DUNE Near Detectors: Oscillation and Cross Sections

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On Behalf of the DUNE Collaboration

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Overview

- DUNE near detector roles.
- Near detector options under study.
- Near detector constraint on oscillation systematics.
  - Neutrino flux
  - Nuclear effect
  - Cross sections.
    - nu-e inclusive
    - Quasi-Elastic (0π)
    - Resonance π
    - Coherent π

Near Detector for DUNE

- DUNE is a long-baseline neutrino experiment aiming to determine the neutrino mass hierarchy and CP-violation by measuring ν_μ **to** ν_e and $\bar{\nu}_\mu$ **to** $\bar{\nu}_e$ oscillation and to conduct precision measurements of ν_μ **&** $\bar{\nu}_\mu$ disappearance.
- 40 kton LAr TPC as the far detector in Lead, SD: **high statistics**.
- A capable near detector (ND) complex is crucial for DUNE to constrain **systematic uncertainties**.
- A capable ND-complex will also have its own rich physics

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See Michel Sorel's talk on Thursday for the overview of DUNE and Nick Grant's talk (WG1) for the oscillation physics

Near Detector Roles

- Constrain the systematics for oscillation measurement.
  - Measure spectra of all four species of neutrinos: $\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e$
  - Measure the absolute and relative flux (FD/ND(E_ν))
  - Constrain energy scale.
  - Differences between neutrino and antineutrino
  - Constrain background: $\pi^0/\pi^+/\pi^-$/etc.
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- Search for new physics:
  - sterile neutrinos
  - light Dark Matter candidates etc.

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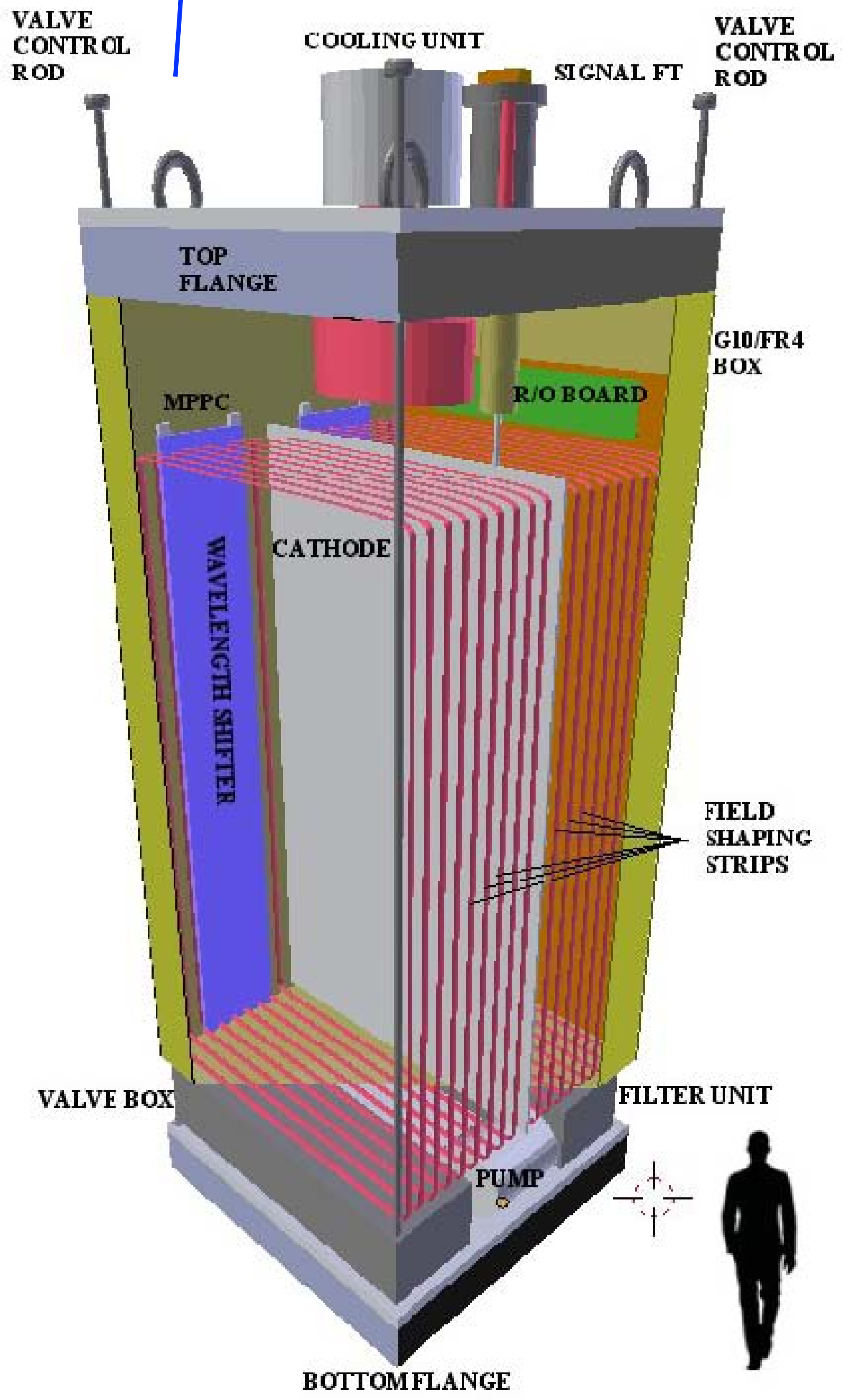

Near Detector Options

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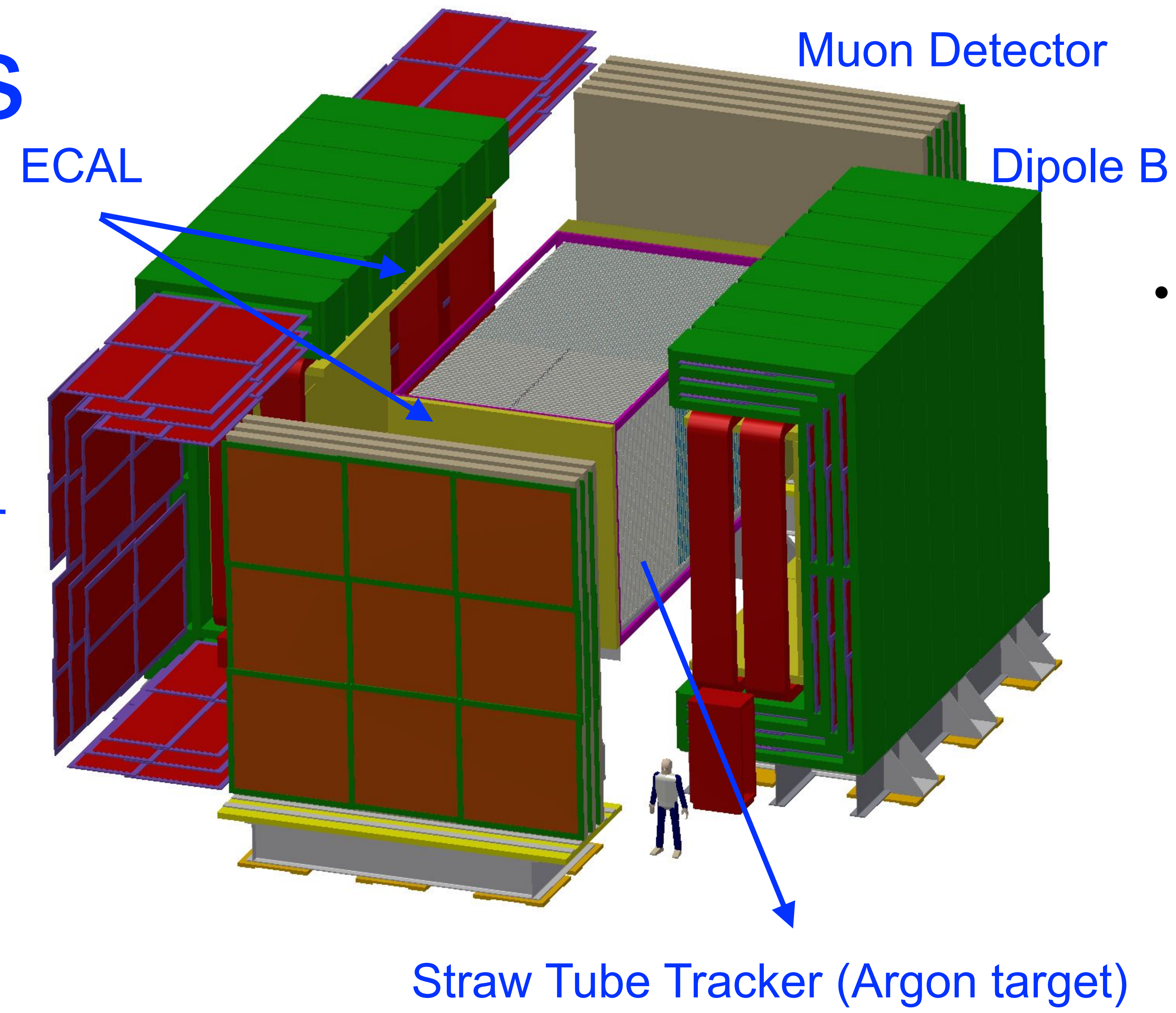
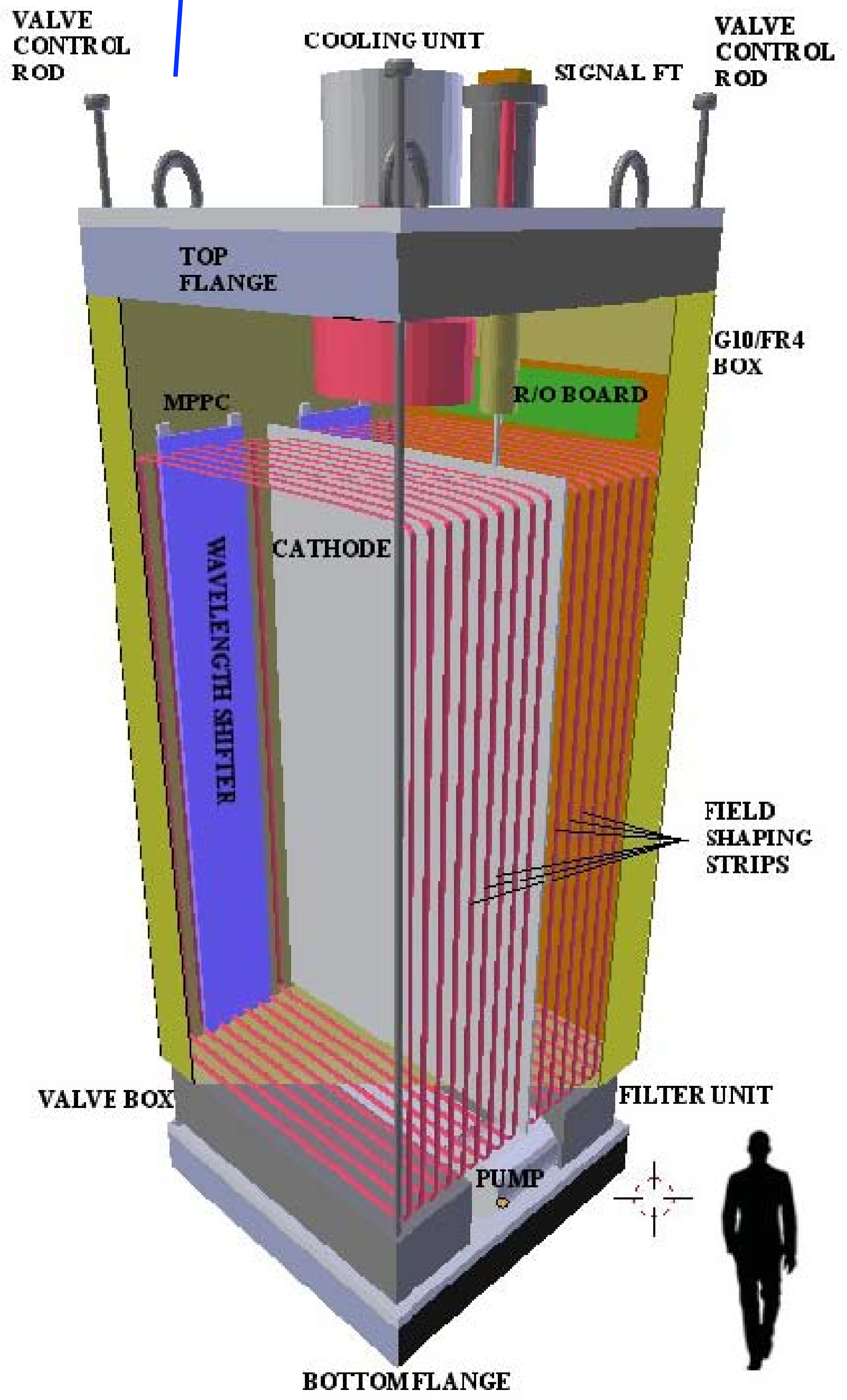
  - LAr TPC
  - Straw Tube Tracker (STT, CDR reference design)





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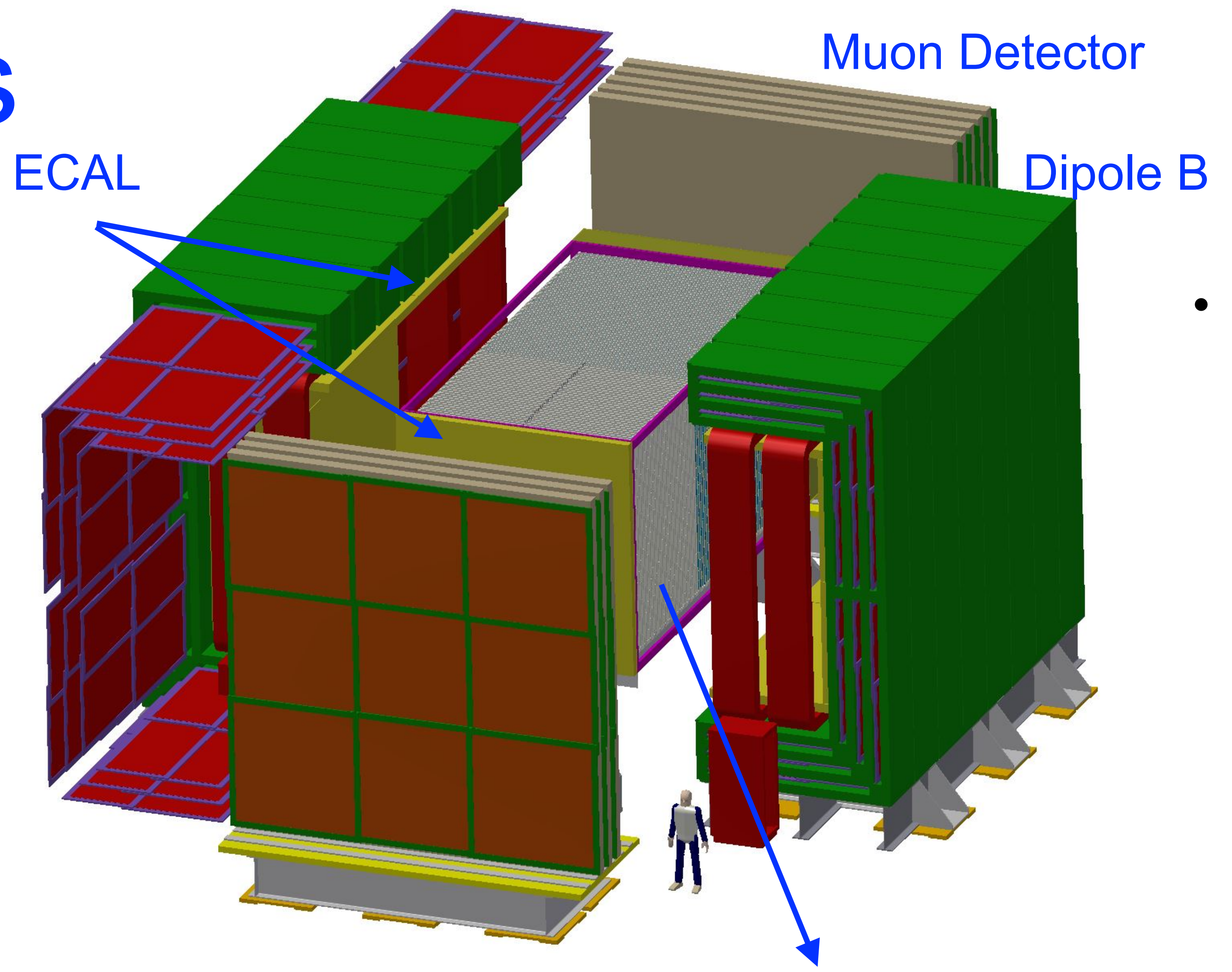

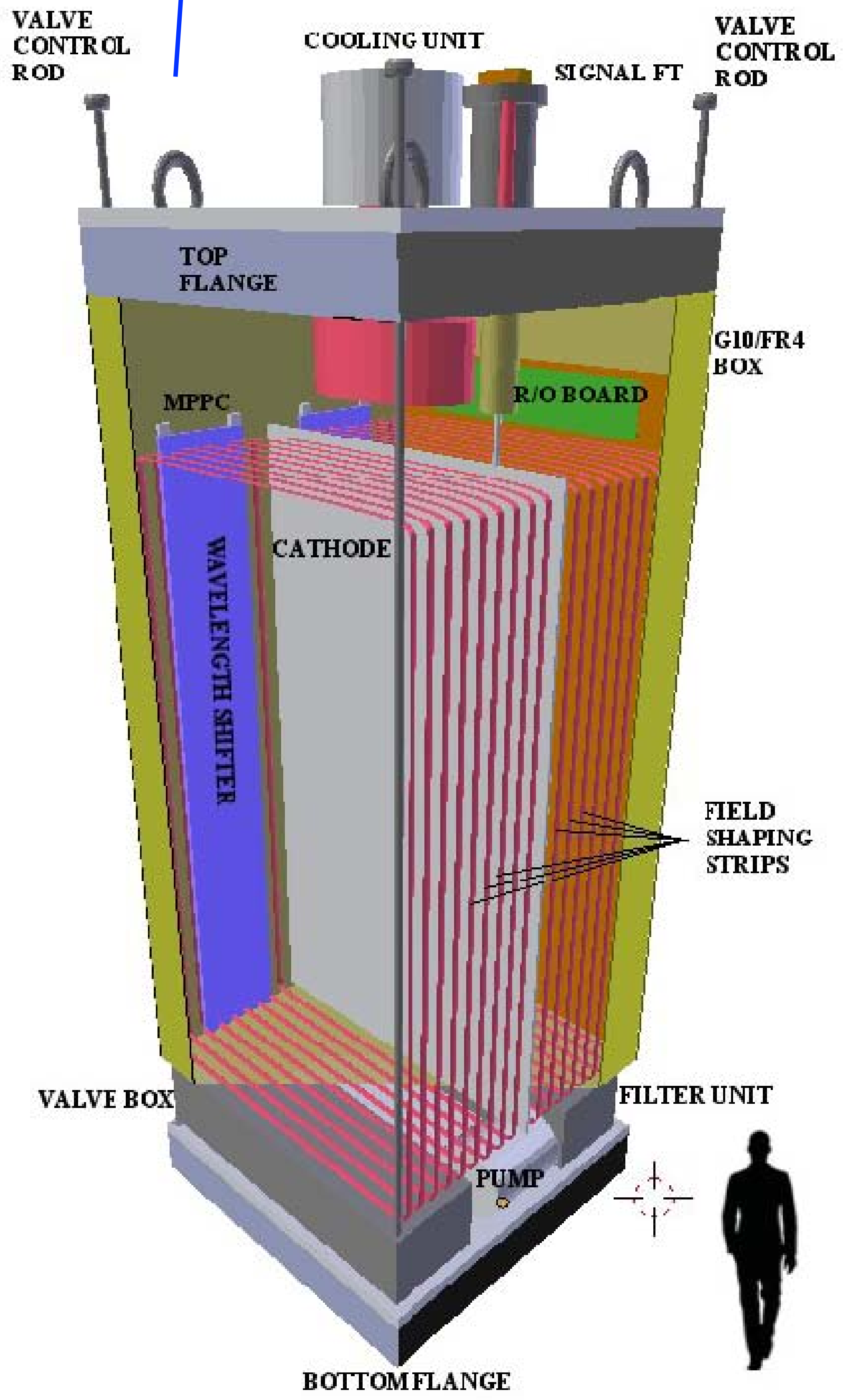

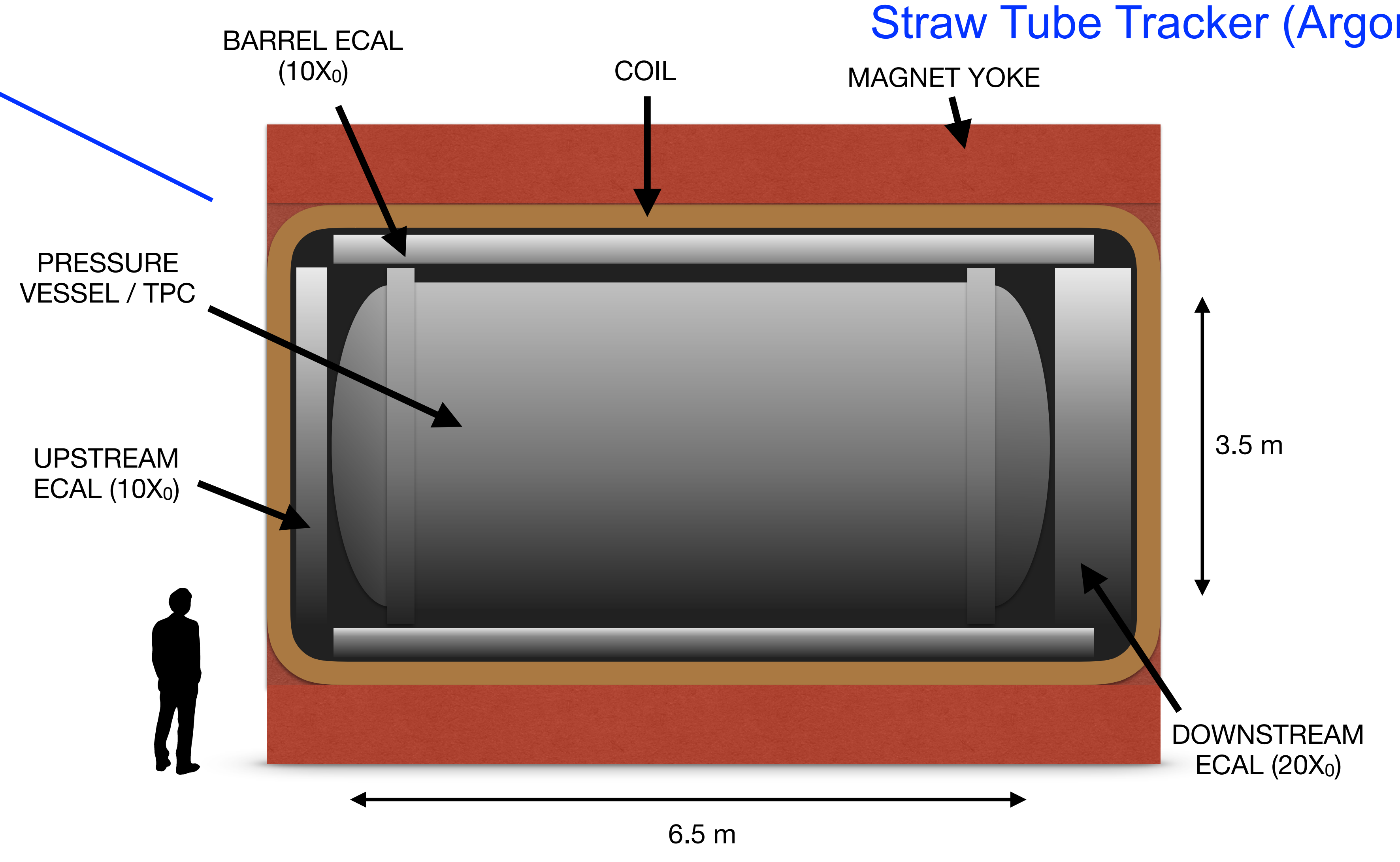

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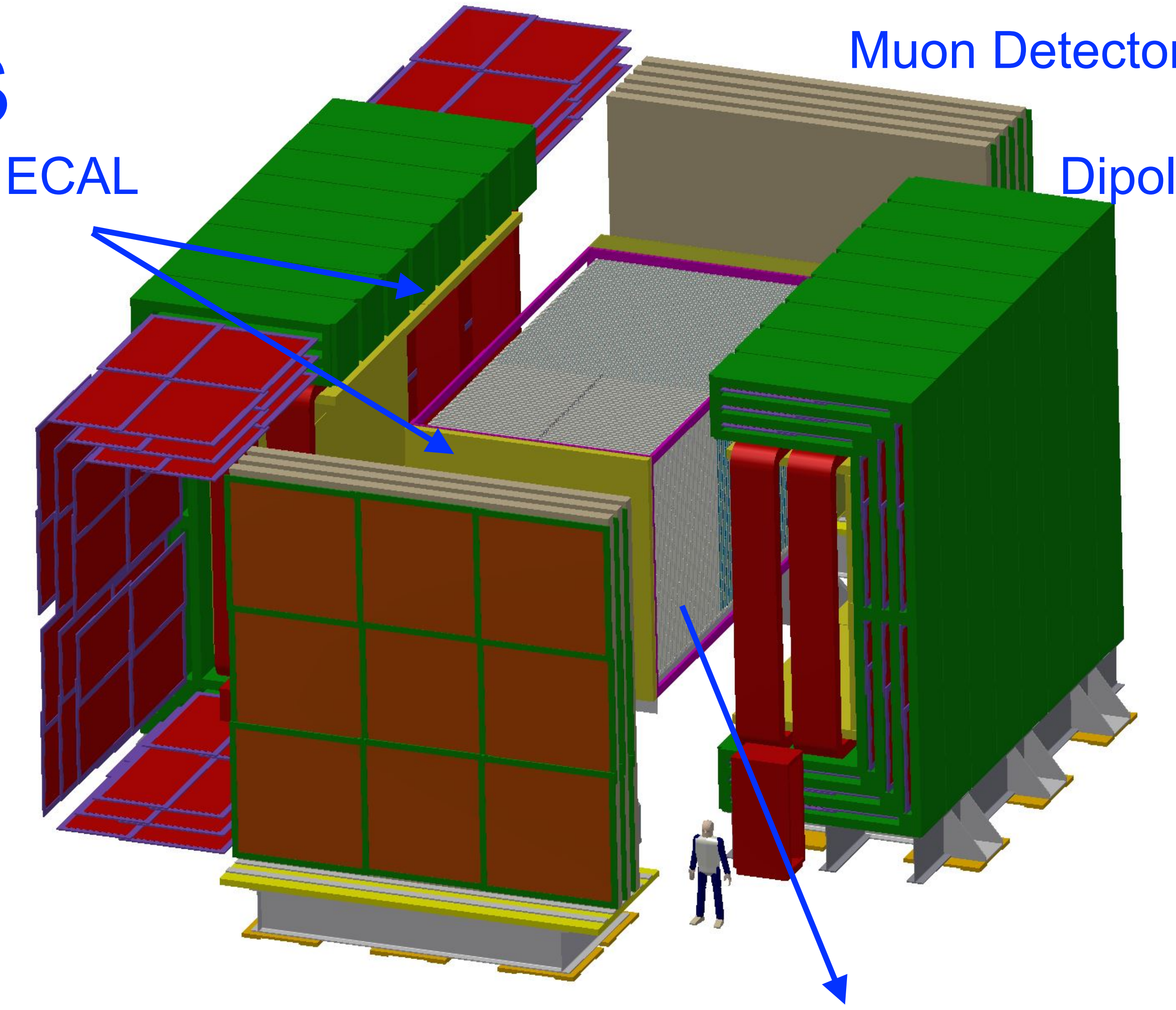

