COMET
(COherent Muon to Electron Transition)
Tracking & Computing

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On behalf of
IHEP & LPNHE

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Outline

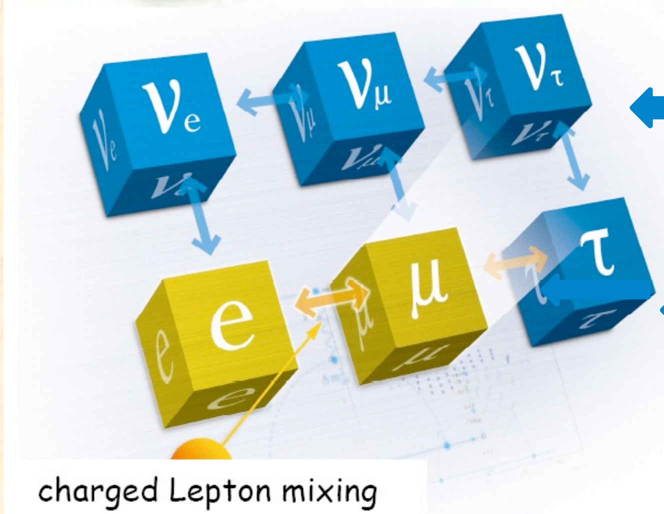
- **CLFV & COMET**
- **Phased approach**
- **Tracking**
- **Computing**
- **Summary**

Why CLFV & COMET?

Quarks, Neutrinos, and then Charged Leptons

Quarks

Leptons



Qurak mixing,
2008 Nobel prize

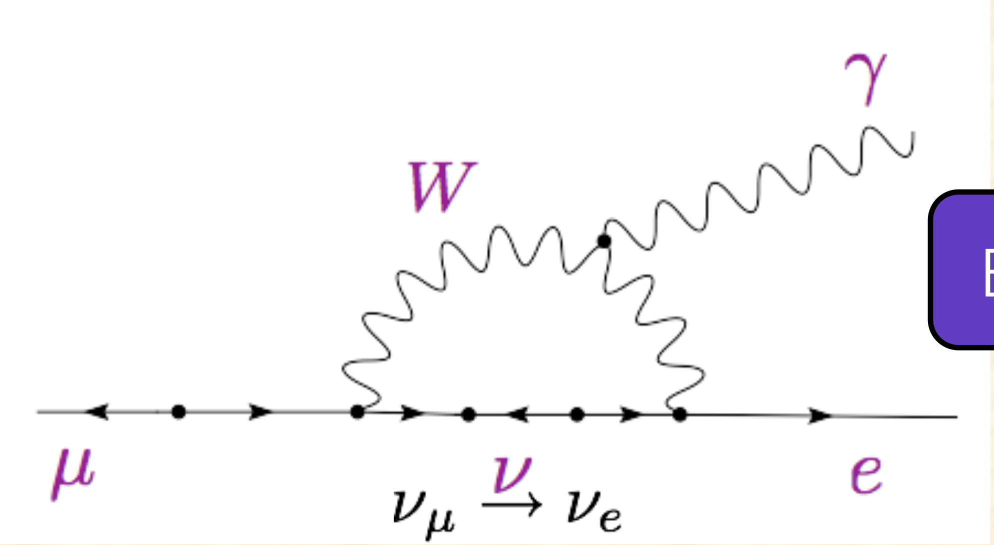
Neutrino oscillation,
2015 Nobel prize

Not observed, why special?

Charged Lepton Flavor Violation (cLFV)

Forbidden in Standard Model

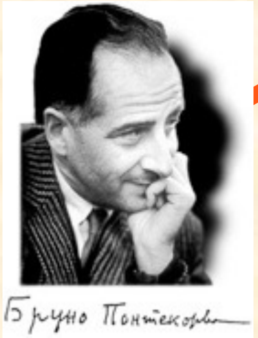
$$B(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_l (V_{MNS})^*_{\mu l}(V_{MNS})_{el}\frac{m^2_{\nu_l}}{M^2_W}\right|^2$$



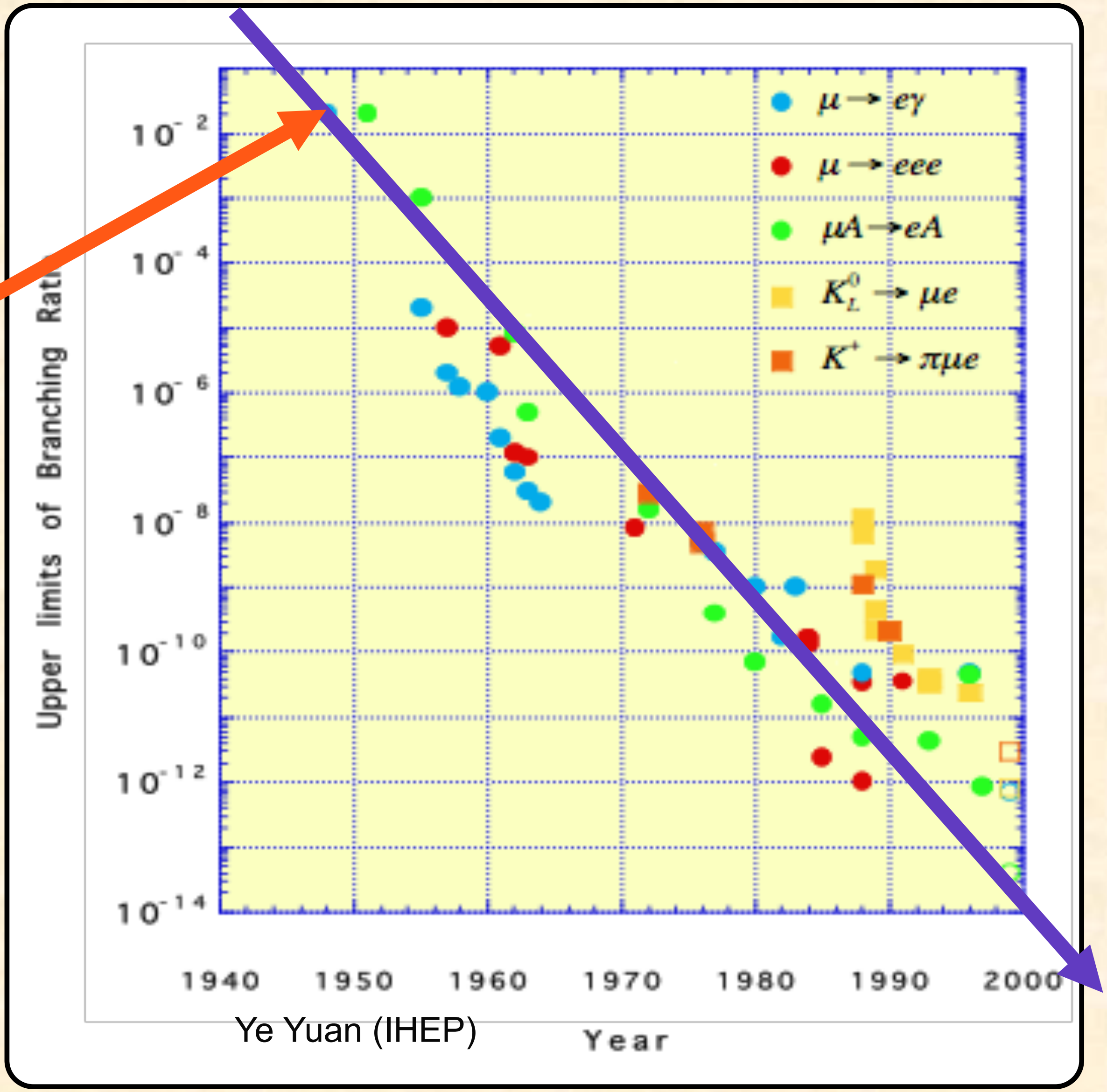
BR~O(10^{-54})

Clear signal of BSM once observed

Pursuit by continuous experiments



Pontecorvo,1947



Current limits and expected future

Latest update

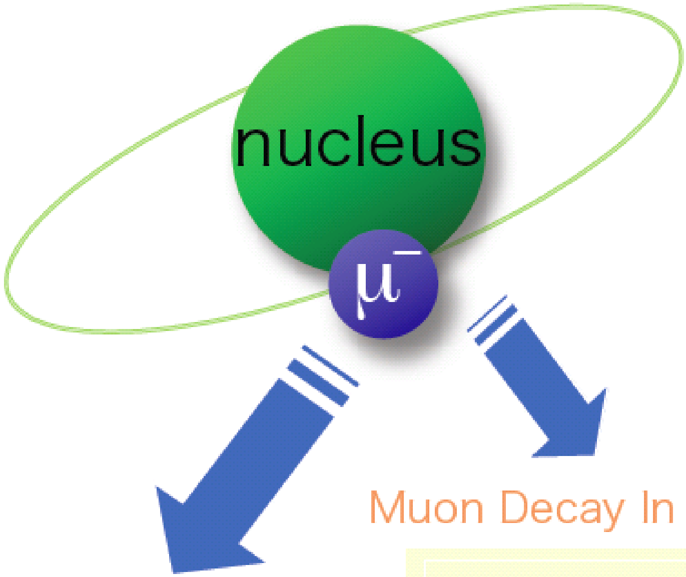
process	present limit	future	
$\mu \to e\gamma$	$<4.2 \times 10^{-13}$	$<10^{-14}$	MEG at PSI
$\mu \to eee$	$<1.0 \times 10^{-12}$	$<10^{-16}$	Mu3e at PSI
$\mu N \to eN$ (in Al)	none	$<10^{-16}/10^{-17}$	Mu2e / COMET
$\mu N \to eN$ (in Ti)	$<4.3 \times 10^{-12}$	$<10^{-19}$	PRISM
$\tau \to e\gamma$	$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

