DC muon beam related physics and experiments

- mainly about charged lepton flavor violation -

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on Neutrinos from Accelerators
(NUFACT2017)
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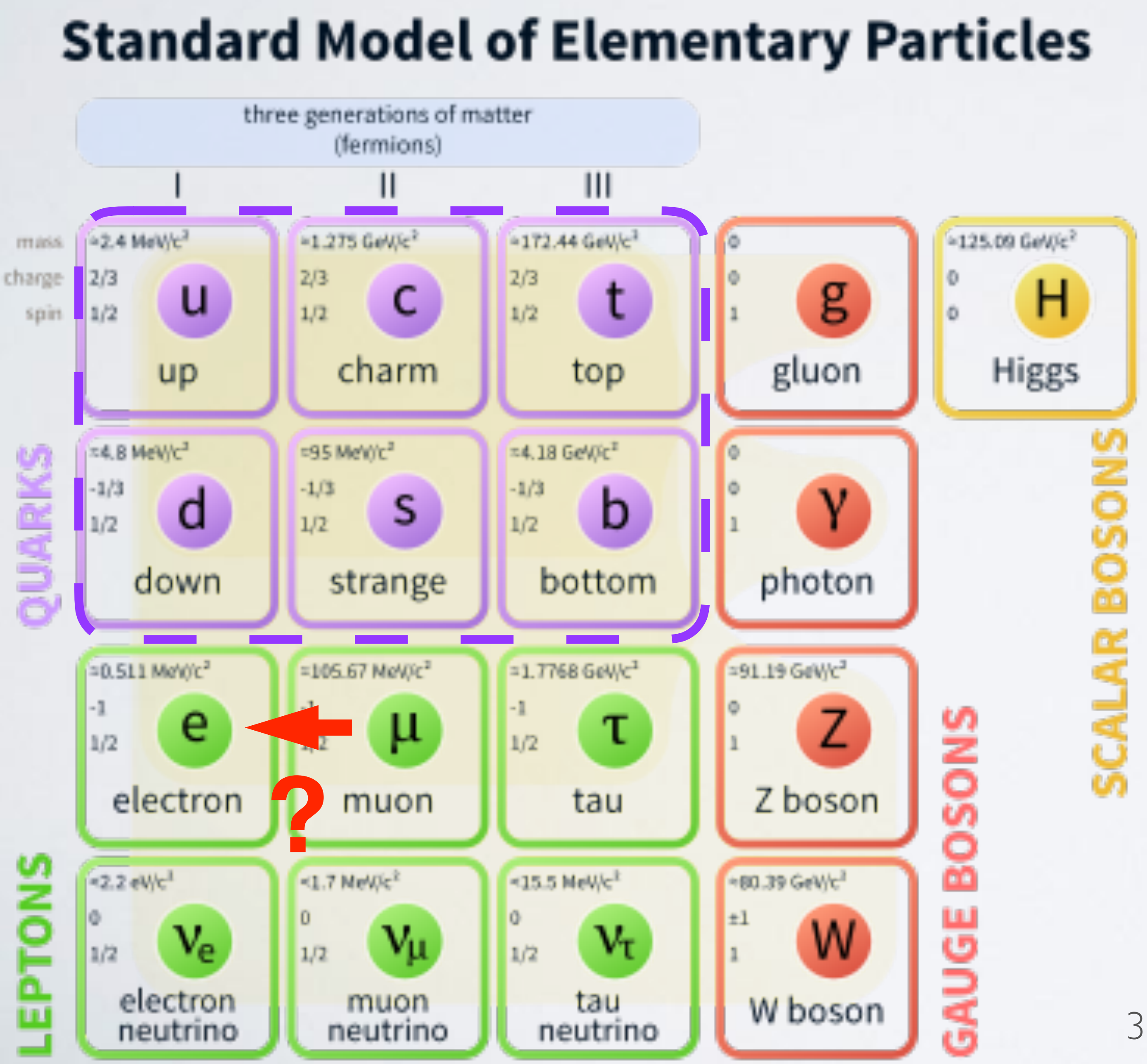
Uppsala University

Outline

- Introduction (cLFV)
- DC muon beam (PSI/πE5)
- Experiments with DC beams (MEG/MEG II/Mu3e)
- Prospects
  - PSI/HiMB, Mu3e phase II/next generation of $\mu \rightarrow e\gamma$?
- Muon precision physics (PSI/muCool, MuSIC)

CLFV

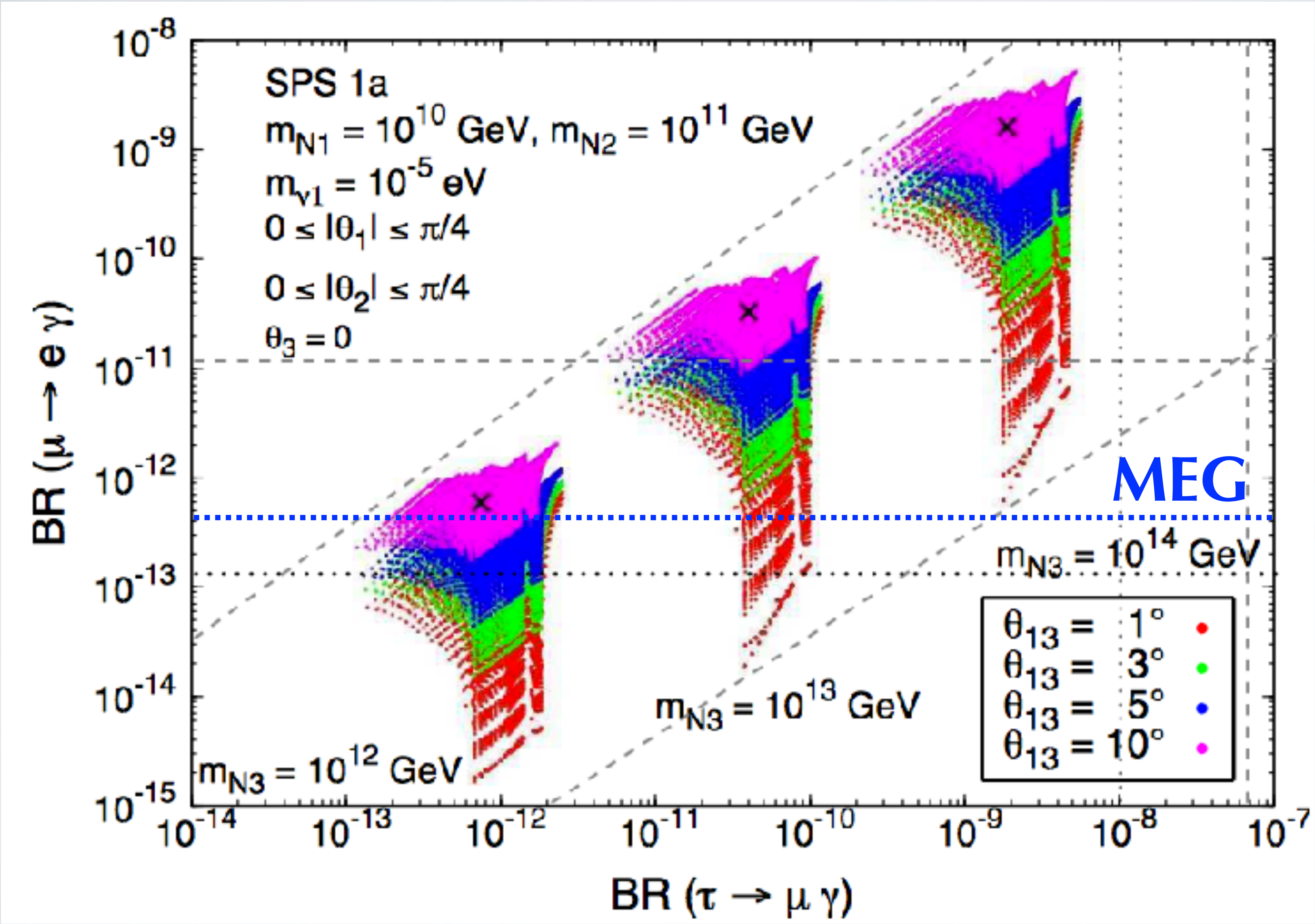
- Standard model has a great success…
- No explanation for many parameters and dark matter etc.
- New physics beyond the SM?



- Charged Lepton Flavor Violation
  - is practically forbidden in SM
  - Experimentally violated in neutrino oscillations
  - Prediction w/ neutrino masses and oscillations
    - $Br(\mu \to e\gamma) \approx 10^{-54}$ (not measurable!)

cLFV

SUSY-Seesaw

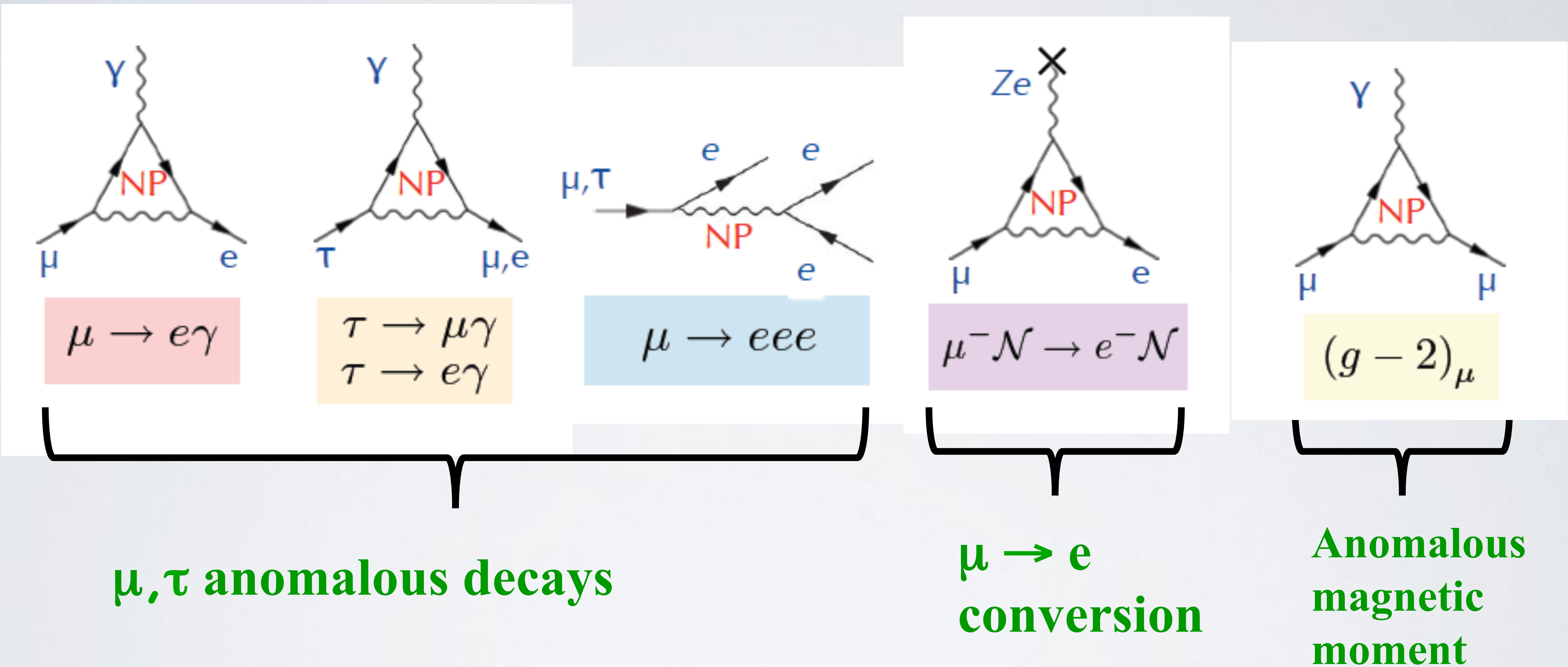


S. Antusch et al, JHEP 0611:090(2006)

- Most new physics predict large cLFV rates
- Observation of cLFV is clear evidence for new physics beyond SM
- cLFV experiment already reaches BSM region

CLFV Experiment

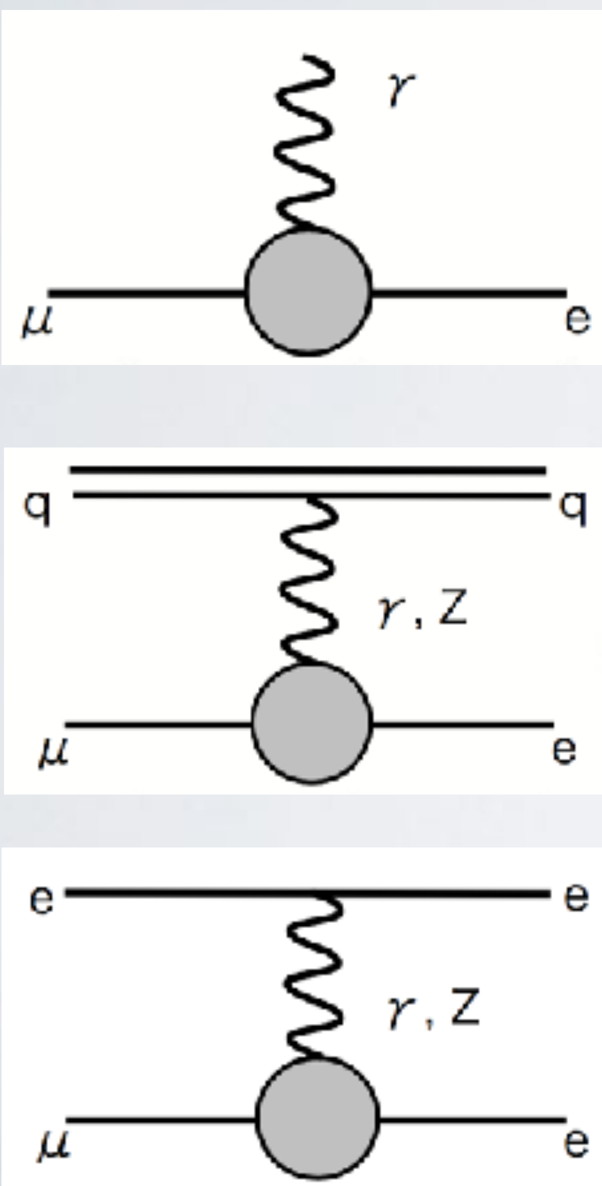
- Many LFV processes sensitive to new physics

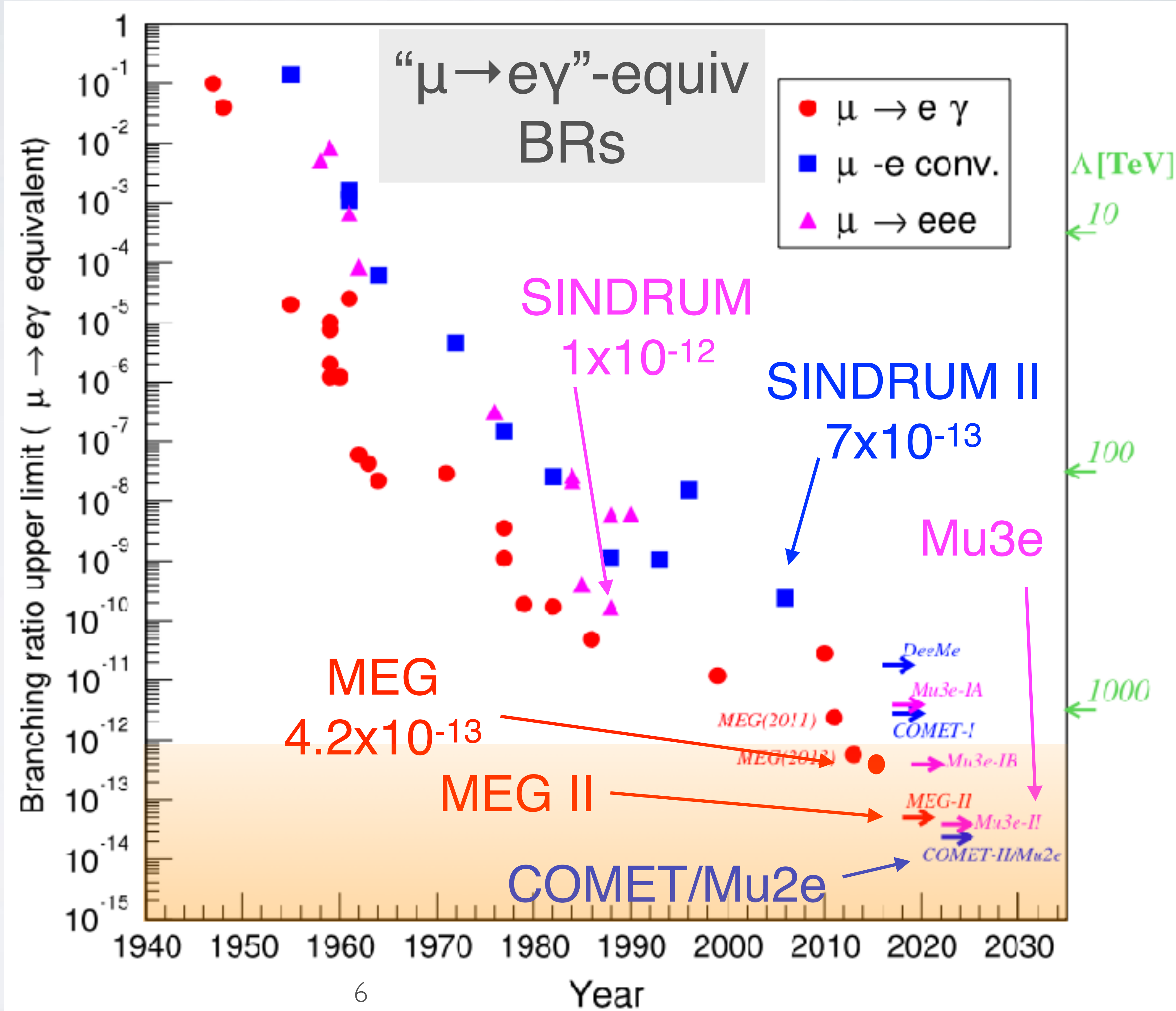


- Muons are very clean, sensitive probes to study LFV
- Intense muon beams available

History of CLFV Search

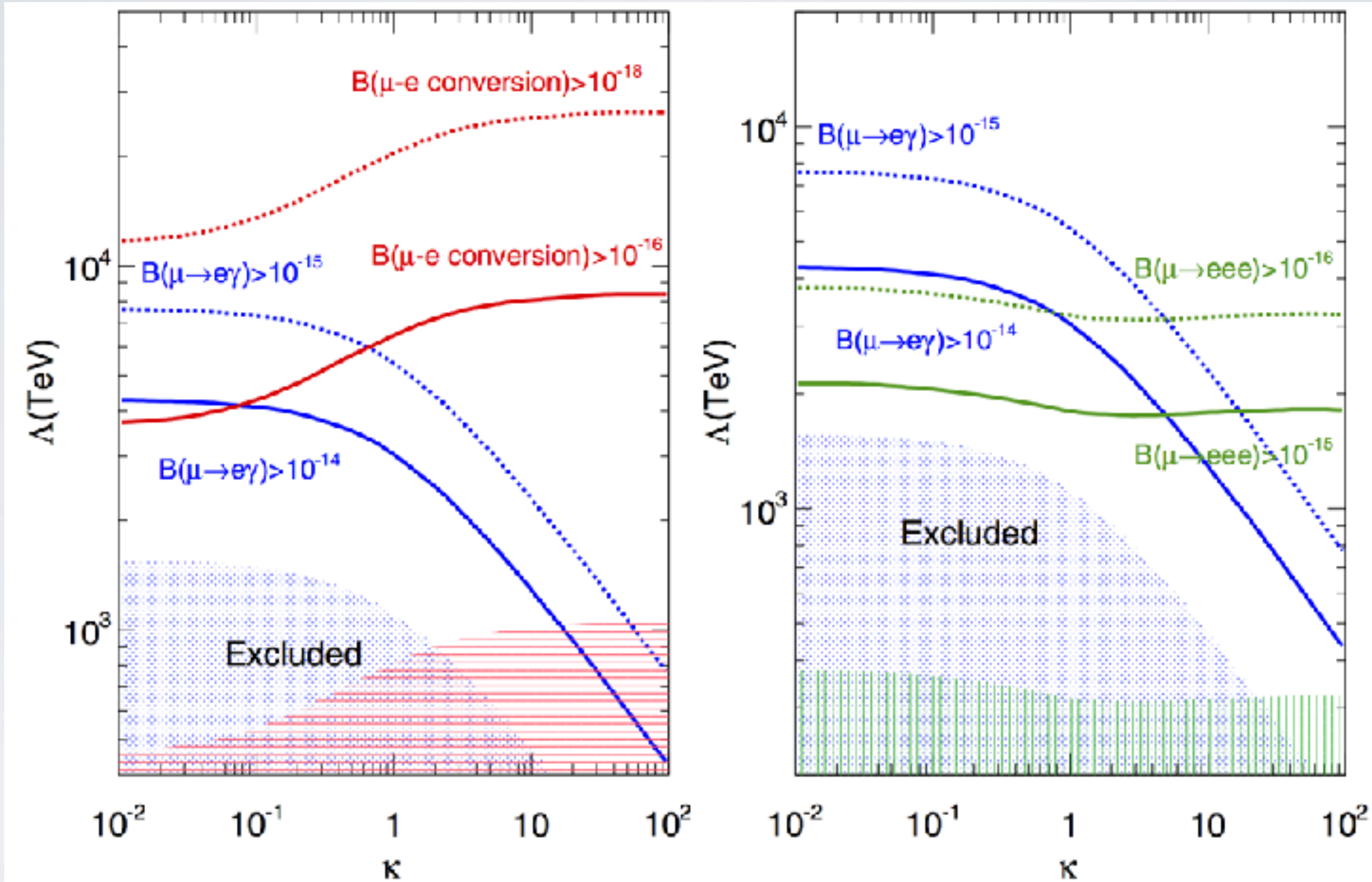
If LFV is dominated by Loop (photonic)





