Status update on FLArE simulations

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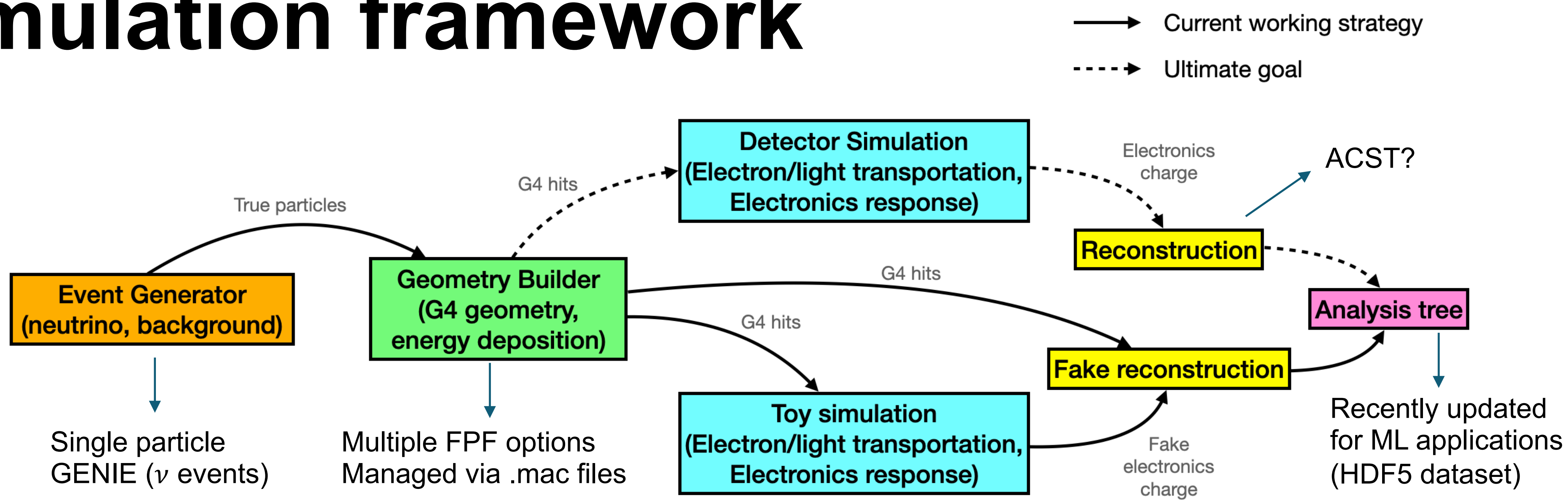
FLArE Technical Meeting

Technical note in progress

- We have a draft of the technical note on the simulation studies: https://www.overleaf.com/1625521614bgrvrfzsgqhx#2c82dd
- Currently a collection of semi-independent studies, lacks a common theme.
- Some sections need to be finalized (e.g: momentum reconstruction).
- Clear conclusions for the studies need to be drawn.

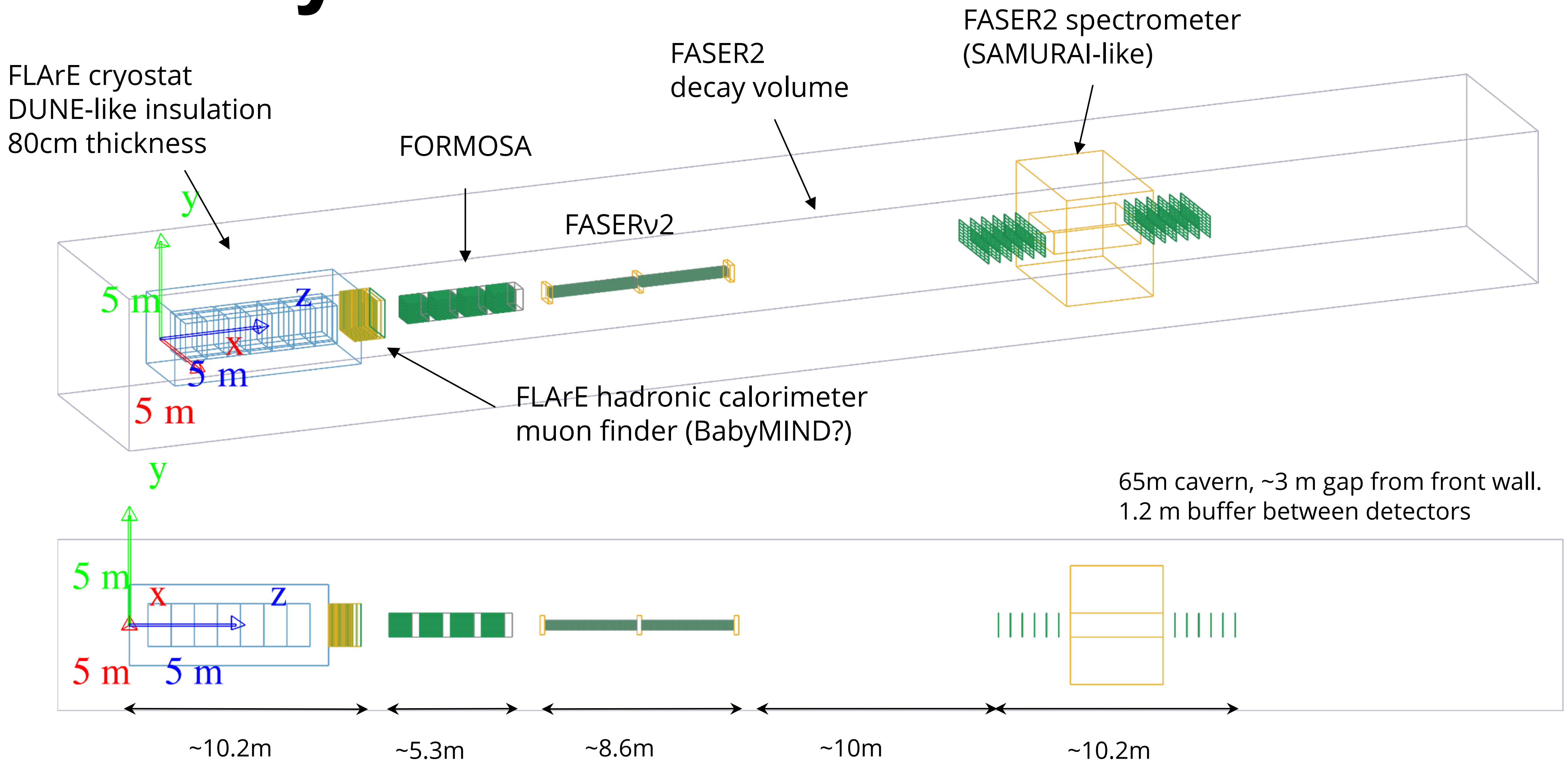
Contents

Simulation framework



- Simulation package: GENIE + GEANT4 + toy/pseudo-reconstruction
- No scintillation-light simulation, no charge transportation, no electronic simulation. Limits technical R&D, even if we had detailed geometry.
- Will soon need dedicated resources (machines, job cluster…)

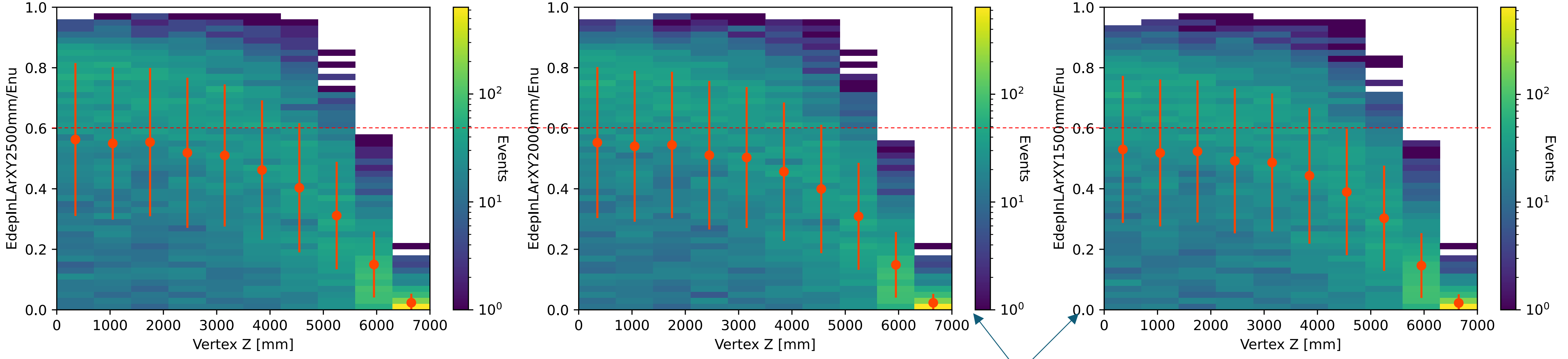
Geometry


FLArE cryostat
DUNE-like insulation
80cm thickness
FORMOSA
FASER2
decay volume
FASER2 spectrometer
(SAMURAI-like)
FASERν2
FLArE hadronic calorimeter
muon finder (BabyMIND?)
y
5 m
z
x
5 m
5 m
65m cavern, ~3 m gap from front wall.
1.2 m buffer between detectors
~10.2m
~5.3m
~8.6m
~10m
~10.2m

Overview of studies in the technical note

Energy containment

- Energy containment is guaranteed for 1x1x7 m^3 fiducial volume, with no more than 2 meters in transverse direction.
  - Looking at ν_τ events, fraction of contained energy as a function of the vertex z position:



Transverse size: 2.5 m

2.0 m

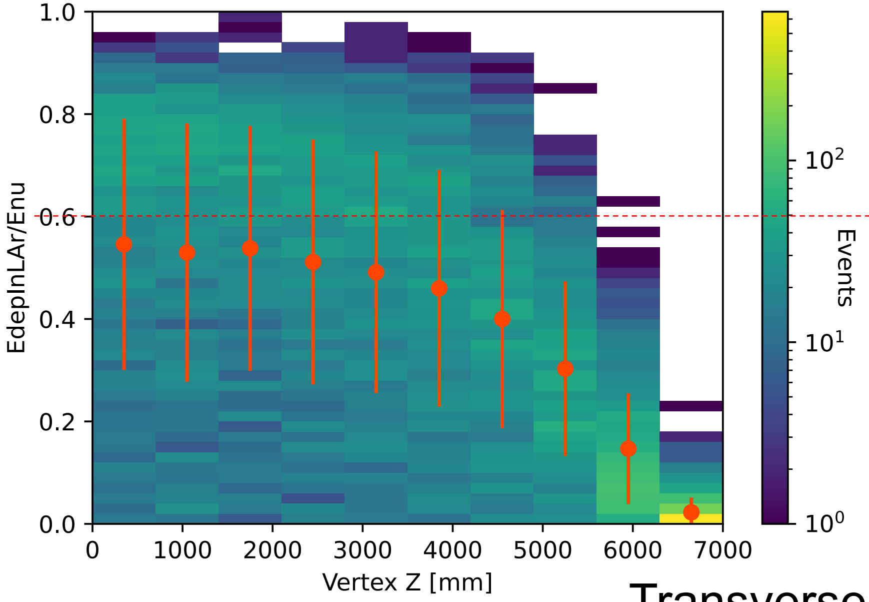
Sudden drop of containment

1.5 m

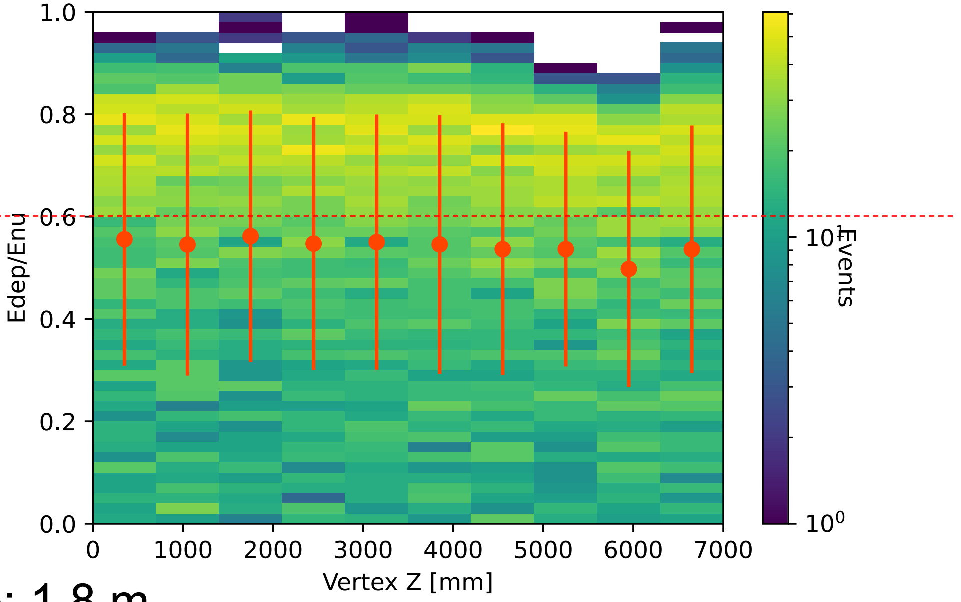
Energy containment

- Hadronic calorimeter (15 layers, ~105cm total) is effective in recovering the missing energy from the downstream z bins.

