Timing - Semi Digital Hadronic Calorimeter
T-SDHCAL

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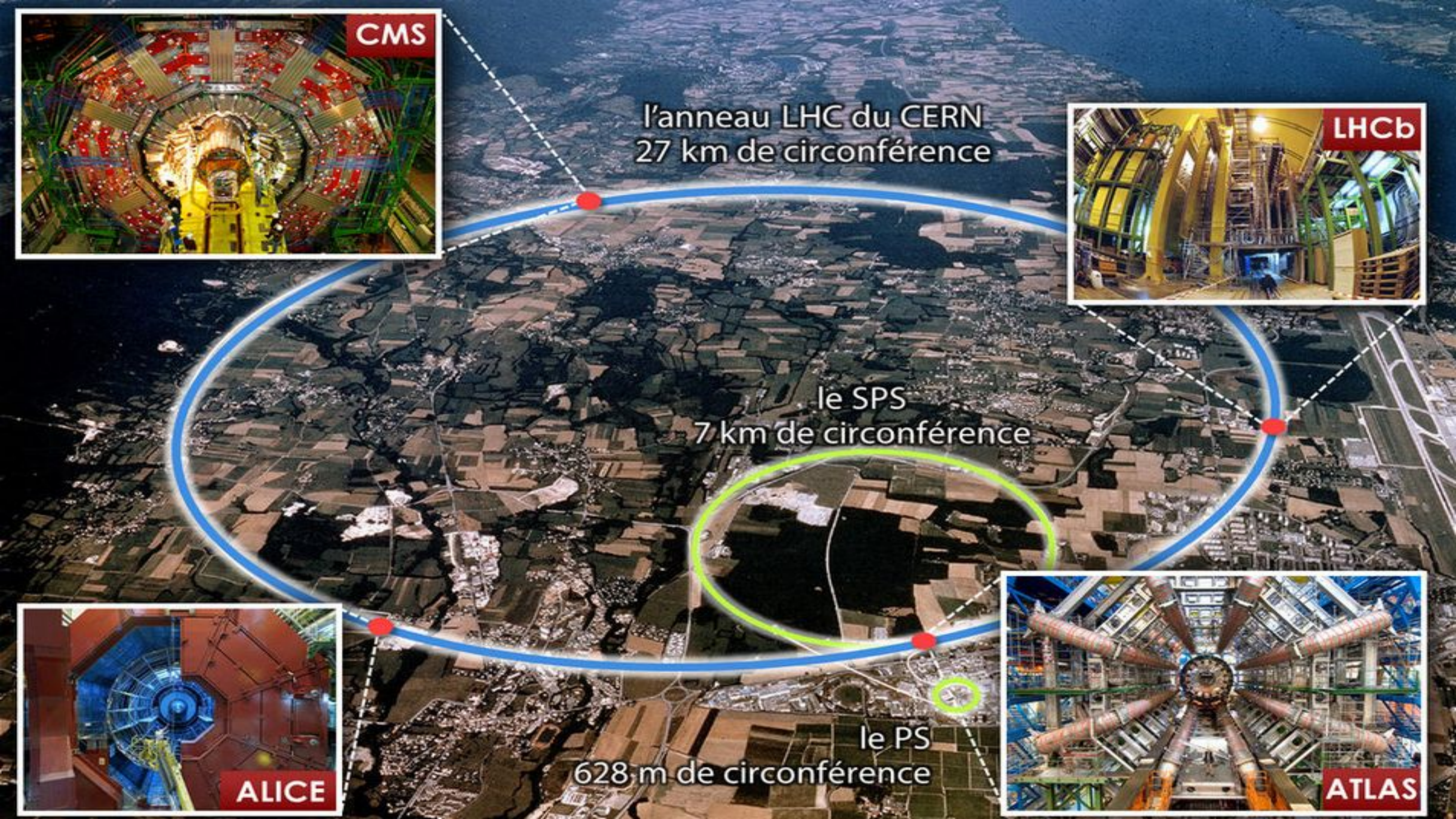
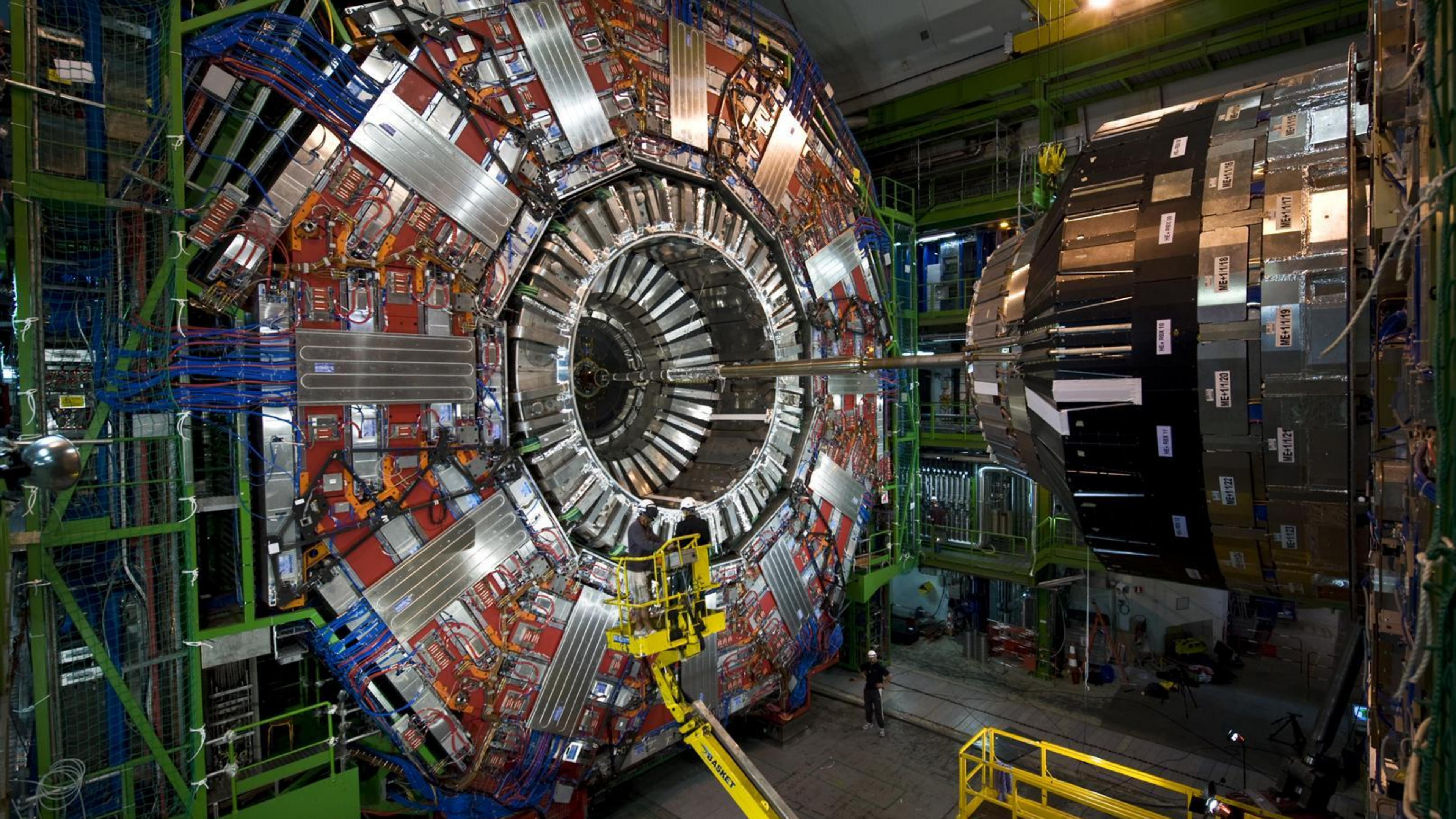
with Gerald Grenier and Imad Laktineh

PhD Days 23/04/2026


CMS
l'anneau LHC du CERN
27 km de circonférence
LHCb
le SPS
7 km de circonférence
ALICE
le PS
628 m de circonférence
ATLAS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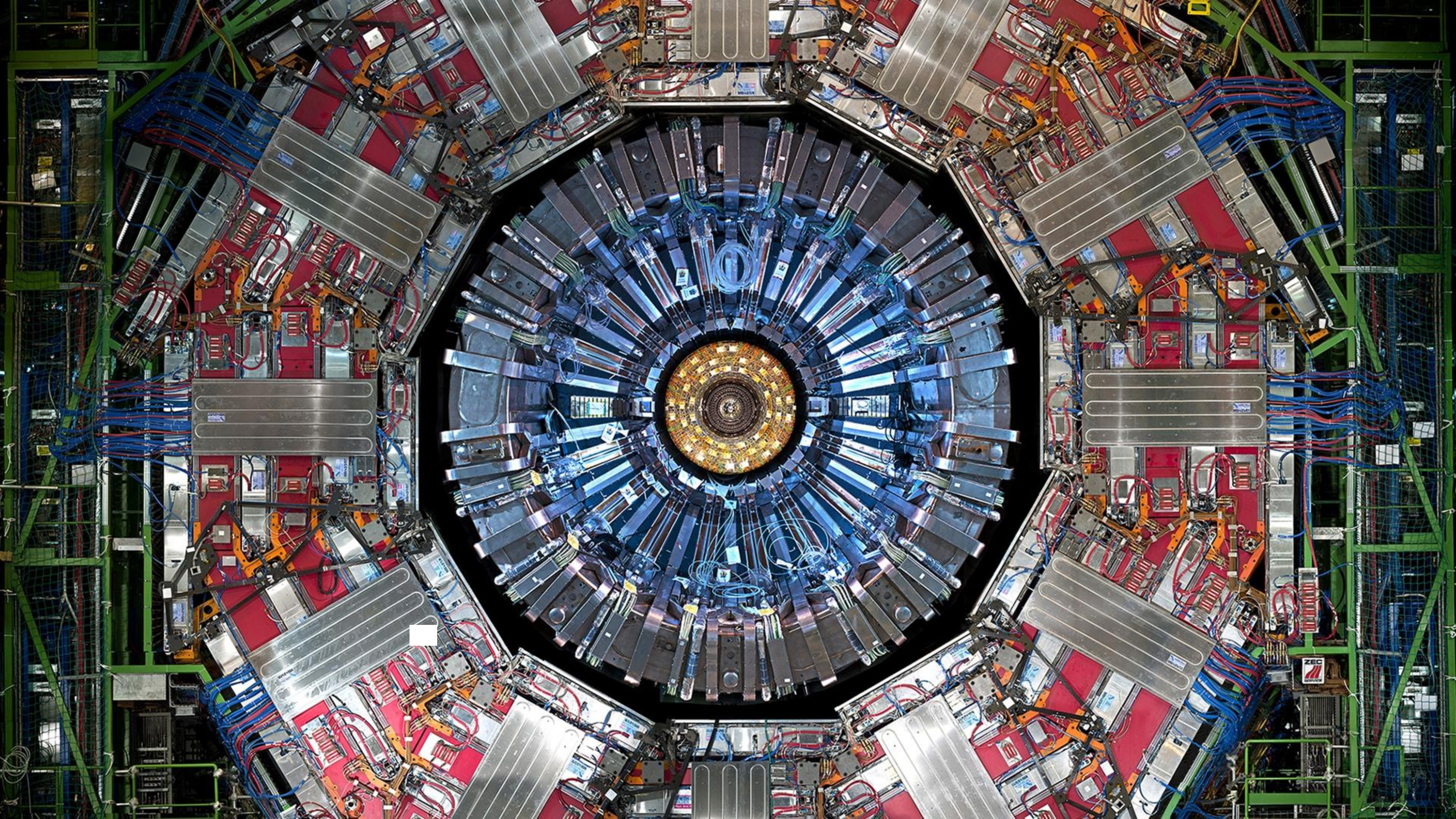
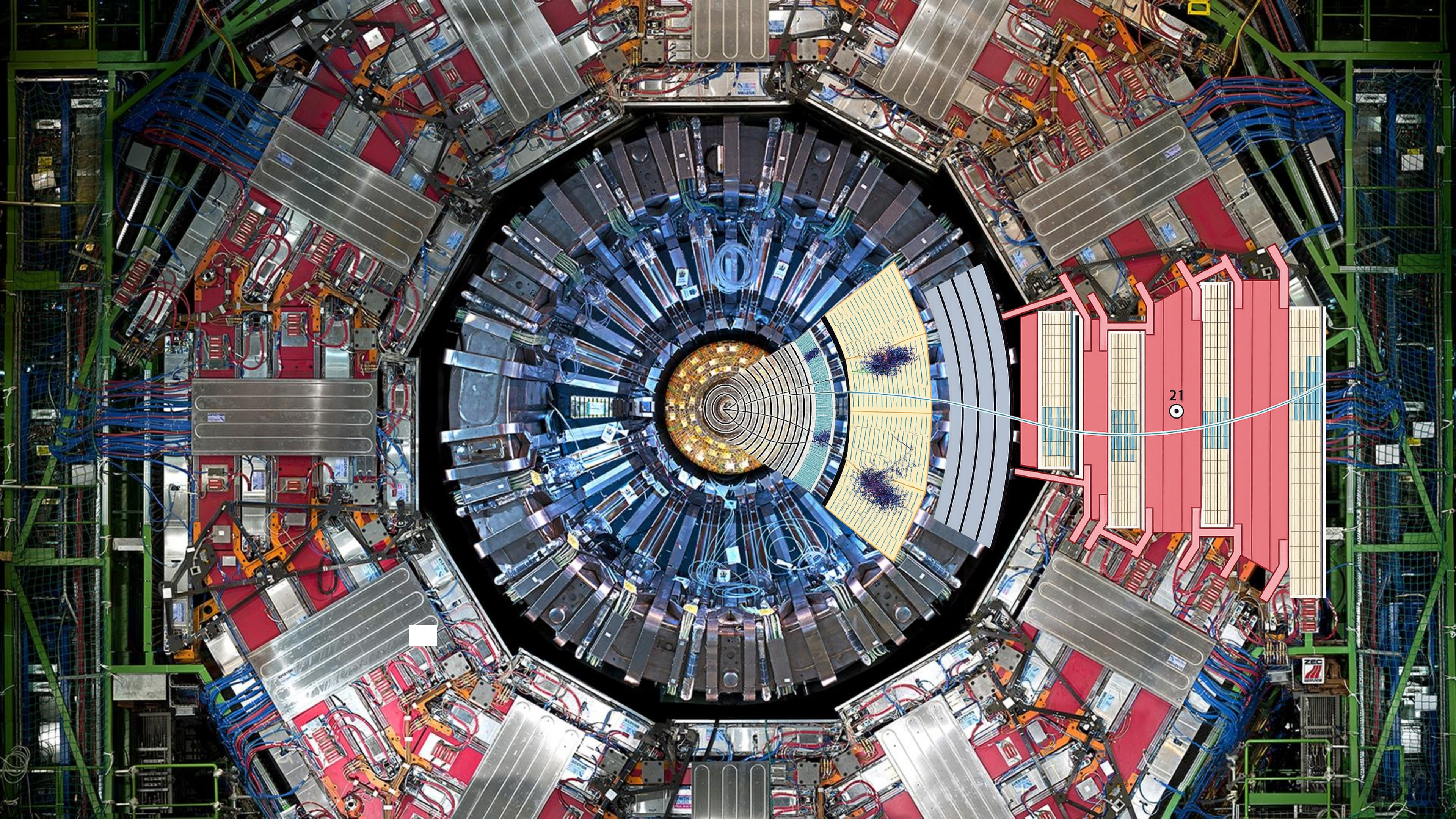
BASKET

