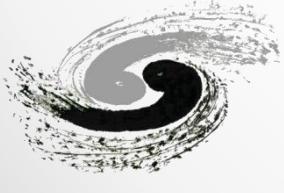


Search for the cLFV by muon to electron conversion: COMET and Mu2e

在COMET和Mu2e实验上寻找带电轻子味破坏

Yao Zhang (张瑶) Zhengyun You (尤郑昀)
Institute of High Energy Physics (高能物理研究所)
Sun Yat-Sen University (中山大学)

On behalf of COMET and Mu2e experiment group
8/18/2021



Overview



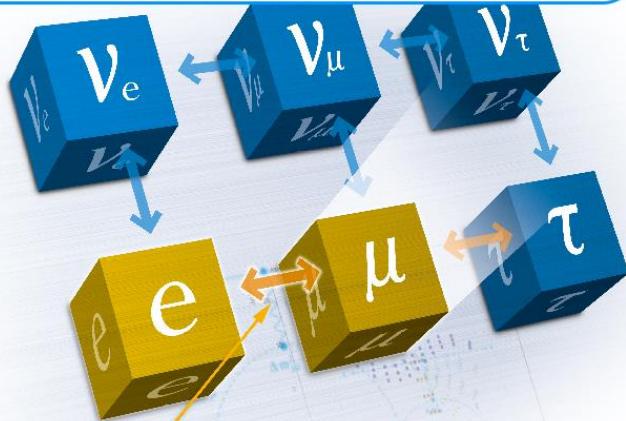
- **Charged Lepton Flavor Violation (CLFV)**
- **Muon to electron conversion search on COMET&Mu2e**
- **The experimental apparatus**
- **Signal and Backgrounds**
- **Current status**
- **Summary**



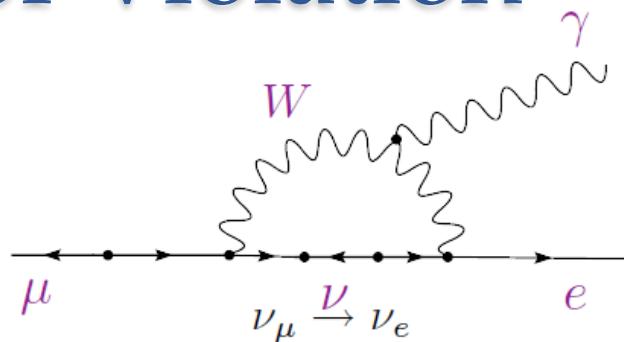


Charged Lepton Flavor Violation

Neutrino Flavor Violation is observed !



charged Lepton Flavor Violation !? (cLFV)



cLFV highly suppressed in SM+ m_ν :

$$\mathcal{B}(\mu \rightarrow e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U_{\mu i}^* U_{ei} \frac{\Delta m_{i1}^2}{M_W^2} \right|^2 \sim 10^{-54}$$

S.T. Petcov, Sov.J. Nucl. Phys. 25 (1977)
340

Current upper limits on \mathcal{B}_i

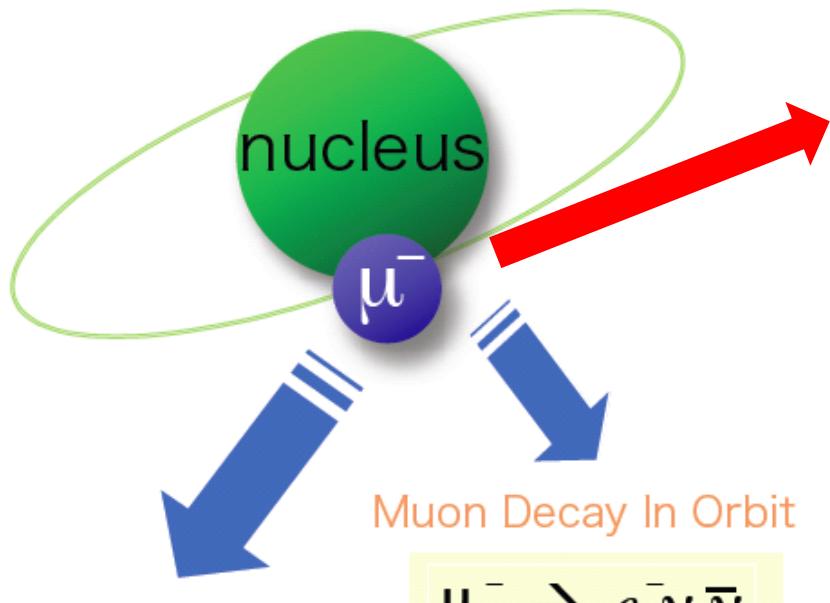


Any observe is the evidence of New Physics

$\mu N \rightarrow e N$ Conversion



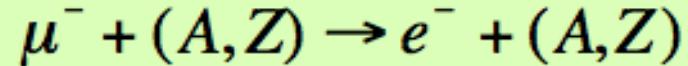
1s state in a muonic atom



nuclear muon capture



$\mu - e$ conversion: neutrinoless muon nuclear capture



Charged lepton flavor violated

- **Background signature:**
 - No accidental background
 - Can utilize high luminosity
 - Beam background can be suppressed by pulsed beam
 - Physics background can be handled with current detector technology

$\mu N \rightarrow e N$ Conversion

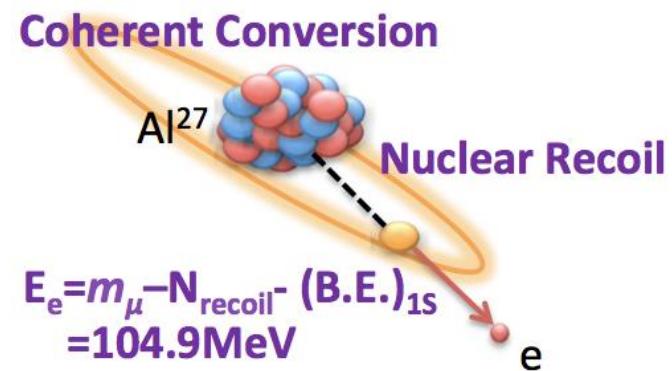


What to measure

- The ratio of muon to electron conversions to the number of muon captures by nuclei

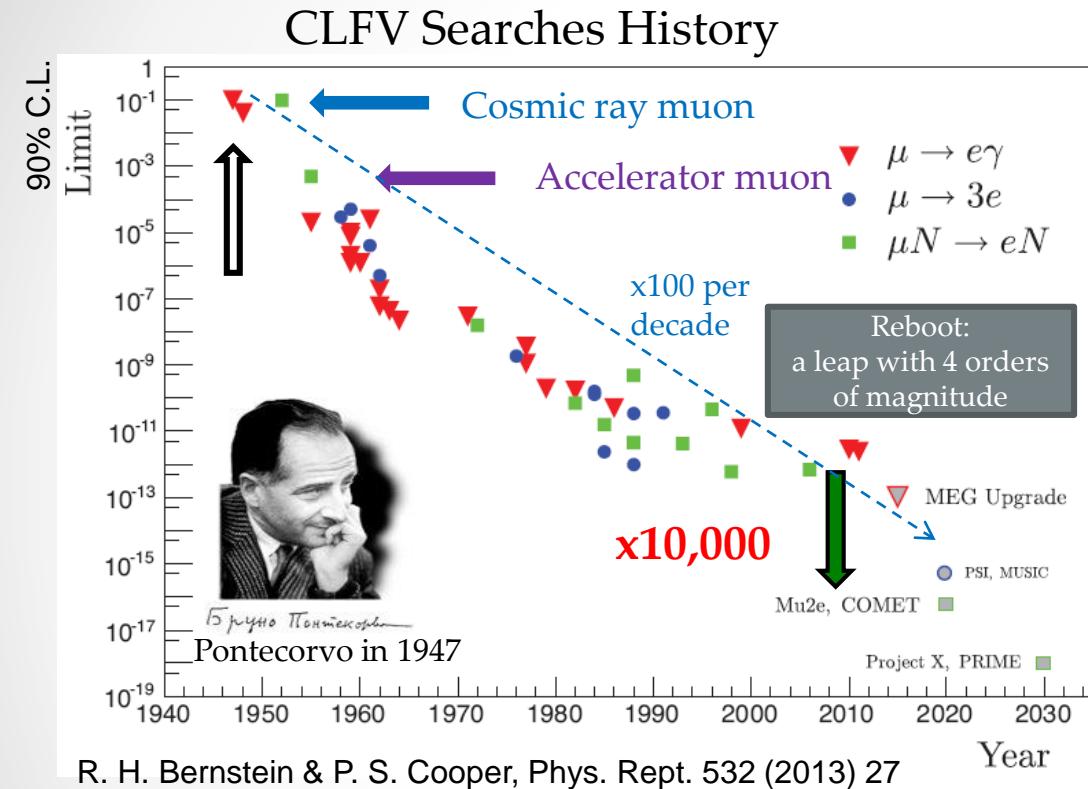
$$R_{\mu e} = \frac{\mu^- + {}^{27}_{13} Al \rightarrow e^- + {}^{27}_{13} Al}{\mu^- + {}^{27}_{13} Al \rightarrow \text{nuclear capture}}$$

- Signal: Neutrinoless conversion of a muon to electron in the field of a nucleus
- Experimental signature
 - Mono-energetic of 105MeV electron



Clean field to search for new physics!

Muon CLFV search history



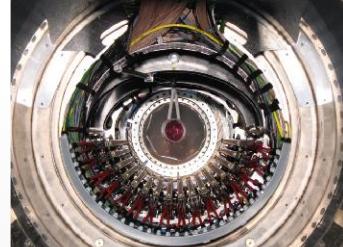
R. H. Bernstein & P. S. Cooper, Phys. Rept. 532 (2013) 27

- **Current best limit**
MEG $<4.2 \times 10^{-13}$ (90% C.L.)
 - **Next goal $<6 \times 10^{-17}$ (90% C.L.)**
 - **Next generation experiments ...**
- ↓



Mu3e @PSI

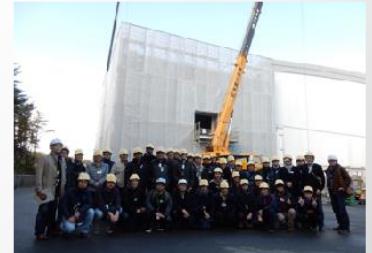
MEG Upgrade @PSI



Mu2e @FNAL



COMET @KEK



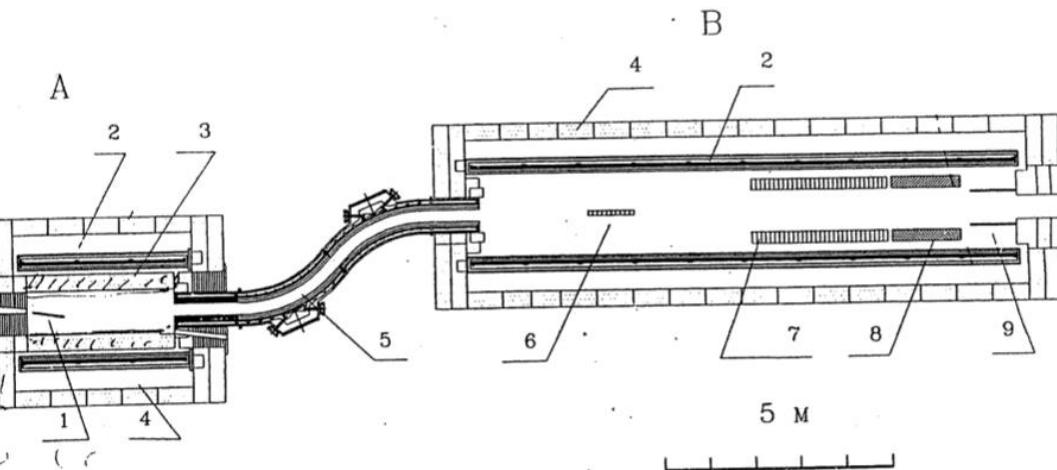
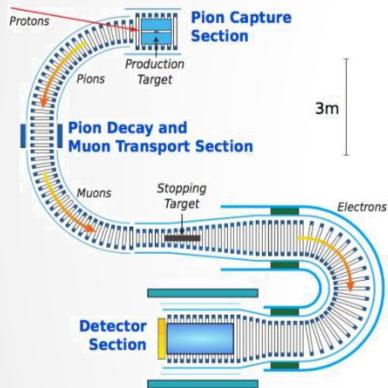


The “new idea”: MELC

PREPRINT INR-786/92
NOVEMBER 1992

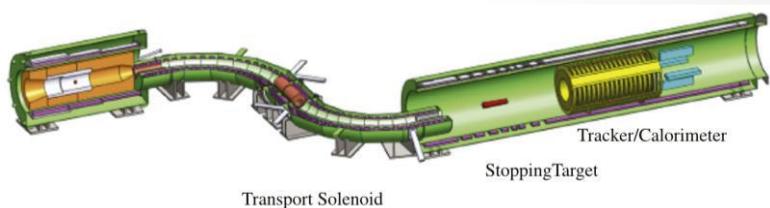
V.S. Abadjev, B.N. Bakhtin, O.N. Goncharenko, R.M. Djilkibaev,
V.V. Edlichka, V.M. Lobashev, V.I. Parfenov, I.A. Plisco,
V.V. Popov, S.K. Popov, A.L. Proscuryakov, I.V. Sekachev,
A.K. Skasyrskaya, O.B. Sokolova, A.P. Solodukhin,
A.N. Toropin, S.P. Toropov

