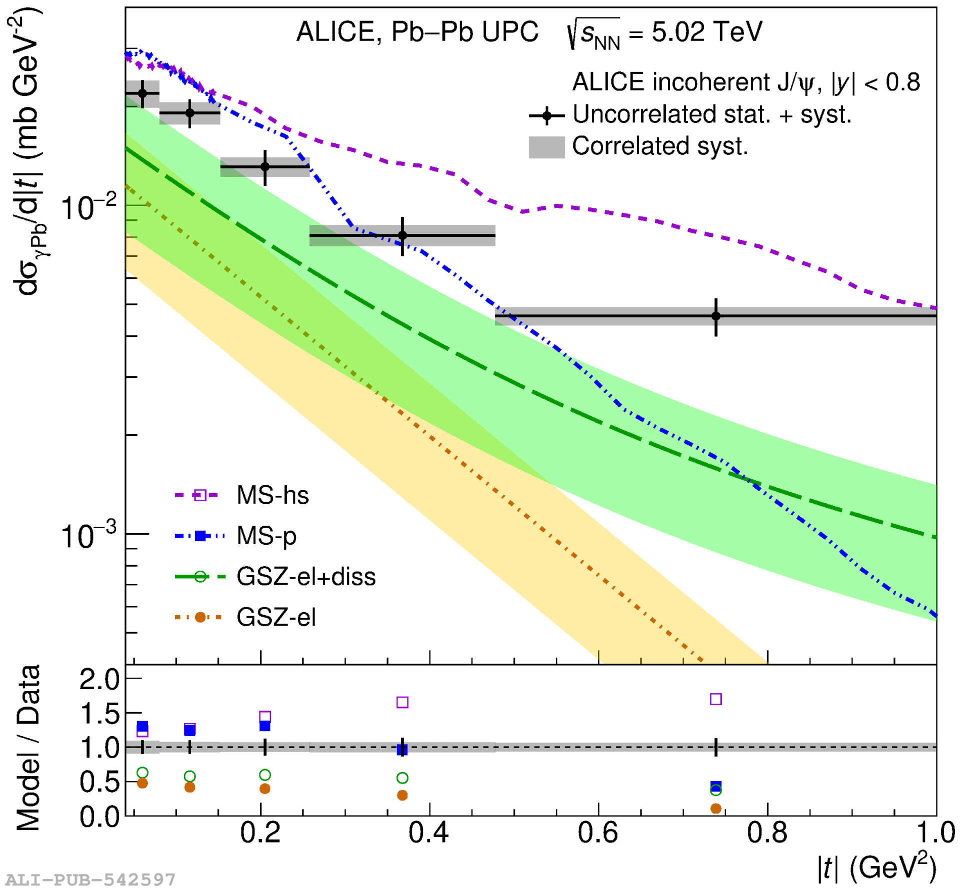



Image:CERN

# INCOHERENT $J/\psi$ PHOTOPRODUCTION

**Incoherent** $\gamma + \text{Pb} \rightarrow \text{J}/\psi + \text{Pb}$

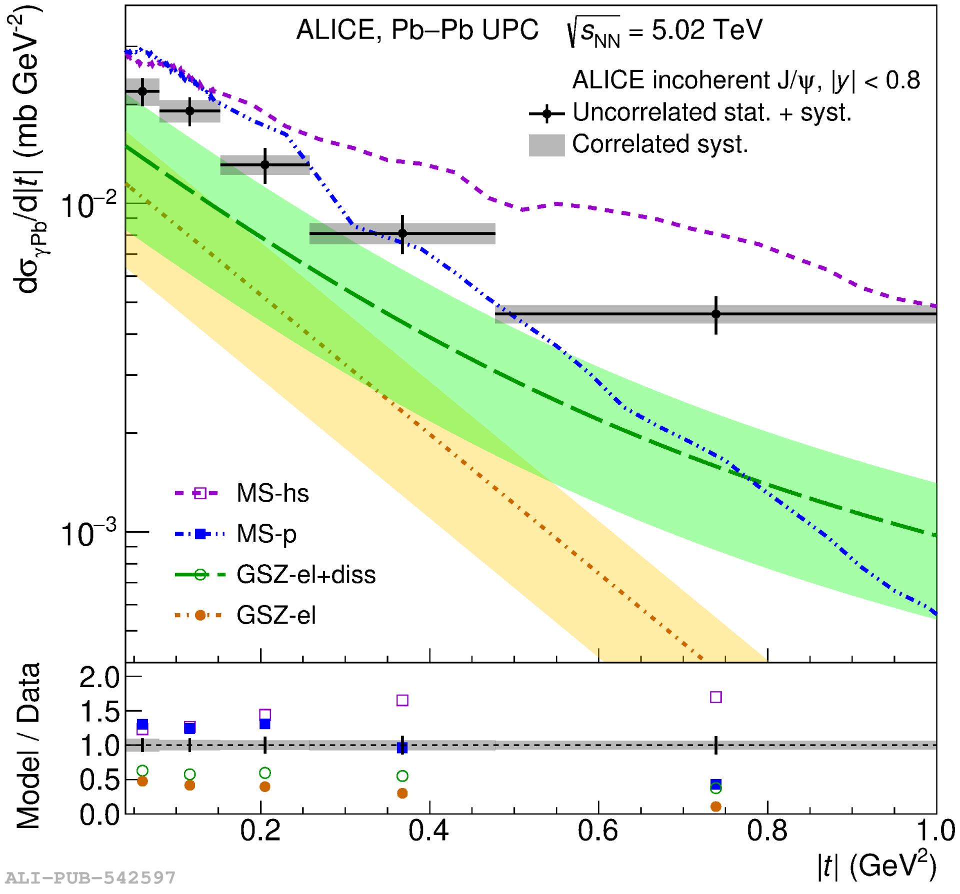


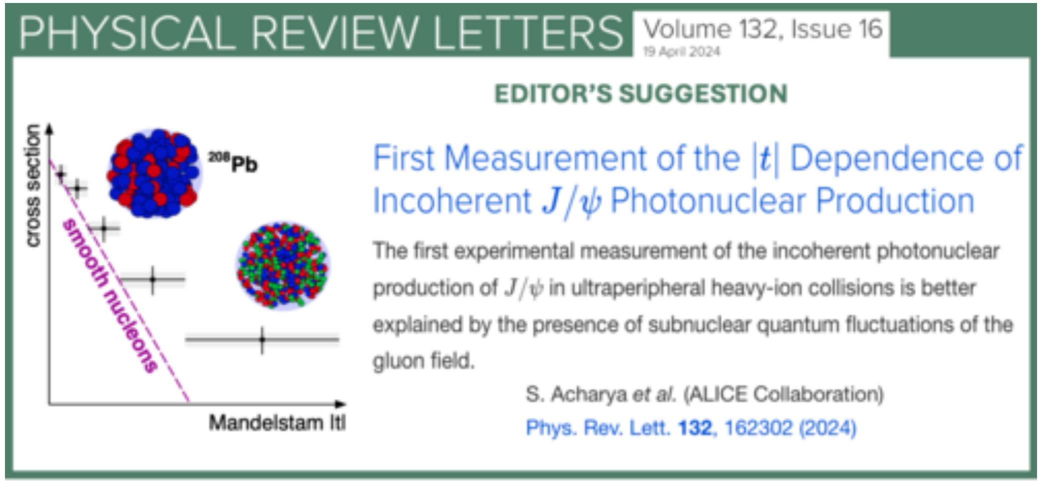

arXiv:2305.06169 [nucl-ex]

Models including scattering structures at a sub-nucleon scale (large $|t|$) provide a better description of the data including **large fluctuations of spatial distribution**, "gluonic hotspots"

# INCOHERENT $J/\psi$ PHOTOPRODUCTION

**Incoherent** $\gamma + \mathrm{Pb} \rightarrow \mathrm{J}/\psi + \mathrm{Pb}$



PHYSICAL REVIEW LETTERS Volume 132, Issue 16
19 April 2024

EDITOR'S SUGGESTION



First Measurement of the $|t|$ Dependence of Incoherent $J/\psi$ Photonuclear Production

