# ALICE detector upgrade physics and Energy–energy correlators

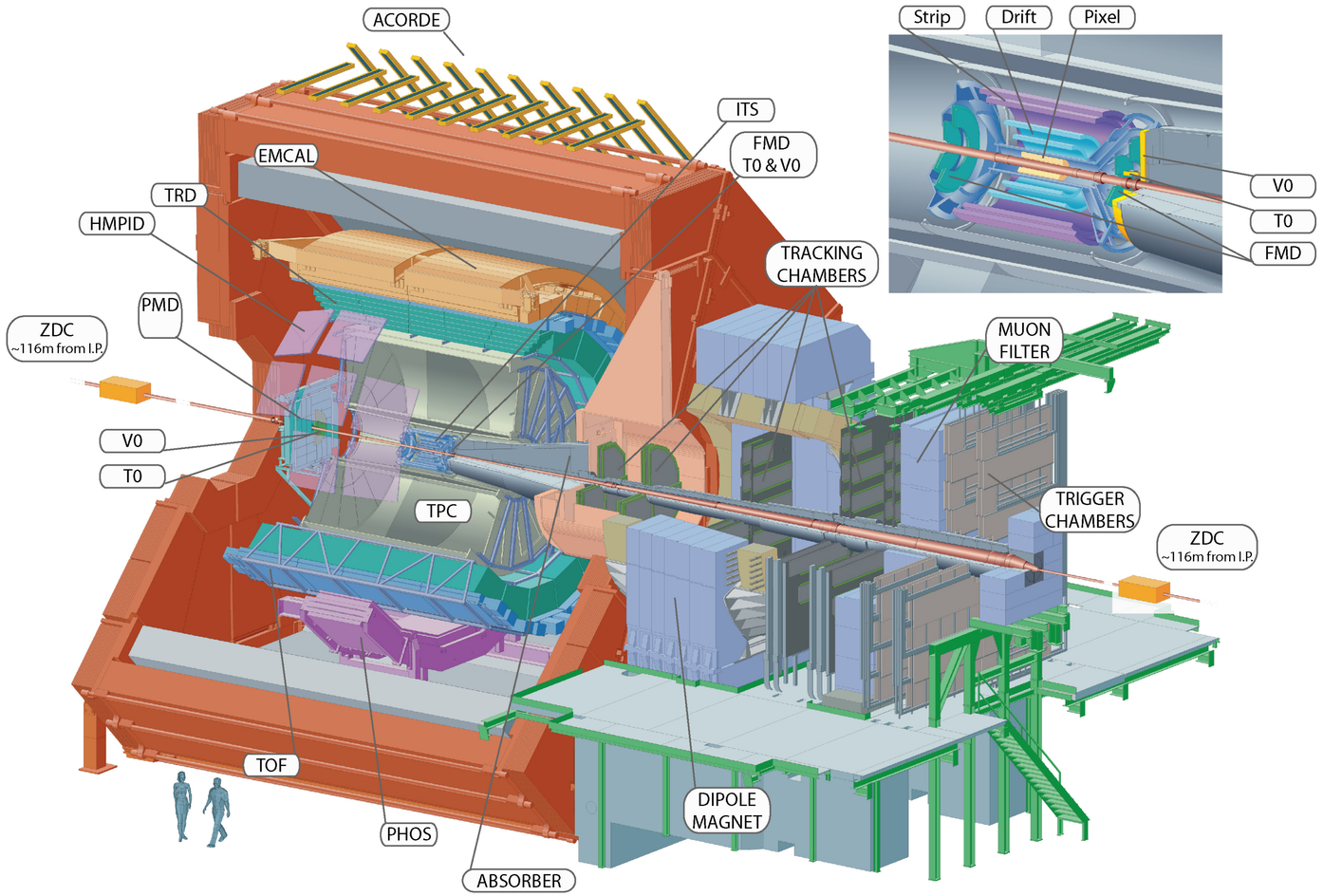
**Xiaoming Zhang (张晓明)**

**Central China Normal University**

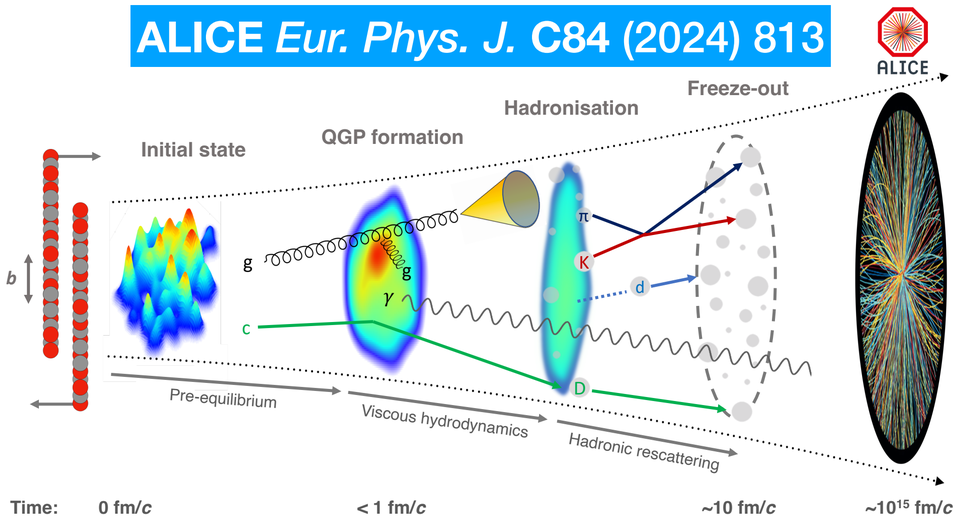
高能与低能核物理交叉学术研讨会
15–18 May 2026, Shanghai, China

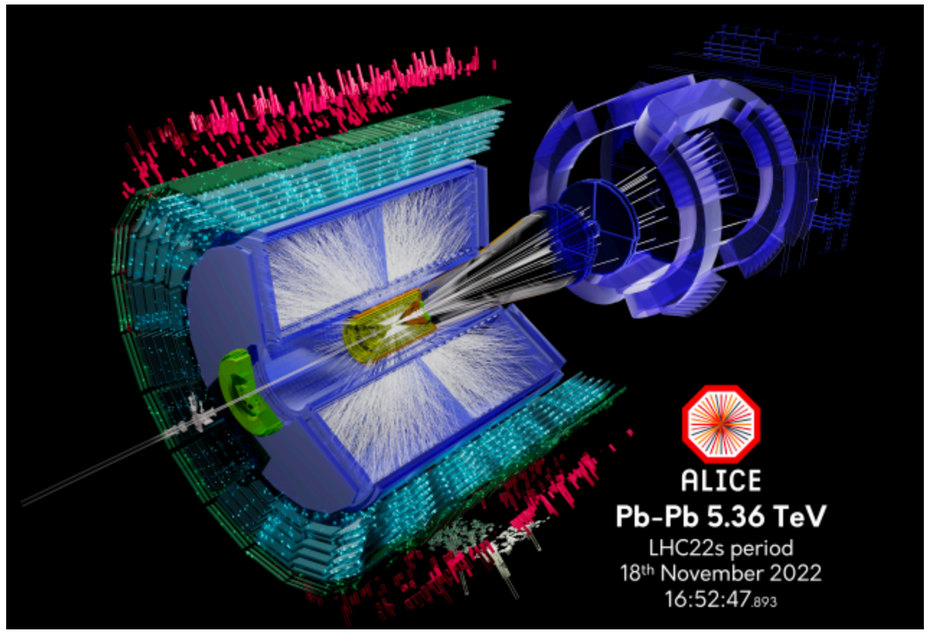
# ALICE experiment at the LHC

- ALICE: A heavy-ion detector at the LHC
- Study of strongly-interacting matter at extreme temperatures and energy densities




**ALICE *Eur. Phys. J.* C84 (2024) 813**



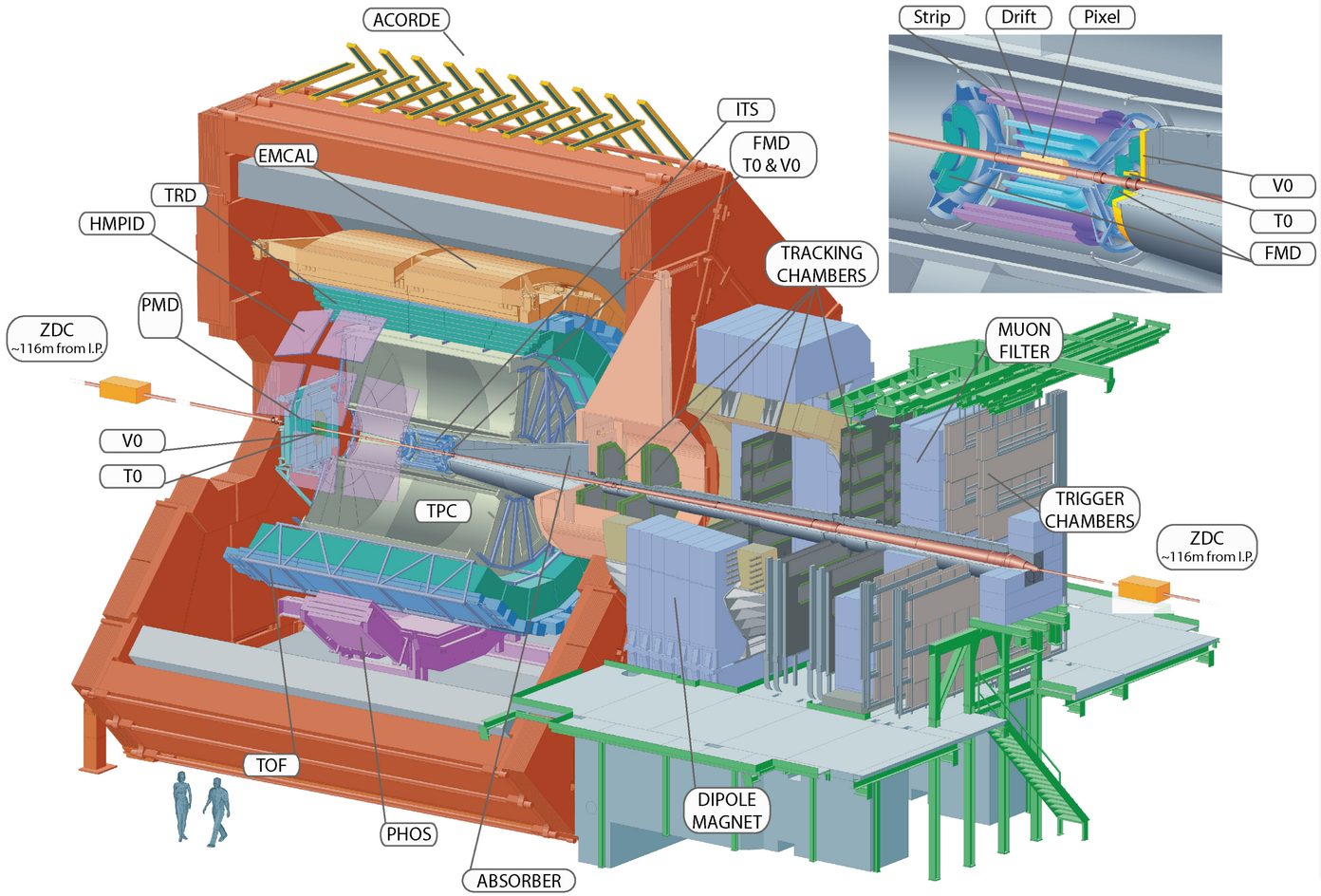



# A journey through QCD

2010-2013 | 2015-2018

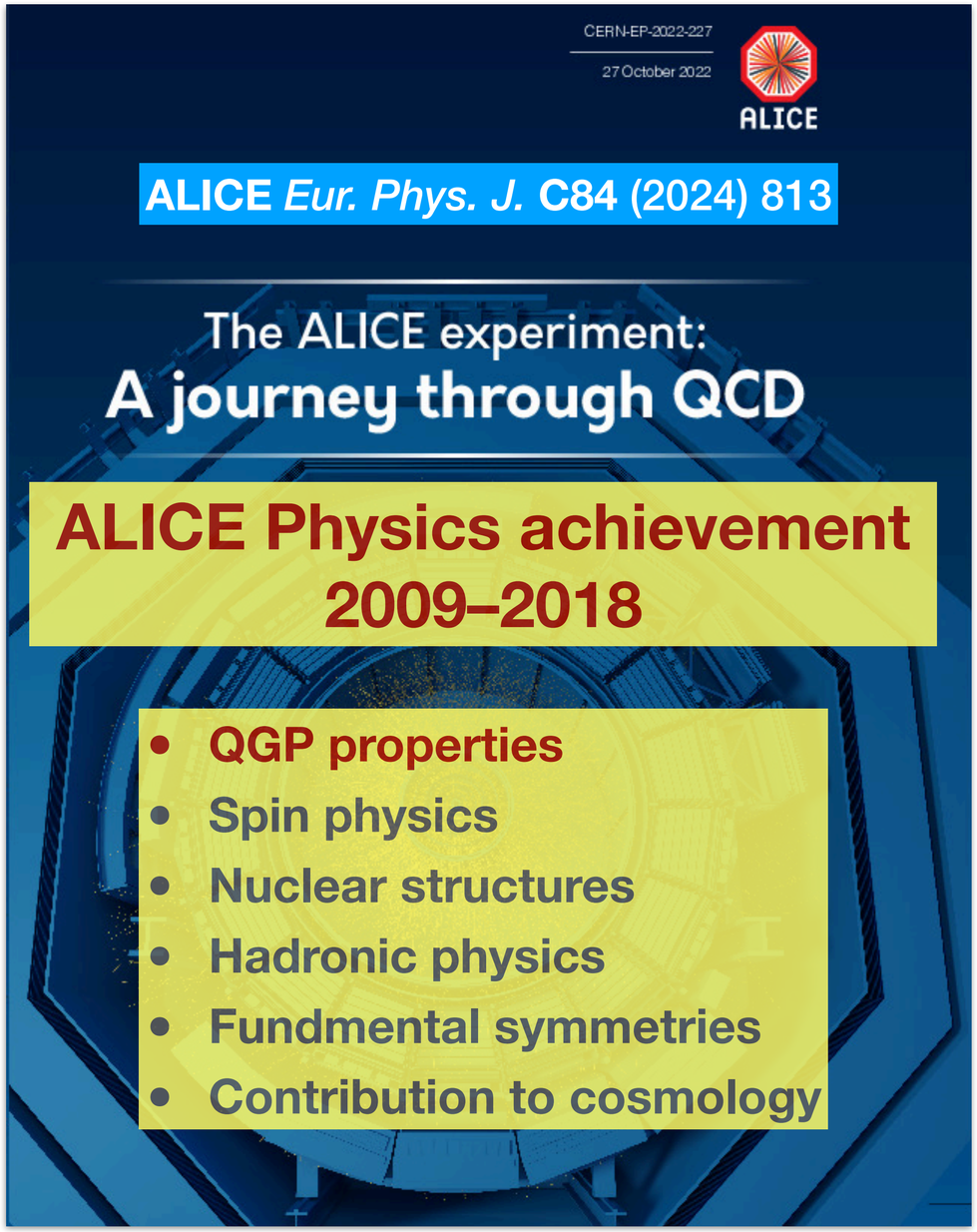
Run 1 → LS1 → Run 2

ALICE 1







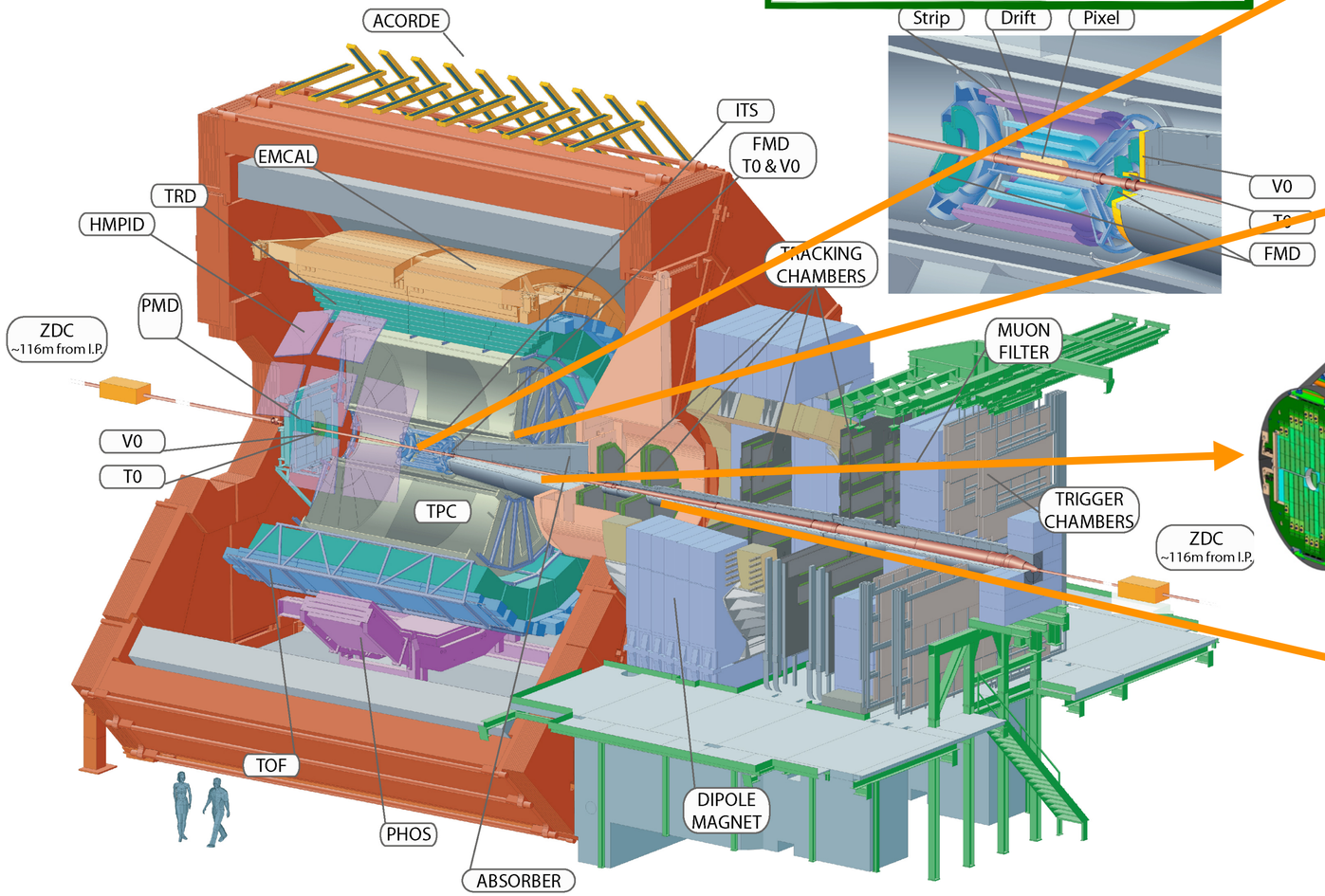


# ALICE at LHC Run 3 (2022–now)

2010-2013 | 2015-2018 | 2022-2026

Run 1 → LS1 → Run 2 → LS2 → Run 3

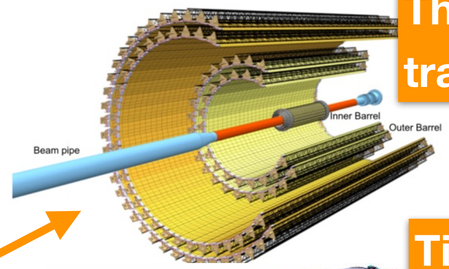
ALICE 1 | ALICE 2



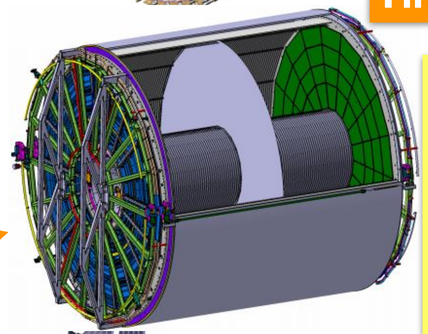




## The 2nd generation inner tracking system (ITS2)

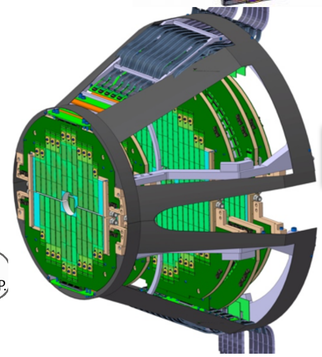



## Time projection chamber (TPC)

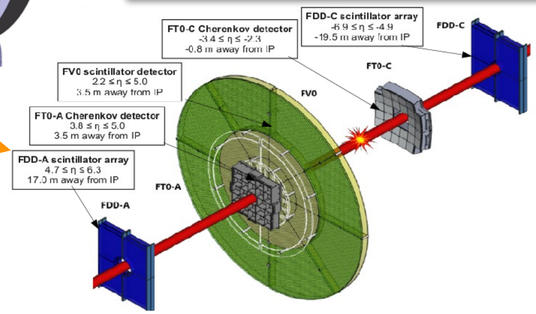


- pp data taking at 500 kHz
- Pb–Pb data taking up to 50 kHz
- Improved vertexing
- Improved tracking at low $p_T$

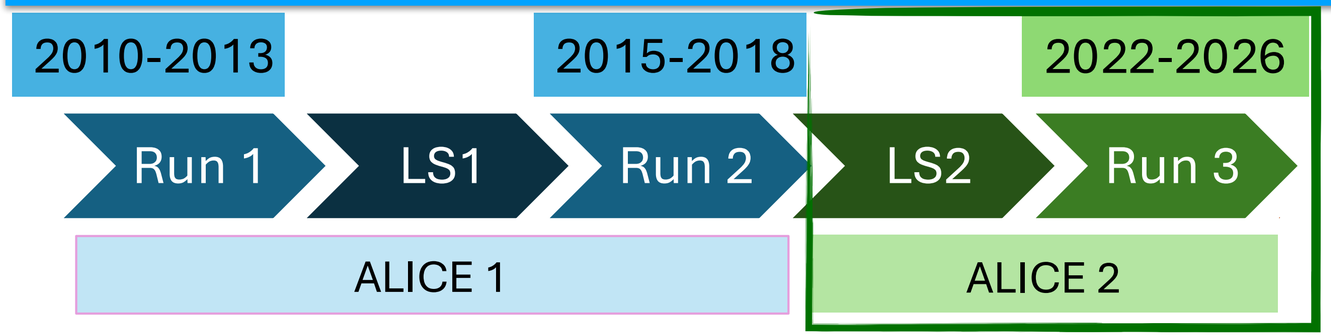
## Muon forward tracker (MFT)



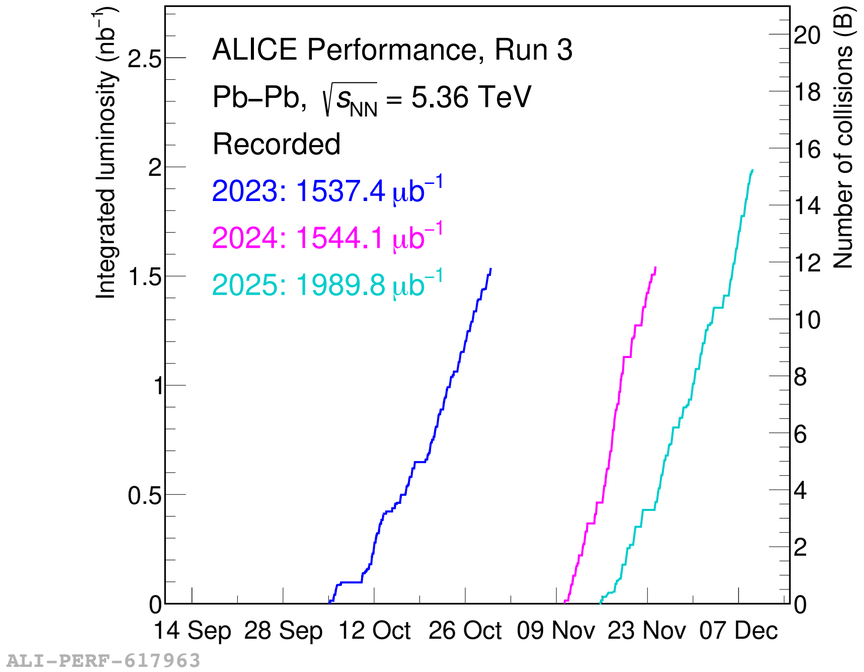
## Fast integration trigger (FIT)

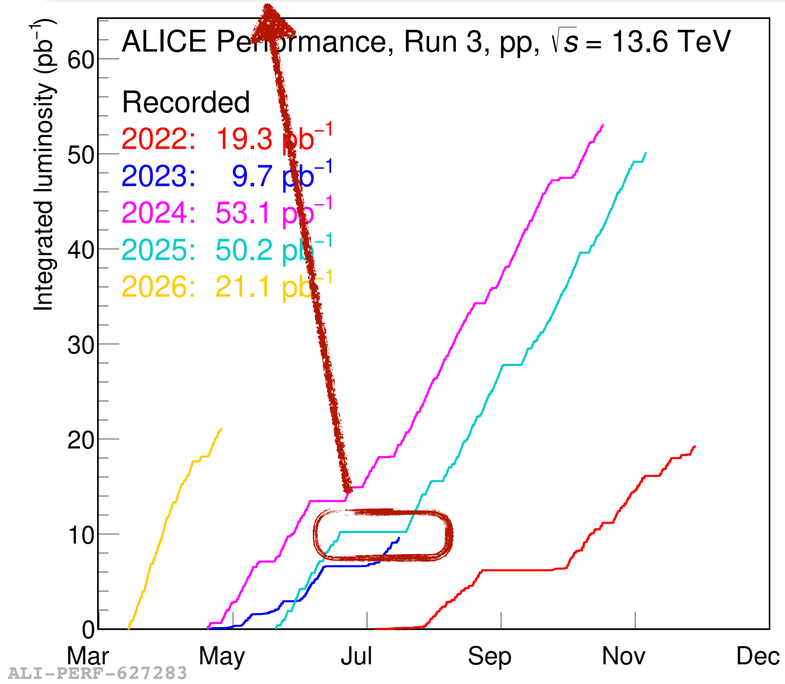


# ALICE data taking in Run 3




| | $L_{int}$ | MB events |
|---|---|---|
| **p–O** | 7.27 nb$^{-1}$ | 3×10$^9$ |
| **OO** | 5.01 nb$^{-1}$ | 6×10$^9$ |
| **Ne–Ne** | 0.84 nb$^{-1}$ | 10$^9$ |




Pb–Pb: 40 billion MB events

**×110 more** than Run 1+2

pp: 7.5 trillion MB events

**×2000** more than Run 1+2

# Ω-baryon masses

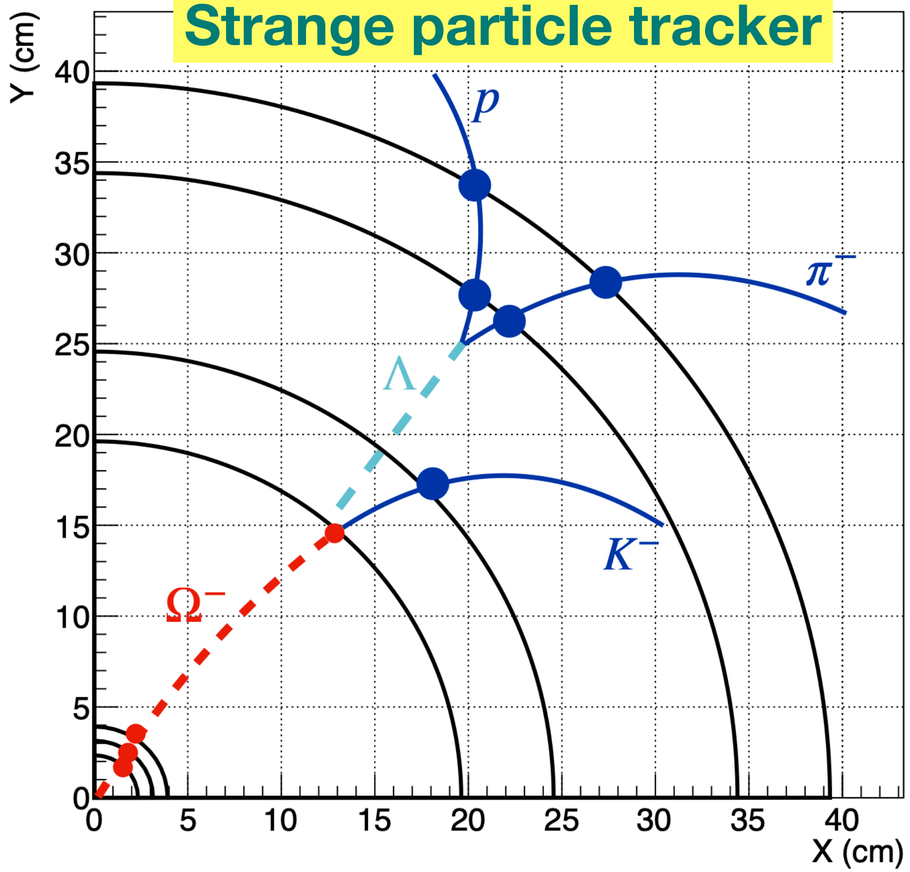
2010-2013 | 2015-2018 | 2022-2026

Run 1 → LS1 → Run 2 → LS2 → Run 3

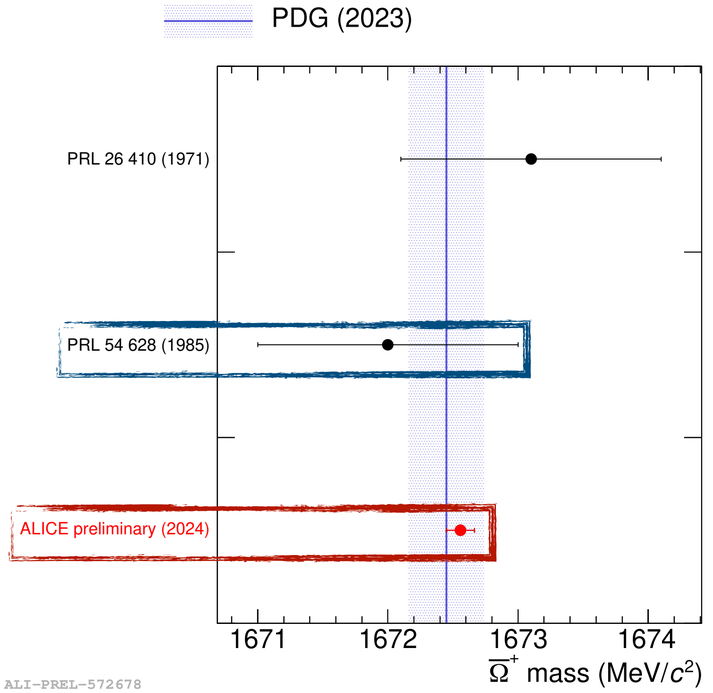
ALICE 1 | ALICE 2

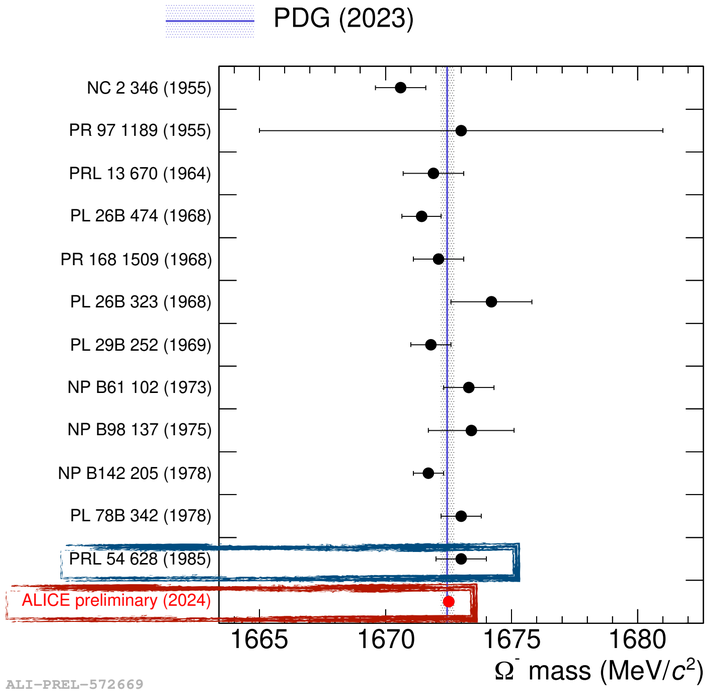
- ➡ New input for lattice calculation
- ➡ New constraints of CPT at strange sector

**Strange particle tracker**




Last update was 40 years ago!



