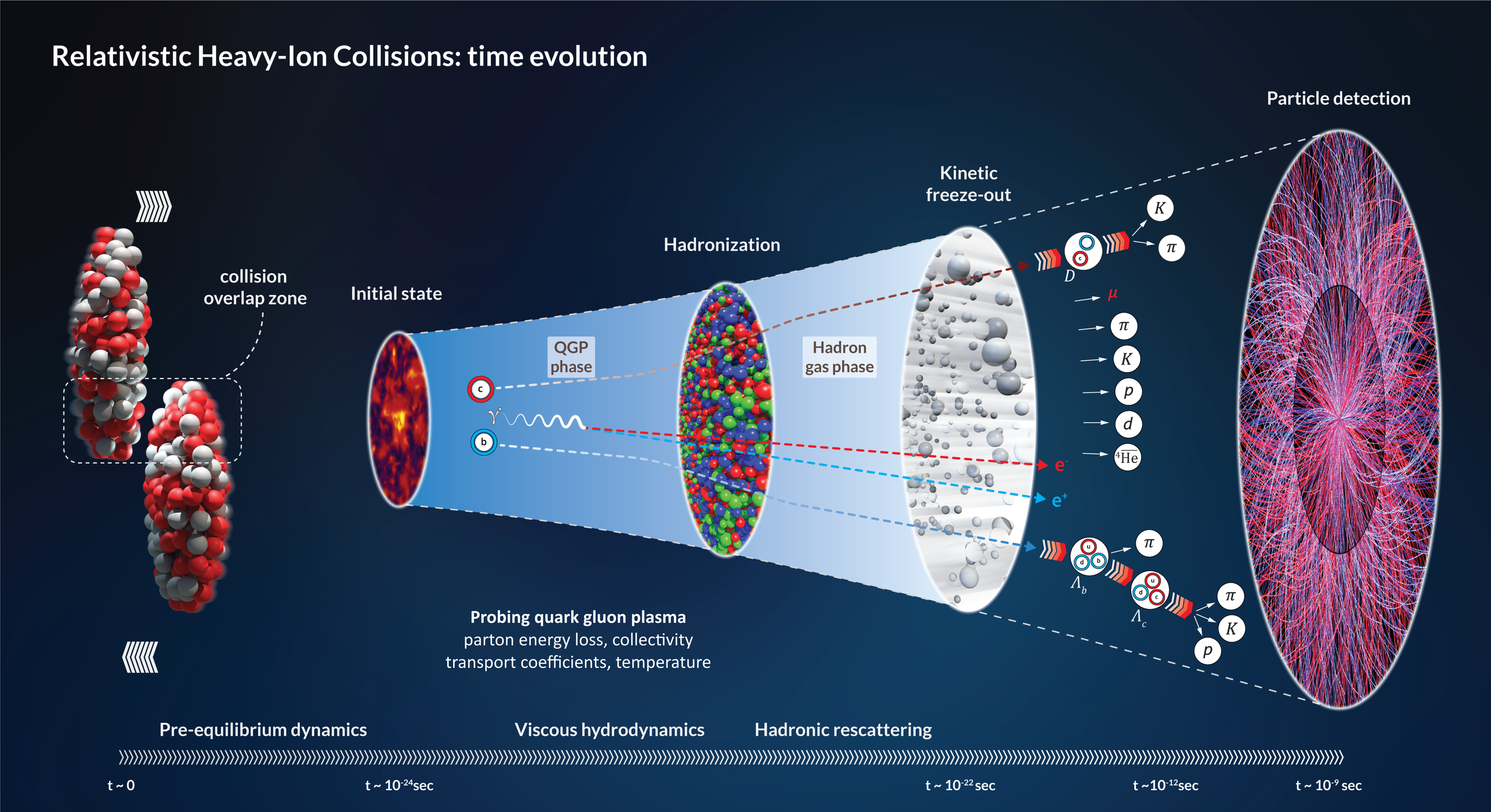
From Charm to ALICE 3: Statistical Hadronization and the Quest for Multiply Charmed Baryons

Kai Schweda (GSI, CERN)

CCNU, Wuhan, China



Relativistic Heavy-Ion Collisions: time evolution

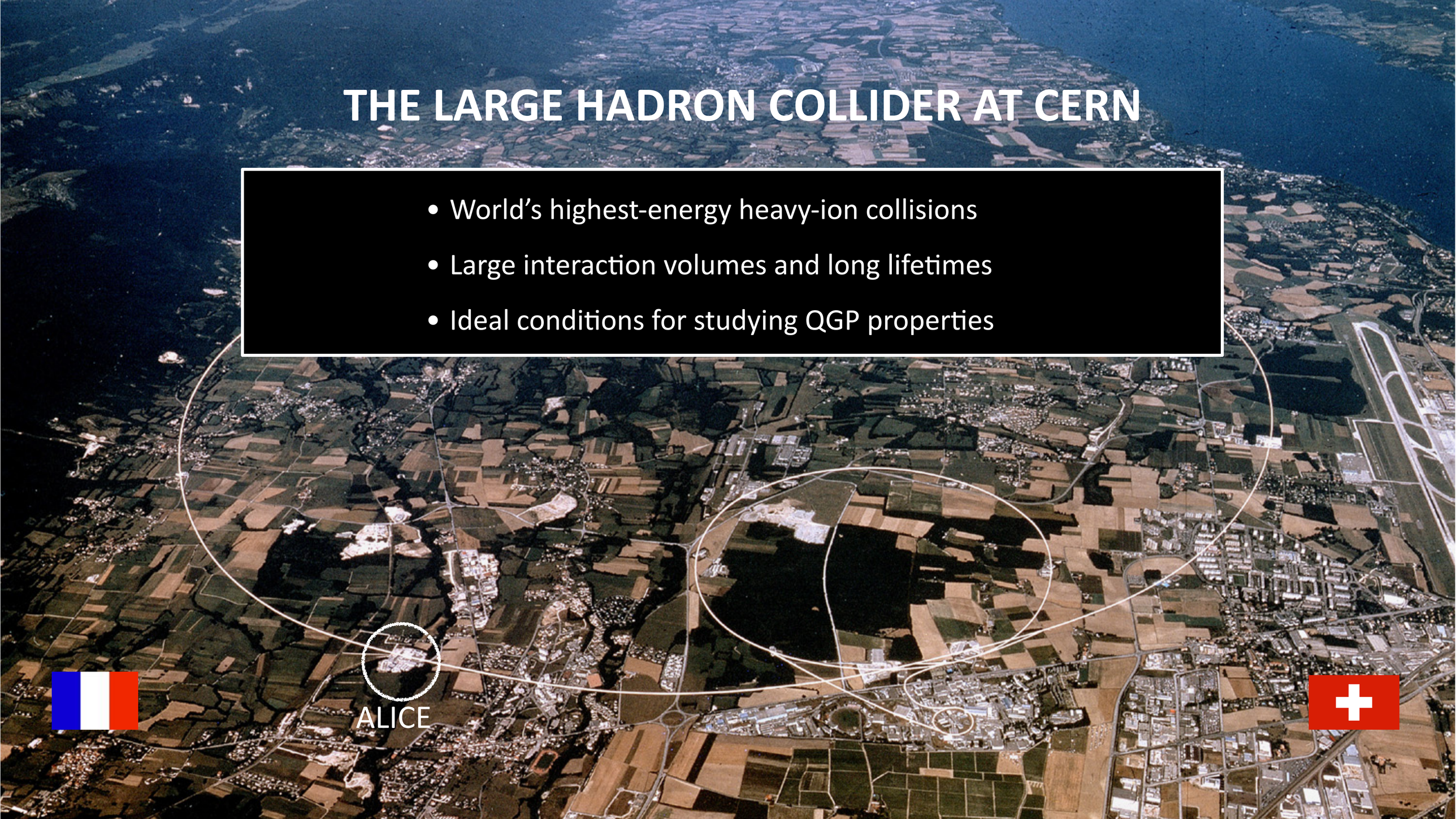


THE LARGE HADRON COLLIDER AT CERN



THE LARGE HADRON COLLIDER AT CERN

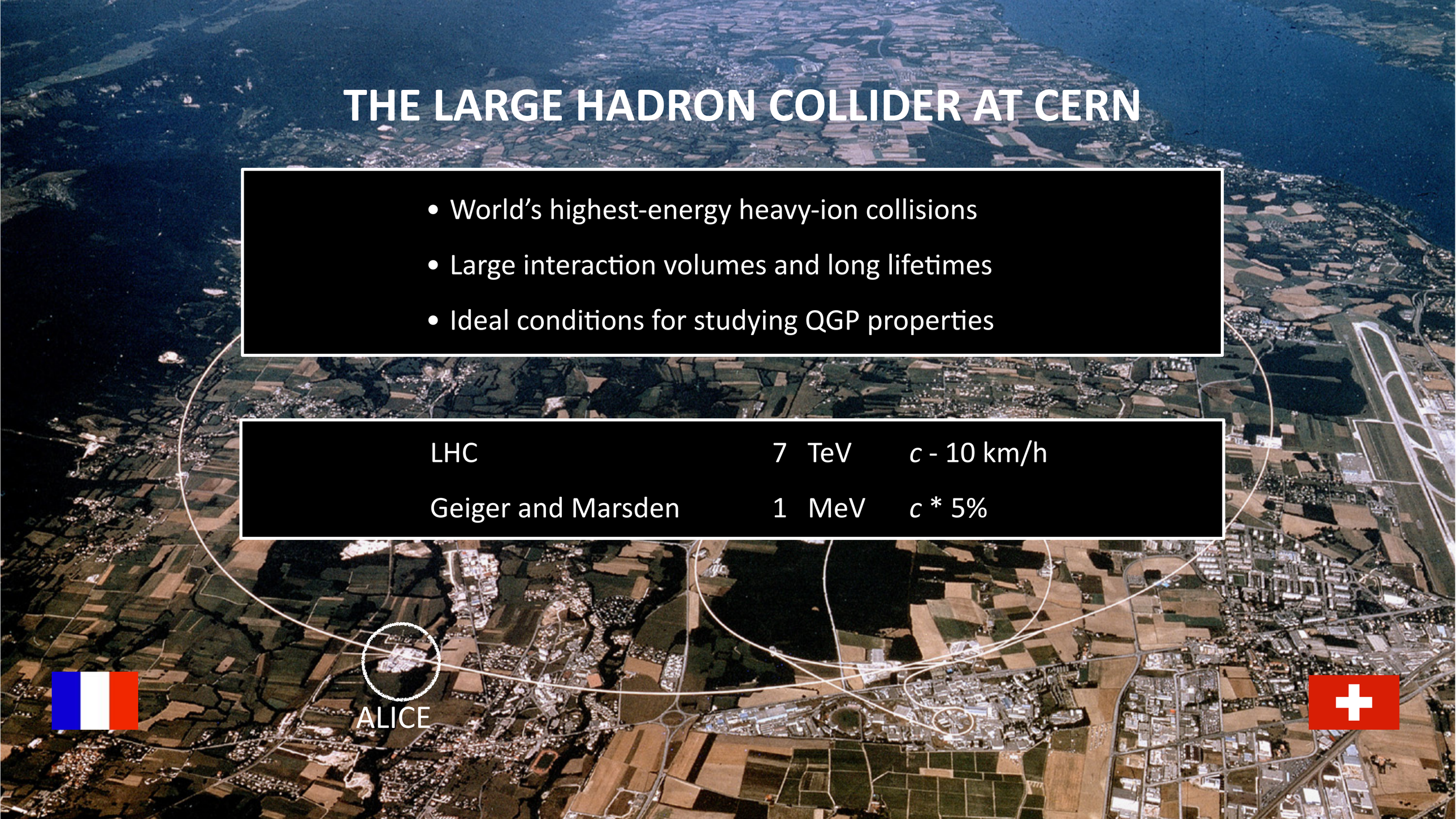
- World’s highest-energy heavy-ion collisions
- Large interaction volumes and long lifetimes
- Ideal conditions for studying QGP properties

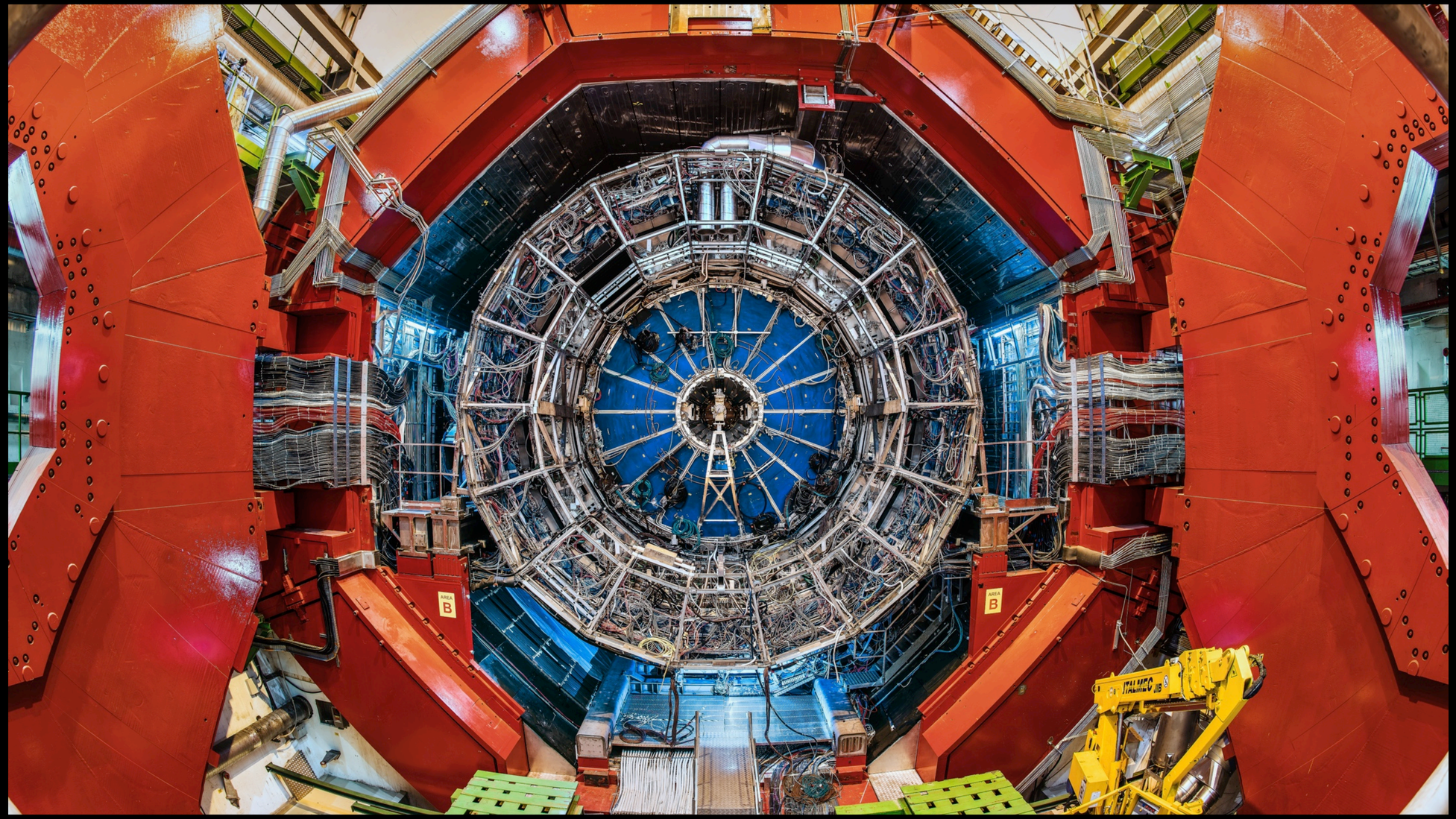


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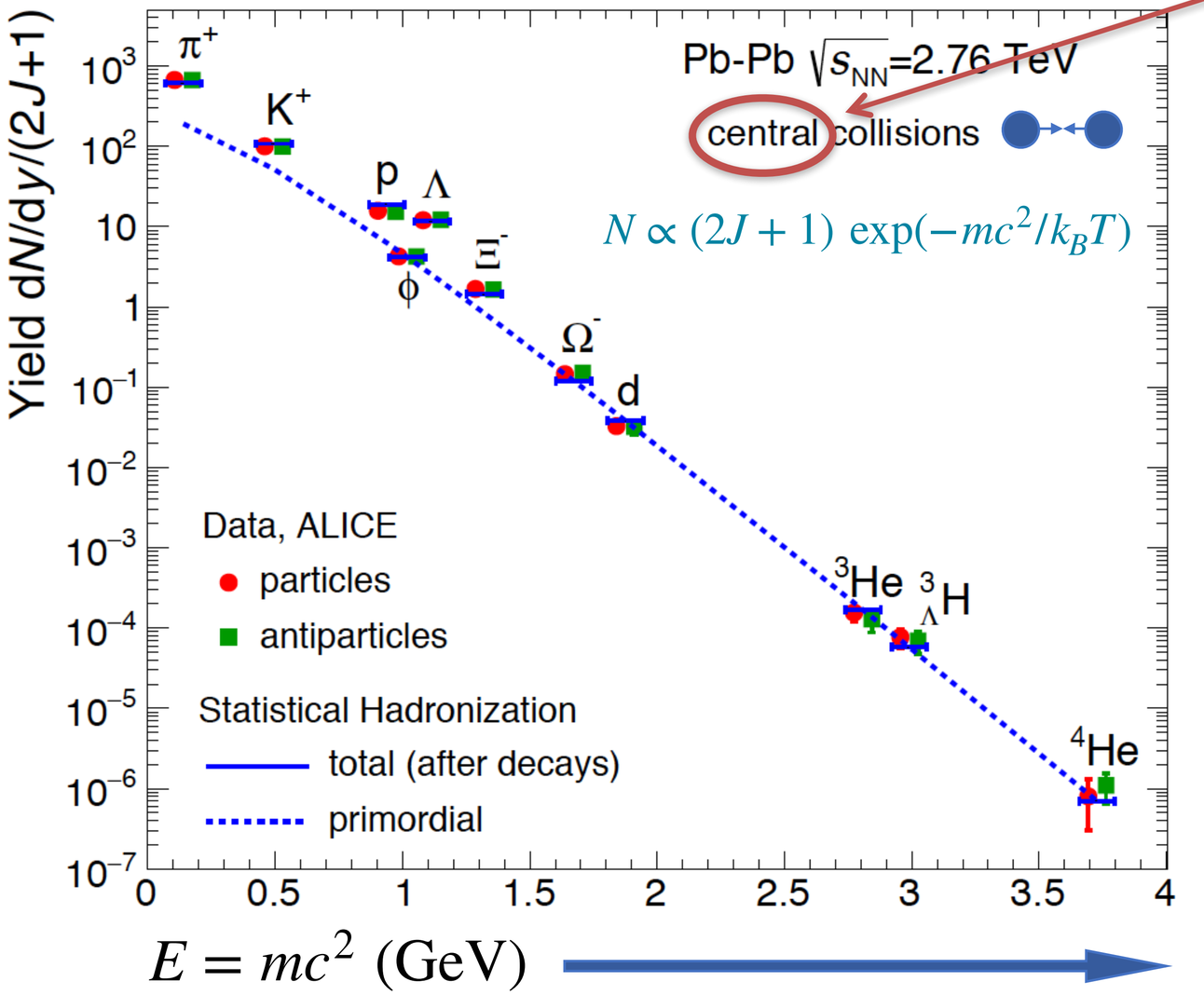
- World's highest-energy heavy-ion collisions
- Large interaction volumes and long lifetimes
- Ideal conditions for studying QGP properties