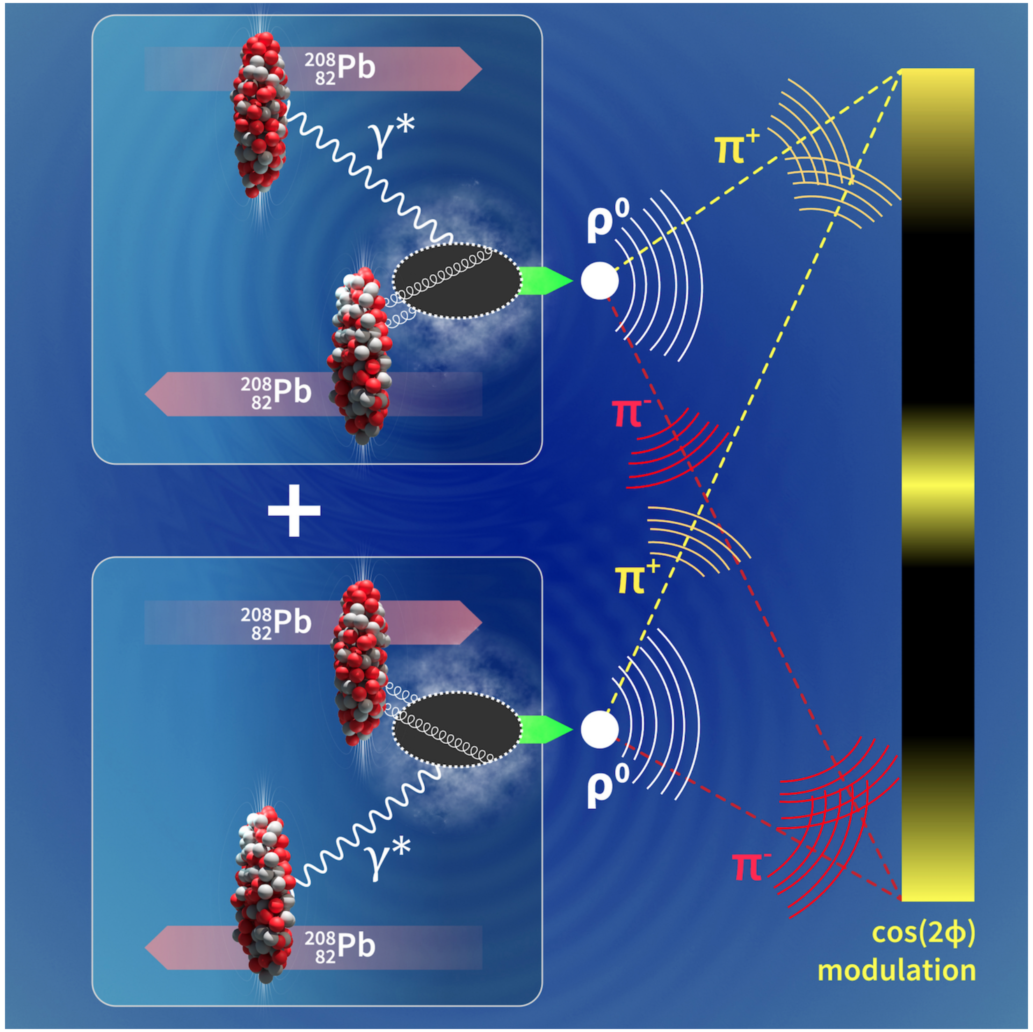
The first experimental measurement of the incoherent photonuclear production of $J/\psi$ in ultraperipheral heavy-ion collisions is better explained by the presence of subnuclear quantum fluctuations of the gluon field.

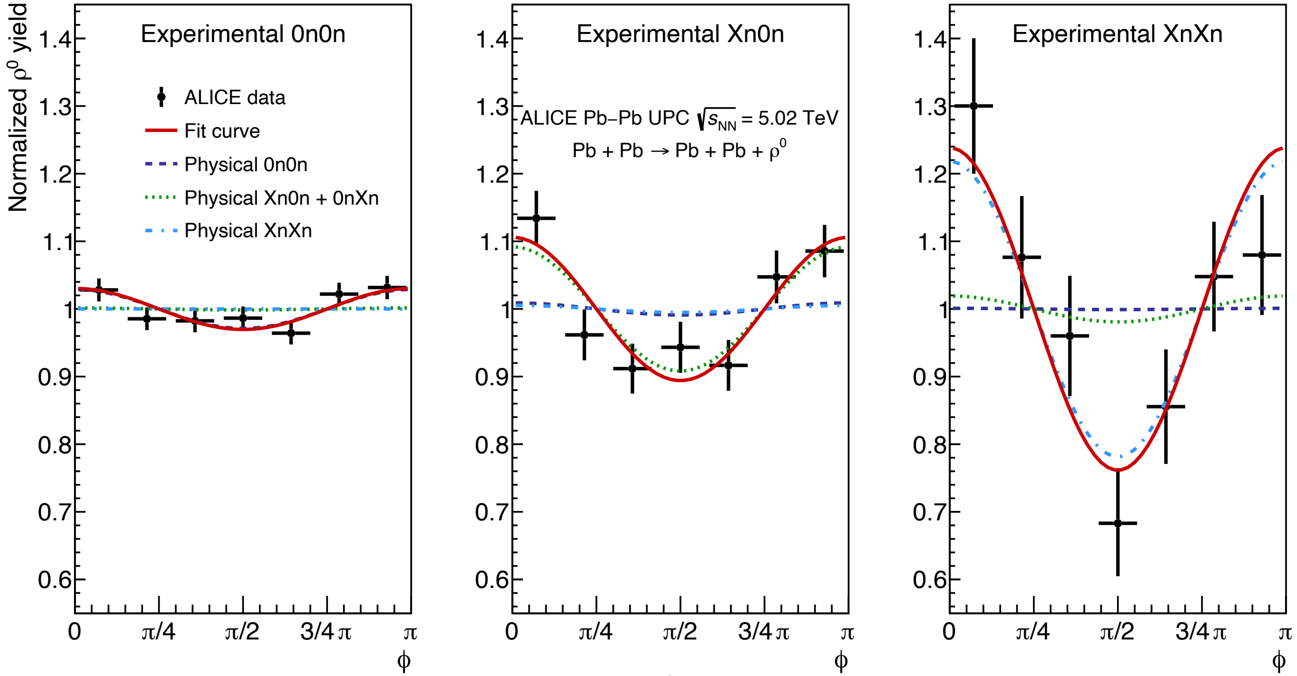
S. Acharya *et al.* (ALICE Collaboration)
Phys. Rev. Lett. **132**, 162302 (2024)

Models including scattering structures at a sub-nucleon scale (large $|t|$) provide a better description of the data including **large fluctuations of spatial distribution**, "gluonic hotspots"

[arXiv:2305.06169 [nucl-ex]]