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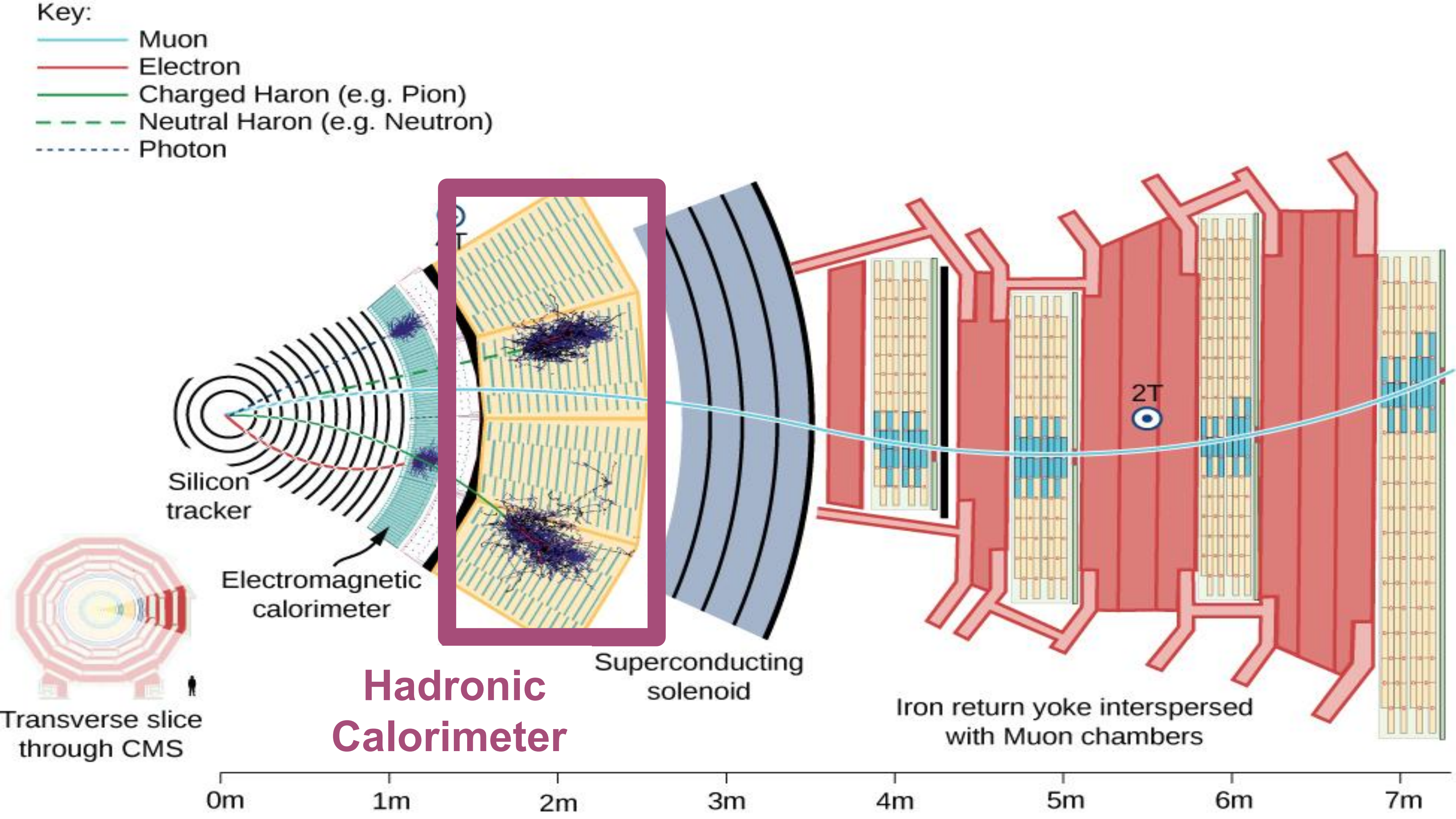
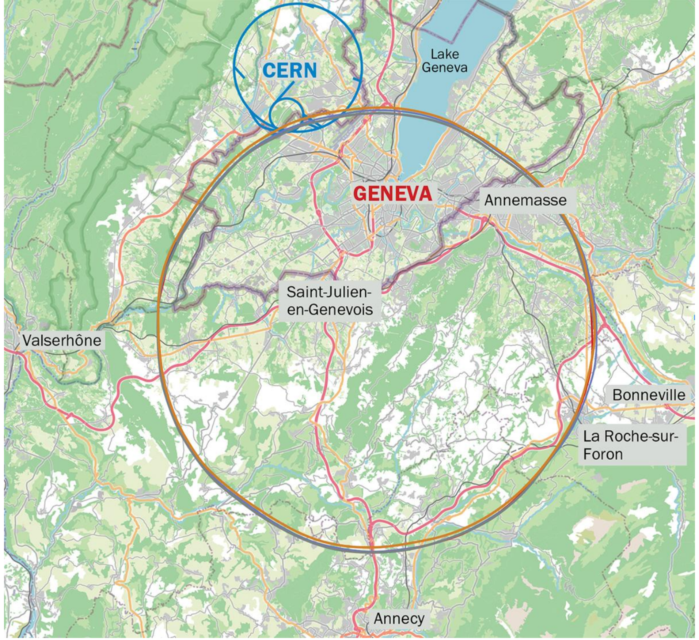
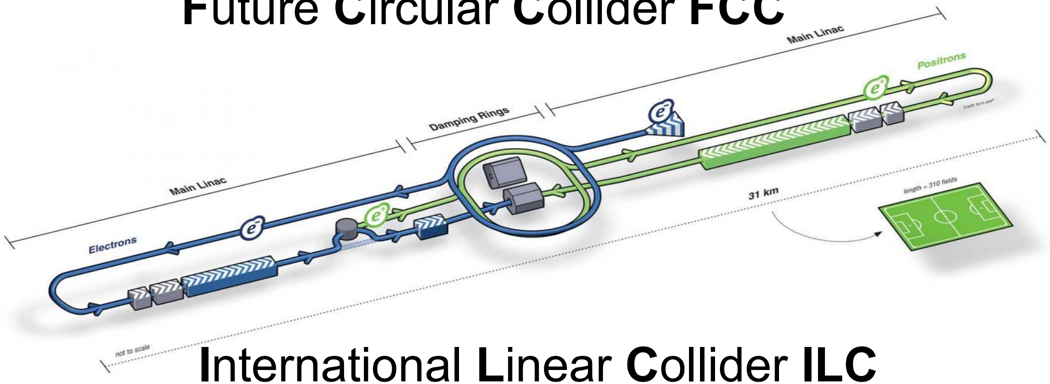


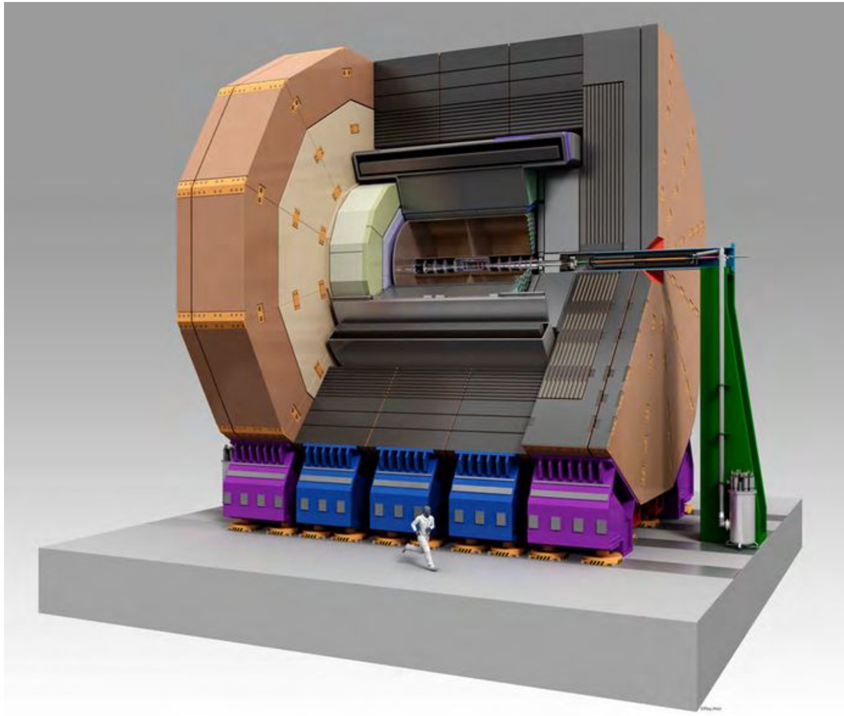
Key:
Muon
Electron
Charged Haron (e.g. Pion)
Neutral Haron (e.g. Neutron)
Photon
4T
2T
Silicon tracker
Electromagnetic calorimeter
Hadronic Calorimeter
Superconducting solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS
0m
1m
2m
3m
4m
5m
6m
7m



Future **C**ircular **C**ollider **FCC**



International **L**inear **C**ollider **ILC**

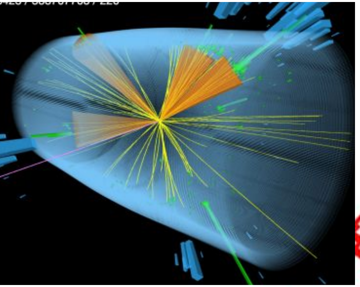


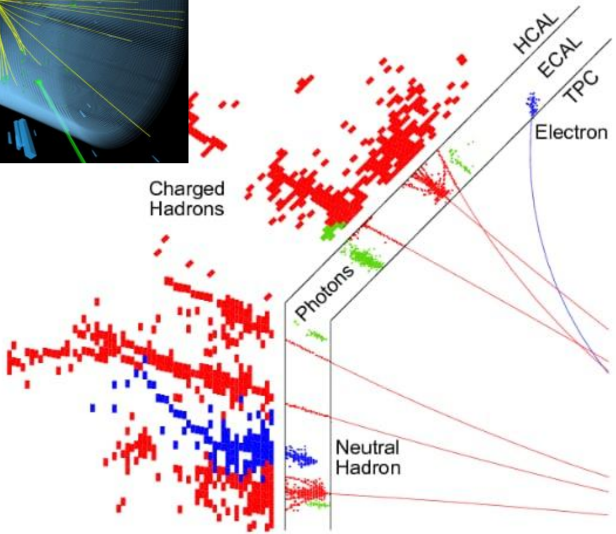
International **L**arge **D**etector **ILD**

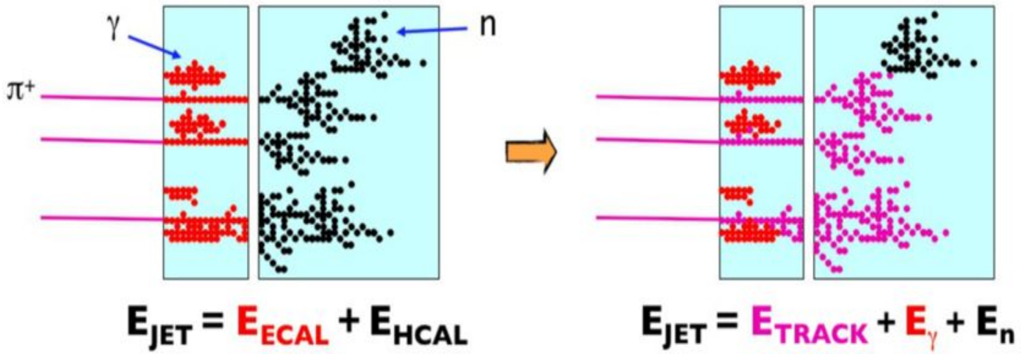
Traditional vs **Particle Flow Algorithms PFA** Calorimetry

In a typical jet :

- 60% of jet energy in charged hadrons
- 30% in photons (mainly from $\pi^0 \rightarrow \gamma\gamma$)
- 10% in neutral hadrons (mainly n / K_L)







Traditional calorimetry :

