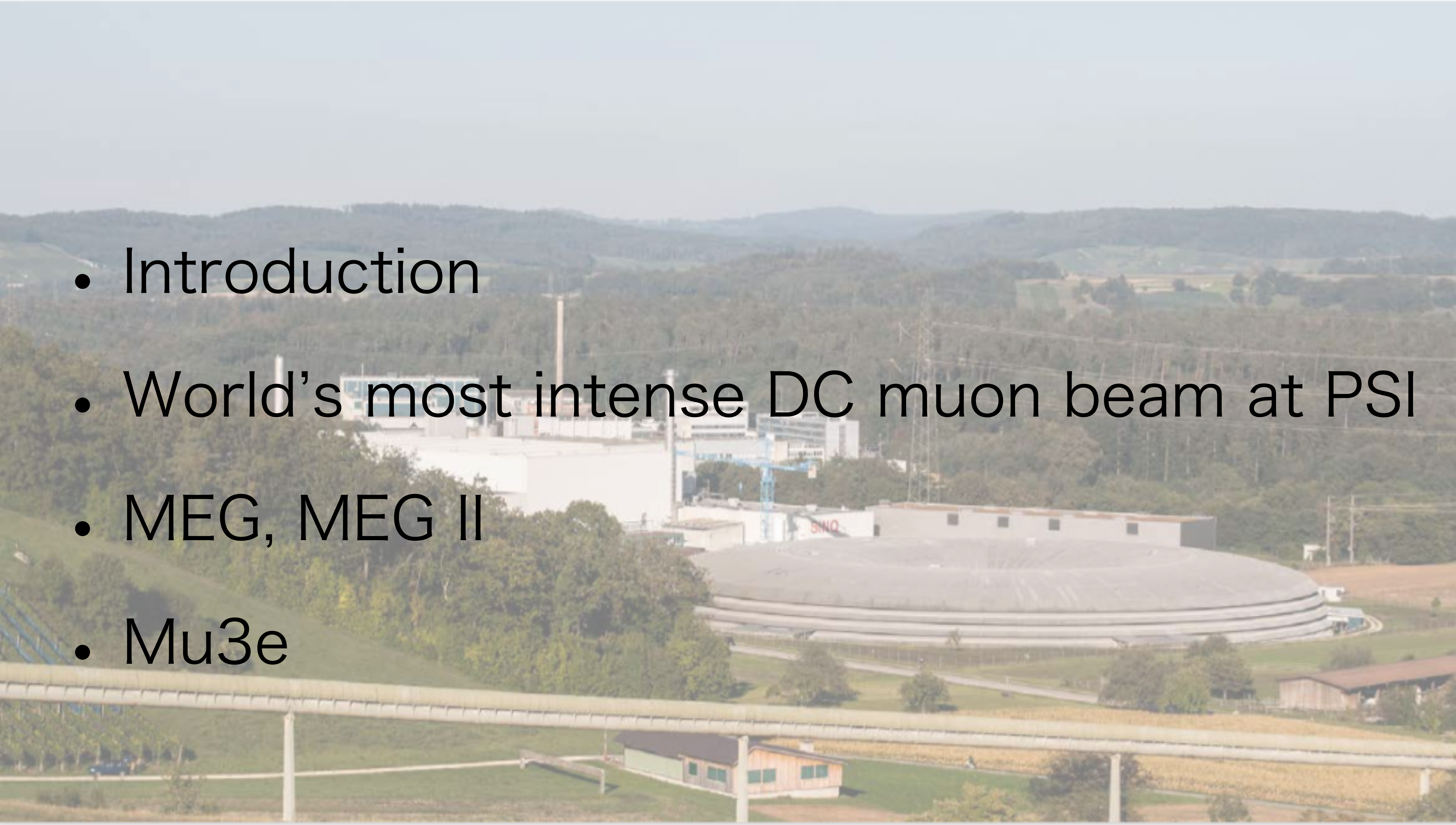
# cLFV searches using DC muon beam at PSI

Satoshi MIHARA
KEK / Sokendai

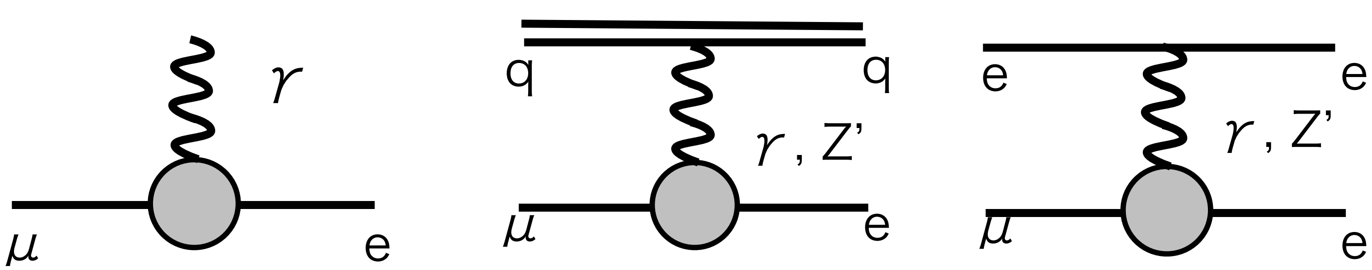
# Contents

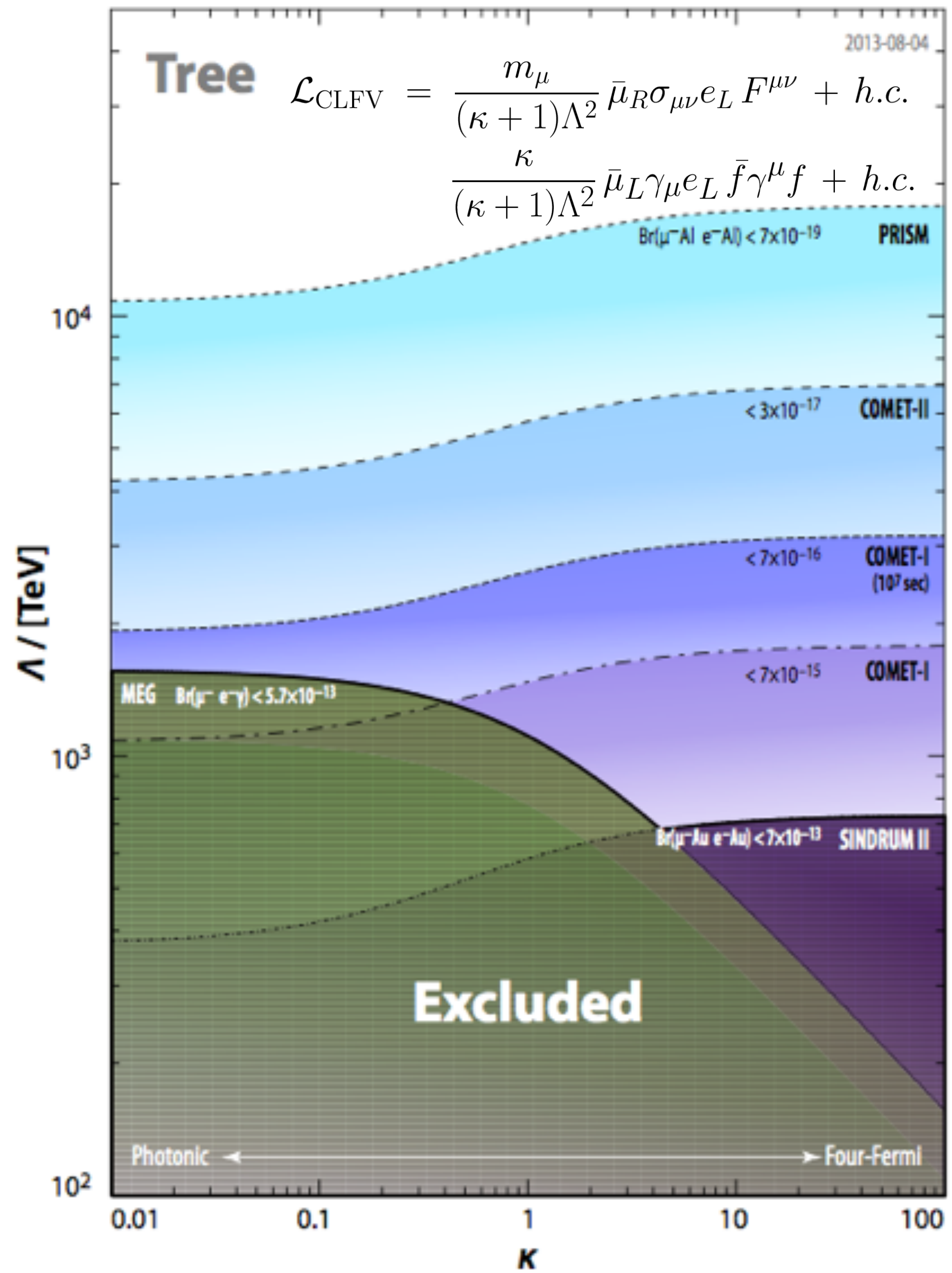


- Introduction
- World's most intense DC muon beam at PSI
- MEG, MEG II
- Mu3e

# cLFV Searches using muon

- No sign of new physics from High Energy Frontier experiments so far
- Survey a large area in high energy region using forbidden process in SM with extremely large statistics
  - Role of Flavor Physics
- No SM background in muon LFV process
- Intense muon beam at high-power proton machines



# DC or Pulse?

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  - $\mu \to e \gamma$, $\mu \to e\ e\ e$

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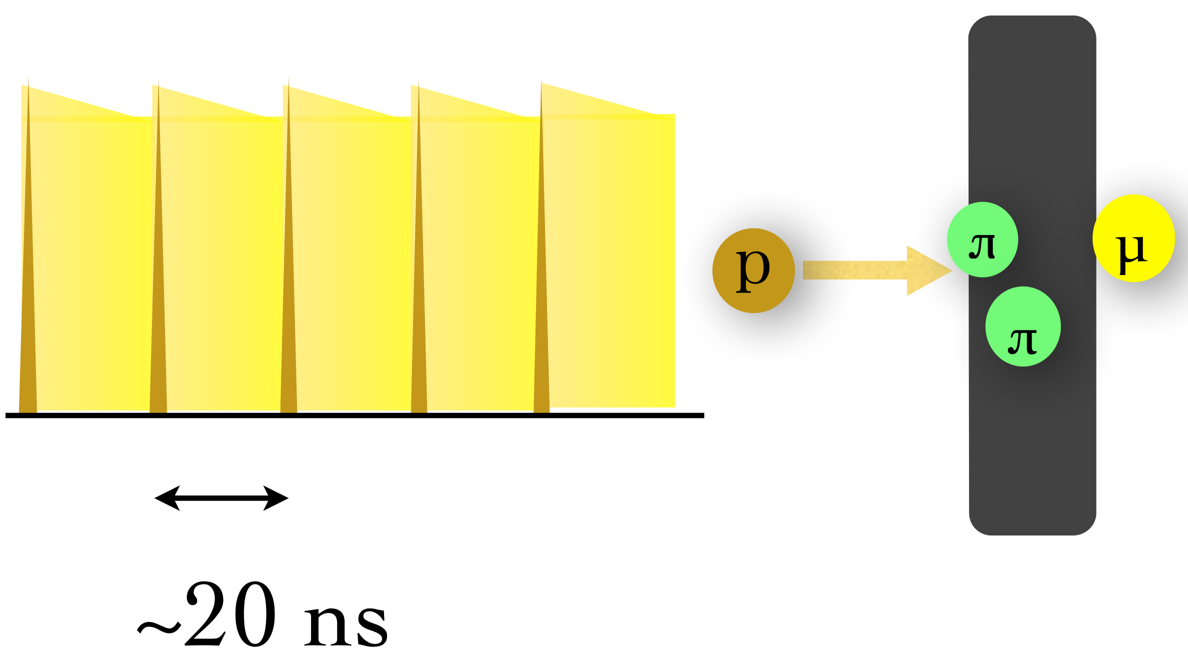

