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DARKNESS ON THE TABLE, BUSAN, AUGUST 09, 2021

Search for Elementary Magnetic Monopoles in Electron-Positron Annihilation at Rest

150 years mystery

KoreA Experiment on Magnetic Monopole

Photograph courtesy CERN

Maxwell's Equations in 1865

No evidence for magnetic monopoles

$$\nabla \cdot \mathbf{E} = \rho_e \qquad -\nabla \times \mathbf{E} = \partial \mathbf{B}/\partial t$$

$$\nabla \cdot \mathbf{B} = 0 \qquad \nabla \times \mathbf{B} = \partial \mathbf{E}/\partial t + \mathbf{j}_e$$

Electromagnetic force law: $\mathbf{F} = e(\mathbf{E} + \mathbf{v} \times \mathbf{B})$

Maxwell's Equations with a Magnetic Monopole

Beautiful Symmetry of Maxwell's Equations

$$\nabla \cdot \mathbf{E} = \rho_e \qquad -\nabla \times \mathbf{E} = \partial \mathbf{B}/\partial t + \mathbf{j}_m$$

$$\nabla \cdot \mathbf{B} = \rho_m \qquad \nabla \times \mathbf{B} = \partial \mathbf{E}/\partial t + \mathbf{j}_e$$

Electromagnetic force law: $\mathbf{F} = e(\mathbf{E} + \mathbf{v} \times \mathbf{B}) + g(\mathbf{B} - (\mathbf{v}/c^2) \times \mathbf{E})$

Dirac Monopoles (1931)

Dirac's quantization condition for electric (e) and magnetic (g) charges

$$eg = n\hbar c/2 \rightarrow g = ne/2\alpha \approx 68.5e$$

Zero evidence of any particle with this large charge in

1. Time Projection Chamber (PEP, TRISTAN, PETRA, LEP)
2. Drift Chamber (D0 and CDF)
3. All LHC detectors including MoEDAL
4. Moon rocks, IR Material, Cosmic rays

Other theories

Theoretical arguments for the existence of magnetic charges

- George Lochak [quant-ph/0801.2752]
  - Another solution for the Dirac system of electron-monopole
  - Contrary to other theories, our monopole is light, fermionic and interacting electromagnetically and weakly
- D. Fryberger, M. Sullivan[hep-ex/1707.05295]
  - Proposed a magnetic charged particle with magnetic charge g=e
- Milli-charged particle [hep-ph/0001179v2], milli-magnetic particle [Phys. Rev. D 96 (2017) 05510]

Theoretical arguments against the existence of magnetic charges

- K. McDonald [http://kirkmcd.princeton.edu/examples/comay.pdf]
  - Comay's paradox: magnetic charges are incompatible with classical electrodynamics
- K. Milton [Rep. Prog. Phys. 69 (2006) 1637-1712]
  - There is no classical Hamiltonian theory of magnetic charge

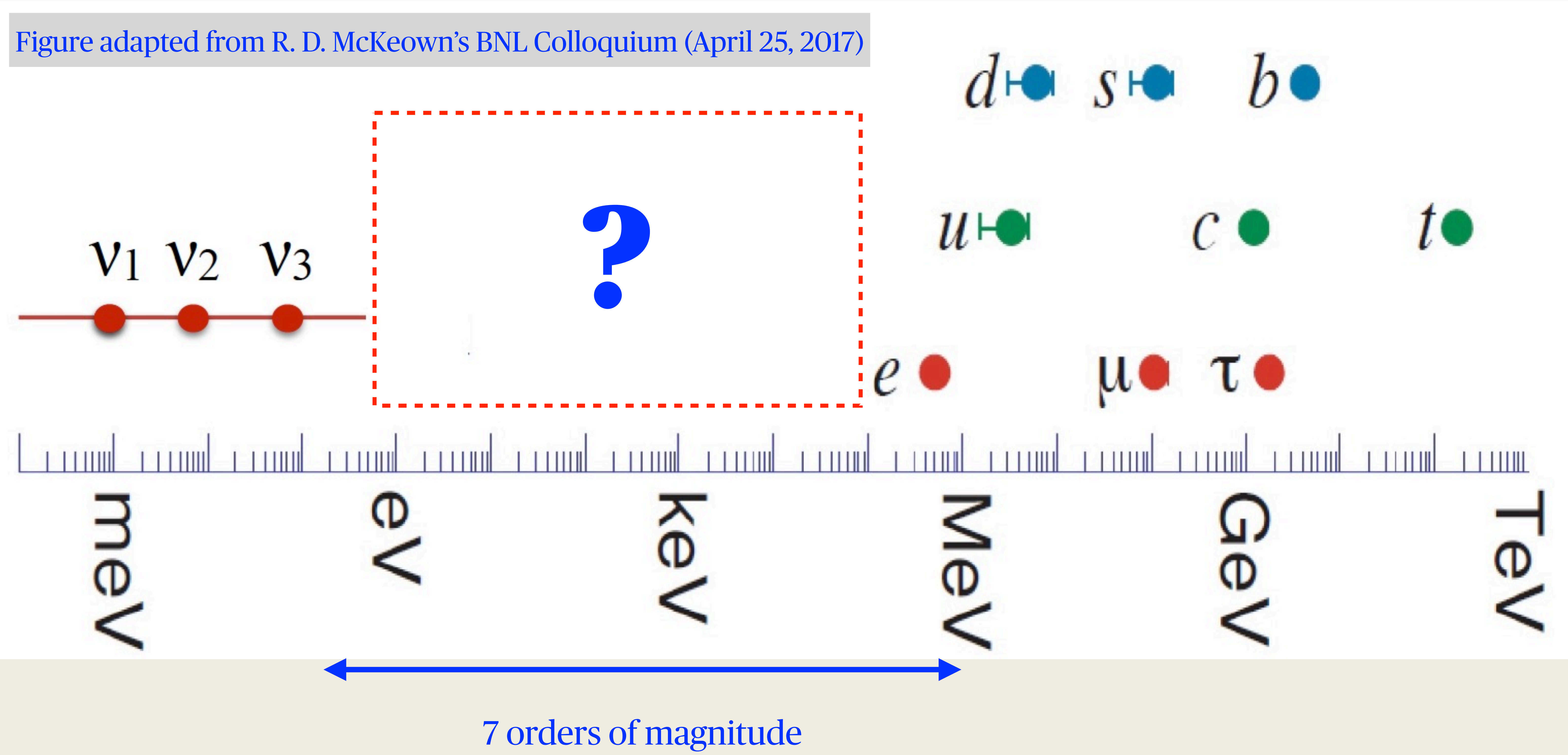
The Symmetry of E and B in Maxwell's Equations

$$m_m \leq m_e$$

$$g \leq e$$

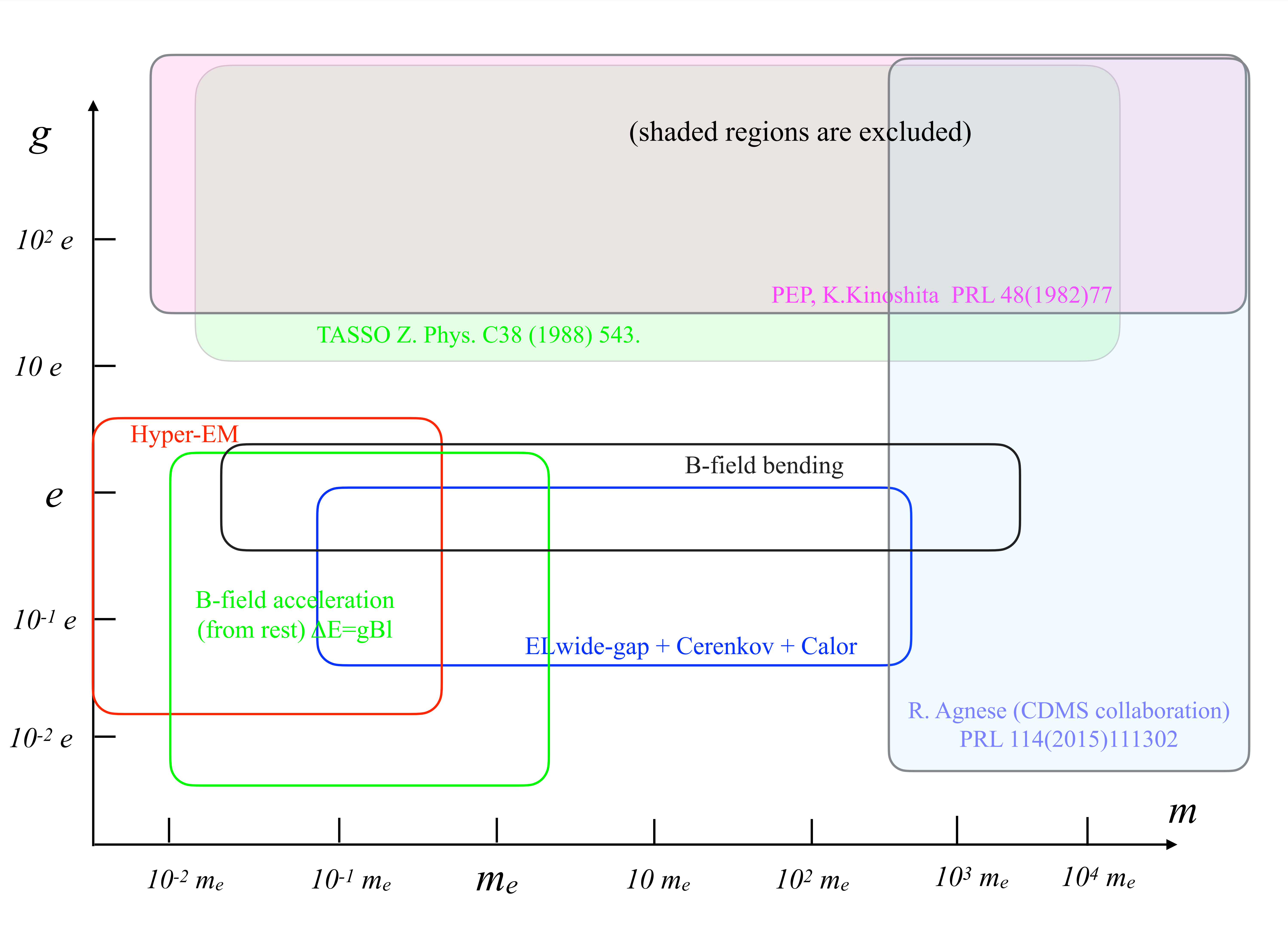
A huge charge (~68.5e) and huge mass (>>1 TeV/c^2) of a magnetic monopole may be unreasonable since they are physically incompatible with the charge and mass of an electron.

Masses of Fermions
(Matter Particles)

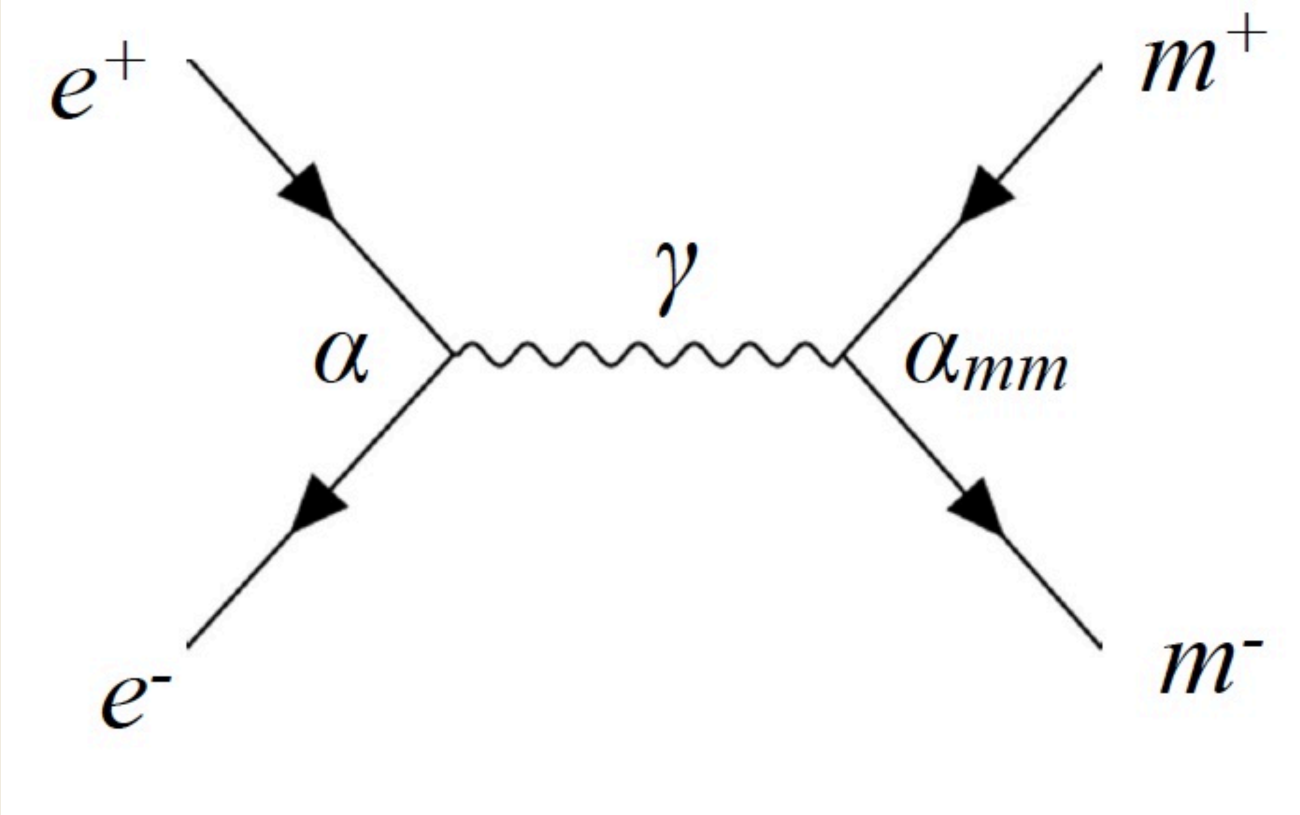


Could magnetic monopoles, SUSY particles, axions, skyrmions, dyons, dilations, and other particles exist in this mass region?

Our Exploring Area



Magnetic Monopole Production



$$e^+e^- \to \gamma^* \to m^+m^-$$

$$\sigma(e^+e^- \to m^+m^-) = \frac{4\pi}{3}\frac{\alpha\alpha_{m^+m^-}}{s}\sqrt{\frac{1-4m_m^2/s}{1-4m_e^2/s}}(1+2m_e^2/s)(1+2m_m^2/s)$$

Coupling strength (or production probability)

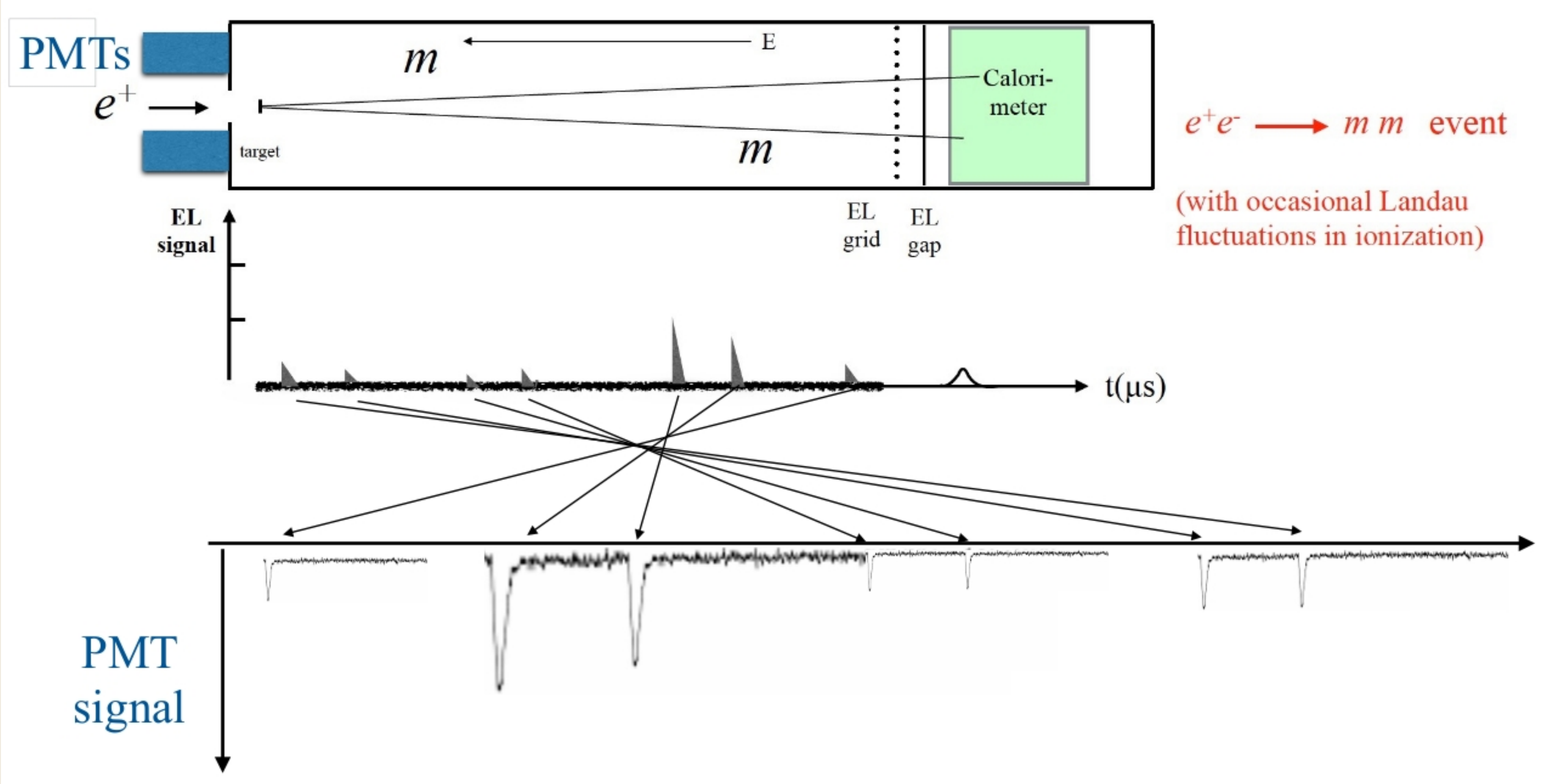
$$\alpha = e^2/4\pi\epsilon_0\hbar c \approx 1/137 \qquad \alpha_{m^+m^-} = \frac{g^2}{4\pi\epsilon_0\hbar c}$$

For small magnetic charge, g < e ➔
- **small energy transfer in ionization energy loss**
- **small radiation energy losses**
- **small magnetic Cerenkov light generation**

