Measurement of isolated photon-hadron correlations in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the ALICE experiment at LHC

Run 2 data: 2015-2018

Séminaires doctorants - Carolina Arata
27/03/23

Thesis supervisors
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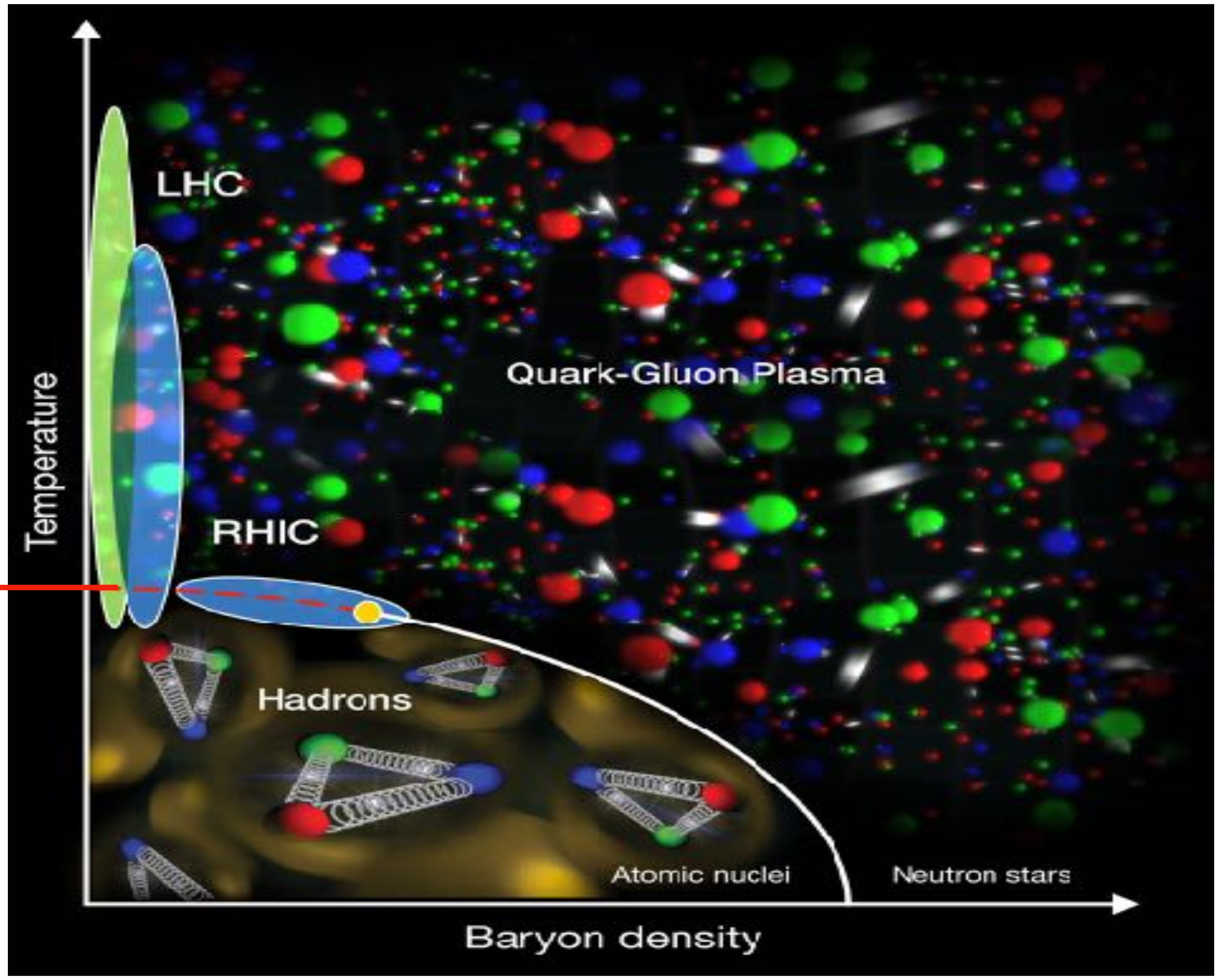
Julien Faivre (UGA - LPSC)

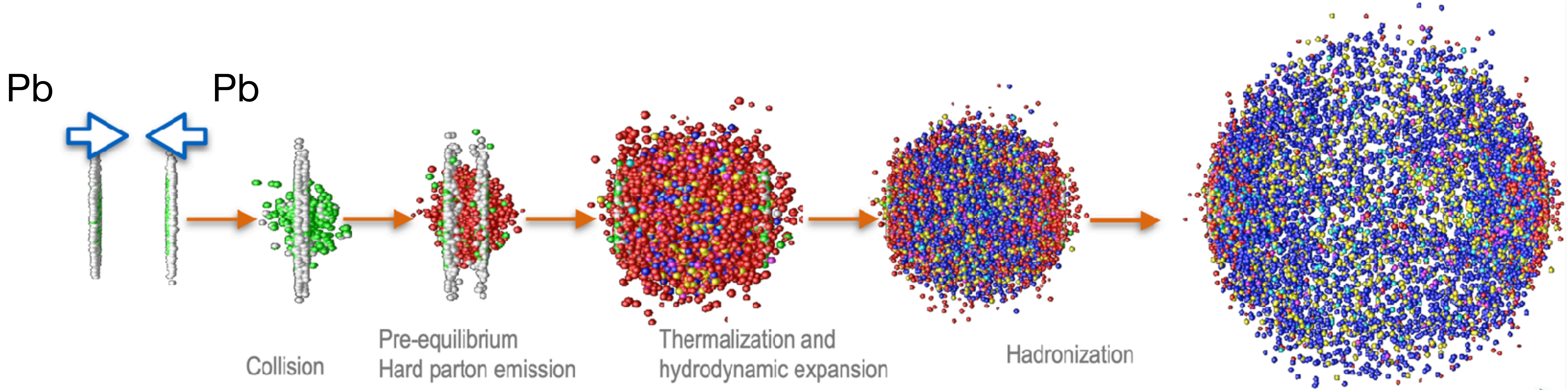
Dense QCD matter: quark-gluon plasma

- The QCD phase diagram predicts a phase transition at high energy density from ***hadronic matter*** to a colour-deconfined medium, the ***quark-gluon plasma*** (QGP)

- **WHY?** Study the strong interaction
- **HOW?** Via ultra-relativistic heavy-ion (nuclei) collisions
- **WHERE?** ***LHC at CERN***, RHIC USA

150 MeV





Probes for the QGP

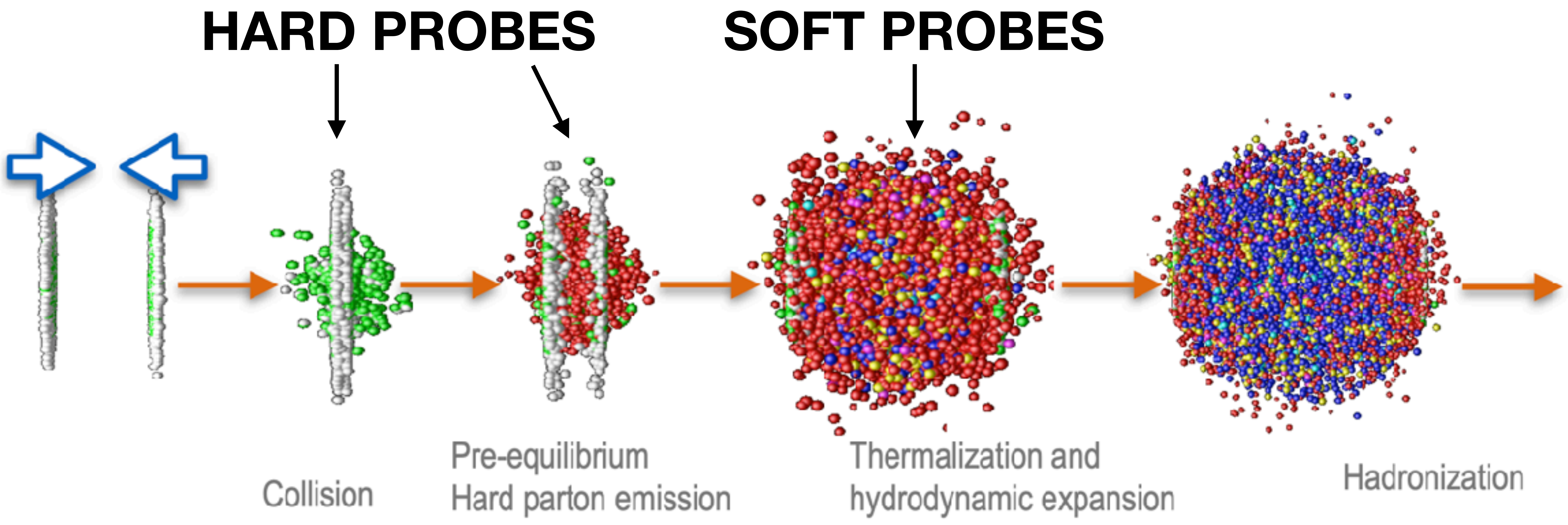
- **SOFT PROBES**: low energy particles ($E < 5$ GeV)

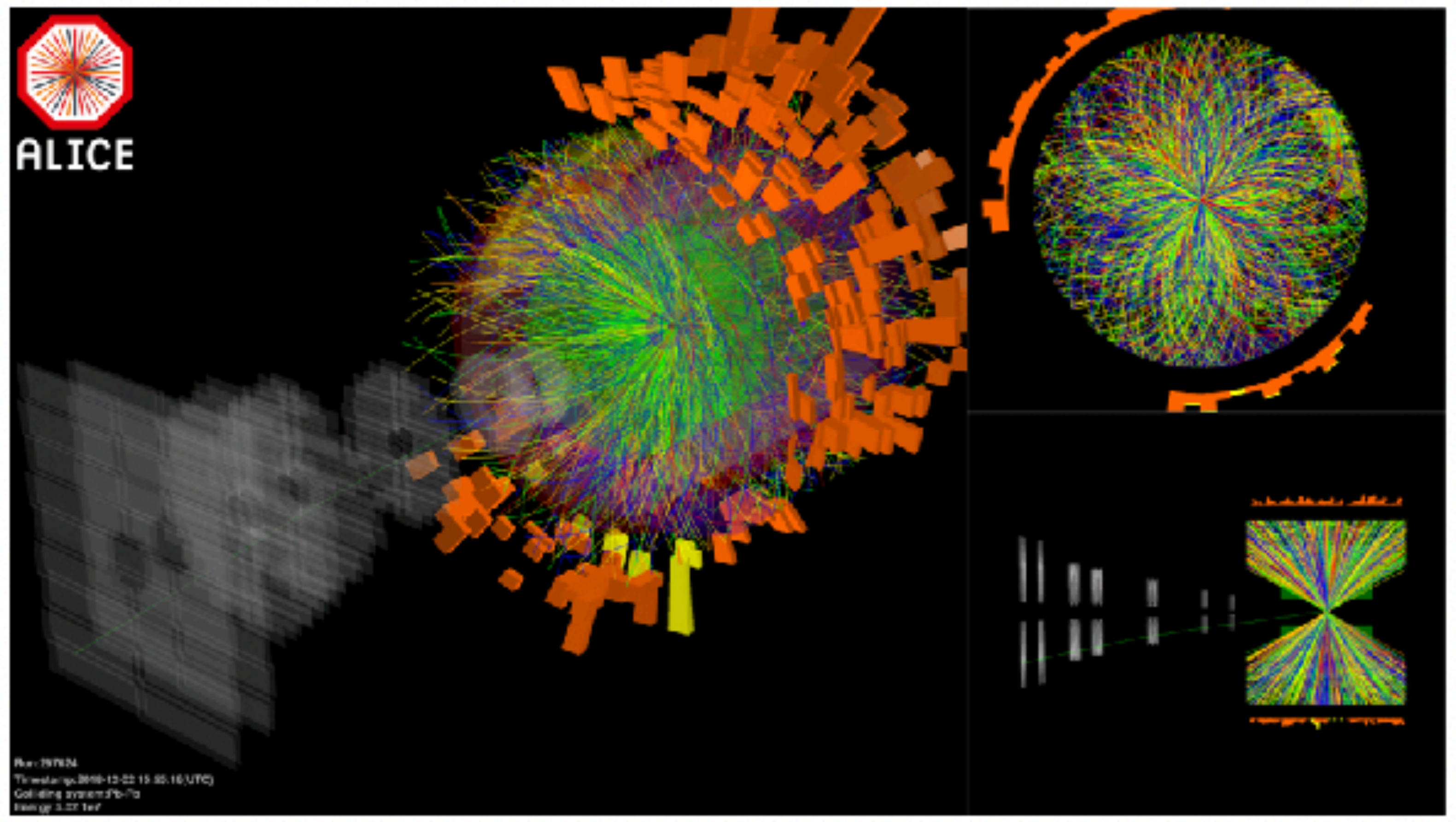
  to study thermodynamic and hydrodynamic properties and collectivity effects of the QGP

- **HARD PROBES**: High-energy partons (quarks and gluons) produced in the early stage of the collision

  to study how particles interact with the QGP medium and lose energy.

All particles not coming from the hard process are **underlying event (UE)** for the **HARD PROBES**





Hard Probes

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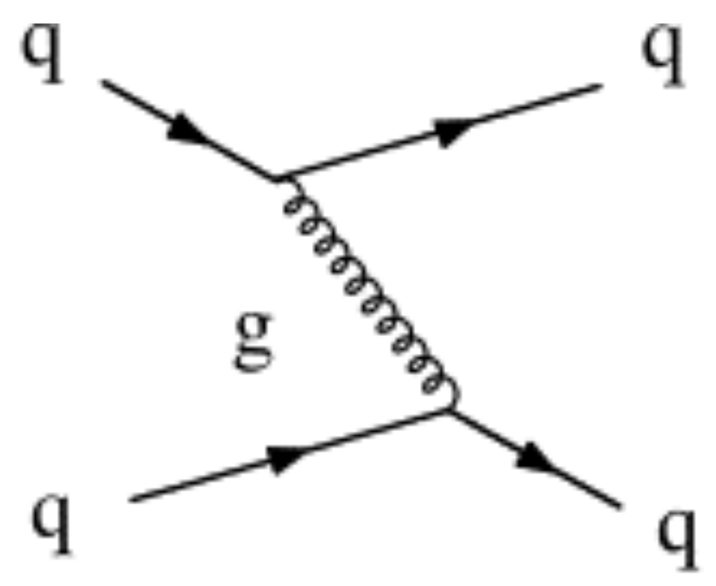
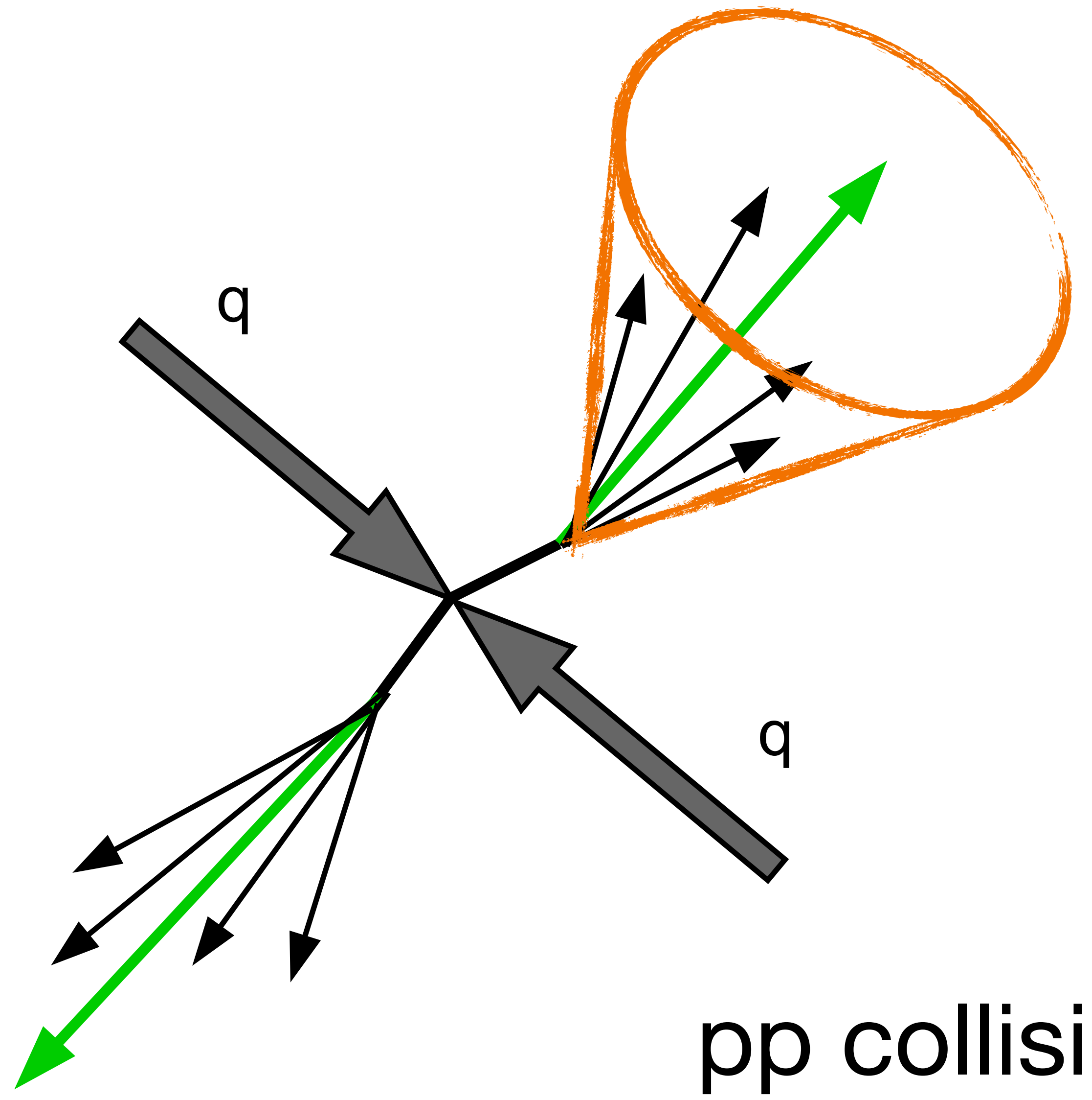
- In vacuum (collisions pp):

  partons fragment into a **jet of particles**





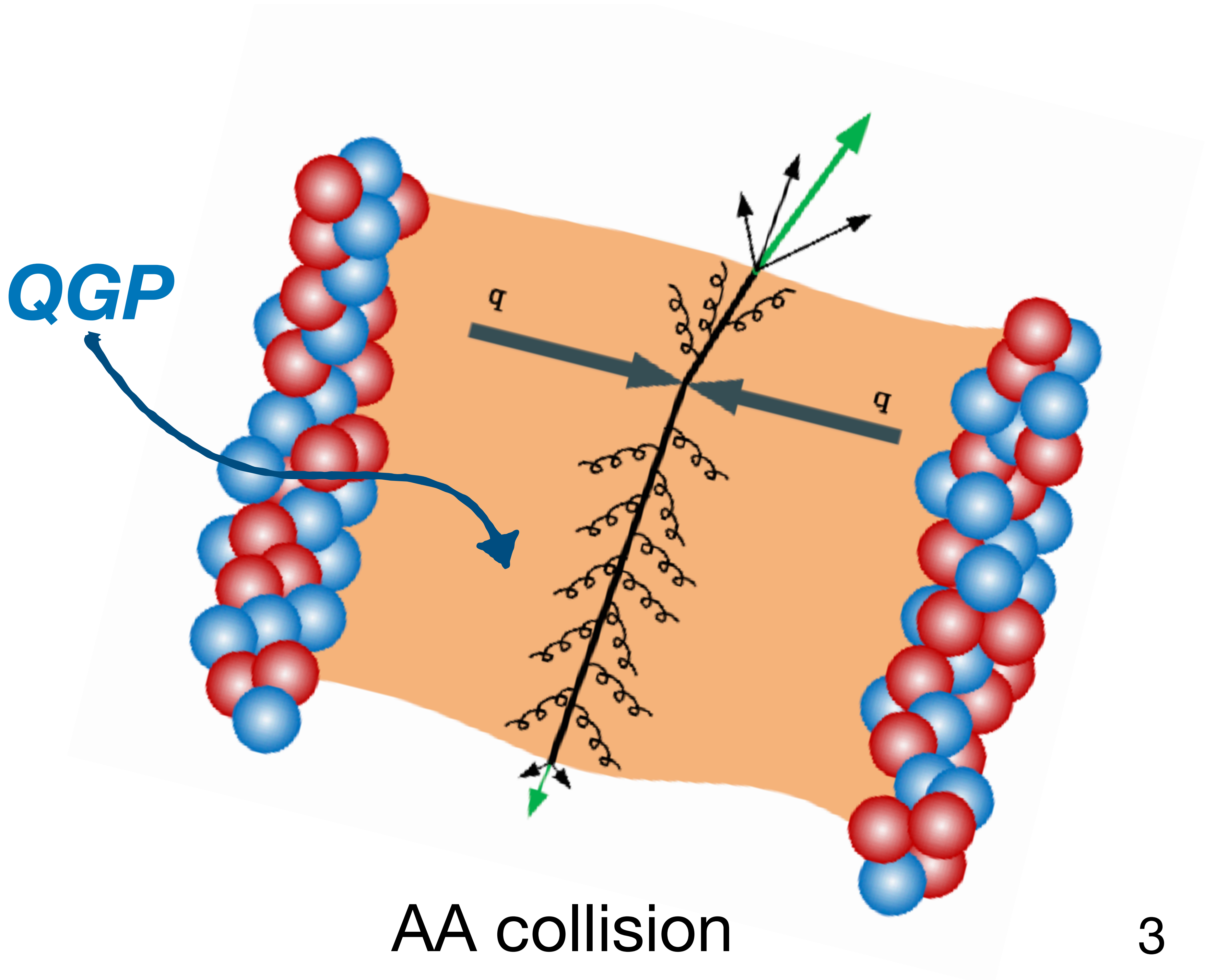
pp collision

- In Pb-Pb collisions:

  partons traverse the QGP,

  lose energy via ***radiational*** (gluon emission) **+** collisional processes, then fragment into a **jet of particles**

Loss of energy in medium = Jet Quenching



AA collision

- Observable: ***fragmentation function*** $D(z_{\mathrm{T}}) = \frac{1}{N^{trig}} \frac{dN^{ch}}{dz_{\mathrm{T}}}$,

where $z_{\mathrm{T}} = p_{\mathrm{T}}^{hadrons} / p_{\mathrm{T}}^{parton}$ (p_{T} = transverse momentum)

$$D(z_{\mathrm{T}})_{\mathrm{AA}} \neq D(z_{\mathrm{T}})_{\mathrm{pp}}$$

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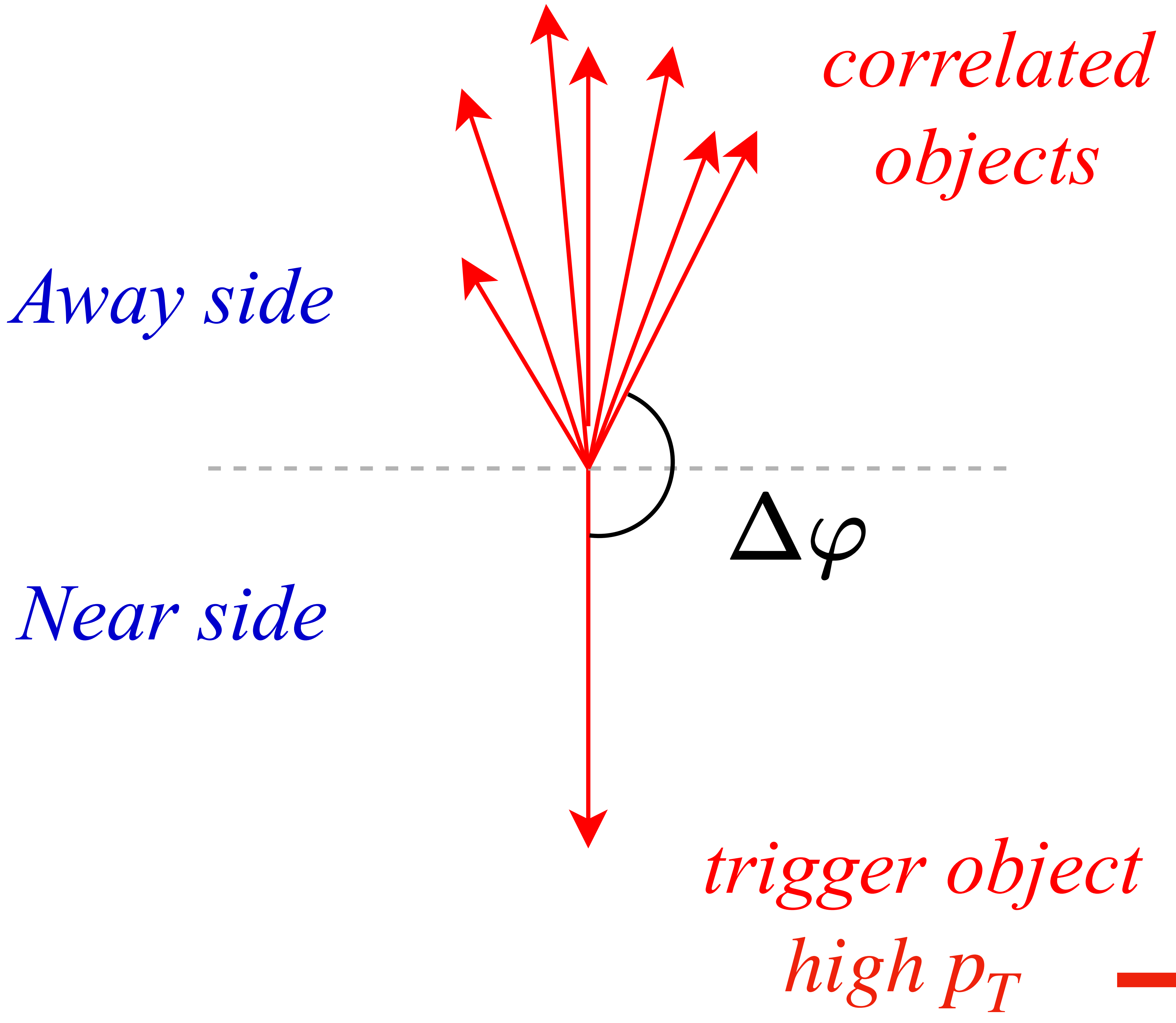
How can we quantify jet quenching?

Azimuthal correlations distribution

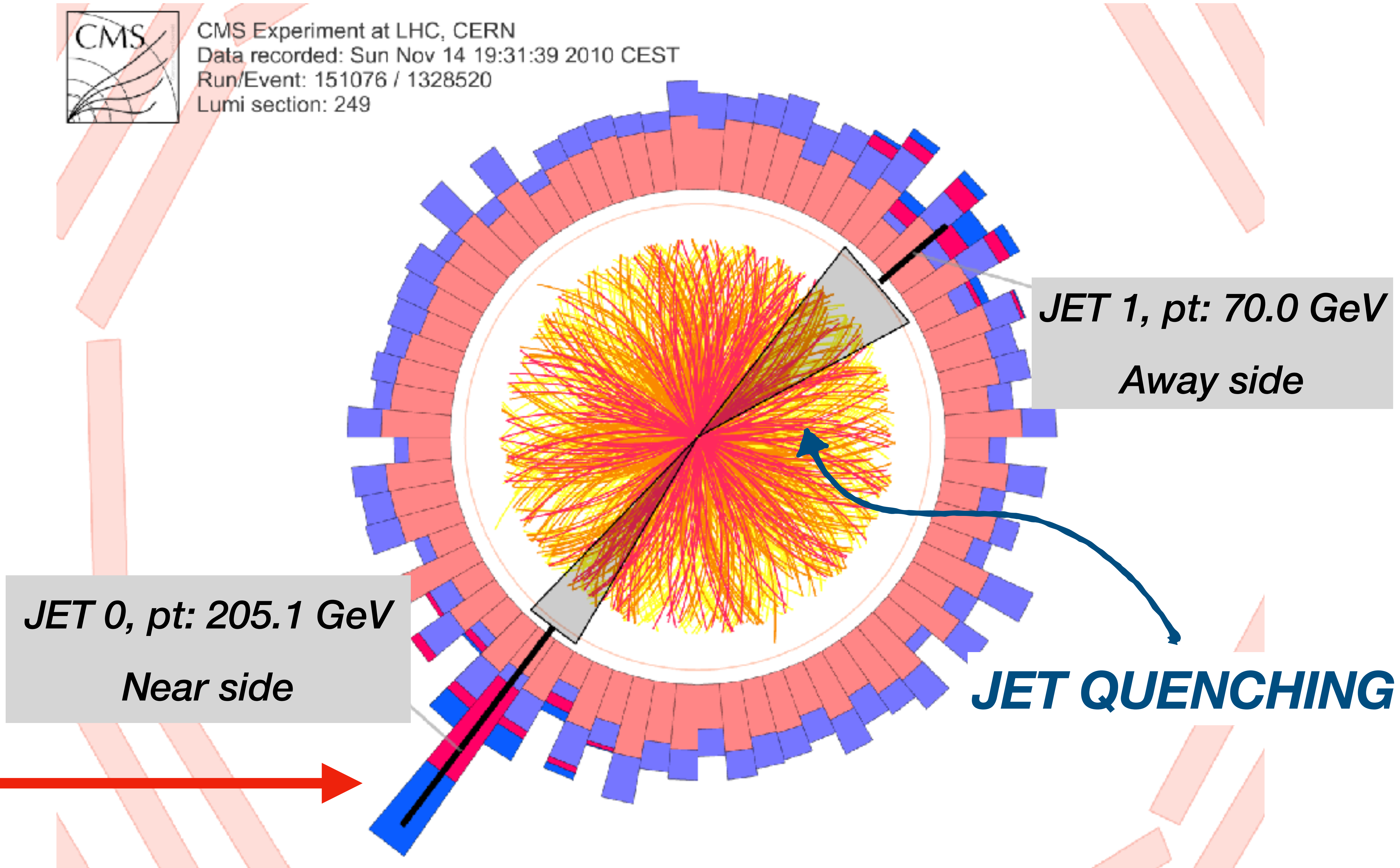
between the trigger and associated particles

$$\Delta\varphi = (\varphi^{trig} - \varphi^{assoc})$$



Jet-jet correlations:

@ CMS experiment-LHC, PbPb, $\sqrt{s_{NN}} = 2.76$ TeV



Suppression in AA → medium!

