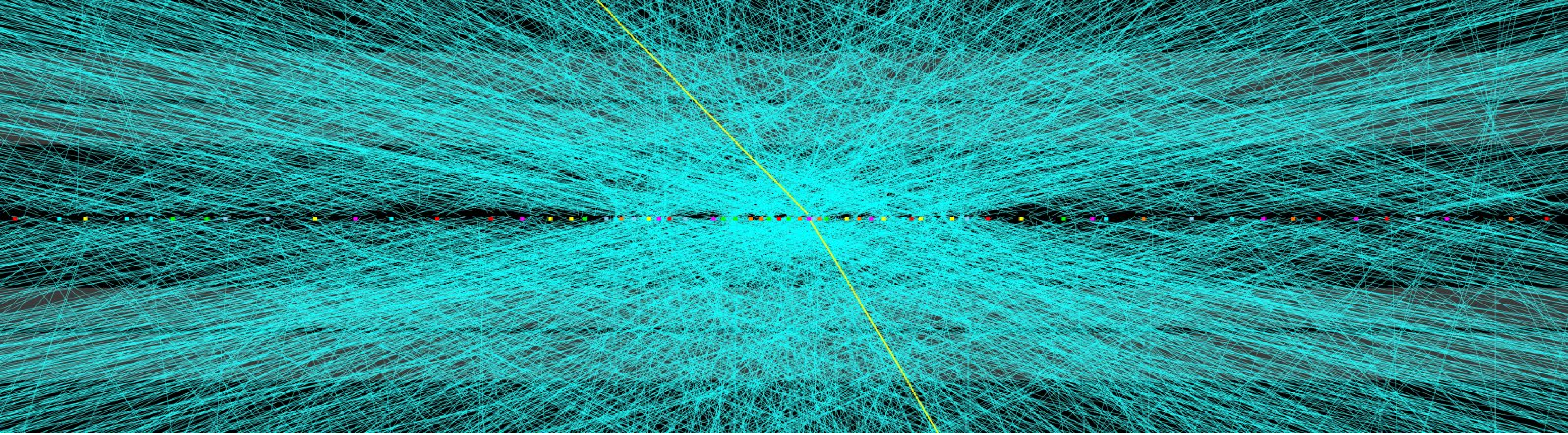


Luminosity studies with Pixel Cluster Counting at the ATLAS experiment

DESY Summer Student Programme

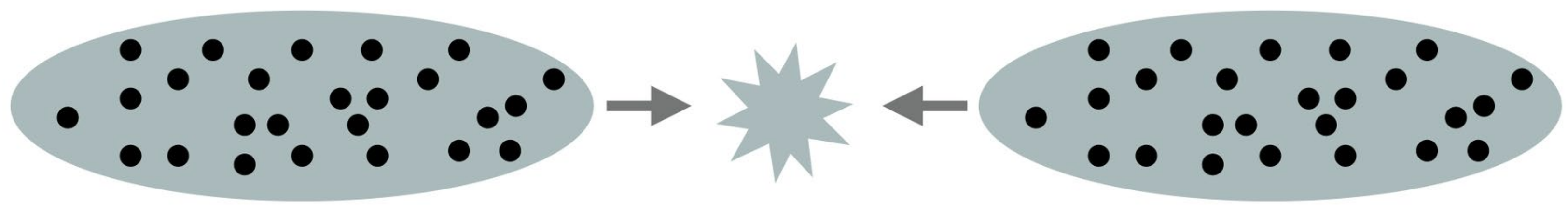
Oleksandra Khrul

Supervisors: Filippo Dattola, Claudia Seitz

Introduction

Luminosity basics

- Luminosity ($\mathcal{L}$) measures **number of proton collisions** produced by LHC.



- Determining luminosity with high precision is **crucial for cross section measurements:**

$$\sigma(pp \to X) = \frac{N(pp \to X)}{\int \mathscr{L} \mathrm{dt}}$$

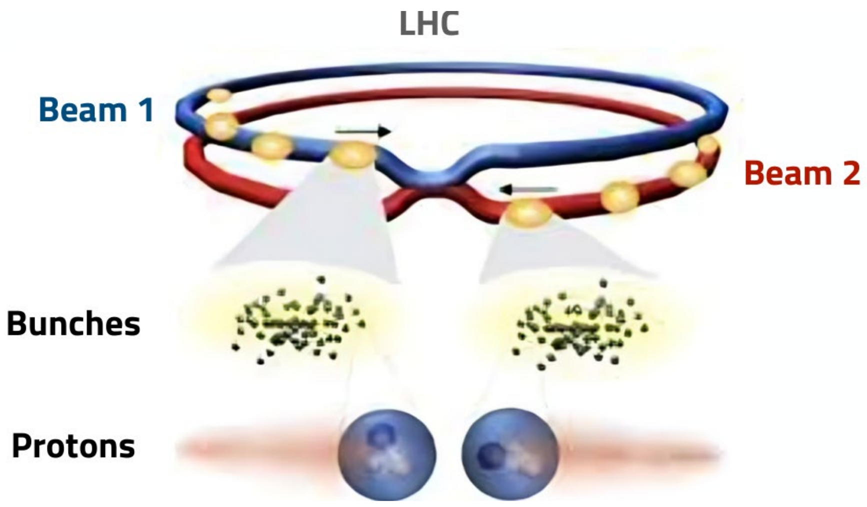
  - Luminosity uncertainty dominant in $t\bar{t}$/W/Z cross section measurements.

    E.g. $\sigma_{t\bar{t}} = 826.4 \pm 3.6\,(\text{stat}) \pm 11.5\,(\text{syst}) \pm 15.7\,(\text{lumi}) \pm 1.9\,(\text{beam})\,\text{pb},$ [Eur.Phys.J.C 80 (2020) 528]

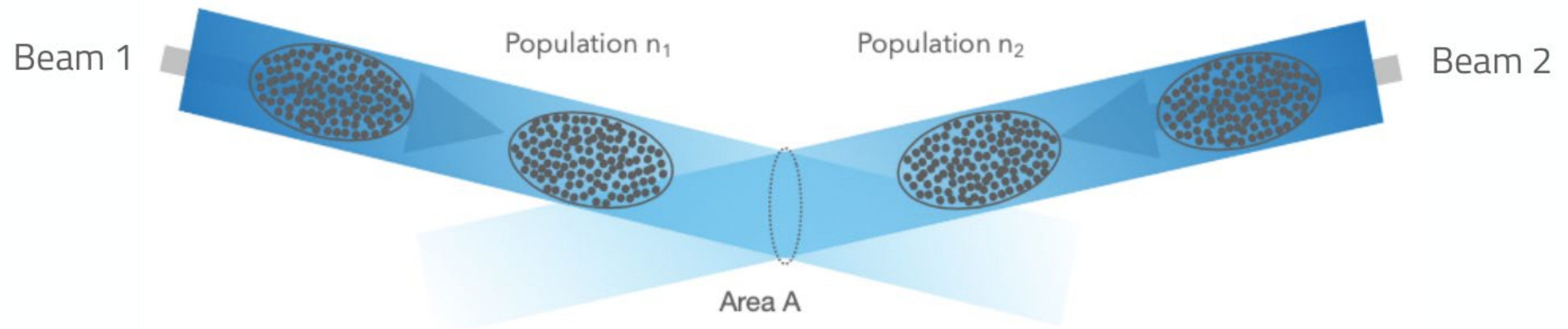
  - Record **0.83% uncertainty** achieved **in Run 2** [Eur.Phys.J.C 83 (2023) 10, 982]

Introduction

Luminosity basics



- How do LHC beams look like?



- **Trains** of filled bunches: several consecutive filled slots.

- **Isolated** bunches: filled bunch with several empty ones before and after.

Introduction

Luminosity basics

- $\mathcal{L}$ is related to the rate of observed events and LHC parameters.

$$\mathcal{L} \propto \boxed{\frac{n_1 n_2 f_r}{A}} = \boxed{\frac{\mu_{\text{vis}}\, f_r}{\sigma_{\text{vis}}}}$$

LHC beam parameters:

n_i – bunch populations
A – transverse beam size
f_r – LHC revolution frequency

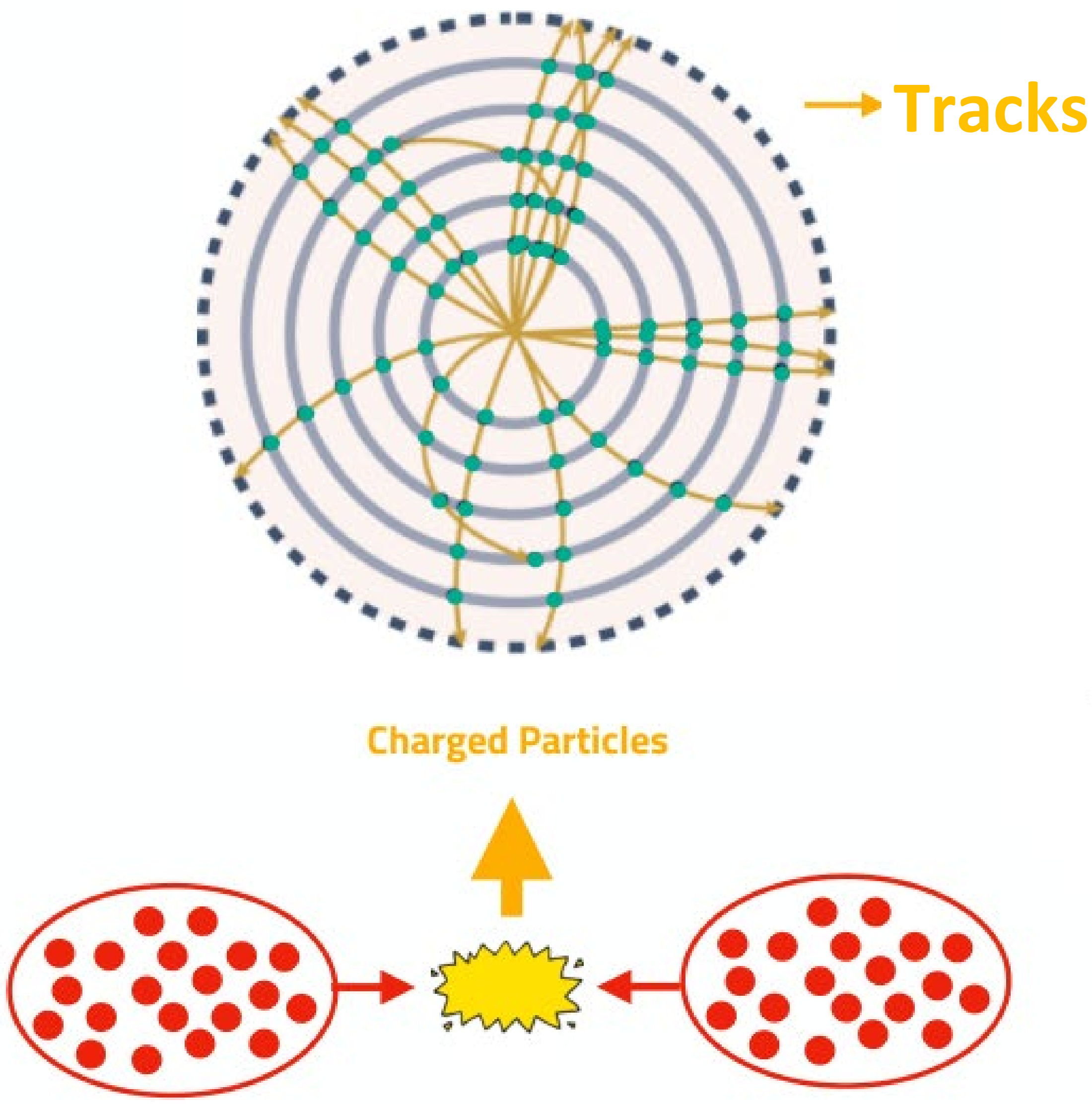
μ_{vis} = visible interaction rate per bunch crossing
σ_{vis} = calibration constant

