Towards a 10 TeV detector concept

Federico Meloni (DESY),
presenting the work of many

IMCC Annual Meeting 2023
21/06/2023

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

International MUON Collider Collaboration

MuCol

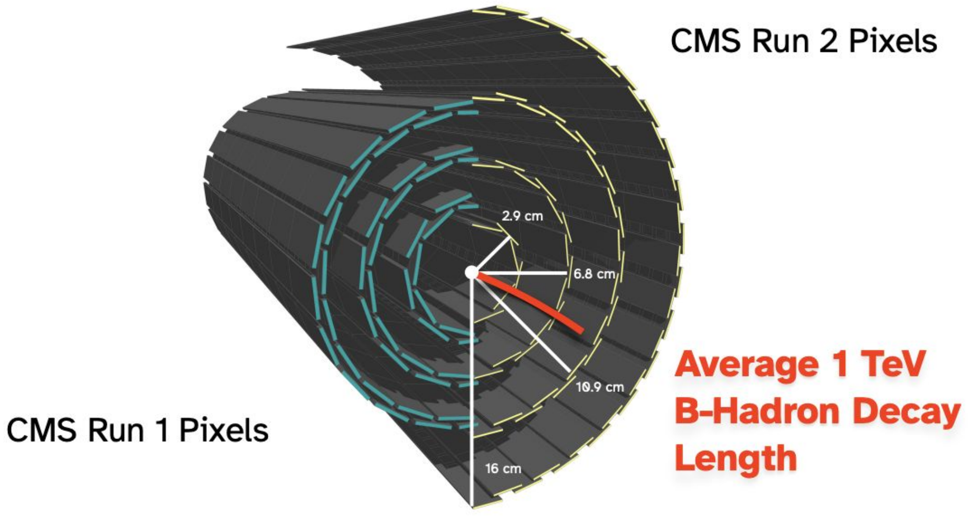
Physics requirements

The detectors need to be ready to **measure both TeV-scale particles** (from s-channel processes) **as well as GeV-scale** (from VBF processes)

- Design a detector which is as “unconventional signature-friendly” as possible

Detector sizes need to grow with energy

- Need thicker calorimeters / bigger trackers with high precision in more places

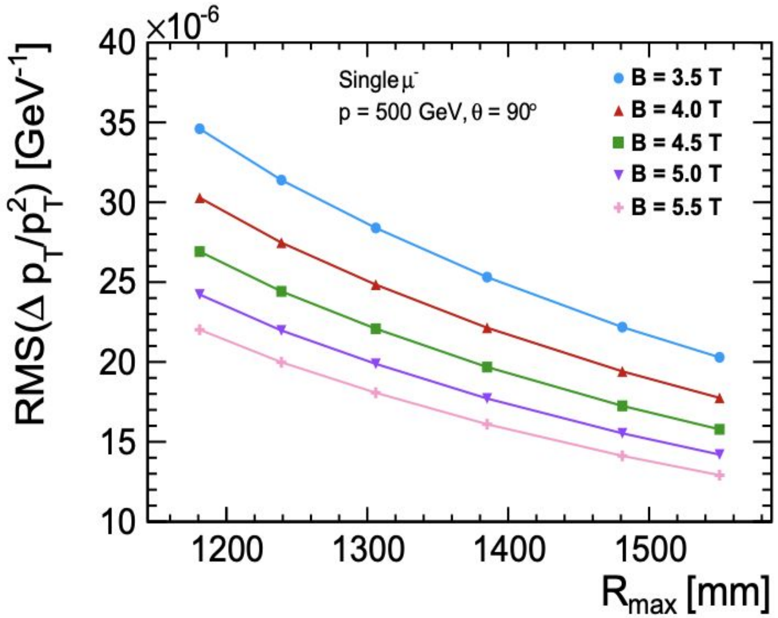


Sketch: L. Lee

"Trivially needed" changes

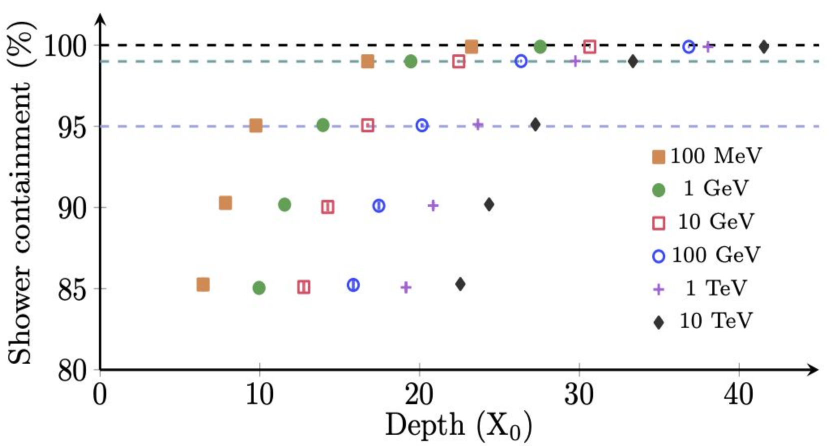
Update the tracker

- Move closer to beam axis for innermost layer
- Increase granularity at large radii
- Reconsider double layers
- Re-design endcap region close to nozzles



Make the calorimeters thicker

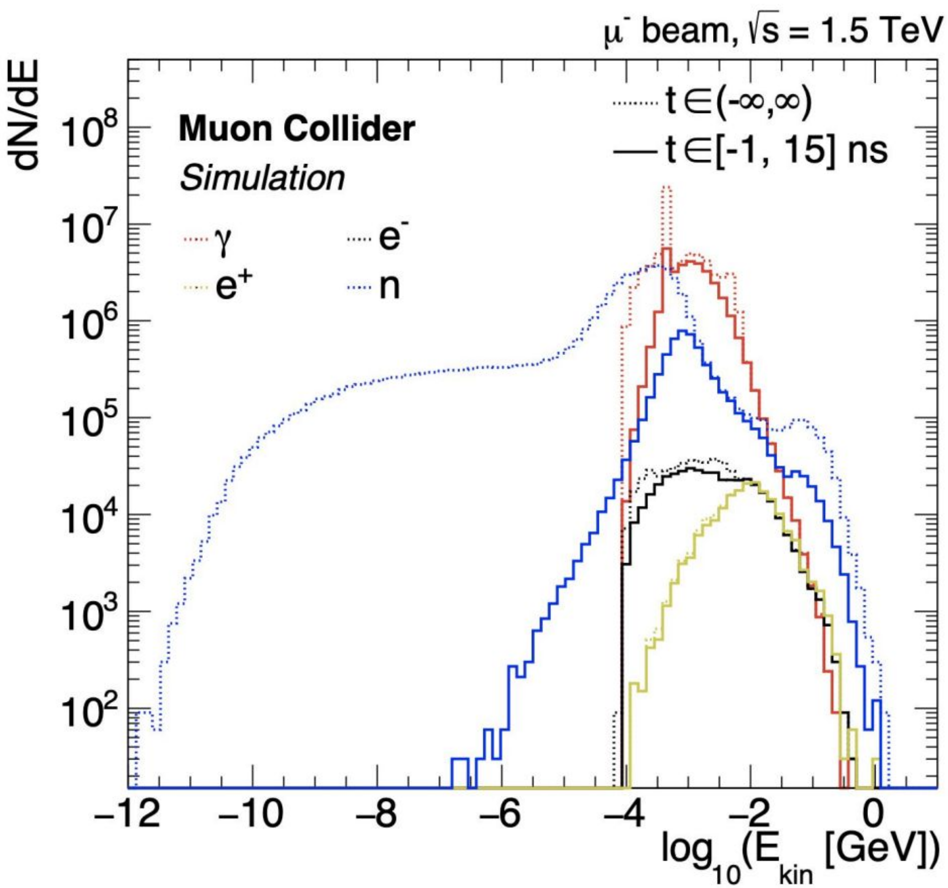
- More energetic showers require more radiation/interaction-lengths to be contained
- Rethink reconstruction for partly-contained showers?
- Revisit cell energy thresholds, or think about some level of "BIB shielding"