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

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

1s state in a muonic atom



Muon Decay In Orbit

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

nuclear muon capture

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

✓ Signal:

monoenergetic electron

104.96 MeV for Al, 95.56 MeV for Au

✓Main background：

Muon Decay in Orbit （10^{-16}）

Radiative muon Capture

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

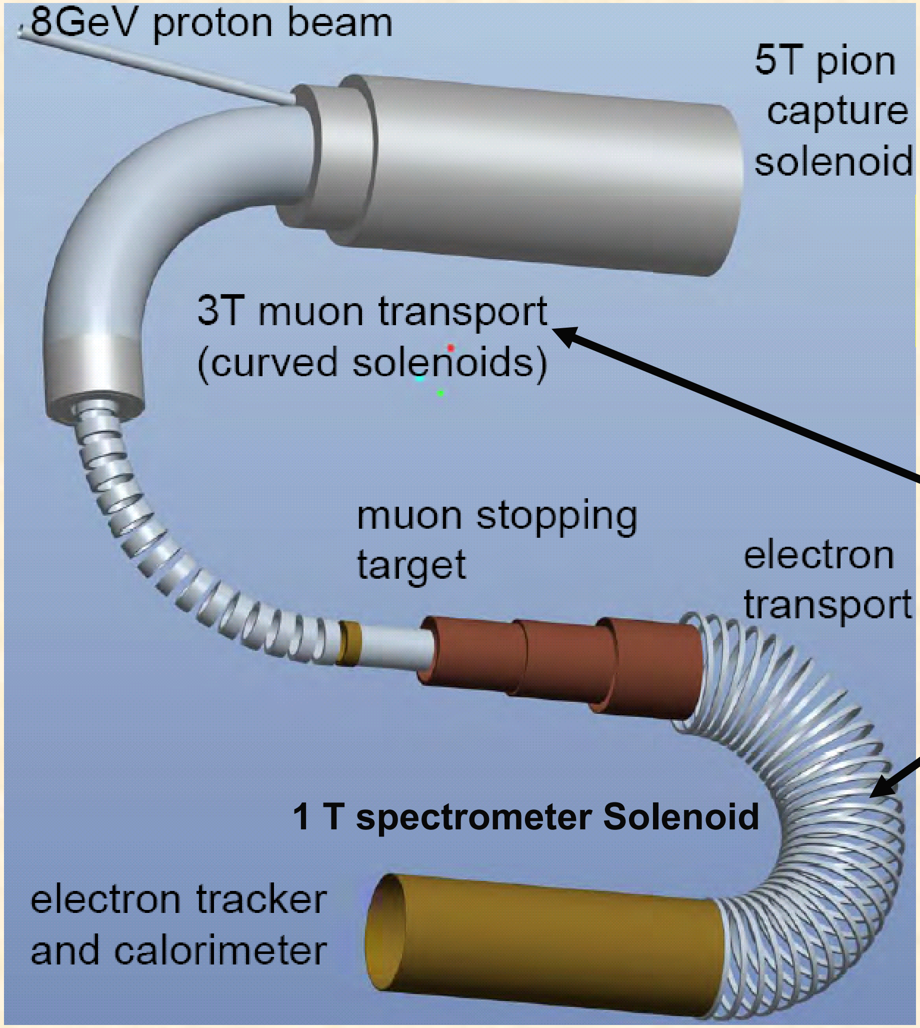
Radiative pion capture

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

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

✓ 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

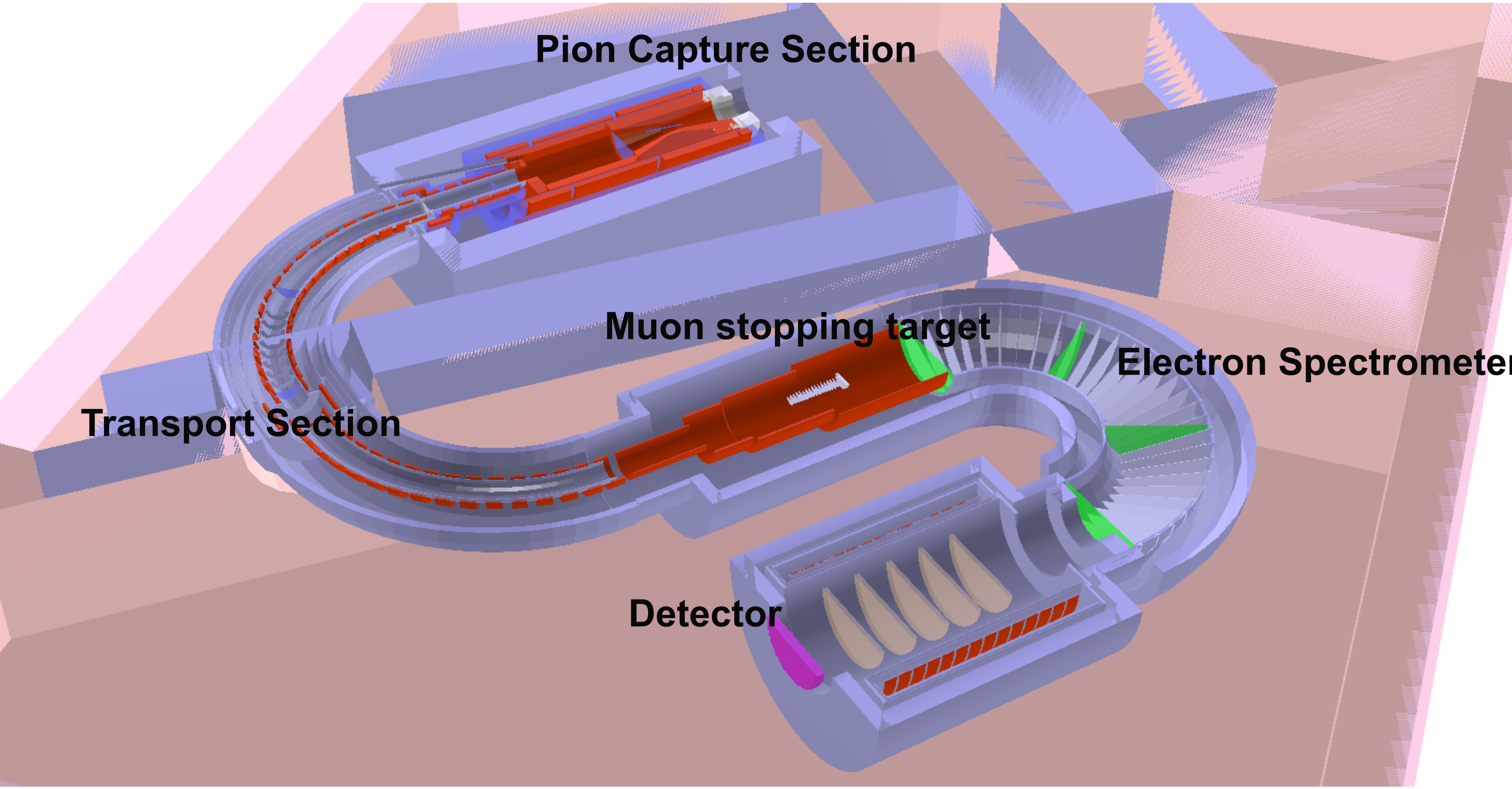
The COMET Collaboration

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

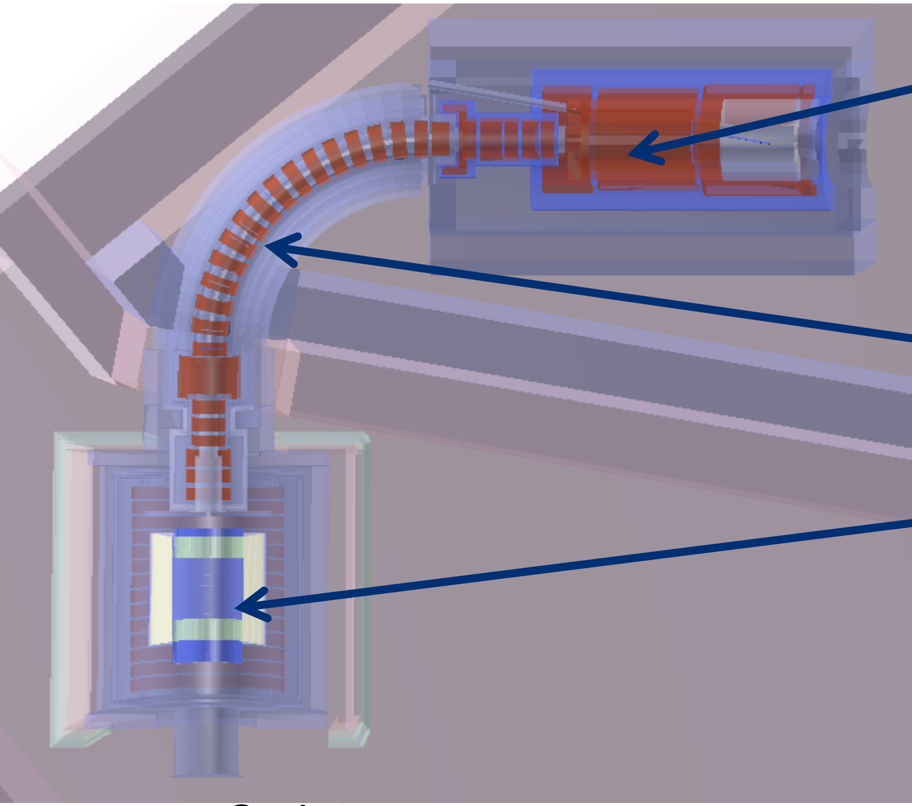
Phased approach

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

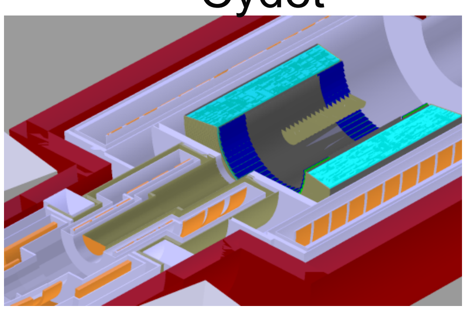
Construct to the first 90 degree

Phase-I Detector

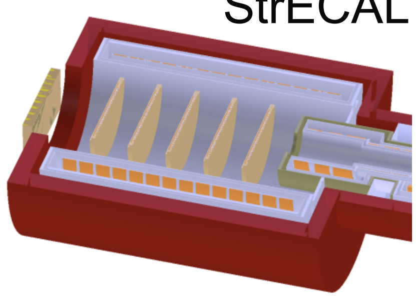
A cylindrical drift chamber system(Cydet) for the μ→e conversion search

A prototype ECAL and straw tube tracker (StrECAL) for beam and background studies

Cydet



StrECAL



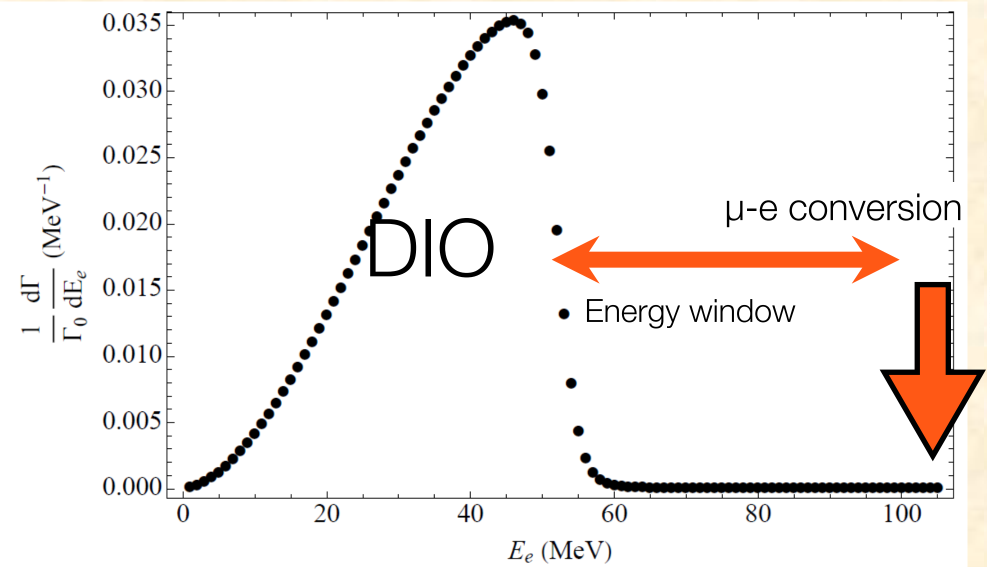
Phase-I Aims

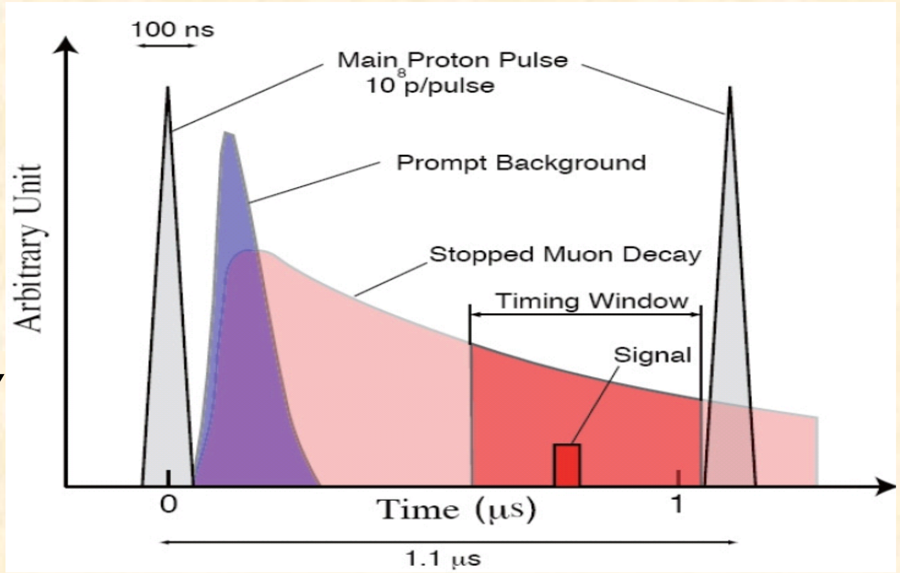
Search for μ→e conversion process with a