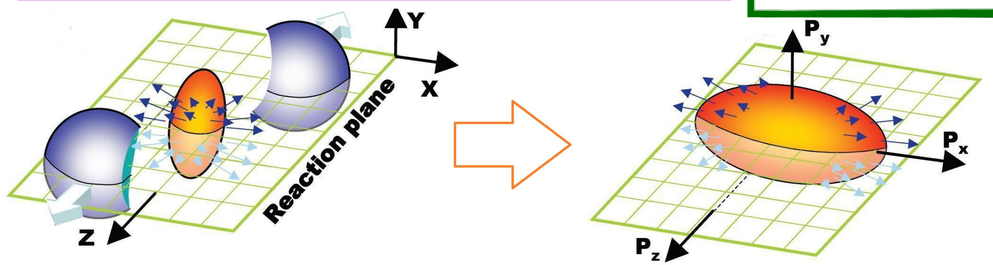



# Flow of charm quarks

2010-2013 | 2015-2018 | 2022-2026

Run 1 | LS1 | Run 2 | LS2 | Run 3

ALICE 1 | ALICE 2




**Low and intermediate–$p_T$**

$$v_2(D_s^{\pm}) < v_2(D^0) \approx v_2(D^{\pm}) < v_2(\pi^{\pm})$$

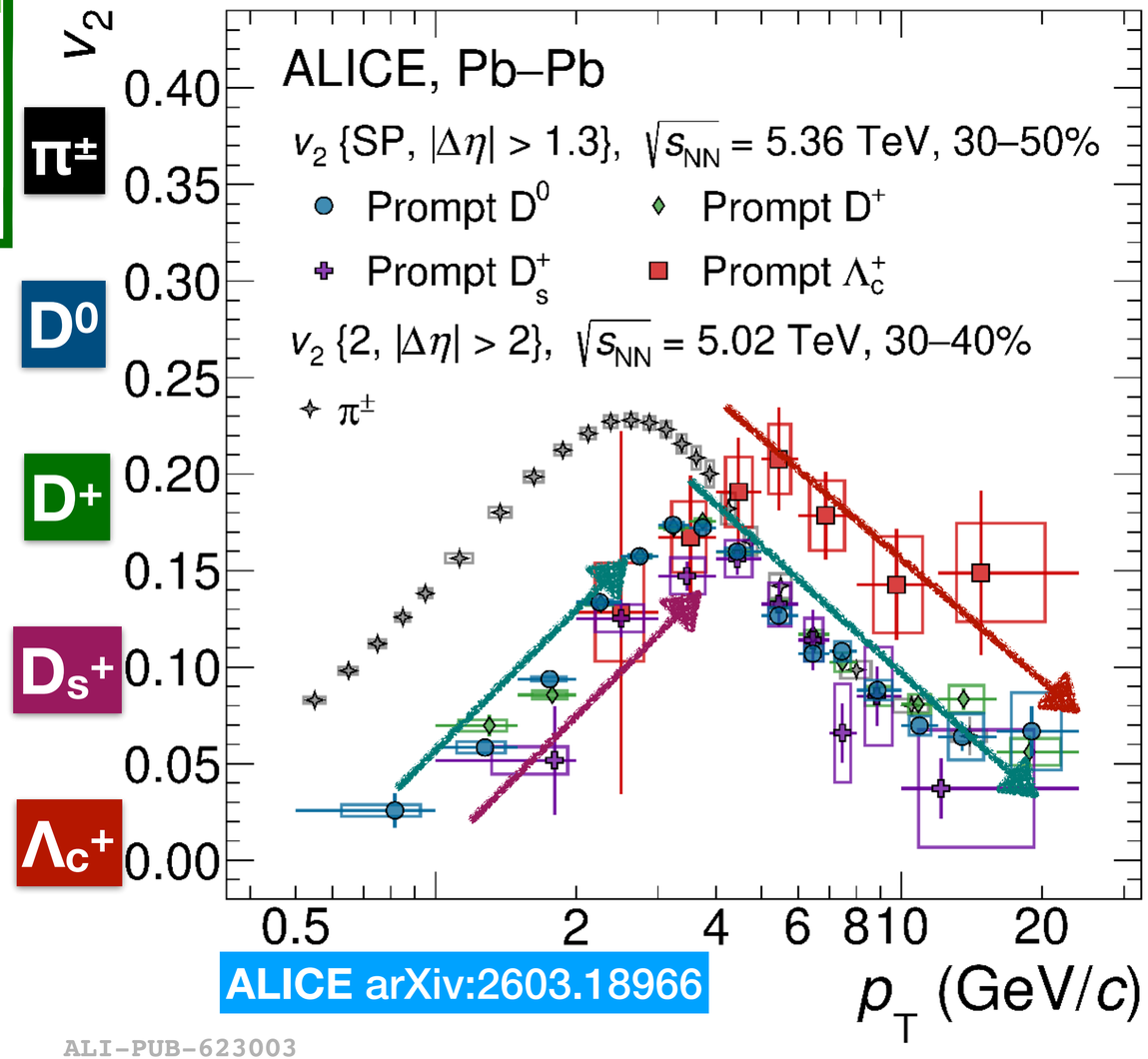
➡ Interplay between radial and elliptic flow

➡ Sequential hadronization Zhao, Shi, Xu, and Zhuang *Springer Proc. Phys.* **250** (2020) 275

**Intermediate and high-$p_T$**

$$v_2(\Lambda_c^+) > v_2(D_s^+) \approx v_2(D^0) \approx v_2(D^+) \approx v_2(\pi^{\pm})$$

➡ Strong evidence of coalescence



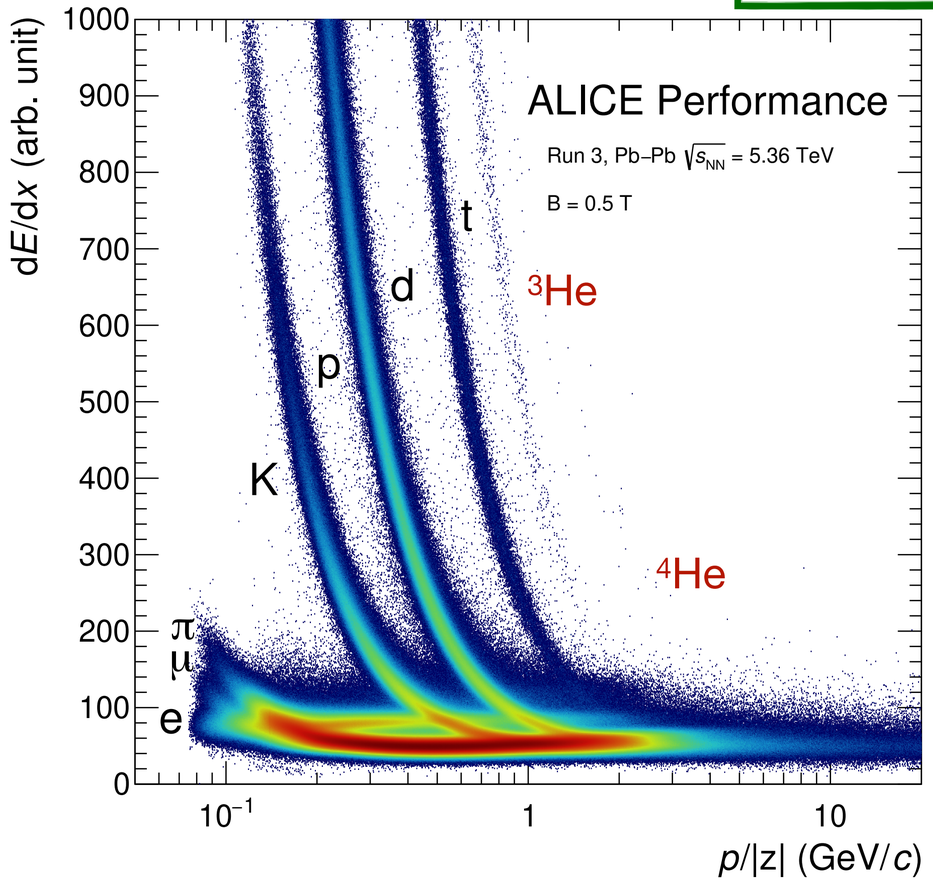

ALI-PUB-623003

# Search for c-deuteron

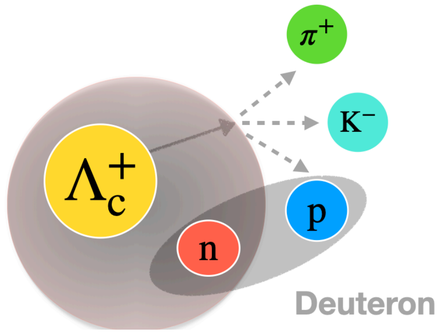
2010-2013 | 2015-2018 | 2022-2026

Run 1 | LS1 | Run 2 | LS2 | Run 3

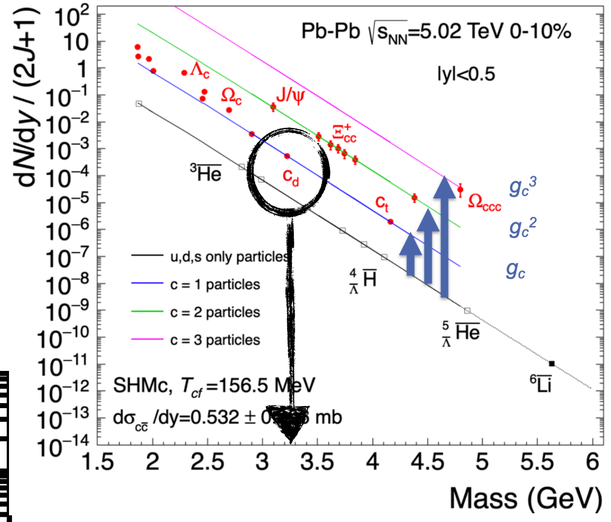
ALICE 1 | ALICE 2

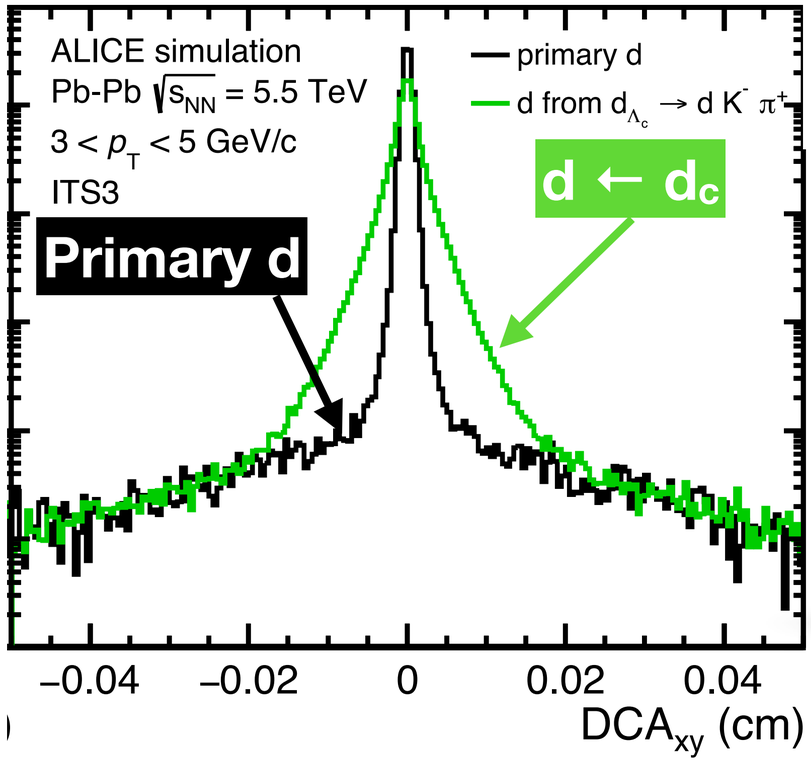



**c-deuteron**




A. Andronic *et al.*, *JHEP* **2107** (2021) 035




**Unique chance of the first discovery of c-deuteron**

**➡ Mysterious will be unveiled soon**

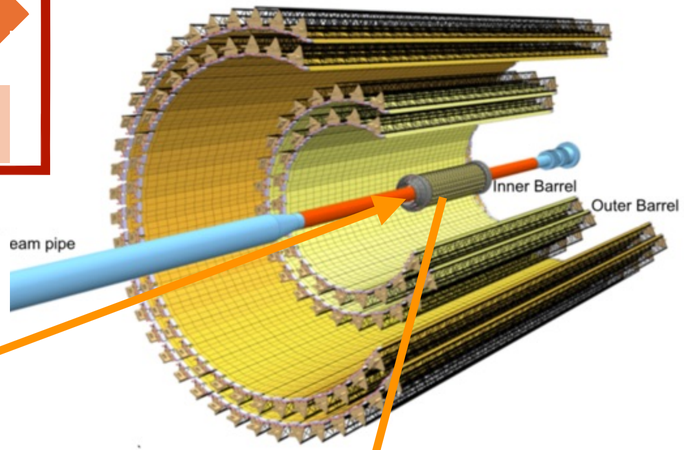
# ALICE in LHC Run 4

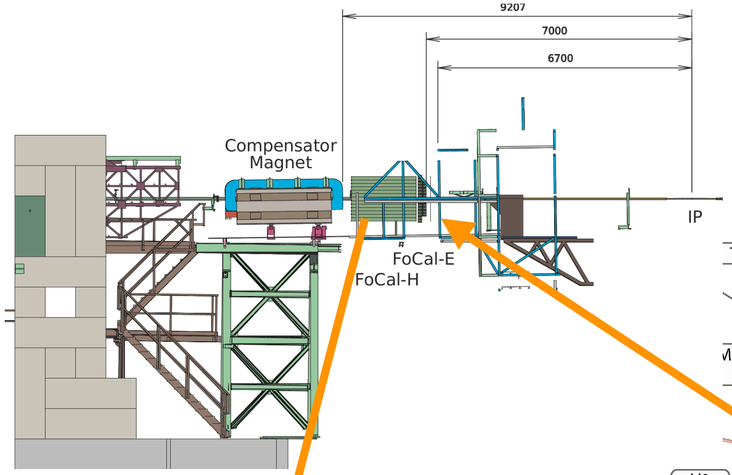
2010-2013 | 2015-2018 | 2022-2026 | 2030-2033

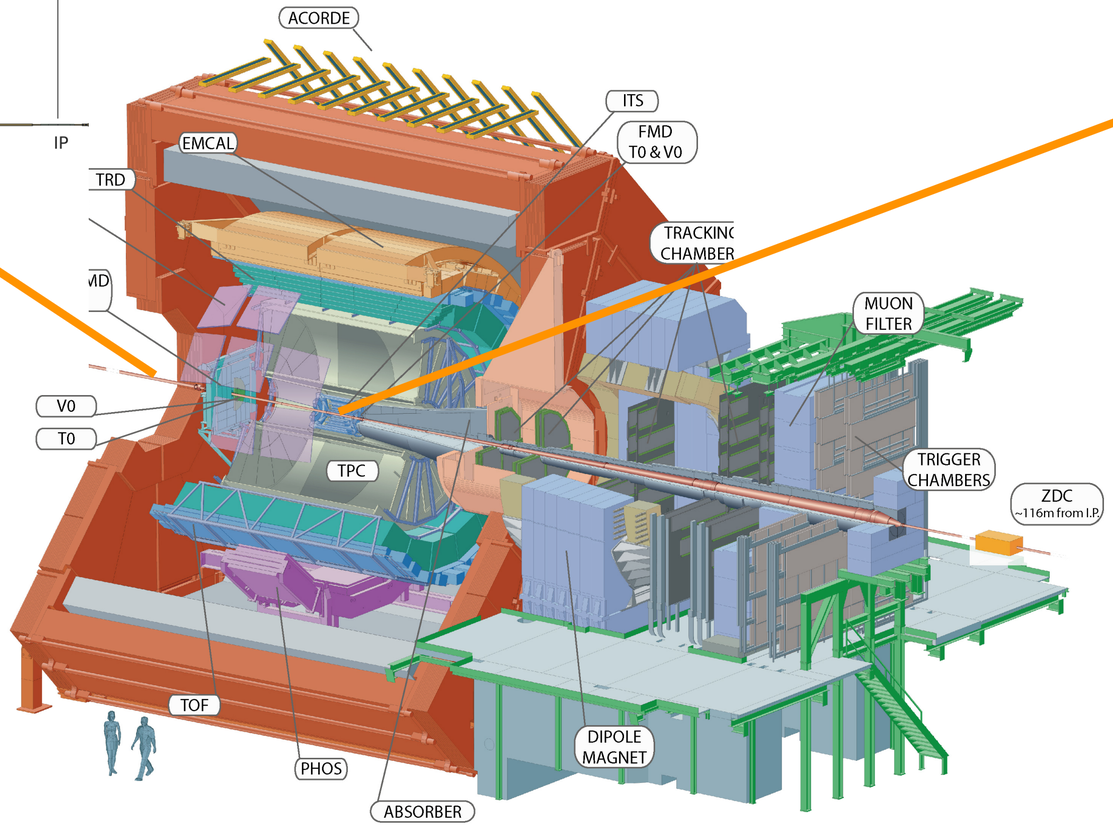
Run 1 → LS1 → Run 2 → LS2 → Run 3 → LS3 → Run 4

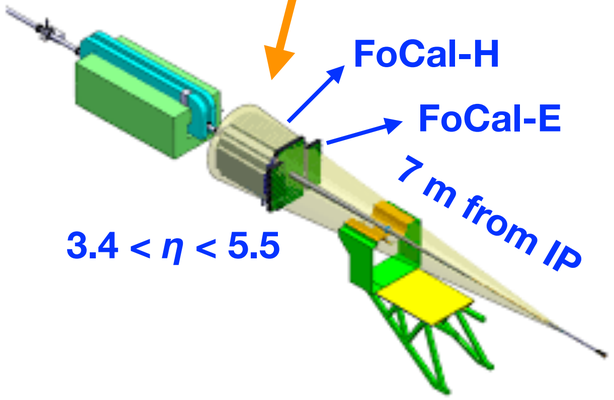
ALICE 1 | ALICE 2 | ALICE 2.1

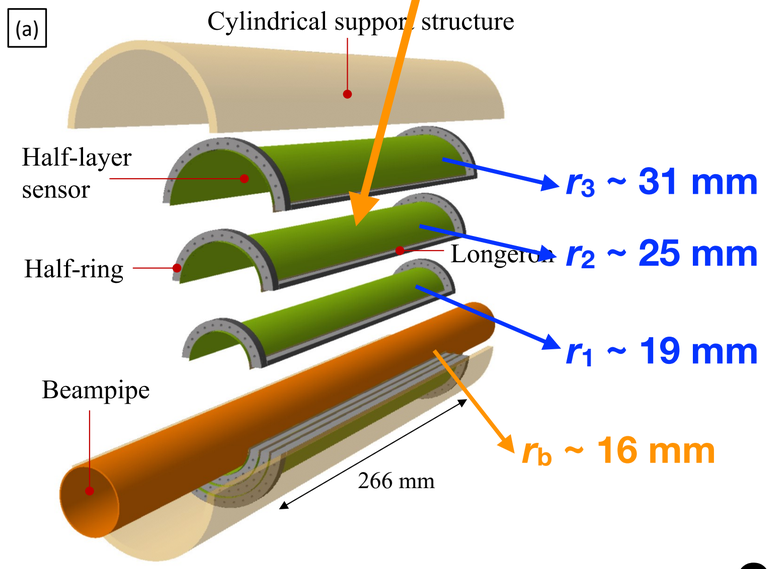
**ALICE ITS3 TDR**
**CERN-LHCC-2024-003**



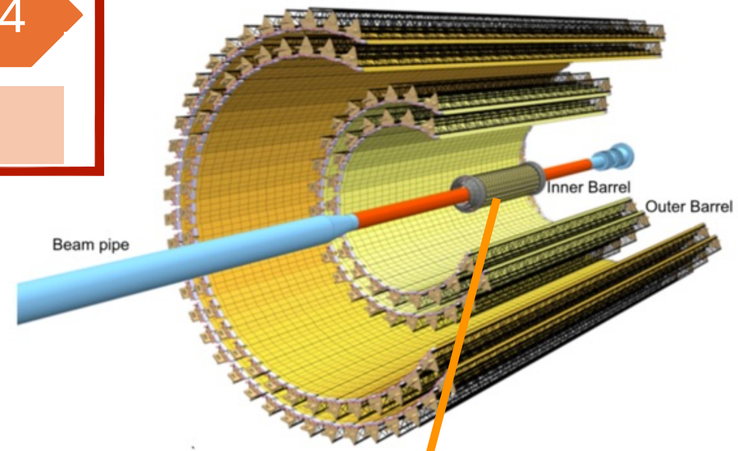
# ALICE ITS3 – Material budget

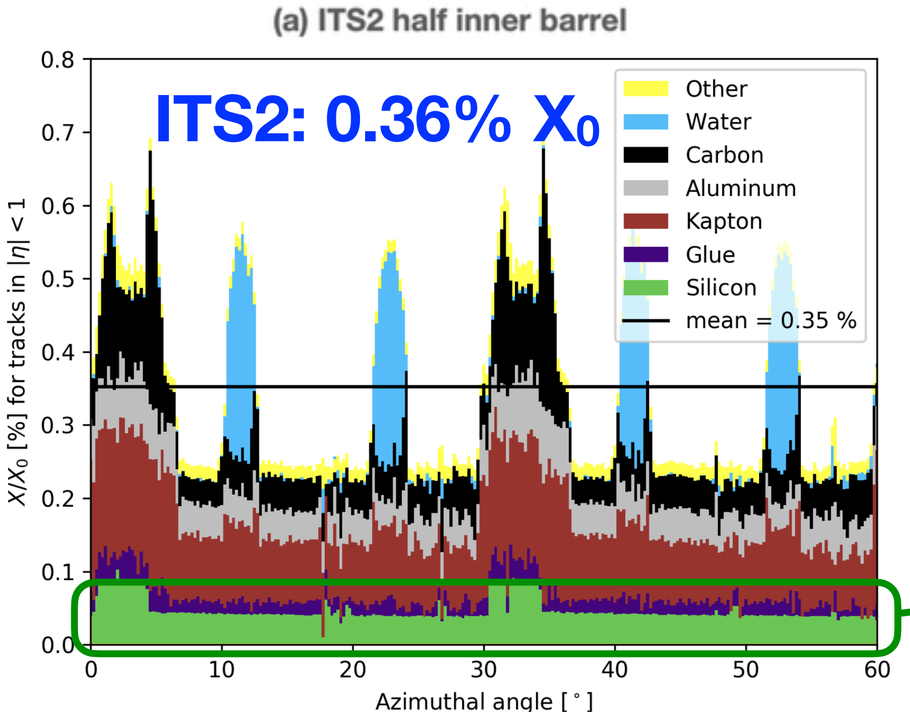
2010-2013 | 2015-2018 | 2022-2026 | 2030-2033

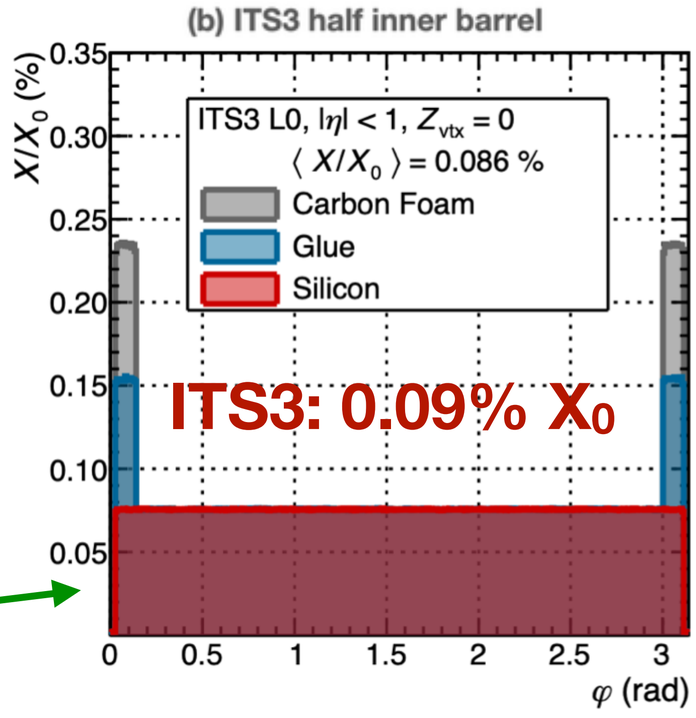
Run 1 | LS1 | Run 2 | LS2 | Run 3 | LS3 | Run 4

