# Muon reconstruction performance and detector-design considerations for a Muon Collider

International MUON Collider Collaboration

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on behalf of the Muon Collider Physics and Detectors working group*

*28th July 2021 – EPS-HEP2021 Online Conference*

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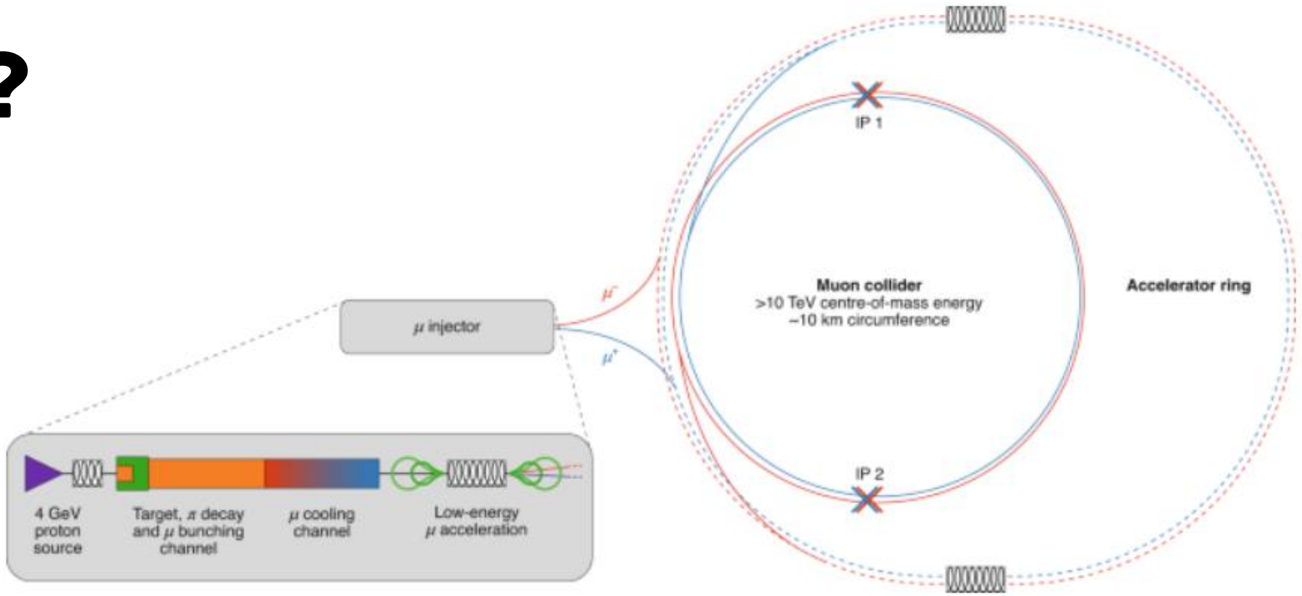
# Why a Muon Collider?




- ✓ Lepton collider = precision physics
- ✓ $m_\mu \sim 207\ m_e$ = low level of synchrotron radiation

→ ***possibility for a multi-TeV, high luminosity, lepton collider***

***Technological challenges:***

- X Need to produce a large number of muons in small emittance bunches
- X Muons decay
  - Beam Induced Background (BIB) in detector
  - Neutrino hazard

https://muoncollider.web.cern.ch/

# Muon collider @ EPS-HEP2021

Not exhaustive list

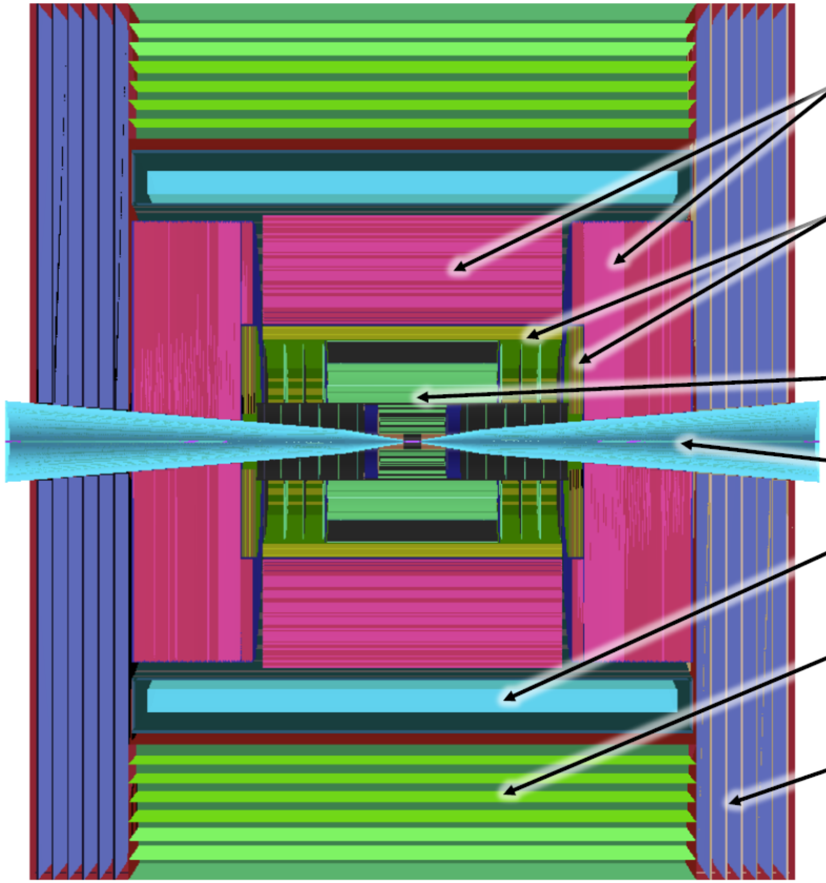
***Talk:***

- Higgs boson couplings at muon collider, L. Buonincontri

***Posters:***

- Design a calorimeter system for the Muon Collider experiment, L. Sestini
- Tracking and track reconstruction at a muon collider in the presence of beam-induced background, H. Weber
- Tracking with ACTS for a Muon Collider detector, K. Krizka
- Using cluster shape for beam-background suppression in a future muon collider experiment, E. D. Resseguie
- Dark-SUSY channels to study muon reconstruction performance at the Muon Collider, C. Aimè
- Prospects for the measurement of $\sigma_H$ x BR($H \rightarrow \mu\mu$) at a 3-TeV muon collider, A. Montella

# Muon system at muon collider




Iron yoke plates instrumented with:

- 7 layers of detectors in the barrel
- 6 layers in the endcap

Detector technology: Glass RPC cells (30x30 mm$^2$)

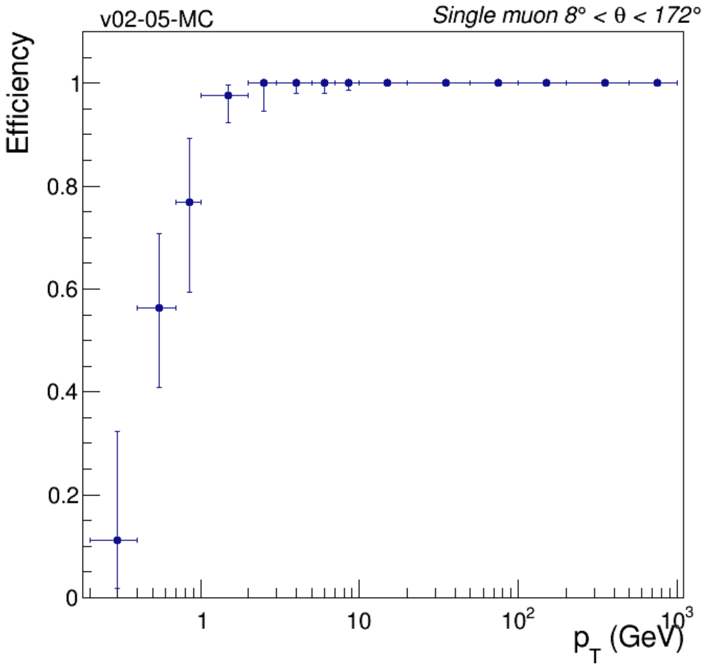
Magnetic field:

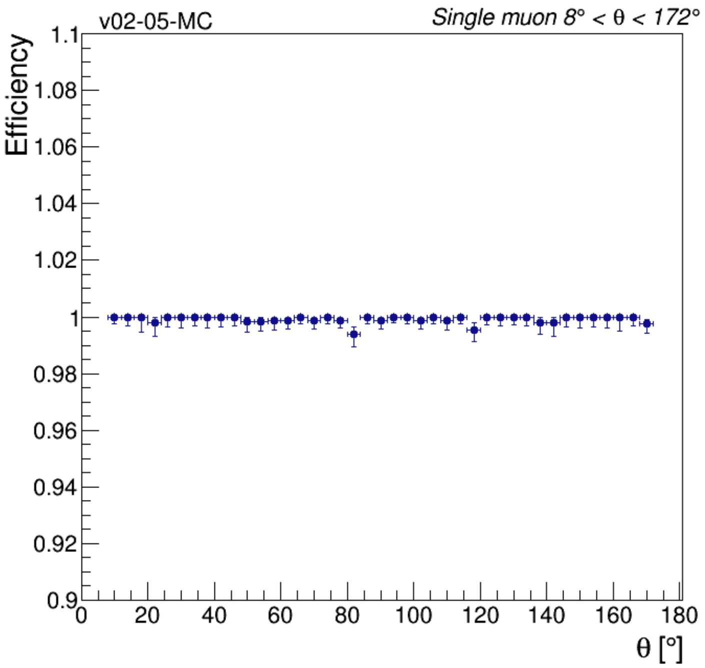
- 1.34 T in the barrel region
- 0.01 T in the endcap region

Based on CLIC detector: arXiv:1202.5940

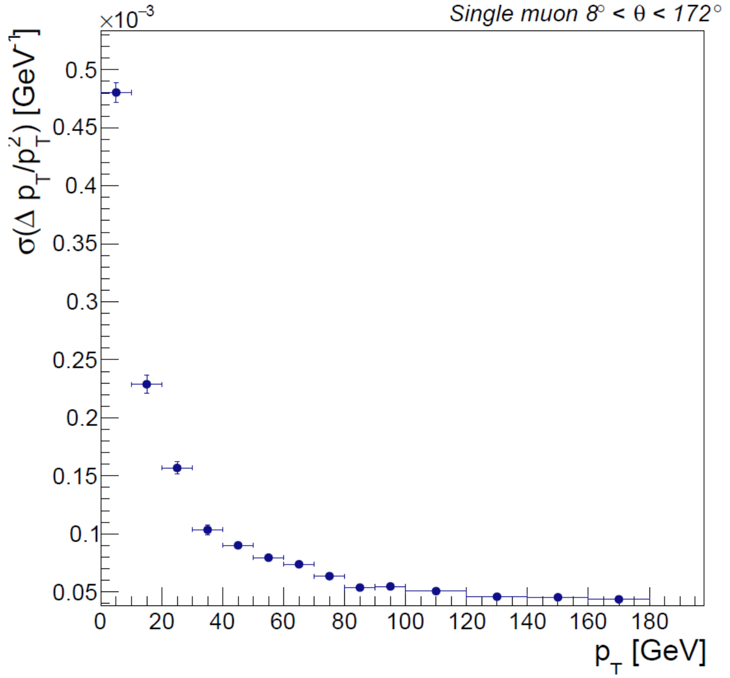
ILCSoft: http://ilcsoft.desy.de/portal

# Muon reconstruction efficiency and resolution



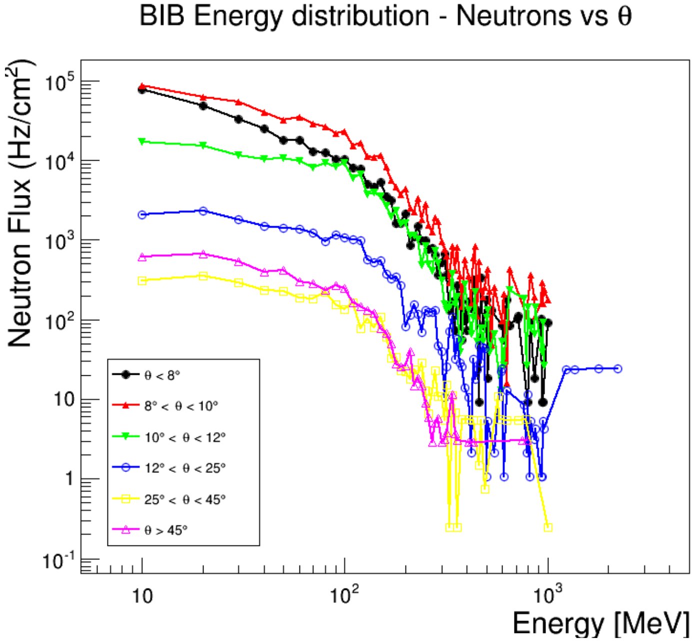

***Single muon efficiency*** defined as the generated particles associated to a cluster divided by the total generated particles.



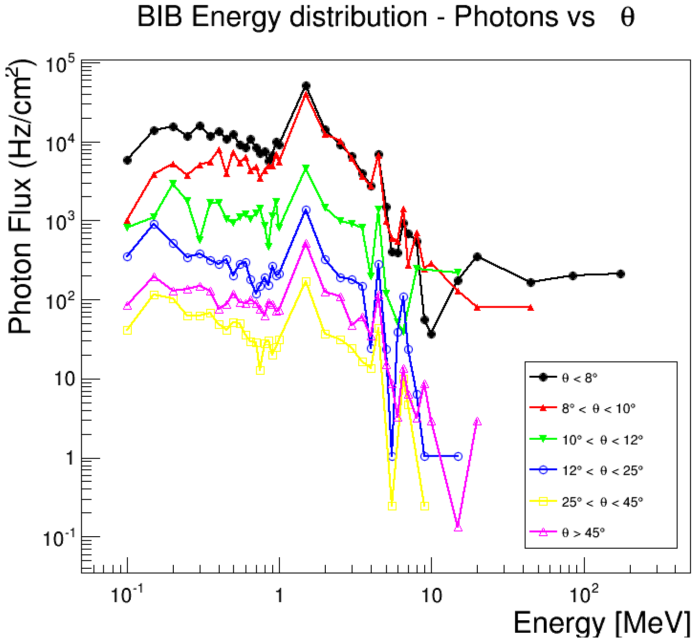

***Single muon efficiency*** ~100 % for muons with $p_T$ in the range 100 MeV – 1 TeV and polar angle $8° < \theta < 172°$ (top plots).

In the right plot, $\Delta p_T$ is the difference between the generated muon $p_T$ and the $p_T$ of the corresponding Pandora reconstructed track.

# Beam Induced Background - 1



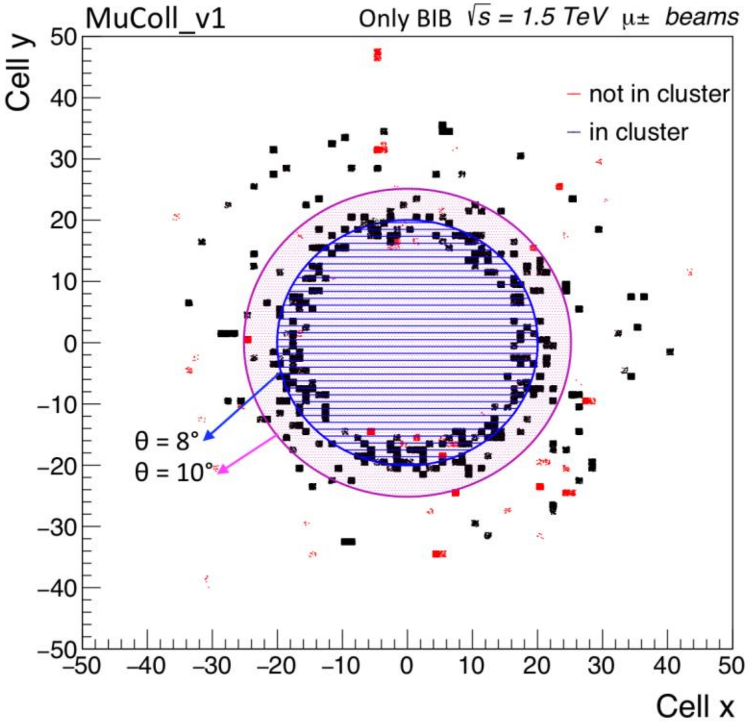

***Beam Induced Background*** (BIB) in the muon system is mainly composed by neutrons and photons.
In the inner regions, the flux is almost 3 orders of magnitude higher than in the outer regions