μ→eγ, μe conversion, and μ→eee

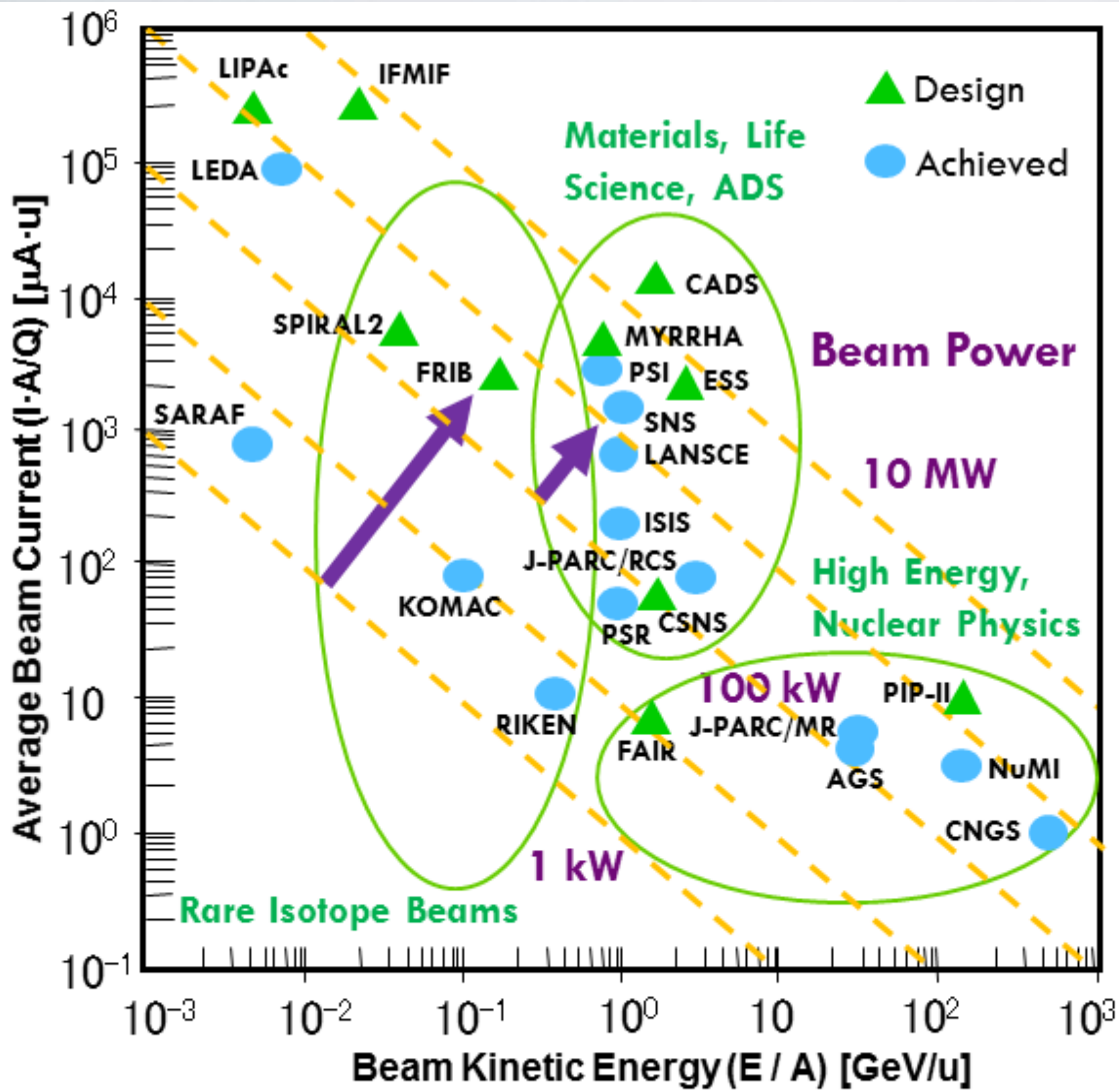
New physics scale



Loops (photonic) **Contact terms (non-photonic)** **Loops (photonic)** **Contact terms (non-photonic)**

- Need to search for different decay modes

World proton accelerator

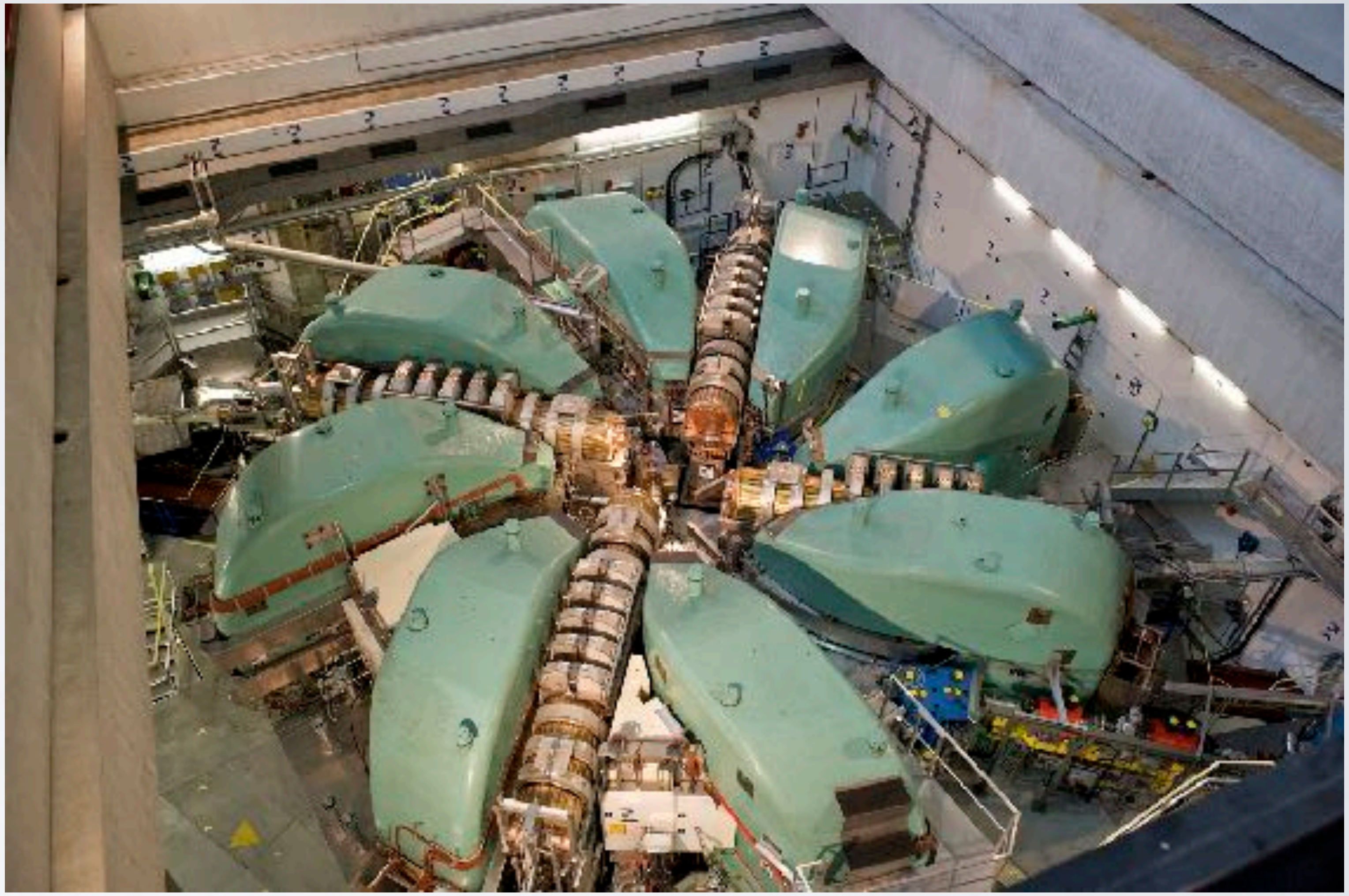


J. Wei, LINAC'16 MO1A01

- Muons are produced from pion decays
- Pion production yield depends on the proton accelerator power
  - 1MW class → Multi-MW potential
- Intense muon beam available at PSI (DC), J-PARC, Fermilab (pulse) etc.

DC muon beam at PSI

- Paul Scherrer Institute in Switzerland
- PSI 2.4mA cyclotron at 590 MeV (1.4MW) produces
  - most intense DC muon beams $>10^8 \mu^+/s$
  - spallation neutron source 10^{14}n/s
  - Possibility up to 3mA after replacing RF cavities



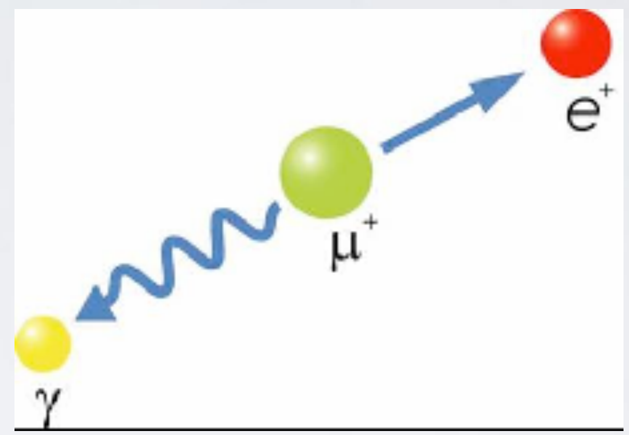
- Current best limits of cLFV are from PSI
  - $\mu \to e\gamma < 4.2 \times 10^{-13}$ (MEG, 2016)
  - $\mu \to e < 7 \times 10^{-13}$ (SINDRUM II, 2006)
  - $\mu \to eee < 1 \times 10^{-12}$ (SINDRUM, 1988)

Experiments with DC beams

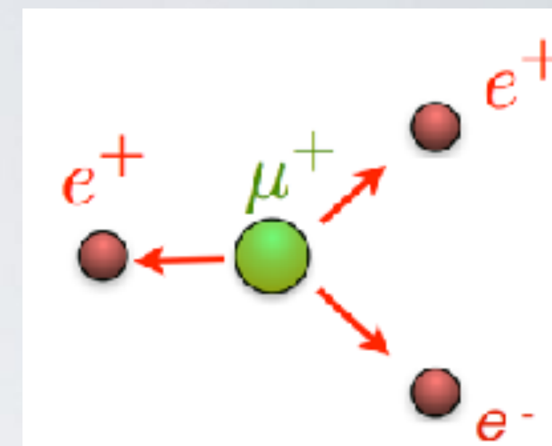
Signal / background

- DC beam suitable for coincidence experiments
  - μ→eγ, μ→eee
- Pulse beam suitable for non-coincidence experiments
  - μ→e conversion

μ→eγ



μ→eee



Signal

Back-to back
Coincident
$E_e=E_\gamma=52.8$MeV

Common vertex
Coincident
$\sum p_e=0$, $\sum E_e=m_\mu$

Background

Accidental e^+ and γ
μ→eννγ (radiative μ decay)

Accidental eee
μ→eeeνν

$$N_{acc} \propto (R_\mu)^2 \times T \times (\Delta E_\gamma)^2 \times \Delta E_e \times (\Delta\Theta_{e\gamma})^2 \times \Delta t_{e\gamma}$$

MEG

MEG experiment :

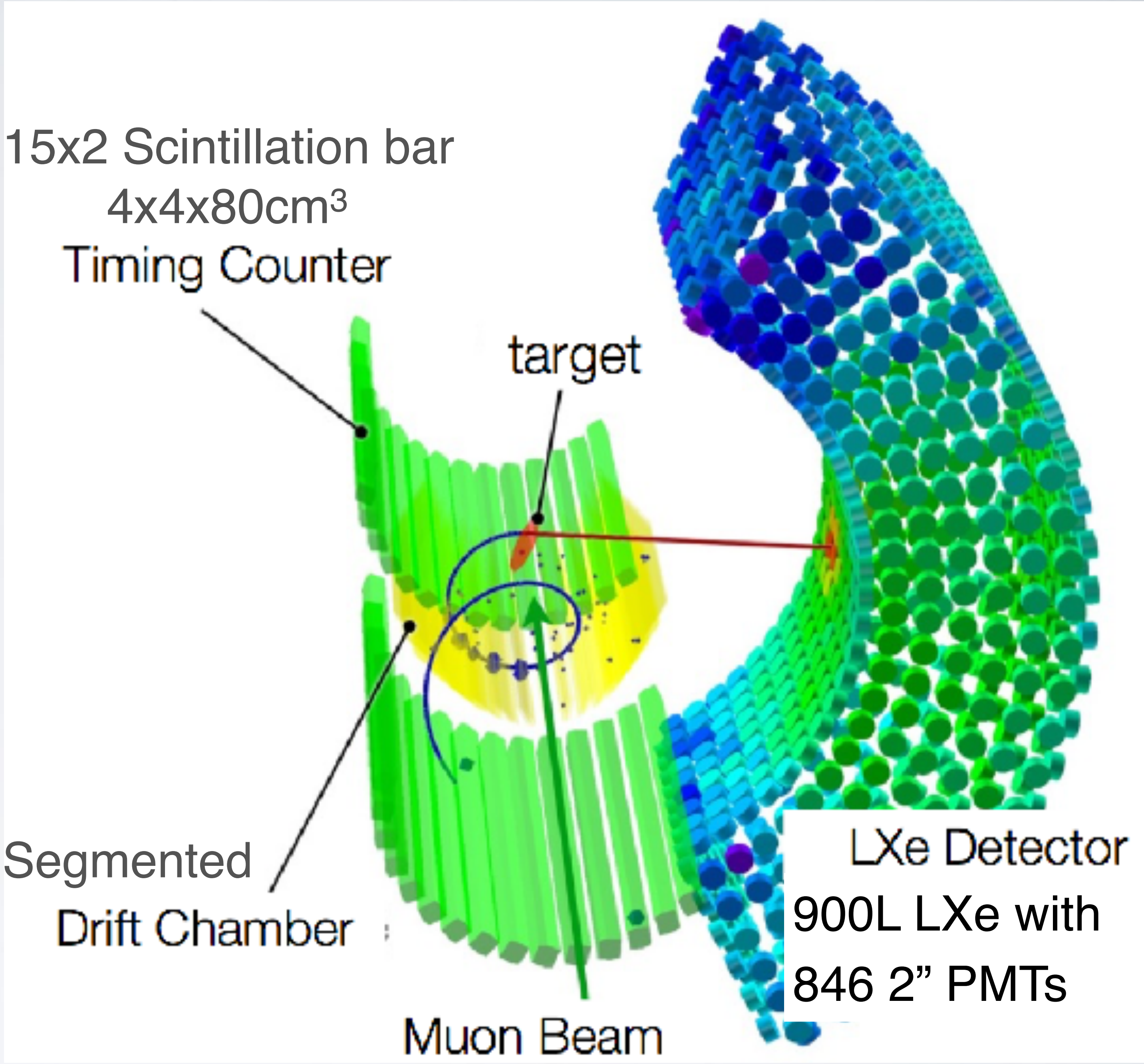
Data taking 2008-2013

Search for lepton flavor violating $\mu^+ \to e^+\gamma$ mode using 3×10^7 μ^+/s beam intensity at PSI

Final result in 2016 :

$Br(\mu^+ \to e^+\gamma) < 4.2\times10^{-13}$ @90%C.L.

(Eur. Phys. J. C (2016) 76: 434)



$3\times10^7\mu$/s

Sensitivity improvement was already limited by accidental background

Detector upgrade proposal to achieve 10 times better sensitivity as quick as possible presented in 2013: MEG II

MEG II Concept

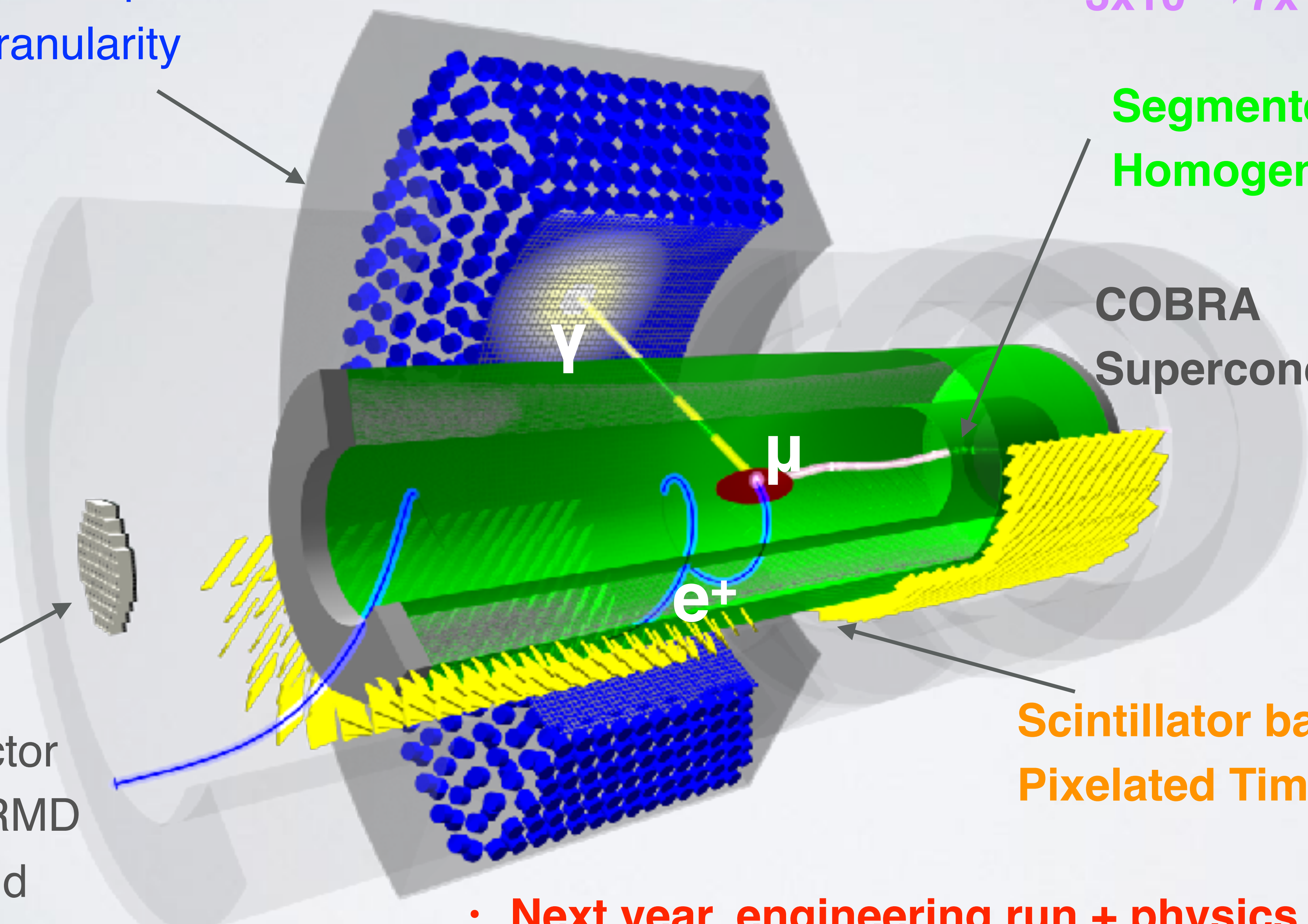
Cecilia Voena

900L LXe with 846 2” PMTs
→ 4092 MPPCs γ incident face + 668 PMTs
→ Better granularity

Muon beam intensity
$3\times10^7 \rightarrow 7\times10^7 \mu/s$

Segmented → Cylindrical
Homogeneous DC

COBRA
Superconducting magnet

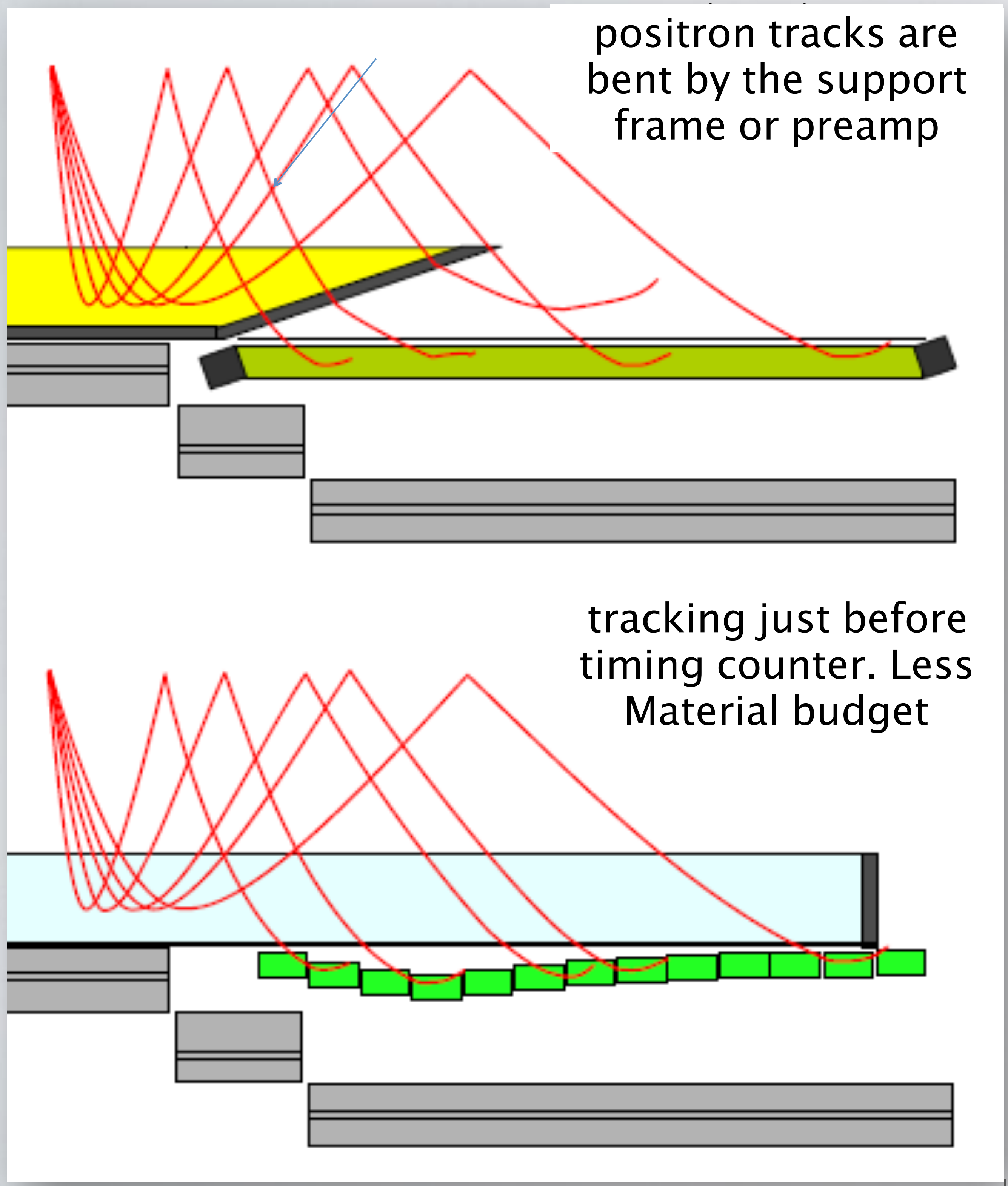


RDC
New detector
to detect RMD
background

Scintillator bars →
Pixelated Timing Counter

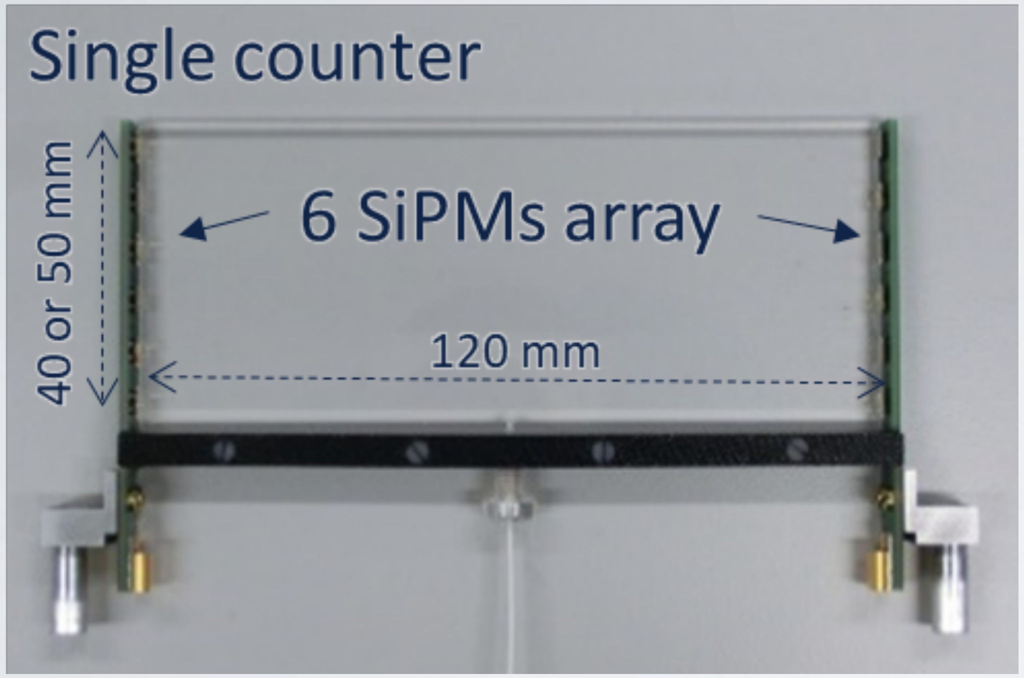
- Next year, engineering run + physics run
- Sensitivity 4×10^{-14}, 10 times improvement from MEG