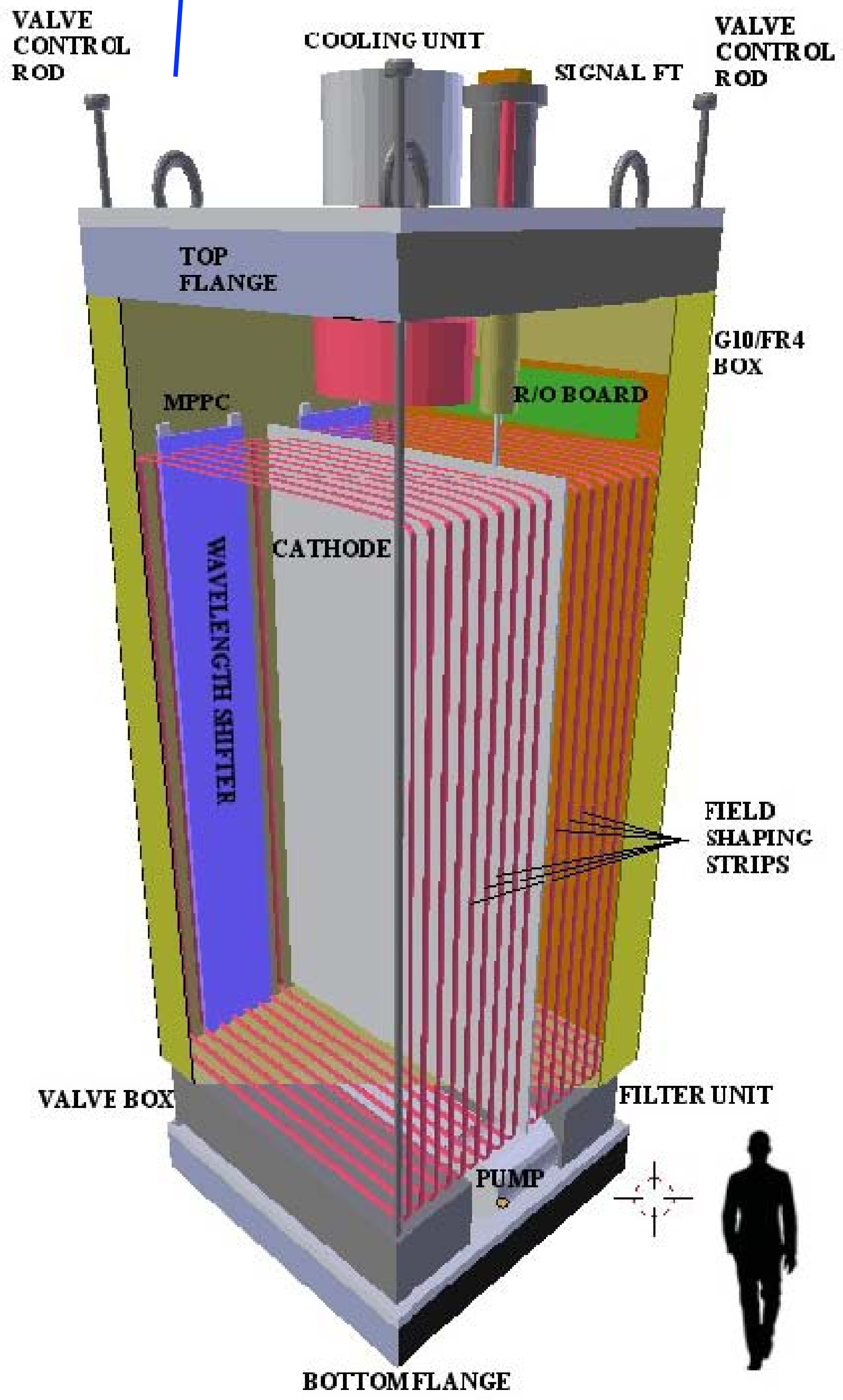

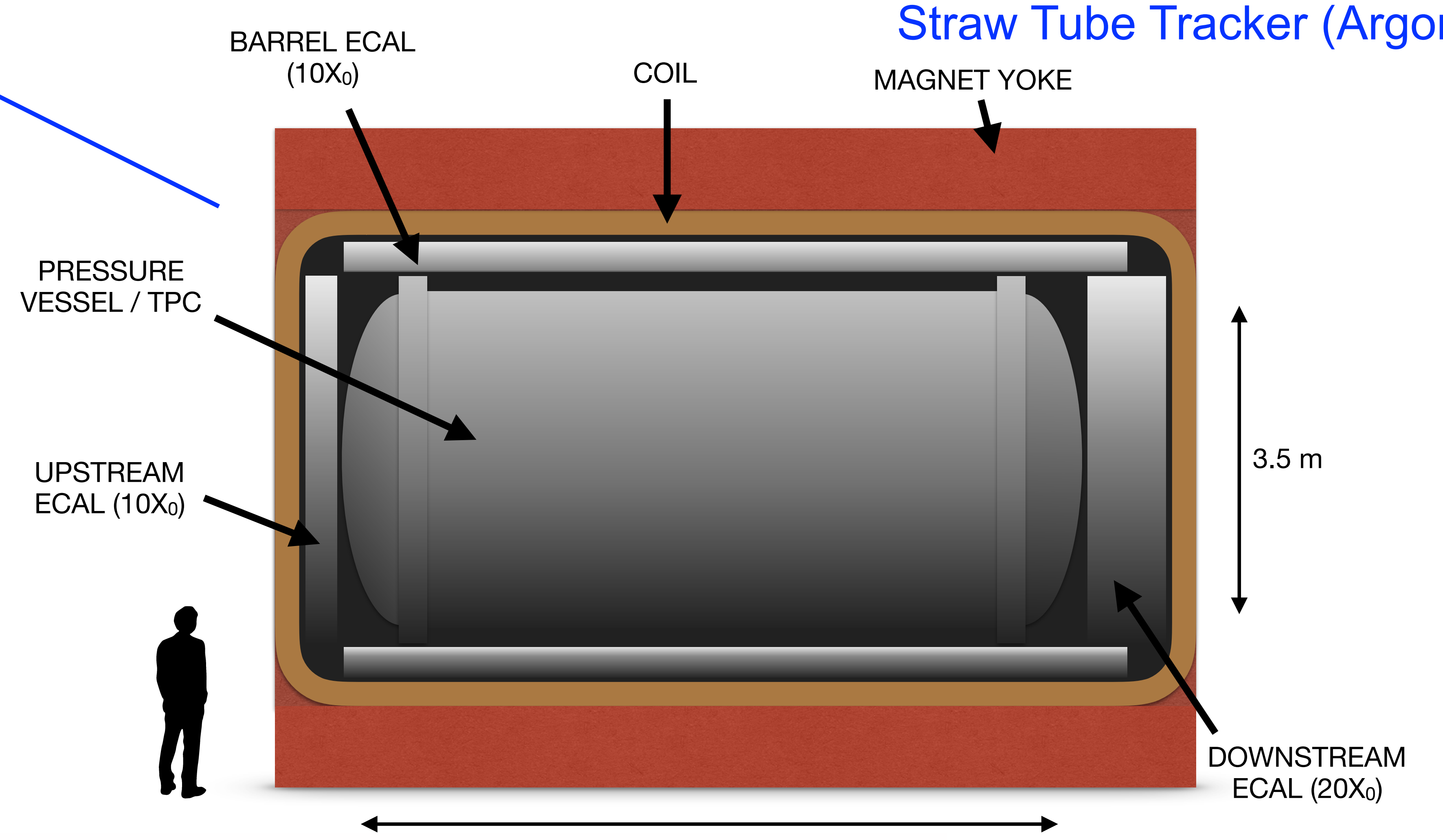

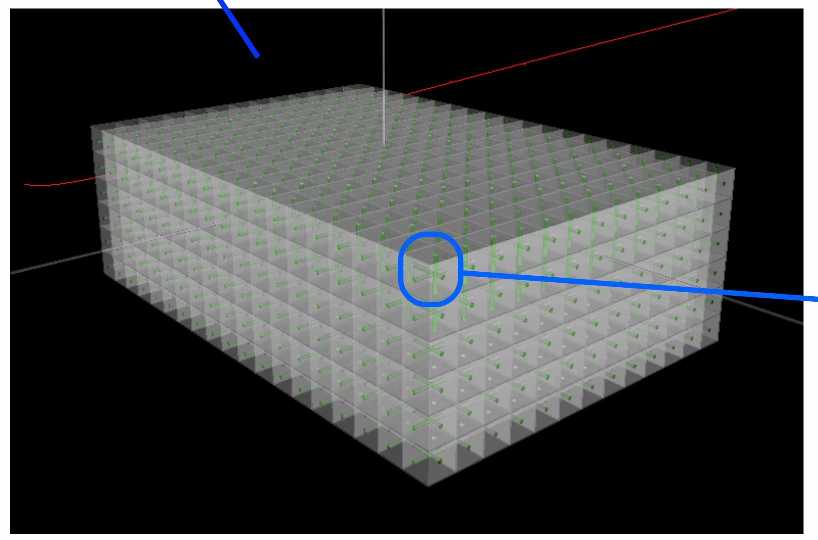

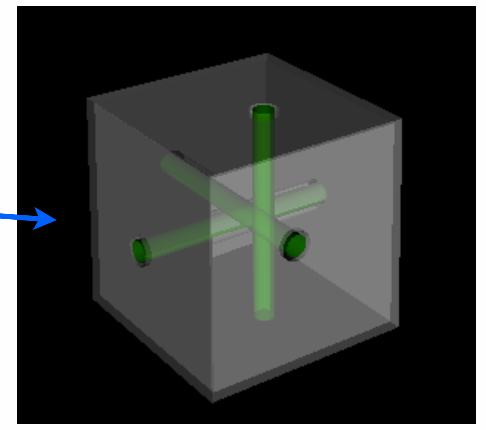

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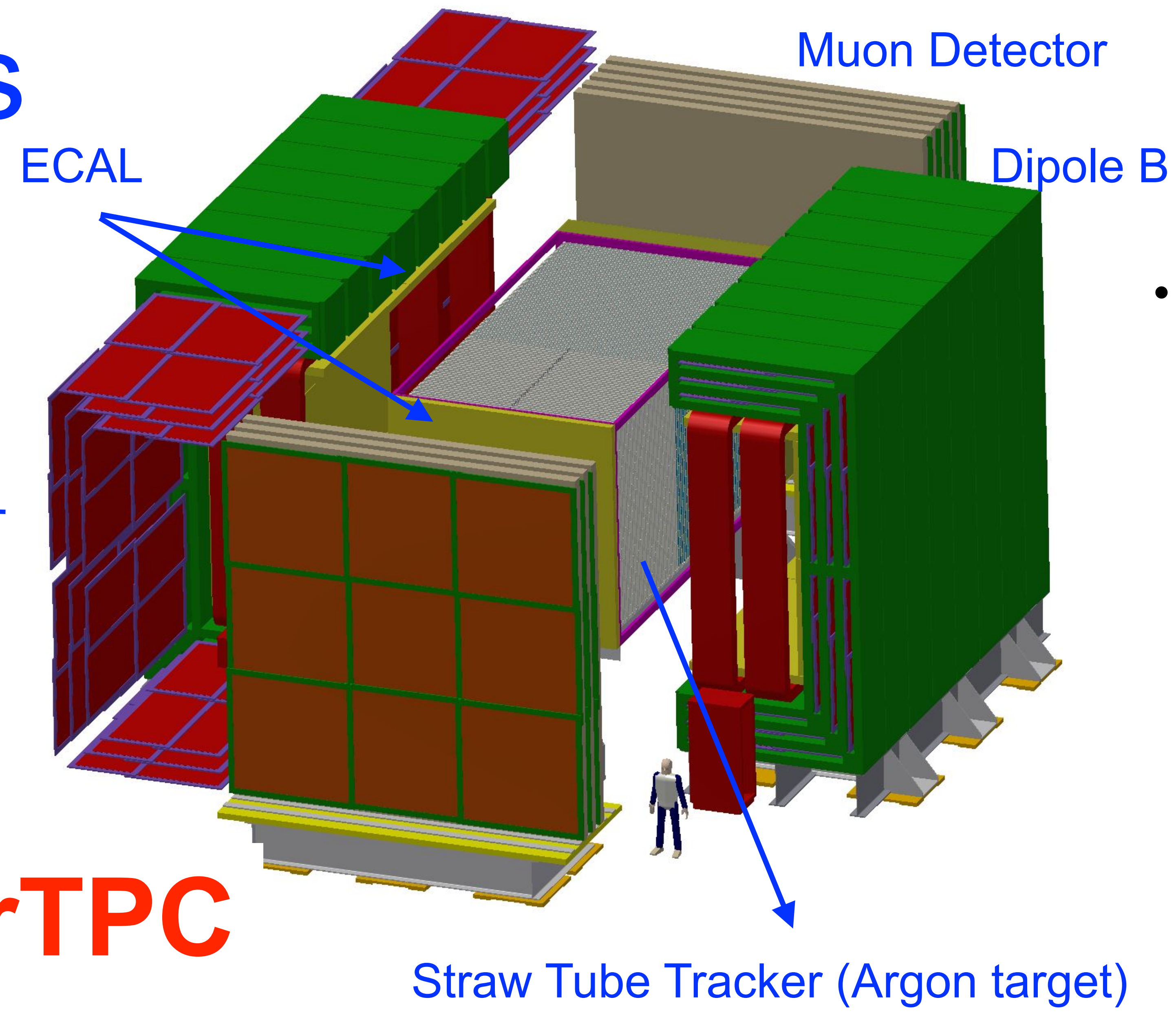
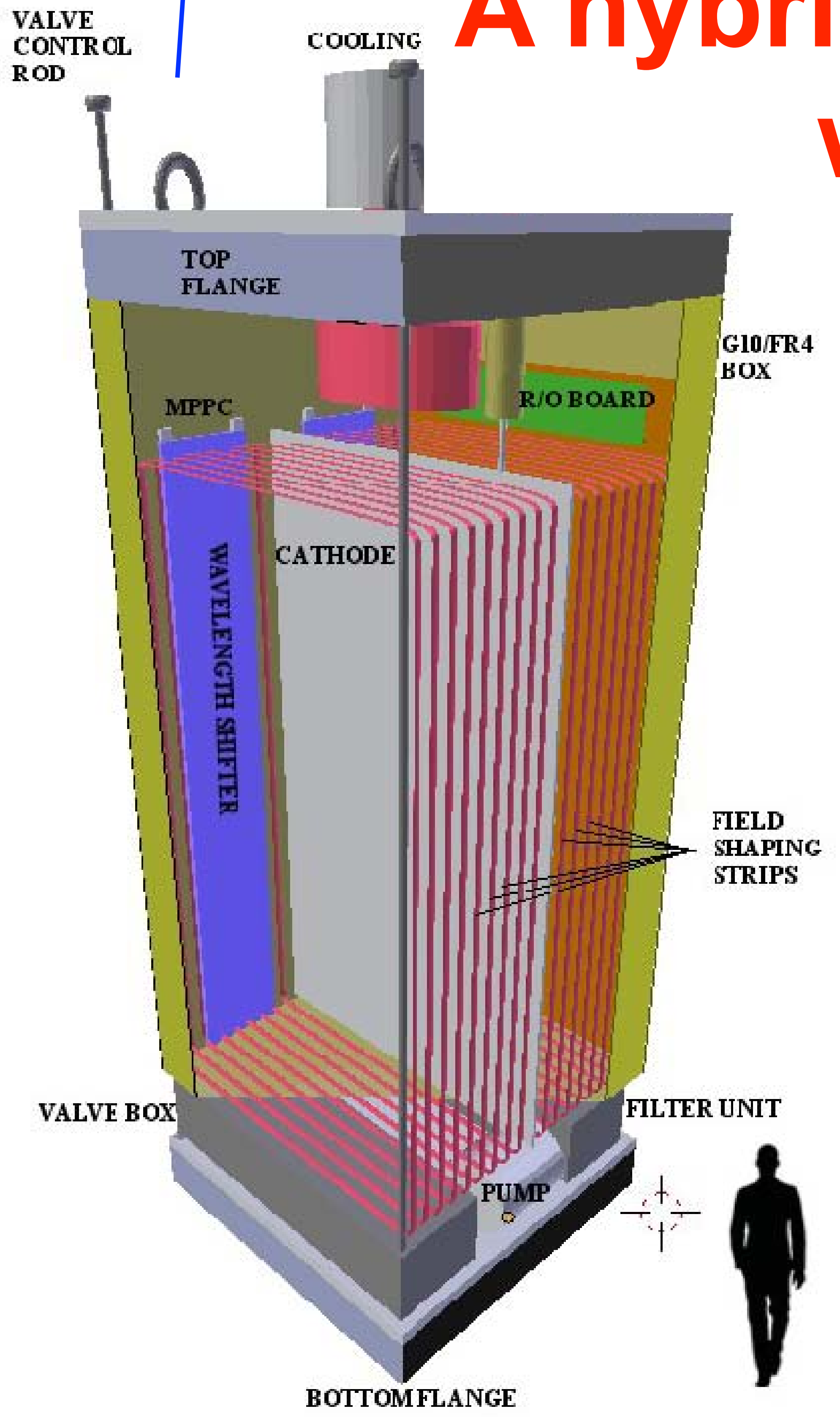
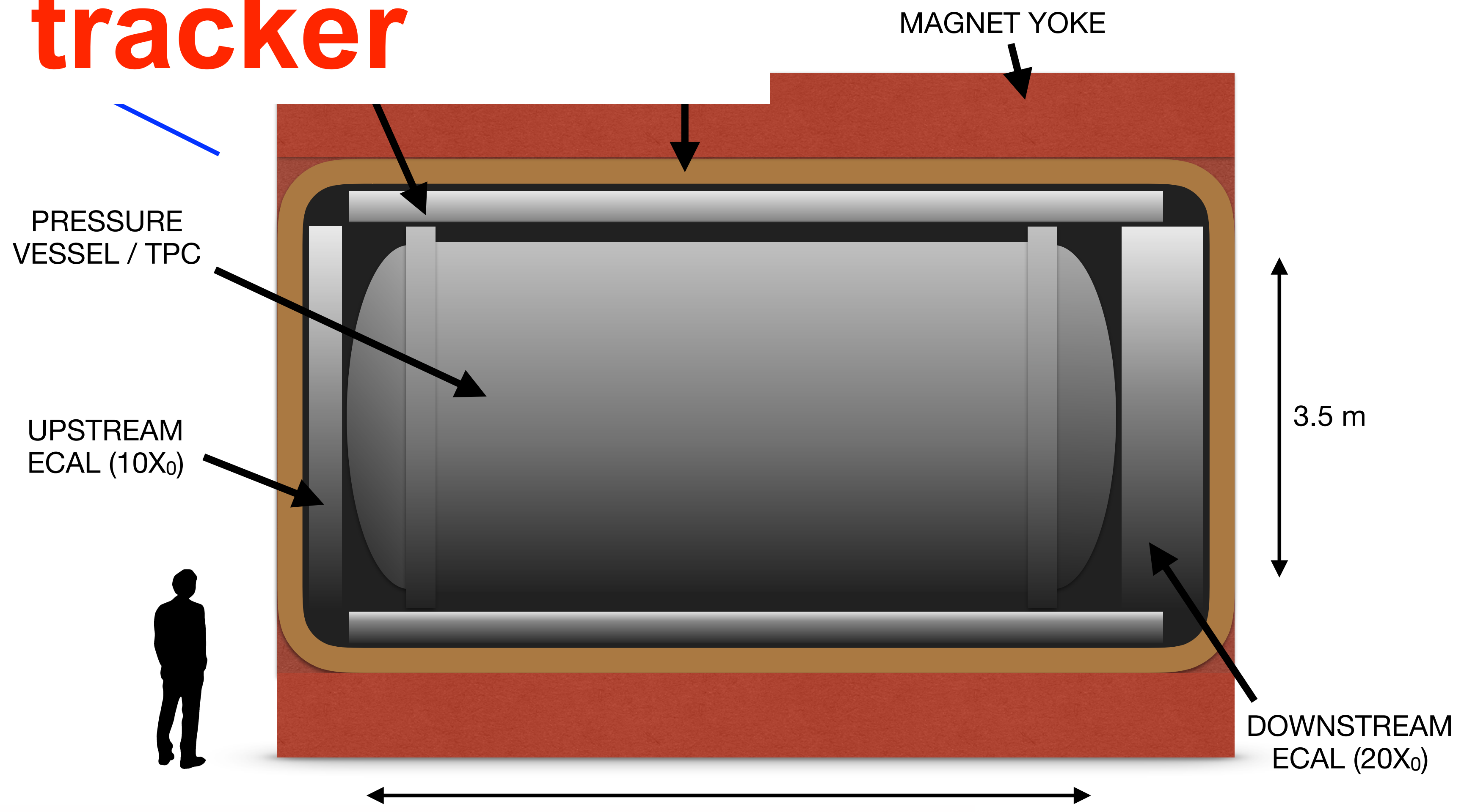
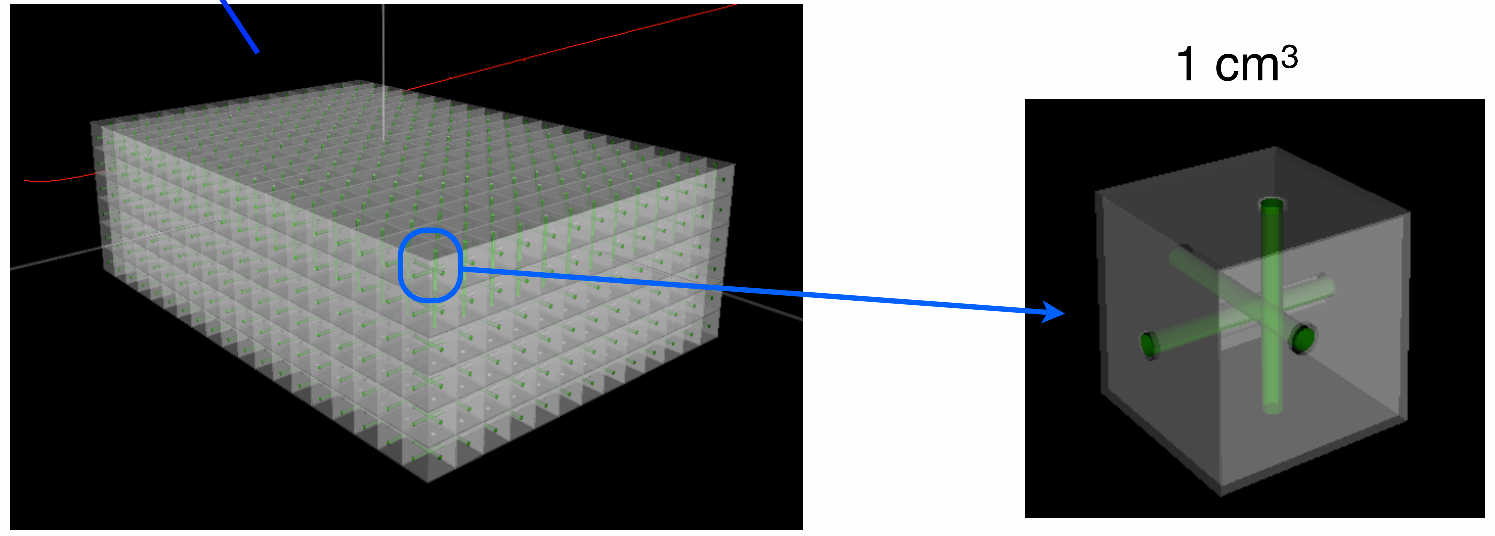


A hybrid detector combining a LArTPC with a low-density tracker







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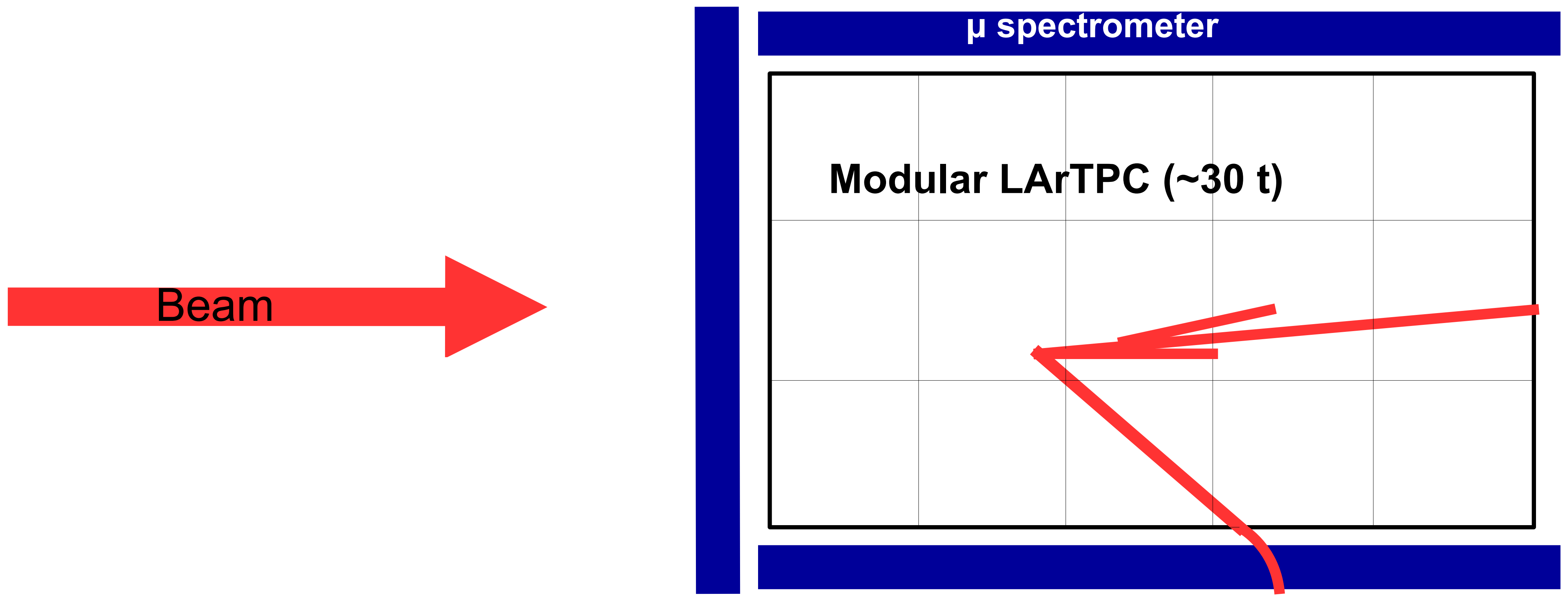

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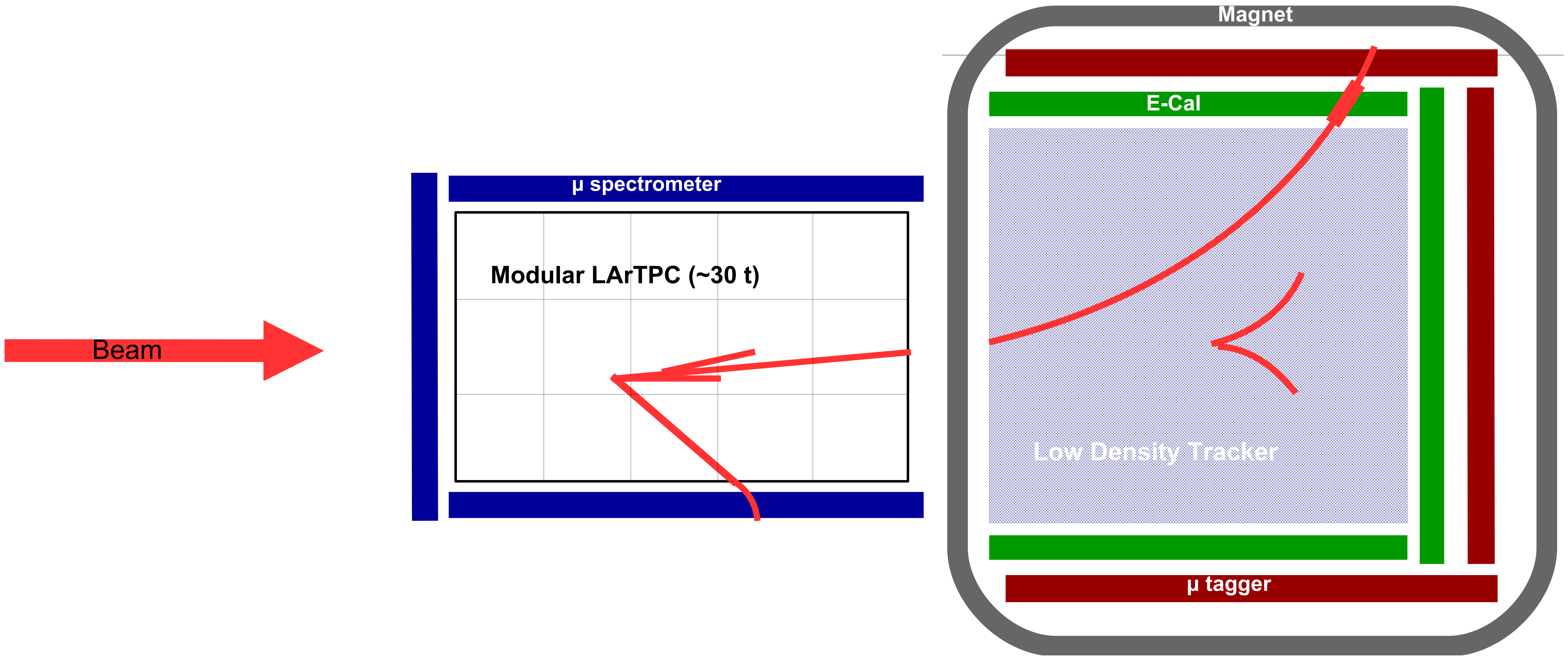

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- Also explore the possibility of DUNE-Prism idea: movable detectors in the ND hall.

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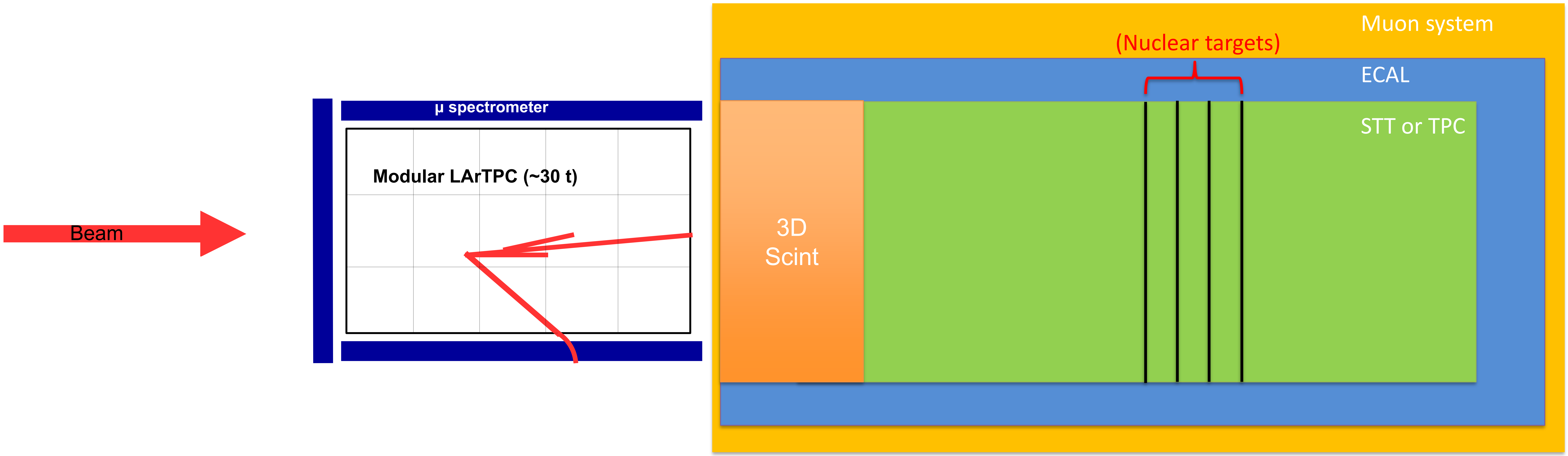

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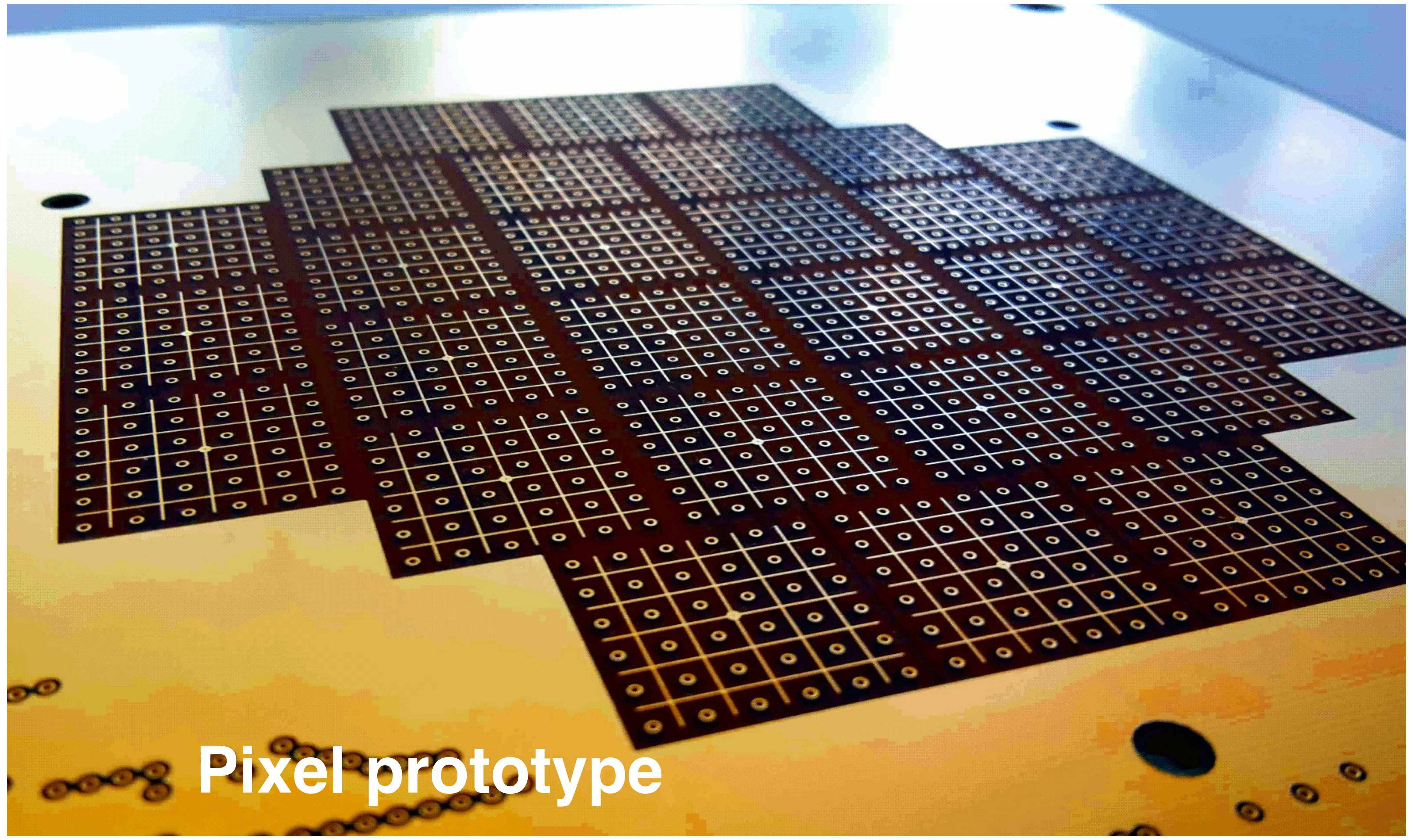
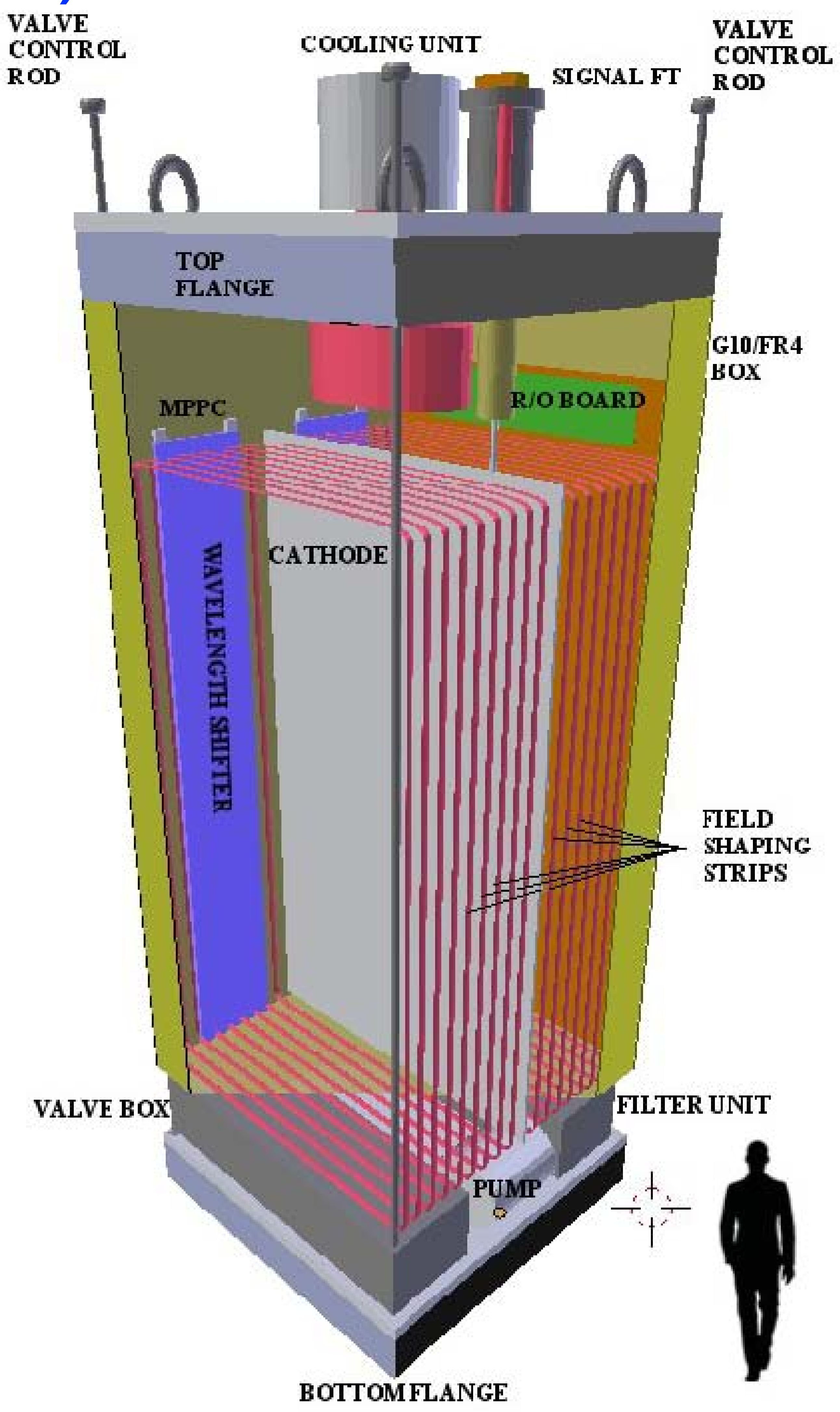
LArTPC (ArgonCube)

