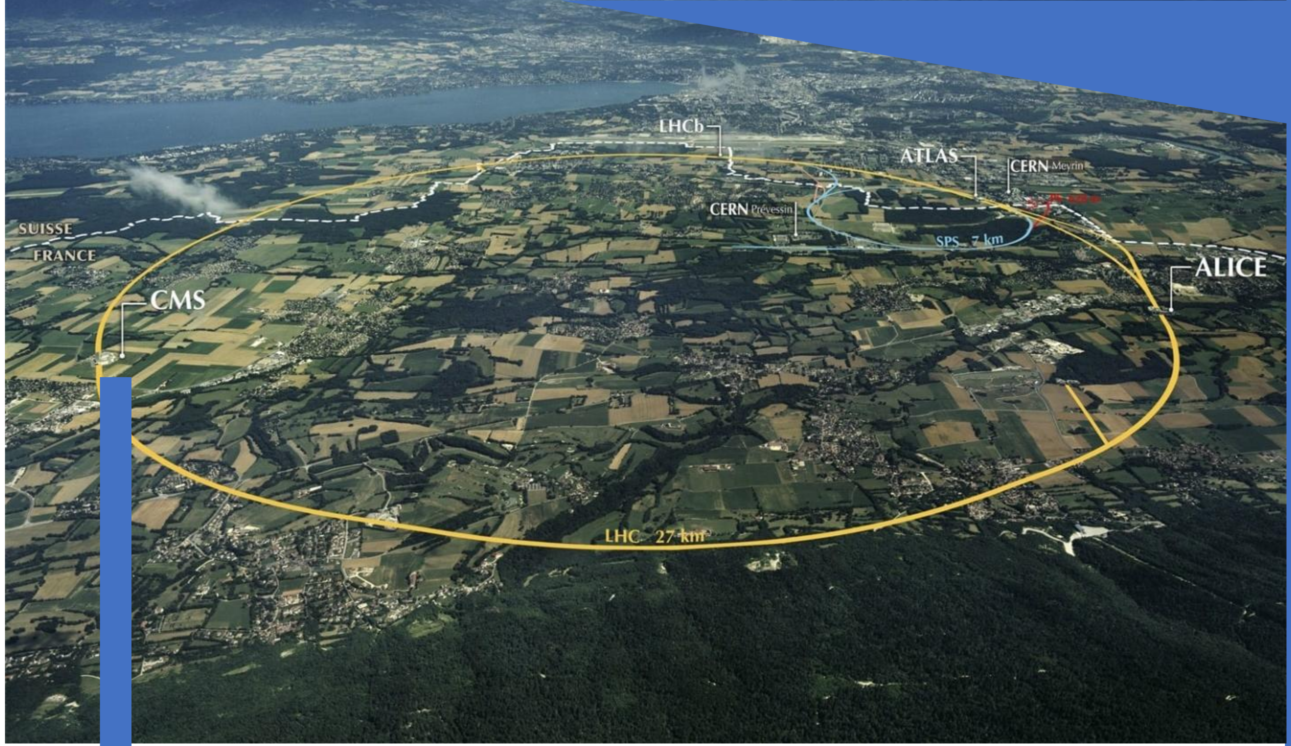
Exploring new long-lived particles at the LHC: signatures by charge and mass.

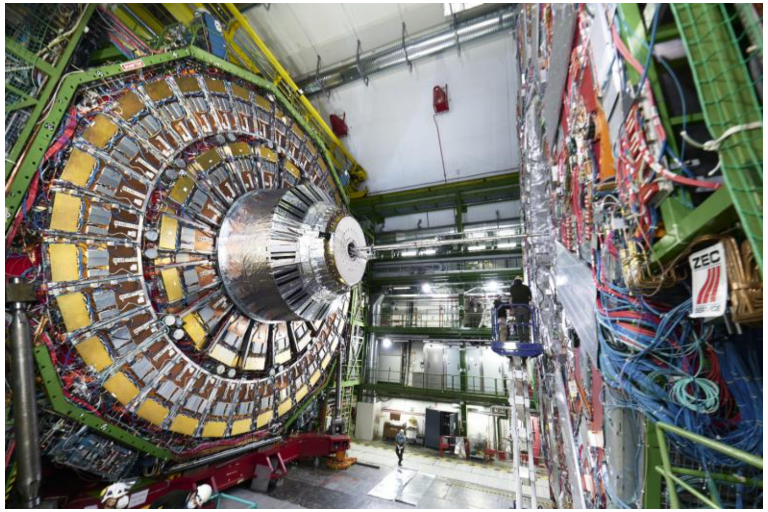
Madre Xavier
Supervisor : Chabert Éric

CMS Experiment

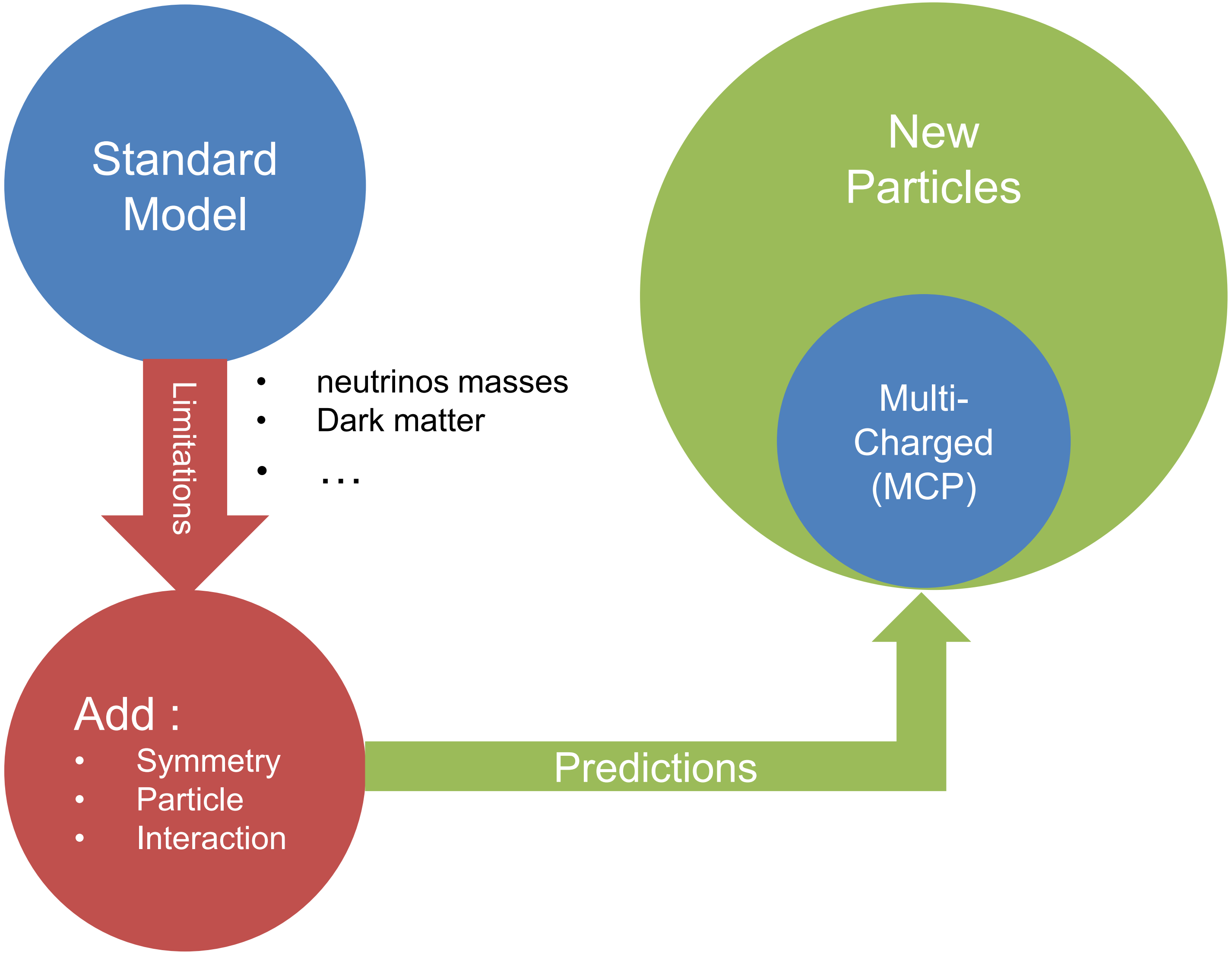
- Compact Muon Solenoid
- Large Hadron Collider
- proton-proton collisions
- International collaboration
- Scientific objective:
  - Standard Model
  - Higgs Physics
  - **New Physics** ★

Run 1	Run 2	Run 3
2009-2013	2015-2018	2022-In progress
7 and 8 TeV	13 TeV	13,6 TeV
5 and 18.8 fb^{-1}	163.6 fb^{-1}	>201.9 fb^{-1}





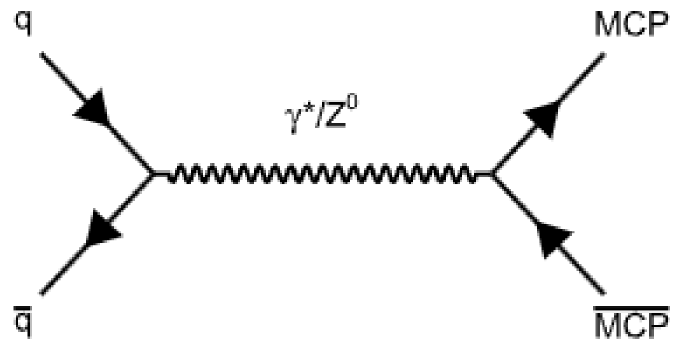
Scientific Motivation



Objective :