- Measure jet energy only in ECAL/HCAL
- ~70% of energy measured in HCAL
  - $\sigma_E/E \sim 60\%/\sqrt{E(GeV)}$

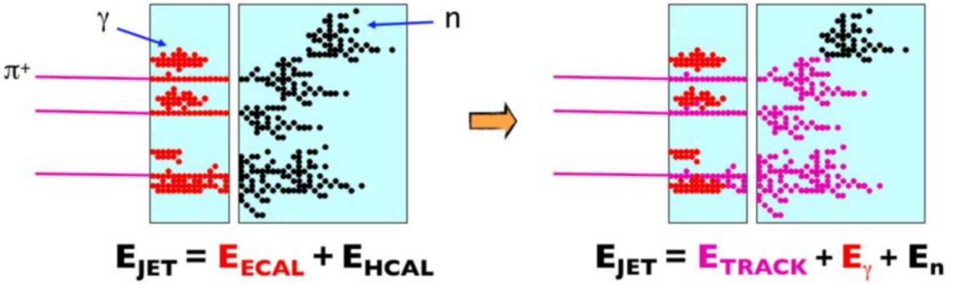
PFA calorimetry :

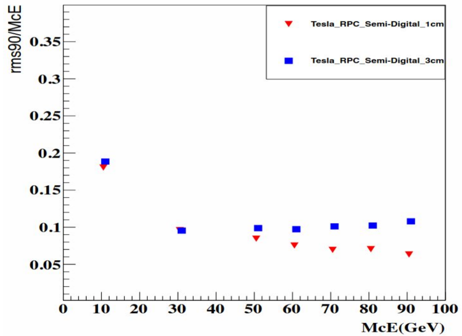
- Charged particles momentum measured in tracker
- Photons energies measured in Ecal
  - $\sigma_E/E \sim 20\%/\sqrt{E(GeV)}$
- Neutral hadron energies measured in HCAL ~10%

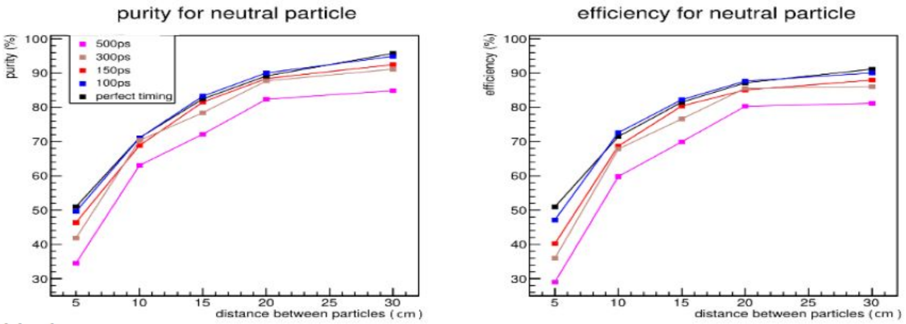
↳ **much improved jet energy resolution**

Spatial and Temporal resolution benefits for PFA

- **High granularity (spatial resolution)** helps to distinguish energy deposits from different particles
- **Timing at object level** could allow event pile-up mitigation and characterization
- **Timing at shower level** could improve particle identification and object reconstruction
- **Timing at cell level** could facilitate shower reconstruction and energy corrections leading to better energy reconstruction



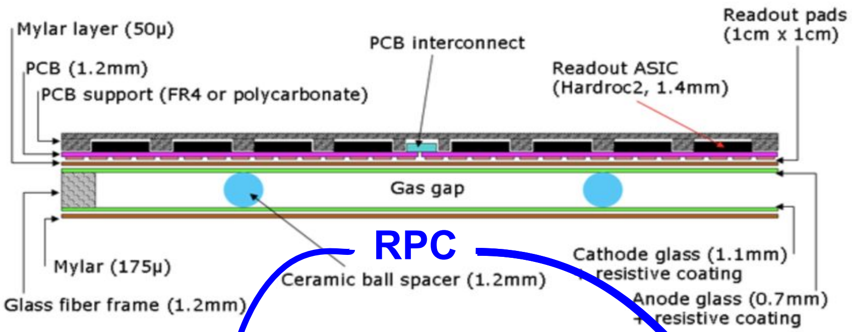




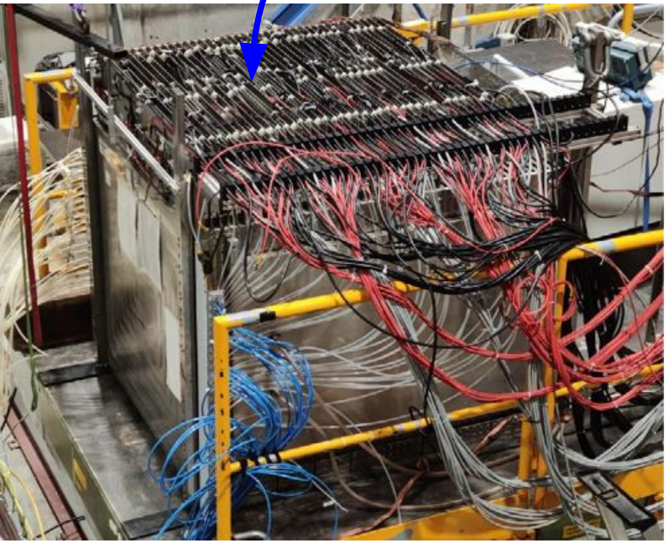
➡ Our goal is to achieve **100ps timing resolution**

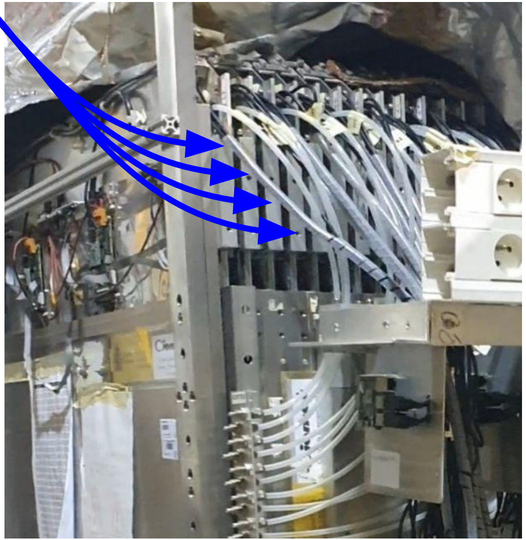
(Timing) - Semi Digital Hadron Calorimeter T-SDHCAL

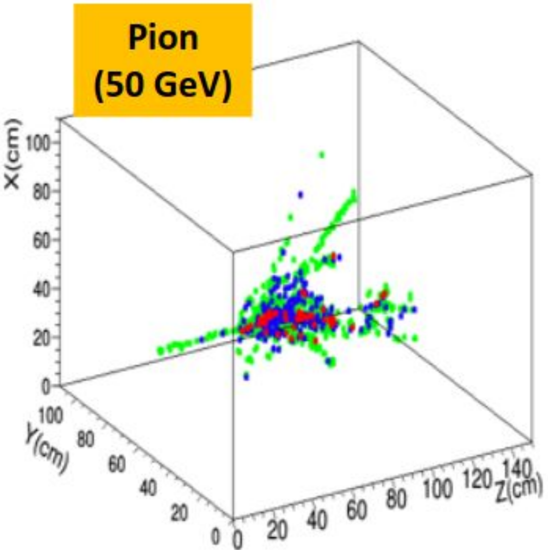
- **Gaseous detector** using **RPC** technology



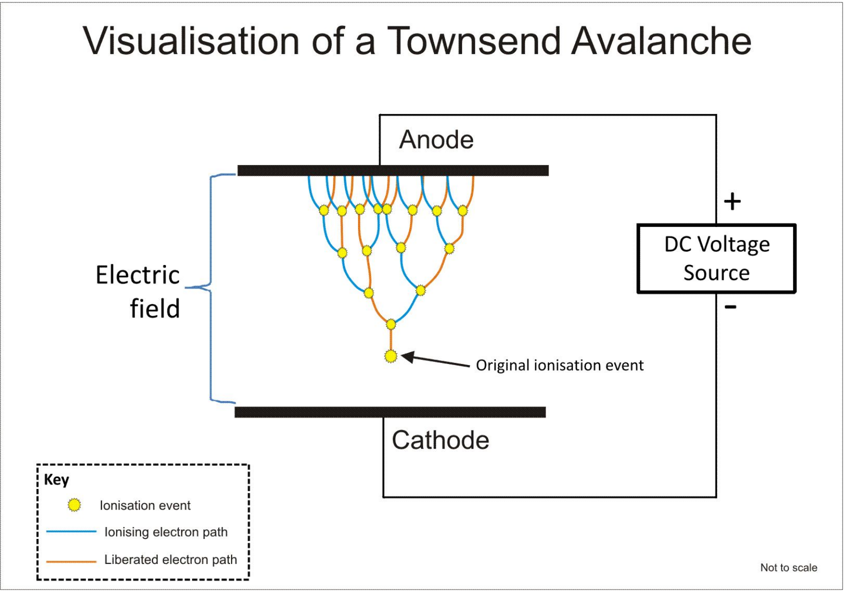
- **48-50 RPC layers** (~6λ_I); **~1.3m³ prototype**
- **RPC gas mixture** : TFE (93%), CO2 (5%) and SF6 (2%)
- **1cm x 1cm granularity**; ~450k channels
- **3-threshold readout** with 64-ch HARDROC ASICs
- Designed originally for **ILC** (**I**nternational **L**inear **C**ollider)
- In adaptation for future circular colliders (**FCC**, CEPC)
  - ↳ **Includes time information** thanks to **RPC -> MRPC**

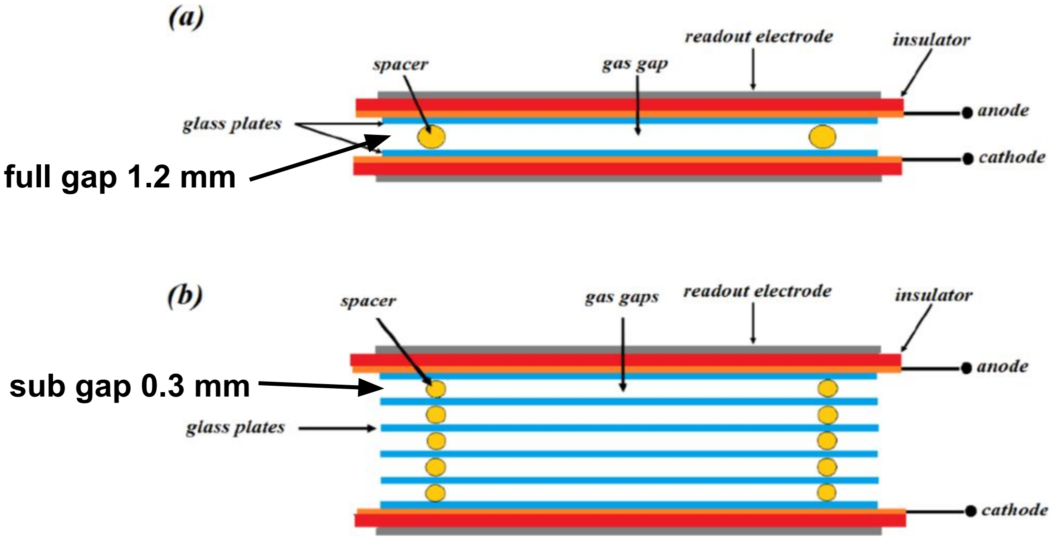






RPC and **MRPC** : **M**ultigap **R**esistive **P**late **C**hamber
From Physics Principles to Signal Production





1. Primary **ionisation** -> Creation of e- A+ pairs
2. Electric field -> Avalanche (**Amplification**)
3. Charge displacement -> Current -> **Electric signal**

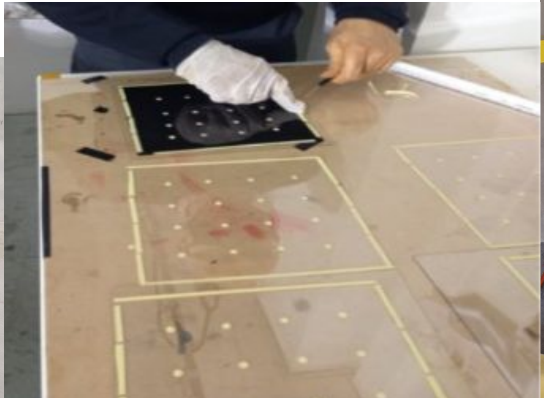
- Approximately same total gas thickness **(NOT SCALED)**
- Signal : sum of sub-gaps contributions
- Less dispersion thanks to thinner sub-gaps

➡ **Better time resolution**

MRPCs prototypes construction at IP2I

1. Cut of **330µm thick glass plates** (from 1mx1m to 50cmx33cm)
2. Application of **conductive paint** on the external glass plates
3. Production of circular and rectangular **mylar spacers**
4. Placement of spacers in a **tiled pitch pattern** on glass plates
5. Realization of **gas inlets** and **outlets**
6. Cut and placement of **epoxy sticks to support the structure**
7. **Stack** of all the glass plates
8. **Sealing** of the detector using **silicone**
9. Connection to **high voltage** by copper strip




Tests of the **MRPCs**

Source : **Cosmic muons**

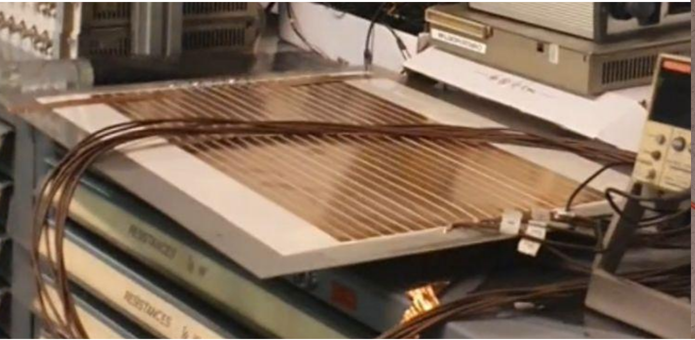
- Naturally available
- But low flux
- And uncontrolled timing

