LFV Experiments

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ZPW 2018

Flavors: light, heavy and dark

University of Zurich

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Searches of Lepton Flavor Violation

LFV

Lepton Decays:

- $\mu \to e \gamma$
- $\mu \to eee$
- $\tau \to e(\mu) \gamma$
- $\tau \to l\,l\,l$ $(l = e, \mu)$
- $\tau \to l\,h$

Meson Decays:

- Φ, $K \to ll'$
- D, $J/\psi \to ll'$
- B, $\Upsilon \to ll'$

Conversion (μ-Capture):

- $\mu N \to e N$

Collider Experiments:

- $e\,p \to \mu(\tau)\,X$ HERA (FCC eh)
- $Z' \to l\,l'$ LHC (ILC, FCC)
- $H \to l\,l'$
- $\chi^{0,\pm} \to l\,l'\,X$

Fixed Target Experiments:

- $\mu N \to \tau N$ proposed
- $e N \to \mu(\tau) N$ proposed

Searches of Lepton Flavor Violation

Lepton Decays:

- $\mu \to e\,\gamma$
  $\mu \to eee$
- $\tau \to e(\mu)\,\gamma$
- $\tau \to l\,l\,l$ $\quad (l = e, \mu)$
- $\tau \to l\,h$

"golden decays"

Meson Decays:

- Φ, K $\to$ ll'
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LFV

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$e\,p \to \mu(\tau)\, X$ — HERA (FCC eh)

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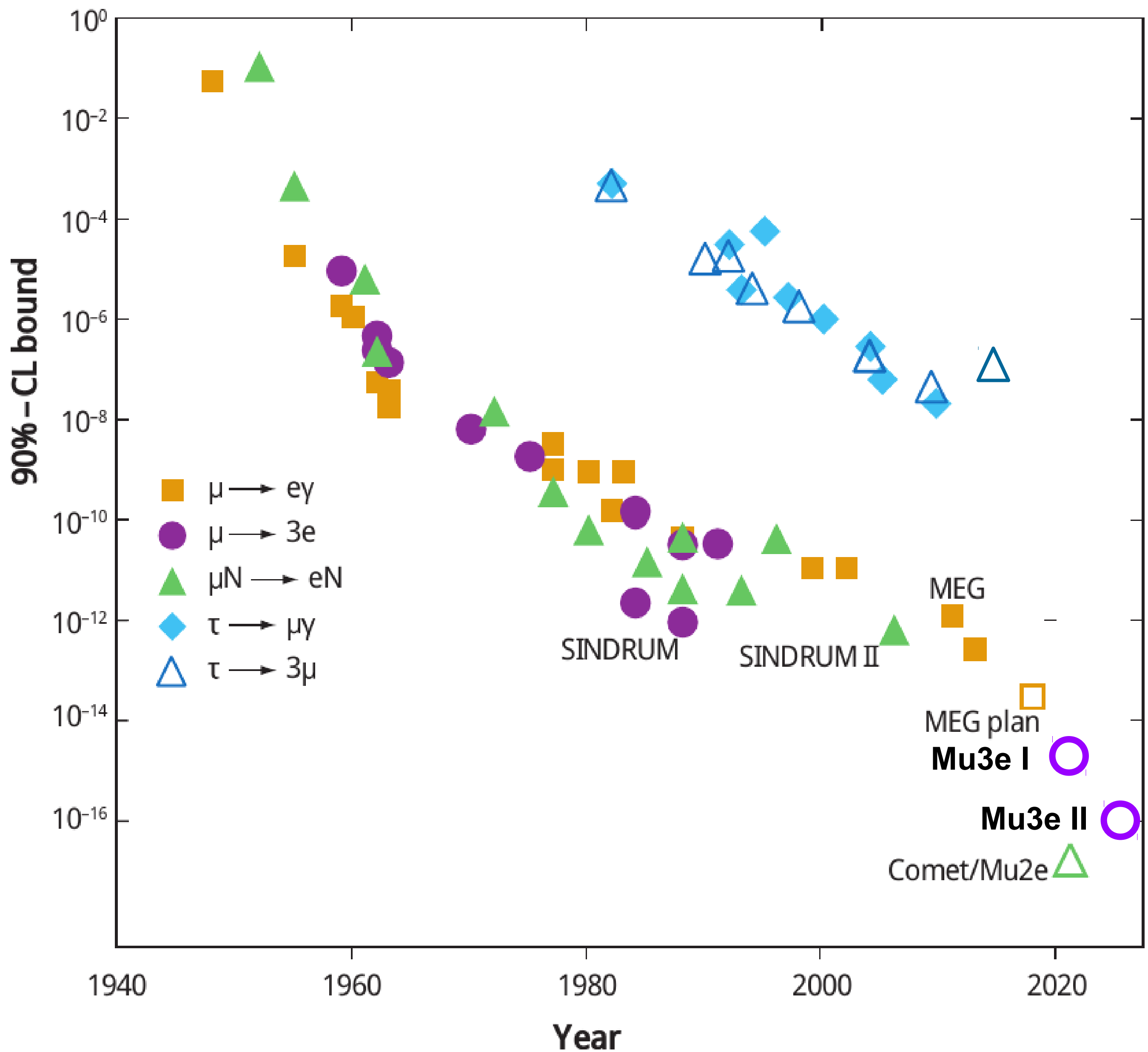
Fixed Target Experiments:

- $\mu\, N \to \tau\, N$ — proposed
- $e\, N \to \mu(\tau)\, N$ — proposed

History of LFV Decay experiments



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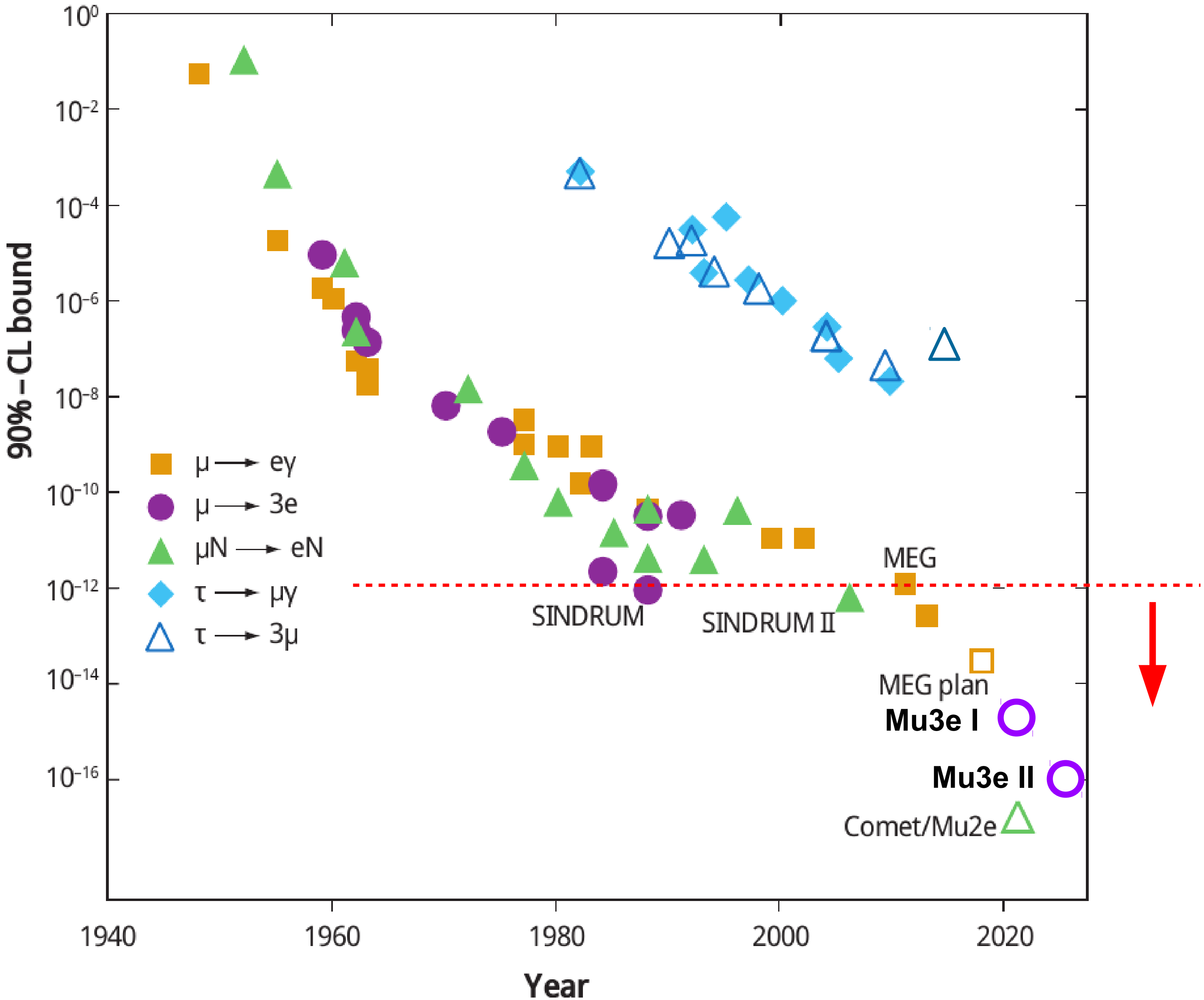
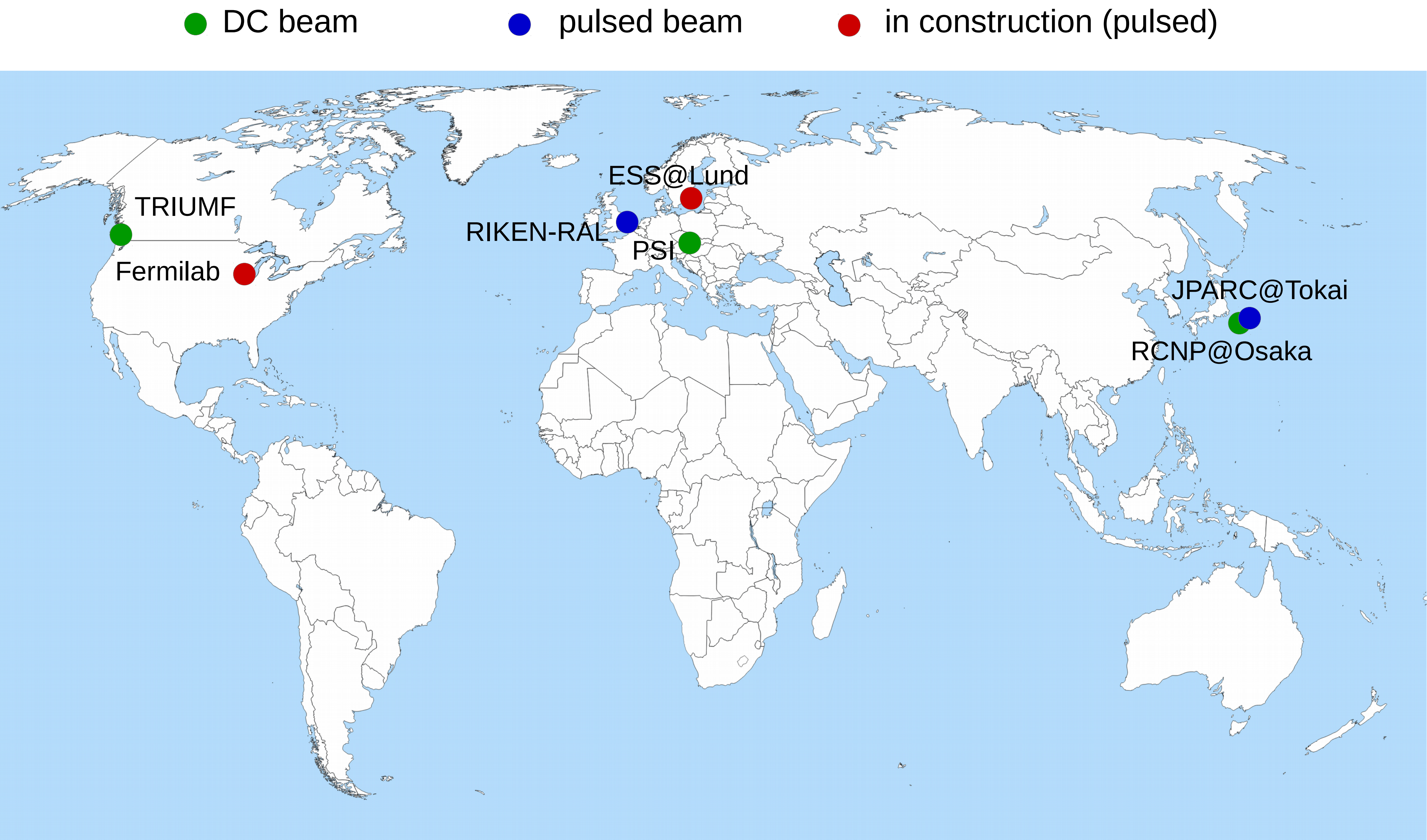


High Intensity Muon Facilities



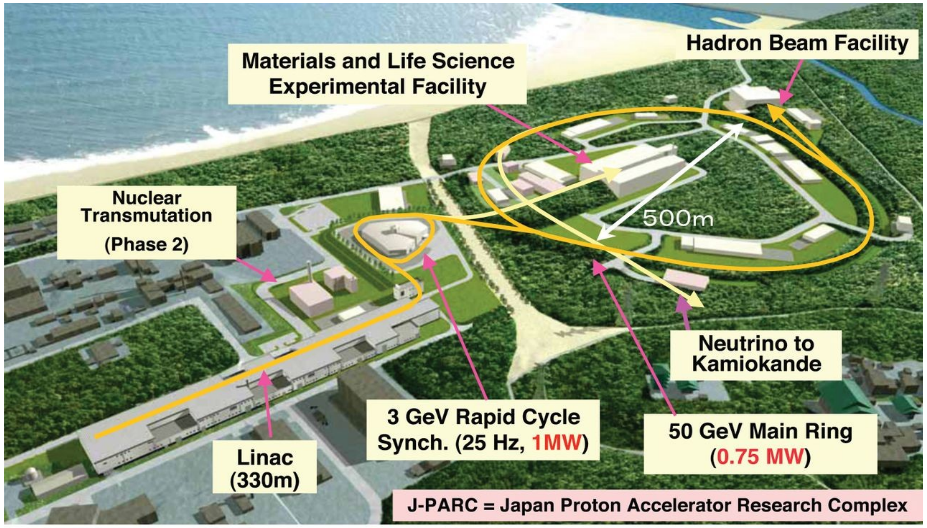
Muon Facilities

High intensity muon beams are produced in **proton-beam** induced hadronic showers

PSI: $E_{k,p}$= 590 MeV, I=2.4mA f=50 MHz

FNAL: Muon Campus with g-2 and Mu2e

PRISM@Osaka: μ storage $E_{k,\mu}$~20 MeV, f=100 Hz



JPARC@Tokay: E_p= 3-50 GeV, P=1 MW

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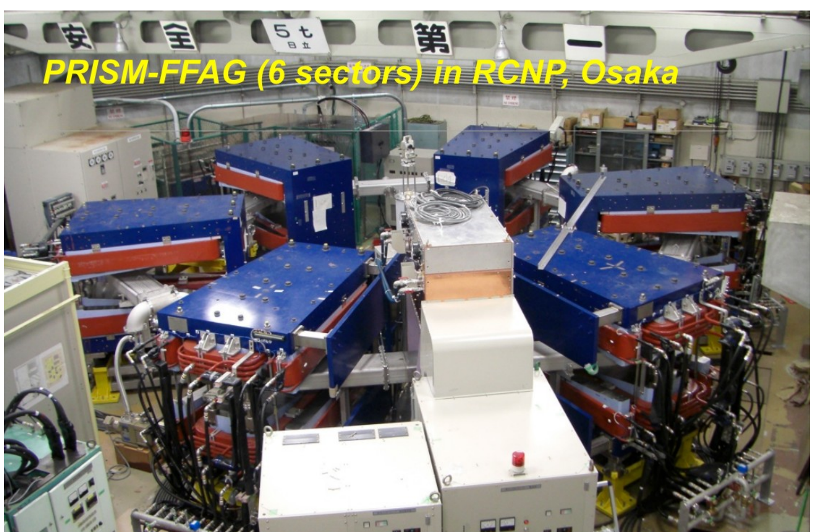

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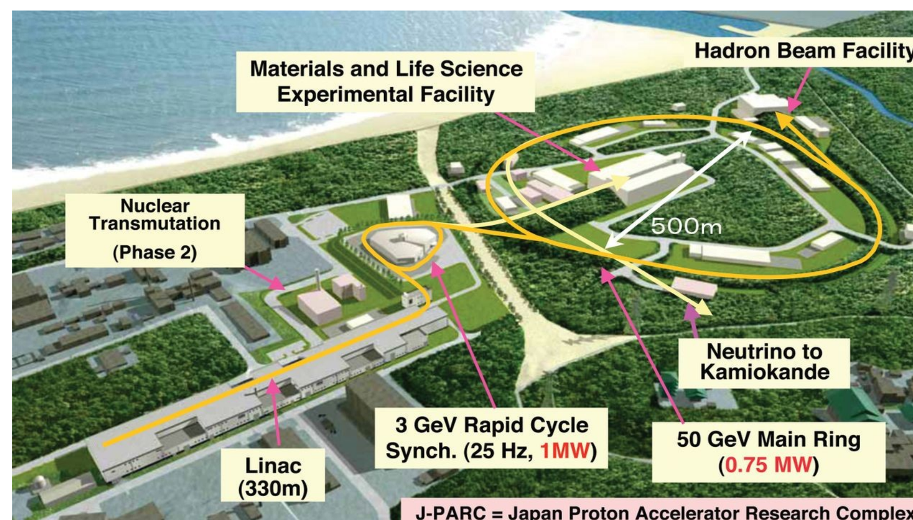


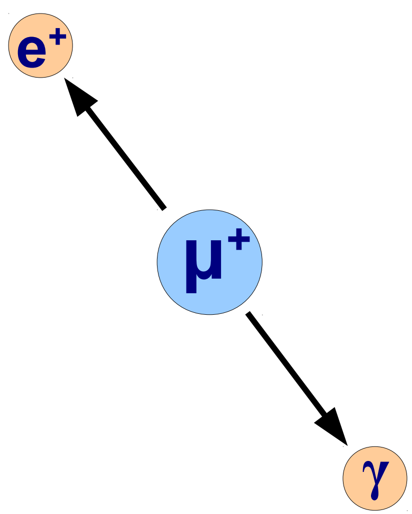
JPARC@Tokay: E_p= 3-50 GeV, P=1 MW

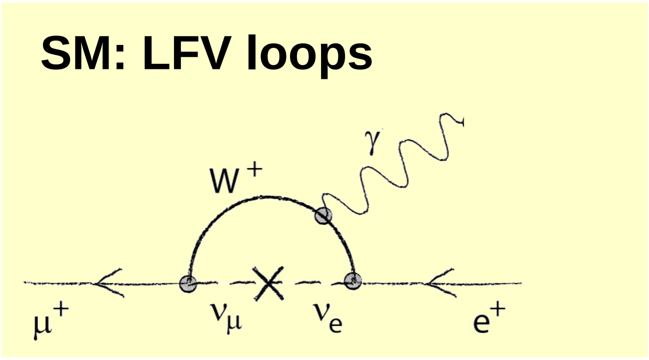
Experimental Overview

- **golden LFV muon experiments**
  - MEG
  - Mu3e
  - Mu2E/COMET/(DeeMe)
  - PRISM/PRIME
- **Tau LFV searches**
  - (LHCb)
  - Belle2

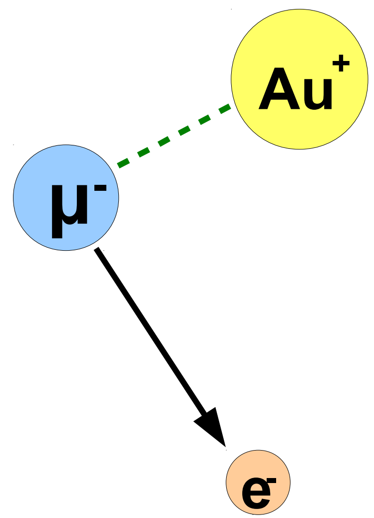
LFV in Standard Model Muon Decays

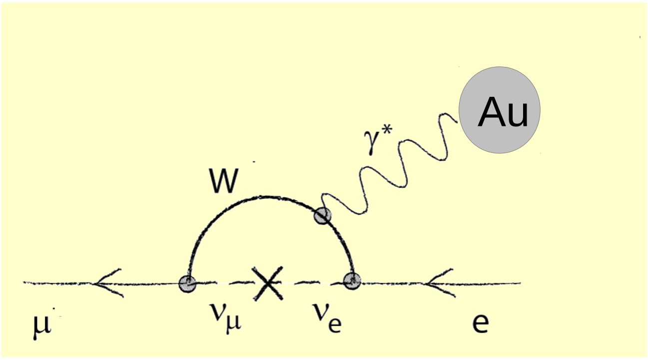
$\mu^+ \rightarrow e^+ \gamma$



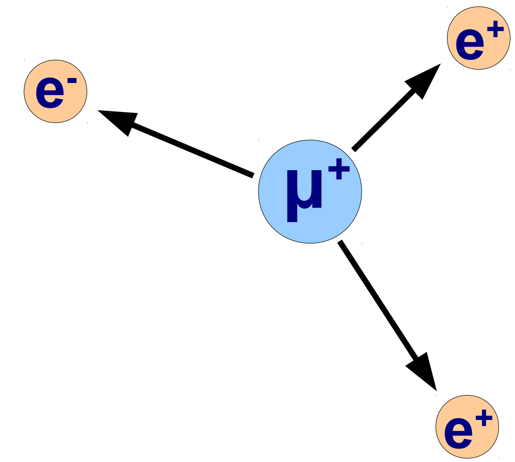


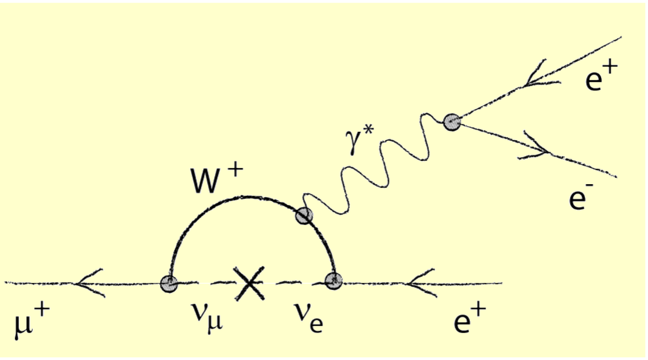
$\mu^- N \rightarrow e^- N$





$\mu^+ \rightarrow e^+ e^+ e^-$

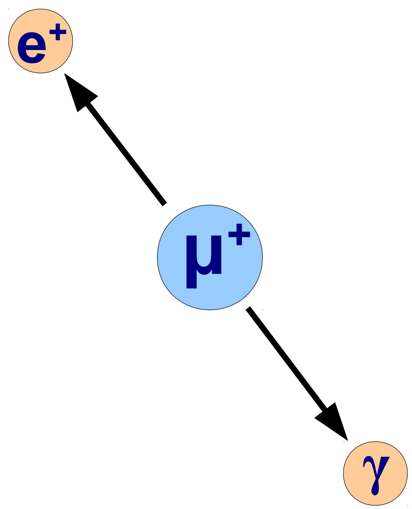




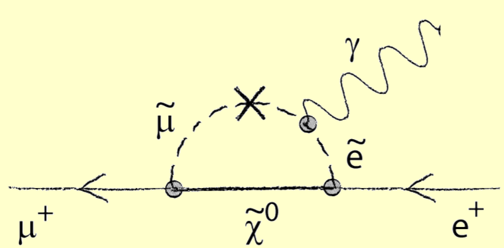
branching ratios suppressed by $\propto \frac{(\Delta m_\nu^2)^2}{m_W^4} \approx 10^{-50}$

LFV Muon Decays in SUSY

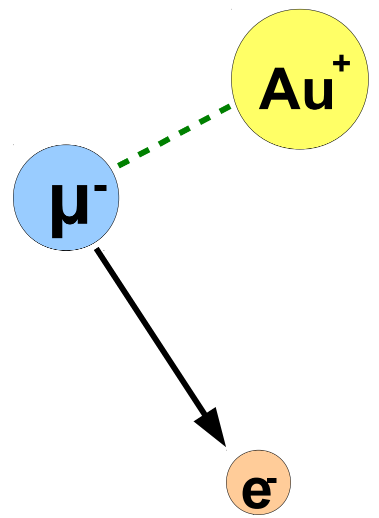
$\mu^+ \rightarrow e^+ \gamma$

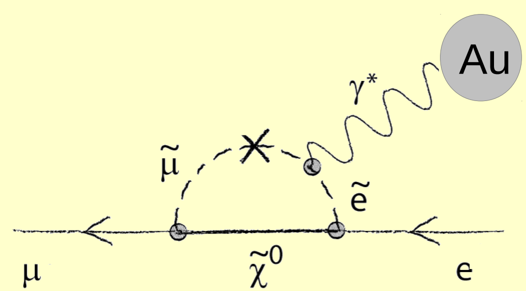


SUSY loops



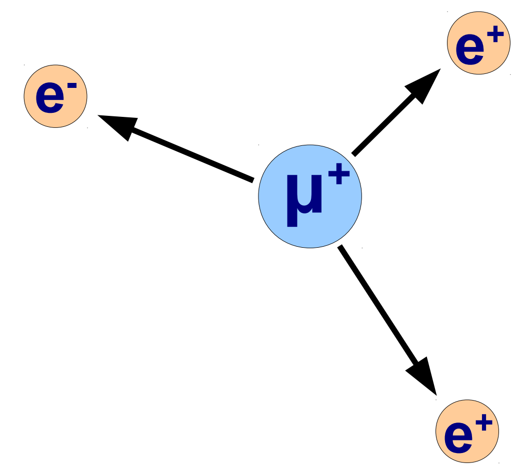
$\mu^- N \rightarrow e^- N$

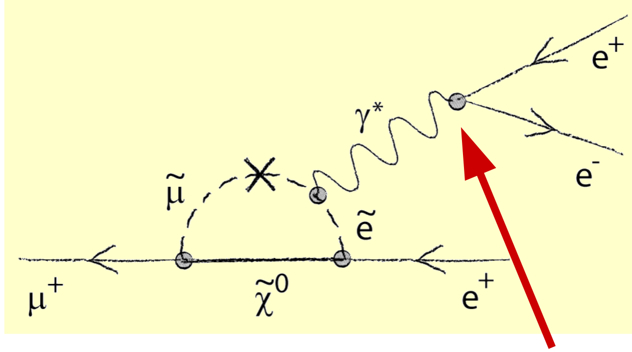




enhanced by
coherent conversion in
nucleus field for $Q^2(\gamma^*)\sim 0$

$\mu^+ \rightarrow e^+ e^+ e^-$

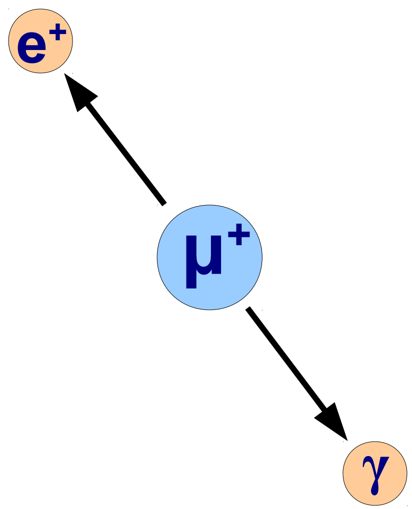


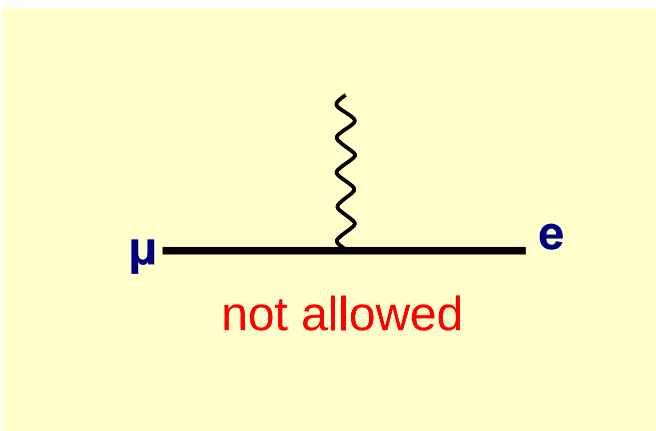


suppressed by extra vertex
with respect to $\mu^+ \rightarrow e^+ \gamma$

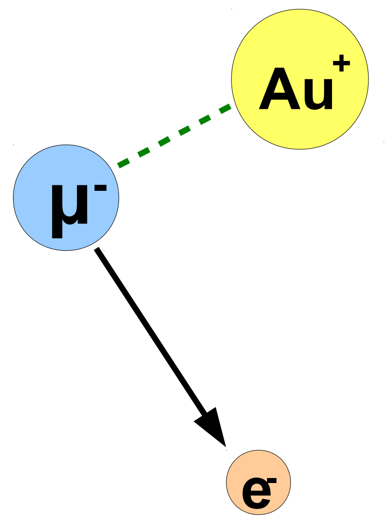
LFV Tree Diagrams

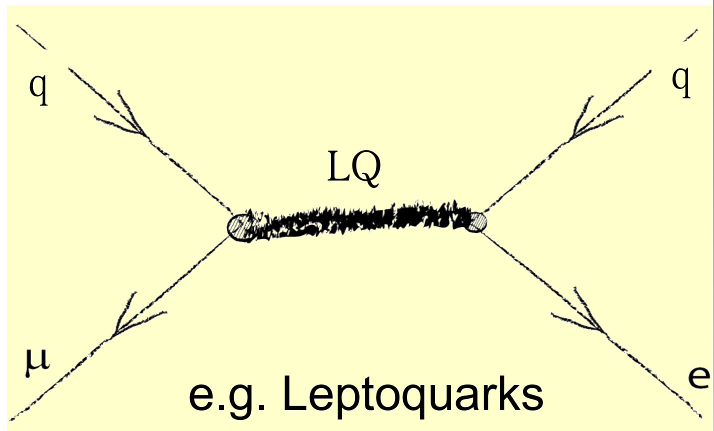
$\mu^+ \to e^+ \gamma$



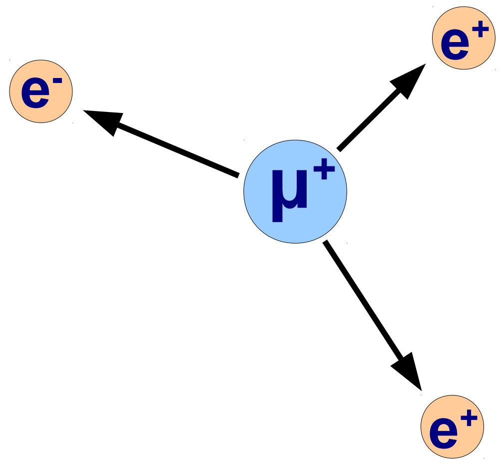


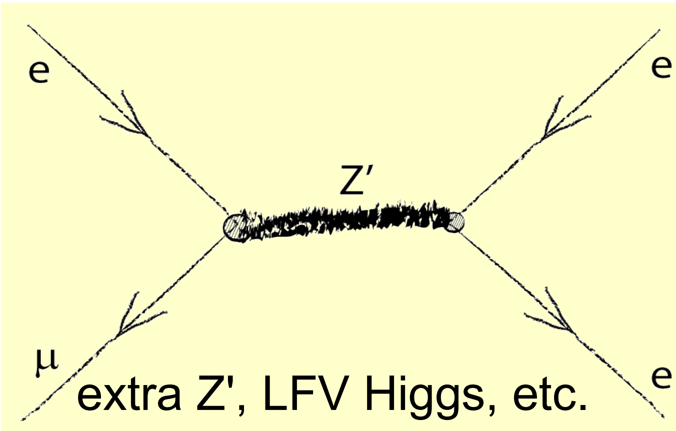
$\mu^- N \to e^- N$





$\mu^+ \to e^+ e^+ e^-$

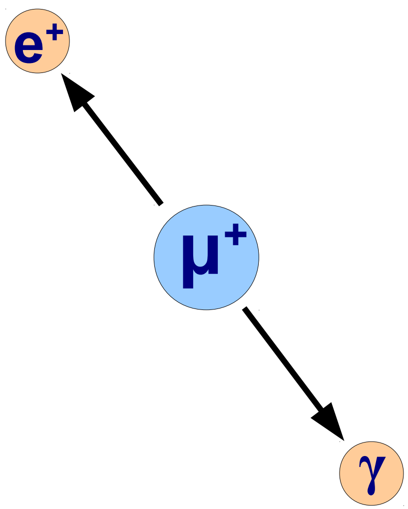




Additional BSM tree diagrams for $\mu N \to eN$ and $\mu N \to eee$

LFV Muon Decays: Experimental Situation

$\mu^+ \to e^+ \gamma$



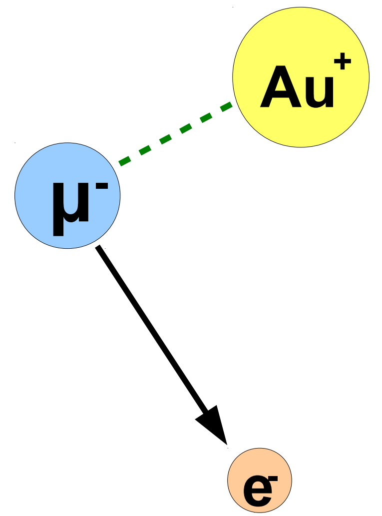
Signal:

- mono-energetic e,γ
- back – to – back
- in time

Background:

- accidentals

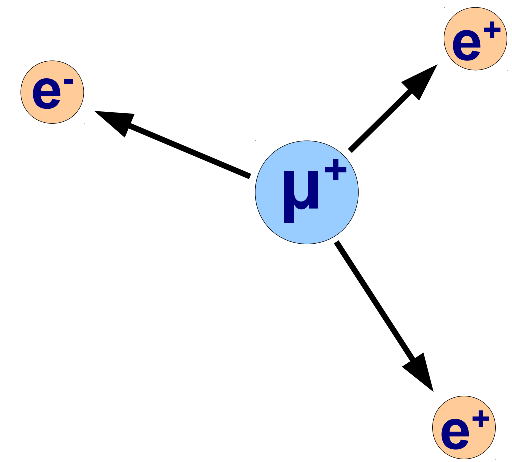
$\mu^- N \to e^- N$



- mono-energetic e
- $E_e = m_\mu$

- large nuclear recoils (DIO)
- pion decays
  → **pulsed beam**

$\mu^+ \to e^+ e^+ e^-$

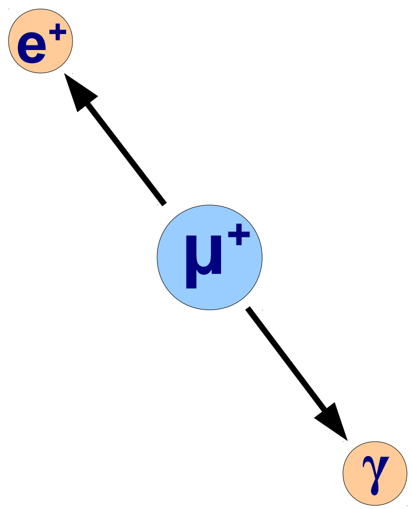


- $\Sigma\, \mathbf{p} = 0$
- $\Sigma\, E_i = m_\mu$
- common vertex
- in time

- radiative decay with internal conversion
- accidentals (Bhabha)

