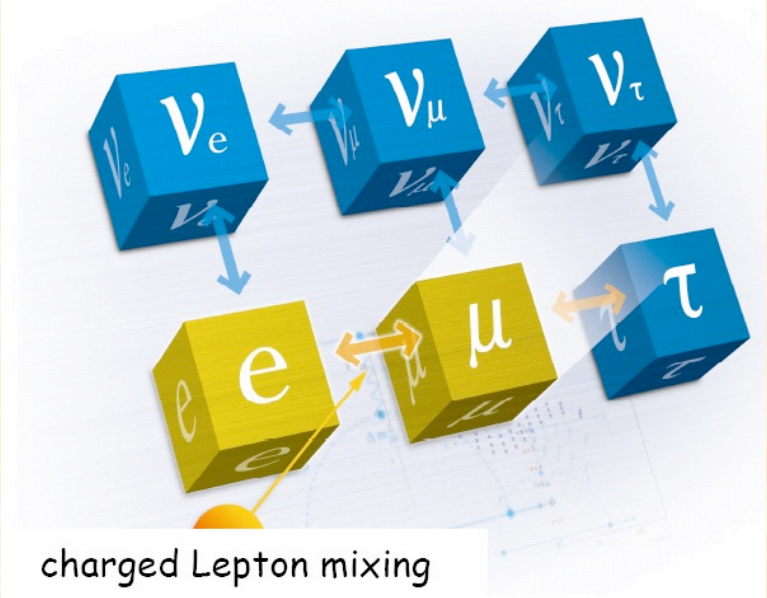
COMET
(COherent Muon to Electron Transition)

Ye YUAN

On behalf of
IHEP & LPNHE

12th FCPPL Workshop
April 24nd, 2019
SJTU



Outline

- **CLFV & COMET**
- **Phased approach**
- **Highlights of Last year**
- **Activities from France & China**
- **Summary**

Why CLFV & COMET?

Quarks, Neutrinos, and then Charged Leptons

Quarks

Qurak mixing,
2008 Nobel prize

Leptons

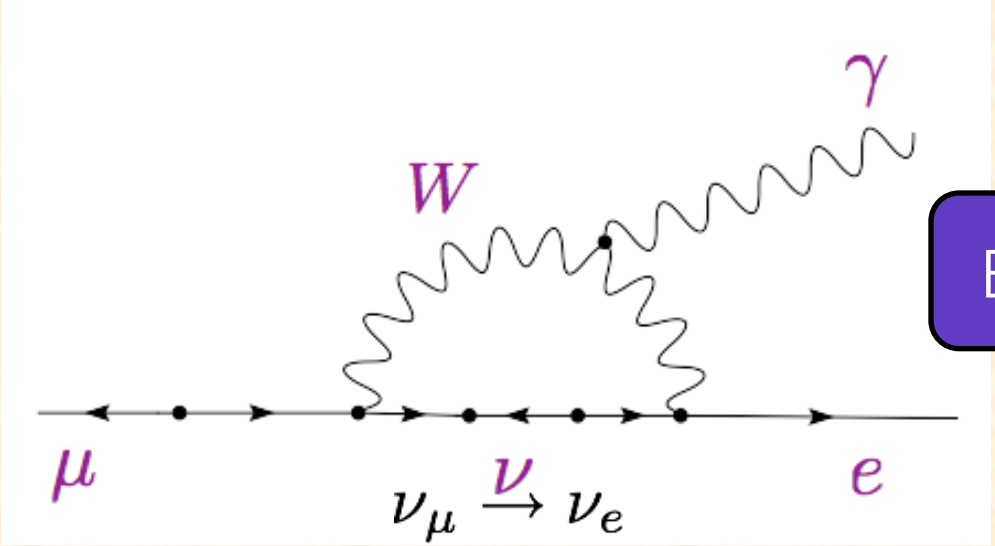
Neutrino oscillation,
2015 Nobel prize

Not observed, why special?

Charged Lepton Flavor Violation (cLFV)

Forbidden in Standard Model

$$B(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_l (V_{MNS})^*_{\mu l}(V_{MNS})_{el}\frac{m^2_{\nu_l}}{M^2_W}\right|^2$$

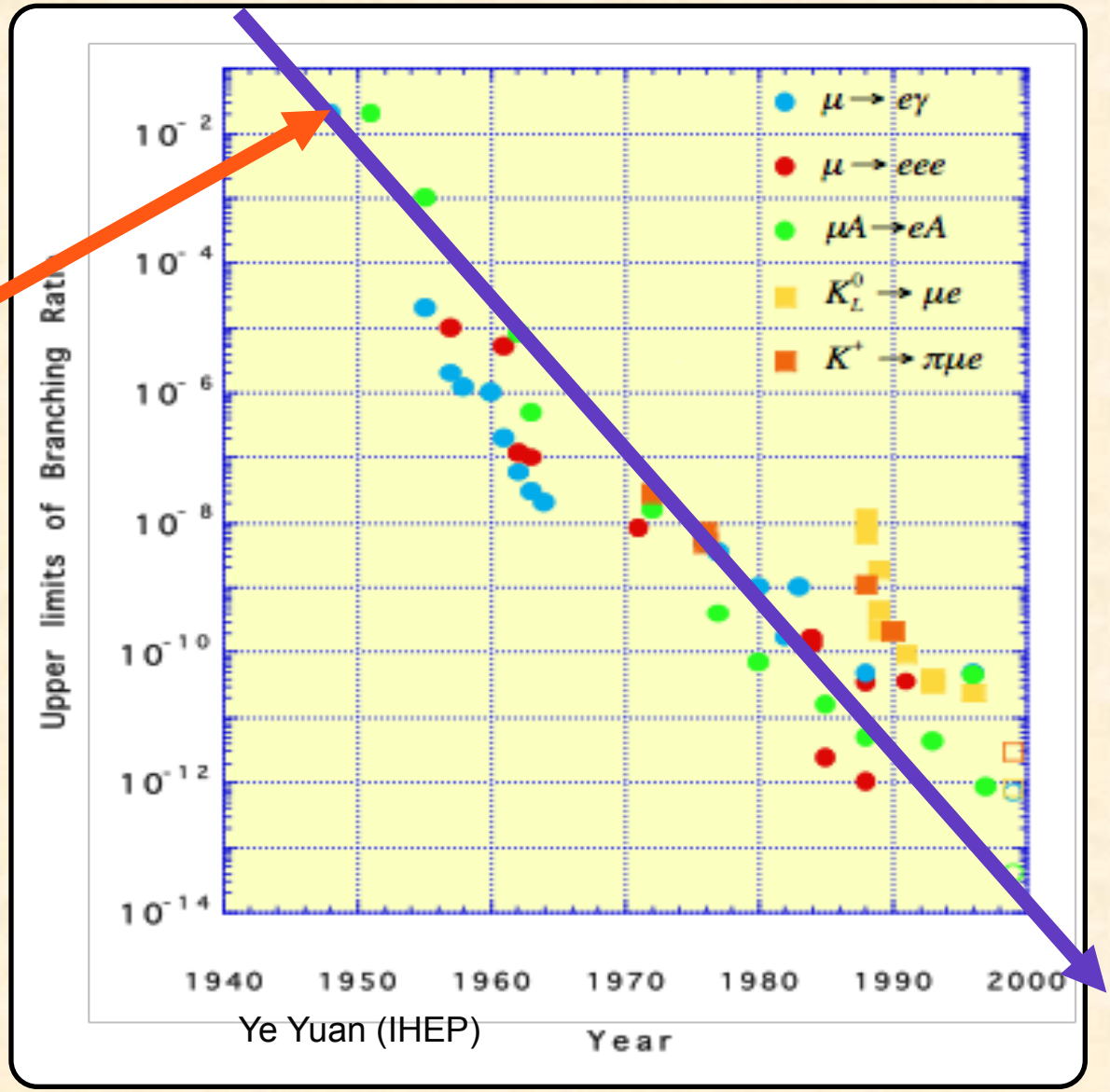


BR~O(10^{-54})

Clear signal of BSM once observed

Pursuit by continuous experiments

Pontecorvo,1947



Ye Yuan (IHEP)

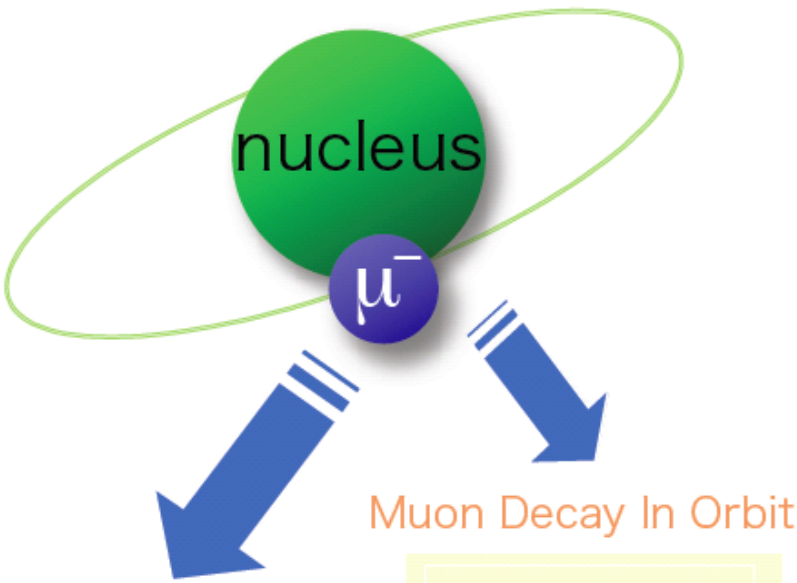
Current limits and expected future

Latest update

process	present limit	future	
$\mu \to e\gamma$	$<4.2 \times 10^{-13}$	$<10^{-14}$	MEG at PSI
$\mu \to eee$	$<1.0 \times 10^{-12}$	$<10^{-16}$	Mu3e at PSI
$\mu N \to eN$ (in Al)	none	$<10^{-16}/10^{-17}$	Mu2e / COMET
$\mu N \to eN$ (in Ti)	$<4.3 \times 10^{-12}$	$<10^{-19}$	PRISM
$\tau \to e\gamma$	$<1.1 \times 10^{-7}$	$<10^{-9} - 10^{-10}$	superKEKB
$\tau \to eee$	$<3.6 \times 10^{-8}$	$<10^{-9} - 10^{-10}$	superKEKB
$\tau \to \mu\gamma$	$<4.5 \times 10^{-8}$	$<10^{-9} - 10^{-10}$	superKEKB
$\tau \to \mu\mu\mu$	$<3.2 \times 10^{-8}$	$<10^{-9} - 10^{-10}$	superKEKB/LHCb