# Interferometry in coherent photo production




**coherently** photo-produced $\rho^0$ **mesons**

**interference** leads to **angular modulation**

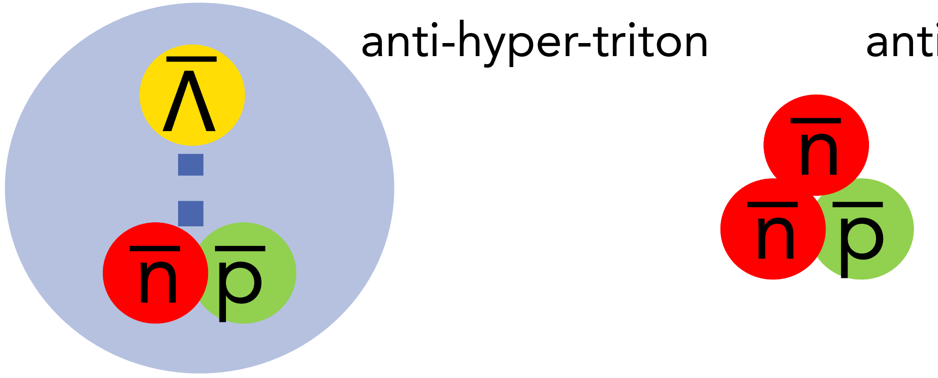
impact-parameter dependent

**double slit experiment** at the **femtometer** scale!

arXiv:2405.14525

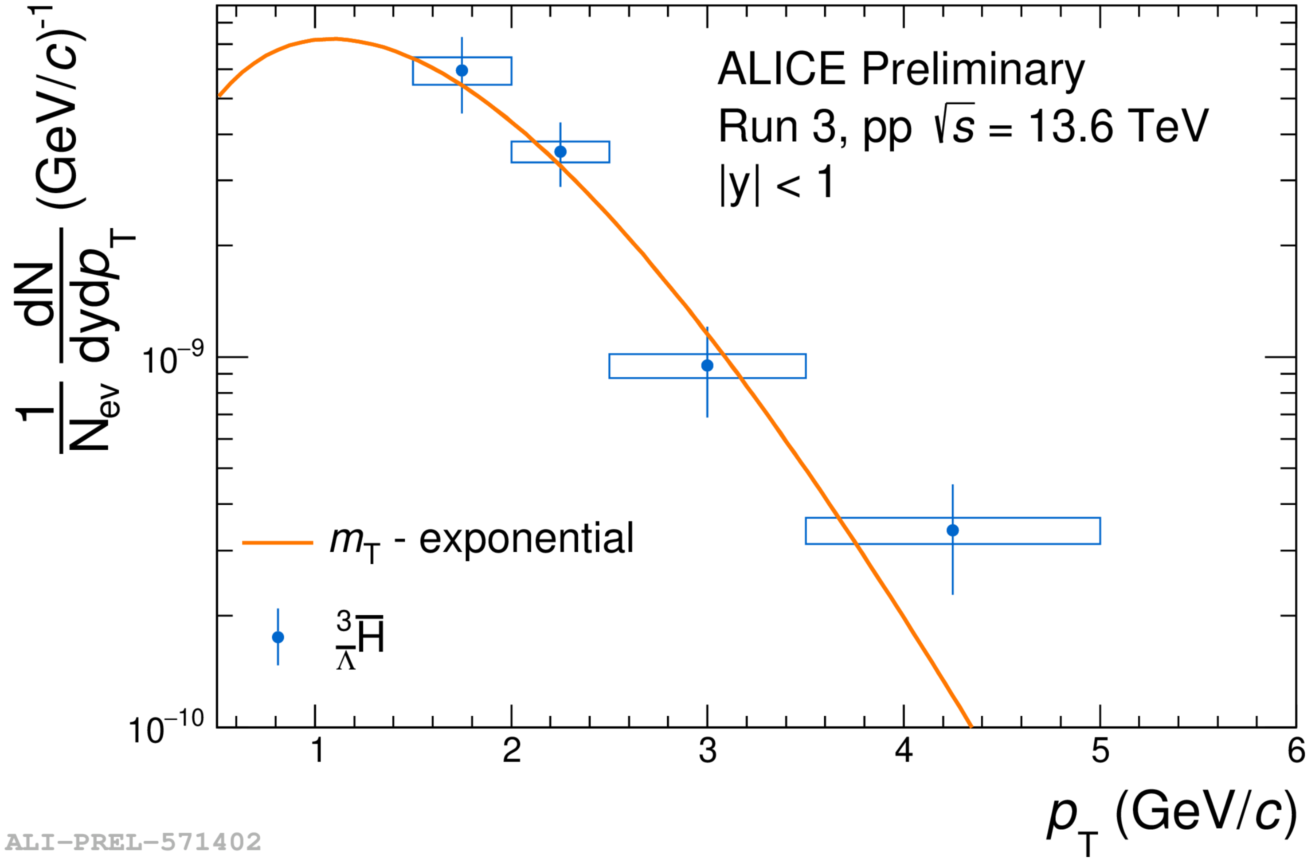
# Results from Run 3: pp collisions at 13.6 TeV

# Hypertriton in pp at 13.6 TeV (1)

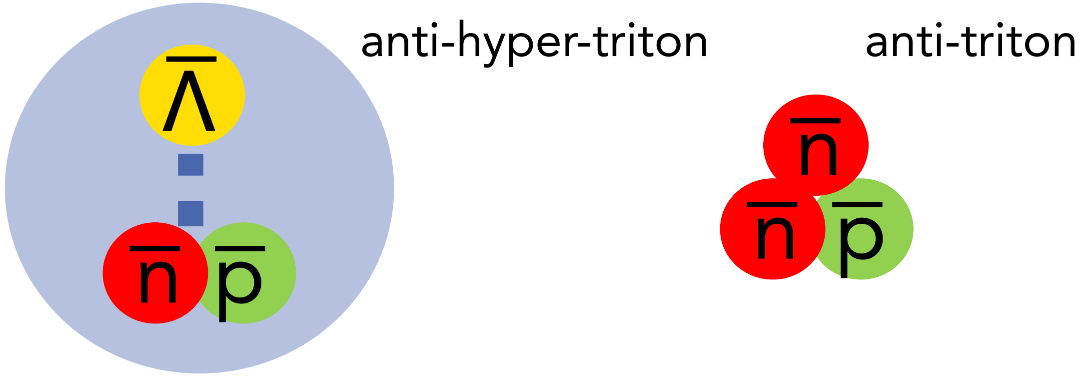



- First $\mathbf{p_T}$ **-differential** measurement of the **hypertriton** production in **pp collisions**
- Already now **challenging** the **precision** of the **Run 2** measurement.
- Favours coalescence model versus SHM production in pp collisions.

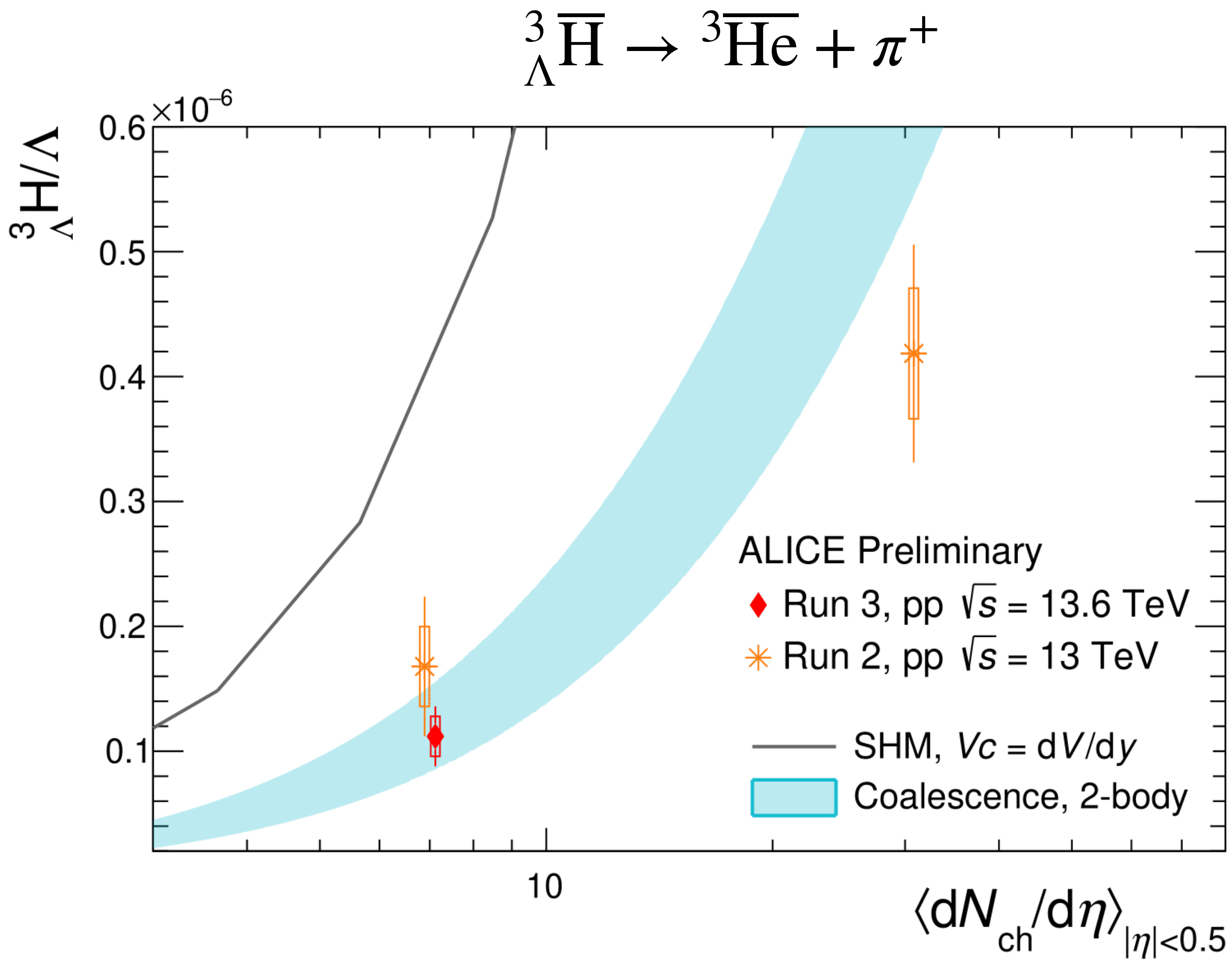
$${}^3_{\Lambda}\overline{\mathrm{H}} \rightarrow {}^3\overline{\mathrm{He}} + \pi^+$$



