Search for new physics of Charged Lepton Flavor Violation on the COMET Experiment

SYSU-PKU Collider Physics forum For Young Scientists

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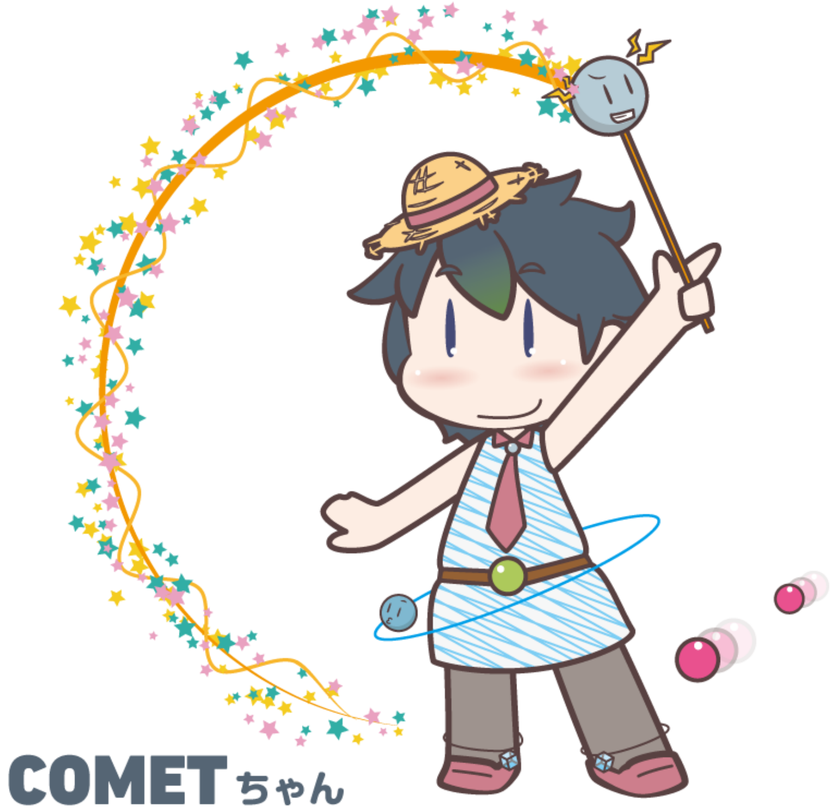
Outline

1. The COMET Experiment
2. Physics Motivation
3. Design of the COMET
4. Development of software
5. Search for Majoron
6. Summary

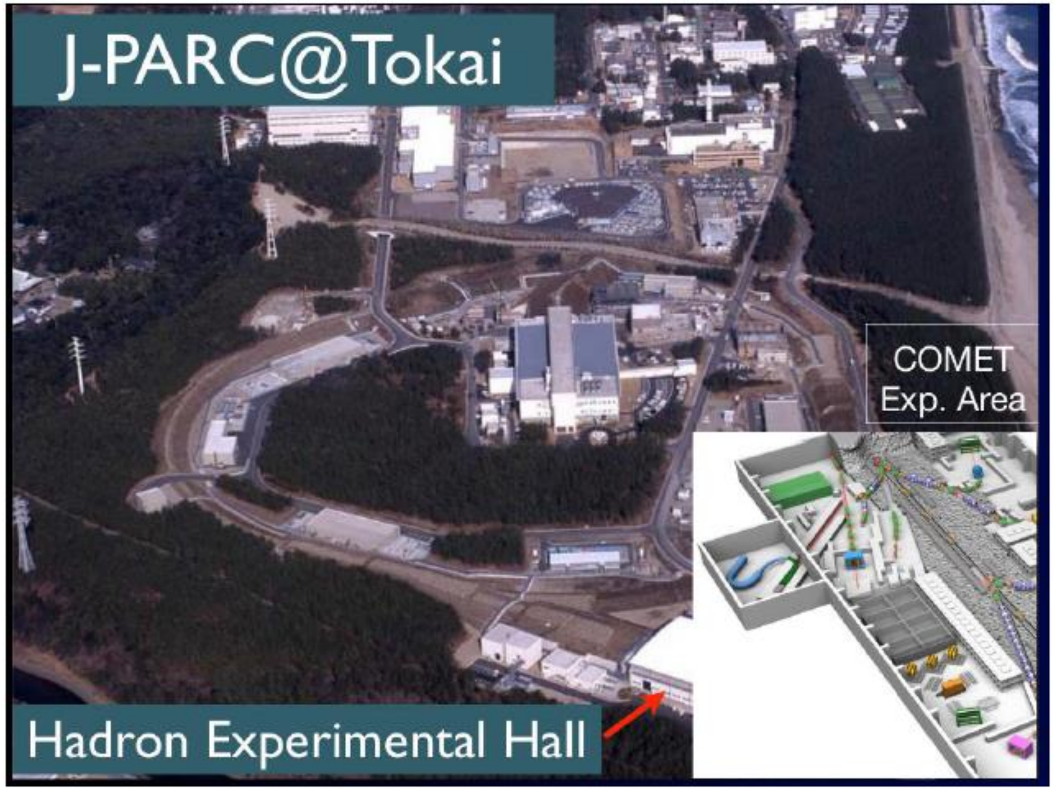
The COMET Experiment



by higgstan.com

COherent Muon Electron Transition

- Search for μ-e conversion in Japan J-PARC hadron hall
  - Using $8\ GeV, 56\ kW$ proton beam to generate muon beam
- Experiment Target:
  - $B(\mu^- + Al \rightarrow e^- + Al) = 2.6 \times 10^{-17}$ (S.E.S)
  - This is 10000 times improvement!
- Current world limit:
  - $B(\mu^- + Au \rightarrow e^- + Au) < 7 \times 10^{-13}$
  - By SINDRUM II experiment (2006)
- Likely to get 100000 times improvement!
  - Still being optimized



The COMET collaboration

Oct 2018, COMET collaboration at Tbilisi

~200 members,
44 institutes from 17 countries

Still growing!

Physics Motivation

Charged Lepton Flavor Violation

The establishment of the Standard Model and the observation of Neutrino Oscillation worked-out very much in the particle physics. However there are still mysteries.

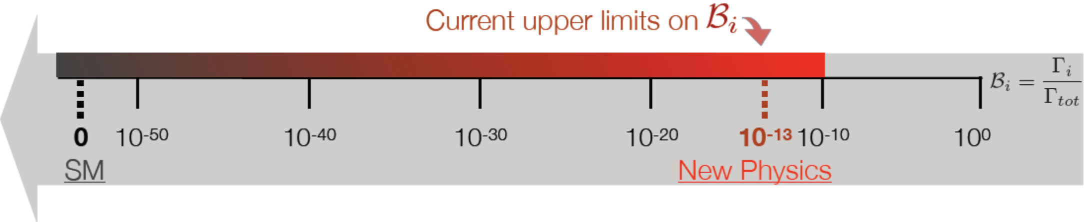
Process of CLFV

- Highly prohibited ($O(<10^{-54})$) in the SM

$$\frac{\Gamma(\mu \to e\gamma)}{\Gamma(\mu \to e\nu\nu)} \propto \left| \sum_i \frac{m_i^2}{m_W^2} U_{\mu i}^* U_{ei} \right|^2 \sim O(10^{-54})$$

small mass ratio of neutrino to weak boson

- No/less background from SM
- Very rare decays and not found yet!
- Clean field to search for new physics!



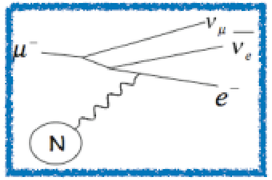
Charged Lepton Flavor Violation

Mode	Upper limit	Experiment (Year)
$\mu^+ \to e^+\gamma$	4.2×10^{-13}	MEG (2016)
$\mu^+ \to e^+e^+e^-$	1.0×10^{-12}	SINDRUM (1988)
$\mu^-\mathrm{Au} \to e^-\mathrm{Au}$	7×10^{-13}	SINDRUM II (2006)
$\mu^+ \to e^+X, X \to \mathrm{inv.}$	$O(10^{-5})$	TWIST (2015)
$\mu^+ \to e^+\gamma X, X \to \mathrm{inv.}$	$O(10^{-9})$	Crystal Box (1988)
$\mu^+ \to e^+X, X \to e^+e^-$	$O(10^{-12})$	SINDRUM (1986)
$\mu^+ \to e^+X, X \to \gamma\gamma$	$O(10^{-10})$	MEG (2012)

μ - e conversion

- Atomic capture of μ^-
  - Generate "muonic atom" by muon stopping at the target
- Measure emitted electron momentum from muonic atom
  - Decay in obit (DIO) is Michael edge up to 105 MeV
  - μ-e conversion signal is **mono-energetic ~105 MeV peak**
- Spectroscopic search for μ-e conversion

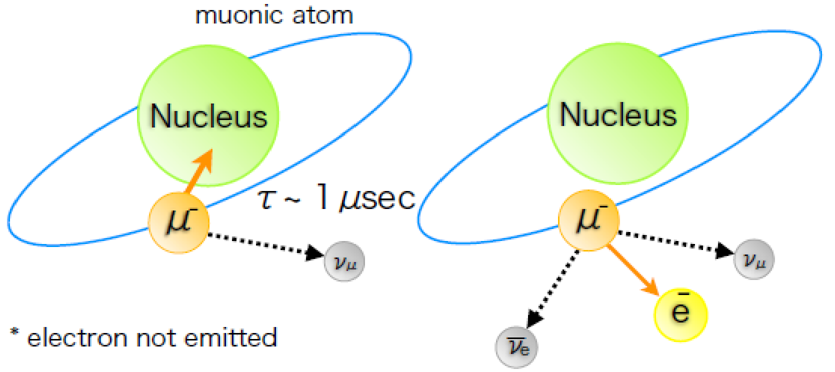
DIO Background



- $E_{\mu e}(\mathrm{Al}) \sim m_\mu - B_\mu = 105\mathrm{MeV}$
  - B_μ: binding energy of the 1s muonic atom

Backgrounds in the SM

Muon Capture | Decay In Orbit (DIO)

