Search for heavy long-lived particles with large ionization energy loss at the CMS experiment

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Motivations

Standard Model

Theory describing elementary particles and their interactions.

↓

Limits

- Dark matter
- Matter-antimatter asymmetry
- ...

↓

Theory beyond the Standard Model

- New interactions, symmetries, particles, ...

properties: *mass, charge, lifetime, ...*

Motivations

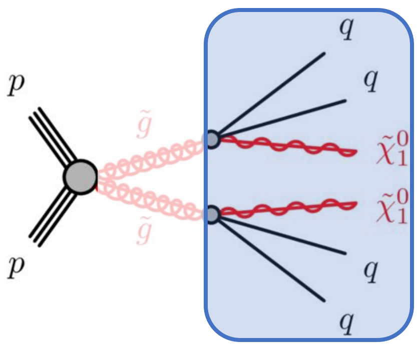
Multiple searches

prompt → *stable* $c\tau$

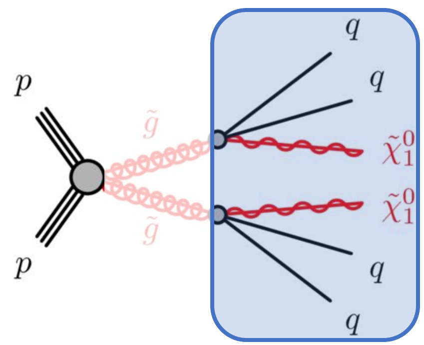
< 1 cm ~ 1 m > 10 m

- If the particle decays we can detect its decay products
- If the particle decays inside the detector, one can find displaced evidence of its decay products
- If the particle is stable, it won't decay inside the detector, and we can't see its decay products

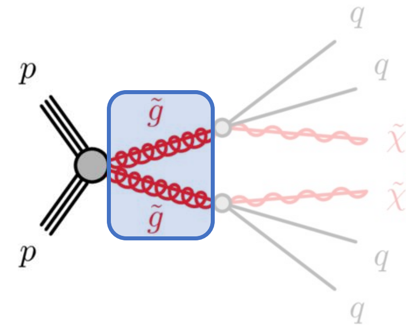
What we see in the detector



Invisible particles (neutral) + jets



displaced vertices + jets



No decay
Particle goes through the whole detector

→ Focus on stable

Motivations

Multiple searches

prompt — *stable* — $c\tau$

< 1 cm ~ 1 m > 10 m

Heavy Stable Charged Particles

→ Beyond Standard Model particles theorized to have **large mass**, **long lifetime** and $|\boldsymbol{Q}| > \mathbf{0}$

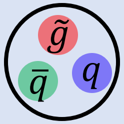
→ Two kind of particles:

- "**Lepton-like**"

Pair-produced stau
Tau-prime ($|Q| = 1e, 2e$)

- "**Hadron-like**": **R-hadrons**

Pair-produced gluino
Pair-produced stop



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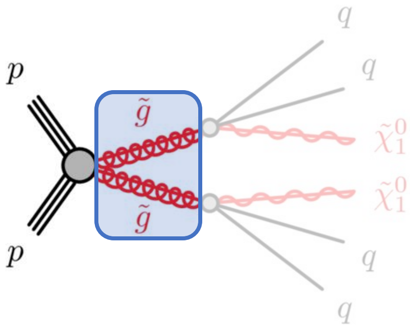

No decay
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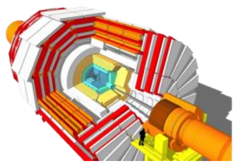
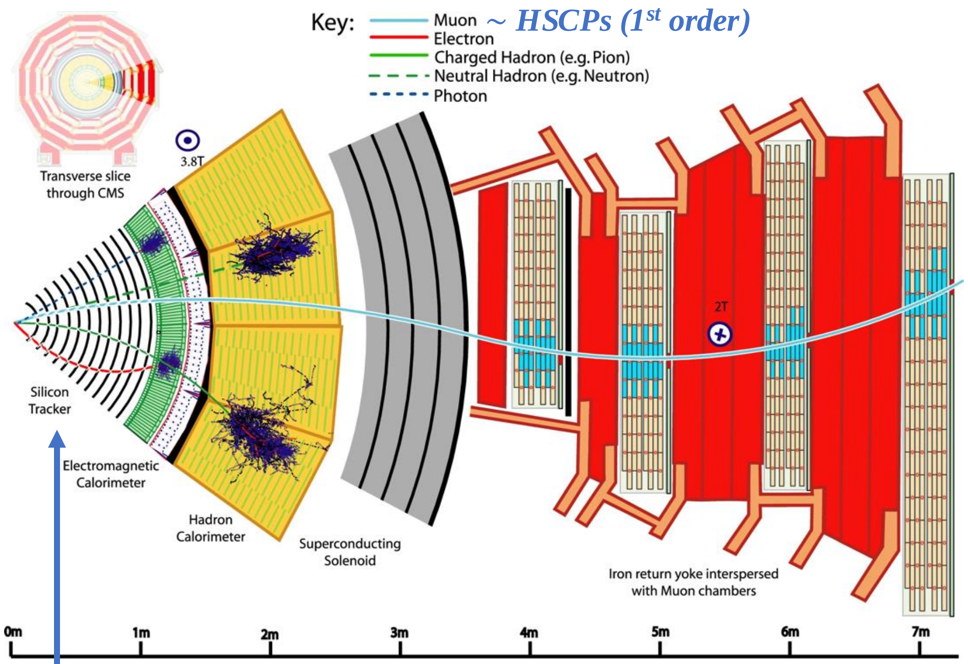
→ Focus on stable

Experimental signature



Compact **M**uon **S**olenoid : Detector installed at one interaction point of **LHC (CERN)**