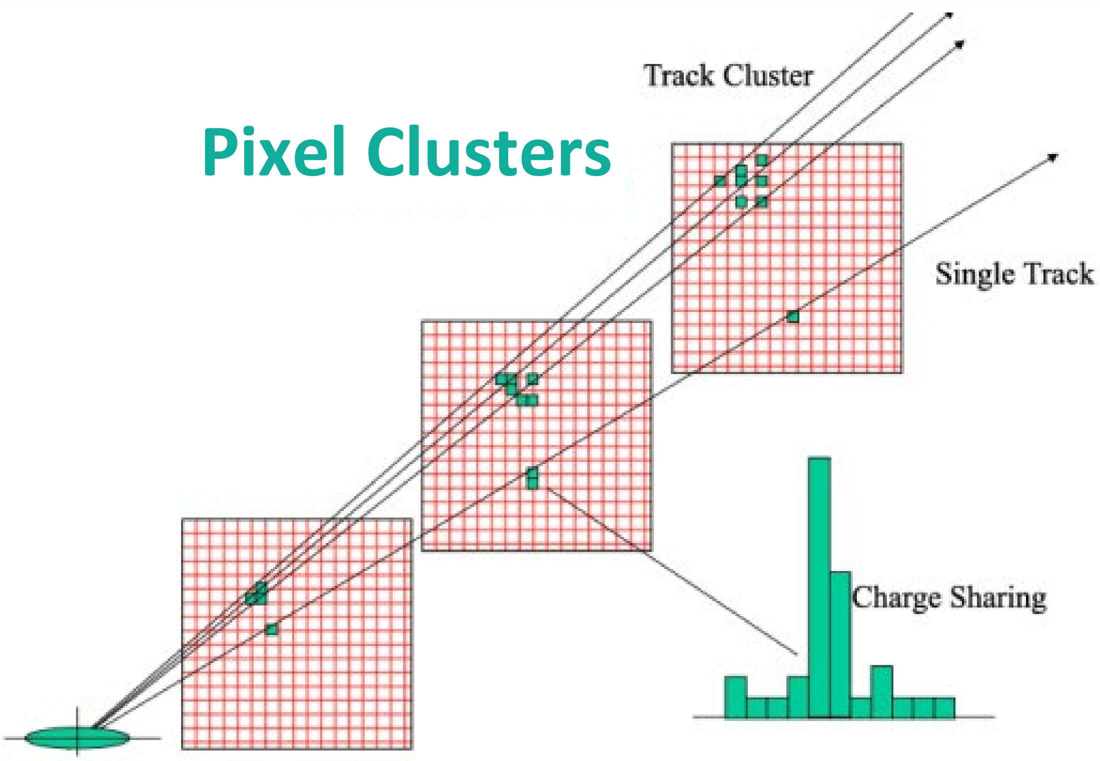
$\Rightarrow$ We can measure luminosity by determining μ_{vis} .

Introduction

Luminosity measurements with the ATLAS Inner Detector

- ATLAS monitors luminosity computing μ_{vis} with different detectors and algorithms that are **linear with luminosity and stable over time.**
- For example: **count reconstructed objects produced by charged particles** in the Inner Detector





Introduction

Track Counting and Pixel Cluster Counting

- **Assumption:** number of tracks (clusters) proportional to number of interactions per bunch crossing (μ).
- Measure μ by counting mean number of tracks (clusters) per event:

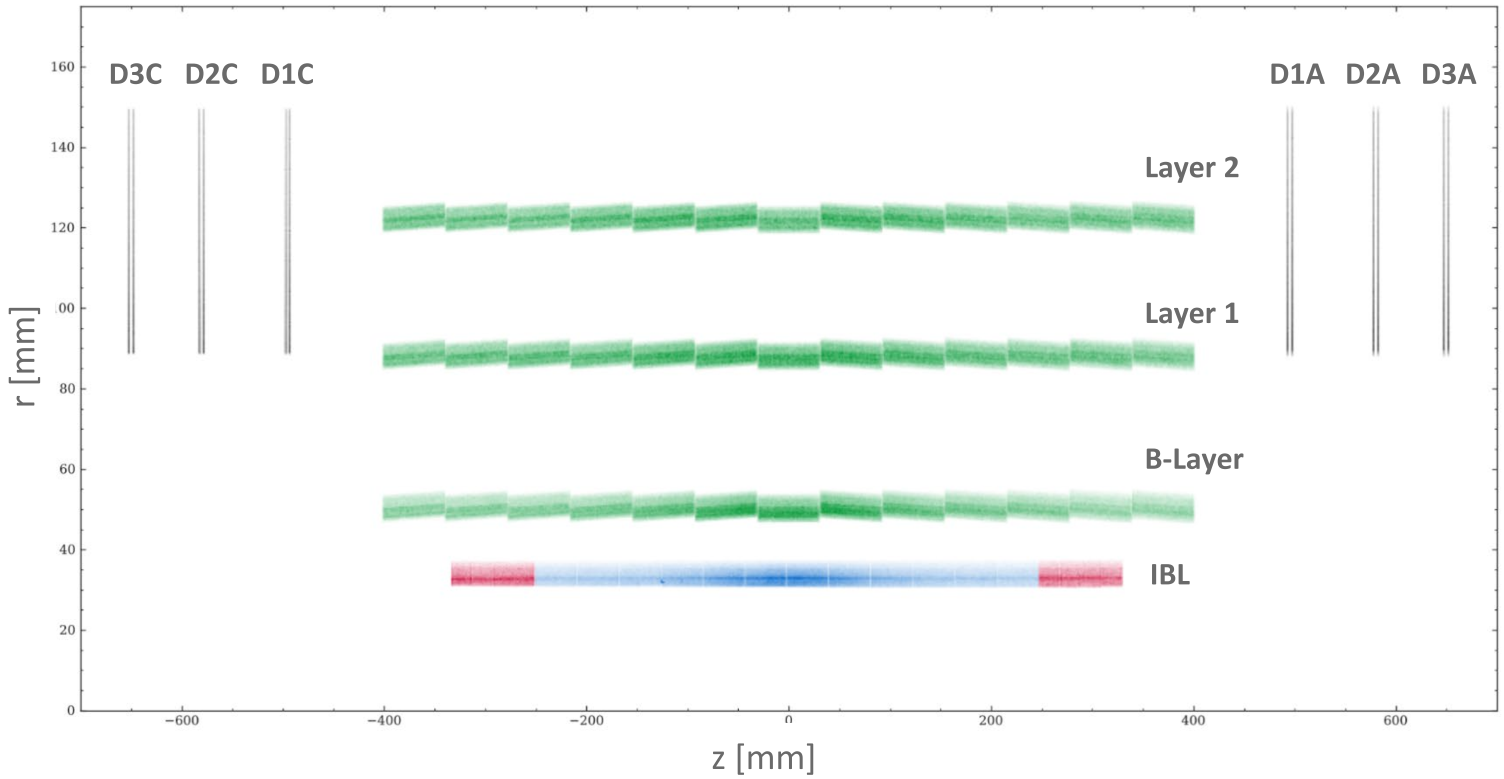
$$\mu_{\text{vis}}^{\text{(TC)PCC}} = \frac{\sum_{i=1}^{N_{\text{events}}} N^{i}_{\text{tracks(clusters)}}}{N_{\text{events}}}$$

- Track Counting (TC) already in use for ATLAS luminosity measurement.
- **Goal is to add Pixel Cluster Counting (PCC) algorithm in Run 3:**
  - Study cluster properties to identify signal clusters and suppress background;
  - Compare performance of PCC against TC.

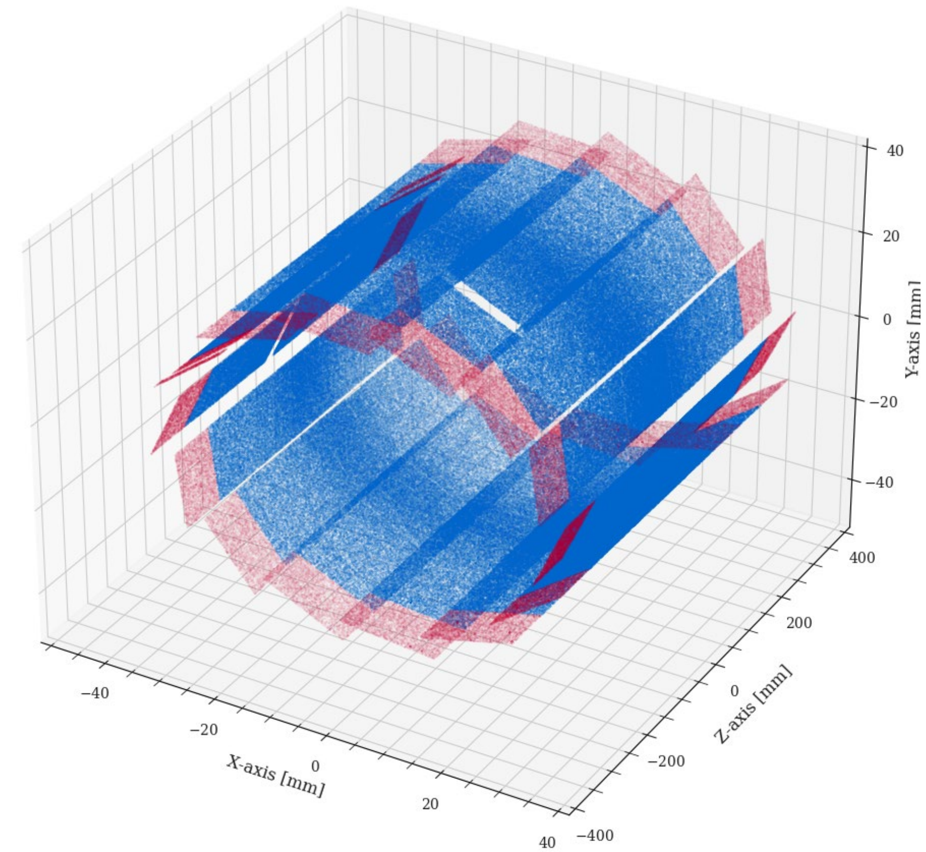
The Pixel Detector

Layout

- The Pixel Detector consists of **4 layers** and **3 disks** of silicon pixel modules.
- **Insertable B-Layer (IBL) is the closest layer to the interaction point:** made of 3D modules on the sides and planar modules in the middle.
- We can visualise the Pixel Detector layout using positions of reconstructed clusters.