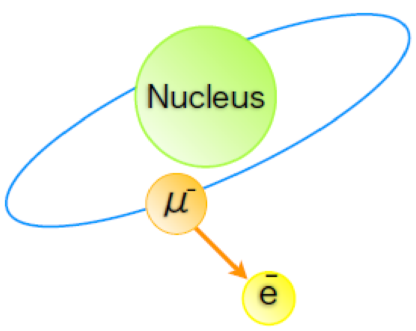


* electron not emitted

$\mu + \mathrm{N} \to \nu_\mu + \mathrm{N}$ | $\mu \to e\ \bar{\nu}_e \nu_\mu$

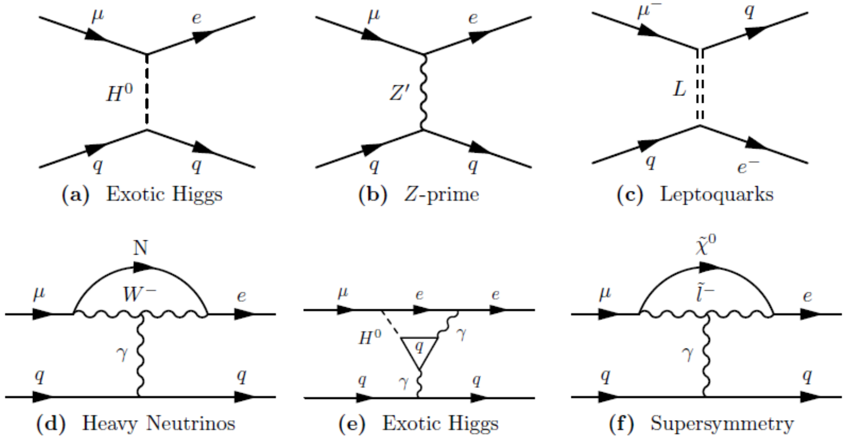
Signal beyond the SM

μ - e conversion

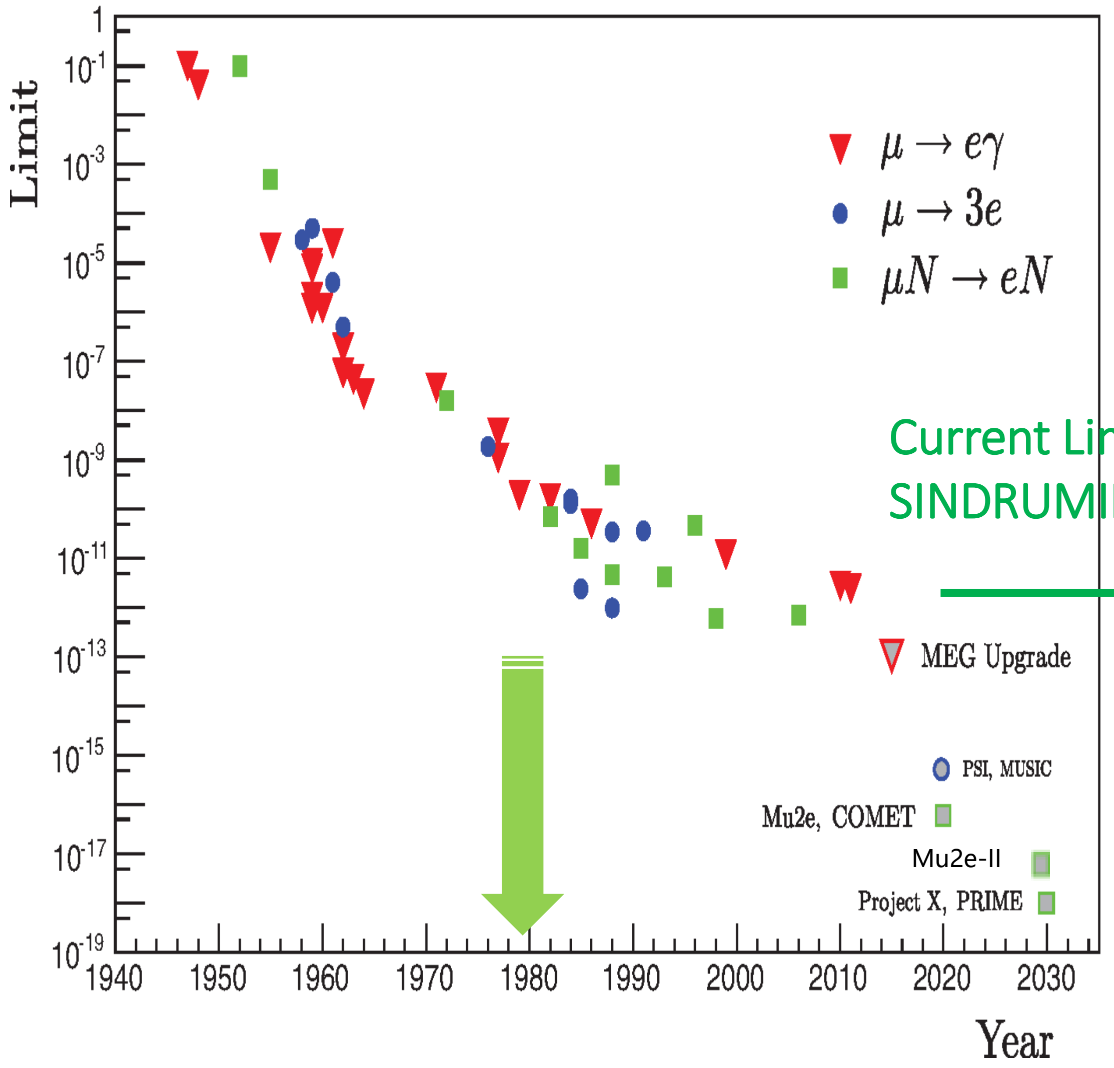


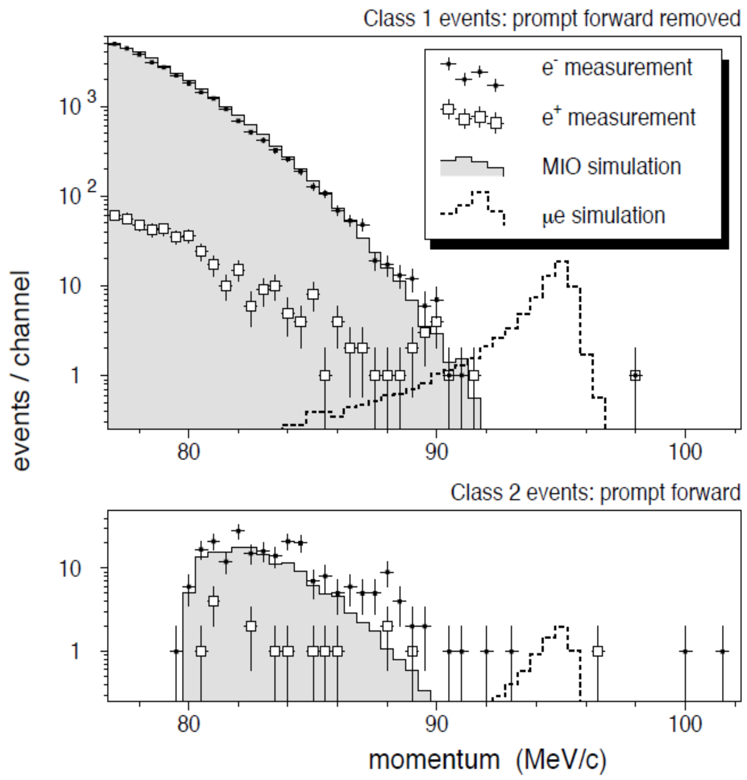
$\mu \mathrm{N} \to e\ \mathrm{N}$

predicted branching ratio
$= 10^{-14} \sim 10^{-18}$



Search for Muon to Electron Conversion





Eur.Phys.J. C47 (2006) 337-346

With a different design, > 4 orders of magnitude improvement is possible!

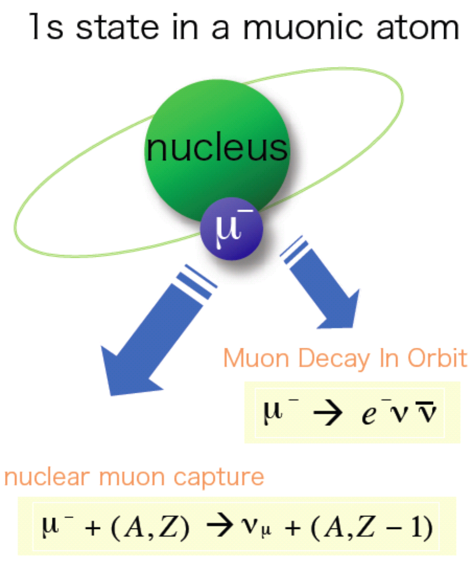
Design of the COMET

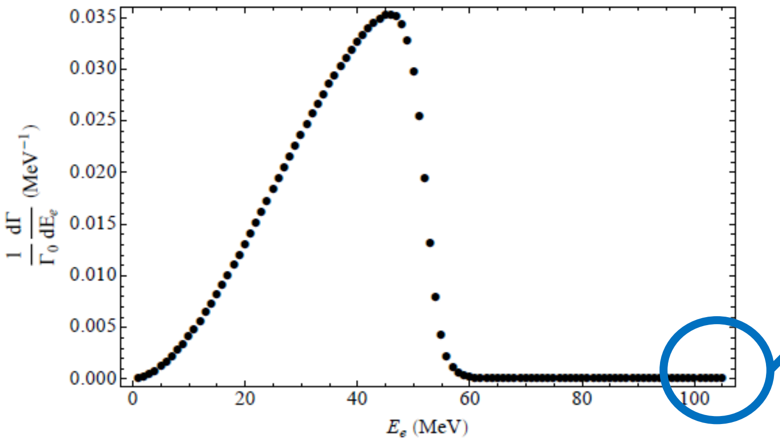
Background rejection (1)

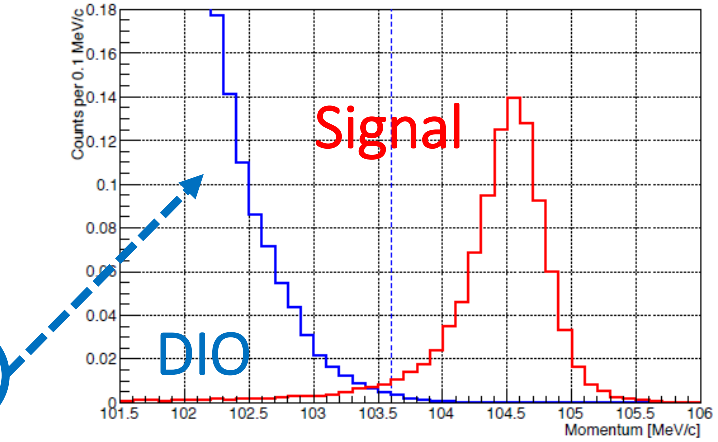
- Intrinsic physics background

➢Mostly from muon decay in orbit (DIO)

- Calculated by Czarnecki with radiative correction. Branching ratio drops very quickly near end point
- Momentum resolution required to be better than 200 keV/c







Background rejection (2)

- **Beam related background**

➢Energetic particles in beam with E>100MeV

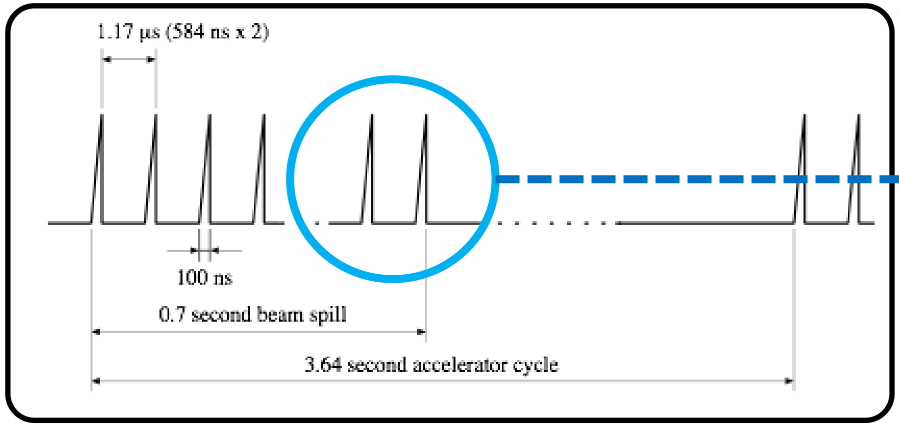
- Radiative pion capture, π^- (A,Z) → (A,Z-1) γ, γ → $e^+ e^-$
- Muon decay in flight, p_μ > 75 MeV/c
- Anti-proton induced, etc.

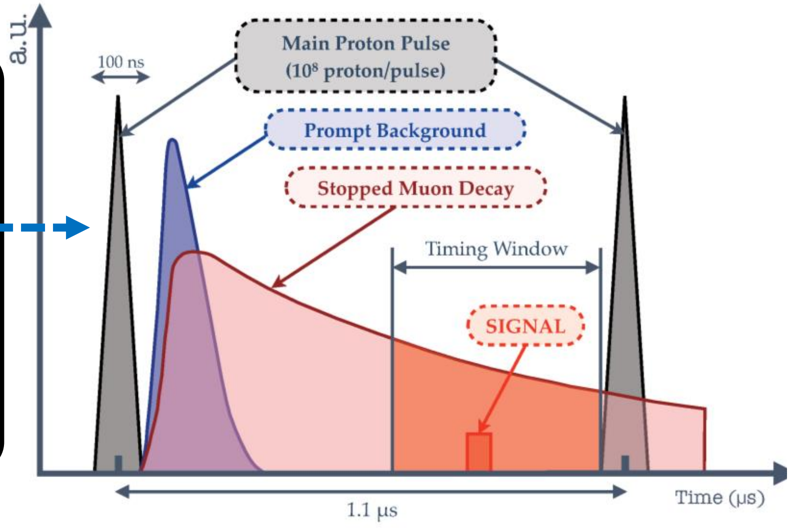
- Long muon beam line
- Can be suppressed by pulse beam and a delayed measurement window (~700 ns)
- Some due to leaked proton. Proton extinction factor required to be < 10^{-10}

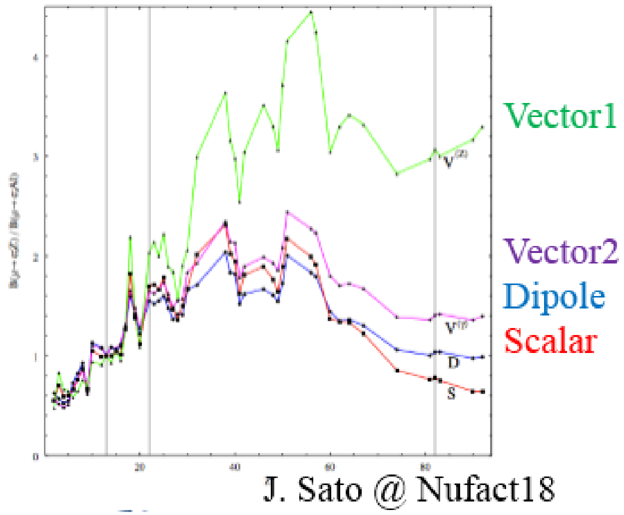
Material of muon stopping target

- Heavier nucleus has large overlap with muon wave function
- Lighter nucleus has longer life time of muon in muonic atoms
- Aluminum stopping target will be used in COMET