w/o HadCal



w/ HadCal

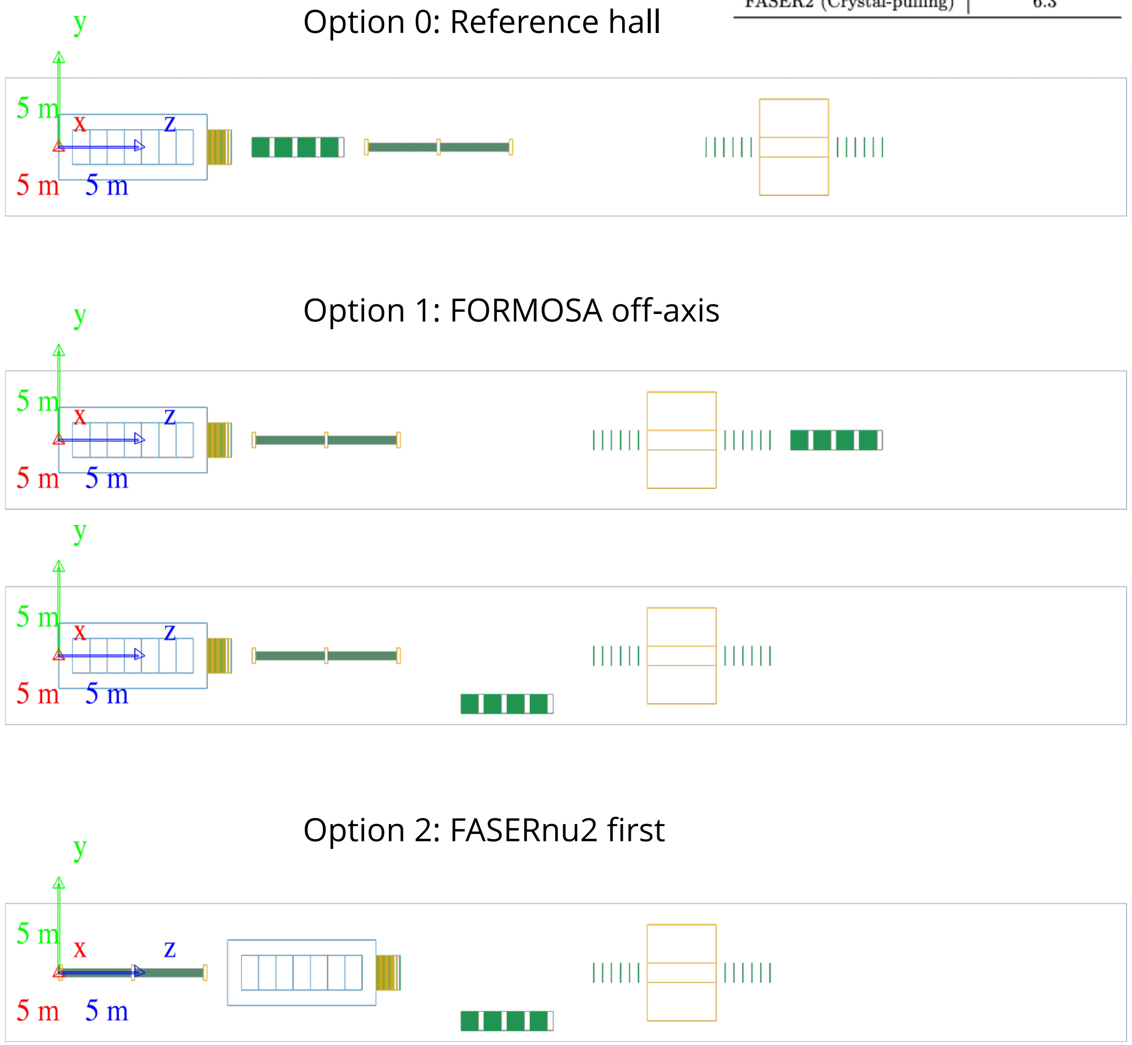


Transverse size: 1.8 m

FPF configurations

- Qualitative description of several alternative FPF configurations implemented in the geometry.
- Already out-of-date?

Detector	Total length [m]
FLArE	10.2
FORMOSA	5.3
FASERν2	8.6
FASER2 (SAMURAI-like)	10.2
FASER2 (Crystal-pulling)	6.3



FPF hall configurations

Name	Comment	FLArE (y,z) [m]	FORMOSA (y,z) [m]	FASERν2 (y,z) [m]	FASER2 (y,z) [m]
Option 0	Reference hall	$(0, 4.3)$	$(0, 13.9)$	$(0, 22.0)$	$(0, 42.6)$
	...with CrystalPulling magnets	$(0, 4.3)$	$(0, 13.9)$	$(0, 22.0)$	$(0, 40.7)$
Option 1a	FORMOSA behind FASER2	$(0, 4.3)$	$(0, 45.1)$	$(0, 15.5)$	$(0, 36.1)$
	...with CrystalPulling magnets	$(0, 4.3)$	$(0, 41.1)$	$(0, 15.5)$	$(0, 34.1)$
Option 1b	FORMOSA below decay volume	$(0, 4.3)$	$(-2.5, 26.0)$	$(0, 15.5)$	$(0, 36.1)$
	...with CrystalPulling magnets	$(0, 4.3)$	$(-2.5, 26.0)$	$(0, 15.5)$	$(0, 34.1)$
Option 2	FASERν2 before FLArE	$(0, 14.1)$	$(-2.5, 26.0)$	$(0, 4.3)$	$(0, 36.1)$
	...with CrystalPulling magnets	$(0, 14.1)$	$(-2.5, 26.0)$	$(0, 4.3)$	$(0, 34.1)$

Table 1: Summary of the FPF configurations. The (y, z) positions of the on-axis detector centers are reported. A 1.2 m buffer between each experiment is assumed. The center of the coordinate system always corresponds to the front of the first detector, 3.1 m from the cavern wall. The z-axis represents the line of sight, while y is the vertical direction. The full length of the cavern is 65 m.

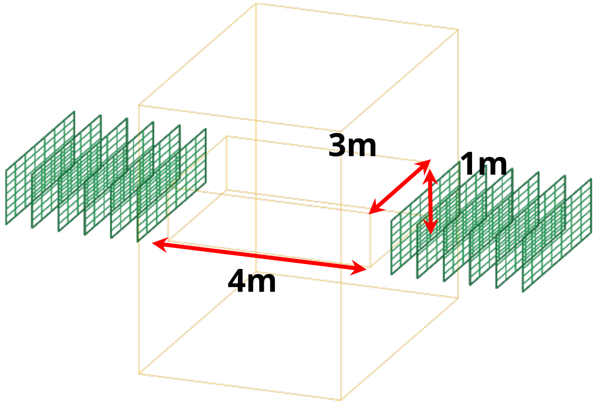
Magnet options

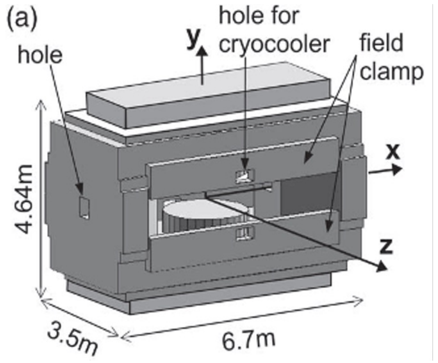
Two magnet designs for the FASER2 spectrometer magnet.

SAMURAI-style:
<u>Pro</u>: 4 Tm, great Pt resolution.
<u>Con</u>: Huge yoke, procurement time and cost, installation.

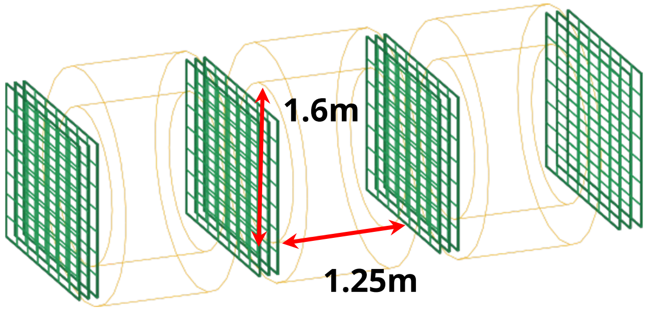
Crystal-pullers:
<u>Pro</u>: Cheap, readily available, small and modular.
<u>Con</u>: 0.75 Tm each, worse Pt resolution.

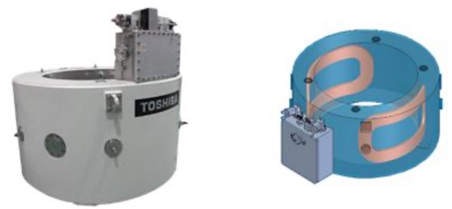
SAMURAI-like magnet





TOSHIBA Crystal-pulling magnets





Magnet option	Qnty	Size	Window	Length	Field	Field integral
SAMURAI-like	1	6 m × 5 m × 4 m	3 m × 1 m	4 m	1 T	4 Tm
Crystal-pulling	3	2.4 m × 2.4 m × 1.25 m	⌀1.6 m	1.25 m	0.6 T	0.75 Tm
Tracking stations	**Sets**	**Number per set**	**Size**	**Thickness**	**Gap to magnet**	**Spacing**
SAMURAI-like	2	6	3 m × 3 m	2 cm	0.5 m	0.5 m
Crystal-pulling	4	3	1.6 m × 1.6 m	2 cm	0.25 m	0.1 m

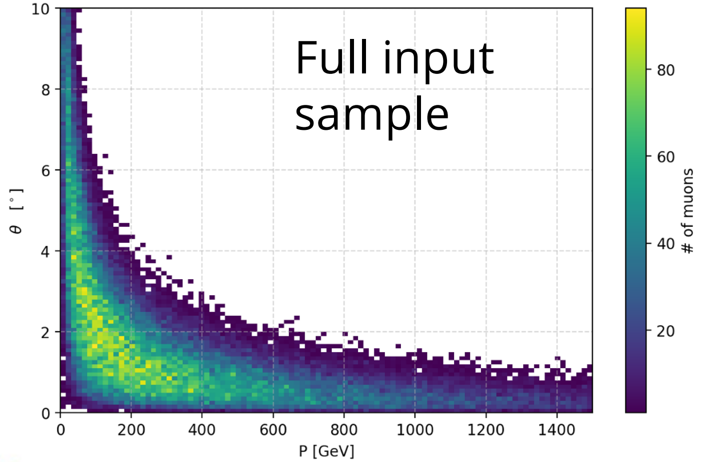
Muon acceptance: SAMURAI (1m gap)

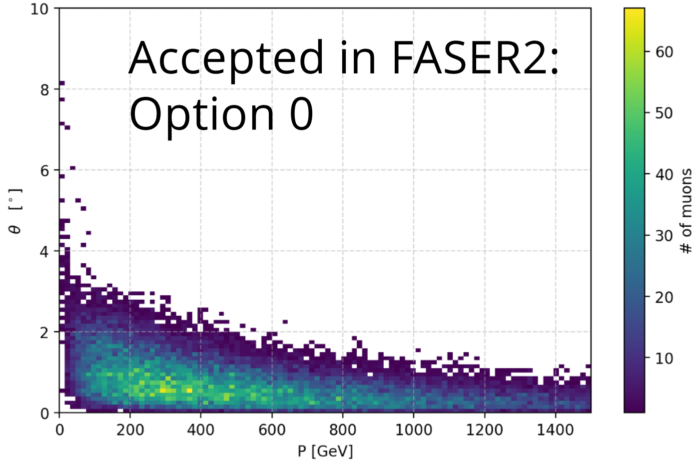
Muons is accepted into FASER2 if:

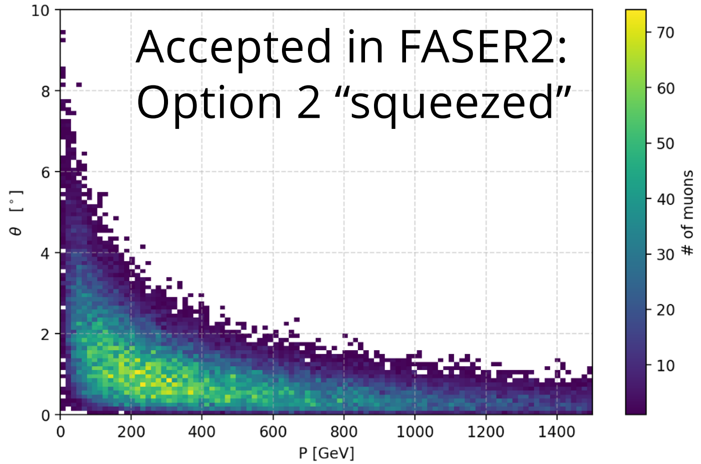
1. >0 pre-magnet trackers crossed
2. >2 post-magnet trackers crossed

FASER2 SAMURAI-like magnet $3\,m \times 1\,m \times 4\,m$					
Option	Distance [m]	FLArE volume	Total	HadCat + MF	FASER2
FLArE + FASER2 only	38.3	All fiducial	76699	66899 (87.2%) 73486 (95.8%)	23760 (31.0%) 30808 (40.2%)
Option 0: Reference hall	38.3	fiducial	76699	73486 (95.8%)	30668 (40.0%)
Option 1a: FORMOSA last Option 1b: FORMOSA below	31.6	fiducial	76699	73486 (95.8%)	34188 (44.5%)
Option 2: FASERν2 first	22	fiducial	76699	73461 (95.8%)	41027 (53.5%)
Option 2 "squeezed"	17	fiducial	76699	73309 (95.6%)	45952 (59.9%)

Table 5: Muon acceptances for the FLArE magnetized spectrometer and the FASER2 "SAMURAI-like" magnet ($3\,m \times 1\,m \times 4\,m$) for different configurations of the FPF cavern. FLArE fiducial volume is $1\,m \times 1\,m \times 7\,m$. The magnetic field both in the FLArE spectrometer and in the FASER2 magnet is 1 T. The distance is computed from the center of the FLArE liquid Argon volume to the center of the FASER2 magnet window.