How can we quantify jet quenching?

Azimuthal correlations distribution

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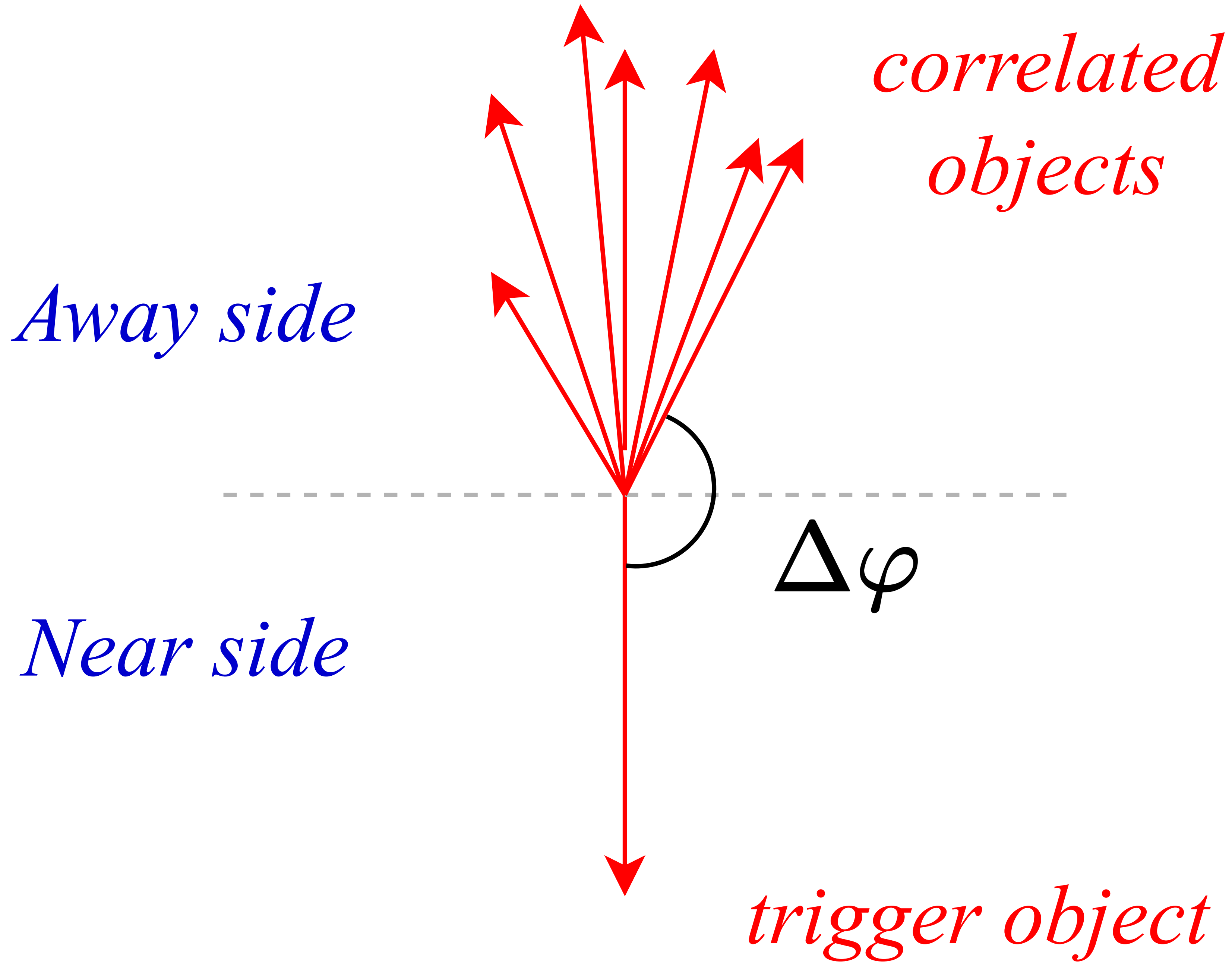
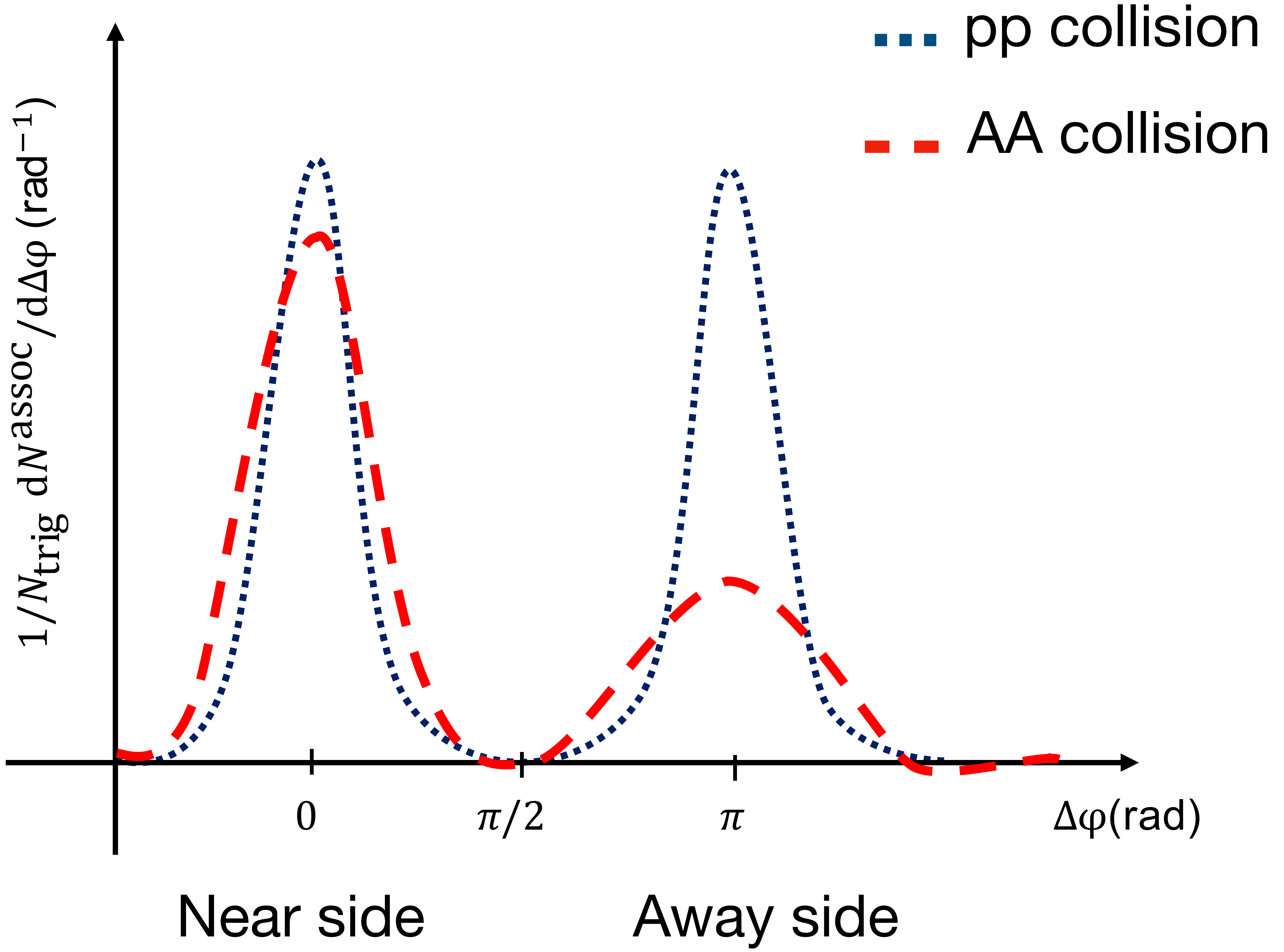
$$\Delta\varphi = (\varphi^{trig} - \varphi^{assoc})$$



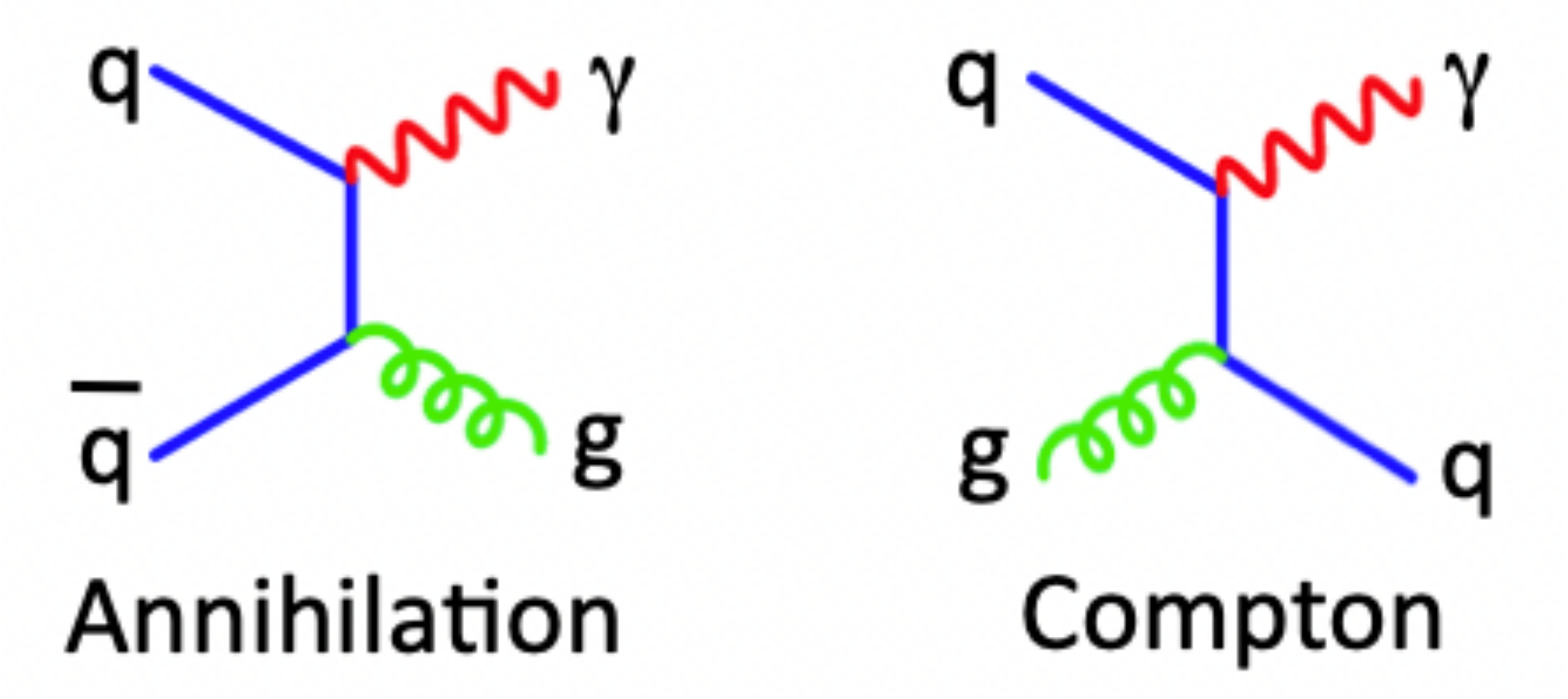


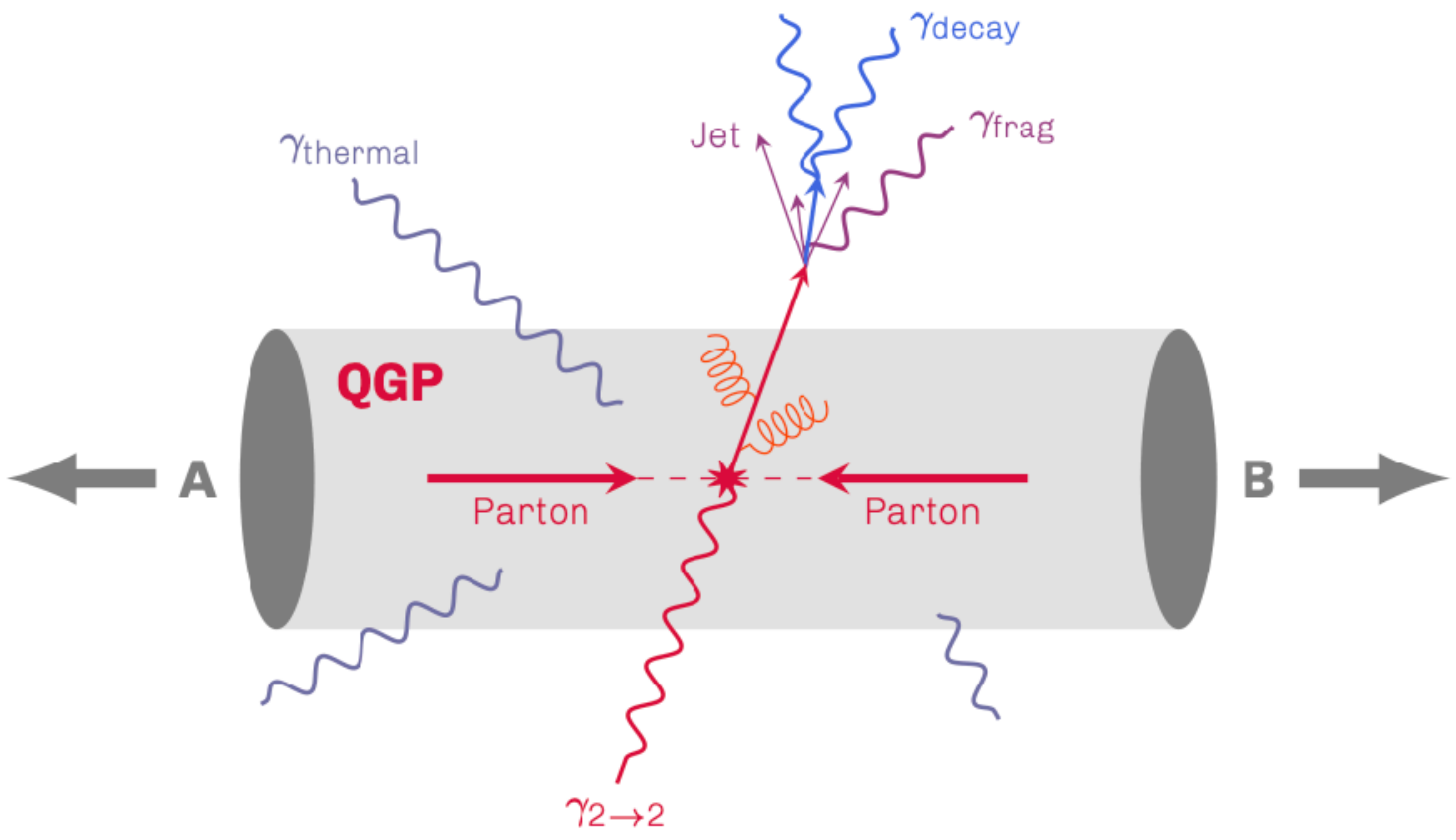
Trigger objects like jets or hadrons **not ideal:**

their parent partons can lose energy in the medium

$p_T^{trigger} \neq p_T^{parton}$ ***BIASED REFERENCE***

Photons to study jet quenching

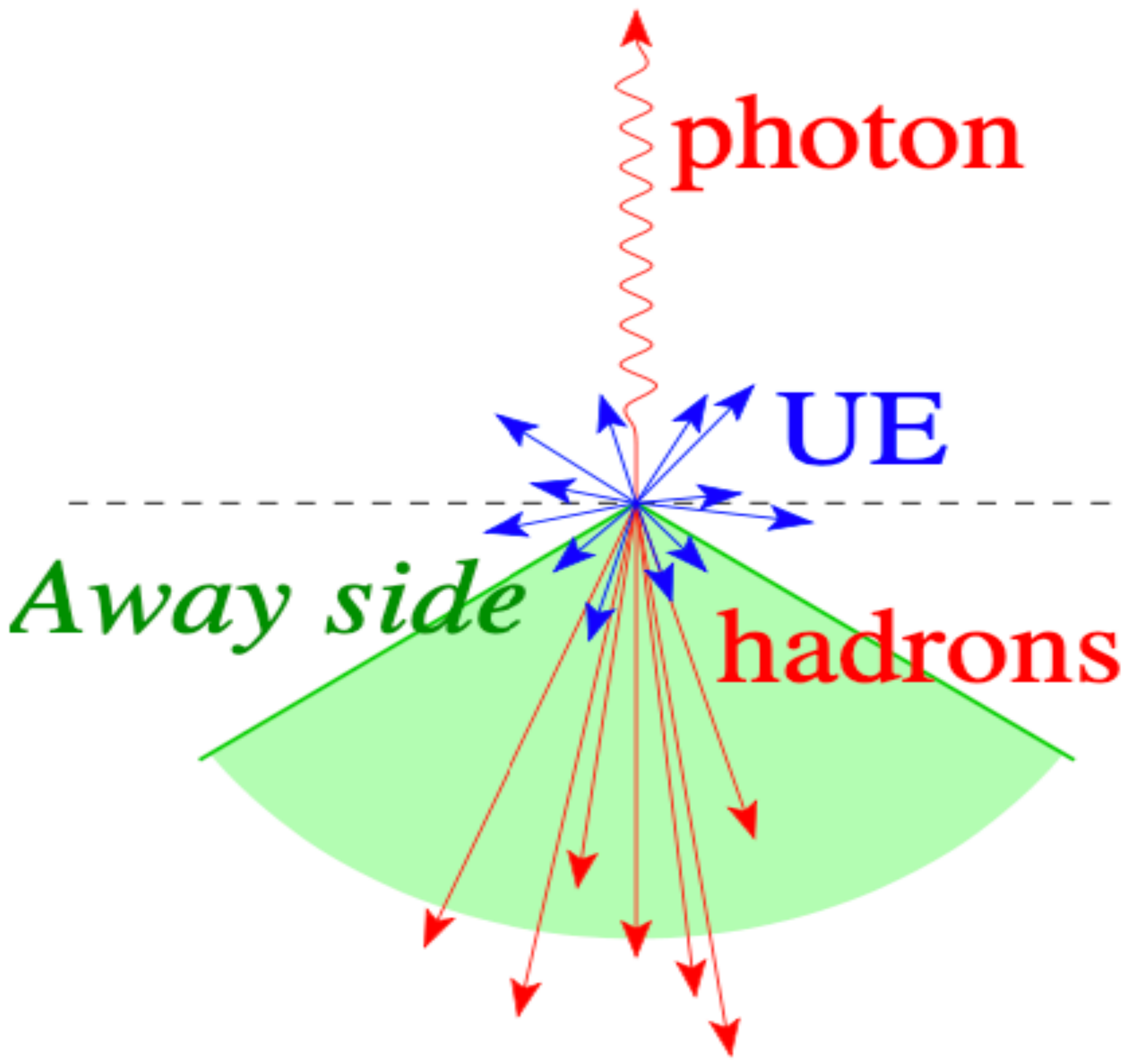


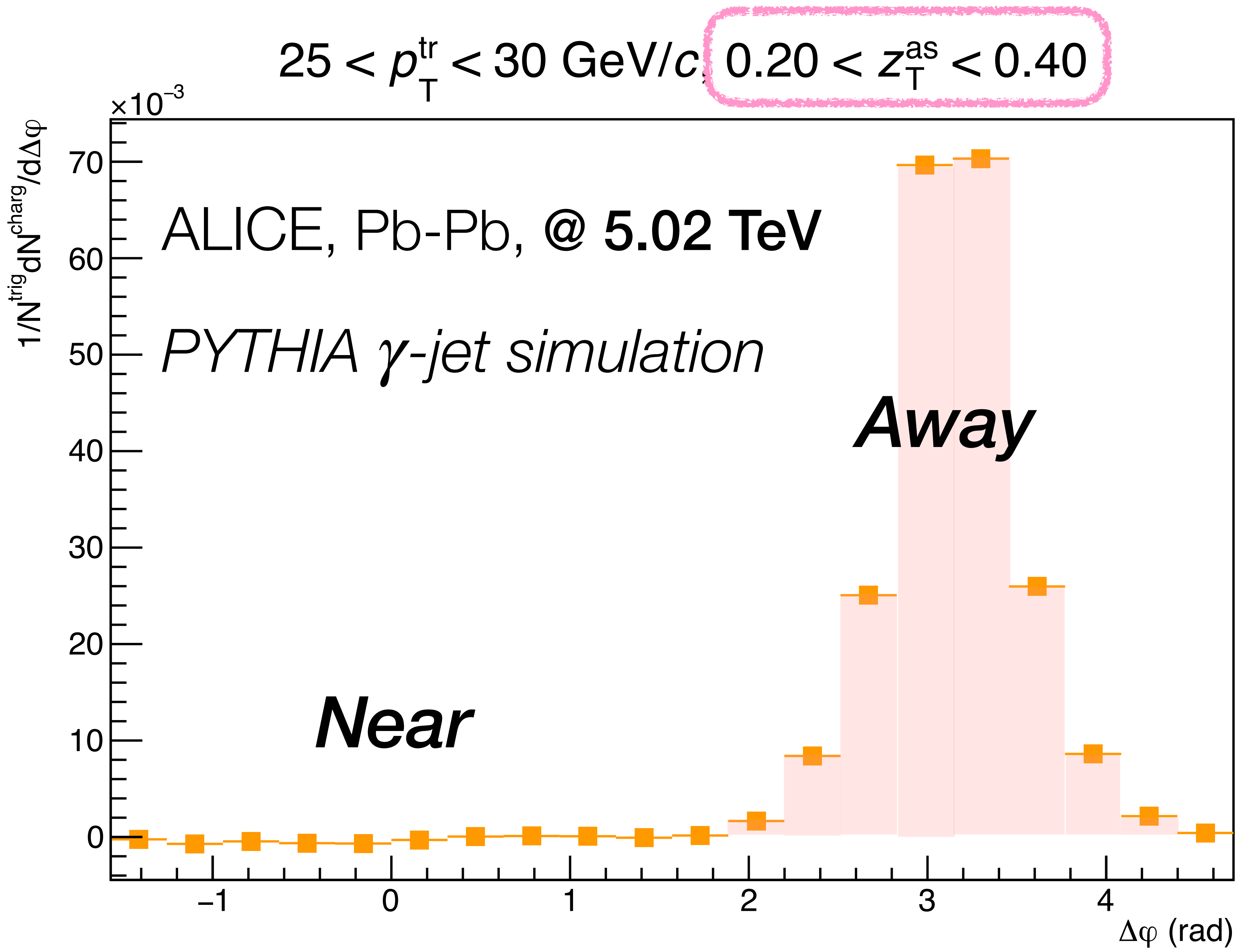


- Photons: neutral to colour, ***not affected*** by QCD medium → valuable probe
- γ_{prompt} from 2→2 processes, ***no hadrons*** emitted in the direction of the photon → ***ISOLATED***

$\gamma_{2\to2}$ allow to **tag the initial energy** of the parton $p_T^{\gamma} \approx p_T^{parton}$ = ***REFERENCE***

$\gamma_{2\rightarrow2}$ - hadron correlations





- *Azimuthal correlations distribution* $\Delta\varphi = (\varphi^{trig} - \varphi^{assoc})$
- $z_T = p_T^{hadr}/p_T^{\gamma}$ → **Observable:** the hadrons p_T distribution $D(z_T) = \frac{1}{N^{trig}}\frac{dN^{ch}}{dz_T}$

$\gamma_{2\to2}$ - hadron correlations

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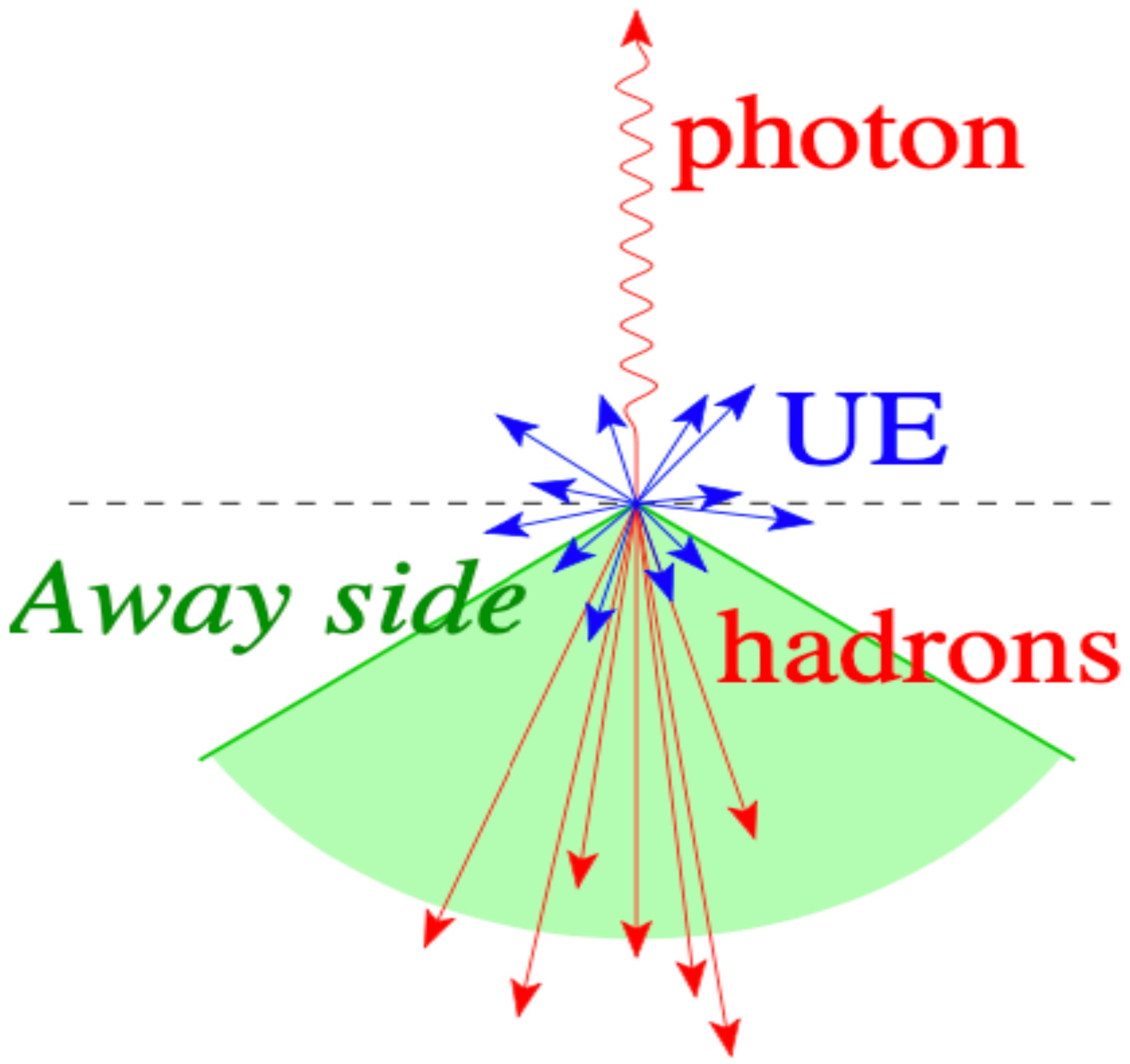
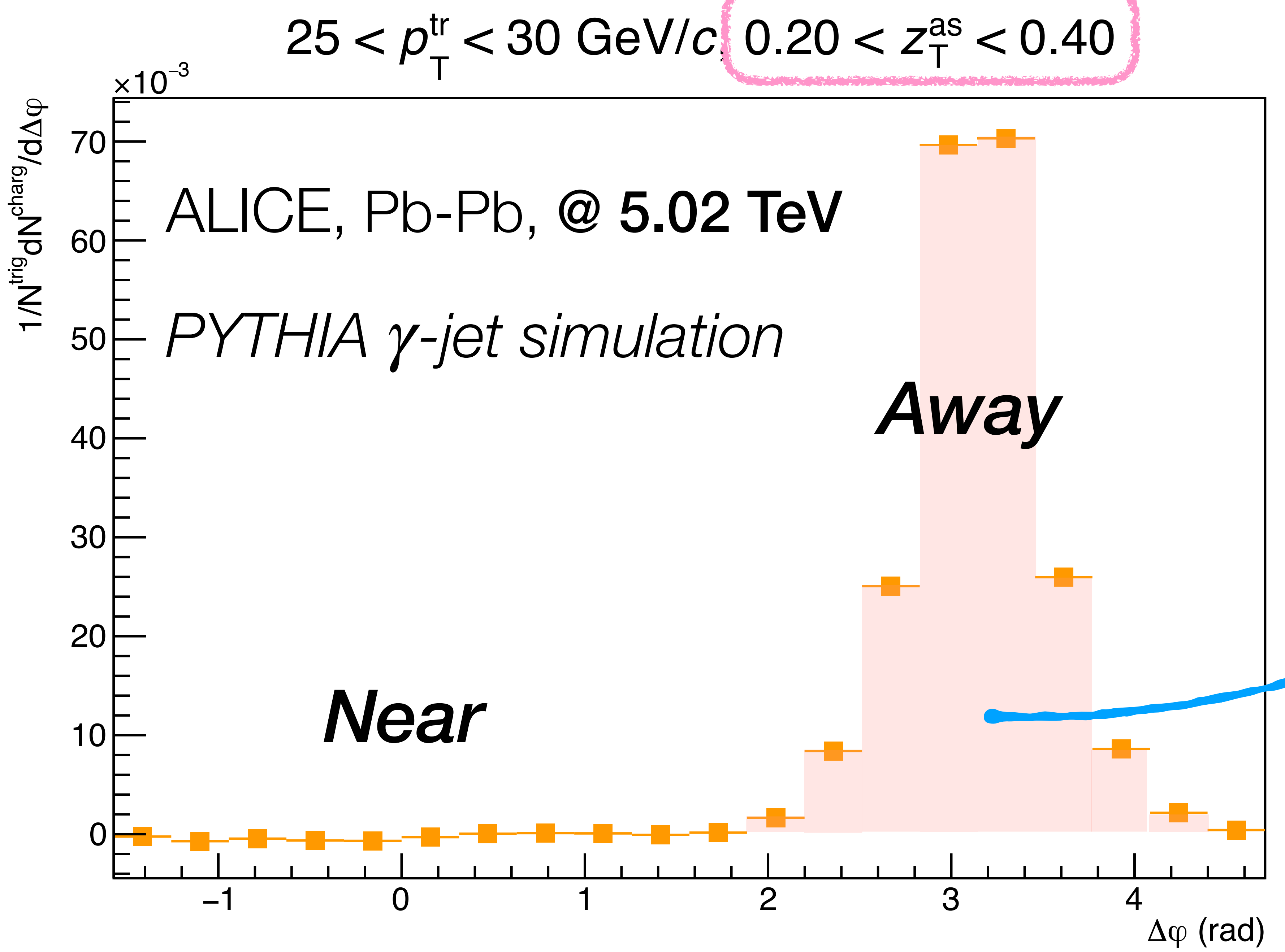
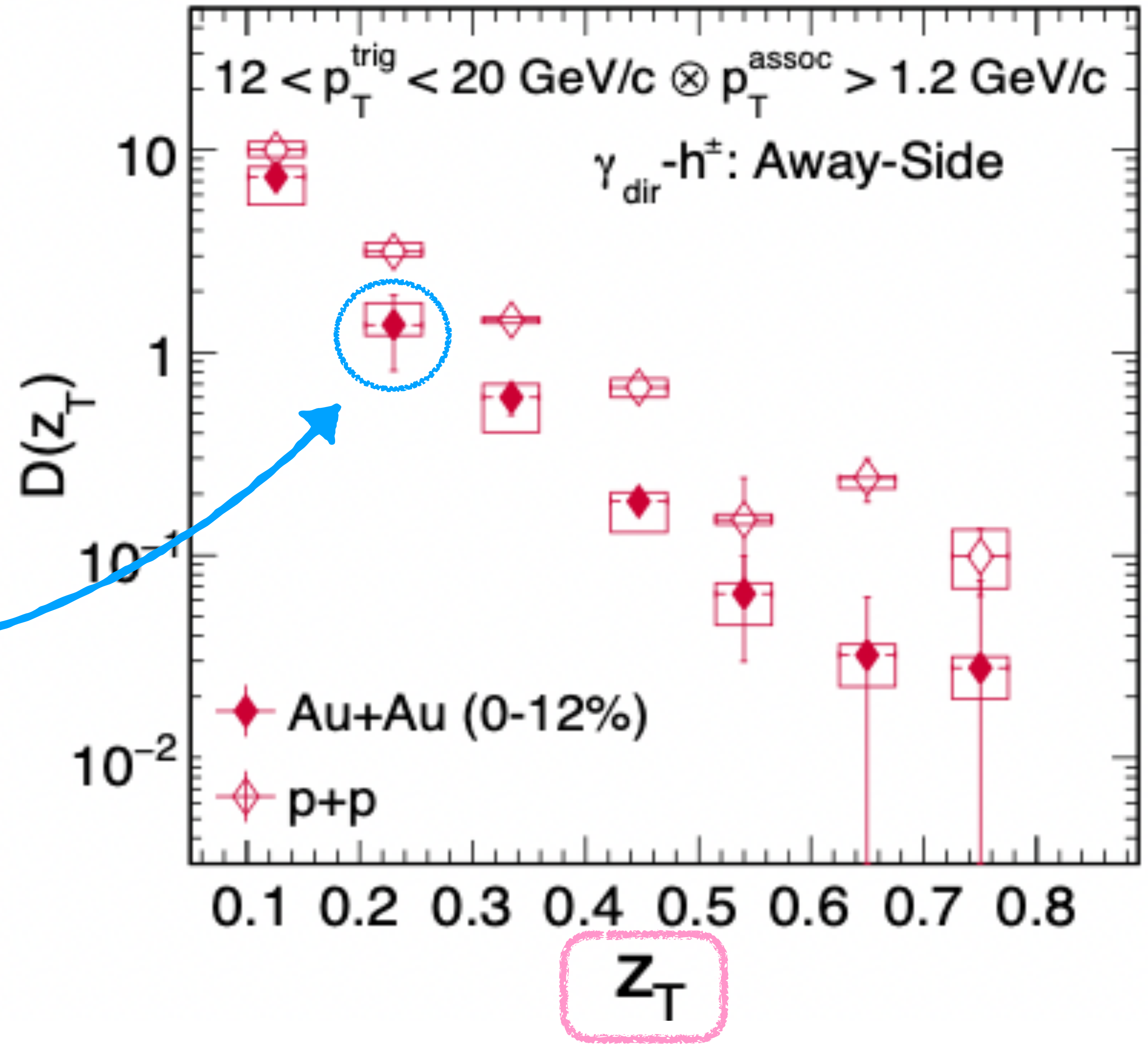
- STAR, **@ 200 GeV**, arXiv:1610.09568







