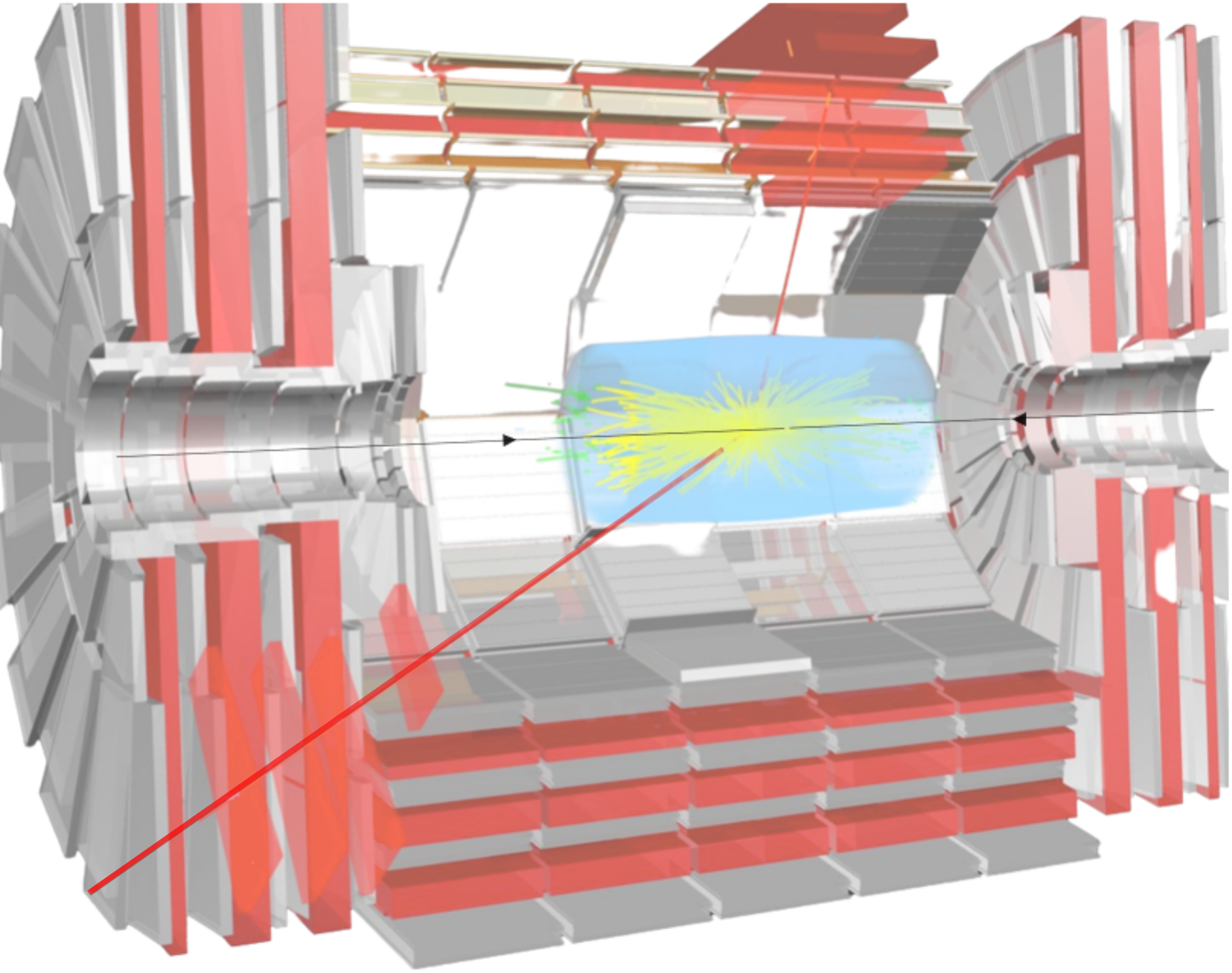


CMS Detector — Muon : long-lived particle

Search for **new** heavy stable charged particles with the CMS experiment

Haeberle Raphael

Under the supervision of
Eric CHABERT

Tuesday 25th October 2022

Physical Motivation

Split-SUSY

- Super-symmetry -> each particle of the SM has an associated super-partner (spin symmetry)
- Many supersymmetric theories : focus on **Split**-SUSY
- In **Split**-SUSY, fermions partners have very high masses, whereas bosons partners very low

Split-SUSY

- Predicts the existence of **new** particles
- The observation of those particles will depend on
  - *Their lifetime*
  - *Their masses*
  - *Their decay modes*

$$d = \beta * \gamma * \tau * c$$

d : pathlength
τ : lifetime
γ : relativistic factor
c : celerity
β : relativistic factor

Physical Motivation

One candidate

- Study is focused on the **gluino g̃** (supersymmetric partner of the gluon, gauge boson of the strong interaction)

- **Long-lived** gluinos predicted

  (up to 100s)

- Not observed yet, mass limits have been determined by CMS previously :

  $\mathbf{M_{gluino} > 1.4\ TeV}$

Multiple searches

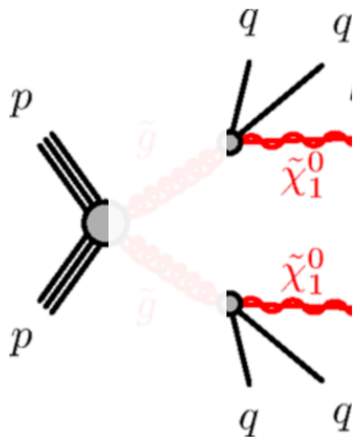
Prompt searches

- If the particle decays we **can** detect its decay products

- Search was done and no discovery yet

<u>What we see in the detector</u>

Invisible particles (neutral)
+ jets



Physical Motivation

One candidate

- Study is focused on the **gluino g̃** (supersymmetric partner of the gluon, gauge boson of the strong interaction)

- **Long-lived** gluinos predicted

  (up to 100s)

- Not observed yet, mass limits have been determined by CMS previously :

  M_{gluino} > 1.4 TeV

Multiple searches

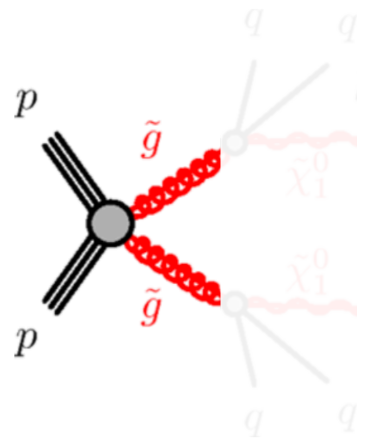
Long-lived Searches

Focus on long-lived

- If the particle is long-lived, it won't decay inside the detector, and we **can't** see its decay products

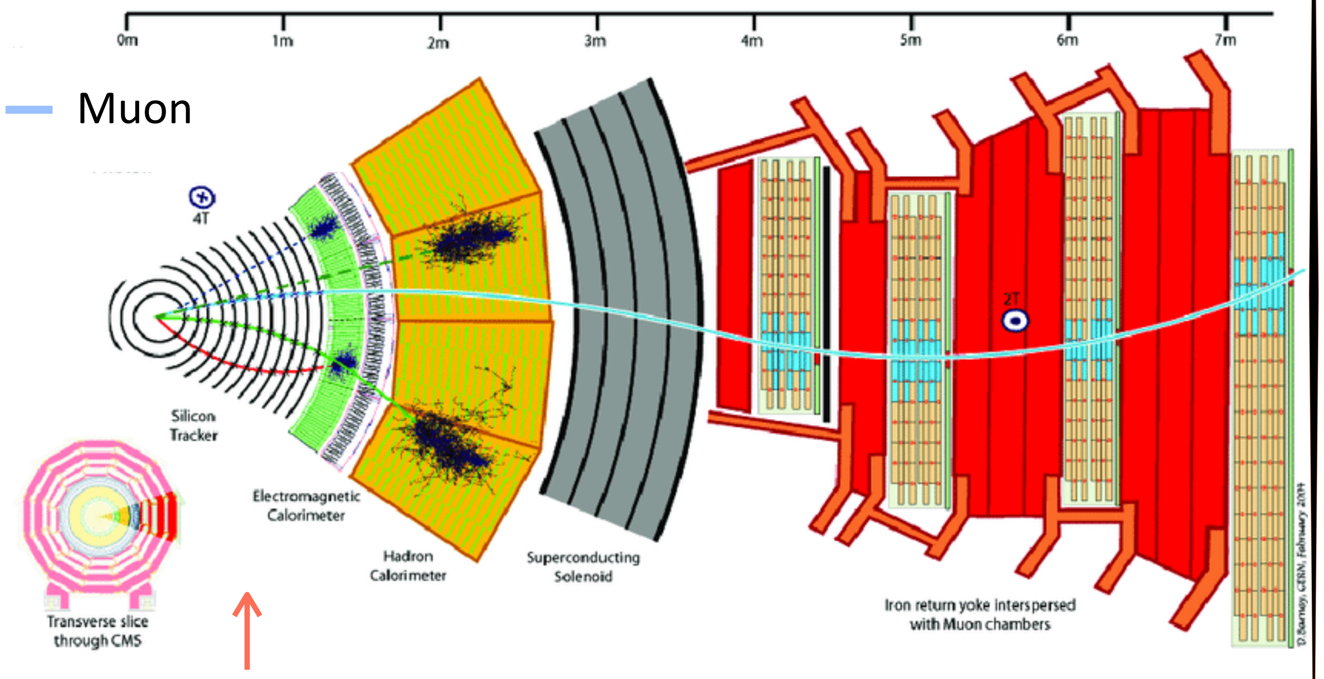
What we see in the detector

No decay
Particle goes through the whole detector



Experimental Signatures

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



Ionization

<u>Stable</u>

- They can decay outside of the detector

cτ > 7m

<u>Heavy</u>

- M_{gluino} **> 1400 GeV**

⇕

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

- *p = momentum*
- *m = mass*
- $\beta = \frac{v}{c}$
- γ *= relativistic factor*

- *Non ultra-relativistic regime induces a delay within the detector* → ***loss of signal***

<u>Charged</u>

- Electromagnetic interactions leave tracks in the detector

$$-\frac{dE}{dx} \approx \frac{1}{\beta^2} \quad \xleftrightarrow{\beta < 1} \quad \text{Highly Ionising Particles}$$

HSCP studies context

HSCP -> Heavy Stable Charged Particles

1 Trigger / Preselection

High quality isolated track

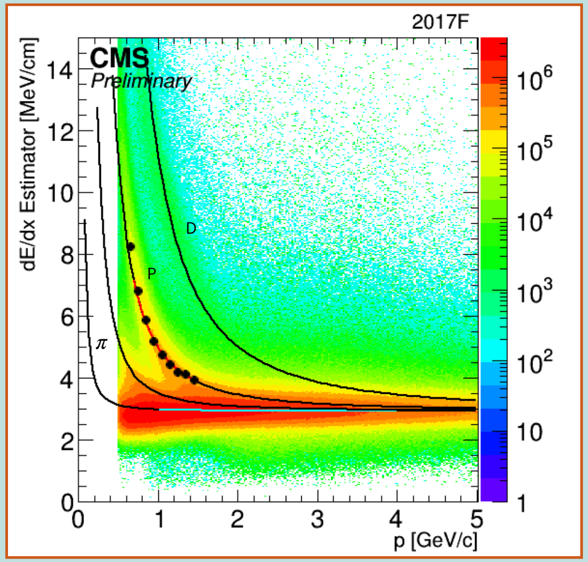
2 Selection

p_T and I_{as} *(Ionization Discriminator)*

3 dE/dx vs P

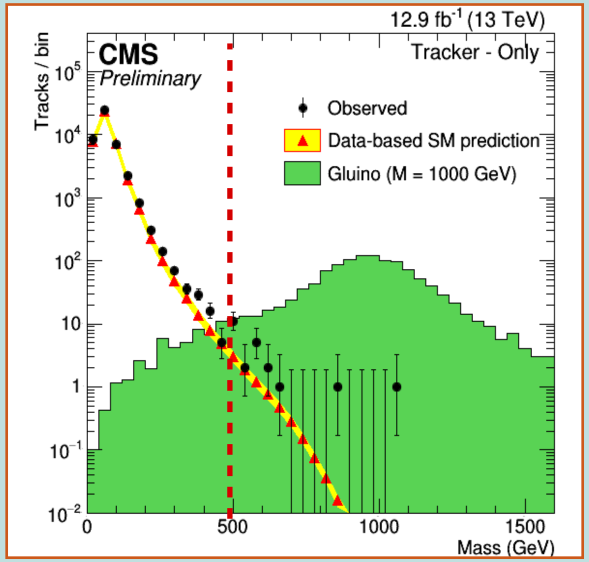
Using Bethe-Bloch Formula

dE/dx estimator I_h

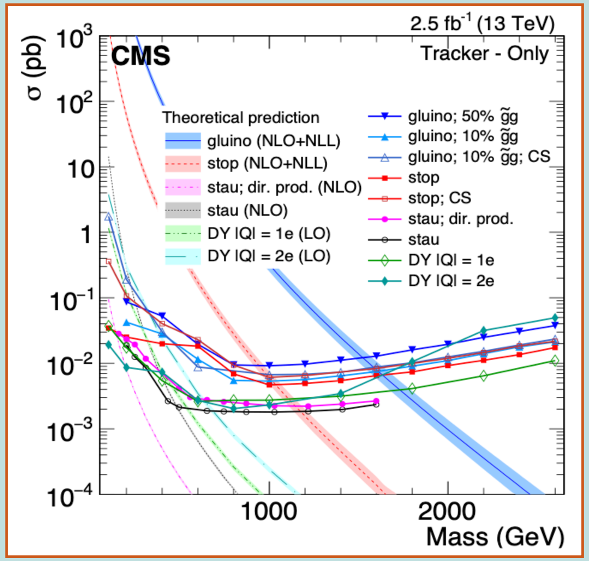


Track momenta

4 Mass Reconstruction



5 Limits computation



Mass Cut

Did we save physics of interest ?