MEG II e^+ tracking : drift chamber

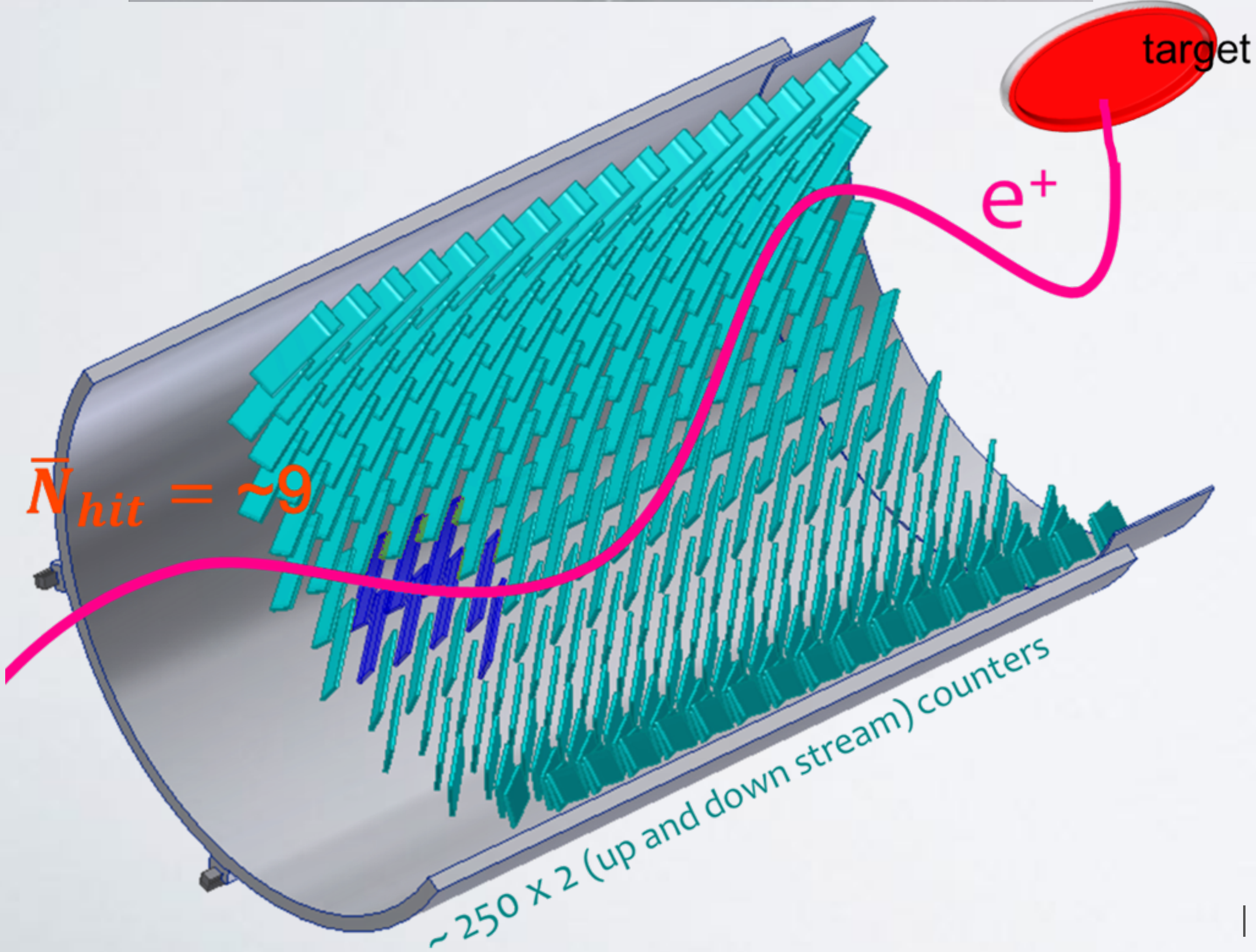


- Single volume wire drift chamber with 1200 sense wires
  - 1.93m long, 20μmφ
- Improved hit resolution
  - $\sigma_r < 120\mu m$
- High granularity / increased number of hits per track
  - σ_p : 306 keV → 130 keV
  - σ_θ : 9.4 mrad →5.3 mrad
  - σ_ϕ : 8.7 mrad → 3.7 mrad
- Less material
- High transparency towards the TC
  - detection efficiency : 30% → 70%

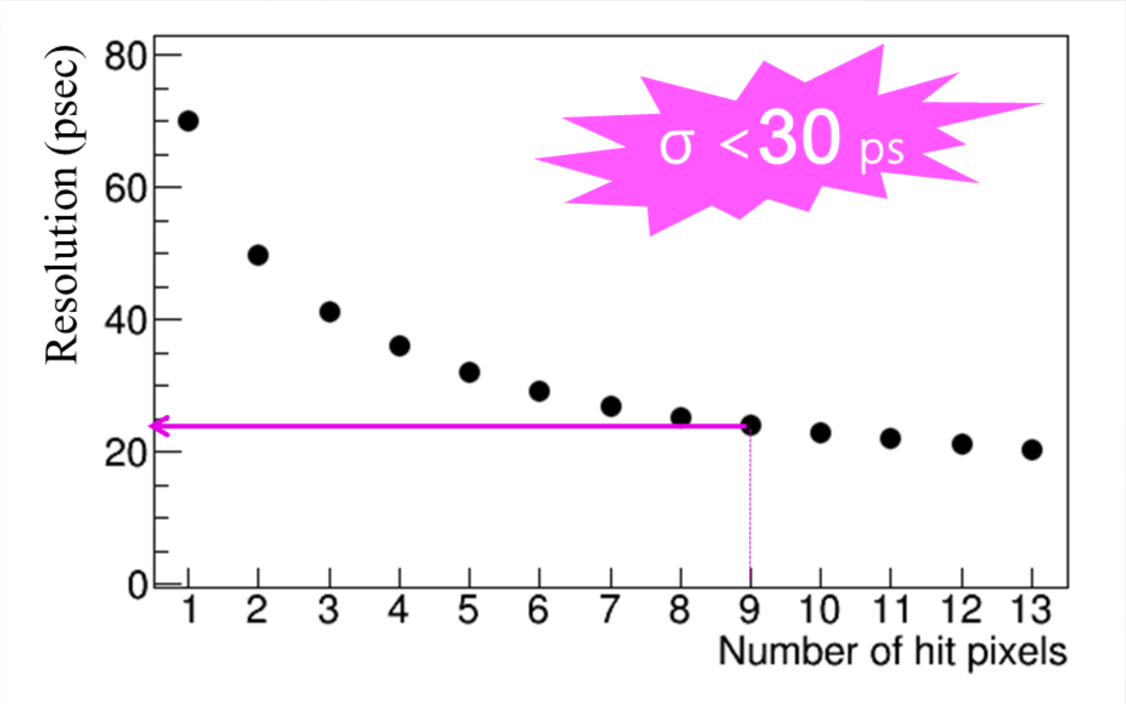
MEG II e+ timing counter



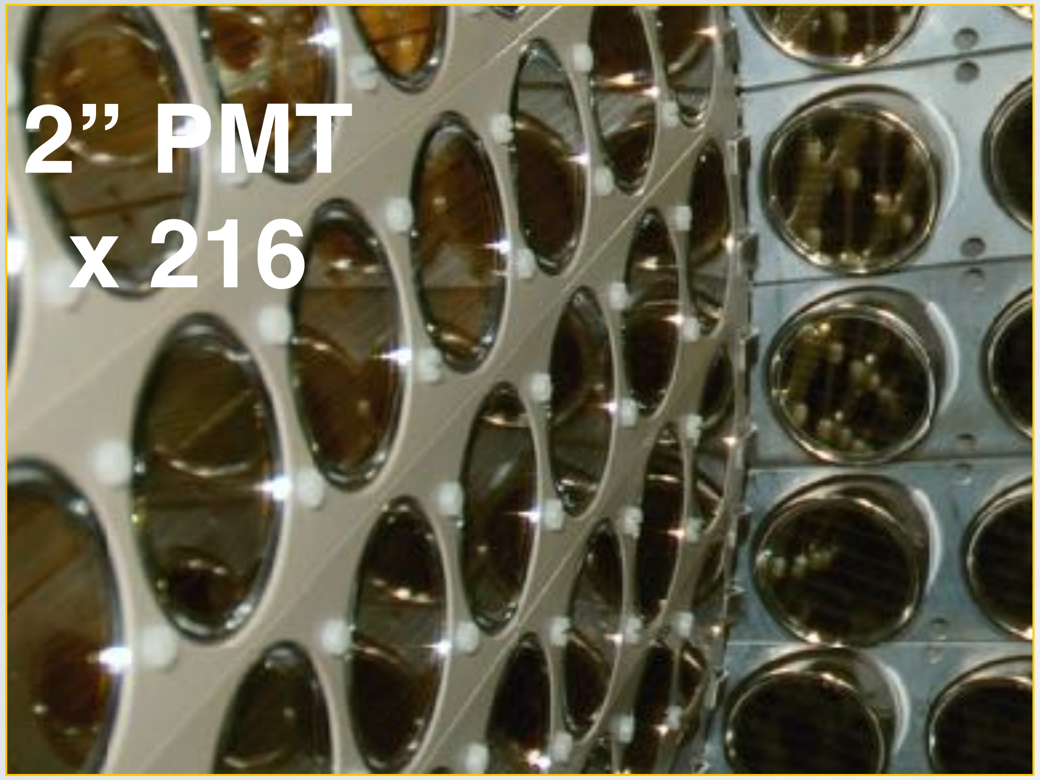
- Higher granularity (pixelated)
  - 2x256 BC422 scintillator plates
  - 120x40(or 50)x5mm^3 readout by SiPM

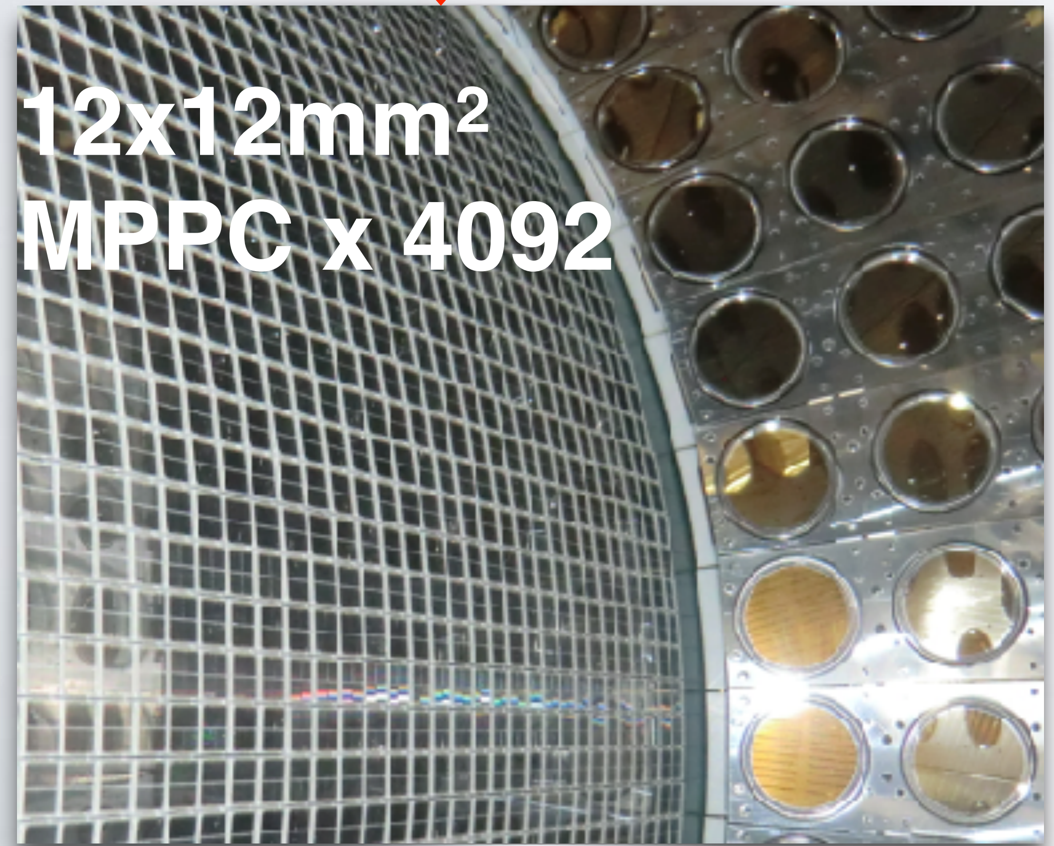


- Improved timing resolution : 70ps → 30ps (multi-hits)



MEG II γ calorimeter

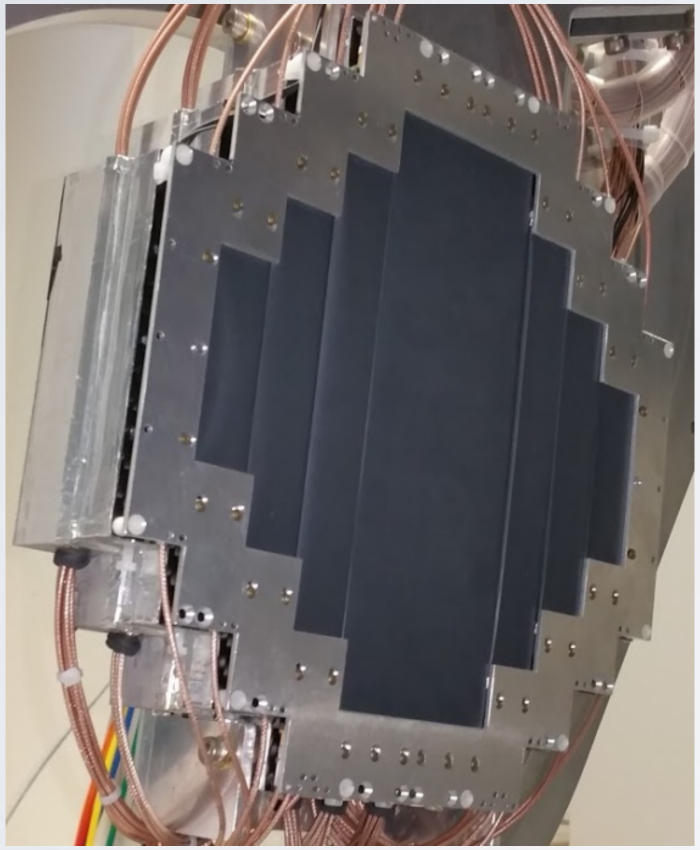




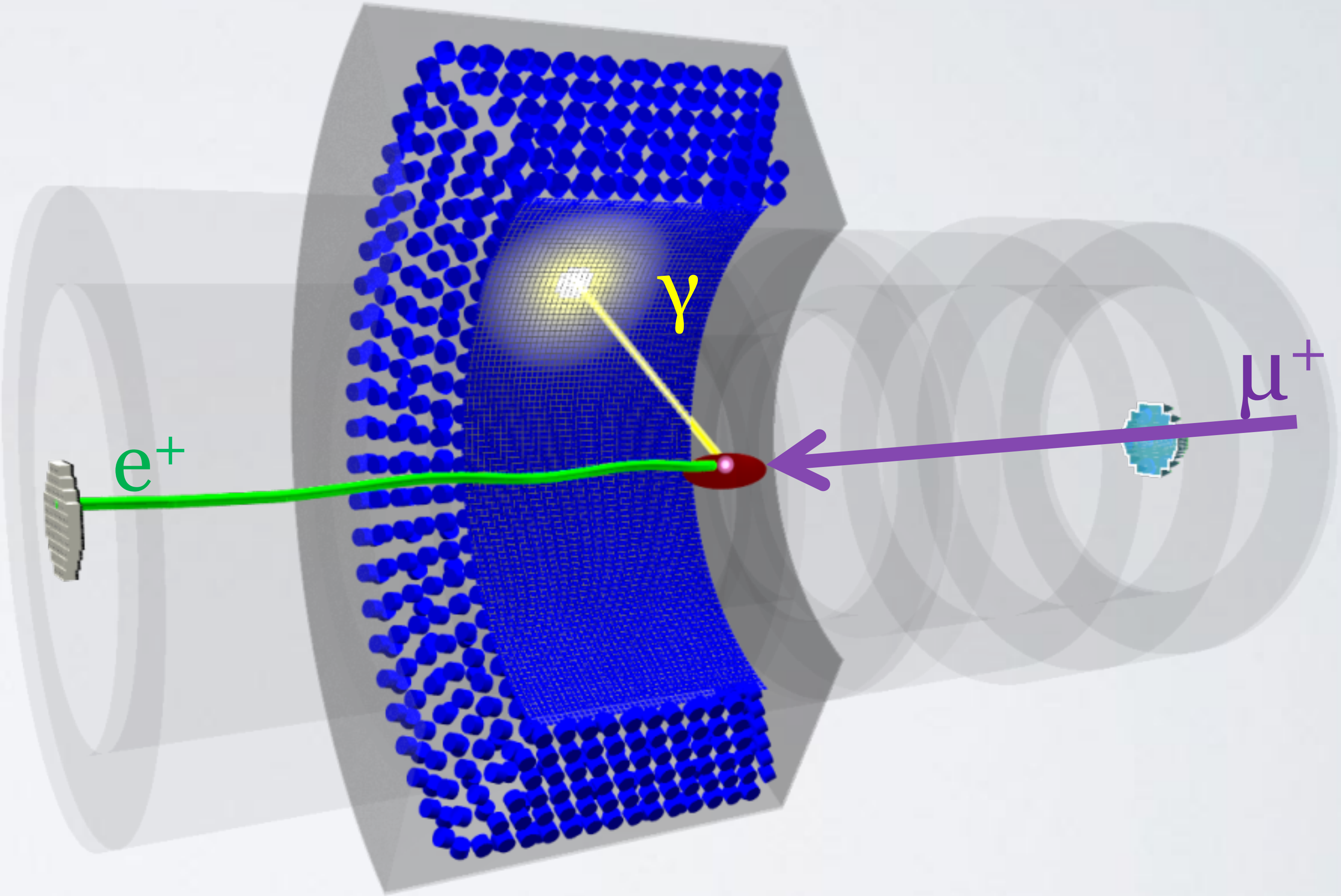
- 900L LXe (cryostat reused)
- 4092 new VUV-sensitive SiPM developed with Hamamatsu (MPPC) installed on the γ incident face
- Higher granularity for γ incident face
  - position resolution (5mm→2.5mm)
  - energy resolution (2%→0.7-1.5%)
  - timing resolution 67ps →50-70ps
- Less material for γ incident face
  - detection efficiency 65% → 70% higher

Radiative decay counter (RDC)

- Additional detector, new in MEG II
- Identifies μ→eννγ by tagging low momentum e^+ associated with high energy γ