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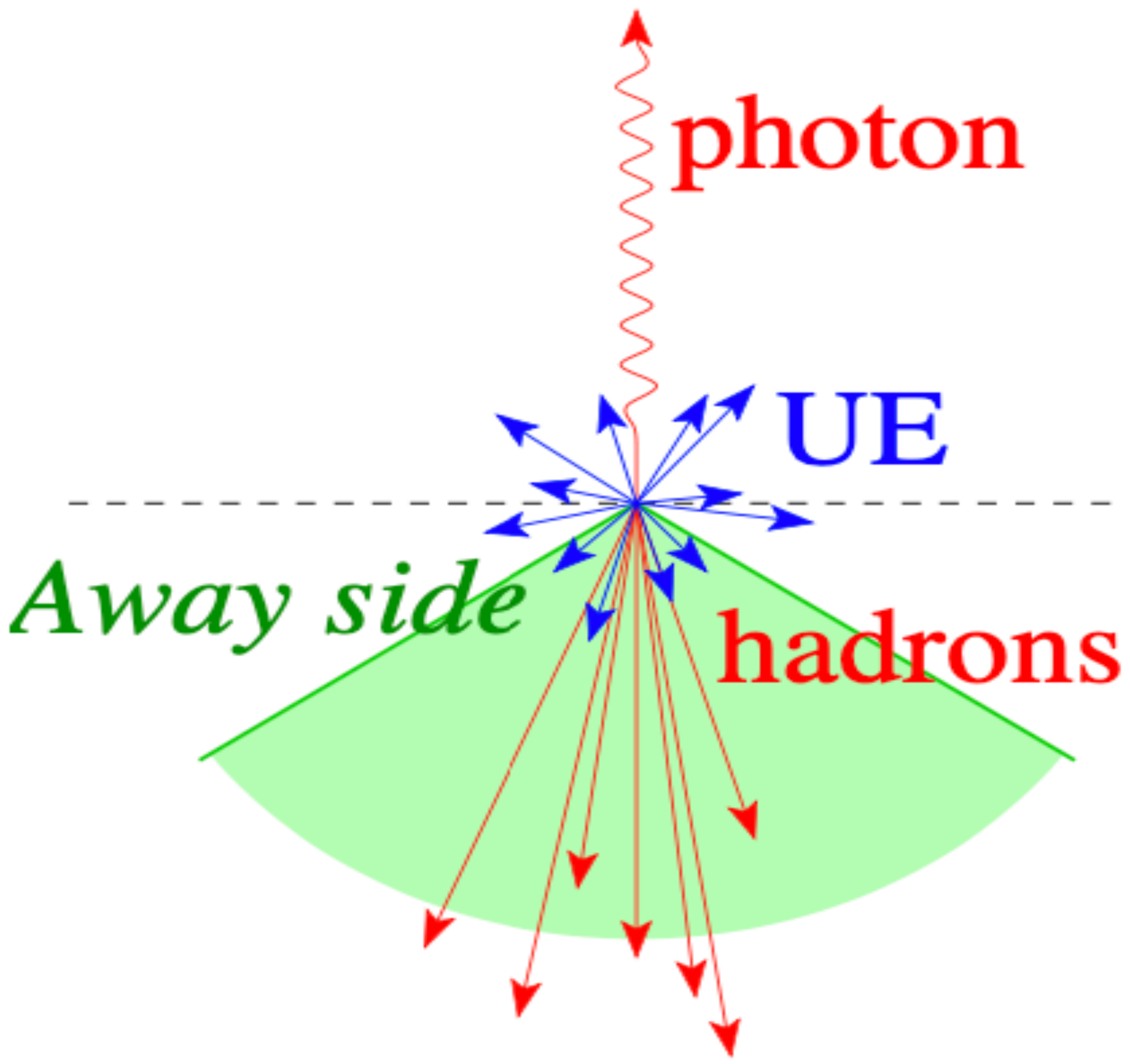
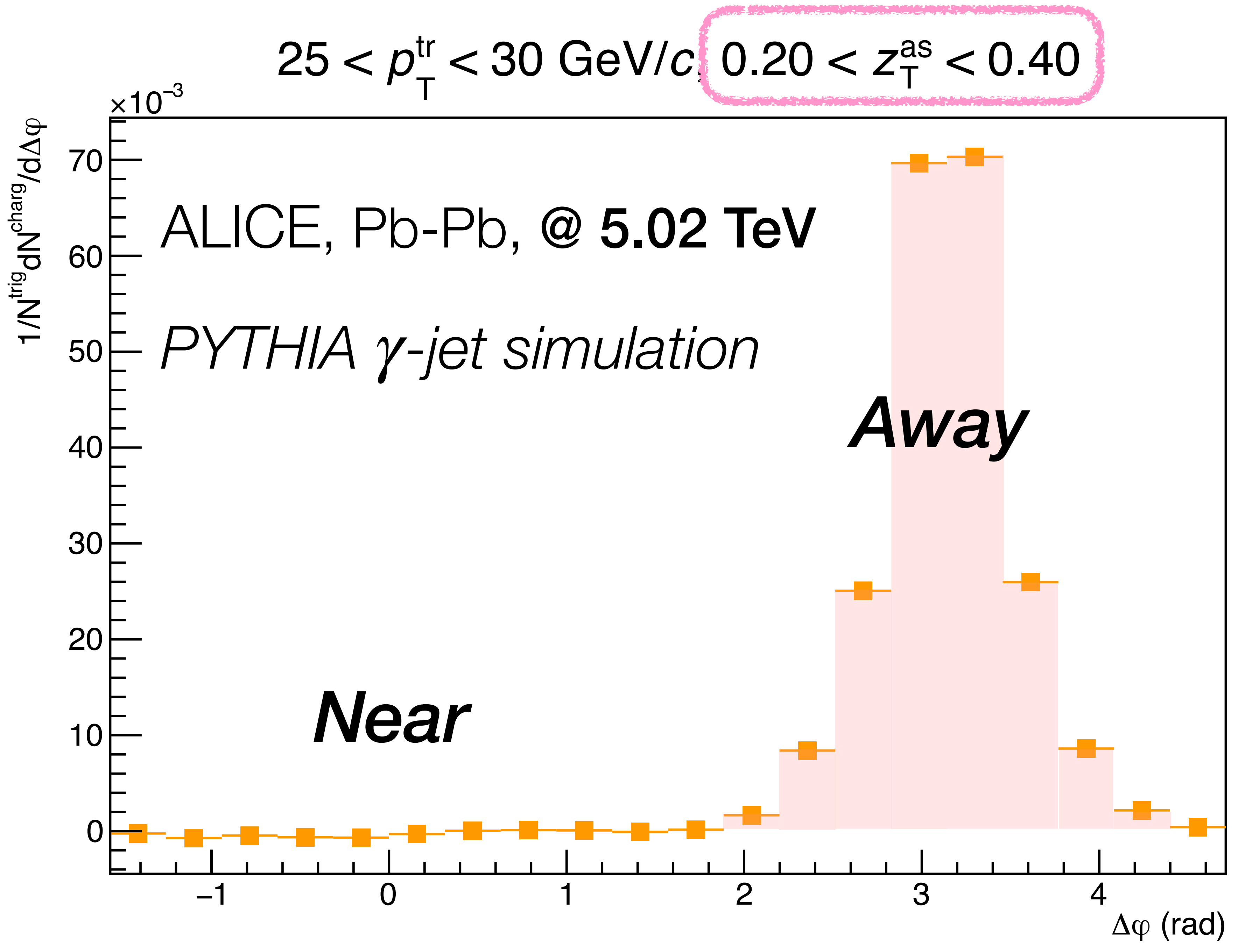
- $D(z_T)$ is ***a proxy for the jet fragmentation function***

$\gamma_{2\to2}$ - hadron correlations





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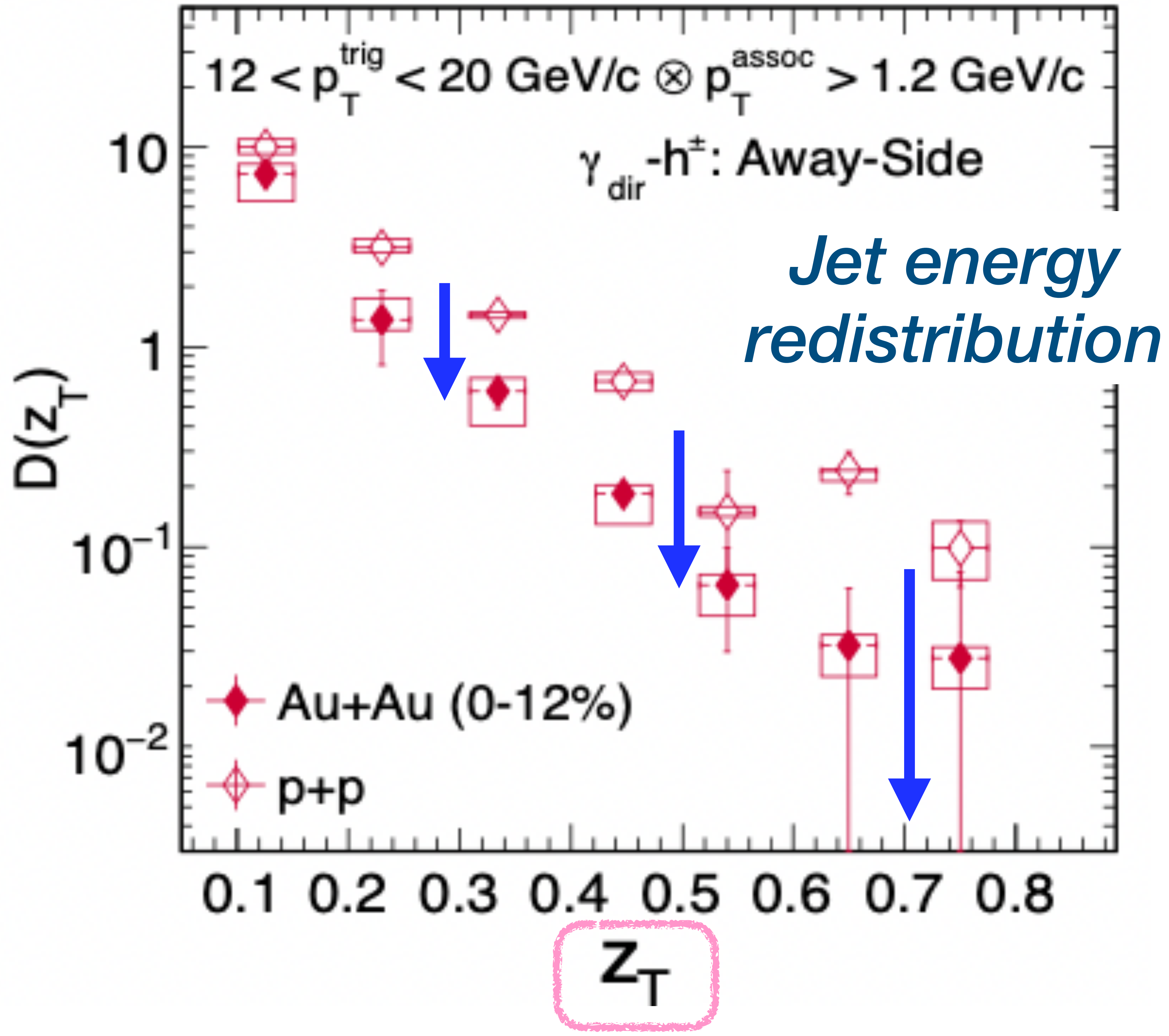

- *Azimuthal correlations distribution* $\Delta\varphi = (\varphi^{trig} - \varphi^{assoc})$
- $z_T = p_T^{hadr}/p_T^{\gamma}$ → **Observable:** hadrons p_T distribution $D(z_T) = \frac{1}{N^{trig}}\frac{dN^{ch}}{dz_T}$
- $D(z_T)$ is ***a proxy for the jet fragmentation function*** → $D(z_T)_{AA} \neq D(z_T)_{pp}$

Distribution modified: information on parton energy loss (high p_T particle suppression)

ALICE - *A Large Ion Collider Experiment*

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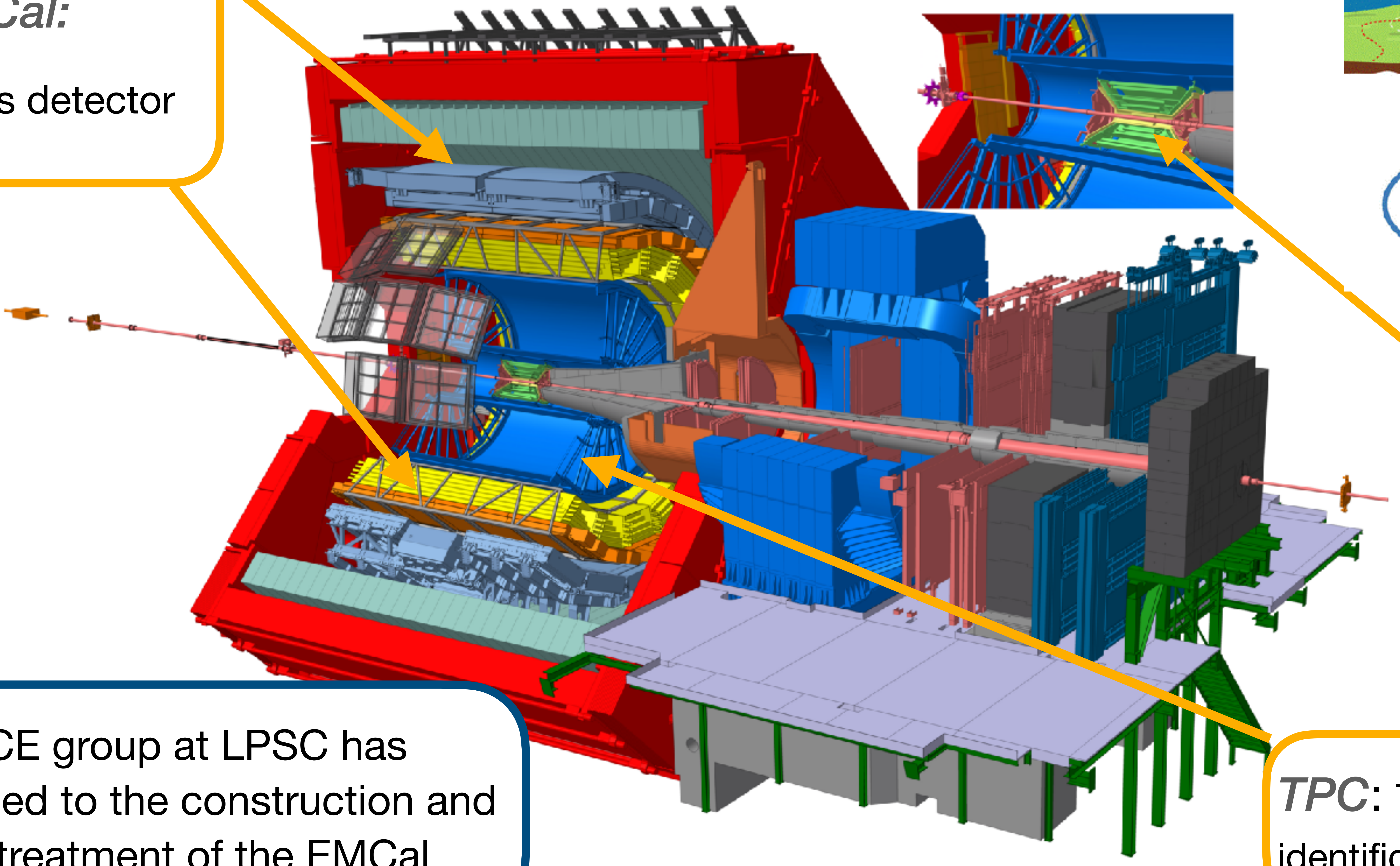
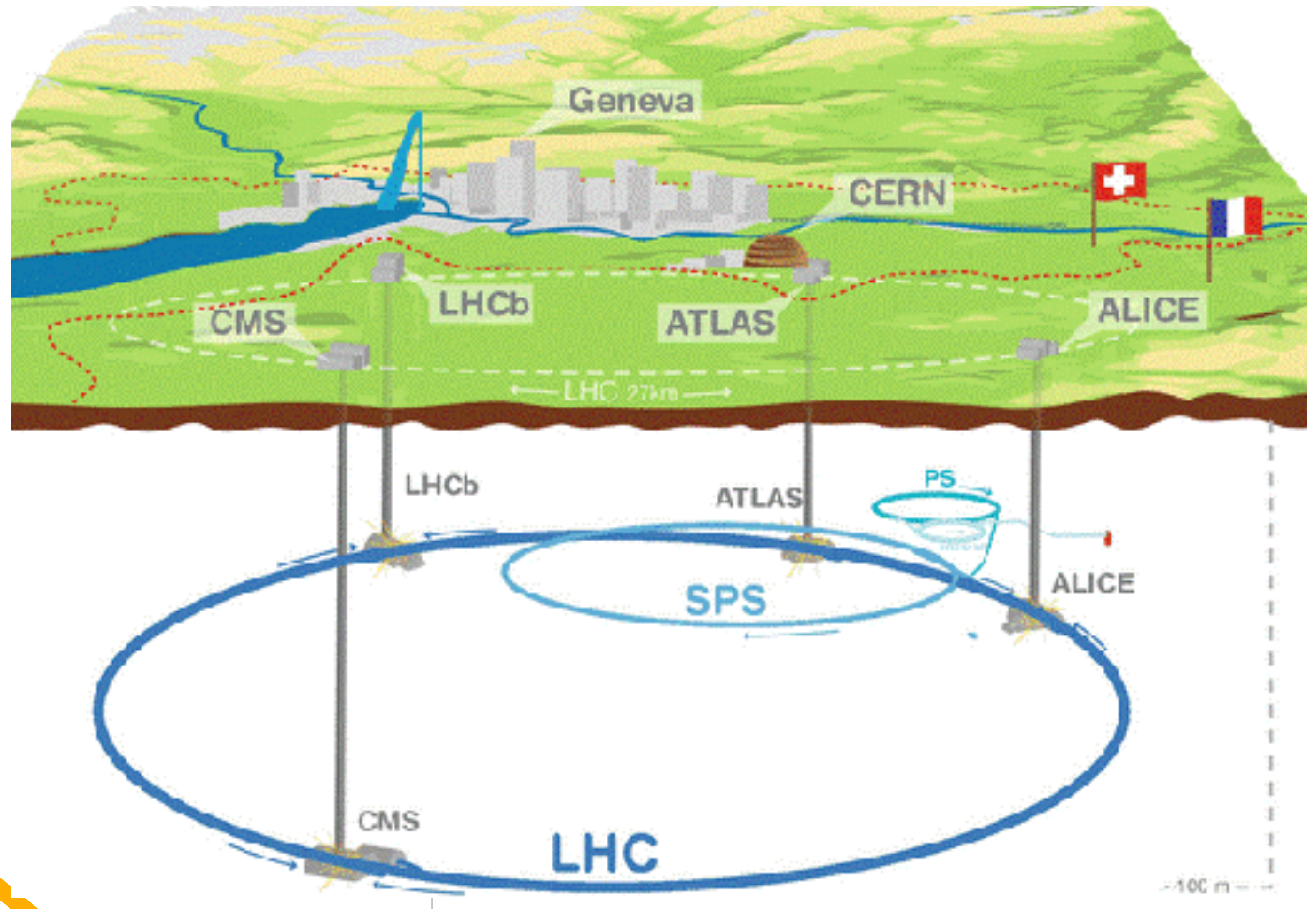
EMCal/DCal:

γ/jet triggers detector





ITS: Primary/secondary vertex determination

TPC: Tracking and particle identification (PID)

ALICE group at LPSC has contributed to the construction and data treatment of the EMCal


Calorimeter identification
+
Isolation
$\gamma_{2\to2}$
trigger selection
Photon-hadron raw azimuthal distribution
Subtraction of the UE
Purity Correction
Systematic errors
Correlation

Calorimeter identification

+

Isolation

$\gamma_{2\to 2}$ *trigger selection*

Photon-hadron raw azimuthal distribution

Subtraction of the UE

Purity Correction

Systematic errors

Correlation

Photon identification with EMCal

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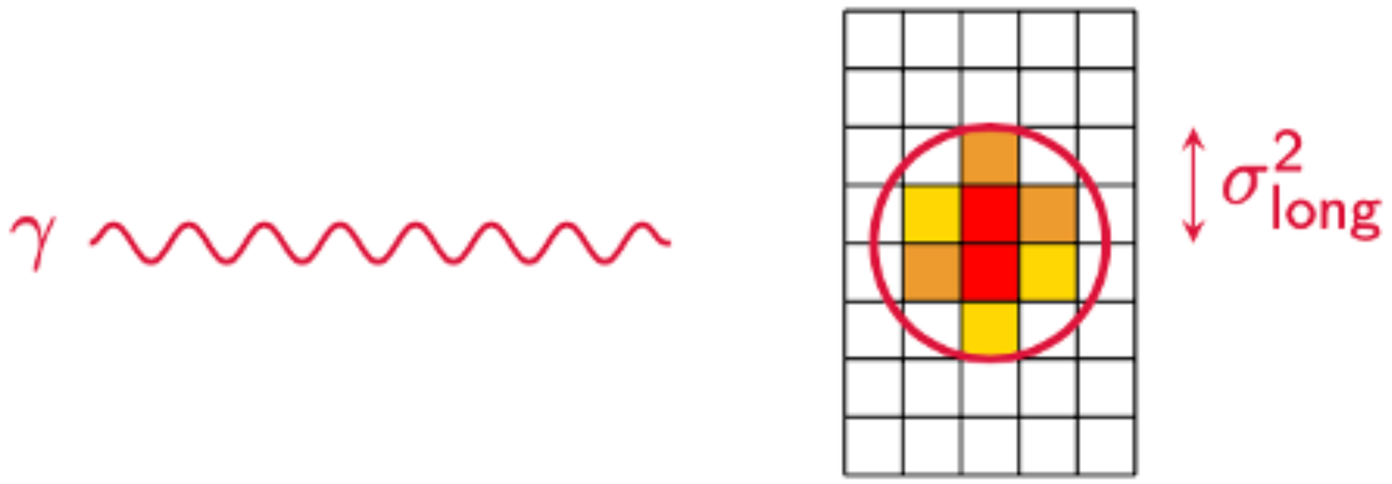
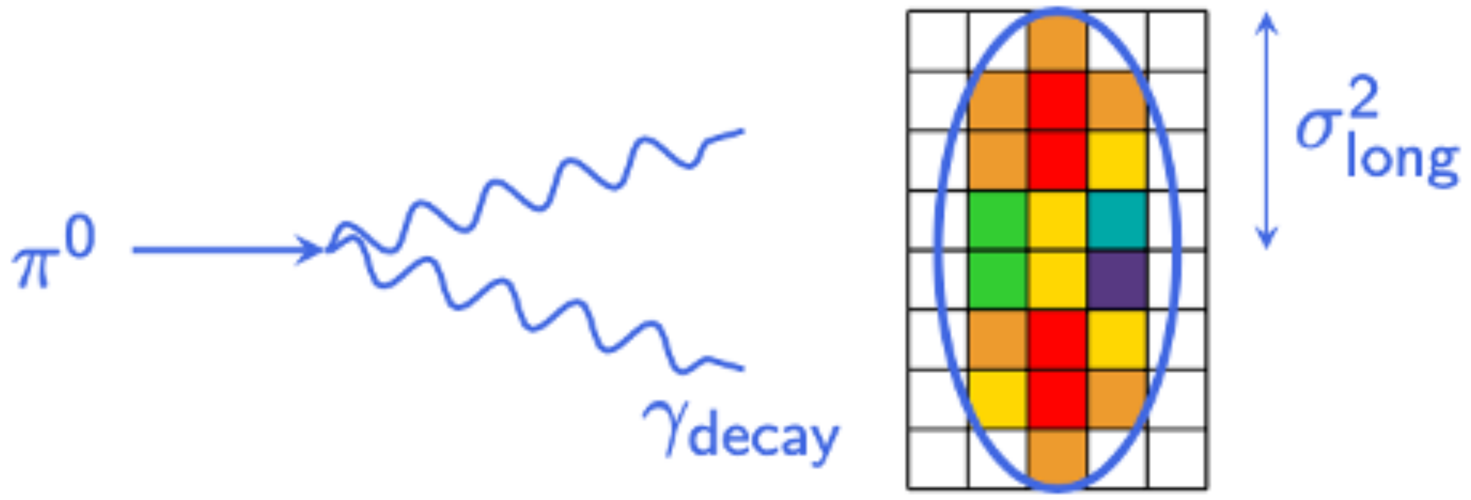
A particle interacting with the ***cell material*** produces a shower spreading its energy over ***neighbouring cells***.