S.E.S. of 3×10^{-15}

Beam and background study for Phase-II

What we needed





Require:

High momentum resolution

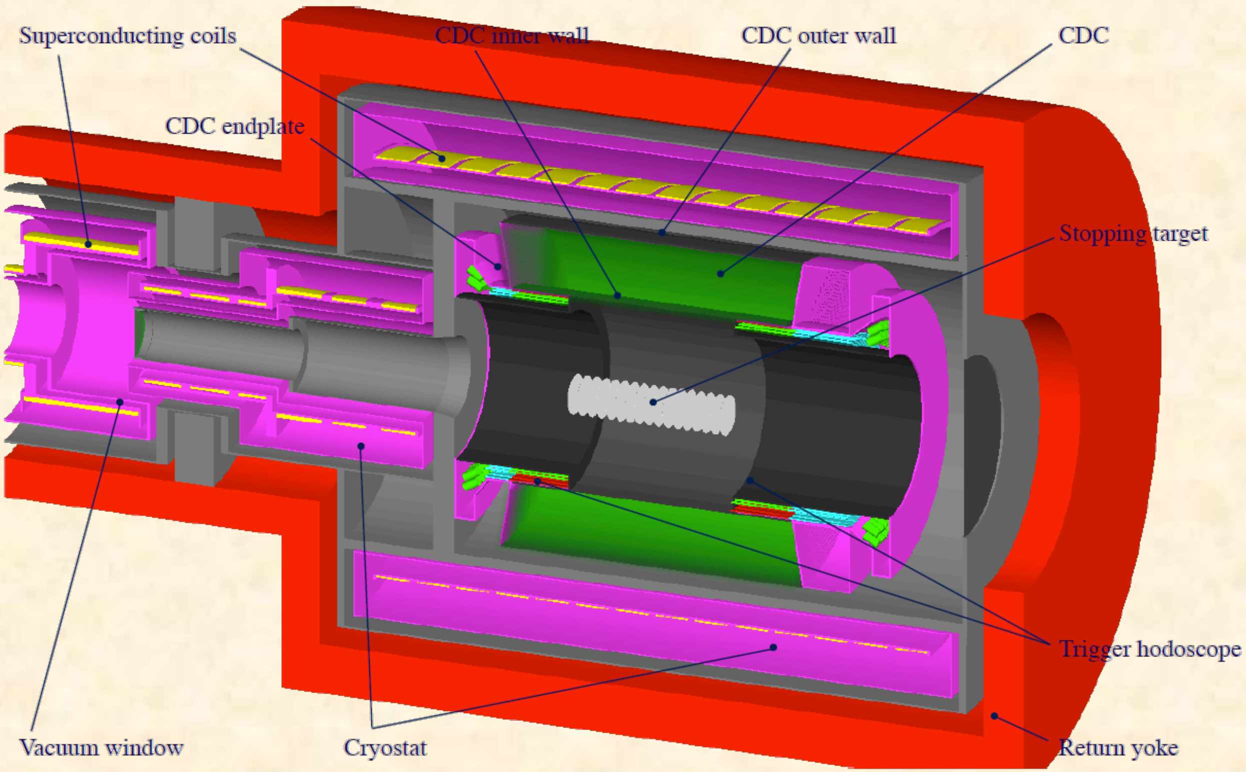
Pulsed beam

Excellent proton extinction

Perfect background suppress

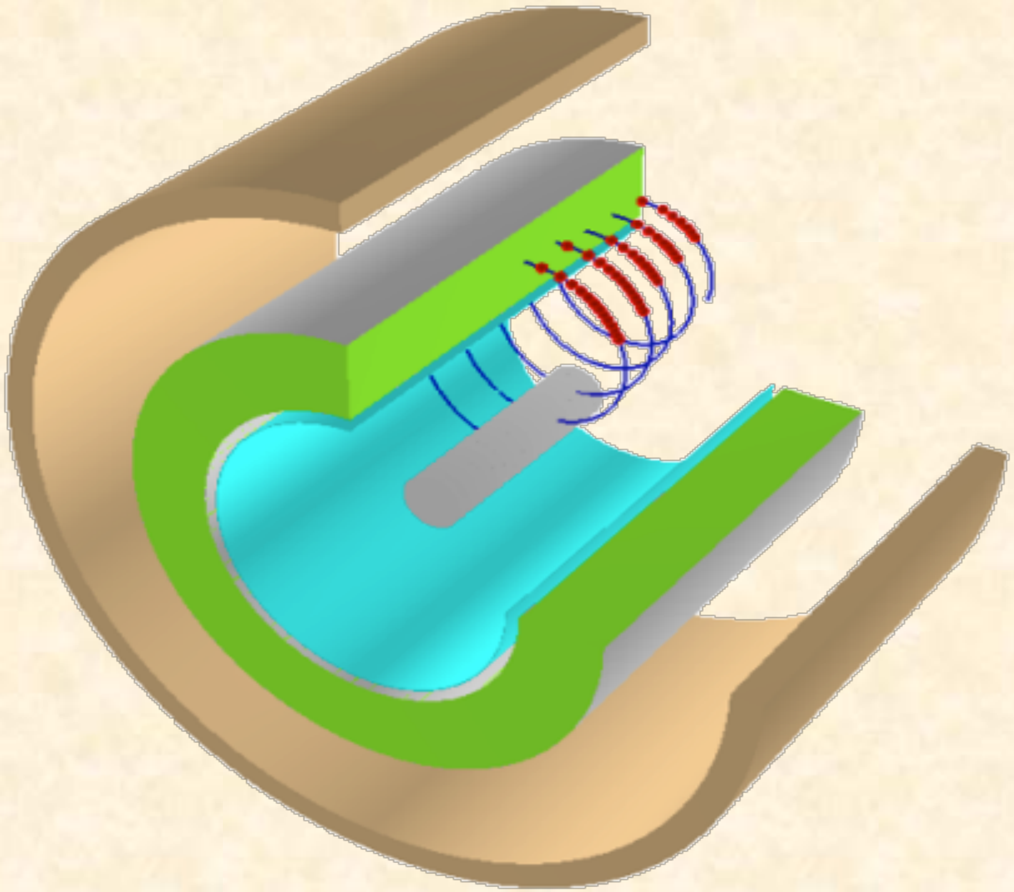
High intensity beam

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

Tracking



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

Cylindrical drift chamber (CDC)

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

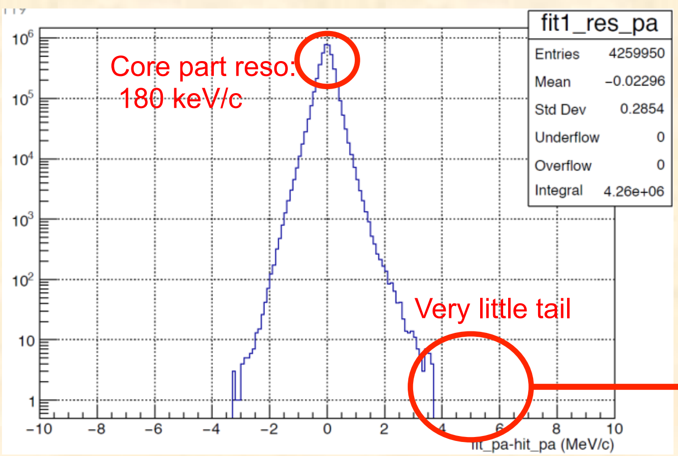
Prototype chamber tests show spatial resolution <200μm, momentum resolution σ_p ~200keV/c

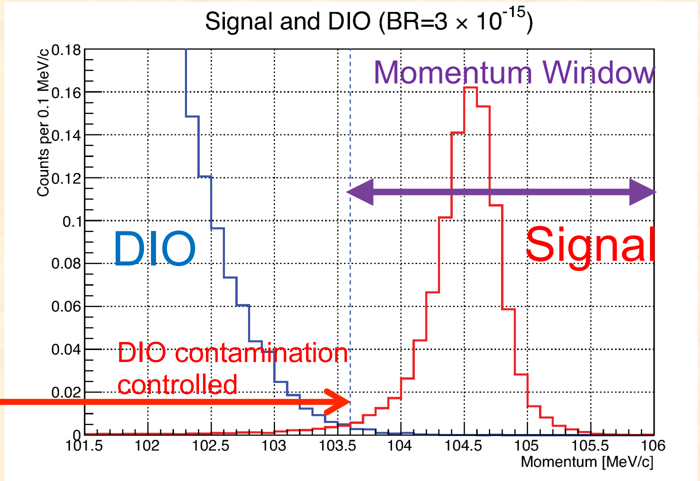
Construction started in 2014 and completed on June 2016

Pilot tracking

- Two independent fitting: Osaka U. & IHEP
  - good efficiency (~20%),
  - decent resolution (~180 keV/c)
  - Very little tail (1% DIO)

Capable for Phase-I S.E.S.





- However it’s based on many assumptions:
  - Good initial values; 0 noise hits; ideal detector response; etc.

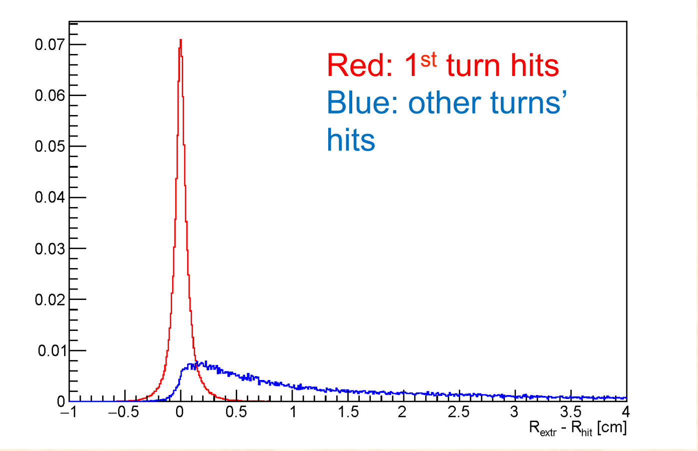
We need to work hard to achieve it in a complete way!

