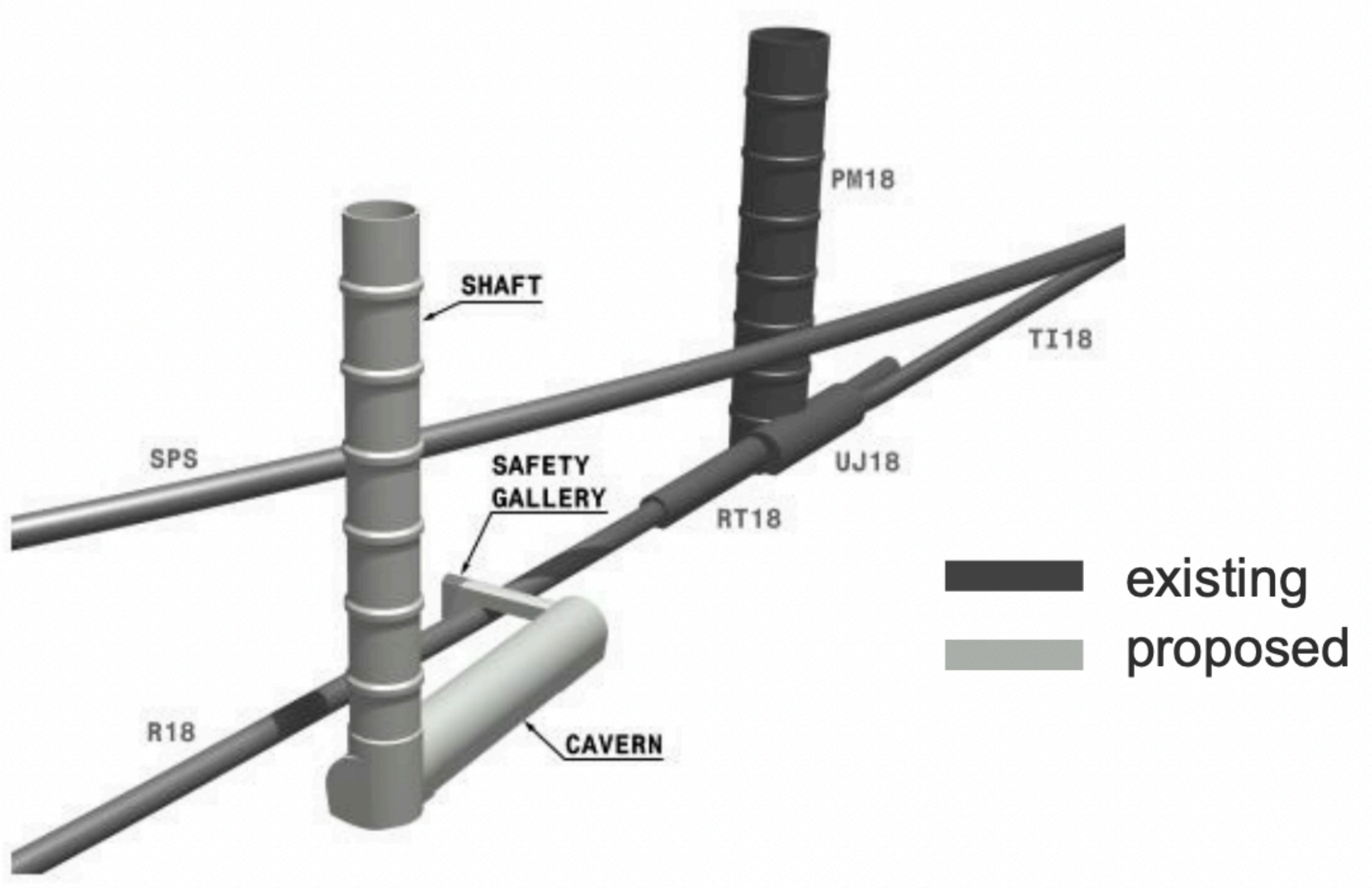
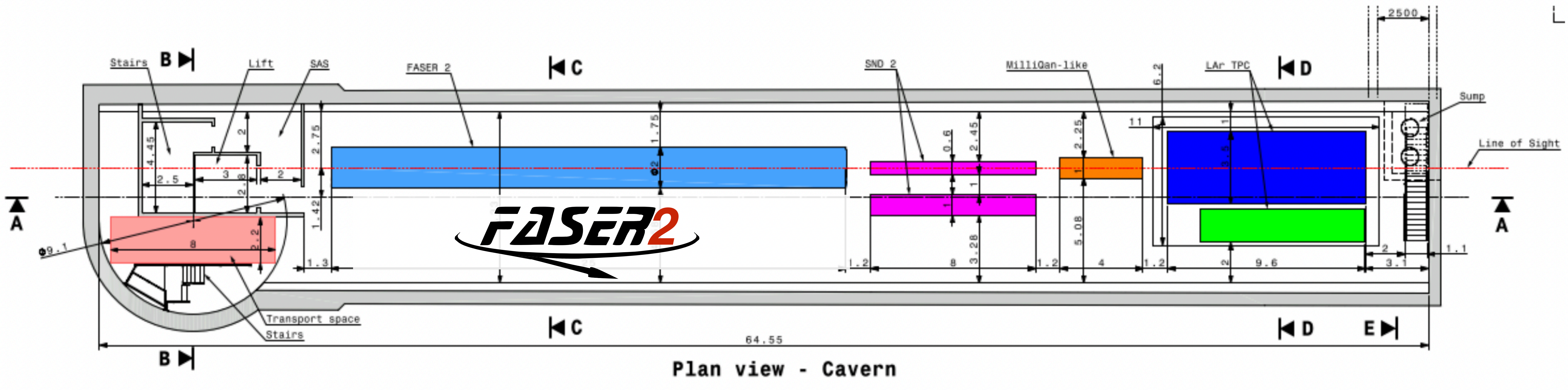
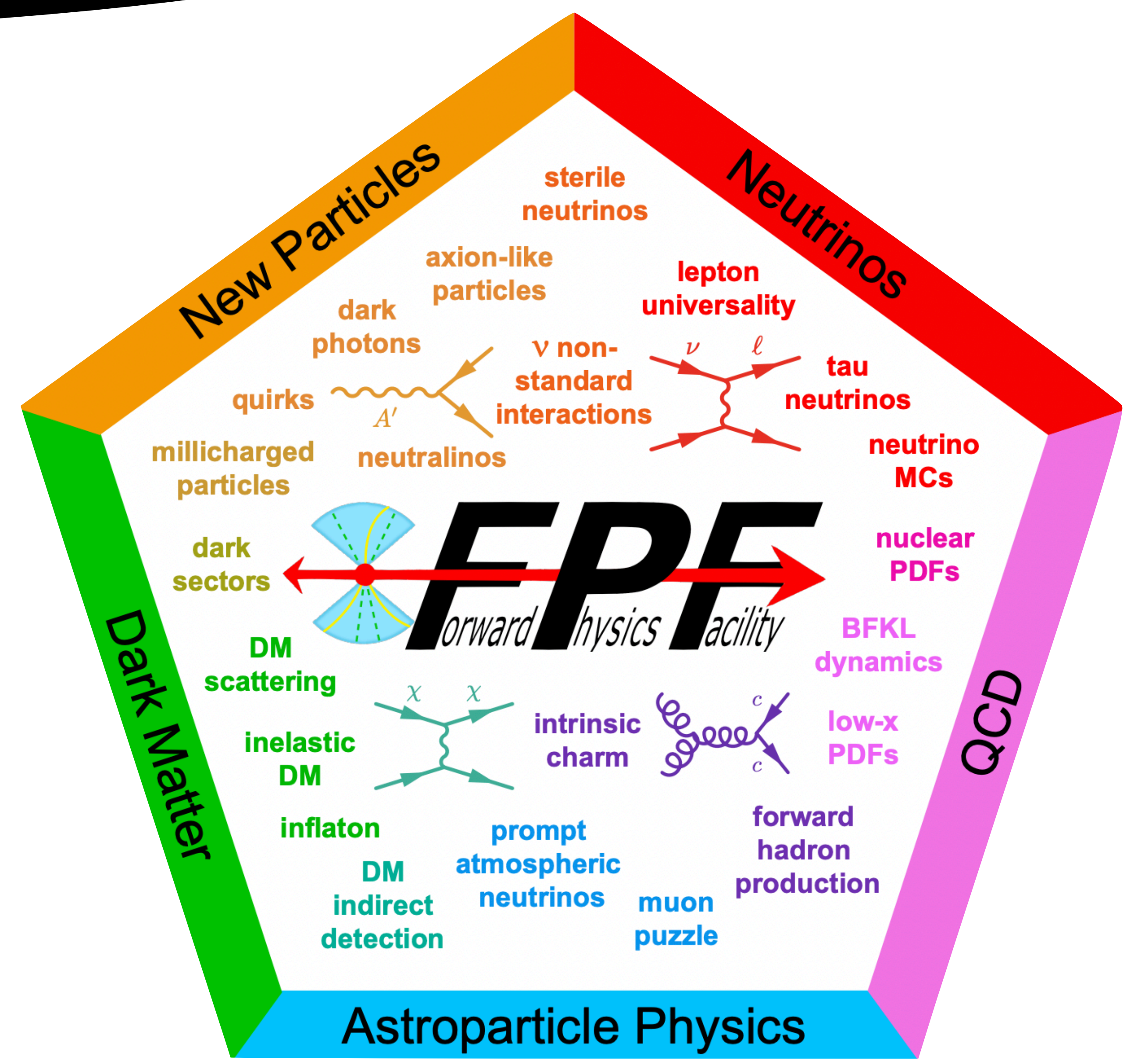




FASER2 Update

FPF6 Workshop

6/6/2023

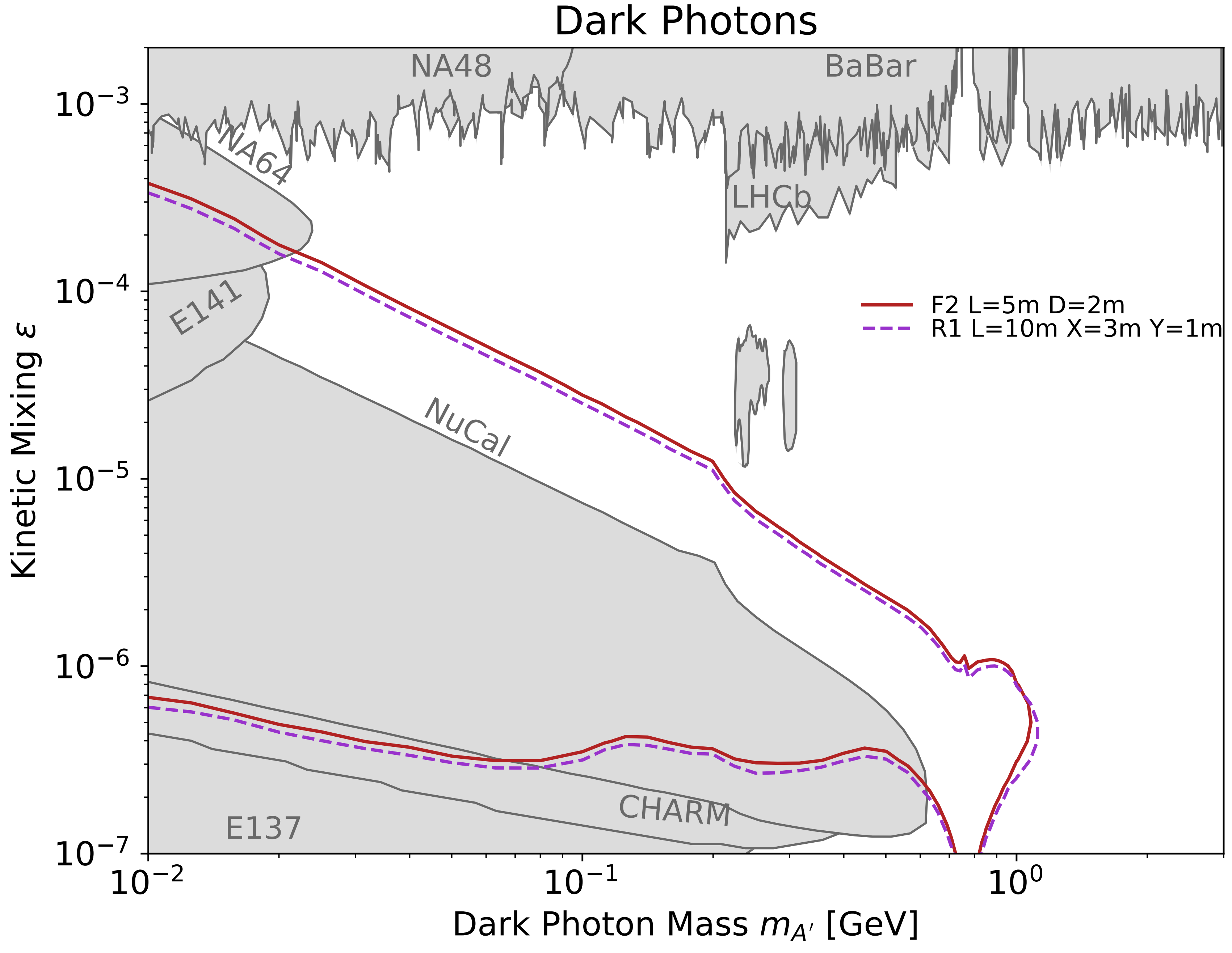


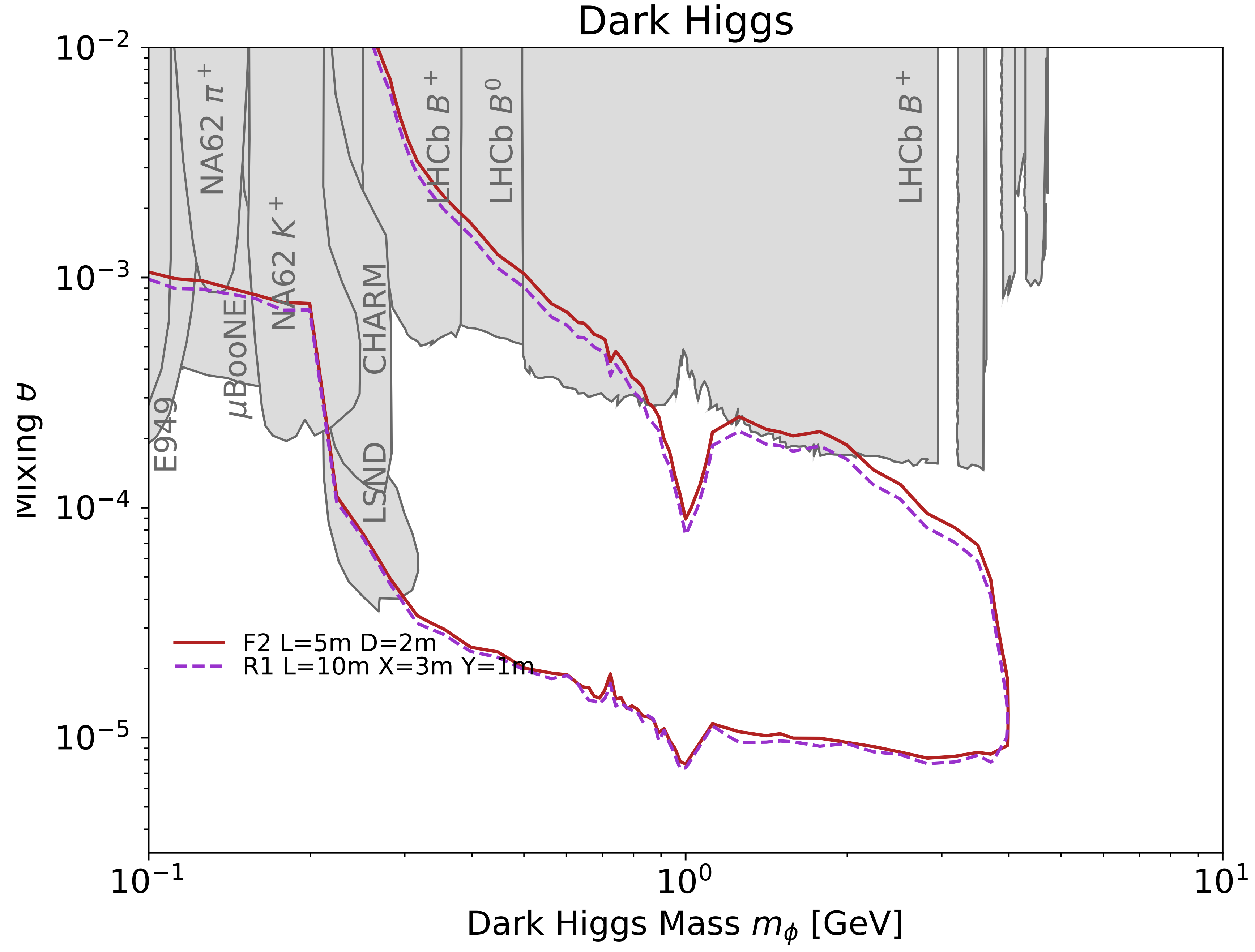
Baseline detector | Geometry

Previous

Baseline

- Updated baseline geometry driven by magnet technology
  - Rectangular aperture
  - Comparable sensitivity to previous design





Baseline detector | Geometry

Baseline

- Previous costing
  - Magnet based on SAMURAI Experiment
  - Tracker based on LHCb's SciFi
  - Calorimeter based on dual-readout technology

	Cost
Magnet	10 MCHF
Tracker (SciFi)	4-6 MCHF
Calorimeter	3-5 MCHF
Total	**~20 MCHF**

Baseline detector | Simulation

- GDML/Geant4 simulation created with pyg4ometry

Baseline detector | Details

Veto

- Plastic scintillator-based veto system
- Expected to reject muon rates of ~ 20kHz

Tracker

- Silicon photomultiplier and scintillating fiber tracker technology
- Based on LHCb's SciFi[4] tracker
- Spatial resolution of ~ 100 μm
- Each station consists of vertical and horizontal SciFi modules

Magnet

- Rectangular aperture: 1 m in height, 3 m in width, 4 m depth
- Superconducting magnet technology
- Based on SAMURAI[5] experiment magnet
- BField 4 Tm bending power for particle separation, momentum resolution, and charge ID

EM Calorimeter

Hadronic Calorimeter

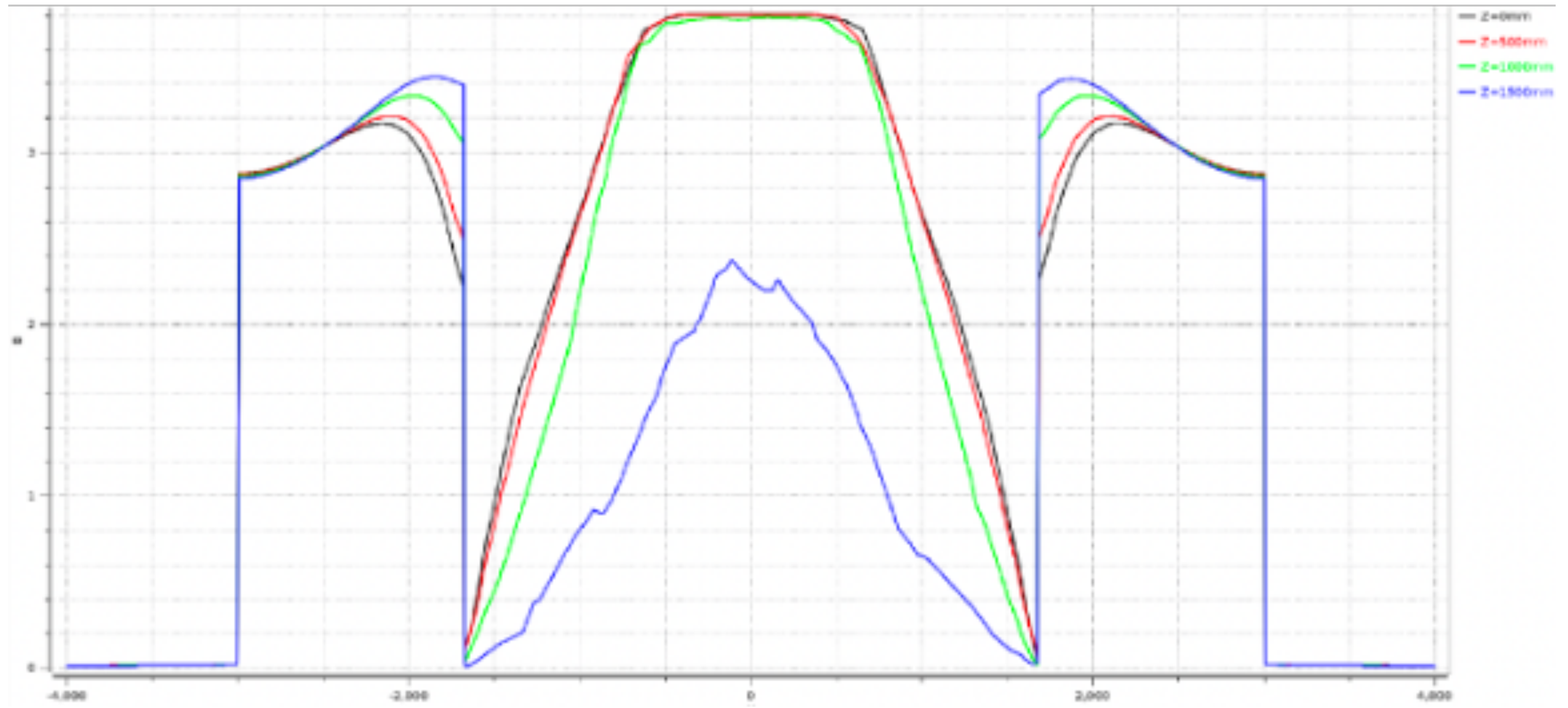
- Dual-readout calorimetry[6] technology
- Spatial resolution for particle identification at ~ 1-10 mm separation
- Particle identification capabilities

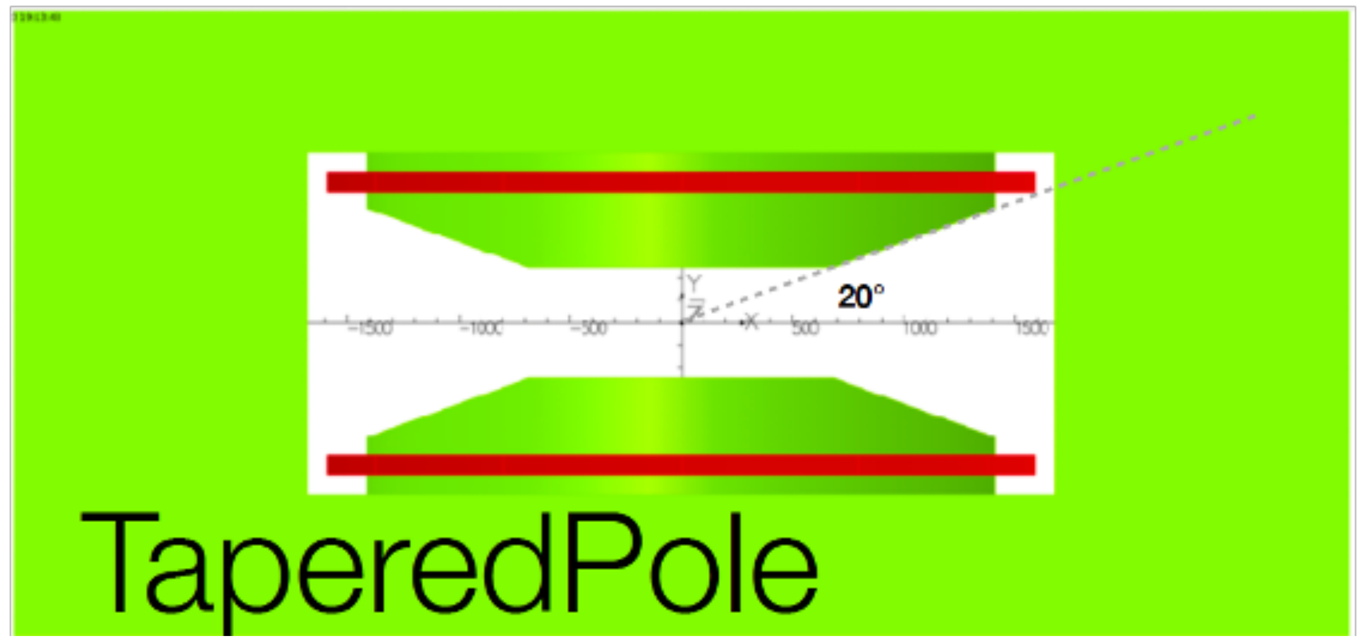
- Program for BSM and SM physics (main spectrometer to neutrino exps.)
- Currently considering, SciFi tracker and dual-readout calorimetry.

Magnet | Design

- SAMURAI Dipole Magnet is a good reference
  - Aperture: 88 cm x 340 cm
  - Field integral along beam axis: 7.0 Tm
- Estimation with reduced the magnetic field to 4 Tm
  - 3D simulation in progress for various designs with KEK experts (Naoyuki Sumi and Yasuhiro Makida)
- Also studying further reduced field to e.g. 2 Tm
  - Could potentially reduce a lot the magnet cost and complexity

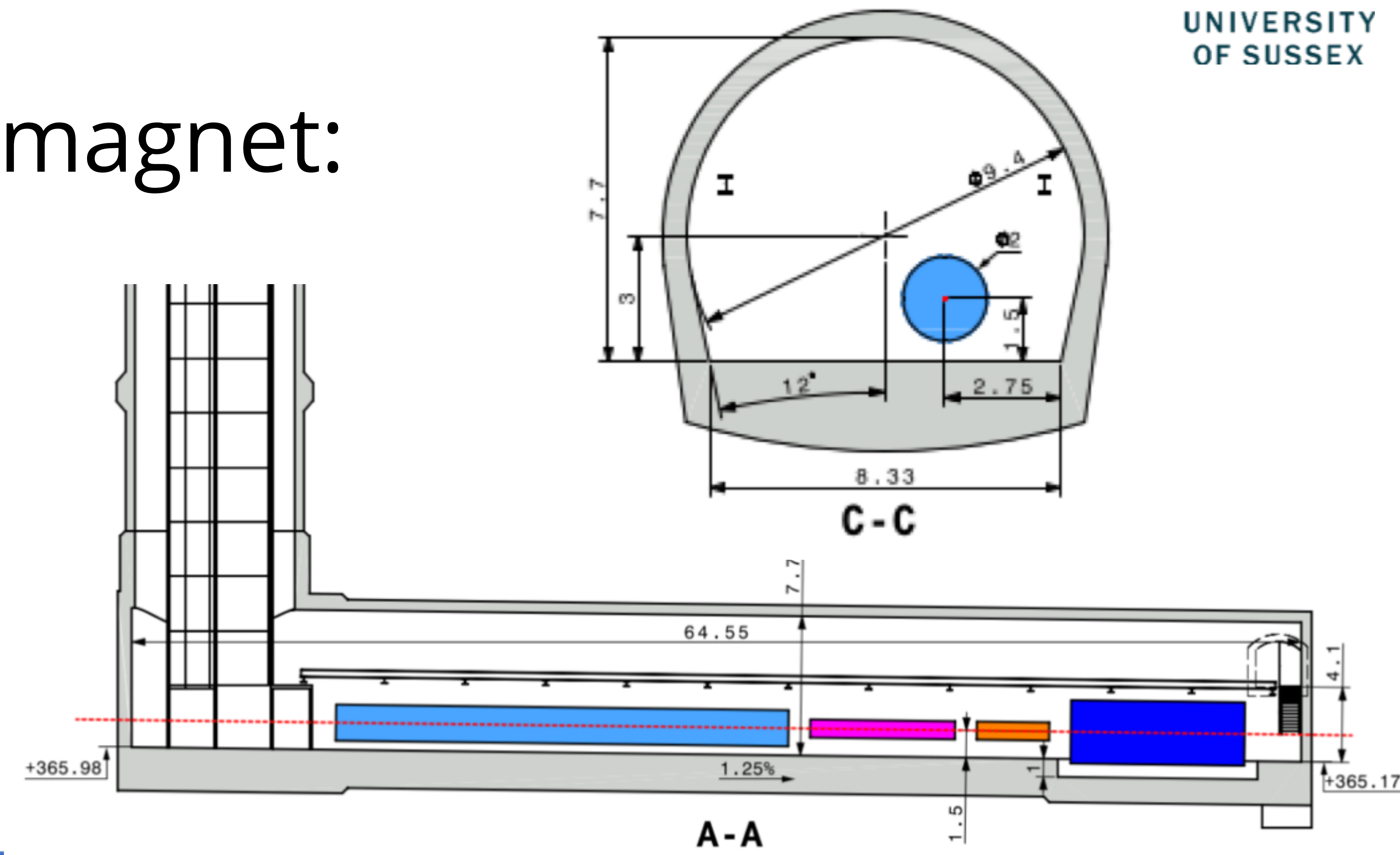
Item	Unit	Value	Remarks
Magnet		Dipole magnet	
Magnetic field	T	2	
Magnetic path length	T・m	4.7	Rough estimation from SAMURAI
Stored energy	MJ	15	
Magnetic pole gap distance	mm	880	same as SAMURAI
Magnetic pole radius	mm	2000	circular poles
Coil		Solenoid	
Total weight	ton	400	