-**Characterization** of multi-charged particles signals in the CMS detector

-Proposed a new **analysis strategy** based on Run 2 and 3 data

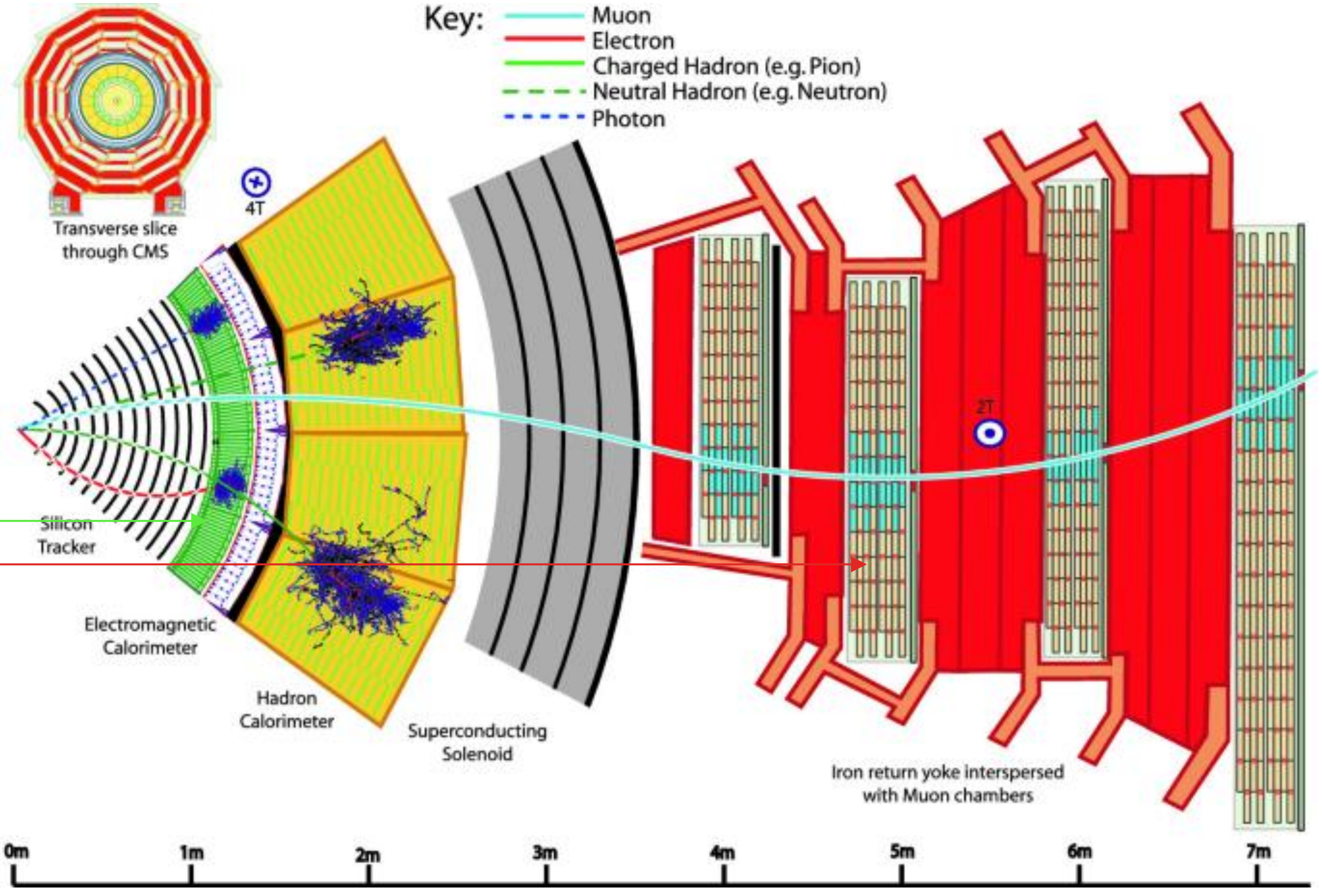


Mutli-charged particles property retained:

- Stable : $c\tau >> 1$ m
- Heavy : M>100GeV
- Spin =1/2

Experimental signature

- $\beta\gamma = \frac{P}{M}$
- Heavy particle -> low β
- Ionization $\propto \frac{Q^2}{\beta^2}$; $\beta = \frac{V}{c}$
- Tracker -> dE/dx
- Velocity measurement (β)
  - Ecal
  - Muon chamber



https://link.springer.com/chapter/10.1007/978-3-030-90206-3_3

Signature : Muon-like, slow, very ionizing

Tracker

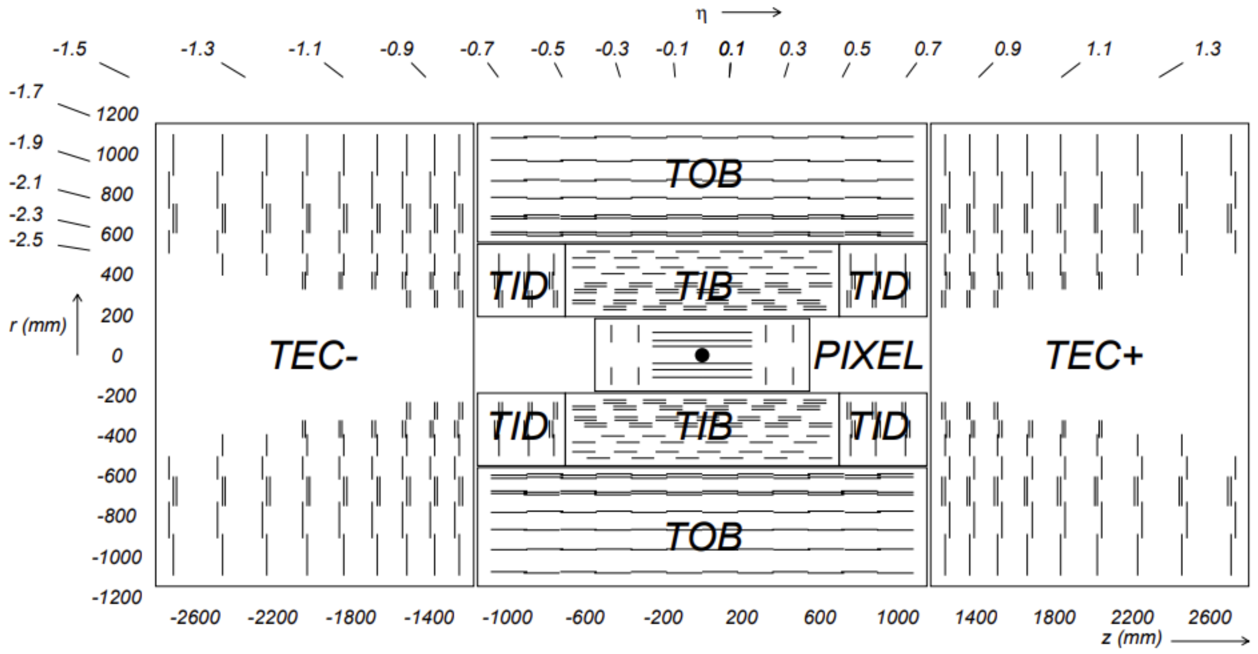
- Semi-conductor sensor

- 22 strips layers
  - 10 layers in the barrel
  - 12 layers in the endap

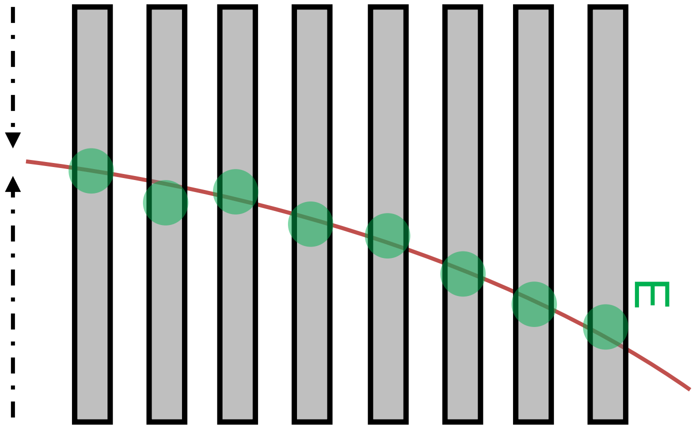
- Reconstruction:
  - Track
  - dE/dx

- Track → 14 clusters on average

- $R_{curvature} \propto p_T/Q$
  - Algorithm for Q=1e

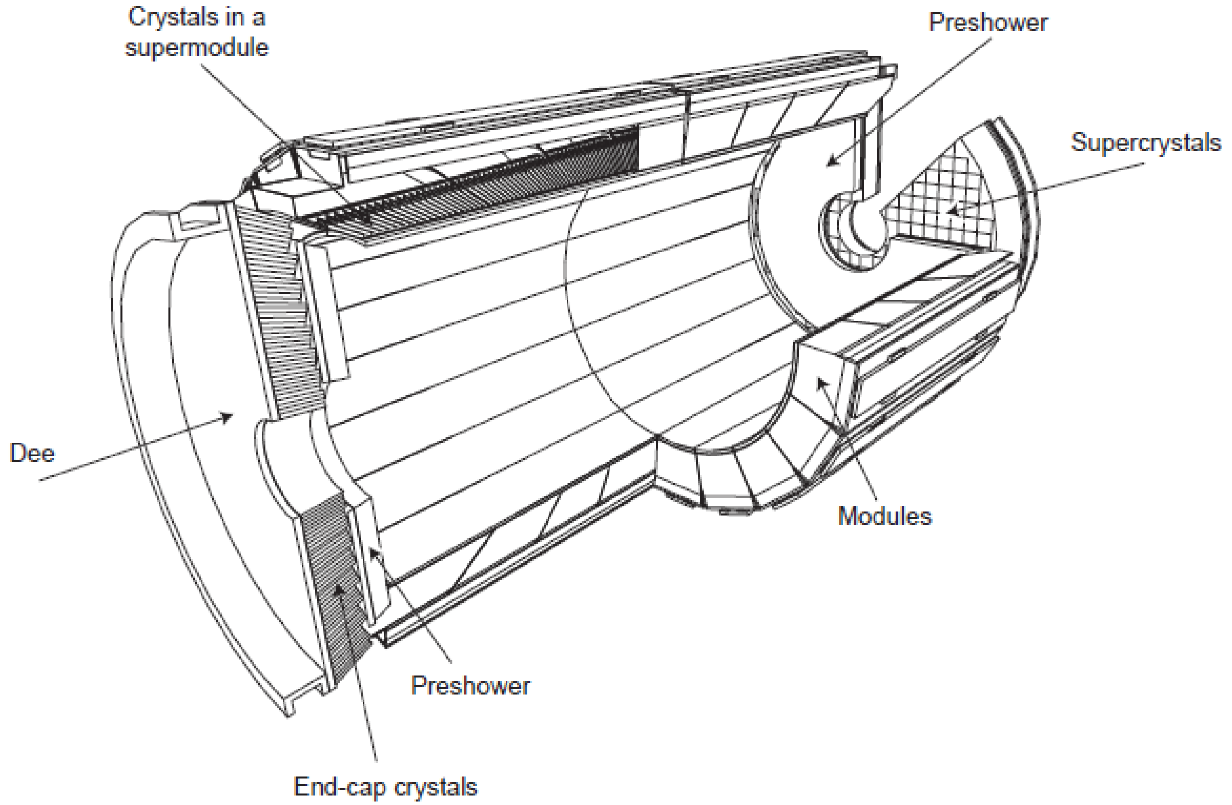


10.1088/1748-0221/3/08/S08004



Electromagnetic calorimeter

- Scintillator made of $PbWO_4$
- Surrounding the tracker
- Measure of:
  - Energy
  - Time
- Design for :
  - Electron
  - Photon