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,⋯

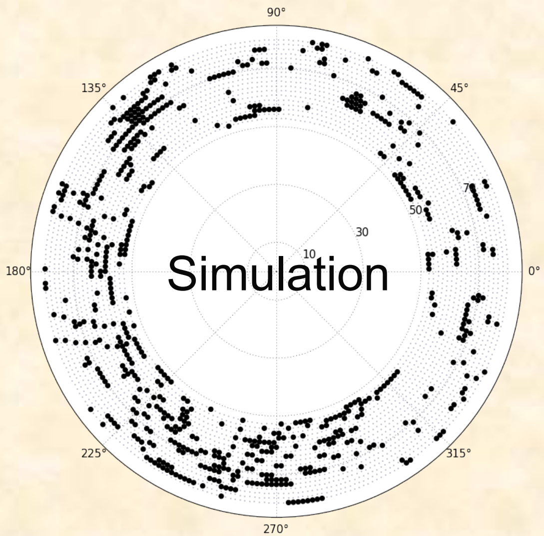
- Parallel algorithm study & corporate

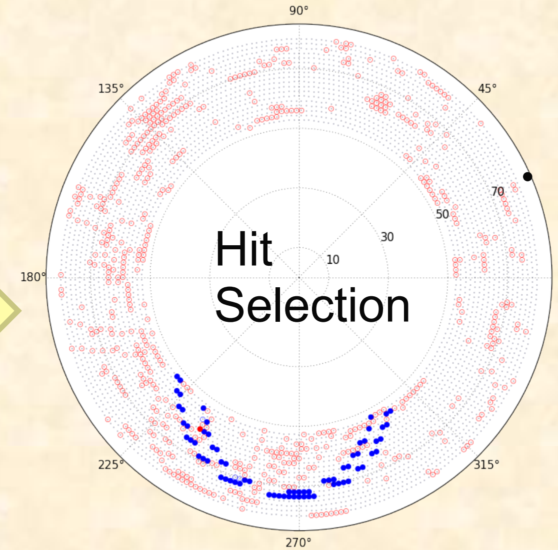
- Traditional methods and novel ideas

  Machine learning, Persistent Homology,⋯

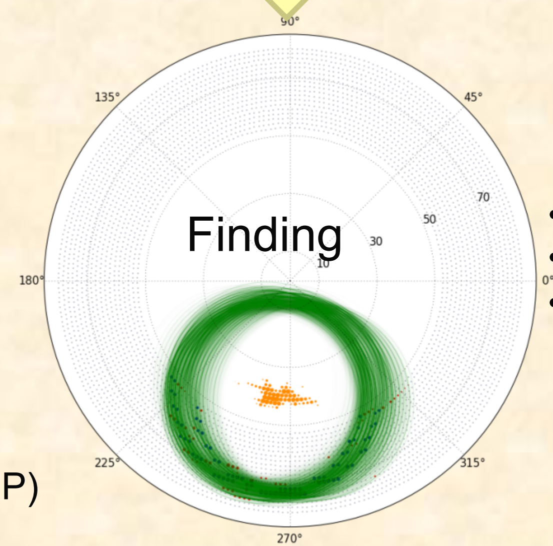
Tracking Procedure

- Signal track
- BG hit merge
- Detector response



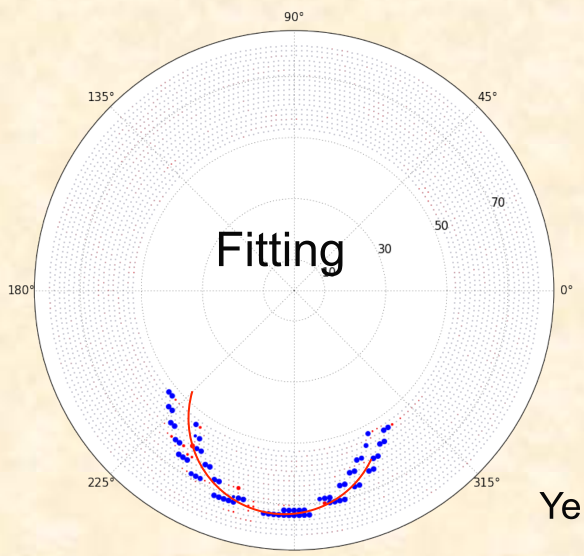


- Evaluate each hit with a weight to indicate signal/noise



- Find tracks
- Find turns
- Decide initial value

iteration

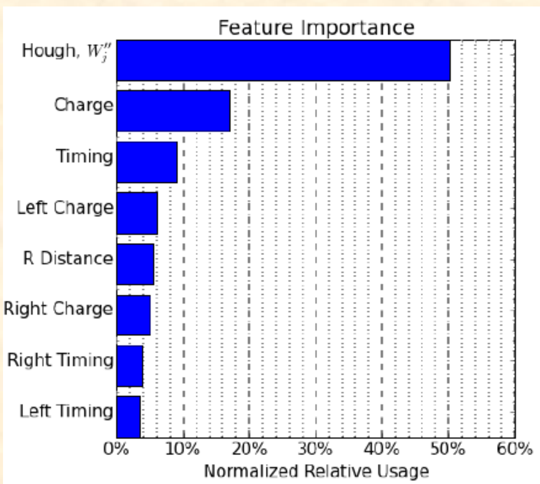


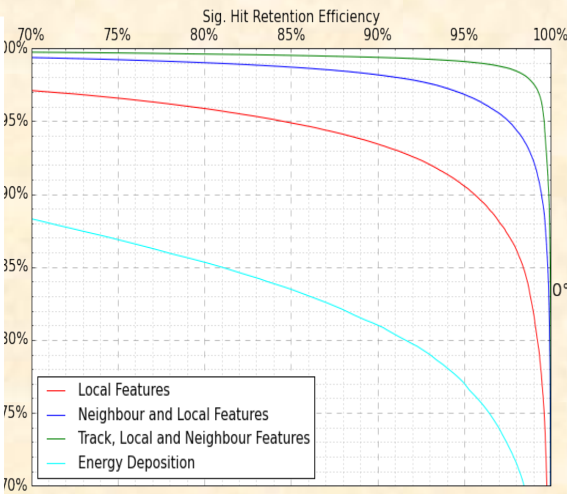
- Fitting with Kalman filter

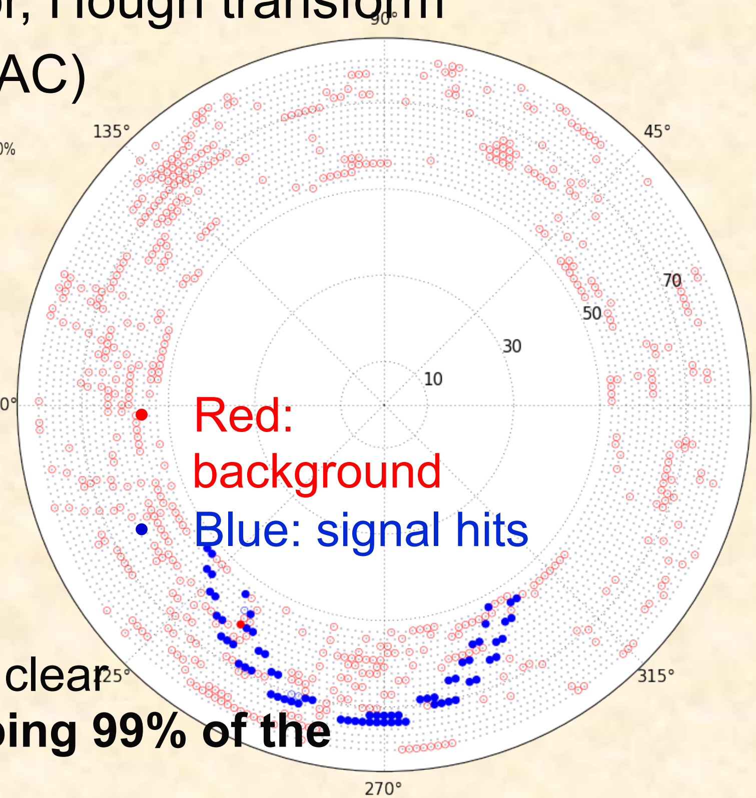
Hit Selection

(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)







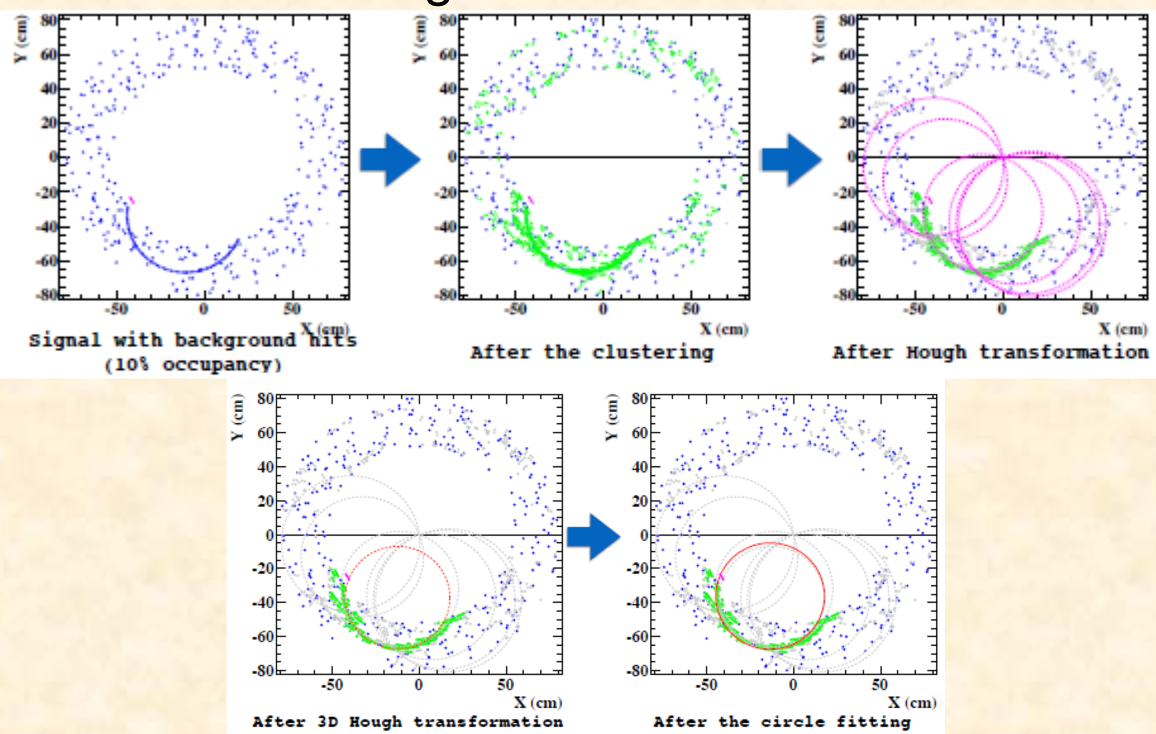
Separation between background and signal hits is clear