Muon acceptance: Crystal-pullers

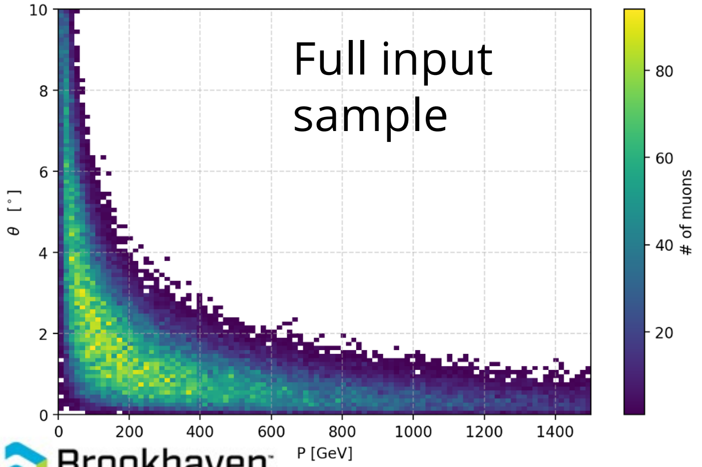
Muons is accepted into FASER2 if:

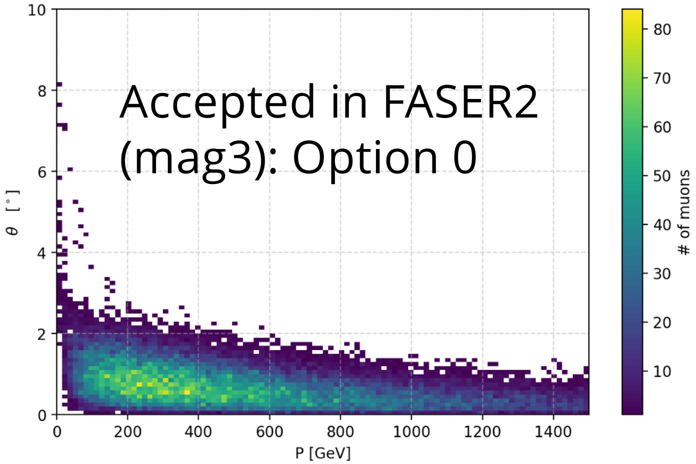
1. >0 pre-magnet trackers crossed
2. >2 post-magnet trackers crossed

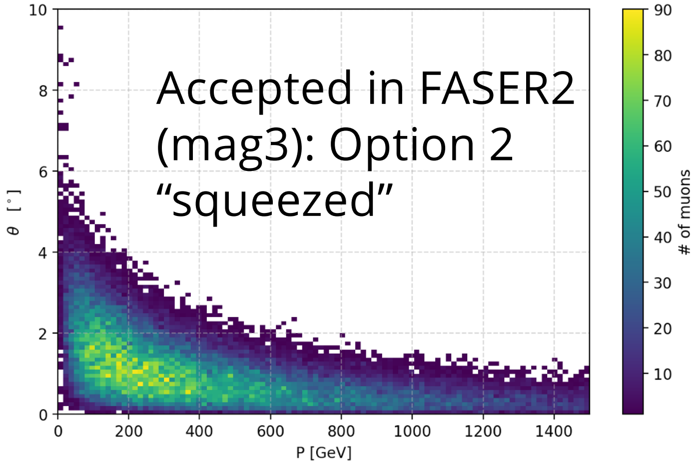
FASER2 crystal-pulling magnets					
Option	Distance [m]	Total	FASER2 Mag. 1	FASER2 Mag. 2	FASER2 Mag. 3
Option 0: Reference hall	36.4	76699	41048 (53.5%)	39645 (51.7%)	38281 (49.9%)
Option 1a: FORMOSA last Option 1b: FORMOSA below	29.8	76699	46077 (60.1%)	44360 (57.8%)	42764 (55.7%)
Option 2: FASERν2 first	20	76699	55689 (72.6%)	53514 (69.8%)	51502 (67.1%)
Option 2 "squeezed"	16.8	76699	59351 (77.4%)	57001 (74.3%)	54749 (71.4%)

Table 6: Muon acceptances for the FASER2 "crystal-pulling" magnets for different configurations of the FPF cavern. FLArE fiducial volume is $1\,\mathrm{m} \times 1\,\mathrm{m} \times 7\,\mathrm{m}$. The magnetic field in the FLArE spectrometer is 1 T, while the field in each FASER2 magnet is 0.6 T. The distance is computed from the center of the FLArE liquid Argon volume to the center of the FASER2 magnet assembly.

Each magnet is independent.
However mag3 ≅ mag3 && mag1 && mag2





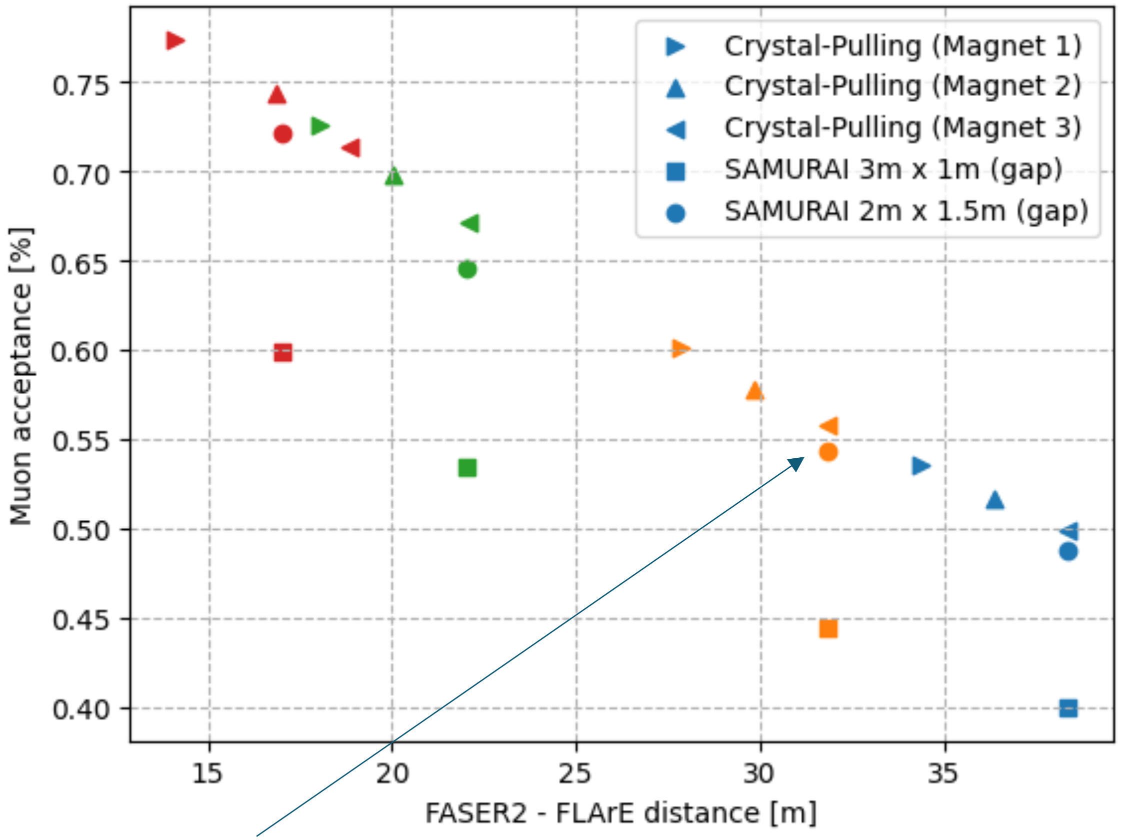


Acceptance vs distance

Acceptance is mainly driven by the FLArE-FASER2 distance, which depends on the FPF configuration.

- Blue: reference option
- Orange: option 1a/1b
- Green: option 2
- Red: option 2 “squeezed”

The crystal-pulling magnets (⌀1.6 m) and the SAMURAI-like magnet (1.5m gap) are comparable!



Small difference to be investigated.. bias due to the corners of tracking stations?

Momentum @ FLArE

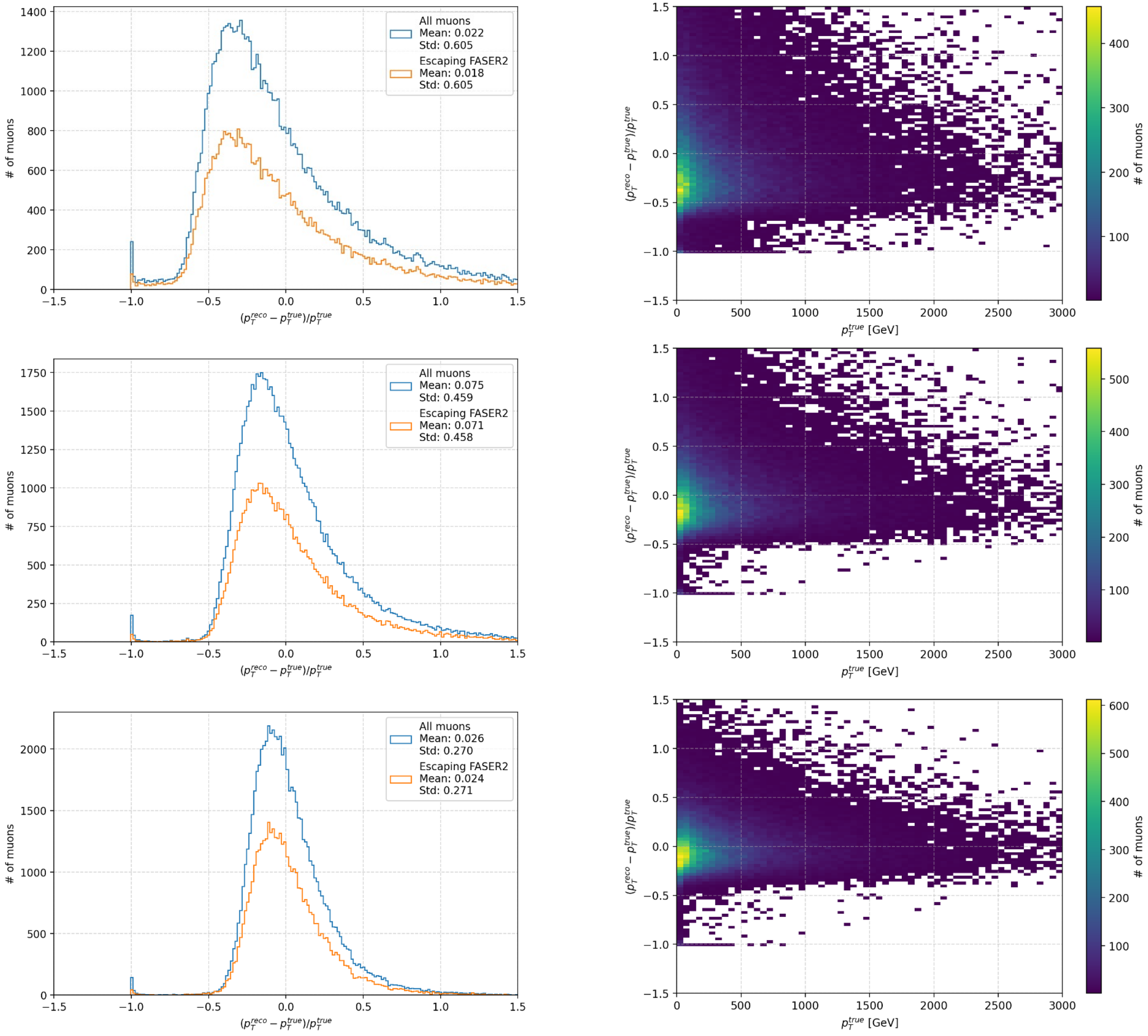
- Momentum resolution @ FLArE is poor.
- Simulation step is 0.5mm. Expected displacement ~1mm for average muon.
- Curvature is not visible, radius is overestimated, large positive tail

- **Optimization is needed**: BabyMIND or NuTeV-like detector?