LFV Muon Decays: Experimental Situation

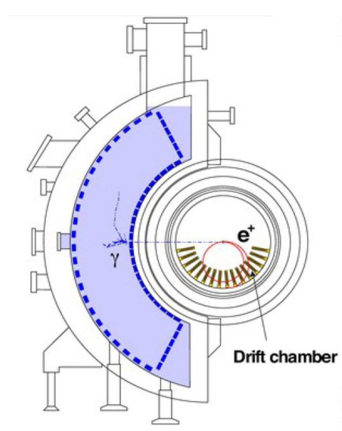
$\mu^+ \rightarrow e^+ \gamma$



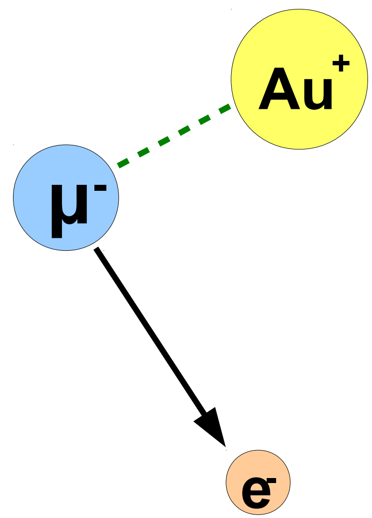
MEG (PSI)

$B(\mu^+ \rightarrow e^+\gamma) \leq 4.2\cdot10^{-13}$ (2016)

being upgraded



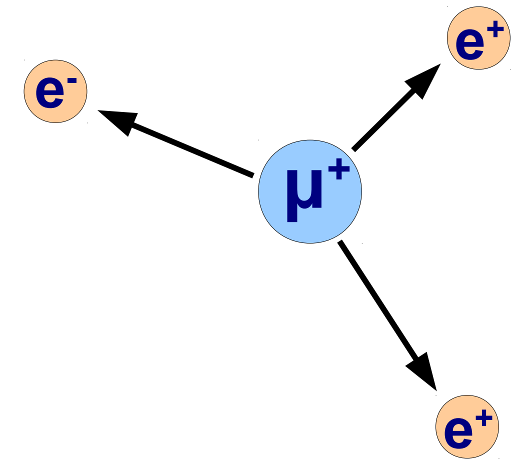
$\mu^- N \rightarrow e^- N$



SINDRUM II (PSI)

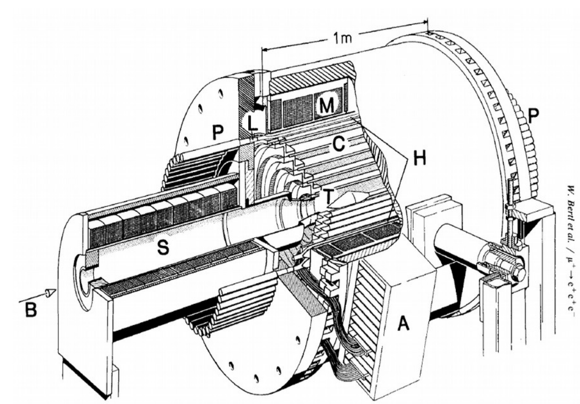
$B(\mu\ Au \rightarrow e\ Au) \leq 7\cdot10^{-13}$ (2006)

$\mu^+ \rightarrow e^+e^+e^-$



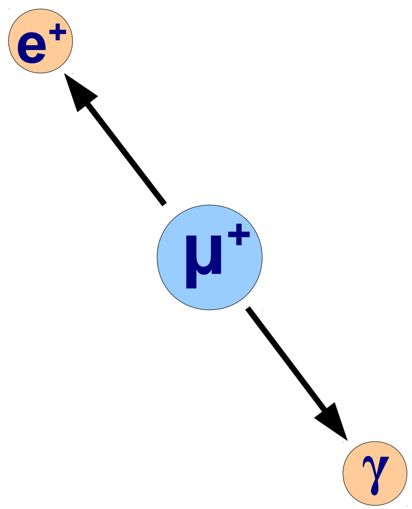
SINDRUM (PSI)

$B(\mu^+ \rightarrow e^+e^+e^-) \leq 10^{-12}$ (1988)



LFV Muon Decays: Experimental Situation

$\mu^+ \rightarrow e^+ \gamma$



MEG (PSI)

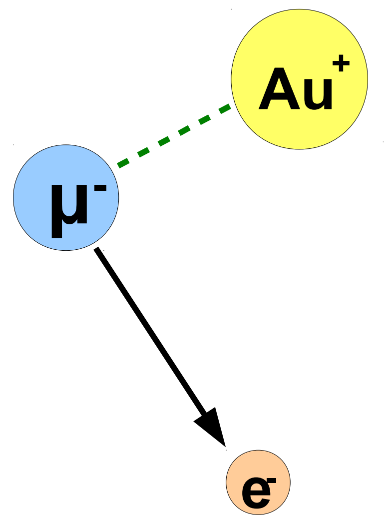
$B(\mu^+ \rightarrow e^+\gamma) \leq 4.2 \cdot 10^{-13}$ (2016)

↓

MEGII (PSI)

$B(\mu^+ \rightarrow e^+\gamma) \leq \mathbf{4 \cdot 10^{-14}}$ (~2020)

$\mu^- N \rightarrow e^- N$



SINDRUM II (PSI)

$B(\mu\ Au \rightarrow e\ Au) \leq 7 \cdot 10^{-13}$ (2006)

↓

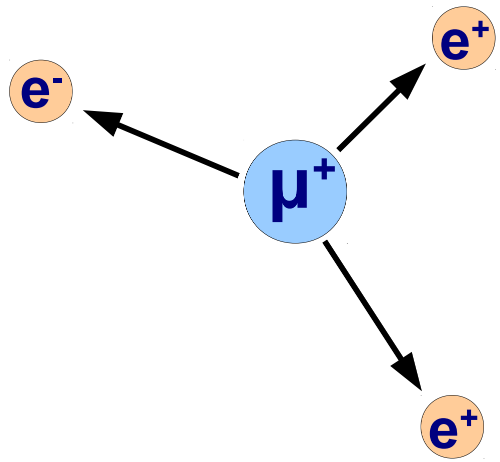
Mu2e (Fermilab)

$B(\mu\ Al \rightarrow e\ Al) \leq \mathbf{6 \cdot 10^{-17}}$ (>2021)

Comet I/II (JPARC)

$B(\mu\ Al \rightarrow e\ Al) \leq \mathbf{6 \cdot 10^{-17}}$ (>2019)

$\mu^+ \rightarrow e^+e^+e^-$



SINDRUM (PSI)

$B(\mu^+ \rightarrow e^+e^+e^-) \leq 10^{-12}$ (1988)

↓

Mu3e I/II (PSI)

$B(\mu^+ \rightarrow e^+e^+e^-) \leq \mathbf{2 \cdot 10^{-15}}$ (>2020)

$B(\mu^+ \rightarrow e^+e^+e^-) \leq \mathbf{10^{-16}}$ (>2025)

LFV Experiments with Muons

Technology advances in

- accelerator physics
- detector instrumentation
- data acquisition
- computing

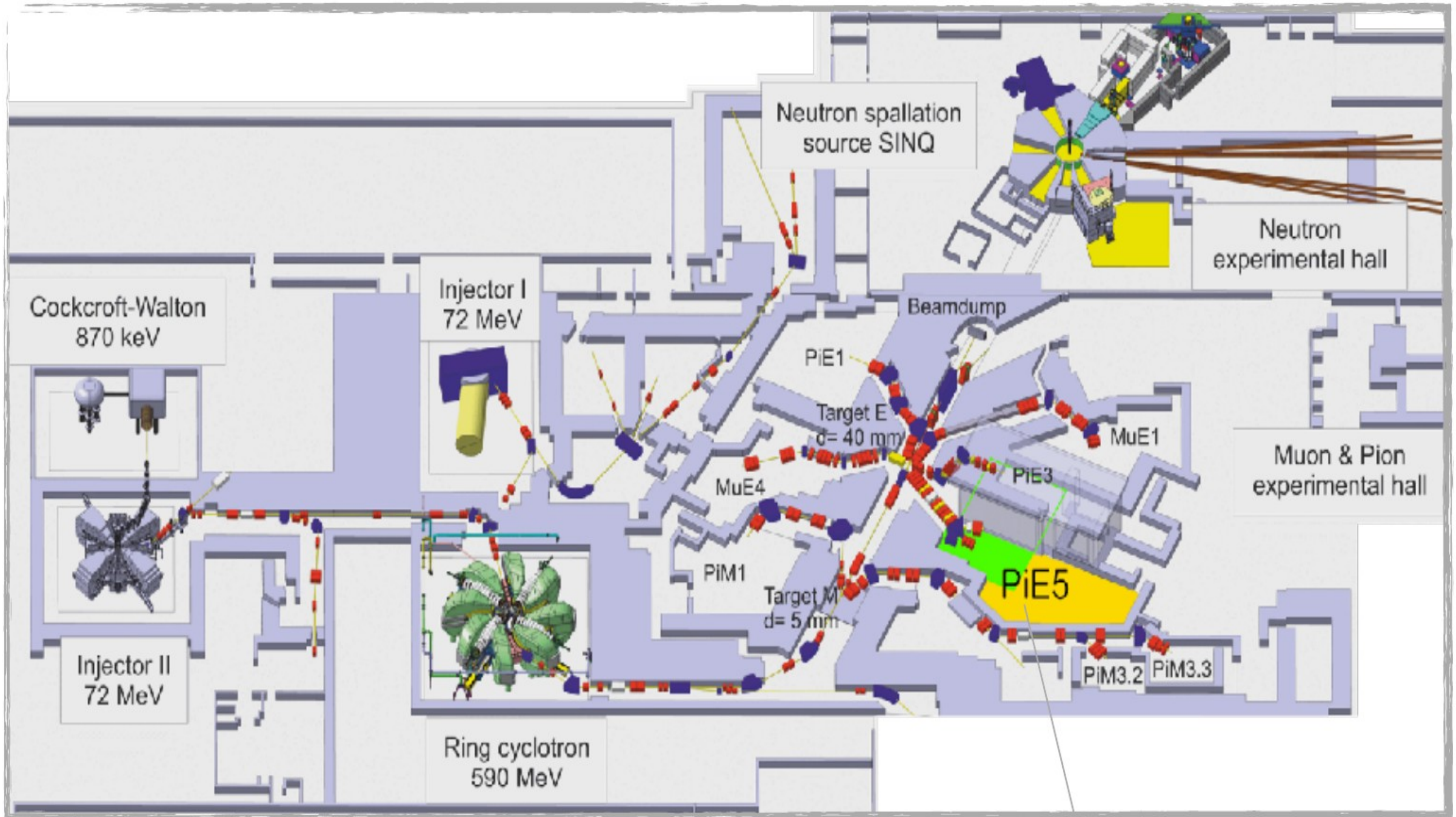
allow for increase of sensitivity by up to **five orders** of magnitude!

MEG and Mu3e @ PSI

- World's most intense continuous muon beam
- 2.4 mA protons at 590 MeV → 1.5 MW

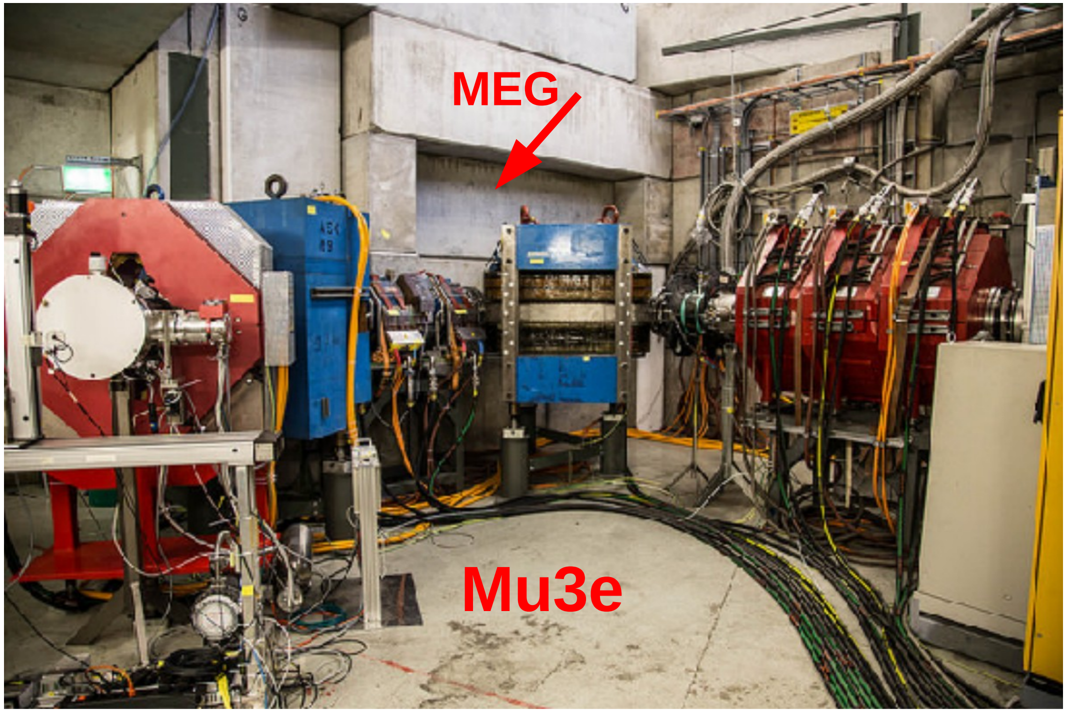
PiE5 Muon Beamline @ PSI

- $O(10^8)$ muons per second
- low momentum muons 29 MeV/c
- PiE5 beamline shared between MEGII and Mu3e

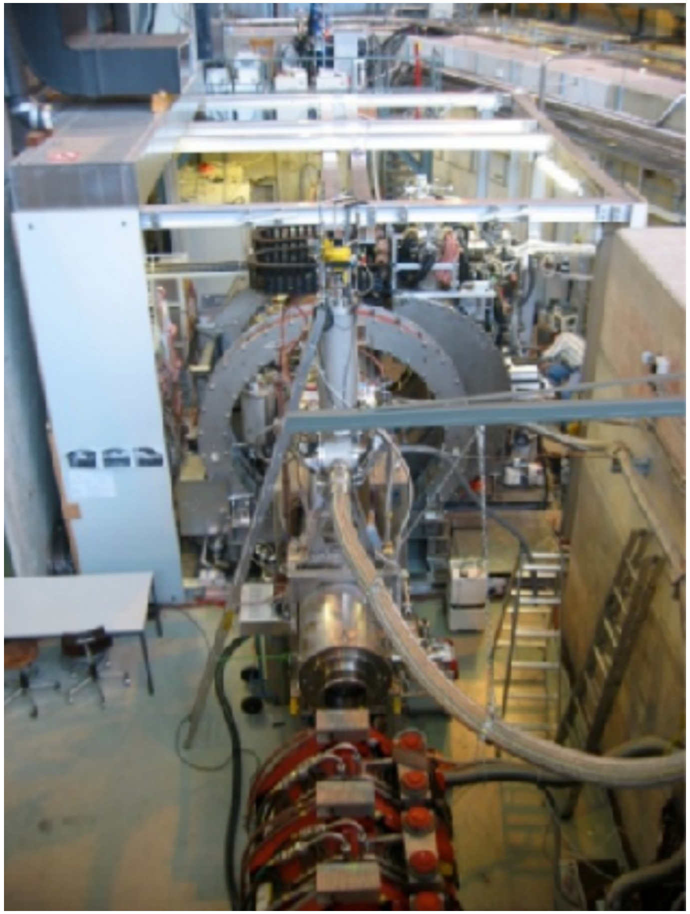


PiE5 Area

Compact Muon Beamline (CMBL) for Mu3e

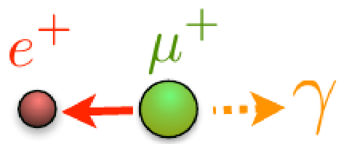


Beamline for MEG



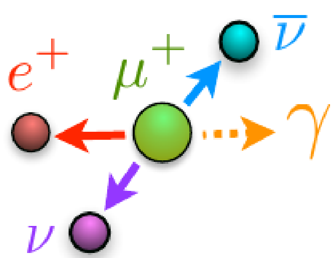
Muon → Electron + Photon (MEG)

Signature

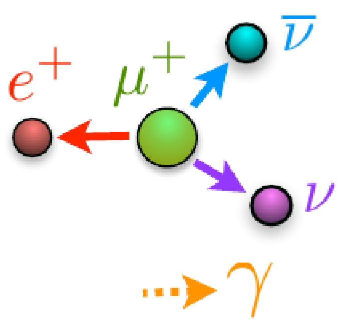


searching for...

Backgrounds



radiative muon decay:
→ depends on detector **resolution**

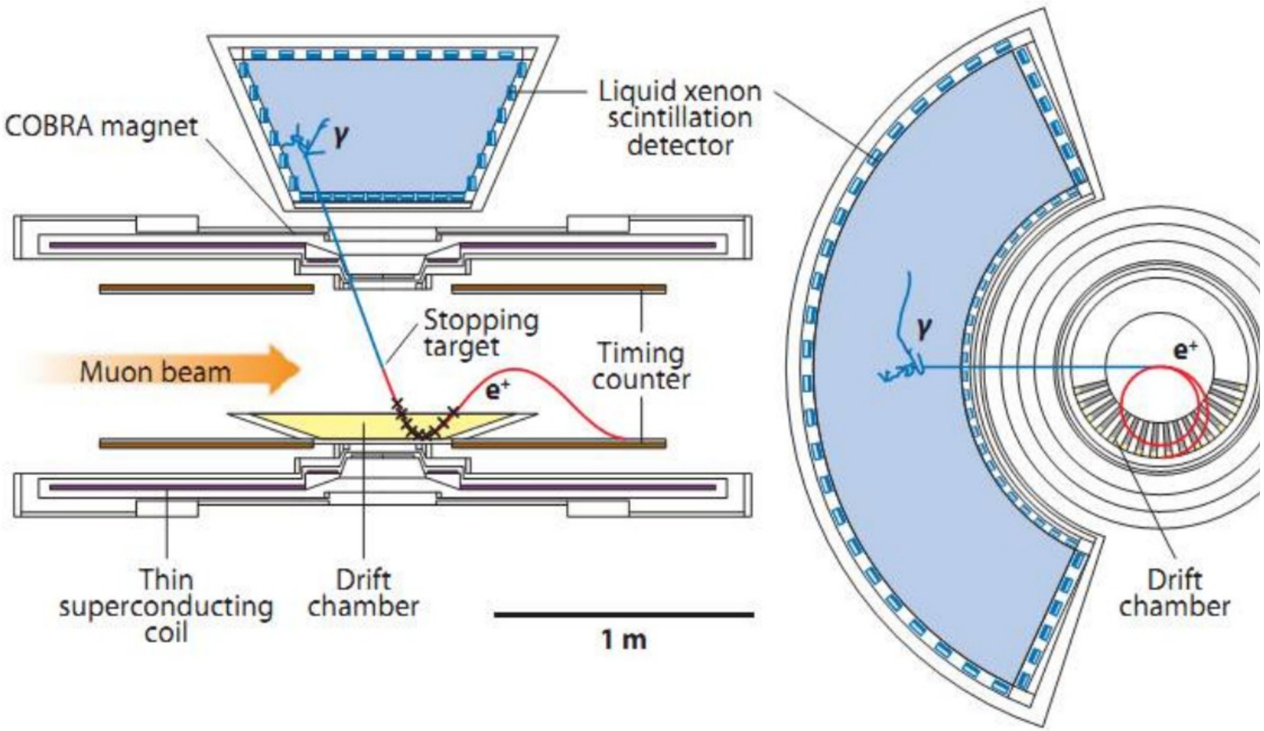


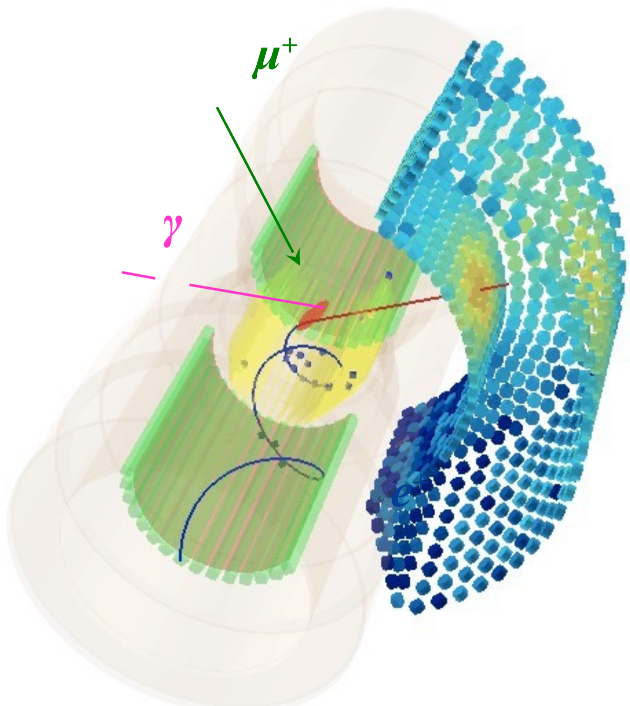
accidental BG:
→ depends on muon stopping **rate**, detector **design** and **resolution**

$$B_{acc} \propto \sqrt{\delta t_e^2 + \delta t_\gamma^2}\ Rate_\mu\ \delta\Theta_{e-\gamma}\ \delta E_e\ \delta E_\gamma^2$$

(from A.Papa)

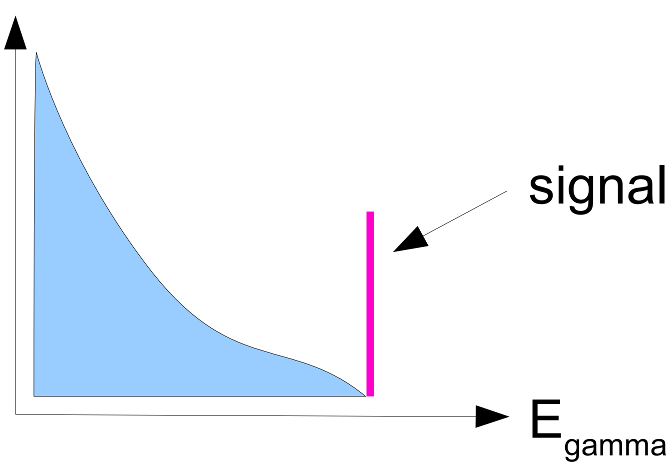
MEG Experiment @ PSI: Search for $\mu \to e\,\gamma$





$B(\mu^+ \to e^+\gamma) \leq 4.2\cdot10^{-13}$ (2016)

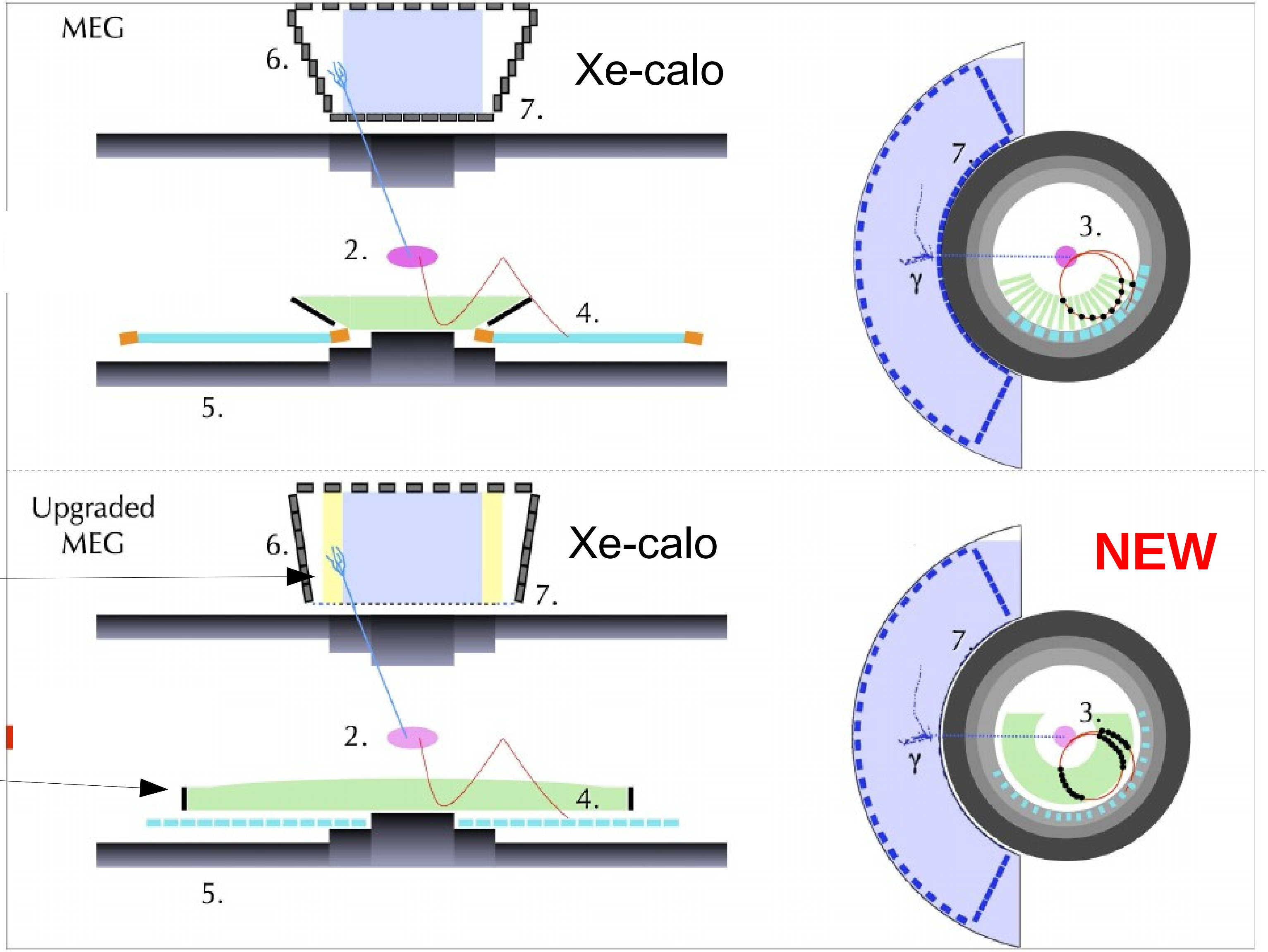
- Search for back-back monochromatic positron-photon pair
- coincident in time
- background: accidentals



MEG II Upgrade @ PSI: Search for μ → e γ

twice the number of photomultipliers

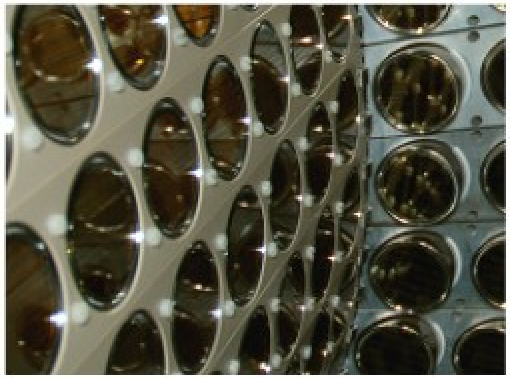
new homogeneous drift chamber



Upgrade will allow to run at much higher muon rates ($7 \cdot 10^7$ muons/s)

MEG II Upgrade @ PSI: Search for $\mu \rightarrow e\,\gamma$

LXe detector: modifications in lateral faces & finer photon sensors at entrance face

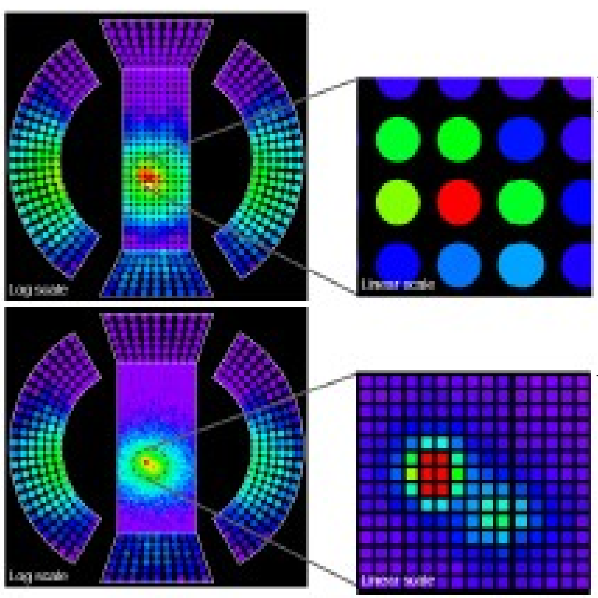


(a) Present detector

(b) Upgraded detector (CG)

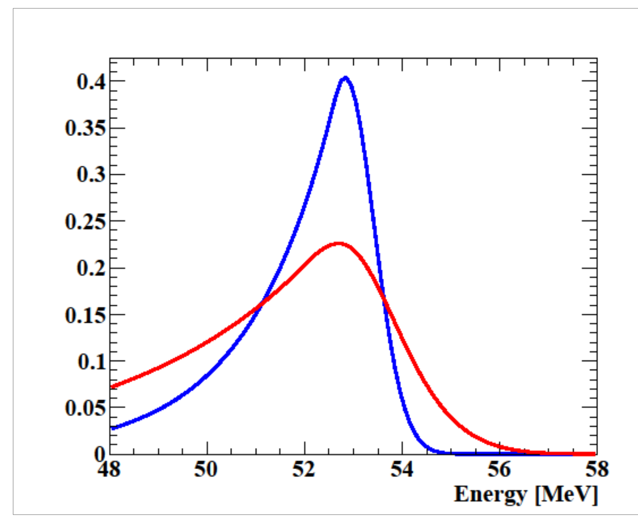
12 x 12 mm^2
SiPM sensitive to LXe scintillation light.

Expected a factor 2 better resolution in position and almost a factor 2 in energy.



Present detector:
2-inch PMTS

Upgraded detector:
12 x 12 mm^2 SIPM



improved $\rightarrow$ E_{gamma} resolution

Summary MEG/MEG II

MEGA Collaboration (1999) **$B(\mu \to e\,\gamma) < 10^{-11}$**

MEG Collaboratin 2016: **$B(\mu \to e\,\gamma) < 4.2\cdot 10^{-13}$**

Expected post-upgrade sensitivity: **$B(\mu \to e\,\gamma) < \sim 4\cdot 10^{-14}$**

(commissioning has started in 2017)

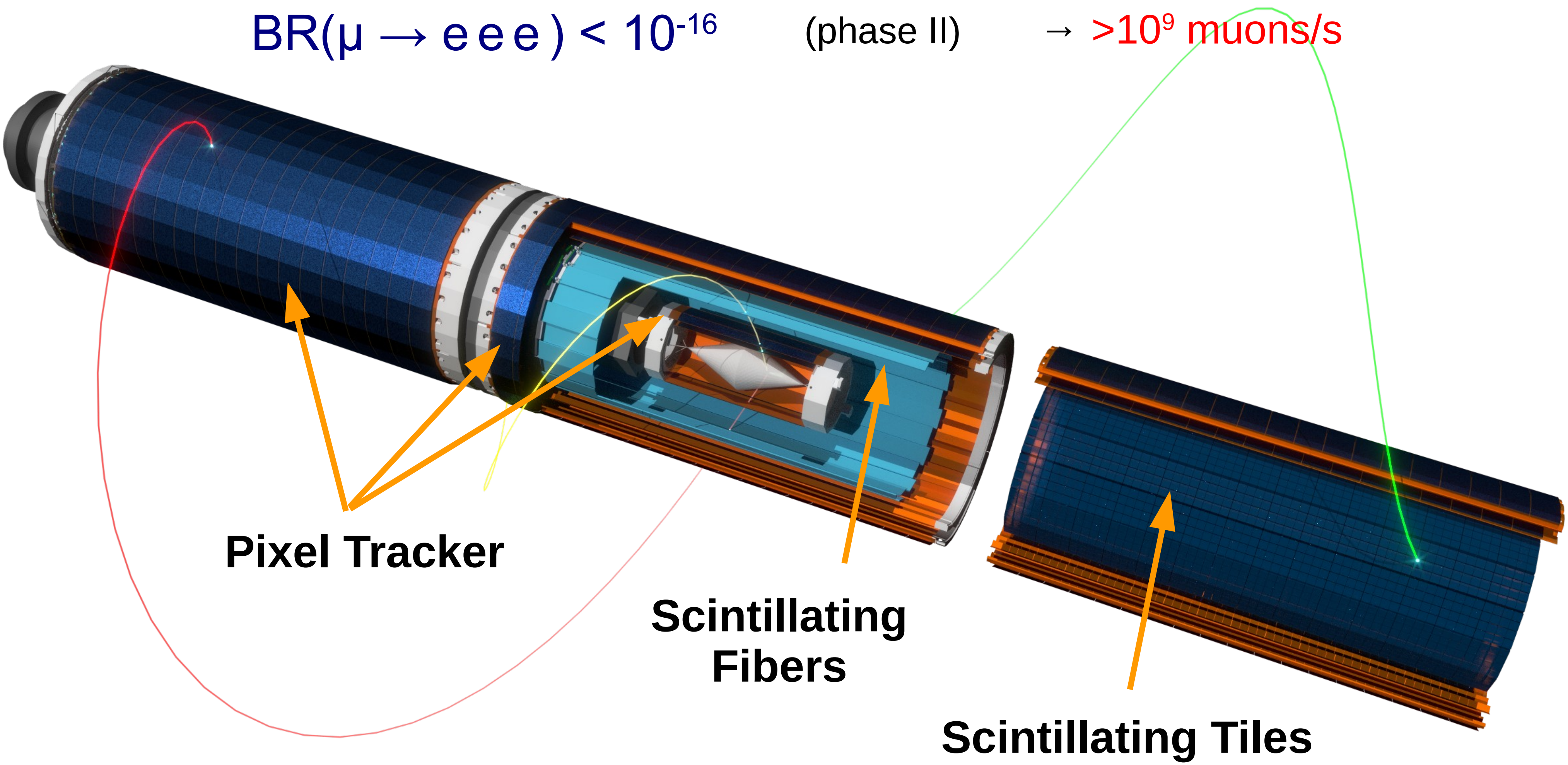
improvement by a **factor 300** compared to MEGA!