# Hypertriton in pp at 13.6 TeV (1)



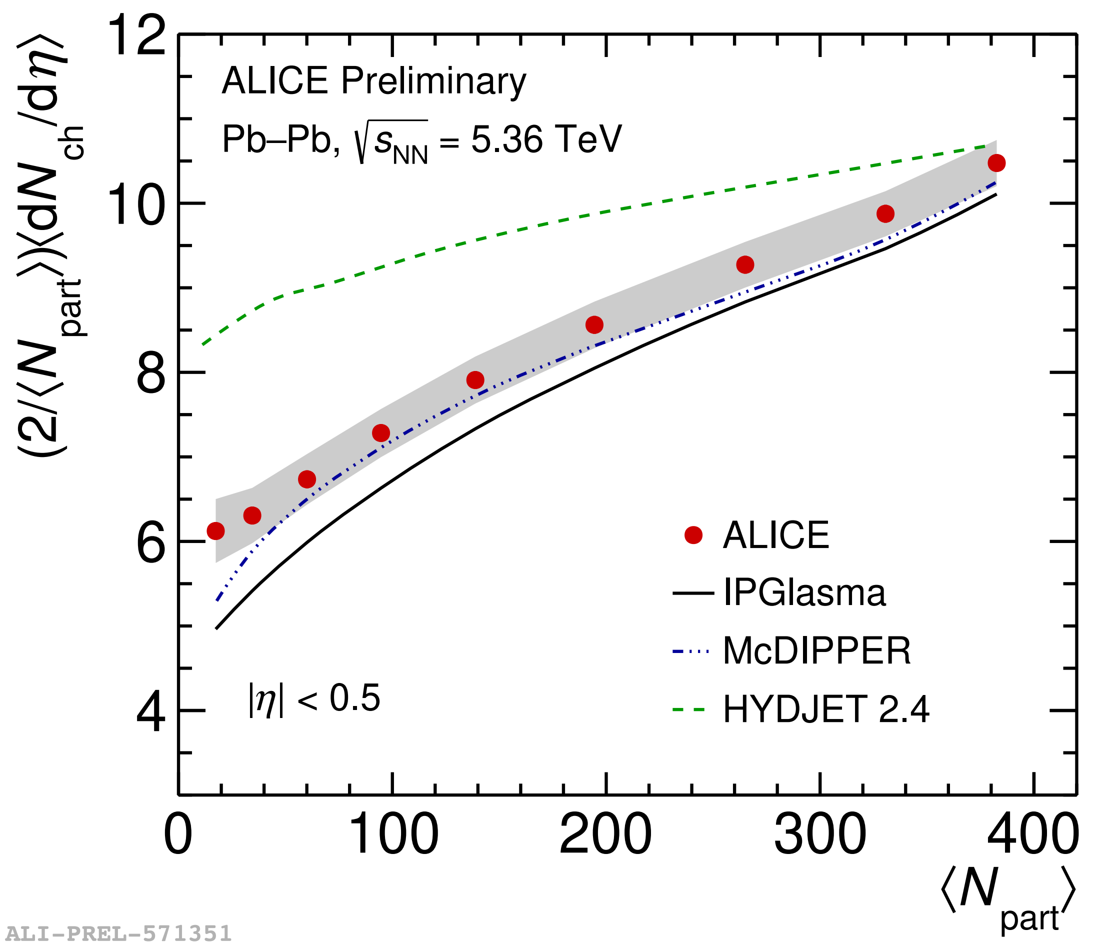

- First **$p_T$ -differential** measurement of the **hypertriton** production in **pp collisions**
- Already now **challenging** the **precision** of the **Run 2** measurement.
- Favours coalescence model versus SHM production in pp collisions.