FLArE B=0.5T

FLArE B=1T

FLArE B=1.5T



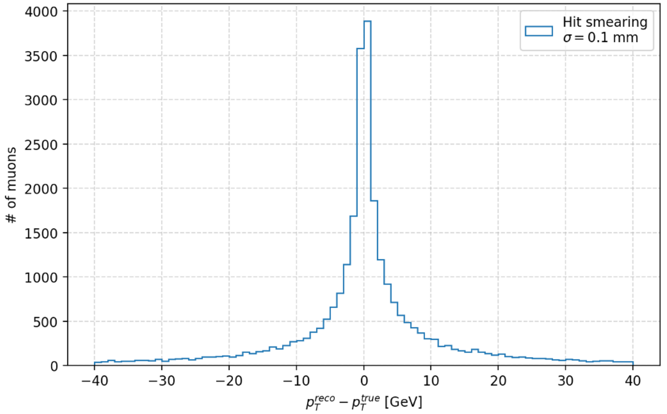
(Preco - Ptrue)/Ptrue

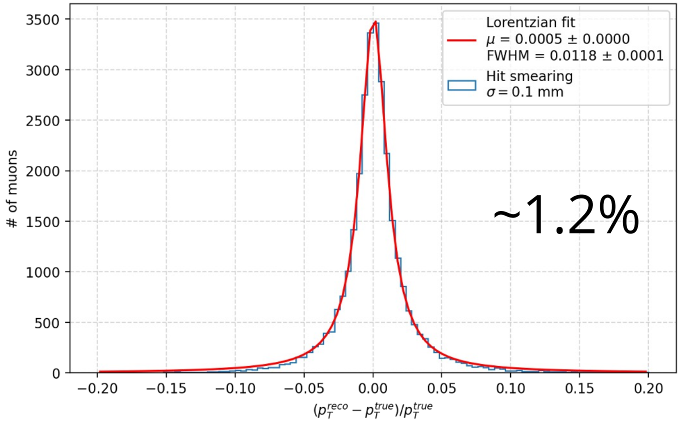
(Preco - Ptrue)/Ptrue vs Ptrue

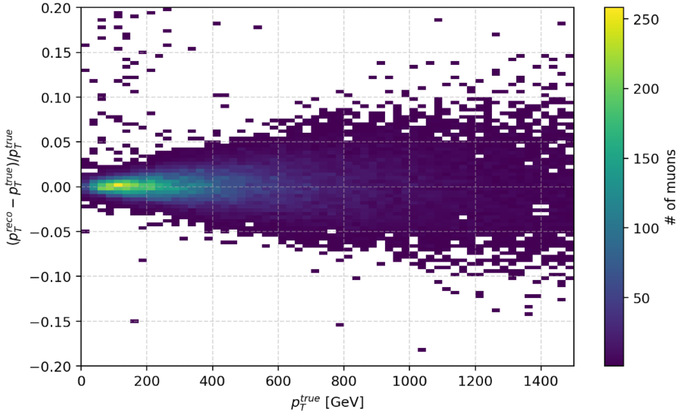
Momentum @ FASER2

Momentum resolution with sigma=0.1mm Gaussian smearing

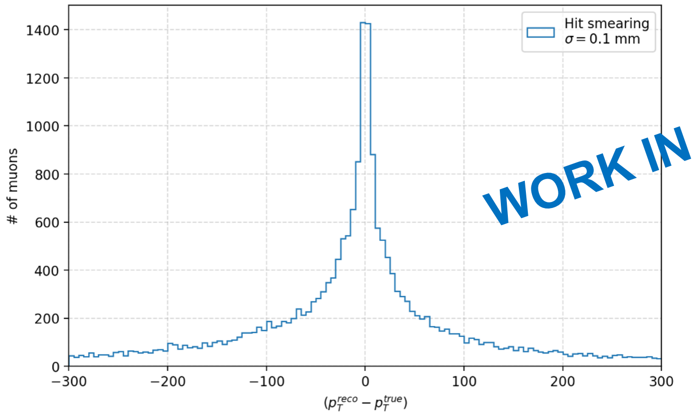
SAMURAI



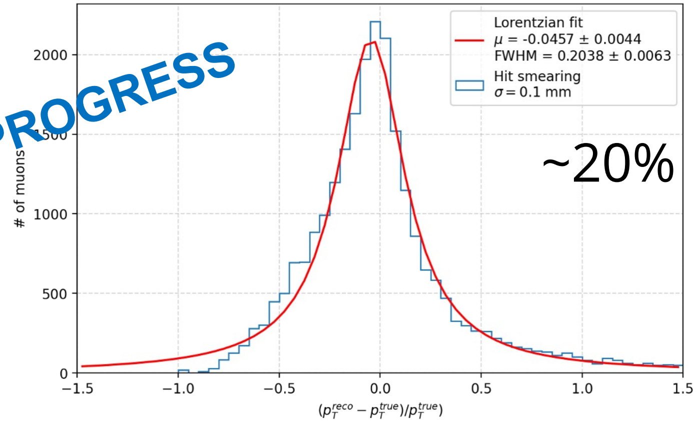


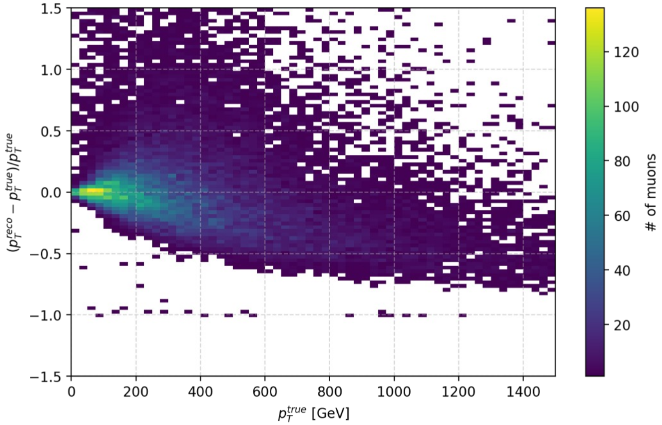


3 combined crystal-pullers



WORK IN PROGRESS

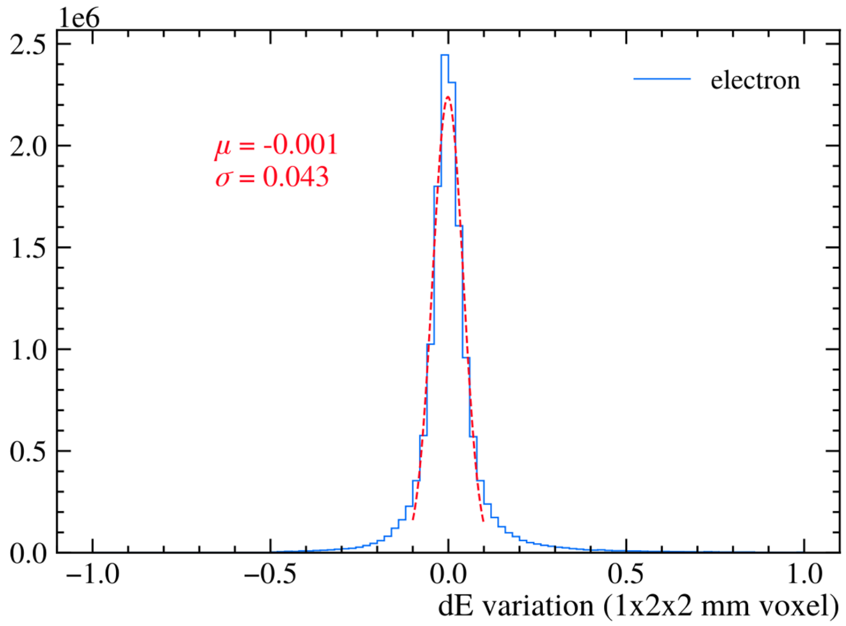


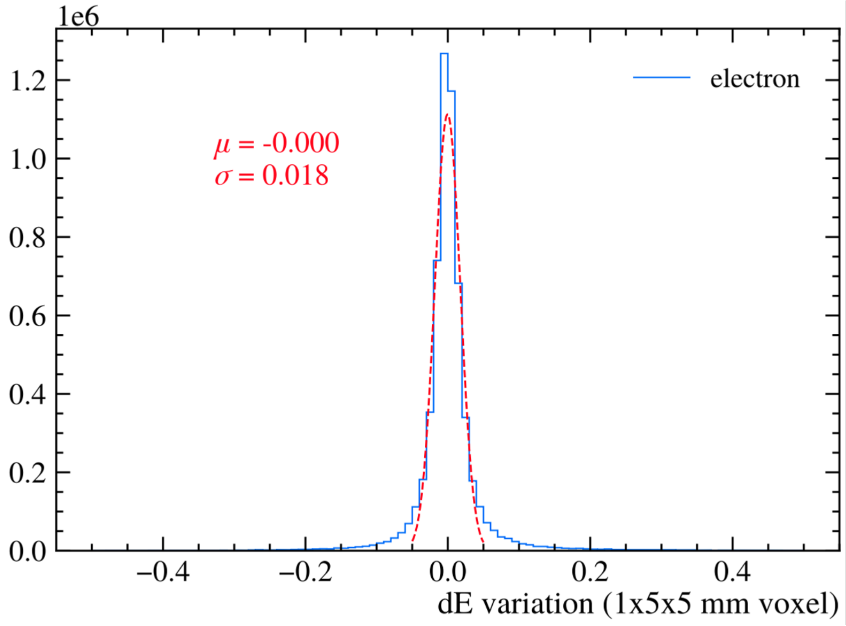


Approximate method to combine all 3 magnets starting from total deflection angle —> **needs full treatment + add another magnet?**

Pixel size studies

- The distribution of collected electrons depends on the diffusion effect and the pixel size.
- Emulate different pixel sizes by using different binning of the Y-Z plane
  - 5x5 mm^2: a similar size to DUNE ND-LAr's configuration
  - 2x2 mm^2: limited by the large amount of readout channels
- Variation of electron dE/dx in each voxel, for different voxel size.