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Measure of the timing

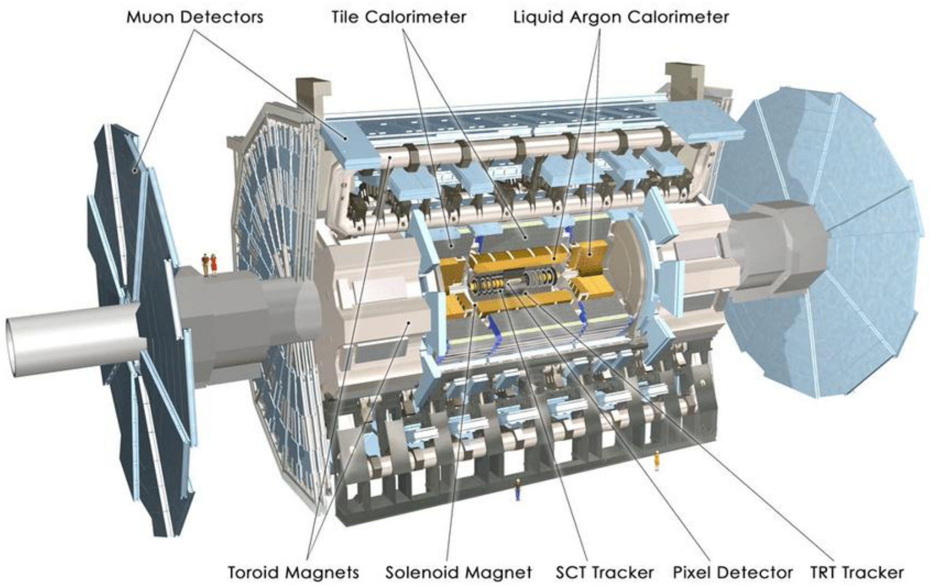
State of art

CMS RUN 1
HSCP analysis (2013)
arXiv:1305.0491v2

- Energy = 7 and 8 TeV
- Luminosity = 5 and 18.8 fb^{-1}
- Signal selection:
  - Tracker
    - Track quality
    - Isolation
    - Ionization
  - Muon chamber
    - Track quality
    - β

ATLAS RUN 2
MCP analysis (2023)
arXiv:2303.13613v2

- Energy = 13 TeV
- Luminosity = 139 fb^{-1}
- Signal selection:
  - Tracker
    - Track quality
    - Isolation
    - Ionization
  - Muon chamber
    - Ionization



10.1088/1742-6596/623/1/012024

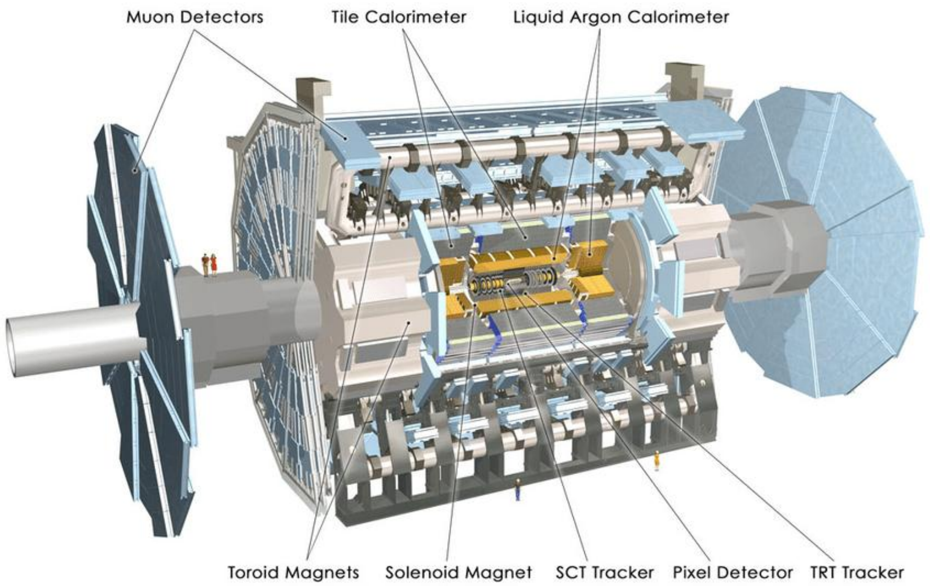
State of art

CMS RUN 1
HSCP analysis (2013)
arXiv:1305.0491v2

- Energie = 7 et 8 TeV
- Luminosity = 5 and 18,8 fb^{-1}
- Signal efficency :
  - M=800GeV
    - Q= 2e → 56%
    - Q= 7e → 9.9%

ATLAS RUN 2
MCP analysis (2023)
arXiv:2303.13613v2

- Energie = 13 TeV
- Luminosity = 139 fb^{-1}
- Signal efficency :
  - M=1100GeV
    - Q= 2e → 29.1%
    - Q= 7e → 7.6%



10.1088/1742-6596/623/1/012024

Current limits:

Q=2 e M>1060 GeV
Q ∈ [3;7] e M>1390 à 1600 GeV

Analysis with low background → expected background <2 event

My work

- Use of **simulations** generating multi-charged particles
- **Data analysis** : CMS internal software : C++; ROOT; python
- **Characterization** the experimental signature of multi-charged particles using :
  - Tracker
  - Electromagnetic calorimeter (ECAL)
- Implementation of a **new analysis** strategy for Run 2 and Run 3

Ionization inside the tracker

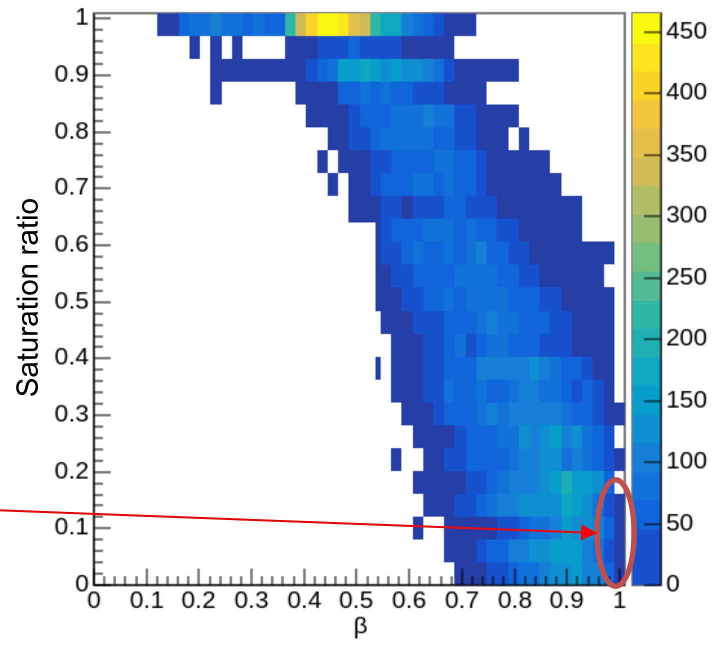
- Ionization $\propto \frac{Q^2}{\beta^2}$ → Saturation
  - Reading electronics -> 8 bits

- Saturation ratio per track :

$$R_{sat} = \frac{\#\ saturated\ clusters}{\#\ clusters}$$

- Standard model background: $\beta \approx 1$

Saturation ratio for Q=1



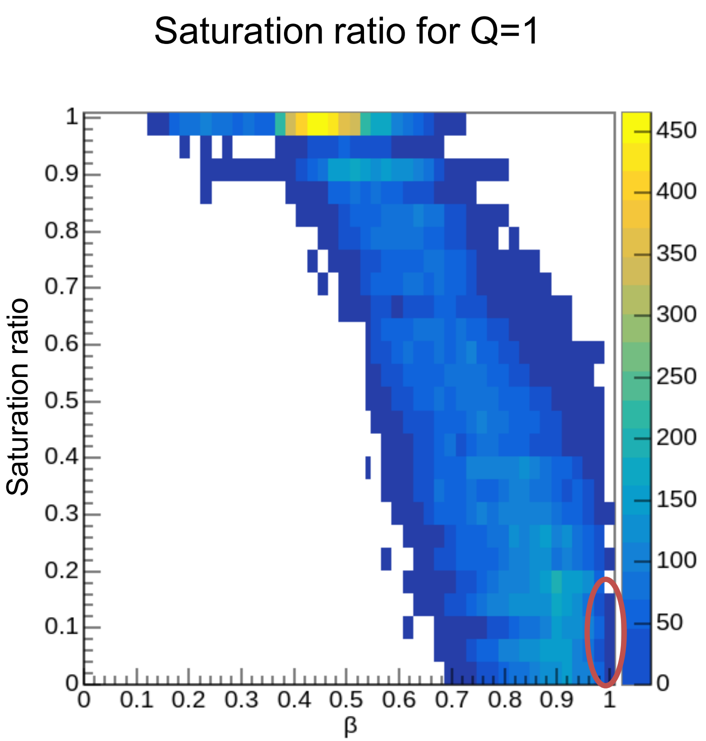
- Q= 1:
  - Low β : High saturation (Beth-Bloch)
  - High β : Decrease in saturation