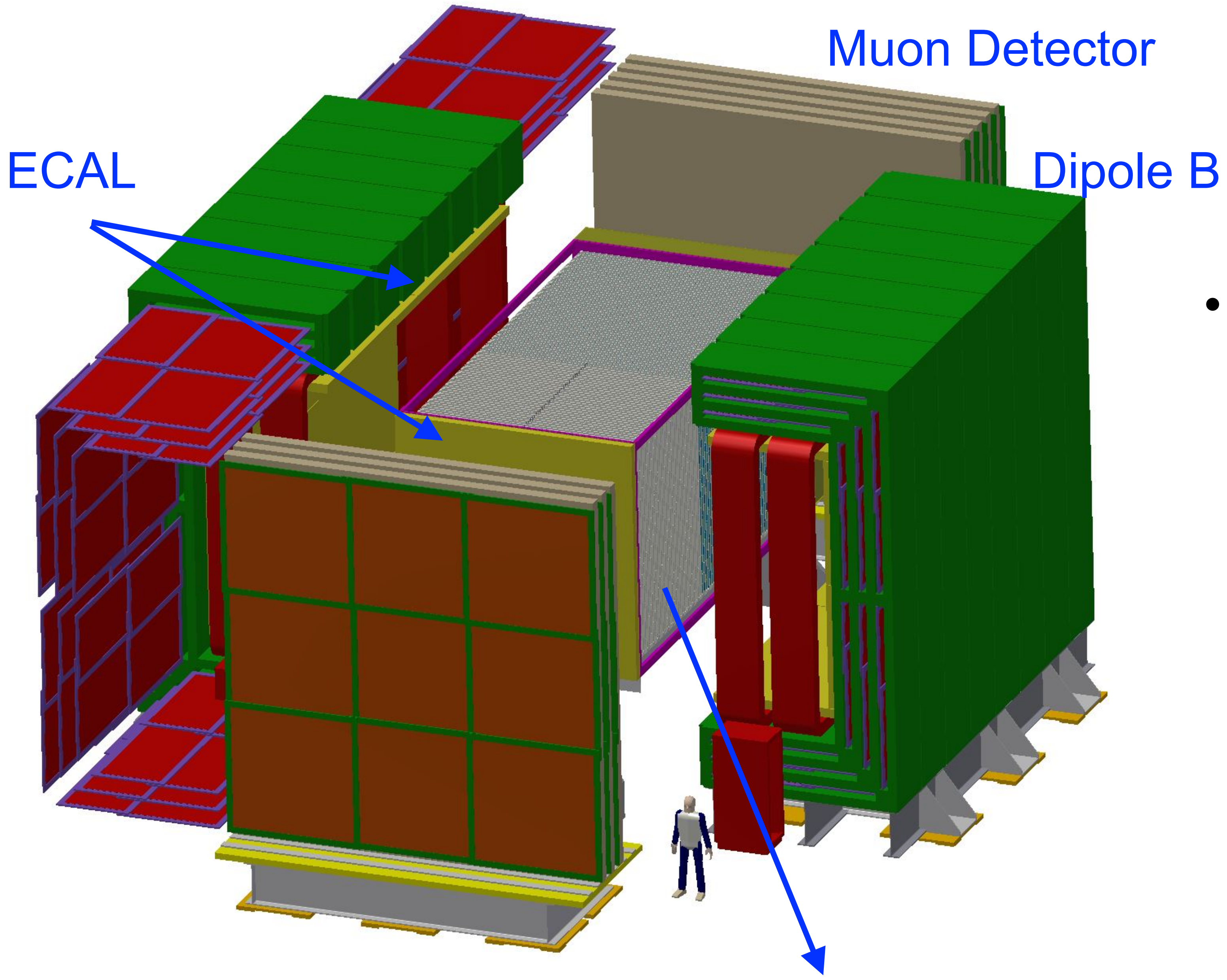
- Same nuclear target and similar detector respond as FD
- Segmented modular detector.
- Pixel readout: high rate capability.
- Will not be magnetized: similar detector respond as FD





- R&D program progressing.

Straw Tube Tracker (STT)



Radiator (Target) Mass	7 tons
Other Nuclear Target Mass	1–2 tons
Vertex Resolution	0.1 mm
Angular Resolution	2 mrad
E_e Resolution	$6\%/\sqrt{E}$ (4% at 3 GeV)
E_μ Resolution	3.5%
$\nu_\mu/\bar{\nu}_\mu$ ID	Yes
$\nu_e/\bar{\nu}_e$ ID	Yes
π^- .vs. π^+ ID	Yes
π^+ .vs. *proton* .vs. K^+	Yes
NCπ^0/CCe Rejection	0.1%
NCγ/CCe Rejection	0.2%
CCμ/CCe Rejection	0.01%

- ~3.5m×3.5m×6.5m, $\rho \simeq 0.1$ g/cm^3, $X_0 \simeq 6$m.
- Magnetic field for charge and momentum measurement.
- 4π ECAL coverage.
- 4π MuID (RPC) in dipole and up/downstream.
- Multiple nuclear targets: Pressurized ^{40}**Ar** target (≃×69 FD-stat), & ^{40}**Ca, C** (~×220 FD-stat).
- Mature technology based upon NOMAD experience. (Validation using NOMAD data)

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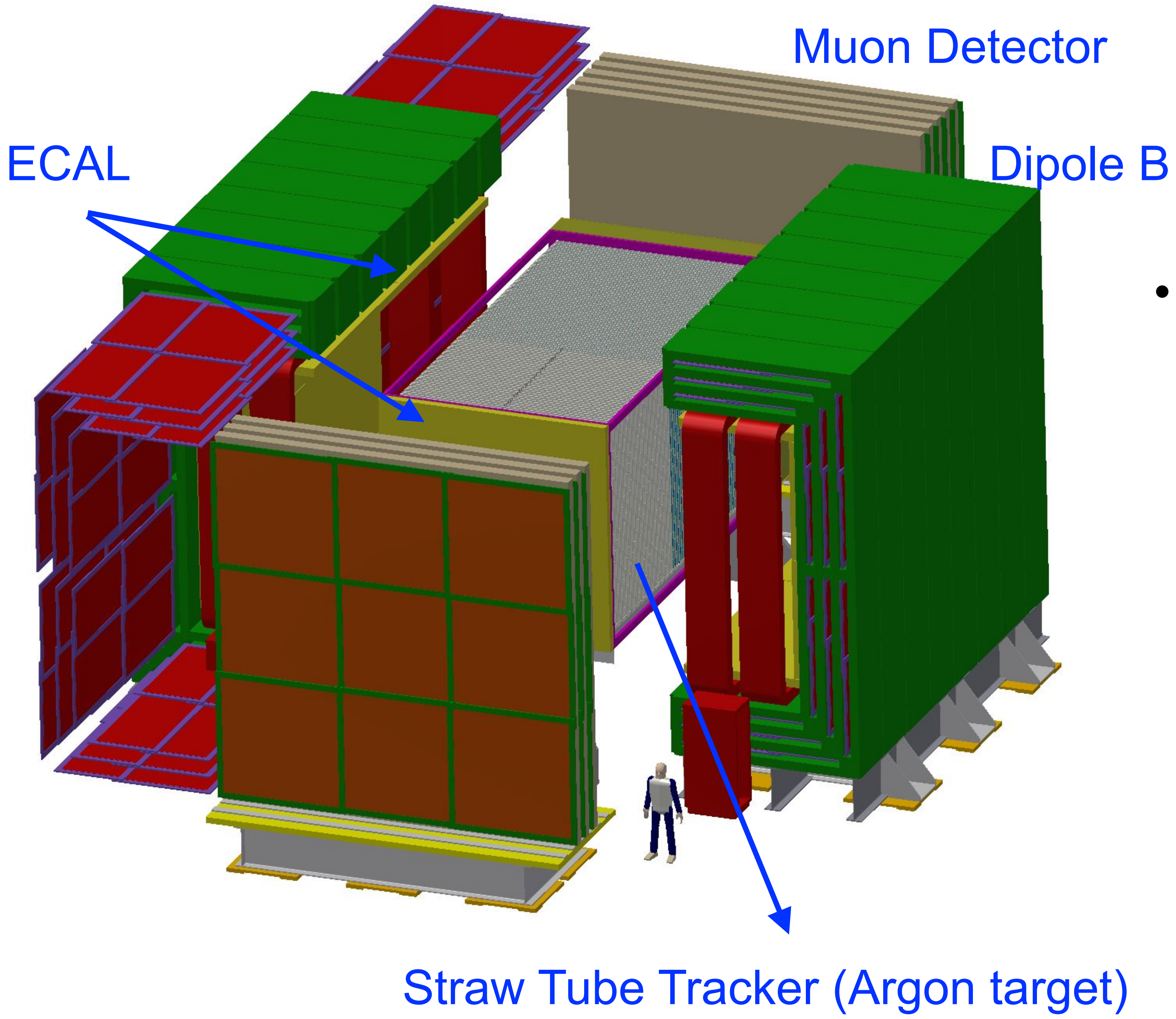

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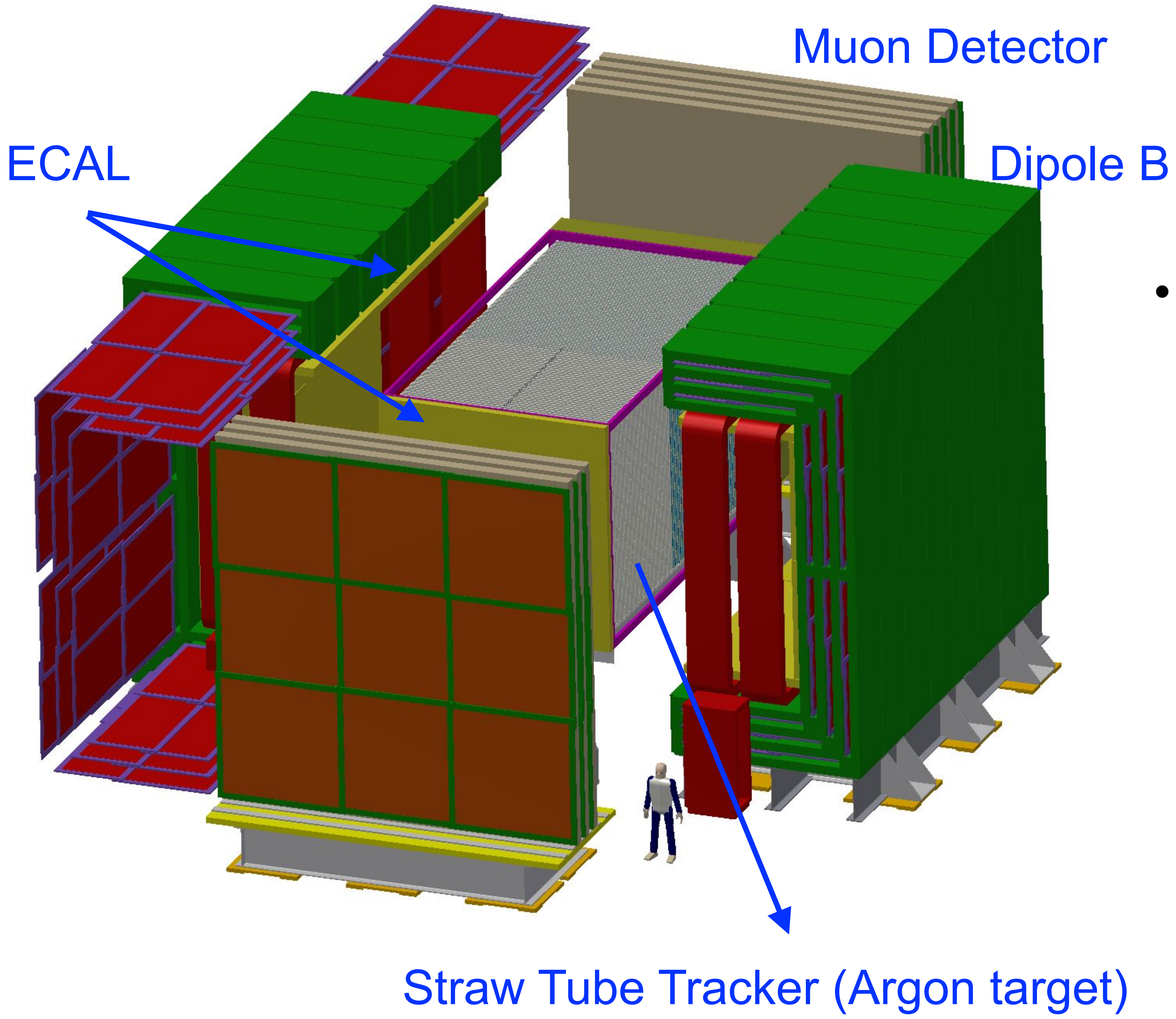

Particle Identification

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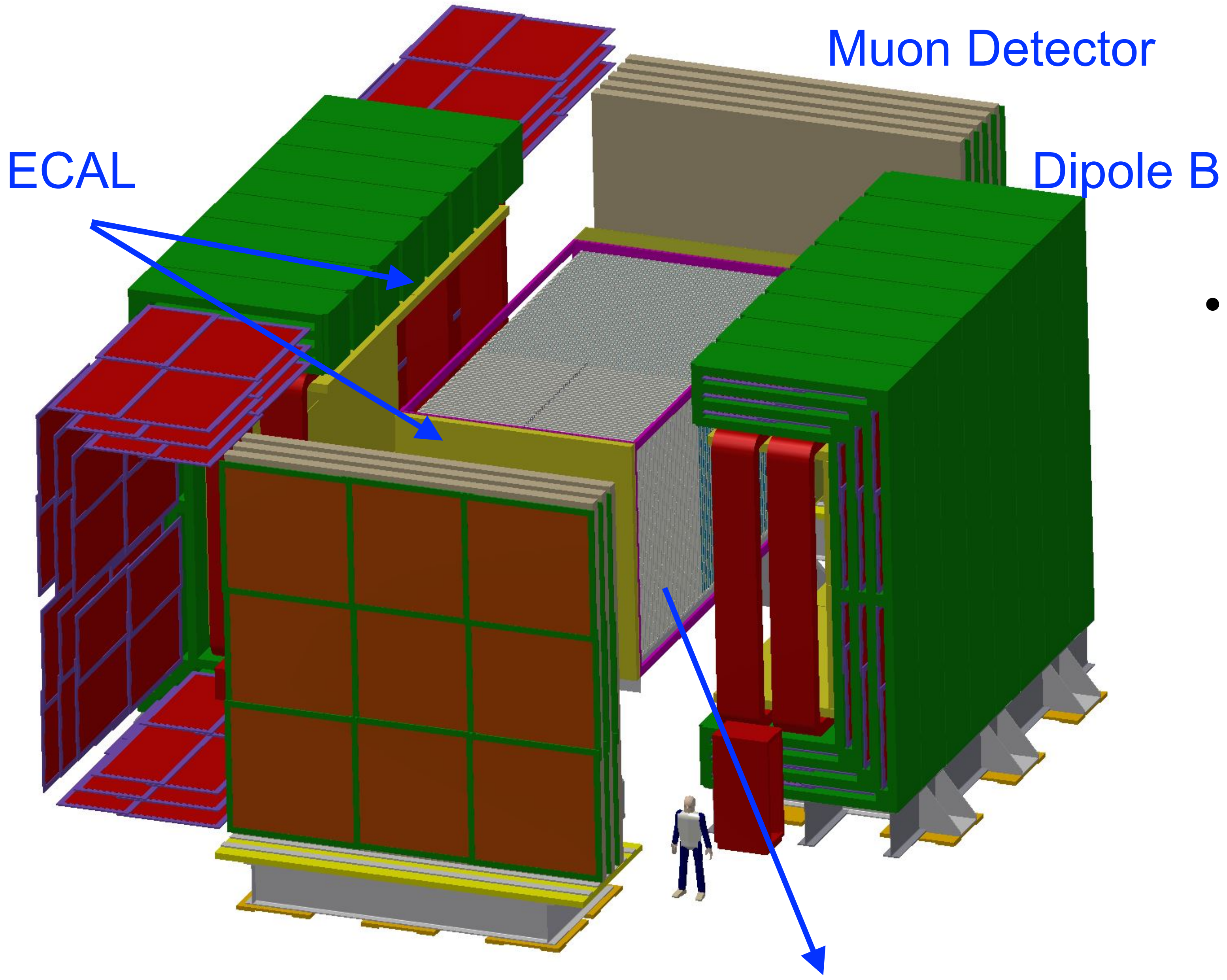

Straw Tube Tracker (Argon target)

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Background Rejection

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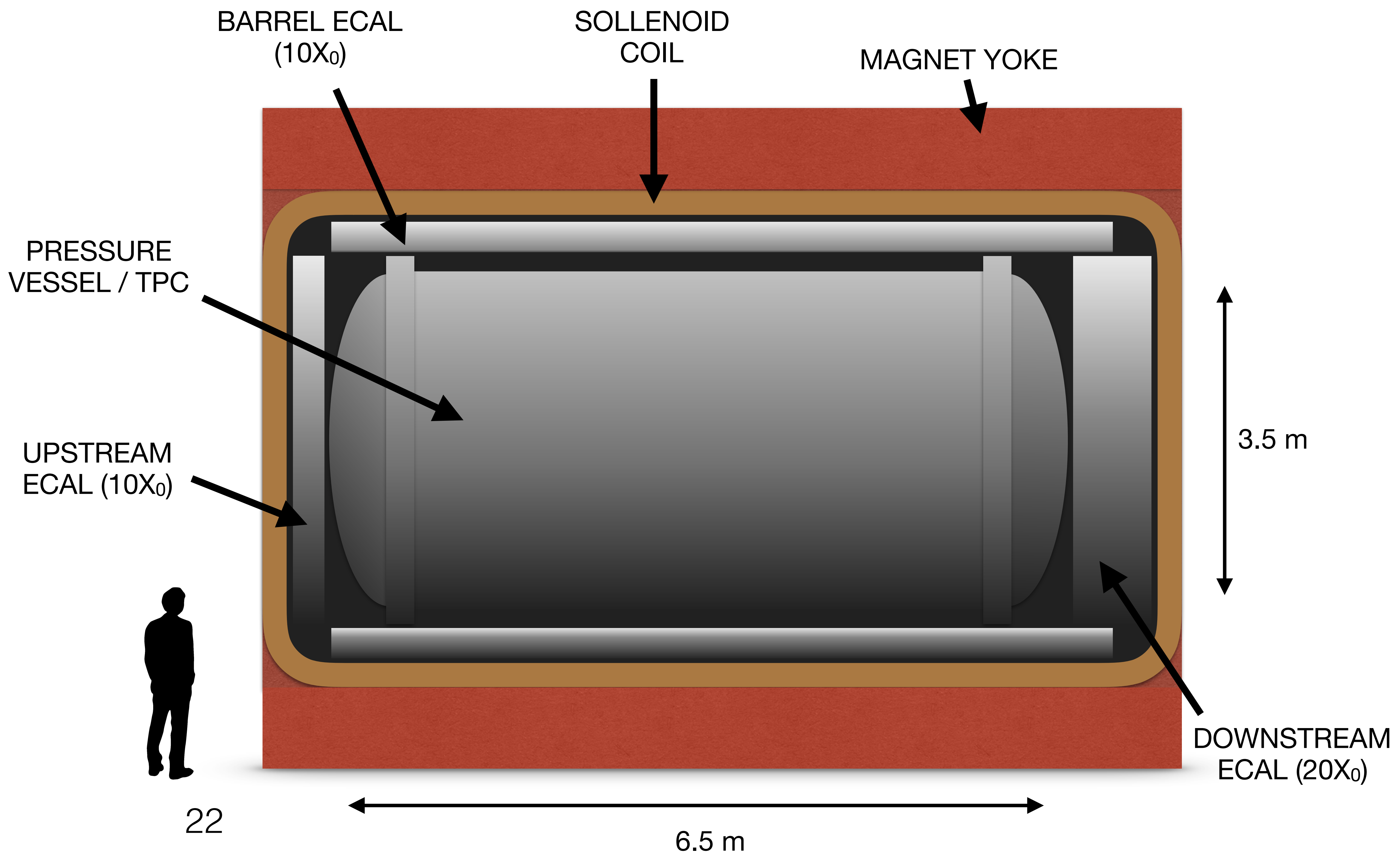
High Pressure Ar Gas TPC

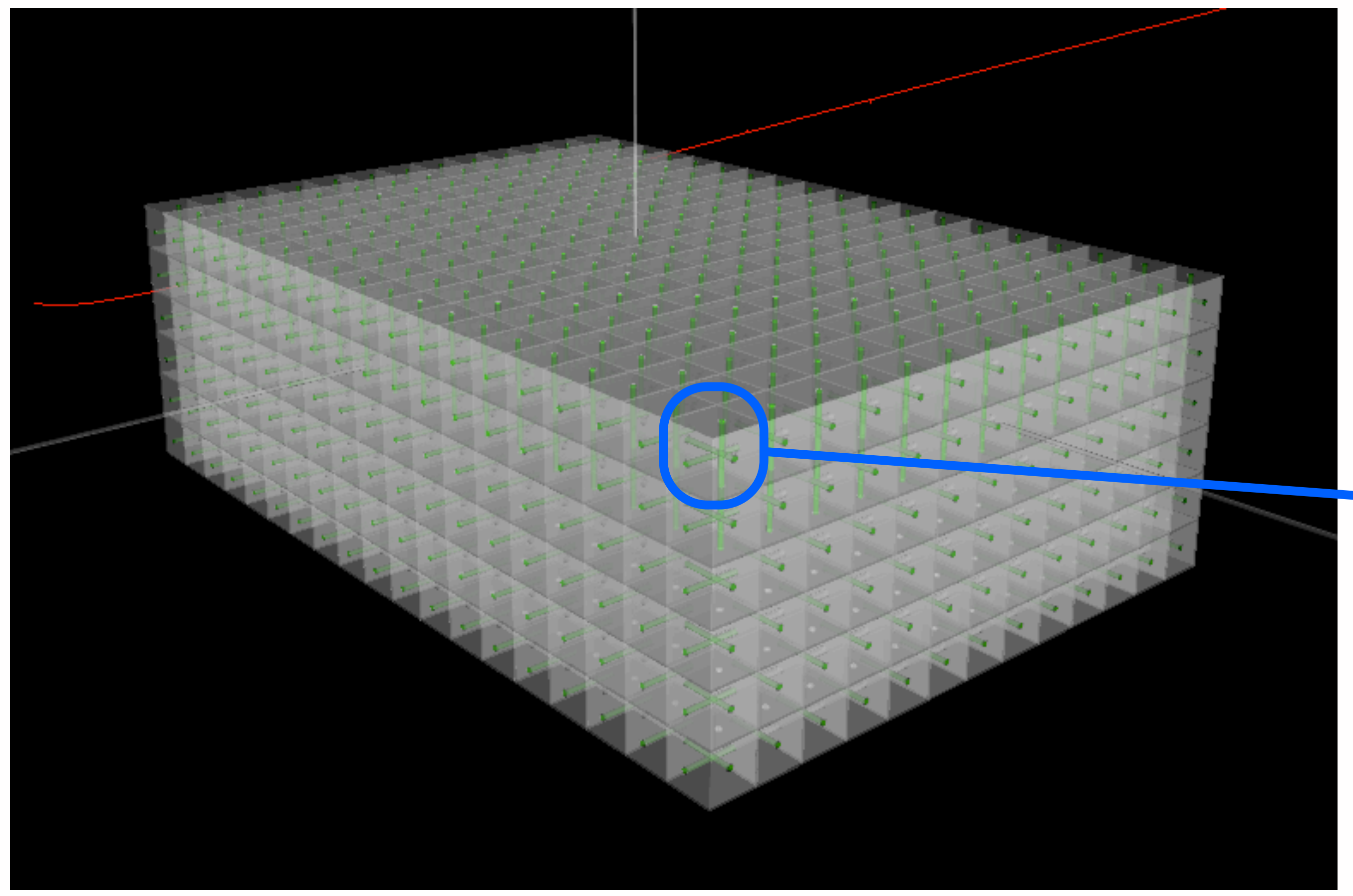
- HP Ar Gas: Same target as FD, low density, low thresholds.
- Compatible with magnetic field.
- A central large time projection chamber with argon gas pressurized at 10 bar.
- A pressure vessel that houses the TPC.
- An electromagnetic sampling calorimeter made of layers of lead and plastic scintillator.

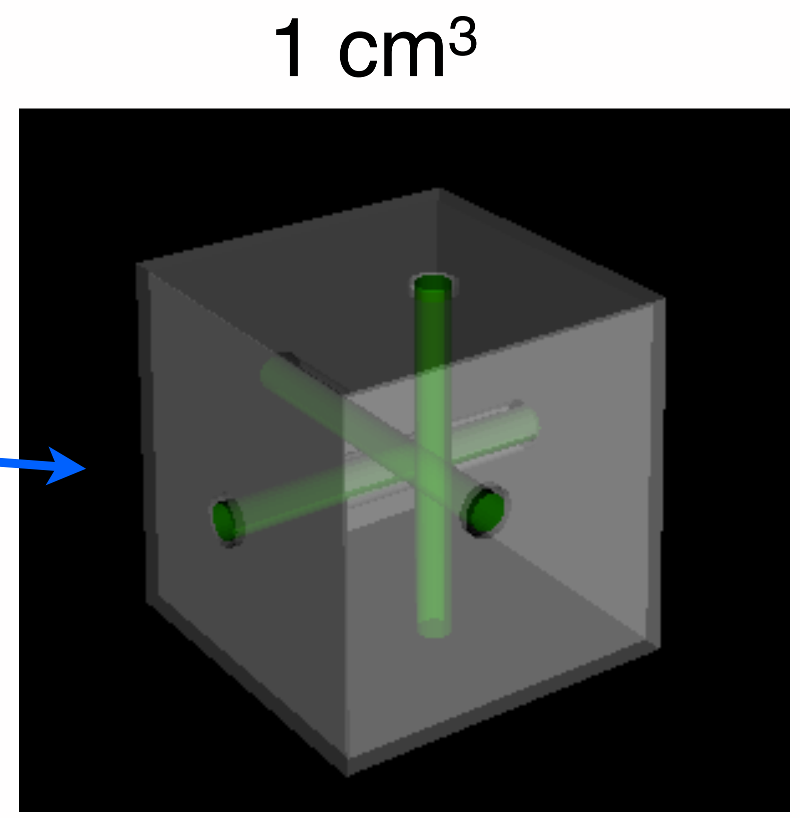
- Good tracking performance and resolution
- R&D work progressing.

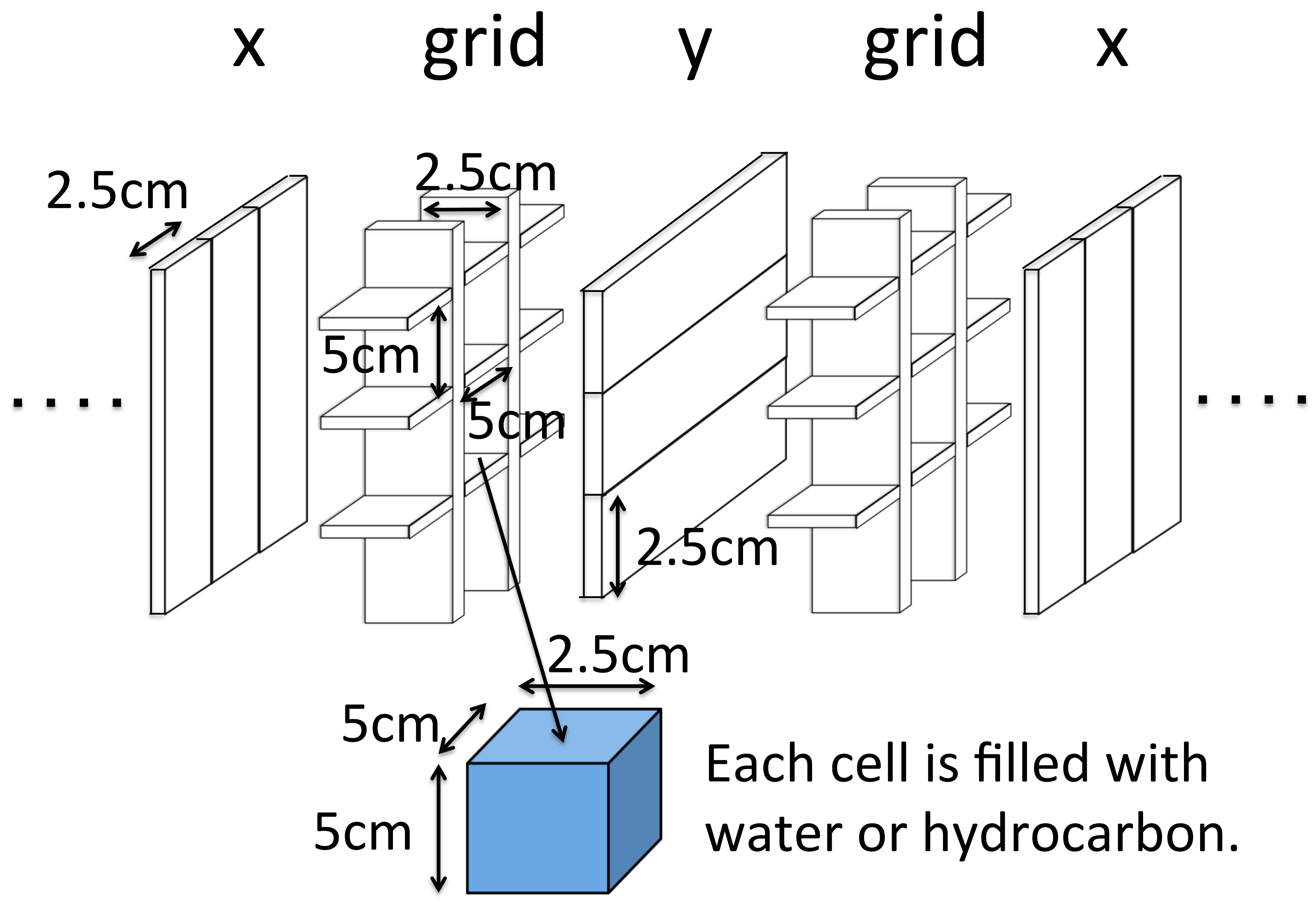


Scintillating Plastic Tracker

- Mature technology.
- Compatible with magnetic field.
- Take advantage of the knowledge from current scintillator experiments (T2K, MINERvA, NOvA).
- Fast perfomance.
- 3D readout.