μ→e conversion

1s state in a muonic atom



$$\mu^- \rightarrow e^- \nu \bar{\nu}$$

nuclear muon capture

$$\mu^- + (A,Z) \rightarrow \nu_\mu + (A,Z-1)$$

Neutrino-less muon nuclear capture (=μ-e conversion)

$$\mu^- + (A,Z) \rightarrow e^- + (A,Z)$$

✓ Signal:

monoenergetic electron

104.96 MeV for Al, 95.56 MeV for Au

✓Main background：

Muon Decay in Orbit （10^{-16}）

Radiative muon Capture

$$\mu^-(A,Z) \rightarrow \gamma(A,Z-1)^* \nu_\mu$$

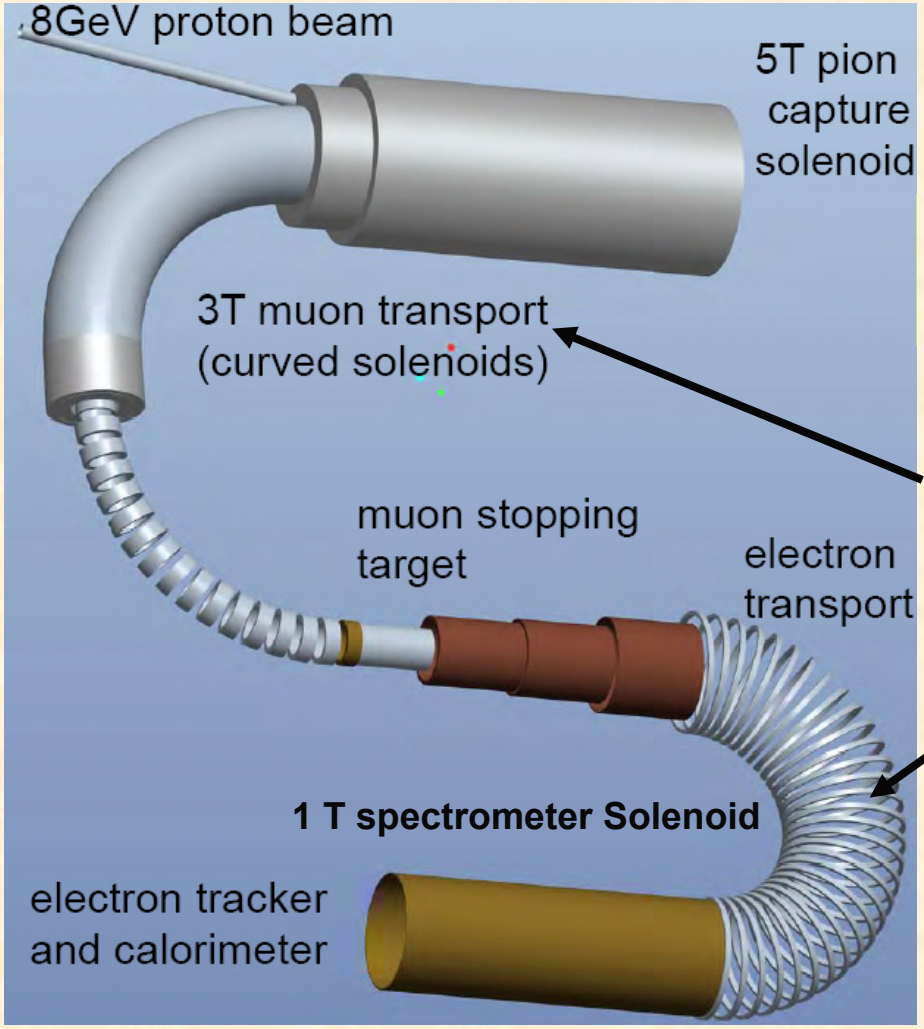
Radiative pion capture

$$\pi^- + (A,Z) \rightarrow (A,Z-1)^* \rightarrow \gamma + (A,Z-1)$$

$$\gamma \rightarrow e^+ e^-$$

✓ No limit from random background

μ→e conversion: COMET(E21) at J-PARC



- Pulsed proton beam
- 10^{11} muons/stops/sec. for 56kW proton beam power
- Curved solenoids for muon charge and momentum selection
- C-shaped transport for better Pμ selection
- C-shaped detector section eliminates low-*E DIO* **electron** and protons.

COMET Collaboration

175+collaborators,
34 institutes
From 15 countries

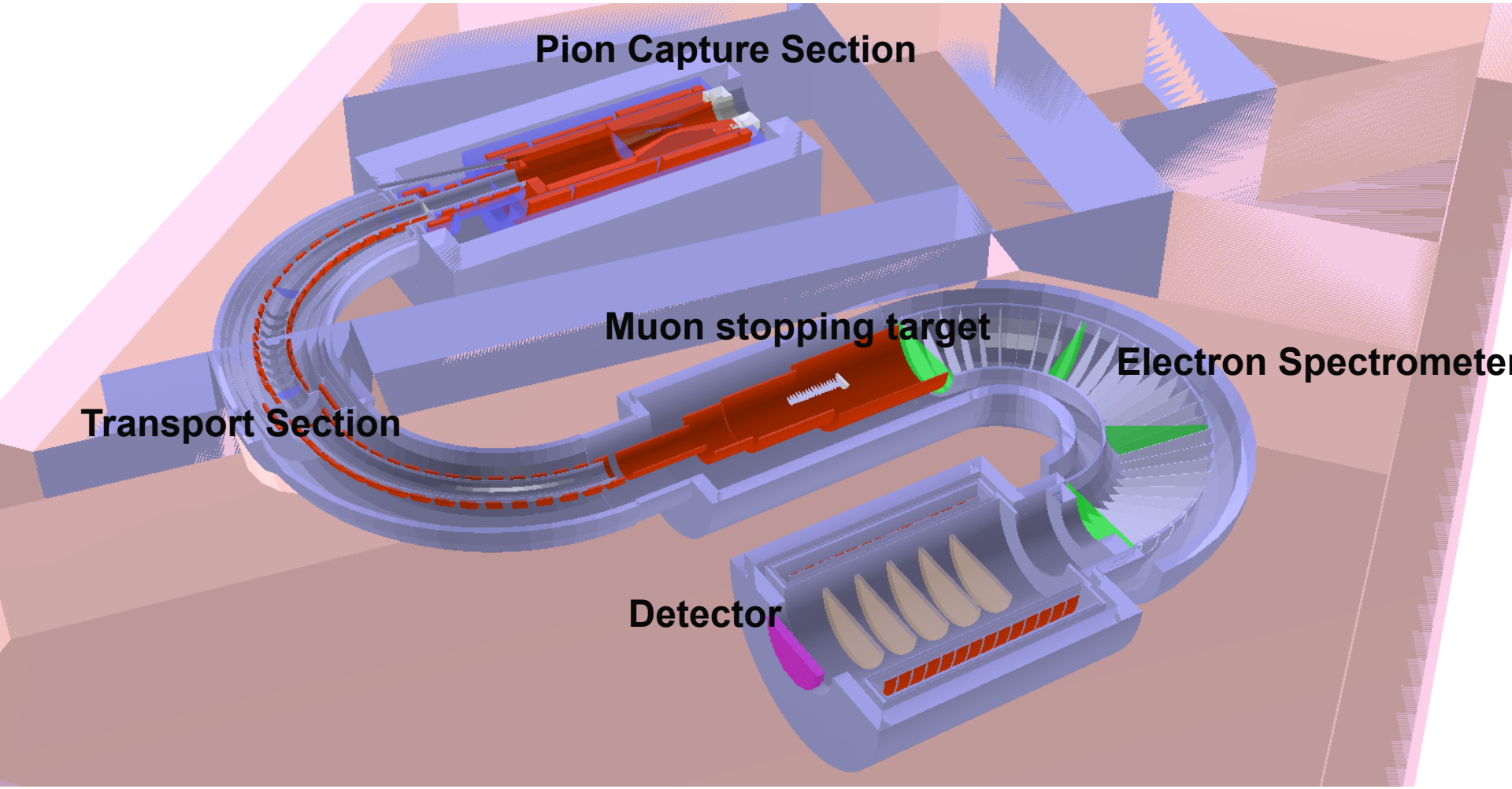
The COMET Collaboration

R. Abramishvili[11], G. Adamov[11], R. Akhmetshin[6,31], V. Anishchik[4], M. Aoki[32], Y. Arimoto[18], I. Bagaturia[11], Y. Ban[3], A. Bondar[6,31], Y. Calas[7], S. Canfer[33], Y. Cardenas[7], S. Chen[28], Y. E. Cheung[28], B. Chiladze[35], D. Clarke[33], M. Danilov[15,26], P. D. Dauncey[14], W. Da Silva[23], C. Densham[33], G. Devidze[35], P. Dornan[14], A. Drutskoy[15,26], V. Duginov[16], L. Epshteyn[6,30,31], P. Evtoukhovich[16], G. Fedotovich[6,31], M. Finger[8], M. Finger Jr[8], Y. Fujii[18], Y. Fukao[18], E. Gillies[14], D. Grigoriev[6,30,31], K. Gritsay[16], E. Hamada[18], R. Han[1], K. Hasegawa[18], I. H. Hasim[32], O. Hayashi[32], Z. A. Ibrahim[24], Y. Igarashi[18], F. Ignatov[6,31], M. Iio[18], M. Ikeno[18], K. Ishibashi[22], S. Ishimoto[18], T. Itahashi[32], S. Ito[32], T. Iwami[32], X. S. Jiang[2], P. Jonsson[14], T. Kachelhoffer[7], V. Kalinnikov[16], F. Kapusta[23], H. Katayama[32], K. Kawagoe[22], N. Kazak[5], V. Kazanin[6,31], B. Khazin[6,31], A. Khvedelidze[16,11], T. K. Ki[18], M. Koike[39], G. A. Kozlov[16], B. Krikler[14], A. Kulikov[16], E. Kulish[16], Y. Kuno[32], Y. Kuriyama[21], Y. Kurochkin[5], A. Kurup[14], B. Lagrange[14,21], M. Lancaster[38], M. J. Lee[12], H. B. Li[2], W. G. Li[2], R. P. Litchfield[14,38], T. Loan[29], D. Lomidze[11], I. Lomidze[11], P. Loveridge[33], G. Macharashvili[35], Y. Makida[18], Y. Mao[3], O. Markin[15], Y. Matsumoto[32], A. Melnik[5], T. Mibe[18], S. Mihara[18], F. Mohamad Idris[24], K. A. Mohamed Kamal Azmi[24], A. Moiseenko[16], Y. Mori[21], M. Moritsu[32], E. Motuk[38], Y. Nakai[22], T. Nakamoto[18], Y. Nakazawa[32], J. Nash[14], J. -Y. Nief[7], M. Nioradze[35], H. Nishiguchi[18], T. Numao[36], J. O'Dell[33], T. Ogitsu[18], K. Oishi[22], K. Okamoto[32], C. Omori[18], T. Ota[34], J. Pasternak[14], C. Plostinar[33], V. Ponariadov[45], A. Popov[6,31], V. Rusinov[15,26], B. Sabirov[16], N. Saito[18], H. Sakamoto[32], P. Sarin[13], K. Sasaki[18], A. Sato[32], J. Sato[34], Y. K. Semertzidis[12,17], N. Shigyo[22], D. Shoukavy[5], M. Slunecka[8], A. Straessner[37], D. Stöckinger[37], M. Sugano[18], Y. Takubo[18], M. Tanaka[18], S. Tanaka[22], C. V. Tao[29], E. Tarkovsky[15,26], Y. Tevzadze[35], T. Thanh[29], N. D. Thong[32], J. Tojo[22], M. Tomasek[10], M. Tomizawa[18], N. H. Tran[32], H. Trang[29], I. Trekov[35], N. M. Truong[32], Z. Tsamalaidze[16,11], N. Tsverava[16,35], T. Uchida[18], Y. Uchida[14], K. Ueno[18], E. Velicheva[16], A. Volkov[16], V. Vrba[10], W. A. T. Wan Abdullah[24], M. Warren[38], M. Wing[38], M. L. Wong[32], T. S. Wong[32], C. Wu[2,28], H. Yamaguchi[22], A. Yamamoto[18], T. Yamane[32], Y. Yang[22], W. Yao[2], B. K. Yeo[12], H. Yoshida[32], M. Yoshida[18], Y. Yoshii[18], T. Yoshioka[22], Y. Yuan[2], Yu. Yudin[6,31], J. Zhang[2], Y. Zhang[2], K. Zuber[37]

+more

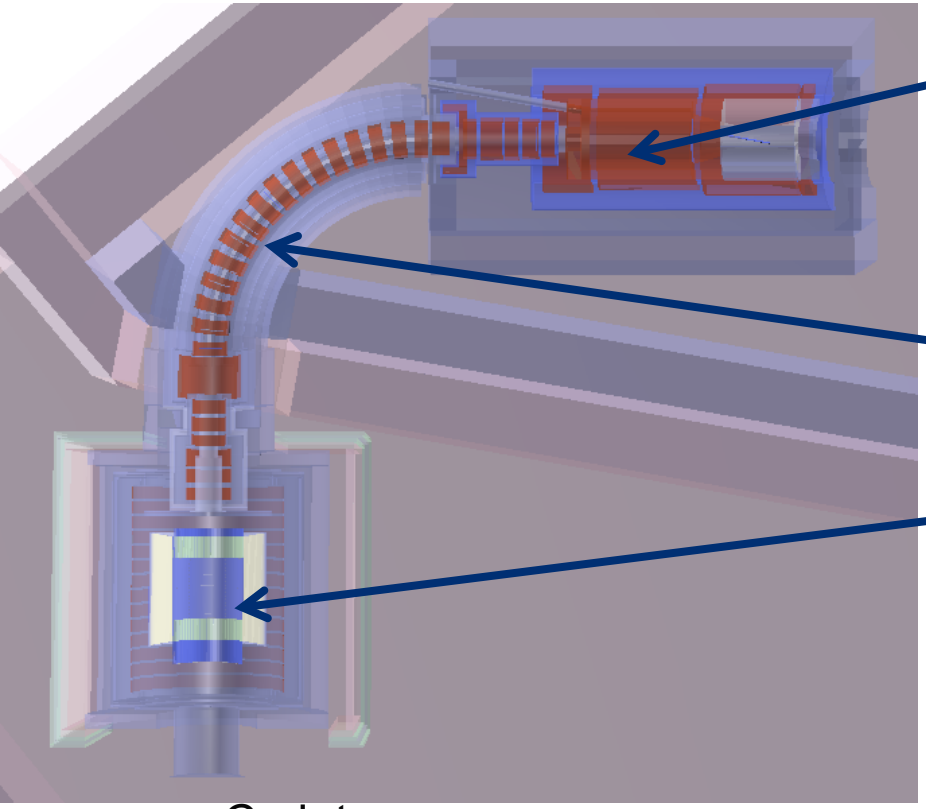
Phased approach

COMET(Phase-II)