Pixel Detector

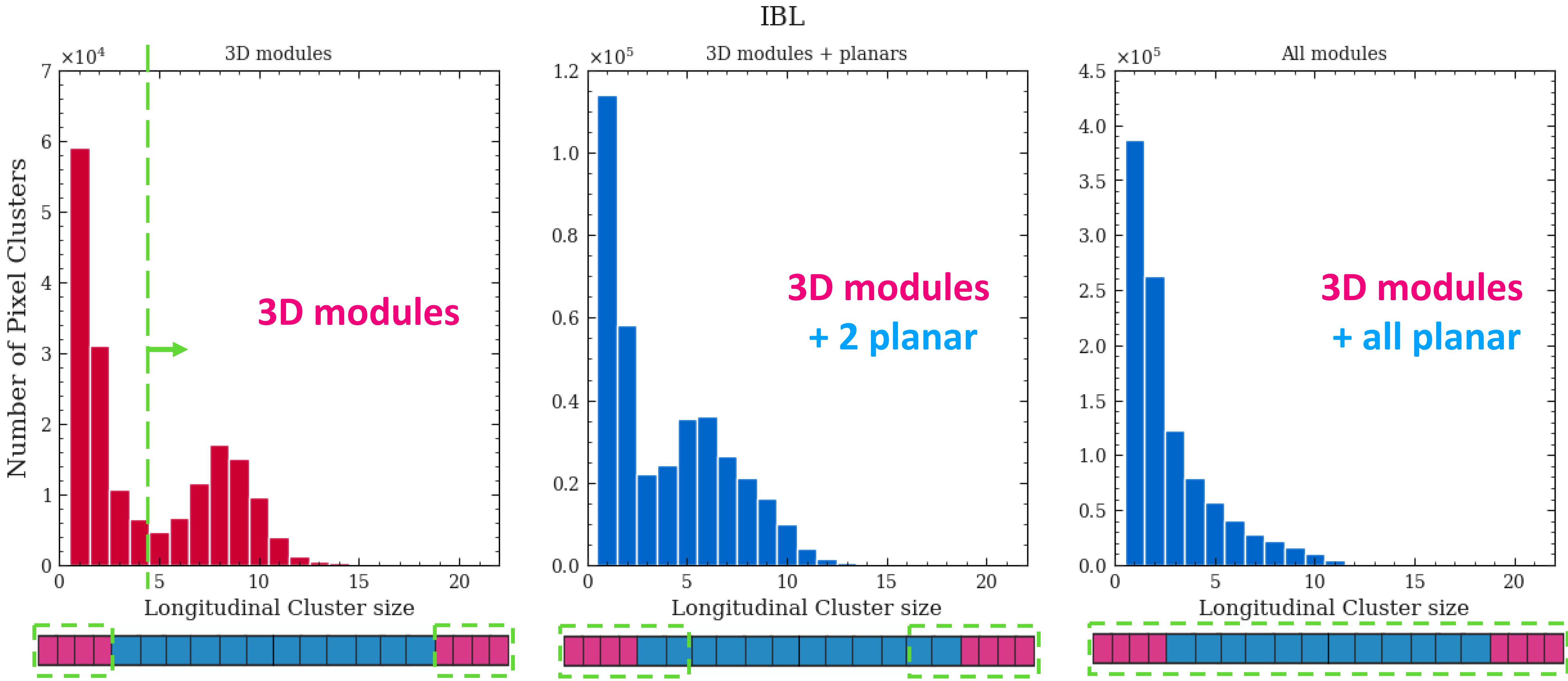


IBL

Pixel Cluster Properties

Longitudinal cluster size

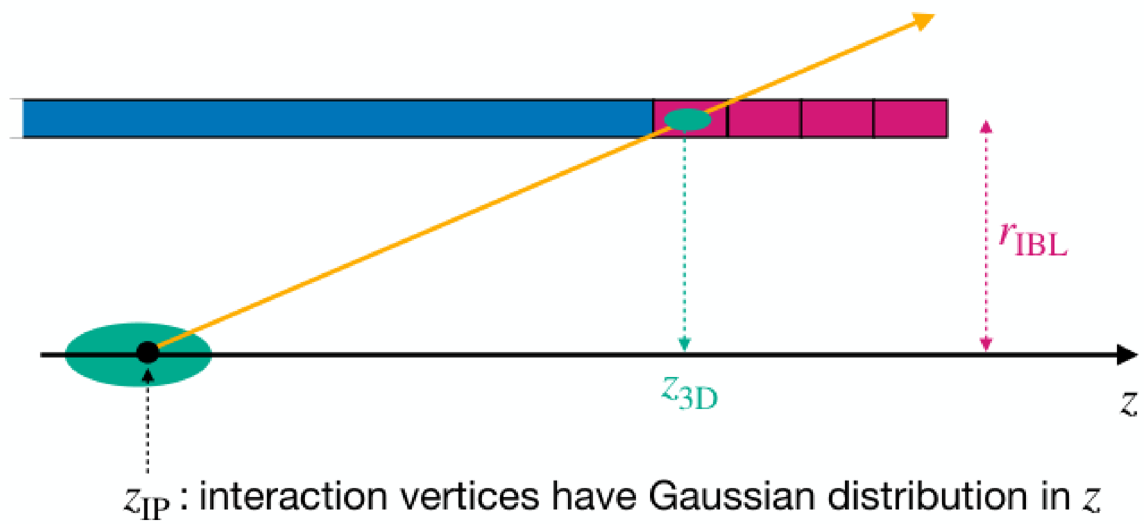
- Primary clusters in **IBL 3D modules** are long in *z*-direction
  $\Rightarrow$ **good signal/background separation.**
  - Primary long clusters ($CL_z > 4$) in 3D modules have **Gaussian-like** distribution.
  - Background clusters typically short ~1-2 pixels.

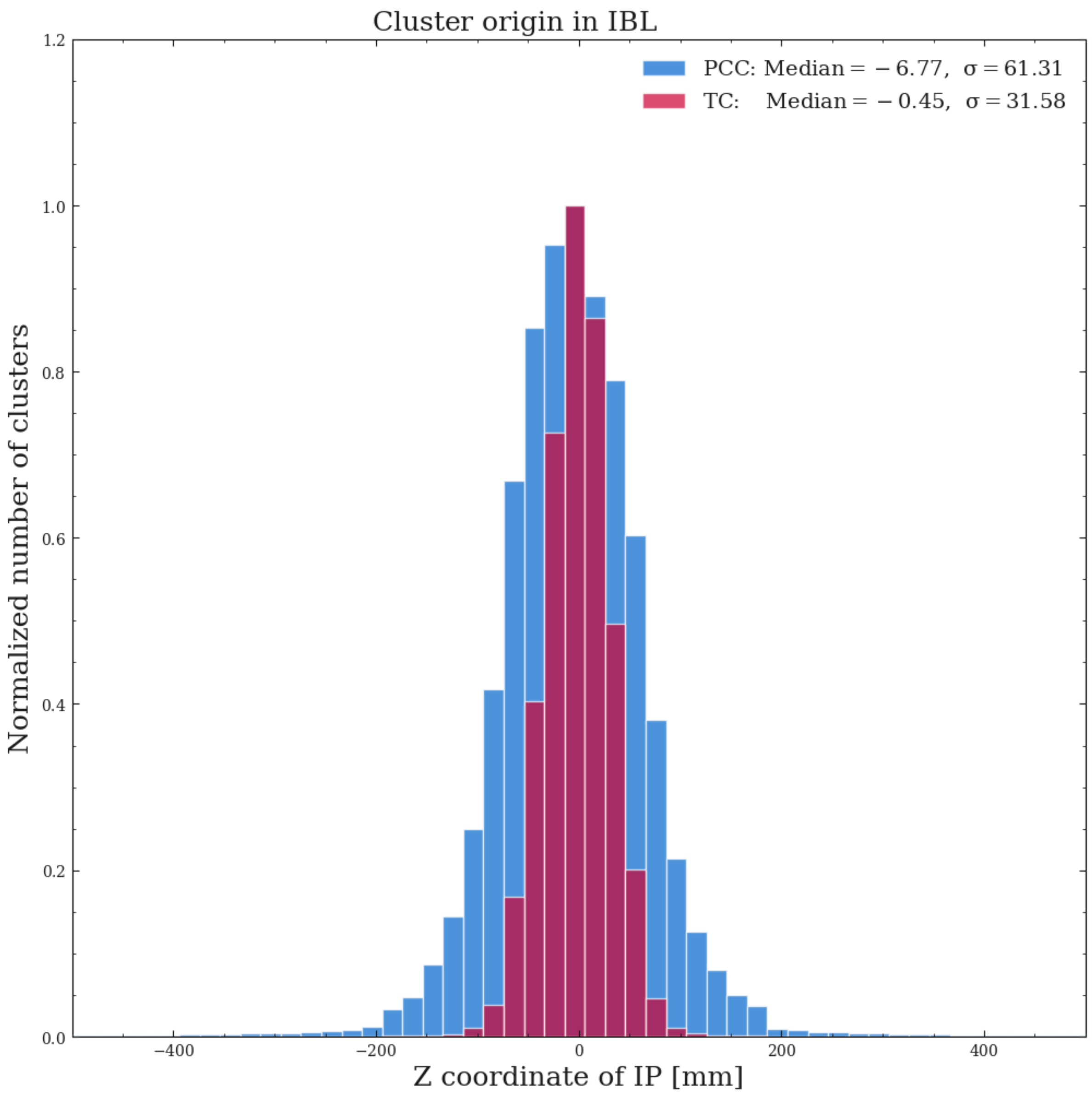


Pixel Cluster Properties

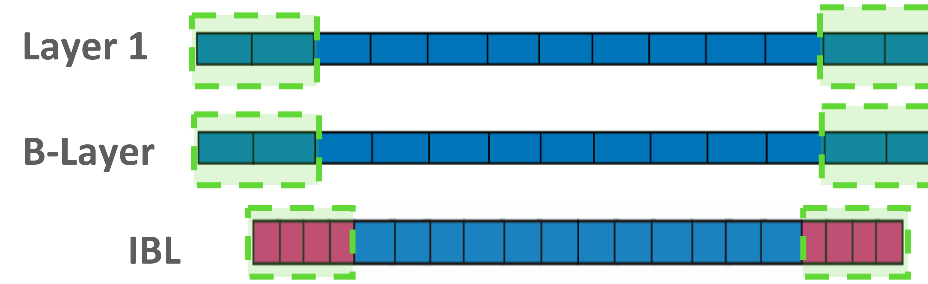
Longitudinal cluster size ⇒ estimation of cluster origin

- We can estimate cluster origin (z_{IP}) from $CL_z = \frac{\text{sensor thickness}}{\text{pixel pitch}} \frac{|z_{IP} - z_{3D}|}{r_{IBL}}$
- Selecting IBL 3D clusters with $CL_z > 4$ we focus on primary clusters produced by particles originating at the interaction point (IP).
- z_{IP} estimated from clusters CL_z compatible with tracks origin.