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




AREA
B
AREA
B

THERMAL PARTICLE PRODUCTION



Highest multiplicity

QCD-analog of **Planck spectrum**

T = 156.2 ± 2 MeV

pbm, Johanna, et al. Nature 561, 321 (2018)

pbm, Johanna, et al. nucl-th/0304013

Baryo-chemical potential

$\mu_B = 0.71 \pm 0.45$ MeV

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

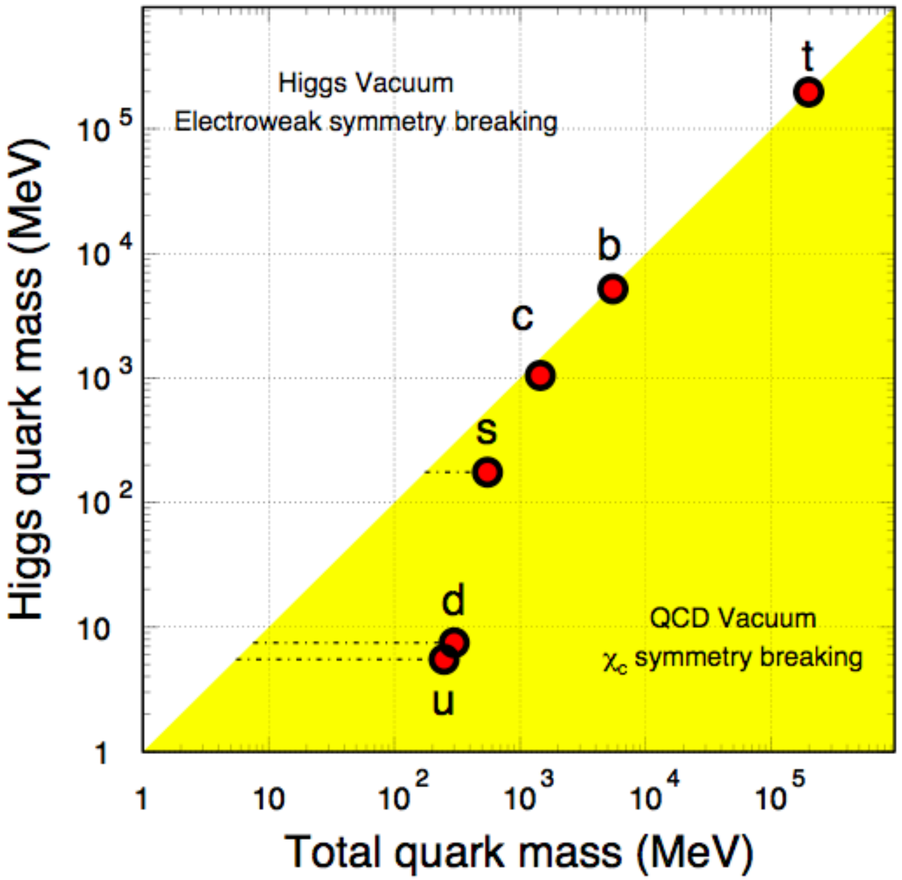
arXiv:2311.13332

Lattice-QCD results **agree**

T_{pc} = 156.5 ±1.5 MeV

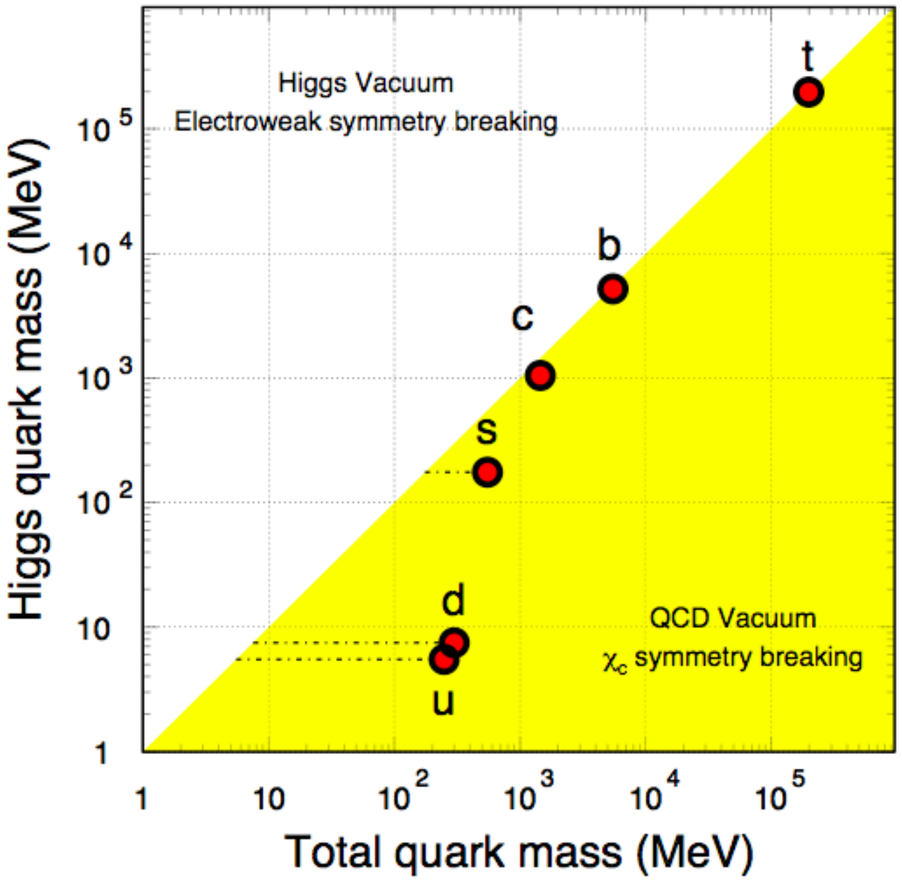
A. Bazavov et al. (Hot QCD) arXiv:1812.08235

HEAVY - FLAVOR: A UNIQUE PROBE



X. Zhu, M. Bleicher, S.L. Huang, K.S., H. Stöcker,
N. Xu, and P. Zhuang, PLB 647 (2007) 366.

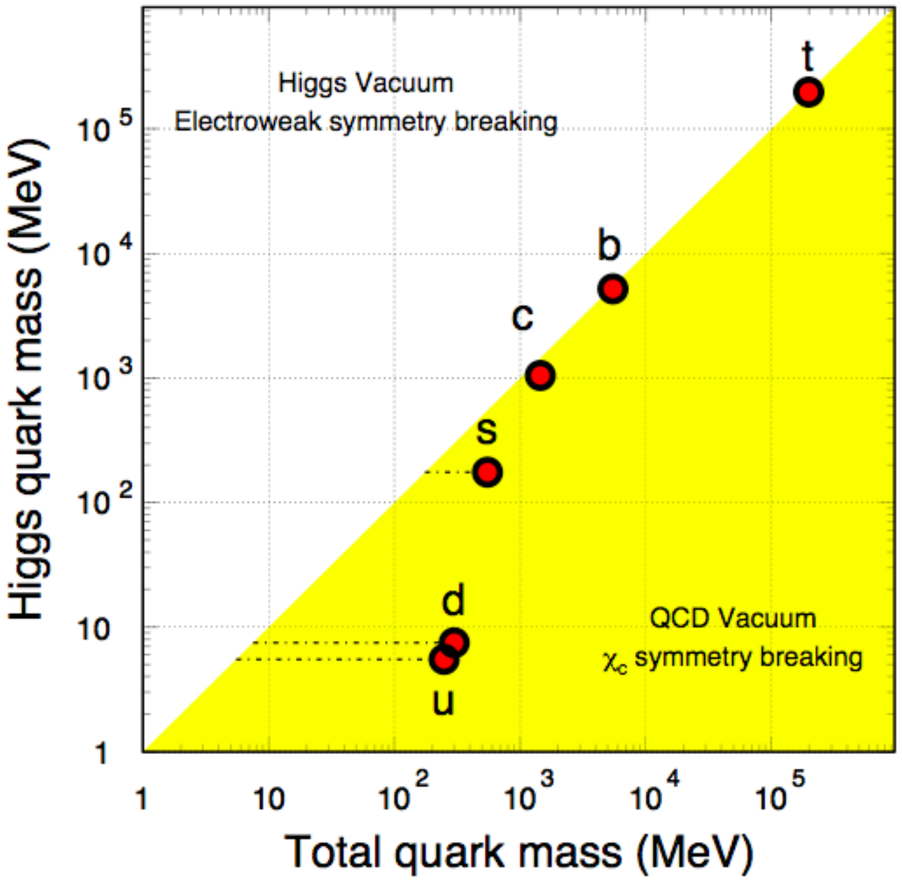
HEAVY - FLAVOR: A UNIQUE PROBE



$m_{c,b}$ » Λ_{QCD} : new scale

X. Zhu, M. Bleicher, S.L. Huang, K.S., H. Stöcker,
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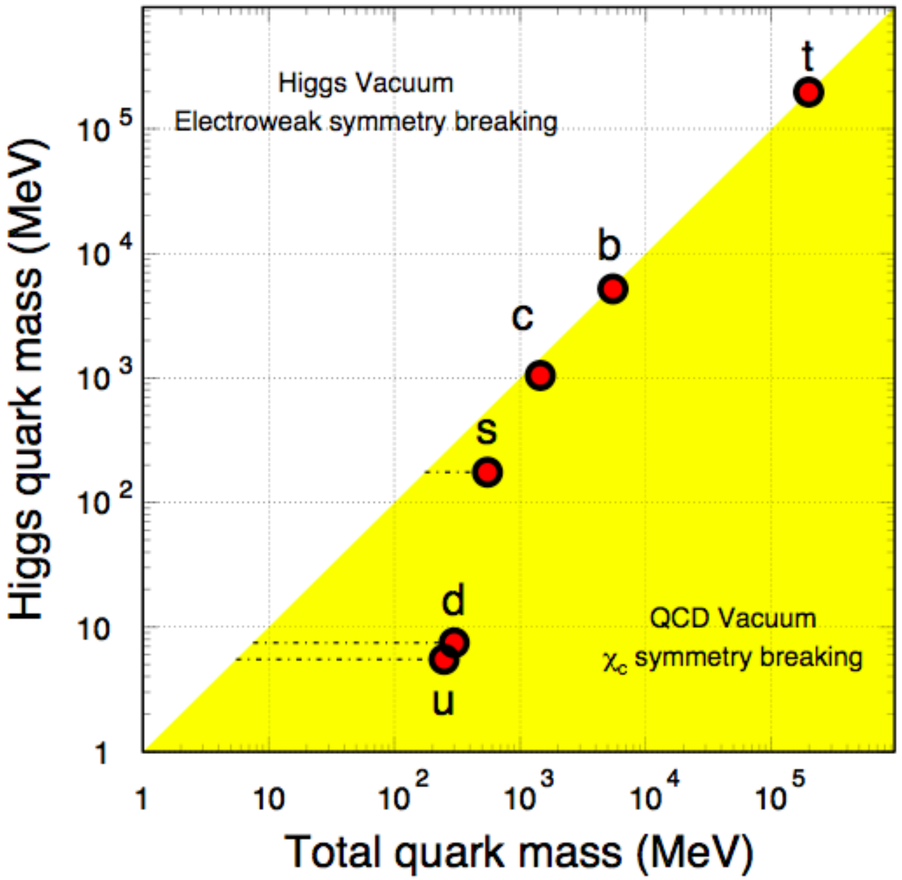
$m_{c,b}$ ≈ const., $m_{u,d,s} \neq$ const.

initial conditions

test pQCD, μ_R, μ_F

probe gluon distribution

HEAVY - FLAVOR: A UNIQUE PROBE



X. Zhu, M. Bleicher, S.L. Huang, K.S., H. Stöcker, N. Xu, and P. Zhuang, PLB 647 (2007) 366.

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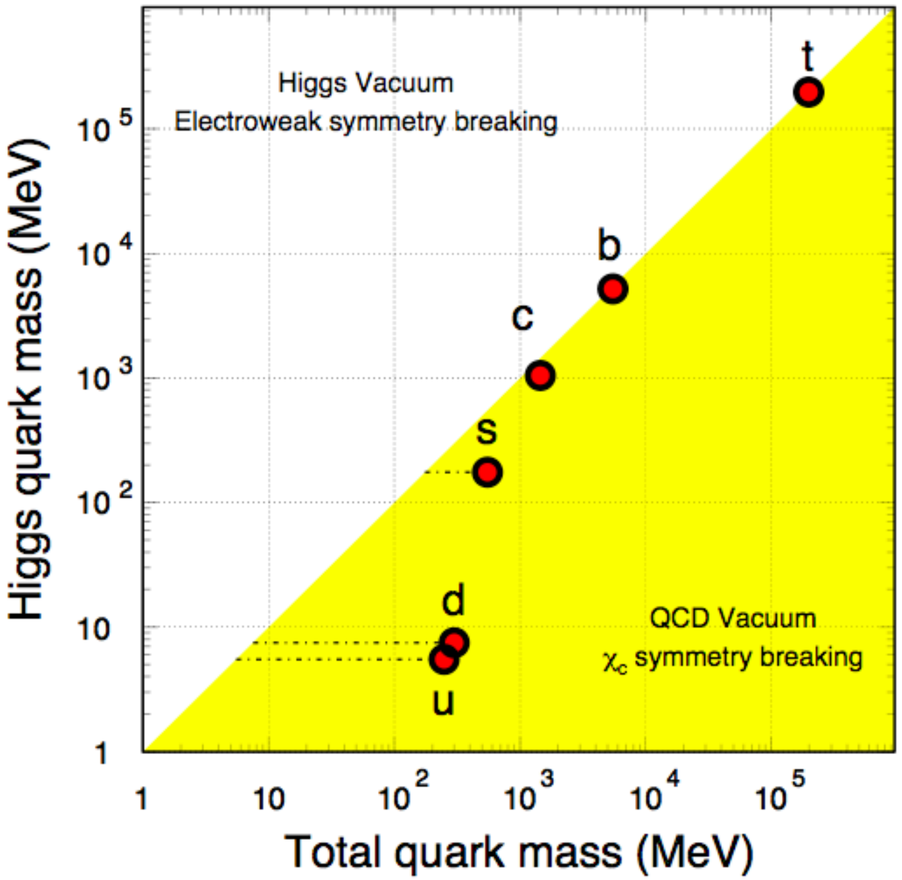
early partonic stage

diffusion (γ), drag (α)

flow, jets, correlations

probe thermalization

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hadronization

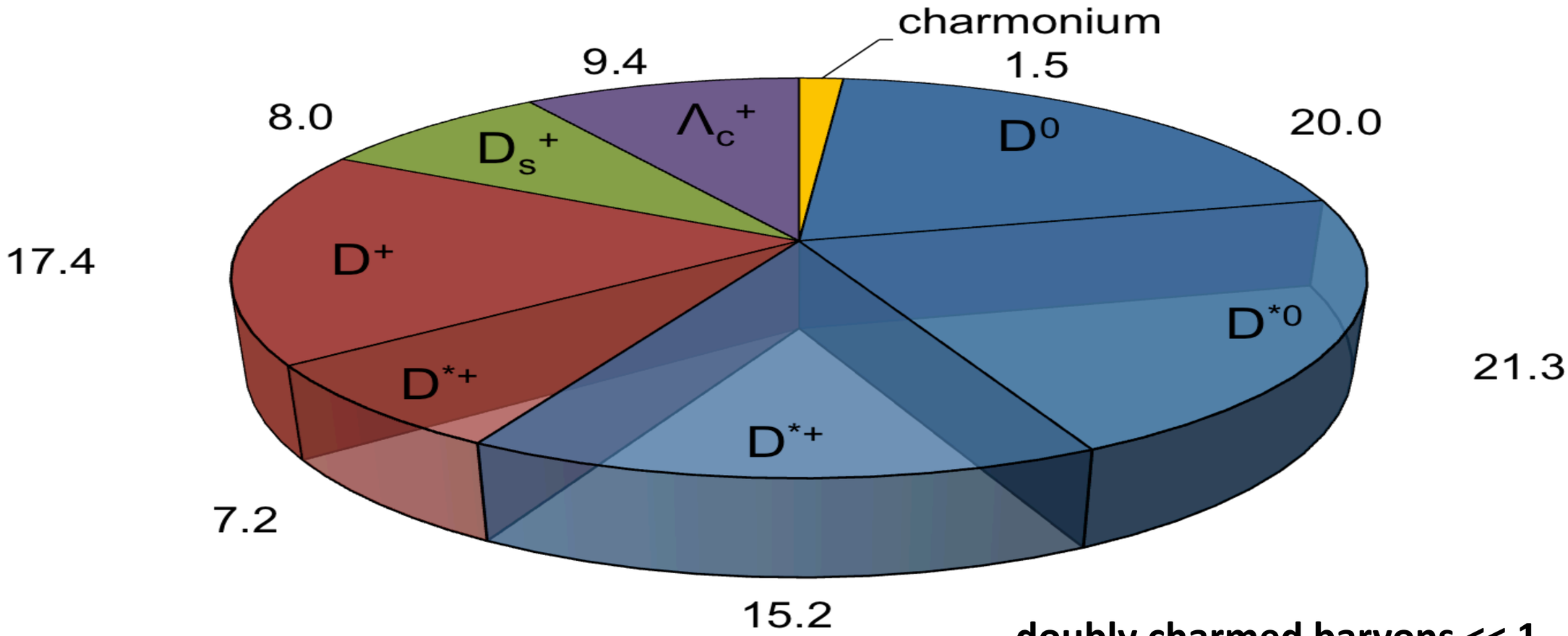
chiral symmetry restoration

confinement

statistical coalescence

J/ψ enhancement / suppression

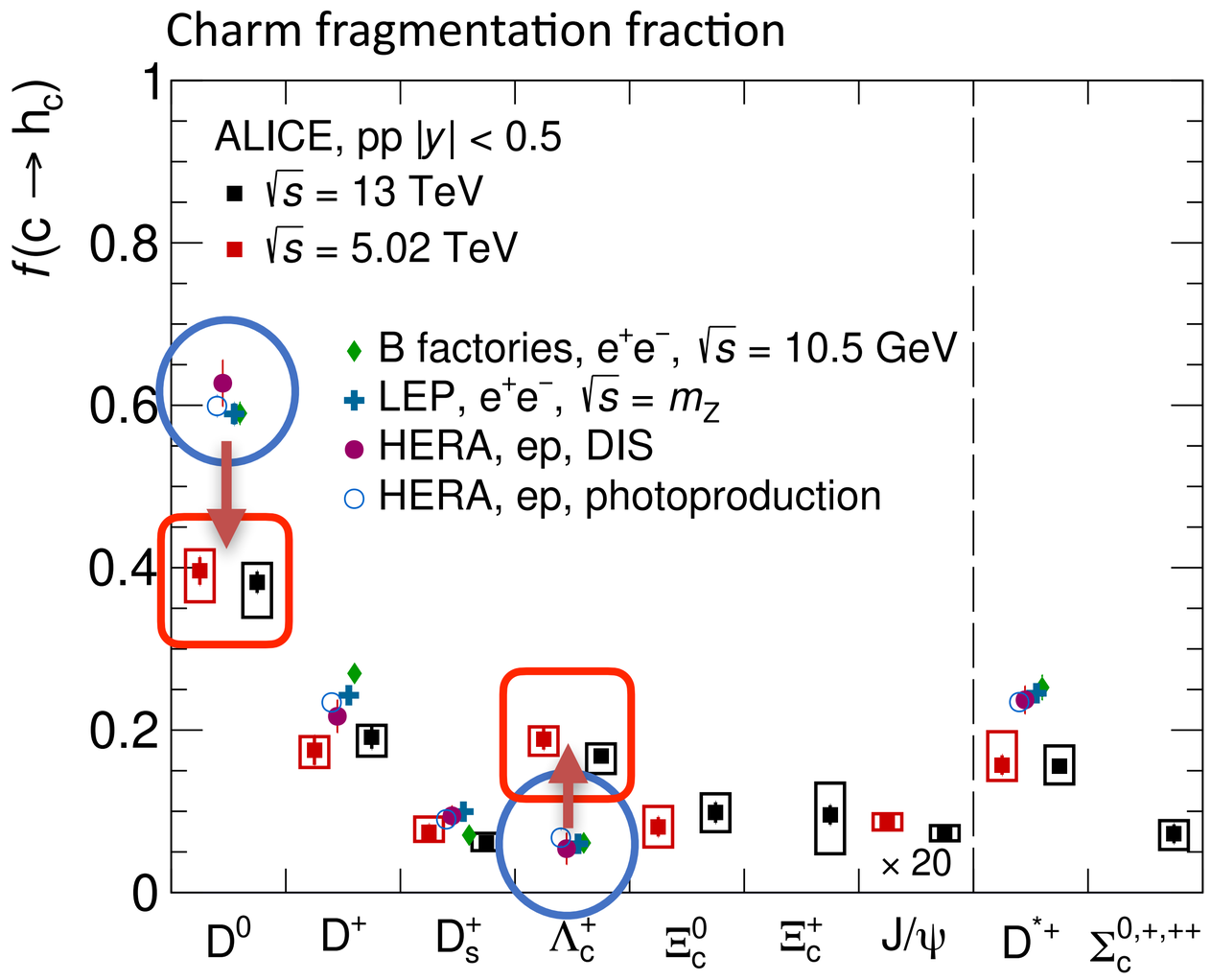
WHERE DOES ALL THE CHARM GO ?