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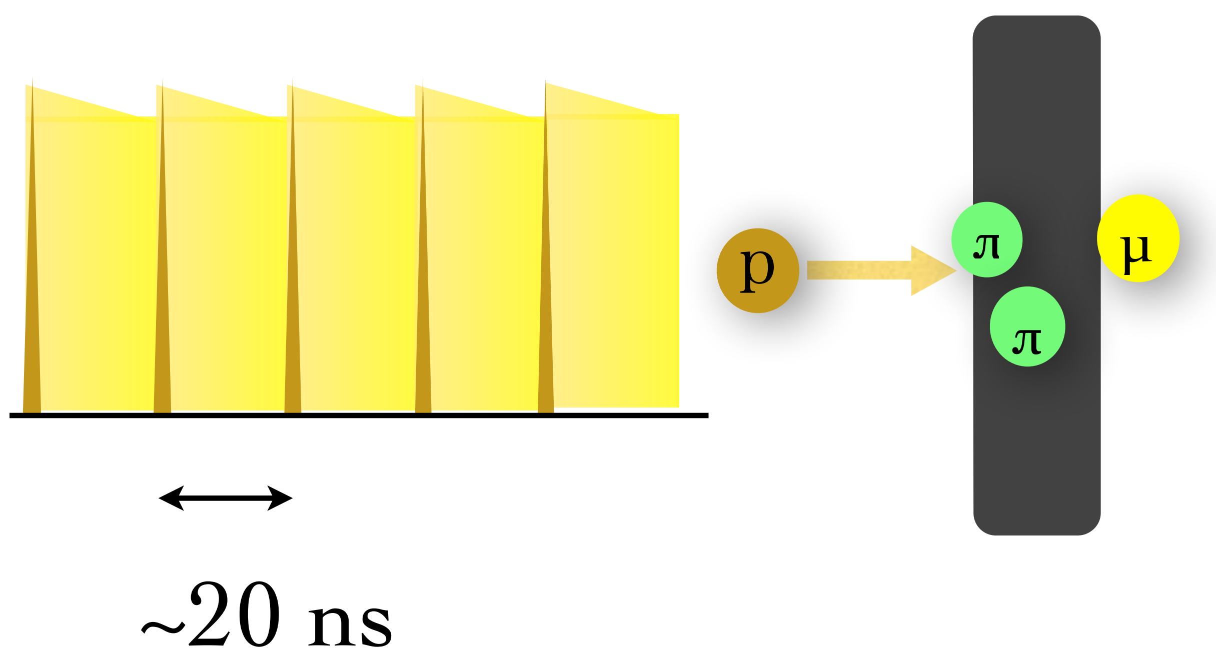
  - $\mu$-e conversion



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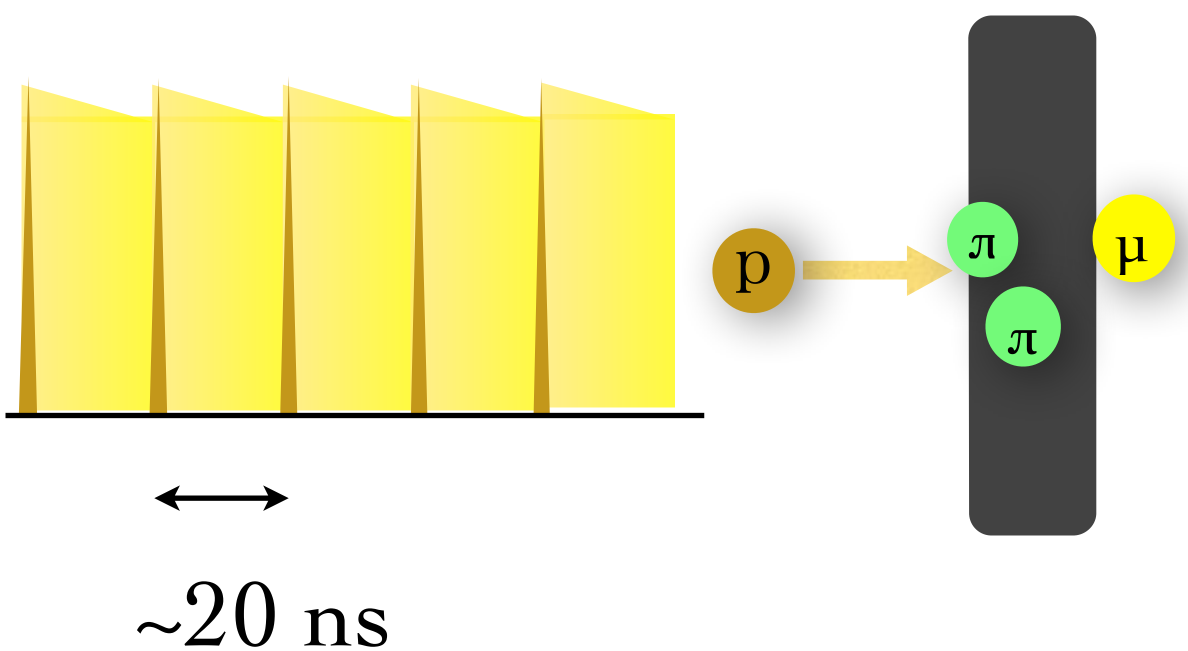
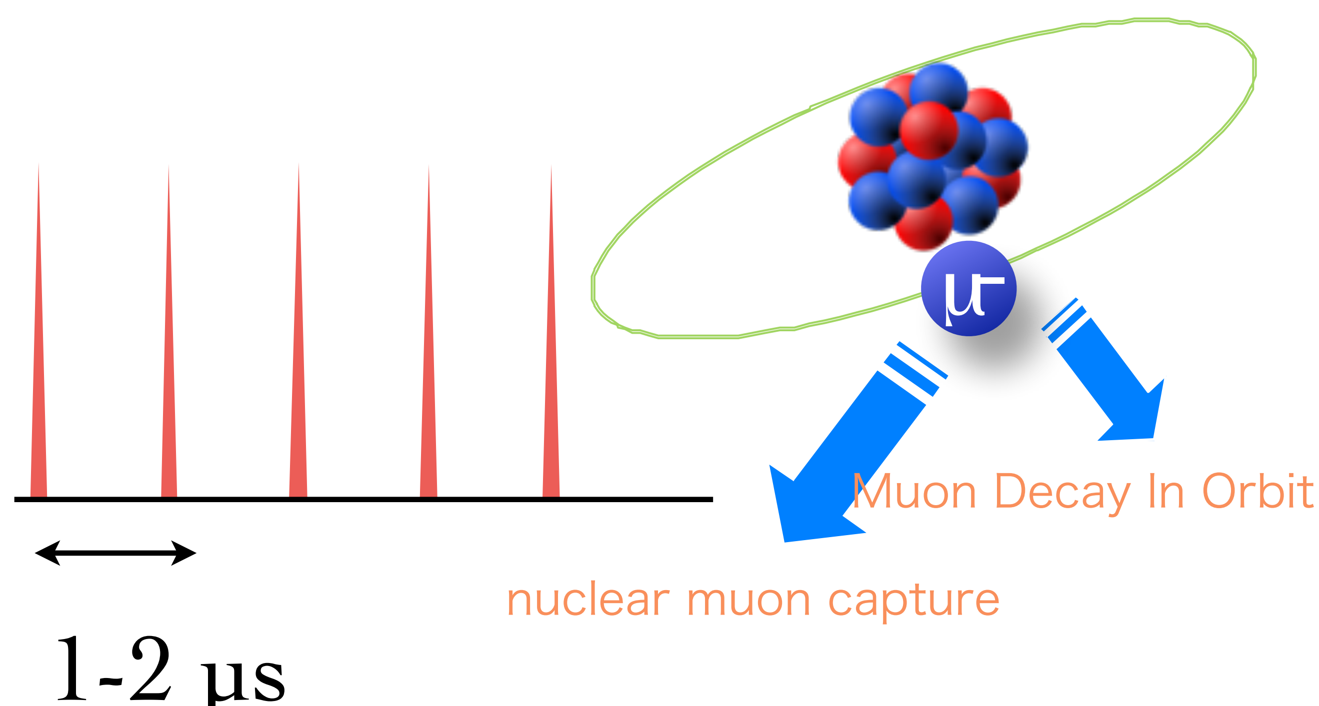
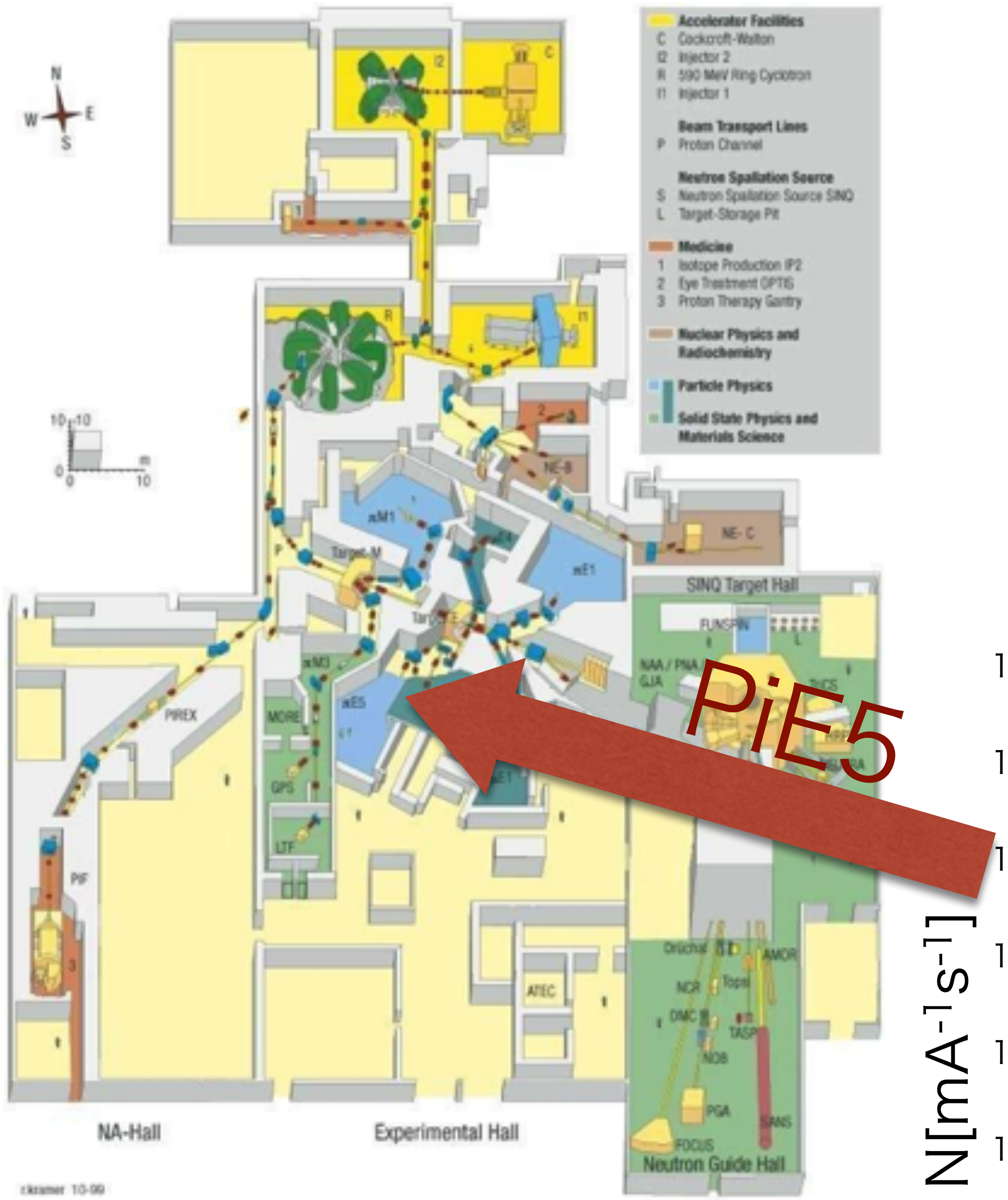