  τ_μ in Al ~ 0.9µsec

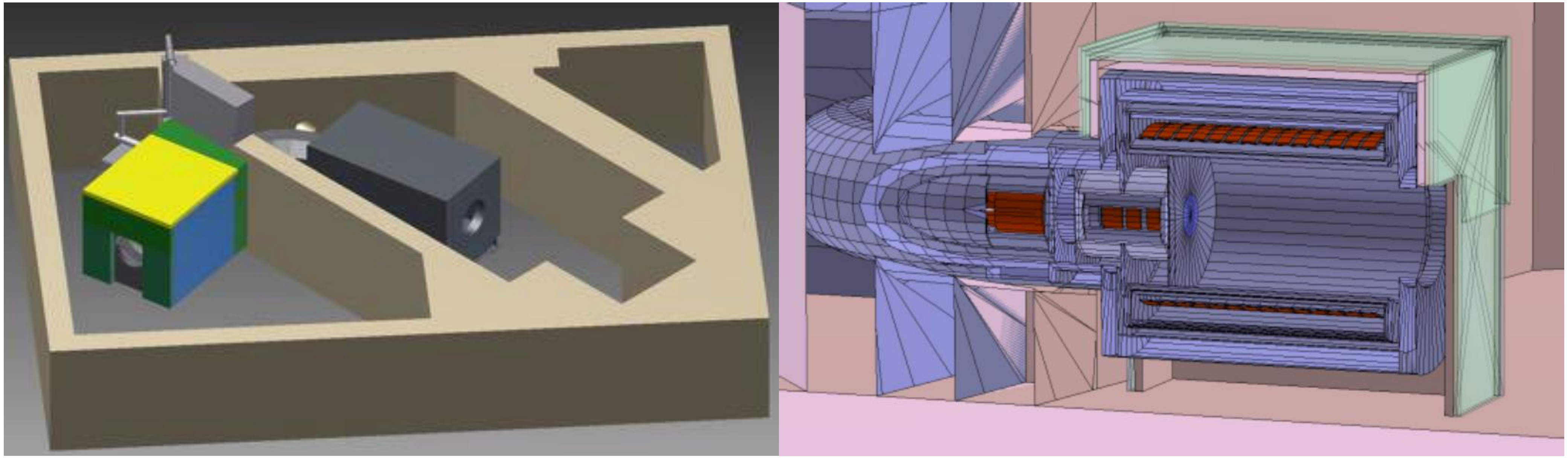






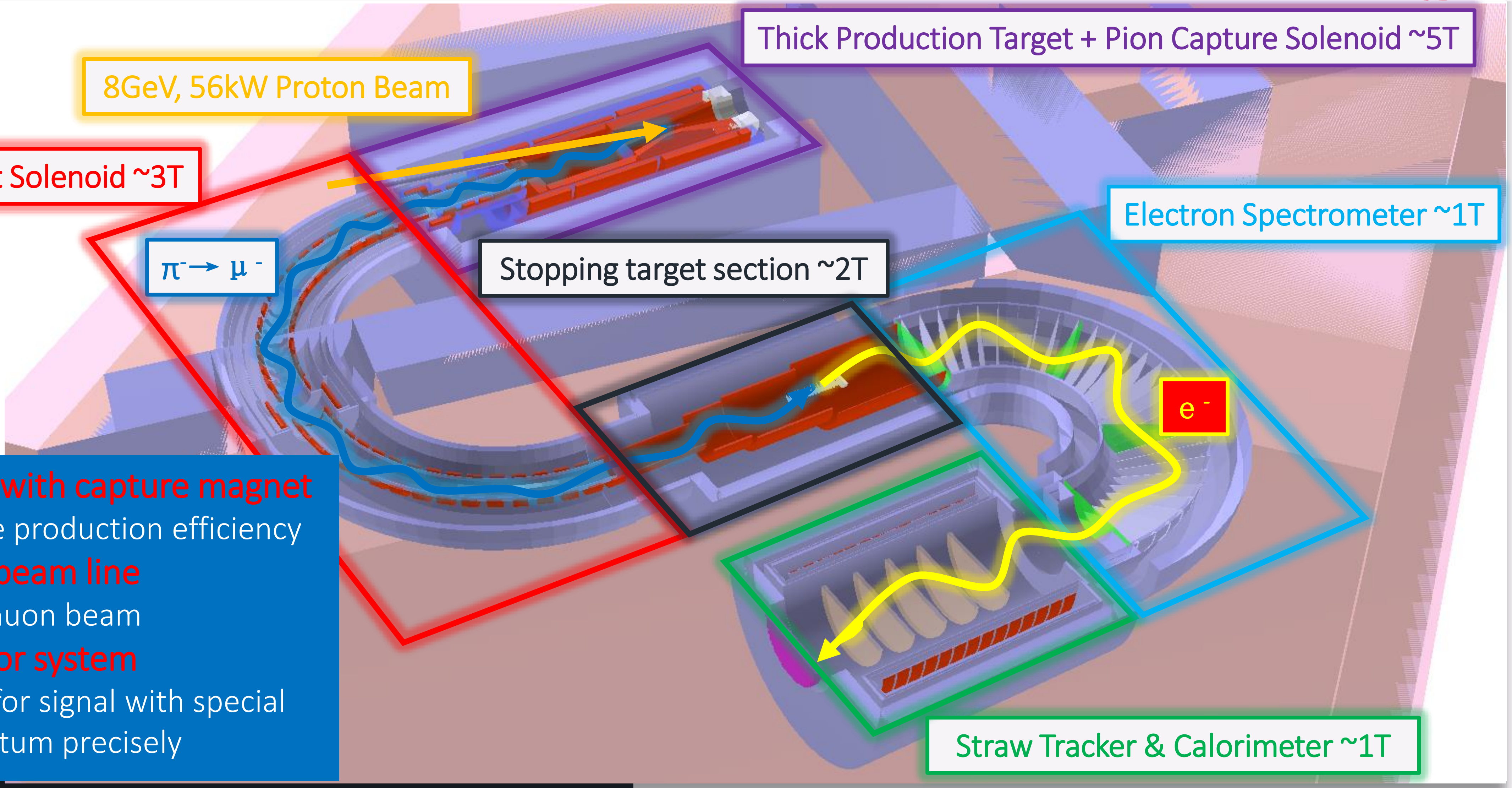
Background rejection (3)

- Cosmic ray background



➢ Cosmic rays may create e^- in signal region that come into a detector and make trigger.
  - To avoid these CR induced BG, target and detector region have to be **covered by veto counters**.
  - Required performance: CRV inefficiency ~ 10^{-4}
  - CR background ∝ data taking time (shorter running time with higher beam intensity is better)

Overview



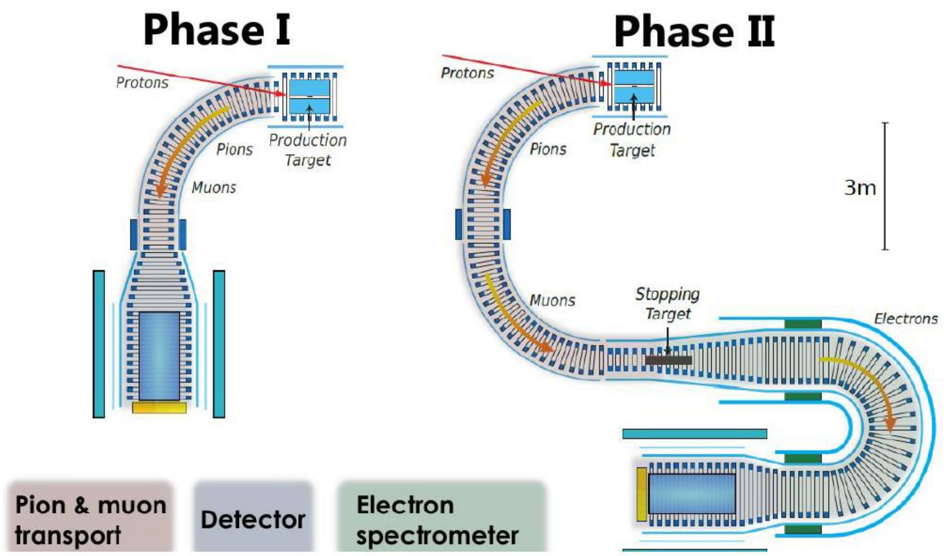
- Thick target with capture magnet
  - Improve production efficiency
- Long muon beam line
  - Clean muon beam
- Light detector system
  - Search for signal with special momentum precisely

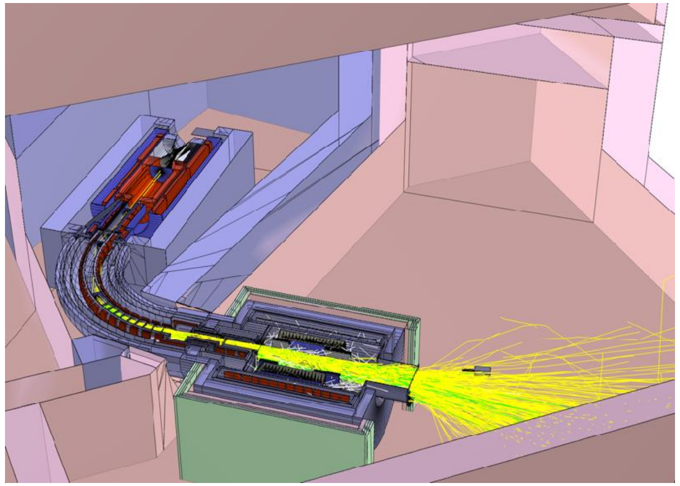
Staged plan of COMET

COMET Phase-I, 150 days data taking

Proton beam: 8 GeV, 0.4 mA, 3.2 kW

- Search for $\mu - e$ conversino with cylindrical detector (CyDet) with:
  S.E.S. = 3×10^{-15}
  (2 orders of magnitude improvement).
- Directly measure the muon beam with prototypes of Phase-II detector.
  - Very useful to guide Phase-II





Physics Sensitivity

COMET Phase-II, One year data taking, 8 GeV, 7 mA, 56 kW proton beam

- Search for $\mu - e$ conversion with S.E.S. = 2.6×10^{-17} (4 orders of magnitude improvement)
- Further optimization on the way
  - Likely to improve sensitivity by factor of 10 ($\mathcal{O}(10^{-18})$)
  - with the same beam power and beam time
  - More muons with in-depth optimization of target
  - Higher acceptance after redesigning of collimator

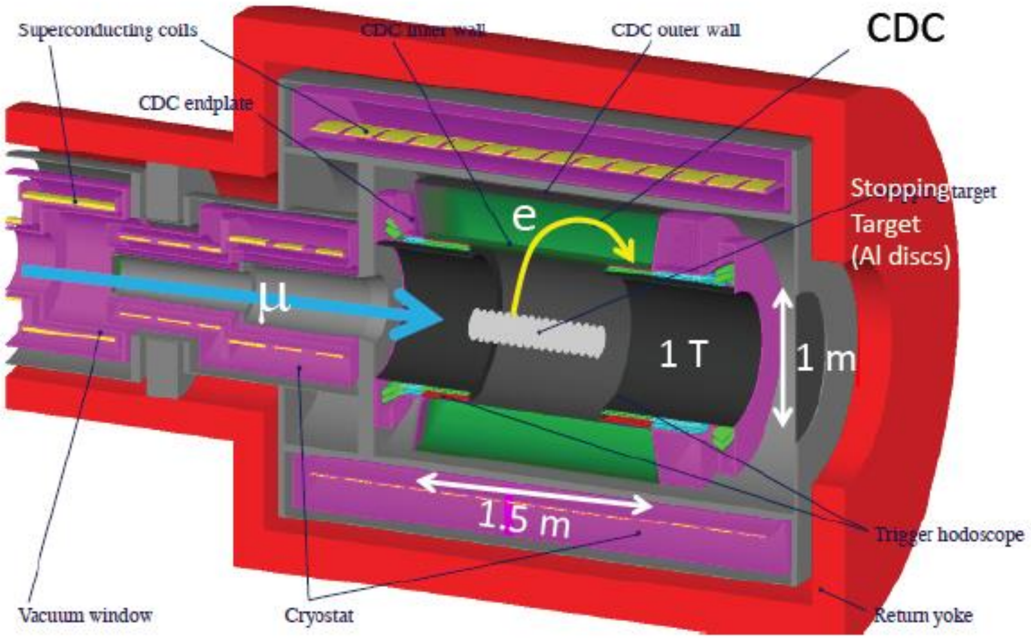
Event selection	Value
Online event selection efficiency	0.9
DAQ efficiency	0.9
Track finding efficiency	0.99
Geometrical acceptance + Track quality cuts	0.18
Momentum window (ε_{mom})	0.93
Timing window ($\varepsilon_{\text{time}}$)	0.3
Total	0.041

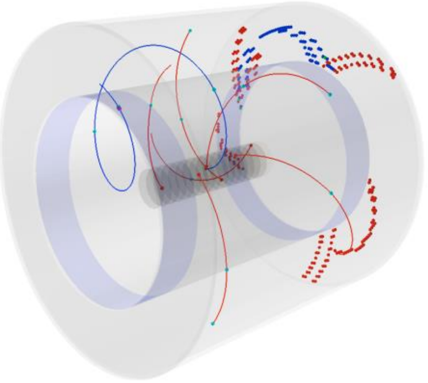
Parameter	Phase-I	Phase-II
Bending	90^0 (beam)+0^0(detector)	180^0 (beam)+180^0(detector)
Beam power	3.2 kW (8 GeV)	56 kW (8 GeV)
Running time	$9.5 \cdot 10^6$ sec	$2 \cdot 10^7$ sec
POT	$3.2 \cdot 10^{19}$	$8.5 \cdot 10^{20}$
Stopped muons on target	$1.5 \cdot 10^{16}$	$2 \cdot 10^{18}$
S.E.S.	$3.1 \cdot 10^{-15}$	$2.6 \cdot 10^{-17}$

Cylindrical Detector (CyDet)

Specially designed for Phase-I. Consists of:

- Cylindrical trigger hodoscope (CTH):
  - Two layers: plastic scintillator for trigger time and Cerenkov counter for PID.
  - Finemesh PMT readout
  - 4-fold coincidence trigger
- Cylindrical drift chamber (CDC):
  - 20 stereo layers: z information with few layers' hits
  - Helium based gas: minimize multiple scattering.
  - Large inner bore: to avoid beam flash and DIO electrons.
  - Momentum resolution: 200 keV/c (for p=105 MeV/c)
- Stopping target
  - Aluminum target with 17 disks
  - 100-mm radius, 0.2-mm thickness, 50-mm spacing.





Monte Carlo study of COMET Phase-I

- The optimization of COMET Phase I is finished. Detailed performance is estimated with Monte Carlo studies. TDR was published on arXiv (arXiv:1812.09018 [physics.ins-det])
- Sensitivity:
  - Total acceptance of signal is 0.041.
  - Can reach **3×10^{-15} SES in 150 days**.

$$B(\mu^- + \mathrm{Al} \to e^- + \mathrm{Al}) = \frac{1}{N_\mu \cdot f_{\mathrm{cap}} \cdot f_{\mathrm{gnd}} \cdot A_{\mu\text{-}e}}$$

$$B(\mu^- + Al \to e^- + Al) = 3 \times 10^{-15} \quad \text{(S.E.S)}$$
$$B(\mu^- + Al \to e^- + Al) < 7 \times 10^{-15} \quad (90\% C.L.)$$

- Background:
  - With 99.99% CRV total expected BG is 0.032
- Trigger rate:
  - Average trigger rate ~10kHz (after trigger with drift chamber hits)

Type	Background	Estimated events
Physics	Muon decay in orbit	0.01
	Radiative muon capture	0.0019
	Neutron emission after muon capture	< 0.001
	Charged particle emission after muon capture	< 0.001
Prompt Beam	* Beam electrons	
	* Muon decay in flight	
	* Pion decay in flight	
	* Other beam particles	
	All (*) Combined	$\lesssim 0.0038$
	Radiative pion capture	0.0028
	Neutrons	$\sim 10^{-9}$
Delayed Beam	Beam electrons	~ 0
	Muon decay in flight	~ 0
	Pion decay in flight	~ 0
	Radiative pion capture	~ 0
	Anti-proton induced backgrounds	0.0012
Others	Cosmic rays†	< 0.01
Total		0.032

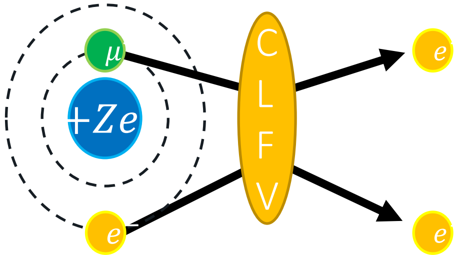
† This estimate is currently limited by computing resources.