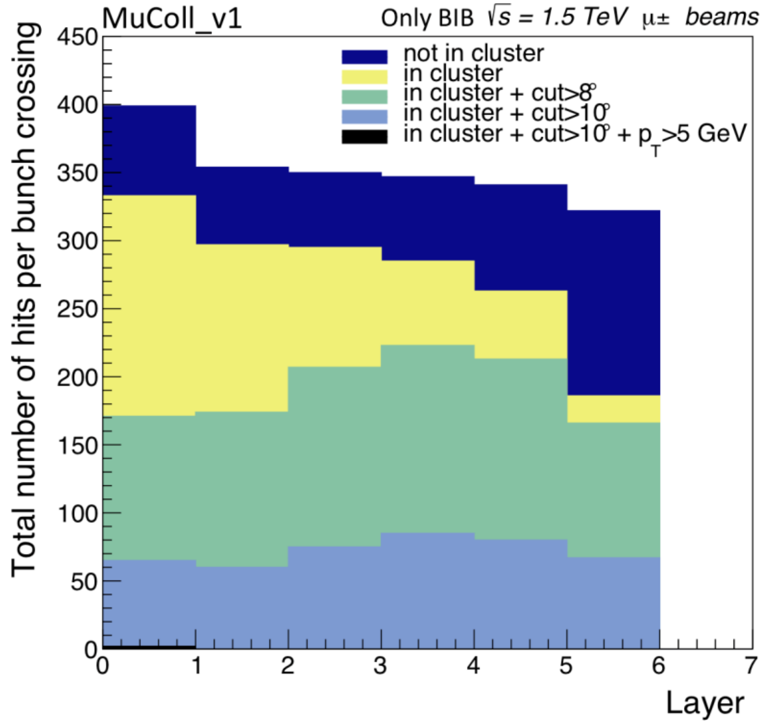

**At** $\sqrt{s} = 1.5\, TeV$:

- Neutrons: energies up to 2.5 GeV
- Photons: energies up to 200 MeV

# Beam Induced Background - 2




A geometrical cut combined, for example, with a cut on the track transverse momentum allows to get rid of almost all BIB hits in the muon system.




BIB hits in the muon system are concentrated around the beam axis in the endcaps in a region small with respect to the whole layer region of 500×500 cells.

# Which other detector can we consider for the muon system?

Not exhaustive list

1. ***Double-gap Glass RPC***
   a) Currently implemented in the muon collider simulation
2. ***Double-gap HPL RPC***
   a) Classical version of the detector
3. ***Triple-GEM***
   a) Micropattern gaseous detector with better space resolution w.r.t. RPC
4. ***PicoSec***
   a) New generation MPGD with improved time resolution

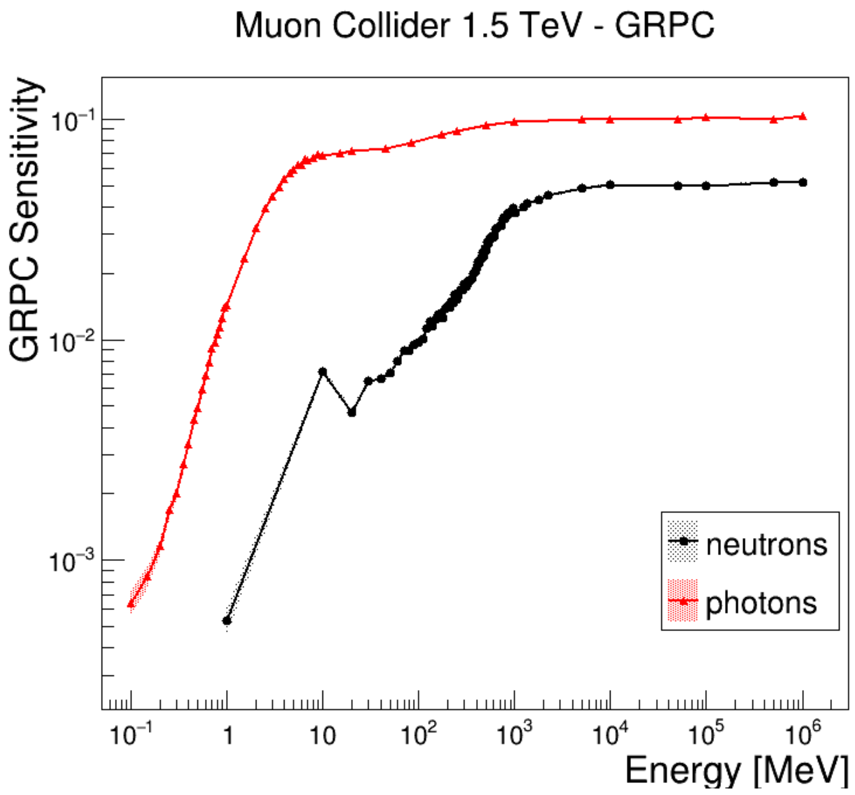
*All the detectors were simulated in Geant4.10.06 p02 with a «basic» geometry; no electronics, cooling, shielding, etc.. were implemented.*

# Detector sensitivity

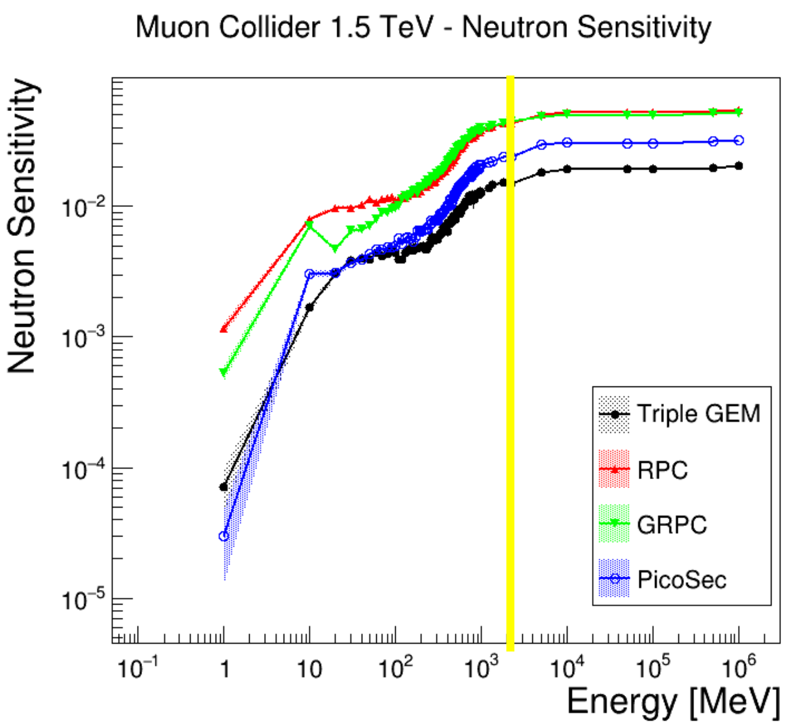
## Sensitivity

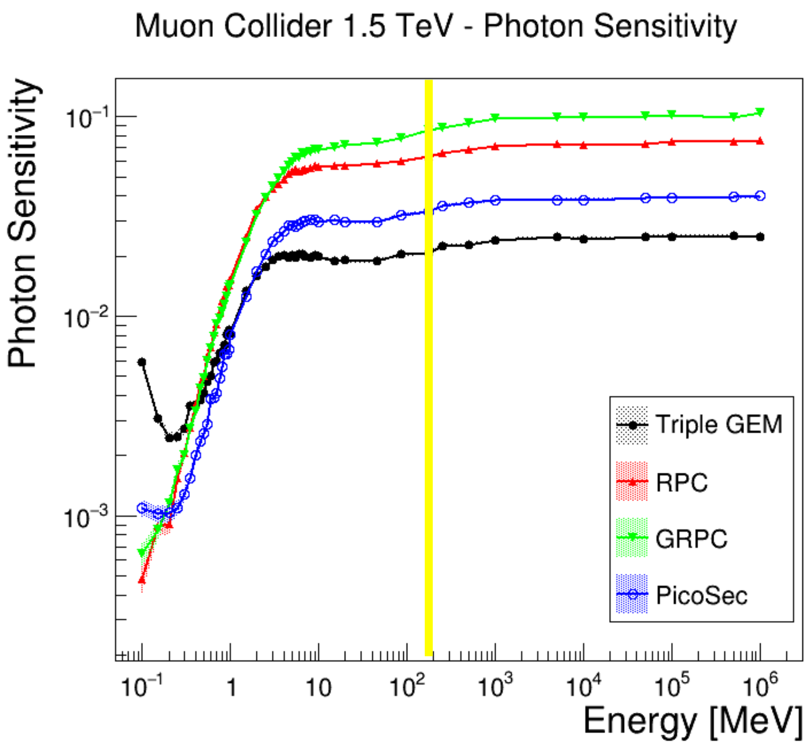
$$s = \frac{N}{M}$$

- $N$ = number of events in which at least one charged particle reaches a sensitive gap
- $M$ = number of incident particles (counted with a fake layer of air on top of the detector)