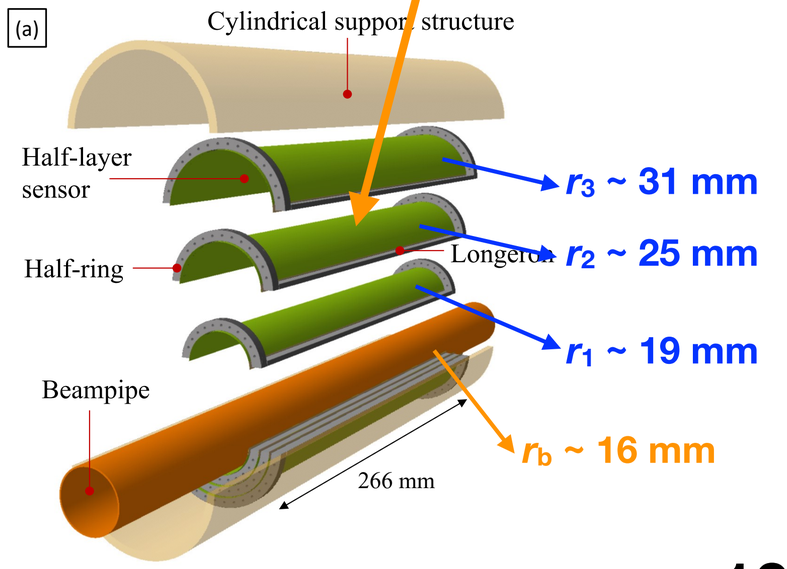
ALICE 1 | ALICE 2 | ALICE 2.1

**ALICE ITS3 TDR**
**CERN-LHCC-2024-003**



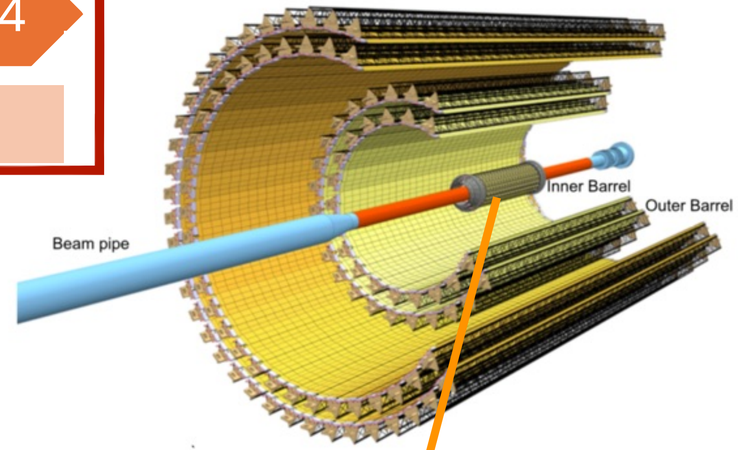
# ALICE ITS3 – Open heavy flavors

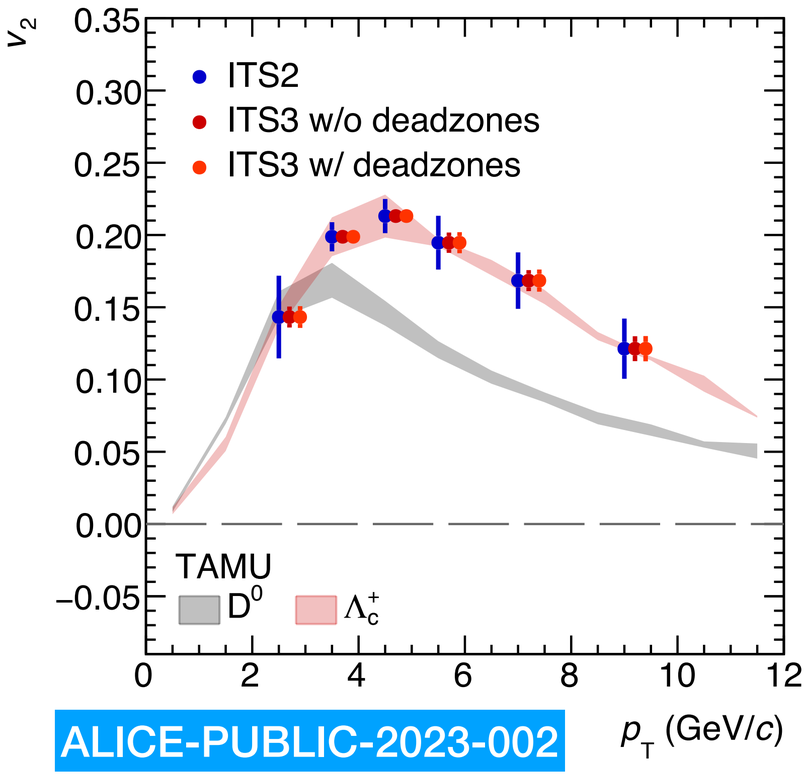
2010-2013 | 2015-2018 | 2022-2026 | 2030-2033

Run 1 | LS1 | Run 2 | LS2 | Run 3 | LS3 | Run 4

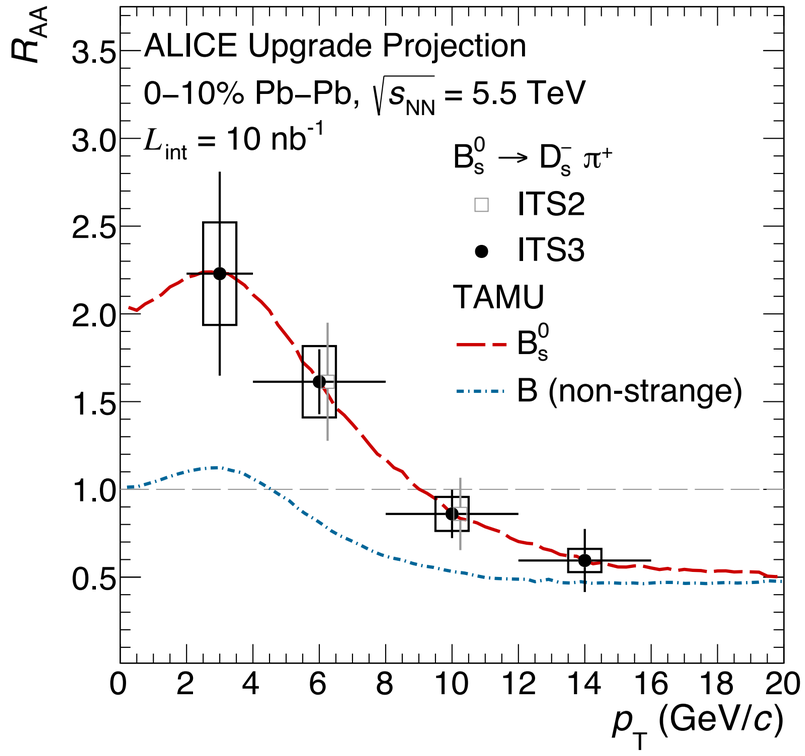
ALICE 1 | ALICE 2 | ALICE 2.1

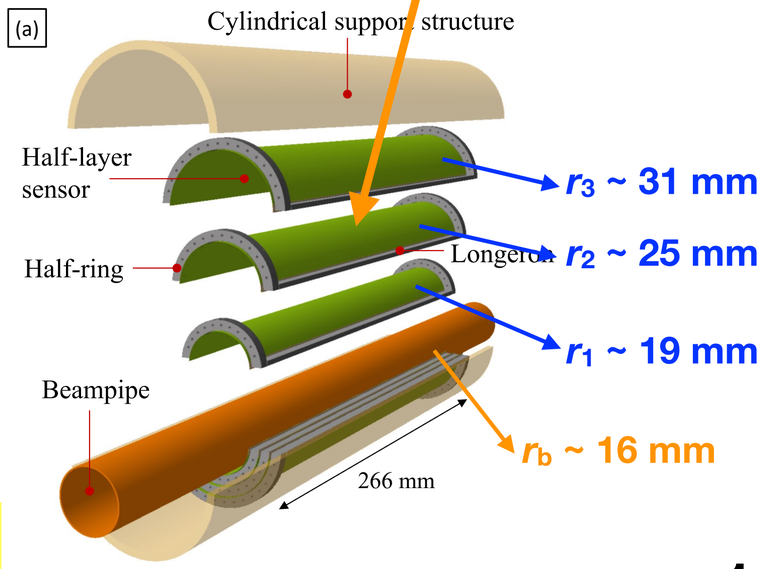
ALICE ITS3 TDR
CERN-LHCC-2024-003




ALICE-PUBLIC-2023-002




**Precisely constrain on *c*, *b* transport properties in QGP**

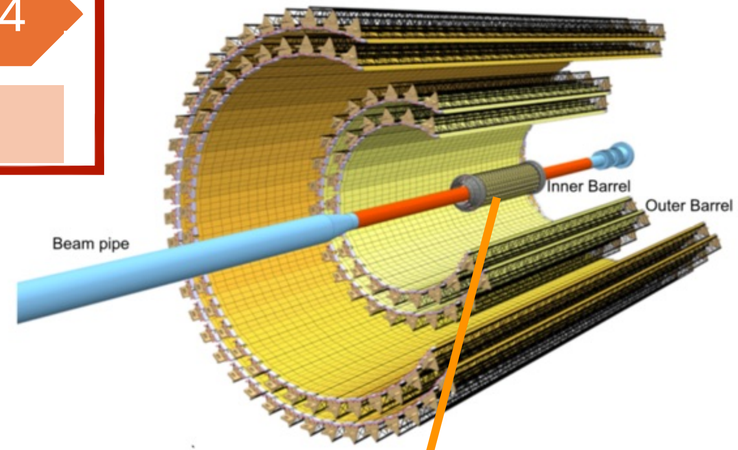
# ALICE ITS3 – Multi-charmed baryons

2010-2013 | 2015-2018 | 2022-2026 | 2030-2033

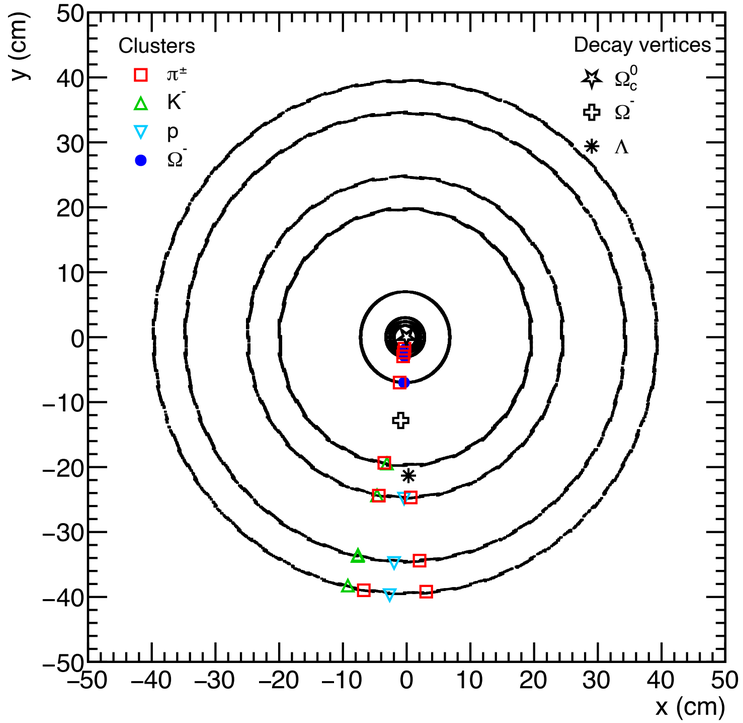
Run 1 → LS1 → Run 2 → LS2 → Run 3 → LS3 → Run 4

ALICE 1 | ALICE 2 | ALICE 2.1

ALICE ITS3 TDR
CERN-LHCC-2024-003

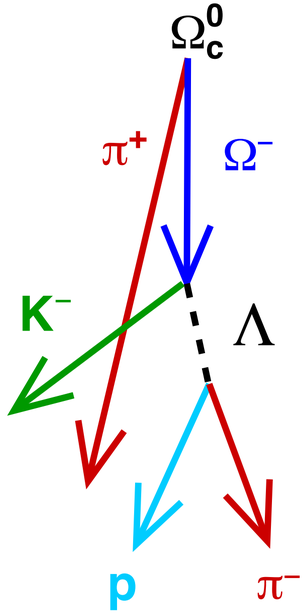



ITS 3 + 1 layer

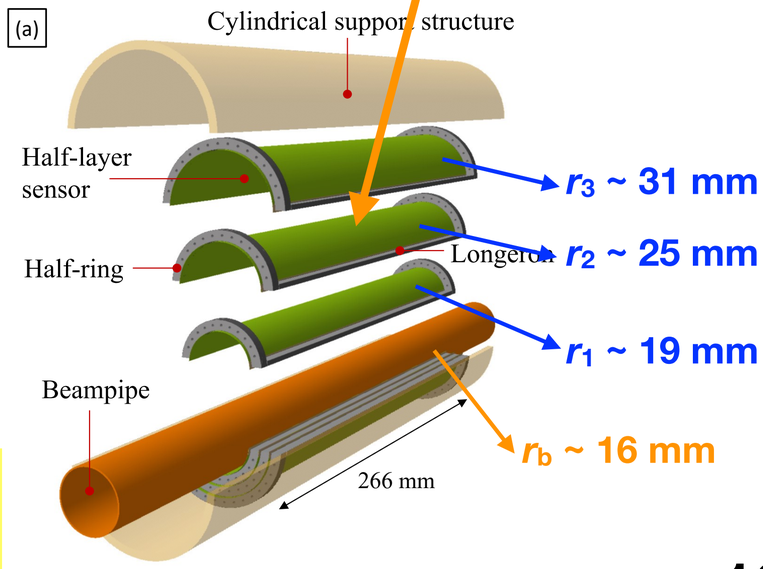



ALICE-PUBLIC-2023-002

Pythia 8 + GEANT 4 simulation




**Reveal multi-charmed baryon production in the QCD matter**



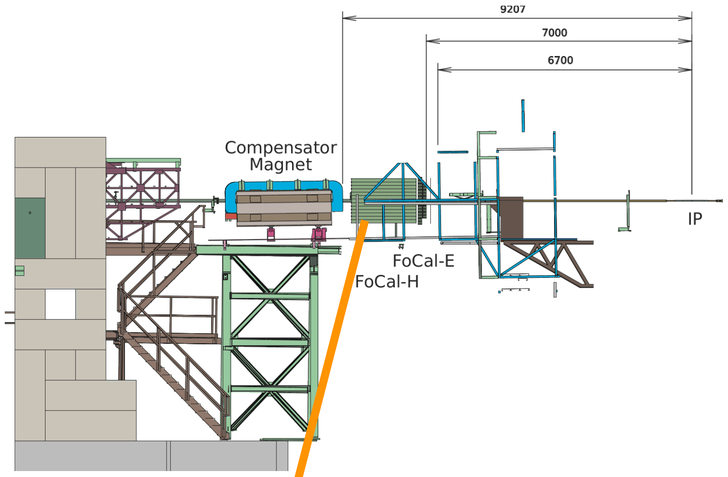
# ALICE FoCal — Prototype

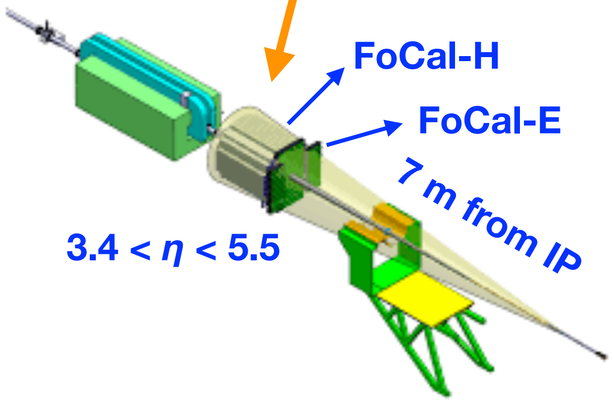
2010-2013 | 2015-2018 | 2022-2026 | 2030-2033

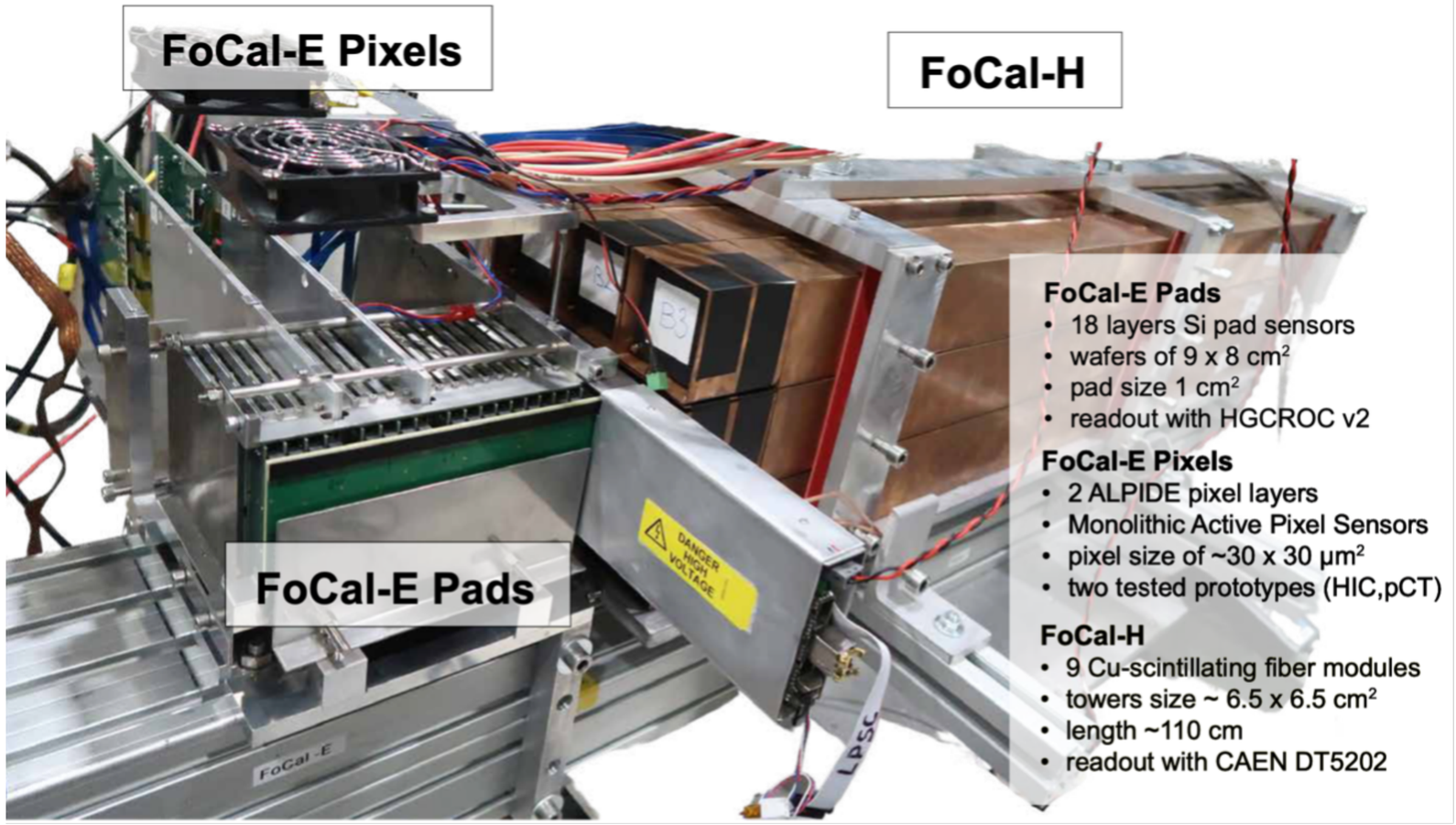
Run 1 → LS1 → Run 2 → LS2 → Run 3 → LS3 → Run 4

ALICE 1 | ALICE 2 | ALICE 2.1

**ALICE** FoCal
LoI: CERN-LHCC-2020-009
TDR: CERN-LHCC-2024-004




**FoCal-E Pads**
- 18 layers Si pad sensors
- wafers of 9 x 8 cm²
- pad size 1 cm²
- readout with HGCROC v2

**FoCal-E Pixels**
- 2 ALPIDE pixel layers
- Monolithic Active Pixel Sensors
- pixel size of ~30 x 30 μm²
- two tested prototypes (HIC,pCT)

**FoCal-H**
- 9 Cu-scintillating fiber modules
- towers size ~ 6.5 x 6.5 cm²
- length ~110 cm
- readout with CAEN DT5202

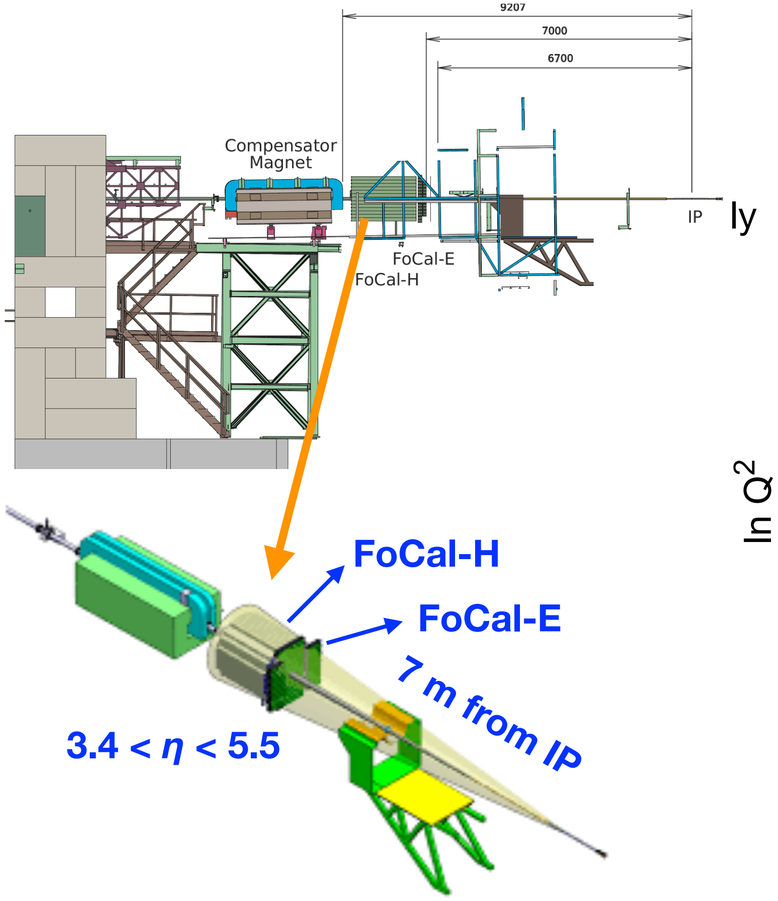
# ALICE FoCal — Performance

2010-2013 | 2015-2018 | 2022-2026 | 2030-2033

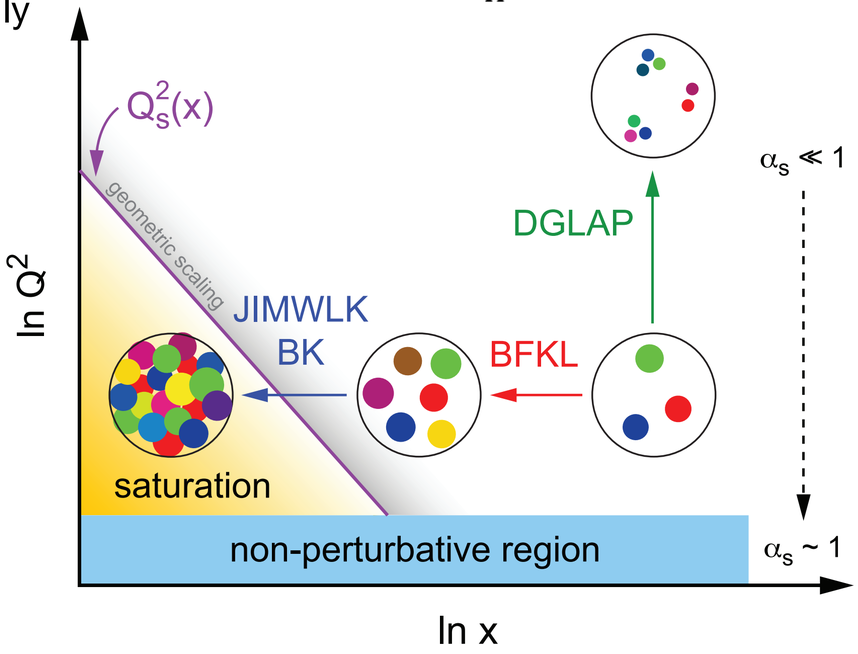
Run 1 → LS1 → Run 2 → LS2 → Run 3 → LS3 → Run 4

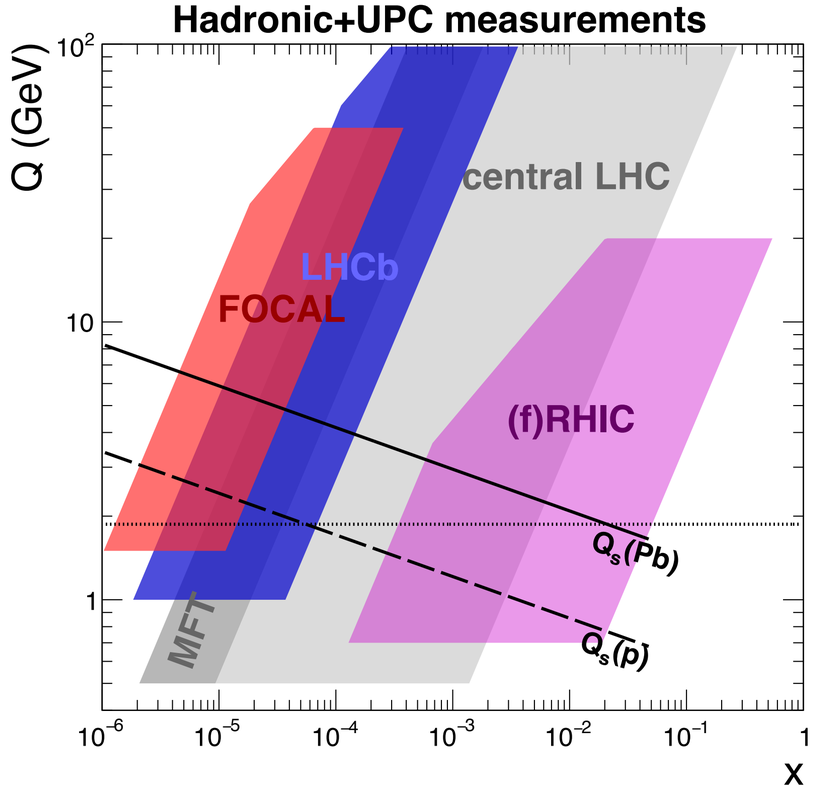
ALICE 1 | ALICE 2 | ALICE 2.1

**ALICE** FoCal
LoI: CERN-LHCC-2020-009
TDR: CERN-LHCC-2024-004

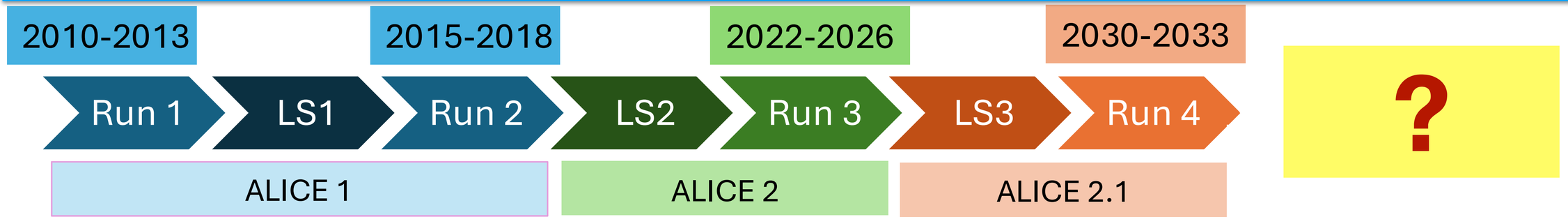



$$Q_s^2(x) \approx \frac{xG_A(x,Q^2)}{\pi R_A^2} \propto A^{1/3}x^{-\lambda}$$



# Beyond LHC Run 4 — Questions




Understanding the thermalization of heavy quarks in the quark-gluon plasma

➡ QQbar correlations, multi-charm baryons, p-wave quarkonia, exotic hadrons

Accessing the quark-gluon plasma temperature evolution with thermal radiation

➡ Azimuthal asymmetry of electromagnetic radiation

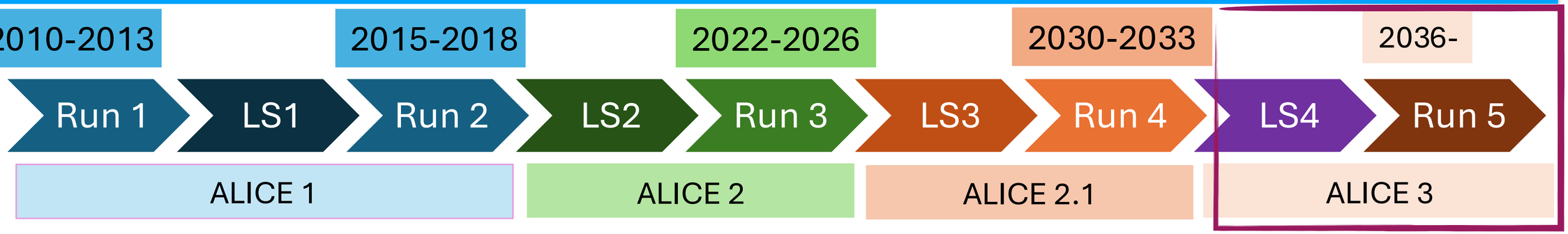
Characterizing the cross-over to the quark-gluon plasma phase