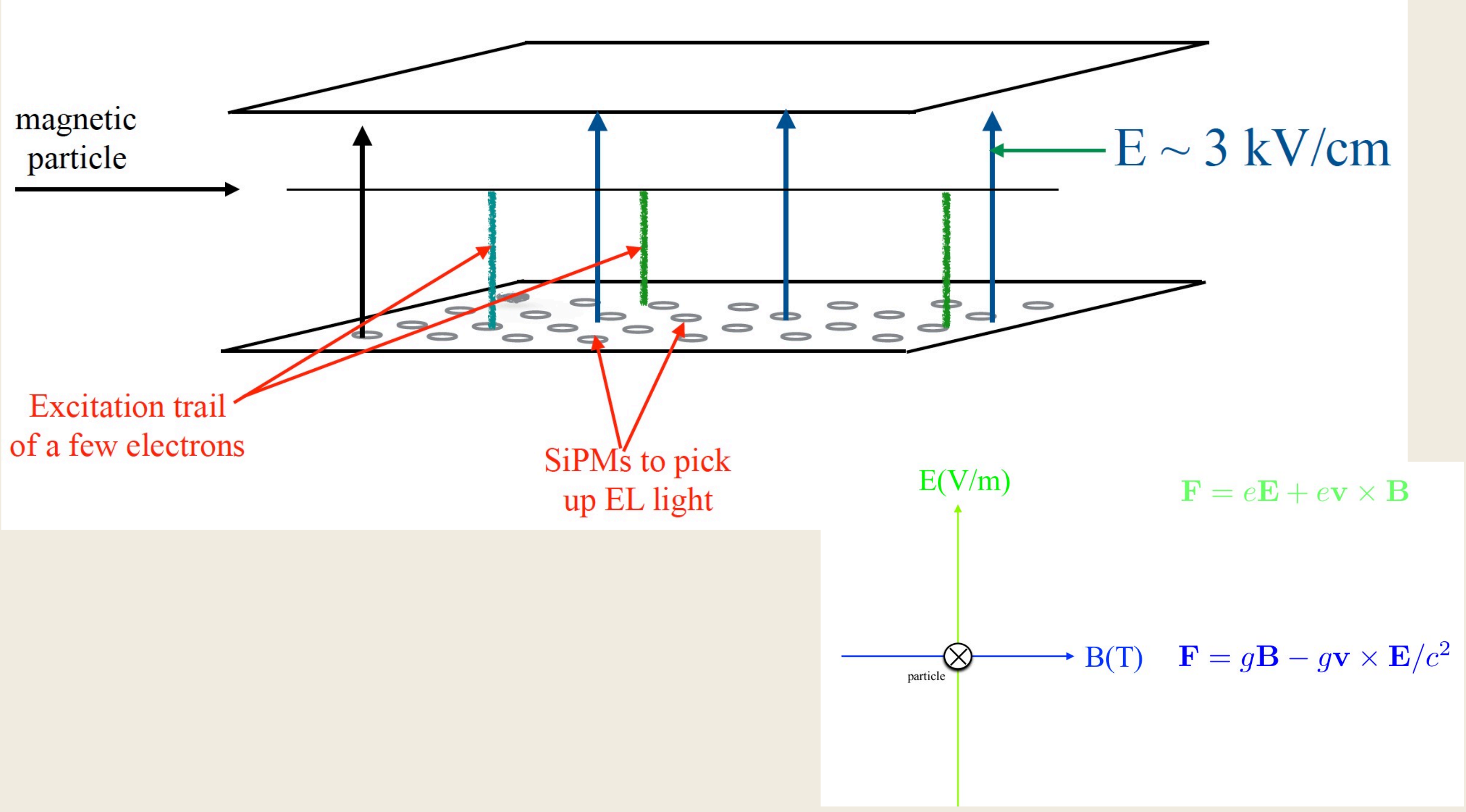
➔ the design of new detectors

Detection Methods

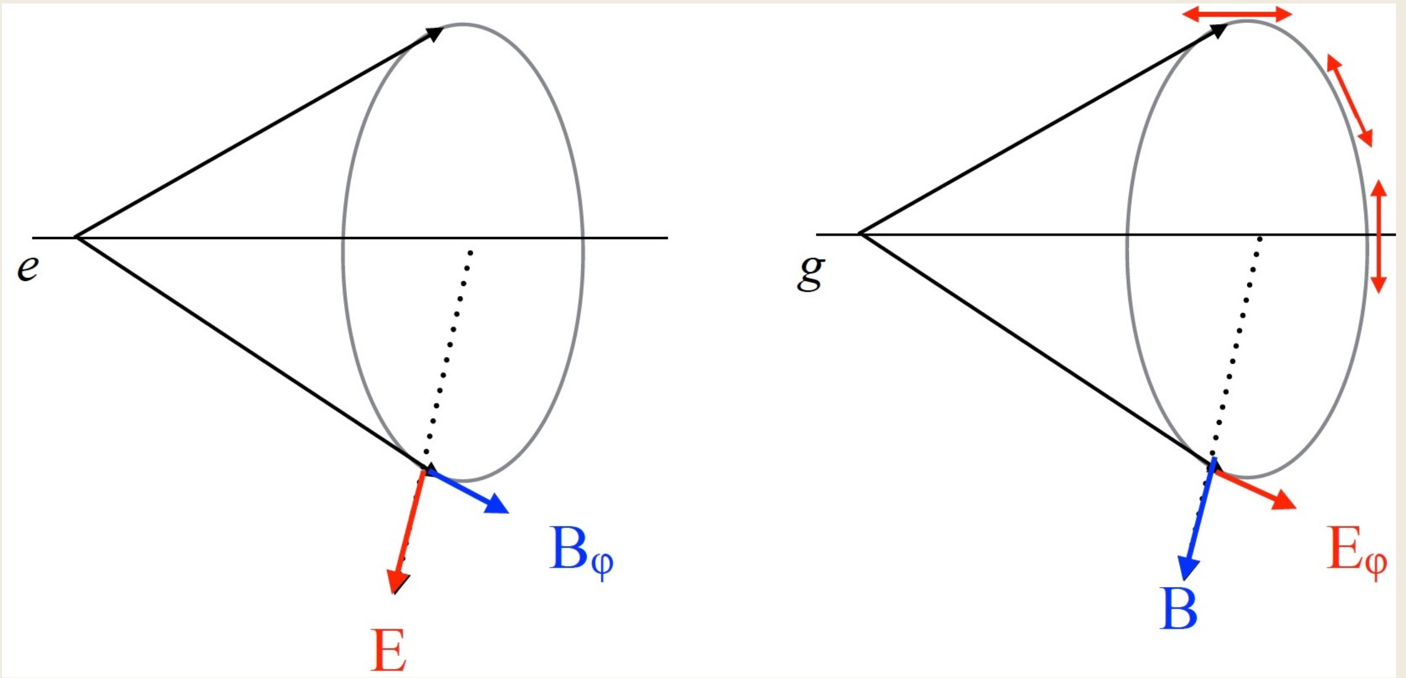
1. Electroluminescence (EL) TPC (Ar or Xe)



2. Wide-gap EL detector



3. Magnetic Cerenkov Light



4. Hyper-EM low-mass particles:

- Plastic Scintillator

$$X_0 \approx (2\ \mathrm{cm}) \times \frac{(m/m_e)^2}{(g/e)^4}$$

5. Electromagnetic Calorimeter

- LYSO, $LaBr_3$:Ce, $CeBr_3$, ...
- total absorption at the far downstream end

6. Other ideas...

- NV Center
- Magnon

Magnetic Acceleration

- Main idea for experimental design
- Magnetic charges m^+m^- will be accelerated in opposites directions in a magnetic field by F=gB

$$\Delta E = gB\ell$$ the obtained energy of magnetic monopoles

$$\Delta E = 68.5e \times (1T \times c) \times 1 \text{ meter} \approx 20.5 \text{ GeV}$$

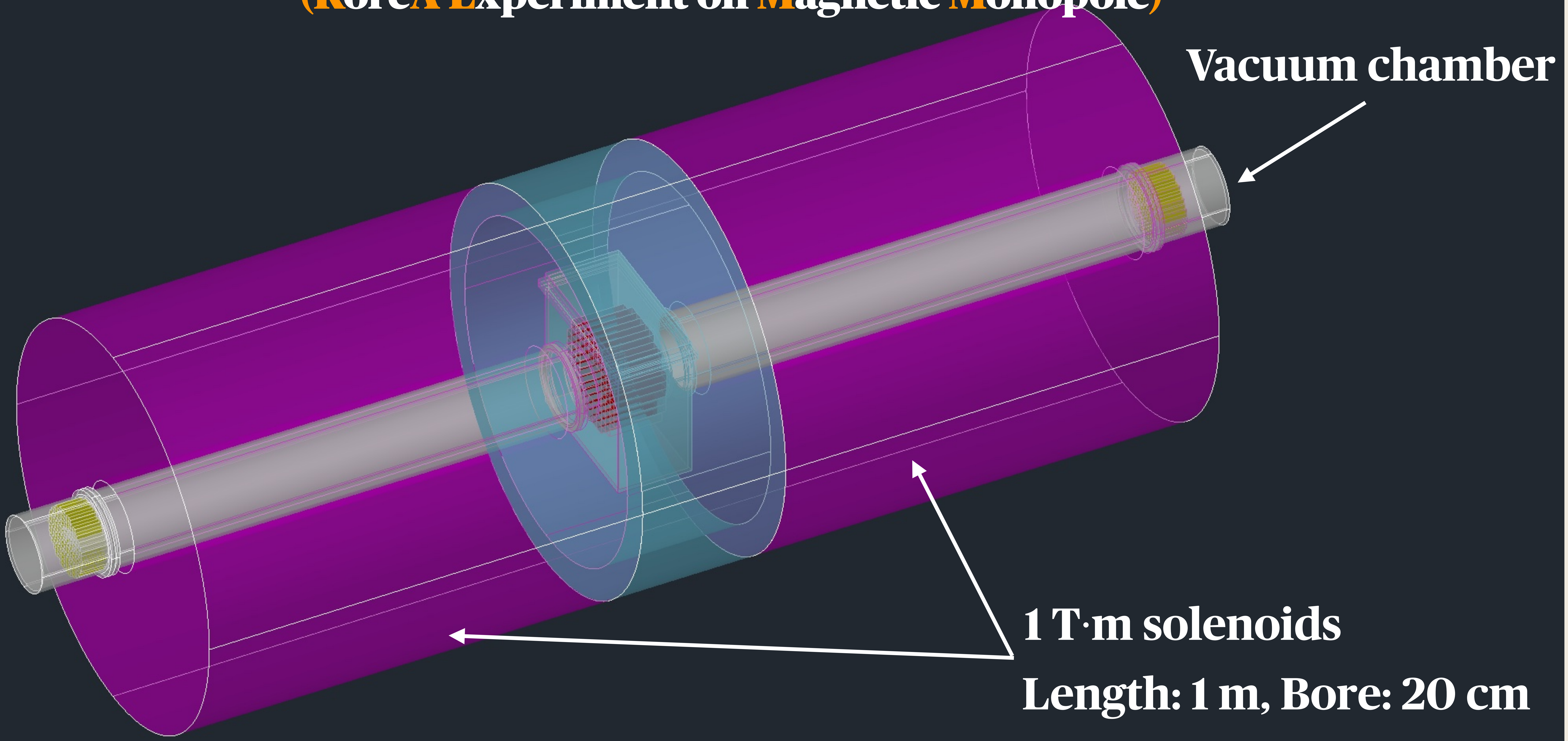
$$\Delta E = (300 \text{ MeV}) \times g/e$$ ← the signature of monopole

Main background: two 511 keV photons

Experimental design

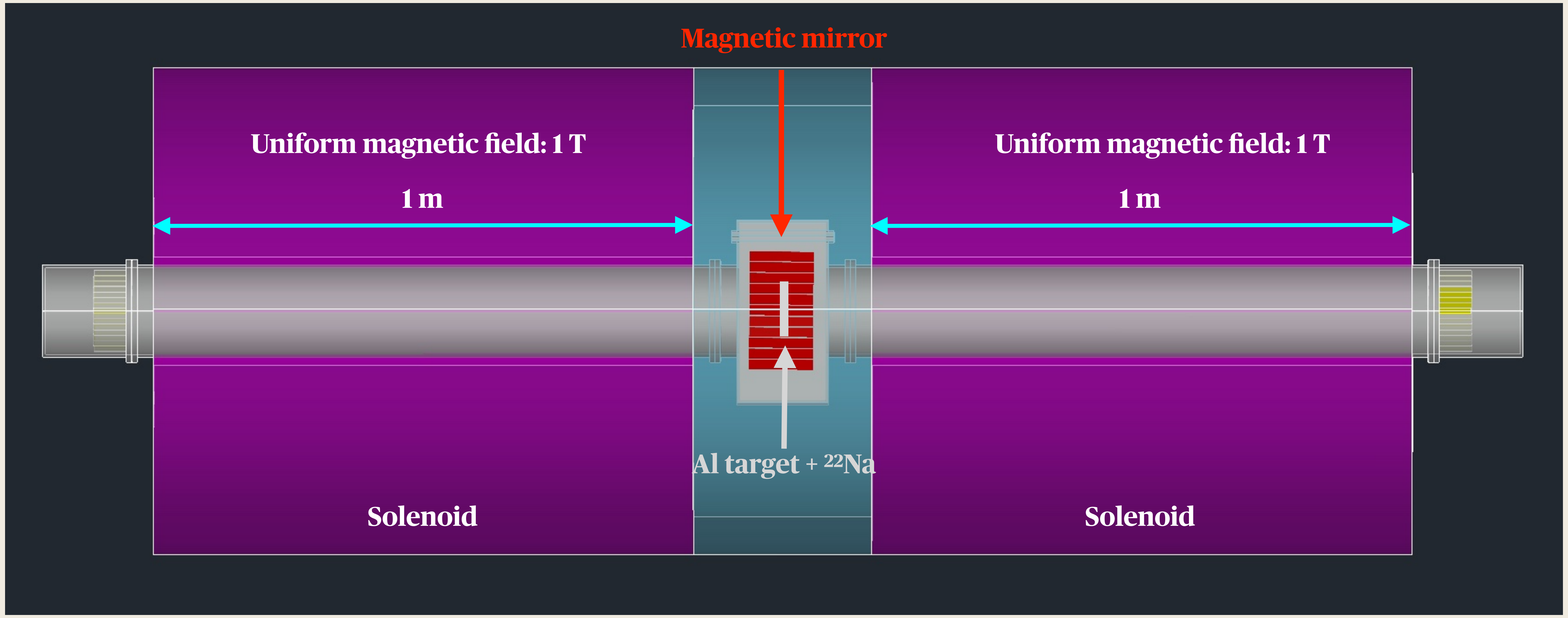
KæM

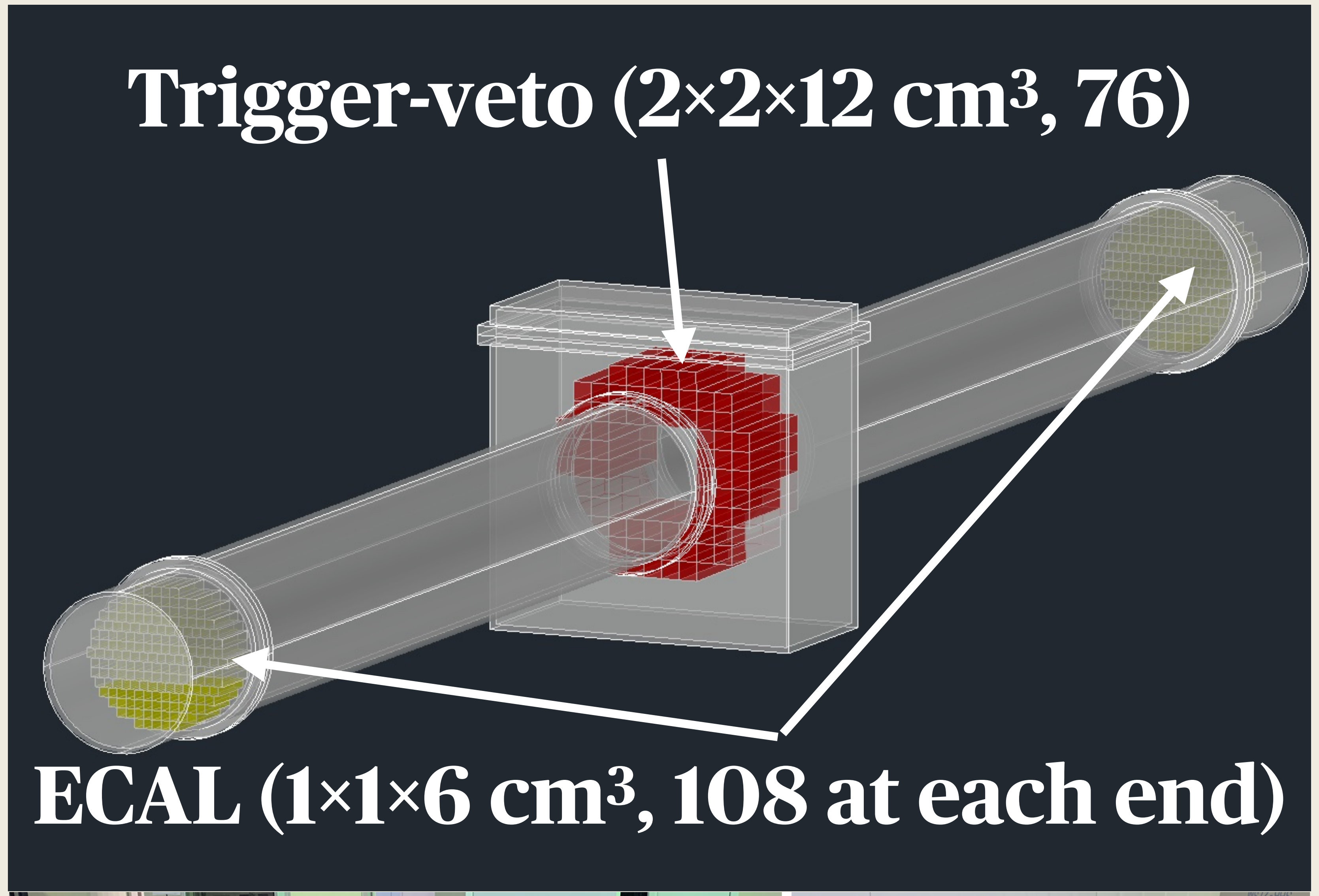
(KoreA Experiment on Magnetic Monopole)