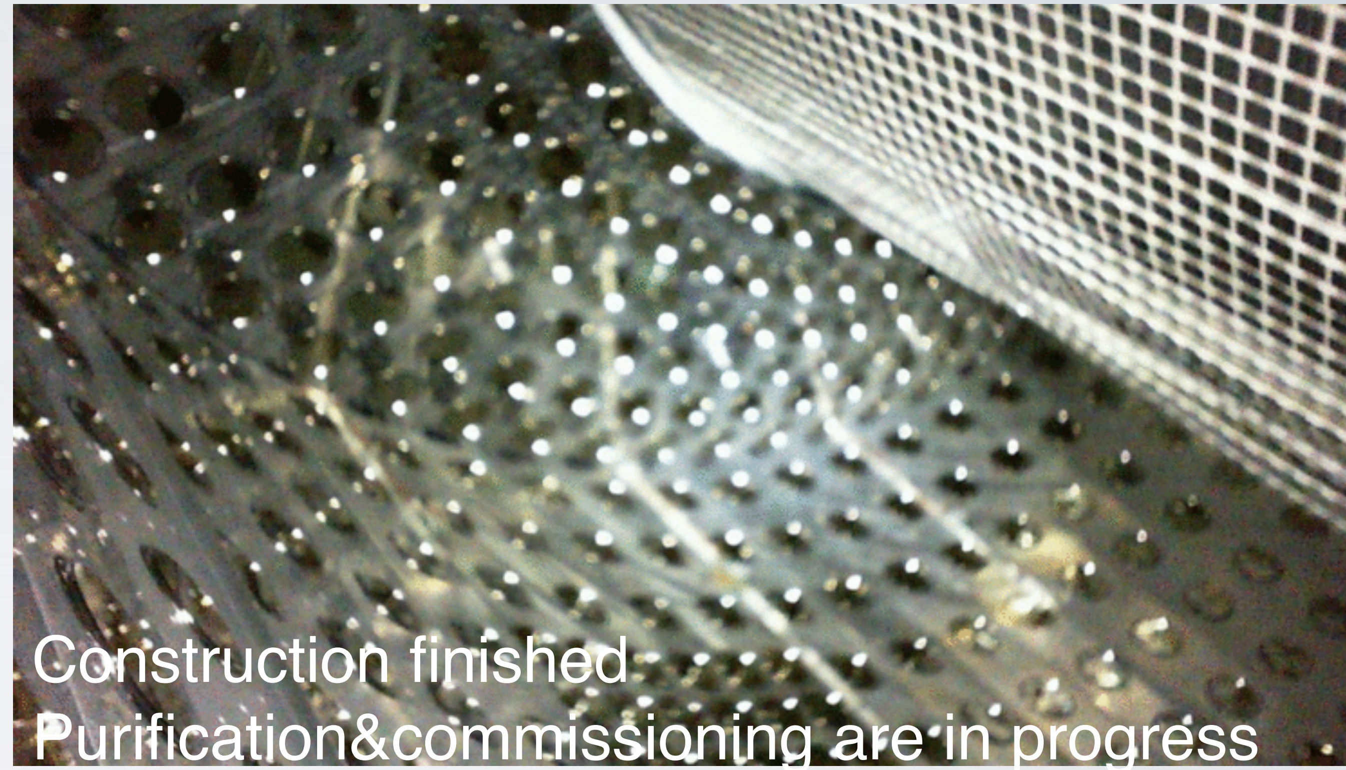
Plastic scintillator x 12
+ LYSO calorimeter x 76



Construction is finished.
Expected to further reduce the BG from μ→eννγ by 40%

MEG II Status

Construction finished
Ready to install



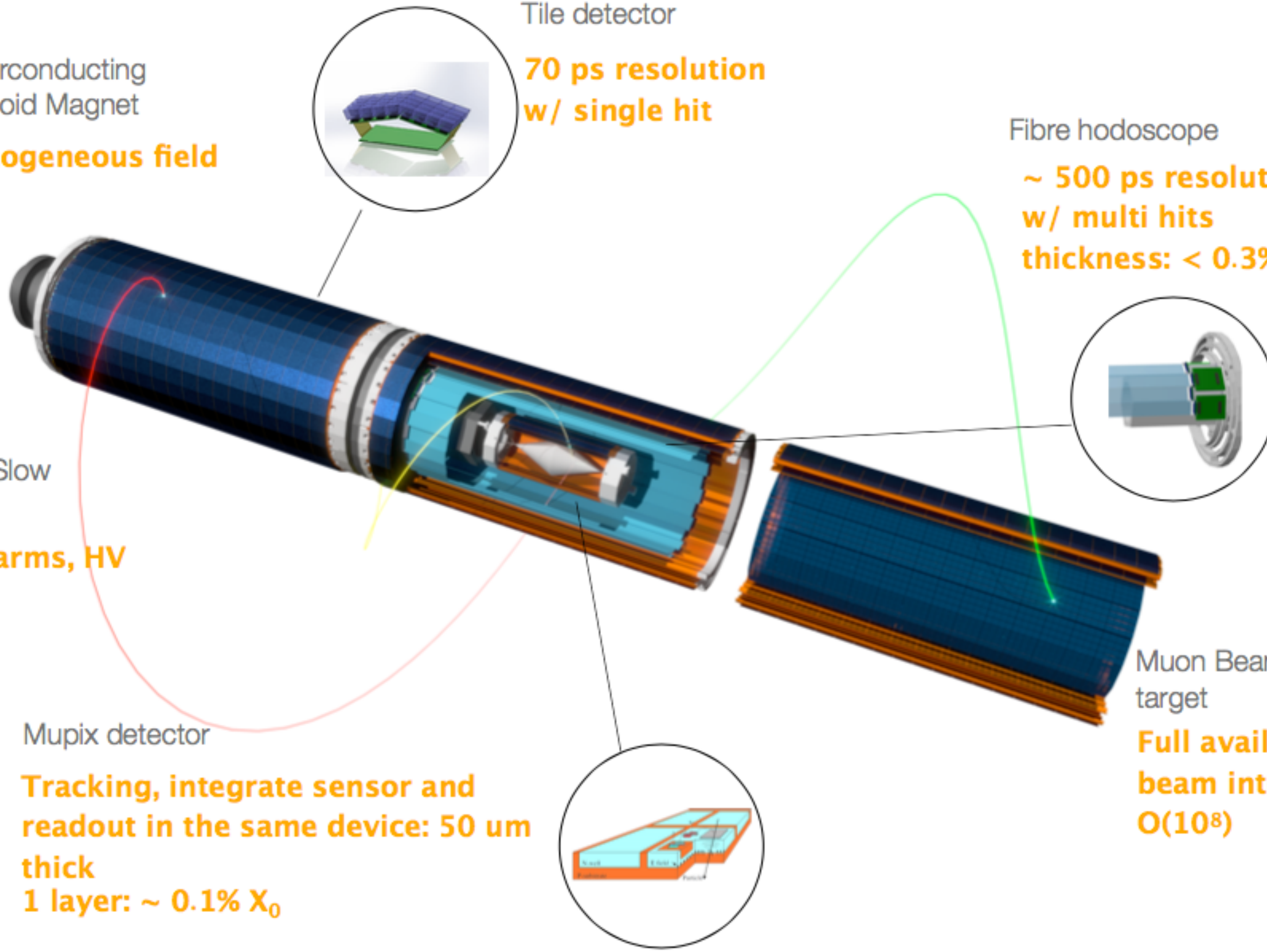
Construction finished
Purification&commissioning are in progress

Construction is in progress. Will be ready in 2018

- Engineering run in 2018

Mu3e

Ann-Kathrin Perrevoort



Superconducting solenoid Magnet

Homogeneous field 1T

Tile detector

70 ps resolution w/ single hit

Fibre hodoscope

~ 500 ps resolution w/ multi hits thickness: < 0.3% X_0

MIDAS DAQ and Slow Control

Run, history, alarms, HV etc.

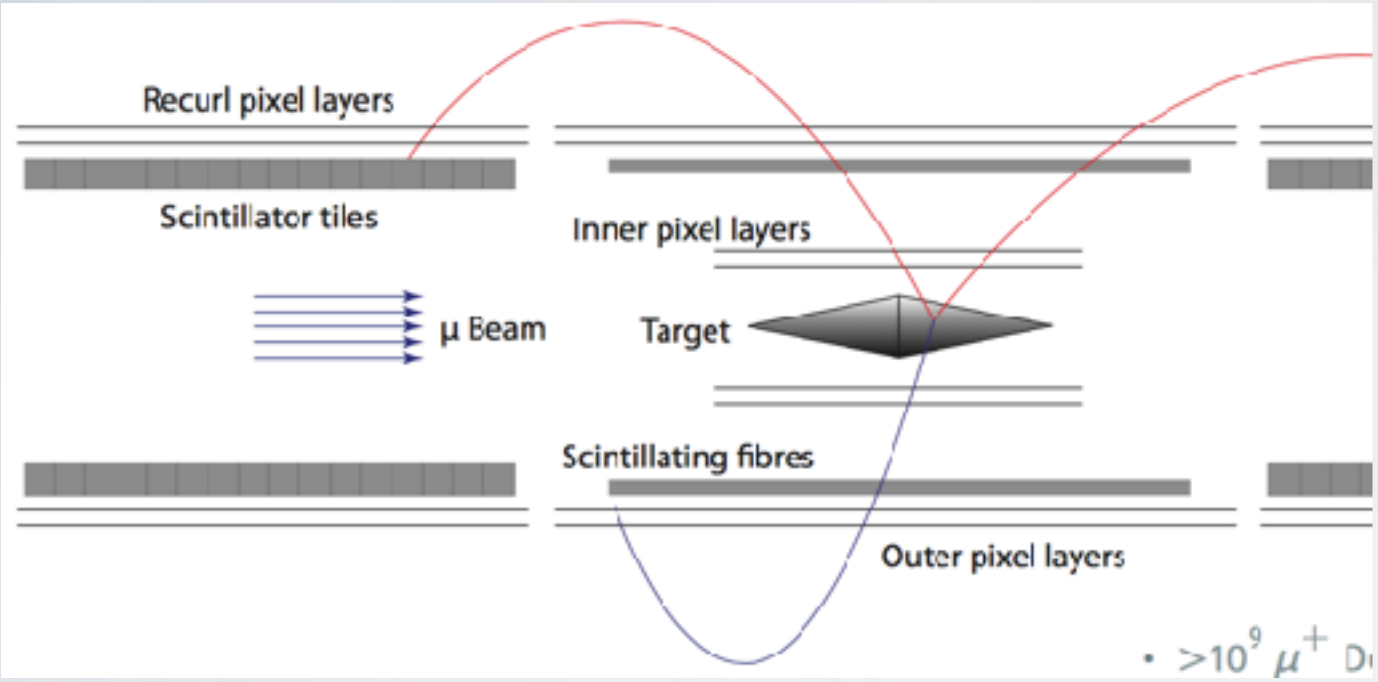
Muon Beam and target

Full available beam intensity O(10^8)

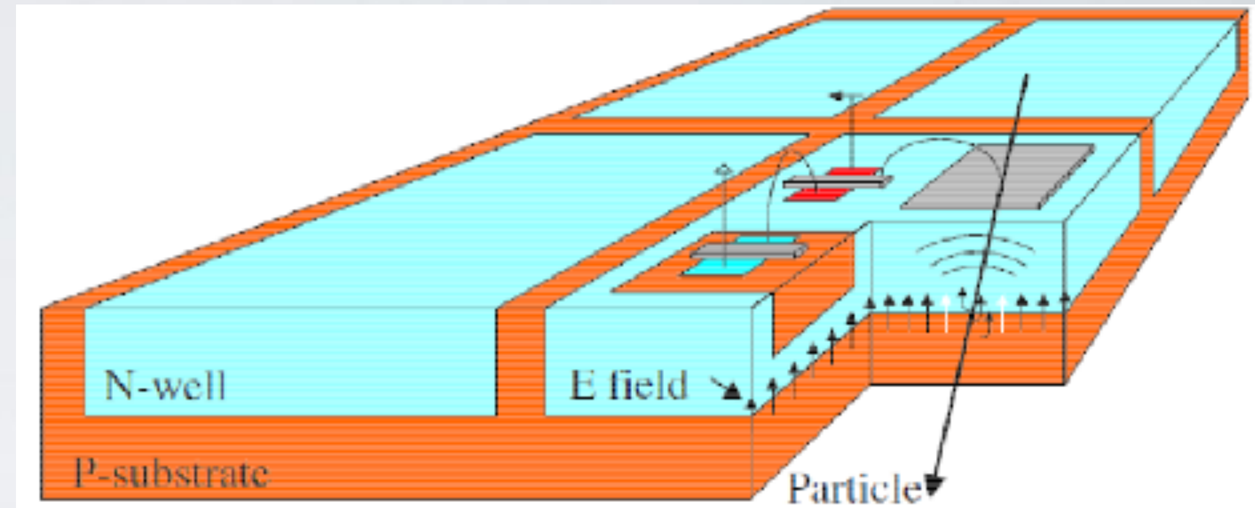
Mupix detector

Tracking, integrate sensor and readout in the same device: 50 um thick
1 layer: ~ 0.1% X_0

Mu3e pixel tracker

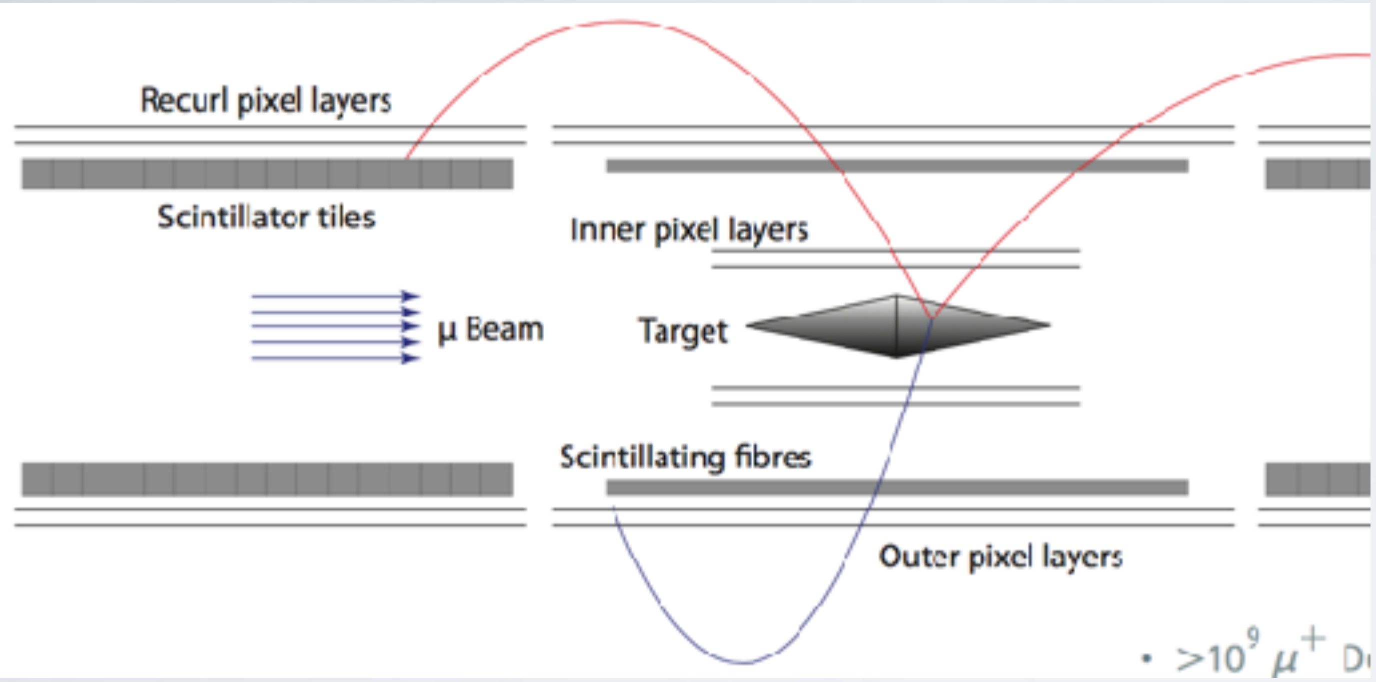


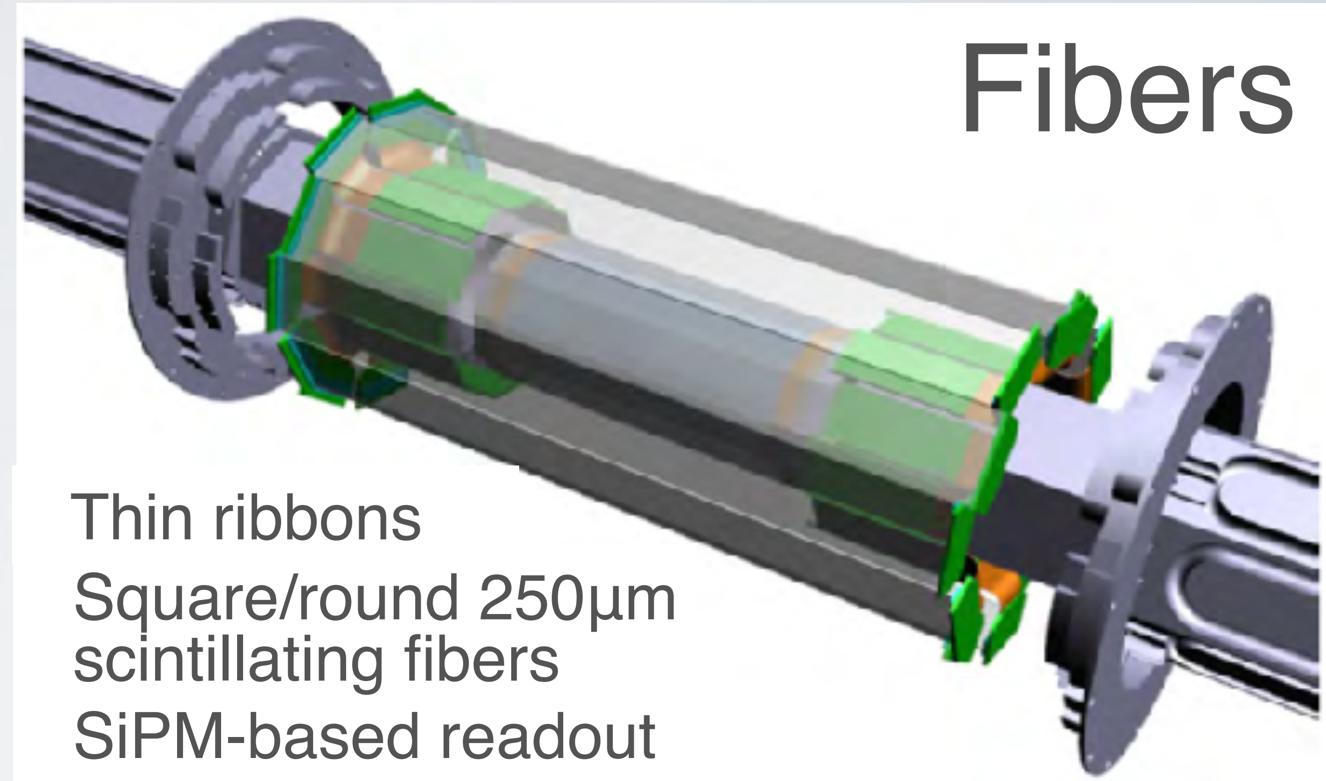
- Central tracker: Four layers
- Re-curl tracker: Two layers
- Minimum material budget: Multiple scattering dominates
- $\sigma_p < 0.5$MeV/c



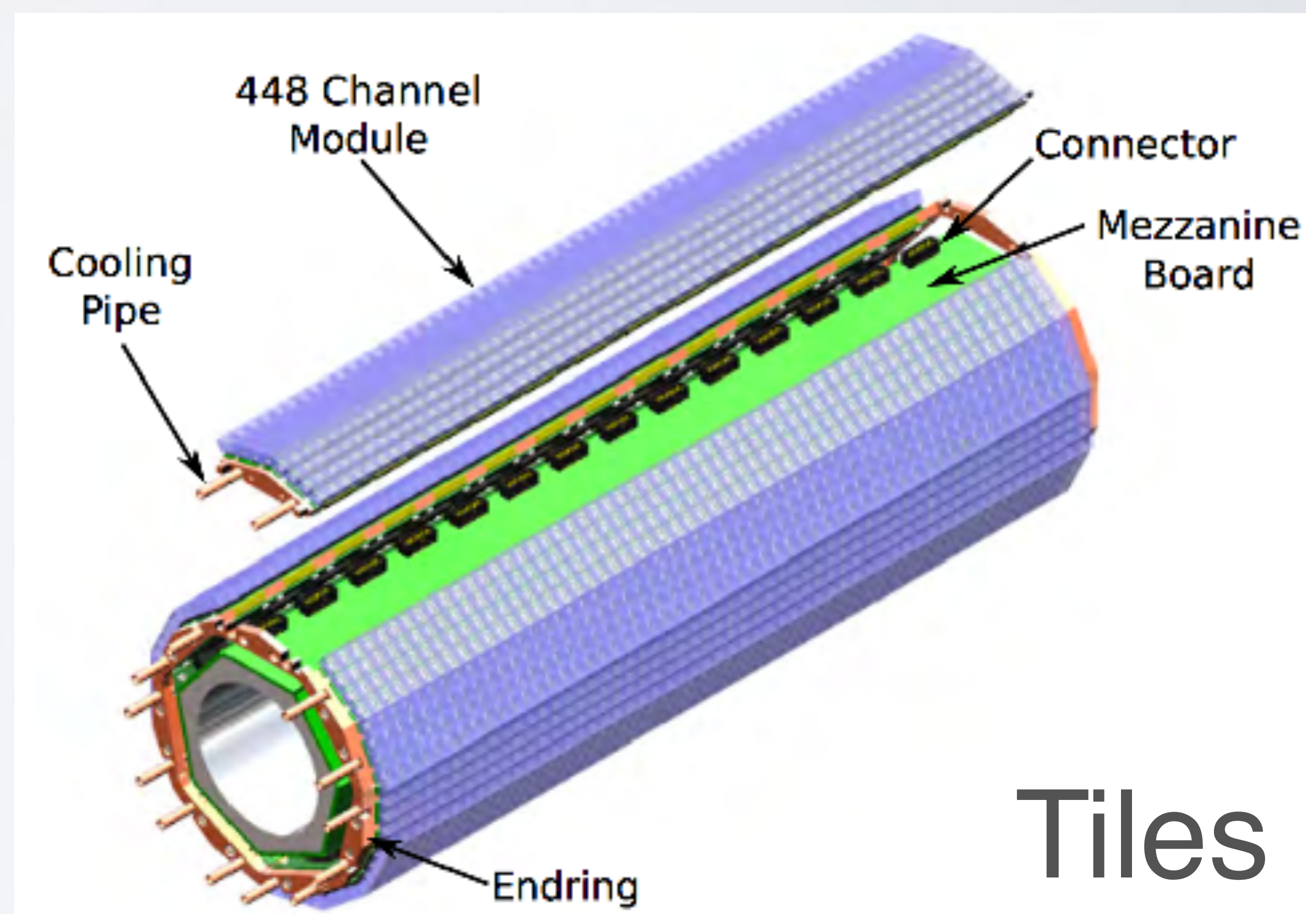
- High Voltage - Monolithic Active Pixel Sensor (HV-MAPS)
- Ultra-lightweight mechanics
  - 50μm Silicon sensor
  - 25μm Kapton flexprint with Al traces
  - 25μm Kapton support frame
- Time resolution < 20ns
- Active area chip: 20x20mm^2
- Under development