LHC Run II (2015-2018)

- ❑ proton-proton collisions at 13 TeV
- ❑ Cross-section $\sigma_{p\text{-}p}$ = 110 mb
- ❑ Integrated Luminosity : 139 fb^{-1}

Total : ***1.1 x 10^{16} collisions***

Estimated gluino production

- ❑ Cross-section : $\sigma_{pp\to\tilde{g}\tilde{g}(m=2TeV)} \approx$ 1fb

Total ≈ ***150 events***

$$\frac{150}{1.1. * 10^{16}} \approx 10^{-14}$$

2 trigger systems

Level-1 Trigger

Electronic cards
40 MHz → 100 kHz
(0,25%)

Interesting physics
≤ 4 μs

High Level Trigger

Computer farm
100 kHz→ 1000 Hz
(1%)

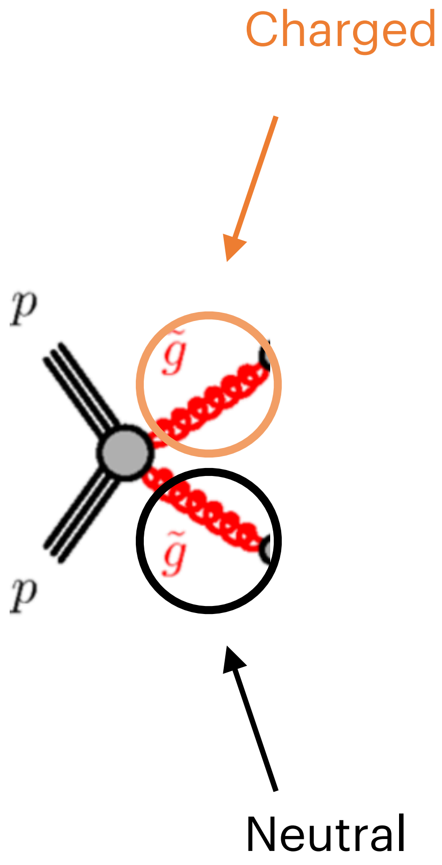
Software track reconstruction
≤ 150 ms

1 barn = 10^{-24} cm^2

Part I

Triggers

Hadronization



- Gluinos can hadronize into **charged** or **neutral** hadrons
- They are produced by pairs (r-parity conservation)
  - 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**

Trigger efficiencies

Efficiency

$$\epsilon_i = \frac{N_i^{selection}}{N^{selection}}$$

Problem : small efficiencies

Pre-selection	**Efficiencies (%)**
IsoMu20	14.7 ± 0.27
Mu50	14.83 ± 0.26
PFMET120	34.06 ± 0.51
PFHT500	11.75 ± 0.27
PFHT1050	10.3 ± 0.41

Private work (CMS simulation)

Correlations

$$C_{ij} = \frac{N_{i\&j}^{selection}}{N_{i\|j}^{selection}}$$

The lower the best

- **Let's assume 2 triggers, A and B :**

If $\mathbf{A_{true}}$ **<=>** $\mathbf{B_{true}}$: A and B are **highly** correlated

- The goal is to improve detection efficiency by having uncorrelated triggers that we can combine (next slide)

  - After correlation study, we will combine those 3 triggers

Mu50, PFMET120, PFHT500

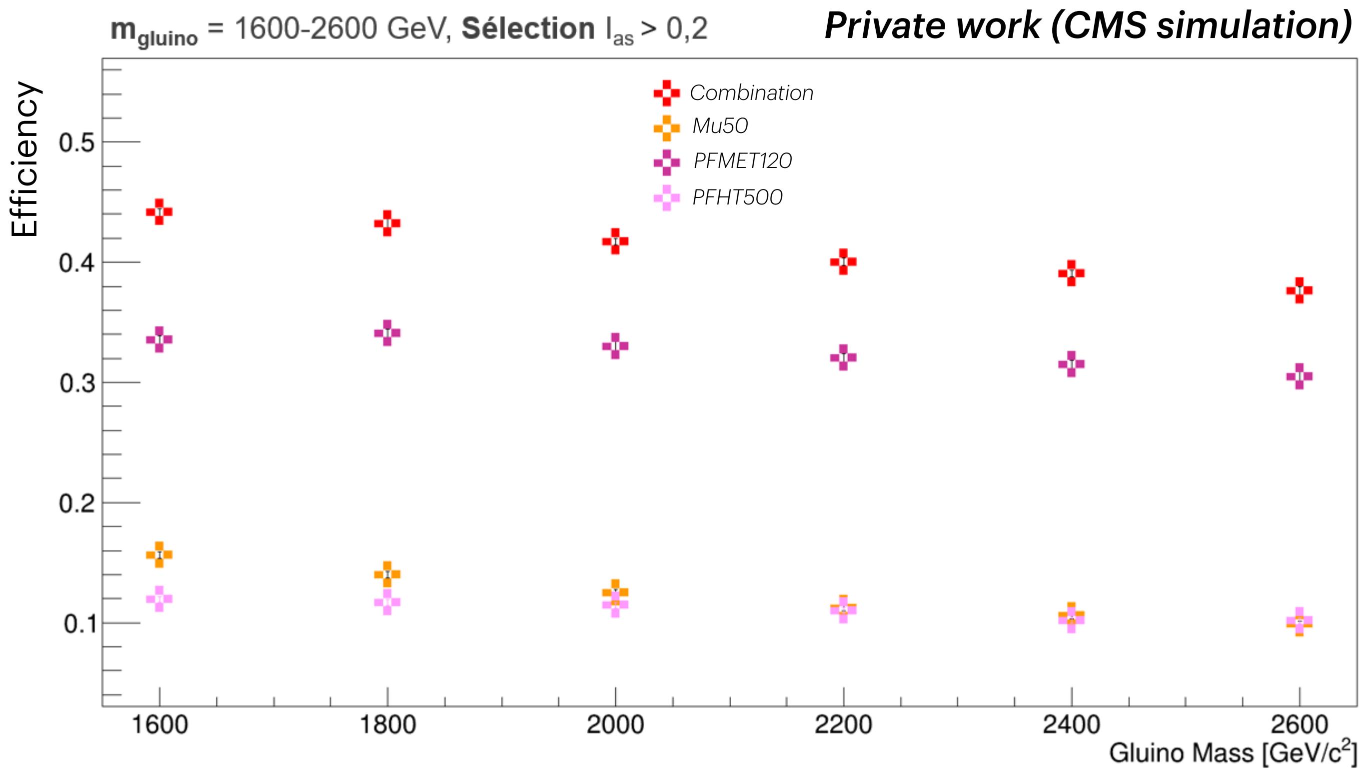
Trigger efficiencies as function of Mass

- Study performed with different selections in I_{as}

Gluino mass (GeV/c²)	Pre-selection	Selection
1800	**49.1 ± 0.4**	**45.1 ± 0.3**

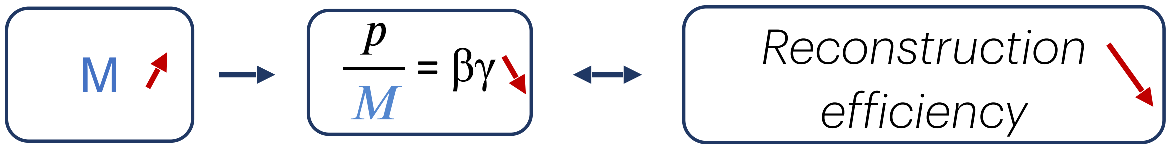
Efficiency of the combined triggers as a function of the selection

- ***Low efficiencies based on muons !***
- ***Higher capacity to get signal via MET triggers***



Combined and raw trigger efficiencies

- Efficiency decreases as the mass increases



Trigger Results

- Observations :
  - Efficiencies are below 35%
  - Efficiencies decrease as mass gets higher

- This study allowed to go from 35 to **45%** efficiency by combining multiple triggers

- What about developing a new trigger at HLT level ?

(Coming next)

Developing a new Trigger for run 3

Since the trigger efficiencies for run 2 are low, the development of a new trigger for run 3 was brought up

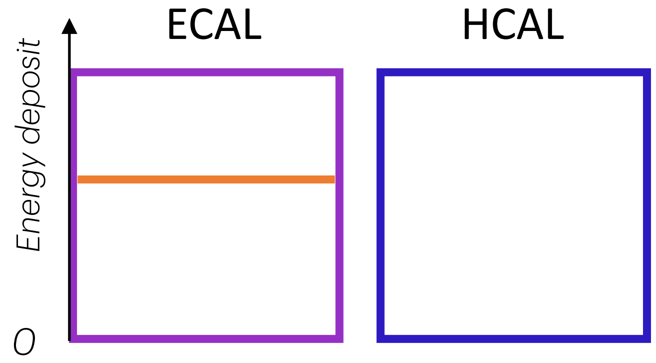
High Level Trigger

Computer farm
100 kHz→ 1000 Hz (1%)
Software track reconstruction
≤ 150 ms

- ❑ Any High Level Trigger : sequence of filters / producers, quick response (150 ms)
- ❑ First filter applied in the HLT has only calorimetric information

Can we identify HSCP using only that ?

Simplistic view of a Calo Tower



2 components : One HCAL and one ECAL part

How do we identify HSCP's ?