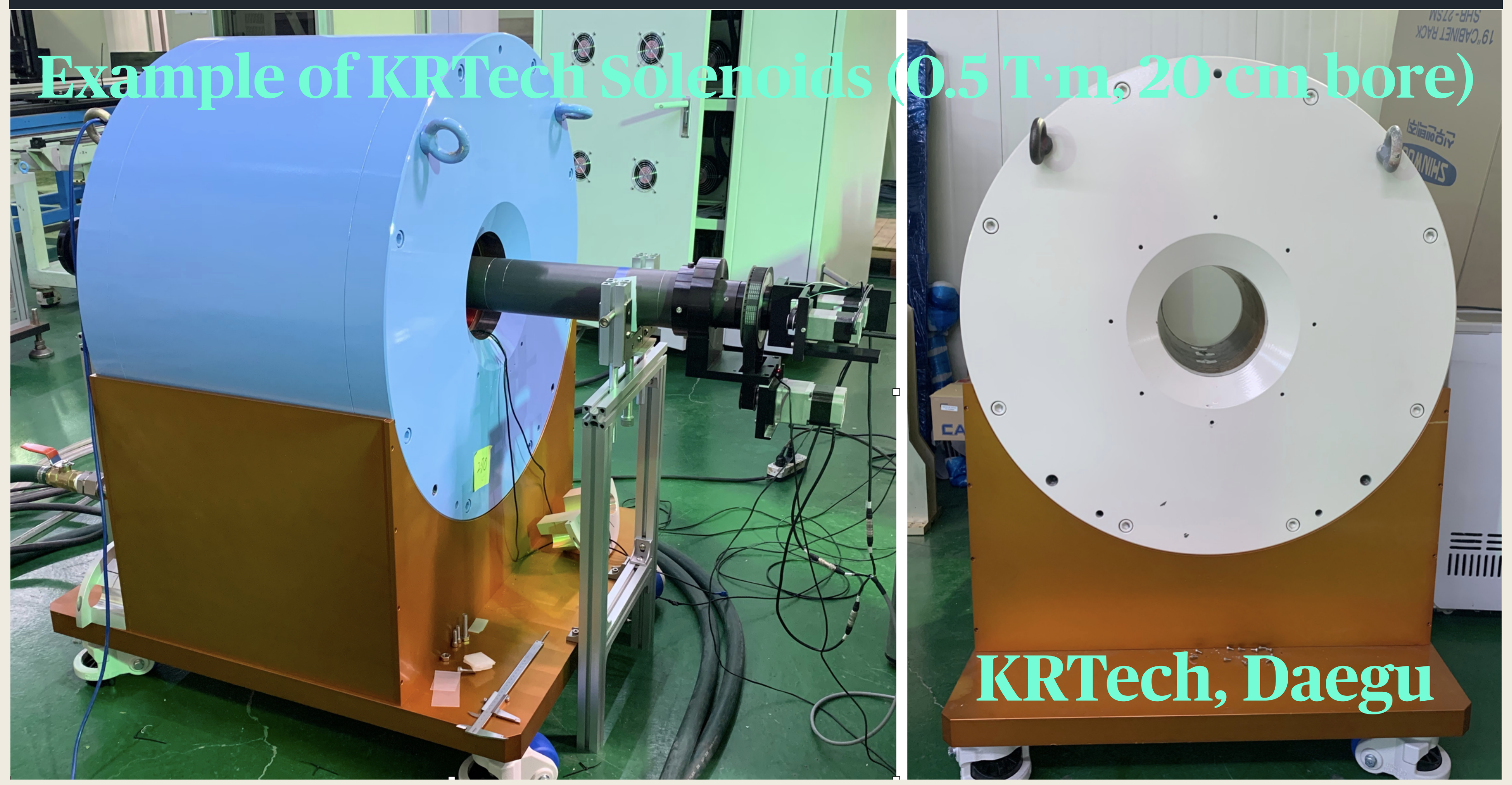


KæM
KoreA Experiment on Magnetic Monopole

Electron-Positron Annihilation near Rest

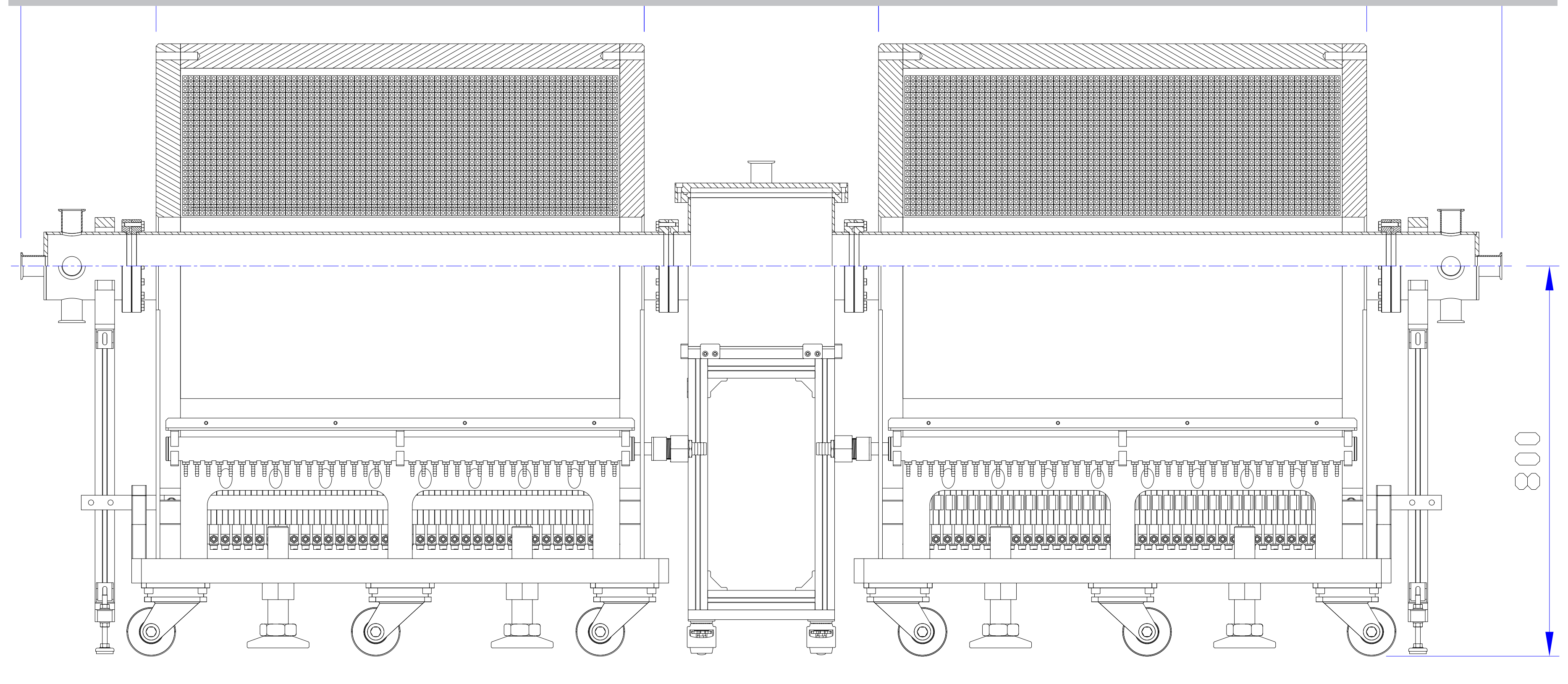






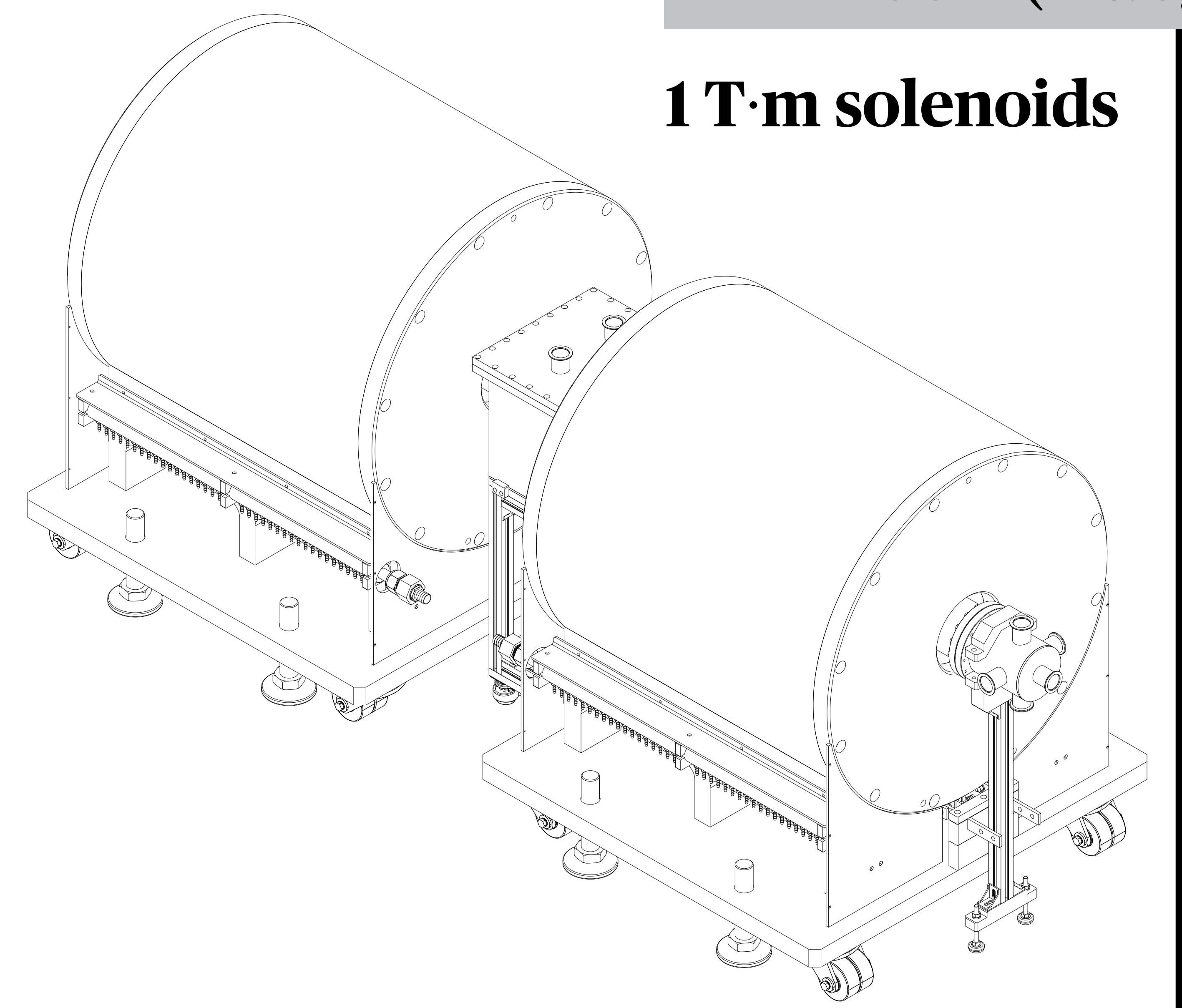
KæM

Solenoids will be installed in Dec., 2021

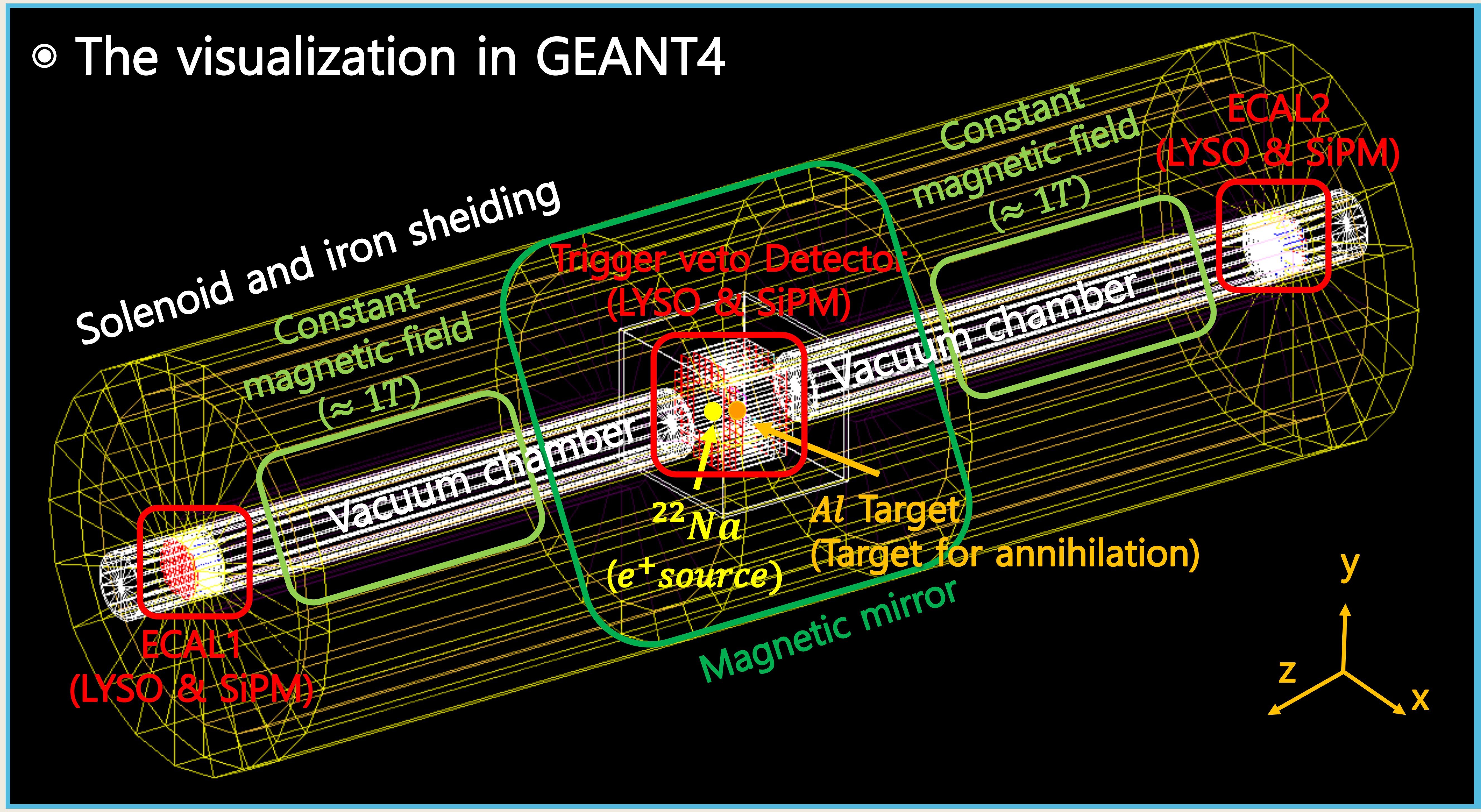


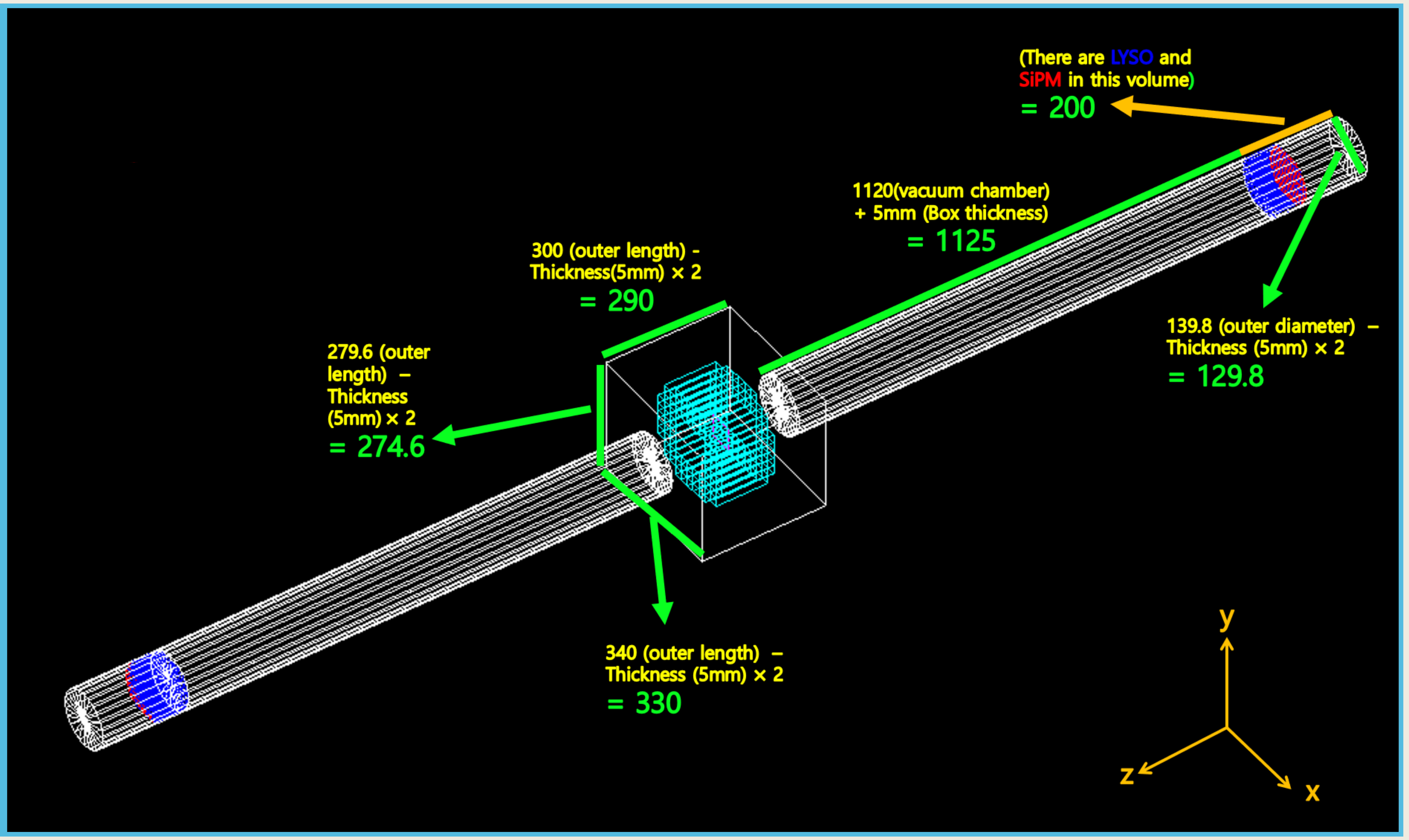
KR Tech (Daegu)