➡ Chiral symmetry restoration, fluctuations of conserved charges

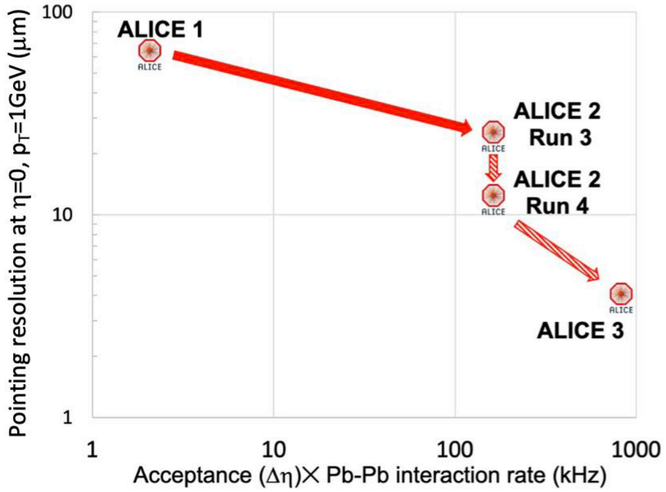
Exploiting a new laboratory for hadronic physics

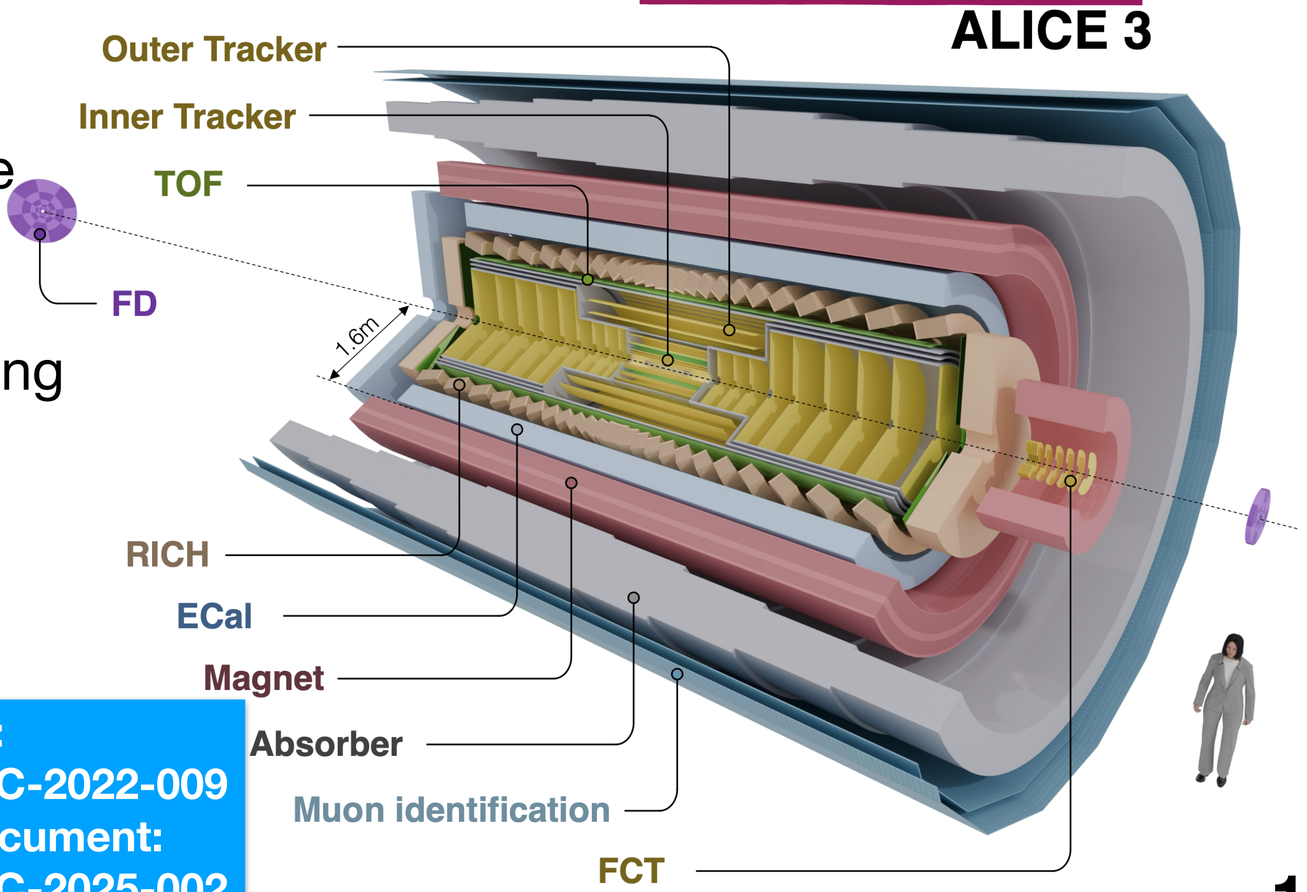
➡ Nuclear bound states and hadronic interactions, ultra-soft photons and tests of quantum field theories

# ALICE3 detector conception




- Compact all-silicon tracker with a high-resolution retractable vertex detector
- Large acceptance and extensive particle identification
- Superconducting 2T solenoid
- Continuous readout and online processing

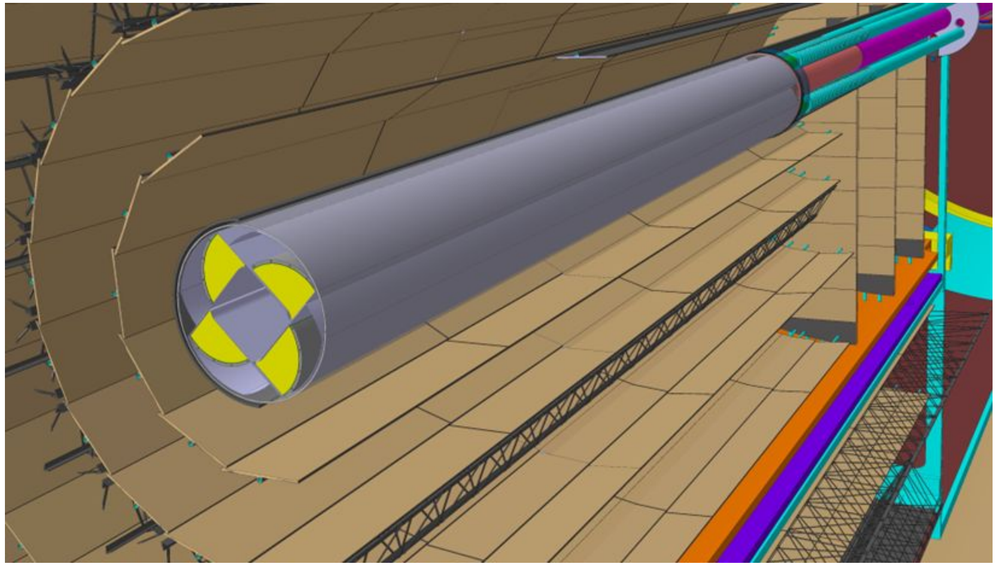


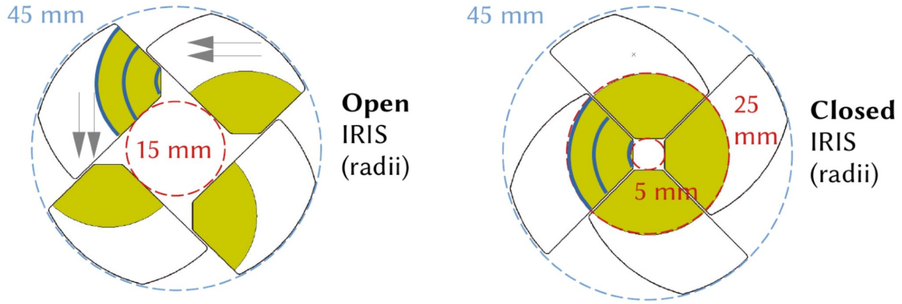



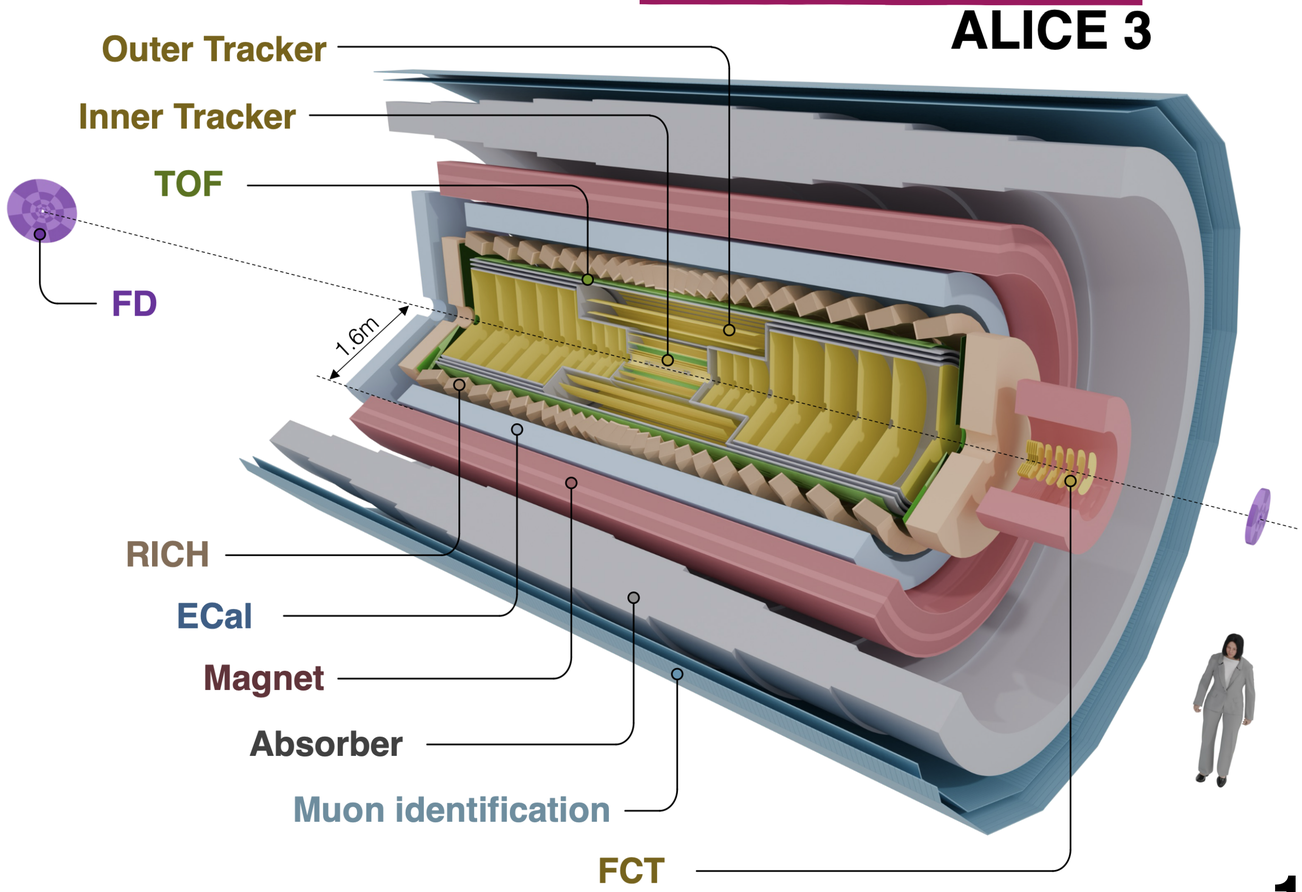

**ALICE3 LoI: CERN-LHCC-2022-009**
**Scoping document: CERN-LHCC-2025-002**

# Inner tracker

| 2010-2013 | 2015-2018 | 2022-2026 | 2030-2033 | 2036- |
|---|---|---|---|---|
| Run 1 | LS1 | Run 2 | LS2 | Run 3 | LS3 | Run 4 | LS4 | Run 5 |
| ALICE 1 | | ALICE 2 | | ALICE 2.1 | | ALICE 3 | | |

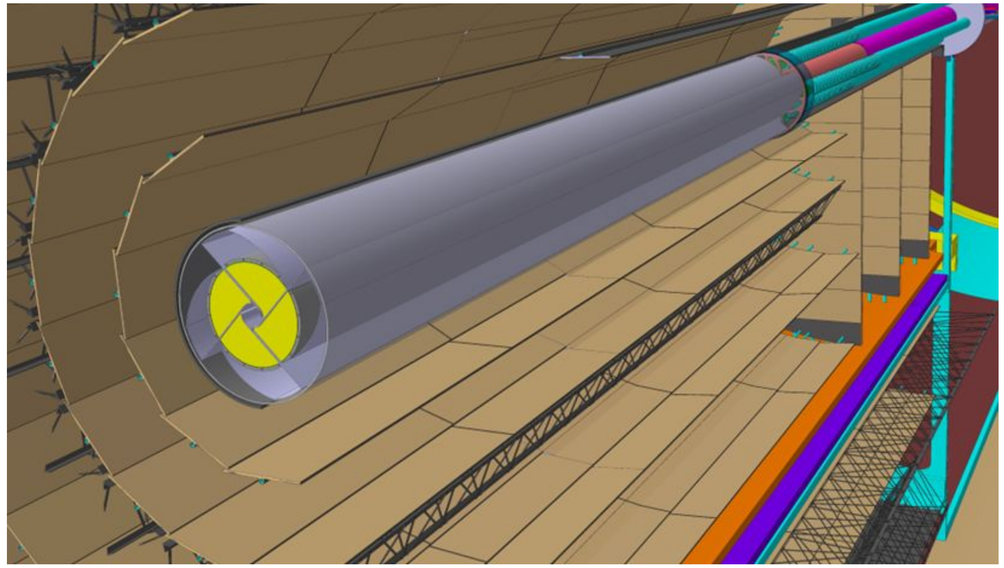


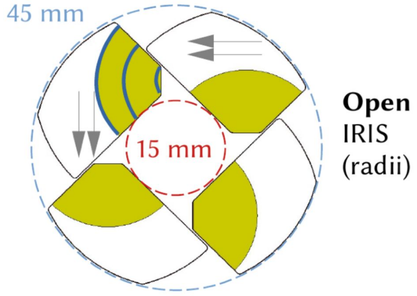


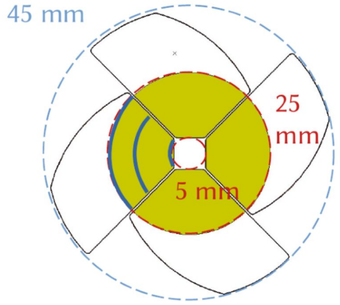
# Inner tracker

| 2010-2013 | 2015-2018 | 2022-2026 | 2030-2033 | 2036- |
|---|---|---|---|---|
| Run 1 | LS1 | Run 2 | LS2 | Run 3 | LS3 | Run 4 | LS4 | Run 5 |
| ALICE 1 | | ALICE 2 | | ALICE 2.1 | | ALICE 3 | | |

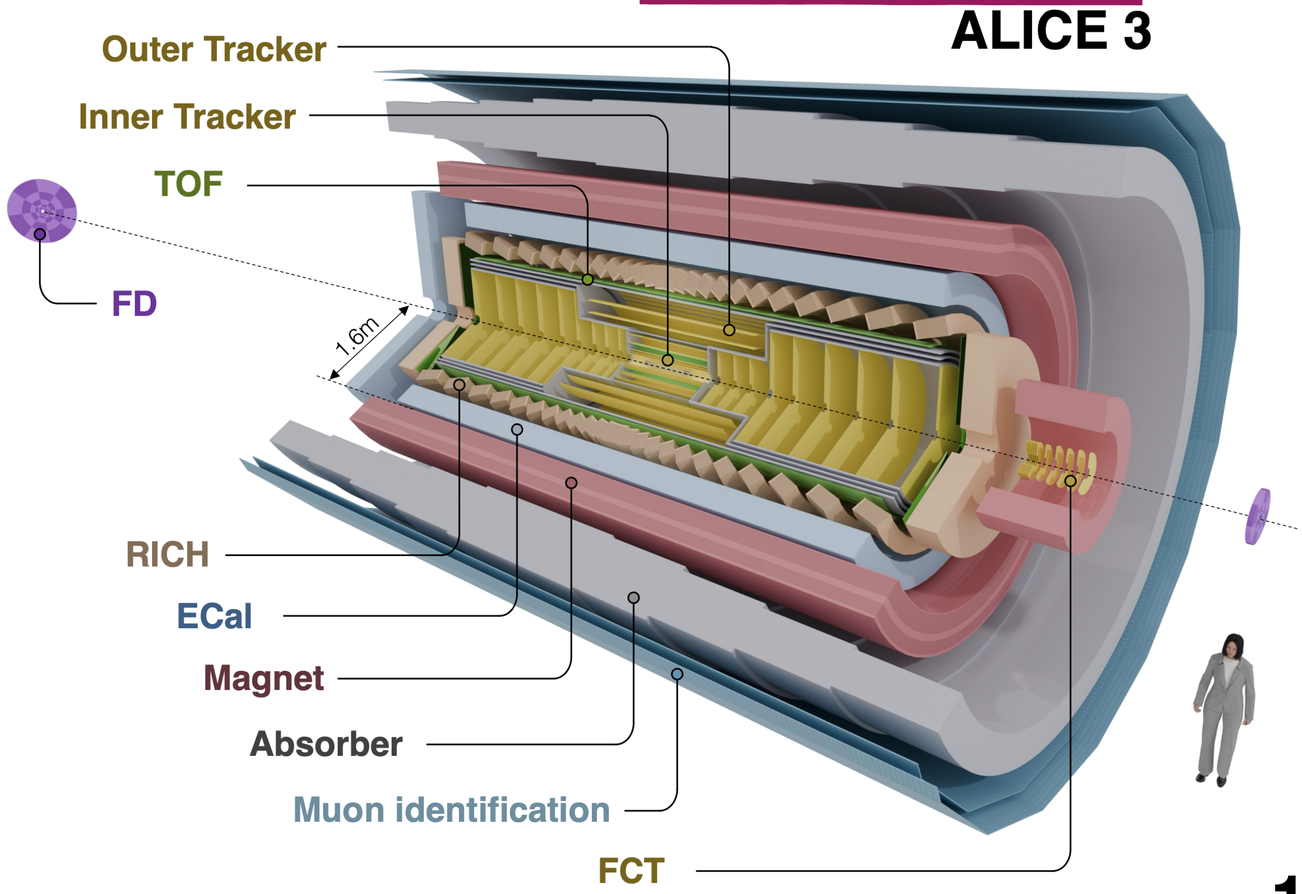





Open
IRIS
(radii)




Closed
IRIS
(radii)