MELC EXPERIMENT TO SEARCH FOR
THE $\mu^- A \rightarrow e^- A$ PROCESS



COMET

Mu2e



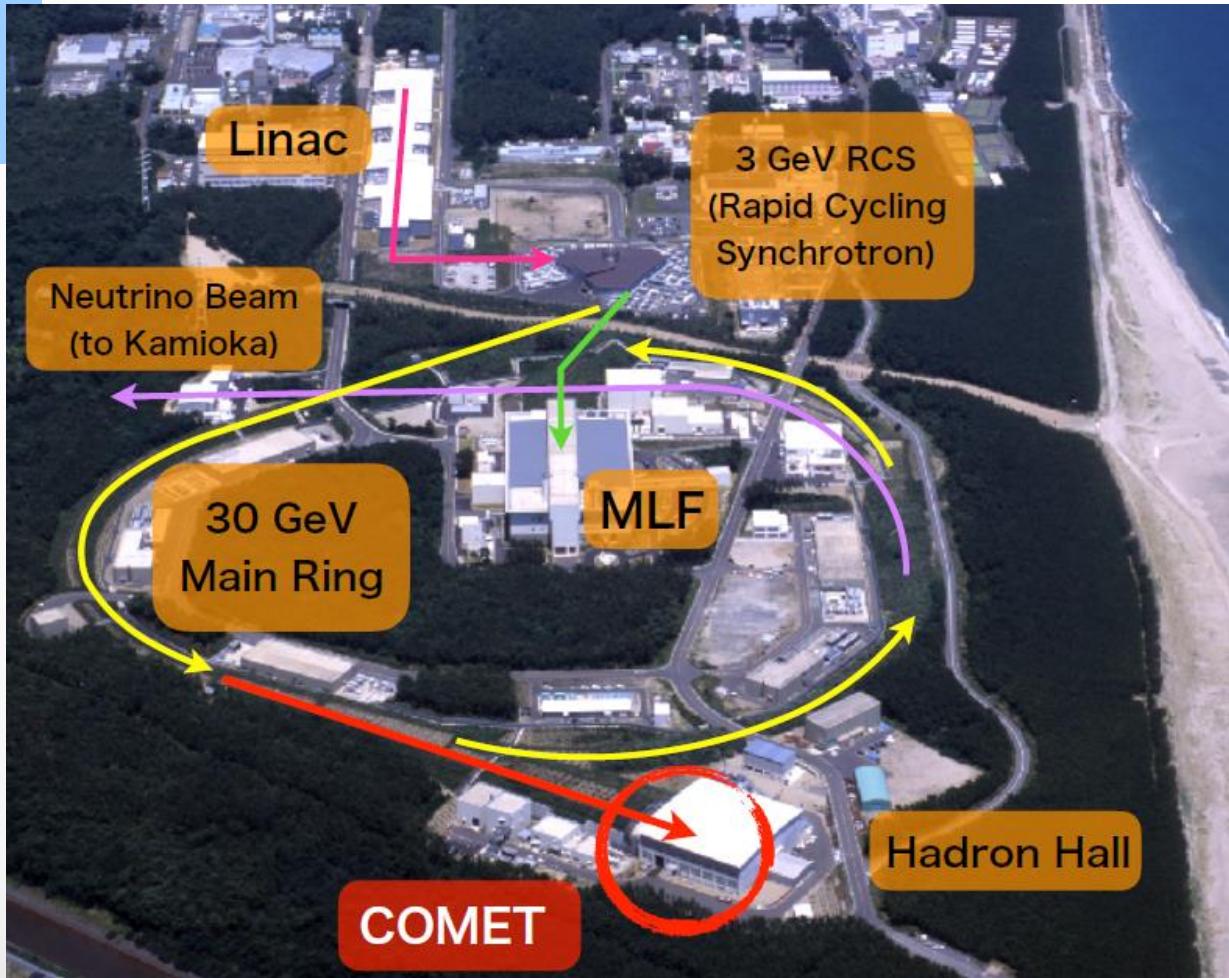
- Improve the production and capture efficiency
 - Thick target with super conducting solenoid as capture magnet
- Clean muon beam
 - Long beam line with momentum selection
- Search for signal with the special momentum
 - Light detector to provide precise measurement



Overview on COMET (COherent Muon Electron Transition)



Located in the Japan Proton Accelerator Research Complex (J-PARC) in Tokai, Japan.



8GeV
3.2kW for Phase-I
56kW for Phase-II

COMET Collaboration



The COMET Collaboration

中国组于2012年参加COMET实验
是中国参与首个μ子源实验

高能所，南京大学，中山大学

对COMET实验做出了重要贡献

- 电子学研发和生产
- 本底研究
- 实验设计优化
- 重建分析软件
- 新物理的研究
- muon束流监测探测器

R. Abramishvili¹², G. Adamov¹², R. Akhmetshin^{6,34}, V. Anishchik⁴, M. Aoki³⁵, Y. Arimoto¹⁹, I. Bagaturia¹², Y. Ban³, D. Bauer¹⁵, A. Bondar^{6,34}, Y. Calas⁷, S. Canfer⁵⁶, Y. Cardenas⁷, S. Chen³¹, Y. E. Cheung³¹, B. Chiladze³⁸, D. Clarke³⁶, M. Danilov^{16,28}, P. D. Dauncey¹⁵, W. De Silva²⁵, C. Densham³⁶, G. Devidze³⁸, P. Dorman¹⁵, A. Drutskoy^{16,28}, V. Dugino¹⁷, L. Epshteyn^{6,33,34}, P. Evtoukhovich¹⁷, S. Fayer¹⁵, G. Fedotovich^{6,34}, M. Finger⁸, M. Finger Jr⁸, Y. Fujii¹⁹, Y. Fukao¹⁹, E. Gillies¹⁵, D. Grigoriev^{6,33,34}, K. Gritsay¹⁷, E. Hamada¹⁹, R. Han¹, K. Hasegawa¹⁹, I. H. Hasim³⁵, O. Hayashi³⁵, Z. A. Ibrahim²⁶, Y. Igarashi¹⁹, F. Ignatov^{6,34}, M. Ito¹⁹, M. Ikeno¹⁹, K. Ishibashi^{23,24}, S. Ishimoto¹⁹, T. Itahashi³⁵, S. Ito³⁵, T. Iwami³⁵, X. S. Jiang², P. Jonsson¹⁵, T. Kachelhoffer⁷, V. Kalininikov¹⁷, F. Kapusta²⁵, H. Katayama³⁵, K. Kawagoe^{23,24}, N. Kazak⁴, V. Kazanin^{6,34}, B. Khazin^{6,34}, A. Khvedelidze^{17,12}, T. K. Ki¹⁹, M. Koike⁴², G. A. Kozlov¹⁷, B. Krikler¹⁵, A. Kulikov¹⁷, E. Kulish¹⁷, Y. Kuno³⁵, Y. Kuriyama²², Y. Kurochkin⁵, A. Kurup¹⁵, B. Lagrange^{15,22}, M. J. Lee¹³, H. B. Li², W. G. Li², R. P. Lifschitz¹⁵, T. Loan³², D. Lomidze¹², I. Lomidze¹², P. Loveridge³⁶, G. Macharashvili³⁸, Y. Makida¹⁹, Y. Mao⁵, O. Markin¹⁶, Y. Matsumoto³⁵, A. Melnik⁵, T. Mibe¹⁹, S. Miura¹⁹, F. Mohamad Idris²⁶, K. A. Mohamed Kamal Azmi²⁶, A. Moiseenko¹⁷, Y. Mori²², M. Moritsu³⁵, Y. Nakai^{23,24}, T. Nakamoto¹⁹, Y. Nakazawa³⁵, J. Nash²⁹, H. Natori¹², J. -Y. Nie⁷, M. Niordzwe³⁸, H. Nishiguchi¹⁹, T. Numao³⁹, J. O'Dell³⁶, T. Ogitsu¹⁹, K. Oishi^{23,24}, K. Okamoto³⁵, T. Okamura¹⁹, C. Omori¹⁹, T. Ota³⁷, J. Pasternak¹⁵, C. Plostinar³⁶, V. Ponariadov⁴⁵, A. Popov^{1,34}, V. Rusinov^{16,28}, B. Sabirov¹⁷, N. Saito¹⁹, H. Sakamoto³⁵, P. Sarin¹⁴, K. Sasaki¹⁹, A. Sato³⁵, J. Sato³⁷, Y. K. Semertzidis^{13,18}, N. Shigyo^{23,24}, D. Shoukavy⁵, M. Slunecka⁸, A. Straessner⁴⁰, D. Stöckinger⁴⁰, M. Sugano¹⁹, Y. Takubo¹⁹, M. Tanaka¹⁹, S. Tanaka^{23,24}, C. V. Tao⁵², E. Tarkovsky^{16,28}, A. M. Teixeira⁹, Y. Tevzadze³⁸, T. Thanh³², N. D. Thong³⁵, J. Tojo^{23,24}, M. Tomasiek¹¹, M. Tomizawa¹⁹, N. H. Tran³⁵, H. Trang³², I. Trekov³⁸, N. M. Truong³⁵, Z. Tsamalaidze^{17,12}, N. Tsverava^{17,38}, T. Uchida¹⁹, Y. Uchida^{15,35}, K. Ueno¹⁹, E. Velicheva¹⁷, A. Volkov¹⁷, V. Vrba¹¹, W. A. T. Wan Abdullah²⁶, M. L. Wong³⁵, T. S. Wong³⁵, C. Wu^{2,31}, H. Yamaguchi^{23,24}, A. Yamamoto¹⁹, M. Yamamaka²⁴, T. Yamane³⁵, Y. Yang^{23,24}, W. Yao², B. K. Yeo¹⁵, H. Yoshida³⁵, M. Yoshida¹⁹, Y. Yoshii¹⁹, T. Yoshioka^{23,24}, Y. Yuan², Yu. Yudin^{6,34}, J. Zhang², Y. Zhang², K. Zuber⁴⁰

¹North China Electric Power University, Beijing, People's Republic of China

²Institute of High Energy Physics (IHEP), Beijing, People's Republic of China

³Peking University, Beijing, People's Republic of China

⁴Belarusian State University (BSU), Minsk, Belarus

⁵B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus

⁶Budker Institute of Nuclear Physics (BINP), Novosibirsk, Russia

⁷Computing Center of the National Institute of Nuclear Physics and Particle Physics (CC-IN2P3), Villeurbanne, France

⁸Charles University, Prague, Czech Republic

⁹Laboratoire de Physique de Clermont, CNRS-IN2P3 Auvergne, France

¹⁰Czech Technical University, Prague, Czech Republic

¹¹Georgian Technical University (GTU), Tbilisi, Georgia

¹²Institute for Basic Science, Daejeon, Korea

¹³Indian Institute of Technology, Bombay, India

¹⁴Imperial College London, London, UK

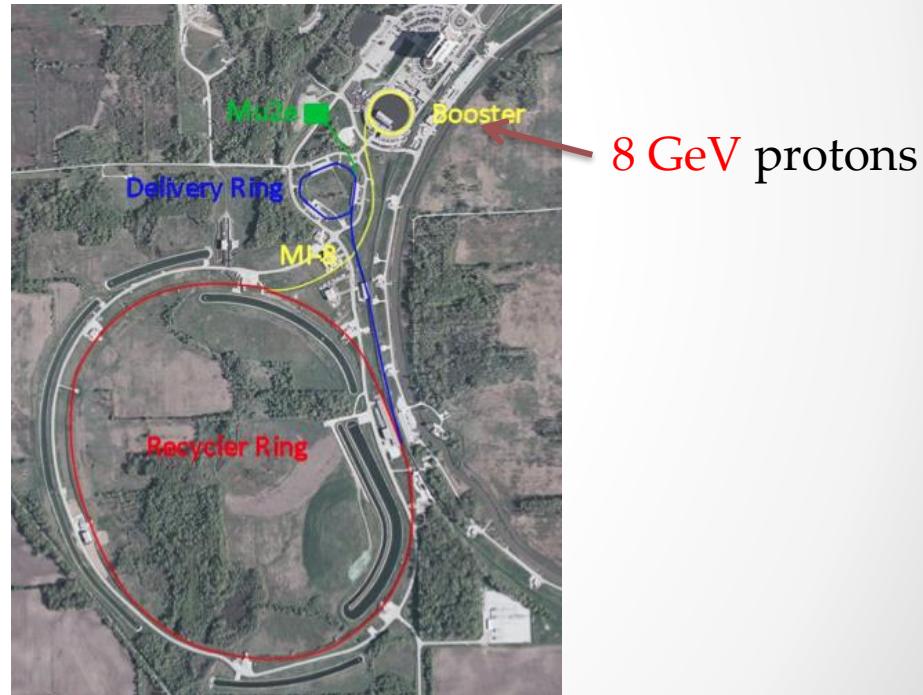
¹⁵Institute for Theoretical and Experimental Physics (ITEP), Russia

16+ countries, 39+ University or institute

Overview of Mu2e



- Located at Fermi National Laboratory
- One of the U.S. Intensity Frontier top priority projects
- Cost ~\$275 M dollars (US accounting)



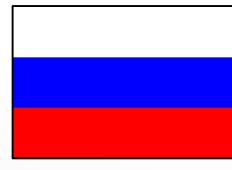
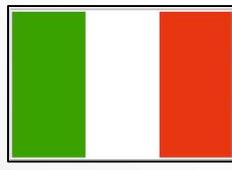
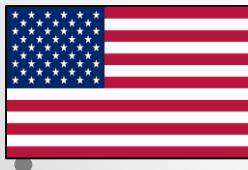
Mu2e Collaboration



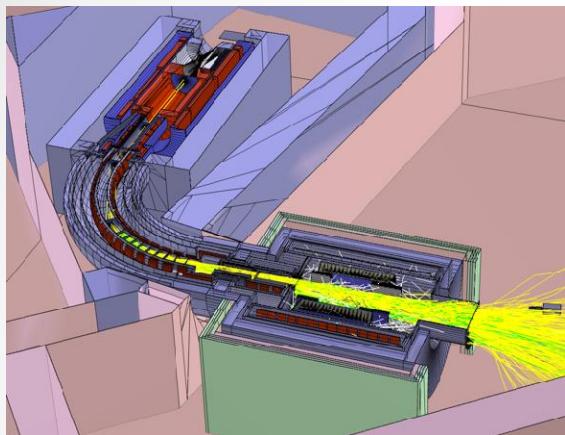
- > 220 scientists from 38 institutions
- Sun Yat-Sen University joined Mu2e in Feb. 2016

Argonne National Laboratory,
Boston University,
University of California Berkeley,
University of California Irvine,
California Institute of Technology,
City University of New York,
Joint Institute of Nuclear Research Dubna,
Duke University,
Fermi National Accelerator Laboratory,
Laboratori Nazionale di Frascati,
University of Houston,
Helmholtz-Zentrum Dresden-Rossendorf,
INFN Genova,
Institute for High Energy Physics, Protvino,
Kansas State University,
Lawrence Berkeley National Laboratory,
INFN Lecce, University Marconi Rome,
Lewis University,
University of Liverpool,

University College London,
University of Louisville,
University of Manchester,
University of Michigan,
University of Minnesota,
Muon Inc.,
Northwestern University,
Institute for Nuclear Research Moscow,
INFN Pisa,
Northern Illinois University,
Purdue University,
Rice University,
Sun Yat-Sen University,
University of South Alabama,
Novosibirsk State University
Budker Institute of Nuclear Physics,
University of Virginia,
University of Washington,
Yale University



COMET Phase-I and Phase-II



Detectors:

Cylindrical drift chamber
Straw Tracker + ECAL

Goals of Phase- I

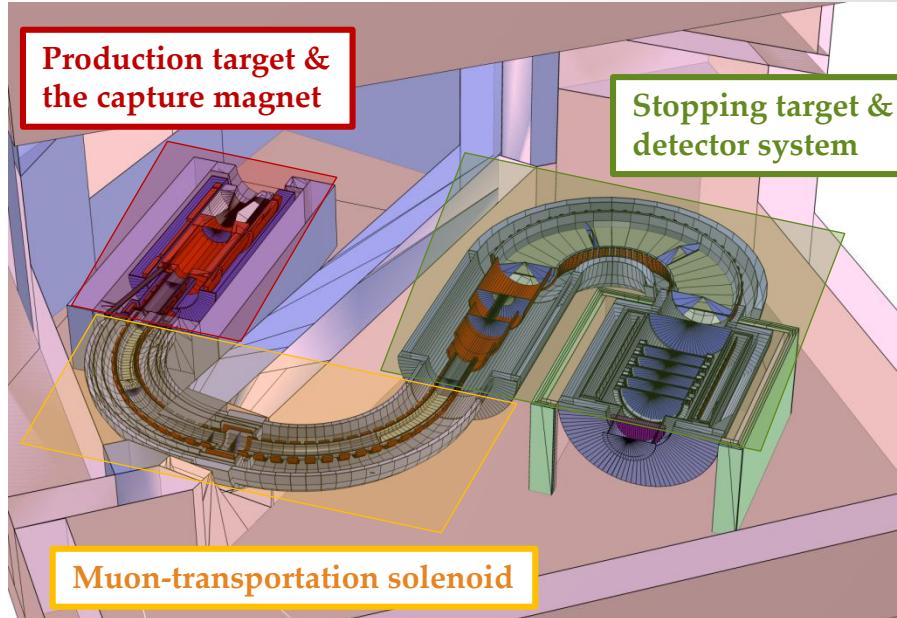
1. Background measurements

direct measurement of potential background sources for the full COMET experiment by using the actual COMET beam line