1 T·m solenoids

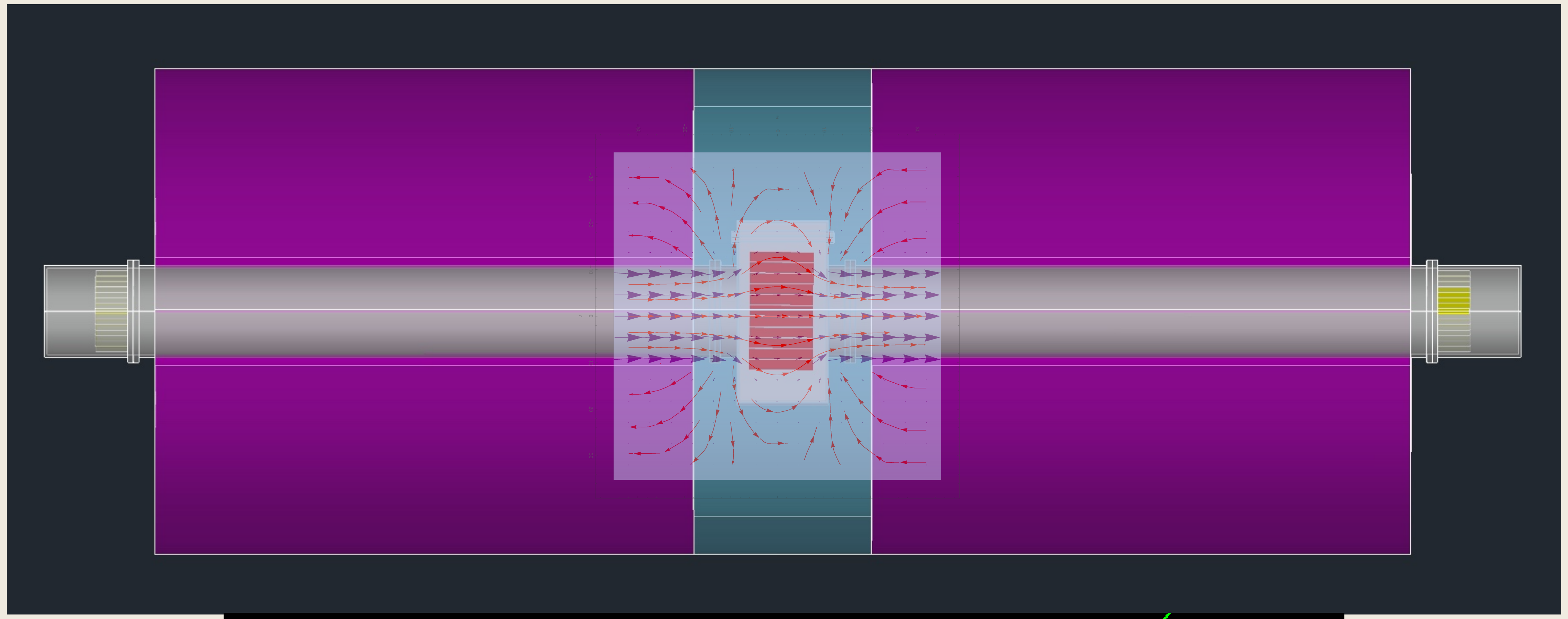


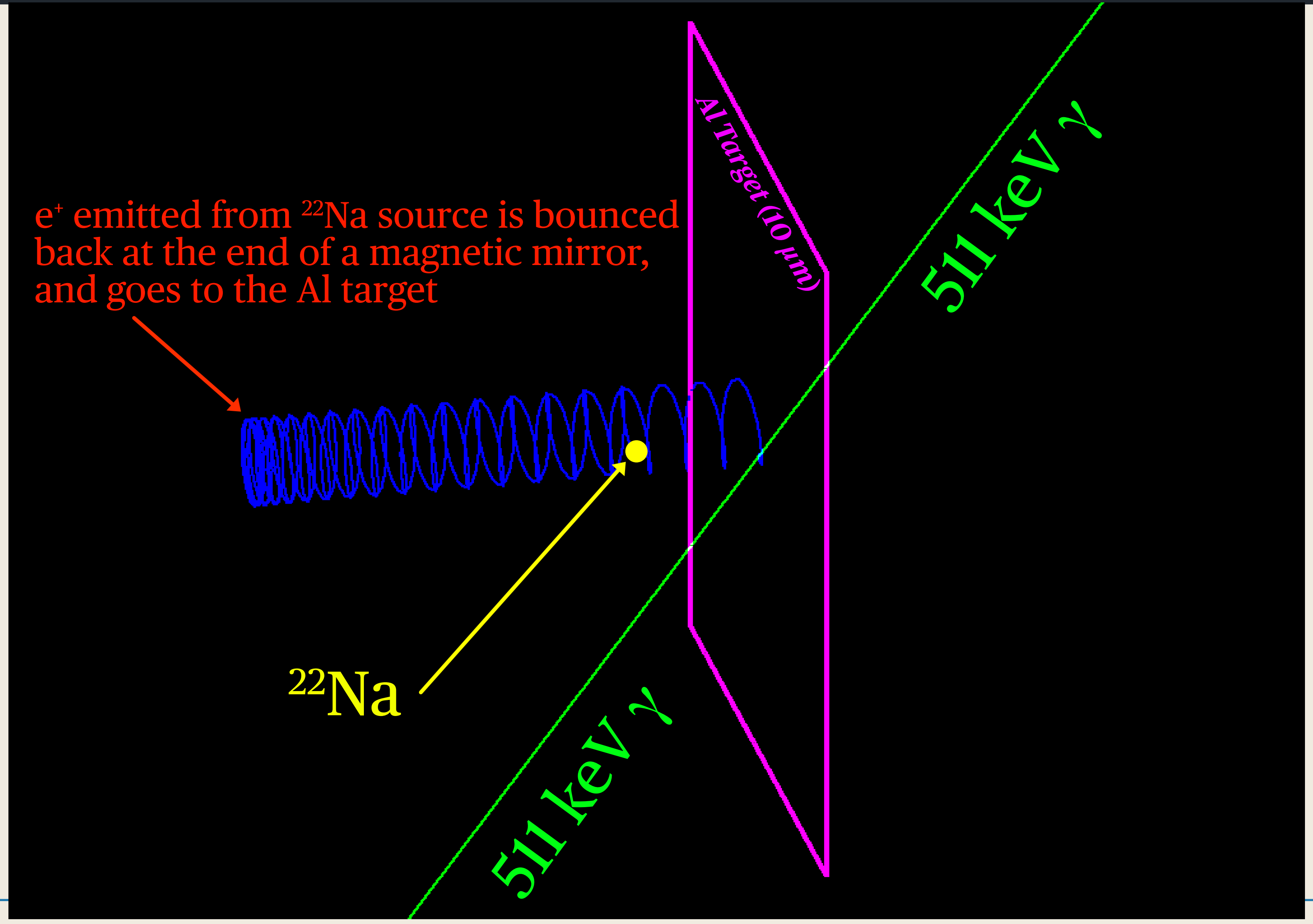
GEANT 4 Simulations



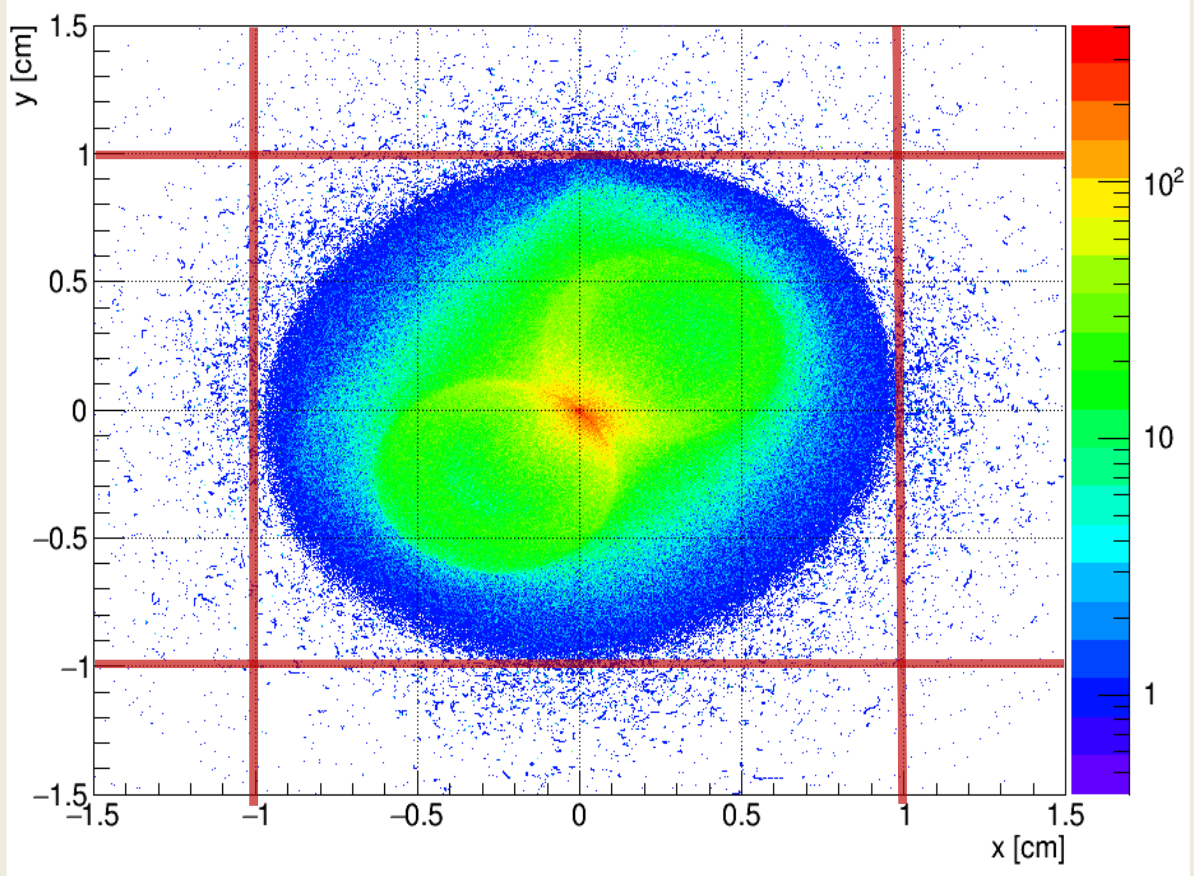


Magnetic Mirror for the e+ Annihilation Target

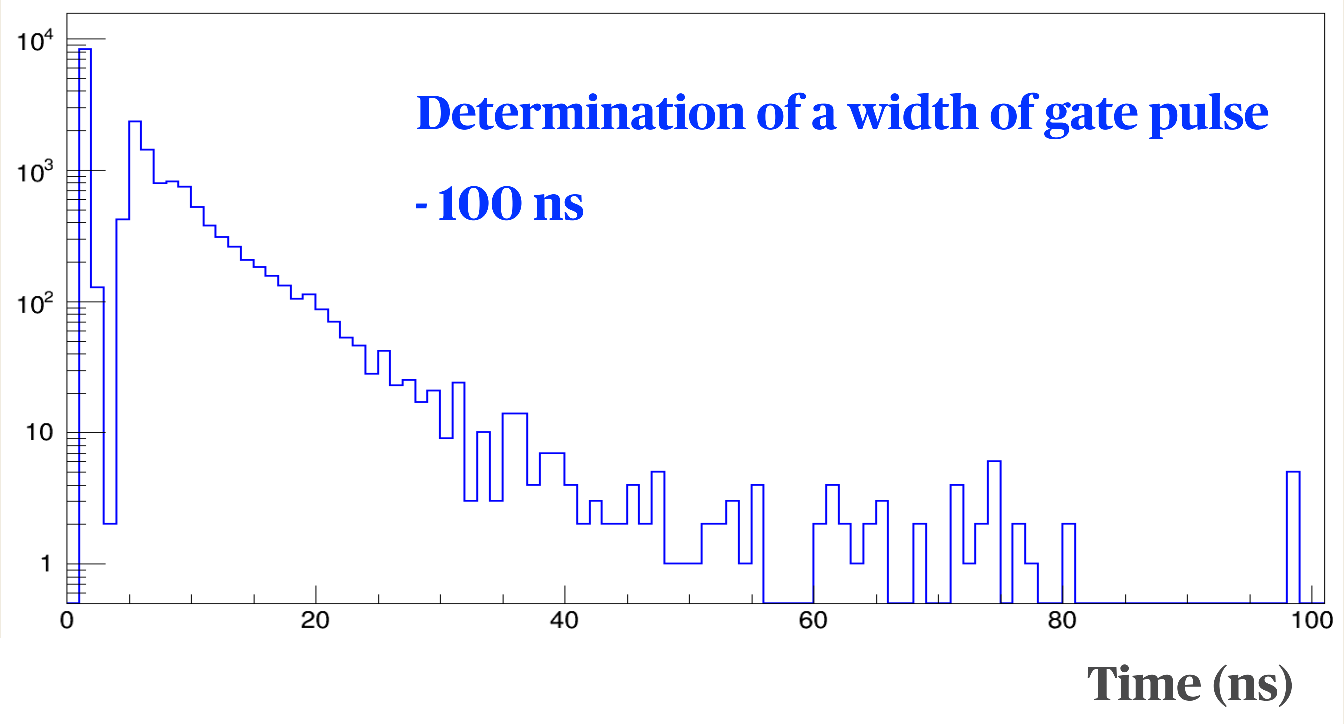




Determination of target size



Time from e+ emission to the arrival of γ at ECAL



$$\epsilon_{\text{Trapped by magnetic mirror}} = \frac{\text{trapped positron}}{\text{total positron}}$$

$$\epsilon_{\text{Geometrical acceptance}} = \frac{\text{detected number of photon pair}}{\text{total number of photon pair}}$$

	Number of event	Exclusive efficiency	Cumulated efficiency
Generate	1000000	100%	100%
e+ emission from 22Na decay	903814	90.38%	90.38%
Trapped by magnetic mirror	448693	49.64%	44.87%
Geometric acceptance	7927	1.77%	0.79%

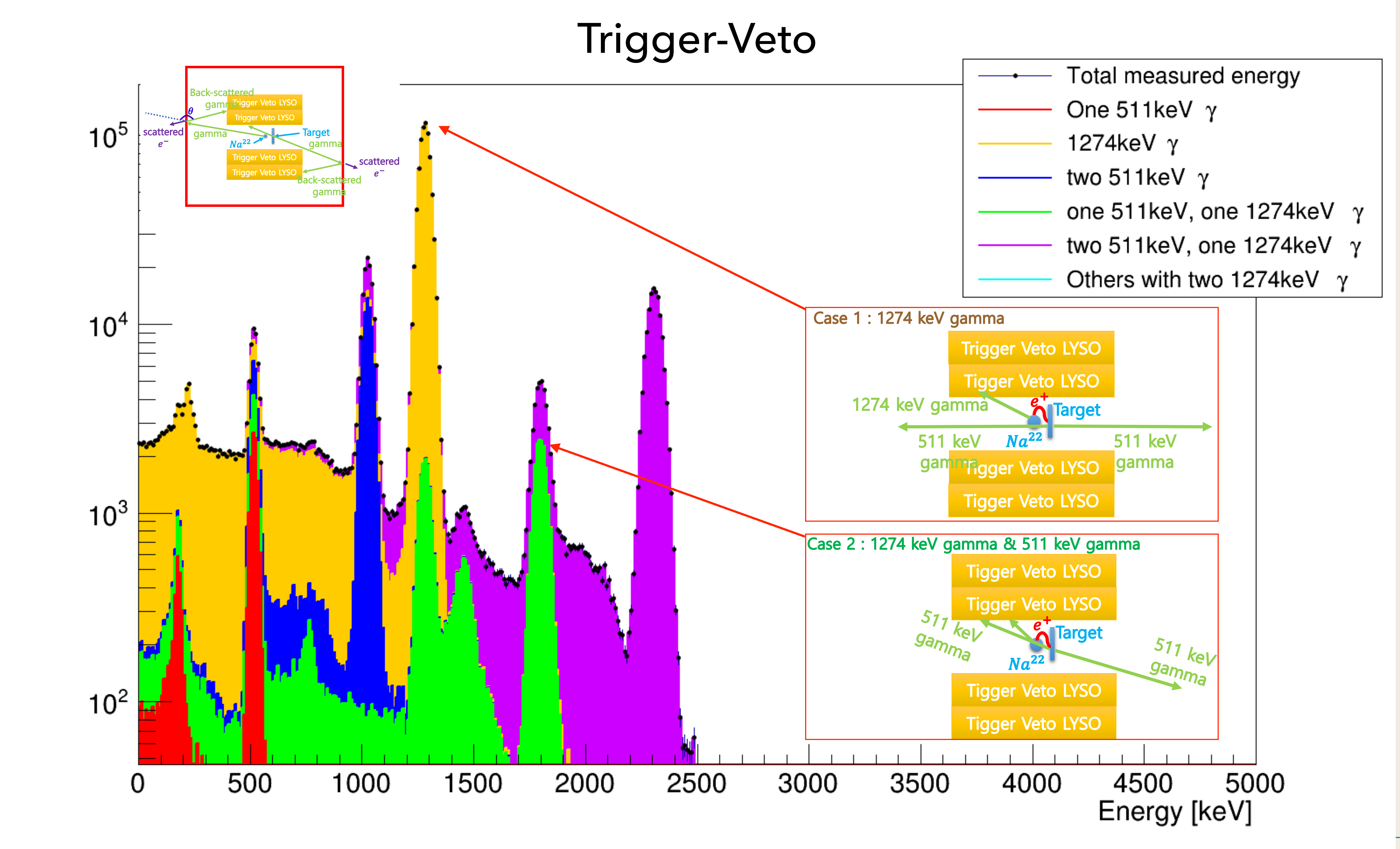
More studies to be done for target design

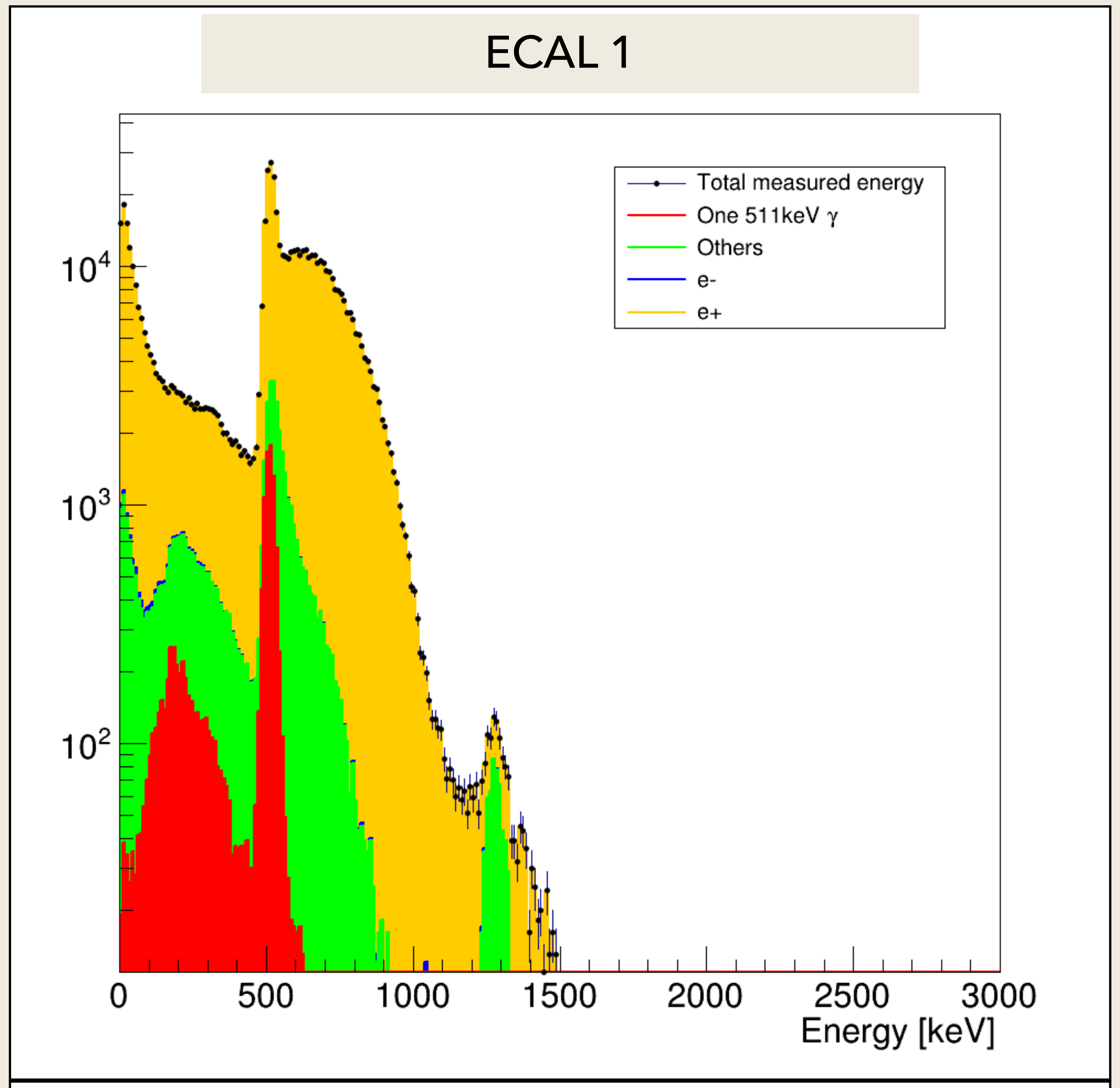
- **target thickness (Hyper EM)** (implement the effective radiation length and ionization energy loss for magnetic particles into GEANT 4)
- **reduction of inefficiency by loss cone** (steep gradient of magnetic field between solenoids using μ-metal or permanent magnet)