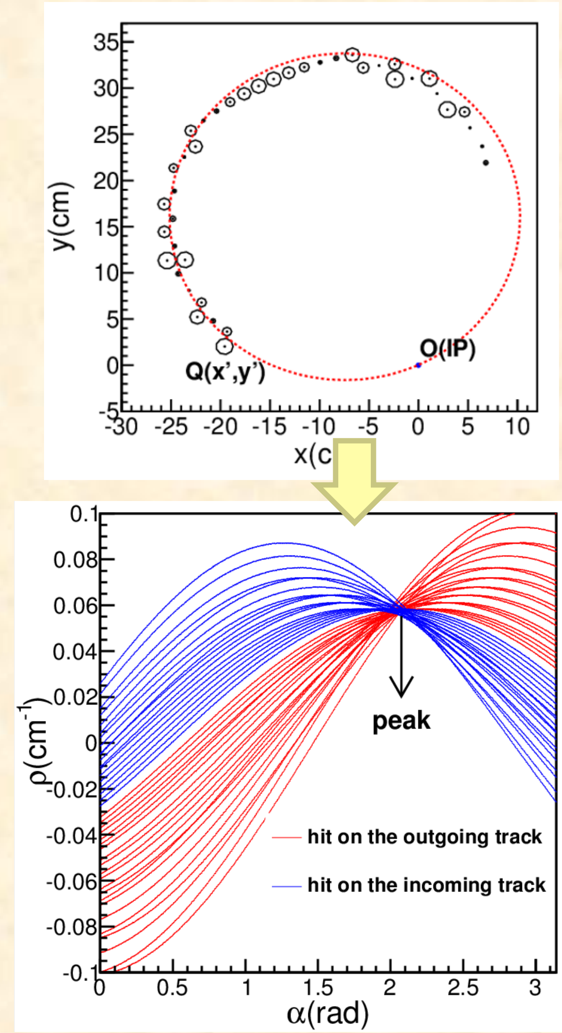
98 % of background can be rejected while keeping 99% of the signals， for the case of hit occupancy of 15%

Track Finding 1

(IHEP)

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





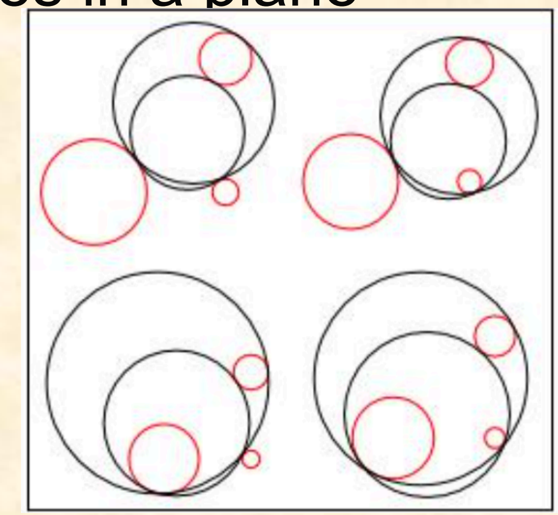
Track Finding 2

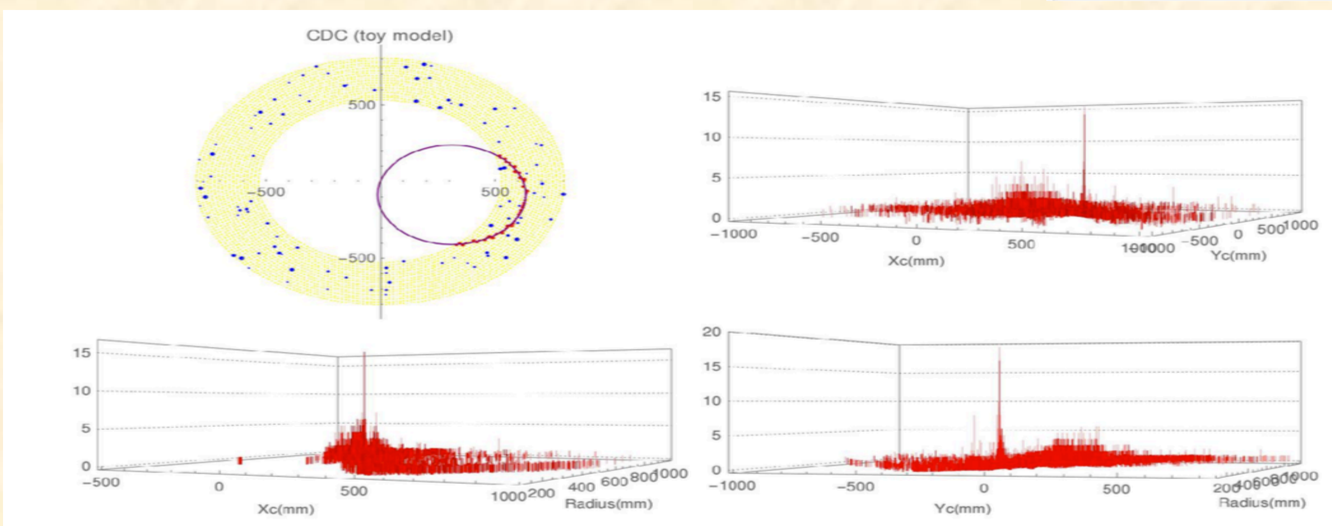
- Apollonius circle

(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)



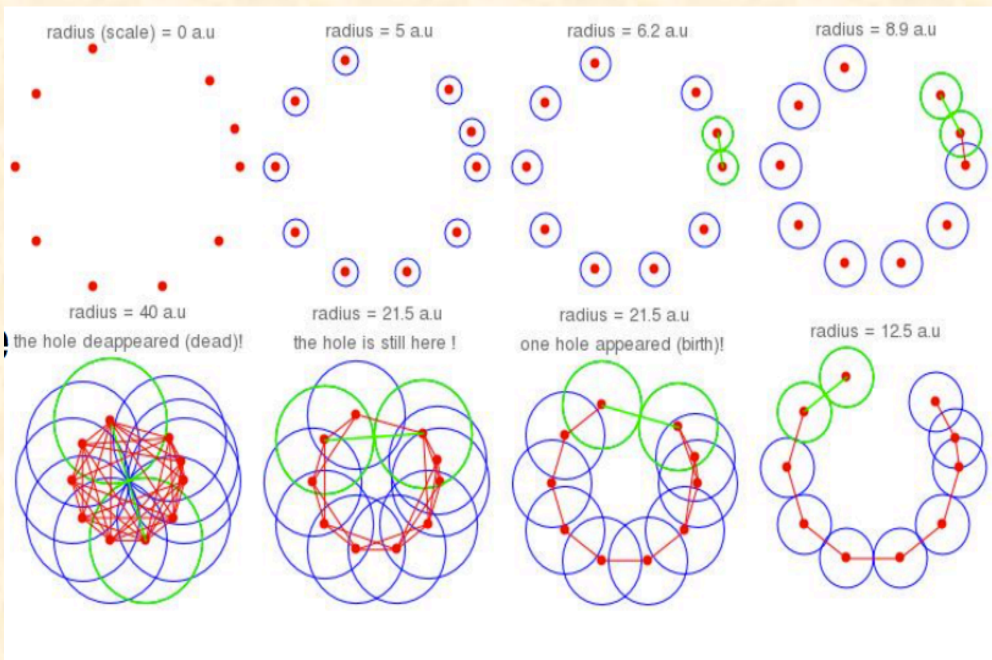


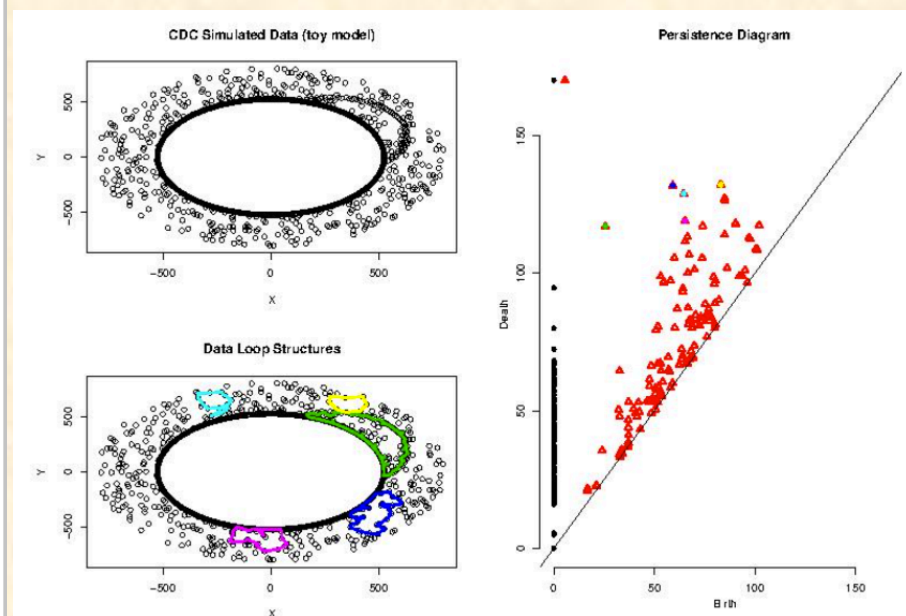
Track Finding 3

(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, · · ·)

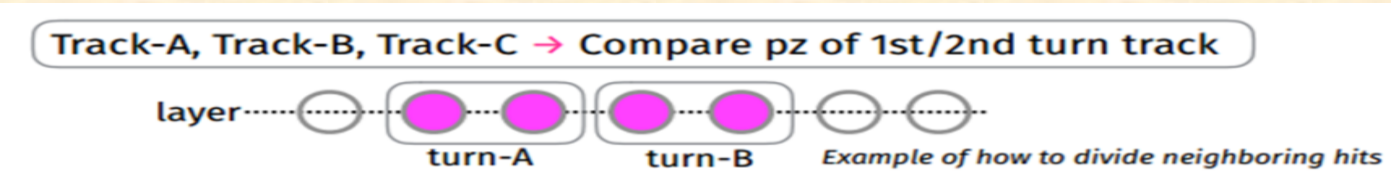


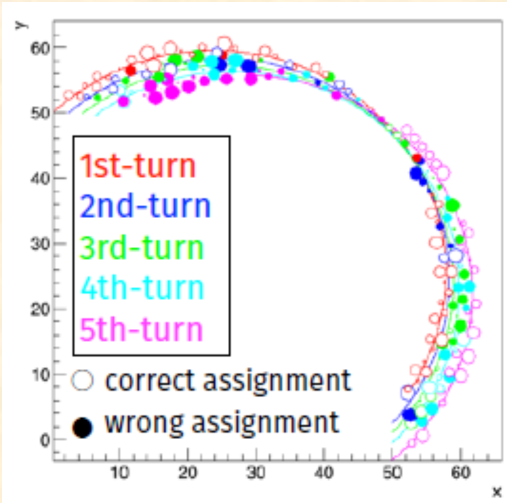


Track Fitting method 1

(Osaka U.)