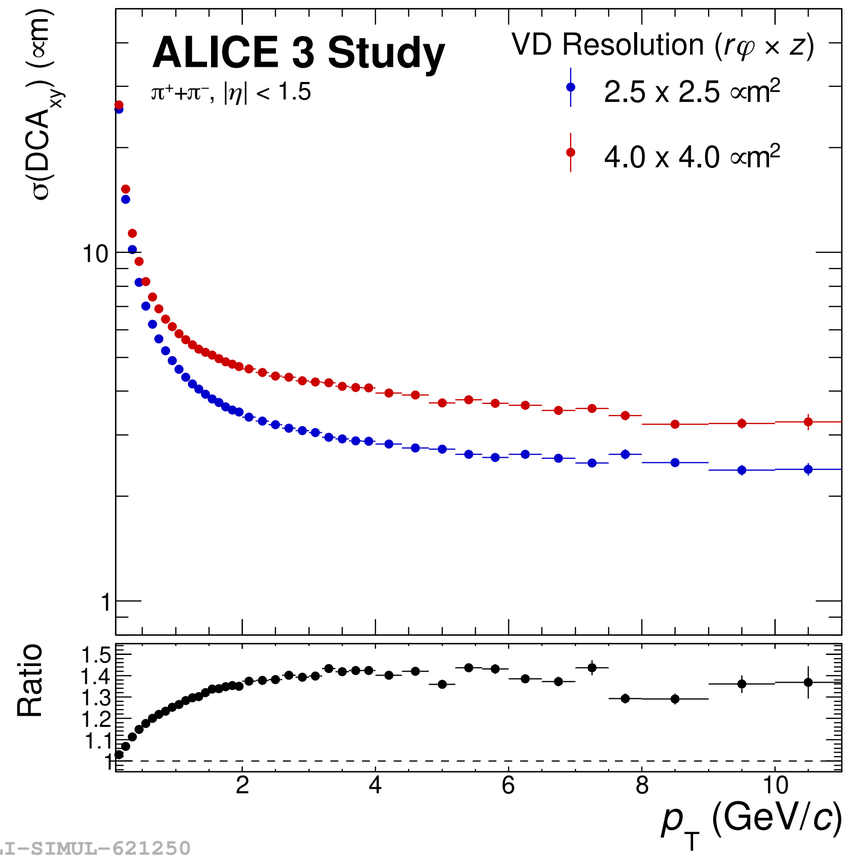


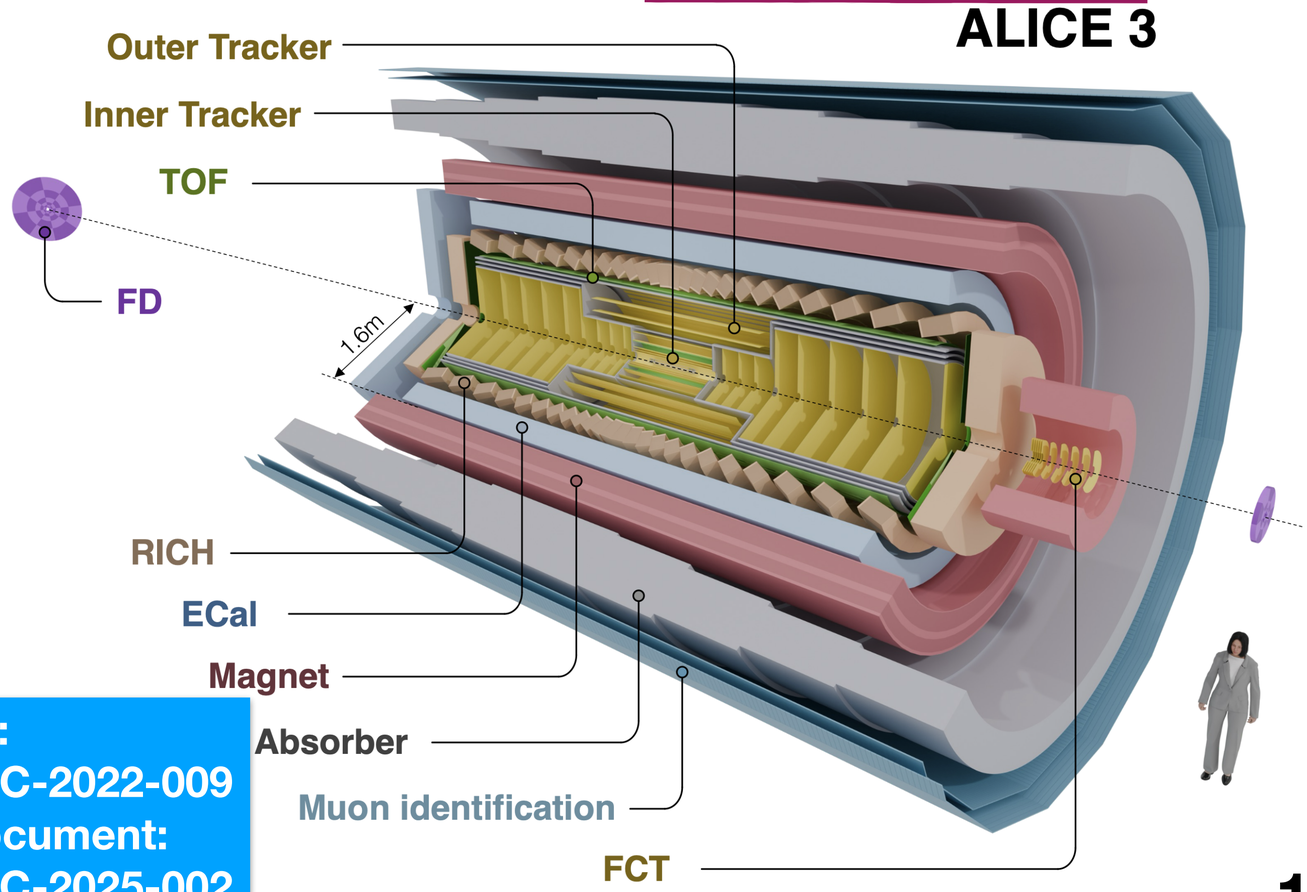
# Inner tracker

2010-2013 | 2015-2018 | 2022-2026 | 2030-2033 | 2036-

Run 1 | LS1 | Run 2 | LS2 | Run 3 | LS3 | Run 4 | LS4 | Run 5

ALICE 1 | ALICE 2 | ALICE 2.1 | ALICE 3

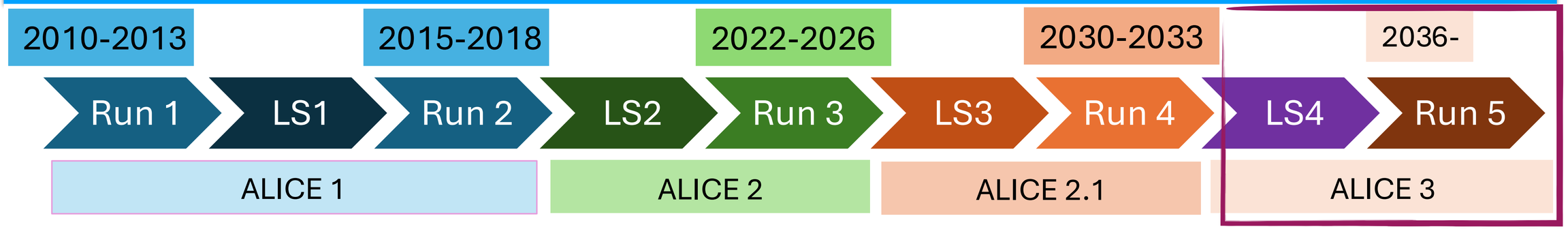



**ALICE3 LoI: CERN-LHCC-2022-009**
**Scoping document: CERN-LHCC-2025-002**

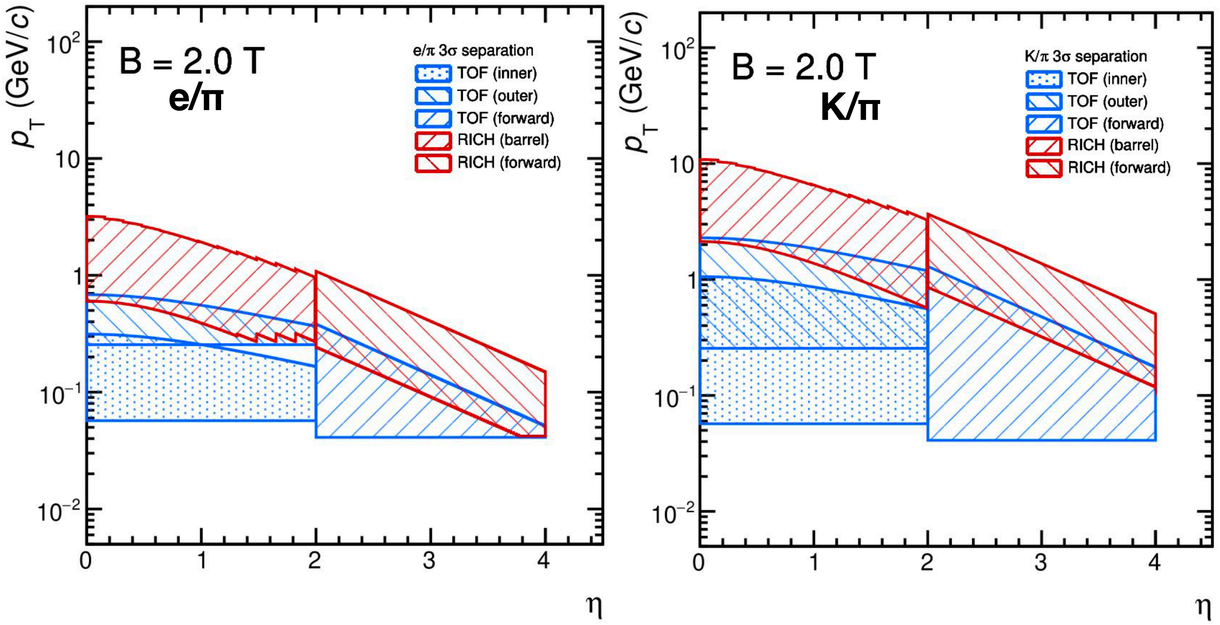
ALI-SIMUL-621250

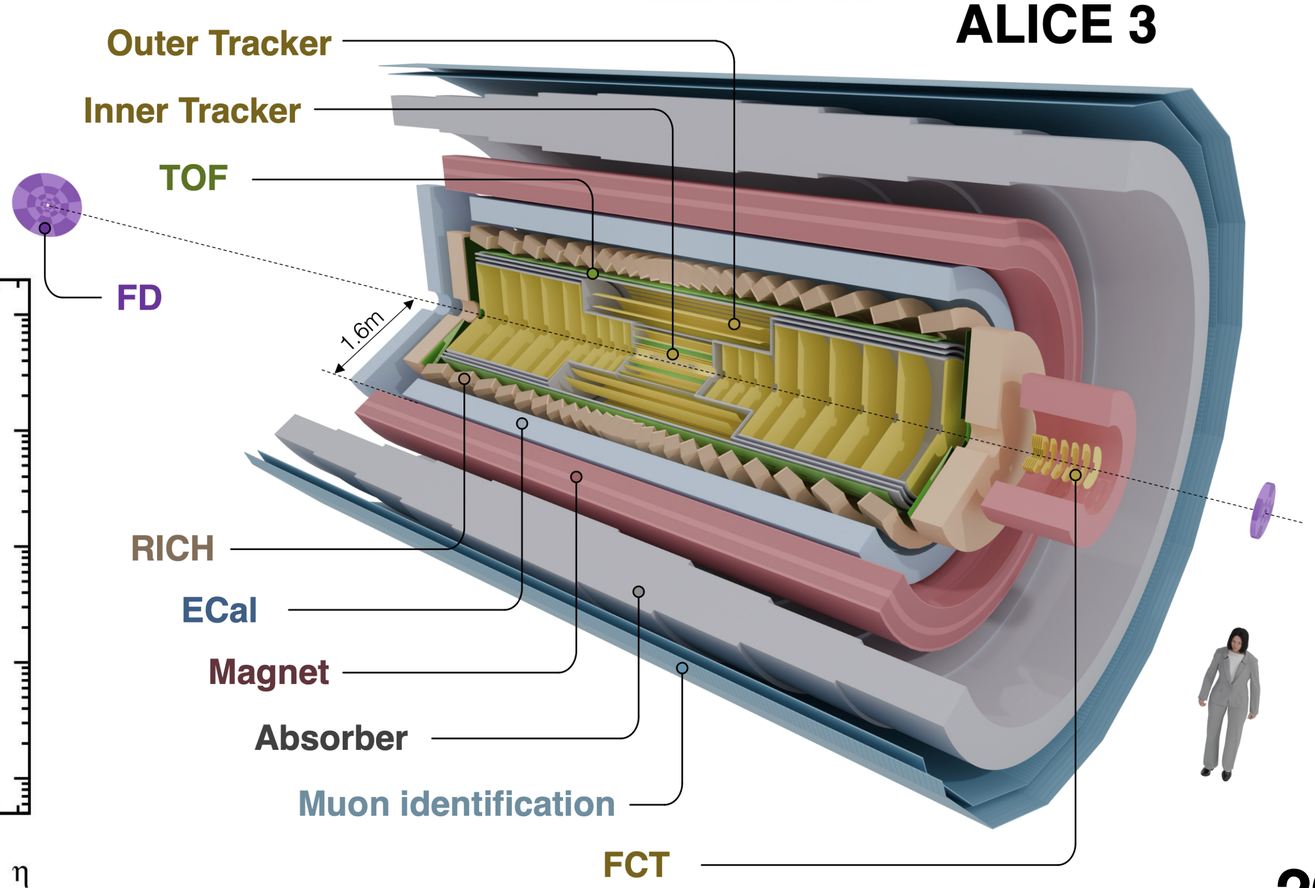
# Particle identification



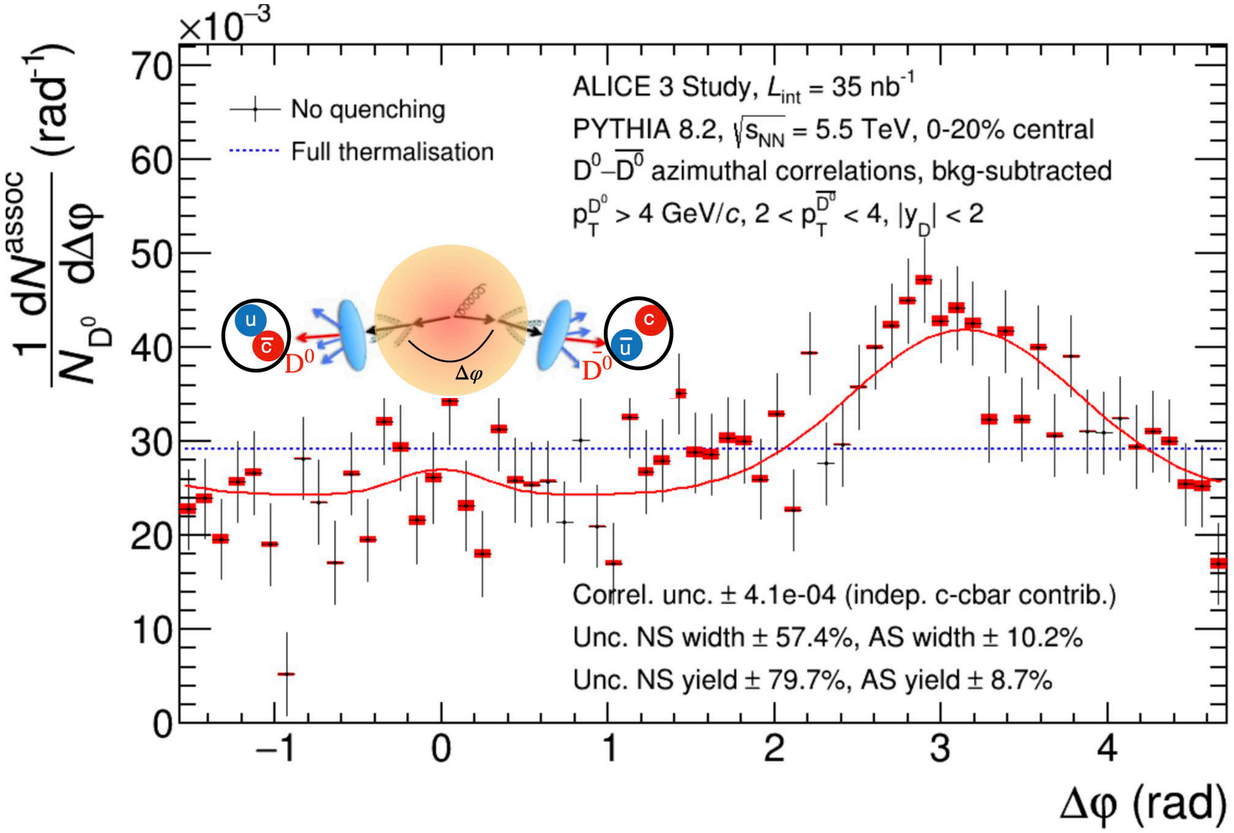

Requires

- ➡ $\sigma_{TOF}$ ~ 20 ps
- ➡ $\sigma_{RICH}$ ~ 1.5 mrad at saturation

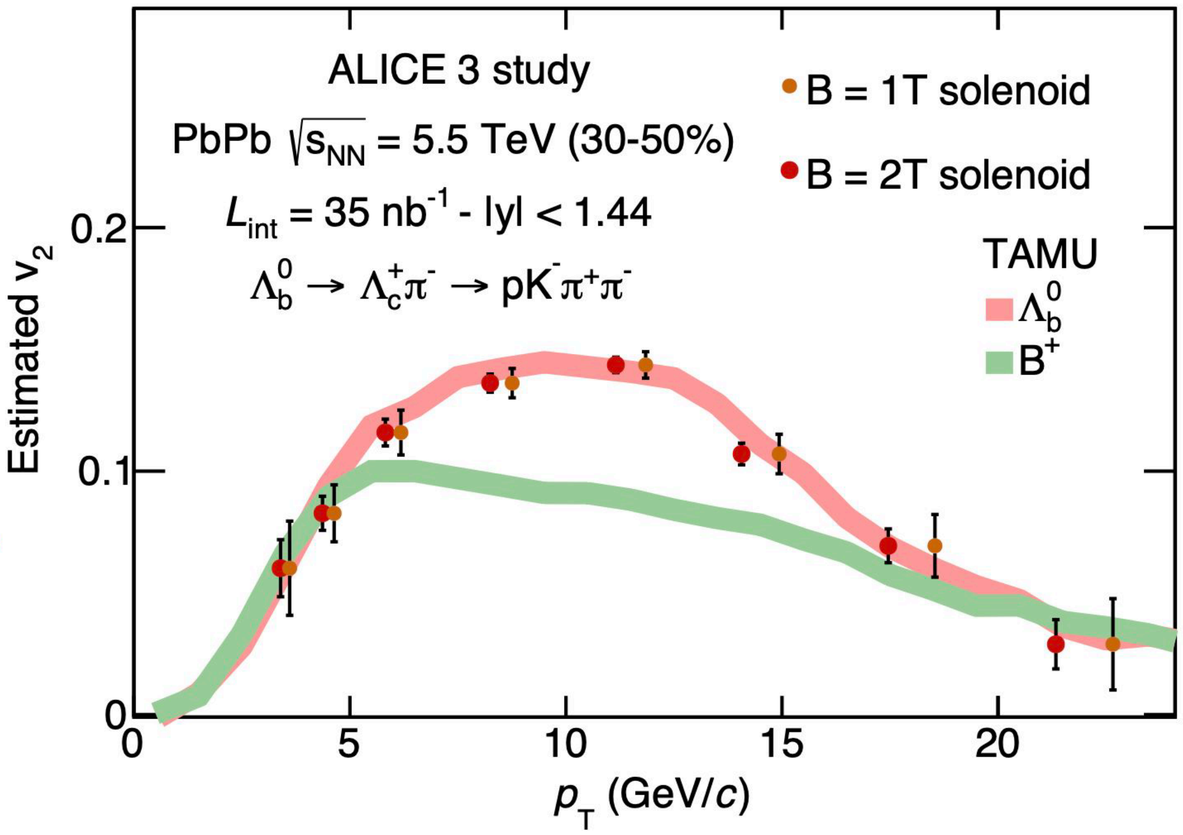


# Heavy quark correlation and flow




D-meson pair azimuthal de-correlation is sensitive to the thermalization degree and to the energy loss

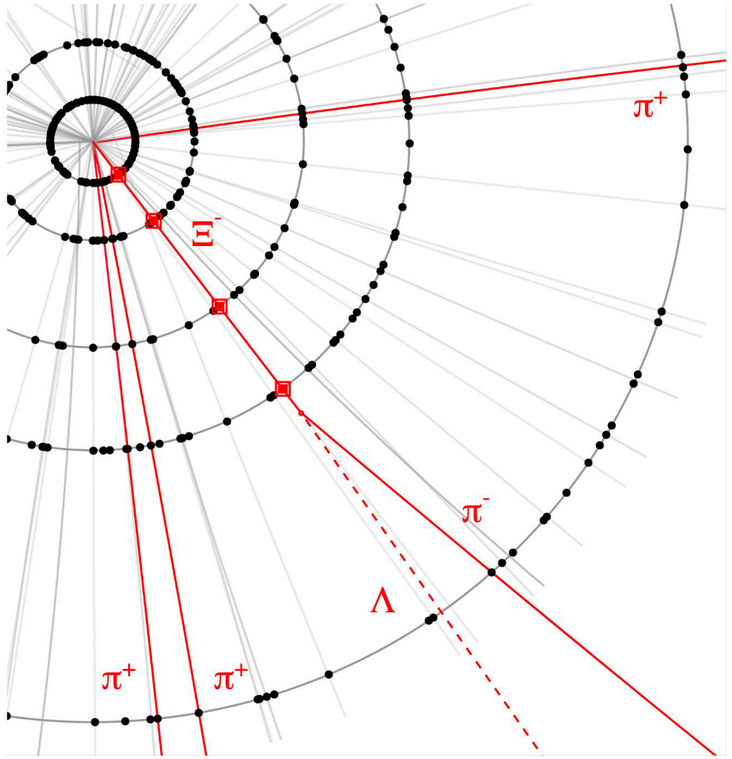



Direct reconstruction of beauty hadrons allows us to test beauty quark thermalization and hadronization

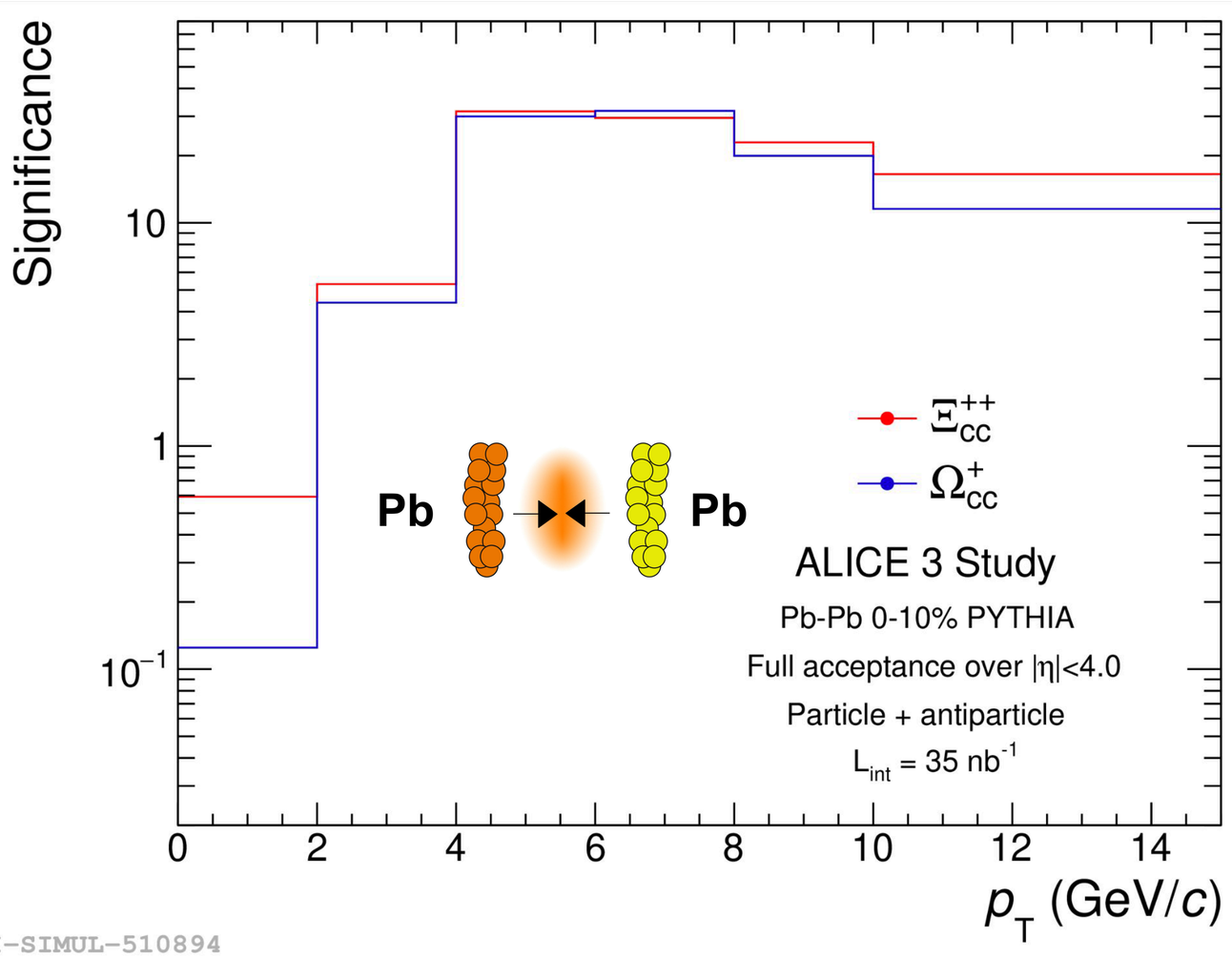
# HF-tracker of multicharm baryons

$$\Xi_{cc}^{++} \rightarrow \Xi_c^+ + \pi^+ \rightarrow \Xi^- + 3\pi^+$$

$$\Xi^- \rightarrow \Lambda + \pi^- \rightarrow p + 2\pi^-$$

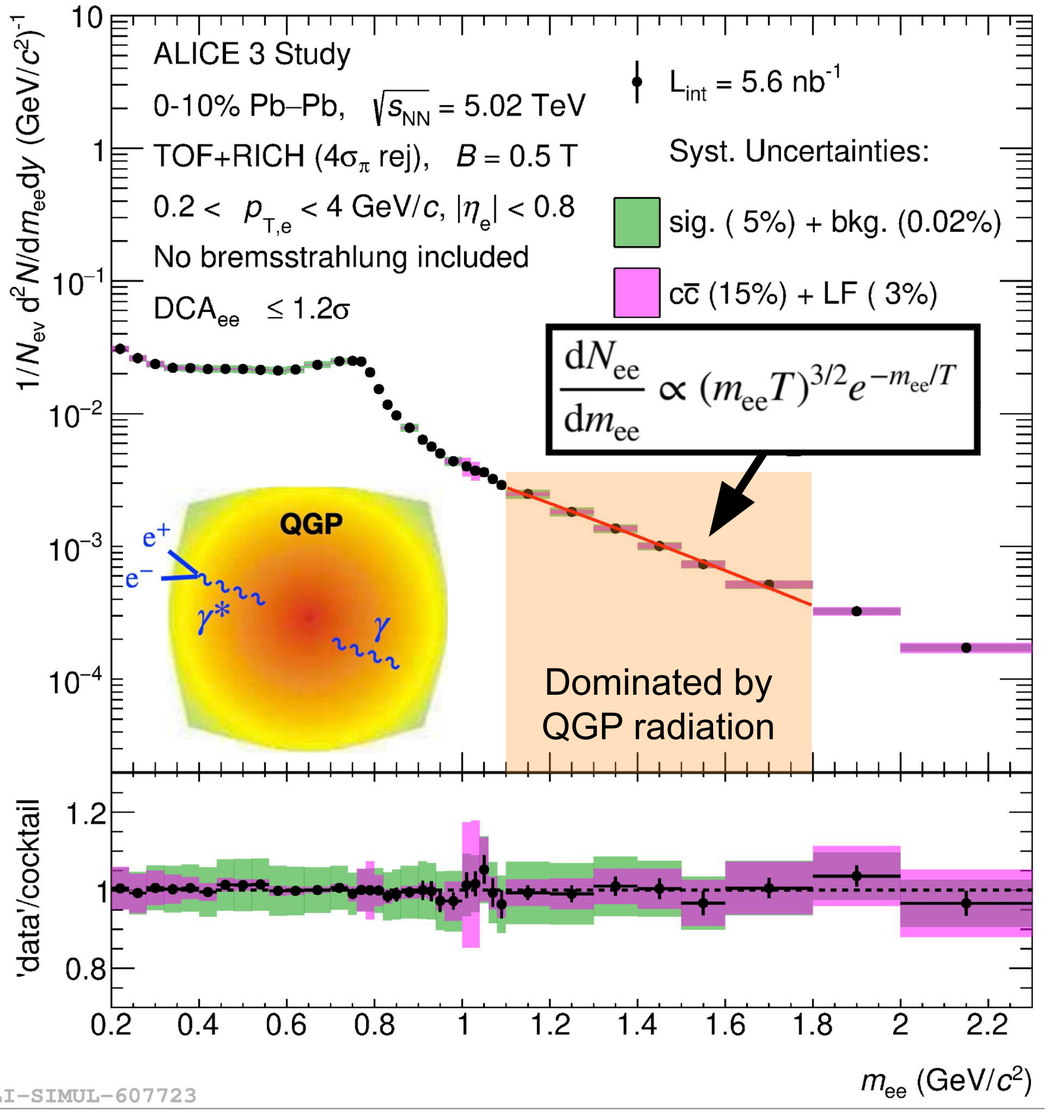



Match hits to topologically reconstructed candidate to greatly improve precision

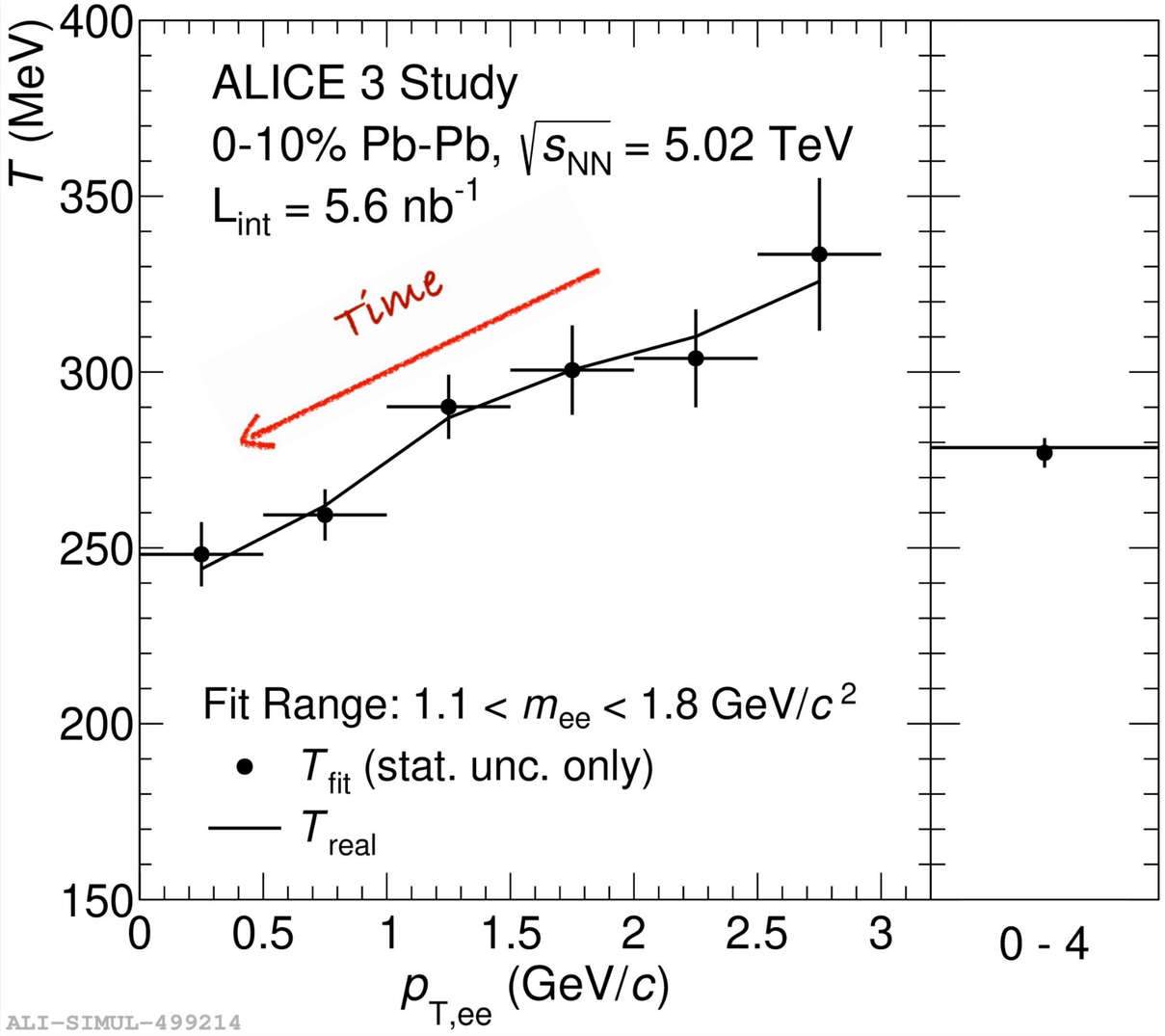



Highly efficient reduction of background from primary hyperons thanks to the pointing resolution!