Aiming at 3×10^{-17}, 10000 times better than the current limit

COMET(Phase-I）

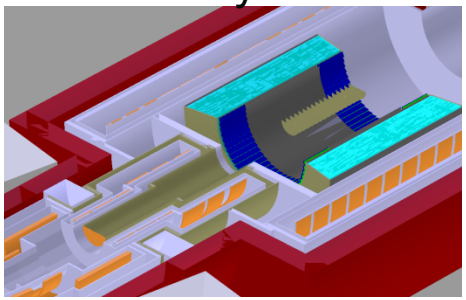


Pion Capture Section
Has a high(5T) magnetic field to collect the low momentum, backwards travelling pions, same to Phase-II, 3.2KW proton beam

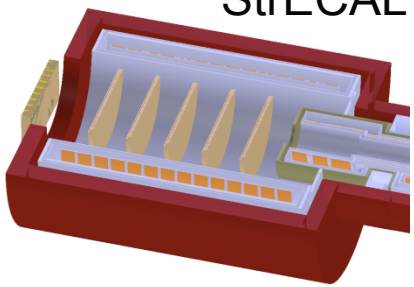
Muon Transport section
Construct to the first 90 degree

Phase-I Detector
A cylindrical drift chamber system(Cydet) for the μ→e conversion search
A prototype ECAL and straw tube tracker (StrECAL) for beam and background studies

Cydet



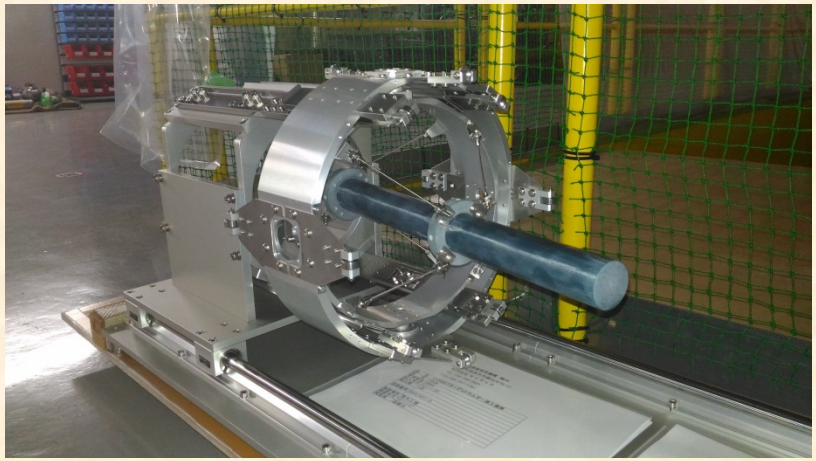
StrECAL

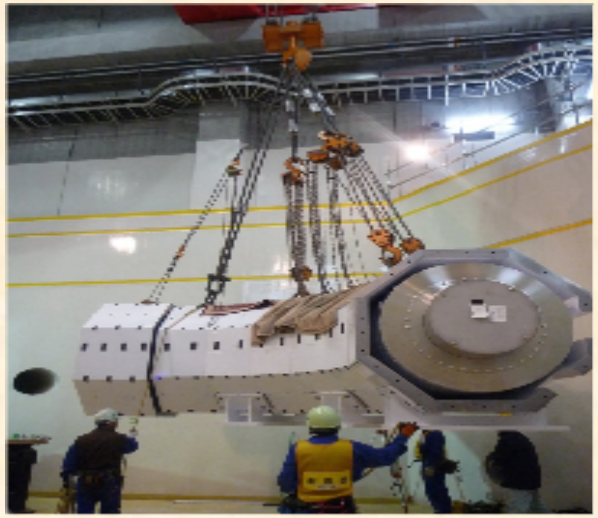


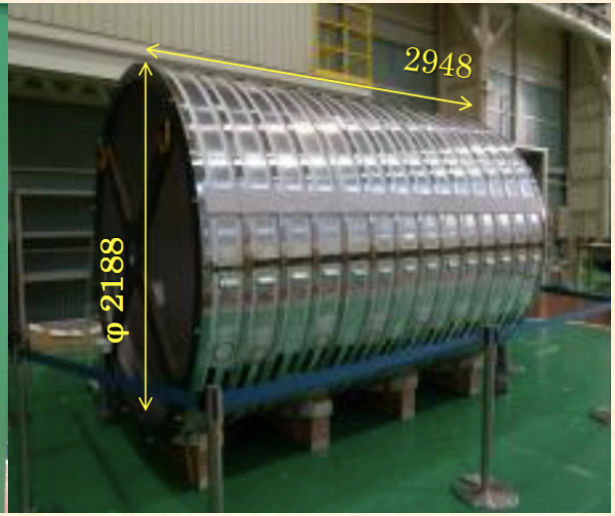
Phase-I Aims
Search for μ→e conversion process with a
S.E.S. of 3×10^{-15}
Beam and background study for Phase-II

Magnet and target

- Proton target: R=13mm, L=700mm, prototype is maked
- Muon transport solenoid completed
- Pion capture solenoid is under winding
- Detector solenoid is assembled







COMET Hall

Hall construct completed;
Beamline under constructing

Cylindrical drift chamber (CDC)

- All stereo layers
- He base gas
- 19 layers structure
  - ~5,000 sense wires
  - ~15,000 filed wires

Prototype chamber tests show spatial resolution <200μm, momentum resolution σ_p ~200keV/c

Construction started in 2014 and completed on June 2016

Highlights of Last year

TDR had been submitted

TDR

Choice of Journal for Publication

Proposal from host nation/laboratory:

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Progress of Experimental and Theoretical Physics
------------------------------------------------
https://academic.oup.com/ptep
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Progress of Theoretical and Experimental Physics (PTEP) is an international journal that publishes articles on theoretical and experimental physics. PTEP is a fully open access, online-only journal published by the Physical Society of Japan.

PTEP is the successor to Progress of Theoretical Physics (PTP), which terminated in December 2012 and merged into PTEP in January 2013.

PTP was founded in 1946 by Hideki Yukawa, the first Japanese Nobel Laureate. PTEP, the successor journal to PTP, has a broader scope than that of PTP covering both theoretical and experimental physics.

PTEP mainly covers areas including particles and fields, nuclear physics, astrophysics and cosmology, beam physics and instrumentation, and general and mathematical physics.

The journal is published by Oxford University Press on behalf of the Physical Society of Japan, and in the past has published design or physics potential reports for Hyper-K, T2K, J-PARC, KEKB, SuperKEKB, amongst others.

Unanimous agreement by CB to submit TDR Part 1 to PTEP

Can we achieve more?

Competition from Mu2e-II: 10^{-18}

The Phase-II study group has started some optimization as follows.

Proton target

Muon target

Beam Blocker and DIO blocker

Single Event Sensitivity

$$\mathrm{SES} = \frac{1}{N_p \cdot R_{\mu/p} \cdot B_{\mathrm{cap}} \cdot A_{\mu\to e} \cdot t_{\mathrm{run}}},$$

	this study	Ben's study [4]	Improvement factor	
N_{p}	4.3×10^{13}	4.3×10^{13}		
$R_{\mu/p}$	4.8×10^{-3}	1.61×10^{-3}	3	3.7
B_{cap}	0.61	0.61		
$A_{\mu\to e}$	0.114	0.057	2	
t_{run}	3×10^{7}	1.57×10^{7}	1.9	1.3
S.E.S	2.3×10^{-18}	2.6×10^{-17}	11	14

1.8×10^{-18}

Preliminary

White Paper: COMET

COMET white paper to the 2020 update of the European Strategy for Particle Physics, by COMET collaborations.

- Scientific context
- Methodology
  - COMET Phase-II
  - Phase-I
  - PRISM
- European Contribution
- Summary

COMET

J.-C. Angélique, C. Cârloganu, W. da Silva, A. Drutskoy, M. Finger, D. N. Grigoriev, T. Kachelhoffer, F. Kapusta, Y. Kuno[1], P. Lebrun, R. P. Litchfield, D. Lomidze, D. Shoukavy, A. M. Teixeira, I. Tevzadze, Z. B. Tsamalaidze, Y. Uchida, V. Vrba, K. Zuber

A submission to the 2020 update of the European Strategy for Particle Physics on behalf of the COMET collaboration.

Abstract

The search for charged lepton flavour violation (CLFV) has enormous discovery potential in probing new physics Beyond the Standard Model (BSM). The observation of a CLFV transition would be an undeniable sign of the presence of BSM physics which goes beyond non-zero masses for neutrinos. Furthermore, CLFV measurements can provide a way to distinguish between different BSM models, which may not be possible through other means. So far muonic CLFV processes have the best experimental sensitivity because of the huge number of muons which can be produced at several facilities world-wide, and in the near future, new muon beam-lines will be built, leading to increases in beam intensity by several orders of magnitude. Among the muonic CLFV processes, $\mu \to e$ conversion is one of the most important processes, having several advantages compared to other such processes.

We describe the COMET experiment, which is searching for $\mu \to e$ conversion in a muonic atom at the J-PARC proton accelerator laboratory in Japan. The COMET experiment has taken a staged approach; the first stage, COMET Phase-I, is currently under construction at J-PARC, and is aiming at a factor 100 improvement over the current limit. The second stage, COMET Phase-II is seeking another 100 improvement (a total of 10,000), allowing a single event sensitivity (SES) of 2.6×10^{-17} with 2×10^7 seconds of data-taking. Further improvements by one order of magnitude, which arise from refinements to the experimental design and operation, are being considered whilst staying within the originally-assumed beam power and beam time. Such a sensitivity could be translated into probing many new physics constructions up to $\mathcal{O}(10^4)$ TeV energy scales, which would go far beyond the level that can be reached directly by collider experiments. The search for CLFV $\mu \to e$ conversion is thus highly complementary to BSM searches at the LHC.

[1]contact person: kuno@phys.sci.osala-u.ac.jp.

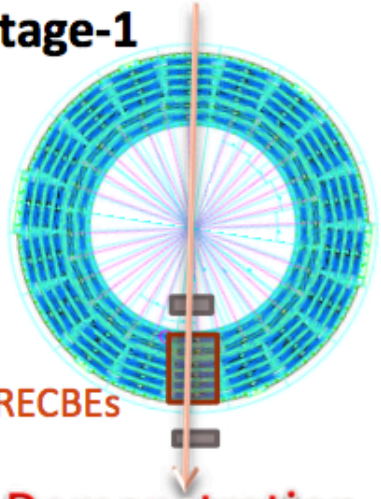
Cosmic-ray Test

- CDC cosmic-ray test (CRT) is ongoing.
- @ Fuji hall in KEK, Tsukuba
- Step-by-step upgrade
- Electronics, DAQ, Slow control, Analysis
- Bringing up experts

Plan of CDC cosmic-ray test

We are here now !!