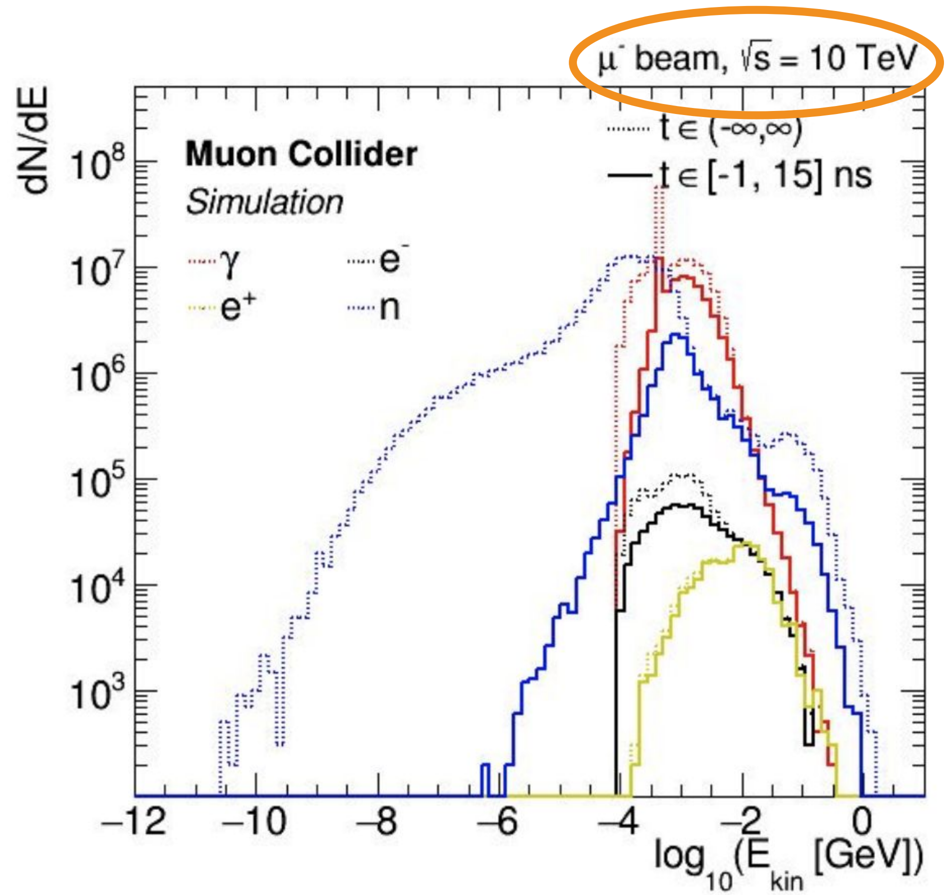


Early look at 10 TeV BIB: energy

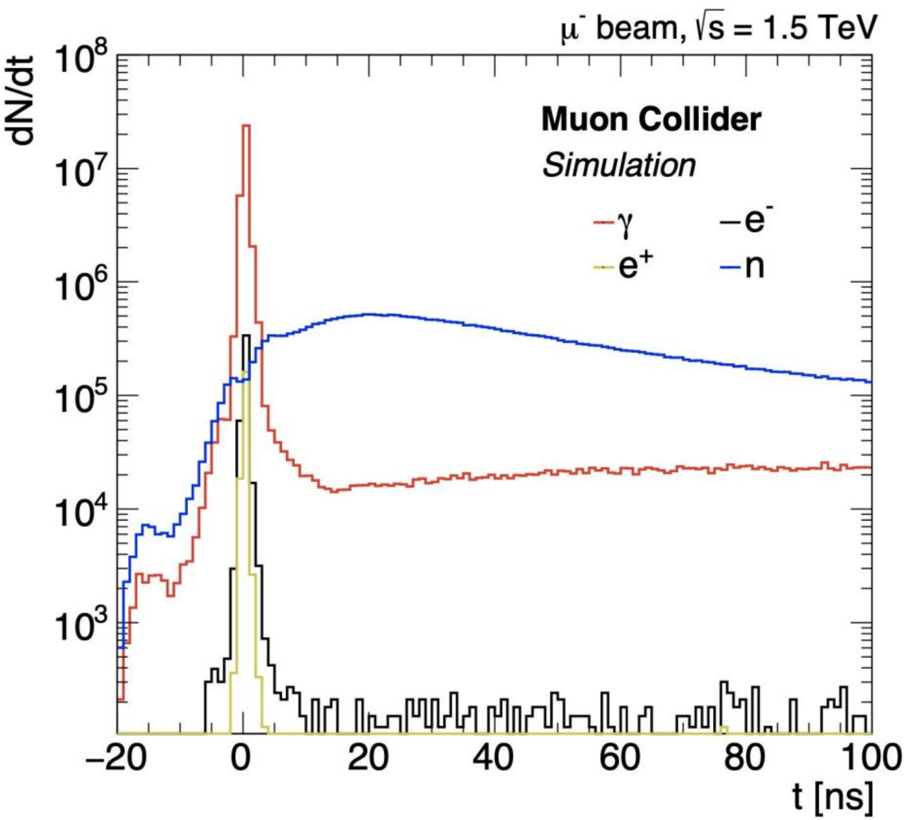
Simulated BIB particles starting from FLUKA (version: synchrad_on_v1).

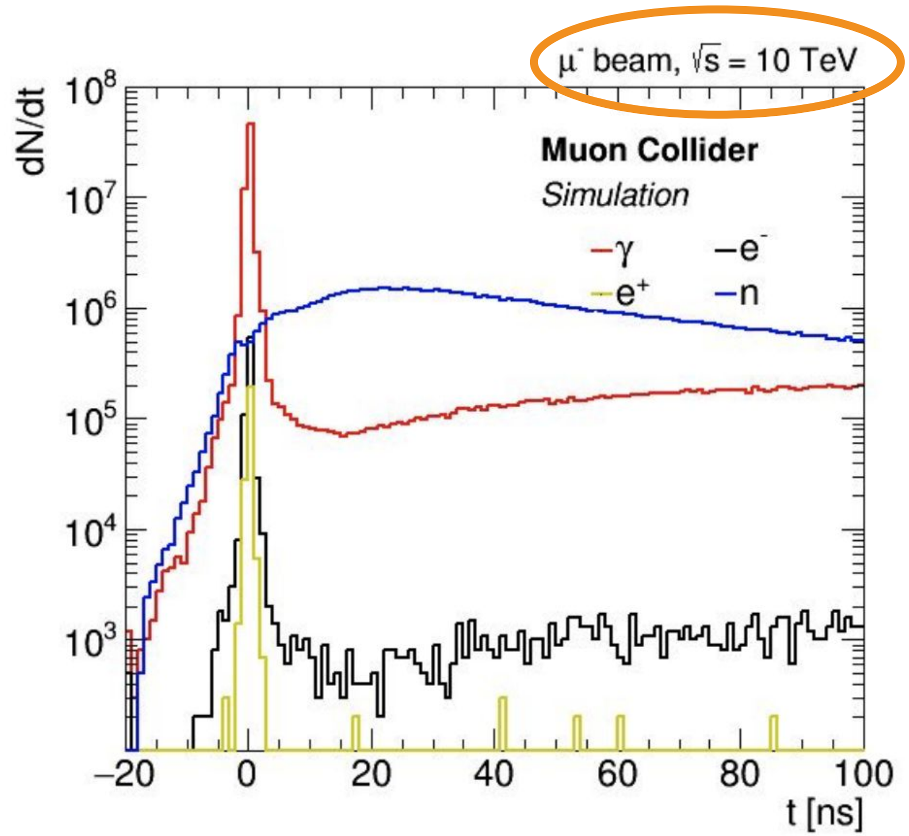
- Later results based on flipped μ^+ beam (was validated against simulation of the μ^- beam finding good agreement)