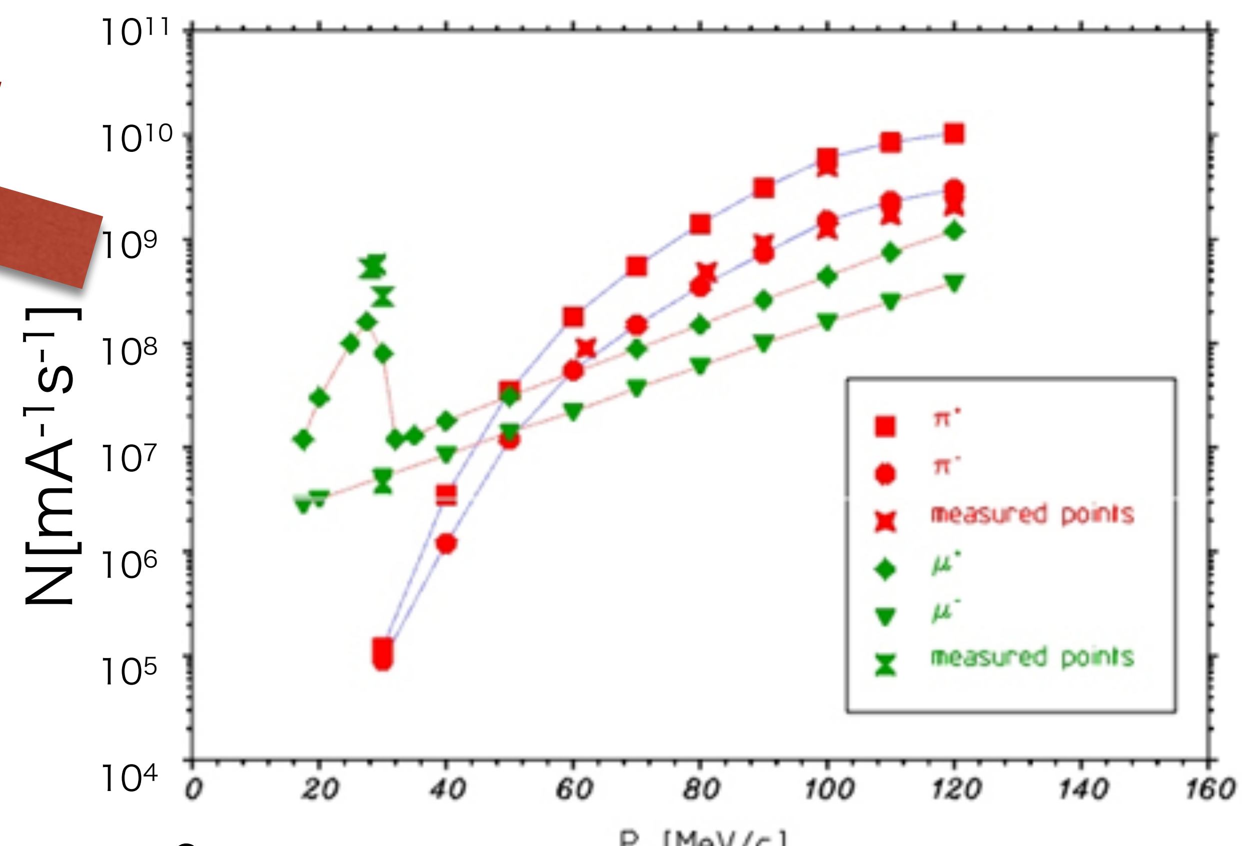
# PSI Cyclotron

- 2.2mA at 590 MeV: 1.3MW beam power

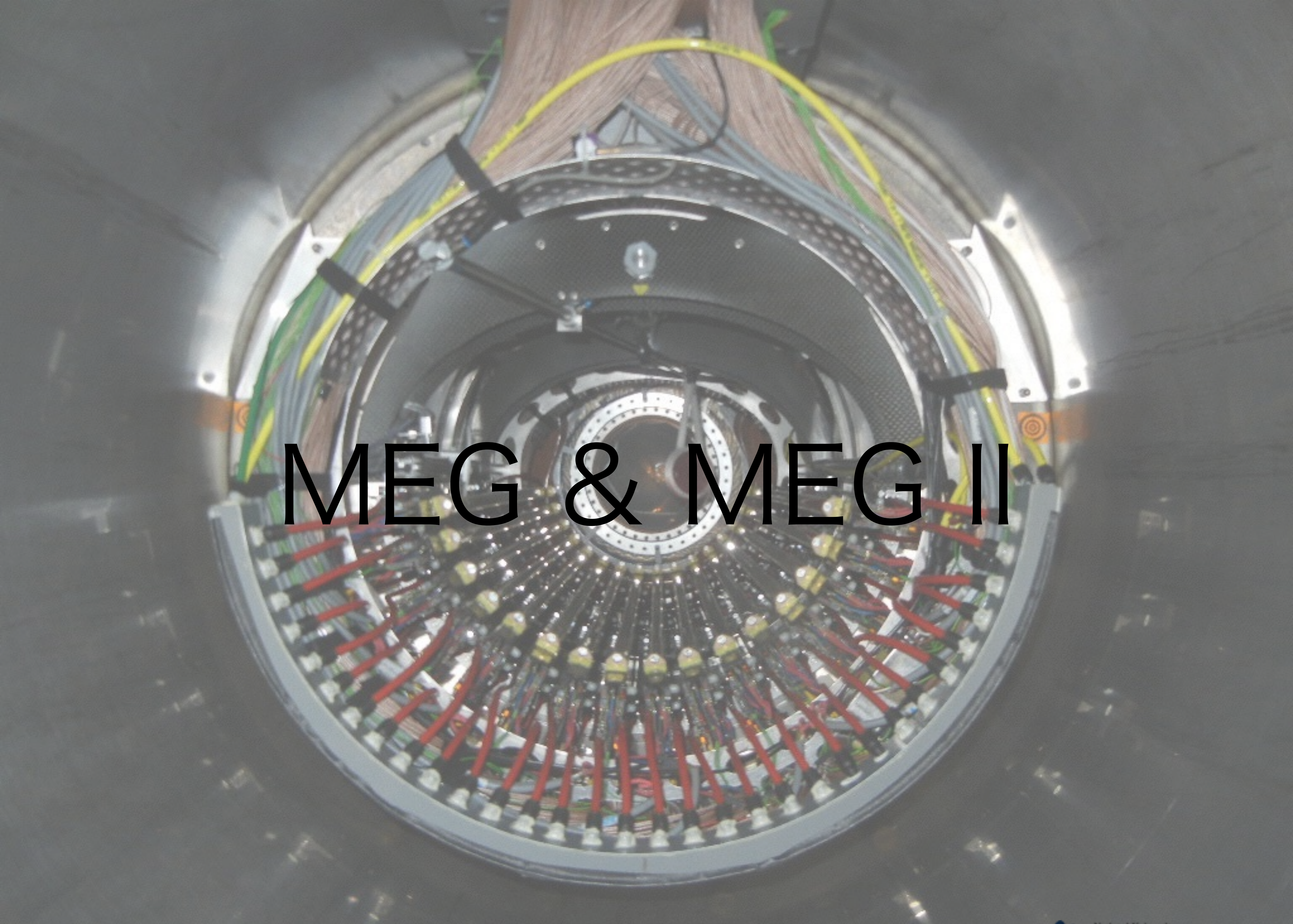
# PSI DC Muon Beam



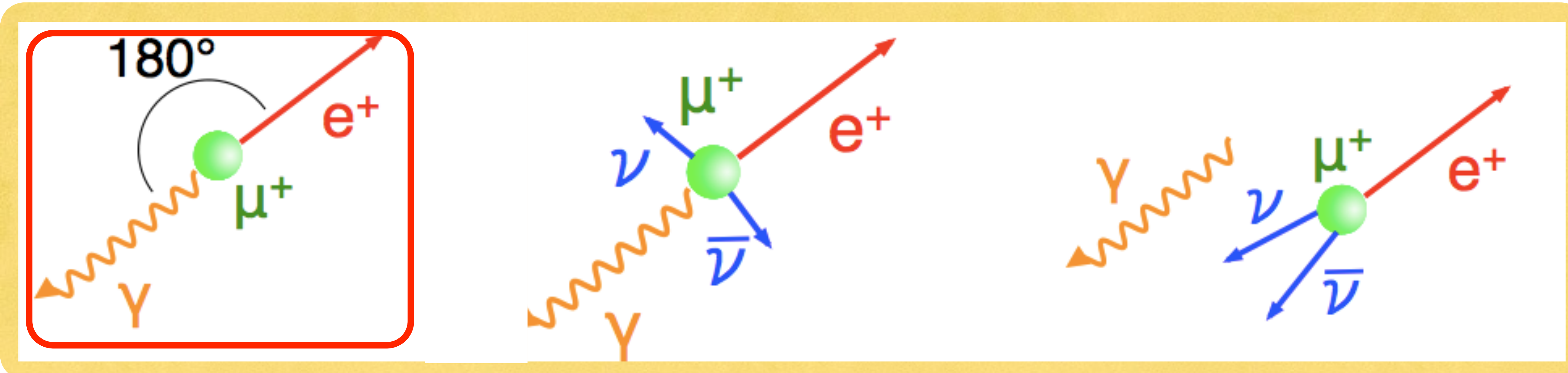

| | |
|---|---|
| Injection Energy | 72 MeV |
| Extraction Energy | 590 MeV |
| Extraction Momentum | 1.2 GeV/c |
| Energy spread (FWHM) | ca. 0.2 % |
| Beam Emittance | ca. 2π mm×mrad |
| Beam Current | 2.2 mA DC |
| Accelerator Frequency | 50.63 MHz |
| Time Between Pulses | 19.75 ns |
| Bunch Width | ca. 0.3 ns |
| Extraction Losses | ca. 0.03% |



# MEG & MEG II



# Signal and Background




## Signal

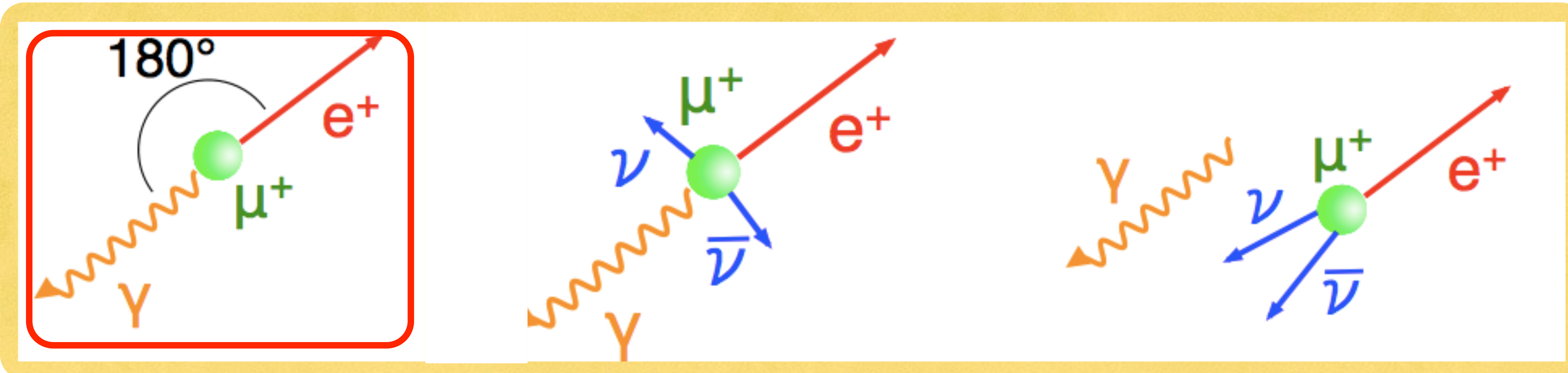
- $E_\gamma = E_{e^+} = 52.8$ MeV
- Back to back
- time coincidence

## Background

- Radiative muon decay
- $E_\gamma, E_{e^+} < 52.8$ MeV
  - any angle
  - time coincidence