Ionization

Stable

→ Particles propagate through the entire detector

$$c\tau > 7 \text{ m}$$

Heavy

→ *ex:* $m_{gluino} > 1800 \text{ GeV}/c^2$

$$\Updownarrow$$

$$\frac{p}{m} = \beta\gamma < 1$$

- m: mass
- p: momentum
- $\beta = v/c$
- $\gamma = (1-\beta^2)^{-1/2}$

→ **slow moving particles**

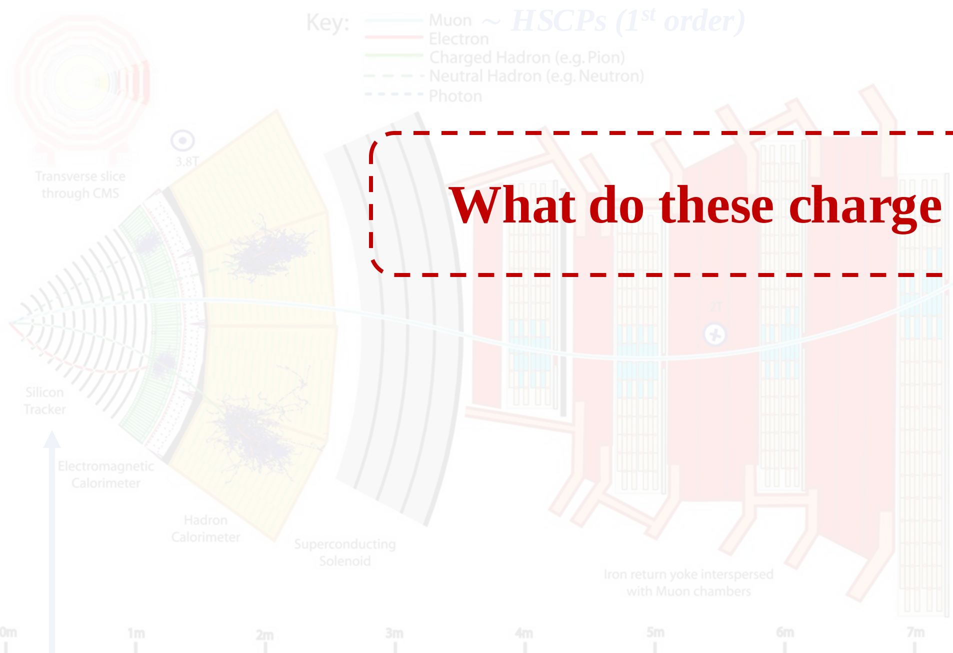
Charged

→ Charged particles leave tracks in the detector

$$-\frac{dE}{dx} \propto \frac{1}{\beta^2} \xrightarrow{\beta < 1}$$ **Highly ionizing particles**

Experimental signature

Compact **M**uon **S**olenoid : Detector installed at one interaction point of **LHC (CERN)**



Ionization

Stable

→ Particles propagate through the entire detector $c\tau > 7$ m

Heavy

→ *ex:* $m_{gluino} > 1800$ GeV/c^2

⇓

$$\frac{p}{m} = \beta\gamma < 1$$

- m: mass
- p: momentum
- $\beta = v/c$
- $\gamma = (1-\beta^2)^{-1/2}$

→ slow moving particles

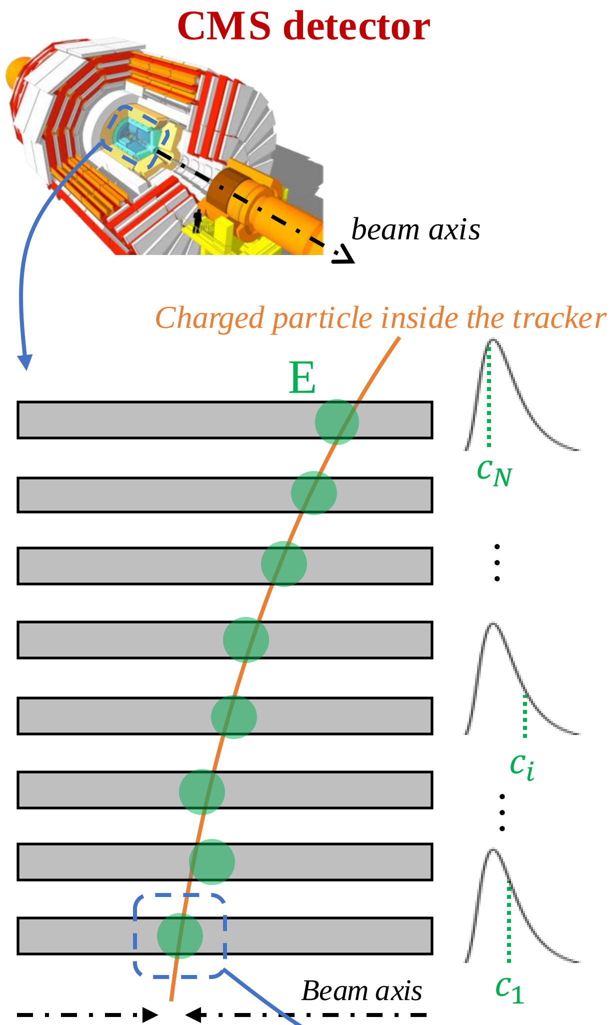
What do these charge deposits look like ?

Charged

→ Charged particles leave tracks in the detector

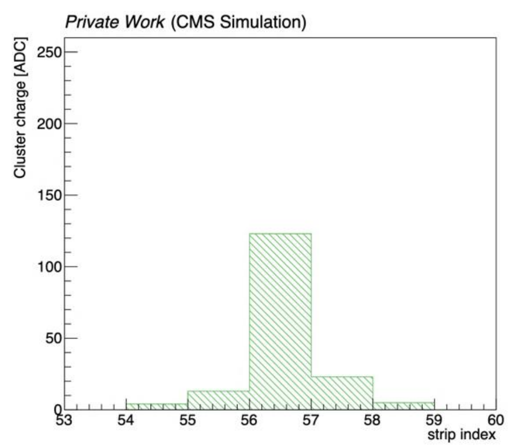
$$-\frac{dE}{dx} \propto \frac{1}{\beta^2} \xrightarrow{\beta < 1} \textbf{Highly ionizing particles}$$

Saturated charge deposits

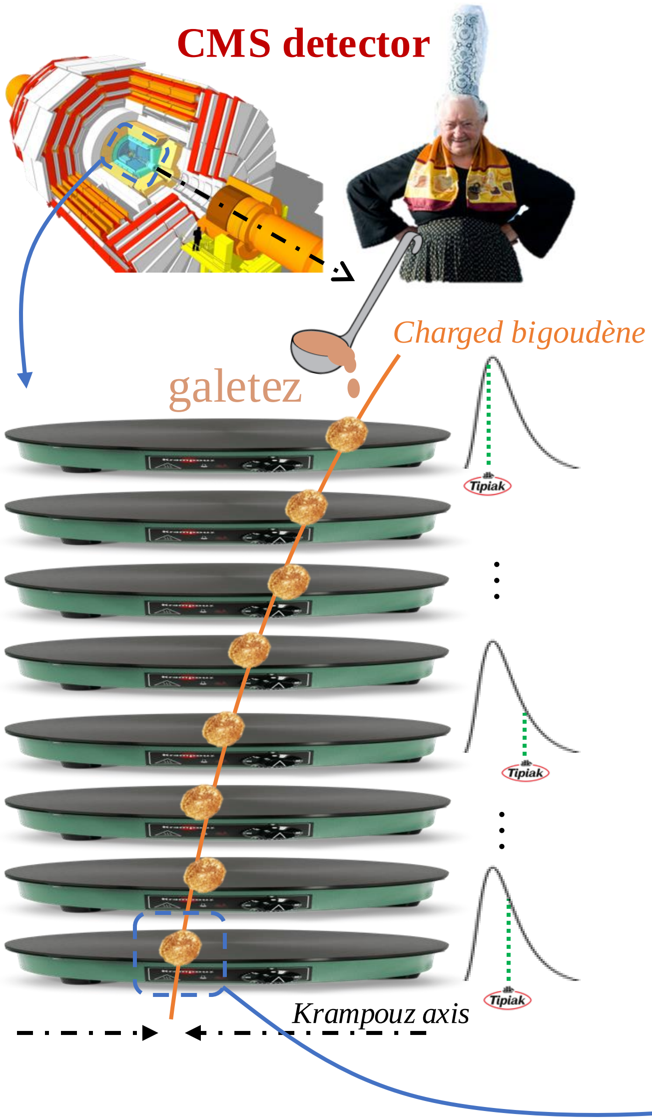


- The charge c_i deposited in a module layer i follows a **Landau distribution**.
- The charge c_i spreads out several strips in the module.
  → **cross-talk**
- The value for the charge in each strip is then converted to a numeric value between 0 and 255 ADC.

