A Highly Granular ECAL Concept for the DUNE Near Detector

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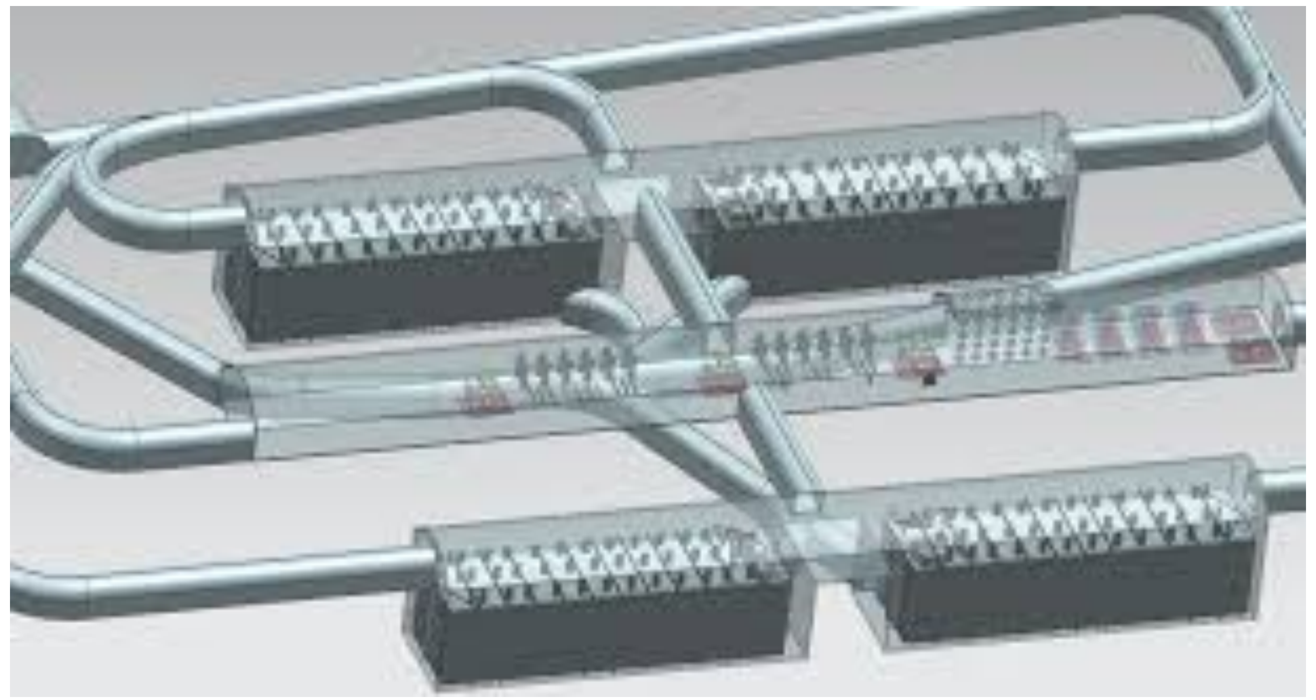
Virtual DPG 2021

DESY.

MAX-PLANCK-INSTITUT FÜR PHYSIK

The DUNE Experiment

The DUNE Experiment



Liquid Argon TPC:

- 40kt fiducial volume
- Measure ν_e appearance

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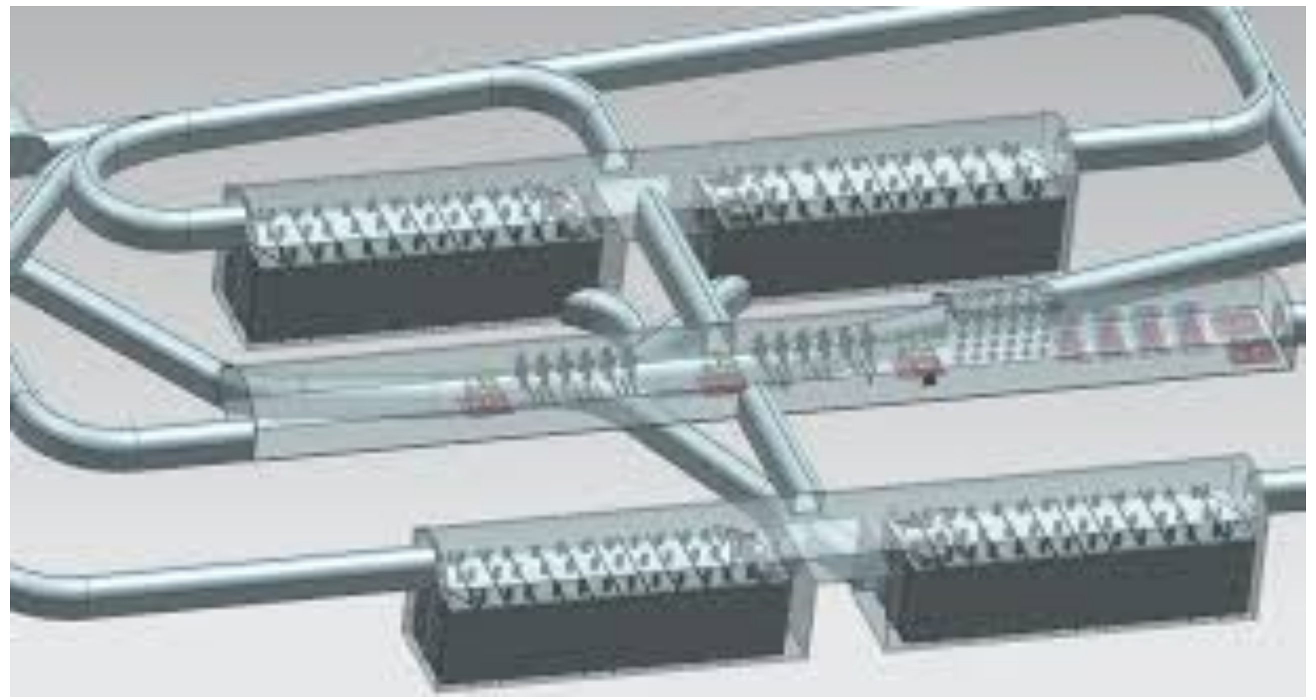

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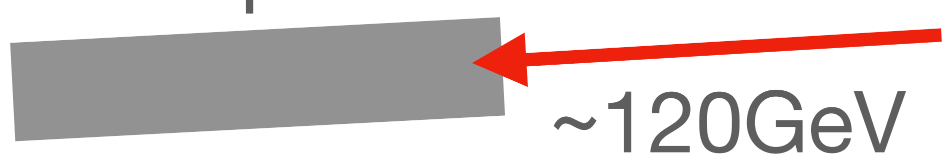
Multiple detectors:

- Measure initial beam composition and energy spectrum
- Rich ancillary neutrino interaction measurement program

The DUNE Near Site



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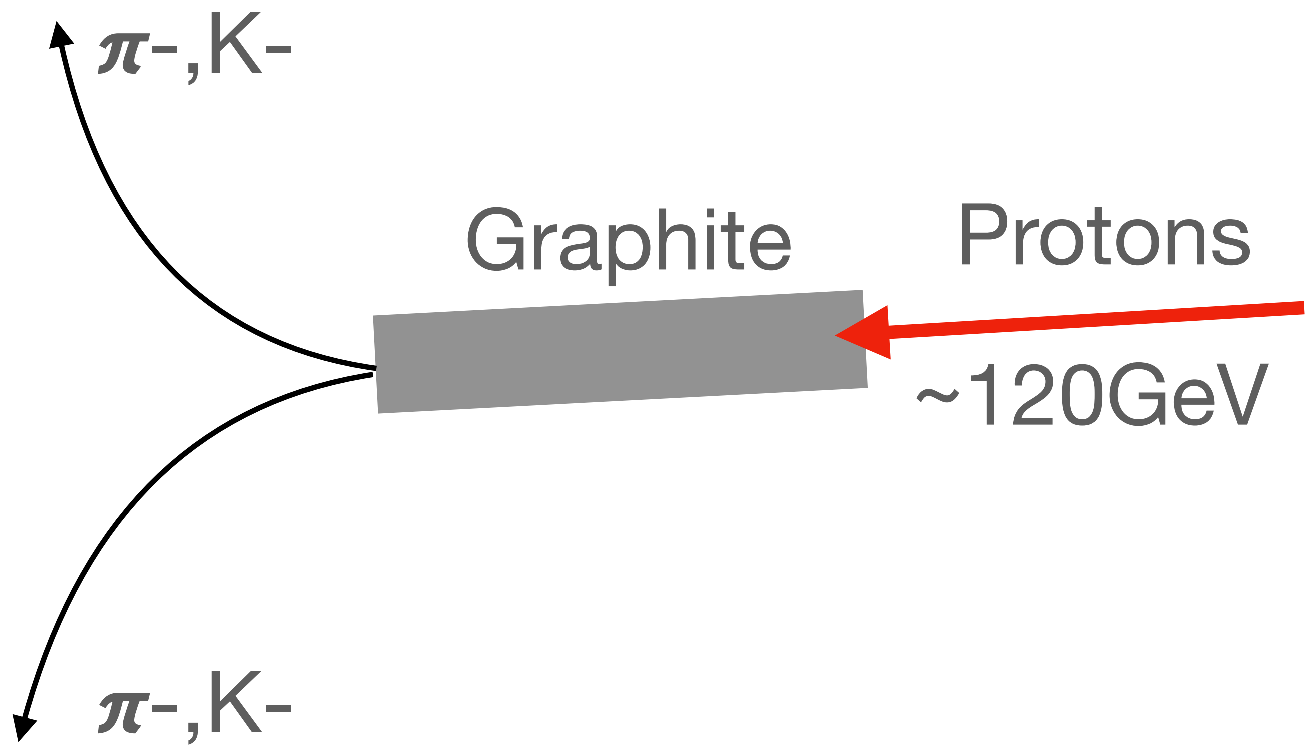

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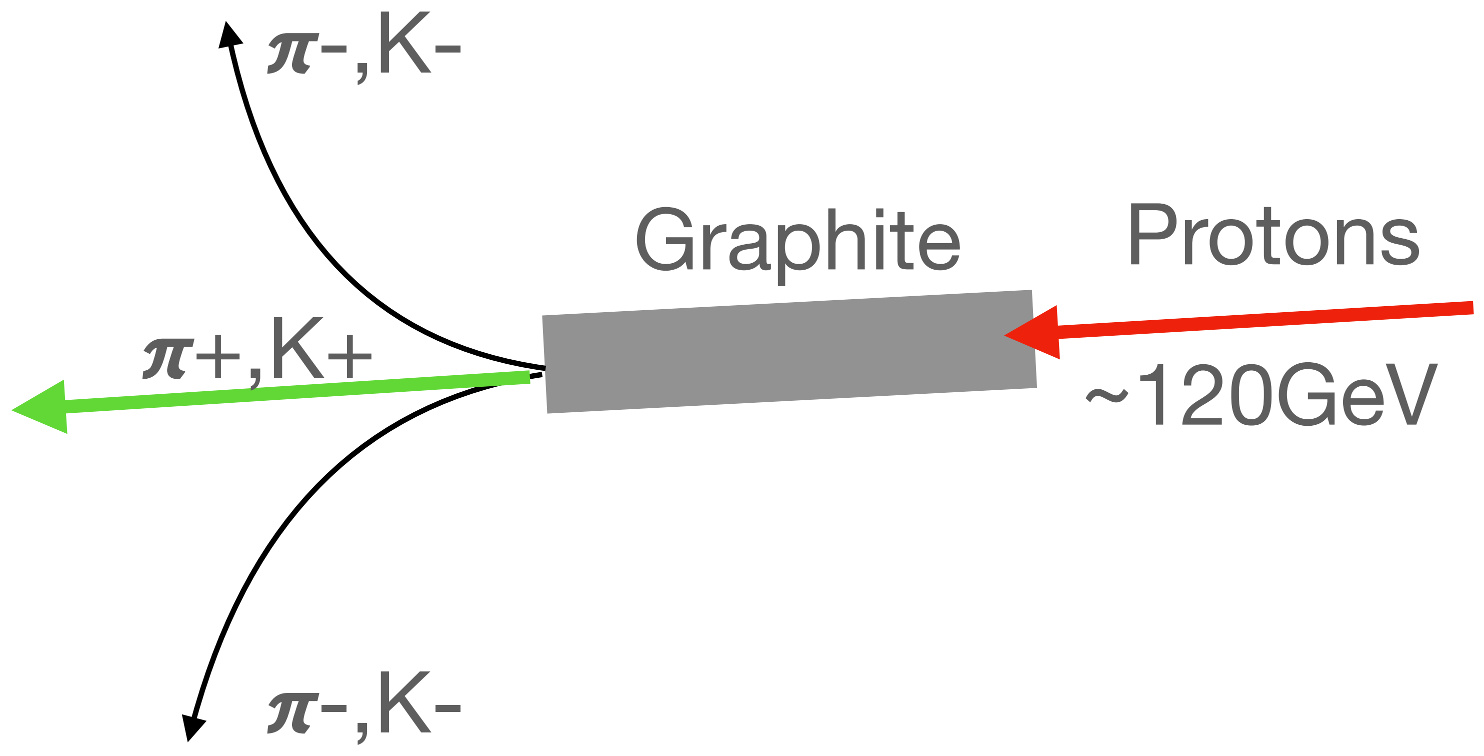

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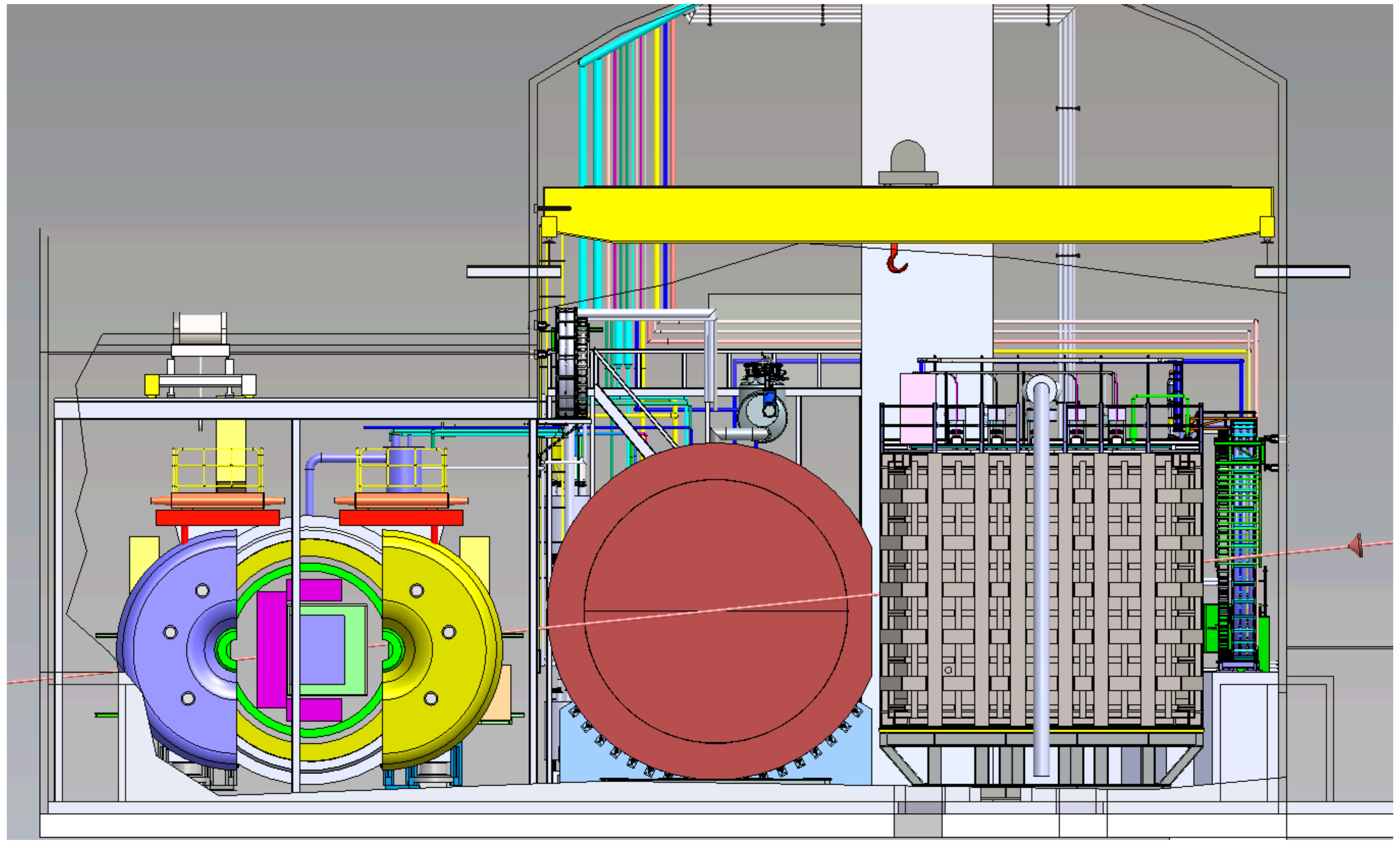

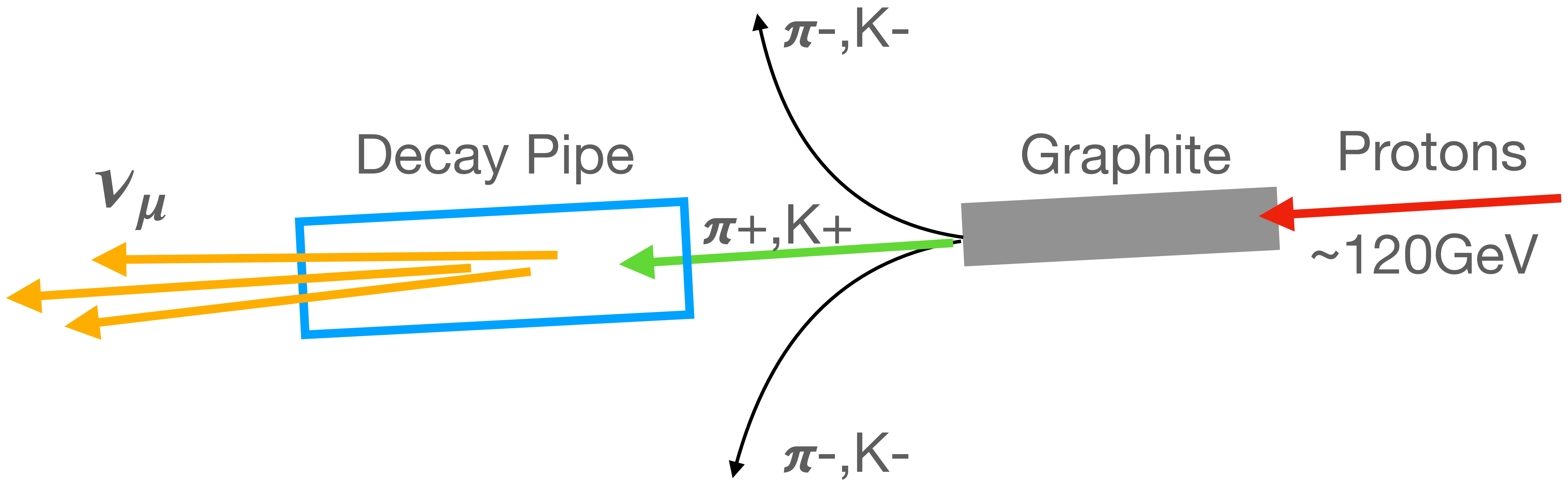

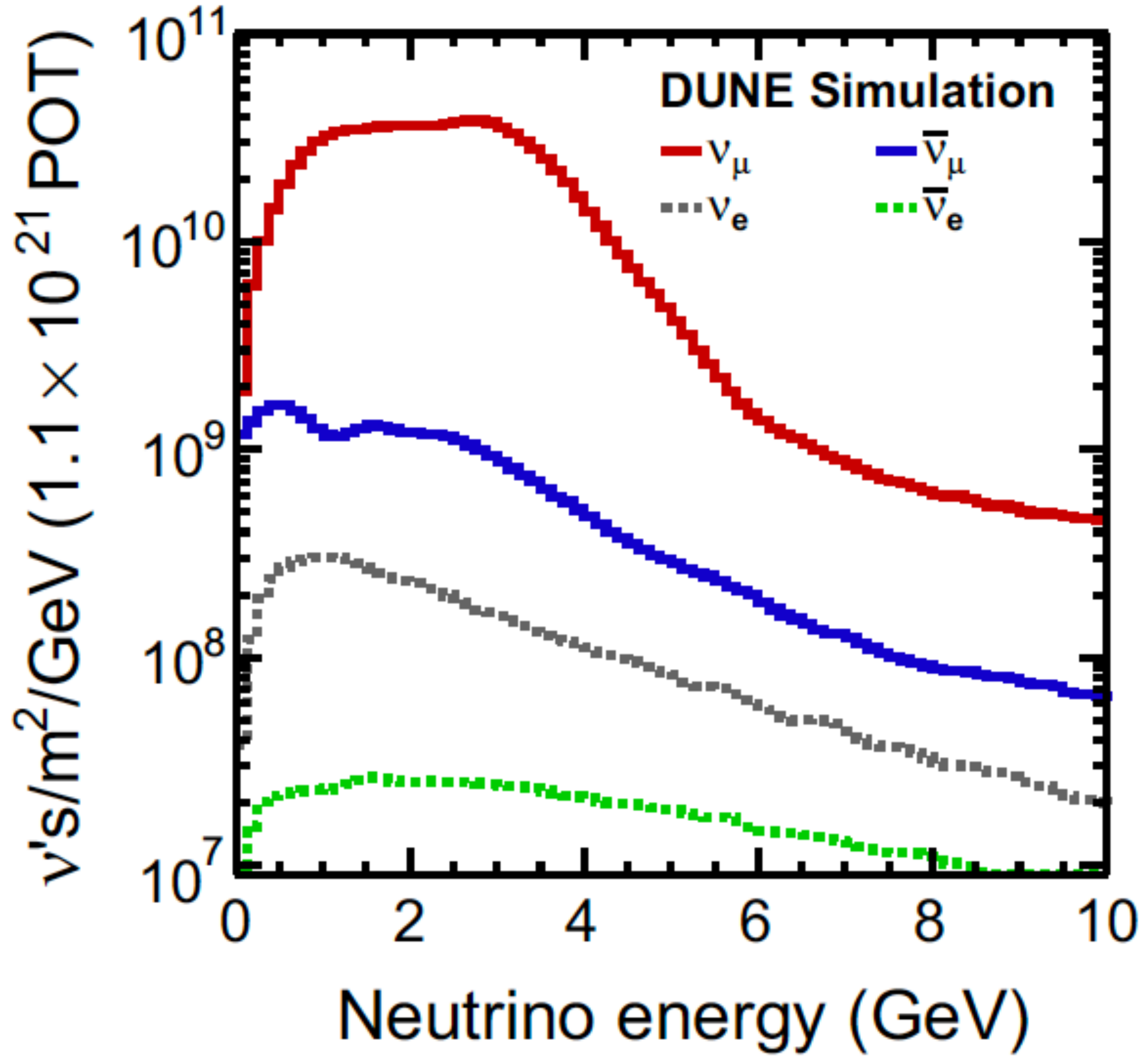

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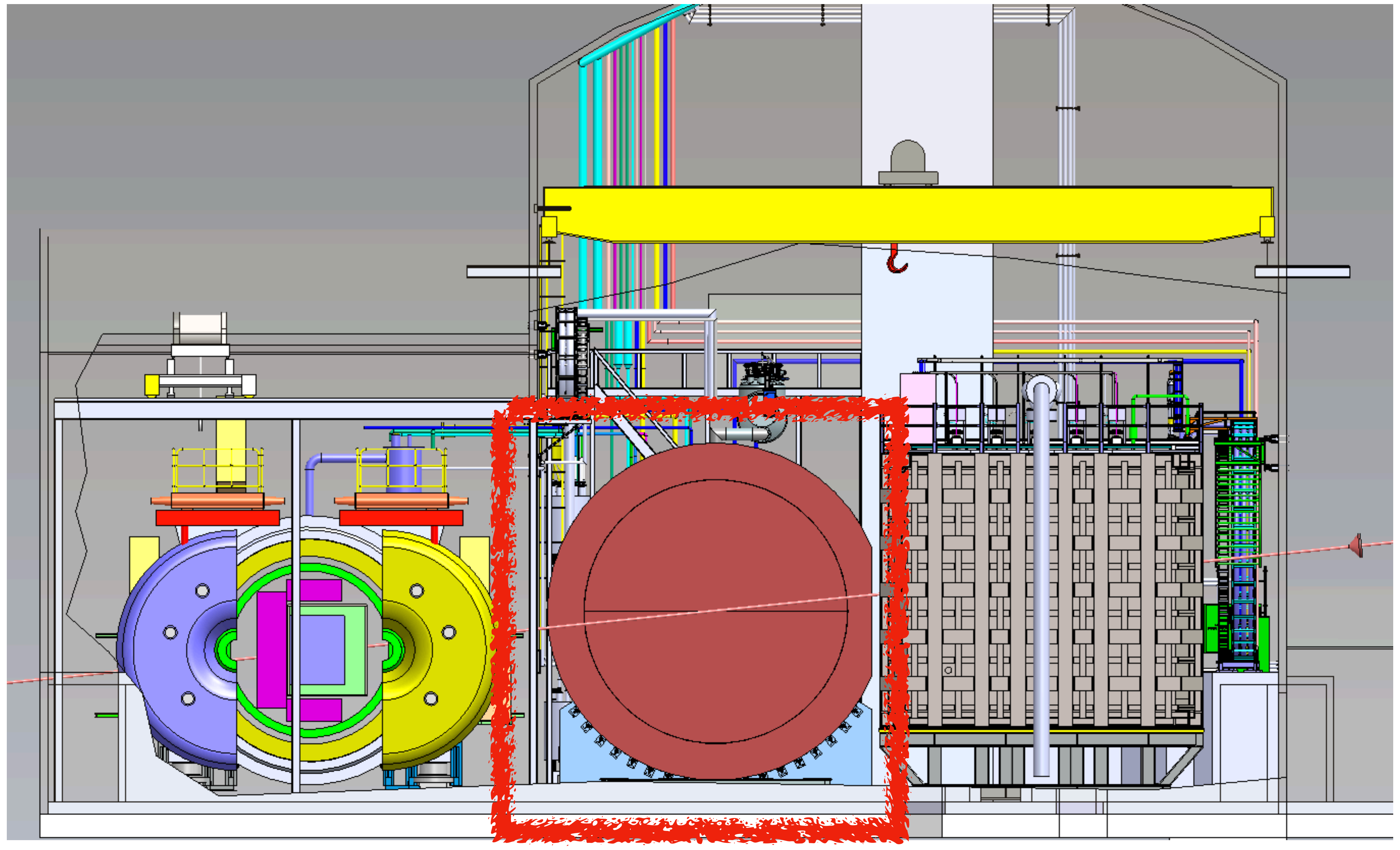
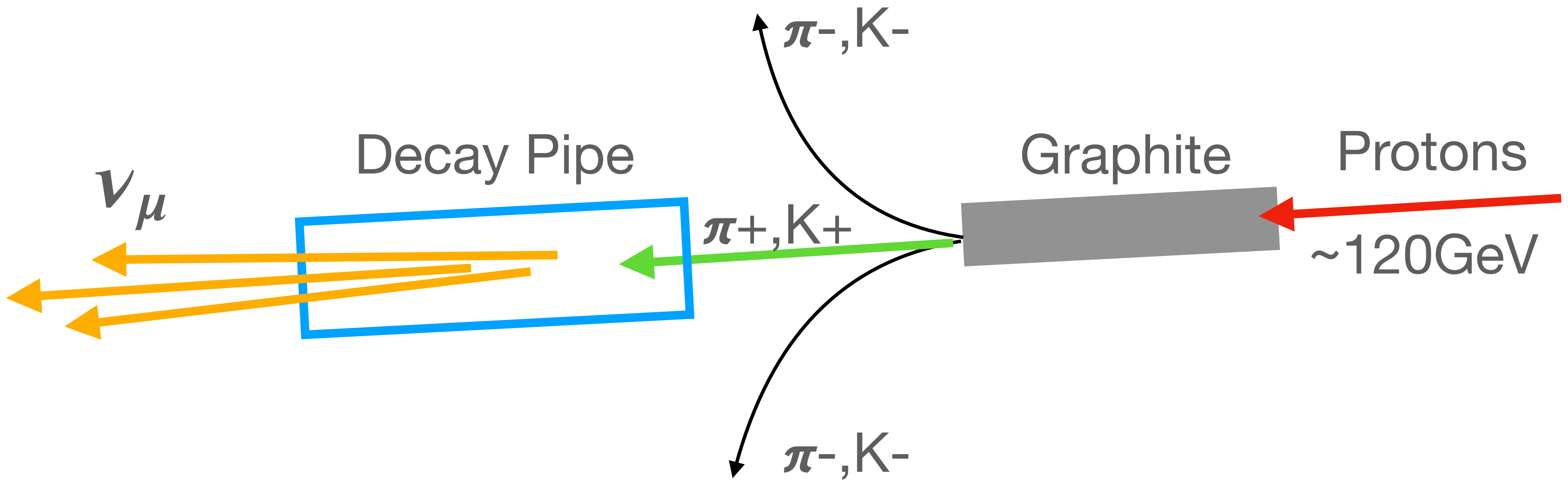
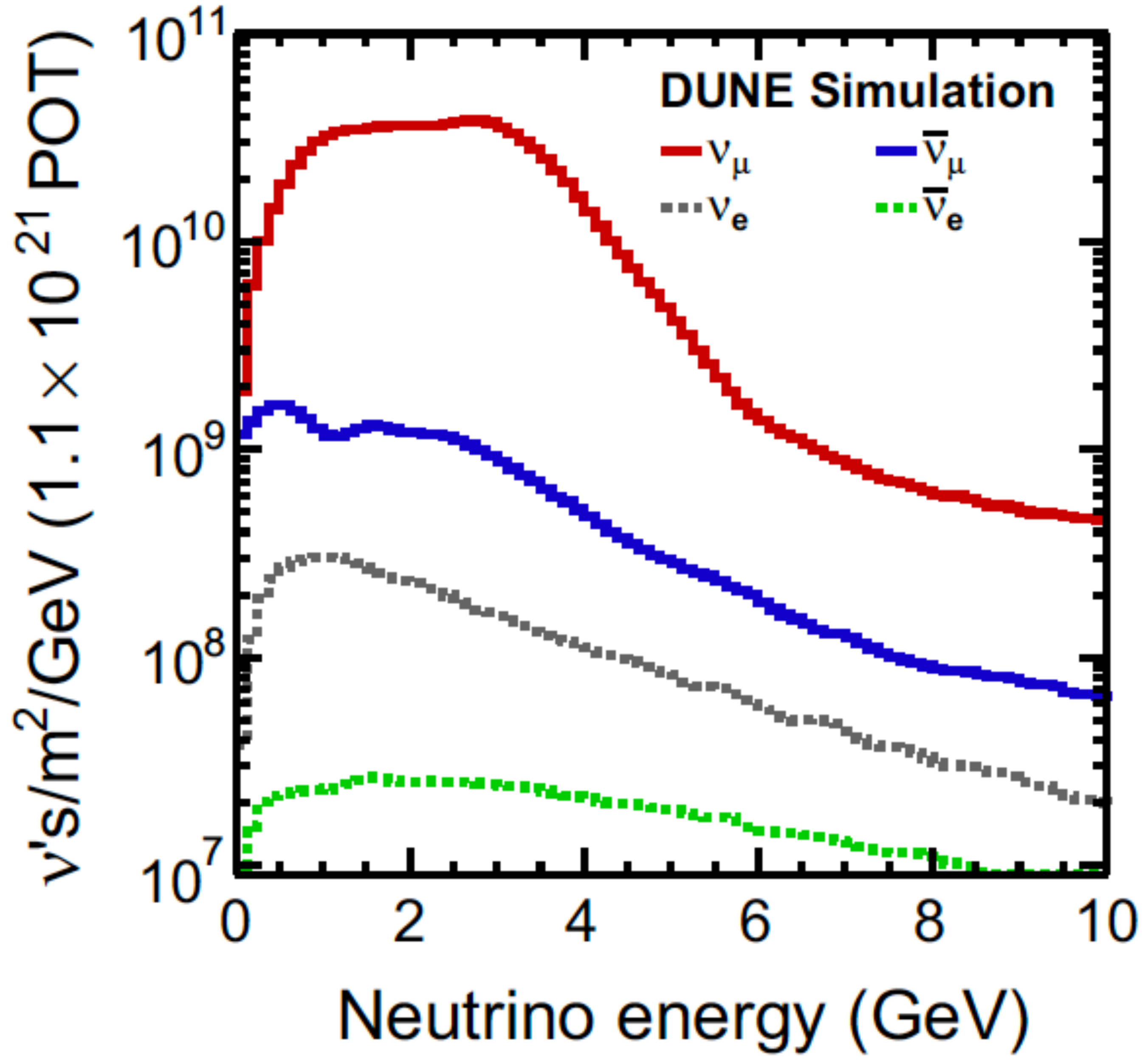


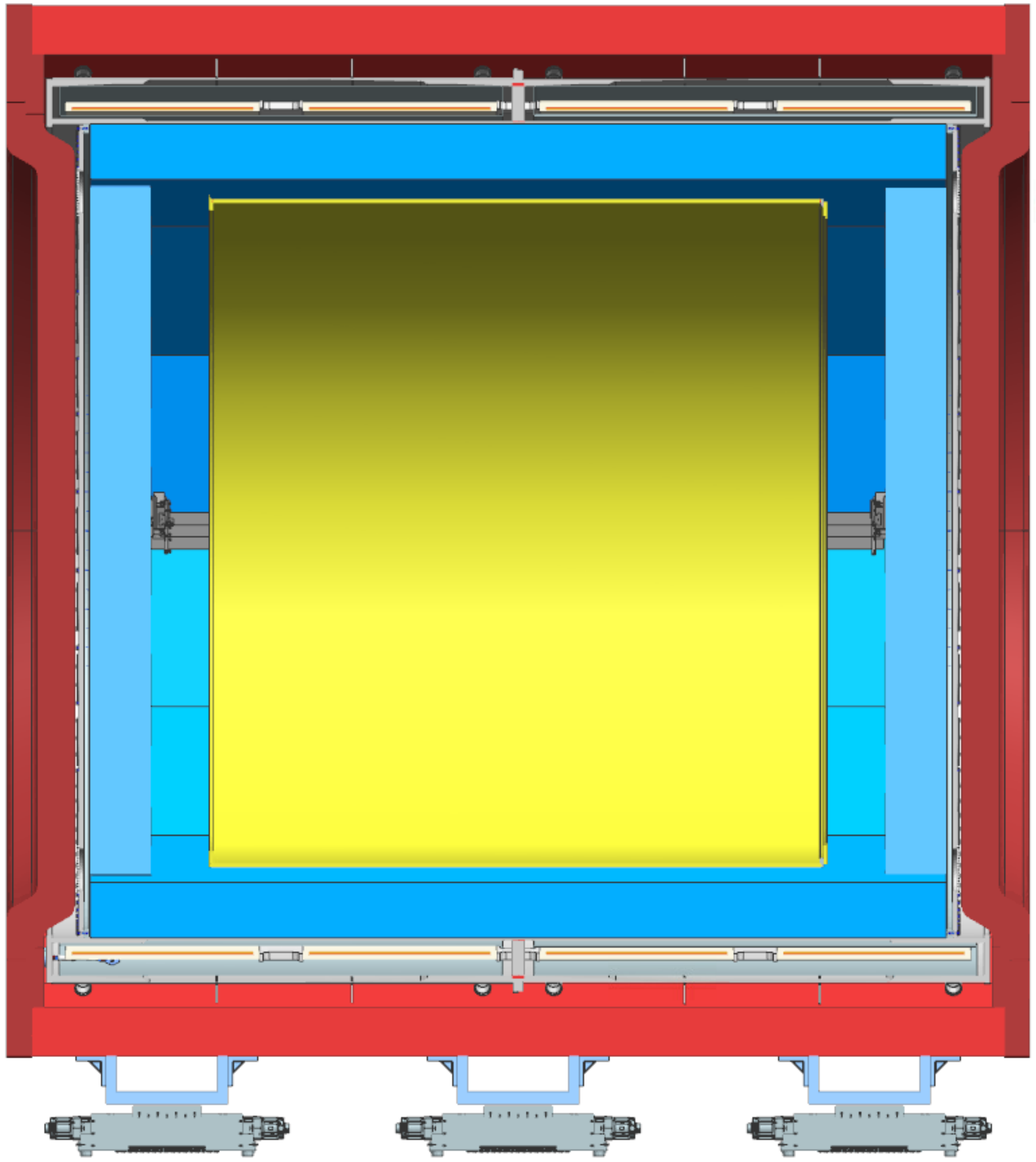


Gaseous Argon TPC:

- Gaseous target, low detection threshold and clean events
- Surrounded by ECAL and muon detector for complete reconstruction of final states
- High sensitivity to rare neutrino interactions



ND-GAr Design



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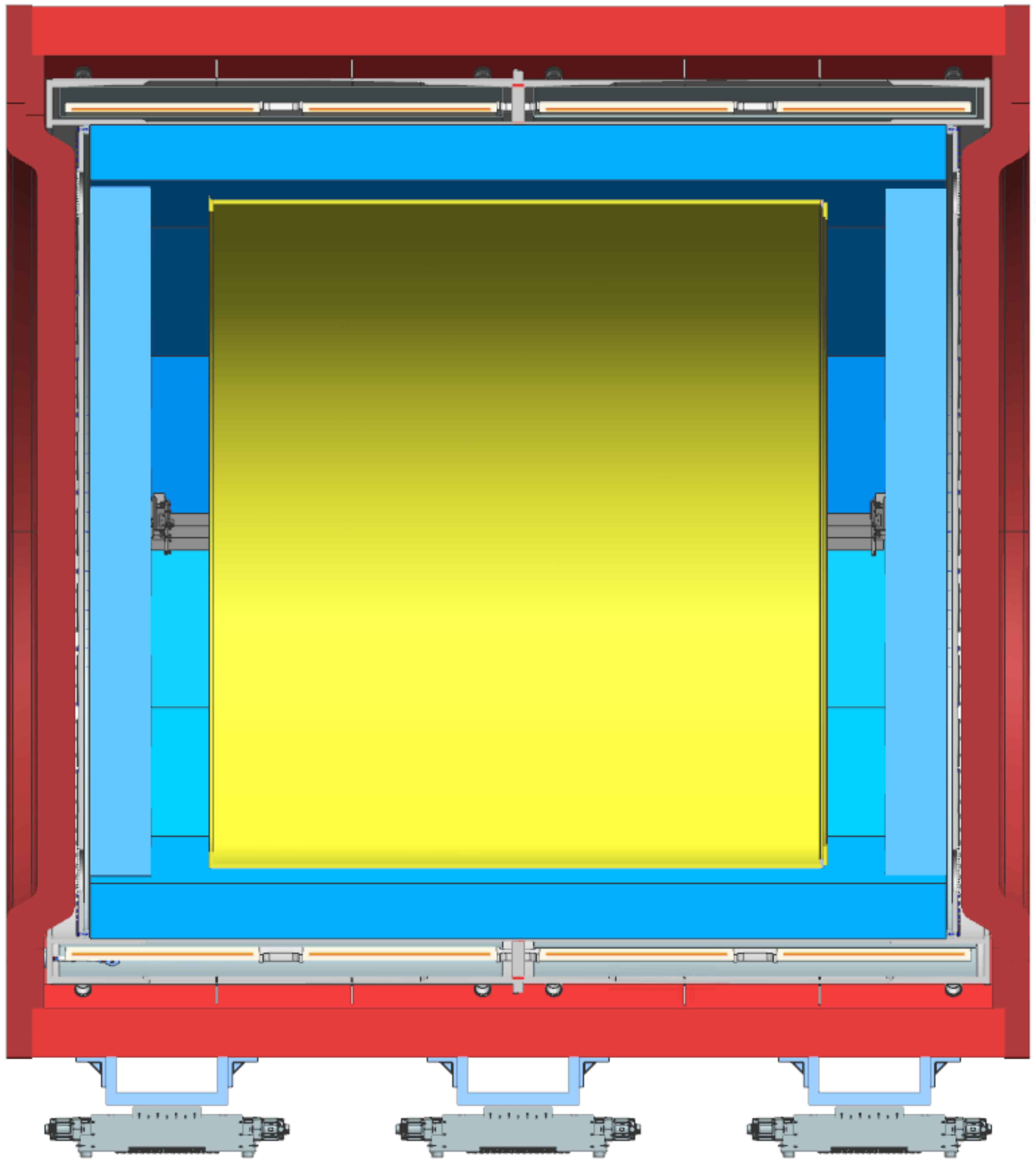
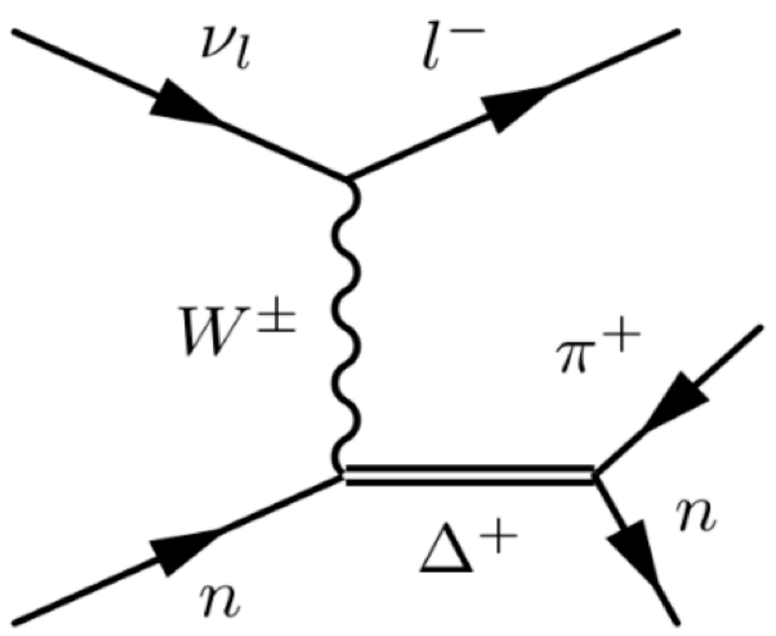
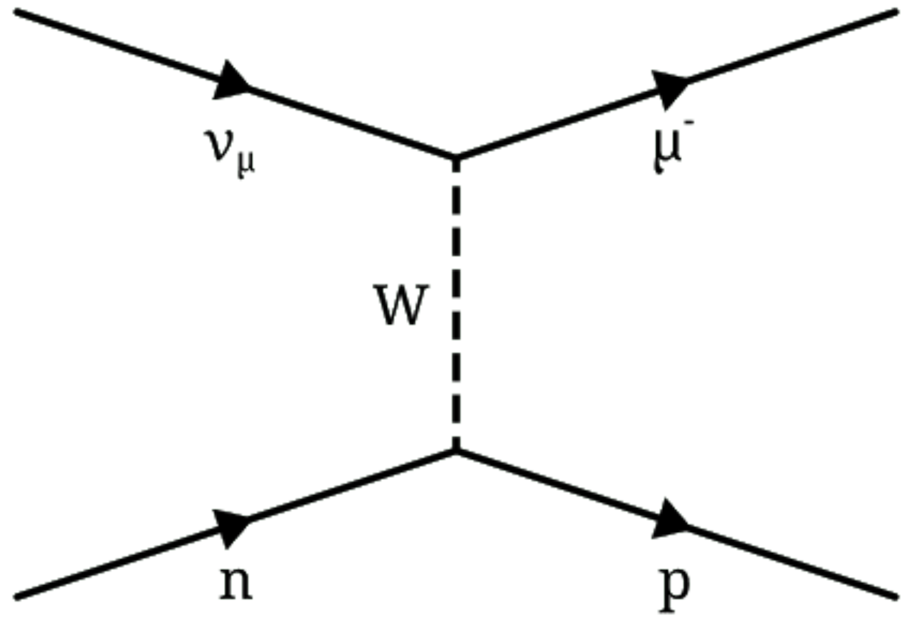