- genfit2 based fitting using Kalman filtering(DAF)
- Multi-turn fitting based on neighboring hits pile-up pattern
  - "Divide" sequential hits in same layer, odd/even, first/last 90 deg turn
  - Make ~50 different sets of hit candidates
  - Fit for each set and keep if fit result is "good" (NDF>20)
  - Using remaining hits, repeat fit procedure
  - Compare p_z of 1st and 2nd max. momentum tracks
  - If difference of p_z is smaller than 20 MeV/c, finish



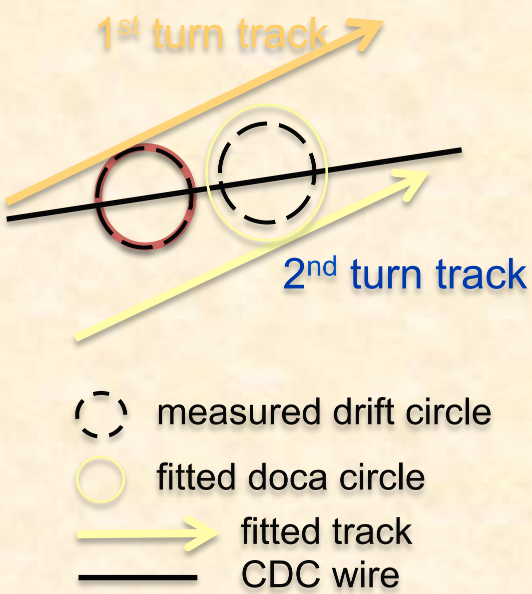


Track Fitting method 2

(IHEP)

- Multi-turn fitting based on hit competition
  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



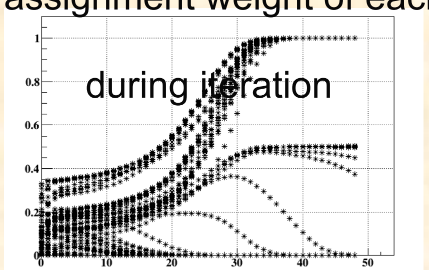
The possibility of hit *i* assigned to track *j* is defined as matrix Φ

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

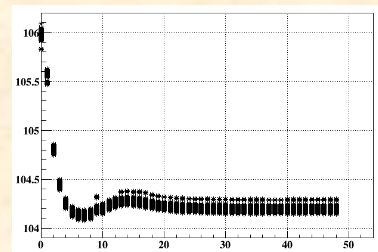
$$p_{i_k j} = \frac{\varphi_{i_k j}}{\sum_l \sum_\alpha \varphi_{i_\alpha l} + c}.$$

Assignment weight of hit i to track j

Hit assignment weight of each hit



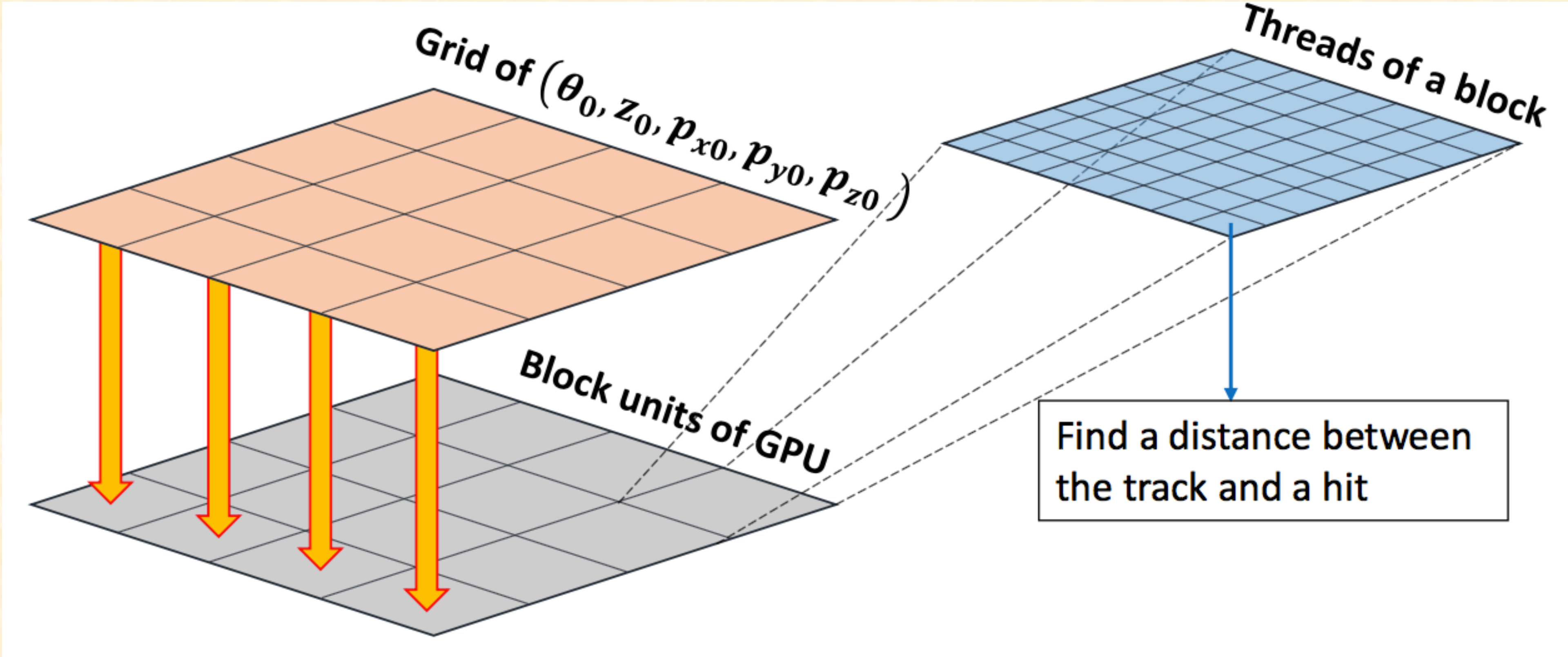
fitted momentum at each iteration



Track Fitting method 3

(KAIST)

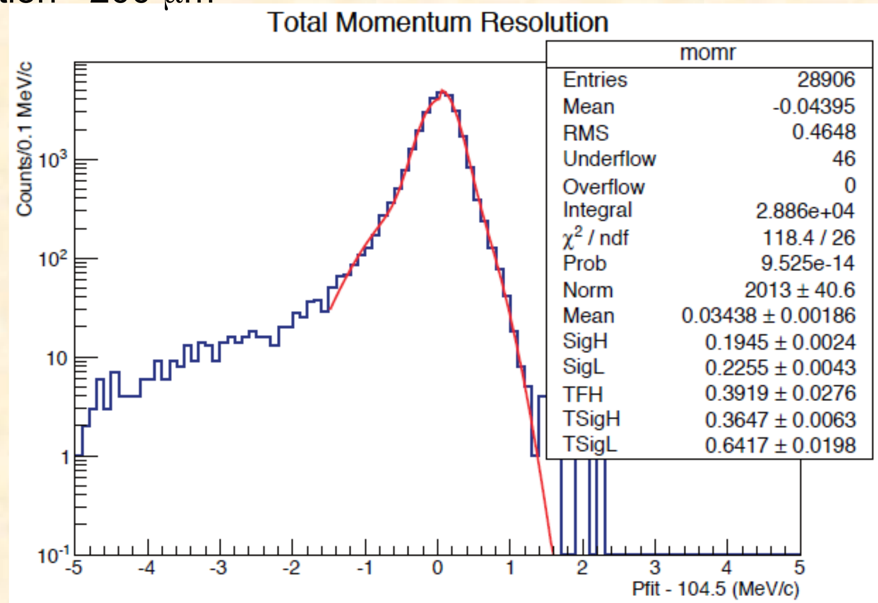
- Initial parameter scanning by GPU(CUDA)



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

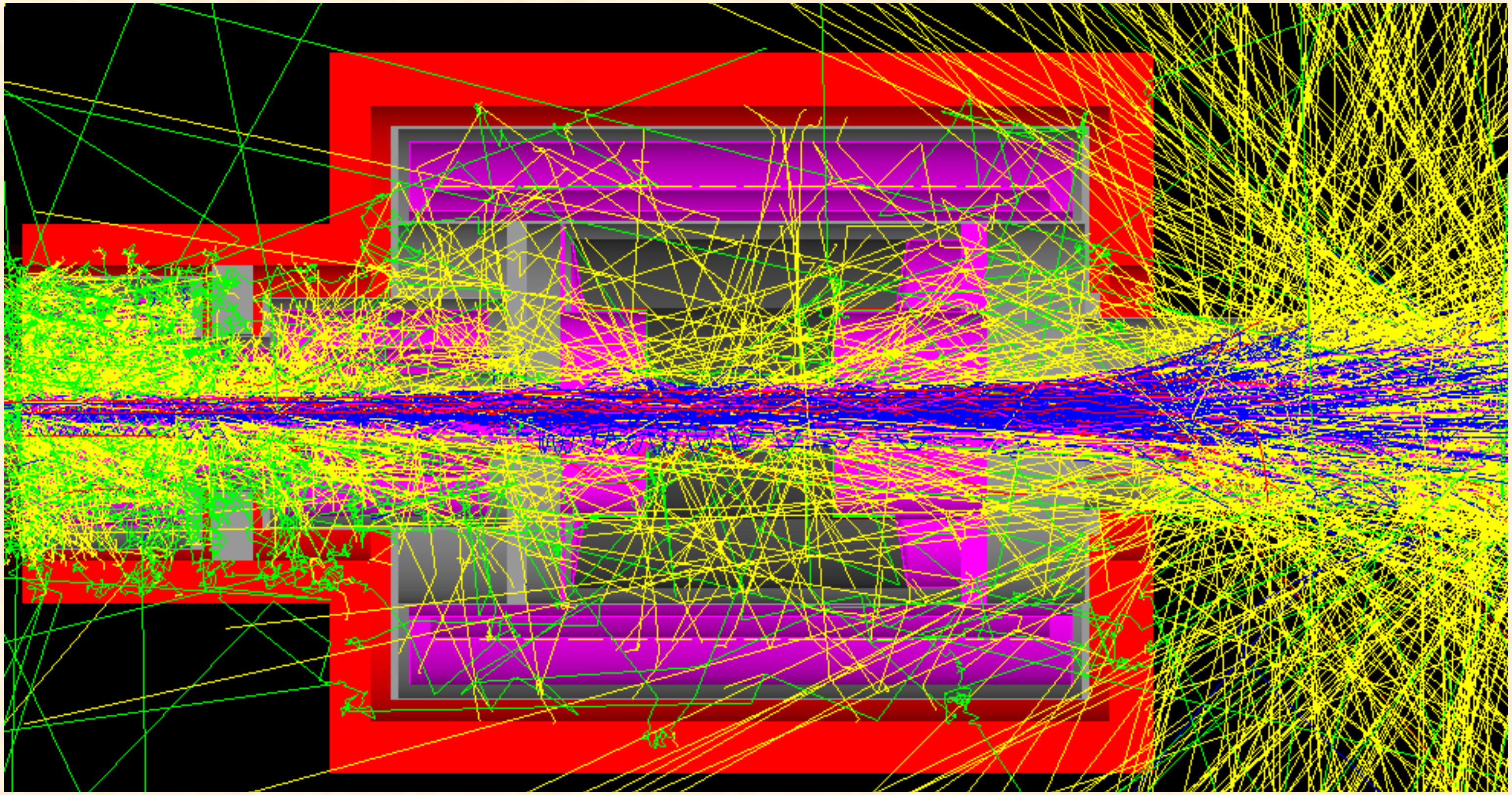


Core	σ of high-momentum half-Gaussian (SigH)	195 keV/c
	σ of low-momentum half-Gaussian (SigL)	226 keV/c
Fraction in tail distribution (TFH)		39%
Tail	σ of high-momentum half-Gaussian (TSigH)	365 keV/c
	σ of low-momentum half-Gaussian (TSigL)	642 keV/c

