Faculté de **Physique et Ingénierie**
Université de Strasbourg

Search for exotic, massive, stable and electrically charged particles in the CMS experiment

Under the supervision of C. Collard

General overview

Theoretical and experimental context

Search for exotic particles in CMS
Pile-up
Experimental signature

Search for signal, and pile-up issue

Impact of pile-up on the energy estimator
Filtering algorithm

Problematic
Study of the impact of pile-up on the measurement of energy clusters

Work done

Study of the ratio of simulated charges
Cut-off efficiency

Theoretical and experimental context

Standard Model and search for exotic particles

Standard Model

Theory describing elementary particles and their interactions.

↓

Limits

- Unexplained dark matter
- Matter-antimatter asymmetry

↓

Theory beyond the Standard Model

- New interactions, symmetries, particles ...

Properties : mass, charge, lifetime, ...

Heavy Stable Charged Particles

$\tau > 30$ ns

$m > 200$ GeV/c^2

$Q = e$

ex : R-hadron obtained from a gluino $\tilde{g}$ at m=2 TeV/c^2

Theoretical and experimental context

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$\tau > 30$ ns

$m > 200$ GeV/c^2

$Q = e$

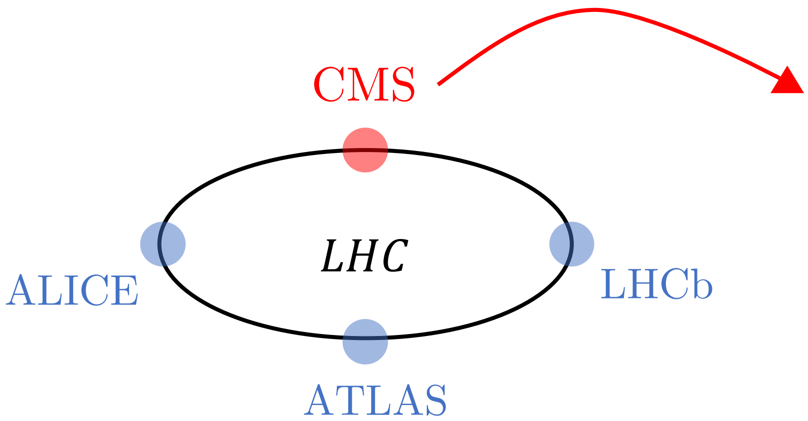
ex : R-hadron obtained from a gluino $\tilde{g}$ at m=2 TeV/c^2

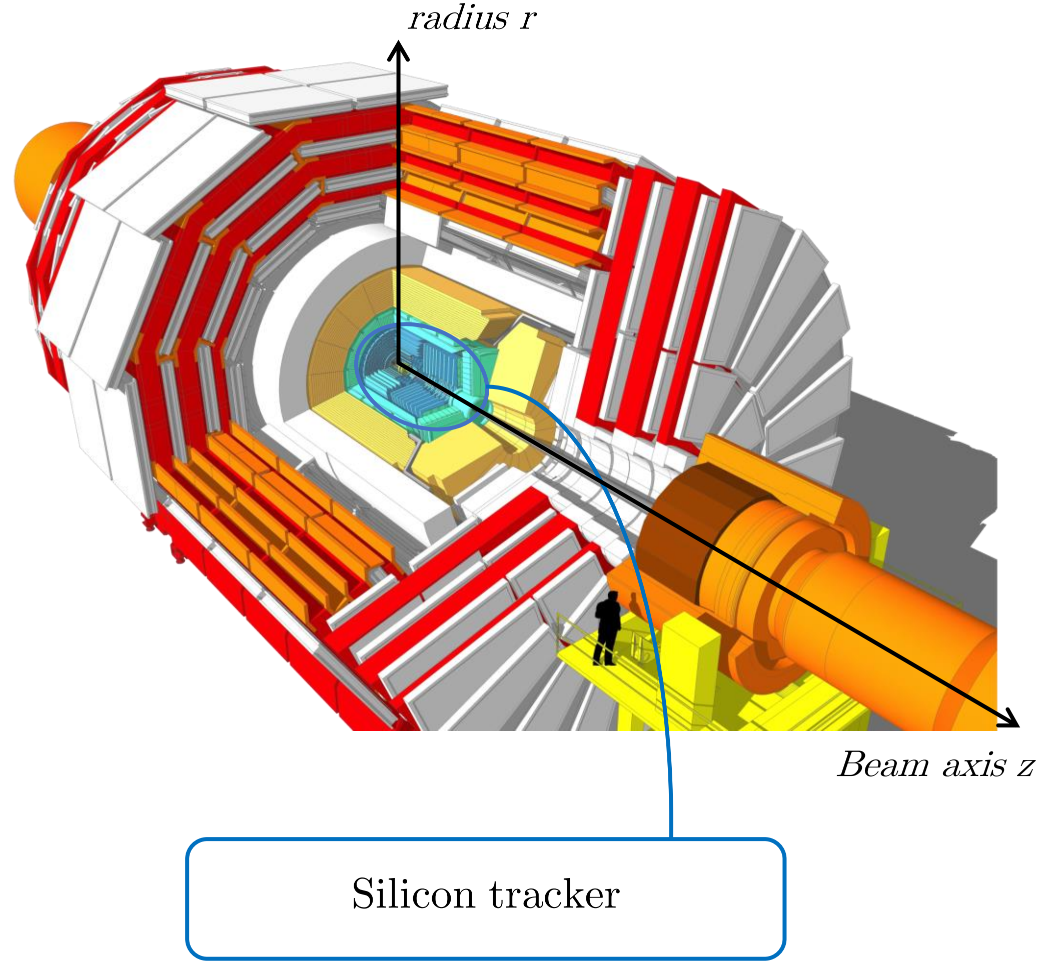
Looks like a muon at first order

$m = 105$ MeV/c^2 $\tau = 2.2\ \mu s$

Theoretical and experimental context

LHC, CMS and the tracker



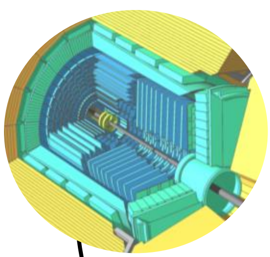


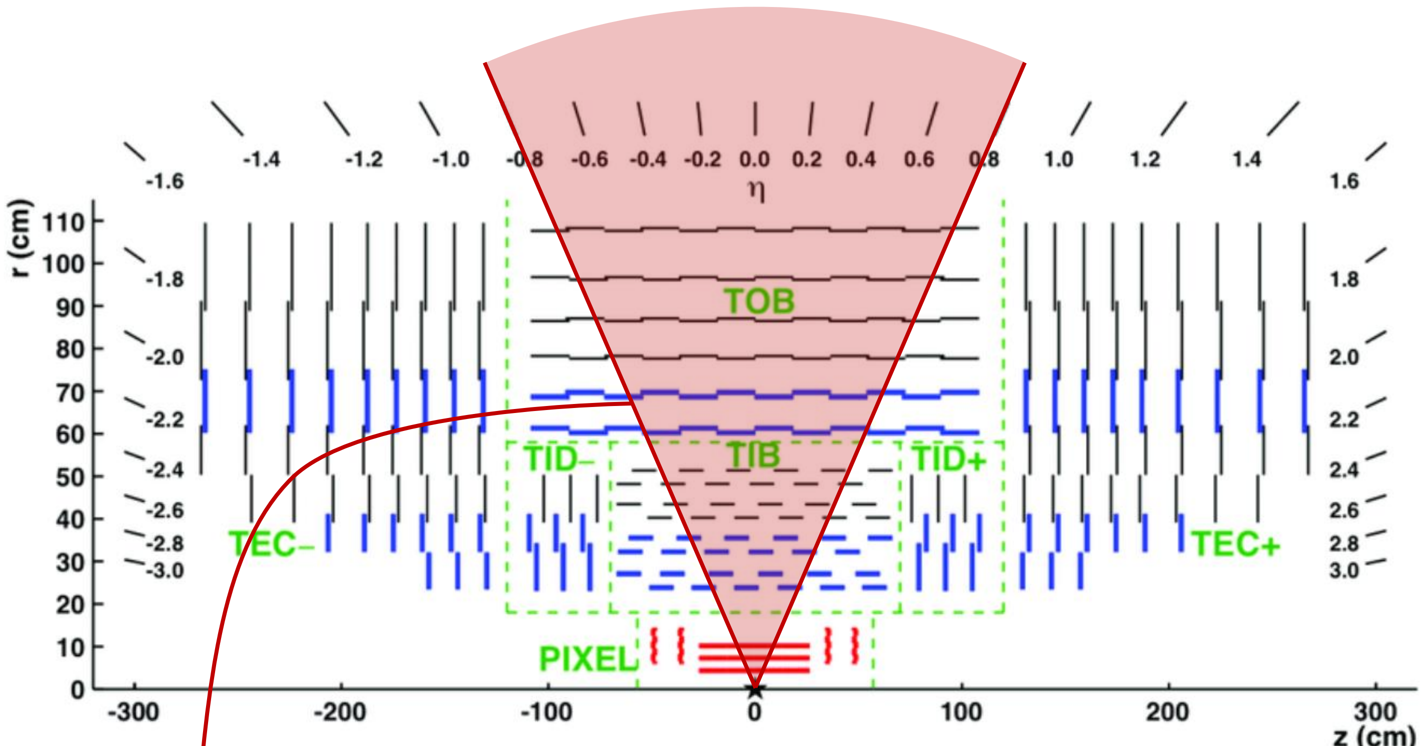
LHC Run II (2015-2018)

- Crossings of proton bunch beams at $\sqrt{s}$ =13 TeV every 25 ns.
- ~ 100 billion protons per bunch.

Theoretical and experimental context

LHC, CMS and the tracker





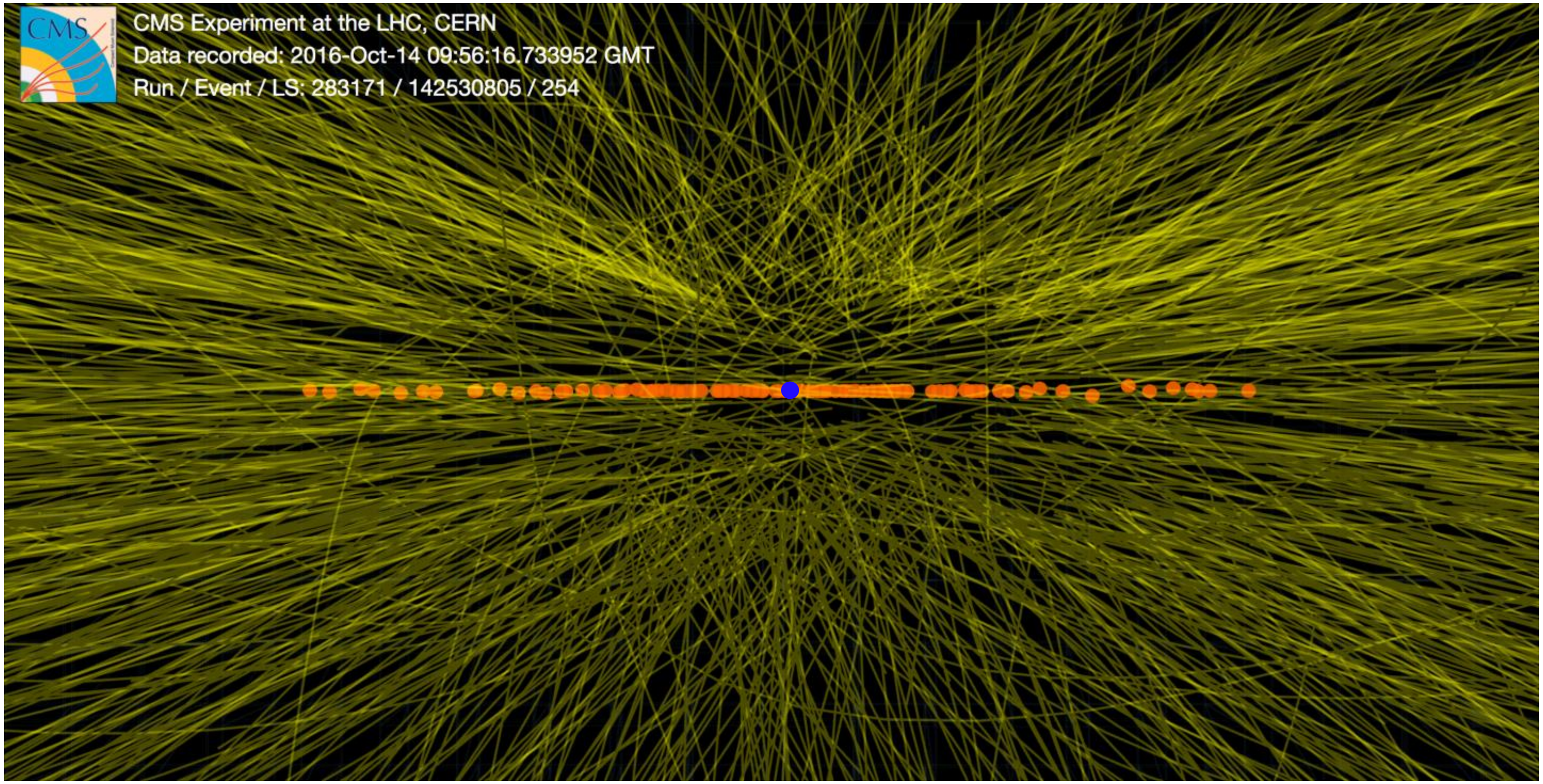
CMS tracker (2016)

Area of interest for my internship : $|\eta| < 0.8$ (TIB+TOB)

Theoretical and experimental context

Pile-up

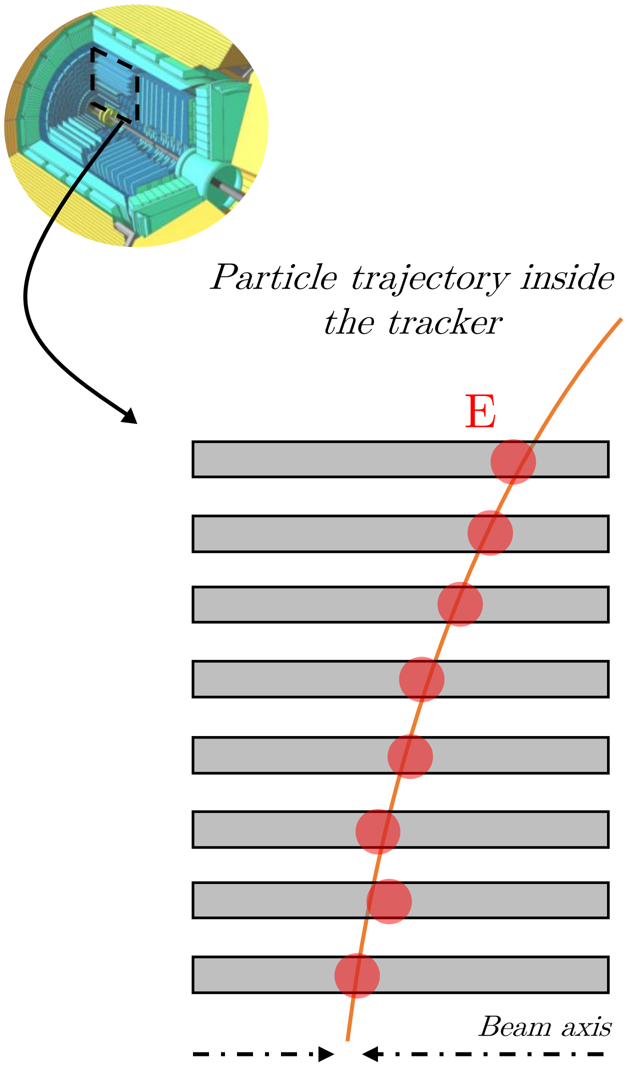
Example of a beam crossing



→ **Pile-up** Many additional proton-proton interactions are superimposed in the detector when beams cross.