Mu3e Experiment

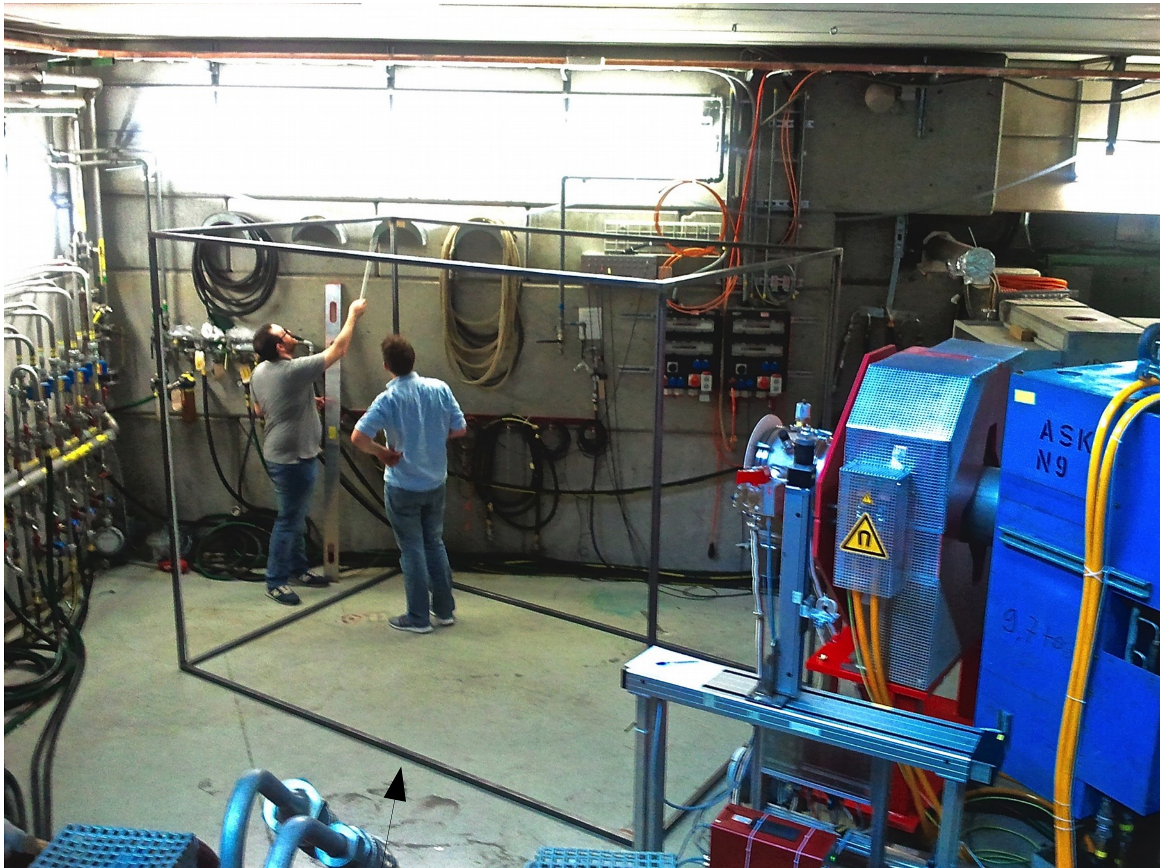
Aiming for a sensitivity of — requires:

$BR(\mu \rightarrow e\,e\,e) < 2 \cdot 10^{-15}$ (phase I) → 10^8 muons/s (existing)

$BR(\mu \rightarrow e\,e\,e) < 10^{-16}$ (phase II) → $>10^9$ muons/s

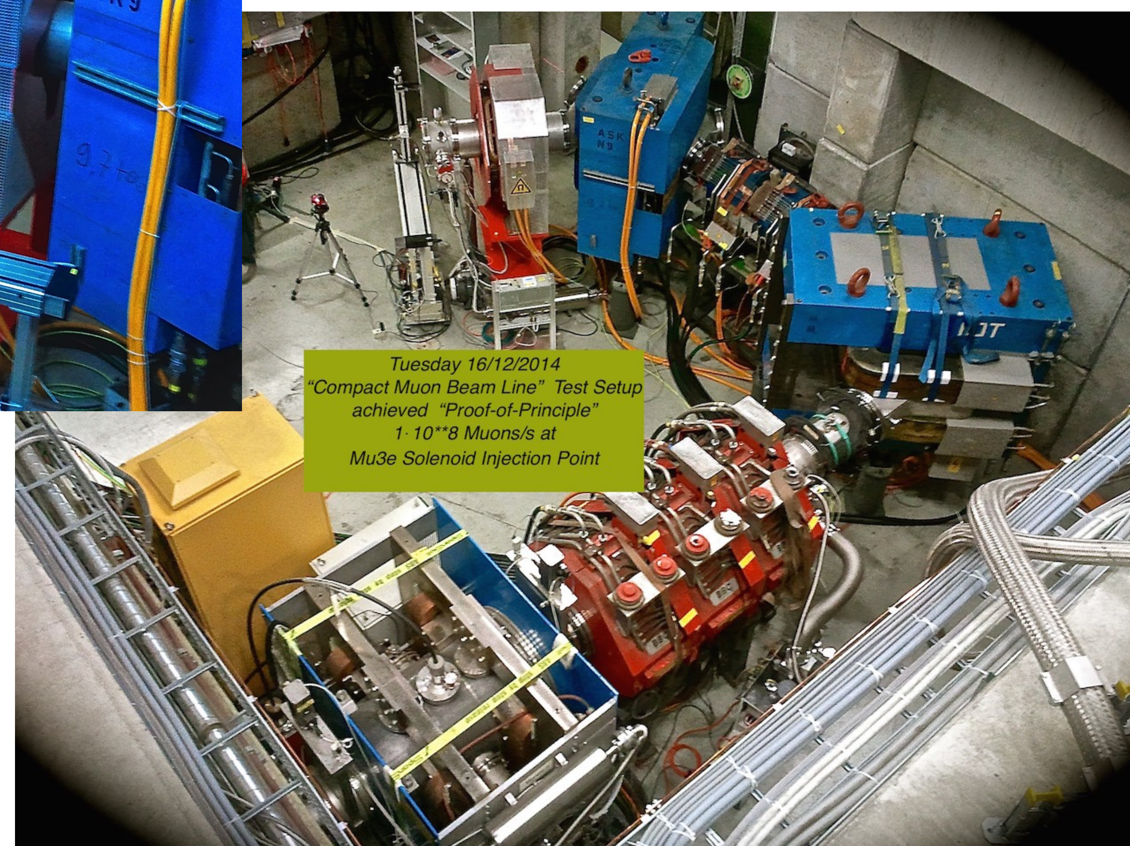


PiE5 Beamline + Target Region



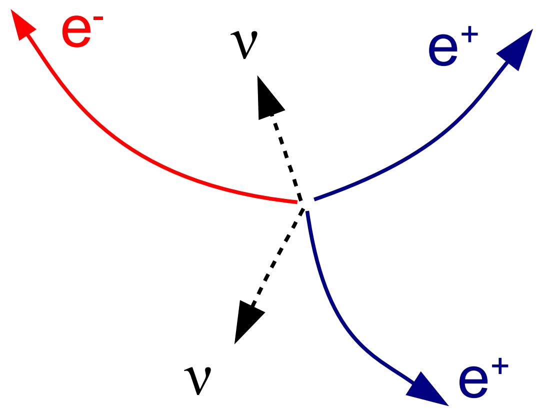
mockup for Mu3e solenoid

Compact Muon Beamline was successfully commissioned providing up to 10^8 muons/s

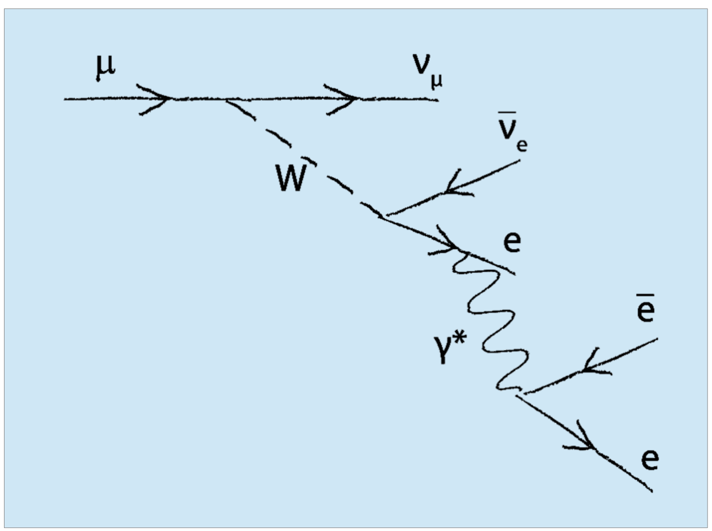


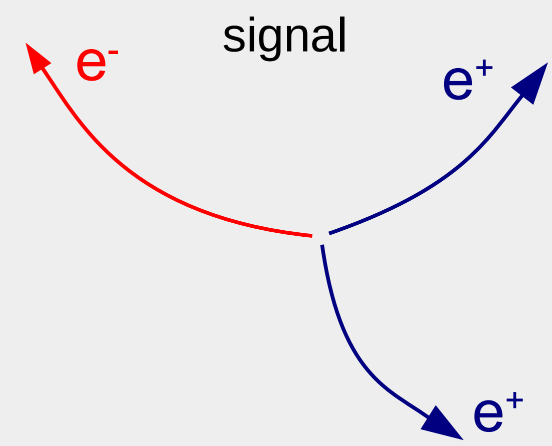
Irreducible Background

radiative decay with internal conversion



B($\mu^+ \rightarrow e^+e^+e^- \nu\nu$) = 3.4 ·10^{-5}

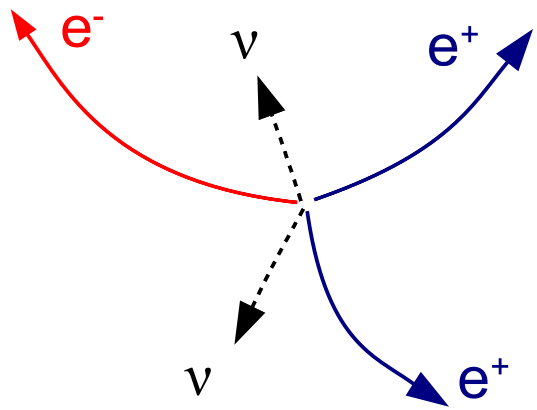




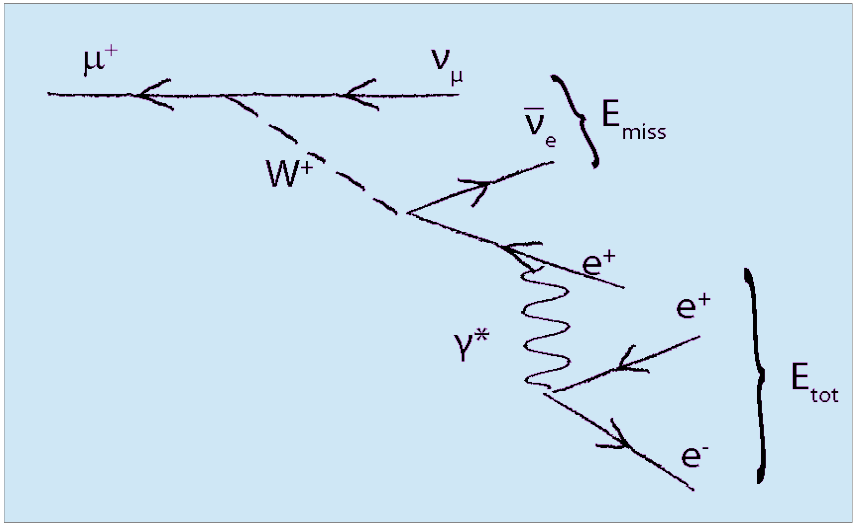
$$\sum_i E_i = m_\mu$$
$$\sum_i \vec{p}_i = 0$$

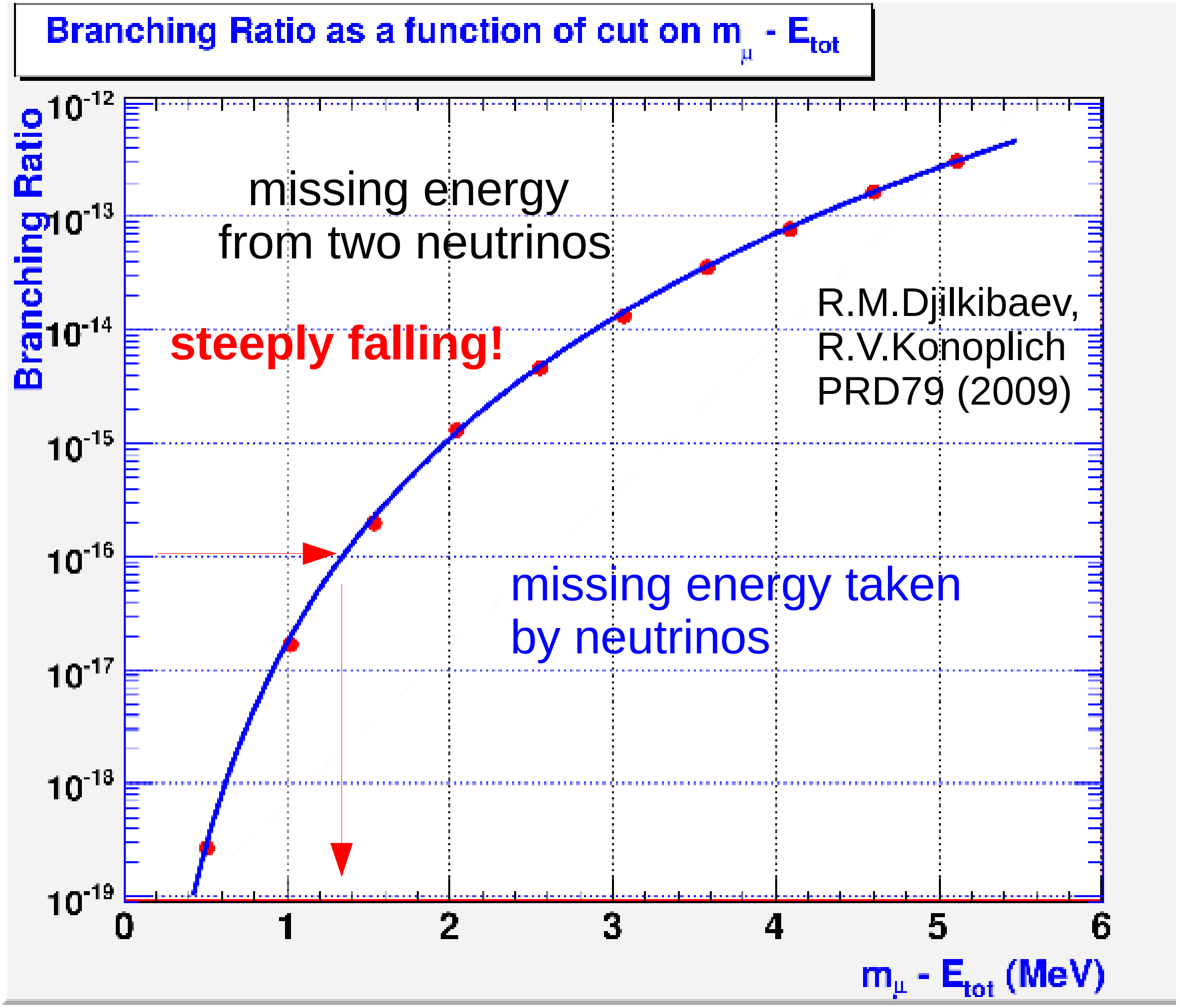
Irreducible Background

radiative decay with internal conversion



B($\mu^+ \rightarrow e^+e^+e^- \nu\nu$) = 3.4 ·$10^{-5}$

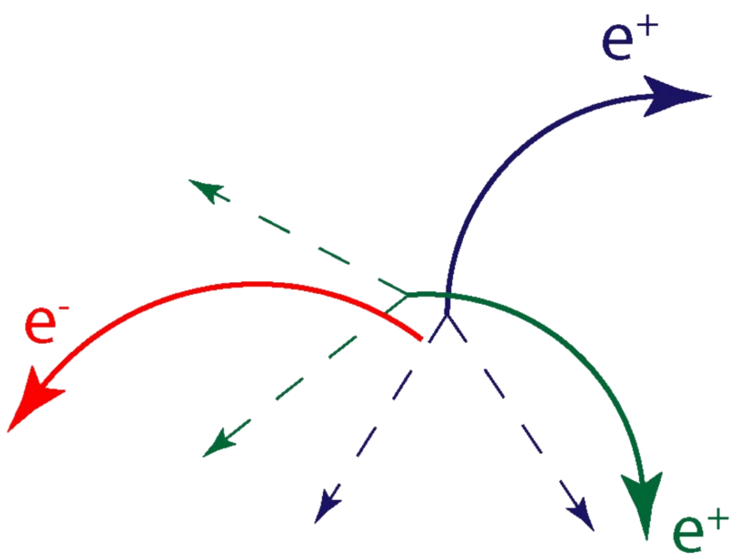


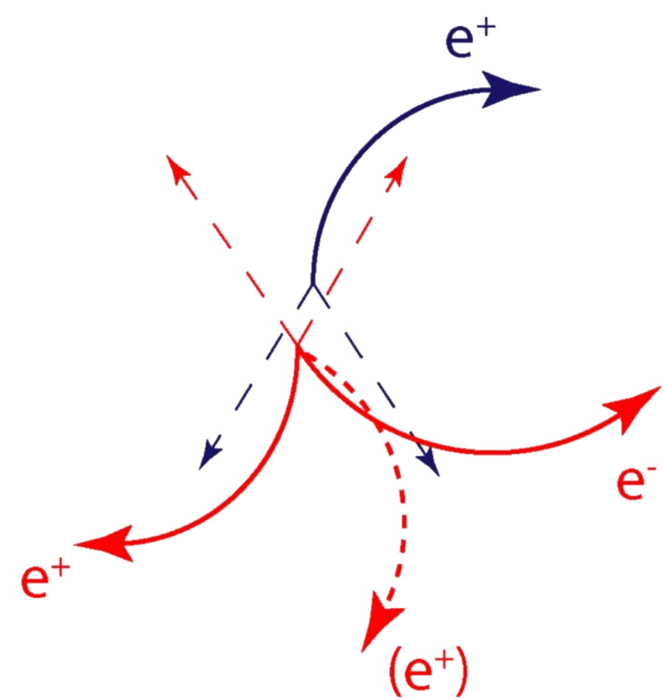


very good momentum +
total energy resolution required!

Accidental Backgrounds

- **Overlays** of two ordinary **μ^+ decays** with a (fake) **electron (e^-)**
- Electrons from: **Bhabha** scattering, photon conversion, mis-reconstruction





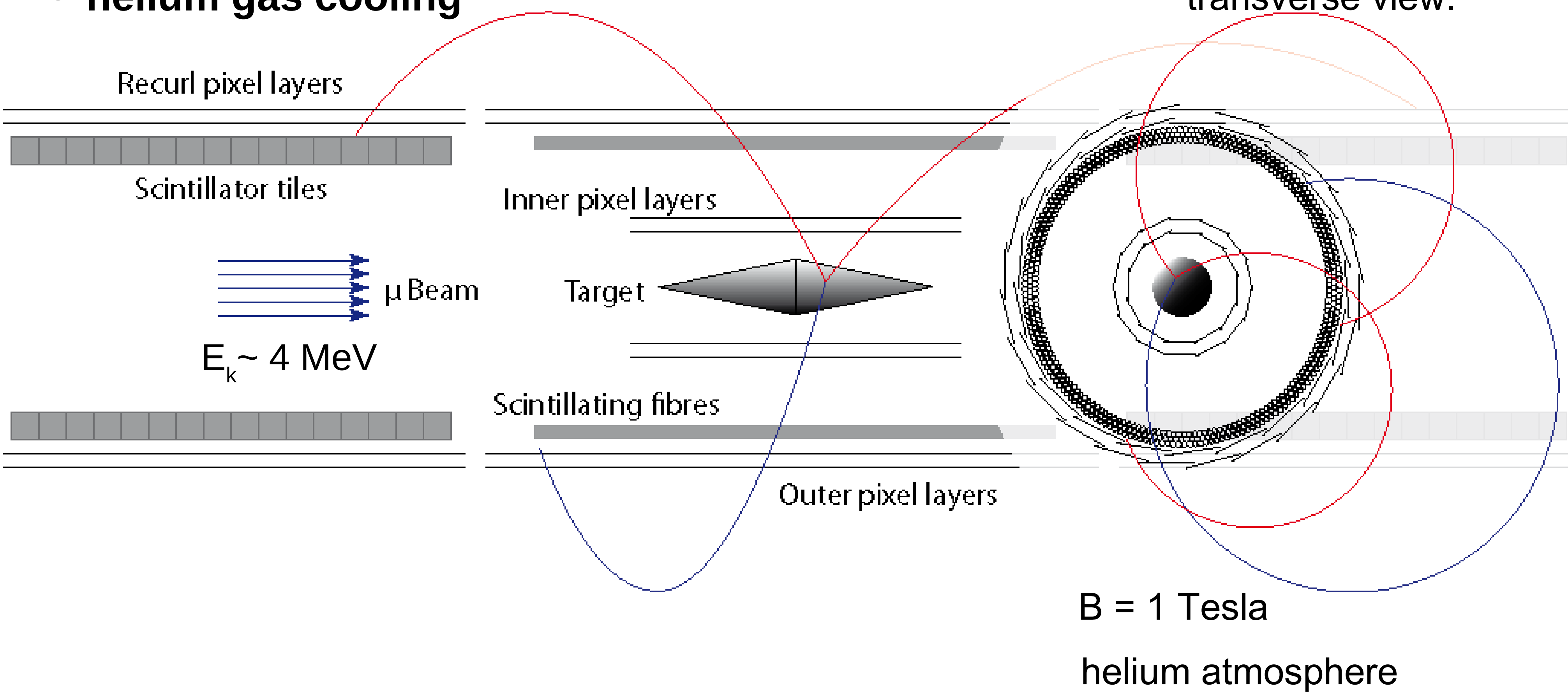
Need excellent:

- **Vertex resolution**
- **Timing resolution**
- **Kinematic reconstruction**

Mu3e Design

Features:

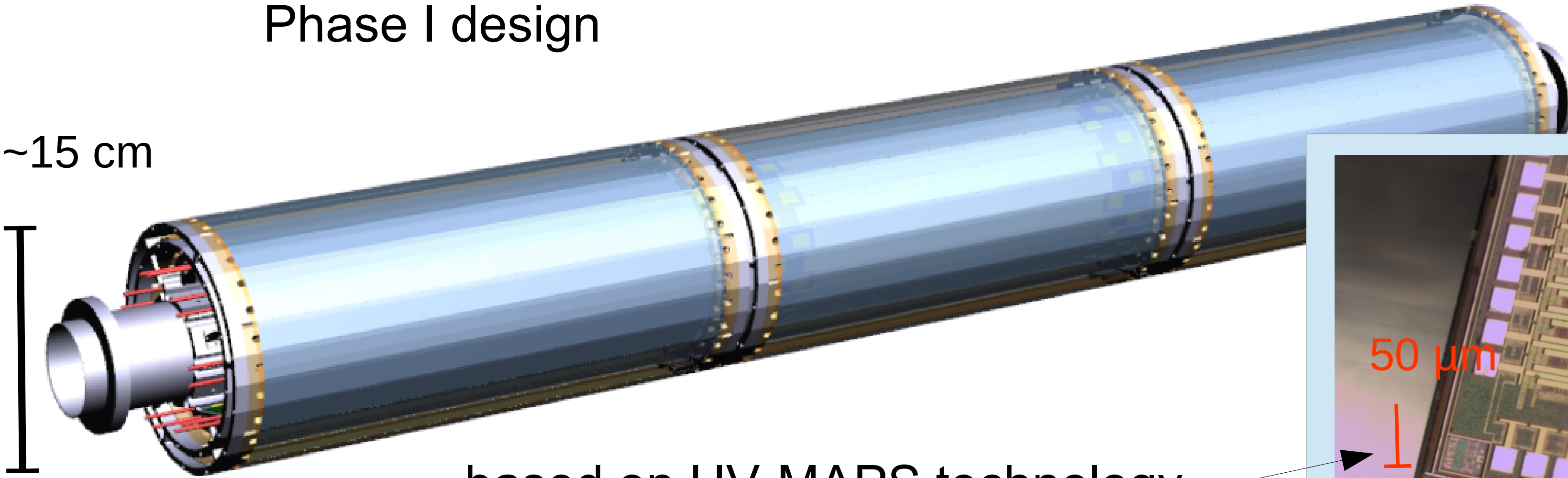
- surface muons (p=29 MeV/c, DC) stopped on target at high rate: **10^8 - 10^9 /s**
- ultra thin **silicon pixel detector** (HV-MAPS) with **1 per mill radiation length** / layer
- high precision tracking using **recurling tracks** in strong magnetic field
- **fast timing** detectors (scintillating fibers & tiles)
- **helium gas cooling**



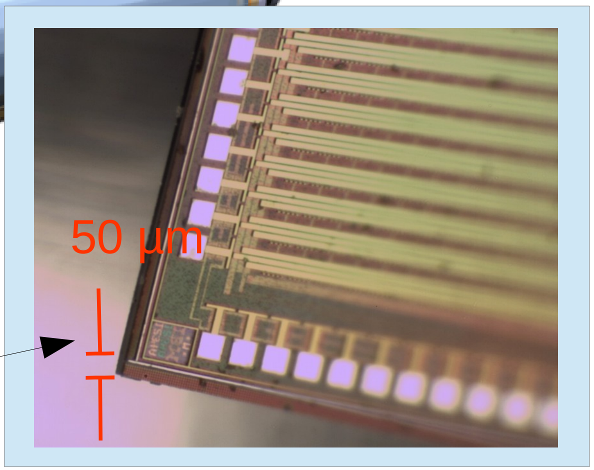
Pixel Detector + Helium Gas Cooling

Phase I design

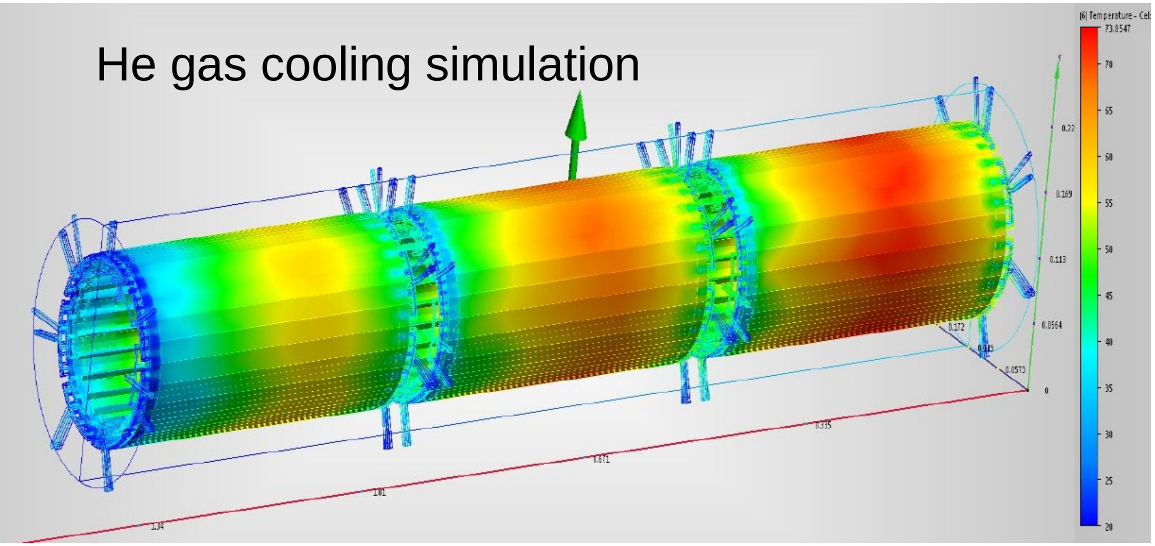
~15 cm



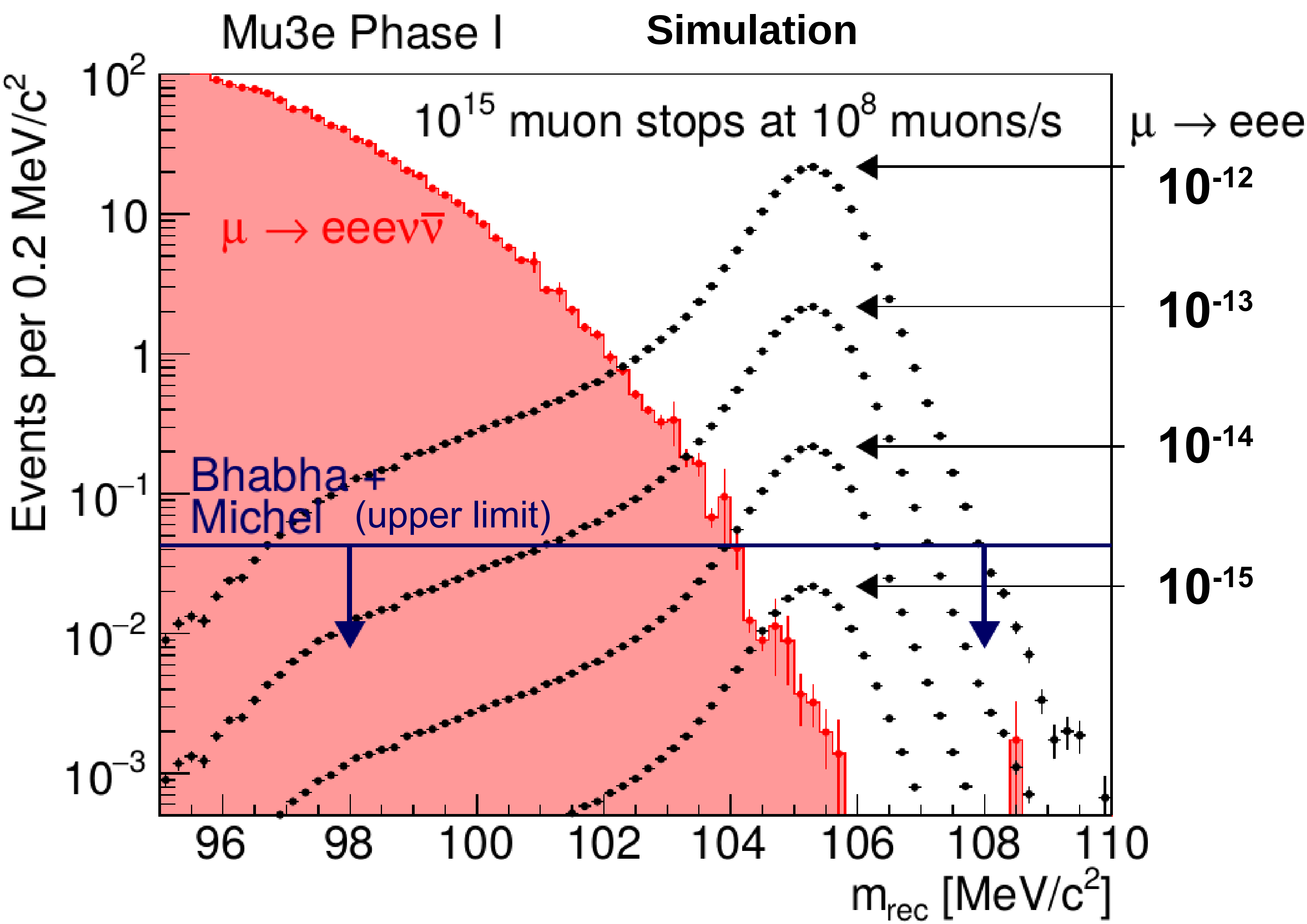
based on HV-MAPS technology



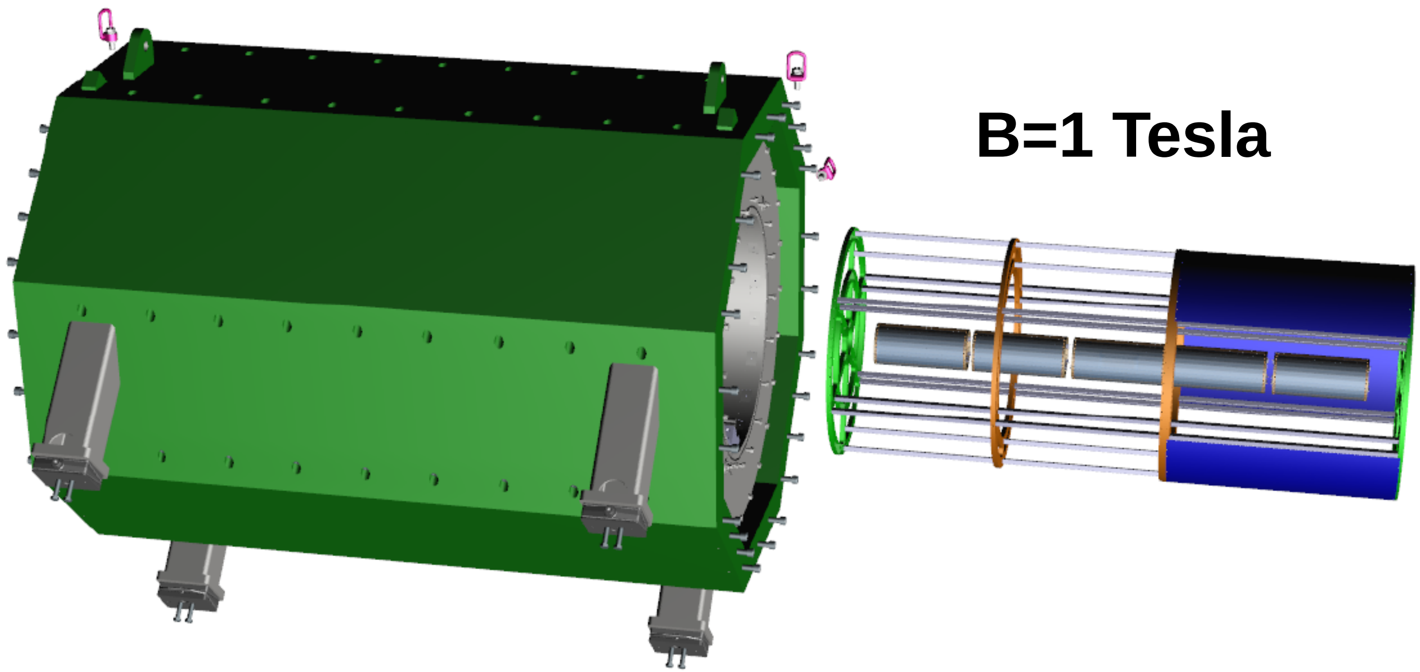
He gas cooling concept
→ temperatures 20-50 °C