doubly charmed baryons << 1

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

CHARM PRODUCTION AND FRAGMENTATION



Charmed baryon production **larger**

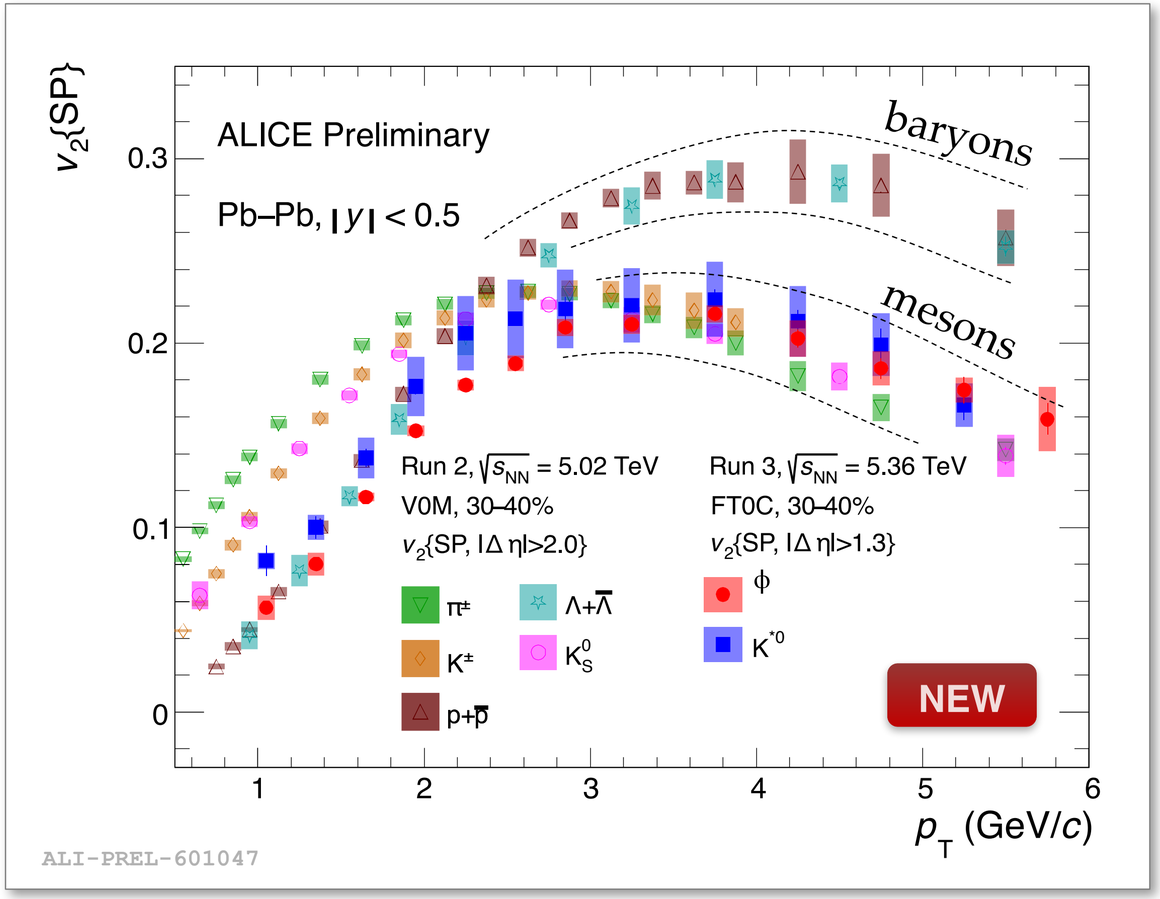
in **pp** than in **e⁺e⁻**

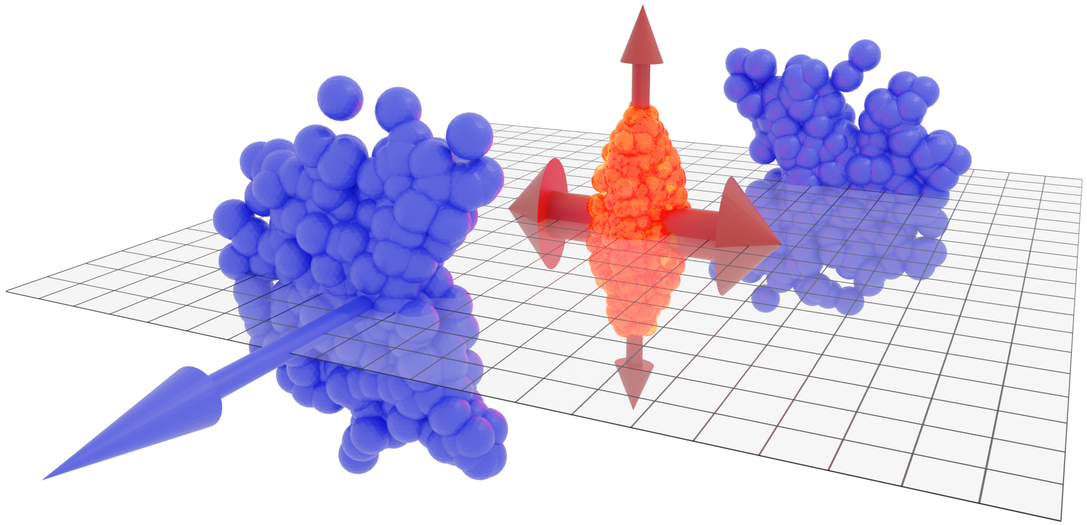
Λ_c, Ξ_c, Σ_c measured

charm hadronization not universal

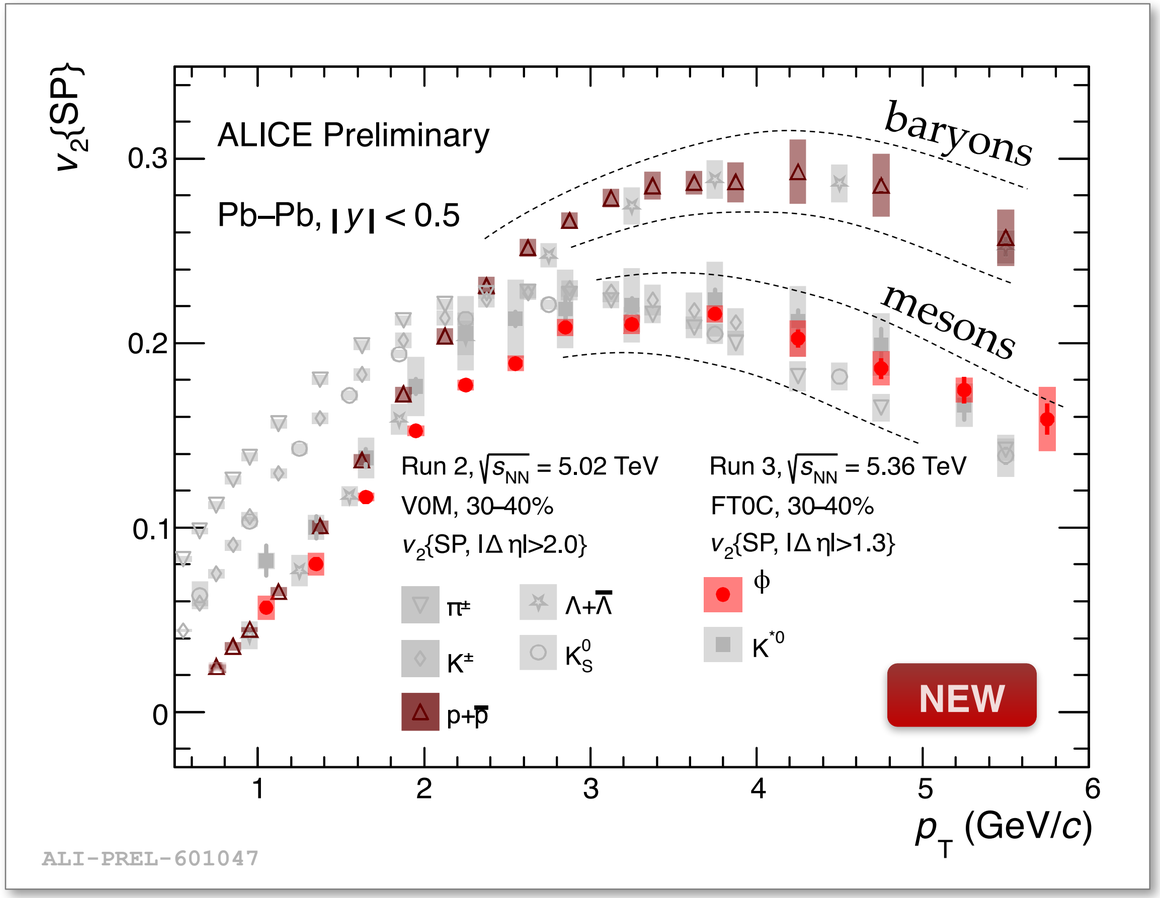
pbm, Johanna, Natasha Sharma et al. arXiv:2408.07496
ALICE arXiv:2308.04877

THE QGP EXPANDS: COLLECTIVE FLOW





THE QGP EXPANDS: COLLECTIVE FLOW

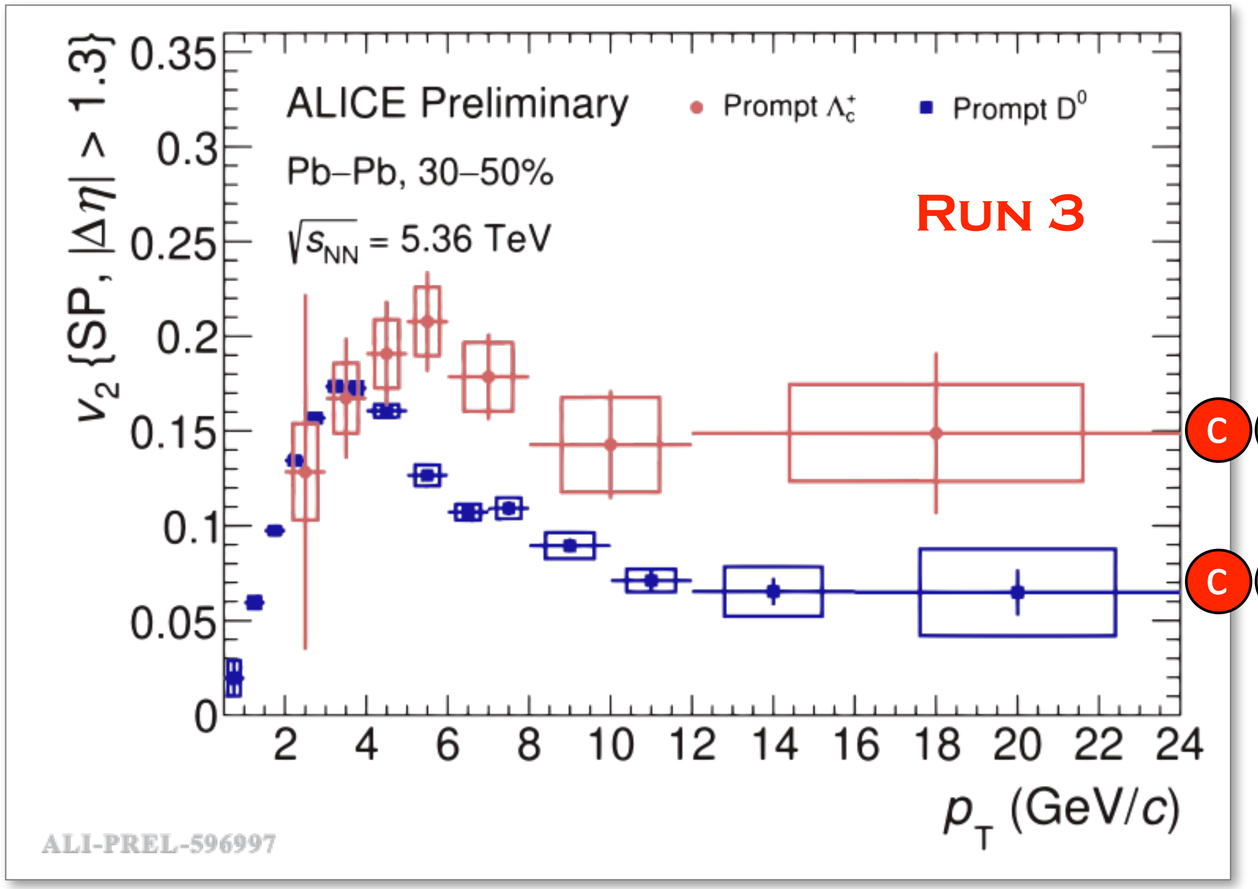


- **Nearly all particle species participate in collective flow**
  - quantified via a Fourier decomposition:

$$\frac{dN}{d\varphi} \propto \left(1 + 2\sum_{n=1}^{\infty} v_n \left(cos\left[n\left(\varphi - \Psi_n\right)\right]\right)\right)$$

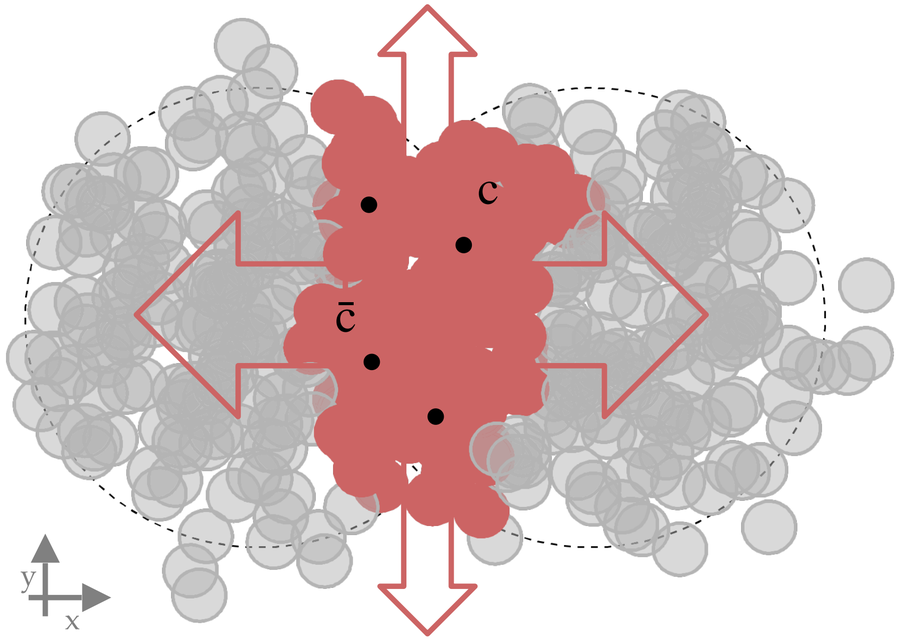
- Leading term: v_2, “elliptic flow”
- **Light flavour sector**: $\pi^{\pm}$, $K^{\pm}$, p, K^0_S, Λ, ϕ, K^{*0}
  - low p_T: mass-dependent → common velocity field
  - high p_T: baryon/meson grouping → quark coalescence

THE QGP EXPANDS: COLLECTIVE FLOW



c u d

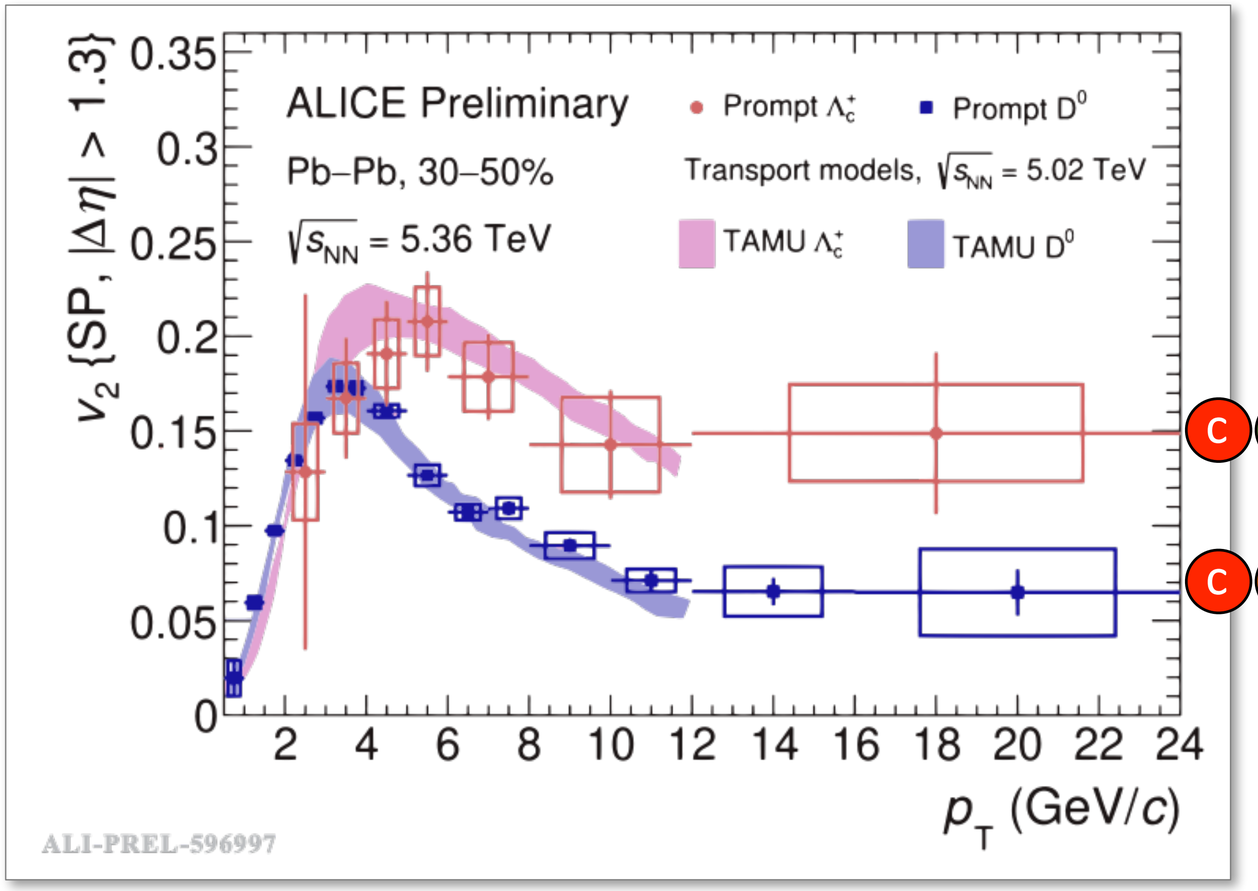
c $\bar{u}$



- **World-first measurement of Λ_c^+ baryon v_2**
  - Viable with **Run 3 samples** + **upgraded precision (ITS2)**
  - $\Lambda_c : c\tau \approx 60\mu\mathrm{m}$
- Significantly different vs D^0: **baryon** / **meson** effect
- demonstrates that **charm** quarks take part in **qgp expansion** and hadronize via coalescence with light quarks from the QGP

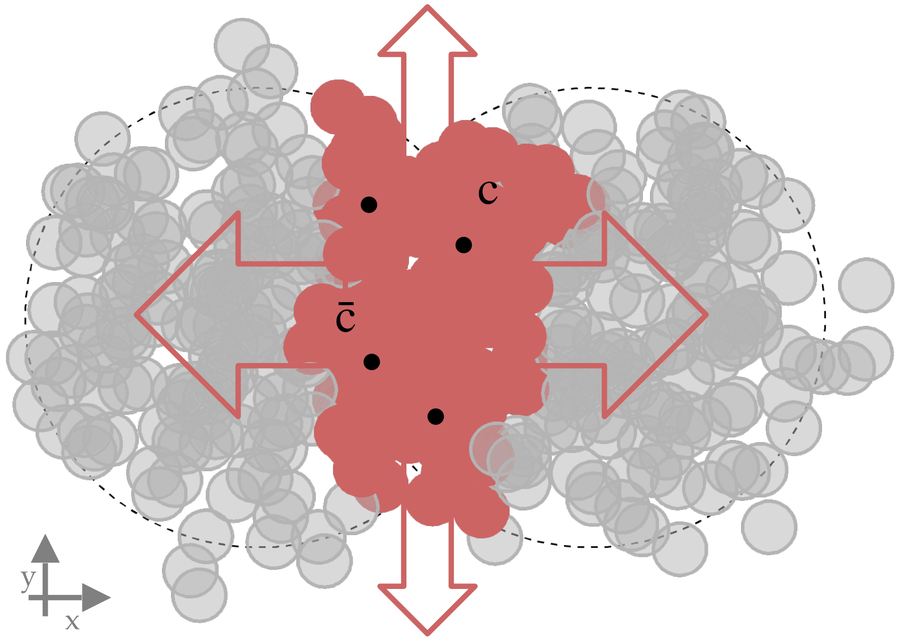
arXiv:2603.18966

THE QGP EXPANDS: COLLECTIVE FLOW



c u d

c $\bar{u}$

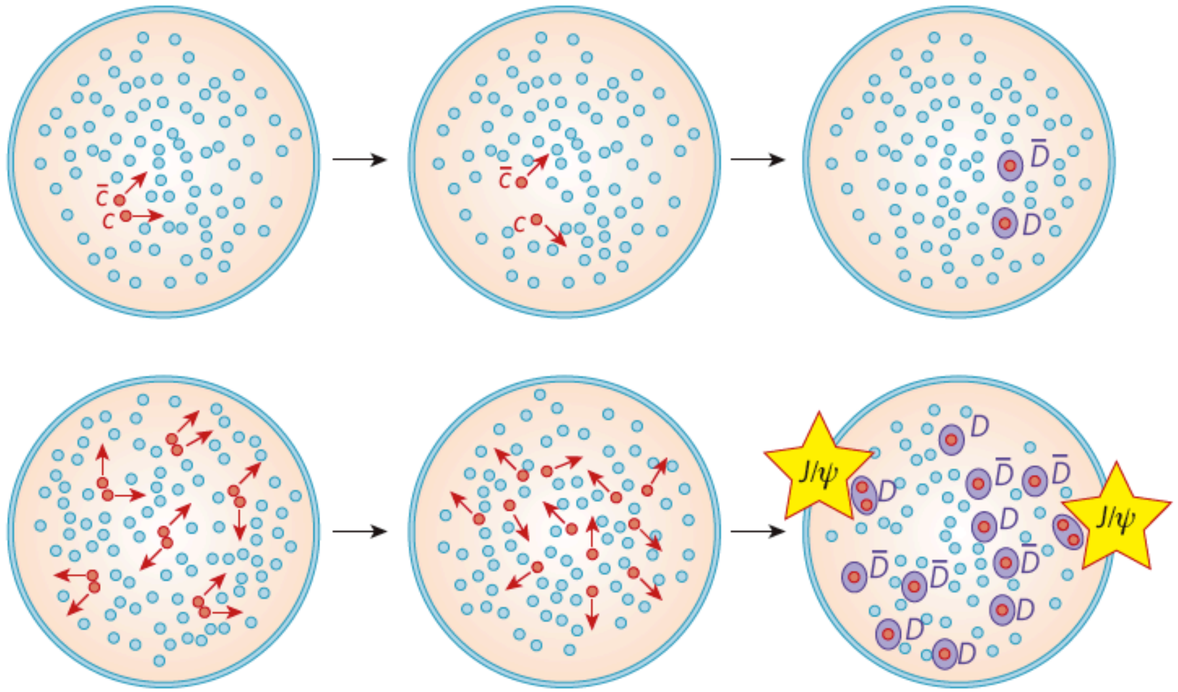


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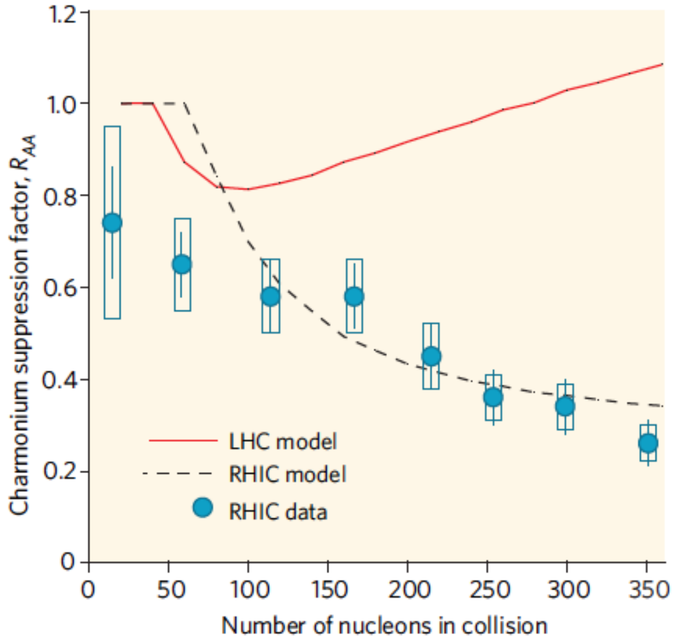
J/Ψ (CHARM-ANTICHARM) PRODUCTION

