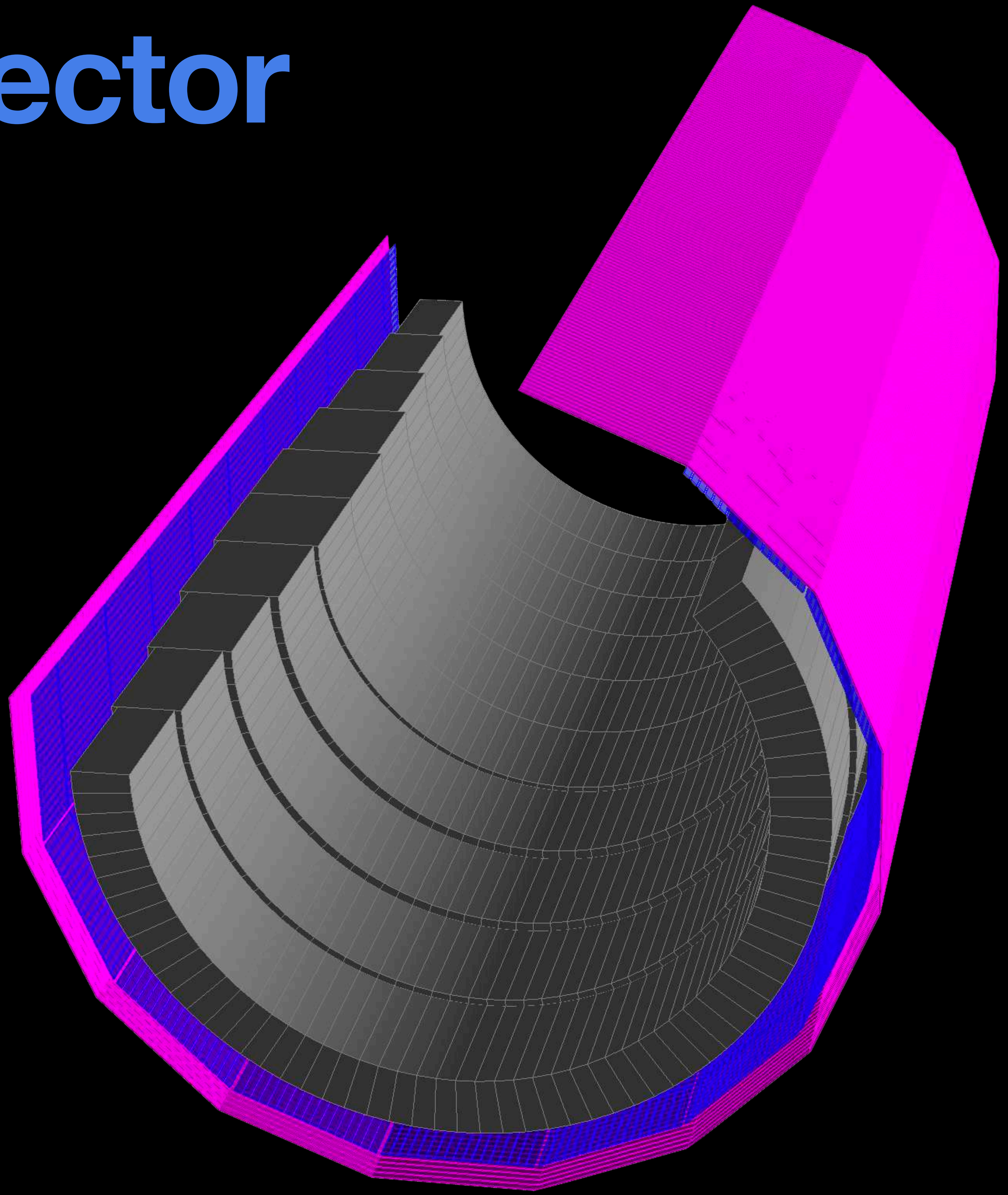
MID: a muon detector for the ALICE 3 upgrade project

Jesús Eduardo Muñoz Méndez,
for the ALICE collaboration

XXXVIII Annual Meeting of the
Division of Particles and Fields

5-7 June, 2024



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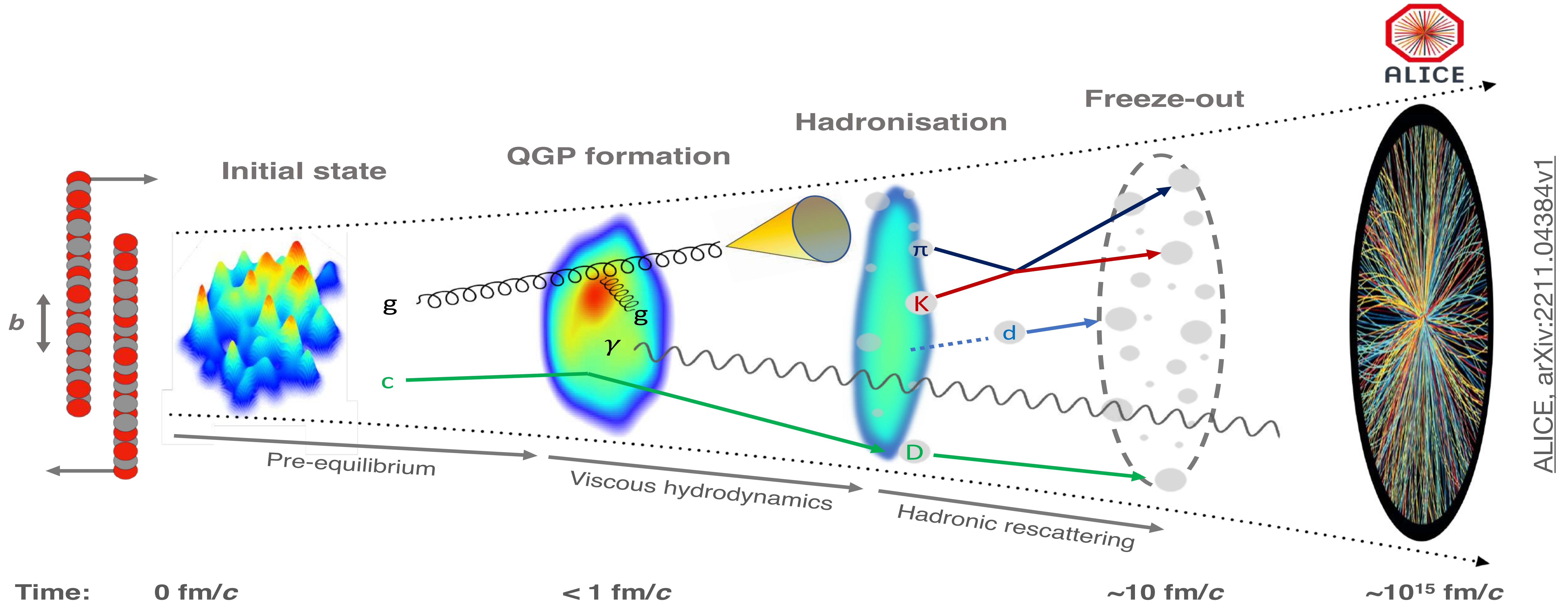
ALICE

Evolution of a heavy-ion collision

- Right after a relativistic heavy-ion collision, processes involving high momentum transfer take place, leading to the creation of jets and heavy quarks
- As the system evolves, LQCD predicts the formation of a medium where quarks and gluons are no longer confined within hadrons: **the quark-gluon plasma (QGP)**
- As QGP expands and cools down, partons recombine to form hadrons
- The resulting particles can be studied using detectors to infer the properties of QGP



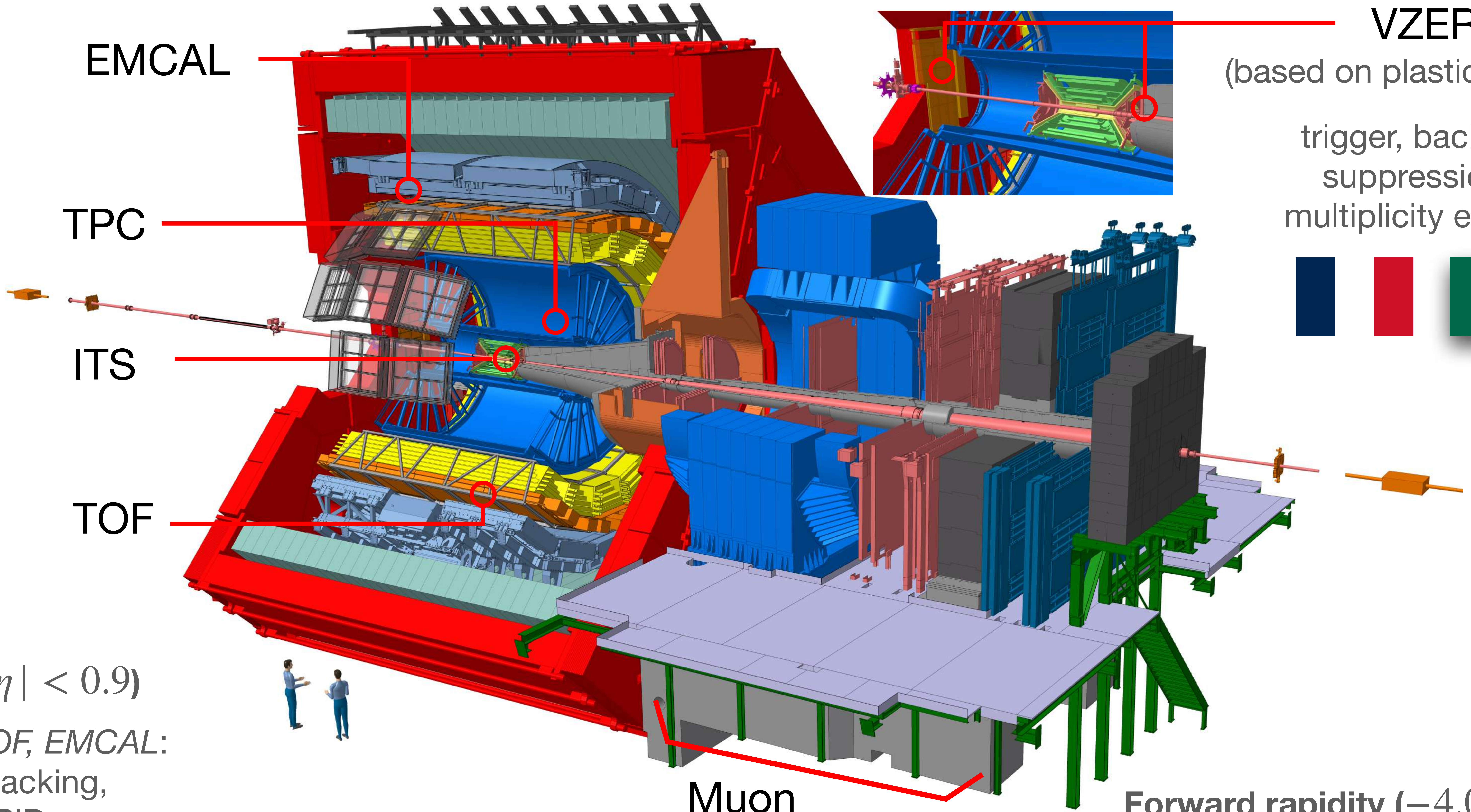
ALICE Collaboration

The aim of **ALICE** is to study the physics of strongly interacting matter at the **highest energy densities reached so far in the laboratory**

39 countries, 174 institutes, 1927 members

Active participation of different mexican institutes

ALICE in Run 2



trigger, background suppression and multiplicity estimation

Midrapidity ($|\eta| < 0.9$)

- *ITS, TPC, TOF, EMCAL*: Vertexing, Tracking, Multiplicity, PID

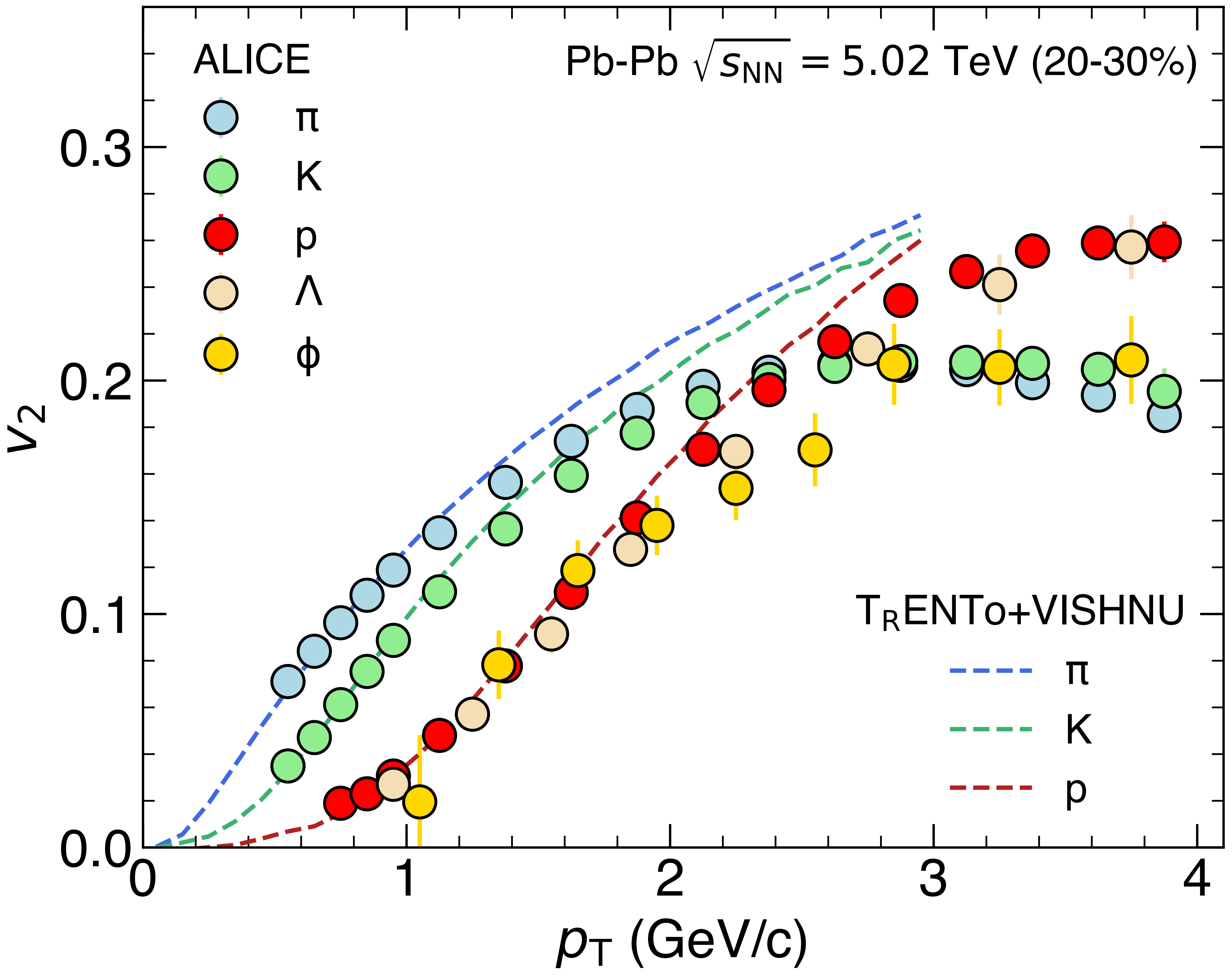
Forward rapidity ($-4.0 < \eta < -2.5$)

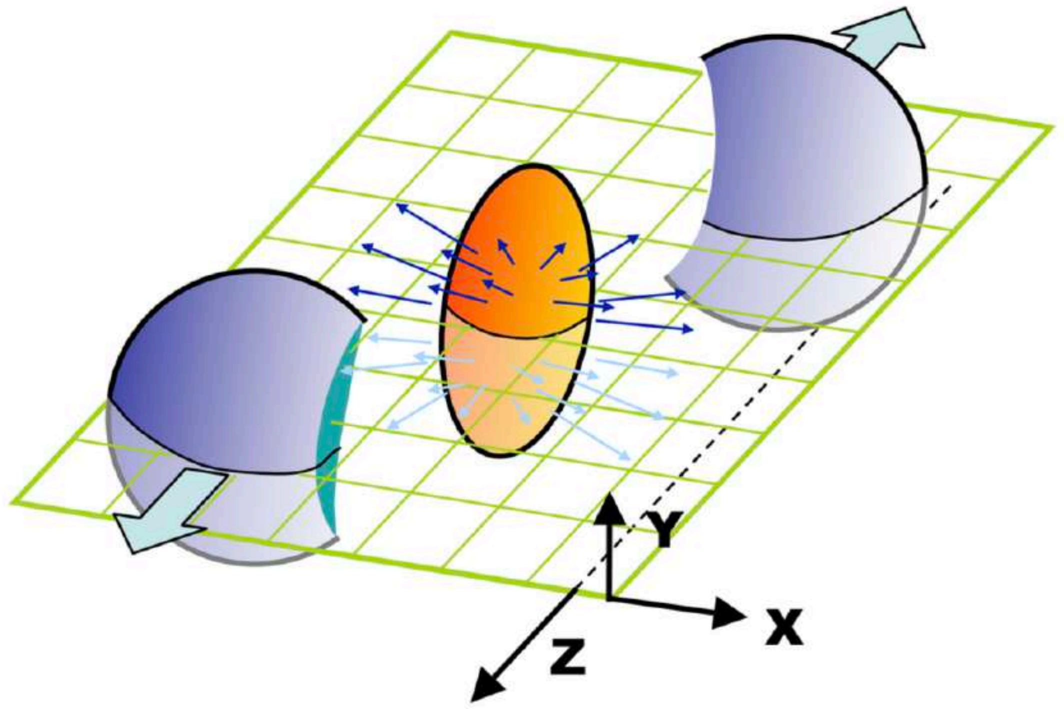
- $J/\psi \to \mu^+\mu^-$

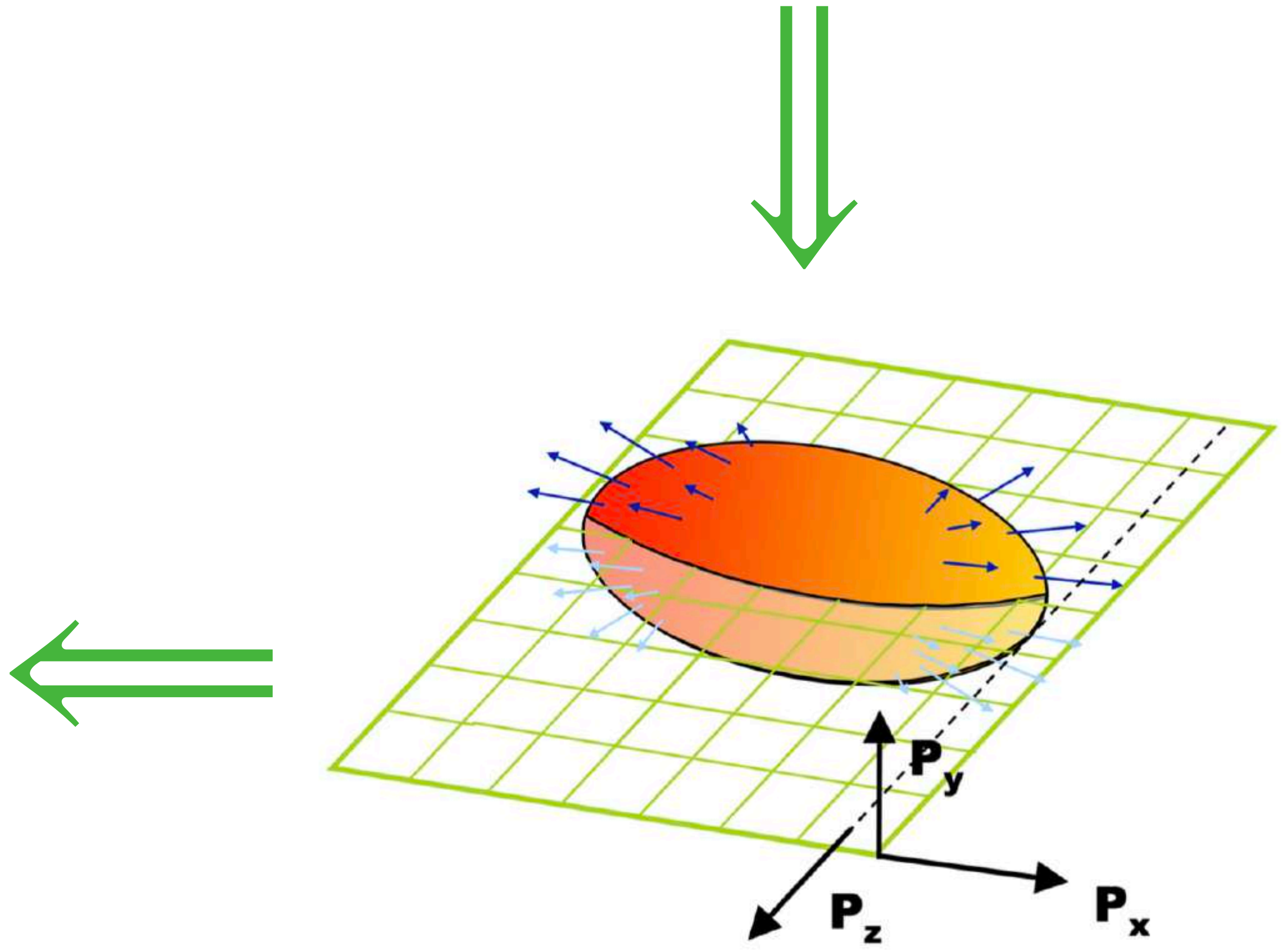
QGP evidences in Pb-Pb collisions

Hydrodynamic models of a **perfect fluid** offer a good description of the anisotropic distribution of final particles

M. Arslandok et. al., arXiv:2303.17254







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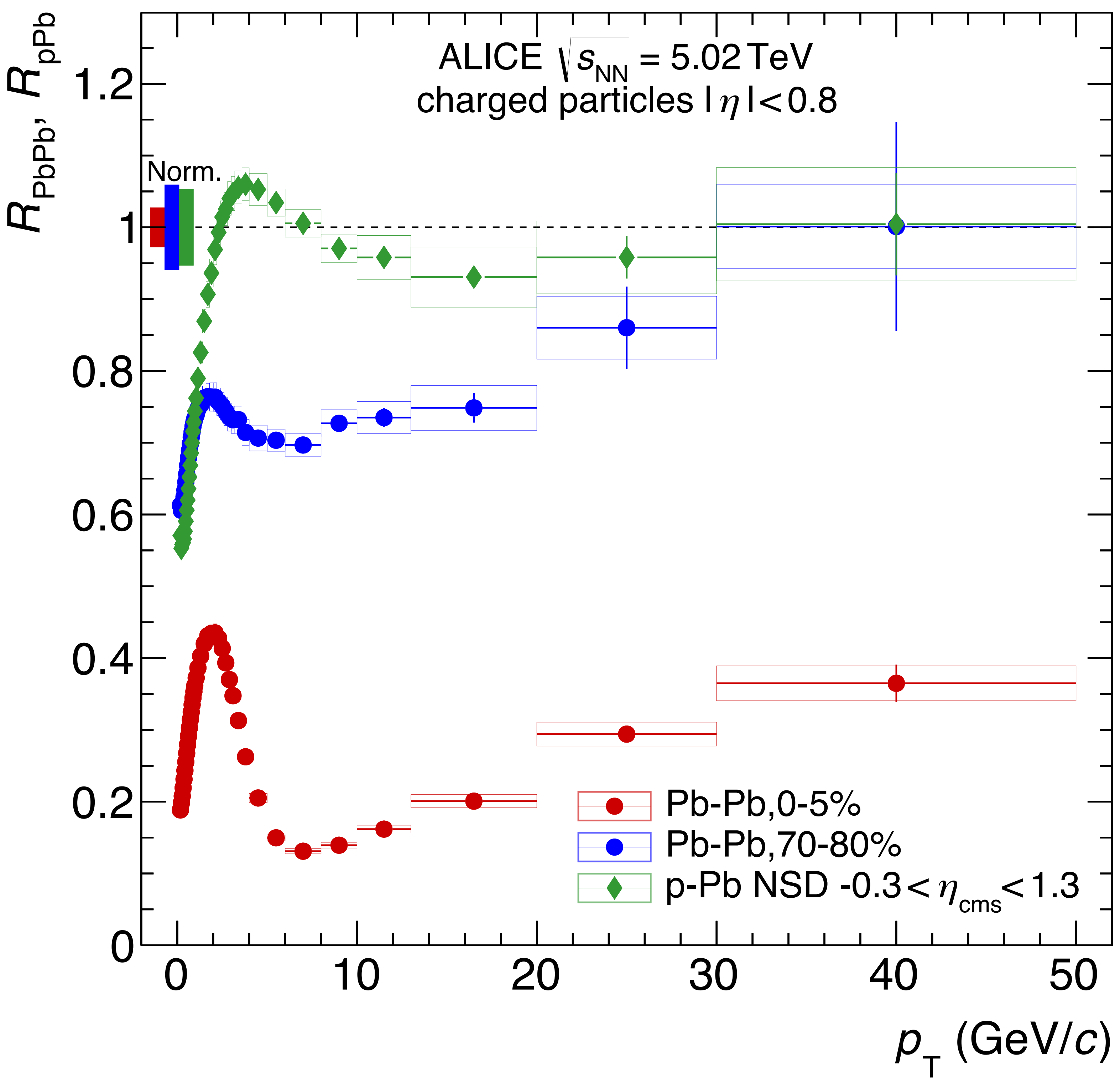
The nuclear modification factor is a measure of the **suppression or enhancement** of jets or heavy-flavor hadrons due to the interaction of the parent parton with the medium