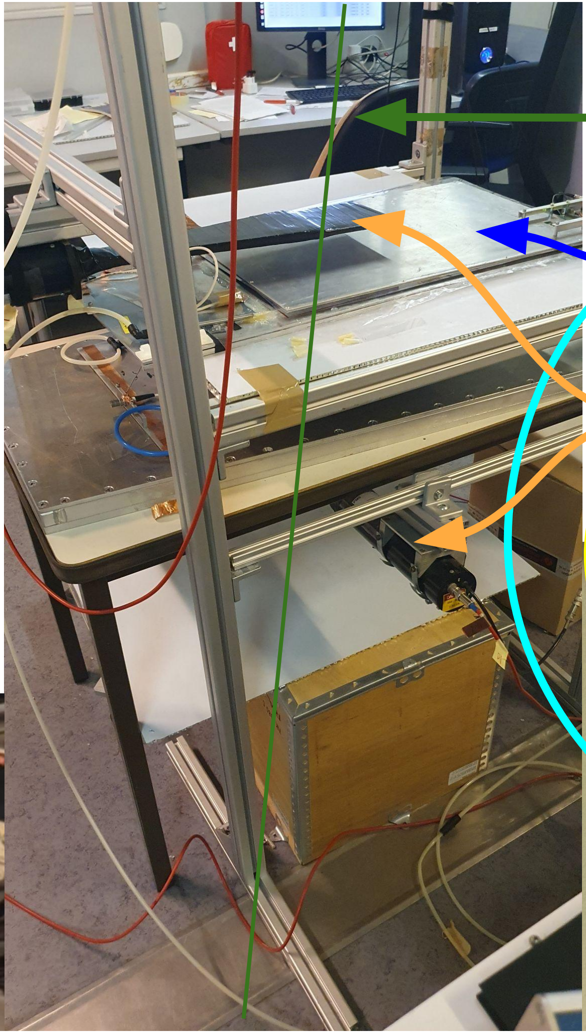
Trigger : **PMs in coincidence**

- Clean trigger
- But reduced acceptance

Electronics

- PCB with copper strips
- Oscilloscope

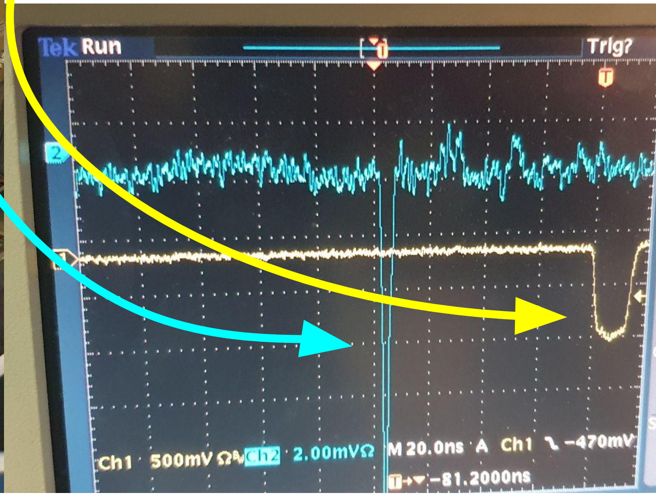




Cosmic muon

MRPC + Electronics

Photomultipliers



Characterization of the **MRPCs**

Threshold

- MRPC signal ≥ threshold ▶ **hit**

Electronics

- PCB with 1 x 1cm^2 copper pads
- Read out by 64-ch HARDROC ASICs

Efficiency

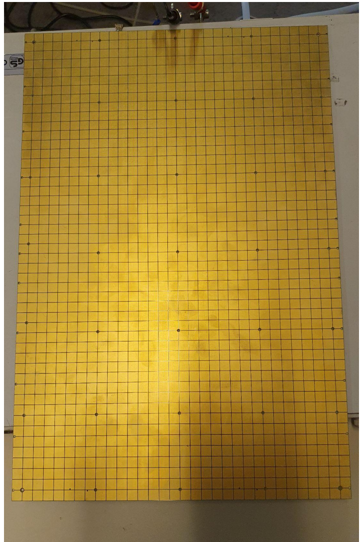
- Trigger-correlated hits / triggers (%)

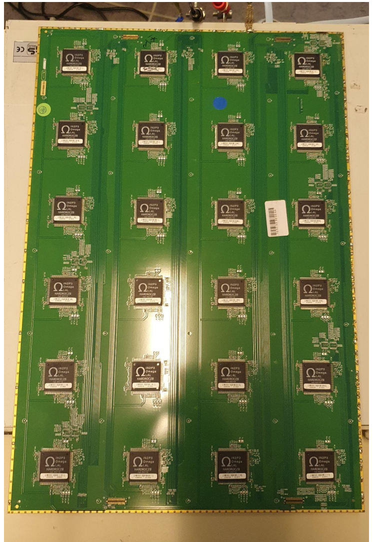
Noise

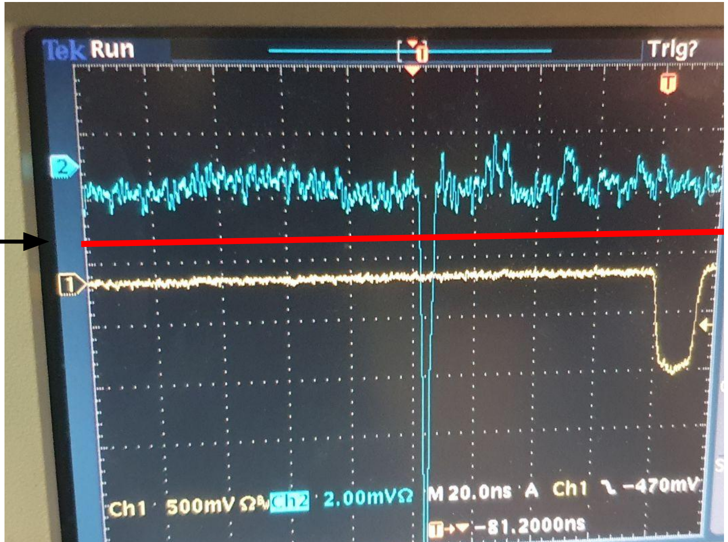
- Non-trigger-correlated hits per pad (Hz)

Timing

- Correlated with leading-edge slope







Characterization of the MRPCs - Efficiency and Noise plots

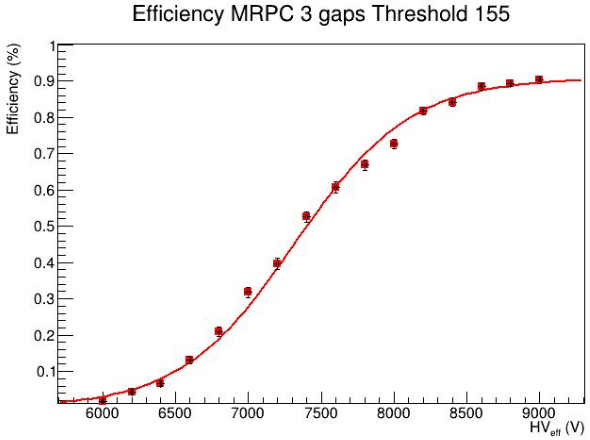
Voltage Scan :

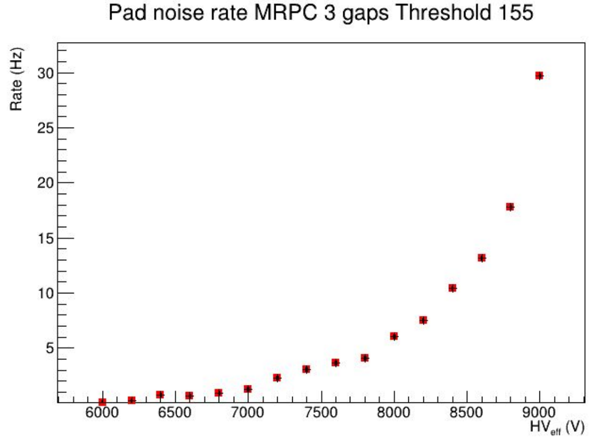
- At **low voltage**, the electric field is too low for the primary ionizations to start avalanches, **no signal detected**
- At **medium voltage**, the probability of primary ionizations starting avalanches is increasing rapidly with the voltage, **transition regime**
- At **high voltage**, all of primary ionizations start avalanches, **efficiency plateau**

100% efficiency is never achieved because the probability of no primary ionizations is non zero.

Allows us to find the **Working Point** of the **MRPCs**:
$HV_{WP} = HV_{95\%} + 120V$, where $HV_{95\%}$ corresponds to the HV at which the efficiency reaches 95% of its maximum

Working Point at **lower voltage** means **less noise**





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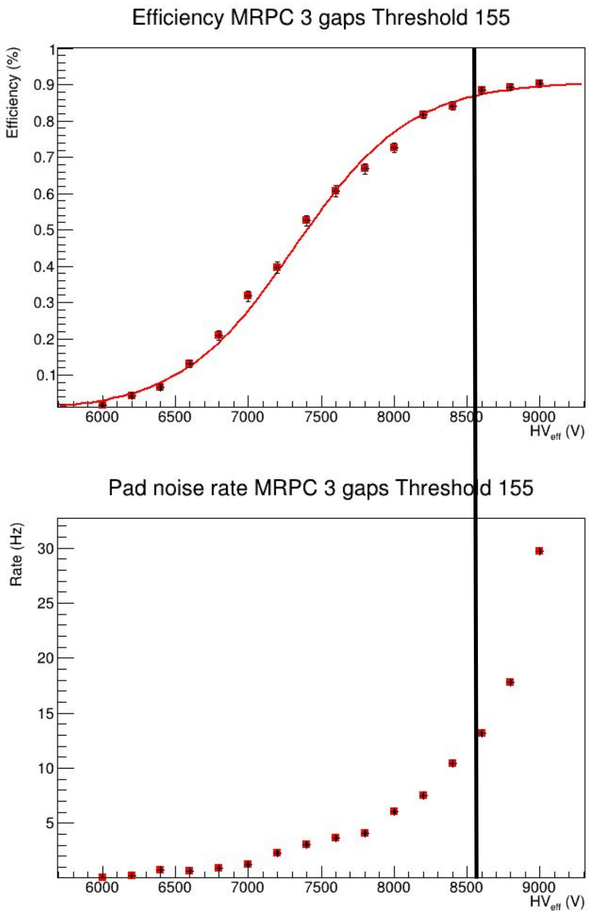
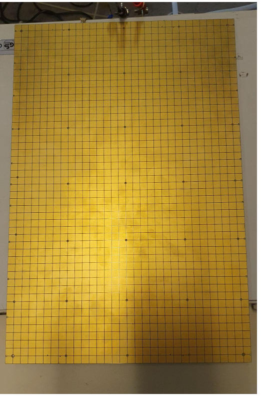
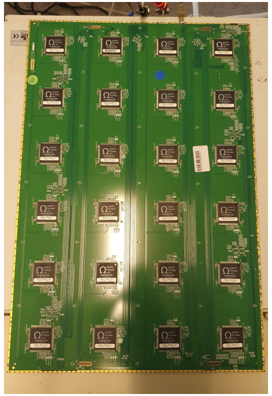


Characterization of the **MRPCs** - Noise study

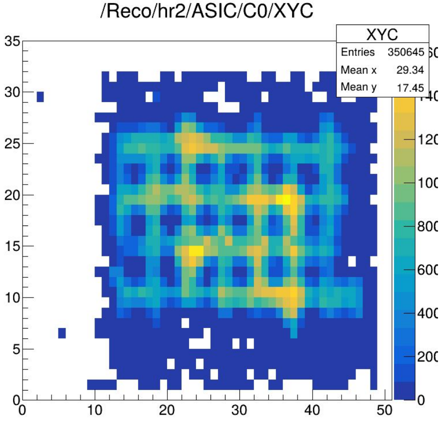


1cm² pads

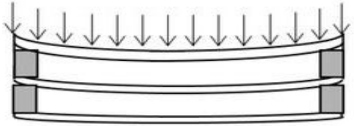


ASICS

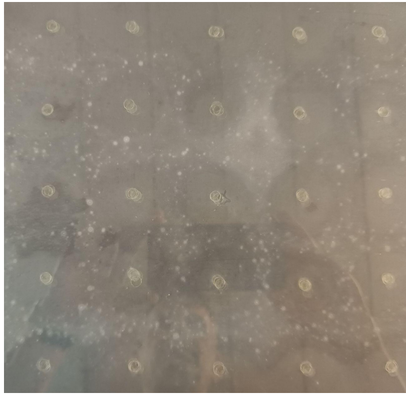
Signal recorded by 24 HARDROC ASICs 64 channels (1 channel = 1 pad 1cm²)



5cm pitch : **Noise structure**



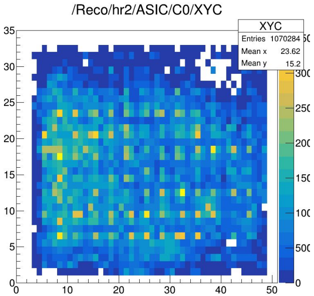
Glass deflection



5cm pitch
Visible HF deposits

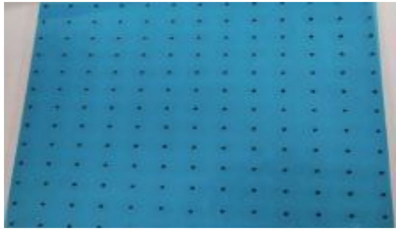
Spacers too far apart ► Glass deflection ► Higher EM field ► Discharges ► Creation of **hydrofluoric** acid (HF) ► **OUCH**