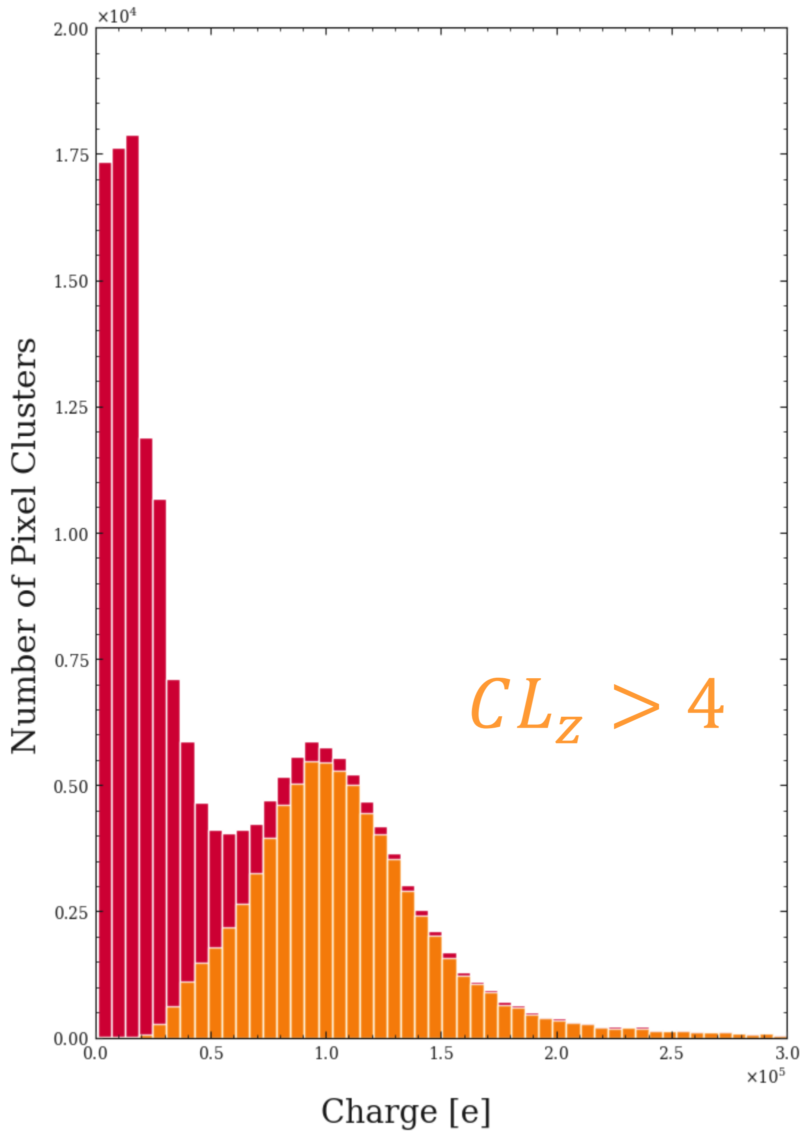
Pixel Cluster Properties



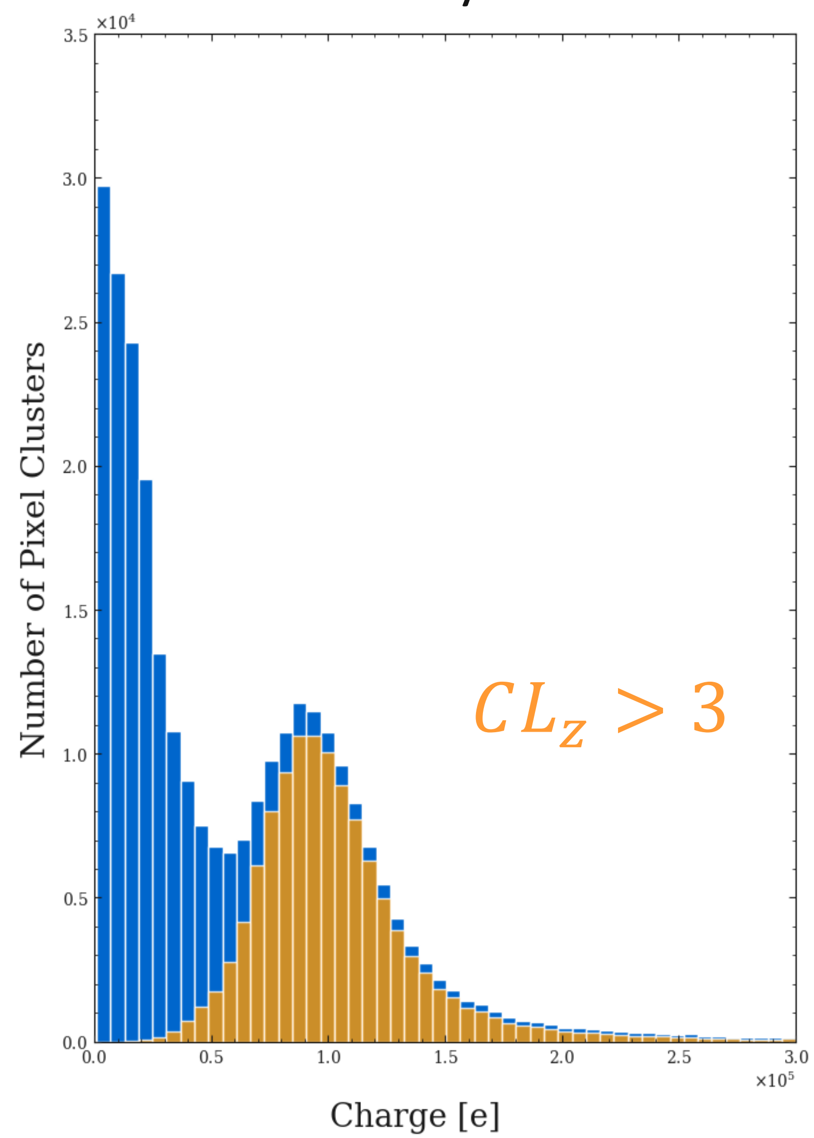
Cluster charge

- Charge distribution is **bimodal in all layers** with a Gaussian component.
- Gaussian part due to primary clusters
  $\Rightarrow$ cutting on CL_z removes peak at low charge.