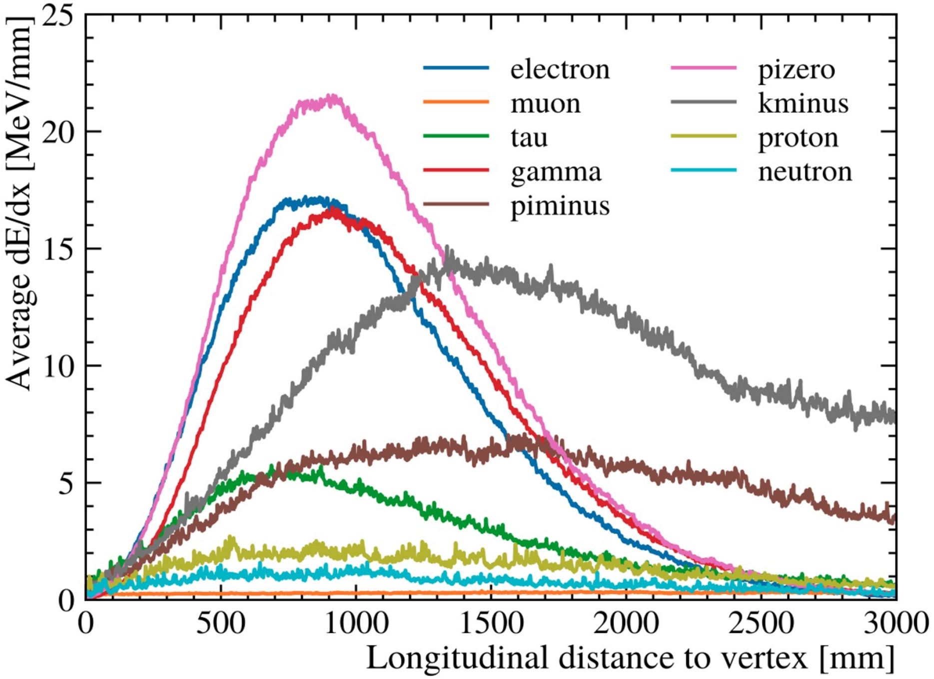


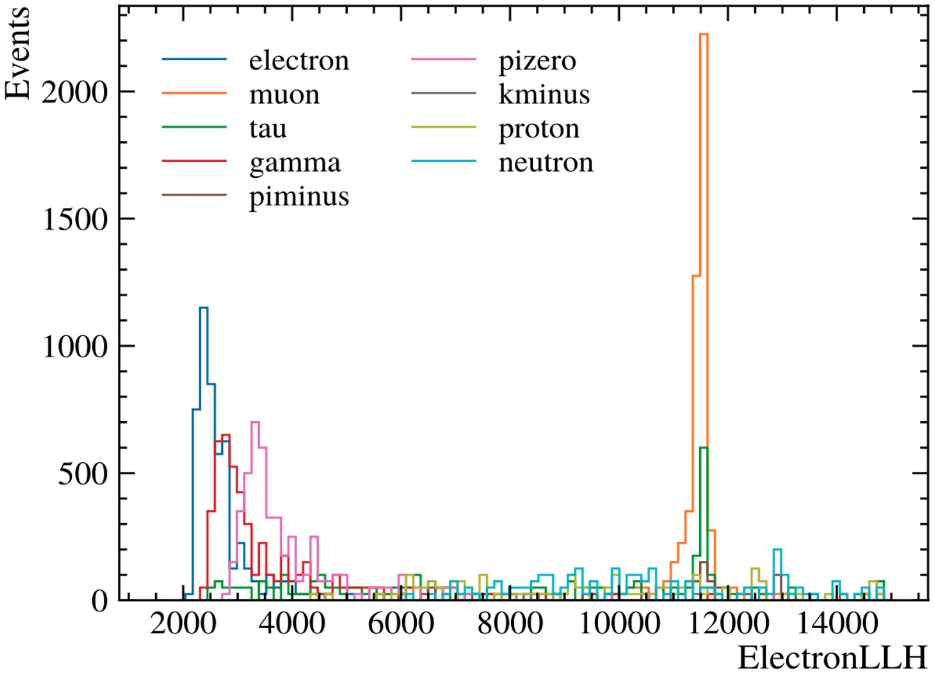
Particle ID from dE/dx

- Different types of particles have various of ways to deposit energies in liquid argon.
- Construct a log-likelihood based on the dE/dx distribution in the longitudinal direction of each type of particle (in total 9 types of particles)
- Use these 9 log-likelihood functions as the input of a boosted decision tree for particle identification

$$-LLH = \sum_{i=1}^{1500} \ln(P_i(dE/dx \mid \text{type},\ \text{step in 2 mm})$$

Distance to the vertex: 0 - 3000 mm, with 2 mm step

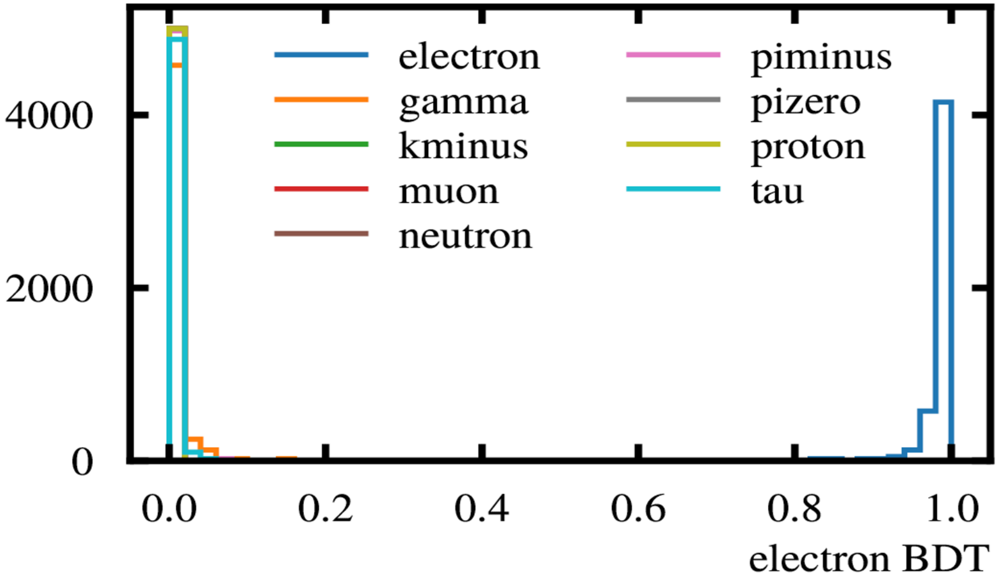




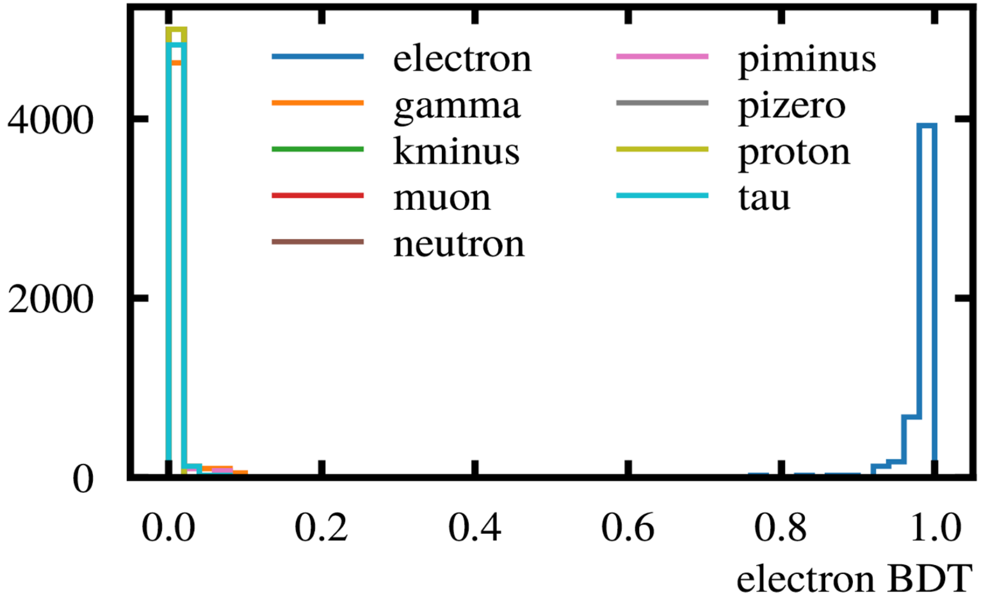
BDT score

- The BDT output the scores of 9 classes, as the prediction probability of the particle to be each type of the particles
  - Will quantify the identification capability
  - Will extend this method for neutrino identification

1x2x2



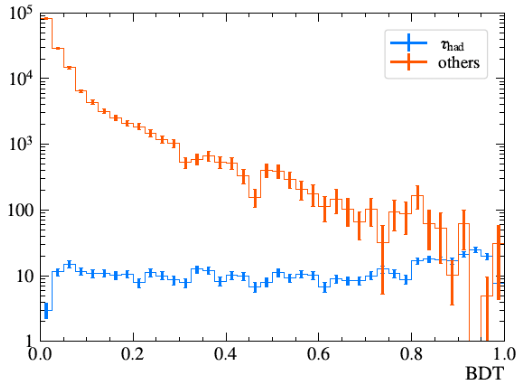
1x5x5



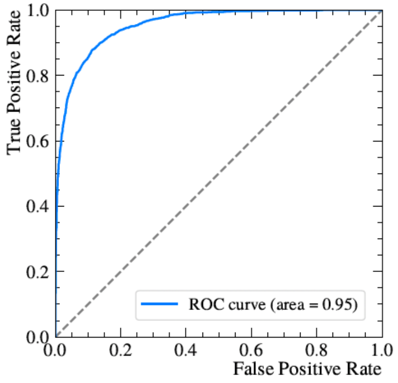
Tau neutrino ID

- Two BDTs based on kinematics variables of the final state particles, one per decay channel (hadronic, leptonic).
  - Using true information from G4.

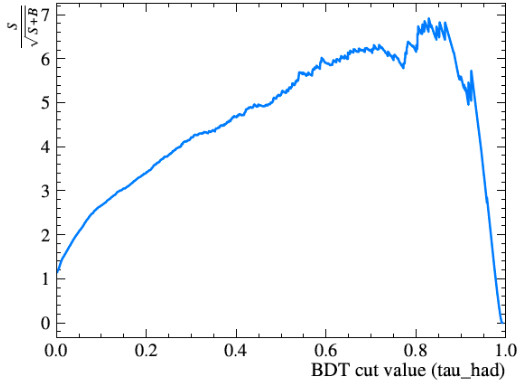
Hadronic decay channel (τ_{had})



(a) BDT score.

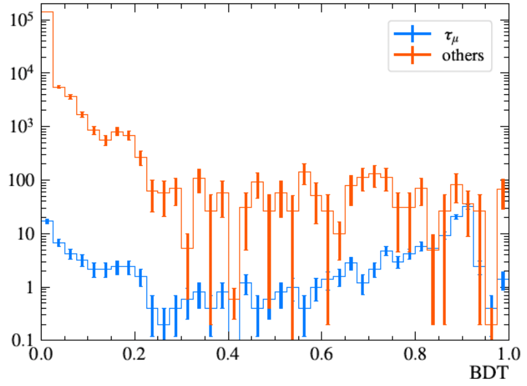


(b) ROC curve.

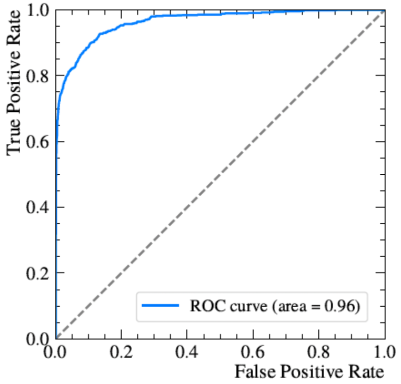


(c) Figure of merit (FOM).

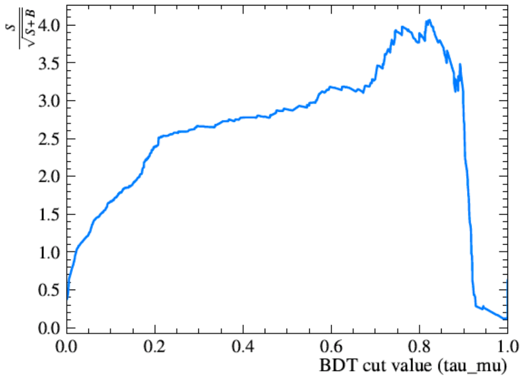
Leptonic decay Channel (τ_{μ})



(a) BDT score.



(b) ROC curve.



(c) Figure of merit (FOM).

Next steps

What's next

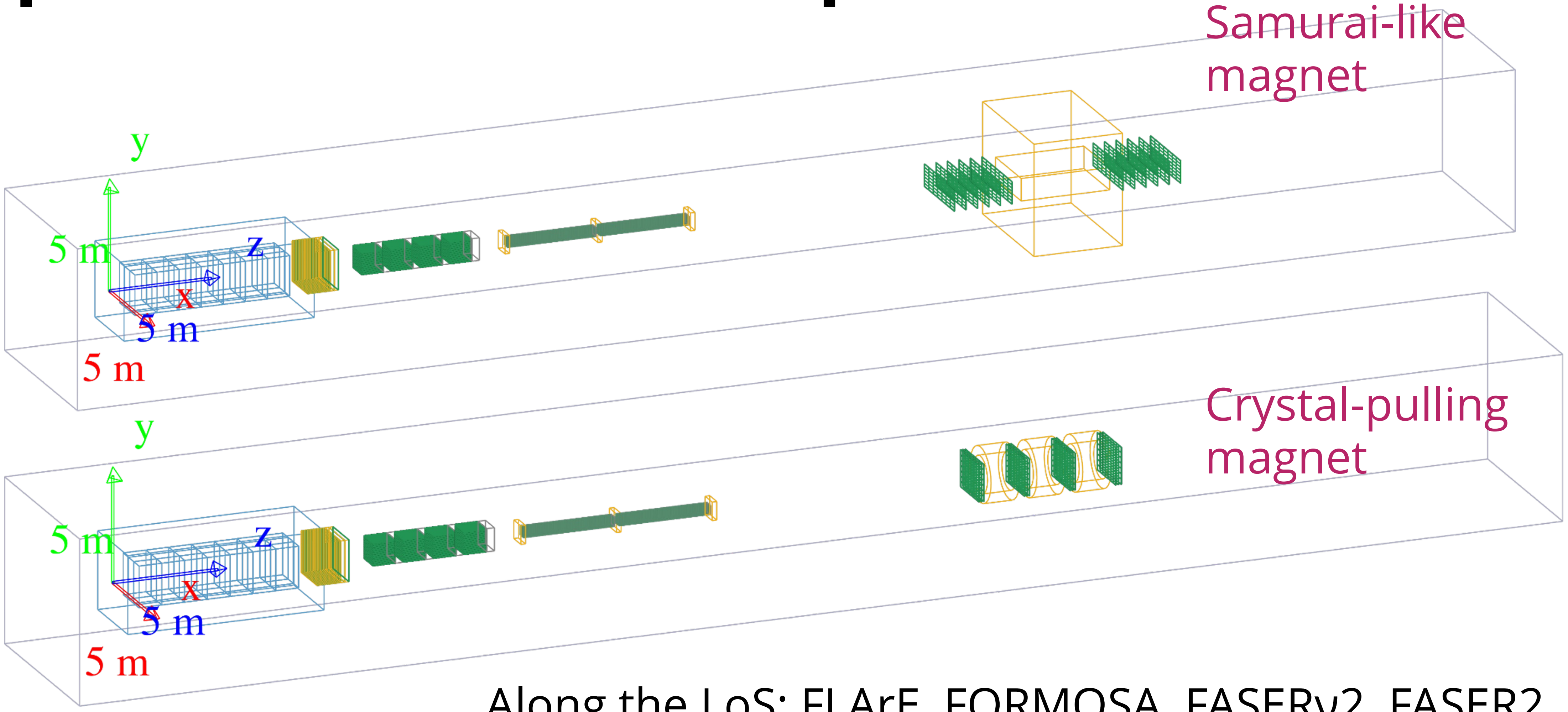
- Finalizing the tech-note studies
  - Wrap-up muon acceptance/reconstruction studies
- Calculation of muon-induced background rates for γ, n, etc.
  - Develop ”background muons” generator.
  - Sample from fluence/flux histograms and re-shoot them in GEANT4.