Theoretical and experimental context

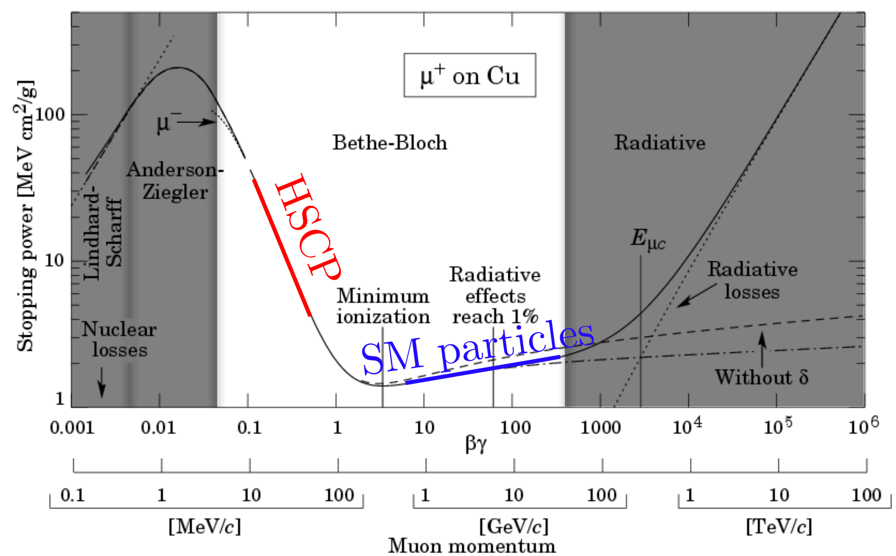
Signature: highly ionizing particles



Search for signatures of stable particles with **high momentum** and **high mass**.

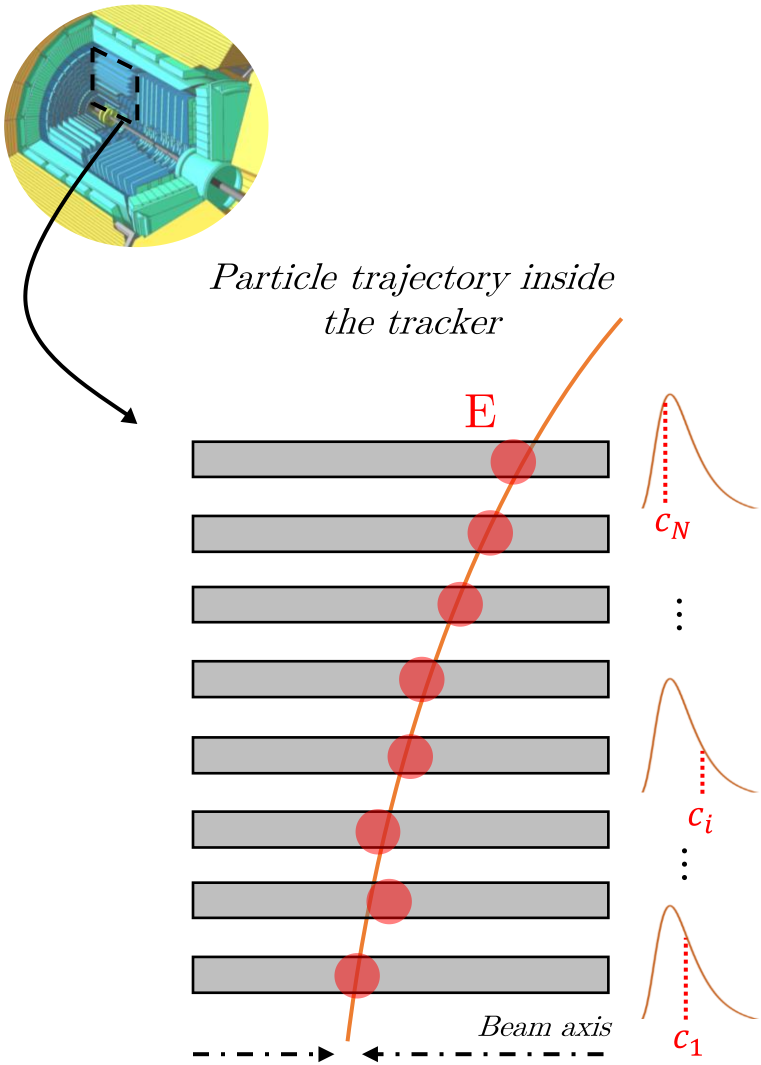
↓

Larger energy deposit (non-relativistic part of the Bethe-Bloch curve).



Search for signal, and pile-up issue

Energy estimator I_h

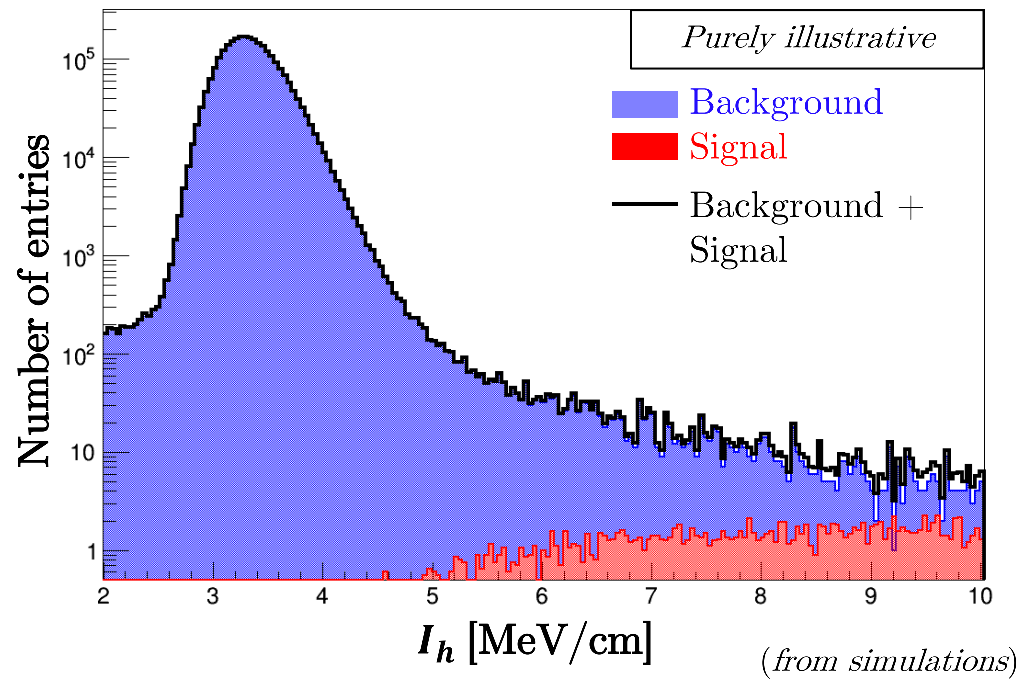


How to measure the deposit mean along the trajectory ?

→ **I_h estimator**

$$I_h = \left(\frac{1}{N} \sum_{i=1}^{N} c_i^{-2} \right)^{-\frac{1}{2}}$$

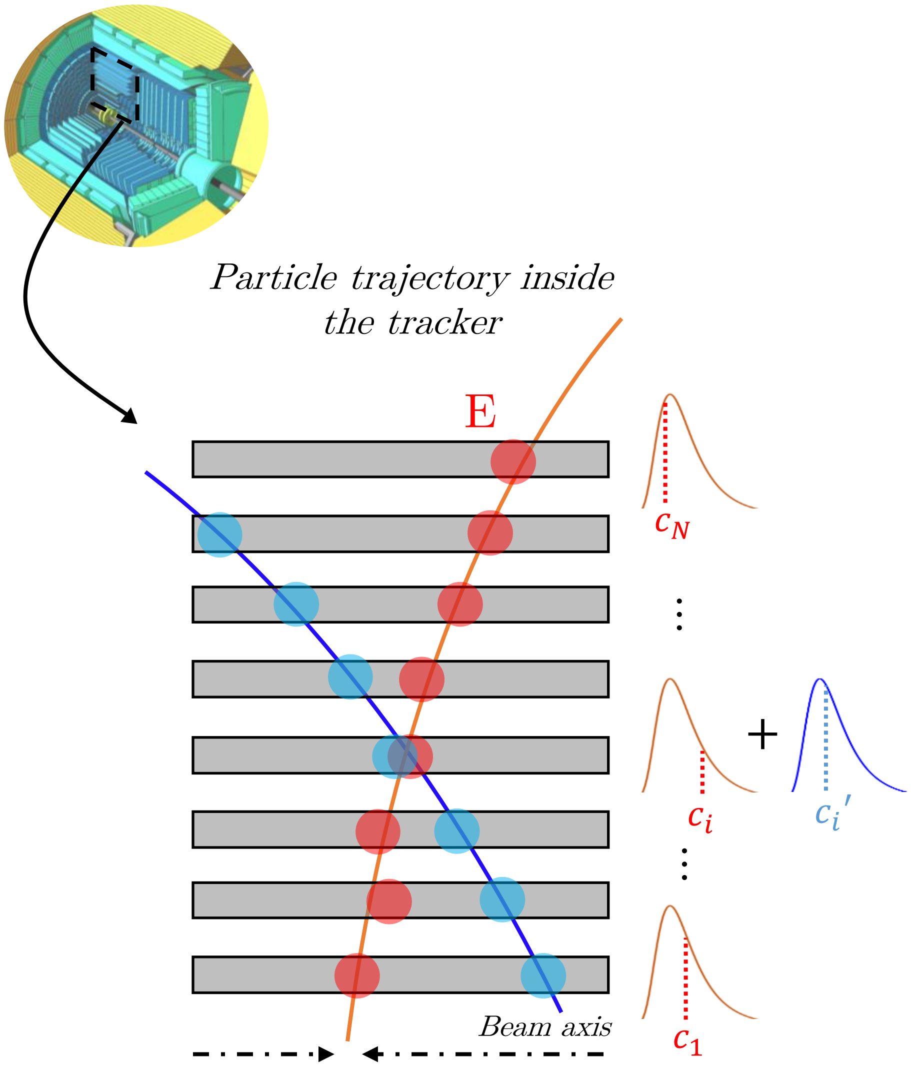
$$c_i = \left(\frac{dE}{dx} \right)_i$$



(from simulations)

Search for signal, and pile-up issue

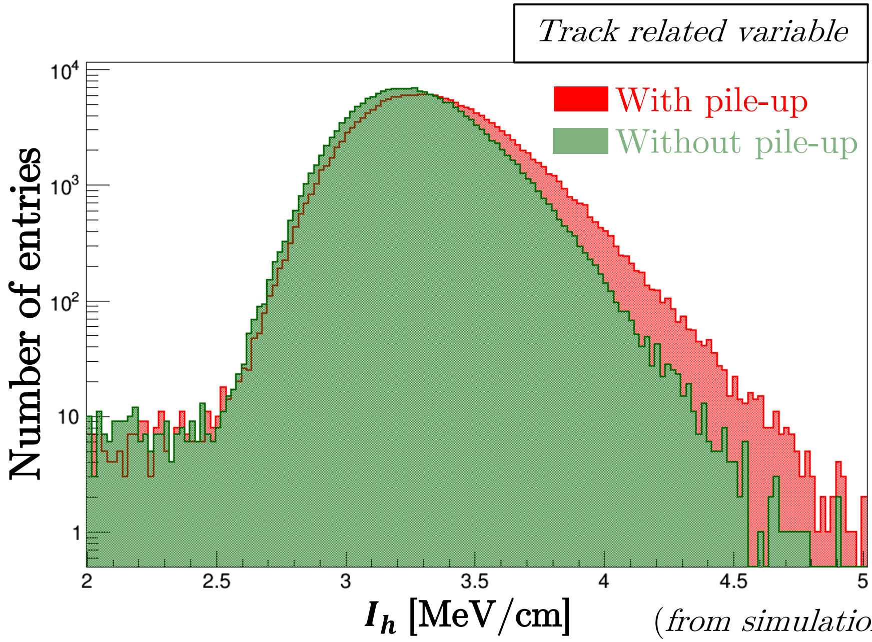
Impact of pile-up on I_h



$$I_h = \left(\frac{1}{N} \sum_{i=1}^{N} c_i^{-2} \right)^{-\frac{1}{2}}$$

$$c_i = \left(\frac{dE}{dx} \right)_i$$

Pile-up $\Longrightarrow$ larger energy deposit $\Longrightarrow$ **larger tail for I_h**



(*from simulations*)