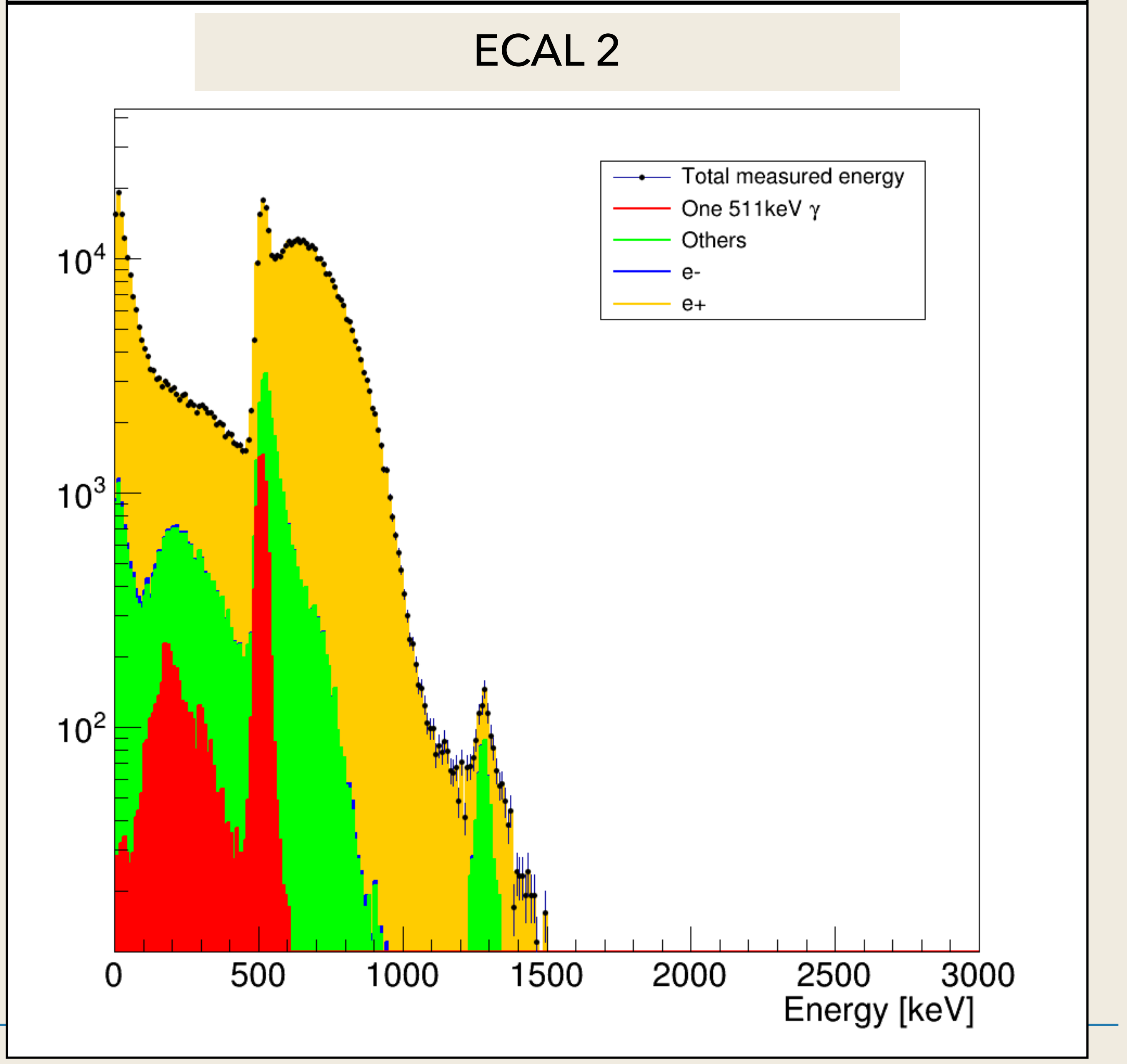
Backgrounds

- Source related:
  - Backward Compton scattering in the e^+ target-source [e^-: slow, too low energy]
  - One or both γs from e^+e^- annihilation hit vacuum chamber, Compton scattered electrons go in to crystal detectors [e^-: slow and late, poor energy balance]
  - Mismeasurements of energy or time from the crystal detector waveforms
  - Double simultaneous decays and e^+ annihilations
- Cosmic related:
  - Electromagnetic: a local EM shower in the roof initiated by a high energy cosmic electron
  - Electromagnetic: the EM shower at random (whatever) incoming zenith angle
  - Muonic: multi-muons resulted from a hadron-initiated event several nuclear absorption lengths above the detector
  - Muonic: ultra high-energy muons
  - Muonic: random muons hitting detectors
- Internal background of LYSO crystal
  - ^{176}Lu decay: β: 182 keV, 593 keV, γ: 88 keV, 202 keV, 307 keV

Source Related Backgrounds (^{22}Na)







Ongoing Simulations

- Background studies
  - Double ^{22}Na decay
  - Cosmic muons + ^{22}Na decay
  - ^{176}Lu+^{22}Na decays
- Target thickness optimization for Hyper-EM
  - A low-mass magnetic charge (m/me=0.01e, g/e≈1) may be highly radiative
  - This particle may not come out from a target
  - We need a very thin target (for example, less than 10 μm for Al target ($X_0 \approx 9$ μm)

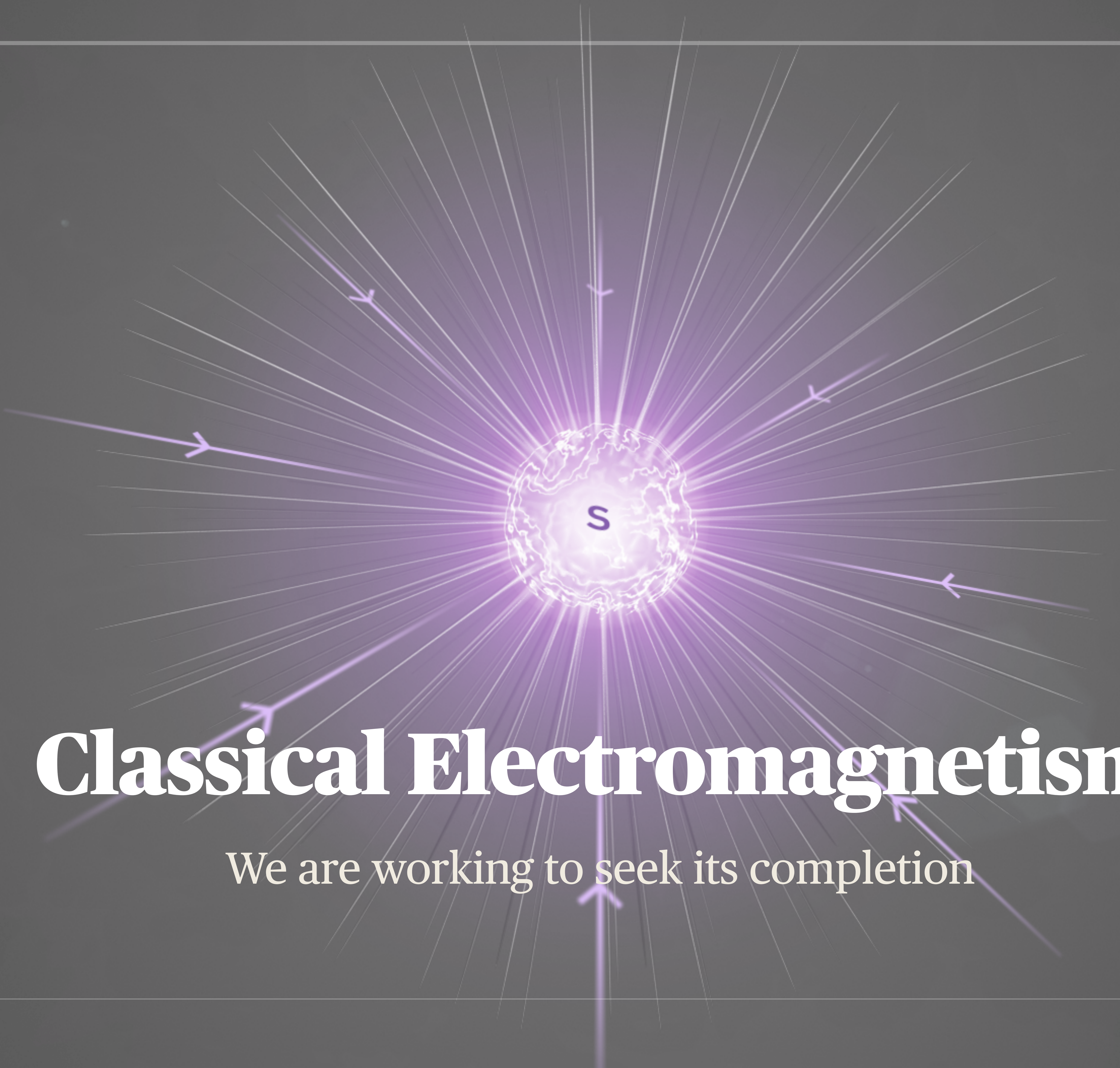
$$X_m = \left[\frac{4}{3\pi}\frac{\rho}{A}Z^2\frac{\alpha K}{mc^2}\left[\frac{(g/e)^2}{m/m_e}\right]^2 \ln\left(\frac{233\gamma(m/m_e)}{Z^{1/3}}\right)\right]^{-1}$$

The effective radiation length for a magnetic charge

$$\boxed{X_m = \frac{(m/m_e)^2}{(g/e)^4}X_0}$$

Summary

- Unexplored world for magnetic monopole search (**low mass and low charge**)
- Many interesting ideas to detect magnetic monopoles
- Ongoing studies
  - magnetic mirror and target design
    - steeper B-field gradient, target thickness optimization
  - customized electronics for DAQ in production
  - KRTech is building two solenoids (1 T·m)
  - background studies with GEANT 4
  - NV Center
- beam test with the trigger-veto when electronics is ready
- EL TPC design and will start production

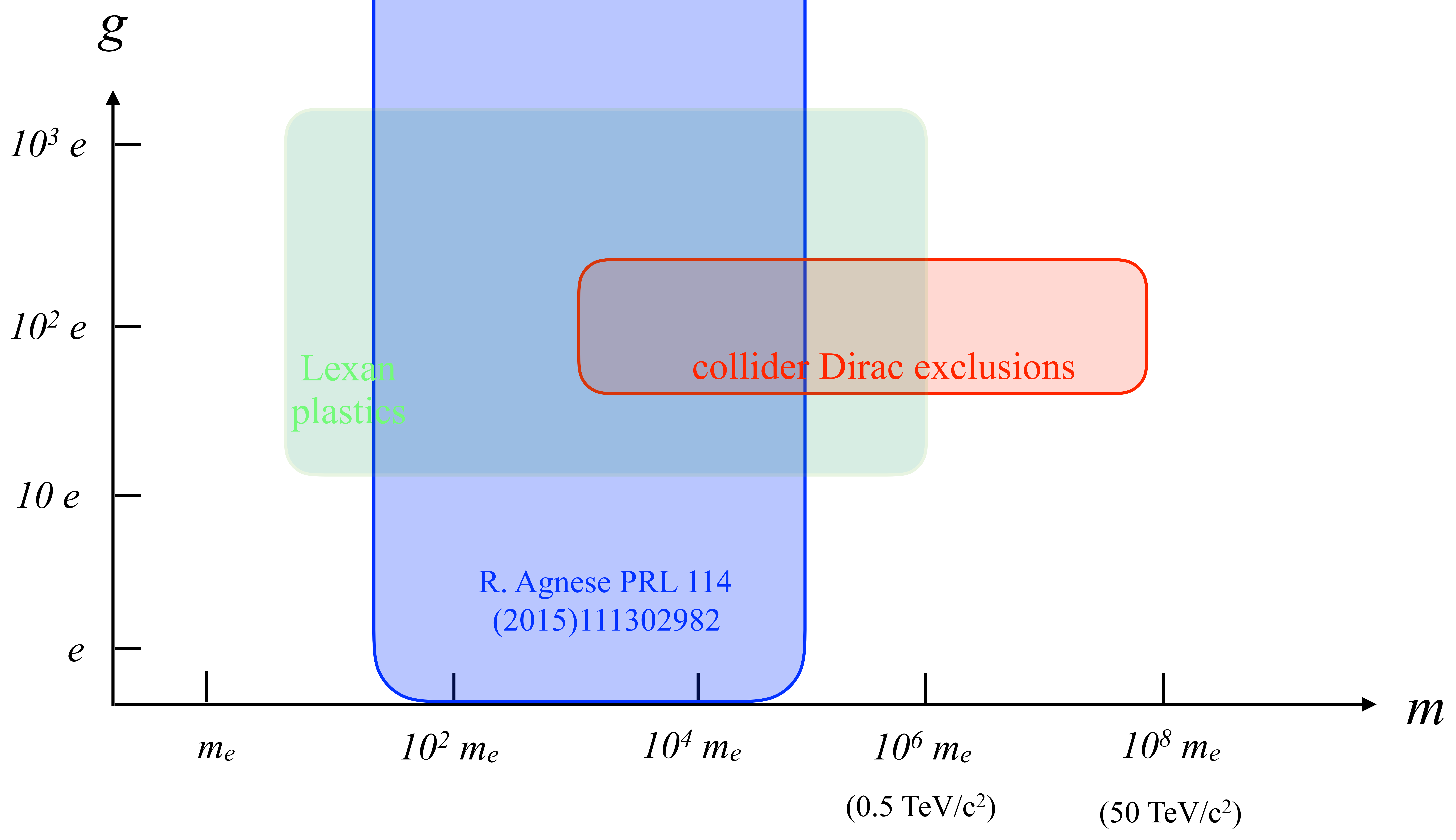


Classical Electromagnetism

We are working to seek its completion

Photograph courtesy CERN

Spares



g
$10^3\ e$
$10^2\ e$
$10\ e$
e
Lexan plastics
collider Dirac exclusions
R. Agnese PRL 114 (2015)111302982
m_e
$10^2\ m_e$
$10^4\ m_e$
$10^6\ m_e$
(0.5 TeV/c^2)
$10^8\ m_e$
(50 TeV/c^2)
m

Magnetic Mirror

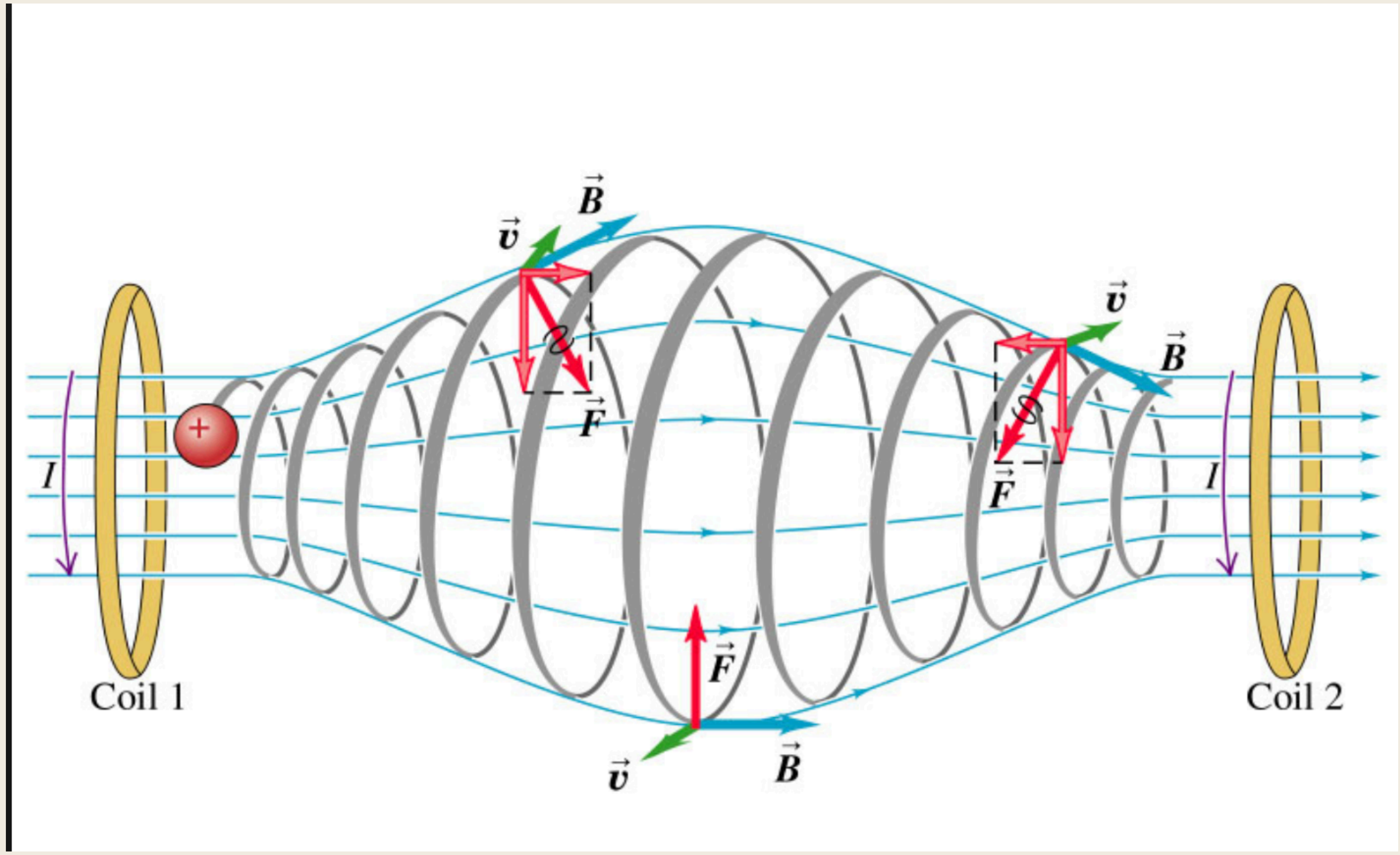
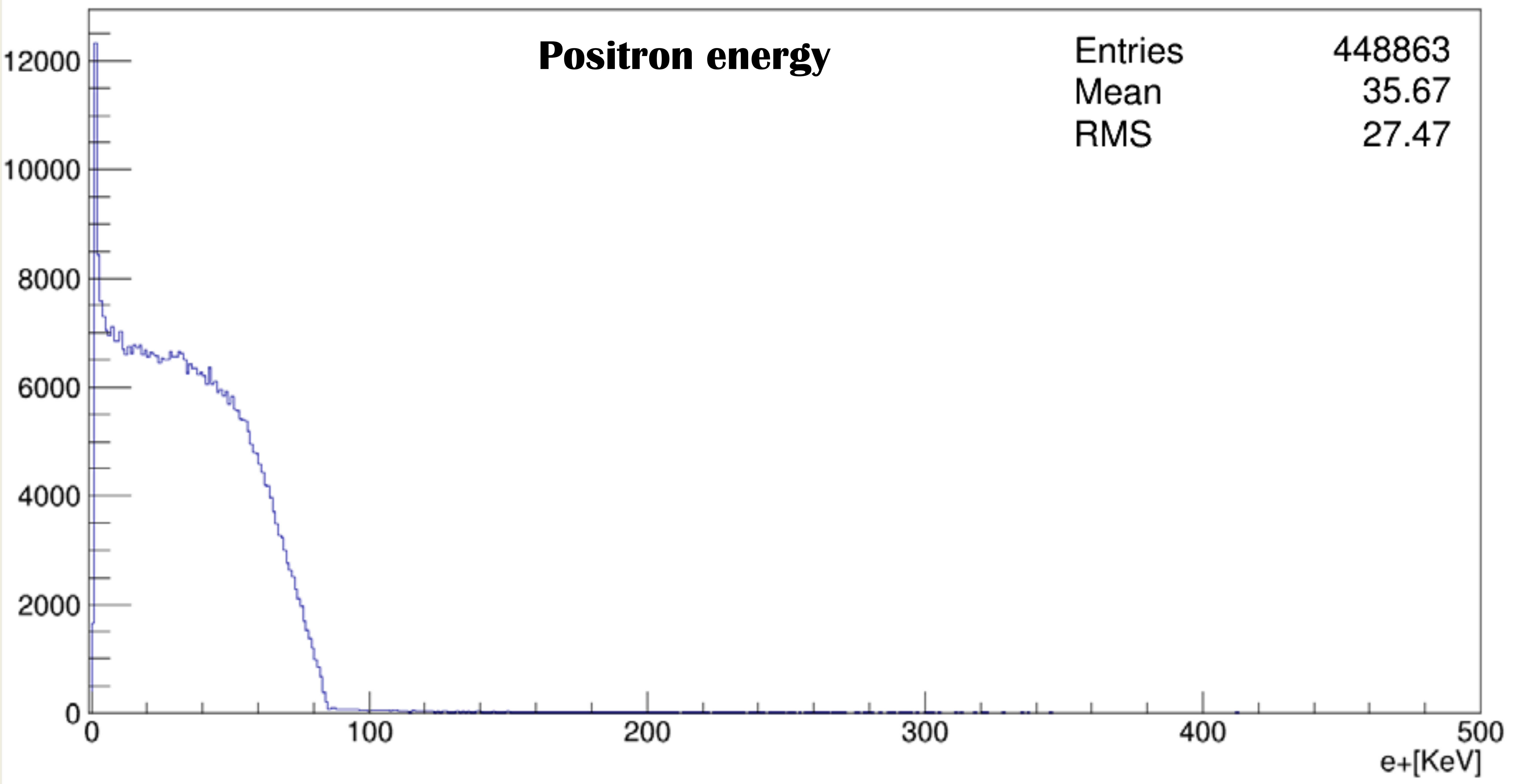


Figure 1: Magnetic bottle. When the particle making cyclotron orbits veers to the right, the Lorentz force has a component to the left due to the negative radial component of B. The e^+ will oscillate back and forth between the mirrors. Note that "adiabatic invariance" means that the number of flux lines ("Webers") threading the orbit remains constant. The e^+ energy is constant.