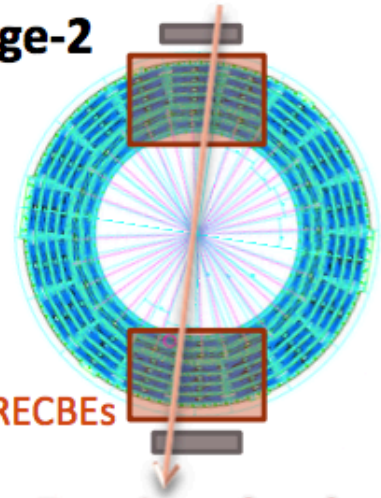
Stage-1



Demonstration

Establish cosmic-ray test setup and analysis

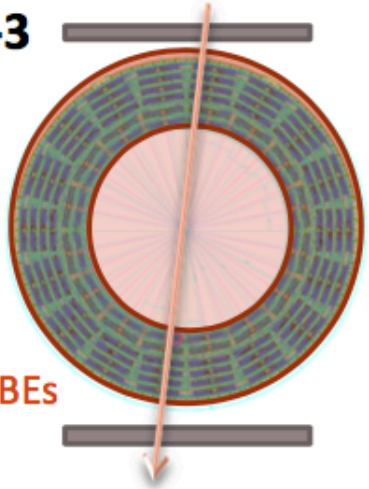
Stage-2



Precise check

Elec. trigger upgrade &
Detail performance check

Stage-3

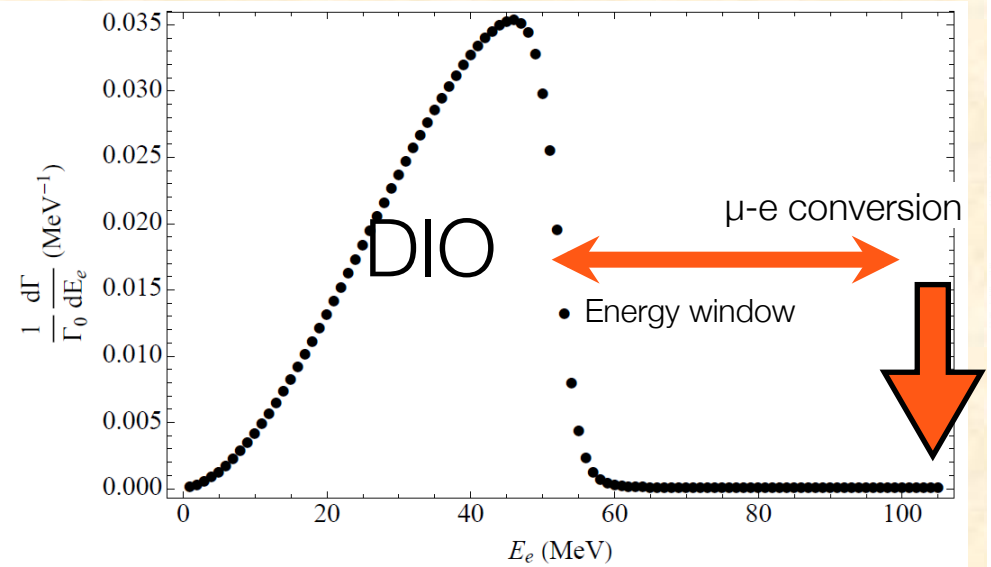


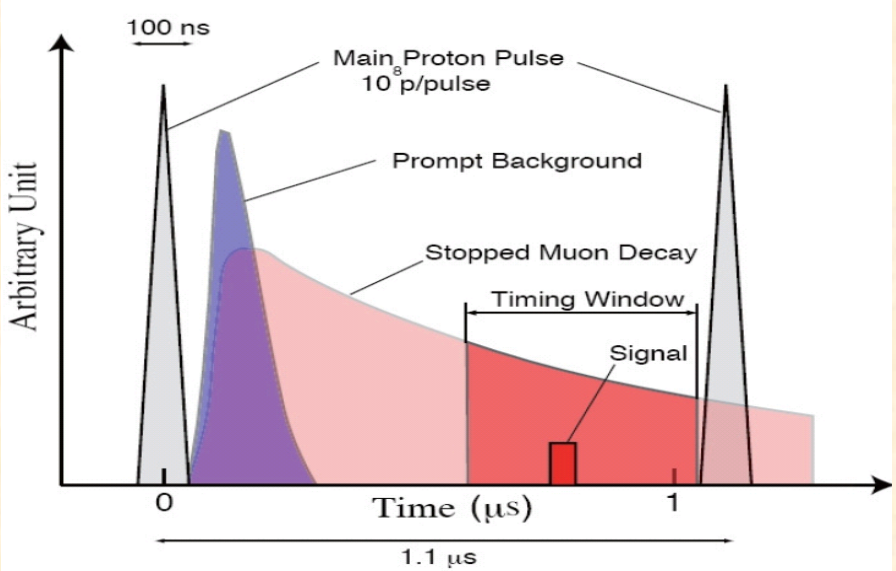
Full test

Full setup operation

Activities from France & China

What we needed





Require:

High momentum resolution

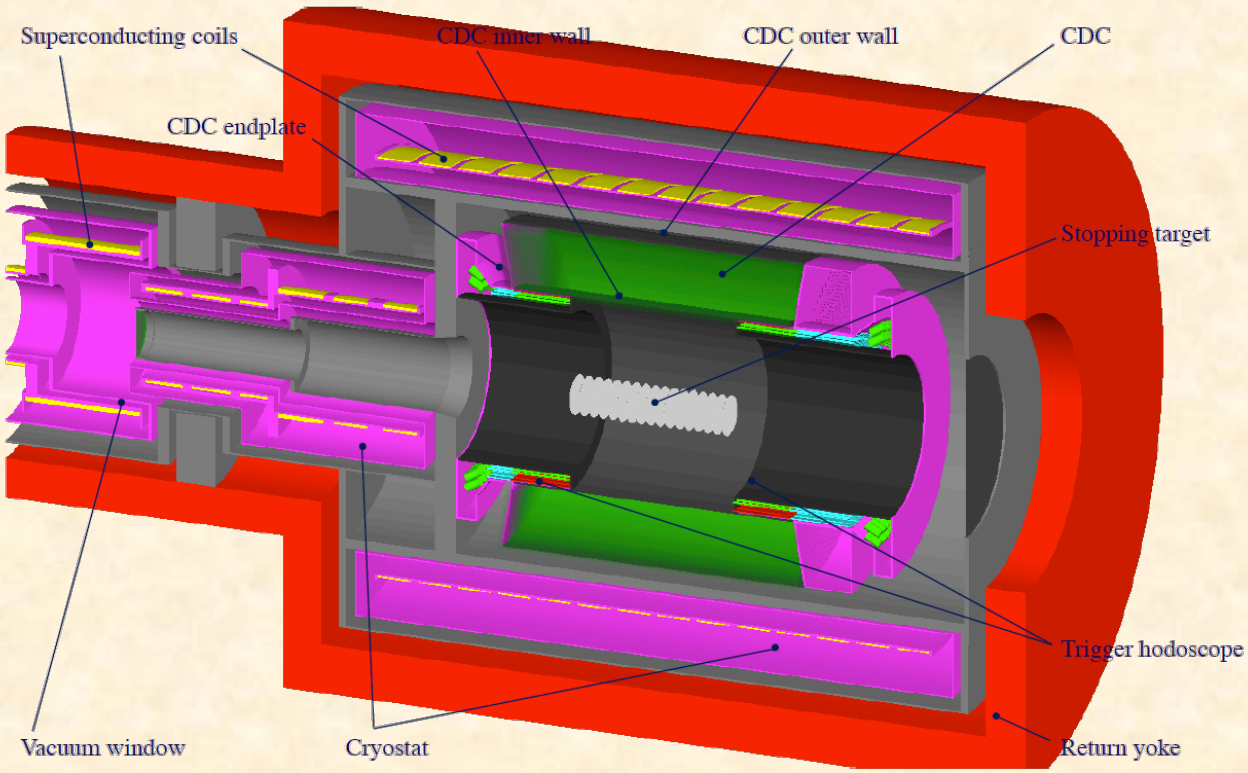
Pulsed beam

Excellent proton extinction

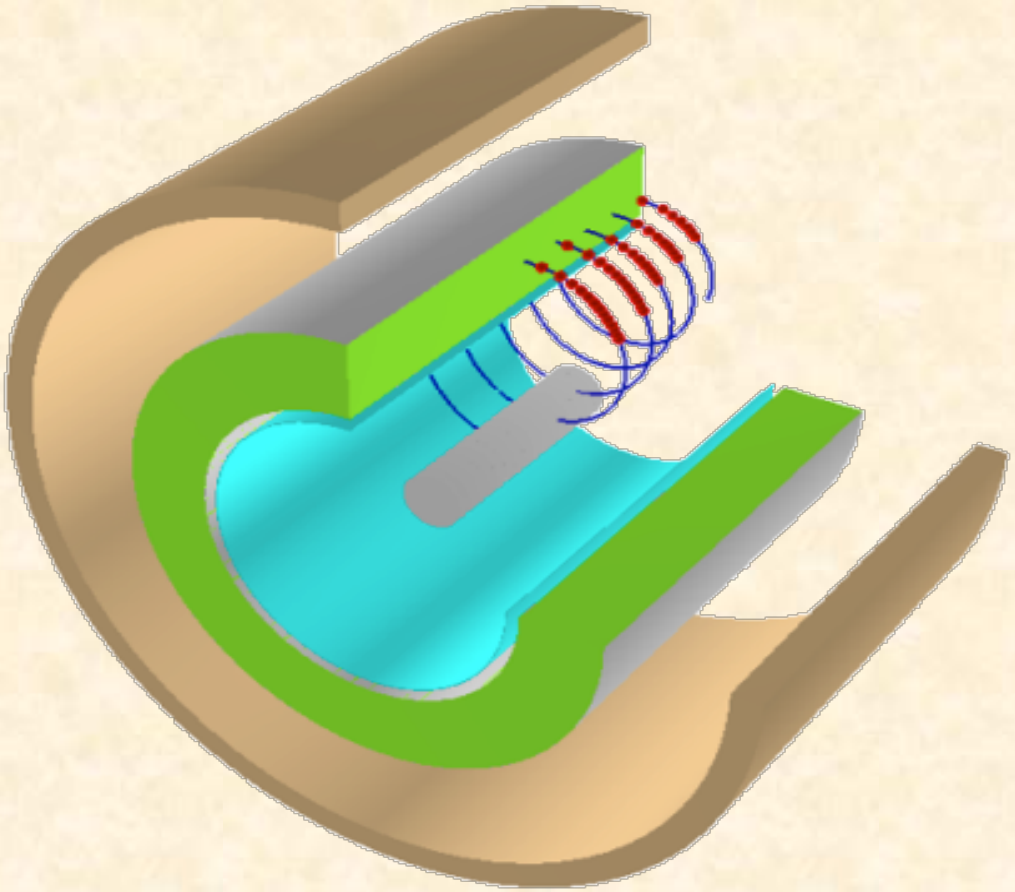
Perfect background suppress

High intensity beam

COMET Phase-I Detector -- CyDet

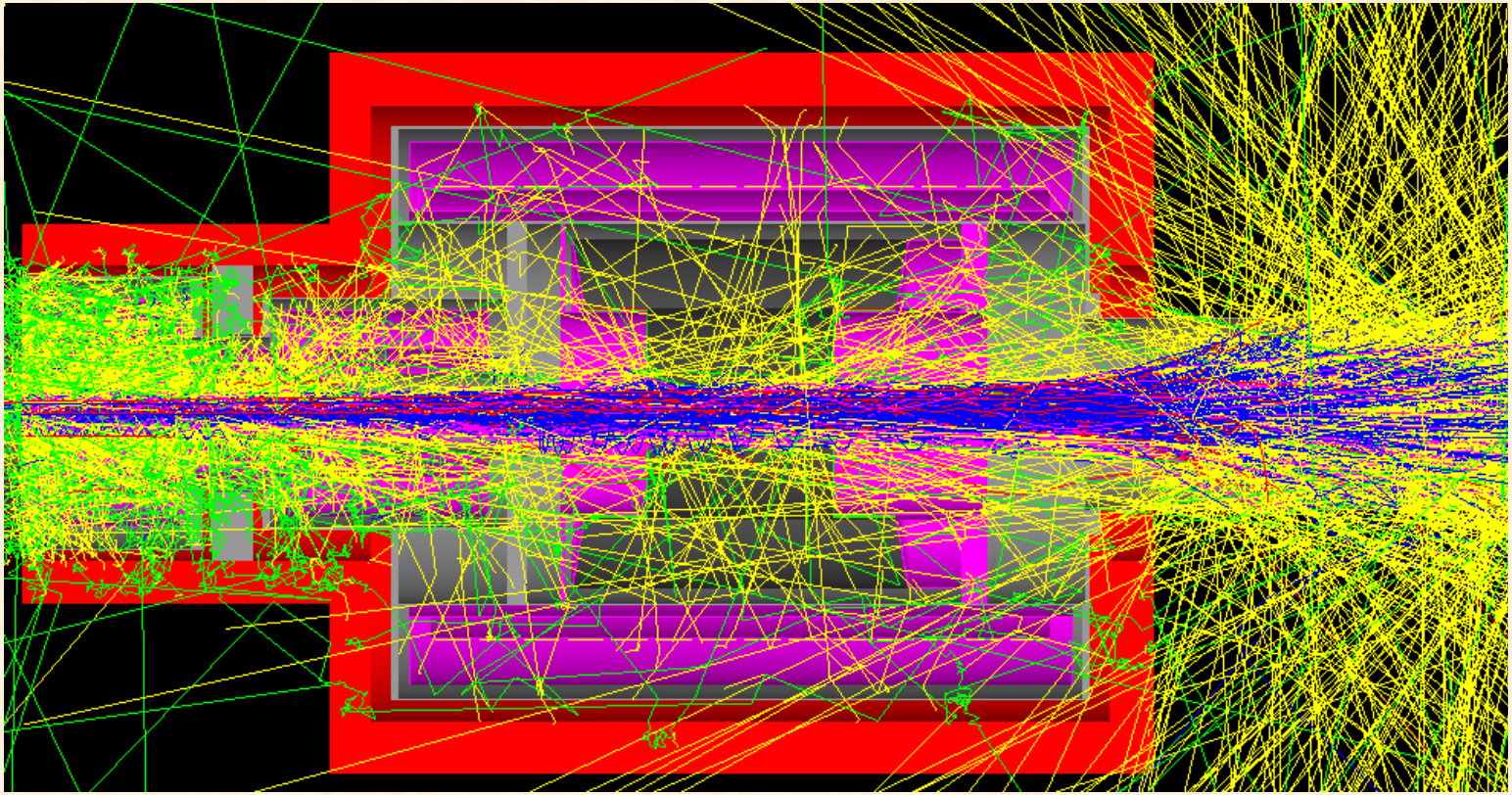


- A large Cylindrical drift chamber in a 1T solenoid magnet
- Trigger hodoscope (Plastic scintillator + Cherenkov)
- **Excellent momentum resolution** ~200keV needed



Particles curved before reach trigger,
38% tracks after trigger will be multi-turn,
at most 3 turns of track are hoped to be reconstructed,
so multi-turn hits distinguish is important

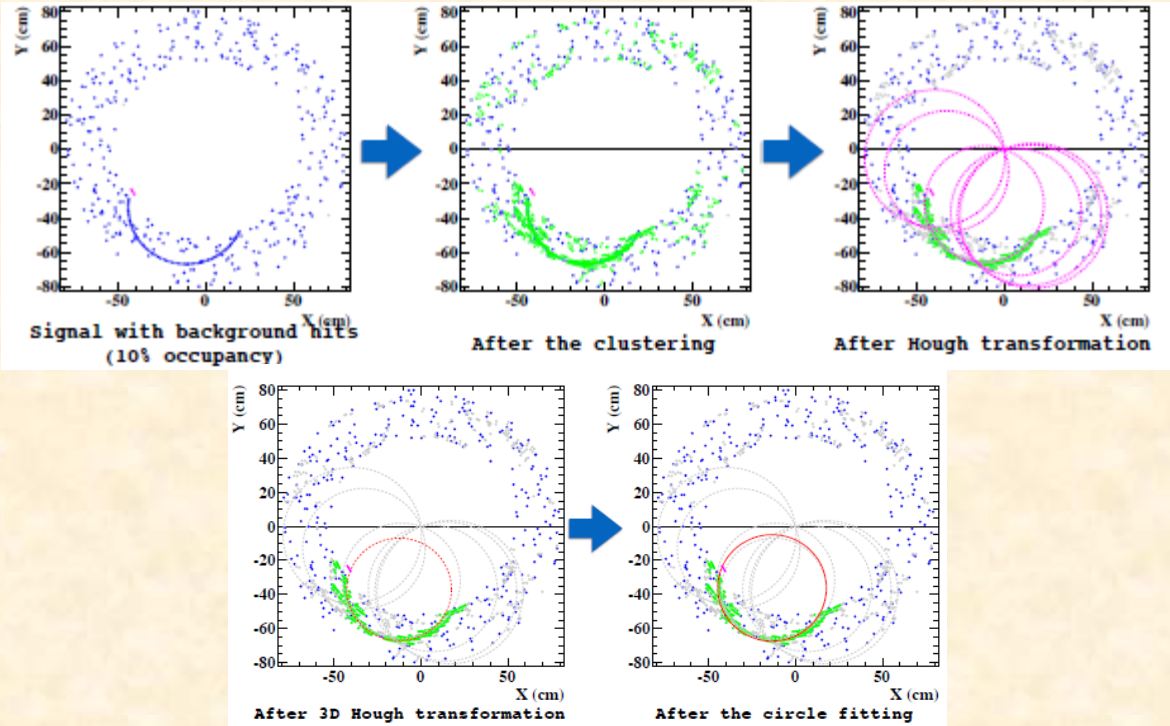
Mass simulation is essential for COMET for background suppress and tracking study

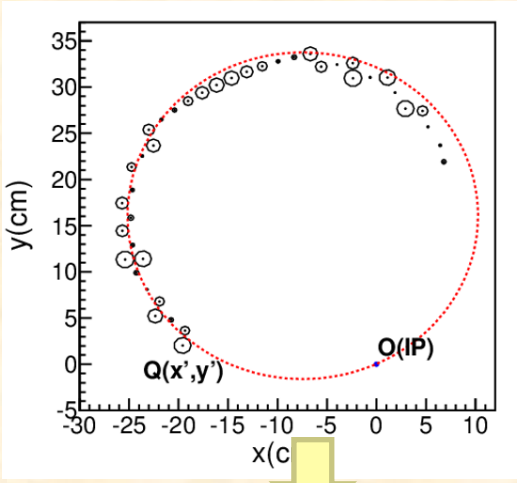


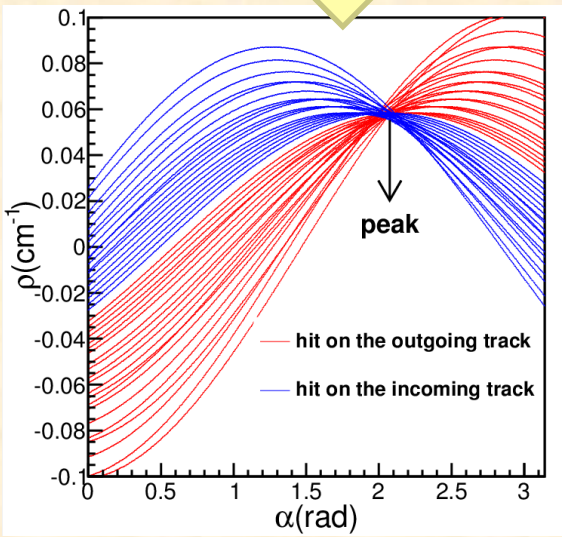
Track Finding 1

(IHEP)

- Hough transformation
  - Clustering neighbor layer hits
  - Conformal mapping and Hough transform
  - 3D Hough transform
  - Circle fitting



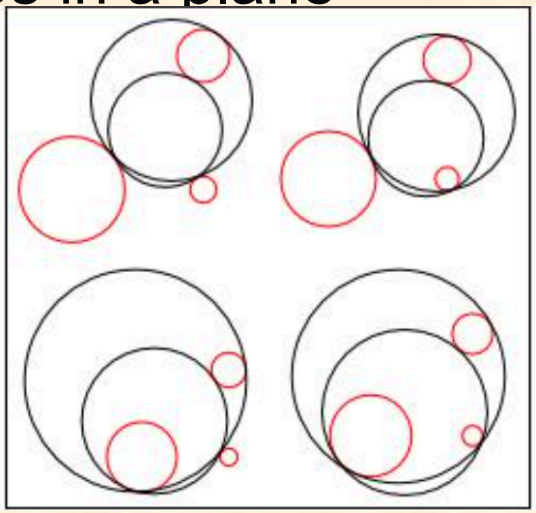




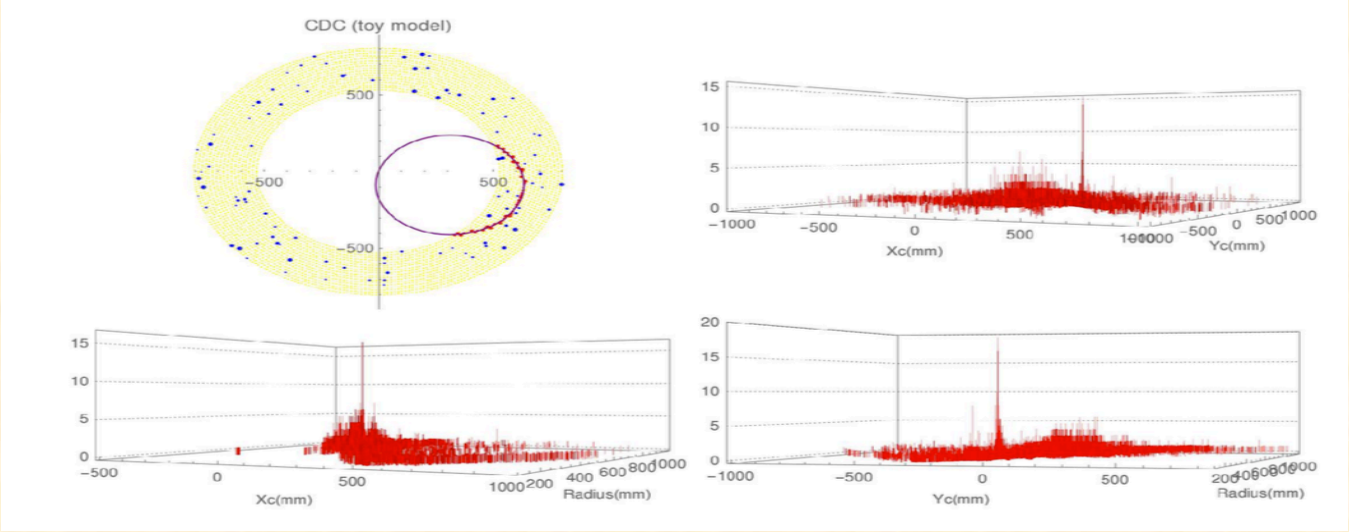
Track Finding 2

- Apollonius circle (LPHNE)

8 circles that are tangent to three given circles in a plane



1.Order hits by nearest distance
2 Take 3 hits not too near
3 Compute the 8 Apollonius circles
4 Store Xc, Yc center and Radius of all Apollonius circle in 3D accumulator,
5 Redo with 3 new hits · · · until end.
6 Plot distribution results (left figure)