ALICE, arXiv:2211.04384v1



$$R_{AA}(p_T) = \frac{1}{\langle N_{col} \rangle} \frac{dN^{AA}/dp_T}{dN^{pp}/dp_T} \rightarrow \frac{\text{QGP-effects}}{\text{absence of QGP}}$$

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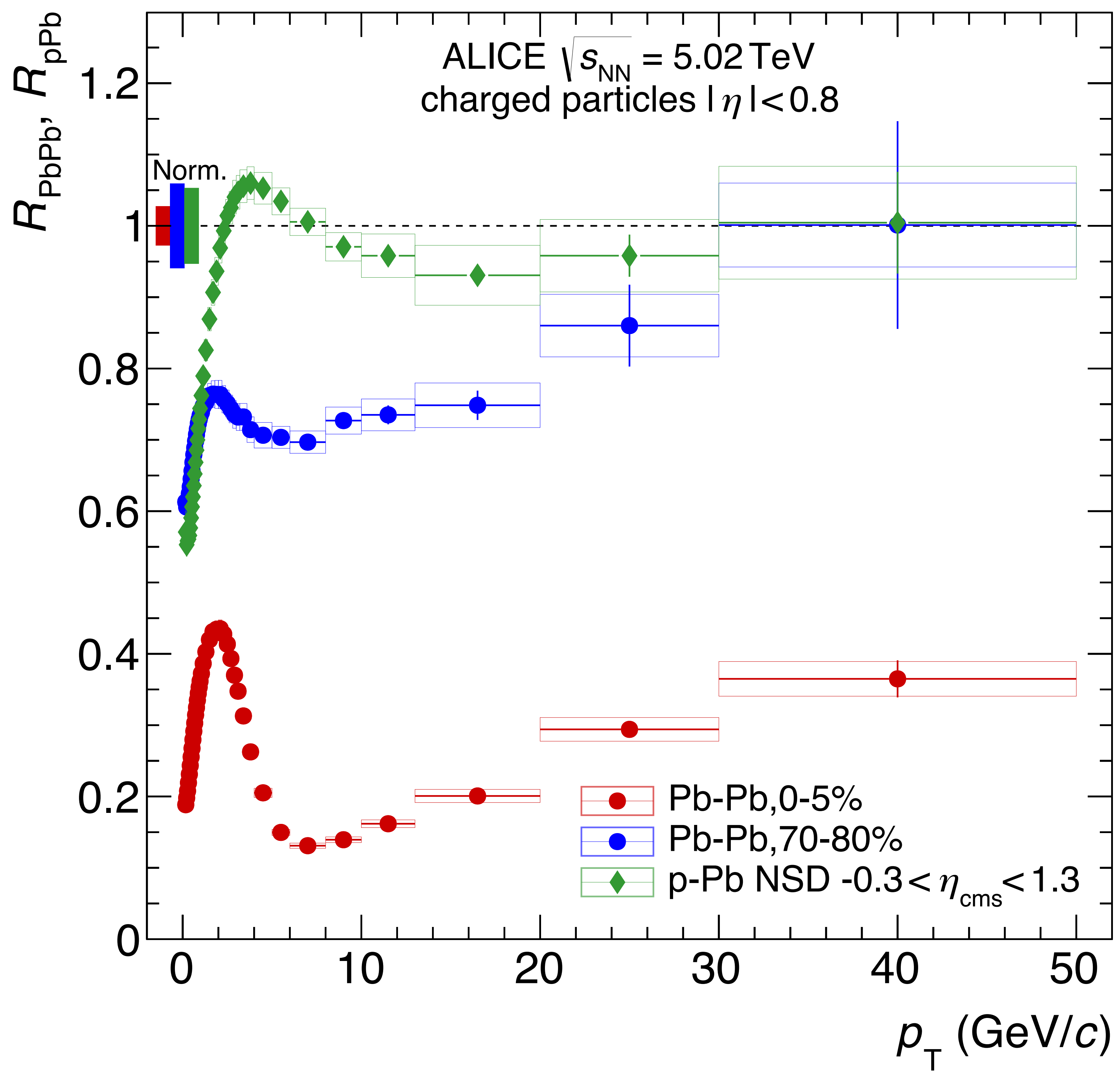
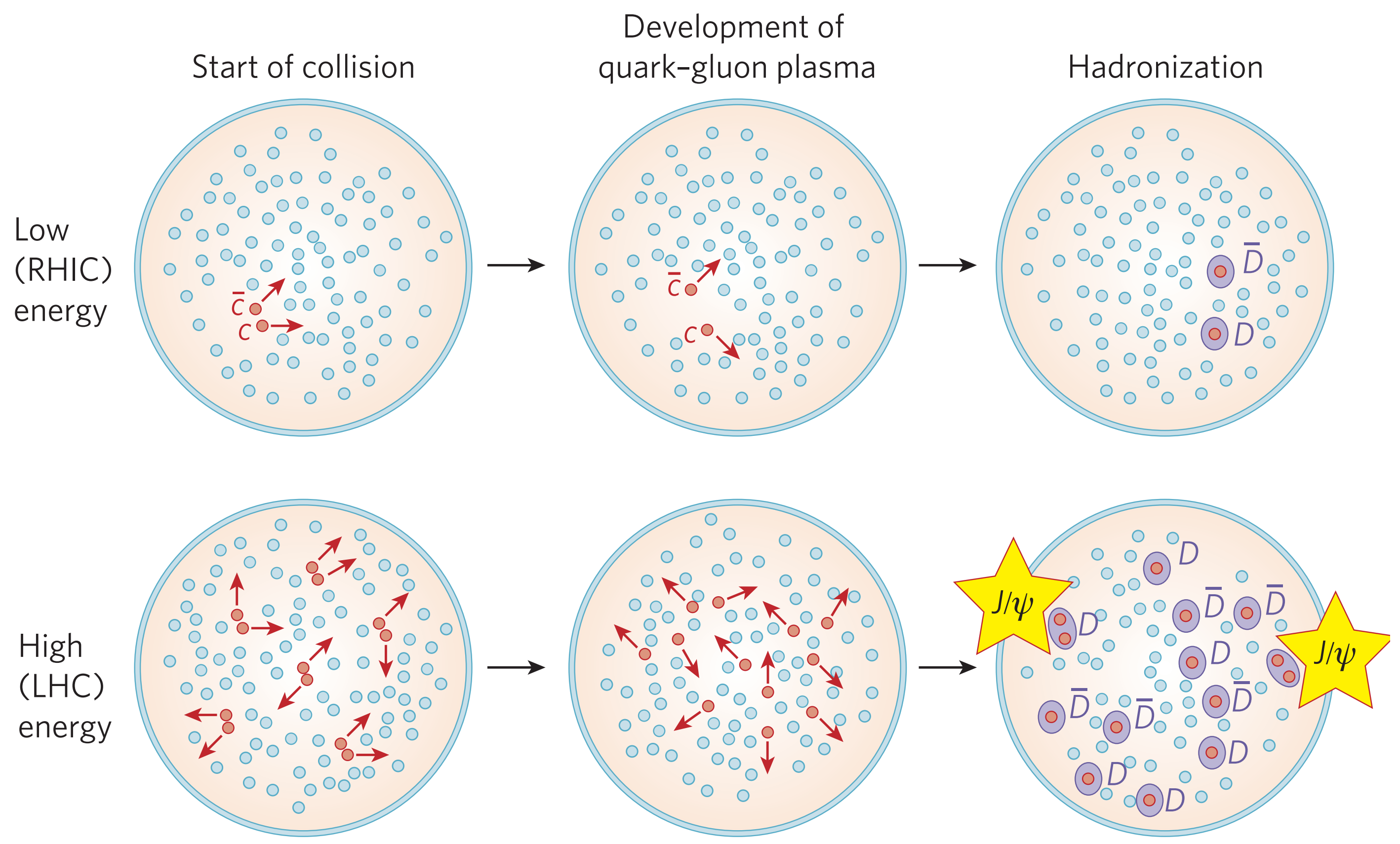
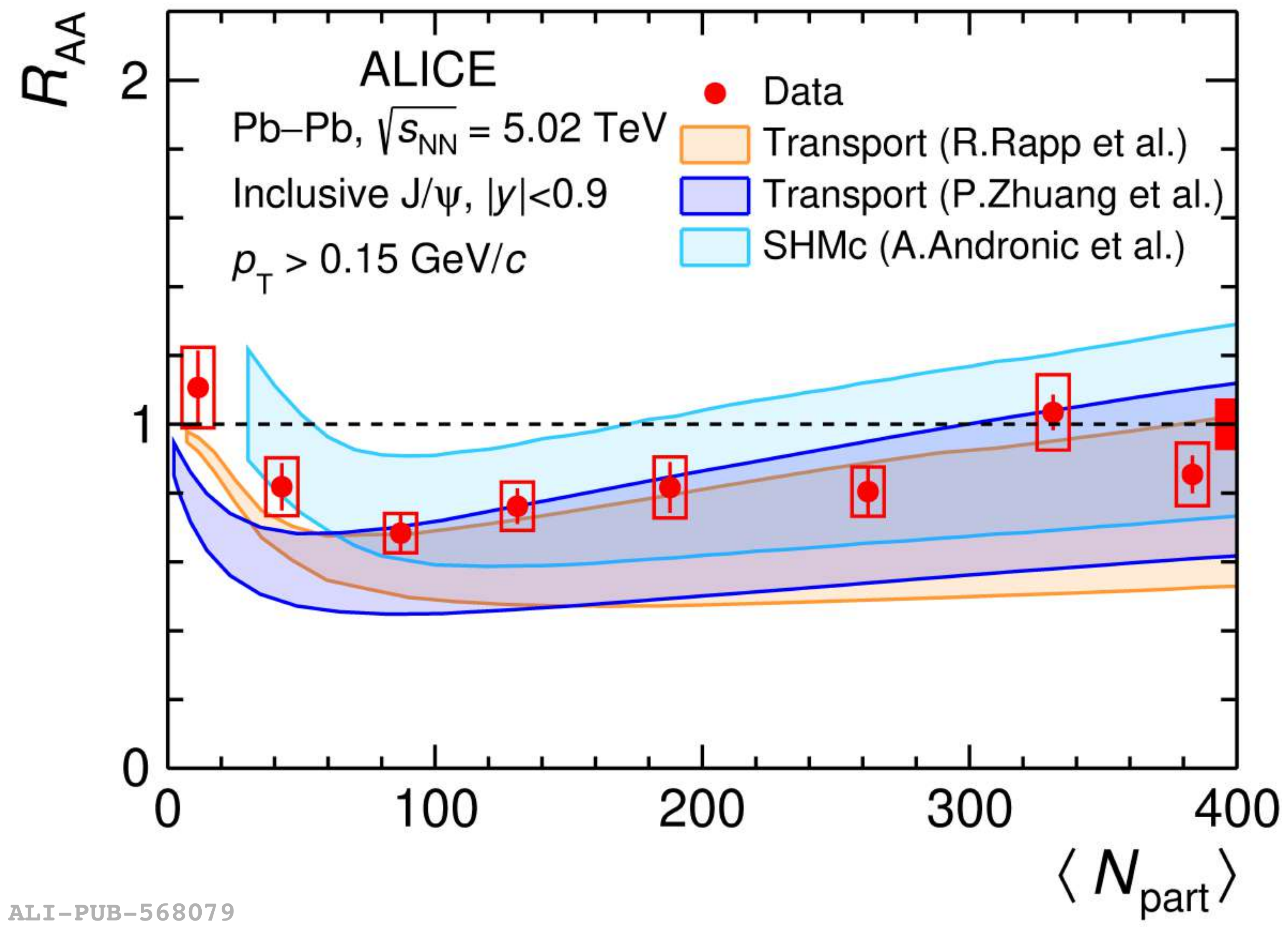


P. Braun-Munzinger et al., Nature 448, 302 (2007)



ALICE, Phys.Lett.B 849 (2024) 138451



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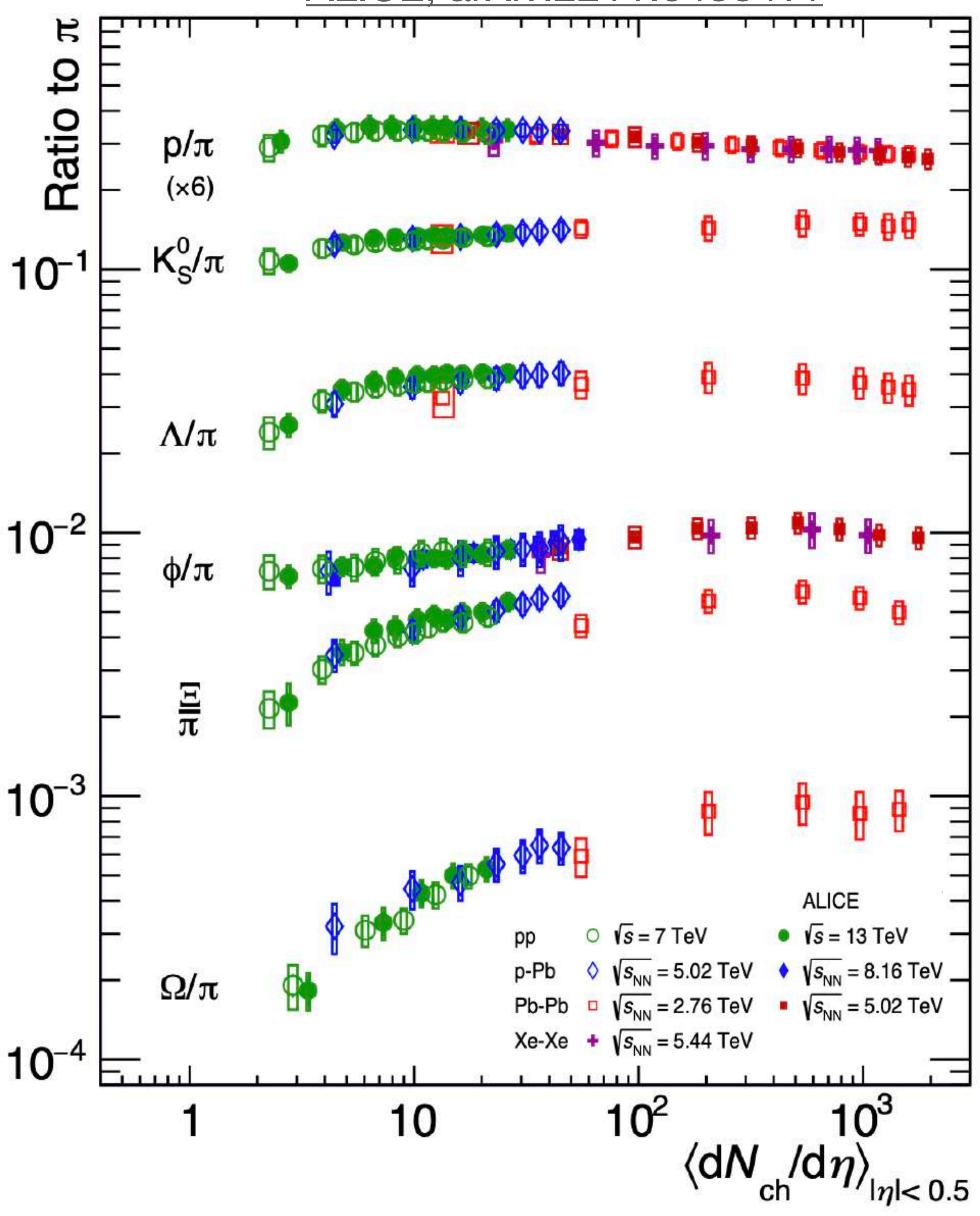
ALICE, arXiv:2211.04384v1

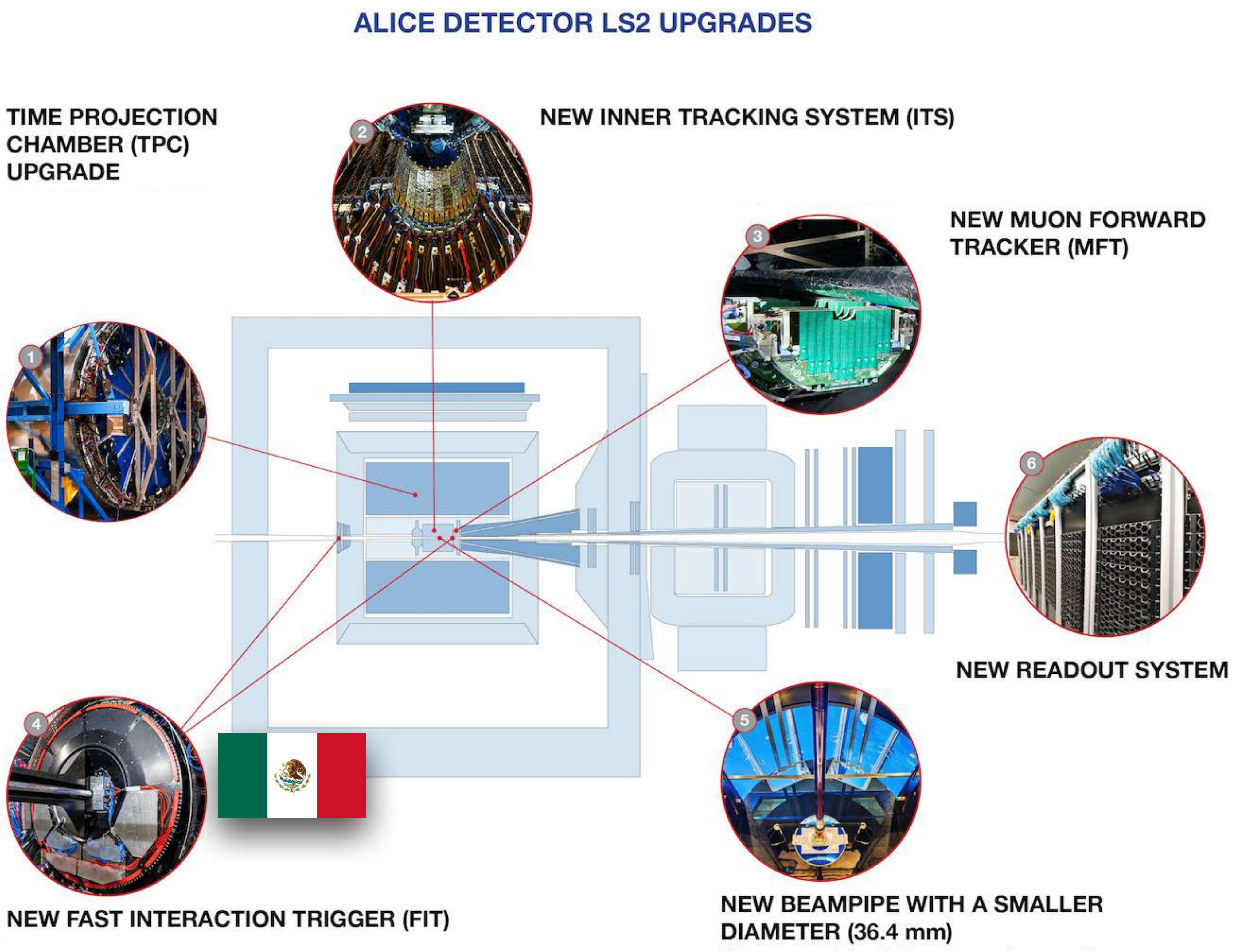
Thermal gluons have enough energy to produce $s\bar{s}$ pairs, **enhancing** the production of strange hadrons

ALICE, arXiv:2211.04384v1

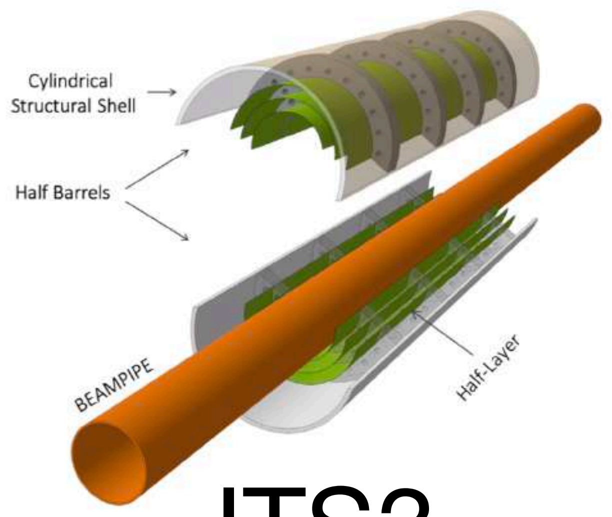


ALICE in Run 3 and 4

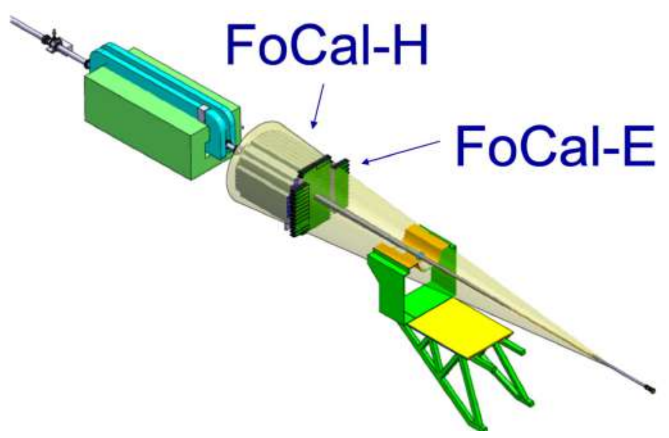
ALICE in current Run 3:



Upcoming upgrades for Run 4:



ITS3



FoCal

Several upgrades to the detector have been done, and some are on the way..

Among the expected measurements during Runs 3 and 4 we have

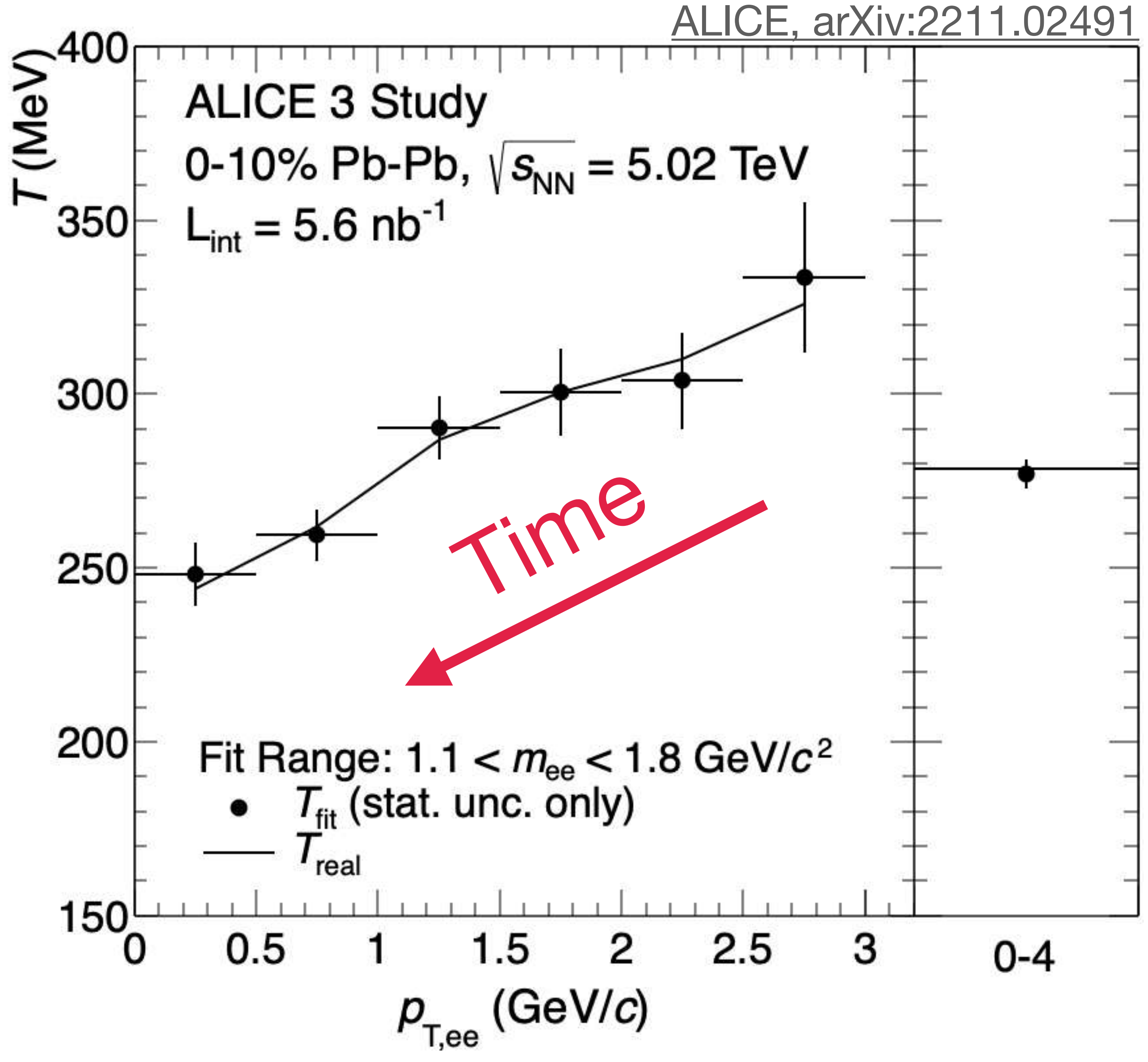
- Medium effects on single heavy-flavour hadrons
- Time averaged thermal QGP radiation
- Collective effects from small to large systems