Common interactions on argon target:





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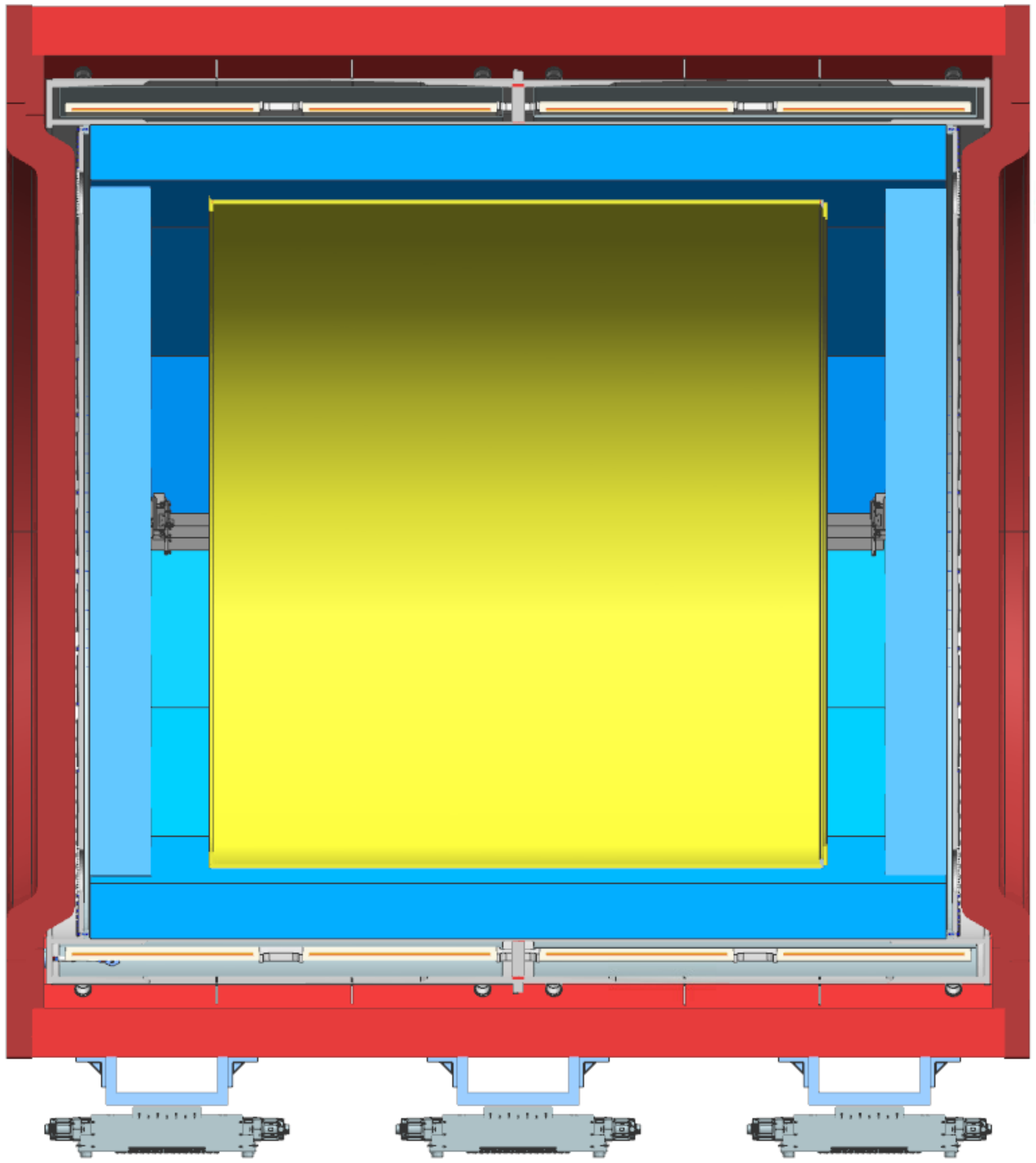

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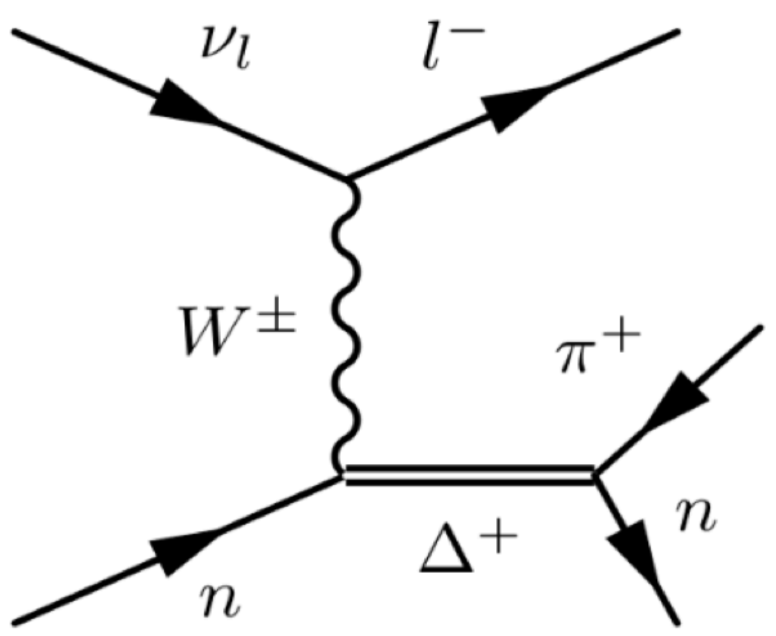
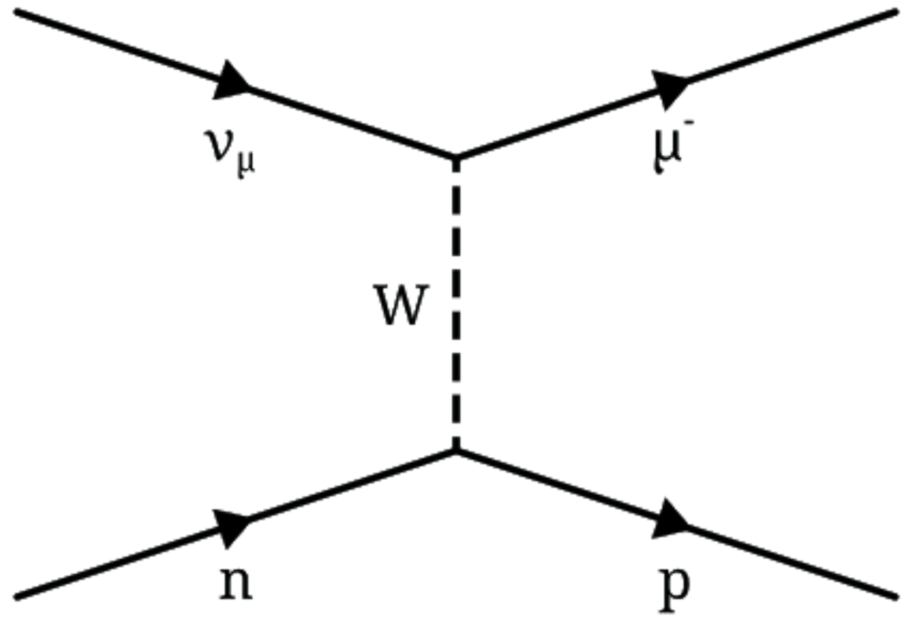
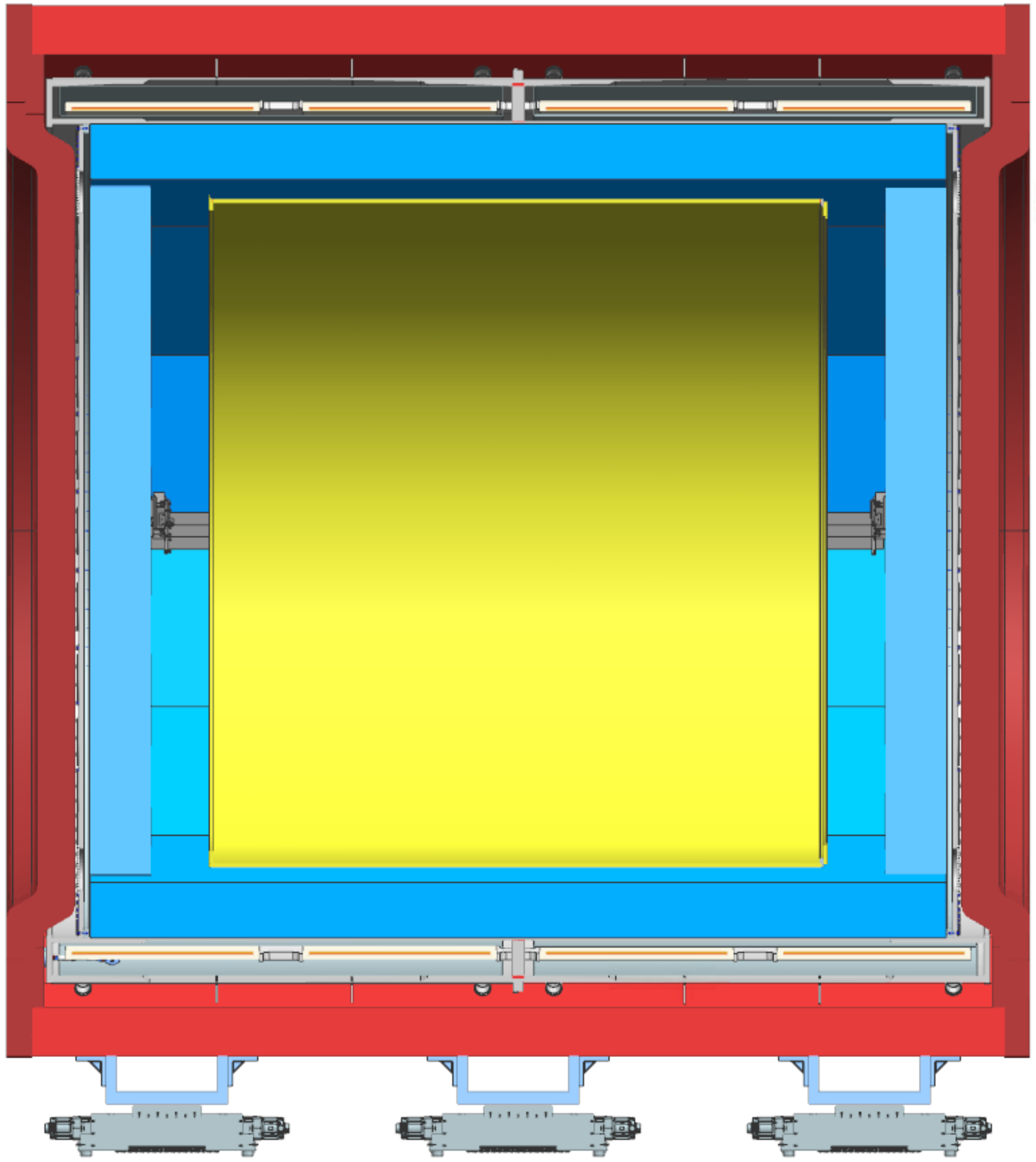




- Momentum and charge reconstruction of charged particles in TPC

ND-GAr Design



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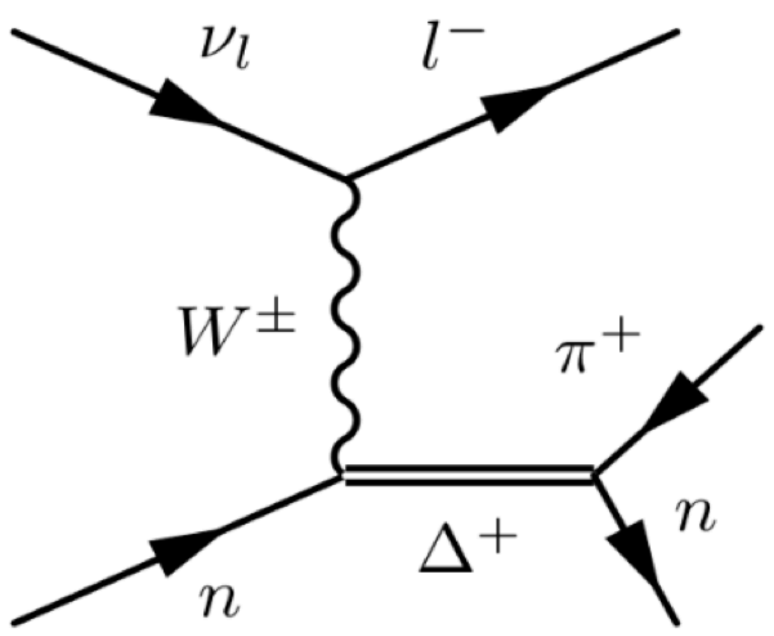

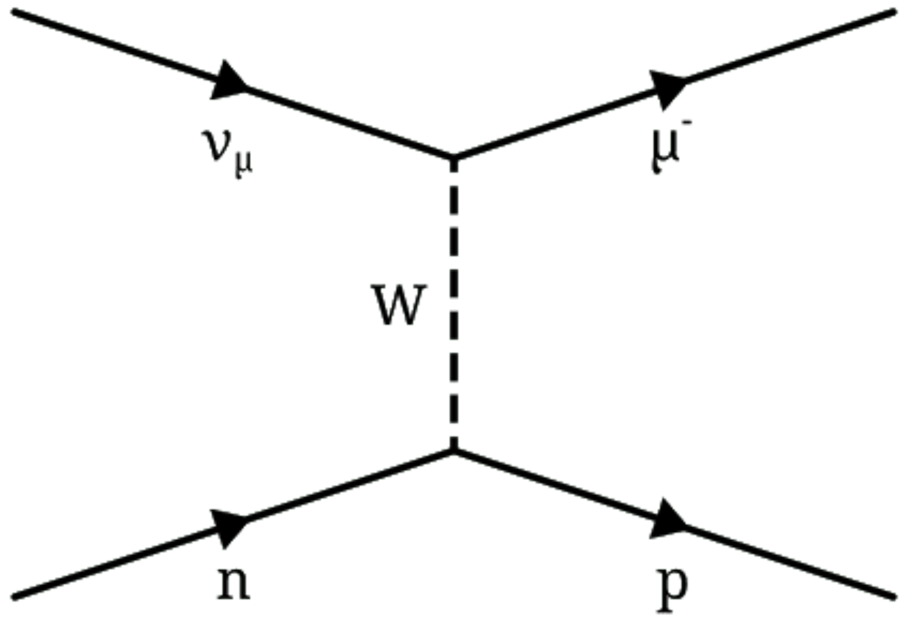

- Momentum and charge reconstruction of charged particles in TPC
- Reconstruction of photons and neutrons in highly granular scintillator ECAL

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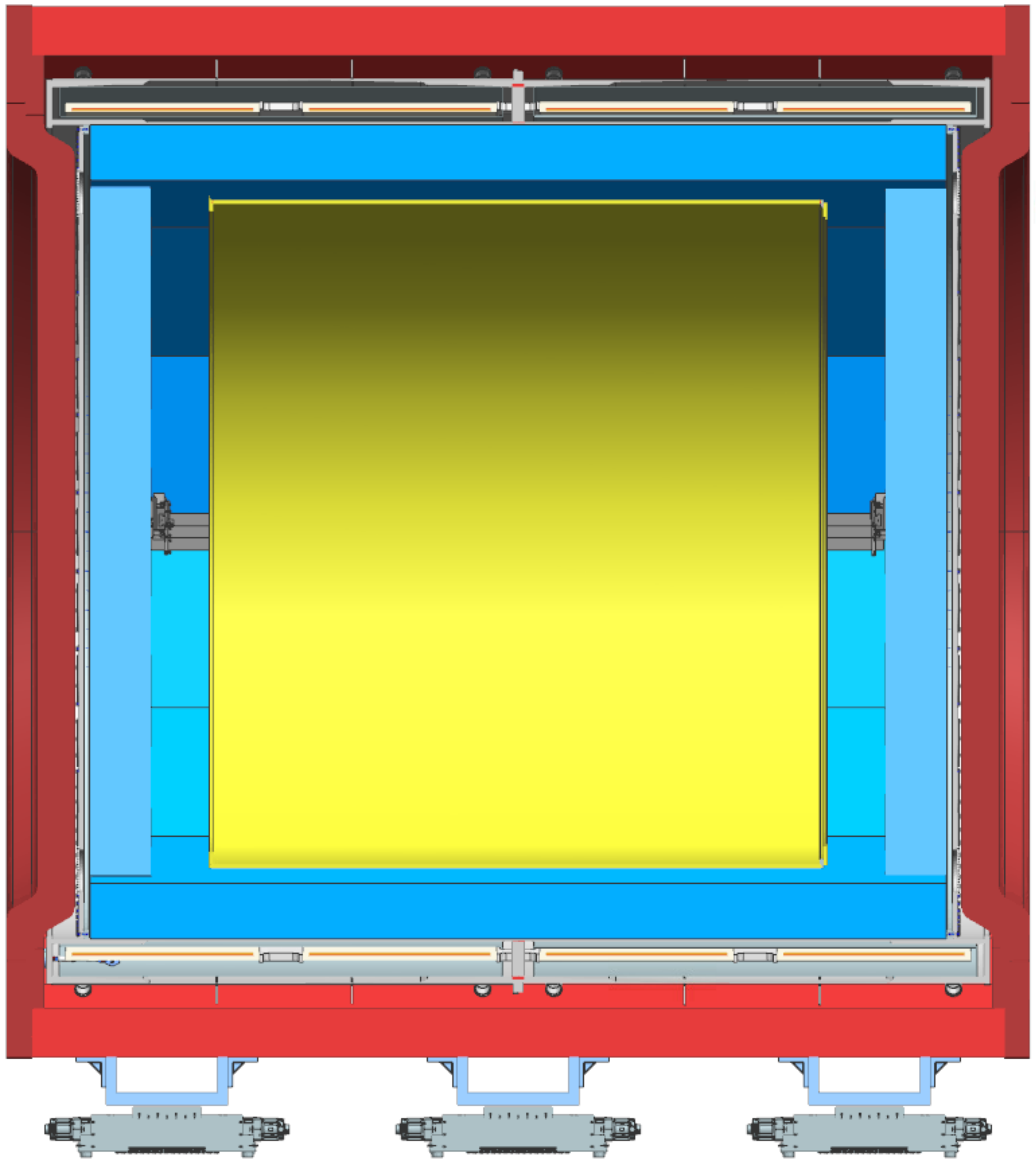

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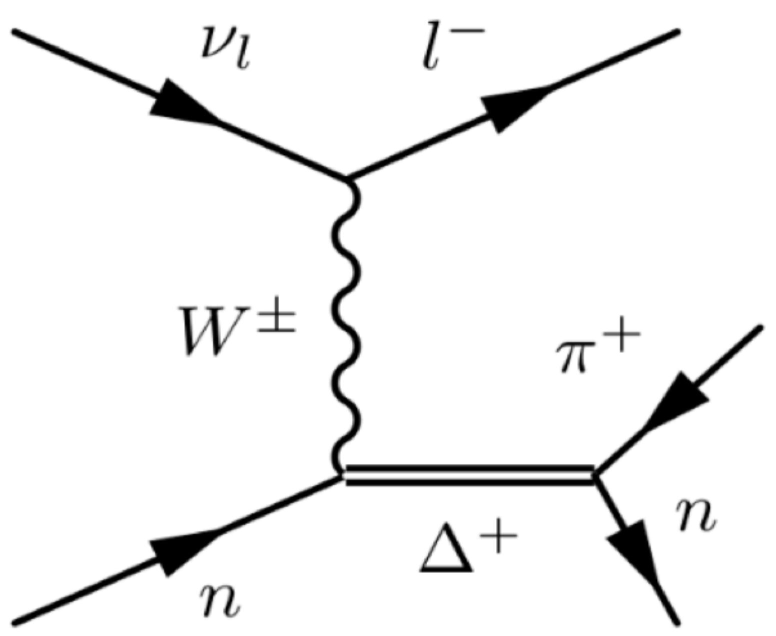

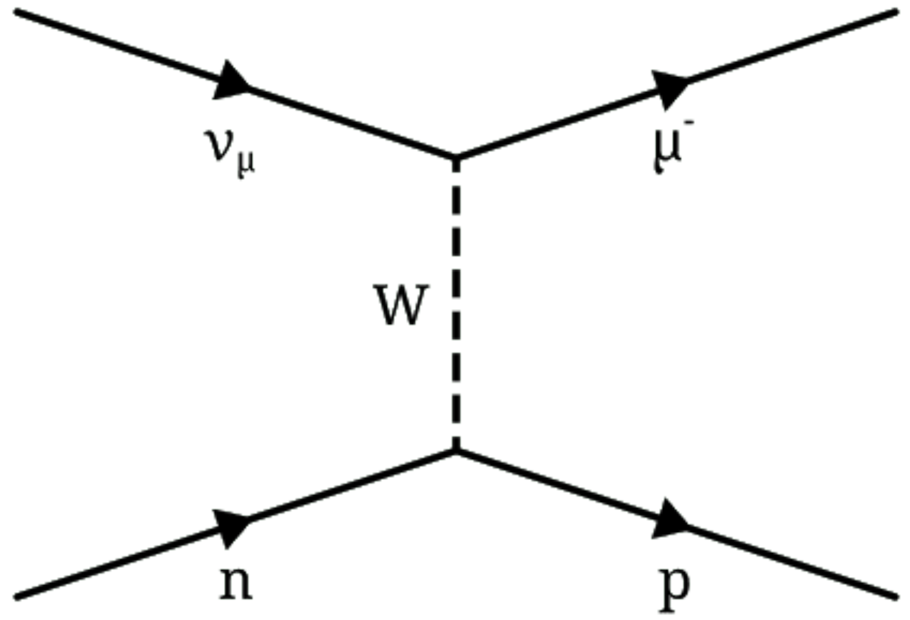

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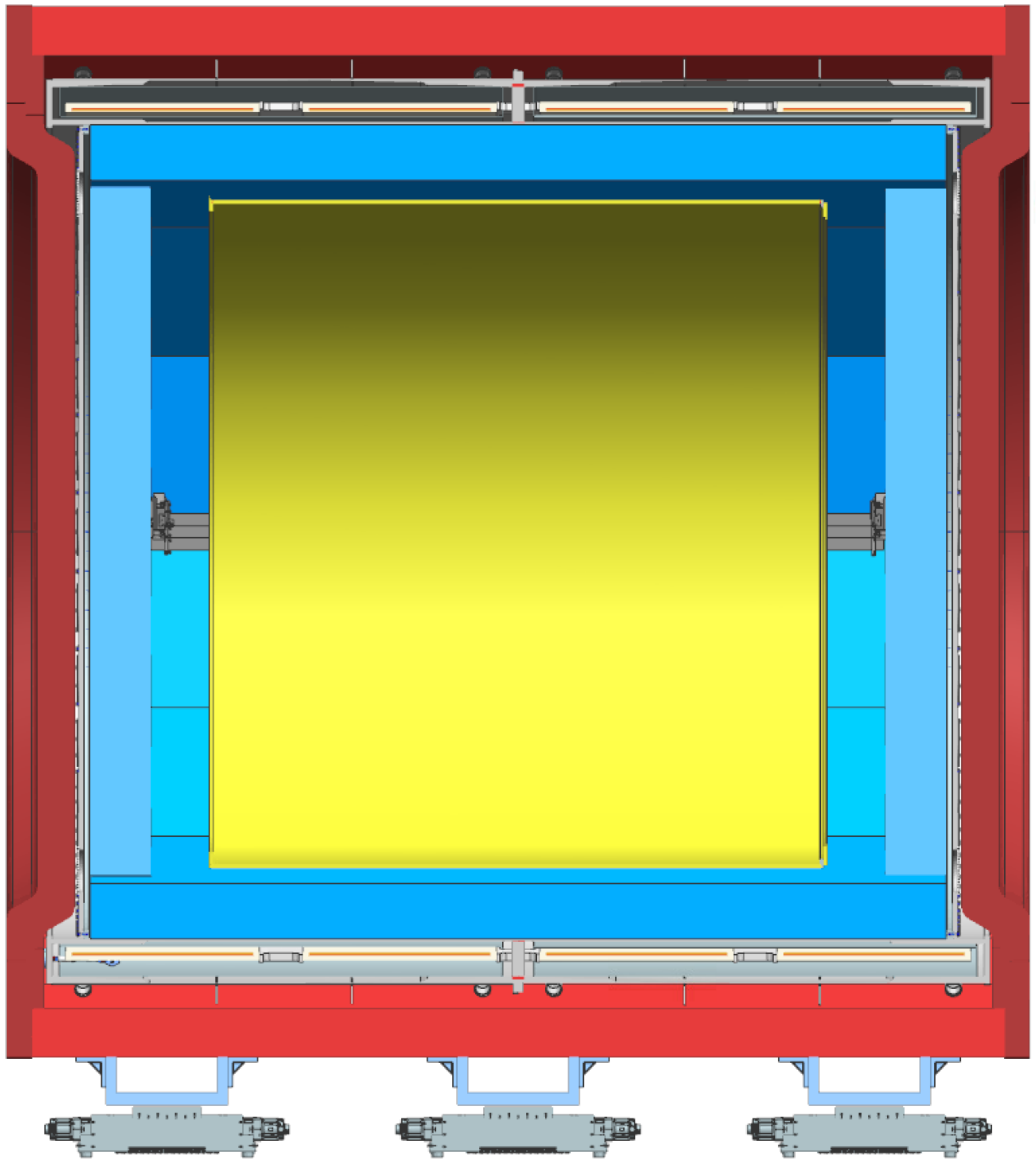

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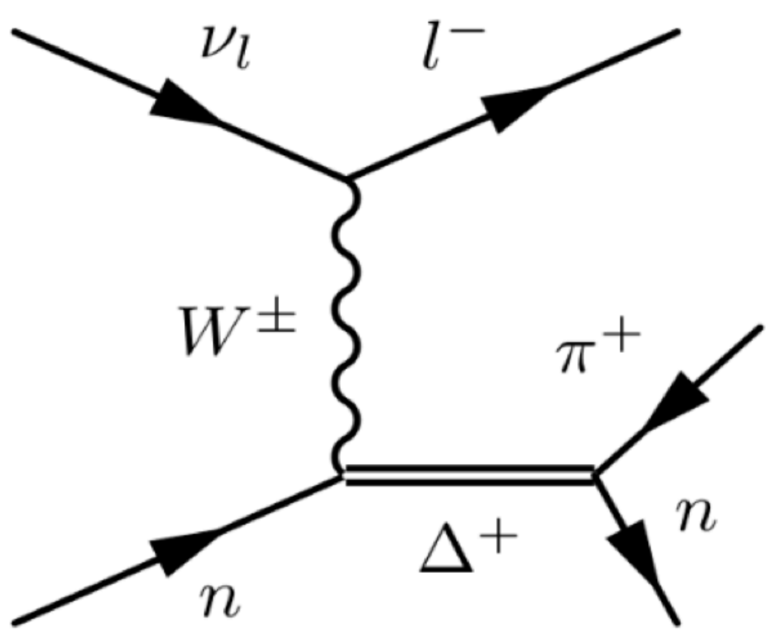

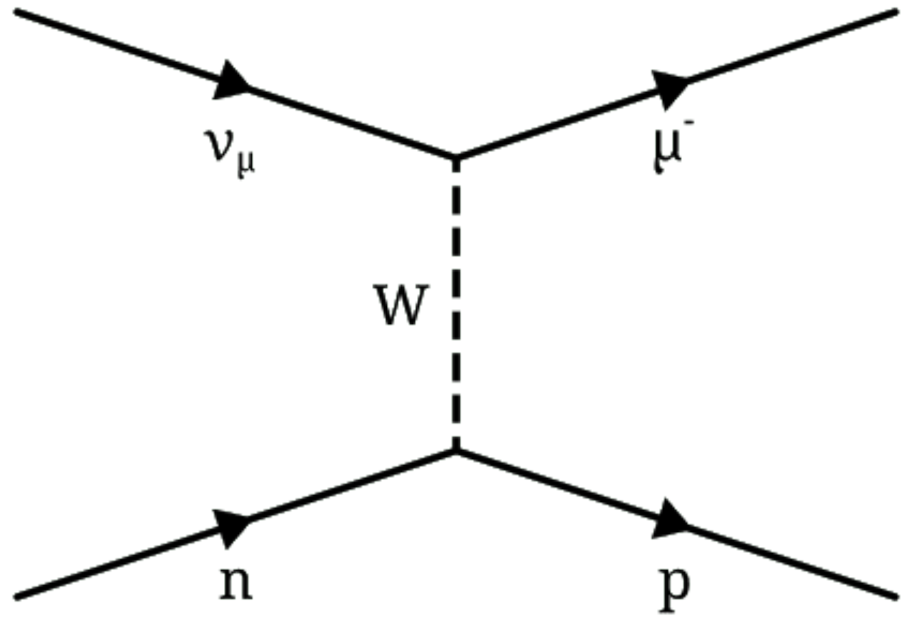

- Momentum and charge reconstruction of charged particles in TPC
- Reconstruction of photons and neutrons in highly granular scintillator ECAL
- 0.5T solenoid field
- Surrounded by a muon detector (technology tbd)

ECAL Design Drivers

Key roles of the ECAL:

1. Photon reconstruction

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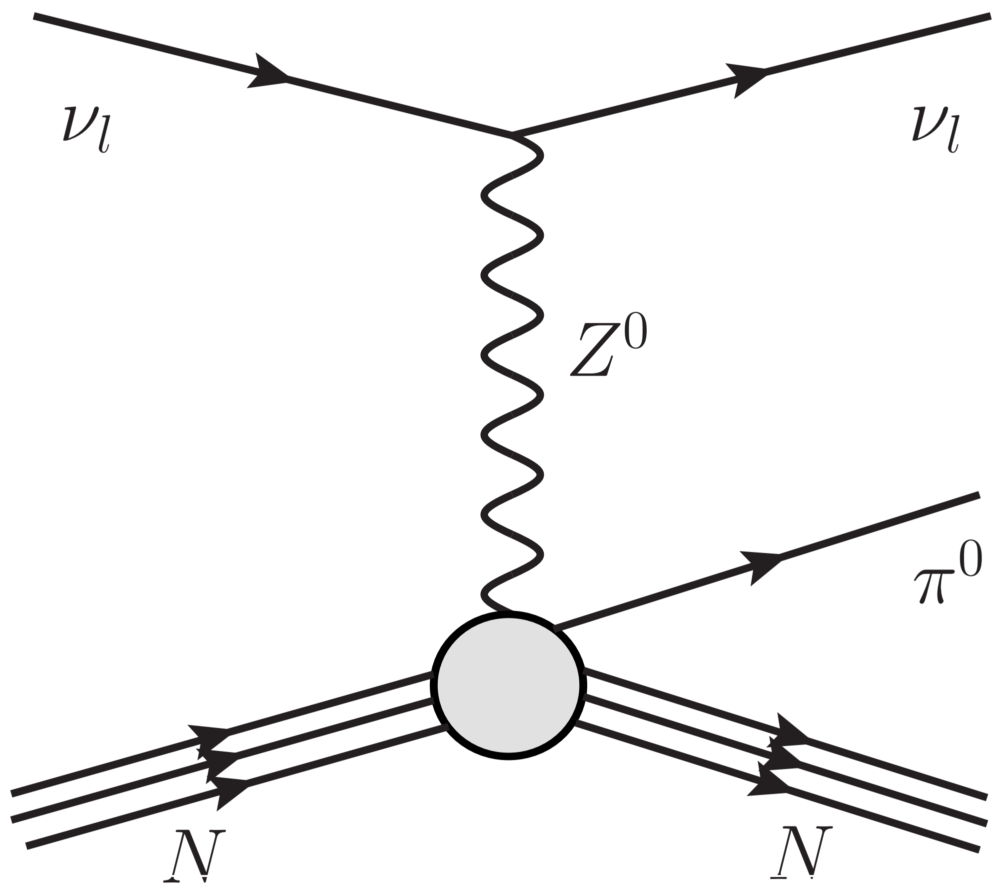
NC/CC neutral pion production:



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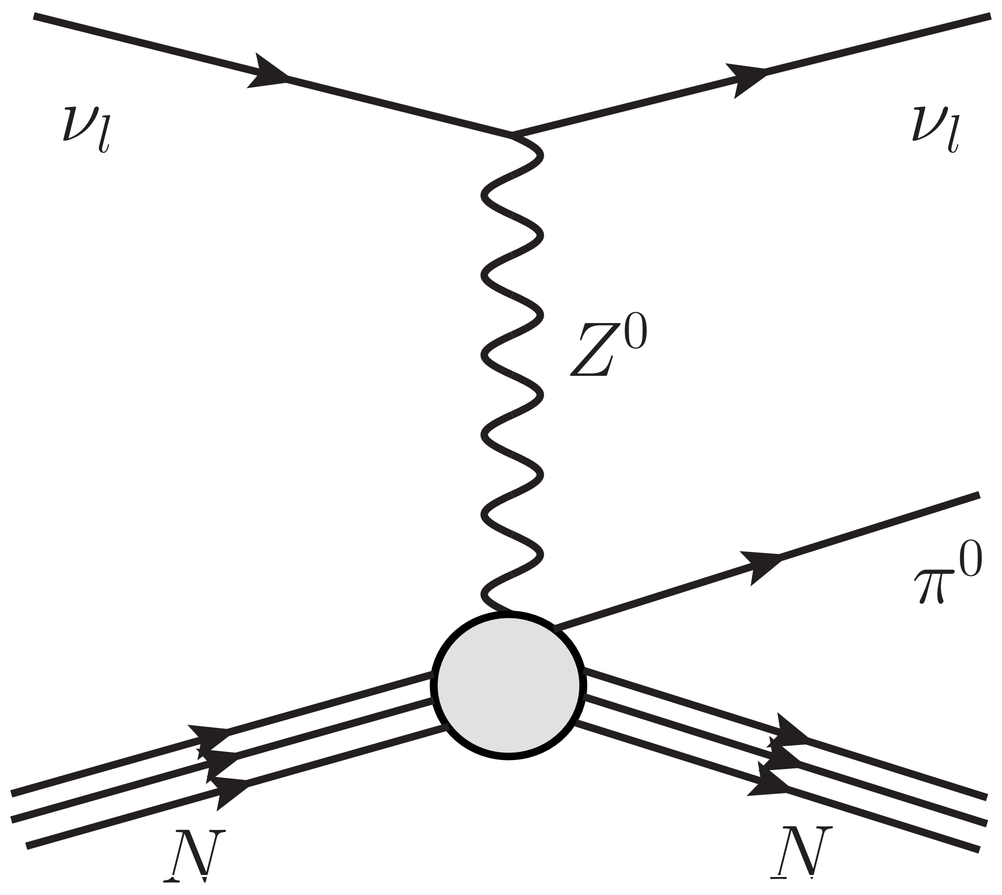

- Low momentum transfer

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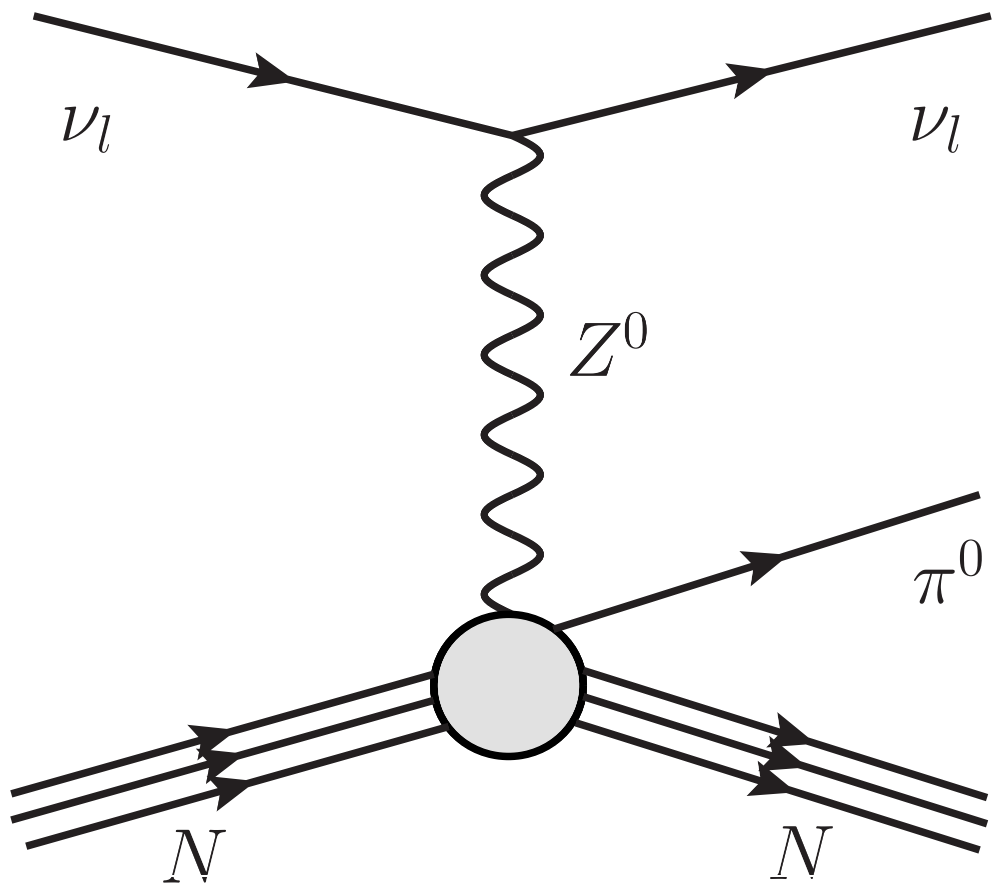

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- $\pi^0 \rightarrow \gamma\gamma$
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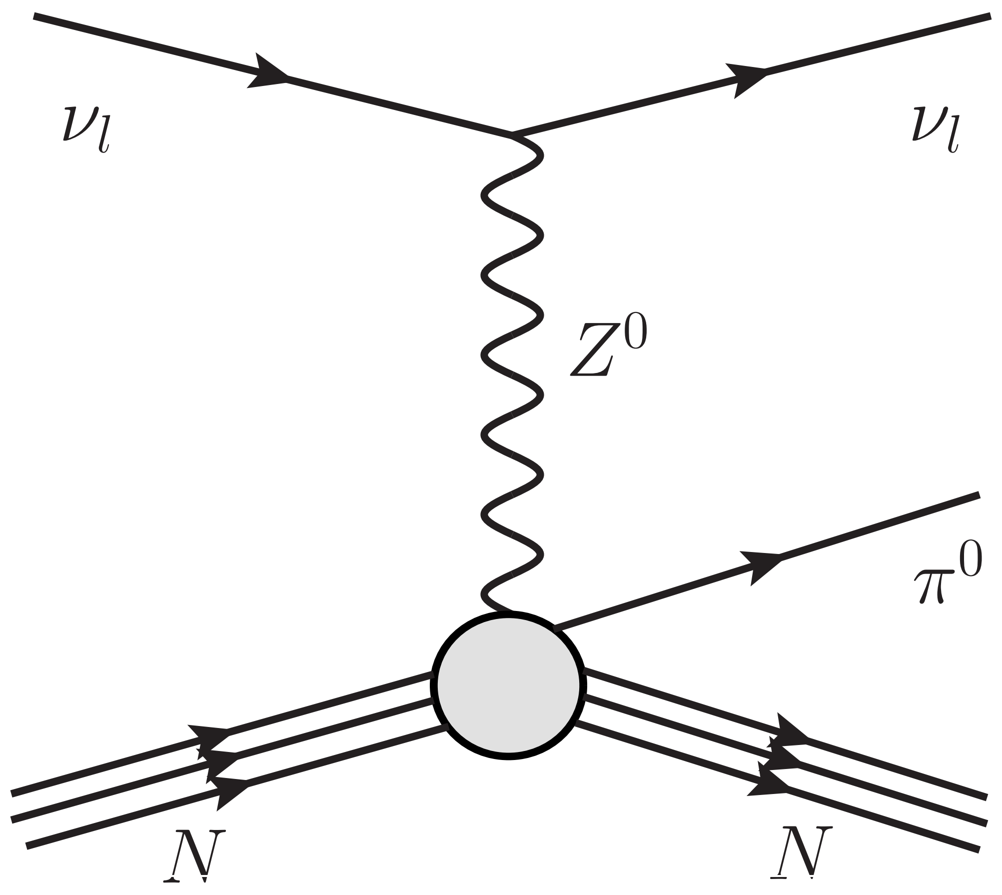

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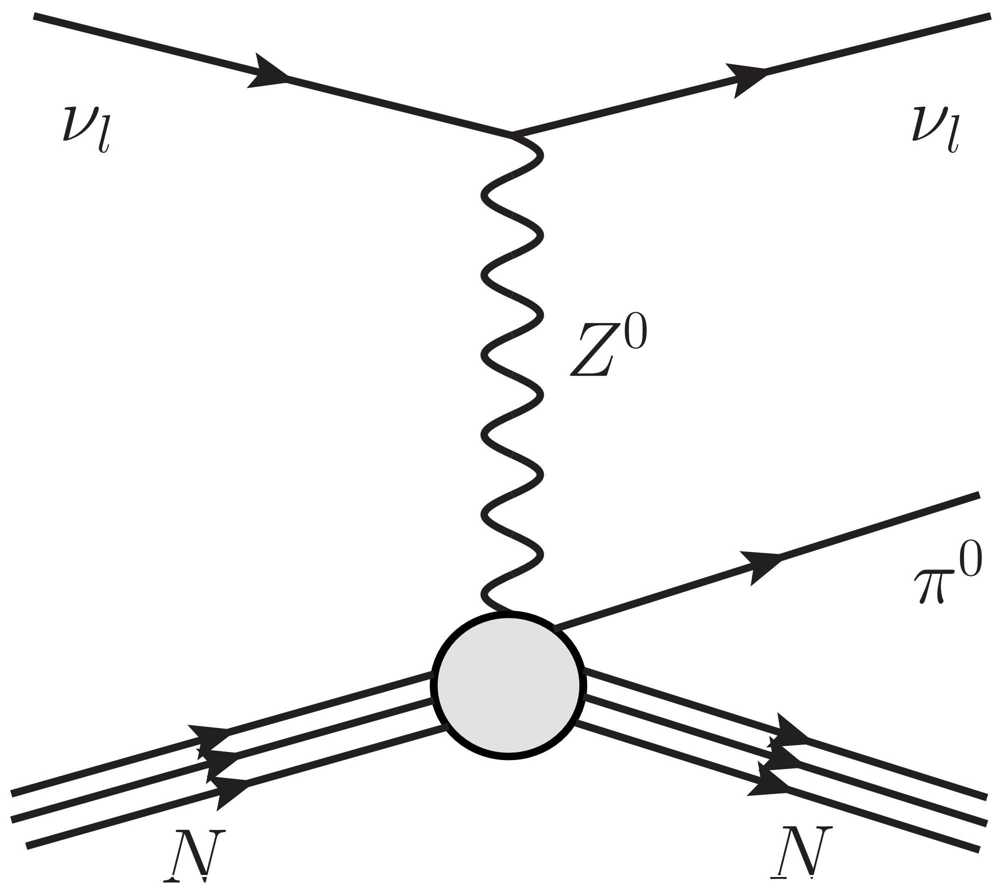

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Electron neutrino appearance signal in an electron!