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

Computing

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



Resource

- CC-IN2P3
  90 M HS06.hours on bqs
  500TB disk space

- Tianhe-2 Supercomputer @ SYSU
  8 M CPU hours

- TAURUS @ TU-Dresden
  1M CPU hours

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

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

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

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}**

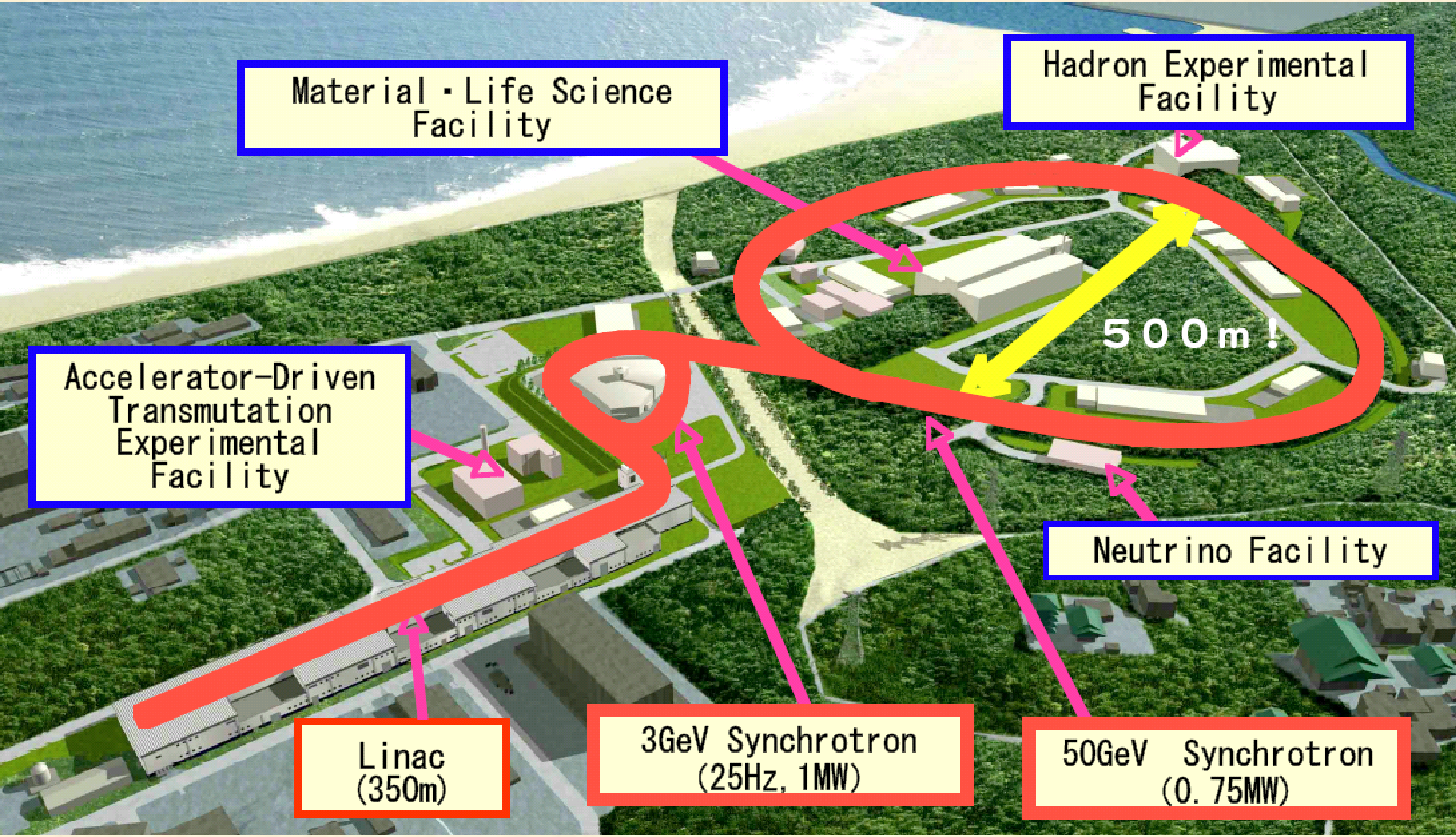
✓**Tracking and computing are the key challenges of COMET**

✓**Synergy between China & France is important**

Thanks!

Back up slides

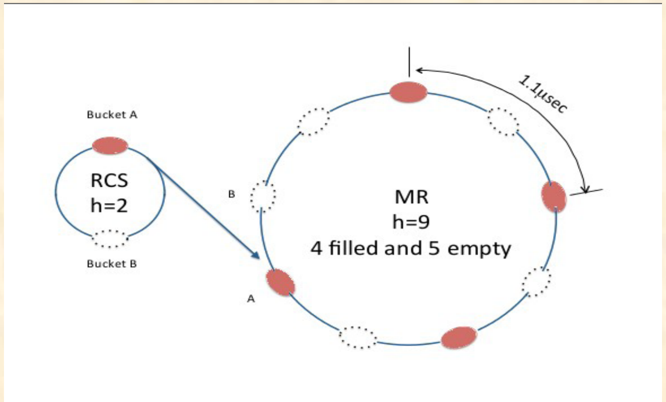
J-PARC layout

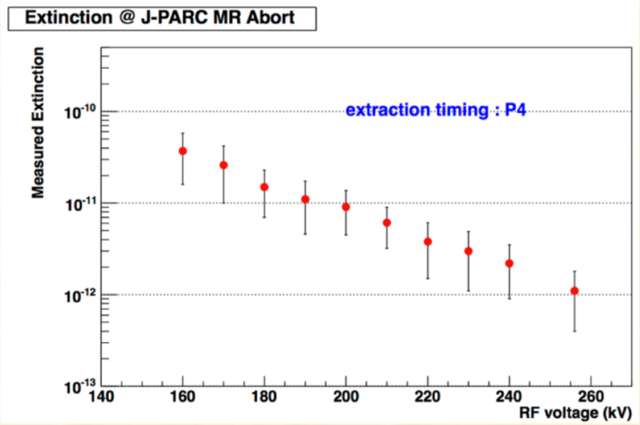


COMET Hall

Hall construct completed;
Beamline under constructing

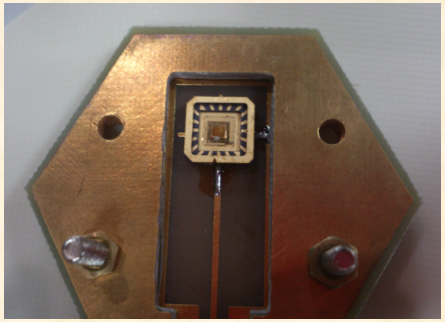
Proton beam

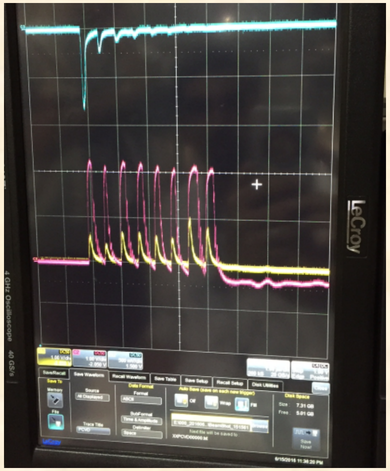




$$R_{ext} = \frac{\text{number of proton between pulses}}{\text{number of proton in a pulse}}$$

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

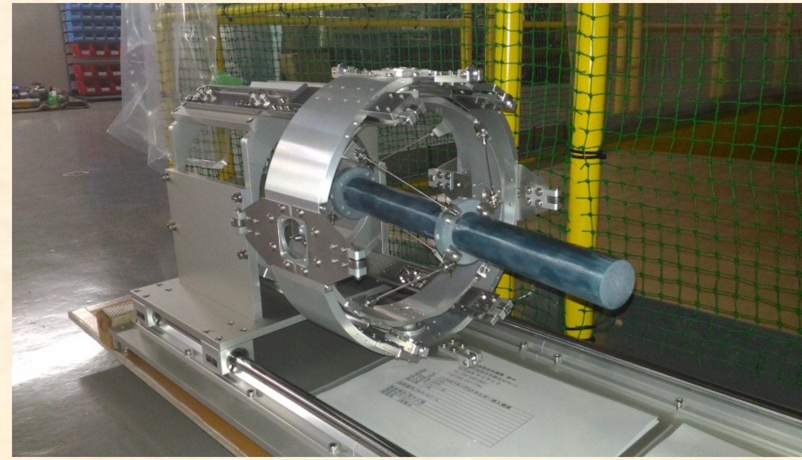


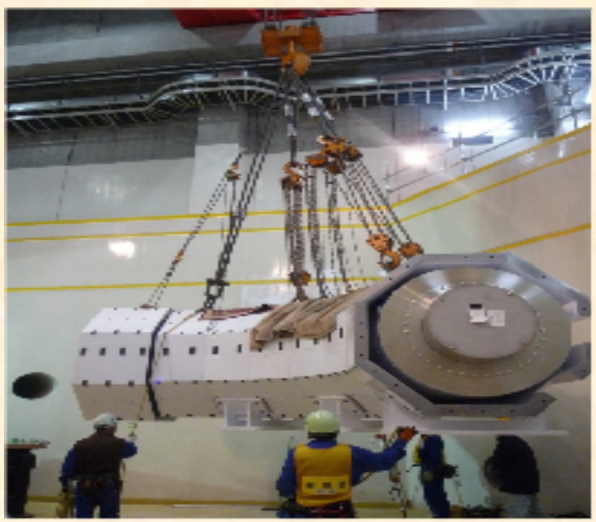


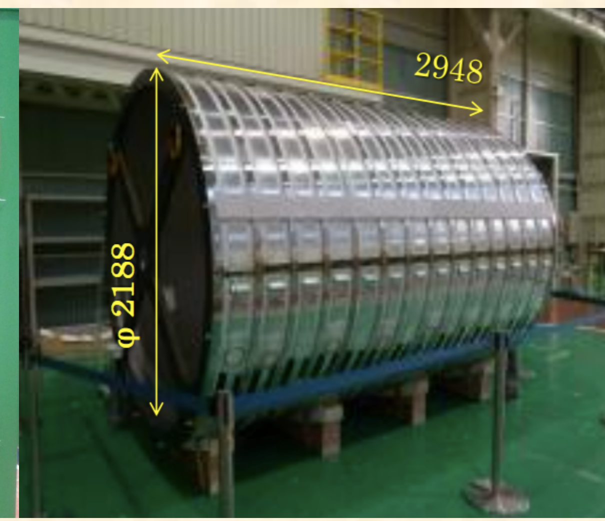
Proton Beam Monitor:
innovative diamond detector
First beam test for diamond prototype is ongoing @J-PARC MR