# QGP time evolution

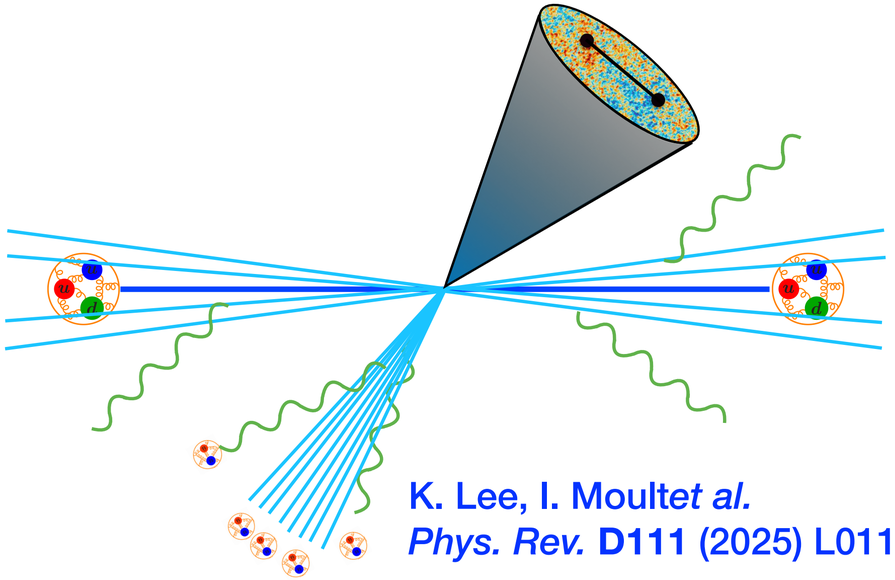



ALI-SIMUL-607723

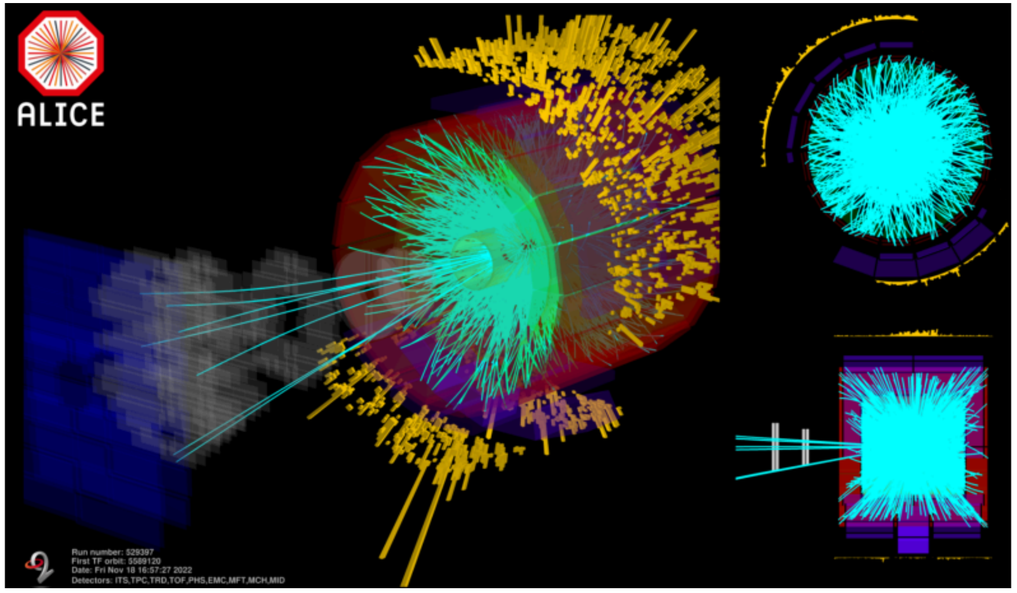



ALI-SIMUL-499214

# Conformal colliders meet the LHC

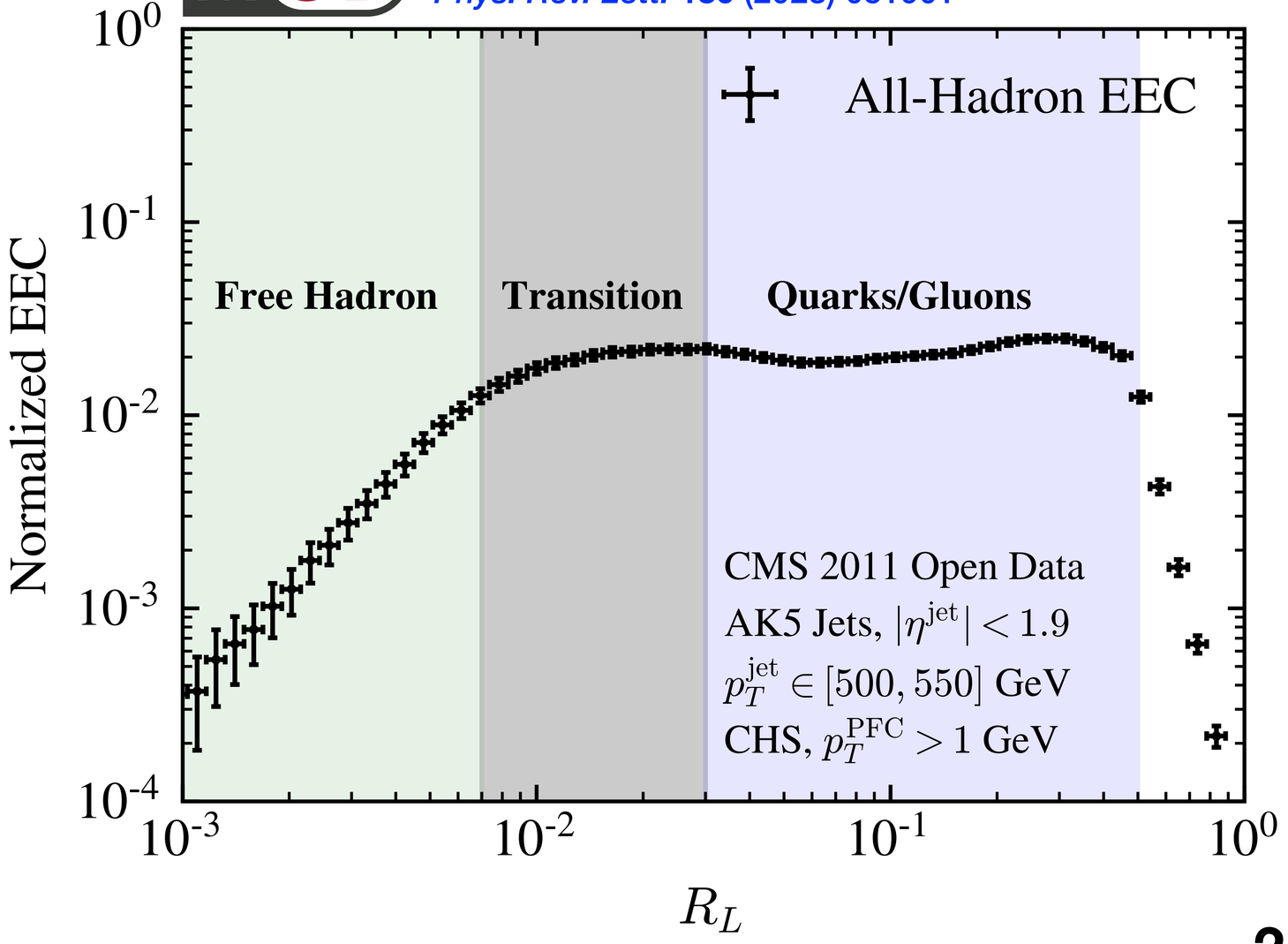


K. Lee, I. Moult*et al.*
*Phys. Rev.* **D111** (2025) L011502

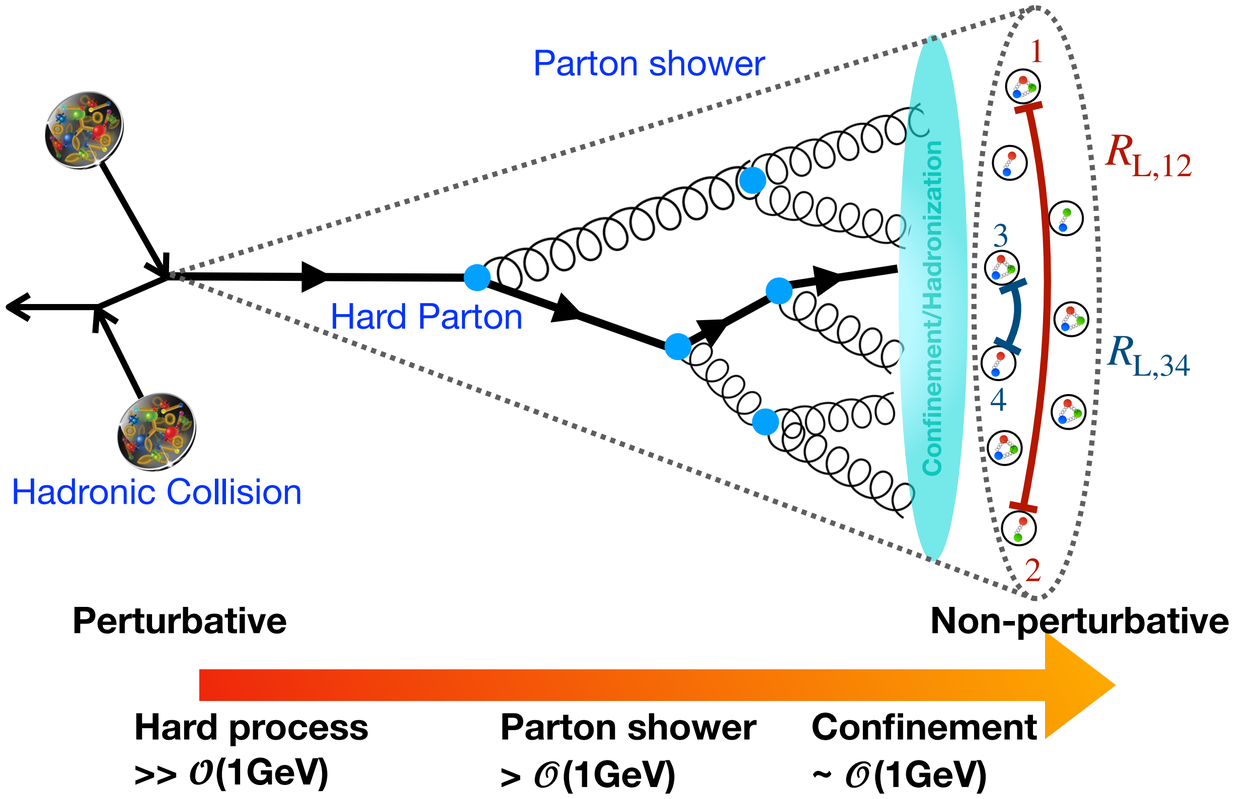



MOD

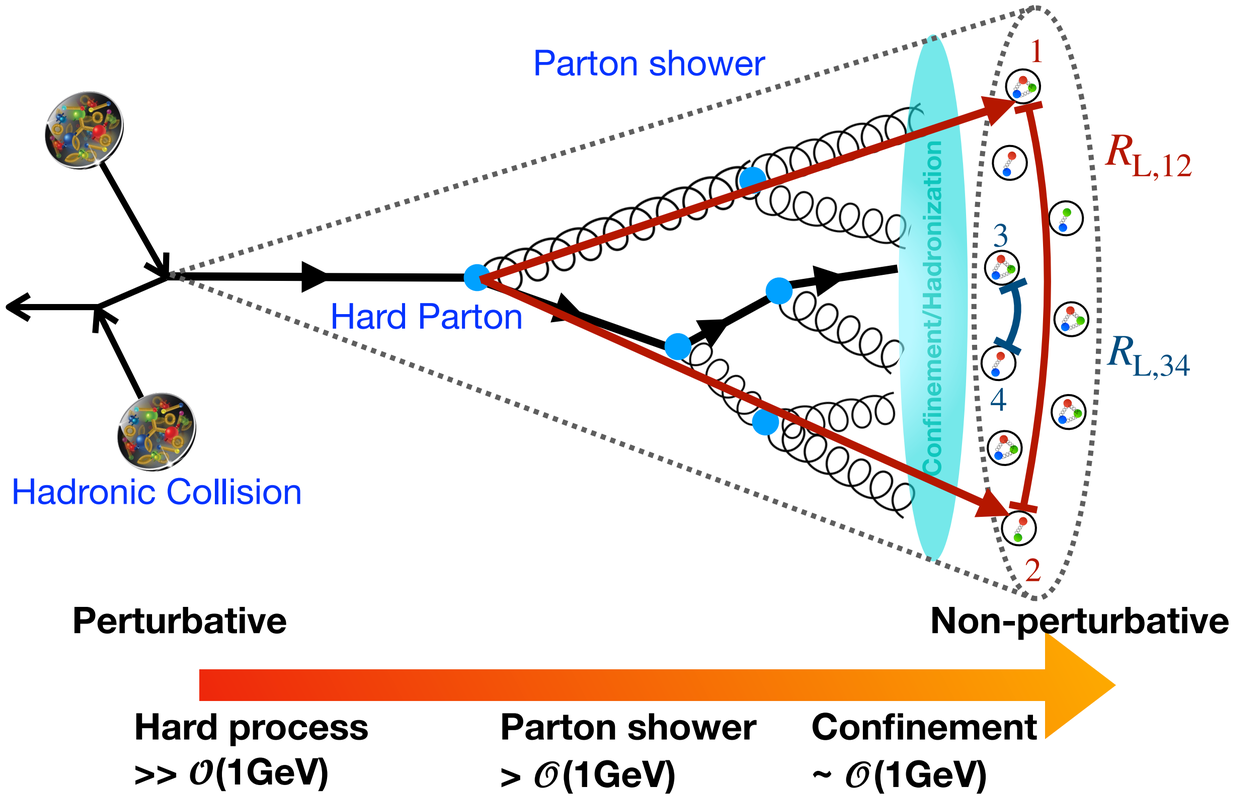
I. Moult, H.-X. Zhu *et al.*
*Phys. Rev. Lett.* **130** (2023) 051901



# 2-point energy correlators in jets



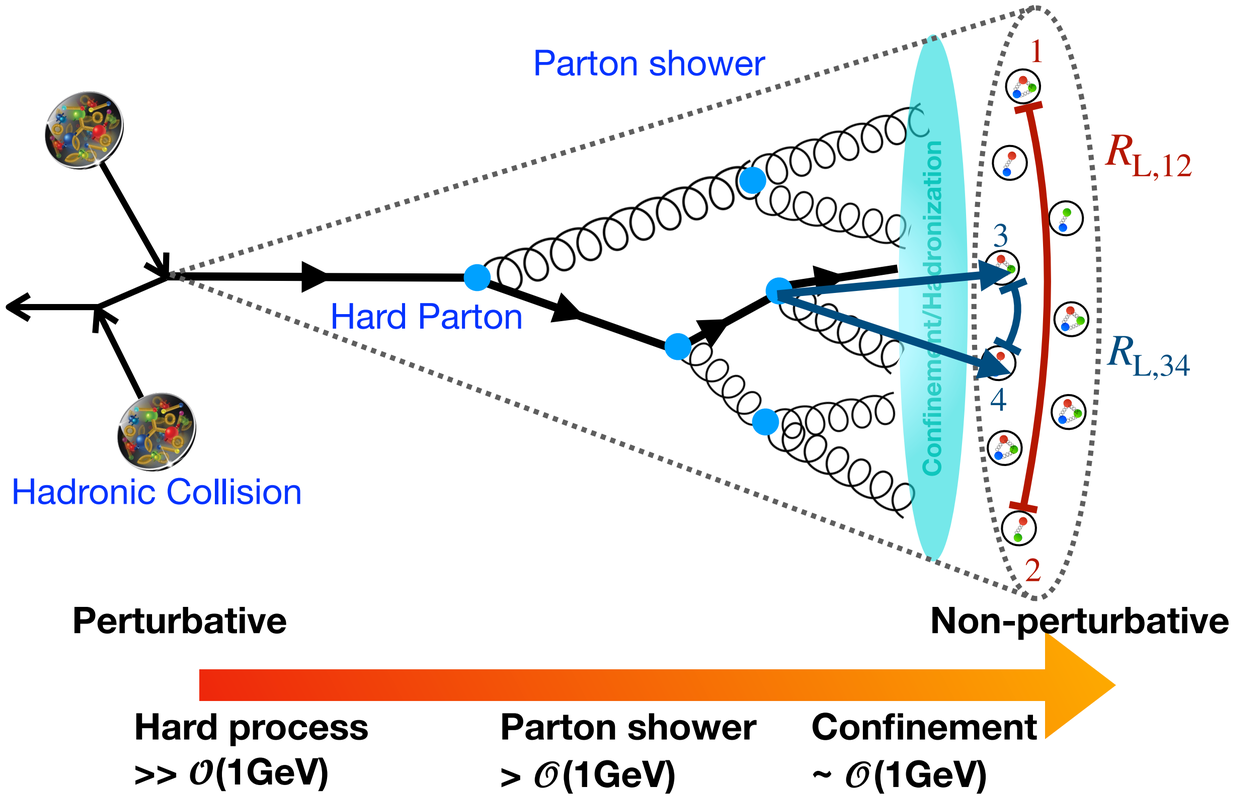
# 2-point energy correlators in jets




QCD emissions in parton showers are angular ordered

➡ Early splittings (perturbative) wider $R_L$

# 2-point energy correlators in jets

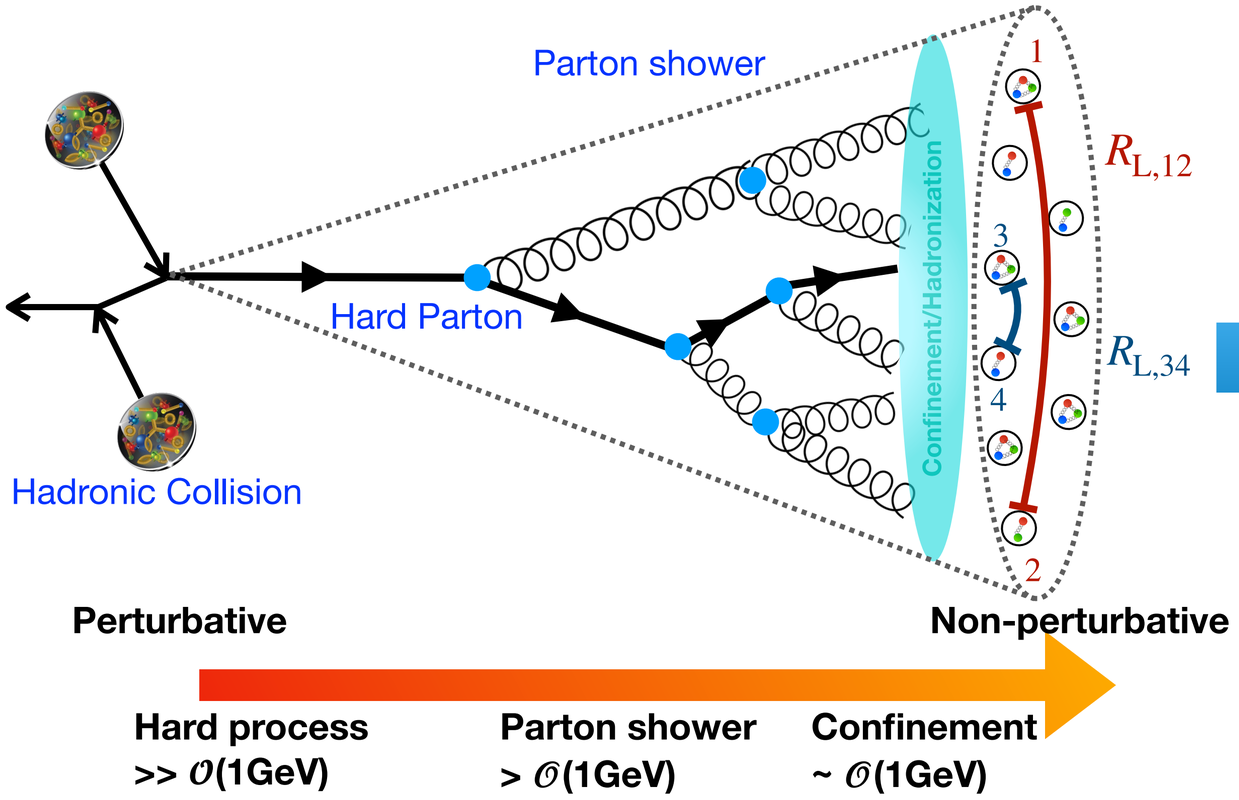


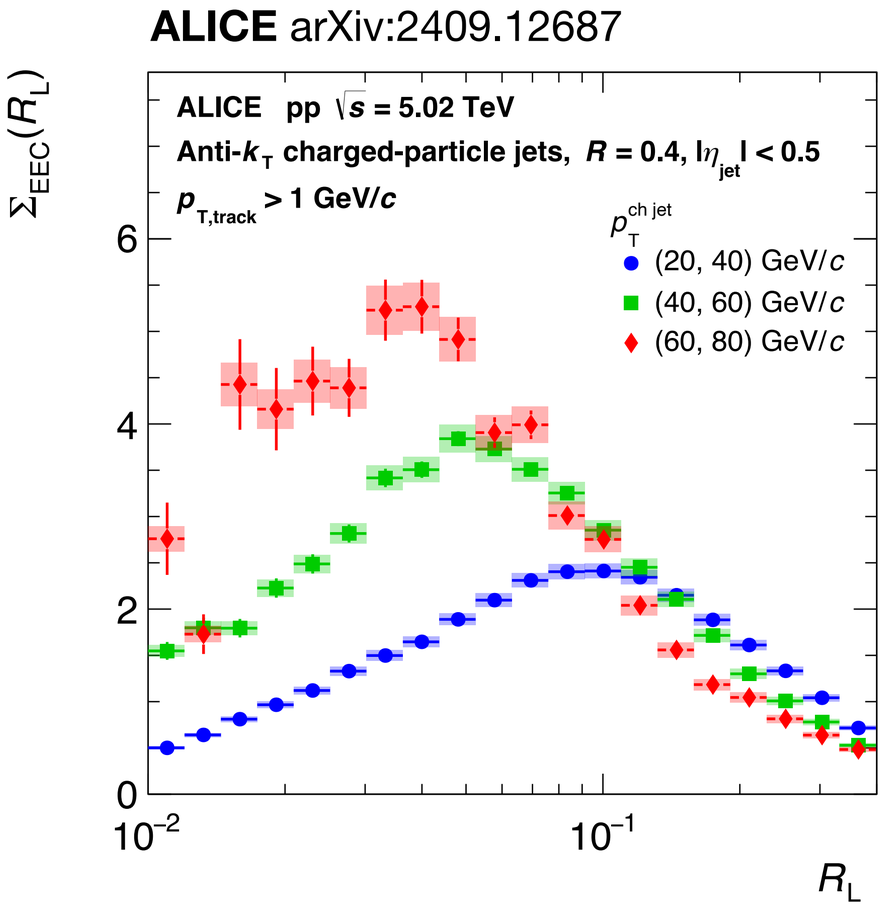

QCD emissions in parton showers are angular ordered

➡ Early splittings (perturbative) wider $R_L$

➡ Late splittings (non-perturbative) narrower $R_L$

# 2-point energy correlators in jets

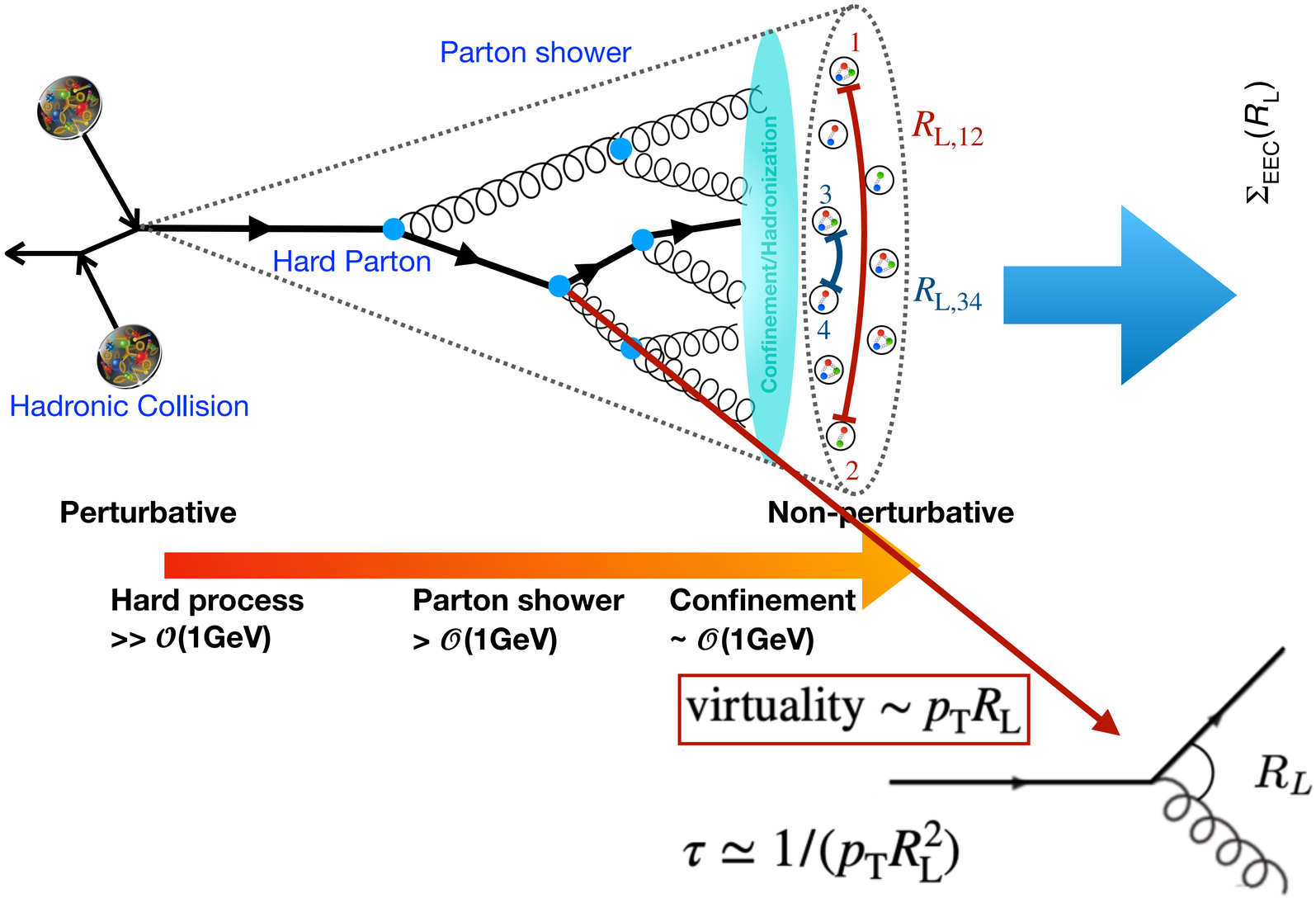


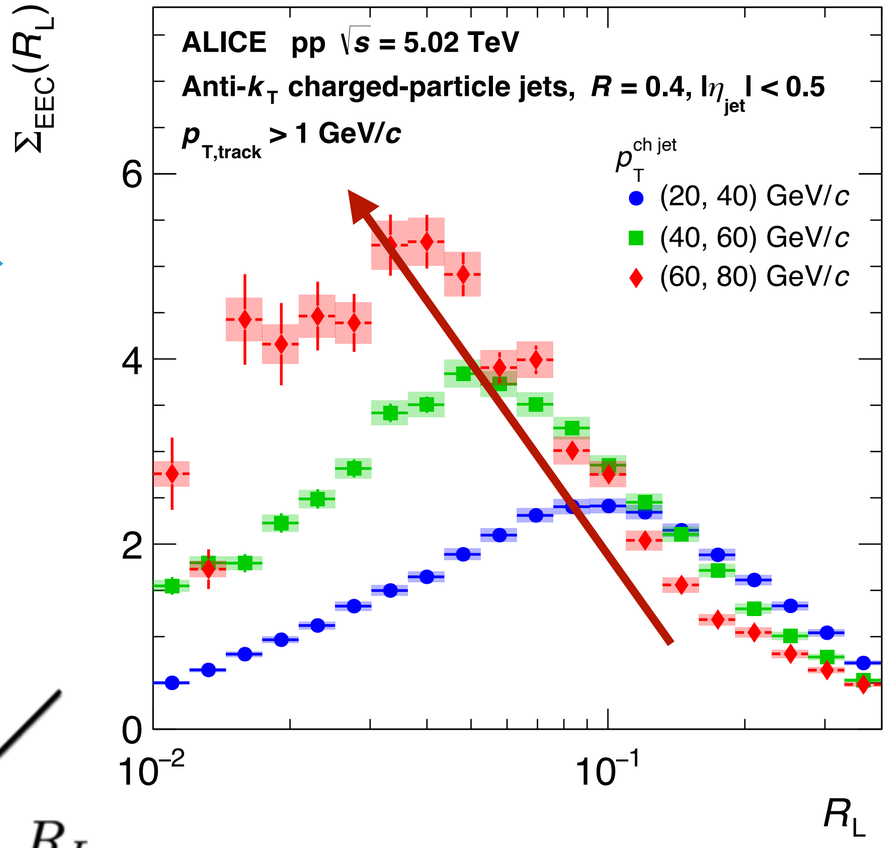

$$\mathrm{EEC}(R_\mathrm{L}) = \frac{1}{N_\mathrm{jet}} \sum_{i,j} \int \mathrm{d}R'_\mathrm{L} \delta(R_\mathrm{L} - R'_\mathrm{L}) \frac{p_{\mathrm{T},i} p_{\mathrm{T},j}}{p^2_{\mathrm{T,jet}}}$$