Search for signal, and pile-up issue

Impact of pile-up on I_h

$$I_h = \left(\frac{1}{N}\sum_{i=1}^{N} c_i^{-2}\right)^{-\frac{1}{2}}$$

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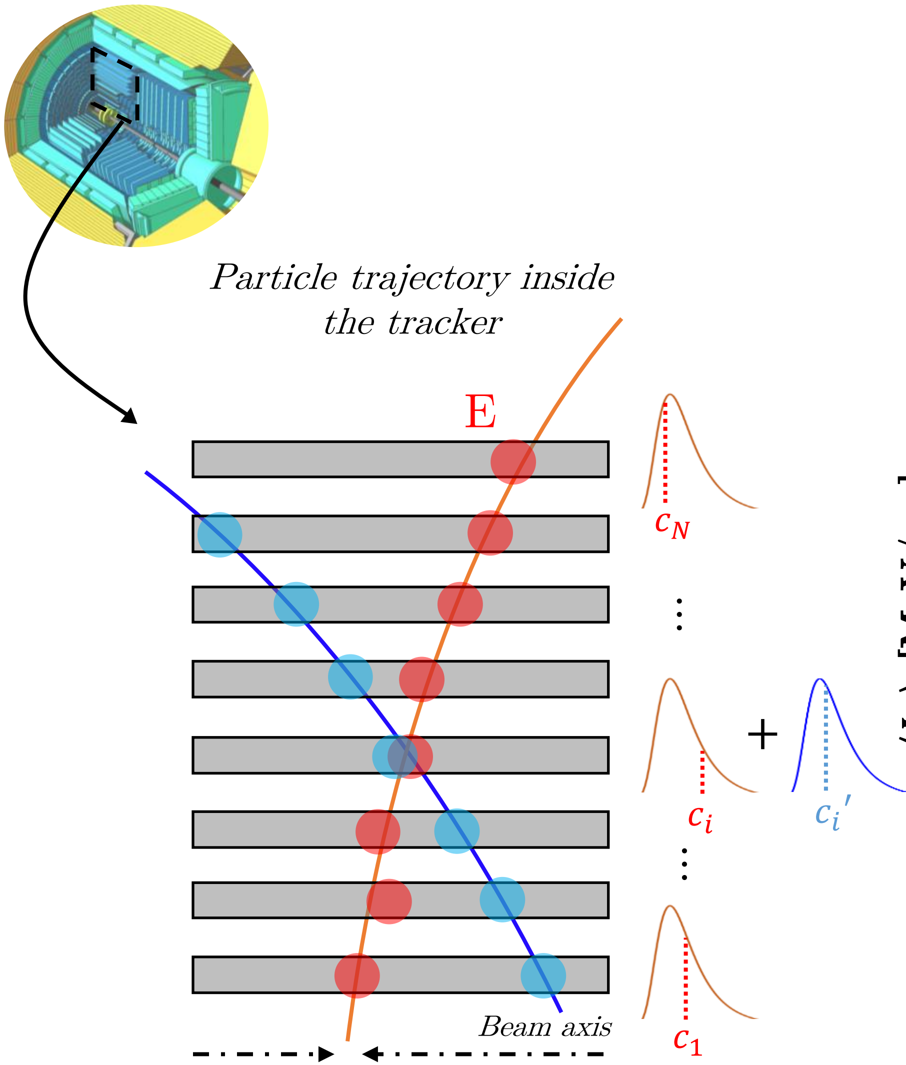
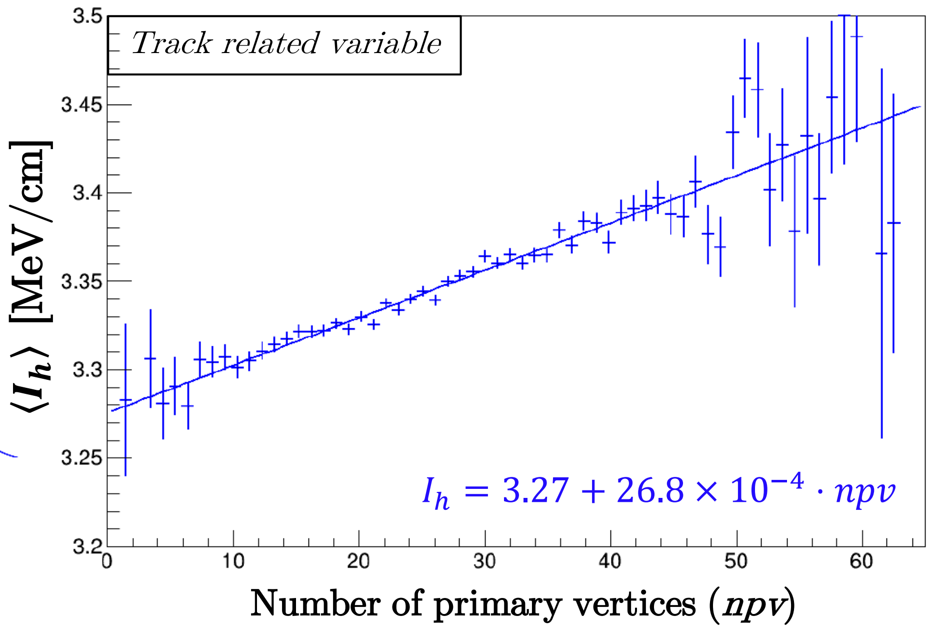




(*from simulations*)

Search for signal, and pile-up issue

Problematic of the internship

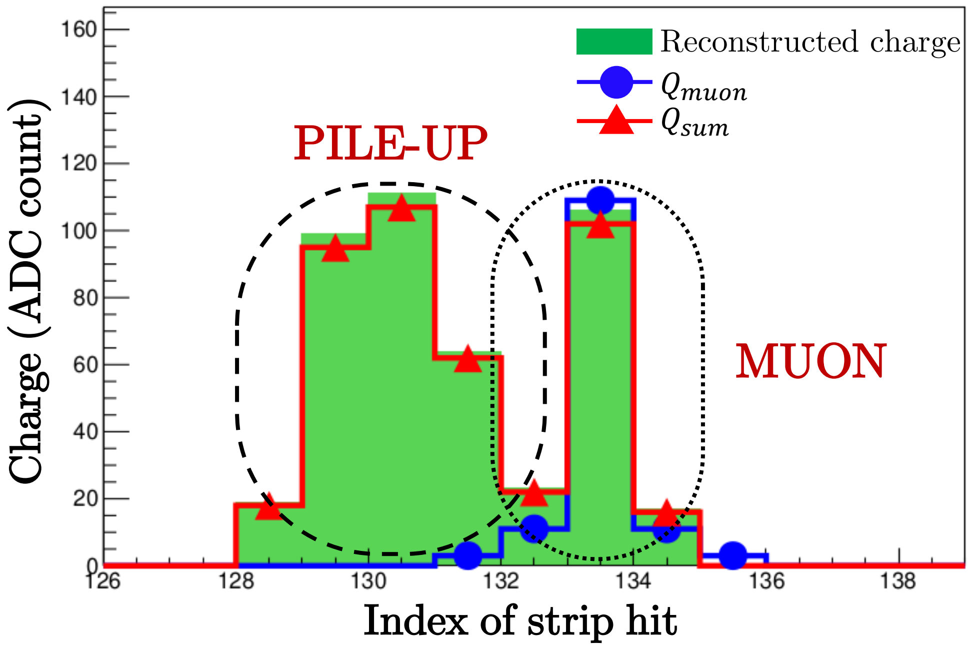
Pile-up

⇘ Larger clusters

⇘ Incorrect estimation of I_h

Study of the impact of pile-up on the measurement of energy clusters

Example of a cluster reconstructed with pile-up



Q_{muon} : Simulated charge alone.

Q_{sum} : Simulated charge with external contributions (electronic noise and pile-up).

Data specific to the simulation studied

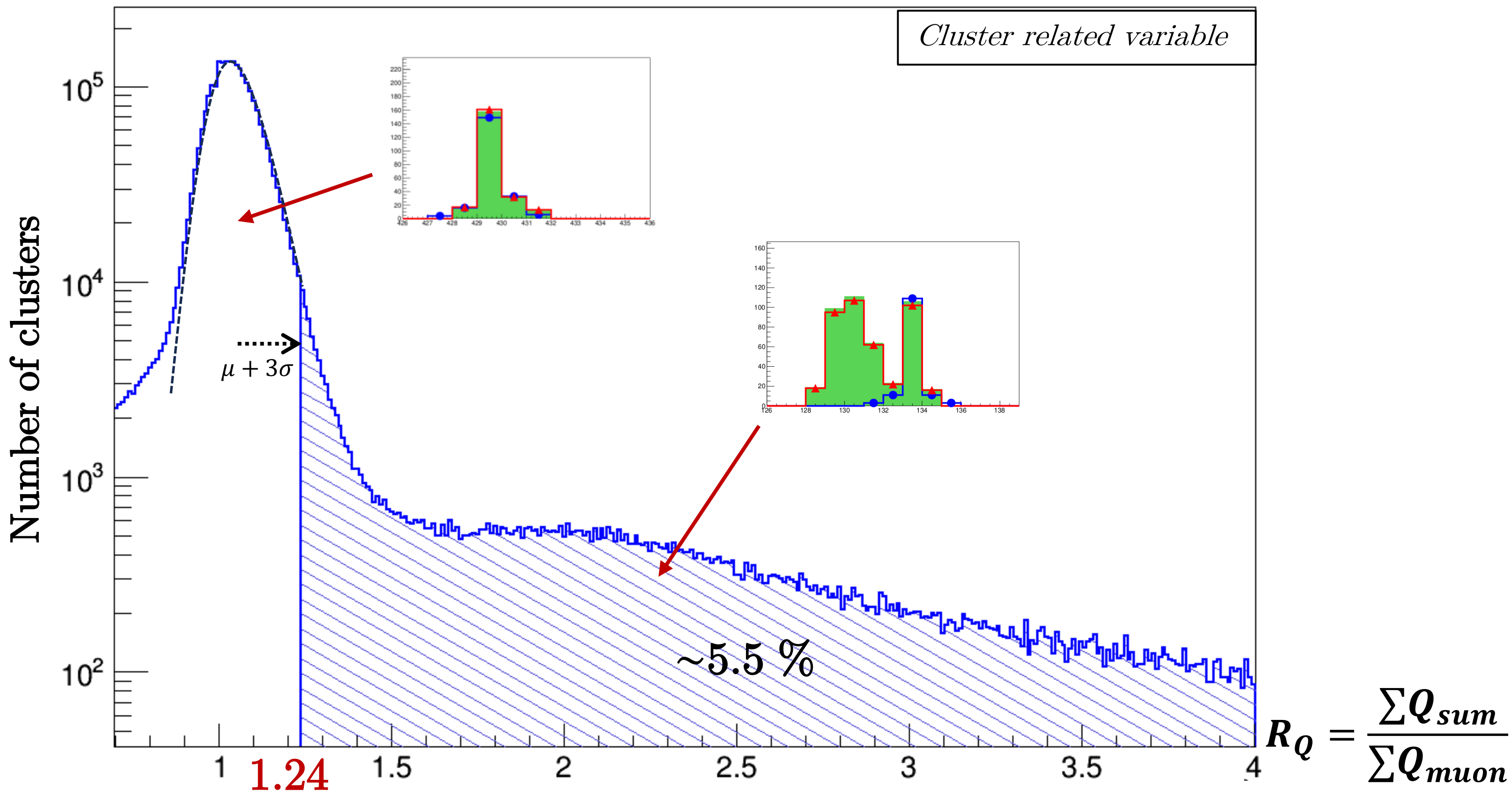
Simulation with a generated muon

Work done

For all clusters

Measure pile-up ? Take a look of the R_Q ratio between $\sum Q_{sum}$ and $\sum Q_{muon}$

→ There are simulated charge Q_{sum} bigger than they should be.



Work done

For <u>all</u> clusters

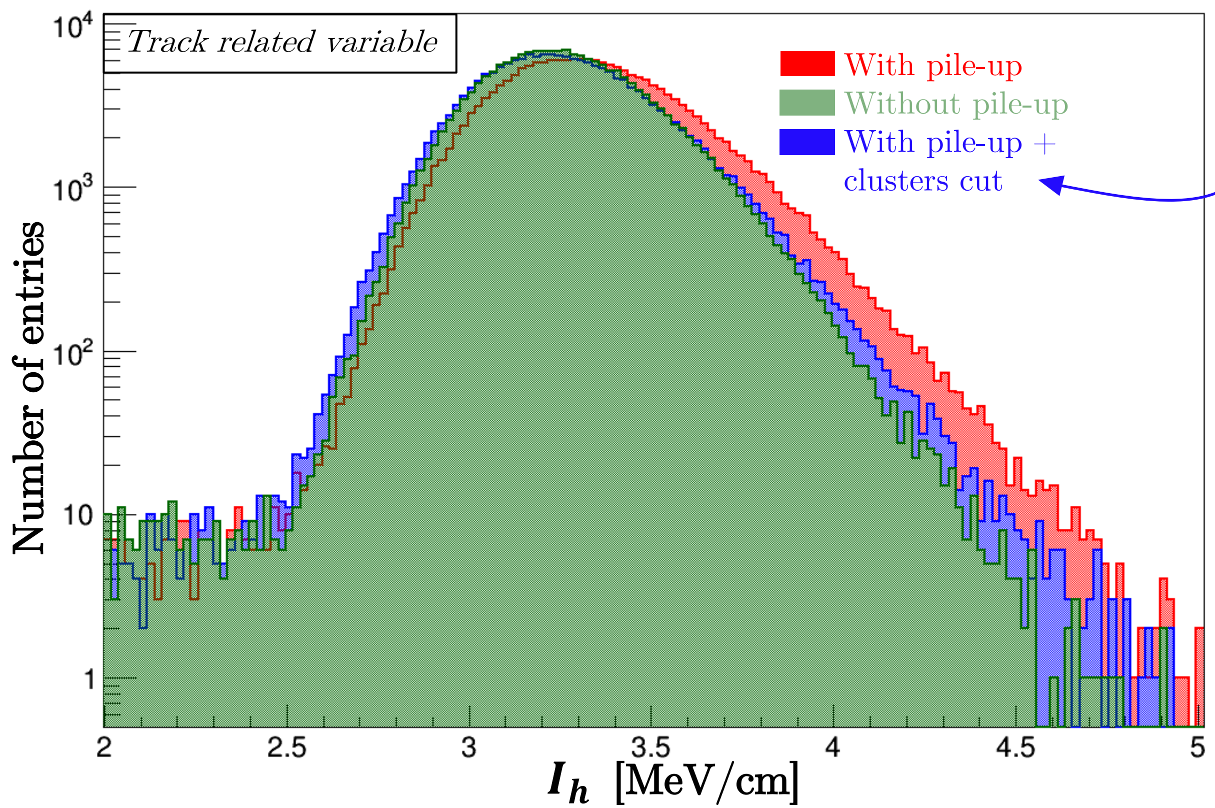
What is the impact on I_h if the ratio $R_Q = \frac{\sum Q_{sum}}{\sum Q_{muon}}$ is cut ?

Clusters such that $R_Q > 1.24$ are not taken into account.

$$I_h = \left(\frac{1}{N} \sum_{\substack{i=1 \\ R_Q < 1.24}}^{N} c_i^{-2} \right)^{-\frac{1}{2}}$$

$$c_i = \left(\frac{dE}{dx} \right)_i$$

→ **Reduction in high I_h contributions.**



Simulation with a generated muon

Work done

clusclean filtering algorithm

The search for strong ionization left by HSCPs requires **a filtering algorithm to reject abnormally shaped clusters**.