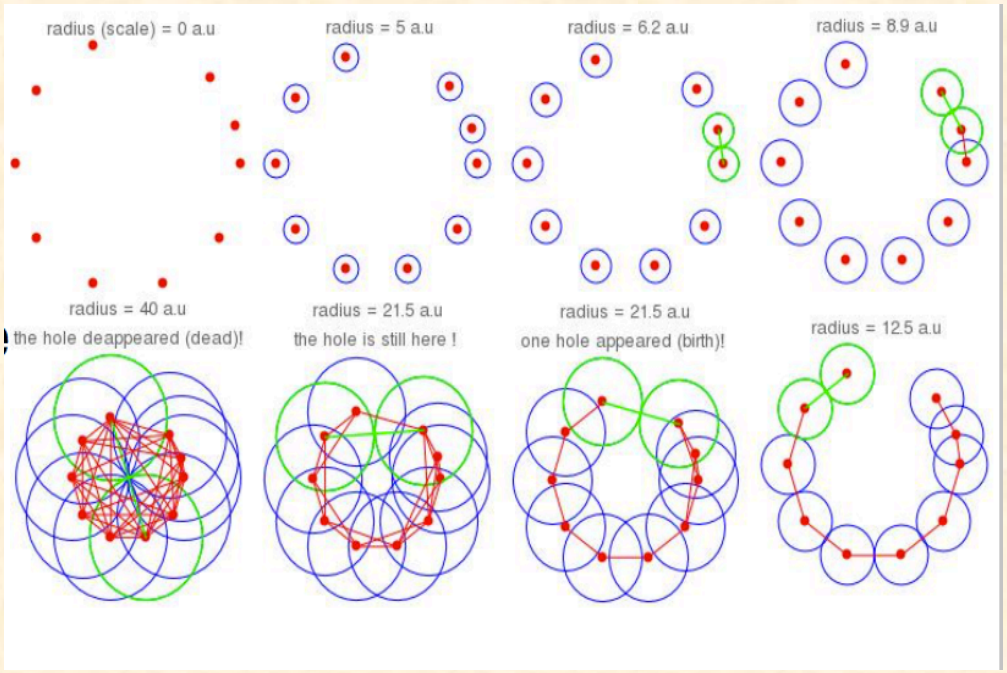


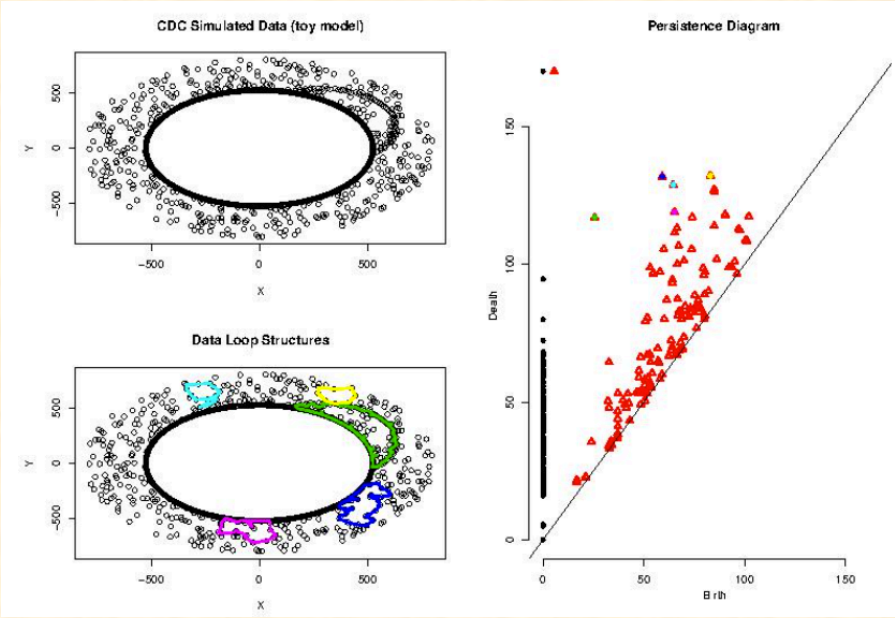
Track Finding 3

(LPHNE)

- Persistent Homology in Topological Data Analysis (TDA)

A general mathematical framework to encode the evolution of the topoly (homology) of famillies of nested spaces (filtered complex, sublevel set, · · ·)



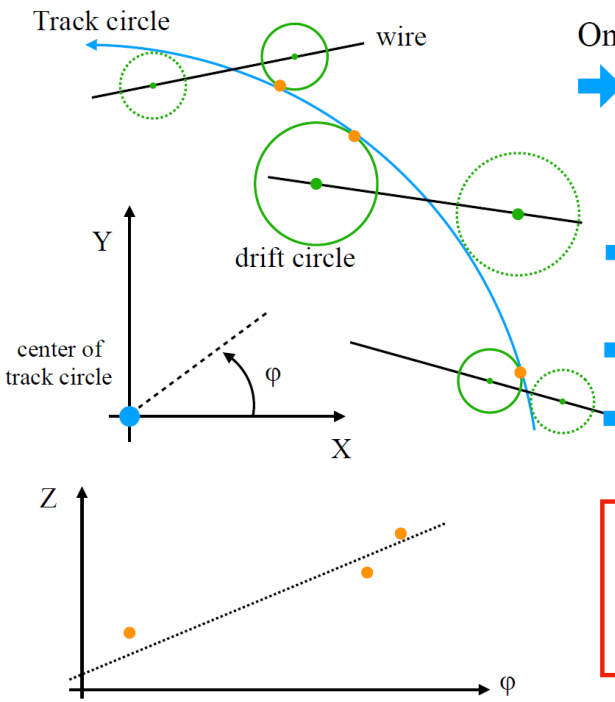


Drift Chamber Circle-Linear Fitting(China)

Circle-Linear Fitting

Assuming Track is Helix

Initial circle parameter (X_{center}, Y_{center}, radius)
… by Hough Transform & rough fitting in XY



Once circle parameters are geven…

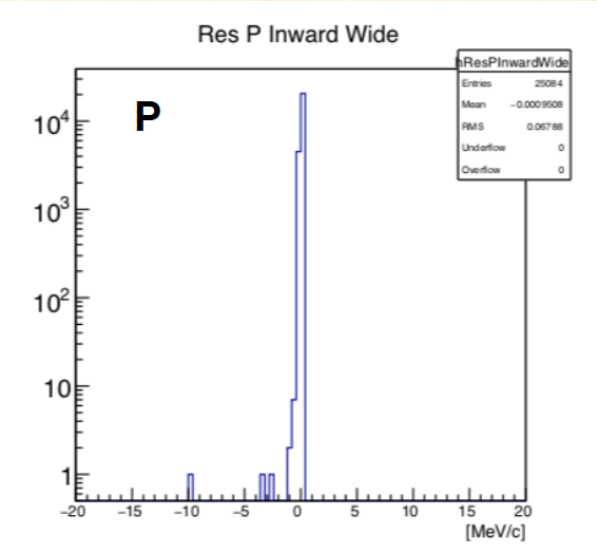
- Contact point between track and drift circle
  (sliding the center of drift circle along wire)

  <u>for fixed Left-Right assignment</u>

- Position of drift circle on wire
  → Z coordinate
- φ - Z coordinate
- Linear Fitting in φ-Z plane

The Point of This Method

Minimize chi square of linear fitting
by
<u>optimizing circle parameters</u>

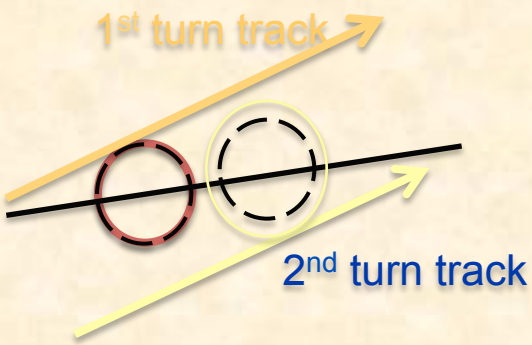


Helix Fitting

(IHEP&LPNHE)

- Multi-turn fitting based on hit competition by Genfit2
  1. Fit track with different turn hypothesis in parallel
  2. Hits associated to at least one track and calc. assignment weight to each track
  3. fit tracks iteratively with annealing scheme to avoid local minimum

one hit associated with two tracks



measured drift circle

fitted doca circle

fitted track

CDC wire

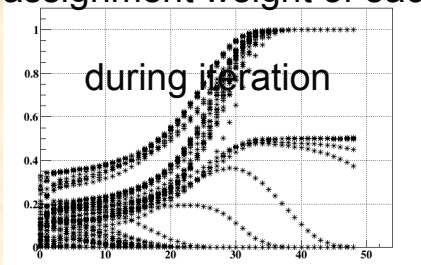
The possibility of hit *i* assigned to track *j* is defined as matrix Φ

$$(\Phi)_{ij} = \varphi_{ij} = \varphi(y_i; Hx_j, V_i),$$

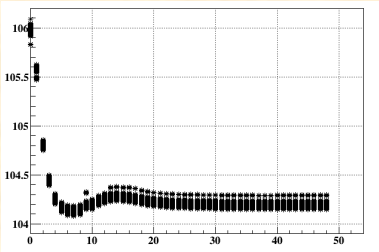
$$p_{i_k j} = \frac{\varphi_{i_k j}}{\sum_l \sum_\alpha \varphi_{i_\alpha l} + c}.$$

Assignment weight of hit i to track j

Hit assignment weight of each hit during iteration



fitted momentum at each iteration



Computing --- France, CCIN2P3

- CCIN2P3 is the main site of COMET computing
- Software version control
  - https://gitlab.in2p3.fr/
- CPU
  - 16 M HS06.hours per year
  - important consequences for high statistics MC production.
- Storage
  - iRODS, HPSS, SPS, XROOTD

Storage of CCIN2P3

- HPSS quota 215 TB
- XROOTD : 68 TB as HPSS Front End
- iRODS for storage also for data transfers between sites
  - space used : around 100 TB
- SPS ”hep/sps/comet” disk space quota : 25 TB.

GPU can be used from IN2P3 now

V100@CC-IN2P3 unboxing

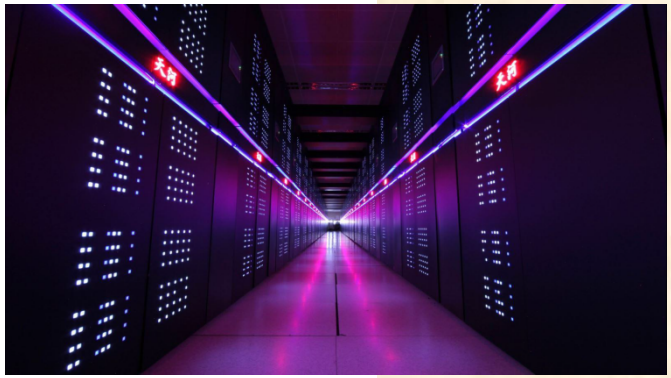
Track finding
Parallel fitting
Machine learning

Computing at China

中山大學 SUN YAT-SEN UNIVERSITY

国家超级计算广州中心 NATIONAL SUPERCOMPUTER CENTER IN GUANGZHOU

- Core hours 8,000,000 in 3 years for COMET
  - 50,000 core hours for test available now
- Job submission with 2000 nodes
  - 2000 nodes x 24 cords = 48,000 cords
- Data storage can extended to 10TB
- In theory data transfer speed from memory to disk : 20GB/s



- COMET Simulate 6000 CPU*hours(1 bunch) on Tianhe2

Communications

- W. da Silva and F. Kapusta visit IHEP for 3 days on Dec. 2018
- We had the discussion on software development and computing
- They gave two seminars on COMET and LEP experiments

- COMET and g-2/EDM Computing and Tracking Workshop

was hold in Paris on July 2018, Prof. YUAN Ye joined workshop

The Workshop helped to start the COMET-France project with LPNHE, LPC-Caen, LPC-Clermont, IPNL and CC-IN2P3

- Prof. YUAN Ye will visit LPNHE and cc-in2p3 on July 2019

Summary

- ✓ **CLFV has SM-free signal for New Physics at low energy and complementary to other physics.**
- ✓ **The COMET Phase-I is aiming at S.E. sensitivity of 3×10^{-15}**
- ✓ **Tracking and computing are the key challenges of COMET**
- ✓ **Synergy between China & France is important and improving**

Thanks!