Quick solution :
Reduce 5cm pitch to 3cm pitch
-> **Noise factor reduction of 10**
BUT
-> Time consuming
-> More deadzone



3cm pitch : **No noise structure**

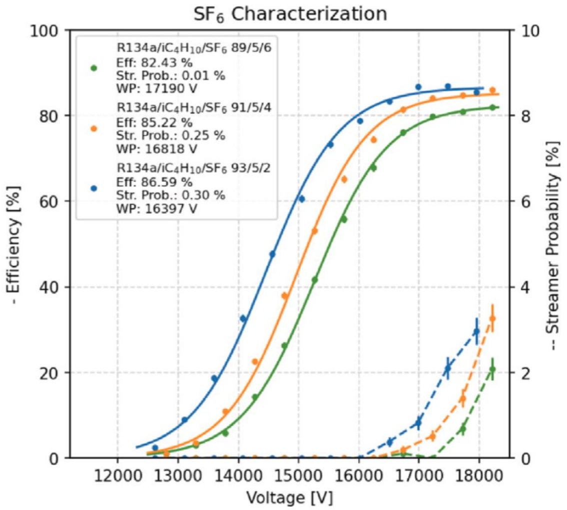
Long term solution :
Prepared sheet of finer spacers pitch
-> Time efficient
-> Less deadzone

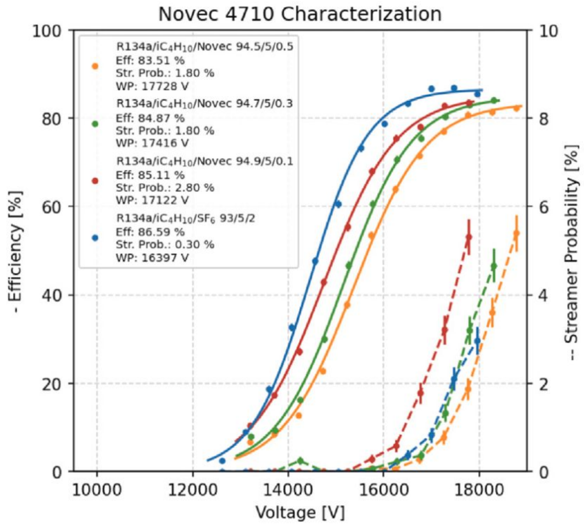


1.6cm pitch, 1.23% dead zone

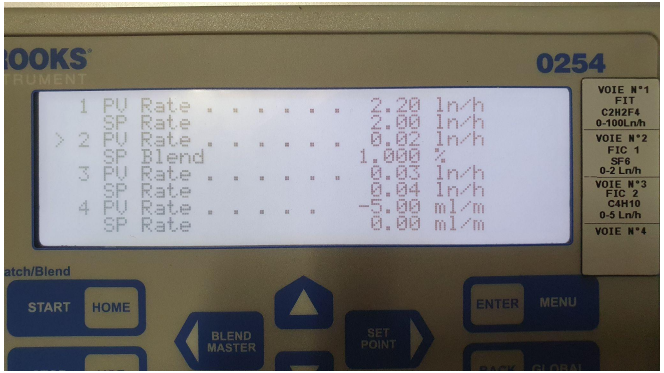
Characterization of the **MRPCs** - Gas mixture study

TFE (Fluor gas)	GWP = **~1400**	Low Ionization Potential (**93%**)
↳ HFO-1234z	GWP = **7**	Low Ionization Potential
Isobutane (or CO_2)	GWP = **3**	Photon Quencher (**5%**)
SF6 (Fluor gas)	GWP = **22800**	Electron Quencher (**2%**)
↳ NOVEC 4710	GWP = **~ 2000**	Electron Quencher





M. Verzeroli et al, NIMA 1078 (2025) 170591



Carrying out these gas studies at Lyon in the coming months is planned

Software - Energy Reconstruction

Linear dependence between **energy** and **number of hits** at low energies, then **saturation**

3 Thresholds = 2 bit (Semi-Digital)
Used to **correct saturation**

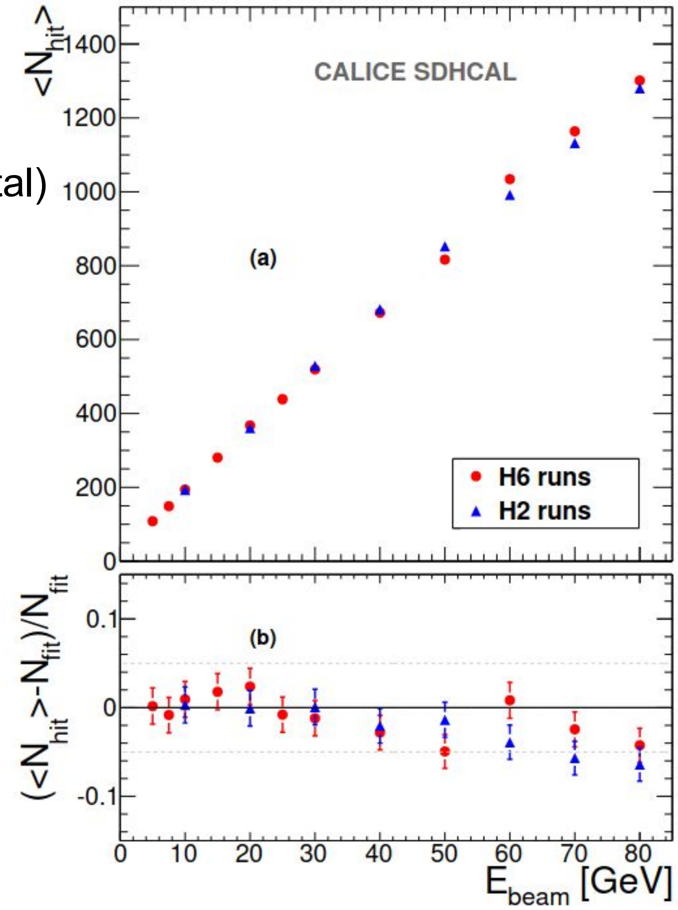
Classical formula

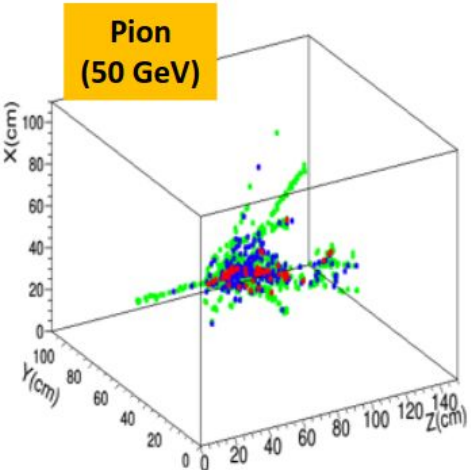
$$E_{reco} = \alpha_1 N_1 + \alpha_2 N_2 + \alpha_3 N_3$$

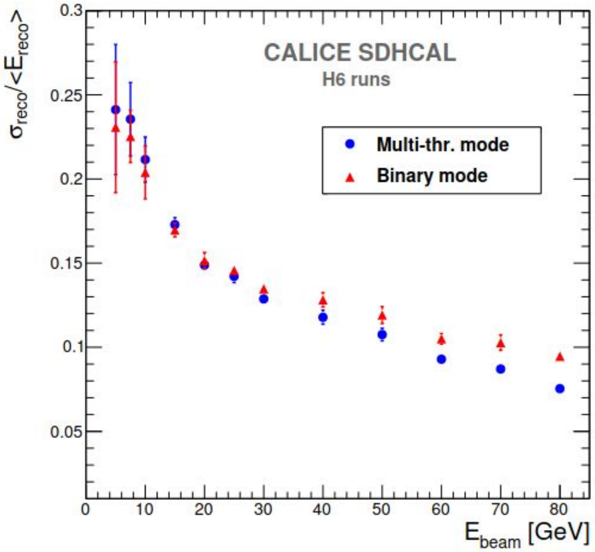
$$\alpha_i = a_i N_{hit}^2 + b_i N_{hit} + c_i$$

Boosted Decision Tree BDT
Event level features
coming from Physics Variables

Deep Learning models
Hit level features
Position, Threshold, Timing







Software - Energy Reconstruction - Analysis Setup

Simulated single particles in the (T)-SDHCAL prototype

- **Particles type** : 100k π- or 100k proton
- **Initial position and incident angle** : centered in X-Y with a little gaussian in incident angle
- **Applied cuts** : remove hits with time > 10ns, remove events that did not start showering within the (T)-SDHCAL
- **Smearing of 100ps** for time information

Continuous Datasets for training :

- **Uniform energy from 1MeV to 100GeV**

Discrete Dataset for testing :

- **Discrete energy from 5GeV to 80GeV each 5GeV**

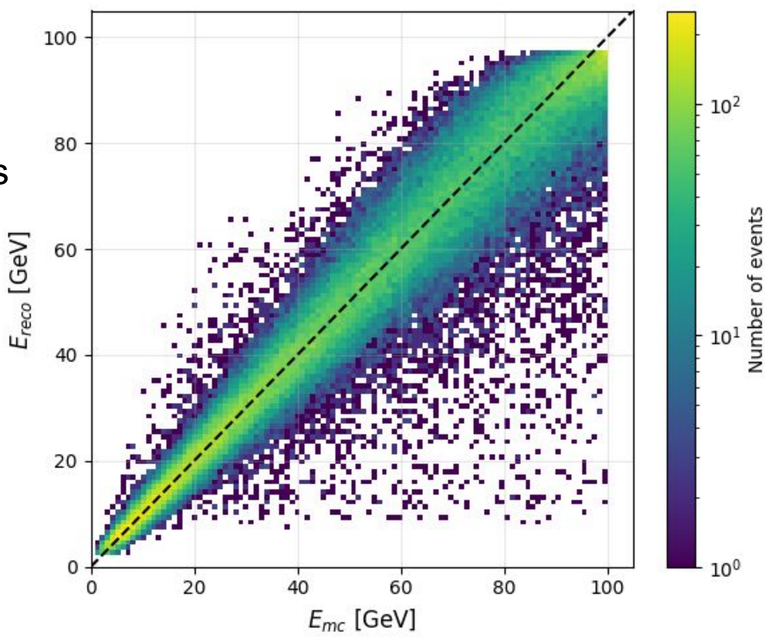
Machine Learning model used :

- **Point cloud based model**

Inputs : Hits as nodes

- Hit level features : **Position, Threshold, Timing**
- Event level features : **Number of hits, ratio of threshold 3, number of hits in last layer, first interaction layer**

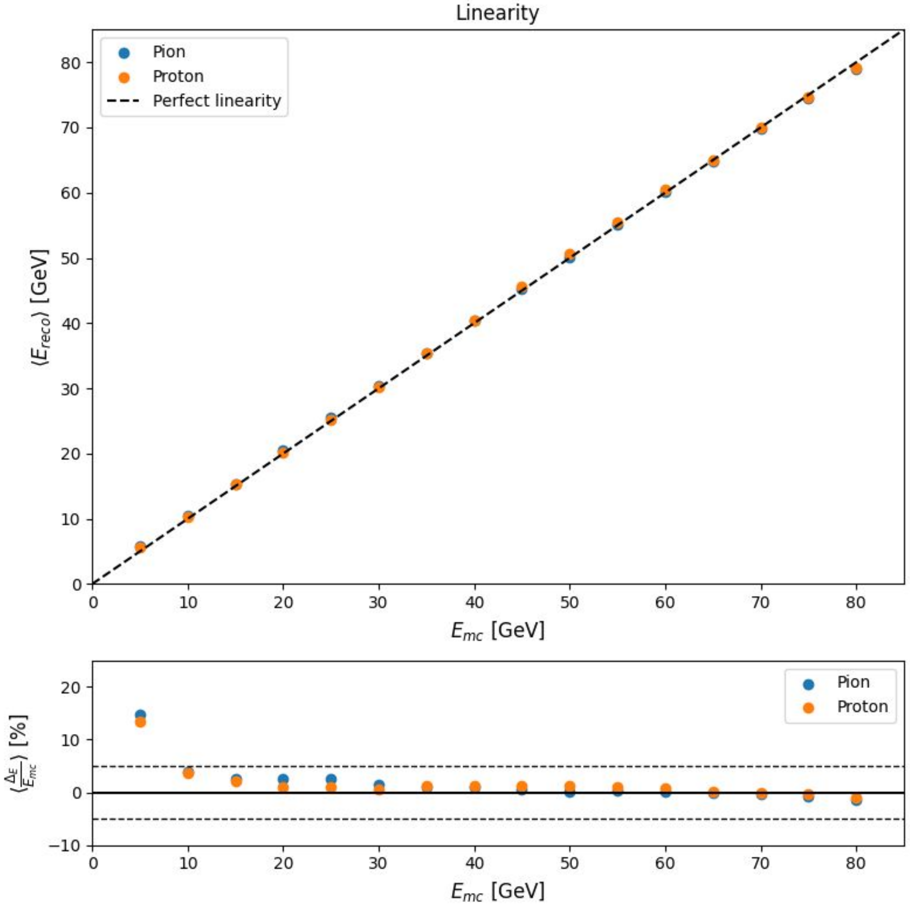
Single π-



Datasets :