start of collision quark gluon plasma hadronization



Low energy (SPS, RHIC):
screening of J/ψ ⇒ suppression

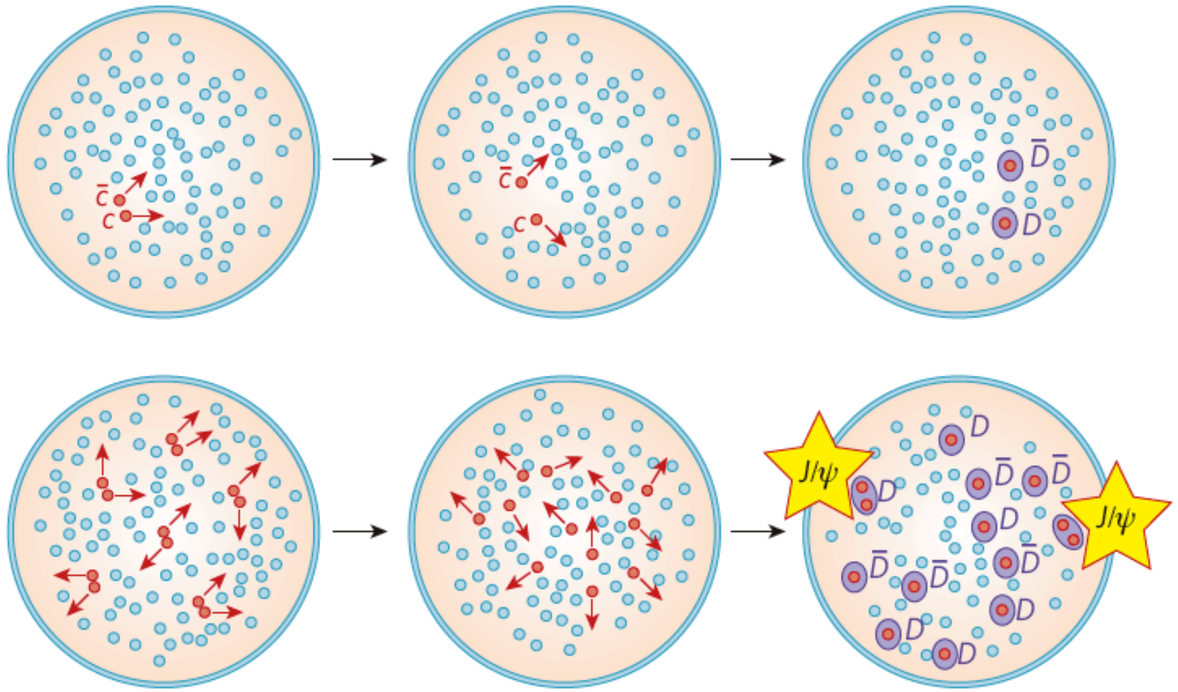
High energy (LHC):
generation at phase boundary
⇒ enhancement



P. Braun-Munzinger and J. Stachel, Nature 448 (2007) 302.

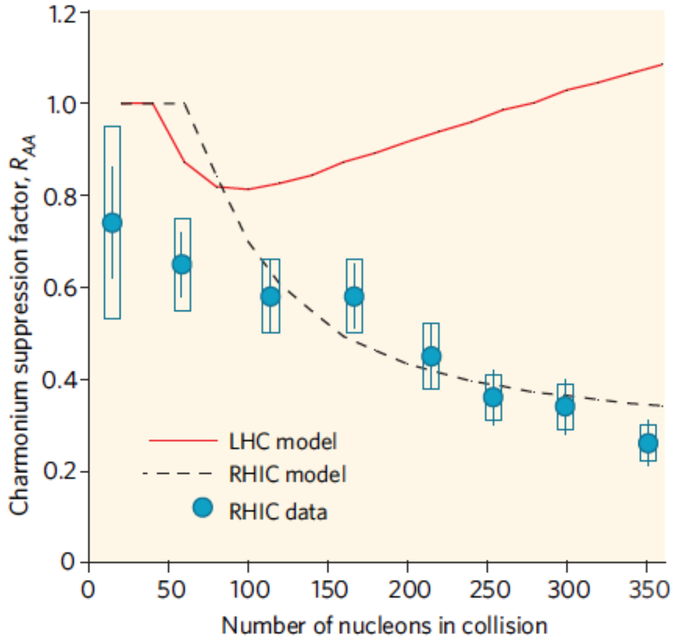
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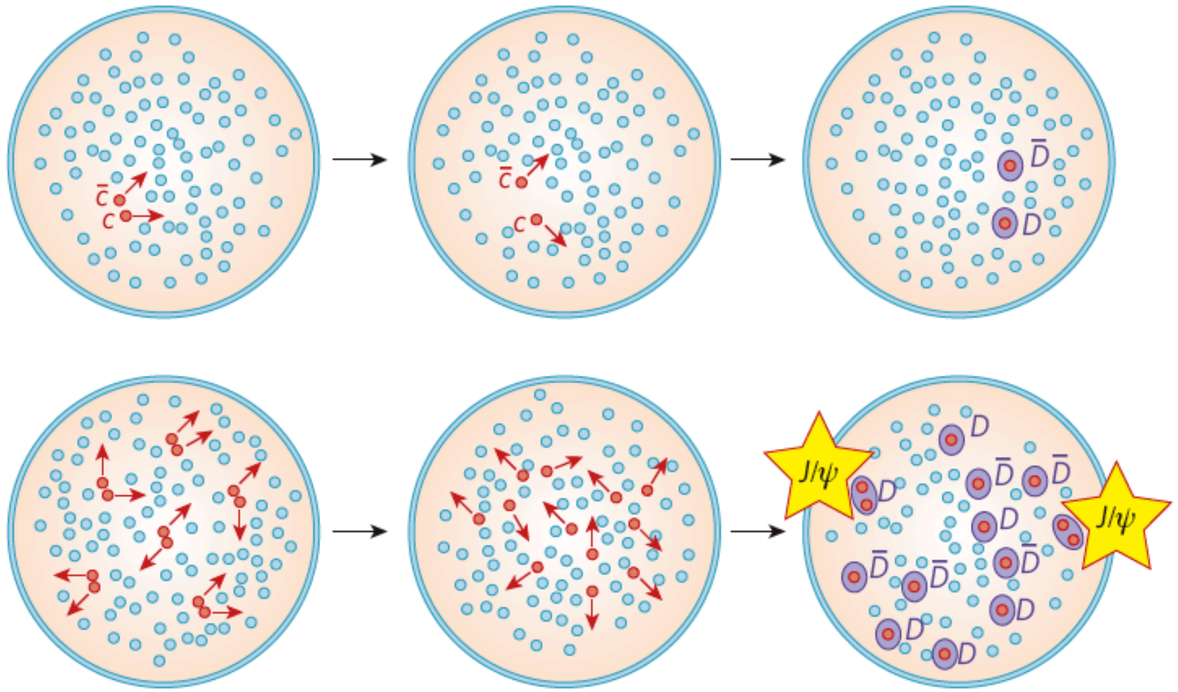


additional production mechanism at high-energy

P. Braun-Munzinger and J. Stachel, Nature 448 (2007) 302.

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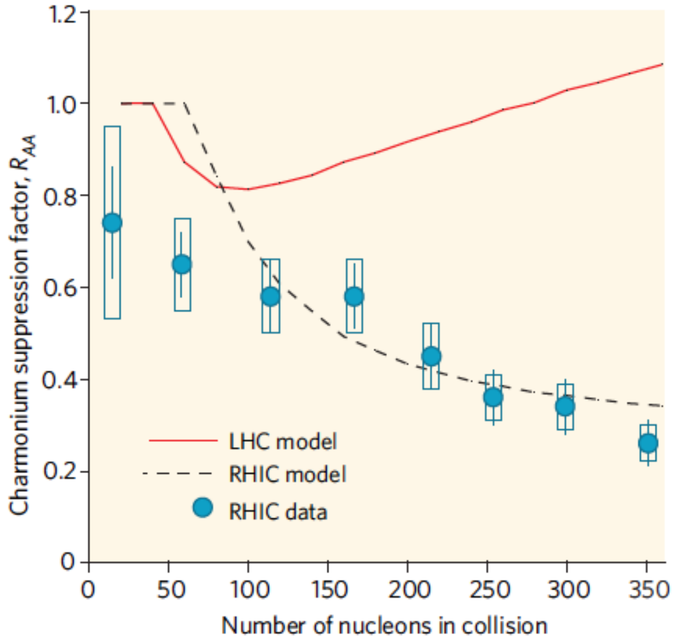
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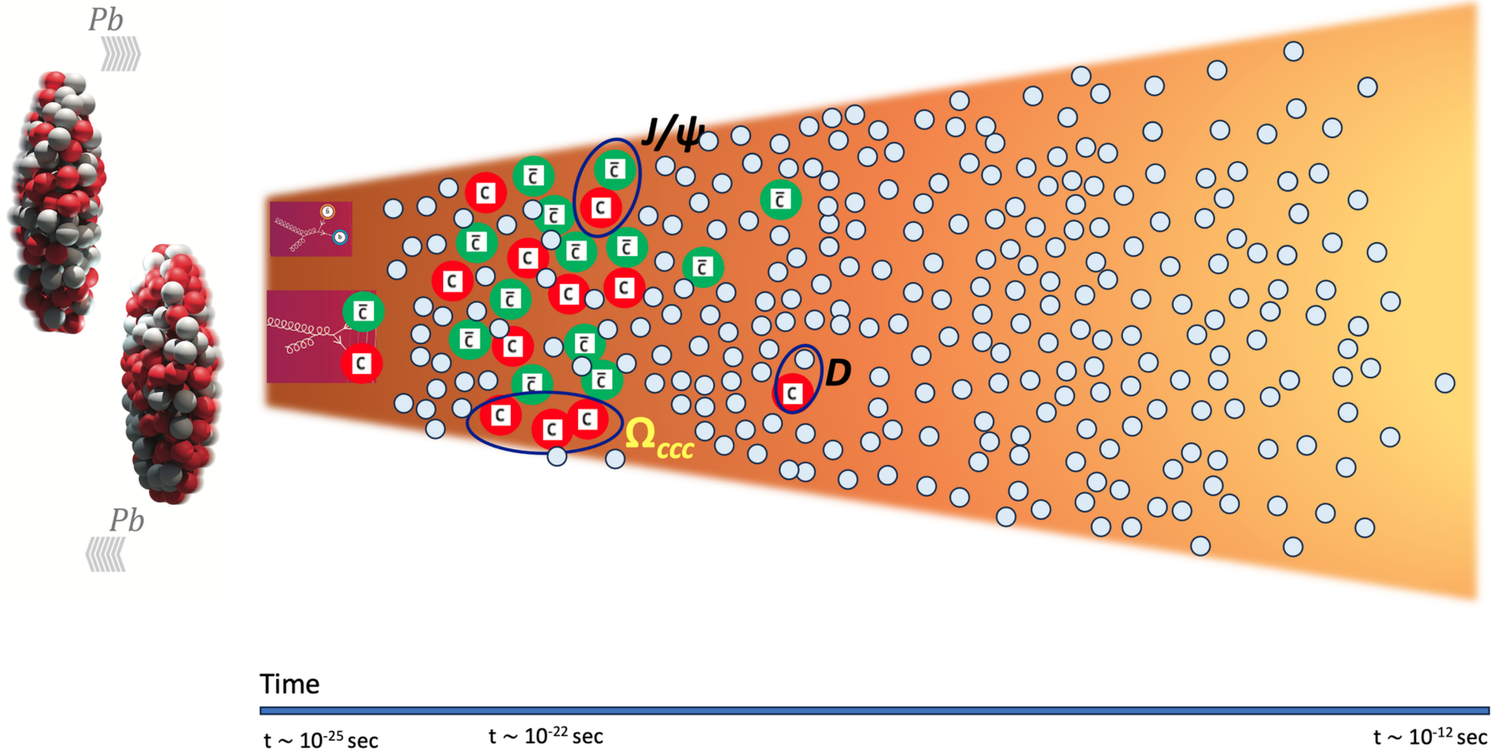
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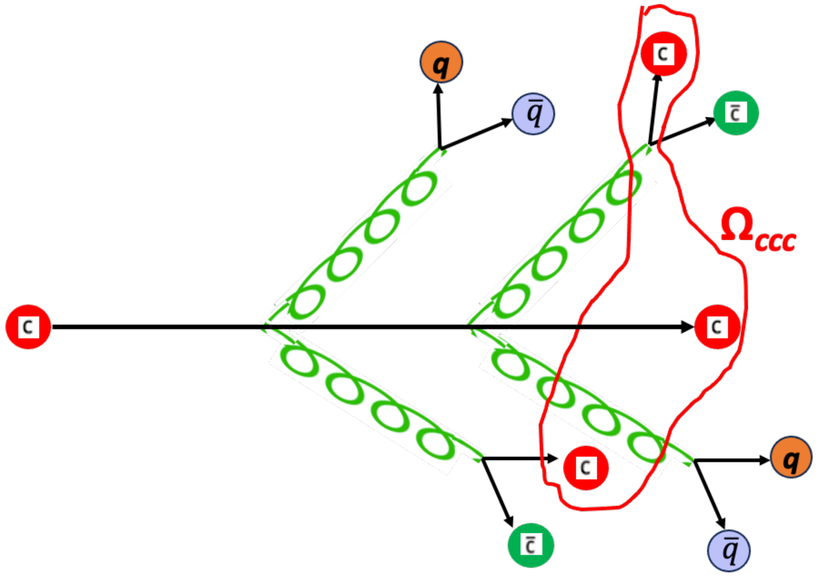
High energy (LHC):
generation at phase boundary
⇒ enhancement



additional production mechanism at high-energy
fingerprint of de-confinement

CHARM QUARK HADRONIZATION



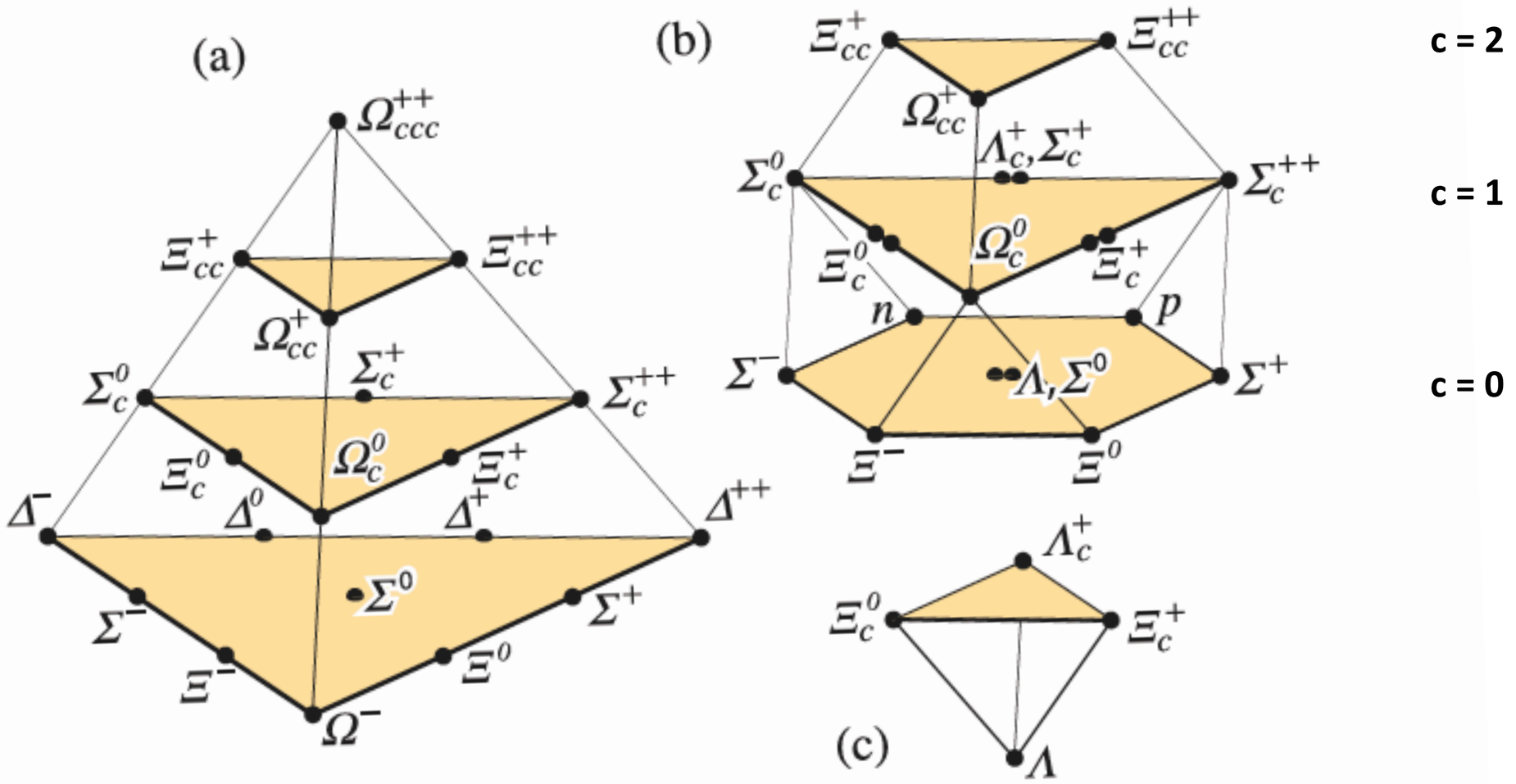


statistical **combination** in quark-gluon plasma

signals charm quark **deconfinement** and **thermalization**

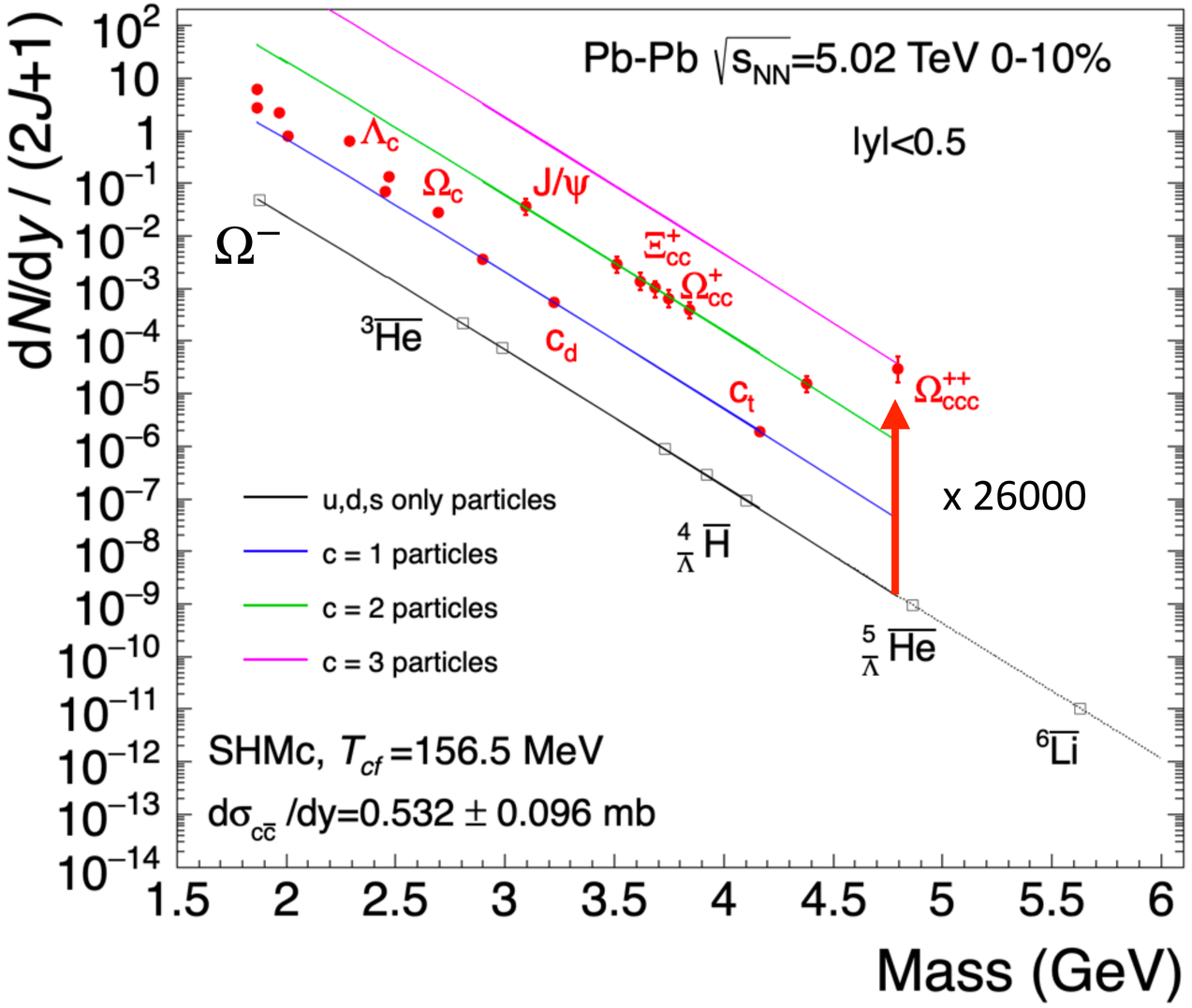
fragmentation in vacuo

CHARMED BARYONS - SU(4)