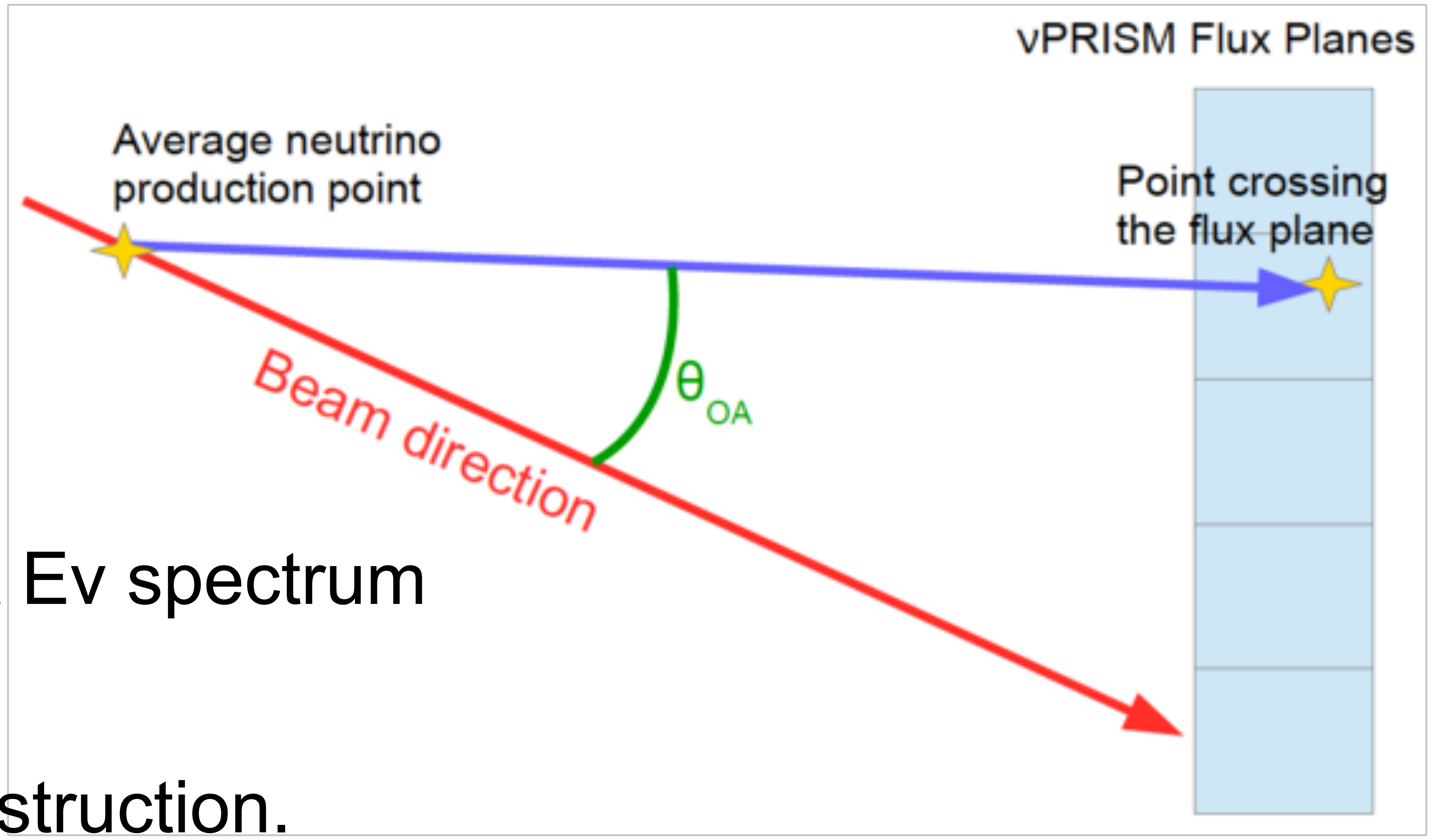




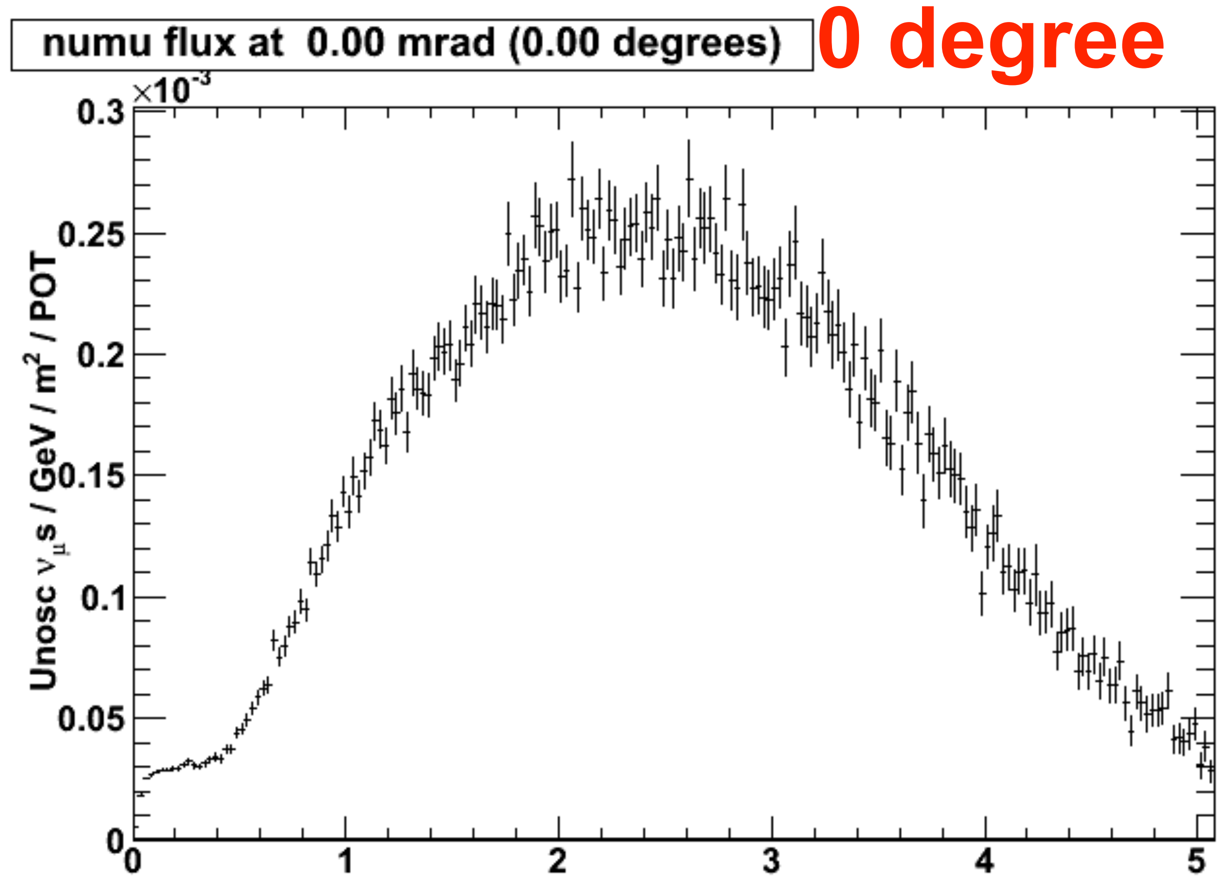


DUNE-Prism

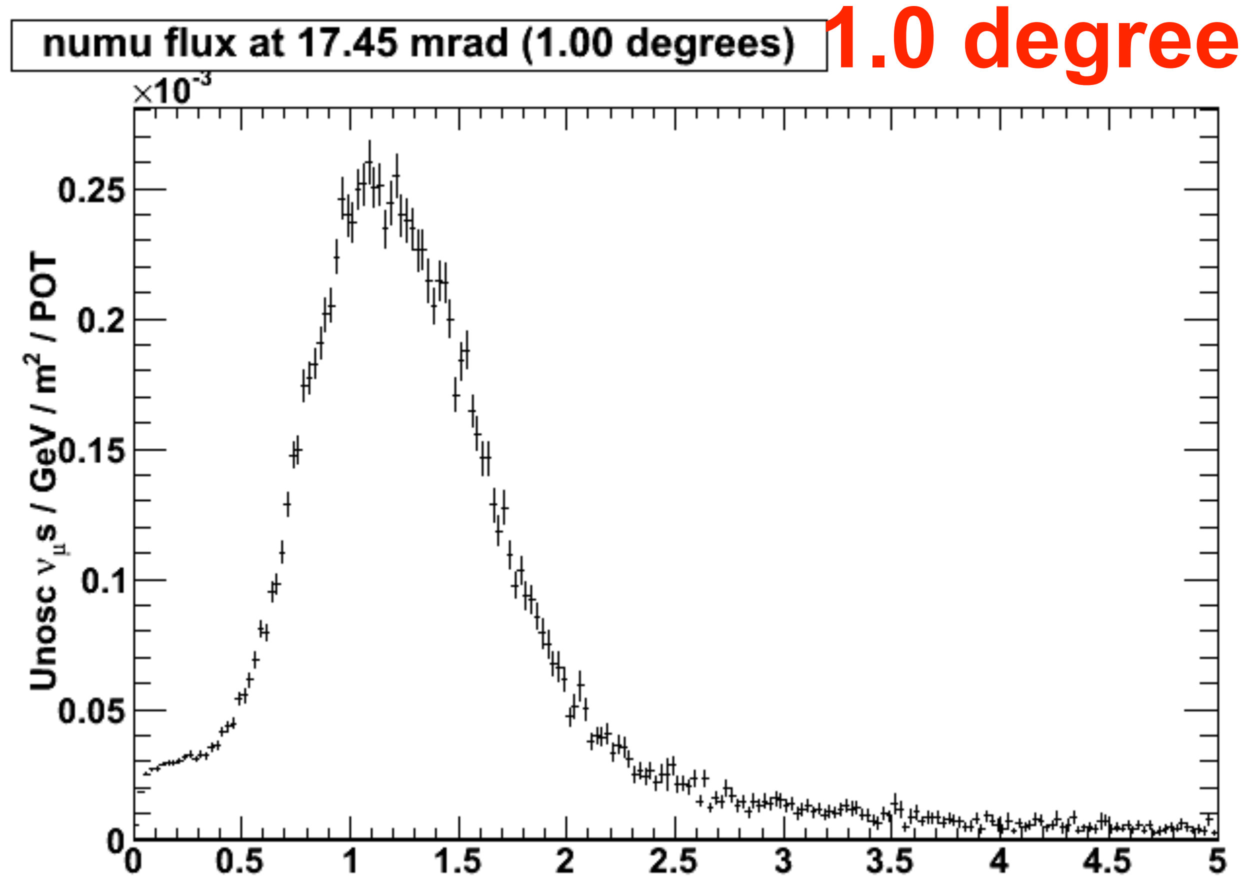
- FD sees different flux from ND.
- Neutrino energy reconstruction from observable final-state particles is model-dependent.



- Movable ND to different off-axis locations with different Eν spectrum
  - Re-produce oscillated Eν spectrum in the FD.
  - Create mono-energetic beam to check energy reconstruction.
  - Helps disentangle cross section from flux.



ν_μ **Energy (GeV)**



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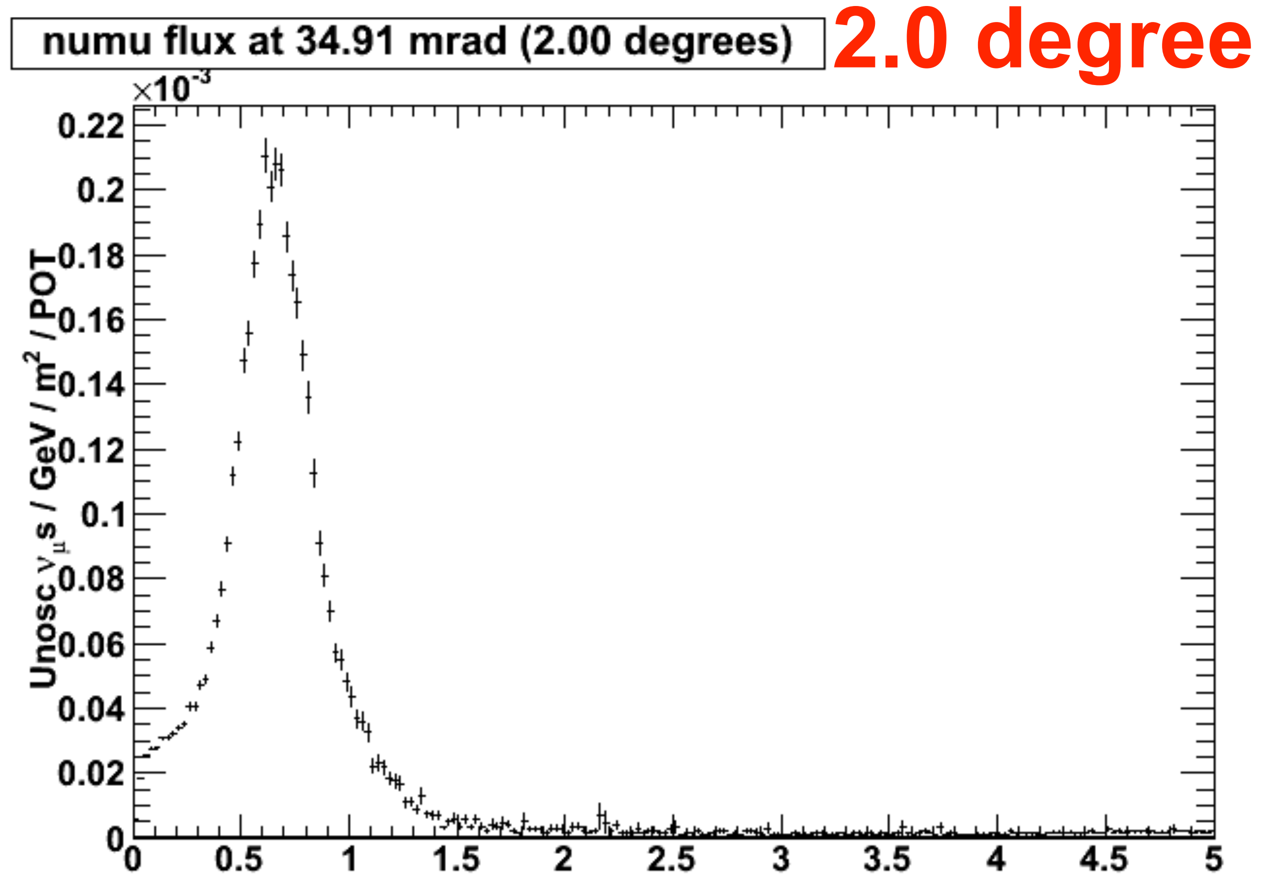

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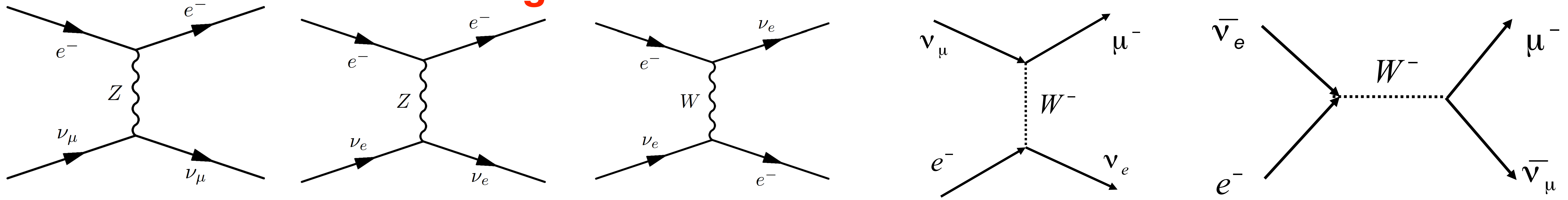
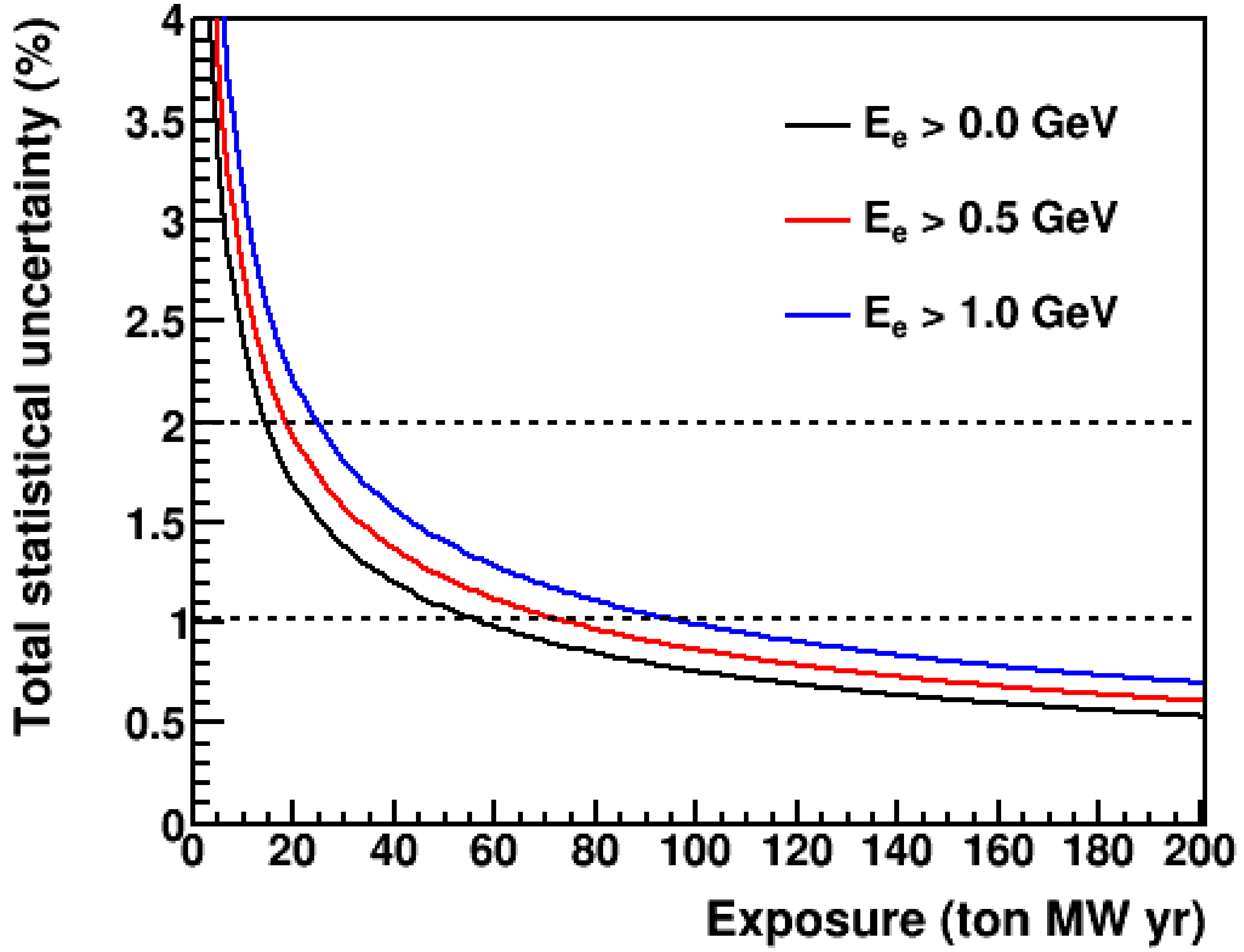
Flux Measurement: Neutrino-Electron Scattering

ν-e scattering **IMD**



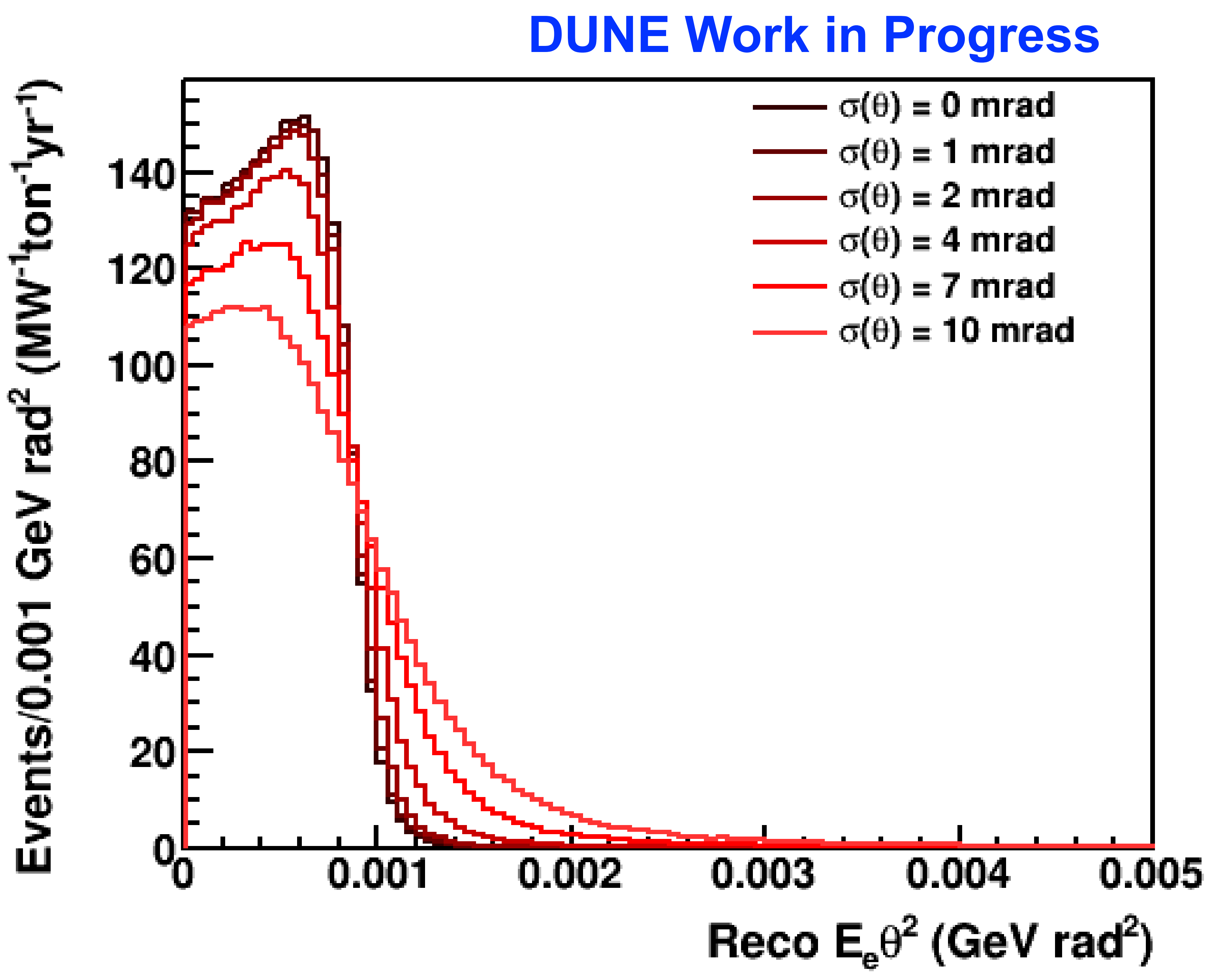
- Pure electroweak process with small, but very well known cross section: Good for measurement of absolute flux.
- Very forward-going electron
  <u>$E_e\theta^2 = 2m_e(1-y)<2m_e$.</u>
  in final state with no other particles.
- Uncertainty will be dominated by statistics: need enough detector mass.

DUNE Work in Progress



Flux Measurement: Neutrino-Electron Scattering

- **$E_e\theta^2 = 2m_e(1-y) < 2m_e$.**
- Good angular resolution is critical to reduce background.
- With ~2 mrad angular resolution, 6% background is expected.



- Background from π^0 and ν_e-CC (QE) events:
  - e^+ sample to control π^0 background: need e^+/e^- ID.
  - 2-track ν_e-CC QE-like events to constrain ν_e-CC QE background (50% efficiency in STT).
- Expect **2%** uncertainty in absolute flux
- Also possible to do a flux shape measurement (work in progress).

Flux Measurement: Low-ν method

- At very low $\nu = E_\nu - E_l$, the cross section is independent from E_ν:

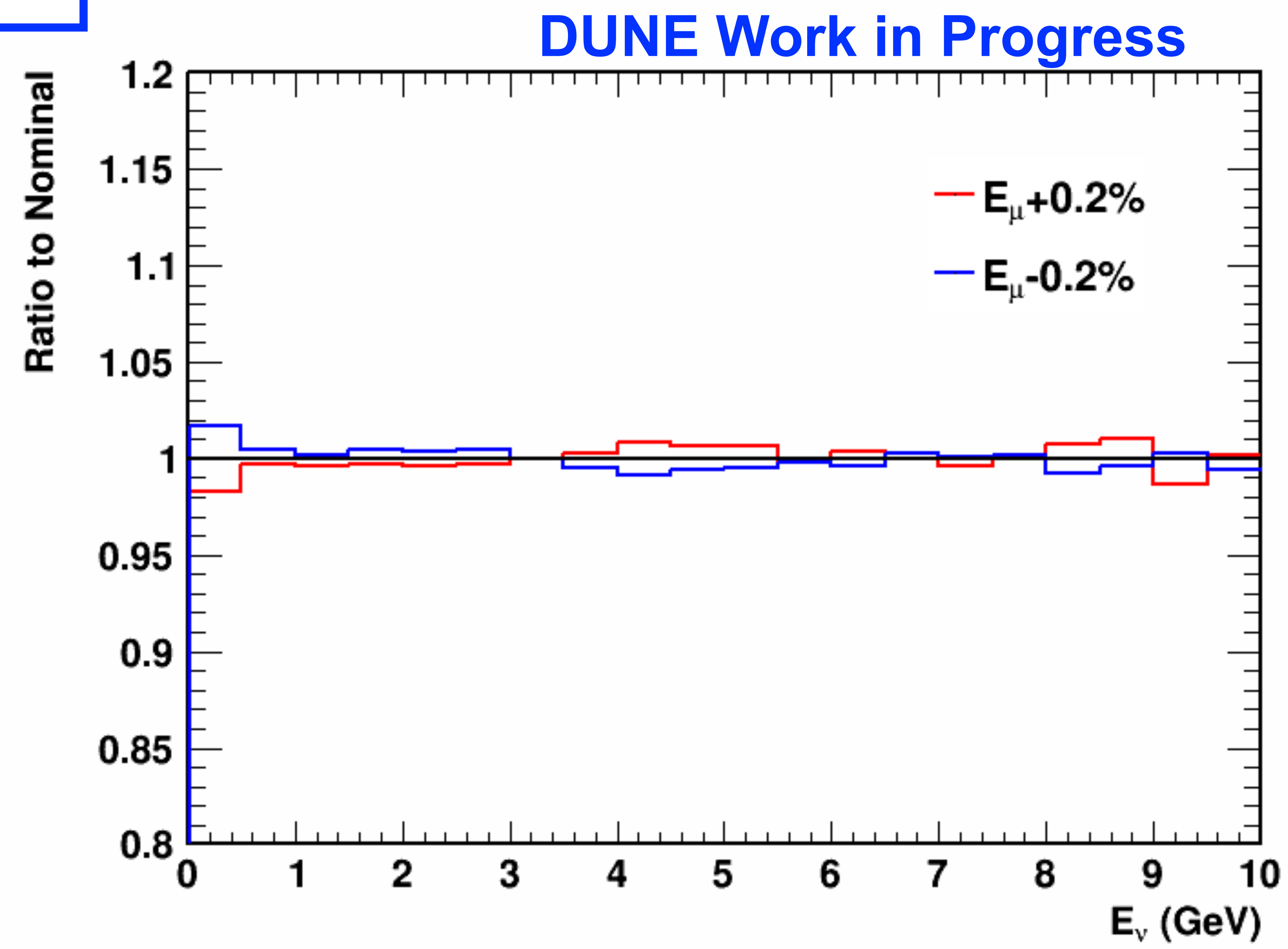
$$\boxed{\frac{d\sigma}{d\nu} = A\left(1 + \frac{B}{A}\frac{\nu}{E} - \frac{C}{A}\frac{\nu^2}{2E^2}\right)}$$

(A, B and C are parameters formed by nuclear structure functions.)

- the measurement of low ν spectrum is approximately a measurement of flux shape.
- The effect of non-zero ν cut is account for by a theoretical correction:

$$\boxed{S(E) = \frac{\sigma(E)^{\nu<\nu_0}}{\sigma(E)^{\nu\to 0}} = \frac{\sigma(E)^{\nu<\nu_0}}{\sigma(E\to\infty)^{\nu<\nu_0}}}$$

- Uncertainty is systematic dominant:
  - Muon energy
  - Hadronic energy (ν)
  - Theoretical correction
- Given good muon/hadron energy resolution expect an **1~2%** precision in 0.5~50 GeV.