# Comparison between technologies

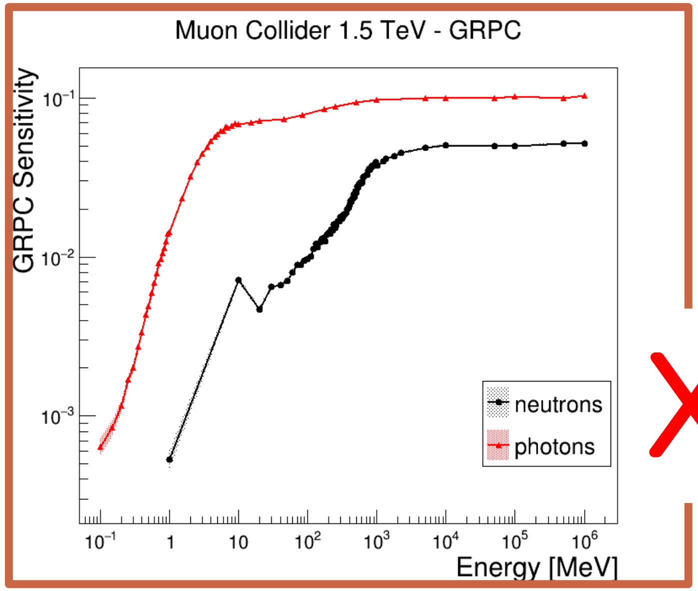



**Sensitivity of MPGDs** in general **lower than RPCs** (both for neutrons and photons) due to the lower material budget.

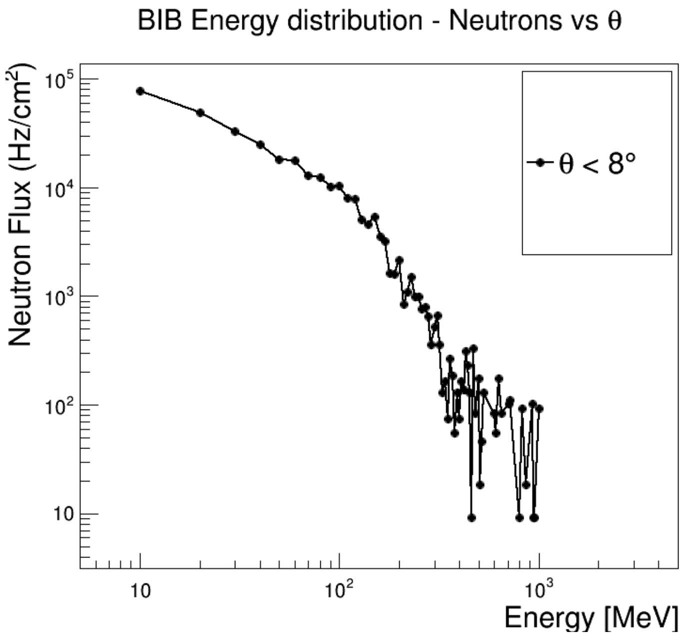
The yellow vertical line shows the energy limit of BIB @ 1.5 TeV

# Hit rate estimation




X

$$Hit\,rate = s \times flux$$

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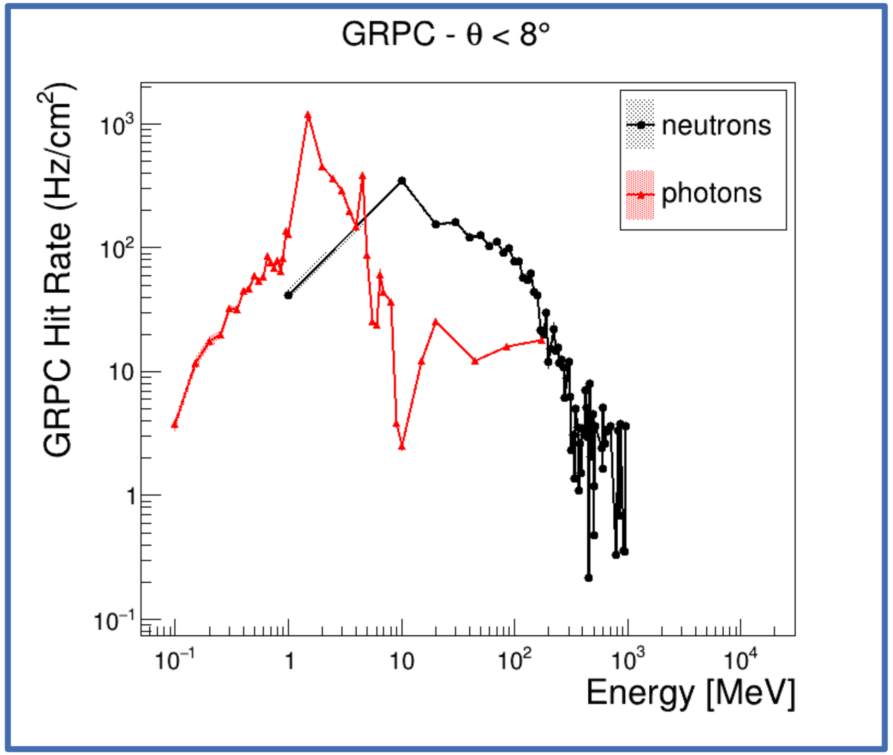
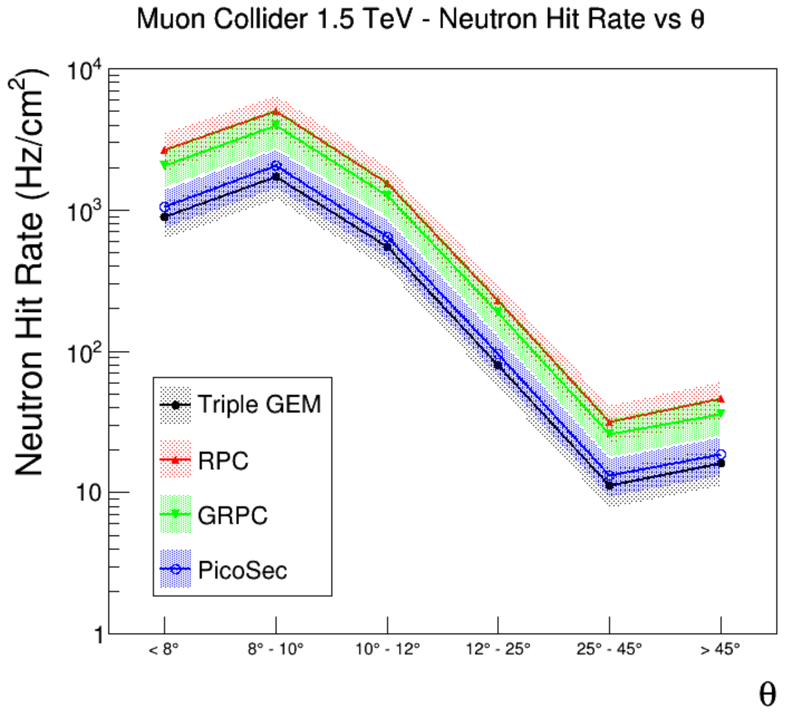
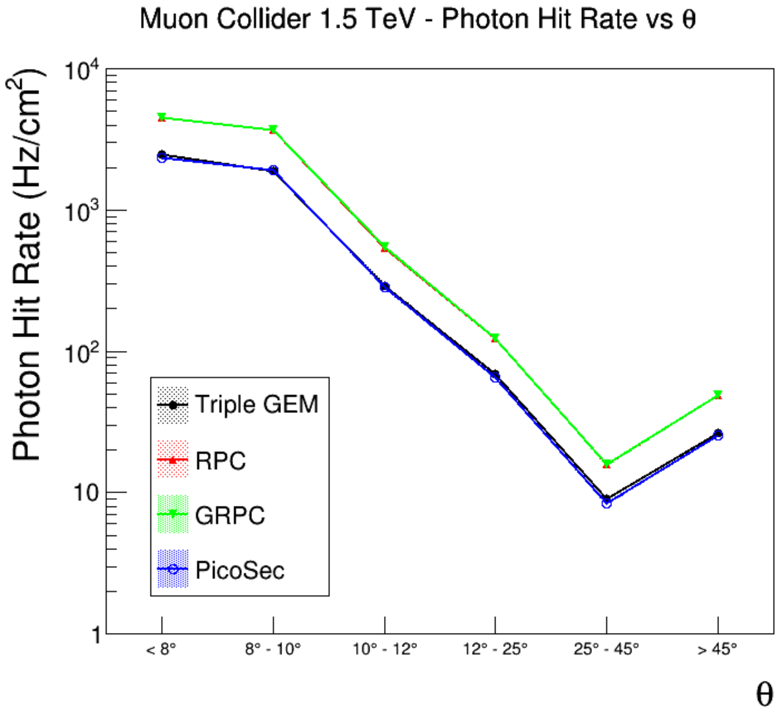



Region $\theta < 8°$ used as example

# Comparison between technologies

$$Total\ Hit\ Rate = \sum_{E} Hit\ Rate\ (E)$$




As a consequence the ***expected hit rate with MPGDs is lower than the one from RPCs***.