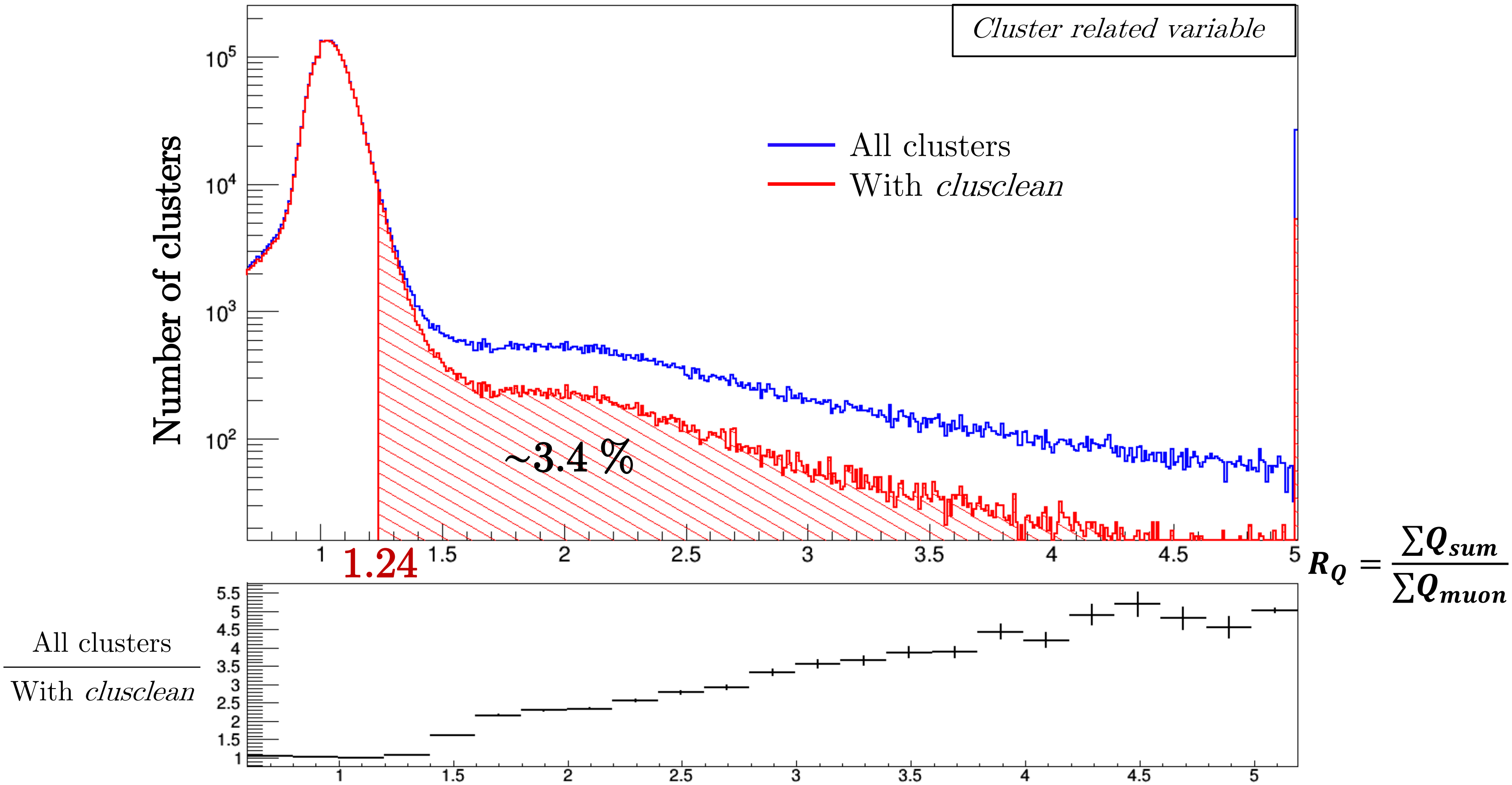
To be retained, clusters must comply with :

- ✓ presence of a **single maximum**
- ✓ **symmetrical spread**
- ✓ **thresholds not to be exceeded** for tracks neighbouring the maximum (size as a percentage of the maximum and other neighbours)

→ ***clusclean*** function

Work done

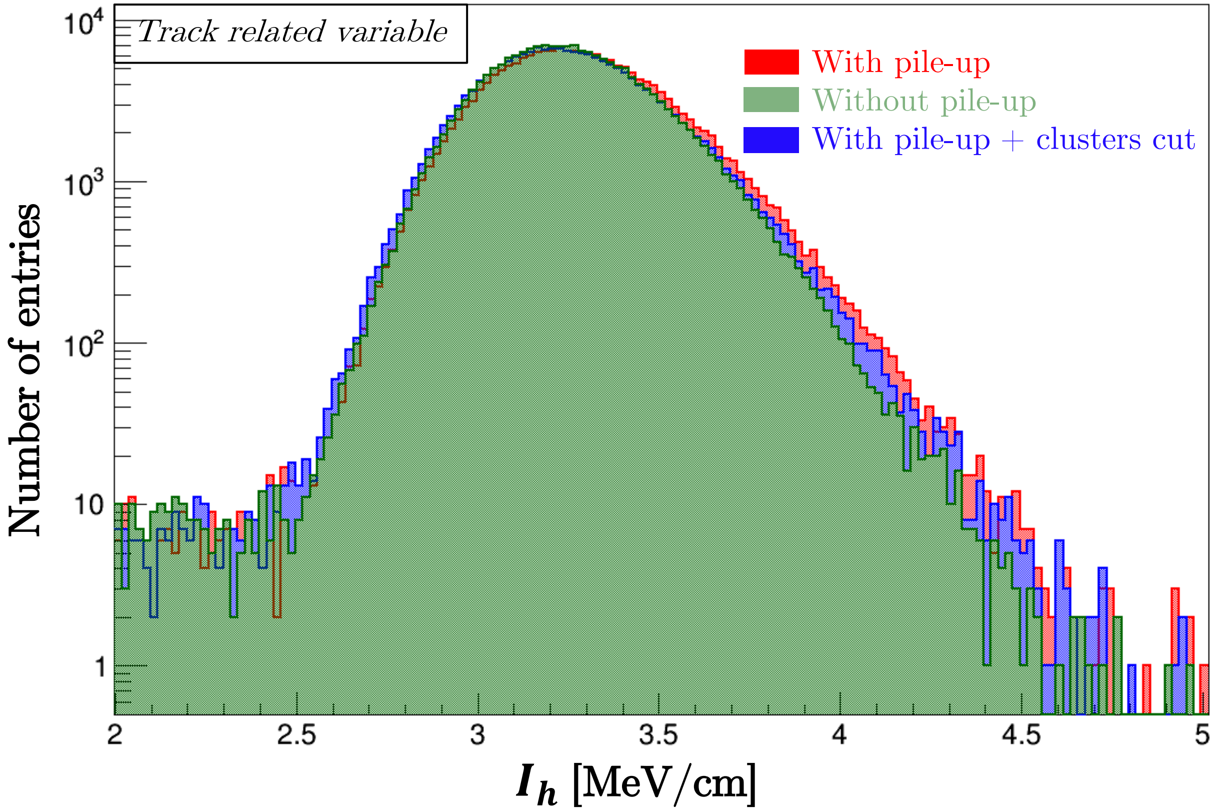
For clusters selected by clusclean



- The ratio for all clusters is **3 to 5 times higher** than those kept by *clusclean* above $R_Q = 2.5$

Work done

For clusters selected by clusclean



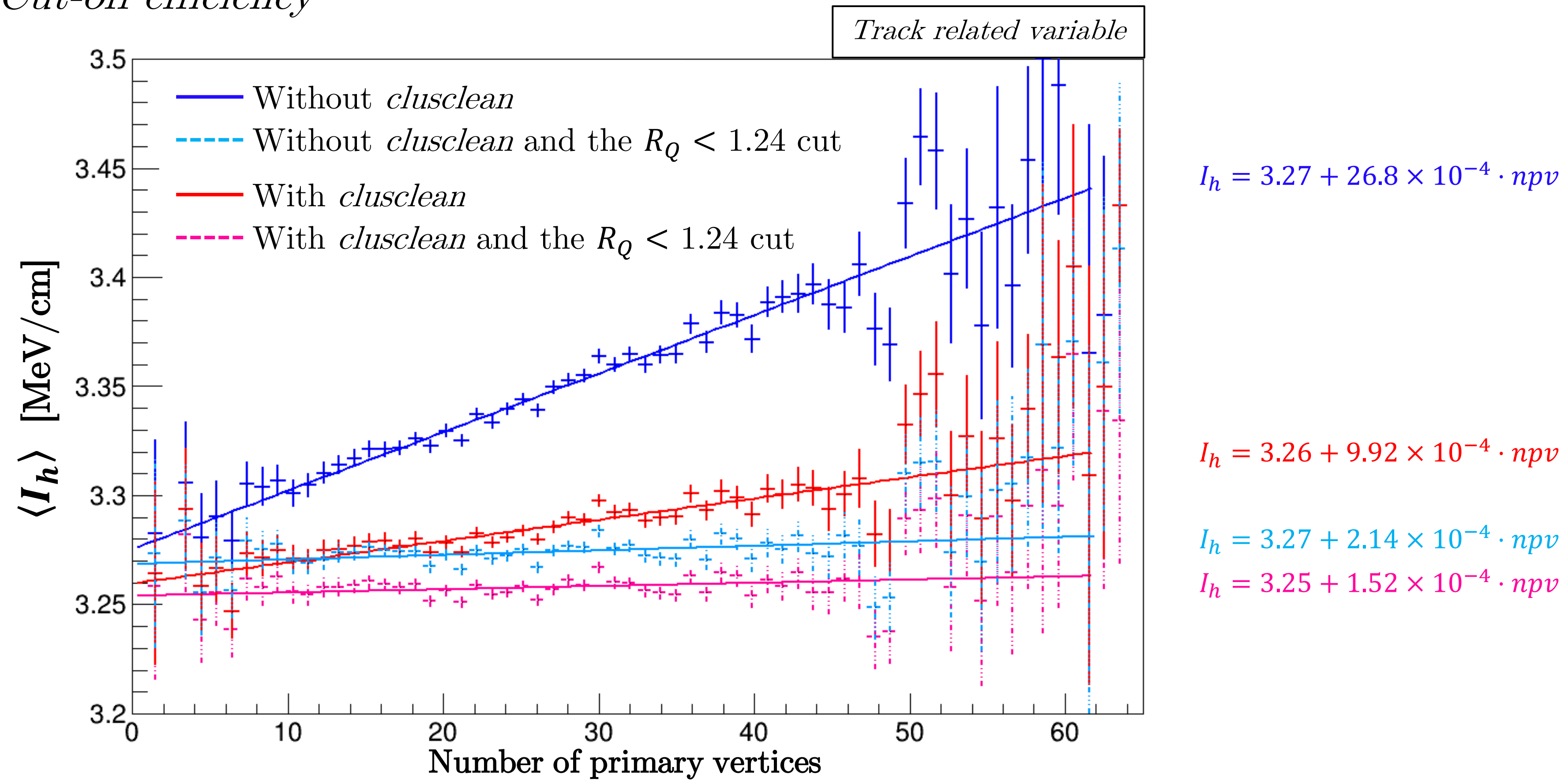
Simulation with a generated muon

~14 clusters/tracks ⟶ ~ 13 pass the *clusclean* algorithm (**6.8% removed**)

➢ Allure of ***I_h* broadly unchanged** with or without pile-up: *clusclean* is efficient, except for **high *I_h* values**.

Work done

Cut-off efficiency



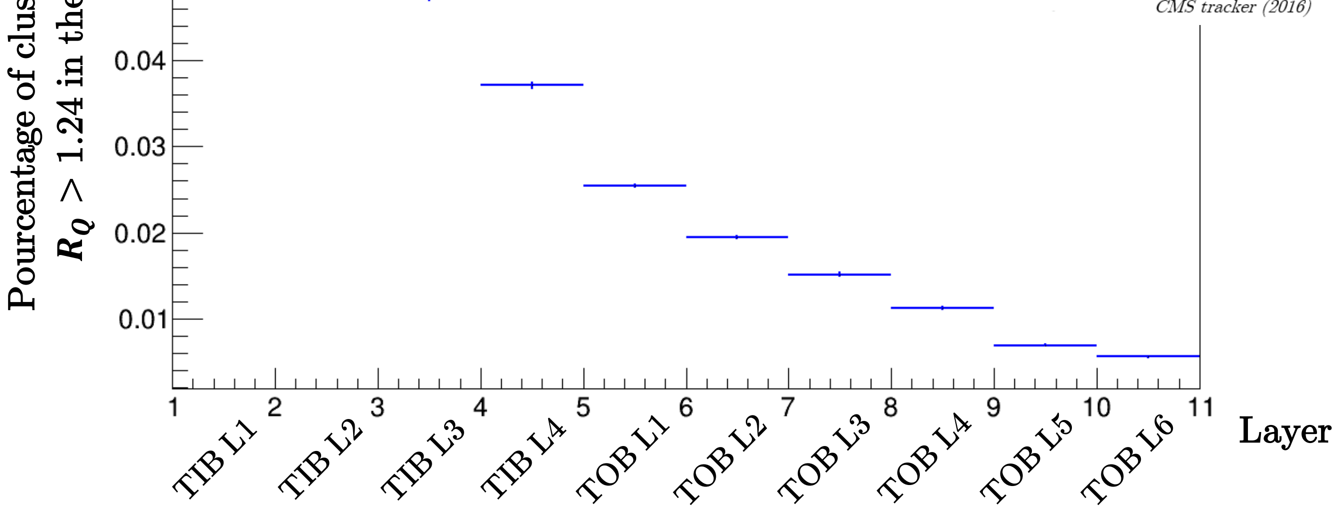
- Slope reduction with the $R_Q < 1.24$ cut: **12.5 (without *clusclean*)** and **6.5 (with *clusclean*)**.
- **Less reduction than in the case without *clusclean***: expected, since *clusclean* already removes a large proportion of clusters such as $R_Q > 1.24$.