2. Search for μ -e conversion

a search for μ -e conversion at the intermediate sensitivity which would be 3.1×10^{-15} which is 100-times better than the present limit (SINDRUM-II)

3. Beam characterization



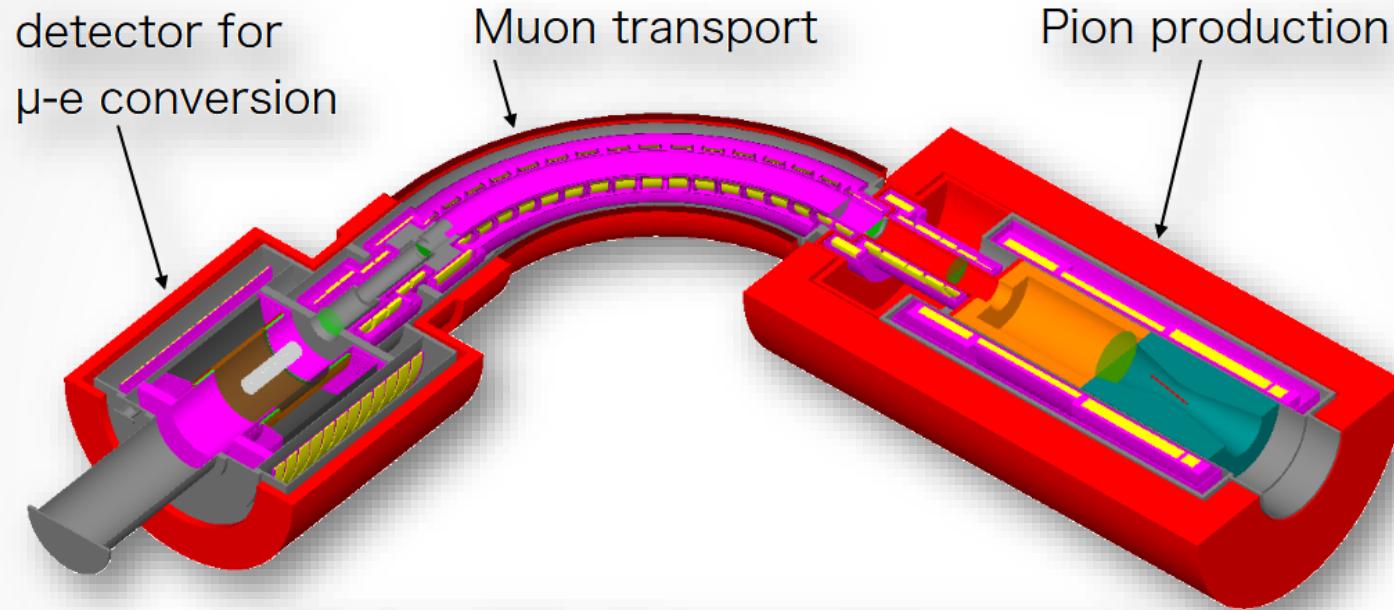
Detectors: Straw Tracker + ECAL

Goal of Phase- II

- search of μ -e conversion**

single event sensitivity: 2.6×10^{-17} which is 10,000 better than the current limit

Overview of COMET Phase-I



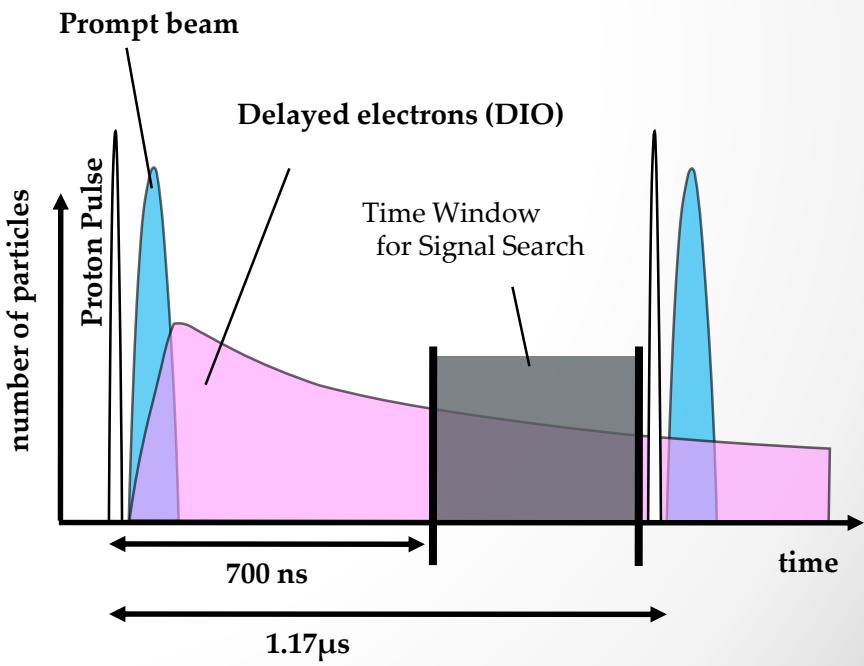
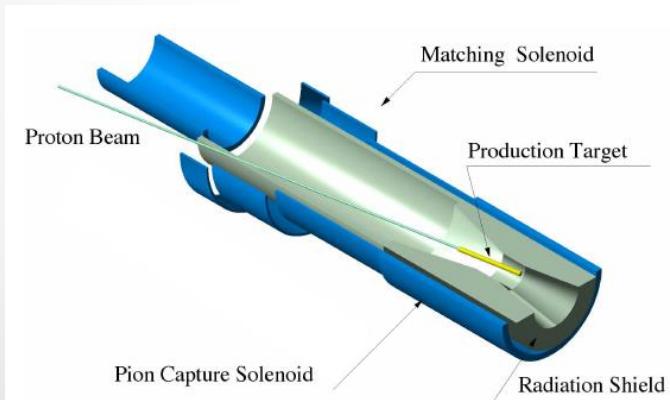
COMET Phase-I Layout

1. Proton on production targets and produce pions
2. Pions decay to muons and transported to detector sections
3. Muons stopped and decay in the stopping target

COMET Proton Beam



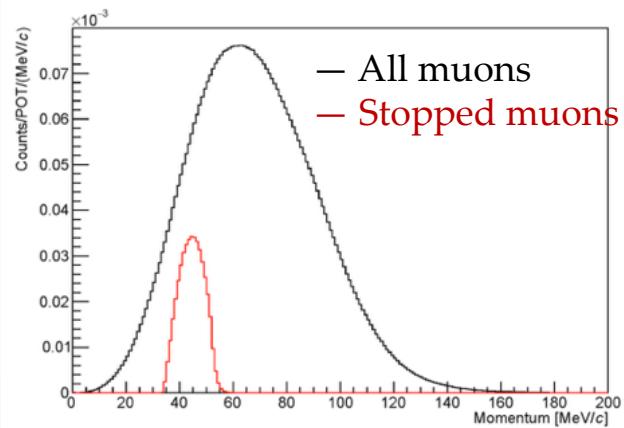
- 3kW proton prompt beam:
 - $\sim 10^{19}$ protons on pion targets (in 150 days running time)
- Bunch structure of proton beam
 - Bunch size $\sim 10^7$ POT
 - Bunch spill/width $\sim 100\text{ns}$
 - Extinction factor 3×10^{-11}
 - Bunch separation time = 1170ns .



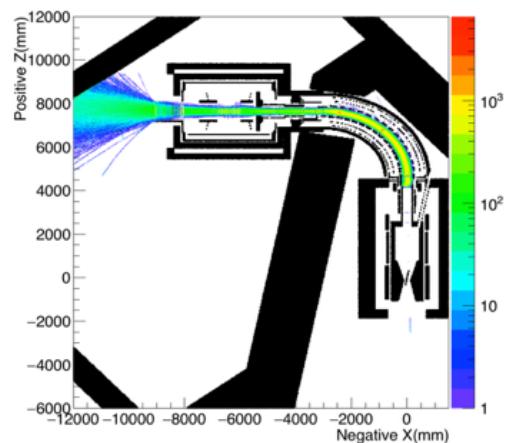
Time structure of proton beam bunch

Muon Beam

- 90 degree and long muon transport solenoid
- High efficiency and stopping rate for $\sim 40 \text{ MeV}/c$ muons
- Collimator to block high momentum muons $\sim 75 \text{ MeV}/c$



Initial momentum of stopped muons and all muons



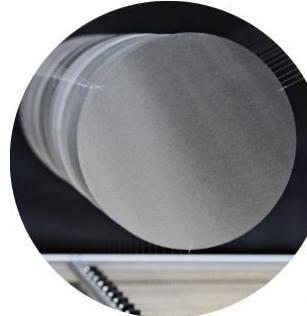
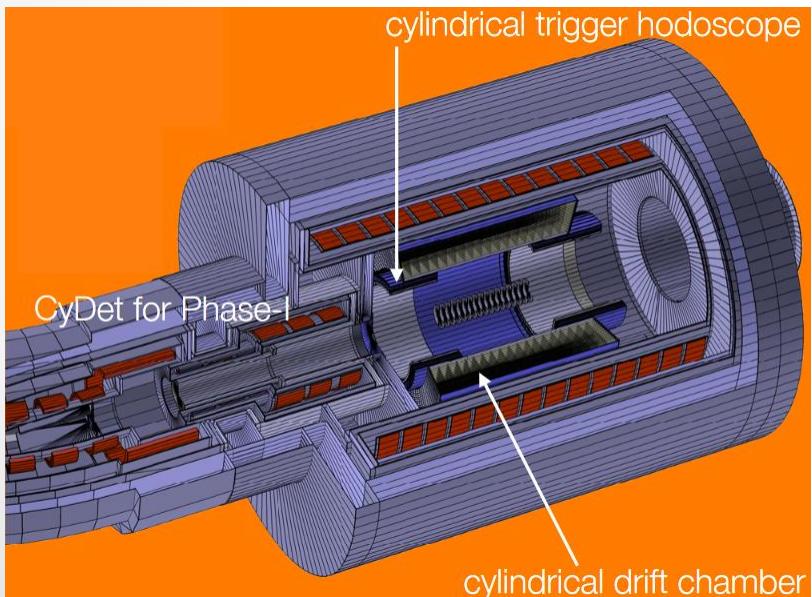
The bird view of muon beam intensity

| Yield (per proton): | After muon transport section | Stopped in muon target |
|---------------------|------------------------------|------------------------|
| Muons | 5.0×10^{-3} | 4.7×10^{-4} |
| Pions | 3.5×10^{-4} | 3.0×10^{-6} |

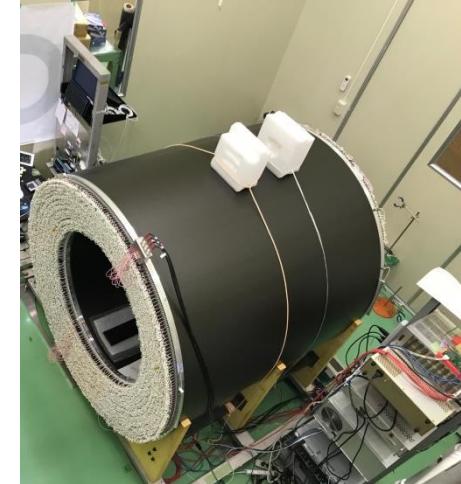
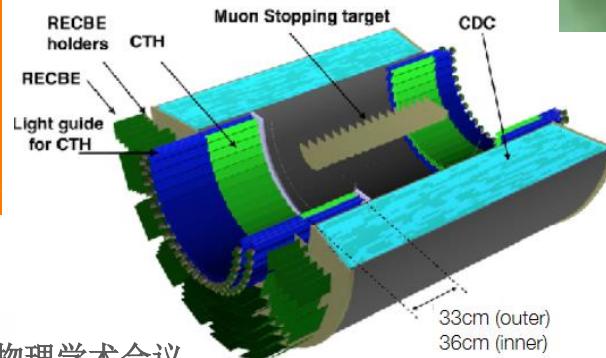
Muon and pion yields per proton at end of the muon beam line and stopped in the stopping target

COMET Phase-I Cylindrical Detector

- Cylindrical Drift chamber (CDC)
- Trigger hodoscope: Cherenkov radiator + plastic scintillator
- Al muon-stopping target