RPCs and GRPCs in the inner region are at the limit of the standard rate capability.

# Summary

The ***Muon Collider*** is a great opportunity for precision physics at high energy and high luminosity. However, its unique environment requires a careful design of the most suitable detectors.

In this context, a first study of ***BIB hit rate*** in the muon system of a Muon Collider experiment has been performed with a standalone Geant4 simulation.

GRPC – currently implemented in the muon collider simulation – have been compared to Triple GEM, classical RPC and PicoSec prototypes. Generally, MPGDs turn out to have lower sensitivities to BIB and then lower expected hit rate.

Additional studies will be implemented once the BIB simulation at higher $\sqrt{s}$ will be available. In parallel, analyses focused on the determination of the requested time and space resolutions are ongoing.

**Thanks!**

# Backup

# Muon collider parameters

Table 3. Main parameters of the various phases of an MC as developed by the MAP effort.

| Parameter | Units | Higgs | Top-high resolution | Top-high luminosity | Multi-TeV | | |
|---|---|---|---|---|---|---|---|
| CoM energy | TeV | 0.126 | 0.35 | 0.35 | 1.5 | 3.0 | 6.0* |
| Avg. luminosity | $10^{34}$ cm$^{-2}s^{-1}$ | 0.008 | 0.07 | 0.6 | 1.25 | 4.4 | 12 |
| Beam energy spread | % | 0.004 | 0.01 | 0.1 | 0.1 | 0.1 | 0.1 |
| Higgs production/$10^7$ sec | | 13,500 | 7000 | 60,000 | 37,500 | 200,000 | 820,000 |
| Circumference | km | 0.3 | 0.7 | 0.7 | 2.5 | 4.5 | 6 |
| Ring depth [1] | m | 135 | 135 | 135 | 135 | 135 | 540 |
| No. of IPs | | 1 | 1 | 1 | 2 | 2 | 2 |
| Repetition rate | Hz | 15 | 15 | 15 | 15 | 12 | 6 |
| $\beta^*_{x,y}$ | cm | 1.7 | 1.5 | 0.5 | 1 (0.5–2) | 0.5 (0.3–3) | 0.25 |
| No. muons/bunch | $10^{12}$ | 4 | 4 | 3 | 2 | 2 | 2 |
| Norm. trans. emittance, $\varepsilon_T$ | $\pi$ mm-rad | 0.2 | 0.2 | 0.05 | 0.025 | 0.025 | 0.025 |
| Norm. long. emittance, $\varepsilon_L$ | $\pi$ mm-rad | 1.5 | 1.5 | 10 | 70 | 70 | 70 |
| Bunch length, $\sigma_s$ | cm | 6.3 | 0.9 | 0.5 | 1 | 0.5 | 0.2 |
| Proton driver power | MW | 4 | 4 | 4 | 4 | 4 | 1.6 |
| Wall plug power | MW | 200 | 203 | 203 | 216 | 230 | 270 |

* Accounts for off-site neutrino radiation

https://cds.cern.ch/record/2633584/files/1808.01858.pdf

# GRPC Geometry

```
"AluminumT1","AirT1",
"PyrexGlassT1",
"GasGap1",
"PyrexGlassB1",
"AirB1","AluminumB1",
"AluminumT2","AirT2",
"PyrexGlassT2",
"GasGap2",
"PyrexGlassB2",
"AirB2","AluminumB2",
```

```
1*mm,3.5*mm,        //Aluminum + Air
2*mm,               //Pirex Glass
2*mm,               //GasGap1
2*mm,               //Pirex Glass
3.5*mm,1*mm,        //Aluminum + Air
1*mm,3.5*mm,        //Aluminum + Air
2*mm,               //PirexGlass
2*mm,               //GasGap2
2*mm,               //PirexGlass
3.5*mm,1*mm,        //Aluminum + Air
```

- Geometry as it is currently implemented in MuCollv1
- Dominant materials are:
  - Aluminum
  - Pyrex Glass = $SiO_2$ (80.6%) + $B_2O_3$ (13%) + $Na_2O$ (4%) + $Al_2O_3$ (2.3%)
- Gas: isobutane (4.5%) + $C_2H_2F_4$ (95.2%) + $SF_6$ (0.3%)

# Double Gap RPC Geometry

```
"MylarElecIns1","totMylarHV1","CopperGND1",              0.2*mm,0.4*mm,0.038*mm,             //Insulator
"HPL1",                                                  2*mm,                               //HPL
"GasGap1",                                               2*mm,                               //GasGap1
"HPL2",                                                  2*mm,                               //HPL
"totMylarGND1","CuStrips","FR4Strips","totMylarGND2",    0.2*mm,0.017*mm,0.4*mm,0.2*mm,      //Strips
"HPL3",                                                  2*mm,                               //HPL
"GasGap2",                                               2*mm,                               //GasGap2
"HPL4",                                                  2*mm,                               //HPL
"CopperGND2","totMylarHV2","MylarElecIns2",              0.038*mm,0.4*mm,0.2*mm,             //Readout Board
"AlPanel",                                               5*mm,                               //Aluminum Panel
```

- CMS geometry
- Dominant materials are:
  - HPL (High Pressure Laminate) = H (5.74%) + C (77.46%) + O (16.8%)
  - Mylar (Geant4 Material DB)
  - Aluminum
- Gas: isobutane (4.5%) + $C_2H_2F_4$ (95.2%) + $SF_6$ (0.3%)

# Triple GEM Geometry

| | | |
|---|---|---|
| "PCB", | 1.2*mm, | //PCB on top |
| "KaptonFoil", | 50*um, | //Kapton window |
| "DriftKapton","DriftCopper2", | 50*um,35.*um, | //Drift Foil |
| "GasGap1", | 3.*mm, | //Drift Gap |
| "Gem1Copper1","Gem1","Gem1Copper2", | 5.*um,50*um,5.*um, | //gem1 |
| "GasGap2", | 1.*mm, | //Transfer I Gap |
| "Gem2Copper1","Gem2","Gem2Copper2", | 5.*um,50*um,5.*um, | //gem2 |
| "GasGap3", | 2.*mm, | //Transfer II Gap |
| "Gem3Copper1","Gem3","Gem3Copper2", | 5.*um,50.*um,5.*um, | //gem3 |
| "GasGap4", | 1.*mm, | //Induction Gap |
| "ReadCopper1","ReadoutBoard", | 35.*um,3.2*mm, | //Readout Board |

- Simple Triple-GEM geometry
- Dominant materials are:
  - Kapton
  - Copper
  - PCB (FR4) →
- Gas: Ar (70%) + $CO_2$ (30%)

```
G4Material* SiO2 =  new G4Material("quartz",density= 2.200*g/cm3, numel=2);
SiO2->AddElement(elSi, natoms=1);
SiO2->AddElement(elO , natoms=2);

//from http://www.physi.uni-heidelberg.de/~adler/TRD/TRDunterlagen/RadiatonLength/tgc2.htm
//Epoxy (for FR4 )
density = 1.2*g/cm3;
G4Material* Epoxy = new G4Material("Epoxy" , density, numel=2);
Epoxy->AddElement(elH, natoms=2);
Epoxy->AddElement(elC, natoms=2);

//FR4 (Glass + Epoxy)
density = 1.86*g/cm3;
G4Material* FR4 = new G4Material("FR4"  , density, numel=2);
FR4->AddMaterial(Epoxy, fractionMass=0.472);
FR4->AddMaterial(SiO2, fractionMass=0.528);
fFR4Mat = FR4;
```