- ***Cluster***: aggregate of cells

The **distribution of energy** within a cluster allows to discriminate between single photons γ shower and overlapping γ showers (γ_{decay}) from high energy $\pi^0 \rightarrow \gamma\gamma$

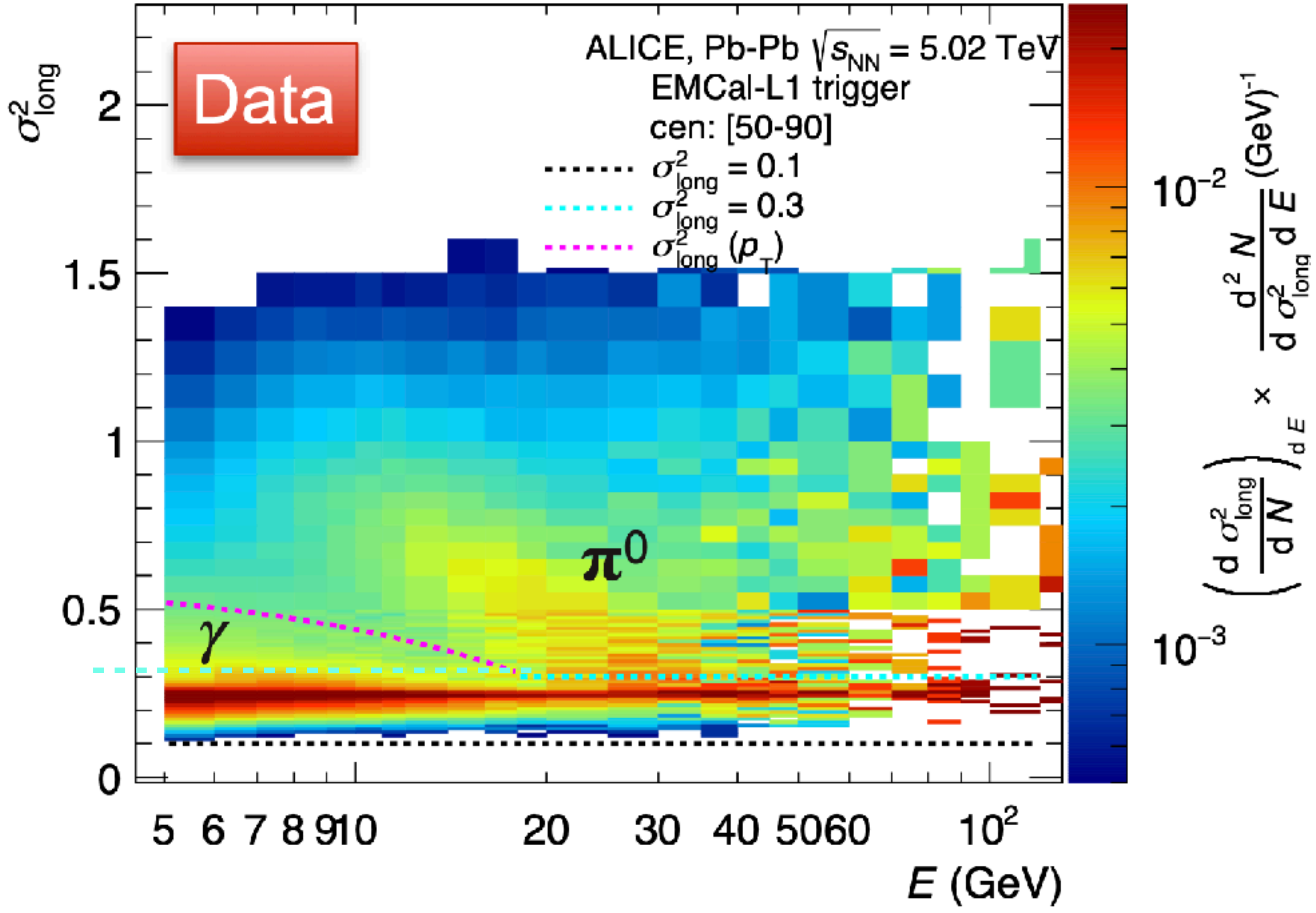


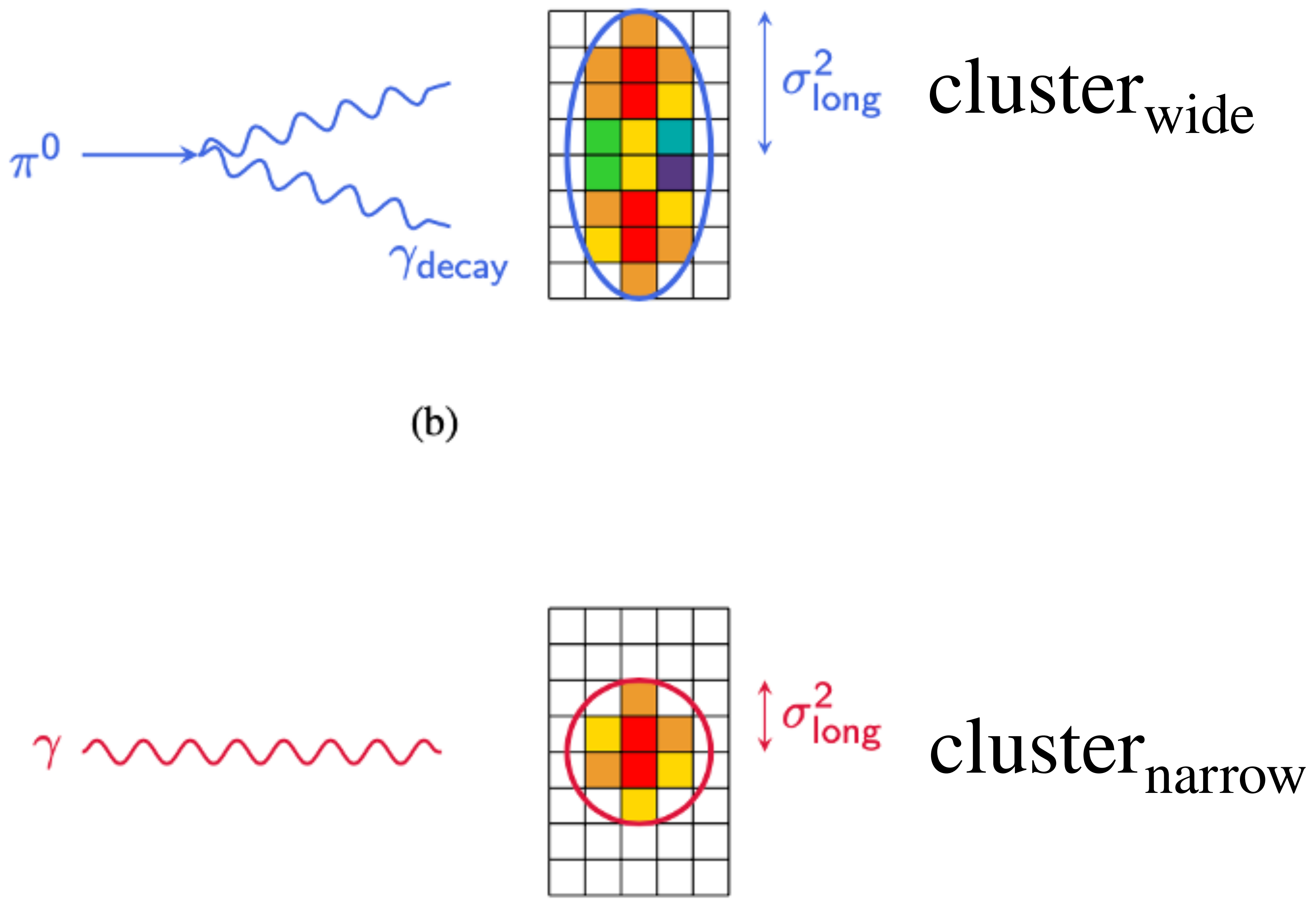
$\gamma \rightarrow \text{cluster}_{\text{narrow}}$:
circular cluster



$\pi^0 \rightarrow \text{cluster}_{\text{wide}}$:
elliptical cluster

Photon identification: Cluster elongation





- γ : population is mainly at $\sigma^2_{long} < 0.3$;
- π^0: - E < 30 GeV, population is mainly at $\sigma^2_{long} > 0.4$;
  - E > 30 GeV, π^0 and γ *bands overlap more and more*

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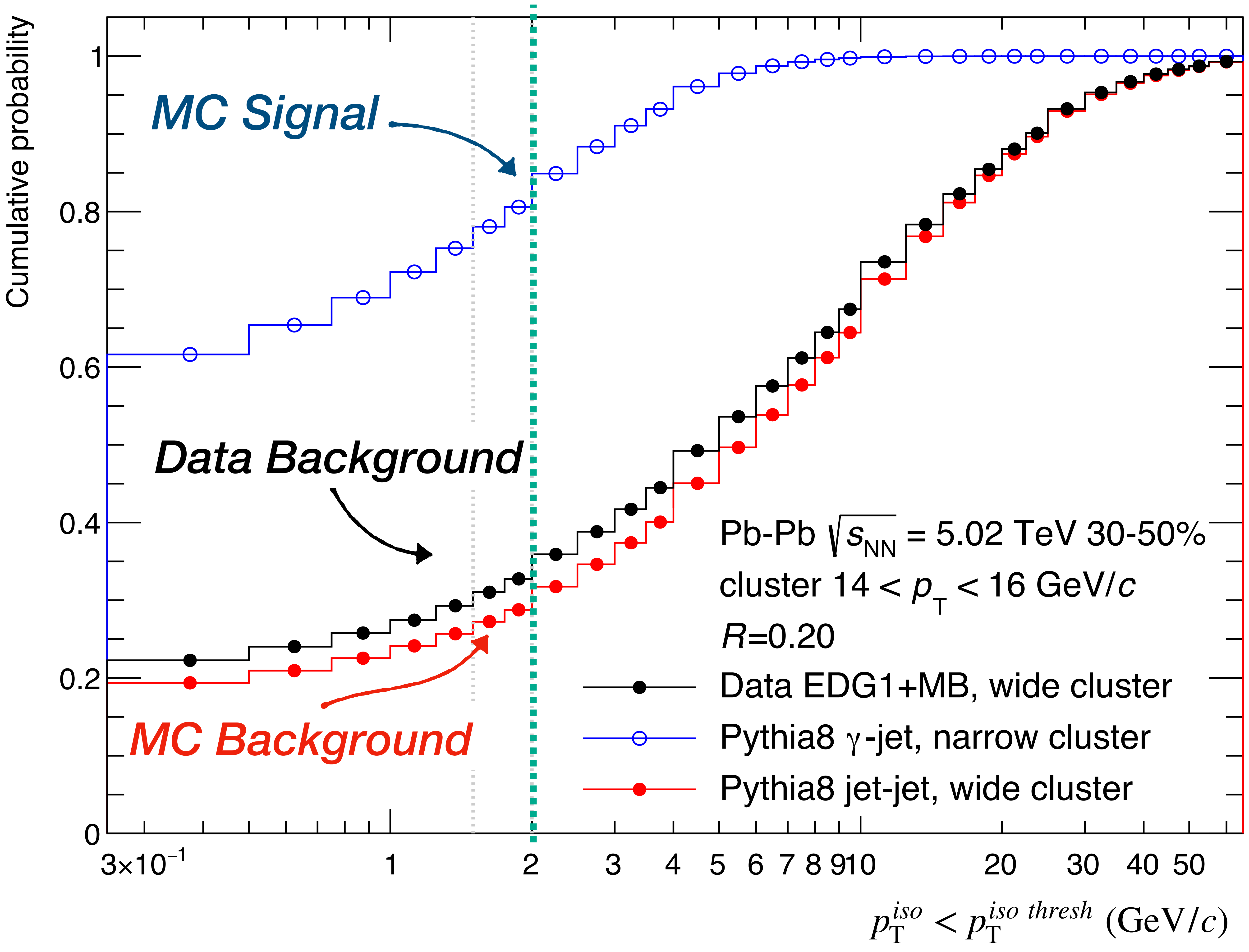
Photon isolation

Necessary to ***reject*** the largest part of ***non*** $\gamma_{2\to2}$ ***photons***: ***isolation criteria***

$\gamma_{2\to2}$ ***photon***: Produced far from other particles (*underlying event* excepted)

- Define a cone radius around a candidate photon: $R_{cone} = \sqrt{(\eta - \eta_\gamma)^2 - (\varphi - \varphi_\gamma)^2} = 0.2$
- Condition on the total p_T inside the cone: $\sum_{cone} p_T^i - (\sum_{UE} p_T^i)_{in\,cone} = p_T^{iso} < 2\ \mathrm{GeV}/c$
  - UE subtracted event by event, estimated in region far from our candidate gamma and jets

Isolation method



Check the ***effectiveness*** of the isolation cut, varying the threshold value

- $p_T^{iso} < p_T^{iso\ thresh} = 2\ \mathrm{GeV}/c$

- ~ 85 % of the signal is accepted 😁
- ~ 70 % of the background is rejected 😁

Calorimeter identification

+

Isolation

$\gamma_{2\to2}$ *trigger selection*

Photon-hadron raw azimuthal distribution

Subtraction of the UE

Purity Correction

Systematic errors

Correlation

Correlations analysis

Photon-hadron raw azimuthal distribution

Subtraction of the UE → Mixed Event

Purity Correction

Systematic errors

Mixed Event: *removal of the underlying event*

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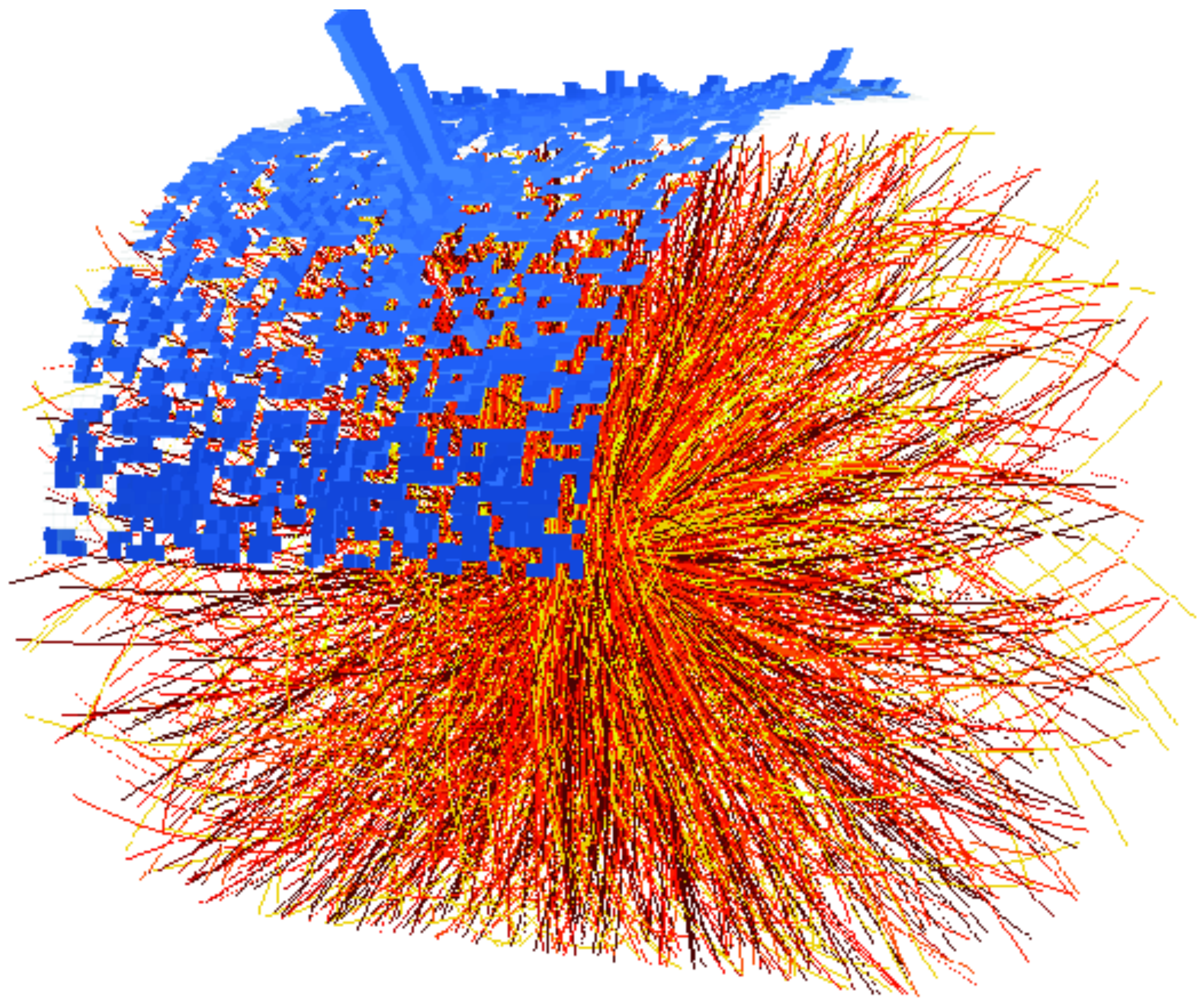
- *Underlying event (UE): tracks uncorrelated to the hard process in a collision*

  UE produces a kind of pedestal on our azimuthal distribution



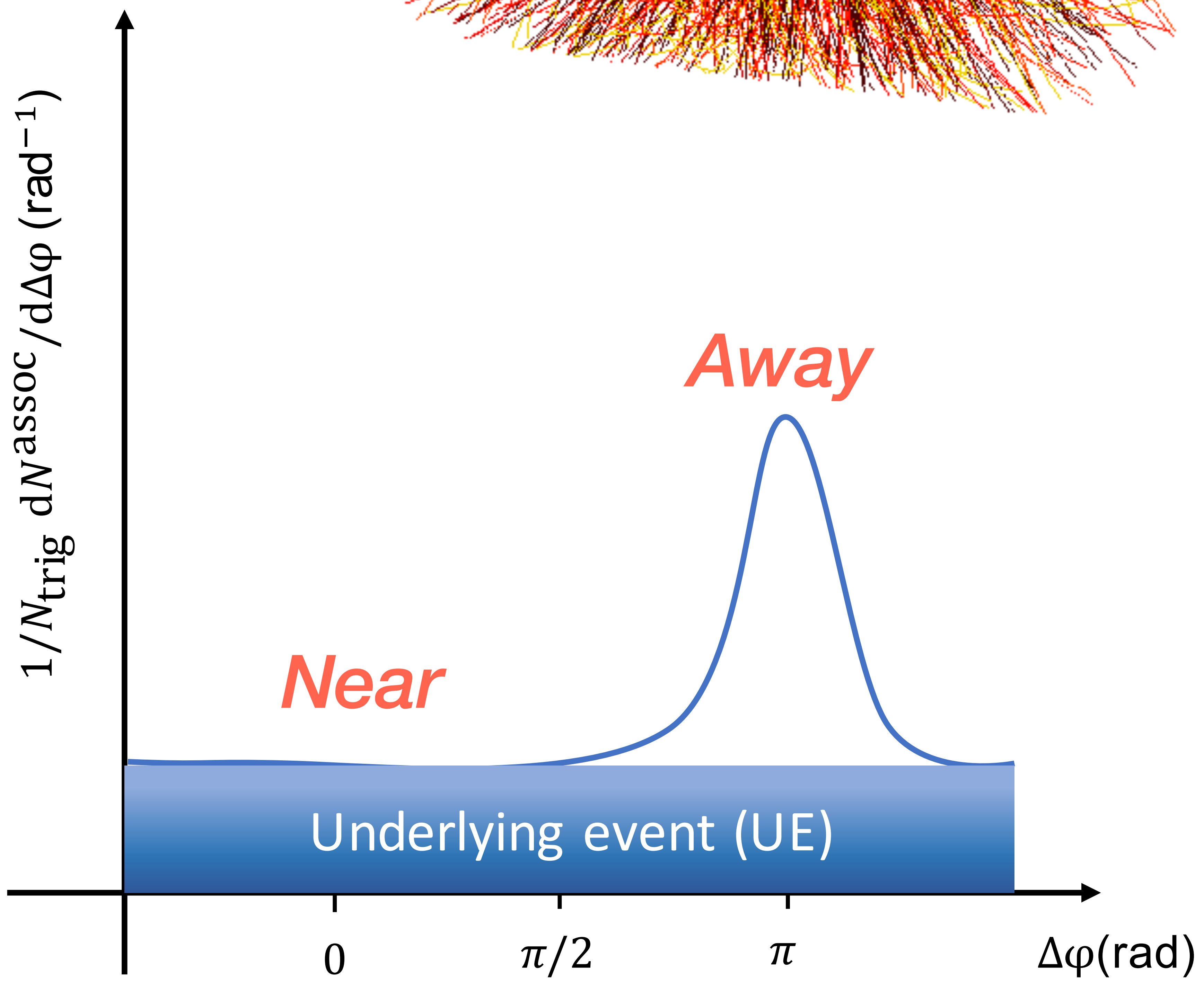
HOW TO REMOVE *UE* AND EXTRACT THE SIGNAL?

- *Mixed Event*:

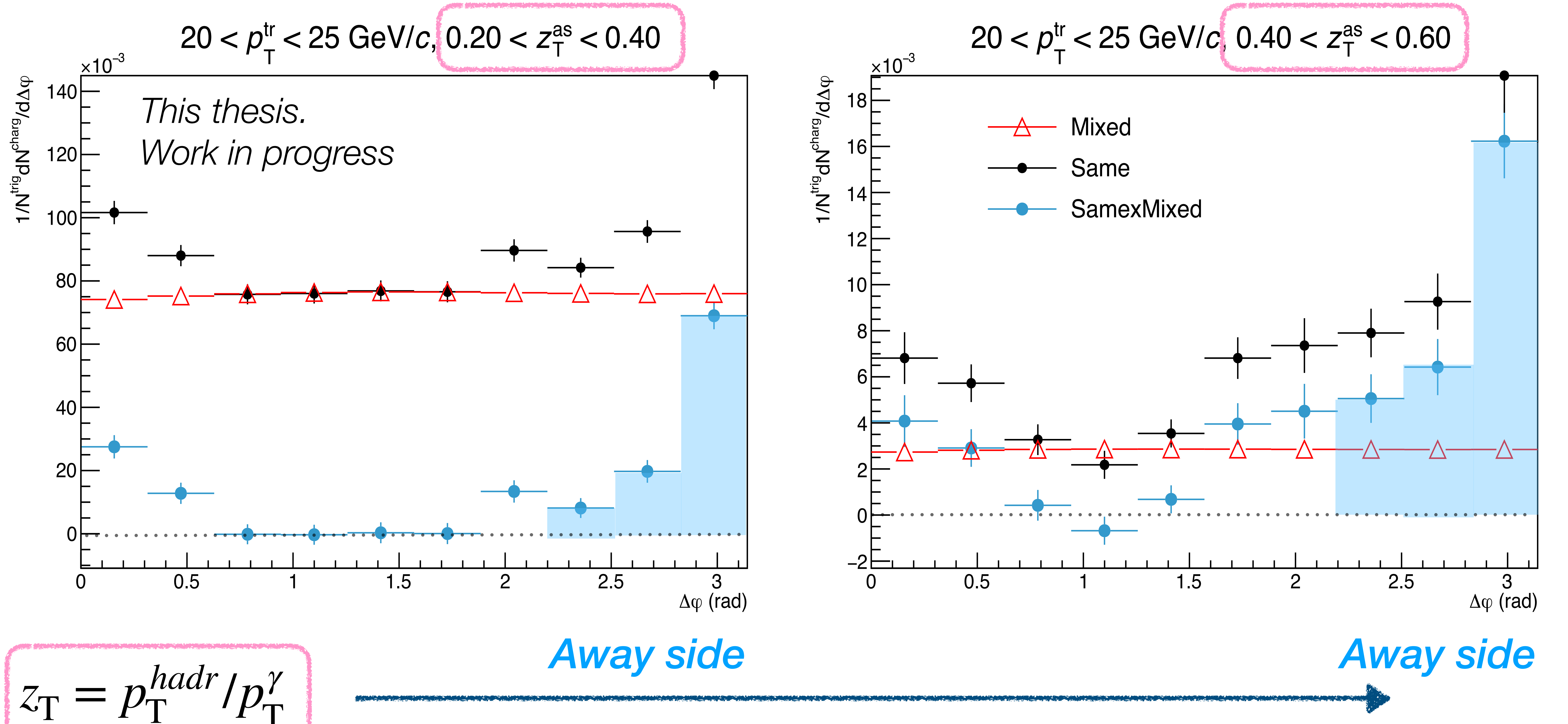
  Artificial dataset created combining our trigger particle from a given collision with tracks from other collisions

- Best way to subtract the ***UE***

  Based on the real data: affected by the detector status + less statistical limitation



UE subtraction: *Mixed event method*



Same - Mixed = Subtracted

$z_T = p_T^{hadr} / p_T^{\gamma}$

- Integration of the ***away side peak*** for every z_T interval: $D(z_T) = \frac{1}{N^{trig}} \frac{dN^{ch}}{dz_T}$ distribution
- But the sample is still not totally pure after the cluster selection and the removal of the UE

Correlation analysis

Photon-hadron azimuthal distribution

Subtraction of the UE → Mixed Event

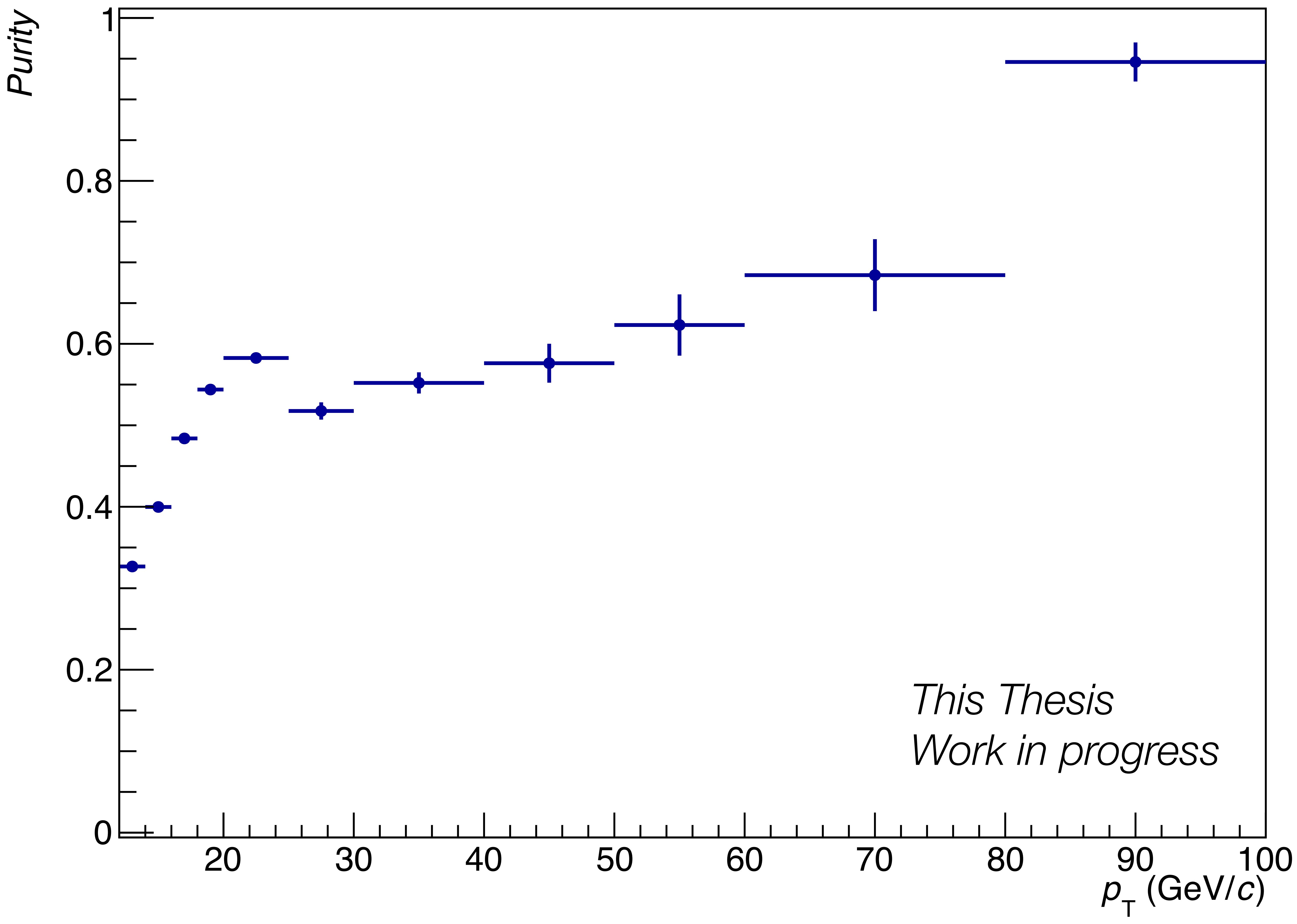
Purity Correction → The sample is still not totally pure

Systematic errors

Purity correction

The isolated γ candidate sample has to be corrected for π^0 accepted

Assume correlation triggered by $\mathrm{cluster}^{iso}_{\mathrm{wide}}$ equivalent to the background for $\mathrm{cluster}^{iso}_{\mathrm{narrow}}$