- Accidental
- $E_\gamma, E_{e^+} < 52.8$ MeV
  - any angle
  - flat in time

# Signal and Background

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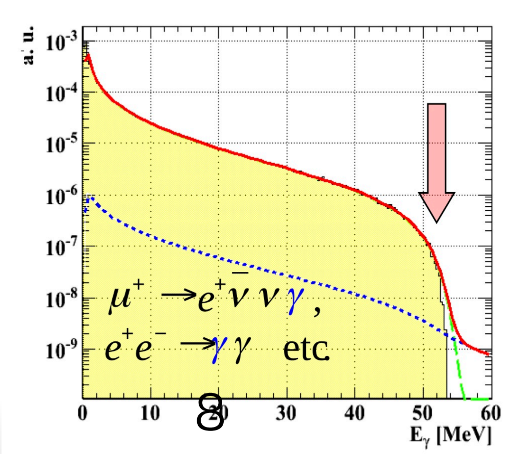
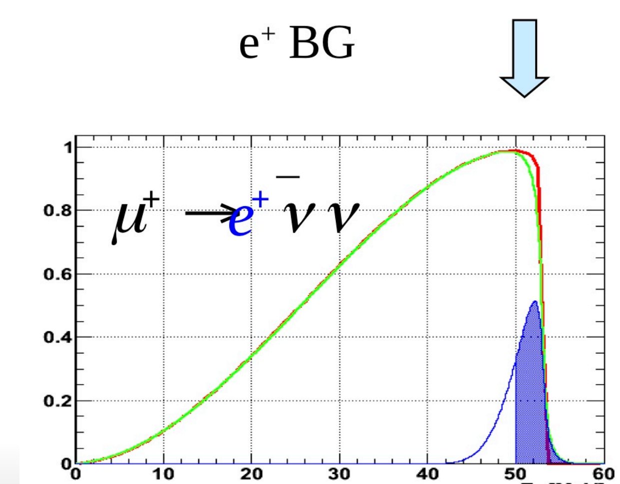