Electron/Photon separation challenging in the far detector
→understand rates of neutral pion production in near detector

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2. Neutron identification

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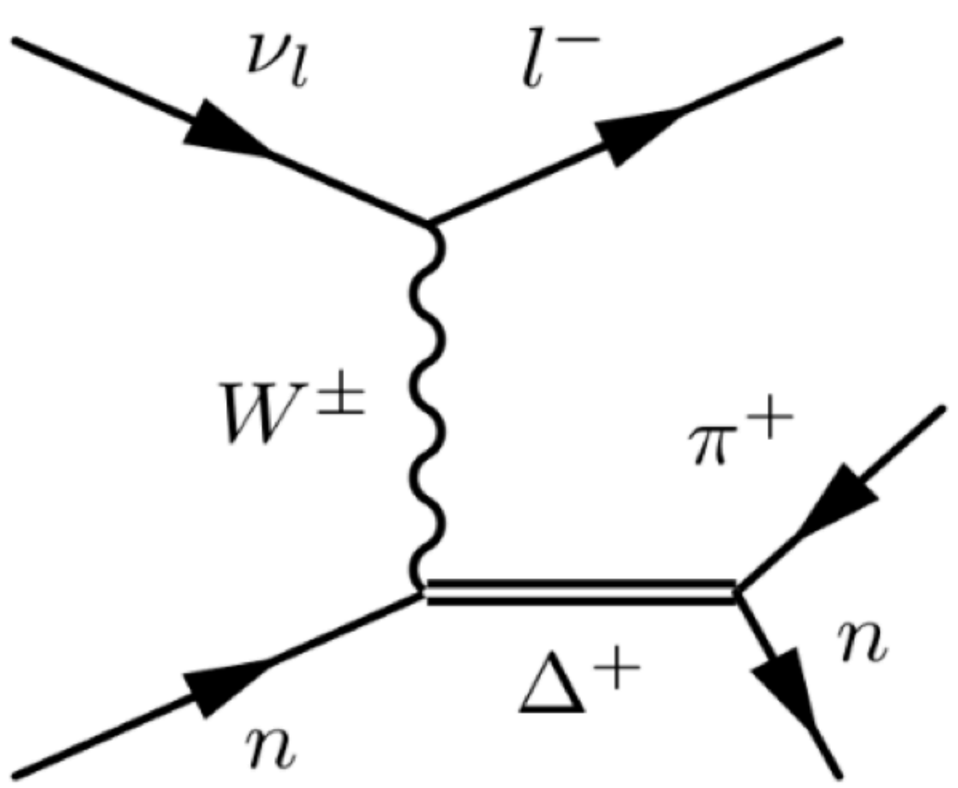

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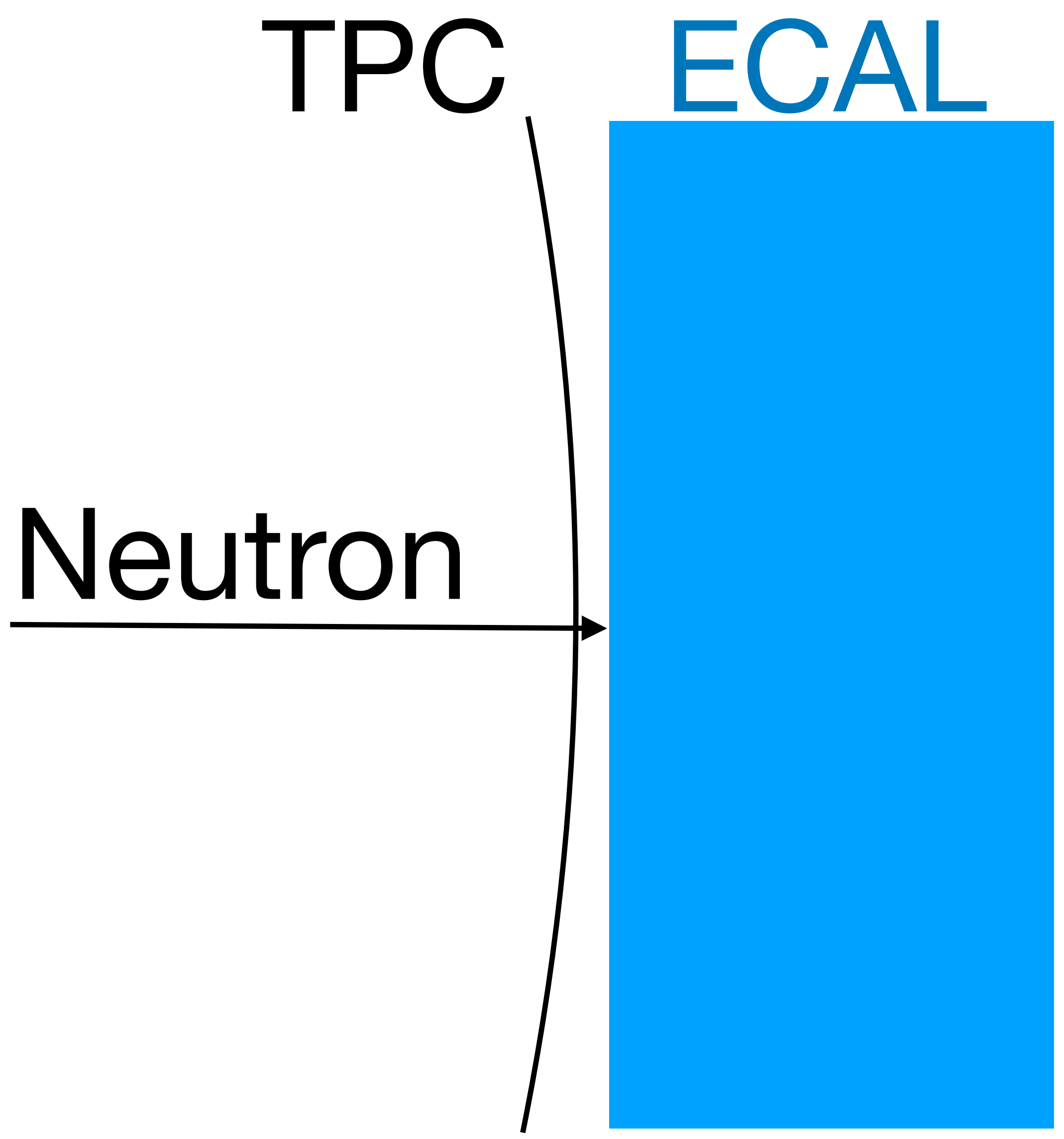

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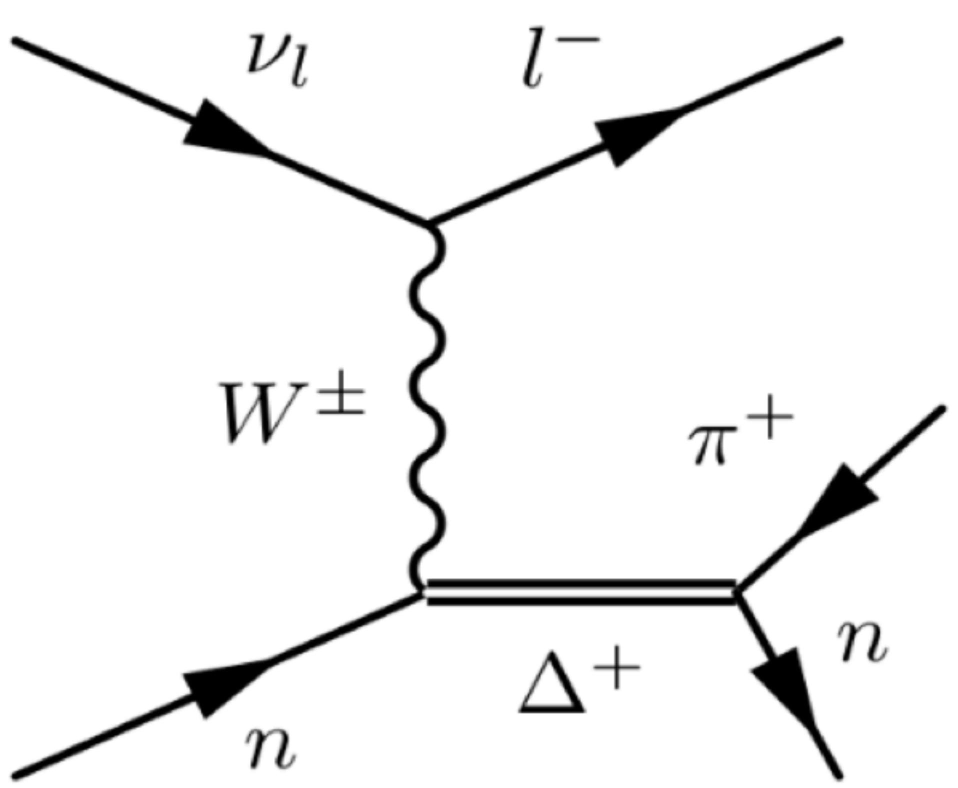

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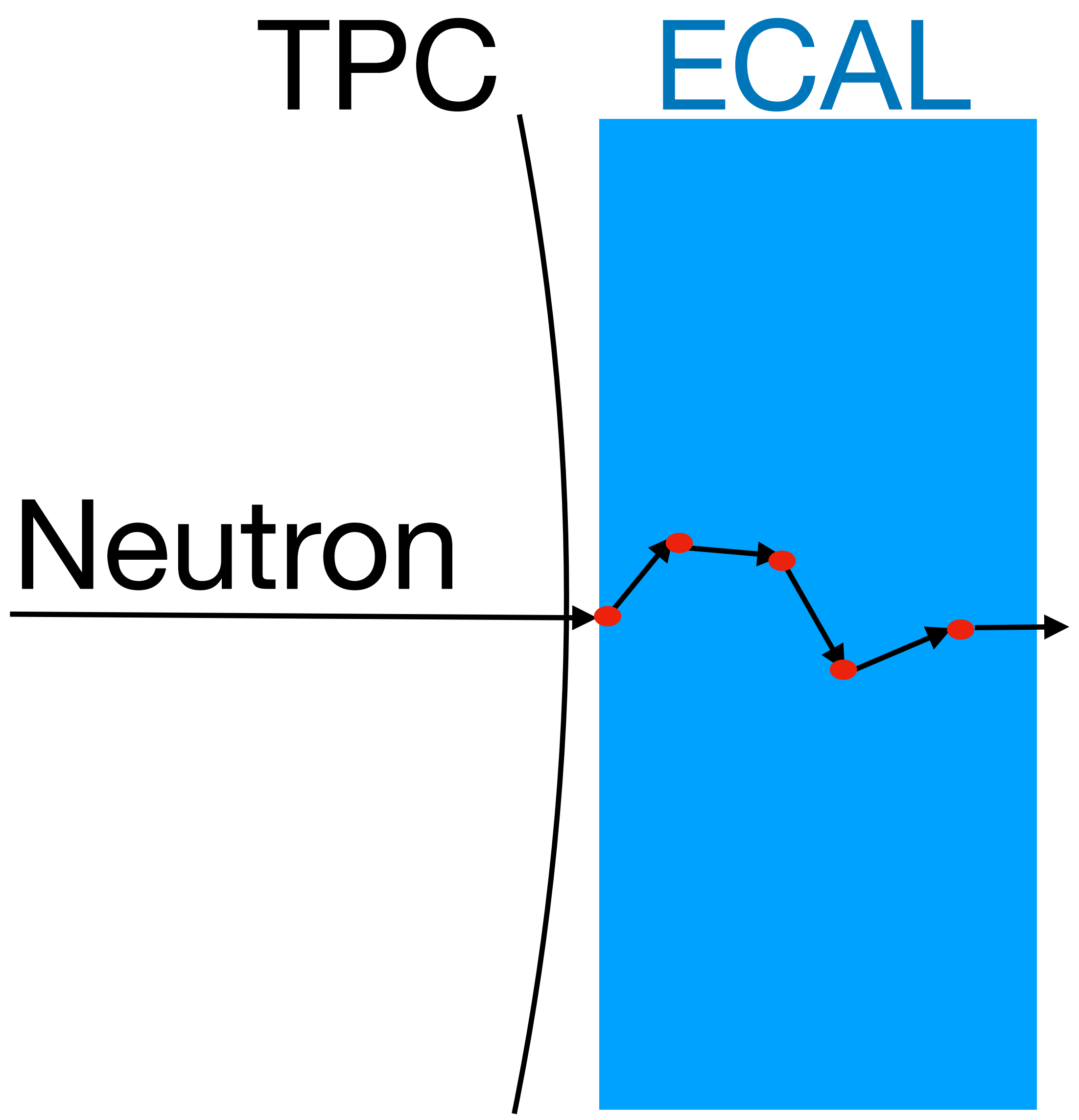

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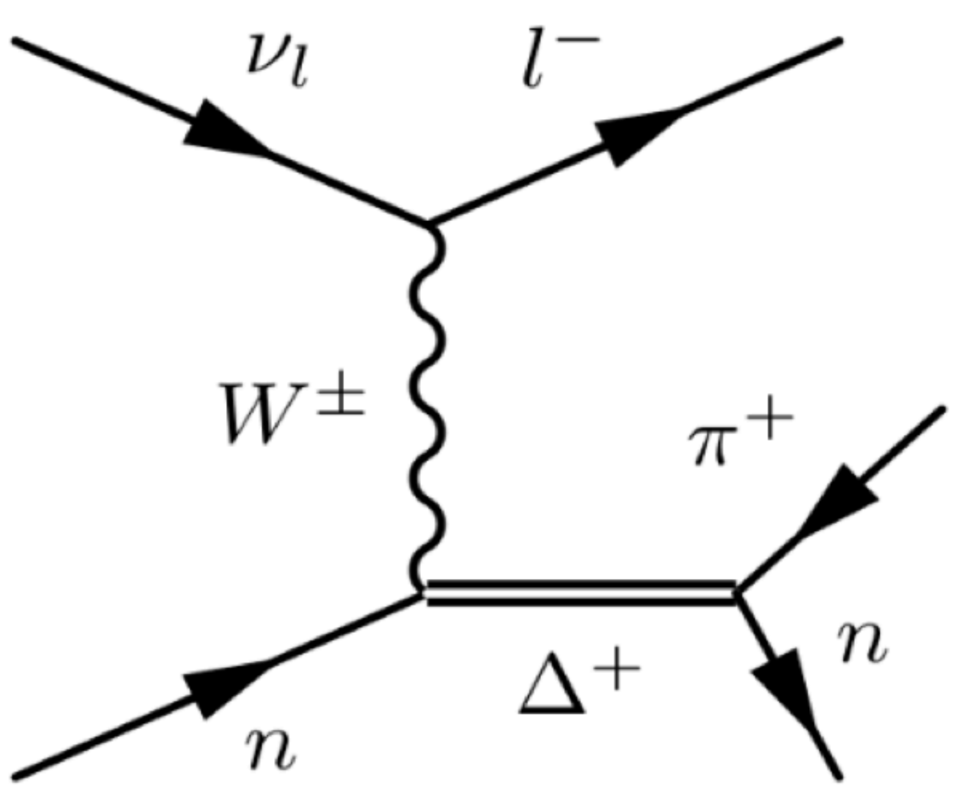

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- Deposited energy is typically small and isolated

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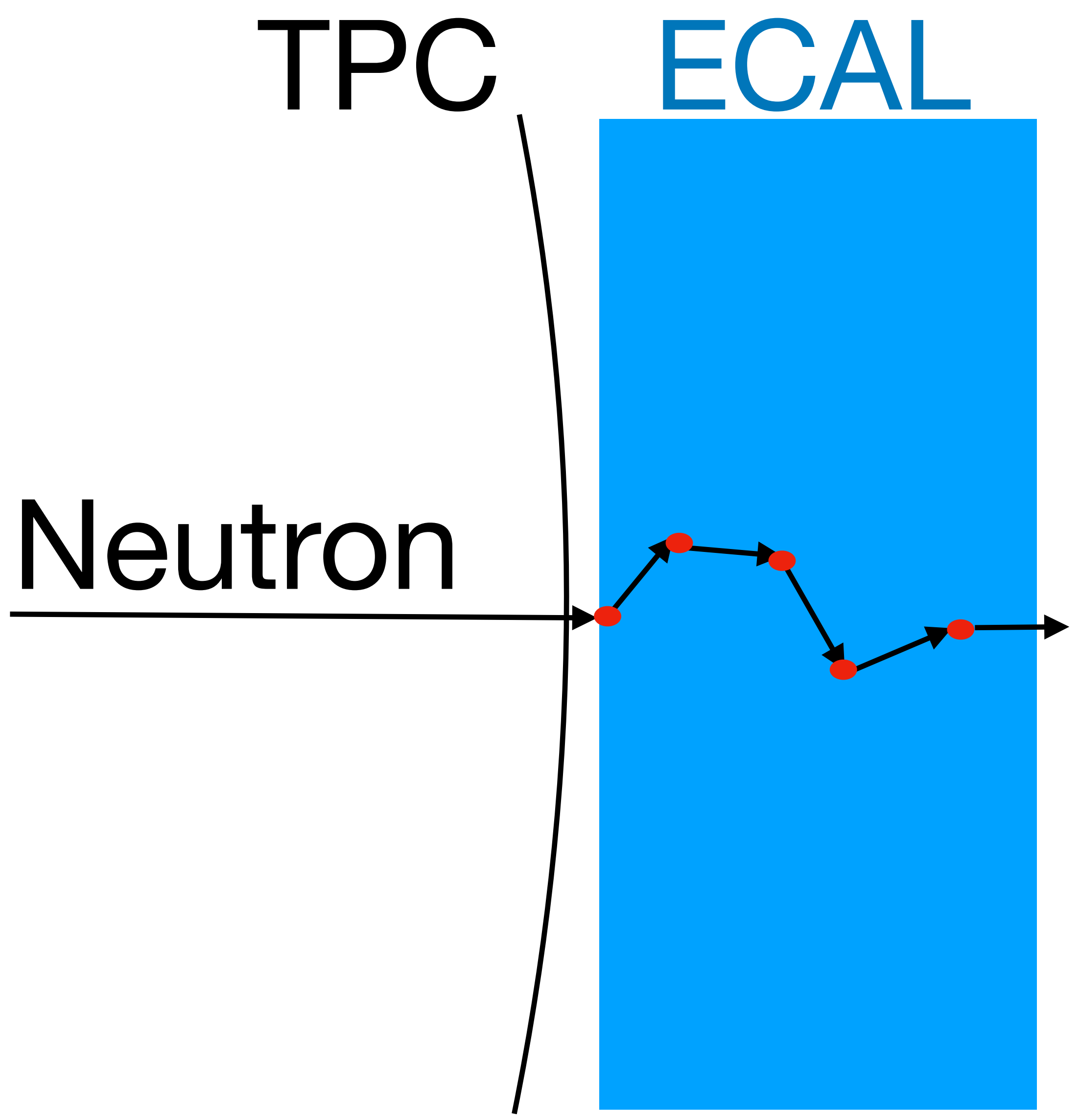

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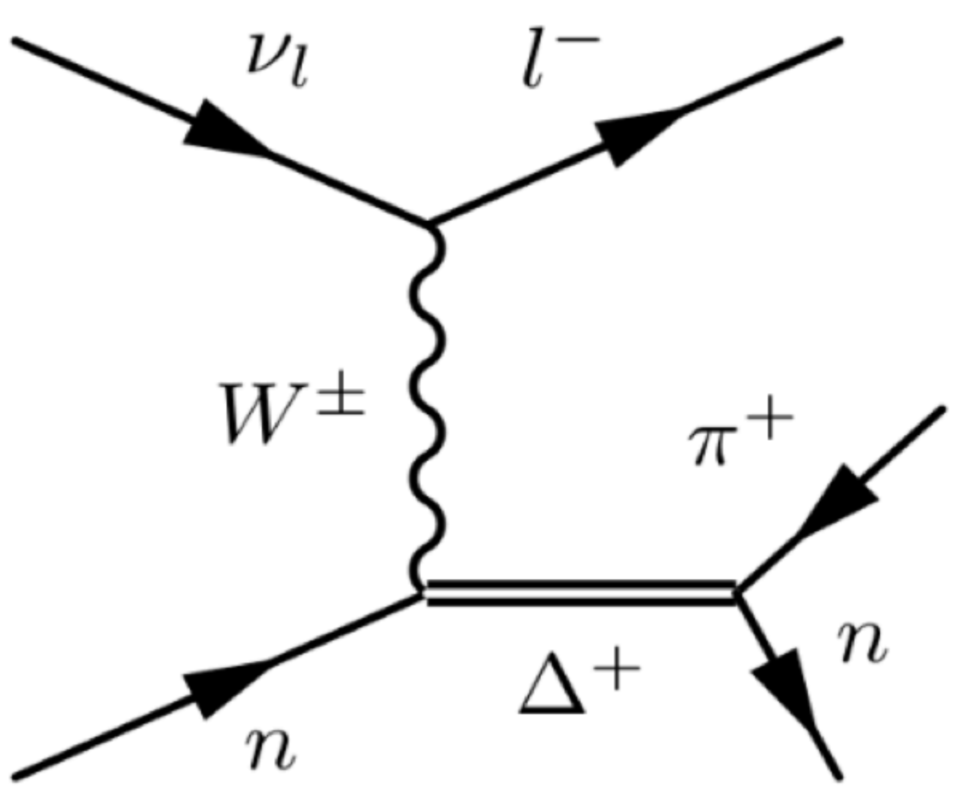

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Challenging identification of neutron hits

→ Important to reconstruct the energy of the neutrino

ECAL Design Drivers

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3. Muon/Pion separation
   (with muon detector)

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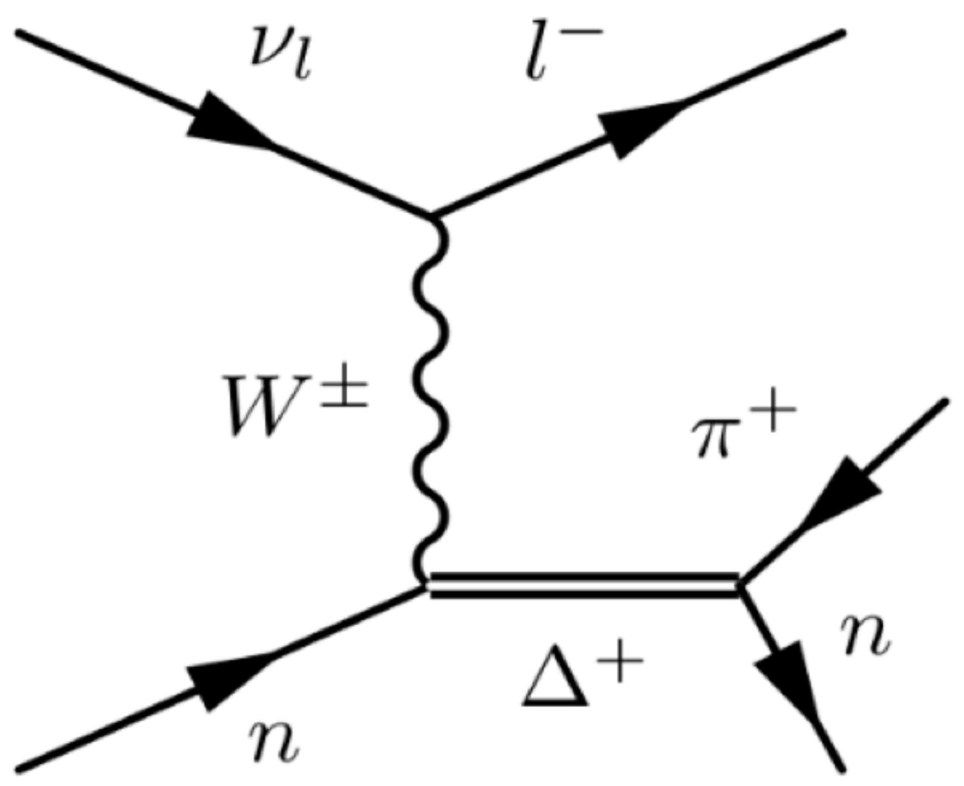

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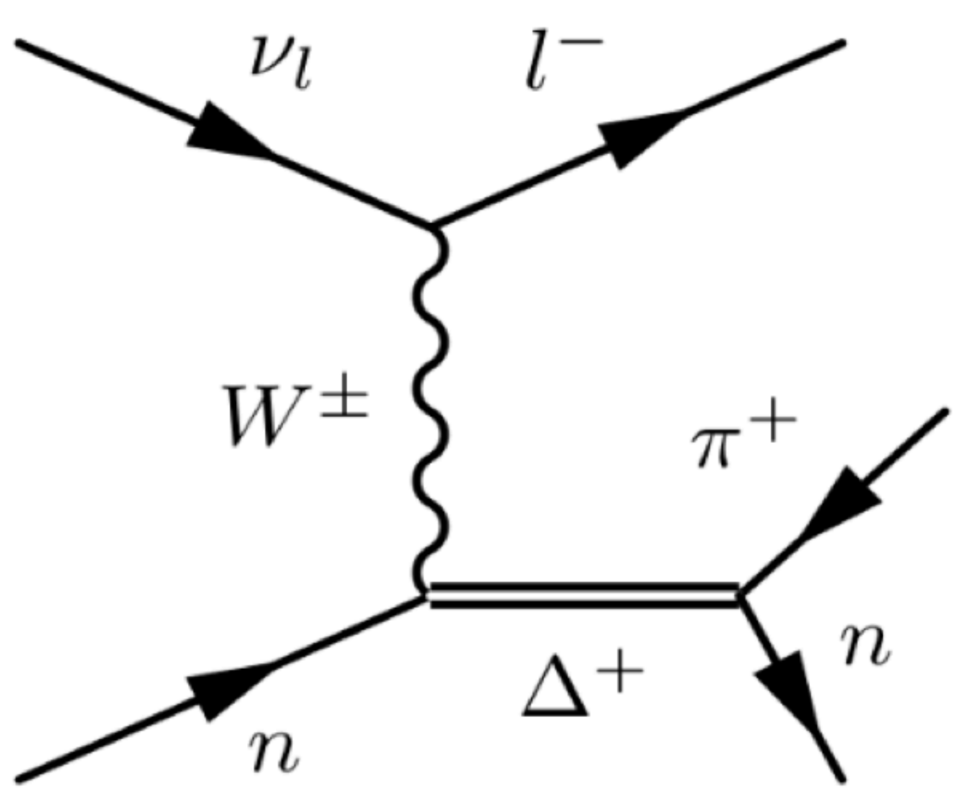

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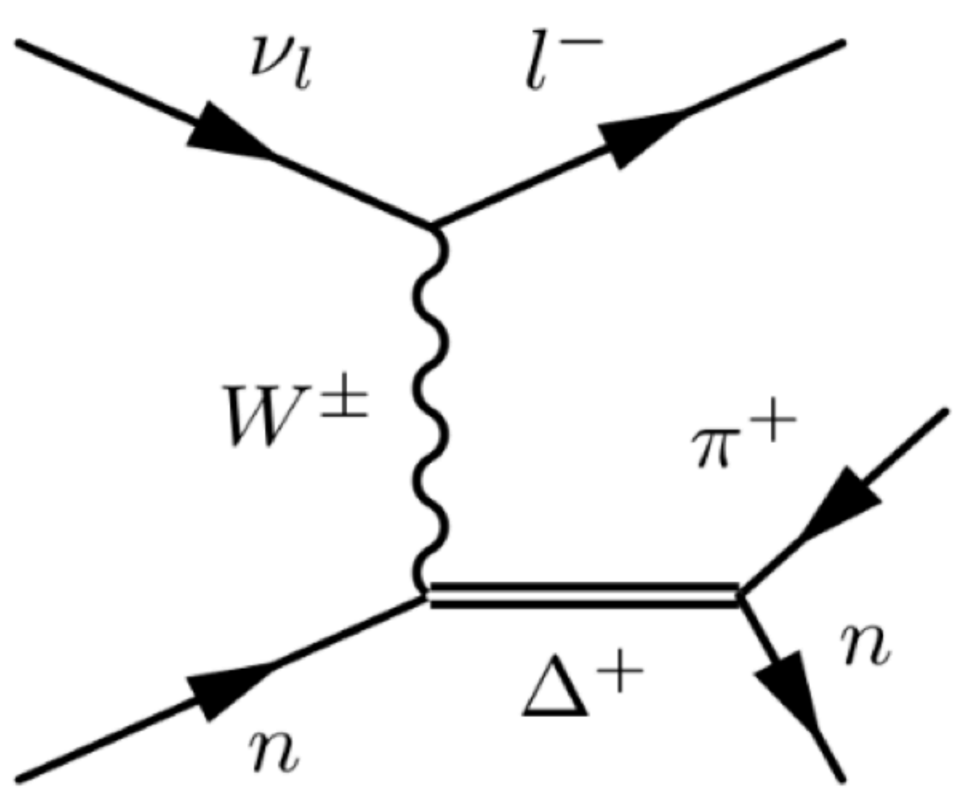

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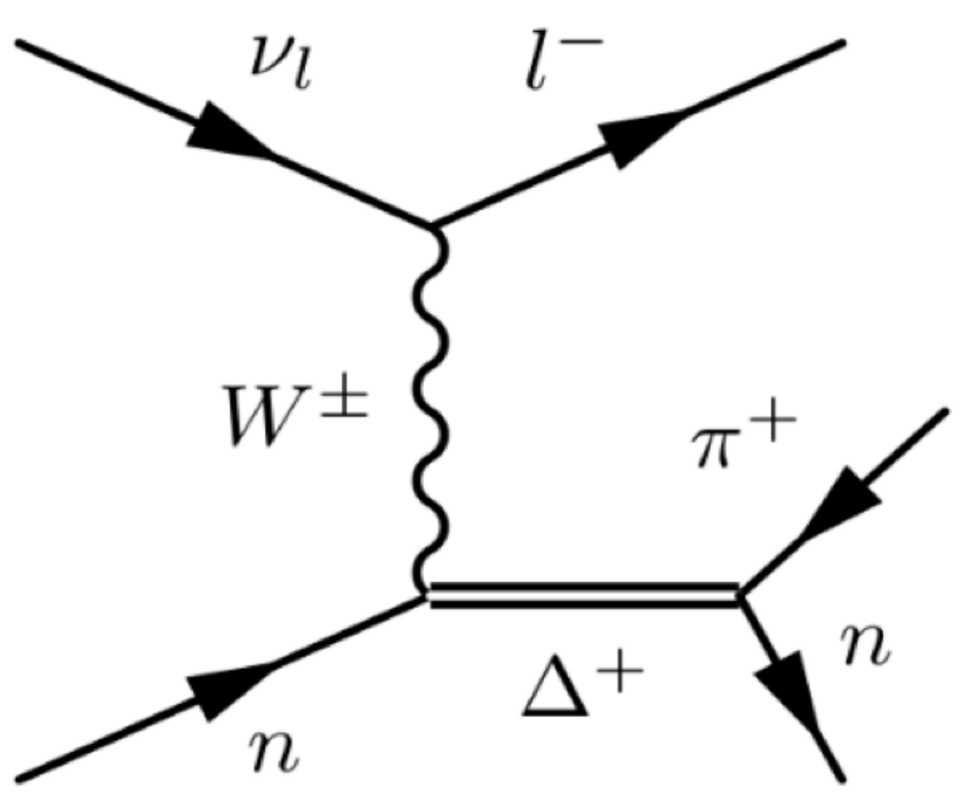

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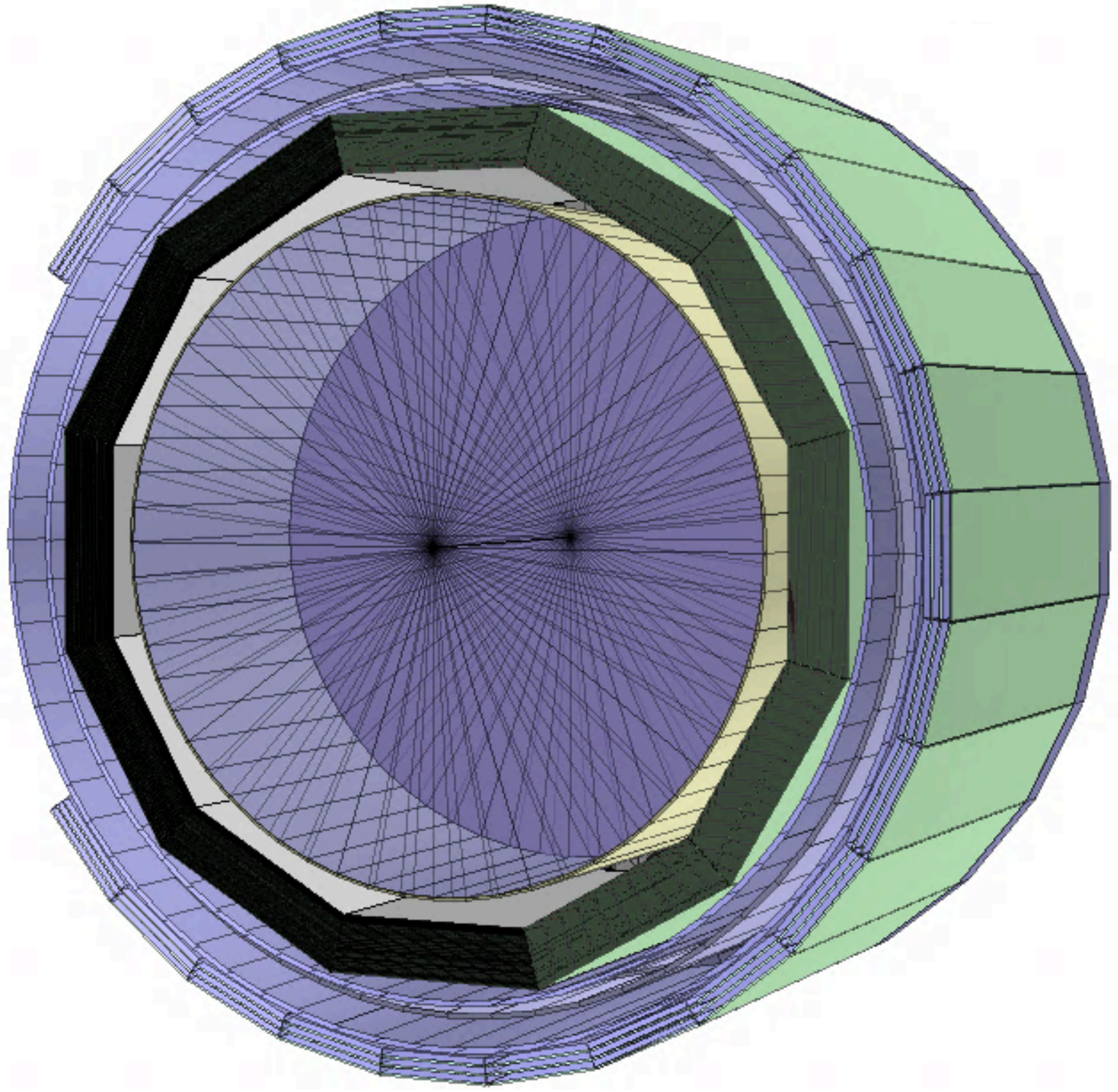
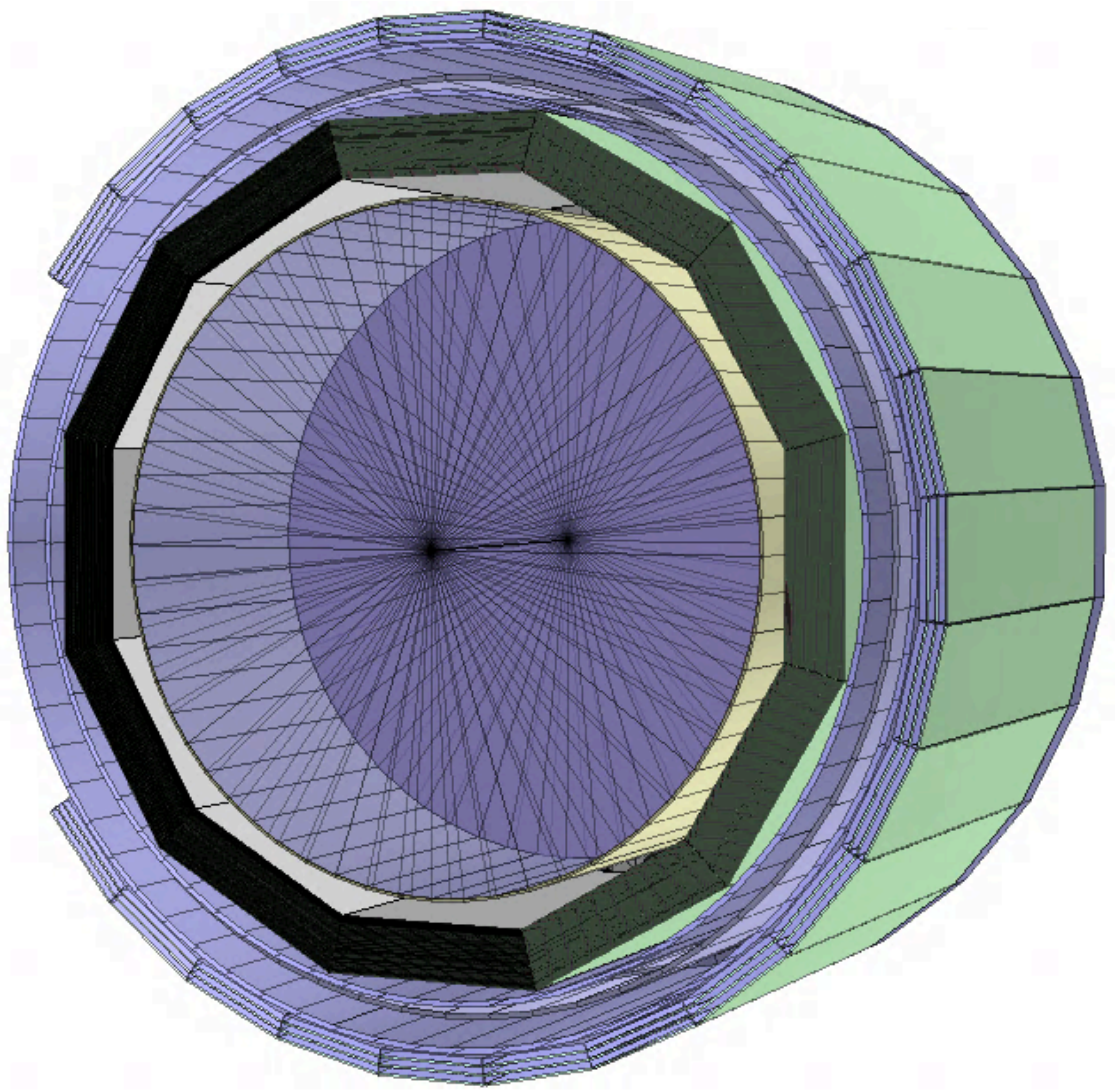
Misidentification of muon on pion will lead to wrong reconstruction of the energy and nature of the interaction→joint task of ECAL and muon detector

ECAL Concept



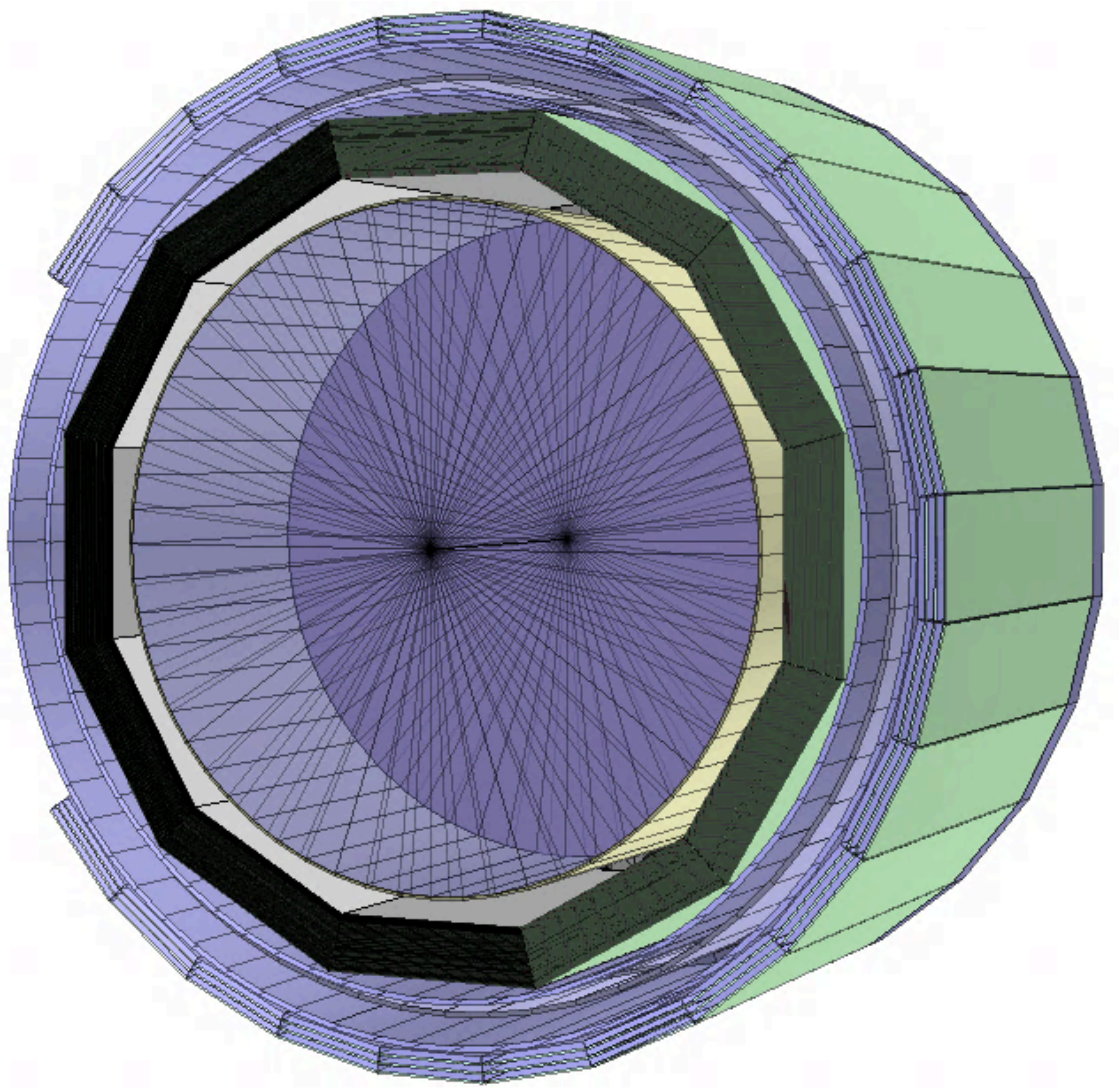
ECAL Concept

- 12-sided geometry



ECAL Concept

- 12-sided geometry
- Key design features:
  - High granular layers based on CALICE R&D (AHCAL SiPM-on-tile design)



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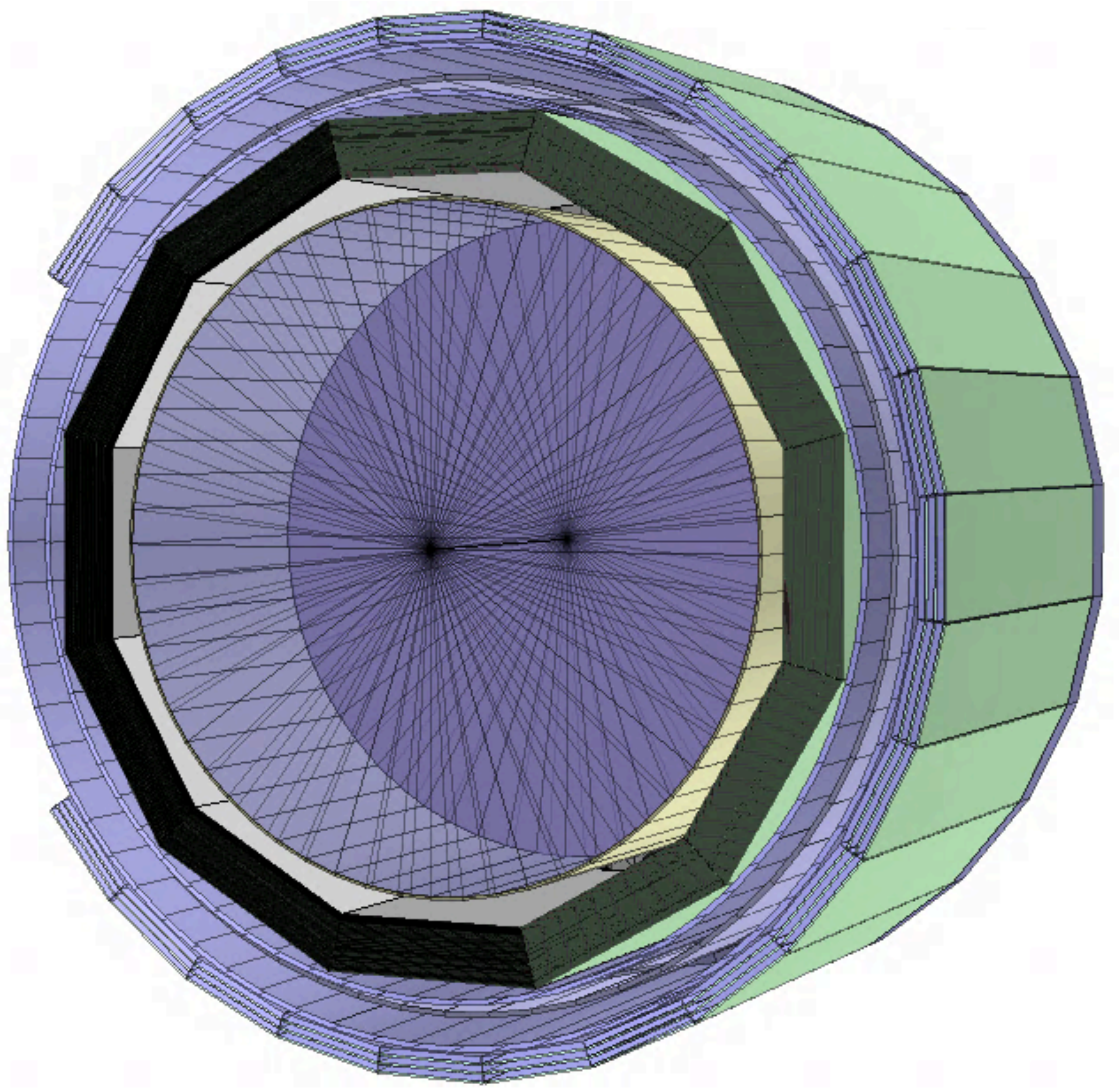