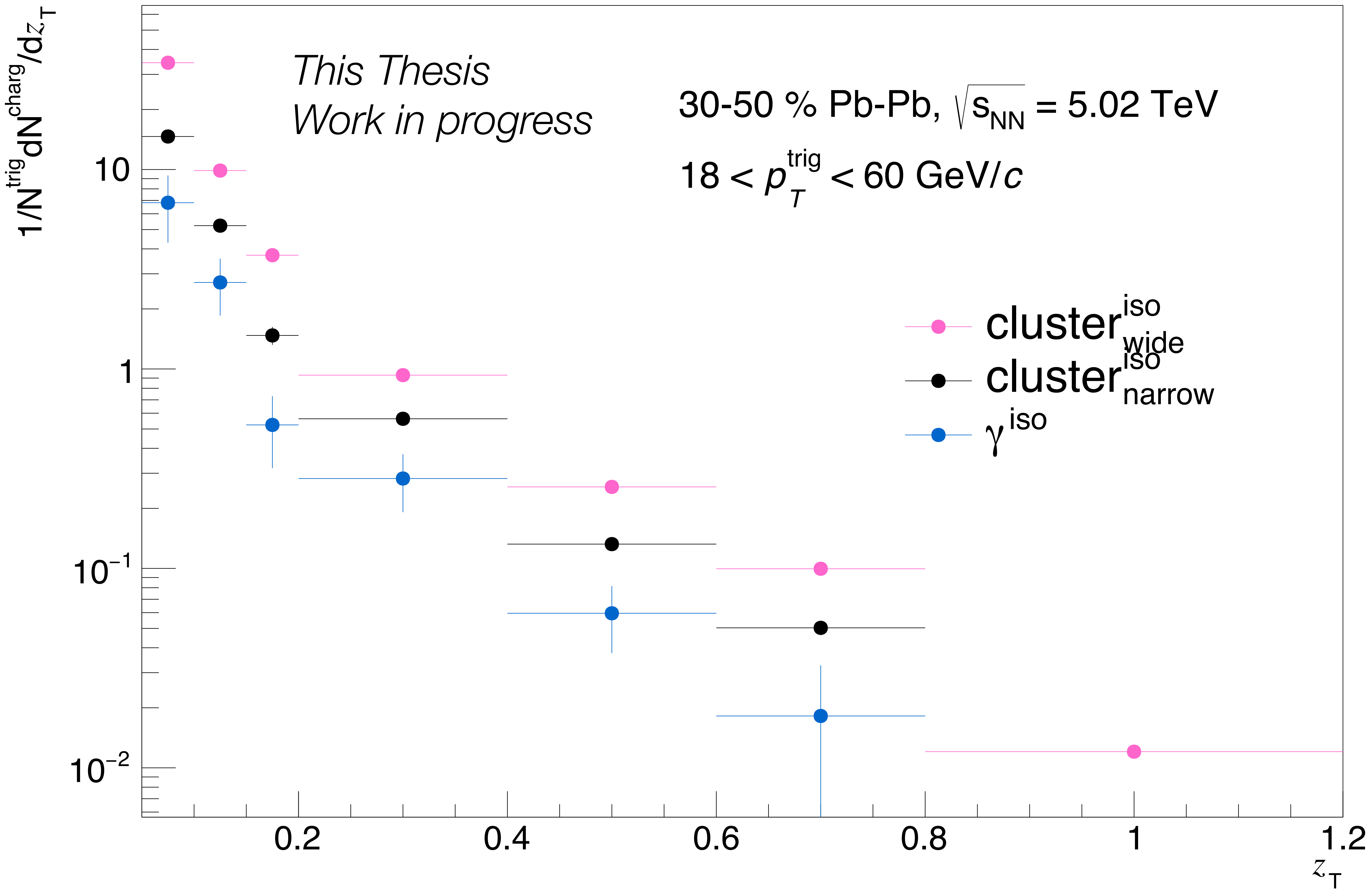
ALICE 2022, Internal, Gustavo Conesa's analysis

Purity P** = **S/N,

the S signal of isolated γ over N = S+B

$$\gamma^{iso} = \frac{\mathrm{cluster}^{iso}_{\mathrm{narrow}} - (1 - P)\ \mathrm{cluster}^{iso}_{\mathrm{wide}}}{P}$$

Purity Correction



$$\gamma^{iso} = \frac{\text{cluster}^{iso}_{\text{narrow}} - (1-P)\,\text{cluster}^{iso}_{\text{wide}}}{P}$$

- Triggers:

  $\text{cluster}^{iso}_{\text{narrow}}$

  $\text{cluster}^{iso}_{\text{wide}}$

- For each trigger: integration of the ***away side peak*** for every z_T interval

  $D(z_\text{T}) = \frac{1}{N^{trig}} \frac{dN^{ch}}{dz_\text{T}}$ distribution

Different p_T^{tr} bins merged: $\frac{1}{\sum_i P_i N_i^{trig}} \sum_i P_i N_i^{trig} f(z_T)_i$, where i is every p_T^{tr} bin

Correlation analysis

Photon-hadron azimuthal distribution

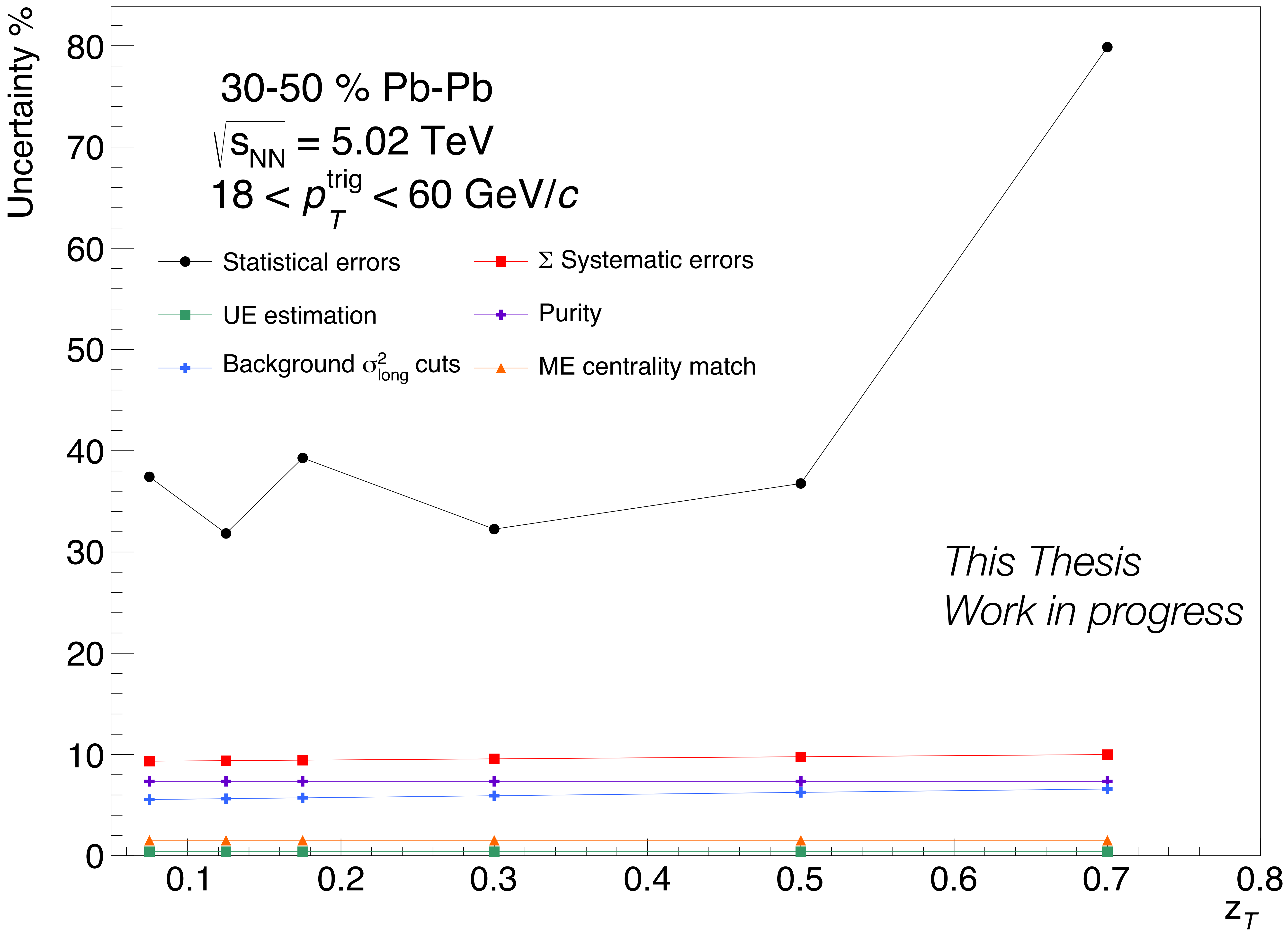
Subtraction of the UE → Mixed Event

Purity Correction → The sample is still not totally pure

Systematic errors

Work in progress: *Systematics errors*

Systematic uncertainties for most sources are estimated with selection criteria variations



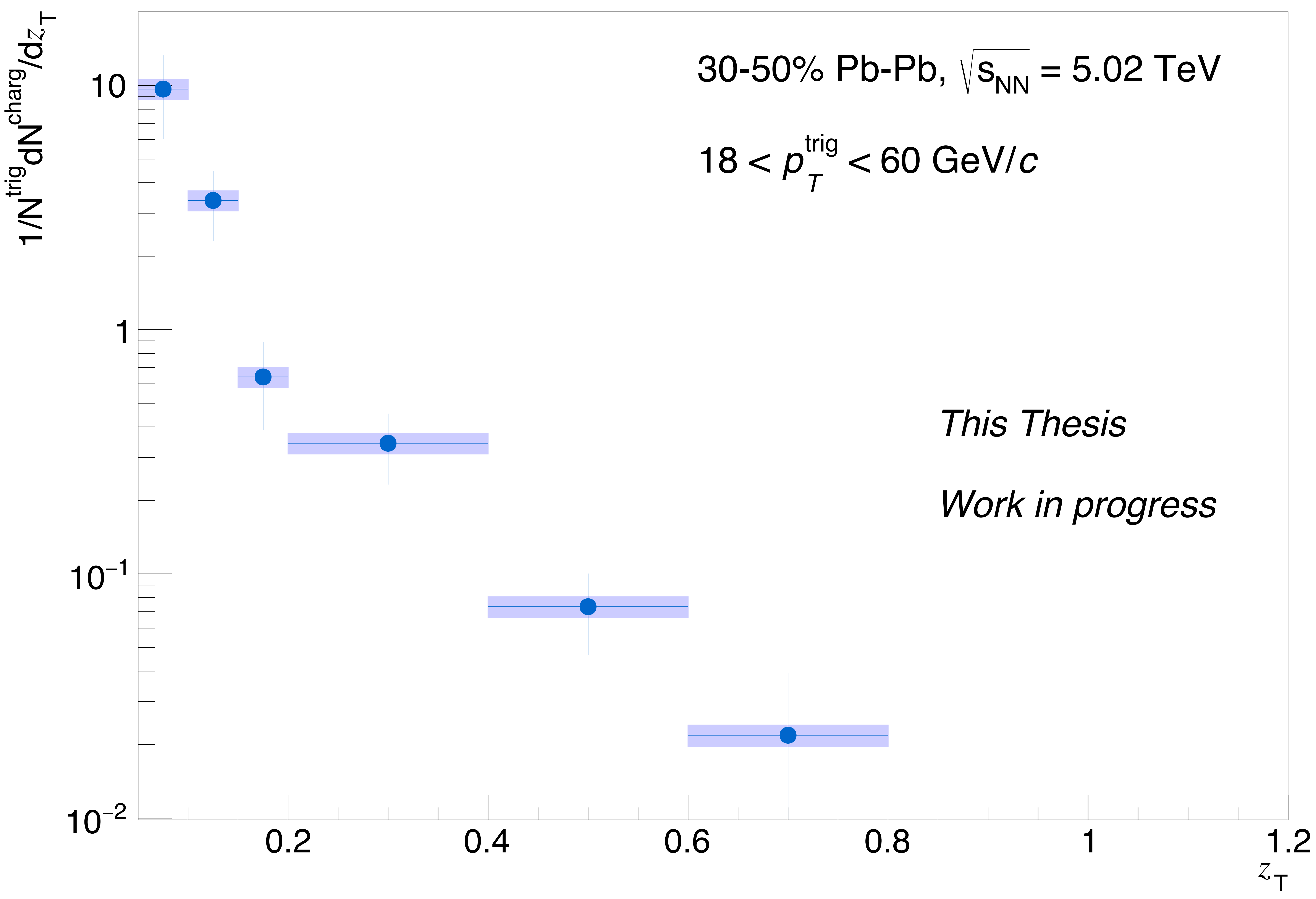
They are evaluated for the z_T function:

- UE estimation uncertainty
- Purity
- Background σ^2_{long} selection
- Variation of the Mixed event selection parameters
- Tracking efficiency (ONGOING)

Among all the uncertainties the statistical error is the highest one.

Statistical limitation is the major difficulty of the analysis

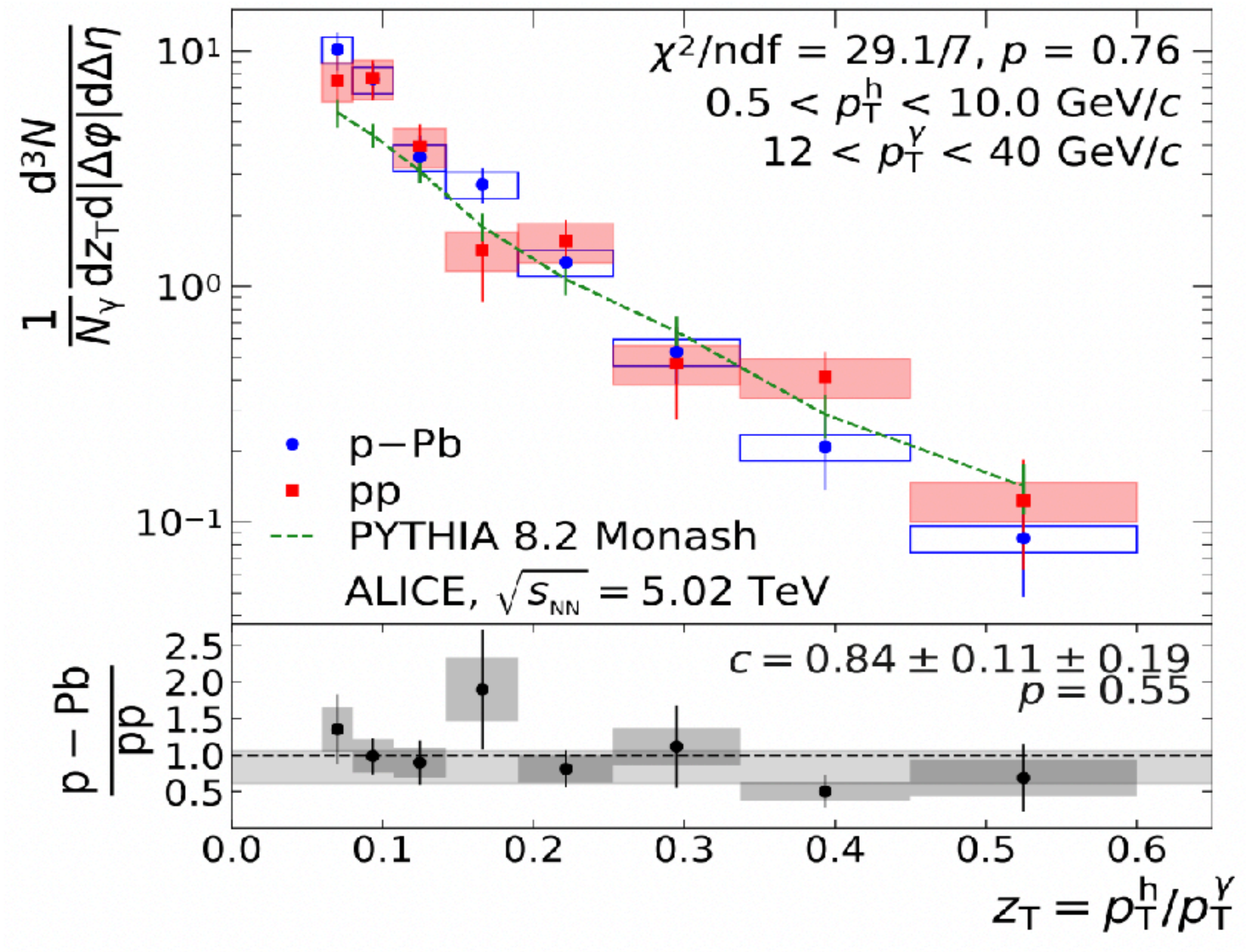
z_T function



- The fluctuations are due to the limited statistics

z_T *function*

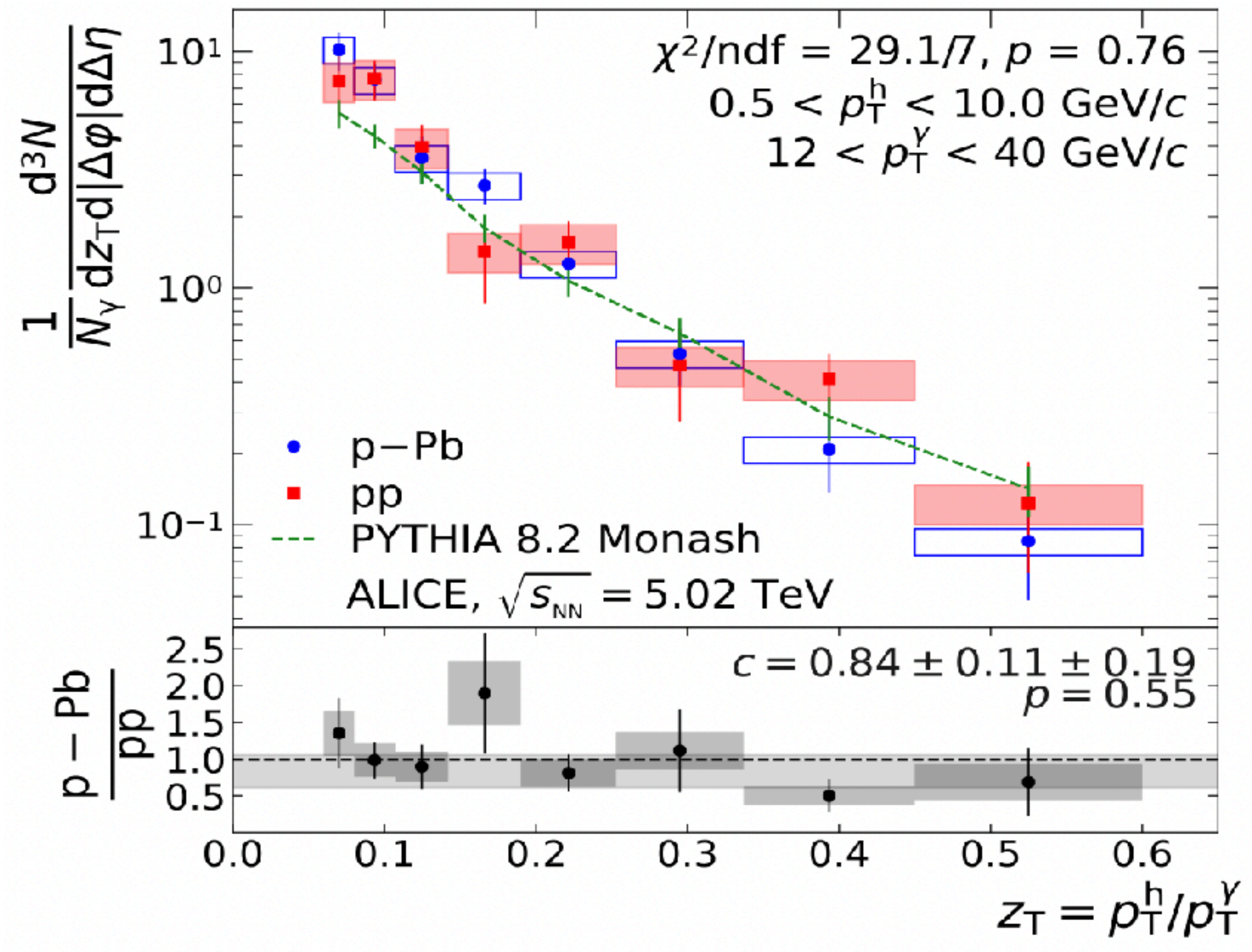
▸ ALICE, arXiv:2005.14637

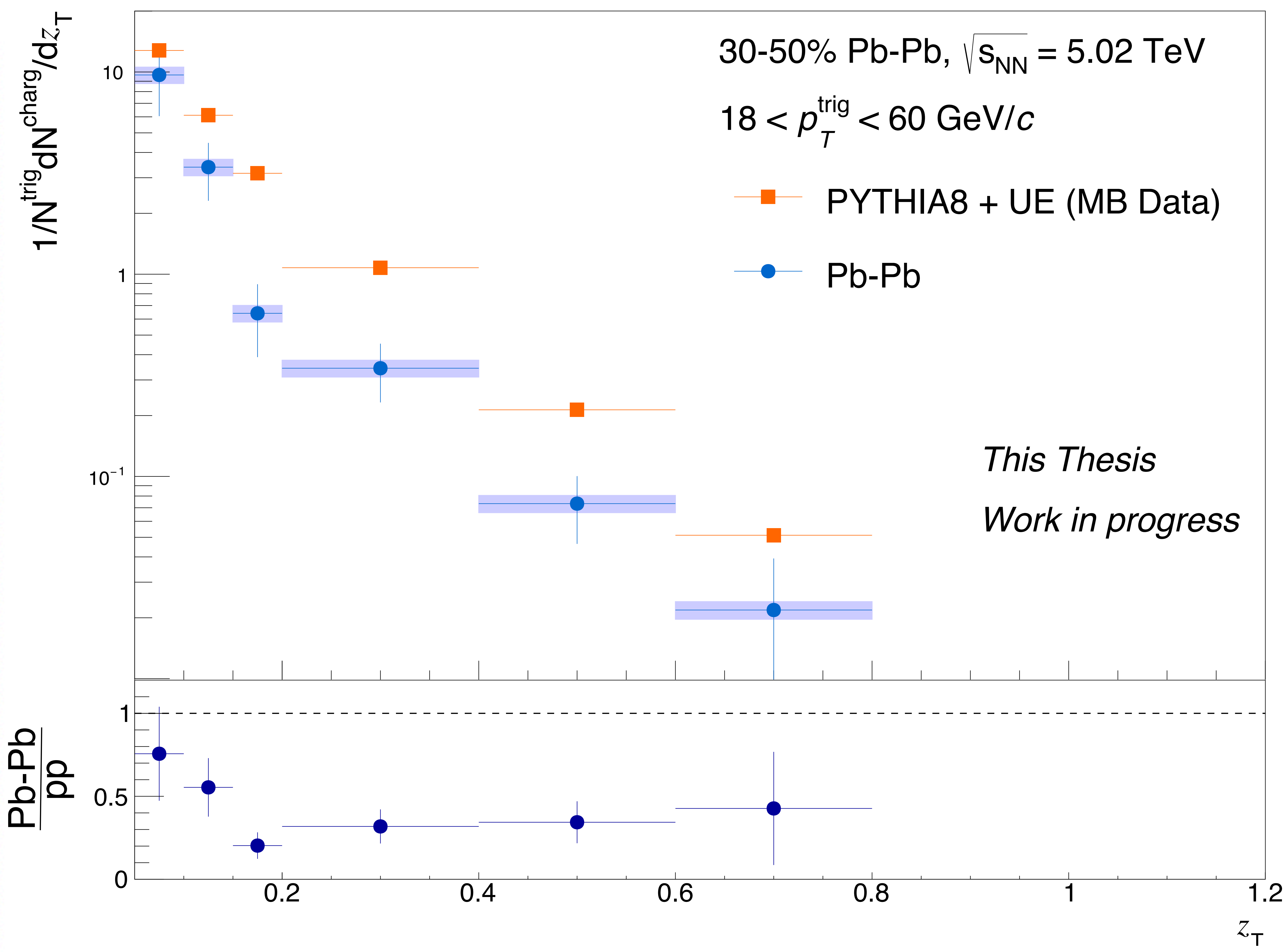


- In pp and p-Pb collisions → agree **no QGP**

z_T function

‣ ALICE, arXiv:2005.14637





- In pp and p-Pb collisions → agree **no QGP**
- The PYTHIA8 embedded into real data Pb-Pb UE, used to represent a Pb-Pb collision **wo quenching**
- There seems to be a suppression in data compared to PYTHIA8, but these results are **work in progress**

Conclusions and perspectives

Challenging to make any strong conclusions due to statistical limitation and significant UE

First analysis of isolated photon-hadron correlations in Pb-Pb at $\sqrt{s_{NN}} = 5.02$ TeV at LHC!

Next Steps:

- Finish the systematics errors
- Investigate different theoretical model prediction for comparison
- Write the analysis documentation in view of the publication

Future prospect for gamma isolation and correlation analysis:

- FoCal, my ALICE technical Service work

FoCal upgrade

FoCal = **For**ward **Cal**orimeter

Goals: direct photons detection in pp, p-Pb and Pb-Pb

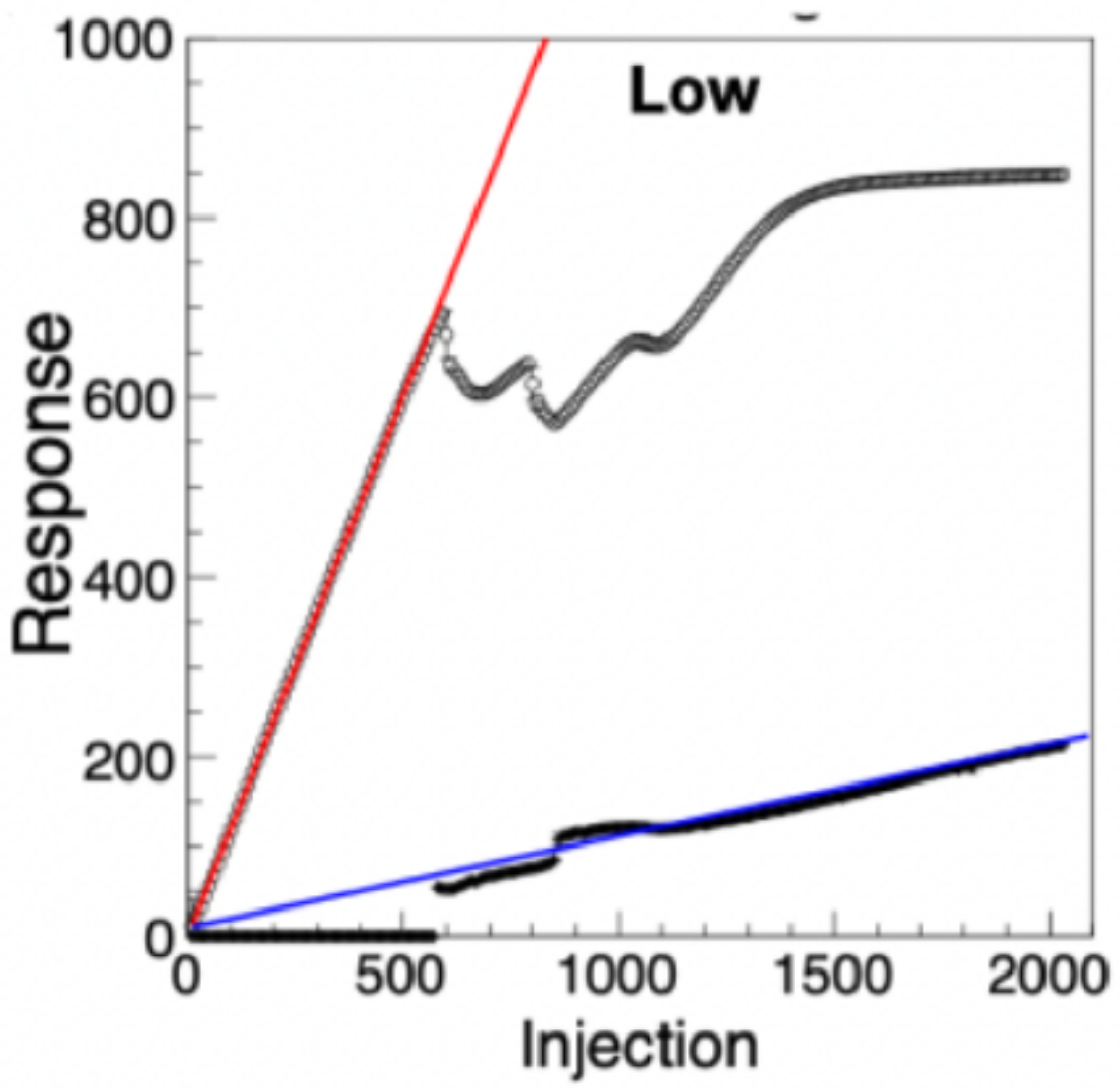
- Installation in ALICE foreseen for 2029