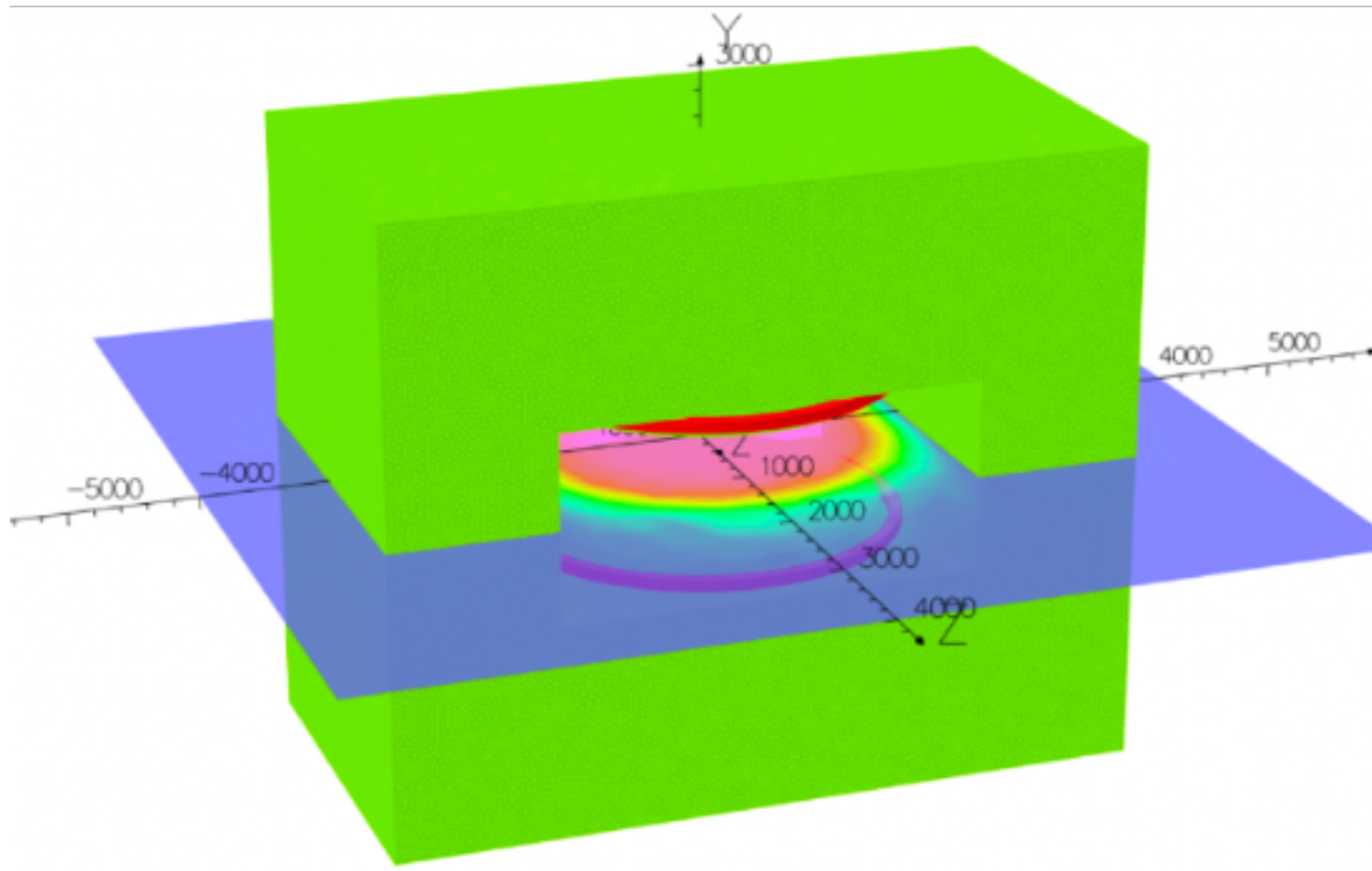


Magnet | Logistics

- Assuming the specification of the SAMURAI magnet:
  - Crane load capacity (25 T) looks fine - split yoke
  - Original SAMURAI magnet would not fit FPF but reduced magnetic field = reduced size
  - Water circulation to the surface from the FPF is preferred to release the heat from cryogenics



	Current design	Comments assuming SAMURAI magnet
Shaft transport space	2.2 m x 8 m	Sufficient for one coil with cryo
Shaft crane load capacity	30 T	Sufficient for a 25cm-thick slice of iron yoke
Cavern crane load capacity	30 T	Sufficient for a 25cm-thick slice of iron yoke
Cavern crane hight	4.1 m	4.6 m + one slice of iron yoke ~25 cm + slack is needed
LoS from floor	1.5m	2.3 m
LoS from the near wall	2.75m	3.35 m
Total power consumption	2 MW	< 100 kW
Ventilation	Air circulation	Need water circulation to release heat



Magnet | Assembly

- Discussions with KEK experts about assembly
- Experience from previous SKS (Superconducting Kaon Spectrometer) magnet in KEK.
  - Similar arrangement of yoke slices

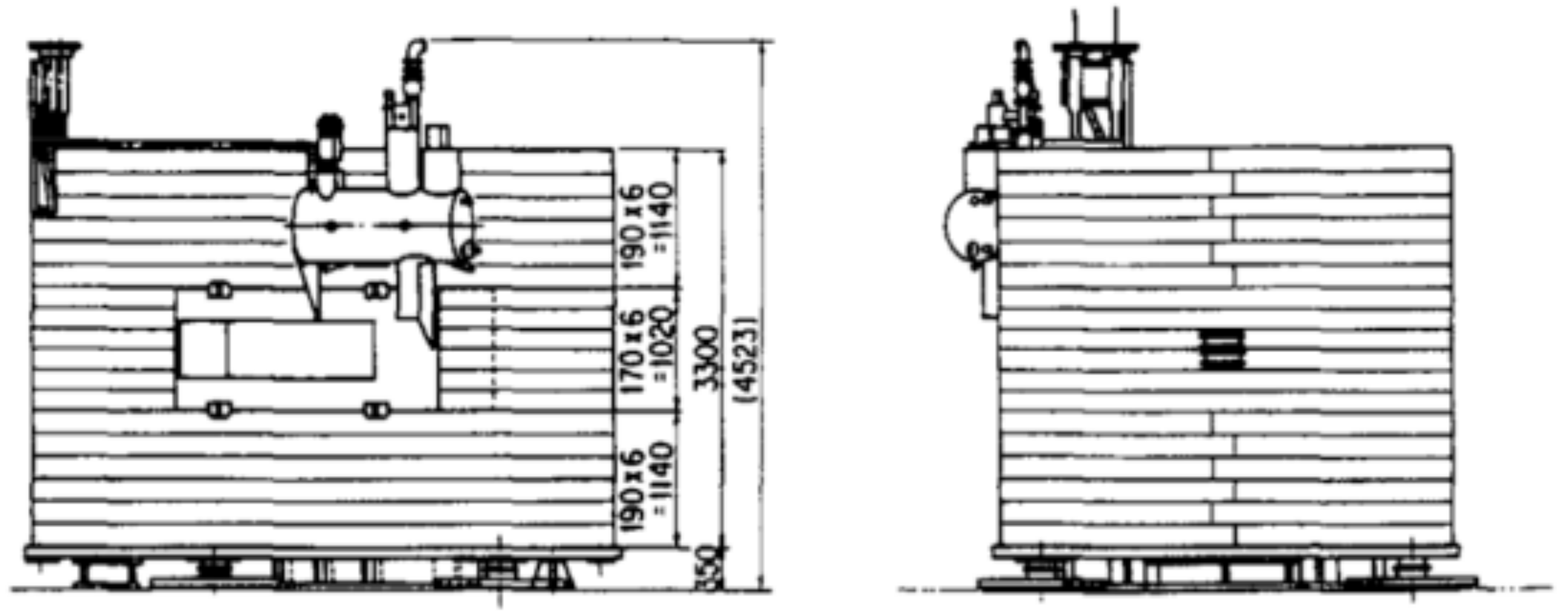
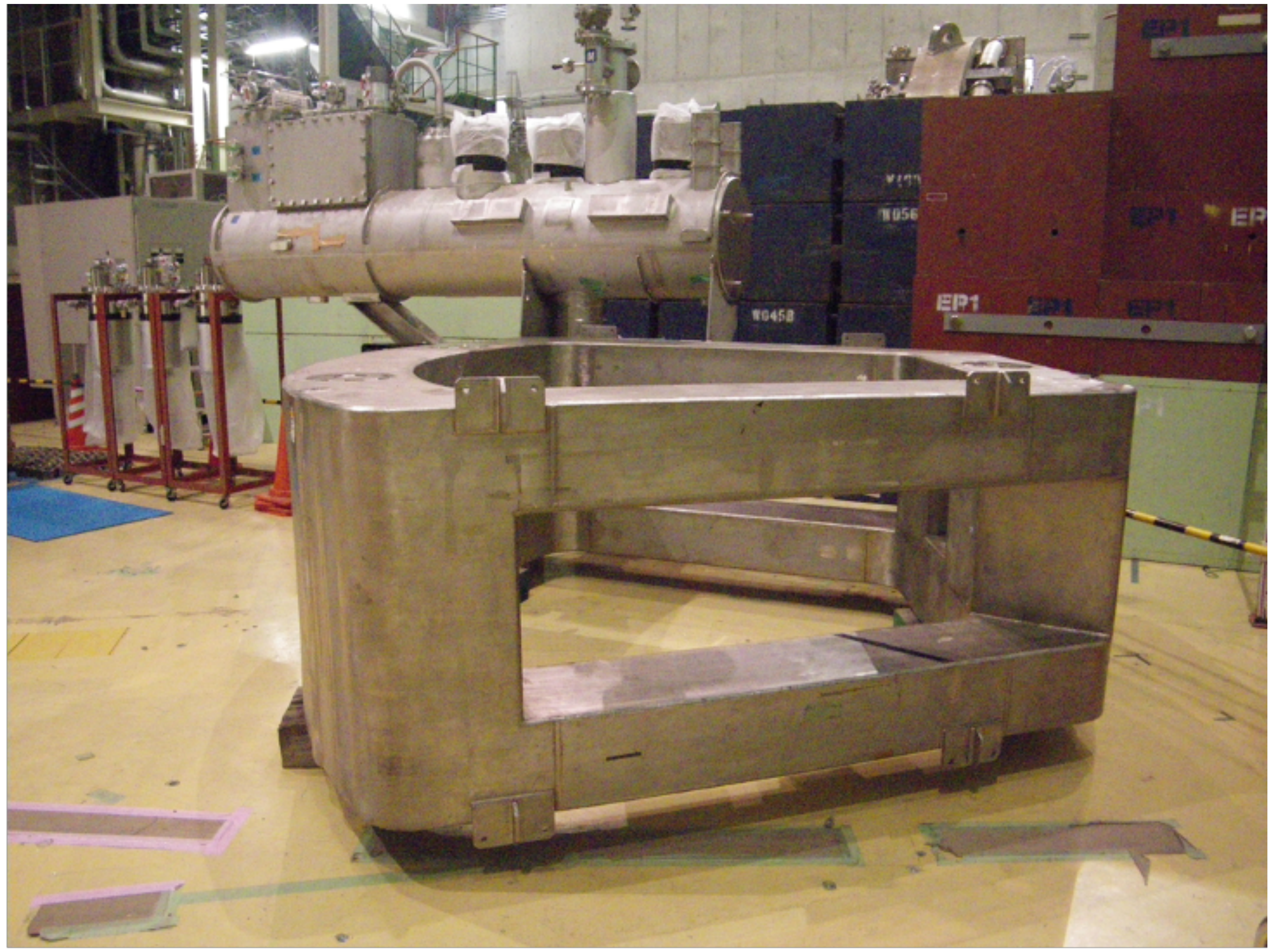
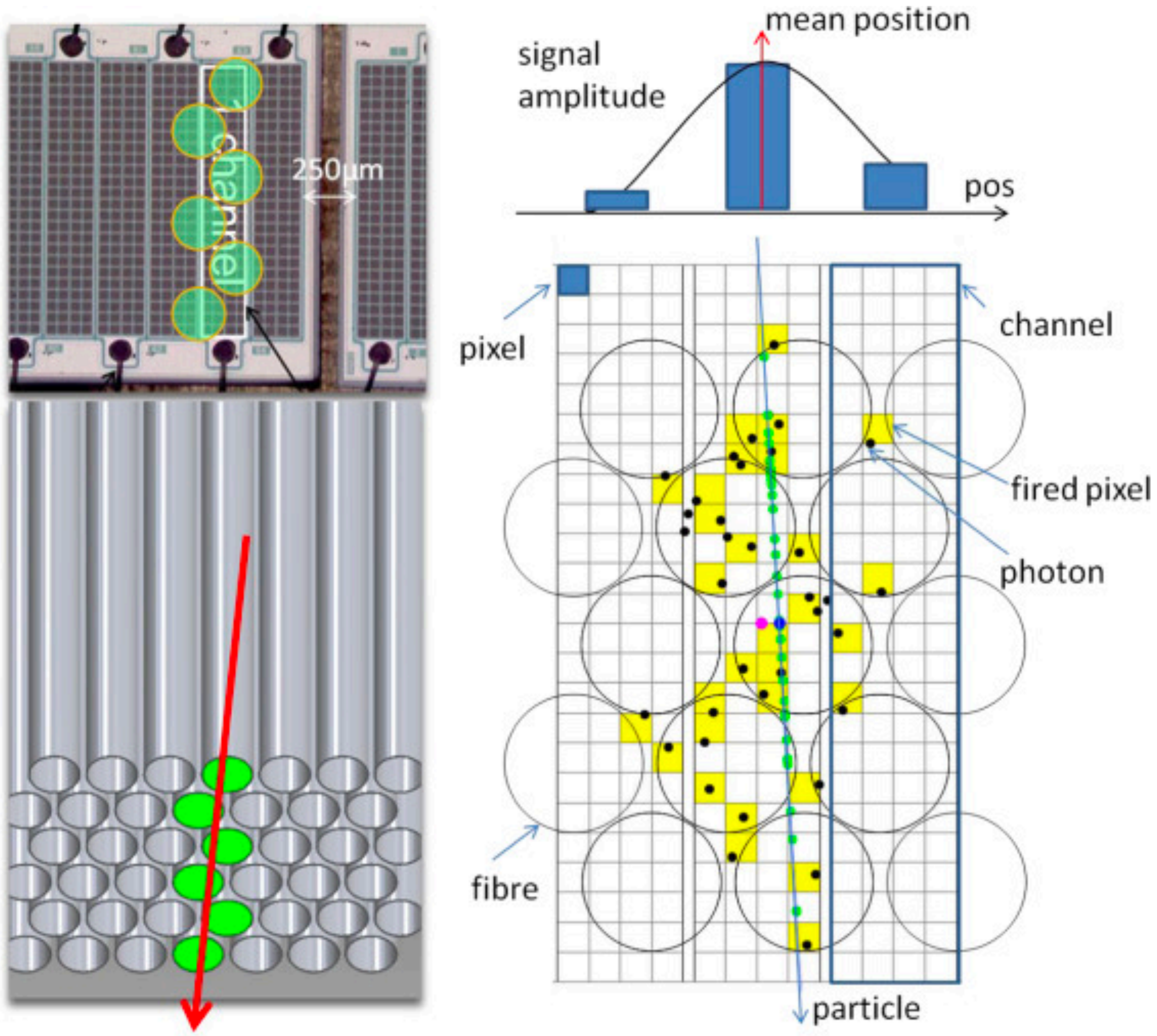


Fig. 3. Schematic drawings of the SKS spectrometer magnet. The return yoke comprises 18 layers of iron plates.



Tracker | SciFi technology

- Based on SciFi detector installed in LHCb in LS2.
  - SiPM+scintillating fibre design
  - Fibres 250um diameter => 80um resolution.
- Each module consists of a mat of 4 fibres, with >99% efficiency.
- Costing done by scaling LHCb detector to the FASER2 design, and includes readout.
- Cost could be reduced by re-using tooling from LHCb if relevant institutes were involved.



The upstream tracker

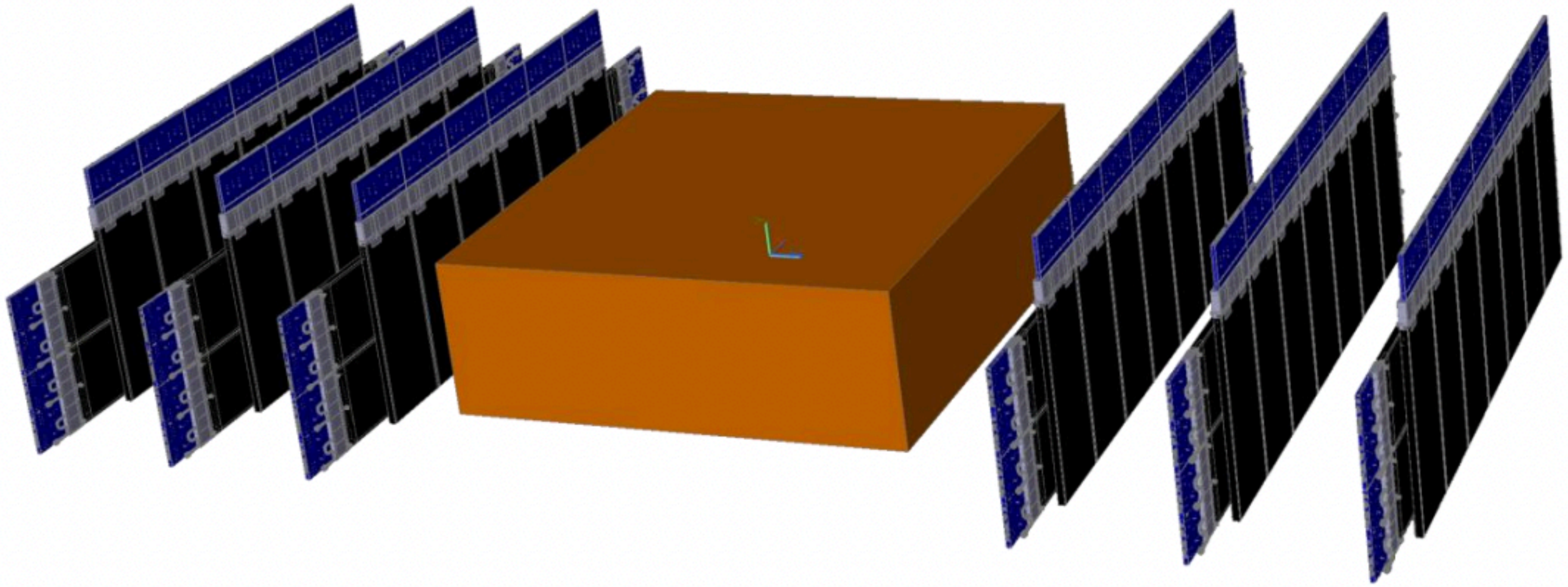
6 vertical + 2 horizontal modules makes up a station.

3 stations.

The downstream tracker

7 vertical + 2 horizontal modules makes up a station.

3 stations.

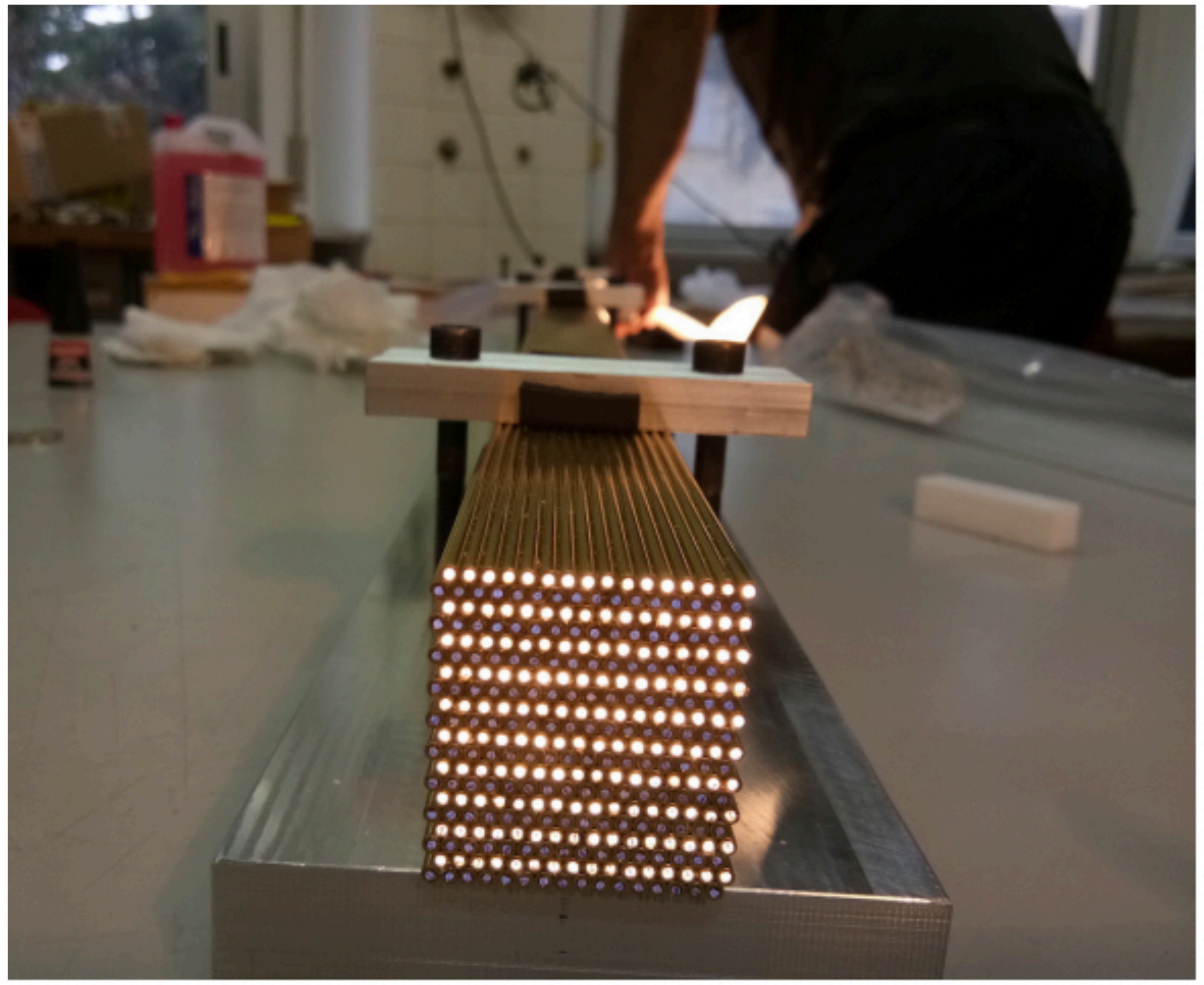


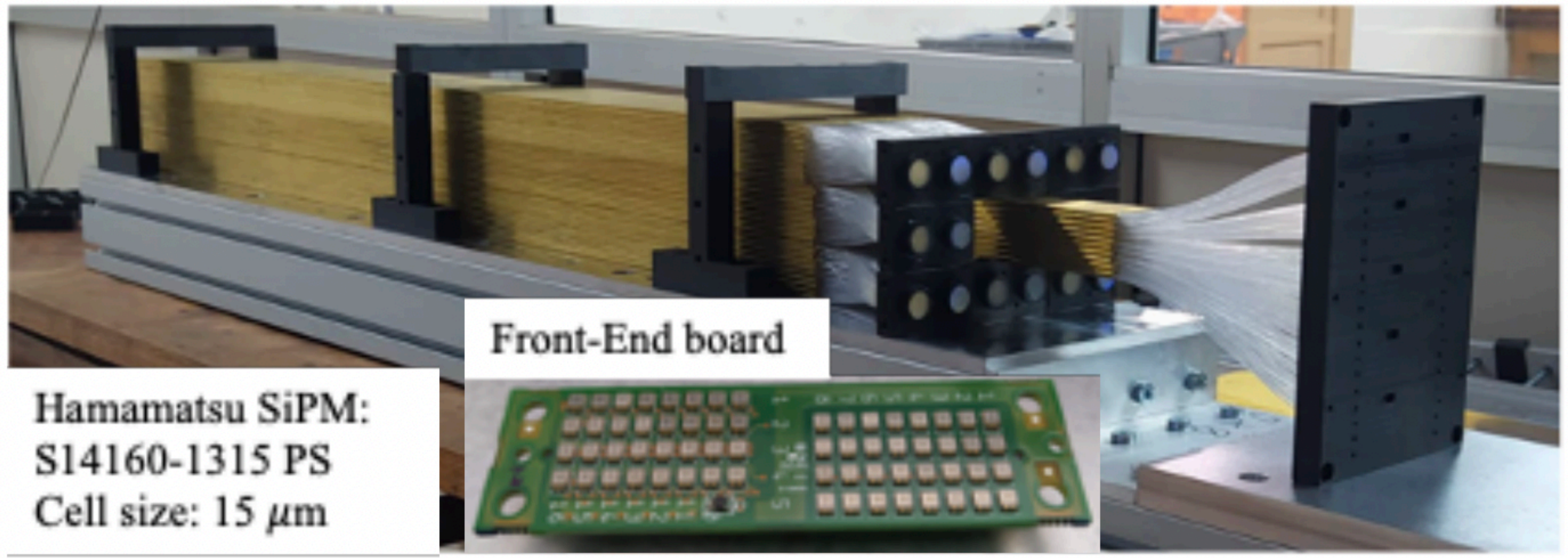
Sune Jakobsen

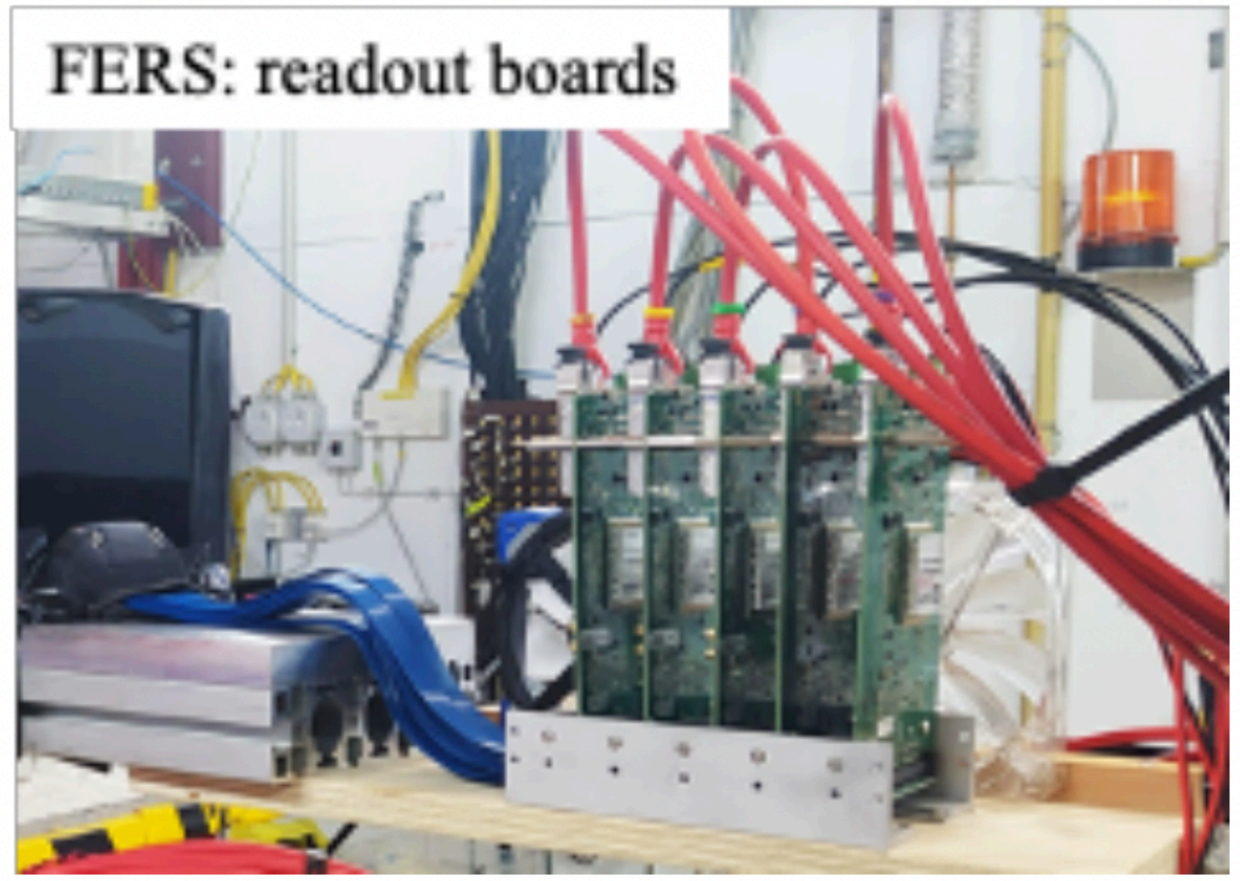
- The stations should be relatively rotated e.g. 1 degree to maximize performance for multi tracks etc.
- Cost: ~3.8M CHF

Calorimeter | Dual-readout

- Existing dual-readout prototypes for Higgs factory detectors
  - EM prototype exists, construction of hadronic-size prototype ongoing
- FASER2 design and costing based on HiDRa “hadronic size” prototype - INFN
  - Spacial Resolution: Tested with fibre diameter of 1mm, 2mm brass collar = ~5 mm resolution
  - EM Energy resolution: 15/√E + ~1% constant term
  - Particle ID: EM vs Hadronic vs MIP PID possible - best performance with longitudinal information