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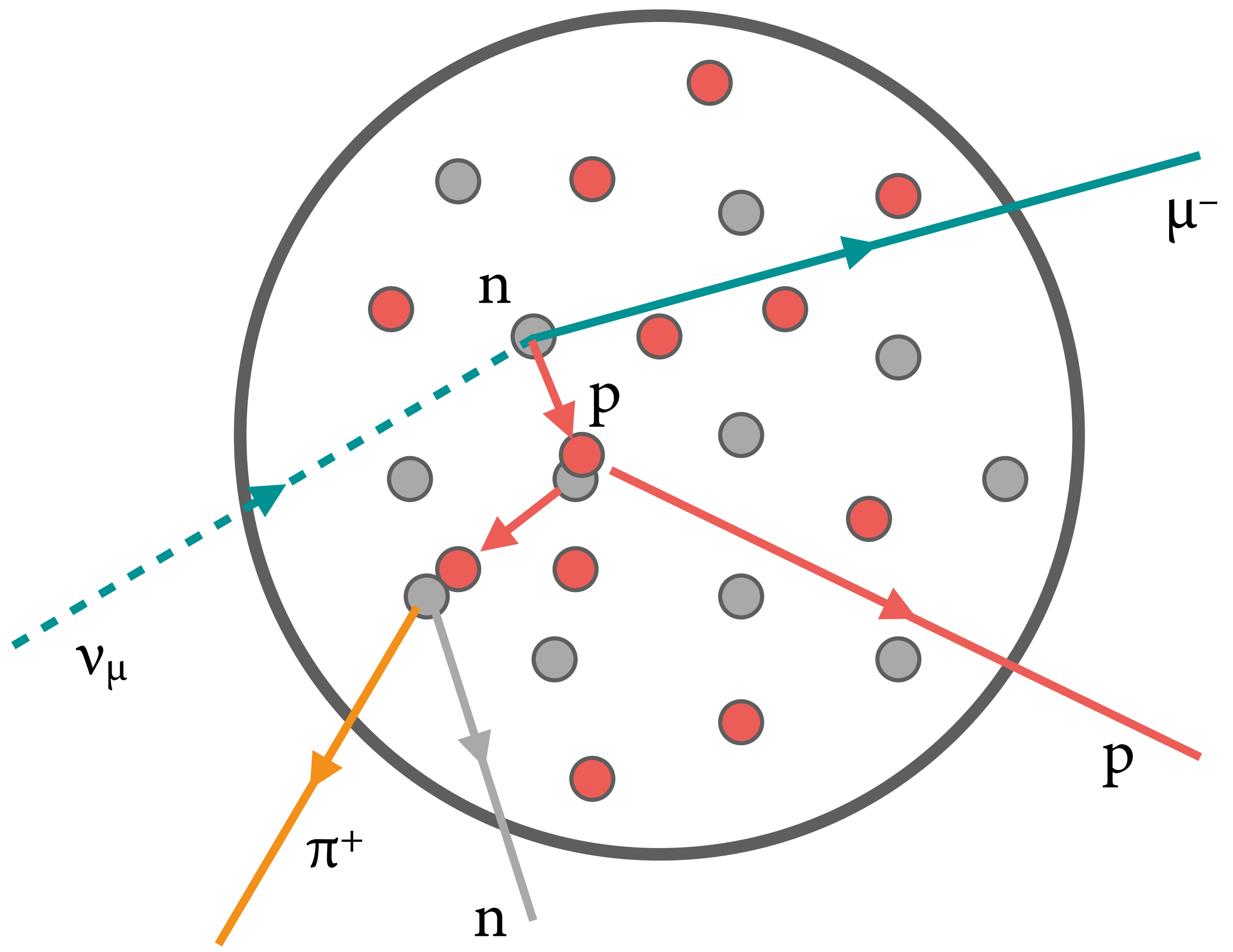
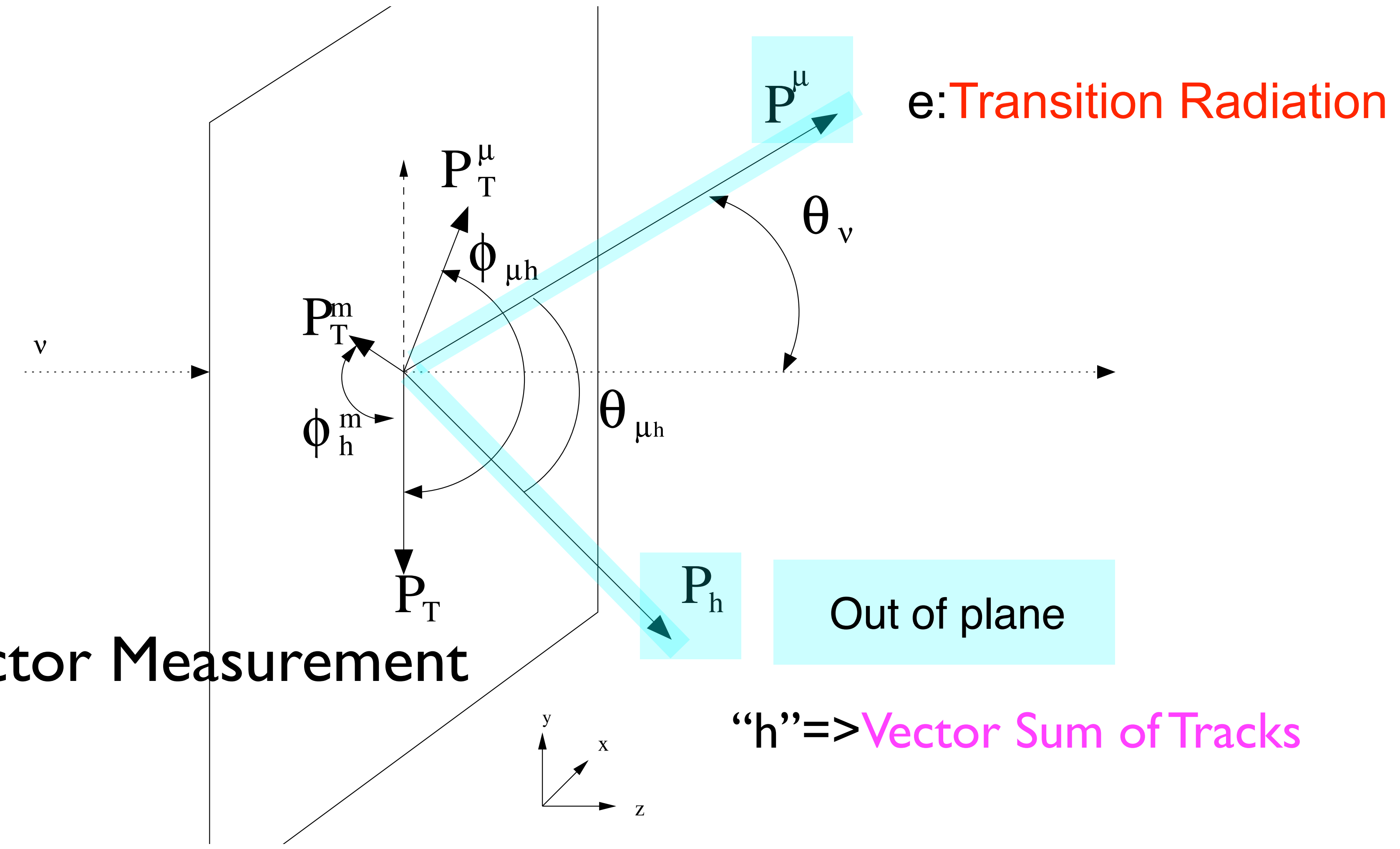
Nuclear Effect



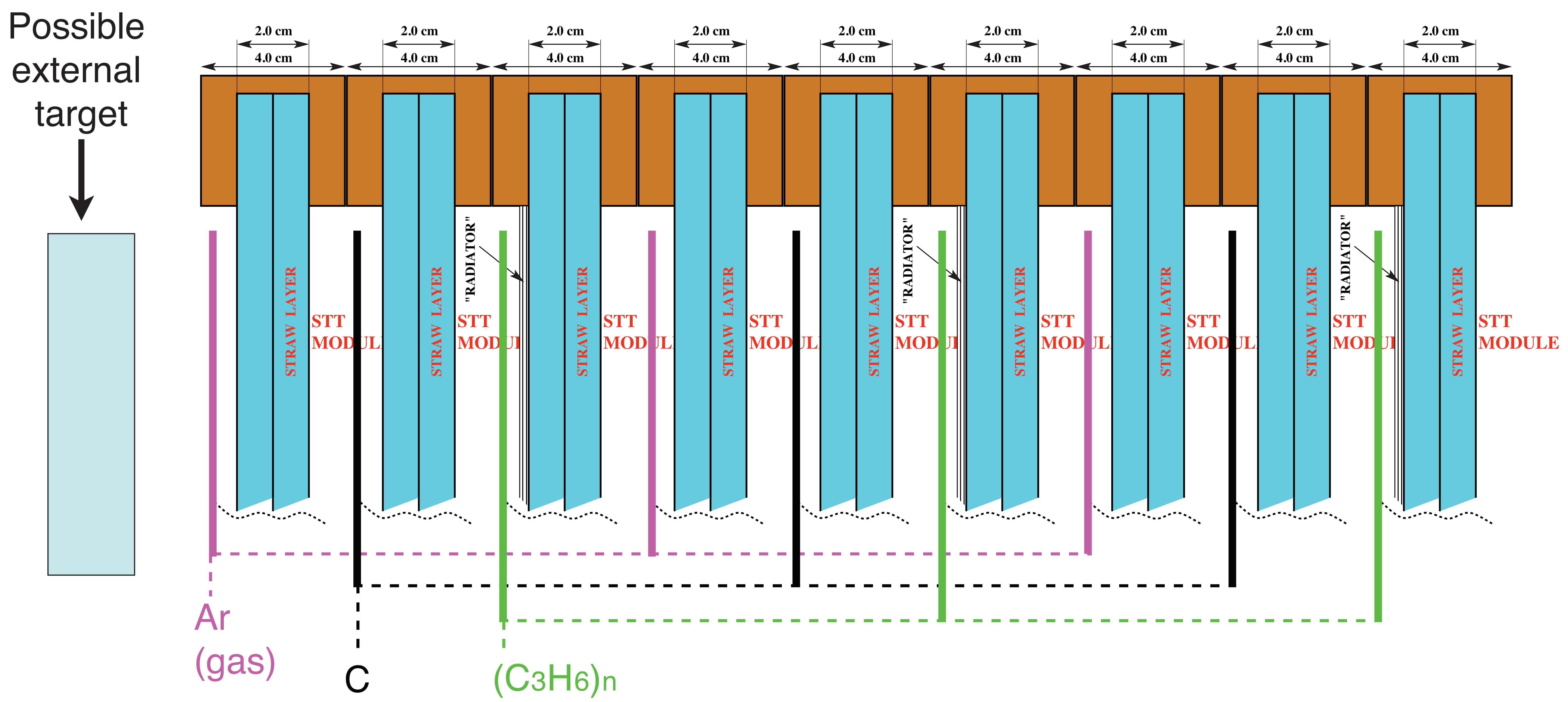


Transverse kinematics helps constrain the E_ν-scale for CC

- Neutrino energy scale are sensitive to nuclear effect: nucleon correlations, FSI…
- Can be different between neutrino and antineutrino!
- A low-density tracker can measure both lepton and hadron momentums with low threshold and high precision: calculate transverse kinematics (**missing p_T, Φ_{LH}** ect.) to constrain nuclear effect.
- **Coherent-π** topology is identical between neutrino and antineutrino, with little nuclear effect.
- Additional constraint from **QE** and **Resonance** interactions.

Nuclear Effect

It is also possible to implement multiple nuclear target in the low-density tracker



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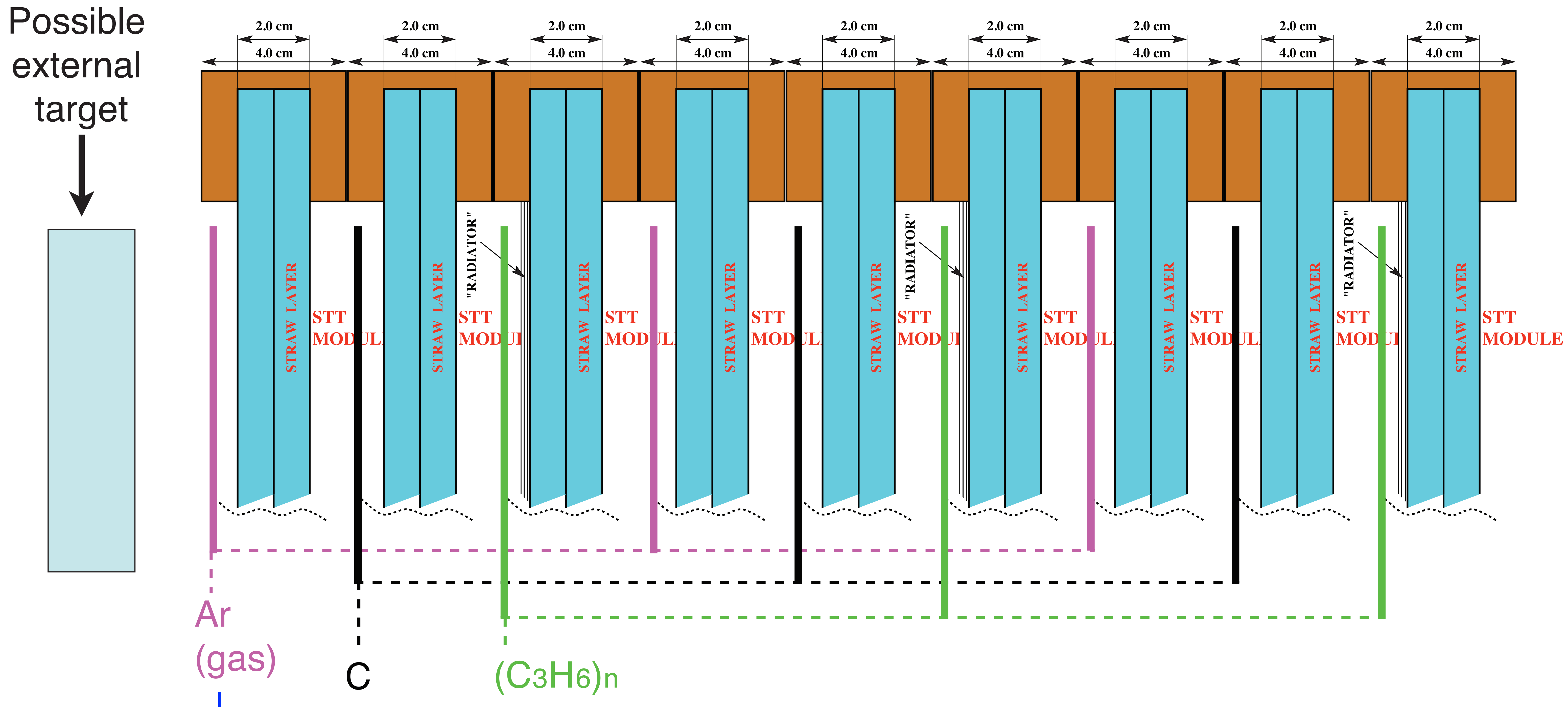

- Pressurized Ar gas and solid Ca target provide detailed understanding of the FD A = 40 target

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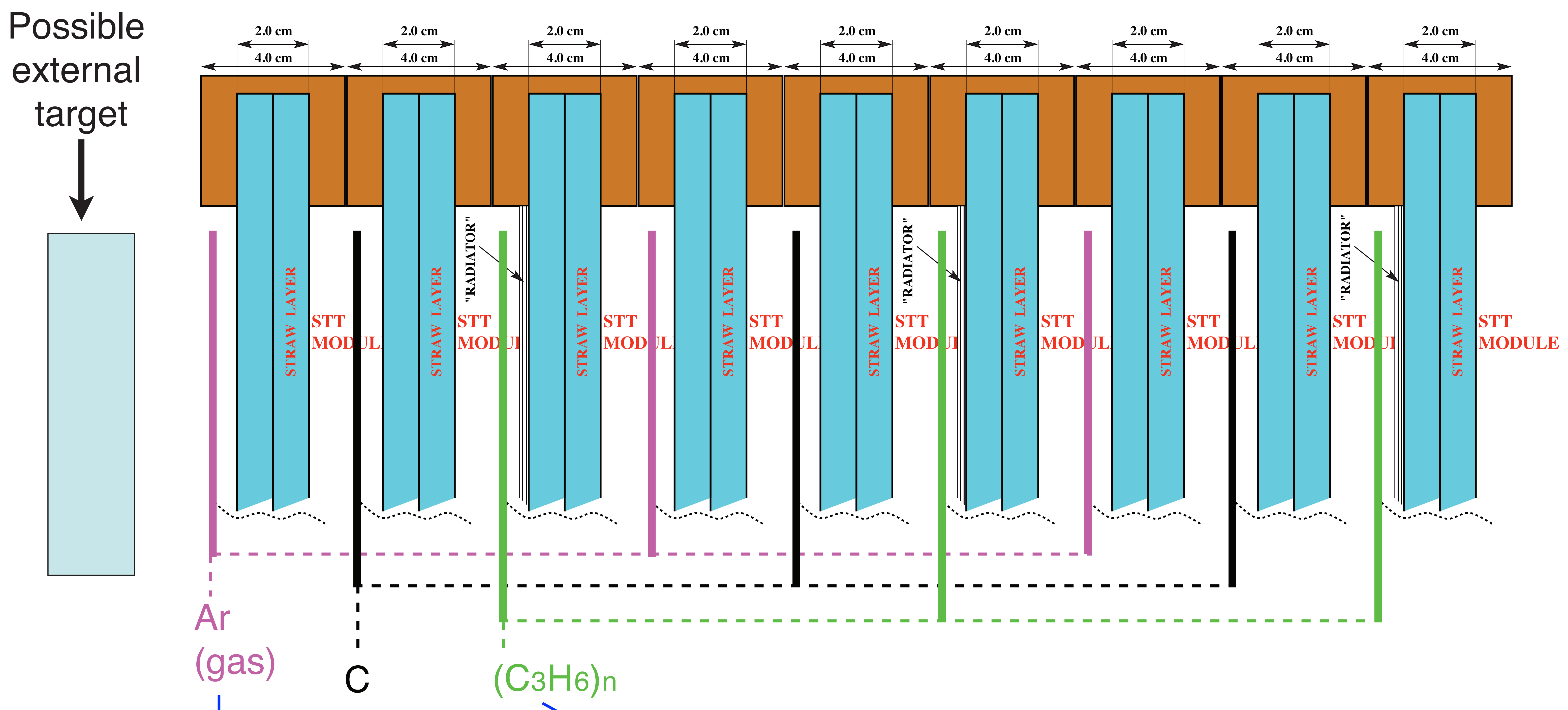

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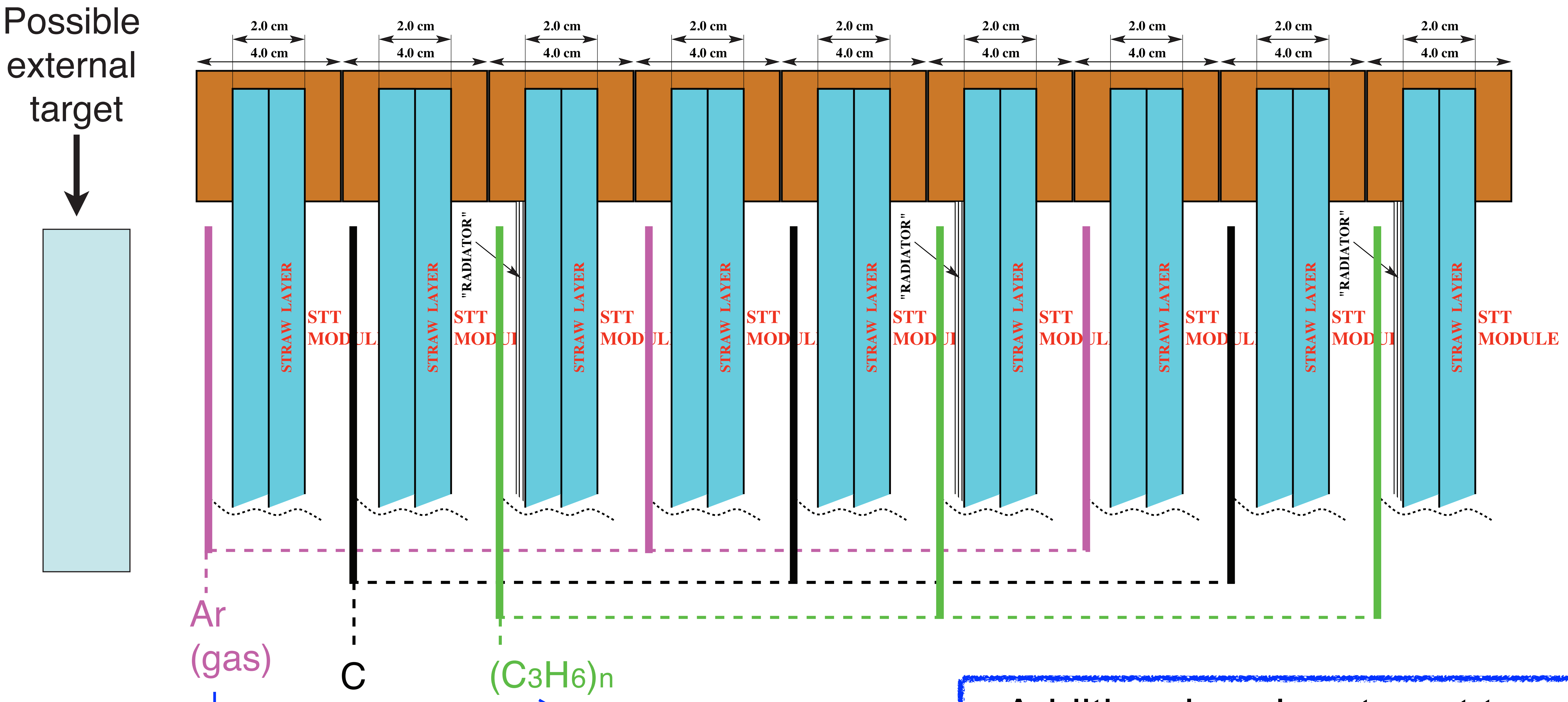

Additional nuclear target to understand A dependence of nuclear effect

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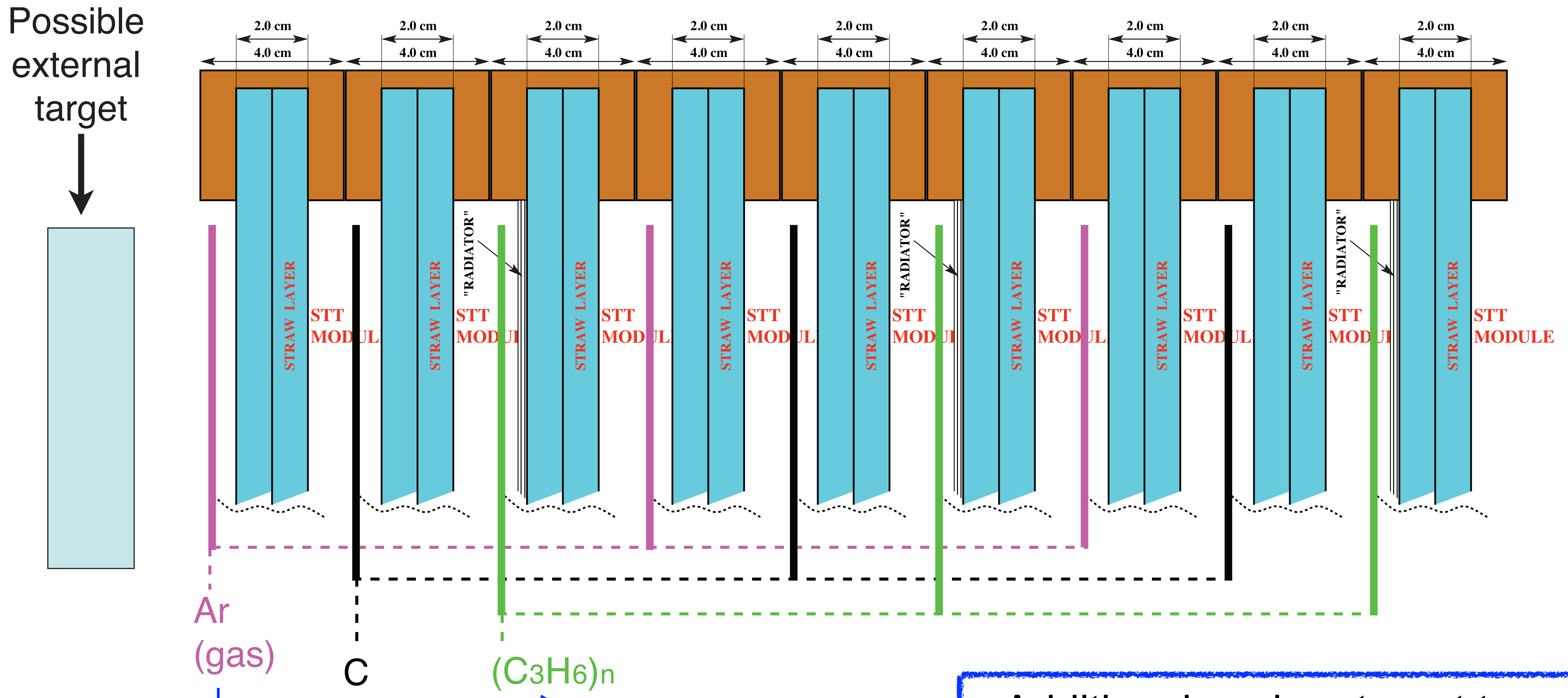


Additional nuclear target to understand A dependence of nuclear effect

Subtraction of C from $(C_3H_6)_n$ provides free proton target

- Pressurized Ar gas and solid Ca target provide detailed understanding of the FD A = 40 target

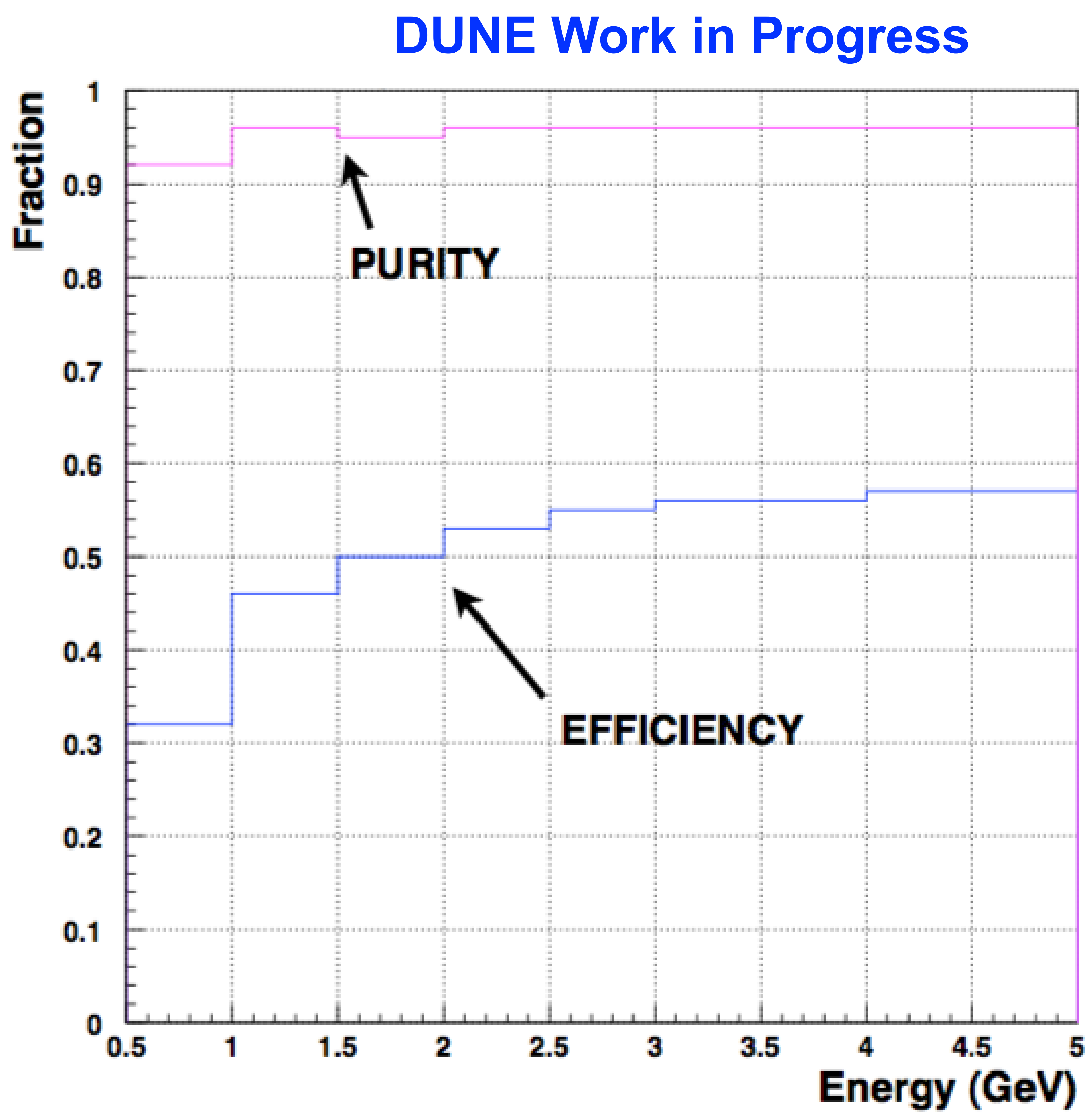
Separation by excellent vertex (~ 100μm) and angular (< 2 mrad) resolution

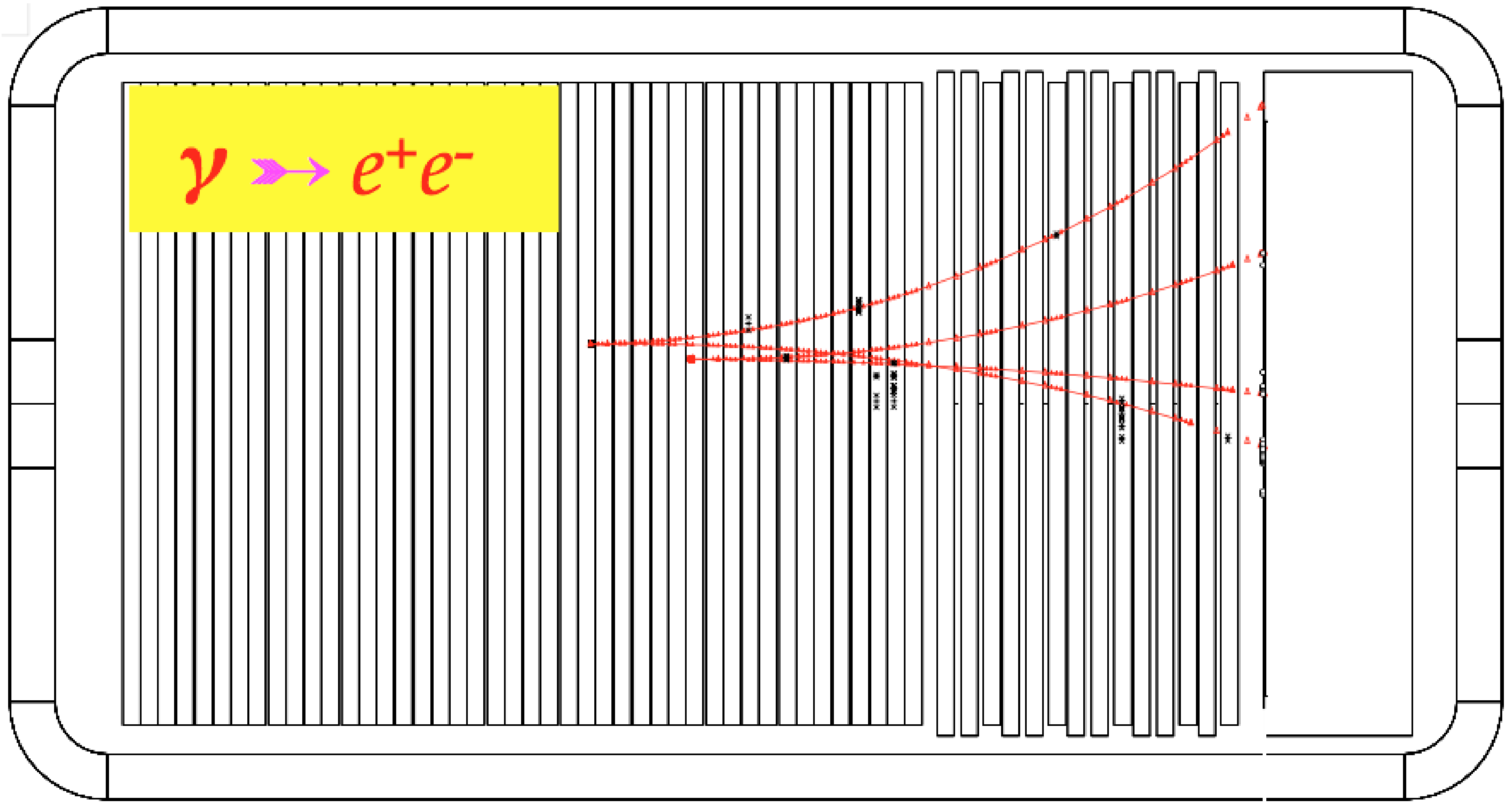
Overview

- DUNE near detector roles.
- Near detector options under study.
- **Near detector constraint on oscillation systematics.**
  - Neutrino flux
  - Nuclear effect
  - **Cross sections.**
    - **nu-e inclusive**
    - **Quasi-Elastic (0π)**
    - **Resonance π**
    - **Coherent π**

ν_e-CC Inclusive

- Signal in ν_e appearance measurement.
- Check universality: **ν_e vs ν_μ**
- Electron momentum measurement:
  - Curvature in B field: |p| and +/-
  - Track fit extrapolate to vertex: direction.
  - ECAL: More precise measurement of energy.
- Electron identification:
  - Transition radiation (STT)
  - Energy deposition pattern in tracker and ECAL.