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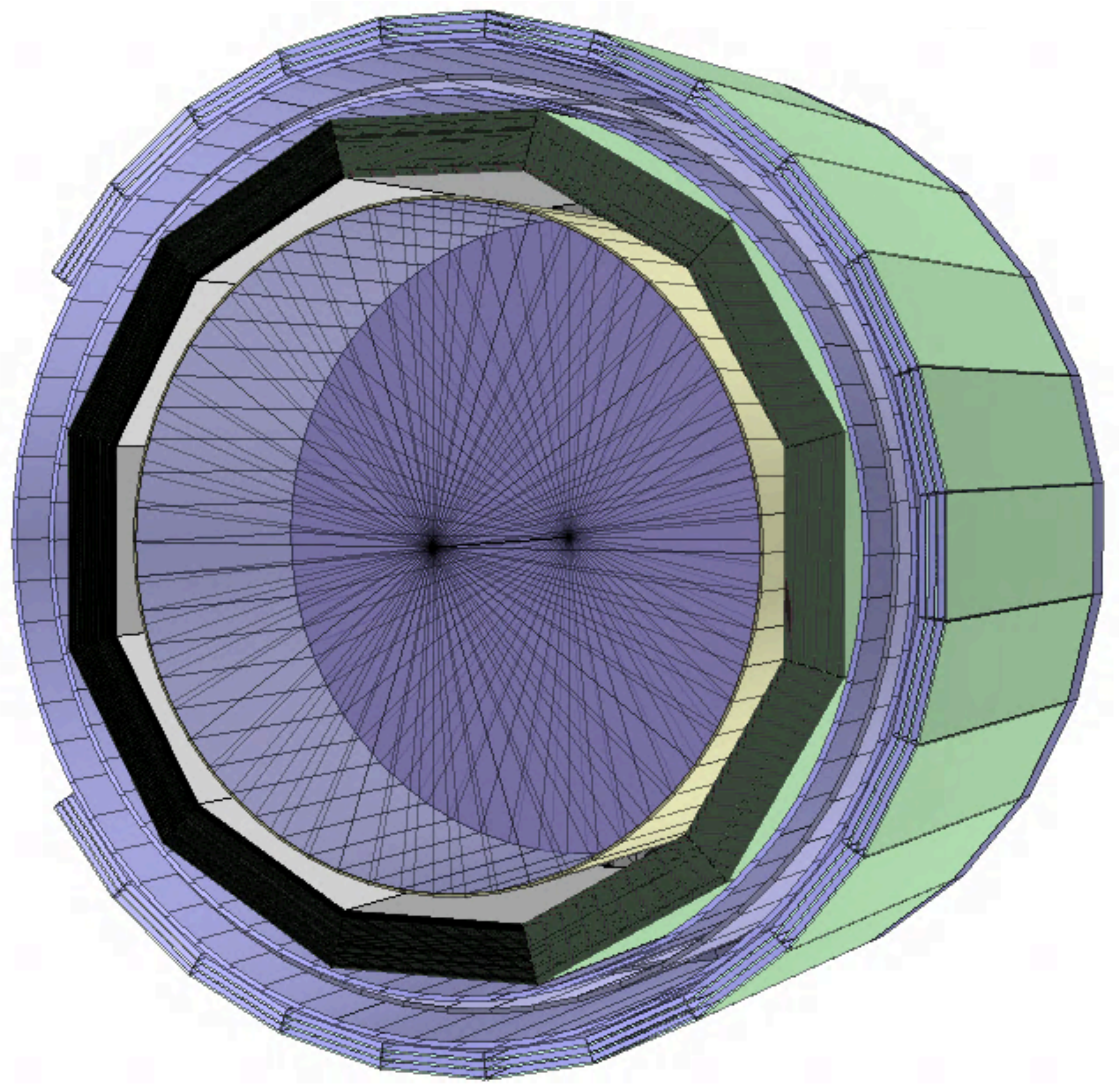

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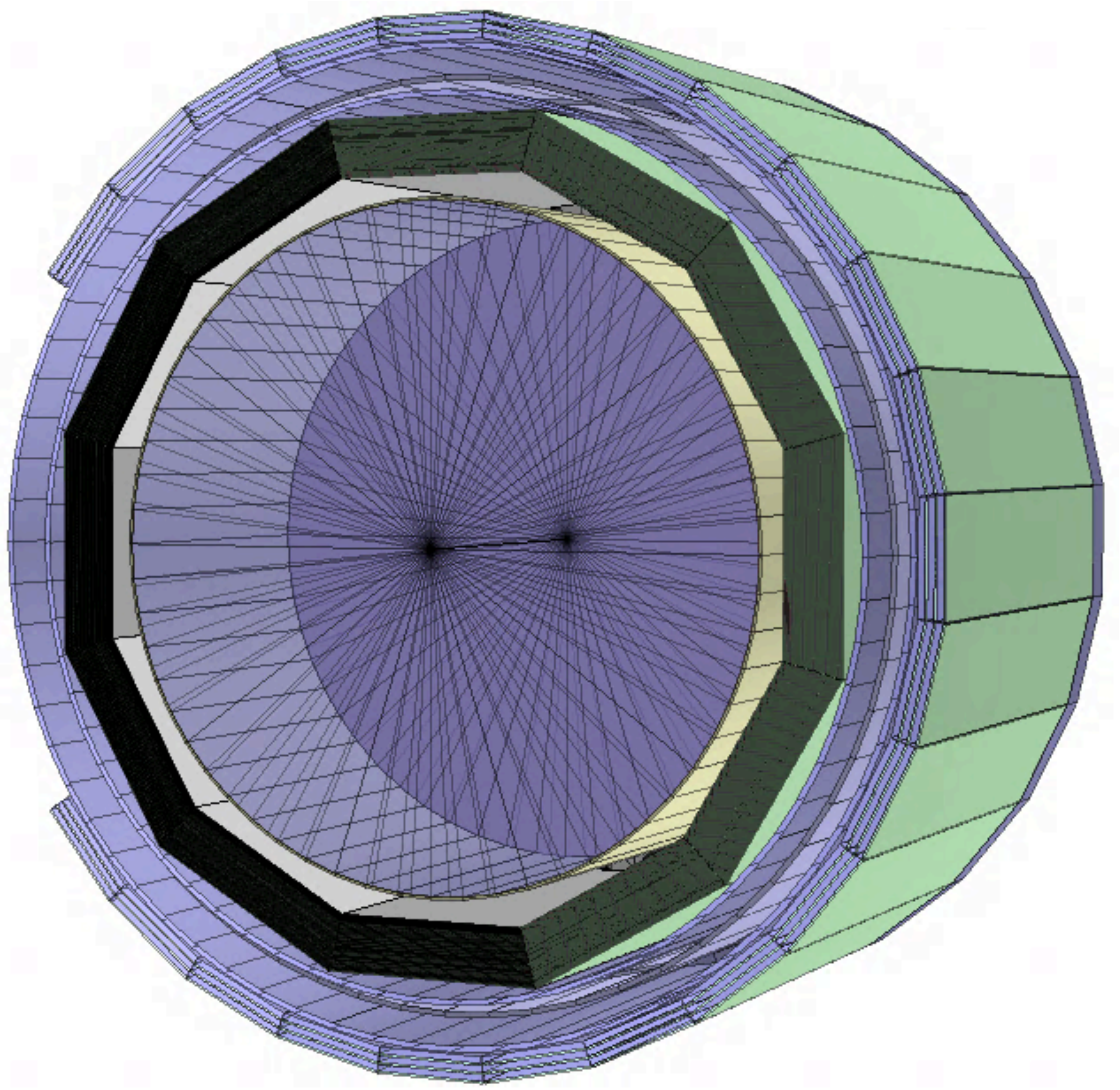
- SiPM readout of ~1- 3M channels



ECAL - Energy Resolution

By Eldwan Brianne

Obtained with a dataset of single photons from 50MeV to 1.7GeV:

- TPC center, downstream direction, 20deg opening angle
- 0.2MIP hit energy cut

* CDR ECAL has more layers and copper absorber

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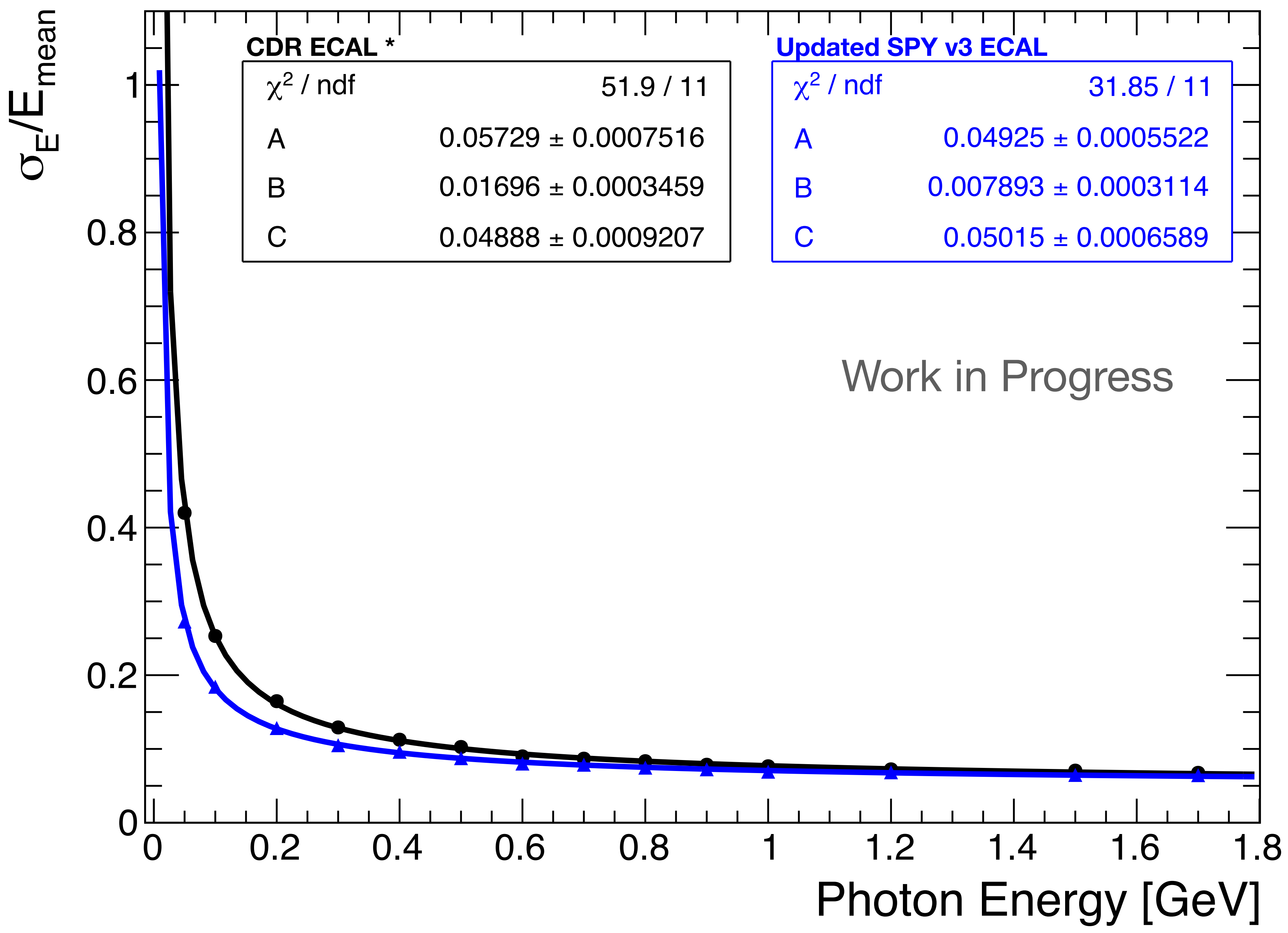
$$\frac{\sigma_E}{E_{mean}} = \frac{A}{\sqrt{E}} \oplus \frac{B}{E} \oplus C$$



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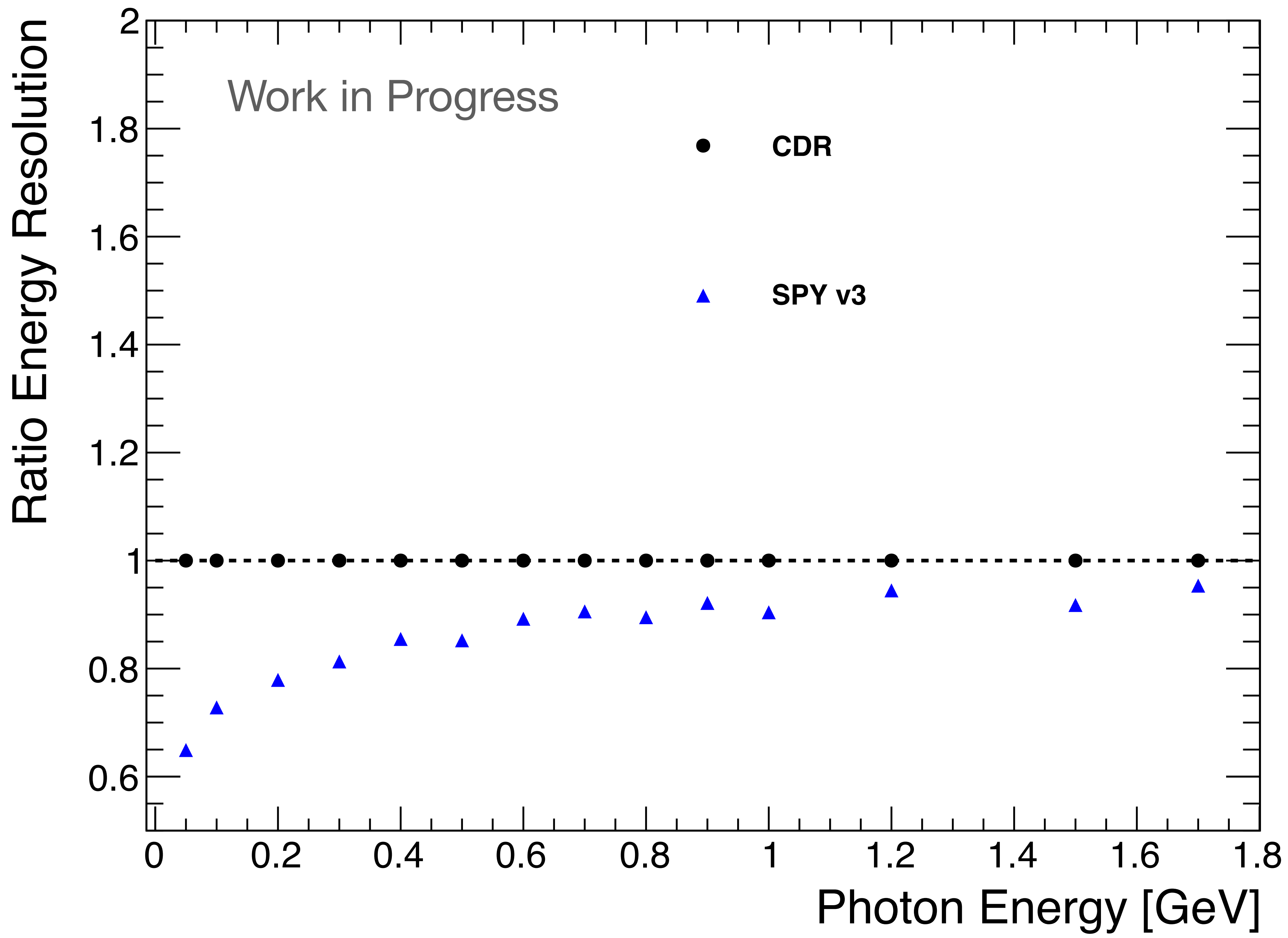

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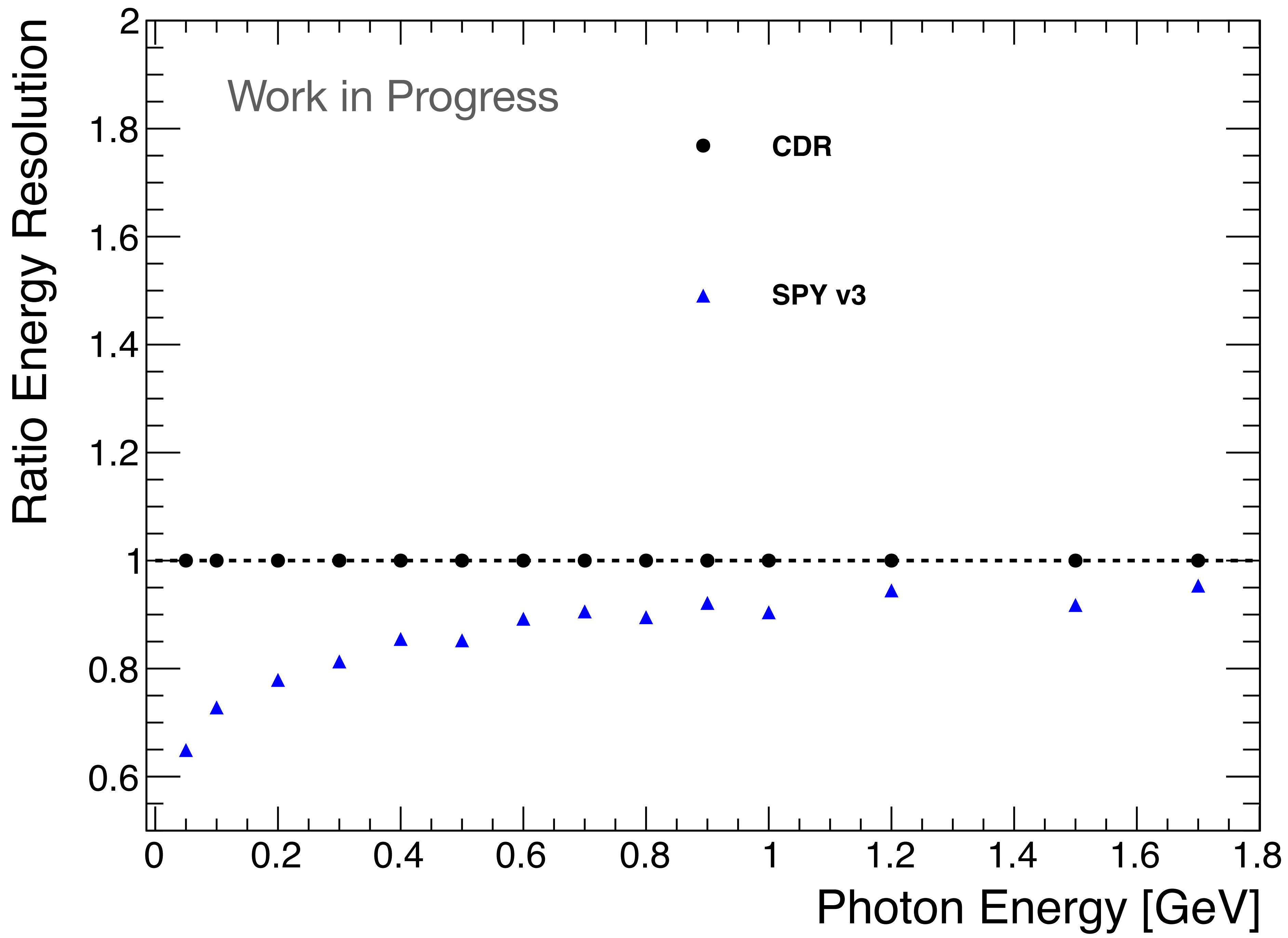
Energy resolution is important to reconstruct the energy of photons:

- $\pi^0 \rightarrow \gamma\gamma$ reconstruction by invariant mass constraint



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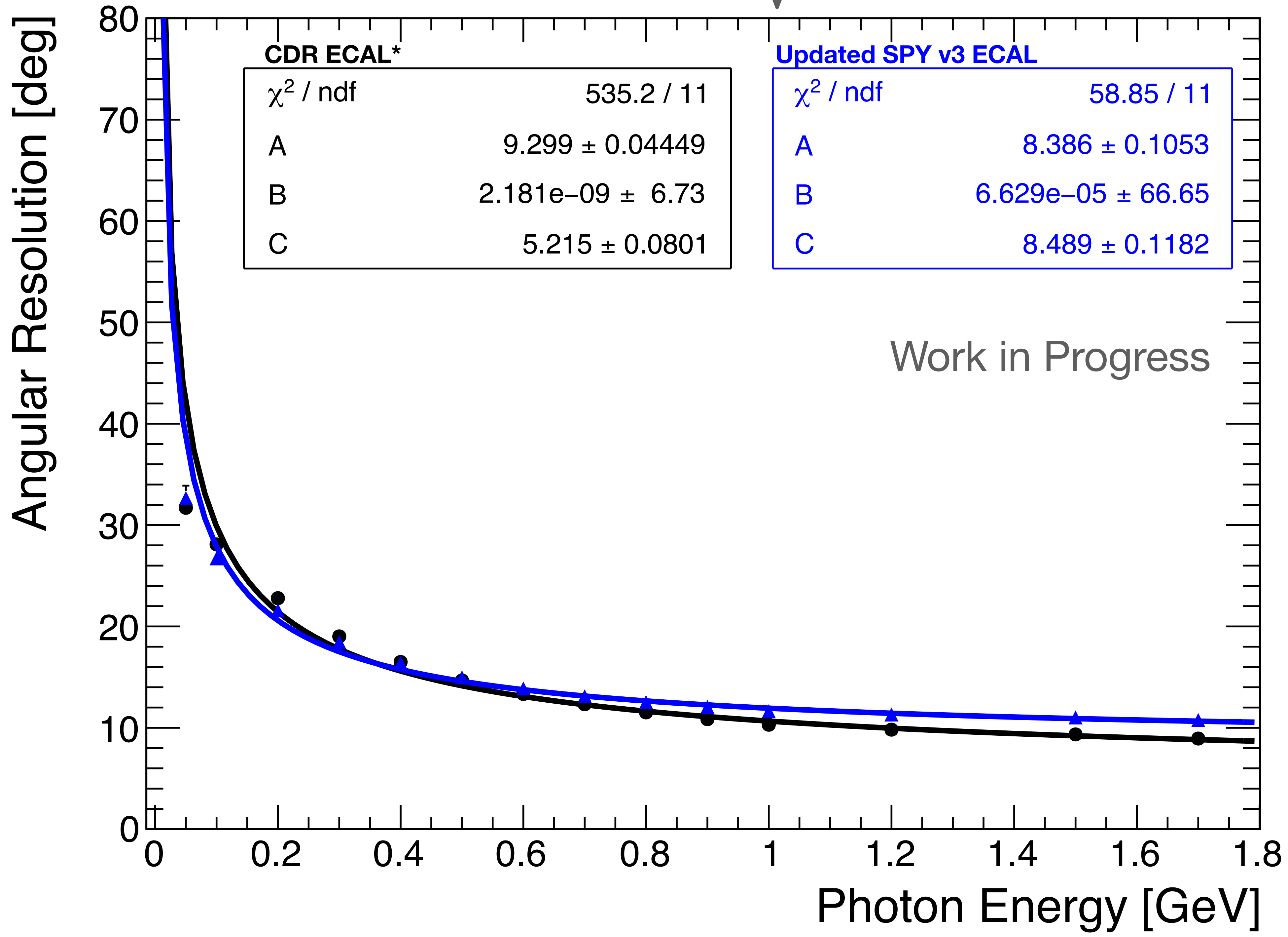
Particle direction obtained by principal component analysis on the calorimeter hits

$$AngularResolution = \frac{A}{\sqrt{E}} \oplus \frac{B}{E} \oplus C$$



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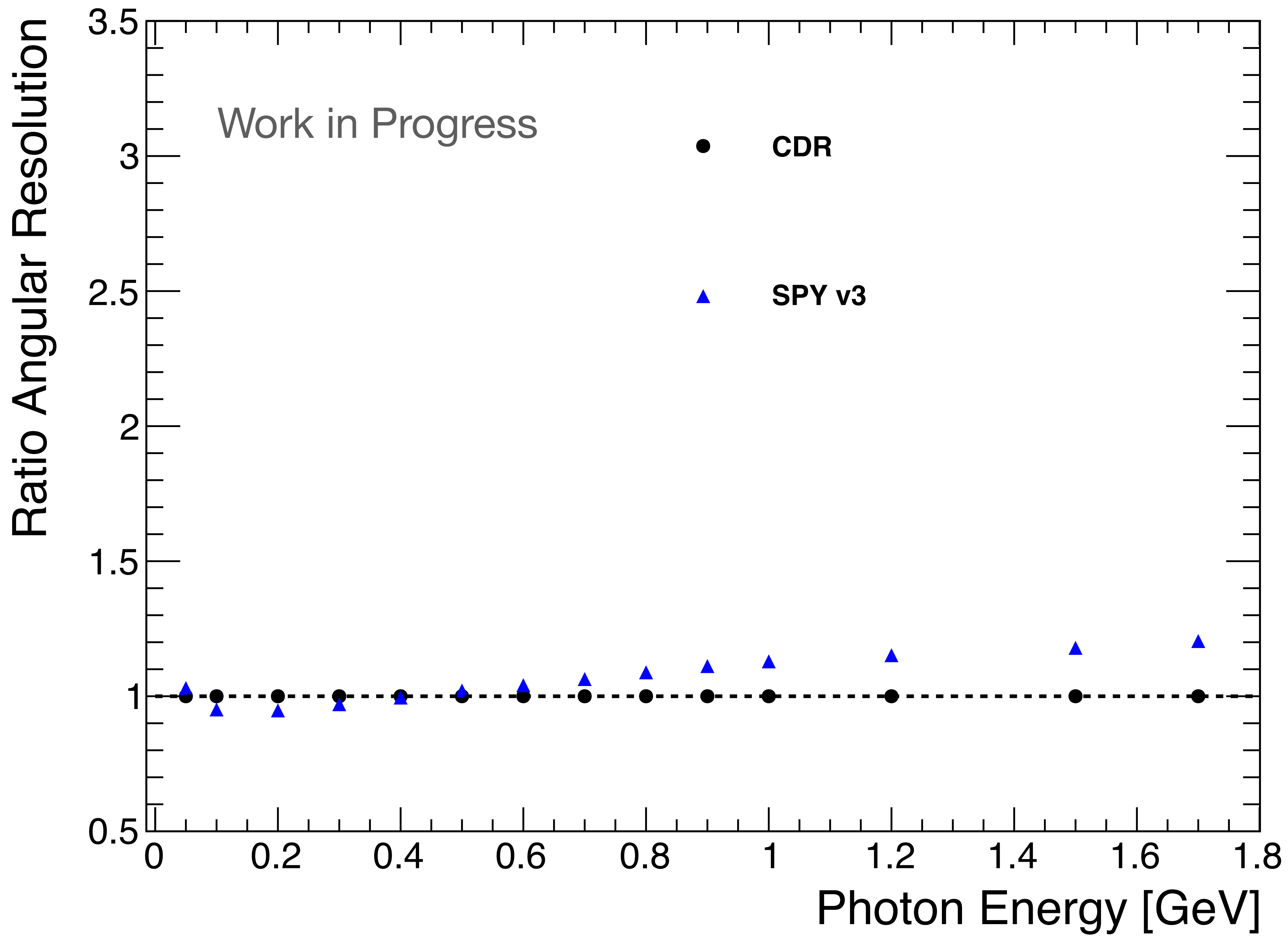

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ECAL - Angular Resolution

By Eldwan Brianne

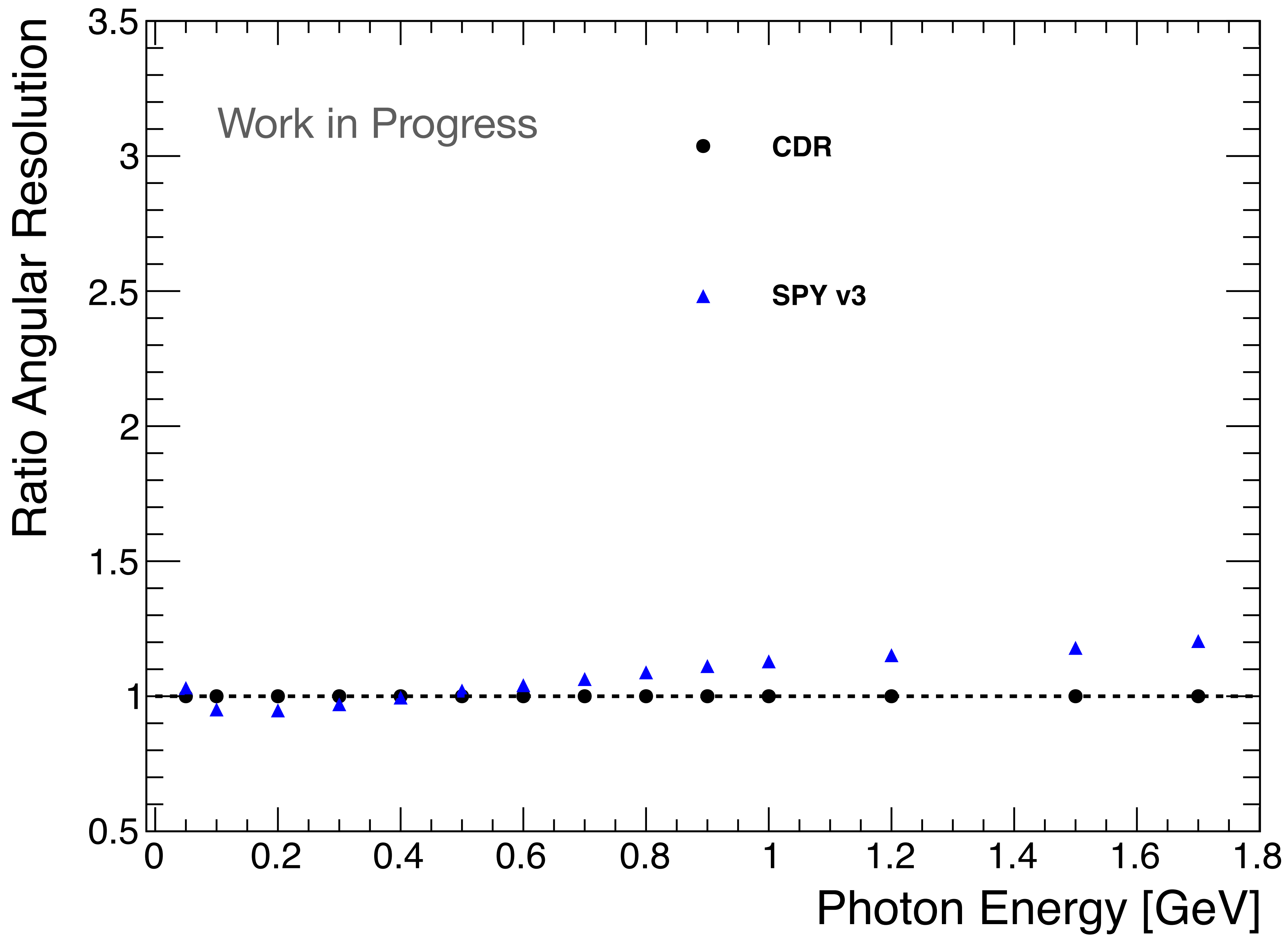
Obtained with a dataset of single photons from 50MeV to 1.7GeV:

- TPC center, downstream direction, 20deg opening angle
- 0.2MIP hit energy cut

Particle direction obtained by principal component analysis on the calorimeter hits

Angular resolution is important to reconstruct the direction of particles:

- $\pi^0 \rightarrow \gamma\gamma$ reconstruction by pointing back from the ECAL to the decay vertex



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Muon/Pion Separation

Monte Carlo samples produced with GENIE event generator:

- Training sample of 90000 muons and 90000 pions
- Validation sample of 10000 muons and 10000 pions
- Testing sample size of ~600000 with muon/pion ratio of 86%/14%
- Vertex position randomized inside TPC

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Gradient BDT Parameters:

- Binary classification, binary logloss
- Maximum tree depth of 3, maximum 7 leaves
- Minimum 40 samples required to create new split

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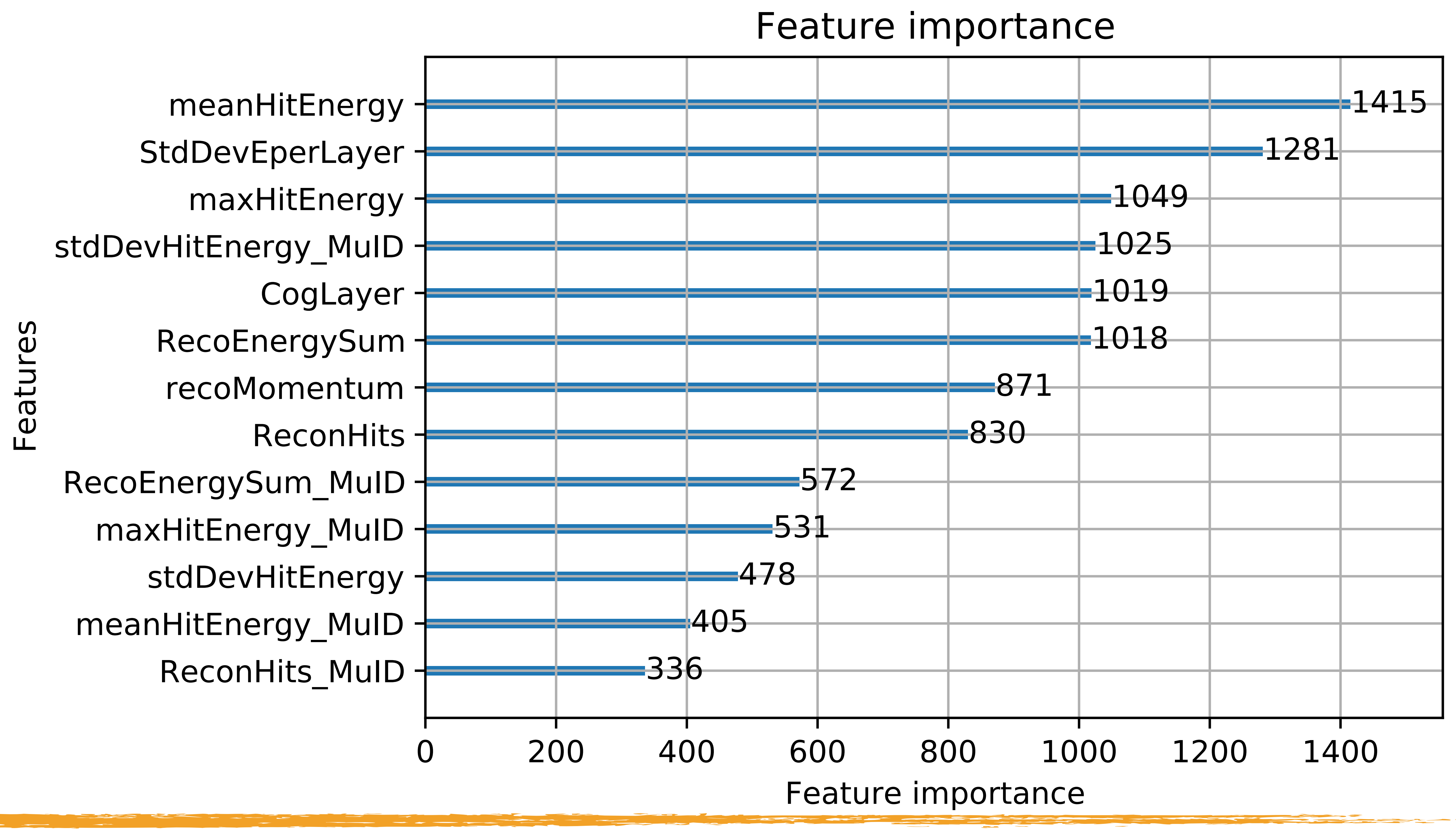

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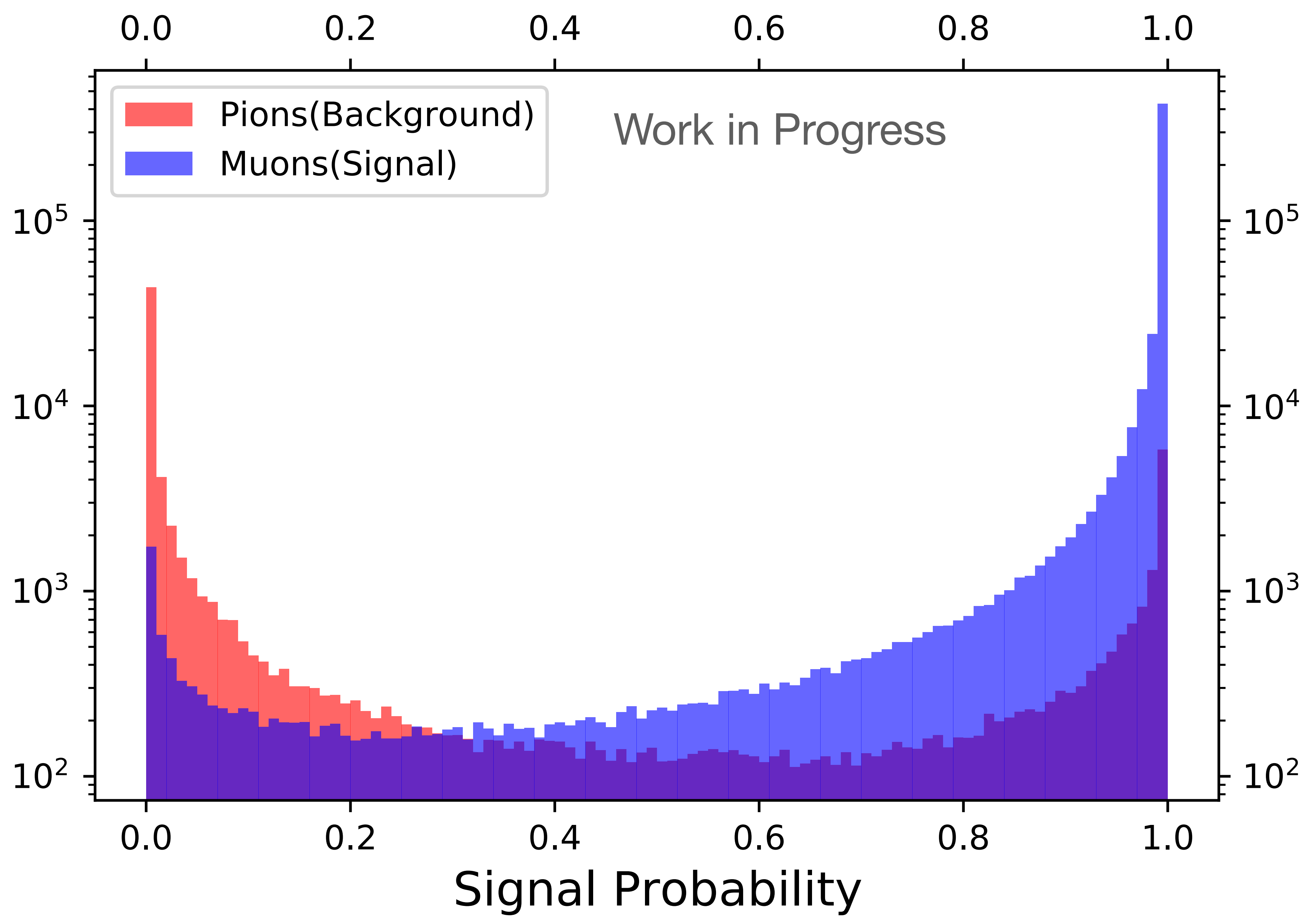