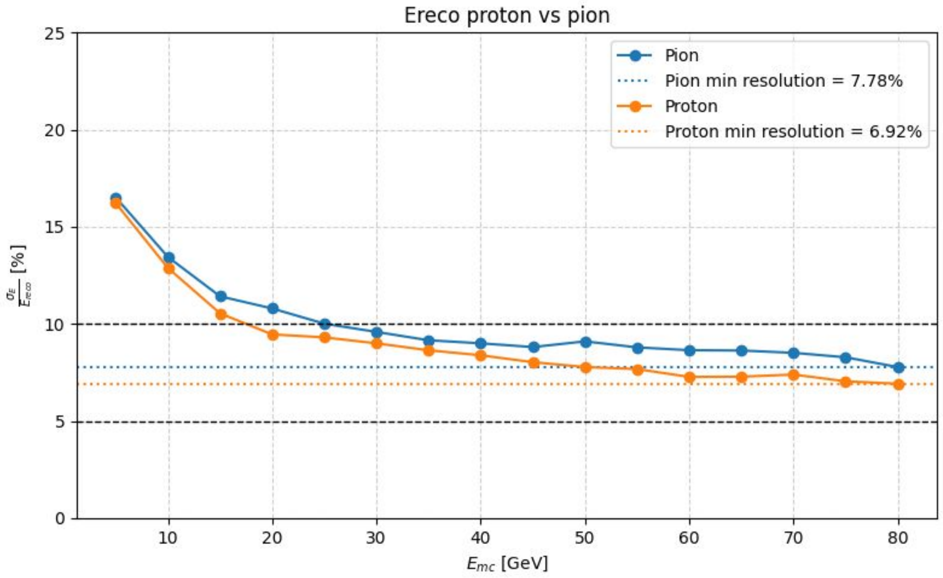
- Train on Continuous
- Test on Continuous

Software - Energy Reconstruction - Linearity and Resolution



<u>Datasets :</u>

- Train on **Continuous**
- Test on **Discrete**

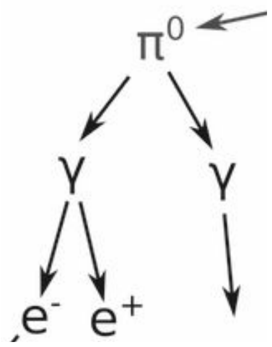


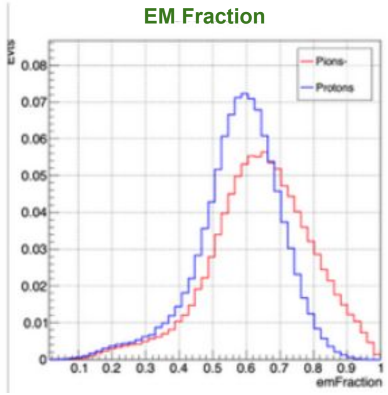
<u>Resolution defined as :</u>

- First gaussian fit giving μ_1 and σ_1
- Second gaussian fit in the $\pm 1.5\sigma_1$ range giving σ_2 as $\boldsymbol{\sigma_E}$ and μ_2 as $\mathbf{E_{reco}}$

Software - Particle Identification PID - protons/pi-

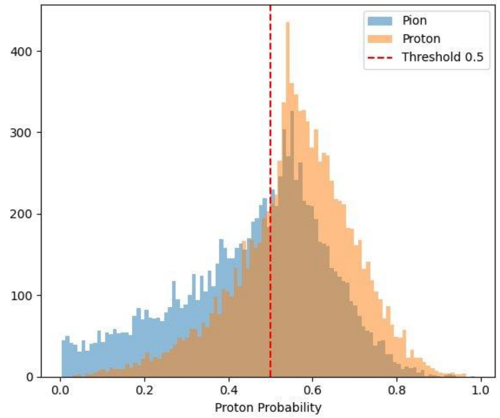
- **Charged pions** produce a lot of neutral pions, which decay only through photons
- The **electromagnetic fraction** is higher for **charged pions** than for **protons**
- **Protons** produce less saturation, leading to better energy reconstruction
- The next step consists in **using the hadron PID prediction to reconstruct the energy** with species-specific models.

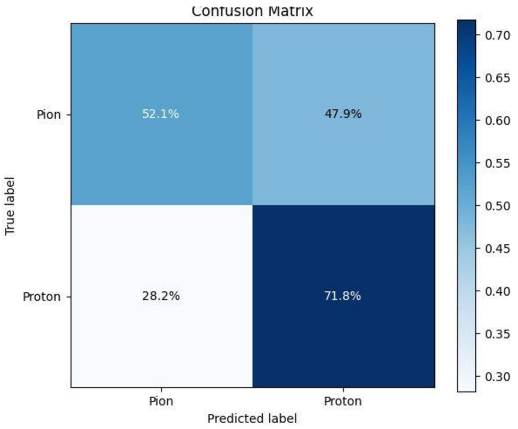




Datasets :

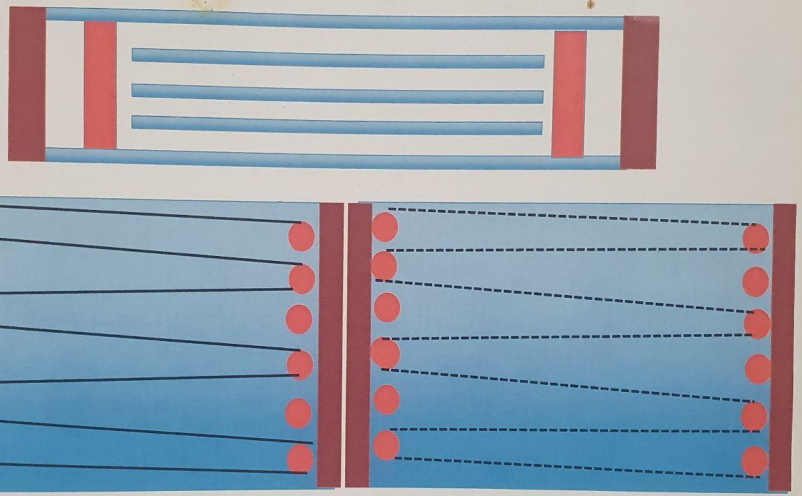
- Train on **Continuous**
- Test on **Continuous**





Thank you for your attention !

Backups



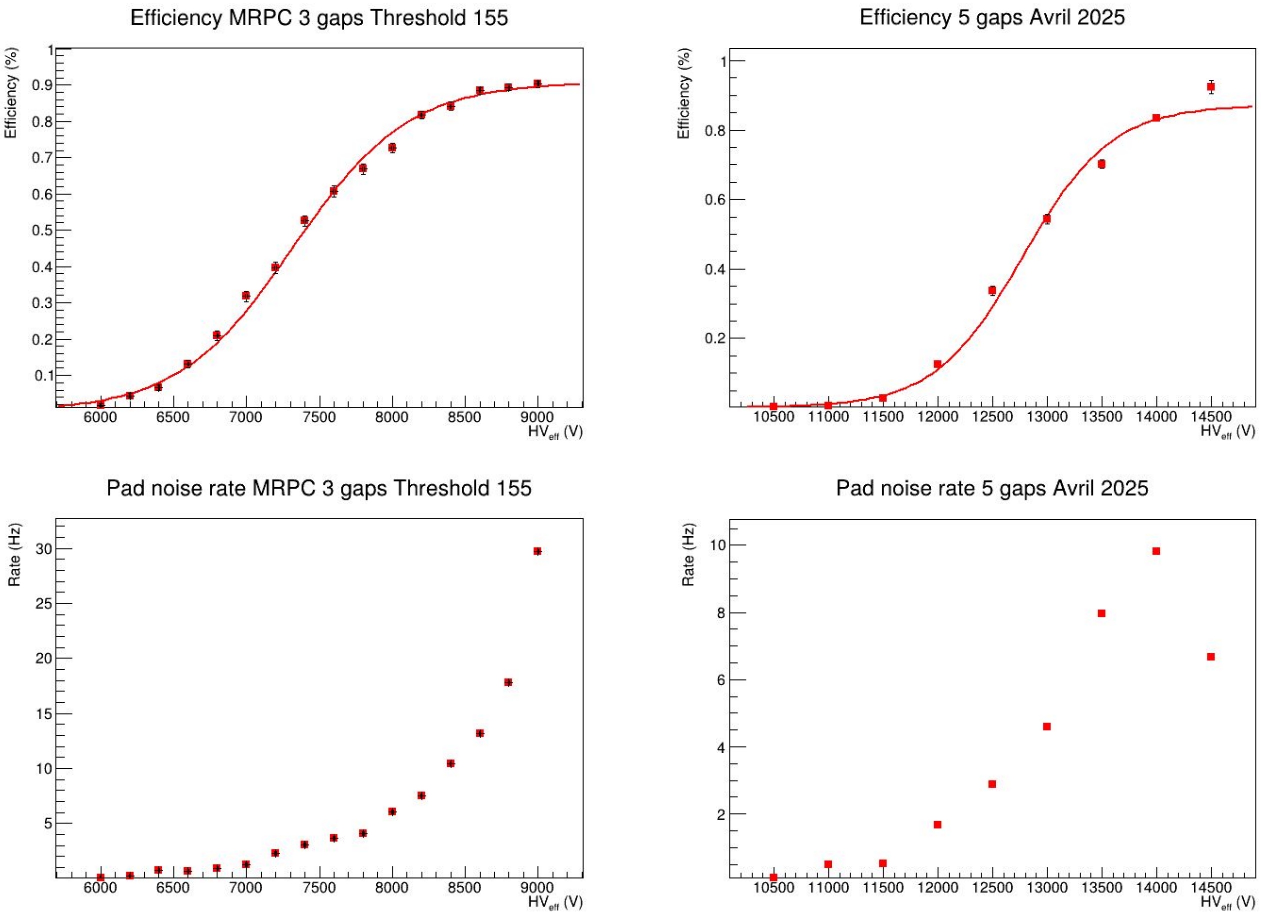
En noir, fils de pêche: A gauche séparation entre deux plans, à droite séparation dans le plan suivant pour alterner les supports. La chambre est fermée avec un cadre et le gaz es injecté entre le cadre (en violet) et les plots en rouge

Characterization of the **MRPCs** - Number of gaps study

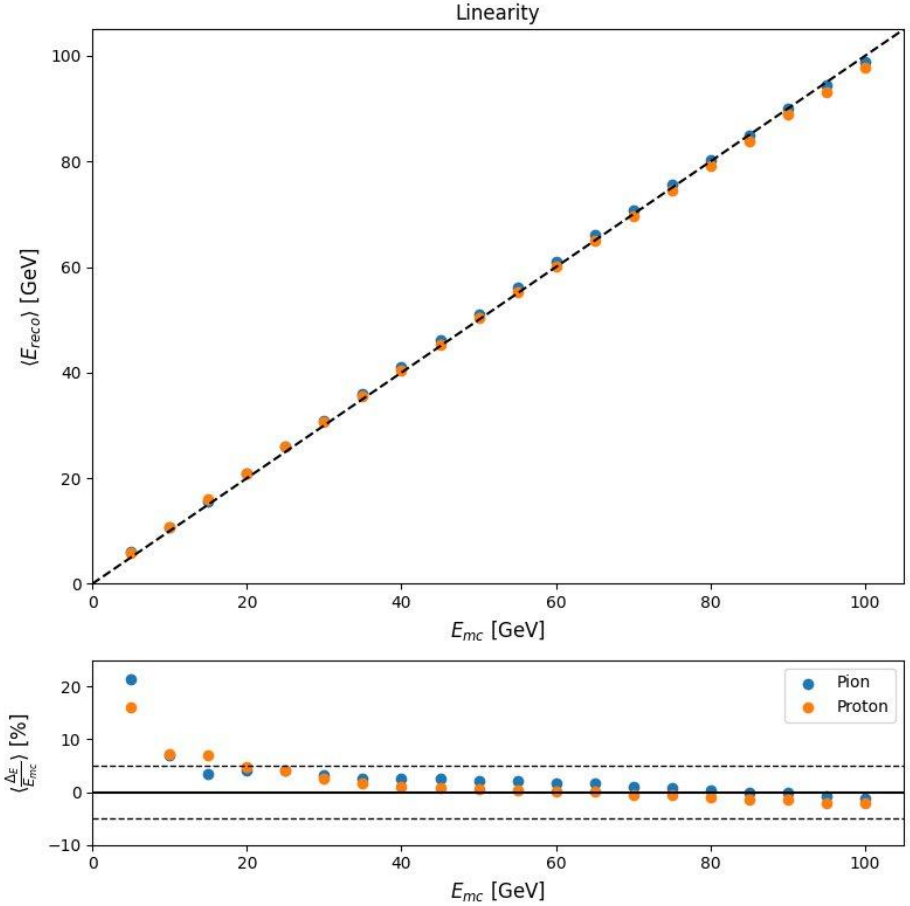
More gaps :