Mu3e timing detectors: Fibers and tiles





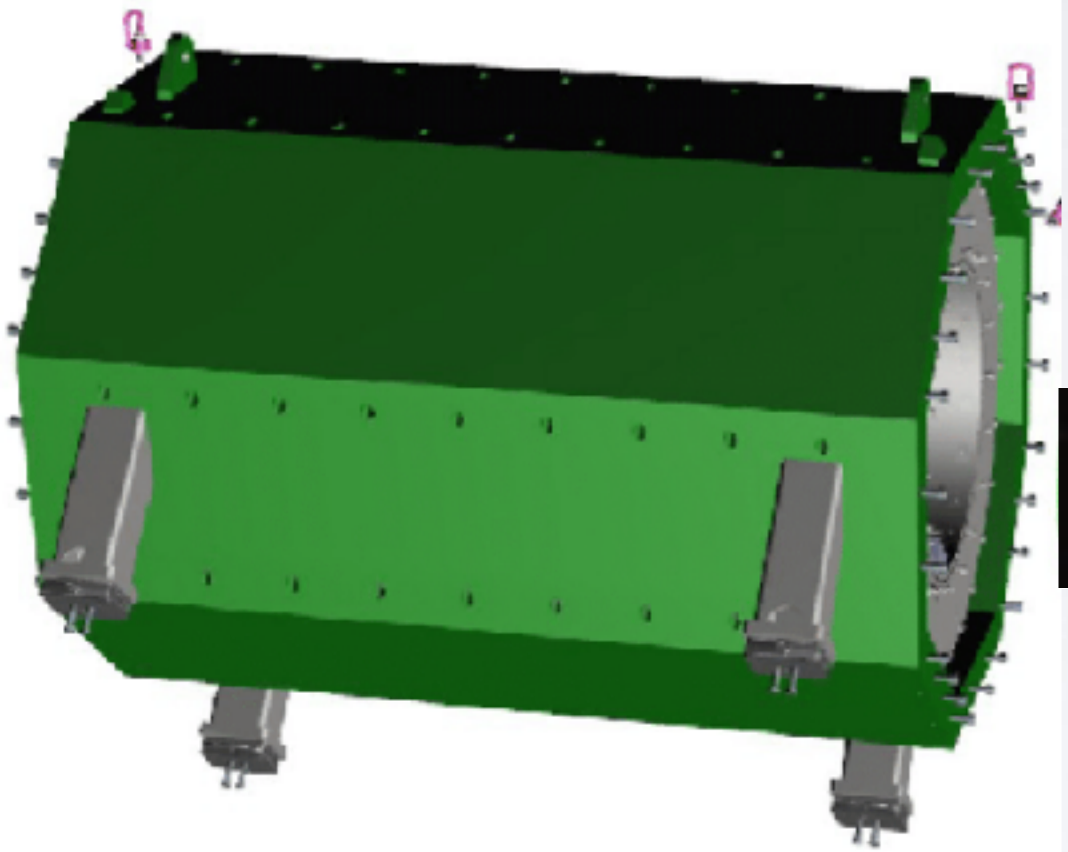
- Fibers (1ns resolution)
  - before outer pixel layers
  - scintillating fibers with SiPMs (3 layers)
  - 32mm wide, 290mm long
- Tiles (100ps resolution)
  - After recurl pixel layers
  - Scintillating tiles: 6.5x6.5x5.0mm^3
  - SiPMs



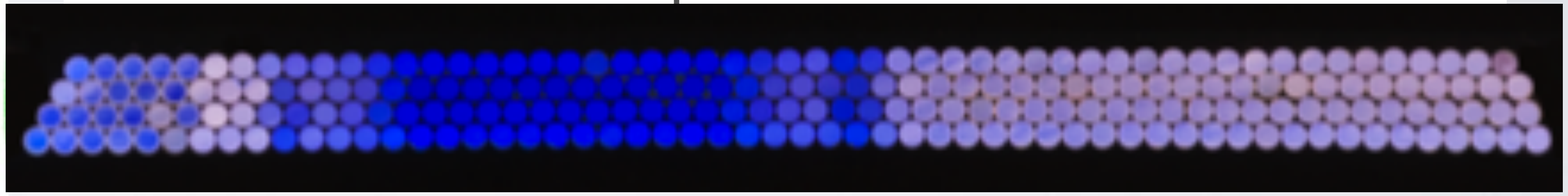
Mu3e status

Pixel tracker:
MuPix8, first full size sensor(1x2cm^2) has arrived last month

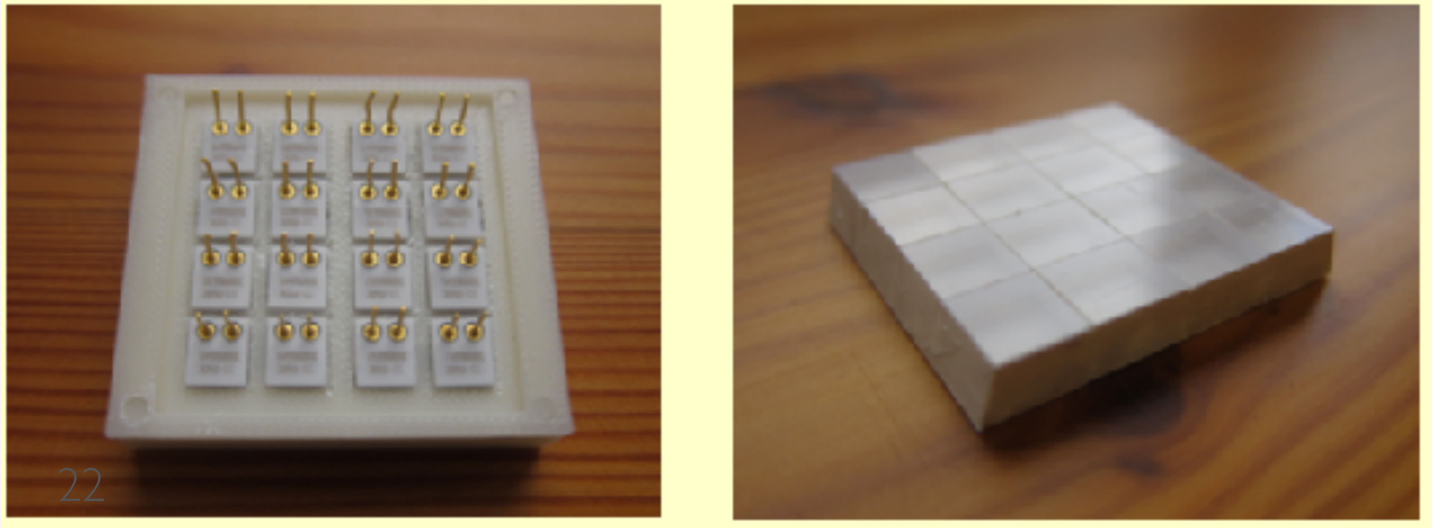
Magnet:
Delivery originally planned in 2016, but cancelled. New date in 2019



Scintillating Fibers:
Prototype of Round (Kuraray SCSF-81M), squared (Saint-Gobain BC418) are tested
Time resolution ~ 600 ps



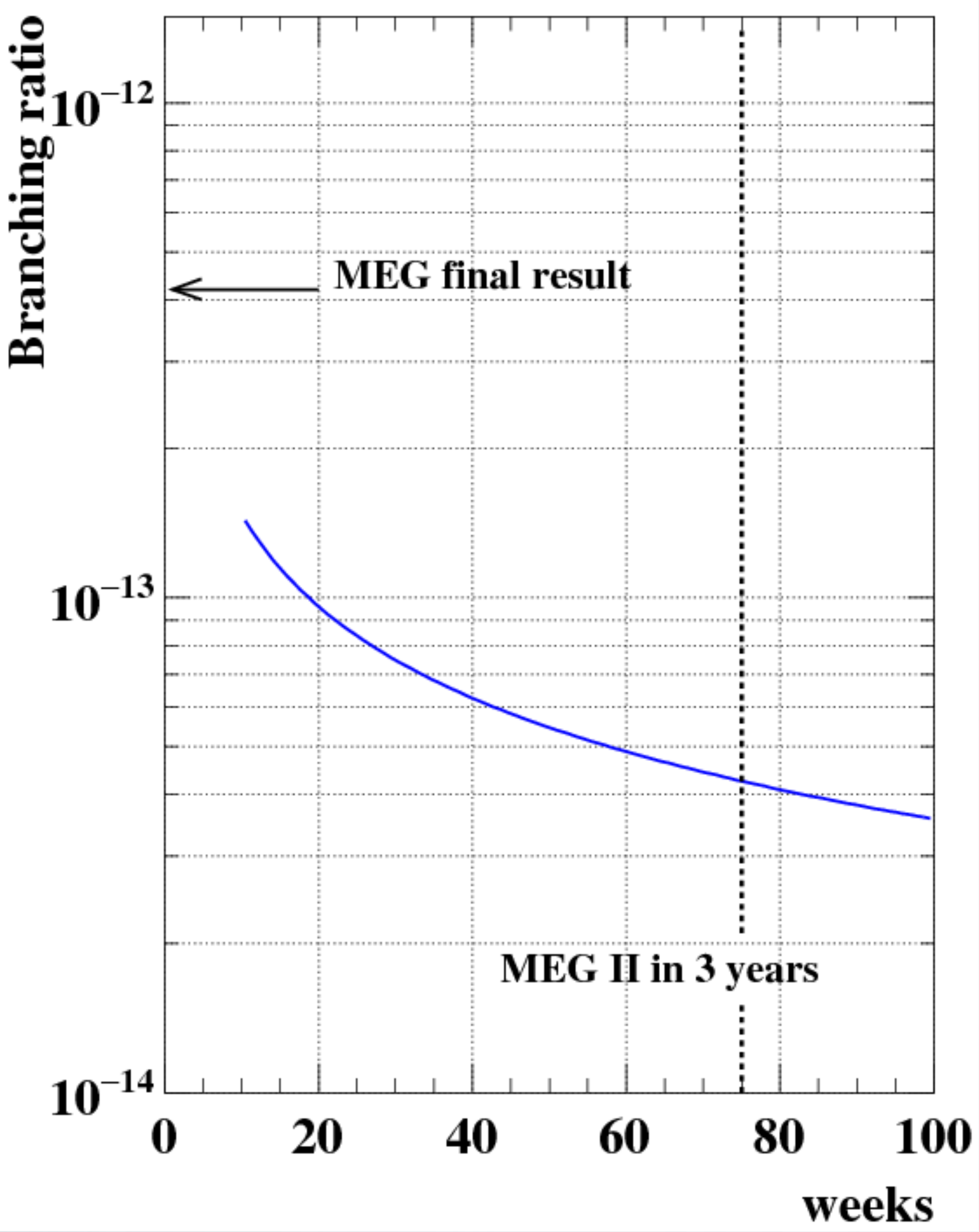
Scintillating Tile Detector:
Promising results from 4x4 array
Time resolution ~ 70 ps



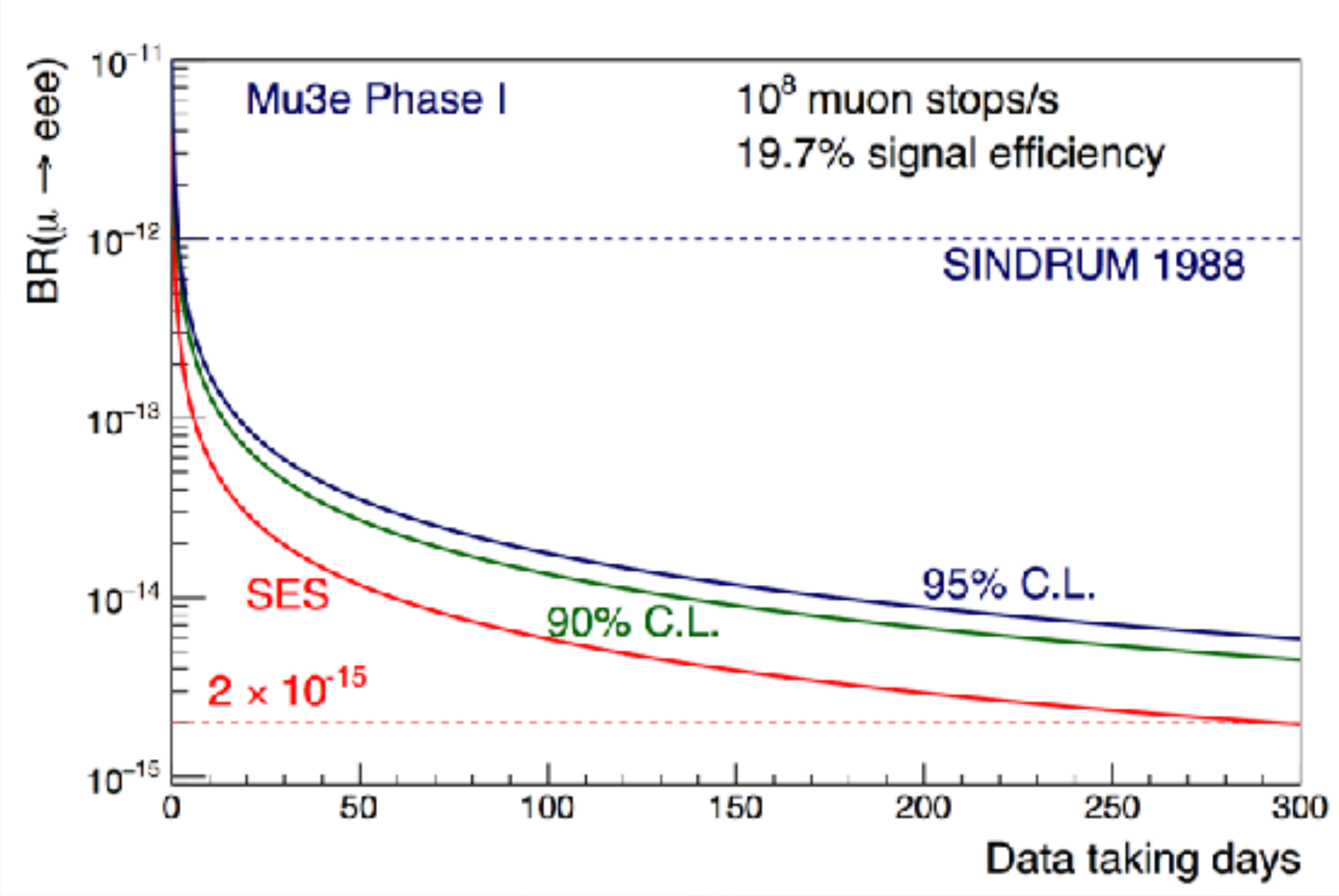
- Engineering run in 2019
- Sensitivity 2×10^{-15} in Mu3e Phase I
  $10^8\ \mu^+/s$

Sensitivity

MEG

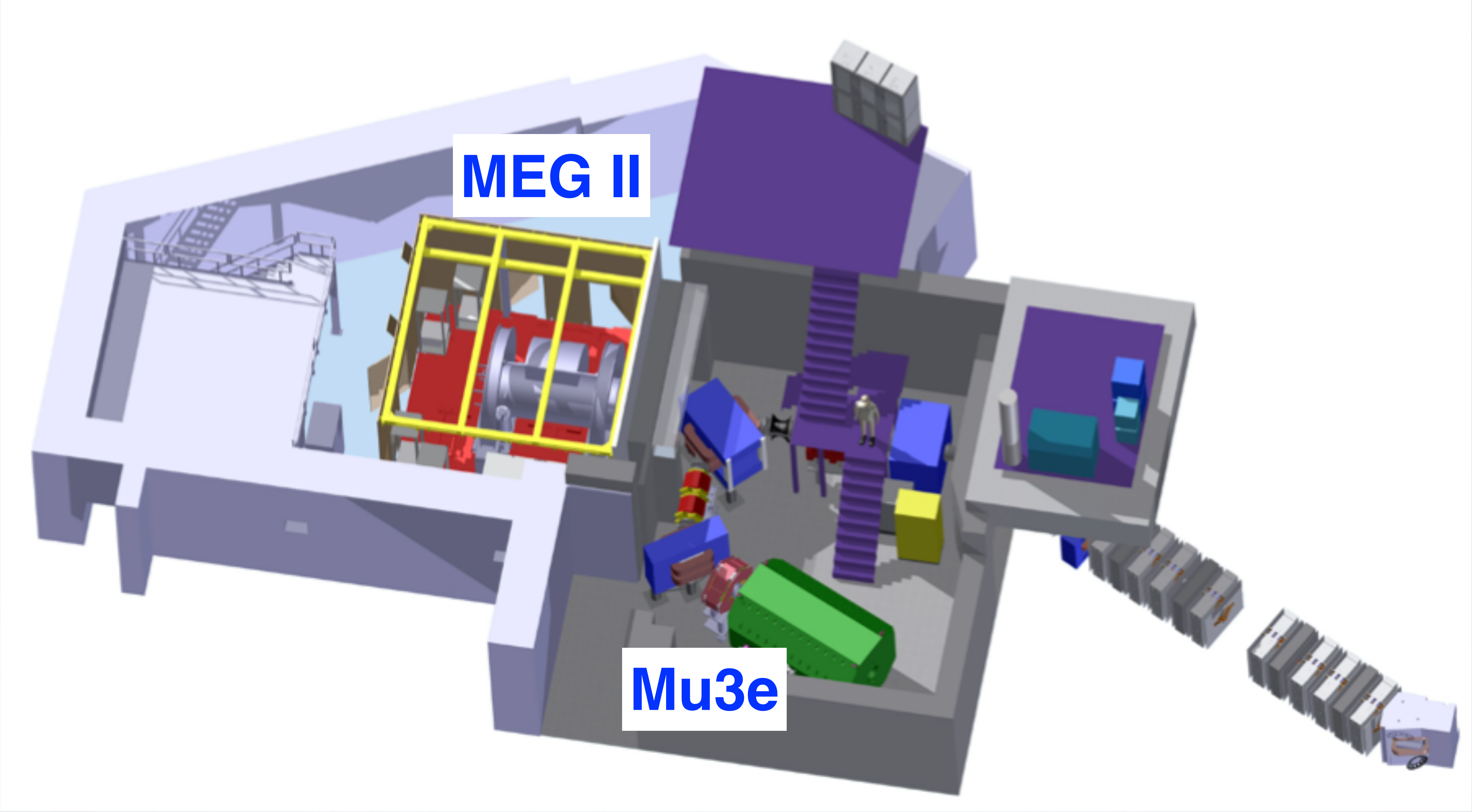


Mu3e



- MEG II engineering run 2018
- Mu3e engineering run 2019

Conflict at πE5 in PSI?



- MEG II and Mu3e will share πE5 beam line in PSI
- MEG II detector can be there even in Mu3e beam time thanks to the compact muon beam line for Mu3e (only upstream side)

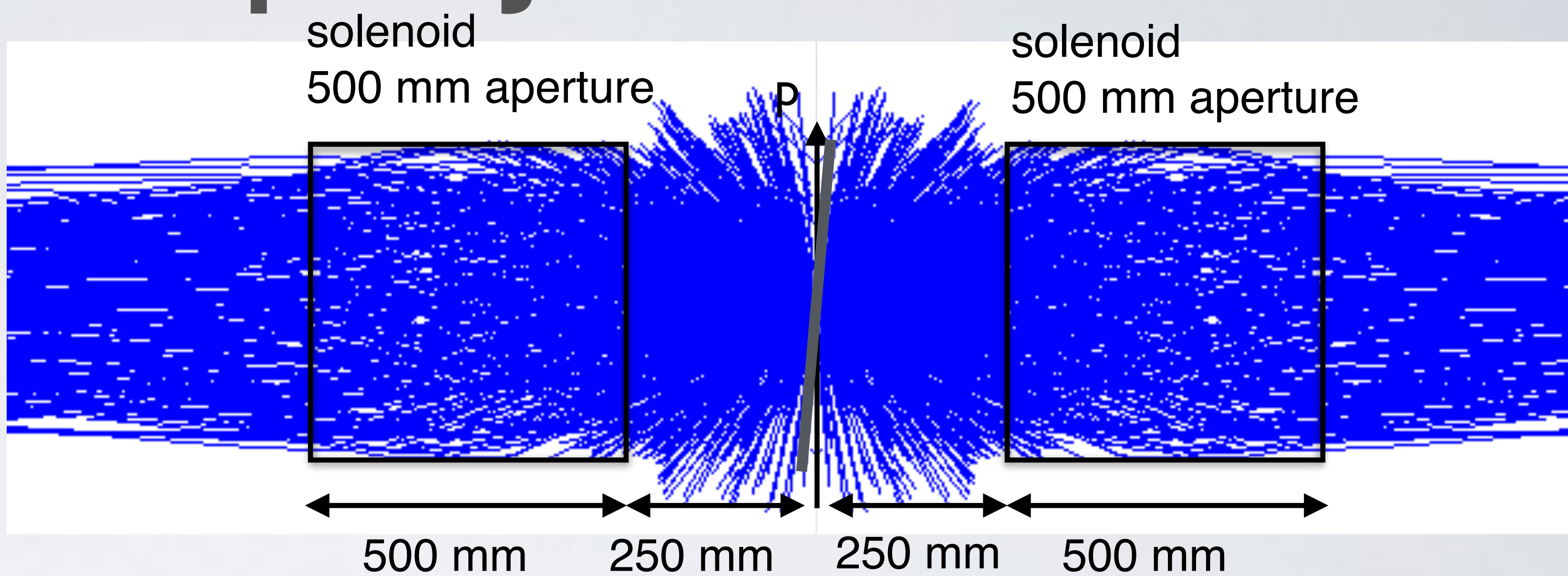
cLFV prospects with DC muon beam

- HiMB project aims at 10^{10}μ/s
  - Main target is Mu3e phase II (10^{-16})
  - Next generation of μ→eγ?