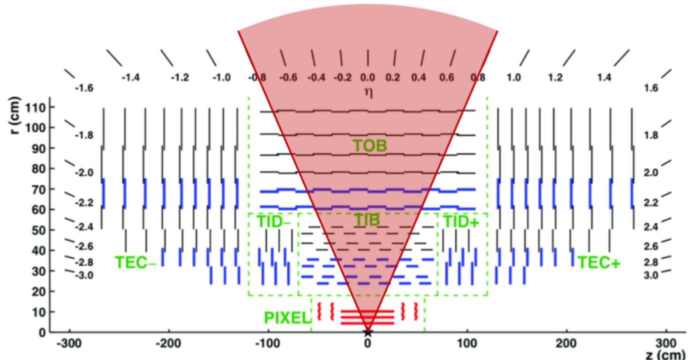
Work done

Outlook

There are still abnormal clusters passing *clusclean*, that should not:

- work on the case of **saturated clusters**
- more **effective cut-off on the first layers**





CMS tracker (2016)

Conclusion

- We are searching for a class of particles: **high mass** and **long lifetime**.
  → Experimental signatures: **high ionization in the tracker**.

- Demonstration of the increasing **dependency between ionization** (track energy estimator I_h) **and pile-up**.

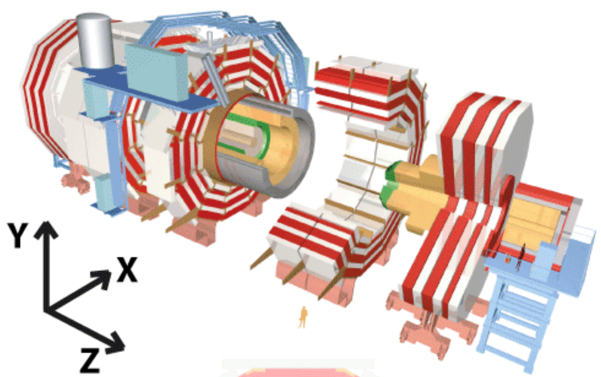
- **Pile-up** study on abnormal energy deposits.

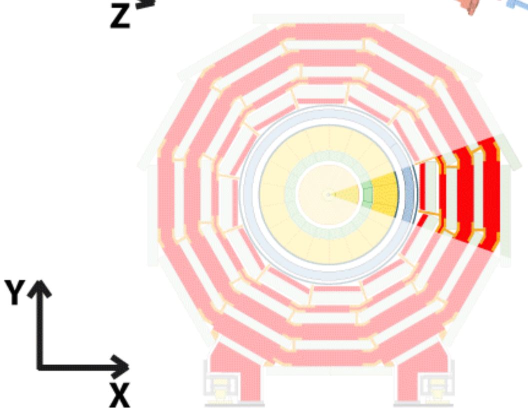
- Quantification of these deposits using the $R_Q = \frac{\sum Q_{sum}}{\sum Q_{muon}}$ ratio, impact on the tail of the mean deposited energy I_h estimator.
  → **High R_Q values lead to large I_h values**.

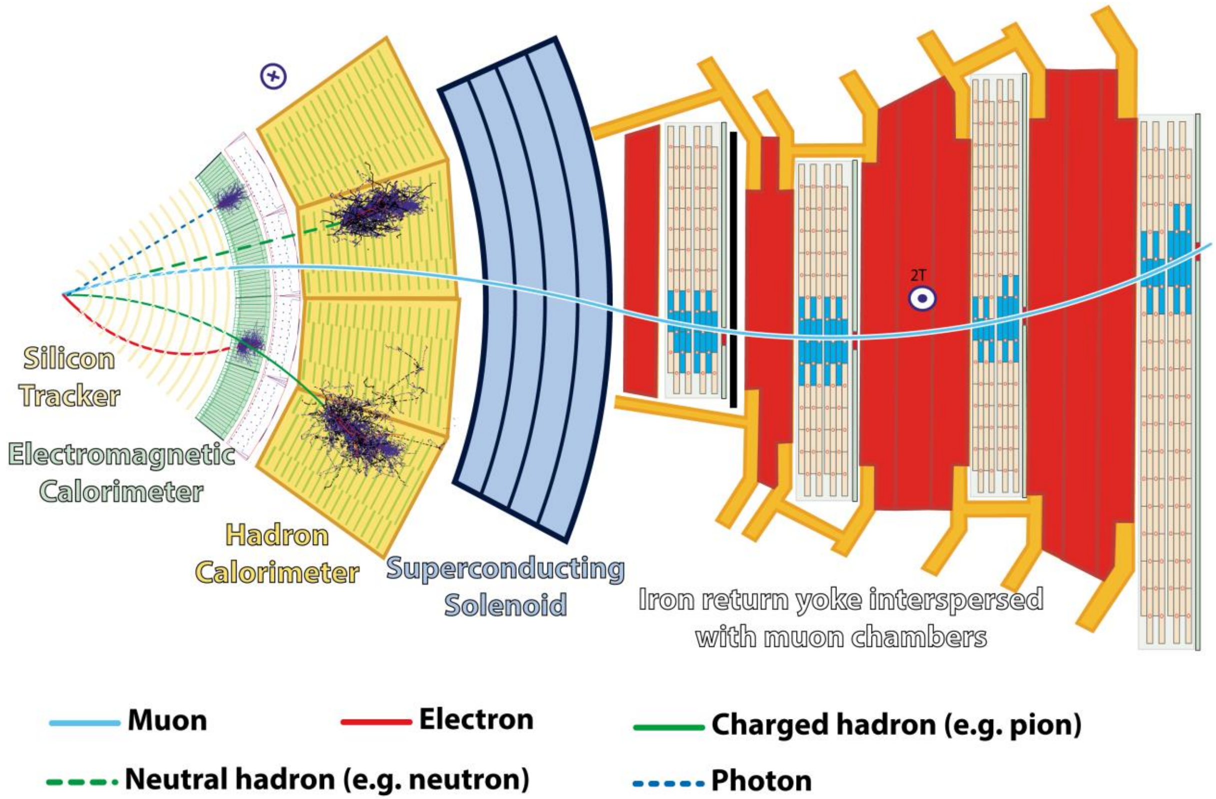
- The *clusclean* algorithm needs to be improved to remove cases of large deposits that ! are abnormal and make the **I_h estimator robust to pile-up**.

Appendix

CMS detector

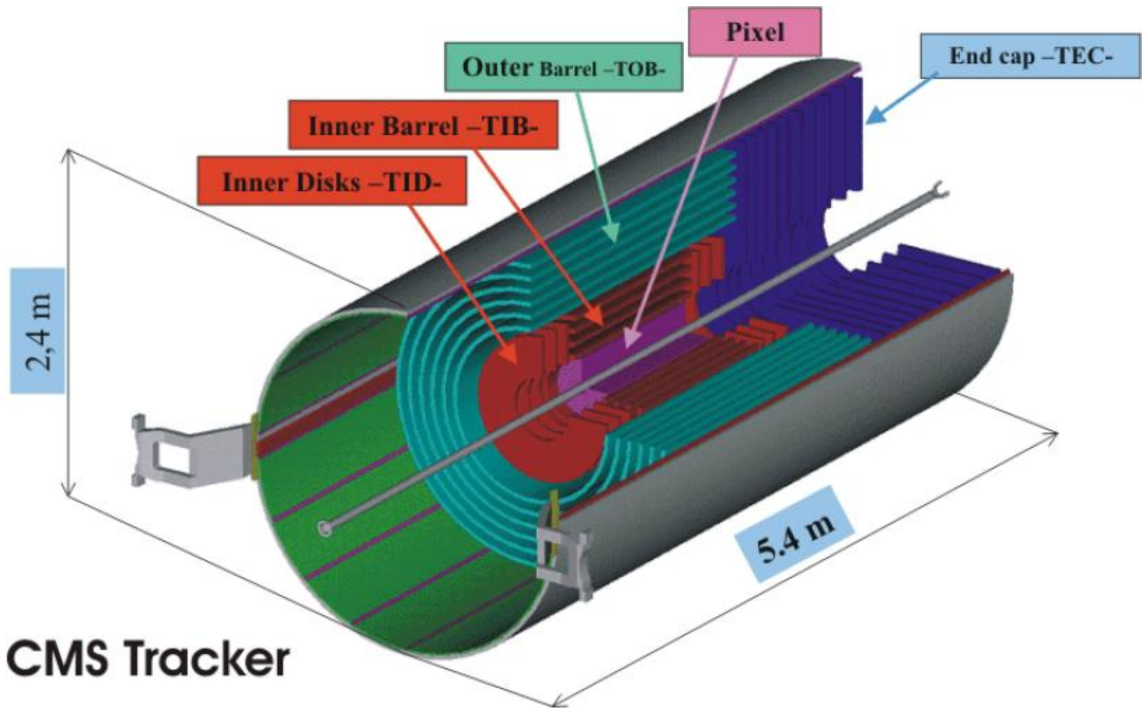






Appendix

CMS tracker



Magnetic field B of **3,8 T** along the beam axis to reconstruct the transverse momentum p_T of charged particles.