Magnet and target

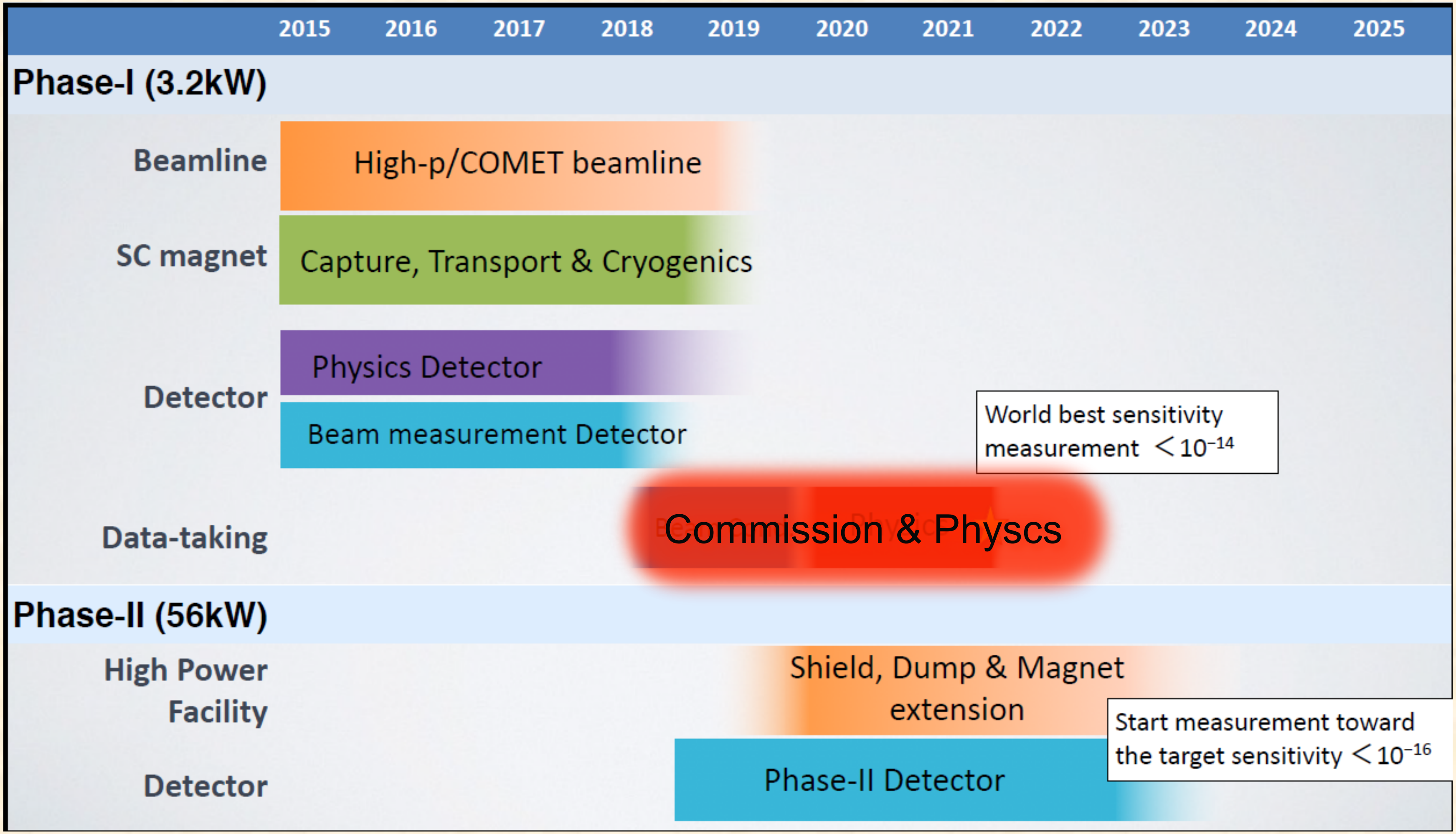
- Proton target: R=13mm, L=700mm,
  prototype is maked
- Muon transport solenoid completed
- Pion capture solenoid is under winding
- Detector solenoid is assembled







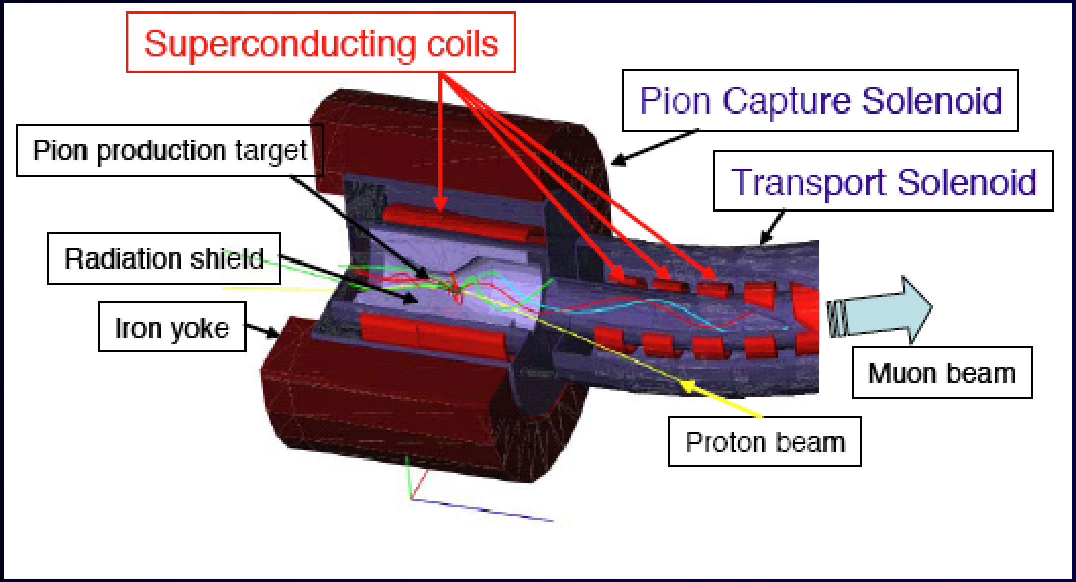
Schedule

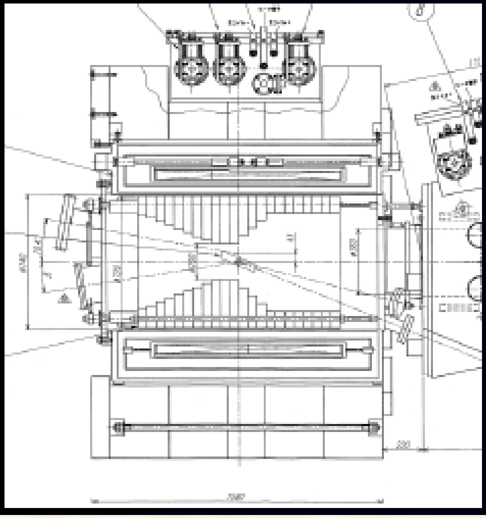


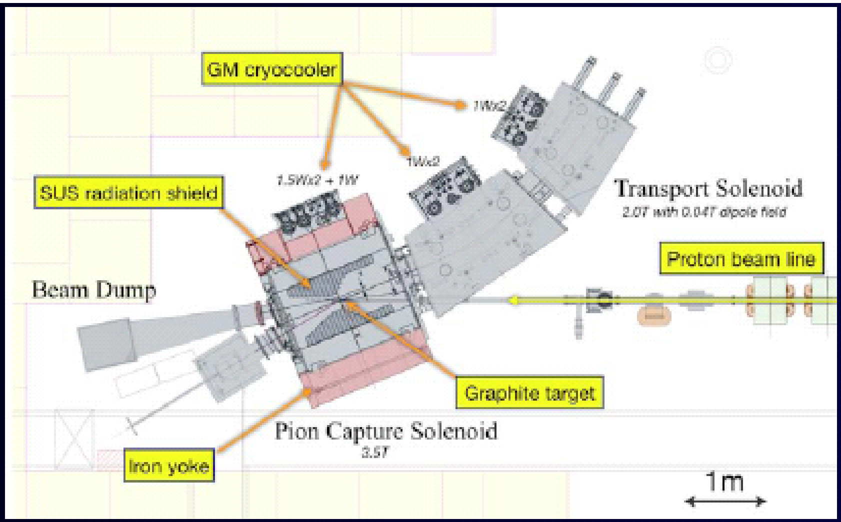
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
Phase-I (3.2kW)
Beamline
High-p/COMET beamline
SC magnet
Capture, Transport & Cryogenics
Detector
Physics Detector
Beam measurement Detector
World best sensitivity measurement $< 10^{-14}$
Data-taking
Commission & Physcs
Phase-II (56kW)
High Power Facility
Shield, Dump & Magnet extension
Detector
Phase-II Detector
Start measurement toward the target sensitivity $< 10^{-16}$

Pion Capture System at MuSIC@Osaka-U

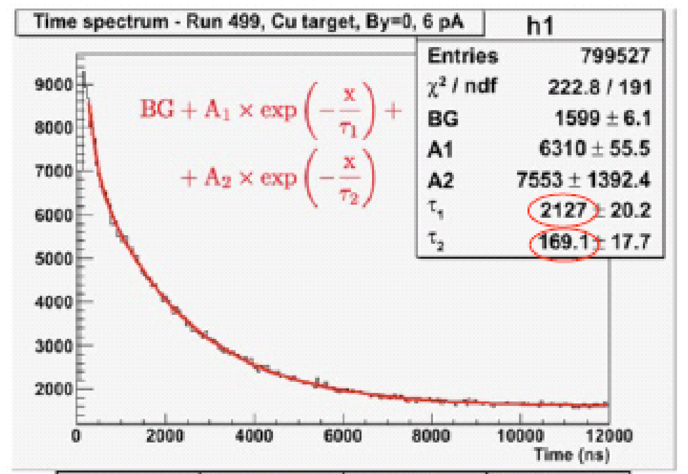
- Pion Capture SC Solenoid :
  - 3.5 T at central
  - diameter 740mm
  - SUS radiation shield
- Transport SC solenoids
  - 2 T magnetic field
  - 8 thin solenoids
- Graphite target for pion production



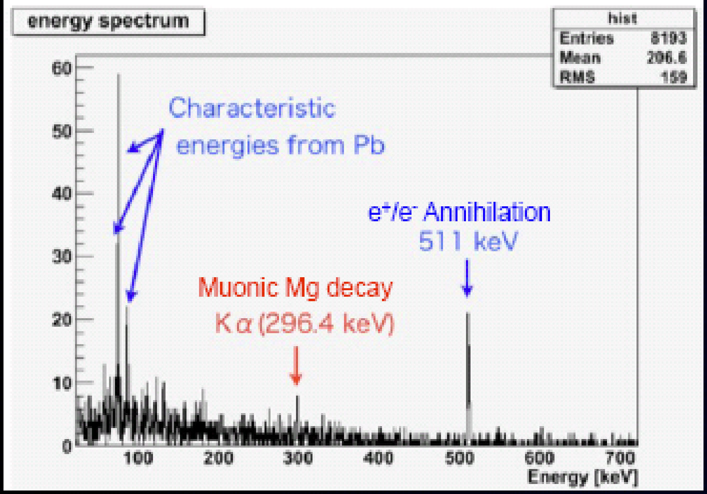




MuSIC Beam Test in 2011



	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 $\times 10^3$ achieved...

Great opportunities to carry out muon particle physics from NOW!

Measurements on June 21, 2011 (6 pA)