Positron energy
Entries 448863
Mean 35.67
RMS 27.47
12000
10000
8000
6000
4000
2000
0
0
100
200
300
400
500
e+[KeV]

Magnetic Monopole Production

Cross section

$$\sigma(e^+e^- \to m^+m^-) = \frac{4\pi}{3}\frac{\alpha\alpha_{m^+m^-}}{s}\sqrt{\frac{1-4m_m^2/s}{1-4m_e^2/s}}(1+2m_e^2/s)(1+2m_m^2/s)$$

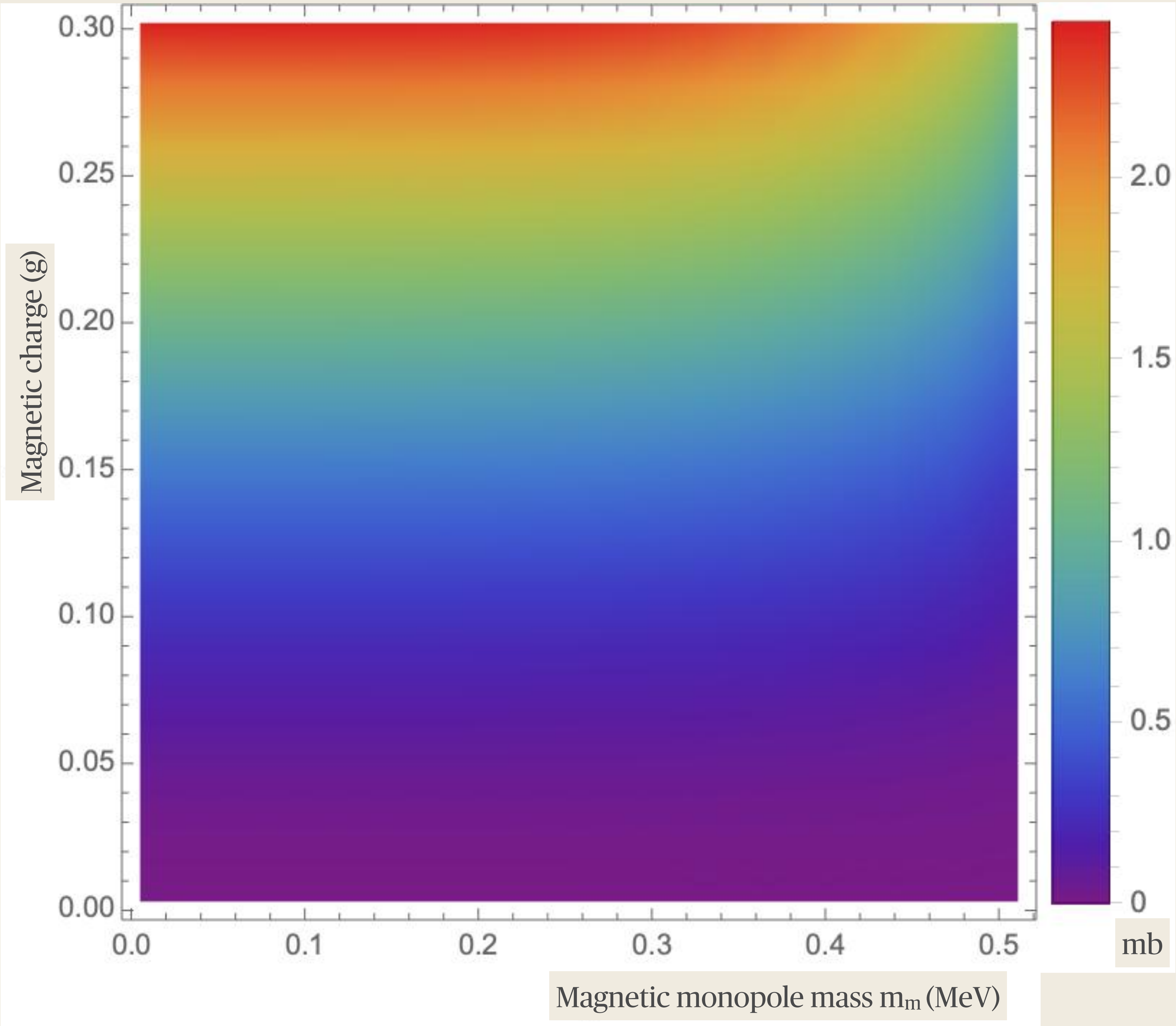
$$\alpha_{m^+m^-} = \frac{g^2}{4\pi\epsilon_0\hbar c}$$

Loss cone inefficiency of magnetic mirror: 50.36%

Geometric acceptance: 1.77%

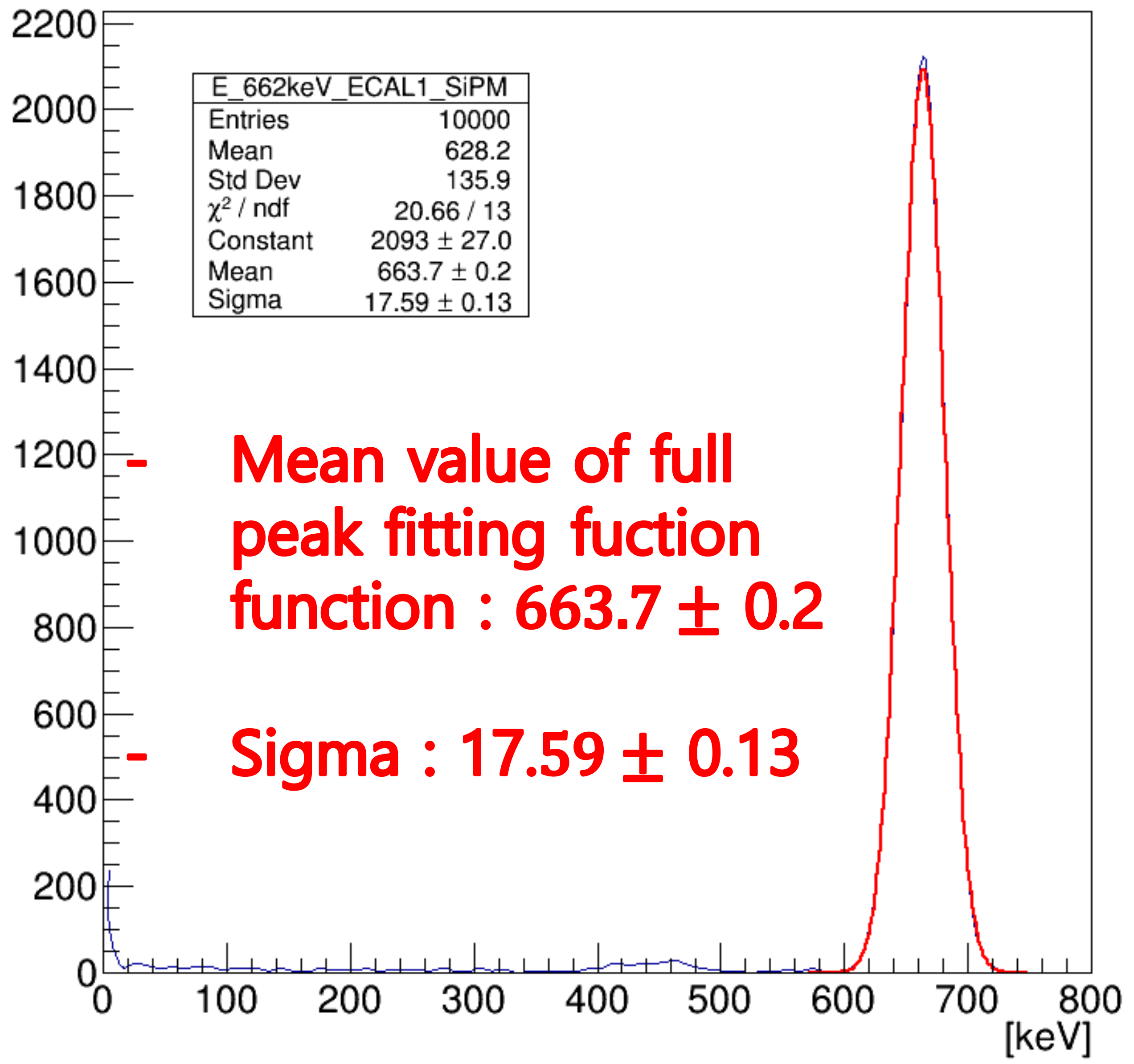
Energy measurement discrimination for g=0.01e: about 10 σ

- **LYSO: energy resolution 8% at 511 keV**
- **main background: $e^+e^- \to \gamma\gamma$**

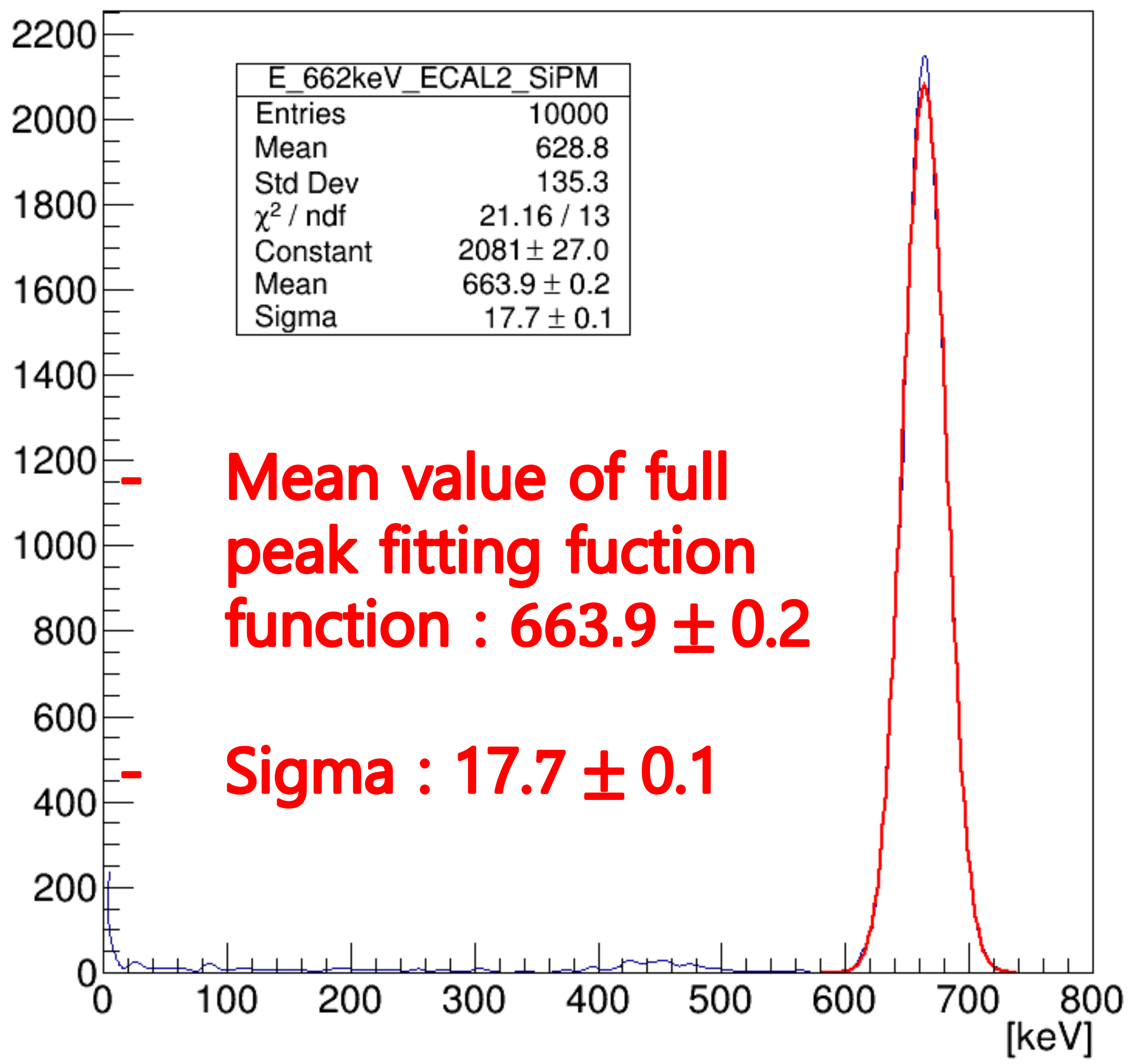


LYSO Calibration

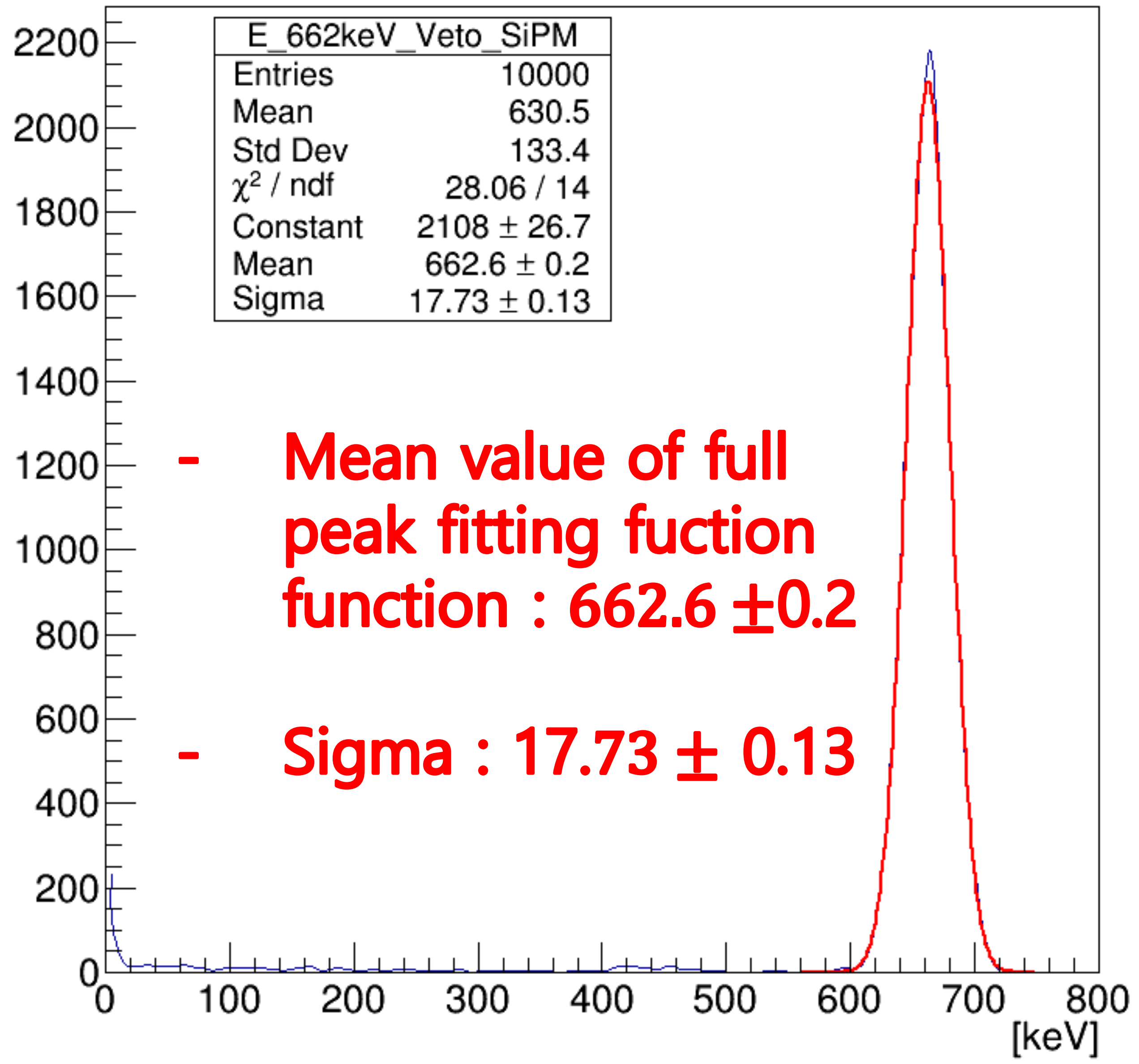
- ECAL1 LYSO 662 keV gamma measured energy distribution



- ECAL2 LYSO 662 keV gamma measured energy distribution



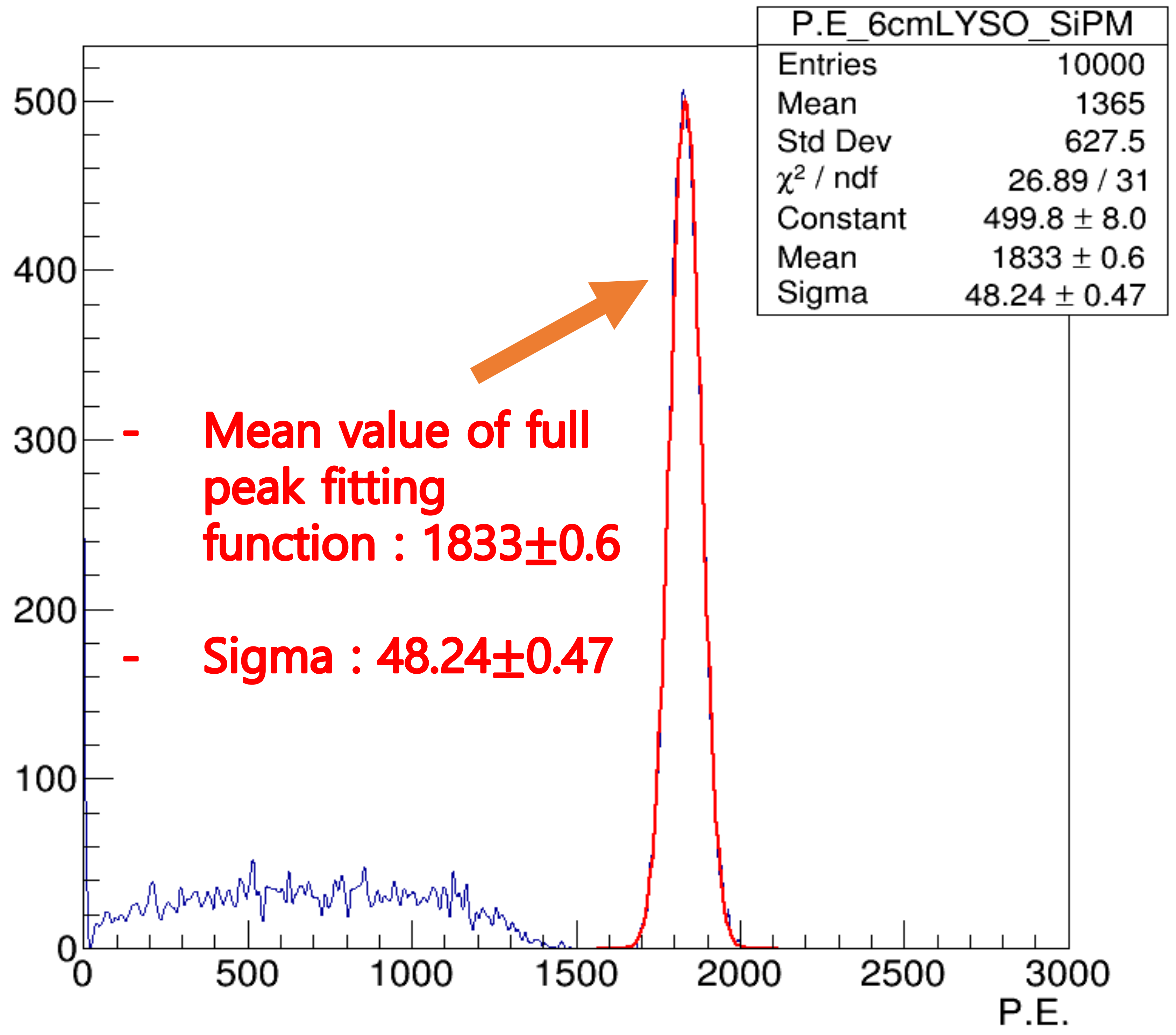
- Trigger Veto LYSO 662 keV gamma measured energy distribution