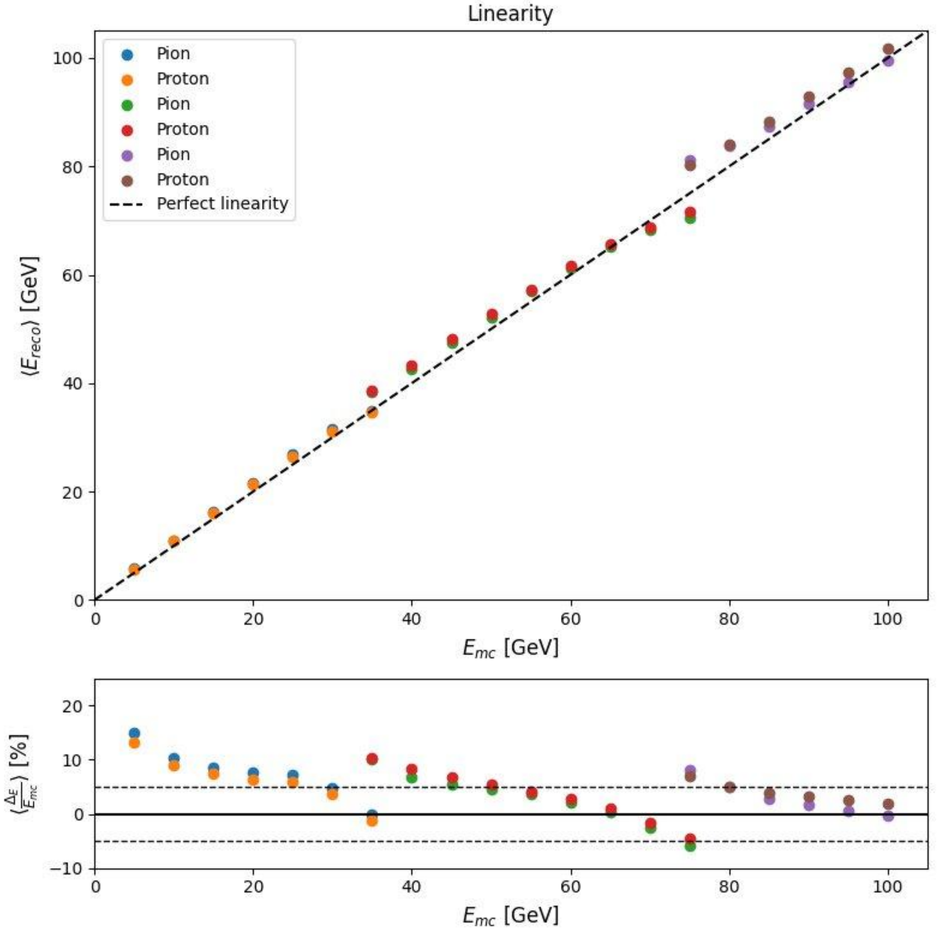
- **Pros**
  - Better efficiency for ~similar noise
  - Better timing resolution
- **Cons**
  - Harder to build
  - More expensive
  - Thicker cassette

The goal of the study is to determine **how many gaps** are needed **to achieve** the time resolution we aim at : **100ps**

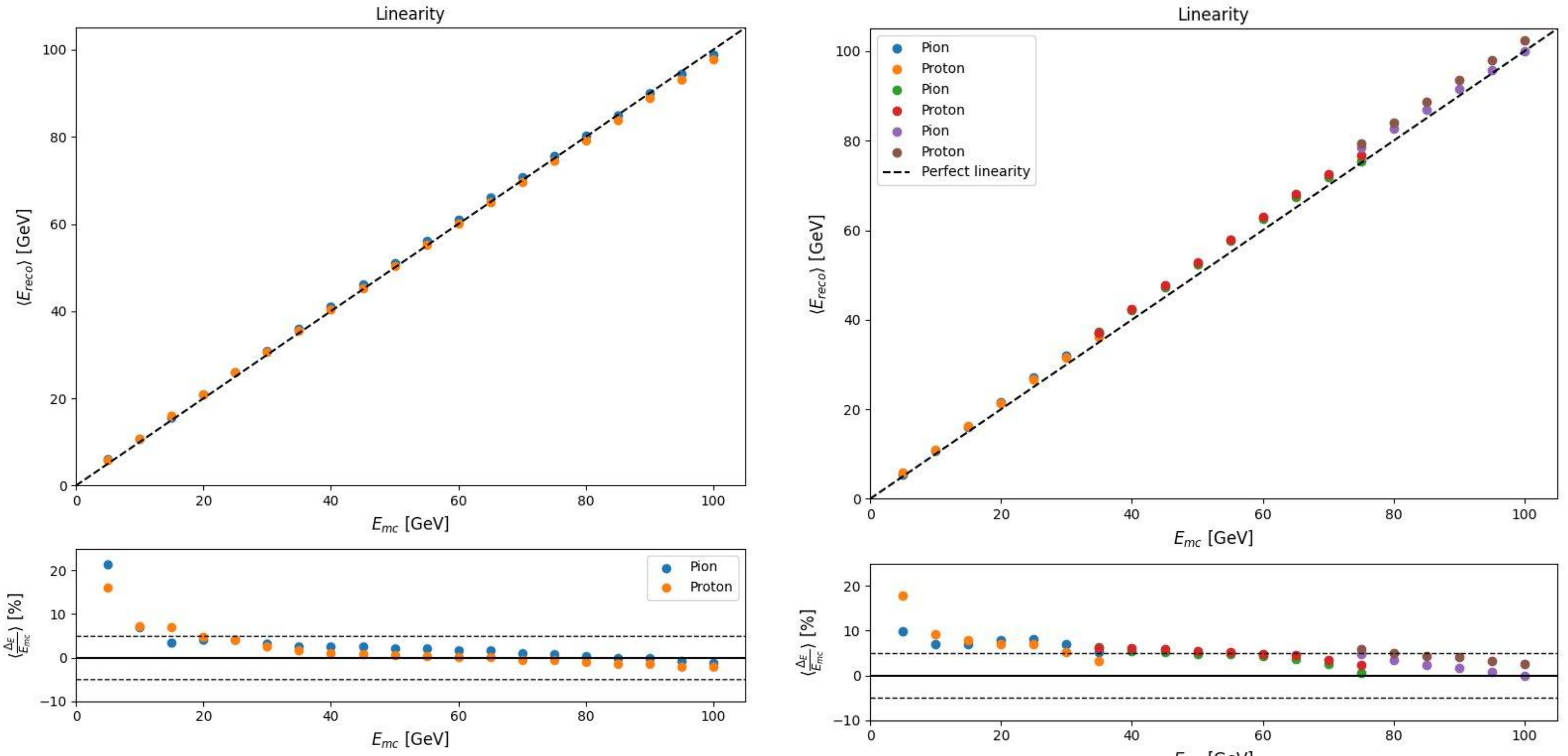


Software - Energy Reconstruction - Linearity multi models

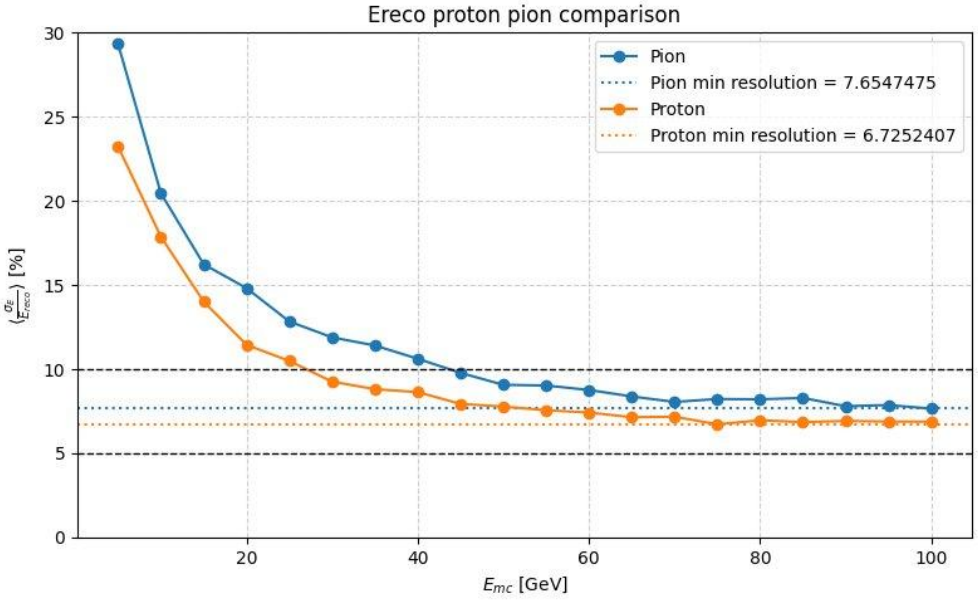


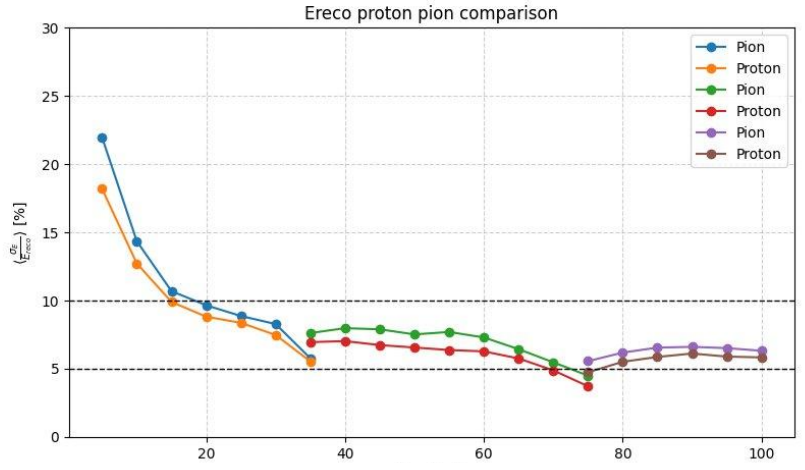


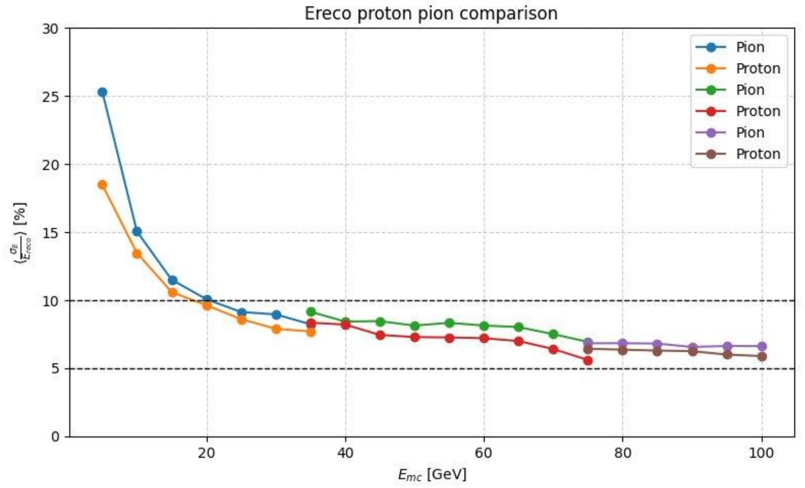
Software - Energy Reconstruction - Linearity multi models



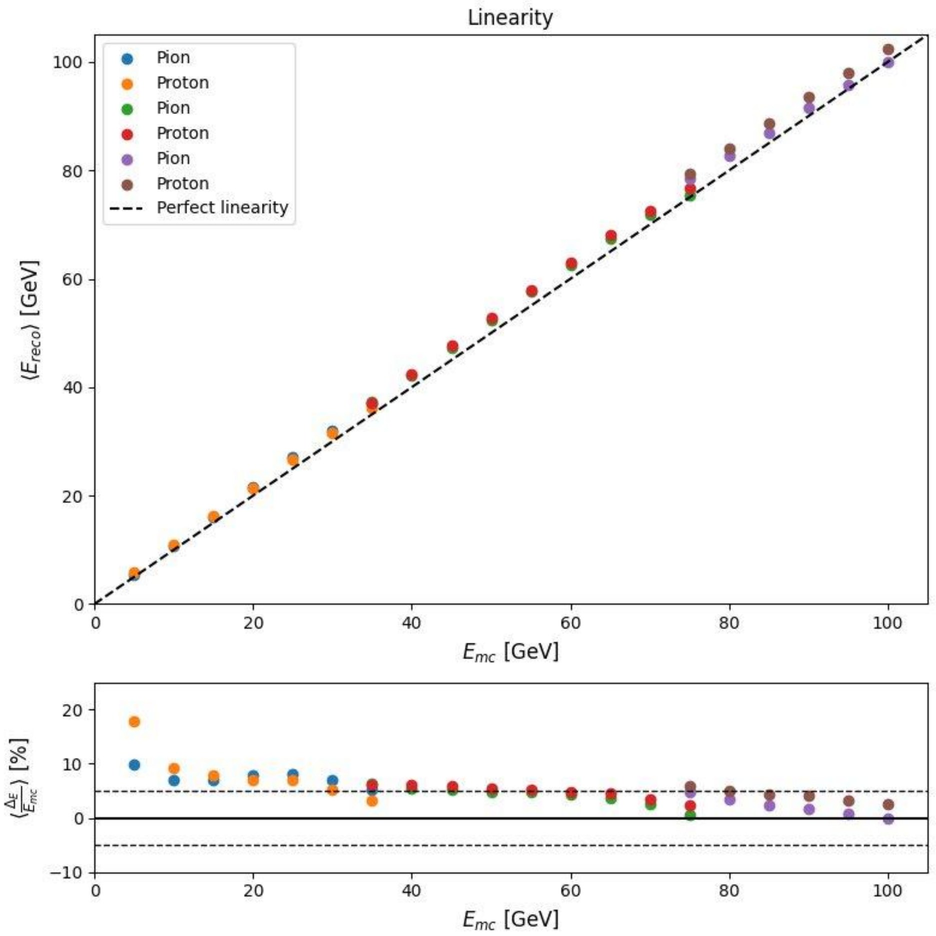
Software - Energy Reconstruction - Resolution multi models