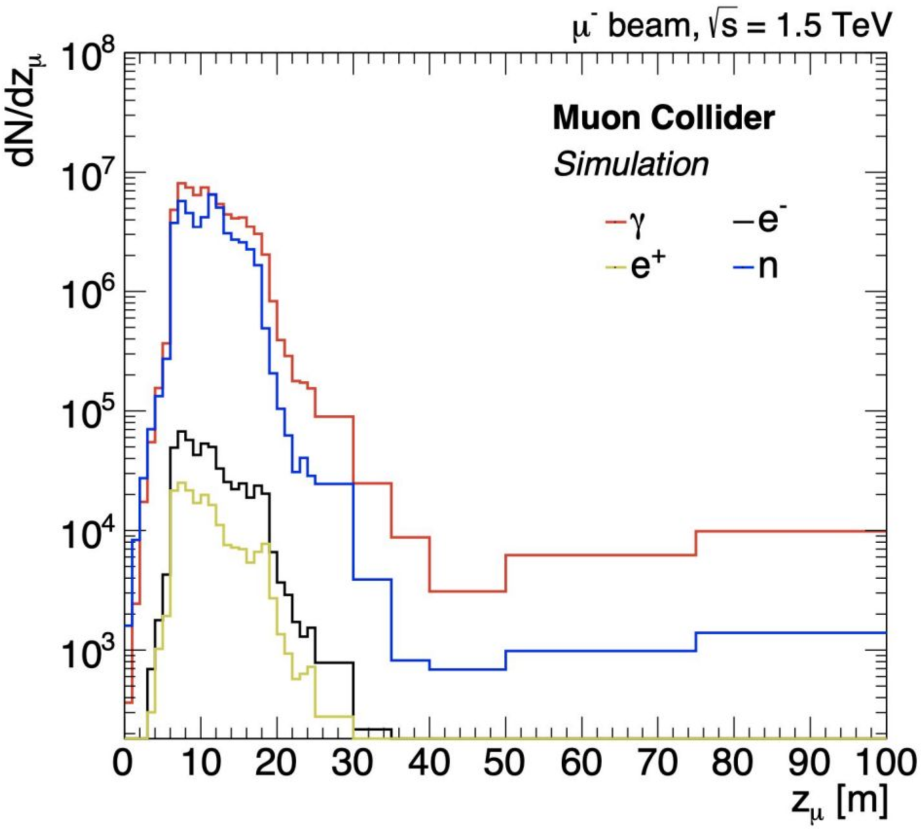
Early look at 10 TeV BIB: time

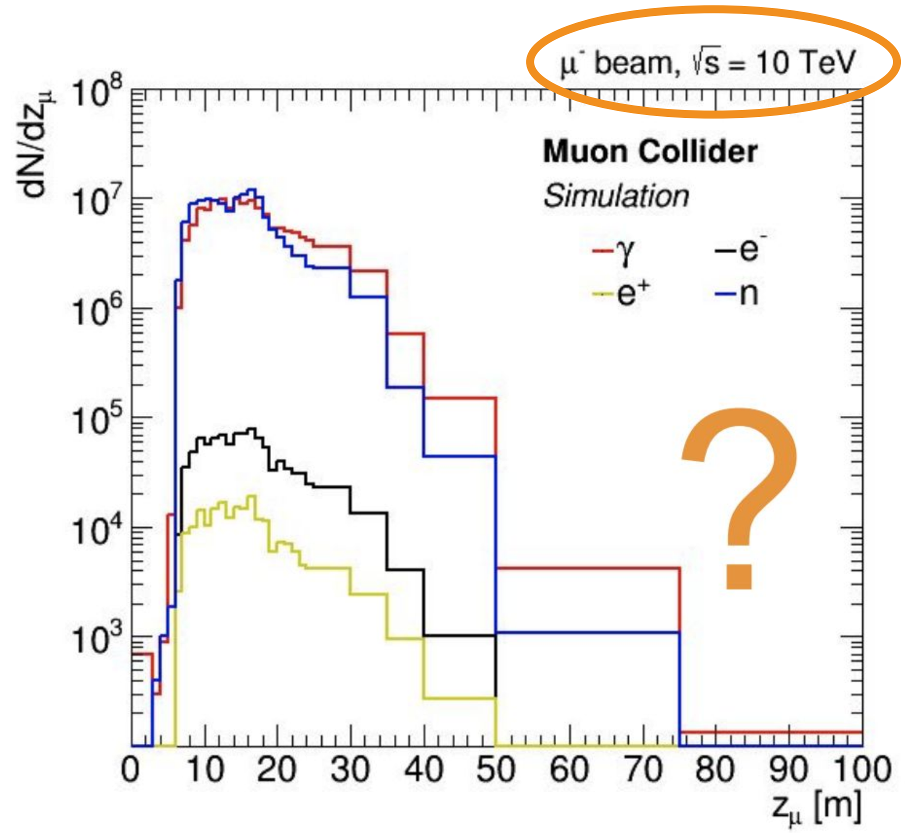




Longer tails compatible with energetic showers coming from further away

Early look at 10 TeV BIB: μ decay position



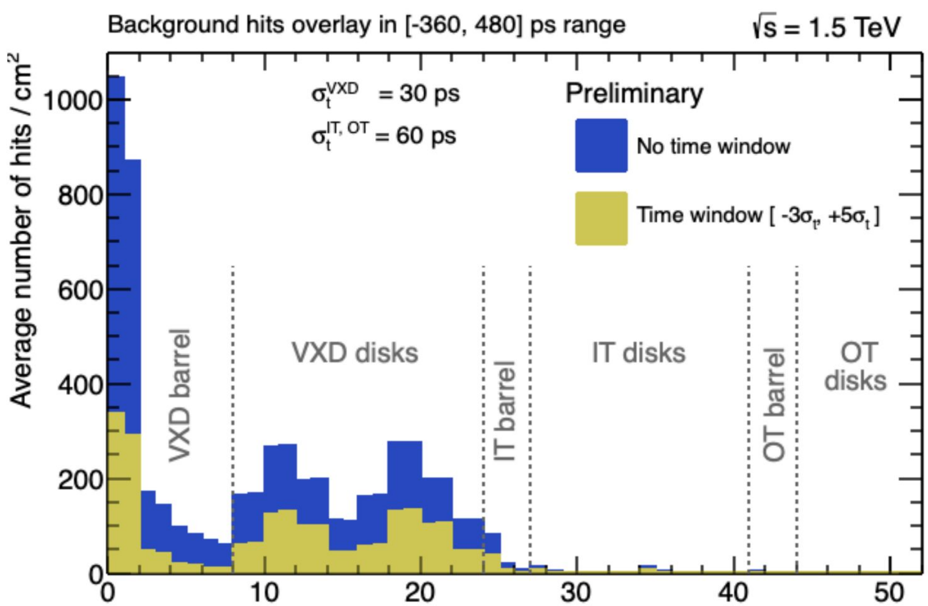


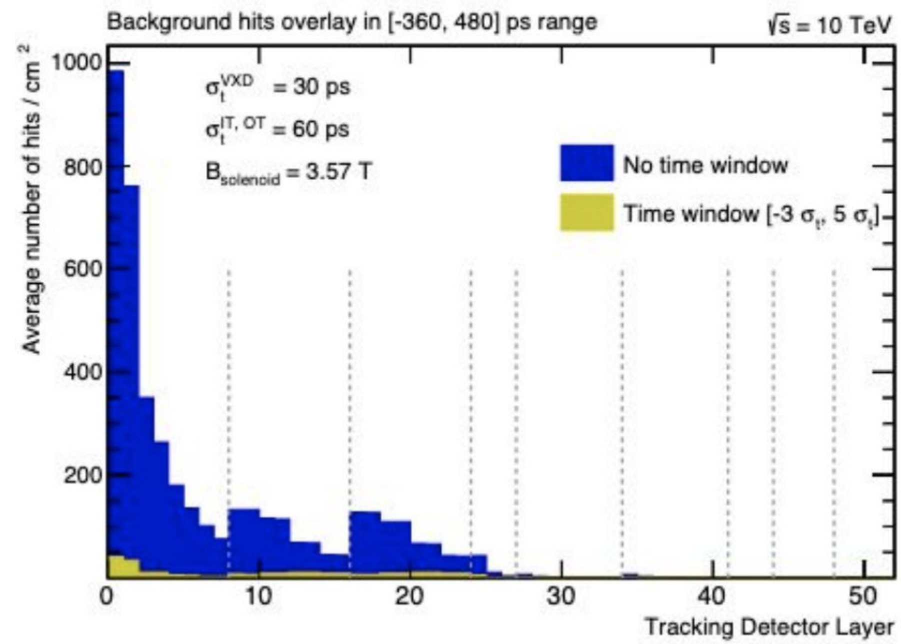
Lack of very-long tail comes from better modelling in FLUKA (now including synchrotron radiation)

- See more in D. Calzolari's talk

Occupancies: tracker

~consistent with
N. Bartosik's 10 TeV BIB
findings



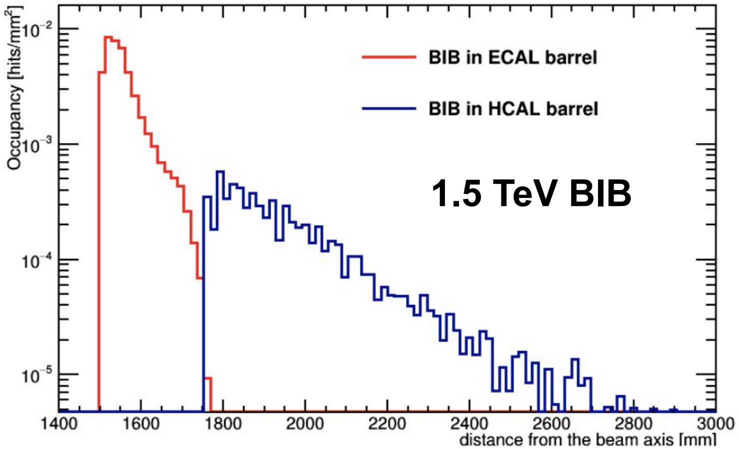


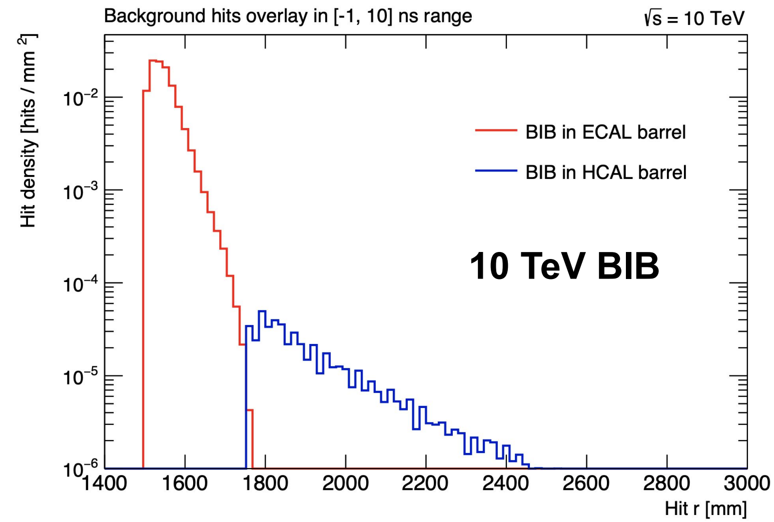
Increasing solenoid field to 5T has an effect of the order of 10% pre-timing

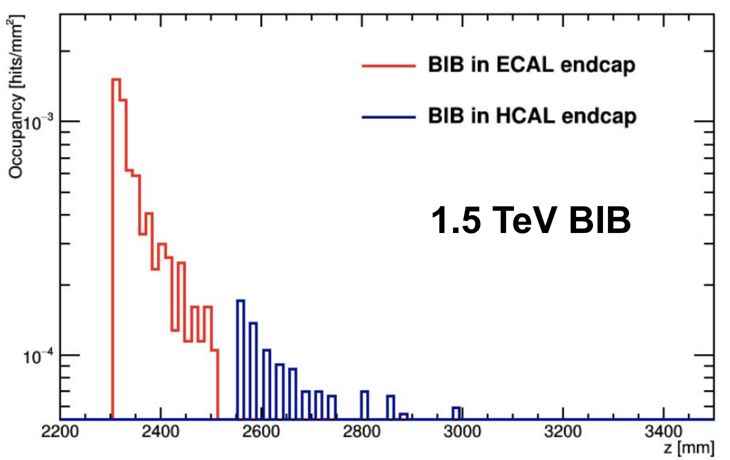
Things to study further:

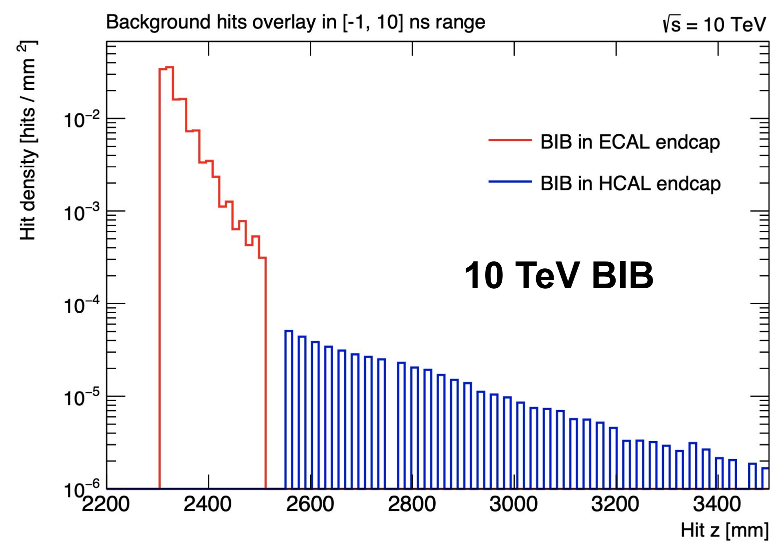
- Different BIB structure in endcaps
- Timing selections seem much more effective than at 3 TeV

Occupancies: calorimeters









Proposed options / concepts under study

Several options (not necessarily exclusive*) are being considered:

1. Evolve the CLIC / 3 TeV / CMS-like detector concept
   a. Push solenoid dimensions and field to the maximum
   b. Change sampling fraction, technologies and volumes to fit in the available space

2. Paradigm-changing ideas
   a. Alternative magnet configuration idea from John Hauptman

3. Break free of the solenoid (a.k.a. the "KITP concept")
   a. Move the solenoid inside the detector to gain freedom on the outer side
      i. Different calorimeter concepts (Dual readout, LAr, …)
      ii. Standalone muon spectrometer (with dedicated magnetic field for better high-p_T muon momentum resolution)
   b. Use solenoid as BIB shield!
   c. Material in front of the calorimeters will degrade energy resolution, but BIB does too. Risky trade-off: unclear without dedicated studies

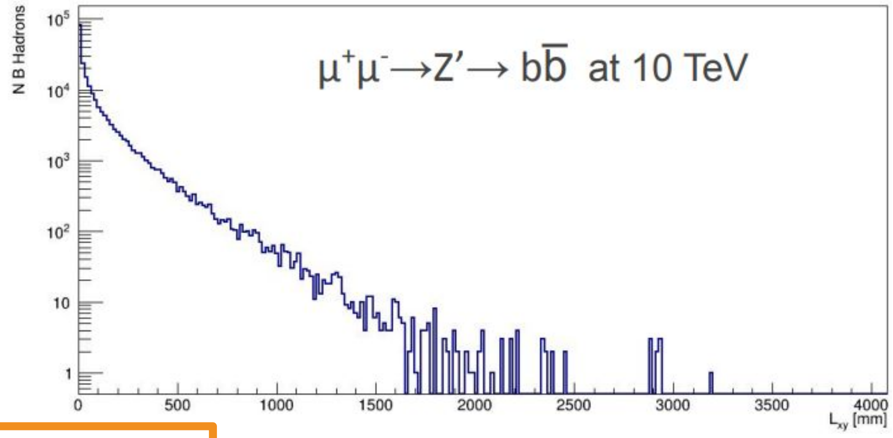
* I have tried to minimise amount of topics covered twice in the talk, more material is available in the references

1. Evolve the 3 TeV concept

(slides based on <u>work</u> from Laura Buonincontri, Luca Giambastiani, Alessandro Montella, Massimo Casarsa, Sergo Jindariani, Luciano Ristori)*

* these are actually generic studies not necessarily targeting a specific detector design

Flavour tagging at 10 TeV



10 TeV simulation

Layer Number	radius[mm]	Ratio in Hbb	Ratio in Z' into b
Layer 1	31	0.97	0.51
Layer2	51	0.990	0.60
Layer3	74	0.998	0.68
Layer4	104	1.	0.74
Layer5	127	1.	0.78
Layer6	340	1.	0.93
Layer7	554	1.	0.97
Layer8	819	1.	0.991
Layer9	1153	1.	0.997
Layer10	1486	1.	0.999

Studied in simulation average decay length for B-hadrons from VBF Higgs and heavy Z' production.

Secondary vertex resolution is driven by the resolution on the tracks impact parameter that depends on:

- number of layers
- radius of the closest layer to the beam pipe

The required resolution on tracks coming from heavy BSM particles needs optimisation.

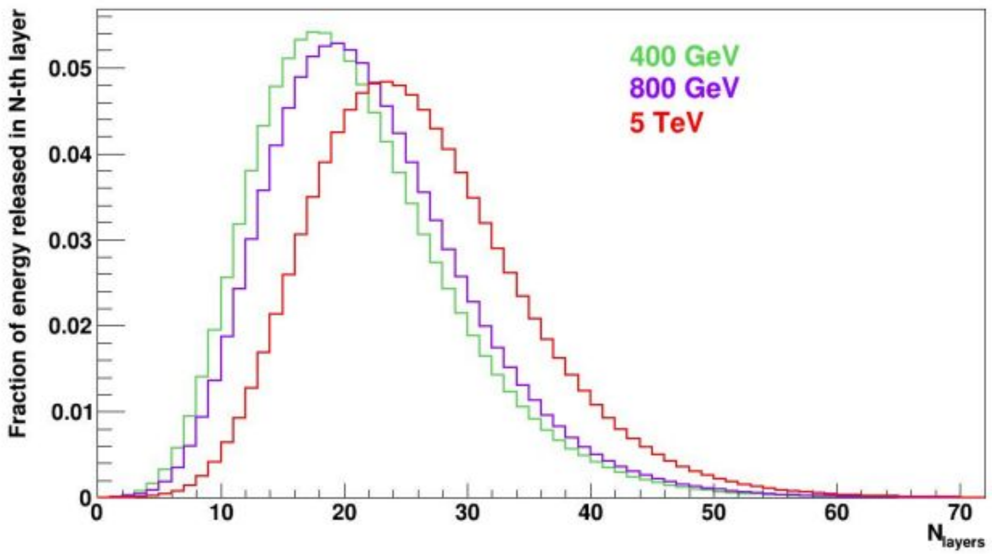
Electron showers up to 5 TeV

Simulation of the Si+W ECAL calorimeter

- Electron particle gun with
  E = 400 GeV, 800 GeV and 5 TeV

Goal: contain ~99% of the energy

Electromagnetic calorimeter depth will have to be increased by ~6 cm



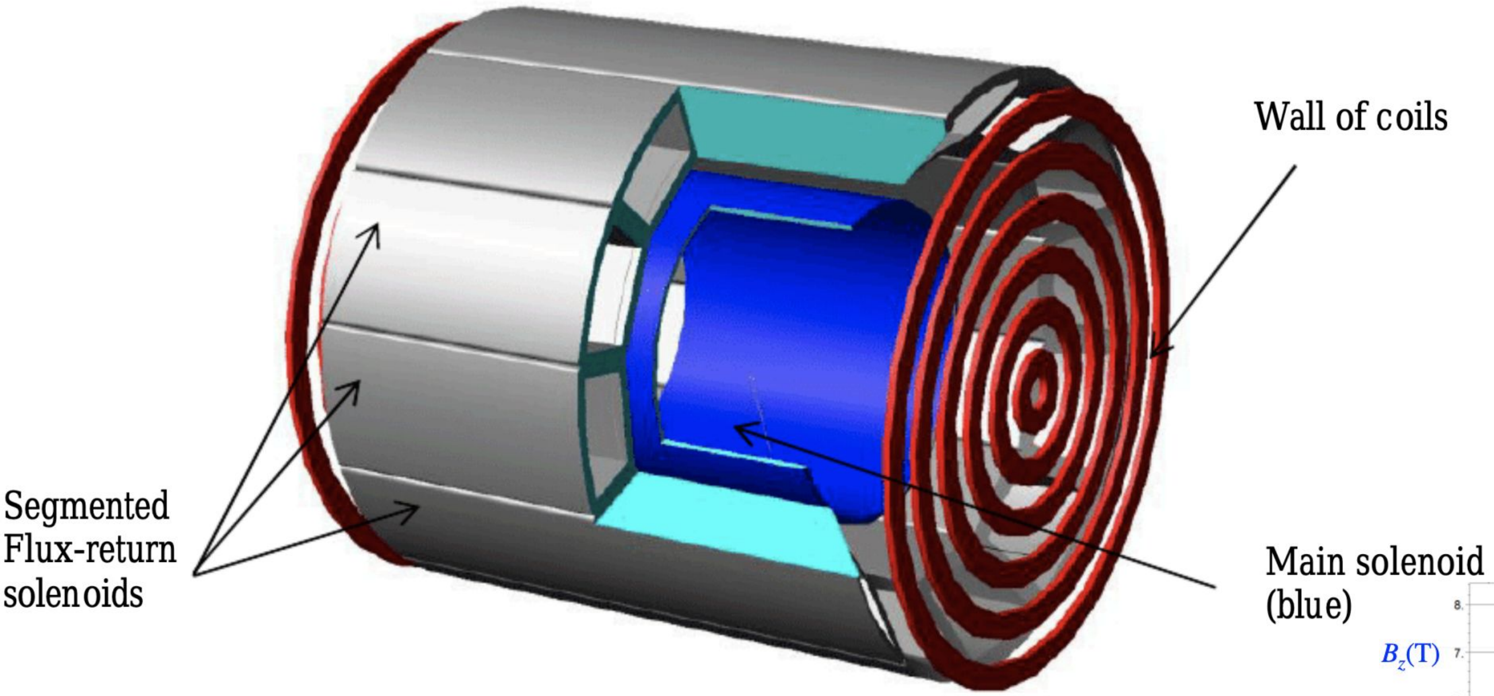
E	Number of X_0	N Layers	ECAL length	λ_I
400 GeV	27.1	45	22.73 cm	1.20
800 GeV	28.3	47	23.73 cm	1.26
5 TeV	30.8	51	25.76 cm	1.36