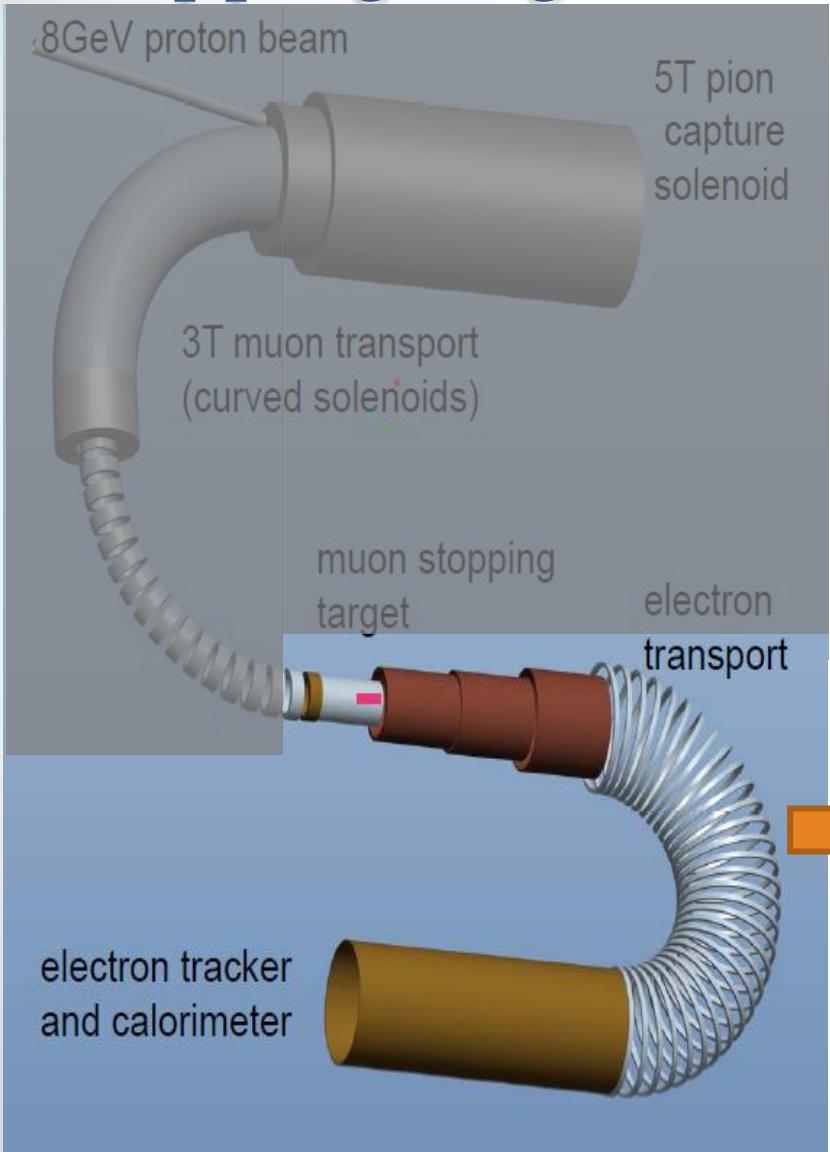
muon-stopping target



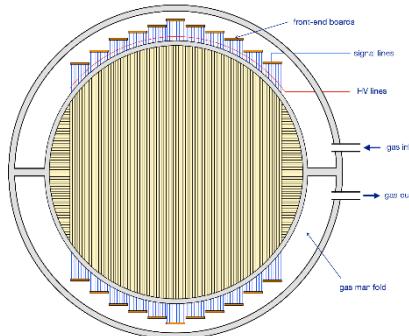
CDC

COMET PhaseII

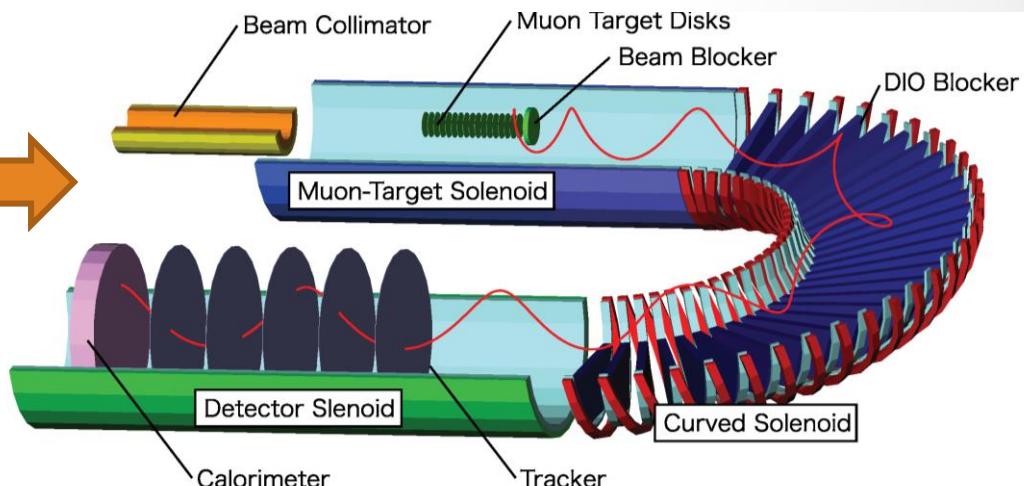
Stopping target and detector system



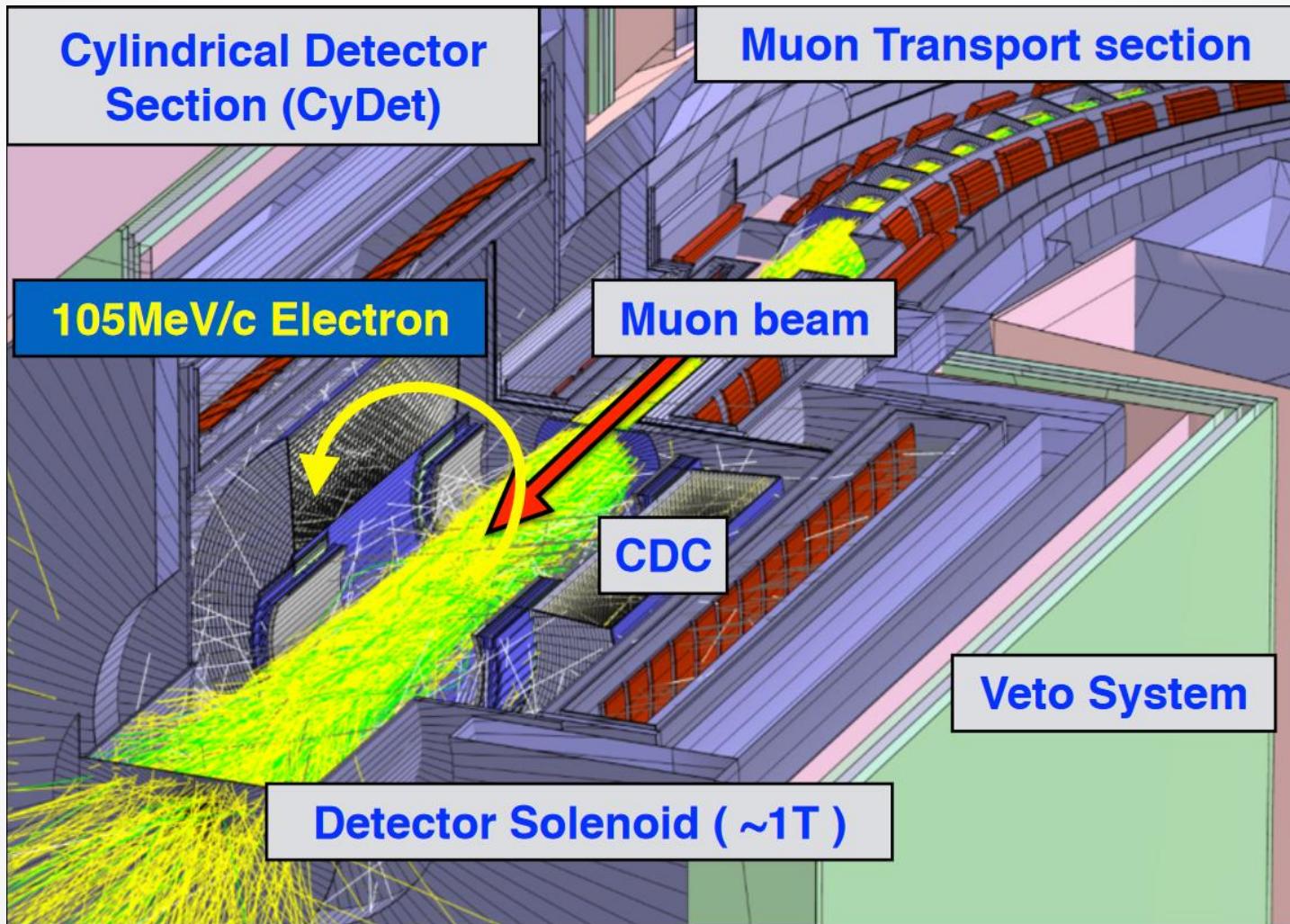
- Use **straw tracker** to measure the momentum
 - Really light: put in vacuum, 12 micro meter thin straw



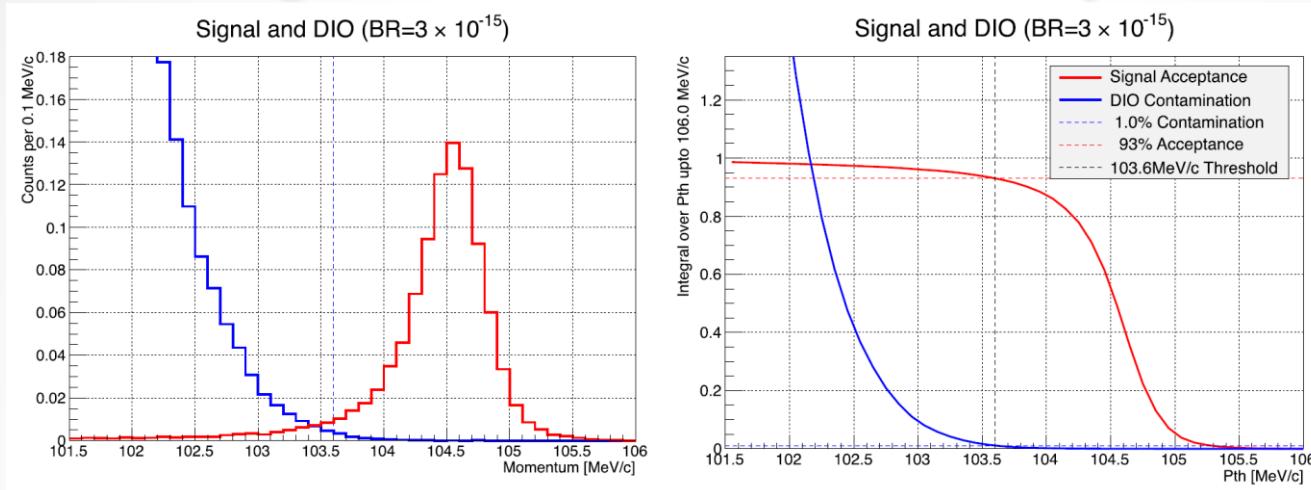
- **Electromagnetic calorimeter**
 - Providing trigger, TOF and PID



An event display of COMET one bunch



COMET Single Event Sensitivity(S.E.S)



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

$f_{cap} = 0.61$ (Al), fraction of muon capture

$f_{gnd} = 0.9$ is the fraction of $\mu-e$ conversion to the ground state in the final state

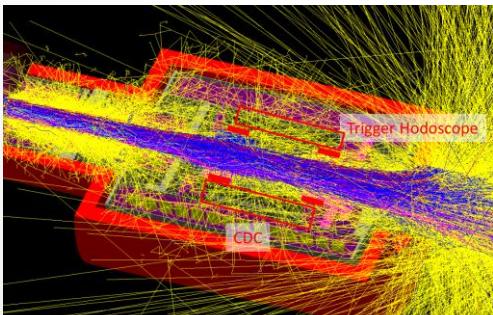
$A_{\mu-e} = 0.041$ is the signal acceptance

N_μ is the number of muons stopping in the muon target

- **Single Event Sensitivity = 3.1×10^{-15}** (~ 150 days)
- At momentum window $103.6 \text{ MeV}/c < p_e < 106 \text{ MeV}/c$, yielding a signal acceptance of **0.93**

COMET Phase-I background study

- The optimization of COMET Phase I is finished. Detailed performance is estimated with Monte Carlo studies.
 - Sensitivity:
 - Total acceptance of signal is **0.041**
 - Can reach 3×10^{-15} SES in 150 days.
 - Background:
 - With 99.99% CRV total expected background is **0.032**
 - Trigger rate:
 - Average trigger rate $\sim 10\text{kHz}$ (after trigger with drift chamber hits)

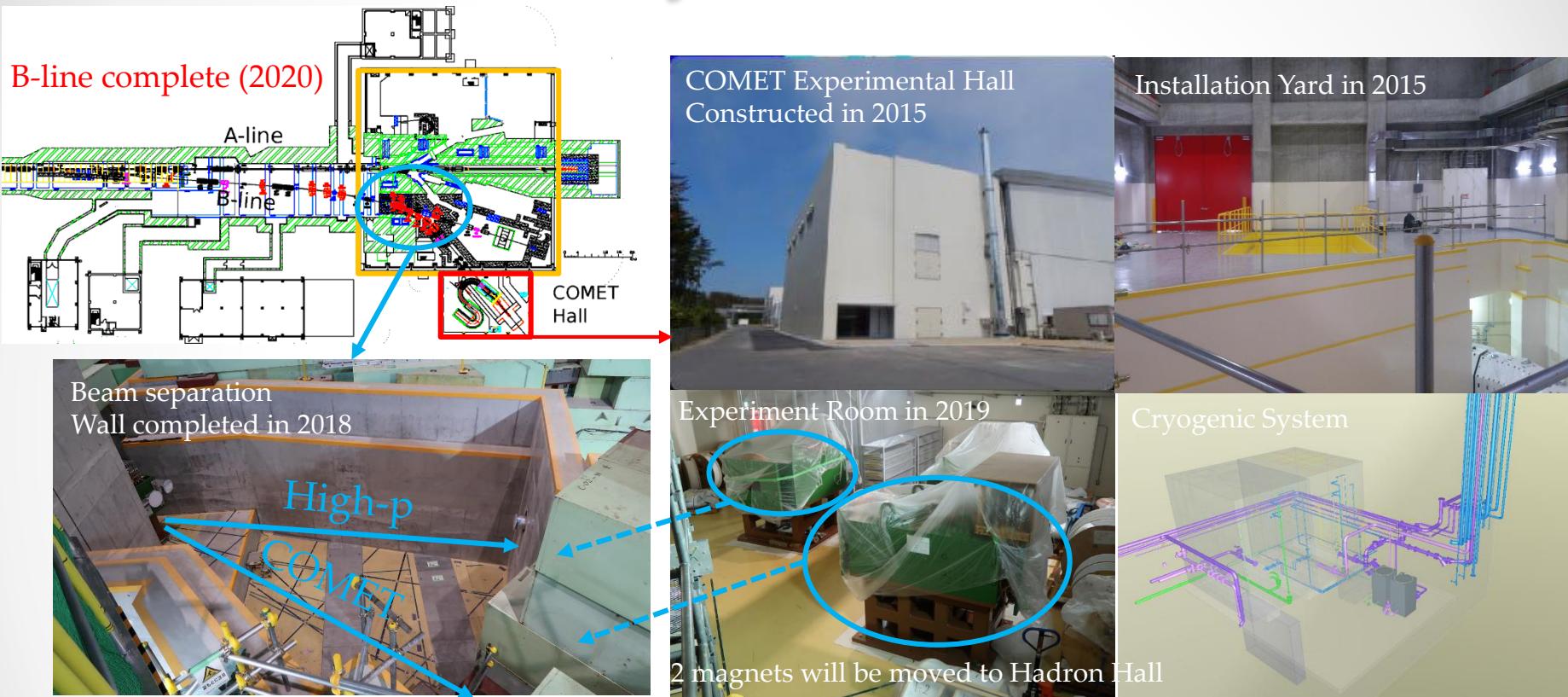


| Event selection | Value |
|--|-------|
| Online event selection efficiency | 0.9 |
| DAQ efficiency | 0.9 |
| Track finding efficiency | 0.99 |
| Geometrical acceptance + Track quality cuts | 0.18 |
| Momentum window (ε_{mom}) | 0.93 |
| Timing window ($\varepsilon_{\text{time}}$) | 0.3 |
| Total |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

| 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 | ~ 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 |

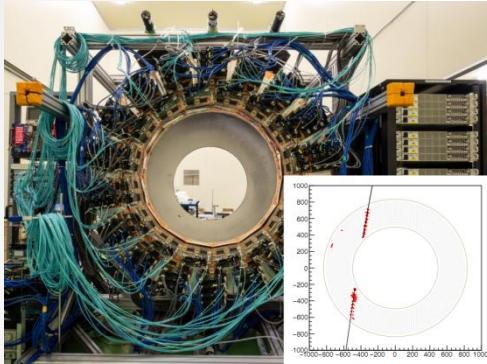
[†] This estimate is currently limited by computing resources.