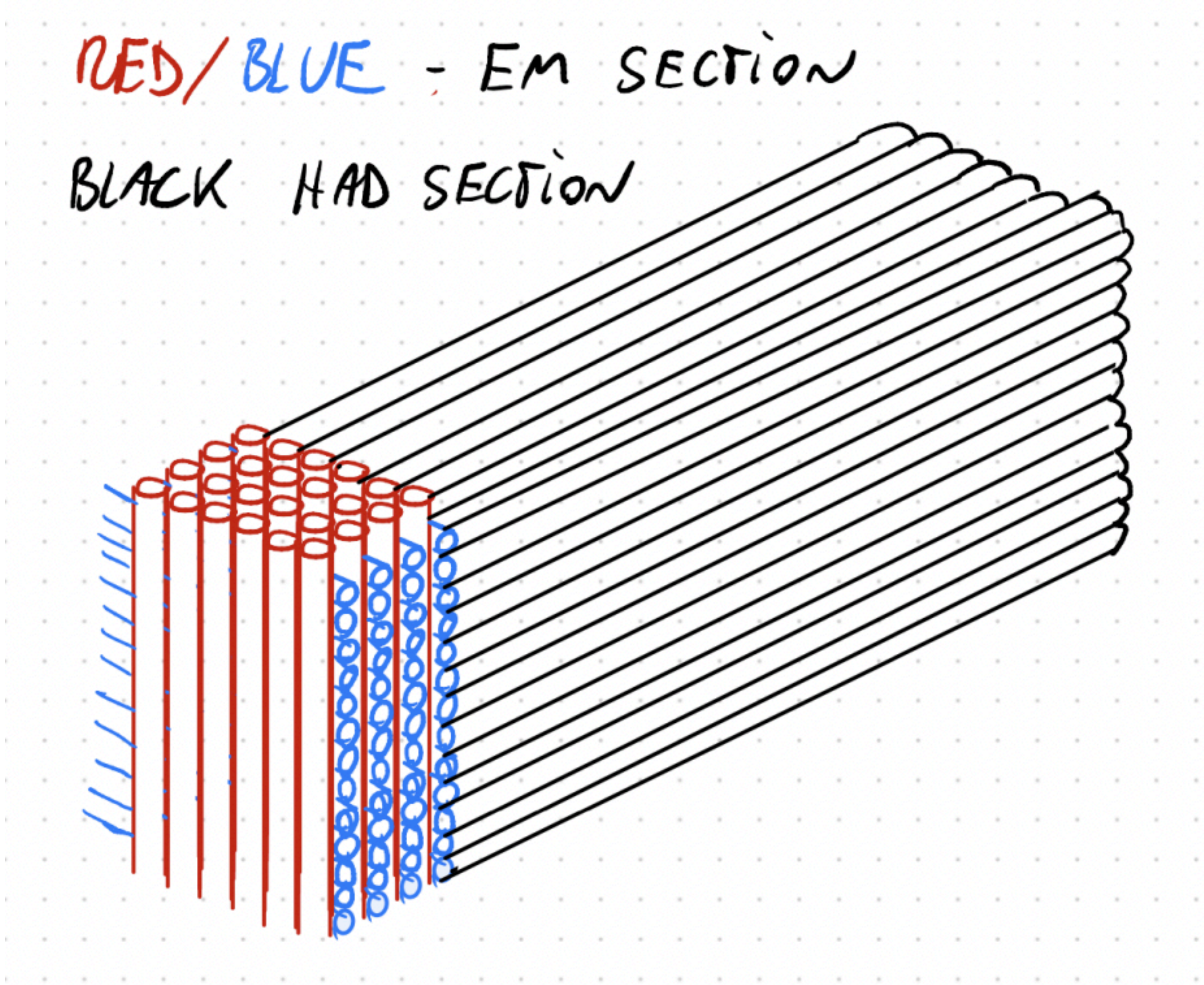


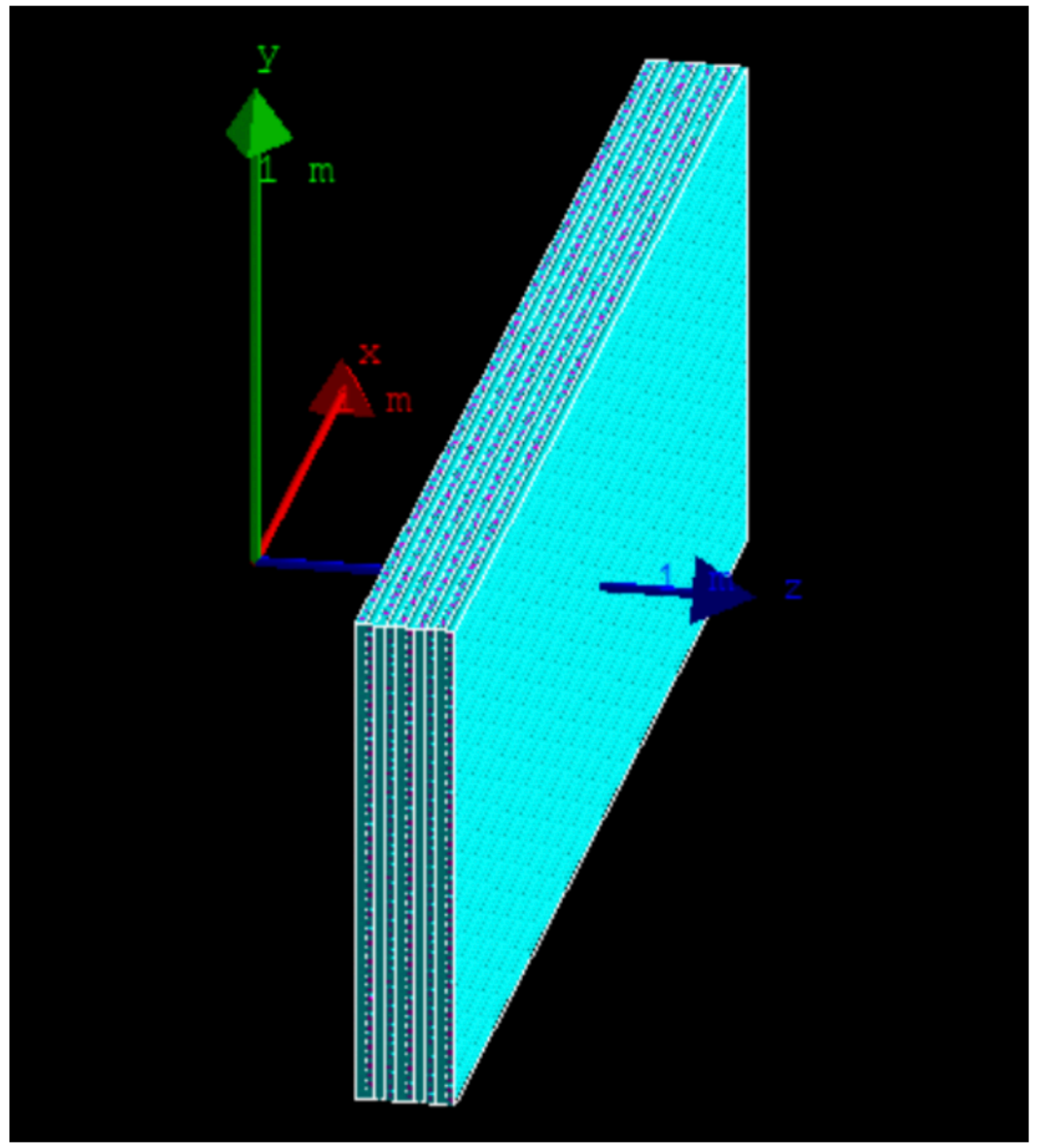
Iacopo Vivarelli

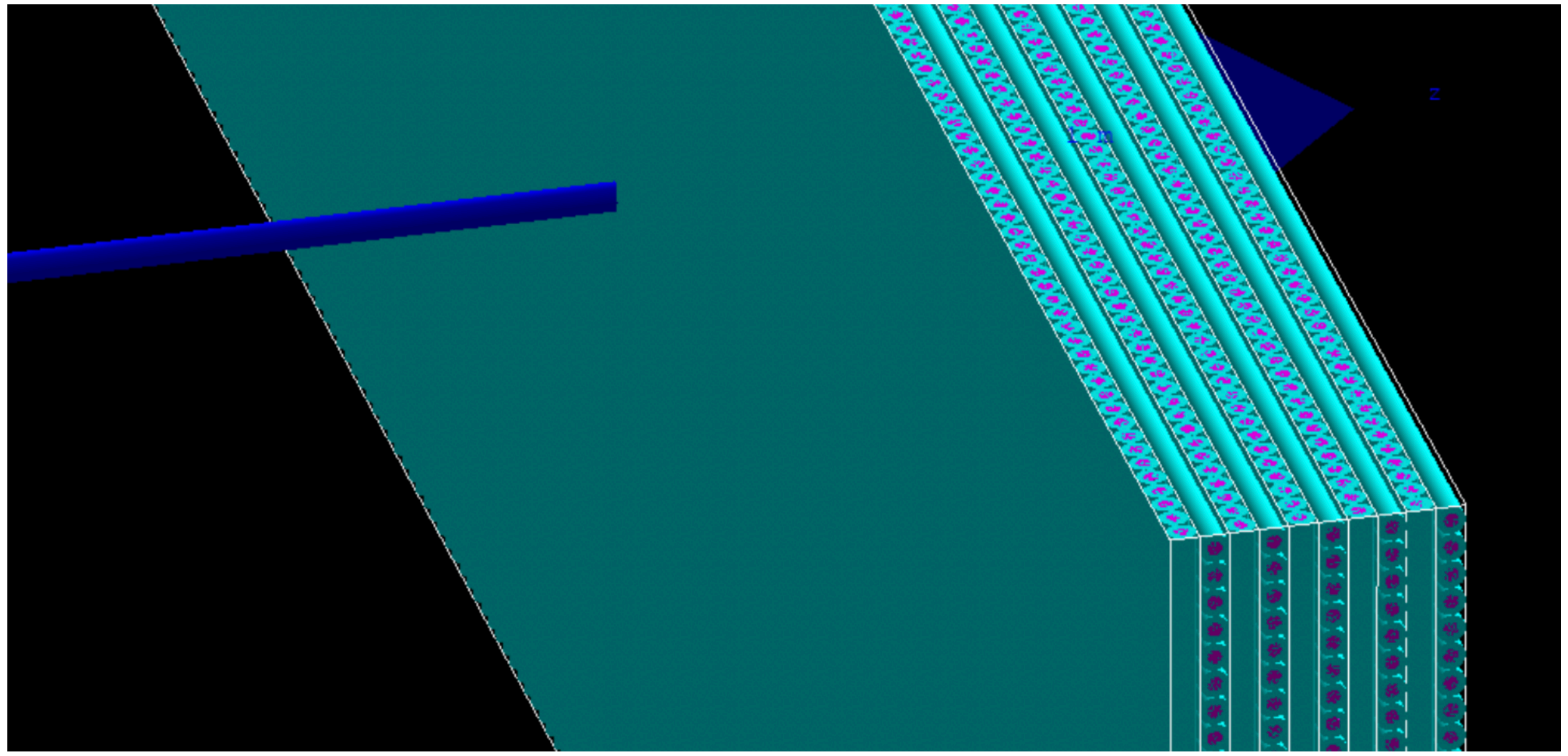
Calorimeter | Design & Simulation

- Fully segmented design
  - Perpendicular crossing of EM layers

- Geometry implemented as part of a simple standalone G4 application
  - Heavily based on the test beam simulation of the bucatini calorimeter.

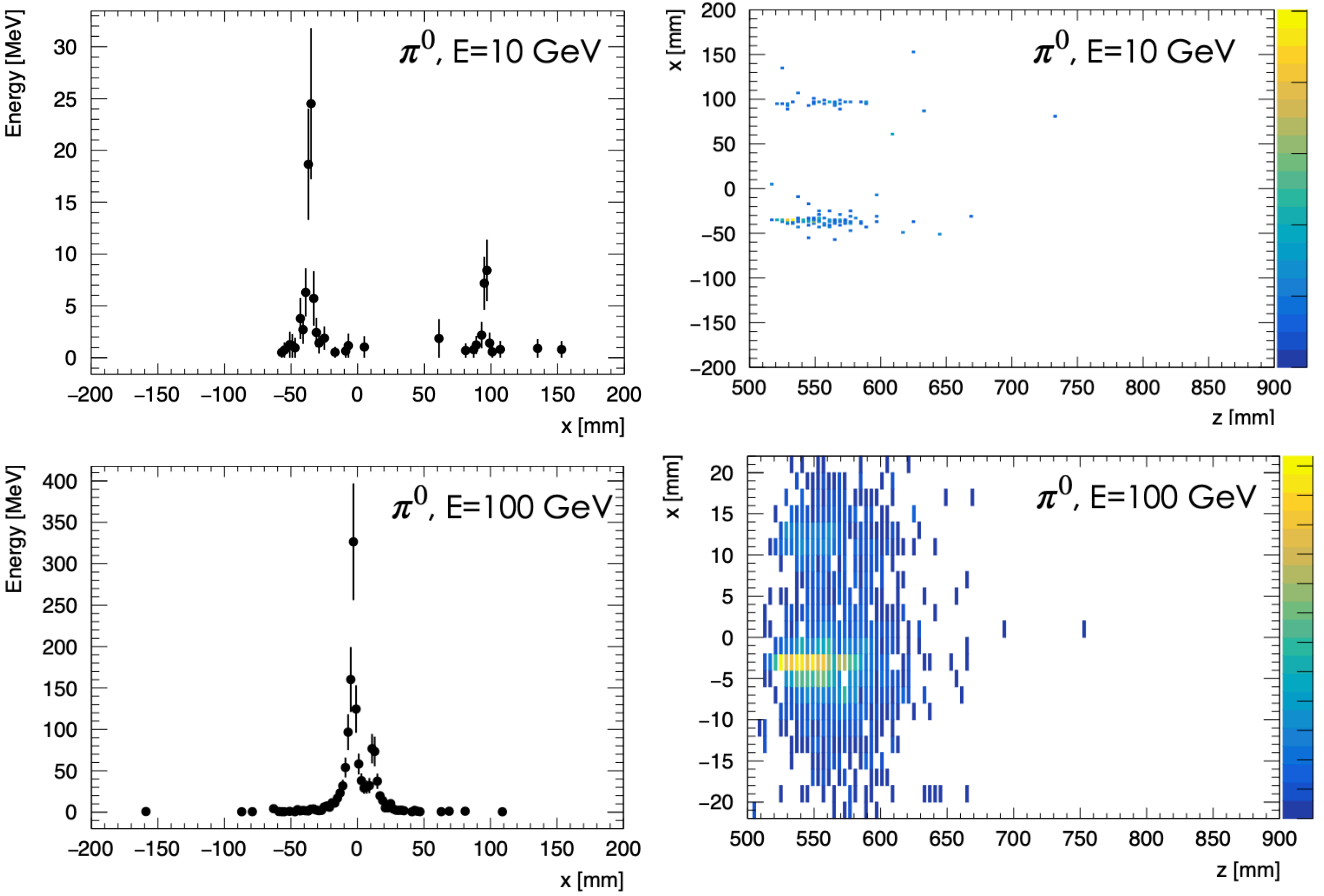






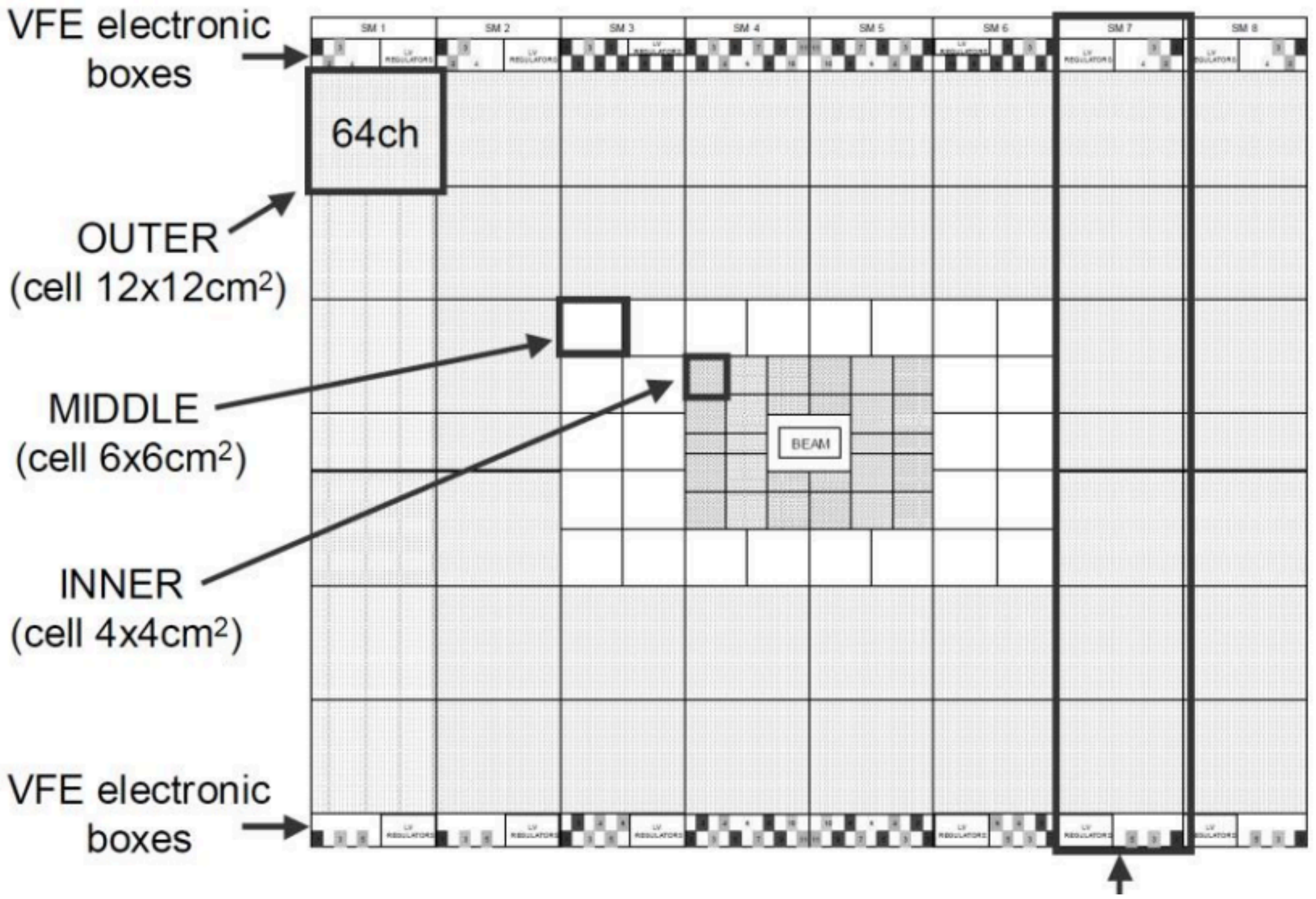
Calorimeter | Performance

- Simulating π⁰→γγ from 5m upstream of calorimeter
  - Similar topology to signal
  - x vs z shown (same information in y vs z)
- 10 GeV:
  - Width of each peak ~2 mm
- 100 GeV:
  - Same sampling fraction as expected
  - Threshold effects on resolution reduced

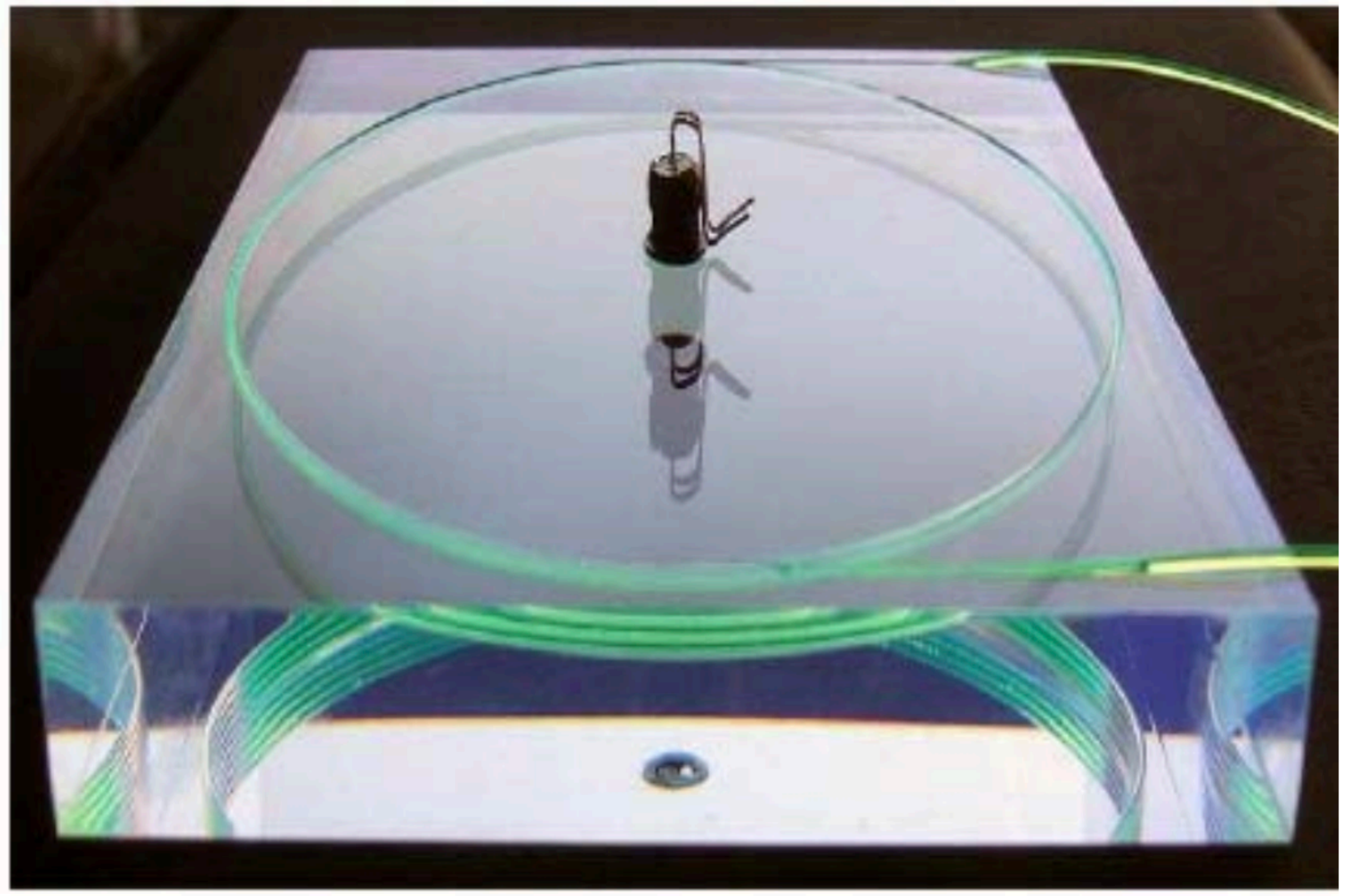


Calorimeter | LHCb preshower & SPD

- Possibility to reuse old LHCb Preshower and Scintillating Pad Detector for FASER2 Calo
  - Scintillator pads with wavelength shifter embedded.
  - Pad size depends on the location:12, 6 and 4 cm^2
  - Pads supported on “super modules” with an active area of ~1 m x 5.8 m



- LHCb technical coord indicate they could store until year end.
  - Is slightly activated - some storage/handling complexity.
- Simulation studies in progress to assess feasibility.

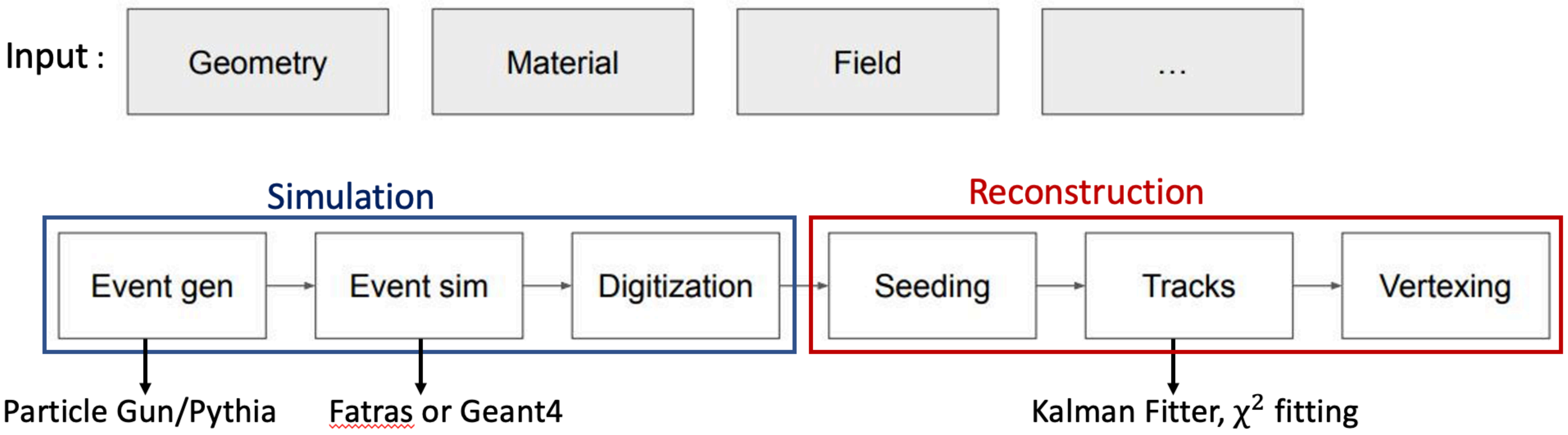


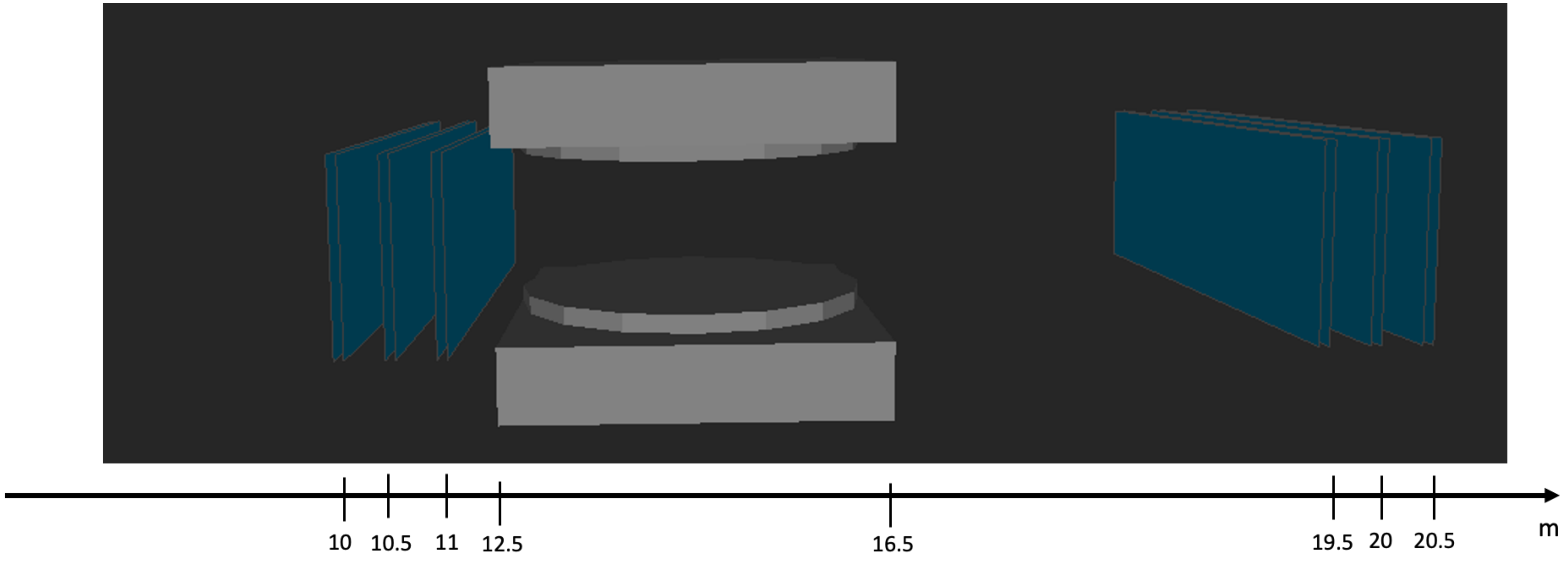
Software | ACTS

Olivier Salin

UNIVERSITY OF SUSSEX

- Using ACTS for track reconstruction
  - Modern experiment-independent tracking toolkit based on LHC experience
- Tracking station simulated with homogenous material with accurate X_0
  - Dimension of the tracker: 1 m X 3m X 4 mm
  - Tracker resolution digitized as 100 μm
  - Constant BField of 1T in volume 1 m X 3 m X 4 m