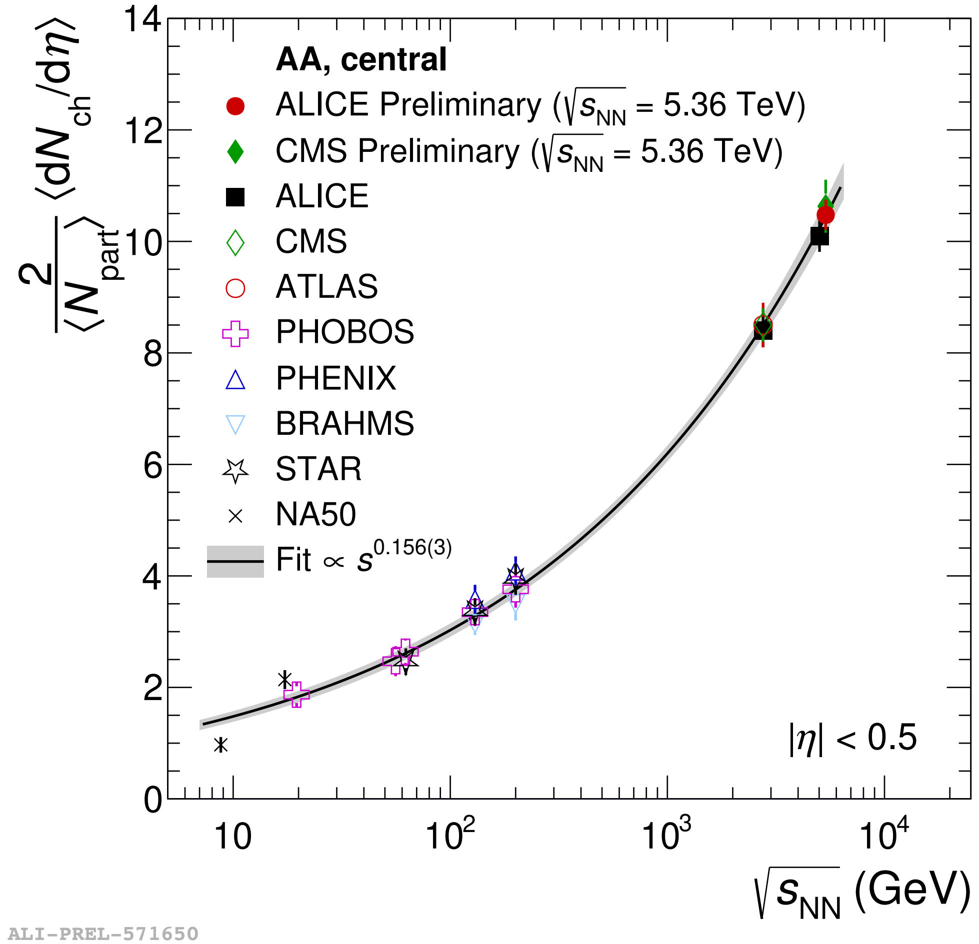


ALICE

# First results from Run 3: Pb-Pb collisions at 5.36 TeV

# Charged-particle dN/dη

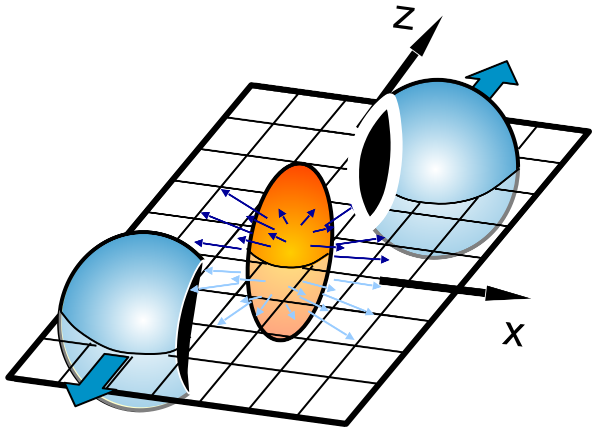



Important **baseline measurement** is in **agreement** with lower energy data

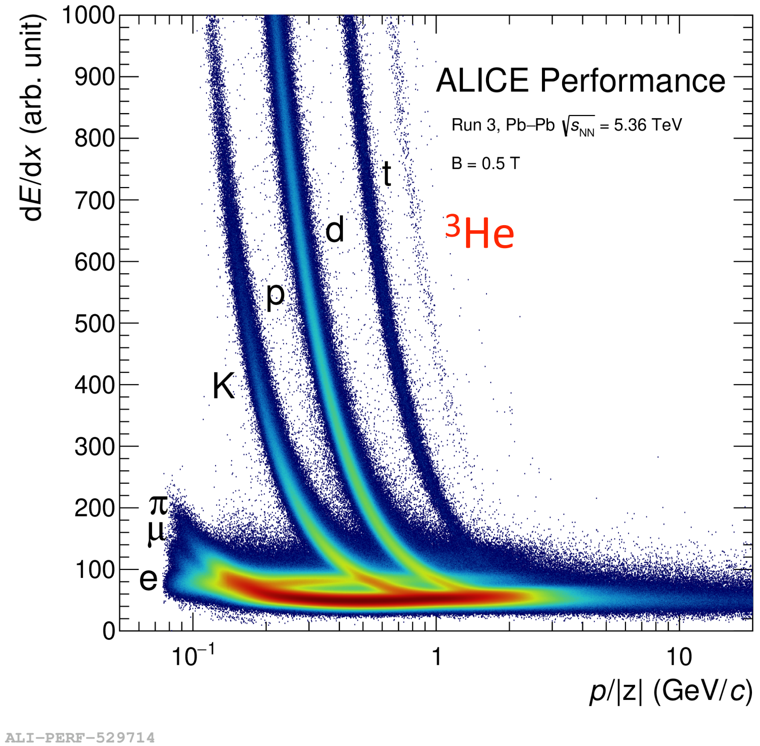
This gives us **confidence** in many basic calibrations, in particular **centrality calibration**

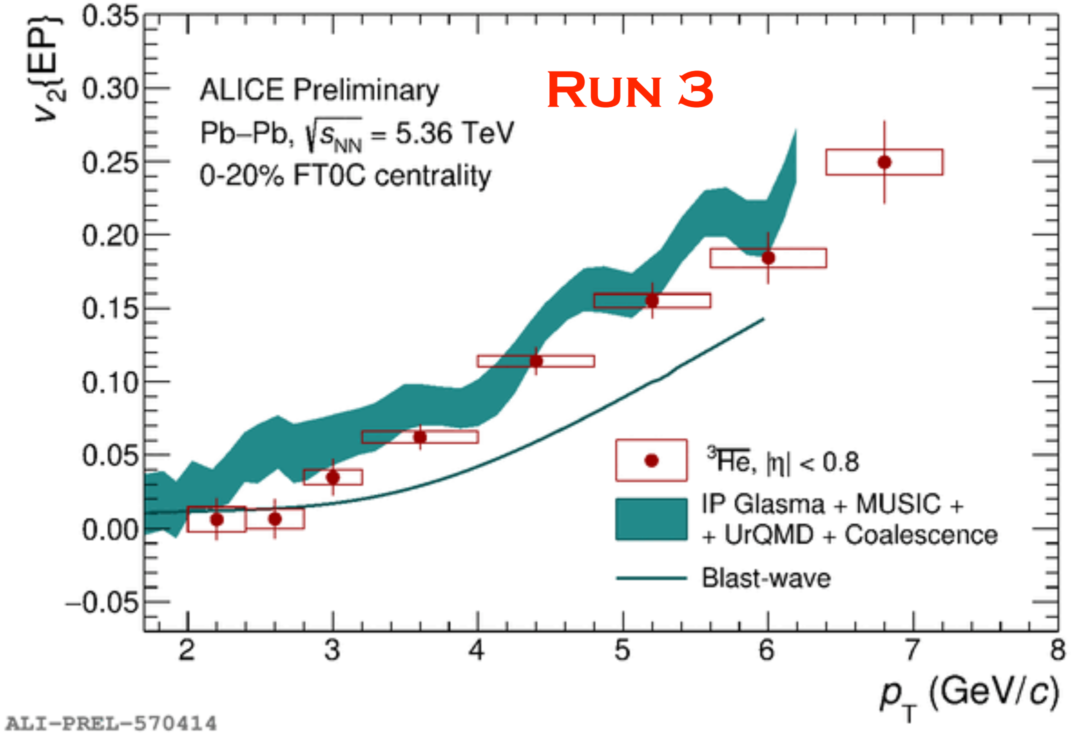
# COLLECTIVE EXPANSION - ANTINUCLEI - $^3\overline{\mathrm{He}}$




$$v_2 = \langle \cos 2\phi \rangle$$

$$\phi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$




initial **spatial configuration**
**momentum space**
sensitive to
**specific entropy** $\eta/s$

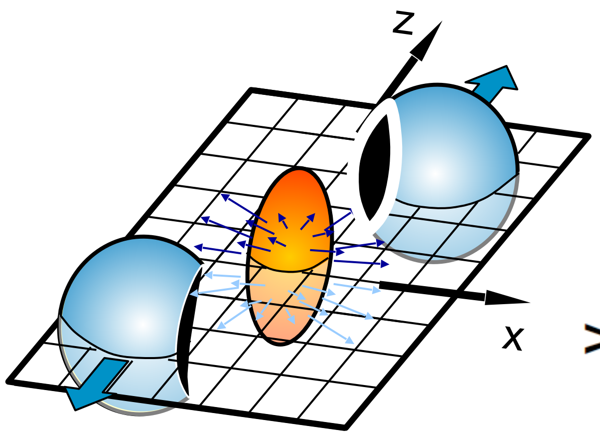
**Helium** nucleus (Z = 2), **clean PID**, rare probe
**control** measurement: $Z^0$ **boson**

collective expansion
**microscopic model describes data**
**10 - 100x** increased **data rate** in **Run 3**


$Z^0$ $v_2$, CMS: PRL 127, 102002 (2021)

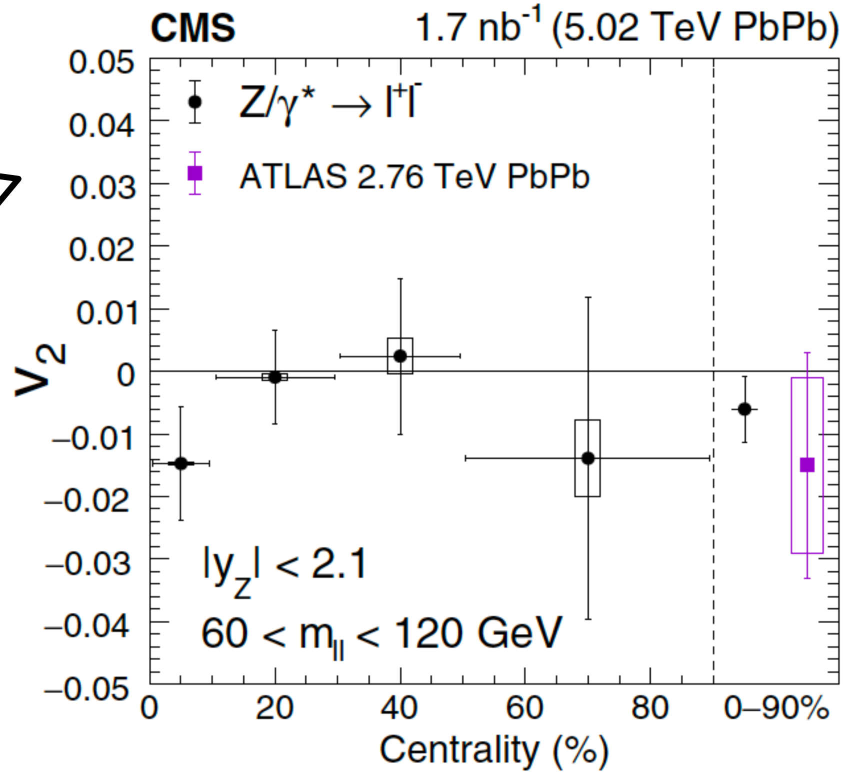
# COLLECTIVE EXPANSION - ANTINUCLEI - $^{3}\overline{\text{He}}$