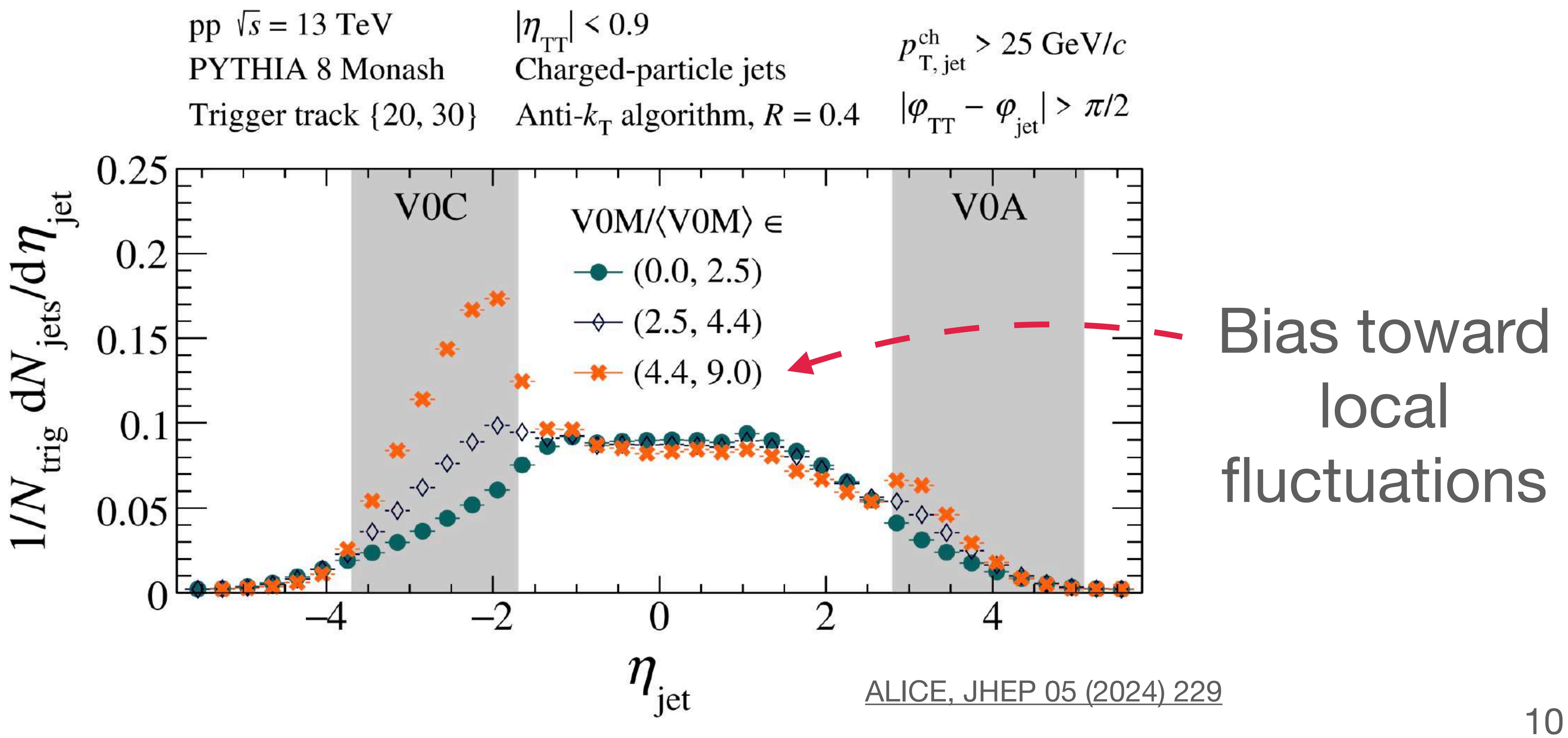
Nonetheless, some fundamental questions will still remain open…

Open questions after Run 4

- More detailed evolution of the QGP through termal radiation
- Evidences of QGP formation in small systems
- Formation and interaction of exotic hadronic states
- Transport and hadronization of heavy flavor hadrons in the medium: azimuthal distributions, n-parton scattering dynamics, multi-charm baryons (Ξ_{cc}^{++} and Ω_{cc}^{+}), suppression and recombination of charm and beauty quarks

ALICE, arXiv:2211.02491





ALICE, JHEP 05 (2024) 229

Open questions after Run 4

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- **Formation and interaction of exotic hadronic states**
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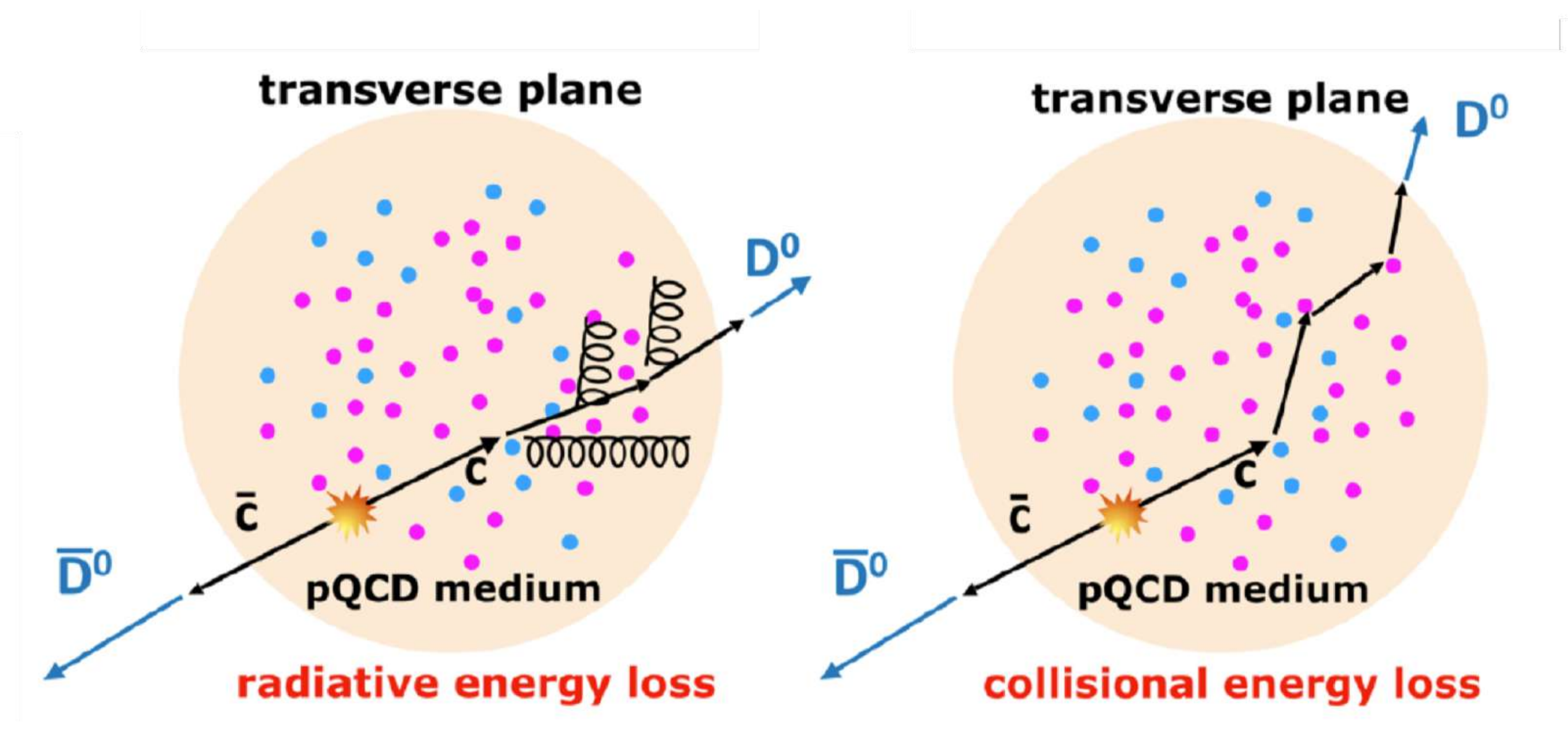
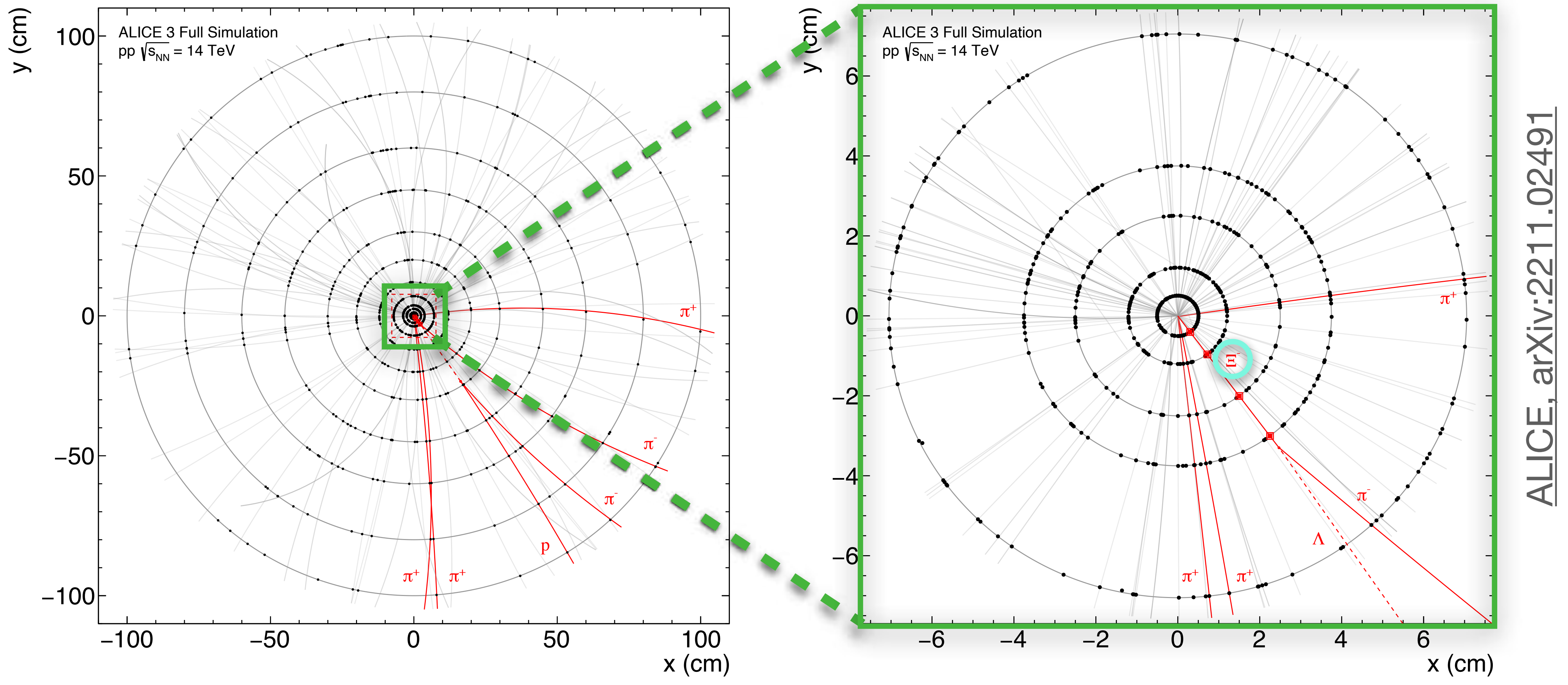


Higher purity and signal efficiency with a bigger acceptance is needed

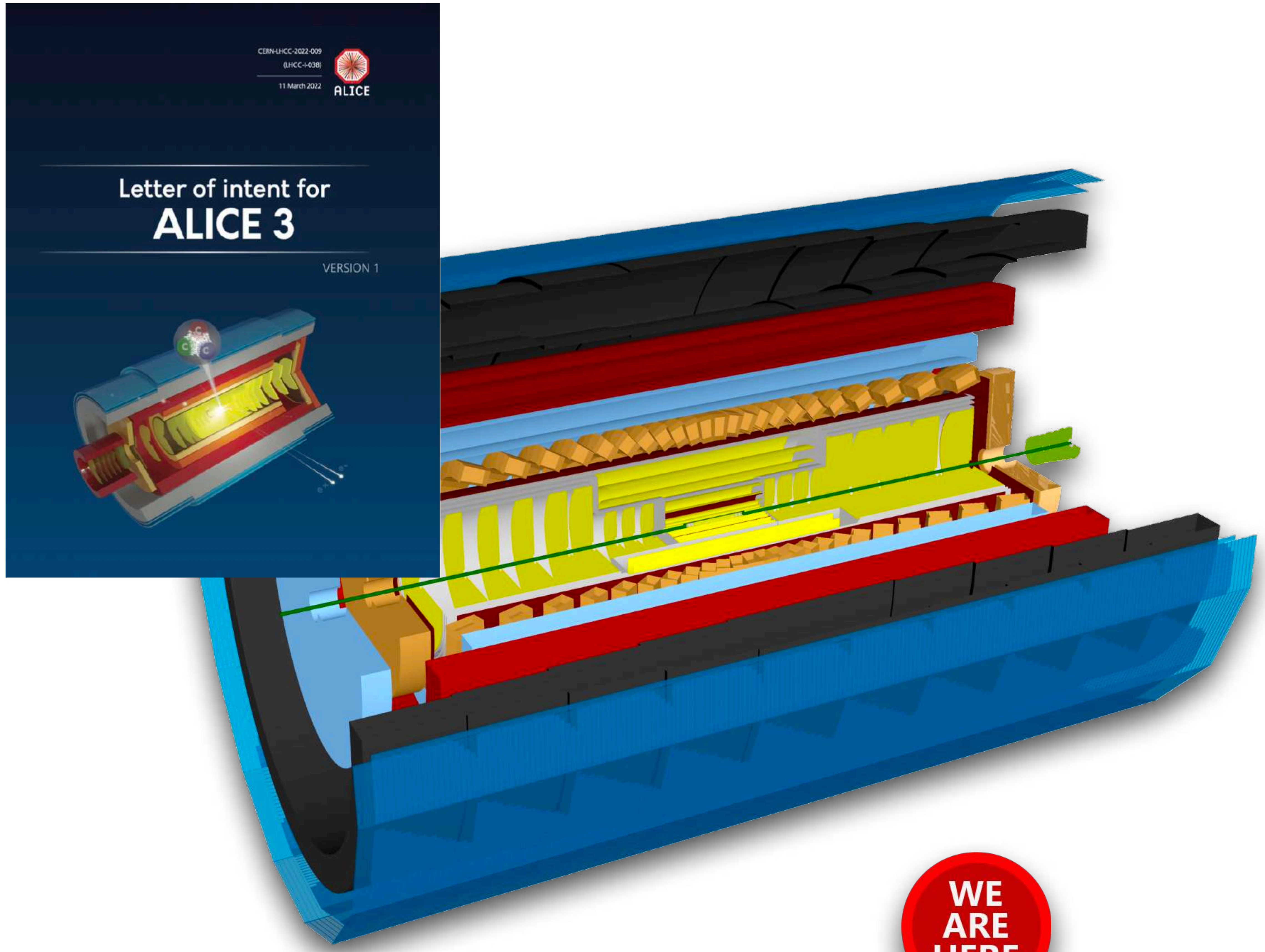
$\Xi_{cc}^{++} \rightarrow \Xi_c^{+} + \pi^{+}$ ····▶ $\Xi_c^{+} \rightarrow \Xi^{-} + 2\pi^{+}$



Outstanding tracking resolution is required

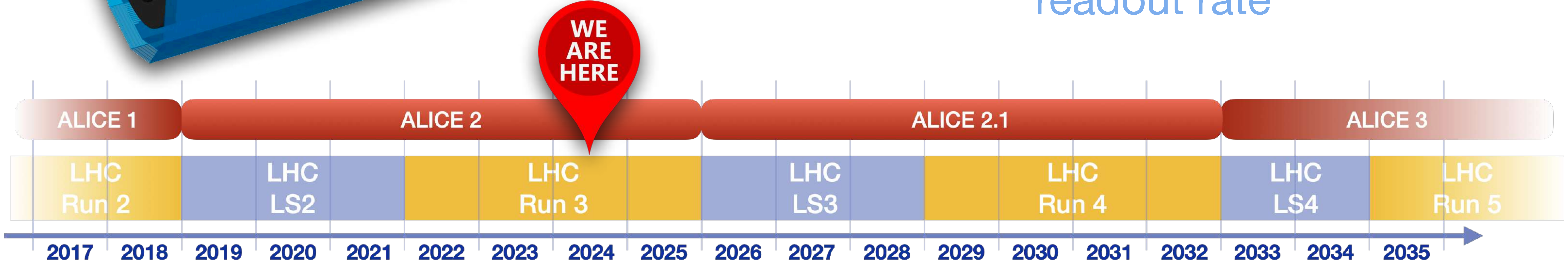
ALICE 3 : a next-generation heavy-ion experiment

ALICE, arXiv:2211.02491

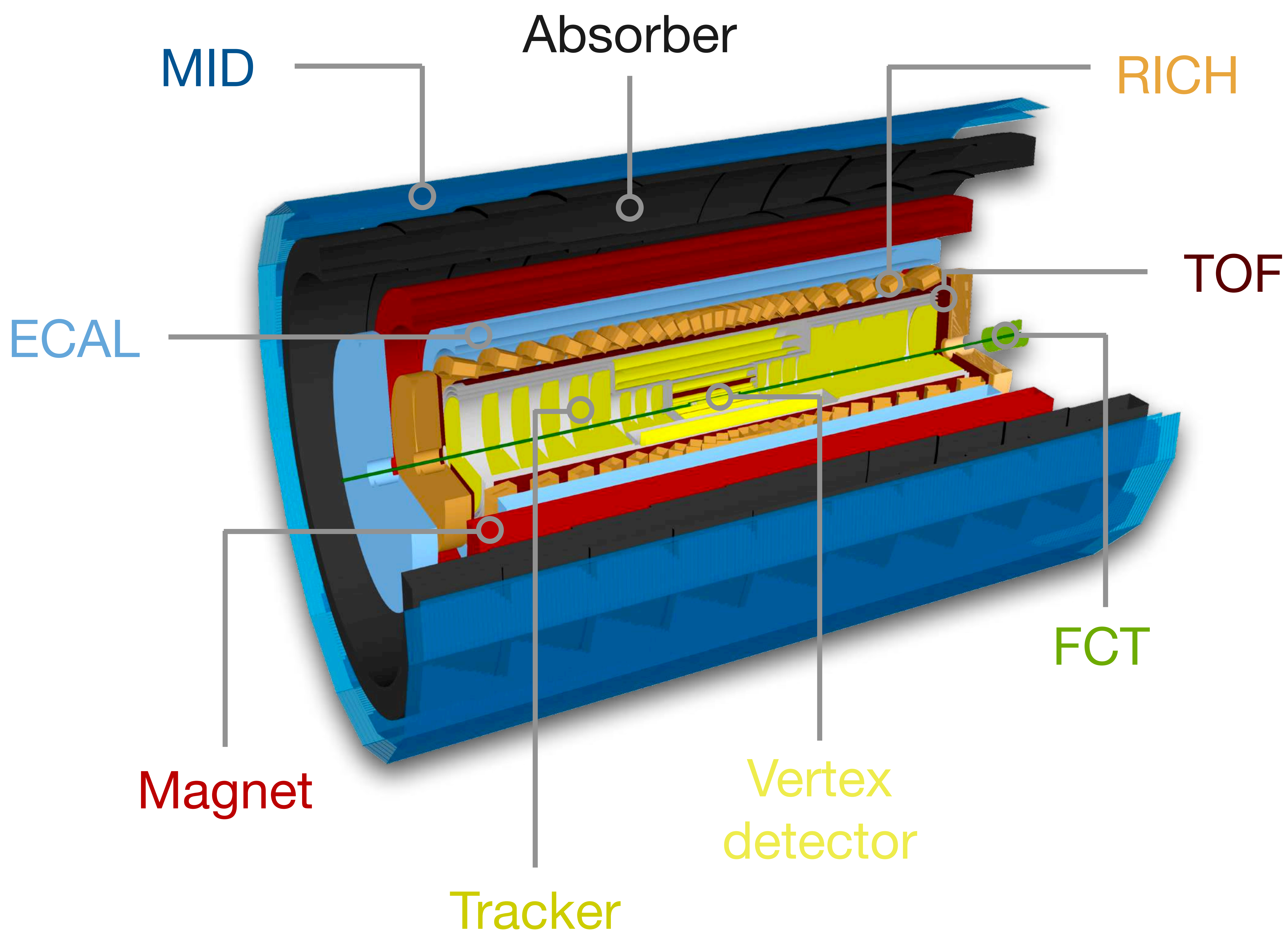


To address these open questions, the ALICE collaboration has proposed an upgrade to the experiment with…

- excellent resolution
- tracking and PID over a greater acceptance: $|\eta| < 4$
- higher interaction and readout rate

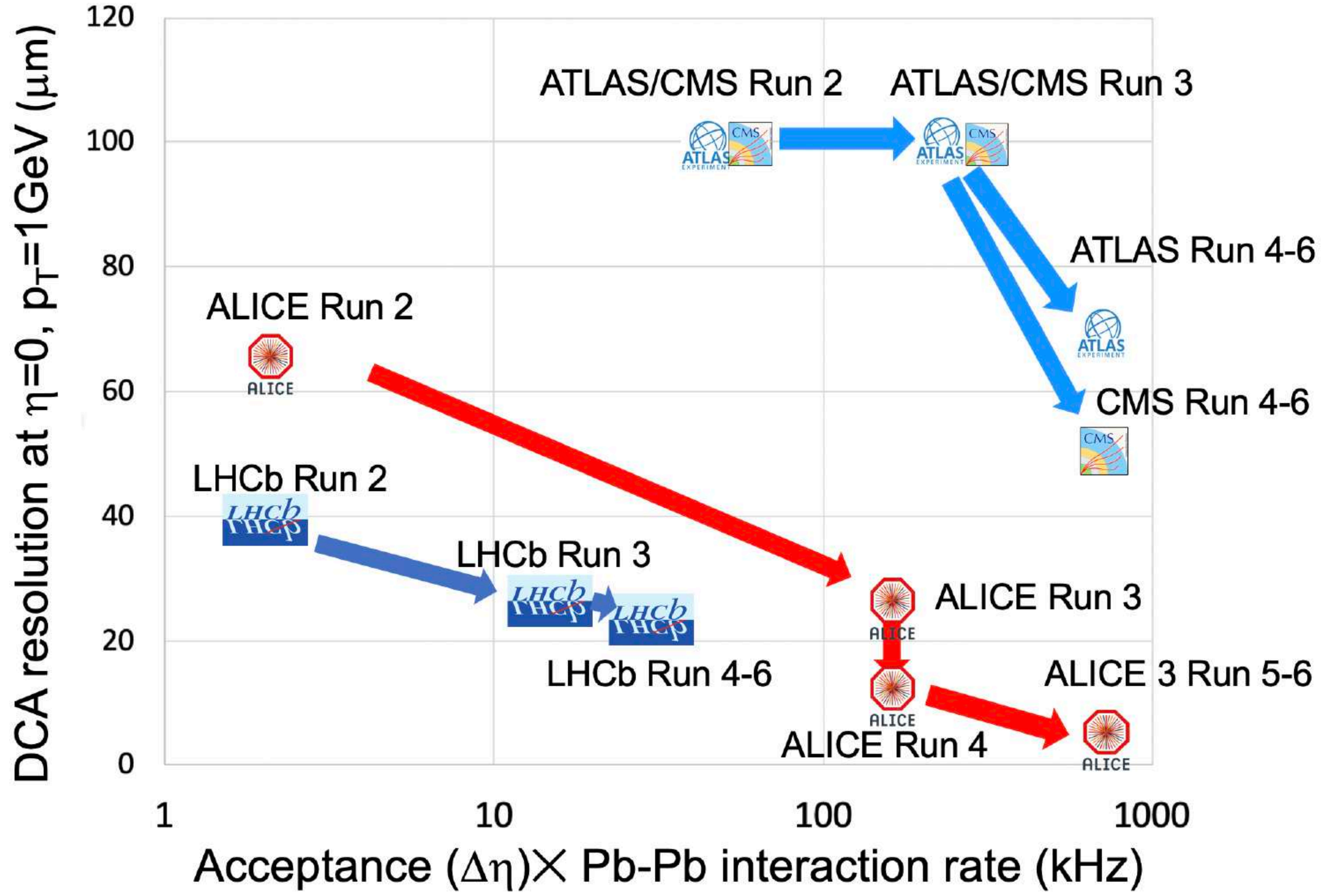


ALICE 3



ALICE 3 features:

Overall, ALICE 3 will bring unique and unprecedented features to LHC combining an excellent tracking and interaction rate