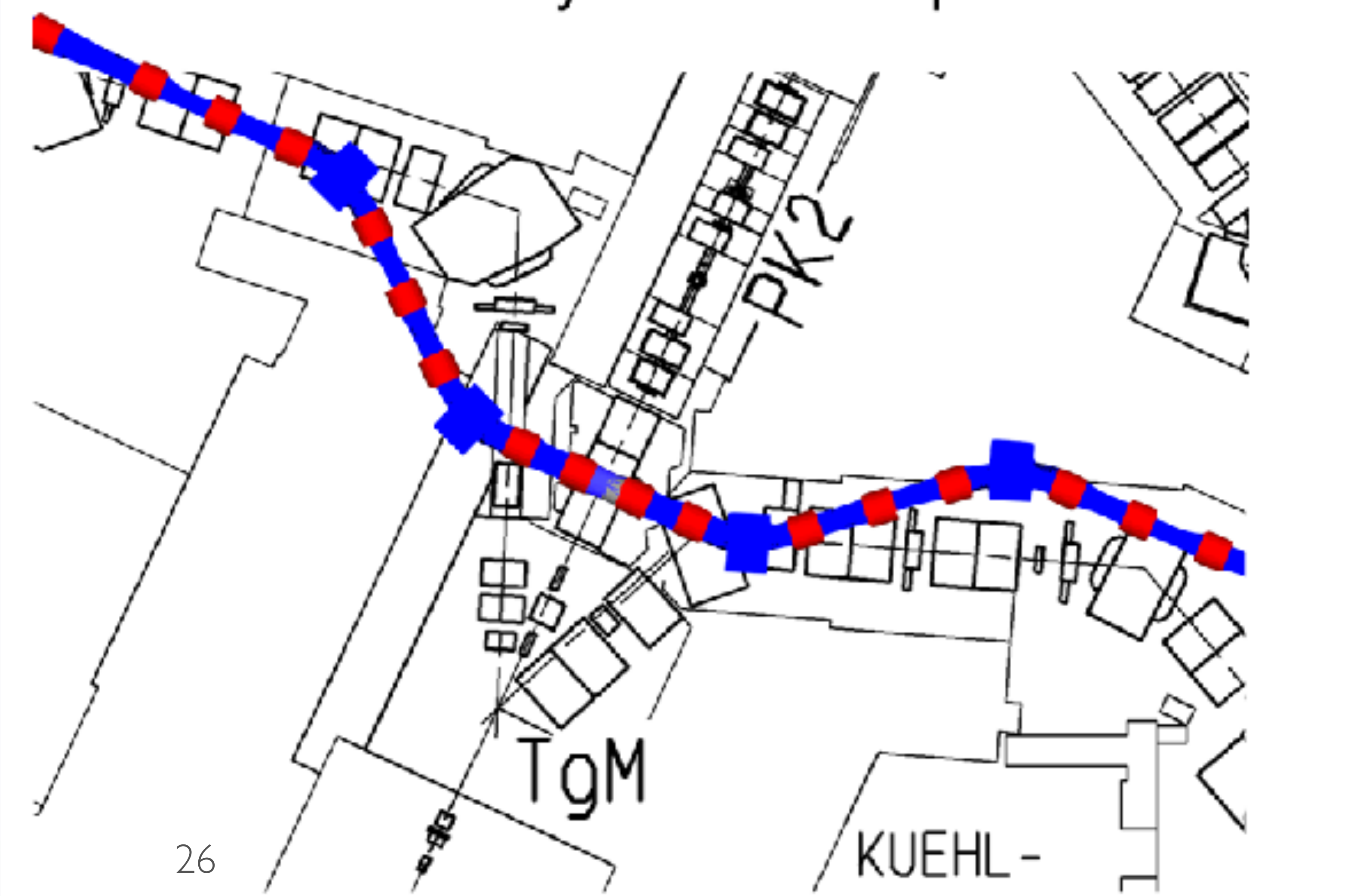
HiMB project

Andreas Knecht

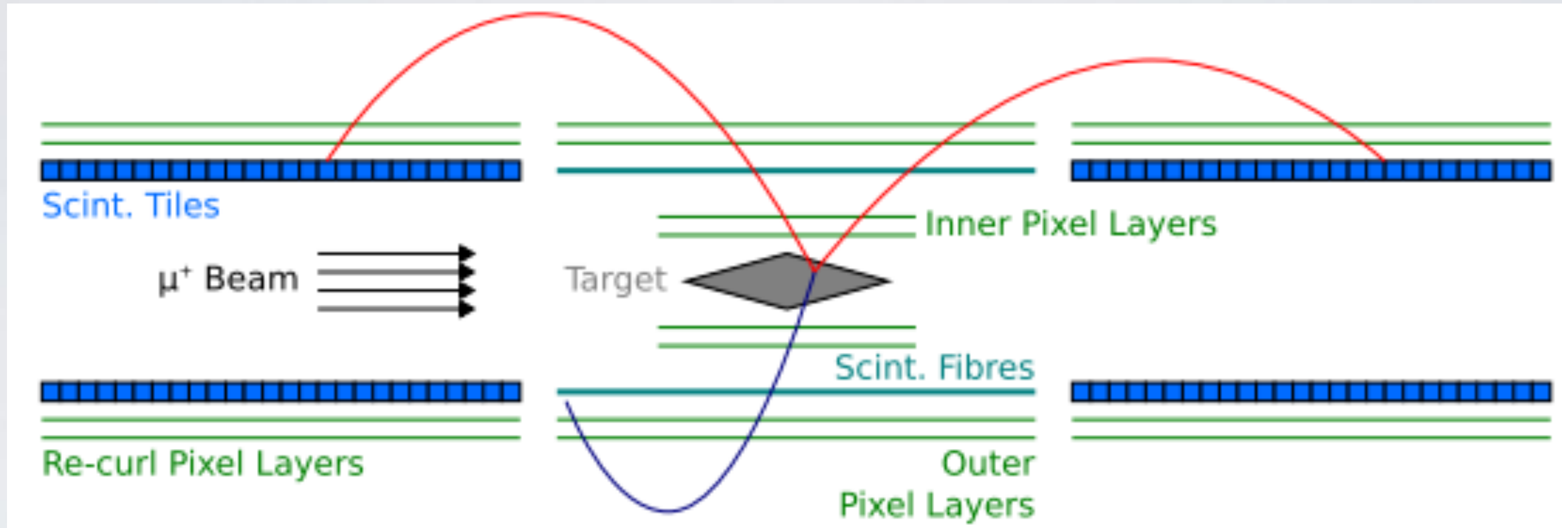
- High intensity Muon Beamline
  - Upgrade plan at PSI
  - Existing target (TgM) to new 20mm effective length 5° slanted target
    - 1.3×10^{11} μ^+/s
  - Capture solenoid (0.35T) at d=250mm
    - $3.4\times10^{10}\mu$/s
  - Solenoidal beam line can transmit (first version of beam optics)
    - $1.3\times10^{10}\mu$/s
- Next : Feasibility test of slant target at target E

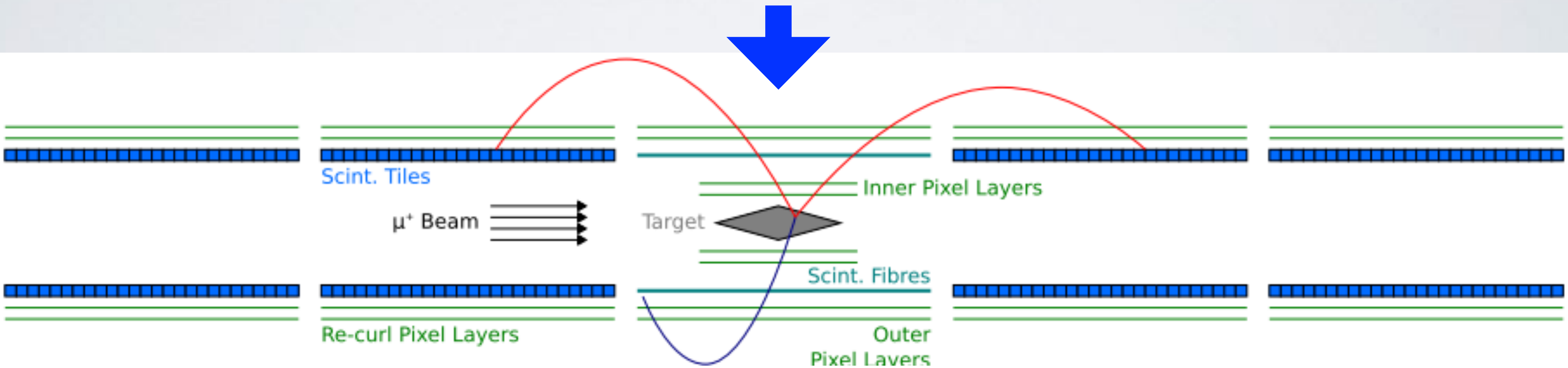


Schematic of the layout in the experimental hall



Mu3e phase II





Sensitivity ~ 10^{-16}

Increase muon stopping rate to $2 \cdot 10^9$ μ/s

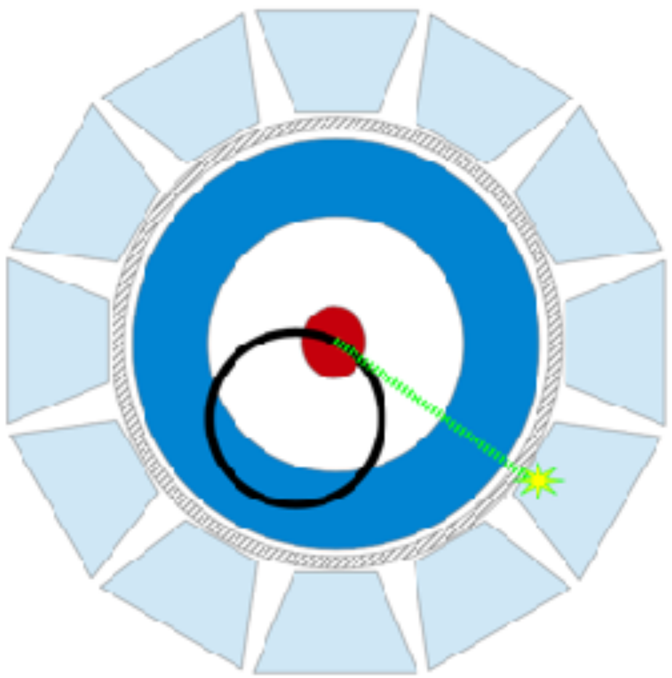
Additional recurl stations increase acceptance for recurler

Smaller beam profile ⇒ smaller target radius

Cecilia Voena

Next generation of μ→eγ searches: photon

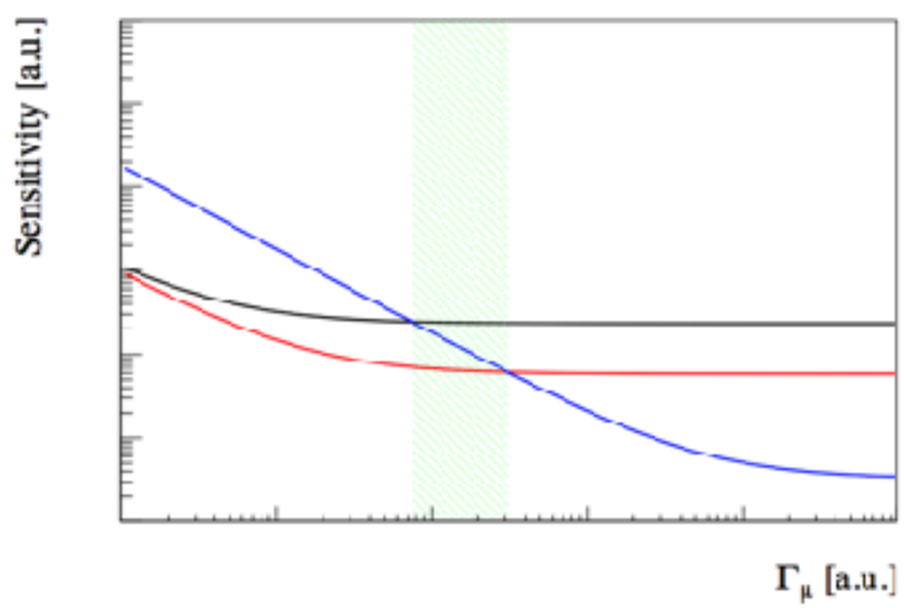
Calorimeter



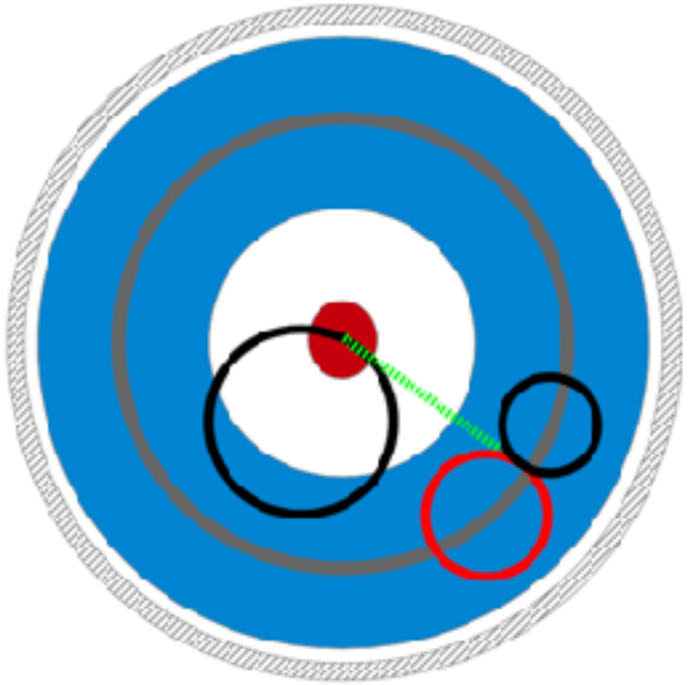
- high efficiency
- good resolution

Requirements:
- high light yield
- fast response

Sensitivity trend vs beam intensity
blue = pair conversion design
black = calorimeter design
red = calorimeter design with x2 resolution



Photon conversion



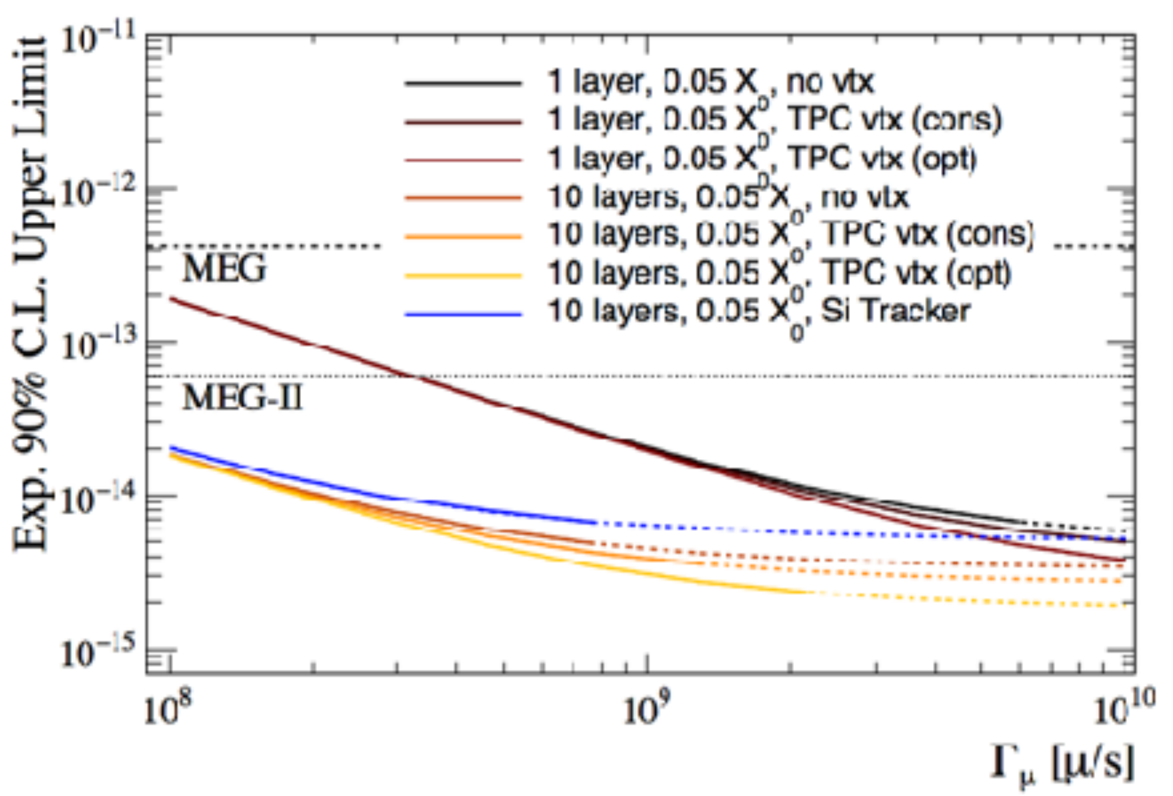
- low efficiency (%)
- extreme resolution
- photon direction

Requirements:
- optimization of converter thickness
(efficiency vs pair energy and angle resolution)

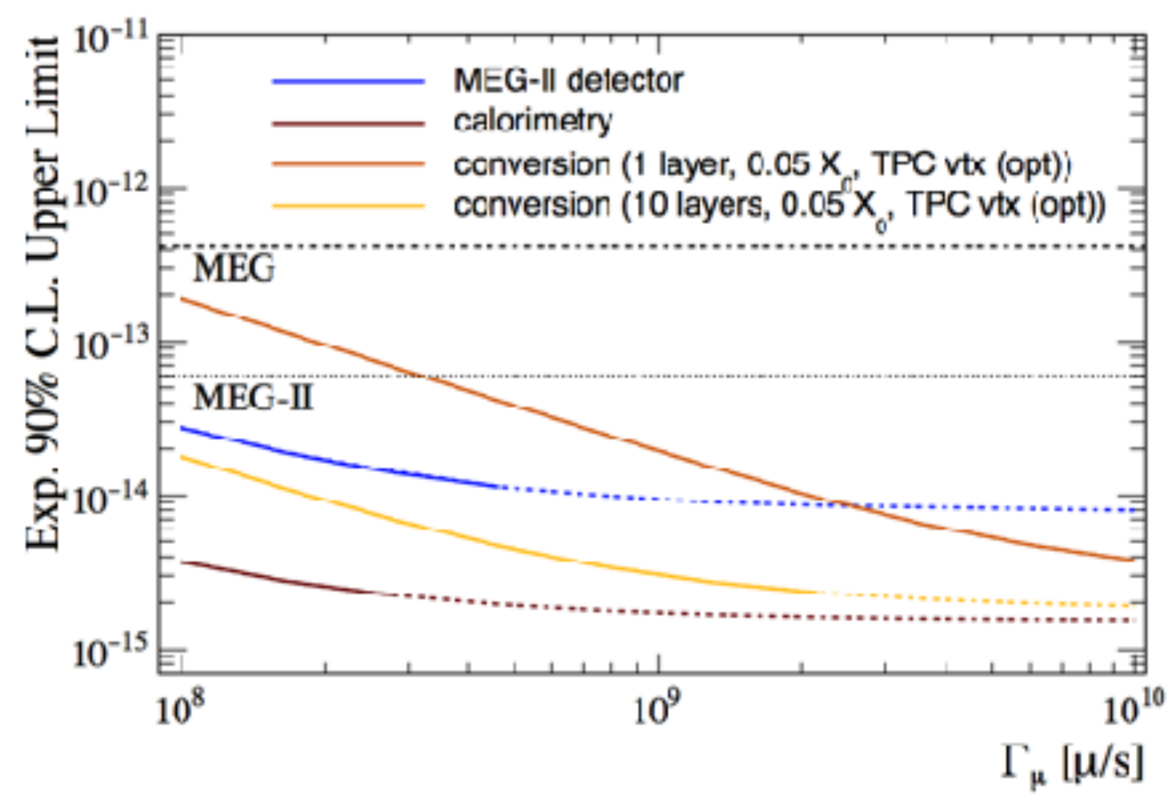
Cecilia Voena

Expected sensitivity

Photon conversion approach



Photon conversion vs calorimetric approach



A few 10^{-15} level seems to be within reach for 3 years running at 10^8 muon/s with calorimetry or 10^9 muons/s with photon conversion

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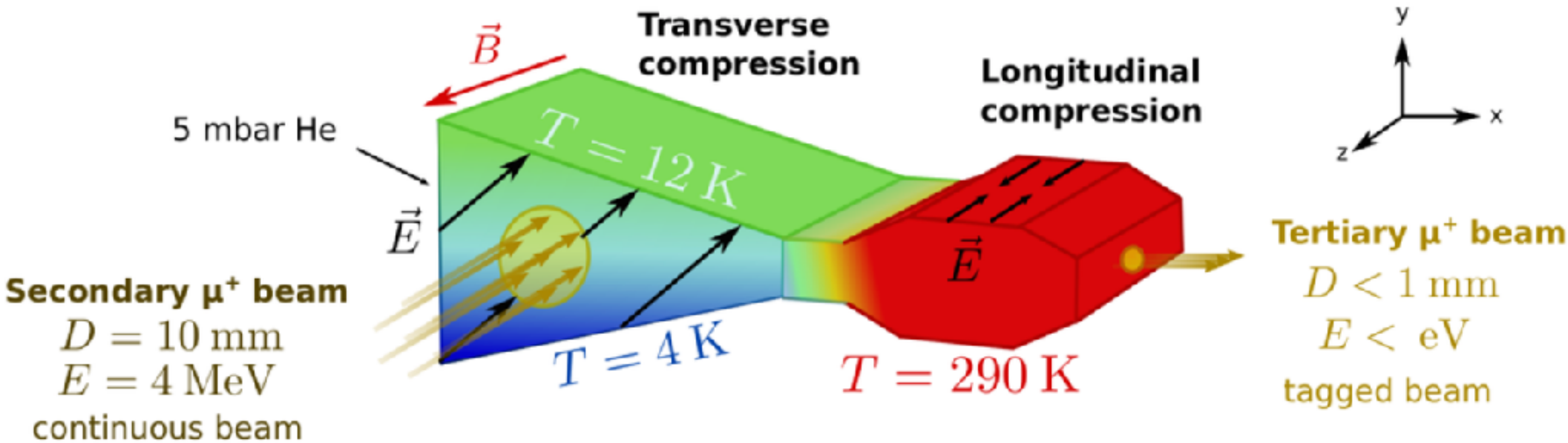
muCool

Ivana Belosevic

D. Taqqu, Phys. Rev. Lett. **97**, 194801 (2006)



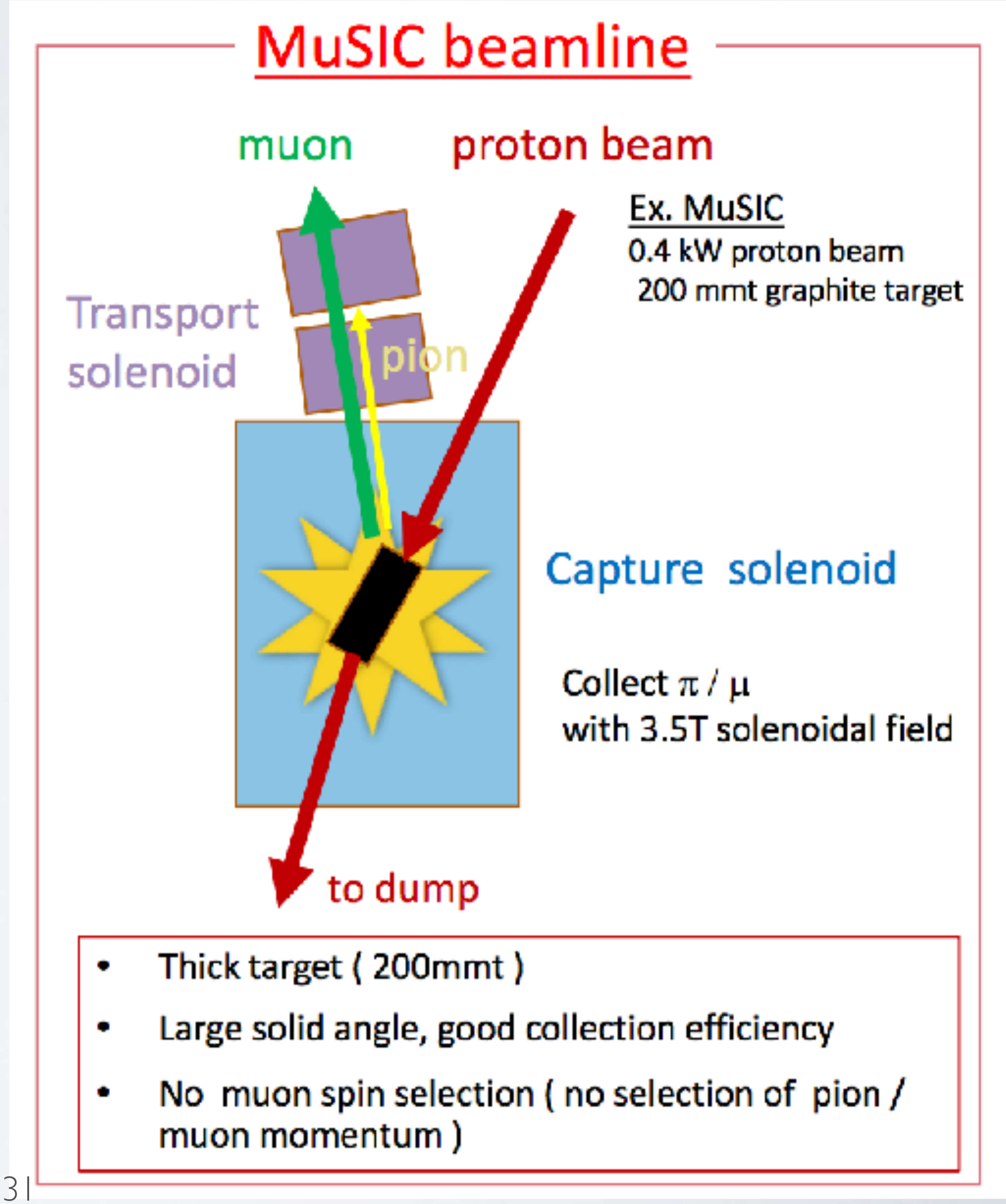
Muon swarm compression inside a He gas target employing position-dependent muon drift velocity.