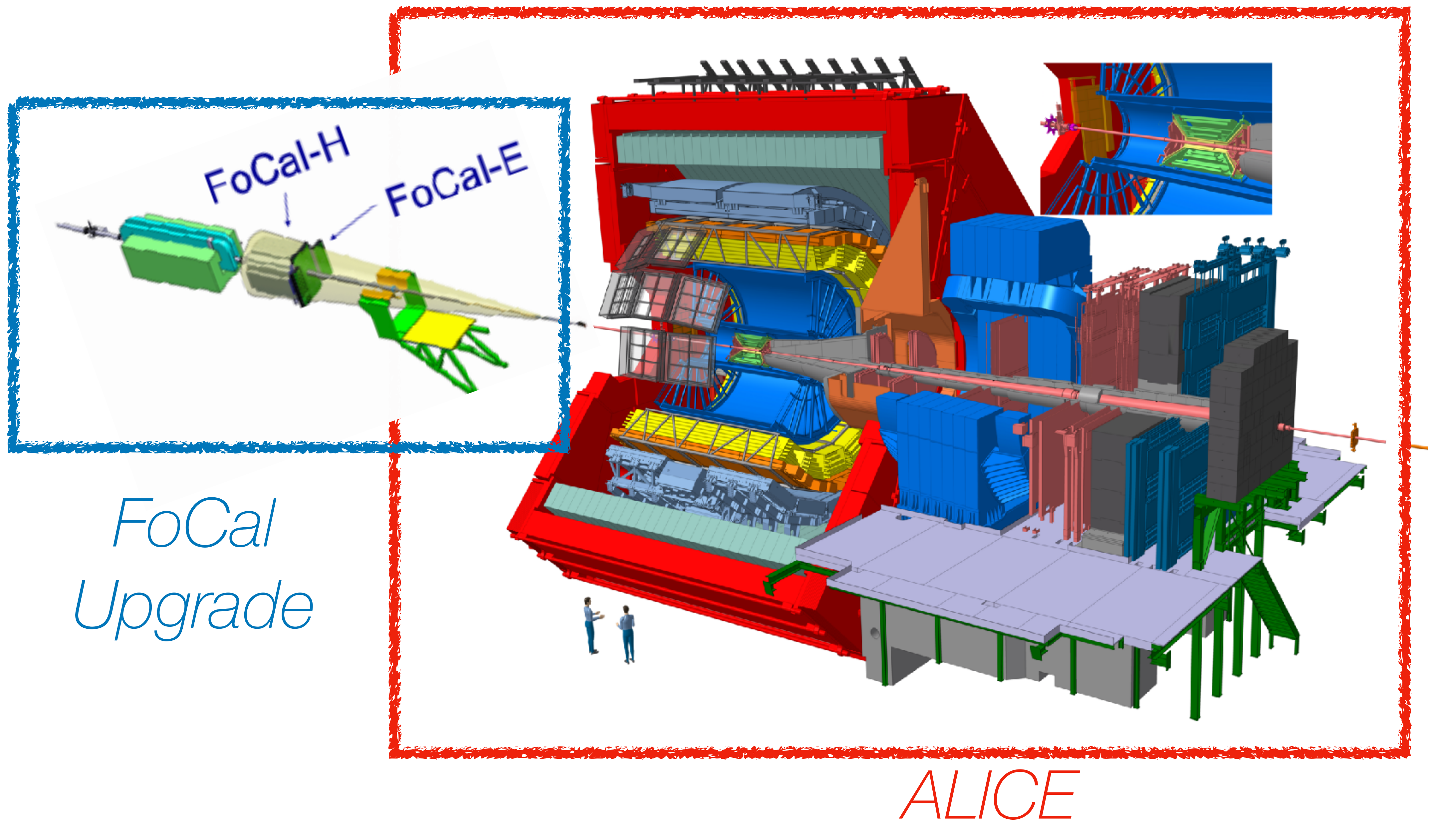
FoCal-E = Electromagnetic calorimeter

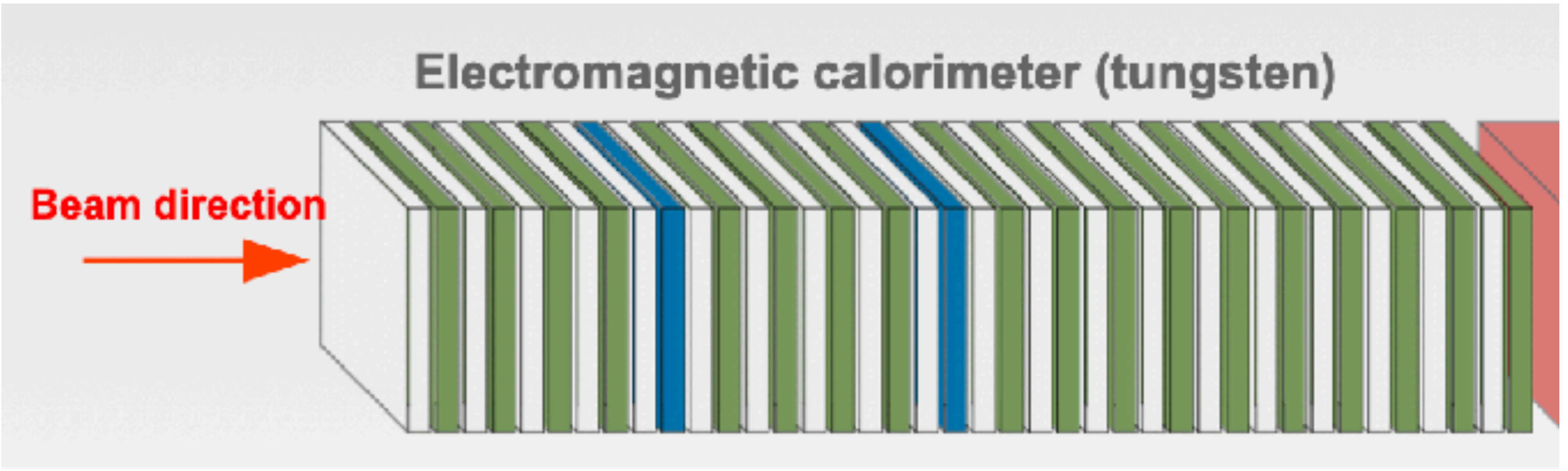
18 layers Si-W calorimeter with 72 channels

Charge deposit in pixels read by an *ASIC*:

- low charge ADC
- high charge ToT (Time over Threshold)







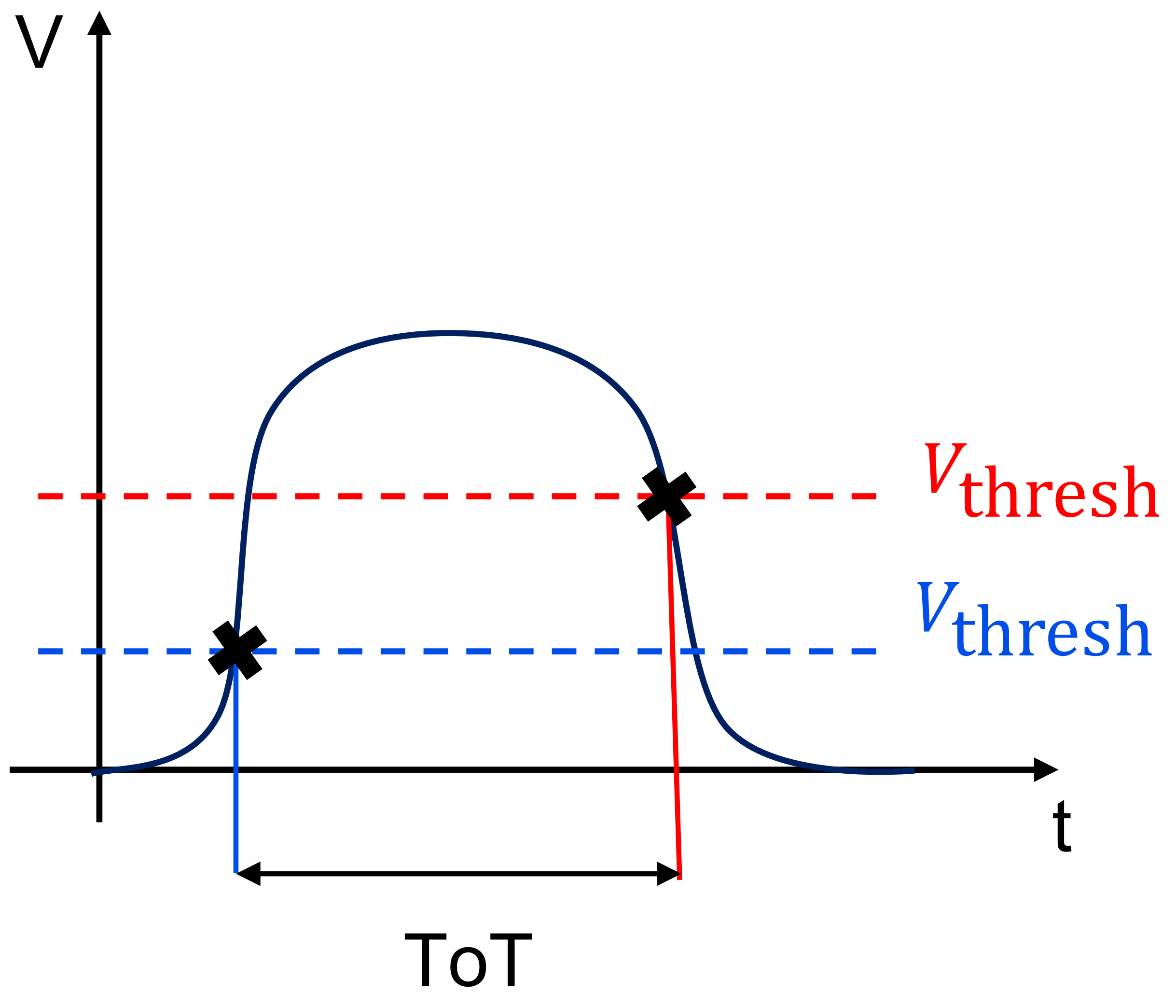
ALICE group at LPSC contribution to:

readout, 18 ASICs FE, interface and DAQ

Time Over Threshold (TOT) calibration

If the deposited charge is too big, the ADC saturates → necessary to use ***TOT***

- **Discriminator:** generation of a trigger signal when the input pulse exceeds a threshold value.

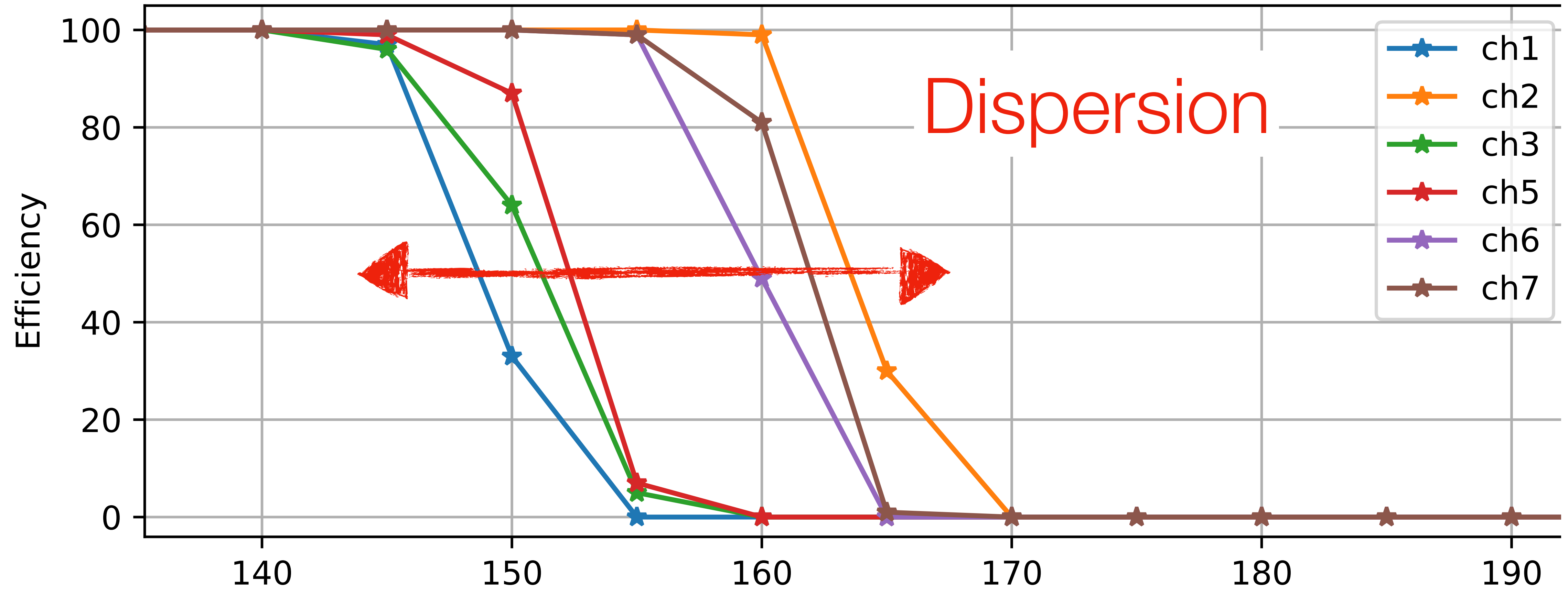


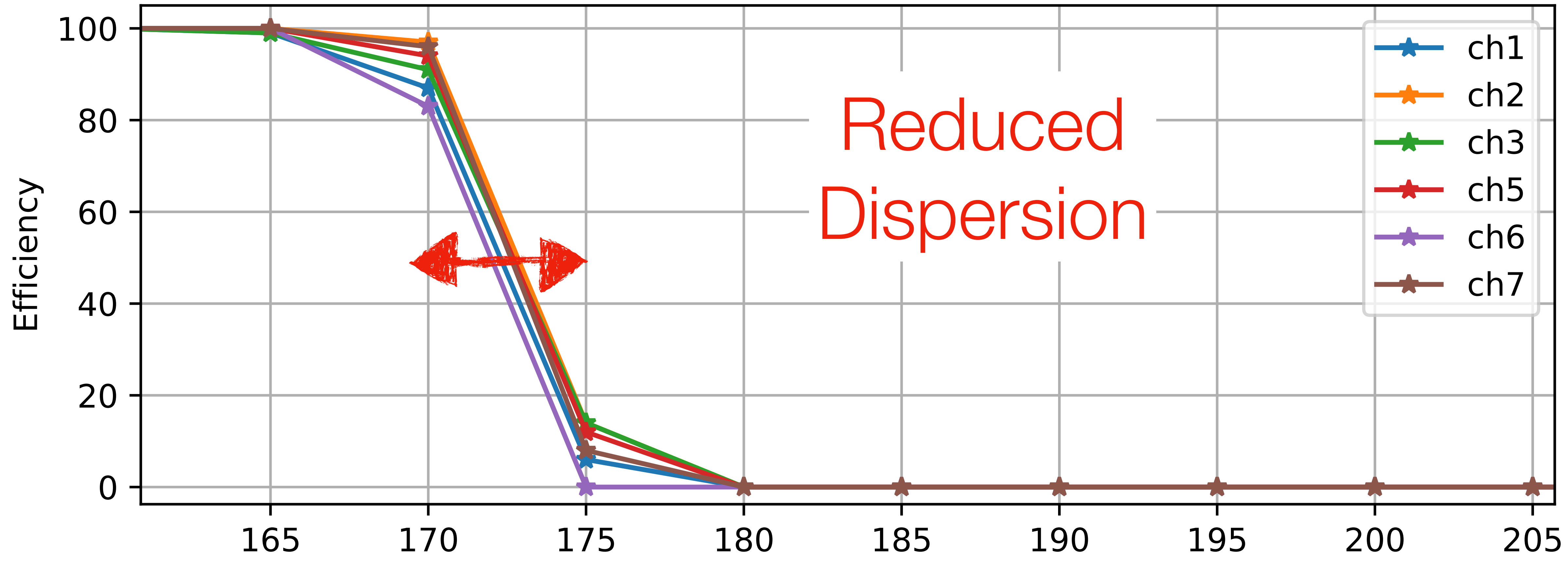
GOAL: reduce dispersion among channels

Calibration procedure:

- test different thresholds: check when signal is triggered
- adjust the characteristic parameters of every channel

★different channels trigger the input signal similarly





Conclusions

FoCal, my ALICE technical Service work

- 6 months already done
- Calibration of the sensor prototype:
  - ADC pedestal, offset correction, …
- Participation to 3 beam tests in CERN
- Part of these activities have been included in this publication:

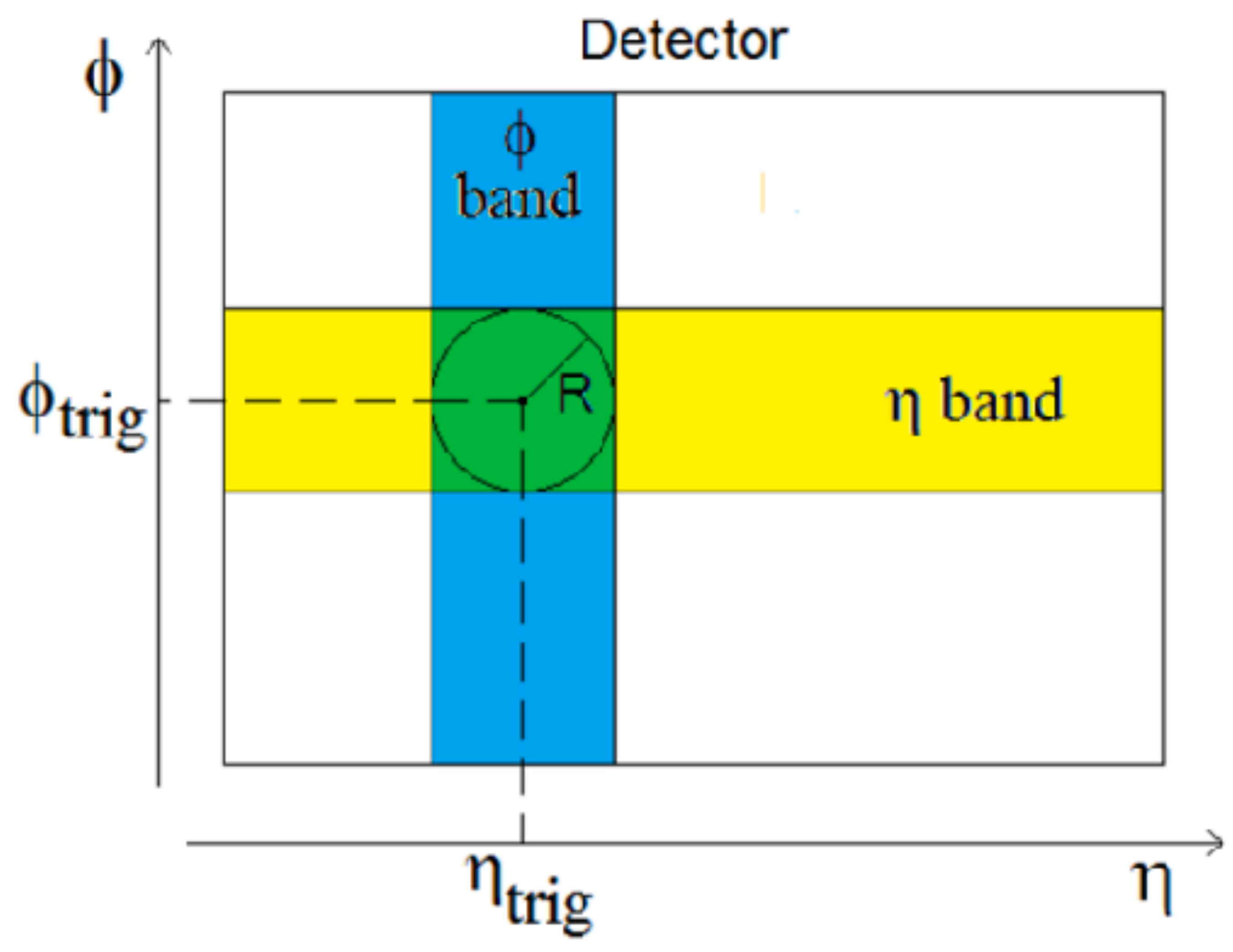
  "Prototype electronics for the silicon pad layers of the future Forward Calorimeter (FoCal) of the ALICE experiment at the LHC", arXiv:2302.13912

Thank you for the attention!

Backup

Isolation method and UE subtraction

$$R_{cone} = \sqrt{(\eta - \eta_\gamma)^2 + (\varphi - \varphi_\gamma)^2}$$



In Pb-Pb high multiplicity in final state →subtracting the UE

How? METHOD <u>η-φ bands</u>

The photon candidate is characterized by a φ_{trig} and η_{trig}.

It is possible two bands φ_{band} and η_{band} with the isolation cone of radius R.

UE subtracted event by event, estimated in region far from our candidate gamma

The contribution of the UE in the cone is ~ $(\Sigma\, p_{\mathrm{T}}^{iso})_{UE} \cdot A_{cone}$

It's removed from the total transverse momentum in the cone

The final condition on p_{T} that defines a isolated γ is :

$$\sum_{cone} p_{\mathrm{T}}^{iso} - (\sum_{UE} p_{\mathrm{T}}^{iso})_{in\,cone} = p_{\mathrm{T}}^{iso} < 2\ \mathrm{GeV}/c$$

C. Arata

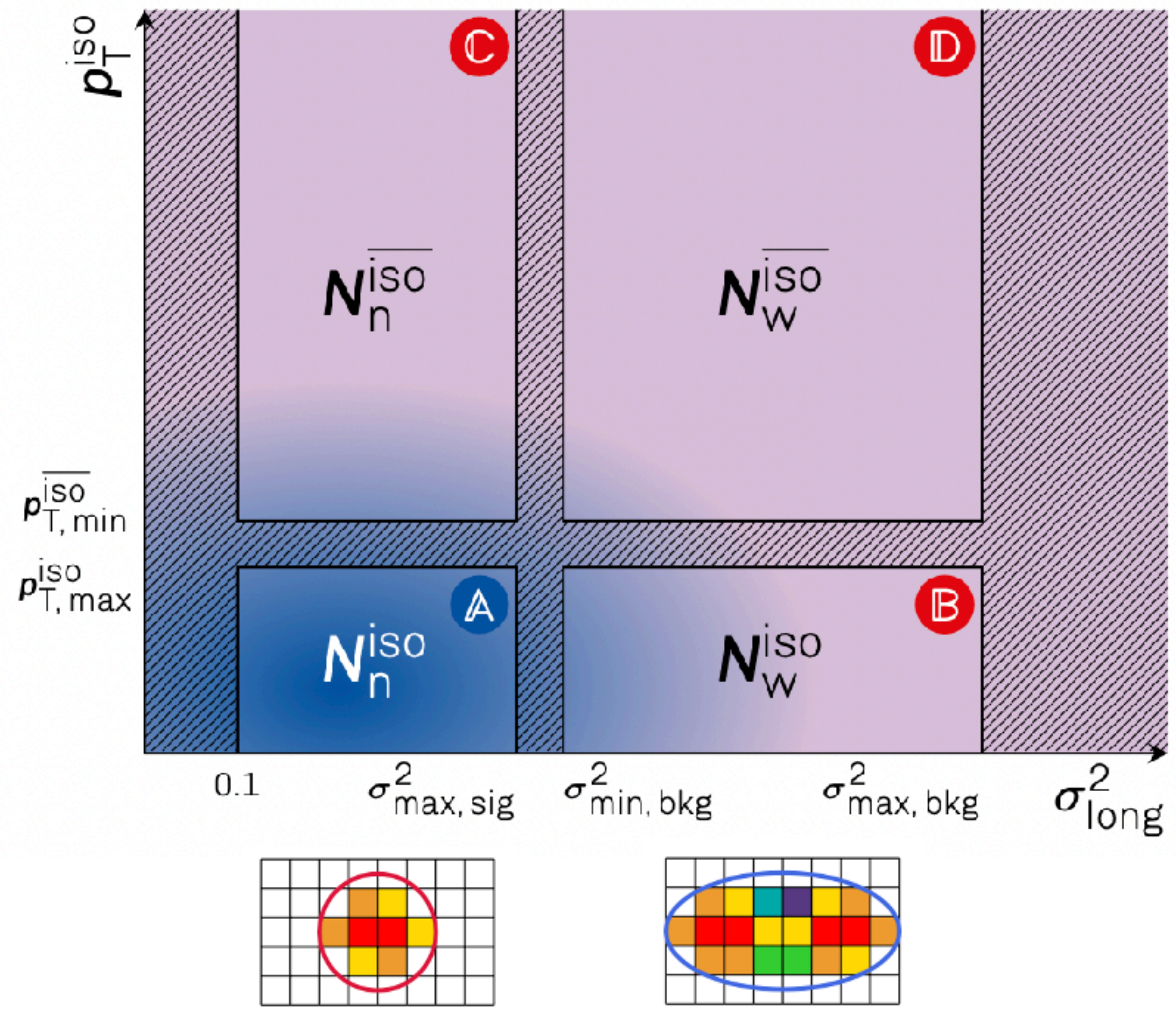
Purity: ABCD method

Divide clusters σ^2_{long}- isolation energy plane into 4 regions ABCD

- A : signal dominated region
- B, C and D : background dominated regions

N = ***S*** + ***B*** = γ_{direct} signal + background

- ***purity*** = ***S***/***N*** in A region



$$purity = \left[1 - \left(\frac{N_n^{\overline{iso}}/N_n^{iso}}{N_w^{\overline{iso}}/N_w^{iso}}\right)_{data}\right] \times \left(\frac{B_n^{\overline{iso}}/N_n^{iso}}{N_w^{\overline{iso}}/N_w^{iso}}\right)_{MC}$$

Data-driven purity

MC correction factor

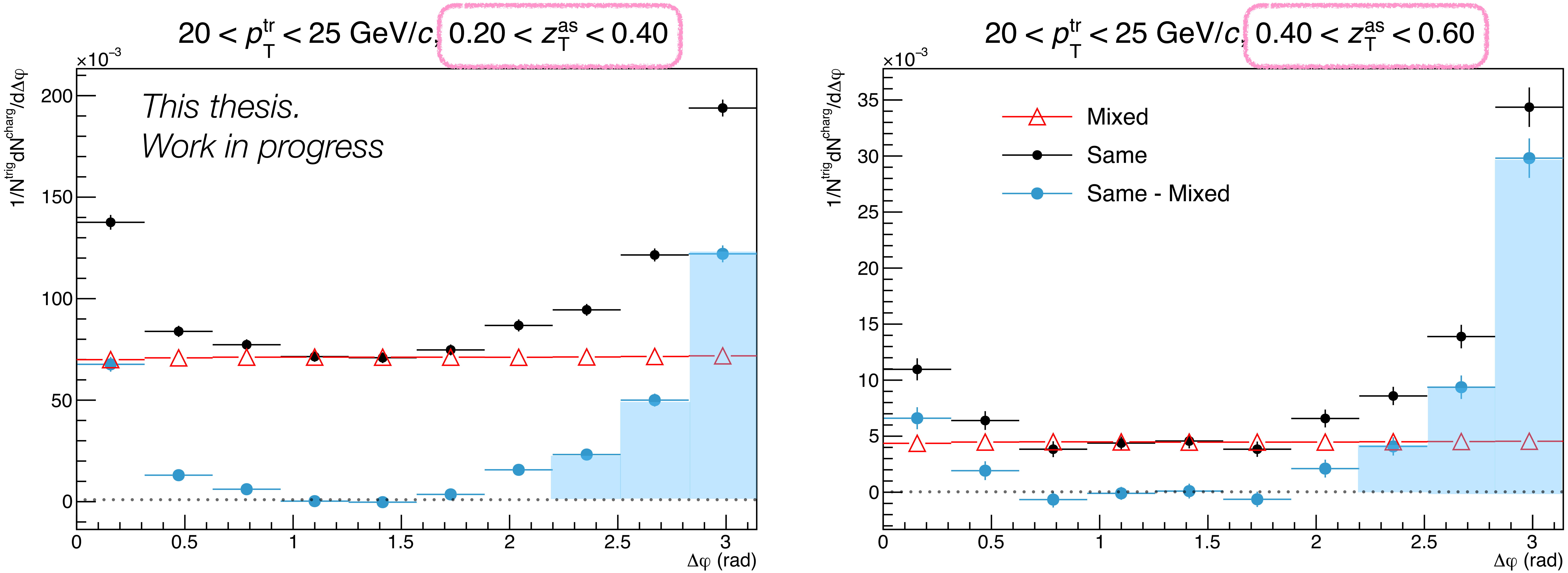
Corrections due to:

B isolation fraction depends on the circularity

S not contained only in A, it spreads over B, C and D regions

UE subtraction: *Mixed event method*

C. Arata



$\text{cluster}^{iso}_{wide}$

Same - Mixed

=

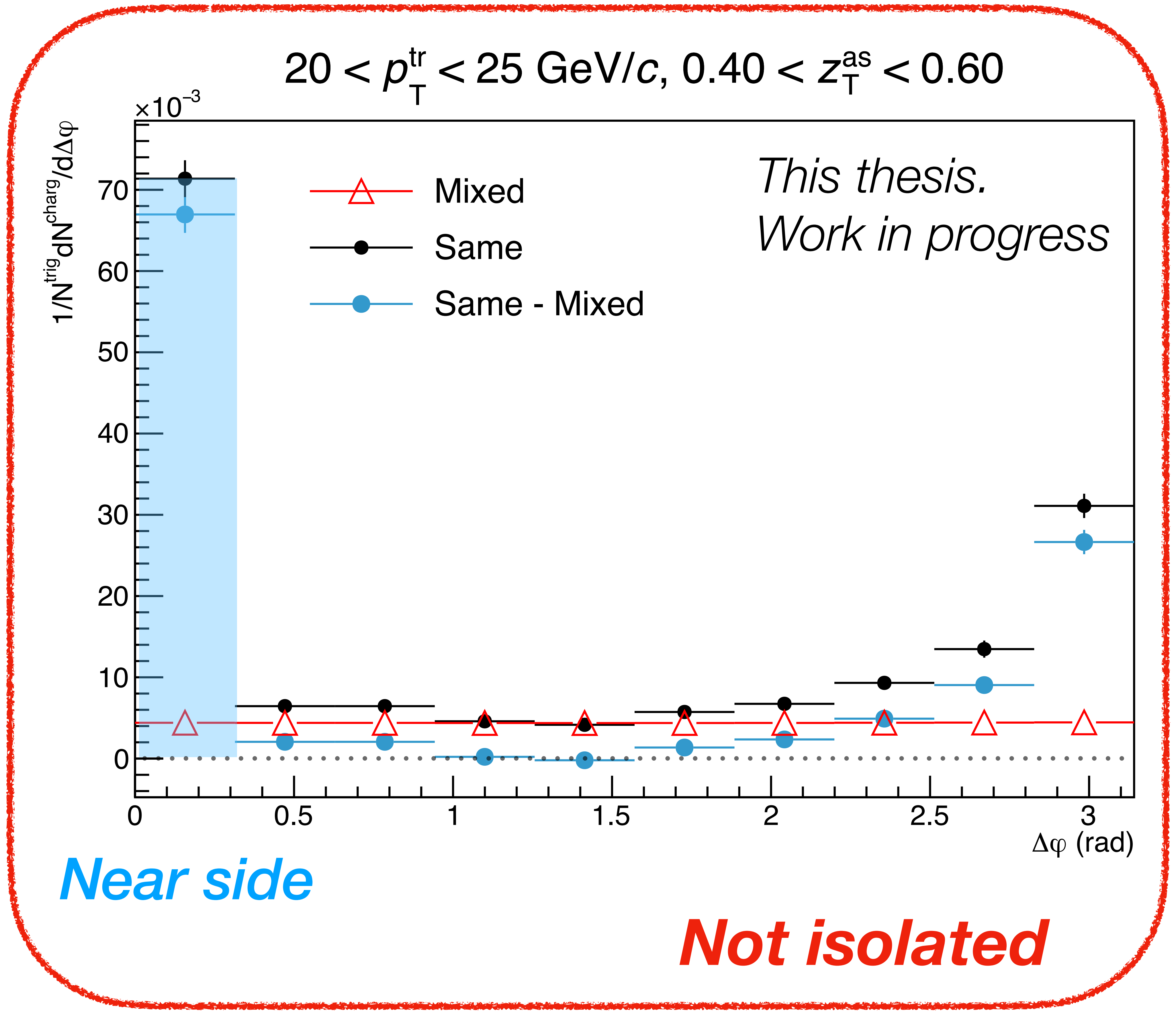
Subtracted

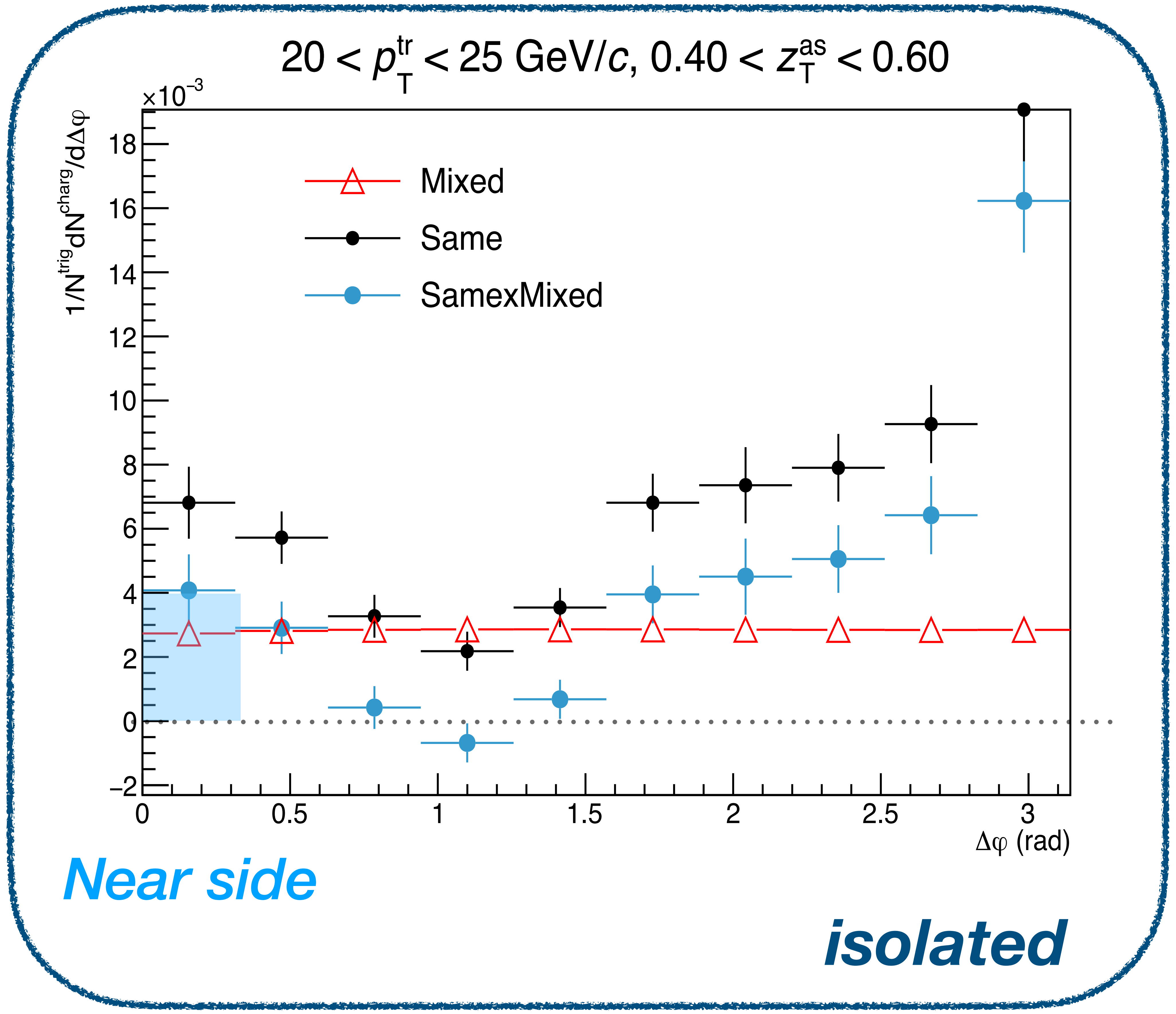
$z_T = p_T^{hadr} / p_T^{\gamma}$

Away side → *Away side*

- Integration of the ***away side peak*** for every z_T interval: $1/N^{trig} dN^{ch}/dz_T$ distribution
- But the sample is still not totally pure after the shower shape cut and the removal of the UE

UE subtraction: NOT isolated and isolated





- ***Not isolated***: there is activity inside the cone → 2 peaks like in di-hadrons correlations
- ***Isolated*** only away side peak: it seems two peaks because the statistics fluctuates

Photon identification with EMCal

C. Arata

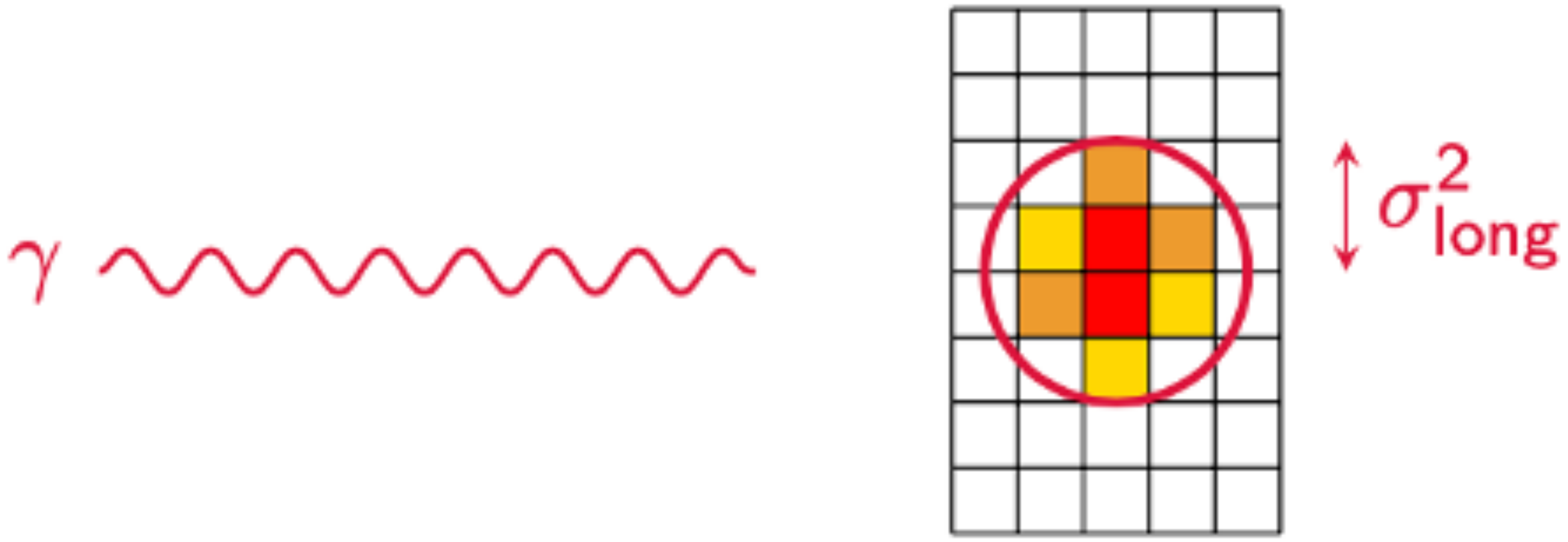
A particle interacting with the ***cell material*** produces a shower spreading its energy over ***neighbouring cells***.

- ***Cluster***: aggregate of cells

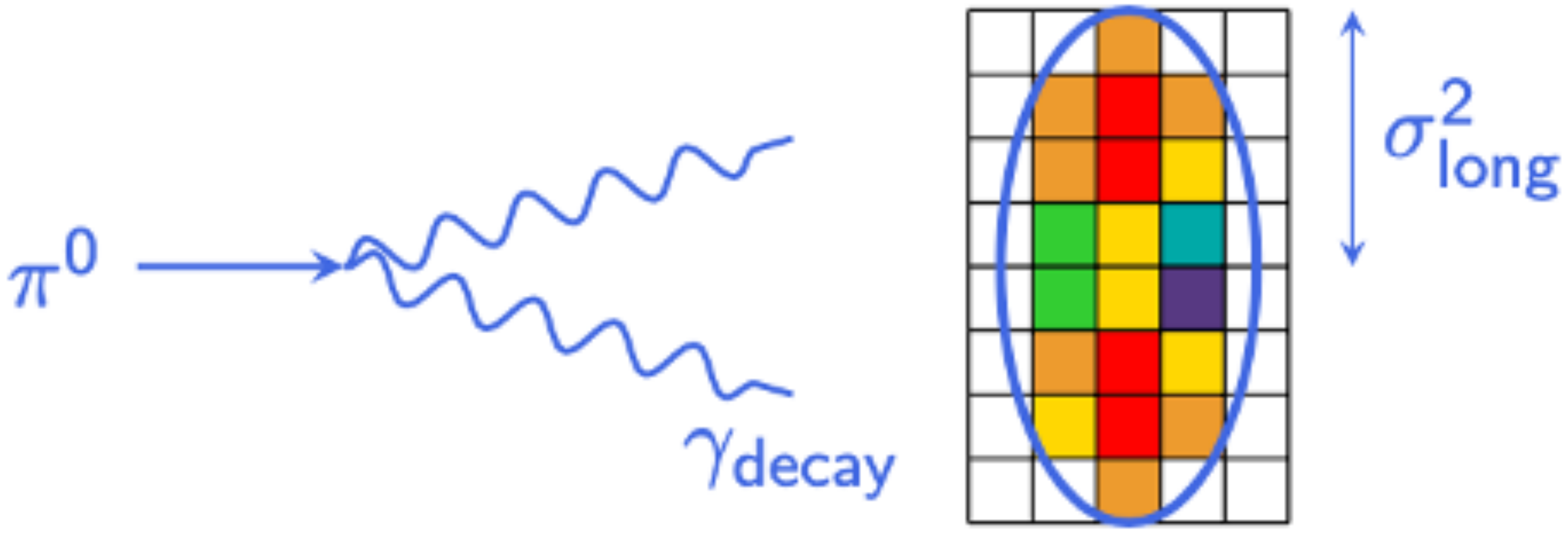
The **distribution of energy** within a cluster is the **shower shape**, describe by:

$$\sigma^2_{\text{long}} = 0.5(\sigma^2_{\varphi\varphi} + \sigma^2_{\eta\eta}) + \sqrt{0.25(\sigma^2_{\varphi\varphi} - \sigma^2_{\eta\eta})^2 + \sigma^2_{\eta\varphi}}, \qquad \sigma^2_{\alpha\beta} = \sum_i \frac{w_i \alpha_i \beta_i}{w_{\text{tot}}} - \sum_i \frac{w_i \alpha_i}{w_{\text{tot}}} \sum_i \frac{w_i \beta_i}{w_{\text{tot}}},$$

- To discriminate between photons and overlapping decay γ^{decay} from high E $\pi^0 \rightarrow$ gamma
- apply a condition on the cluster symmetry



$\gamma \rightarrow \text{cluster}_{\text{narrow}}$: circular cluster



$\pi^0 \rightarrow \text{cluster}_{\text{wide}}$: elliptical cluster

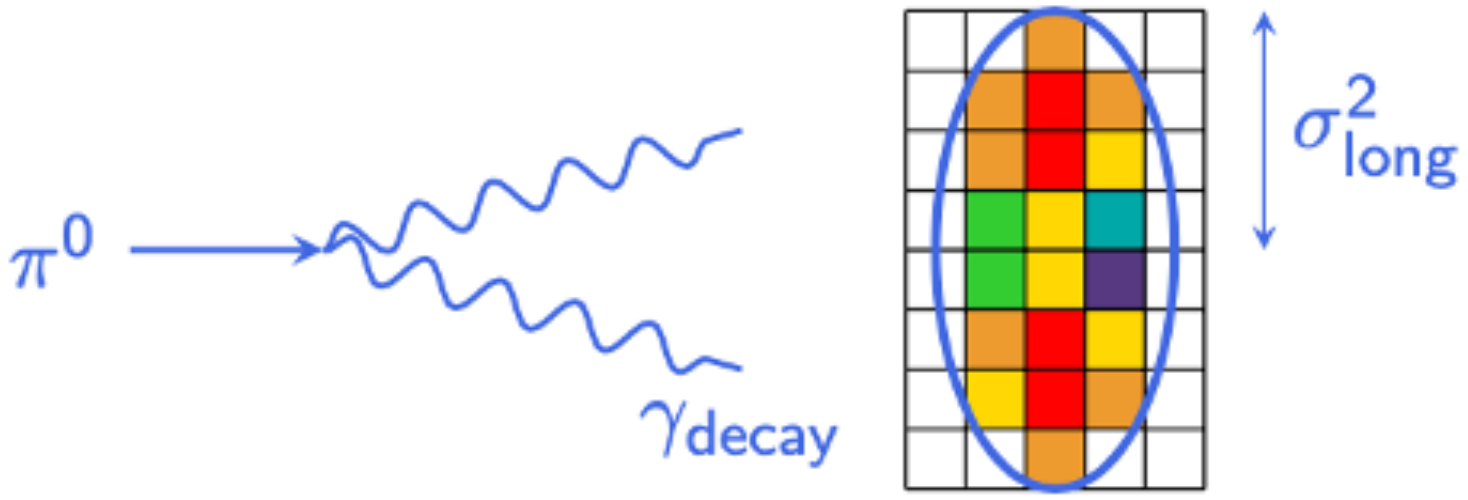
Photon identification with EMCal

C. Arata

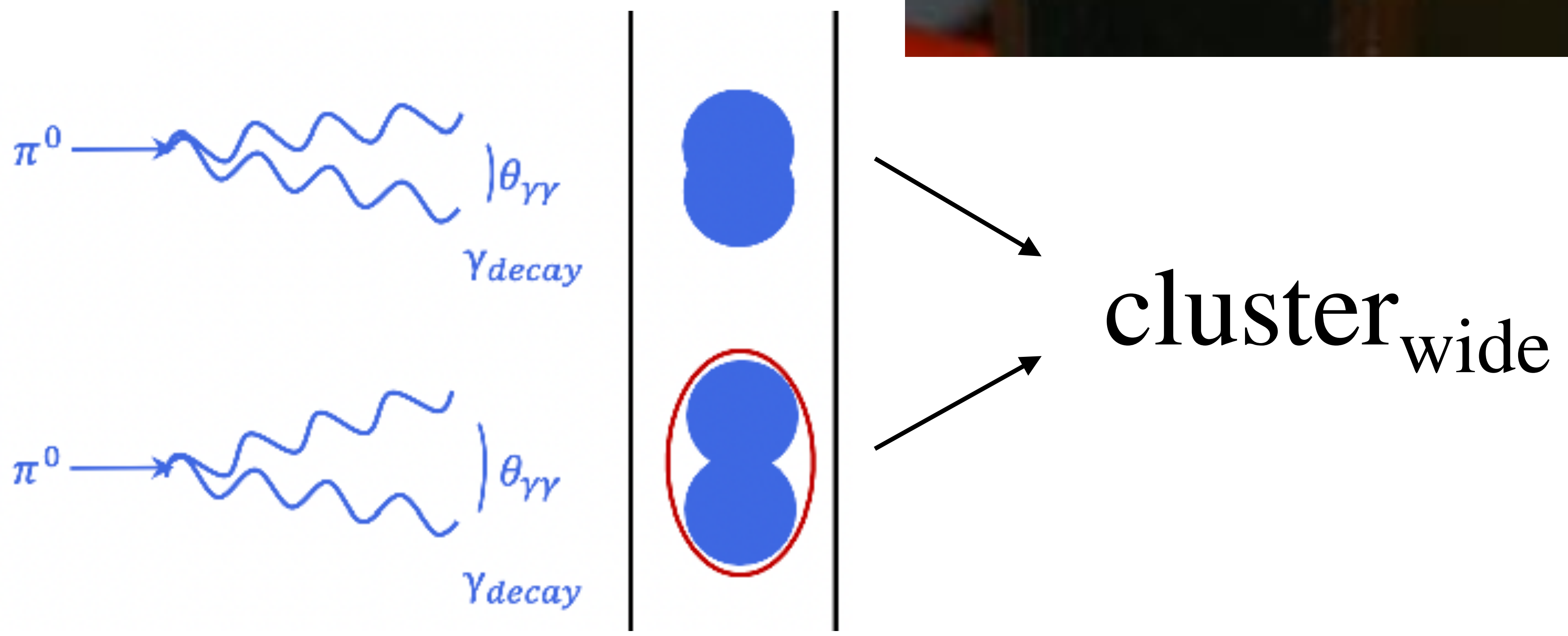
A particle interacting with the ***cell material*** produces a shower spreading its energy over ***neighbouring cells***.

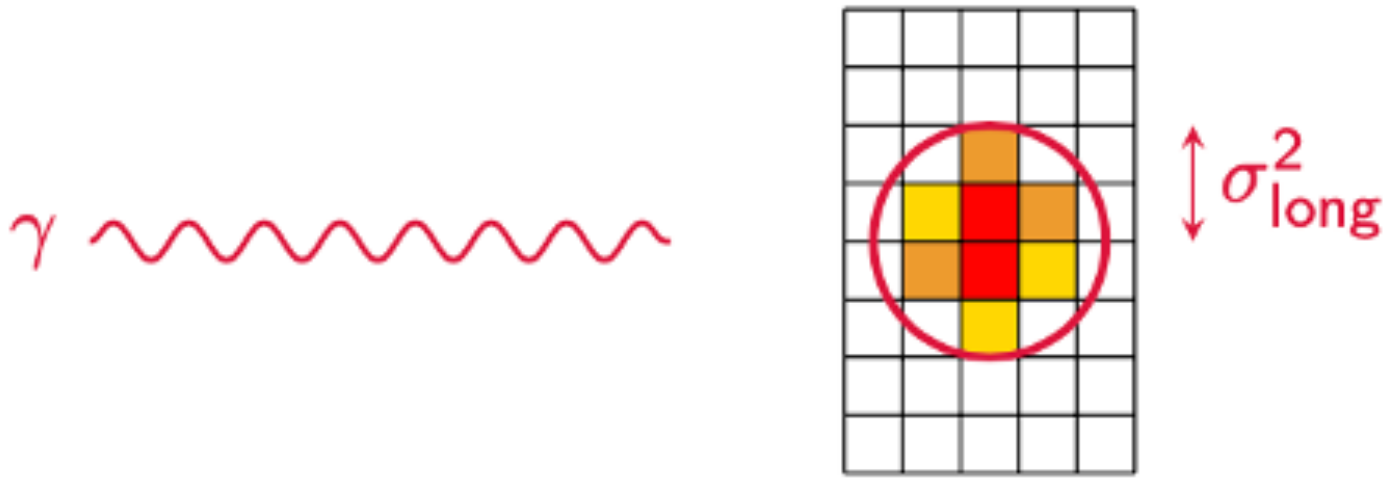
- ***Cluster***: aggregate of cells

The **distribution of energy** within a cluster allows to discriminate between single photons γ shower and overlapping γ_{decay} from high energy $\pi^0 \to \gamma\gamma$

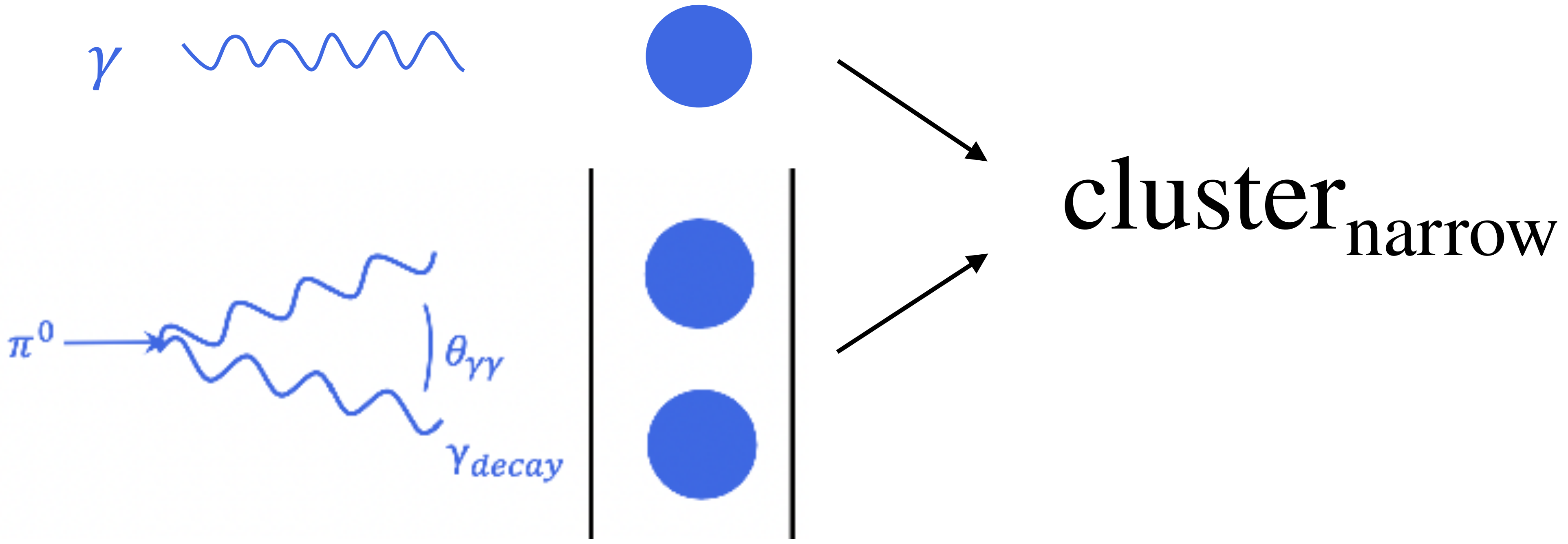


$\pi^0 \to \text{cluster}_{\text{wide}}$:
elliptical cluster





$\gamma \to \text{cluster}_{\text{narrow}}$:
circular cluster



ALICE experiment + FoCal upgrade

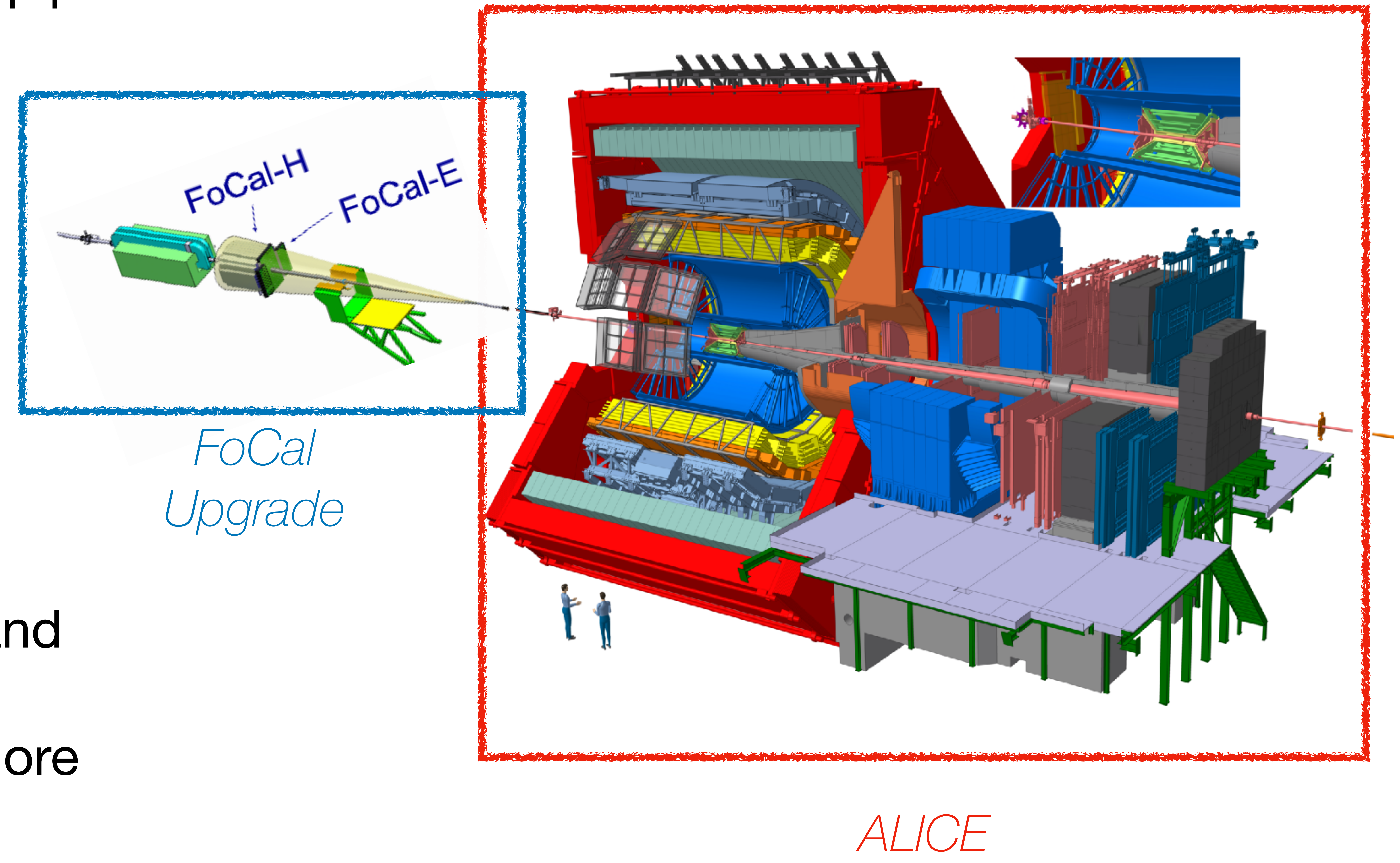
A new forward calorimeter (FoCal) developed as a detector upgrade of the ALICE experiment at LHC

- Installation in ALICE foreseen for LHC Run 4 (2029)

- FoCal unique detector composed of:
  - electromagnetic calorimeter (FoCal-E)
  - hadronic calorimeter (FoCal-H)

- Physics program:

  To measure direct photon production in pp and pPb collisions, to quantify the nuclear modification of the gluon density and to explore possible nonlinear QCD evolution



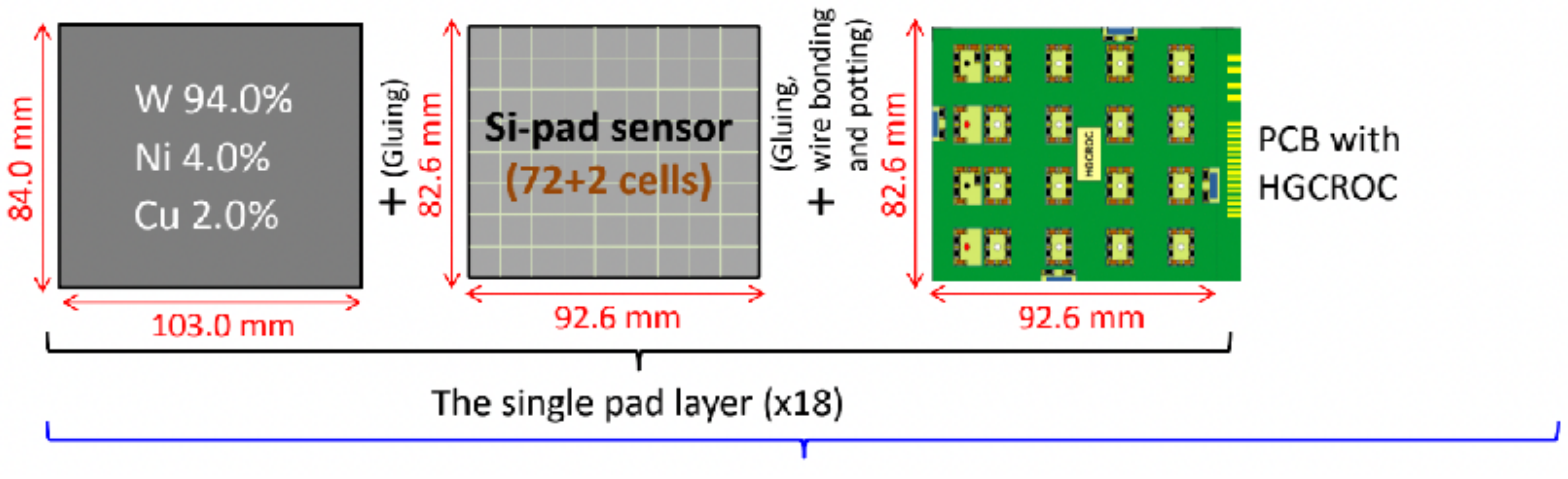
Electromagnetic calorimeter: Focal-E

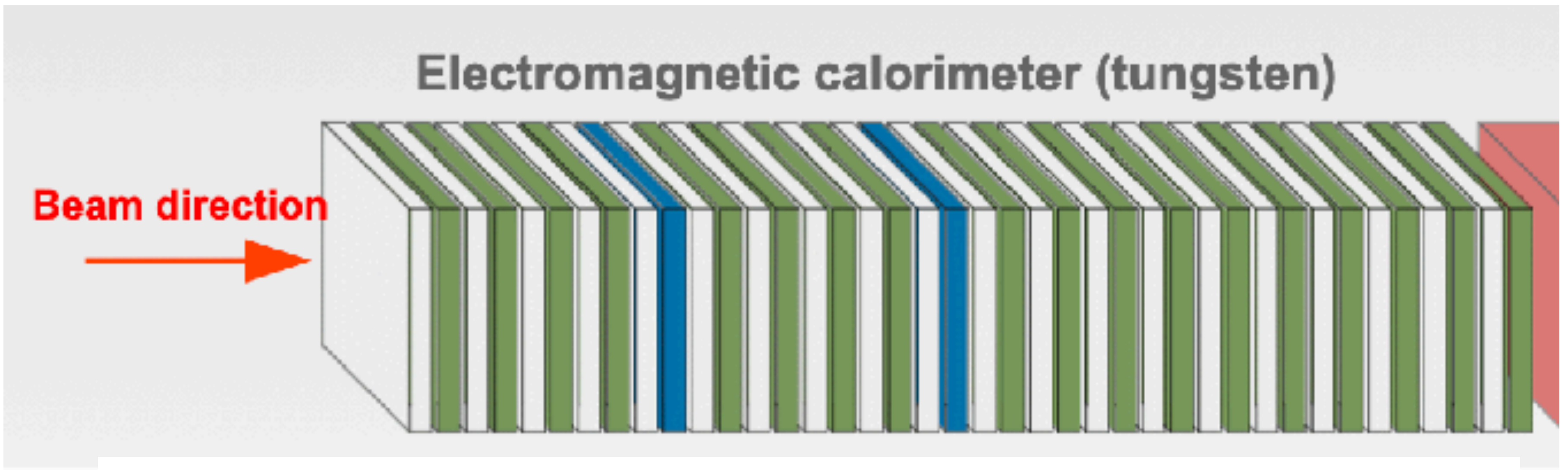
Electromagnetic calorimeter prototype: 18 Si-W layers