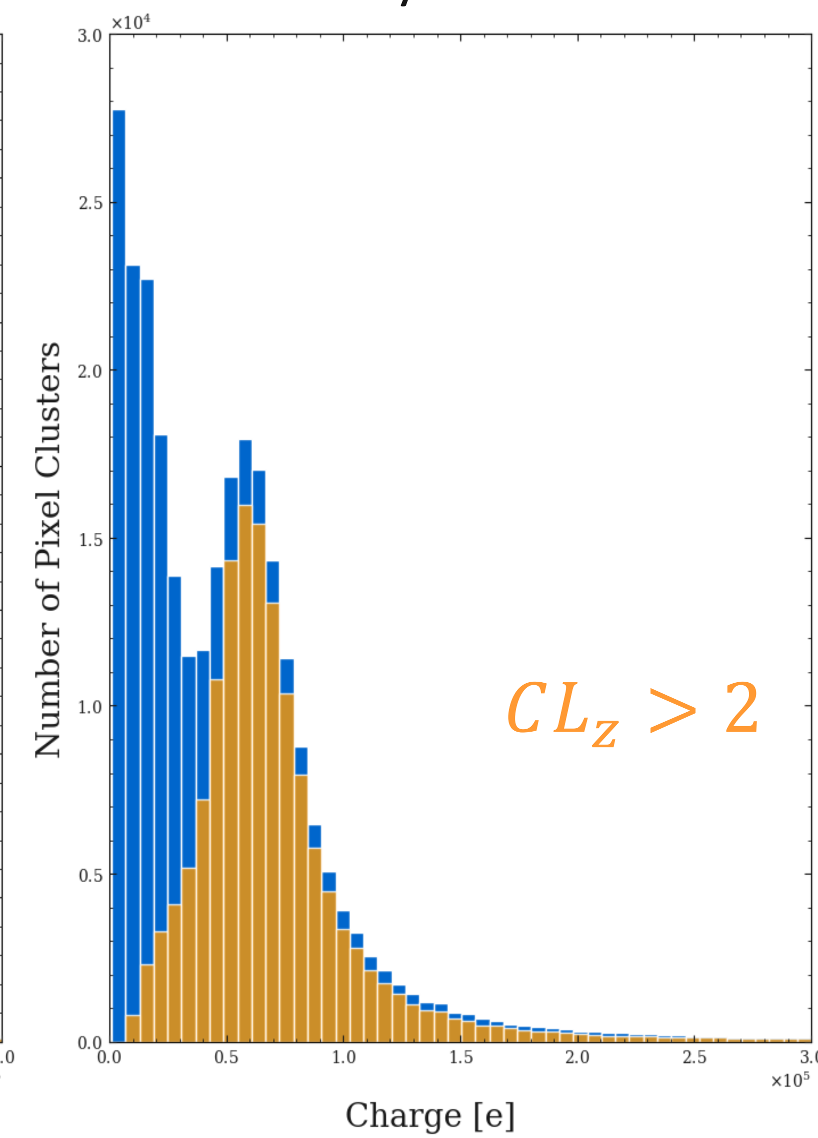
IBL 3D modules



B-Layer



Layer 1

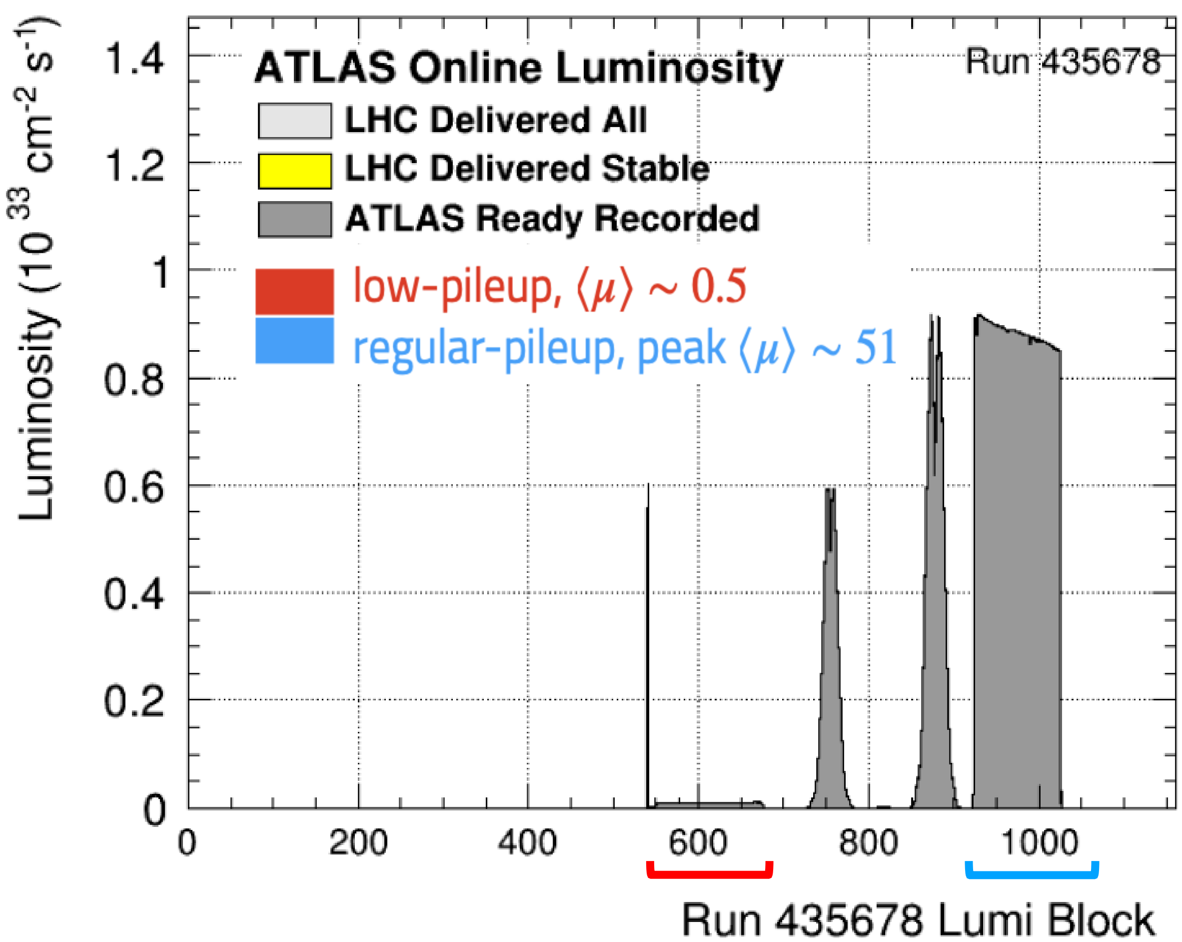


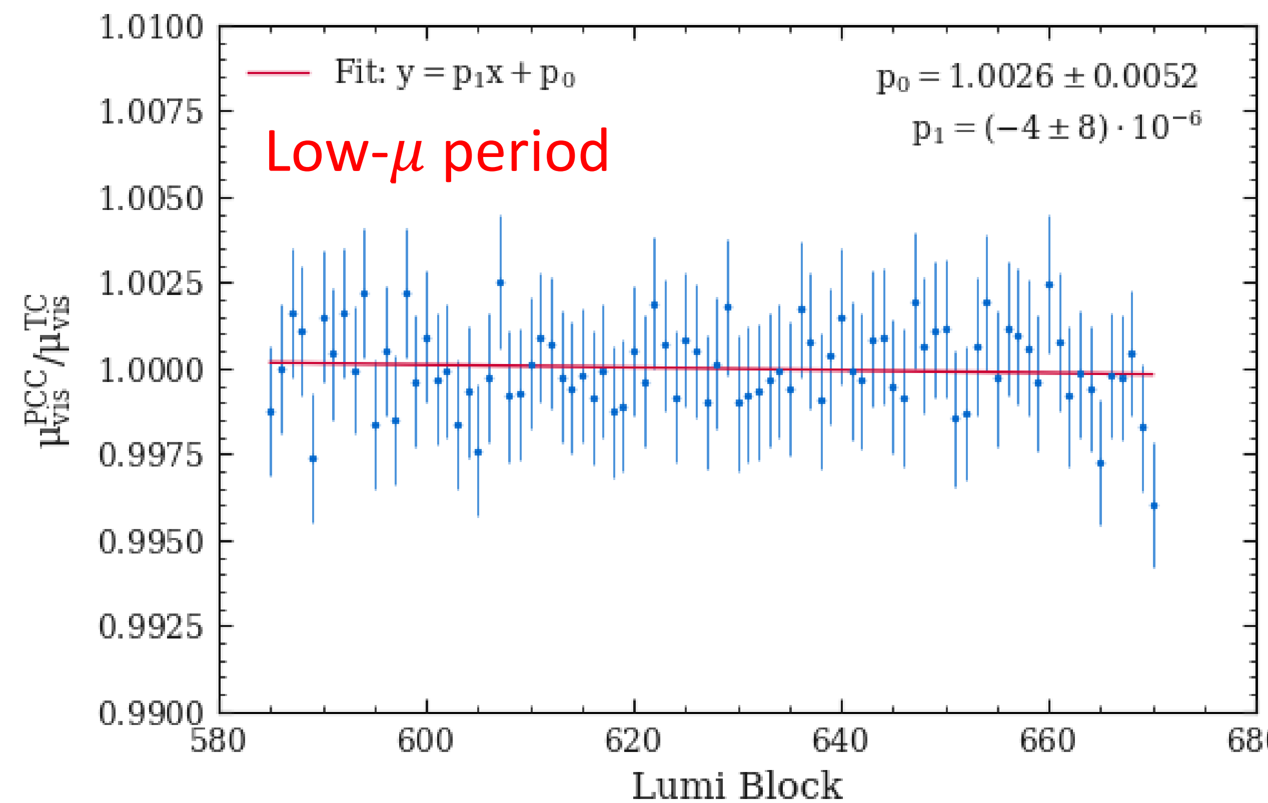
PCC with IBL 3D modules

$$\mu_{\mathrm{vis}}^{\mathrm{PCC(TC)}} = \frac{\sum_{i=1}^{N_{\mathrm{events}}} N^{i}_{\mathrm{clusters(tracks)}}}{N_{\mathrm{events}}}$$

Linearity checks against TC

- First implement PCC using clusters with $CL_z > 4$ in IBL 3D modules.
- Validate PCC linearity by comparison with TC, which is proven to be linear with μ.
- Use a special run with **isolated bunches** that has both low-μ and regular-μ periods: normalise μ_{vis}^{PCC} to μ_{vis}^{TC} at low μ and check the ratio μ_{vis}^{PCC} / μ_{vis}^{TC} at regular μ.





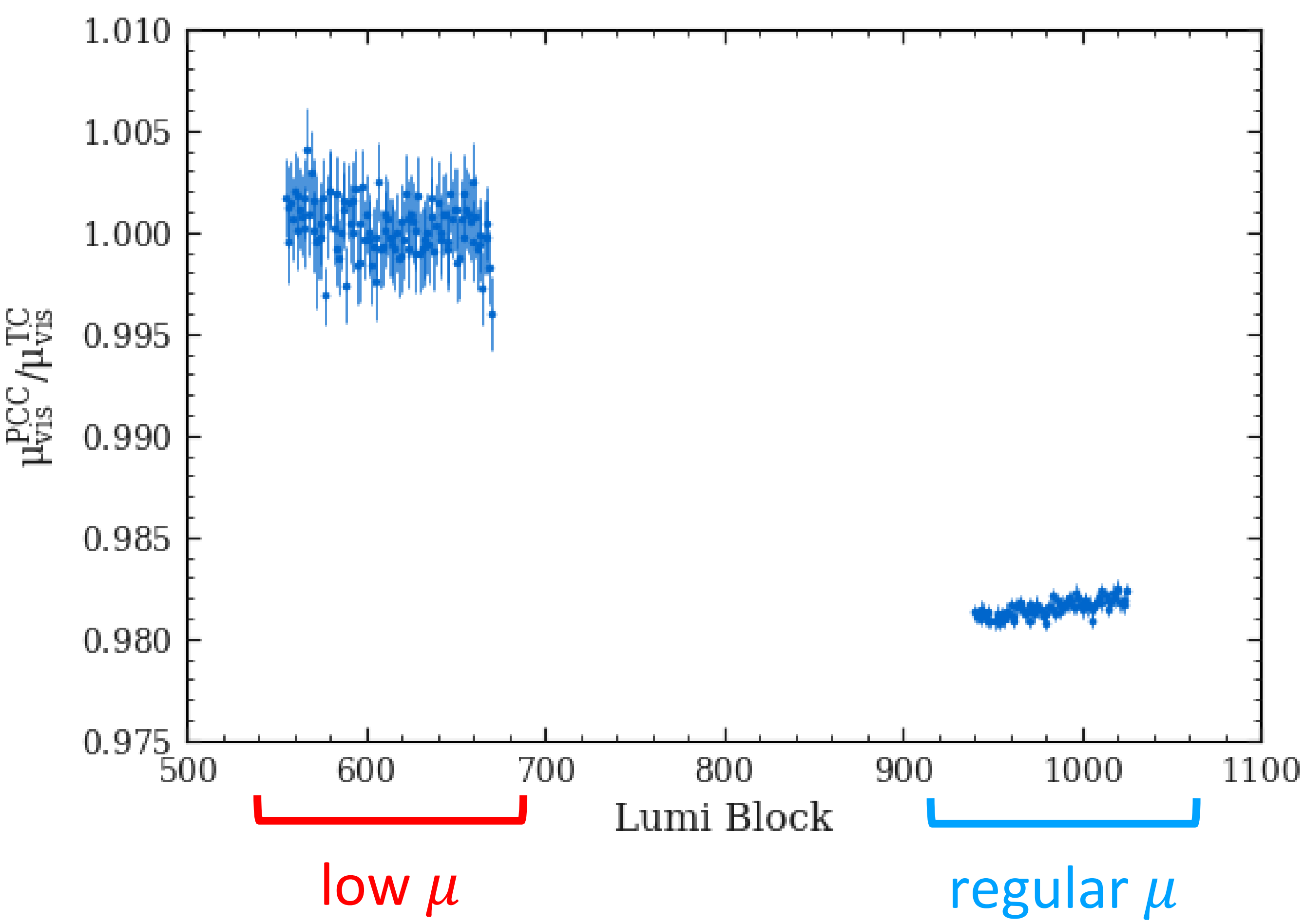
> A **Lumi Block (LB)** is the smallest time unit in a run for luminosity measurements: $\sim 60\,\mathrm{s}$ in which $\mathscr{L}$ can be considered constant.

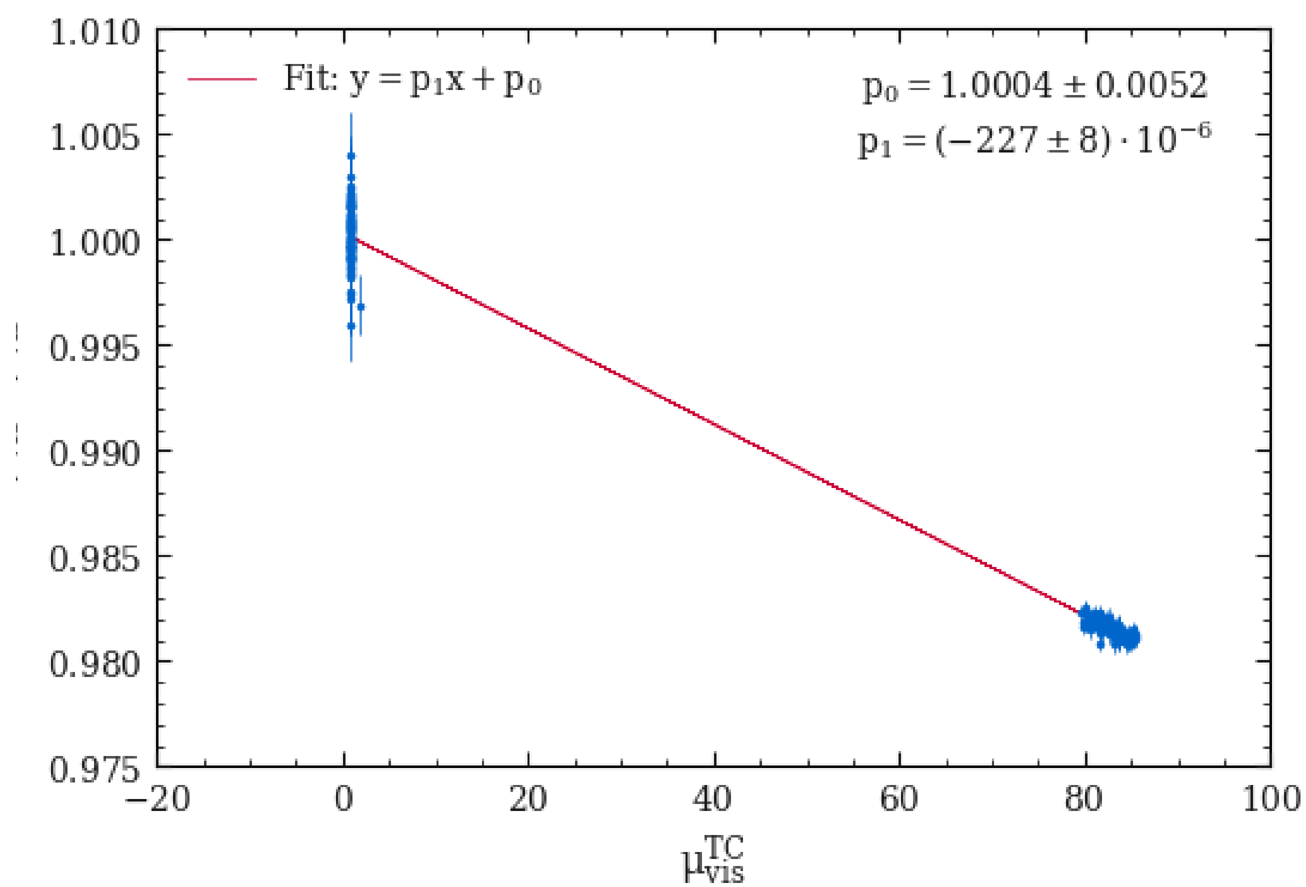
PCC with IBL 3D modules

$$\mu_{\text{vis}}^{\text{PCC(TC)}} = \frac{\sum_{i=1}^{N_{\text{events}}} N^i_{\text{clusters(tracks)}}}{N_{\text{events}}}$$

Linearity check at regular pileup

- Variation in μ_{vis}^{PCC}/ μ_{vis}^{TC} of ~2% from $\mu_{\text{vis}}^{TC} = 0.75$ to $\mu_{\text{vis}}^{TC} = 79$.
- May be due to various sources of **background**, e.g. broken clusters from dead/silent pixels or clusters on module's edge.