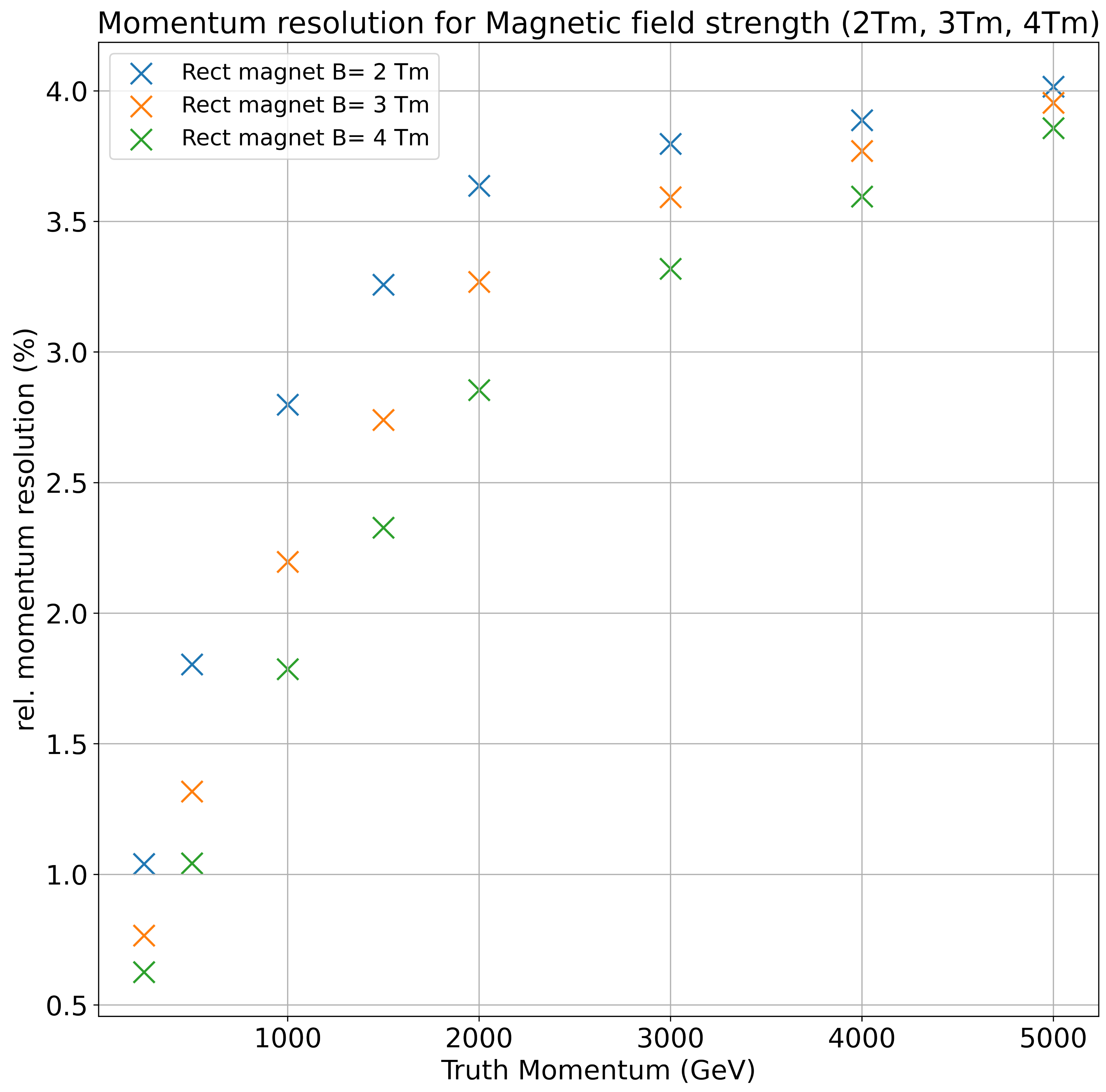


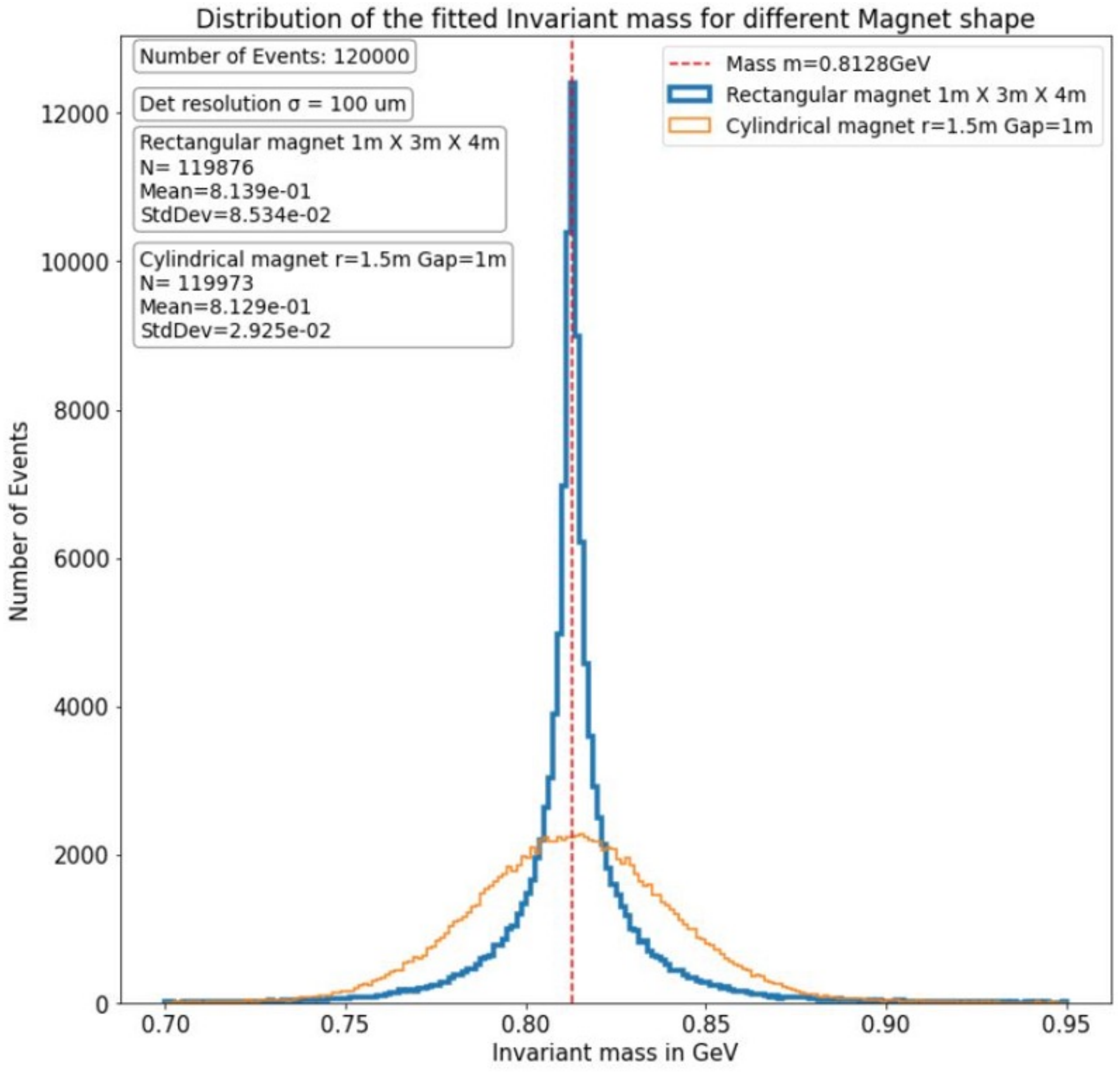


Software | Performance

Olivier Salin

- Studies of tracking performance for different metrics:
  - Resolution
    - momentum
    - mass
    - vertex
  - For different detector configurations:
    - **Magnetic field strength**
    - **Magnetic field profile**
    - Detector resolution
    - Detector alignment





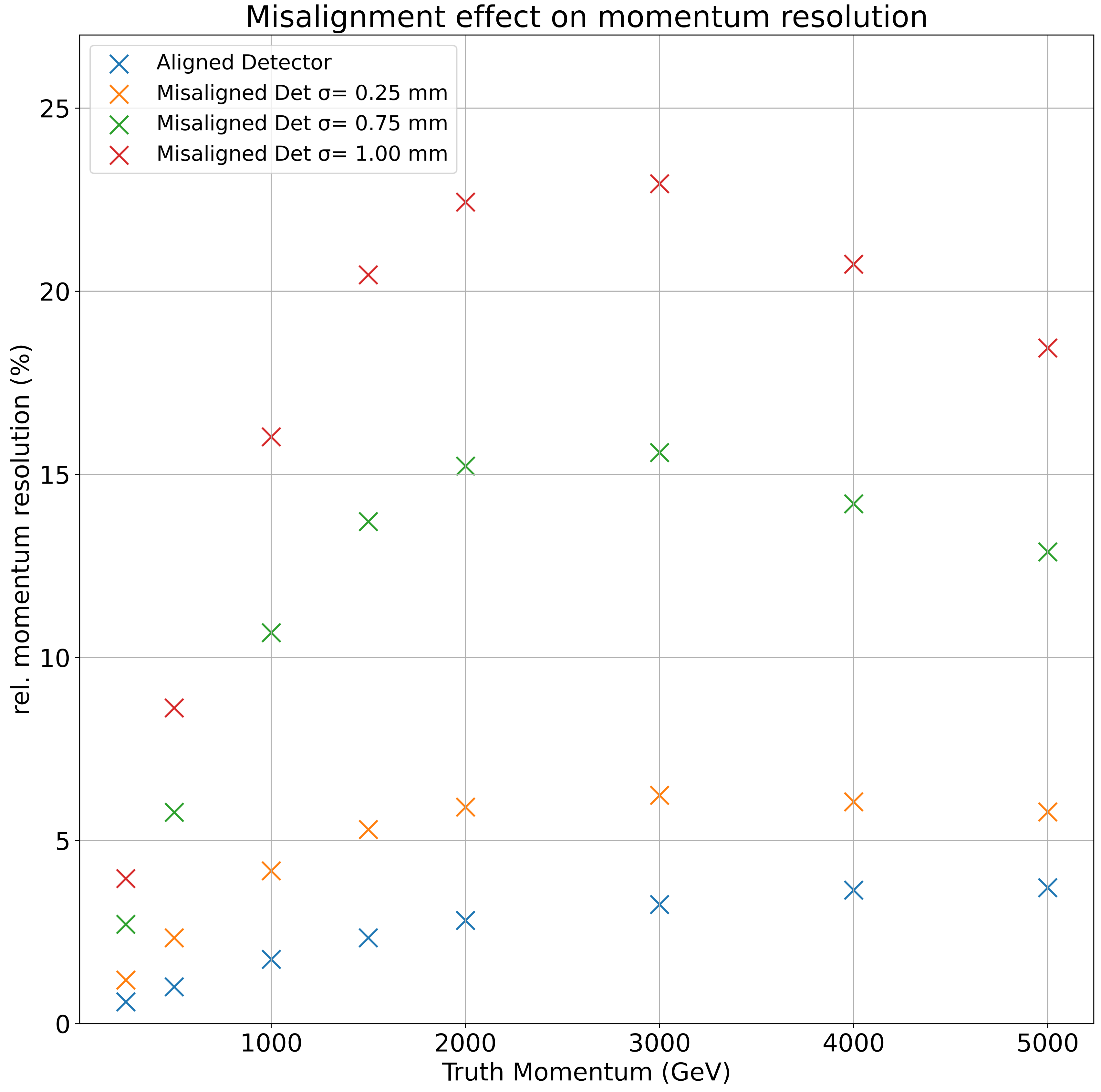
- Scope to reduce magnetic field and keep good performance

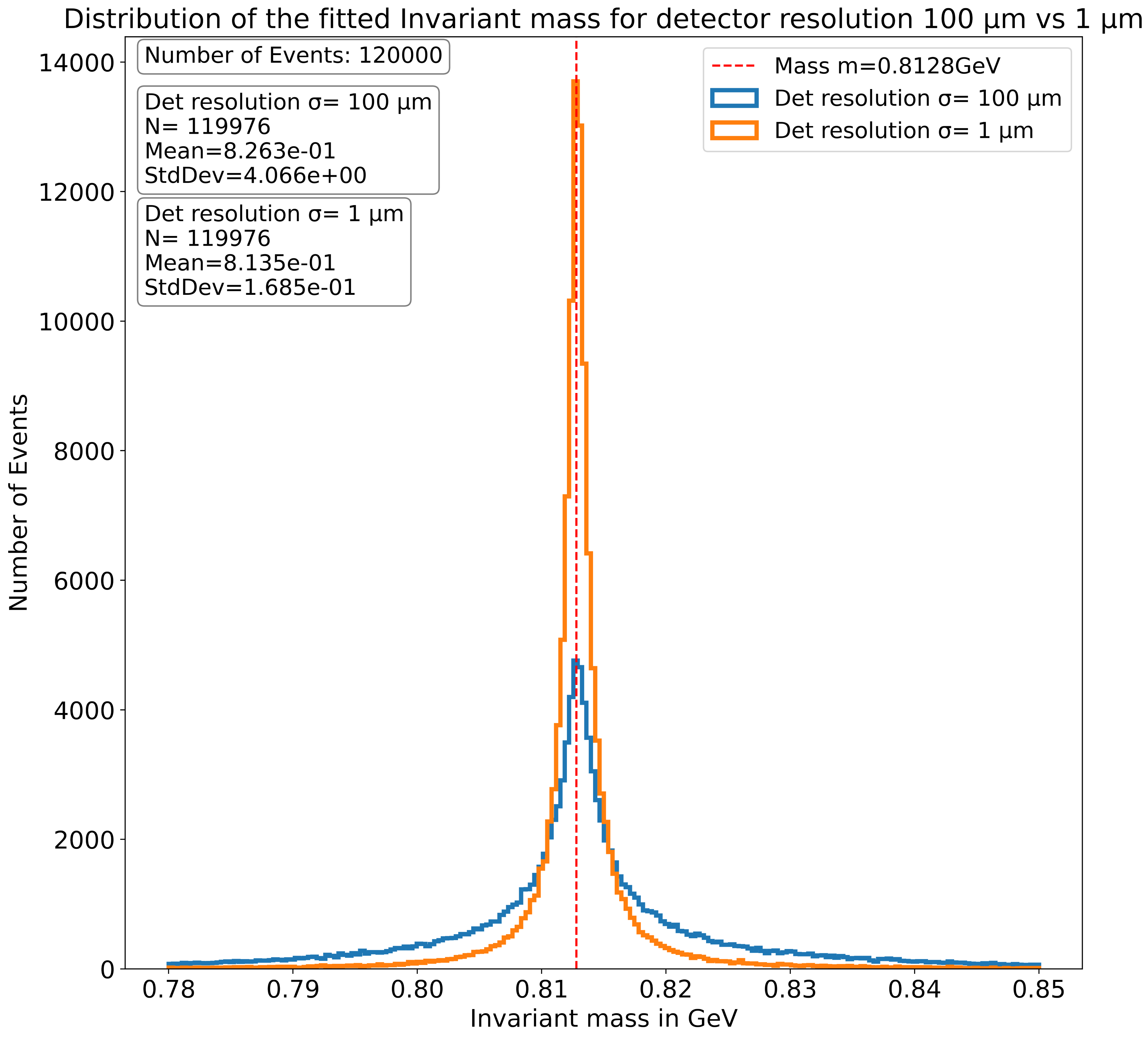
Software | Performance

Olivier Salin

UNIVERSITY OF SUSSEX

- Studies of tracking performance for different metrics:
  - Resolution
    - momentum
    - mass
    - vertex
  - For different detector configurations:
    - Magnetic field strength
    - Magnetic field profile
    - **Detector resolution**
    - **Detector alignment**





- Very good performance observed even in conservative scenarios.

FASER2 Community

UNIVERSITY OF SUSSEX

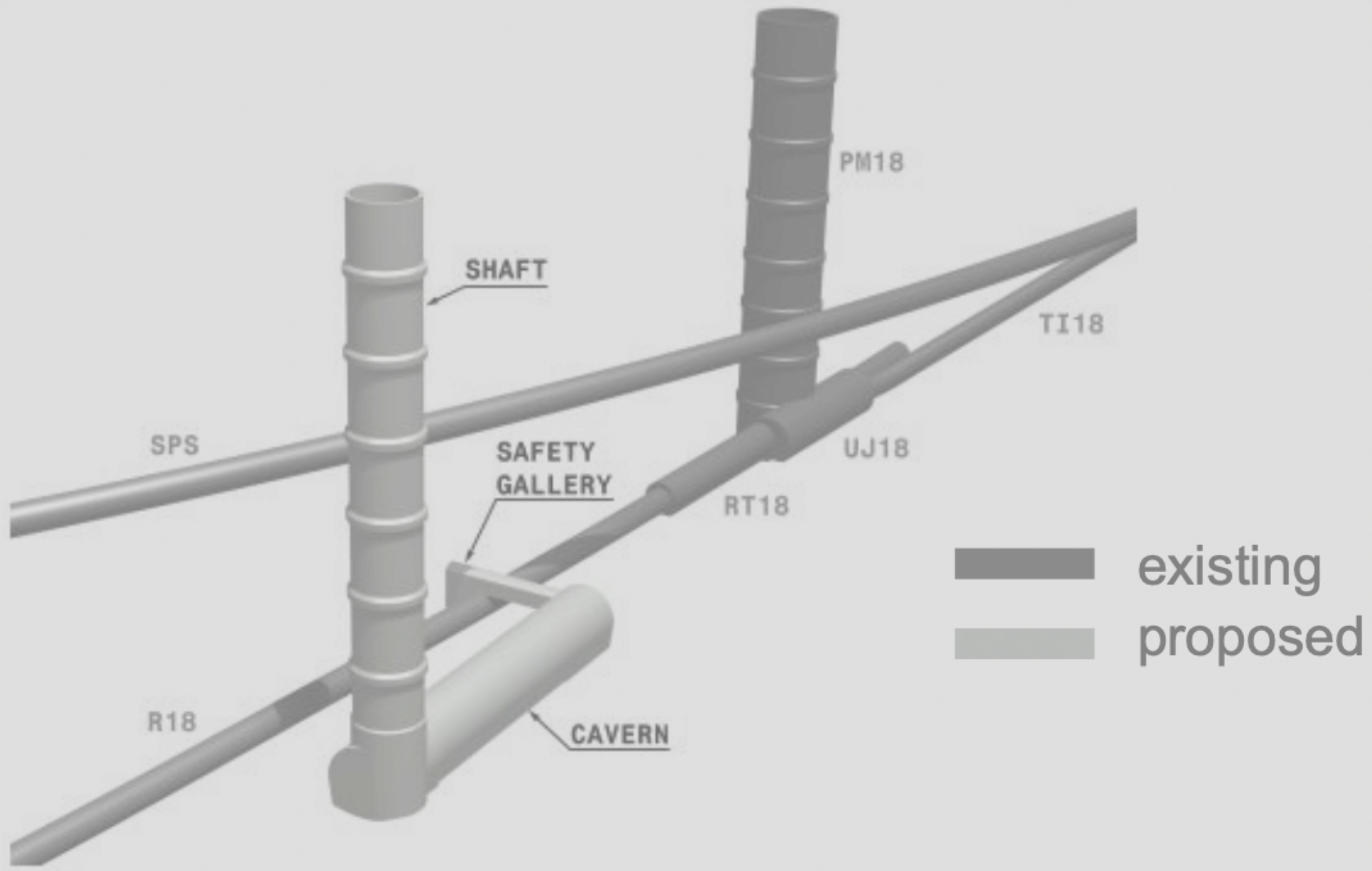
- We are working to build and consolidate the community and possible funding routes for FASER2:
  - Japan: FASER2 & FASERnu2 in process of being included in one of Grand Vision summarised by Science Council of Japan
    - Not directly a budget request, but hoping to broaden funding possibilities
  - US: FASER groups to look at applying for NSF funds for FASER2 detector work.
    - UCI, Washington, Oregon
  - UK: Preparing Statement of Interest with STFC
    - Dual Readout/Tracking/Support structures/Simulation and Data analysis
      - Possible opportunity to exploit overlap with future collider R&D program
    - Liverpool, Manchester, Oxford, Sussex. (Interest also from RAL - strong hardware experience)
    - Community meeting in July on future prospects for UK PP where FPF will be further discussed.
  - Geneva: Investigating options within Switzerland
  - Will approach existing LHCb SciFi institutes about joining FASER2 studies.
  - Expect increased involvement from existing FASER Collaboration

Summary

- Lots of progress made since change in baseline detector layout
  - Very comparable sensitivity achievable with new baseline

- Studies on detector/magnet technology ramping up
  - Extended discussions with KEK experts on magnet design and construction
  - Tracker design and costing advanced building on experience from LHCb SciFi
    - Simulation and track reconstruction studies now quite advanced
    - Next steps to look at muon reconstruction from neutrino interactions
  - Calorimeter design developing with first simulation results
    - Possibility to use LHCb pre shower and SPD being investigated

- Several avenues for funding being pursued in Japan/US/UK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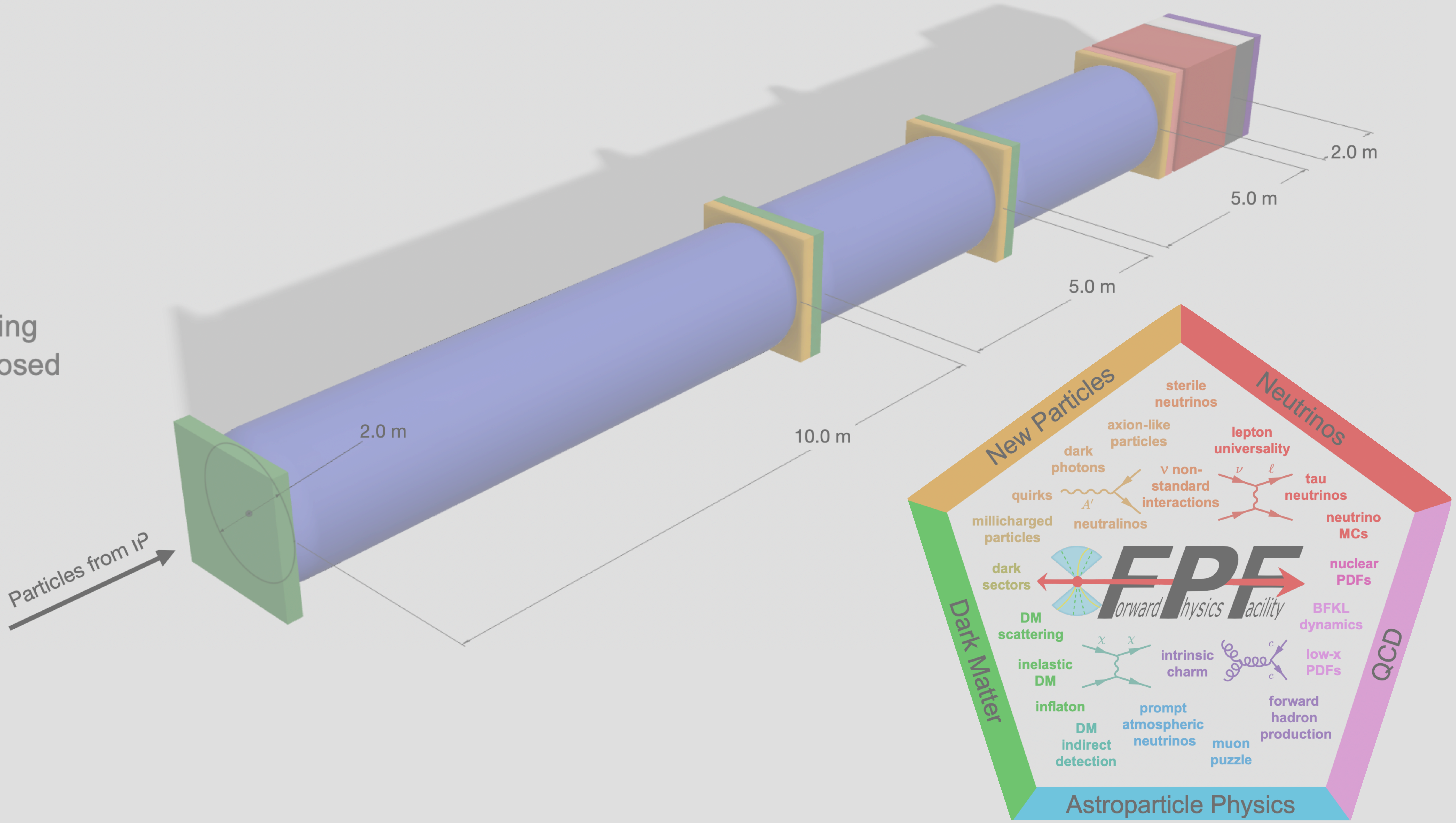
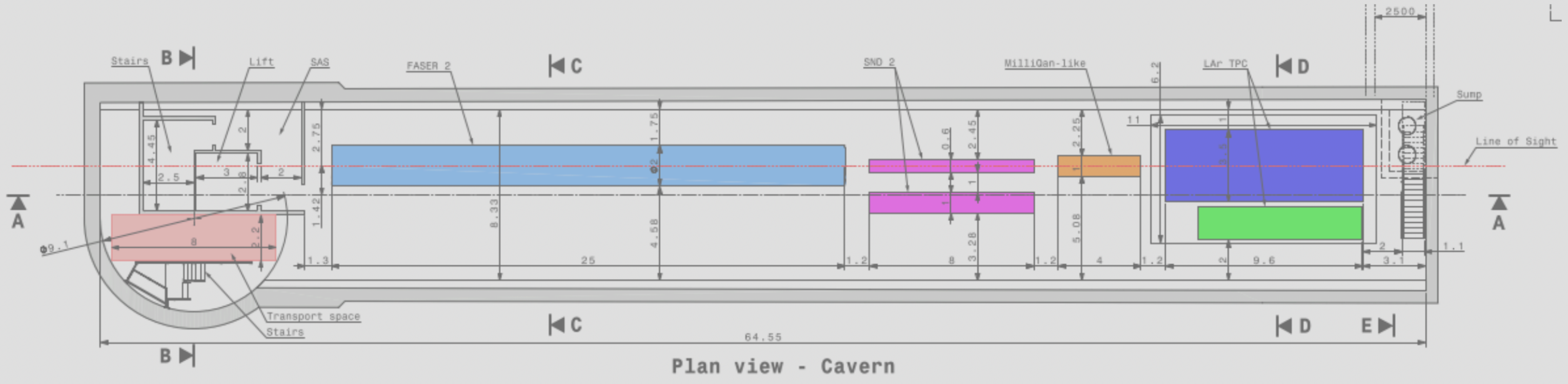
SHAFT
TI18
SPS
SAFETY GALLERY
UJ18
RT18
R18
CAVERN
existing
proposed


2.0 m
5.0 m
5.0 m
10.0 m
2.0 m
Particles from IP
New Particles
Neutrinos
QCD
Astroparticle Physics
Dark Matter
sterile neutrinos
axion-like particles
lepton universality
dark photons
ν non-standard interactions
tau neutrinos
quirks
neutrino MCs
millicharged particles
neutralinos
dark sectors
nuclear PDFs
FPF
Forward Physics Facility
BFKL dynamics
DM scattering
intrinsic charm
low-x PDFs
inelastic DM
forward hadron production
inflaton
prompt atmospheric neutrinos
DM indirect detection
muon puzzle

Back-ups


Stairs
Lift
SAS
FASER 2
SND 2
MilliQan-like
LAr TPC
Sump
Line of Sight
Transport space
Stairs
64.55
Plan view - Cavern

Calorimeter design and costing

Material	brass
External diameter	2 mm
Internal diameter	1 mm
Cost of fibre per meter	1 euros
Cost of brass per meter	0.30 euros
Cost of SiPM (relevant only for EM section)	7 euros
FERS cost	5000 euro/unit
FERS readout	512 SiPM

- Calorimeter parameters:
  - Effective radiation length (brass + fiber + air): 2.47 cm.
  - Effective Moliere radius: 1.97 cm.
- EM section readout: 1 channel per fiber
  - Spacial resolution o(1x1x1 mm^3)
- Had section: granularity less important. Can bundle many fibres in one traditional PMT.
- At this point, cost extrapolated based on assumed length width/height/depth of EM and HAD sections
  - Assuming same width/height for EM and HAD section.

Calorimeter design and costing

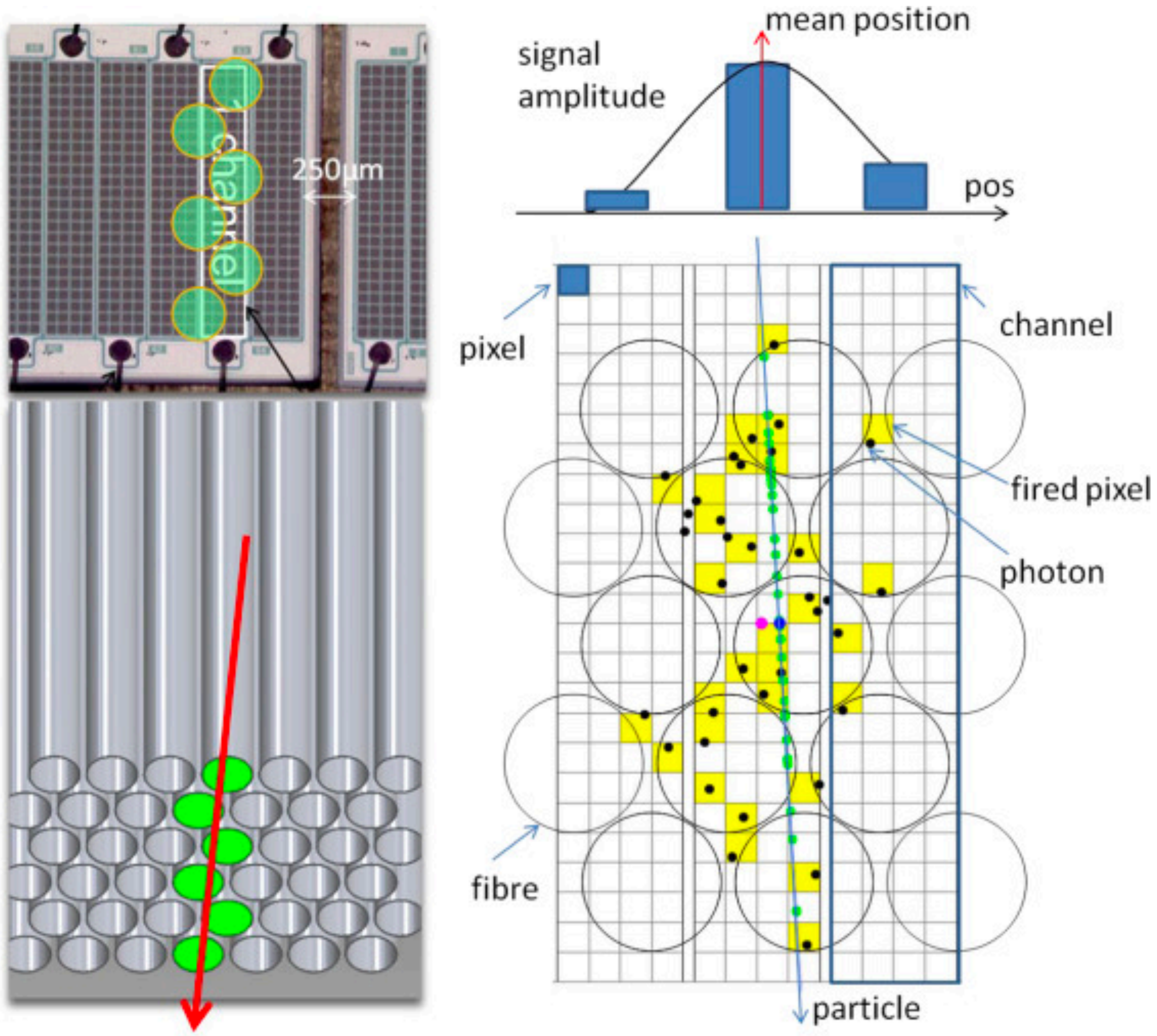
- Costing Option 1
  - EM section 2 m x 2 m x 37 cm (15 X0) (1.85e5 2 m elements)
    - Cost of brass + fibers: 380 k euros
    - Cost of SiPM (1 per element): 1.3 M euros
    - (Cost of FERS: 12.7 M - will need optimisation)
  - HAD section 2 m x 2 m x 2.5 m (1e6 elements)
    - Cost of brass + fibers: 3.2 M euros
    - (Readout cost small w.r.t. EM section)
  - Total (excluding EM FE and HAD readout): ~4.8 M euros

Calorimeter design and costing

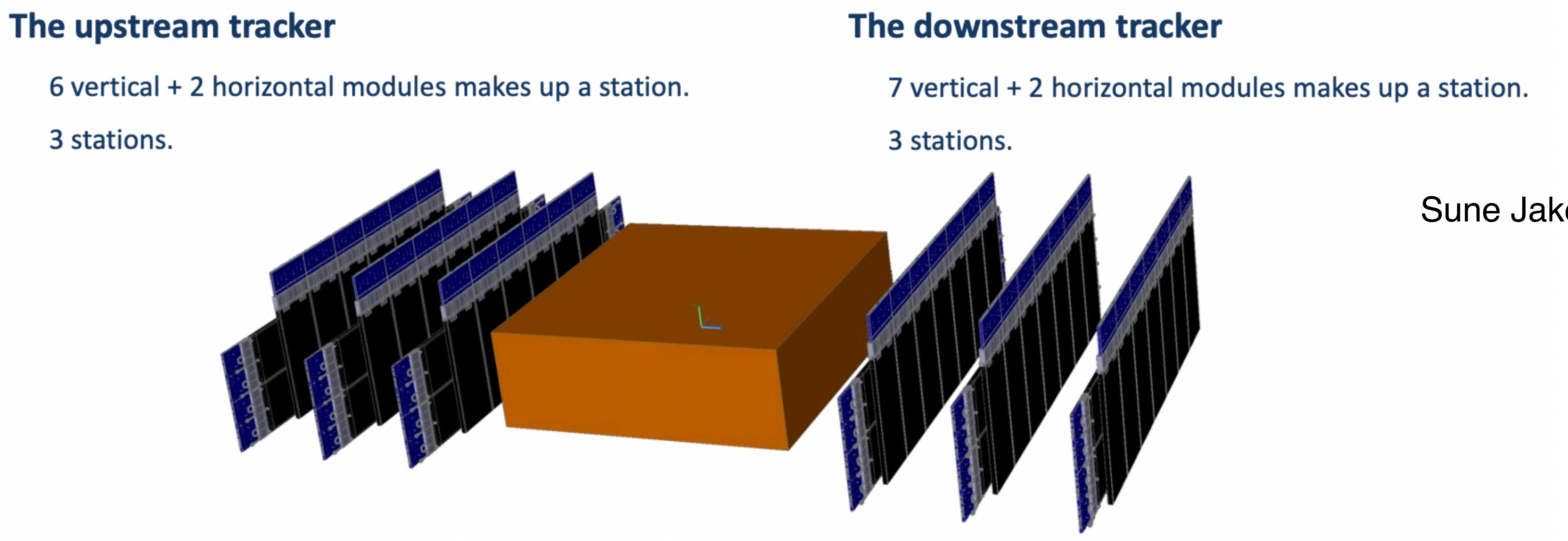
- Option 2
  - EM section 1.5 m x 1.5 m x 37 cm (15 X0) (1.39e5 1.5 m elements):
    - Cost of brass + fibers: 260 k euros
    - Cost of SiPM (1 per element): 970 k euros
    - (Cost of FERS: 9 M - will need optimisation)
  - HAD section 1.5 m x 1.5 m x 2.5 m (5.6e5 elements)
    - Cost of brass + fibers: 1.8 M euros
    - (Readout cost small w.r.t. EM section)
  - Total (excluding EM FE and HAD readout): ~3.0 M euros

Tracker design and costing

- Based on SciFi detector installed in LHCb in LS2.
  - SiPM+scintillating fibre design
  - Fibres 250um diamater => 80um resolution.
- Each module consists of a mat of 4 fibres, with >99% efficiency.
- Costing done by scaling LHCb detector to the FASER2 design, and includes readout.
- Cost could be reduced by re-using tooling from LHCb if relevant institutes were involved.