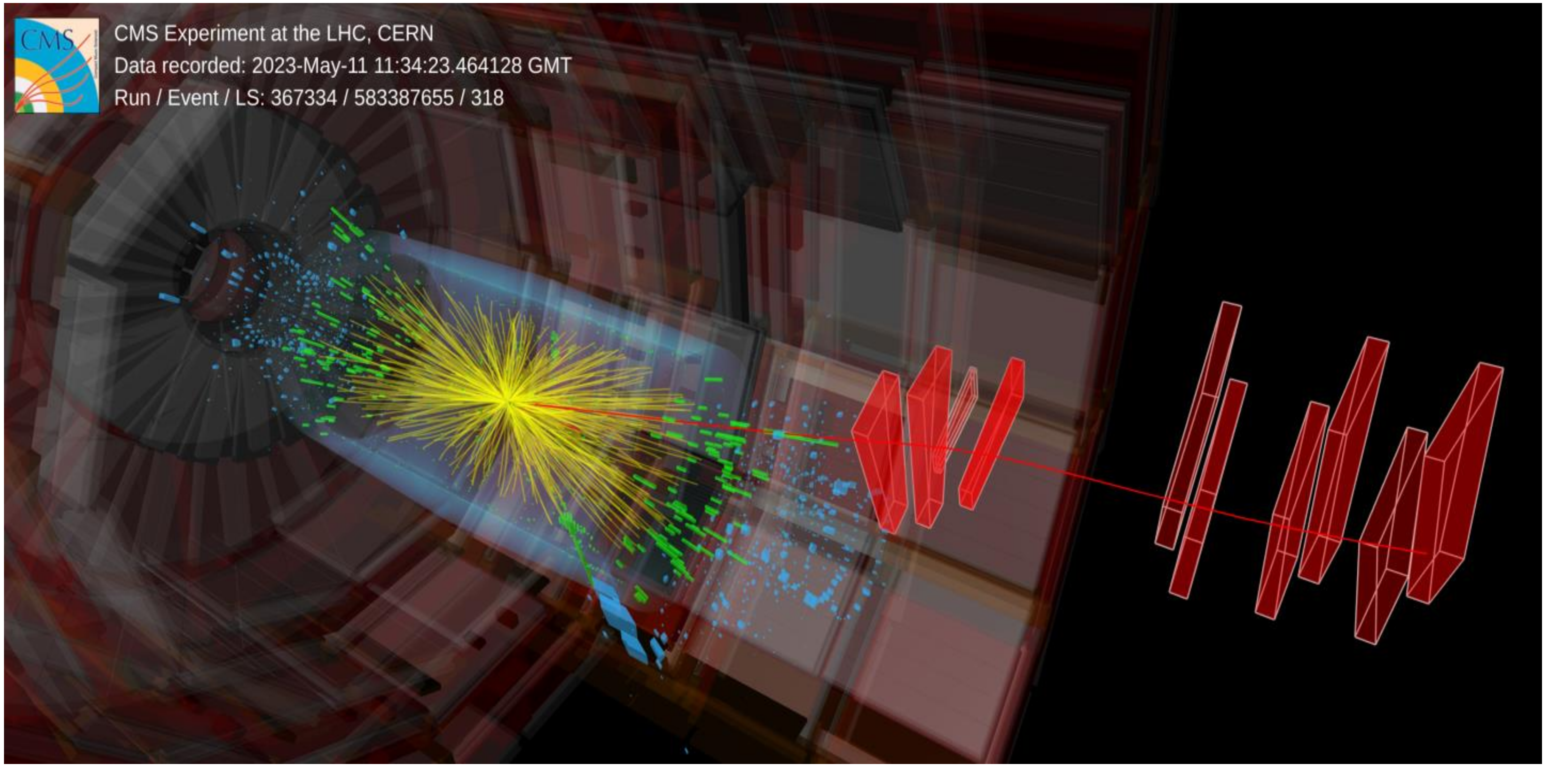
Radius of curvature

$$p_T = 0.3 \cdot z \cdot B \cdot \mathcal{R}_C$$

Algebric charge

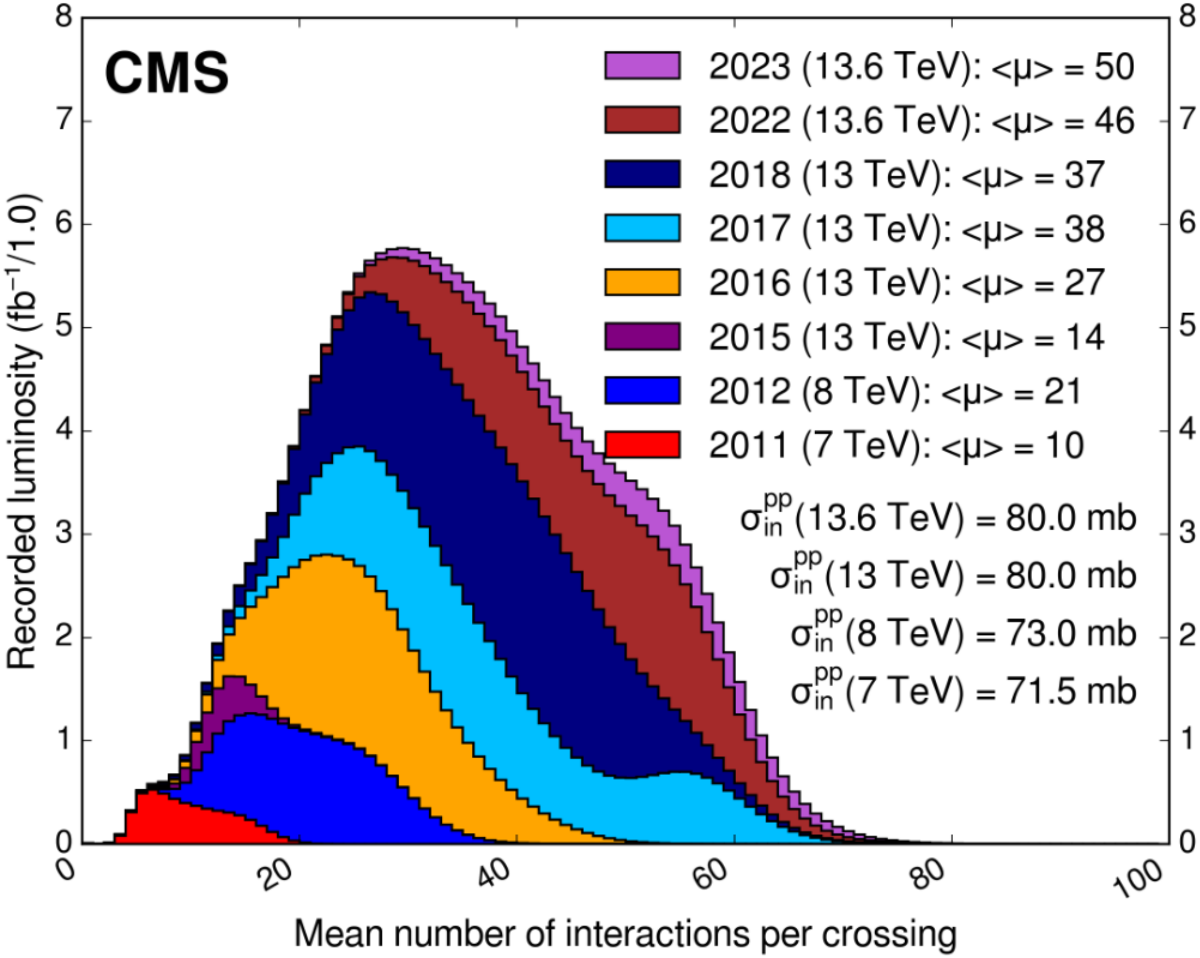
Appendix

Example of a single event in CMS



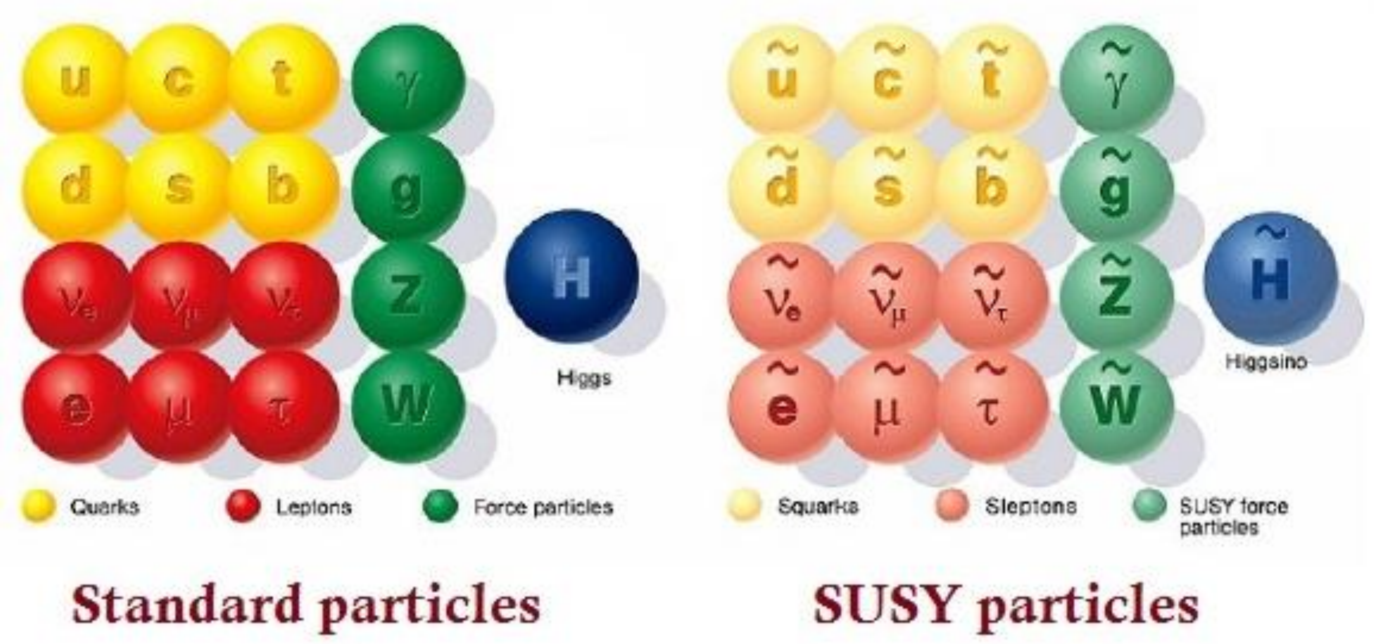
Appendix

Pile-up in the CMS detector over time



Appendix

Supersymmetry



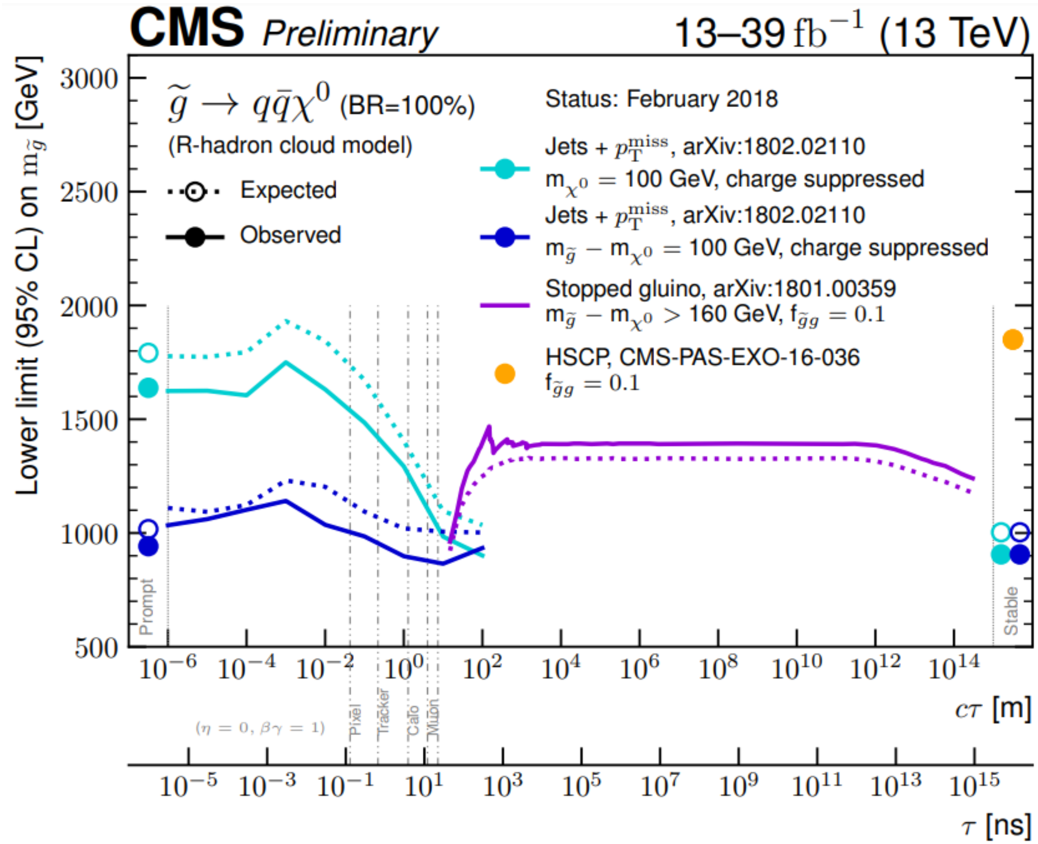
Gluino: signal étudié ici

Extension of the MS, introducing a spin symmetry.

- Propose a **candidate for dark matter**: the lightest and most stable supersymmetric particle (neutralino).
- Unification of interactions beyond 10^{16} GeV.

Appendix

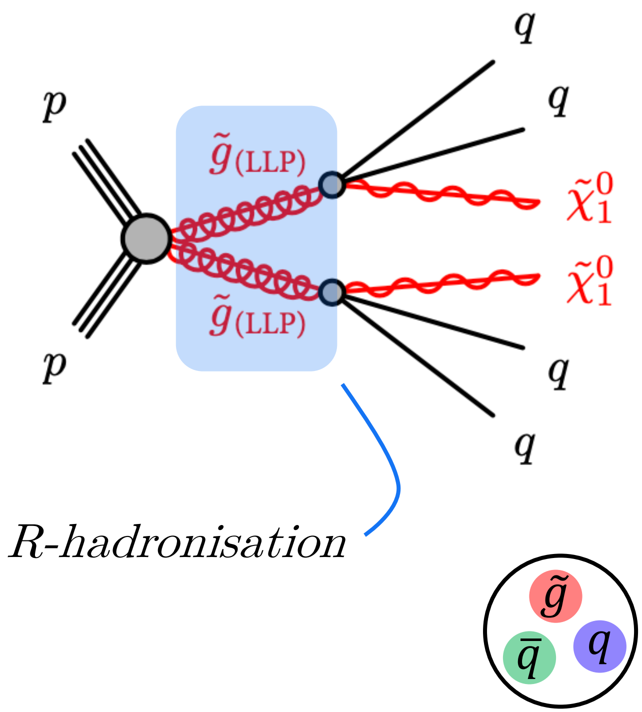
Interest of HSCP research



Search for neutralino $\tilde{\chi}^0$, from a gluino $\tilde{g}$, by different experimental means: the HSCP search (orange dot) leads to the highest exclusion of mass and lifetime for the gluino.

Appendix

Example of HSCP production



- Split SUSY

$$\tau[s] \simeq 8 \left(\frac{m_{\tilde{q}}}{10^9\ \mathrm{GeV}/c^2}\right)^4 \left(\frac{10^3\ \mathrm{GeV}/c^2}{m_{\tilde{g}}}\right)^5$$

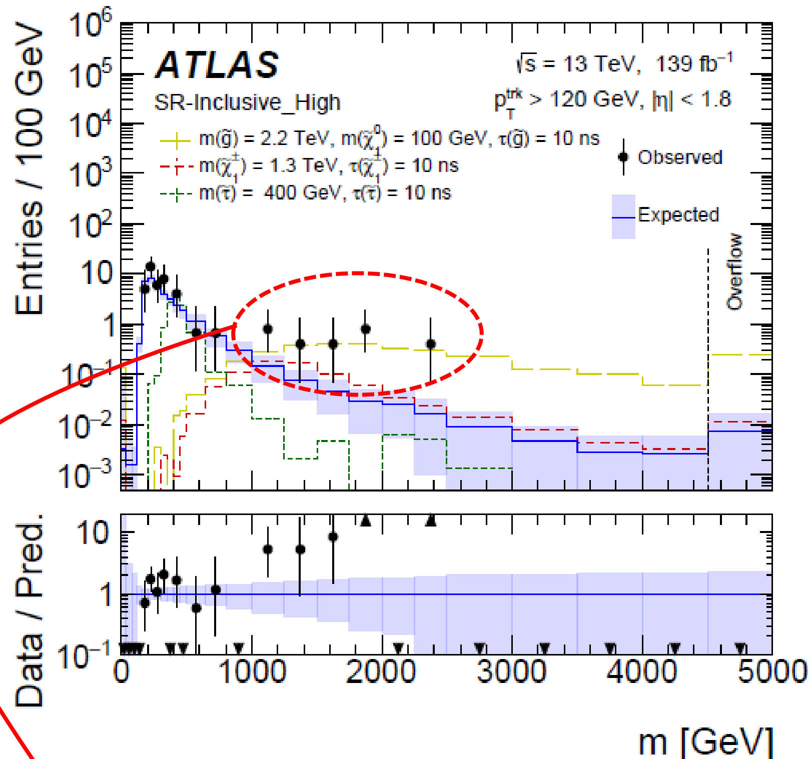
Decay through **virtual squark** at high mass

ex : $\tau \geq 100$ ns and $m_{\tilde{g}} = 2000\ \mathrm{GeV}/c^2$

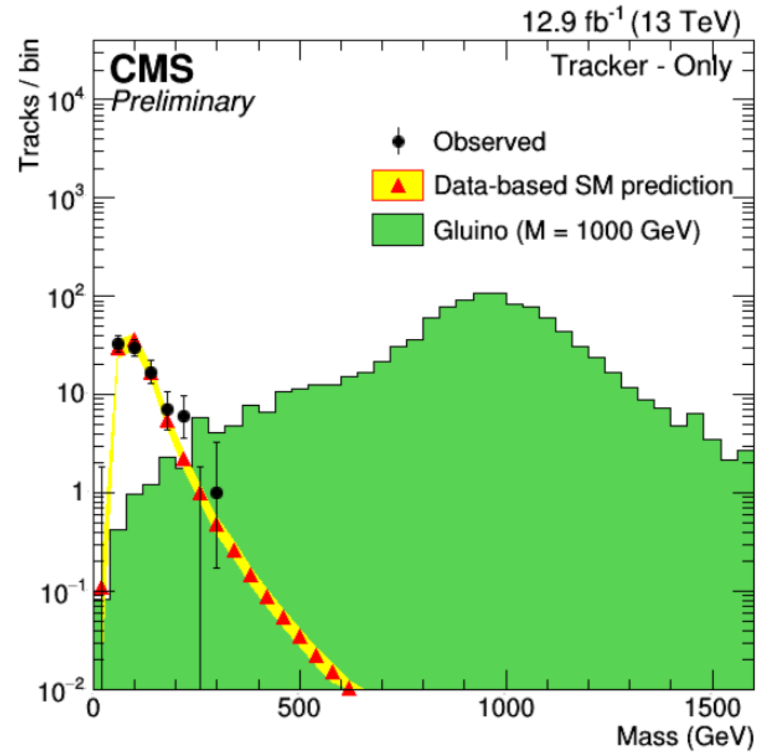
$\rightarrow m_{\tilde{q}} \gtrsim 2 \cdot 10^8\ \mathrm{GeV}/c^2$

Appendix

Summary of current HSCP results



Excess of events observed by the ATLAS collaboration (degree of confidence at 3.3 σ) [1] (Run 2 data – 2022)