COMET Facility status

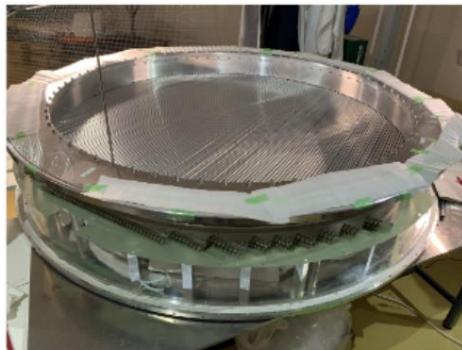


- Experimental Hall building completed
- Cryogenic system under construction
- The final part of the proton beamline (C-line) will be ready this year (2021)
 - Shield wall & power station completed. 2 more magnets to be located soon.

COMET solenoid and detector status



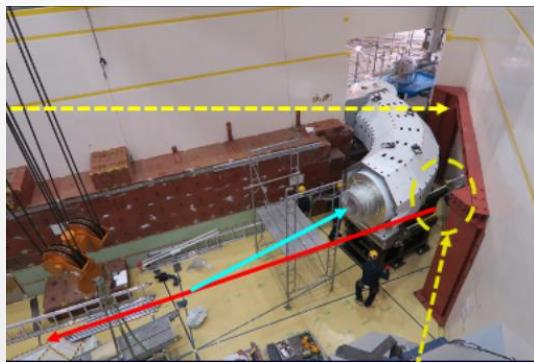
CDC under cosmic ray test



straw installation, completed



ECAL construction started



Pion Transport Solenoid

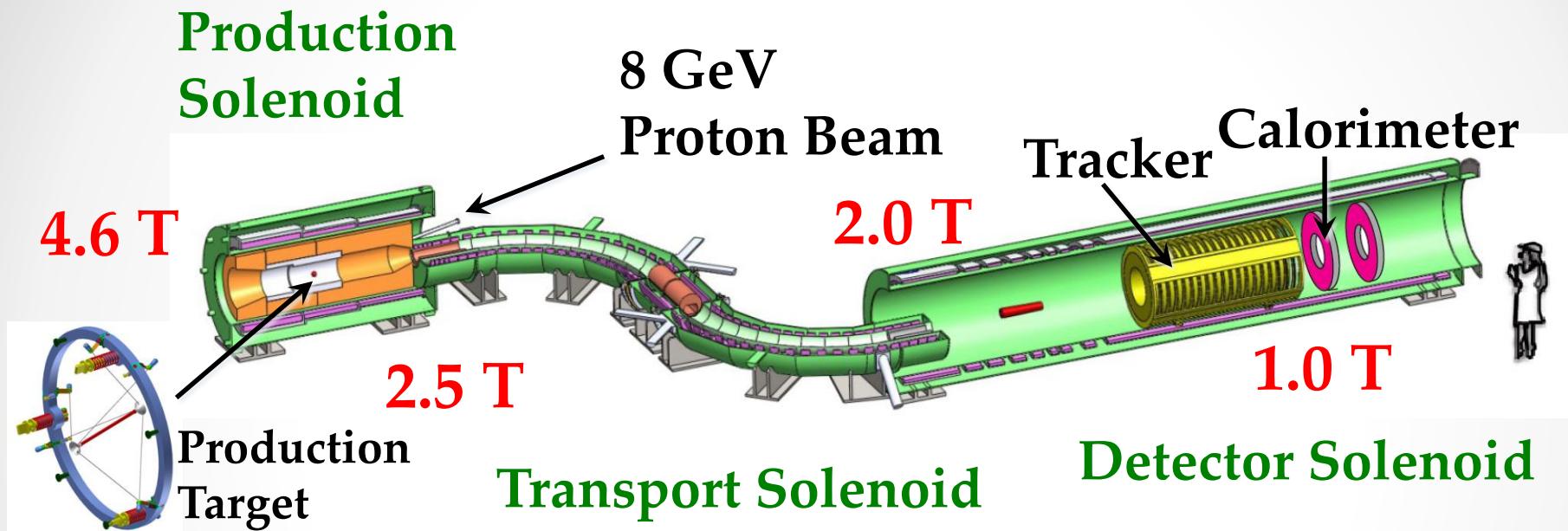


Pion Capture Solenoid CS

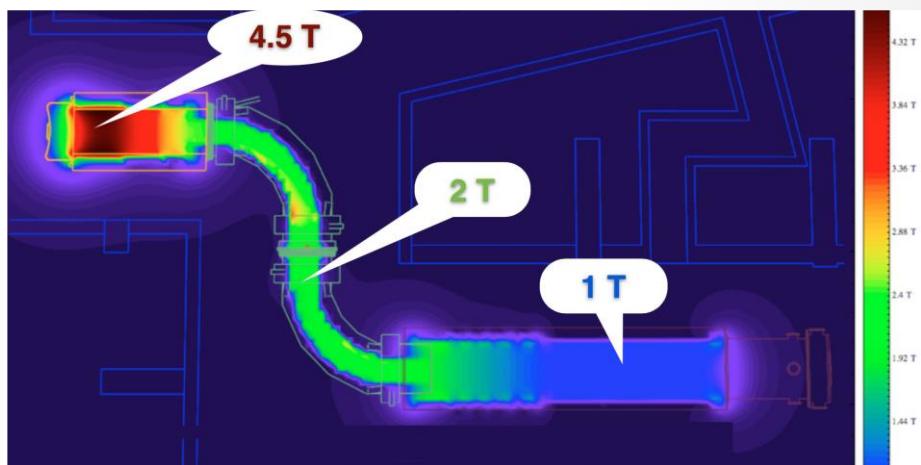


Pion Capture Solenoid TS1

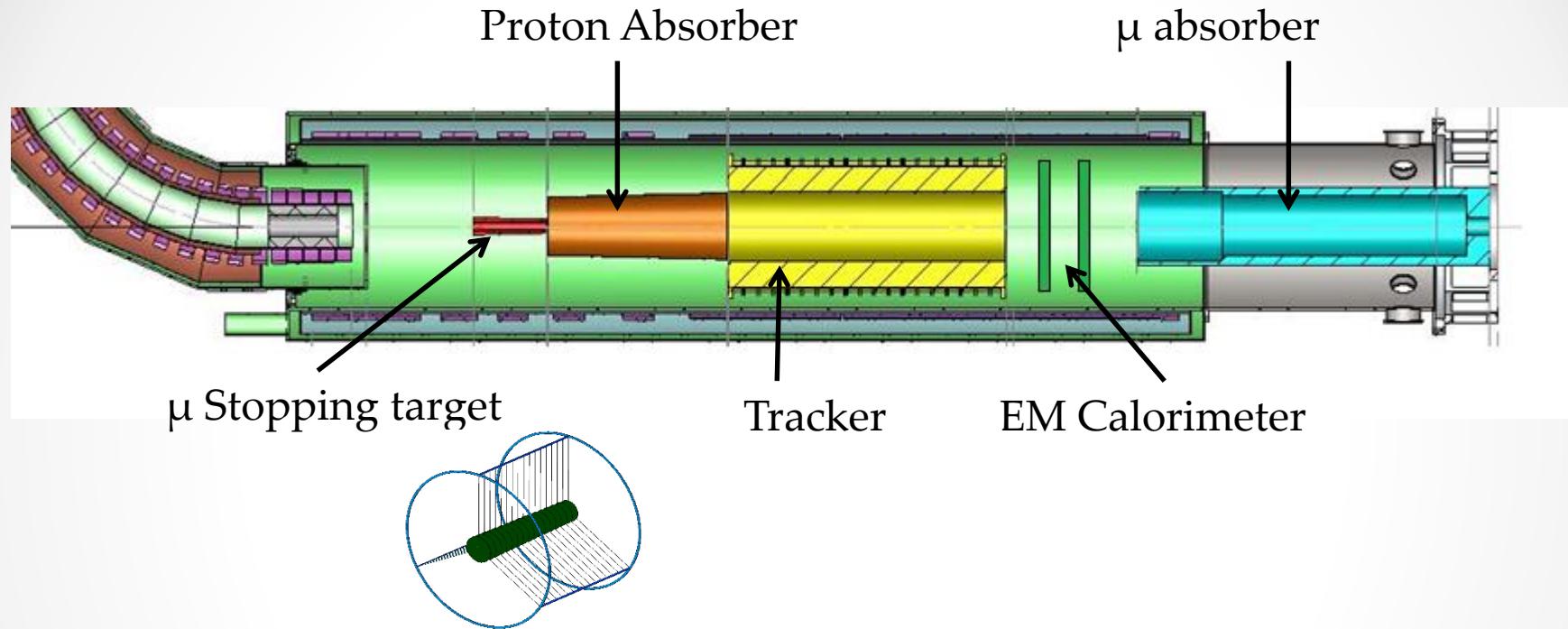
Mu2e Apparatus



Three functional solenoids with graded fields (4.5T – 1T)



Mu2e Detector Solenoid

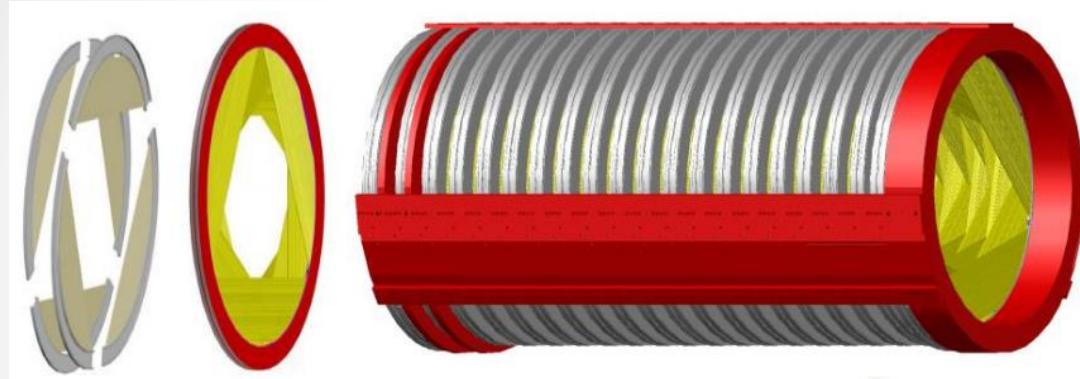


- Stopping target to capture muons
- Graded magnetic field from 2 T to 1 T, captures conversion electrons with bigger acceptance
- Tracker and Calorimeter in a uniform field to reconstruct and identify electrons.

Mu2e Tracker



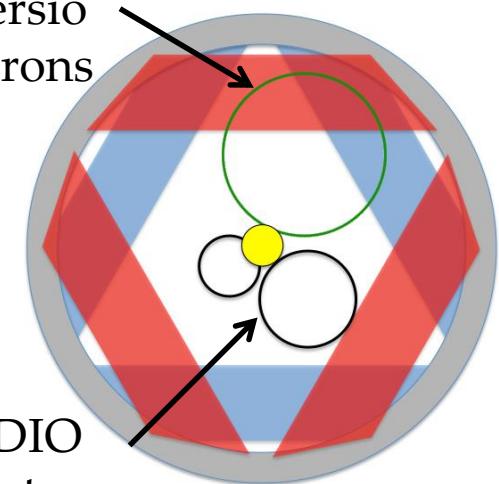
Tracker Structure



- 5 mm diameter straw drift tubes
- 15 μm Mylar walls, filled with Ar:CO₂ (80:20)
- 18 stations, 2 planes/station, 6 panels /plane
- Blind to beam flash and >97% DIO
- Expect 100 μm hit resolution
- Momentum resolution < 180 keV/c
(@105MeV/c)
-

105 MeV
Conversion electrons

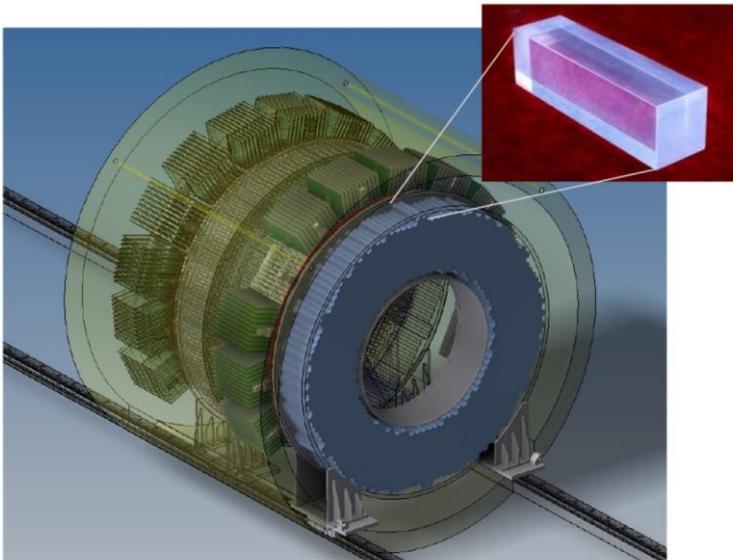
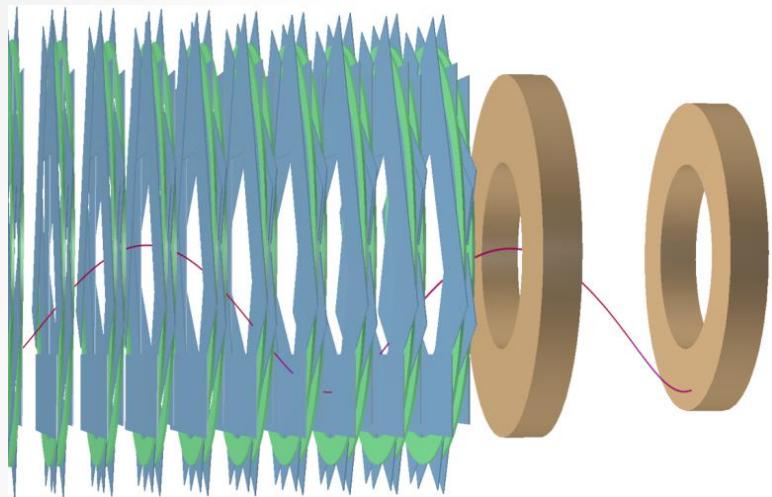
DIO
electrons