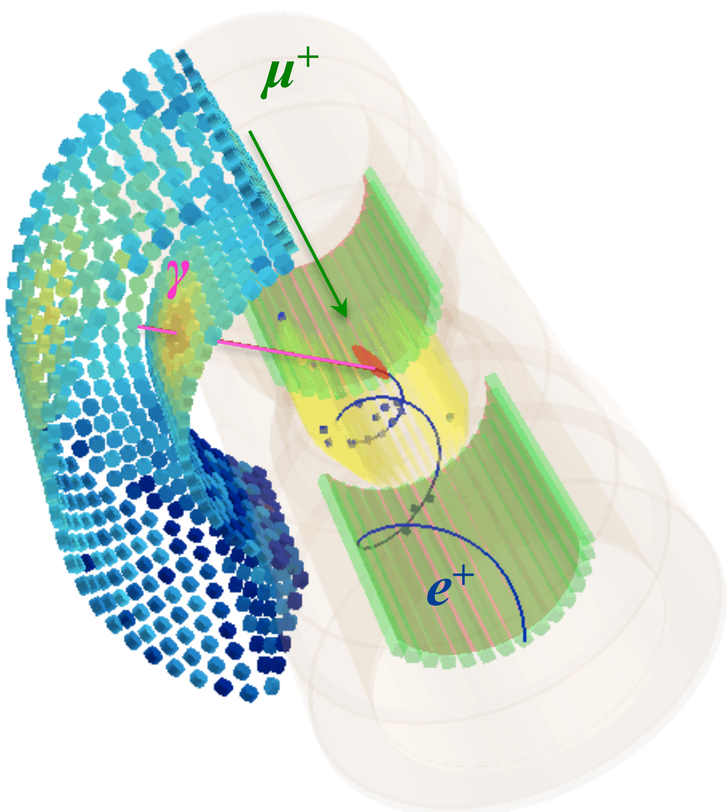

- Accidental
- $E\gamma, Ee^{+} < 52.8$ MeV
  - any angle
  - flat in time

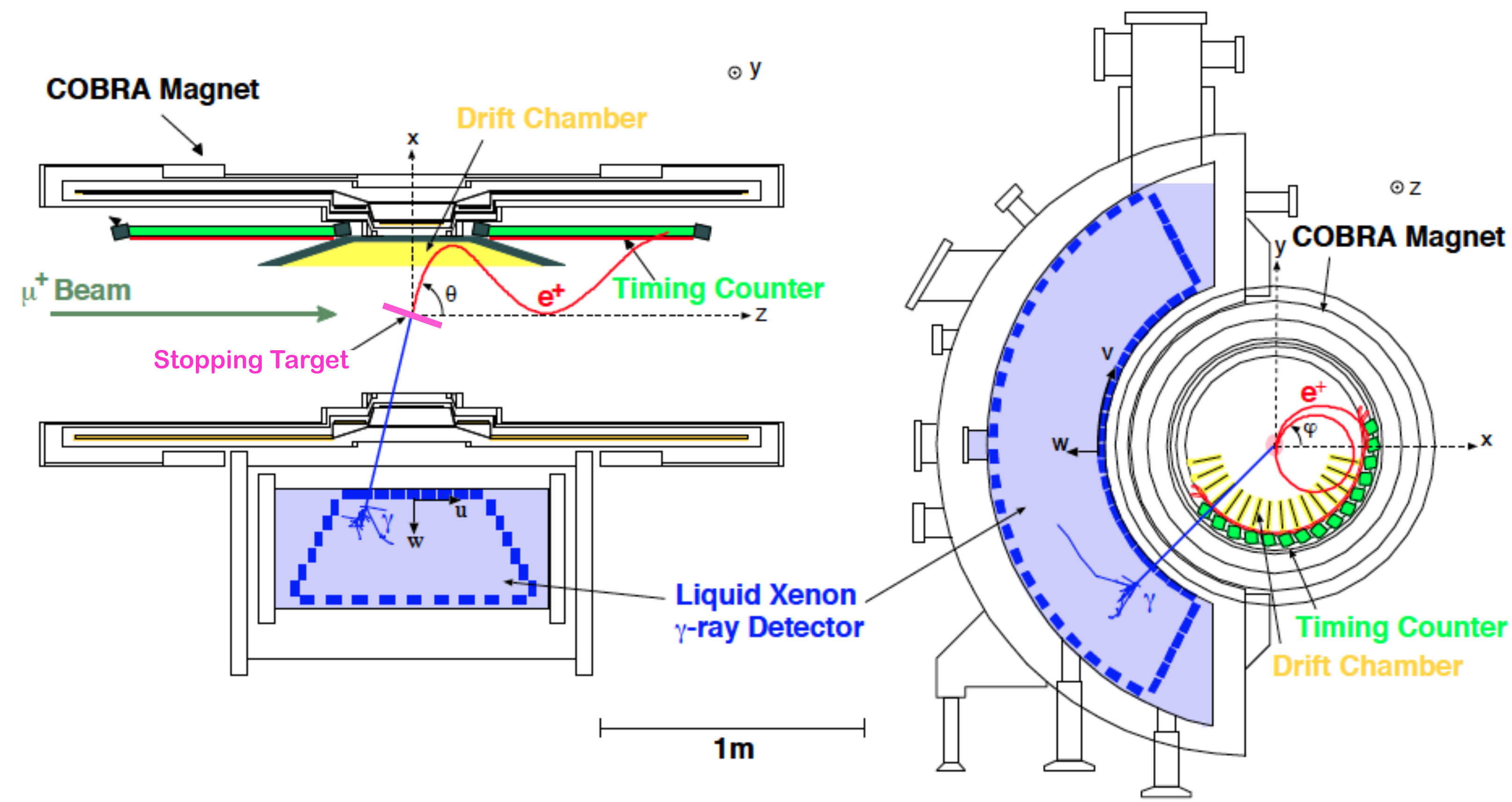
e+ BG



Eur. Phys. J. C 73 (2013) 2365

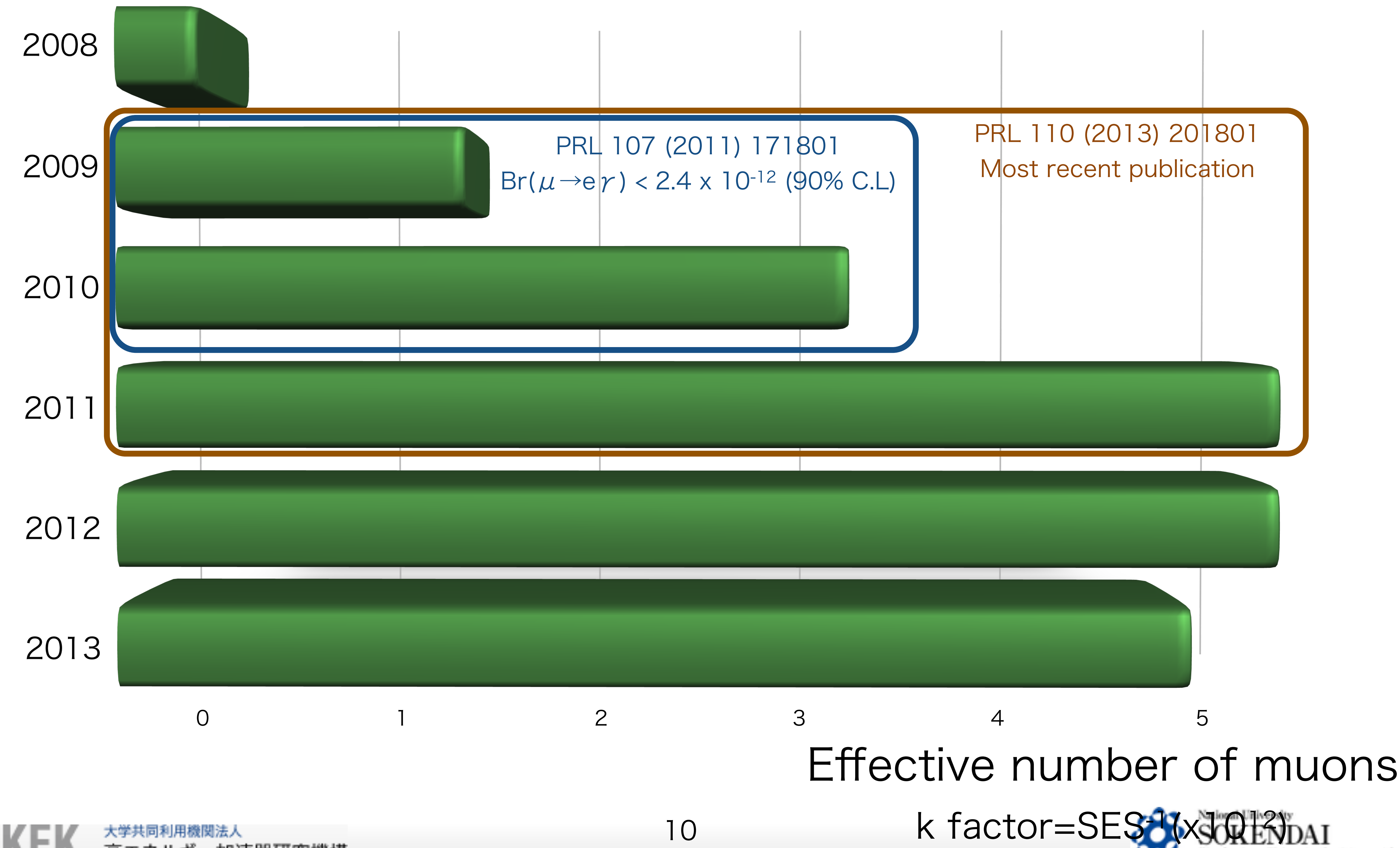
# The MEG Detector



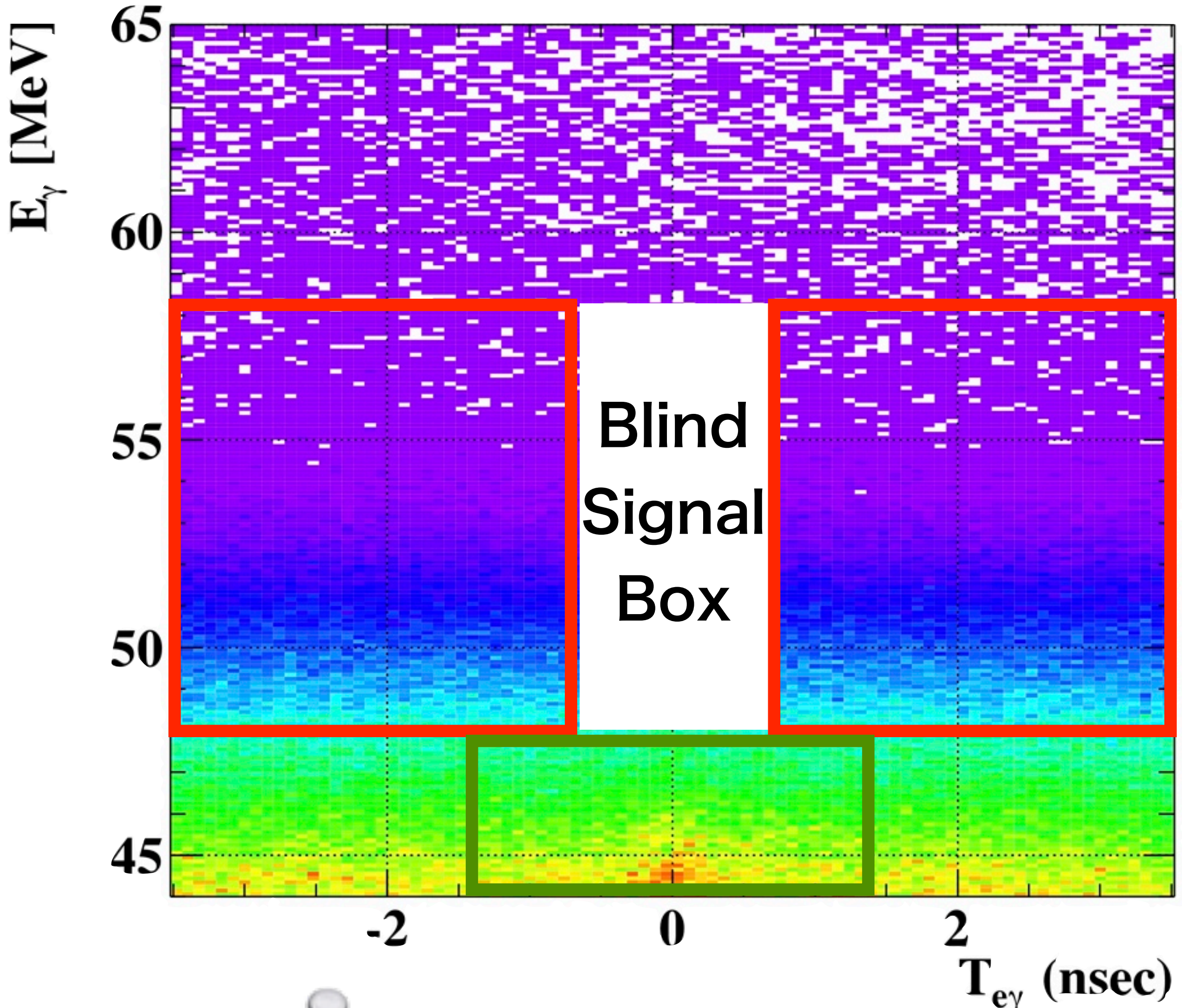




- Beam transport system
- Liquid xenon gamma-ray detector
- Positron spectrometer

# MEG Data Summary



# MEG Data Analysis Procedure

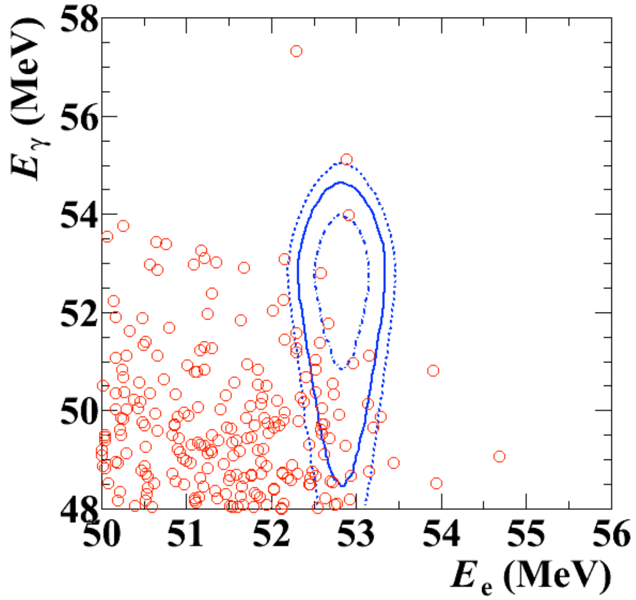


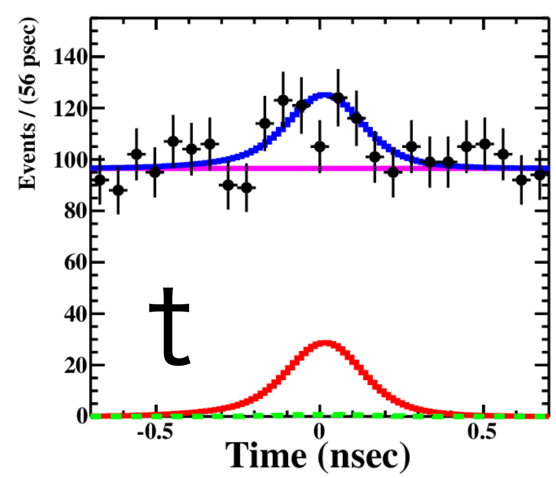

Analysis box (~10σ width)
- $48 \le E_\gamma \le 58$ MeV
- $50 \le E_e \le 56$ MeV
- $|T_{e\gamma}| \le 0.7$ ns
- $|\phi_{e\gamma}|, |\theta_{e\gamma}| \le 50$ mrad

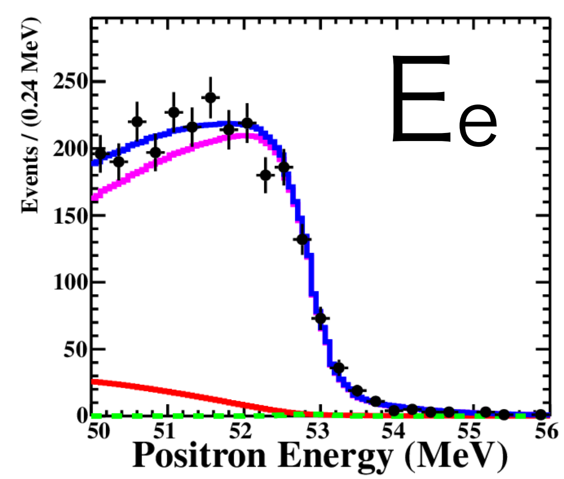
- Analysis box (containing 0.2% data ) was blinded during calibration and optimization of physics analysis
- Side band data (16%) to study background
  - Michel positrons for positron detector response study
  - RMD with low gamma energy to evaluate timing resolutions
- Detector responses (PDFs) from data
- The numbers of signal (S), radiative-muon decay (R), and accidental background (A) events are determined in a maximum likelihood method.

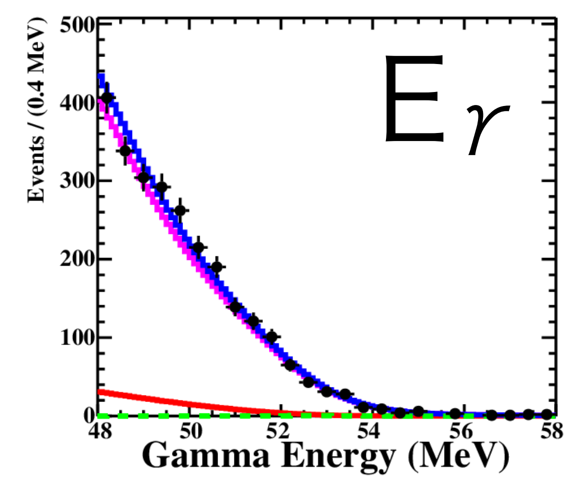
$$\mathcal{L}(\vec{x}_1,\ldots,\vec{x}_N,R_\diamond,A_\diamond|\hat{S},\hat{R},\hat{A}) = \frac{e^{-\hat{N}}}{N!} e^{-\frac{1}{2}\frac{(A_\diamond-\hat{A})^2}{\sigma_A^2}} e^{-\frac{1}{2}\frac{(R_\diamond-\hat{R})^2}{\sigma_R^2}} \prod_{i=1}^{N}\left(\hat{S}s(\vec{x}_i)+\hat{R}r(\vec{x}_i)+\hat{A}a(\vec{x}_i)\right)$$