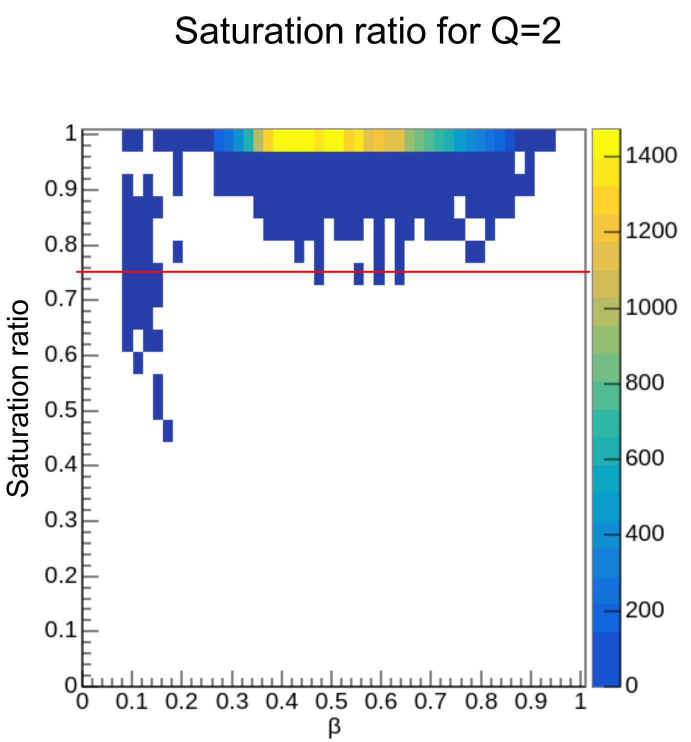
Ionization inside the tracker

- Ionization $\propto \frac{Q^2}{\beta^2}$ → Saturation
  - Reading electronics -> 8 bits

- Saturation ratio per track :

$$R_{sat} = \frac{\#\ saturated\ clusters}{\#\ clusters}$$



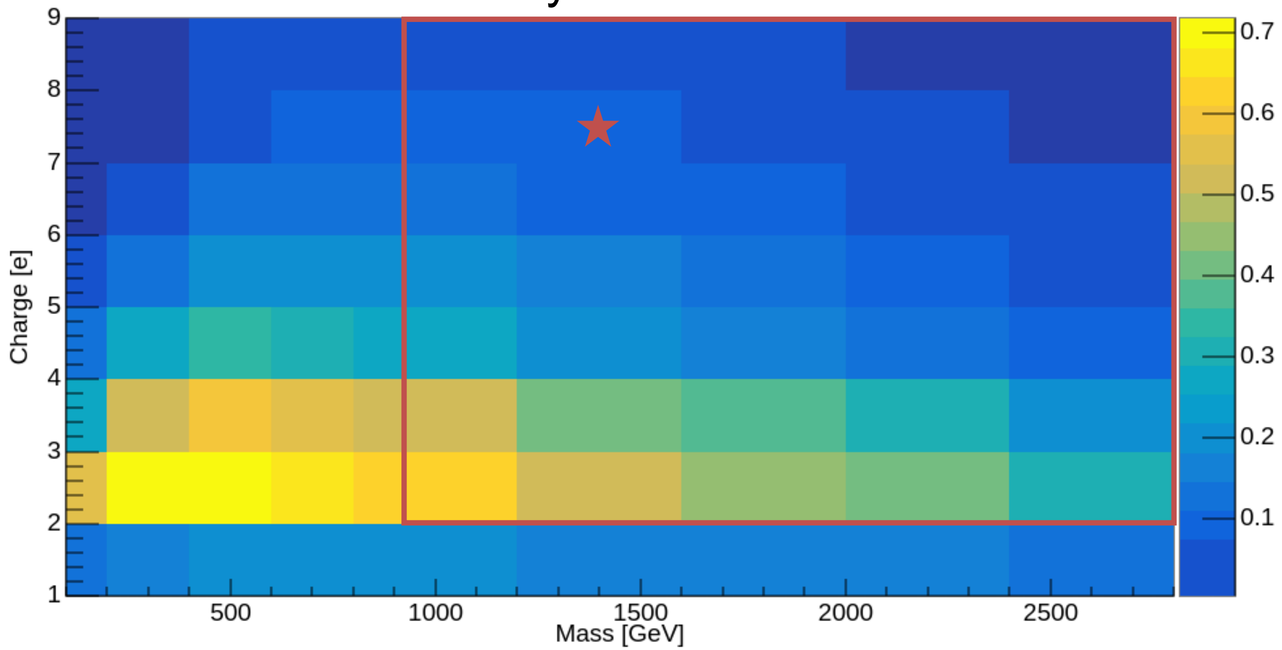


- Q>1 : Important saturation

Discriminant observable → New selection → Cut on $\mathbf{R_{sat}}$

Selection strategy

- Trigger muon
- Reconstruct as a muon
- Track selection
  - p_T
  - Compatibility with primary vertex
  - Muon chamber acceptance
  - Track validity
- Ionization selection
  - $R_{sat}>0,75$
- Region of interest:
  - Q>1
  - M>800GeV



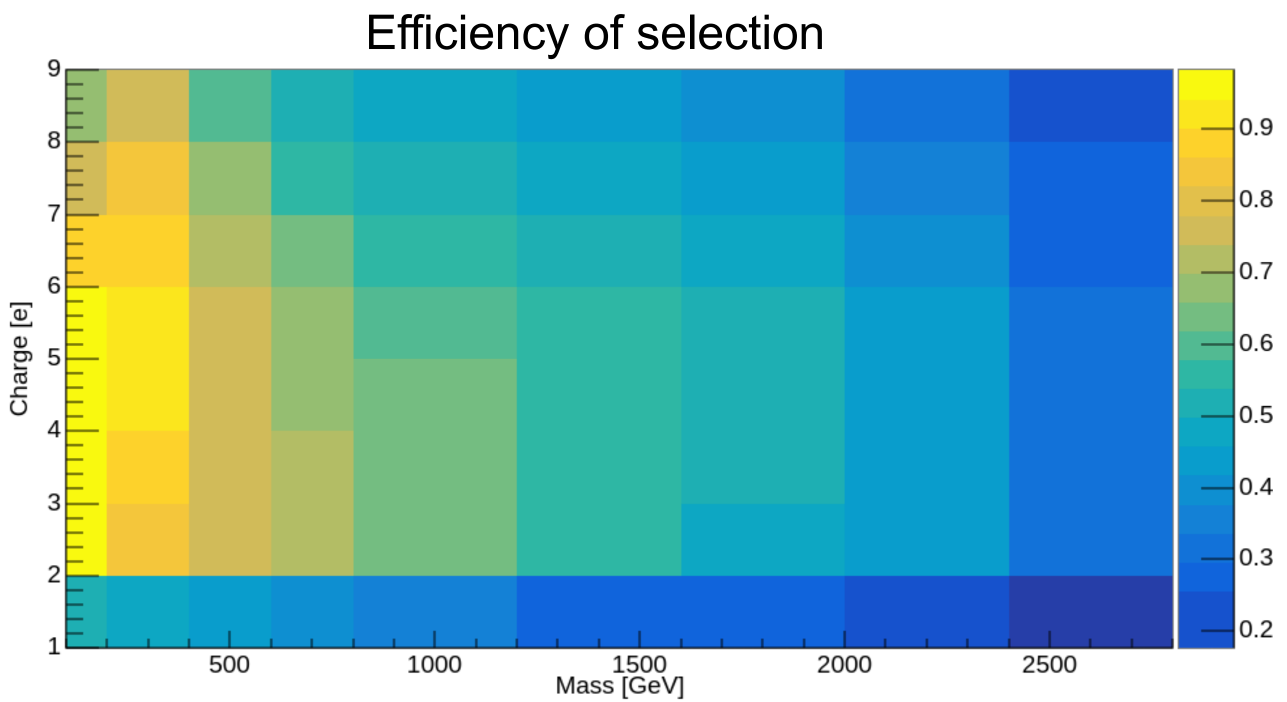
Comparison with ATLAS Run 2:

- Q=7e :
  - ATLAS M=1100GeV → Eff=7.6%
  - Here M=1200GeV → Eff= 8.49% ★

Trigger Muon

What limits Efficiency ?