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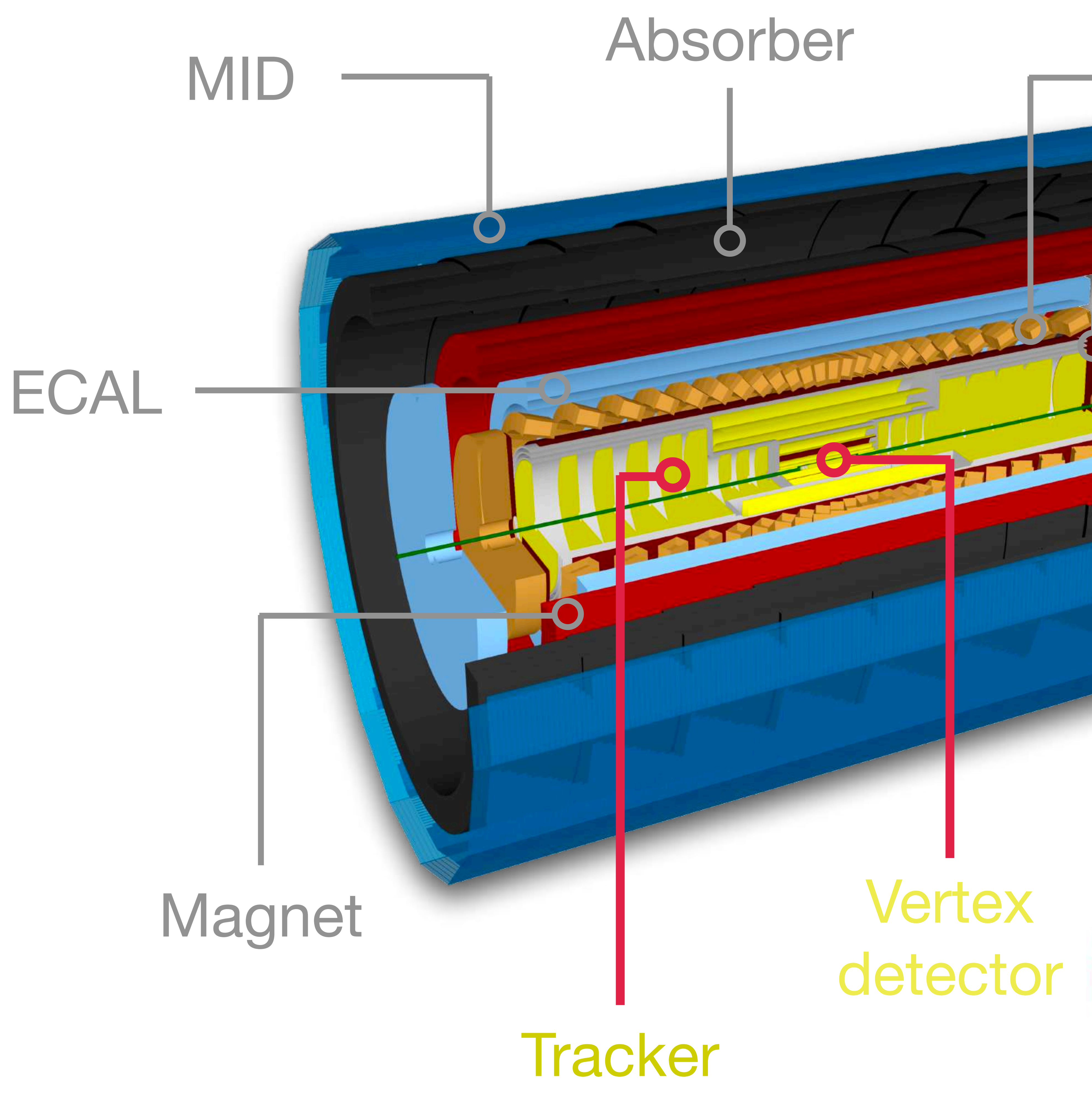
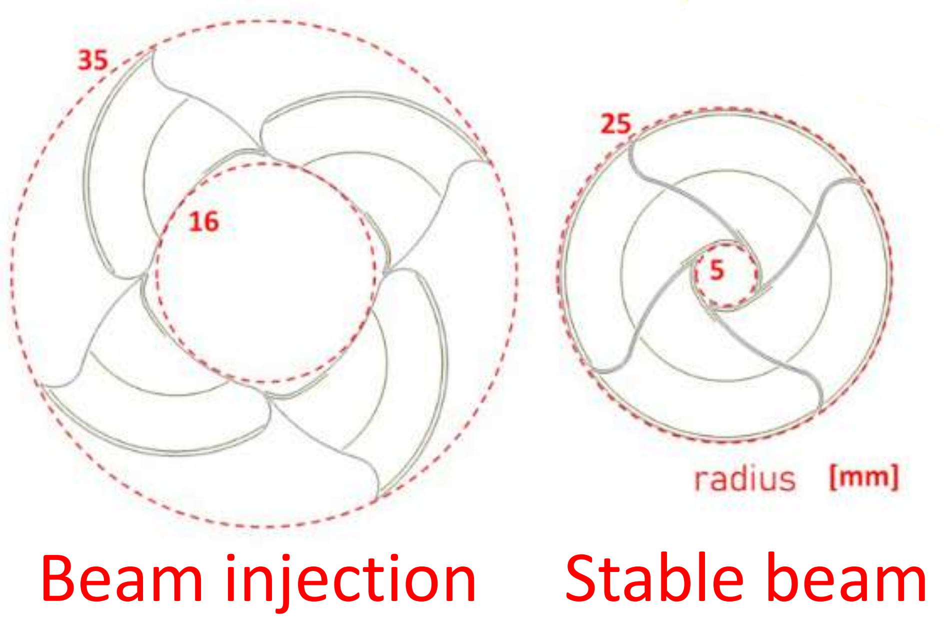
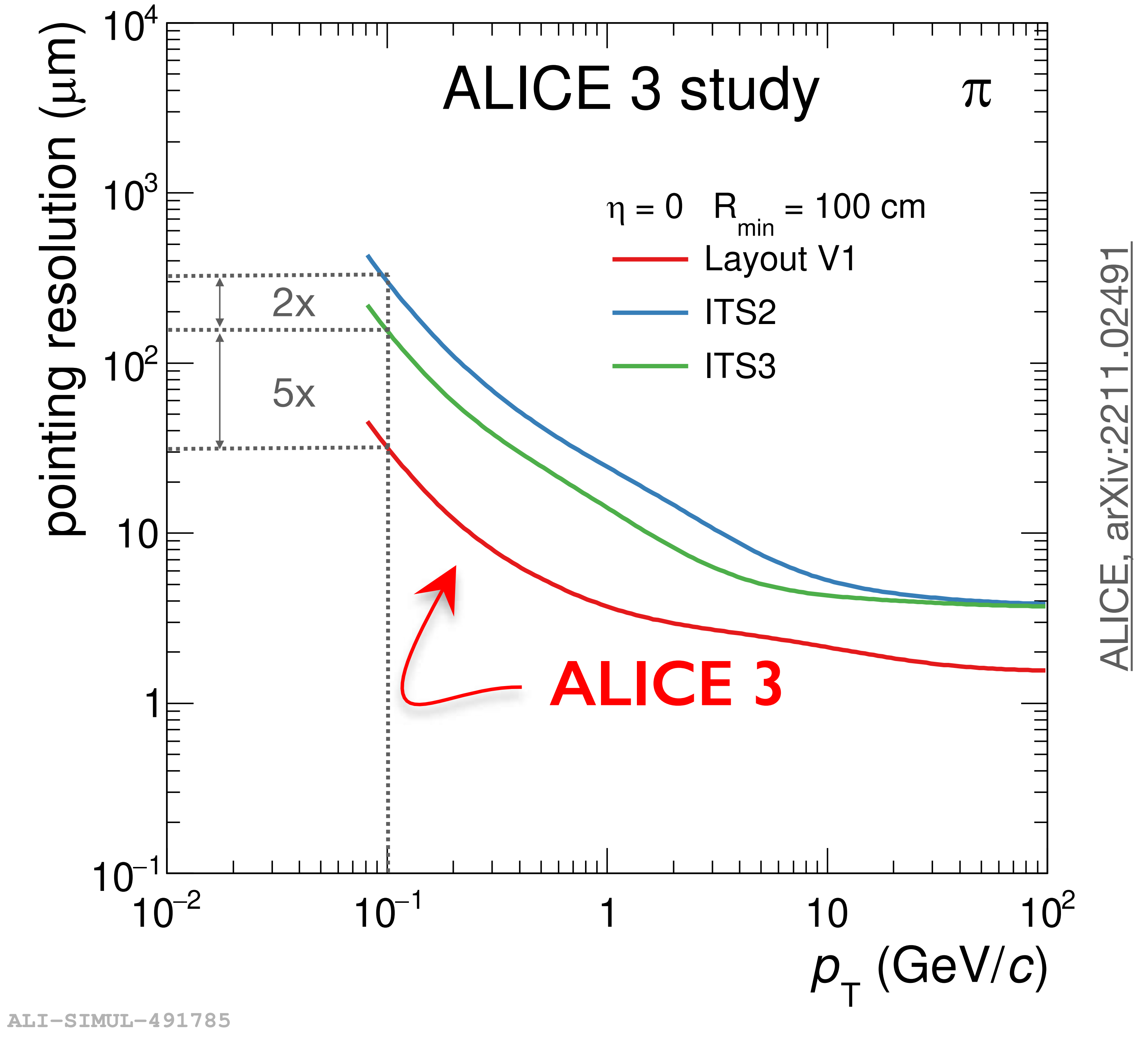




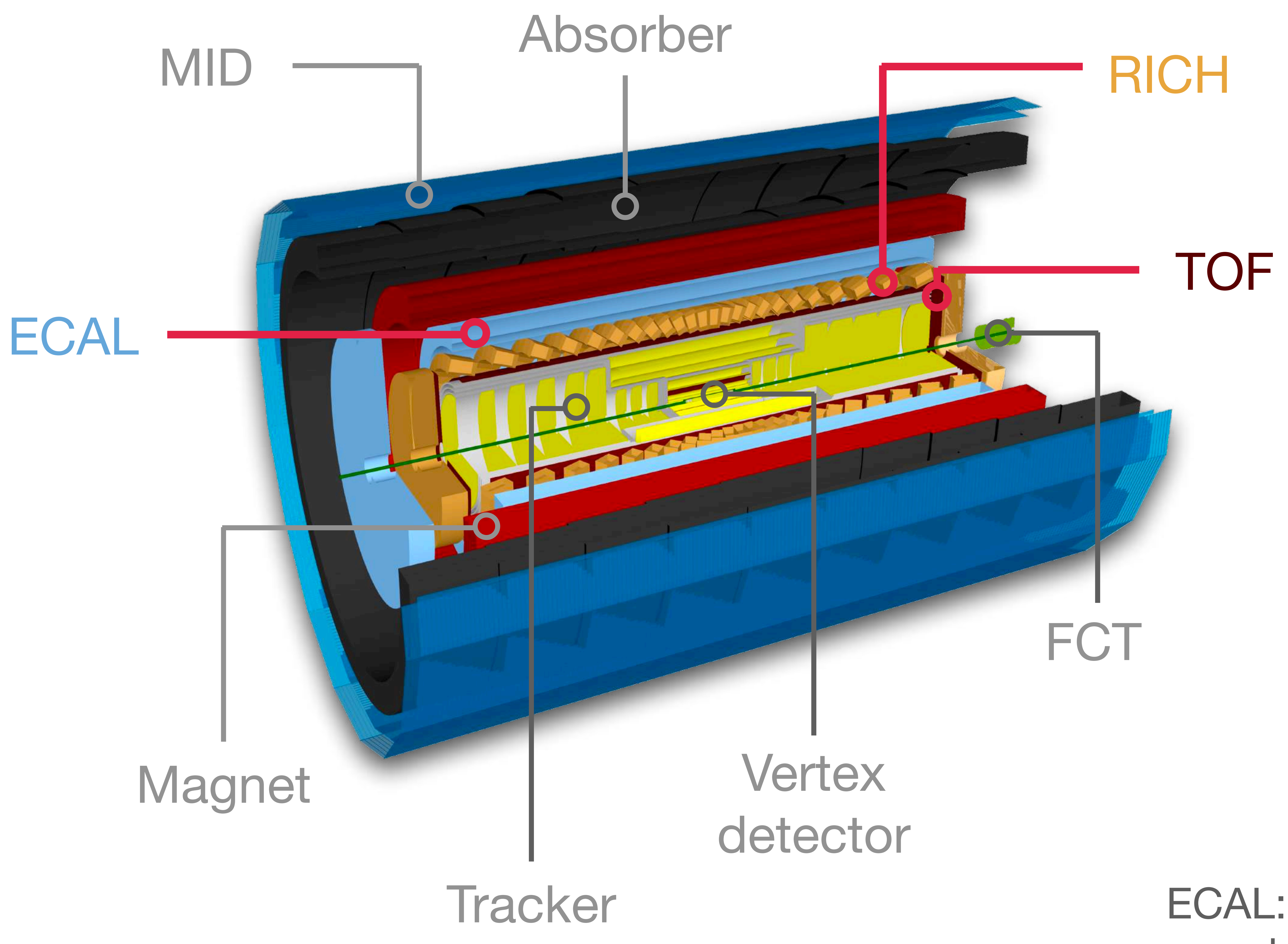
ALICE 3 features:

Silicon pixel tracker with a high resolution



and a retractable vertex detector that can close down to 5 mm

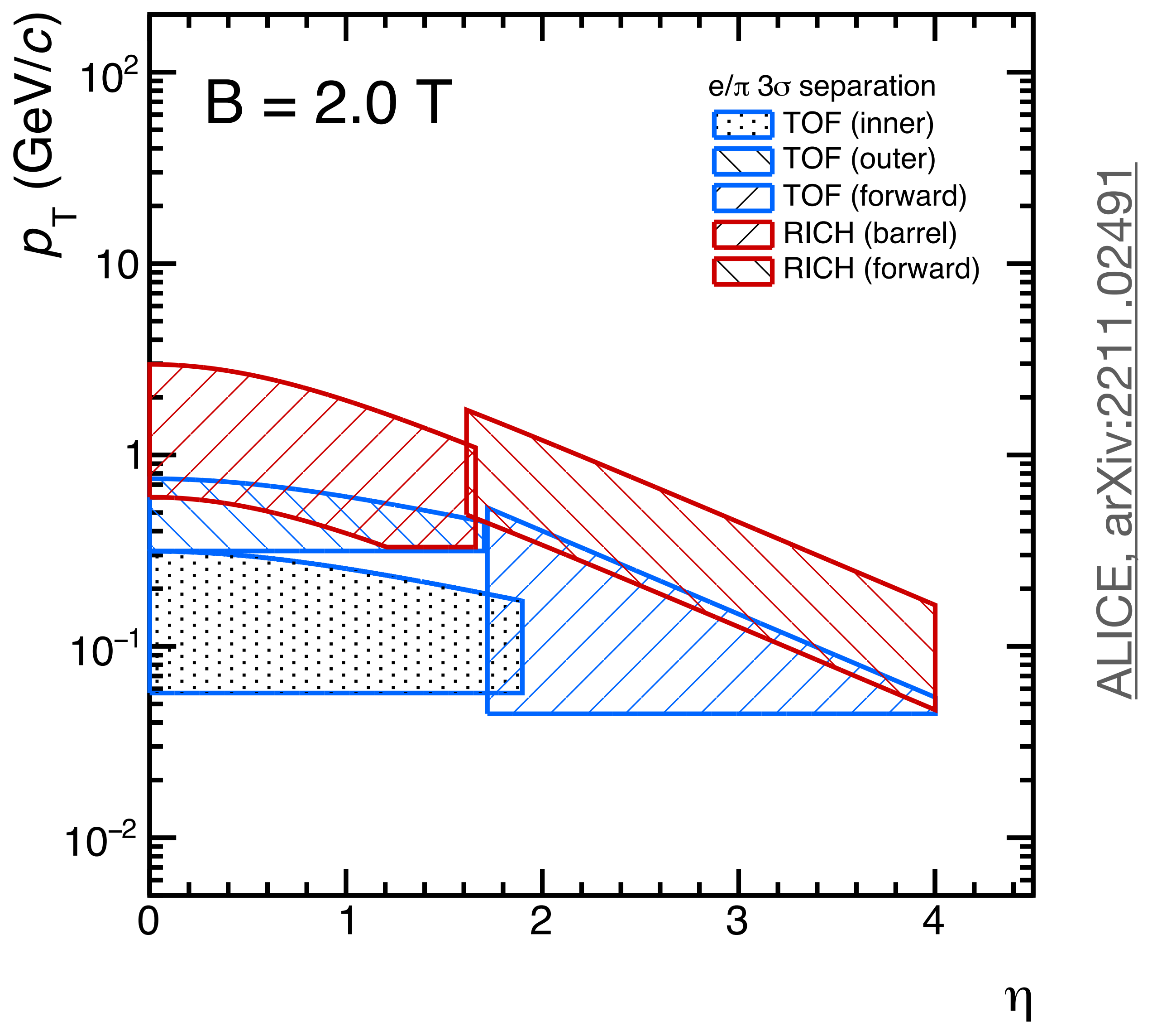
ALICE 3



ALICE 3 features:

e/π/K/p and γ PID over large acceptance

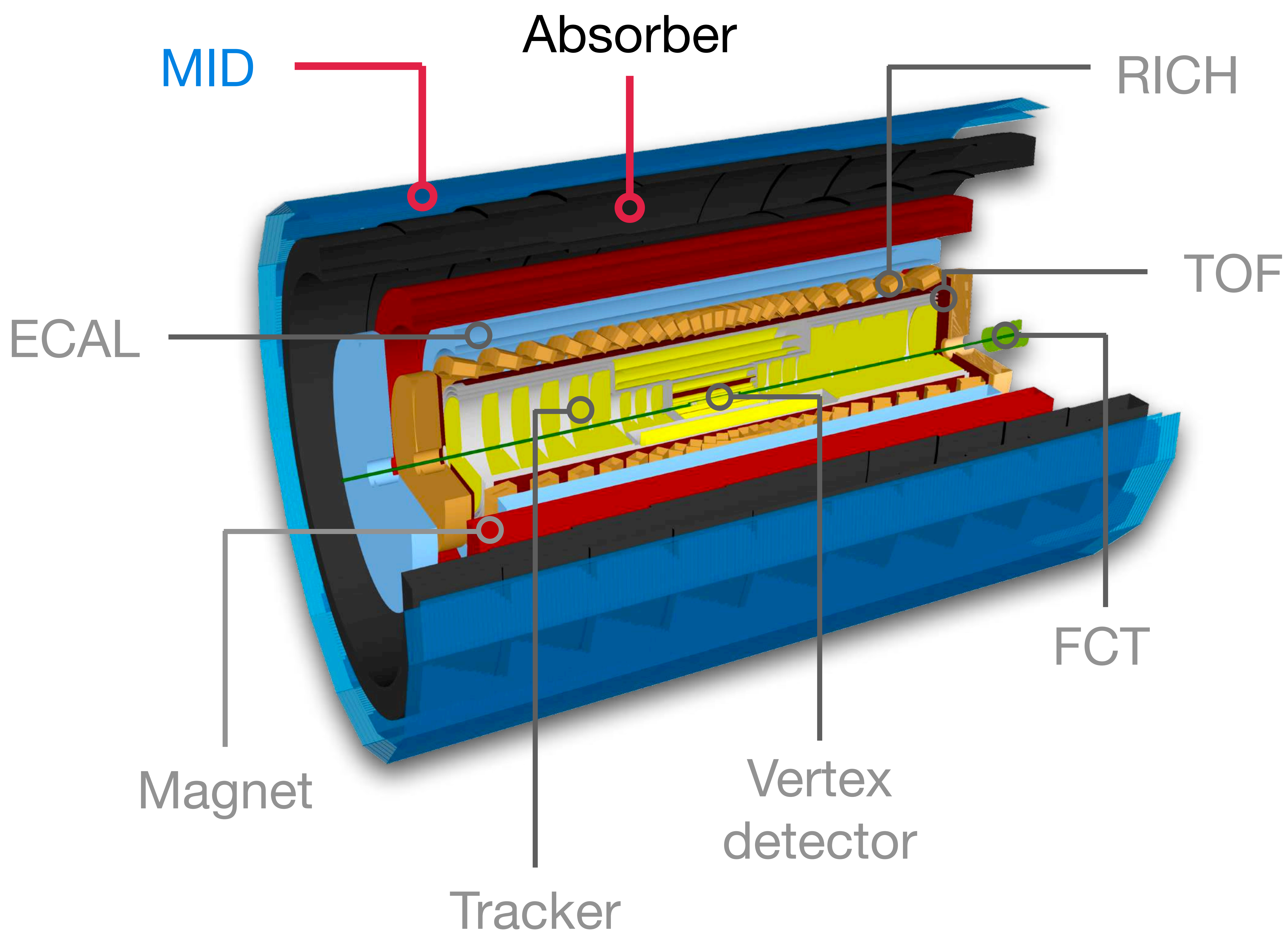
$-4 < \eta < 4$



ECAL: High-energy electrons and photon identification

- Barrel $(|\eta| < 1.5)$
- Endcap $(1.5 < \eta < 4)$

ALICE 3



ALICE 3 features:

Muon identification for charmonia and exotic hadrons

CMS y ATLAS:
μ identification down to $p_{\mathrm{T}} \approx 3-4$ GeV/c

ALICE 3:
optimized to identify μ down to $p_{\mathrm{T}} = 1.5$ GeV/c

vs

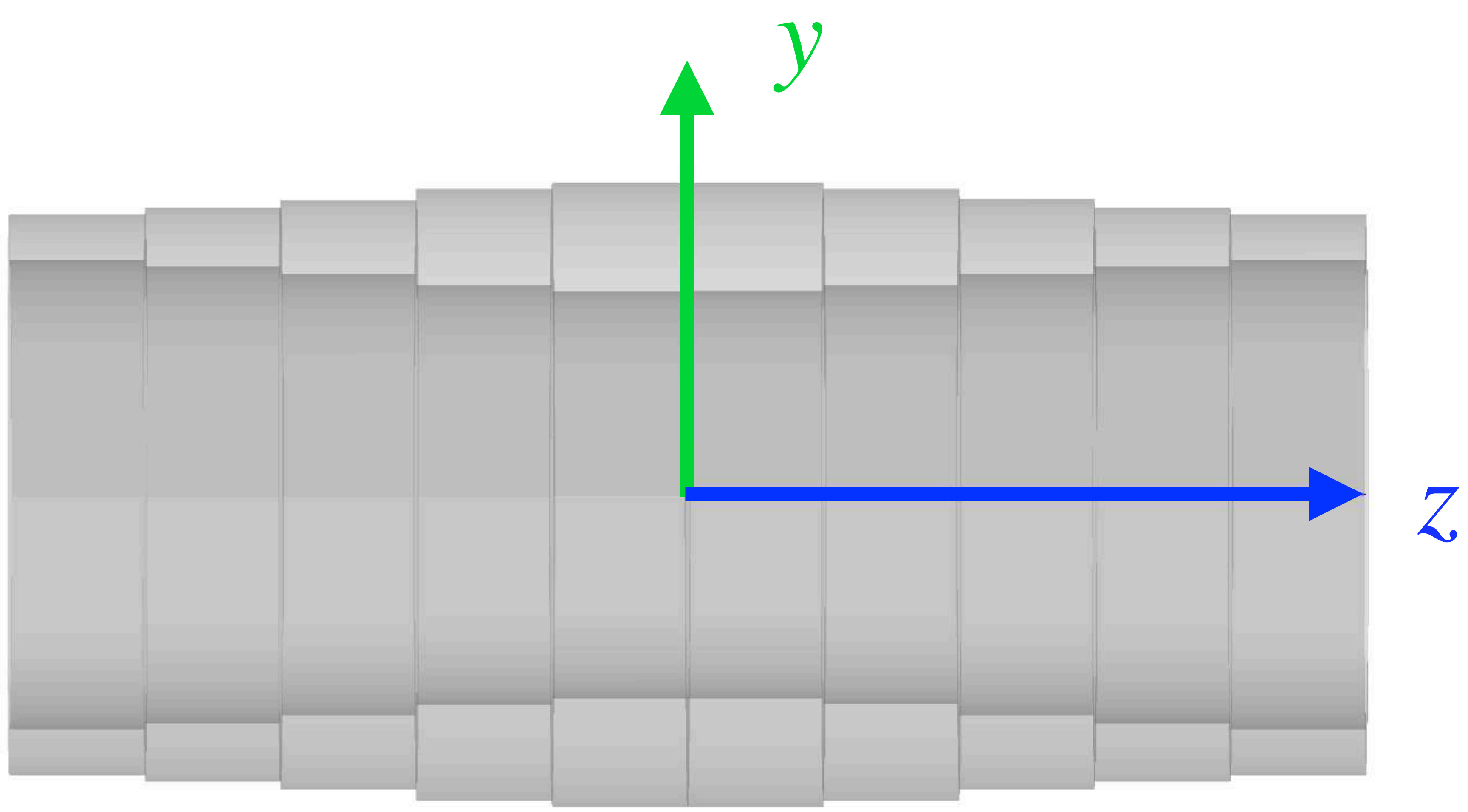
LHCb:
J/ψ at rest but only at forward rapidity

ALICE 3:
J/ψ at rest for a wider rapidity $|y| < 1.24$

ALICE 3 MID

The MID considers a magnetic iron *absorber* with varying thickness

⟹



~4 nuclear interaction lengths

- 10^{-2} hadron rejection factor
- Low charged particle fluence rate: ~4 Hz/cm^2
- Scattering within the absorber: ~5 cm for p=1.5 GeV/c (granularity of 5x5 cm^2 is enough for 1.5-5 GeV/c)