All **ground state** spin-1/2 **doubly charmed** baryons **discovered** by LHCb

POINTING x ACCEPTANCE × INTERACTION RATE: NEW OPPORTUNITIES

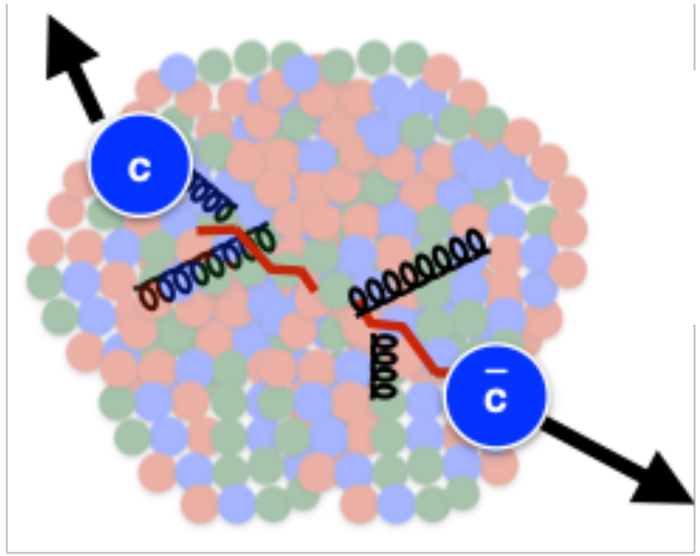


- **u,d,s-hadrons**: mass exponential hierarchy, dominated by quarks created at phase boundary (e.g. Ω^-)
- **charm oversaturated** through initial production, fugacity factor $g_c \approx 30$ per additional **charm quark**
- probe **deconfinement & thermalization** of **charm** quarks

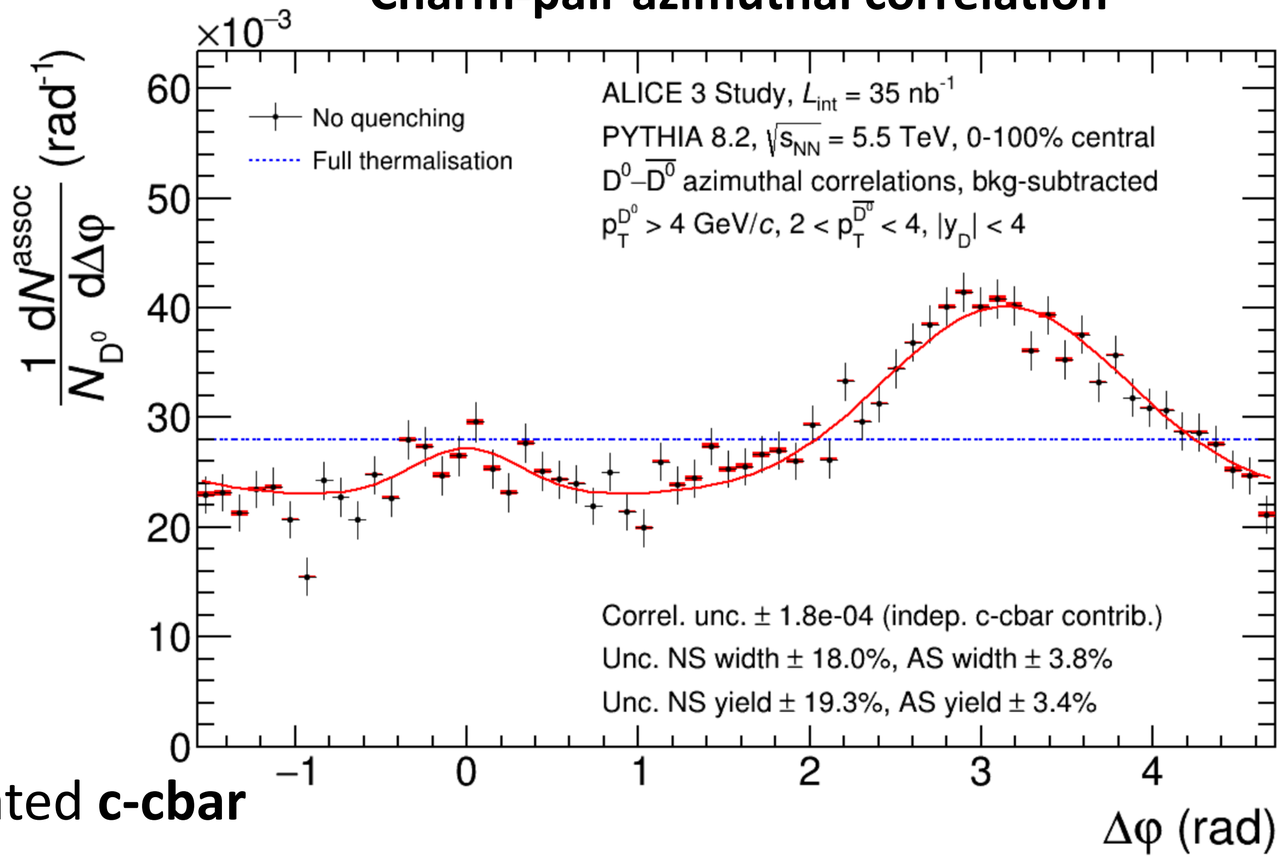
J. Stachel, pbm, et al.
arXiv.org:2104.12754

arXiv:2211.02491

CHARM-ANTICHARM CORRELATIONS



Charm-pair azimuthal correlation



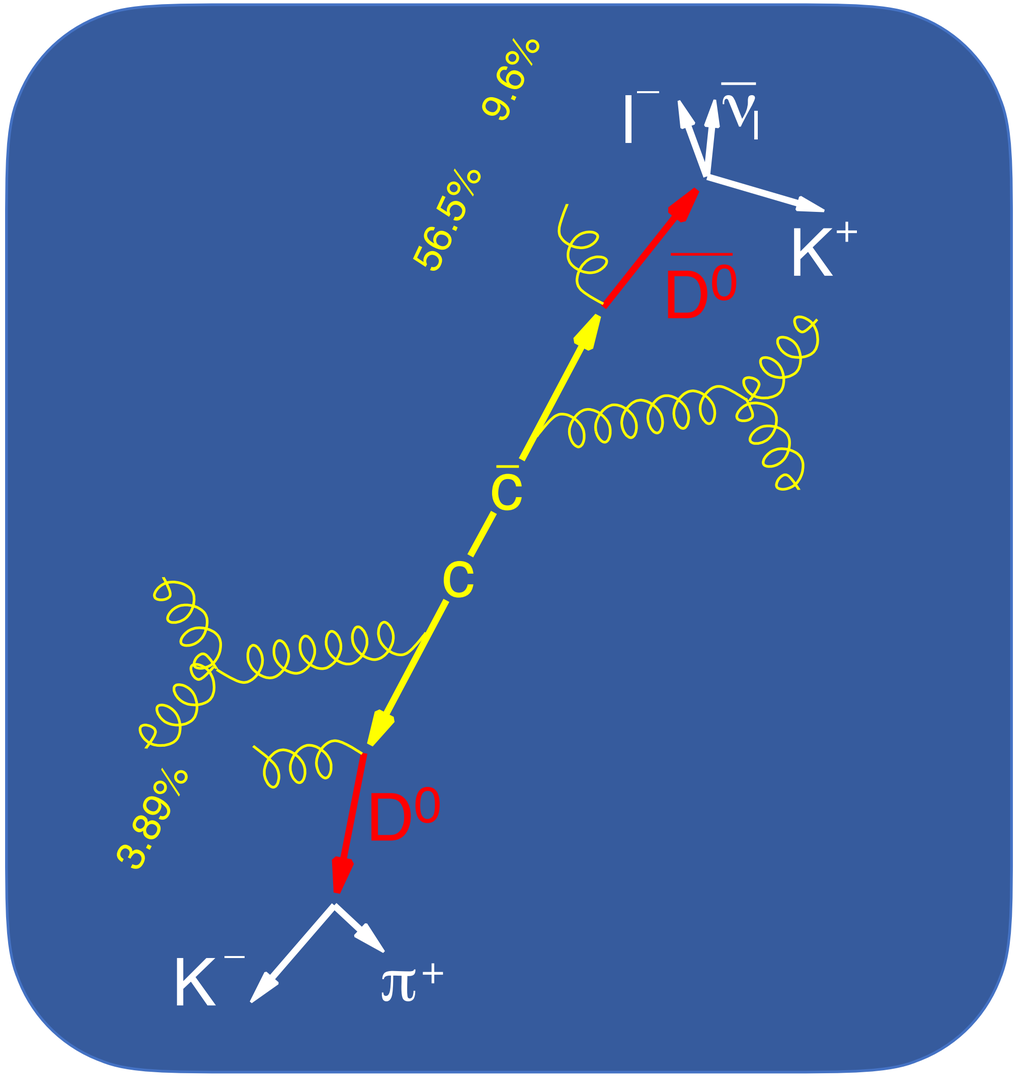
QCD imprint on **initial correlation** of pair-created **c-cbar**

direct access to **charm diffusion**

can be **calculated** from **first principles**

ALICE 3 LoI, CERN-LHCC-2022-009
X. Zhu, M. Bleicher, S.K. Huang, ks, and H. Stoecker, PLB 647 (2007) 366, arXiv:0604178
G. Tsiledakis, H. Appelshauser, ks, J. Stachel NPA 858 (2011) 86; arXiv:0908.0427

HEAVY-QUARK DETECTION



e.g., D^0 ($c\bar{u}$)→ K^- + π^+ , 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

pbm et al. EOI arXiv:1902.01211

TIMELINE ALICE UPGRADES

LS3: FoCal & ITS3

Specific upgrades for Run 4

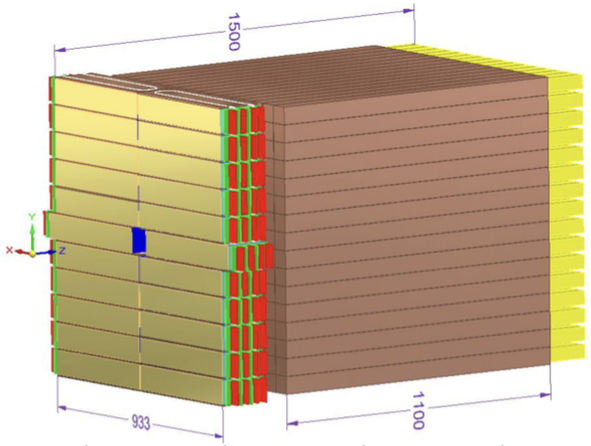
Now proceeding towards final sensors
in view of start of production

LS4: ALICE 3

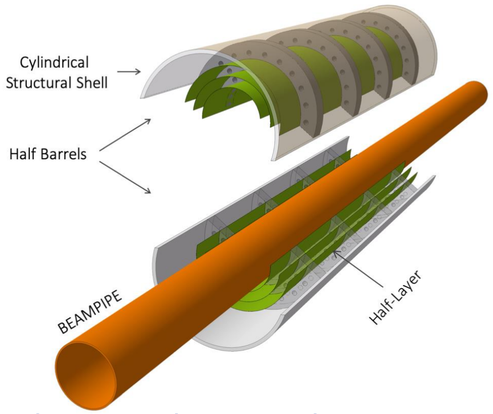
Letter of Intent reviewed in 2022

approval towards TDRs!

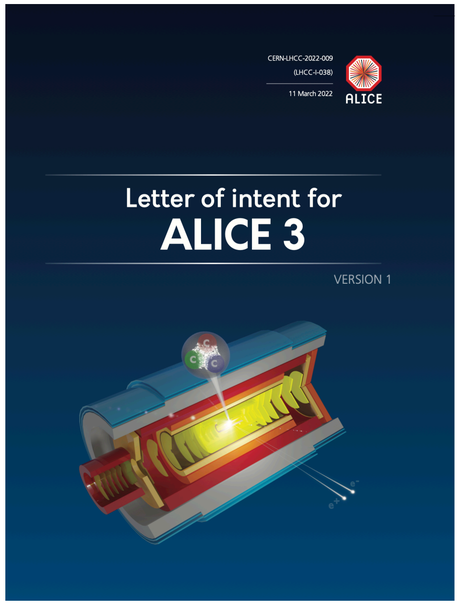
FoCal TDR: CERN-LHCC-2024-004



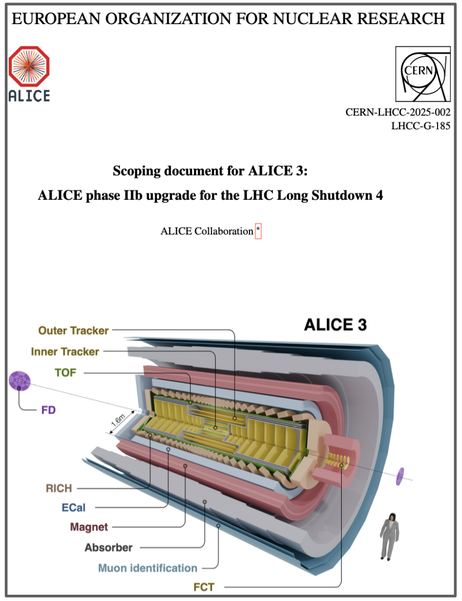
ITS3 TDR: CERN-LHCC-2024-003

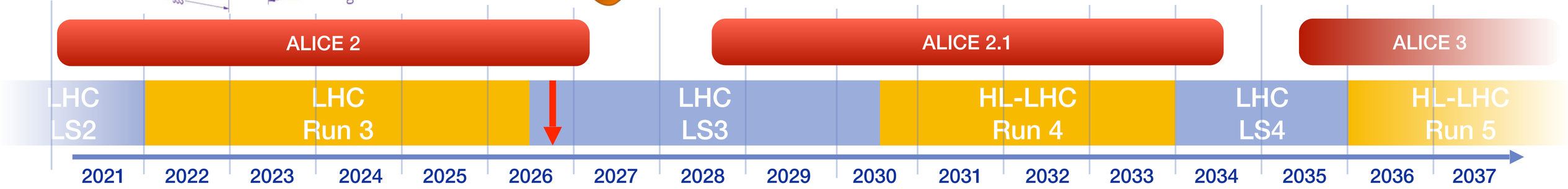


LOI: CERN-LHCC-2022-009



SD: CERN-LHCC-2025-002

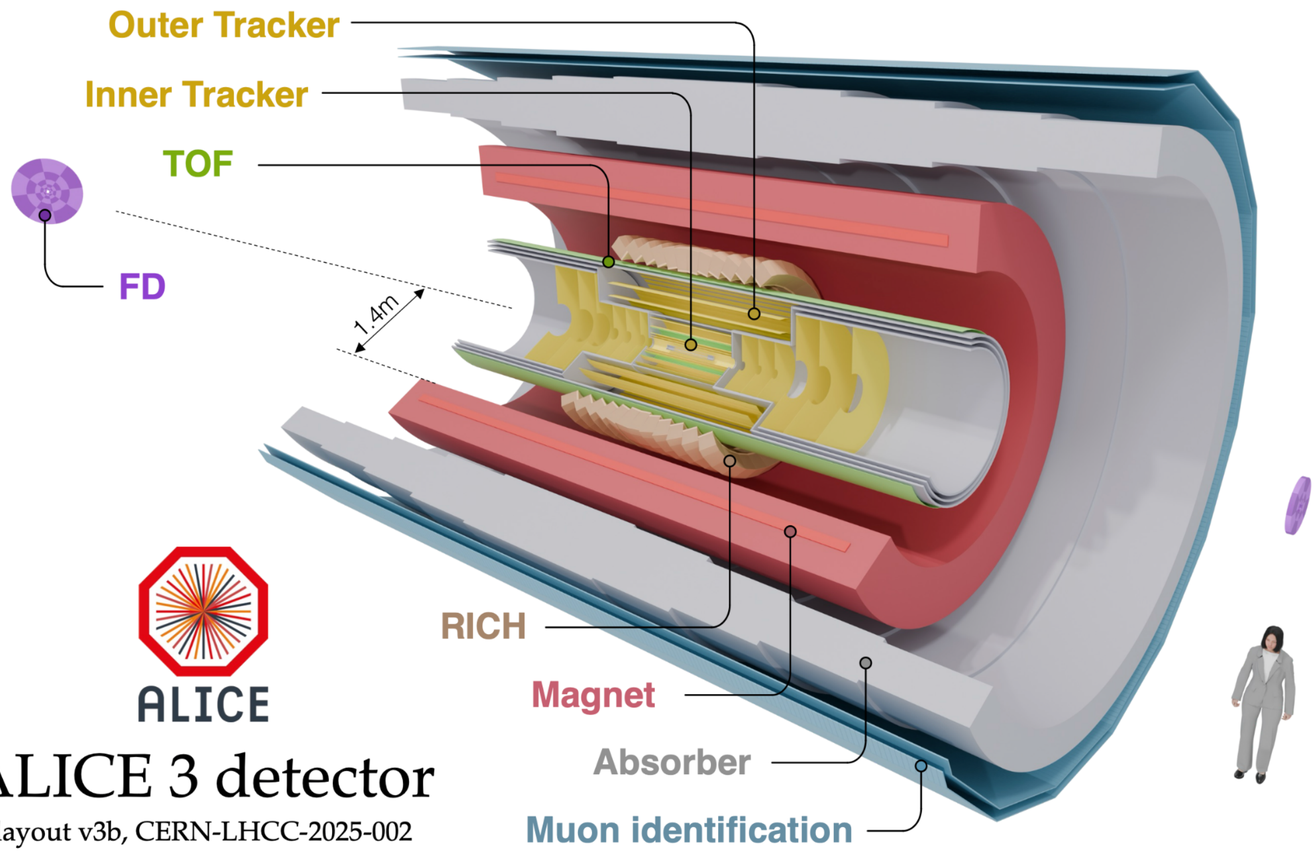




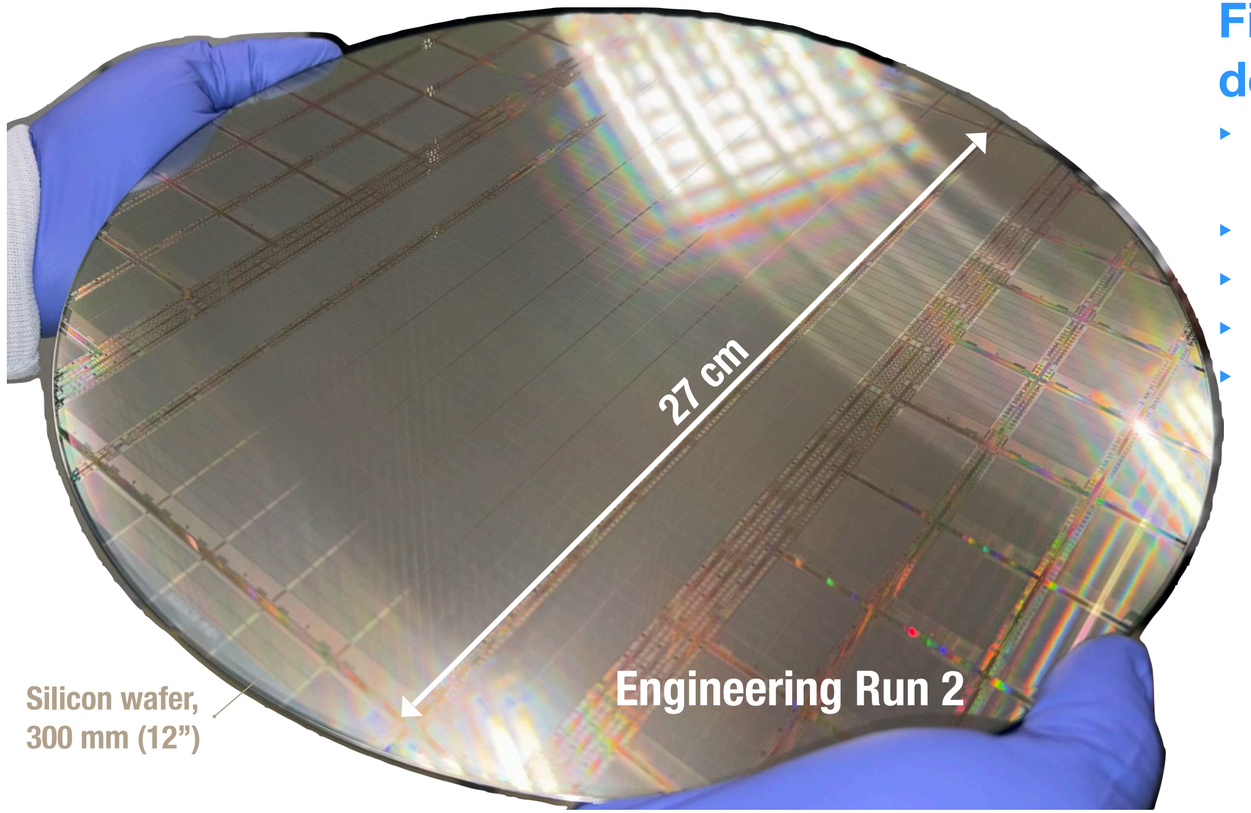
kai.schweda@cern.ch

ALICE 3 - DETECTOR SCOPE

- **ALICE 3 v3b as target layout — approved by CERN Research Board**
- **A v3b-NoRICH layout is better matching the current funding projections**
  - Enables the HF programme (beauty, multi-charm, charm correlations and femtoscopy)
  - Extends by x2.5-3 the acceptance for correlations, jets, UPC programmes
- **RICH** is **essential** for the **dielectron programme** → continue R&D and pursuing a funding plan to enable inclusion of the RICH, possibly staged in time