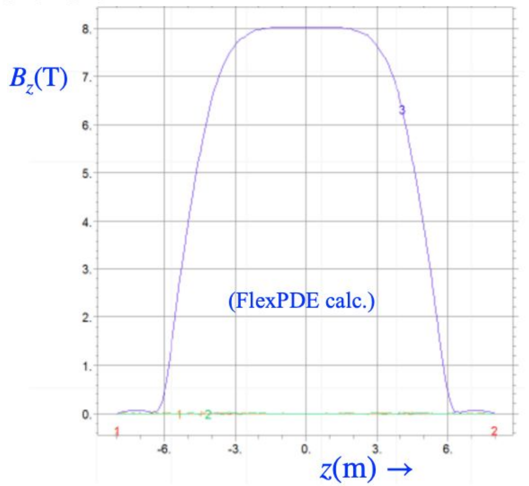
2. Alternative Magnet Configurations

(slides based on ongoing work from John Hauptman)

An iron free detector

Flux return by 12 smaller solenoids (A. Mikailichenko, Cornell LNS)





We can explore large deviations from the current paradigm.

- The B field could be reversed
- Big advantages in terms of detector weight
- Several more details in here

3. KITP concept

(slides based on ongoing work from Daniele Calzolari, Karri DiPetrillo, Robert Hillman, Tova Holmes, Sergo Jindariani, Benjamin Johnson, Lawrence Lee, FM, Isobel Ojalvo, Priscilla Pani, Simone Pagan Griso, Kevin Pedro, Rose Powers, Ben Rosser, Leo Rozanov, Adam Vendrasco, Junjia Zhang)

Modifying the solenoid

B	3.57 T	5 T
Thickness	344 mm	265 mm
R	3821 mm	1500 mm

To first approximation, the size of the solenoid (which is dominated by the material stabilizing the coils, Al) can be scaled according to the following relation*:

$$t_{coil}/X_0 = (R/\sigma_h X_0)(B^2/2\mu_0) \; ,$$

Started from solenoid of 3 TeV detector

- Not a “transparent” solenoid
- About 3.3 X_0 before the ECAL

Atomic and nuclear properties of aluminum (Al)

Quantity	Value	Units	Value	Units
Atomic number	13			
Atomic mass	26.9815385(7)	g mol^{-1}		
Density	2.699	g cm^{-3}		
Mean excitation energy	166.0	eV		
Minimum ionization	1.615	MeV g^{-1}cm^{2}	4.358	MeV cm^{-1}
Nuclear interaction length	107.2	g cm^{-2}	39.70	cm
Nuclear collision length	69.7	g cm^{-2}	25.81	cm
Pion interaction length	136.6	g cm^{-2}	50.62	cm
Pion collision length	95.6	g cm^{-2}	35.41	cm
Radiation length	24.01	g cm^{-2}	8.897	cm
Critical energy	42.70	MeV (for e^-)	41.48	MeV (for e^+)
Muon critical energy	612.	GeV		
Molière radius	11.93	g cm^{-2}	4.419	cm
Plasma energy $\hbar\omega_p$	32.86	eV		
Melting point	933.5	K	660.3	C
Boiling point @ 1 atm	2792.	K	2519.	C

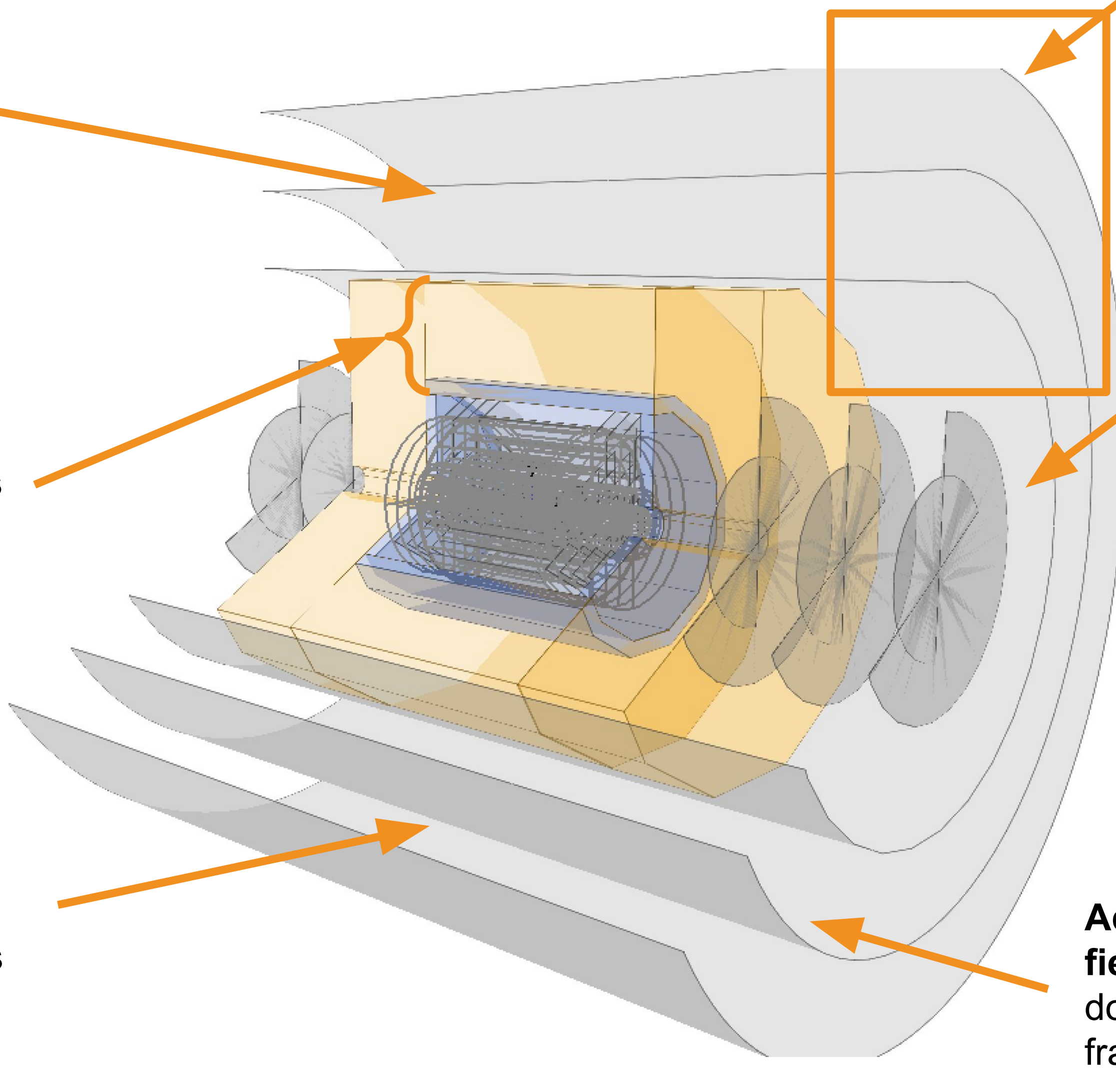
* PDG, and email exchange with
L. Bottura, H. Ten Kate, A. Yamamoto

Early look at detector concept

No need for a Yoke: B field returned by iron in HCAL

Calorimeter depth optimised with photon and pion gun samples (changed both sampling fraction and N_{layers})

Simplified muon detector (implemented as a tracker)