- Filter applied to the selection
- Efficiency trigger muon
- $Eff = \frac{\# \, Event \, after \, cuts + trigger \, muon}{\# \, Event \, after \, cuts}$



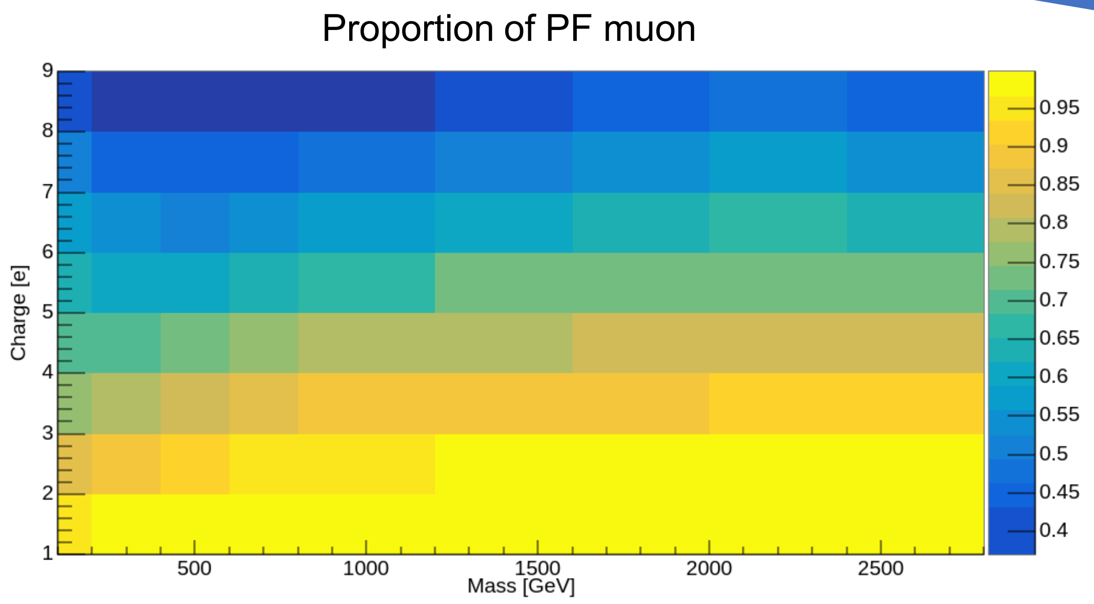
High masses → low β → loss of muon chamber information → low efficiency in region of interest

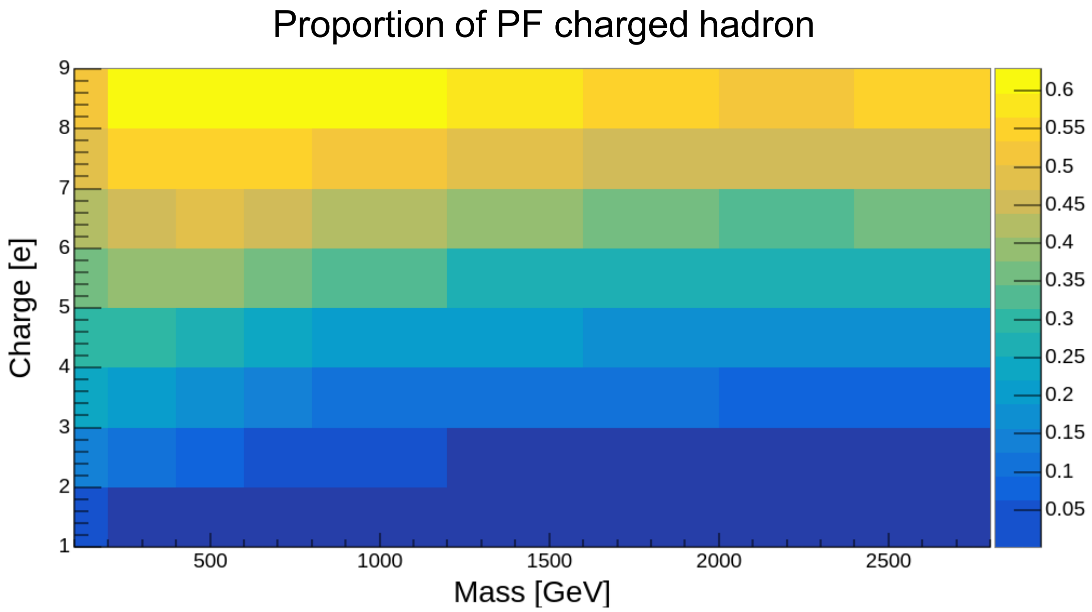
Particle Flow

- Particle Flow (PF) algorithm
  - ECAL
  - HCAL
  - Muon chamber
  - Tracker

- PF reconstruction
  - Charged hadron
  - Electron
  - Muon
  - Photon
  - Neutral hadron

- Proportion:
  - Low charge → muon
  - High charge→ Charged hadron





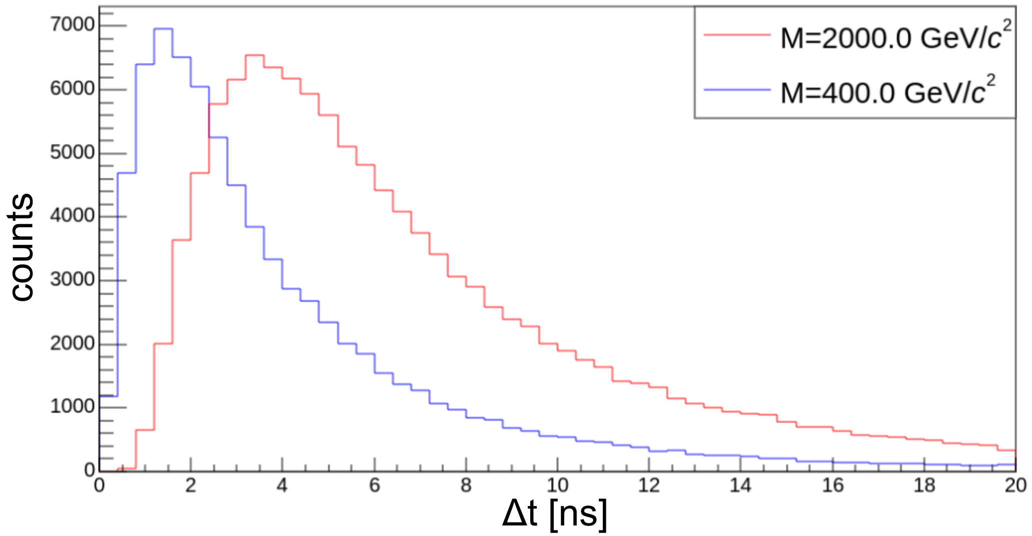
Timing measurement in the ECAL

- Relative time of flight
  - difference with particle β=1

- add Electromagnetic calorimeter
  - Upstream in the detector

$$\beta\gamma = \frac{P}{M}$$ Mass>> → Delay increase

Theoritical delay in the ECAL

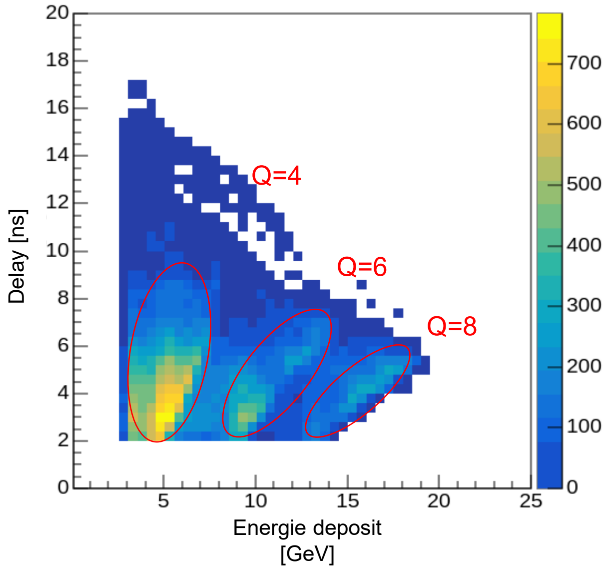


Timing measurement in the ECAL

- Relative time of flight
  - difference with particle β=1
- add Electromagnetic calorimeter
  - Upstream in the detector
- Deposit energy in the calorimeter (ECAL)

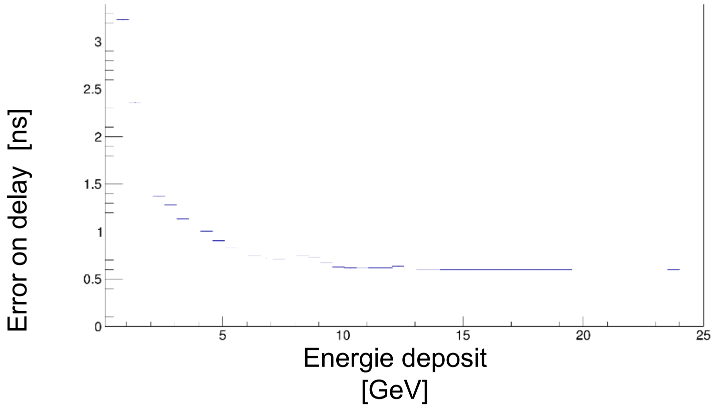
$\beta\gamma = \frac{P}{M}$ → Bethe-Bloch → $E_{deposit} \propto \frac{Q^2}{\beta^2}$ → $E_{MCP} > E_{muon} < 1GeV$

Measured delay for paticle of charge Q∈[4,6,8]