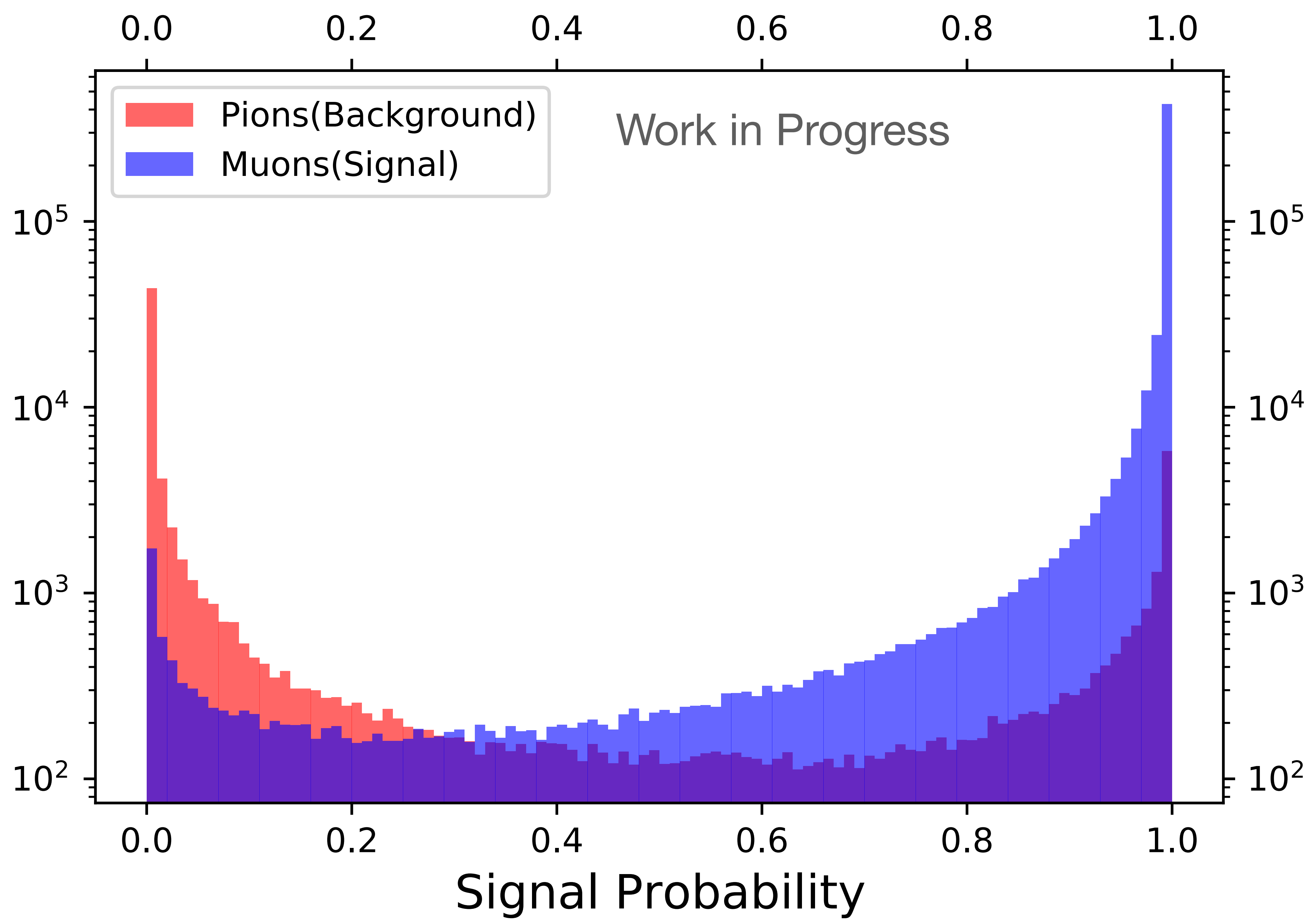
Detection threshold=0.5

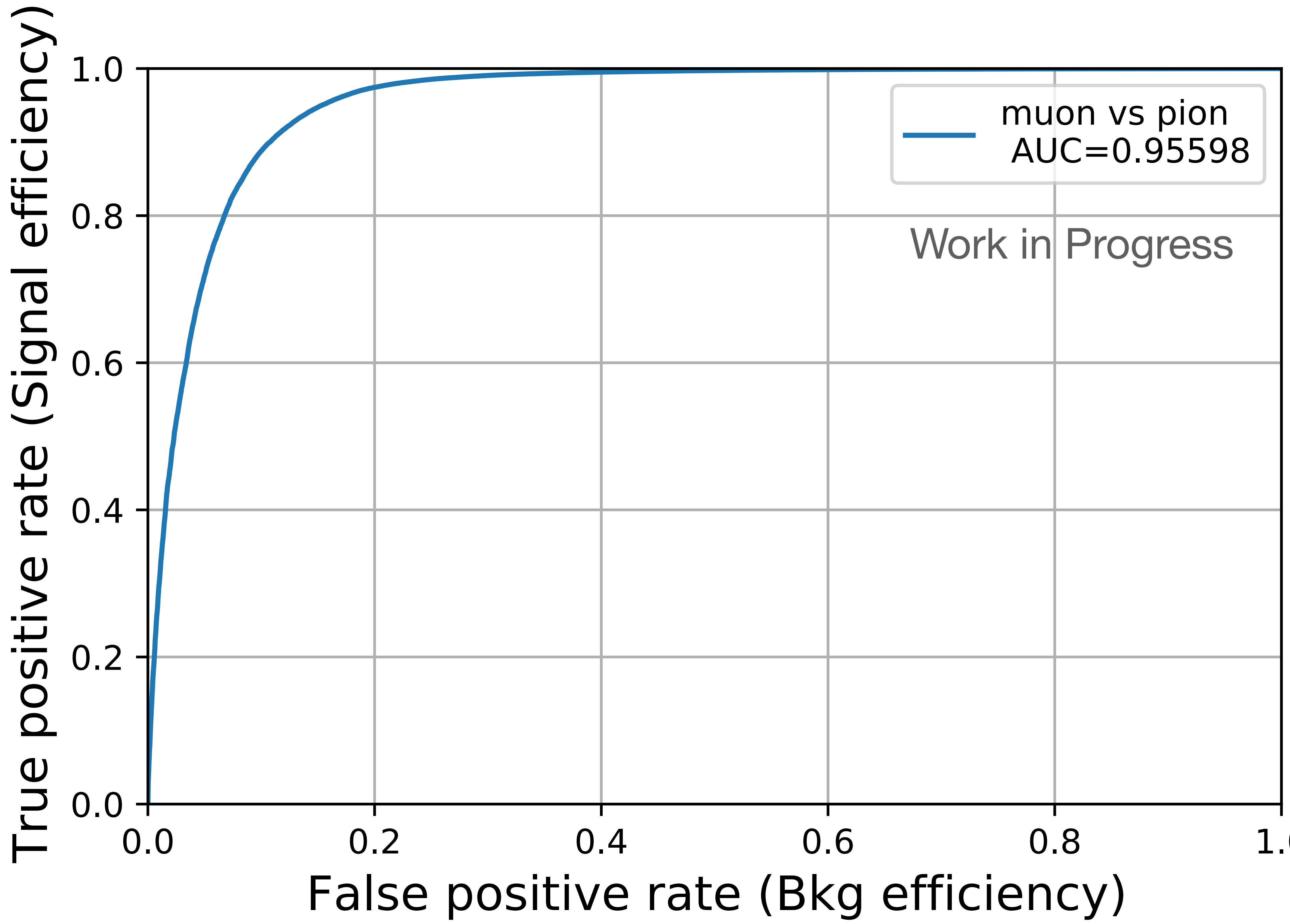
20% of 81950 Pions misidentified

2.3% of 528316 Muons misidentified

Obtained with CDR Geometry

Muon/Pion Separation





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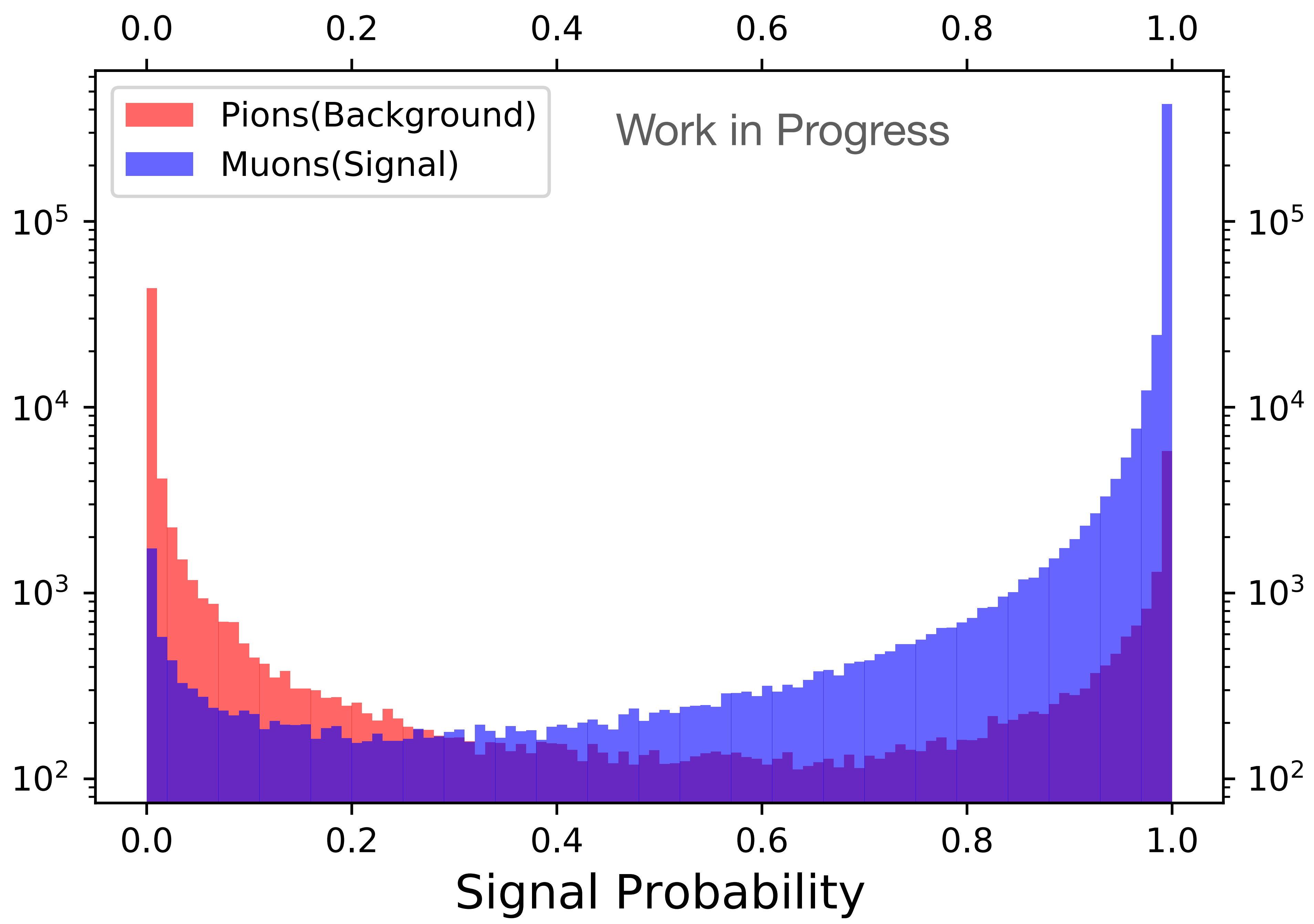

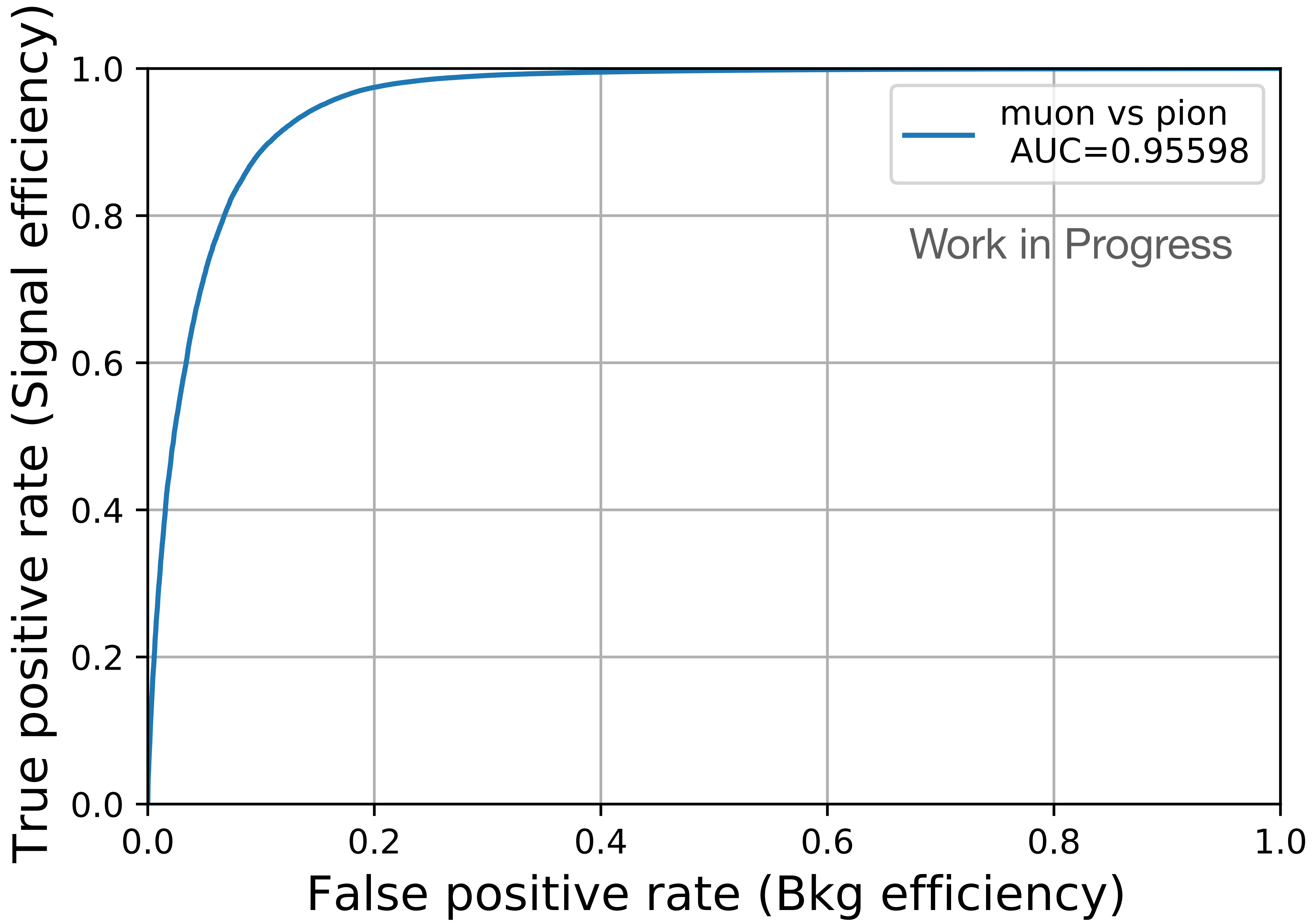

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Mu/Pi ratio of ~2% at
Signal Probability >0.99

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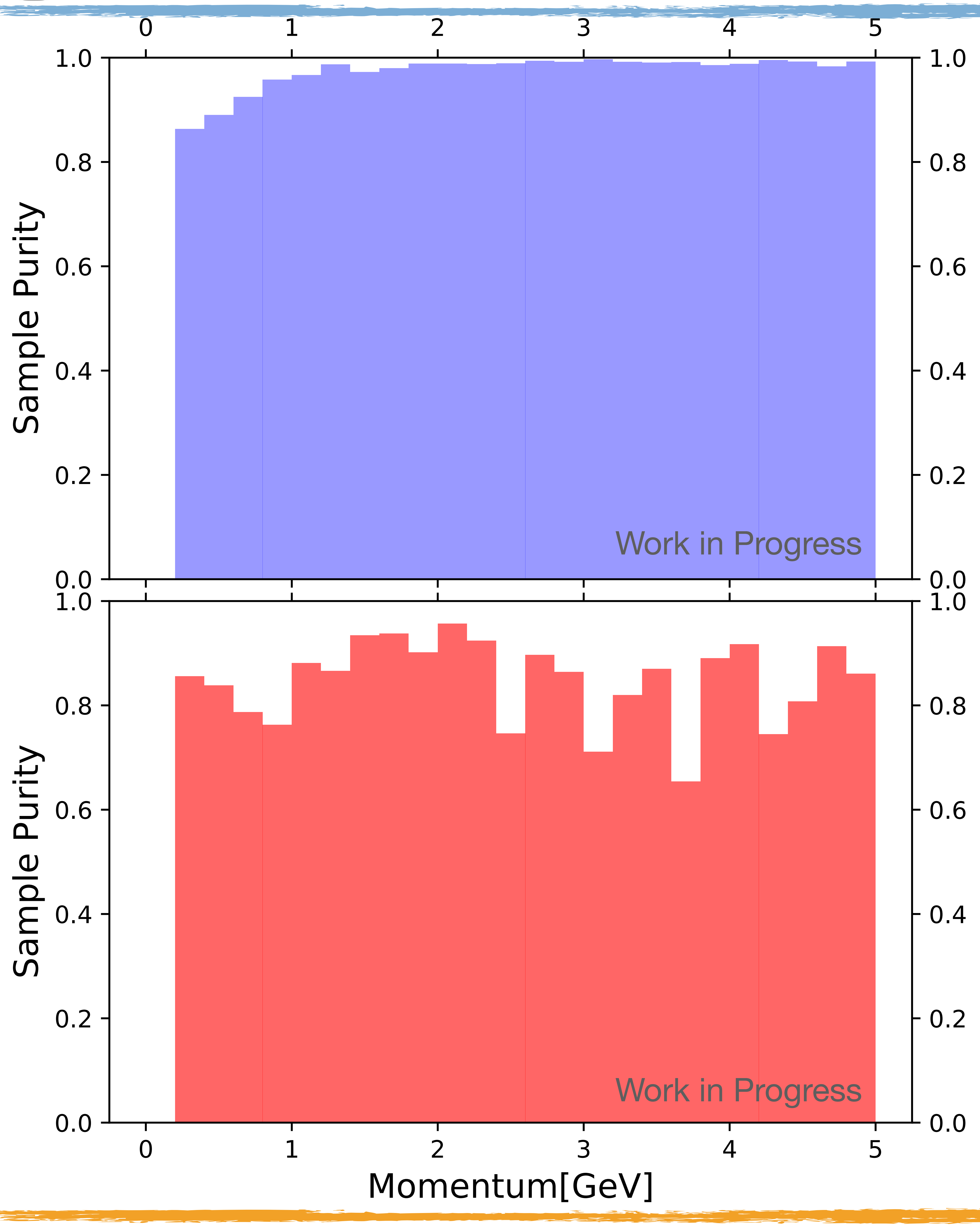

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Muons

Pions

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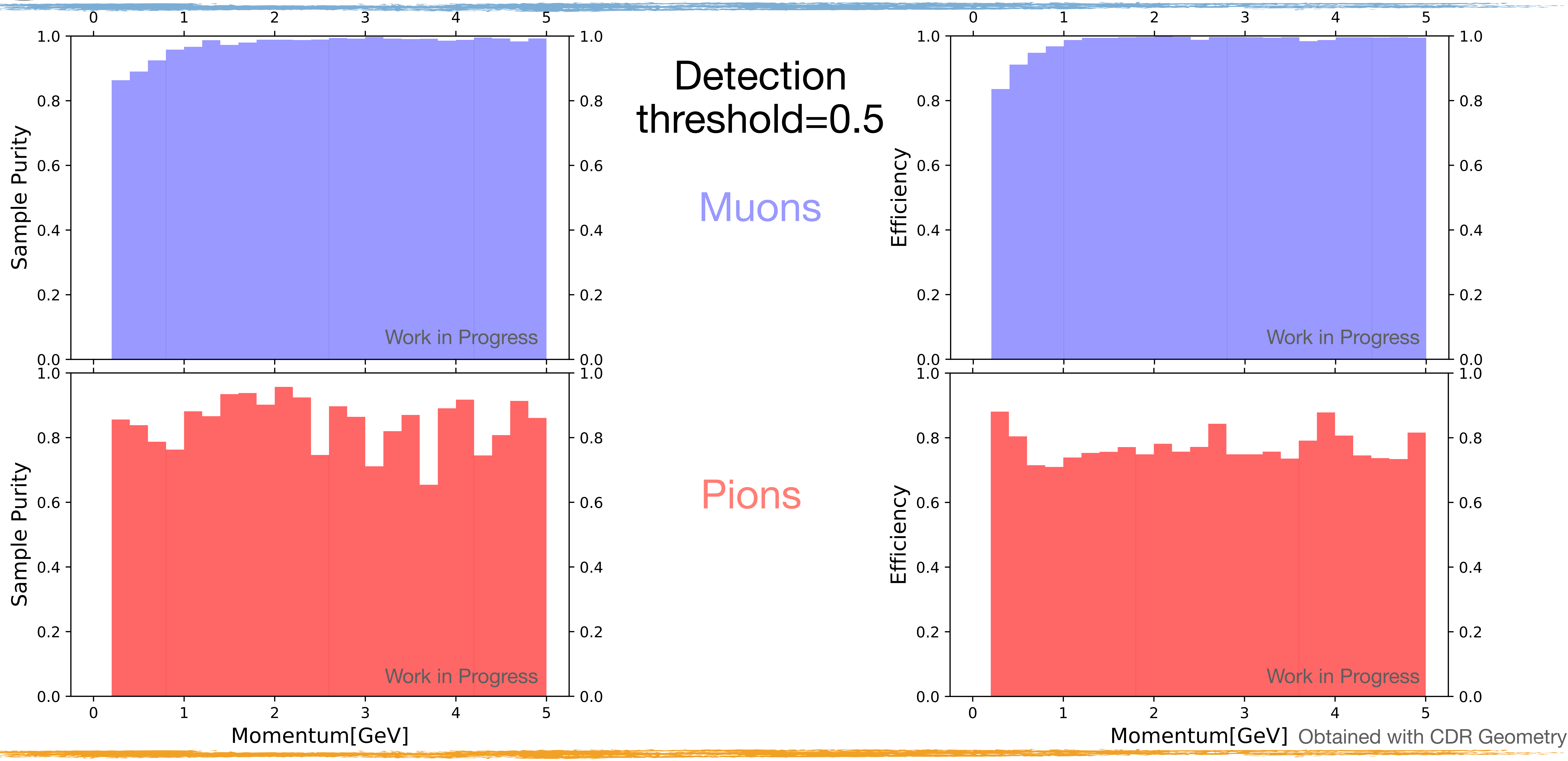


Conclusion

The ECAL in the ND-GAr has serval tasks:

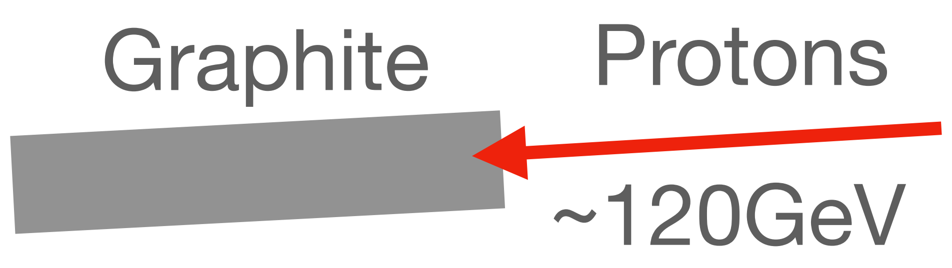
- Photon reconstruction for neutral Pion identification
- Neutron reconstruction -> See next talk by Asma Hadef
- Muon/Pion separation

Simulation results:

- Stochastic energy resolution of ~6%/sqrt(E), angular resolution of ~8.3%/sqrt(E)
- Neutron efficiency of ~40%
- Muon sample purity of ~ 85% to 98% (signal detection threshold of $p_{BDT}>0.5$)
- Pion sample purity of ~80% (background detection threshold of $p_{BDT}<0.5$)

Backup

The DUNE Near Site



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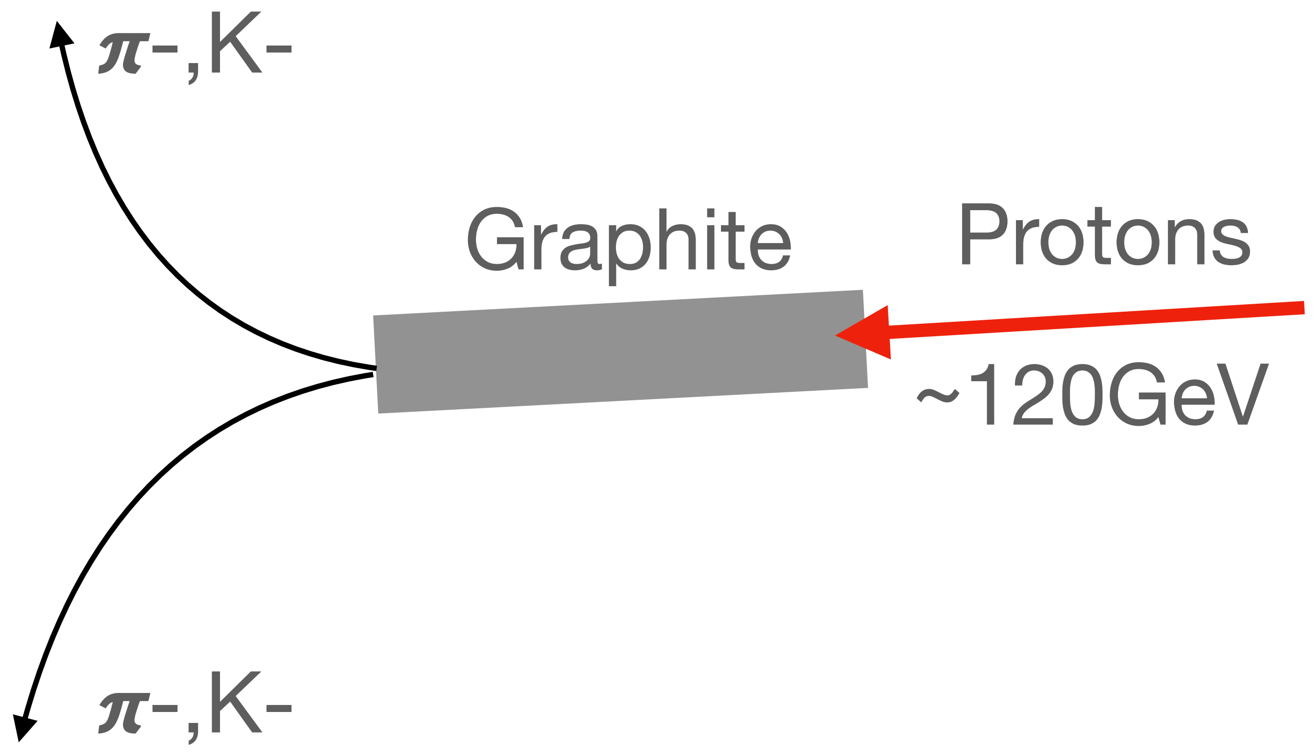

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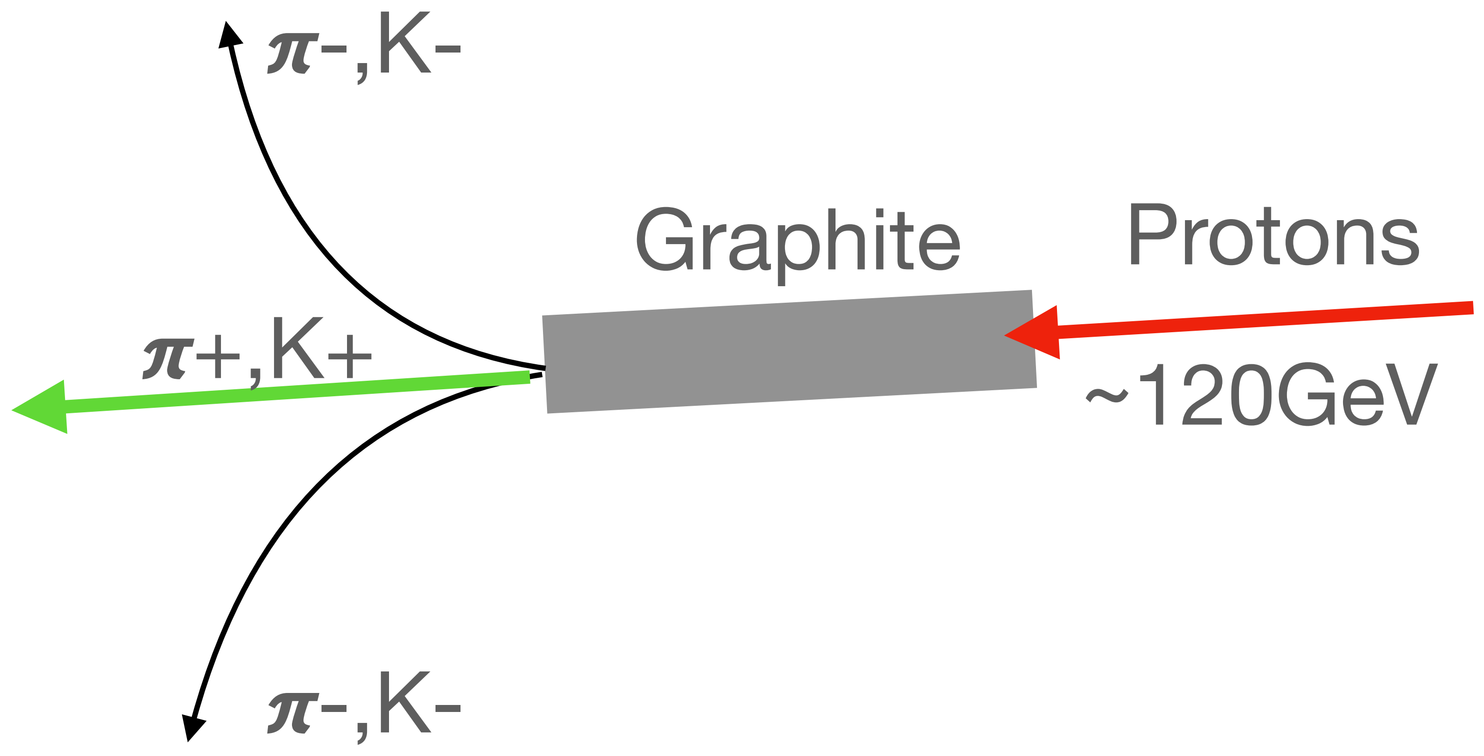

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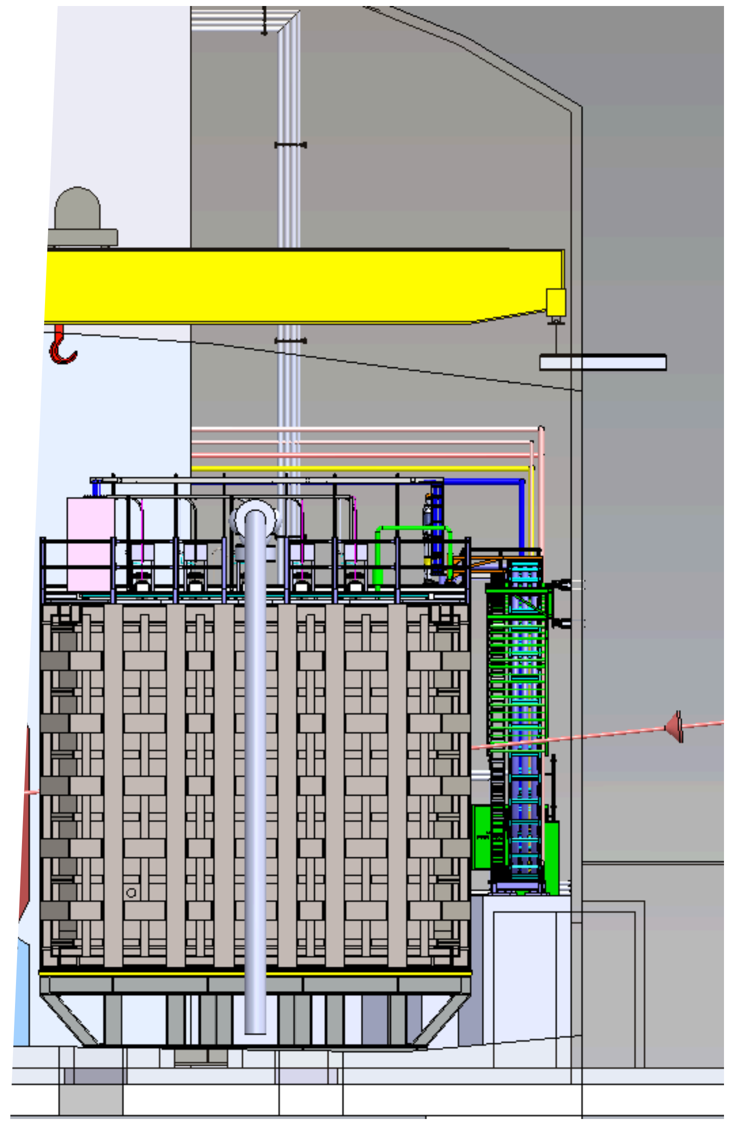
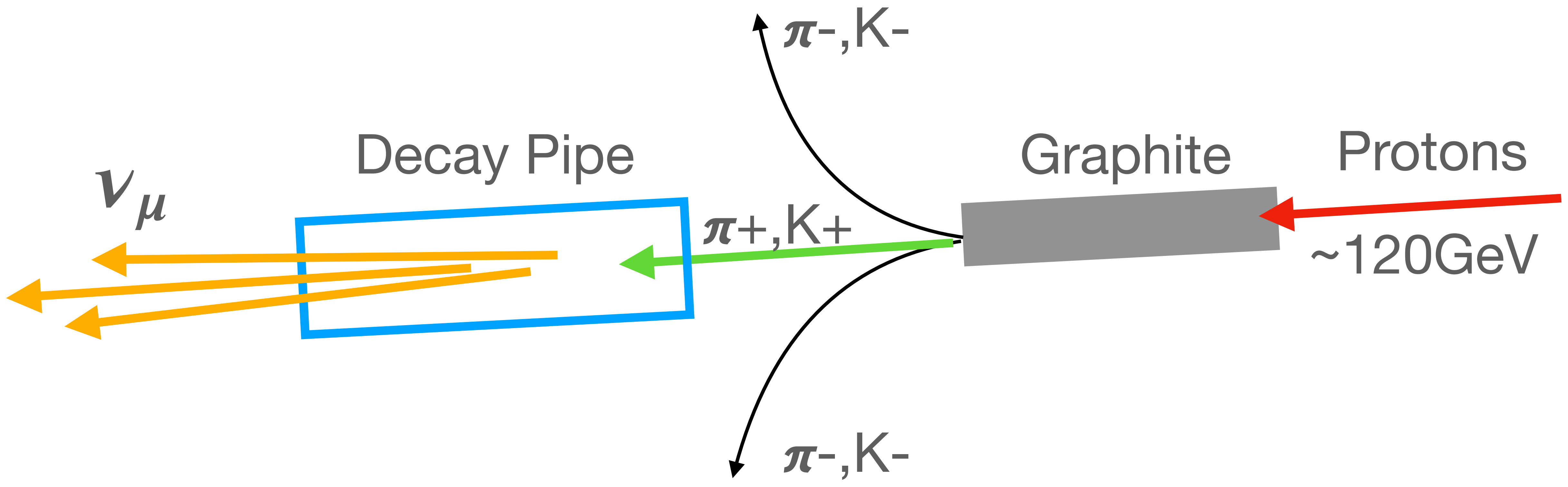
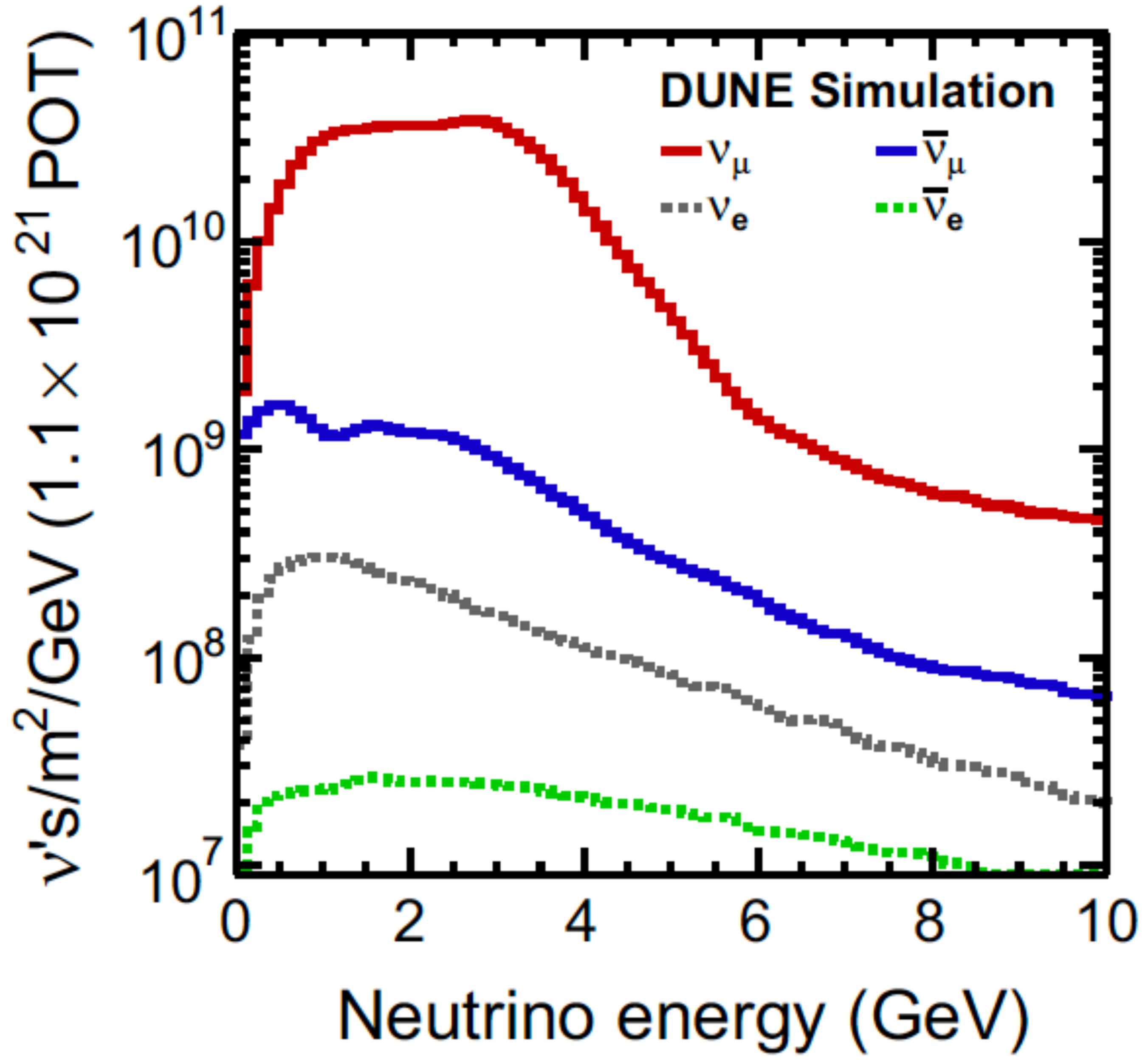




Liquid Argon Time Projection Chamber:



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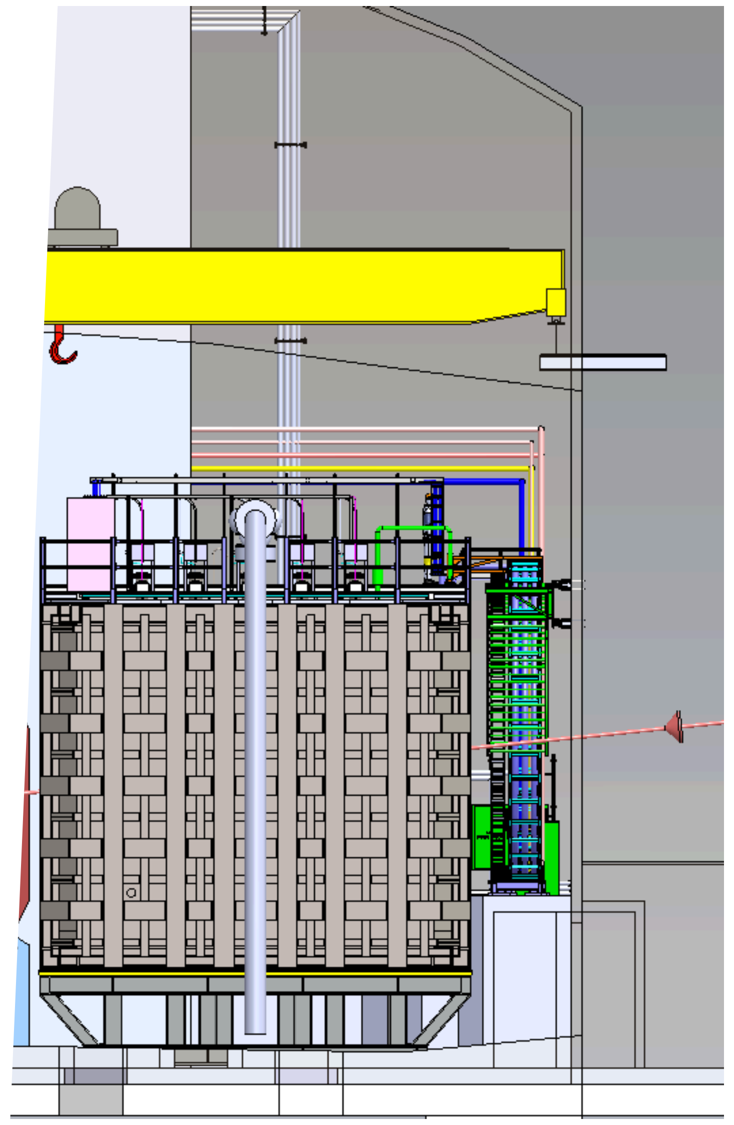

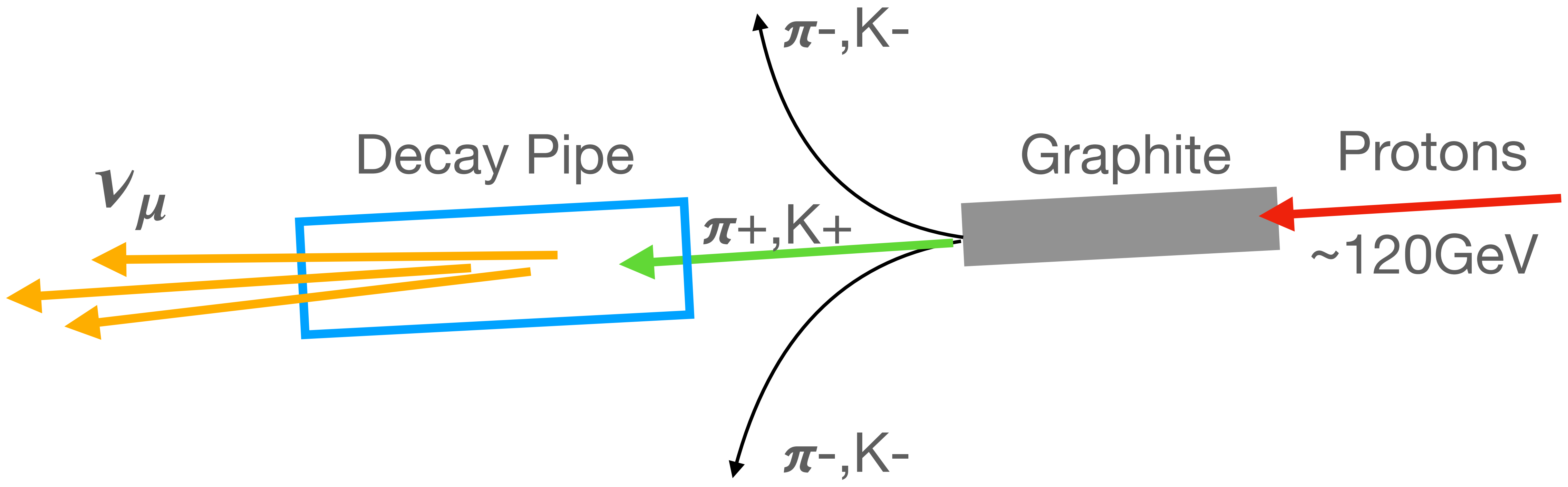

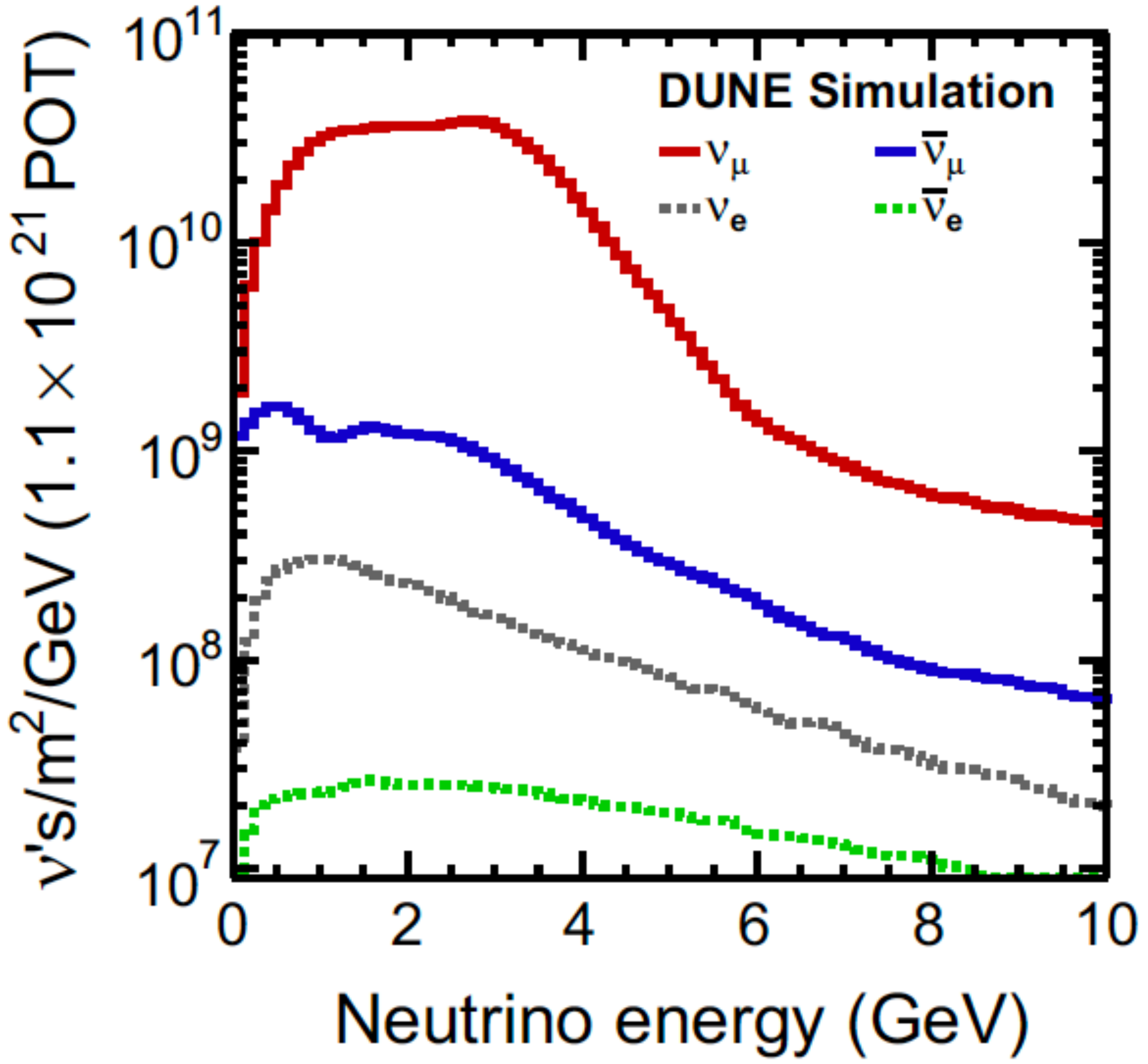

Liquid Argon Time Projection Chamber:

- Same target material as far detector, cancellation of systematics

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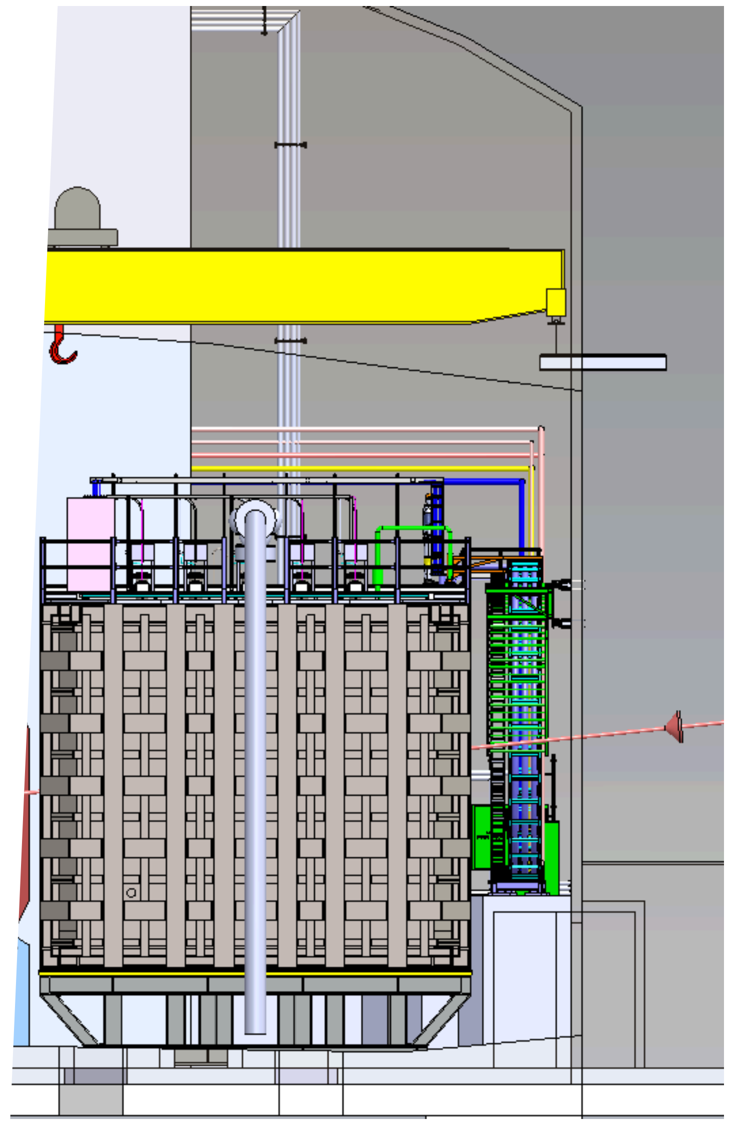

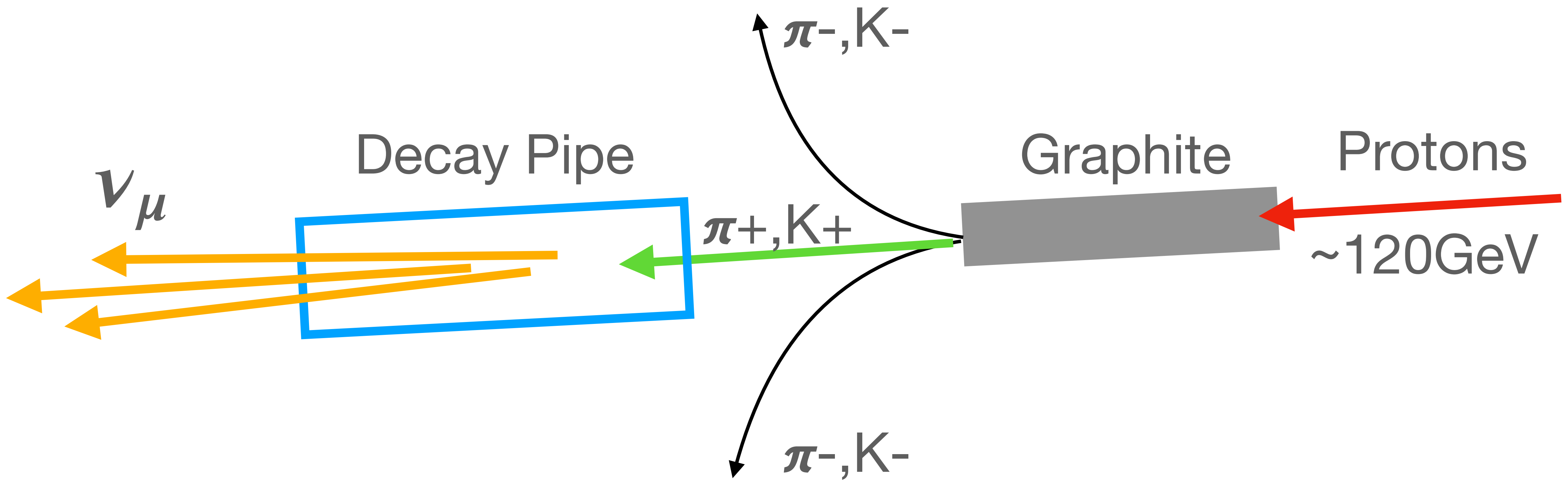

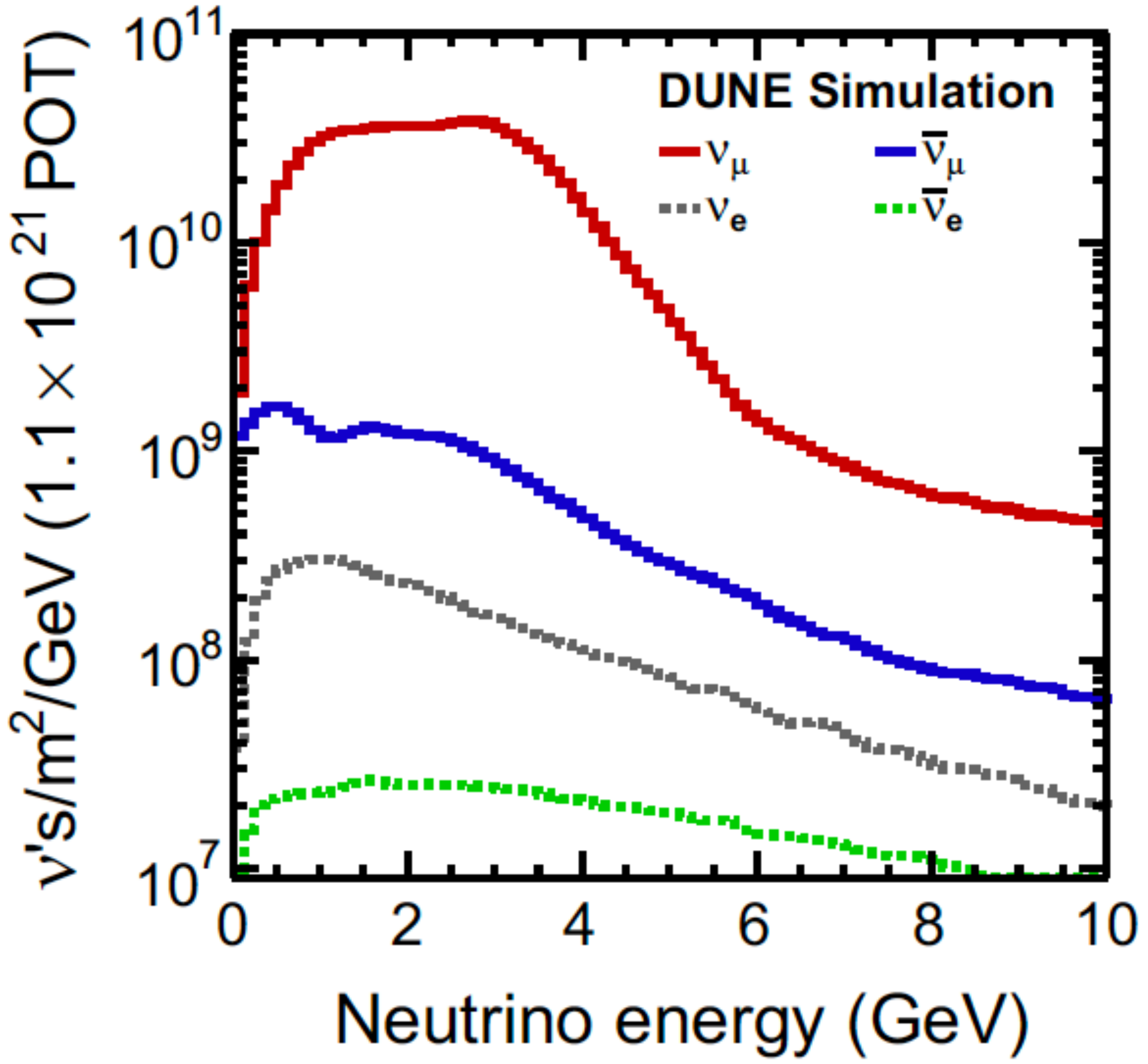

Liquid Argon Time Projection Chamber:

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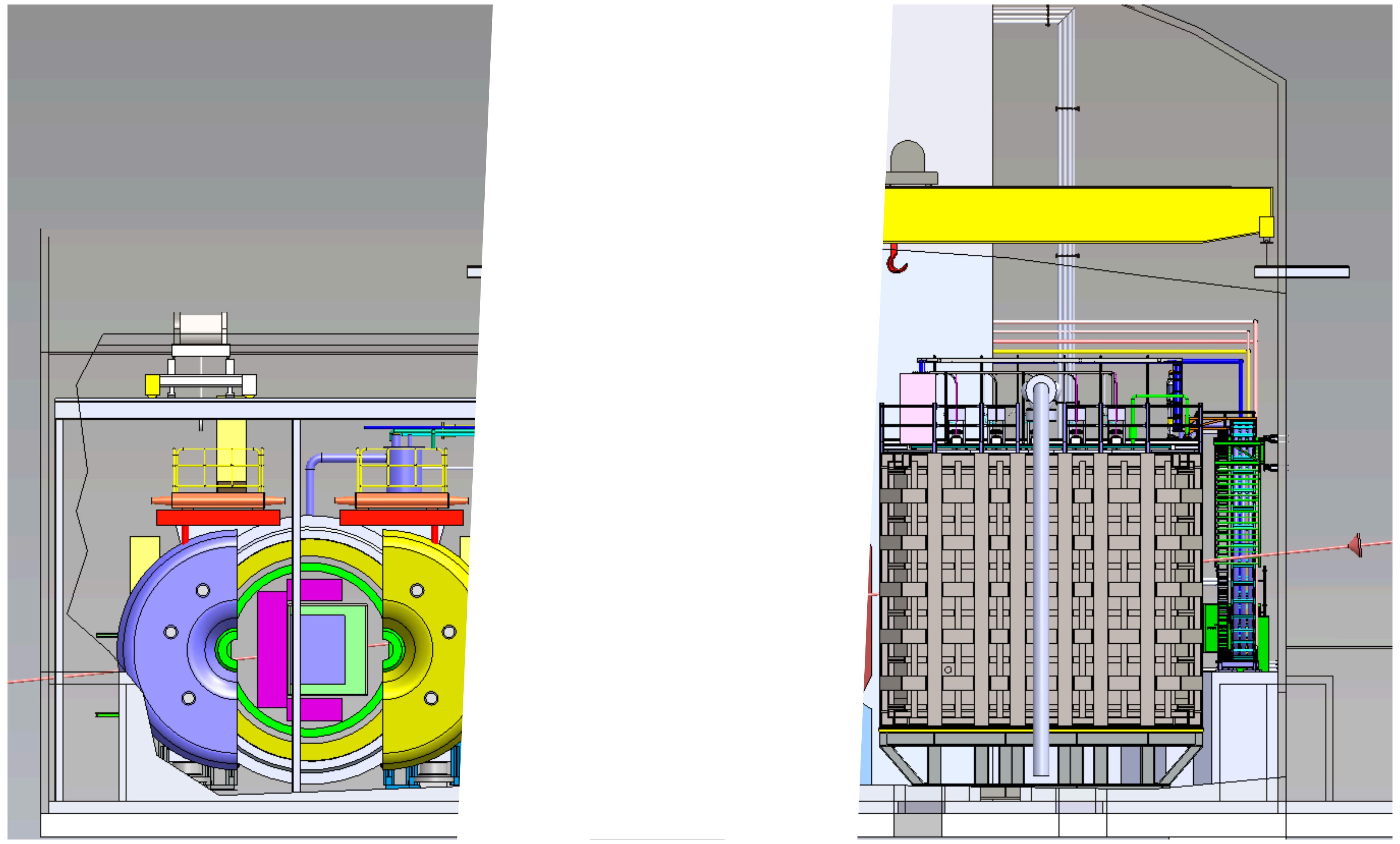
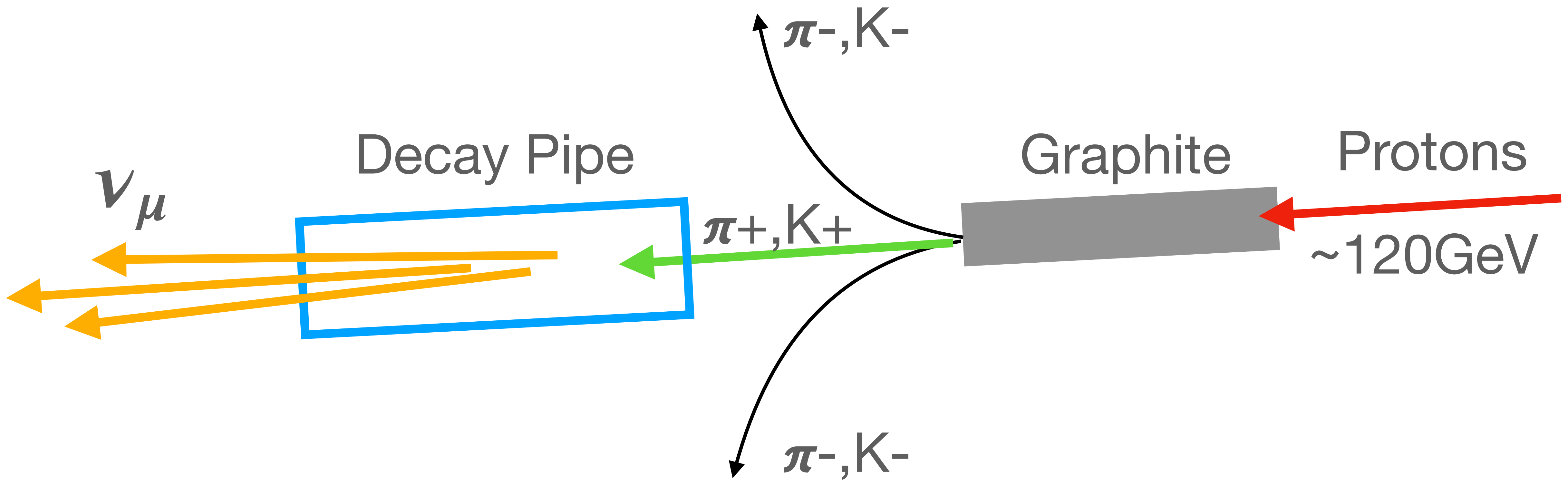
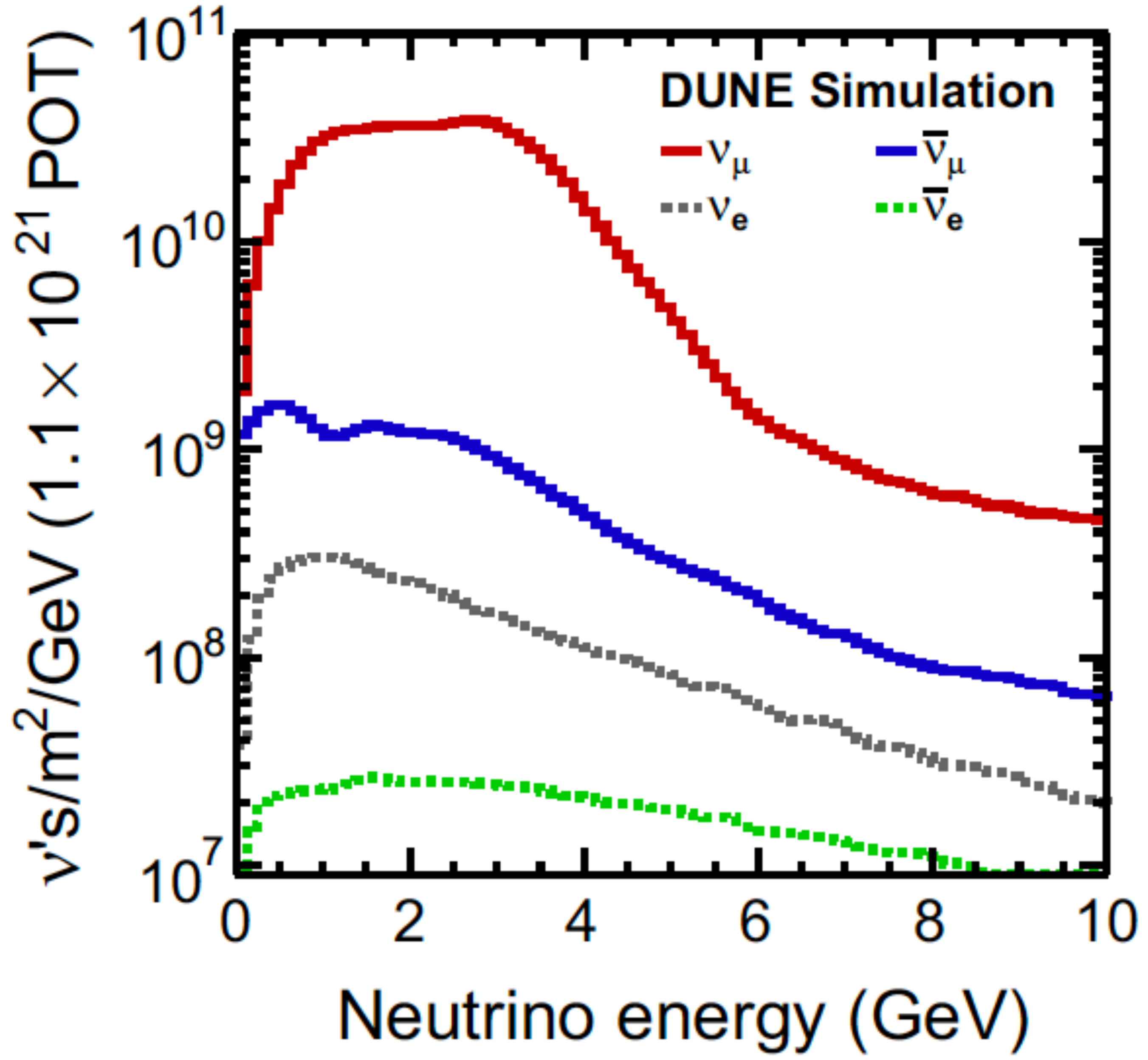
- High neutrino event rates, moveable

The DUNE Near Site





System for on-Axis Neutrino Detection:



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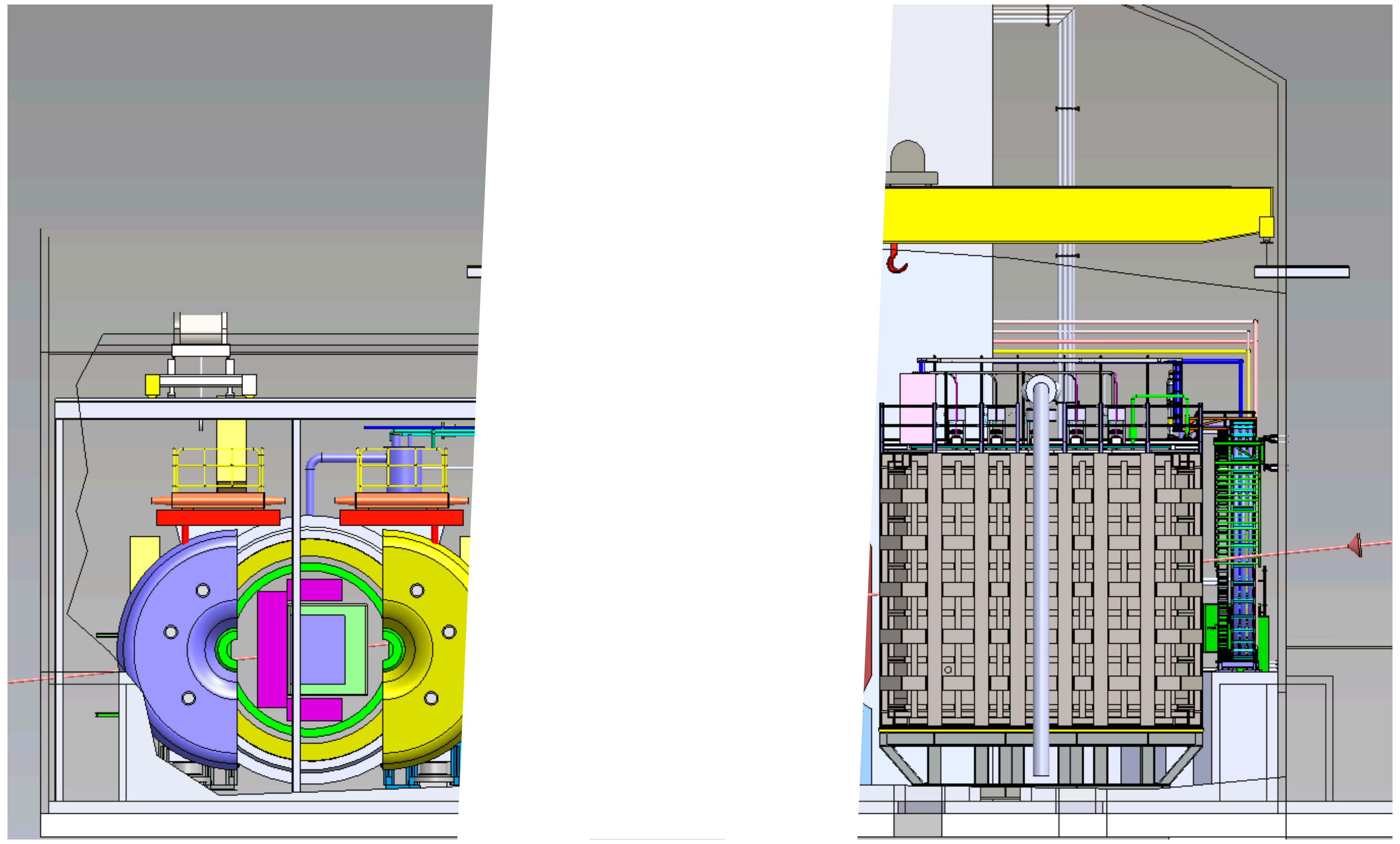

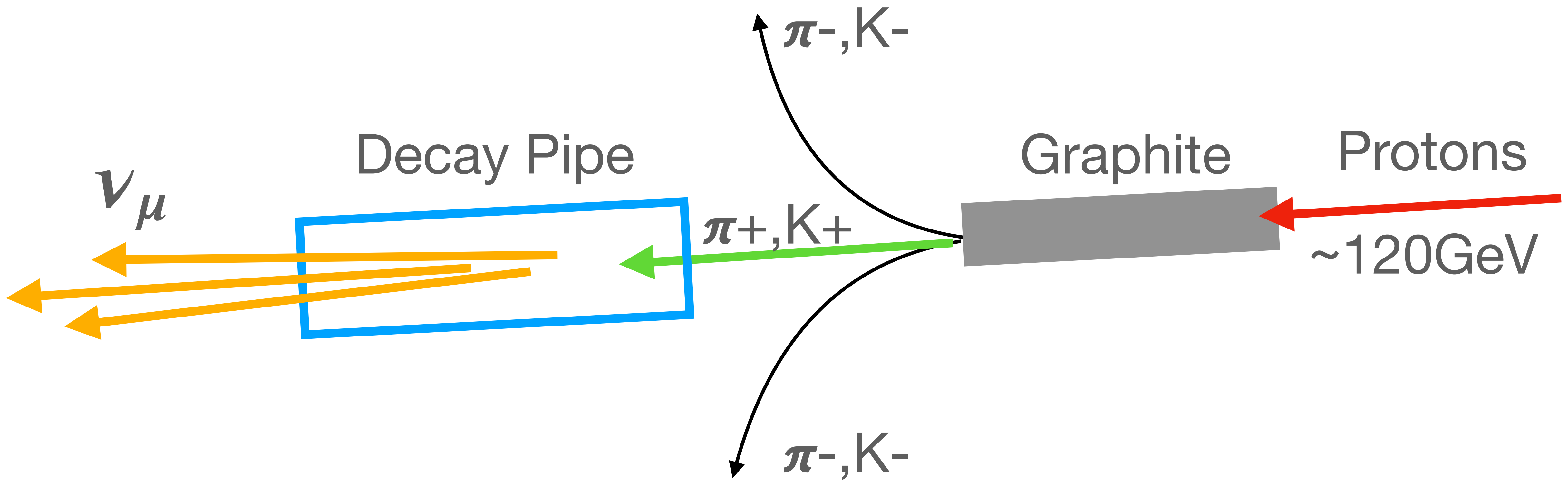

System for on-Axis Neutrino Detection:

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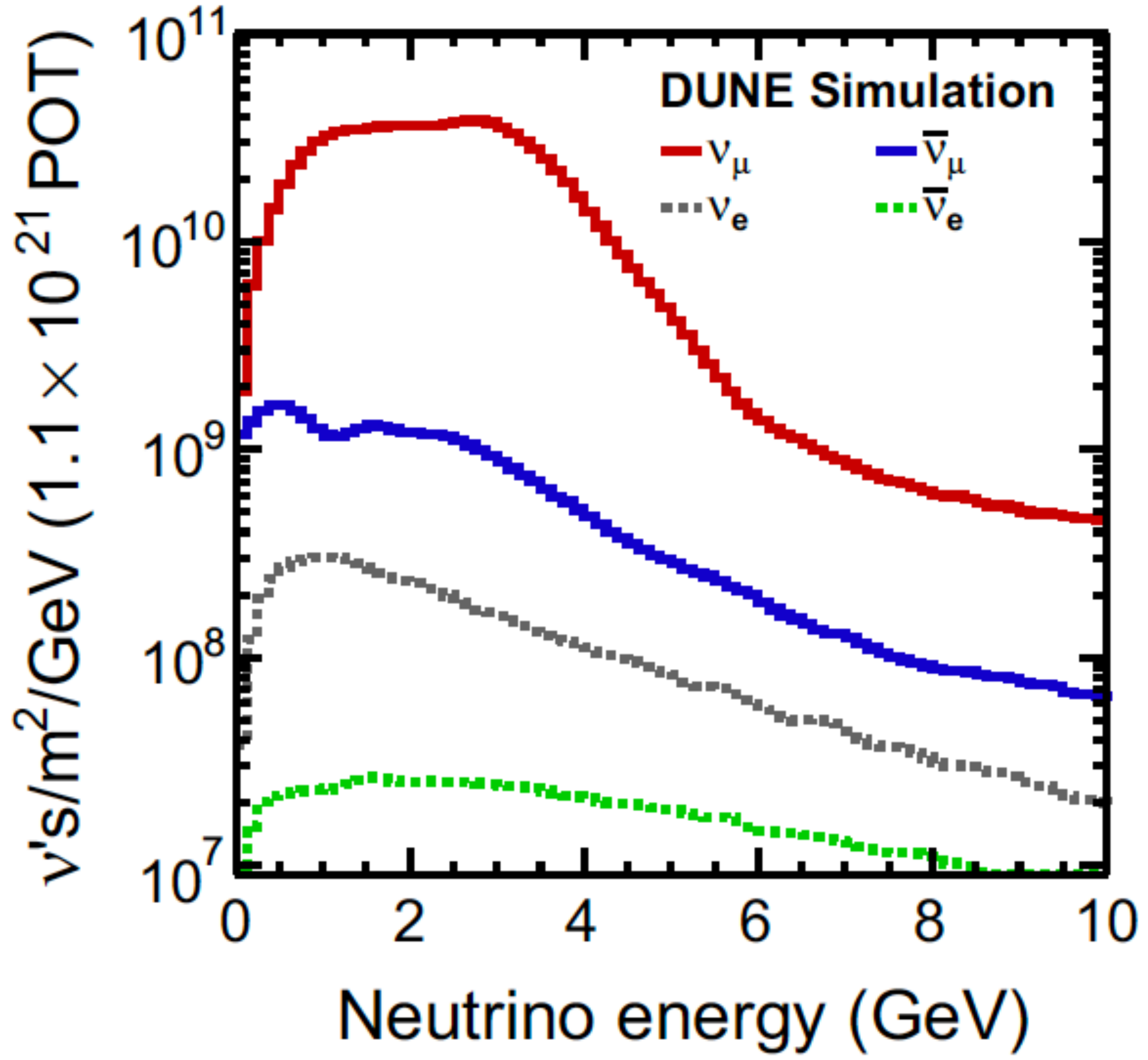
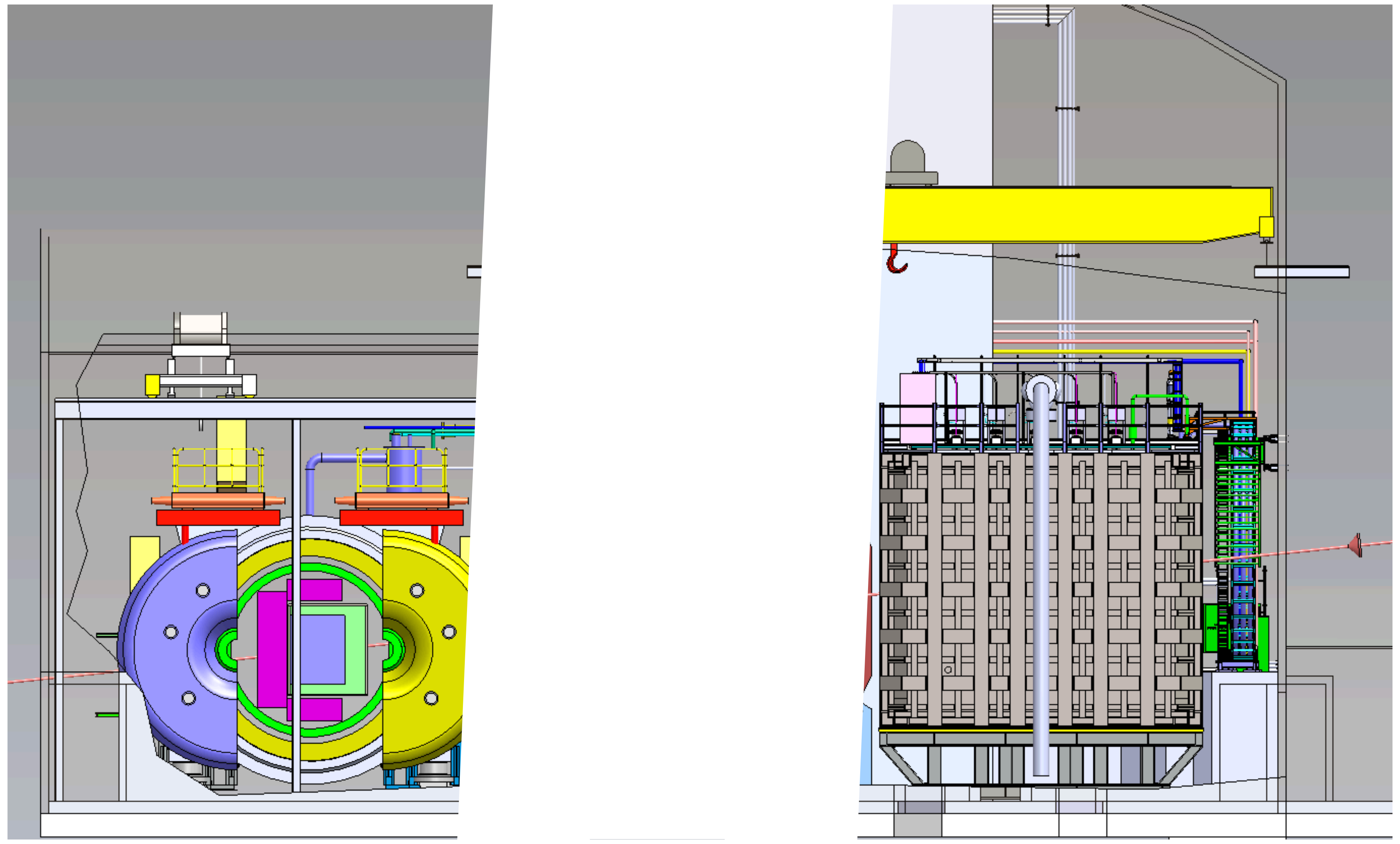
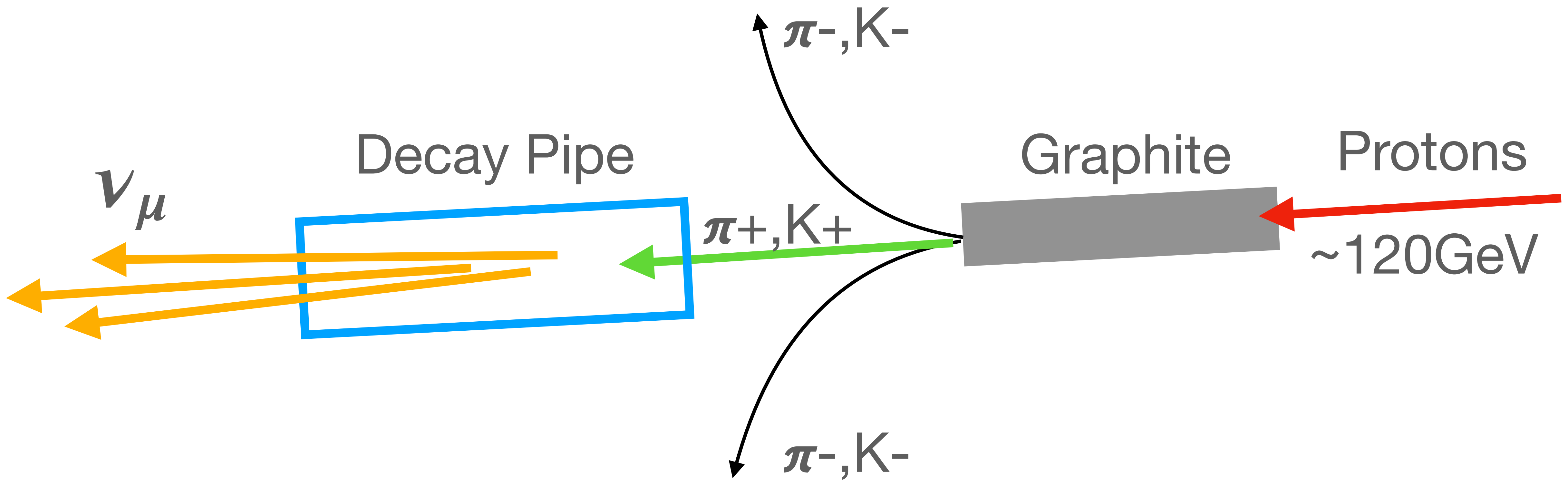
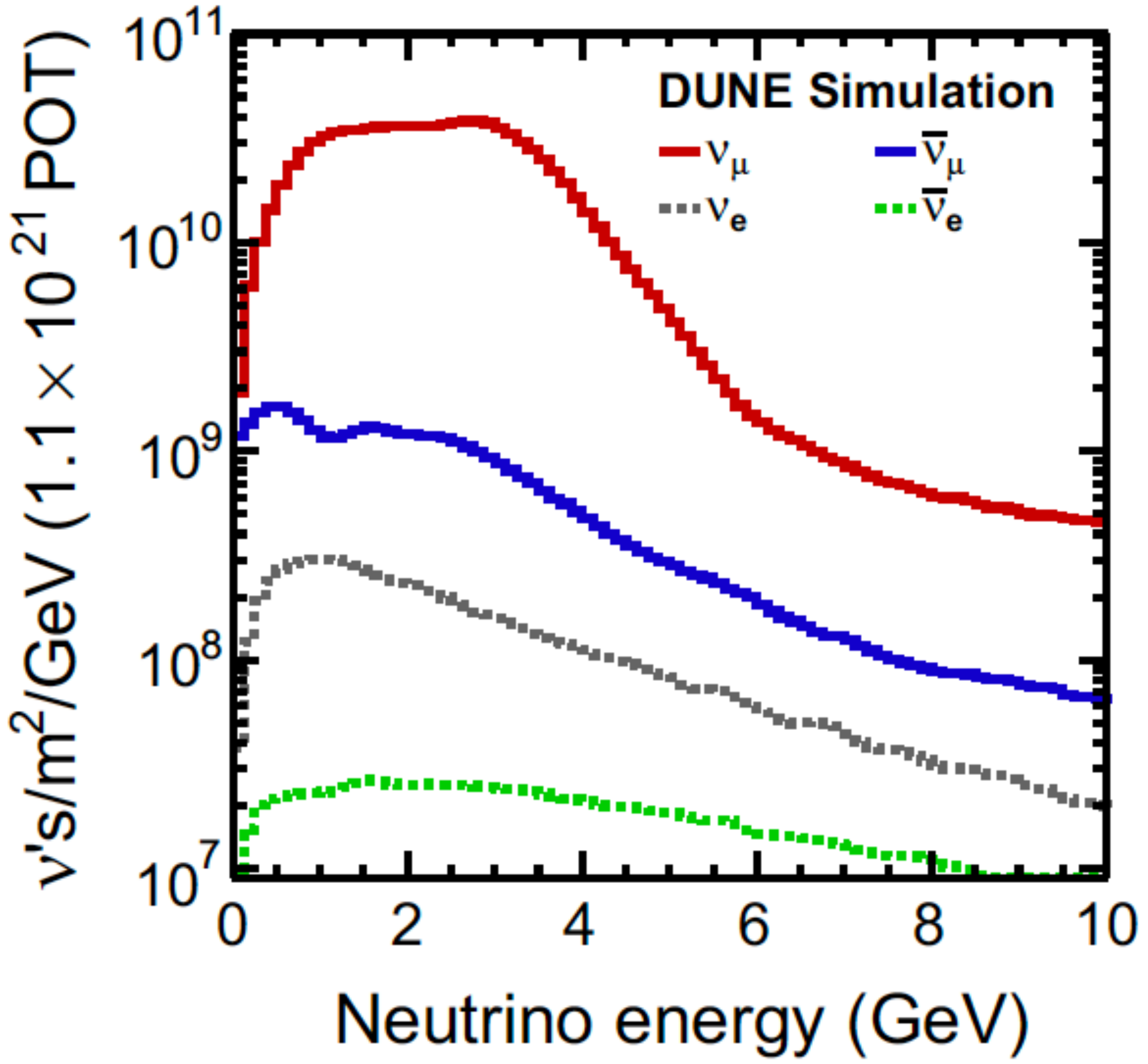






System for on-Axis Neutrino Detection:

- Magnetized tracker and ECAL
- Stationary, measures flux and beam composition



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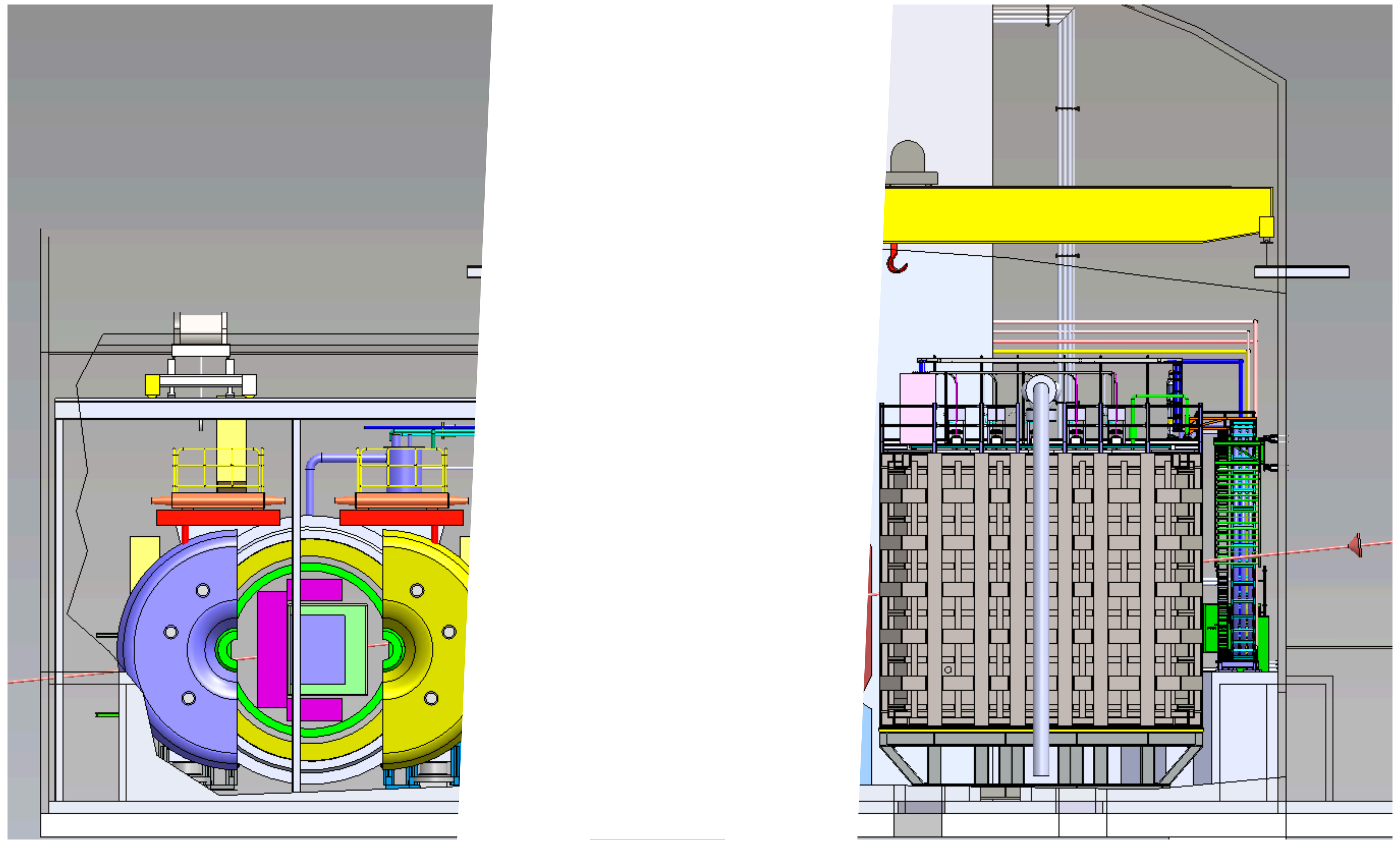