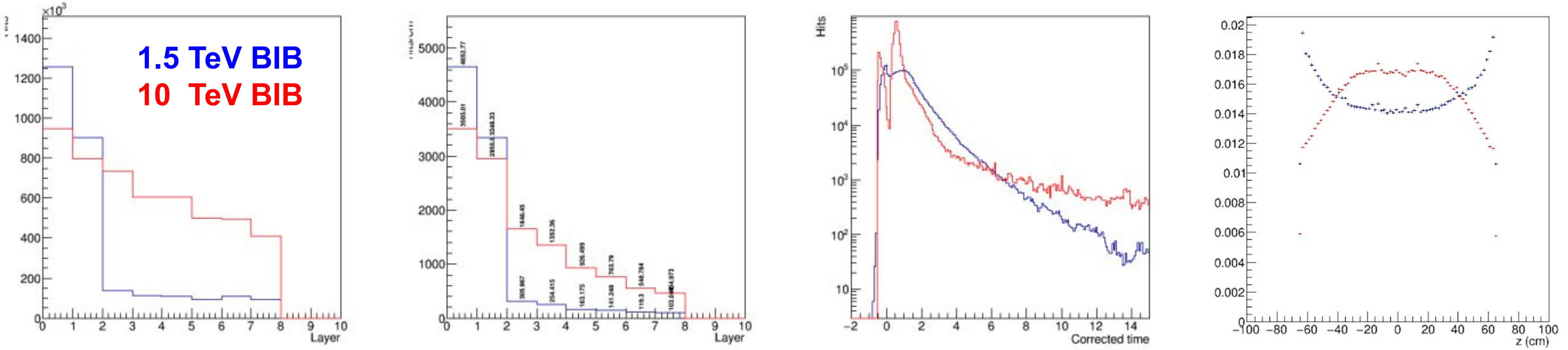
Extension of barrel vs endcap will be optimised to **minimise detector surface**

Radius buggy: **meant to extend up to the barrel**

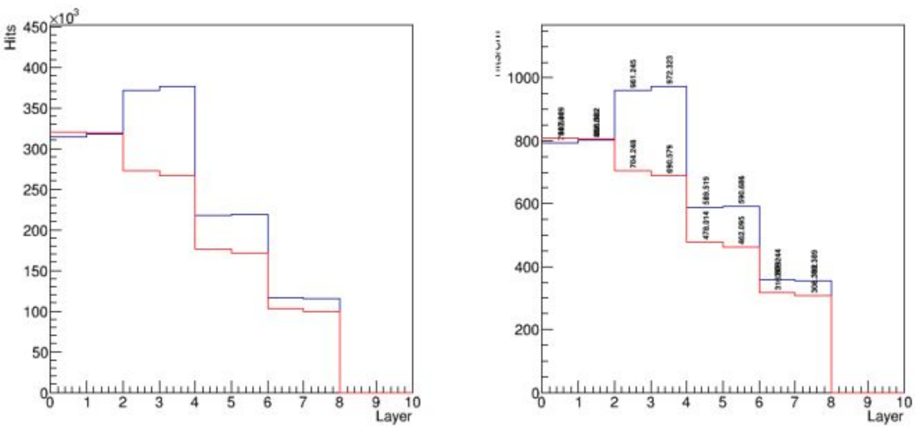
Adding toroidal field never really done in sw framework before

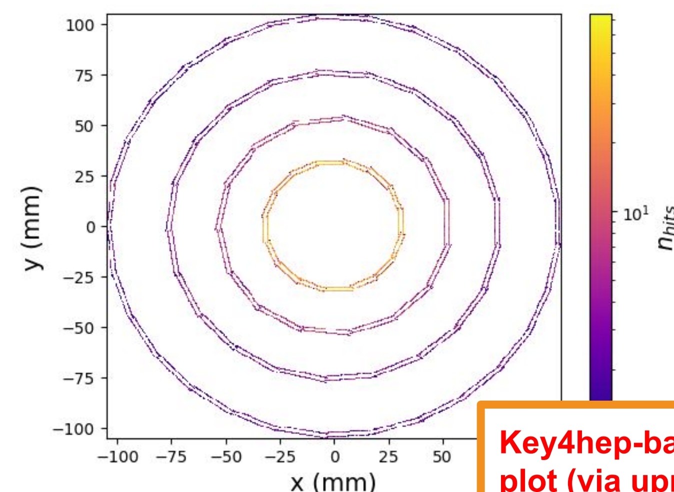
A deeper look at the tracker

Vertex Barrel



Vertex Endcaps





Key4hep-based plot (via uproot)!

Study done on simulated hits (<u>reasonable</u> proxy for smeared ones)

- BIB overlaid in (-1, 15) ns window

Data rates and power

	Upper timing cut (ns)	Module size (cm^2)	Maximum hits/cm^2	Reduction using cluster shapes	Data payload per module (Gbps)	Transmission power per module (W)	Total Transmission Power (W)
VXD barrel L1/L2	15	10	3000	x2	50	0.5	25
VXD barrel L1/L2	1	10	2400	x2	35	0.3	20
VXD barrel L3-8	15	10	1400	-	50	0.5	100
VXD disks	15	10	700	-	21	0.2	60
IT barrel	15	50	170	-	24	0.2	360
IT disks	15	50	60	-	9	0.09	100
OT barrel	15	100	10	-	3	0.03	170
OT disks	15	100	5	-	1.5	0.15	30

L1/L2 rates still require tighter time window (~1ns)

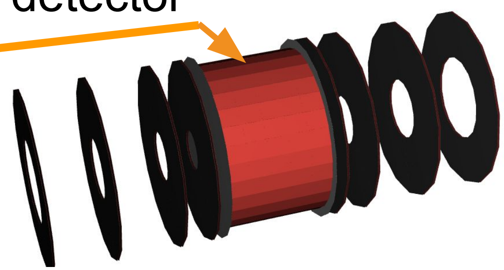
L3/L8 now less comfortable

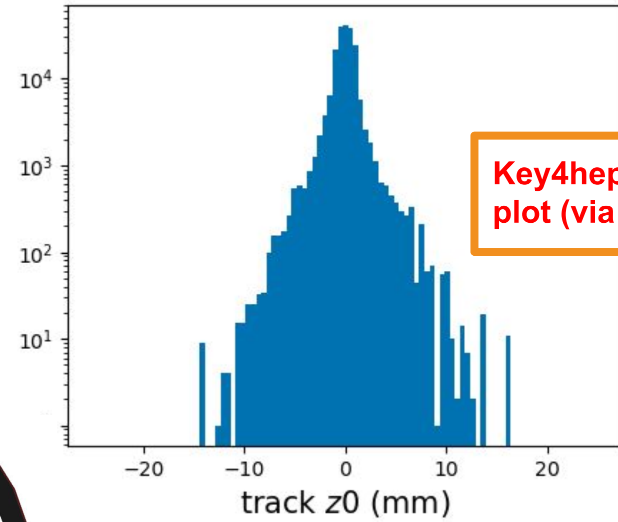
- Total L3/L8 power will be halved by removing the double layers

Tracking performance

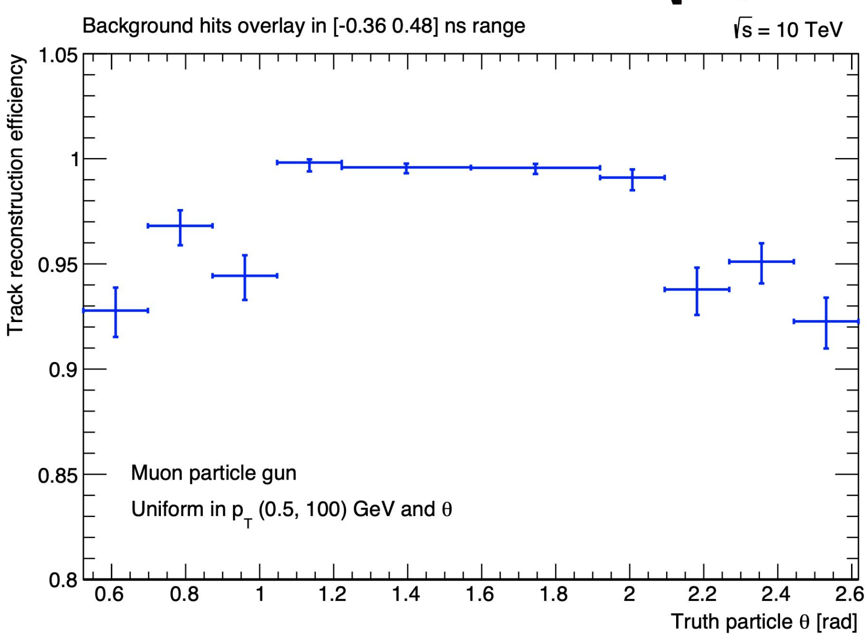
Studied track reconstruction using single muon particle gun with 10 TeV BIB overlay, both with:

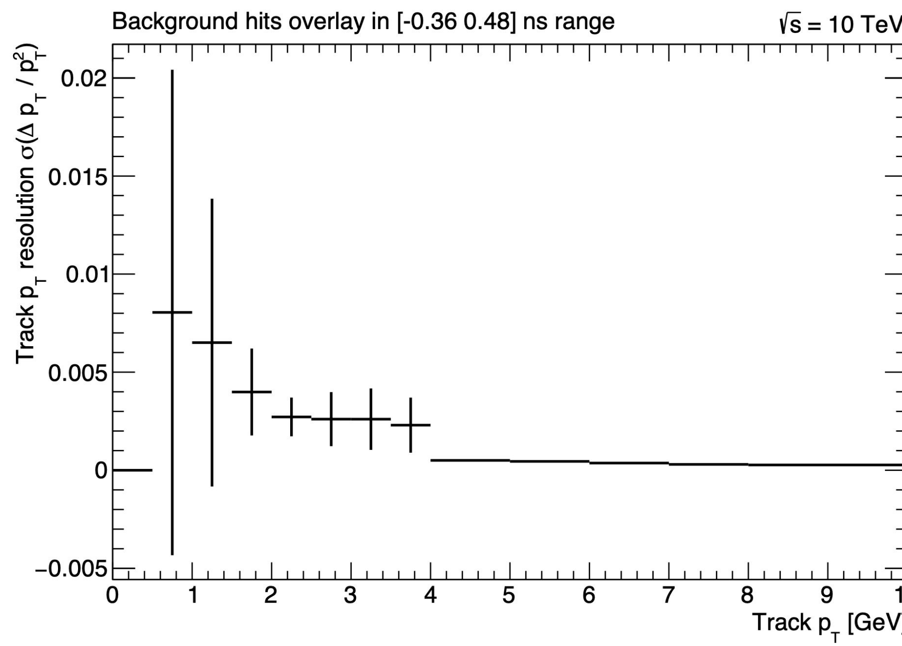
1. Same tracker as 3 TeV detector
2. 2nd-4th barrel double layers removed



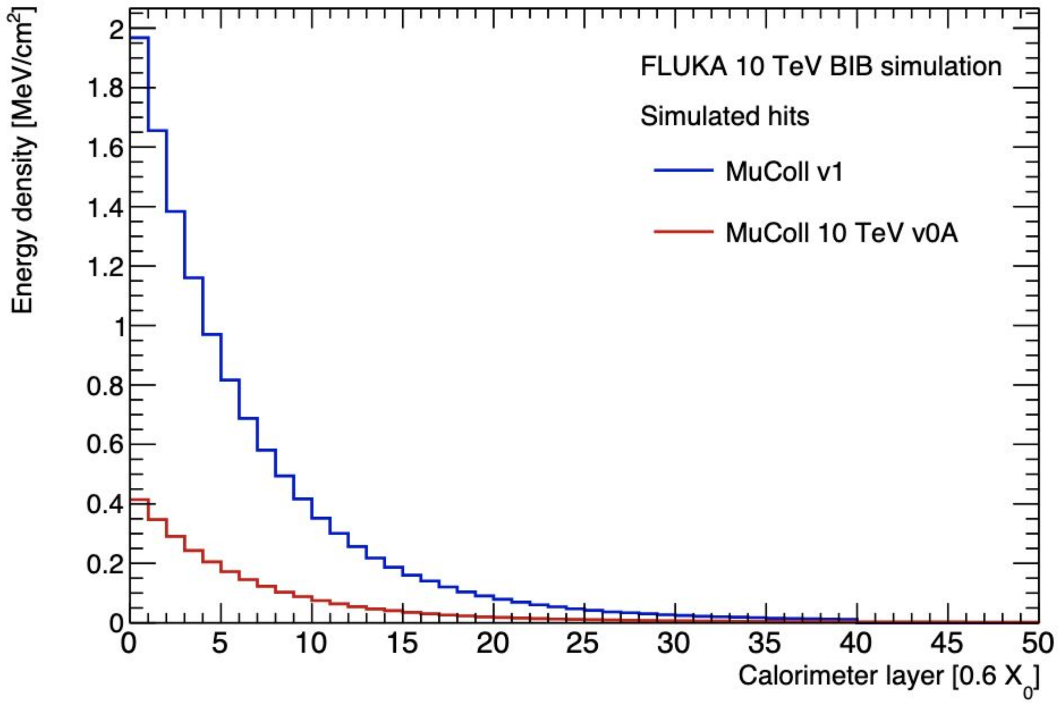


Key4hep-based plot (via uproot)!





Calorimeters: ECAL energy density



The presence of the solenoid acting as “BIB shield” can be seen in the calorimeter energy density.

Enables use of lower thresholds at cell level to improve energy resolution.

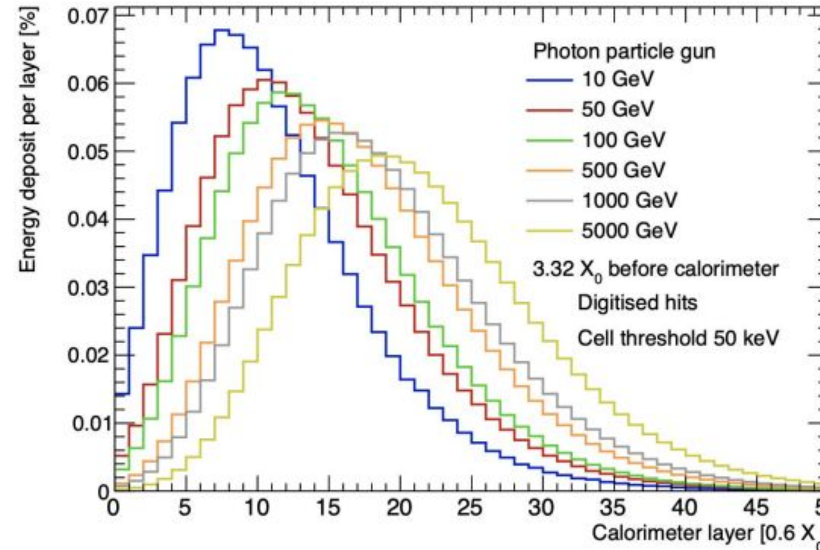
- In the following kept as in EPJC report results (2 MeV) to ease comparison
- Some work needed at Pandora level to handle lower thresholds 🕐

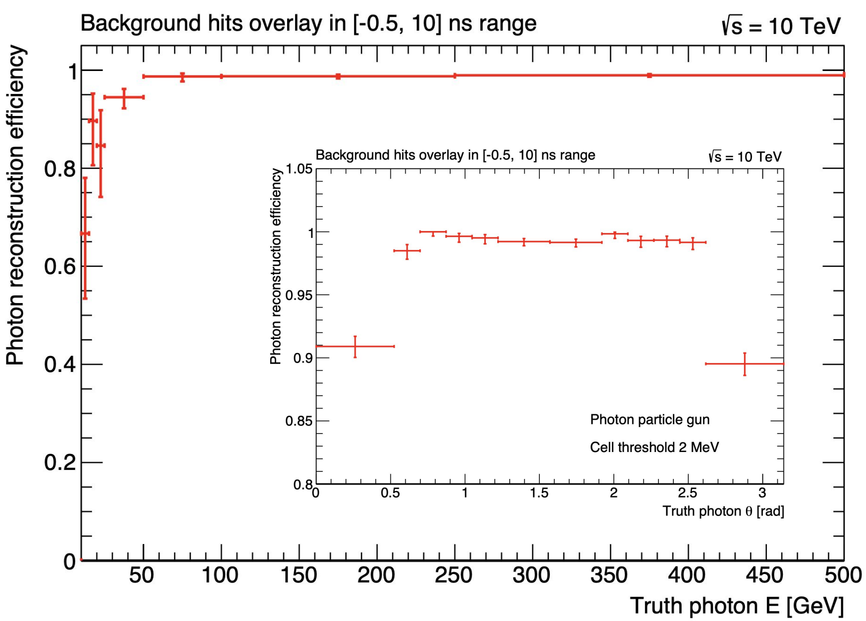
Photon reconstruction

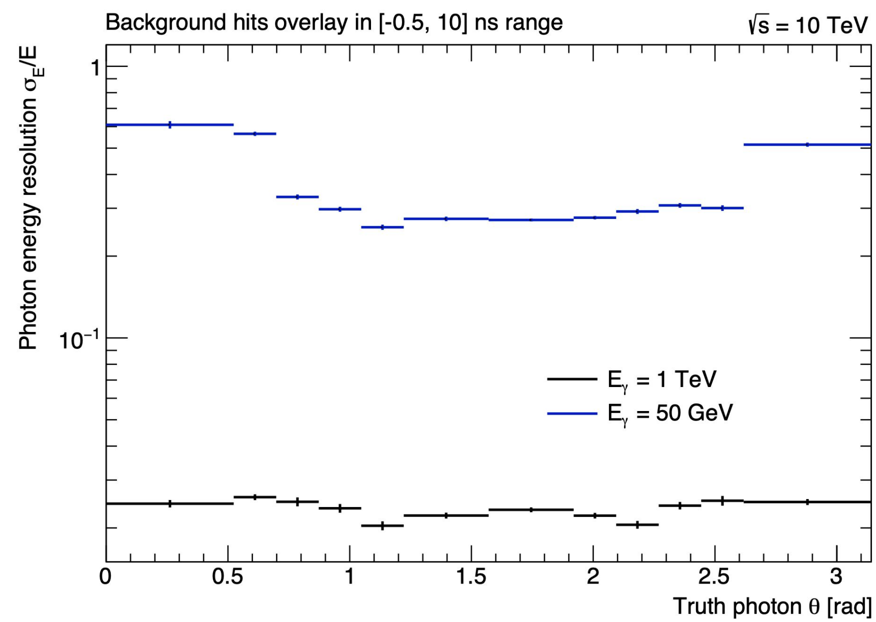
Changes to EM calorimeter:

- Kept same Si-W technology
- 40 → 50 layers
- Tungsten absorber 1.9 → 2.20 mm

Studied photon reconstruction efficiency and energy resolution





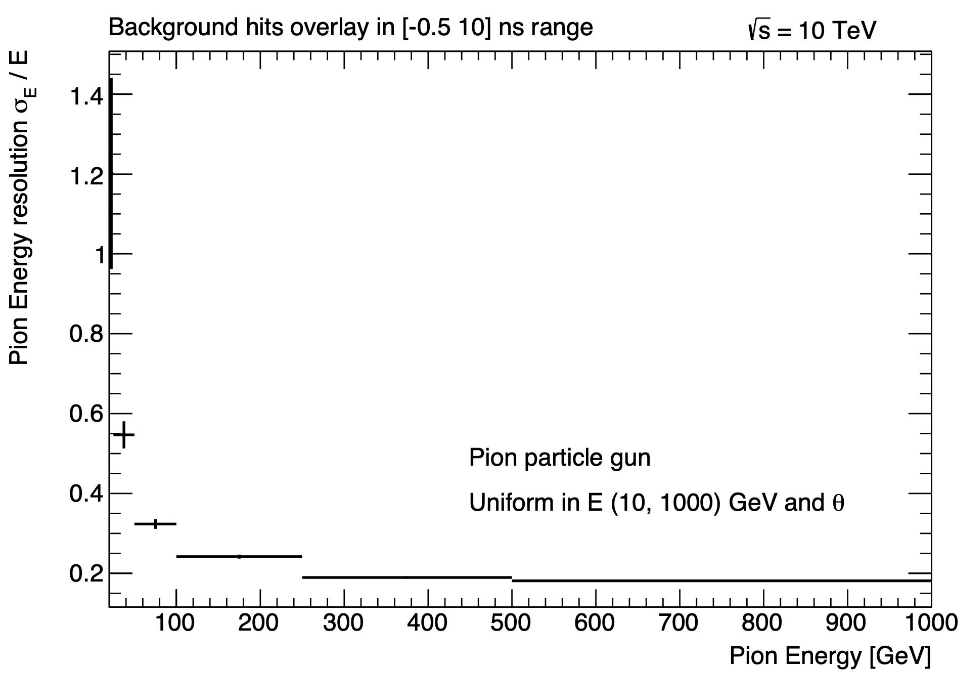


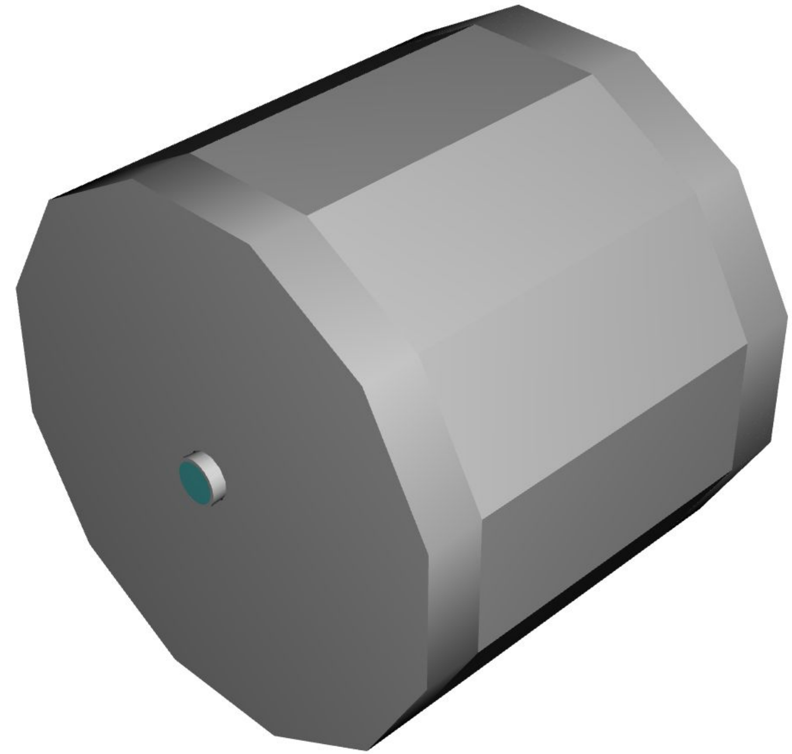
Hadron calorimeter

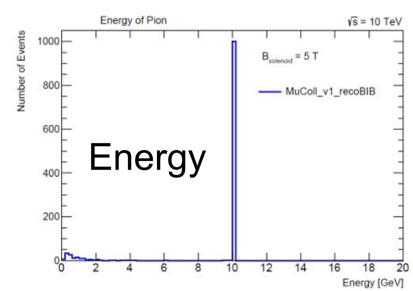
Changes to Hadron calorimeter:

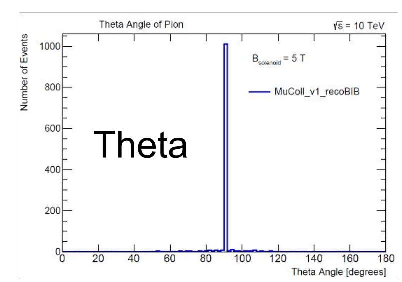
- Kept same Fe-Scin technology
- 60 → 75 layers

Studied pion energy resolution as a function of theta.









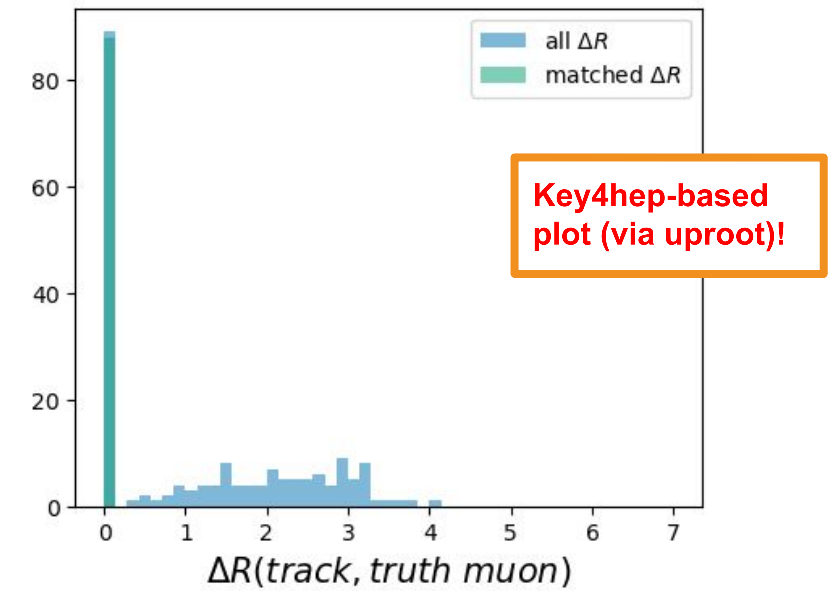
Calorimeter depth optimised with single pion gun samples shot in the centre of the barrel

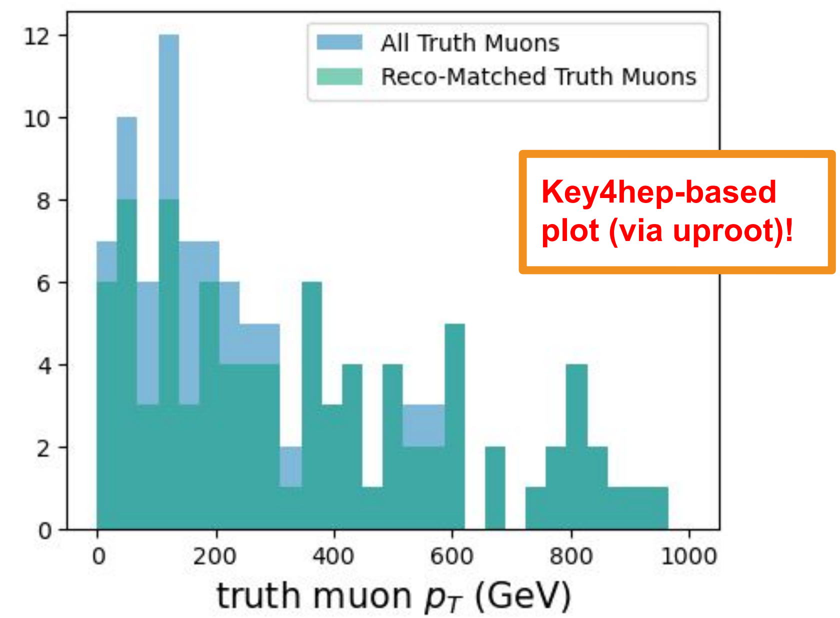
Muon reconstruction

Performed sanity checks with single muon particle gun and 10 TeV BIB overlay with old detector configuration (Yoke+RPCs)

New geometry requires significant development:

1. Add magnetic field map 🕐
2. Define tracking elements and perform material mapping ✅
3. Update ACTS tracking processor to read new geometry ❌
4. Write standalone muon reconstruction (matching trackers with muon spectrometer) ❌





Summary and plans

The work towards defining one or more 10 TeV detector designs is in full swing

Presented the main concepts under study:
- Evolution of 3 TeV detector
- Alternative Magnet configurations
- KITP concept

Presented an initial set of particle-gun level studies

Plan to follow-up and refine during summer:

- Use exercise as training ground for fresh students
- Organise recurrent reports at the off-week detector meetings
- Document and release 10 TeV design and related software as soon as possible

Thank you!