Other Physics Topics on COMET

- $\mu^- N_Z \rightarrow e^+ N_{Z-2}$: Lepton number violation (LNV)
  - Current limits: $\mu^- Ti \rightarrow e^+ Ca(gs) \leq 1.7 \times 10^{-12}$
    $\mu^- Ti \rightarrow e^+ Ca(ex) \leq 3.6 \times 10^{-12}$
  - Can improve with a proper target

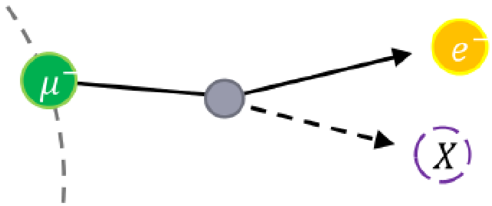
Phys. Lett. B422 (1998)
Phys. Lett. B764 (2017)
Phys. Rev. D96 (2017)

- $\mu^- e^- \rightarrow e^- e^-$: μ^- and e^- overlap proportional to Z^3



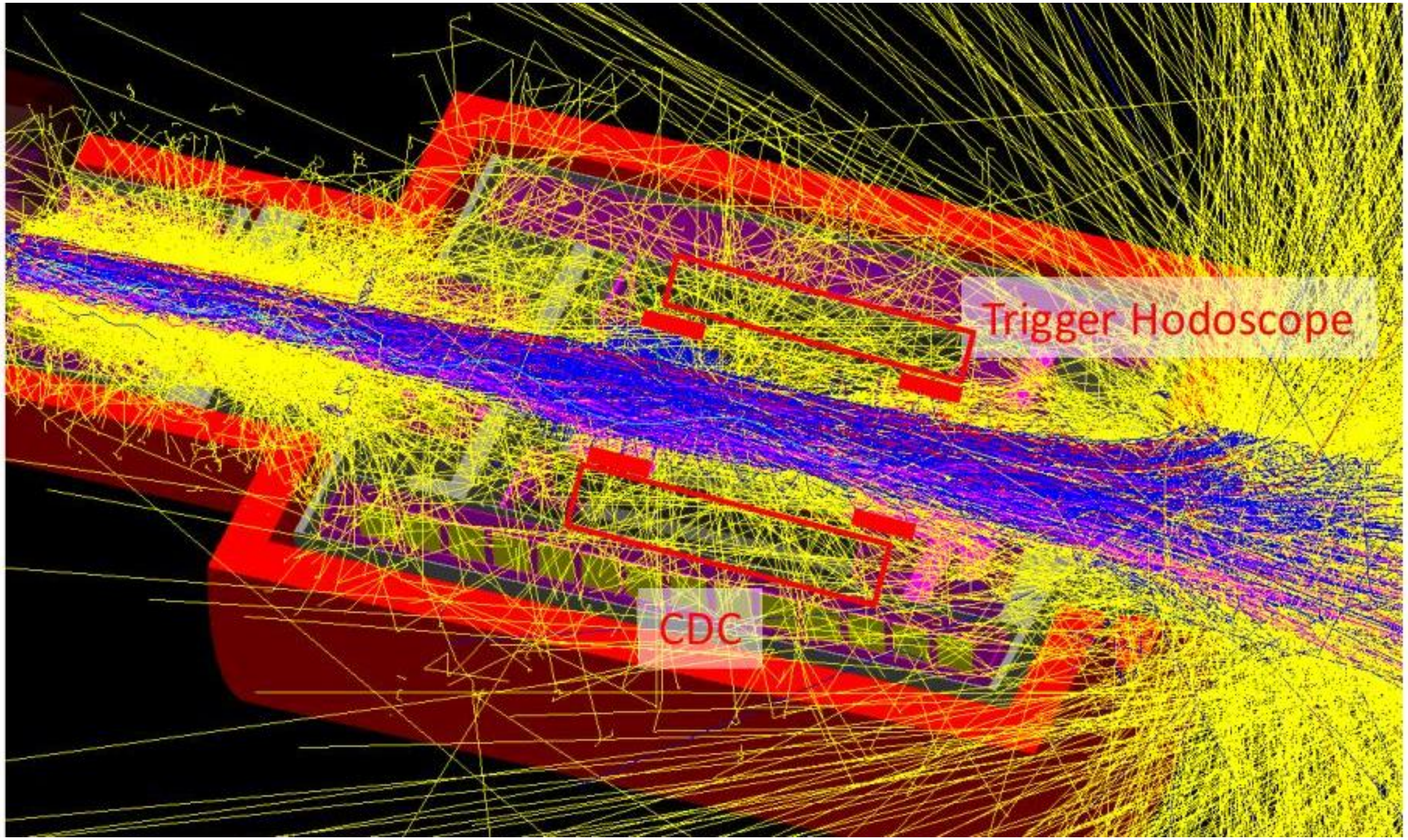
Phys. Rev. Lett. 105 (2010)
Phys. Rev. D93 (2016) 076006
Phys. Rev. D97 (2018) 015017

- $\mu^- \rightarrow e^- X$: X can be a new light boson, ALP, Majoron, etc.
  - feasibility being studied in COMET



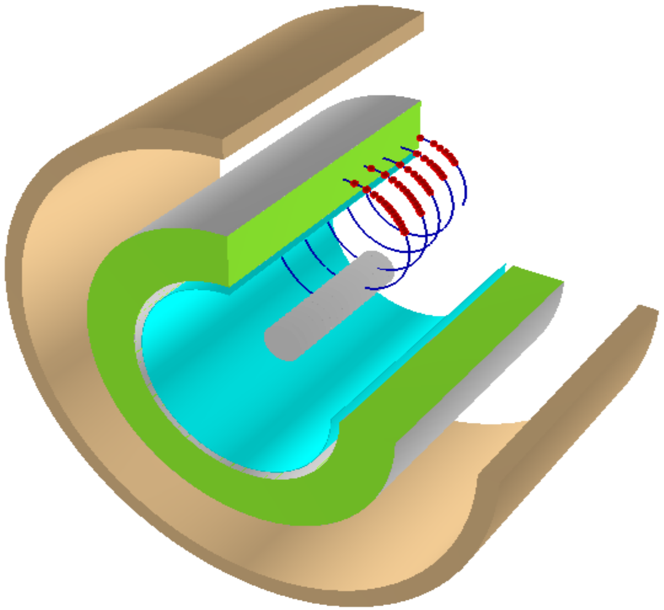
Phys. Rev. D79. 055023 (2009)
Phys. Rev. D84. 113010 (2011)

Development of Software



Reconstruction algorithm for CyDet

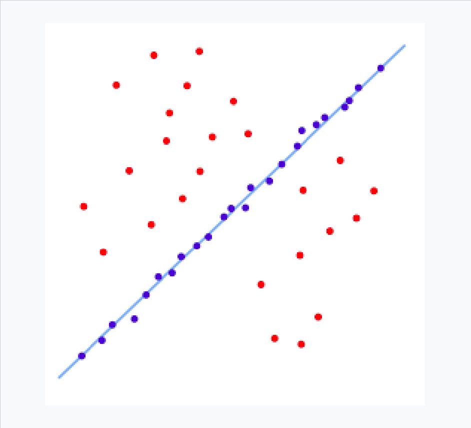
- Detector response algorithm
  - Digitization and offline trigger
- Track finding algorithm
  - Provide seed tracks
- Track fitting algorithm
  - Fit track precisely using Kalman fitter
- Challenge
  - No seed from other sub-detector
  - All stereo layers
  - Overlapping between different turns
- One of the most difficult situations of drift chamber



Track finding algorithm

- RANdom SAmple Consensus (RANSAC)
  - Subsets of data could be described by same model
  - Used to distinguish different turns
- Helix fitting with minimum hits
  - Separated into circle fitting and ϕ-z linear fitting
  - Iteration could improve the resolution

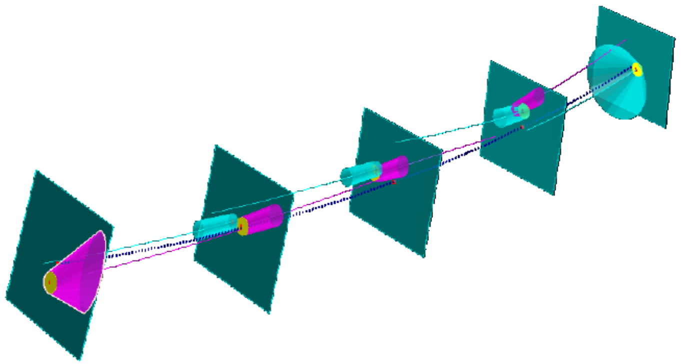
A data set with many outliers for which a line has to be fitted.

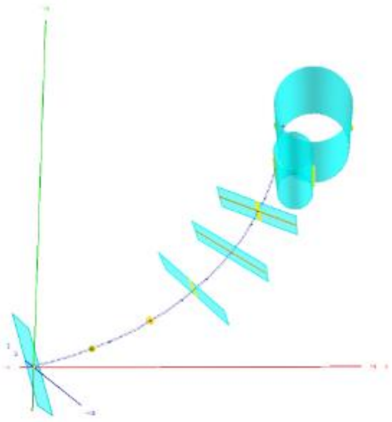


Fitted line with RANSAC; outliers have no influence on the result.

Track fitting algorithm

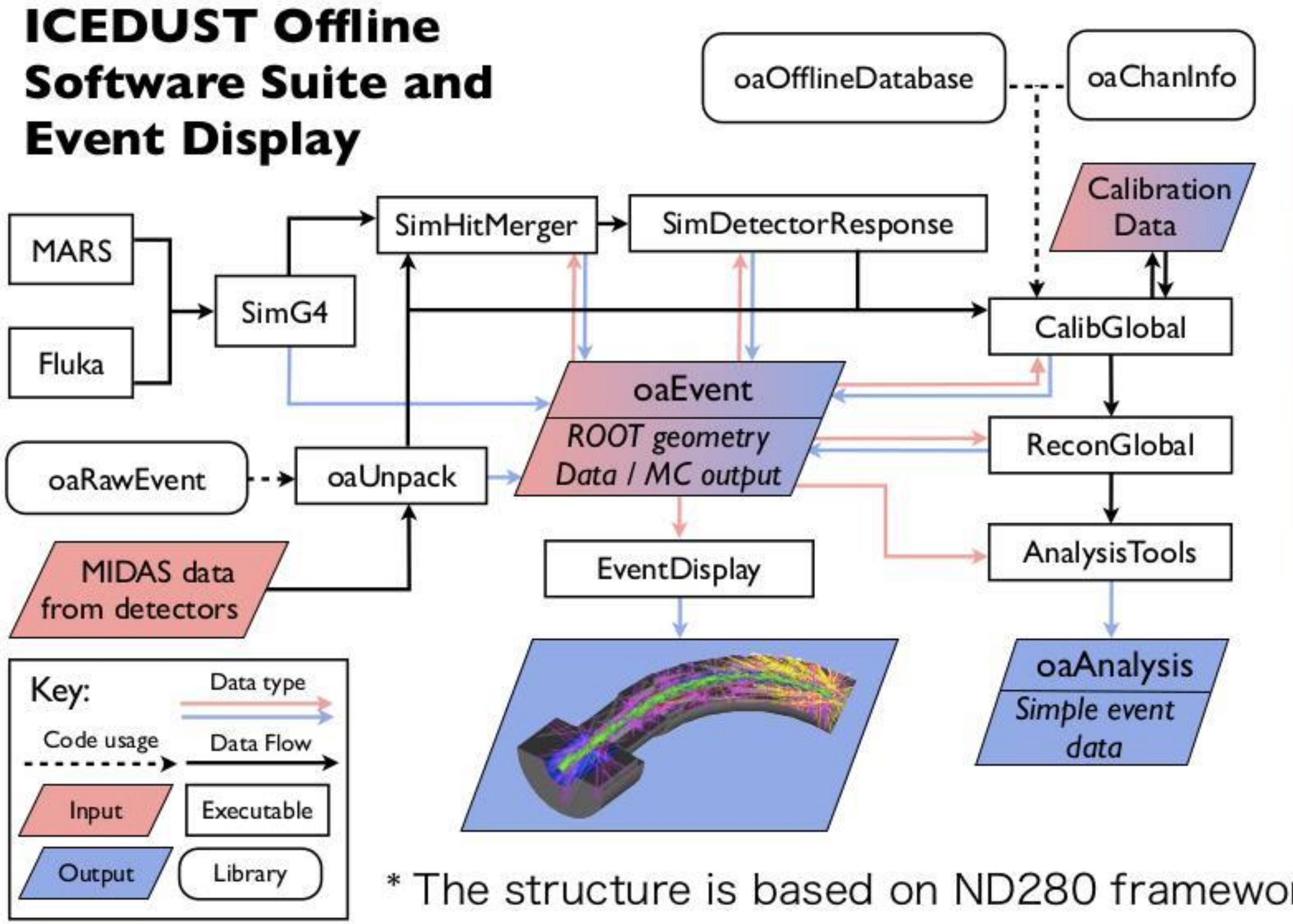
- **Kalman fitter is widely used in reconstruction algorithm**
- **Based on GenFit** (https://github.com/GenFit/GenFit)
  - An experiment-independent **generic track fitting** framework
  - Official track fitting for BelleII, also used by PANDA, CEPC,BESIII, GEM-TPC etc.