Signatures

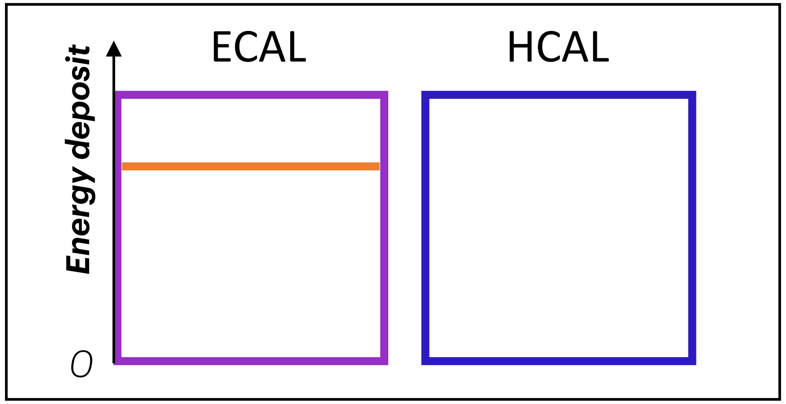
High dE/dx

The energy deposit is higher than a MIP

Electromagnetic interactions

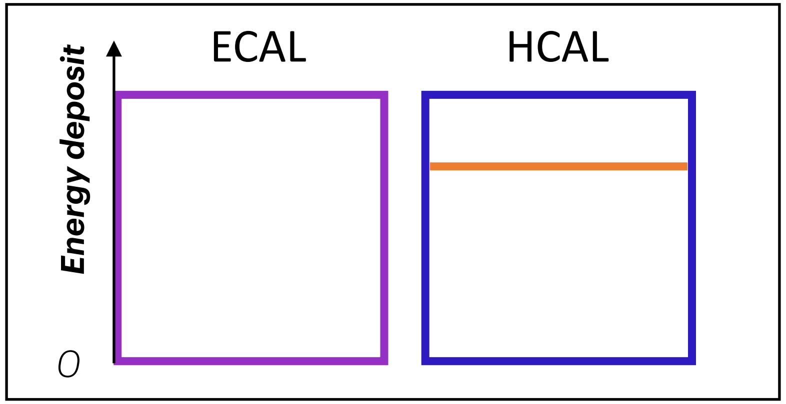
The dE/dx are ~ the same in ECAL and HCAL → *Unique ratio* $\frac{E_{ECAL}}{E_{HCAL}}$

Electrons



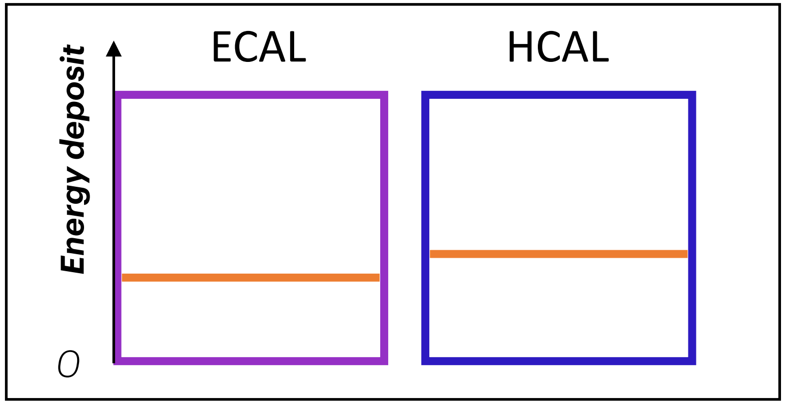
No energy deposit in HCAL

Hadrons



No energy deposit in ECAL

HSCP



Same energy deposit in HCAL and ECAL

Very simplistic view of the filter

Calo Tower based filter

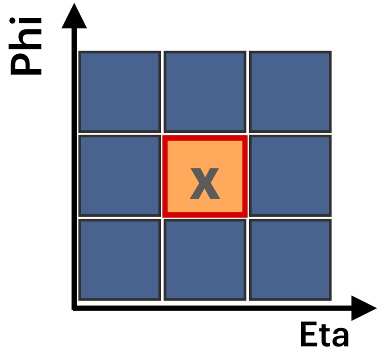
- Find a **seed** **(= tower above thresholds)**

- E_{ECAL} > 2 MIP
- E_{HCAL} > 2 MIP
- (E_{ECAL} + E_{HCAL}) < 10 MIP

seed

$$0 < \frac{E_{ECAL}}{E_{HCAL}} < 0.3$$

Compute an isolation variable based on the **seeds** neighbours



Calo Towers Map

Performances

RUN 2

$$\epsilon^{mtch\ seed}_{hscp} = \frac{N^{HSCP\ presel}_{matched\ seed}}{N^{HSCP\ presel}} = 32.3\ \%$$

RUN 3

$$\epsilon^{mtch\ seed}_{hscp} = \frac{N^{HSCP\ presel}_{matched\ seed}}{N^{HSCP\ presel}} = 31.1\ \%$$

- 30% for the first filter of a trigger means that the whole trigger can be at **BEST** at 30%, this is not very high
- Can be combined to gain efficiency

Part II

Selection

HSCP studies context

HSCP -> Heavy Stable Charged Particles

1 Trigger / Preselection

High quality isolated track

2 Selection

p_T and I_{as} *(Ionization Discriminator)*

3 dE/dx vs P

Using Bethe-Bloch Formula

dE/dx estimator

Ih

Track momenta

4 Mass Reconstruction

5 Limits computation

Mass Cut

Offline Selection

Pre-selection

- *Detectors acceptance*
- *Compatibility between the track and the collision point*

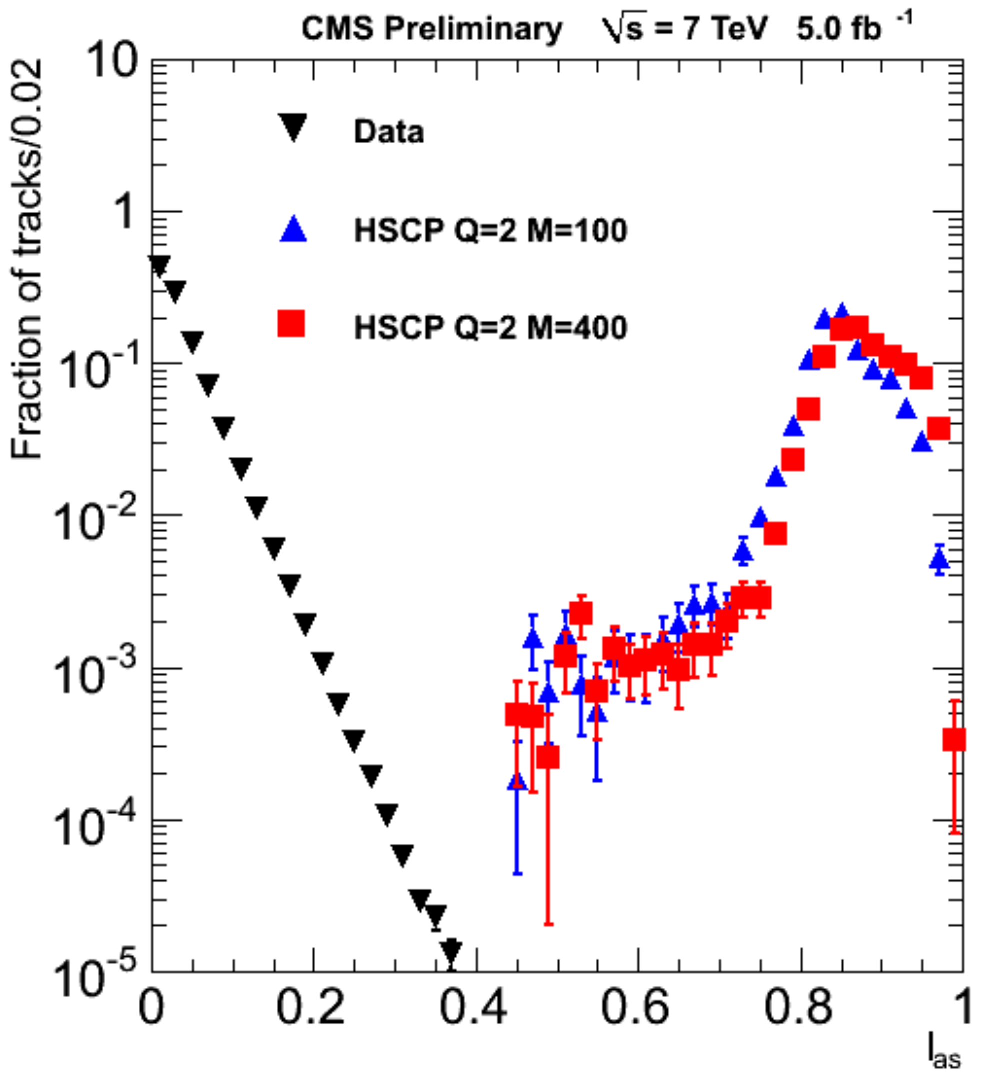
Selection

- **I_{as} > 0.2**

- Ias is a dE/dx discriminator -> Compatibility for a track with the MIP hypothesis

  (MIP = Minimum Ionising Particle)

- It is computed for each track
  - I_{as} c [0,1]
  - MIP : $I_{as} \rightarrow 0$, HSCP : $I_{as} \rightarrow 1$



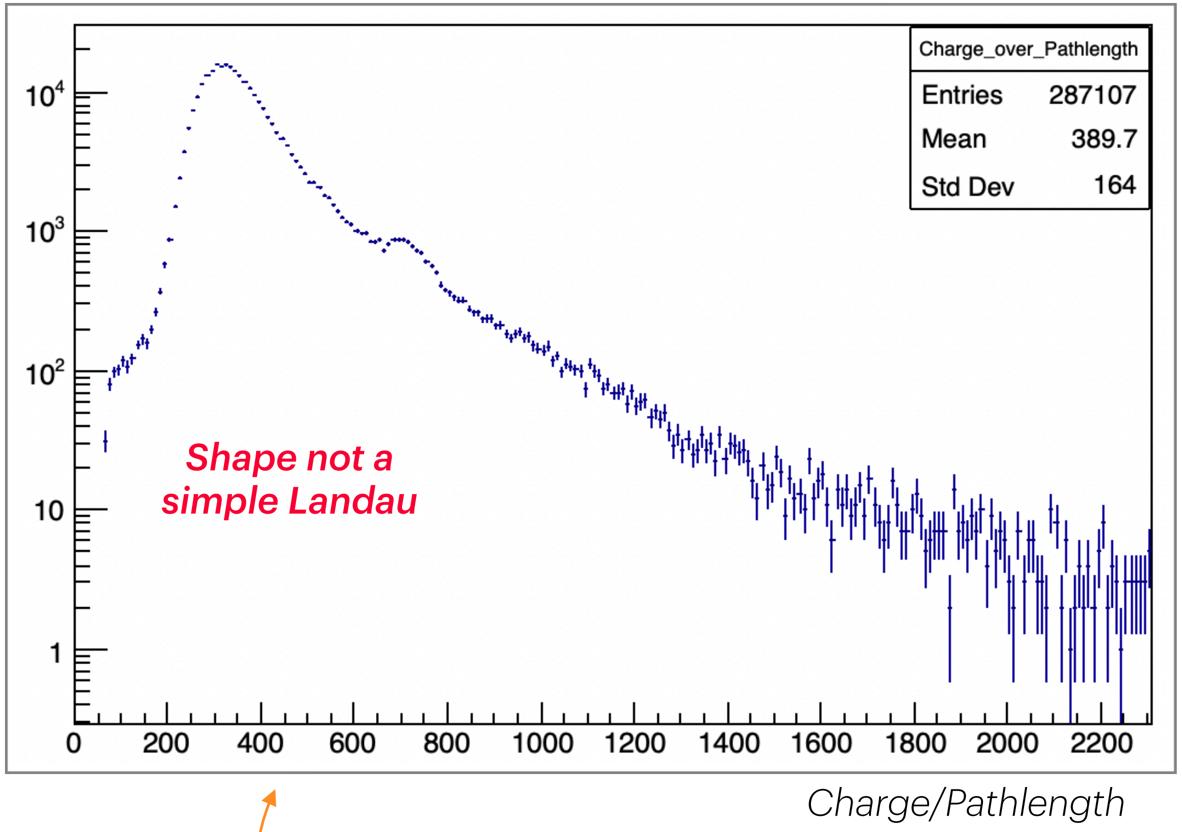
HSCP candidates as a function of d'I_{as}