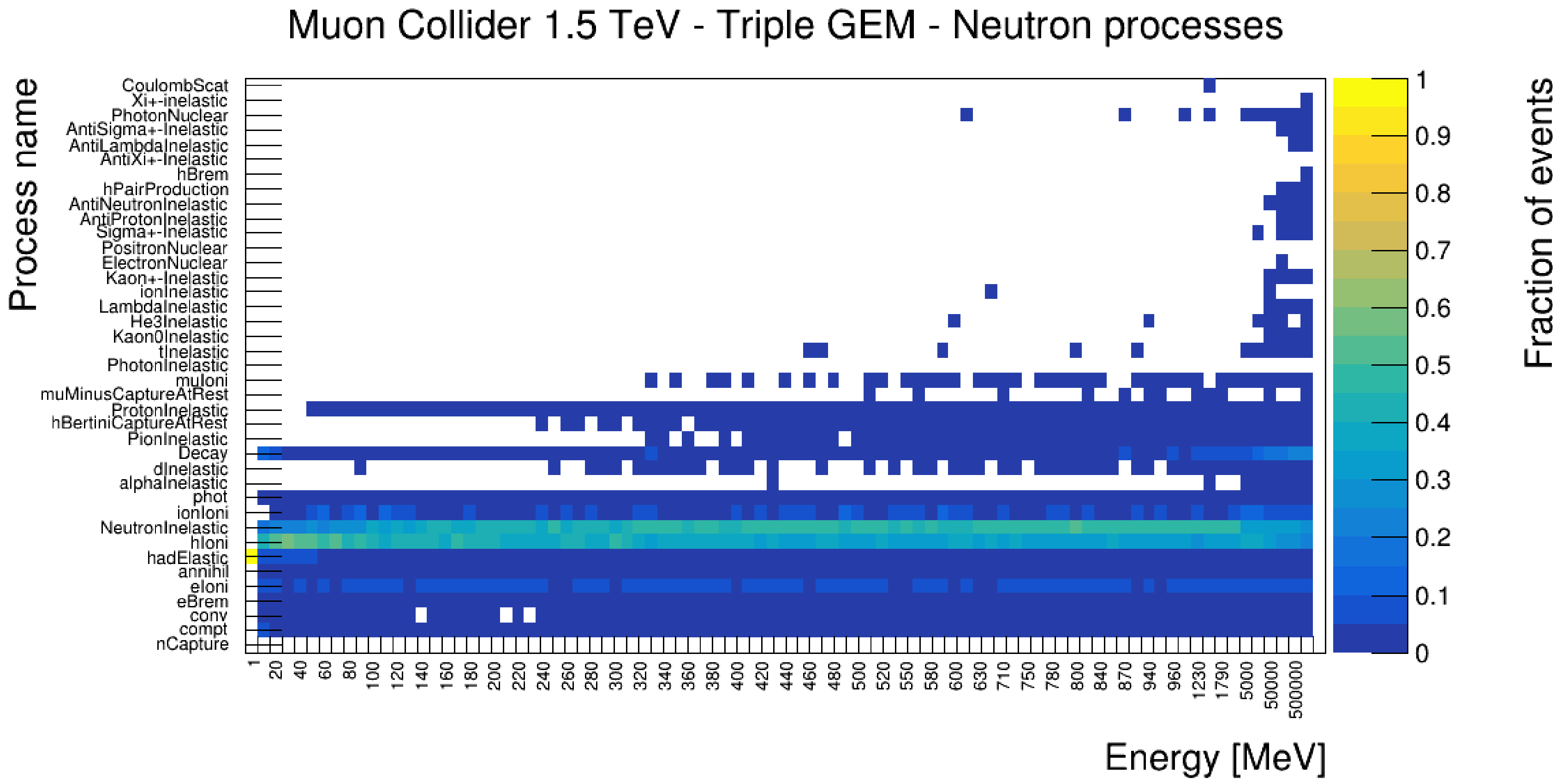
# PicoSec Geometry

https://arxiv.org/pdf/1901.03355.pdf

```
"Radiator",                          3*mm,              //Cherenkov radiator
"Photocathode",                      20*nm,             //Photocathode
"PCSupport",                         10*nm,             //PC Support
"GasGap1",                           200.*um,           //Drift Gap
"Mesh",                              8.*um,             //Mesh
"GasGap2",                           128*um,            //Transfer I Gap
"ReadCopper1","ReadoutBoard"         35.*um,3.2*mm,     //Readout Board
```

- Prototype geometry
- Dominant materials are:
  - Cherenkov Radiator =$MgF_2$
  - Need to understand from interaction position study which are the more relevant materials (photocathode is CsI, PC support is Cr, Mesh is Al…)
- Gas: Ne (80%) + $C_2H_6$ (10%) + $CF_4$ (10%)

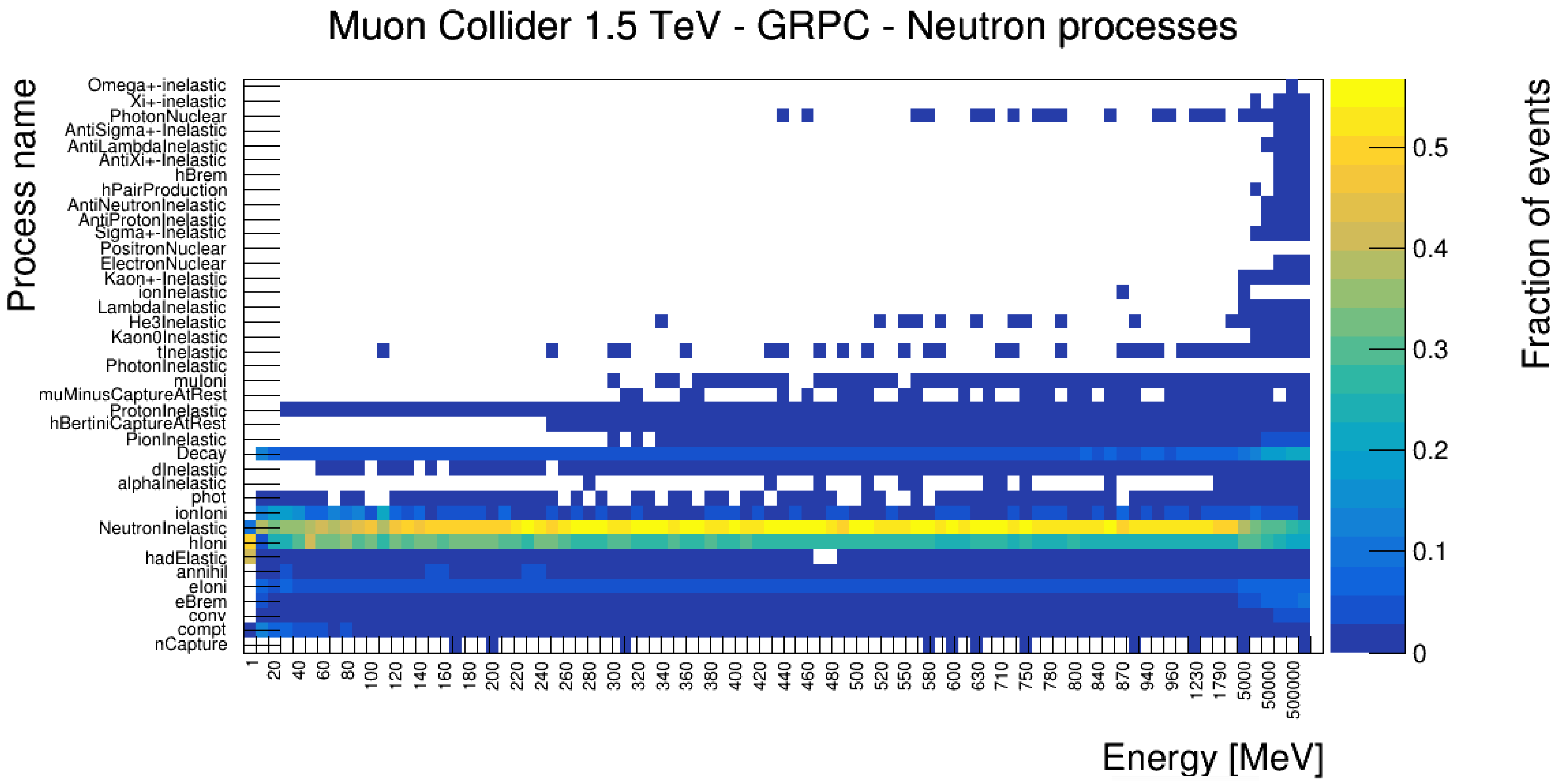
# Interaction processes - Neutrons




In the energy range considered, the dominant process for neutrons is the inelastic scattering, with the production of secondary heavy ions.

# Interaction processes - Neutrons

In the energy range considered, the dominant process for neutrons is the inelastic scattering, with the production of secondary heavy ions.