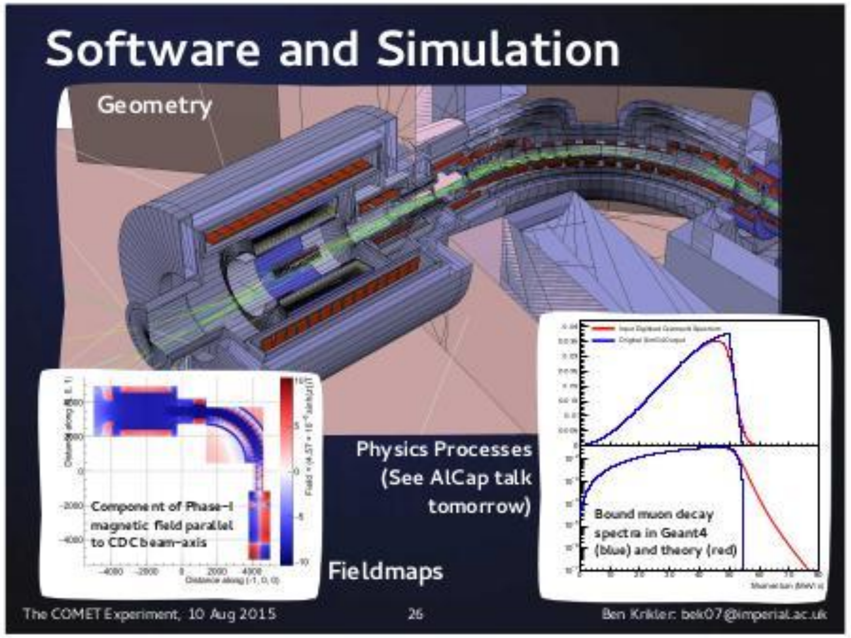




(a) Measurements with covariance (yellow), planar detectors and drift isochrones (cyan), respectively, and reference track (blue).

Introduction of Software Framework



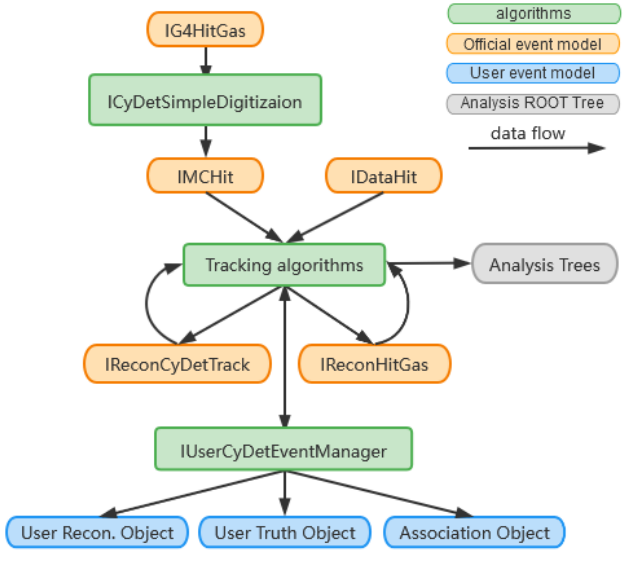


an example for Phase-I

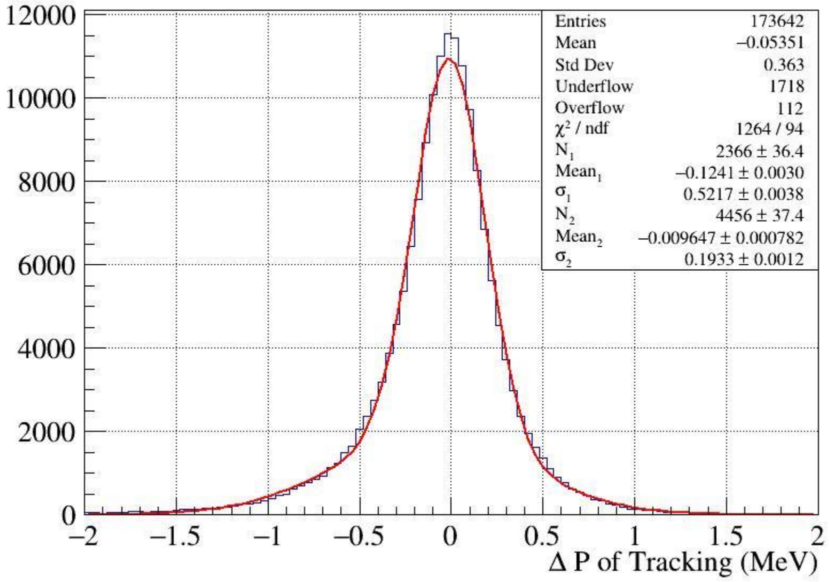
* The structure is based on ND280 framework.

Development for reconstruction

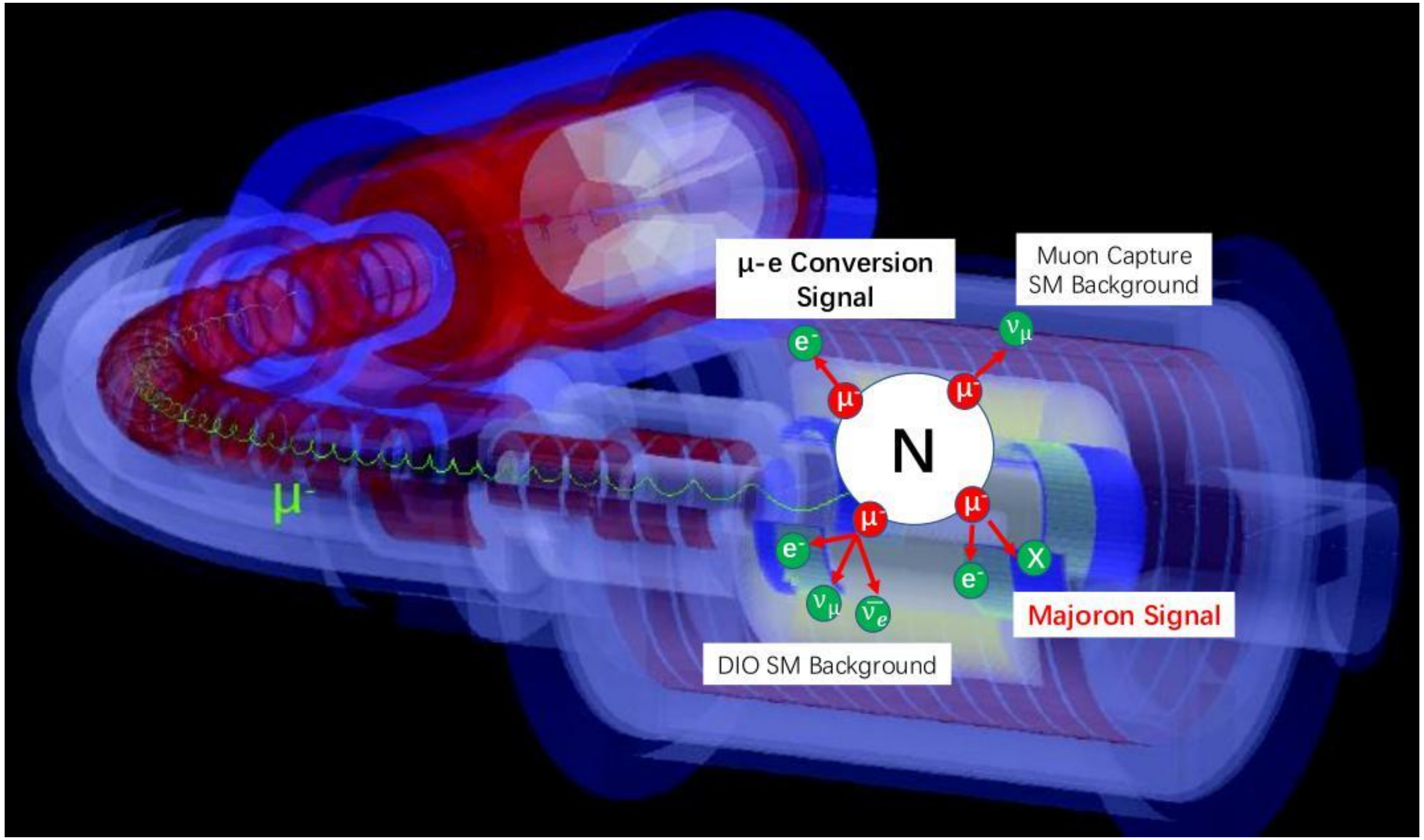
- New design of event model suitable for reconstruction
- Develop a simple digitization algorithm
- Develop a track finding algorithm based on RANSAC
- Optimize track fitting algorithm based on Genfit
- Develop a full reconstruction algorithm for COMET Phase-I



Dataflow of CyDet Tracking



Search for Majoron



Introduction of Majoron

- **Dirac mass term of neutrino**
  - Should be in same level with m_e, m_μ, m_τ
- **Seesaw models to explain the tiny mass of neutrino**
  - Neutrnio mass: $M_R, {M_D}^2/M_R$
- **Majorana mass term of neutrino**
  - Nuetrinoless double beta decay
  - Leads to spontaneous break of lepton number
  - Majoron(J): a massive or massless Goldstone particle
- **Experiments to search for Majoron**
  - Invisible decay width of Z boson but excluded by LEP
  - μ -> e + J
    - Related to μ -> e + X, while X is light (pseudo-)scalars like ALP

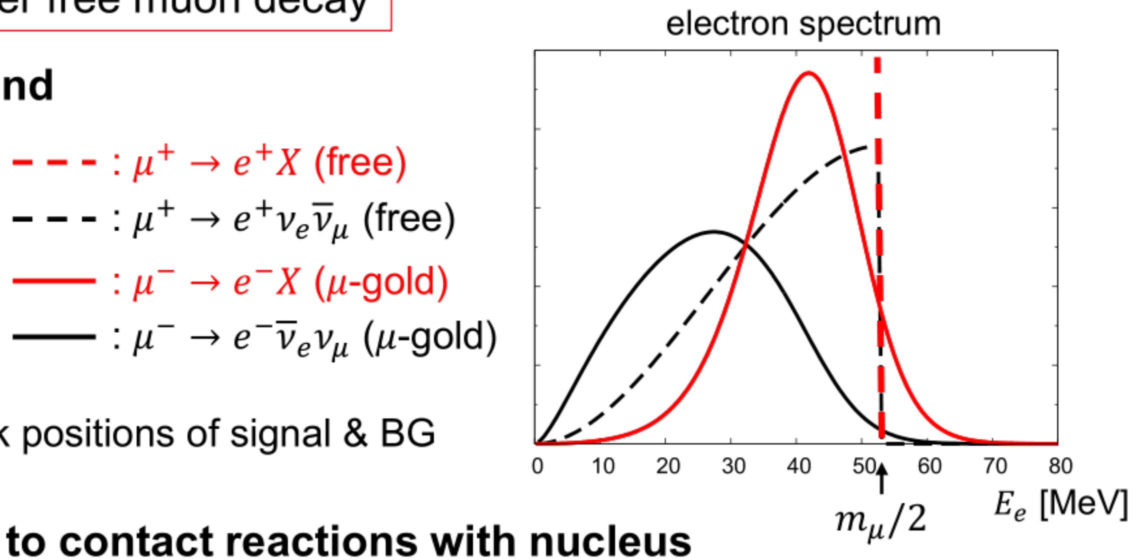
Search for $\mu^- \to e^- J$

$\mu^- \to e^- X$ in a muonic atom

cf. X. G. i Tormo *et al.*, PRD **84**, 113010 (2011).
& H. Natori, Talk at 73th JPS meeting (2018).

Advantage over free muon decay

1. less background



- different peak positions of signal & BG

2. also sensitive to contact reactions with nucleus

3. more information : "spectrum" & "dependence on nucleus"

Reference: Report "New promising CLFV modes in muonic atoms" by Yuichi Uesaka(Saitama U.)