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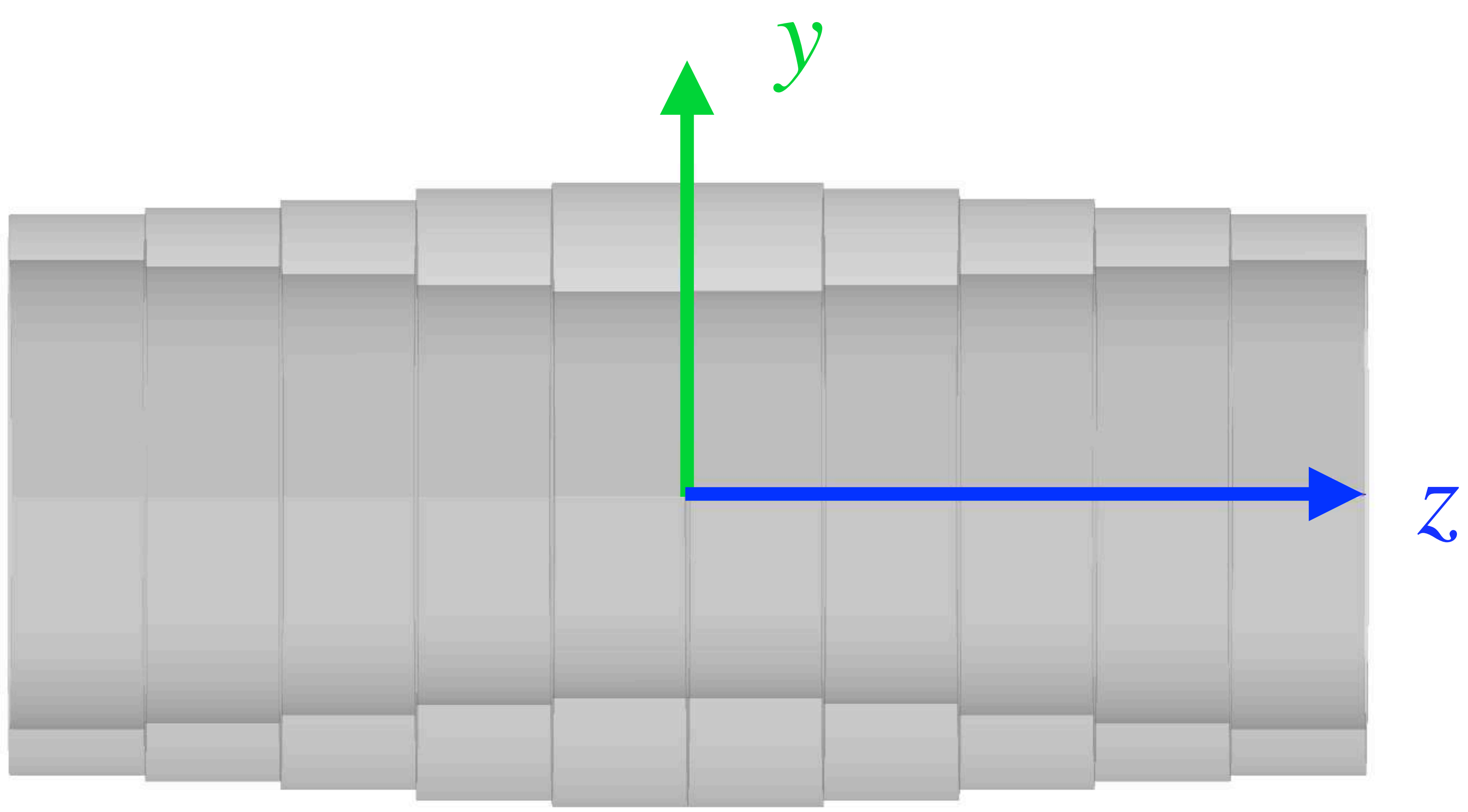

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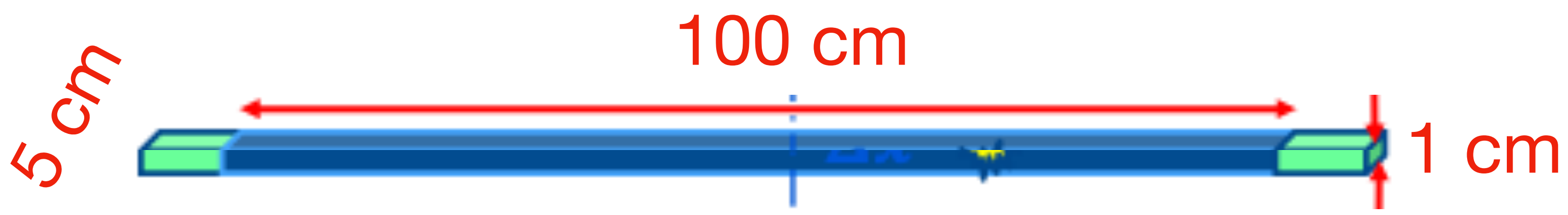
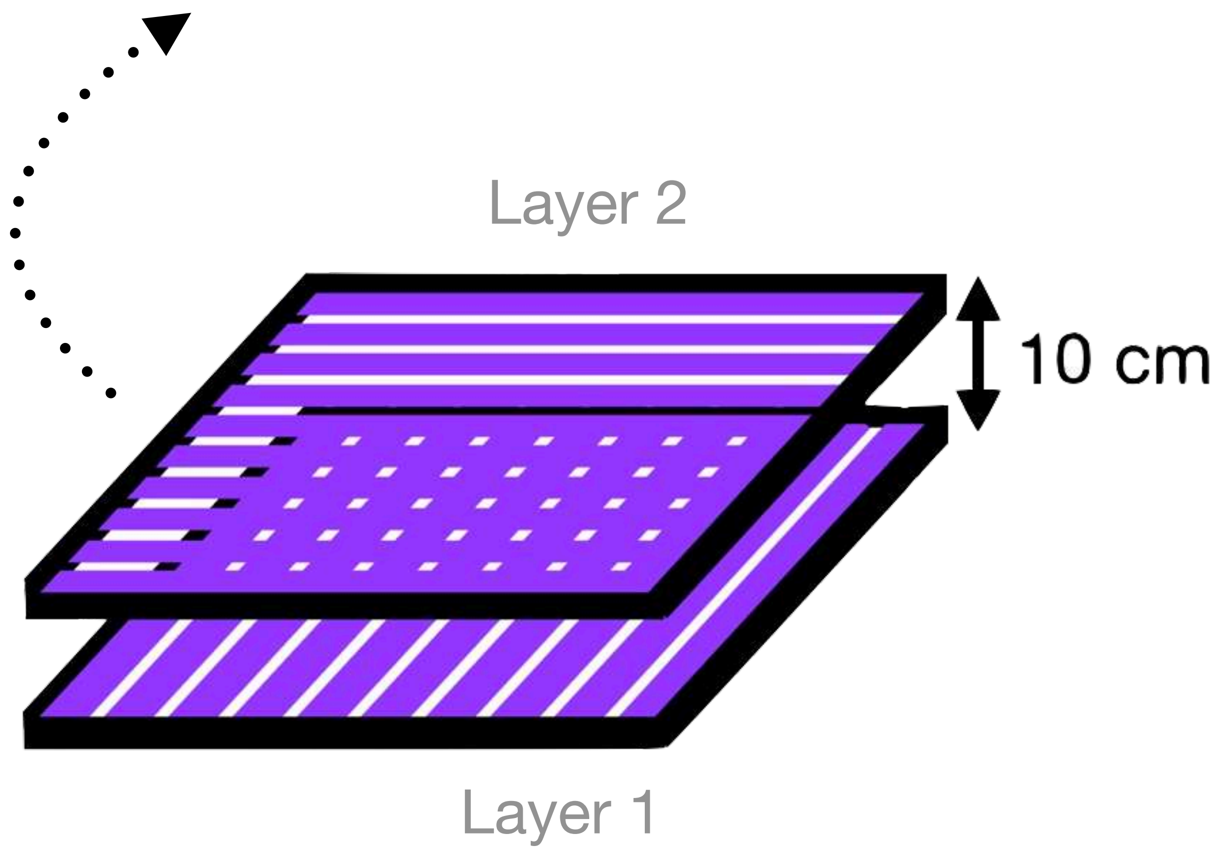




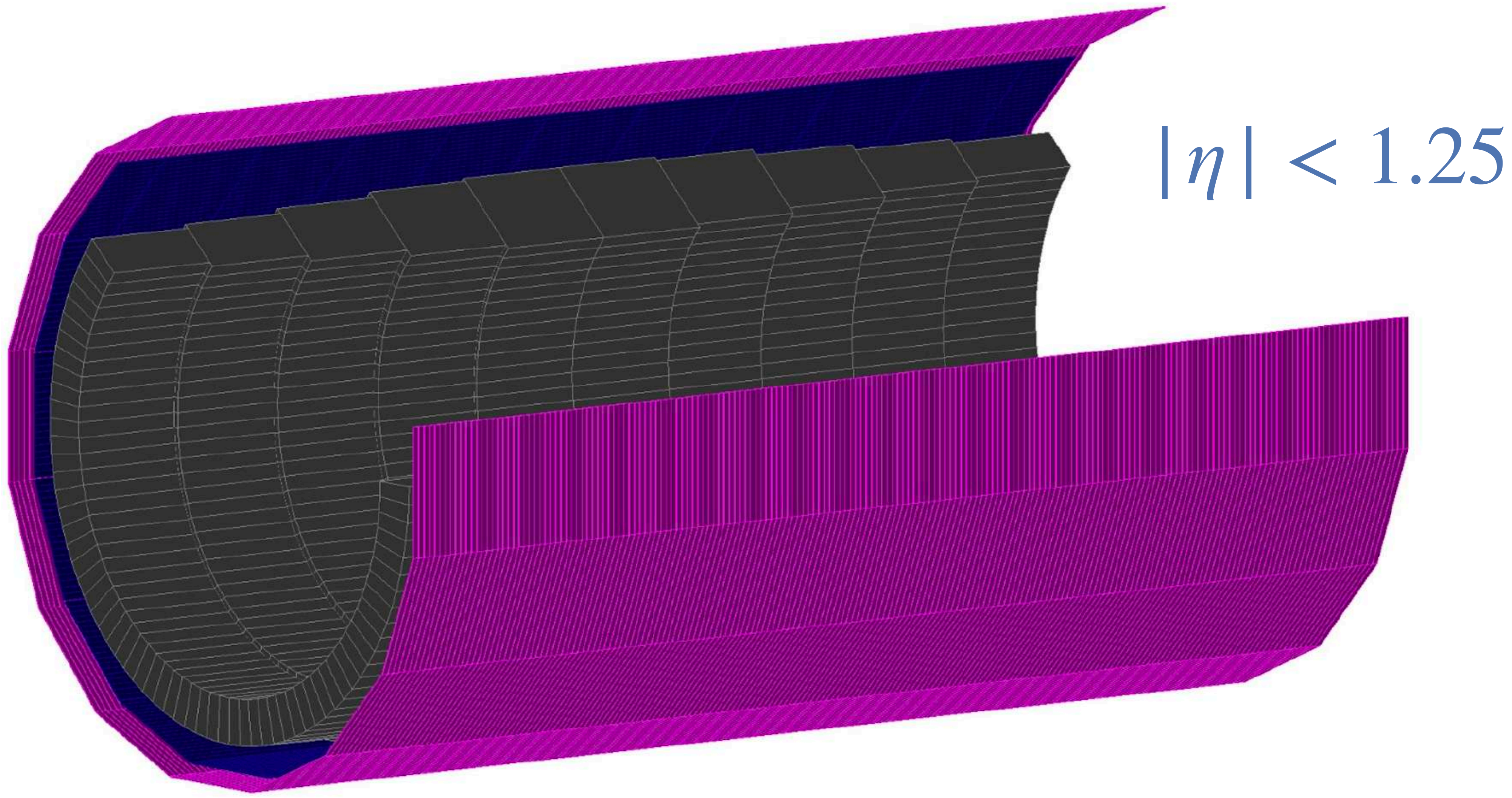
Regarding the muon chambers, there are some candidates

- Plastic scintillators and silicon photomultiplier (SiPM) for readout
- Multi-Wire Proportional Chambers (MWPCs)
- Resistive Plate Chambers (RPCs)

MID (plastic scintillator option)

Baseline option:
Low cost plastic scintillator bars (FNAL-NICADD) equipped with wave-length shifting fibers and SiPM

- **simplicity** (no need of gas mixture)
- **excellent timing resolution** (ns)
- **good performance** under the expected radiation load



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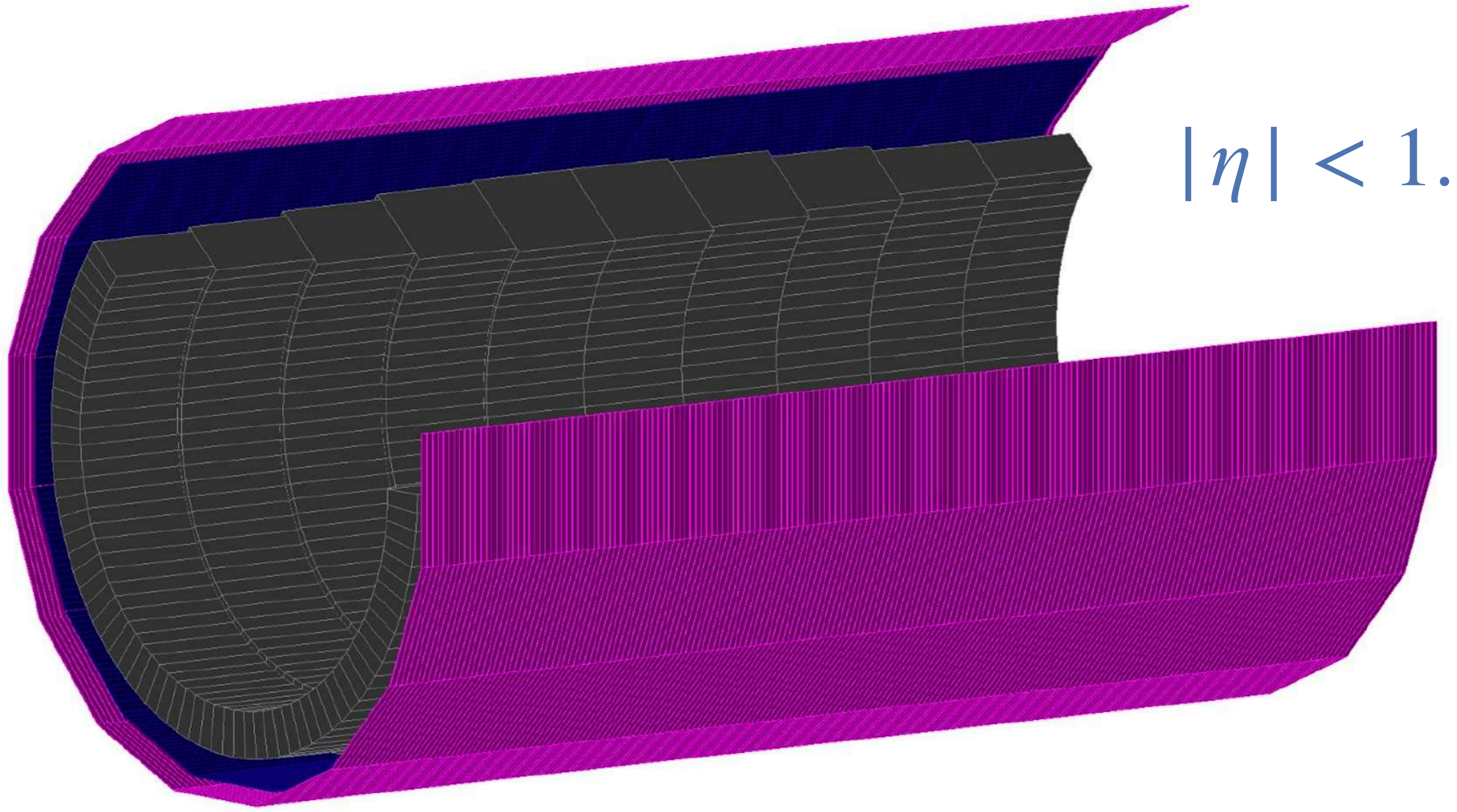


	pp	Pb-Pb
TID (rad)	54	0.94
NIEL (1 MeV neq/cm^2)	3.4 x 10^{10}	4.7 x 10^{8}

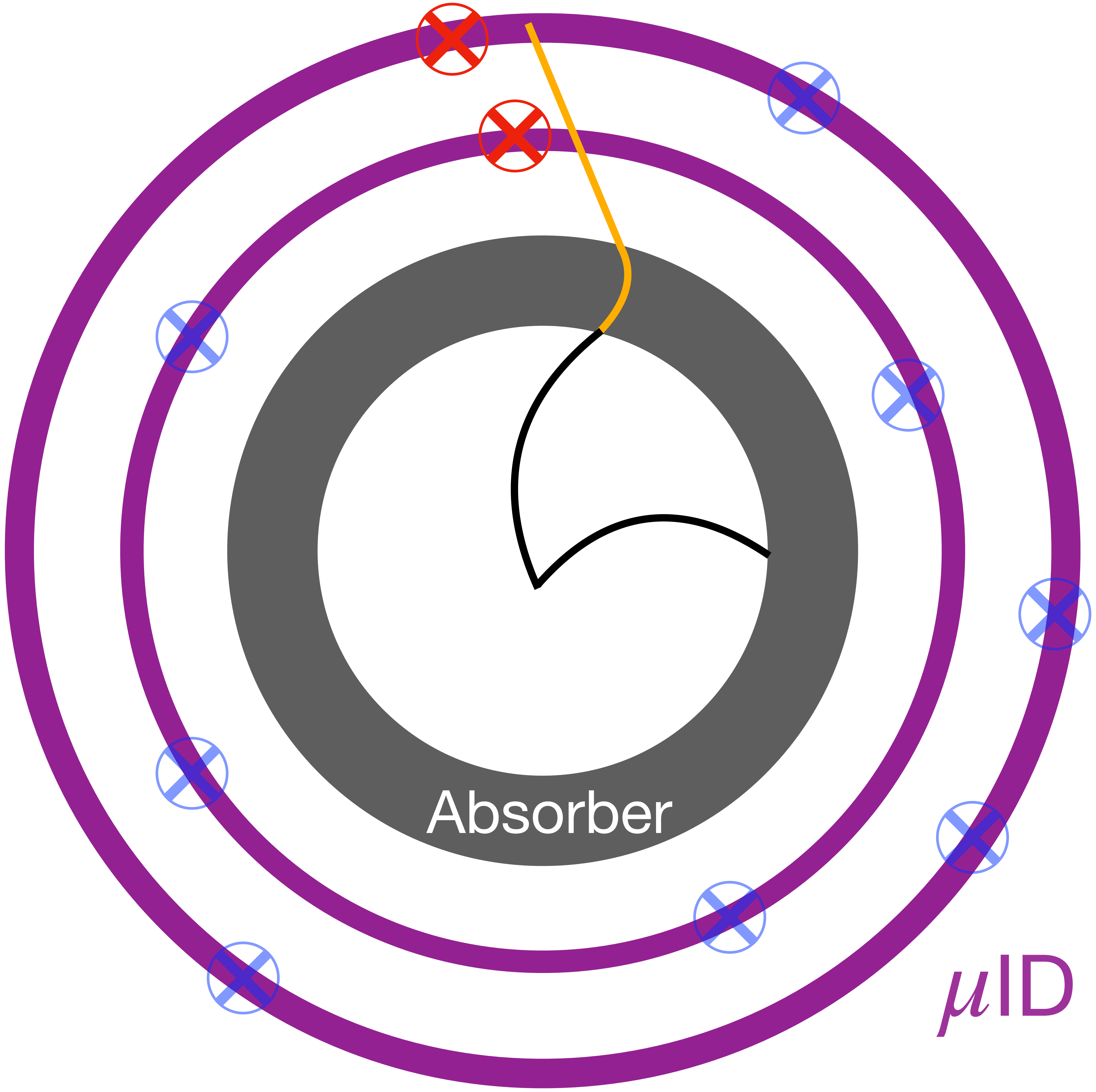
Table. Radiation load in the MID simulated with FLUKA for the Run 5+6 period

- FNAL-NICADD scintillators have a **decrease in light yield of ~5%** after a **dose of 1 Mrad** [FERMILAB-PUB-05-344]
- **Our typical signals ~40 photoelectrons,** therefore single photoelectron detection with the SiPM is not required (impossible at 10^{11} MeV neq/ cm^2 at room temp.)

[Nucl. Instrum. Meth. Phys. Res A, A 922 (2019)]

MC Simulations

Muon tagging



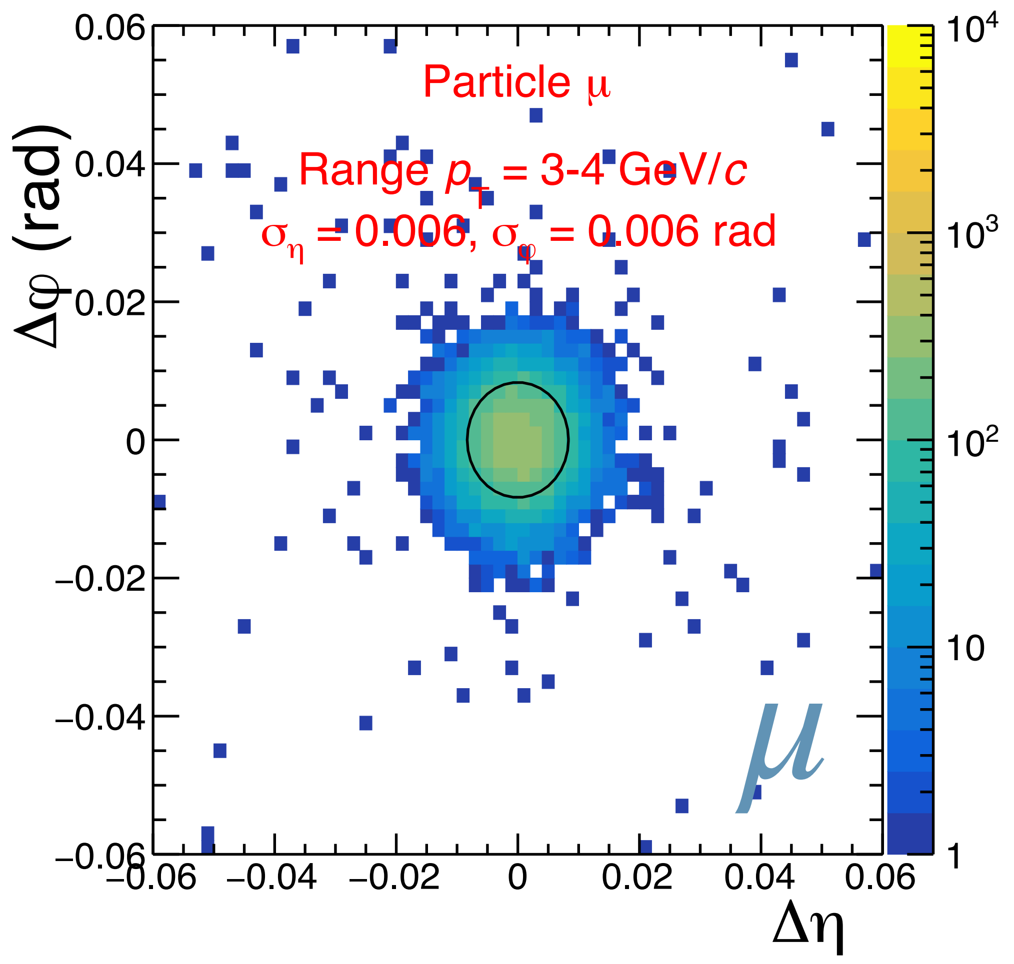
- Muon tagging is done by matching **activated bars** in the MID with tracks from the tracker
- All primary tracks are extrapolated to the MID
- Selection criteria are obtained via boosted decision trees (BDT)

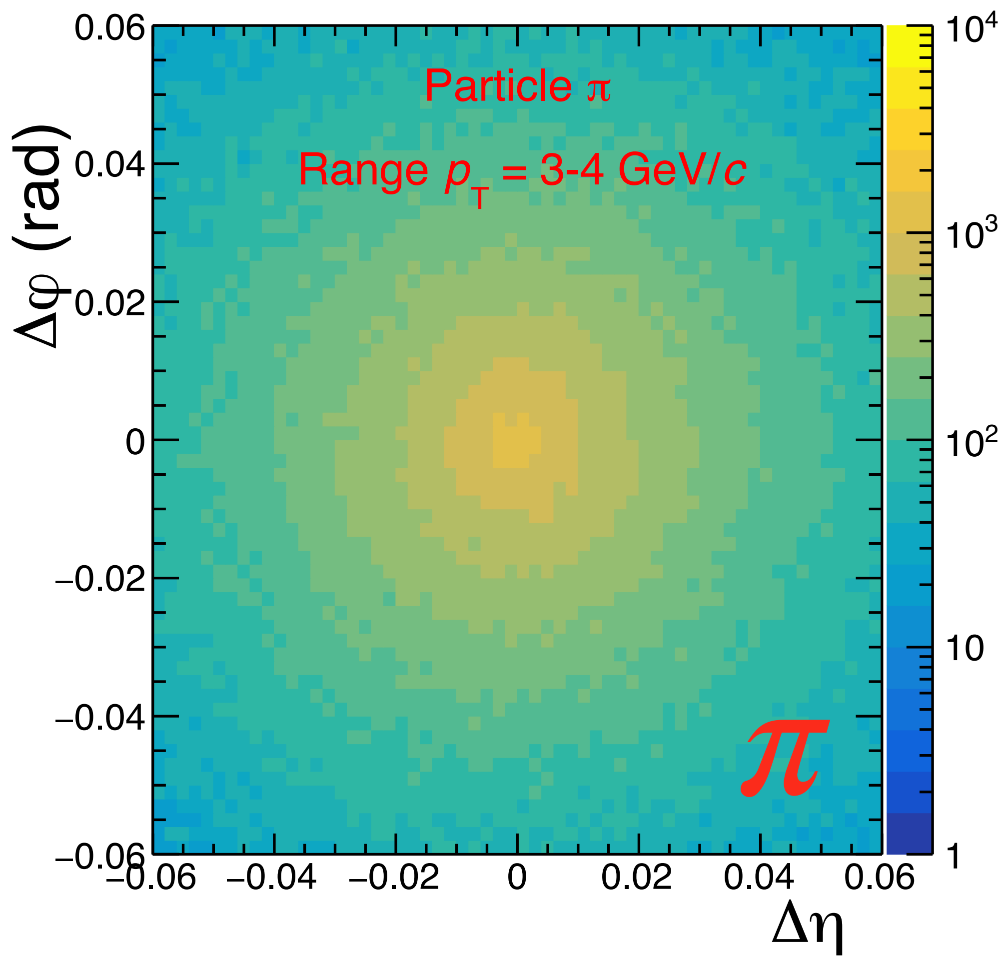
BDT training

How to pick a set of variables for the training of the BDT?