Derived from QFT and precise theoretical calculations

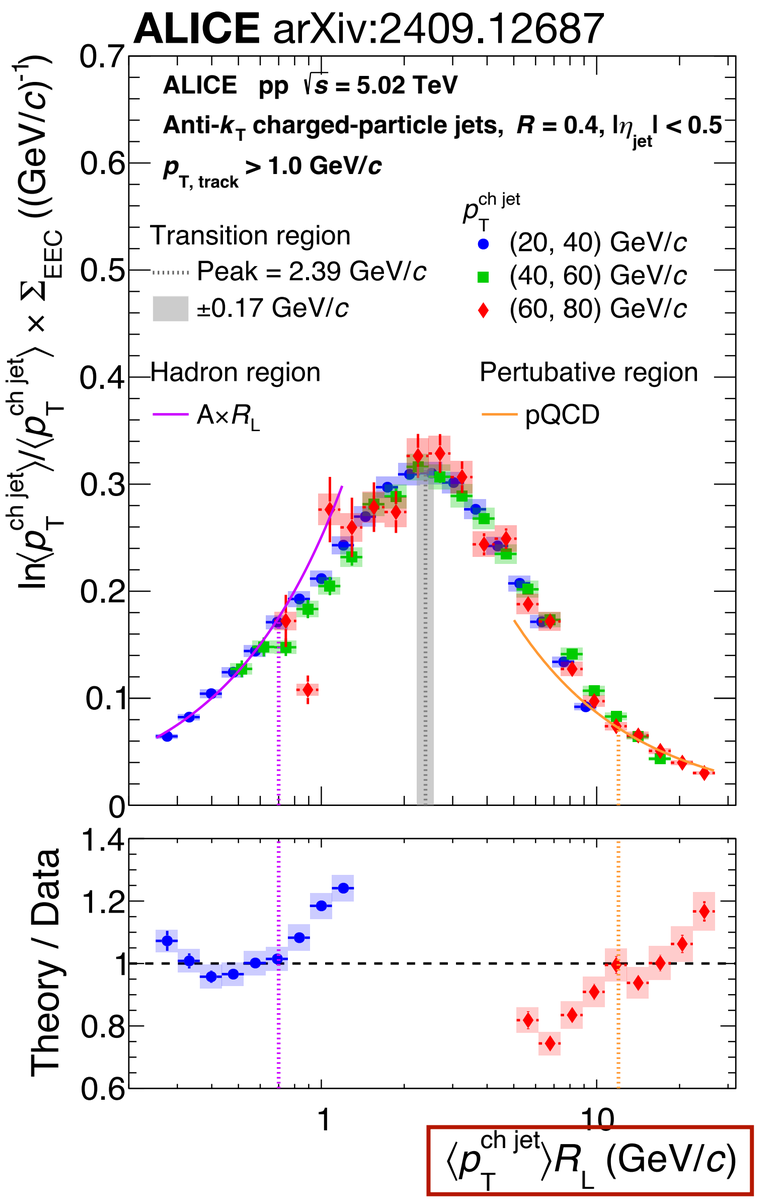
# 2-point energy correlators in jets




**ALICE** arXiv:2409.12687

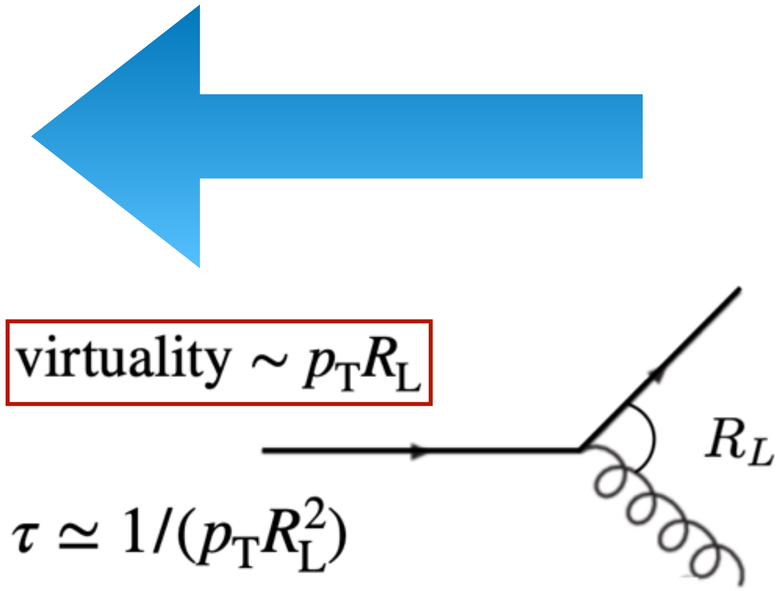


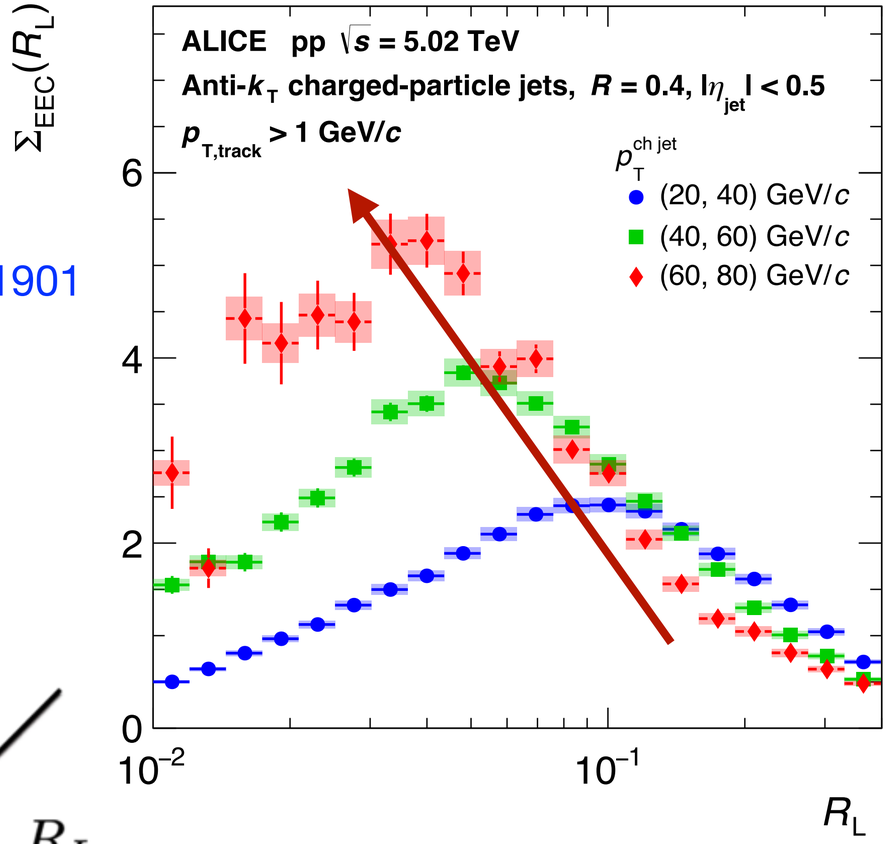
# Parton–hadron transition



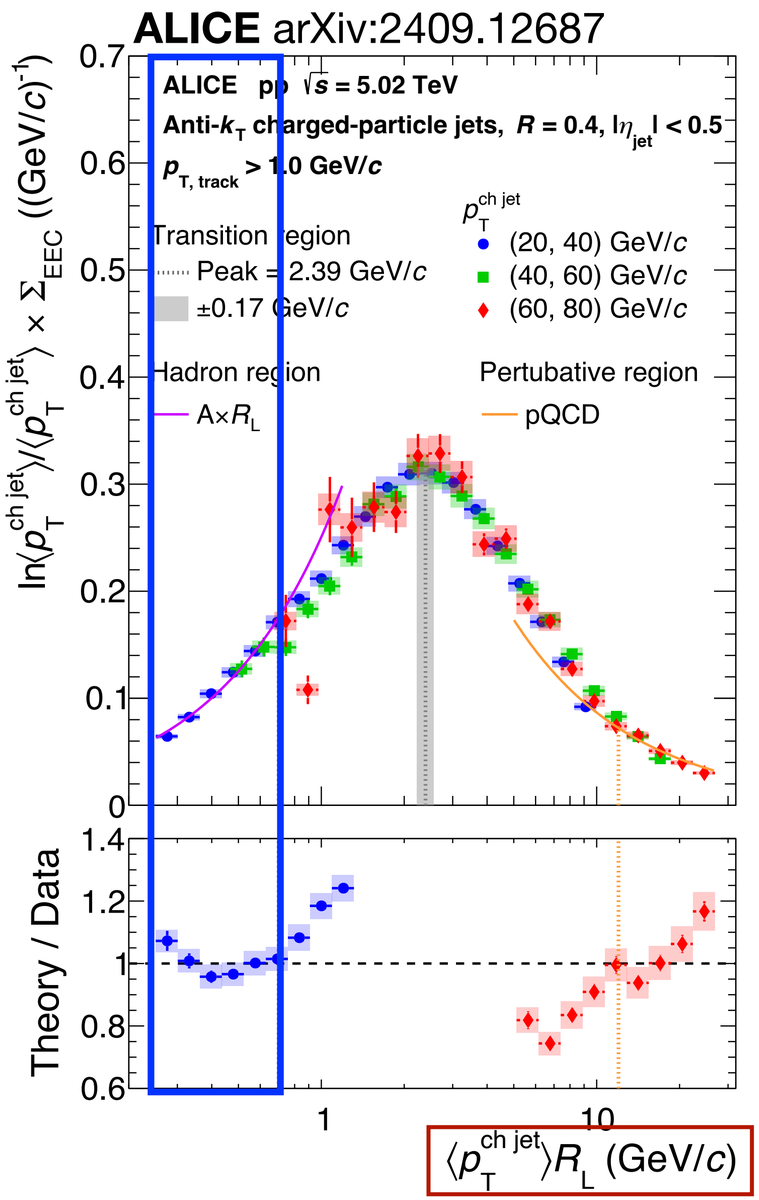

- Scaling $\Sigma_{EEC}$ with $p_{T,jet}R_L$ ⇒ Proportional to virtuality

See also
**STAR** *Phys. Rev. Lett.* **135** (2025) 111901

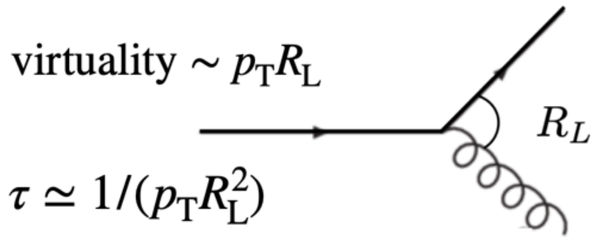


# Parton–hadron transition



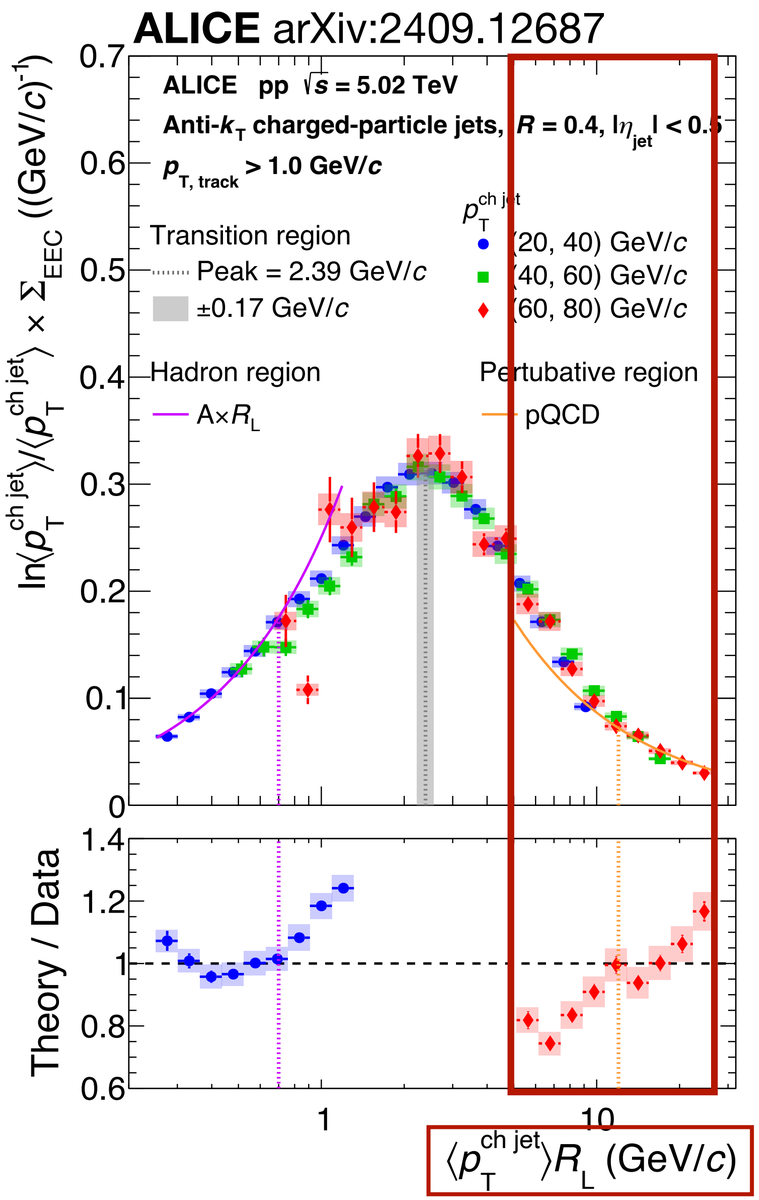

- Scaling $\Sigma_{EEC}$ with $p_{T,jet}R_L$ ⇒ Proportional to virtuality



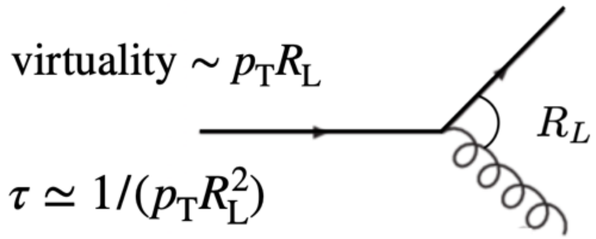

- Small $R_L$: Clear linear scaling ⇒ “free” hadron regime

$$\mathrm{EEC}(R_\mathrm{L}) = \frac{1}{N_\mathrm{jet}} \sum_{i,j} \int \mathrm{d}R'_\mathrm{L} \delta(R_\mathrm{L} - R'_\mathrm{L}) \frac{p_{\mathrm{T},i} p_{\mathrm{T},j}}{p^2_{\mathrm{T,jet}}}$$

# Parton–hadron transition



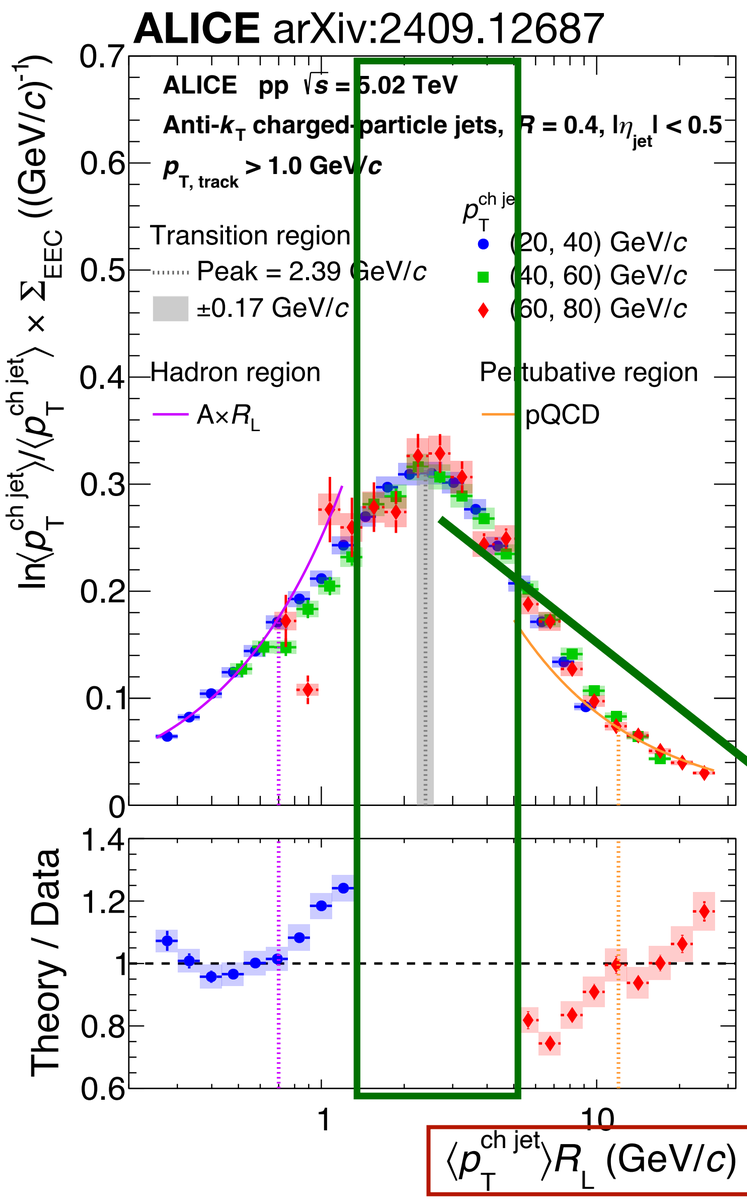

- Scaling $\Sigma_{EEC}$ with $p_{T,jet}R_L$ ⇒ Proportional to virtuality



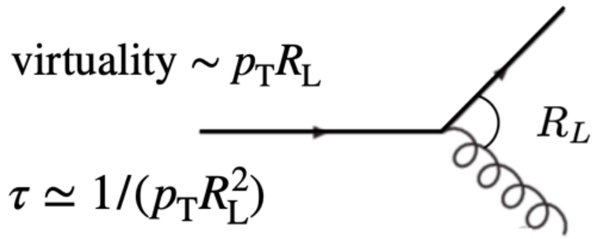

- Small $R_L$: Clear linear scaling ⇒ “free” hadron regime
- Large $R_L$: Well described by pQCD ⇒ max. dev. ~20%

*Phys. Rev.* **D111** (2025) L011502

# Parton–hadron transition




- Scaling $\Sigma_{EEC}$ with $p_{T,jet}R_L$ ⇒ Proportional to virtuality



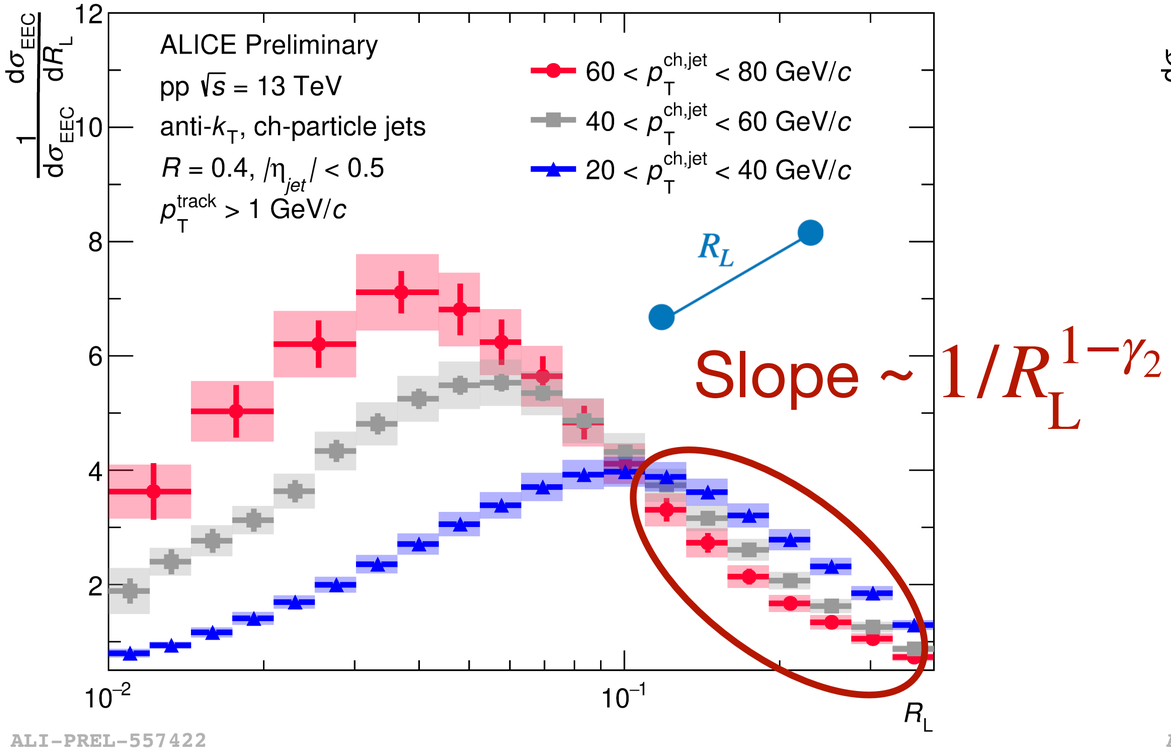

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*Phys. Rev.* **D111** (2025) L011502

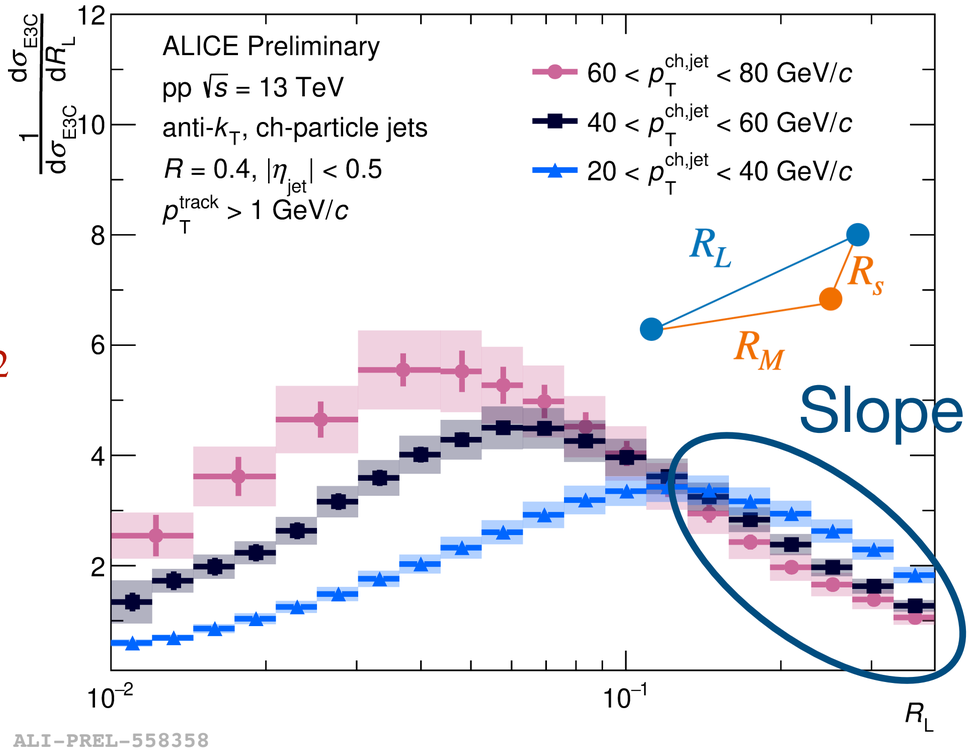
- Peaks are aligned at $p_{T,jet}R_L \approx 2.4$ GeV/$c$

  ➡ Implies a common energy scale for parton–hadron transition

# QFT anomalous demesions




Slope ~ $1/R_L^{1-\gamma_2}$



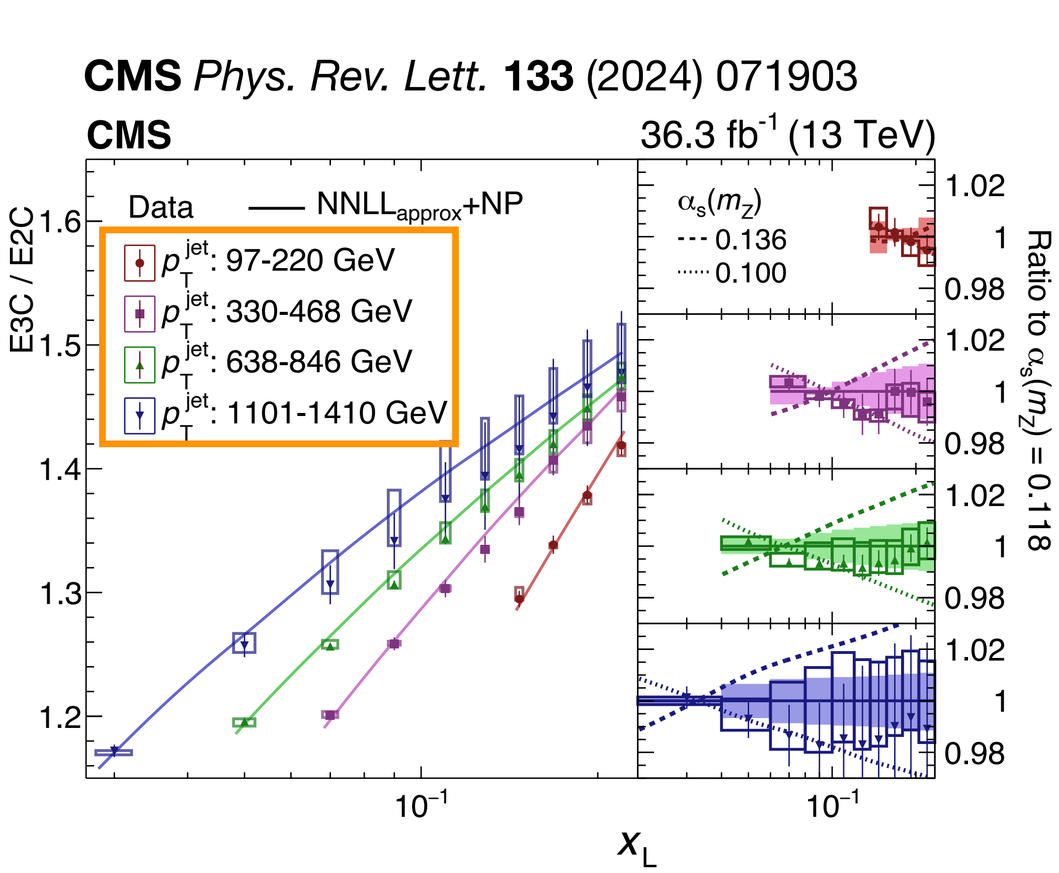

Slope ~ $1/R_L^{1-\gamma_3}$

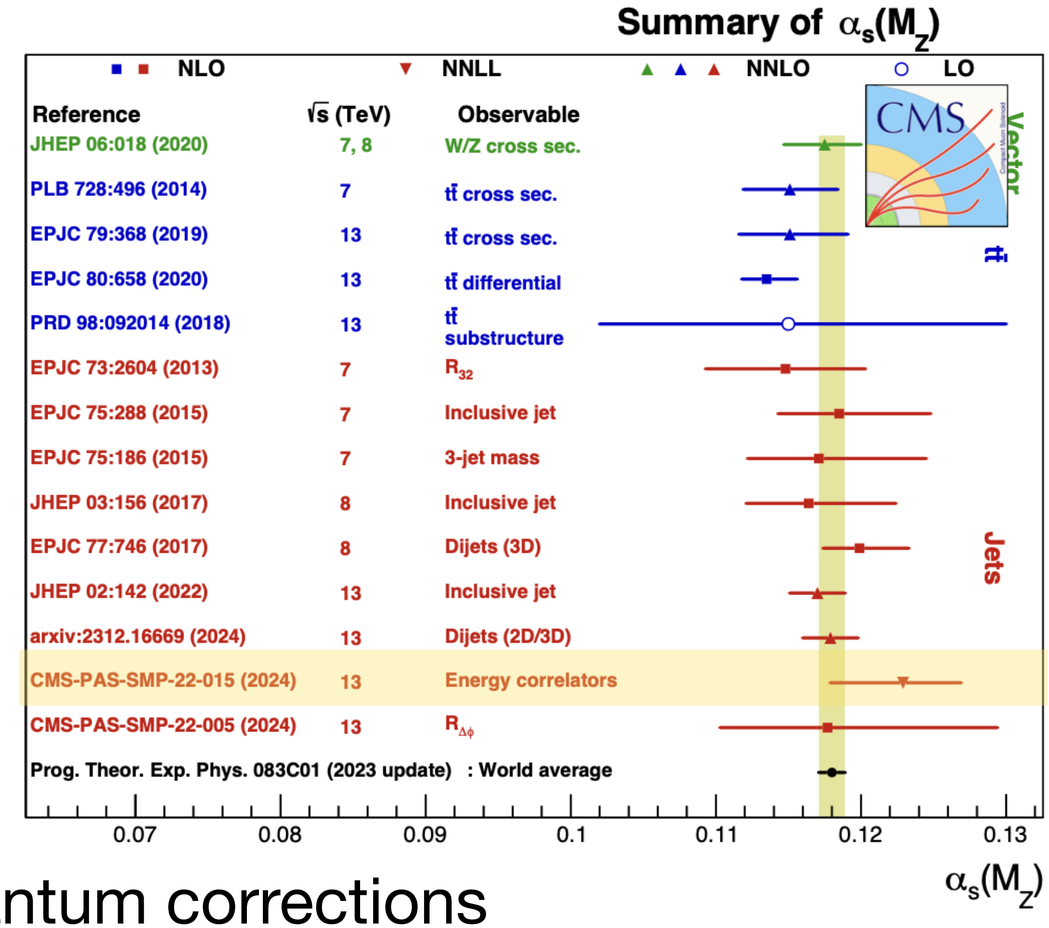
Large-$R_L$ slope: probe the quantum corrections

➡ Anomalous dimensions of EEC ($\gamma 2$) and E3C ($\gamma 3$) operators

➡ EEC/E3C $\propto R_L^{\gamma_3-\gamma_2} \propto \alpha_s \ln R_T$

# Determination of $\alpha_s$



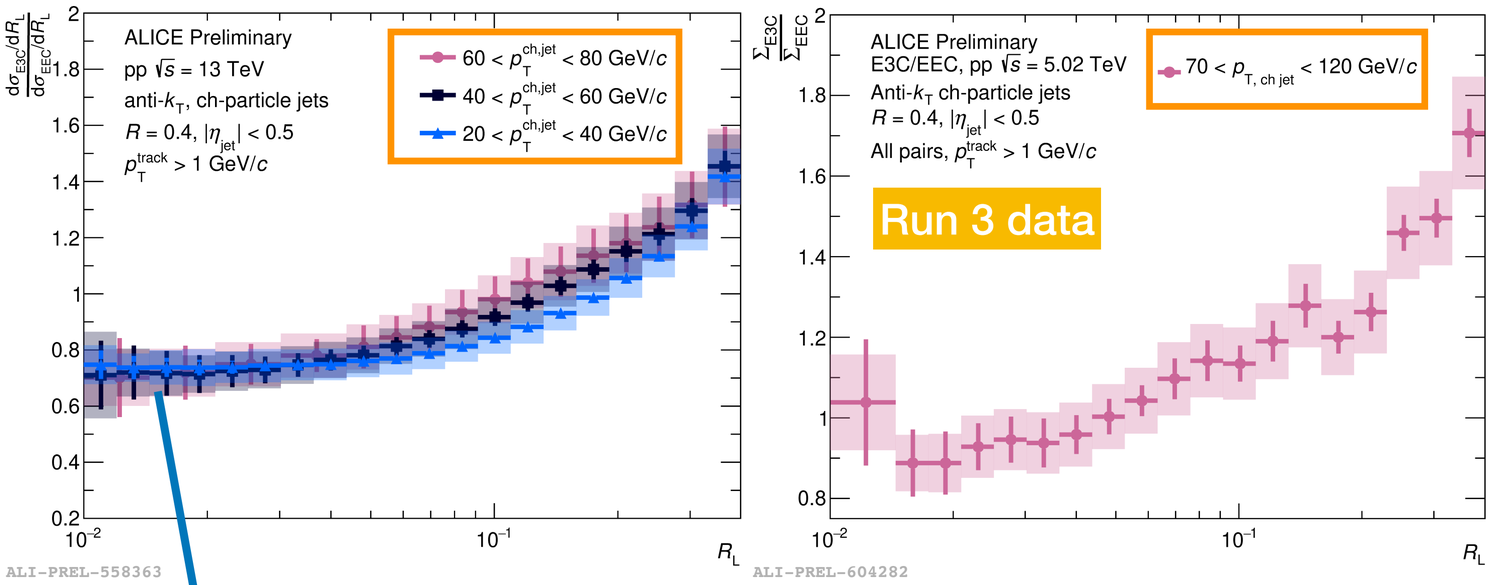




Large-$R_L$ slope: probe the quantum corrections

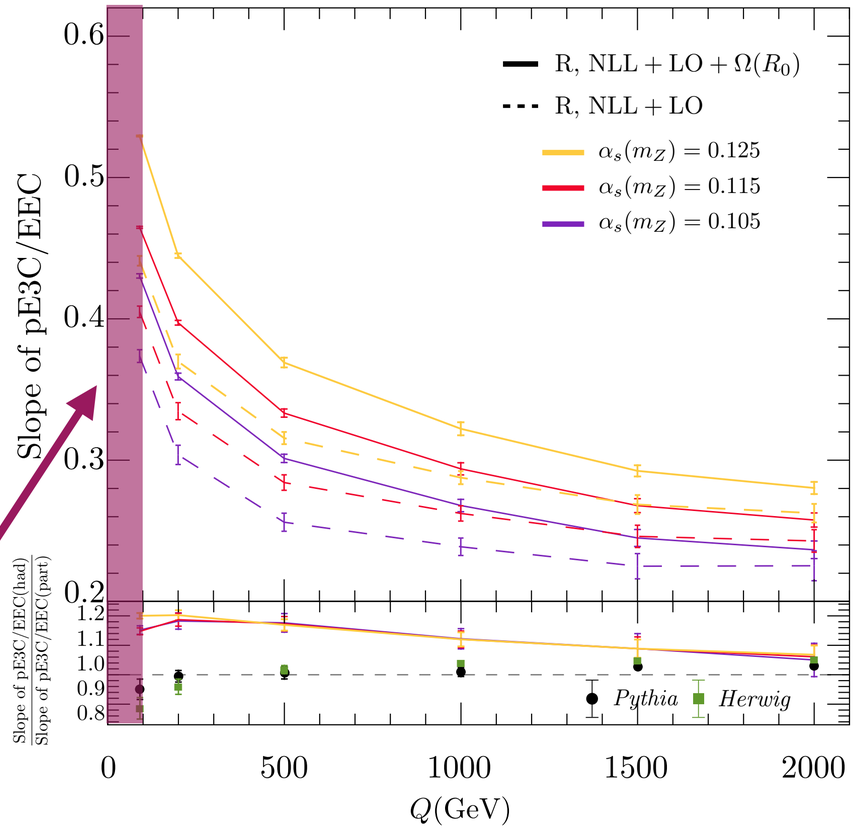
➡ Anomalous dimensions of EEC ($\gamma 2$) and E3C ($\gamma 3$) operators