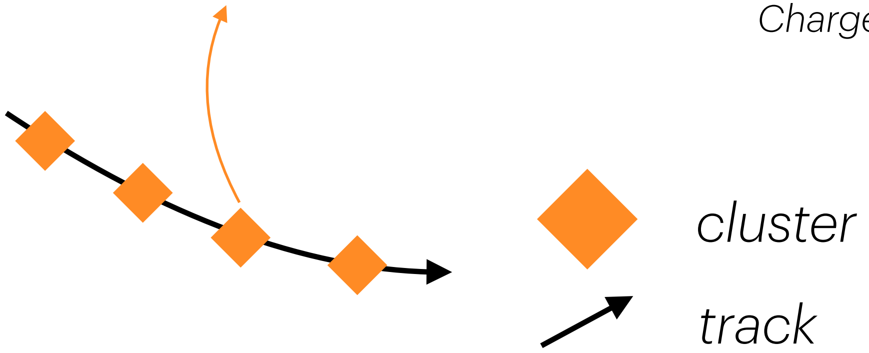
Part III

Ionization Variables

Ionization Variables

For a pathlength = 0.4 mm, given geometry ***Private work (CMS data)***



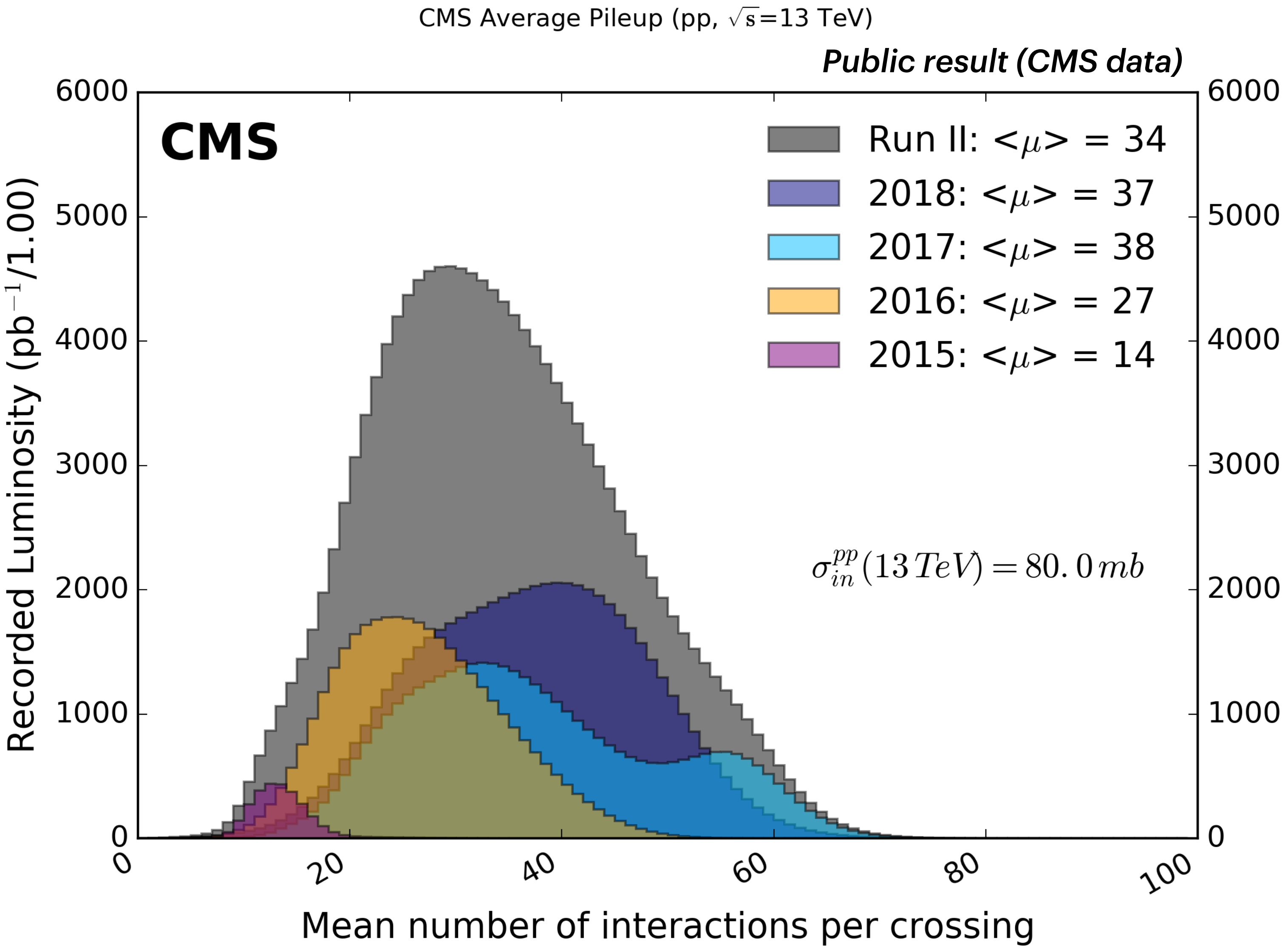


- ❑ I_{as} is based on the combined probability of energy deposit for each clusters

- ❑ Those probabilities are derived from templates (on data)
  - ▸ Depends on pathlength, module geometry etc..

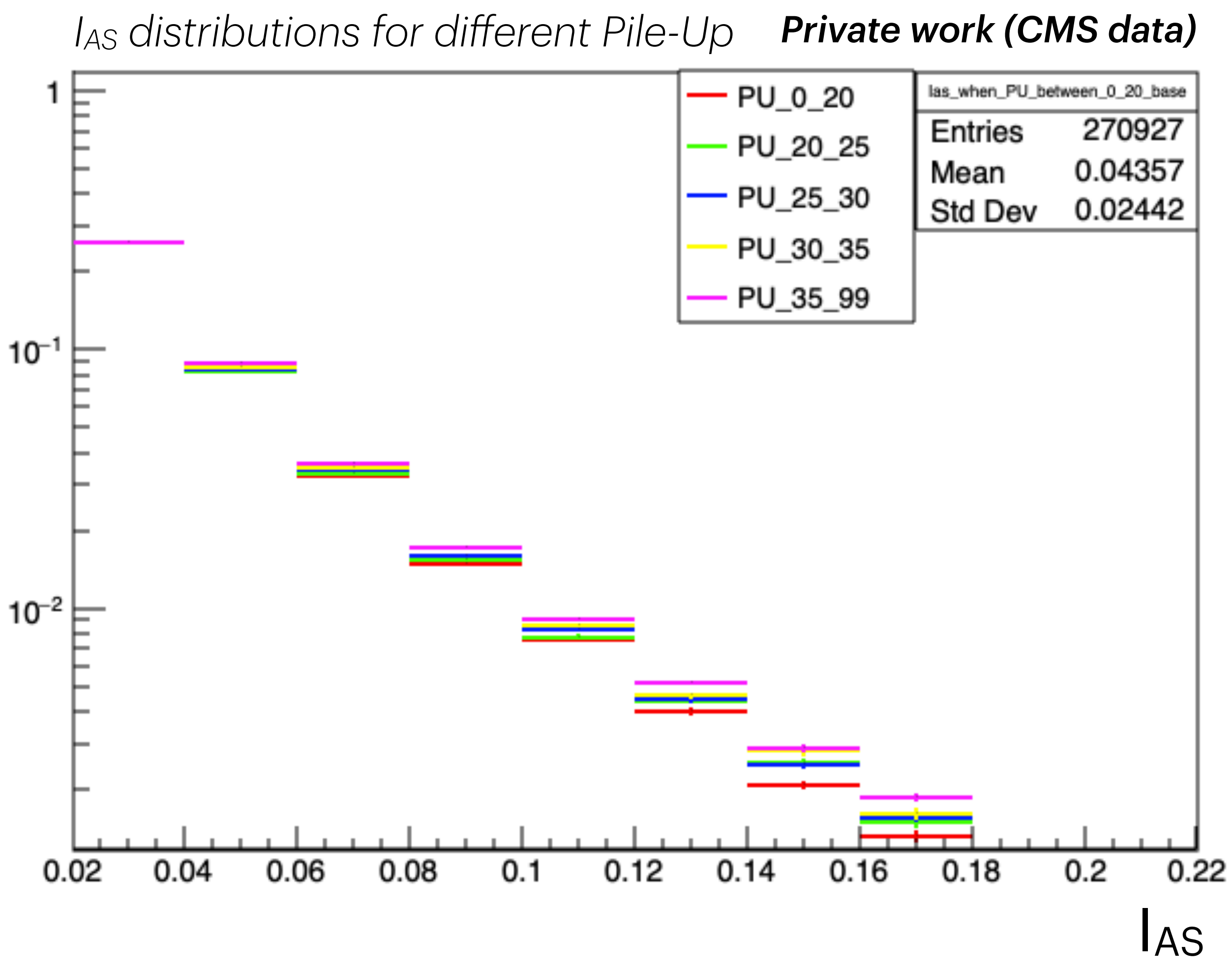
-> ***P***(dx, detector type)

Pile-Up across eras



- ❑ Are Ionization variables ***Pile-up dependent*** ?
- ❑ Pile-up impacts :
  - More fake tracks
  - Worse measurements
- ❑ Those effects can influence our ionization estimation, and thus our signal selection in the end

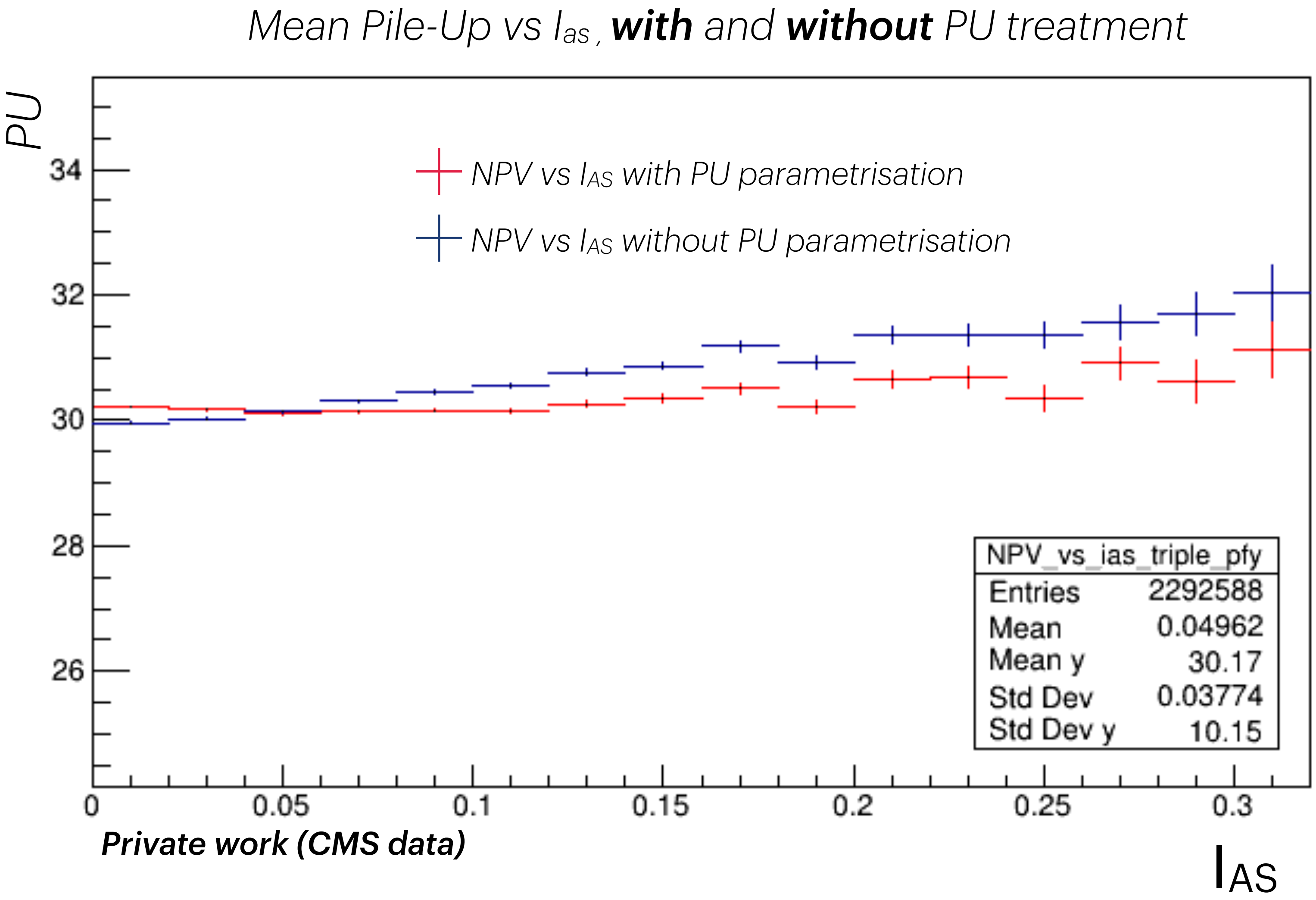
PU Effect on I_{AS} distributions



- We see a Pile-Up effect, the envelope gets wider as I_{AS} grows
- We want to mitigate that effect, and for that we will generate templates for each PU bins

P(dx, detector type) => ***P***(dx, detector type, **Pile-Up**)