Mu3e Mass Plot (Phase I)



Mu3e Status and Plans

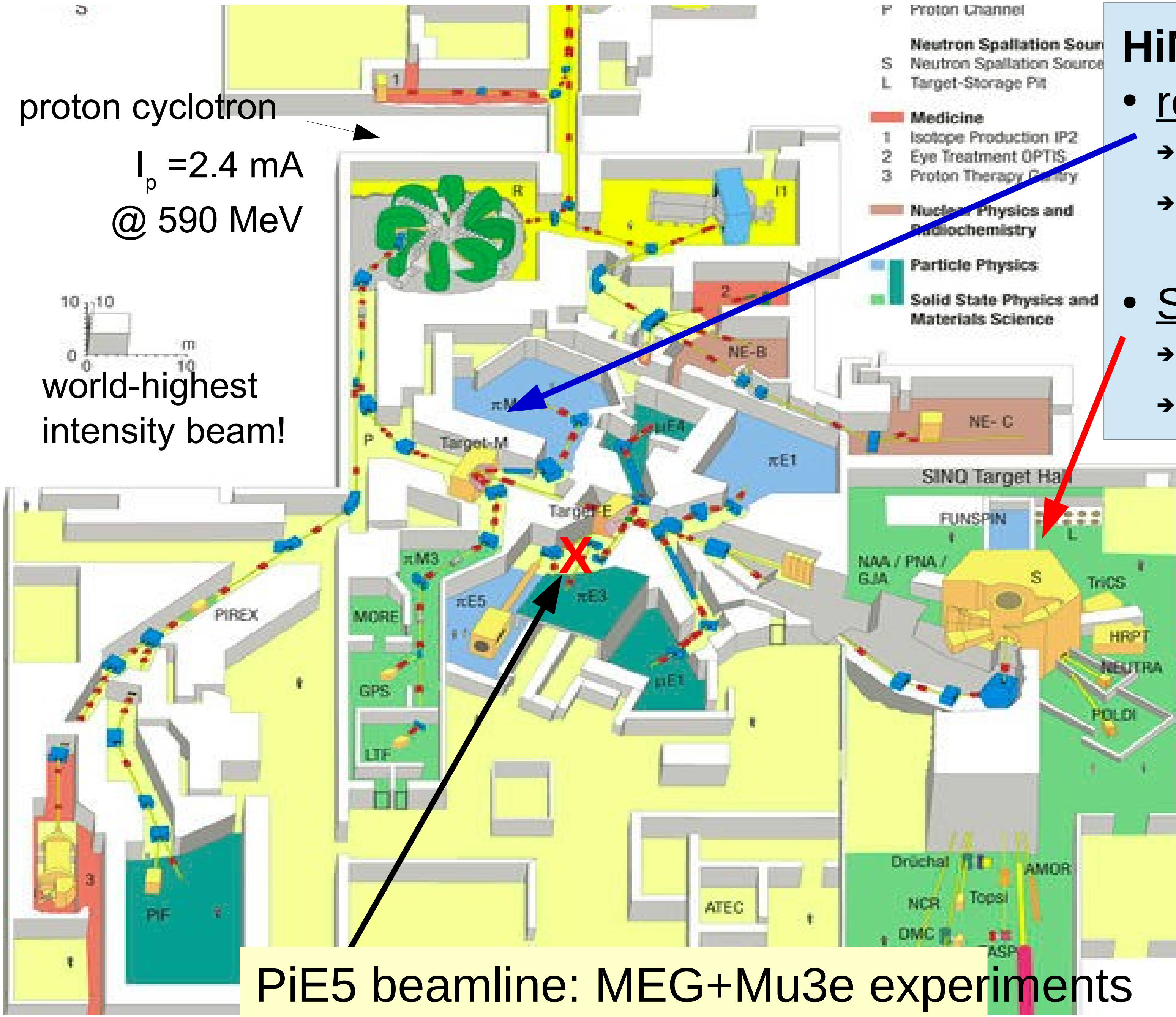


B=1 Tesla

- Comprehensive R&D (HV-MAPS, SciFi) program completed
- Detector construction starting now (2018/19)
- Magnet will be delivered by beginning of 2019
- First data taking in 2020

- Phase II program requires design and approval of **H**i**gh** Intensity **M**uon **B**eam Line (**HiMB**) → not before 2025

High Intensity Muon Beamline (HiMB) @ PSI



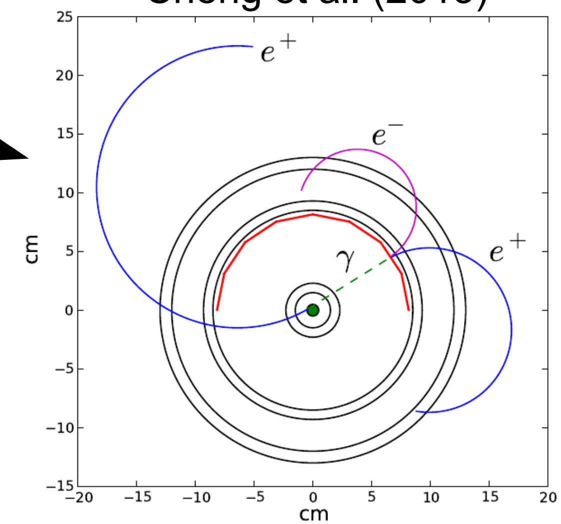
HiMB Studies:

- refurbish target M
  - μ rates >> 10^9/s
  - **promising!**
- SINQ target:
  - rates >10^{10}/s possible
  - but extremely difficult

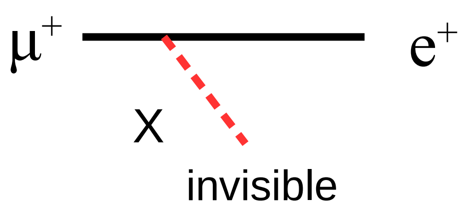
Other Searches with Muons (under study)

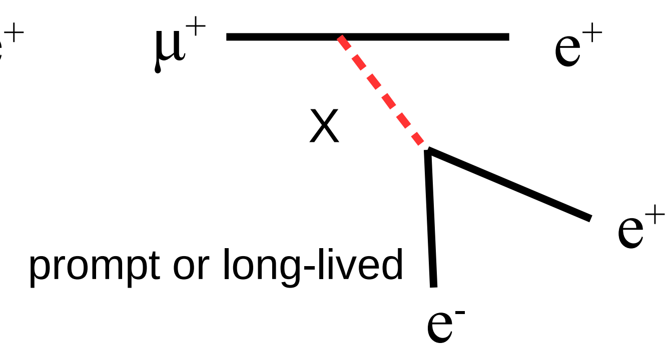
- Search for $\mu \to e\gamma$ with converted photons
  - better reduction of accidental BG than MEG

Cheng et al. (2013)

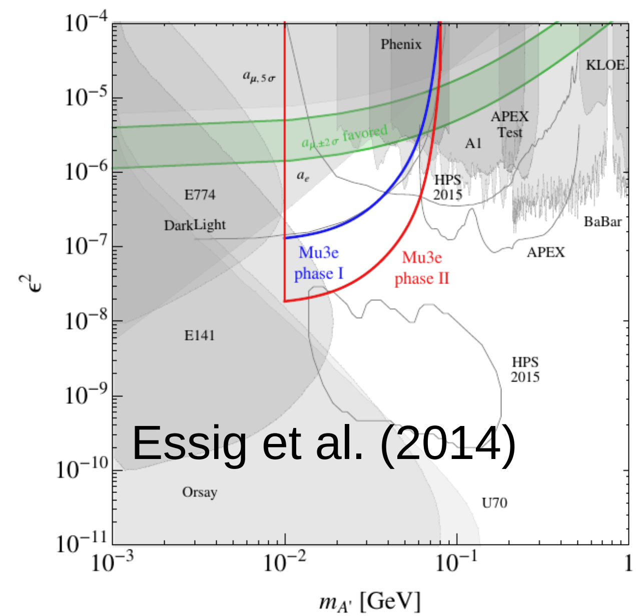


- Search for **familons**
  - pseudo Goldstone bosons of spontaneously broken flavor symmetry
  - dark matter candidate





- Search for **dark photons** A':
  - process $\mu \to e \nu\nu A'$

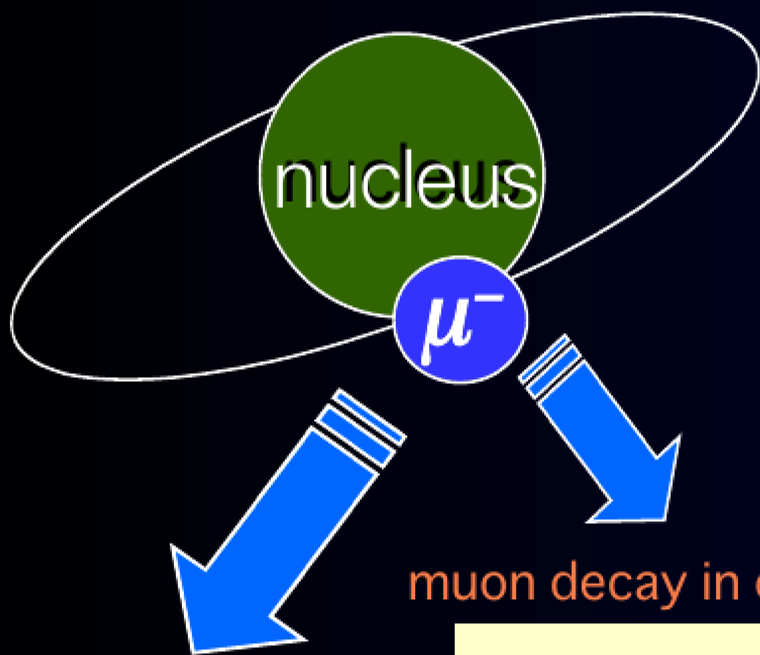


All searches require a continuous beam and a versatile detector like Mu3e

from Kuno-san

What is Muon to Electron Conversion?

1s state in a muonic atom



muon decay in orbit

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

nuclear muon capture

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

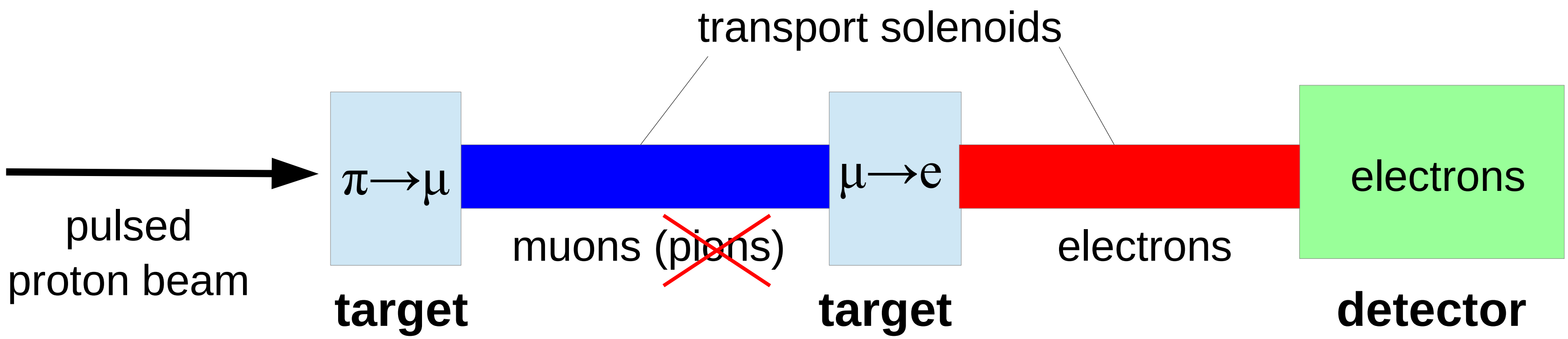
Neutrino-less muon nuclear capture

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

Event Signature :
a single mono-energetic electron of 105 MeV

Backgrounds:
(1) physics backgrounds
ex. muon decay in orbit (DIO)
(2) beam-related backgrounds
ex. radiative pion capture, muon decay in flight,
(3) cosmic rays, false tracking

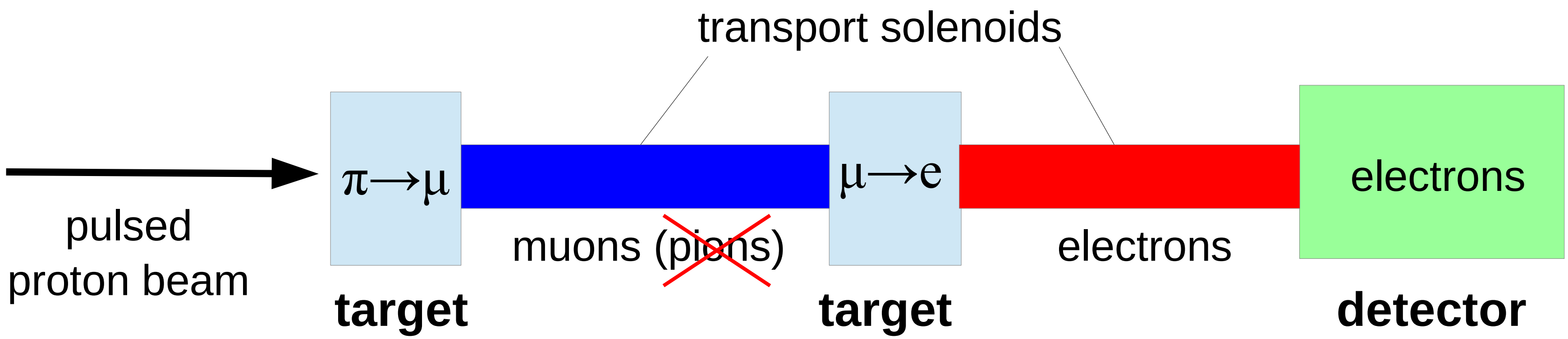
Experimental Concepts for $\mu \rightarrow e$ Conversion



→ **COMET II @JPARC**

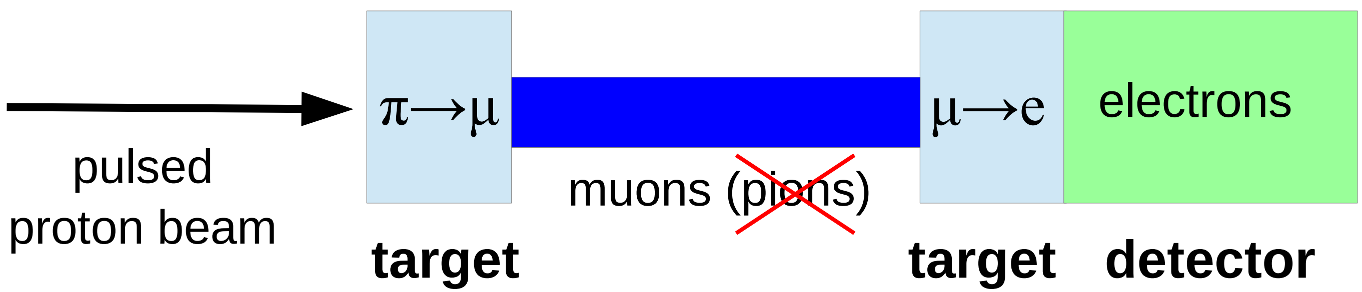
$R_{e\mu} < \sim 10^{-17}$

Experimental Concepts for $\mu \to e$ Conversion



→ **COMET II @JPARC**

$R_{e\mu} < \sim 10^{-17}$

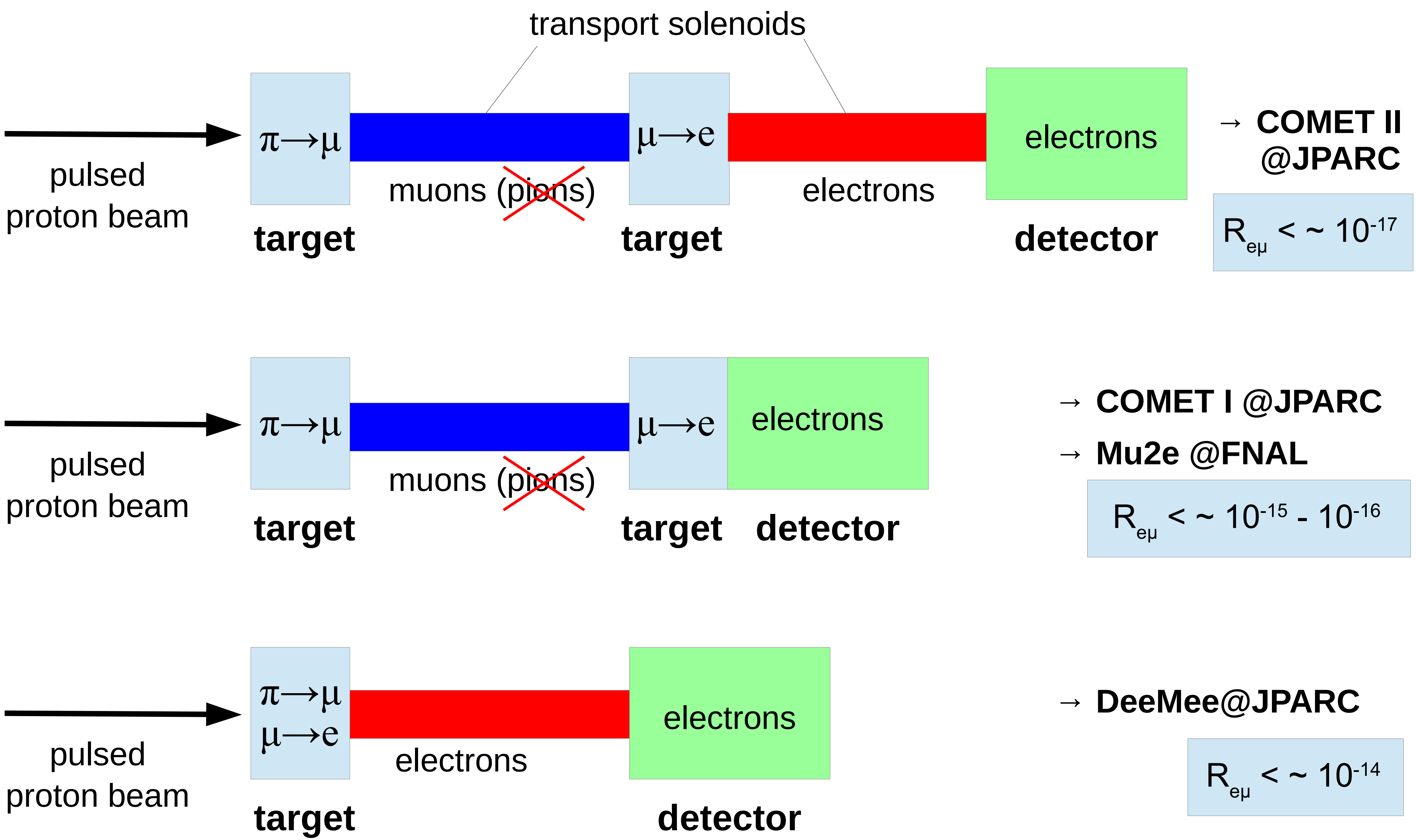


→ **COMET I @JPARC**

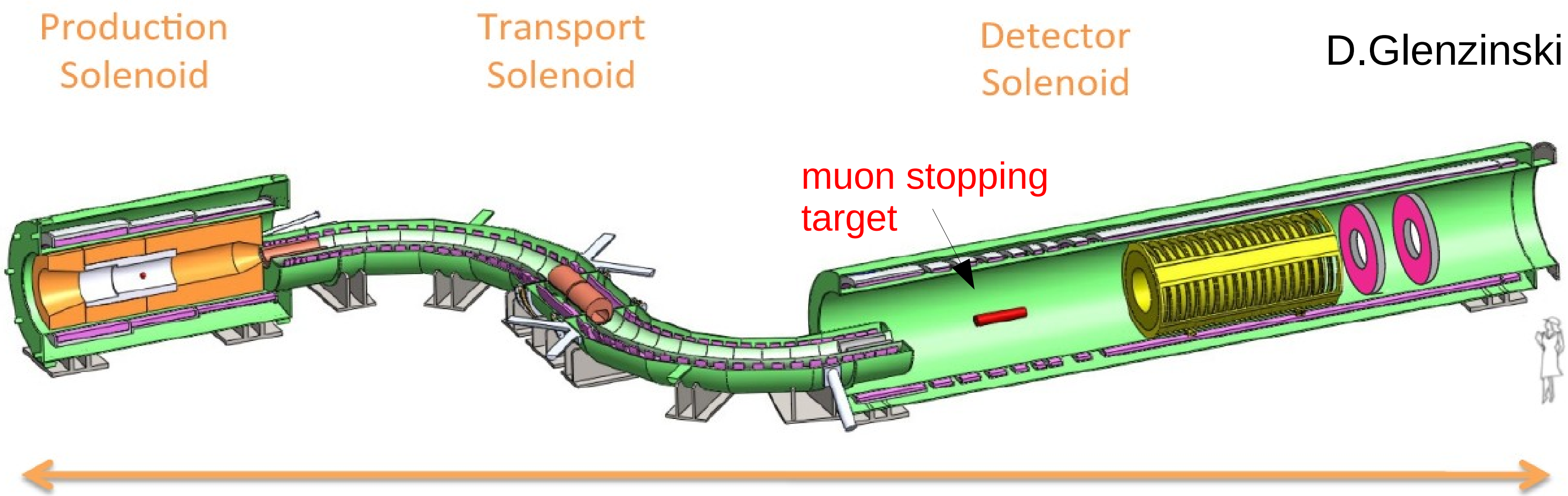
→ **Mu2e @FNAL**

$R_{e\mu} < \sim 10^{-15} - 10^{-16}$

Experimental Concepts for μ→e Conversion



Mu2e Experiment



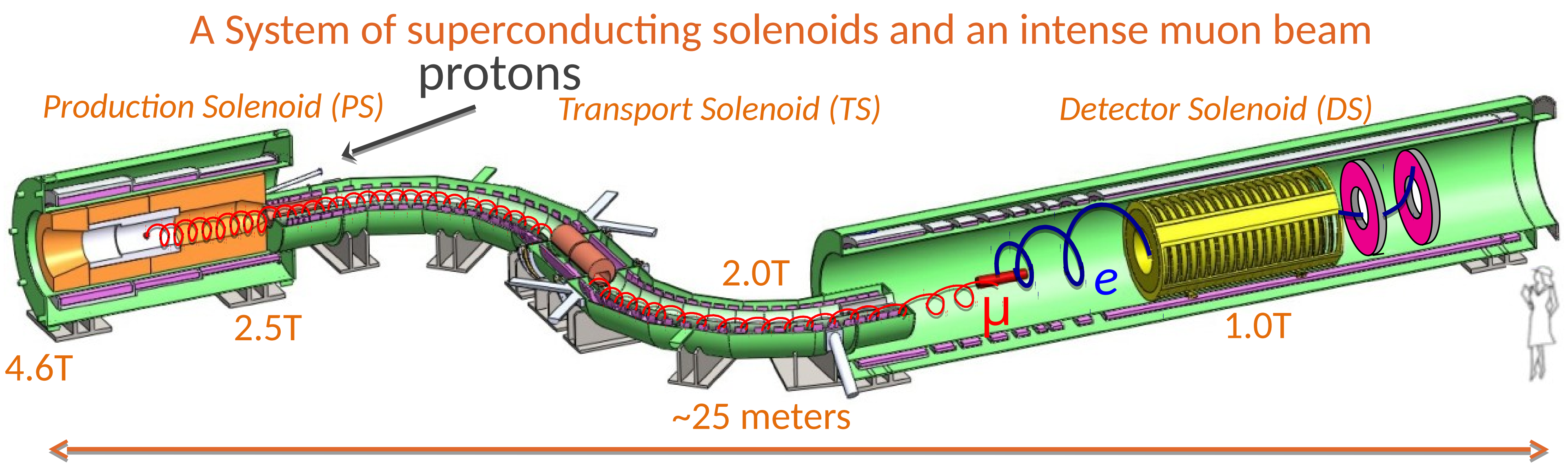
- A search for Charged Lepton Flavor Violation: $\mu N \rightarrow eN$
  - Expected sensitivity of 6×10^{-17} @ 90% CL, x10,000 better than SINDRUM-II
  - Probes effective new physics mass scales up to 10^4 TeV/c^2
  - *Discovery* sensitivity to broad swath of NP parameter space

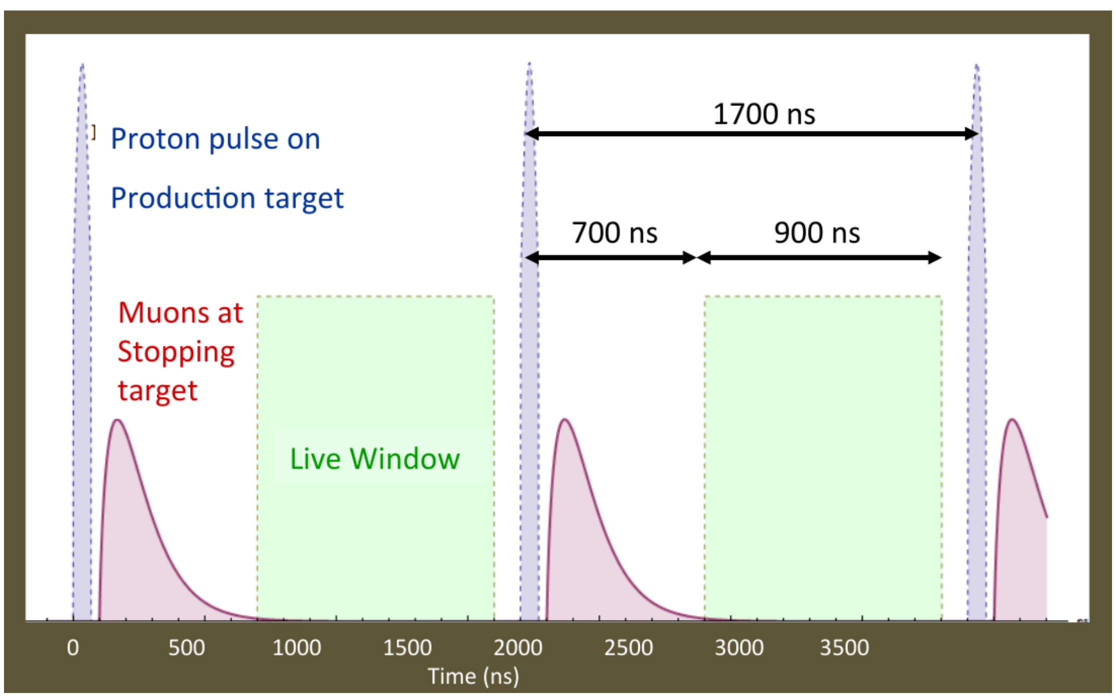
- Experiment scope includes
  - Proton Beam line
  - Solenoid systems
  - Detector elements

    (tracker, calorimeter, cosmic veto, DAQ, beam monitoring)
  - Experimental hall
  - Commissioning begins in 2020

provided by Doug Glenzinski

Mu2e Experiment at Fermilab

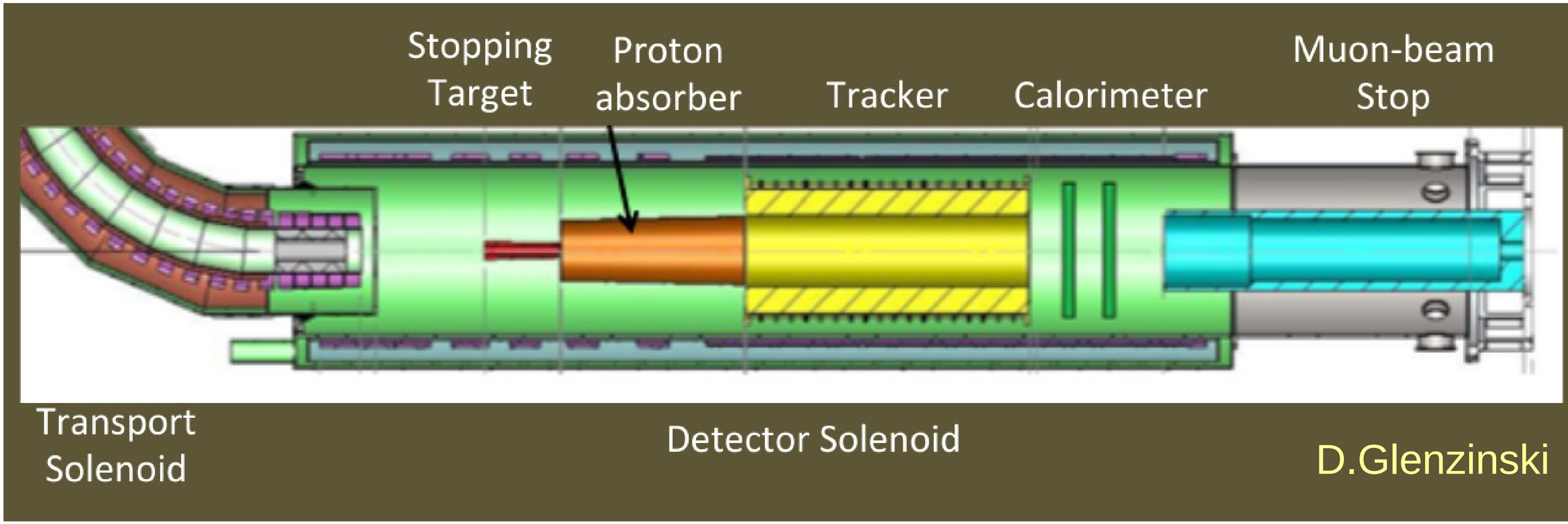




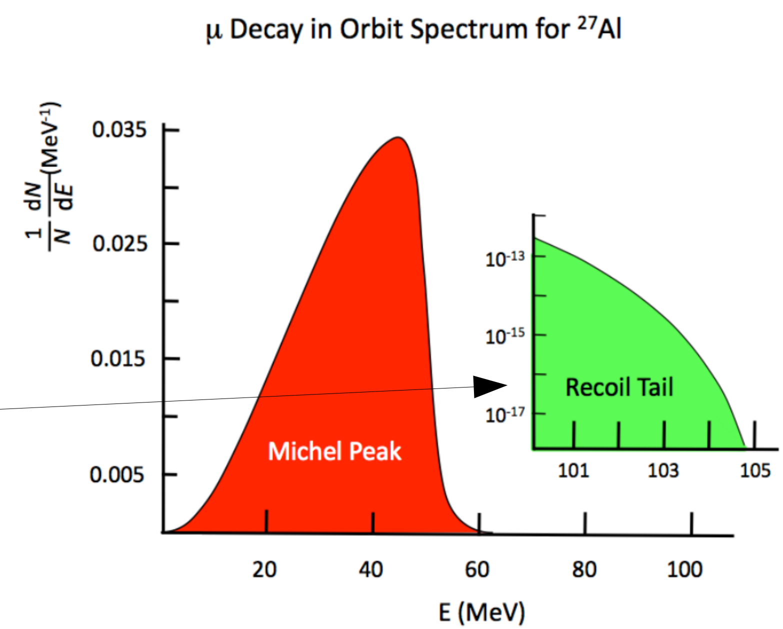
pulsed muons beam
with ~10^{20} protons on target

$R_{e\mu} < 6\cdot10^{-17}$ (90% CL)

Mu2e Experiment at Fermilab



- Detector acceptance only for high momentum tracks (filter)
- precise momentum determination using straw tube tracker
- background from recoils
- other BG: cosmics, pions, etc.