Example of a charge deposit



Saturated charge deposits



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  → **cross-talk**
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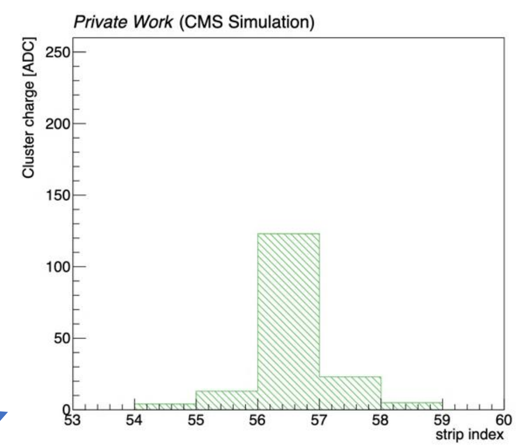
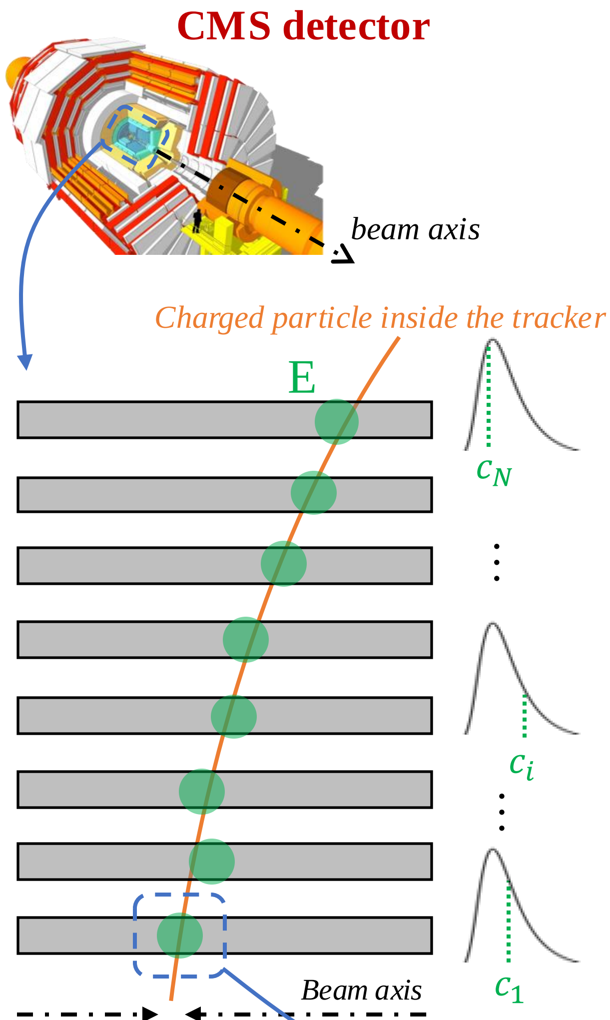
Example of a galetez deposit



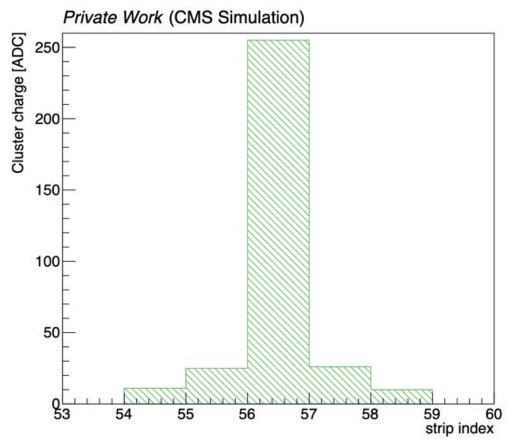
Saturated charge deposits



But when the collected charge c_i is too important in a strip (Landau tail, low speed regime, multiple charge deposits, ...), the strip is **saturated** (**> 255 ADC**).

→ One can not know the actual value of the charge.

Example of a saturated charge deposit

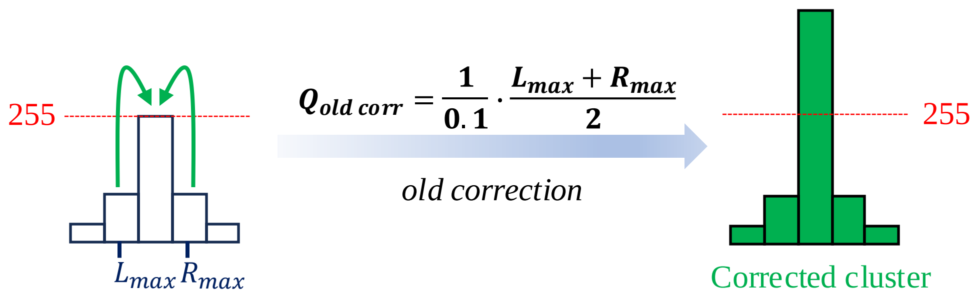


Saturated charge deposits

High charge deposits saturate the electronics and create a **bias on the charge reconstruction**:
∼ **9 %** of clusters are **saturated in data** instead of almost **50 % for MC gluino samples**.

- The HSCPs analysis is based on energy deposit measurements.
→ The key is to recover the charge information on the strips modules for every clusters based only on neighbours information to reconstruct the initial charge.

My correction is **based on an existing version** (labelled *old correction*) that is good but not optimal on the fraction of the corrected cluster by the method. The correction is a **cross-talk inversion** by assuming the charges of the adjacent strips correspond to 10% of the total deposit.