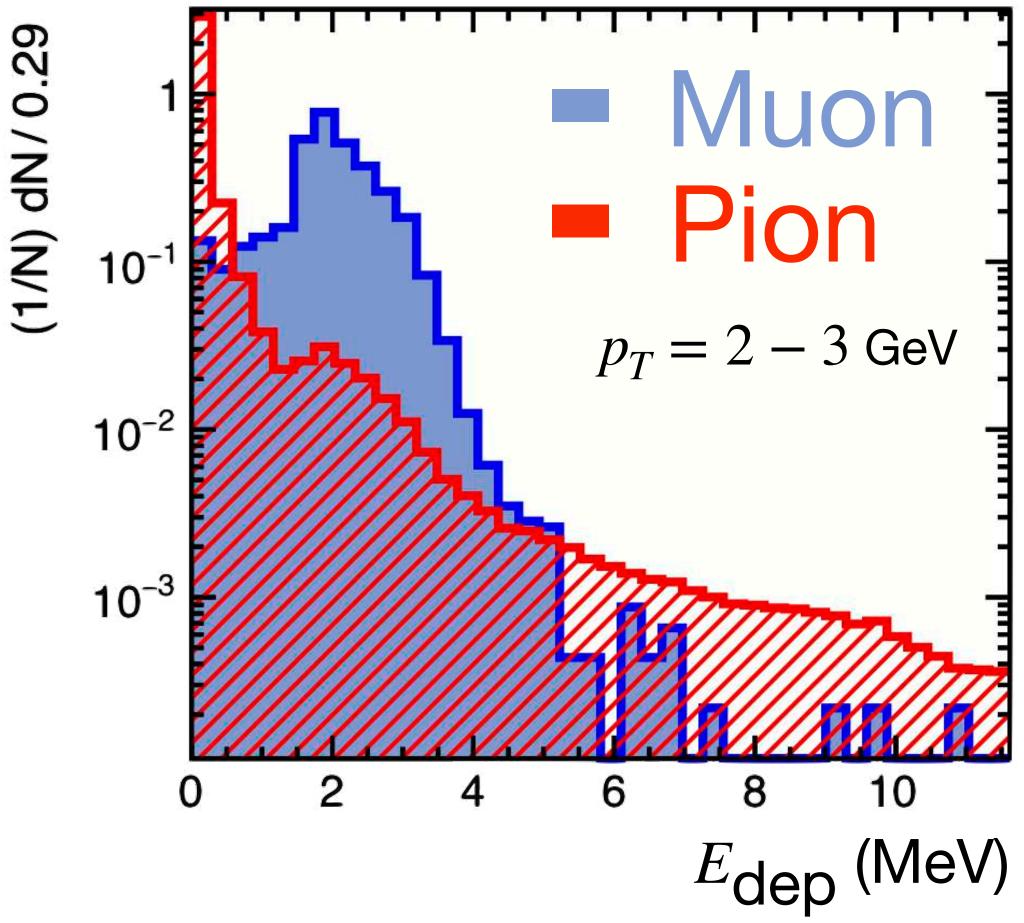
$\Delta\phi = \phi^{\text{extr.}} - \phi^{\text{bar}}$
$\Delta\eta = \eta^{\text{extr.}} - \eta^{\text{bar}}$

- Momentum before the absorber
- **Matching window ($\Delta\eta, \Delta\phi$)**
- Number of bars activated around the extrapolation
- Highest **energy deposition** in the activated bars around to the extrapolation
- Detection time

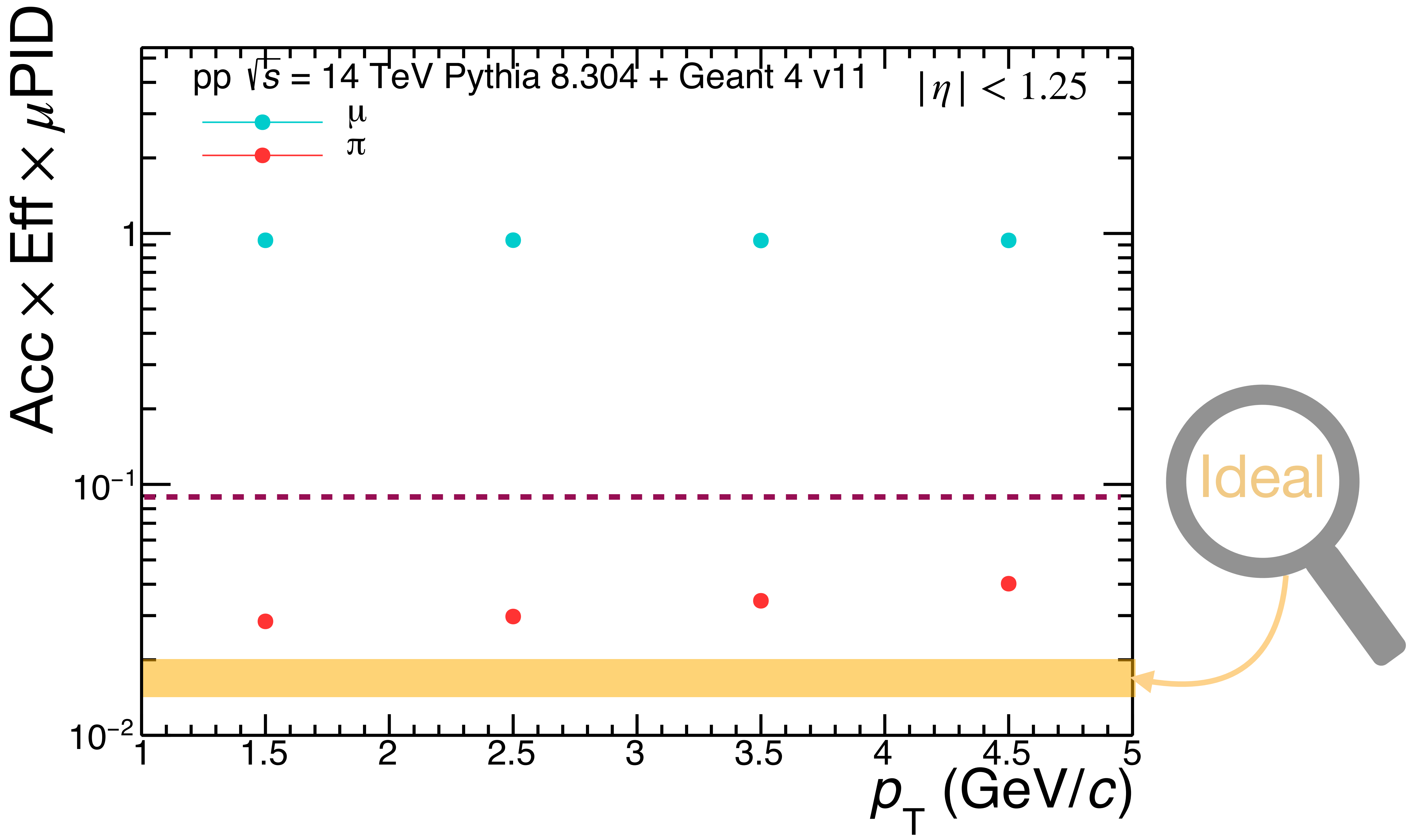




Hadron signal is expected in the form of particle showers

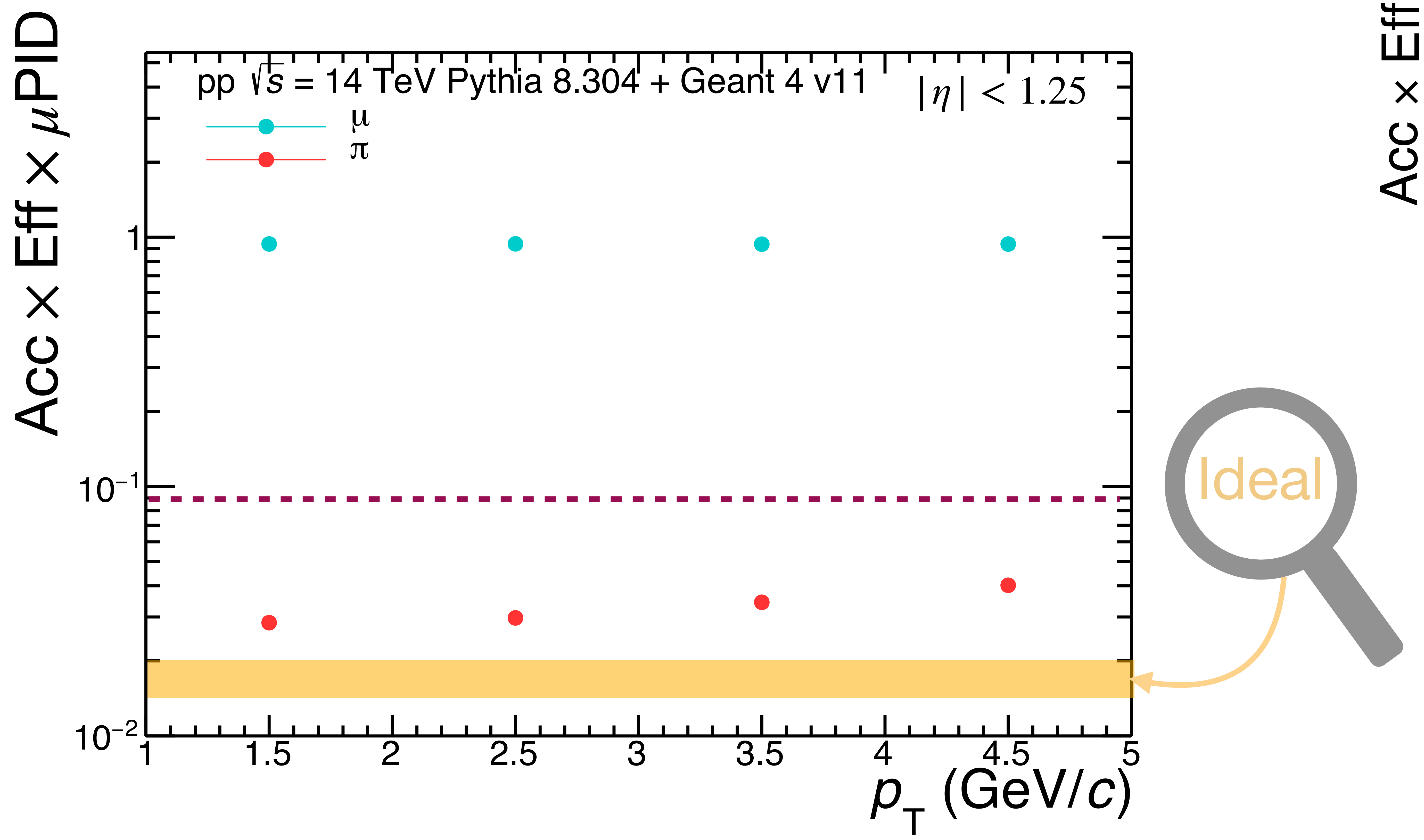


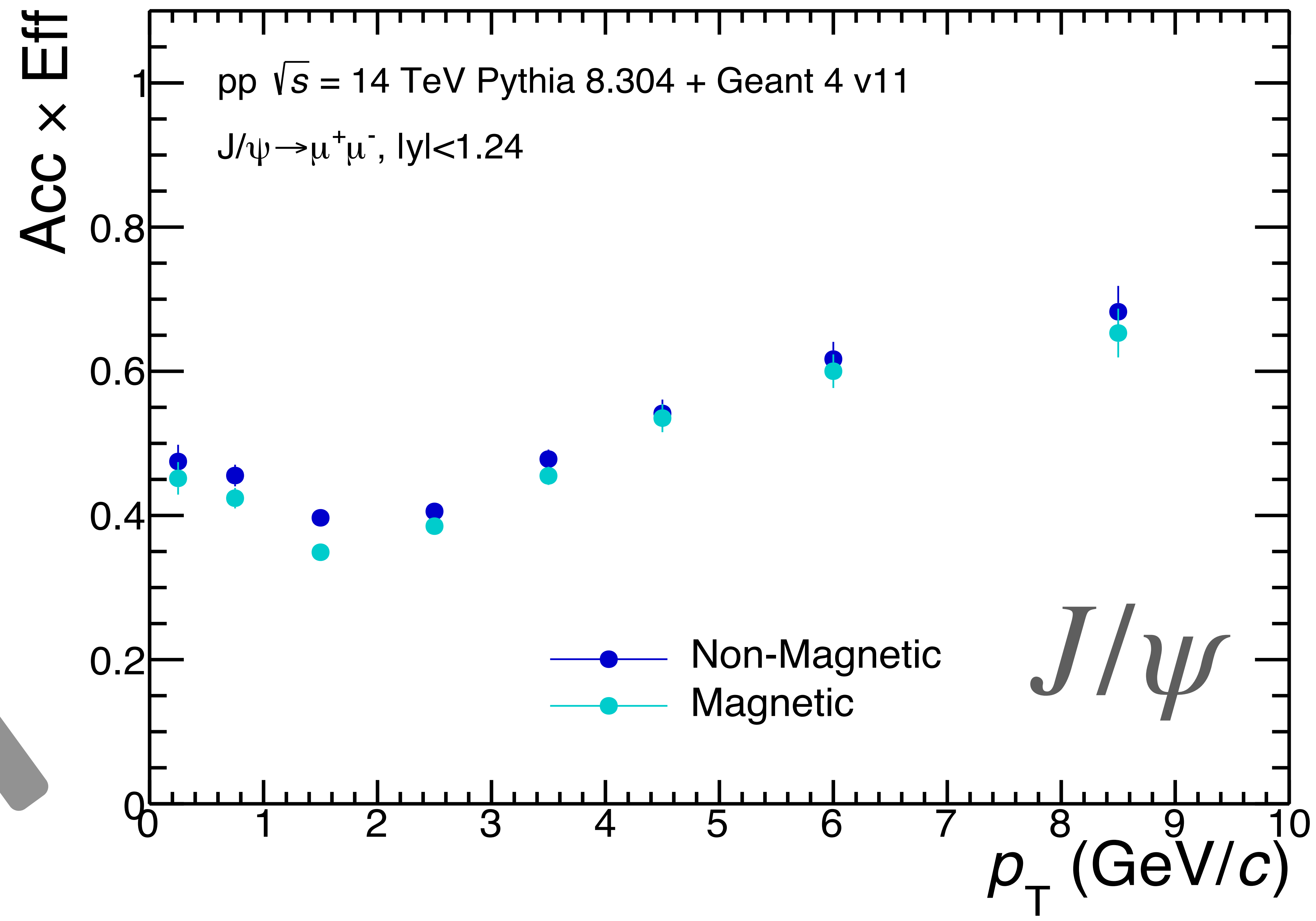
Muon and J/ψ efficiency



- Muon efficiency above 95% in the full p_{T} range
- Pion rejection at the level of 3-4%

Muon and J/ψ efficiency





- Muon efficiency above 95% in the full p_{T} range
- Pion rejection at the level of 3-4%

- Efficiencies are **weakly affected** by the choice of the absorber but

magnetic absorber is cheaper than the non-magnetic

Test beam results

Test beam results

R. Alfaro et. al., JINST 19 (2024) 04, T04006

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TECHNICAL REPORT

Characterisation of plastic scintillator paddles and lightweight MWPCs for the MID subsystem of ALICE 3

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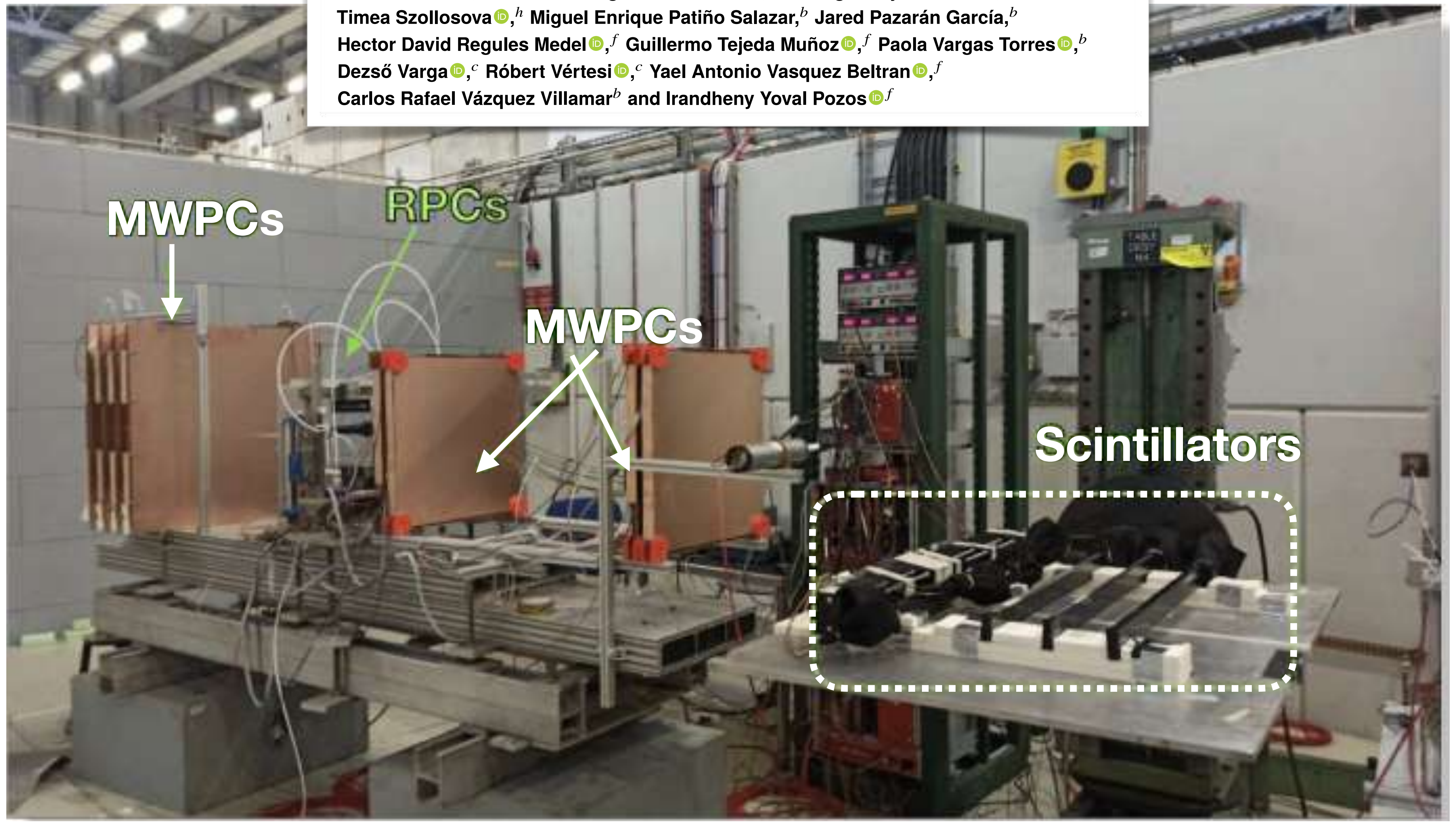

Fig. Experimental setup during the test beam

- **Scintillators and MWPCs** prototypes were tested at the **CERN T10 test beam facility**

Test beam results

R. Alfaro et. al., JINST 19 (2024) 04, T04006

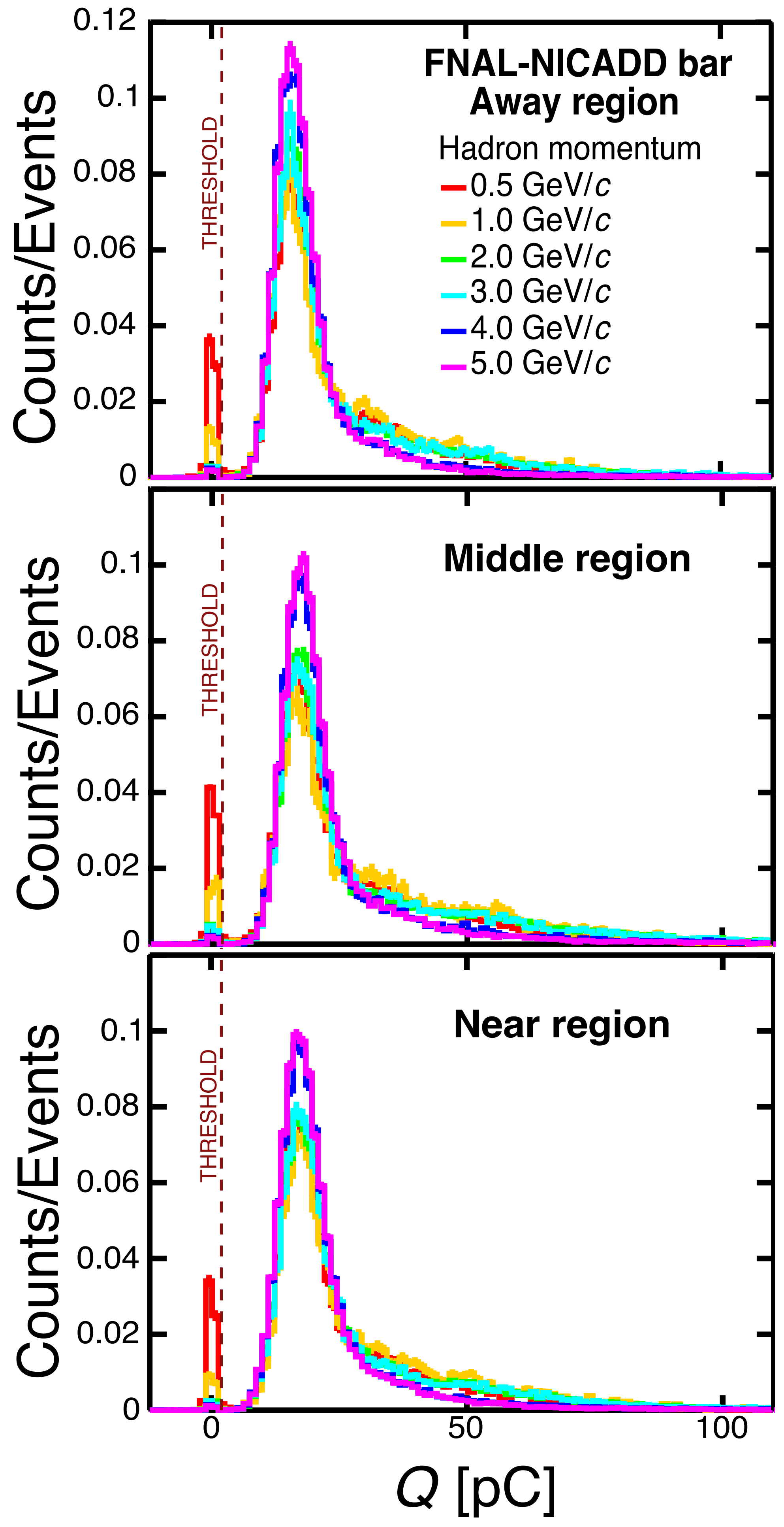

Fig. Charge distributions for three different distances between the hit and the SiPM

- **Scintillators and MWPCs** prototypes were tested at the **CERN T10 test beam facility**
- The FNAL-NICADD scintillator option offers **good performance on light-yield output** (around 40 photoelectrons), **good time resolution** (< 2 ns), and represents a **low cost solution**