Straw Tube

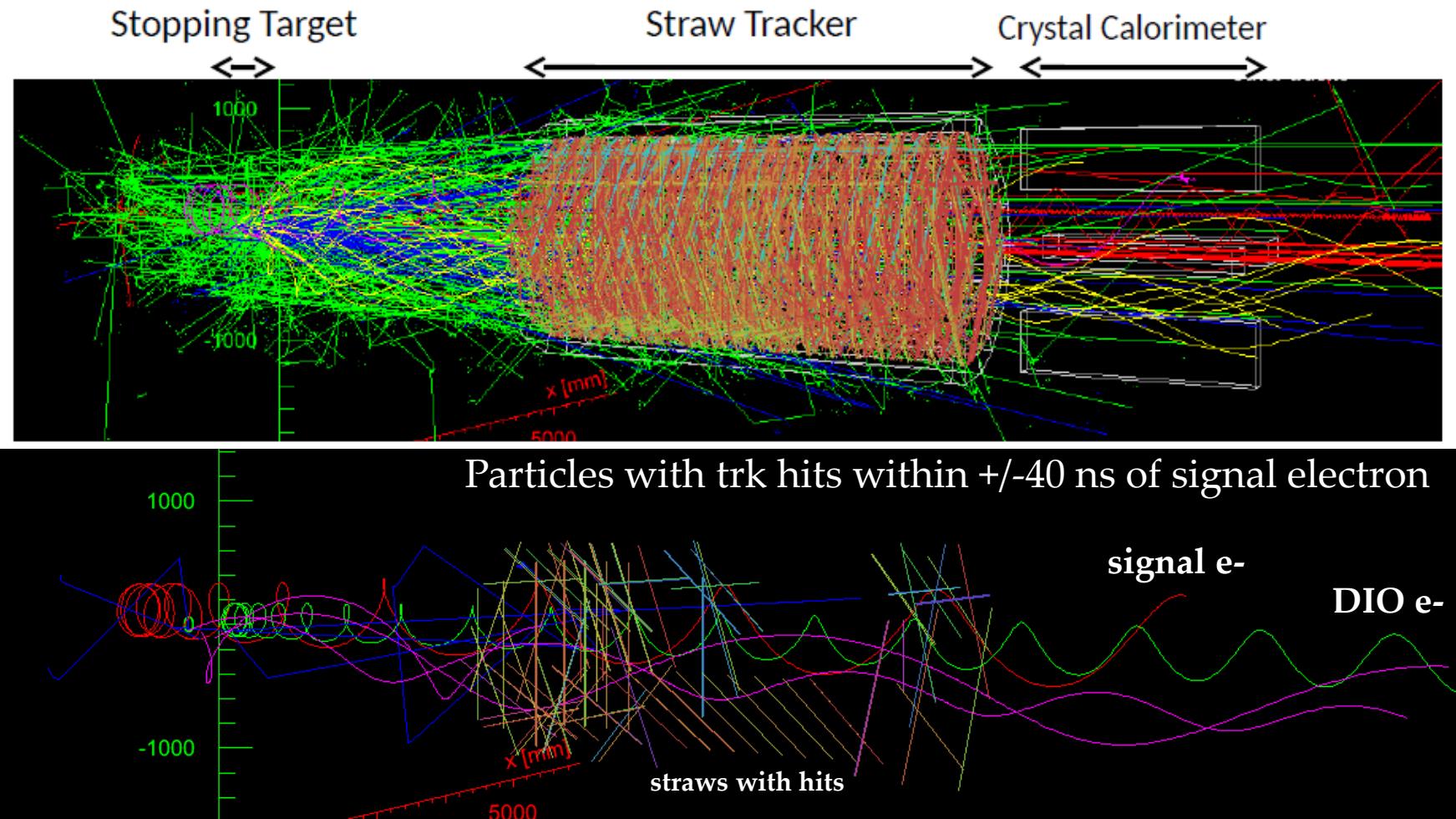


Mu2e Calorimeter



- Two disks separated by 70 cm ($1/2 \lambda$), ~ 674 CsI crystals/disk
- Provides independent energy ($\sigma_E/E < 5\%$), time ($\sigma_t < 0.5\text{ns}$) and position ($\sigma_{\text{pos}} \sim 1\text{cm}$) measurements
- Particle ID, Cosmic Ray rejection, tracking seed
- Independent trigger
-

Mu2e Signal



To find a signal electron near 105 MeV/c from a bunch of track candidates



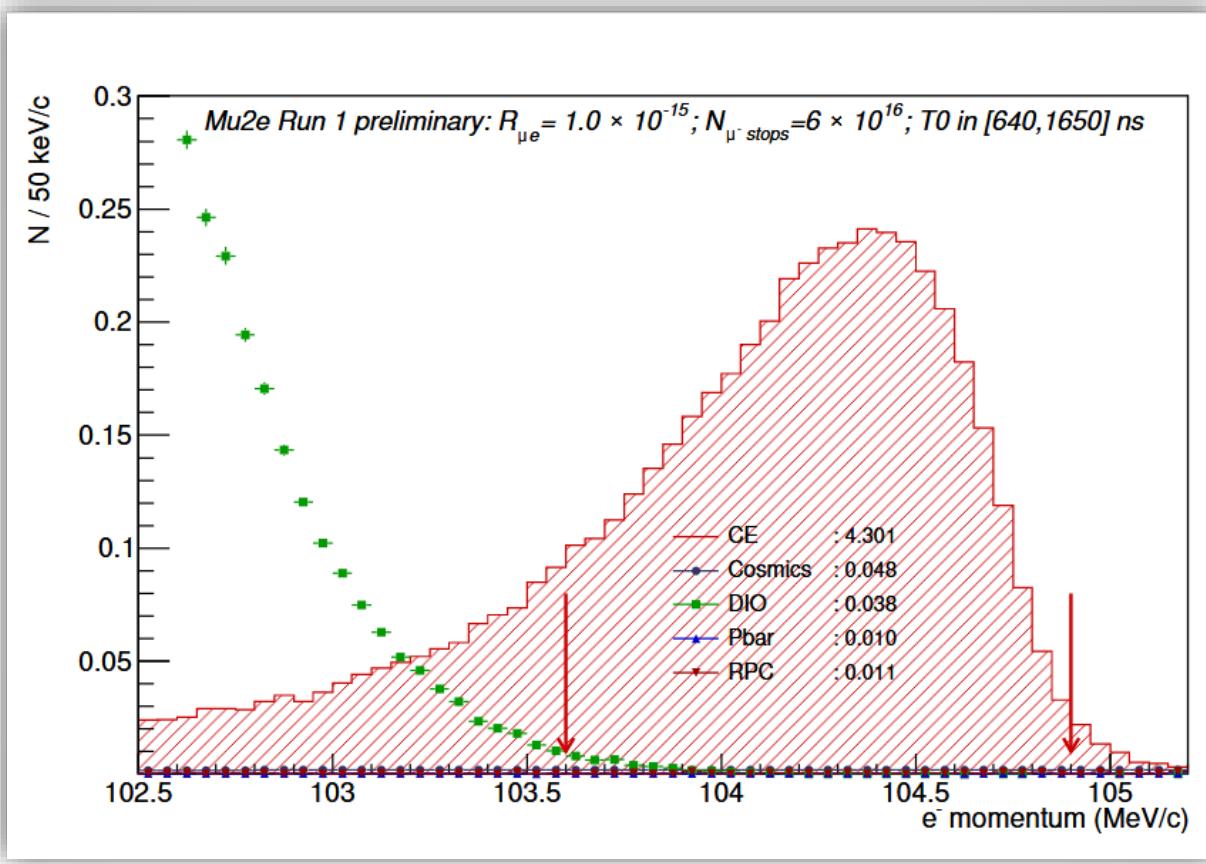
Mu2e Run 1 background expectation

| Channel | Mu2e Run 1 Background Expectation |
|-----------------|--|
| Cosmics | 0.047 ± 0.010 (stat) ± 0.009 (syst) |
| DIO | 0.038 ± 0.002 (stat) $^{+0.026}_{-0.016}$ (syst) |
| Antiprotons | 0.010 ± 0.003 (stat) $^{+0.010}_{-0.004}$ (syst) |
| RPC in-time | 0.011 ± 0.002 (stat) $^{+0.001}_{-0.003}$ (syst) |
| RPC out-of-time | negligibly small |
| RMC | negligibly small |
| Beam electrons | negligibly small |
| Total | 0.106 ± 0.032 (stat+syst) |

For Run 1 (planned 2025-2026, before PIP-II shutdown)

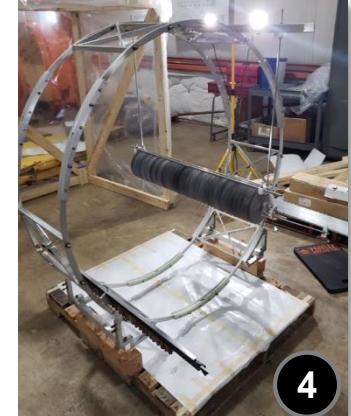
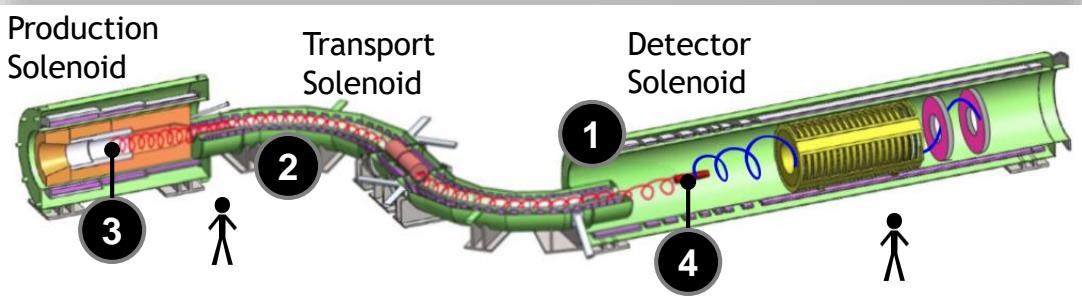
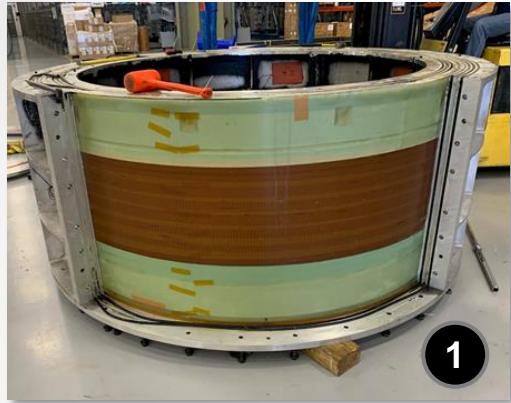
Most realistic simulation so far for Run 1 (before PIP-II shutdown),
overall expected background ~0.1 event

Mu2e Signal and Backgrounds



- Run 1 simulation, $R_{\mu e} < 5.9 \times 10^{-16}$ (90% CL)
- For a conversion ratio of 1×10^{-15} , ~5 signal events, 5 σ discovery of CLFV
- Further 10X improvements with Run II

Mu2e Current Status



**Proton and stopping
targets assembled**

- Simulation of realistic data for Mock Data Challenge
- New estimates of backgrounds from Sensitivity Update 2020 campaign

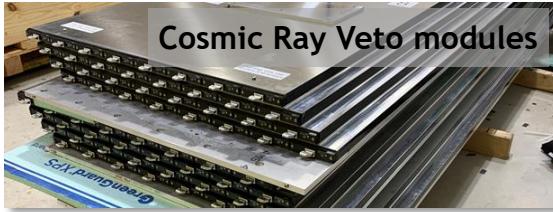
Solenoid fabrication and testing

第十三届全国粒子物理学术会议

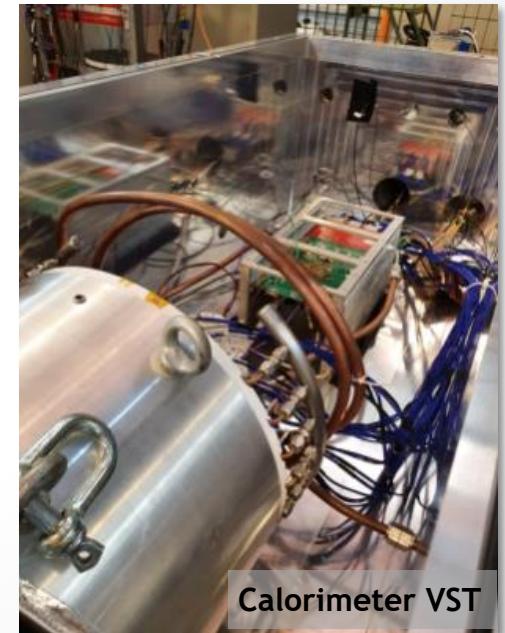
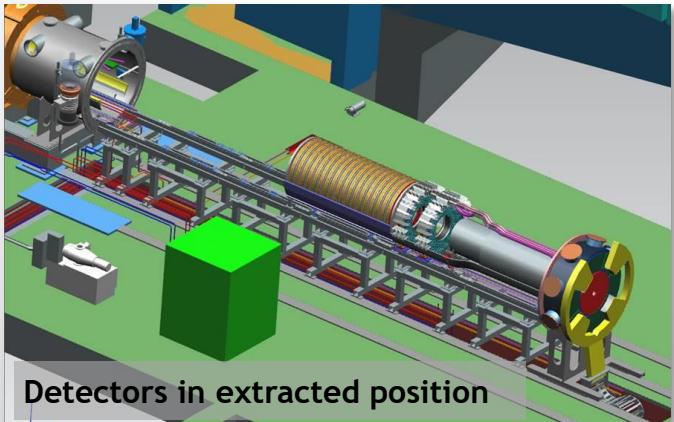
2021/8/18

30

Mu2e Current status



**Integration of detector systems
and preparation for installation**

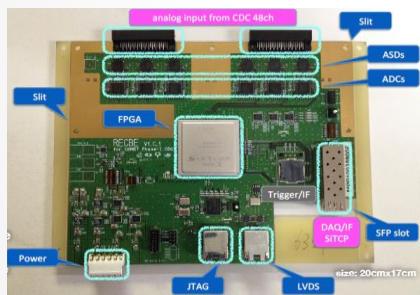


COMET CDC readout board by IHEP

- The production of 128 readout board – RECBE
- Work in the CDC cosmic ray test

Optimization of COMET experiment

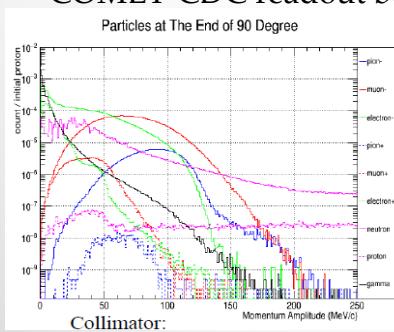
- Leading role to the COMET Phase-I and Phase-II optimization
- Main contribution to the beam simulation, Sensitivity and Backgrounds