PU Effect on I_{AS} distributions

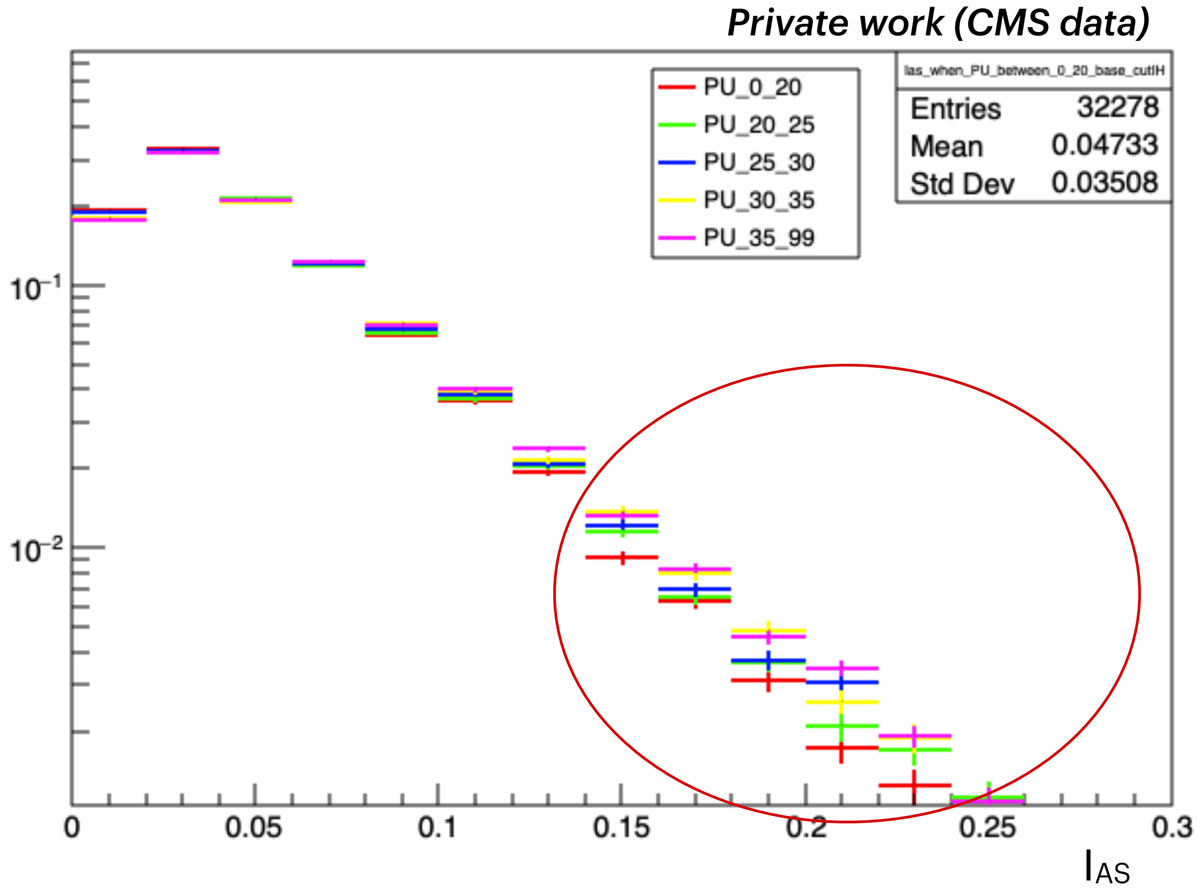


I_{AS} distribution with Pile-Up treatment

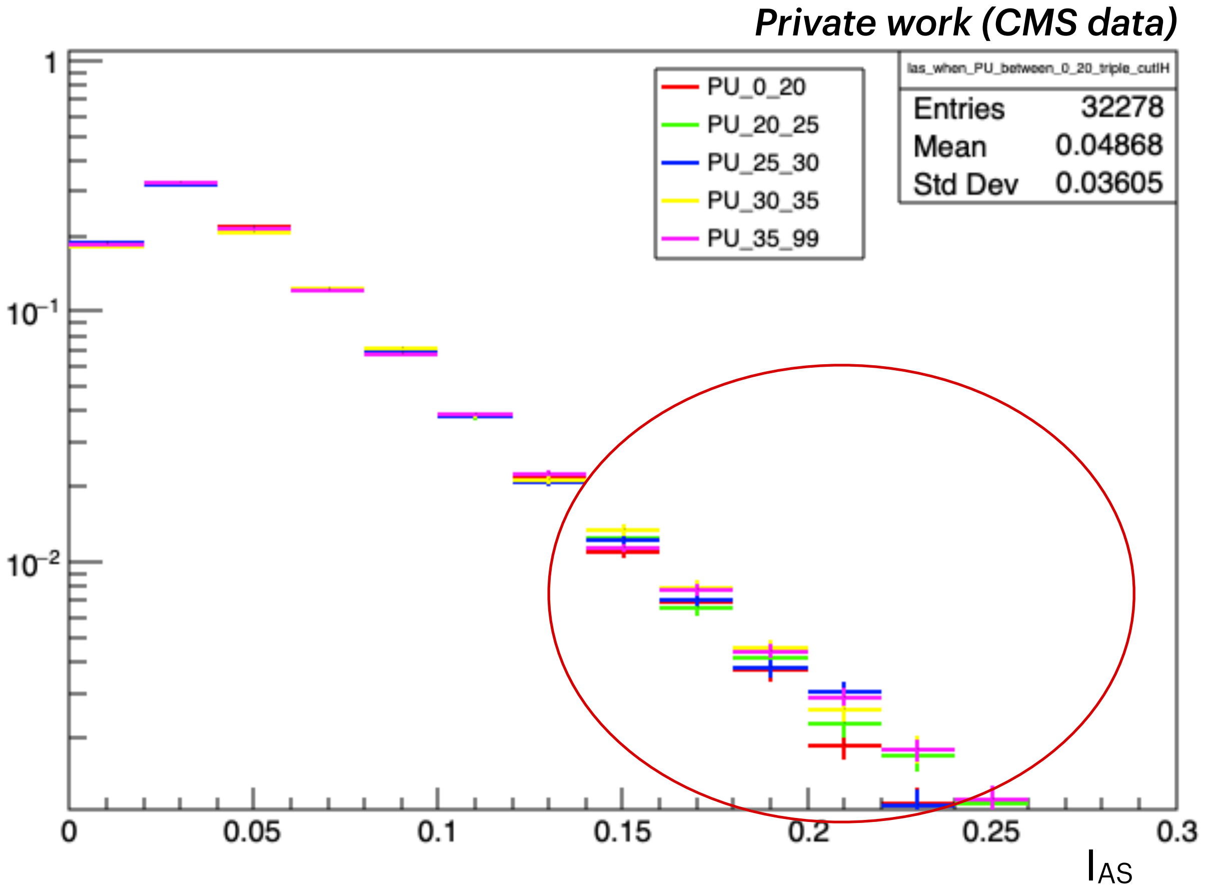
- More stability over the range [0 - 0.2] in I_{AS}
- There is ***still*** a small dependency at higher I_{AS}

PU Effect on I_{AS} distributions

I_{AS} distributions without Pile-Up treatment



I_{AS} distributions with Pile-Up treatment

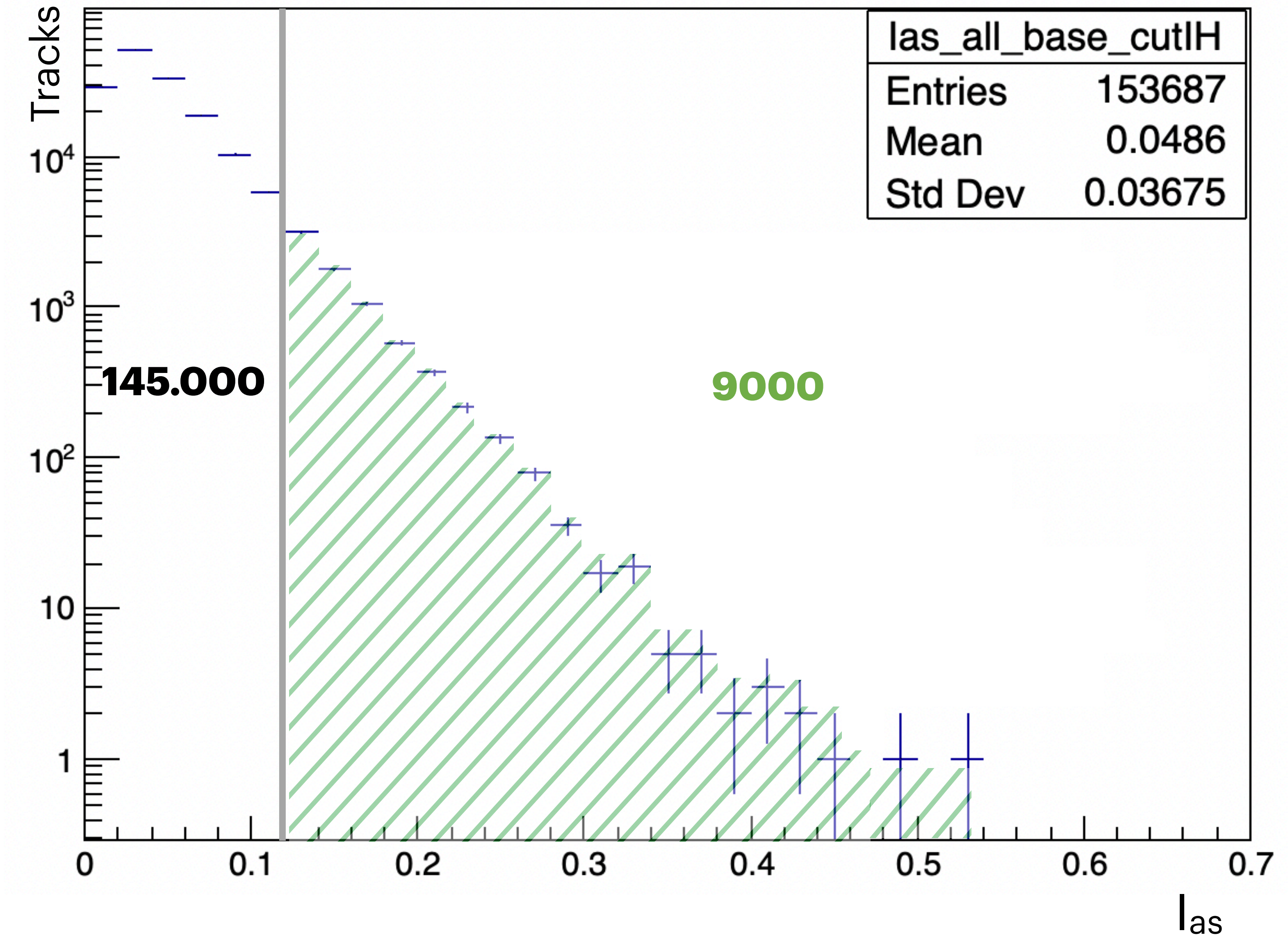


The gap between PU bins is lowered with the Pile-Up treatment, **with potential selection**

The effect is also seen in < I_{AS} >, quantiles plots etc..

PU Effect on I_{AS} distributions

Inclusive I_{as} distribution without Pile-Up treatment ***Private work (CMS data)***



$$R_Q = \frac{\int_Q^1 f(I_{AS})}{\int_0^1 f(I_{AS})}$$

Whole distribution

Probe the tail of the distribution (where we are most sensitive)

Ratio $\boldsymbol{R_Q}$ *of integrals*

PU bins	***No PU treatment***	***PU treatment***
0-20	**7.9%**	**8.7%**
35-99	**9.9%**	**9.2%**

Stability increased !

Conclusion

◉ *Triggers :*

- Trigger efficiencies are below 35%, and efficiency decreases as mass gets higher

- This study allowed to go from 35 to **45%** efficiency by combining multiple triggers

---

◉ *Ionization variables :*

- Distributions of I_{AS} are impacted by the PU, especially in the tails of the distributions (*where we are most sensitive*) : we saw non negligible differences here

  - ***Sensitivity is improved by PU dependent templates !***

↓

- Proposal : ***Take this dependency into account and use the Pile-Up treatment***

Perspectives

- There has been only one paper on 2015 data (beginning of run 2), and our analysis will study the whole run 2 data

- There is ongoing work on the background estimation method, the optimisation of the variables, the selection cuts and more..