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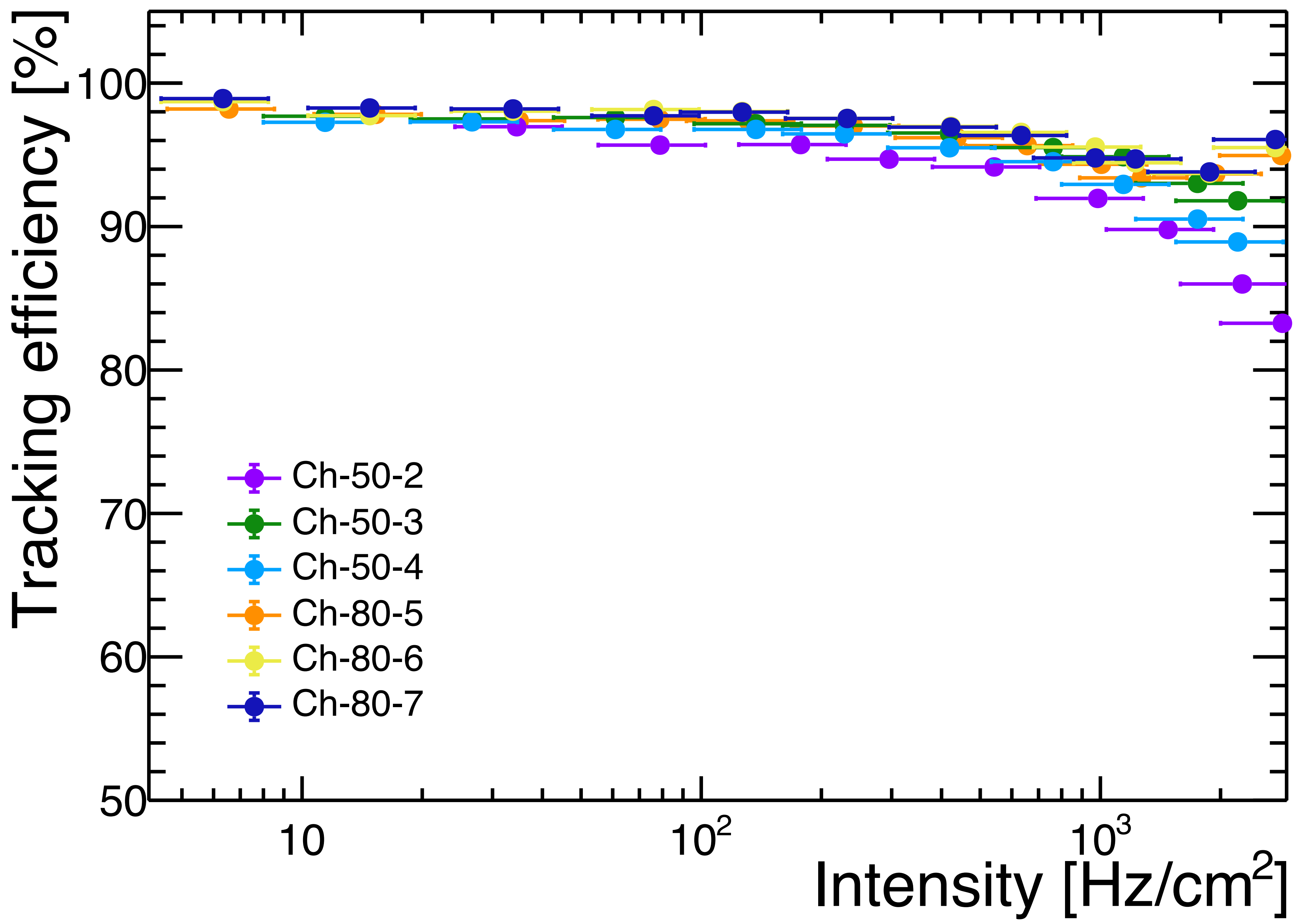
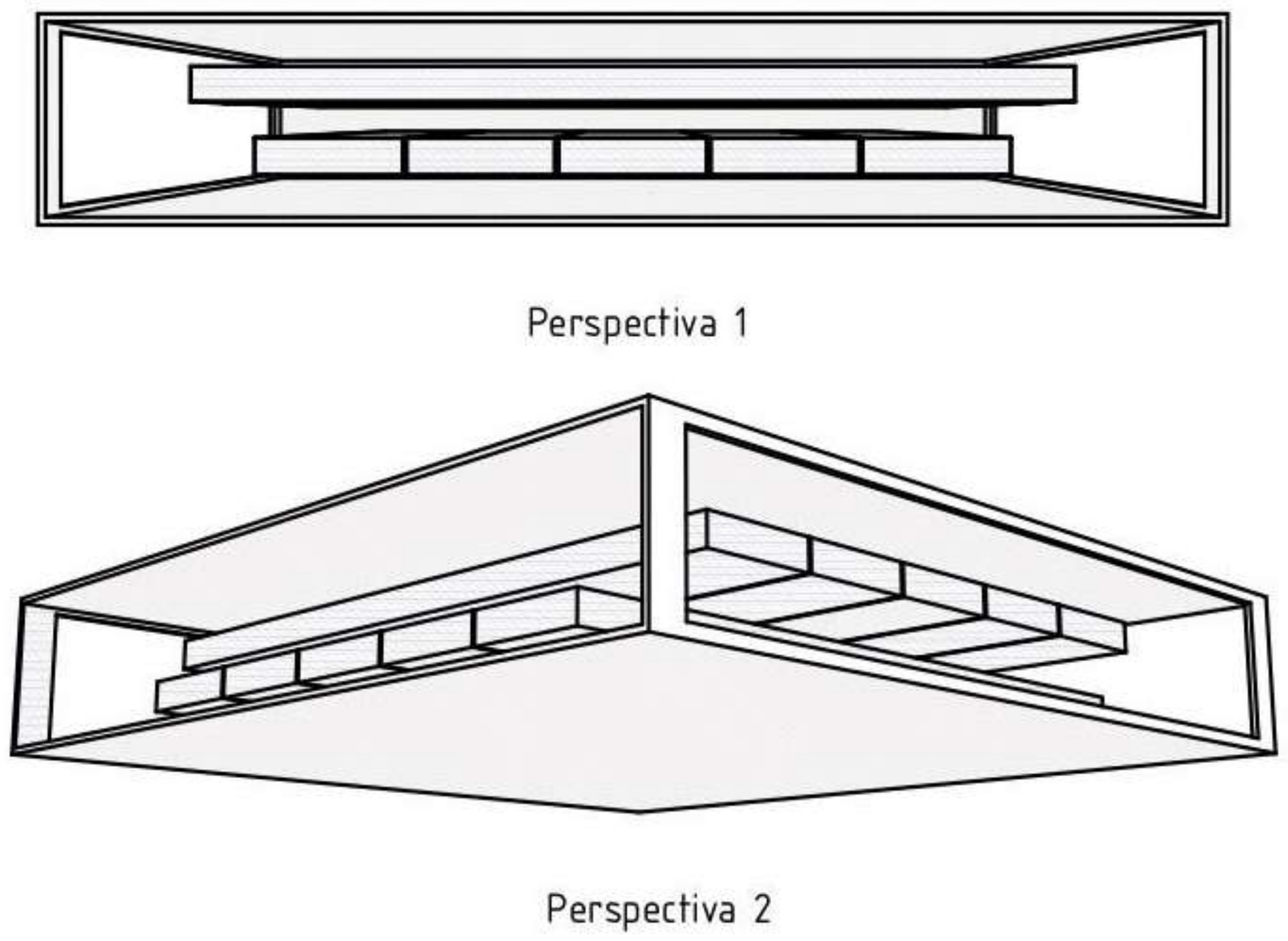


Fig. MWPC detection efficiency measured as a function of beam intensity for beam momentum of 5 GeV/*c*

- **Scintillators and MWPCs** prototypes were tested at the **CERN T10 test beam facility**
- The FNAL-NICADD scintillator option offers **good performance on light-yield output** (around 40 photoelectrons), **good time resolution** (< 2 ns), and represents a **low cost solution**
- The tested MWPC type is competitive, having high efficiency and **excellent position resolution** even beyond the required particle fluence (~ 4 Hz/cm^2). However, an important effort should be done to achieve a good time resolution

Plans for upcoming test beam 2024

Figure by Antonio Paz (UANL)



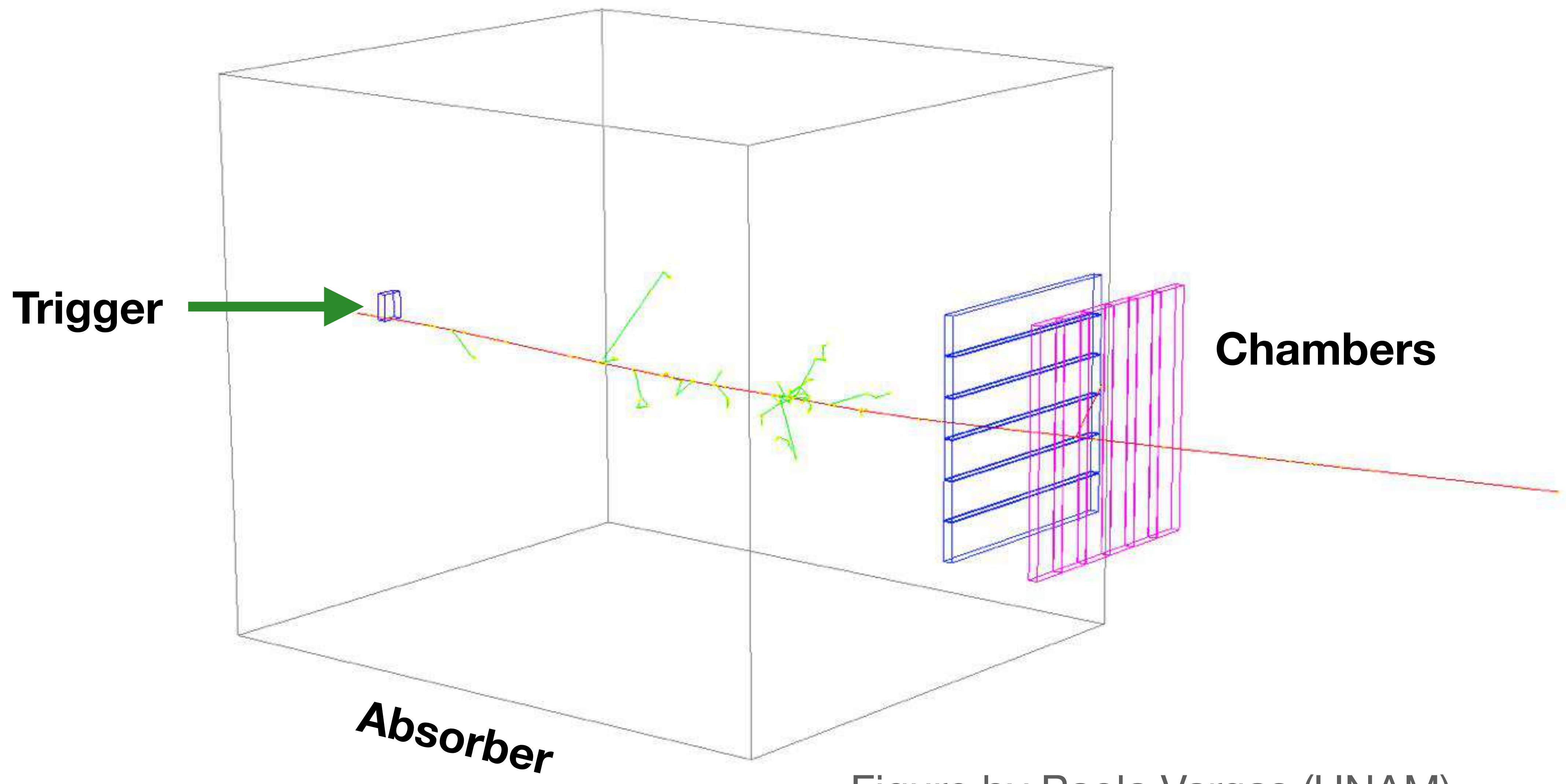


Figure by Paola Vargas (UNAM)

- **Build the first MID chambers based on plastic scintillators and an absorber**
- Test the muon tagging algorithm (ML, position, charge, time) using a pion and a muon beams
- Test commercial electronics specifically developed for arrays of SiPM
- There is an effort to develop a front-end card, if the first version is ready on time, we will also test it at T10

Summary

ALICE 3 will provide access to further understand the hottest- and longest-lived QGP available in any laboratory, with the MID playing an important role in this exploration

- Simulations of MID with two layers of plastic scintillator were performed. BDT were employed to mitigate misidentification of muons

- **Both magnetic and non-magnetic absorbers gave similar performance** and their results are compatible with those reported in the LOI

- **Radiation load expected does not present a problem for plastic scintillators + SiPM**

- Plastic scintillator paddles and MWPCs were studied at the CERN T10 test beam facility, were the plastic scintillators showed an overall good performance in light-yield output and timing

Scintillators represent an excellent candidate for the MID

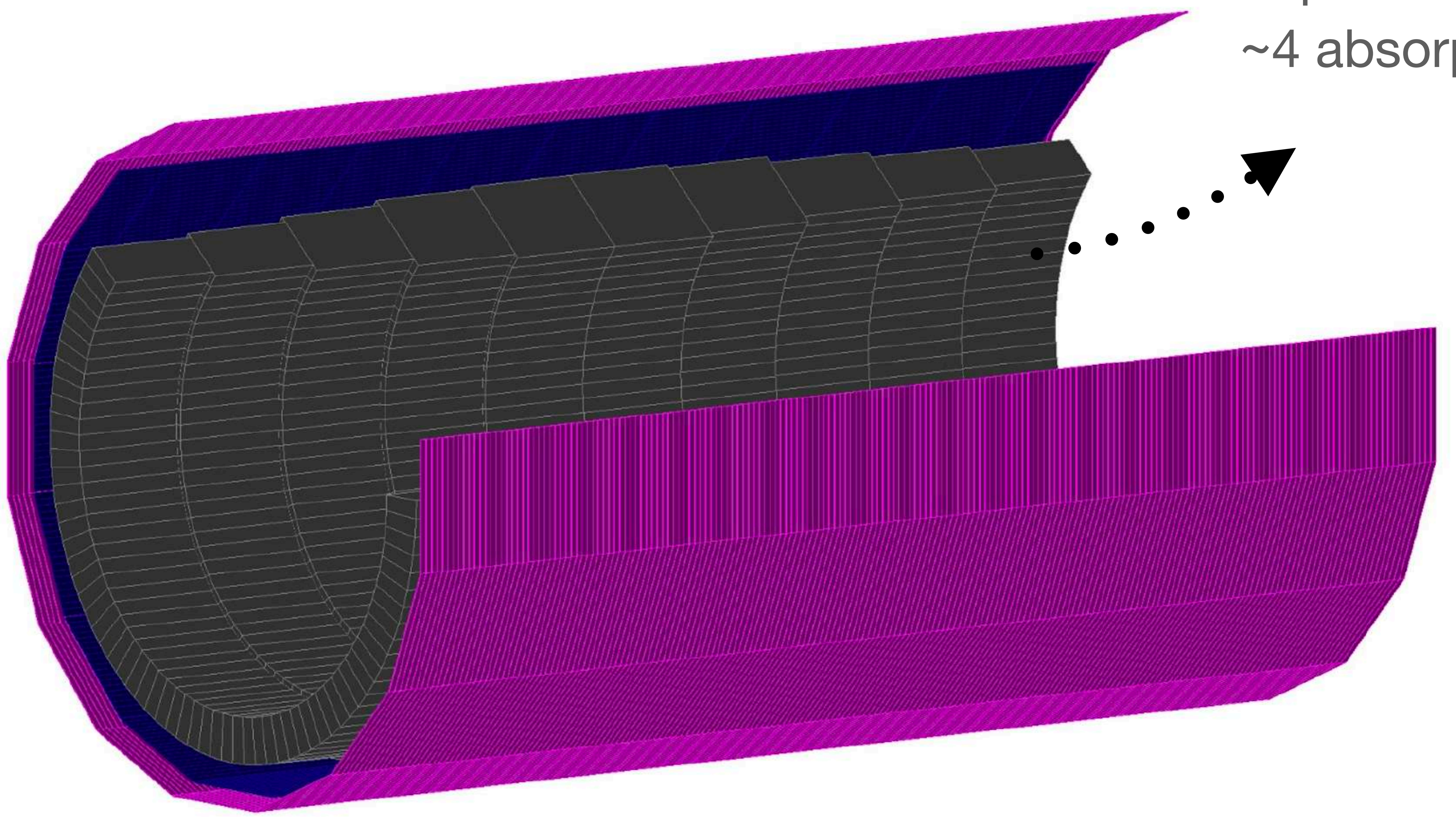
(very simple, robust, cheap, excellent timing performance)

THANK YOU

Backup

MID specifications

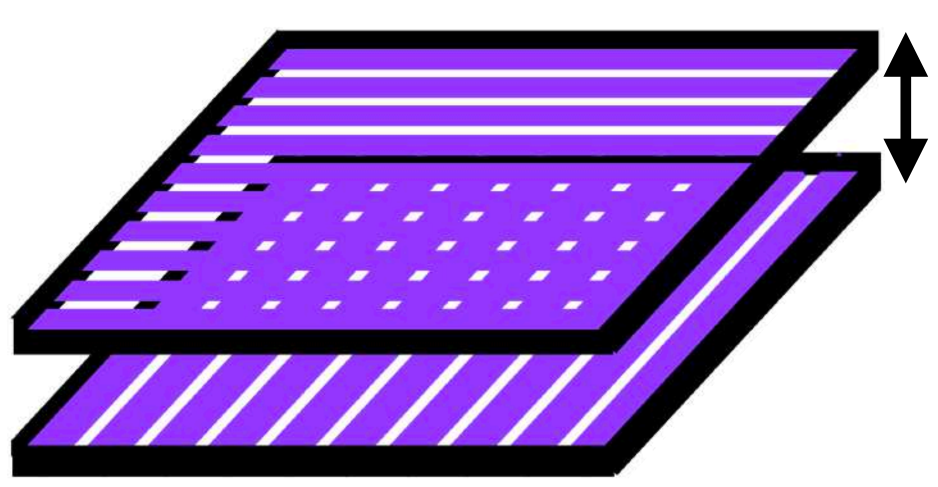
$|\eta| < 1.25$



Iron absorber, pseudorapidity-dependent thickness: ~4 absorption lengths

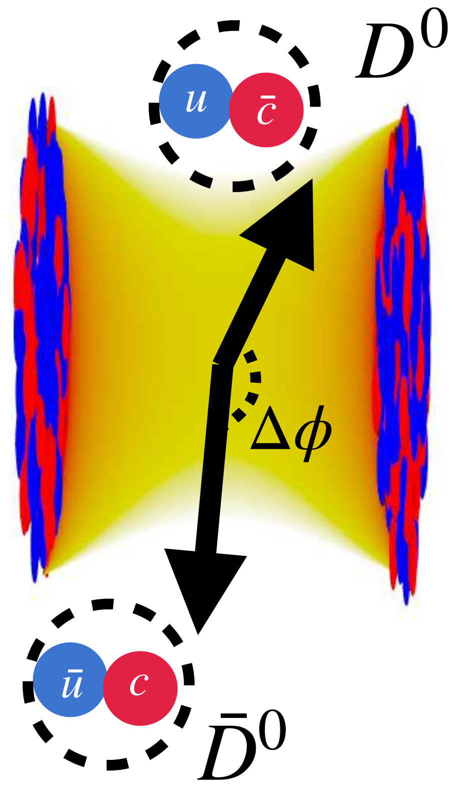
	Absorber	MID layer 1	MID layer 2
Inner radius (m)	220	301	311
Outer radius (m)	290	302	312
z range (m)	10	10	10.5
No. sectors in z	9	10	10
No. sectors in φ	1	16	16
Scint. bar length (cm)		99.8	123.5
Scint. bar width (cm)		5.0	5.0
Scint. bar thickness (cm)		1.0	1.0

No. of bars
4048 in layer 1
3200 in layer 2



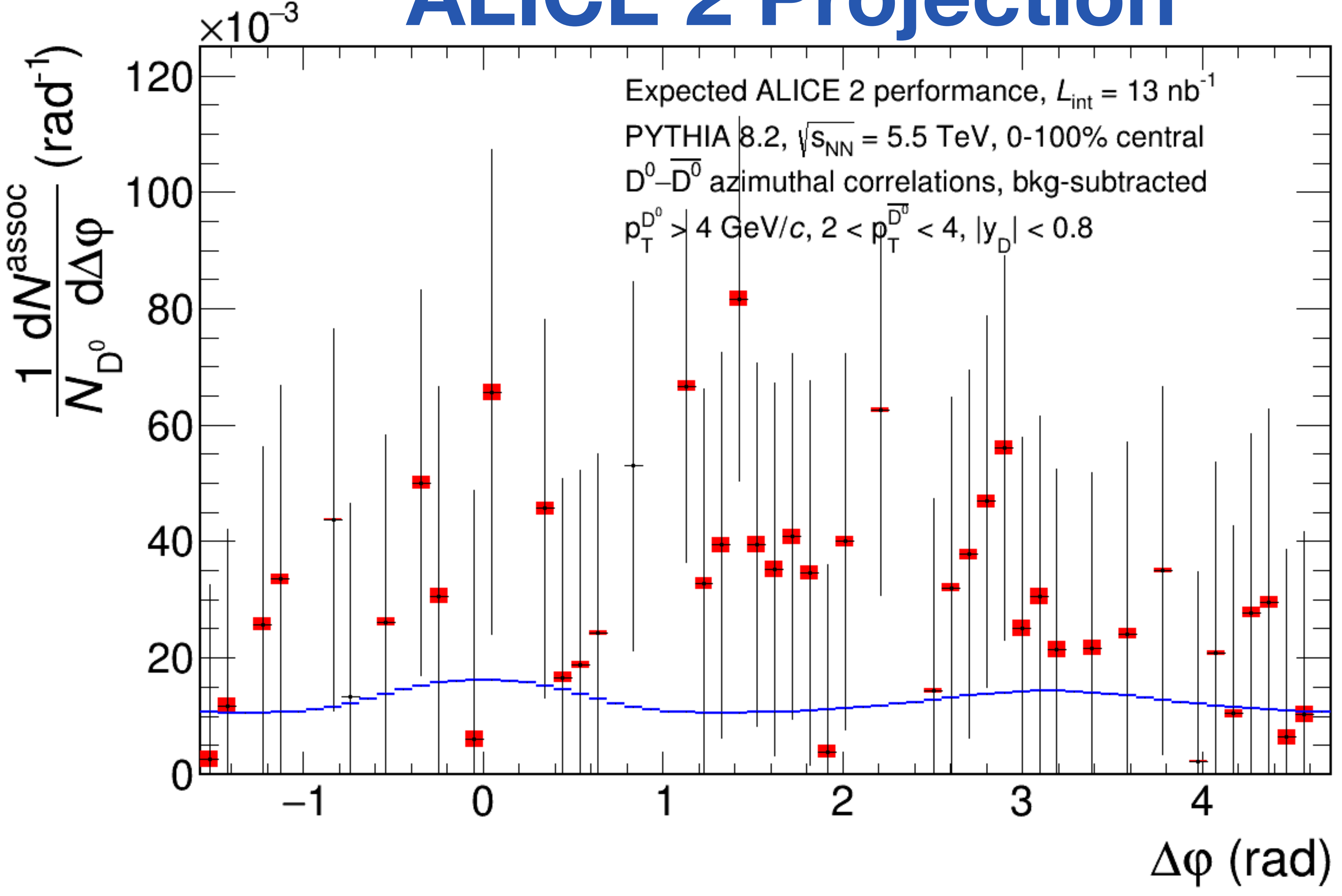
One of the proposals for the MID are **plastic scintillators equipped with wavelength-shifting fiber and SiPM for readout**

$D\bar{D}$ azimutal correlations

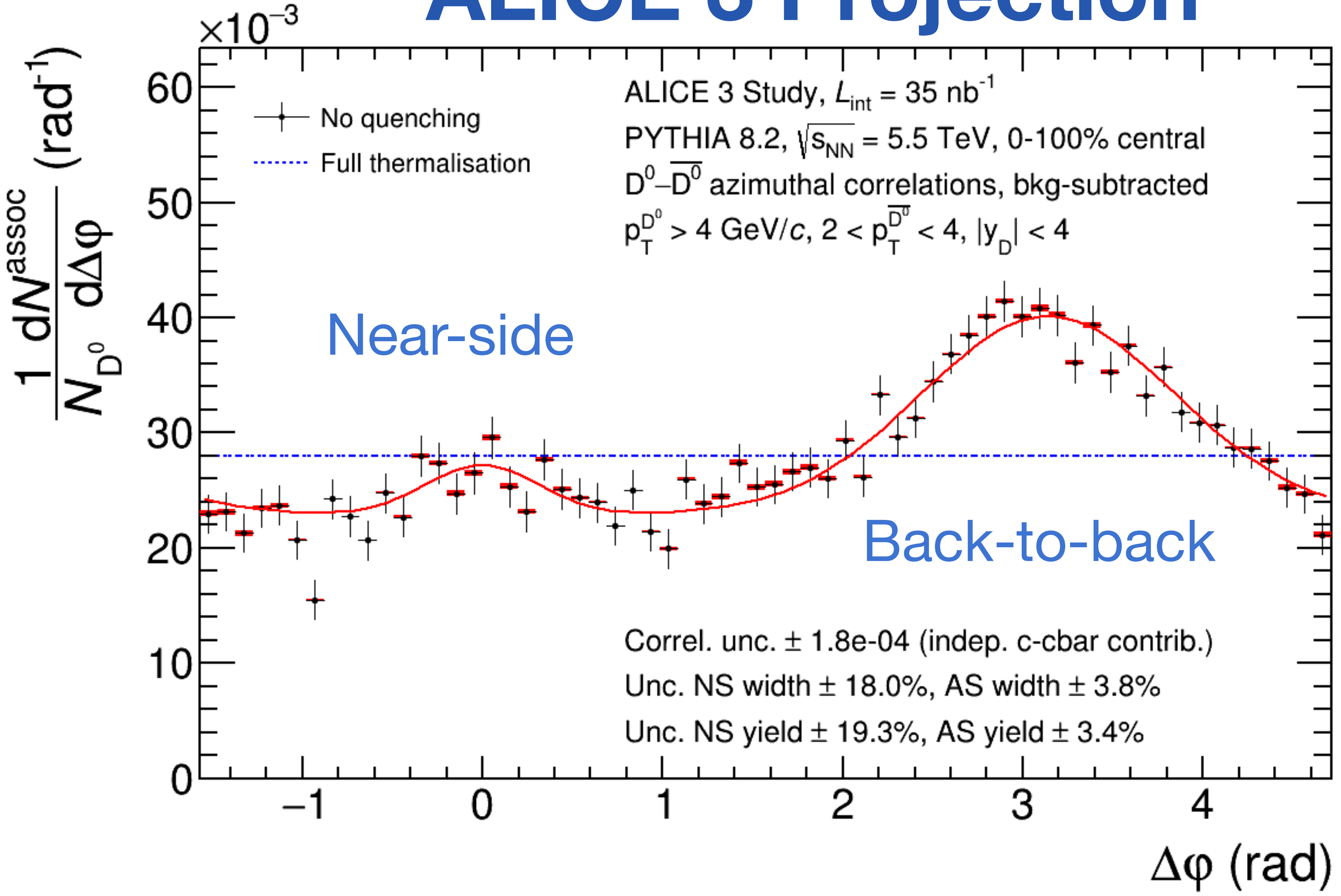


- Broadening in azimuthal correlation: medium-induced effect (Pb-Pb collisions)
- Significant broadening is expected at small p_{T}
- Measurement needs good purity, efficiency and high acceptance

ALICE 2 Projection



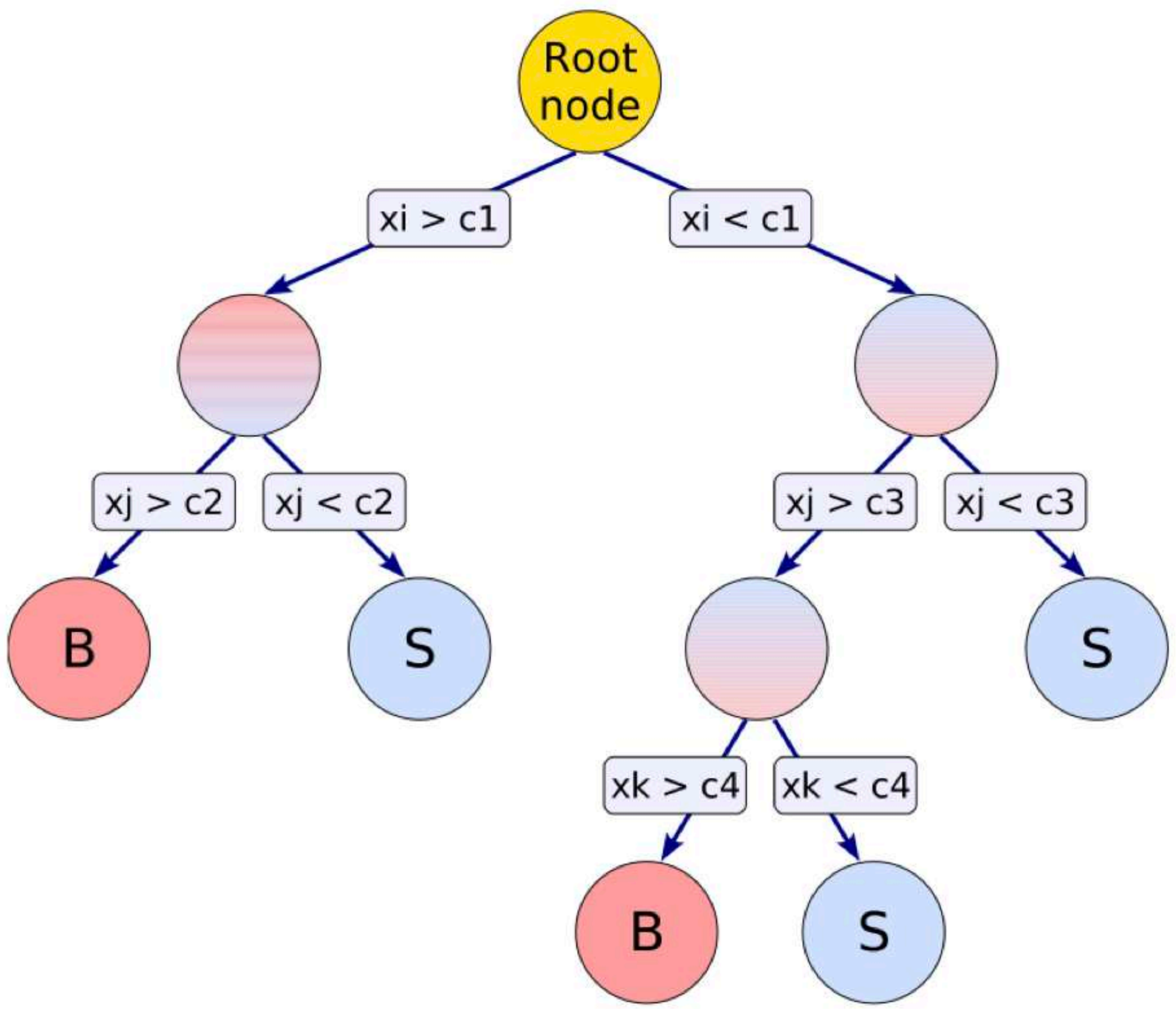
ALICE 3 Projection



Decision Trees

How do we get the most optimal cuts in our selection criteria?