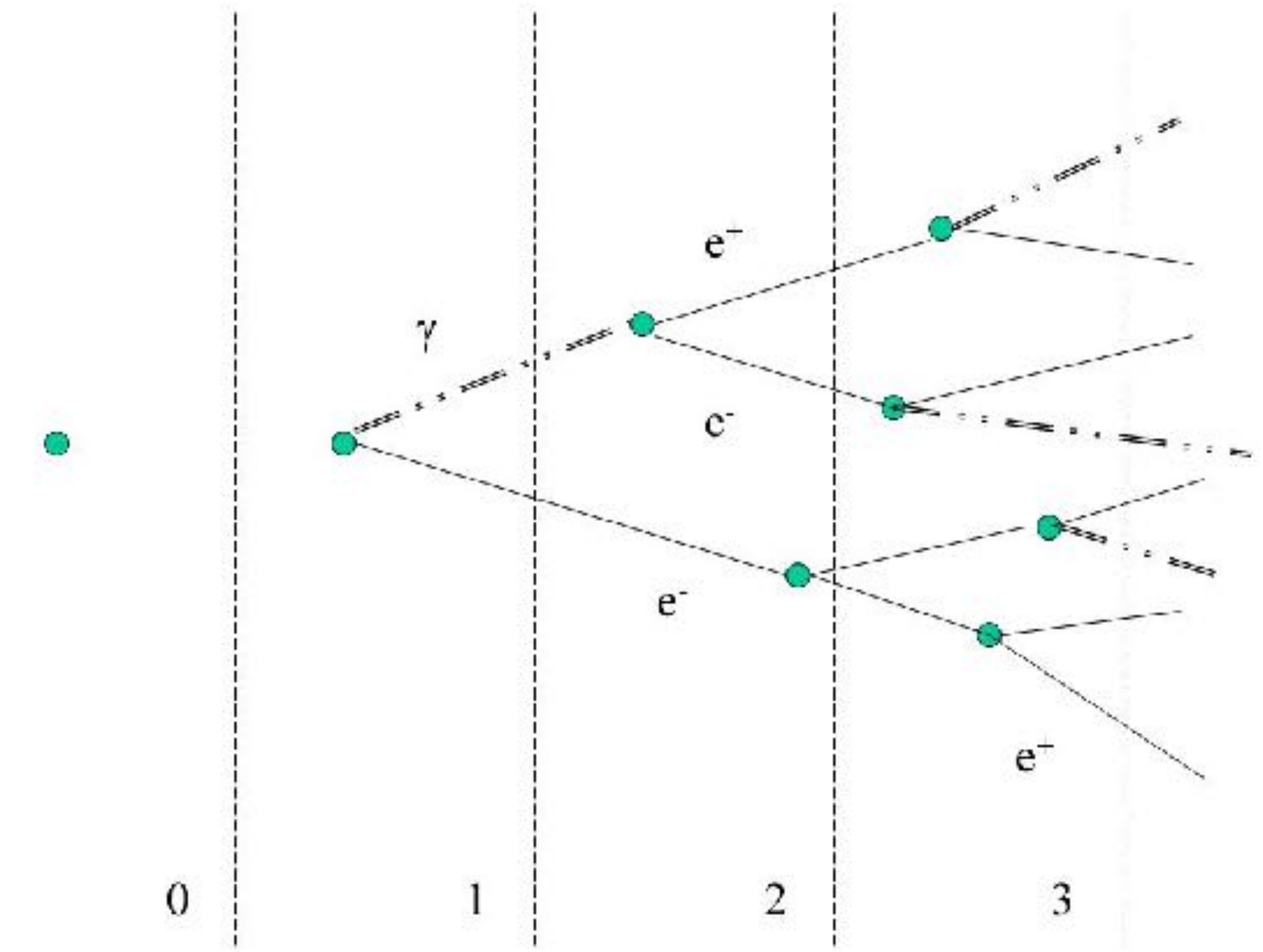
Tungsten (W): the passive absorber

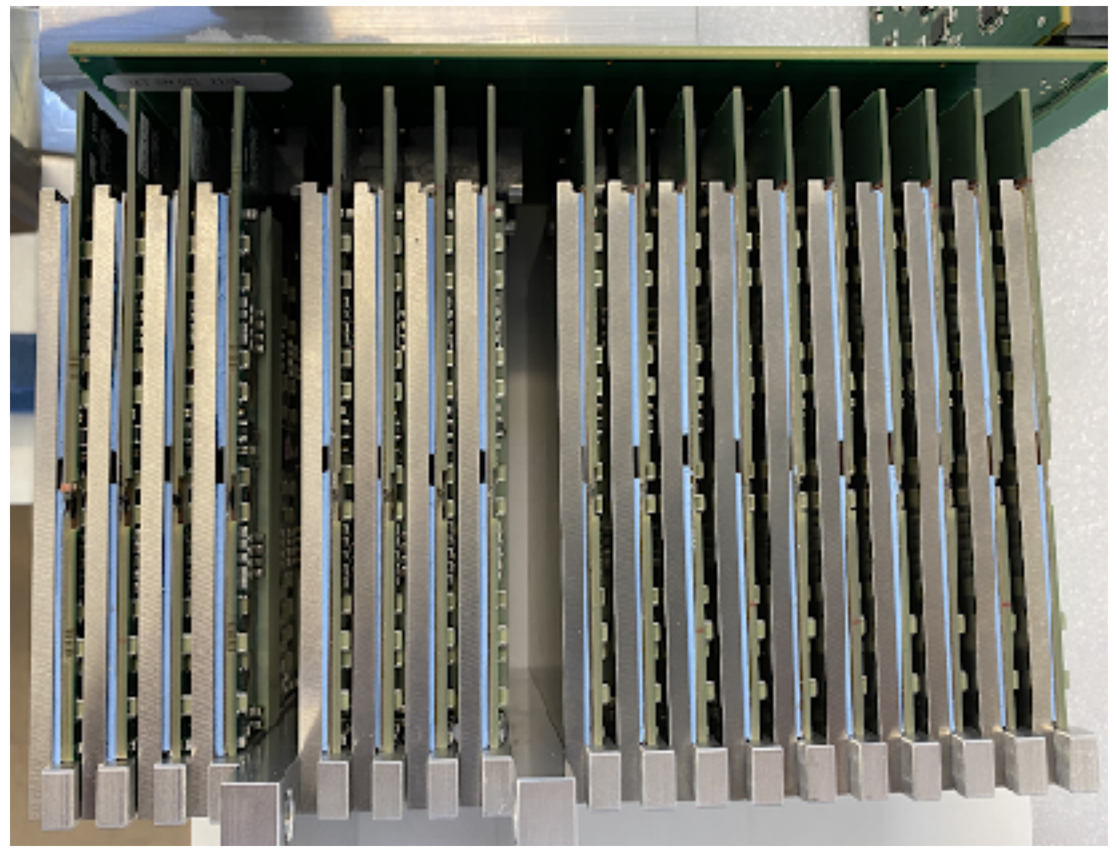
Silicon pad sensor key component of the FoCal-E:

- a good energy resolution and signal-to-noise (S/N) ratio
- a wide dynamic range for the proposed physics programs with FoCal.



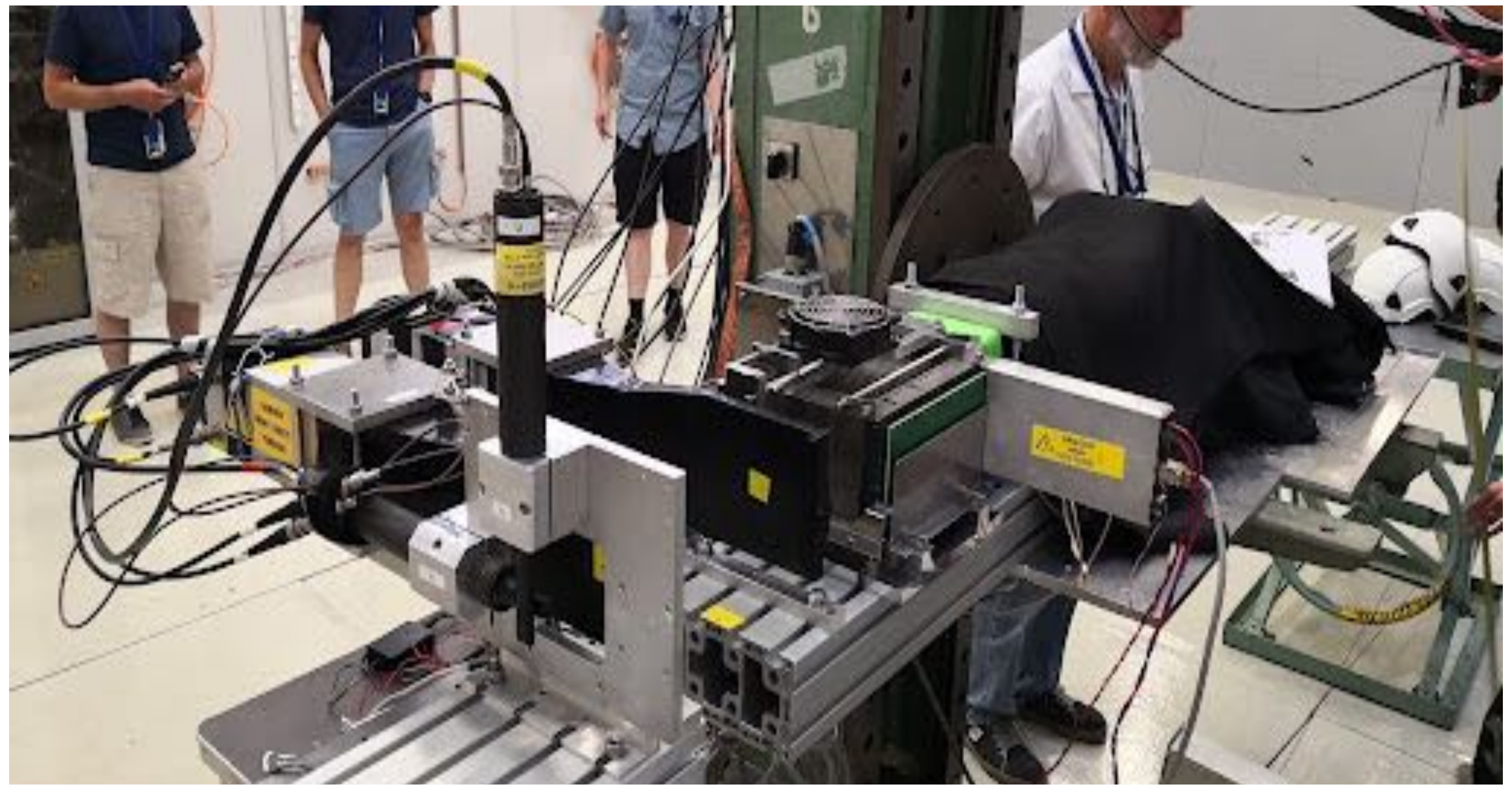


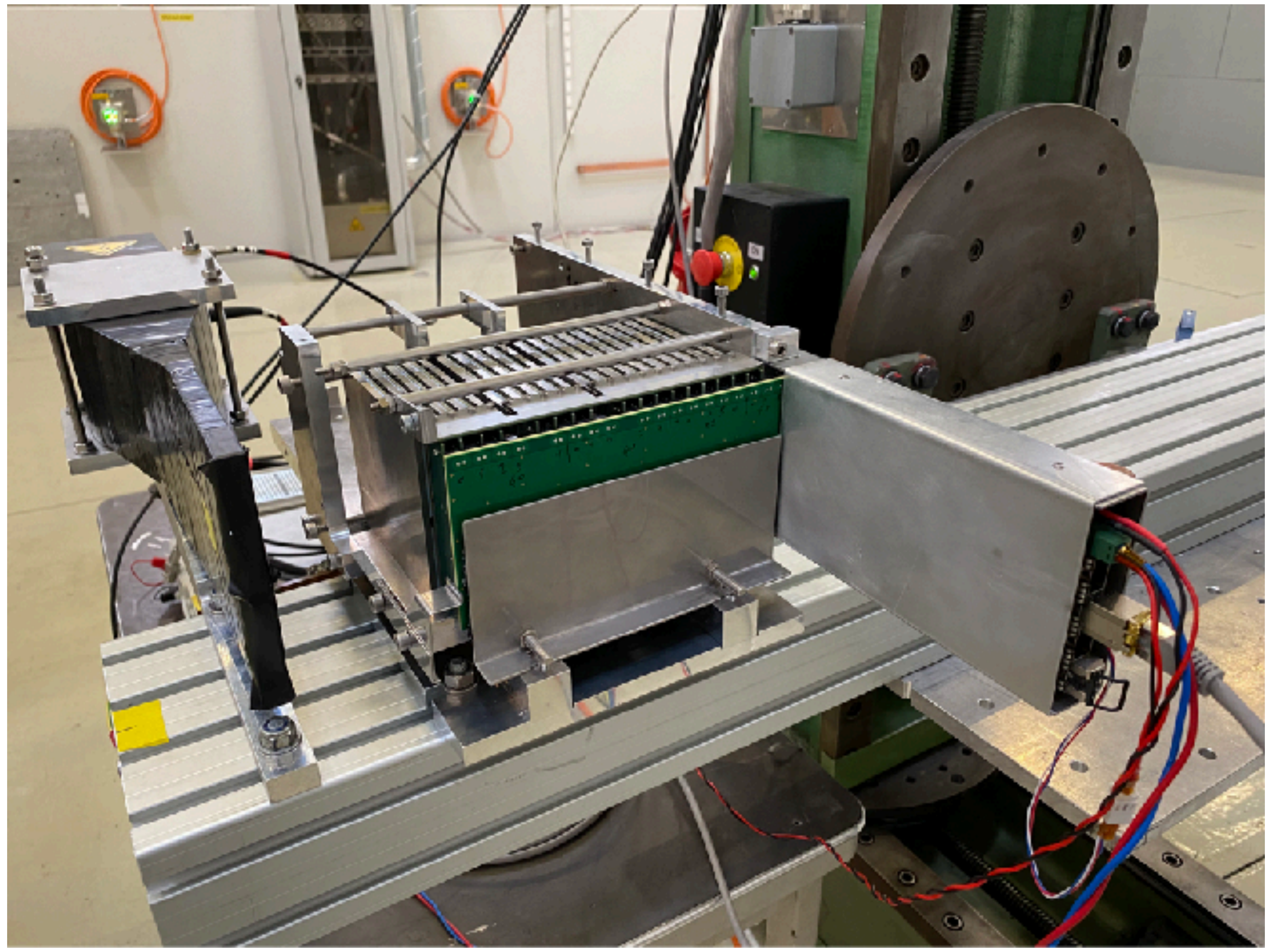




Beam Test: configuration

June 22 @ CERN PS T9





Test of the 18 layers FoCal-E Pad prototype at CERN PS T9

- Configuration:

  3 PMT for the coincidence

  Focal-E Pad

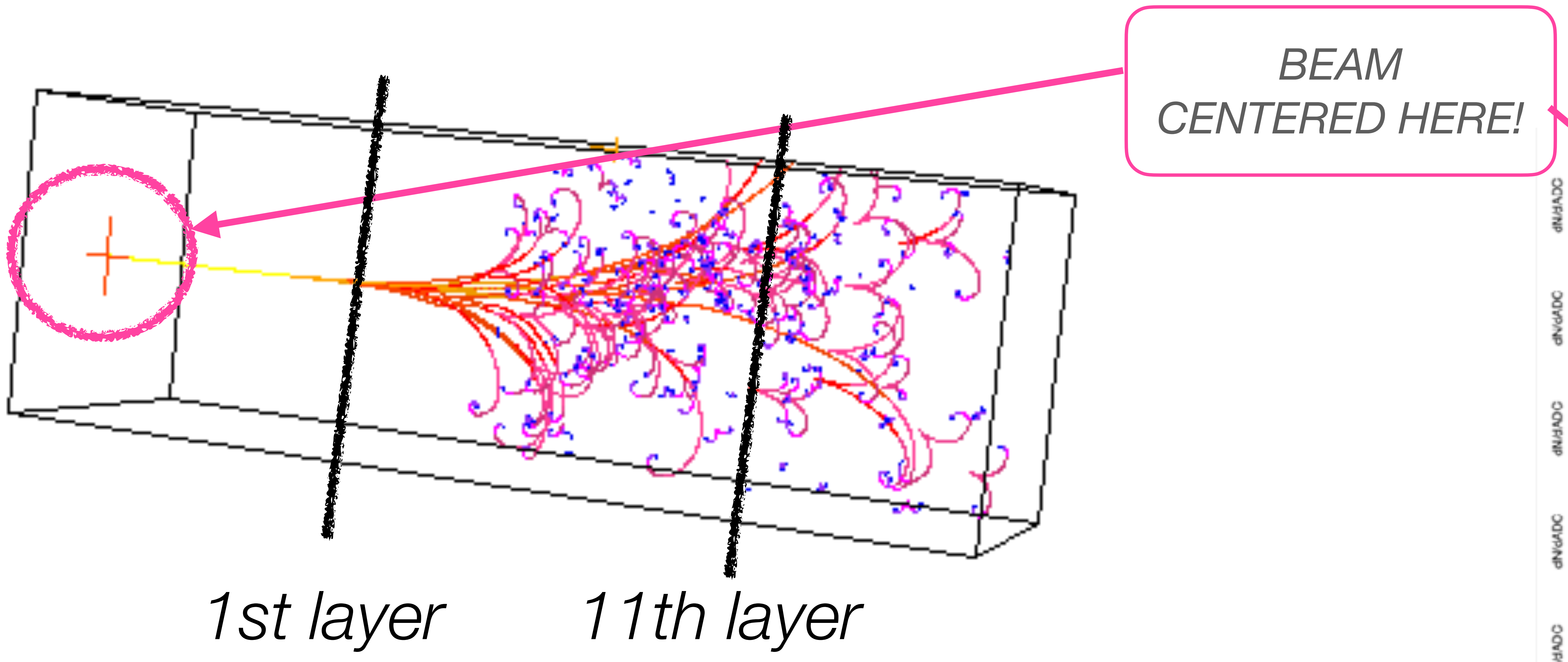
- Beam characteristics:

  Hadrons of 60, 50, 40, 20, 10 GeV

- Objective:

  Characterisation of the sensor with the measure of Minimum Ionizing Particle (MIPs)

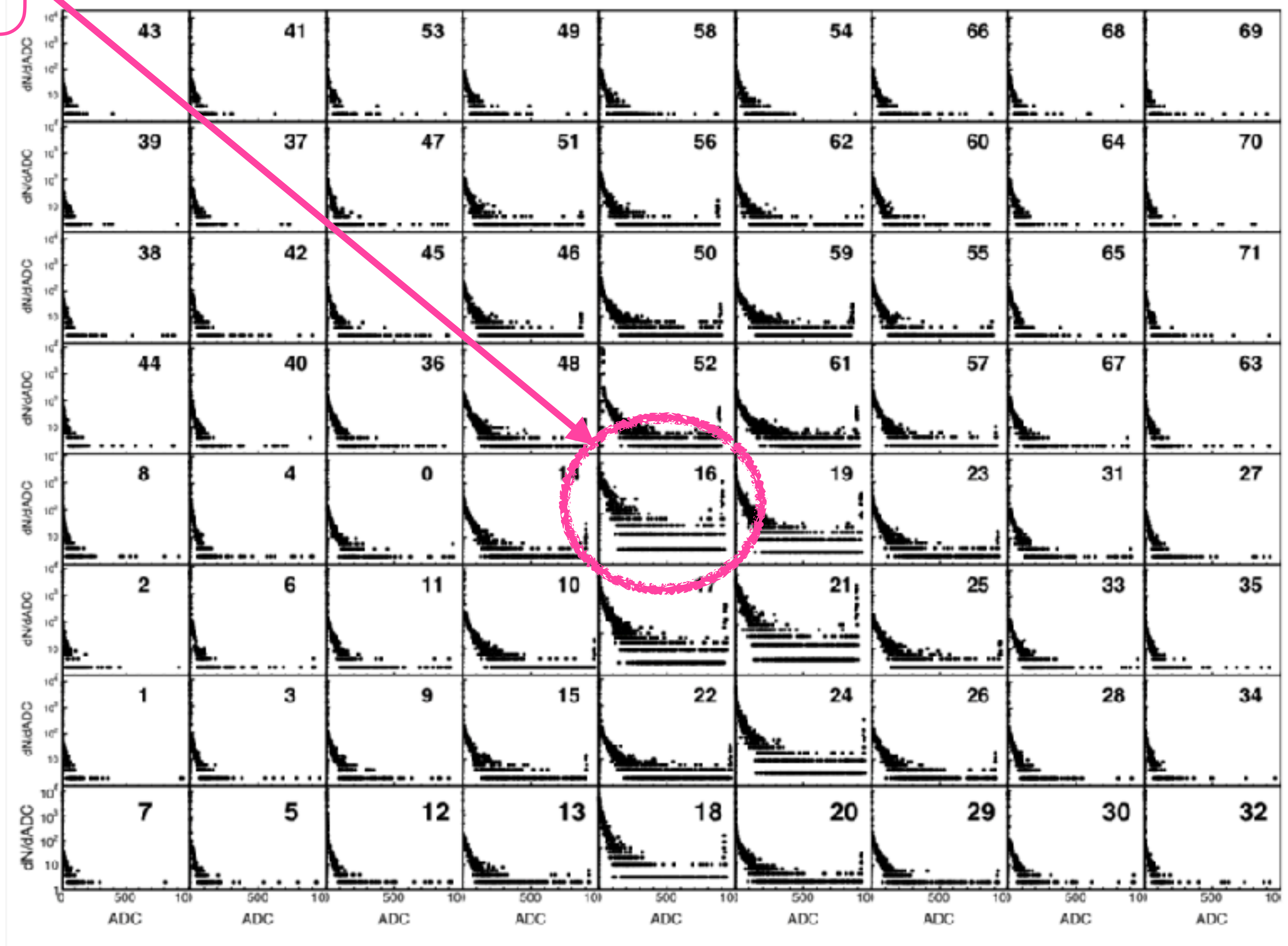
Beam Test measurements: Shower evolution



Check the electromagnetic shower and its evolution.

As the number of layer increases, the shower spreads more and more.

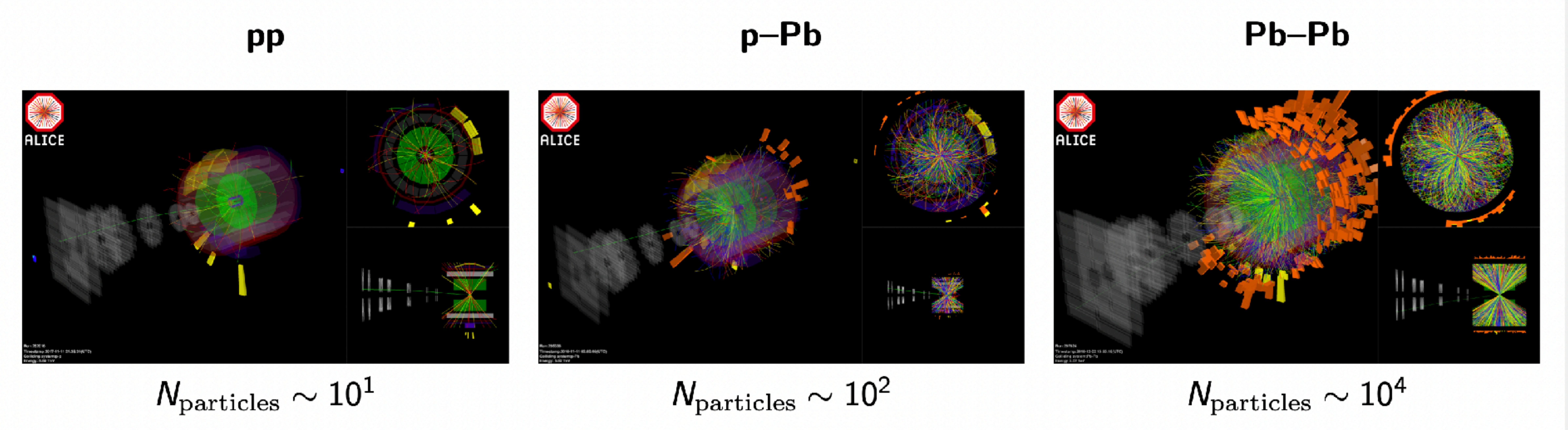
- More channels are activated
- Longitudinal evolution of the shower



11th layer, 60 GeV @ SPS beam test Sept 22

Big questions in heavy ions physics

- How does the Quark Gluon Plasma form, evolve, and transition again into hadronic matter?
- Is there a QGP droplet formed in smaller collision systems (pp, p-Pb)?
- How do the high-energy partons originated in HIC travelling through the colored QGP medium lose energy?



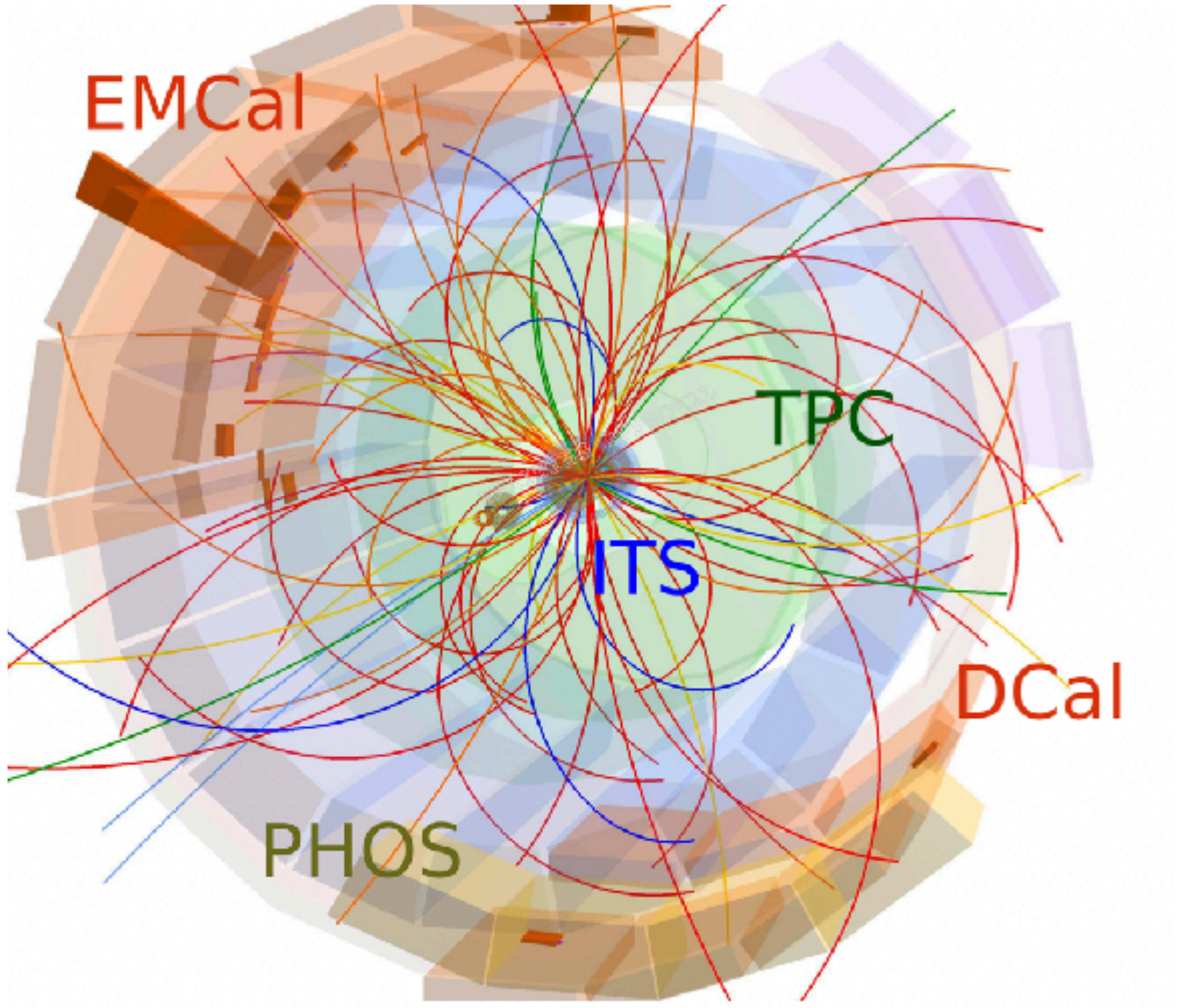
Photon identification with EMCal

C. Arata

A particle interacting with the ***cell material*** produces a shower spreading its energy over ***neighbouring cells***.

- ***Cluster***: aggregate of cells with energy above the noise threshold
- To distinguish between neutral and charged clusters: the track information coming from **ITS**-**TPC** is used.

The distribution of energy within a cluster, referred to as "shower shape", is described using a elliptical parametrization.



$$\sigma^2_{\text{long}} = 0.5(\sigma^2_{\varphi\varphi} + \sigma^2_{\eta\eta}) + \sqrt{0.25(\sigma^2_{\varphi\varphi} - \sigma^2_{\eta\eta})^2 + \sigma^2_{\eta\varphi}},$$

$$\sigma^2_{\text{short}} = 0.5(\sigma^2_{\varphi\varphi} + \sigma^2_{\eta\eta}) - \sqrt{0.25(\sigma^2_{\varphi\varphi} - \sigma^2_{\eta\eta})^2 + \sigma^2_{\eta\varphi}},$$