Disadvantage

✓ non-monochromatic signal ✓ shorter life time of muonic atom

- $\mu^+ \to e^+ J$ with free muon
  - TWIST on 2015
  - Mu3e in the future
- $\mu^- \to e^- J$ in muonic atom
  - No experiment
  - COMET could be the first one

Signal region

- The signal significance is bigger at high energy region
  - DIO is considered as major background

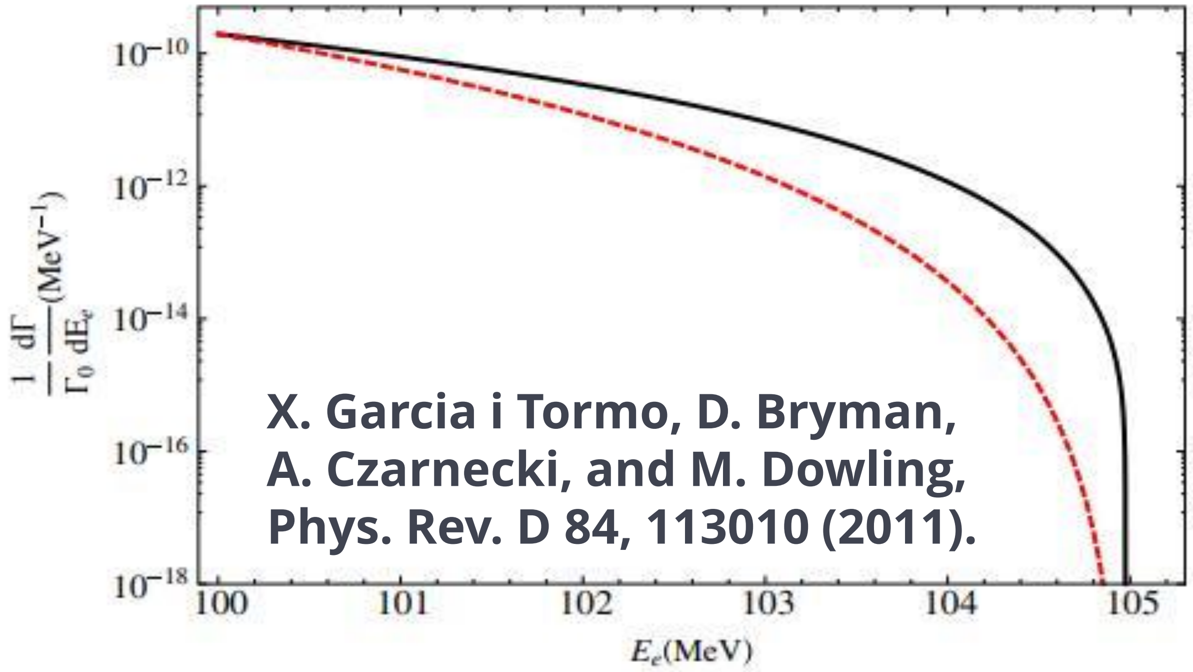
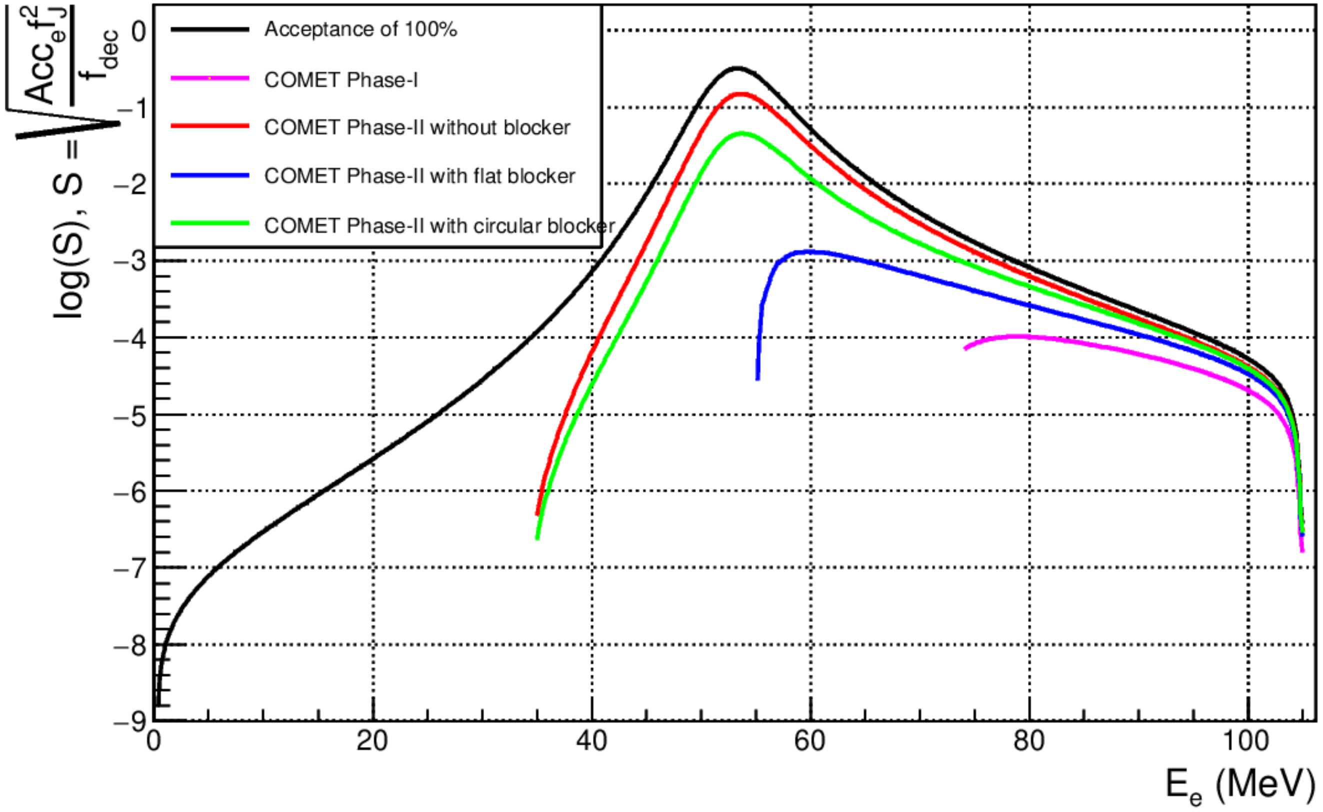


FIG. 2 (color online). Electron spectrum for Majoron emission in orbit for Al (solid line). The second panel is a zoom for $E_e >$ 100 MeV. The dashed line in the second panel is the electron spectrum for DIO in Al, multiplied by a constant ($C = 415$) to make it coincide with the MEIO rate at $E_e = 100$ MeV.

Optimization of signal region

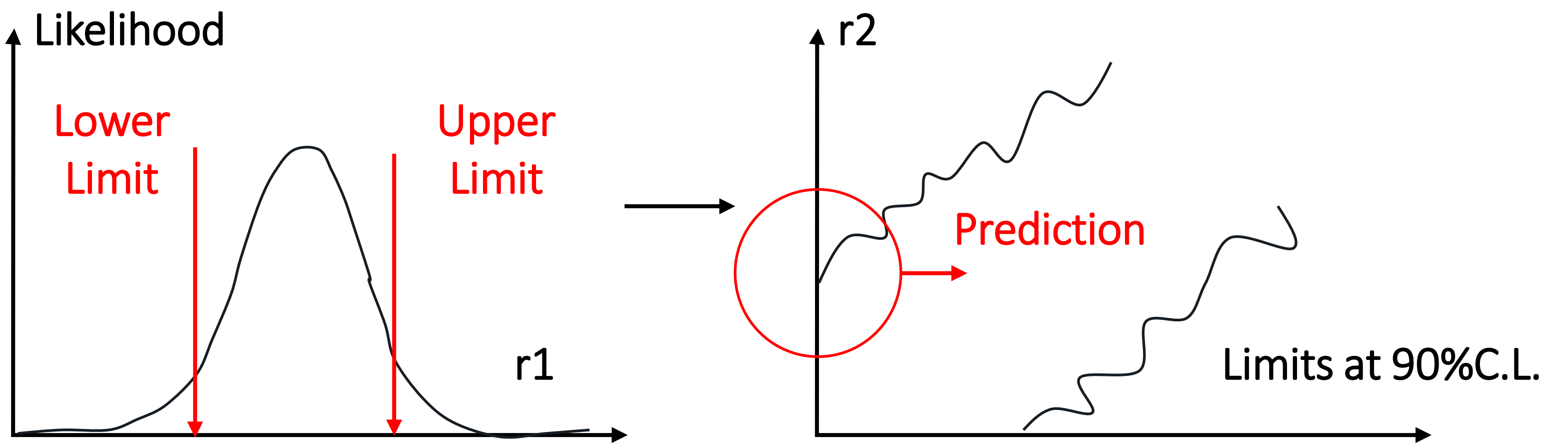
- Considering the acceptance of detector, significance factor is given as:

$$\mathcal{B}(\mu \to eJ) = 1.645 \times \sqrt{\frac{\Gamma_{\rm capture} Acc_{\mu e} S.E.S._{\mu e}}{\Gamma_{\rm decay}} \frac{1}{S}}, \quad S = \sqrt{\frac{Acc_e f_J^2}{f_{\rm dec}}}$$



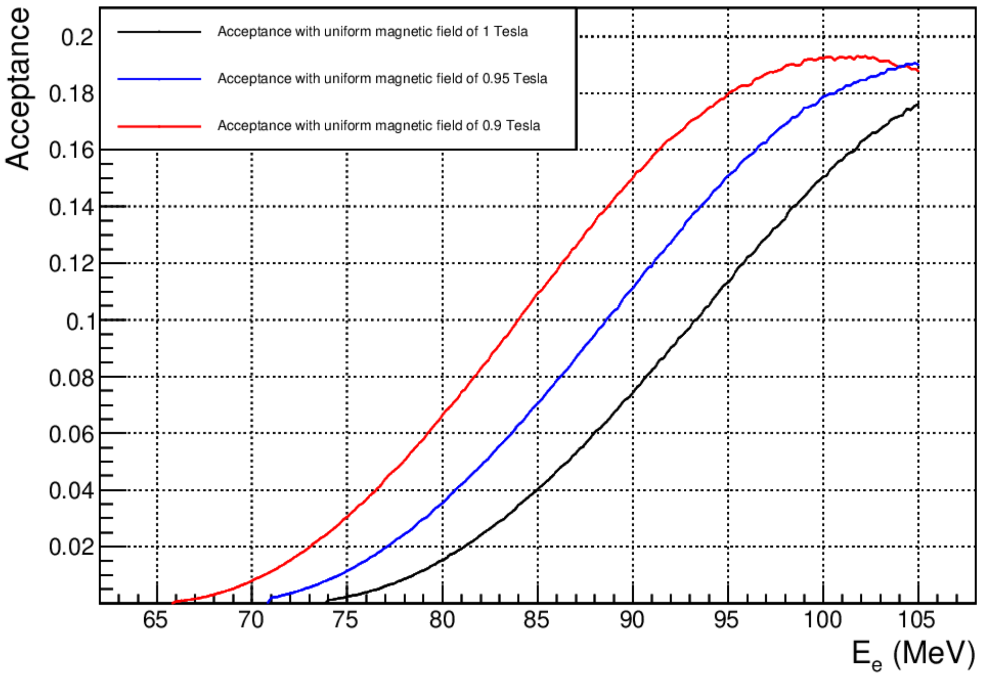
Likelihood analysis method

- The case we already have data $f(E)_{measured}$
  - $f(E)_{excepted} = f(E)_{DIO} + r_1 * f(E)_{MEIO}$
  - Branch ratio of μ -> e + J could be given at 90% C.L.
- The case we don't have data $f(E)_{measured}$
  - $f(E)_{measured} = f(E)_{DIO} + r_2 * f(E)_{MEIO}$
  - Draw all the limits with different r_2 as a confidence belt



Prediction of COMET Phase-I

- Prepare input for likelihood analysis
  - Acceptance and energy loss from full simulation
  - Optimization with different uniform magnetic fields
- The prediction is given as 2.3×10^{-5} considering the event ratio limit



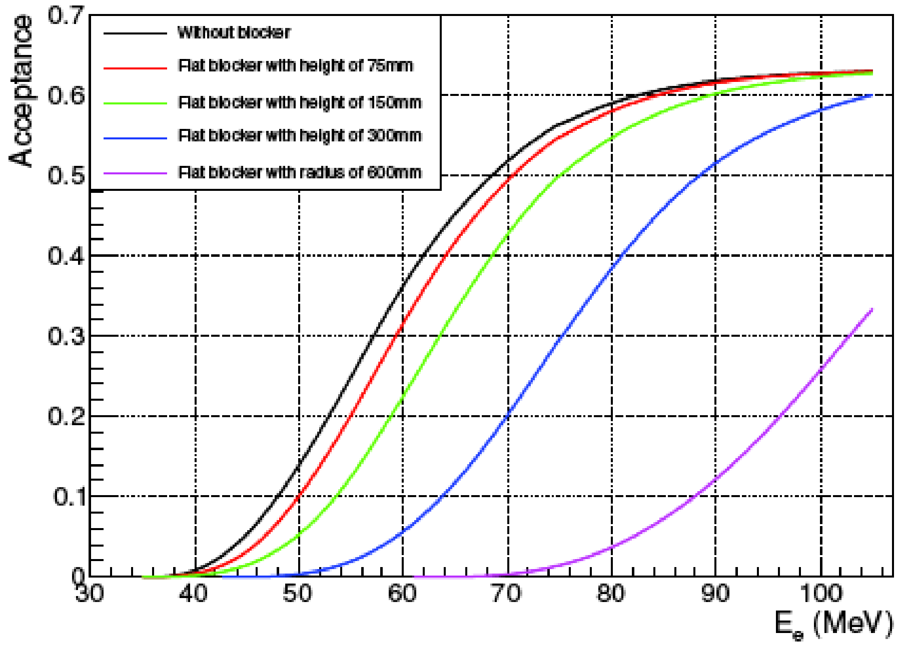
Magnetic Field	1T	0.95T	0.9T
Upper Limit	2.3×10^{-5}	1.4×10^{-5}	6.9×10^{-6}
Event rate of DIO	16.7 kHz	75.3 kHz	394.6 kHz