CLFV Schedule in 2025 and beyond

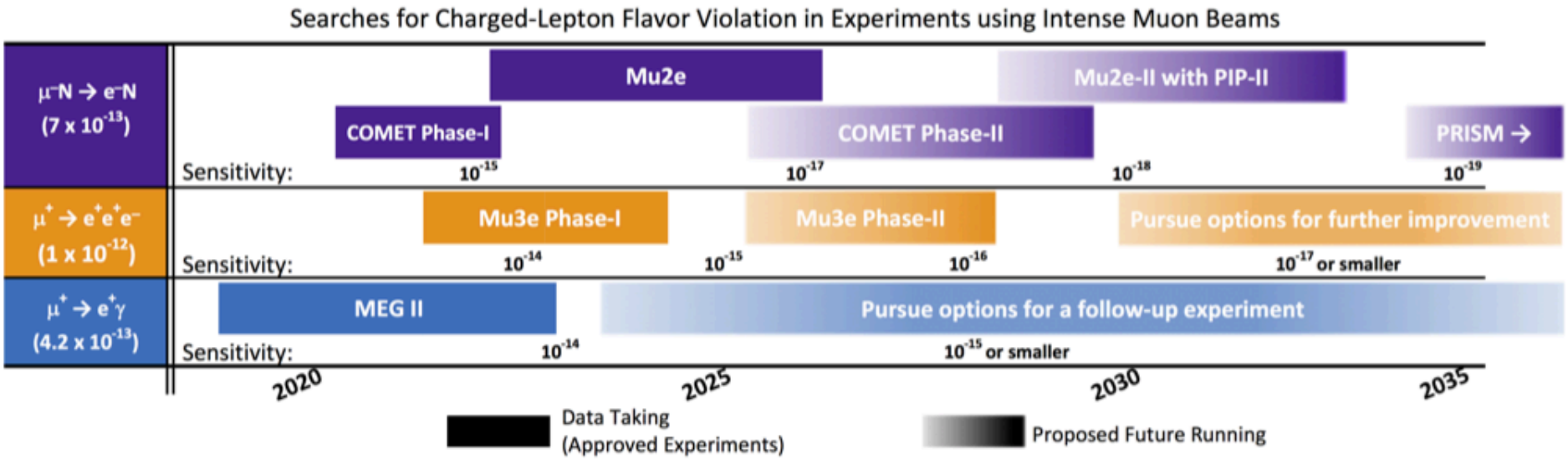


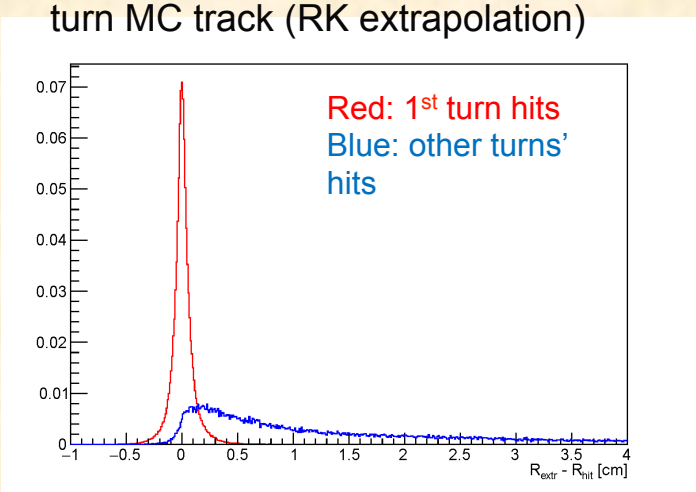
Figure 1: *Planned data taking schedules for current experiments that search for charged-lepton flavor violating $\mu \to e$ transitions. Also shown are possible schedules for future proposed upgrades to these experiments. The current best limits for each process are shown on the left in parentheses, while expected future sensitivities are indicated by order of magnitude along the bottom of each row.*

Tracking difficulty

- When the track is single turn, the tracking process is straightforward and a good result is expected.
  - Decided by spatial resolution and multiple scattering by chamber material (supposing enough hits).

- However multiple turn hits makes things difficult…
  - Hits from other turns are too close (sometimes even closer due to spatial resolution & Multi. Scat.) to the track, providing many local minima.
  - Longitudinal initial values are difficult to get without fitting.

Distance of multi-turn hits to 1st turn MC track (RK extrapolation)



Strategy

- Synergy between countries

  China, France, Japan, England, Korea,…

- Parallel algorithm study & corporate

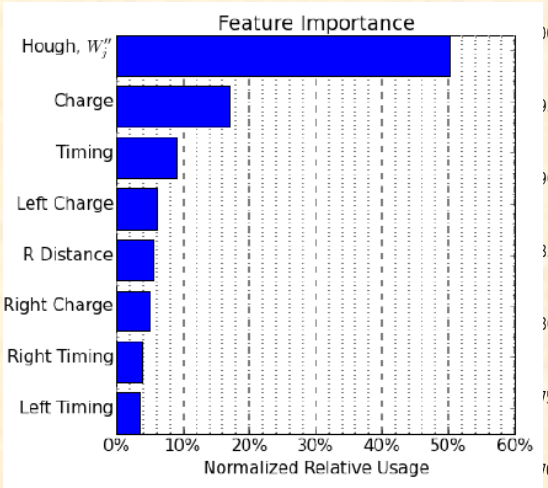
- Traditional methods and novel ideas

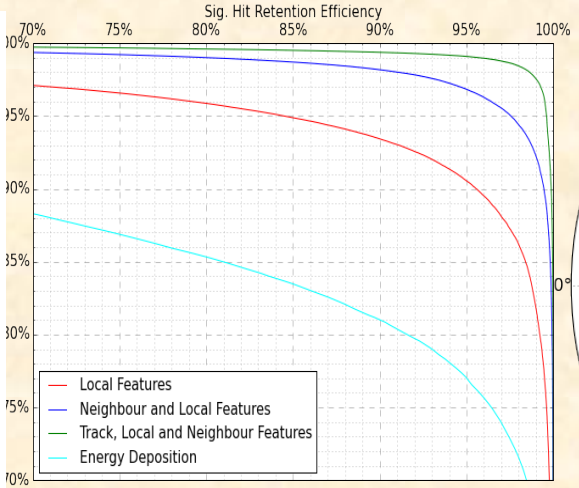
  Machine learning, Persistent Homology,…

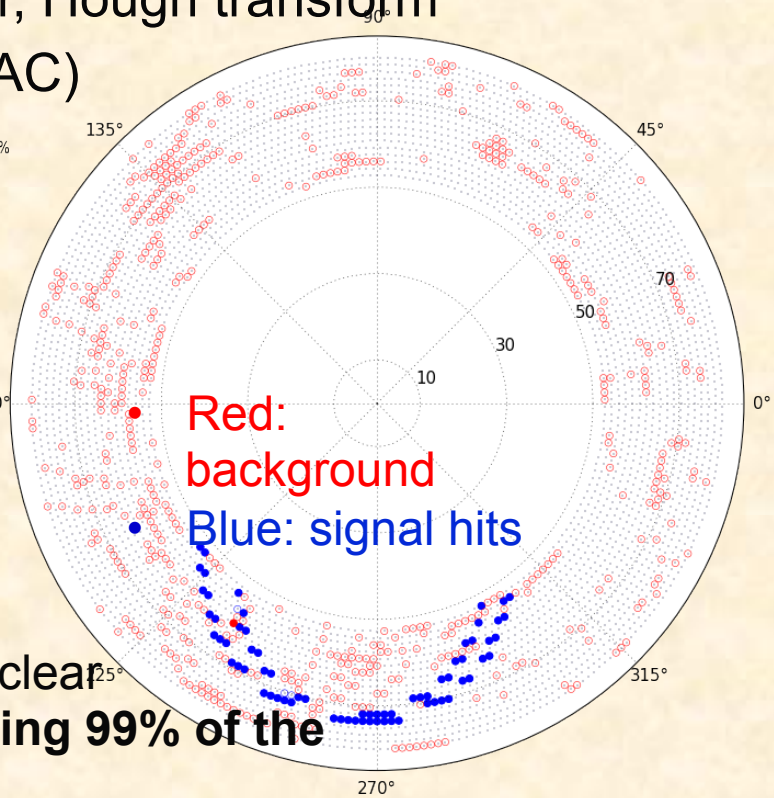
Hit Selection

(Imperial College of London)

- Hit selection using **G**radient **B**oosted **D**ecision **T**rees (GBDT) and Reweighted Inverse Hough Transform
- Classify hits using features: local, neighbor, Hough transform
- Fit track with random hit collection (RANSAC)







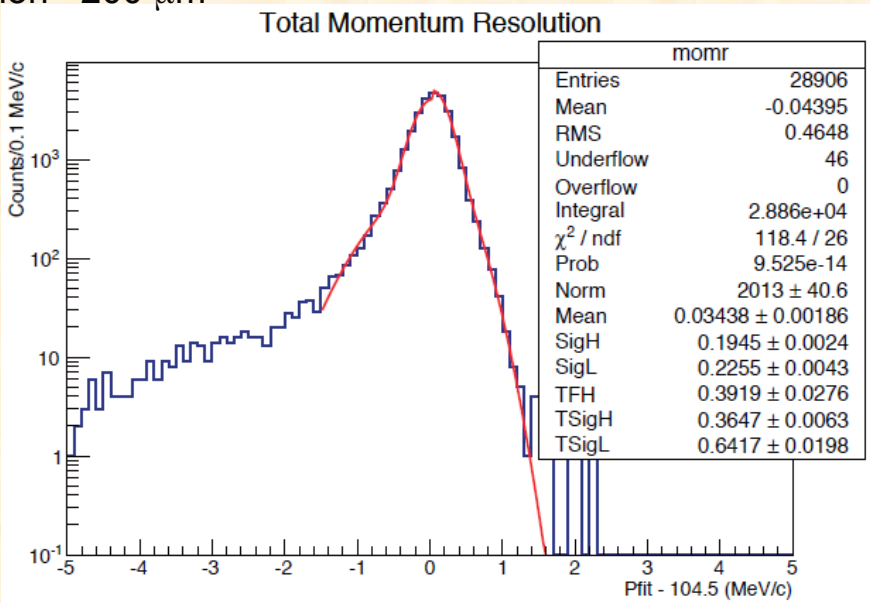
Separation between background and signal hits is clear

98 % of background can be rejected while keeping 99% of the signals，for the case of hit occupancy of 15%

Momentum Resolution at Birth

gas mixture He:i-C4H10 (90:10)
position resolution ~200 μm

- ~60% tracks got 1st turn candidates with 100% purity.
- Tail exists: important hits lost → causing pz biased



Core	σ of high-momentum half-Gaussian (SigH)	195 keV/c
	σ of low-momentum half-Gaussian (SigL)	226 keV/c
Fraction in tail distribution (TFH)		39%
Tail	σ of high-momentum half-Gaussian (TSigH)	365 keV/c
	σ of low-momentum half-Gaussian (TSigL)	642 keV/c

The core part of resolution of the total momentum is below 200keV/c

CPU power consumption task

	# file	Proton/file	CPU time/proton
Tianhe-2	230	4e4	**2.4 second**
IN2P3	122	8e6	2.76 second
TAURUS	122	4e4	2.7 second

10,000 years needed for 1 second @ 1 core

8000 bunches produced by now,
1% of 1 second beam commission

Overall background & performance estimate: Phase-I

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	≤ 0.0038
	Radiative pion capture	0.0028
	Neutrons	$\sim 10^{-9}$
Delayed Beam	Beam electrons	$\sim$ (
	Muon decay in flight	$\sim$ (
	Pion decay in flight	$\sim$ (
	Radiative pion capture	~ 0
	Anti-proton induced backgrounds	0.0012
Others	Cosmic rays†	< 0.01
Total		0.032

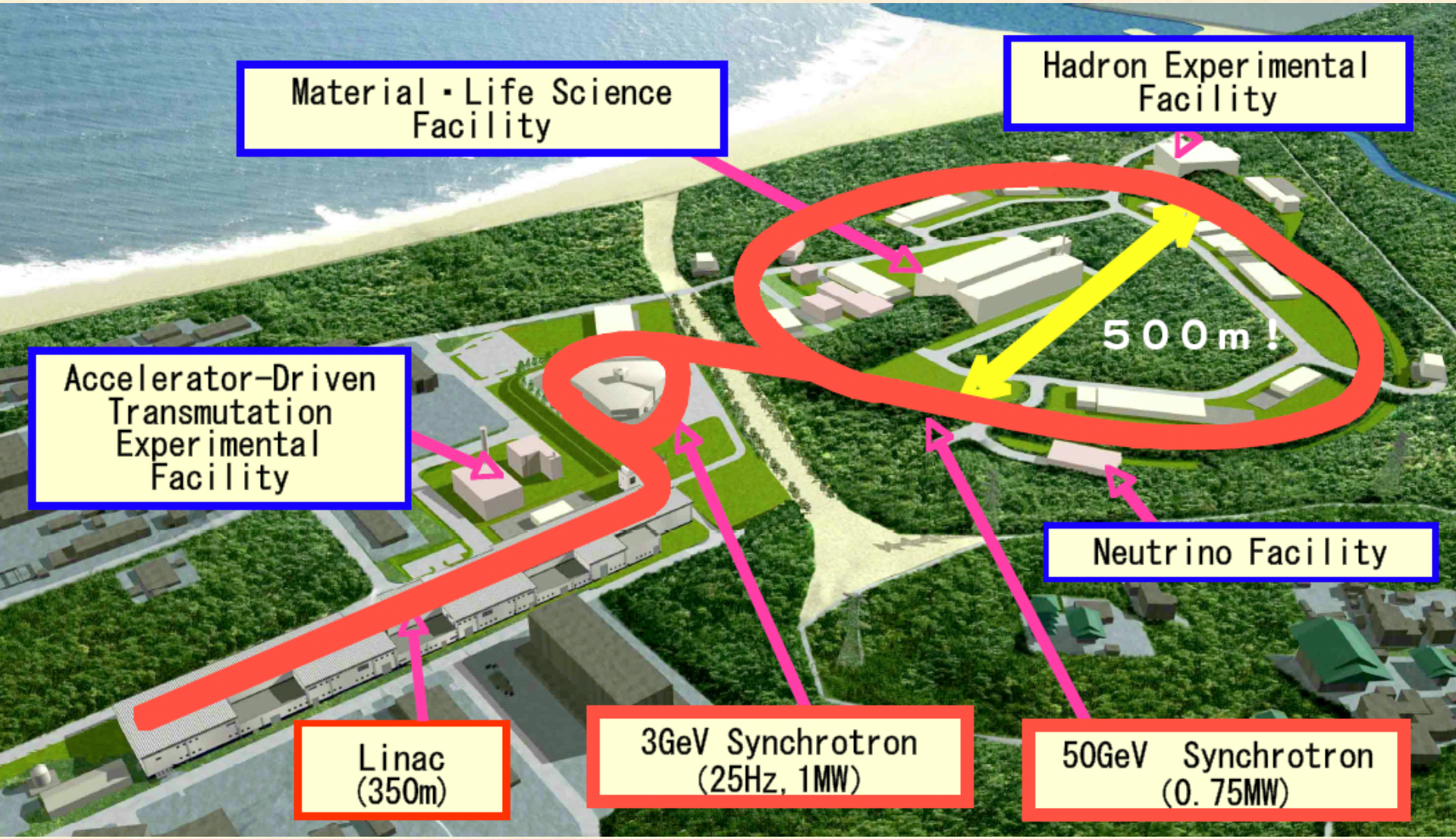
† This estimate is currently limited by computing resources.