Long-term goals

- Develop tools for full electronics/light simulation (electron transportation, electronics response, etc).
  - Find and allocate adequate computing resources!
- Develop interface for integration with ACST reconstruction package.
  - Framework useful for all FPF detectors!

Back-up

Option 0: Reference option



Along the LoS: FLArE, FORMOSA, FASERν2, FASER2

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Option 1(b): FORMOSA off-axis

Moving FORMOSA in a pit below the decay volume:

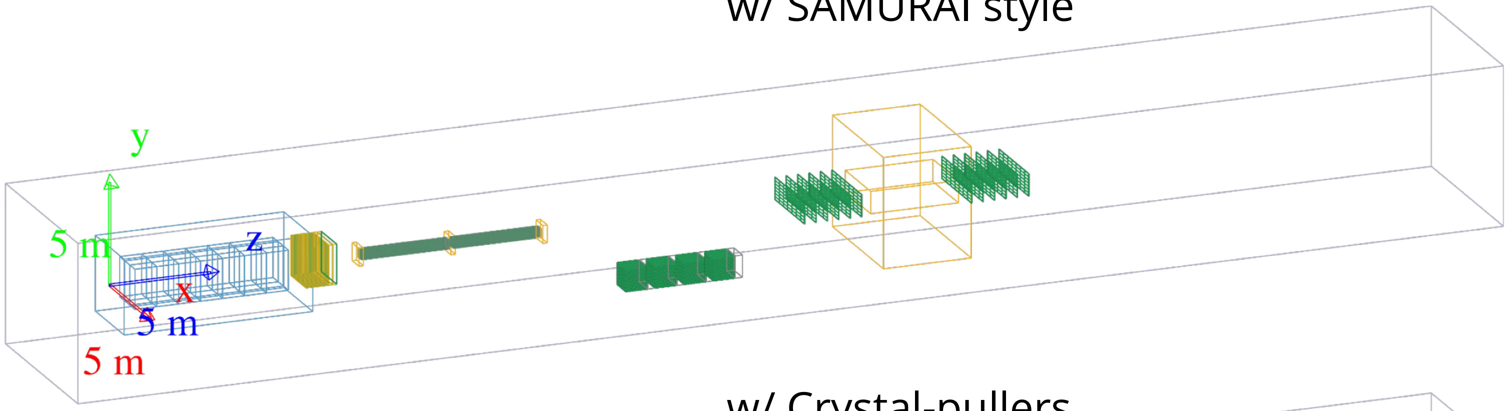
PRO:

- No need to be on-axis for mCPs
- Shorter distance between FLArE and FASER2
- Optimization of “dead” volume.
- Muon background cold spots?

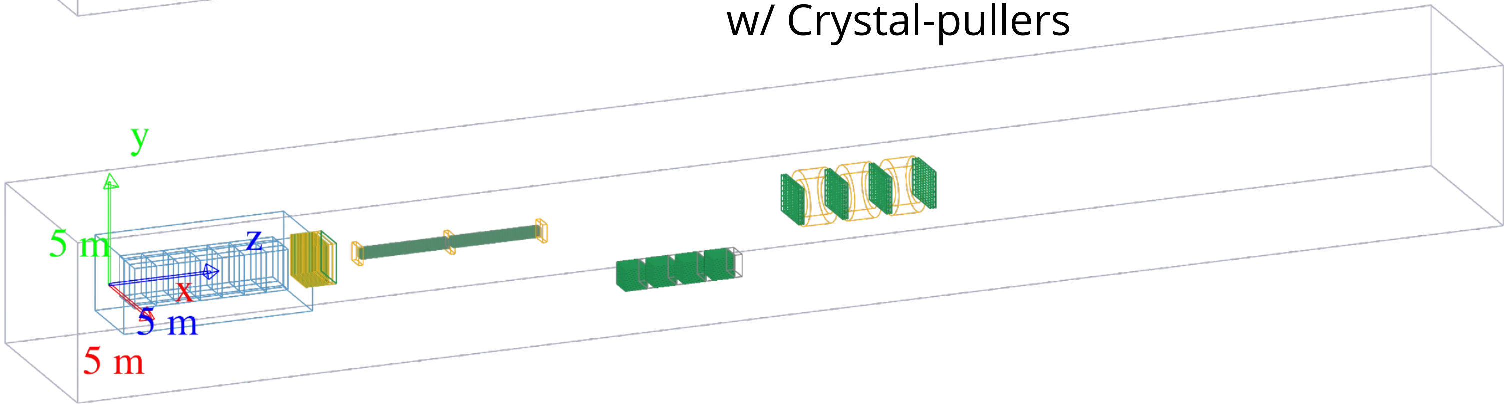
CON:

- Degraded background rejection w/ FLArE
- Degraded common searches w/ FLArE ?

w/ SAMURAI style



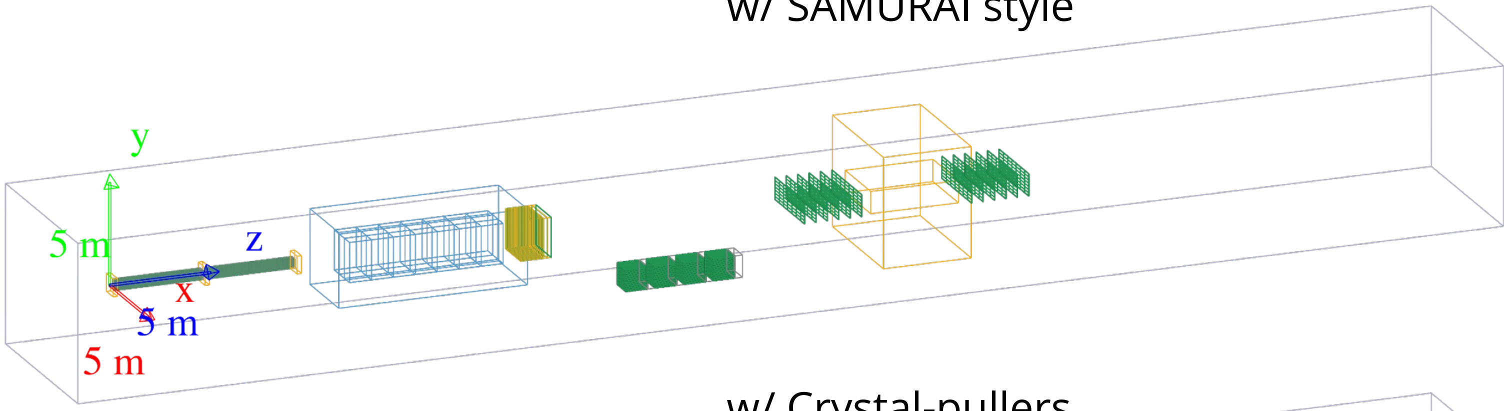
w/ Crystal-pullers



Option 2: FASERv2 first

Moving FASERν2 in the front of the cavern, FORMOSA in the decay volume pit

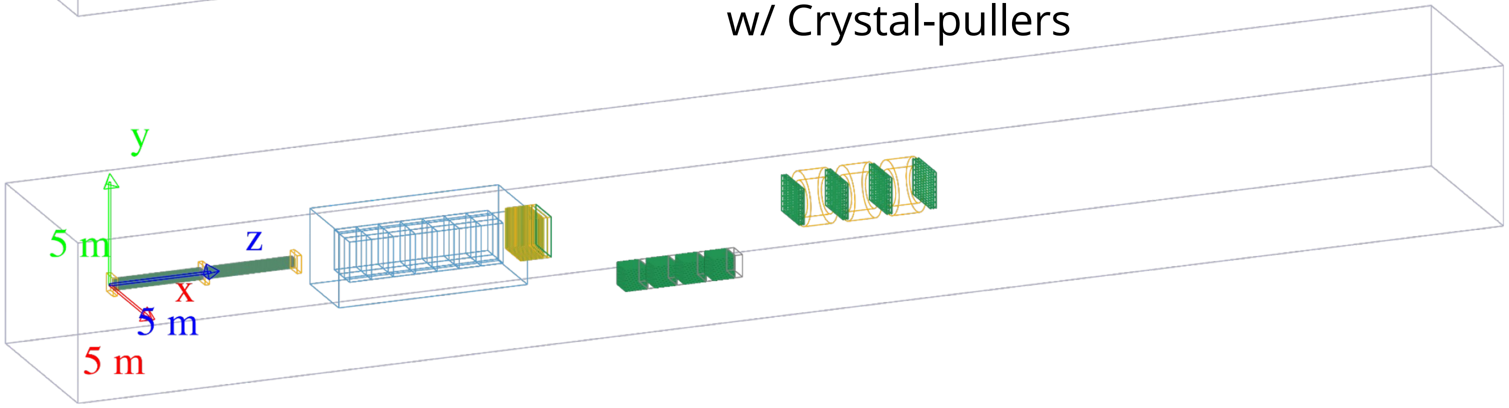
w/ SAMURAI style



PRO:

- Shorter distance between FLArE and FASER2
- No need for magnetized FLArE muon finder?
- FLArE as tracker for FASERν2

w/ Crystal-pullers



CON:

- Degraded synergy between FASERν2 and FASER2
- ?

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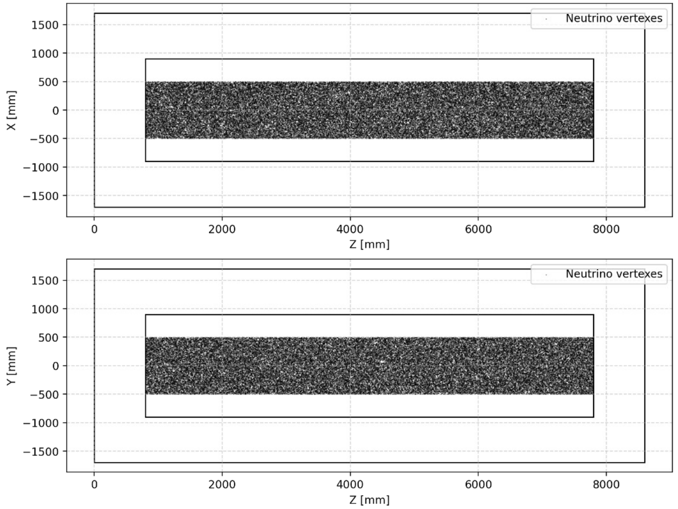
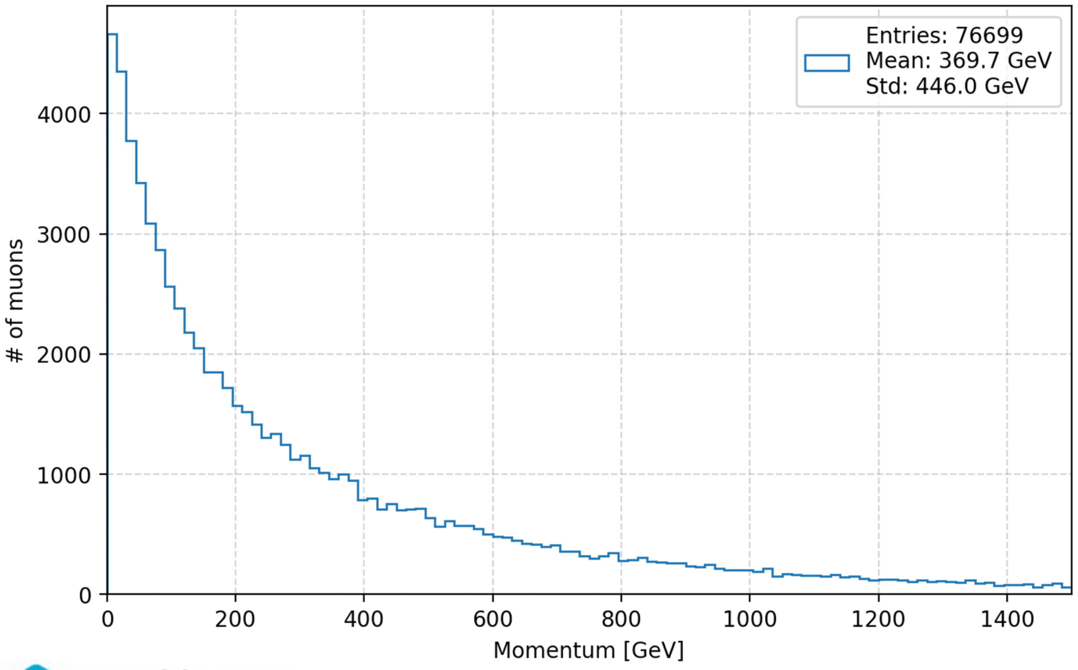
Input sample