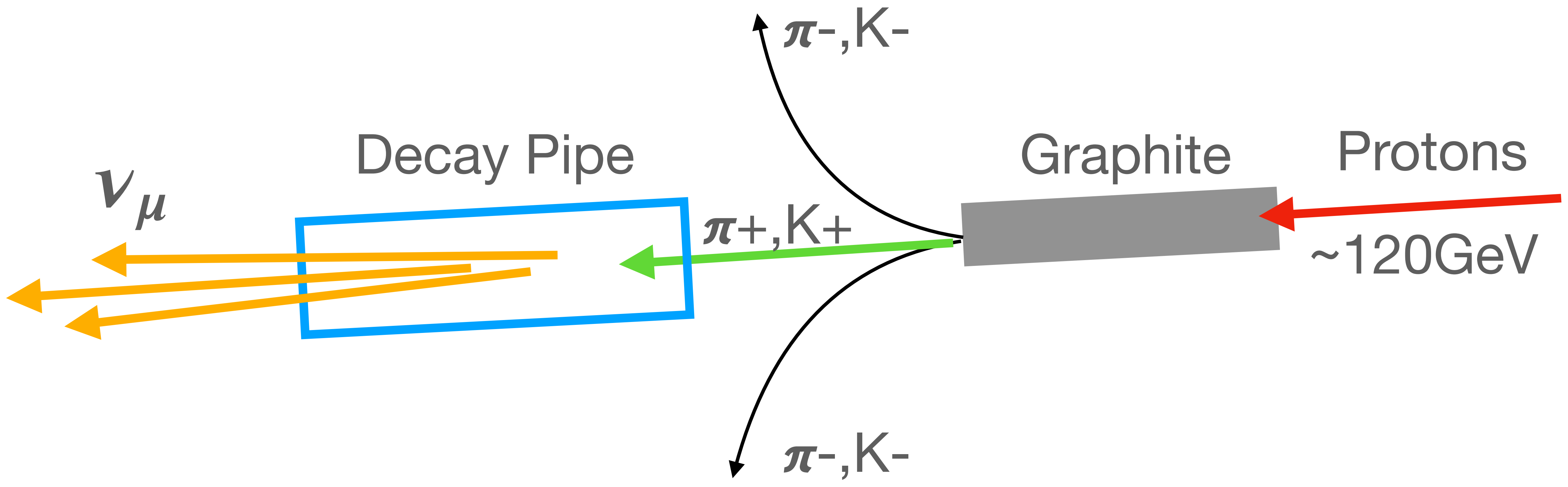

System for on-Axis Neutrino Detection:

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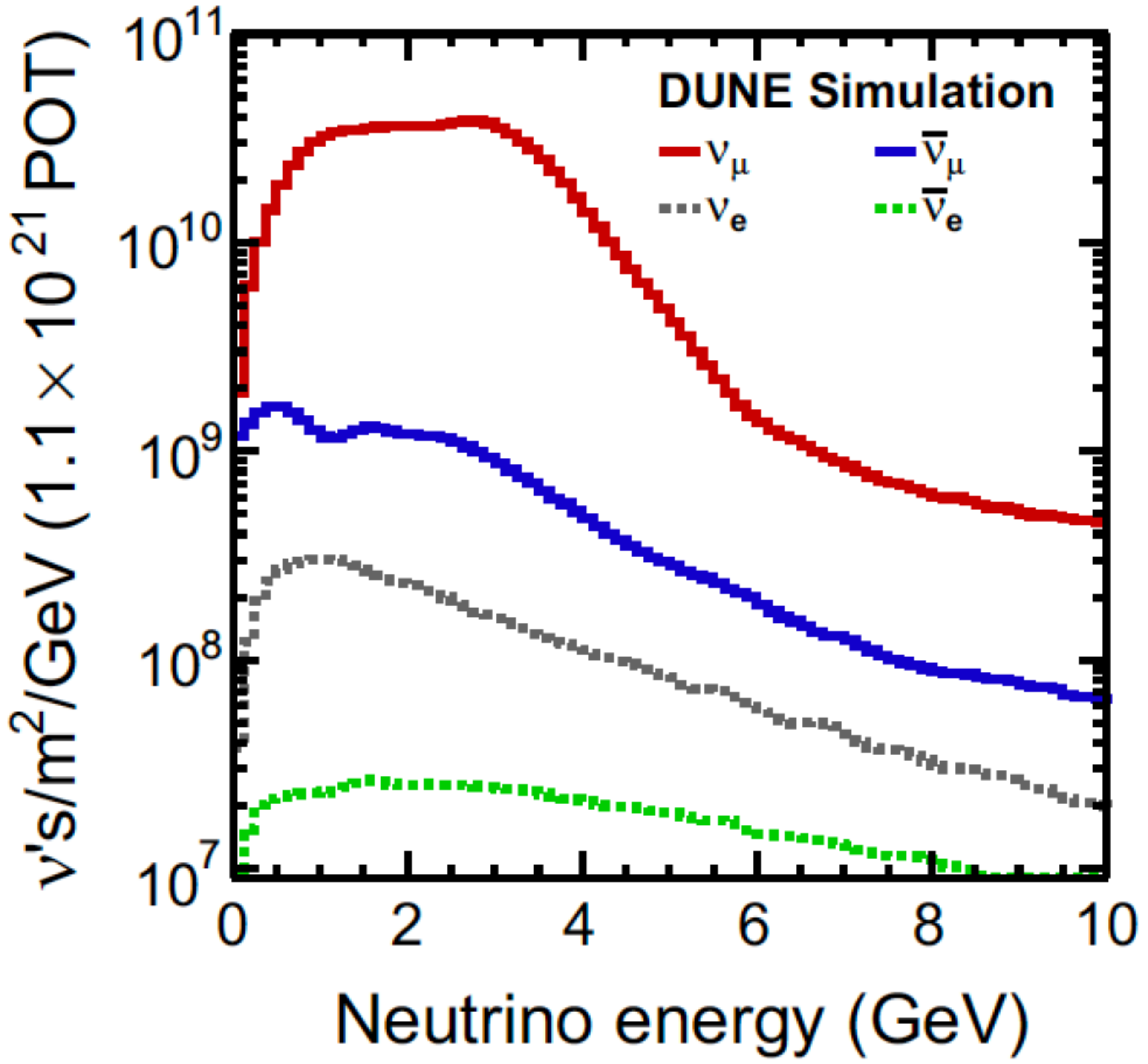
- High neutron efficiency



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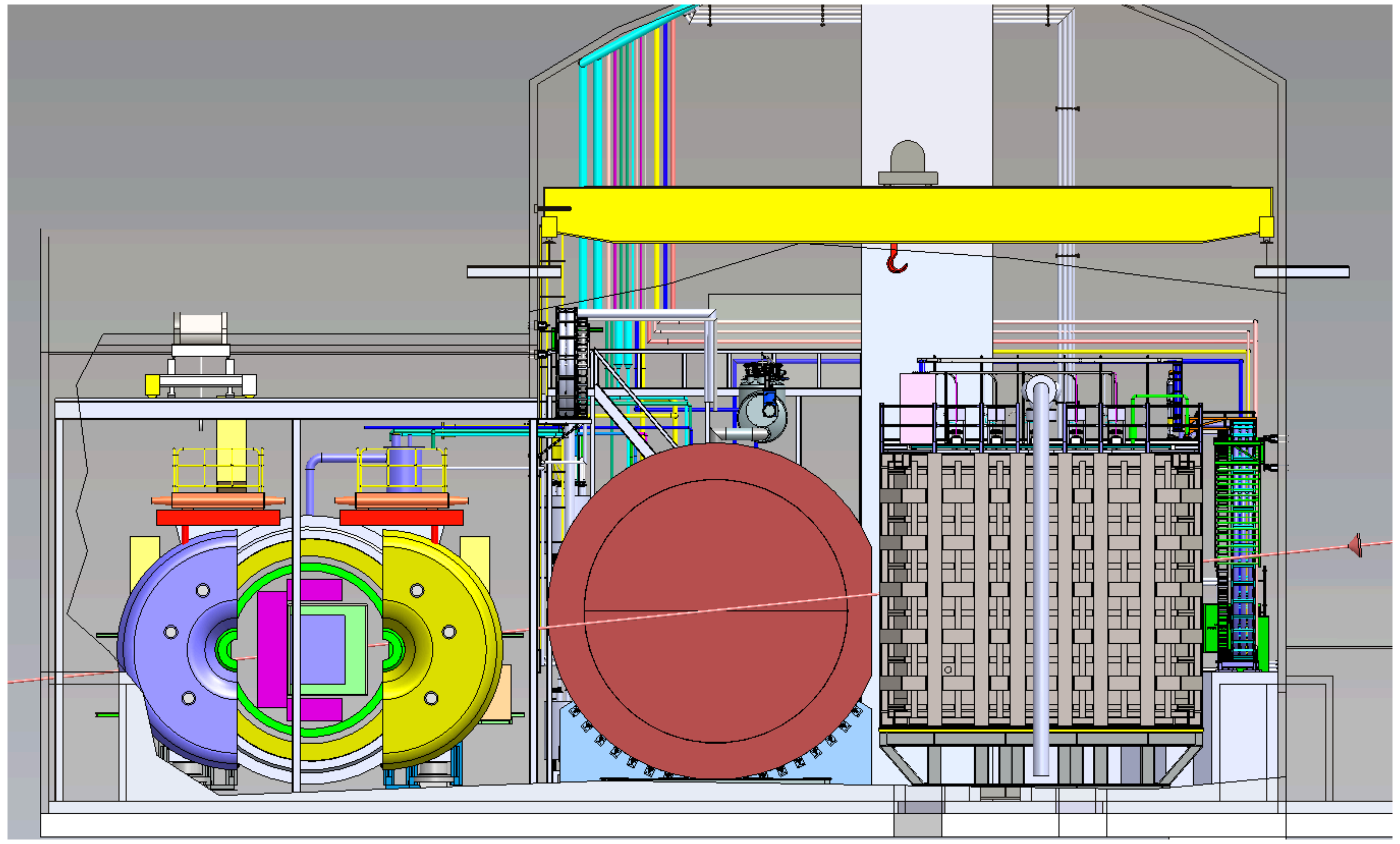

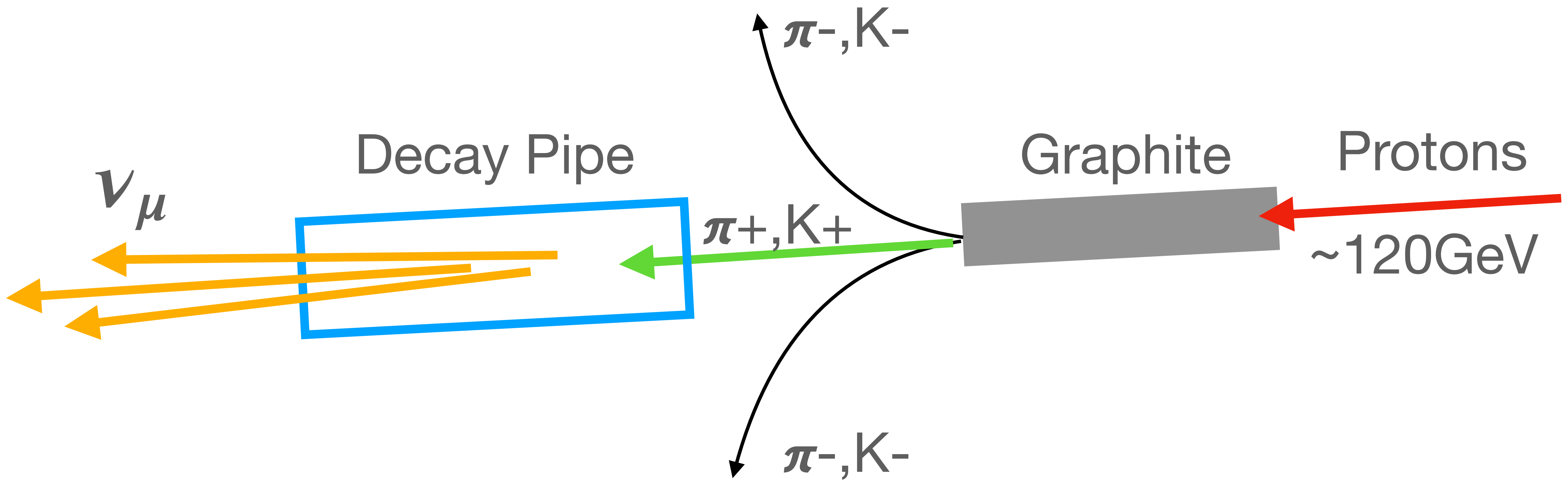

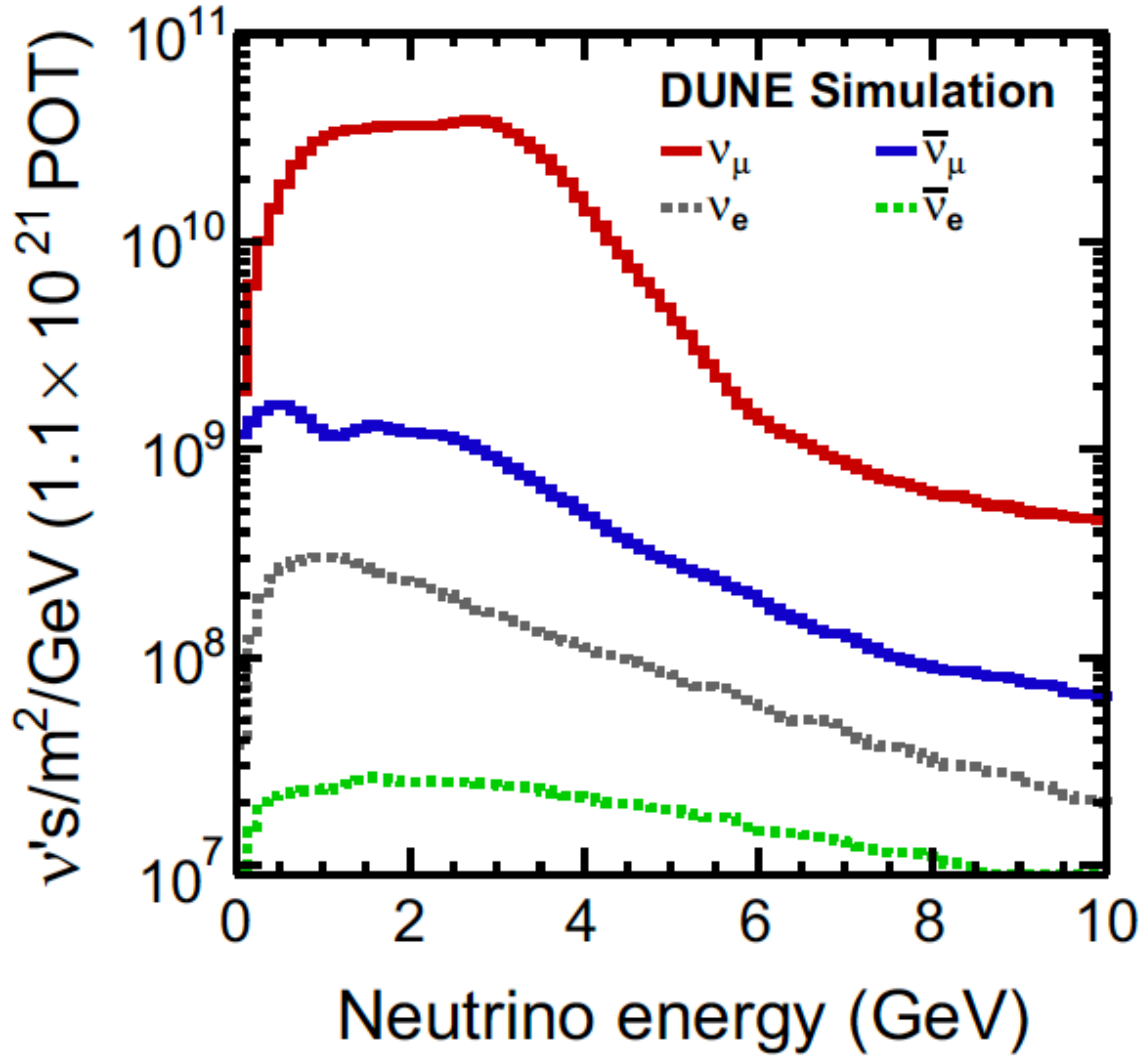

Gaseous Argon TPC:

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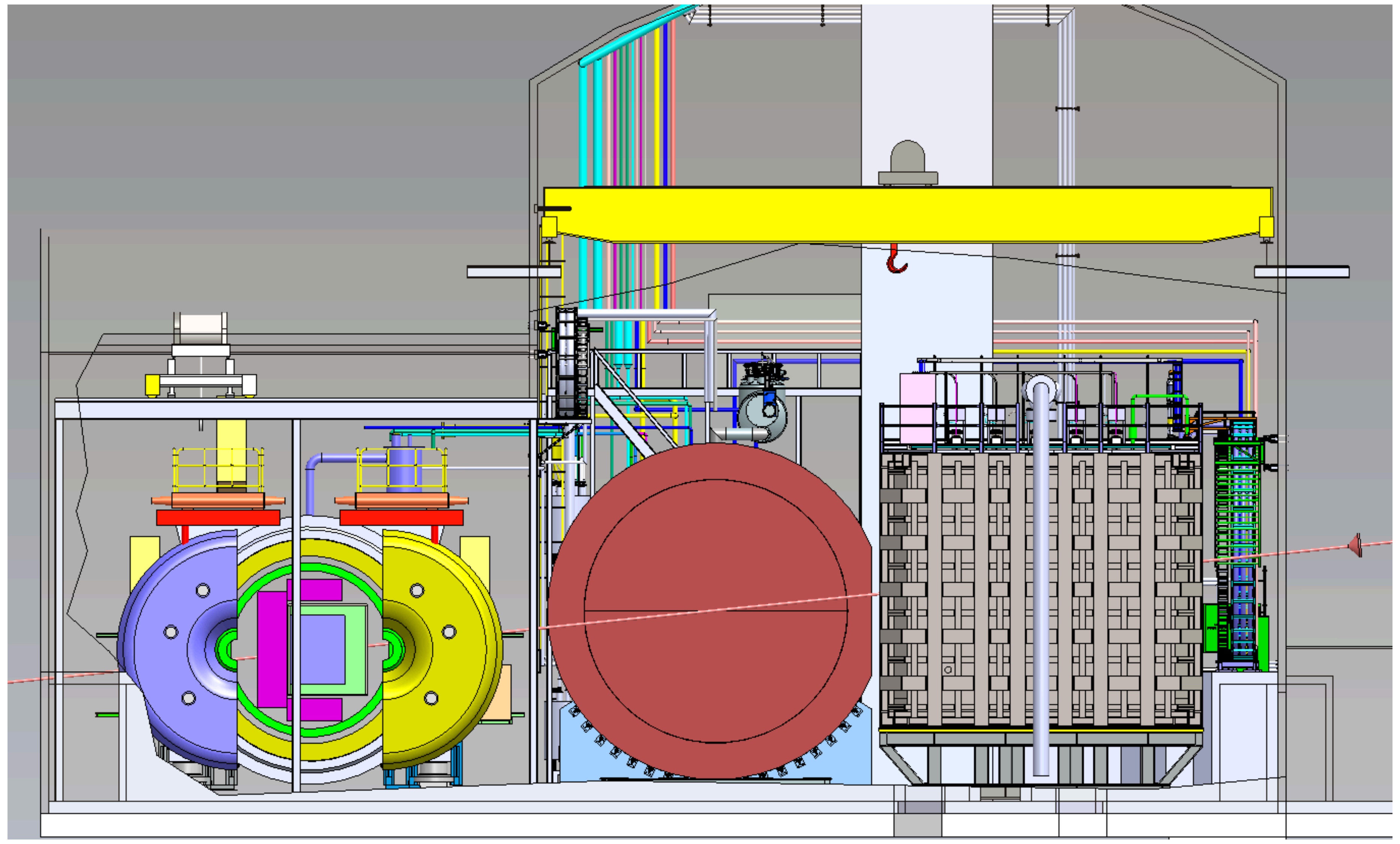

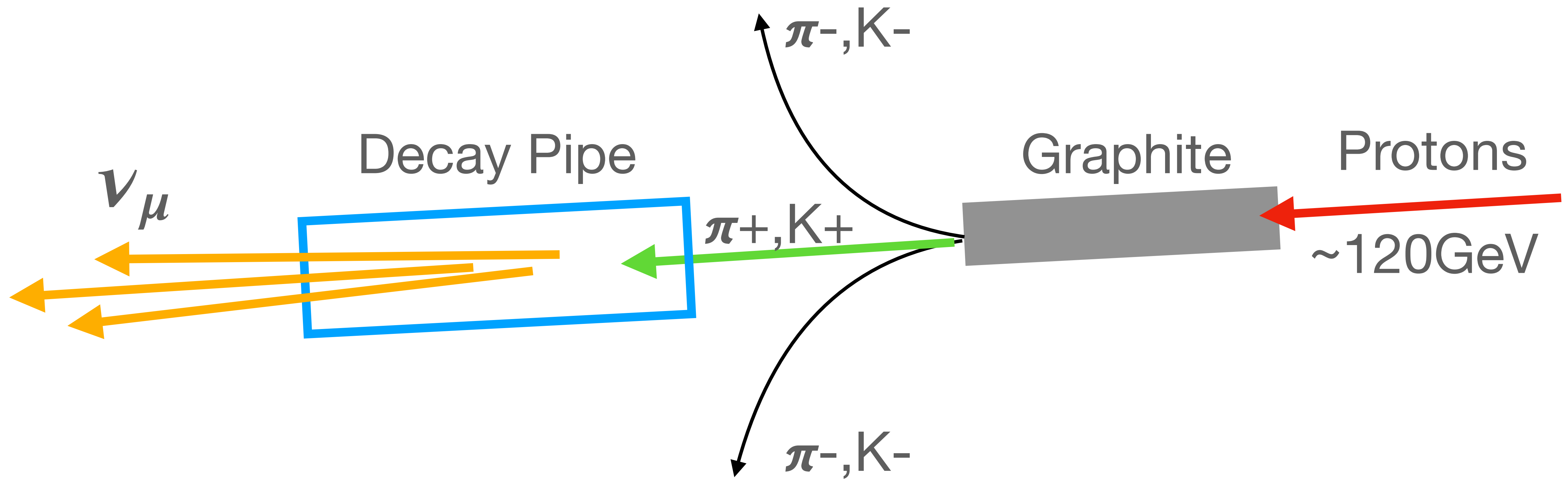

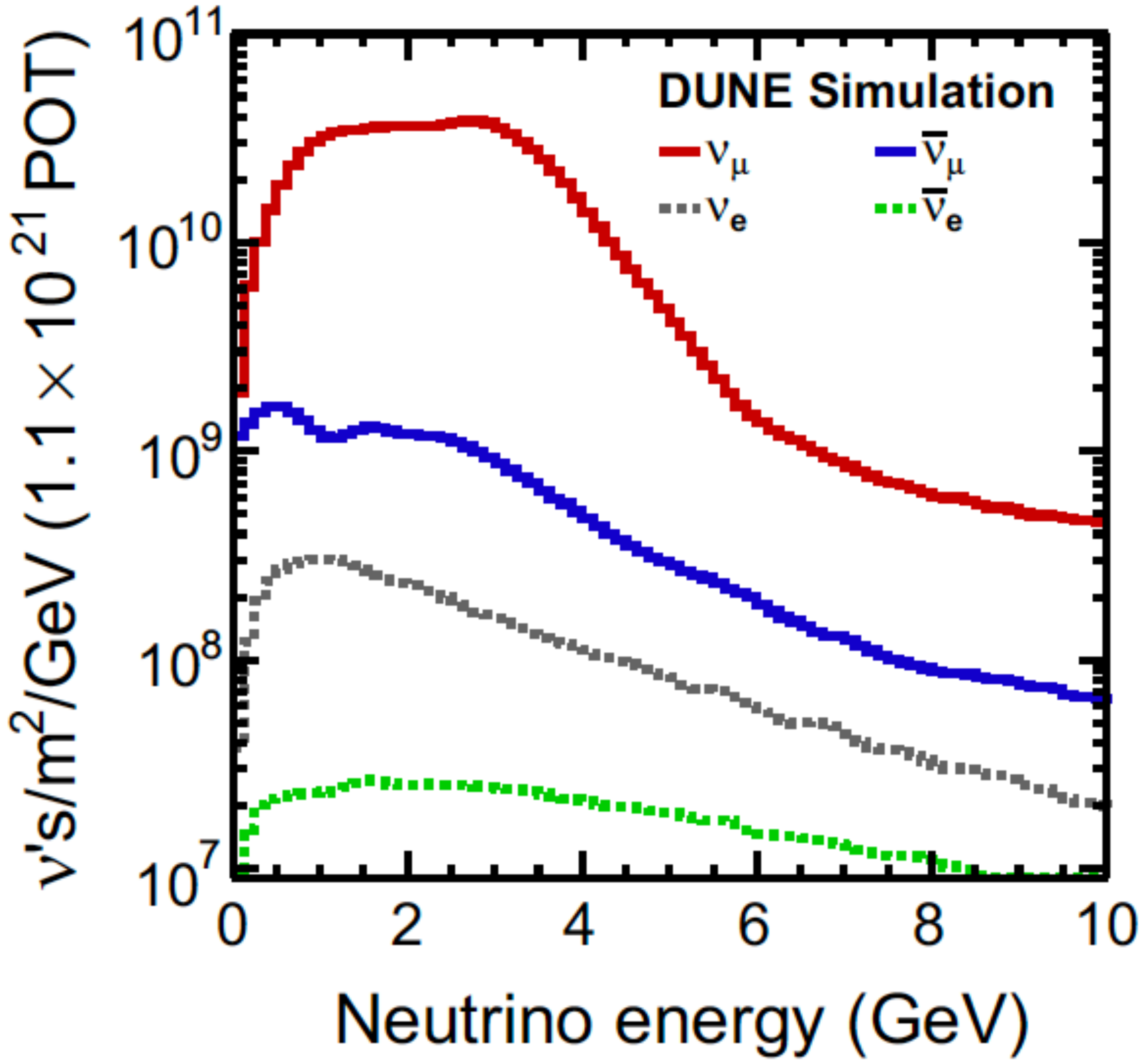

Gaseous Argon TPC:

- Gaseous target, low detection threshold and clean events

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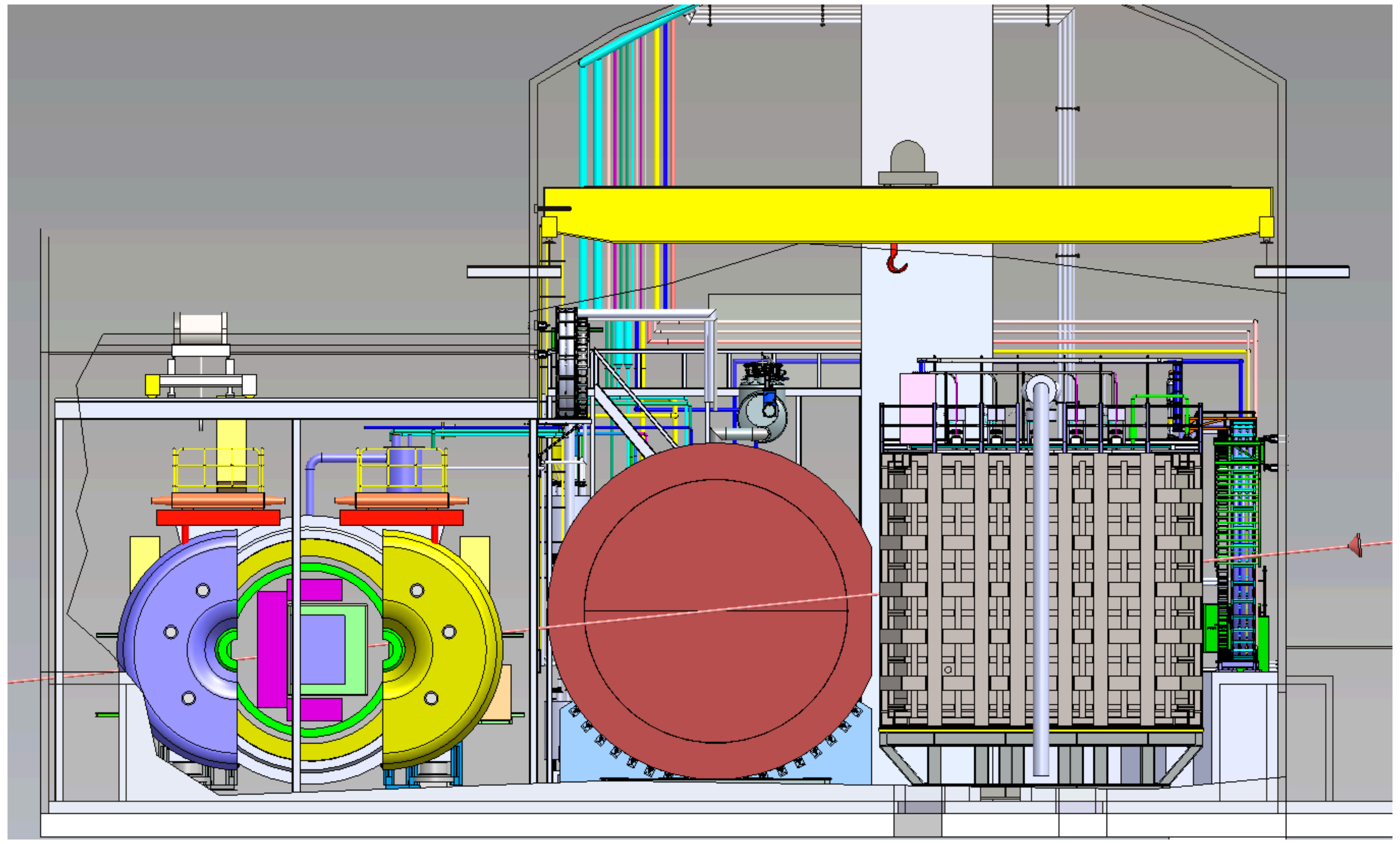

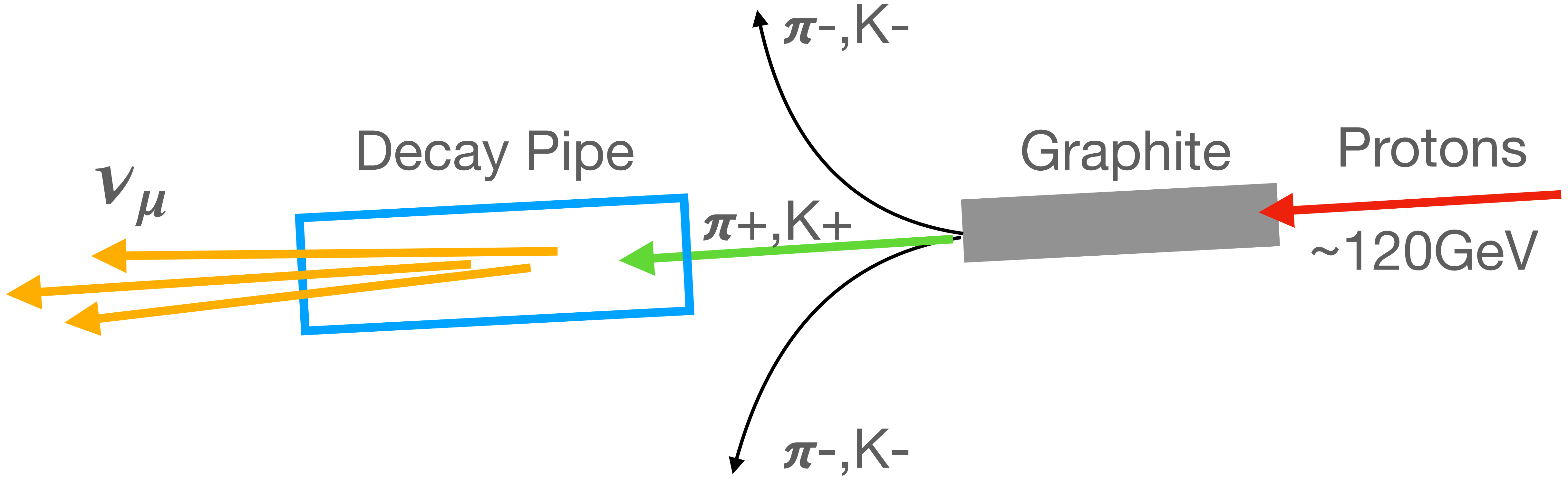

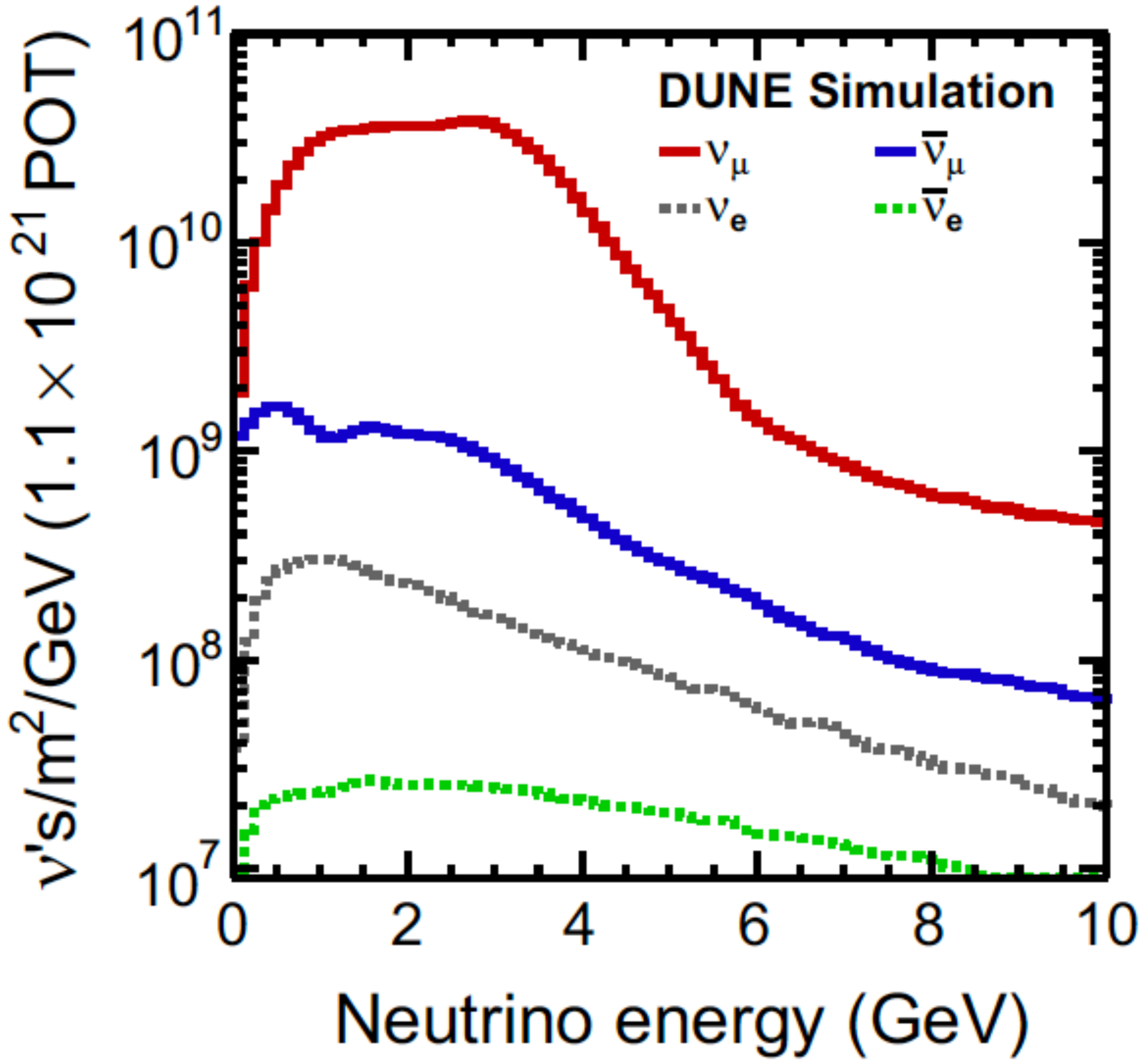

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- Surrounded by ECAL and muon detector for complete reconstruction of final states

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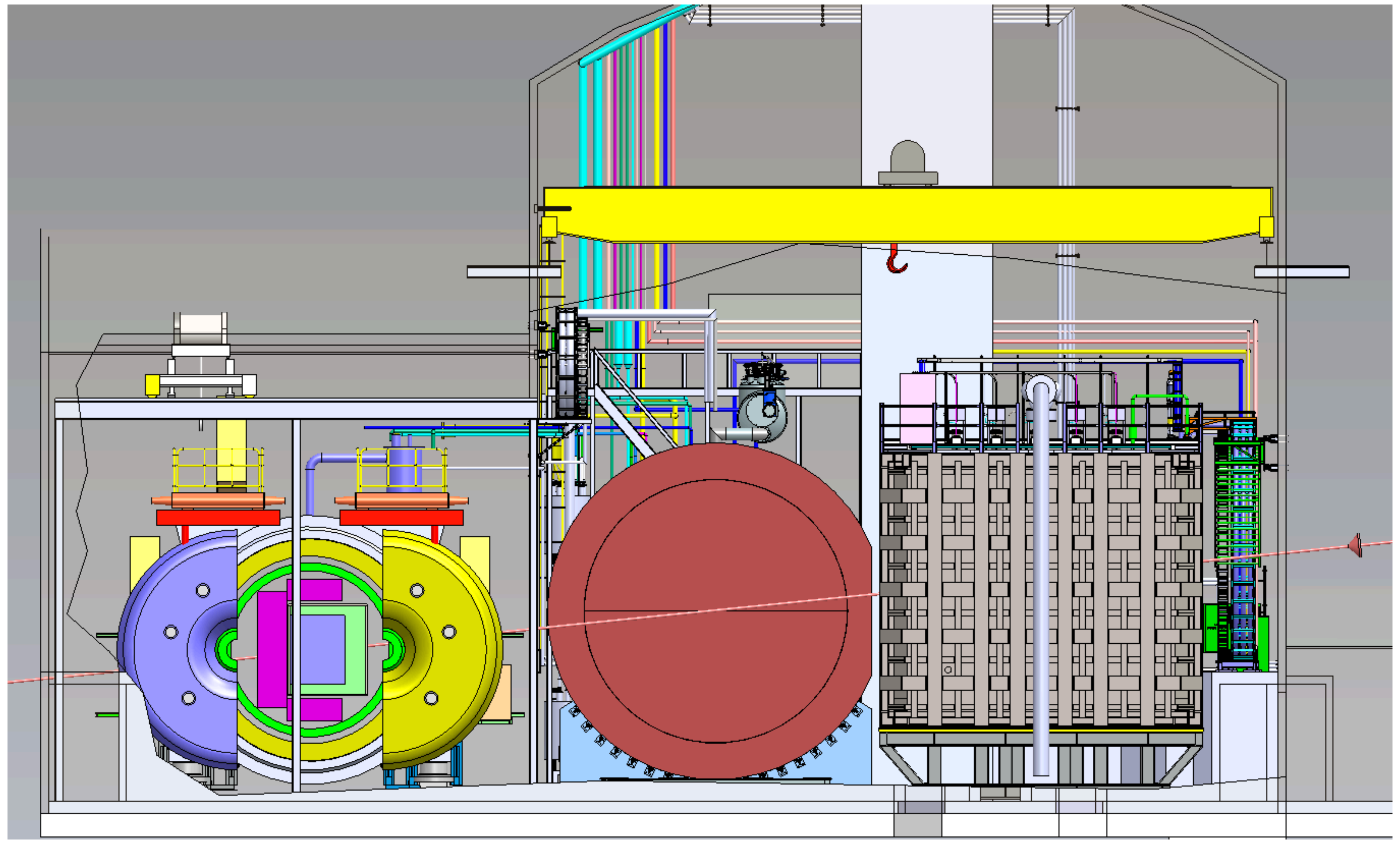
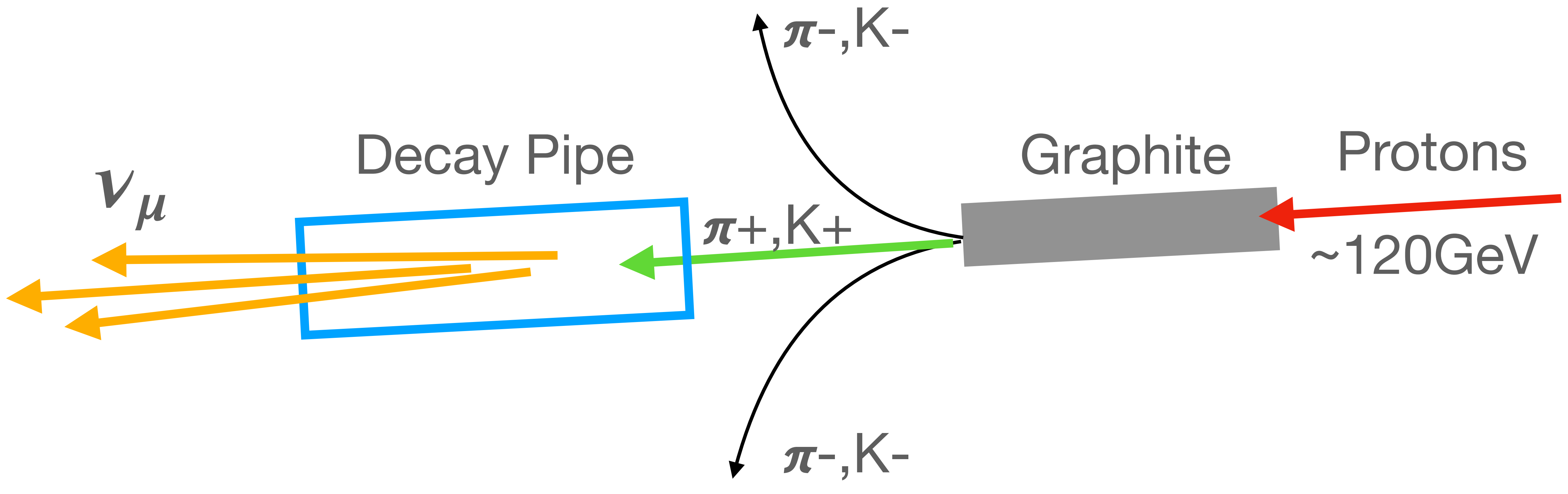
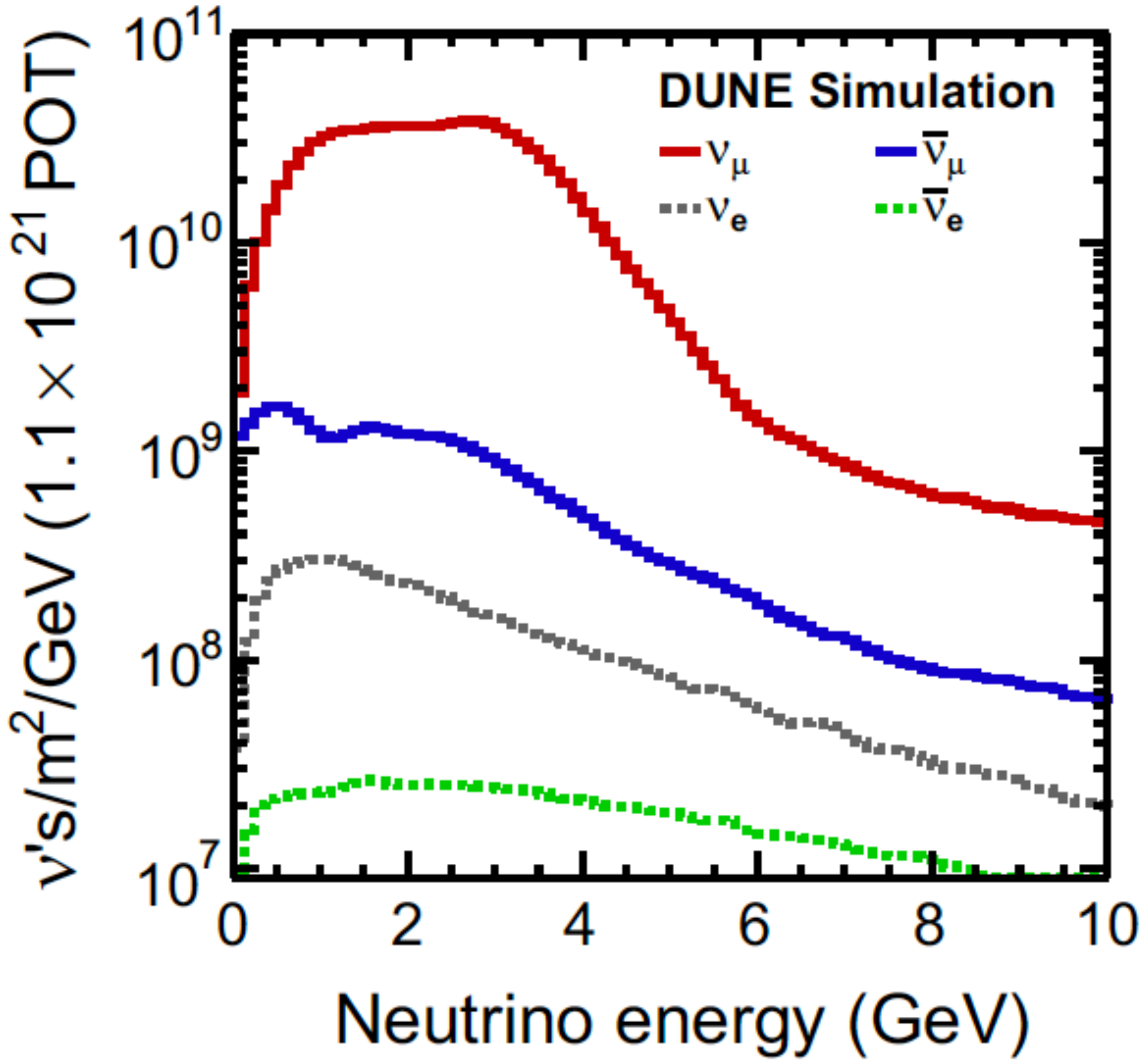