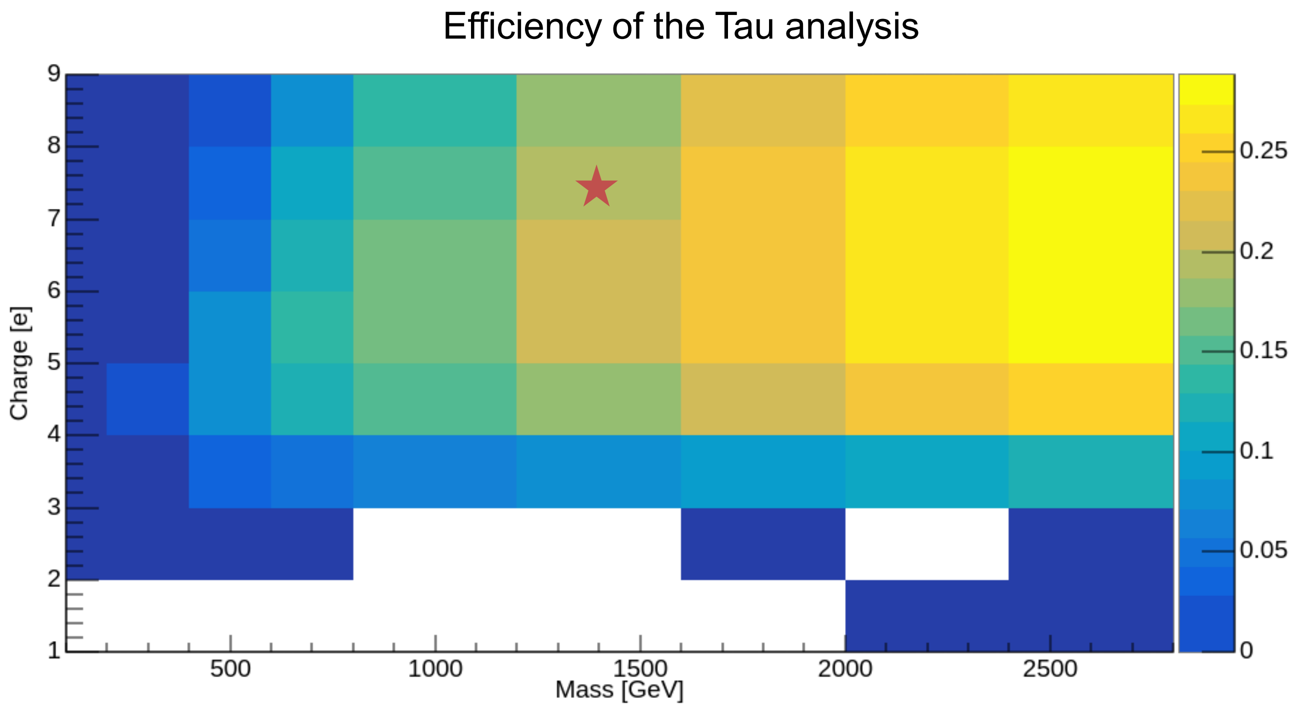
E>3GeV; t>2ns

Error on the measured delay



Selection strategy

- Trigger tau
- Reconstruct as a charged hadron
- Track selection
  - p_T
  - Compatibility with primary vertex
  - Muon chamber acceptance
  - Track validity
- Ionization selection
  - $R_{sat}>0,75$
- Velocity selection (ECAL)
  - $E_{deposit}>3$ GeV
  - t>2 ns



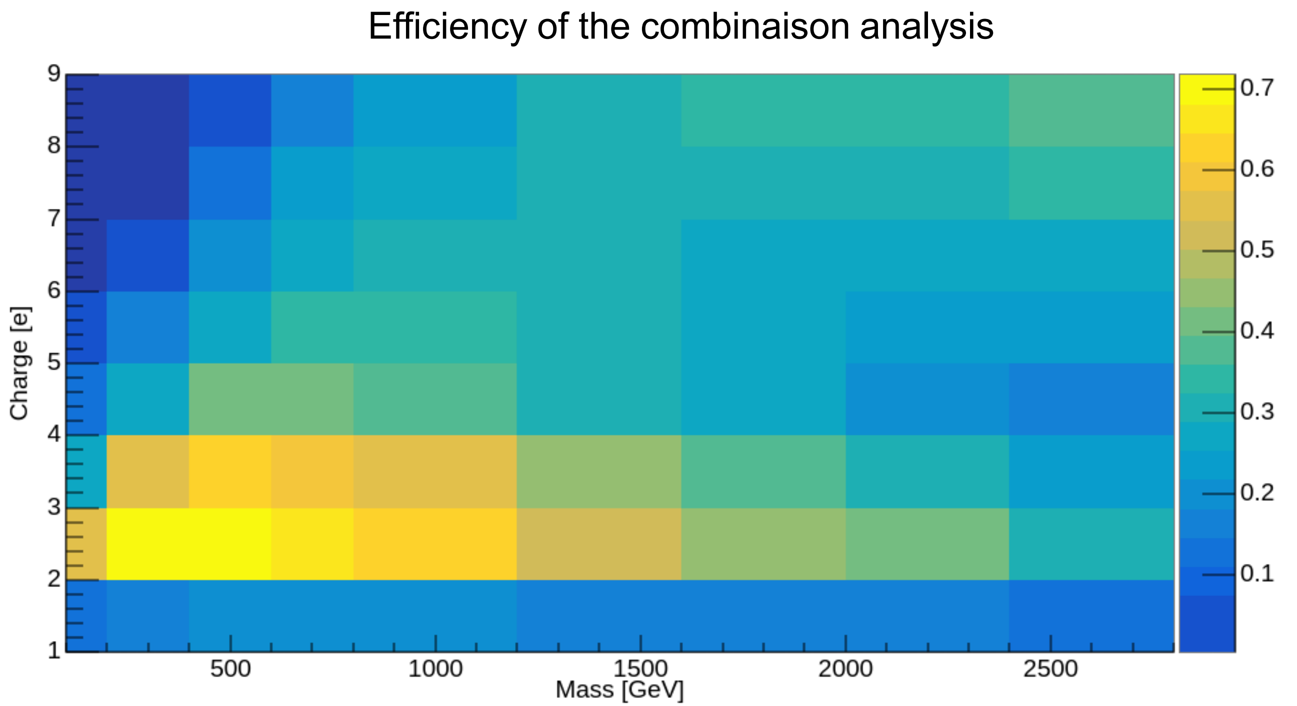
Comparison with ATLAS Run 2:

- Q=7e :
  - ATLAS M=1100GeV → Eff=4.1%
  - Here M=1200GeV → **Eff=22.5%** ★

Selection combination

Muon + Charged hadron

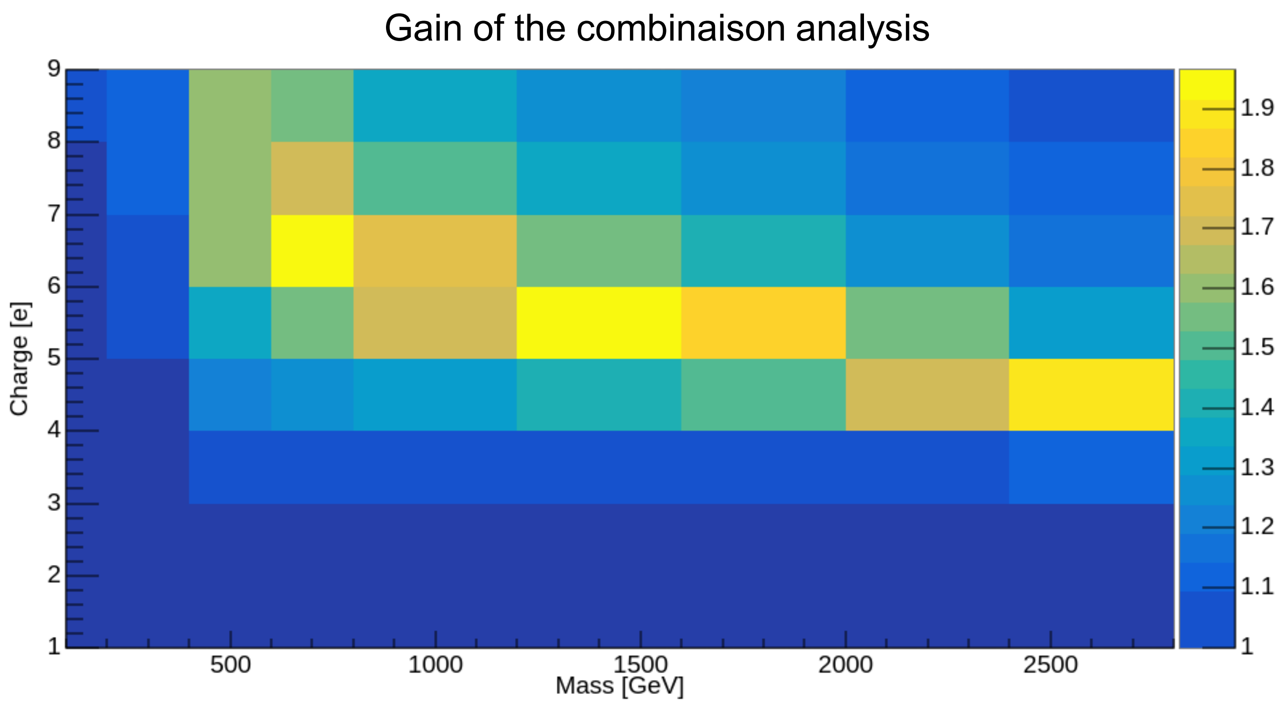
- ATLAS Run 2 efficiency :
  - Q= 2e and M=1100GeV :
    - ATLAS → 29.1%
    - Here → **53.1**%
  - Q= 4e and M=1100GeV :
    - ATLAS → 33.1%
    - Here → 30.8%
  - Q= 7e and M=1100GeV :
    - ATLAS → 7.6%
    - Here → **31.0**%



Encouraging efficiency compared to ATLAS Run 2 analysis

Gain with combination

- Gain combinaison of two analysis
- $Gain = \frac{Eff_{Muon} + Eff_{Charged\ hadron}}{Max(Eff_{Muon}\,;Eff_{Charged\ hadron})}$
- Double the efficiency at the center



Conclusion

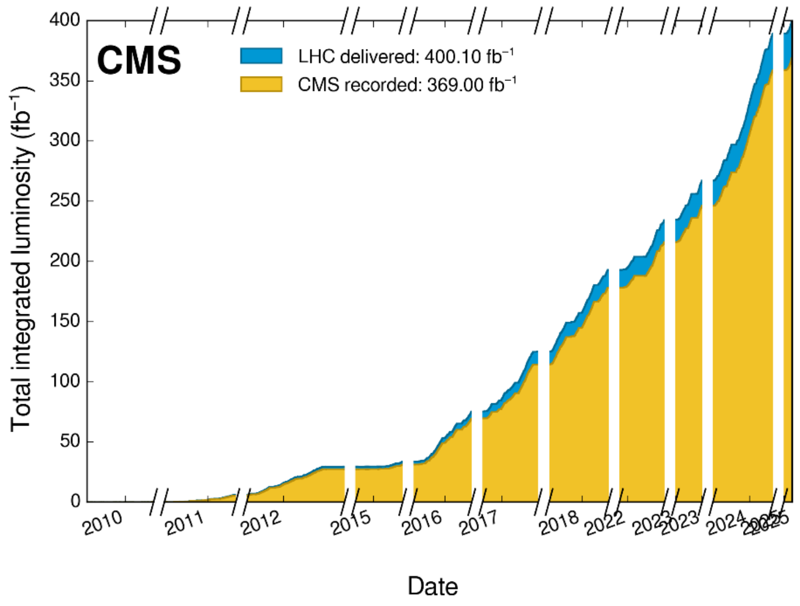
MCPs signal → Multi-Charged → High ionization → $\mathbf{R_{sat}}$
High charges → Using **ECAL** timing information