Mean value of fit function in full peak ≈ 662 keV

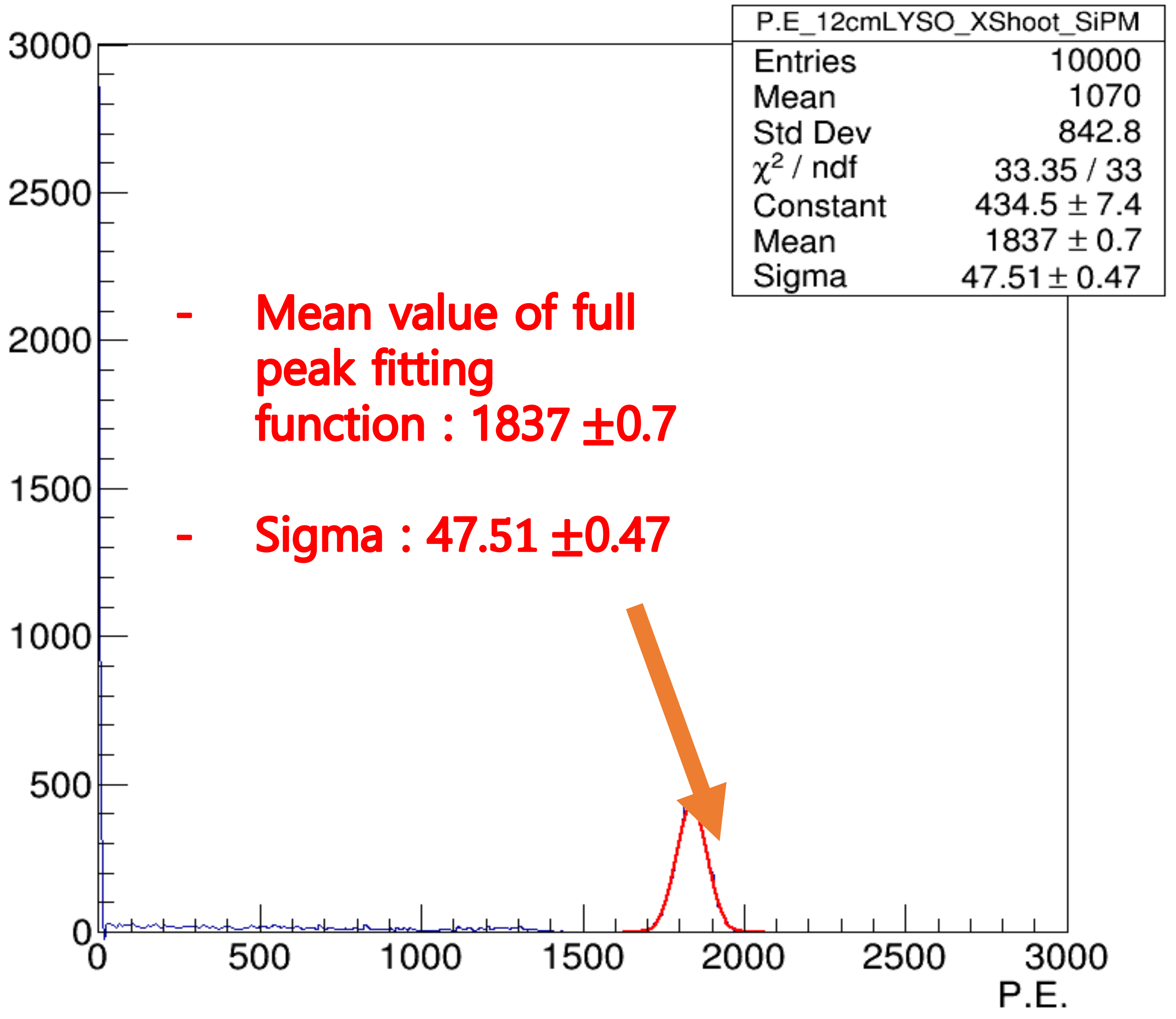
LYSO Calibration

- Single ECAL LYSO 662 keV gamma photoelectron number distribution



Calibration constant of ECAL LYSO = 662keV / mean of full peak's photoelectron = 0.361

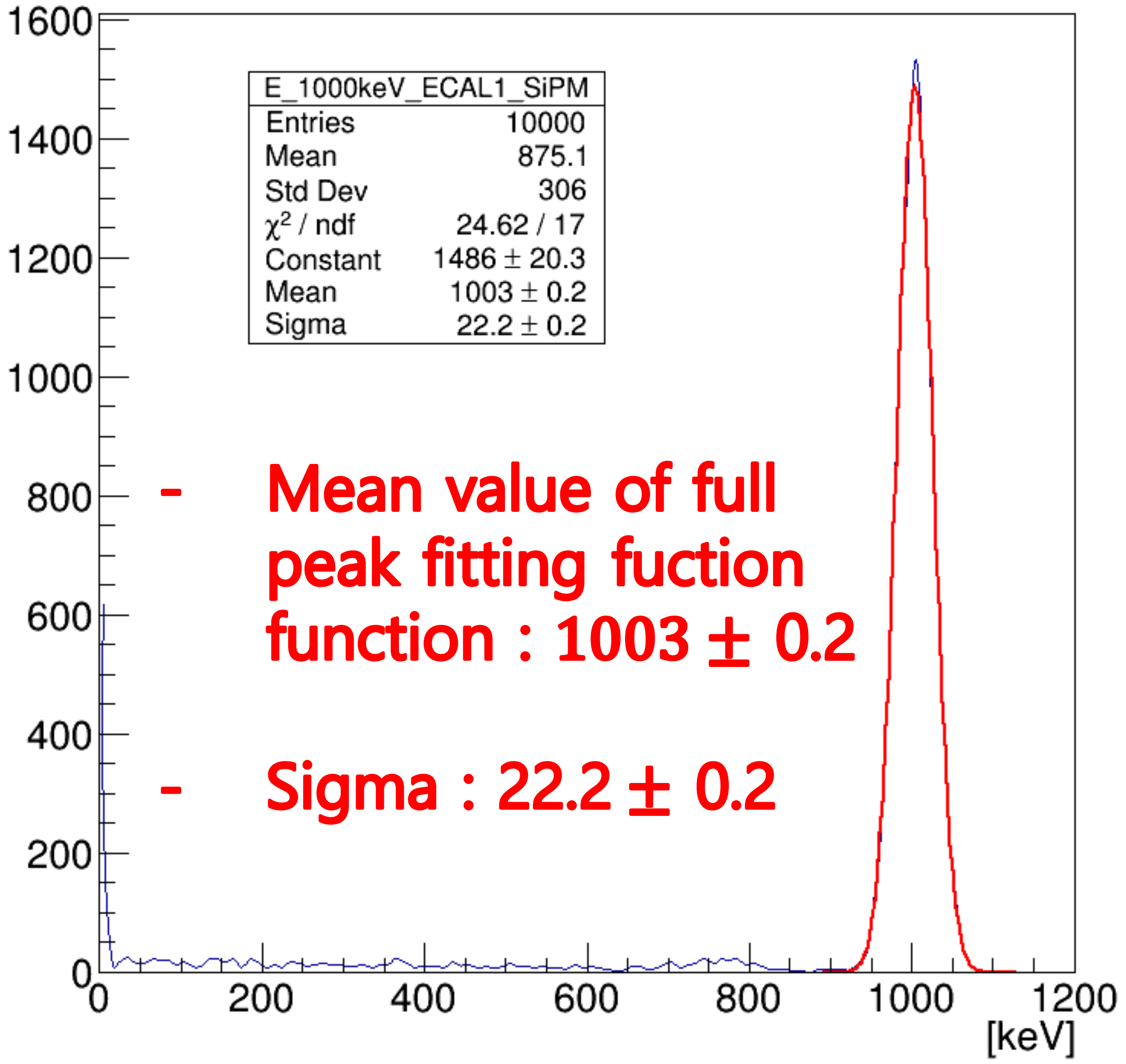
- Single Trigger Veto LYSO 662 keV gamma photoelectron number distribution



Calibration constant of Trigger Veto LYSO = 0.360

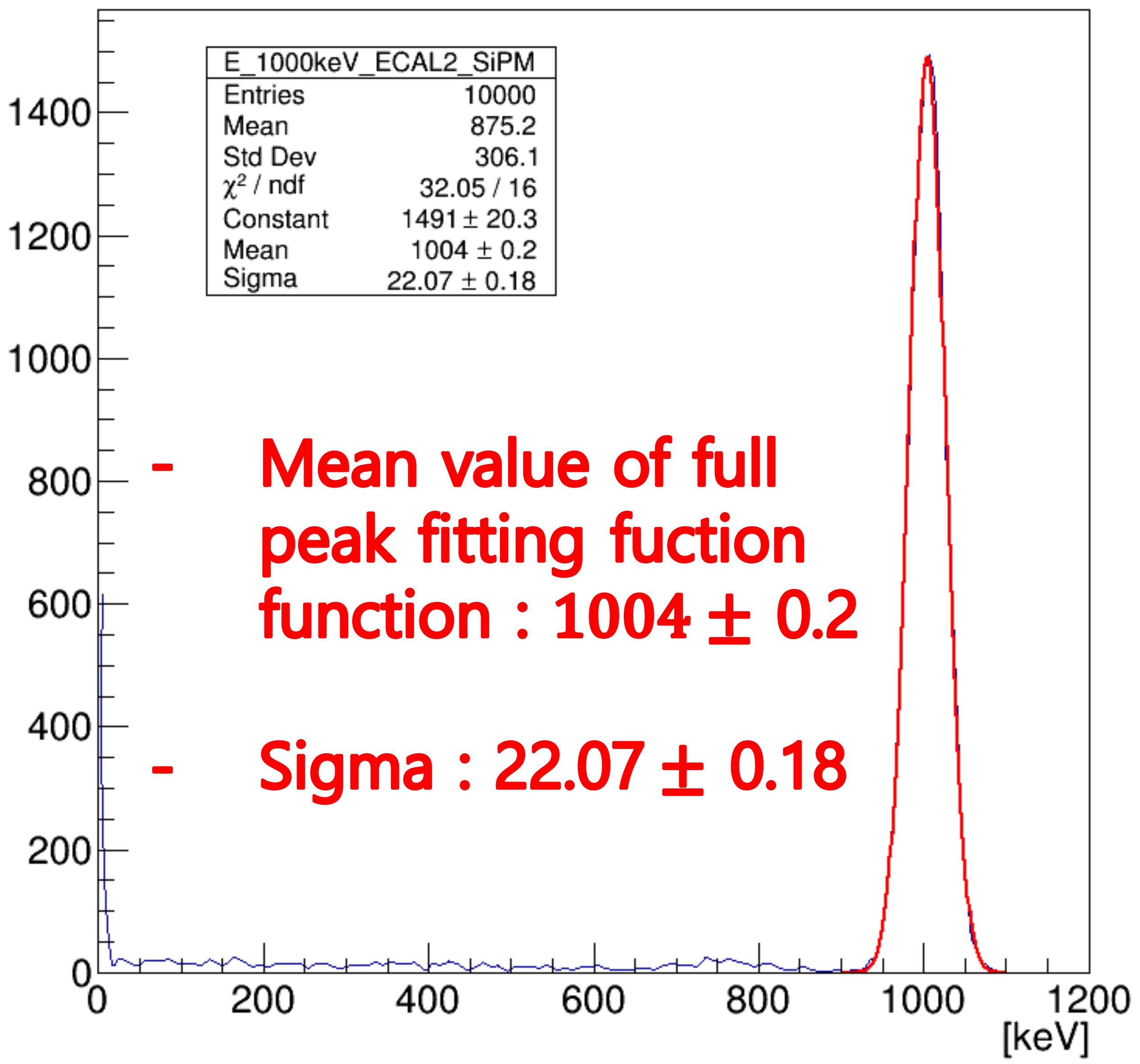
LYSO Calibration

- ECAL1 LYSO 1 MeV gamma measured energy distribution



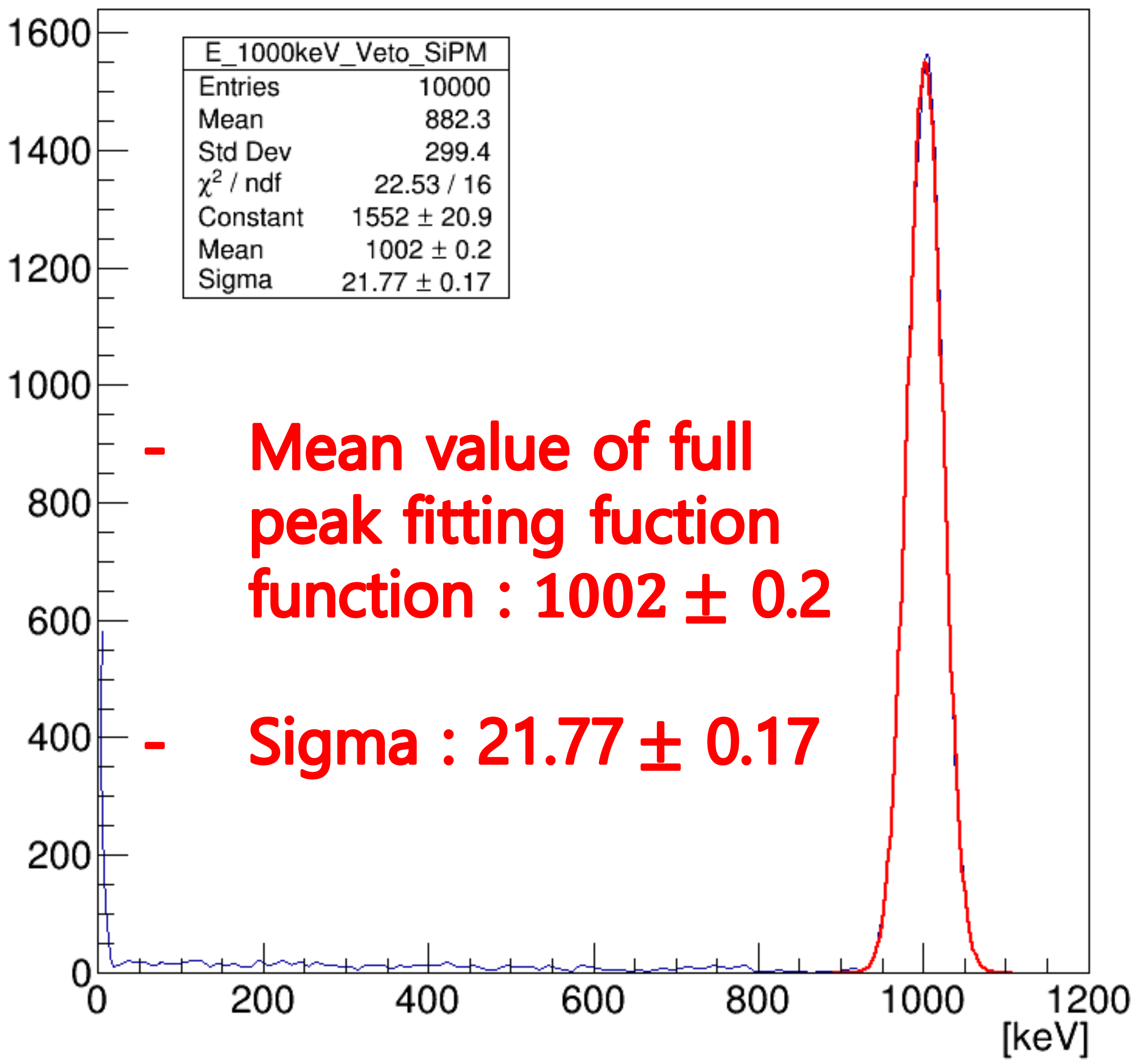
- Mean value of full peak fitting fuction function : 1003 ± 0.2
- Sigma : 22.2 ± 0.2

- ECAL2 LYSO 1 MeV gamma measured energy distribution



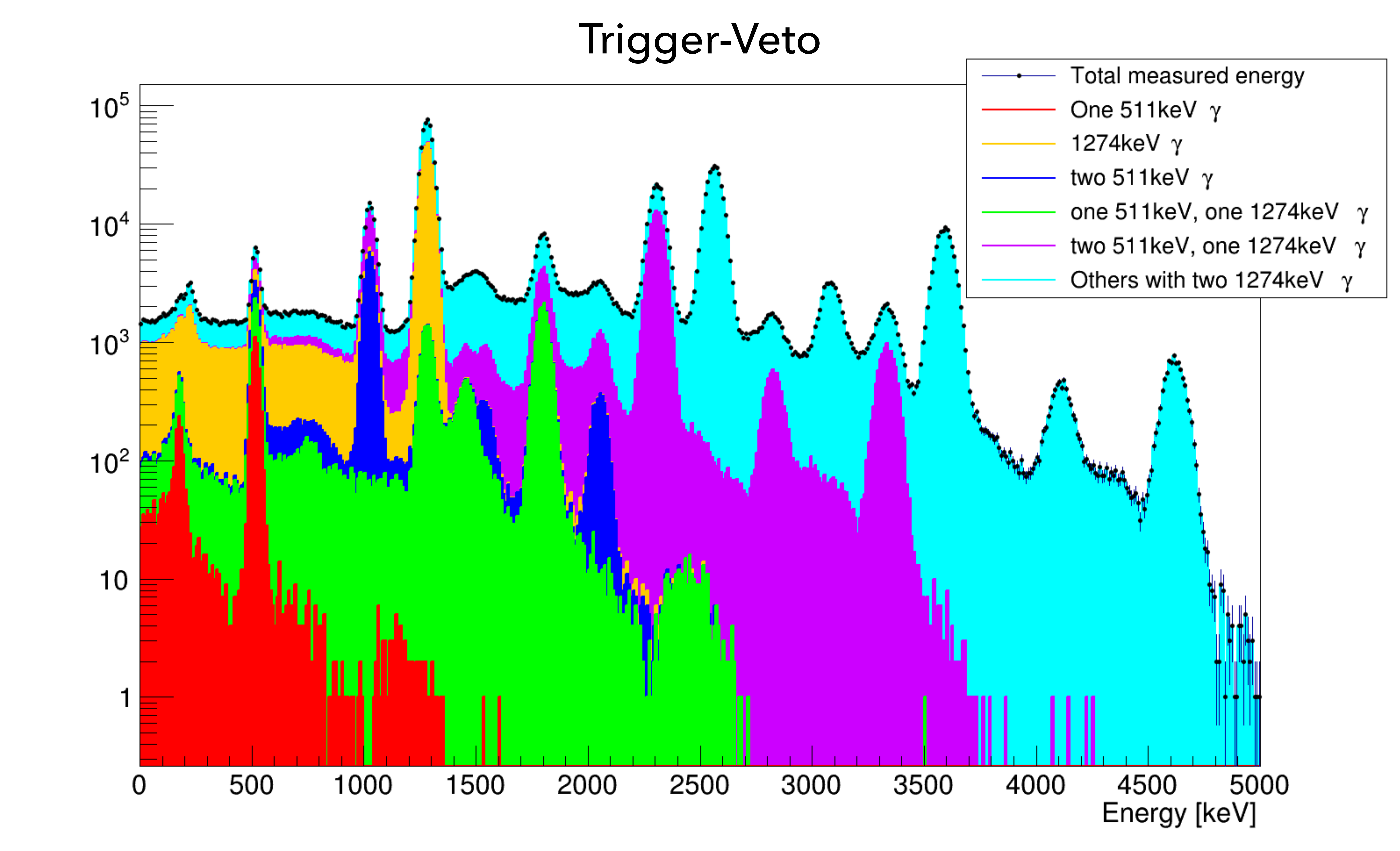
- Mean value of full peak fitting fuction function : 1004 ± 0.2
- Sigma : 22.07 ± 0.18