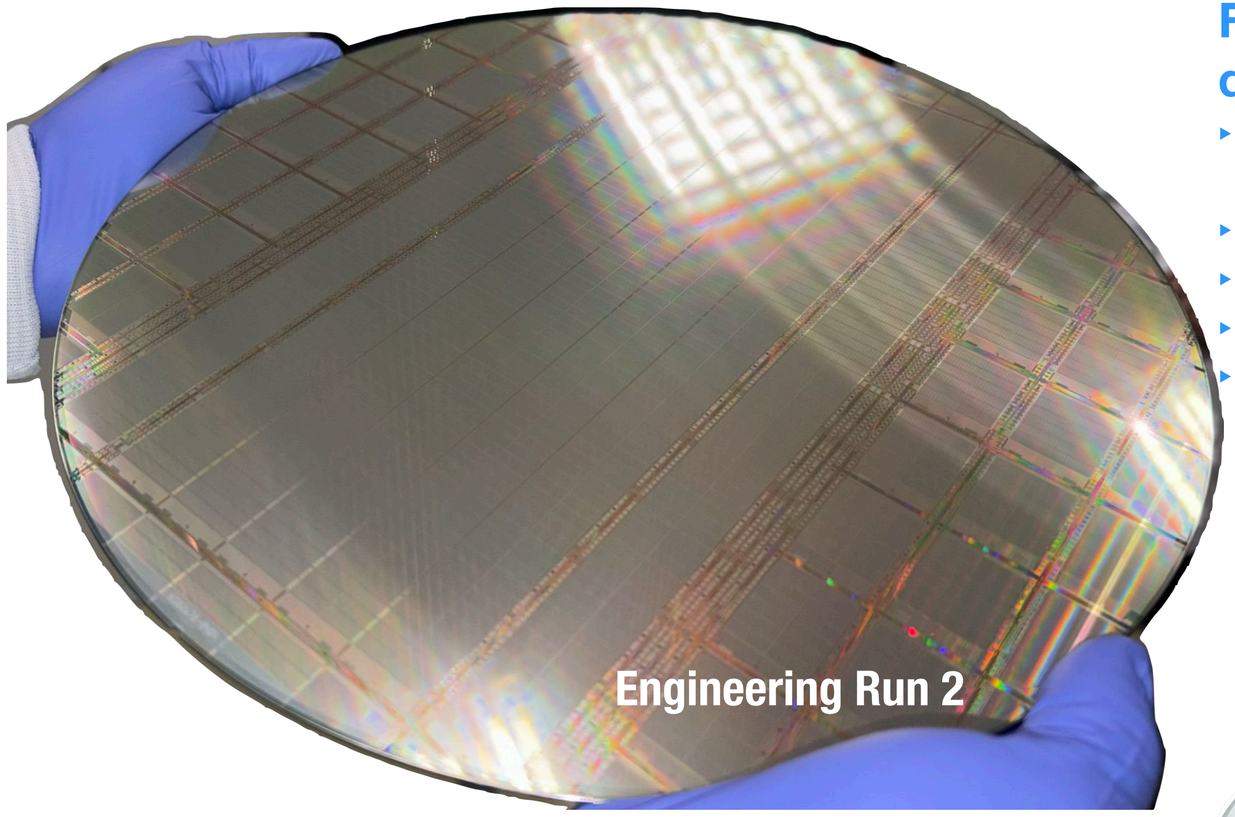
INNER TRACKING SYSTEM 3



First Engineering Run 2 (ER2) wafers delivered in February

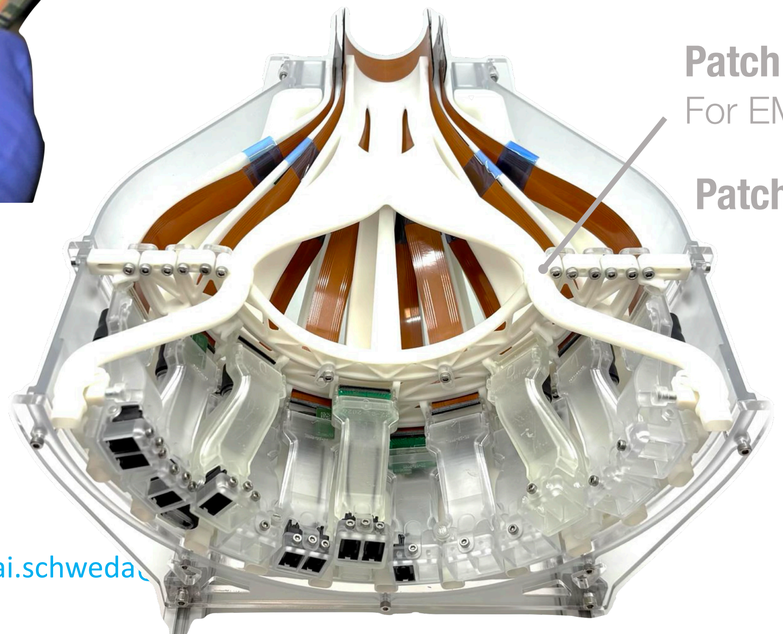
- MOSAIX (ER2 sensors) being tested (thanks to a huge campaign preparation with emulators along 2024-2025)
- Tests on wafer probing
- In parallel: thinning/dicing (for **Q**ualification **M**odel)
- In a second step: bonding on carriers
- tape out of final ER3 in December

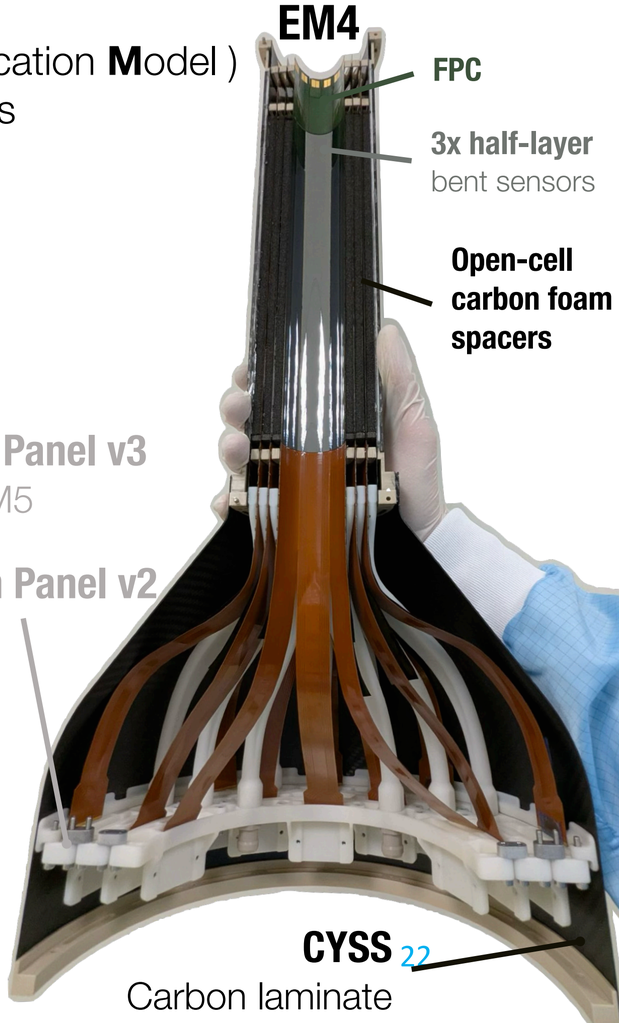
INNER TRACKING SYSTEM 3



First Engineering Run 2 (ER2) wafers delivered in February

- MOSAIX (ER2 sensors) being tested (thanks to a huge campaign preparation with emulators along 2024-2025)
- Tests on wafer probing
- In parallel: thinning/dicing (for Qualification Model)
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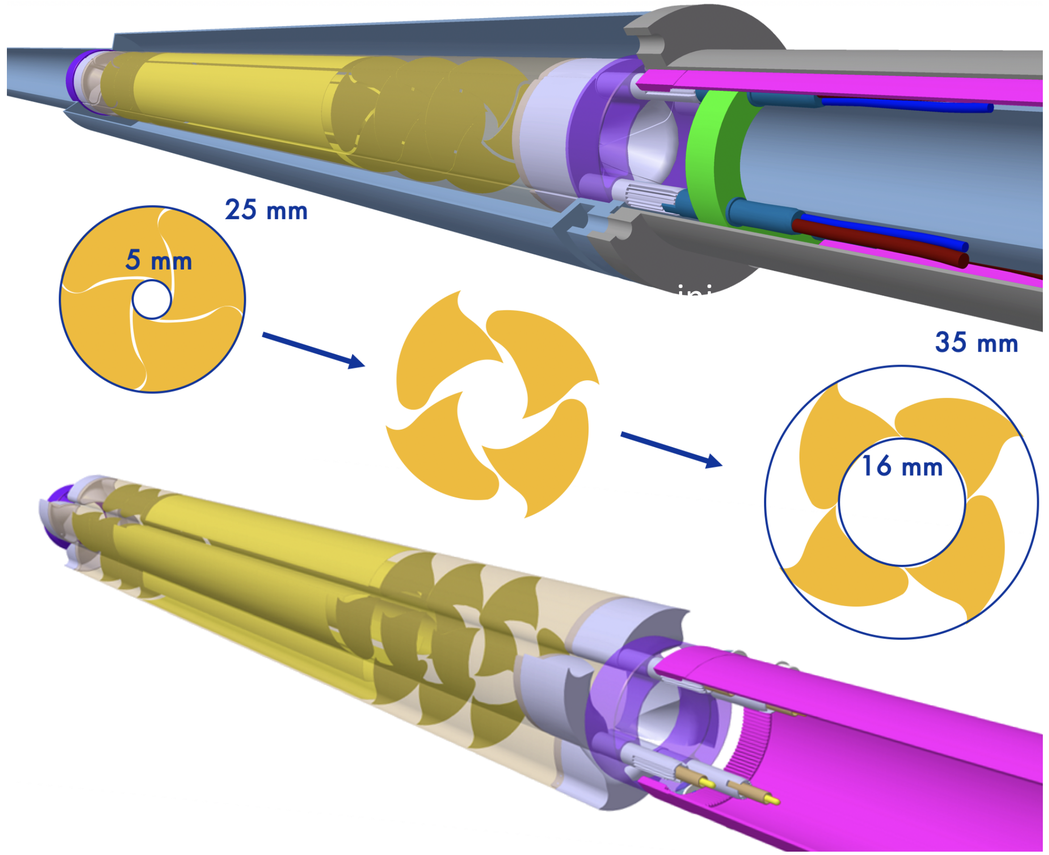


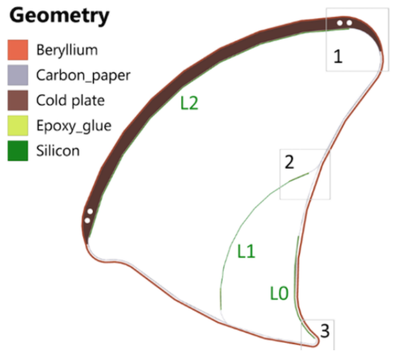
Engineering Models

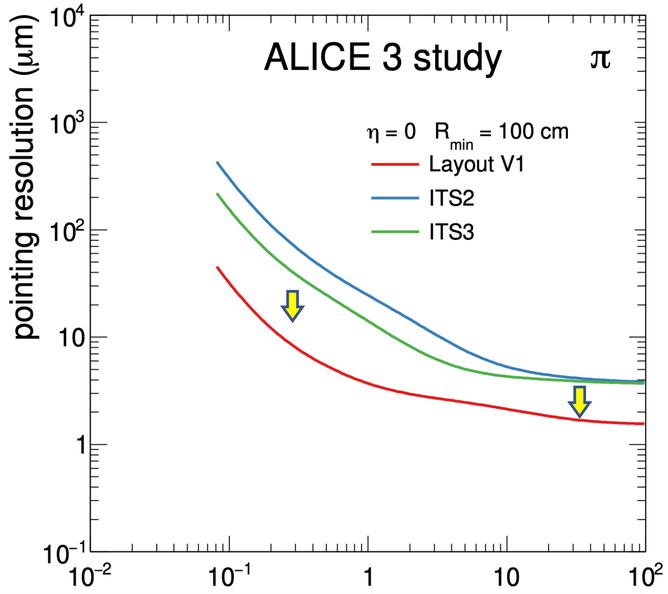
- For layout, assembly and installation procedures validation

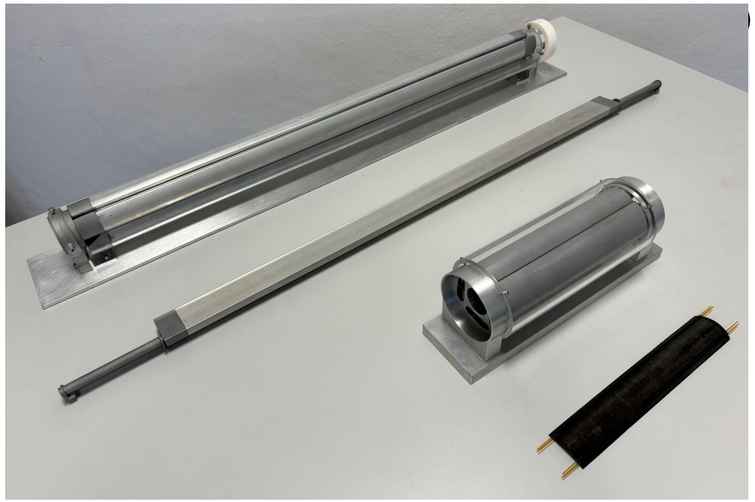
VERTEX DETECTOR CONCEPT AND R&D

- Retractable vertex detector inside beam pipe (Iris)
- Target specifications for pixel sensor: 10x10 μm^2 pixels, <50 μm thickness, NIEL: ~10^{16} 1 MeV n_{eq}/cm^2

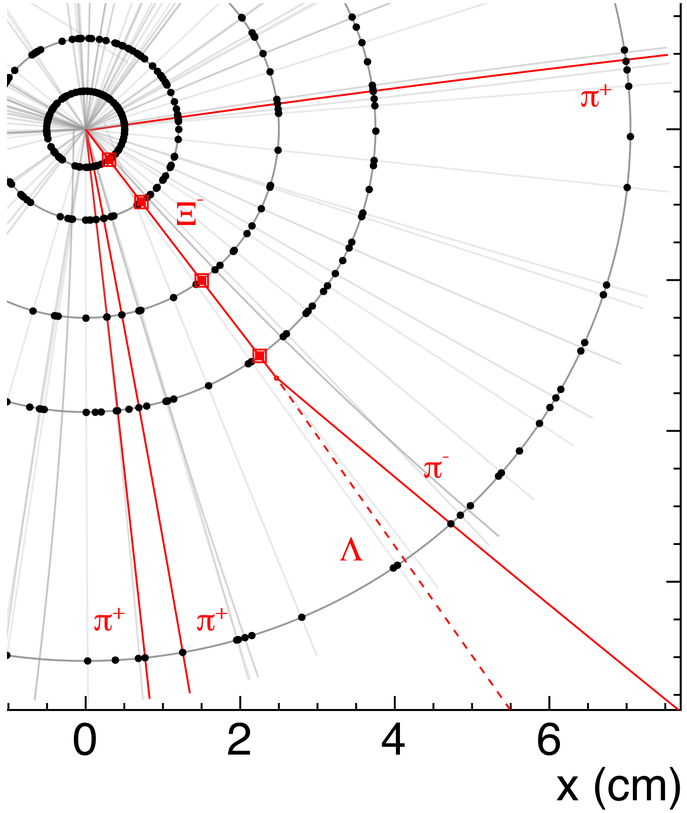






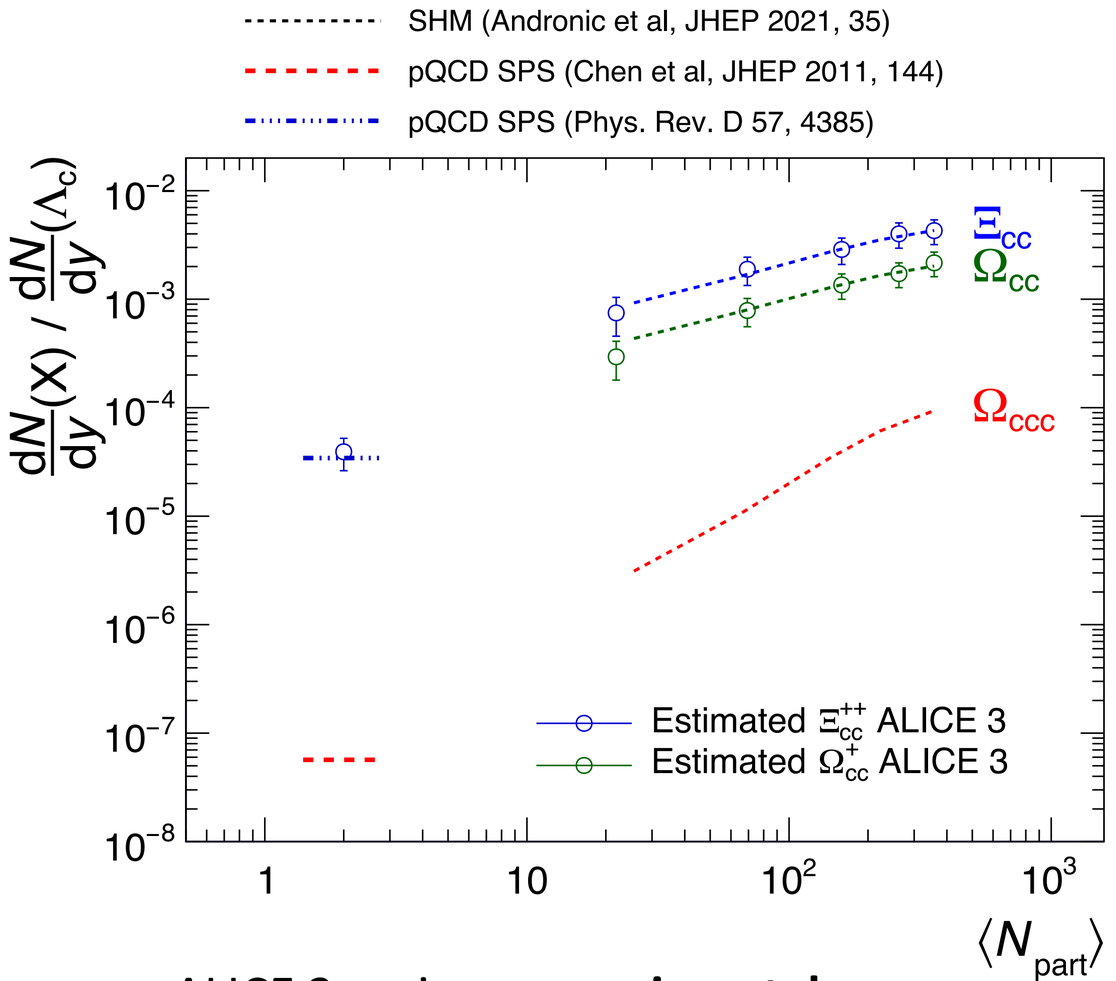


STRANGENESS TRACKING



$$\Xi_{cc}^{++} \rightarrow \Xi_c^+ + \pi^+$$

$$\Xi_c^+ \rightarrow \Xi^- + 2\pi^+$$



ALICE 3: unique **experimental** access to **multiply-charmed baryons**

kai.schweda@cern.ch

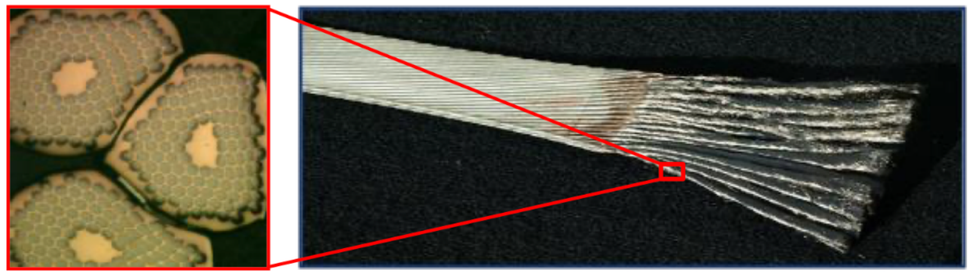
SUPERCONDUCTING CABLE

- **Two-pronged procurement strategy:**
  - **China - Wuxi-Toly**. Recent order of ***supply for first ALICE-3 prototype unit length***. (Similar EMuS cable size and other CEPC sample unit were produced).
  - **Italy – ICAS**, with whom CERN, through EP-R&D WP8, is collaborating since 2025 to resume the co-extrusion – cold work process. ***Plan to qualify ICAS for next series conductor tender.***
- **Testing:**
  - Upon delivery, qualification and test are paramount and will be conducted at **CERN** (via **EN MME** group) and in **Twente Univ.**