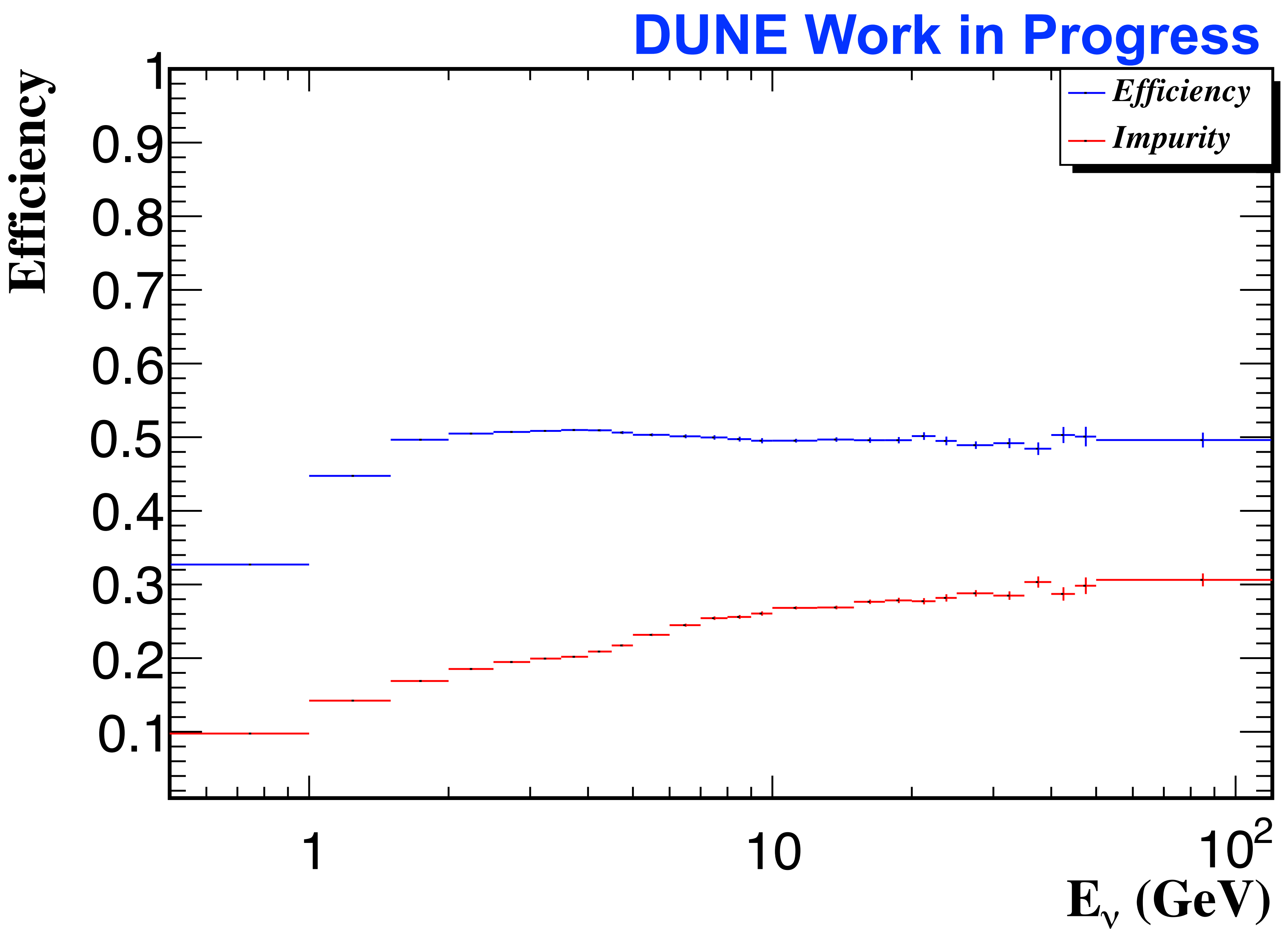
- Background dominantly from π^0: constraint by e+ sample.

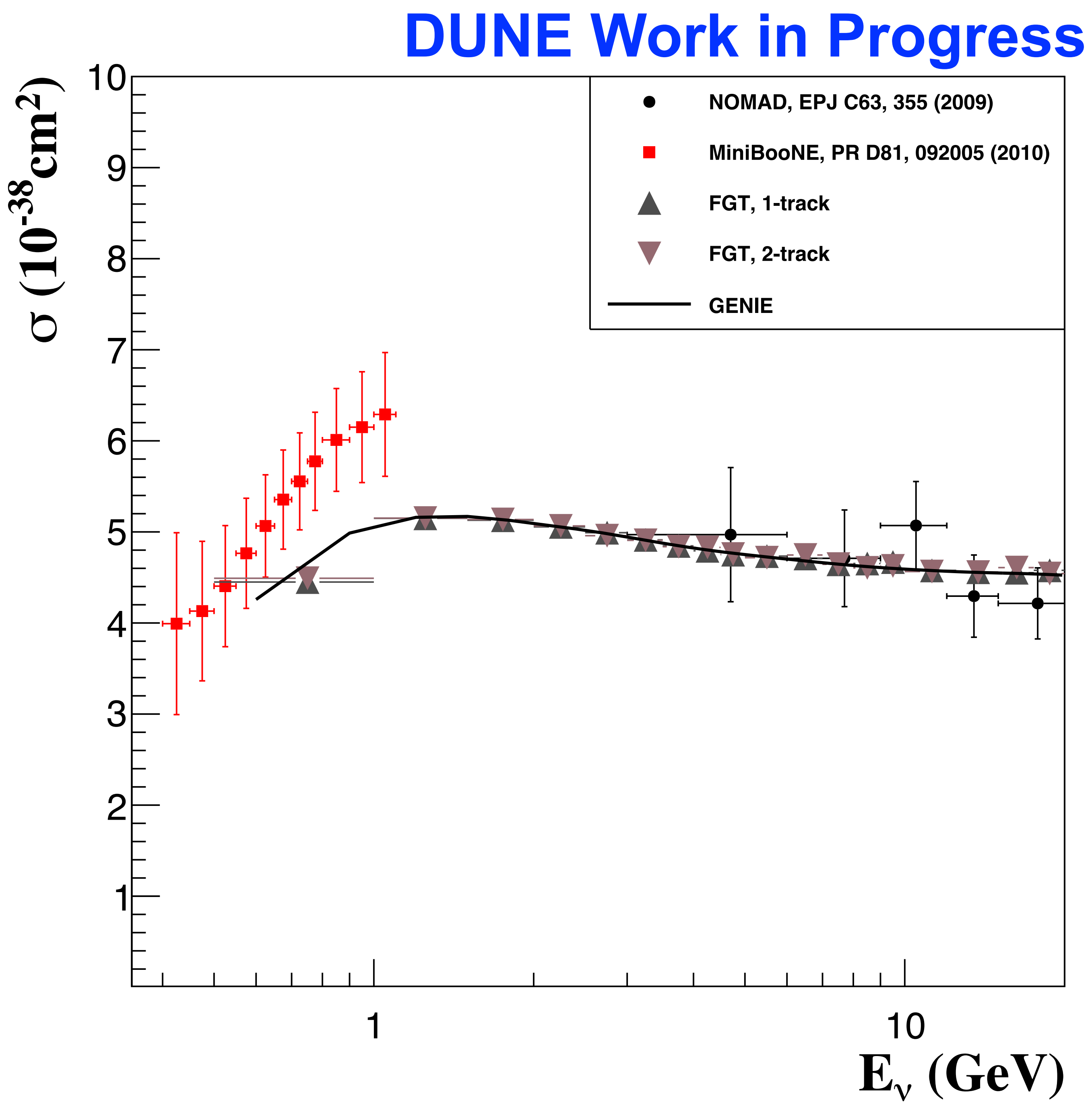
Quasi-Elastic (0π)

- QE-like (0π) is an important channel in DUNE oscillation measurement.
  - 2-track (1μ0p) or 1-track (1μ1p) topology.
- Constrain nuclear effect:
  - Transverse variables
  - Comparing E_ν calculated from muon momentum with total visible energy.

$$\boxed{E_\nu^{\mathrm{calc}} = \frac{2(M_n - E_B)E_\mu - (E_B^2 - 2M_nE_B + m_\mu^2 + \delta M^2)}{2[(M_n - E_B) - E_\mu + p_\mu \cos\theta_\mu]}}$$

- Sensitivity study using fast MC shows signal **efficiency ~48%, purity ~76%** (STT).



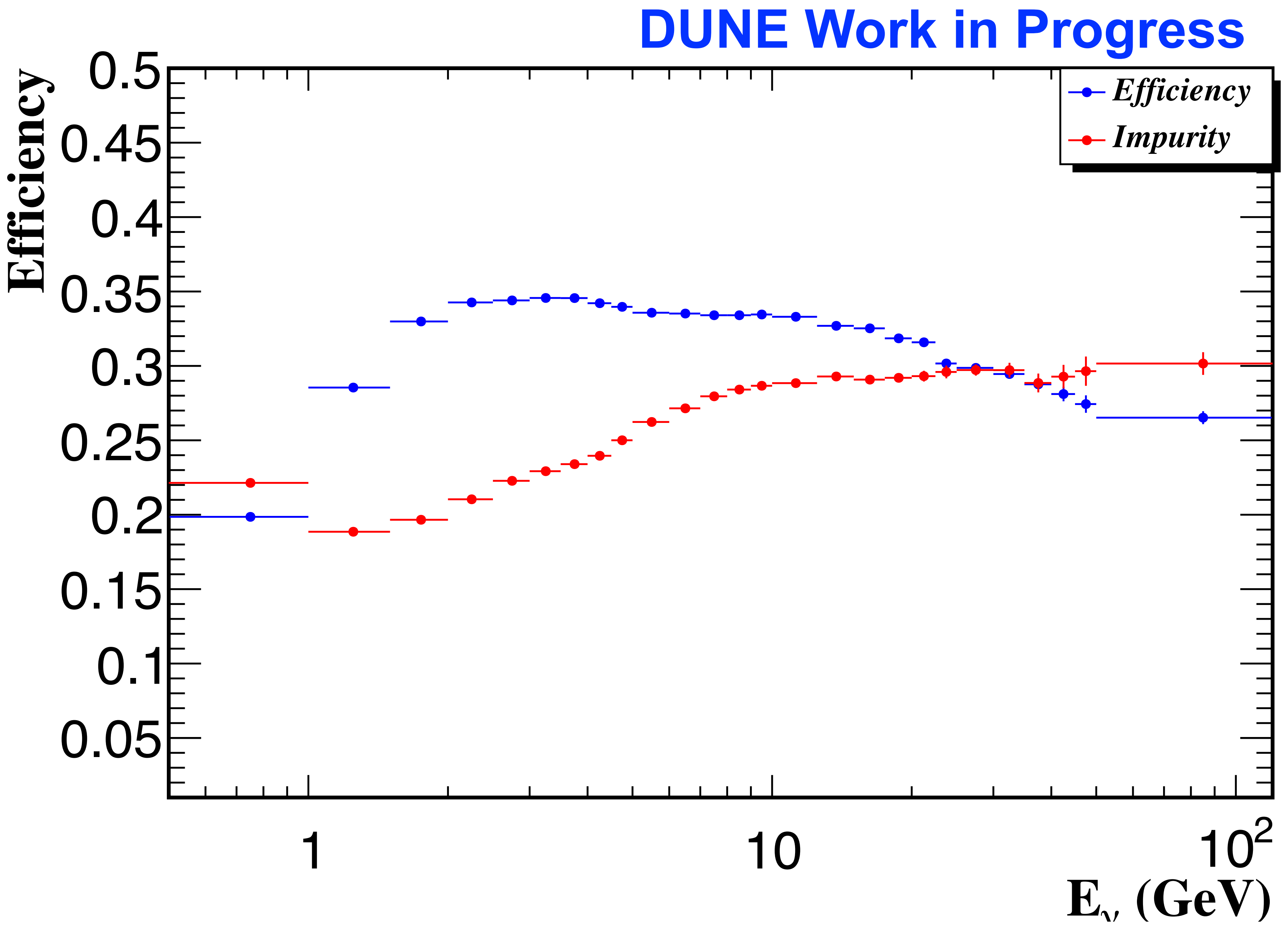


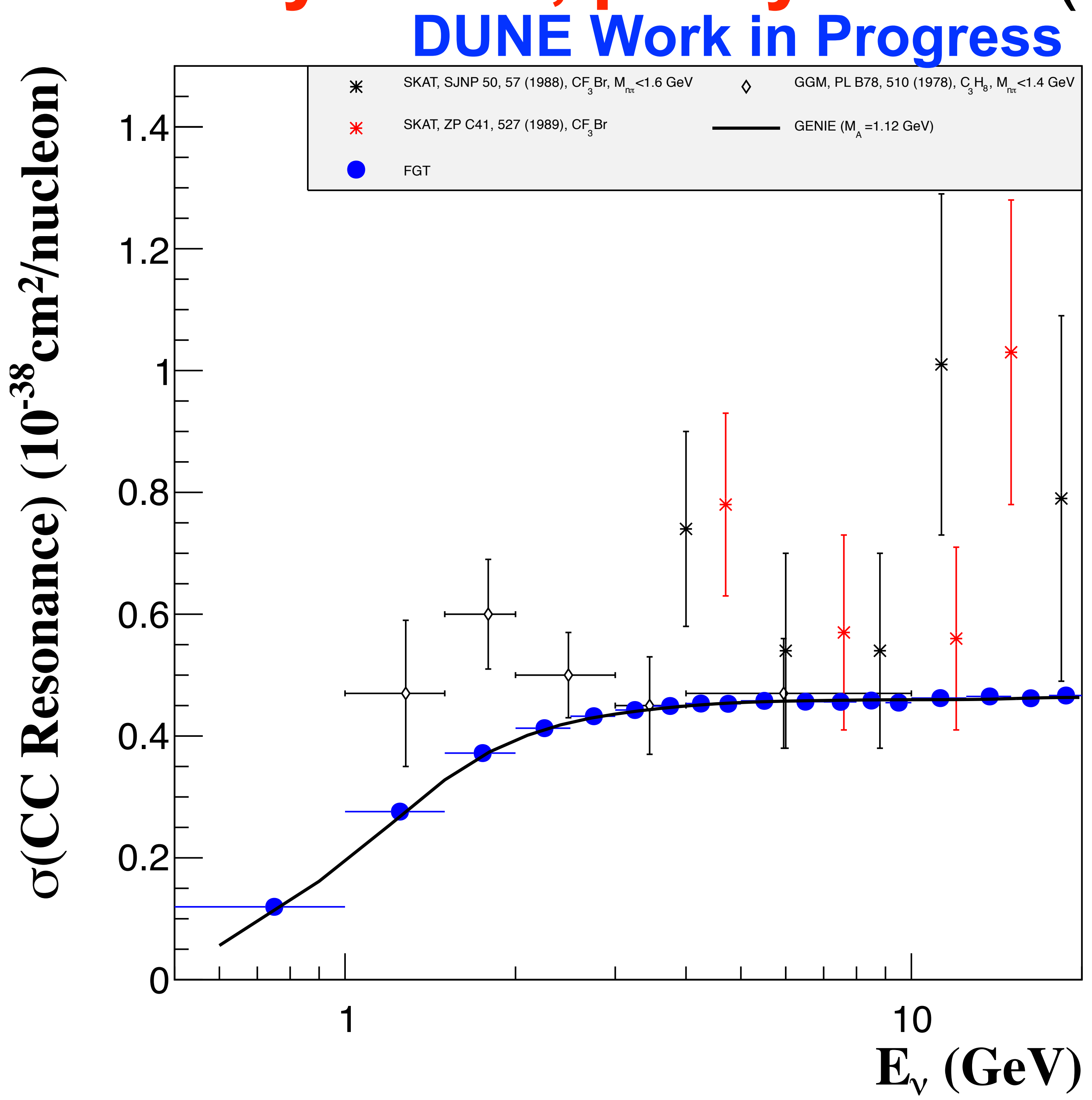
Resonance π

- Resonance will be the most abundant interaction in DUNE detectors.
  - 2-track ($1\mu 1\pi$) or 3-track ($1\mu 1\pi 1p$) topology.
- Constrain nuclear effect
  - Transverse variables
  - E_ν calculated from muon and pion momentum with total visible energy.

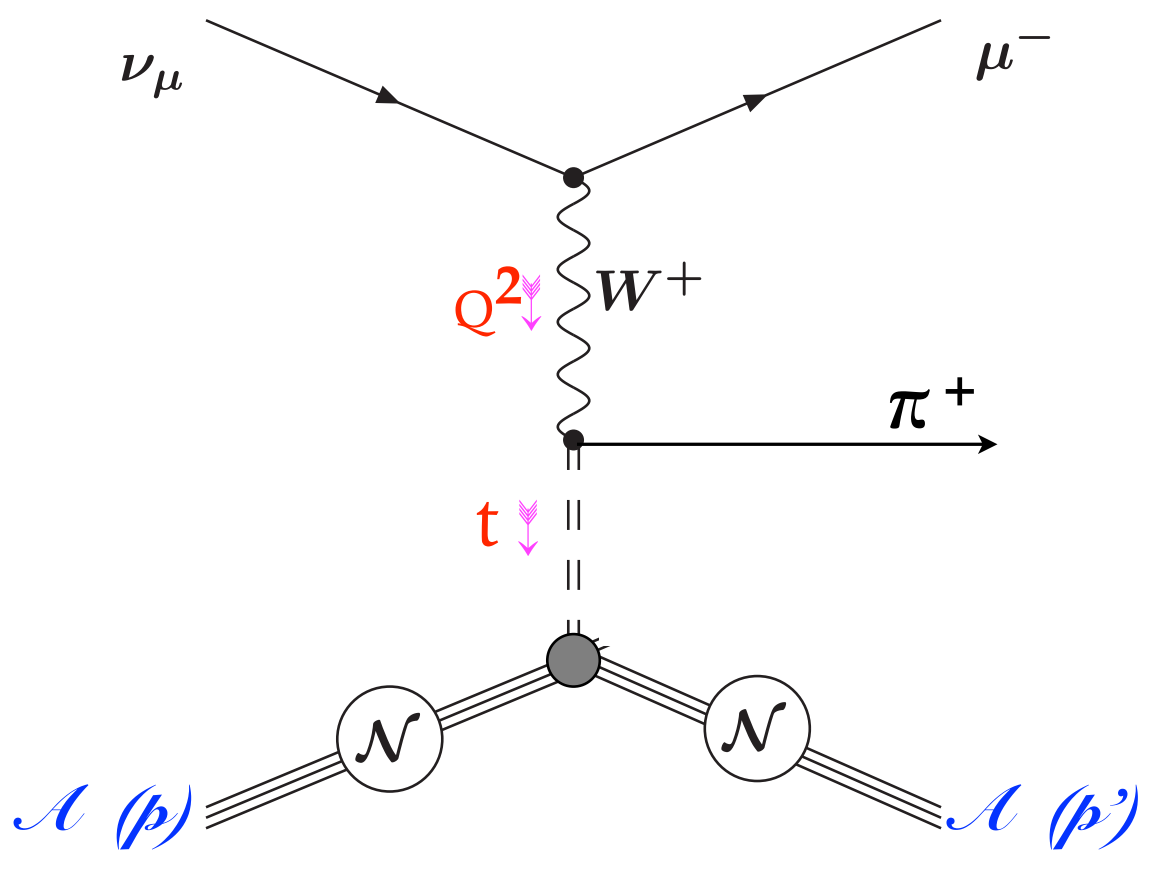
$$\boxed{E_\nu = \frac{m_\mu^2 + m_\pi^2 - 2M_p(E_\mu + E_\pi) + 2p_\mu \cdot p_\pi}{2(E_\mu + E_\pi - |\mathbf{P}_\mu|\cos\theta_\mu - |\mathbf{P}_\pi|\cos\theta_\pi - M_p)},}$$

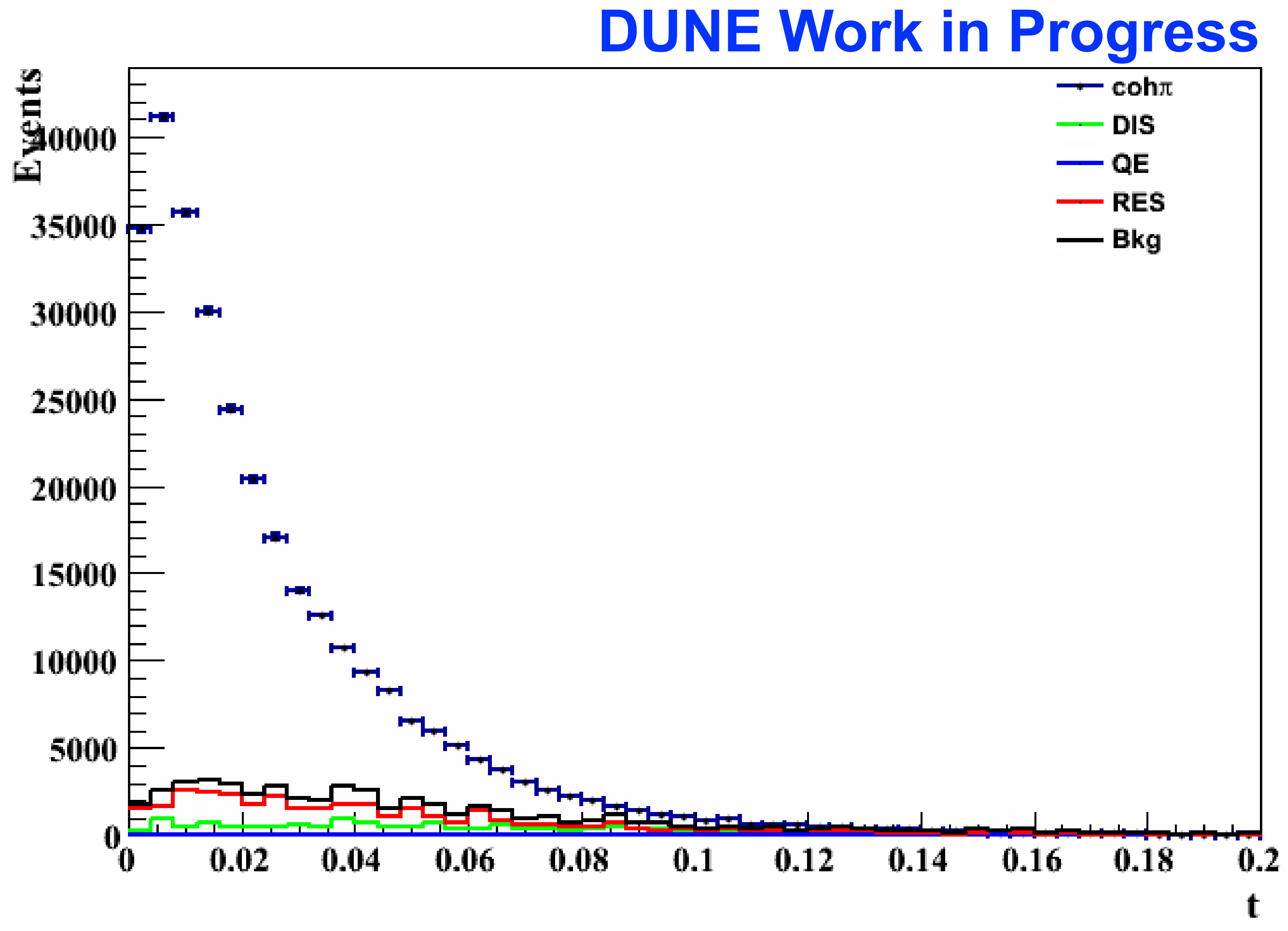
- Sensitivity study using fast MC shows signal **efficiency ~33%, purity ~77%** (STT).





Coherent π





- Final state muon and pion collinear with incident neutrino with little nuclear effect.
- The only channel with identical topology between neutrino and antineutrino to the first order.
- Requires good momentum resolution for muon and pion.
- Constraint on $\bar{\nu}/\nu$ flux, energy scale and beam divergence.

Summary

- A capable near detector is crucial to DUNE to reach its scientific goal of determine mass hierarchy and CP-violation
- Several ND options under study:
  - Liquid Argon TPC (ArgonCube)
  - Straw Tube Tracker
  - High-Pressure Ar Gas TPC
  - Scintillating Plastic Tracker
- A lot of work in progress to study systematic constrains for oscillation measurement:
  - Measure absolute and relative flux.
  - Constrain nuclear effect.
  - Cross sections
  - And much more…
- The ND also has rich physics by itself.
- The DUNE collaboration will reach a decision on the ND design concept by early next year.

Summary

DUNE collaboration meeting August 2017

Thanks and stay tuned!

Back Up Slides

Relative Flux Measurement: Low-nu Method

S.R.Mishra, World Sci (1990):
Cross-section of hadron production using structure functions ($2xF_1$, F_2, xF_3):

$$\frac{d\sigma^{\nu(\bar{\nu})}}{dxdy} = \frac{G_F^2 ME}{\pi} \times \left[\left(1 - y - \frac{Mxy}{2E}\right) F_2^{\nu(\bar{\nu})} + \frac{y^2}{2} 2xF_1^{\nu(\bar{\nu})} \pm y \left(1 - \frac{y}{2}\right) xF_3^{\nu(\bar{\nu})} \right]$$

Integrating over x:

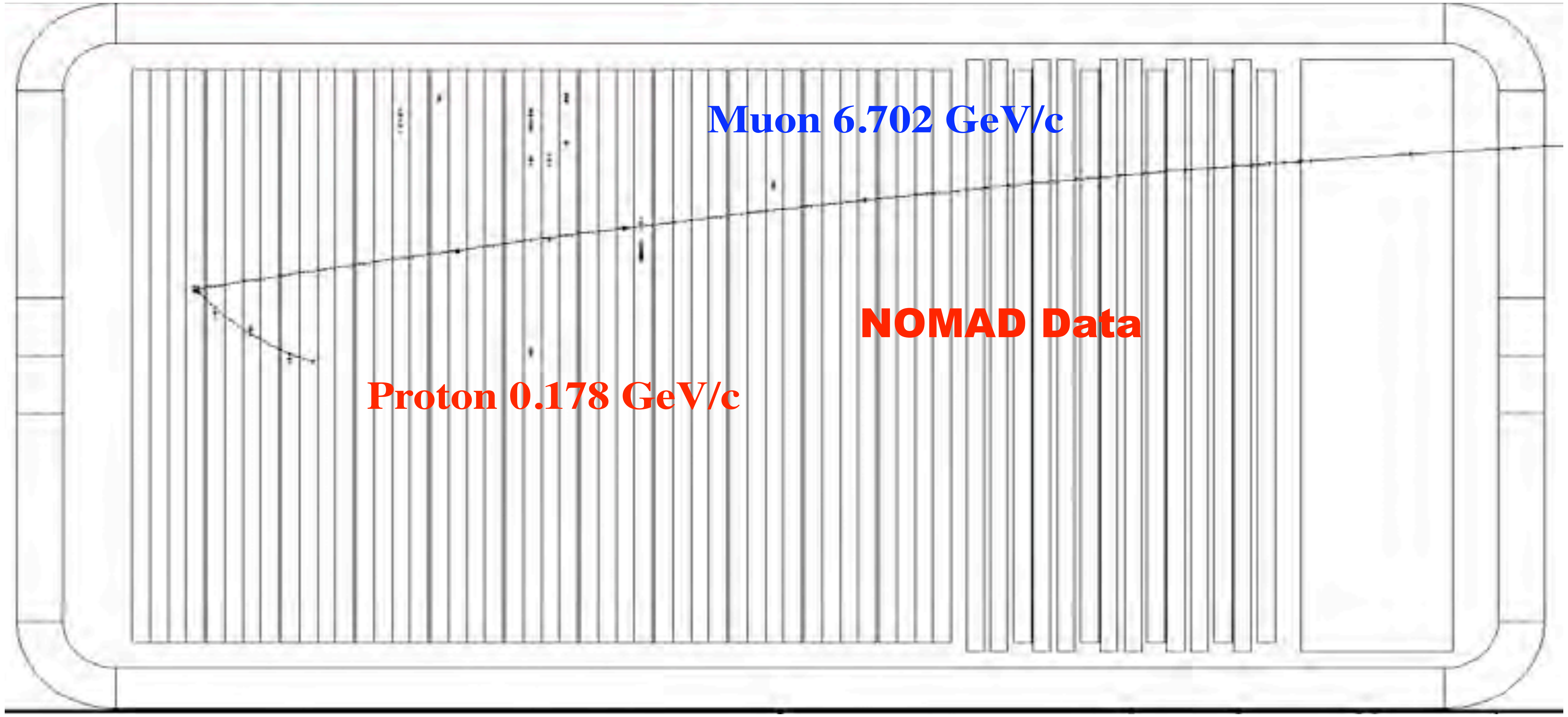
$$\frac{d\sigma}{d\nu} = A\left(1 + \frac{B}{A}\frac{\nu}{E} - \frac{C}{A}\frac{\nu^2}{2E^2}\right)$$

$$\begin{aligned} A &= \frac{G_F^2 M}{\pi} \int F_2(x) dx \\ B &= -\frac{G_F^2 M}{\pi} \int (F_2(x) \mp xF_3(x)) \\ C &= B - \frac{G_F^2 M}{\pi} \int F_2(x) R_{TERM} dx \end{aligned}$$

$$N(E)_{(\nu \le 1)} = \Phi(E) \cdot A \int_0^1 \left(1 + \frac{B}{A}\frac{\nu}{E} - \frac{C}{A}\frac{\nu^2}{2E^2}\right) d\nu$$

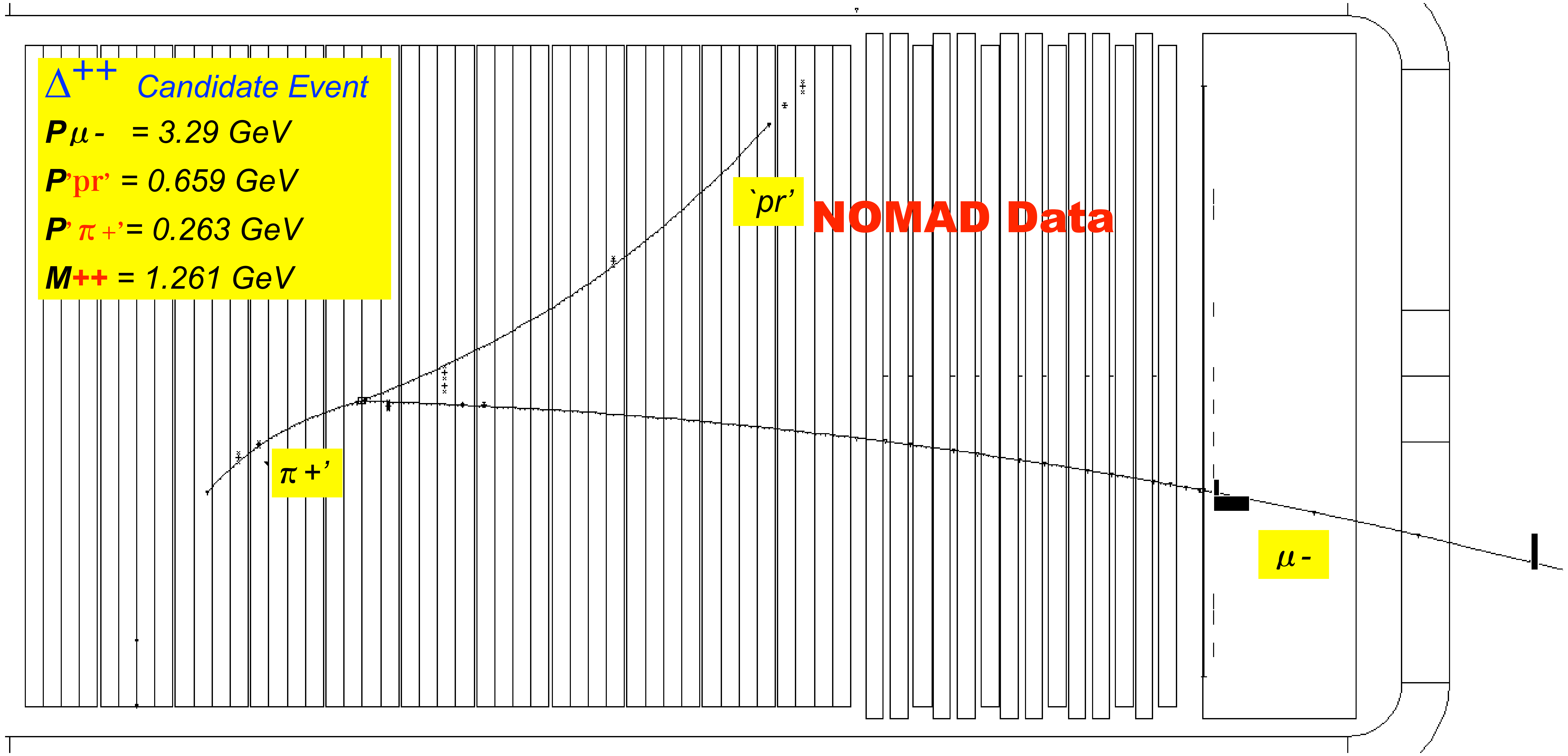
At low-ν, the number of events in a given energy bin is proportional to the neutrino flux: $N(E)_{\nu<1} = k\Phi(E) f_c(\frac{\nu}{E_\nu})$