Mu2e Beamline

- Installation of beamline magnets well along

provided by Doug Glenzinski

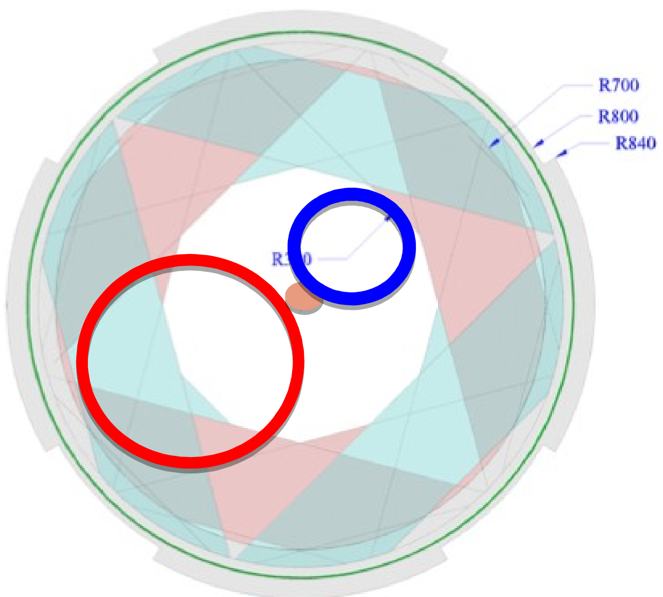
Mu2e Solenoids

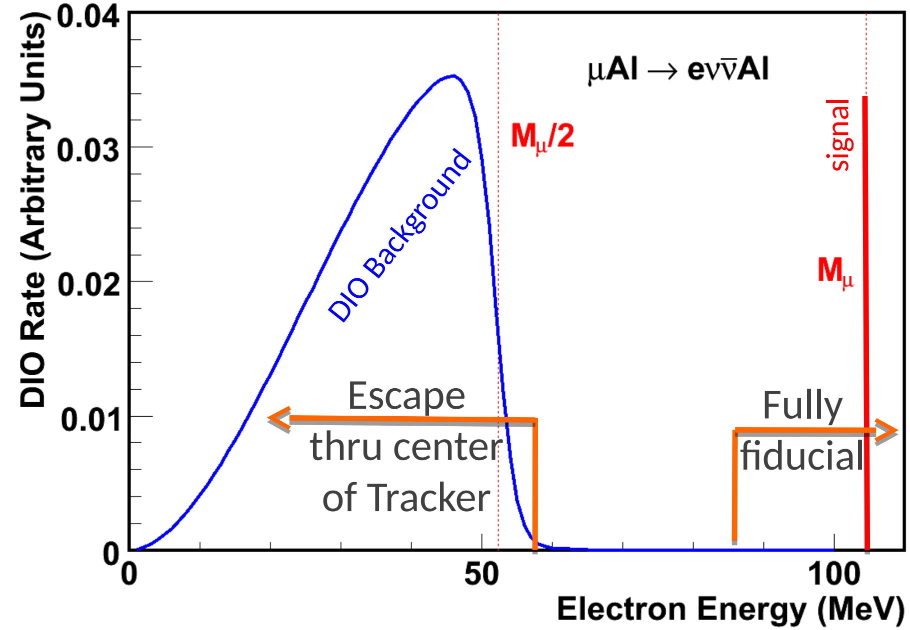
50% of coils winded

- Successful R&D and prototype campaign completed
- All superconductors for the three solenoids in hand
- Fabrication has begun at both ASG (TS) and General Atomics (DS & PS)
- Solenoids are scheduled to begin arriving at Fermilab in 2019

provided by Doug Glenzinski

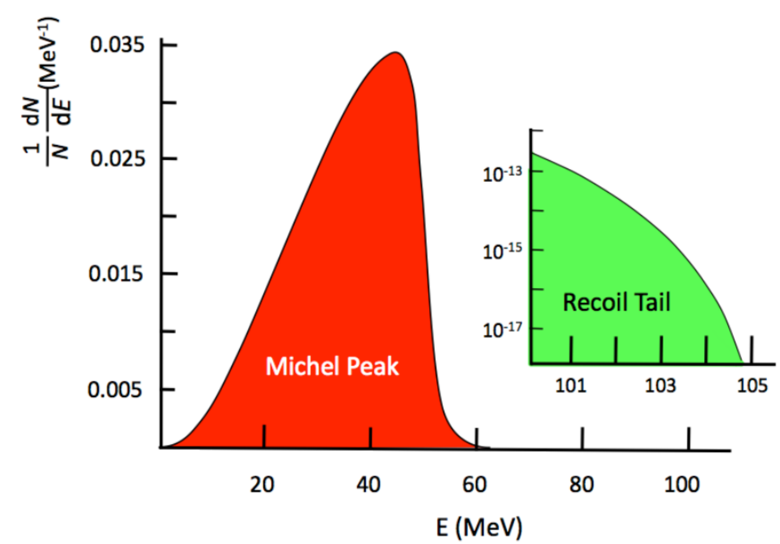
Mu2e Tracker





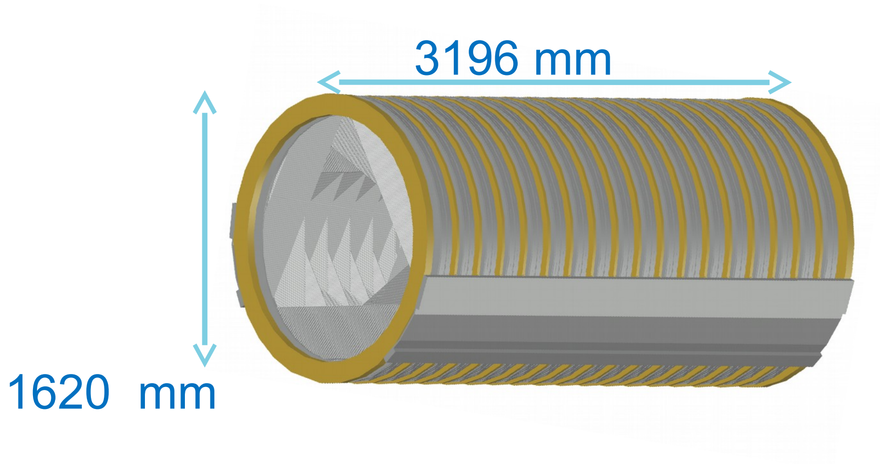
- Inner 38 cm is purposefully un-instrumented
  - Blind to beam flash
  - Blind to >99% of DIO spectrum

μ Decay in Orbit Spectrum for ^{27}Al

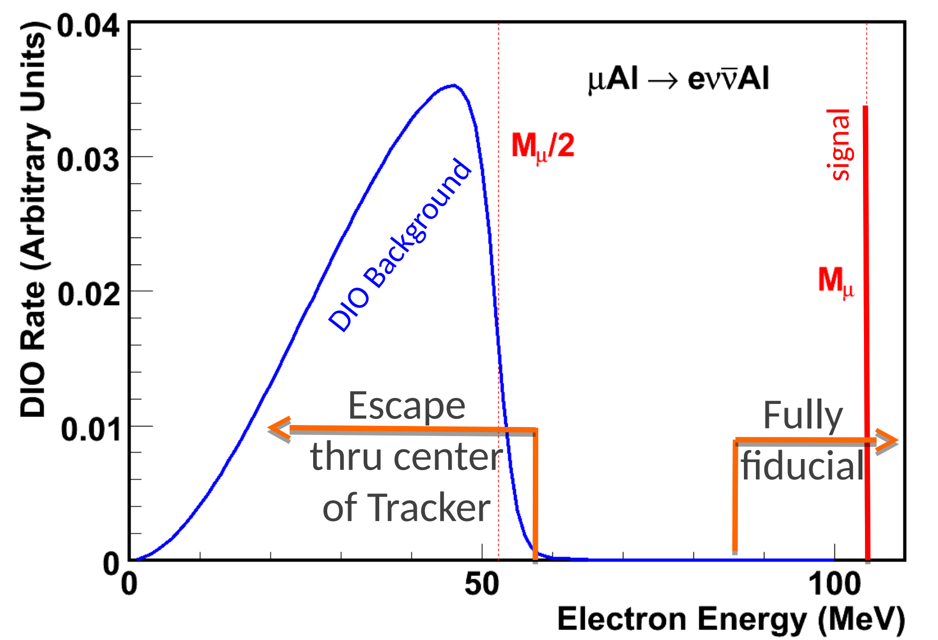


provided by Doug Glenzinski

Mu2e Tracker



18 tracking planes



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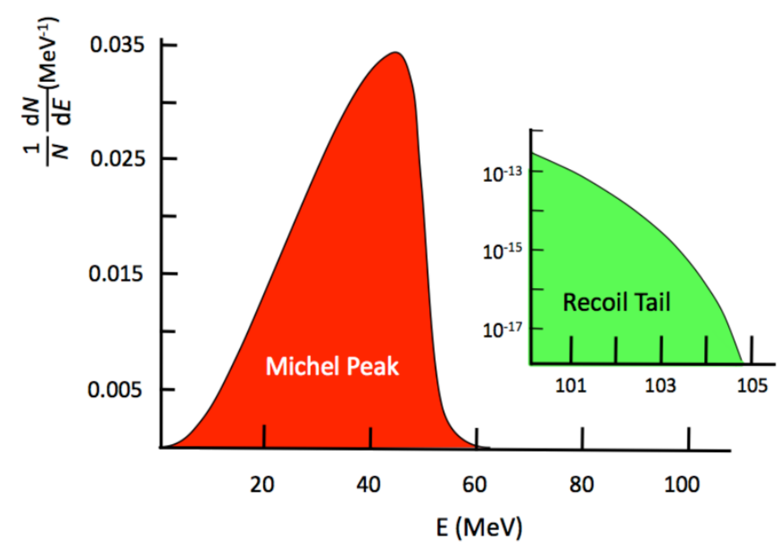
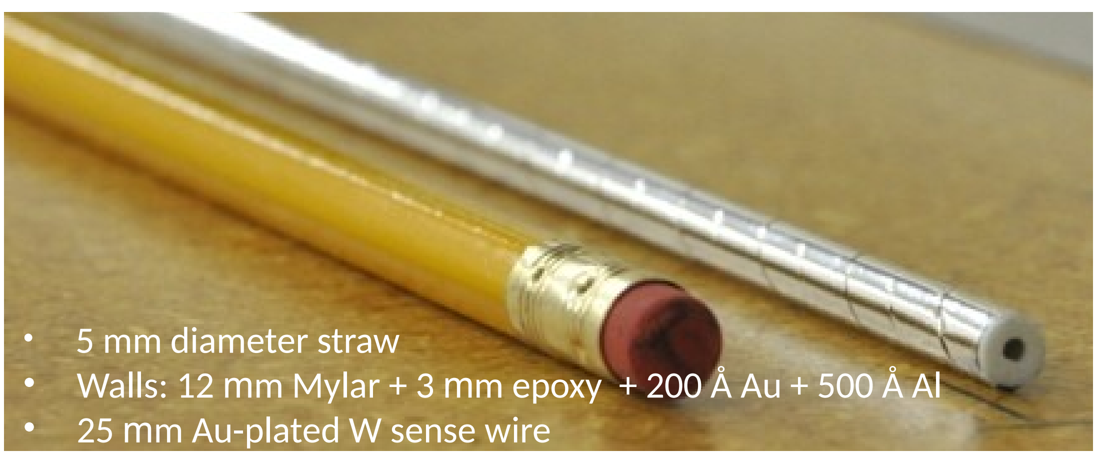
µ Decay in Orbit Spectrum for ^{27}Al



provided by Doug Glenzinski

Mu2e Tracker

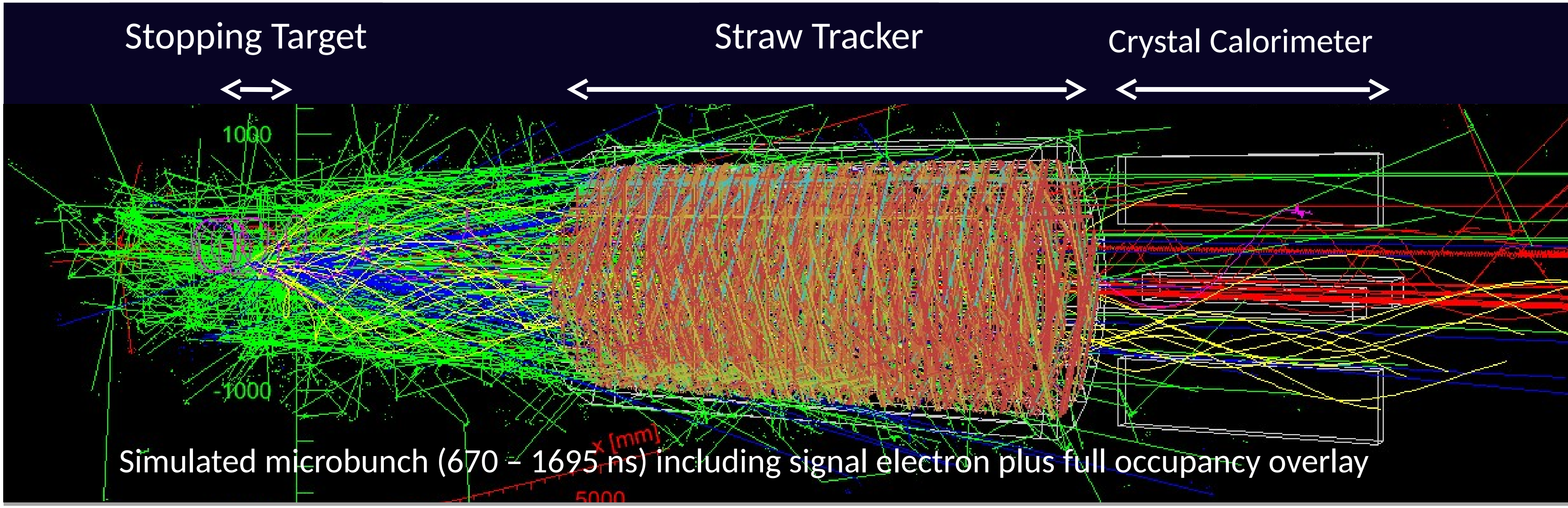
- 20k Straw tubes oriented transverse to beam line
  - R_{in} = 38 cm, R_{out} = 70 cm, L = 320 cm
  - Readout and support at large radii, outside active volume
- High efficiency, excellent resolution
  - Momentum resolution 120 keV/c core for 105 MeV electrons



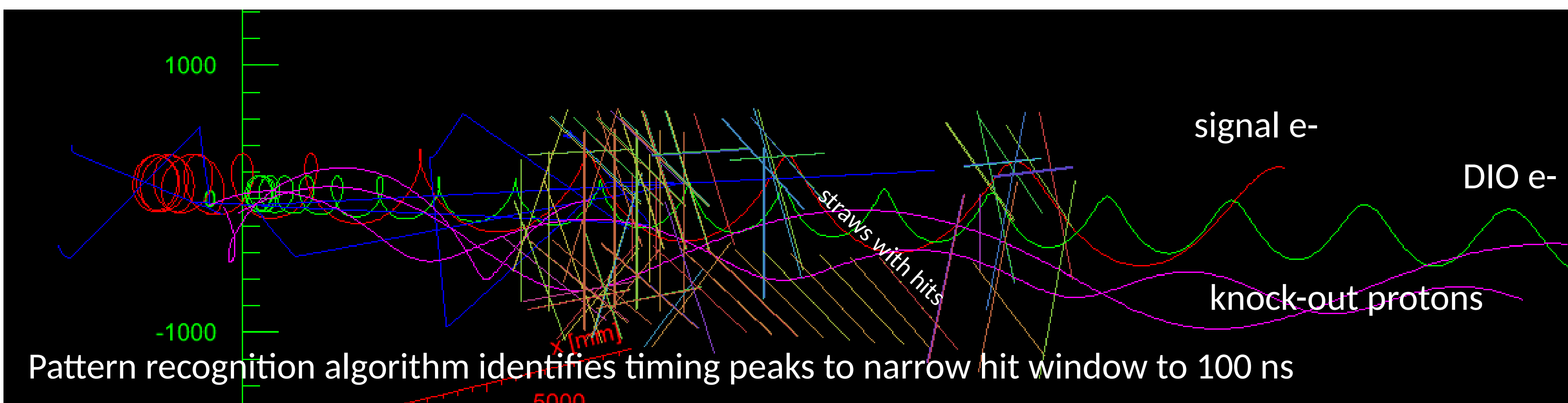
- panel prototype (96 straws) for testing

provided by Doug Glenzinski

Mu2e Pileup Simulation

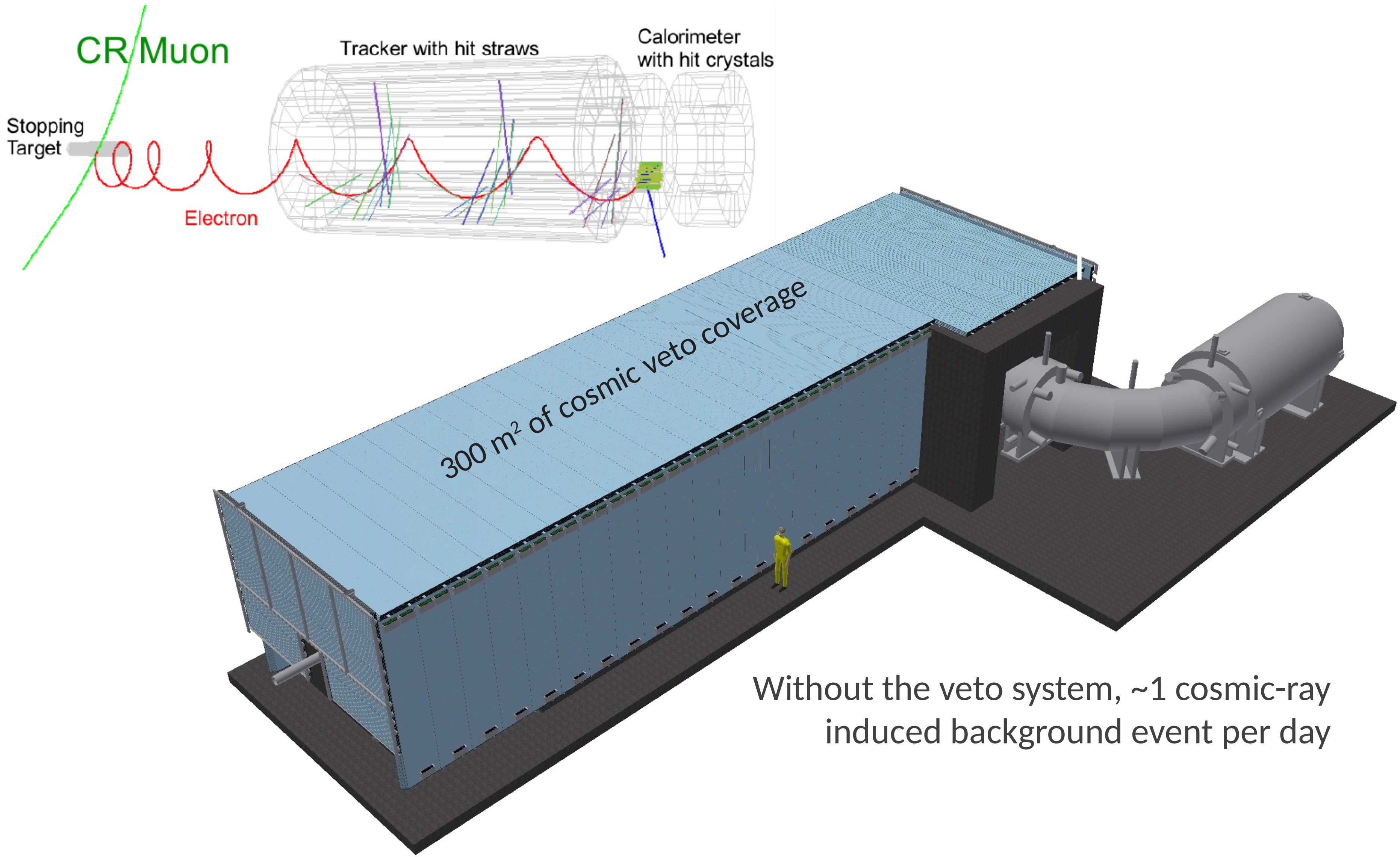


fast timing detectors



provided by Doug Glenzinski

Mu2e Cosmic Veto



- Veto system covers entire DS and half TS

provided by Doug Glenzinski

Mu2e Civil Construction

- Mu2e beam line and experimental hall are complete

provided by Doug Glenzinski

Mu2e Status & Progress

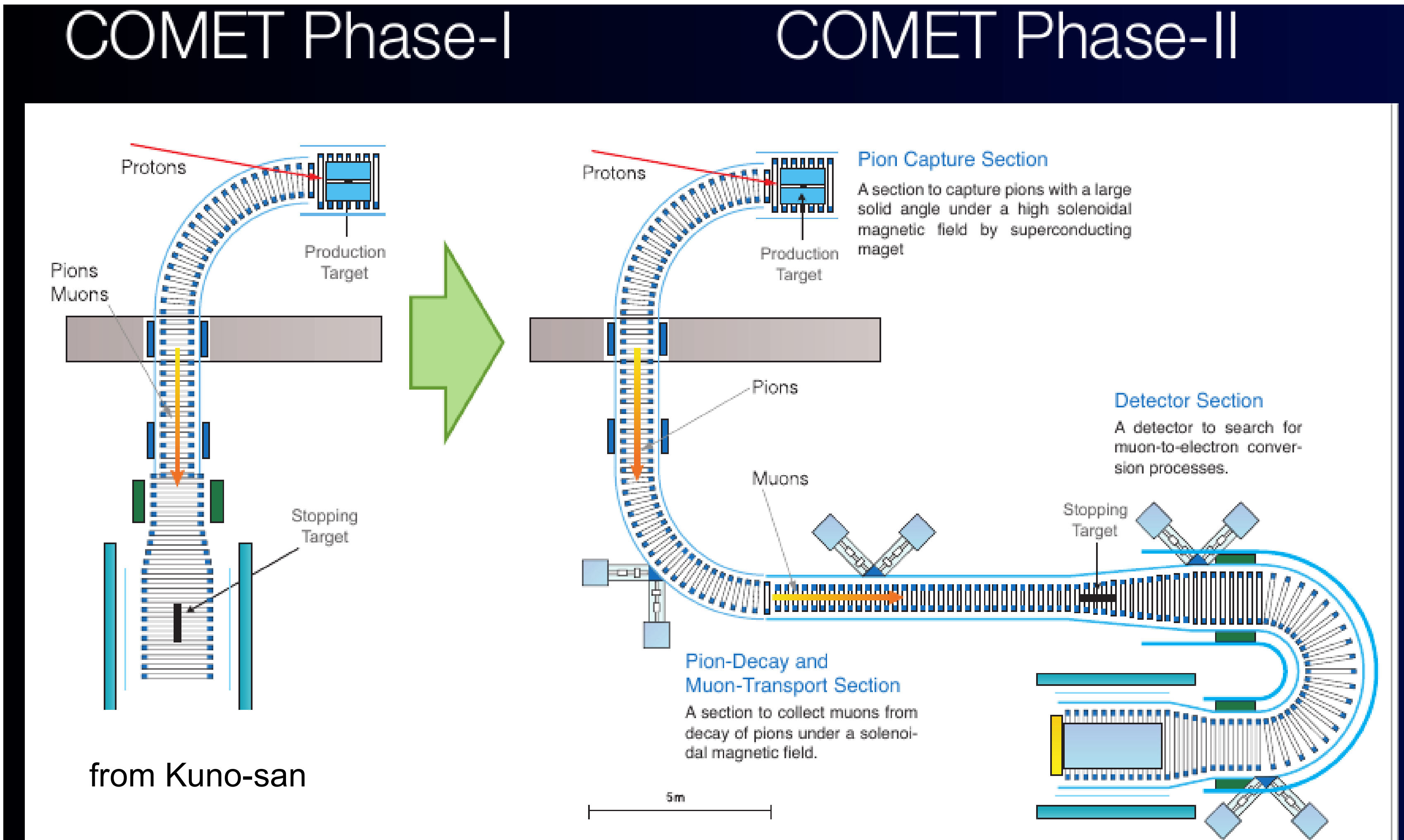
- **first physics beam** has been delivered to the Fermilab muon campus
- **extinction measurements** (no protons in live window!) planned for **2018** later tt portion of the Mu2e beam line
- successful completion of our prototyping of all major detector components
- large scale detector construction has started
- **experiment commissioning in 2020**

Discussion on Mu2e Upgrade has started!

Sensitivity Goals COMET @ JPARC

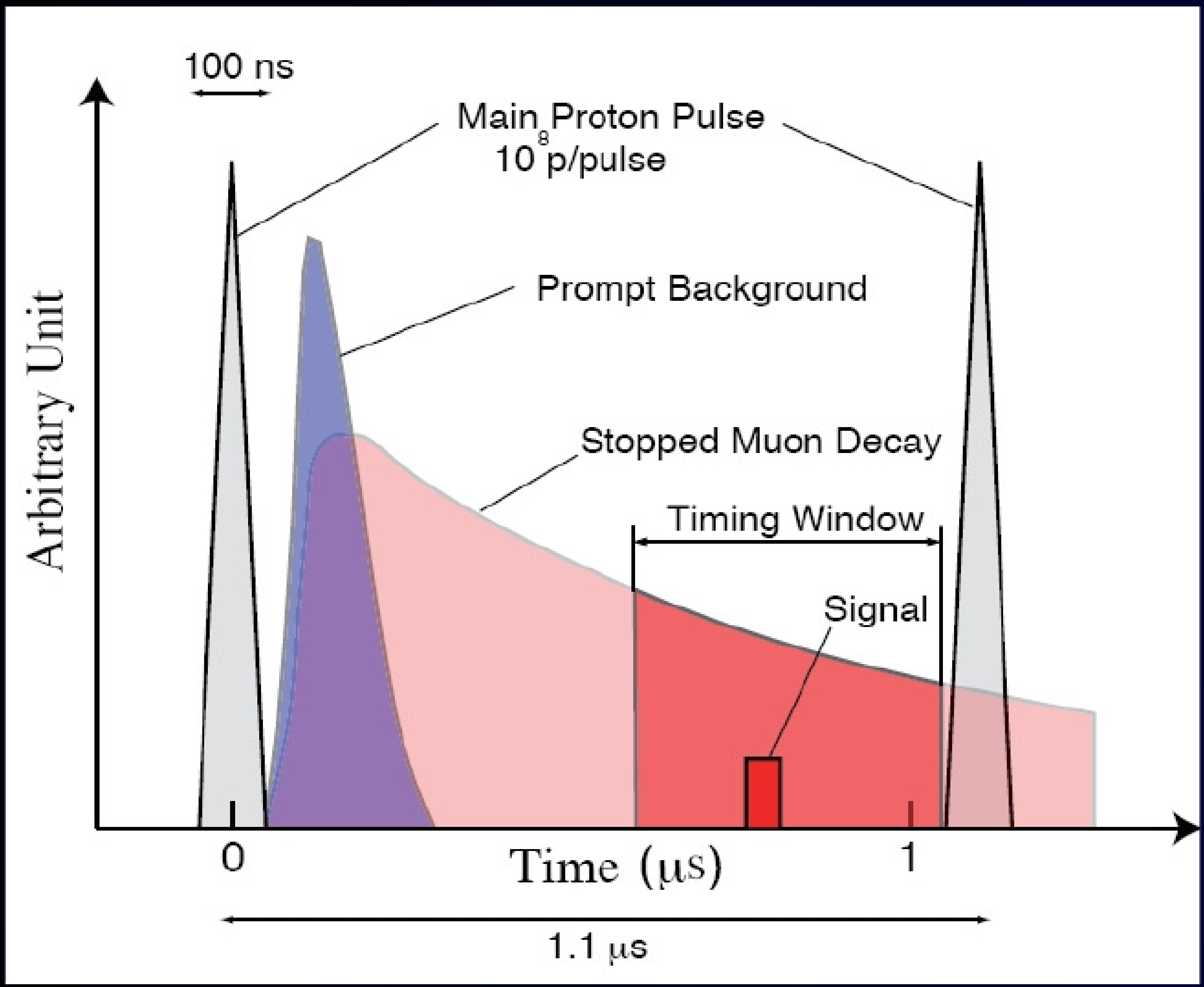
2018/19: $R_{e\mu} < O(10^{-15})$

2021: $R_{e\mu} < \sim O(10^{-17})$



from Kuno-san

COMET Beam Timing

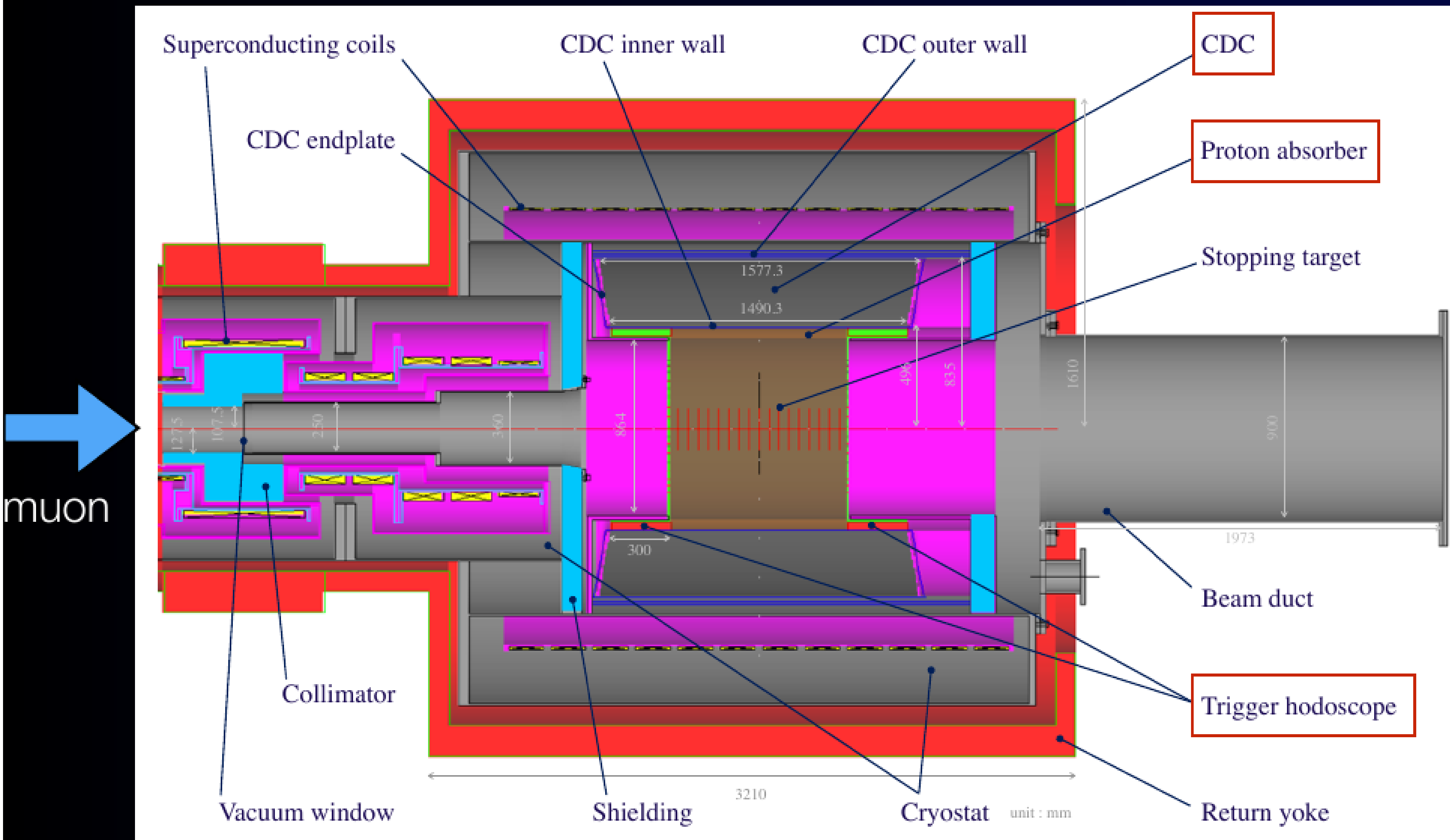


The measurement window opens about 700µsec after the beam prompt.

For aluminum, a lifetime of a muonic atom is about 0.8 µsec.

CyDet (Cylindrical Detector): Layout

from Kuno-san



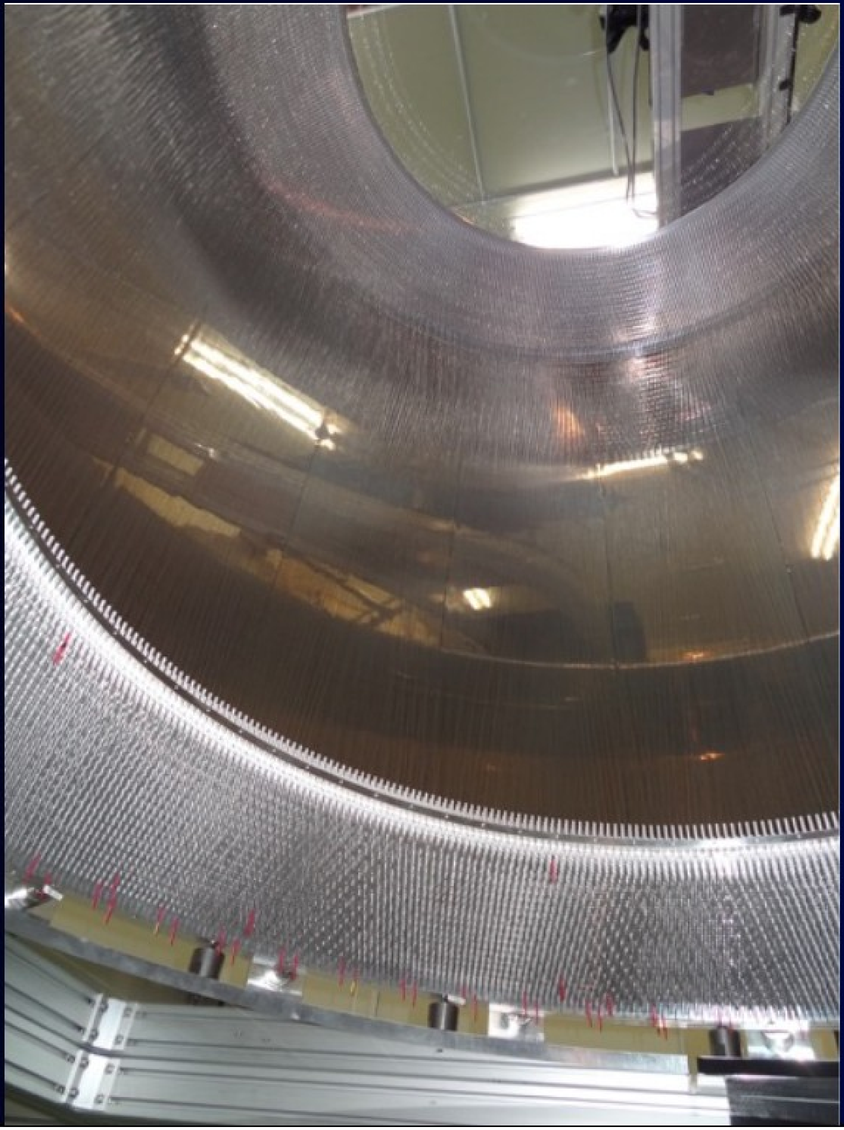
from Kuno-san

CDC Wire Stringing Completed!

Osaka University

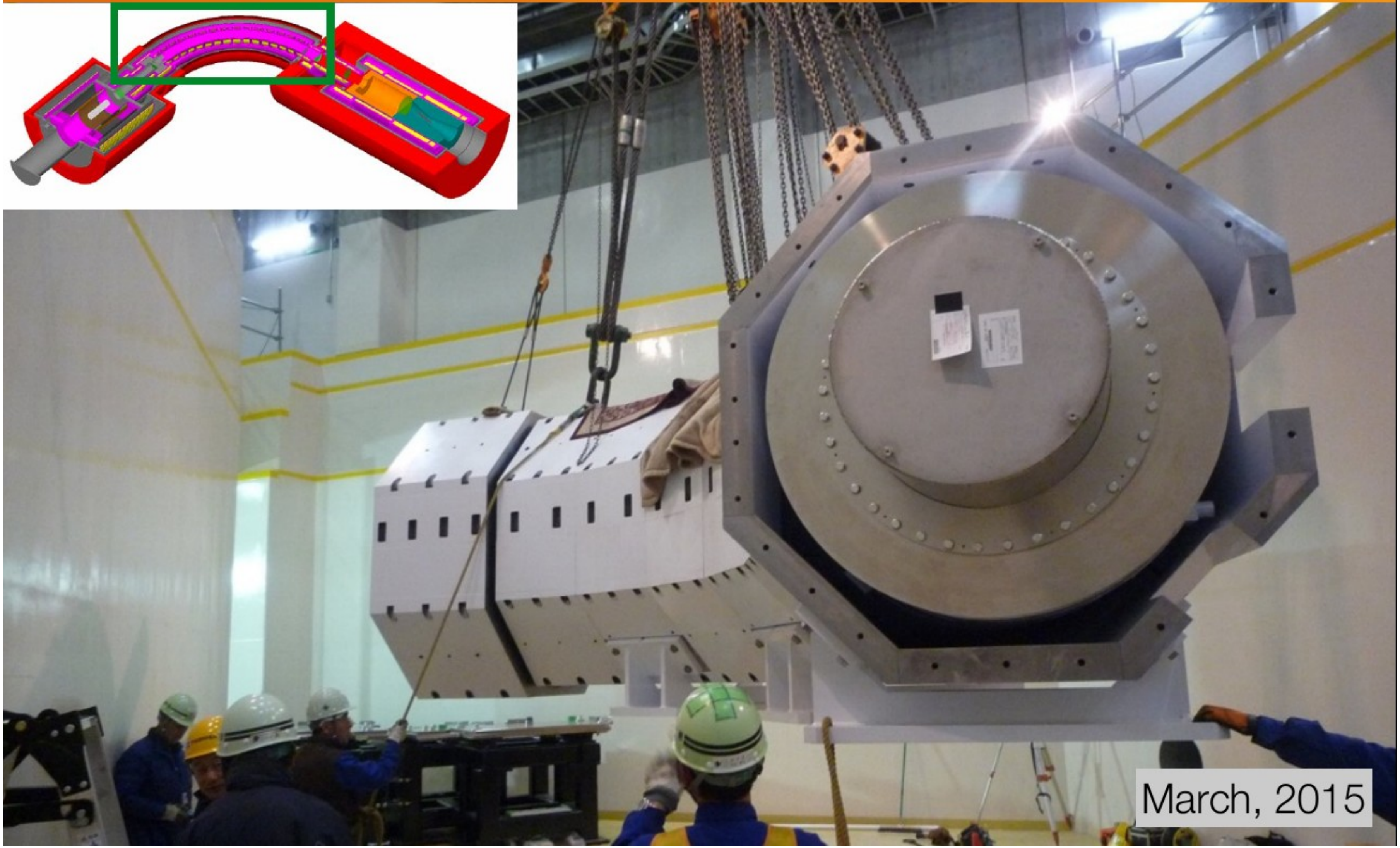
CDC

Completed on Nov. 24th, 2015, about 20,000 wires in122 working days (about 6 months).