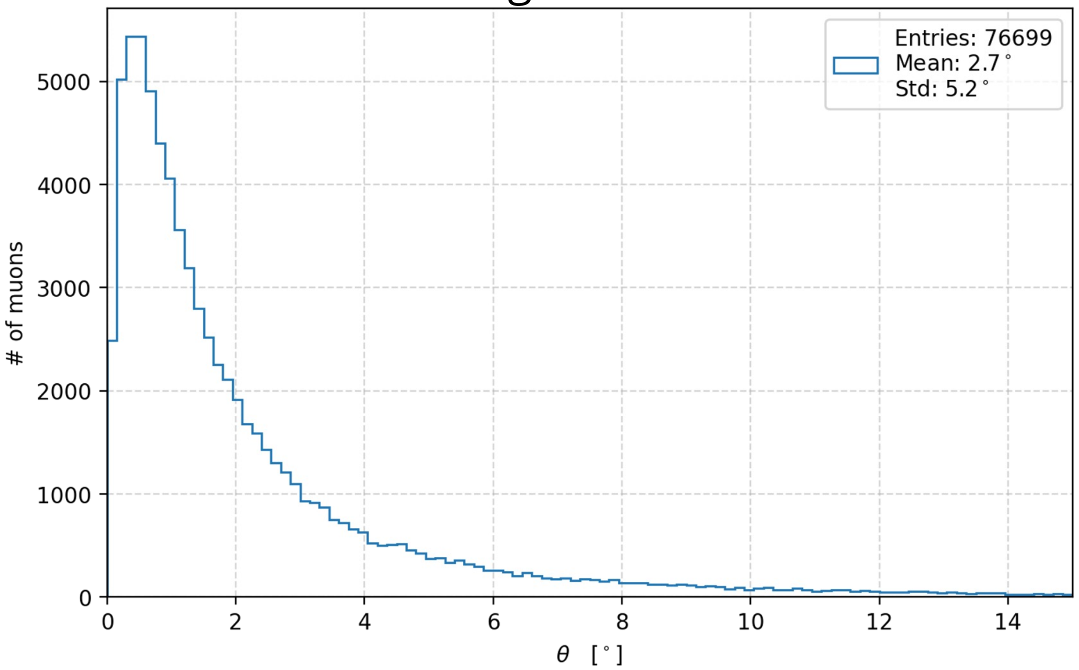
- Muons from numu interactions in FLArE fiducial volume (1m x 1m x 7m).
- 100k numu → 76.7k muons (CC fraction)
- Average muon momentum ~370 GeV



Muon momentum



Muon angle w.r.t. z-axis

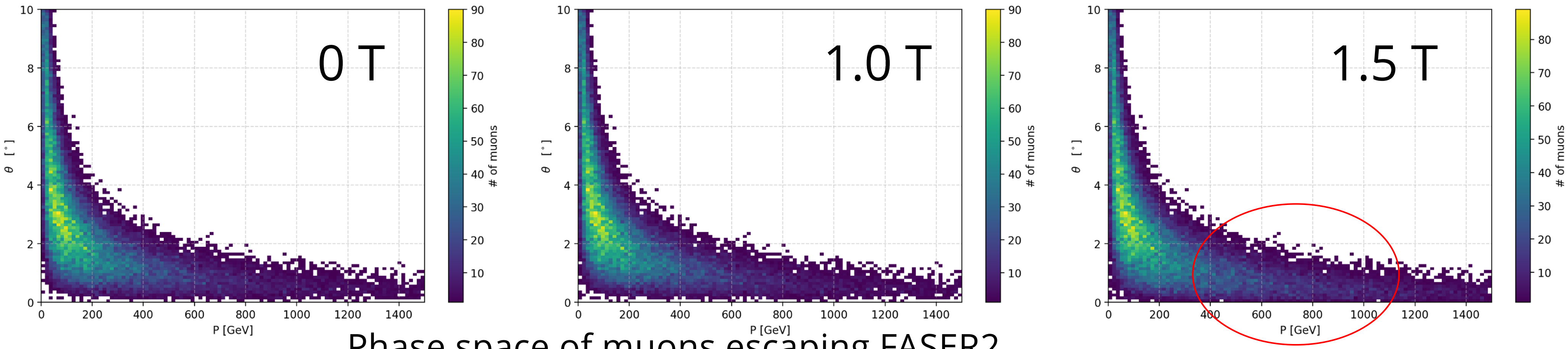


Dependence on FLArE B-field

- The nominal B-field @ FLArE magnetized calorimeter/spectrometer is 1T.
- Stronger fields start affecting the muon acceptance by sweeping away muons

Option	Distance [m]	B [T]	FLArE volume	Total	HadCat + MF	FASER2
FLArE + FASER2 only	38.3	0	fiducial	76699	73284 (95.5%)	30680 (40.0%)
		0.5			73487 (95.8%)	30837 (40.2%)
		1			73486 (95.8%)	30808 (40.2%)
		1.5			69440 (90.5%)	26381 (34.4%)

Table 8: Muon acceptances for the FLArE magnetized spectrometer and the FASER2 "SAMURAI-like" magnet for different magnetic fields in the FLArE spectrometer.



Phase space of muons escaping FASER2

Dependence on FLArE fiducial volume

SAMURAI-like magnet window is 3 m x 1 m.
Cuts on x-axis have small effect, cuts on y-axis dominate the acceptance.

Option	Distance [m]	FLArE volume	Total	HadCat + MF	FASER2
FLArE + FASER2 only	38.3	All	76699	66899 (87.2%)	23760 (31.0%)
		$1\,\text{m} \times 1\,\text{m} \times 7\,\text{m}$	76699	73486 (95.8%)	30808 (40.2%)
		$1\,\text{m} \times 1.8\,\text{m} \times 7\,\text{m}$	42554	38885 (91.4%)	13364 (31.4%)
		$1.8\,\text{m} \times 1\,\text{m} \times 7\,\text{m}$	42799	39061 (91.3%)	16917 (39.5%)

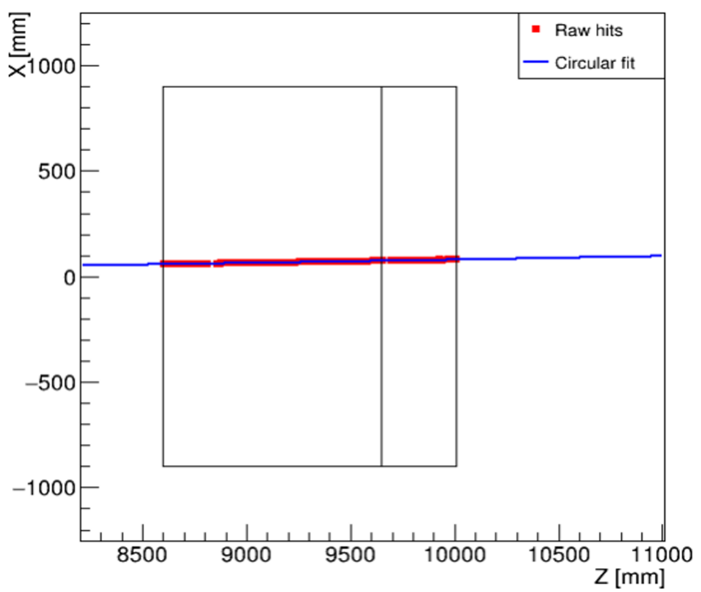
Table 7: Muon acceptances for the FLArE magnetized spectrometer and the FASER2 "SAMURAI-like" magnet for different definitions of the FLArE fiducial volume.

Full volume → 31.0%
|x| < 0.5m → 31.4%
|y| < 0.5m → 39.5%
|x| < 0.5m && |y| < 0.5m → 40.2%

Momentum reconstruction

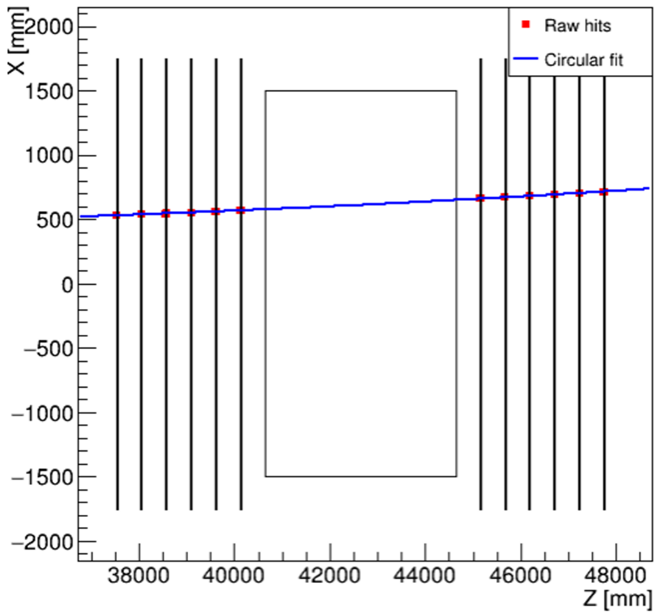
FLArE HadCat+MF: analytical circular fit on the raw hits to extract curvature radius

Avg muon P = 300 GeV
B = 1T, total length = 1.41m
Expected deflection: ~0.08 deg
Expected displacement: **~1mm (!!)**



FASER2: linear fits to the tracking stations, analytical computation of the circumference tangent to both lines

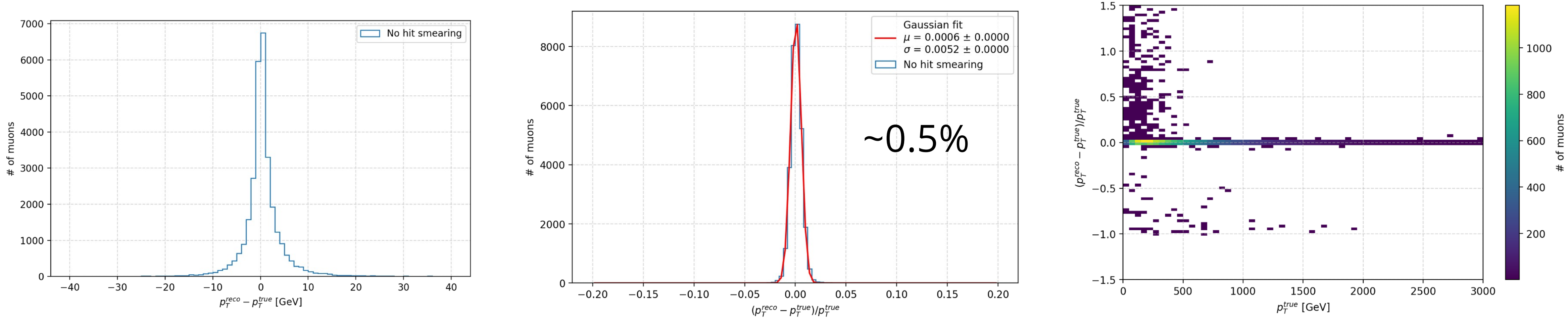
Avg muon P = 300 GeV
B = 1T, total length = 4m (SAMURAI)
Expected deflection: ~0.23 deg
Expected displacement: **~8mm**



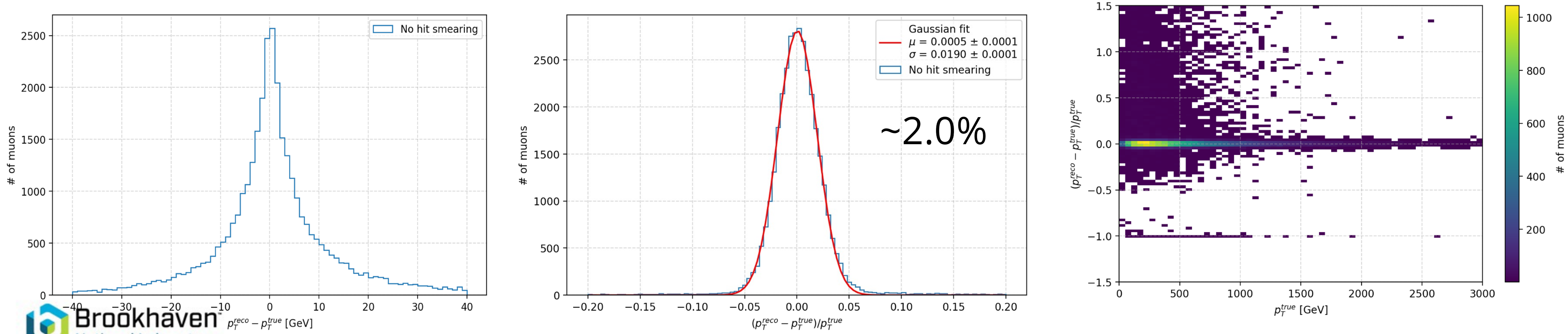
Momentum @ FASER2

Momentum resolution on raw hits (no smearing, unrealistic)