QE in FGT



FGT will have $\sim \times$ 10 higher granularity vs NOMAD

Resonance in FGT



FGT will have $\sim \times$ 10 higher granularity vs NOMAD

Search for New Physics

- The ability to identify/reconstruct :
  - (1) Leptons e^+, e^-, μ^+, μ^- with high resolution
  - (2) Hadrons π^0, π^-, π^+, p, K^0_s, Λ, etc. with high eff/purity

⇛ sensitive search for new physics

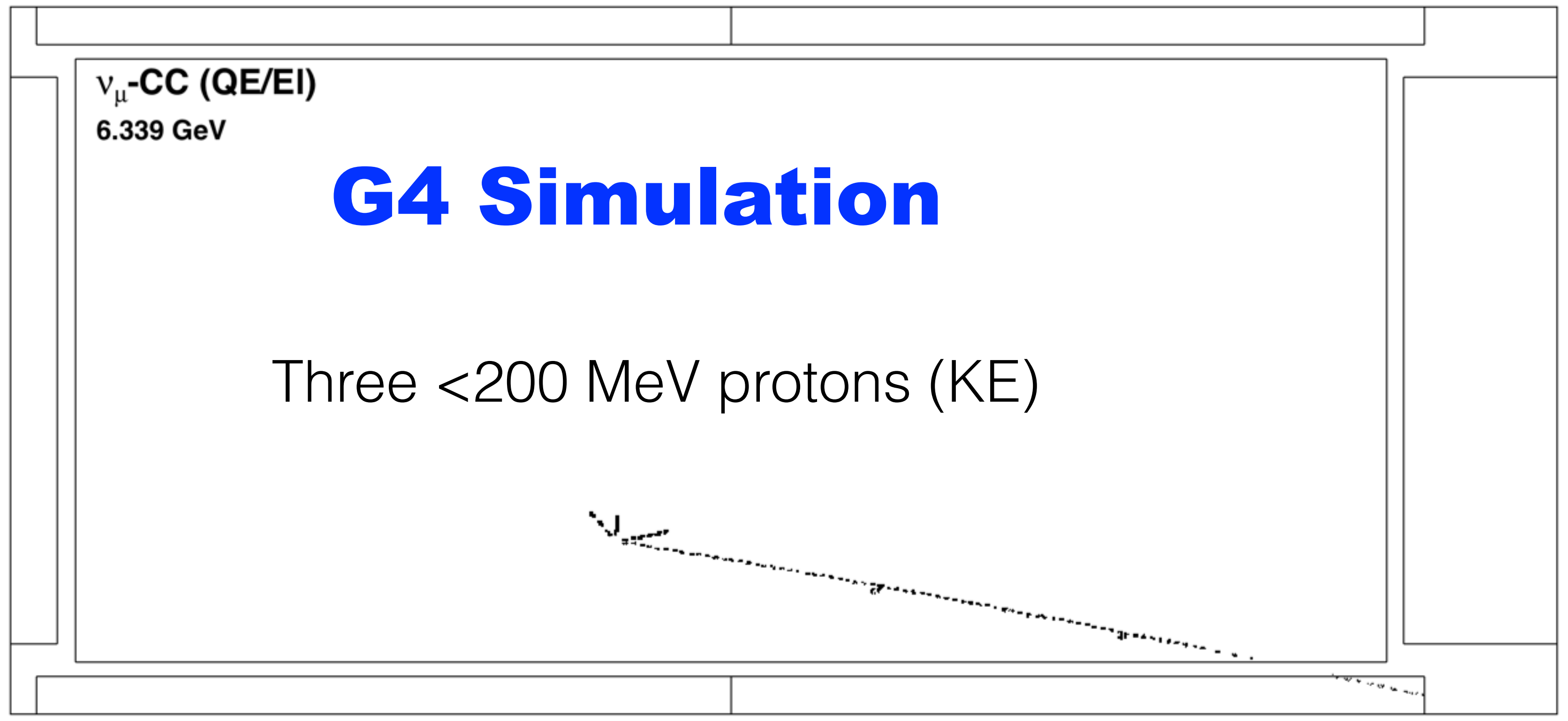
- Examples include search for :
  - High Δm^2 o(>0.5 eV^2)scillation
  - Neutral heavy leptons
  - light dark-matter particles

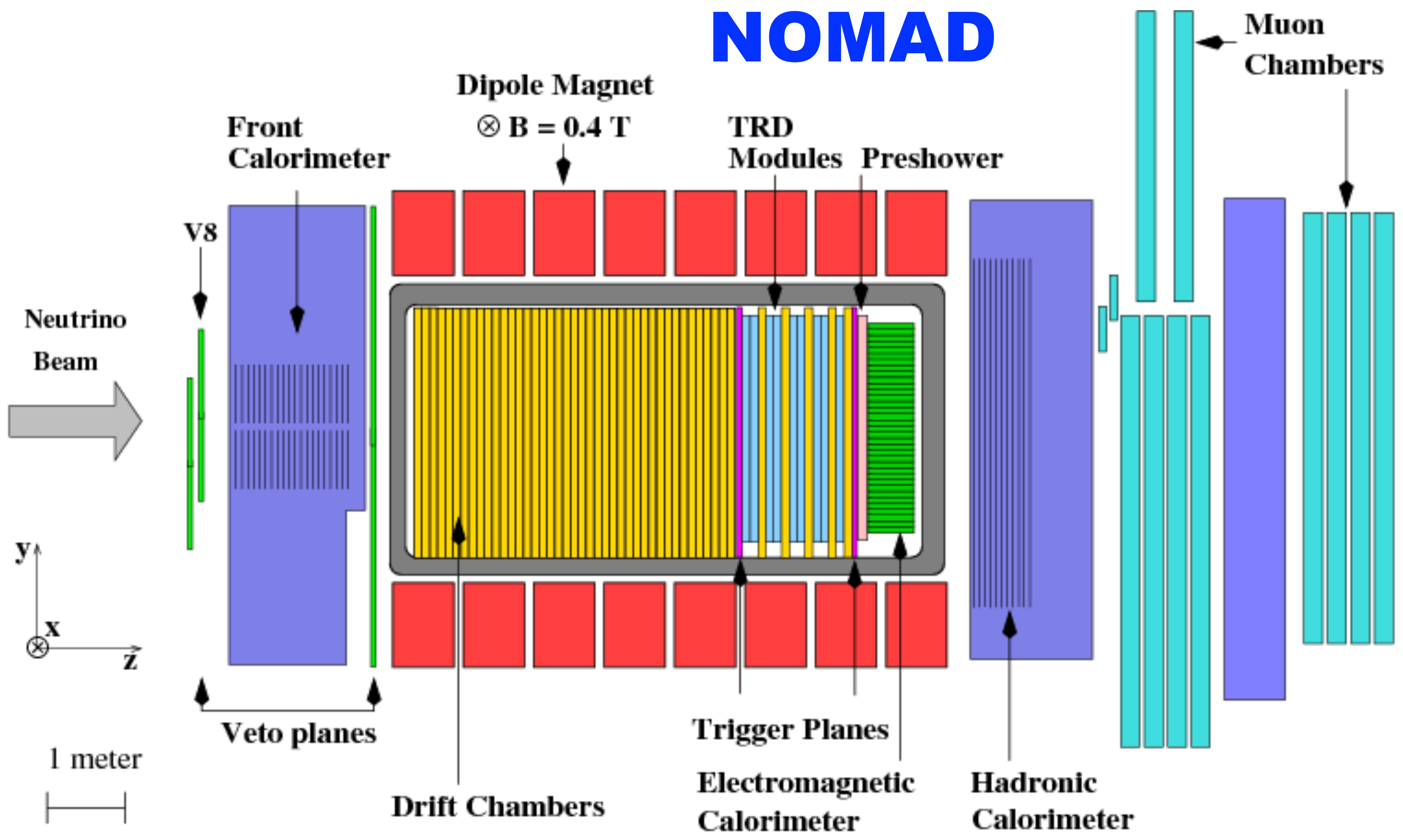
- Rich physics with overall >100 topics

FGT Study Strategy

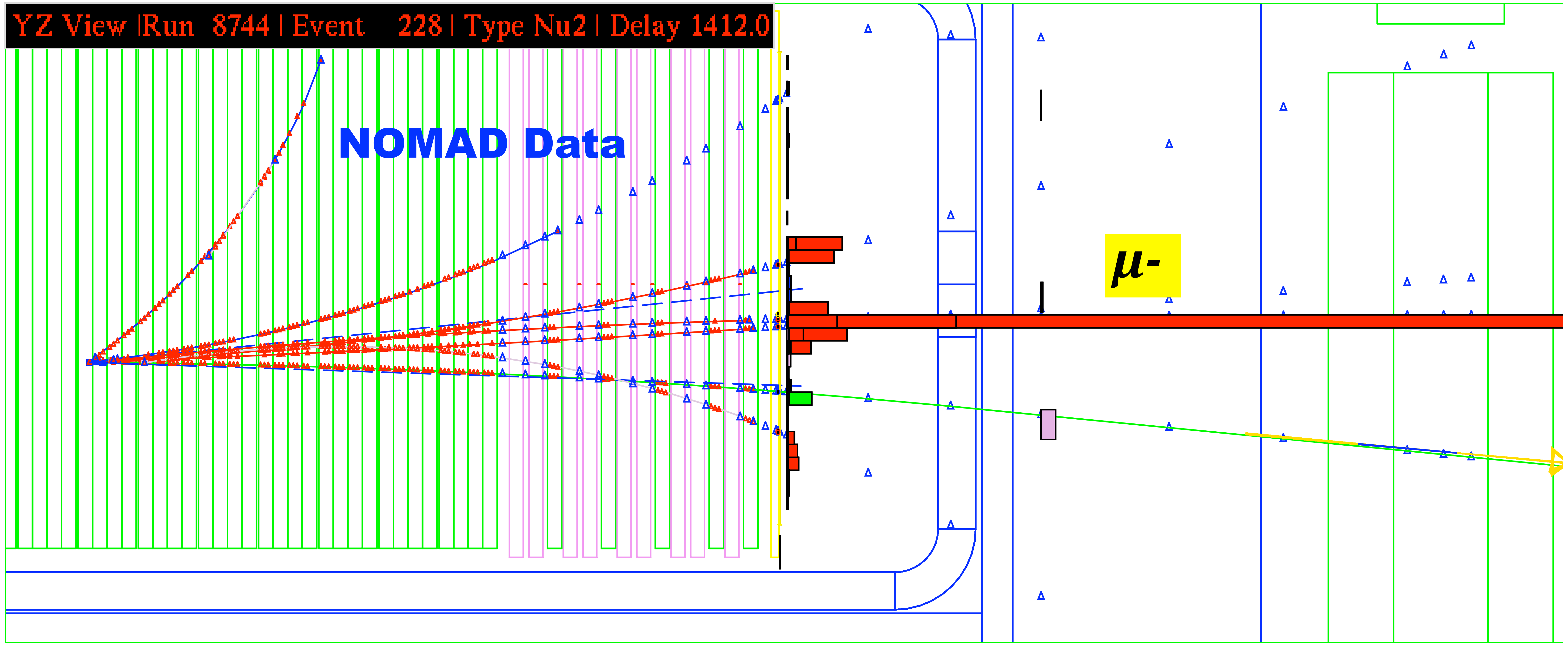
G4LBNE → GENIE → Detector response → Root Output

- **Fast MC** to do quick study of detector performance.
- Full **GEANT4 simulation** complete.
    - Based upon ART framework.
    - Working on reconstruction.
- **NOMAD data** to benchmark the ideas.
    - FGT concept is built upon the NOMAD detector, with better resolution, granularity, 4π Ecal & μID coverage & ~x100 higher statistics.



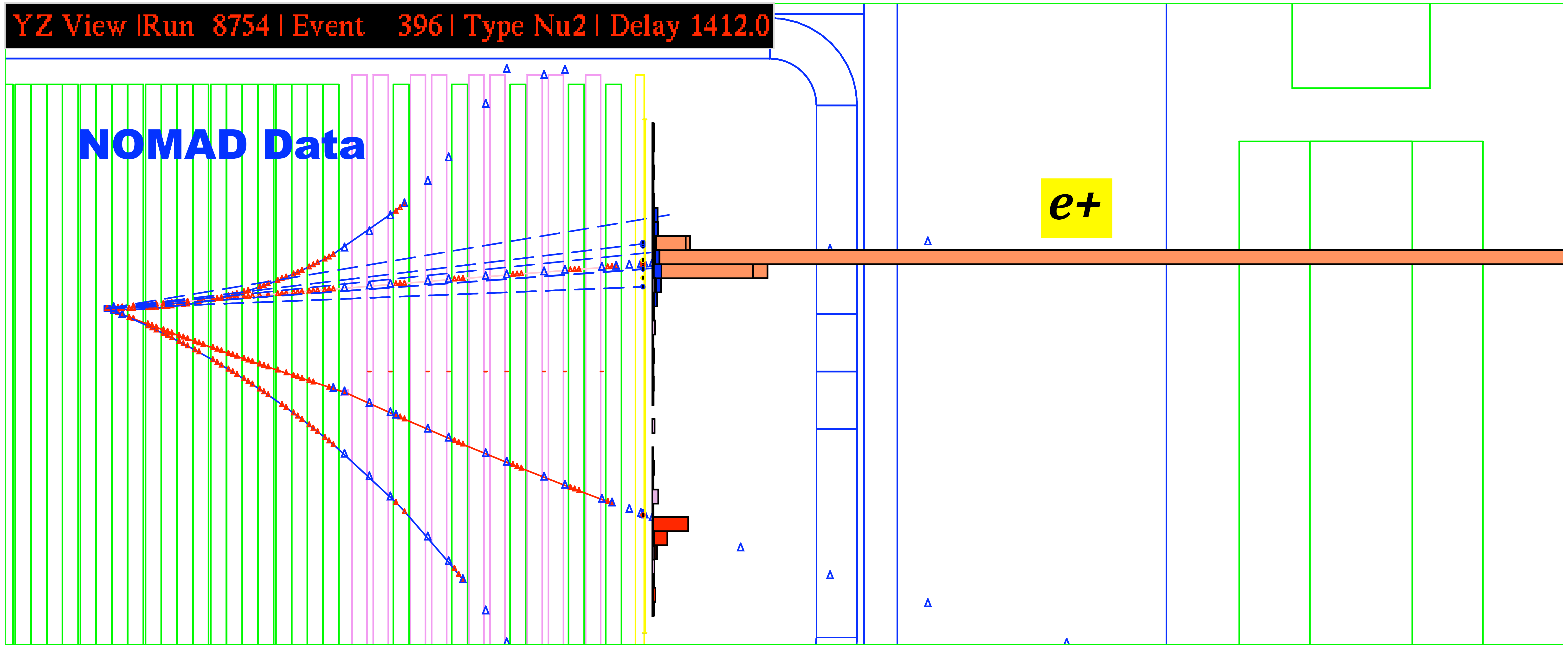


ν_μ-CC Candidate



- Hadrons are tracks.
- Muon is kinematically separated from hadron vectors.

ν_e-CC Candidate

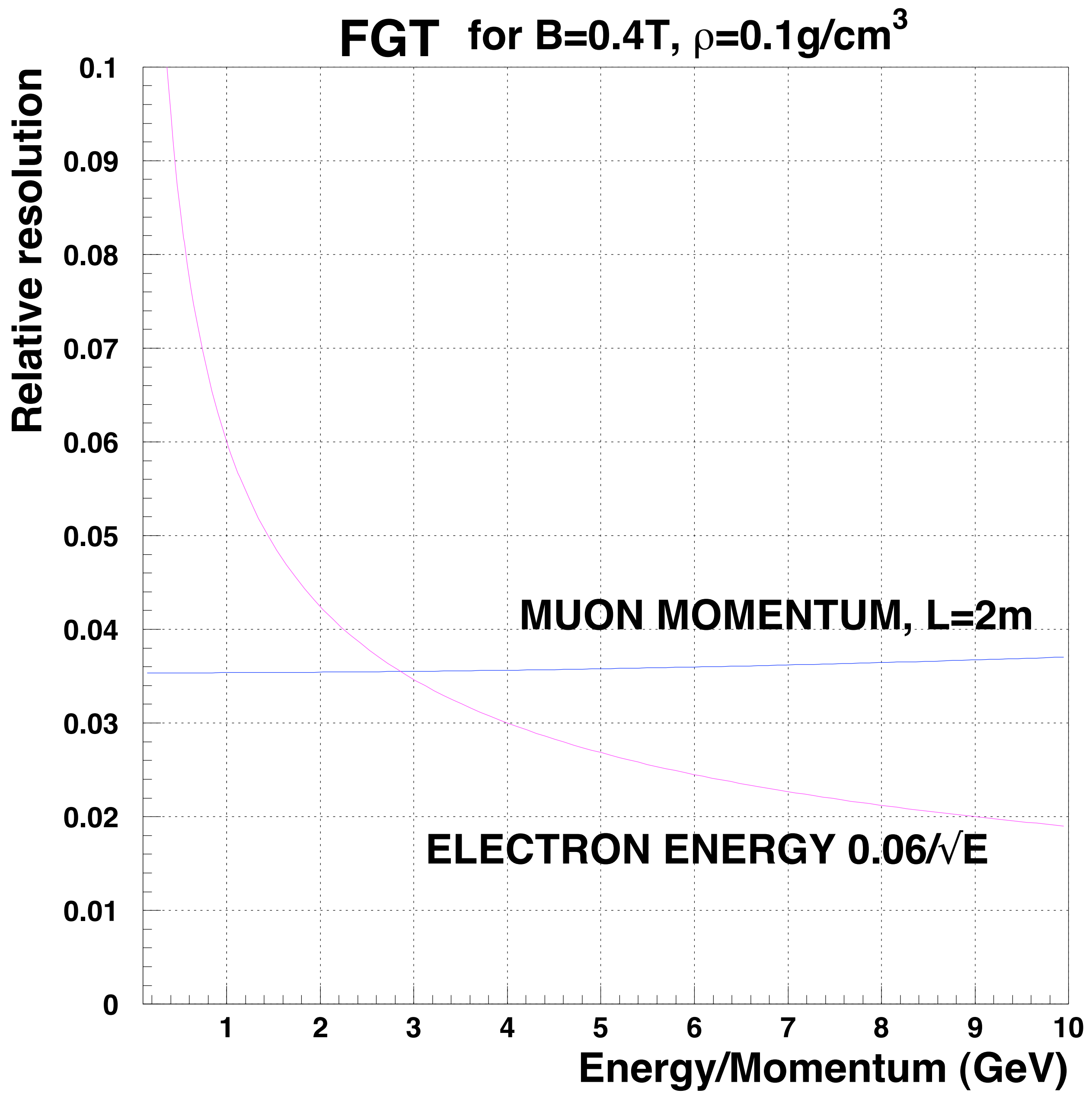


- Electrons are also tracks in FGT： high precision measurement:
  - Universality equivalence with muon from ν_μ.
- Dipole magnetic field allows distinguish e+ from e-:
  - Measure $\bar{\nu}_e$ content of the beam.

e+/e- Measurement

Electron Momentum:

- **Curvature** in B field for momentum and charge (+/-) measurement.
- Track fit extrapolate to the vertex for direction measurement.
- **ECAL** for more precise energy measurement
- Momentum resolution **~ 3.5% (at ~3 GeV)**, from STT curvature + ECAL.



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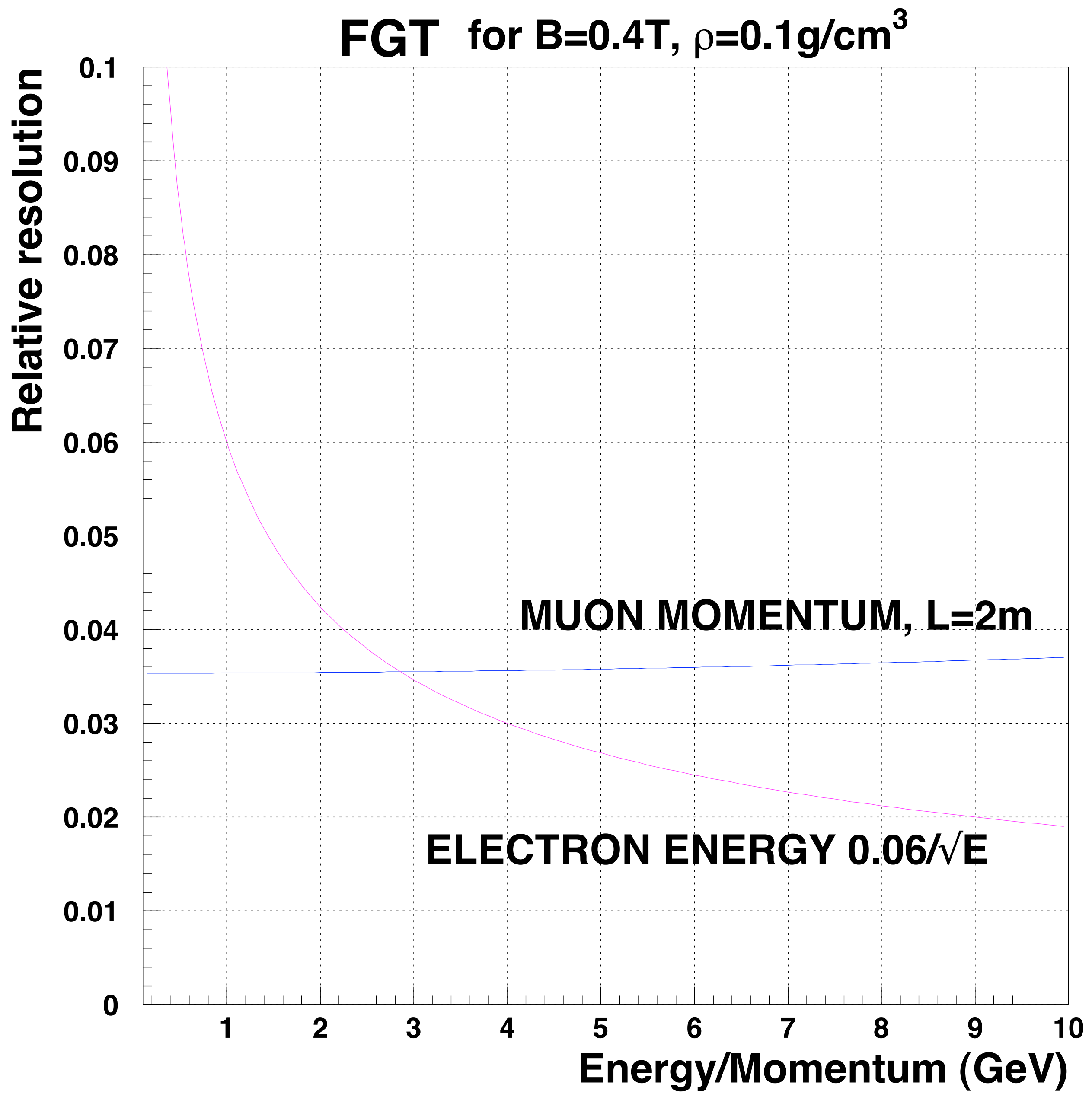
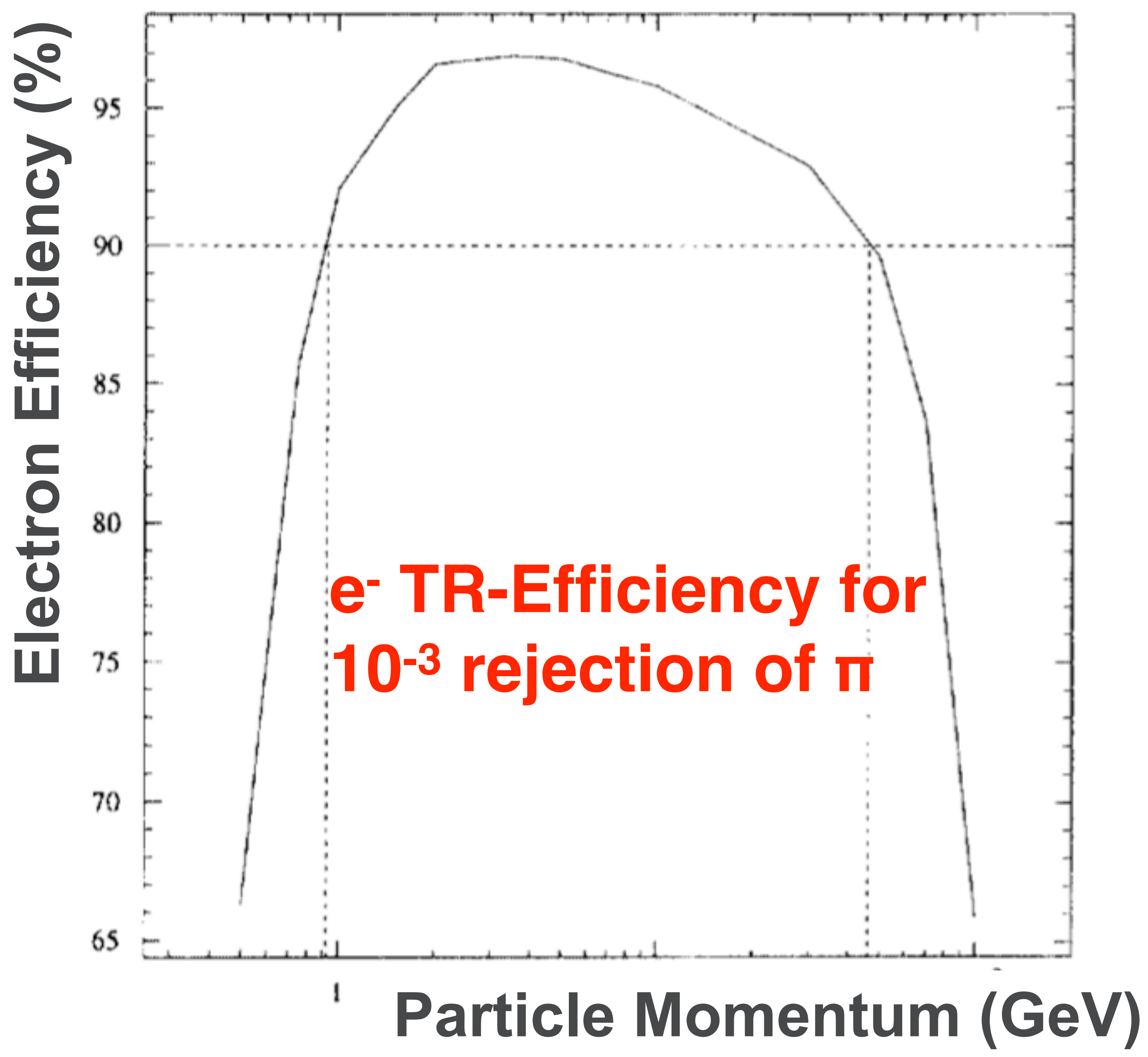


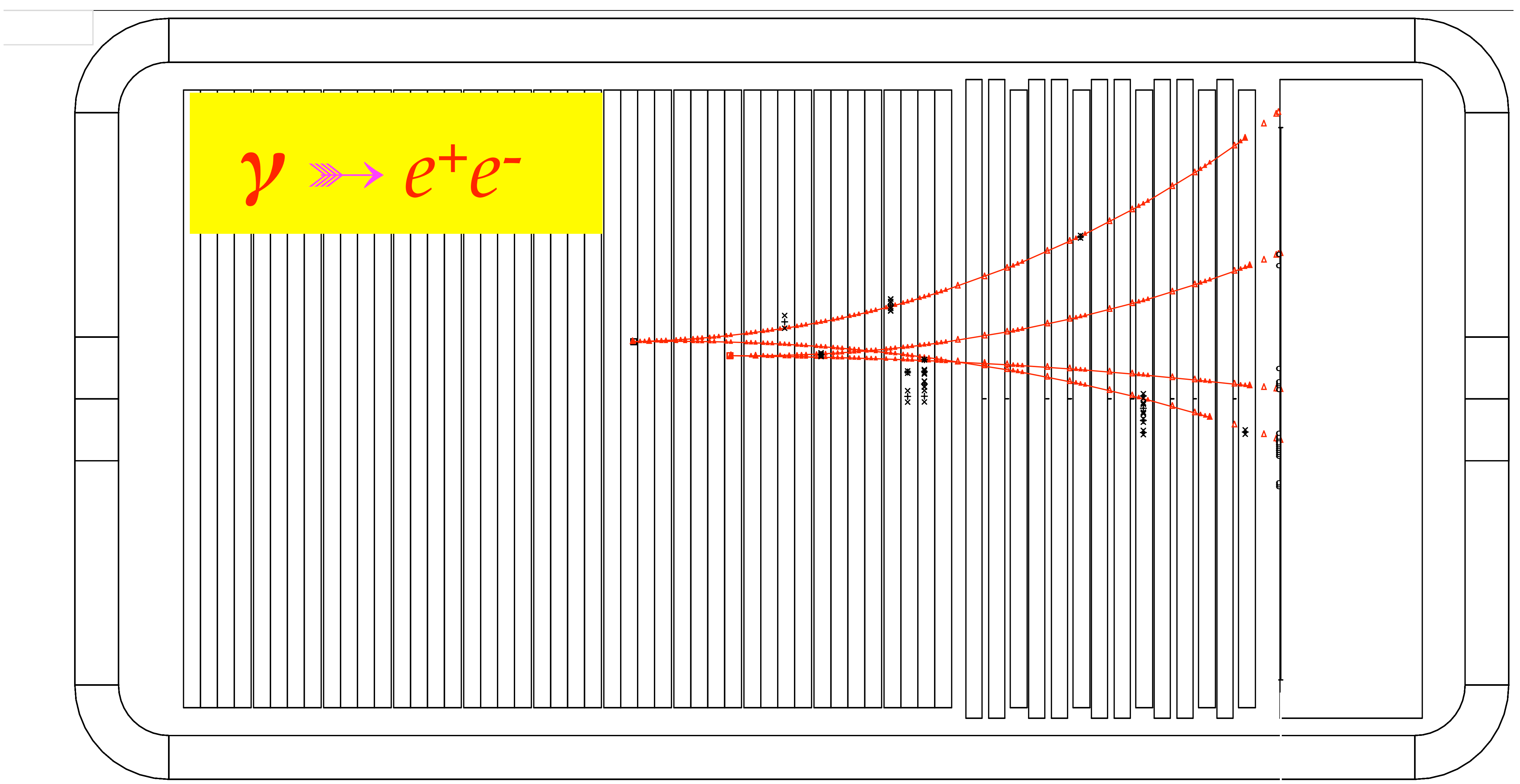


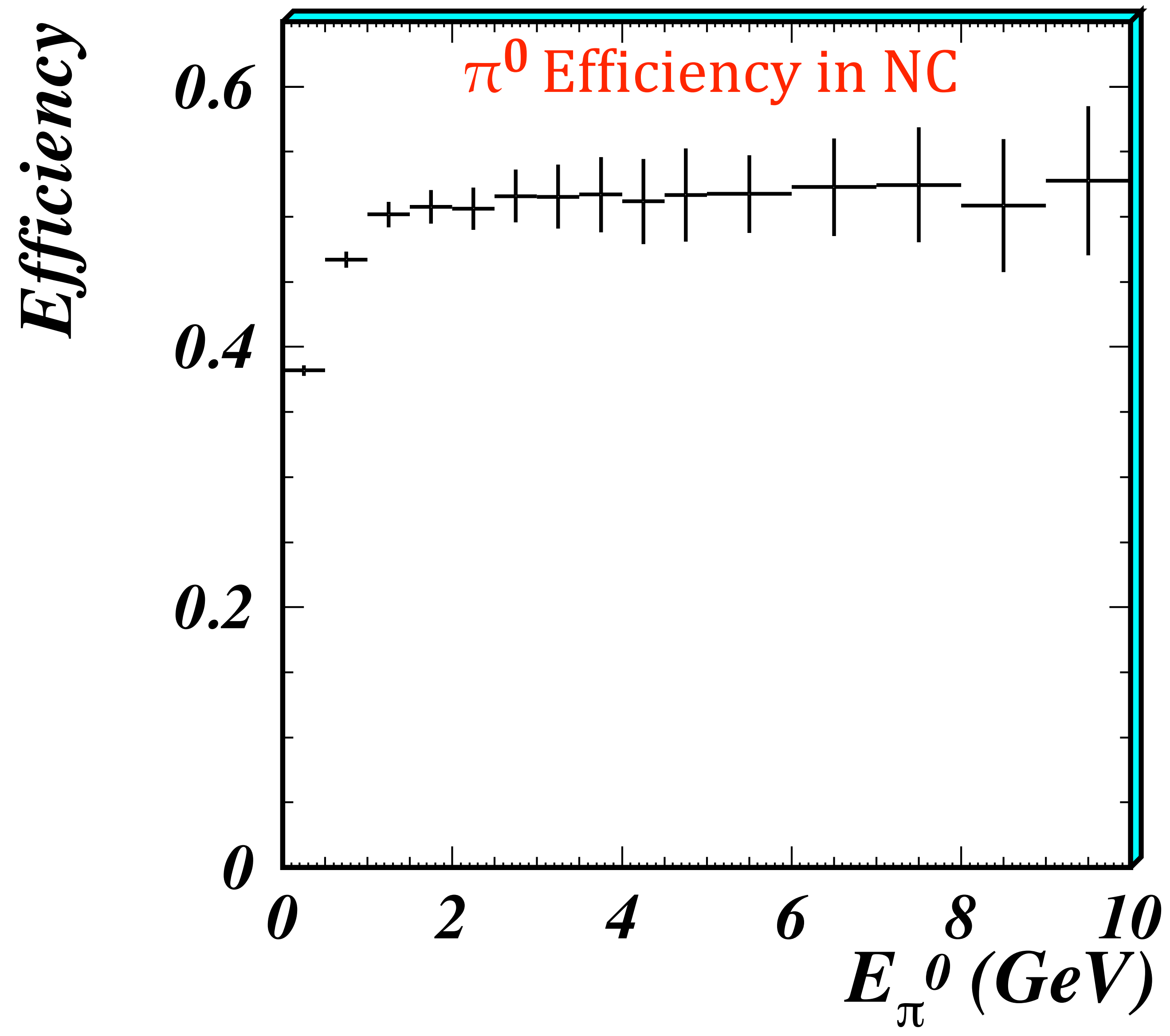
Electron ID:

- **Transition radiation (TR)** measurement in STT
- **Energy deposition pattern (dE/dx)** in the ECAL.