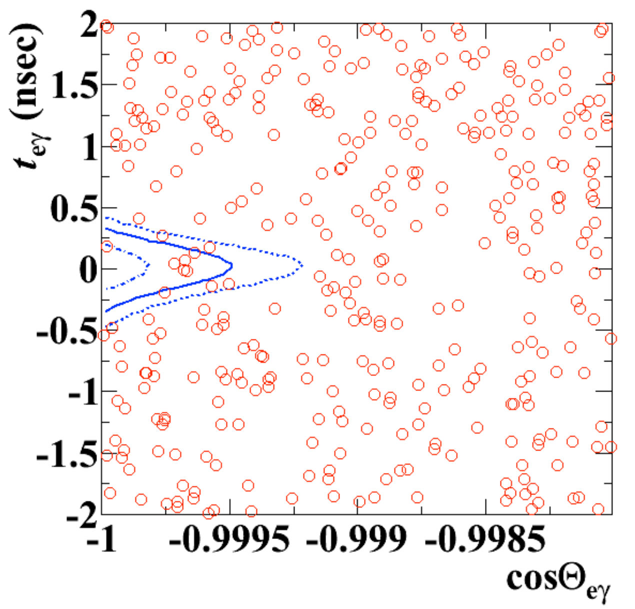
# Event Distribution

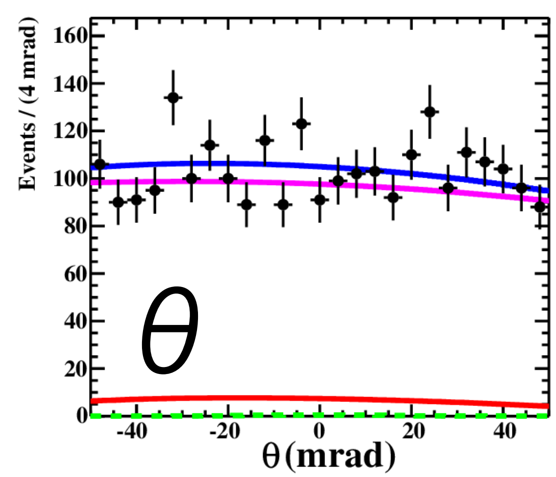


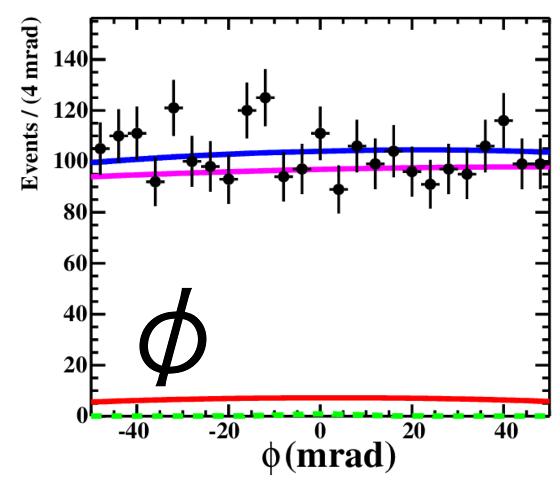




$N_{obs}$ = 2574

$N_{sig}$ = $-0.4^{+4.8}_{-1.9}$

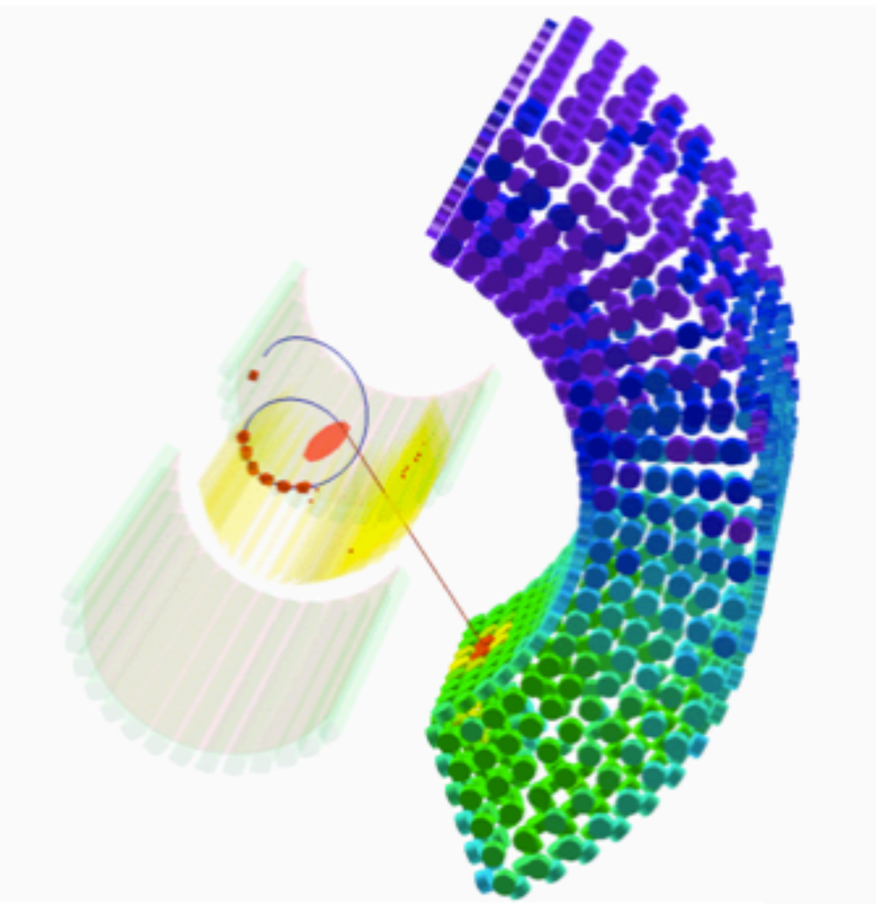
$N_R$ = 167 ± 24

$N_A$ = 2413 ± 37

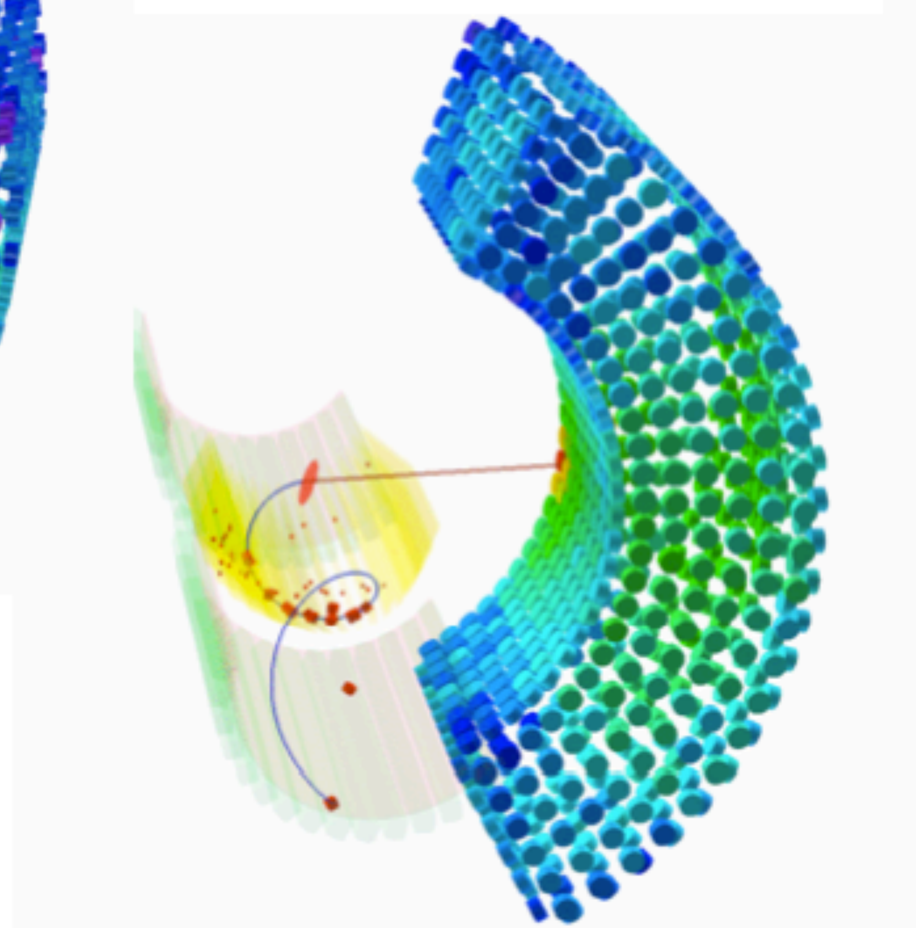
- Signal PDF contours at 1, 1.64, and 2 sigmas
- No excess in the data distribution

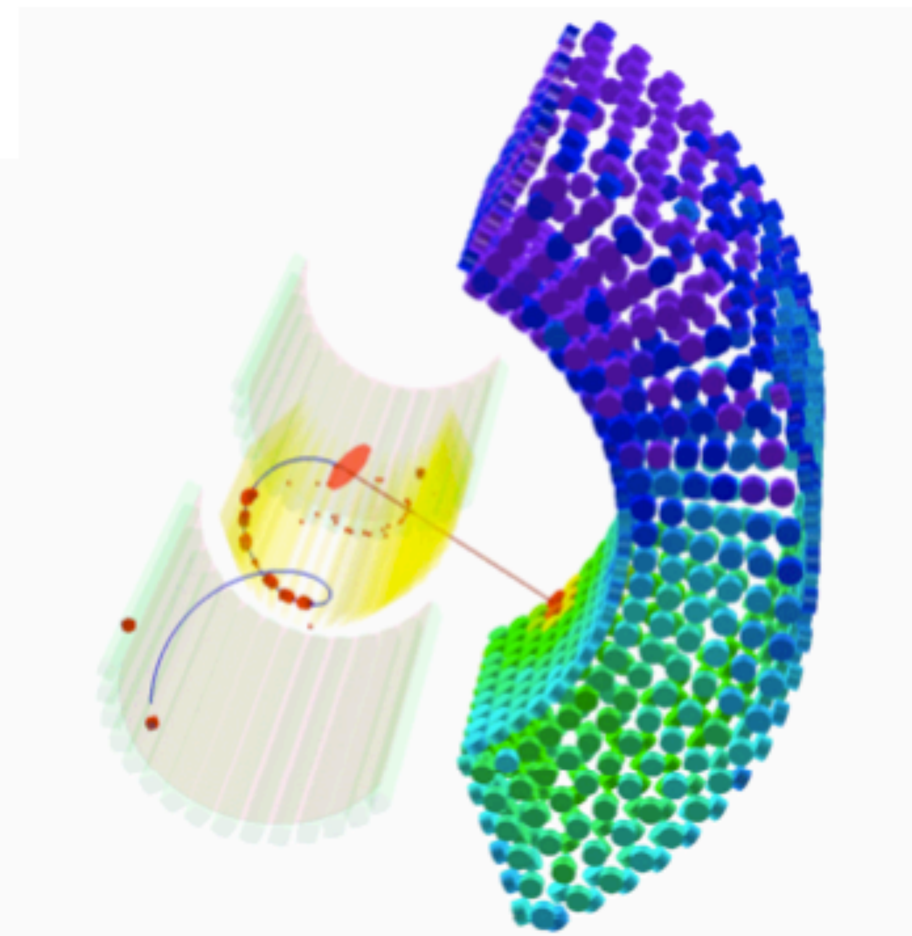
# Highly Ranked Events

**Run:102907 Event:559**
**($E_\gamma$=50.27MeV, $E_e$=52.34MeV, $T_{e\gamma}$=-78.7ps, $\Phi_{e\gamma}$=17.83mrad, $\theta_{e\gamma}$=7.77mrad)**



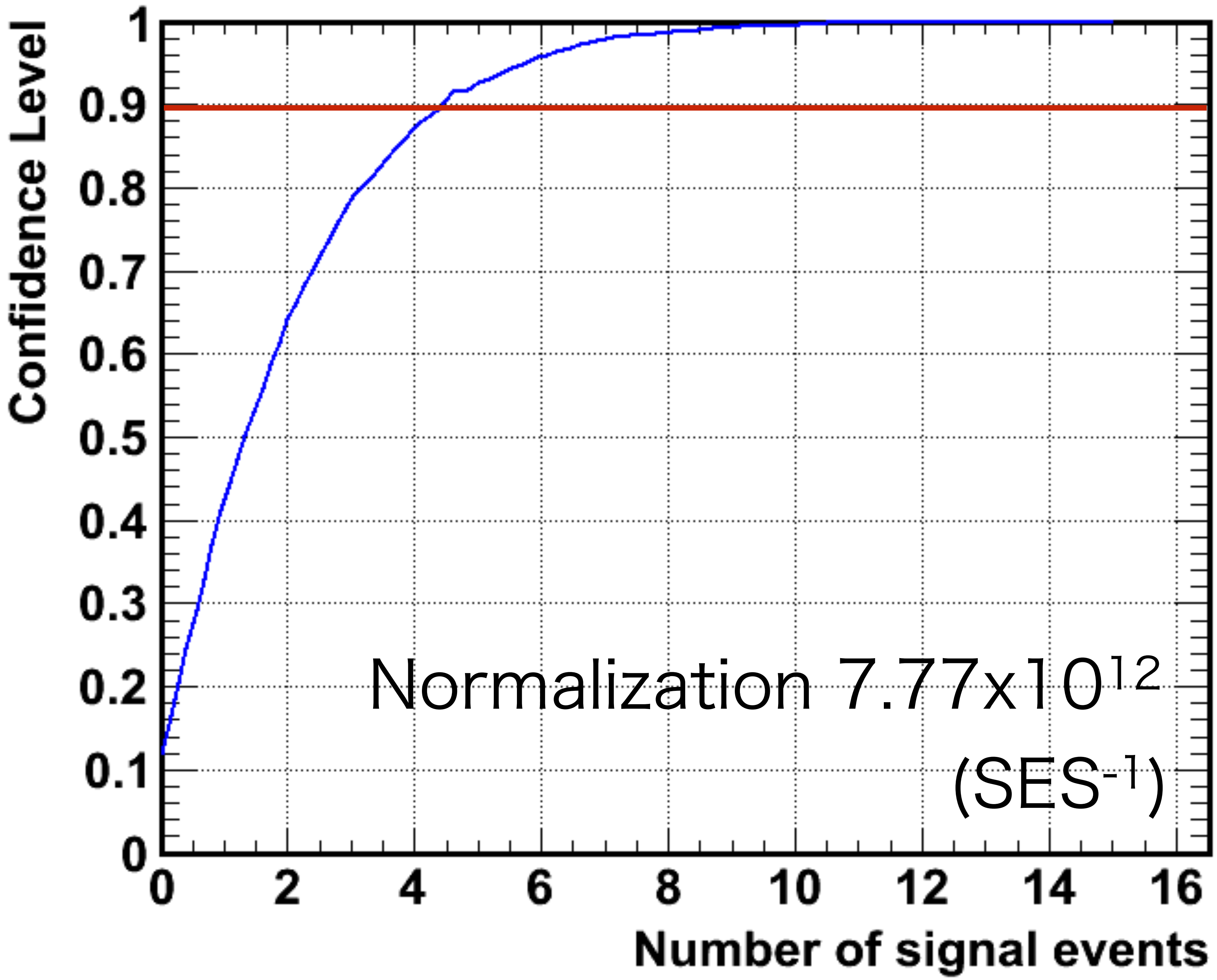
**Run:100452 Event:1878**
**($E_\gamma$=49.27MeV, $E_e$=52.87MeV, $T_{e\gamma}$=-9.3ps, $\Phi_{e\gamma}$=17.51mrad, $\theta_{e\gamma}$=-10.65mrad)**





**Run:123579 Event:1318**
**($E_\gamma$=55.13MeV, $E_e$=52.89MeV, $T_{e\gamma}$=-14.9ps, $\Phi_{e\gamma}$=5.58mrad, $\theta_{e\gamma}$=-25.27mrad)**