Curved Solenoids for Muon Transport Completed!

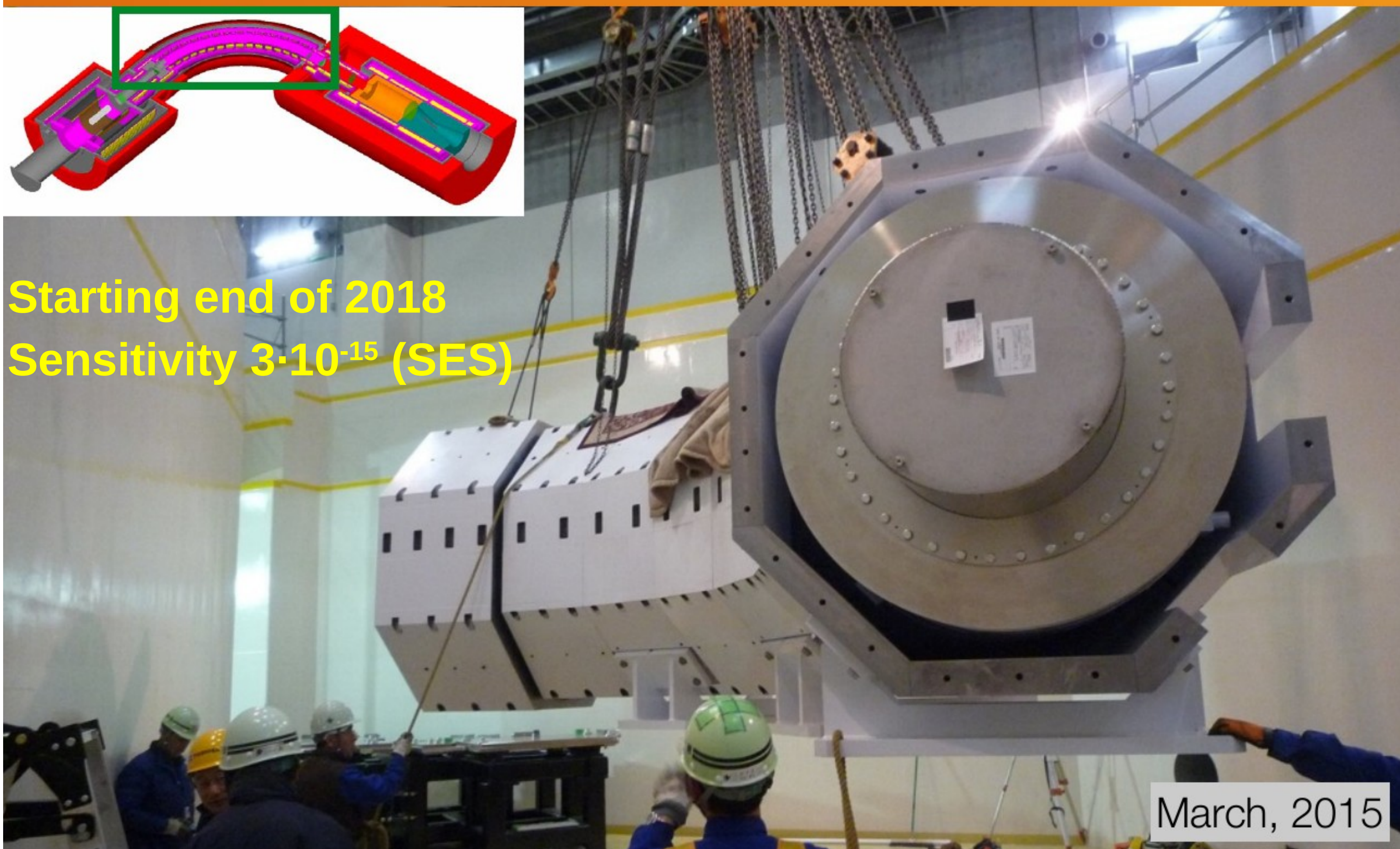
from Kuno-san



Curved Solenoids for Muon Transport Completed!

from Kuno-san

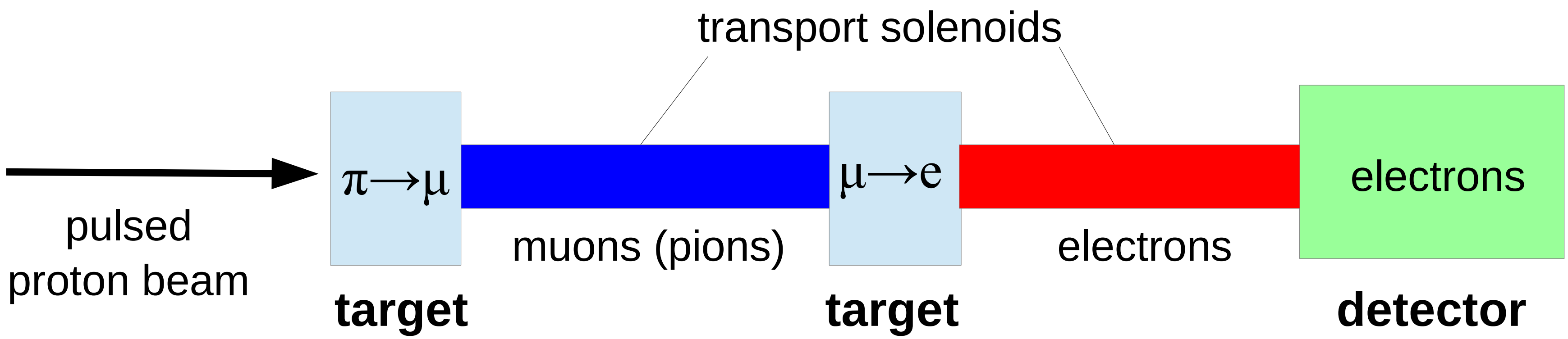
Osaka University



Starting end of 2018

Sensitivity $3{\cdot}10^{-15}$ (SES)

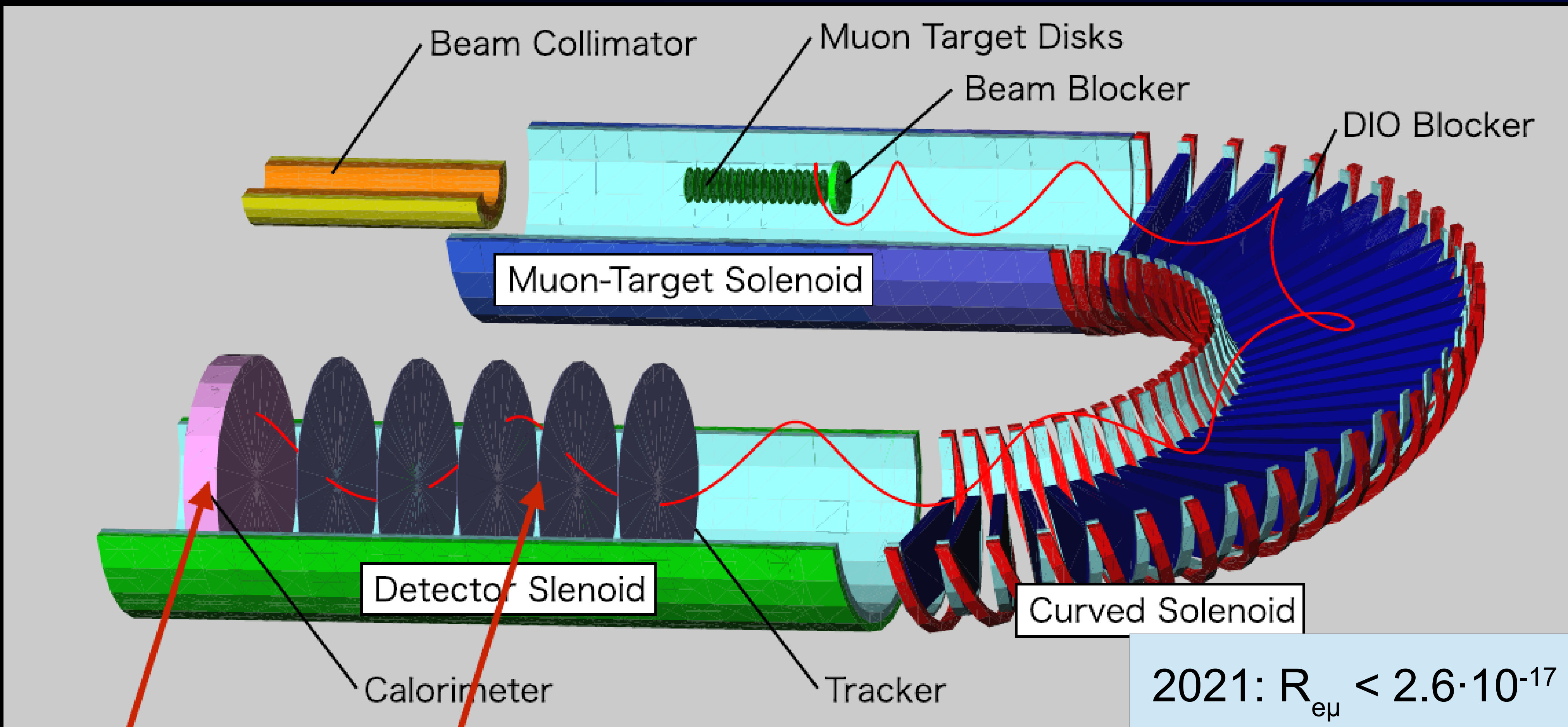
Experimental Concepts for μ→e Conversion



COMET II
@JPARC

COMET II

COMET Detectors



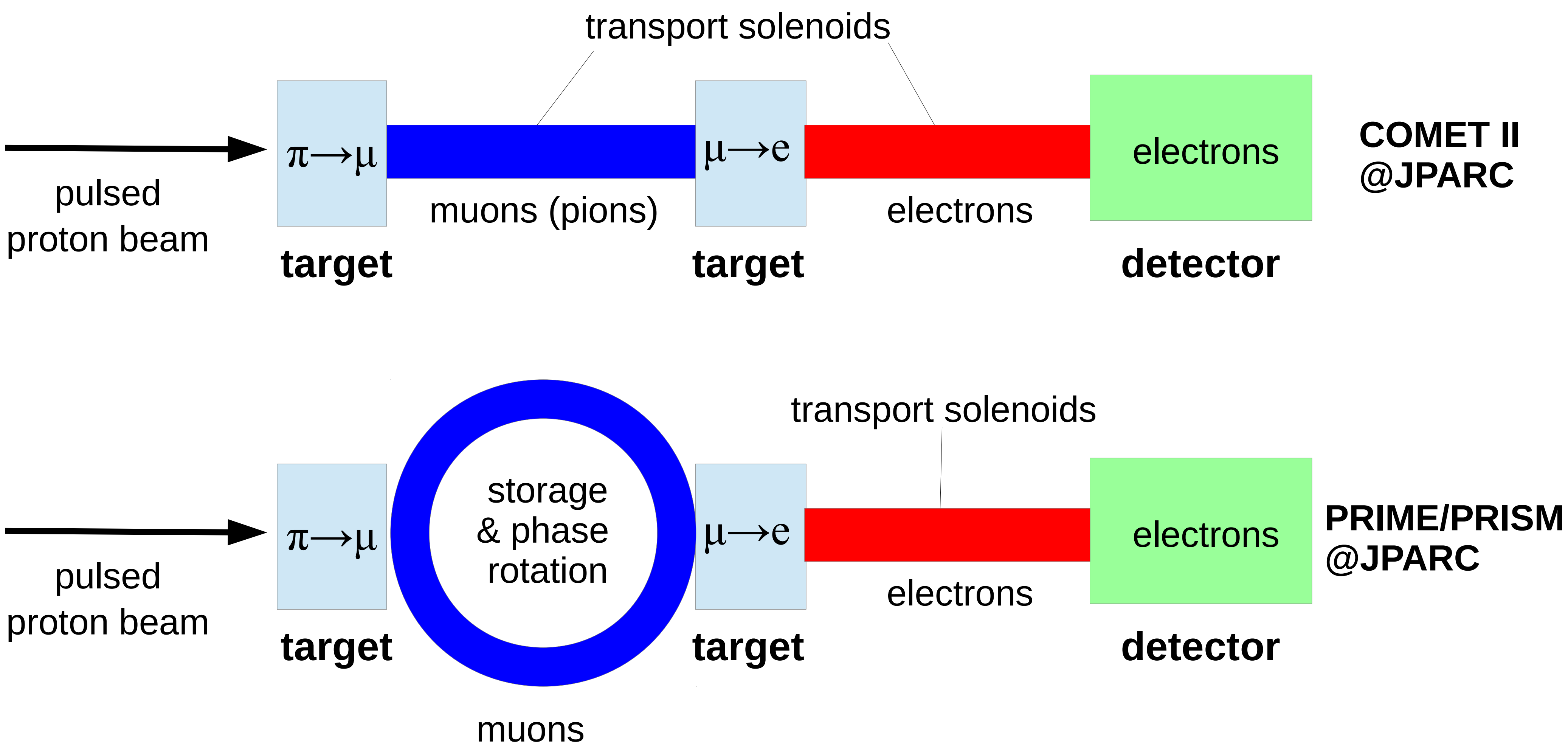
ECAL

Straw Tracker

(# of straw stations is not determined)

in vacuum under 1T magnetic field

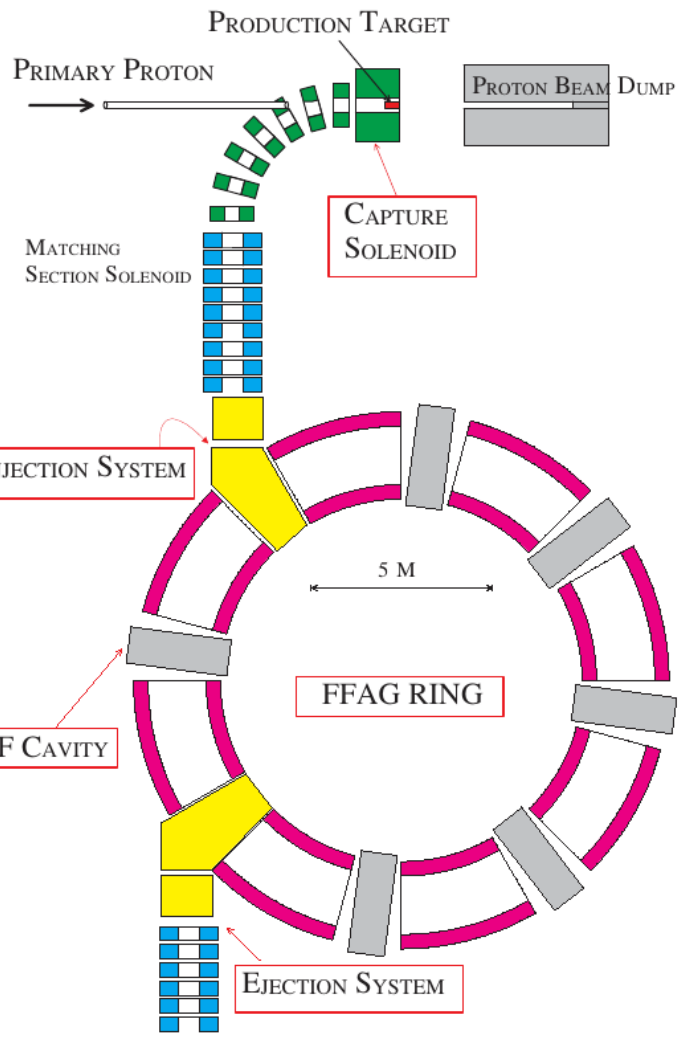
Future μ→e Conversion @ JPARC



→ design improves muon beam energy spread and BG

FFAG test facility and PRISM/PRIME Project

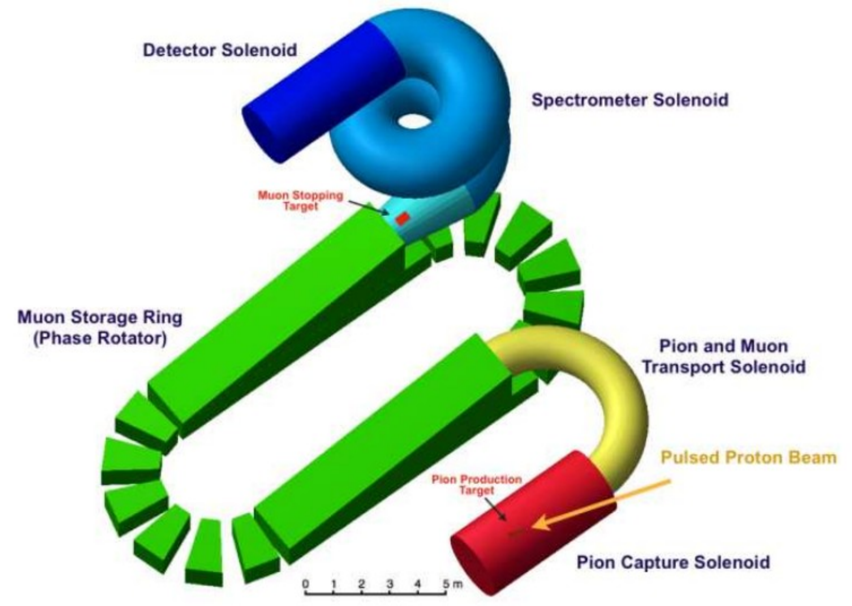
Fixed Field Alternating Gradient Phase Rotator:



PRISM Goals:

- muon rate: 10^{11}-10^{12} μ /sec
- kinetic energy: E_k=20 MeV
- energy spread: σ(E)= 0.5-1 MeV
- repetition rate: f=100 Hz

Future: Search for μ → e conversion at PRISM with PRIME Detector



ultimate precision $R_{e\mu} < 10^{-18}$?

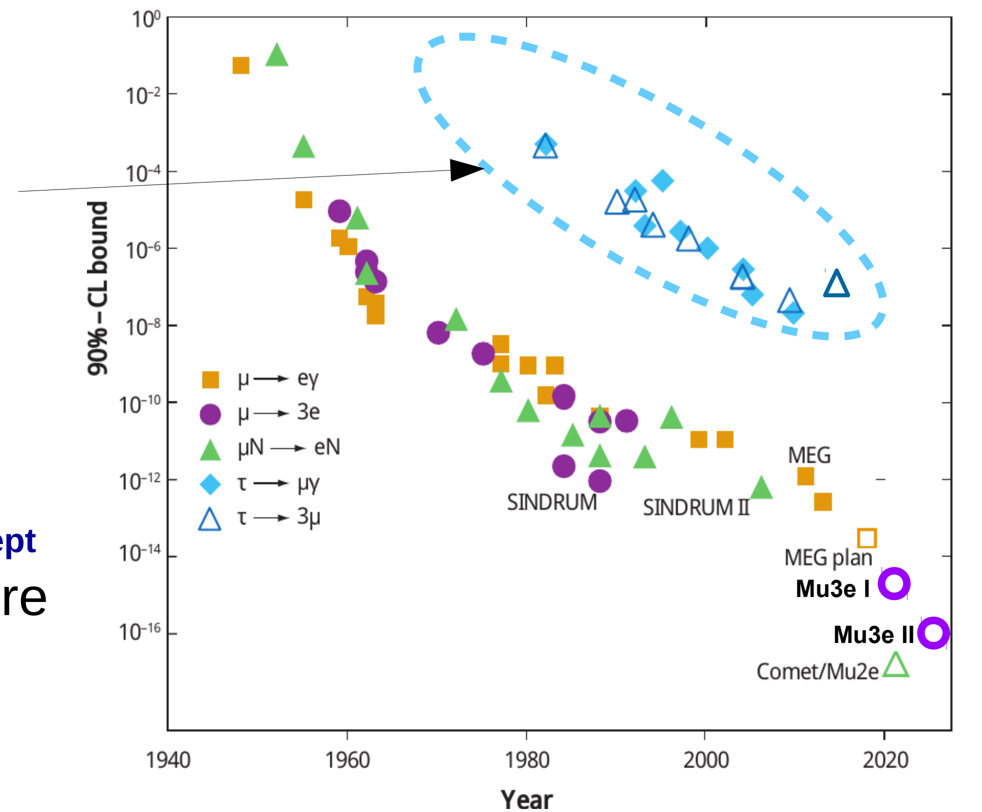
Muon storage ring test facility

demonstration of phase rotation has been done.

Search for LFV with Taus

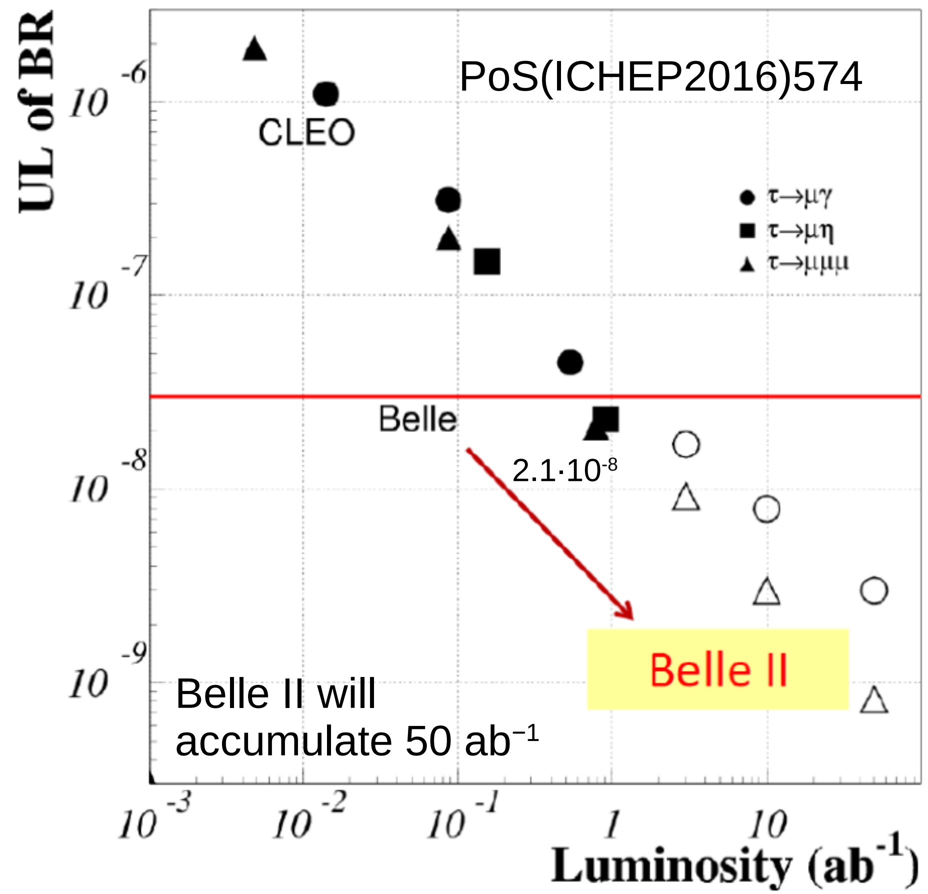
- In general LFV Tau decays are **most sensitive** to New Physics
- But experimental limits on LFV Tau BRs are currently more than **four orders** of magnitude **worse** compared to muons

- LFV Tau decays are only competitive:
  - if new physics scales with at least m^4_{lept}
  - in LFV models (e.g. lepton triality) where L_e - L_τ or L_μ - L_τ is gauged
  - special models (e.g. A4 group)



Experimental Prospects for Tau LFV

- Best LFV Tau constraints from **BaBar** and **Belle** $B(\tau\rightarrow\mu\gamma) < 2\text{-}3\cdot 10^{-8}$
- Also a high sensitivity search at **LHCb**: $B(\tau\rightarrow\mu\mu\mu) < 4.6\cdot 10^{-8}$



Future prospects:

	Belle2	LHCb
$B(\tau\rightarrow\mu\gamma)$	BG limited	impossible
$B(\tau\rightarrow\mu\mu\mu)$	statistics limited	BG limited

- **Belle2** (SHIP) can reach $B(\tau\rightarrow\mu\mu\mu) < O(10^{-9})$ - $O(10^{-10})$
- **ATLAS/CMS** have also unique discovery potential e.g. for $H\rightarrow \mu\tau$

Conclusion

LFV in muon decays

- New muon facilities being constructed at FNAL, JPARC, HiMB@PSI?
- New dedicated muon experiments are starting commissioning and will deliver new data in the coming years:
  - upgraded MEG
  - Mu3e
  - DeeMee, COMET I, Mu2e, COMET II (PRISM/PRIME)
- New technologies allow to perform **LFV searches** at **highest rates** reaching the $\mathbf{10^{-16} - 10^{-17}}$ level

LFV with tau decays

- Belle2 (SHIP?) will improve sensitivity of: $B(\tau \to \mu\mu\mu) < O(10^{-9} - 10^{-10})$
- ATLAS/CMS has potential to find the unexpected:
  → LFV Higgs decay (tau), → new LFV particles, ...

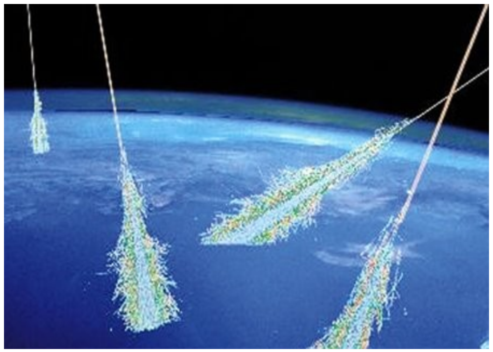
Many Thanks

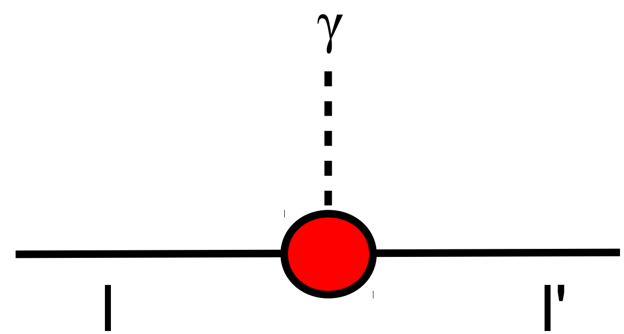
for providing material to

- Robert Bernstein
- Douglas Glenzinski
- Yoshitaka Kuno
- Angela Papa

Backup

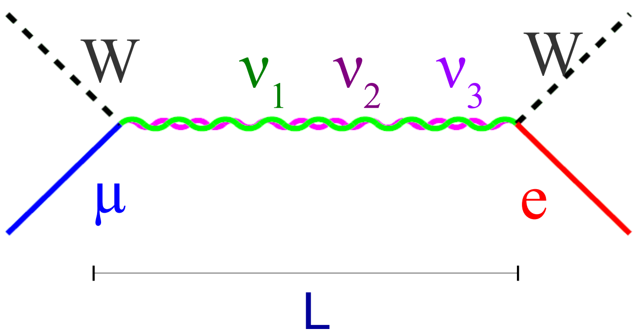
Lepton Mixing and Lepton Flavor Violation





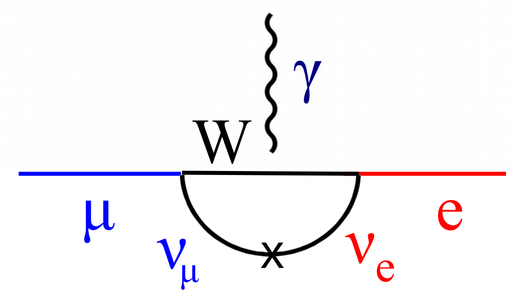
$\mu \rightarrow e$ via ν-oscillation

$\mu \rightarrow e\,\gamma$ via quantum loop



$L \rightarrow 1/m_W$

$E_\nu \rightarrow m_W$



$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\Theta)\,\sin^2\left(\Delta m^2_{\alpha\beta}\,\frac{L}{E_\nu}\right)$$

$$B(\mu \rightarrow e\gamma) \propto \sin^2(2\Theta)\,\left(\Delta m^2_{\alpha\beta}/m^2_W\right)^2$$

$$\propto \frac{(\Delta m^2_\nu)^2}{m^4_t} \approx y^4_\nu \approx 10^{-50}$$

Some CLFV Processes

D.Glenzinski

Process	Current Limit	Next Generation exp
$\tau \to \mu\eta$	BR < 6.5 E-8	
$\tau \to \mu\gamma$	BR < 6.8 E-8	10^{-9} - 10^{-10} (Belle II)
$\tau \to \mu\mu\mu$	BR < 3.2 E-8	
$\tau \to eee$	BR < 3.6 E-8	
$K_L \to e\mu$	BR < 4.7 E-12	
$K^+ \to \pi^+ e^- \mu^+$	BR < 1.3 E-11	
$B^0 \to e\mu$	BR < 7.8 E-8	
$B^+ \to K^+ e\mu$	BR < 9.1 E-8	
$\mu^+ \to e^+\gamma$	BR < ~~5.7~~ 4.2 E-13	10^{-14} (MEG)
$\mu^+ \to e^+e^+e^-$	BR < 1.0 E-12	10^{-16} (PSI)
$\mu N \to eN$	$R_{\mu e}$ < 7.0 E-13	10^{-17} (Mu2e, COMET)

(current limits from the PDG)

- Most promising CLFV measurements use μ

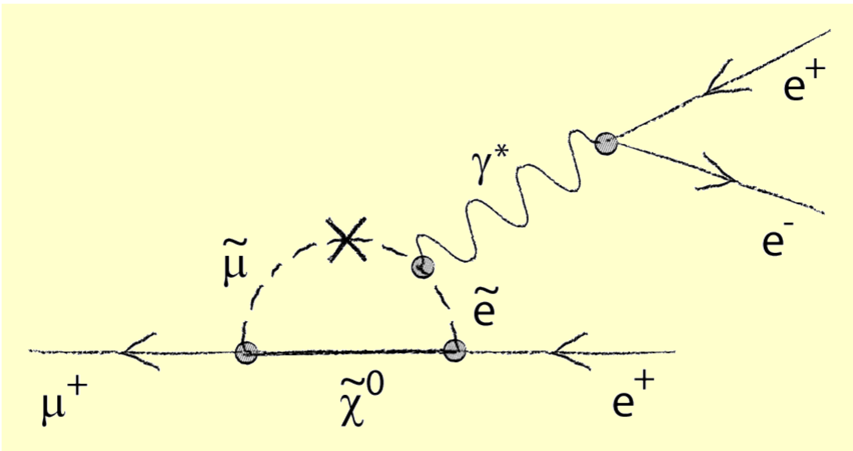
Complementarity of LFV Processes

Blanke et al., Acta Phys.Polon. B41 (2010) 657-683

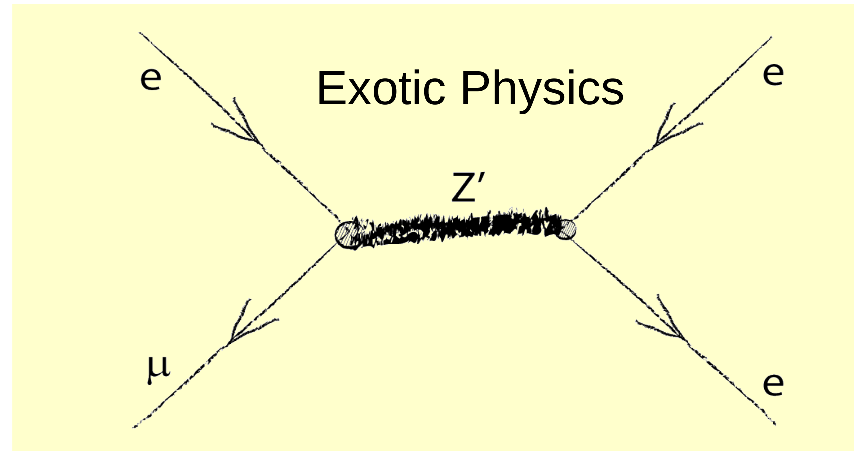
ratio	LHT	MSSM (dipole)	MSSM (Higgs)
$\frac{Br(\mu^- \to e^- e^+ e^-)}{Br(\mu \to e\gamma)}$	$0.02 \ldots 1$	$\sim 6 \cdot 10^{-3}$	$\sim 6 \cdot 10^{-3}$
$\frac{Br(\tau^- \to e^- e^+ e^-)}{Br(\tau \to e\gamma)}$	$0.04 \ldots 0.4$	$\sim 1 \cdot 10^{-2}$	$\sim 1 \cdot 10^{-2}$
$\frac{Br(\tau^- \to \mu^- \mu^+ \mu^-)}{Br(\tau \to \mu\gamma)}$	$0.04 \ldots 0.4$	$\sim 2 \cdot 10^{-3}$	$0.06 \ldots 0.1$
$\frac{Br(\tau^- \to e^- \mu^+ \mu^-)}{Br(\tau \to e\gamma)}$	$0.04 \ldots 0.3$	$\sim 2 \cdot 10^{-3}$	$0.02 \ldots 0.04$
$\frac{Br(\tau^- \to \mu^- e^+ e^-)}{Br(\tau \to \mu\gamma)}$	$0.04 \ldots 0.3$	$\sim 1 \cdot 10^{-2}$	$\sim 1 \cdot 10^{-2}$
$\frac{Br(\tau^- \to e^- e^+ e^-)}{Br(\tau^- \to e^- \mu^+ \mu^-)}$	$0.8 \ldots 2.0$	~ 5	$0.3 \ldots 0.5$
$\frac{Br(\tau^- \to \mu^- \mu^+ \mu^-)}{Br(\tau^- \to \mu^- e^+ e^-)}$	$0.7 \ldots 1.6$	~ 0.2	$5 \ldots 10$
$\frac{R(\mu\mathrm{Ti} \to e\mathrm{Ti})}{Br(\mu \to e\gamma)}$	$10^{-3} \ldots 10^{2}$	$\sim 5 \cdot 10^{-3}$	$0.08 \ldots 0.15$

Table 3: *Comparison of various ratios of branching ratios in the LHT model ($f = 1\,\mathrm{TeV}$) and in the MSSM without [92, 93] and with [96, 97] significant Higgs contributions.*

Lepton Flavor Violating Decay: $\mu^+ \rightarrow e^+e^+e^-$



loop diagrams



tree diagram

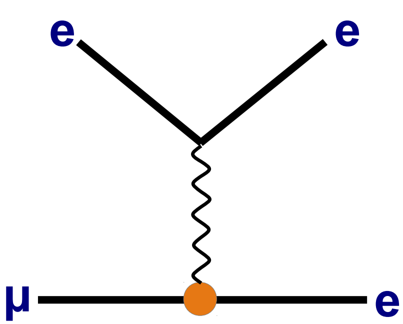
- **Supersymmetry**
- **Little Higgs Models**
- **Seesaw Models**
- **GUT models (Leptoquarks)**
- **many other models**

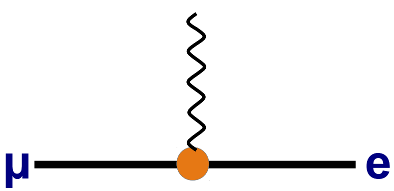
- **Higgs Triplet Model**
- **New Heavy Vector bosons (Z')**
- **Extra Dimensions (KK towers)**

Most models "naturally" induce lepton flavcor violation!