π^0 Reconstruction

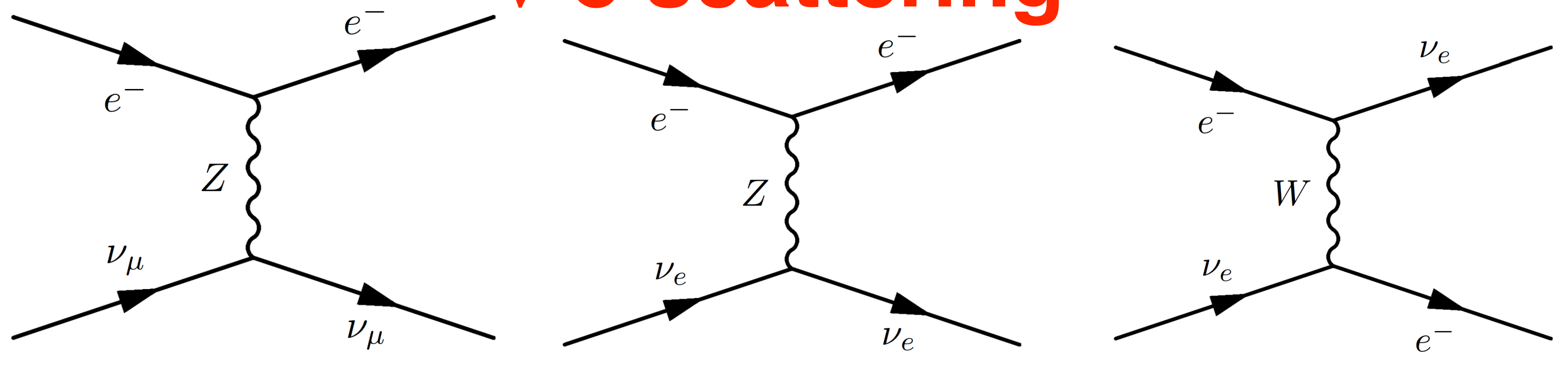
- π^0s are background to $\nu_e/\bar{\nu}_e$ appearance.
- FGT sees clean π^0 signatures:
  - 50% of the γ convert in STT, away from the primary vertex.
- We can also use electrons γ-conversion to calibrate the electron measurement and identification.



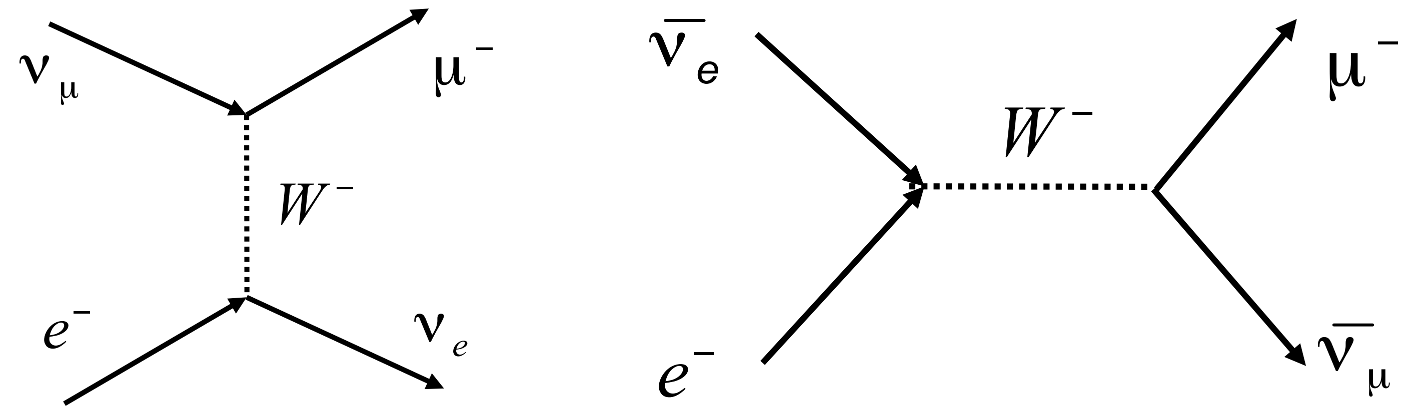


Absolute Flux Measurement

ν-e scattering

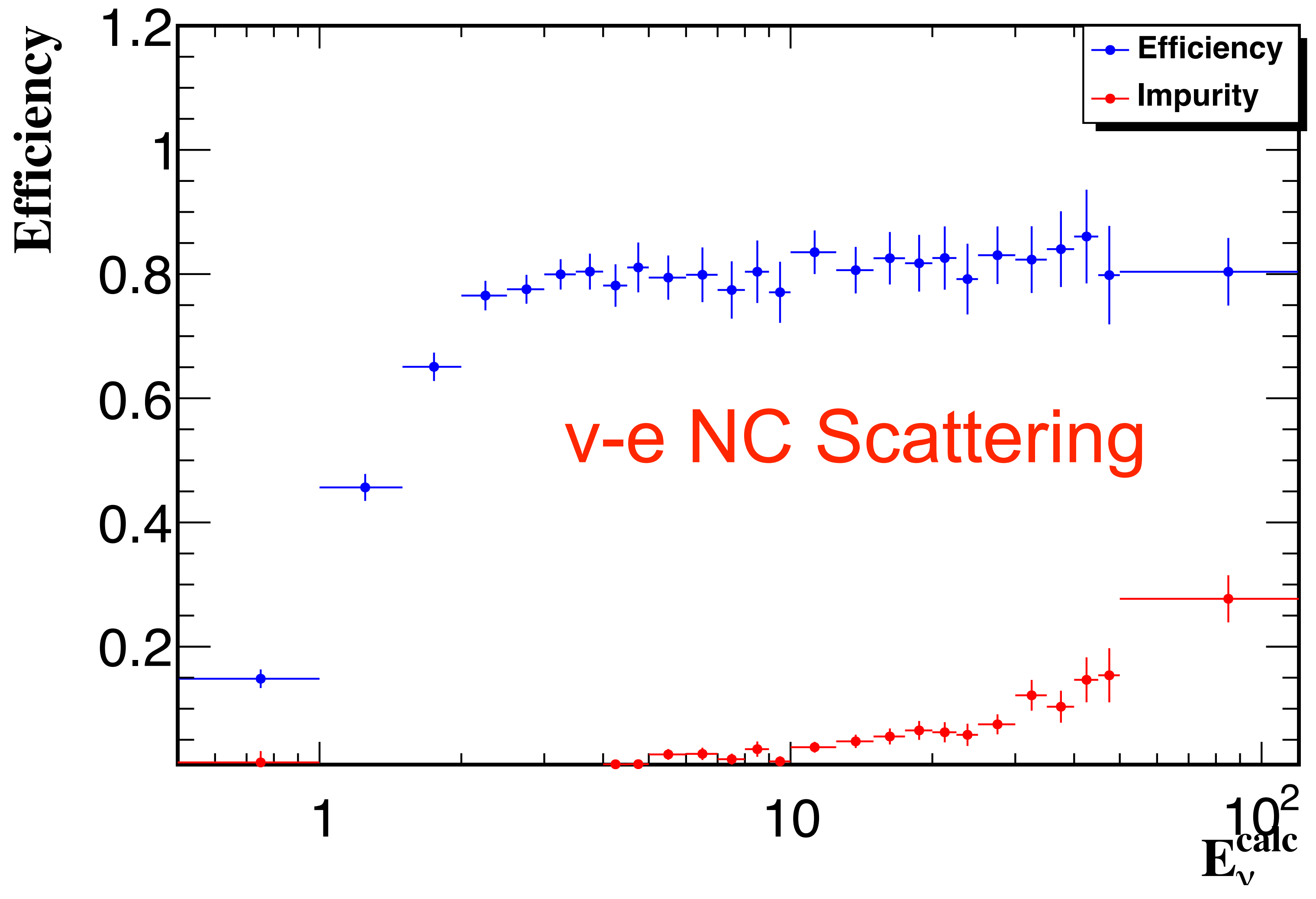


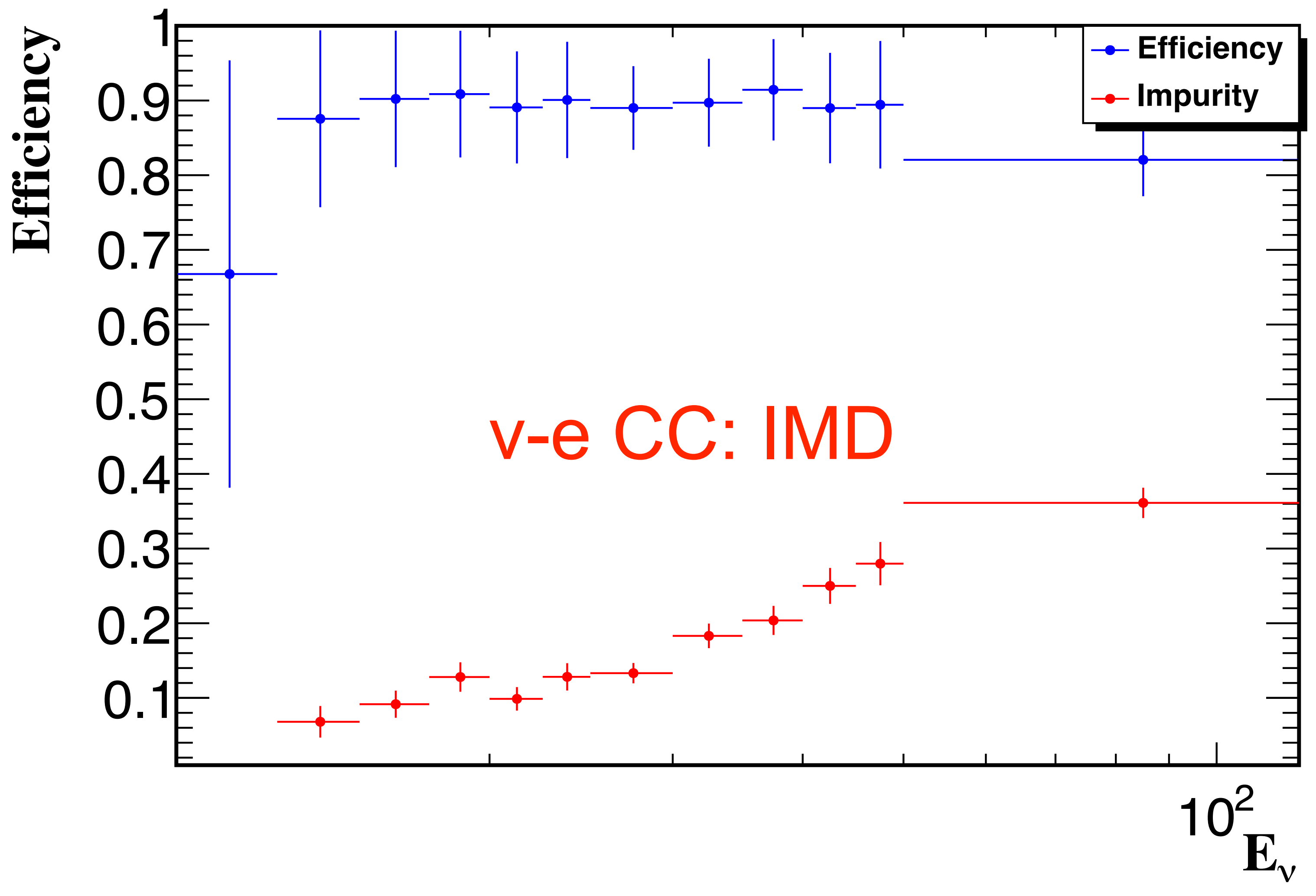
IMD



Pure leptonic processes: small but very well known cross-sections.

- Assuming 1.2 MW beam power, 5 tons ND fiducial mass, 5 years neutrino running we expect:
  - **~7.8k** $\nu_\mu + e^- \rightarrow \nu_\mu + e^-$: **~2%** precision in 2.5~10 GeV.
  - **~4k** $\nu_\mu + e^- \rightarrow \nu_e + \mu^-$: **~2.5%** precision in 11~50 GeV.



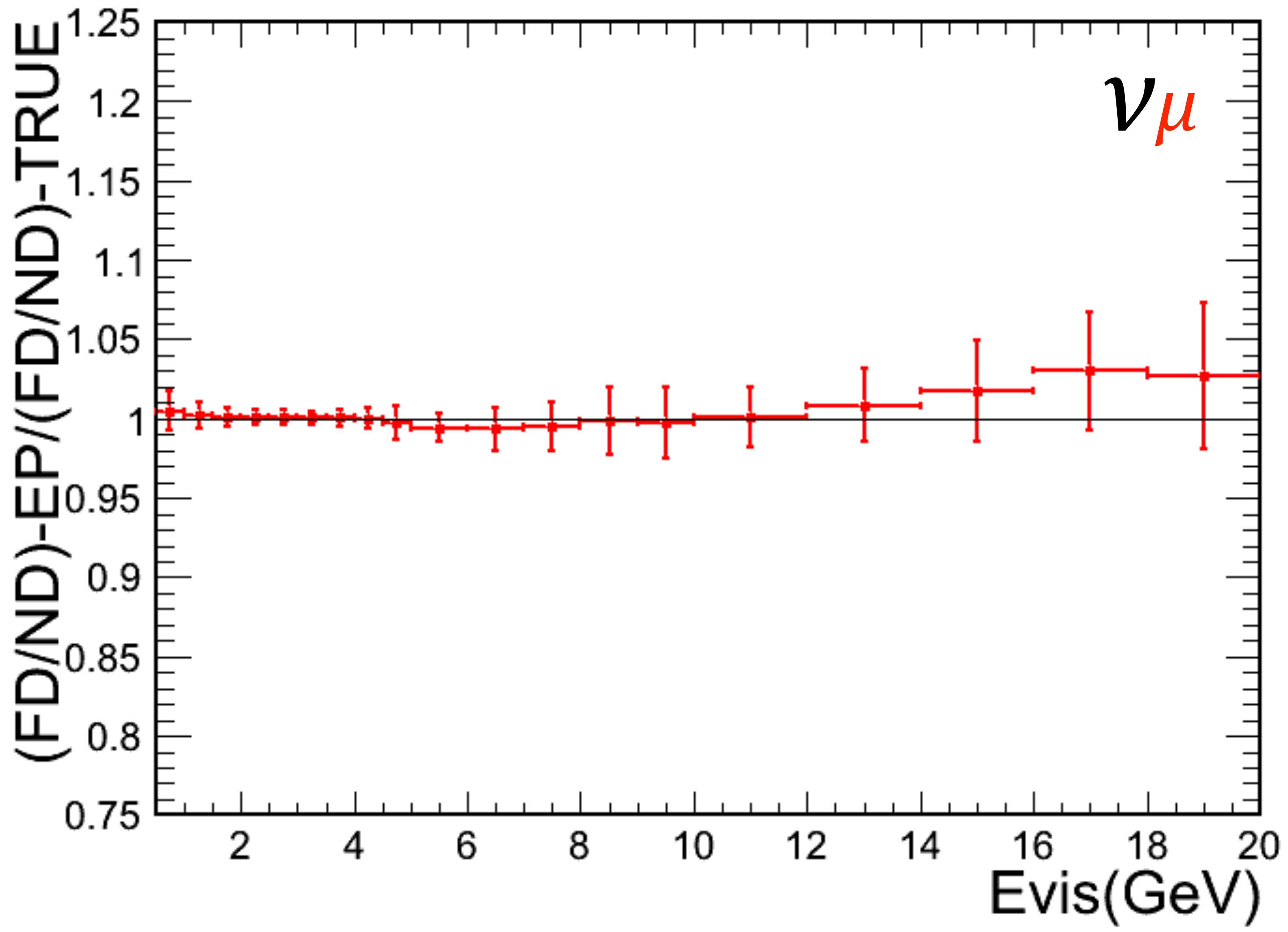


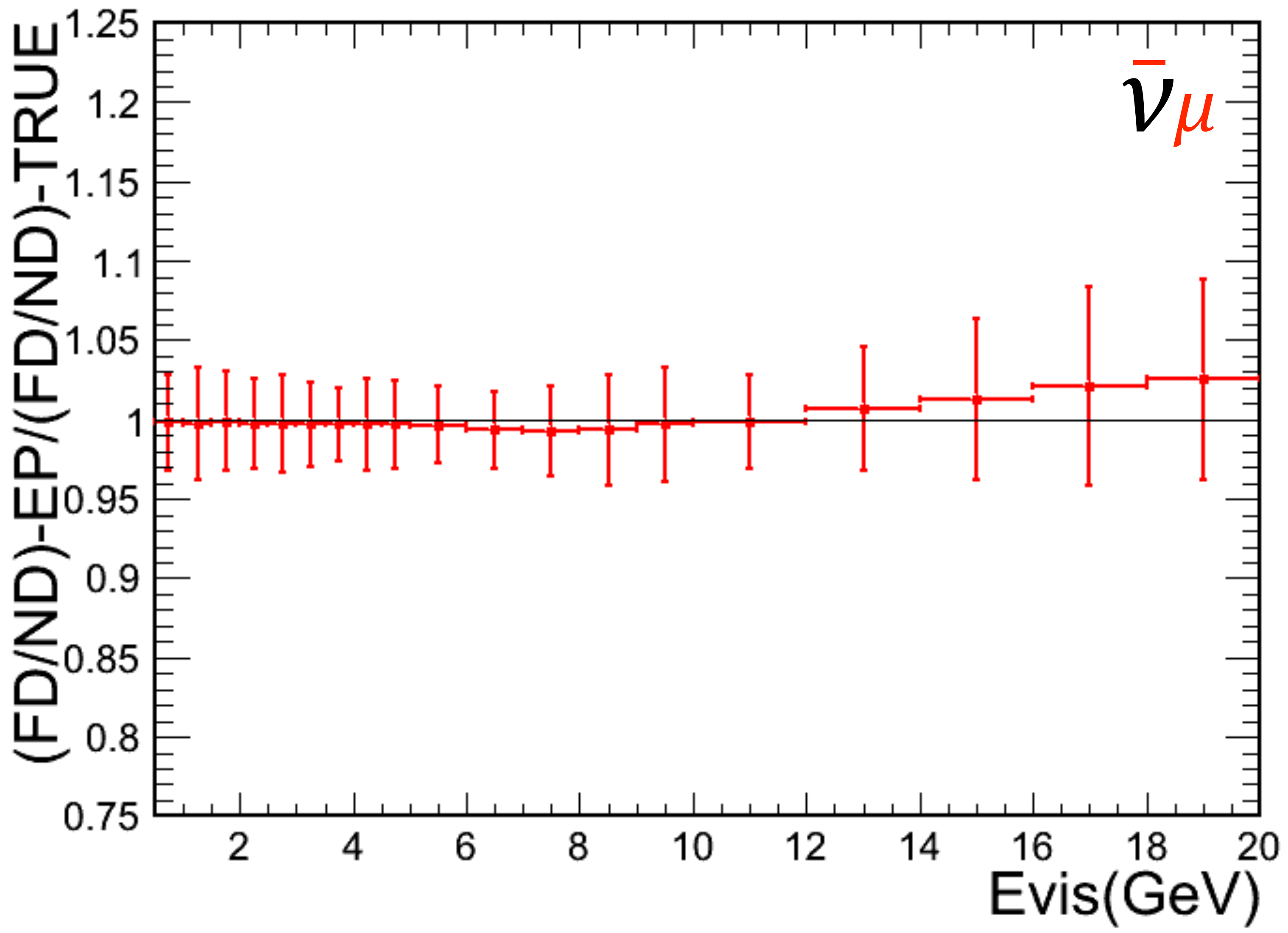
Relative Flux Measurement

- **Low-ν method**: at low ν, the number of events in a given energy bin is proportional to the neutrino flux.

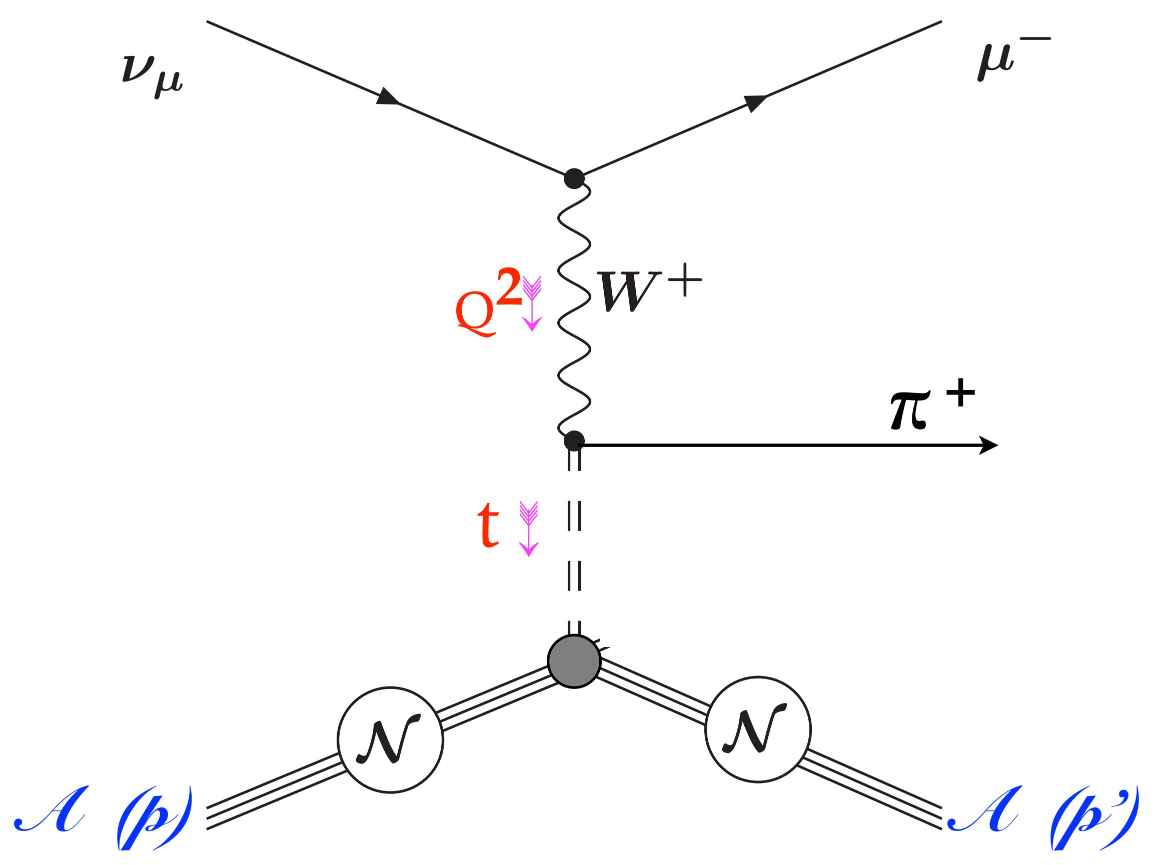
$$N(E)_{\nu<1} = k\Phi(E) f_c\left(\frac{\nu}{E_\nu}\right)$$

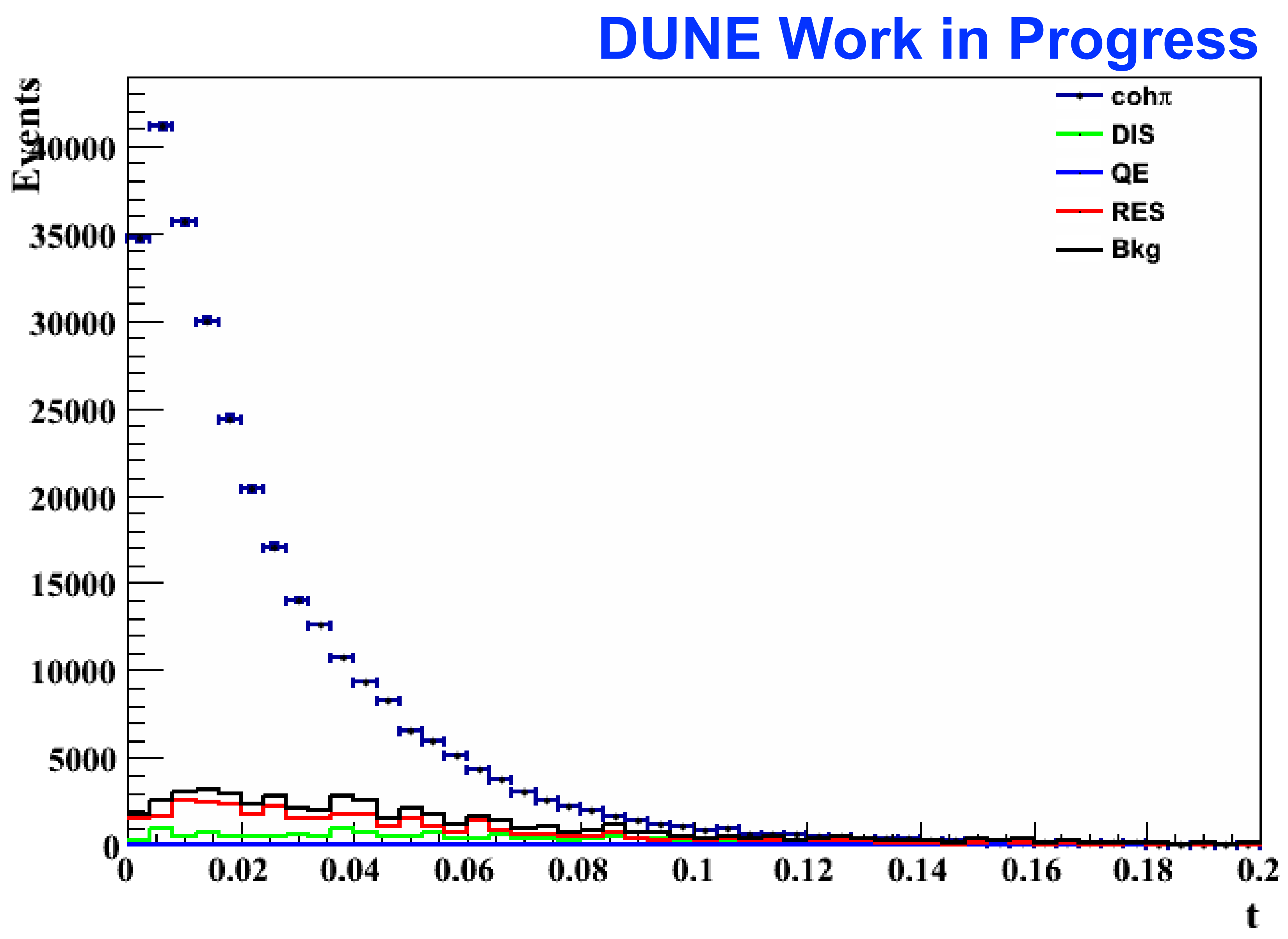
- Dominant uncertainty is muon energy scale and resolution.
- Use ND low-ν data to constrain beam hadron productions.
- Expect an FD/ND ratio at **1~2%** precision in 0.5~50 GeV

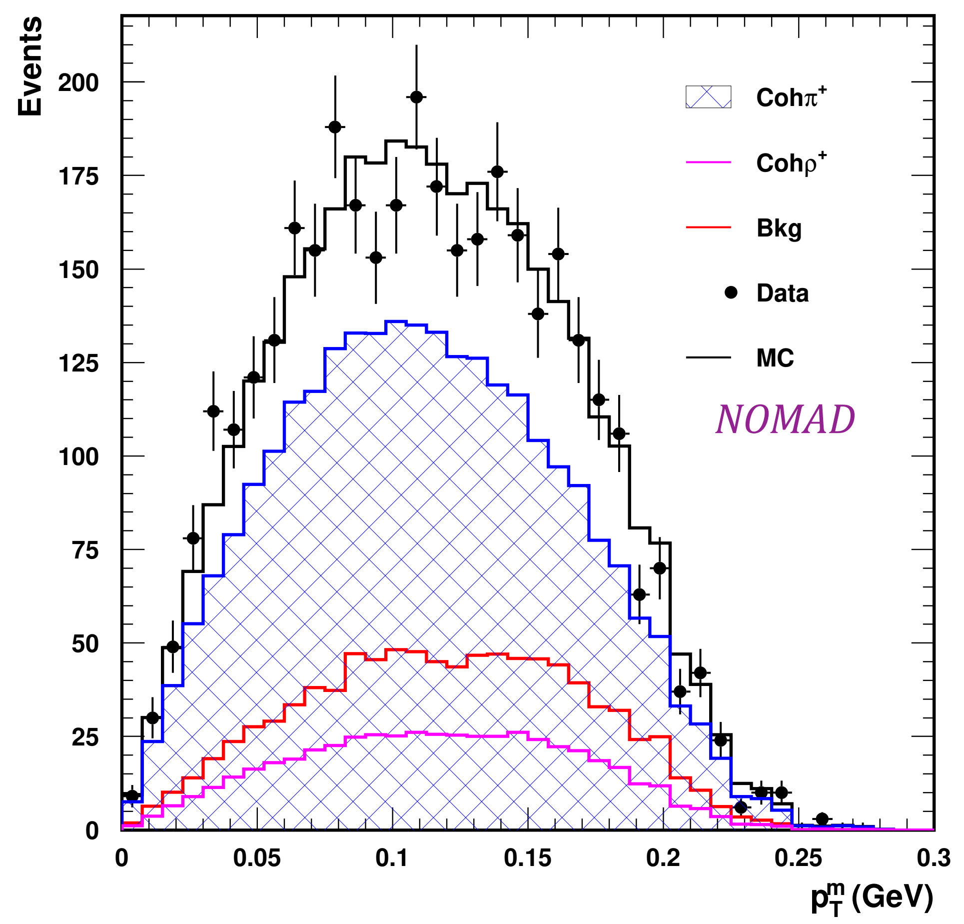




Coherent π







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