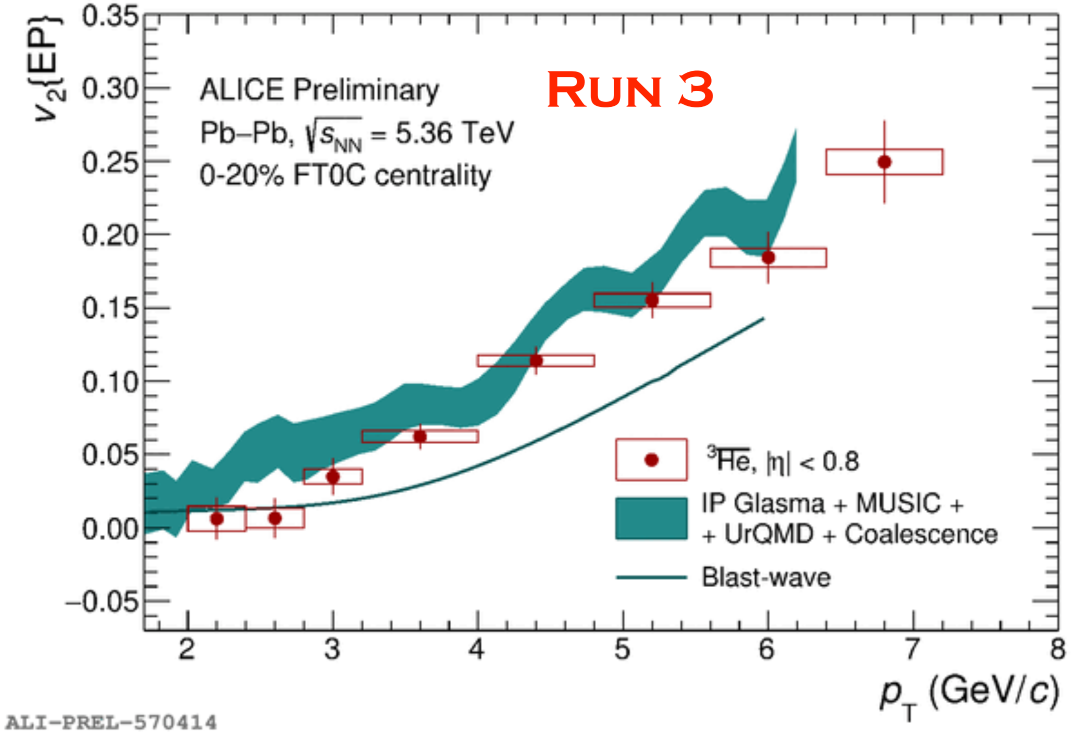
ALICE




$v_2 = \langle \cos 2\phi \rangle$

$\phi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$




initial **spatial configuration**

**momentum space**

sensitive to

**specific entropy** $\eta/s$

**Helium** nucleus (Z = 2), **clean PID**, rare probe

**control** measurement: $Z^0$ **boson**

collective expansion

**microscopic model describes data**

**10 - 100x** increased **data rate** in **Run 3**



$Z^0$ $v_2$, CMS: [PRL 127, 102002 (2021)]

# ALICE 3 DETECTOR


high-efficiency for heavy-quark identification and reconstruction of low-mass dielectrons e.g. **chiral symmetry restoration, proton mass**

vertexing close to the beam with unprecedentedly low material budget

large acceptance with excellent coverage down to low $p_T$

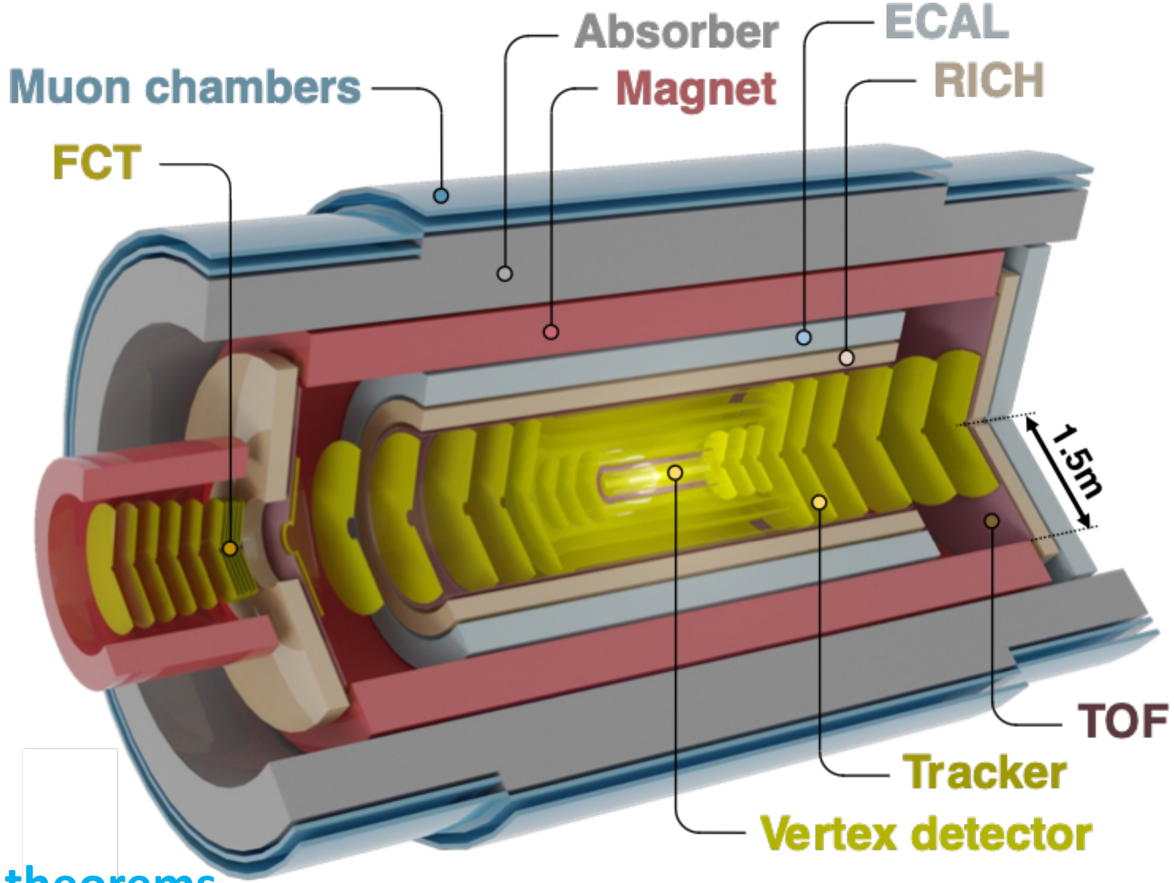
excellent particle ID (muons, electrons, photons, hadrons)

➪ **Vertexing precision x 3**: 10μm at $p_T$ = 200 MeV/$c$

➪ **Acceptance x 4.5**: $|\eta| < 4$ (with particle ID)