SciFi design and costing



Sune Jakobsen

- The stations should be relatively rotated e.g. 1 degree to maximize performance for multi tracks etc.
- Cost: ~3.8M CHF

SciFi design and costing

The upstream tracker

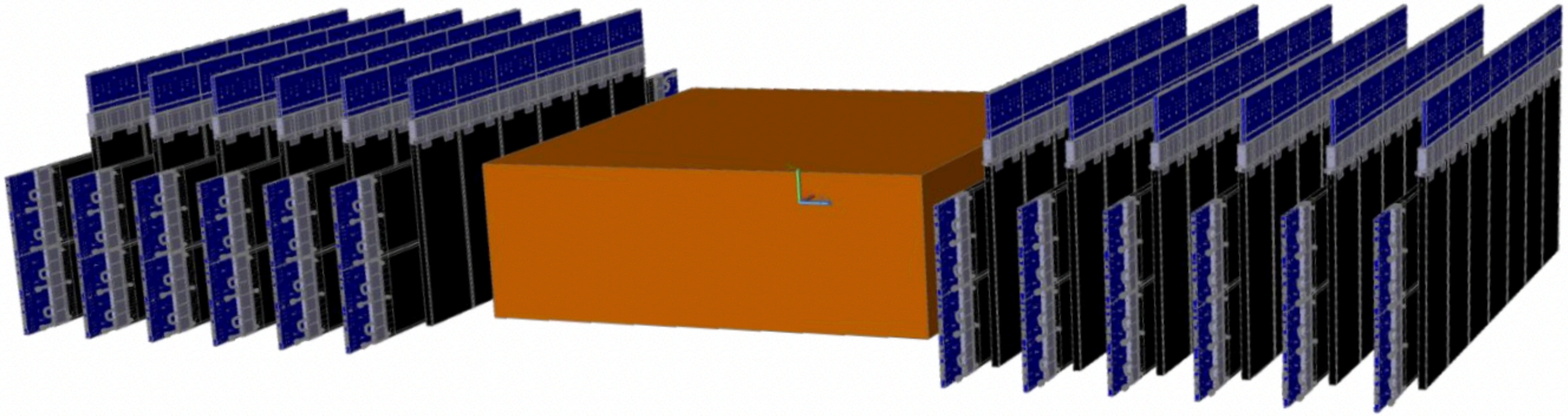
6 vertical + 2 horizontal modules makes up a station.

6 stations.

The downstream tracker

7 vertical + 2 horizontal modules makes up a station.

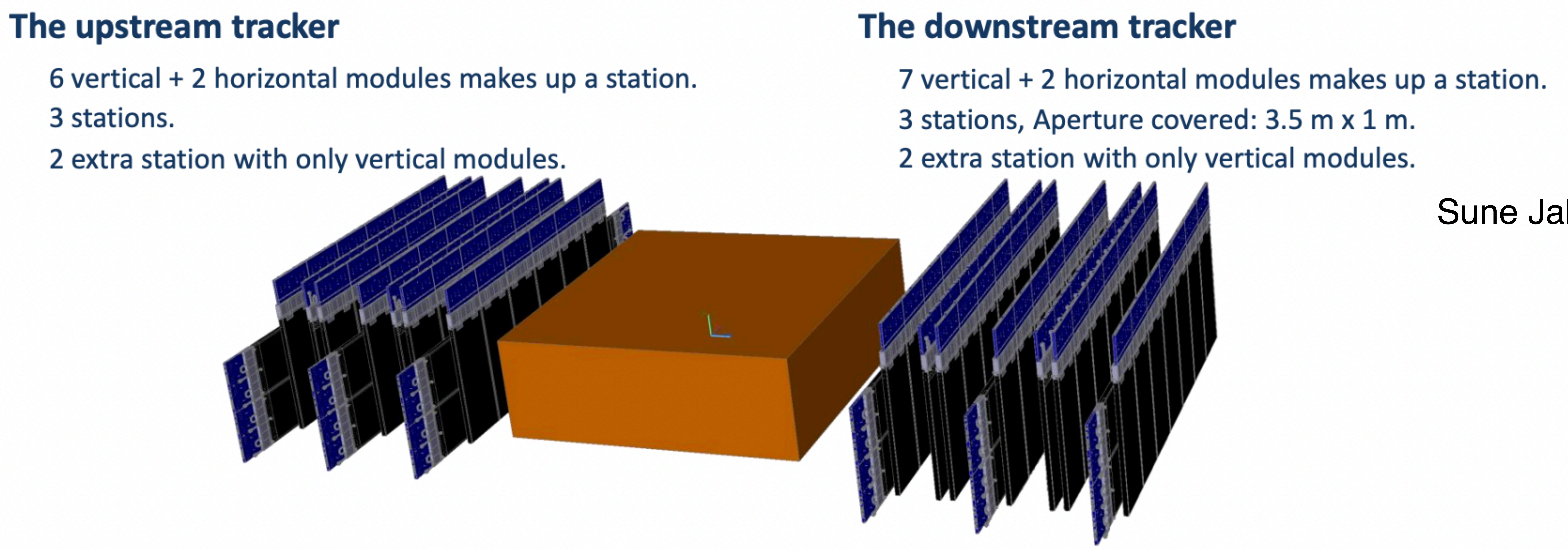
6 stations.



Sune Jakobsen

- The stations should be relatively rotated e.g. 1 degree to maximize performance for multi tracks etc.
- Cost: ~6.7M CHF

SciFi design and costing

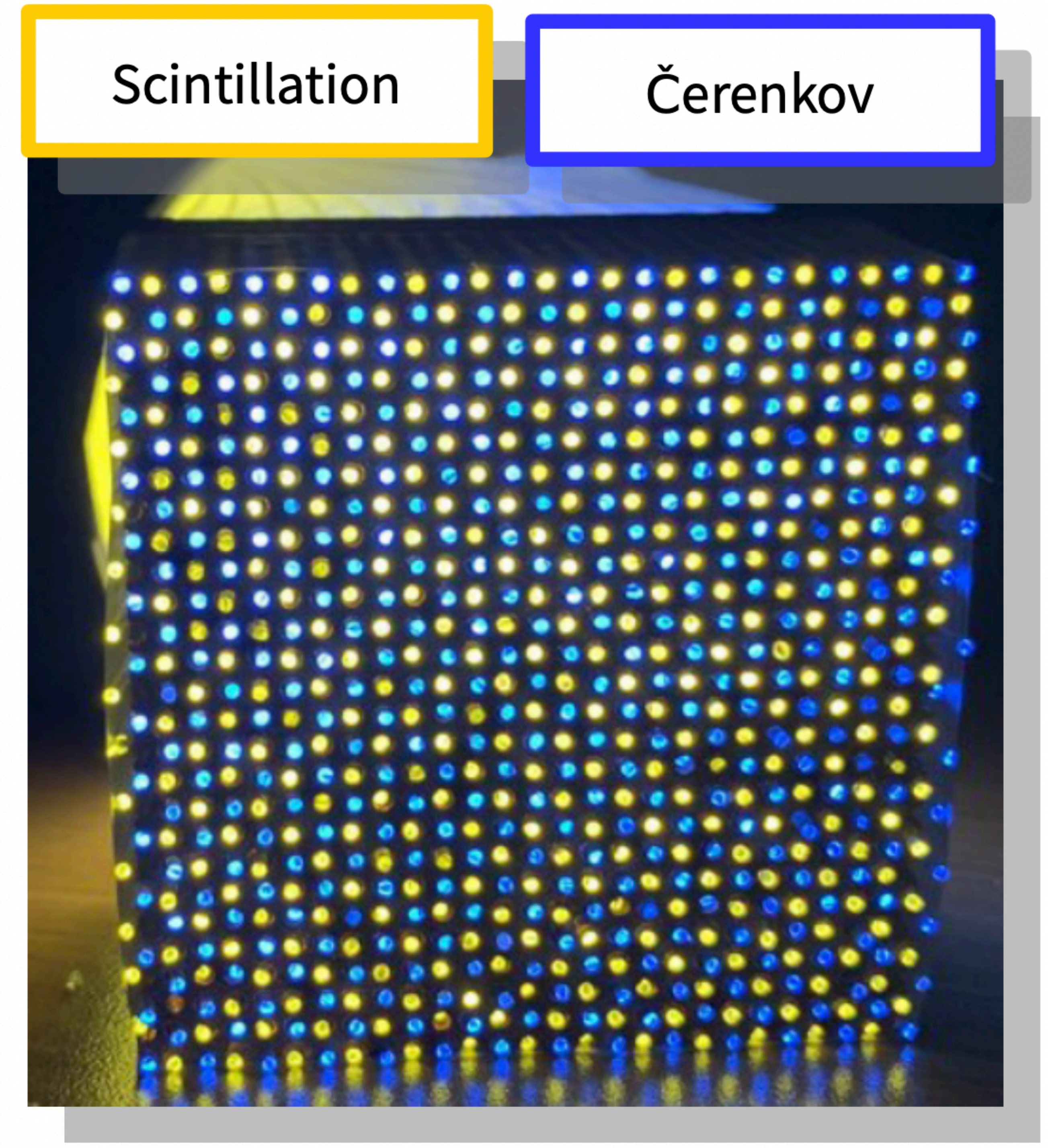


Sune Jakobsen

- The stations should be relatively rotated e.g. 1 degree to maximize performance for multi tracks etc.
- Cost: ~6.3M CHF

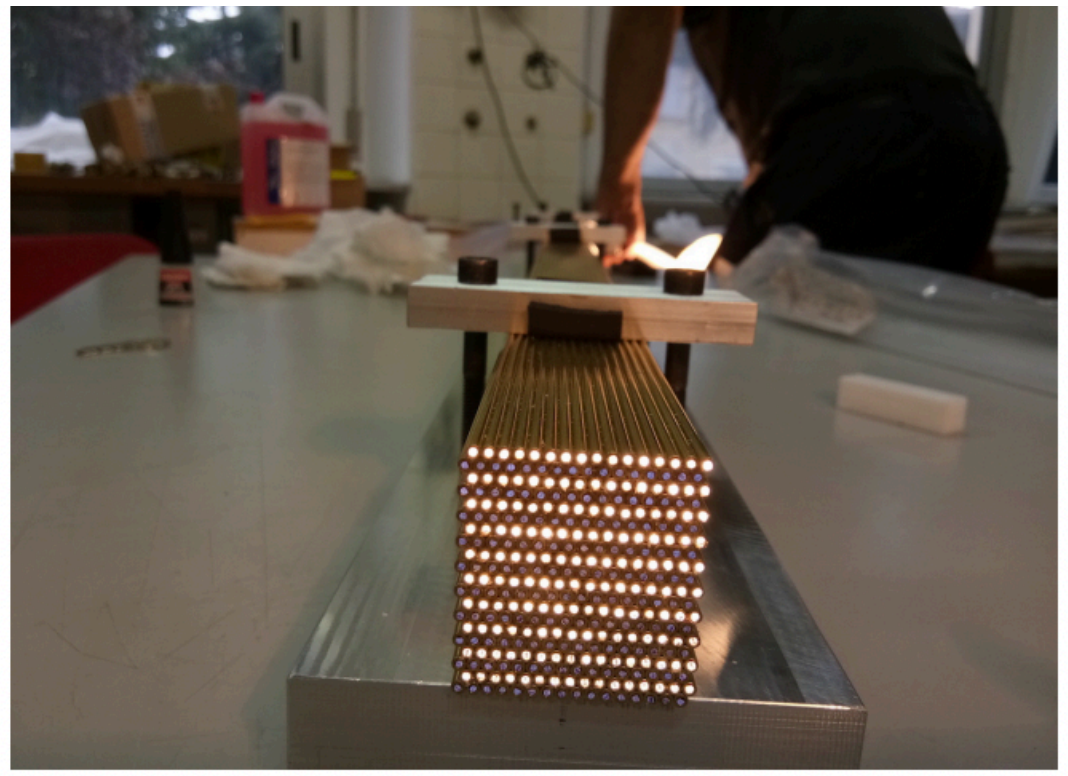
Calorimeter | Dual-readout

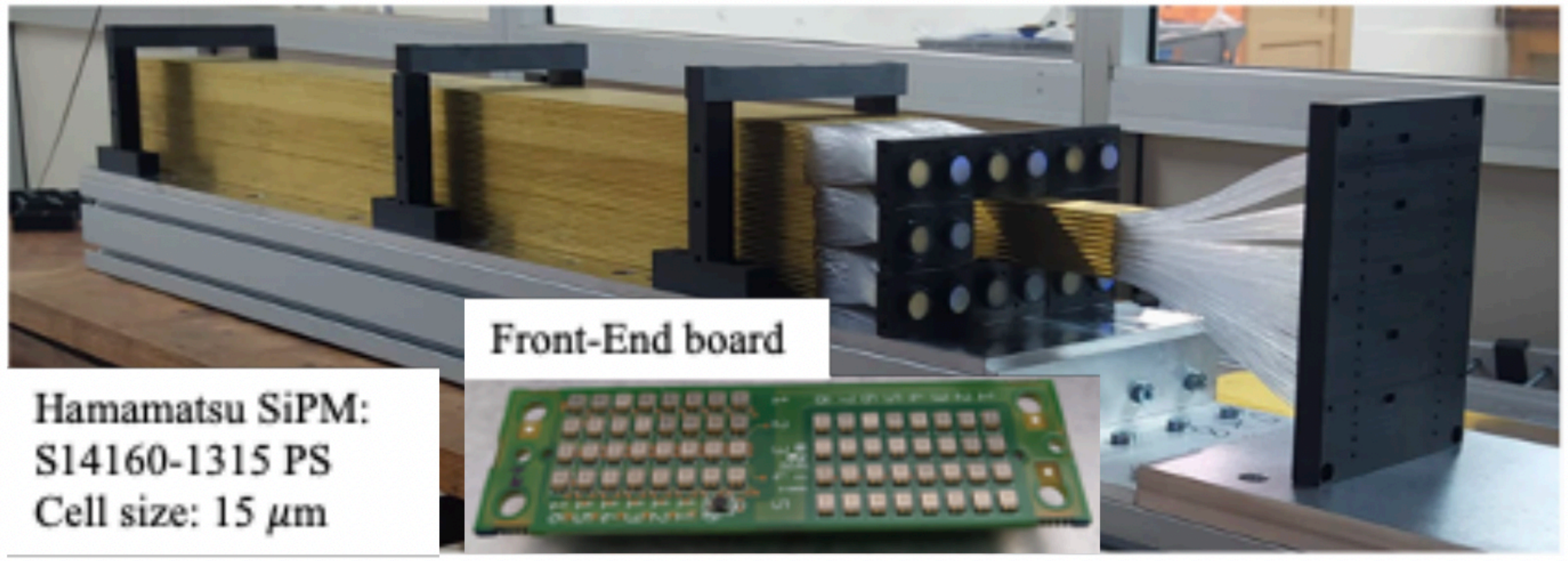
- Design based on Dual Readout calorimeter design
  - Being studied in context of e+e- Higgs factories
- Spacial Resolution:
  - Tested with fibre diameter of 1mm. 2mm brass collar.
  - So ~5 mm resolution possible.
- EM Energy resolution: 15/√E + ~1% constant term
- Particle ID
  - EM vs Hadronic vs MIP PID possible - best performance would need longitudinal information.

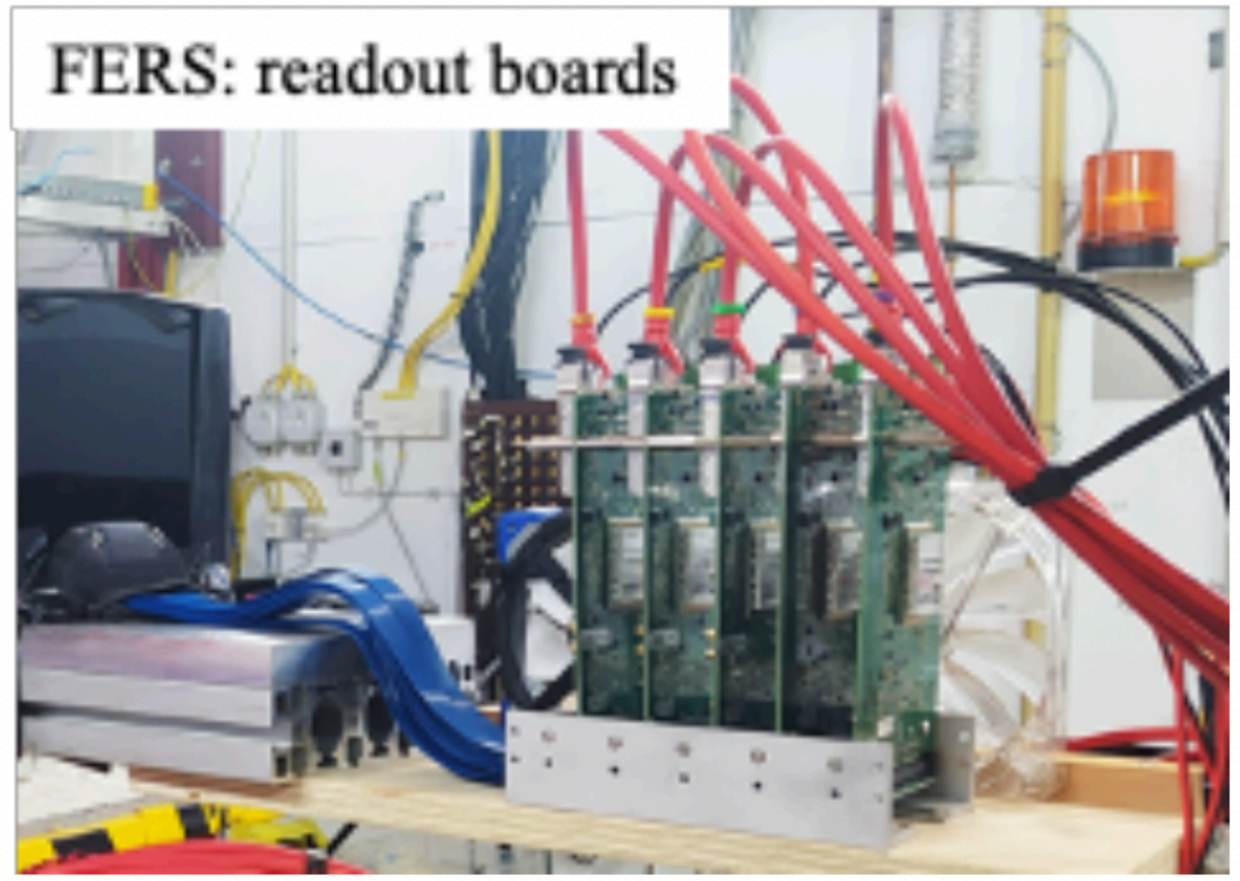


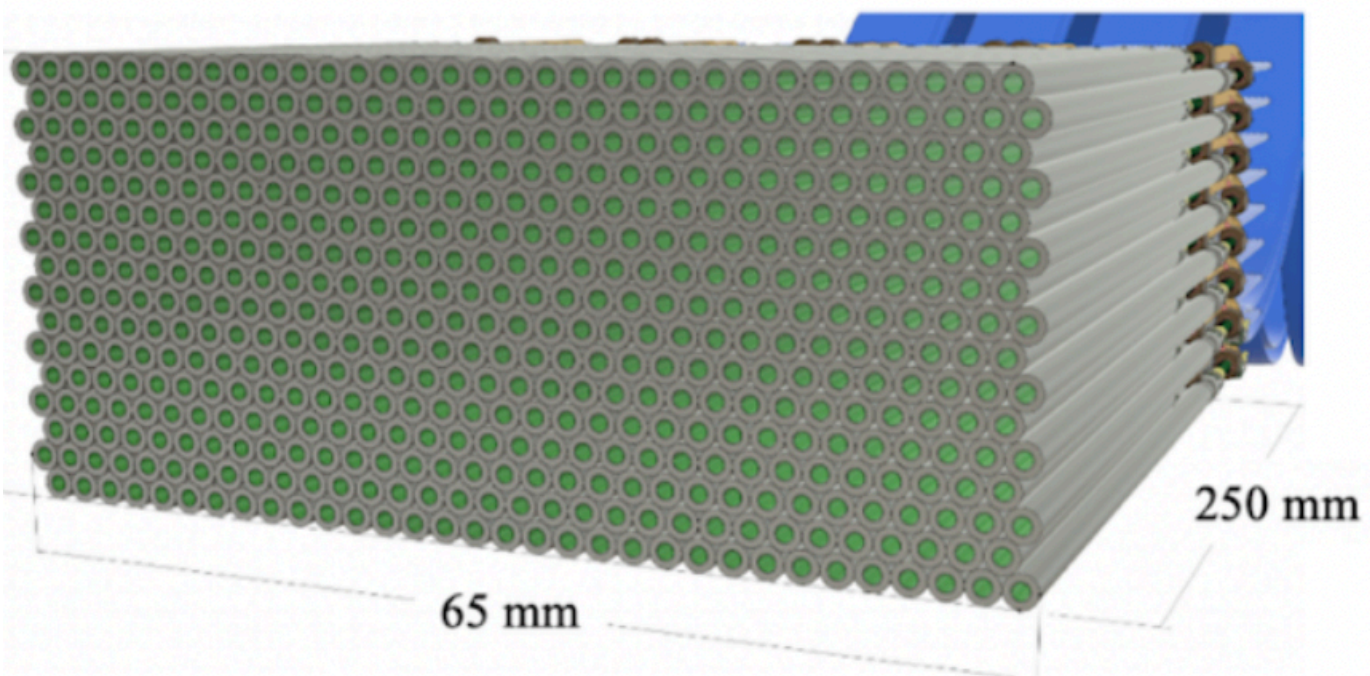
Calorimeter design

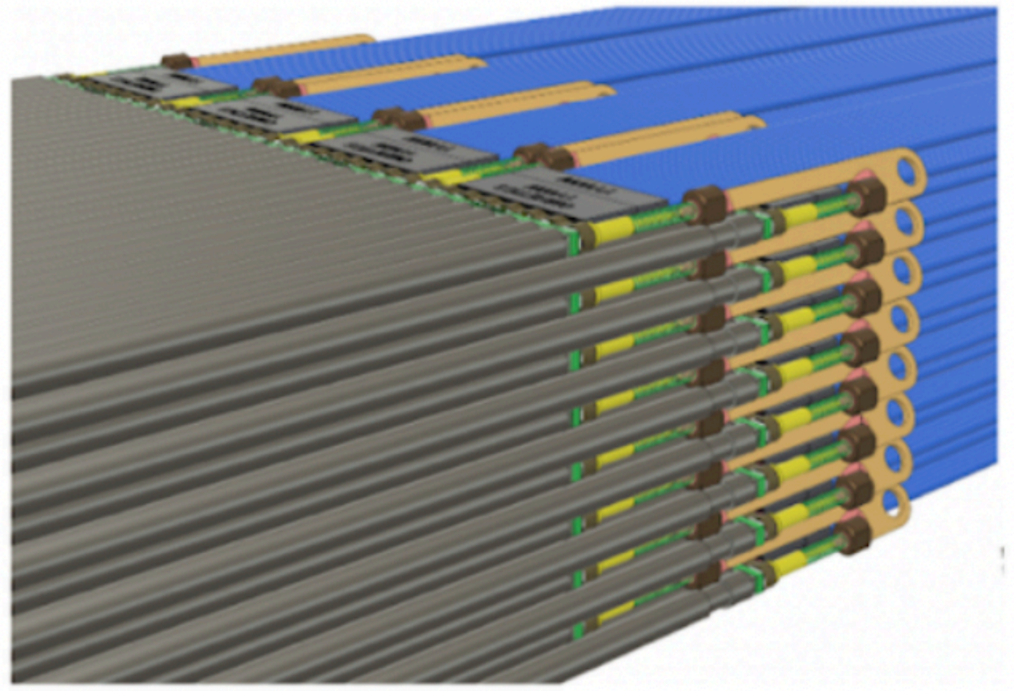
- Costing from existing prototypes
  - EM prototype exists, construction of hadronic-size prototype ongoing
    - Costing based on HiDRa “hadronic size” prototype - INFN
      - 65x65x250 cm (presentation)
      - Aiming for 2023 construction and test beam







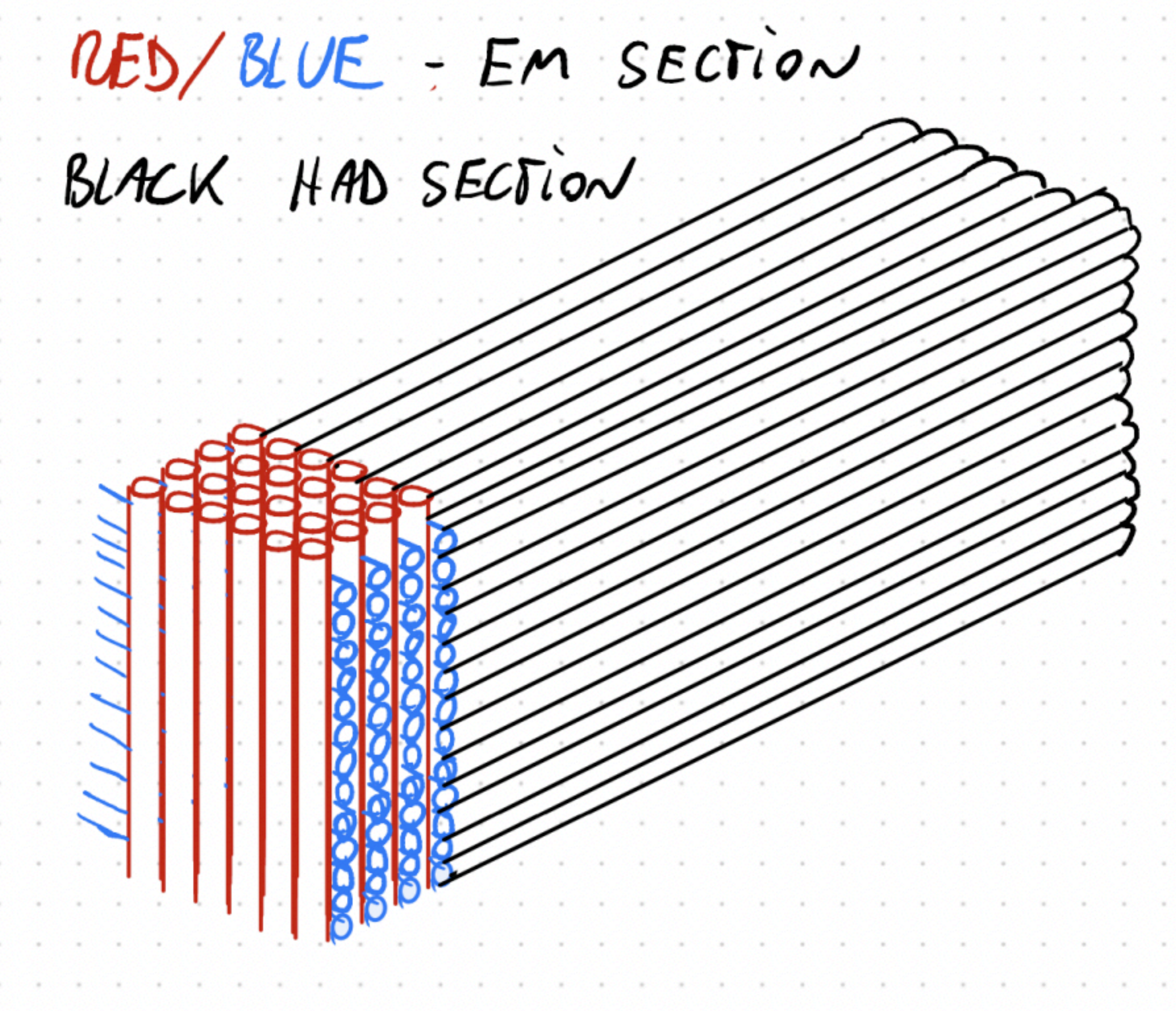




Iacopo Vivarelli

Calorimeter design and costing

- Fully segmented design
  - Perpendicular crossing of EM layers
  - Don't need dual readout - no Cherenkov fibres
  - Very preliminary costing for 2m and 1.5m diameter aperture