SAMURAI



Single crystal-puller



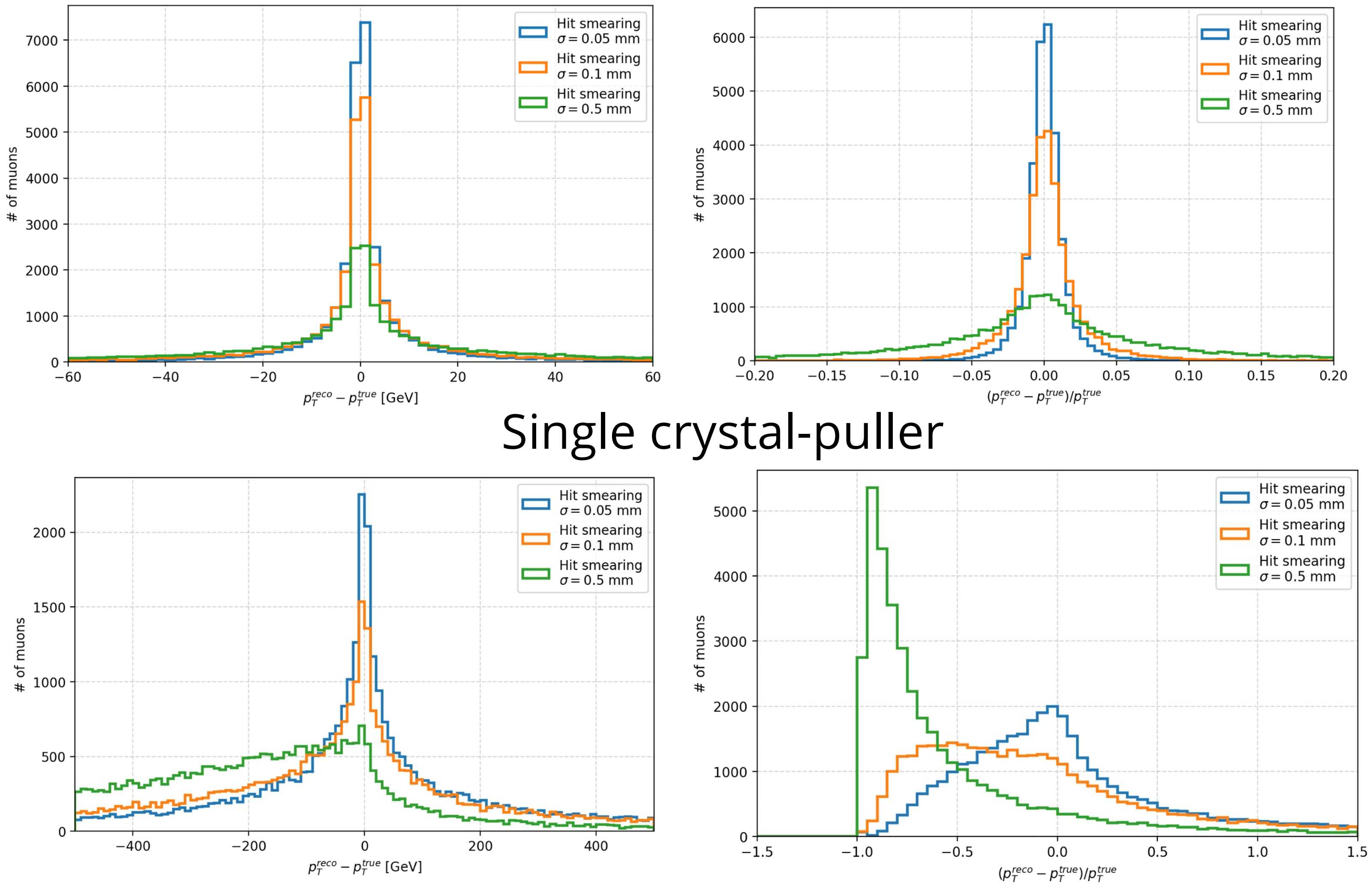
Brookhaven National Laboratory

Gaussian hit smearing

- LHCb SciFi tracker modules ~ 0.1 mm spatial resolution.
- Gaussian smearing of simulated hits, slowly increasing.
- Performance of a *single* crystal puller degrades quickly.
- Current algorithm doesn't readily support combining multiple magnets.

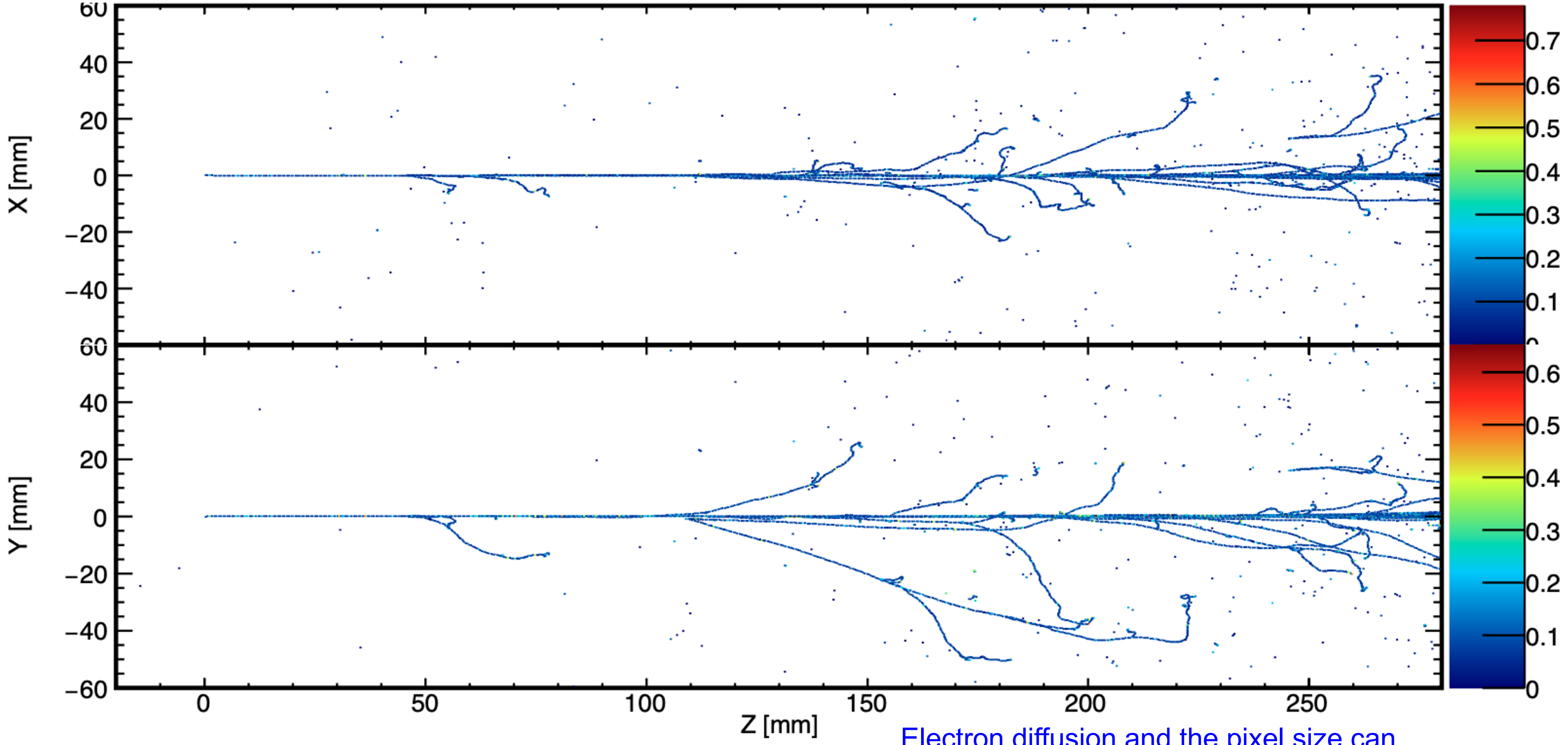
SAMURAI

Single crystal-puller



A single electron

0.2 mm x 0.2 mm



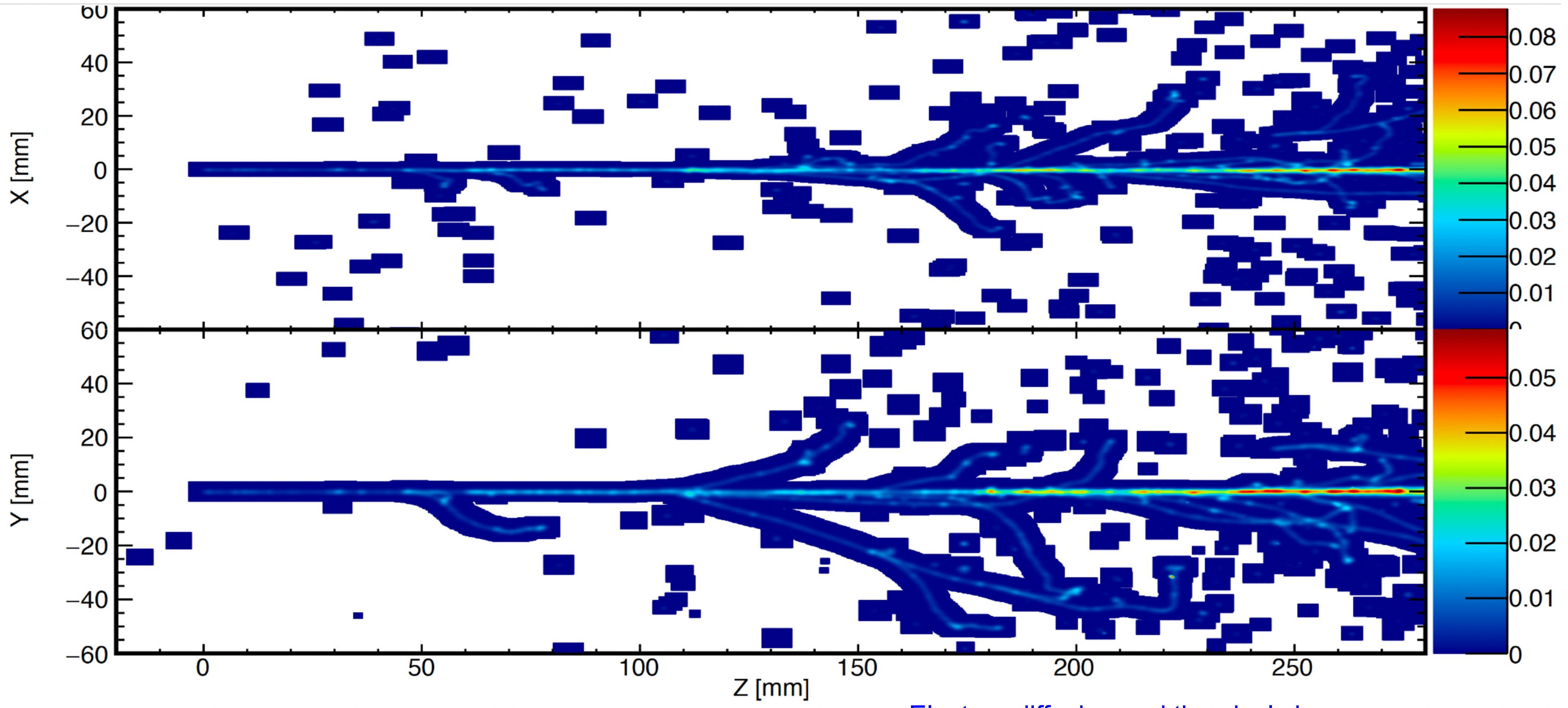
EvtID 4 PDG 11 Etot 20.0 GeV Vtx (0.0, 0.0, 1000.0) mm

Electron diffusion and the pixel size can affect the distribution of detected charge

Electron with diffusion

https://lar.bnl.gov/properties/

Electron transverse diffusion coefficient @ 500 V/cm: 13.2 cm^2/s
Electron longitudinal diffusion coefficient @ 500 V/cm: 6.6 cm^2/s



EvtID 4 PDG 11 Etot 20.0 GeV Vtx (0.0, 0.0, 1000.0) mm

Electron diffusion and the pixel size can affect the distribution of detected charge