➪ **A-A rate x 5 (pp x 25)**

Forward conversion tracker (FCT) : **ultrasoft photons, soft theorems**




➪ **novel technologies relevant for future HEP and NP programs**

# ALICE 3 VERTEX DETECTOR - IRIS

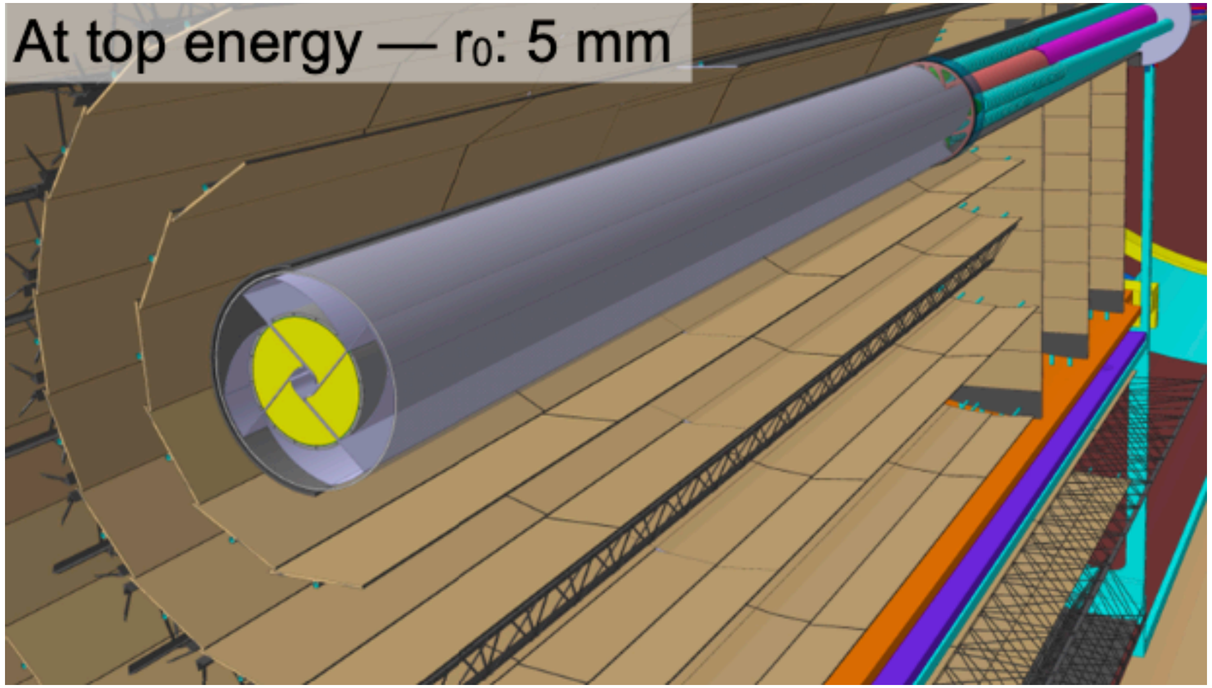
**Pointing resolution** $\propto r_0 \cdot \sqrt{x/X_0}$ (multiple scattering regime)

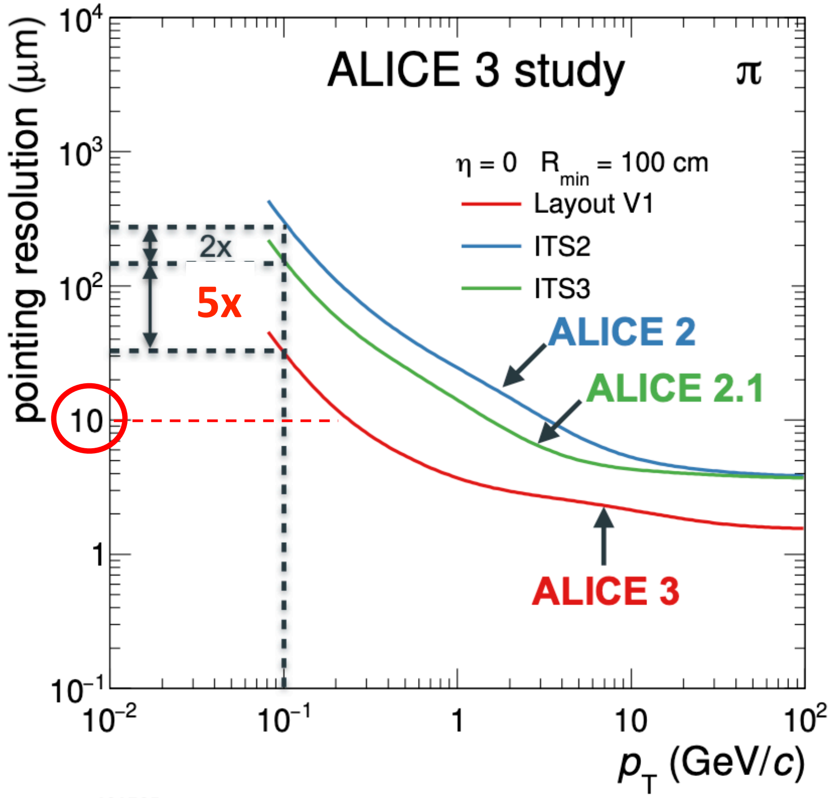
- **driven by radius and material of first layer**
- minimal radius given by required aperture:
  - ***R* ≈ 5 mm at top energy**
  - *R* ≈ 15 mm at injection energy

→ **need retractable vertex detector**

**Key detector characteristics**

- 3 detection layers (barrel + disks)
- Retractable: $r_0$ = 5 mm
- Material budget: **0.1% $X_0$ / layer**
- Unprecedented spatial resolution of **2.5 µm**



# ALICE 3 VERTEX DETECTOR - IRIS

**Pointing resolution** $\propto r_0 \cdot \sqrt{x/X_0}$ (multiple scattering regime)

- **driven by radius and material of first layer**
- minimal radius given by required aperture:

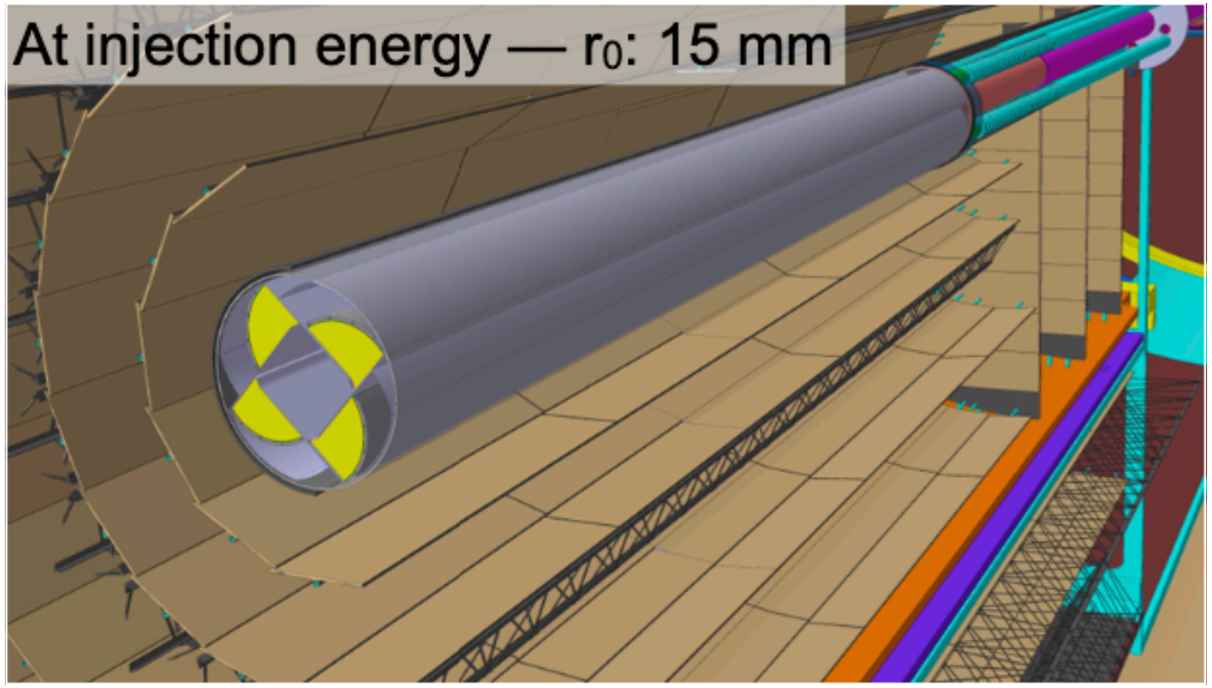
  ***R* ≈ 5 mm at top energy**

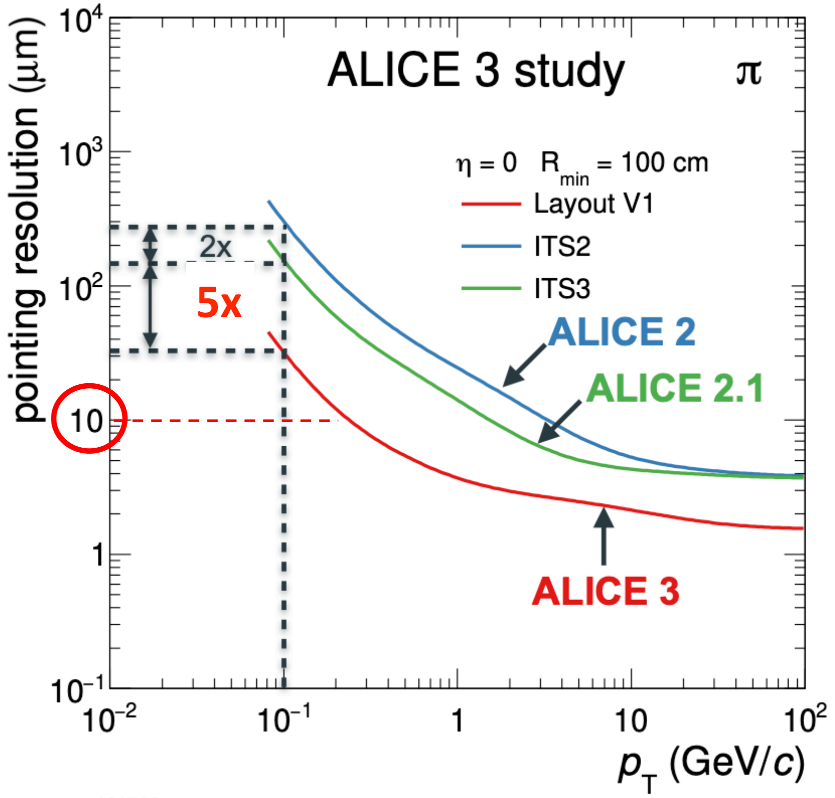
  *R* ≈ 15 mm at injection energy

**→ need retractable vertex detector**

**Key detector characteristics**

- 3 detection layers (barrel + disks)
- Retractable: $r_0$ = 5 mm
- Material budget: **0.1% $X_0$ / layer**
- Unprecedented spatial resolution of **2.5 µm**



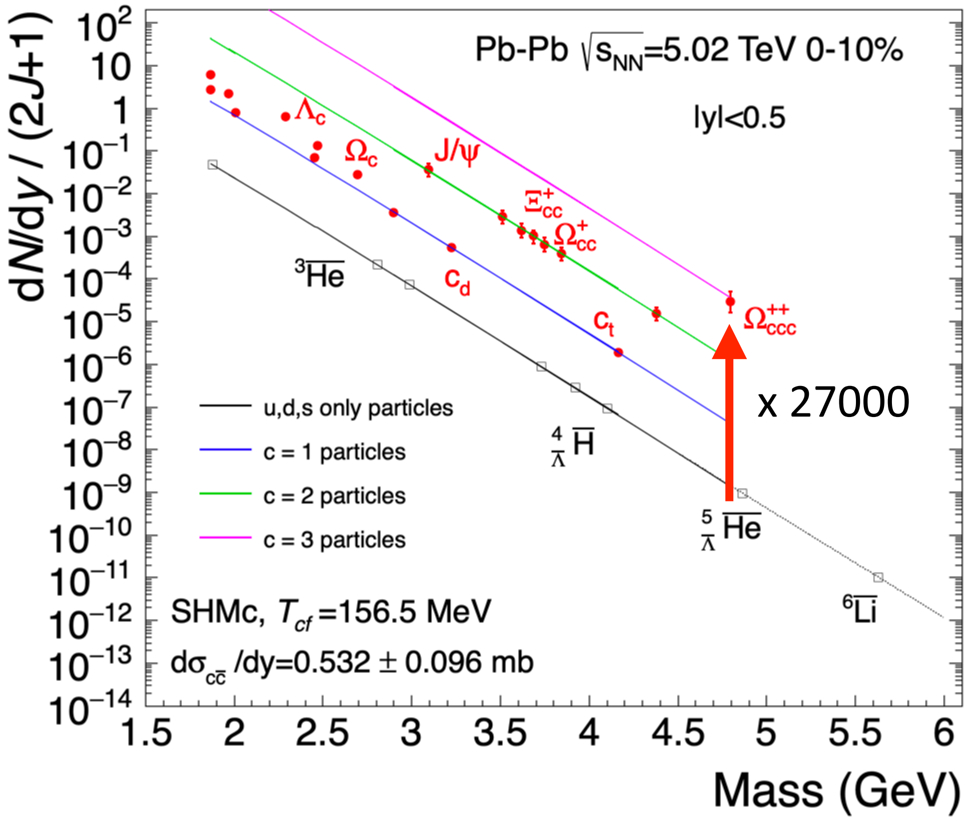



# POINTING x ACCEPTANCE ⨯ INTERACTION RATE: NEW OPPORTUNITIES

ALICE

## Multiply-charmed baryons

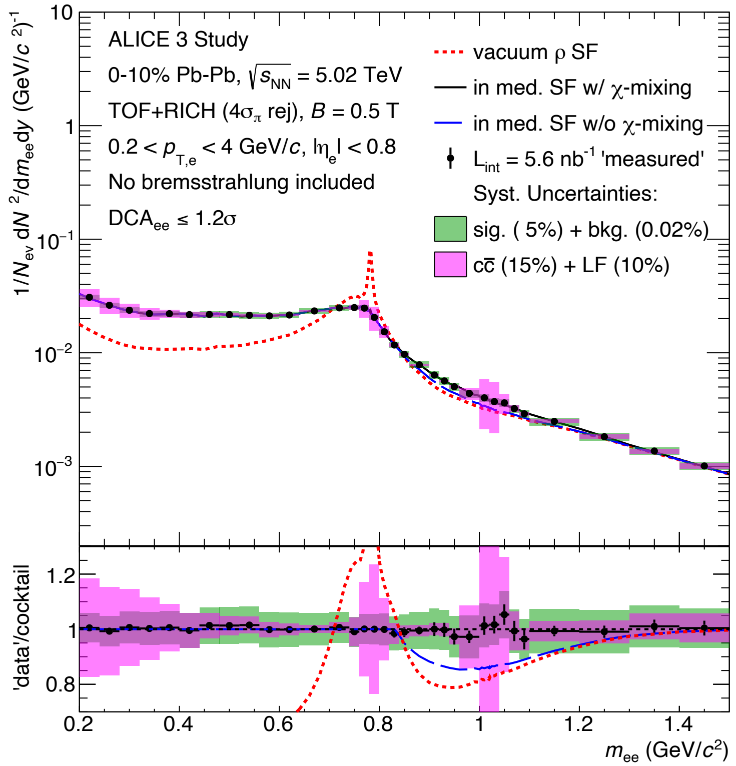
arXiv:2211.02491




→ **charm oversaturated** through direct production

→ probe **deconfinement** of **charm** quarks

## access $\rho - a_1$ mixing




**chiral symmetry restored** in quark-gluon plasma

→ address **origin** of **99%** of **visible mass** in universe

ultimate heavy-flavor background rejection

# CONCLUSIONS

ALICE

The wealth and breadth of results achieved in Run 1 and 2 offer

- detailed insights into **QGP properties**
  - e.g. macroscopic and fluid-dynamic properties, heavy quark interaction, jet modification;
- plus a broader **program**
  - **pQCD**, interaction between hadrons, formation and interactions of **nuclei** and **antinuclei**, **high-precision** measurements, **high-field QED**, …

ALICE completed the Phase I upgrade … and is now enjoying **Run 3** with significantly enhanced capabilities

Future

- In preparation for Run 4: **ITS3** and **FoCal**, Technical Design Reports endorsed by LHCC
- **ALICE 3 LoI** (phase II upgrade, installation during LS4) endorsed by LHCC

⇨ Moving forward to the R&D phase, scoping document submitted for LHCC review