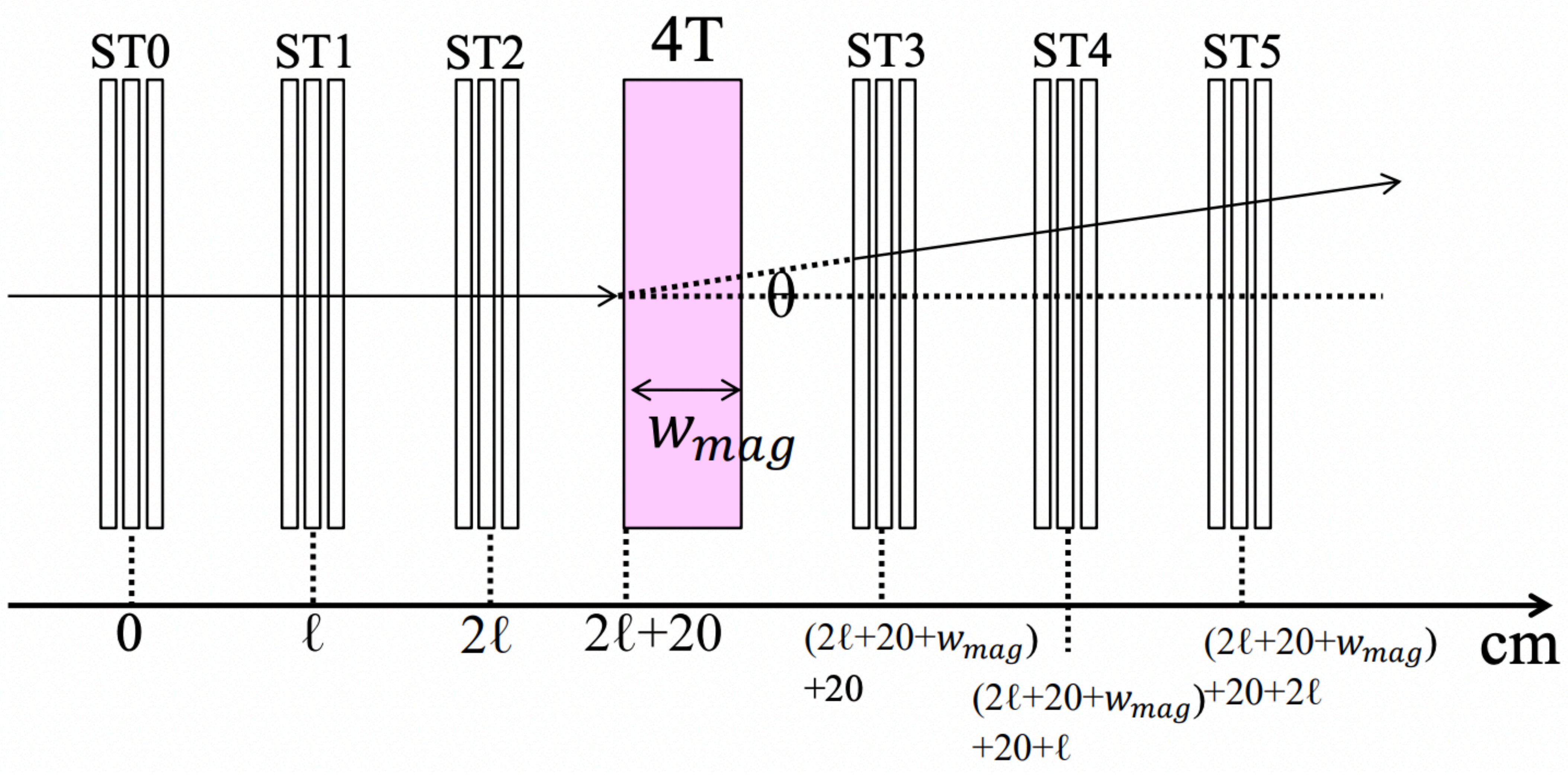


- Costing Option 1:
  - EM section 2 m x 2 m x 37 cm (15 X0) (1.85e5 2 m elements)
  - HAD section 2 m x 2 m x 2.5 m (1e6 elements)
  - Total (excluding EM FE and HAD readout): ~4.8 M euros
- Costing Option 2:
  - EM section 1.5 m x 1.5 m x 37 cm (15 X0) (1.39e5 1.5 m elements):
  - HAD section 1.5 m x 1.5 m x 2.5 m (5.6e5 elements)
  - Total (excluding EM FE and HAD readout): ~3.0 M euros

Iacopo Vivarelli

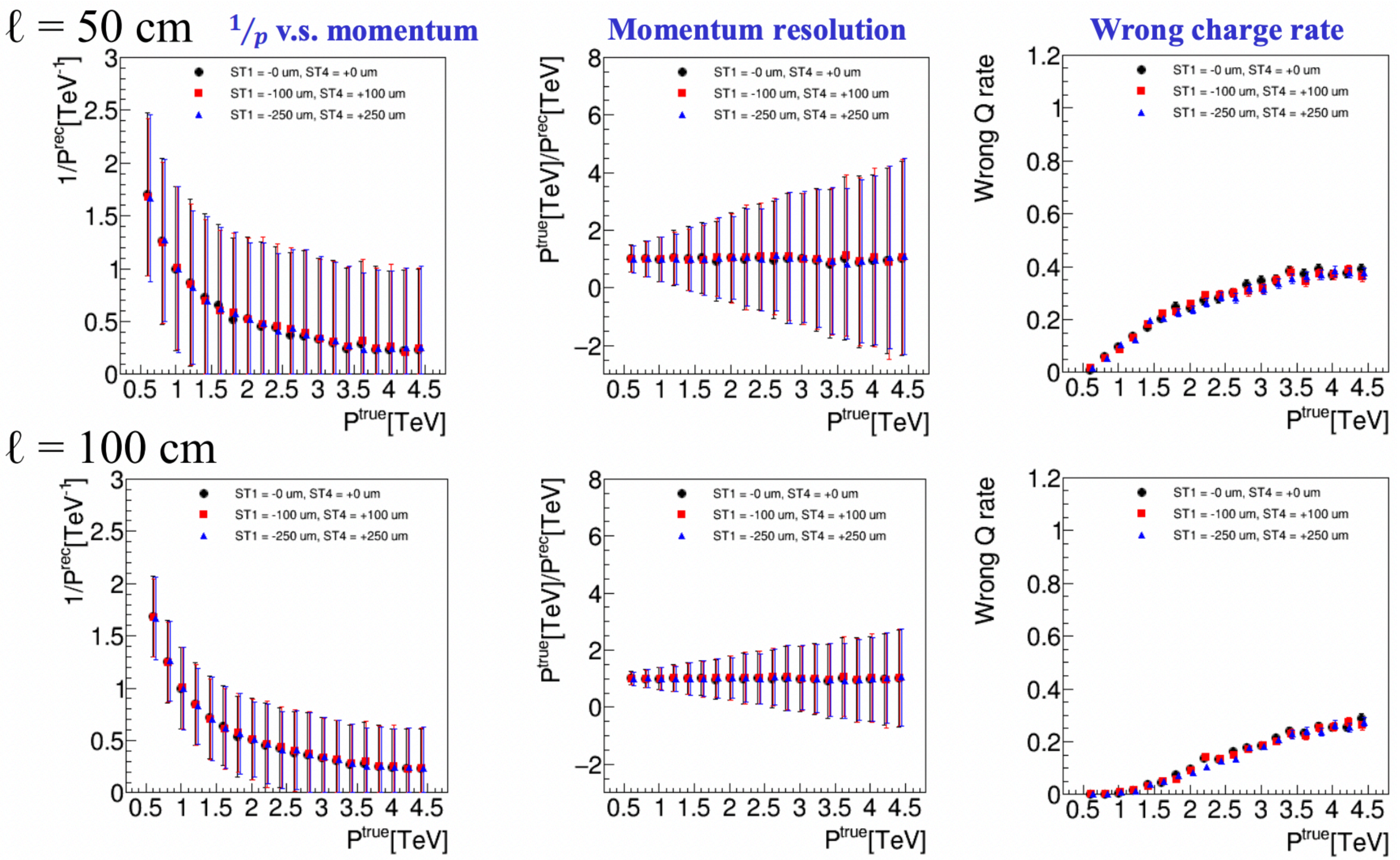
Track momentum resolution

- Studying track momentum resolution and charge misconstruction rate
- Based on sampling assuming 100um resolution using analytic calculation for particle propagation in field
  - Early studies encouraging
    - Further studies on alignment planned



1 Tm

Yosuke Takubo



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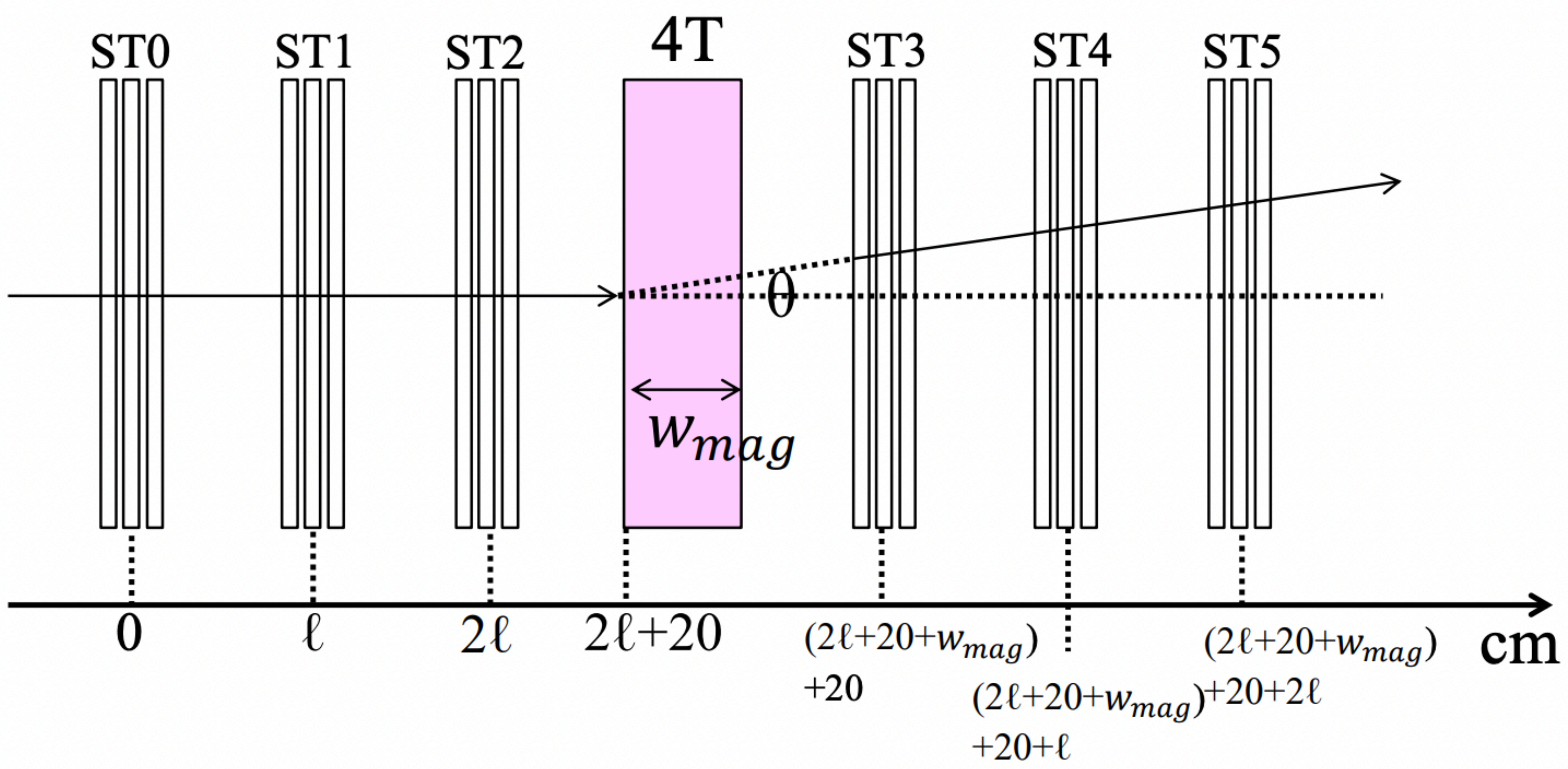
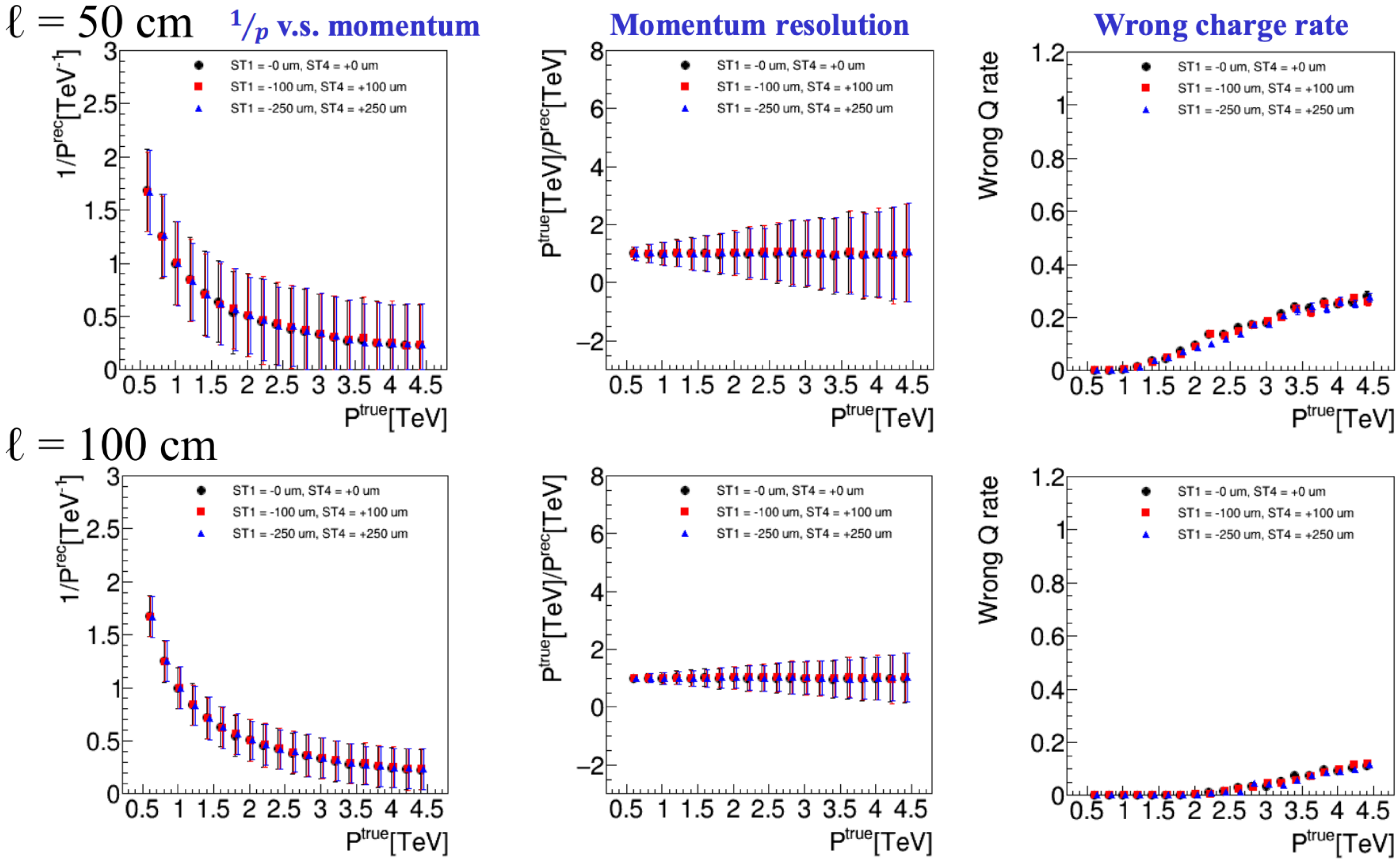


2 Tm

Yosuke Takubo



Track momentum resolution

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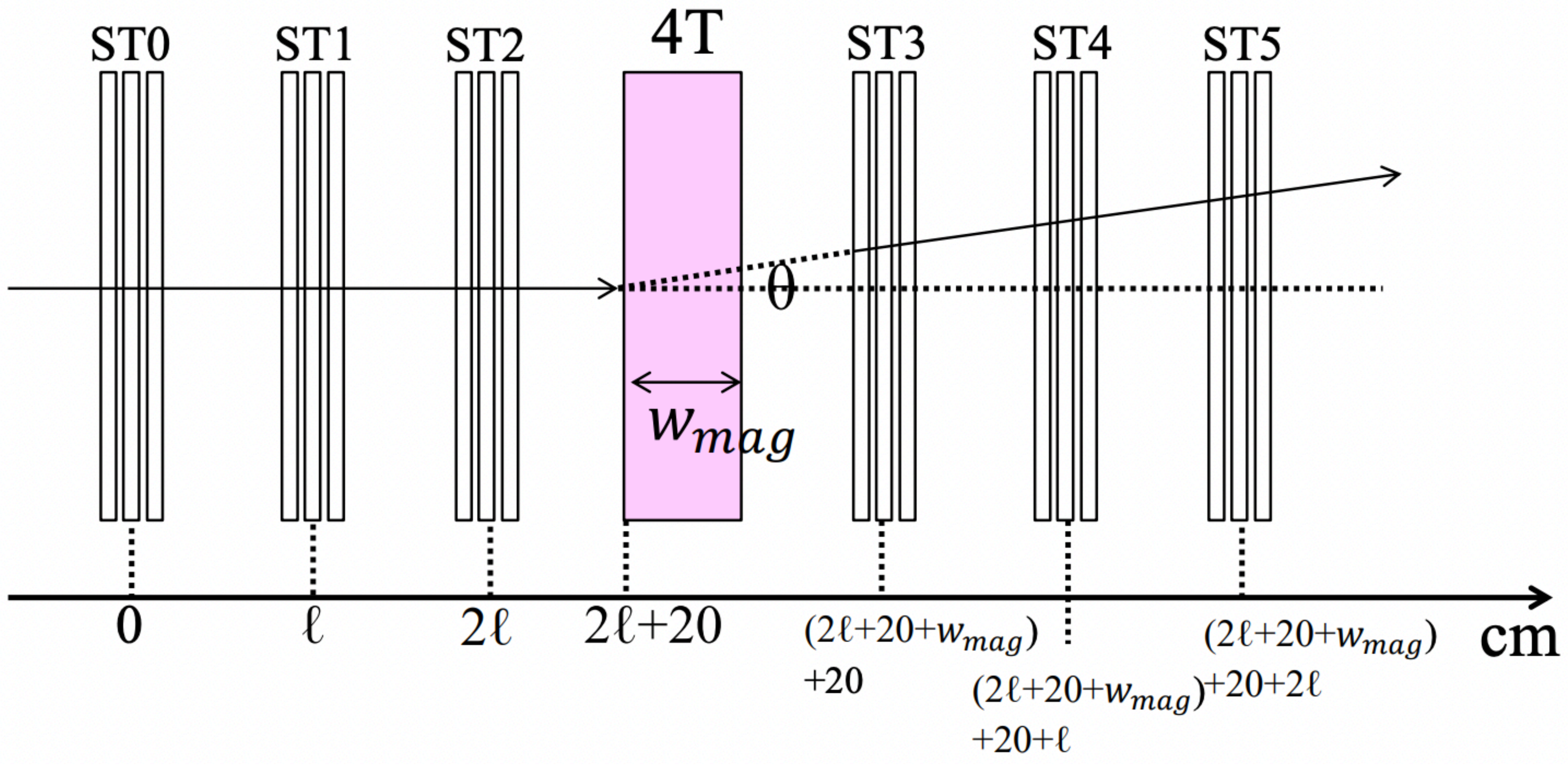
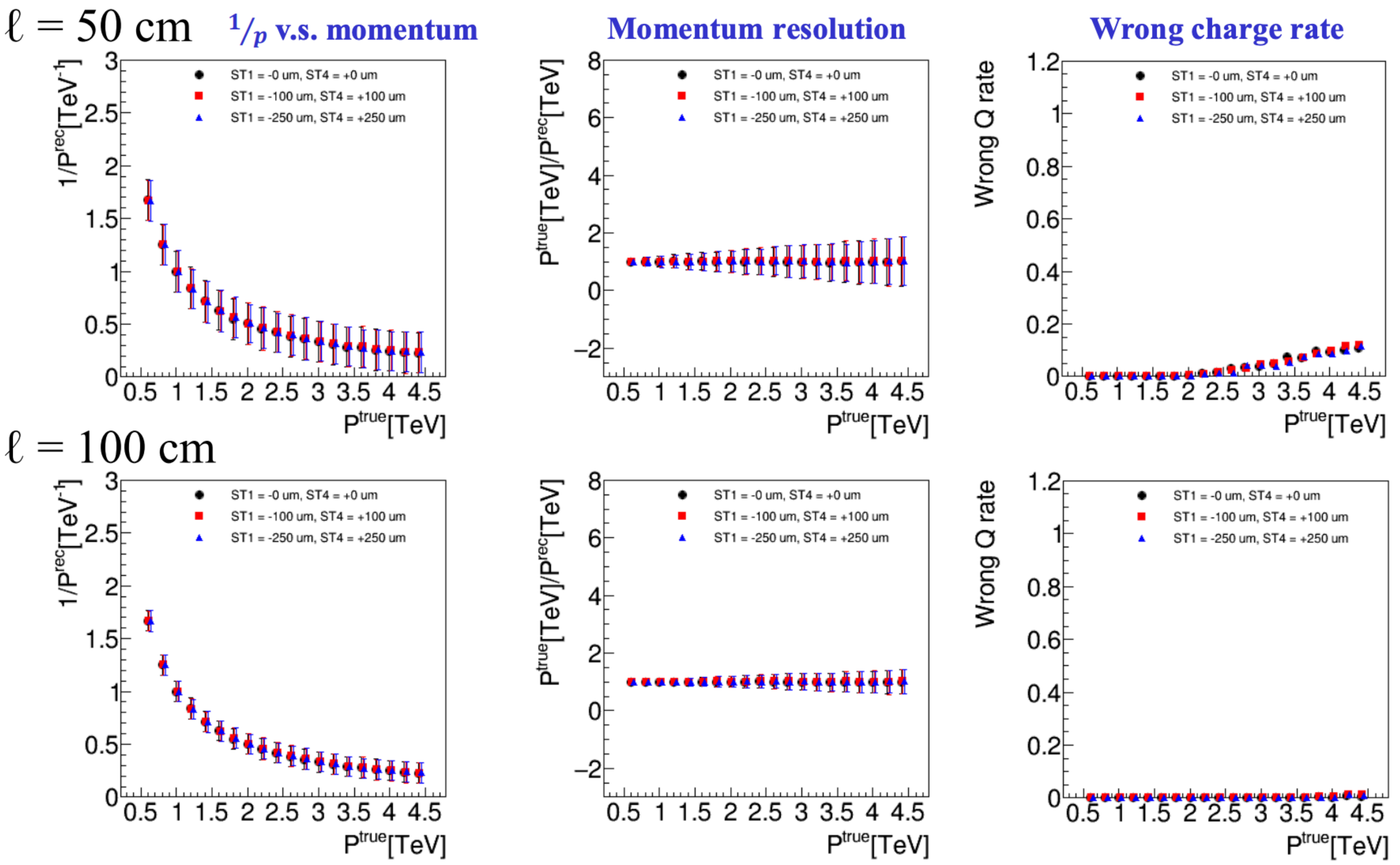




4 Tm

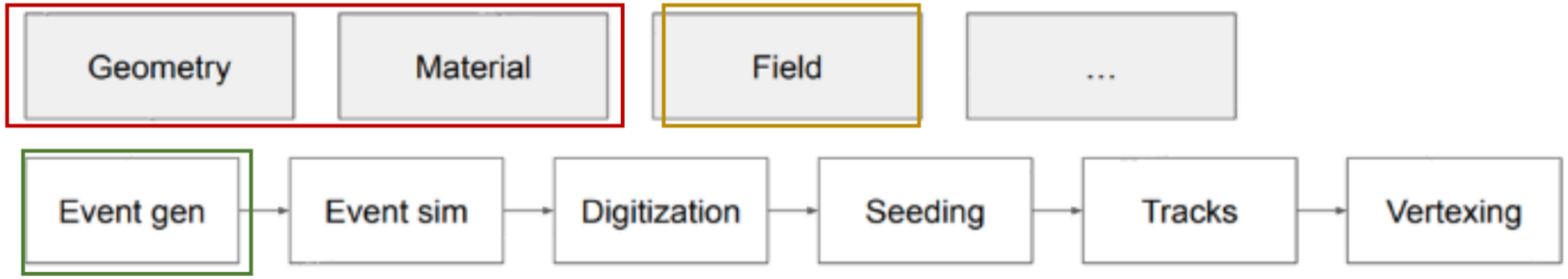
Yosuke Takubo

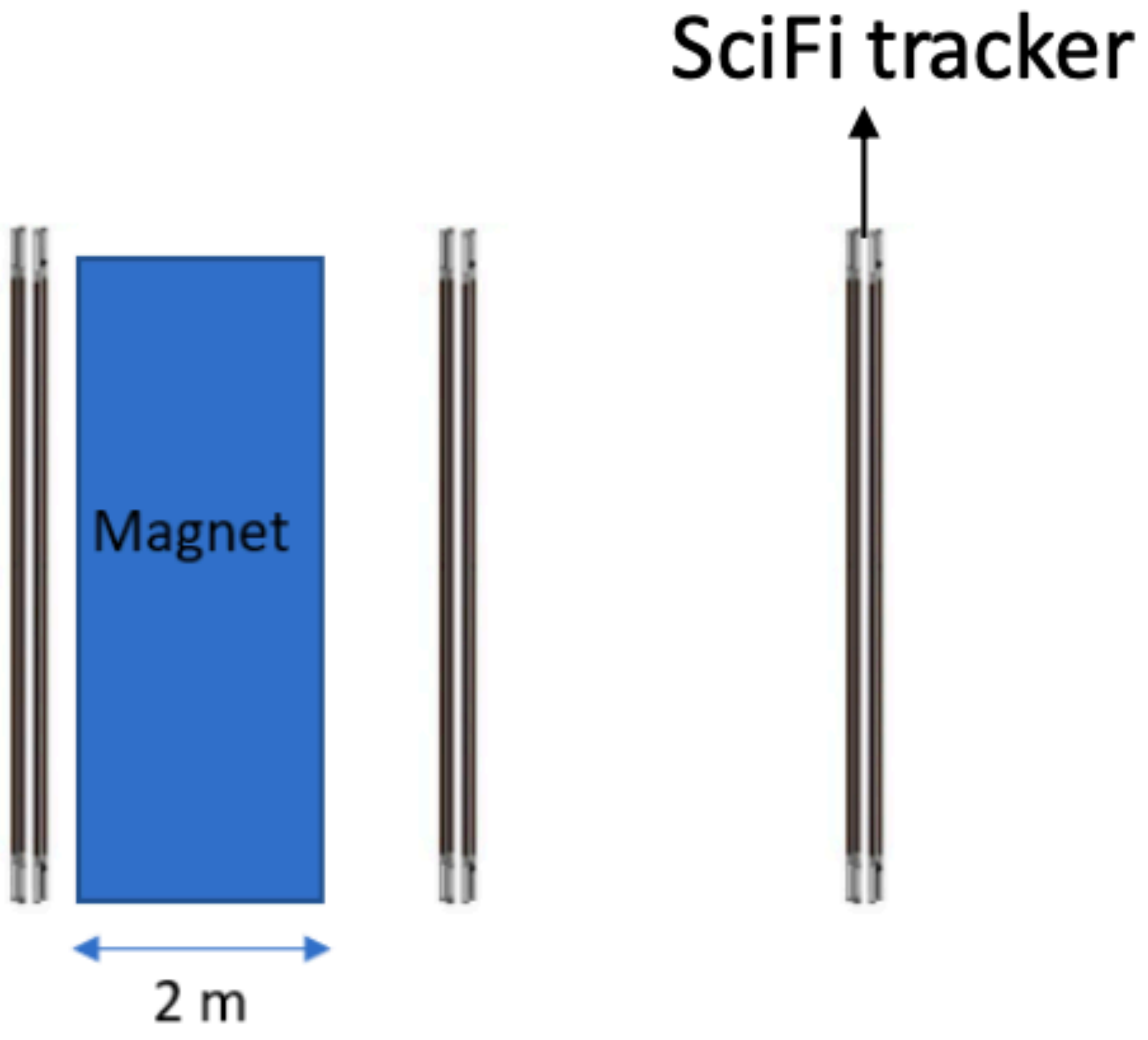
ACTs implementation

- Need more study on FASER2 mass and pointing reconstruction capabilities

- Starting to implement more sophisticated reconstruction framework based on ACTS
  - Used in LHC experiments including FASER, well supported.