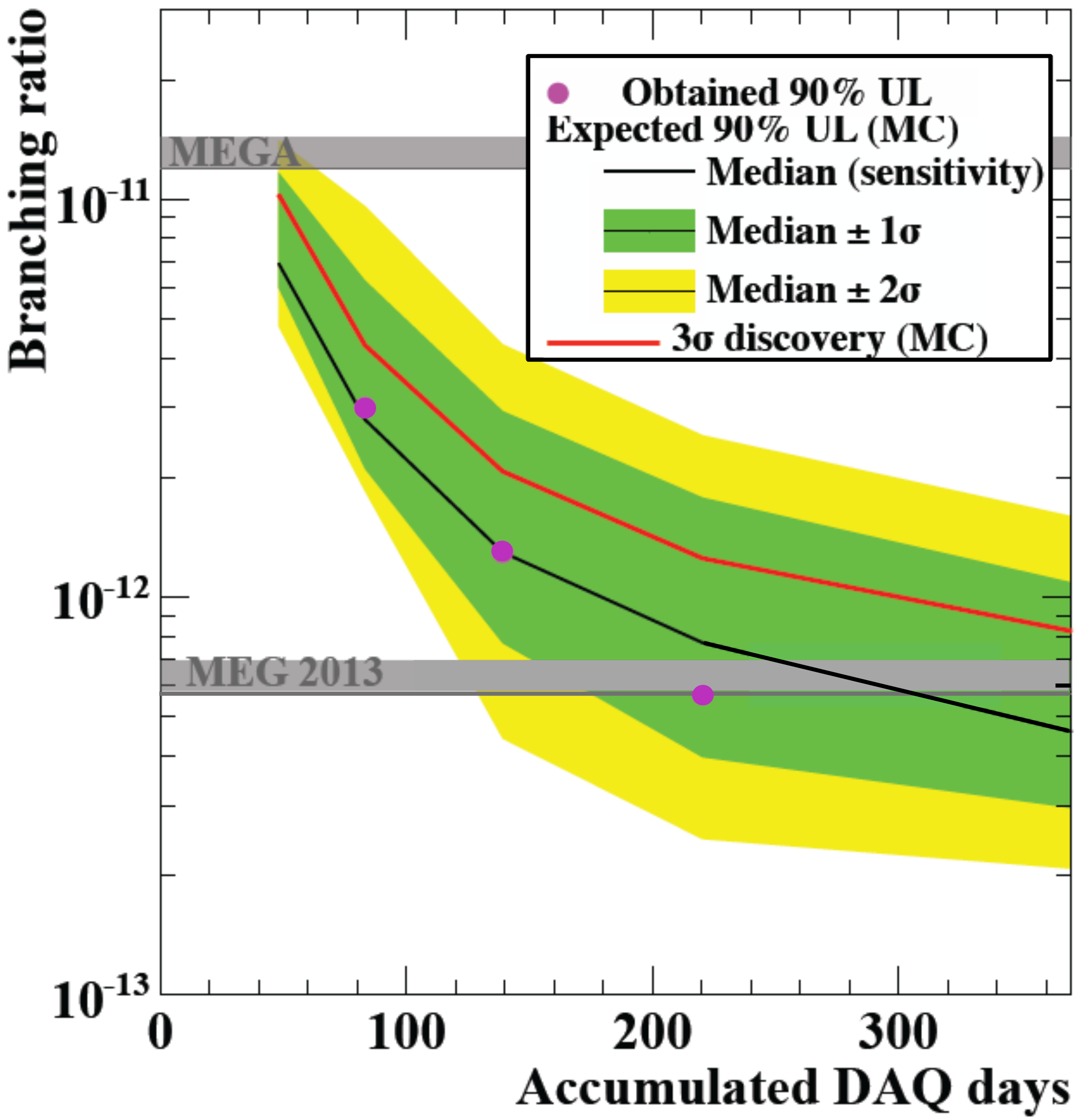
# MEG Data Analysis C.L.




- $Br(\mu^+ \rightarrow e^+\gamma) < 5.7\times10^{-13}$ (@90% C.L.)

# MEG-I Conclusion

- MEG-I set the world's most stringent cLFV limit of $Br(\mu \to e\gamma) < 5.7\text{x}10^{-13}$ at 90% C.L.
- Data acquisition finished in 2013
  - 2012-2013 data in analysis
- Final MEG-I result will show up in this summer

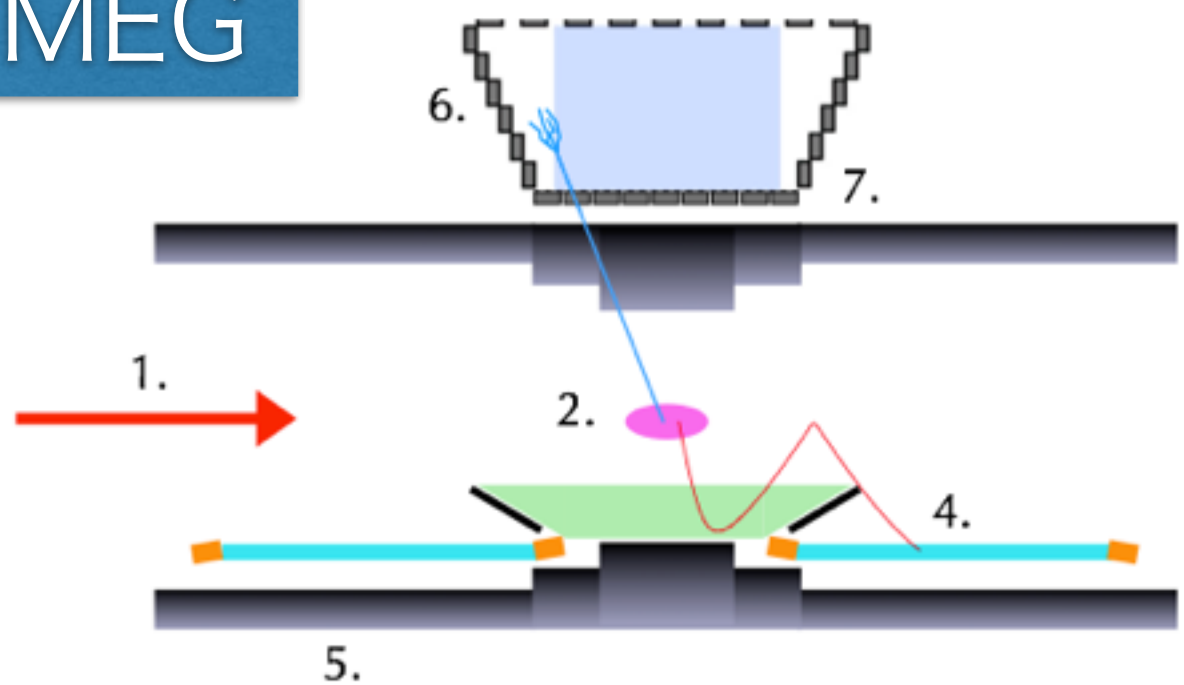


Target Sensitivity of $5\times10^{-14}$ at 90% C.L.