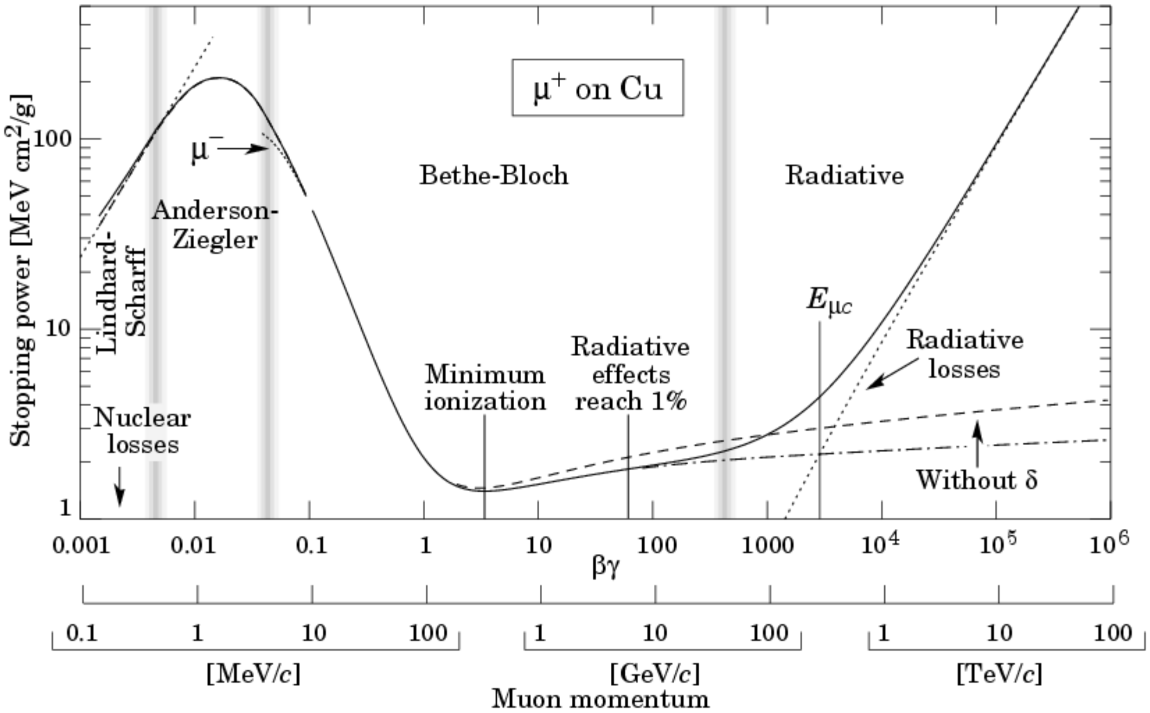


No excess observed by CMS [2] (Run 1 data – 2016)

Appendix

Bethe-Bloch formula

$$\left\langle -\frac{dE}{dx}\right\rangle = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\ln\left(\frac{2m_ec^2\beta^2\gamma^2W_{max}}{I^2}\right)-\beta^2-\frac{\delta(\beta\gamma)}{2}\right]$$



$\beta = \frac{v}{c}$ $\gamma = \frac{1}{\sqrt{1-\beta^2}}$

$\beta\gamma = \frac{p}{Mc}$ $M > m_e$

K : constant

z : algebric charge of the particle

A : atomic number of the material crossed

Z : mass number of the material crossed

$\boldsymbol{W_{max}}$: maximum of energy transfered in a single collision

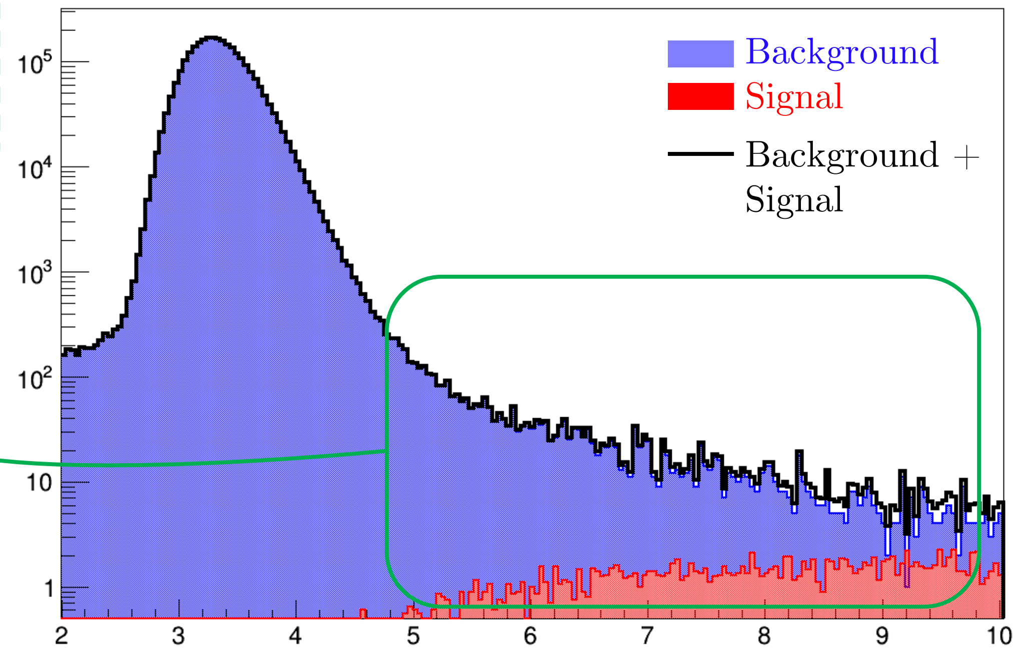
I : mean excitation energy of the material

δ : ultra-relativist correction

Appendix

Sources of contributions to large I_h values

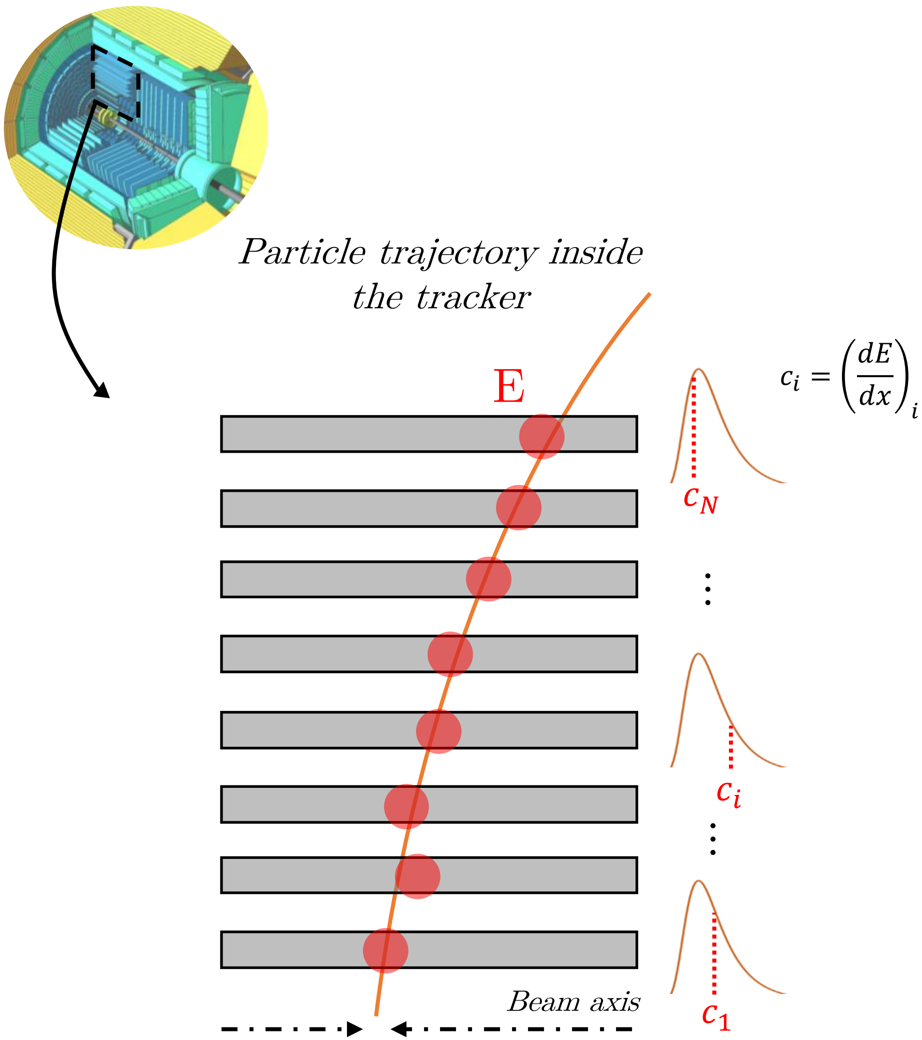
- HSCP (**Signal**).
- MS particles in the Landau tail.
- Pile-up.
- Deposit from another very low momentum particle.



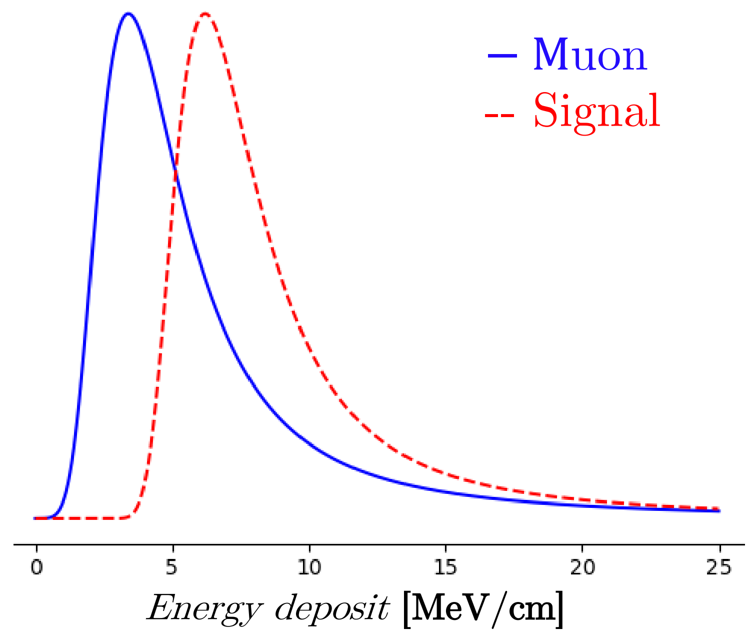
I_h [MeV/cm] (*from simulations*)

Appendix

Energy deposit



Energy deposition follows a Landau law, which is **highly asymmetric**, with a **long tail** of distribution.

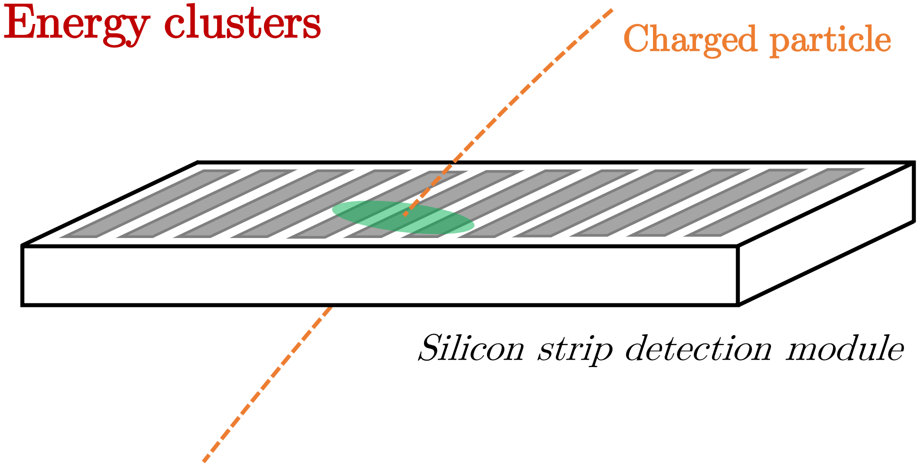


MS: MPV ~ **3-4 MeV/cm**

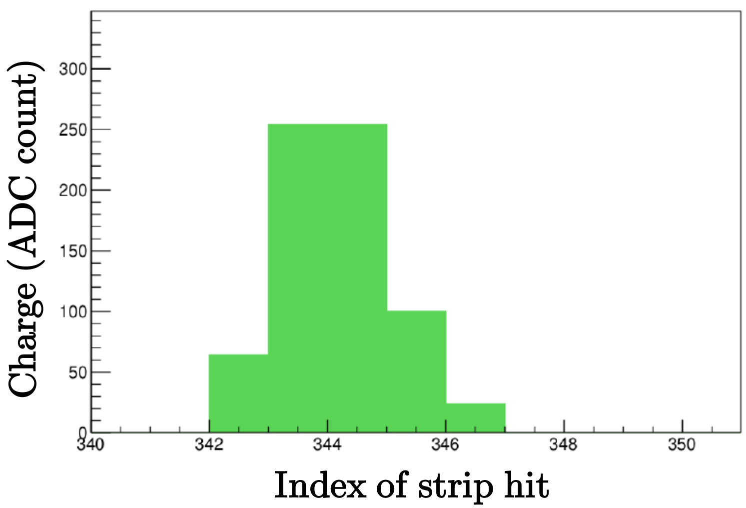
HSCP: MPV $\gtrsim$ **6 MeV/cm**

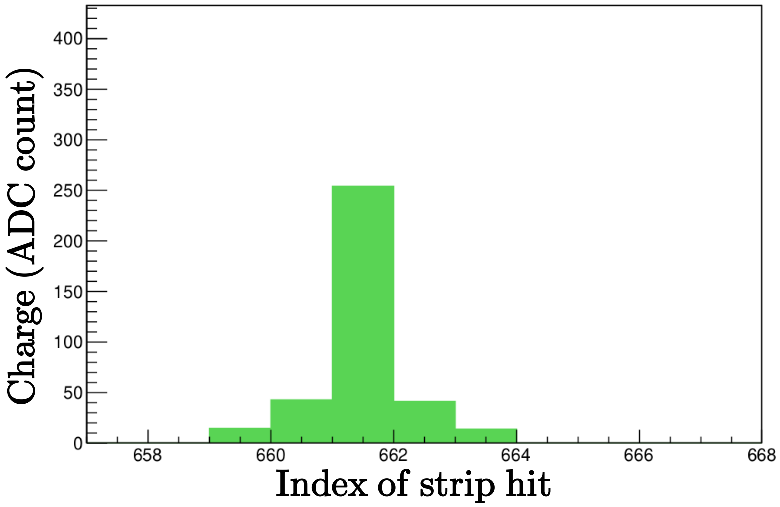
Appendix

Energy clusters



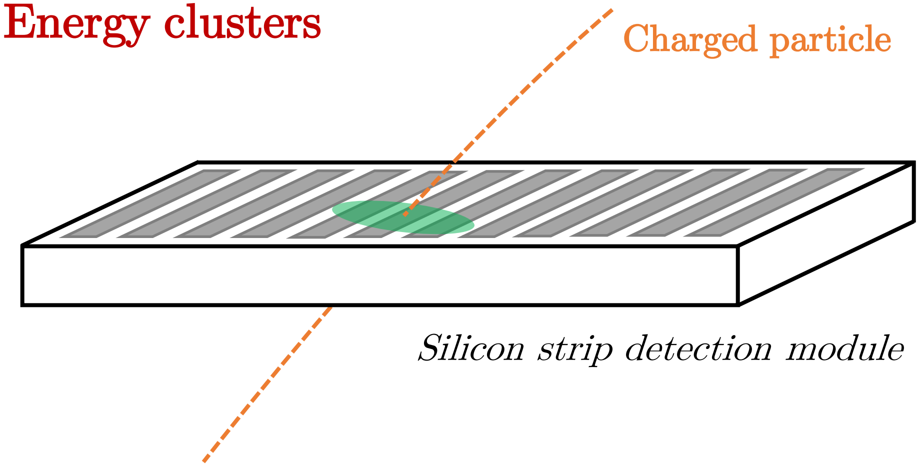
- One or many strips hit
- **Cross-talk** phenomenon (charge spreading due to capacitive coupling between strips)