- Working on implement SciFi tracker geometry and interfacing with FORESEE outputs



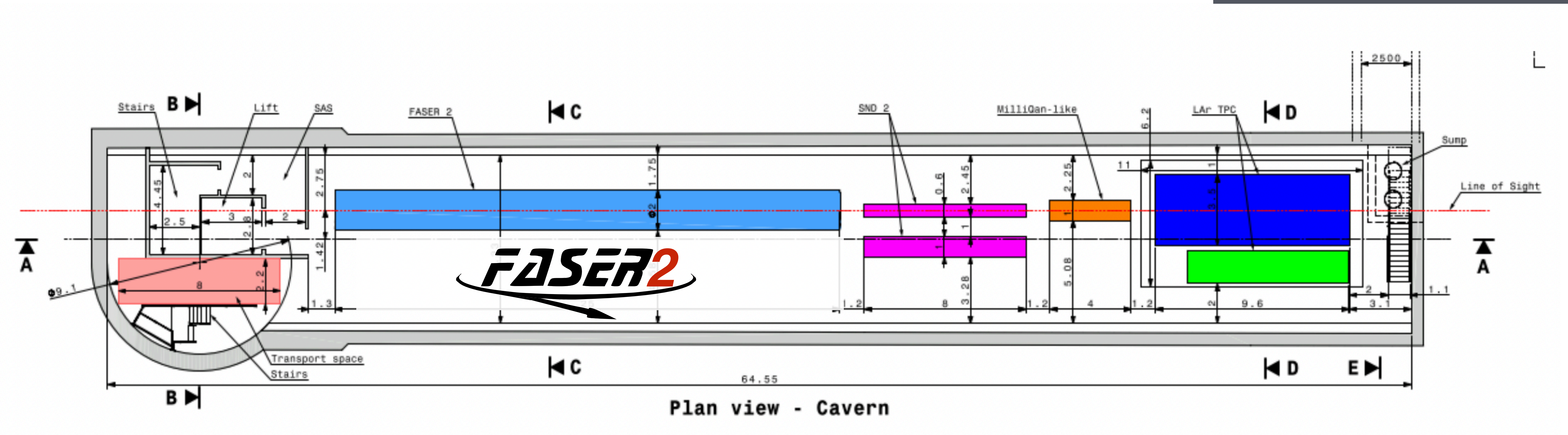


Olivier Salin

Summary of detector costings

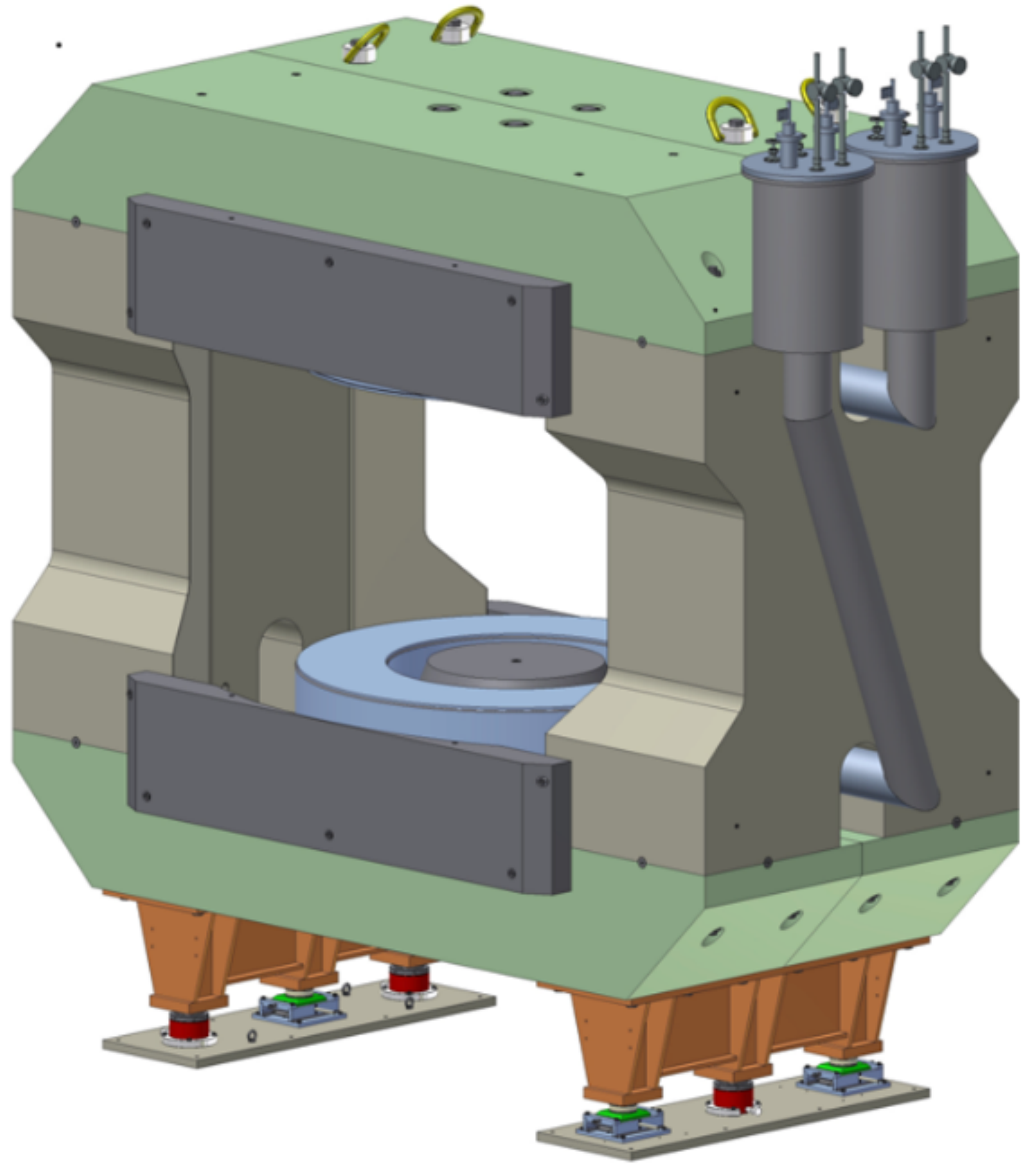
- Very preliminary overall costing of FASER2
  - Cost driven by magnet

	Cost
Magnet	10 MCHF
Tracker (SciFi)	4-6 MCHF
Calorimeter	3-5 MCHF
Total	**~20 MCHF**



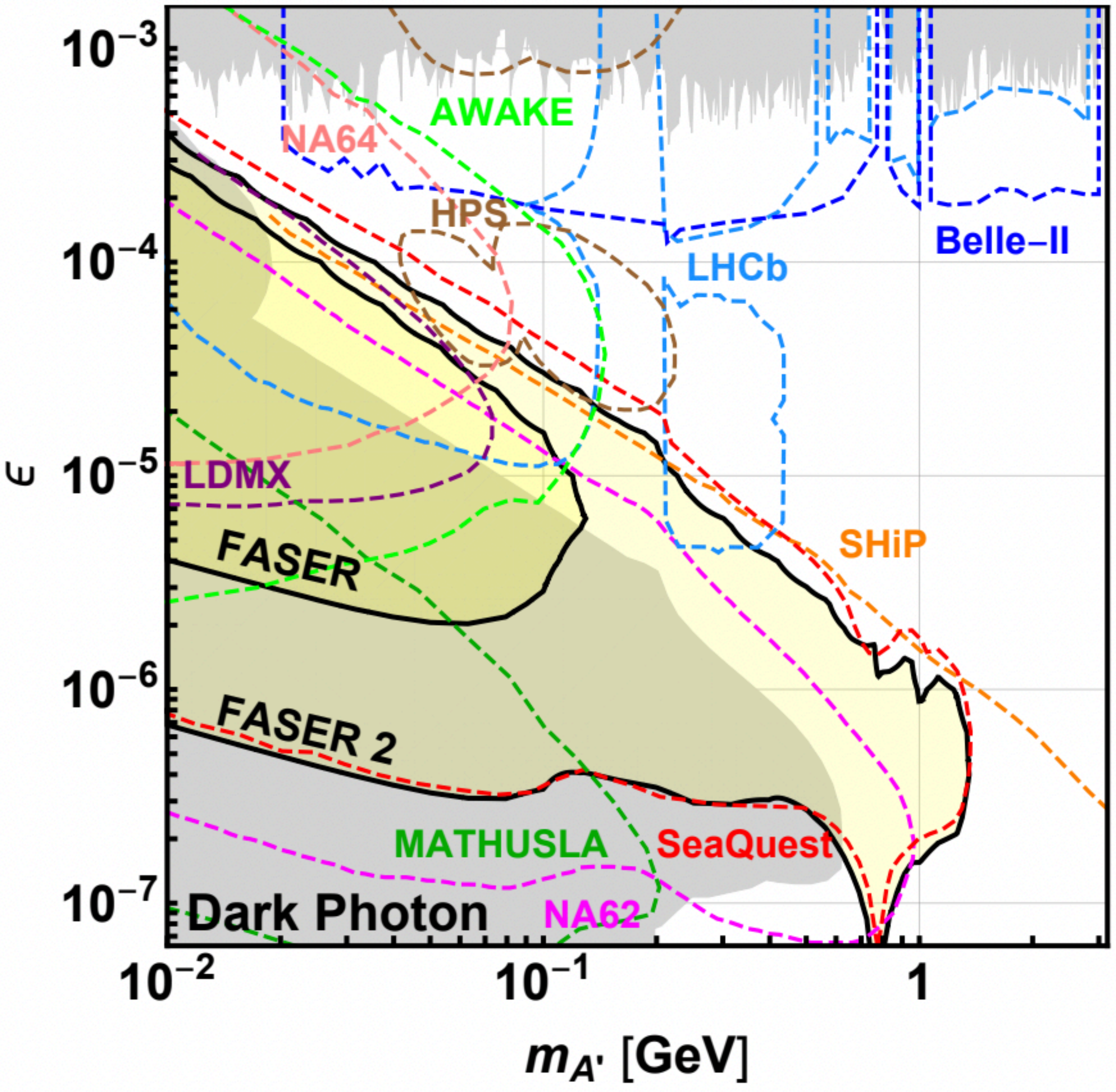
Magnets | Split solenoid dipole

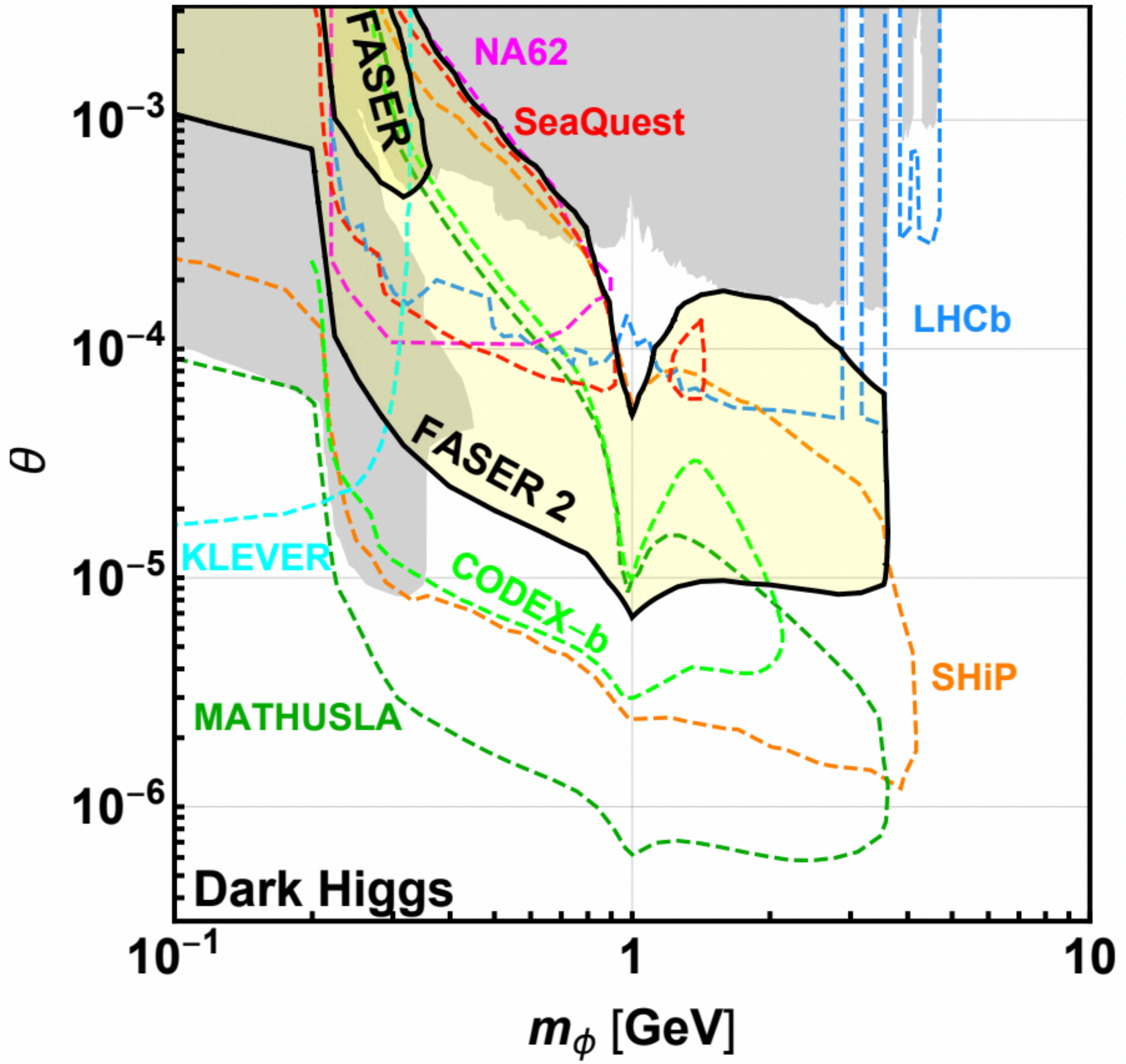
- Split solenoid
  - Simplest design for superconducting dipole
  - Design for CMB experiment at FAIR
  - Use single strand superconductor
  - Easier thermal properties and available on market
  - 1TM bending power, aperture ~1x1x1m (TBC), stored energy 5I
  - Cost from industry (Bilfinger):
    - 3MCHF bare magnet, 4-4.5MCHF with PS/controls (not cryo)
- Much more expensive for much less performance than we
  planning for



type	H-type, SC magnet
Number of turns per coil	1749
Windings of coil	Impregnated close coiling
Maximum current	686 A
Magnetomotive force	1.2 MA turns/coil
Current density,	58 A/mm^2
Maximum field at coil	3.25 T
Central field	1.08 T
Field integral	1 Tm
Inductance	33-19 H
Stored energy	5.15 MJ
Coil cross section (at 4K)	158.8x131.1 mm^2
Yoke (widh/depth/height)	4.4/2.0/3.7 m
Pole type	Tapered
Pole sizes (Rout/Rin/H)	1200/800/500 mm

FASER2 Reach





[arXiv:1811.12522]

FASER2 Reach

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[arXiv:1811.12522]

FASER2 Reach

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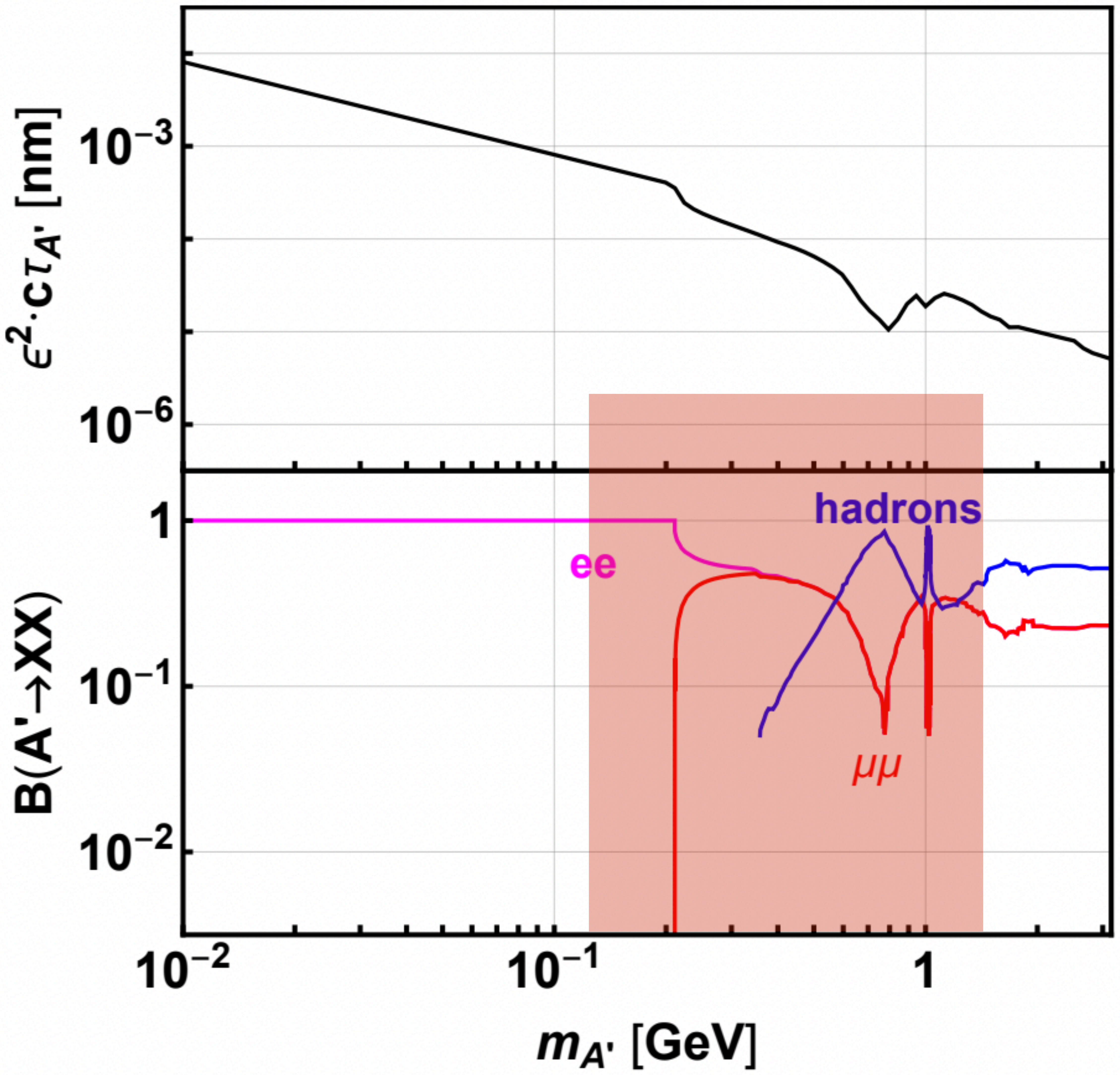
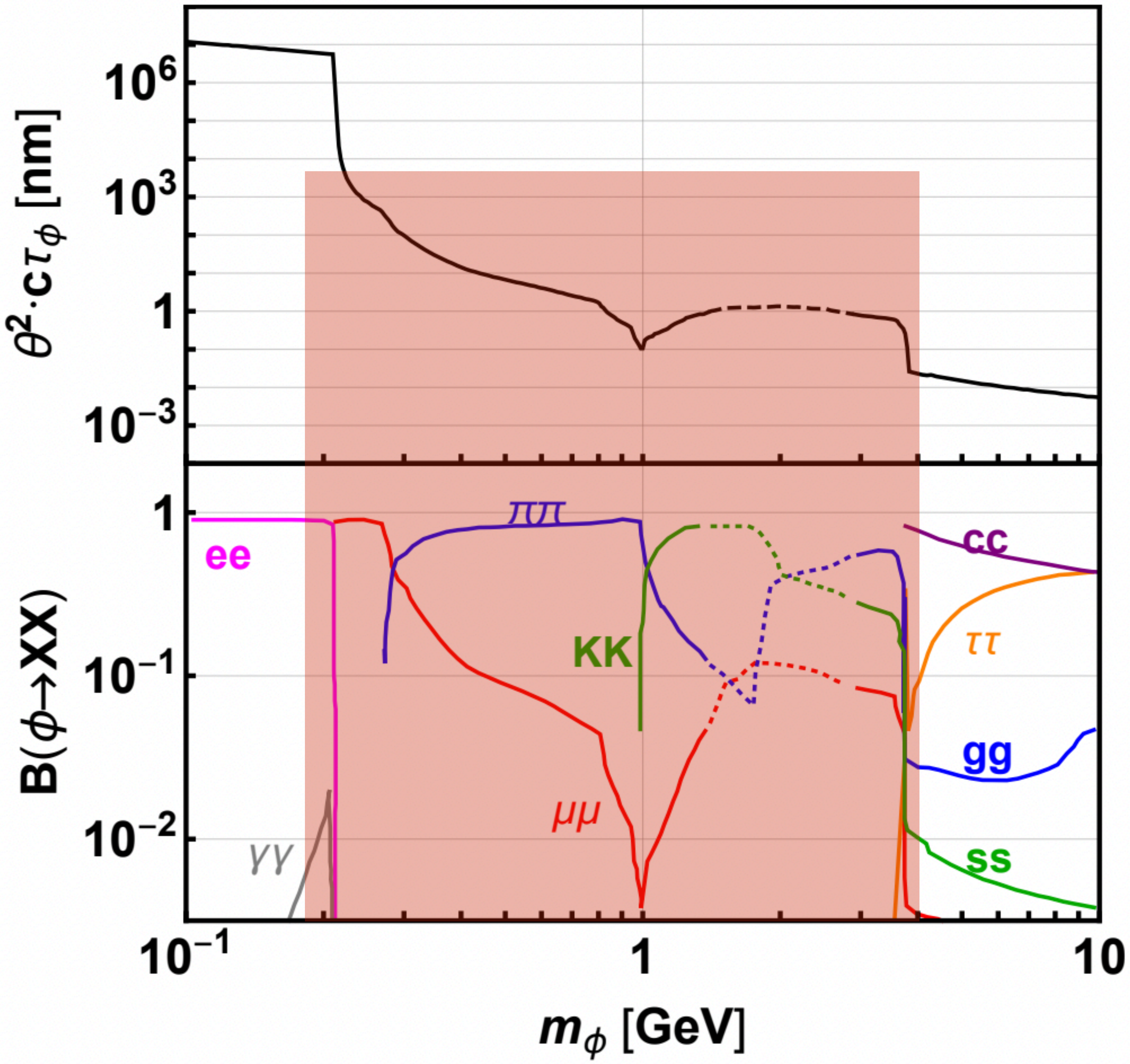




[arXiv:1811.12522]

FASER2 Design

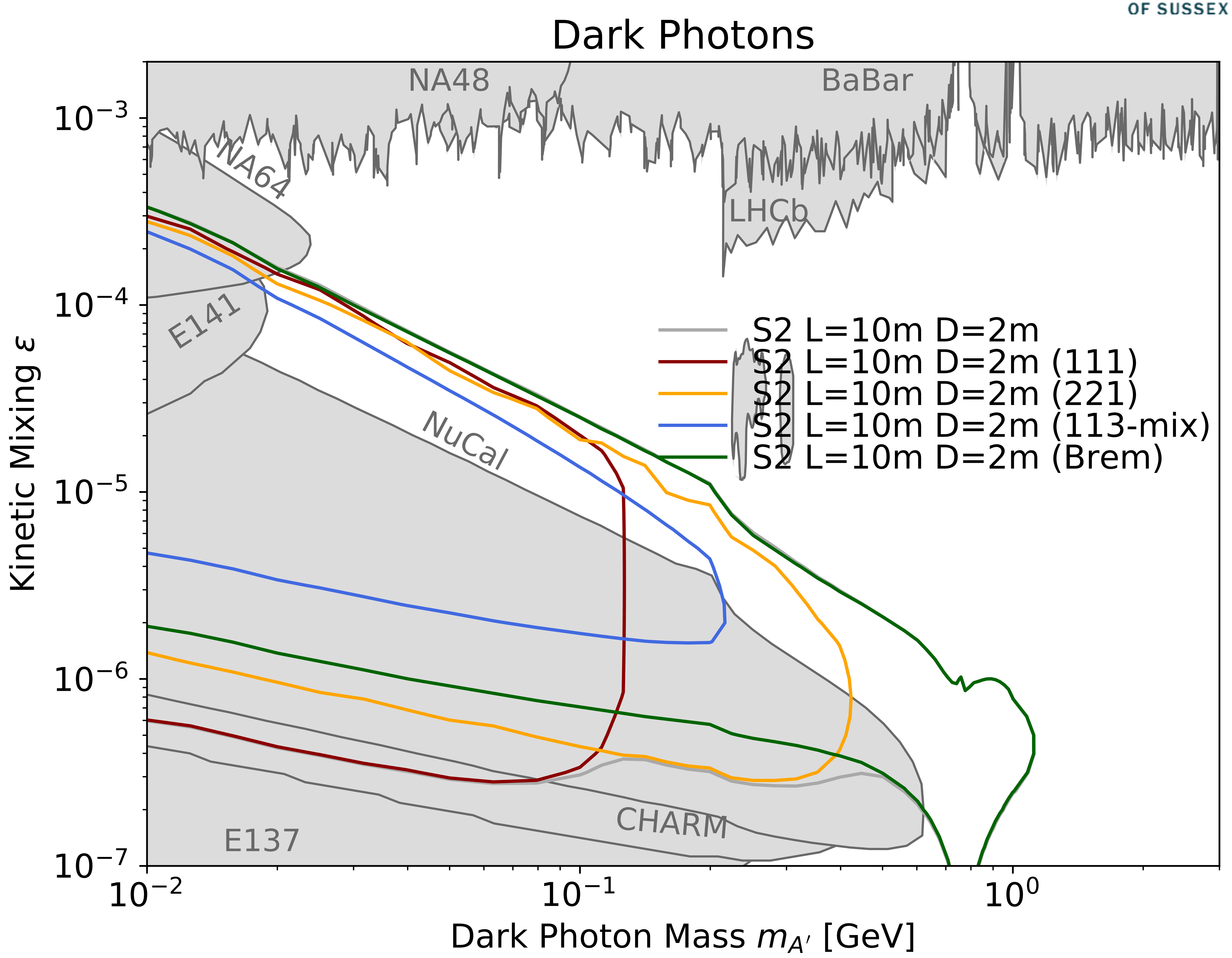
- Design considerations for FASER2
  - Larger radius → Being on-axis less important
  - More decay channels → Need for particle ID
  - Larger detector → Larger background rate
    → Different/cheaper technology
  - Link to FASERν2 → Measure μ charge (and momentum) from (τ and μ) neutrino interactions

- Planned to be similar in philosophy to FASER…
  - Still much to be studied in terms of possible detector configurations and technologies.