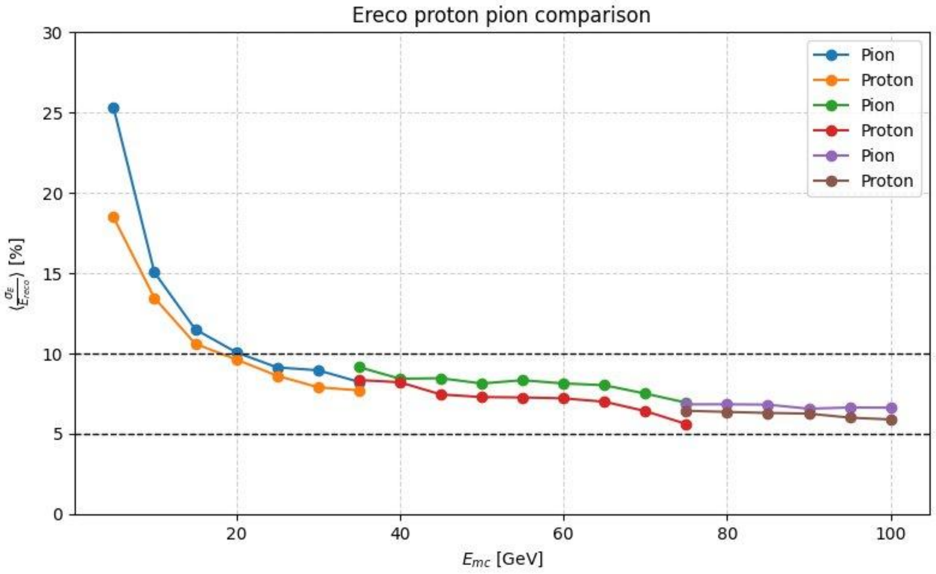




Software - Energy Reconstruction - Linearity and Resolution

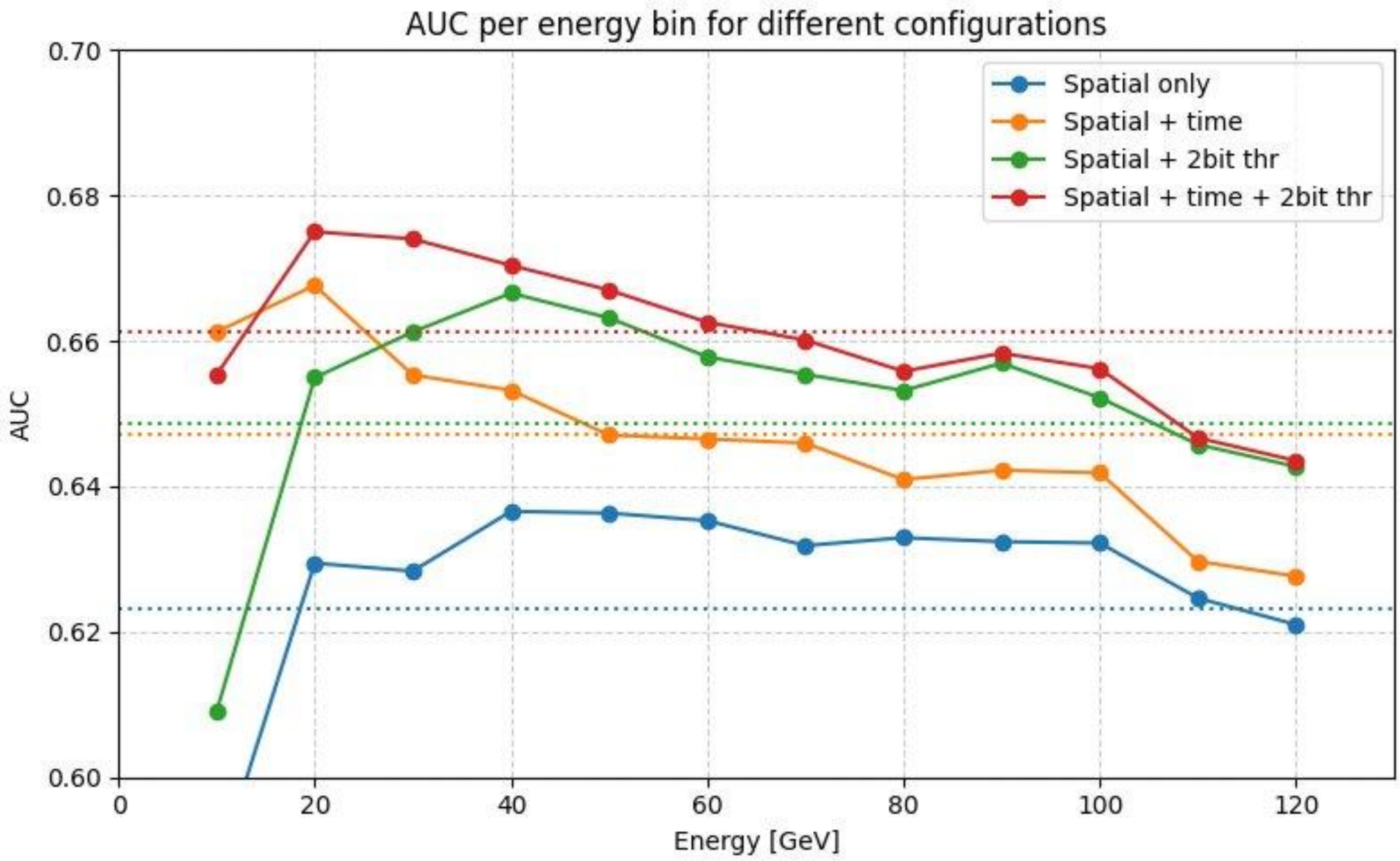


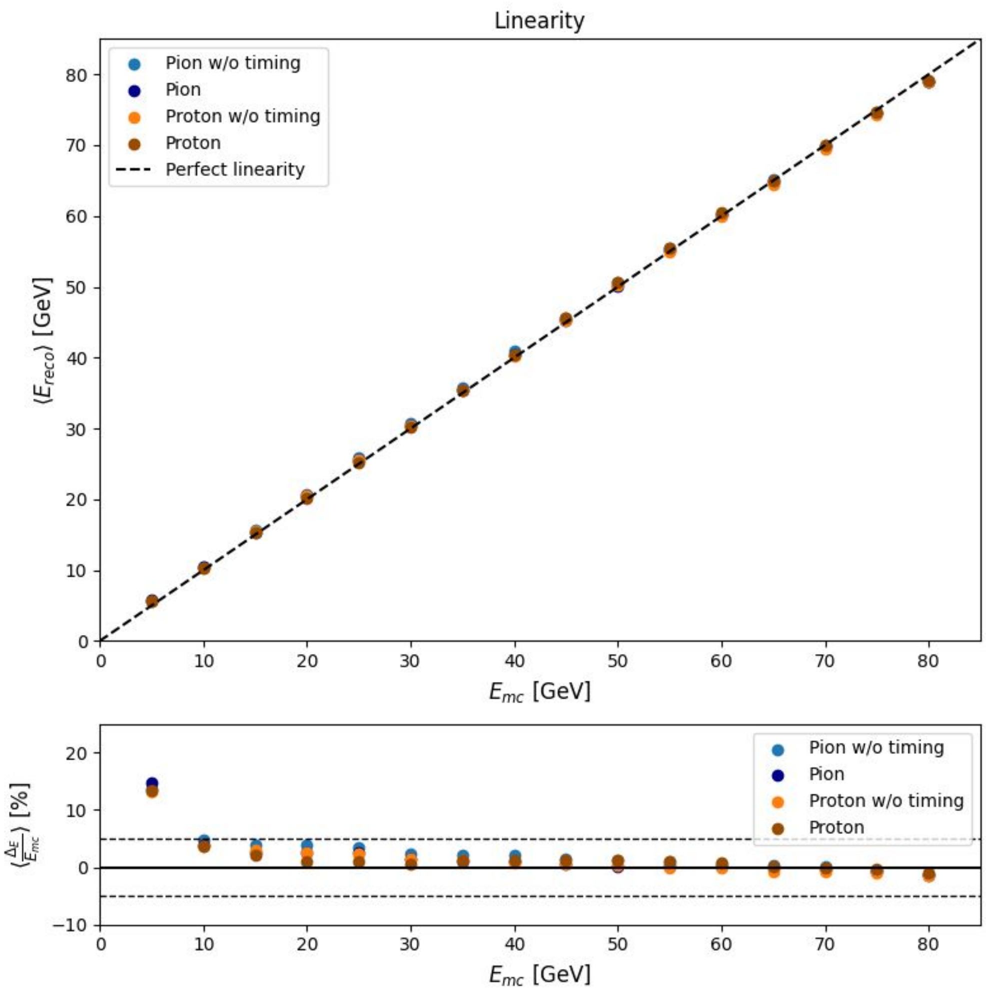
3 models are trained on different energy ranges
[1;50] GeV, [30;90] GeV, [70;130] GeV
So far we ‘cheat’ by using the mc Energy to associate events to models with the right energy range



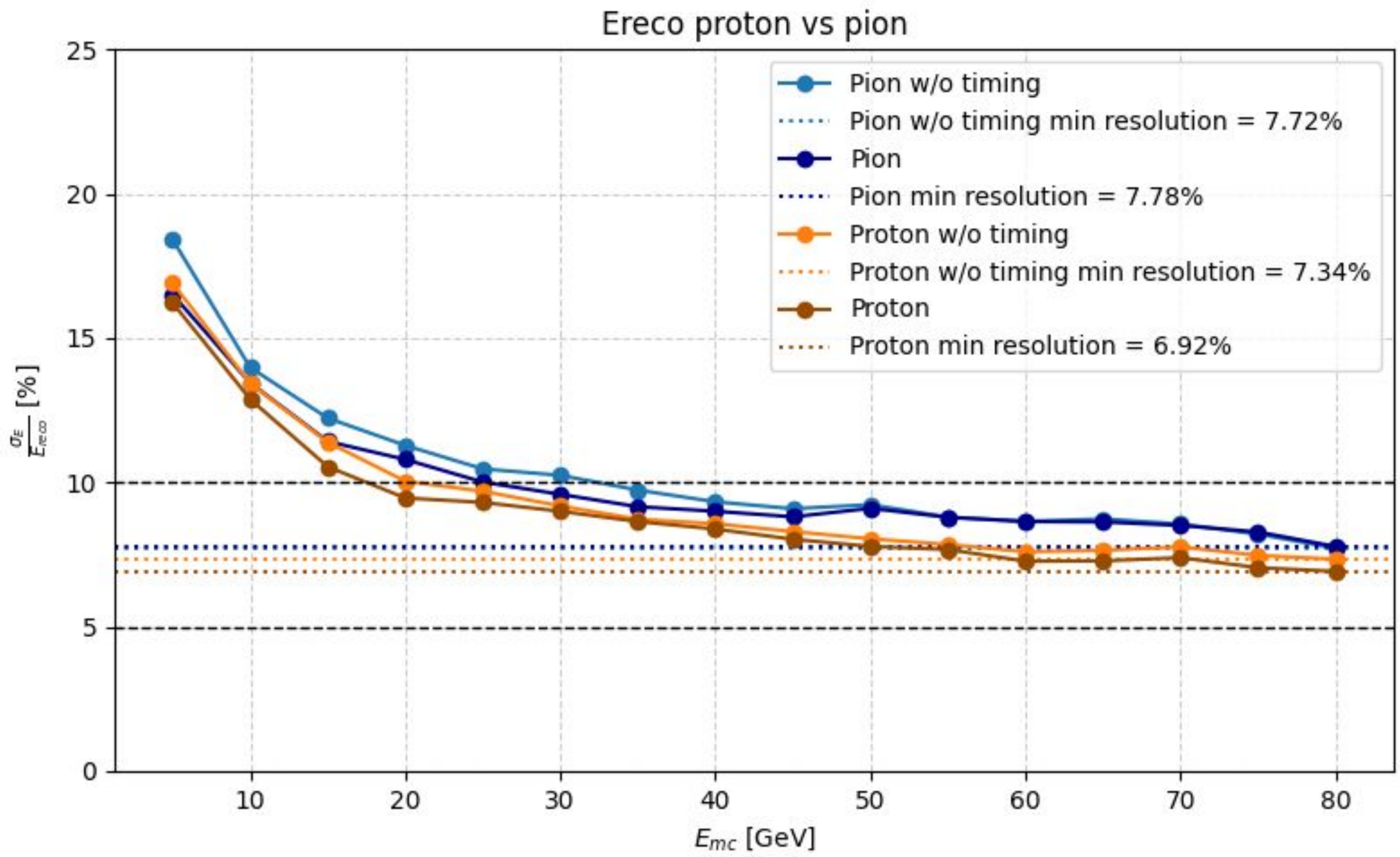
Datasets :

- Train on continuous
- Test on discrete


AUC per energy bin for different configurations
Spatial only
Spatial + time
Spatial + 2bit thr
Spatial + time + 2bit thr
AUC
0.70
0.68
0.66
0.64
0.62
0.60
0
20
40
60
80
100
120
Energy [GeV]



Linearity
Pion w/o timing
Pion
Proton w/o timing
Proton
Perfect linearity
$\langle E_{reco} \rangle$ [GeV]
E_{mc} [GeV]
Pion w/o timing
Pion
Proton w/o timing
Proton
$\langle \frac{\Delta_E}{E_{mc}} \rangle$ [%]
E_{mc} [GeV]



Ereco proton vs pion
Pion w/o timing
Pion w/o timing min resolution = 7.72%
Pion
Pion min resolution = 7.78%
Proton w/o timing
Proton w/o timing min resolution = 7.34%
Proton
Proton min resolution = 6.92%
$\frac{\sigma_E}{E_{reco}}$ [%]
E_{mc} [GeV]
0
5
10
15
20
25
10
20
30
40
50
60
70
80

Deep Learning Model

Model :
PointNet-like neural network for energy regression

Architecture :

- (nb_hits, nb_features)
  - **Shared MLP** (per hit encoding) : nb_features -> 32 -> 64 -> 128 -> hidden
    - Fully connected, Relu, batchNorm
- (nb_hits, hidden)
  - **Global feature aggregation** : max pooling + mean pooling + optional global features
- (2*hidden + extra_dim)
  - **Global MLP** : 2*hidden + extra_dim -> hidden -> hidden -> hidden/2
    - Fully connected, Relu, LayerNorm, Dropout
- (hidden/2)
  - **Regresssion** : hidden/2 -> 1
- 1 (Energy)

Implementation :
PyTorch Geometric