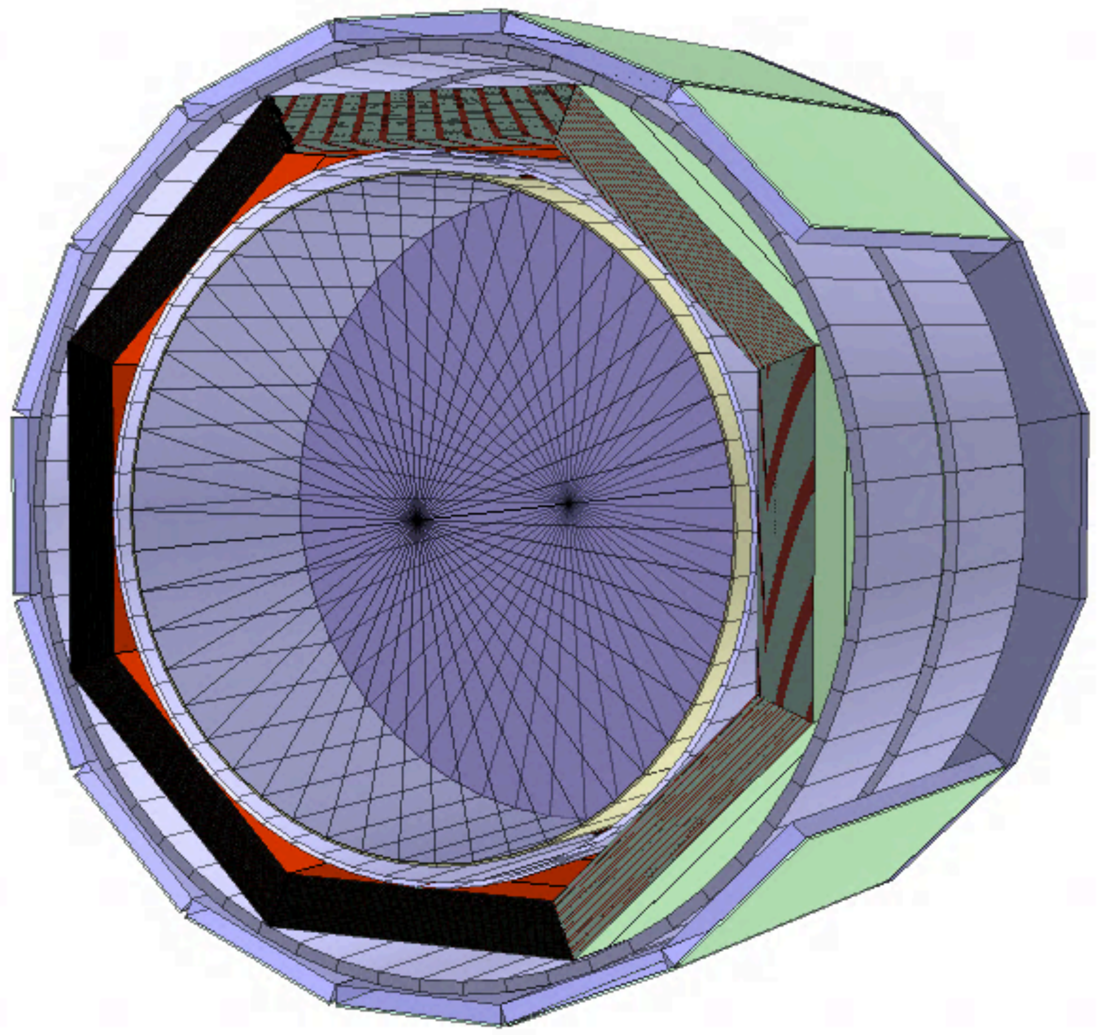




Gaseous Argon TPC:

- Gaseous target, low detection threshold and clean events
- Surrounded by ECAL and muon detector for complete reconstruction of final states
- High sensitivity to rare neutrino interactions

Muon Pion Separation - Simulation



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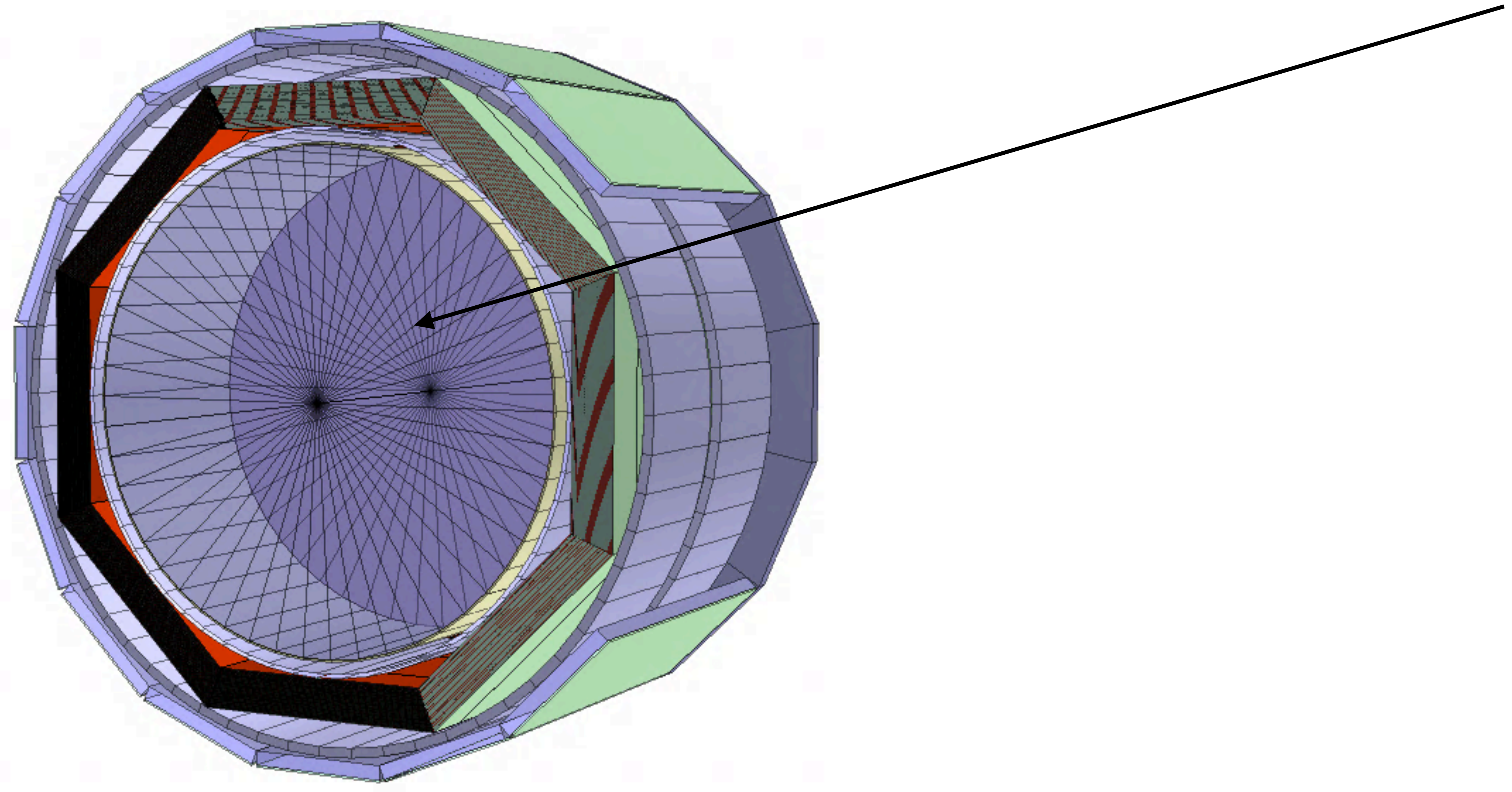

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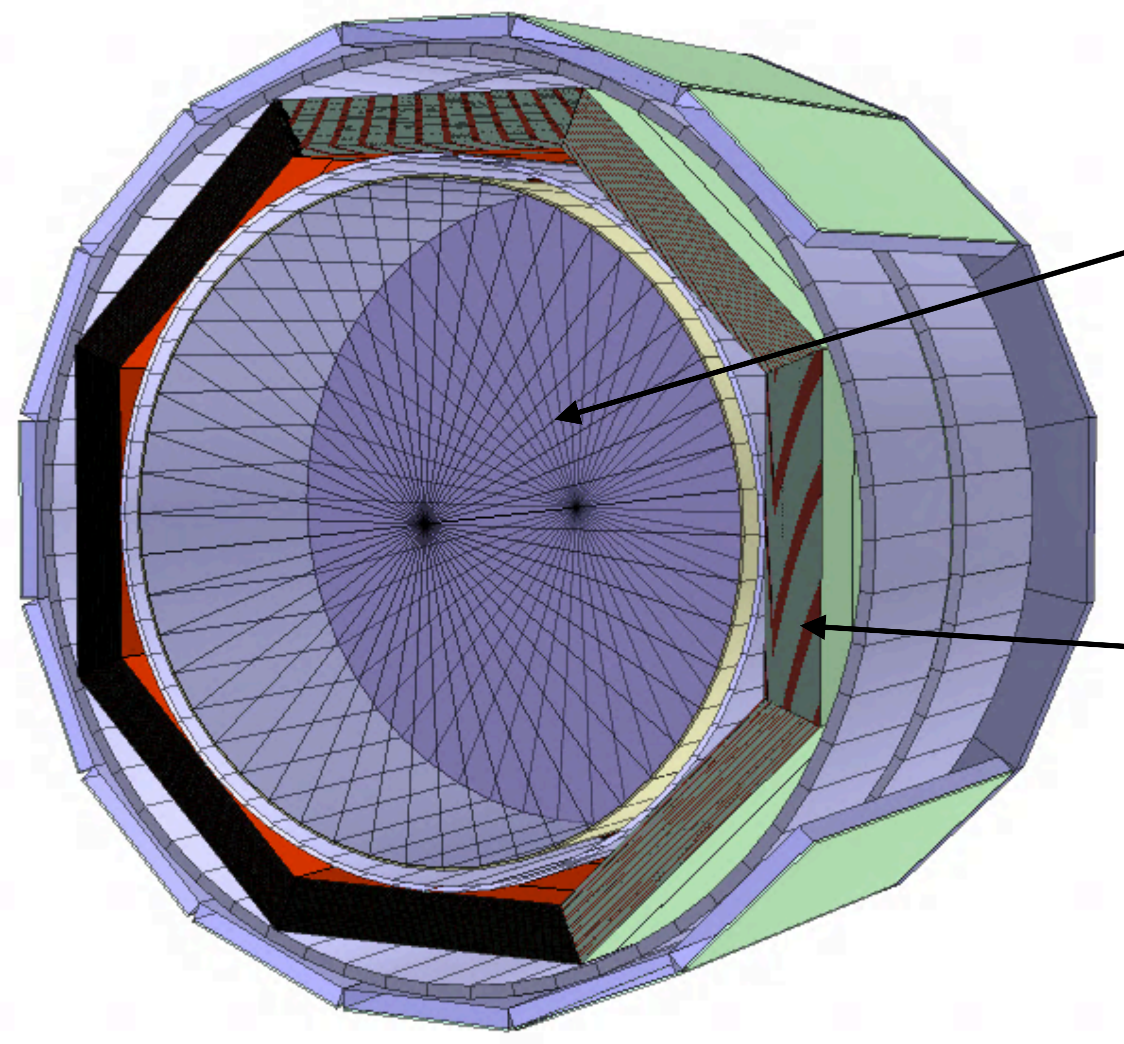

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ECAL:

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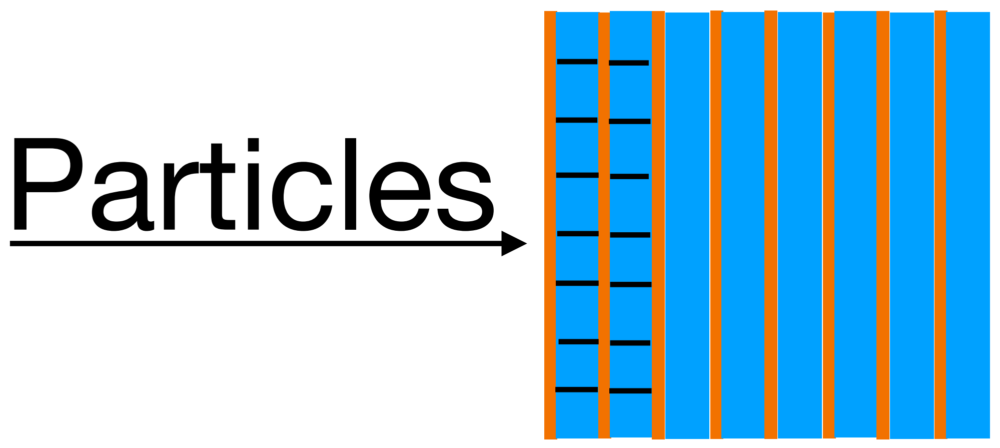
- 2mm copper absorbers
- 5mm plastic scintillator



Fine segmentation in front,

strips in the back

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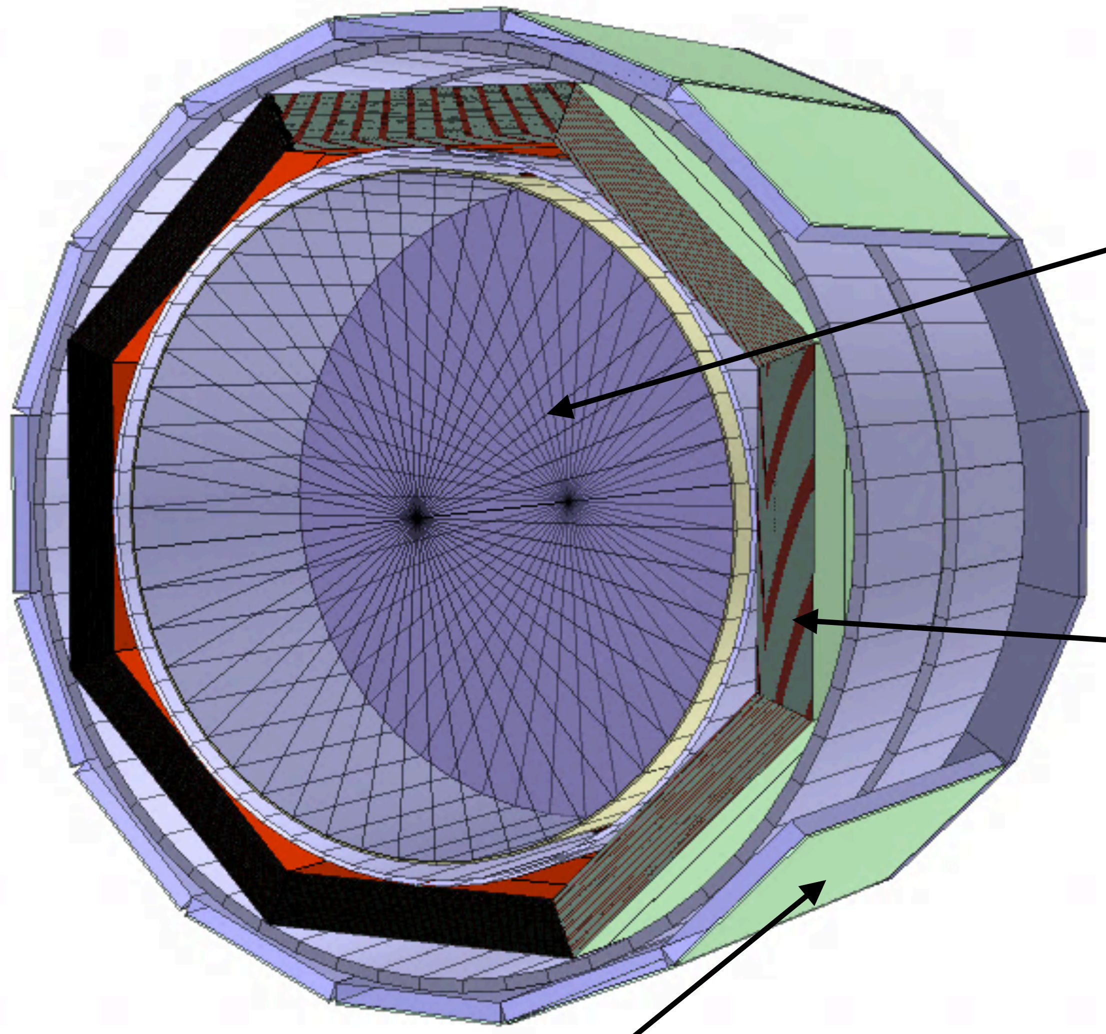

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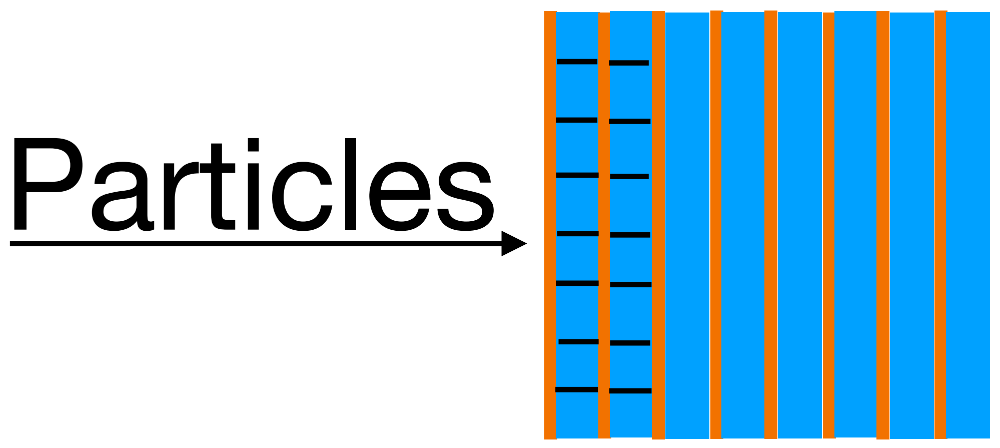

Fine segmentation in front,

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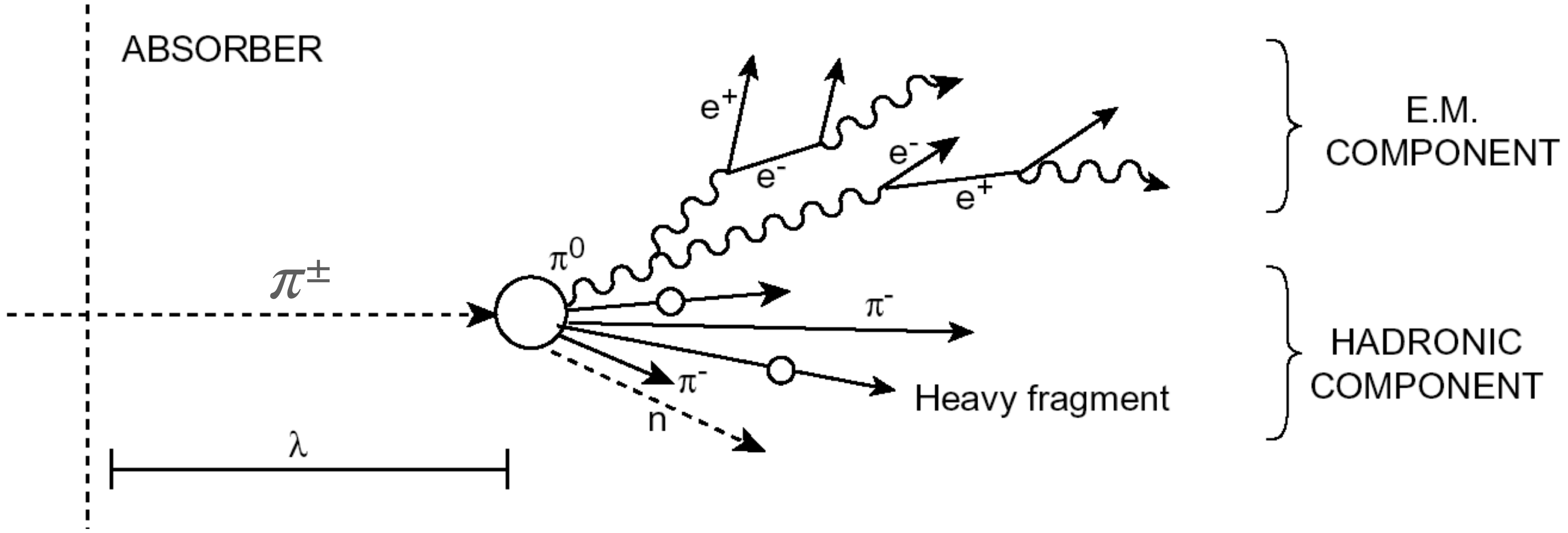
Muon detector:

- 3 layers of scintillating strips
- Embedded in the return yoke of the magnet (preliminary SPY)

Hadronic Interaction



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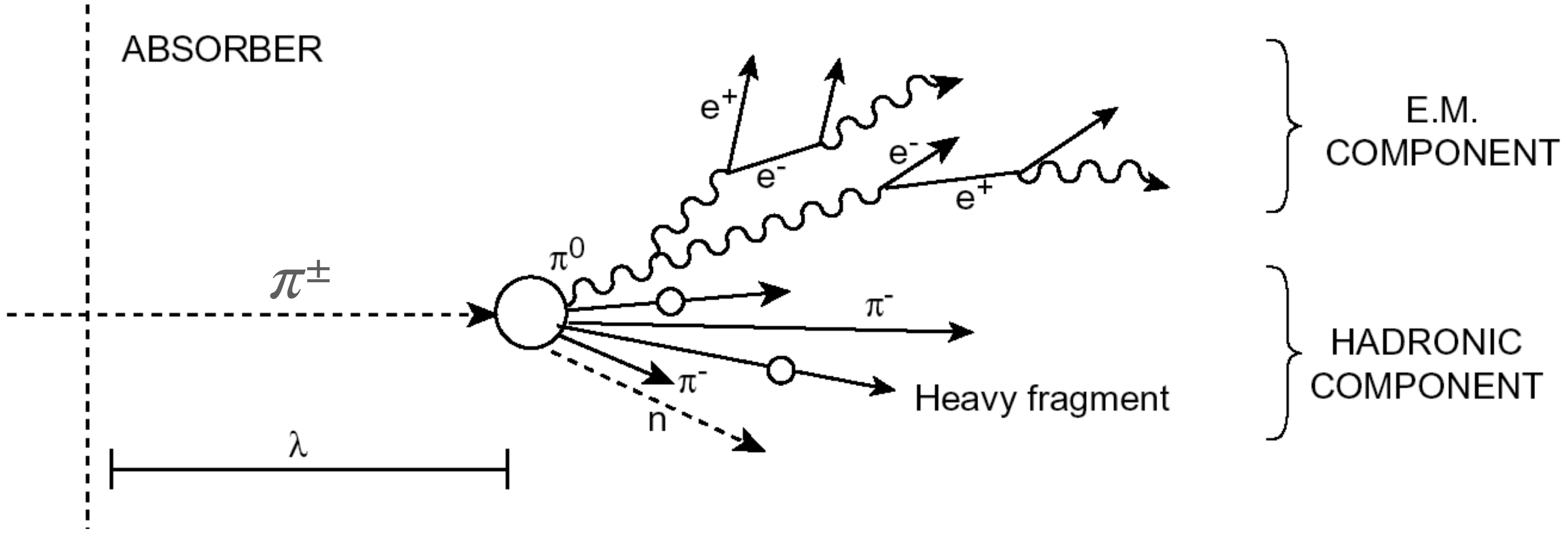

Particle multiplication after inelastic interaction:

- Charged hadrons
- Neutral pions → electrons/positrons

Higher charged particle density leads to high energy calorimeter hits

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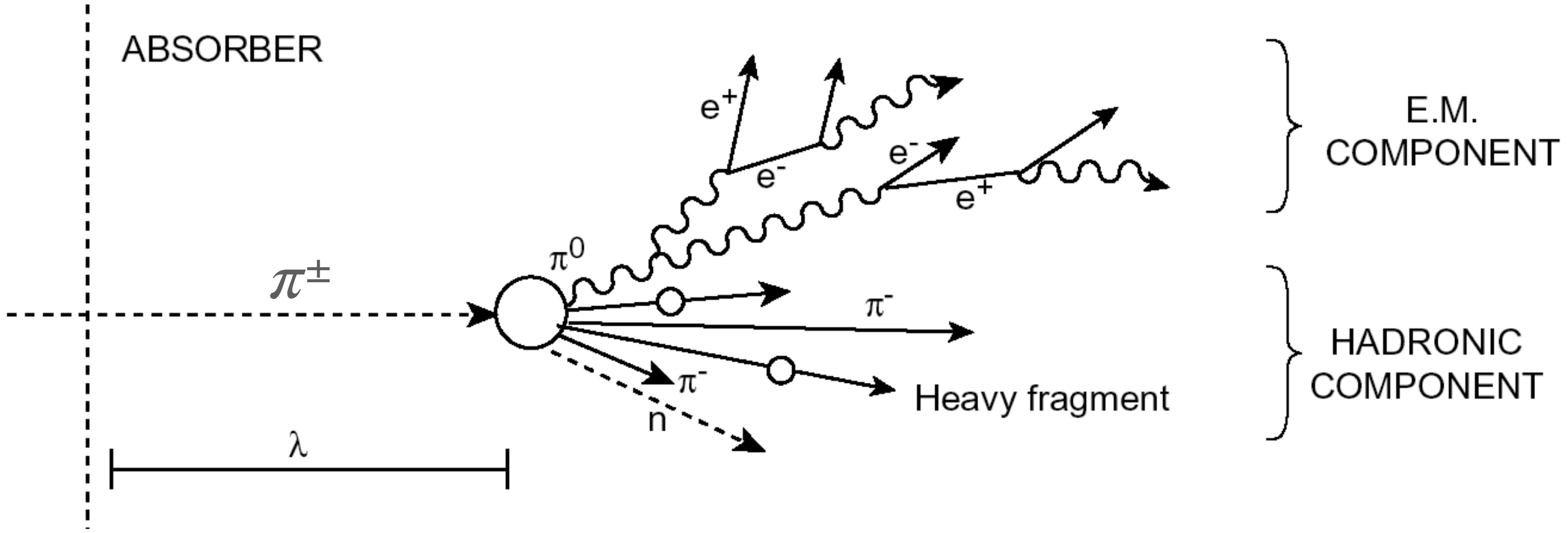

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Nuclear interaction length λ: Mean free path before inelastic interaction

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- Depends on incoming hadron, e.g. Proton: λ_{Iron}=16.77cm, Pion: λ_{Iron}=20.42cm

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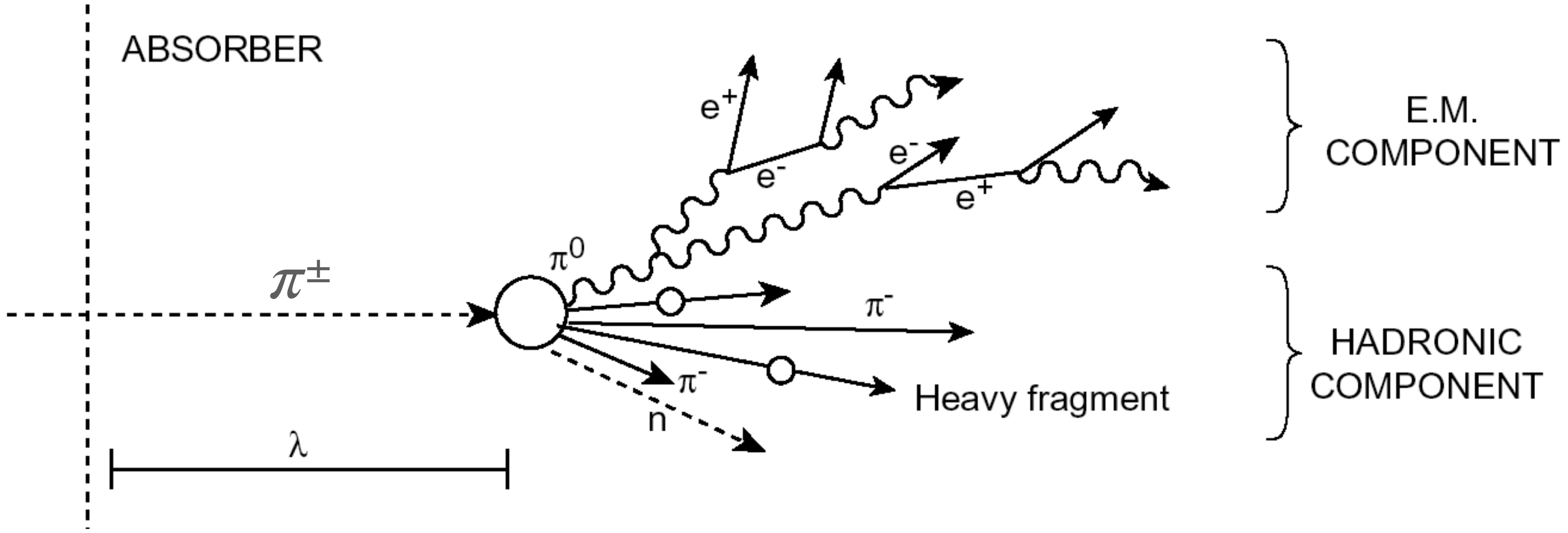

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- Depends on incoming hadron, e.g. Proton: λ_{Iron}=16.77cm, Pion: λ_{Iron}=20.42cm

Punch through probability: Probability of no inelastic interaction in the detector

$P_{PunchThrough} = \exp(-\lambda)$

Initial Considerations

MAX-PLANCK-INSTITUT FÜR PHYSIK

Material budget:

Pressure vessel	4.4cm Al ≙ 0.1λ
ECAL absorber	12cm Cu ≙ 0.65λ
Magnet:	10cm Al ≙ 0.2λ
Return yoke	15cm Fe ≙ 0.75λ
Scintillator	30cm PS ≙ 0.3λ
Total	2.0λ

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- 14% pions

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Simulated muon/pion ratio:

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~2% fake muons from pions if:

- All muons are tagged correctly
- All inelastic pion interactions are resolved

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Magnet:	10cm Al ≙ 0.2λ
Return yoke	15cm Fe ≙ 0.75λ
Scintillator	30cm PS ≙ 0.3λ
Total	2.0λ

$P_{PunchThrough}$ = exp(-2.0)=0.135

Simulated muon/pion ratio:

- 86% muons
- 14% pions

~2% fake muons from pions if:

- All muons are tagged correctly
- All inelastic pion interactions are resolved

Switching to lead absorber: $X0_{Lead} / X0_{Copper}$=0.35 but $\lambda_{Lead}/\lambda_{Copper}$ =1.07

Initial Considerations

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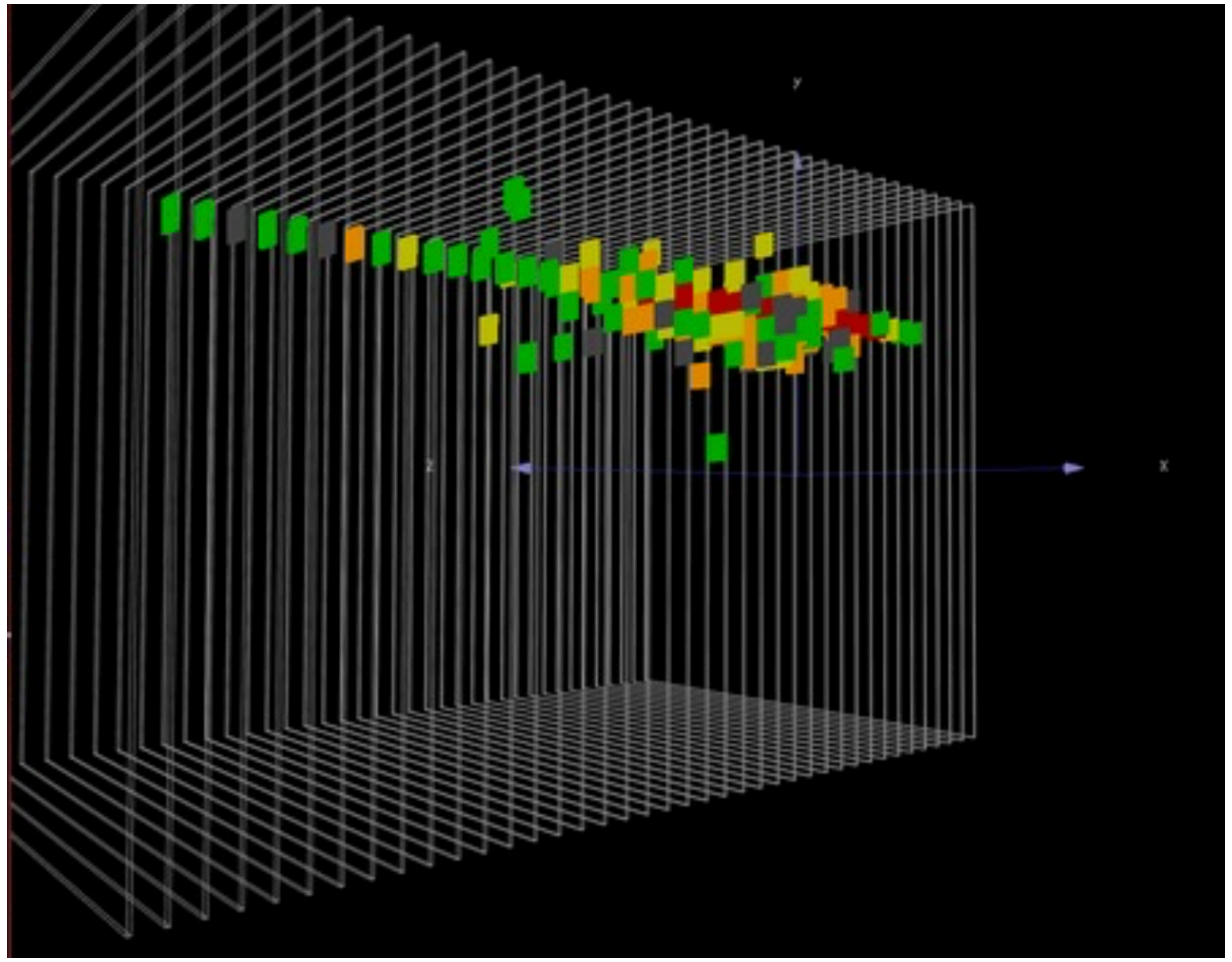
Actual data from CALICE AHCAL beam test

Showering Muon, hard delta electron

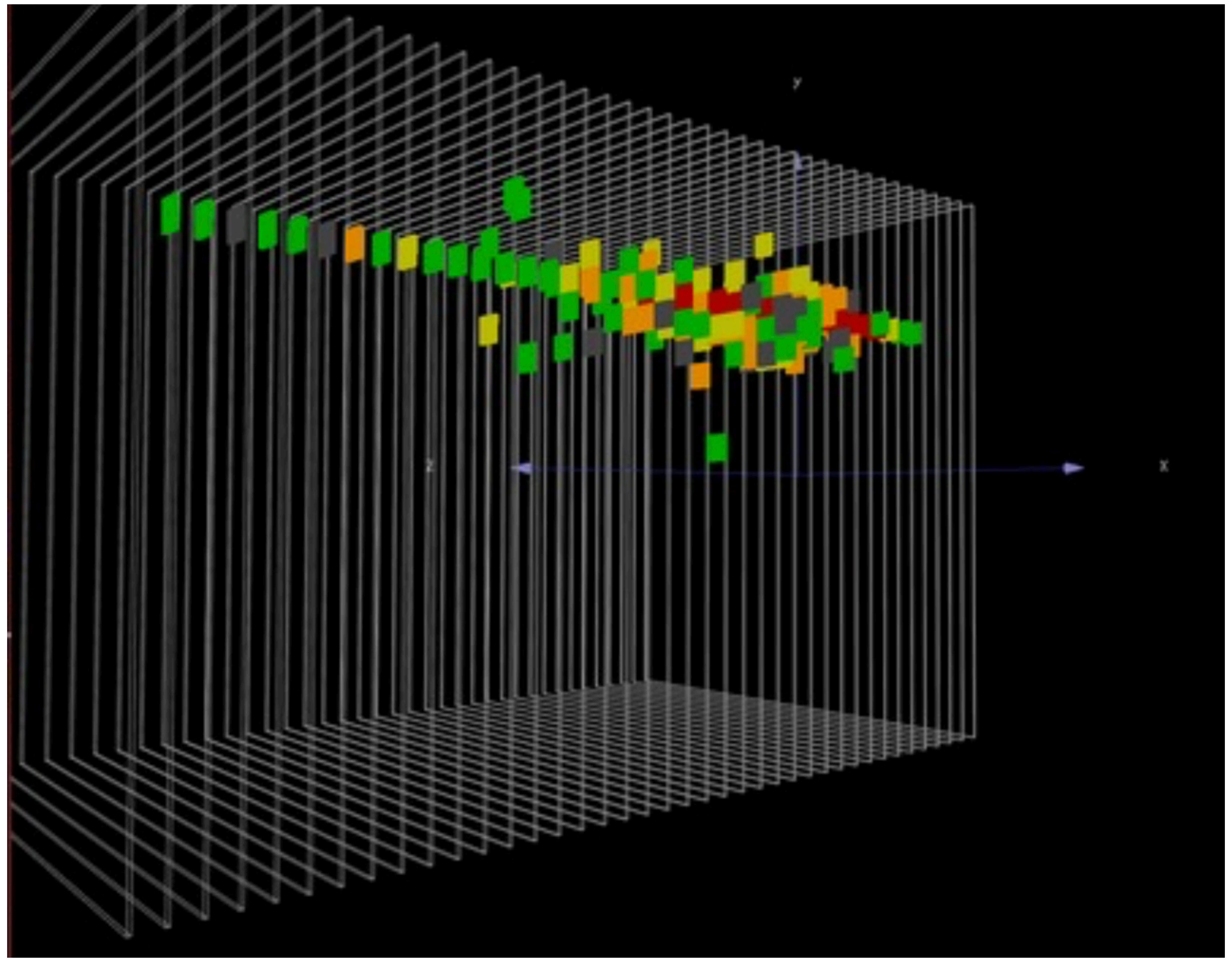


Confusion with Pion shower

Initial Considerations

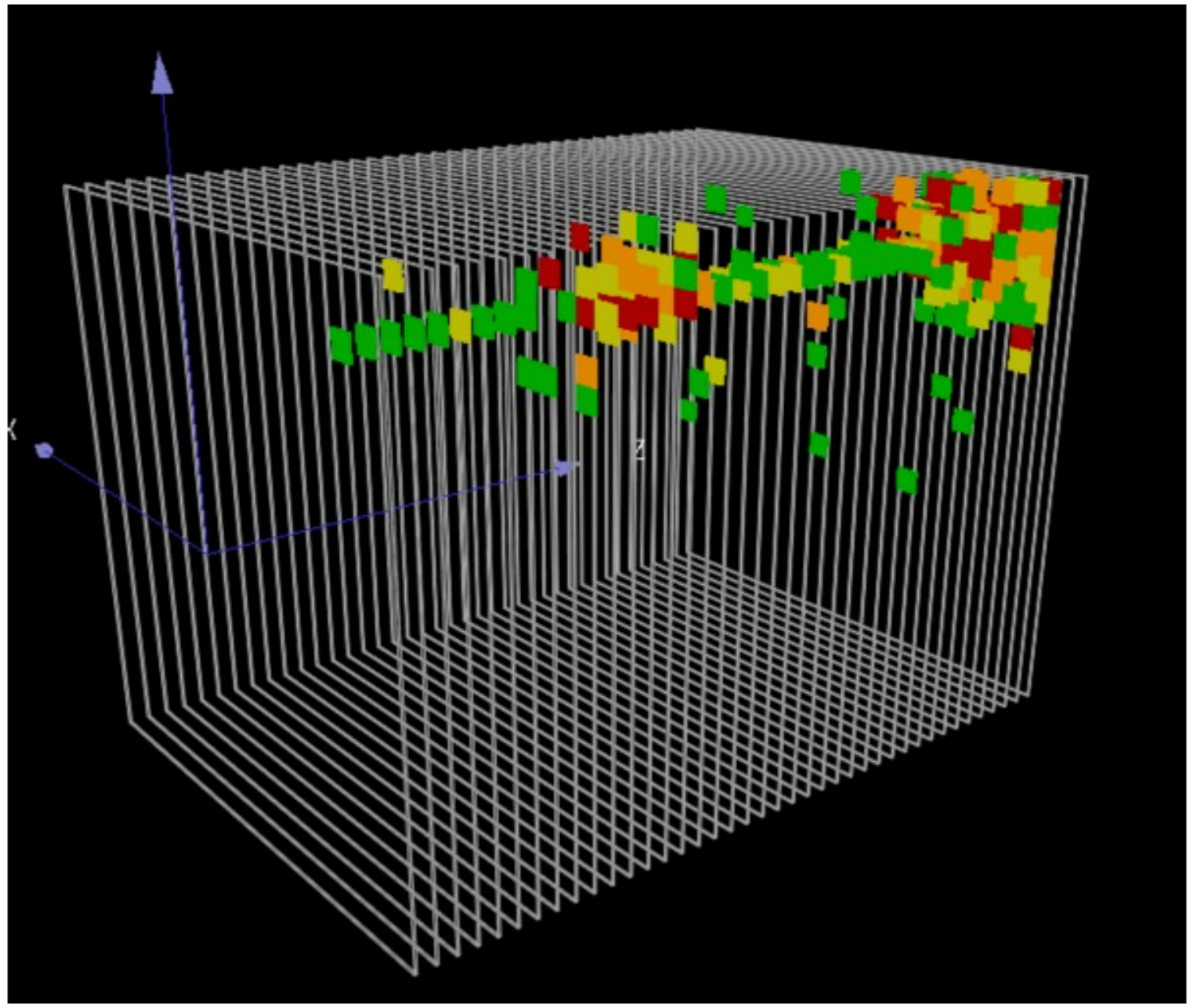
Actual data from CALICE AHCAL beam test

Showering Muon, hard delta electron



Confusion with Pion shower

Pion causing small shower



May look like a muon, if only a small shower develops in the detector