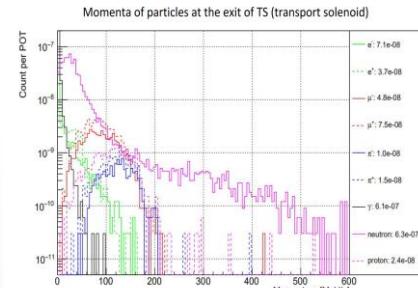
COMET-CDC readout board



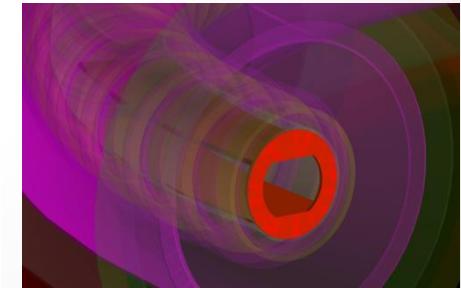
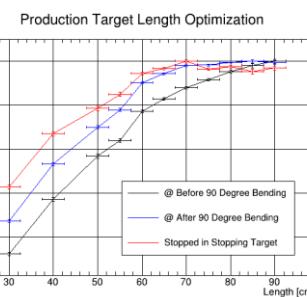
readout board in CRT



Phase-I beam profile



Phase alpha beam profile Production target optimization
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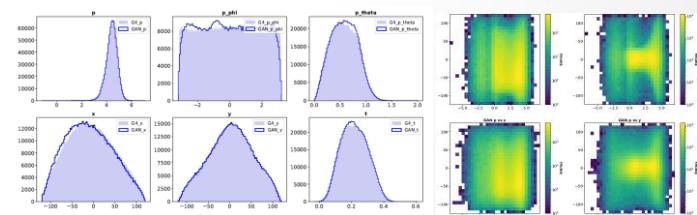
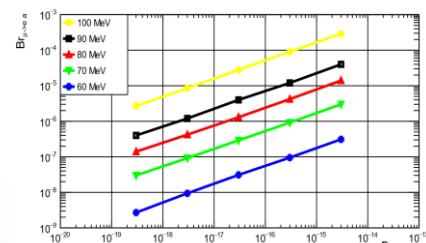
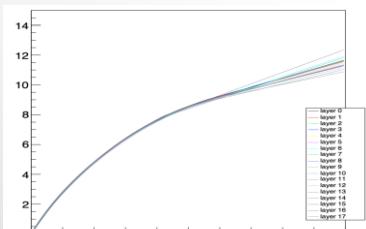
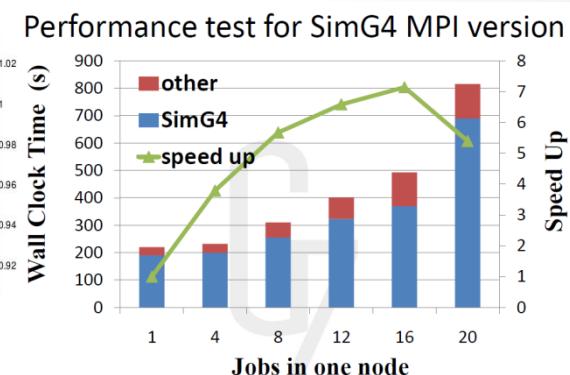
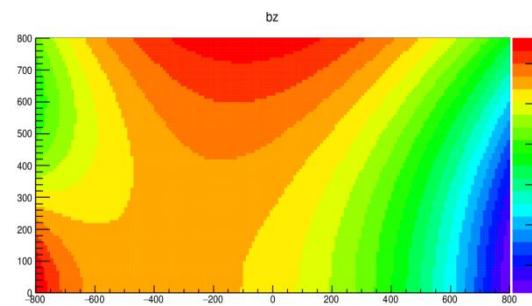
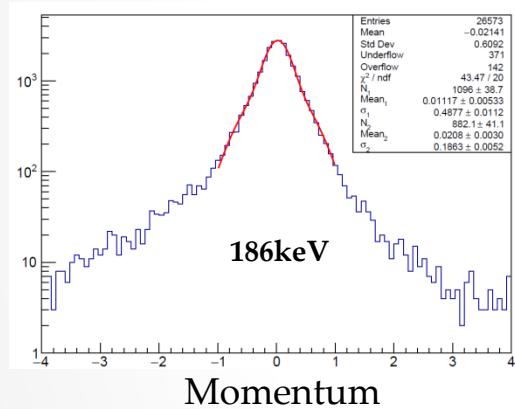


Collimator after optimization
2021/8/18 ● 32

COMET Single event sensitivity

- Main contribution to the COMET drift chamber reconstruction

Framework, simulation, data analysis and new physics



Drift chamber X-T calibration

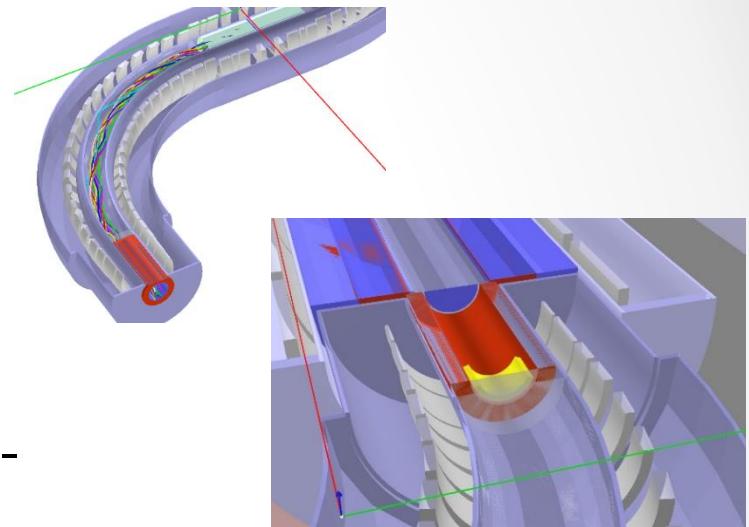
Upper limit of Majoron@COMET
第十三届全国粒子物理学学术会议

Beam resampling with GAN

SYSU work in Mu2e

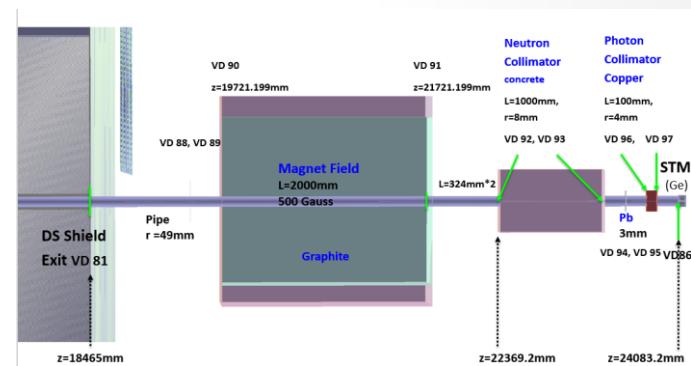
- Anti-proton background simulation

| | |
|--------------|---|
| Cosmic rays | $0.209 \pm 0.022(\text{stat}) \pm 0.055(\text{syst})$ |
| DIO | $0.144 \pm 0.028(\text{stat}) \pm 0.11(\text{syst})$ |
| Antiprotons | $0.040 \pm 0.001(\text{stat}) \pm 0.020(\text{syst})$ |
| Pion capture | $0.021 \pm 0.001(\text{stat}) \pm 0.002(\text{syst})$ |



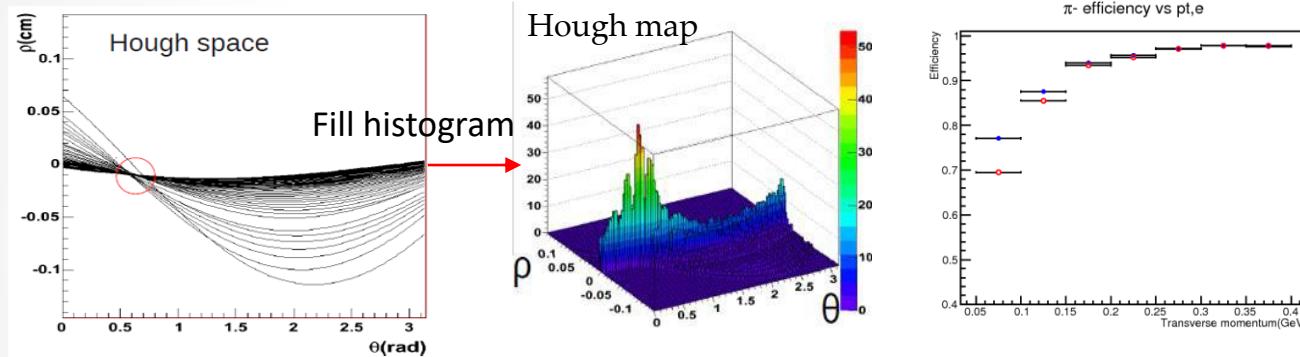
- Detector and track visualization
- Muon beamline optimization with anti-proton absorber design
- Simulation of the Stopping Target Monitor

$$R_{\mu e} = \frac{\mu^- + A(Z, N) \rightarrow e^- + A(Z, N)}{\mu^- + A(Z, N) \rightarrow \nu_\mu + A(Z - 1, N)}$$



Contribution from the experience

1. Low p_T track reconstruction at BESIII



Soft pion efficiency increase
7.6% in 50~100MeV
Signal number from recoil mass fit ↑ **2.76%**

2. BESIII simulation on TianheII supercomputer
3. Pre-design of EMuS



TianheII super computer



Summary

- CLFV has great potentials to probe new physics at the Intensity Frontier
- COMET&Mu2e will search for CLFV with $\mu N \rightarrow e N$
 - Improve the current limit by a factor of **10^4**
 - Search for New Physics with mass scale up to 10^4 TeV
- COMET project plan
 - Phase-I data taking planned at **2024**JPY at S.E.S.= **3.1×10^{-15}**
 - Phase-II will search mu-e conversion at S.E.S.= **2.6×10^{-17}**
- Mu2e project plan
 - **Run I** data taking planned for **2025-2026**, improve SINDRUM II limit by x1000, with **$R_{\mu e} < 5.9 \times 10^{-16}$** (90% CL)
 - Additional data taking after LBNF/PIP-II shutdown, ultimately set the conversion ratio **$R_{\mu e} < 8 \times 10^{-17}$** (90% CL)

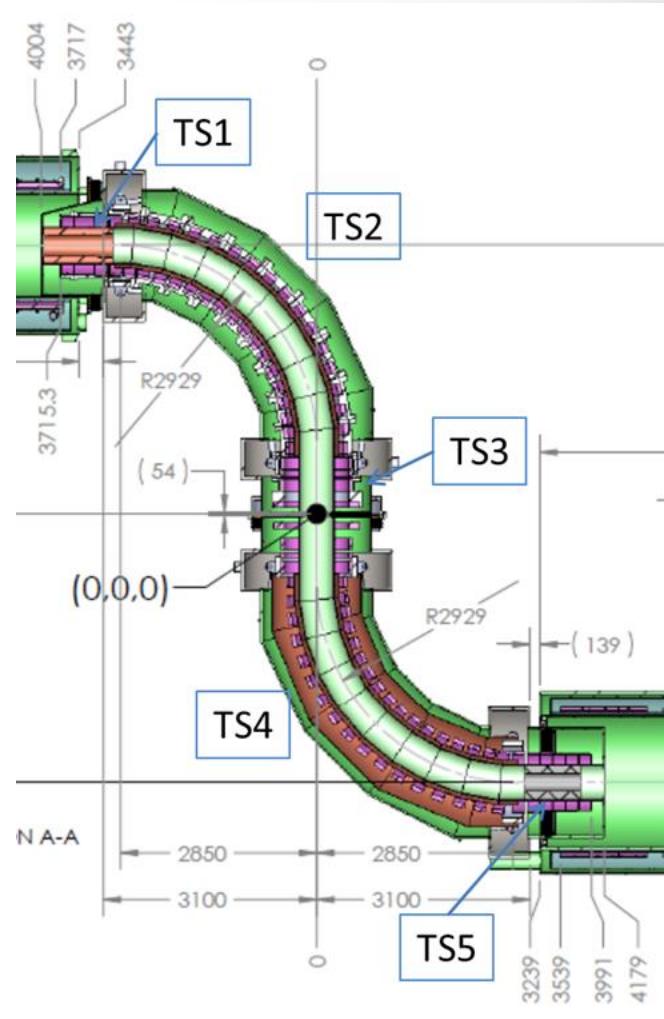
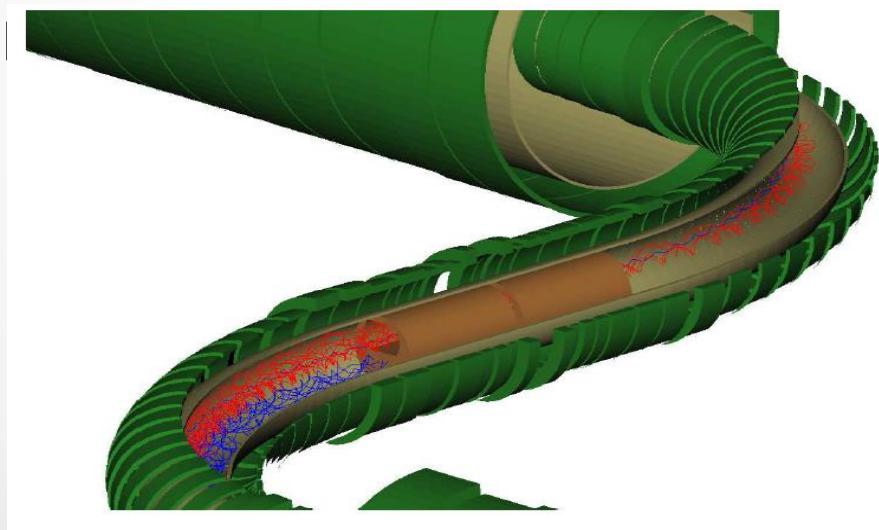
backup



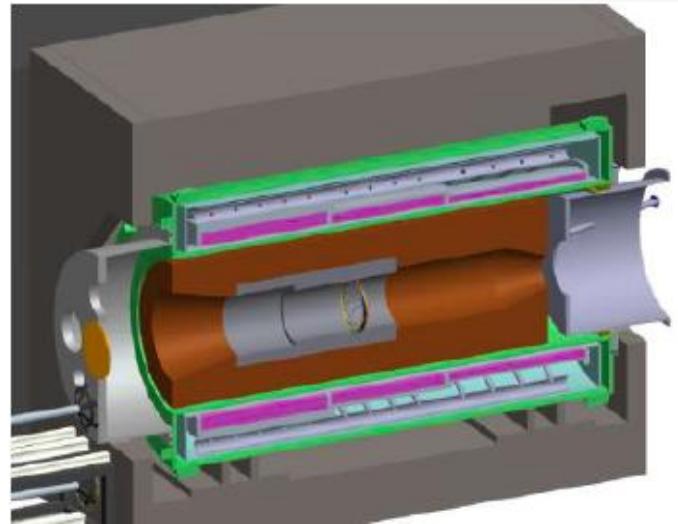
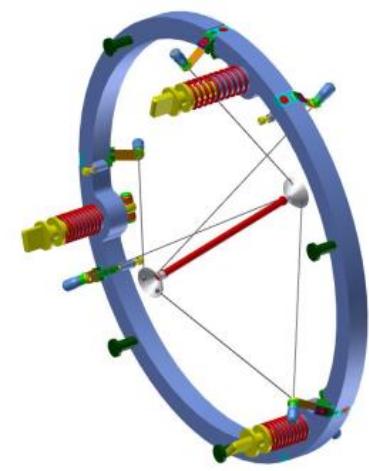
Mu2e Transport Solenoid