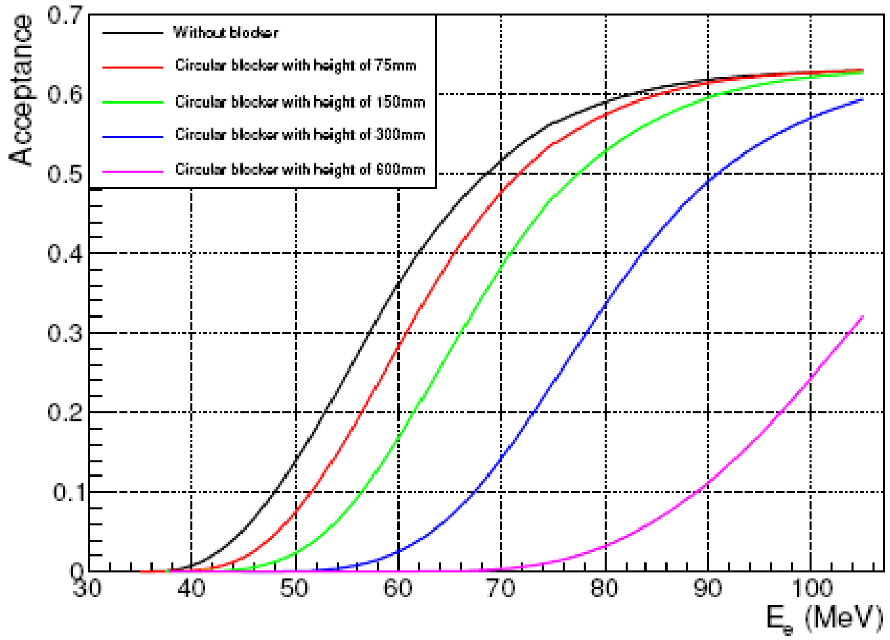
TABLE II. Estimated upper limits after reducing strength of magnetic field of COMET Phase-I

Prediction of COMET Phase-II

Fast Simulation:

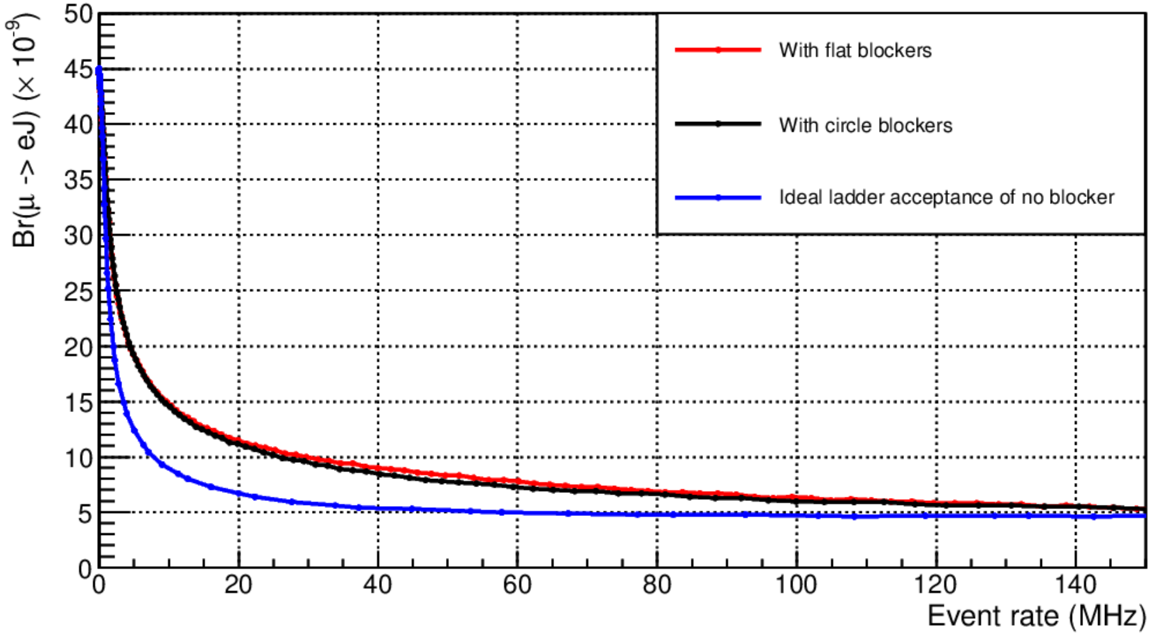
- The tracks of electrons are considered as standard helices
- Material effects and uncertainty of magnetic field are not considered
- A flat blocker and a circular blocker is considered

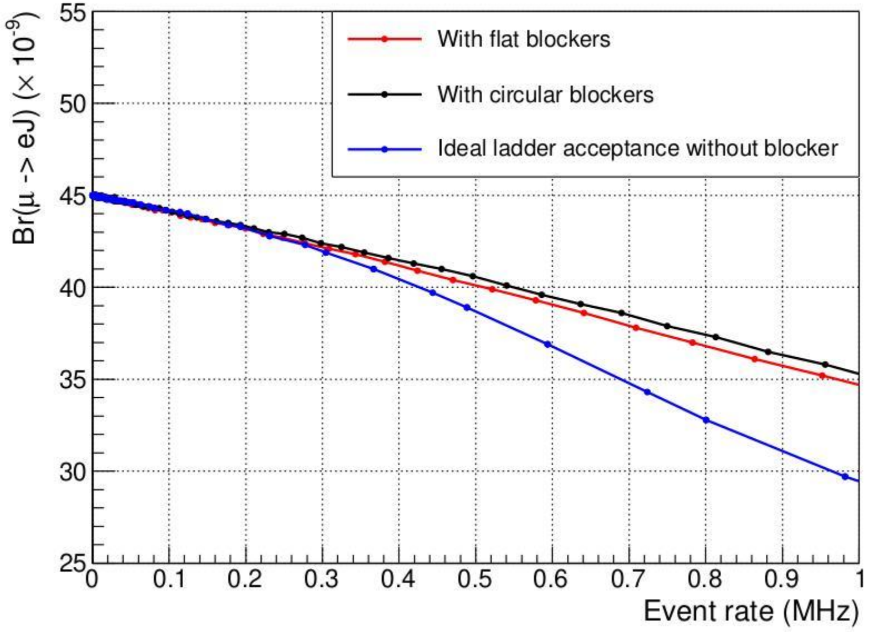




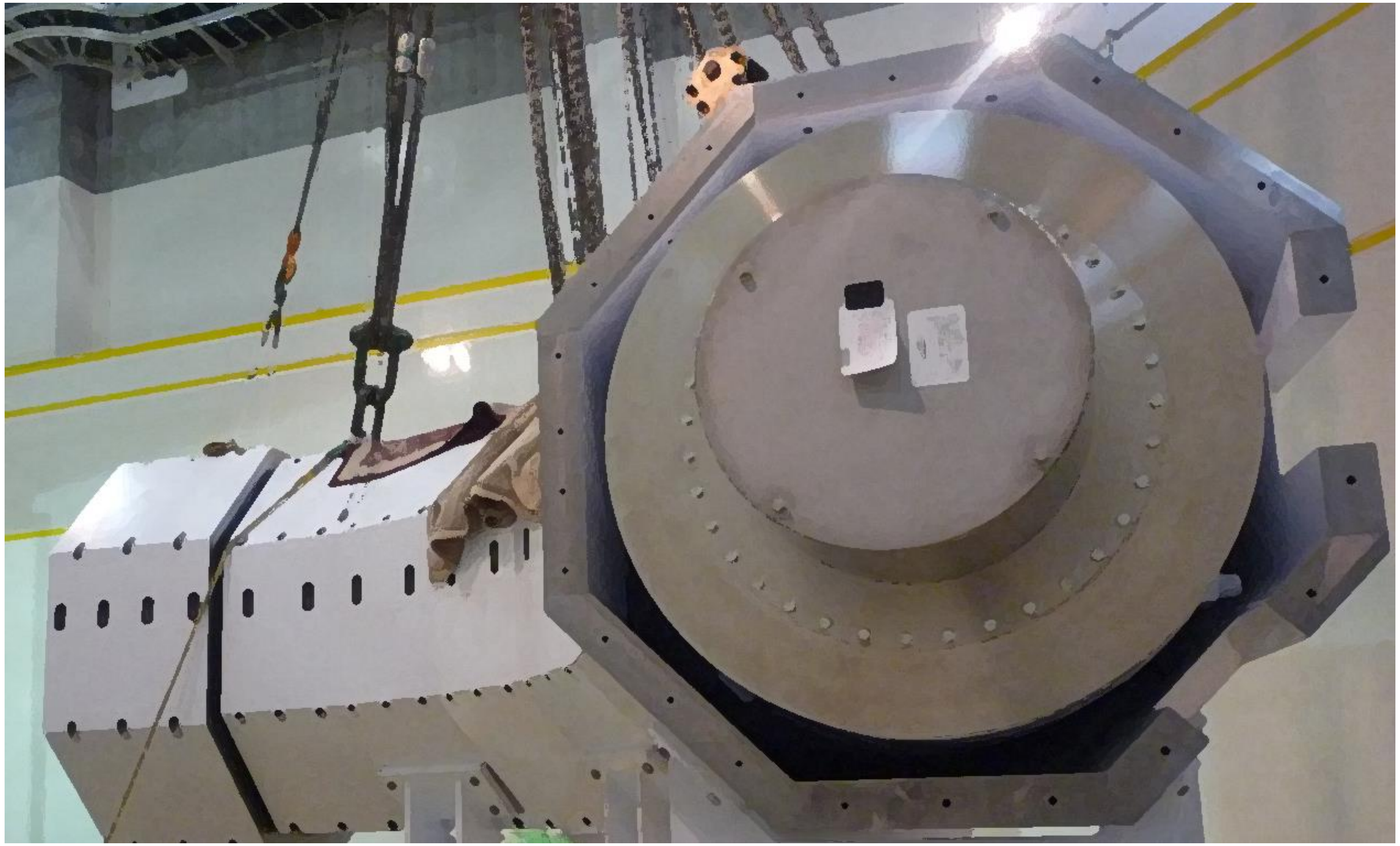
Prediction of COMET Phase-II

- Prepare input for likelihood analysis
  - Acceptance distribution from fast simulation
  - Optimization with different design of blocker
- The prediction is given as $O(10^{-8})$ considering the event ratio limit





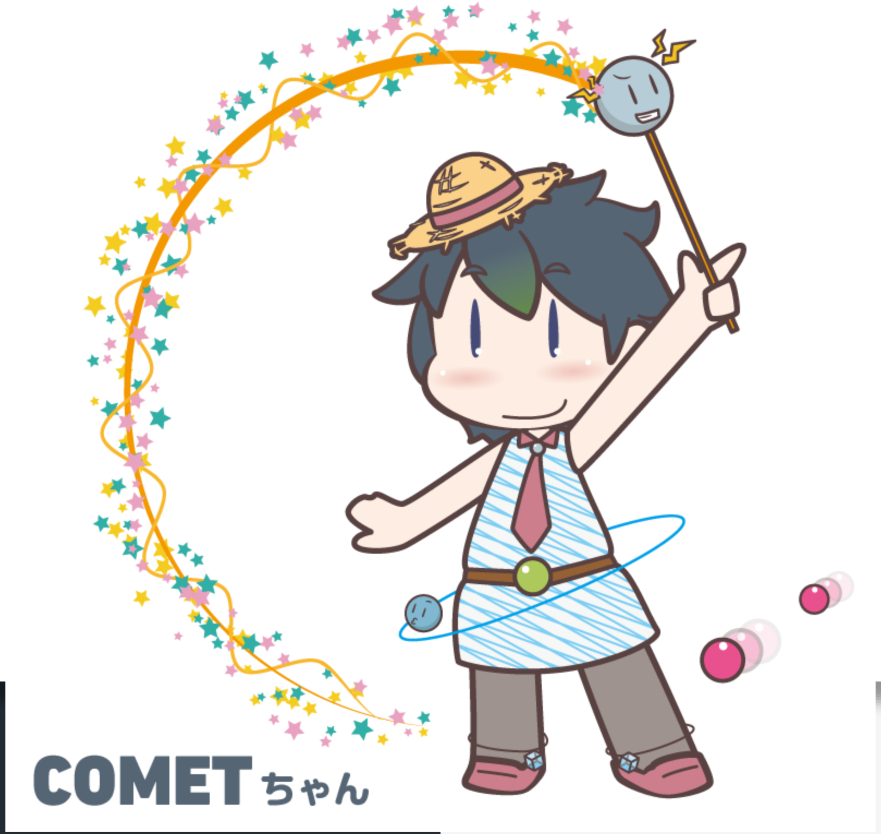
Summary



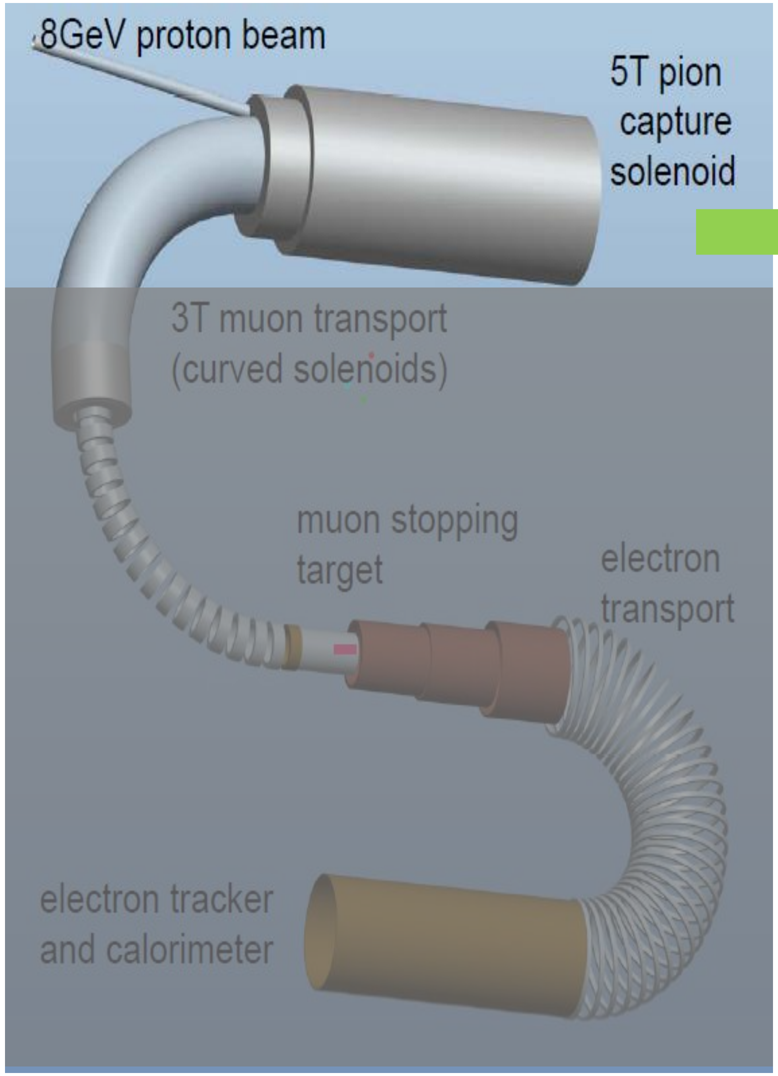
- COMET is an experiment at J-PARC searching for muon to electron process.
  - Aims at S.E.S = 2.6×10^{-17} (4 orders of magnitude improvement) with 1 year beam time.
  - The study to reach S.E.S $\sim 10^{-18}$ is in progress
- COMET will be carried out in two phases and Phase-I is under construction.
  - Aims at S.E.S = 3×10^{-15} (2 orders of magnitude improvement) with 150 days beam time.
- Develop reconstruction algorithm for the drift chamber detector of COMET Phase-I
  - Design and develop new event model for the software framework
  - Develop tracking algorithm with good resolution
- A R&D of searching for Majoron on COMET has been done.
  - The prediction of sensitivity on COMET Phase-II is given as $O(10^{-8})$
  - 1000 times improvement compared with current best result.
  - The paper has been accepted by Chinese Physics C (CPC) and will be published as cover article.
  - DOI: 10.1088/1674-1137/ac9897