-> **The goal is to publish the paper soon**

- This work will be important because **ATLAS has recently published an excess** (local significance > 3.6 σ) on long-lived particles, and we are the only analysis that has the tools to confirm/deny this excess https://arxiv.org/abs/2205.06013

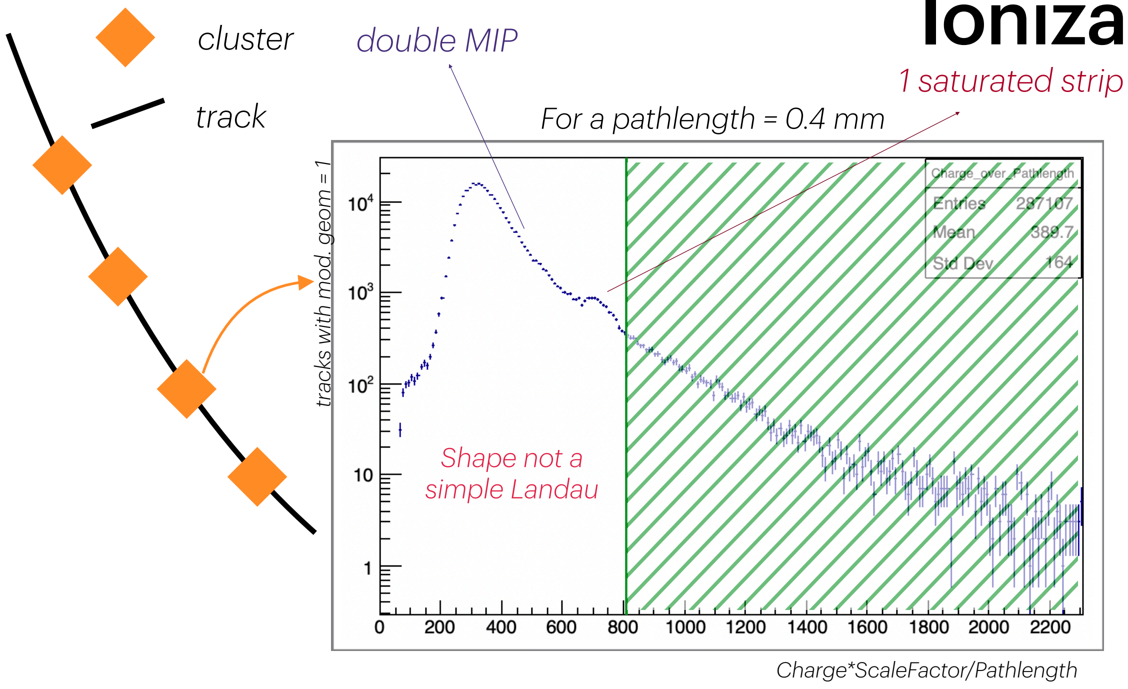
Thank you all !

***Enjoy your evening**

** Don't drink too much*

Ionization Variables

Depend de la taille des piste a MEME pathlength



From this we can calculate the probability for a cluster to have a high energy deposit (I.E not a MIP)

By combining each cluster's probability, one can create two Smirnov discriminators as following :

- The *Smirnov discriminator* is given by:

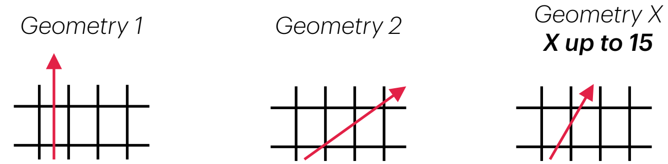
$$I_s^d = \frac{3}{N} \times \left(\frac{1}{12N} + \sum_{h=1}^{N} \left[P_h - \frac{2h-1}{2N} \right]^2 \right)$$

- The *Asymmetric Smirnov discriminator* is given by:

$$I_{as}^d = \frac{3}{N} \times \left(\frac{1}{12N} + \sum_{h=1}^{N} \left[P_h \times \left(P_h - \frac{2h-1}{2N} \right)^2 \right] \right)$$

Dependencies

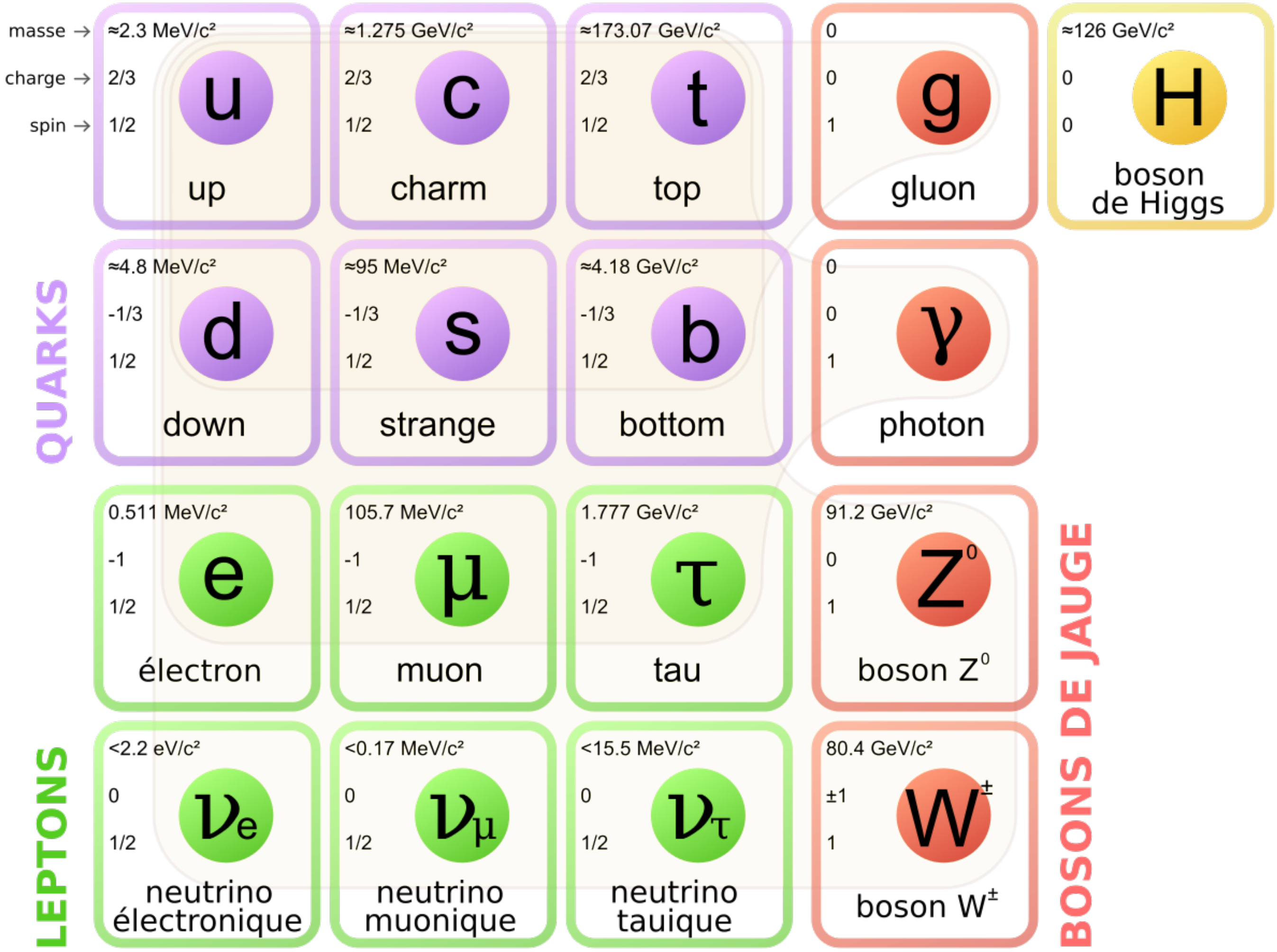
- **Pathlength** → **Charge/pathlength width distributions depends on pathlength**
- **Module** → ***Different module geometry*** *(signal is different if you hit single or multiple strips because of thresholds, noise etc..)*



- **Pile-up** → ***Sensitivity to Pile-Up reduced with the following study***
- **Era**
- **Selection** → ***Ongoing study (coherence production/reading templates)***

BACKUP 1

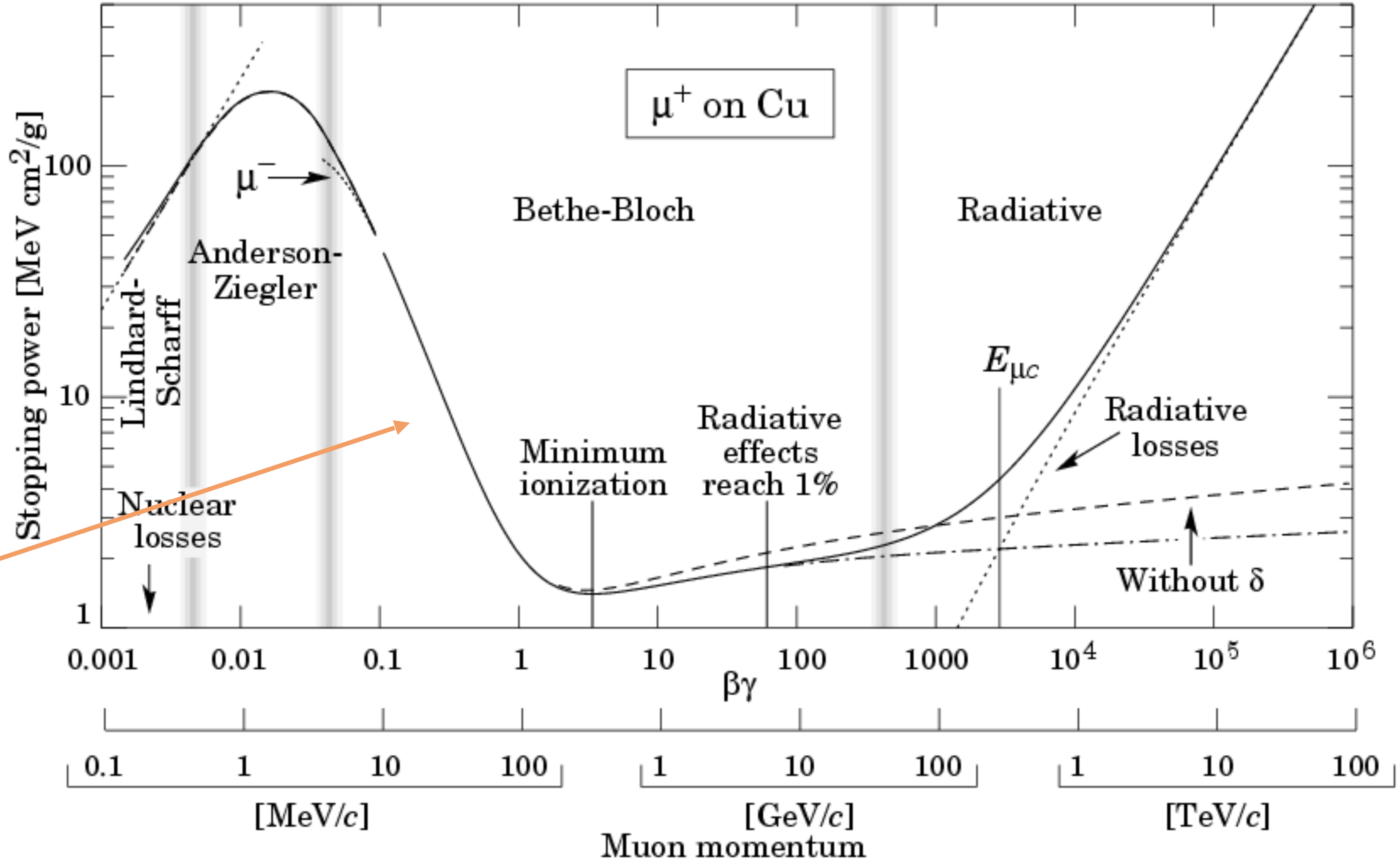
Standard Model



- 4 fundamental forces
- QFT to describe interactions
- 12 fermions + anti-particles