Analysis strategy → Combination of two analysis → **Muon + Charged hadron**
Increase efficency → at high charges → **between 40 – 50%**

Backup

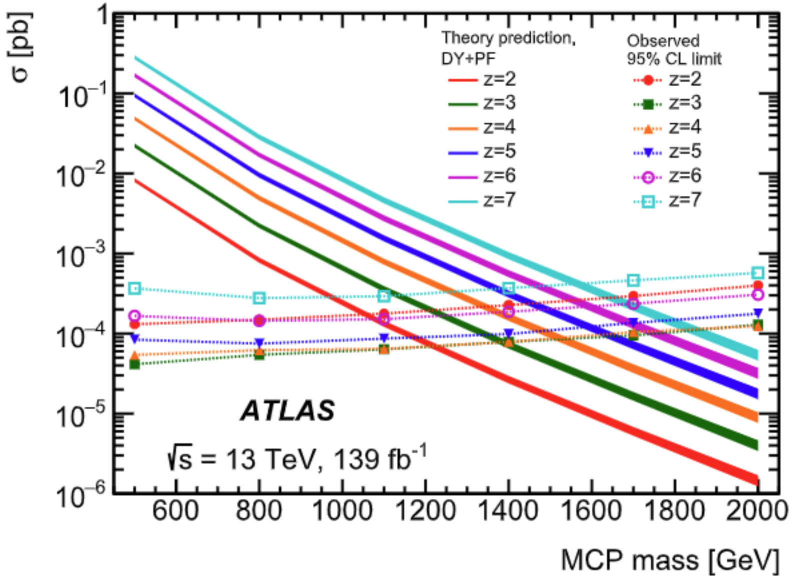
LHC curve

Luminosité intégrée CMS



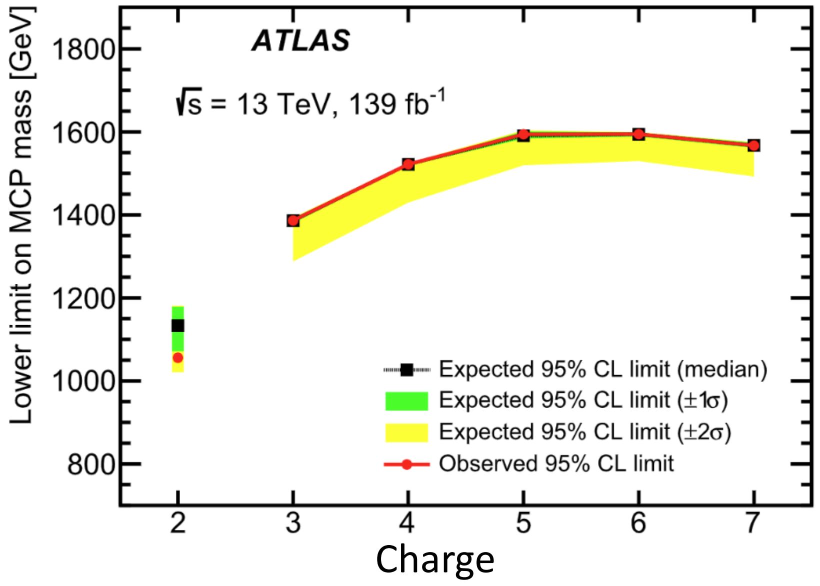
https://twiki.cern.ch/twiki/bin/view/CMSPublic/LumiPublicResults#Full_summary_proton_proton_colli

Section efficace MCP



arXiv:2303.13613v2

Limite expérimentale



arXiv:2303.13613v2

MCP model

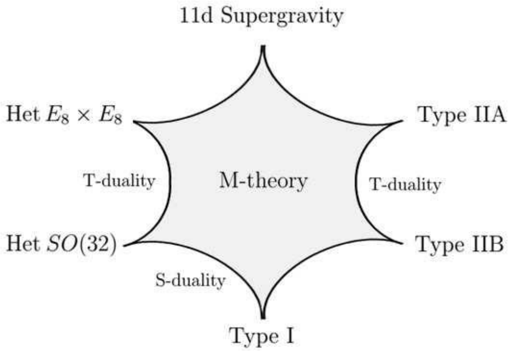
Type II seesaw :

$$\Delta^{++} \rightarrow \mu^{+}\mu^{+}, ee, \tau\tau$$
$$\Delta^{++} \rightarrow H^{+}H^{+}$$

https://slideplayer.com/slide/13852635/

→ Neutrinos masses

Super-string :

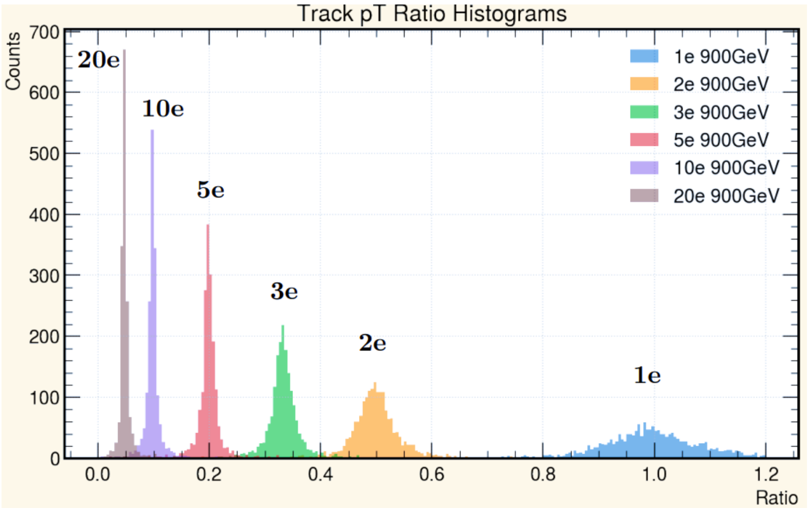


arXiv:2204.01165v1

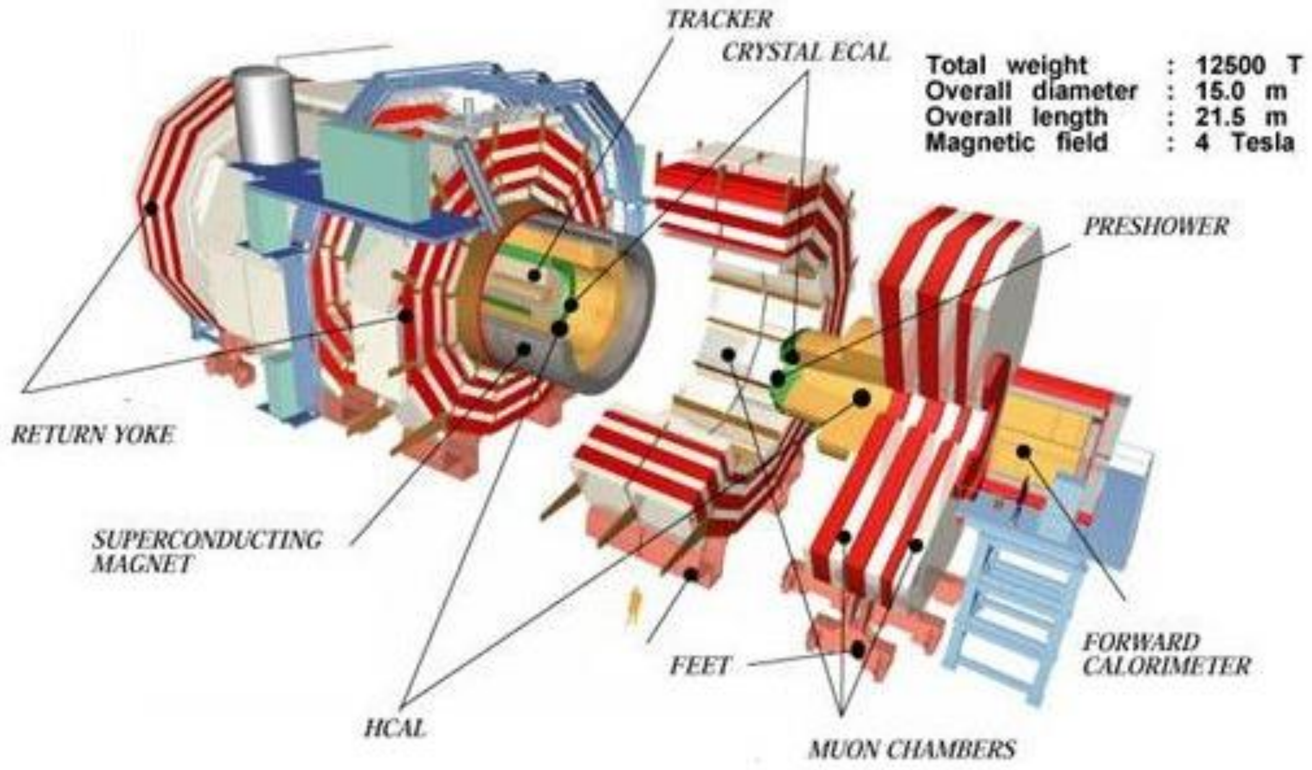
→ Dark matter
Quantum gravity

PT Reconstruction

Ratio=$\frac{p_t\, Track}{p_t\, Gen}$



EXO workshop London 2025 Rafey Hashmi



https://cds.cern.ch/record/1407706/plots#0

State of art selection

CMS preselection :

Trajectographe :

	$\lvert Q\rvert < 1e$	tracker+TOF	tracker-only	$\lvert Q\rvert > 1e$
$\lvert\eta\rvert$	<2.1			
p_T (GeV/c)	>45			
d_z and d_{xy} (cm)	<0.5			
σ_{p_T}/p_T	<0.25			
Track χ^2/n_d	<5			
# Pixel hits	>1			
# Tracker hits	>7			
Frac. Valid hits	>0.8			
$\Sigma p_T^{trk}(\Delta R < 0.3)$ (GeV/c)	<50			
# dE/dx measurements	>5			
dE/dx strip shape test	yes			no
$E_{cal}(\Delta R < 0.3)/p$	<0.3			–
I_h (MeV/cm)	<2.8	>3.0		
ΔR to another track	$<\pi - 0.3$	–		

Chambres à muons :

	tracker+TOF	$\lvert Q\rvert > 1e$	muon-only
# TOF measurements	>7		
$\sigma_{1/\beta}$	<0.07		
$1/\beta$	>1		
$\lvert\eta\rvert$	–		<2.1
p_T (GeV/c)	–		>80
d_z and d_{xy} (cm)	–		<15
# DT or CSC stations	–		>1
Opp. segment $\lvert\eta\rvert$ difference	–		>0.1
$\lvert\phi\rvert$	–		<1.2 OR >1.9
$\lvert\delta t\rvert$ to another beam crossing (ns)	–		>5

ATLAS :

Table 1
Summary of the offline-selection requirements.