Model Independent Comparison

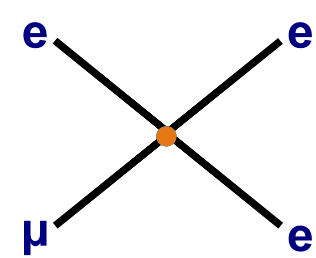
dipole





$\kappa \rightarrow 0$

μeee contact IA



$\kappa \rightarrow \infty$

Effective cLFV Lagrangian:

$$L = \frac{m_\mu}{\Lambda^2 (1+\kappa)} H^{dipole} + \frac{\kappa}{\Lambda^2 (1+\kappa)} J_\nu^{e\mu} J^{\nu,ee}$$

κ = parameter

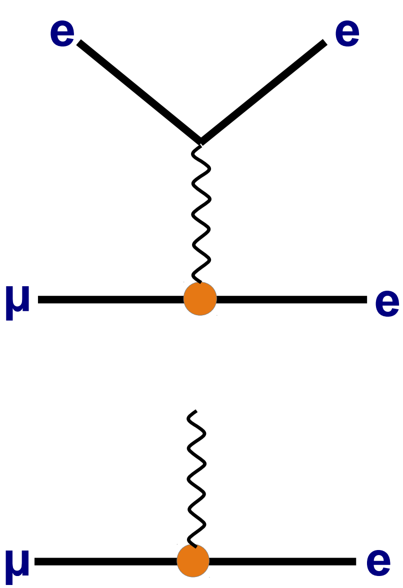
Λ = common effective mass scale

$$\frac{B(\mu^+ \rightarrow e^+e^+e^-)}{B(\mu^+ \rightarrow e^+\gamma)} \sim 0.006$$

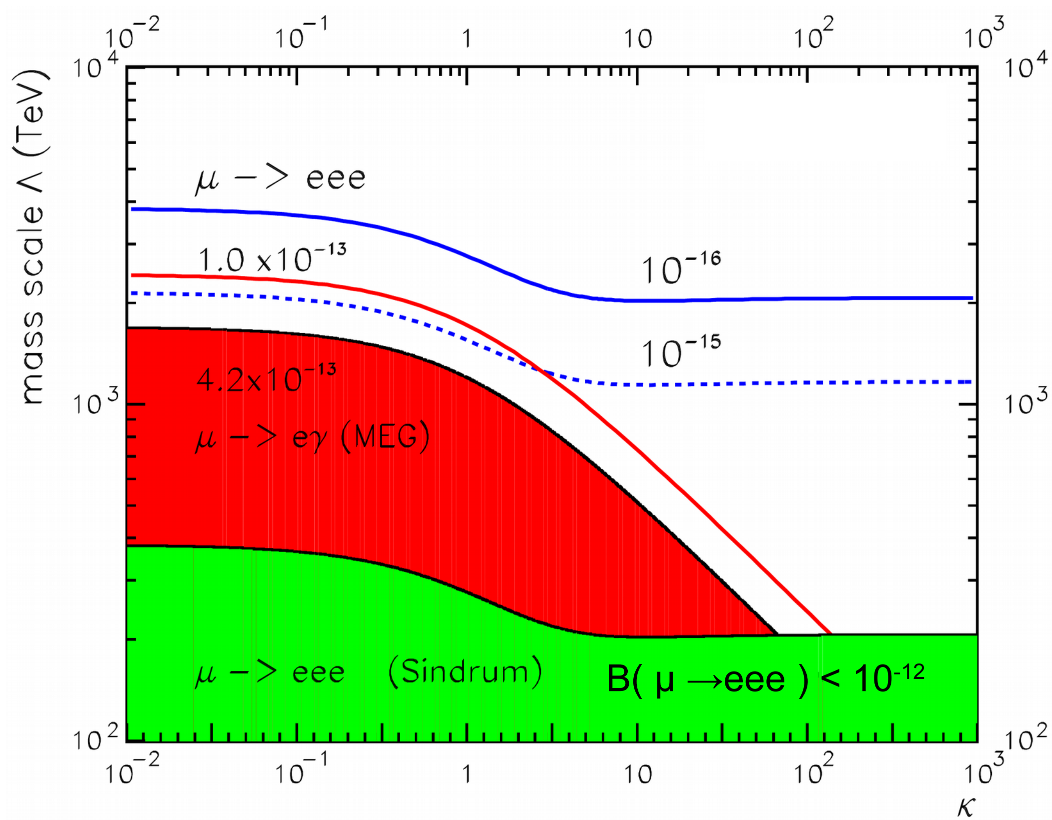
$$\frac{B(\mu^+ \rightarrow e^+e^+e^-)}{\cancel{B(\mu^+ \rightarrow e^+\gamma)}} \rightarrow \infty$$

Model Independent Comparison I

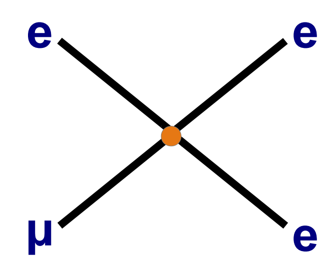
dipole



κ → 0



μeee contact IA



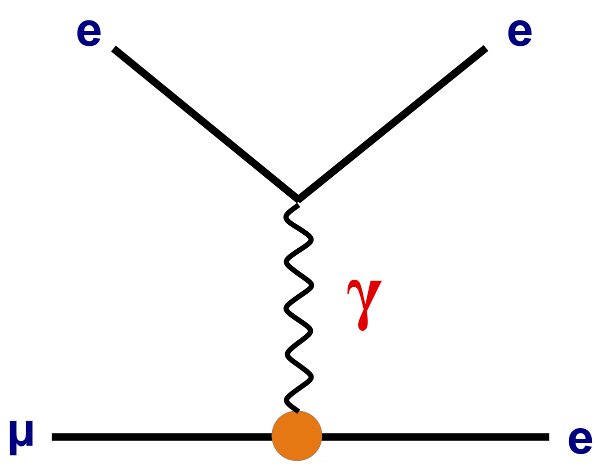
κ → ∞

$$\frac{B(\mu^+ \to e^+e^+e^-)}{B(\mu^+ \to e^+\gamma)} \sim 0.006$$

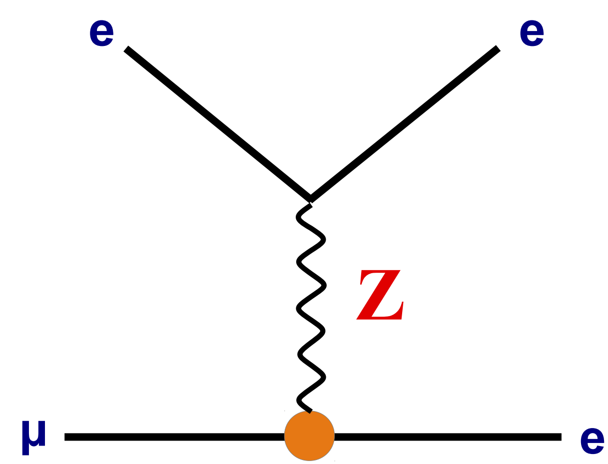
$$\frac{B(\mu^+ \to e^+e^+e^-)}{\cancel{B(\mu^+ \to e^+\gamma)}} \to \infty$$

$\mu^+ \rightarrow e^+e^+e^-$ Diagrams

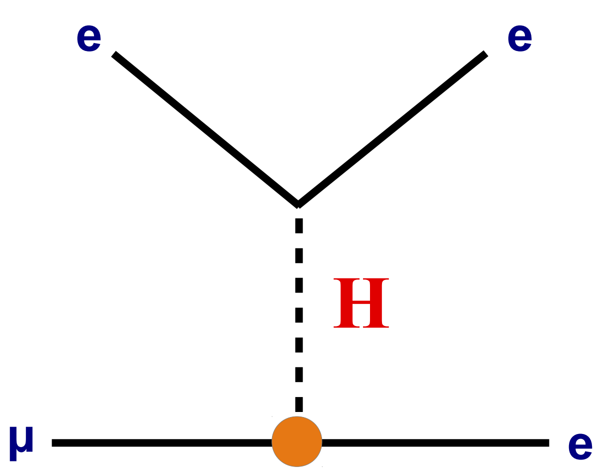
$\mu^+ \rightarrow e^+e^+e^-$



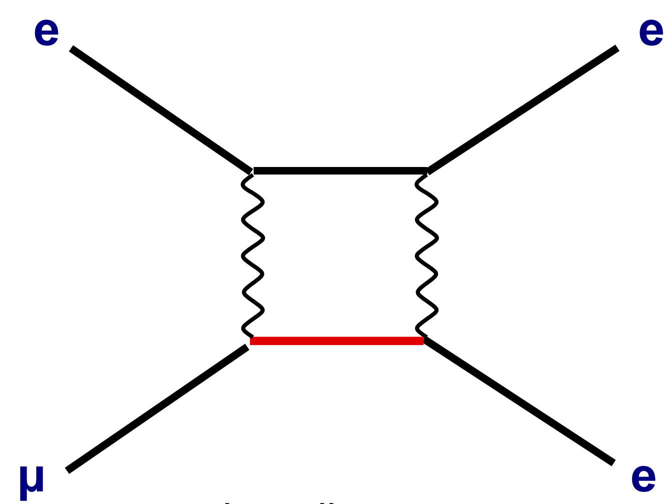
photon penguin



Z - penguin



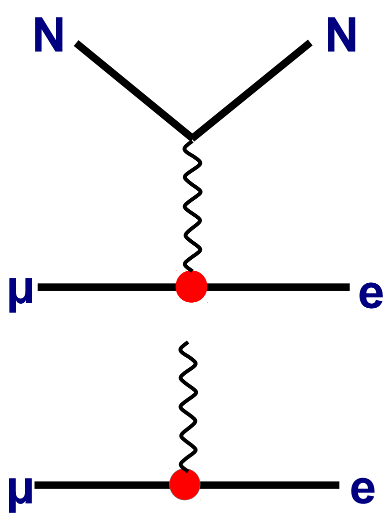
Higgs-penguin



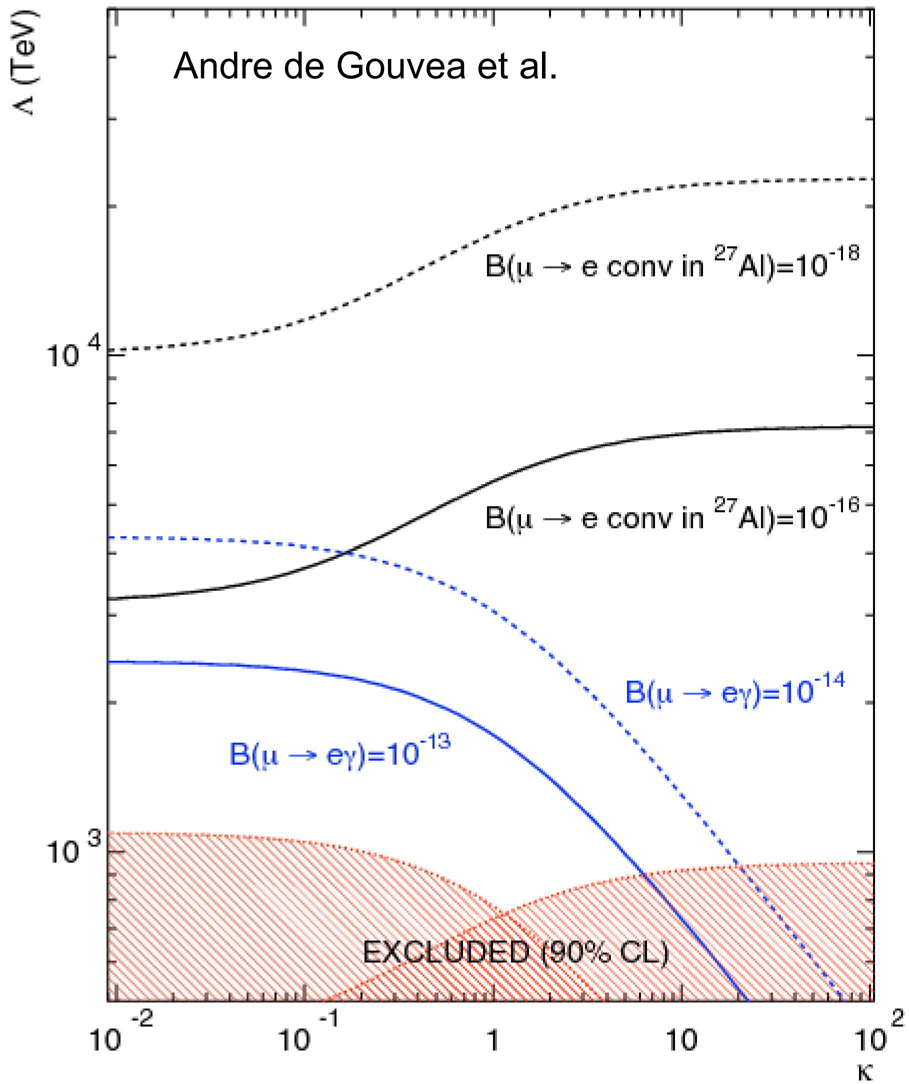
box diagram

Model Independent Comparison II

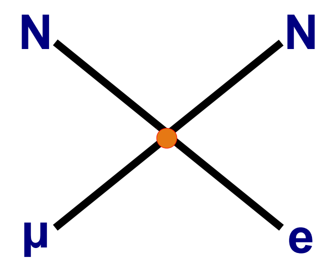
dipole



$\kappa \rightarrow 0$



μeNN contact IA



$\kappa \rightarrow \infty$

→ LFV processes are highly complementary!

LFV-Effective Field Theory

A.Crivellin et al., PSI-PR-16-15

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm QED+QCD} + \frac{1}{\Lambda}\sum_k C_k^{(5)} Q_k^{(5)} + \frac{1}{\Lambda^2}\sum_k C_k^{(6)} Q_k^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

Representation by Wilson coefficients and higher-dimensional operators:

$$O_L^D = e\, m_\mu \,(\bar{e}\sigma^{\mu\nu} P_L \mu)\, F_{\mu\nu},$$

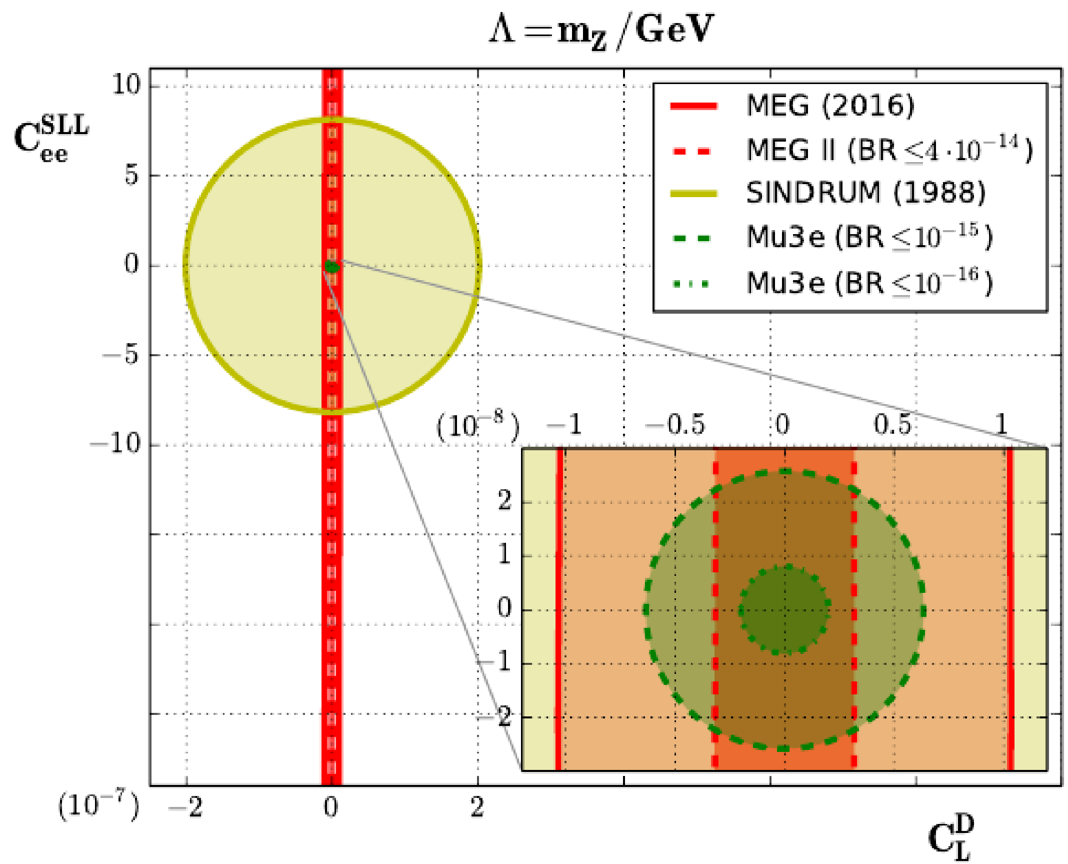
$$O_{ff}^{V\,LL} = (\bar{e}\gamma^\mu P_L \mu)\left(\bar{f}\gamma_\mu P_L f\right),$$

$$O_{ff}^{V\,LR} = (\bar{e}\gamma^\mu P_L \mu)\left(\bar{f}\gamma_\mu P_R f\right),$$

$$O_{ff}^{S\,LL} = (\bar{e} P_L \mu)\left(\bar{f} P_L f\right),$$

$$O_{ff}^{S\,LR} = (\bar{e} P_L \mu)\left(\bar{f} P_R f\right),$$

$$O_{ff}^{T\,LL} = (\bar{e}\sigma_{\mu\nu} P_L \mu)\left(\bar{f}\sigma^{\mu\nu} P_L f\right),$$



LFV Higgs Couplings I

Framework

$$Y_{ij} = \frac{m_i}{v}\delta_{ij} + \frac{v^2}{\sqrt{2}\Lambda^2}\hat{\lambda}_{ij}$$

LFV

LFV decays of SM Higgs:

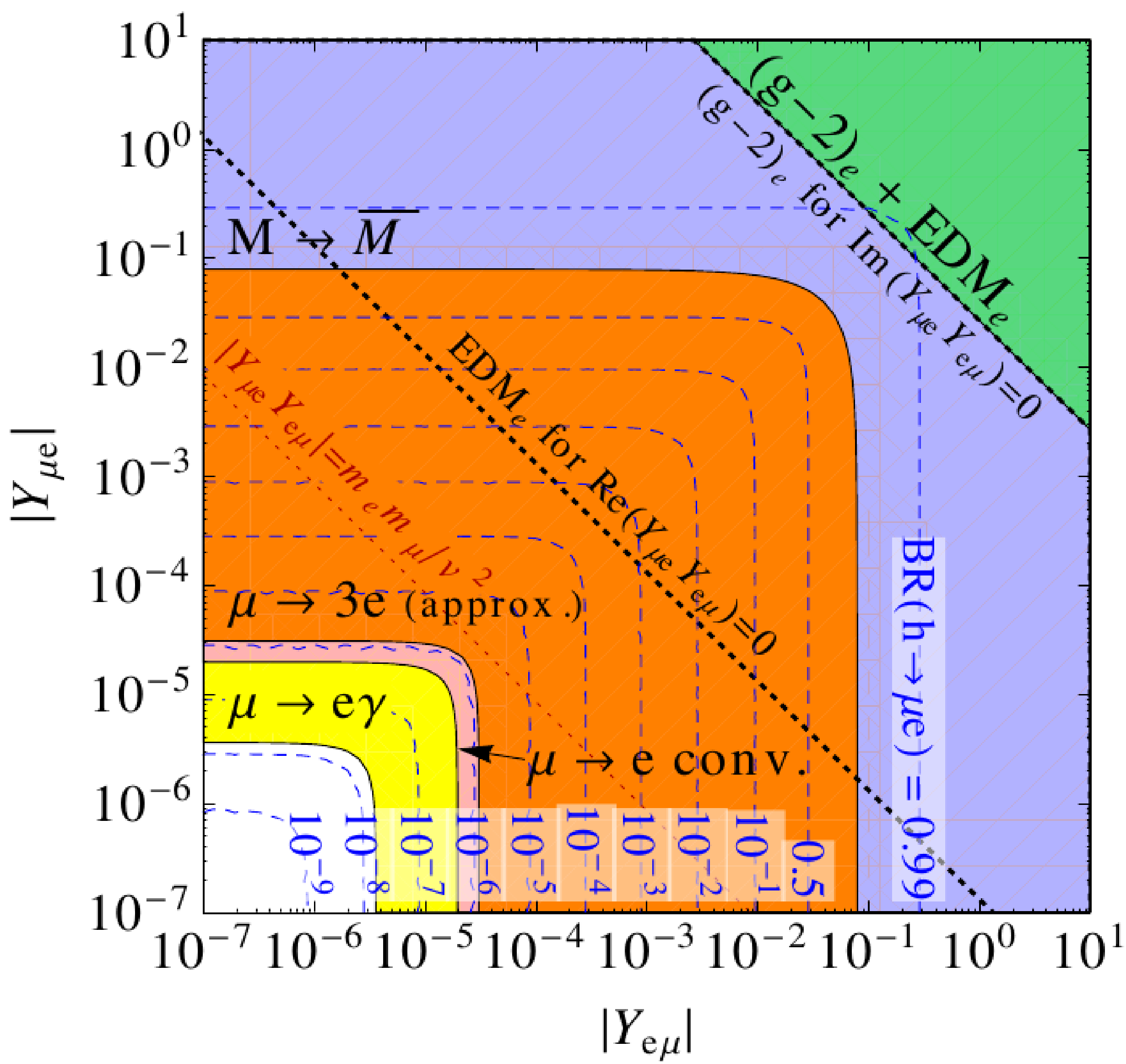
$$\mathrm{BR}(h \to \ell^\alpha \ell^\beta) = \frac{\Gamma(h \to \ell^\alpha \ell^\beta)}{\Gamma(h \to \ell^\alpha \ell^\beta) + \Gamma_{\mathrm{SM}}}$$

LFV muon decay:

$$\sim \sqrt{|Y_{\mu e}|^2 + |Y_{e\mu}|^2}$$

LHC not competitive with LFV muon decay searches!

R. Harnik, J. Kopp J, Zupan [arXiv:1206.6497]



LFV Higgs Couplings II

Framework

LFV

$$Y_{ij} = \frac{m_i}{v}\delta_{ij} + \frac{v^2}{\sqrt{2}\Lambda^2}\hat{\lambda}_{ij}$$

LFV decays of SM Higgs:

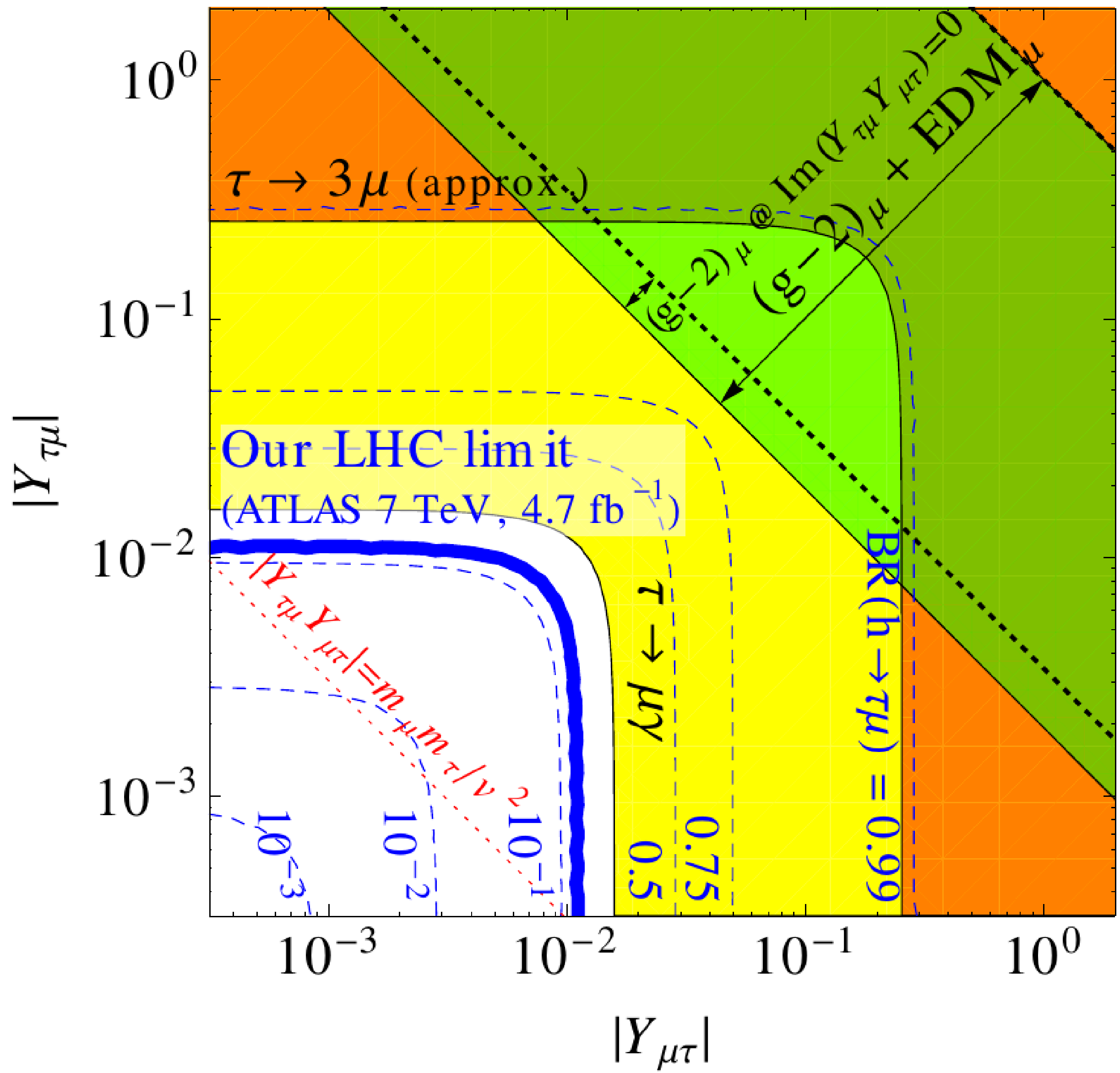
$$\mathrm{BR}(h \to \ell^\alpha \ell^\beta) = \frac{\Gamma(h \to \ell^\alpha \ell^\beta)}{\Gamma(h \to \ell^\alpha \ell^\beta) + \Gamma_{\mathrm{SM}}}$$

decay: h → τ μ

$$\sqrt{|Y_{\tau\mu}|^2 + |Y_{\mu\tau}|^2} < 1.6 \times 10^{-2}$$

LHC competitive with LFV tau decays
→ testing new territory!

R. Harnik, J. Kopp J, Zupan [arXiv:1209.1397]



Comparison of Muon LFV-Processes

	Beam	background	challenge	beam intensity
$\mu \to e\gamma$	continuous	accidentals	detector resolution	limited
$\mu \to eee$	continuous	accidentals / $\mu \to ee e\nu\nu$	detector resolution	limited
$\mu \to e$	pulsed	beam-related	beam-BG	no limitation

Mu3e Collaboration

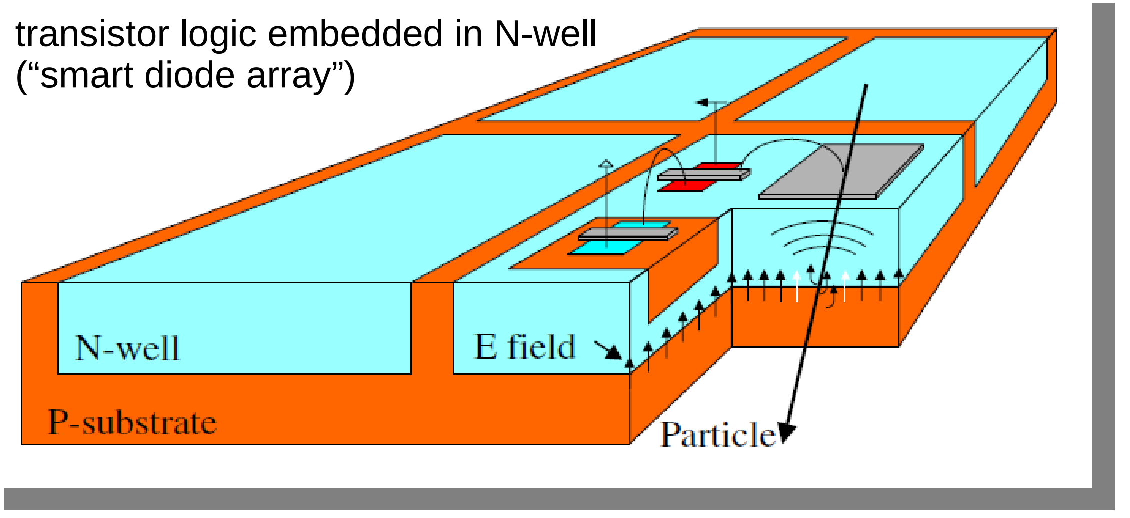
- **University of Geneva (CH)**
- **University Heidelberg (D)**
- **Karlsruhe Institute of Technology (D)**
- **University Mainz (D)**
- **Paul Scherrer Institute (CH)**
- **ETH Zurich (CH)**
- **University Zurich (CH)**

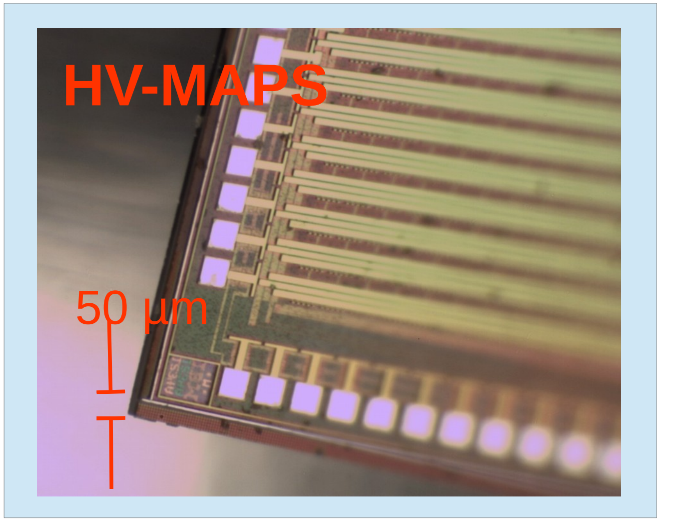
Several UK institutes interested to join

- **Bristol**
- **Liverpool**
- **Oxford**
- **UC London**

High Voltage-Monolithic Active Pixel Sensors (HV-MAPS)

I.Peric, P. Fischer et al., NIM A 582 (2007) 876

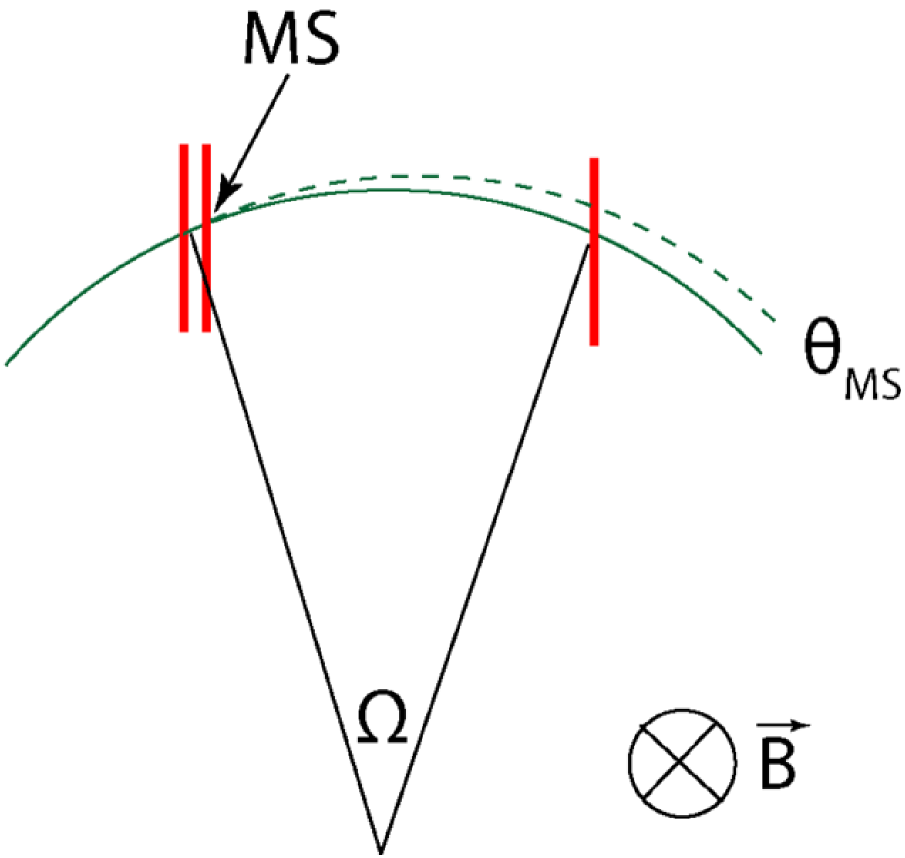




- sensor and readout electronics in same chip
- **active sensors → hit finding + digitisation + serial readout**
- can be "thinned" down to **~50 µm** (~ 0.0005 X_0)
- low production costs (standard HV-CMOS process)
- Mu3e experiment:
  → layer thickness **~1/30** of standard hybrid detectors (ATLAS/CMS)

→ interesting technology for high rate experiments @ low energy

Tracking Design Considerations

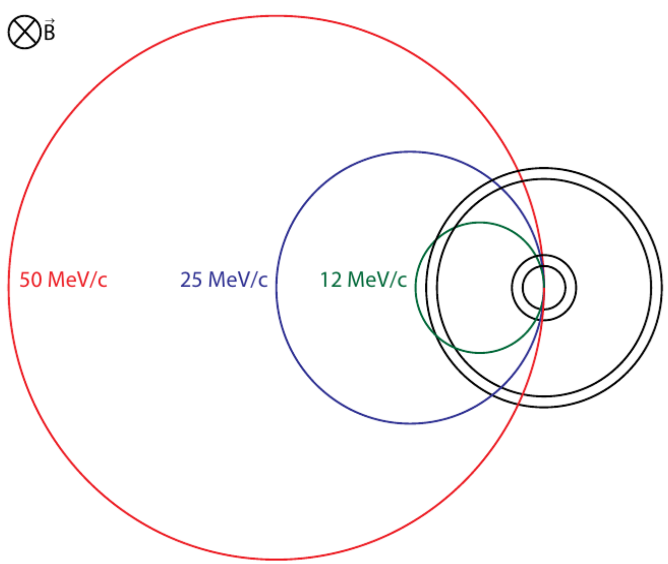


$$\frac{\sigma_p}{P} \sim \frac{\Theta_{MS}}{\Omega}$$

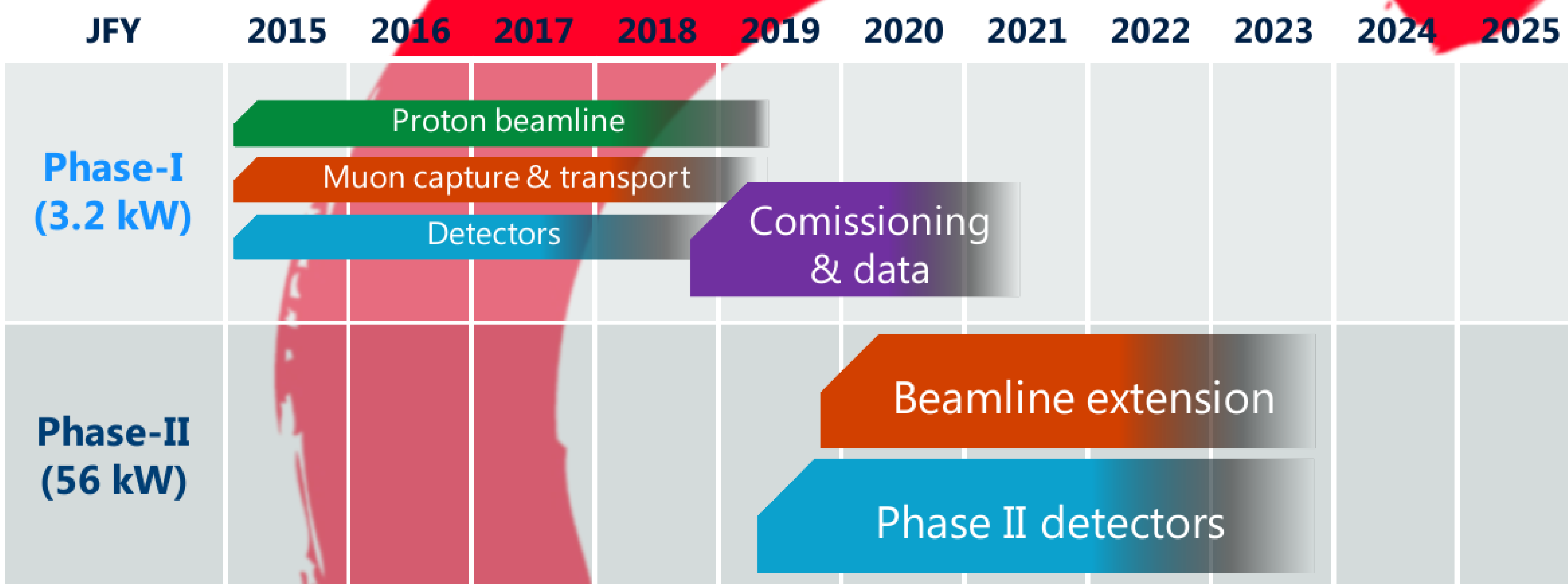
(linearised)

precision requires large lever arm!