A Decision Tree is a binary tree structured classifier

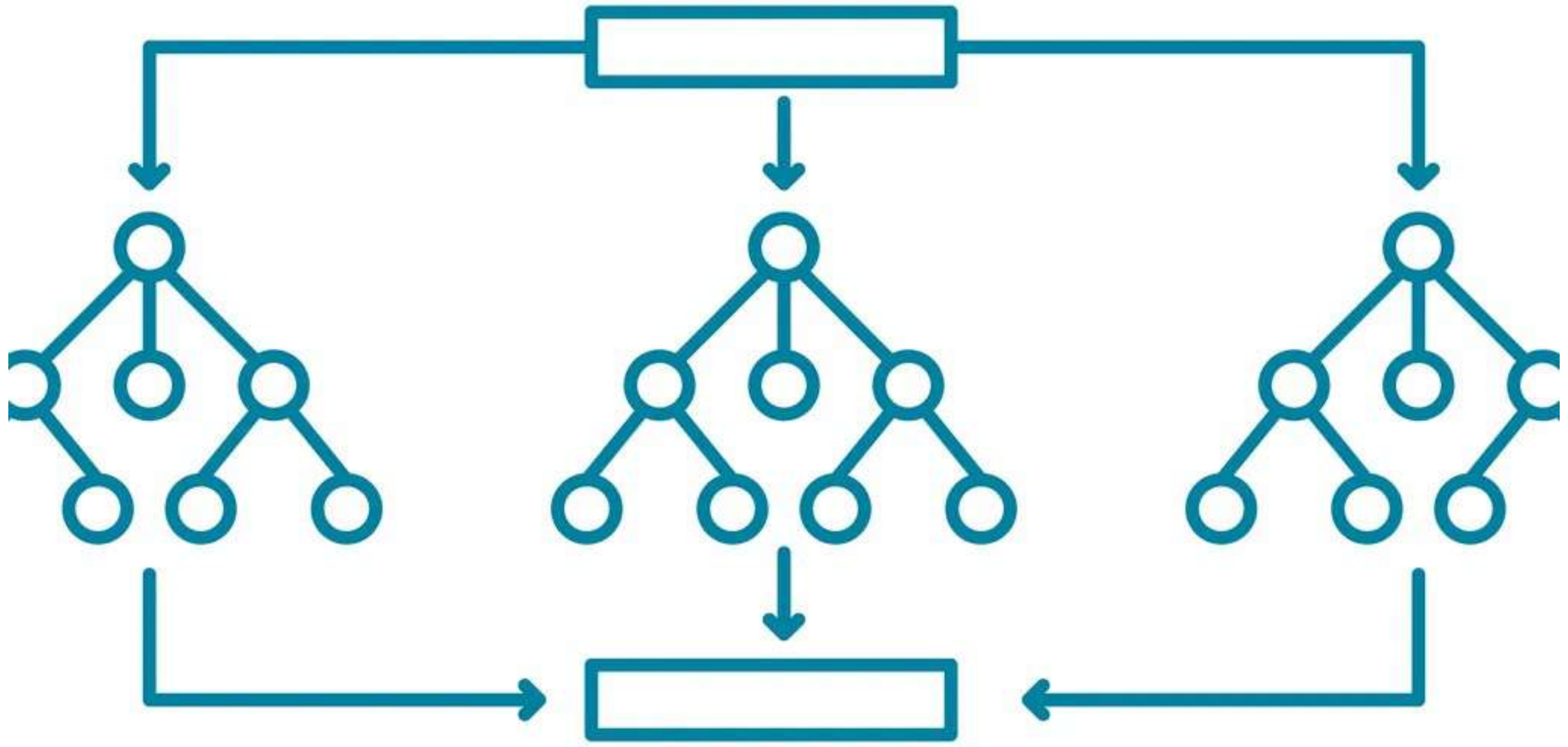


The algorithm searches for optimal splits based on specific criteria

Little tuning is required in order to obtain reasonably good results

Boosted Decision Trees (BDT)

The boosting of a decision tree extends this concept from one tree to several trees which form a forest



An event is classified on the basis of a majority vote done by each tree of the forest.

A **disadvantage** of BDT: large training samples needed

30 M data sample: 10 M for testing and training

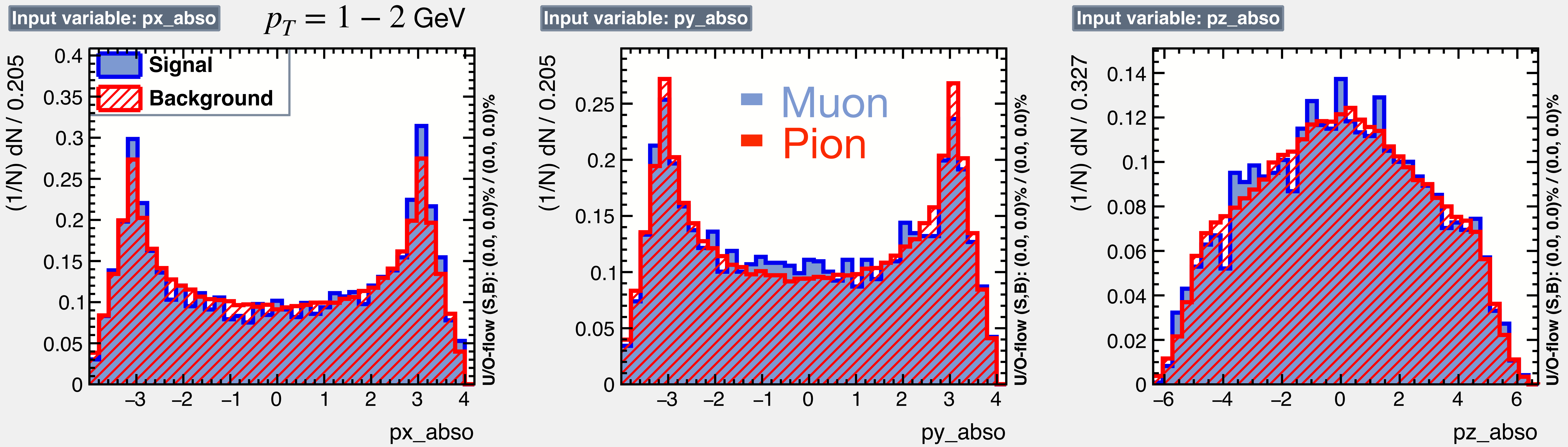
BDT training

How to pick a set of variables for the training of the BDT?

Several previous studies gave us an idea

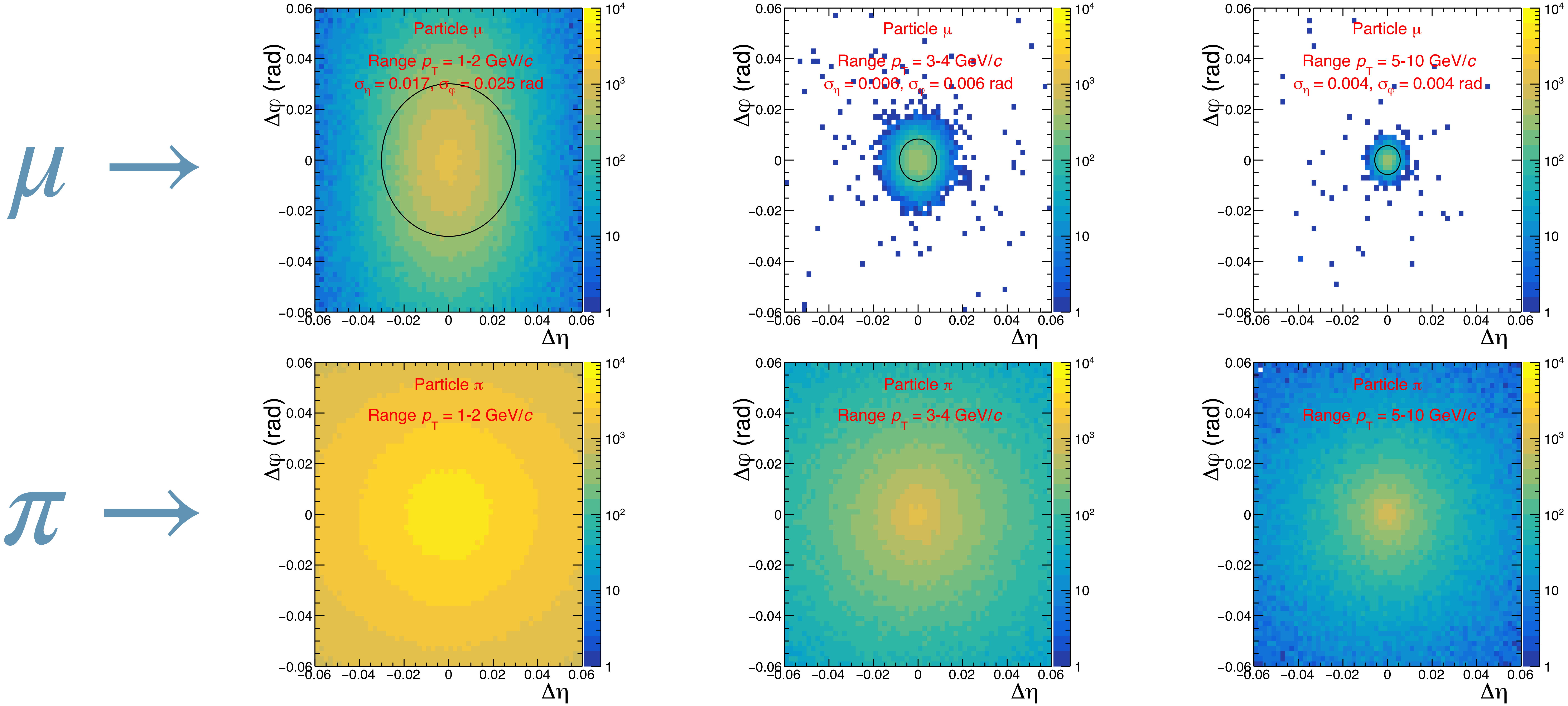
- Kinematic variables available

(momentum before the absorber)



BDT training

- Matching window $(\Delta\eta, \Delta\phi)$



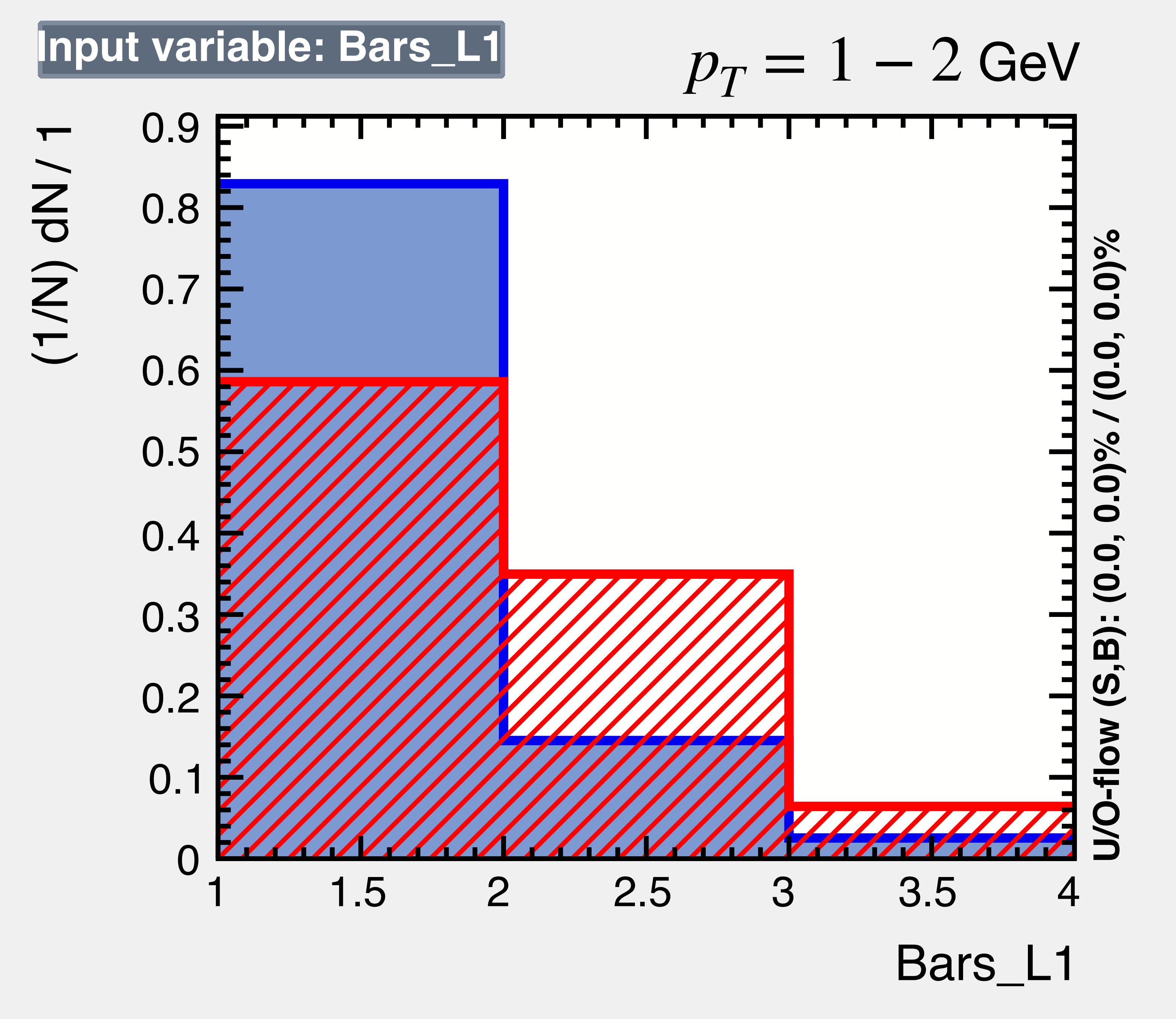
$\Delta\phi = \phi^{\text{extr.}} - \phi^{\text{bar}}$

$\Delta\eta = \eta^{\text{extr.}} - \eta^{\text{bar}}$

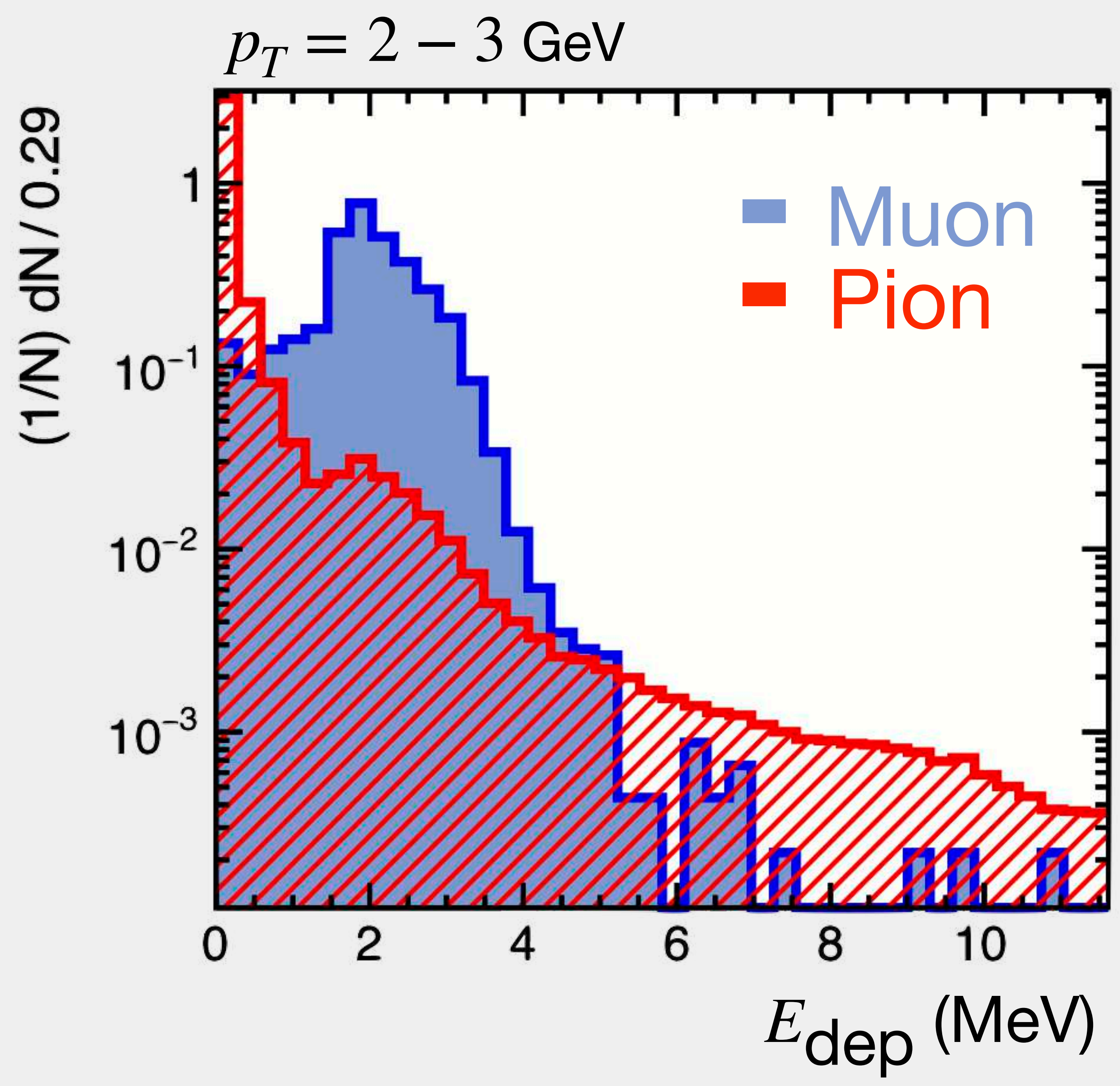
The **muon candidates** are those within the MW: $R = \sqrt{\sigma^2_{\Delta\eta} + \sigma^2_{\Delta\phi}}$

BDT training

- Number of bars activated around the extrapolation

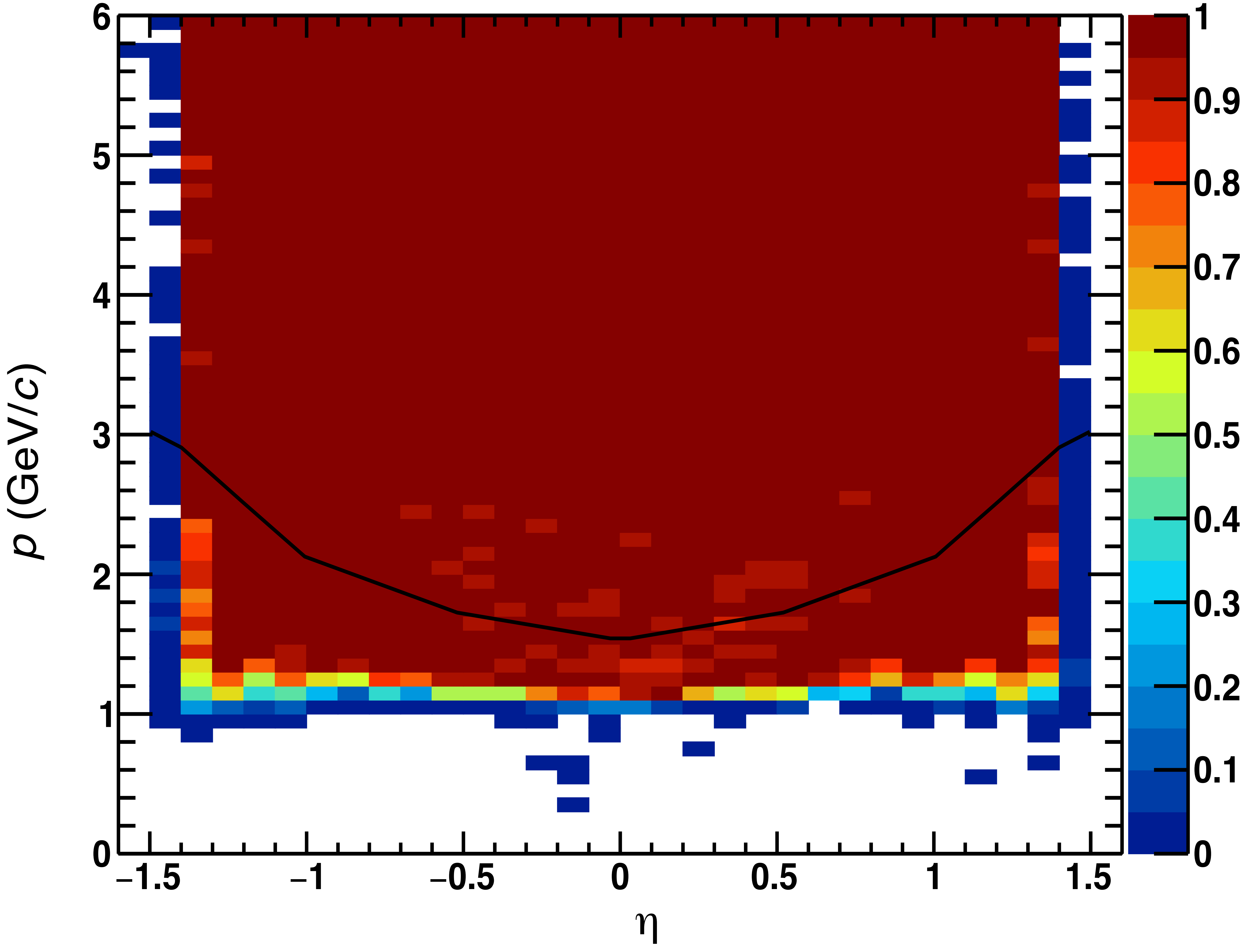


- Highest energy deposition in the activated bars around to the extrapolation



Difference coming from the particle shower created by hadrons

Single muon acceptance vs p and pseudorapidity



Solid black line:

approximate minimum momentum to have non-zero J/ψ acceptance down to

$p_T = 0$ and $|y| < 1.5$

(Calculation by Antonio Uras)

Optimization of the absorber leads to good acceptance for J/ψ