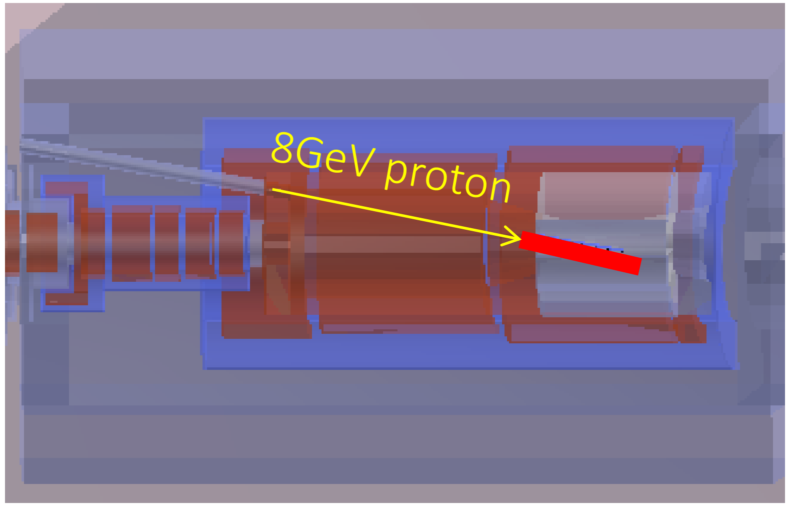
Thank You!

Backup



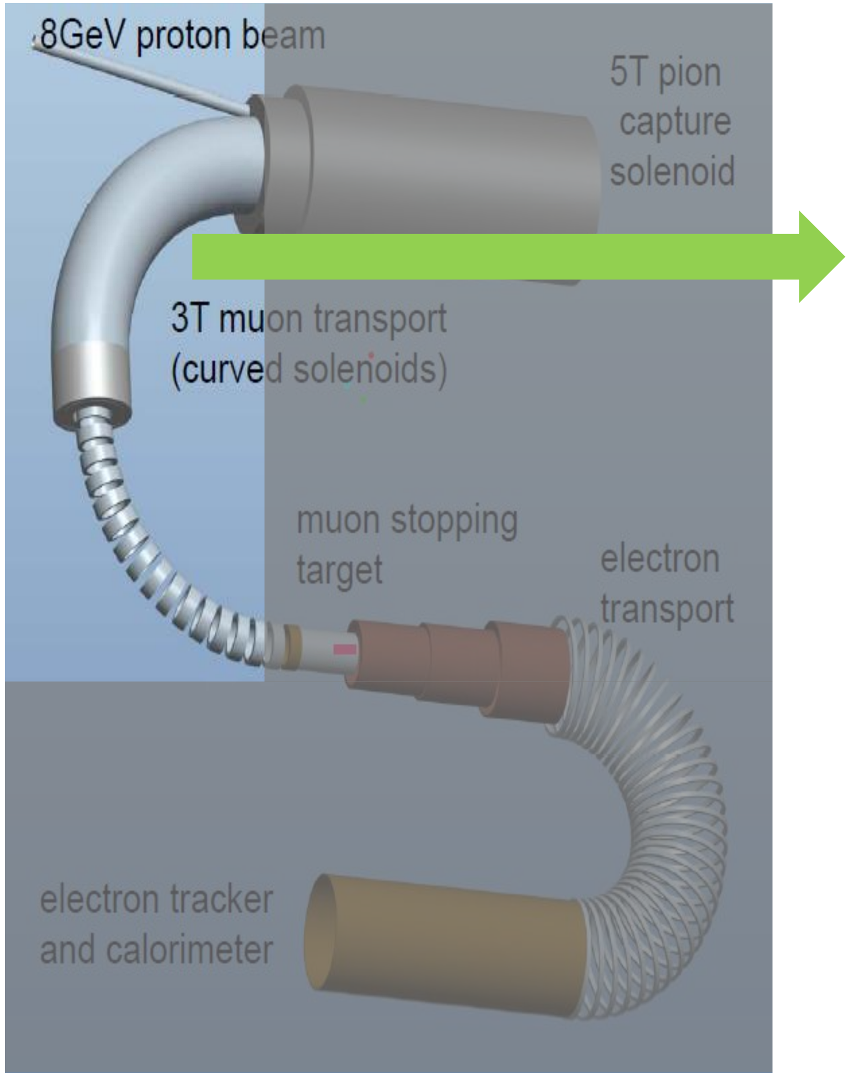
Production target and the capture magnet

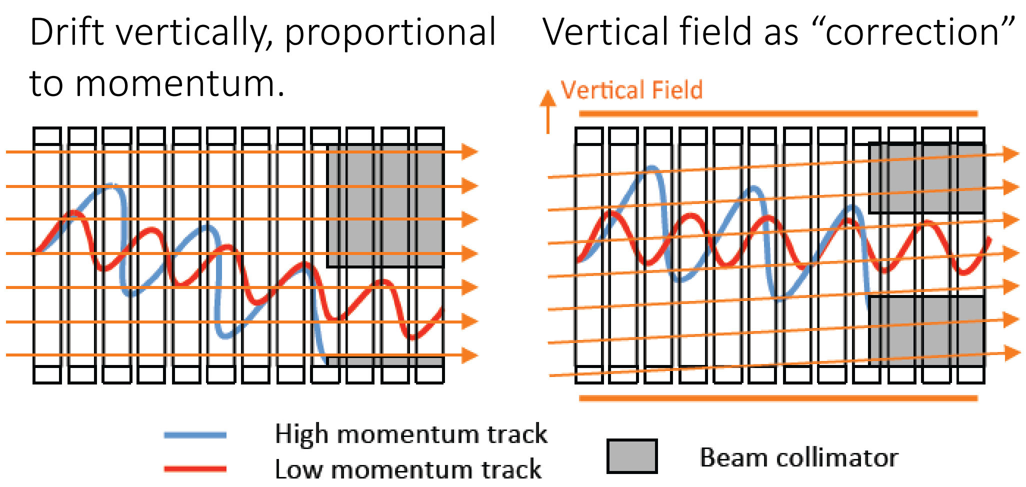




- 8 GeV 56 kW proton beam
- Thick target with 1~2 hadron interaction length
- Powerful capture magnet: 5 T
  - Large inner bore to fit in the shielding
  - Adiabatic decreasing field: focusing and mirroring
- Expected muon yield: 10^{11} muon/sec! $(10^8 @ PSI)$

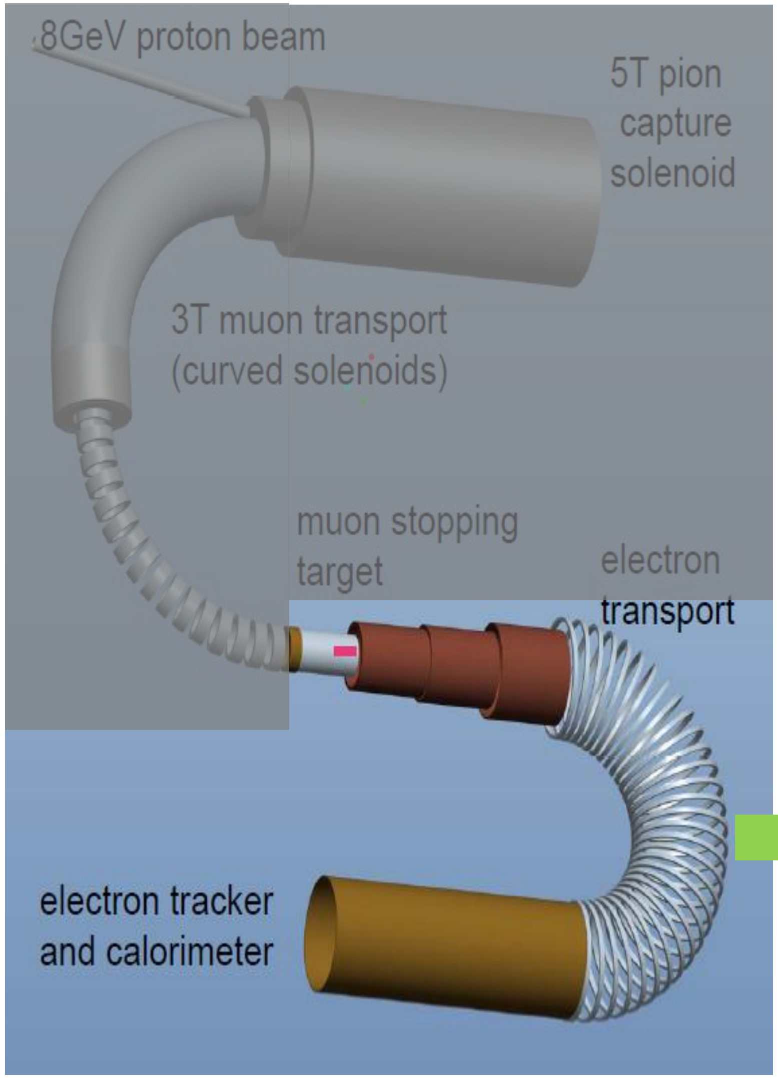
Transportation solenoid



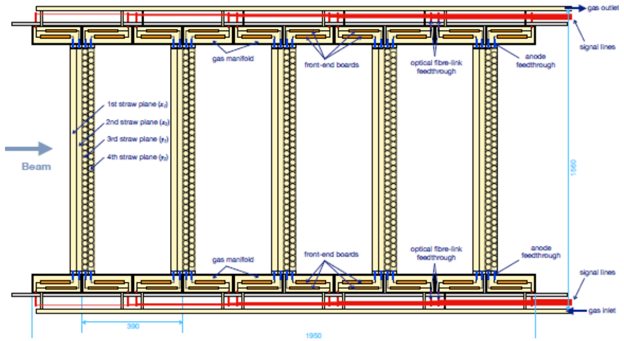


- Use C shape curved solenoid
  - Beam gradually disperses
    - Charge & momentum
  - Dipole field to pull back muon beam
    - Can be used to tune the beam
  - Collimator placed in the end
    - Utilize the dispersion in 180 degrees

Stopping target and detector system

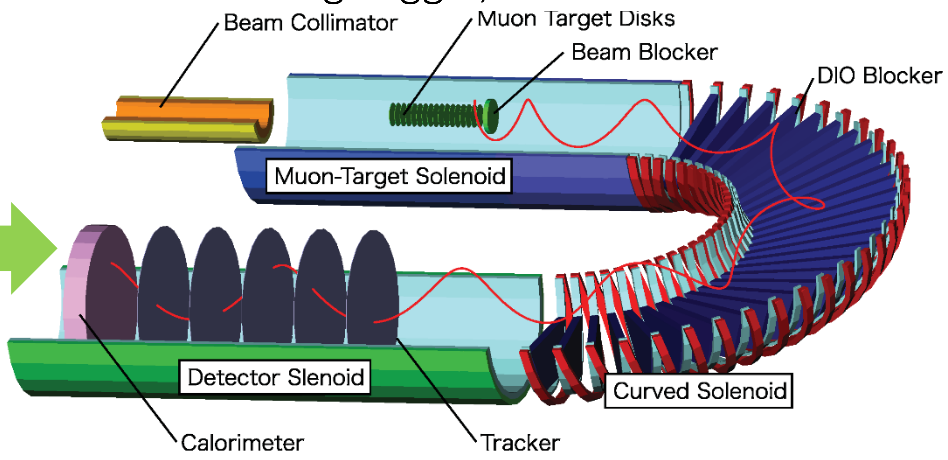


- Use straw tracker to measure the momentum
  - Really light: put in vacuum, 12 micro meter thin straw



Tracker with Straw-tubes
- Operational in vacuum in 1T
- Δp = 150~200 keV/c (for p=105 MeV/c)
- Straw tube
  - 20 µm thick, 9.75 mm diameter for Phase-I
  - 12 µm thick, 5 mm diameter for Phase-II
- More than 5 stations (xx'yy'>5)
- Ar:C_2H_6 (50:50)

- Electromagnetic calorimeter
  - Providing trigger, TOF and PID



- 1,920 LYSO crystals
  - 2×2×12 cm (10.5 radiation length)
- ΔE/E = 5% (for E=105 MeV)
- 40-ns decay time
- APD + read-out(EROS)

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