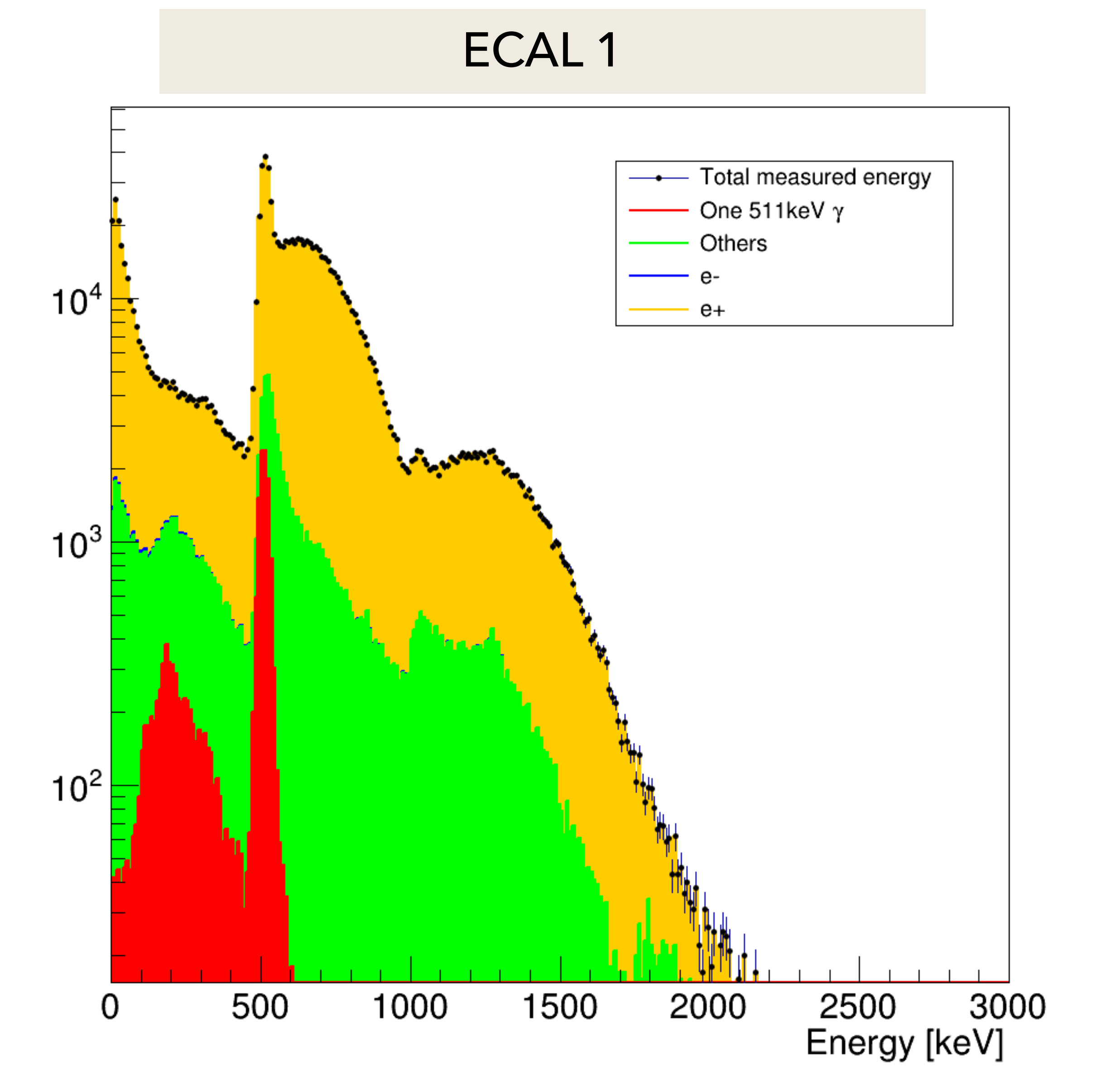
- Trigger Veto LYSO 1 MeV gamma measured energy distribution

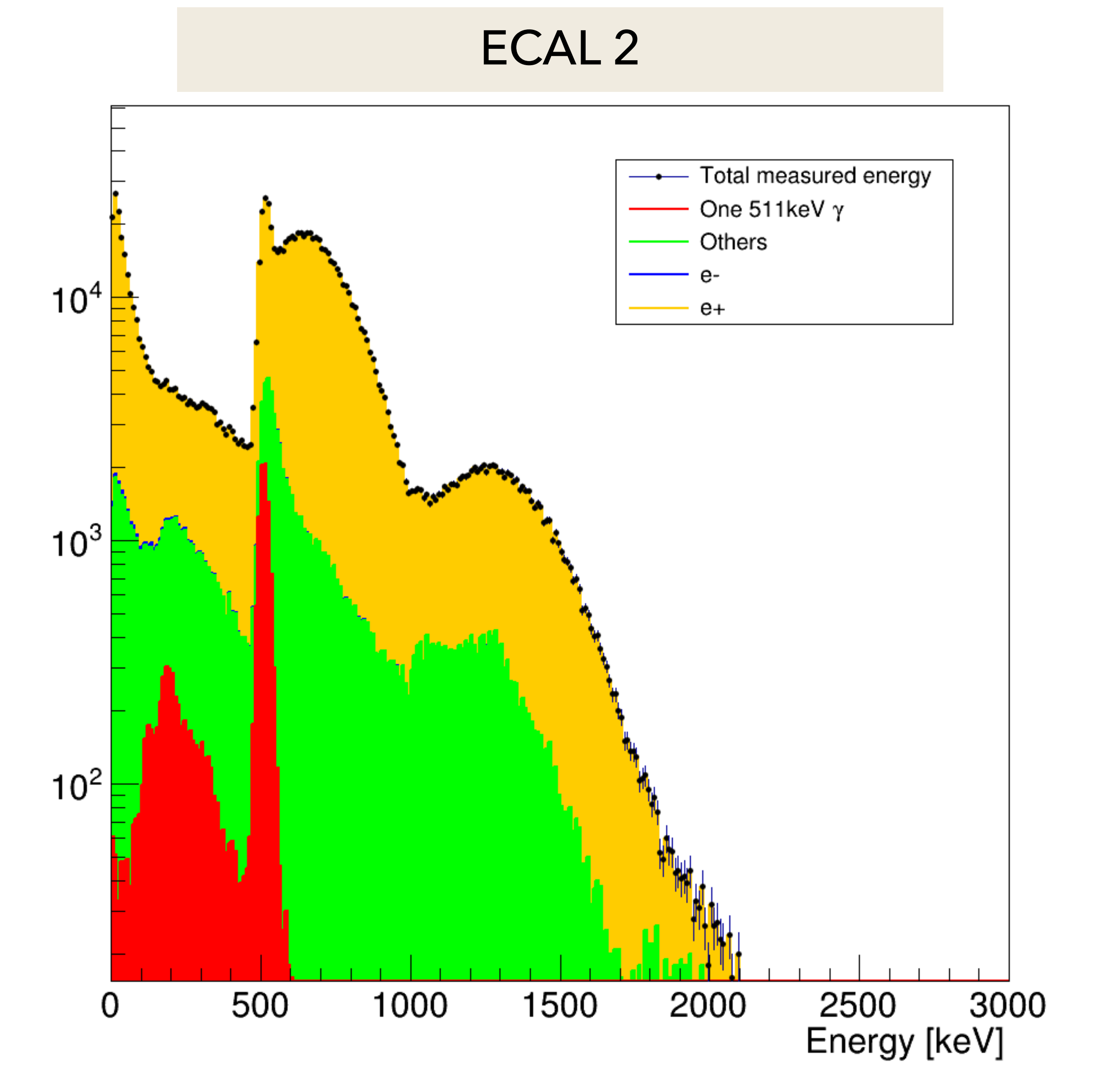


- Mean value of full peak fitting fuction function : 1002 ± 0.2
- Sigma : 21.77 ± 0.17

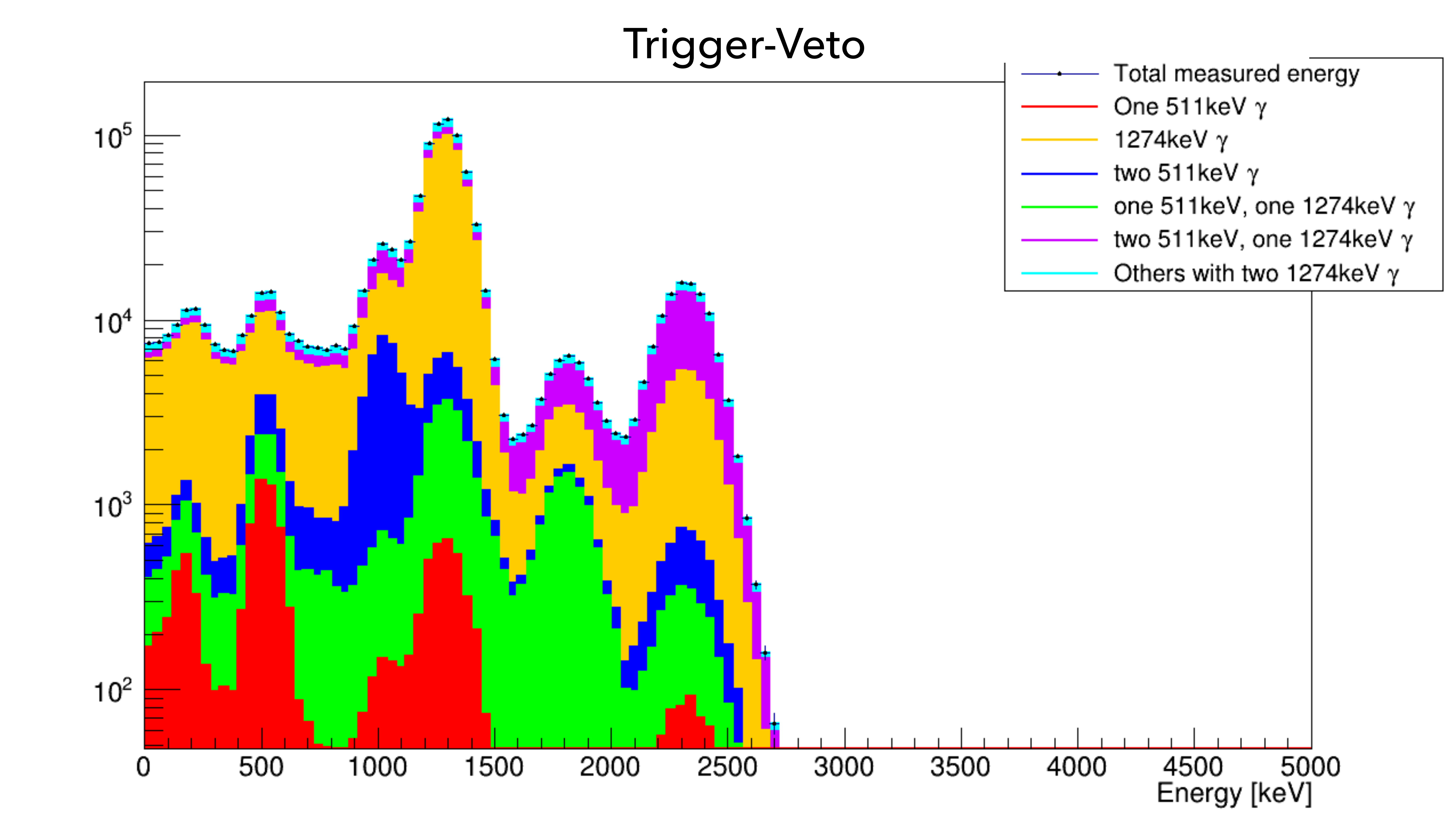
Backgrounds (double ^{22}Na decay)

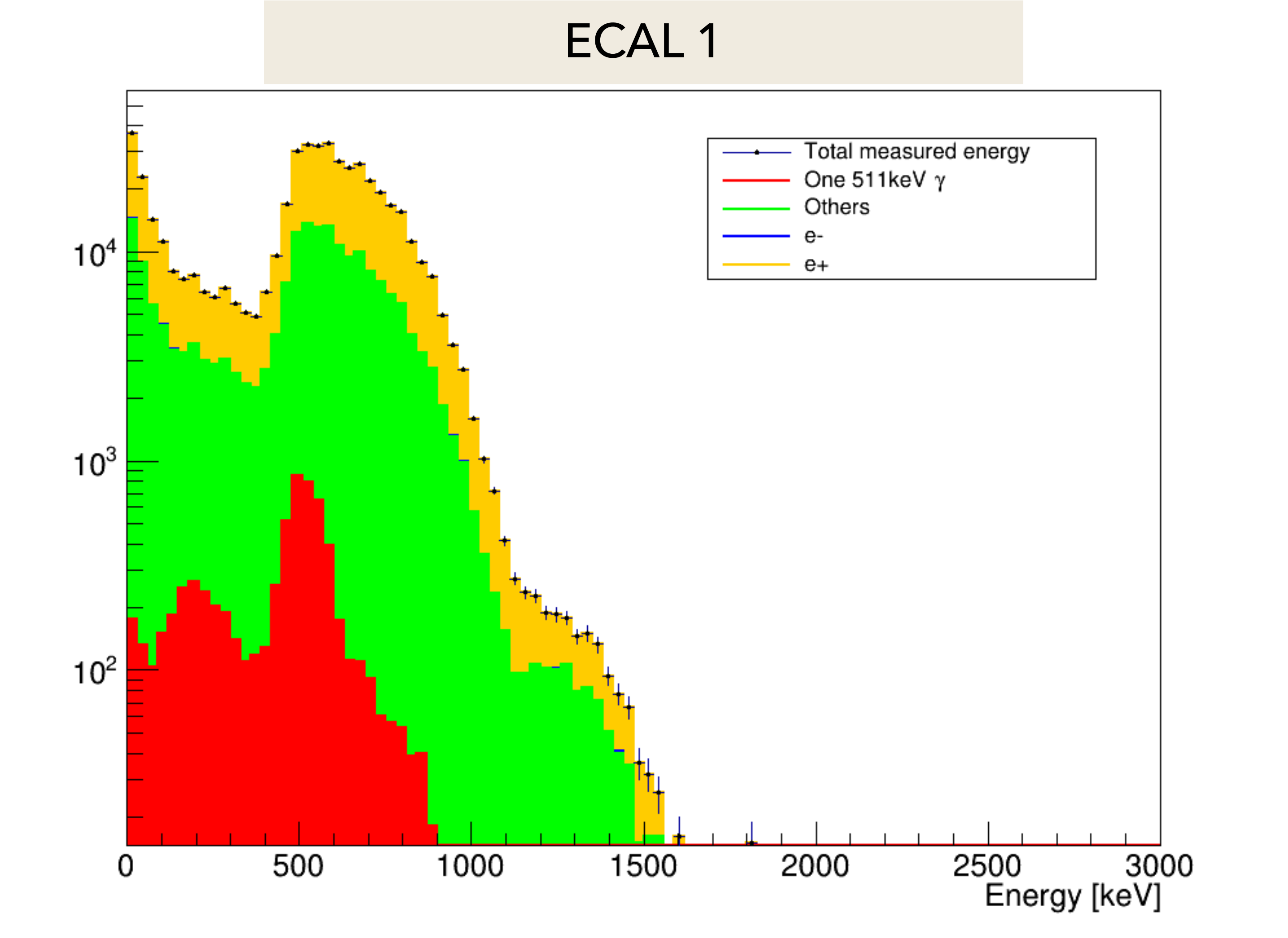


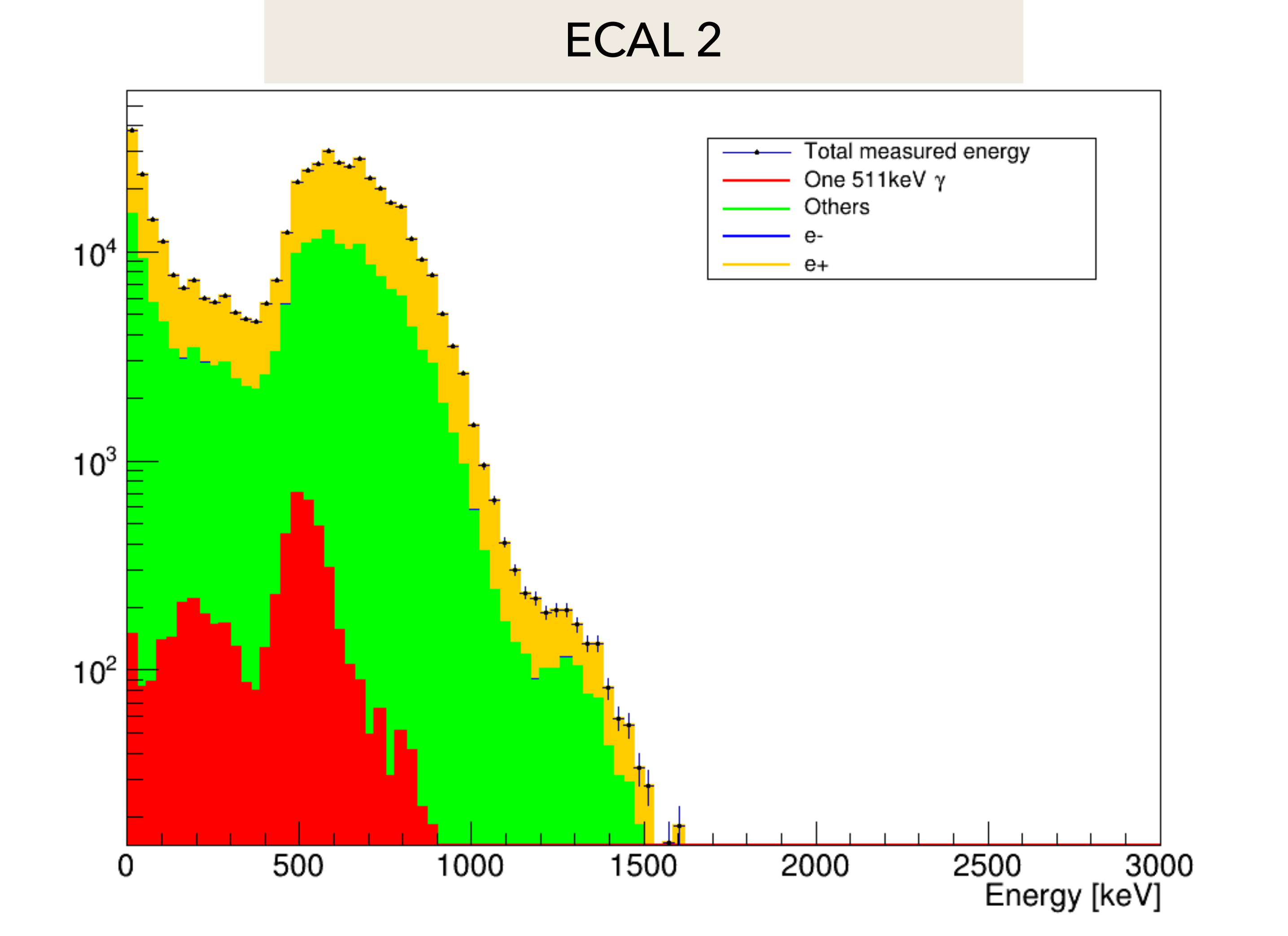




Backgrounds (Cosmic muons + ^{22}Na decay)







Backgrounds ($^{176}Lu+^{22}Na$)