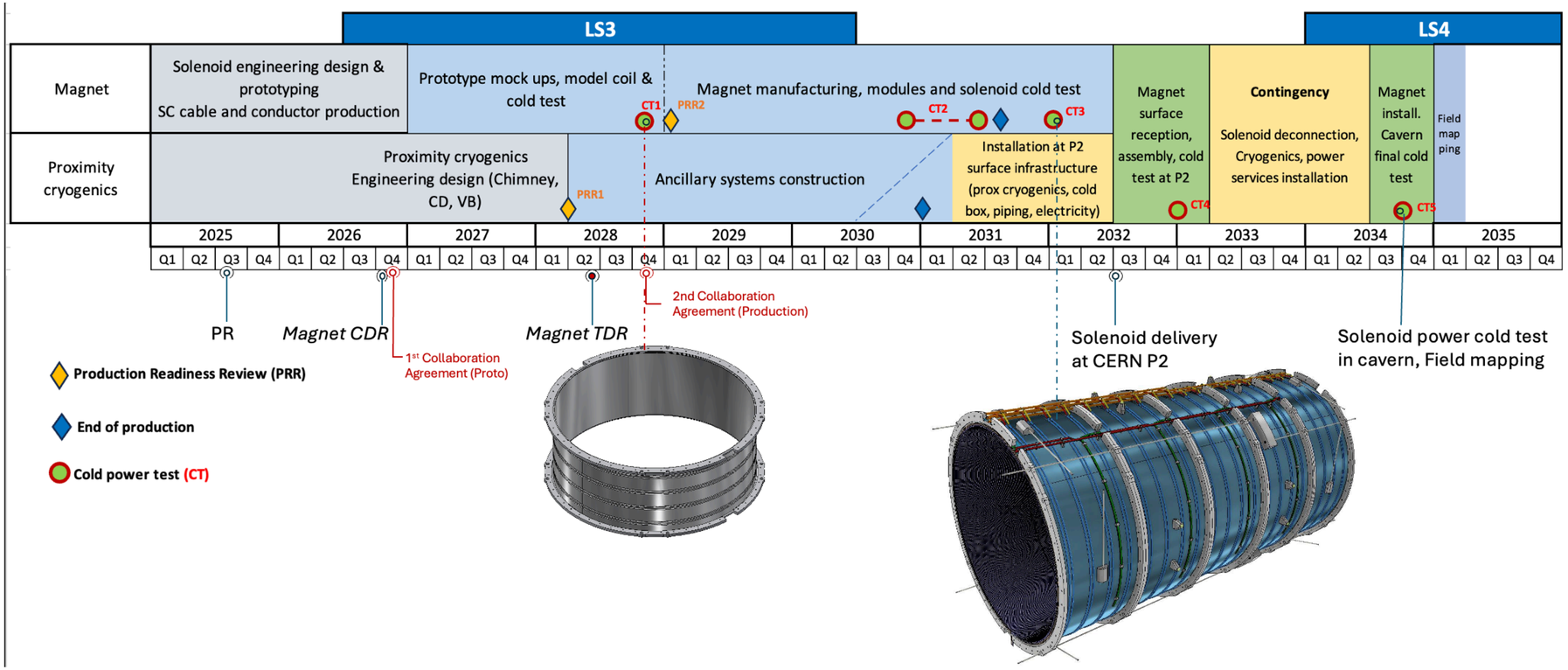
a) First combined processes trial of ALICE3 dummy copper strip conductor sample 24 x 7 mm² (06-2026)

NbTi Rutherford cable specification validated by TE MSC supplier



Validated for magnet prototype

SUPERCONDUCTING SOLENOID - SCHEDULE



Phase 1 – Prototyping (Nov 2026 – 2 years under discussion)

Impregnation and test mock-up with dummy cable

Winding up trials Model coil tested at cold

Phase 2 – Final Construction (2029-2032)

To be launched upon successful completion of Phase 1

Conceptual Design Review (CDR) next 13-14th October 2026 at CNPEM

Review panel: Akira Yamamoto (KEK retiree), Matthias Mentink (CERN), Benoit Cure (CERN) and Stefania Farinon (INFN); Herman Ten Kate (CERN retiree) recently contacted

WHAT WILL BE REMEMBERED LONG AFTER THE LHC HAS SWITCHED OFF?

Multi-charm baryons: Peter's vision of statistical hadronisation as an unambiguous signature of QGP formation

— to be tested by ALICE 3

Beauty hadrons: Peter's pioneering work on statistical hadronisation extending to beauty

— to be tested by ALICE 3

Dear Peter, may ALICE 3 carry your ideas forward and turn them into discoveries

What a wonderful legacy to look forward to — and what a privilege to share the journey with you!

Happy 80th birthday!



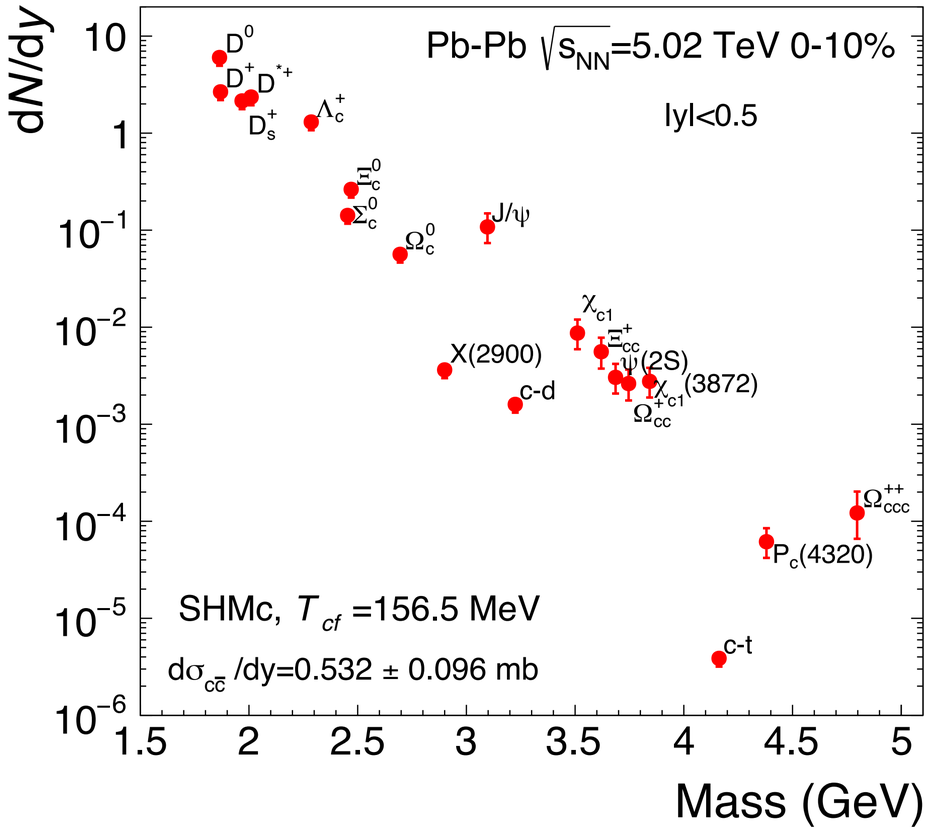
- Peter — My Mentor, My Teacher, My Friend
- **My mentor**: Gave me the freedom to find my own way
- **My teacher**: Inspired me in modern nuclear physics
- **My friend**: Shared an office and countless conversations about physics and life


HAPPY 80th BIRTHDAY!
BOTTOM & CHARM QUARK
HADRONIZATION
FIREWORK
80
Harton
Mesons
Pions
Proton
Neutrons
Proton
Hadrons
Mesons
Kaons
Baryons
Hadrons
b
c
n
B_s
Ξ_{cc}^{++}
Ω_{cc}^{+}
$\Sigma_{cc}^{(*)}$
Λ_b
$\Sigma_b^{(*)}$
Λ_b

BACKUP

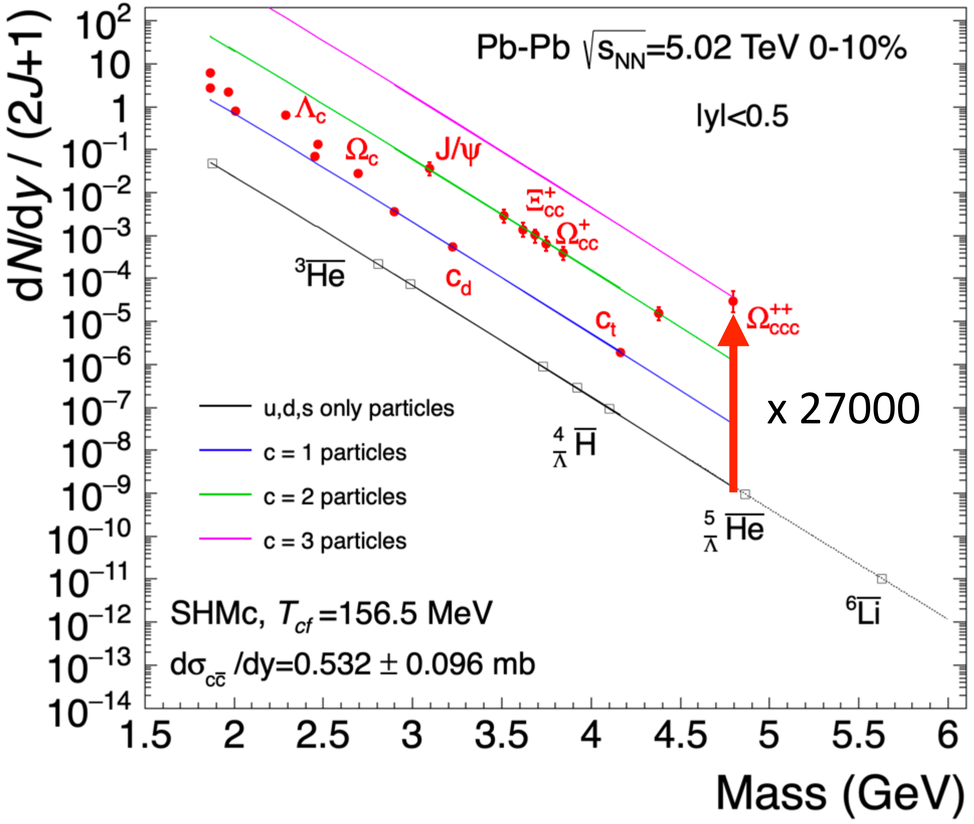
POINTING x ACCEPTANCE × INTERACTION RATE: NEW OPPORTUNITIES

Multiply-charmed baryons



J. Stachel, pbm, et al.
arXiv.org:2104.12754

arXiv:2211.02491



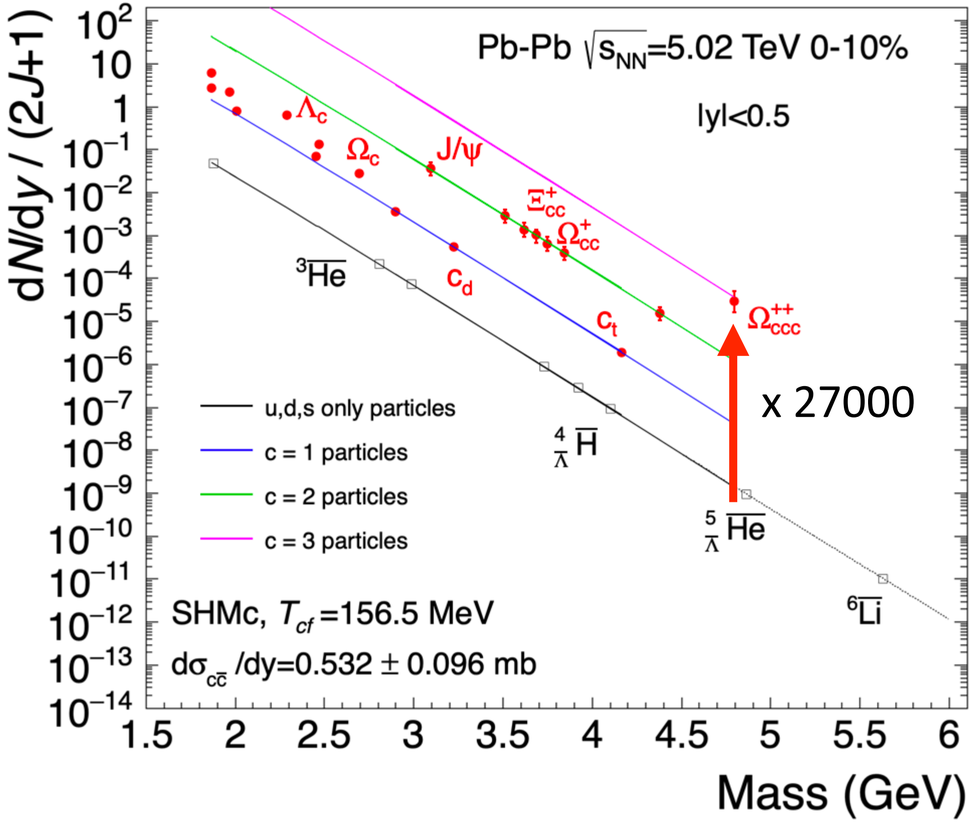
→ **charm oversaturated** through initial production, fugacity factor $g_c \approx 30$ per additional **charm quark**

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

POINTING x ACCEPTANCE × INTERACTION RATE: NEW OPPORTUNITIES

Multiply-charmed baryons

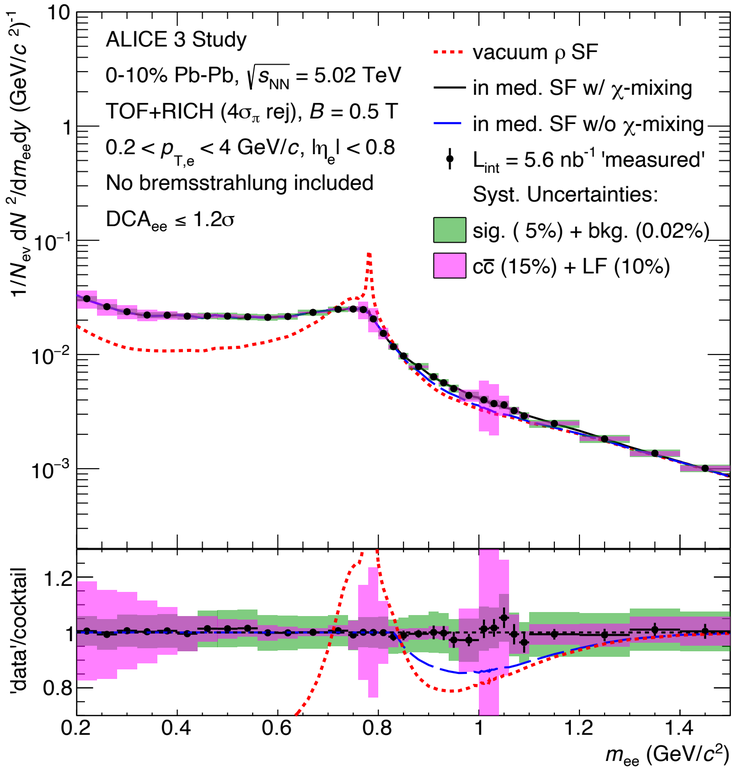
arXiv:2211.02491



→ **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

BREAKTHROUGH PRIZE IN FUNDAMENTAL PHYSICS 2025



Los Angeles, April 5, 2025

Awarded to **ATLAS, CMS, ALICE, and LHCb**

For exploring **nature at the shortest distances and most extreme conditions**

Shared by all authors of **Run-2 publications** (link)

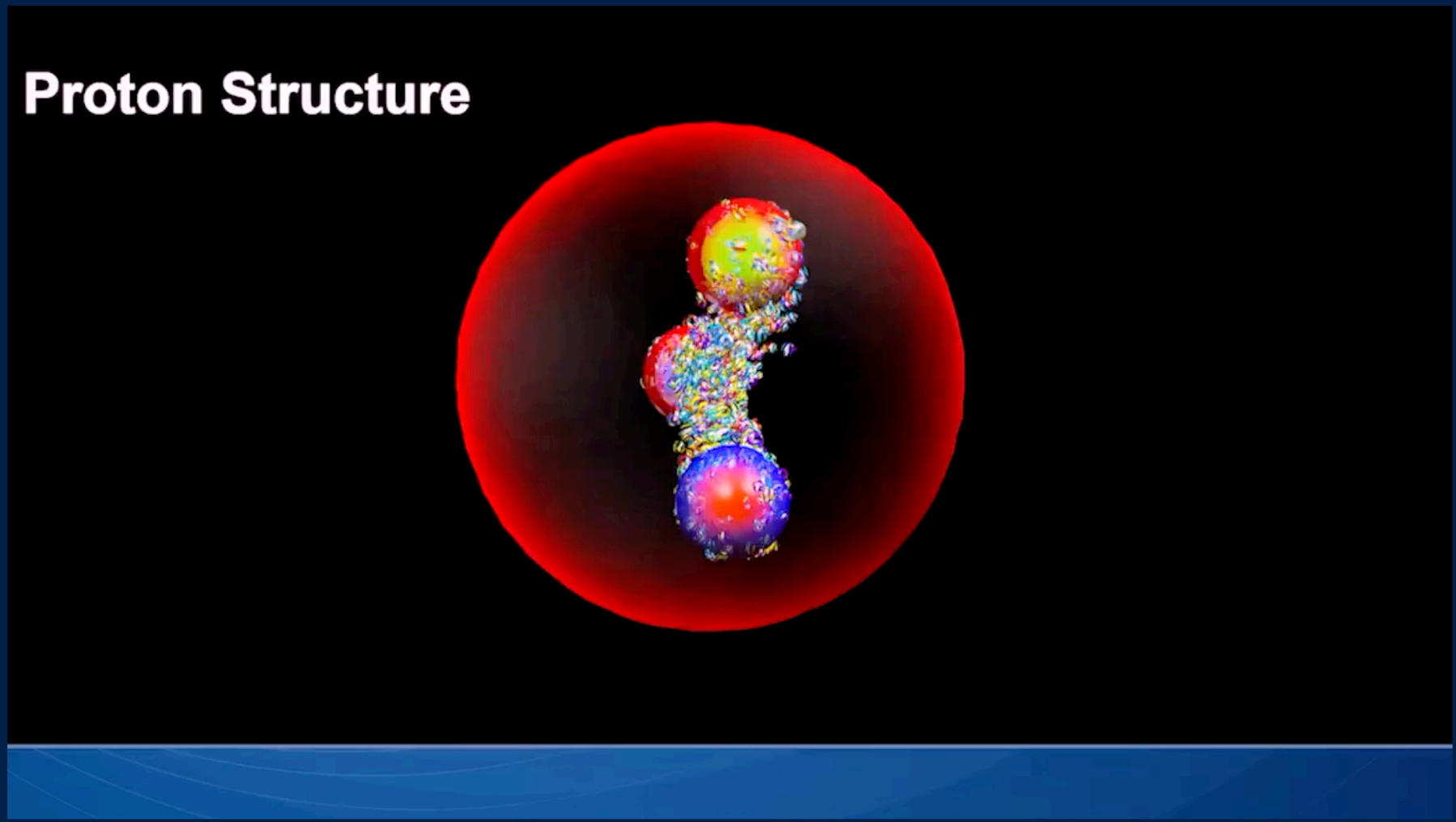
Heavy-ion collisions create macroscopic QCD matter in the laboratory

Nobel Prize 2004



1973: asymptotic freedom
D.J. Gross, F. Wilczek, H.D. Politzer

1975: asymptotic QCD and deconfinement
N. Cabibbo and G. Parisi; J. Collins and M. Perry