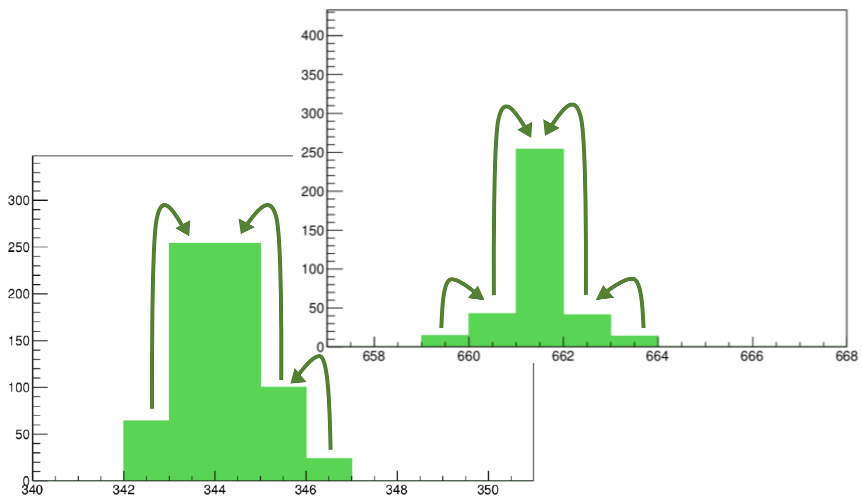
Appendix

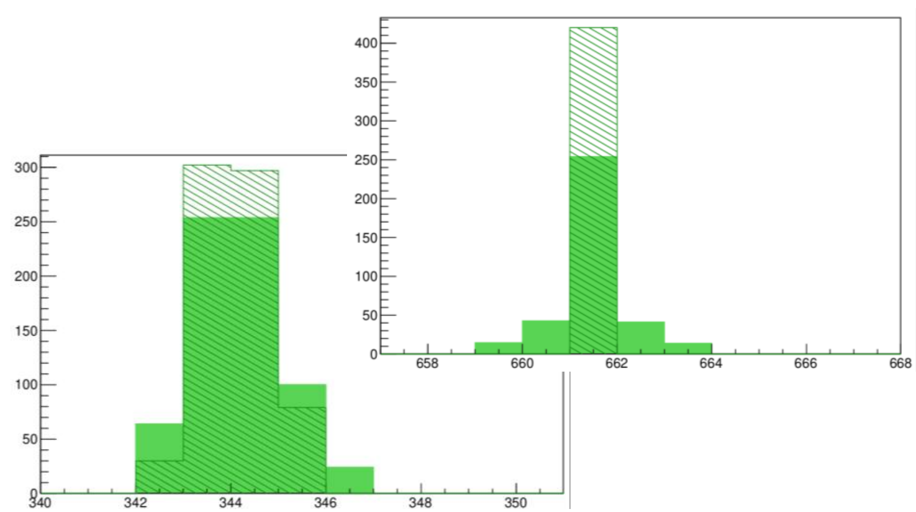
Energy clusters



- One or many strips hit
- Cross-talk phenomenon (charge spreading due to capacitive coupling between strips)

Cross-talk inversion algorithm



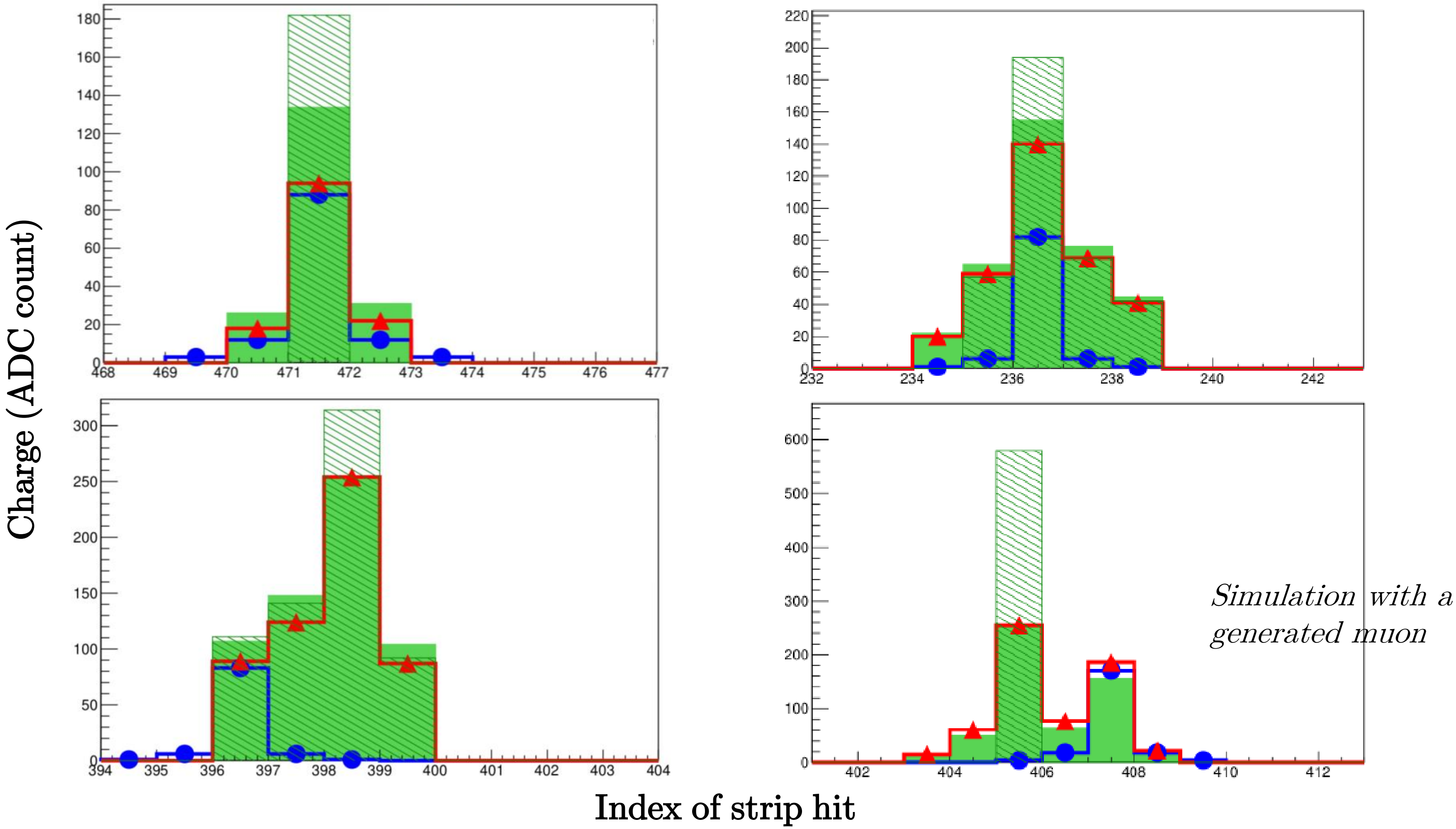


Appendix

Energy clusters

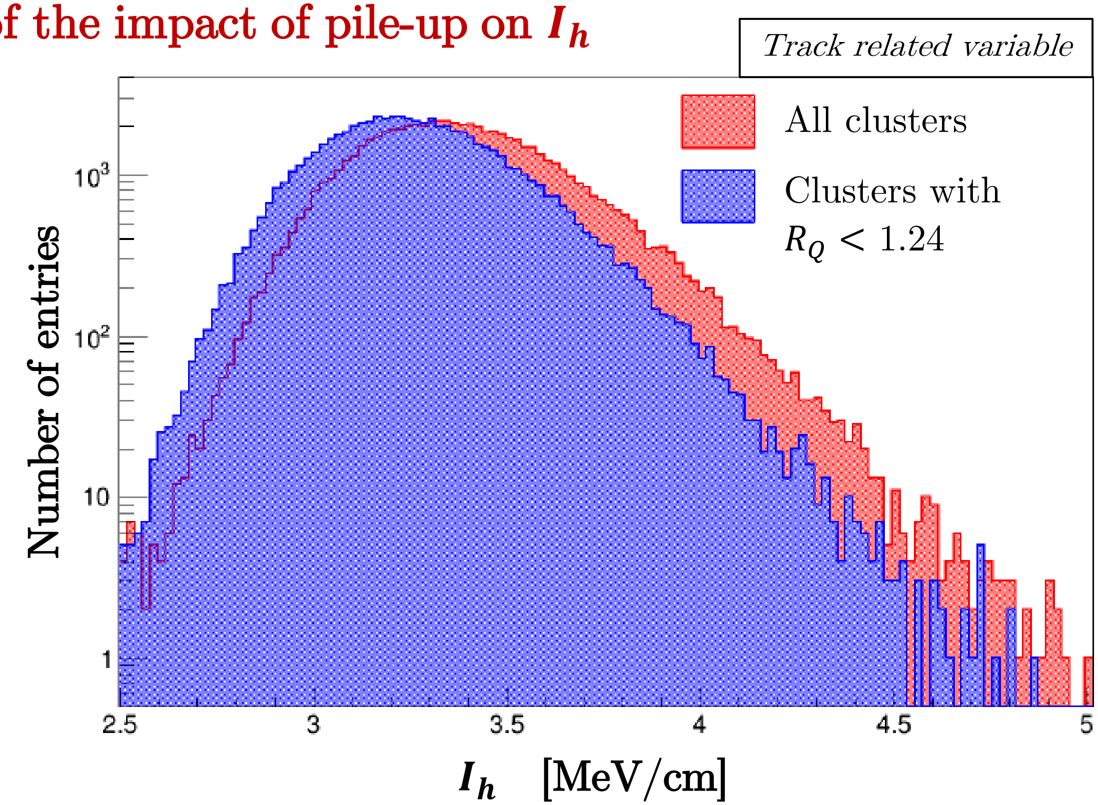
Before cross-talk correction
After cross-talk correction

Q_{muon} : Simulated charge alone.
Q_{sum} : Simulated charge with external contributions (electronic noise and pile-up).



Appendix

Visualisation of the impact of pile-up on I_h

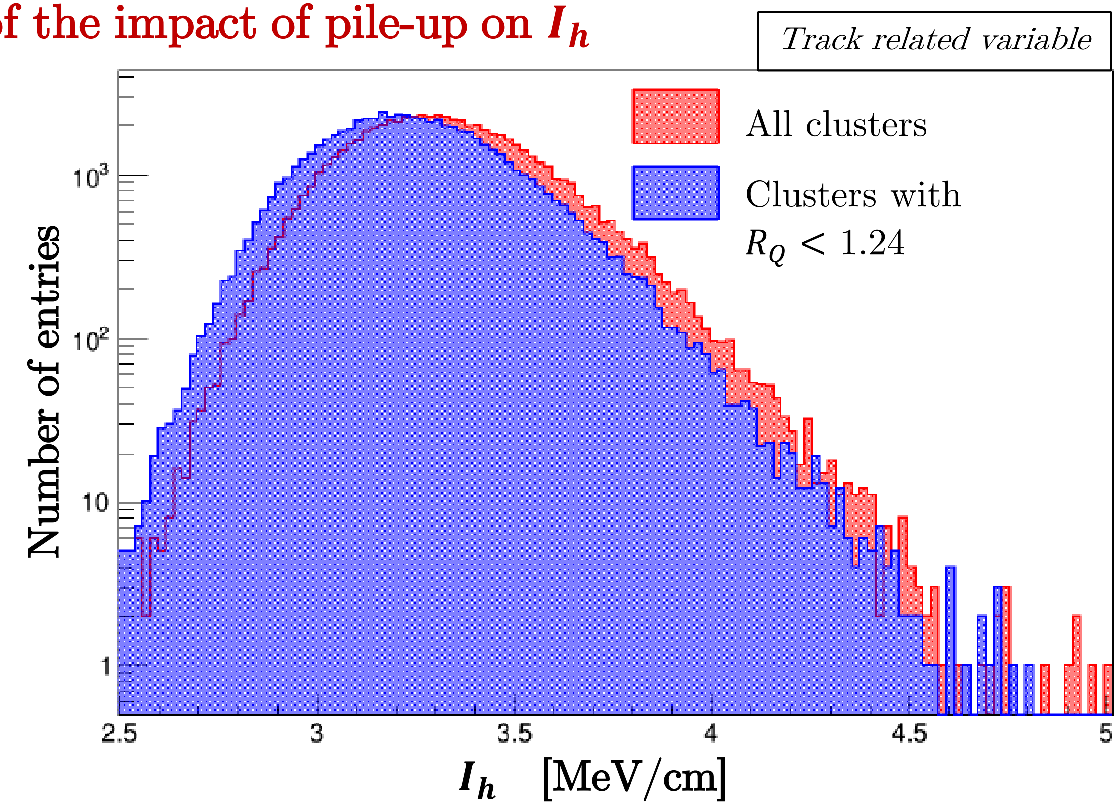


Without *clusclean* filtering before

- I_h only for tracks for which at least one cluster has an $R_Q > 1.24$.
- Reduced number of entries: 190 000 (all tracks) to 110 000 (tracks that have at least one cluster with $R_Q > 1.24$), i.e. **60% of tracks have at least one deposit with a significant external contribution**.

Appendix

Visualisation of the impact of pile-up on I_h



With *clusclean* filtering before

- Same entries reduction, but less this time: **35% of tracks have at least one deposit with a significant external contribution**.
- The difference between the two curves is small, this shows: the **efficiency of *clusclean*** and most of the time, I_h calculated with *clusclean* filtering will **still have at least one cluster with $R_Q > 1.24$**.

Appendix

LHC operating schedule