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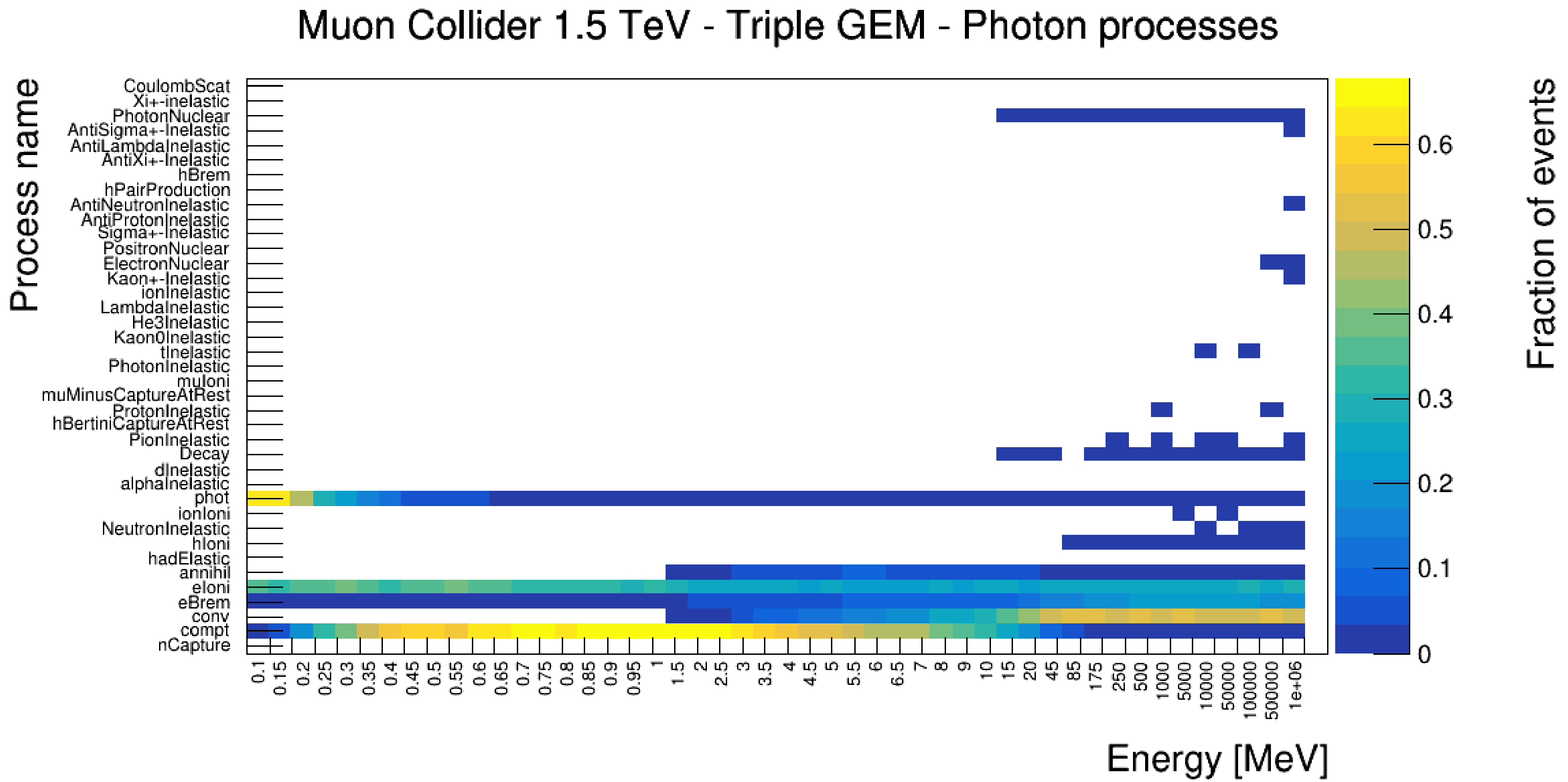
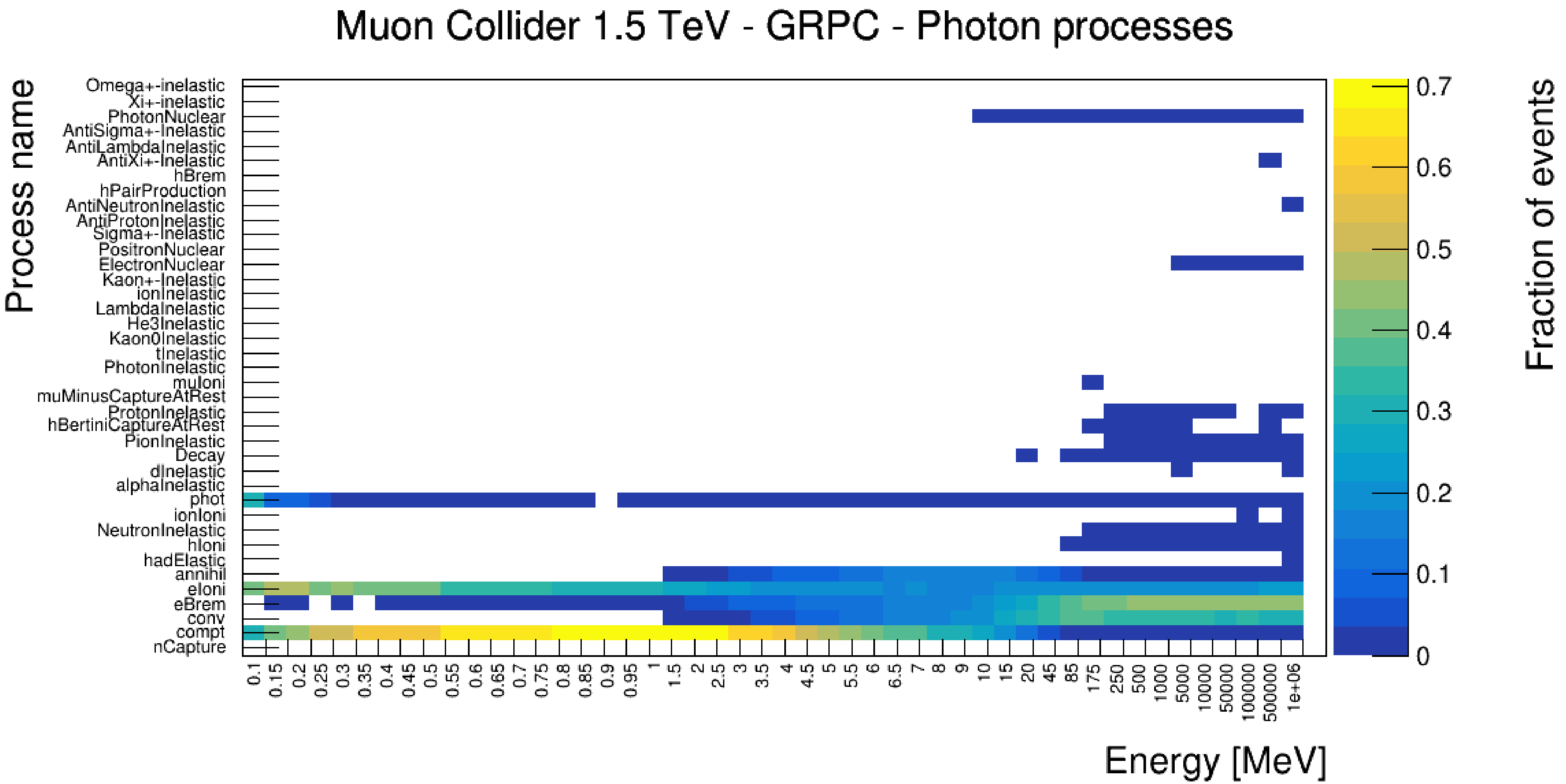
# Interaction processes - Photons