Search category	Preselection	Tight selection	Final selection
$z = 2$	Combined muon with: 'medium' identification criteria, $p_T^{\mu}/z > 50$ GeV, $p_T/z > 10$ GeV, $\lvert\eta\rvert < 2.0$, no other particles with $p_T/z > 0.5$ GeV within $\Delta R = 0.01$	Preselected candidate with $S(\text{pixel } dE/dx) > 13$	Tightly selected candidate with: $S(\text{TRT } dE/dx) > 2$, $S(\text{MDT } dE/dx) > 4$
$z > 2$		–	Preselected candidate with: TRT $f^{\text{HT}} > 0.7$, $S(\text{MDT } dE/dx) > 7$

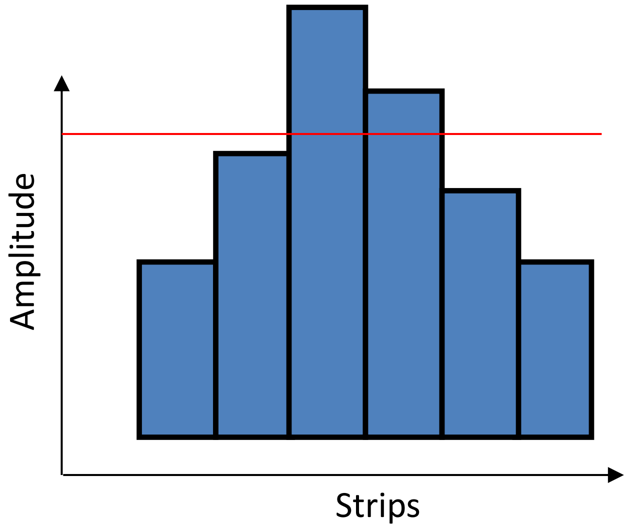
$$S(x) = \frac{x - \langle x \rangle}{\sigma_x}$$

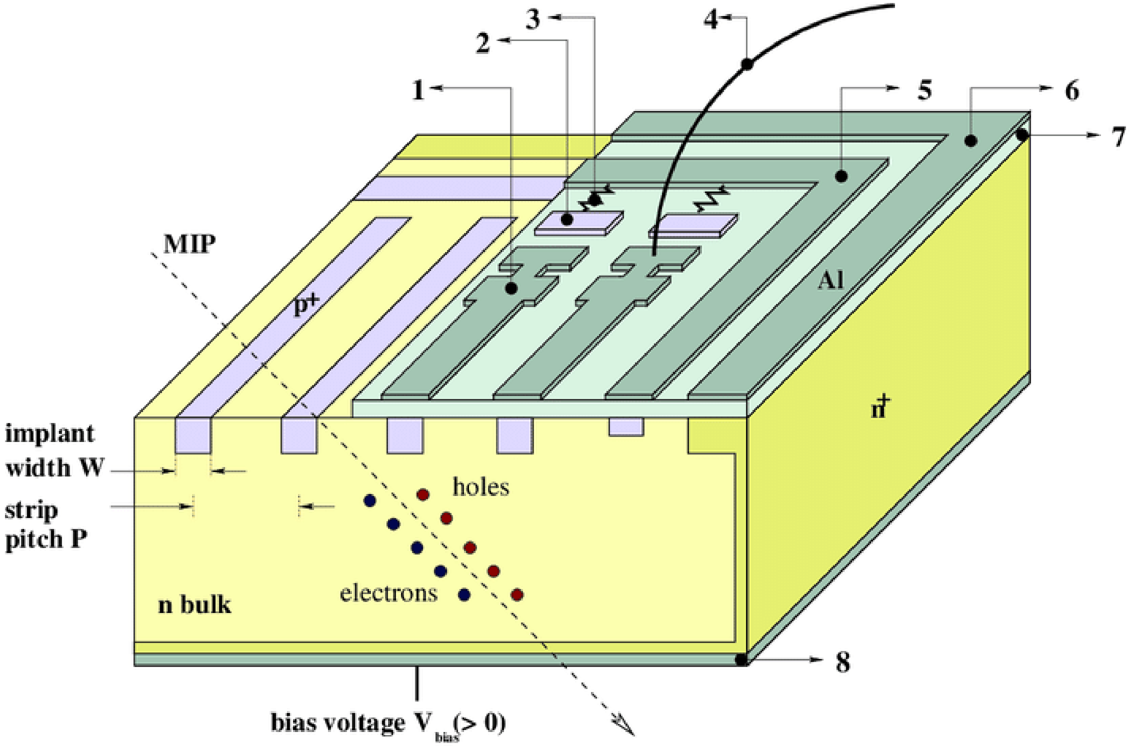
CMS final :

	Selection criteria				Number of events			
					$\sqrt{s} = 7$ TeV		$\sqrt{s} = 8$ TeV	
	p_T (GeV/c)	$I_{as}^{(\prime)}$	$1/\beta$	Mass (GeV/c^2)	Pred.	Obs.	Pred.	Obs.
Tracker-only	>70	>0.4	–	>0	7.1 ± 1.5	8	33 ± 7	41
				>100	6.0 ± 1.3	7	26 ± 5	29
				>200	0.65 ± 0.14	0	3.1 ± 0.6	3
				>300	0.11 ± 0.02	0	0.55 ± 0.11	1
				>400	0.030 ± 0.006	0	0.15 ± 0.03	0
Tracker+TOF	>70	>0.125	>1.225	>0	8.5 ± 1.7	7	44 ± 9	42
				>100	1.0 ± 0.2	3	5.6 ± 1.1	7
				>200	0.11 ± 0.02	1	0.56 ± 0.11	0
				>300	0.020 ± 0.004	0	0.090 ± 0.02	0
Muon-only	>230	–	>1.40	–	–	–	6 ± 3	3
$\lvert Q\rvert > 1e$	–	>0.500	>1.200	–	0.15 ± 0.04	0	0.52 ± 0.11	1
$\lvert Q\rvert < 1e$	>125	>0.275	–	–	0.12 ± 0.07	0	1.0 ± 0.2	0

Tracker: sensor

- Paire eletron-hole
- Electronic readout (ADC)
- Clusters





https://www.researchgate.net/publication/33714340_Developme
nt_of_a_test_system_for_the_quality_assurance_of_silicon_micr
ostrip_detectors_for_the_inner_tracking_system_of_the_CMS_ex
periment

Bethe Bloch

Course M2 radiation interaction matter A.Besson

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

K $4\pi N_A r_e^2 m_e c^2$ (Coefficient for dE/dx)

z = charge number of incoming particle

Z,A = charge and atomic number of material

β = v/c = incident particle velocity

m_e = electron mass

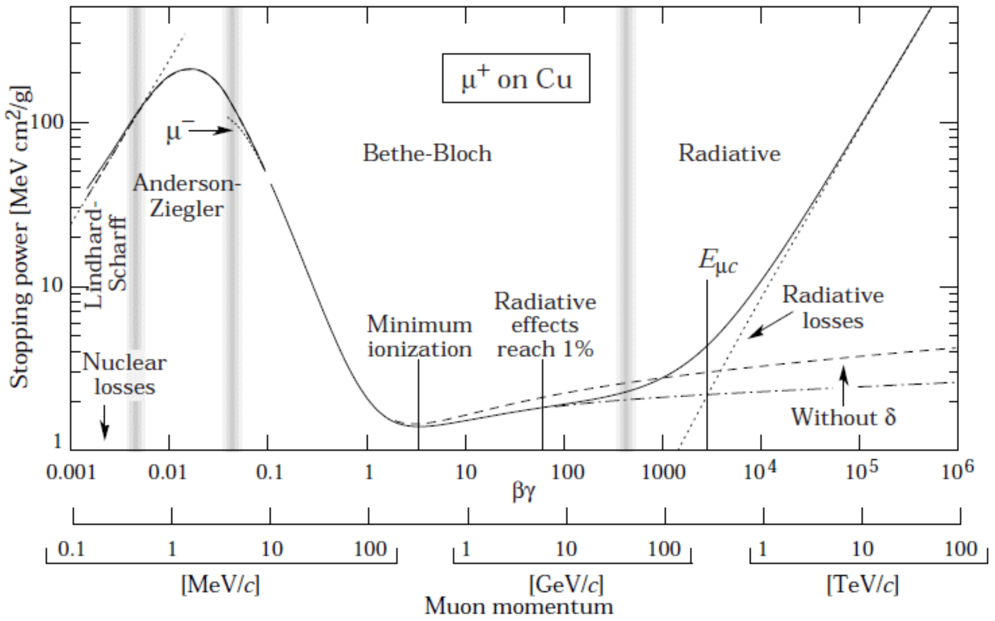
$\gamma = 1/\sqrt{1-\beta^2}$ =Lorentz factor

$W_{max} = T_{max}$ = maximum transfered energy in 1 collision

I = Average excitation energy

δ = correction term: density correction factor

C = correction term (not the speed of light !)



https://www.researchgate.net/publication/48410683_Search_for_New_Physics_with_ATLAS_at_LHC_-_Z'_dilepton_resonance_at_high_mass

Beta distribution

$$\beta = \frac{v}{c} = \frac{P}{E}$$