→ large bending angle Ω



COMET Timeline



Current limit [SINDRUM-II]: $\mathbf{7 \times 10^{-13}}$ **90% U.L.**

~2018: Start COMET Phase I; goal $\mathbf{3 \times 10^{-15}}$ **S.E.S.** (~ 5 mo)

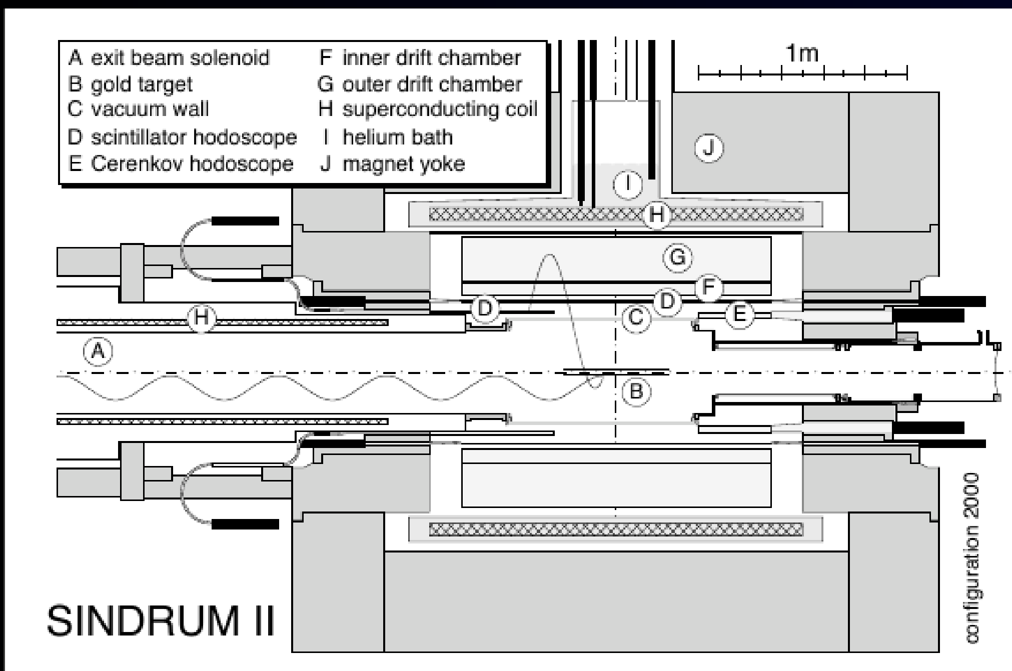
COMET Phase II goal $\mathbf{2.6 \times 10^{-17}}$ **S.E.S.** (~ 1 year)

- Accumulates statistics very quickly thanks to high power 56kW beam from J-PARC main ring

Previous Measurements

from Kuno-san

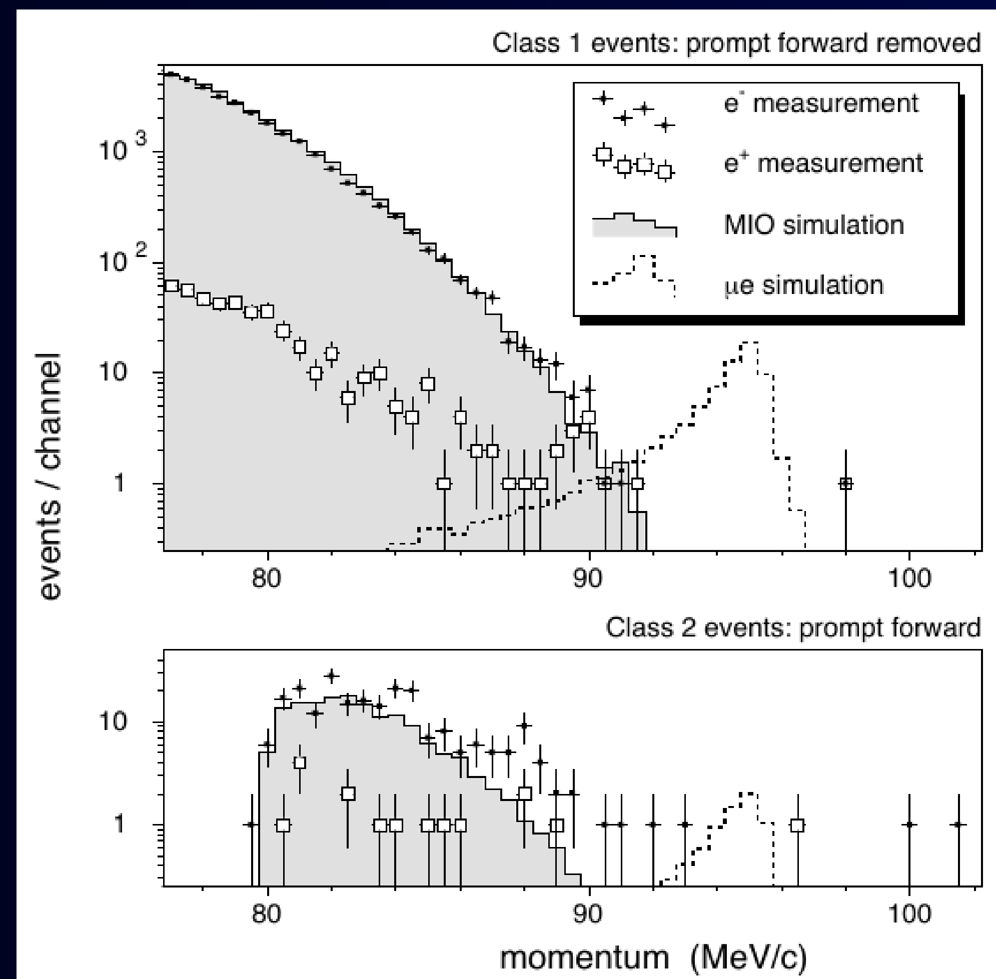
SINDRUM-II (PSI)



PSI muon beam intensity ~ $10^{7\text{-}8}$/sec beam from the PSI cyclotron. To eliminate beam related background from a beam, a beam veto counter was placed. But, it could not work at a high rate.

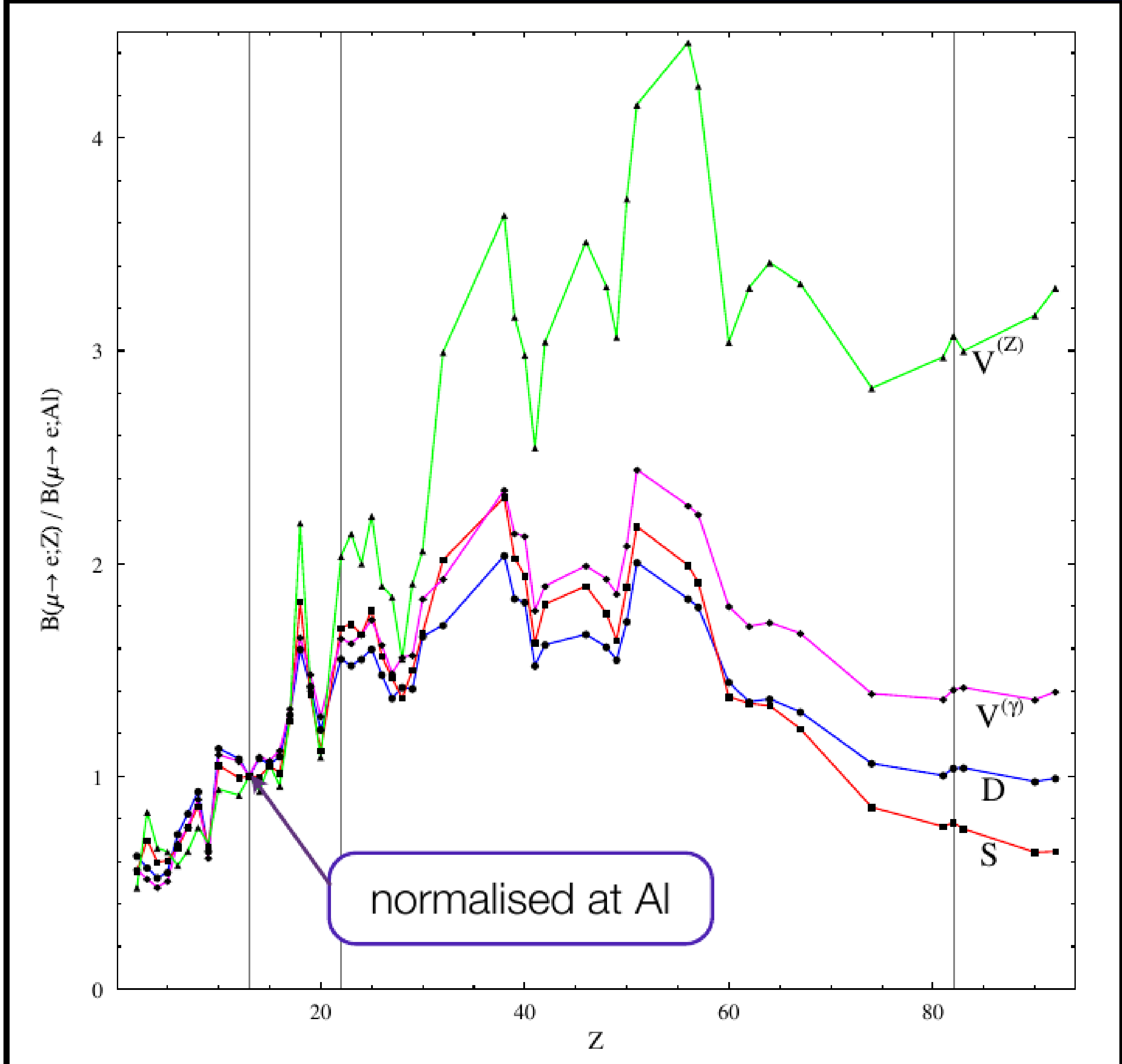
Published Results (2004)

$$B(\mu^- + Au \rightarrow e^- + Au) < 7 \times 10^{-13}$$



μ-e Conversion : Target dependence (discriminating effective interaction)

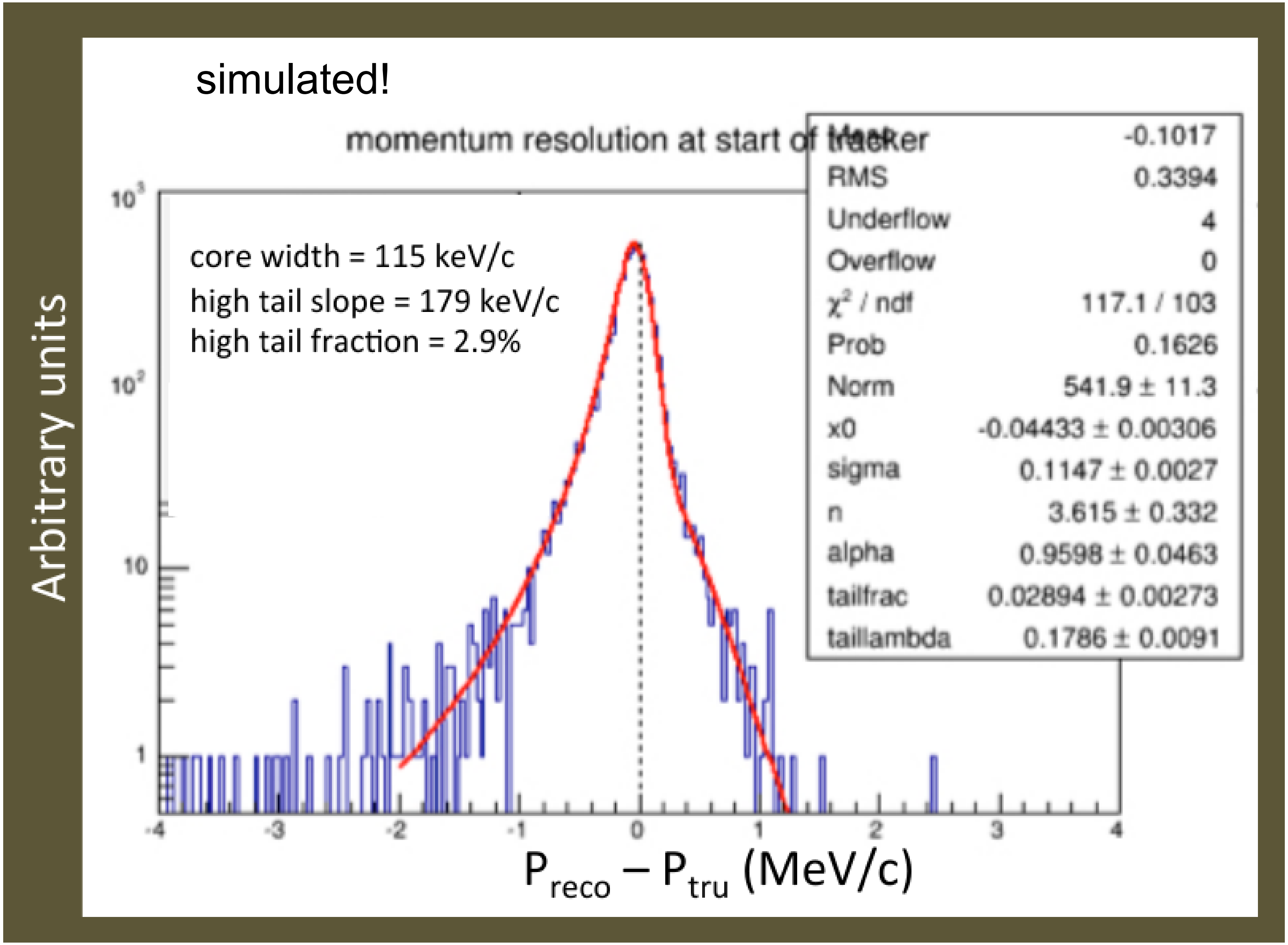
from Kuno-san



V. Cirigliano, R. Kitano, Y. Okada, and P. Tuzon, Phys. Rev. D80, 013002 (2009)

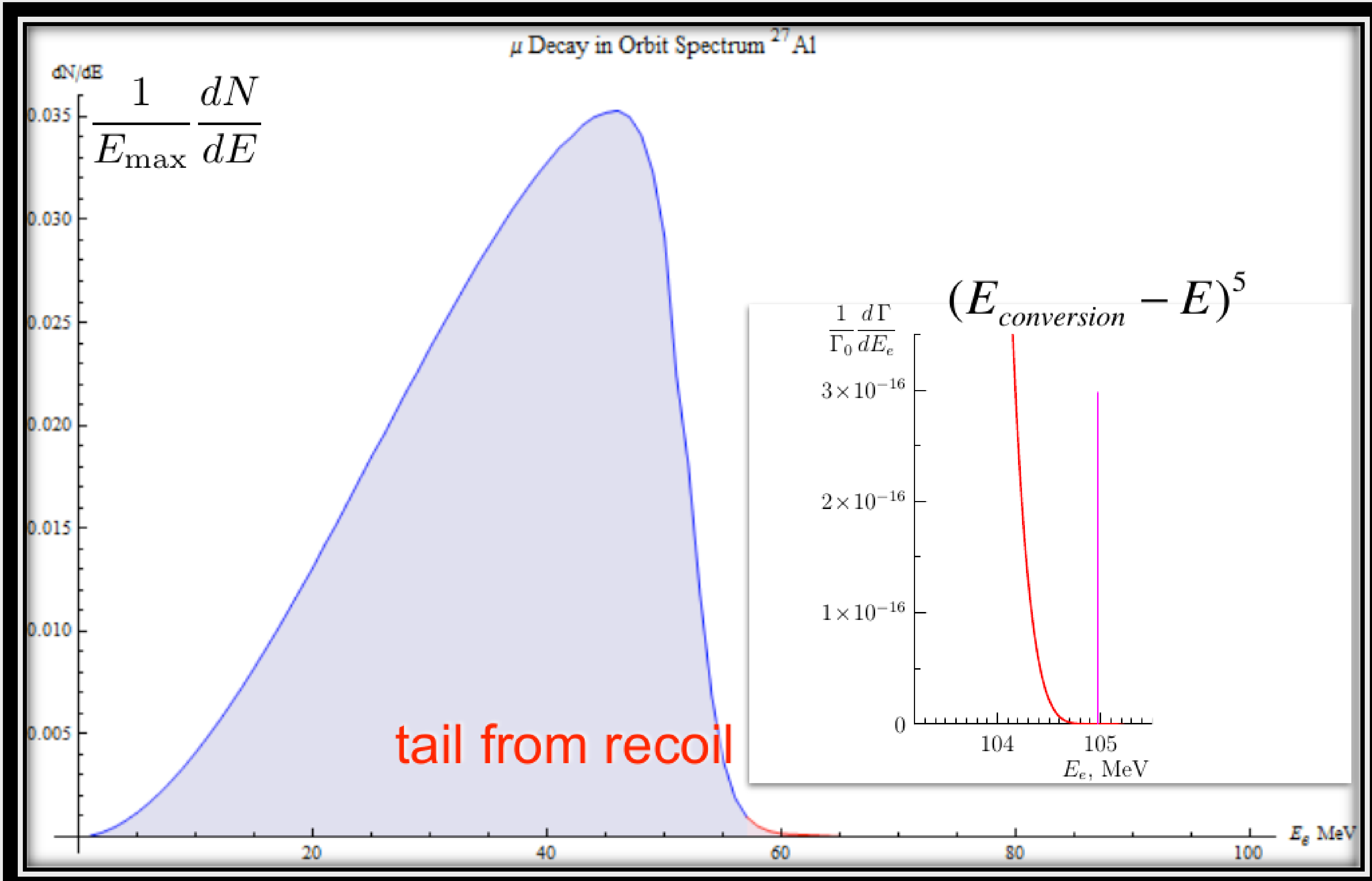
vector interaction (with Z boson)	with Z penguin
vector interaction (with photon - charge radius)	left-right models
dipole interaction	SUSY-GUT
scalar interaction	SUSY seesaw

Mu2e Momentum Resolution



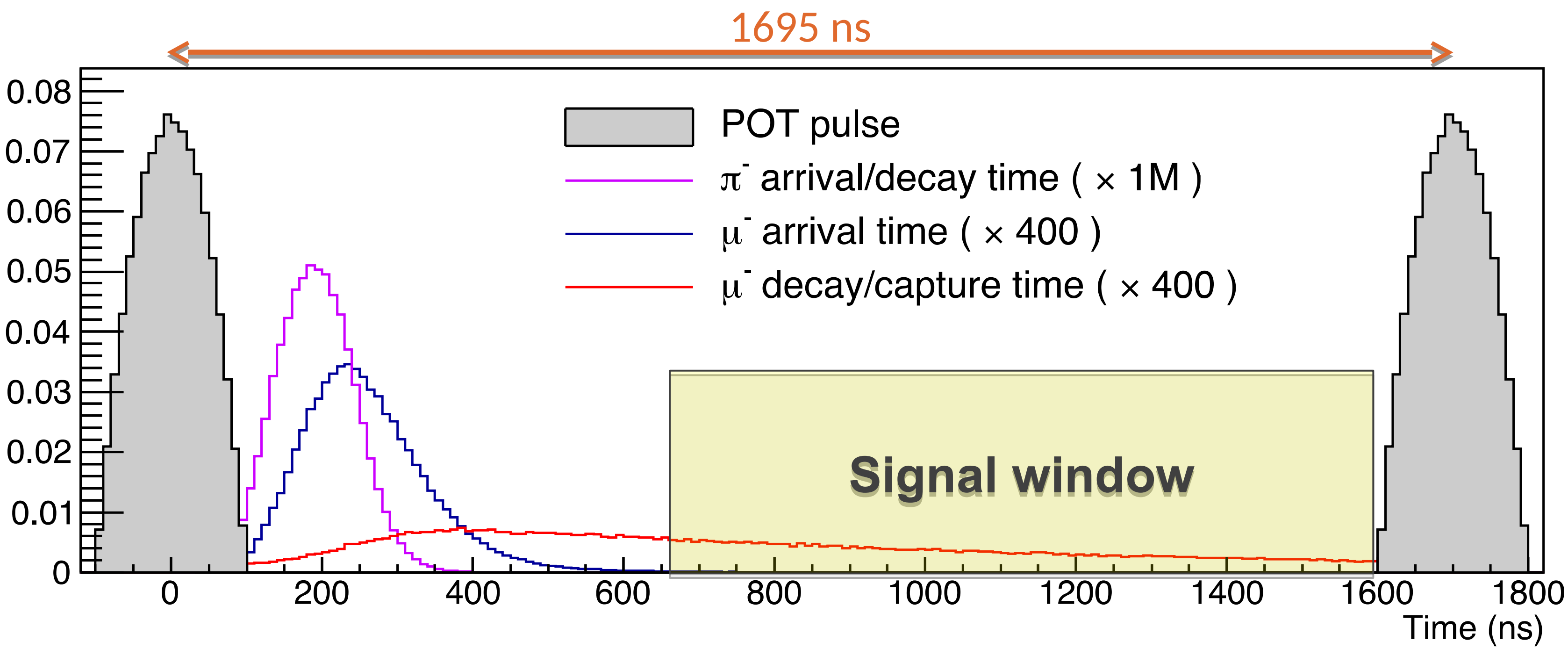
Decay-in-Orbit Shape

Szafron 10.5506/APhysPolB.46.2279: Radiative Corrections



Czarnecki: 10.1016/j.physletb.2015.12.008 many other papers

Mu2e Timing Structure



- To achieve our target sensitivity, out-of-pulse protons must be suppressed by $>10^{10}$ relative to in-pulse protons

provided by Doug Glenzinski

Estimated background yields & sensitivity

Process	Expected event yield
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	$0.021 \pm 0.001(\text{stat}) \pm 0.002(\text{syst})$
Muon DIF	< 0.003
Pion DIF	$0.001 \pm < 0.001$
Beam electrons	$(2.1 \pm 1.0) \times 10^{-4}$
RMC	$0.000^{+0.004}_{-0.000}$
Total	$0.41 \pm 0.13(\text{stat+syst})$

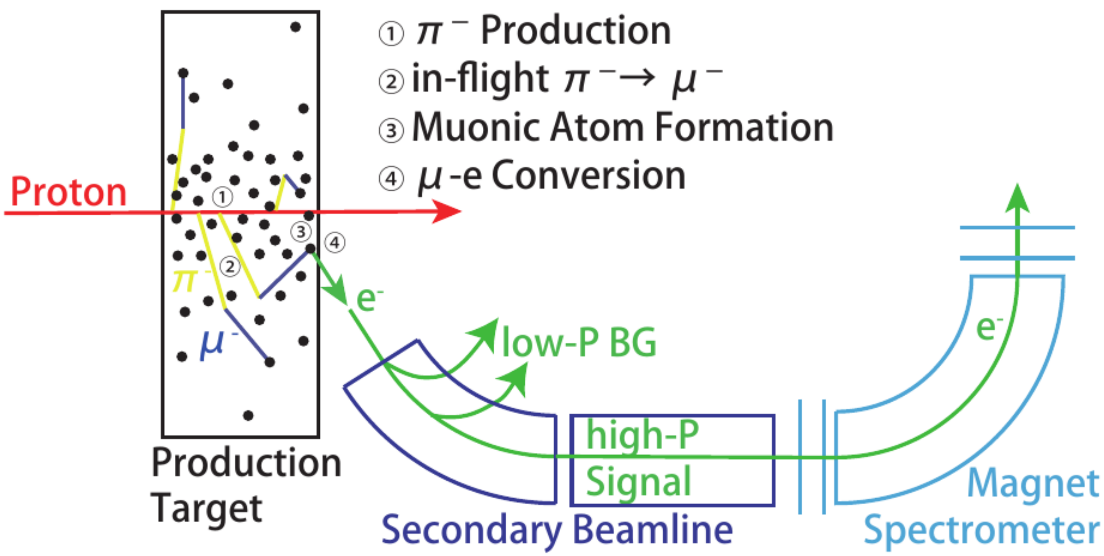
Single event sensitivity = (3.01+/-0.41) x 10^{-17}

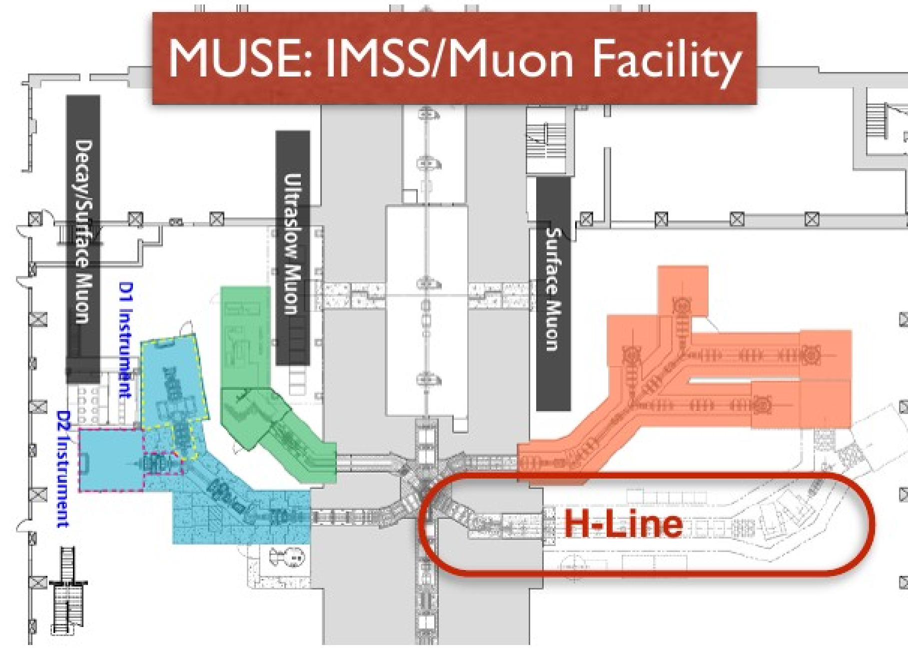
>5s Discovery sensitivity for $R_{m\Box e}$ > 2 x 10^{-16}

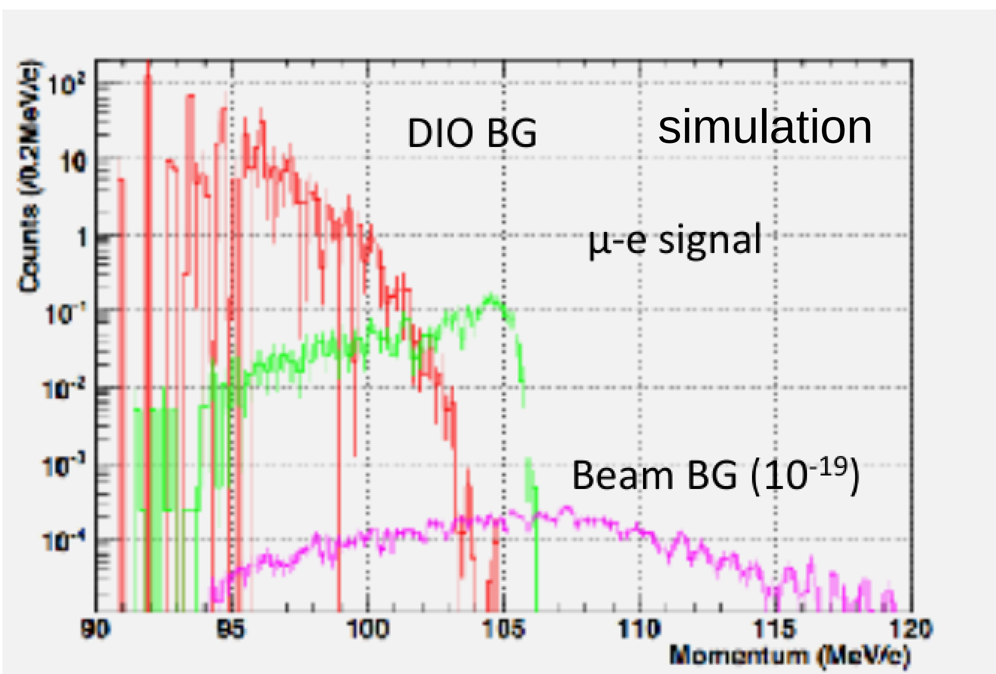
DeeMe @ JPARC

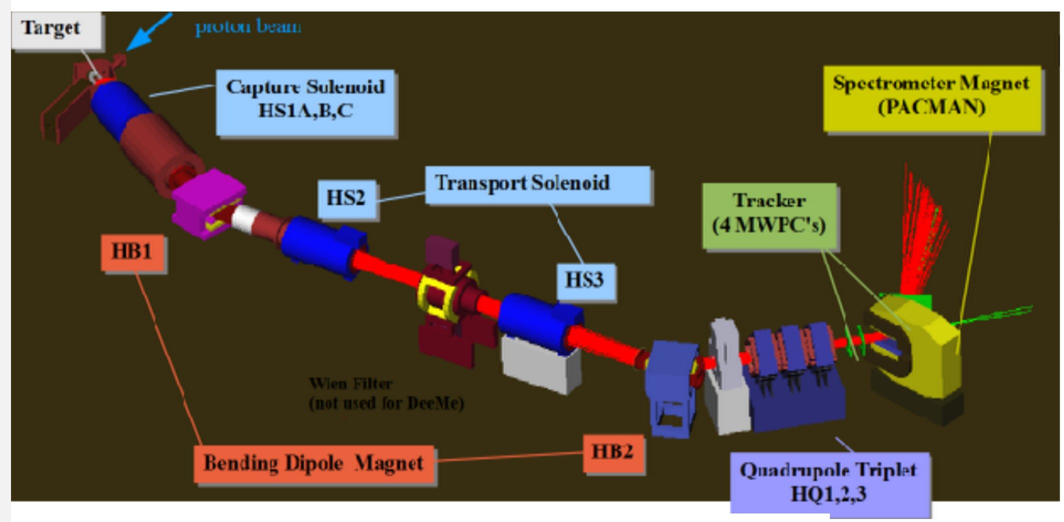
from Aoki-san

Concept:









- Signal Sensitivity (SiC)
  - S.E.S.: 2×10^{-14} (1 MW, 2×10^{7}sec)