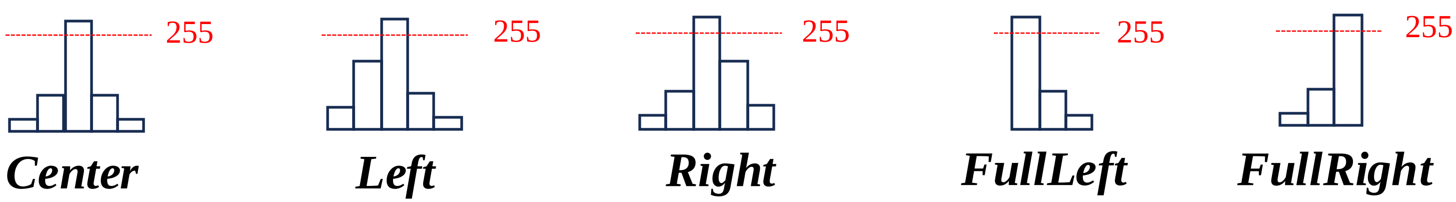


Saturated charge deposits – new algorithm developed

Based on three steps

1. Clusters selection: **size greater than 2** with a **single saturated strip**.

2. Clusters **classified according to their shape**:
   - If adjacent strips similar in size → ***Center***
   - If adjacent strips ratio differs by at least 10 % → ***Left*** or ***Right*** (depends on the ratio)
   - If max on the edge of the cluster → ***FullLeft*** or ***FullRight***

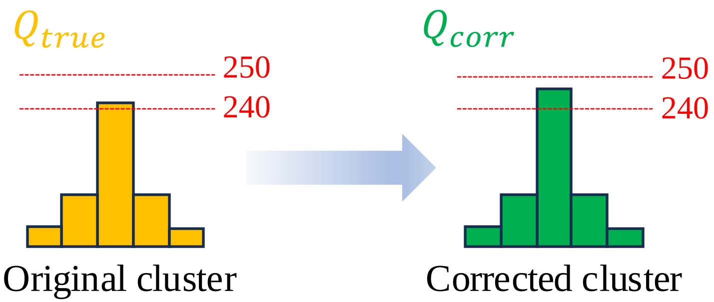


Shape classification ⟹ ***more clusters are corrected***

3. Appropriate correction of the maximum:
   - As a **function of the shape**.
   - As a **function of the tracker layer**.

Tested on clusters with the maximum between 240 and 250 ADC to evaluate the reconstruction efficiency

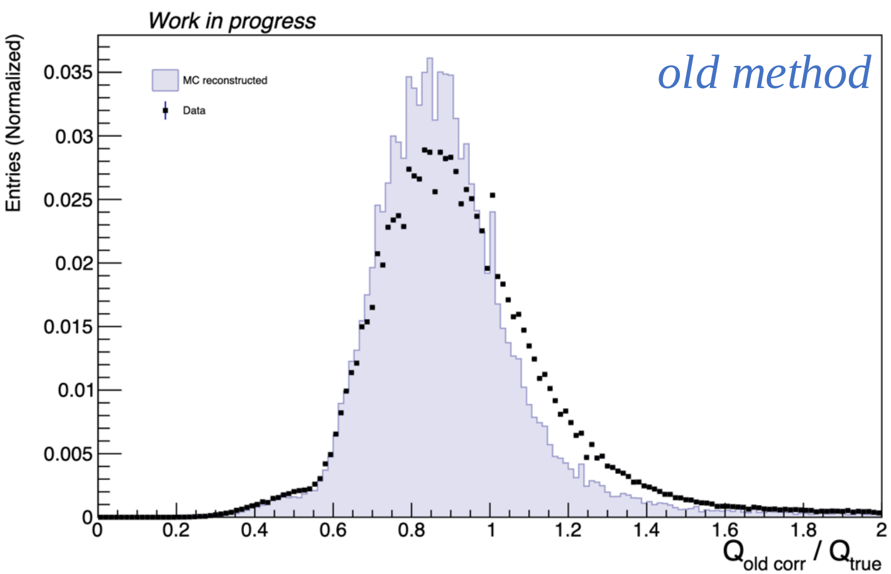
Saturated charge deposits – Validation

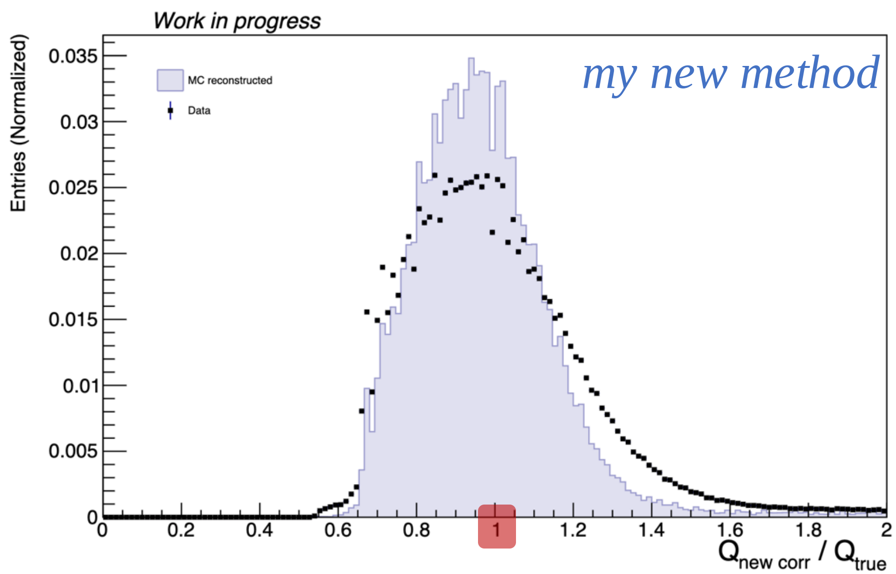


$Q_{old\ corr}$: corrected charge with the original algorithm

$Q_{new\ corr}$: corrected charge with the new algorithm

Q_{true}: actual total charge of the cluster





- Old correction: **biased**, assume a symmetric cluster shape (fixed correction factor).
- New correction: **correction applied for a larger fraction of clusters**, **less biased**, **adapted to the cluster shape**.