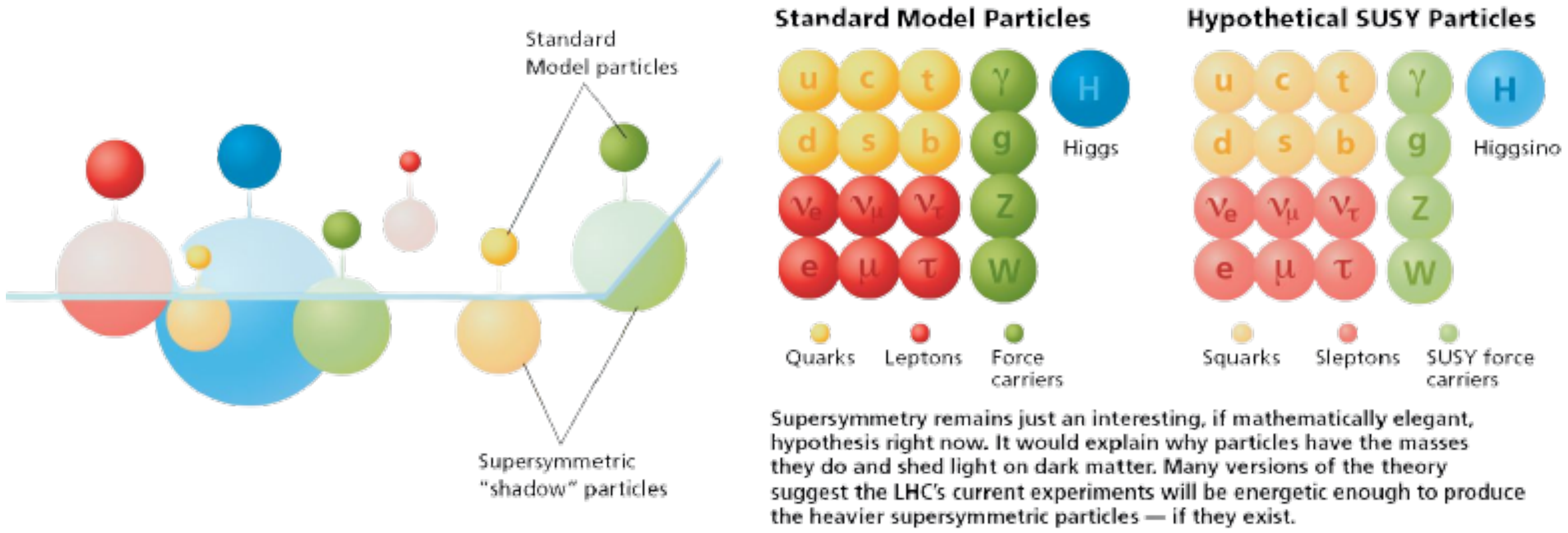
BACKUP 2

Bethe-Bloch



Low βγ regime gives highest dE/dx

BACKUP 3 La Supersymétrie



Extending the standard model by adding a spin symmetry

- Higgs mass divergences can be corrected
- Candidate for dark matter : LSP (Lightest Supersymmetric Particle) stable : neutrino
- Unification of interactions above the scale 10^{16} GeV

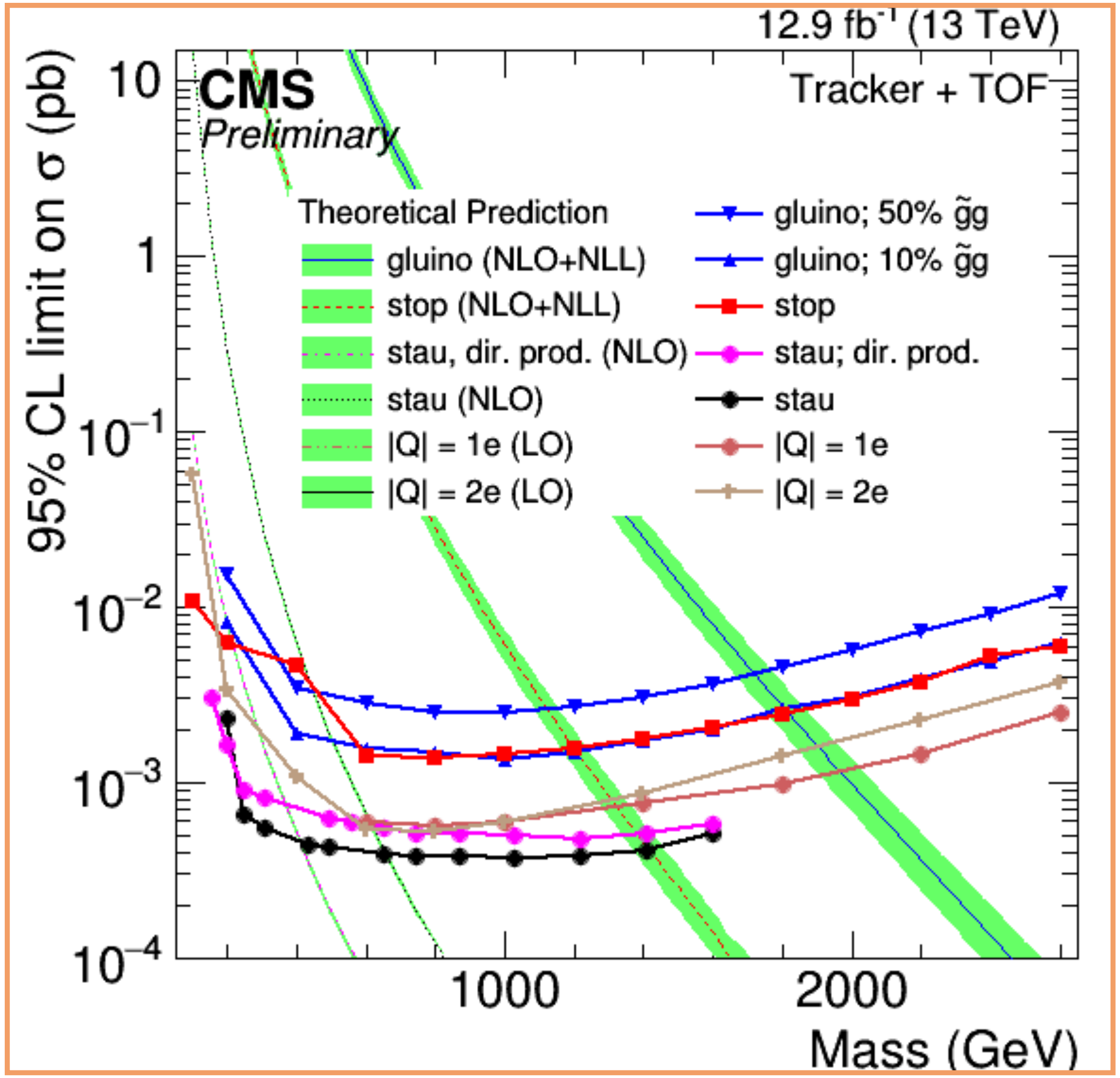
BACKUP 4 Limites HSCP

Gluinos life-time can reach 100 seconds

SPLIT →very heavy squarks :

- A gluino can decay into quark + squark, but this decay mode is suppressed (due to the high masses)

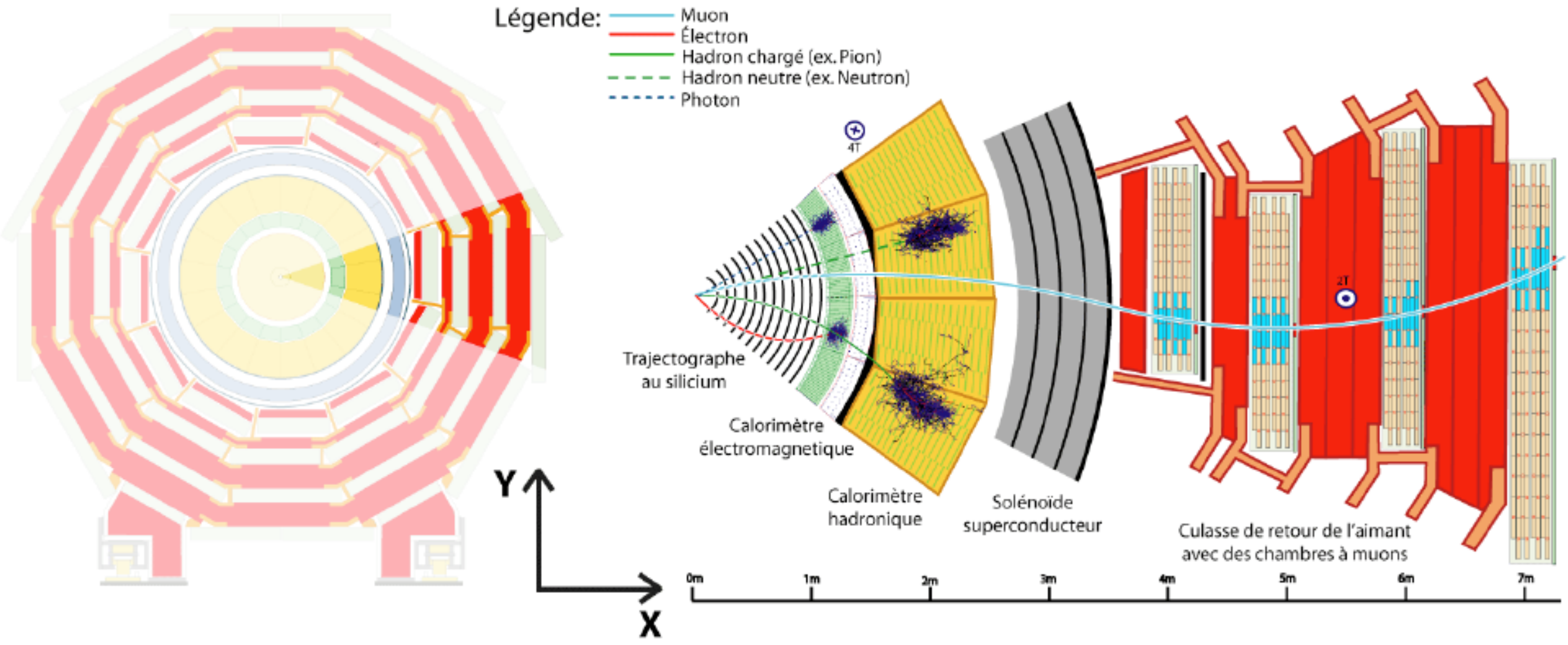
Predictions on gluinos masses for different models →



BACKUP 5

CMS Detector

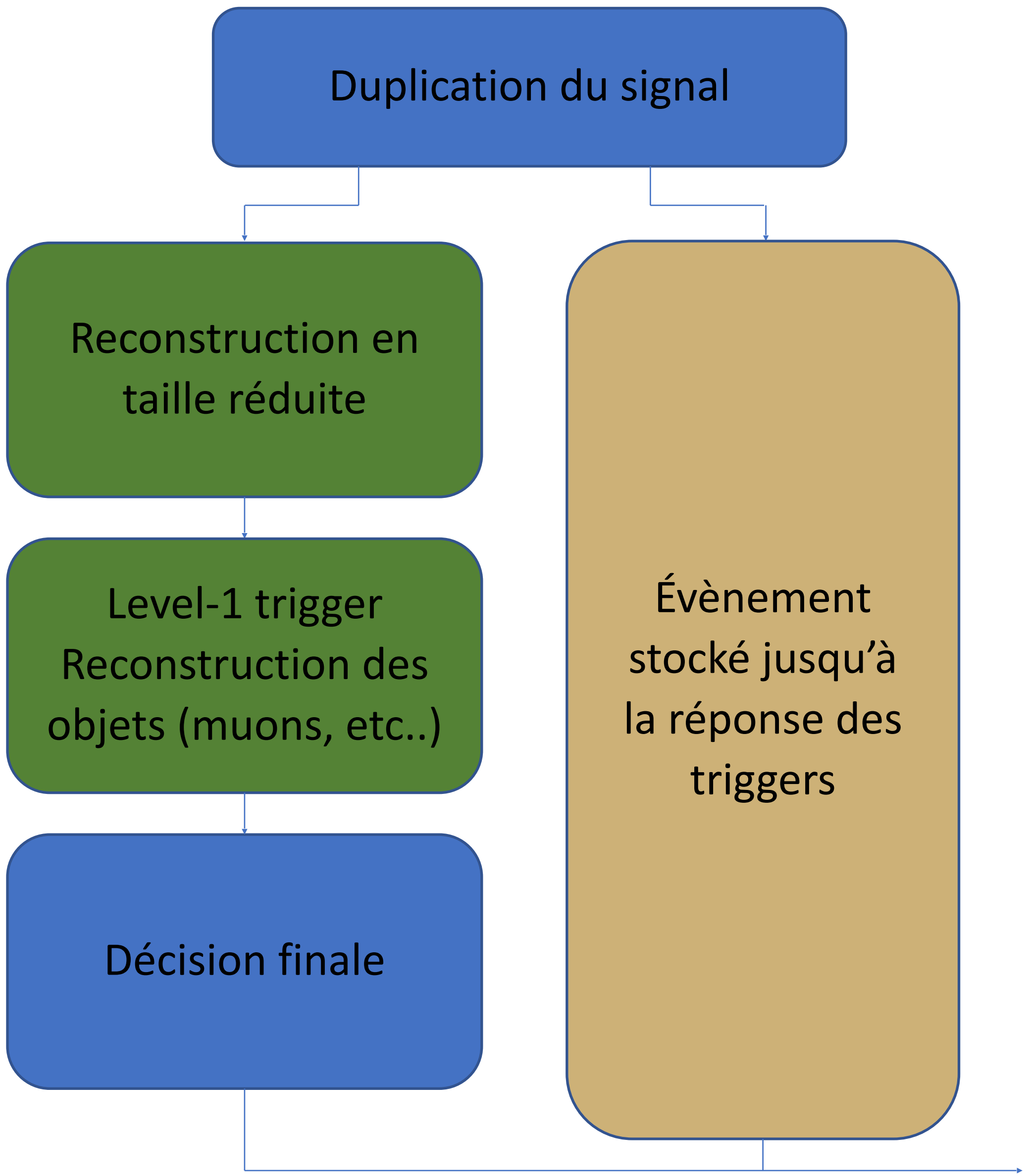
- 21m x 15m
- 14 000 tons
- Magnetic field up to 4 T