- Muonium spectroscopy, Gravity of antimatter, μSR etc.
- Improved beam quality for muon g-2, muon EDM
- Transverse, longitudinal compression demonstrated independently
- Next development : combining two stages

MuSIC

Dai Tomono

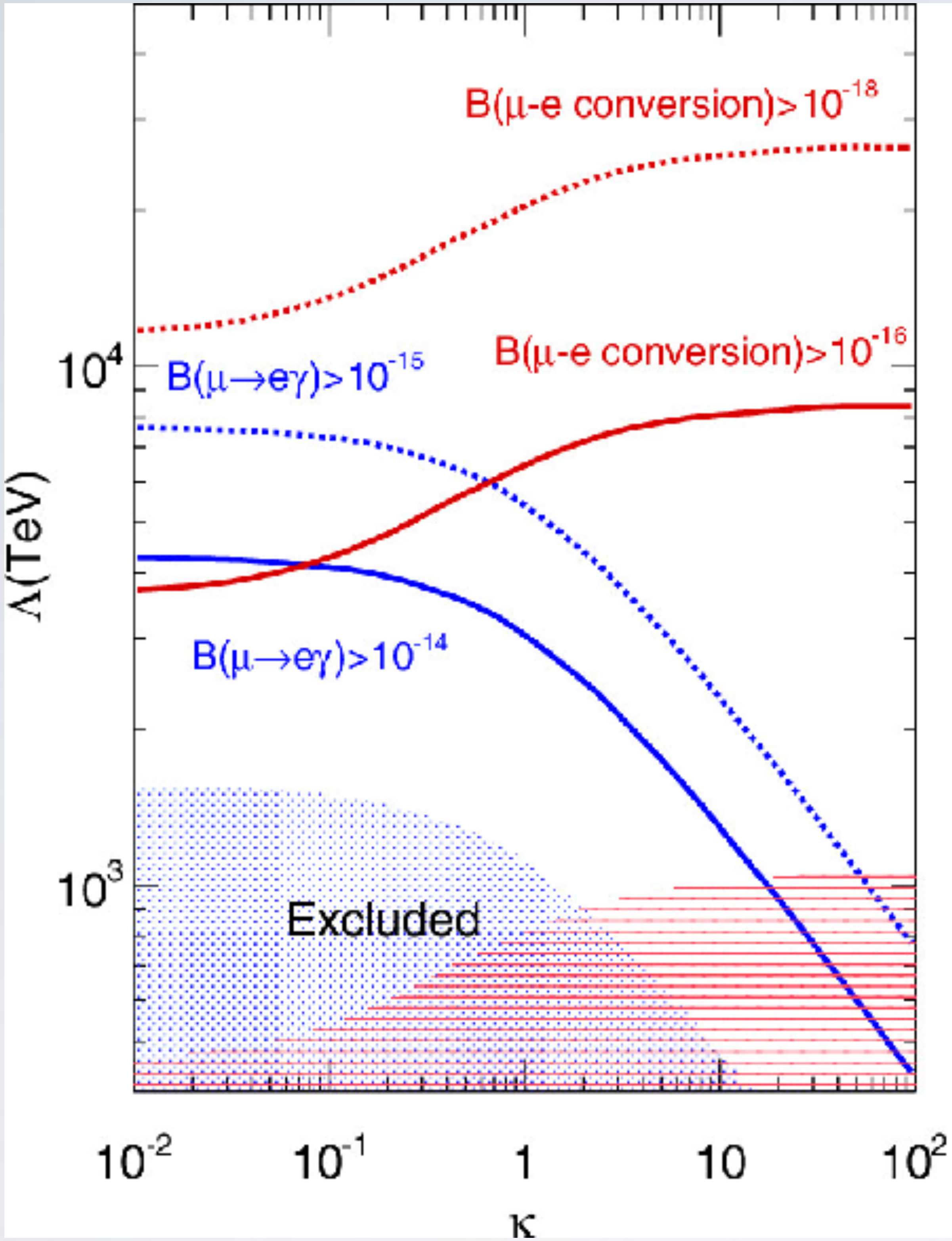
- Muon Science Innovative muon beam Channel
  - @RCNP, Osaka University
  - Ring cyclotron 392MeV, 1μA proton (0.4kW)
  - Thickness of 200 mm graphite target
- World's most efficient DC muon beam source
  - pion capture solenoid + pion collection solenoid + conventional triplet-Q & bends beam line
  - $3\times10^{8}\mu^{+}$/s at capture solenoid
  - 3×10^{4} surface μ^{+}/s at beamline end
- Physics programs
  - Muonic X-ray analysis, non-destructive analysis, μSR, nuclear physics, etc.

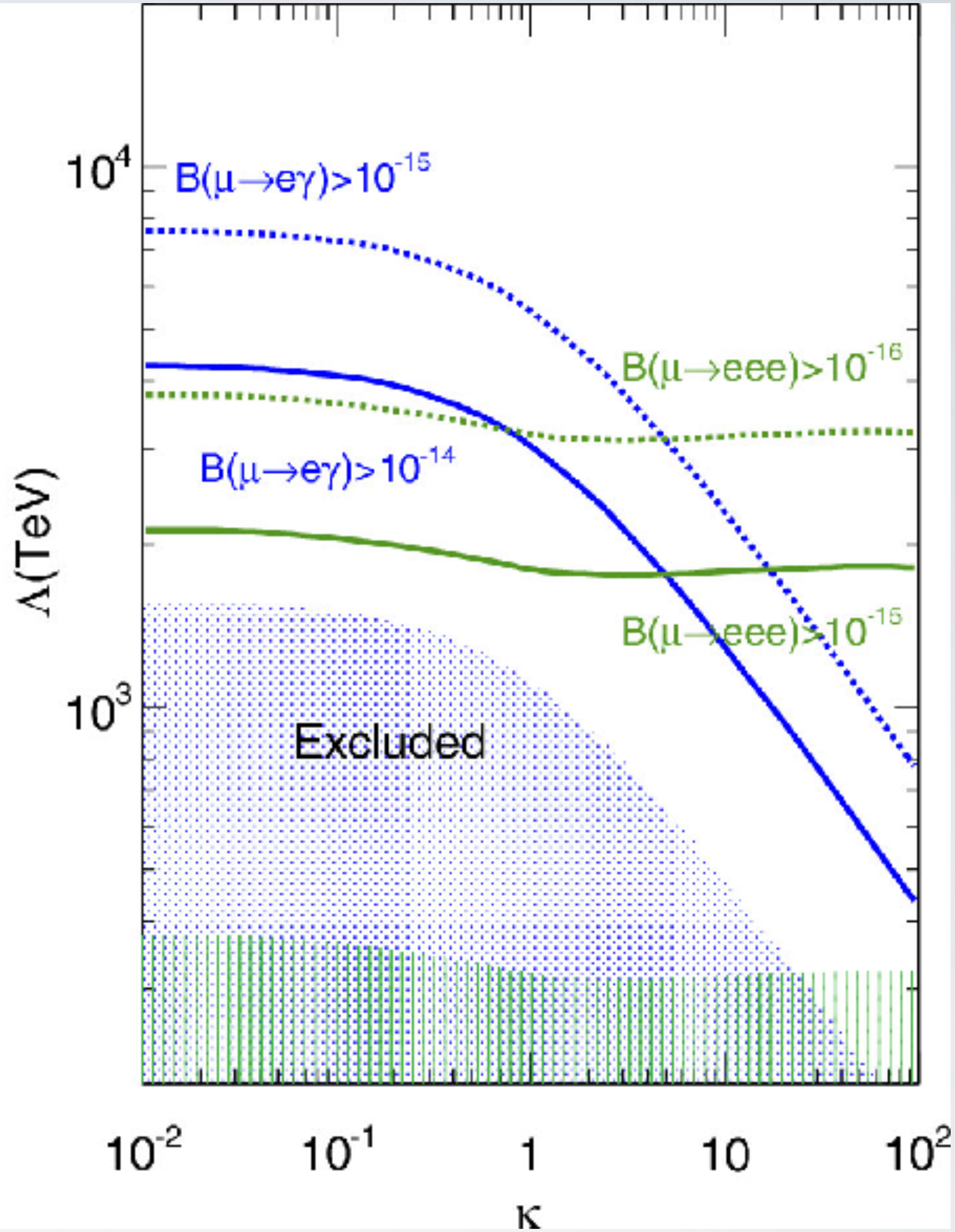


Summary

- CLFV experiments with DC muon beam have real chance to find new physics
- MEG II / Mu3e / DeeMe / COMET / Mu2e will start within ~5 years
- Upgrade projects of DC muon beam are ongoing, and next generation experiments should follow with new technologies.

Backup





$$\mathcal{L}_{\rm CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_{\rm R}\sigma_{\mu\nu}e_{\rm L}F^{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2}\bar{\mu}_{\rm L}\gamma_\mu e_{\rm L}(\bar{u}_{\rm L}\gamma^\mu u_{\rm L} + \bar{d}_{\rm L}\gamma^\mu d_{\rm L}).$$

$$\mathcal{L}_{\rm CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_{\rm R}\sigma_{\mu\nu}e_{\rm L}F^{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2}\bar{\mu}_{\rm L}\gamma_\mu e_{\rm L}(\bar{e}\gamma^\mu e)$$

μ→eγ equivalent BR

$$\frac{R_{\mu e}}{\mathcal{B}(\mu \to e\gamma)} = \frac{G_F^2 m_\mu^4}{96\pi^3\alpha}(3 \times 10^{12})B(A,Z) \simeq \frac{B(A,Z)}{428},$$

$$R(\mu^- \mathrm{Al} \to e^- \mathrm{Al})/\mathcal{B}(\mu \to e\gamma) \simeq 2.6 \times 10^{-3}$$

$$\frac{\mathcal{B}(\mu \to 3e)}{\mathcal{B}(\mu \to e\gamma)} \simeq \frac{\alpha}{3\pi}\left[\ln\left(\frac{m_e^2}{m_\mu^2}\right) - \frac{11}{4}\right] \simeq 6 \times 10^{-3}$$

SINDRUM @ PSI (~ 80s)

beam (πE3 beamline @ PSI):

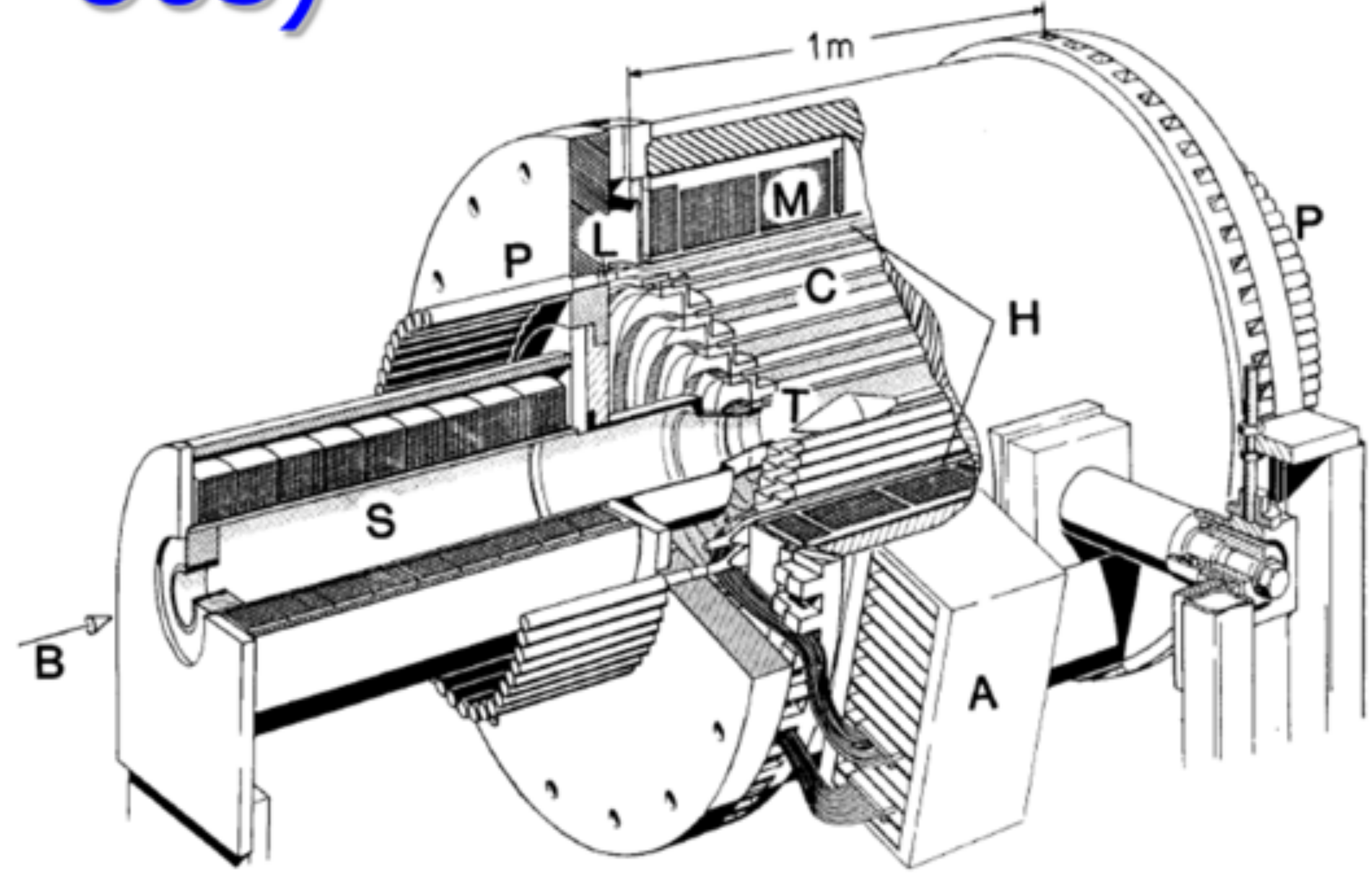
- $5 \times 10^6\ \mu$ / sec
- 28 MeV/c surface muons

resolution:

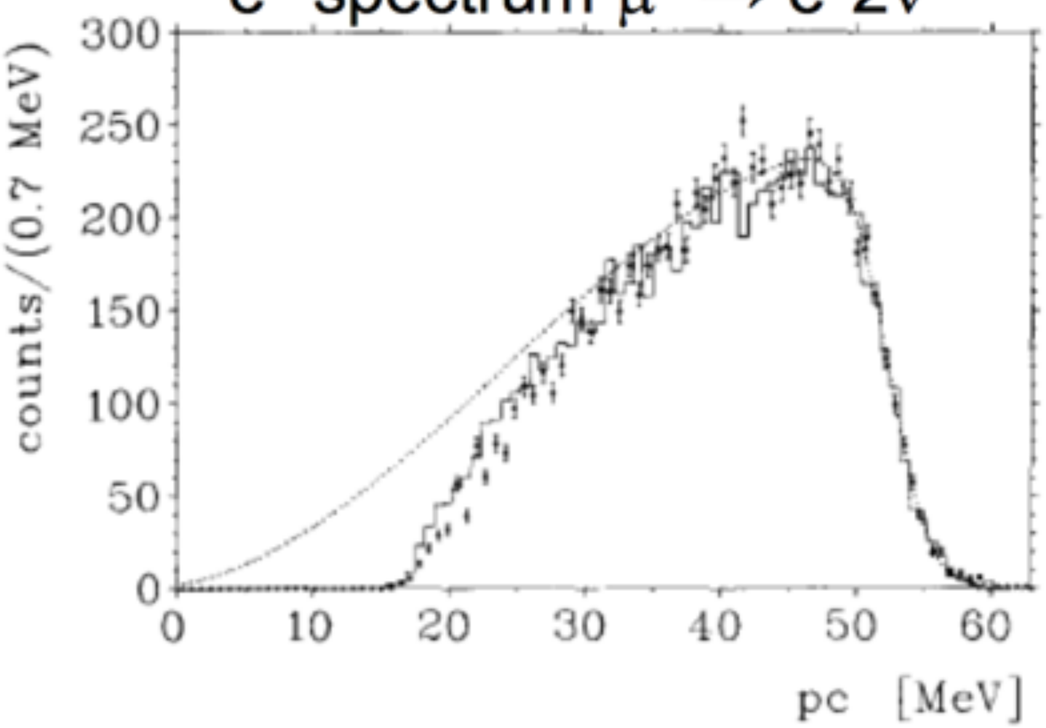
- $\sigma(p_T) = 0.7$ MeV/c^2
- vertex ~ 1 mm

statistics limited!

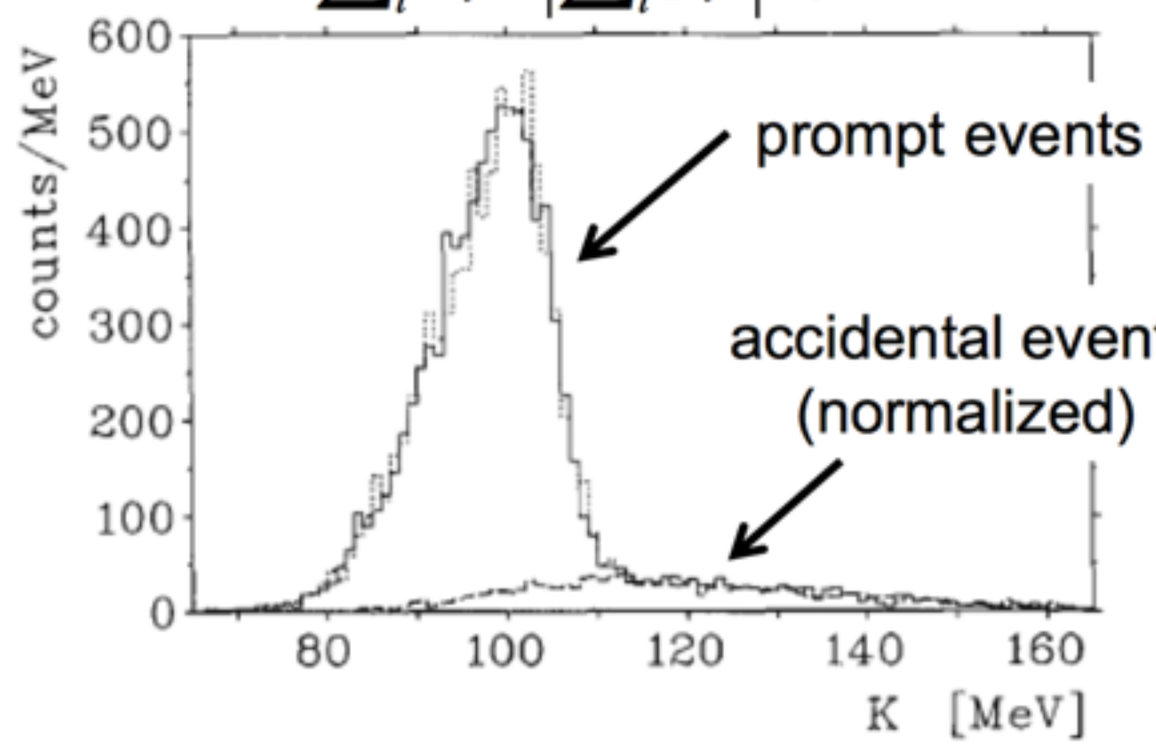
$$\frac{\Gamma\left(\mu^+ \to e^+e^-e^+\right)}{\Gamma\left(\mu^+ \to e^+\bar{\nu}_\mu\nu_e\right)} < 10^{-12} \quad (90\%\ \mathrm{CL})$$