[arXiv:2109.10905]

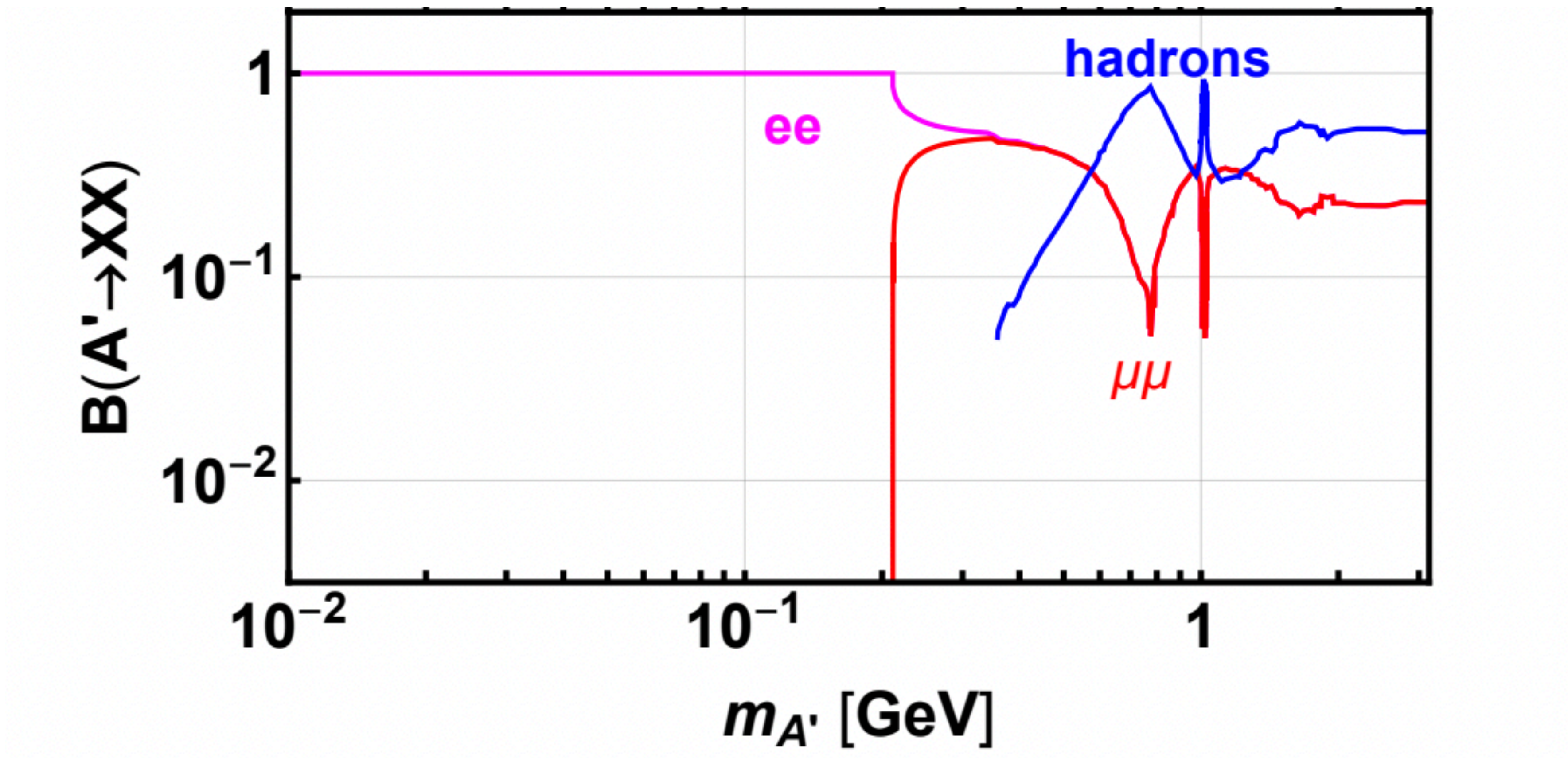
Simulation | FORESEE

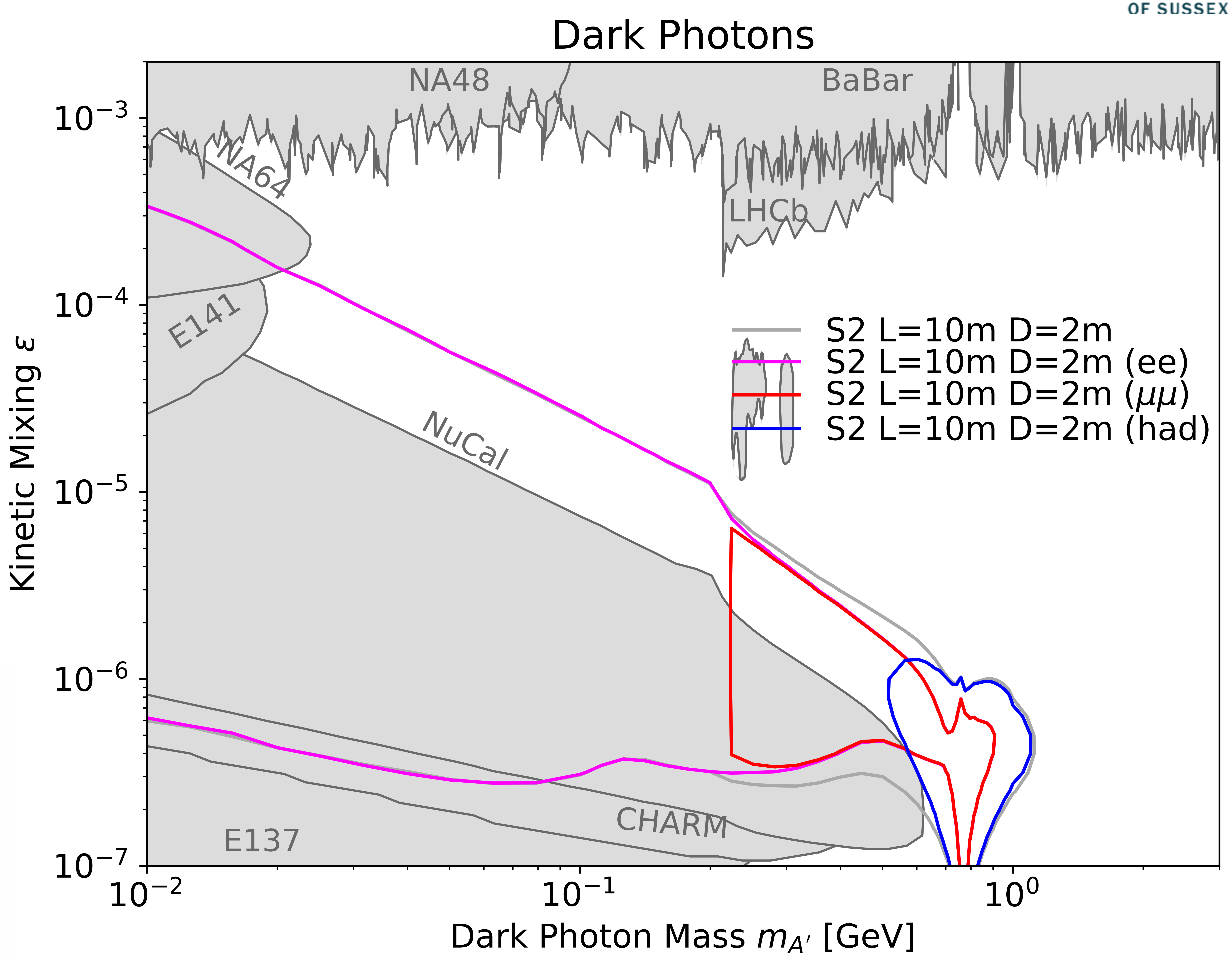
- Starting to use FORESEE ar investigate reach
  - Production modes rather diff
    - Pion decay at low mass
    - Then eta decay
    - Then Dark Bremsstrahlung



Simulation | FORESEE

- Starting to use FORESEE ar investigate reach
  - Decay modes also very differ
    - Electron decay at low mass
    - Muon decay
    - Hadrons





Questions to ask

To see a signal…	Translates to requirements in detector	Translates to detector technologies
• Generic S/B	• Magnet strength and length ??	
• Pointing / z measurements	• Tracker resolution ?? Alignment requirements?? Timing?	• Pixels vs SciFi or a combination
• Mass reconstruction for "bump hunt"? Out of time signal?	• Track / Calorimeter resolution ?? Timing?	• High granularity calo vs Dual Calo read-out
• Track separation from what station?		
• Photon ID and separation?	• Calorimeter / preshower resolution?	
• Can we do anything with MET..?		
To characterise signal if you see it…	**To characterise signal if you see it…**	**To characterise signal if you see it…**
• PID ?	• Timing ??	• CMOS with timing
• Mass measurements	• Tracker resolution ??	
Backgrounds		
• Trigger rates?	• # Scintillator layers??	

Anna Sfyrla (UniGe)

Benchmark models?

Model	Unique in FASER2	Decay mode in FASER	Decay mode in FASER 2	Unique coverage
Dark Photons		ee	ee, hadrons, μμ	++
B-L Gauge bosons	x	ee	ee, hadrons, μμ, MET (dom low mass)	++
Dark Higgs Bosons	x		ee, pions, μμ, kaons, jets	+++
HNLs with e	x		MET + ee, MET (dom low mass), hadrons	+
HNLs with μ	x		MET + ee, MET (dom low mass), hadrons	+
HNLs with τ	x		MET + ee, MET (dom low mass), hadrons	+++
ALPs in photons		γγ	γγ	++
ALPs in fermions	x		ee, μμ, jets	+++
ALPs in gluons	x		γγ, hadrons	+
Dark pseudoscalars	x		γγ, ee, μμ, hadrons, jets	++
OTHER???				

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ALPs in gluons	x		γγ, hadrons	+
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Anna Sfyrla (UniGe)

Benchmark models?

UNIVERSITY OF SUSSEX

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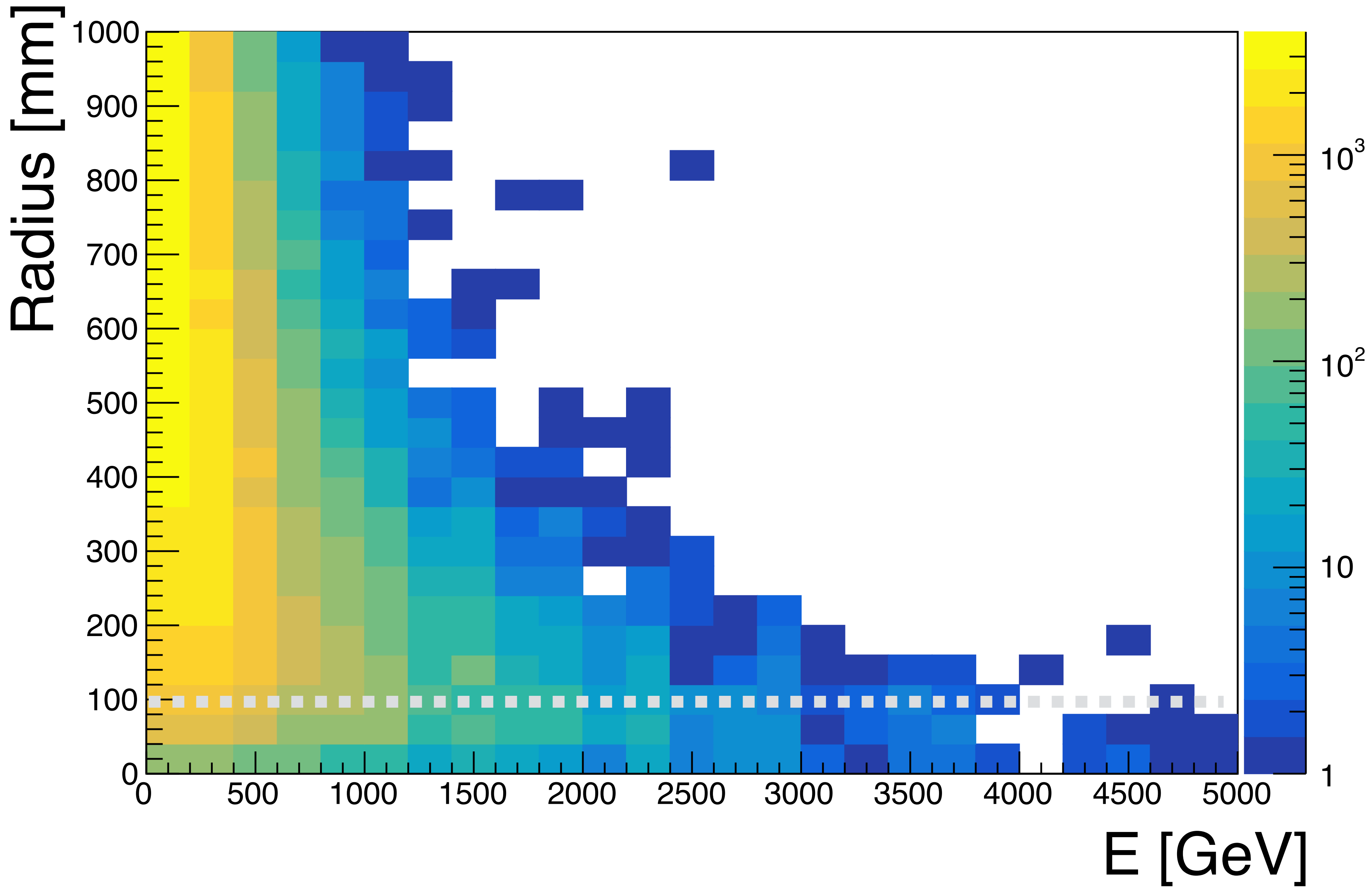
OTHER???				

Anna Sfyrla (UniGe)

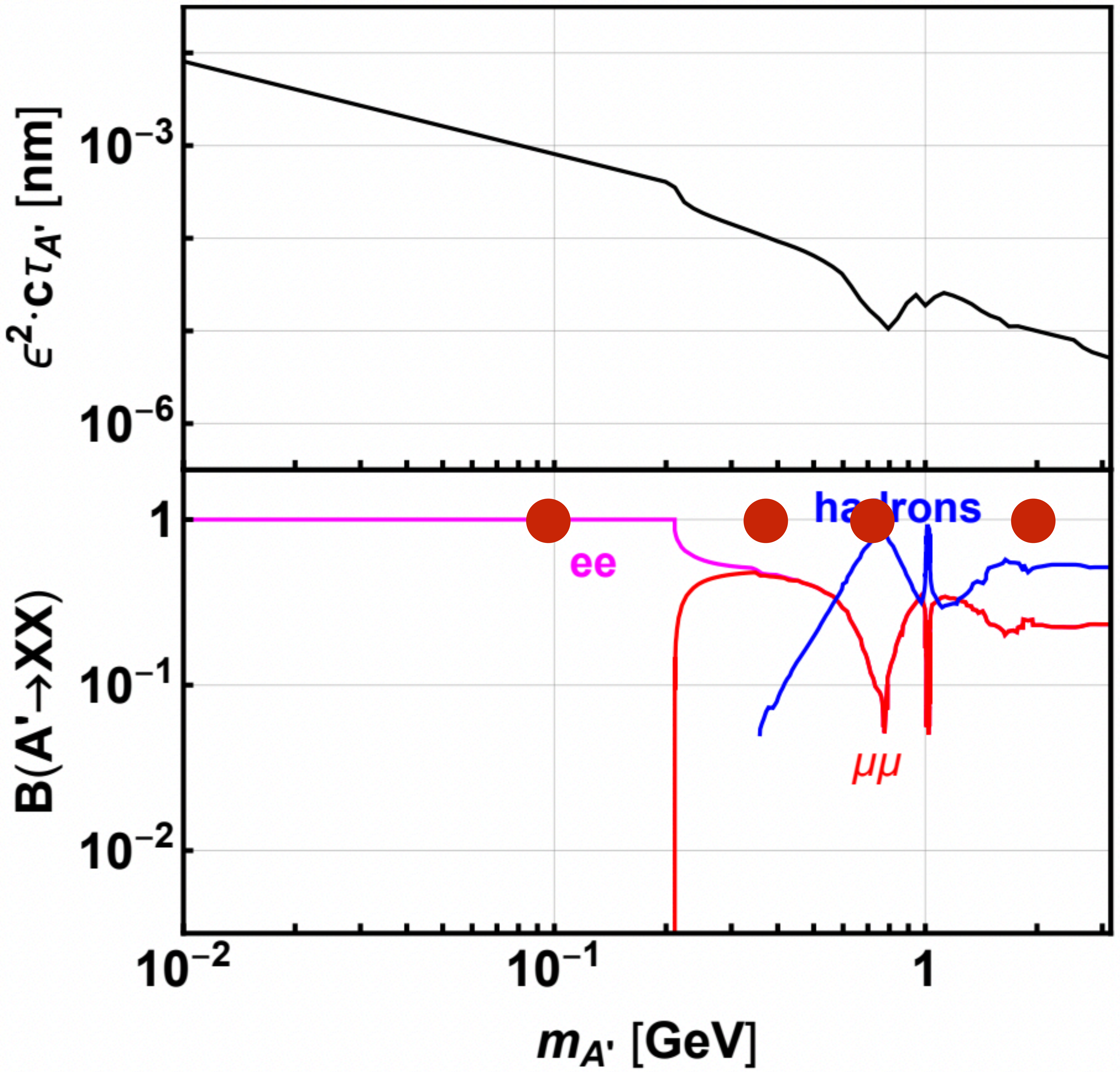
Benchmark models?

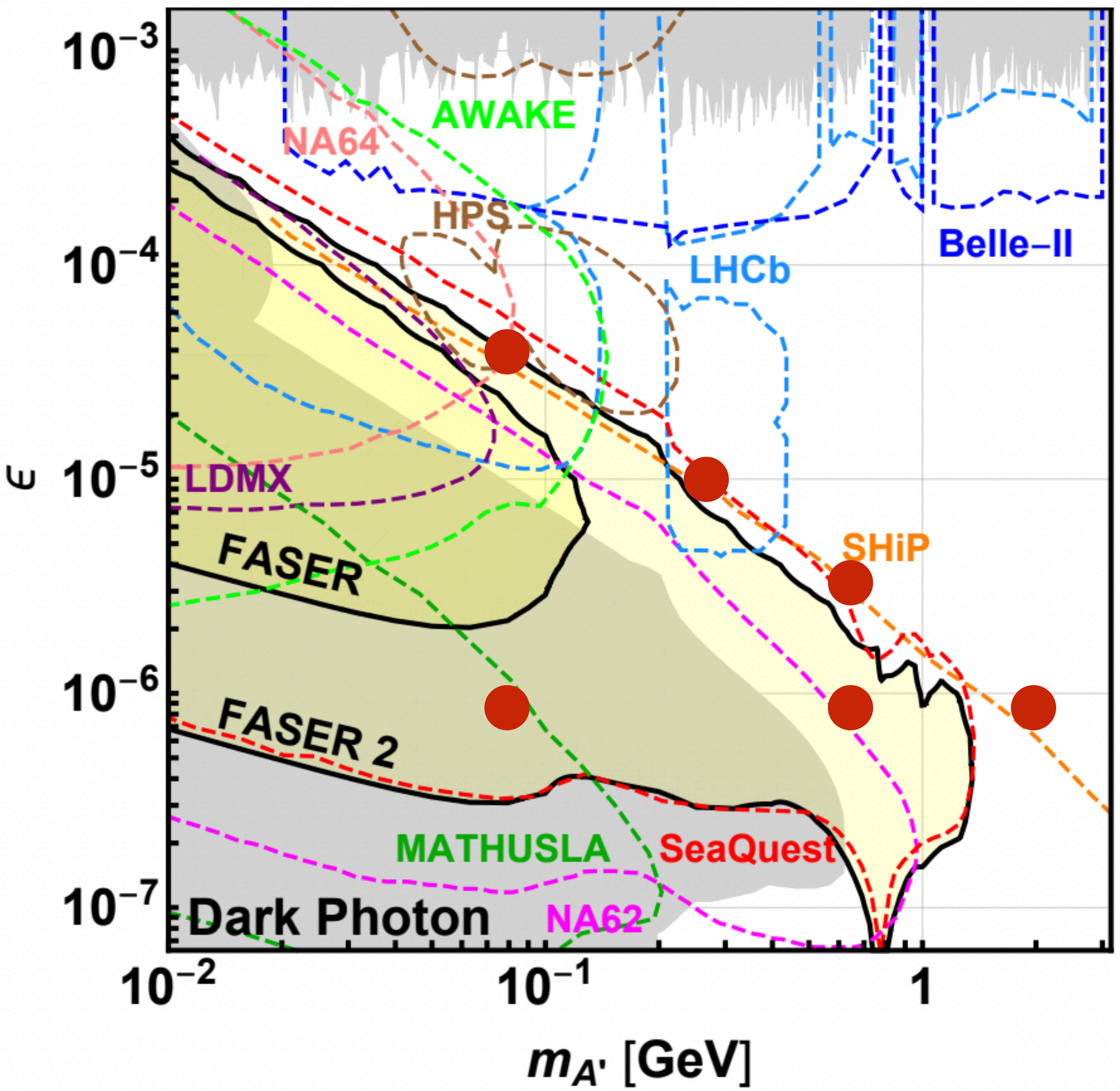
- Select benchmark model points that can be used as "representative" of the physics cases we want to study.
  - That cover various final states of interest
    - Cover different decay modes
  - That have "large enough" cross sections that are not hopeless
    - Scan mass range accessible in current reach estimates
    - But also look at phase-space outside top of existing excluded region



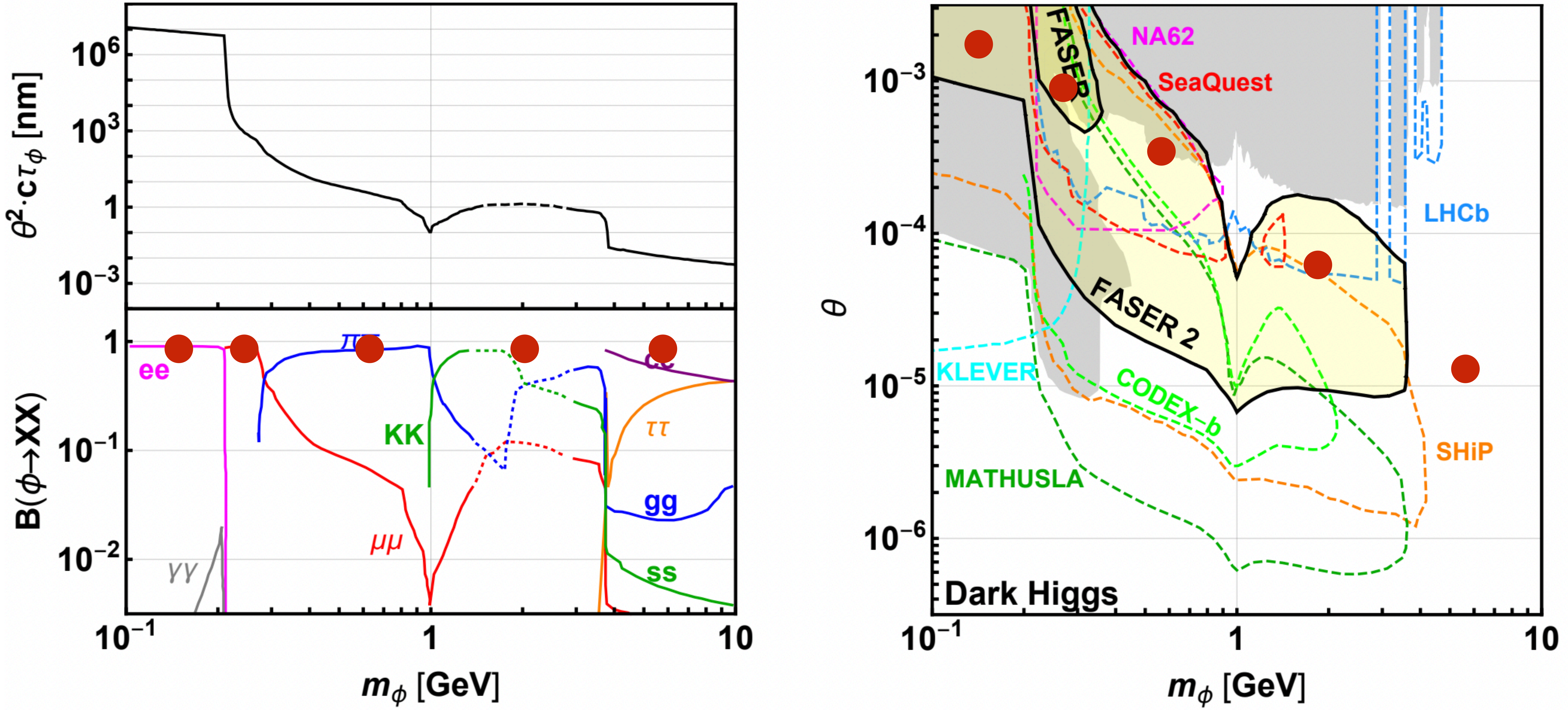
- Also consider different kinematic regions
  - Higher and lower LLP energies

Benchmark models?

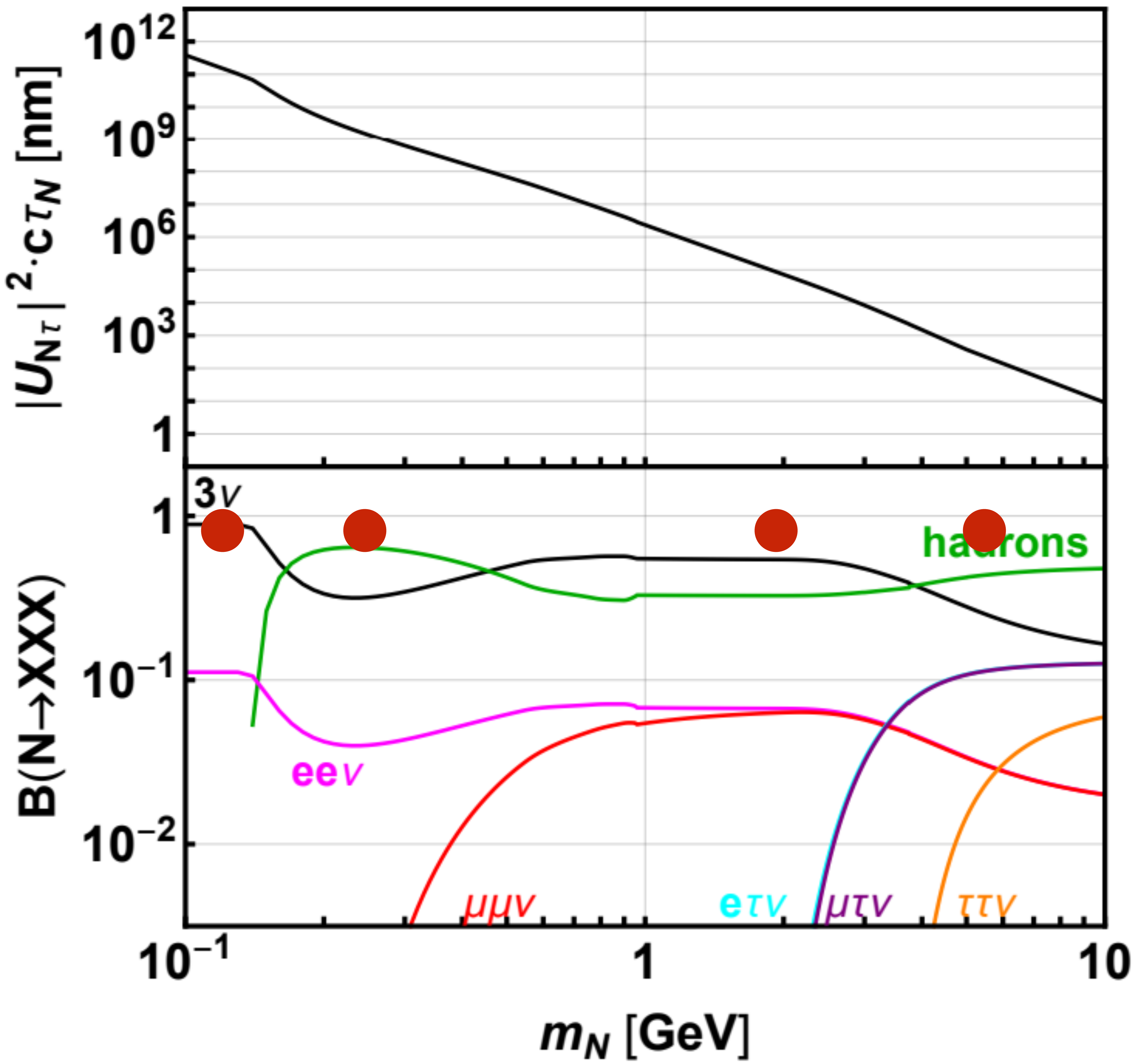


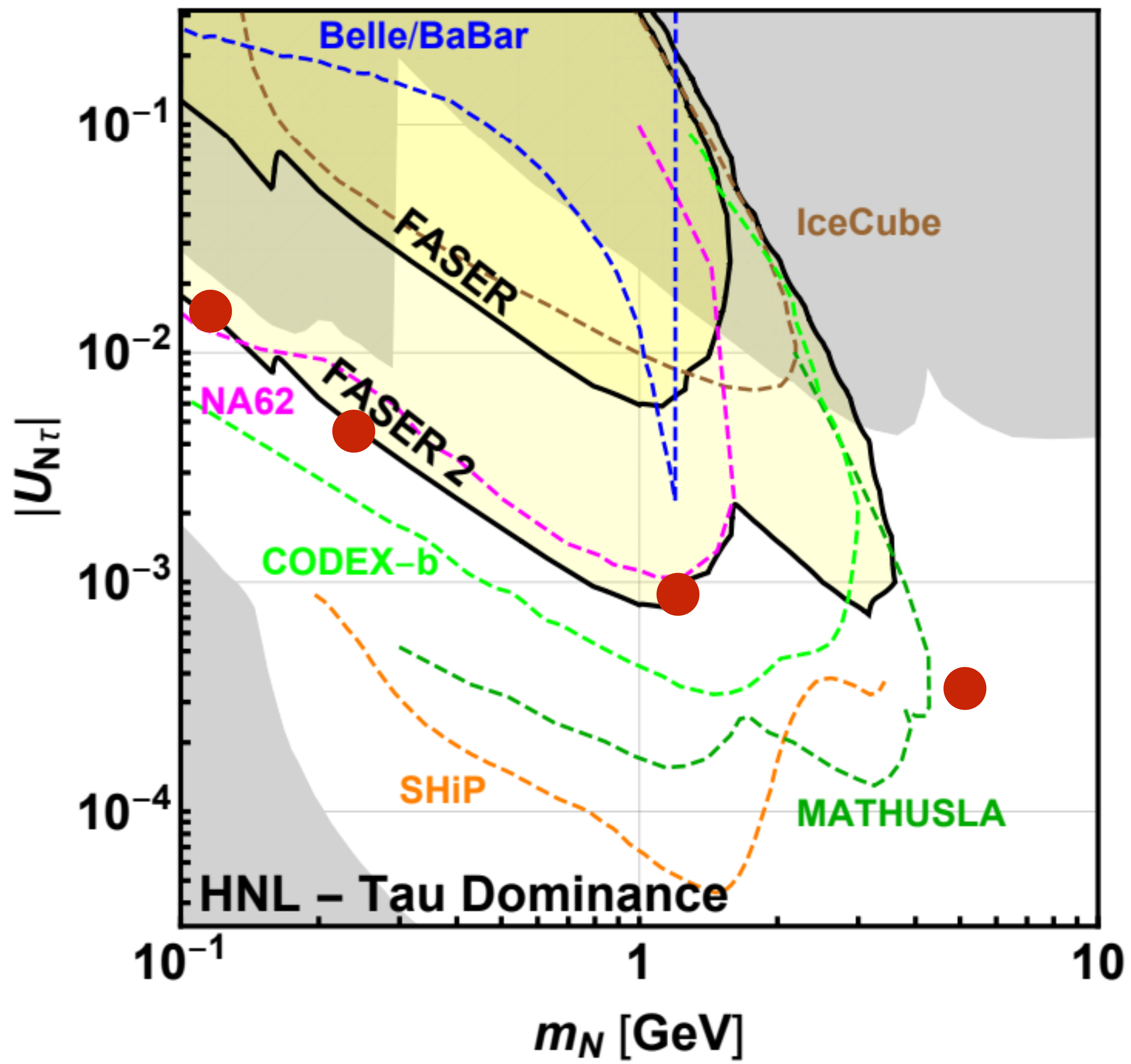


Benchmark models?



Benchmark models?





Benchmark models?