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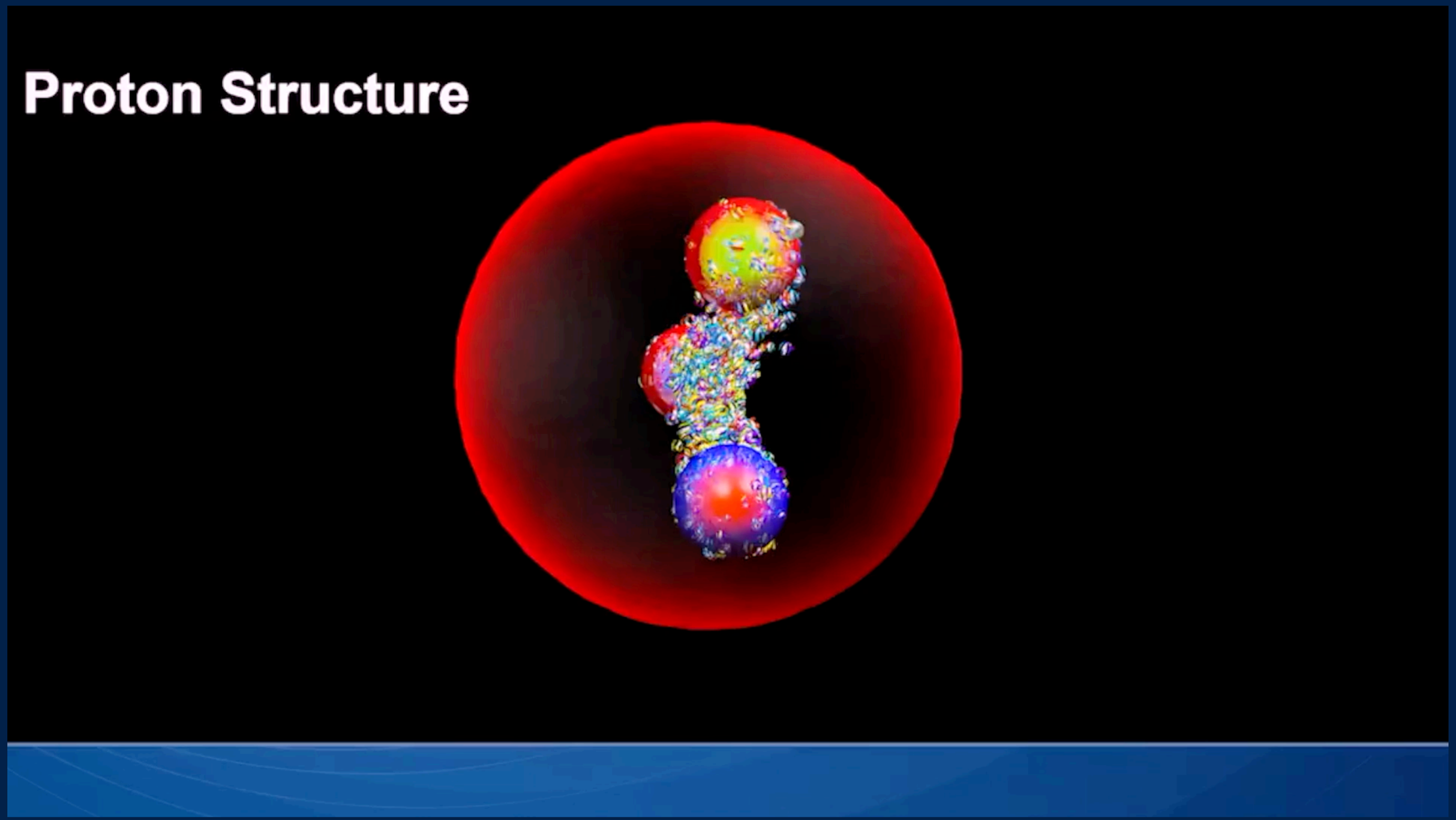
1973: asymptotic freedom
D.J. Gross, F. Wilczek, H.D. Politzer

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QCD governs the strong interaction, yet most of its phenomena are **emergent and non-perturbative**

At high temperature and density:

- quark confinement is lifted
- chiral symmetry is restored



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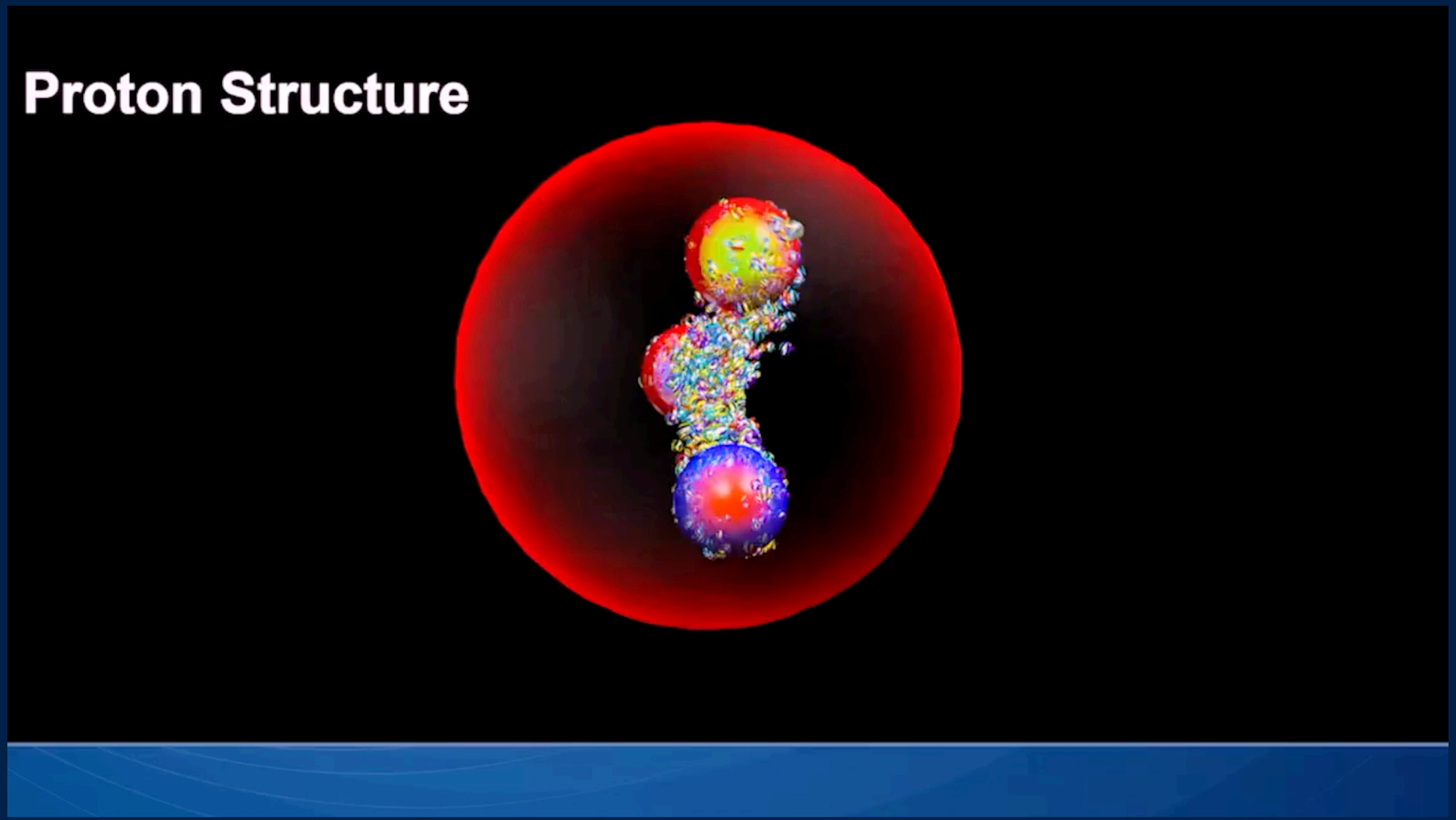
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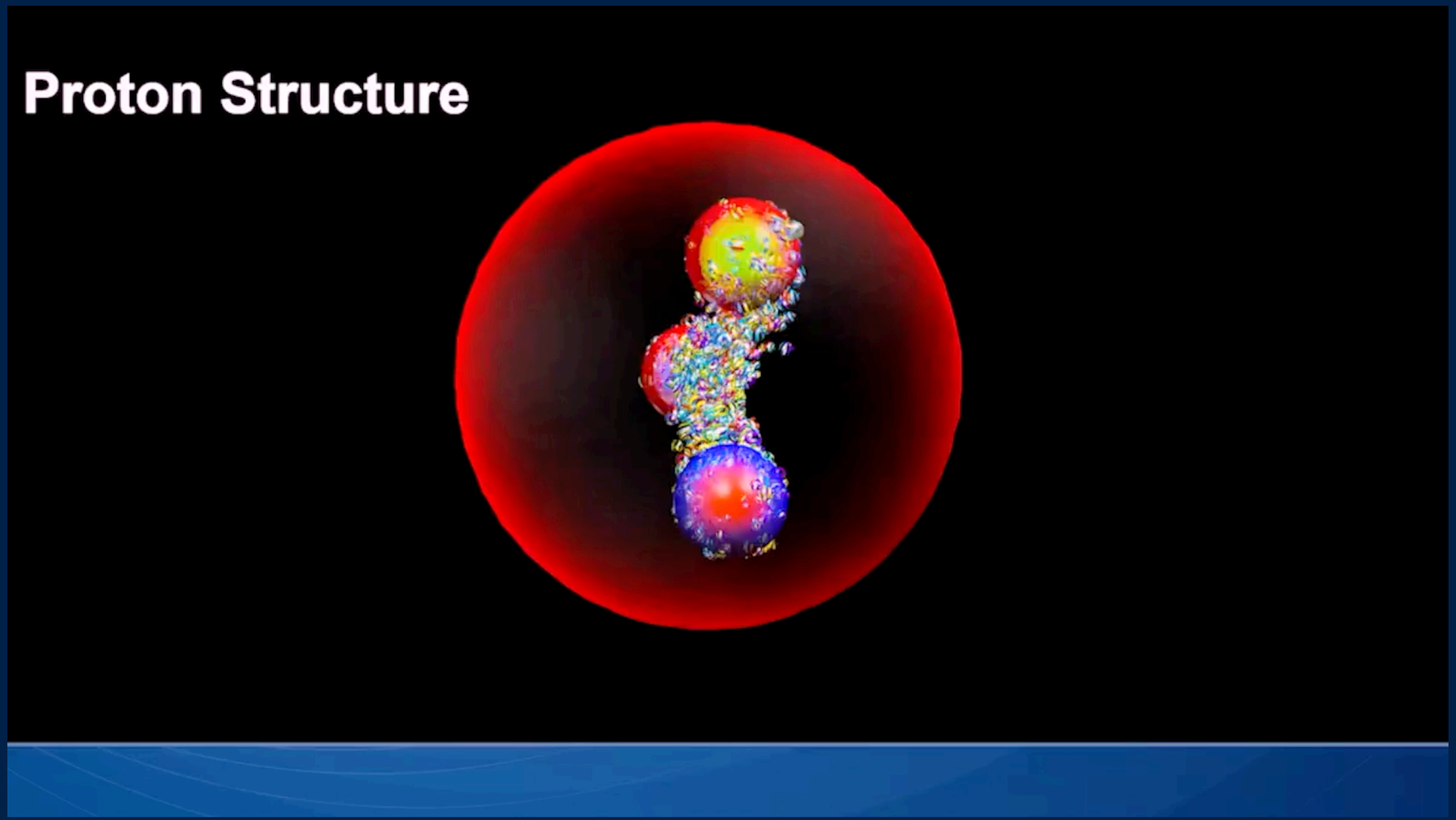
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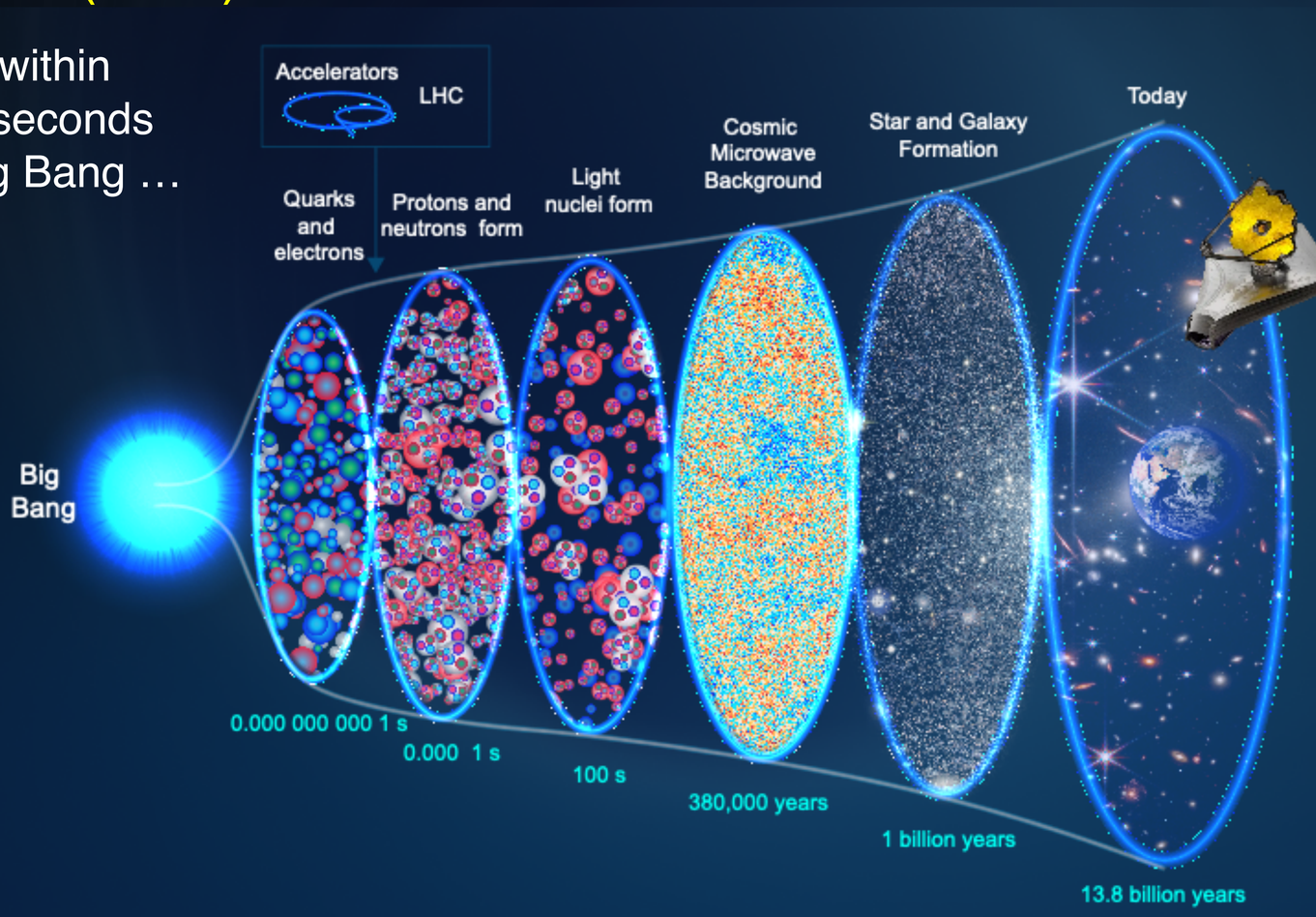
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Tracing the evolution of the Universe

Accelerators (LHC)

back to within
few microseconds
after the Big Bang …



Astrophysical probes

photons: ~ 380 000 years — observed

neutrinos: ~1 second — future probe

gravitational waves: ≪1 s — future probe

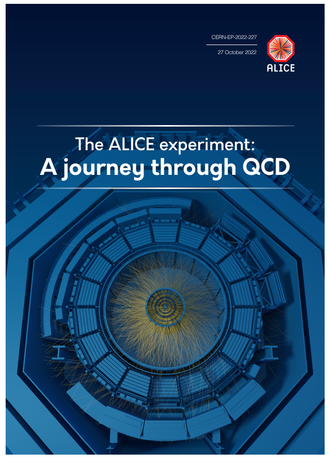
… to study quark-hadron phase transition, and Quark Gluon Plasma

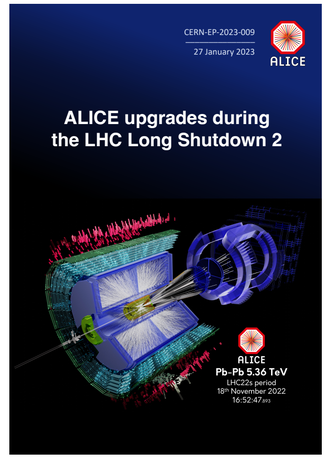
OUTLINE

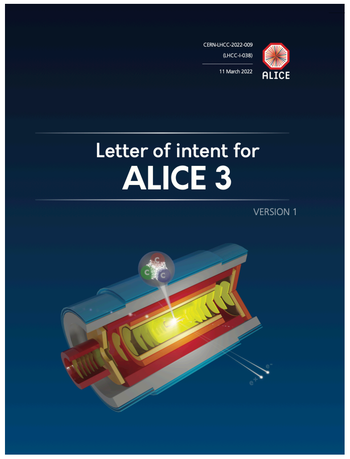
① Introduction

② Selected physics highlights

③ Future upgrades





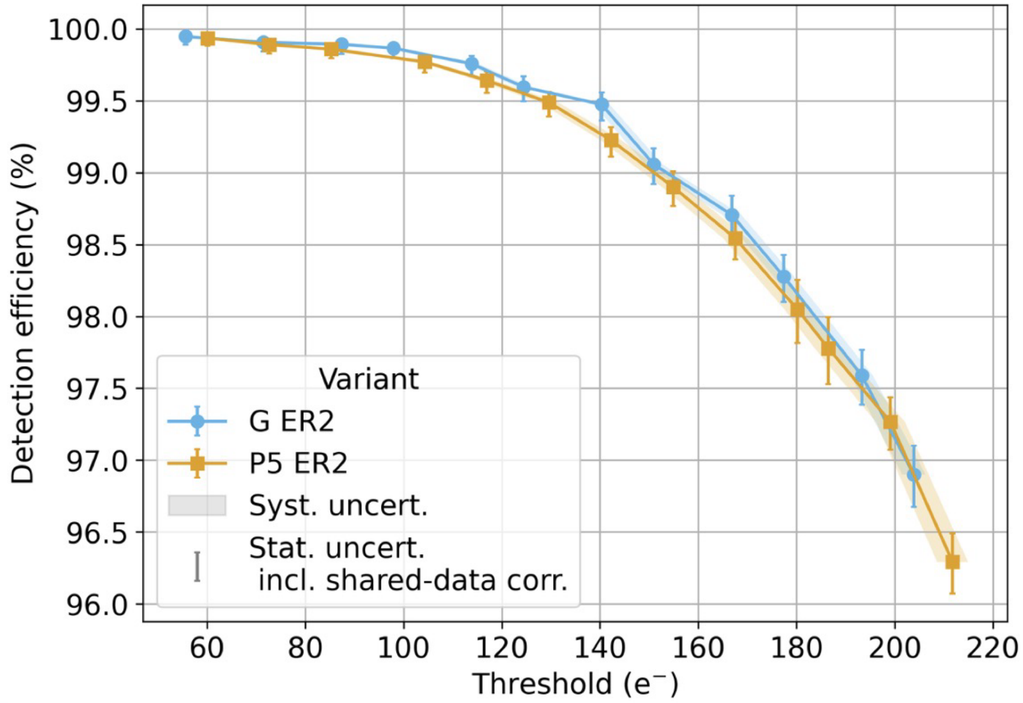


ALICE 3 INNER TRACKER R&D

Sensor development:

- Some of the features of the **Vertex Detector** sensors implemented with **ITS3 ER2**
- Validation with test beams ongoing

Example: 10×10 µm² fully efficient analog test structure



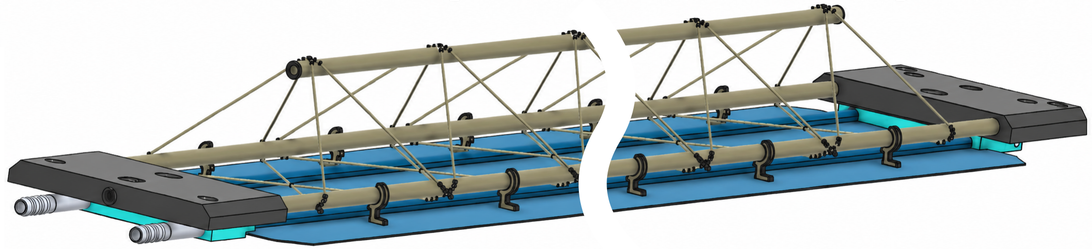
Non-irradiated
Split 7
19.0 °C
Pitch 10x10 µm²

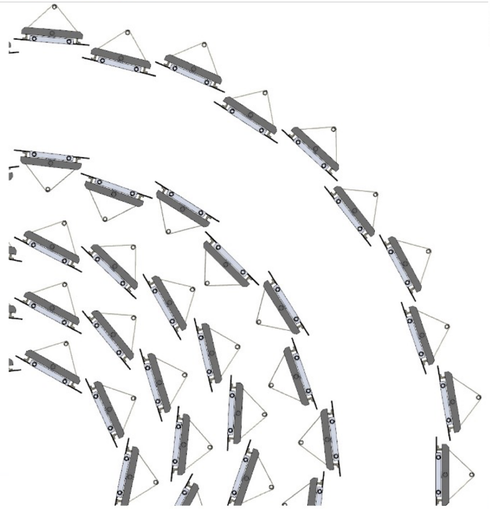
V_{reset}: 500 mV
V_{psub}: -4.8 V
I_{reset}: 100 pA
I_{biasp}: 0.5 µA
I_{biasn}: 5 µA
I_{bias3}: 200 µA
I_{bias4}: 150 µA

Mechanics of middle layers:

- Preliminary layout using an ITS2-derived stave concept
- Next: prototypes

Pultruded longerons with continuous winding





kai.schweda@cern.ch