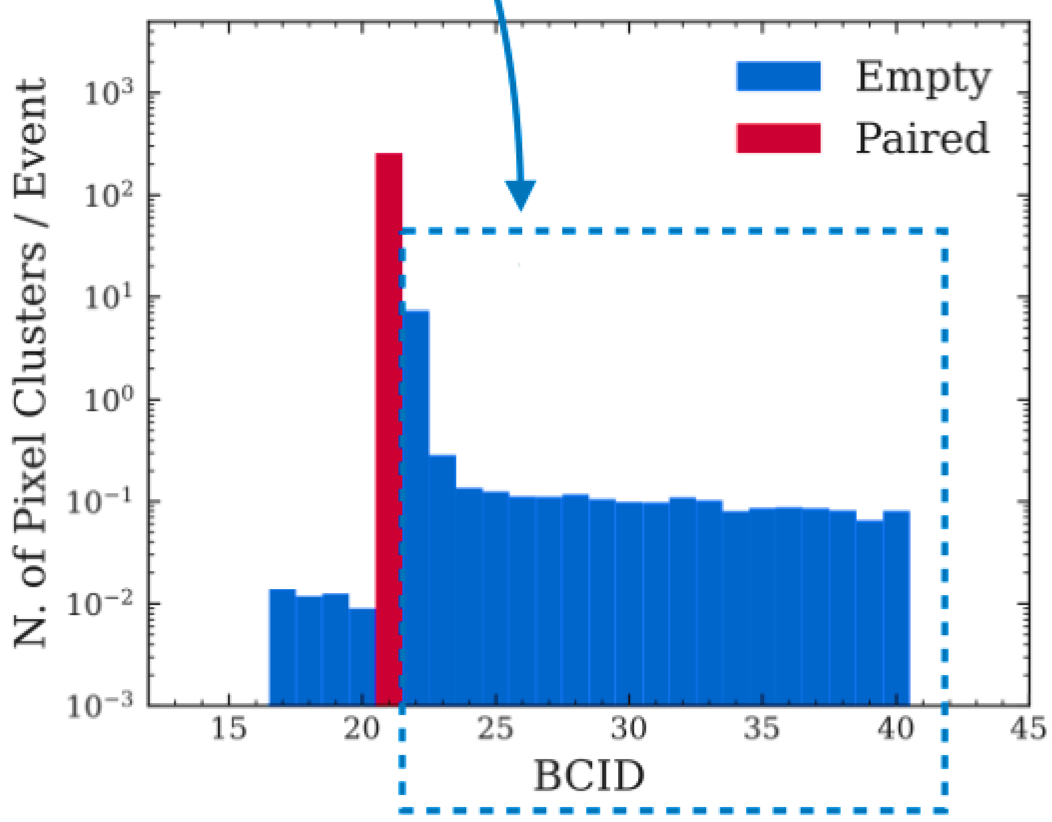


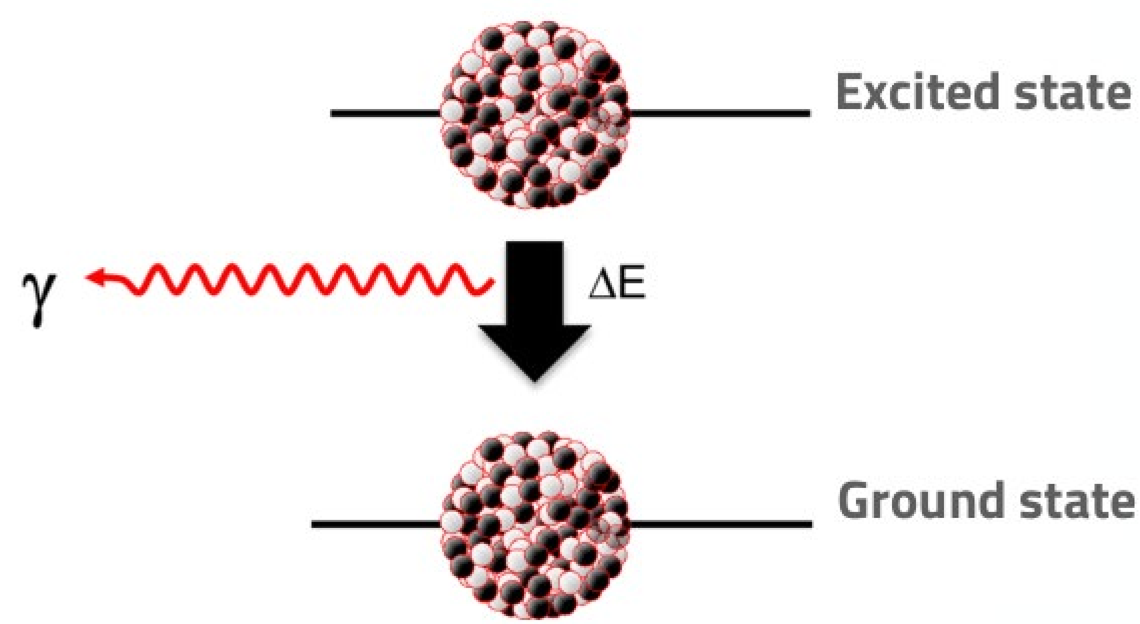


Signal vs background separation

Main types of background in normal physics conditions

- **Intrinsic background**: noisy/hot pixels firing signal at high rate ~1-pixel clusters.
- **Afterglow** after a collision due to photon emission in nuclear de-excitation of the detector material.

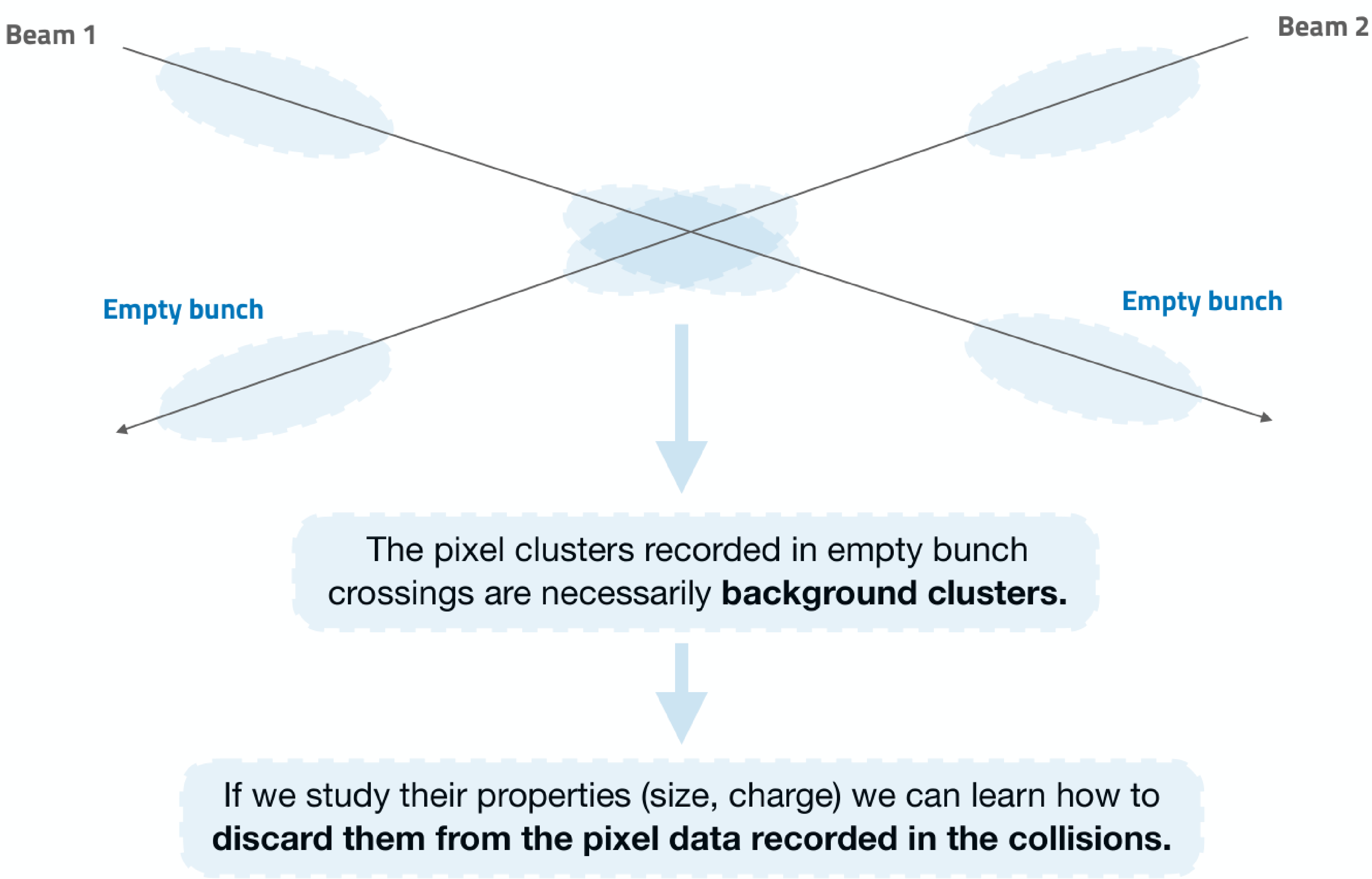




Signal vs background separation

Optimising cluster selections using special runs

- To differentiate between signal and background clusters we can use data recorded with a special random **trigger sampling also empty bunch crossings:**