➡ EEC/E3C $\propto R_L^{\gamma_3-\gamma_2} \propto \alpha_s \ln R_T$

# ALICE: Towards lower jet $p_T$

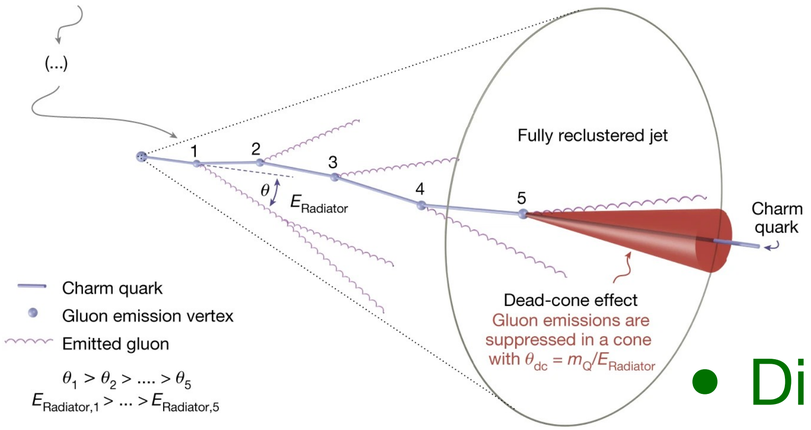



- Charged particle jets down to $p_{T,jet}$ = 20 GeV/$c$
  - ➡ Small $R_L$: identical slope for all $p_{T,jet}$ intervals
  - ➡ Map to $\alpha_s$: access non-perturbative correlations
- Ongoing: map charged to full jets to set energy scale
  - ➡ Track functions, model dependent mapping…



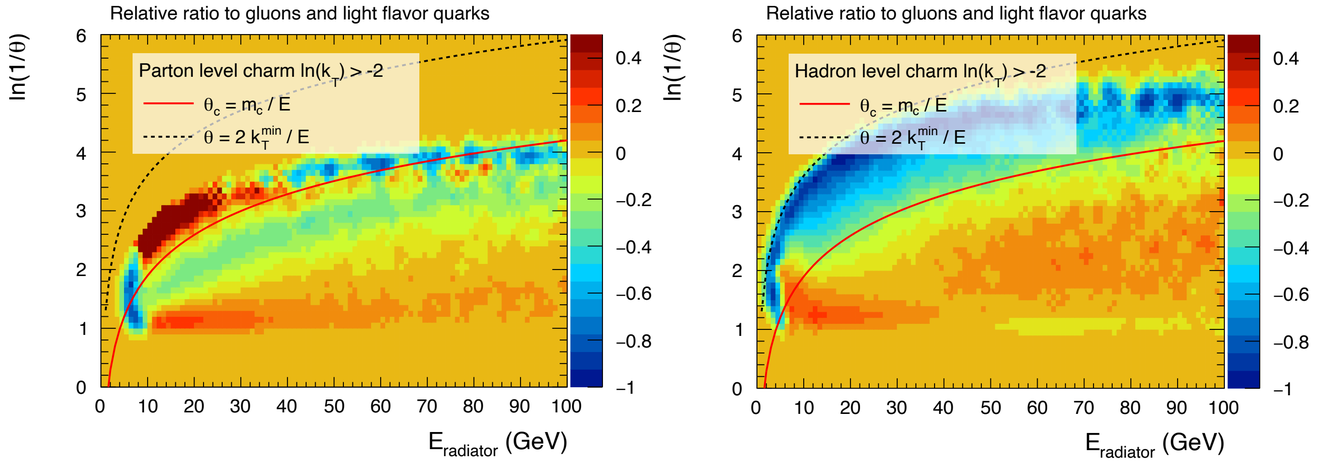

*Phys. Rev. Lett.* **133** (2024) 231902

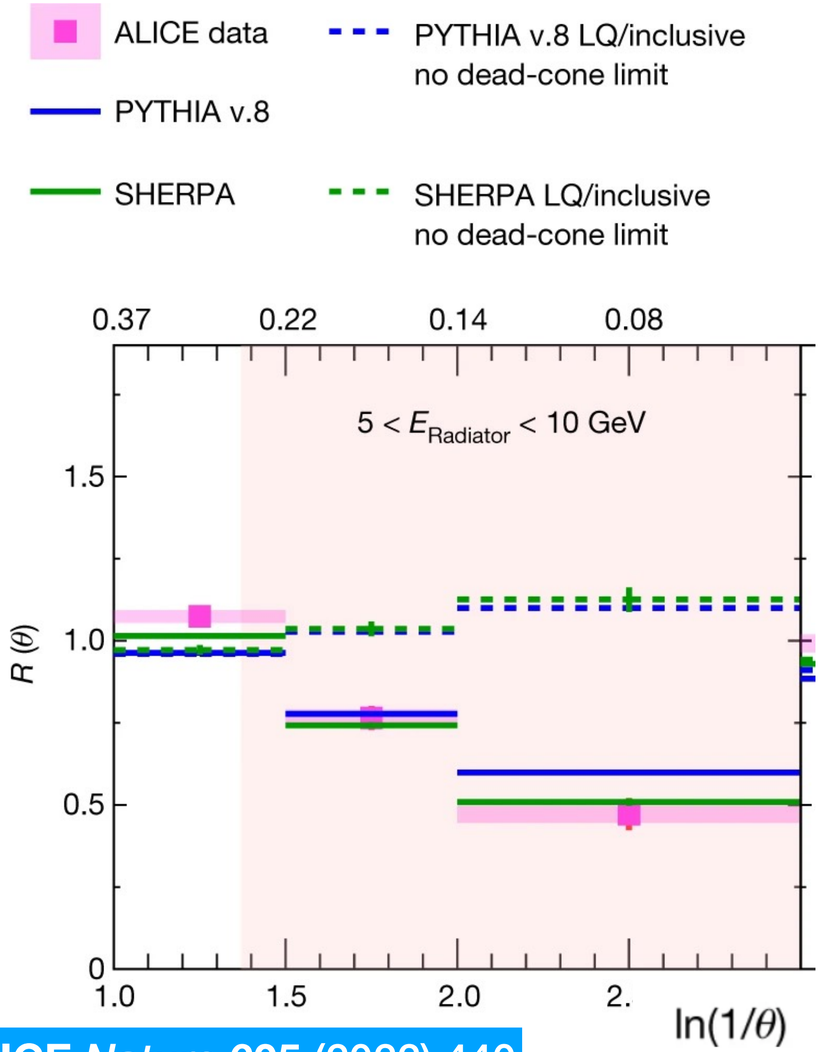
# Dead-cone of heavy quark radiation




One of fundamental properties of QCD: suppression of gluon emissions within cone $\theta < m_Q / E$ — dead-cone effect

- Direct observation for charm quarks in pp — QCD vacuum



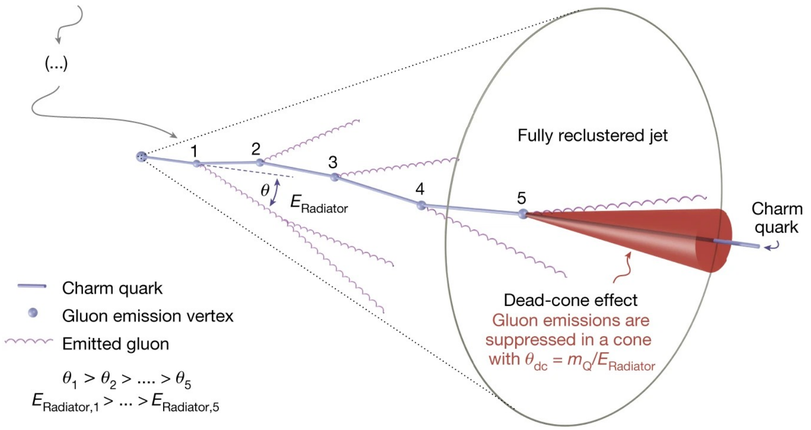




Find a phase space in Laud plan that is less affected by hadronization

**ALICE** *Nature* **605** (2022) 440

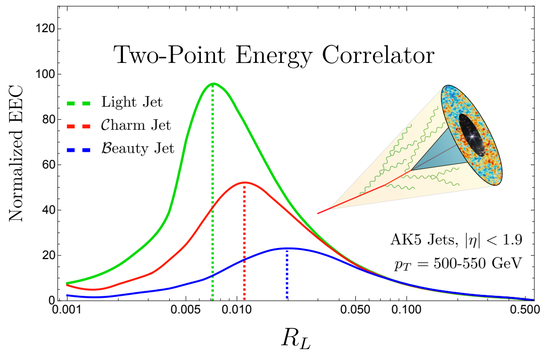
Cunqueiro and Płoskoń *Phys. Rev.* **D99** (2019) 074027

# Dead-cone of heavy quark radiation



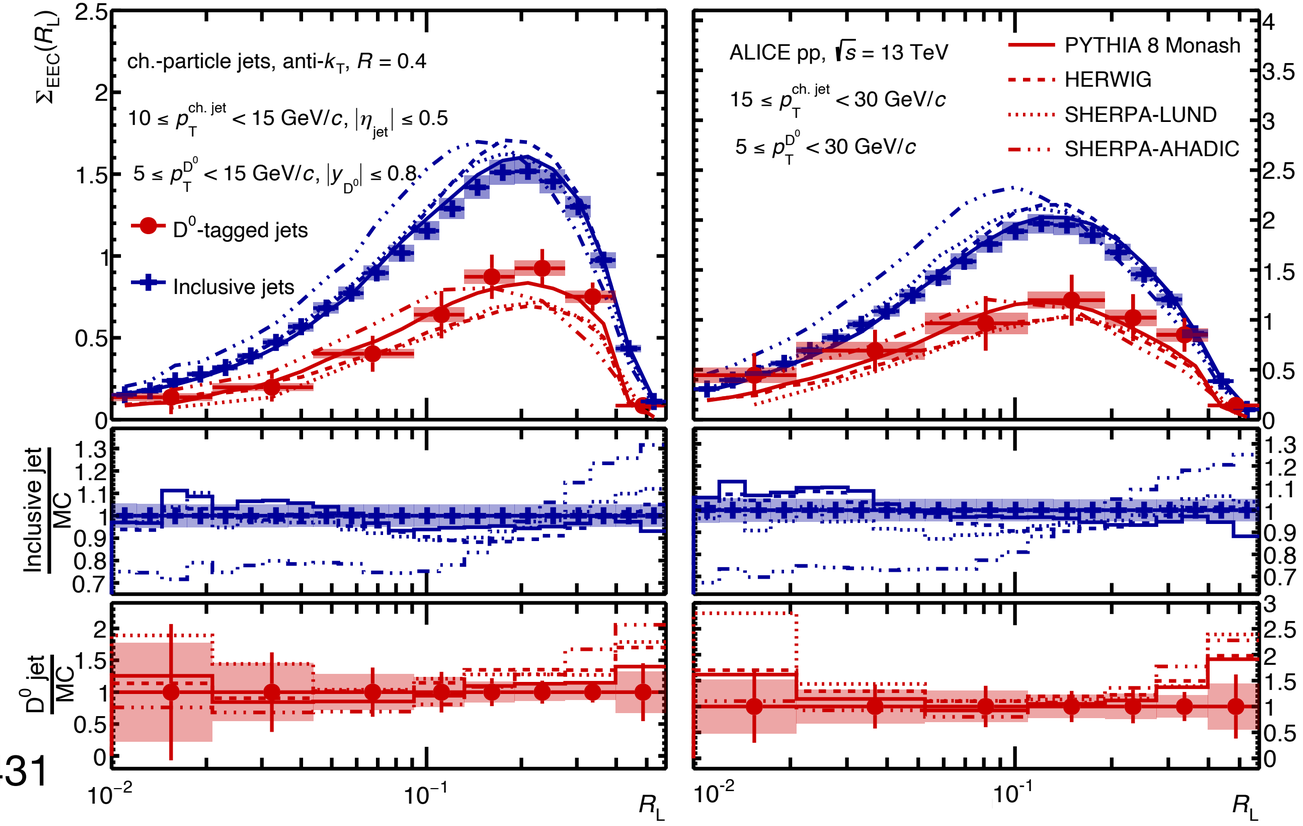

One of fundamental properties of QCD: suppression of gluon emissions within cone $\theta < m_Q / E$ — dead-cone effect

arXiv:2210.09311



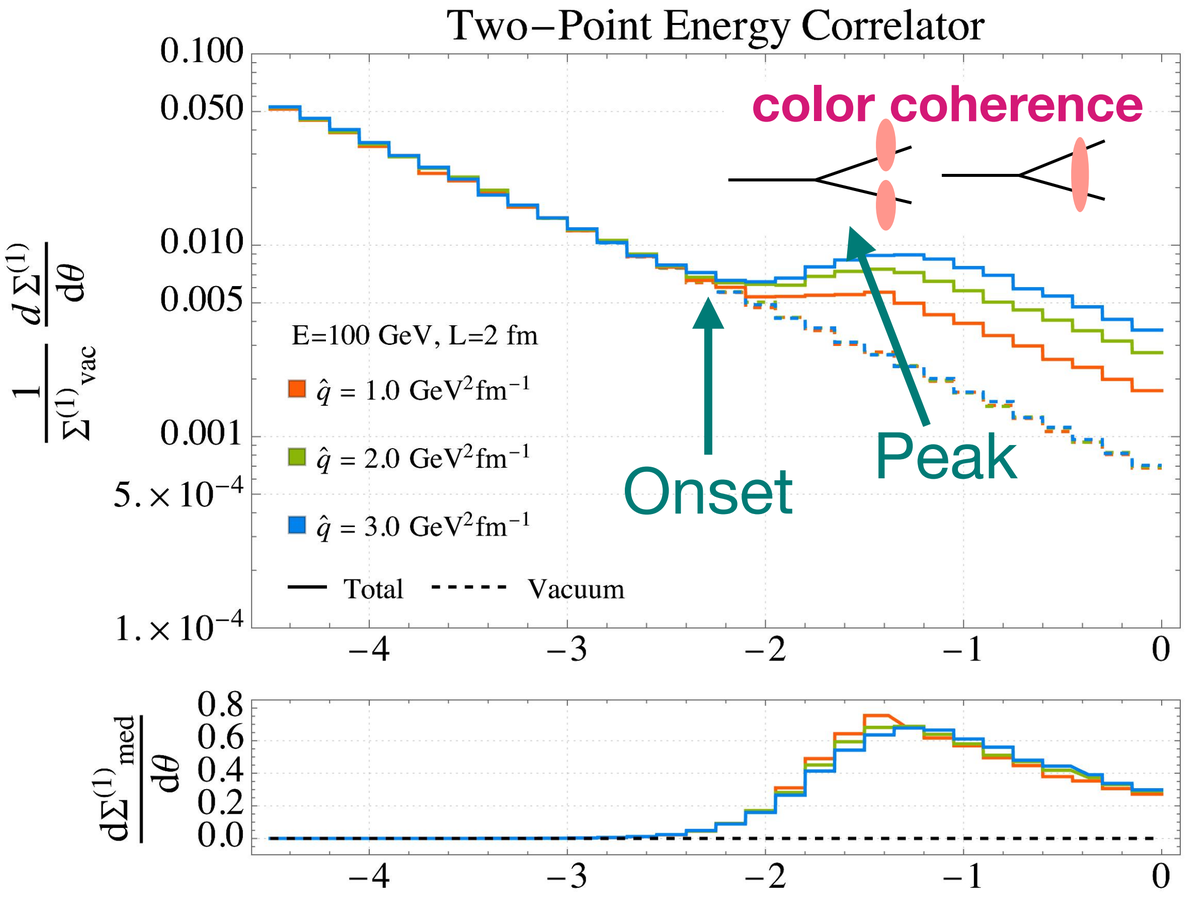

Significant suppression of $D^0$ vs. inclusive jets with similar peak positions

➡ Convolution of Casmir and mass effects



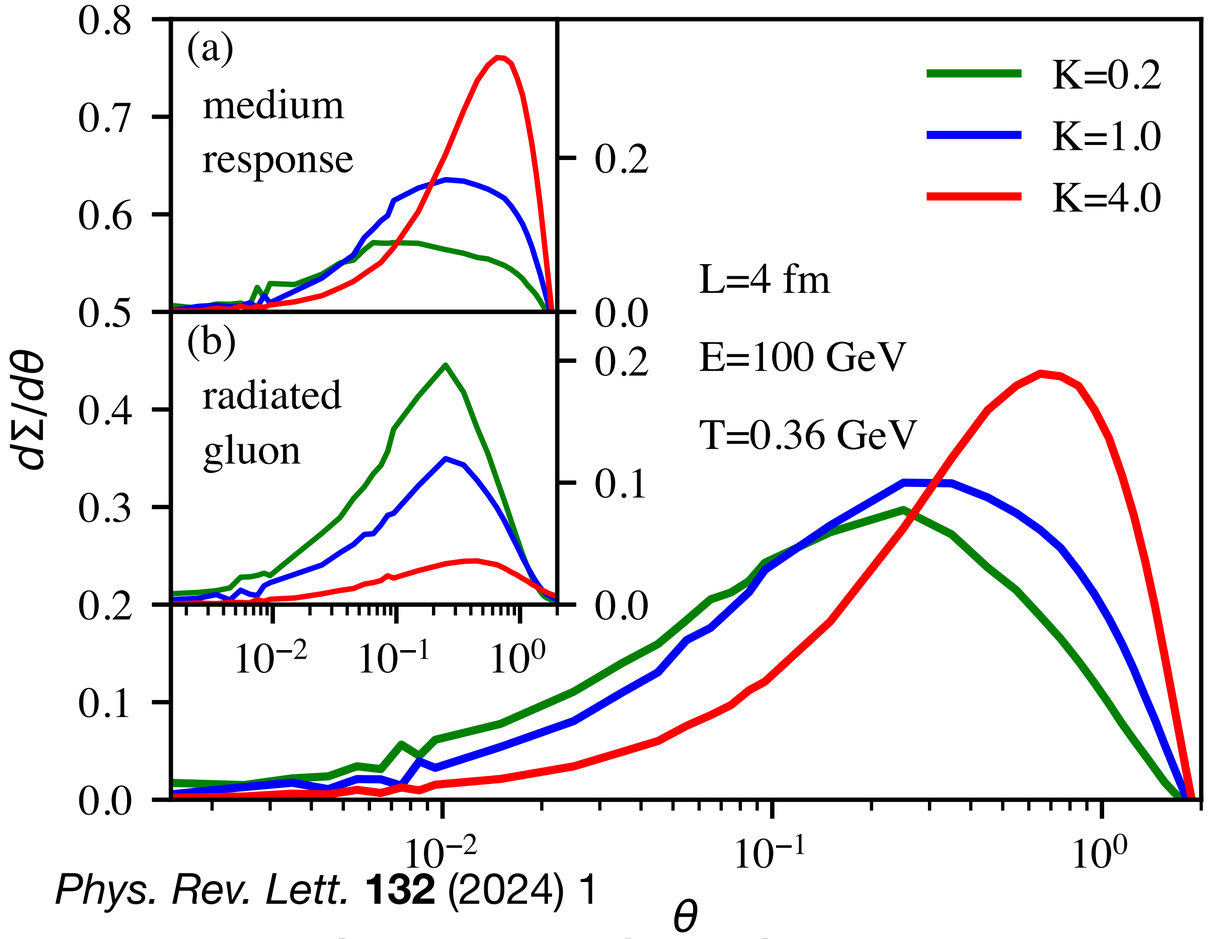

**ALICE** arXiv:2504.03431

# EEC in heavy-ion collisions




*Phys. Rev. Lett.* **130** (2023) 262301

Sensitive to the onset of color coherence



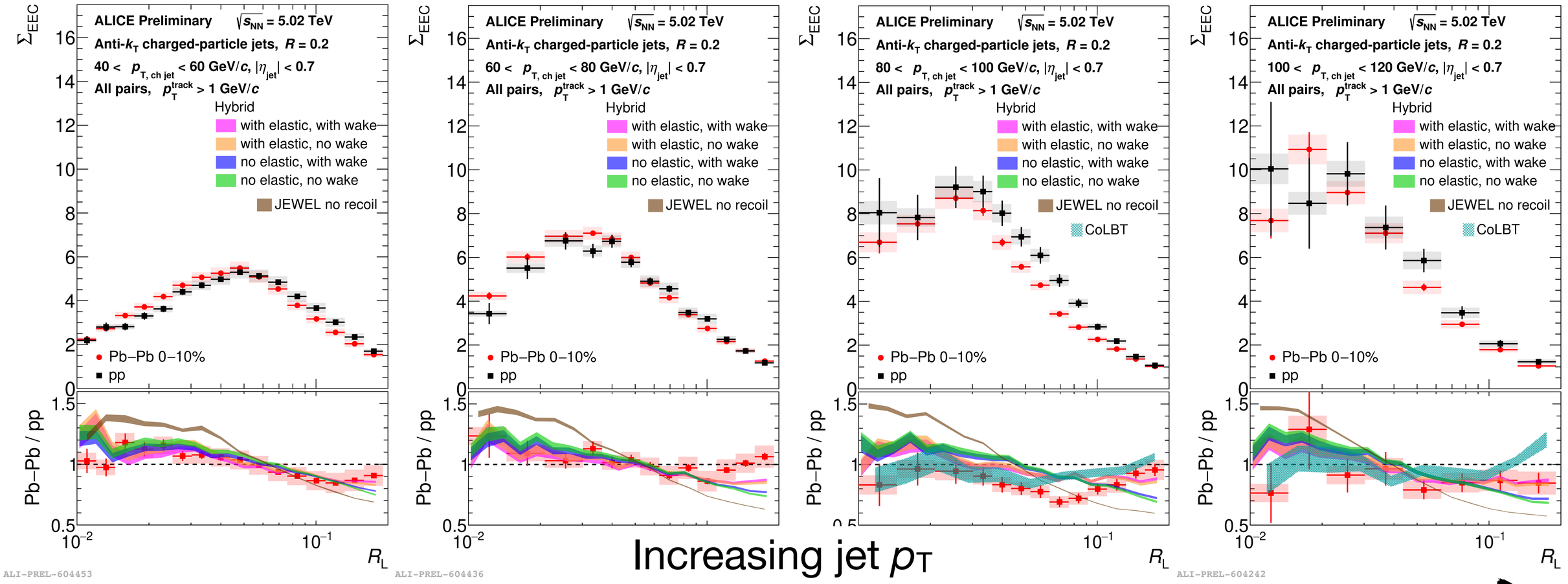

*Phys. Rev. Lett.* **132** (2024) 1

Large angle enhancement due to medium response

**A non-exhaustive list of theoretical activities…**

# EEC in Pb–Pb collisions

See also **CMS** *Phys. Lett.* **B866** (2025) 139556

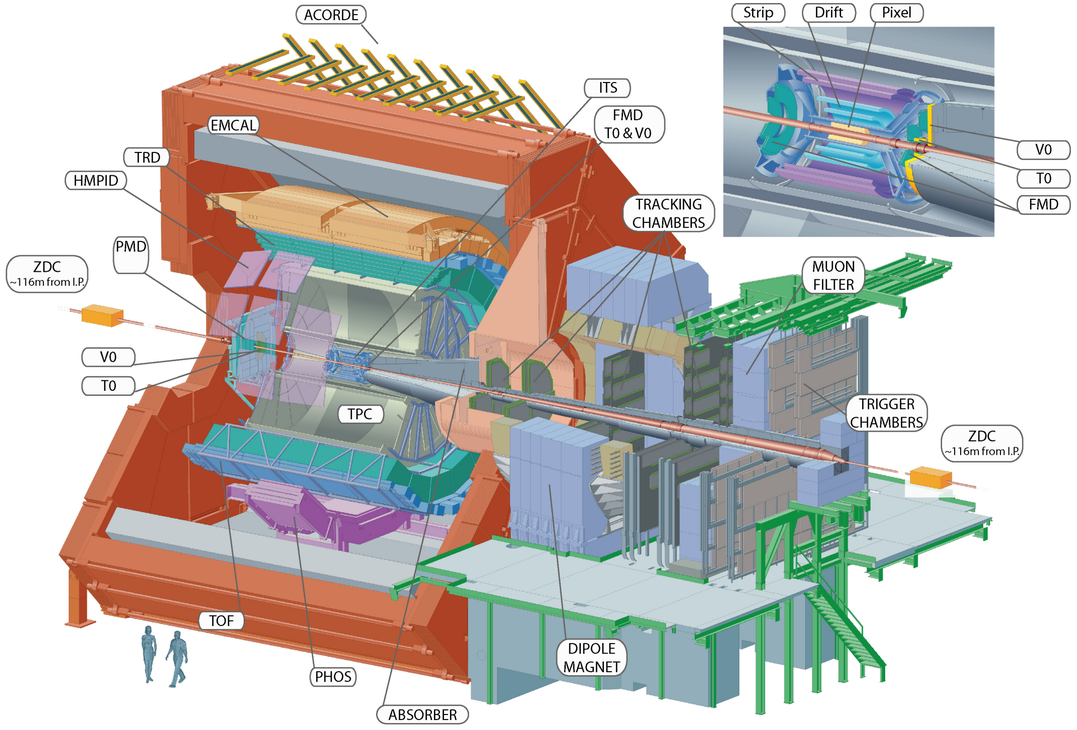


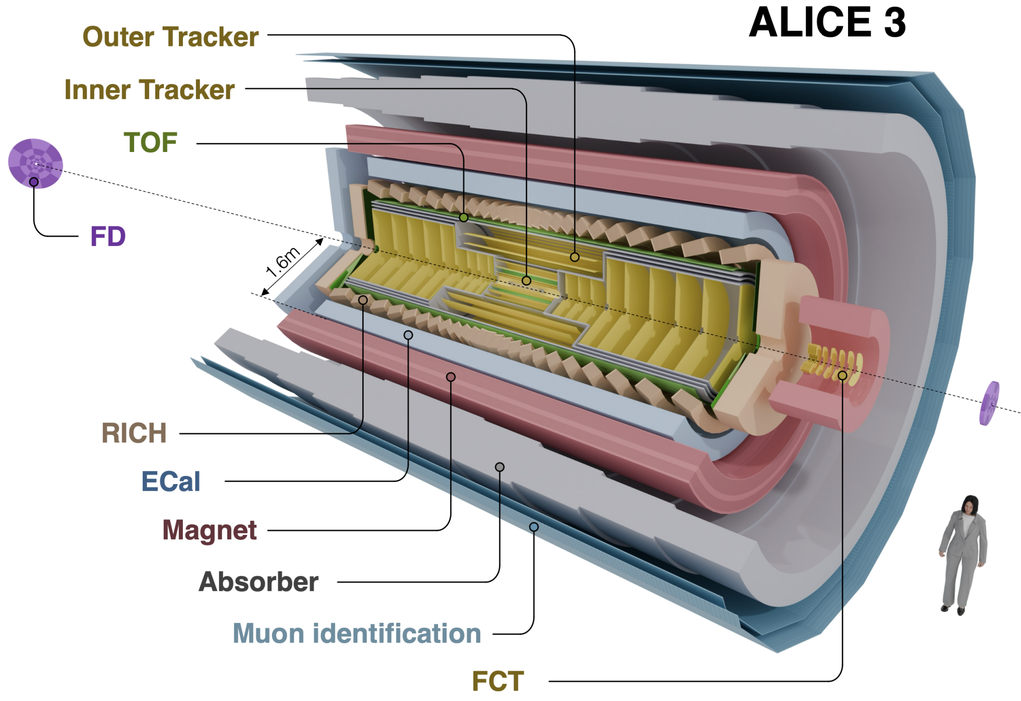

Increasing jet $p_T$

- No significant difference between w and w/o wake, slightly favor elastic scattering?
- JEWEL consistently overestimates the low-$R_L$ enhancement
- CoLBT does well at low-$R_L$ but doesn't capture large-$R_L$ suppression

# Not conclusion

| 2010-2013 | 2015-2018 | 2022-2026 | 2030-2033 | 2036- |
|---|---|---|---|---|
| Run 1 | LS1 Run 2 | LS2 Run 3 | LS3 Run 4 | LS4 Run 5 |
| ALICE 1 | | ALICE 2 | ALICE 2.1 | ALICE 3 |



# Backup

# Beyond LHC Run 4 — Shopping list

| 2010-2013 | | 2015-2018 | | 2022-2026 | | 2030-2033 | | 2036- |
|---|---|---|---|---|---|---|---|---|
| Run 1 | LS1 | Run 2 | LS2 | Run 3 | LS3 | Run 4 | LS4 | Run 5 |
| ALICE 1 | | | ALICE 2 | | ALICE 2.1 | | ALICE 3 | |

- B-hadron production and flow
- Multicharm baryon production
- Angular and momentum correlations of charm meson pairs
- γ+jet correlations for jet quenching
- Production of χc1,2 and χc1(3872)
- Net-proton event-by-event fluctuations
- Dielectron production and elliptic flow
- Low-$p_T$ photon production at forward rapidity
- Axion-like particle searches in γγ →γγ.