Saturated charge deposits – Validation

$Q_{old\ corr}$: corrected charge with the original algorithm

$Q_{new\ corr}$: corrected charge with the new algorithm

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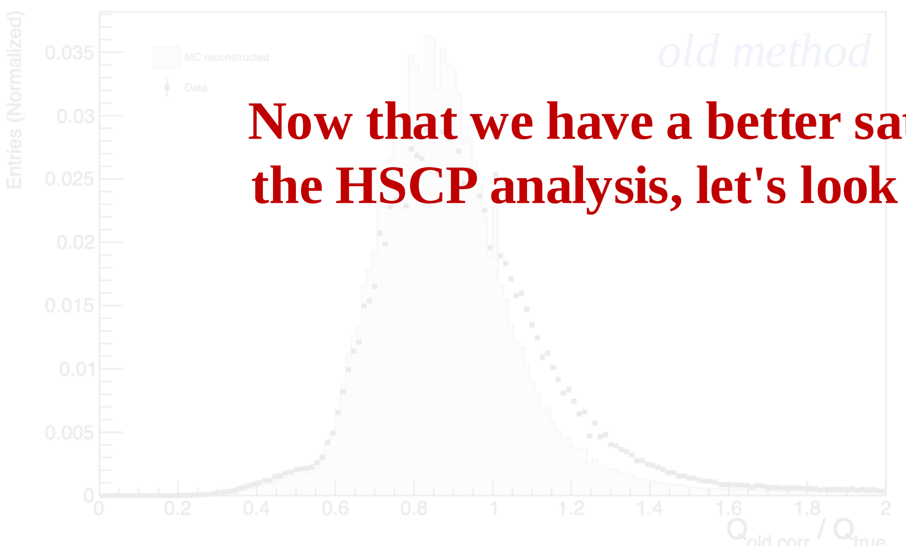
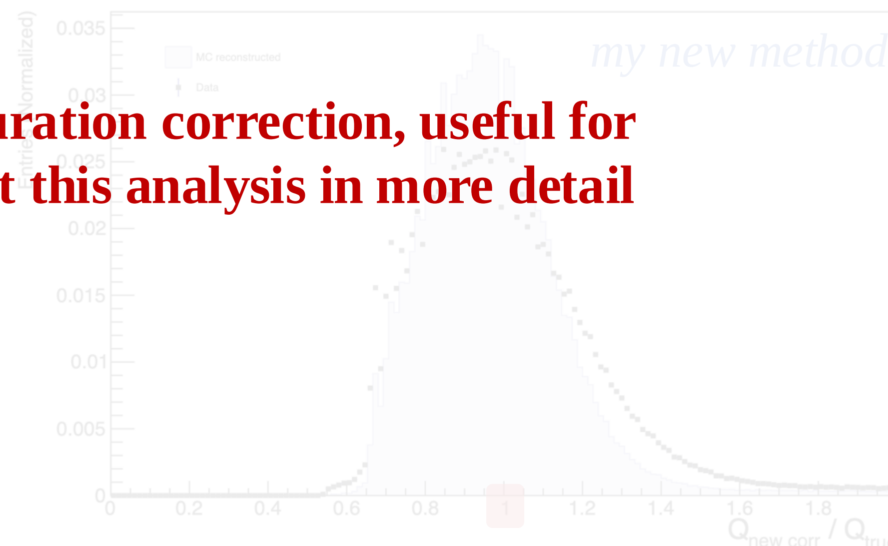




Now that we have a better saturation correction, useful for the HSCP analysis, let's look at this analysis in more detail

- <u>Old correction</u>: **biased**, assume a symmetric cluster shape (fixed correction factor).
- <u>New correction</u>: **correction applied for a larger fraction of clusters, less biased, adapted to the cluster shape**.

HSCP Search – Key steps

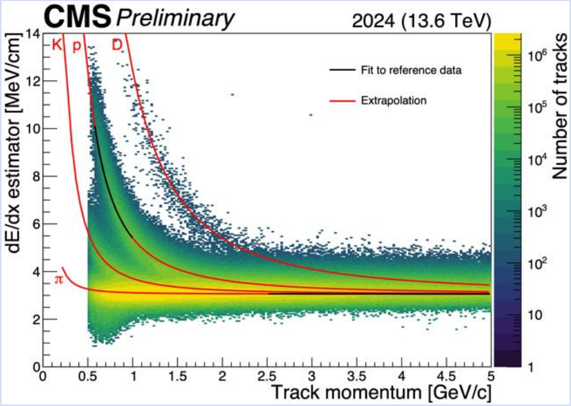
1. Trigger

Select interesting events

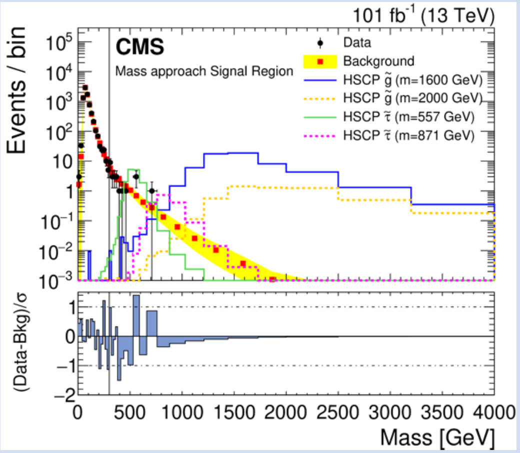
2. Selections

Select good HSCPs candidates

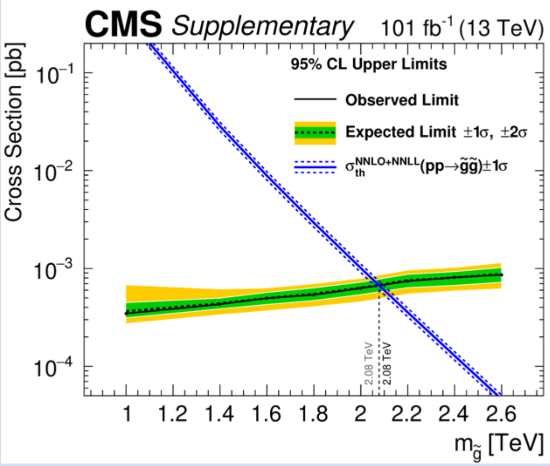
3. Calibration



4. Background estimation



5. Limits computation



HSCP Search – Trigger

1. Trigger

Select interesting events

All events are selected by a trigger **requiring the reconstruction of a muon** with transverse momentum $p_T > 50$ GeV.

→More efficient for **lepton-like HSCPs** than for **R-hadron HSCPs**

LHC 2017-2018

- proton-proton collision at 13 TeV
- Integrated luminosity: 101 fb^{-1}

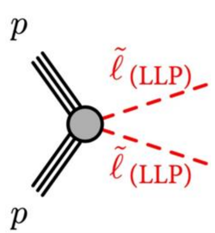
→ ~10^{14} collisions

↓

Estimated gluino production

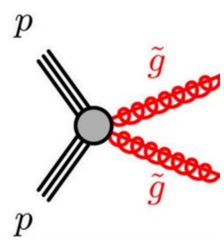
- $\sigma_{pp\to\tilde{g}\tilde{g}(m=1.8\ \mathrm{TeV})} \approx 1.2$ fb

→ 1.2 x 101 ~ 120 gluino



Long-Lived stau

$0.7 < \varepsilon_{trigger} < 0.9$



Long-Lived gluino R-Hadron

$0.07 < \varepsilon_{trigger} < 0.19$

HSCP Search – Trigger

1. Trigger

Select interesting events

LHC 2017-2018

- proton-proton collision at 13 TeV
- Integrated luminosity: 101 fb^{-1}

→ ~10^{14} collisions

↓

Estimated gluino production

- $\sigma_{pp\to\tilde{g}\tilde{g}(m=1.8\ \text{TeV})} \approx 1.2$ fb

→ 1.2 x 101 ~ 120 gluino

Why such low selection efficiency for R-hadrons HSCPs?

- Gluinos are produced by pairs and can hadronize into **charged** or **neutral** hadrons.
- What if one is **neutral** and the other one **charged** ?

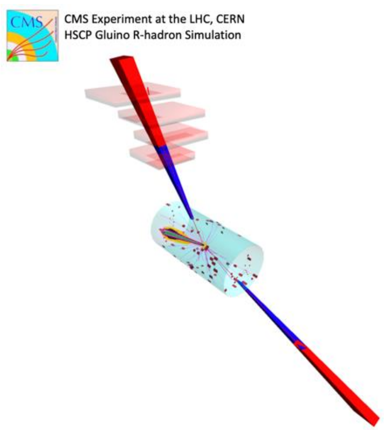
→ The neutral particle can not be directly detected, but one can know when there is **missing energy** in the **transverse** plane.