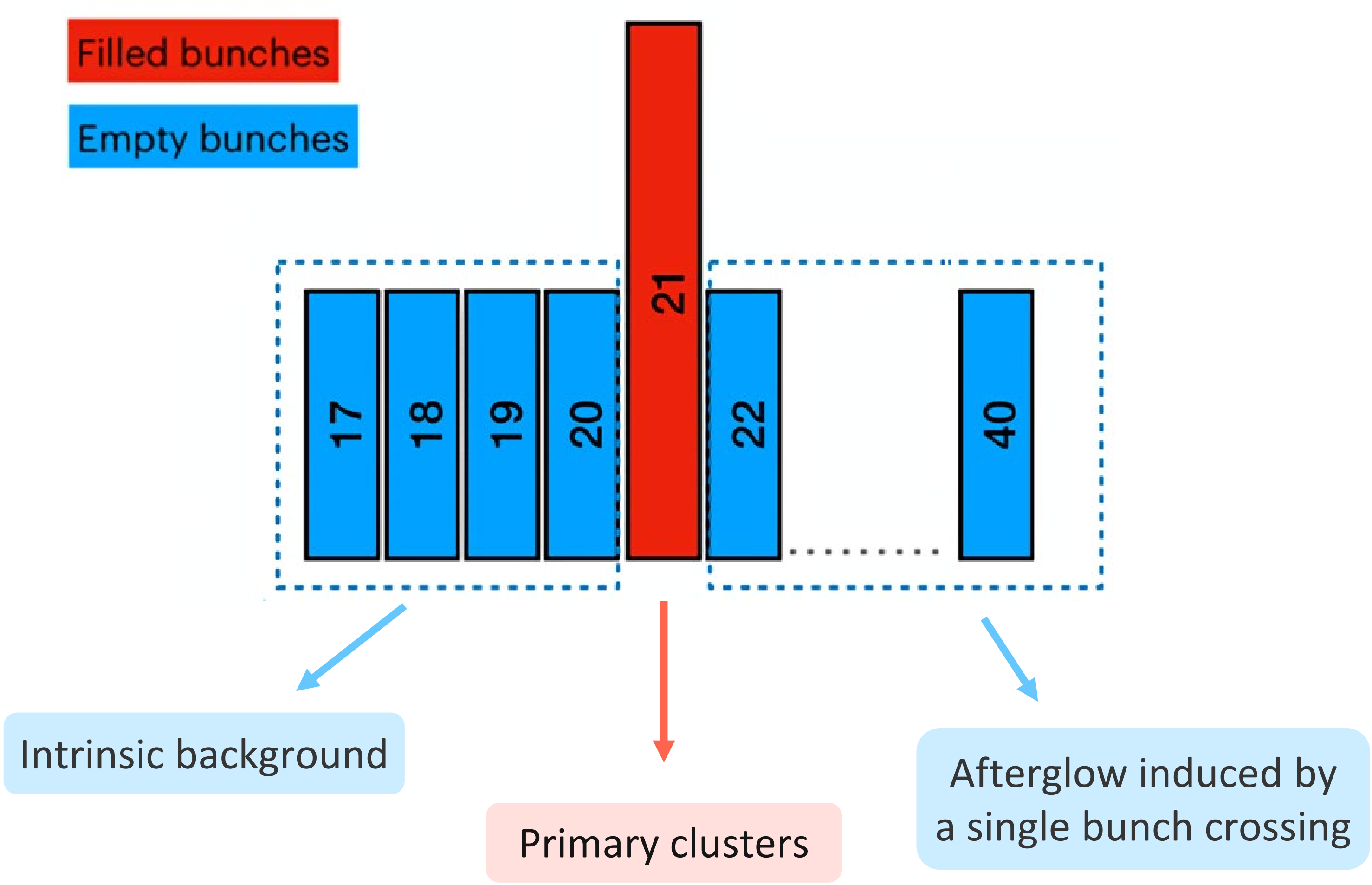
Signal vs background separation

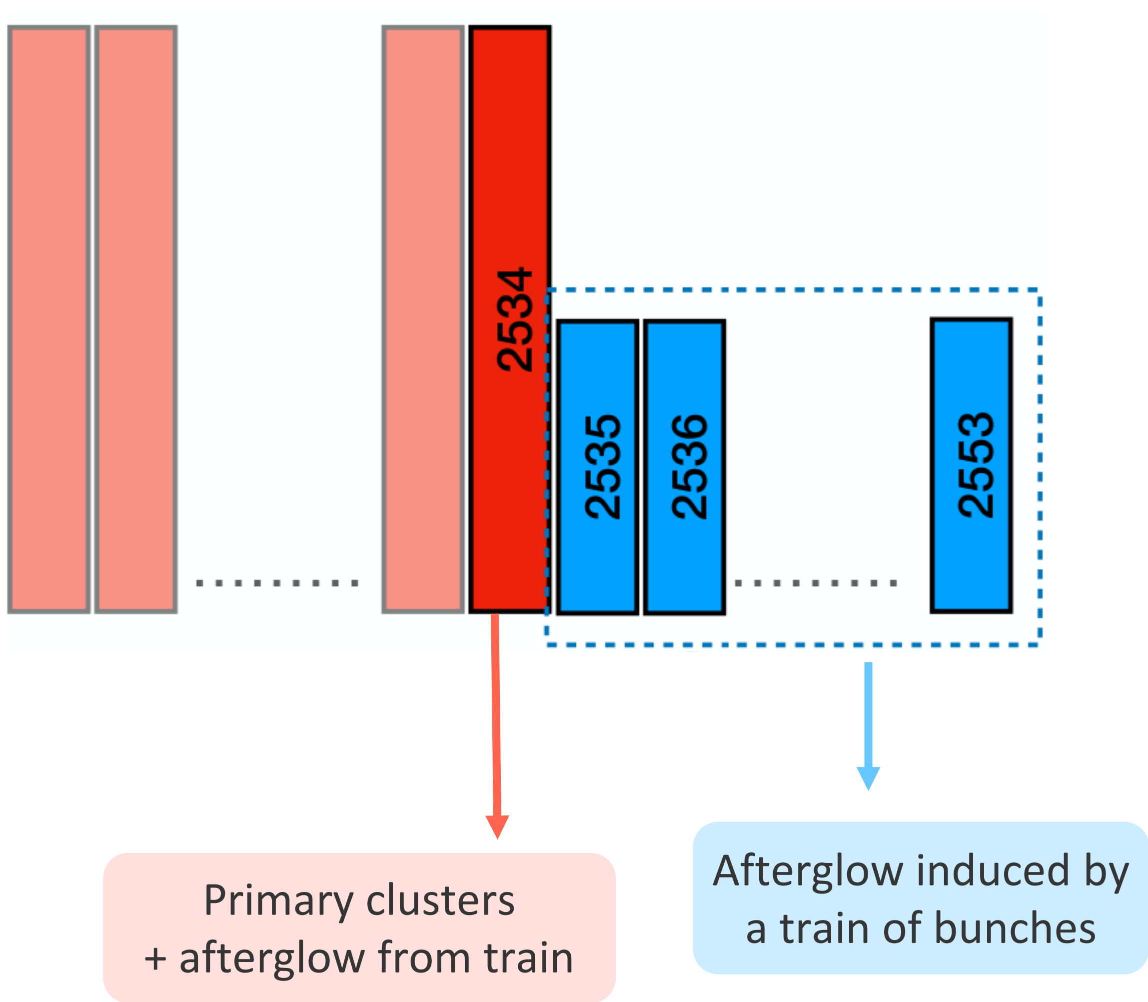
Optimising cluster selections using special runs

- To differentiate between signal and background clusters we can use data recorded with a special random **trigger sampling also empty bunch crossings:**

*A) Empty bunches around **isolated** filled bunch*

*B) Empty bunches after the last bunch in a **train** of 12 filled bunches*





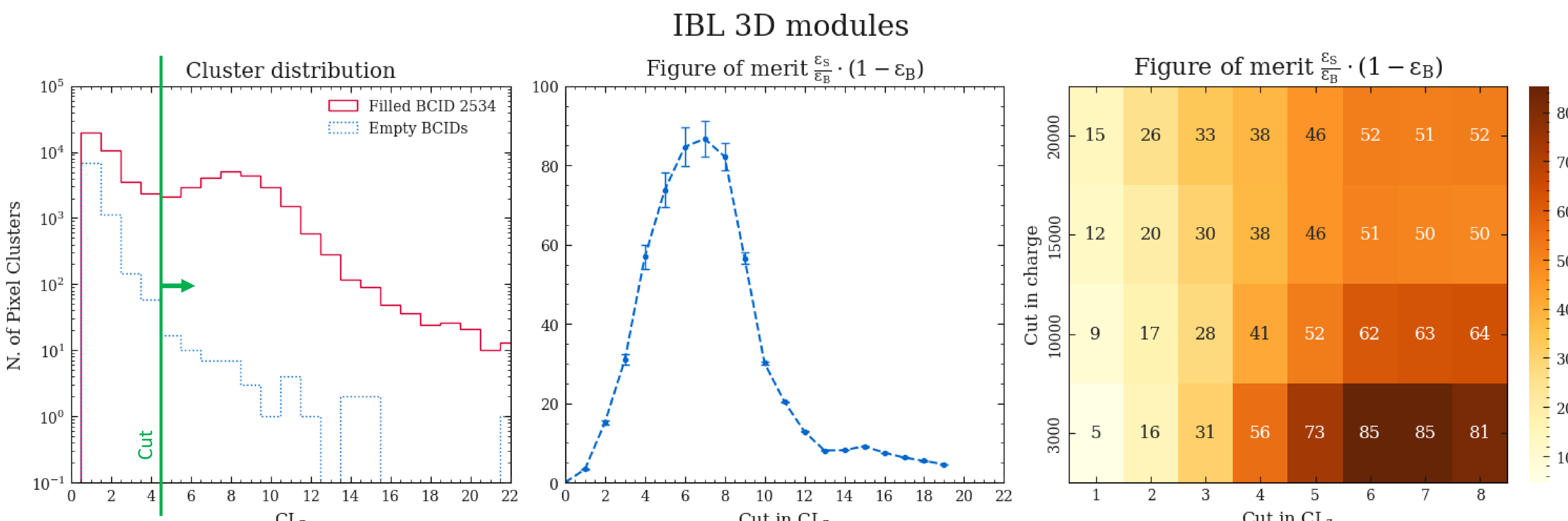
Signal vs background separation

Optimising cluster selections using special runs

- Characterise selections in subregions of the Pixel Detector by monitoring fractions of signal (ε_S) and background (ε_B) clusters passing selections.

$$\varepsilon_S = \frac{N_{sig}(CL_z > cut)}{N_{sig}} \qquad \varepsilon_B = \frac{N_{bkg}(CL_z > cut)}{N_{bkg}}$$

- Optimal cuts for each subregion are those maximizing the **figure of merit** $\frac{\varepsilon_S}{\varepsilon_B}(1-\varepsilon_B)$ in configuration B ($\sim$ normal physics conditions)



Signal vs background separation

B-Layer

Optimising cluster selections using special runs

- Characterise selections in subregions of the Pixel Detector by monitoring fractions of signal (ε_S) and background (ε_B) clusters passing selections.

$$\varepsilon_S = \frac{N_{sig}(CL_z > cut)}{N_{sig}} \qquad \varepsilon_B = \frac{N_{bkg}(CL_z > cut)}{N_{bkg}}$$