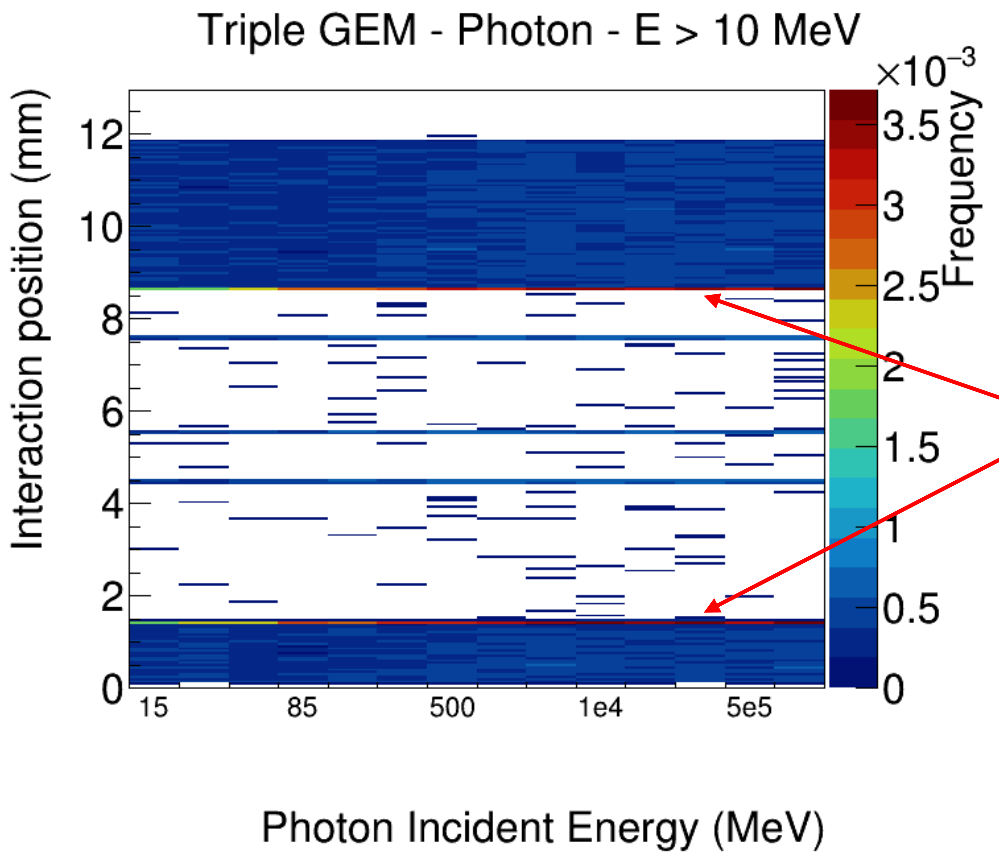

For Triple-GEM, the three main photon processes can be identified clearly. No Al is present, while the Cu (Z=29) contribution is relevant.

# Interaction processes - Photons

For GRPCs, photoelectric effect is suppressed, while Compton scattering is dominant, due to the presence of Al (Z=13)



# Interaction position in the detector – Triple GEM

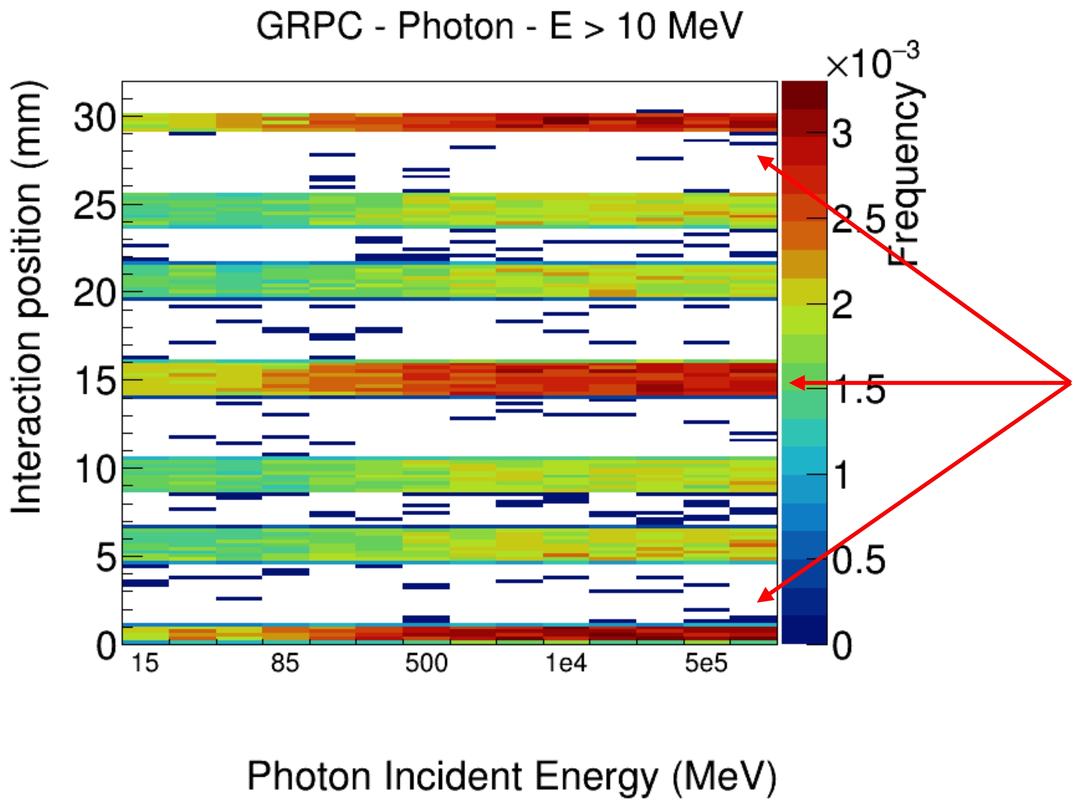



- Z = 0 → front of the detector
- Z = 12 mm → back of the detector

The majority of the interaction happens in the 35 um of Cu of the drift and readout boards

```
"PCB",
"KaptonFoil",
"DriftKapton","DriftCopper2",
"GasGap1",
"Gem1Copper1","Gem1","Gem1Copper2",
"GasGap2",
"Gem2Copper1","Gem2","Gem2Copper2",
"GasGap3",
"Gem3Copper1","Gem3","Gem3Copper2",
"GasGap4",
"ReadCopper1","ReadoutBoard",
```

# Interaction position in the detector – GRPC

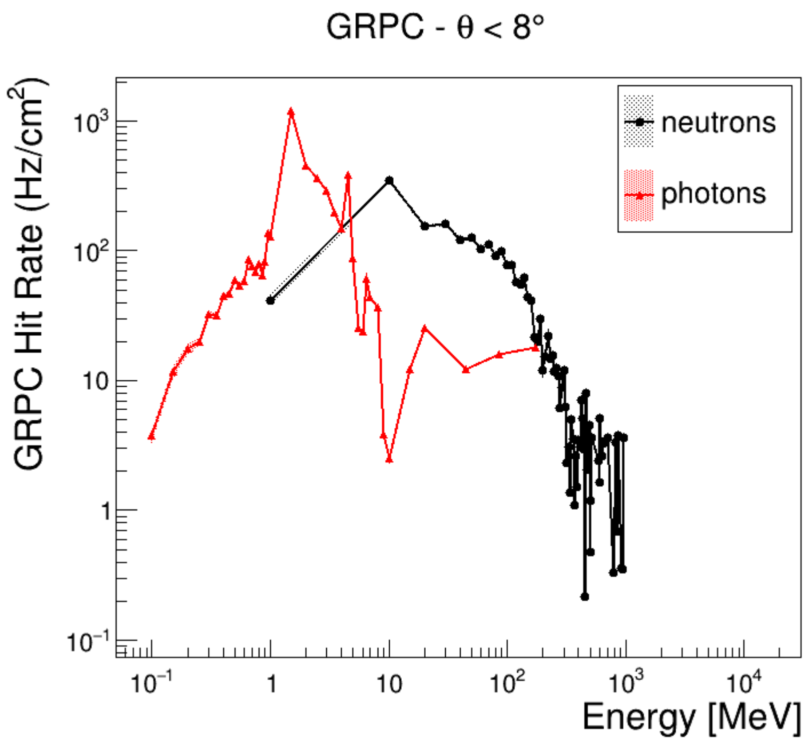



- Z = 0 → front of the detector
- Z = 30 mm → back of the detector

The majority of the interaction happens in the 1 mm Al plates.

```
"AluminumT1","AirT1",
"PyrexGlassT1",
"GasGap1",
"PyrexGlassB1",
"AirB1","AluminumB1",
"AluminumT2","AirT2",
"PyrexGlassT2",
"GasGap2",
"PyrexGlassB2",
"AirB2","AluminumB2",
```

# Total Hit rate
## In each $\theta$ region…




$$Total\ Hit\ Rate = \sum_{E} Hit\ Rate\ (E)$$

| Particle | Total Hit Rate (Hz/cm²) |
|---|---|
| Neutrons | $(2.08 \pm 0.62) \times 10^3$ |
| Photons | $(4.50 \pm 0.05) \times 10^3$ |

Region $\theta < 8°$ used as example