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

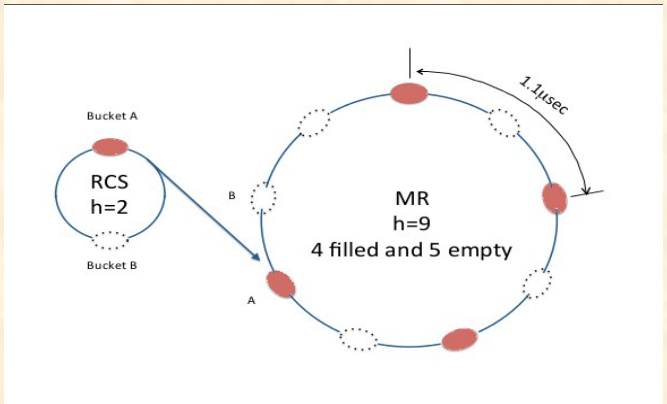
$$B(\mu^- + \text{Al} \rightarrow e^- + \text{Al}) = \frac{1}{N_\mu \cdot f_{\text{cap}} \cdot f_{\text{gnd}} \cdot A_{\mu\text{-}e}},$$

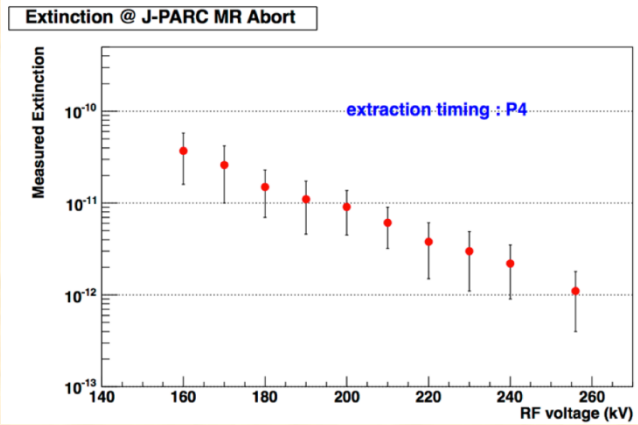
150 days beam time needed for Phase-I correspond to Nμ=1.5x10^{16}

J-PARC layout



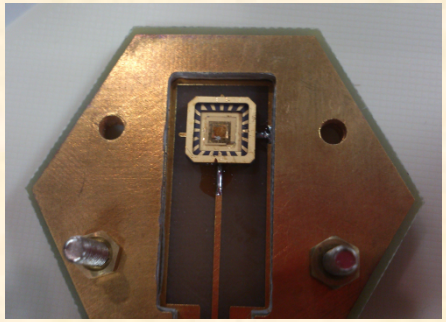
Proton beam

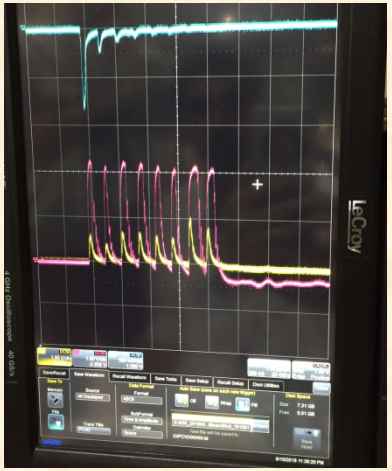




$$R_{ext} = \frac{\text{number of proton between pulses}}{\text{number of proton in a pulse}}$$

Extinction rate reached 10^{-12}, far more better than needed

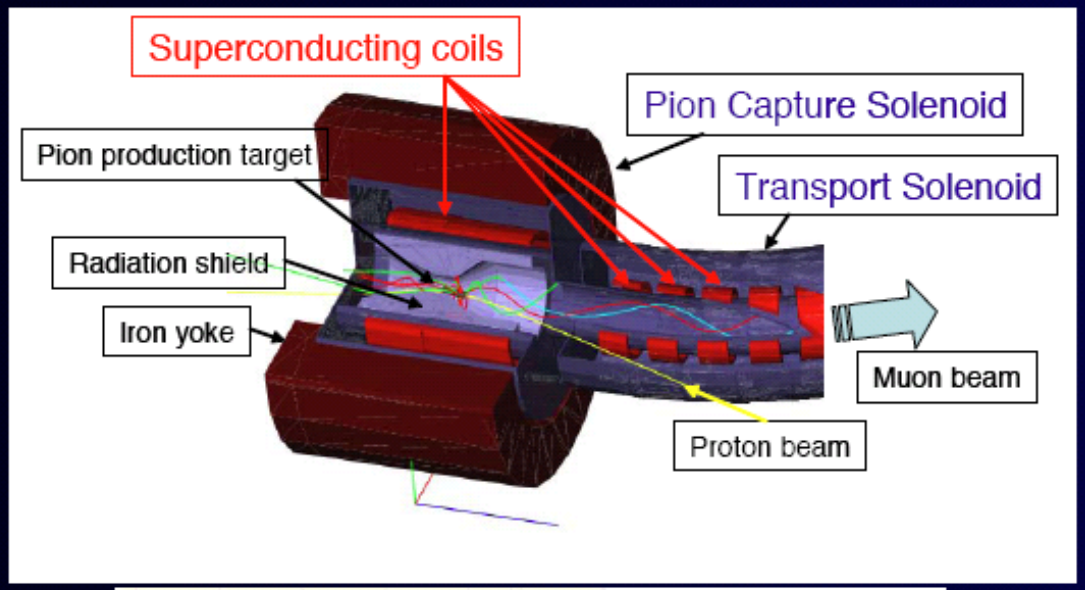


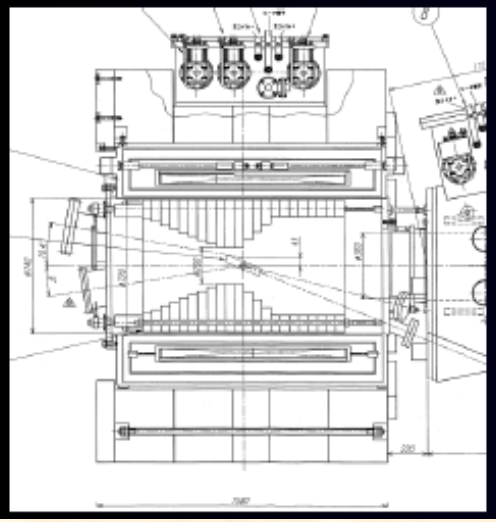


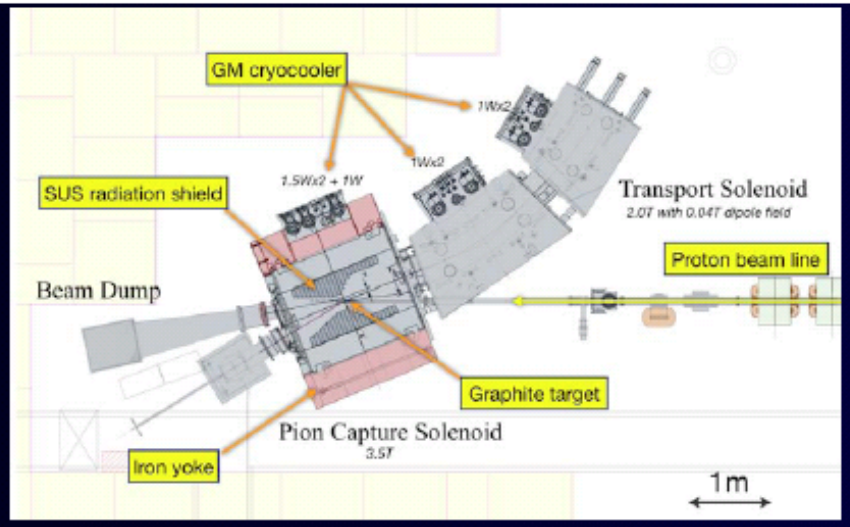
Proton Beam Monitor:
innovative diamond detector
First beam test for diamond prototype is ongoing @J-PARC MR

Pion Capture System at MuSIC@Osaka-U

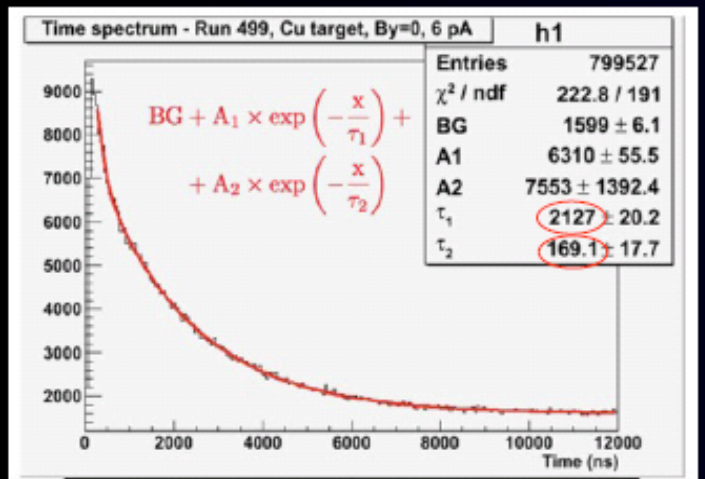
- Pion Capture SC Solenoid :
  - 3.5 T at central
  - diameter 740mm
  - SUS radiation shield
- Transport SC solenoids
  - 2 T magnetic field
  - 8 thin solenoids
- Graphite target for pion production



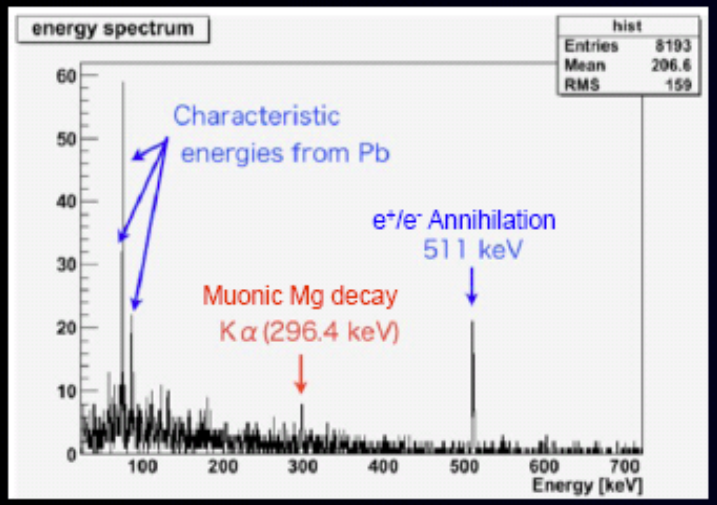




MuSIC Beam Test in 2011



	Free muon*	Cu**	Plastic scint.**
τ (ns)	2197.03 ± 0.04	163.5 ± 1	2026.3 ± 1.5



preliminary

MuSIC muon yields

μ^+ : 3×10^8/s for 400W

μ^- : 1×10^8/s for 400W

cf. 10^8/s for 1MW @PSI
Req. of $\times10^3$ achieved...

Great opportunities to carry out muon particle physics from NOW!

Measurements on June 21, 2011 (6 pA)