- Gradient magnetic field from 2.5 T to 2.0 T
- S-shaped magnetic channel to transmit low-momentum negatively charged particles in helical trajectories
- Collimators to remove positively charged and high-momentum

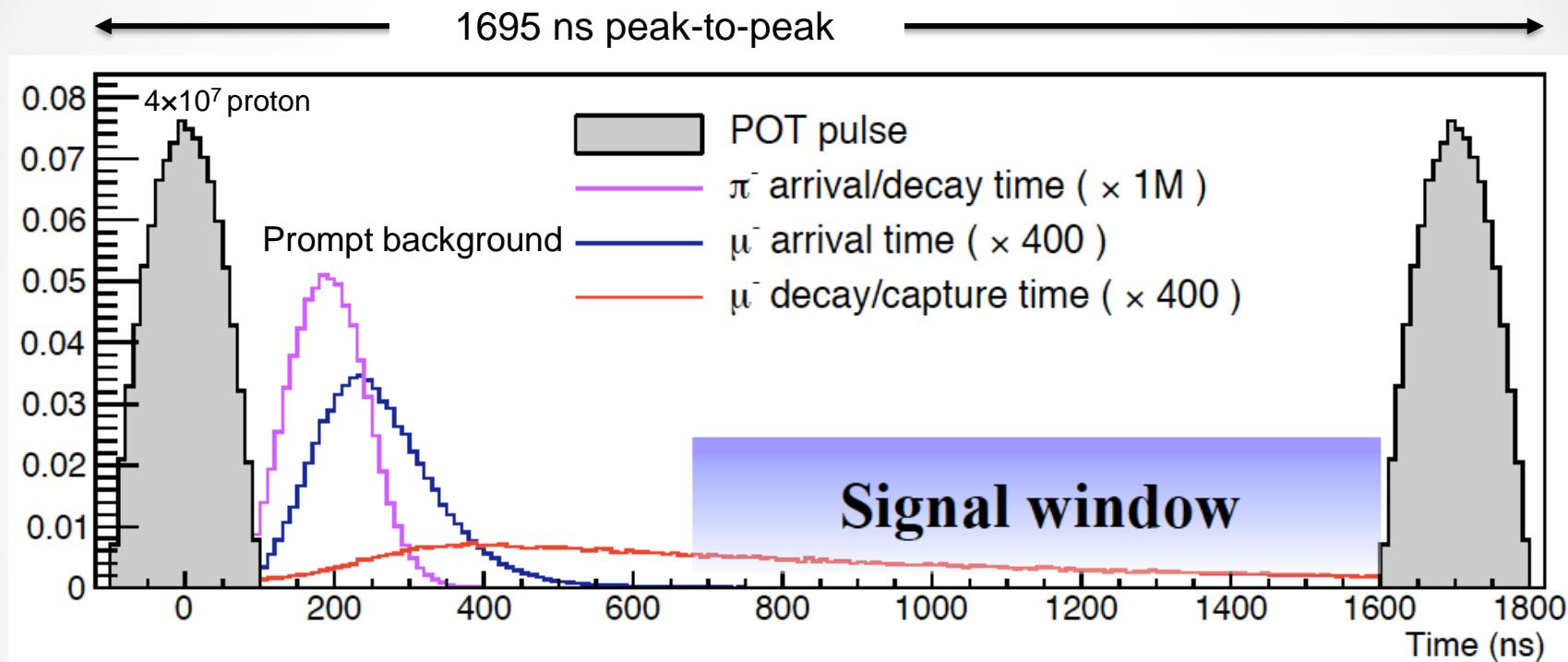


Mu2e Target and Shield



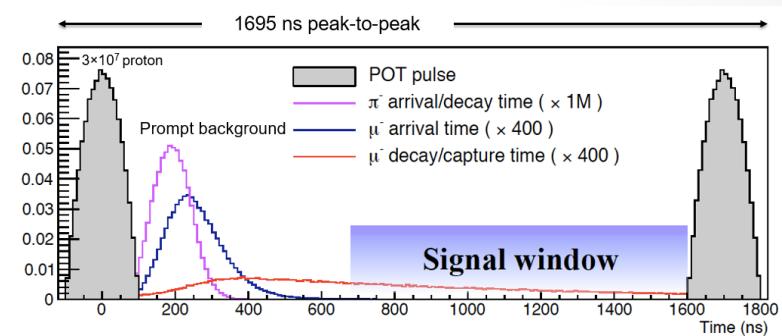
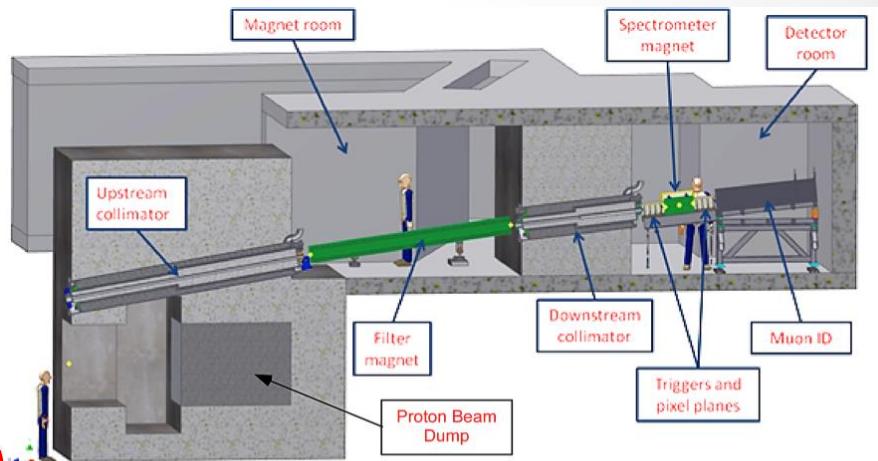
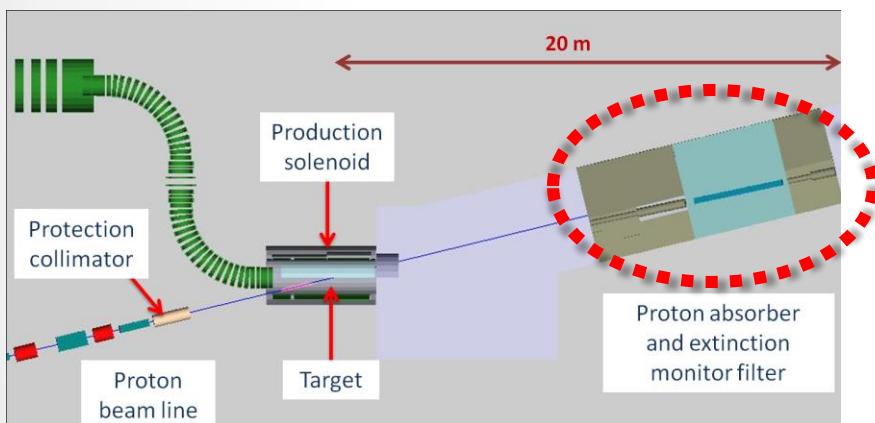
- Production Target
 - Protons + target $\rightarrow \pi + X$; π decay into muons
 - High A and high density material Tungsten to maximize muons production
 - High melting temp, radiative cooling ($\sim 1600^{\circ}\text{C}$), with 8kW beam (700w in target)
- Heat Radiation Shield
 - To protect superconductor of PS and upstream TS
 - To limit heat load and radiation damage
 - ~ 25 tons of Bronze

Mu2e Beam Time Structure



- 4×10^7 protons per bunch, bunch spacing 1695 ns
- 700 ns delay before 1 ms live gate
- Extinction factor (Out-Of-Time proton rate) $< 10^{-10}$.

Extinction Monitor



- Extinction definition: protons between pulses / protons in pulse
- Extinction requirements $< 10^{-10}$
- Extinction measurement is important to success

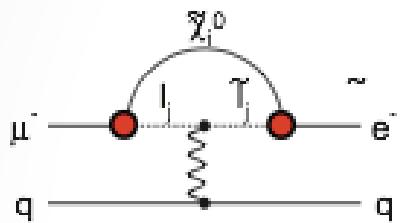


New Physics in $\mu \rightarrow e$

Contact Terms

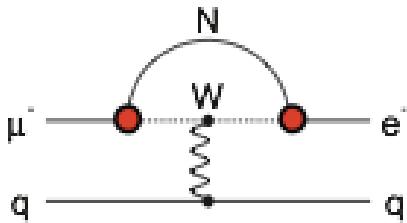
Supersymmetry

rate $\sim 10^{-15}$



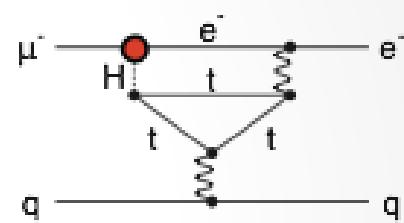
Heavy Neutrinos

$$|U_{\mu N} U_{e N}|^2 \sim 8 \times 10^{-13}$$



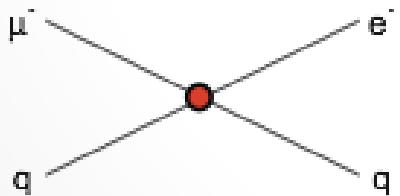
Second Higgs Doublet

$$g(H_{\mu e}) \sim 10^{-4} g(H_{\mu \mu})$$



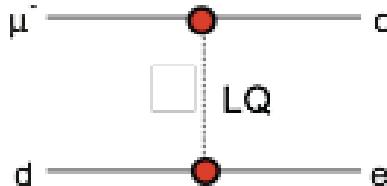
Compositeness

$$\Lambda_c \sim 3000 \text{ TeV}$$



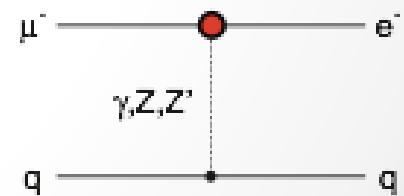
Leptoquark

$$M_{LQ} = 3000 (\lambda_{\mu d} \lambda_{ed})^{1/2} \text{ TeV}/c^2$$



Heavy Z' Anomal. Z Coupling

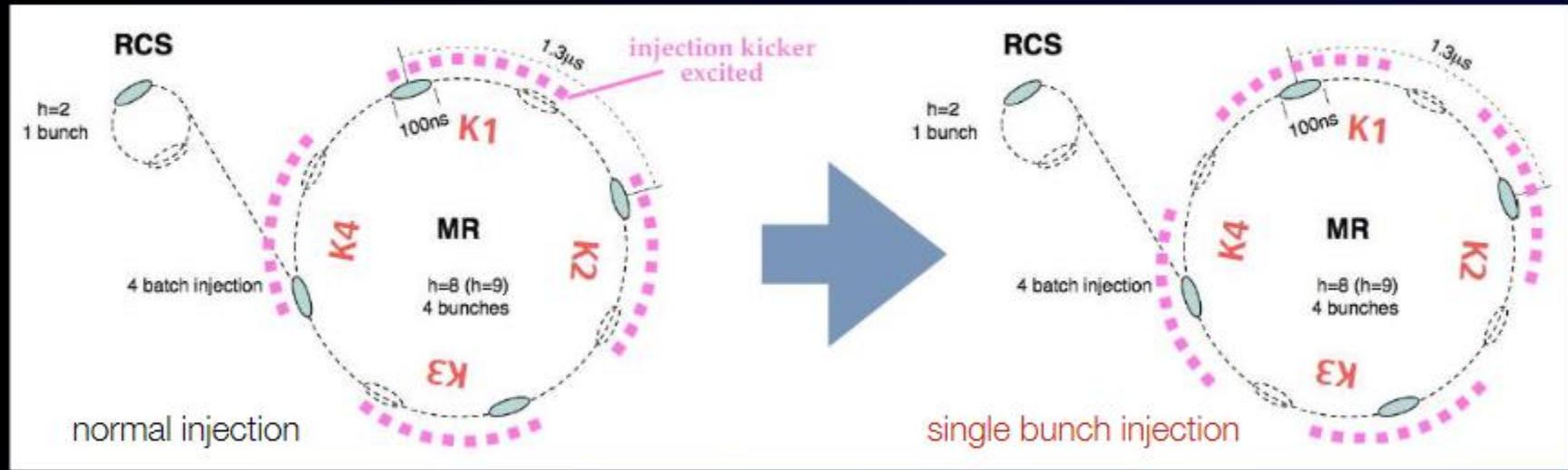
$$M_{Z'} = 3000 \text{ TeV}/c^2$$



Flavor physics of leptons and dipole moments, [arXiv:0801.1826](https://arxiv.org/abs/0801.1826)

8 GeV Proton Beam Extinction (recap)

- Extinction Requirement is $< 10^{-10}$ (to reduce beam-related backgrounds).
- chopper to remove protons in every other pulses at the linac $\rightarrow O(10^{-6})$
- single bunch kick (SBK) : shift the timing of injection kicker to the MR
 - Measured at the main-ring (MR) abort line $\rightarrow 6 \times 10^{-11}$
 - Extinction depends on RF voltage of bunched slow extraction
 - Forward (shift) SBK : fill protons for front bucket (rear empty) tested before
 - Backward (shift) SBK : fill protons for rear bucket (front empty) new in T78

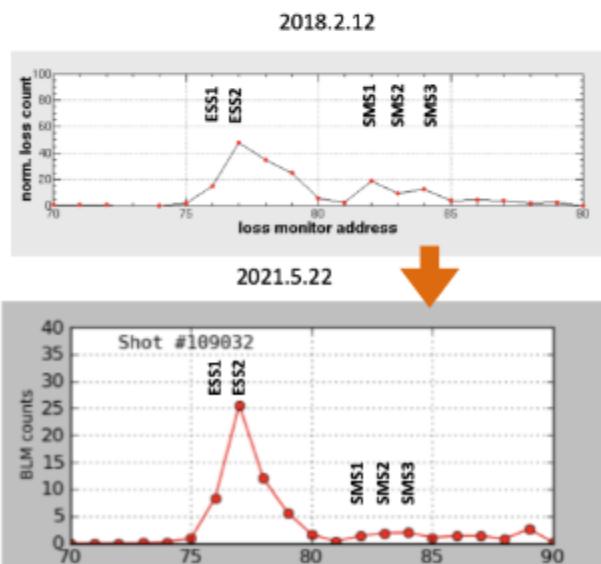


T78 Experiment :

Accelerator Study of 8-GeV bunched SX



- Beam Power = 1.8kW (5.2sec cycle)
 - # of bunch = 4
 - # of proton per pulse = 7.4×10^{12}
 - Equivalent to 3.4kW (Phase-I) with 2.4sec cycle
- Achieved Extraction Efficiency = 99.1%
- Spill duty = 55% (Transverse RF is off)
- Spill length = 0.6sec



Beam loss is dramatically improved in SX area