We call that **MET**.

↓

neutral R-hadrons leave no signal

→ **HSCP not triggered by the muon trigger**



HSCP Search – Selections

2. Selections

Select good HSCPs candidates

Goal: **skimming background**

Selection	*data*	$\tilde{g}$ (m = 1.8 TeV)	pair $\tilde{\tau}$ (m = 557 GeV)
	100 %	**100 %**	**100 %**
Events passing the muon Trigger	**15 %**	**11 %**	**86 %**
Track in the central region of the tracker ($|\eta| < 1$) with high p_T			
Track well reconstructed and with large number of hits (with good dE/dx measurements)			
Track isolated to ensure a clean environment	**1.1 %**	**6.4 %**	**60 %**

mostly due to the muon trigger

HSCP Search – Calibration

3. Calibration

Method to reconstruct the mass

HSCPs deposit a small portion of there energy as they go through tracker modules: one deposit per module passed through.

→ Energy estimate per unit of length for a track crossing N modules ?

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

Importance of my saturation correction method

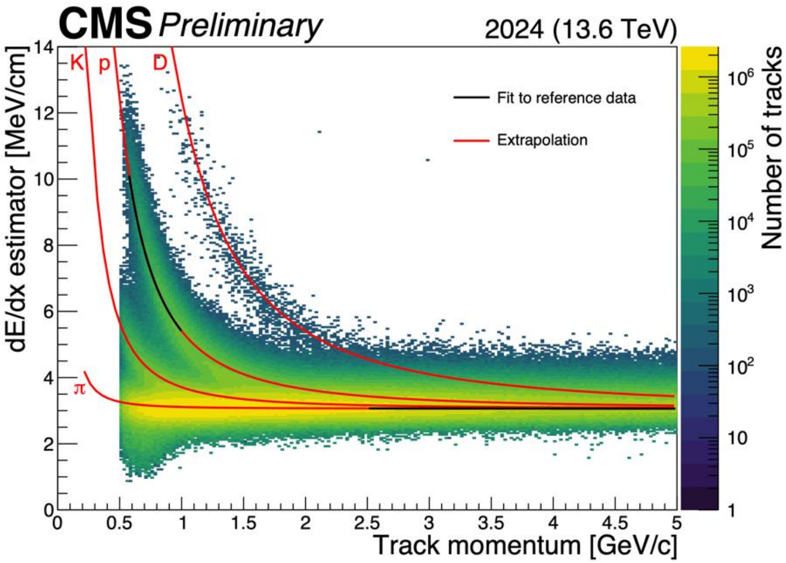
At the first order:

$$\boldsymbol{I_h = \frac{K}{(\beta\gamma)^2} + C = K\left(\frac{p}{m}\right)^2 + C}$$

→ Solve for the mass:

$$\boldsymbol{m = p\sqrt{\frac{I_h - C}{K}}}$$

K and ***C*** are determined using low momentum $\pi^{\pm}, K^{\pm}, p^{\pm}, \ldots$ as standard candles.



https://cds.cern.ch/record/2916532

HSCP Search – Background estimation

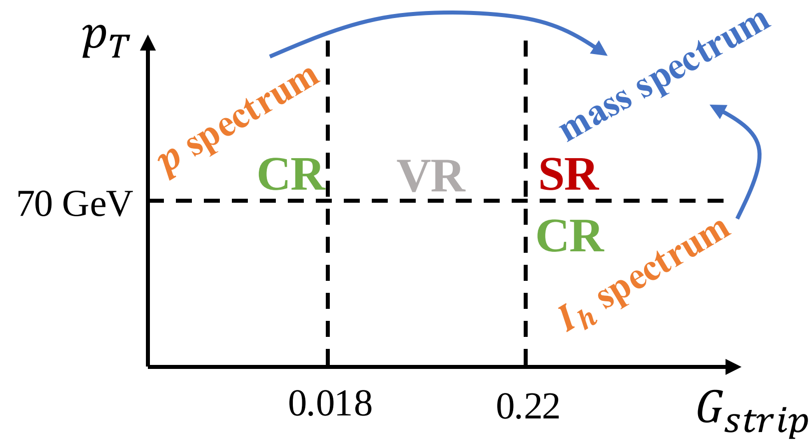
4. Background estimation

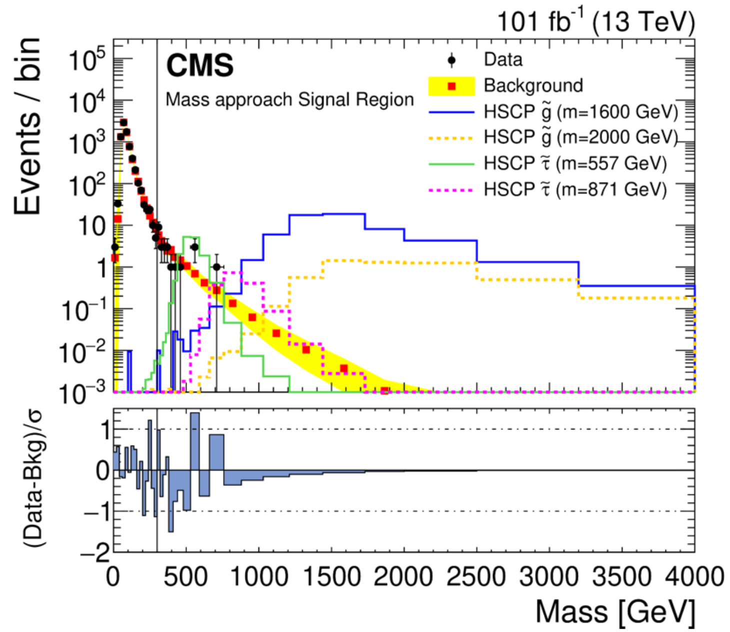
Mix Control Regions data to build mass templates

- In the background, the momentum and ionization should be uncorrelated.
- Mix and match **momentum** and I_h values from different **Control Regions** to create a **mass template** in the **Search Region**.
- **Validate** in intermediate ionization **region**.