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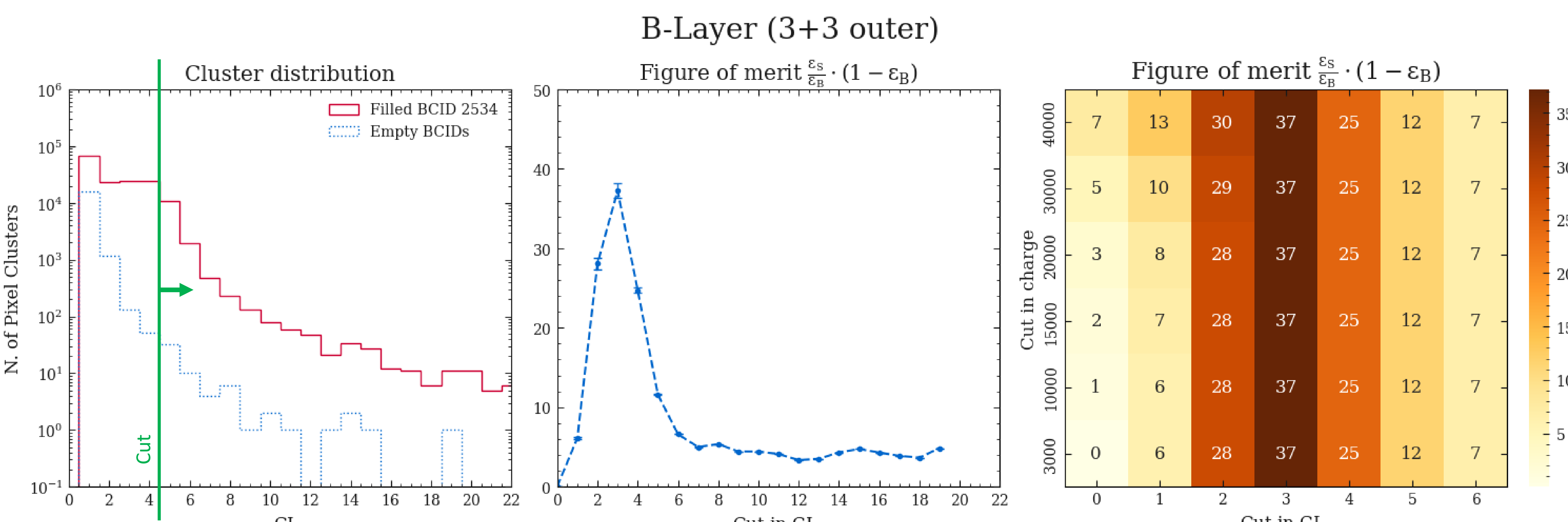
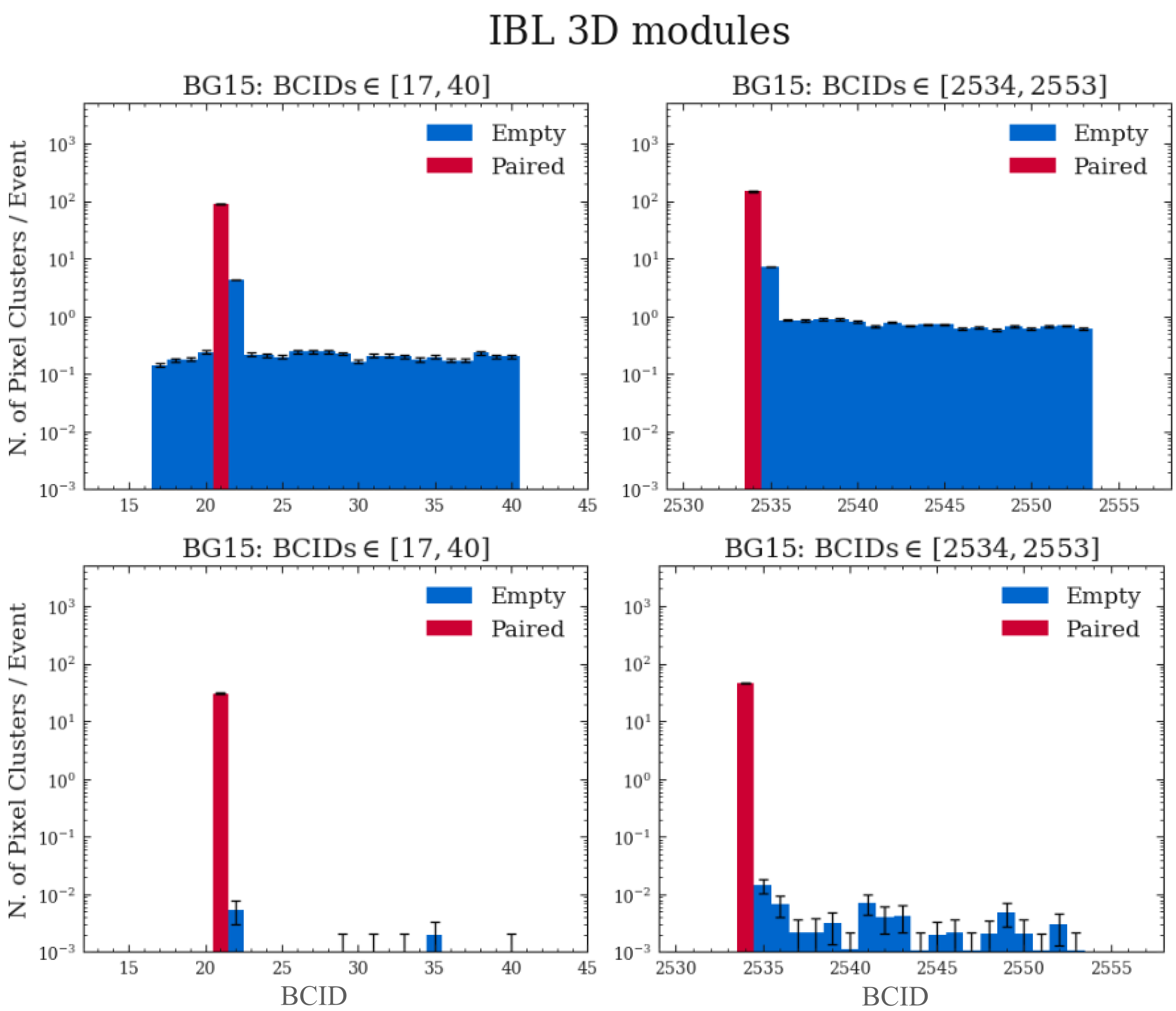


Signal vs background separation

Applying the optimised selections



Selections:

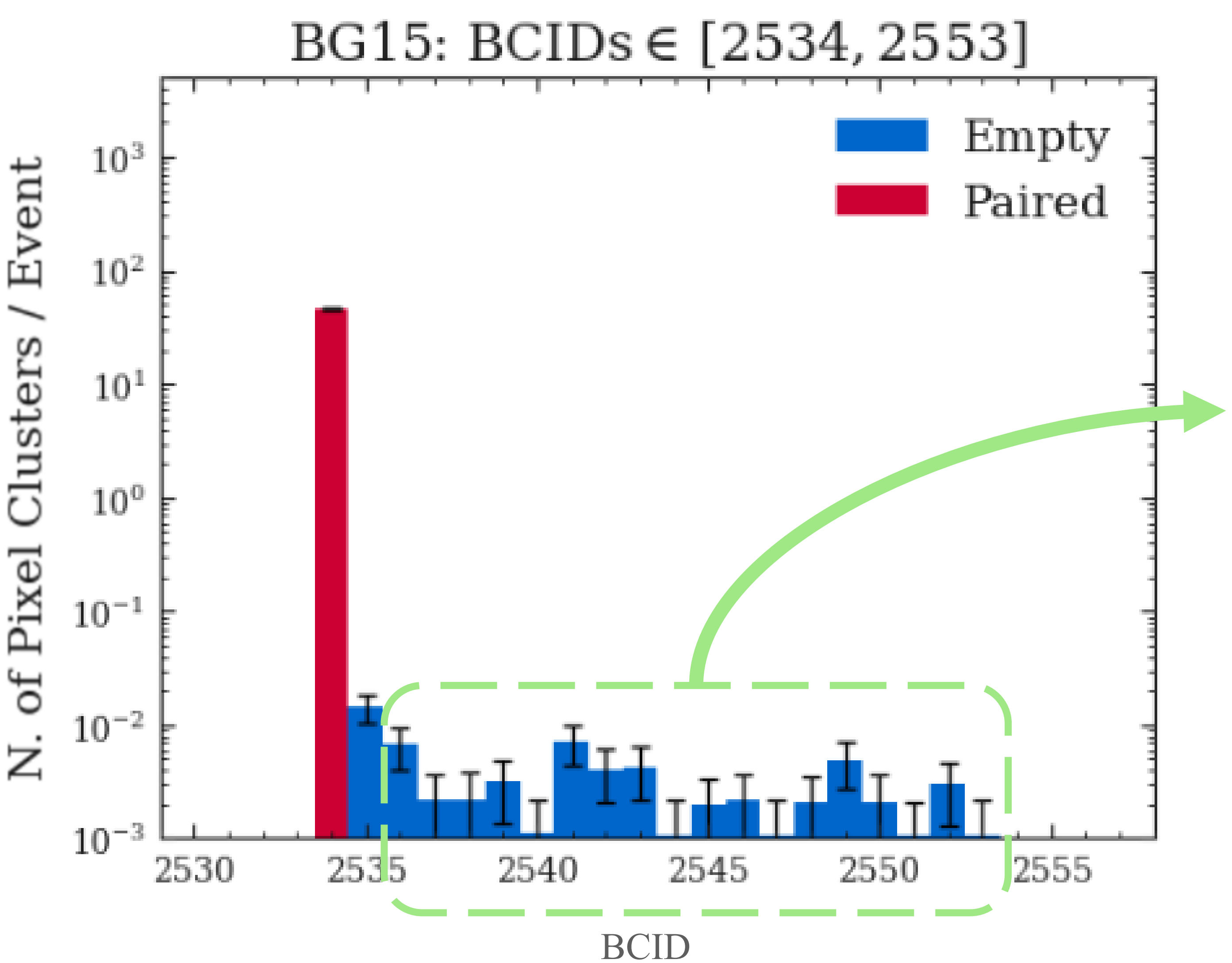
- Charge $> 3000\ e$
- $CL_z > 6$

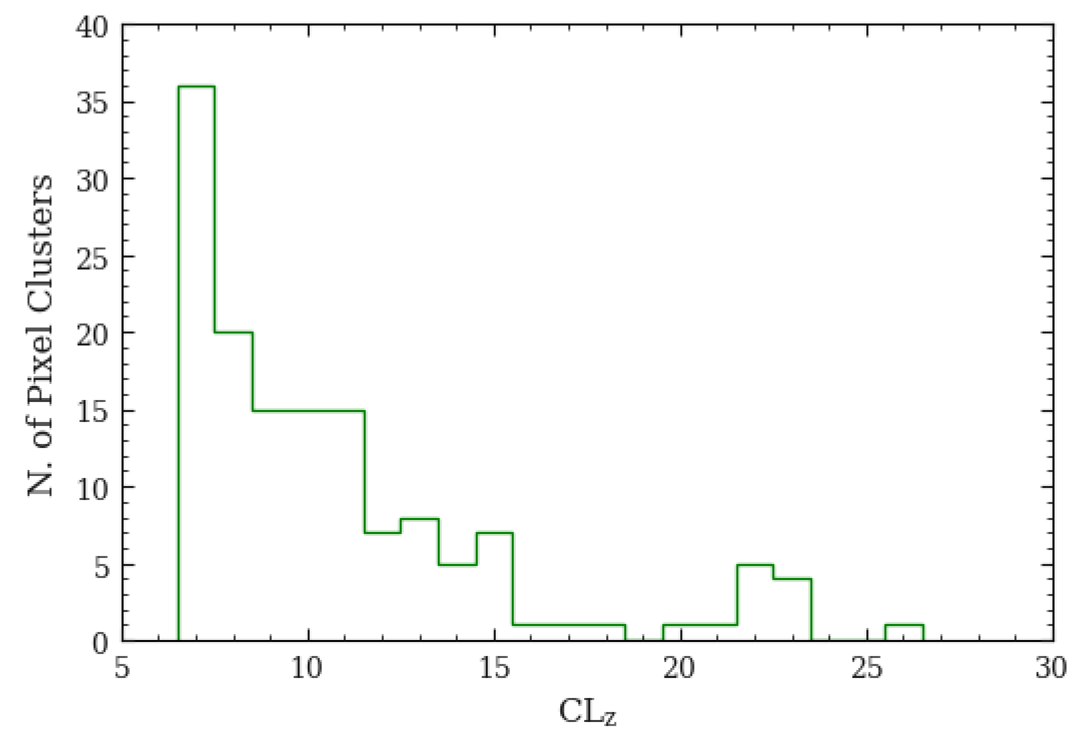
We retain 32% of signal and 0.36% of background

Signal vs background separation

Residual activity in the empty-BCID tail

- Residual clusters with large CL_z and CL_φ are still present after cuts in empty bunch crossings, especially in train configuration.
- This could be explained by **other types of background than afterglow:** interactions of protons with residual gas molecules in the beam pipe?





Signal vs background separation

Summary of selections

- Based on the studies a set of selections can be implemented in the online reconstruction for different subregions of the Pixel Detector:

Layer	Subregion	Selection
IBL	3D	$CL_z > 6,$ Charge > 3000
	Planar	$CL_z > 3,$ Charge > 3000
B-Layer	3A/C side	$CL_z > 3,$ Charge > 3000
	7 central	$CL_z > 1,$ Charge > 3000
Layer 1	3A/C side	$CL_z > 2,$ Charge > 3000
	7 central	$CL_z > 1,$ Charge $> 30\,000$
Layer 2	3A/C side	$CL_z > 2,$ Charge > 3000
	7 central	$CL_z > 1,$ Charge $> 30\,000$
Disks	All	Charge $> 15\,000$

- Selections suppressing most of background and keeping large fraction of signal.

Conclusions

- In this summer project we studied the **Pixel Cluster Counting** method for luminosity measurements at the ATLAS experiment.

- We investigated pixel cluster properties to find **optimal selections** for background rejection in different subregions of the Pixel Detector and validated the **performance of the PCC algorithm** using the IBL 3D modules.

- We identified a set of optimal cuts which allow to **significantly reduce the background** contribution and can be adopted for future ATLAS luminosity measurements with PCC in Run 3.