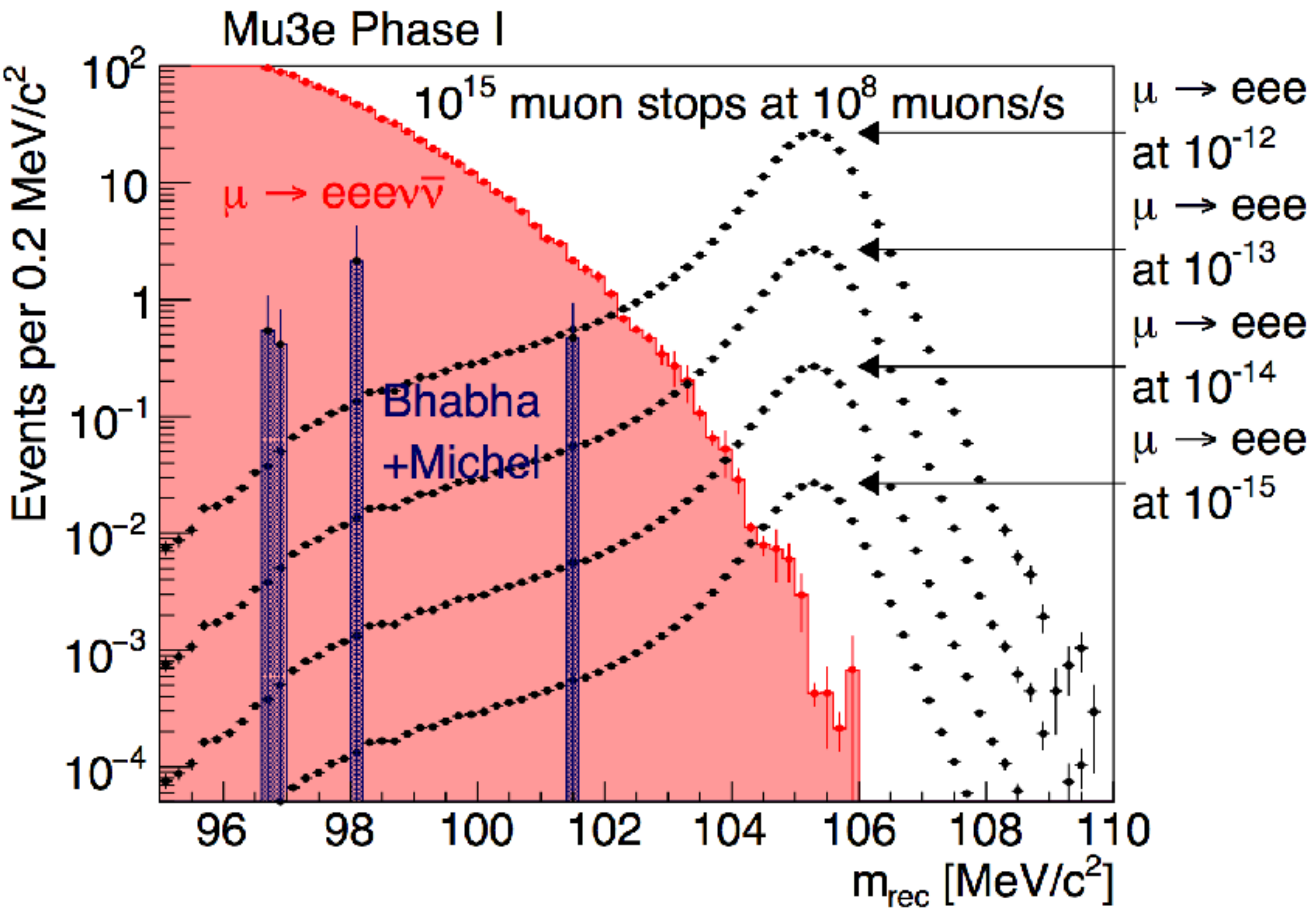
e$^+$ spectrum $\mu^+ \to e^+2\nu$



$K = \sum_i E_i + \left|\sum_i \vec{p}_i c\right| \quad \mu \to 3e2\nu$

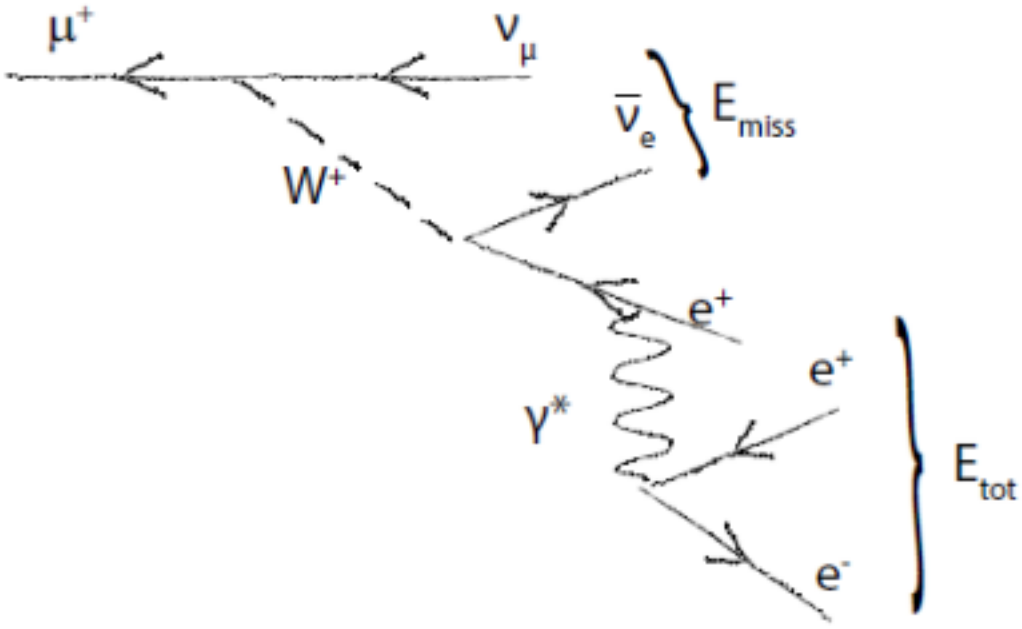


Simulation Results for Phase I

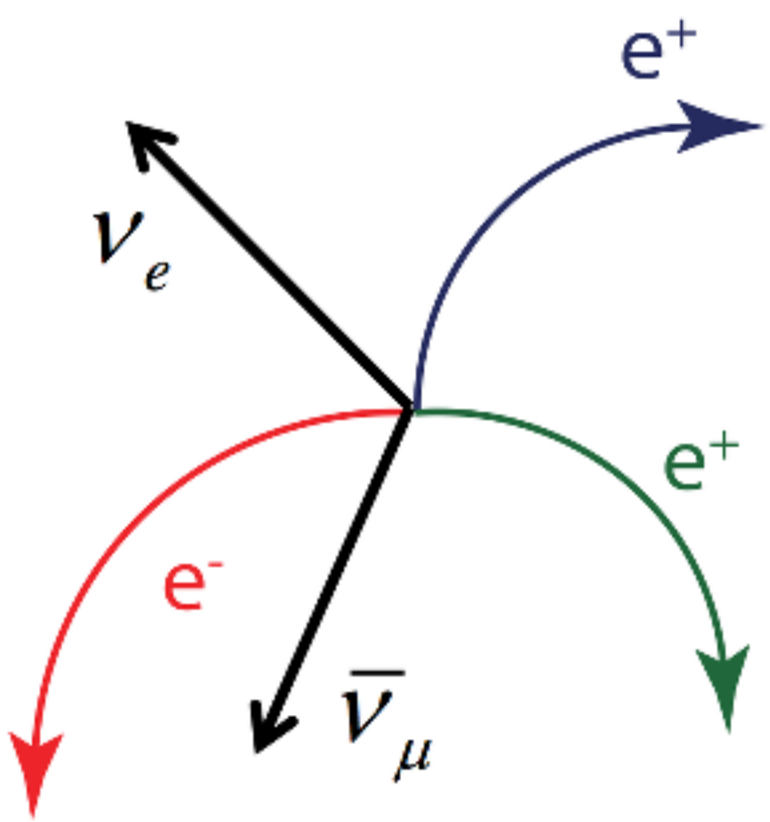


Irreducible Background

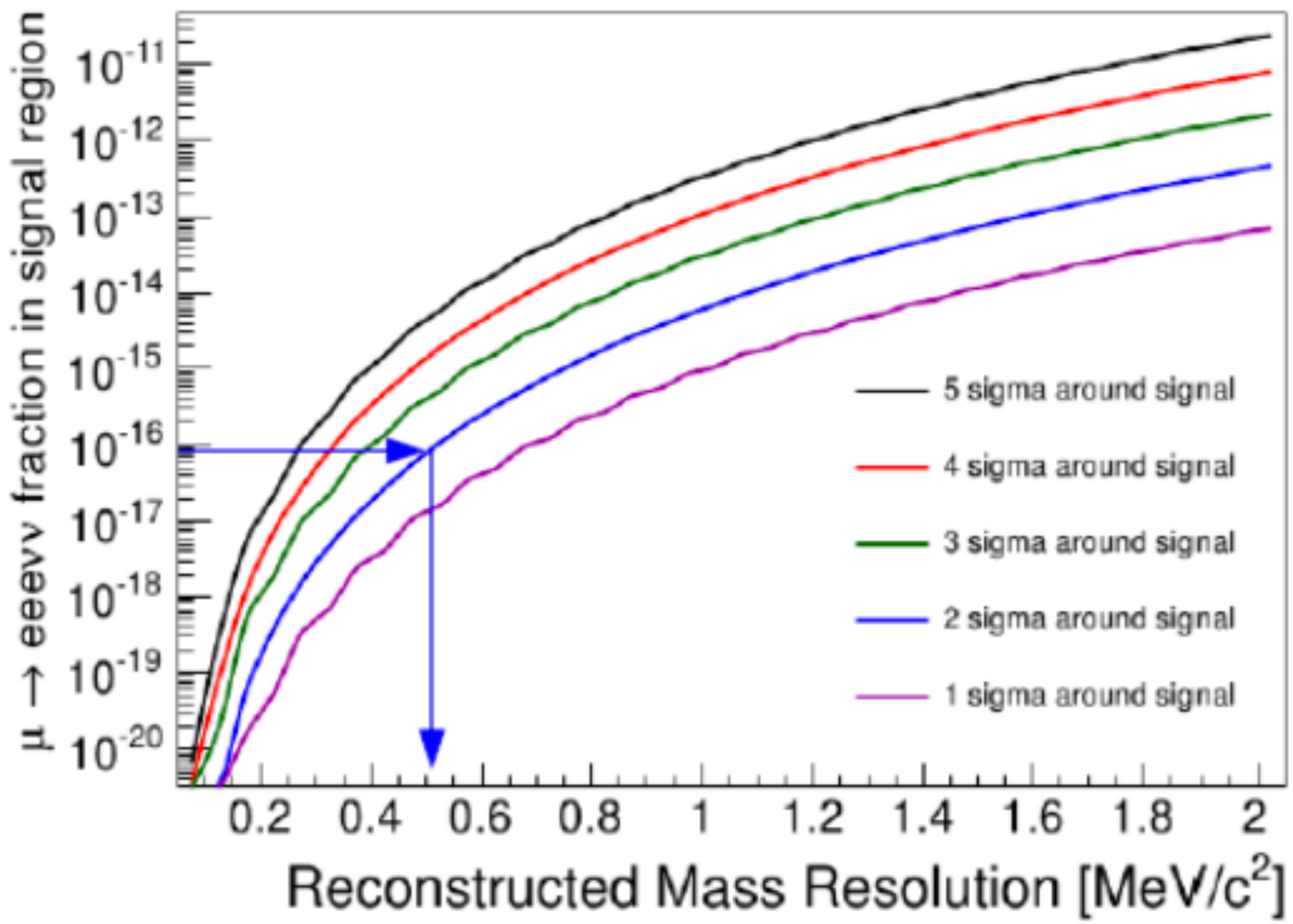
μ radiative decay with internal conversion



BR ($\mu^+ \rightarrow e^+ e^- e^+ \nu_e \nu_\mu$) = 3.5 x 10^{-5}



$\mu^+ \rightarrow e^+ e^- e^+ \nu_e \nu_\mu$ fraction in signal region as a function of Δm_μ



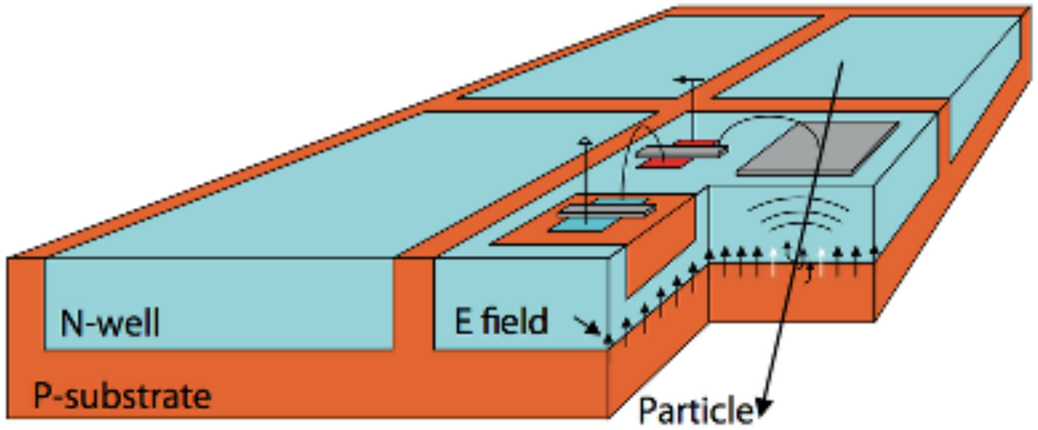
high momentum and energy resolution to suppress this background

$\Delta m_\mu < 0.5$ MeV/c^2

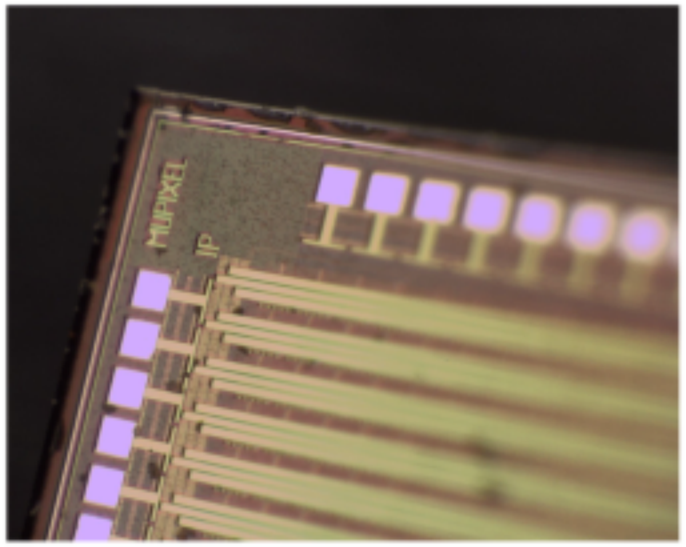
Pixel Sensors: HV-MAPS

High Voltage Monolithic Active Pixel Sensors

- AMS 180 nm HV-CMOS process
- N-well in p-substrate
- Reverse bias of ~ 80 V
  - Fast charge collection via drift
  - Depletion zone of ~ (10 – 20) µm
    Thinning possible (≲ 50 µm)
- Integrated readout electronics
  - Signal amplification and shaping in N-well
  - Digitisation and zero-suppression in periphery
- Pixel size $80 \times 80 \mu m^2$
  Sensor size $2 \times 2 cm^2$

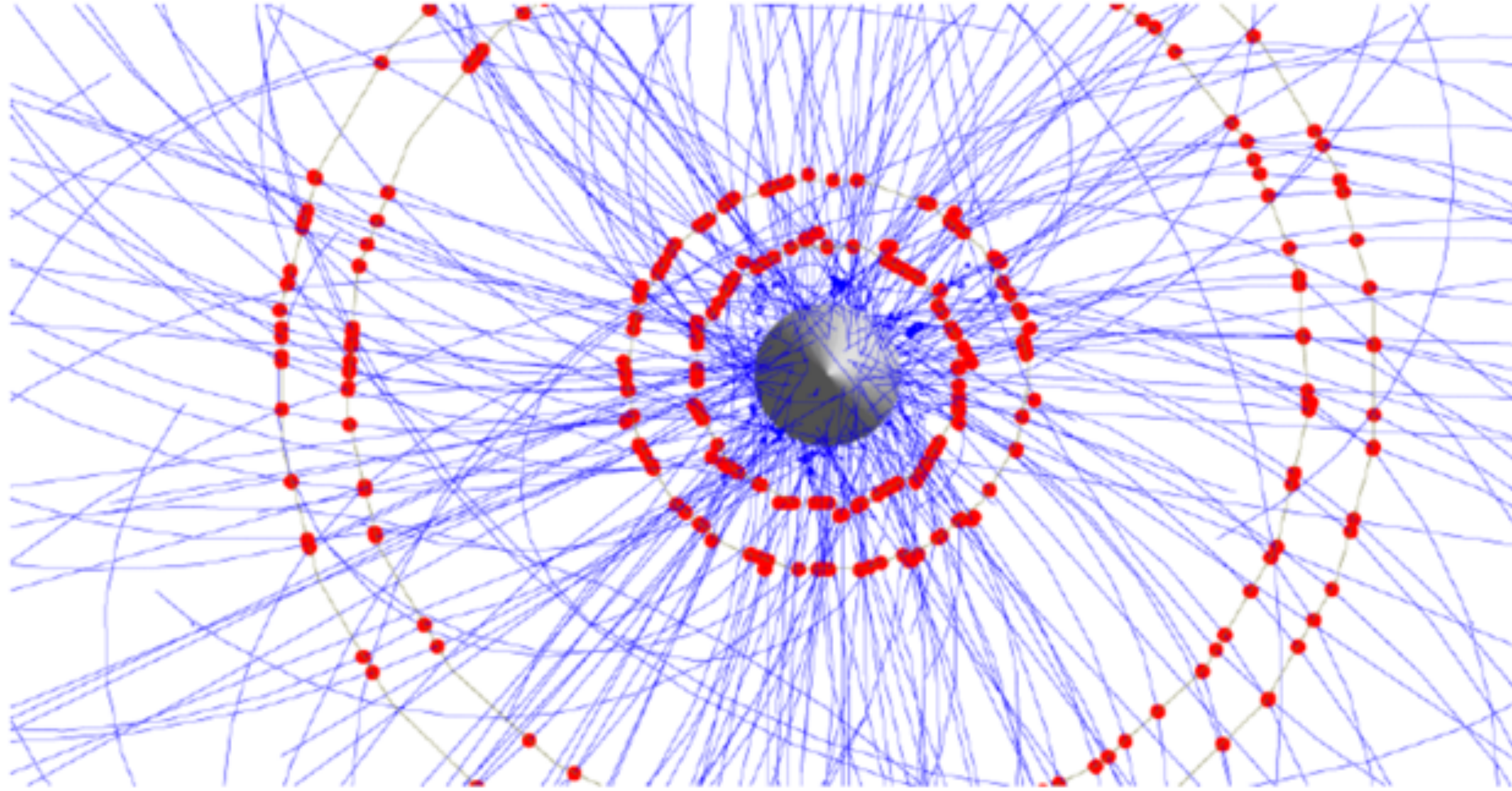


I. Perić, NIM A 582 (2007)

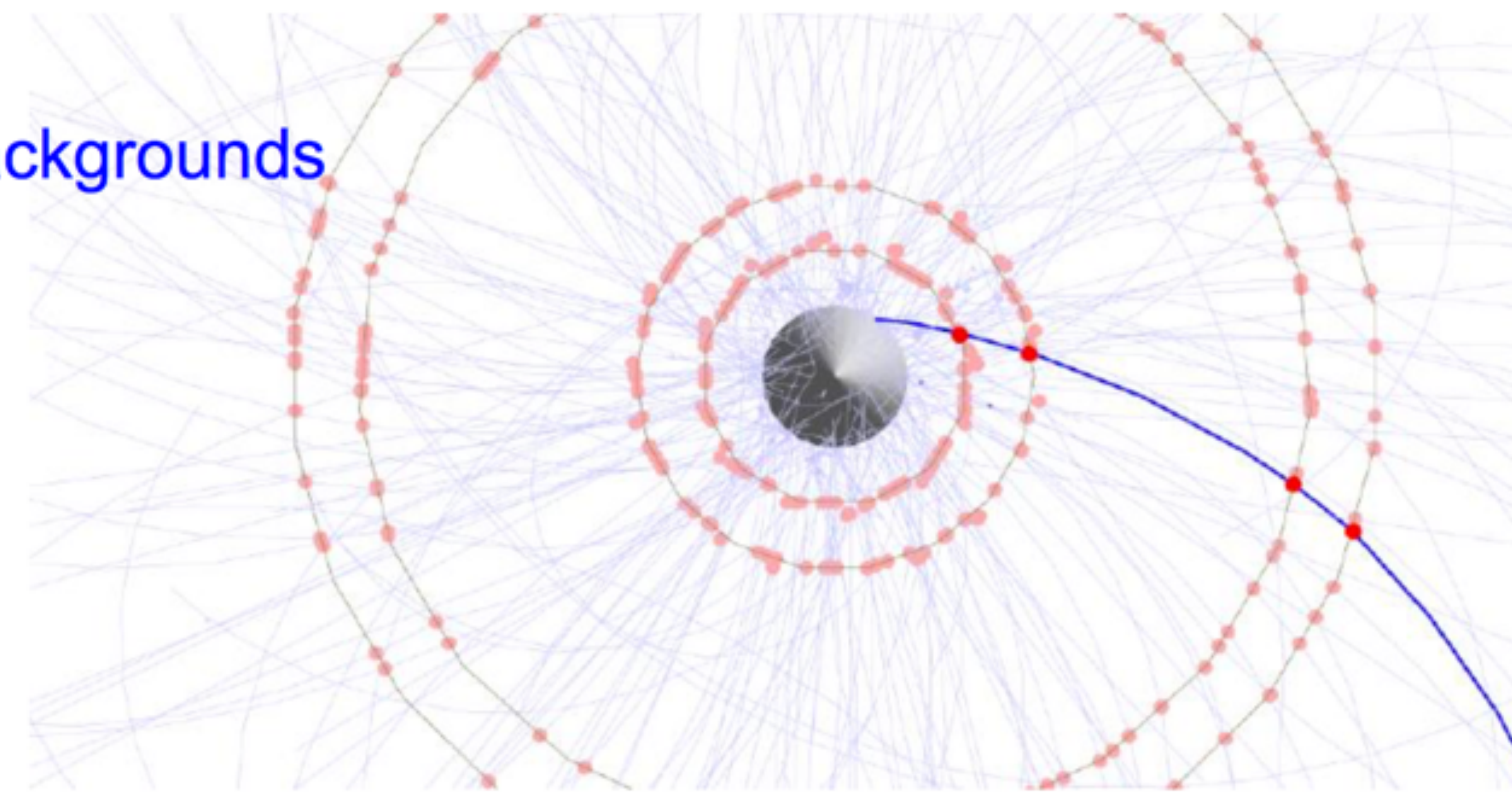


Timing

50 ns snapshot (readout frame): 100 μ decays



additional ToF information < 500 ps



to suppress accidental backgrounds requires excellent timing

< 500 ps SciFis

< 100 ps scint. tiles