Need for a dE/dx *discriminator* : G_{strip}
→ *Compatibility for a track with the MIP hypothesis (MIP = Minimum Ionising Particle)*

MIP Background → 0 and Signal → 1





arXiv:2410.09164

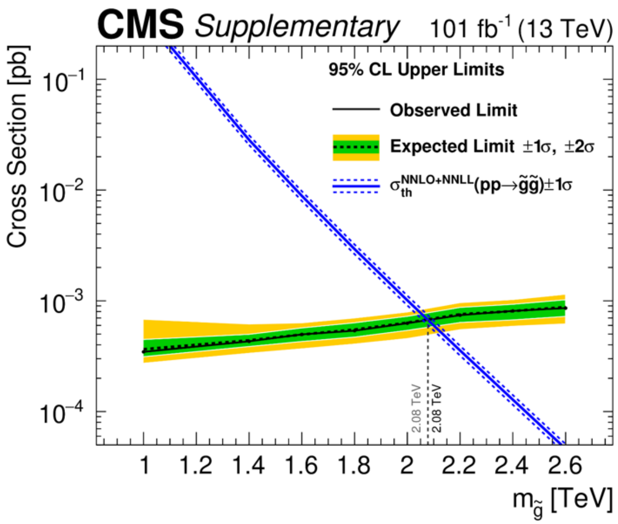
HSCP Search – Limits computation

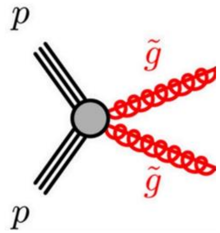
5. Limits computation

Determine model limits based on the results

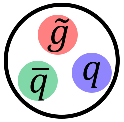
So far: **no excess found**, meaning good agreement with Standard Model expectation.

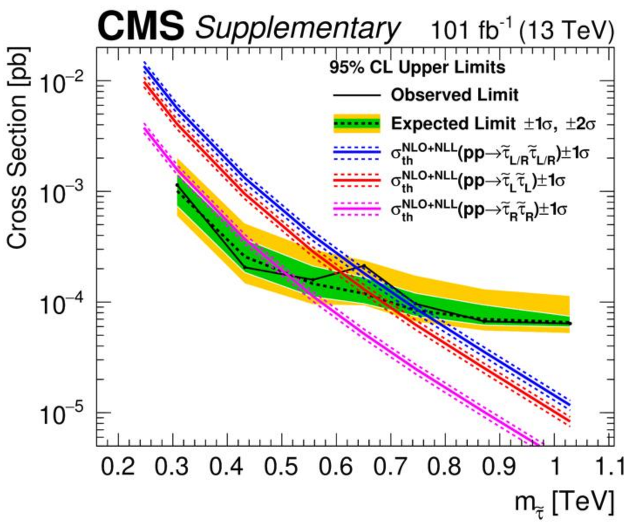
Expected and Observed **limits** are extracted and compared to theoretical predictions.

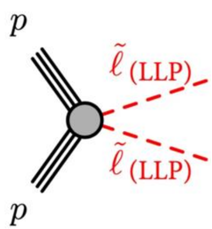




Long-Lived gluino R-Hadron







Long-Lived stau

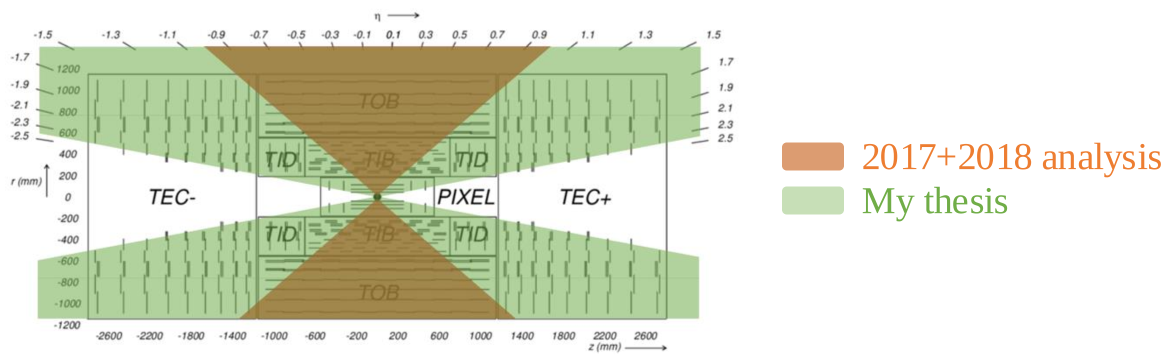
[arXiv:2410.09164](https://arxiv.org/abs/2410.09164)

HSCP Search – Perspectives

So far the search is limited by statistics input, we **need more data**. The next analysis can be improved by considering:

- A **new method to correct saturation** (my algorithm)

- Increase in **eta acceptance**: no more focus on the central region of tracker.



→ Different geometry leads to new G_{strip} templates to be derived

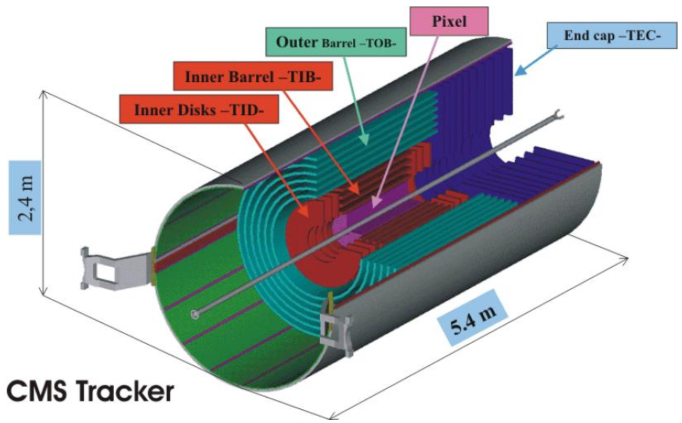
- Considering **MET triggers**: increase signal acceptance on hadron-like HSCP.

  → First studies show a selection of about ∼40 % with MET triggers instead of ∼15 % with a muon trigger.

My thesis: Run 2 (2017 + 2018) MET trigger + partial Run 3 (2022 + 2023) MET trigger

BACKUP

BACKUP 1 – CMS tracker



Layer	Type	#Strips	Thickness [μm]	Pitch [μm]	Geometry label
TIB L1	stereo	768	320	80	IB1
TIB L2	stereo	768	320	80	IB1
TIB L3	mono	512	320	120	IB2
TIB L4	mono	512	320	120	IB2
TOB L1	stereo	768/512	500	122/183	OB2
TOB L2	stereo	768/512	500	122/183	OB2
TOB L3	mono	512	500	183	OB2
TOB L4	mono	512	500	183	OB2
TOB L5	mono	768	500	122	OB1
TOB L6	mono	768	500	122	OB1
TID R1	stereo	768	320	81...112	W1a
TID R2	stereo	768	320	113...143	W2a
TID R3	mono	512	320	124...158	W3a
TEC R1	stereo	768	320	81...112	W1b
TEC R2	stereo	768	320	113...143	W2b
TEC R3	mono	512	320	124...158	W3b
TEC R4	mono	512	320	113...139	W4
TEC R5	stereo	768	500	126...156	W5
TEC R6	mono	512	500	163...205	W6
TEC R7	mono	512	500	140...172	W7

Radius of curvature

Magnetic field B of **3.8 T** along the beam axis to reconstruct the transverse momentum p_T of charged particles.