BACKUP 6 LHC Timetable

BACKUP 7

CMS Level-1 trigger



Duplication du signal à l'entrée

Des buffers stockent l'évènement en attendant la réponse des triggers

Reconstruction réduite

Niveau 1 reconstruit les objets physiques

Décision finale s'il faut garder l'évènement ou pas

Enregistrement sur les disques pour le niveau 2

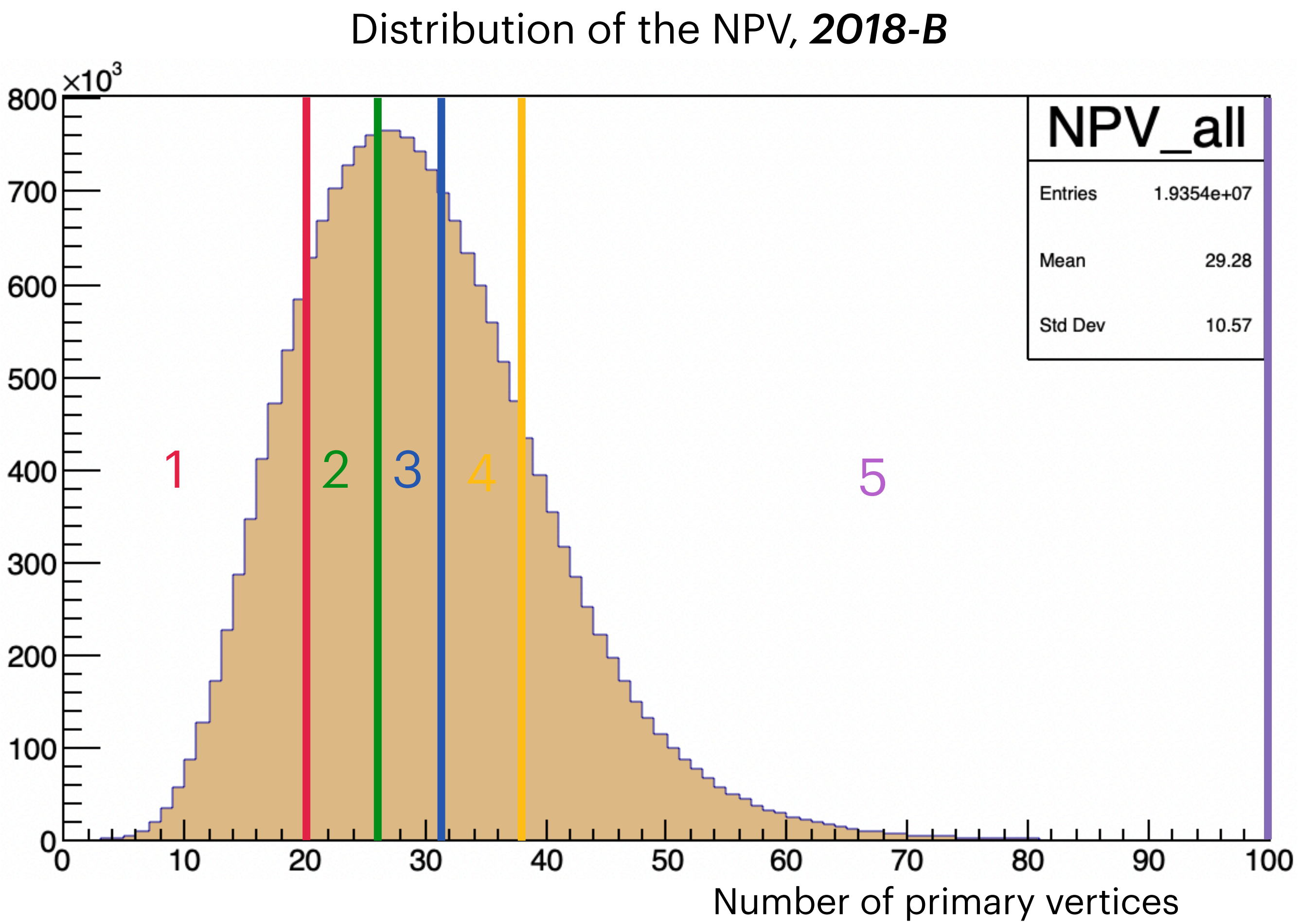
BACKUP 9 New I_{AS} templates as a function of PU

Sample : SingleMuon 2018A

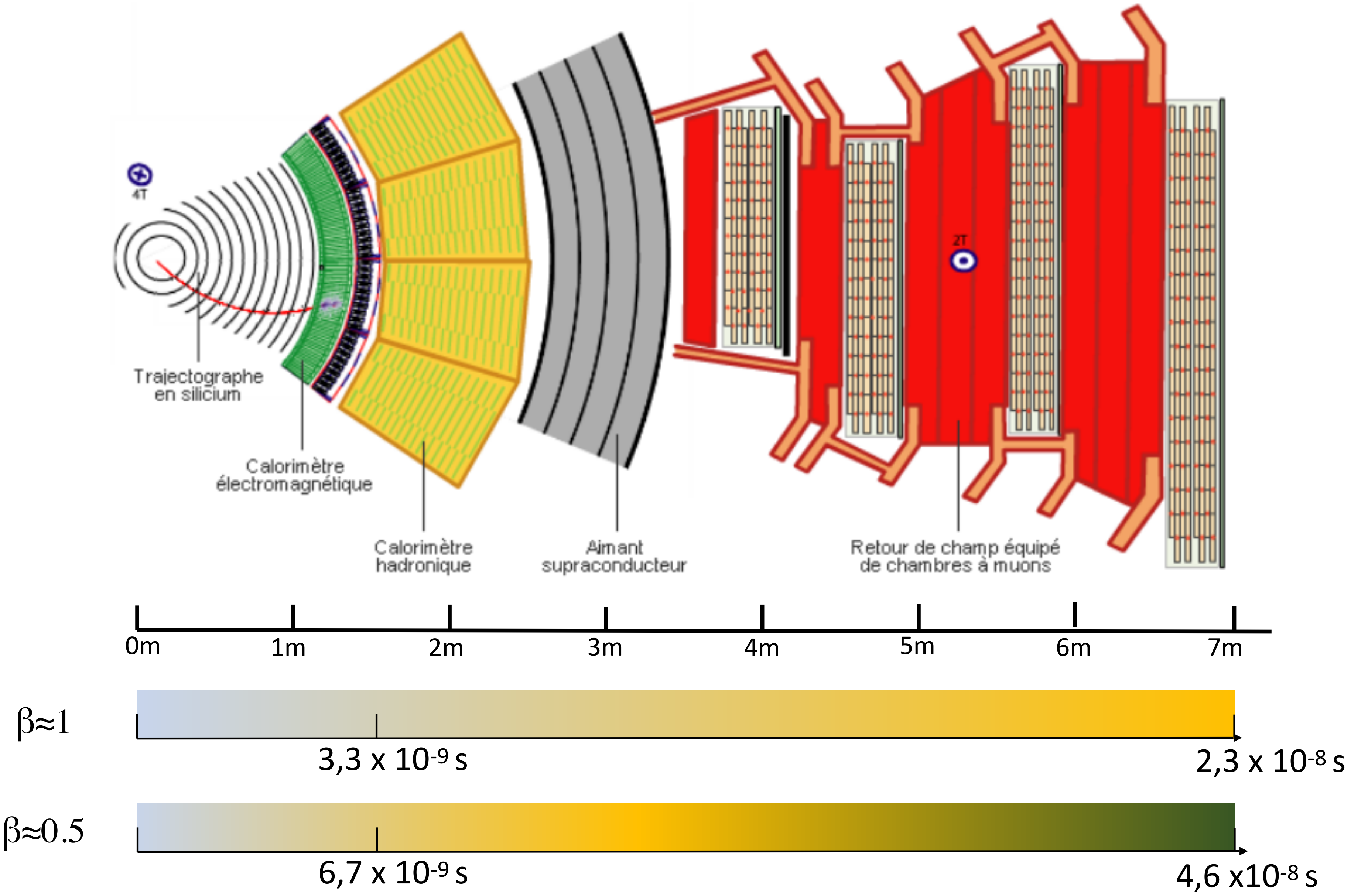
- *We will treat the number of primary vertices (NPV) as an estimation of Pile-Up*

Splitting into categories

- Distribution of PV per event
- Estimation of same statistics PU bins :
  - 1 : PU ⊂ [0,20]
  - 2 : PU ⊂ [20,25]
  - 3 : PU ⊂ [25,30]
  - 4 : PU ⊂ [30,35]
  - 5 : PU ⊂ [35,99]



Delay of particles

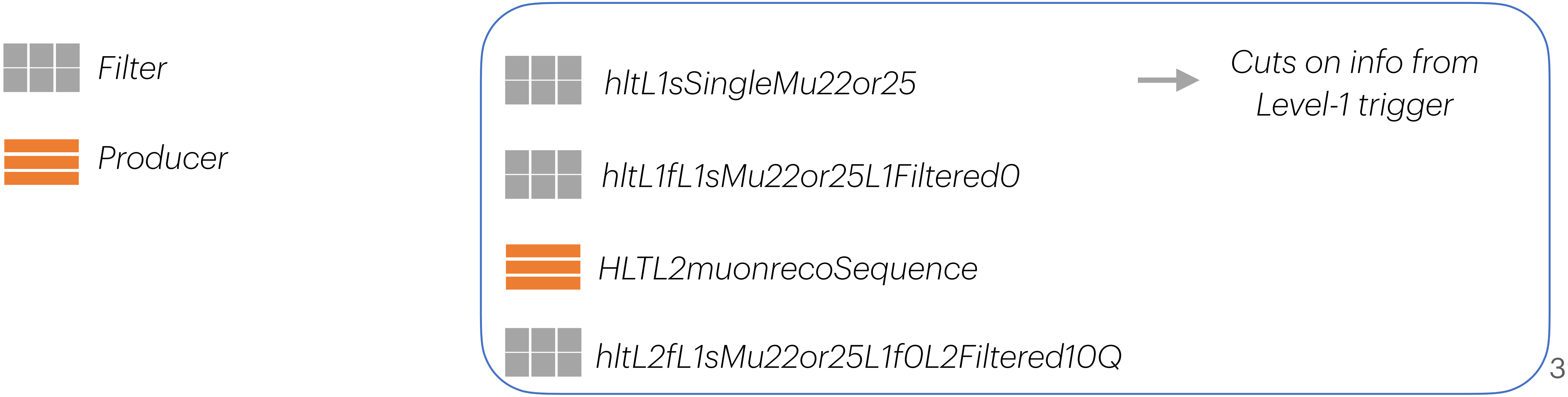


Triggers and Filters

I mentioned a 2-Level trigger system, let's focus on the ***High Level Triggers (HLT)***

- Each HLT path is made of a sequence of ***filters*** / ***producers*** **:**
  - A producer will do the calculations needed to determine a variable (impulsion in the transverse plane for example)
  - A filter will simply cut on that variable

An simplified example of sequences/filters for an HLT_Mu50 path



Generation of IAS templates for each category

- *At first, we thought that the templates sensitivity to Pile-Up was negligible :*
  wrong, effect is ~ 10 %

- *Idea to generate templates (IAS) for multiple Pile-Up bins, with ~ same statistics (studied)*

- *Tests were performed for a range of PU bins (3, 5, 8, 10) with equal statistics :*
  smaller bins = less statistics (impact studied)

- ***Results for 5 PU bins will be presented here***

5 different templates

Charge vs Pathlength vs ModuleGeom

- PU ⊂ [0,20]
- PU ⊂ [20,25]
- PU ⊂ [25,30]
- PU ⊂ [30-35]
- PU ⊂ [64,80]

Run with templates

→

Track quality selection applied

Reading the templates

For a given PU

-> Read the proper template to extract the value of I_{AS}