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

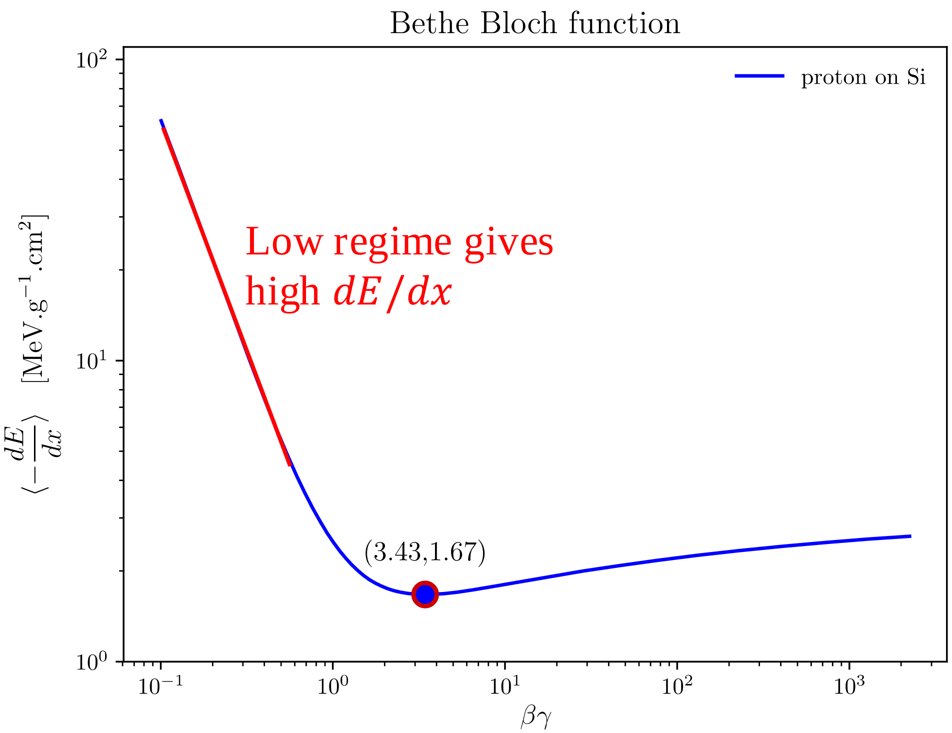
Algebric charge

BACKUP 2 – Bethe-Bloch formula

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

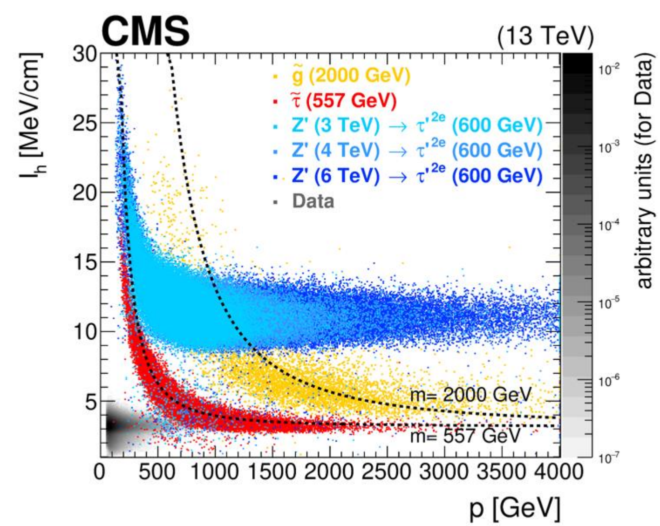
$$\beta = \frac{v}{c} \qquad \gamma = \frac{1}{\sqrt{1-\beta^2}}$$

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



K : constant
z : number of charge of the particle
A : atomic number of the material crossed
Z : mass number of the material crossed
$\boldsymbol{W_{max}}$: maximum of energy transferred in a single collision
I : mean excitation energy of the material
δ : ultra-relativist correction

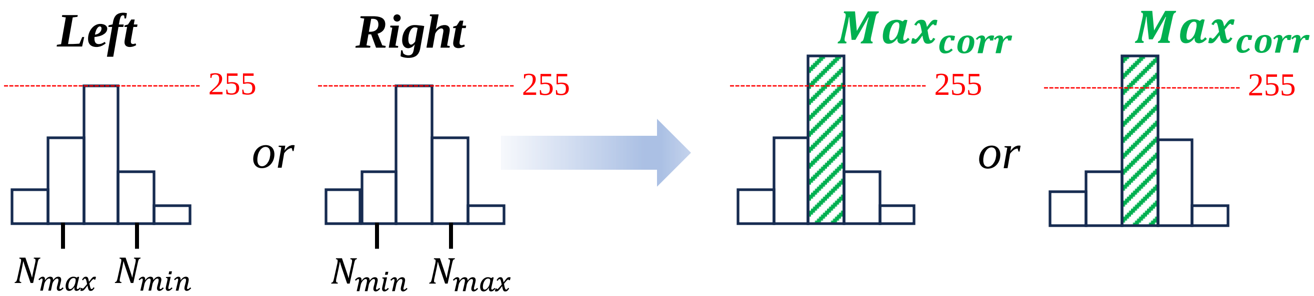
MC HSCPs



BACKUP 3 – Saturation correction for *Left* and *Right* clusters

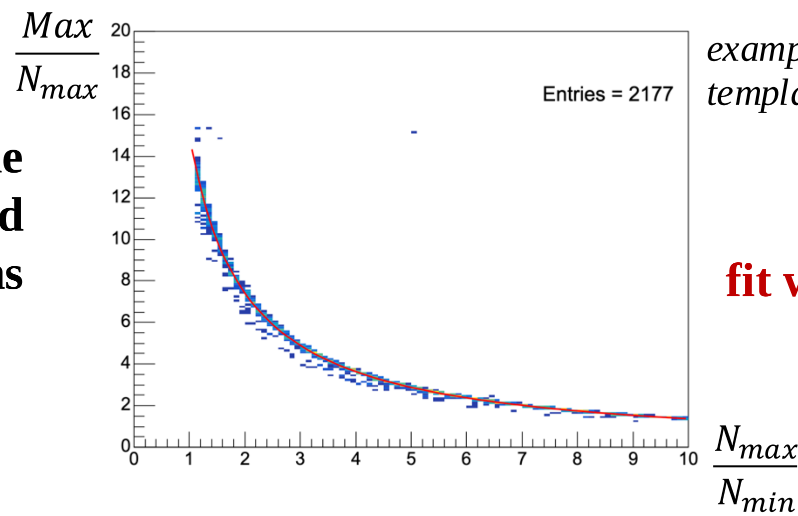
- If ***Left*** or ***Right***: cross-talk inversion using **both neighbours**

$$\boldsymbol{Max_{corr} = a \cdot N_{max} + b \cdot N_{min}}$$



Values of $\boldsymbol{a}$ and $\boldsymbol{b}$ are then computed on upstream cross-talk templates established for each tracker layer:

Templates established with the collection of simulated deposited charge with no other perturbations (with maximum above 255 ADC).



example of a ***Left+Right*** *template in TEC R2*

fit with $\boldsymbol{y = a + \frac{b}{x}}$