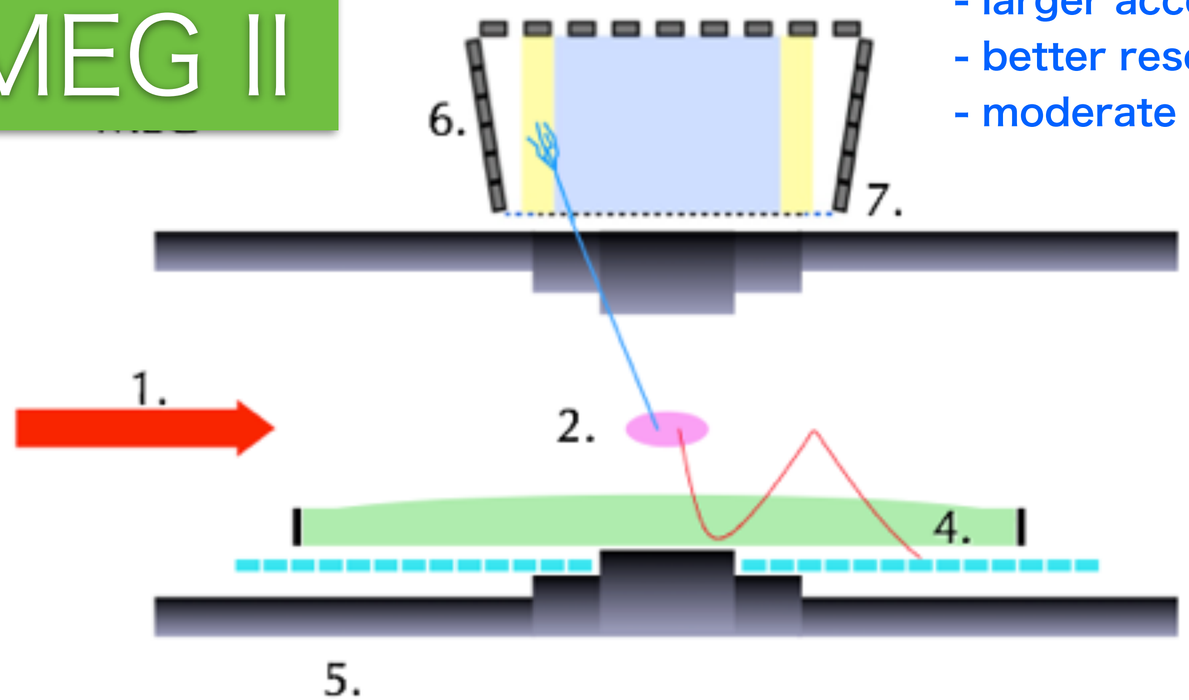
arXiv:1301.7225

# MEG II

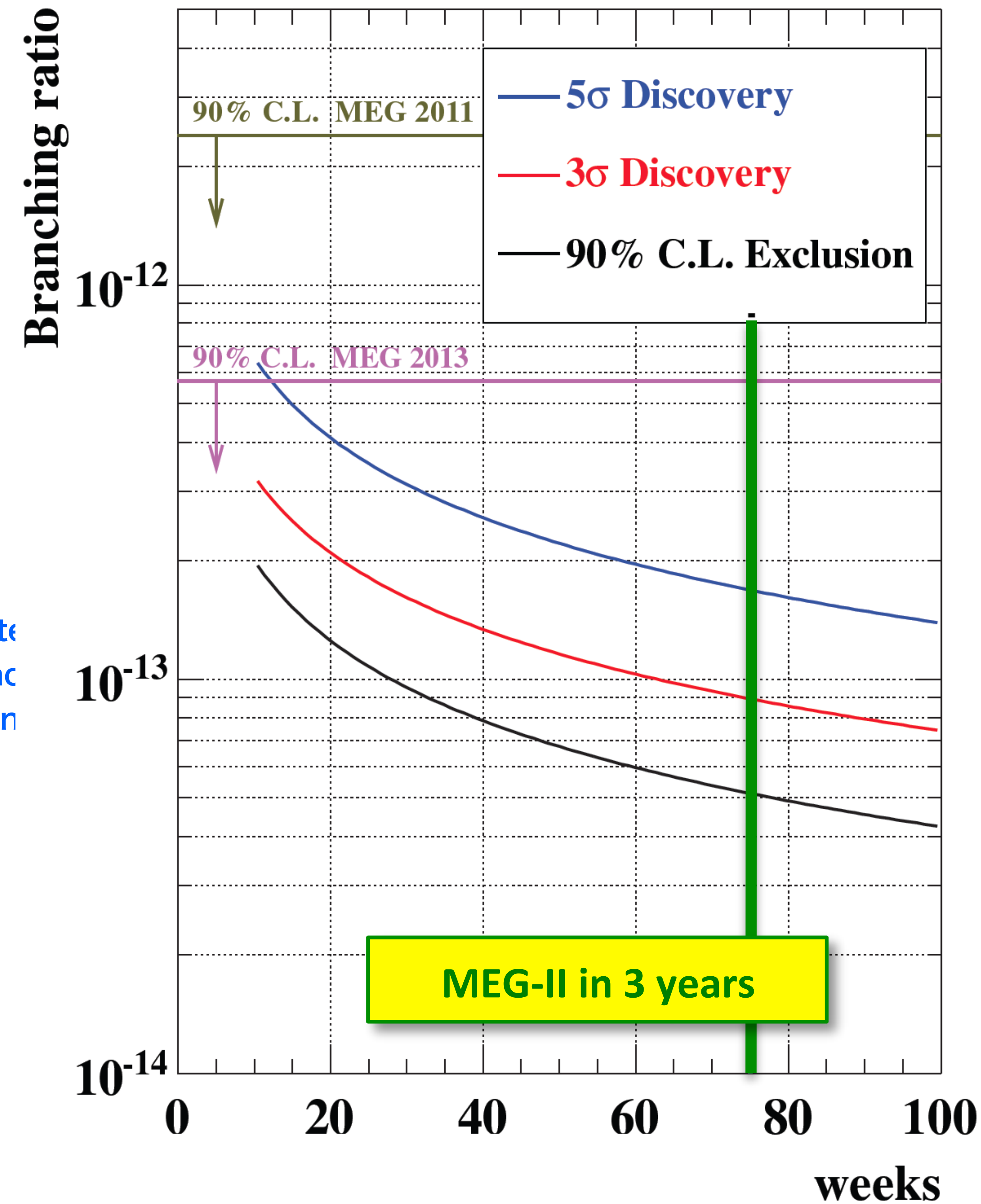
## MEG




## MEG II



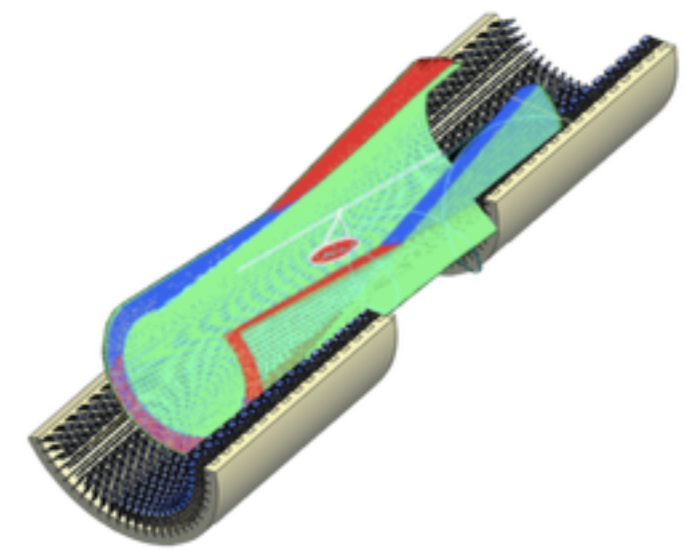

- higher beam rate
- larger acceptanc
- better resolution
- moderate cost

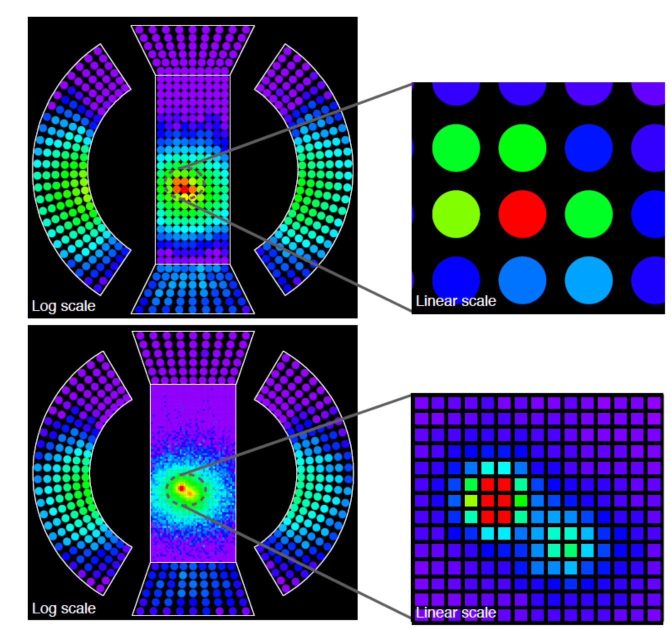



DAQ start in 2016

# Upgrades in MEG II toward $5 \times 10^{-14}$

- Increased beam intensity ($7 \times 10^7\ \mu^+/s$)
- Thinner (140 $\mu$m) or active target
- Enlarged cylindrical single-volume DC
- Pixelated TCs with SiPM readout
- New high-bandwidth DAQ boards
- Enlarged LXe volume, SiPM readout
- Radiative Muon Decay counters





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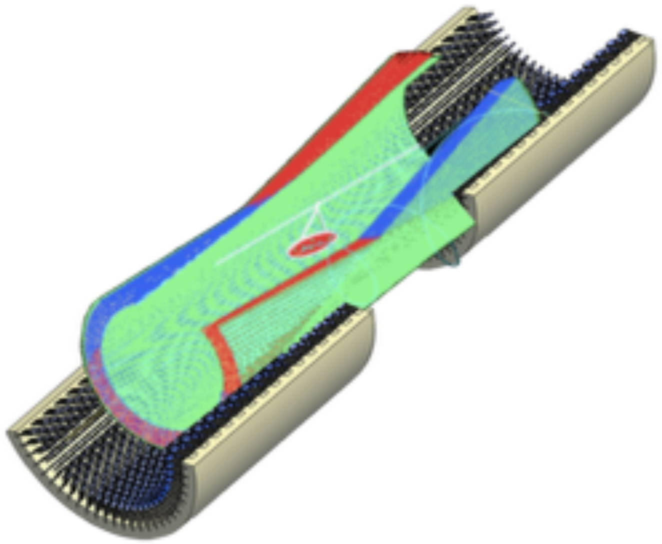
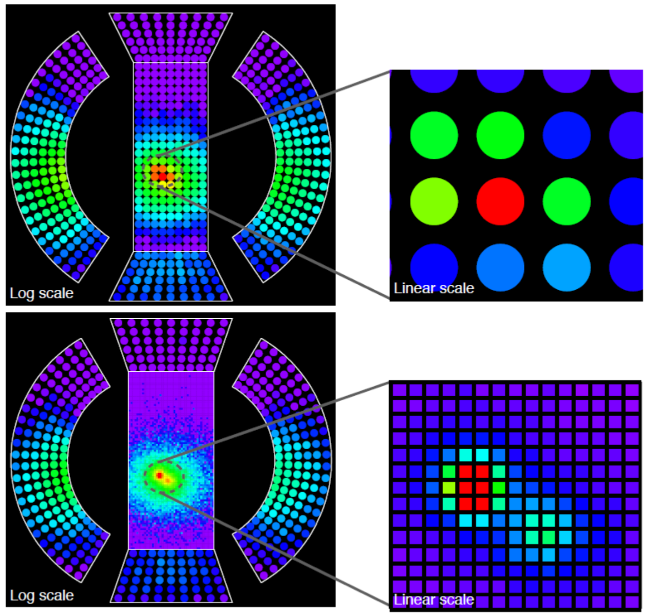
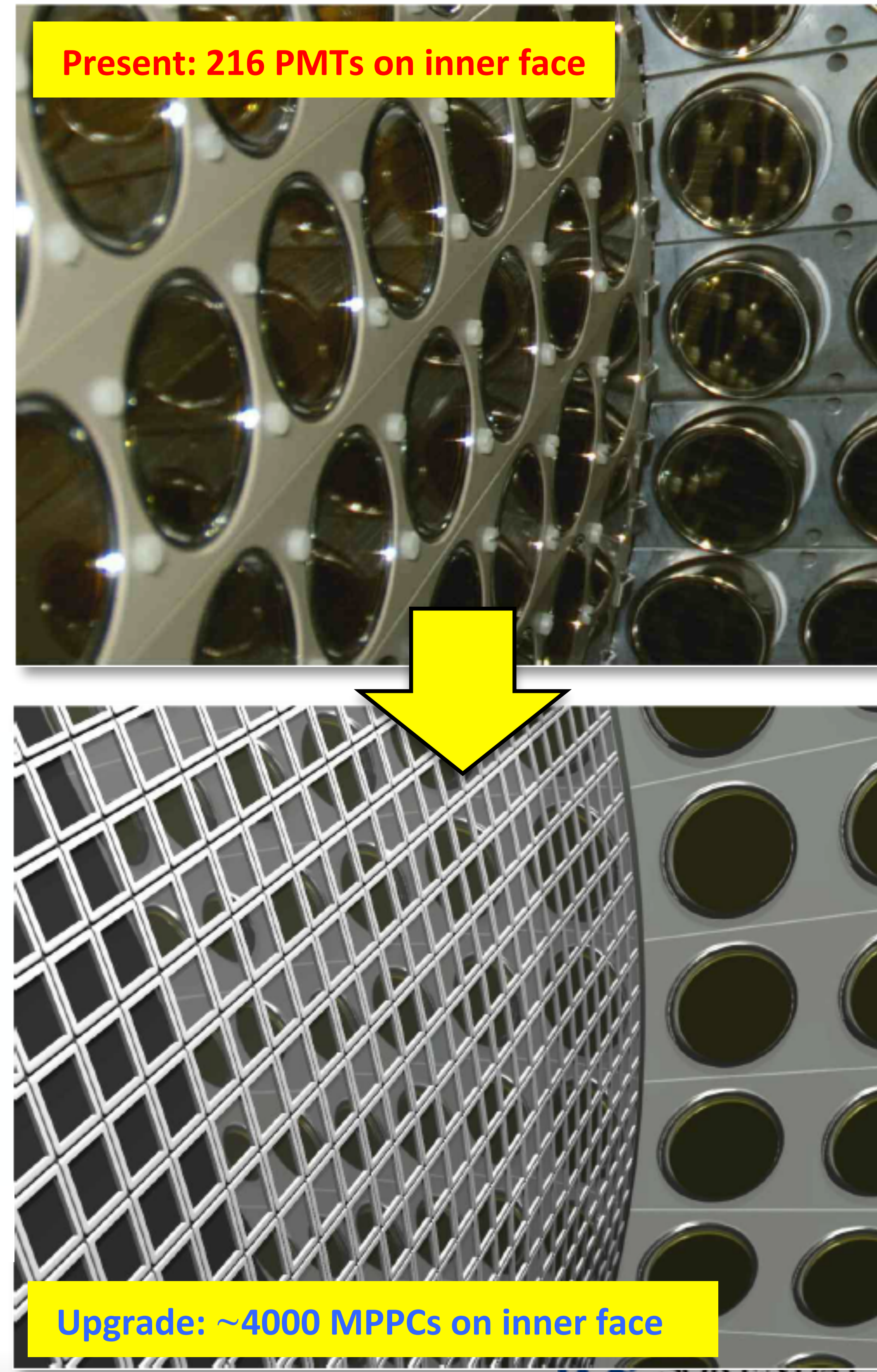
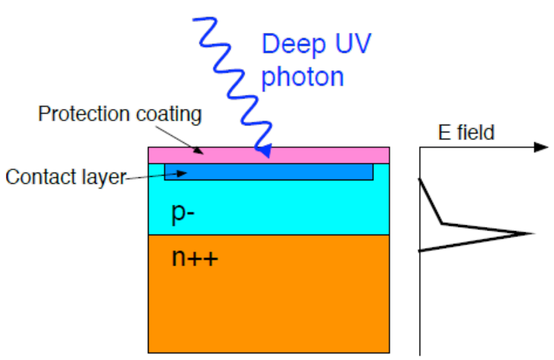




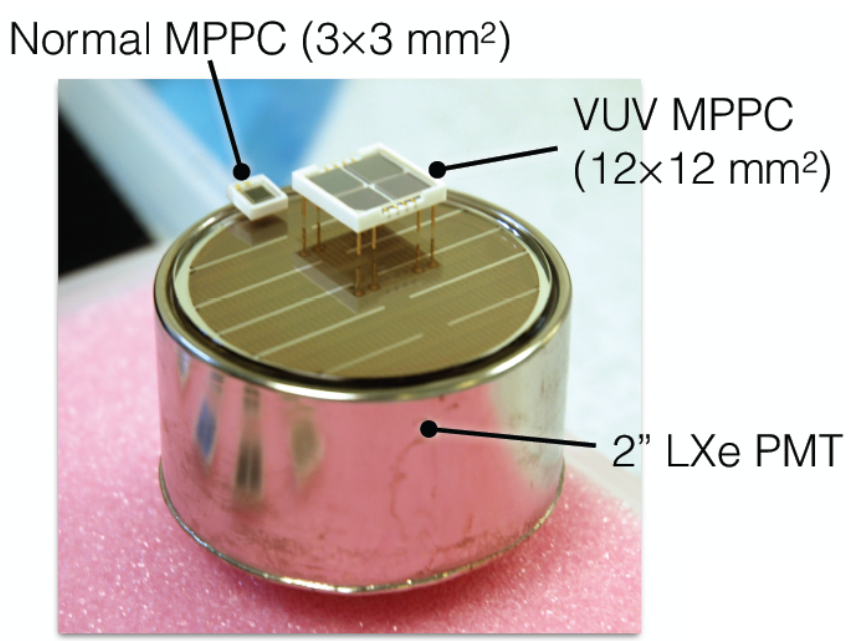
# Photon Detector Upgrade

- Replace 216 inner face PMTs to newly developed SiPM
- Expand the native volume along the z-direction
- Upgrade of the cryogenics




- Remove protective layer
- Fit anti-reflective coating to LXe refraction index
- Protect with quartz




Poster 12 S. Ogawa

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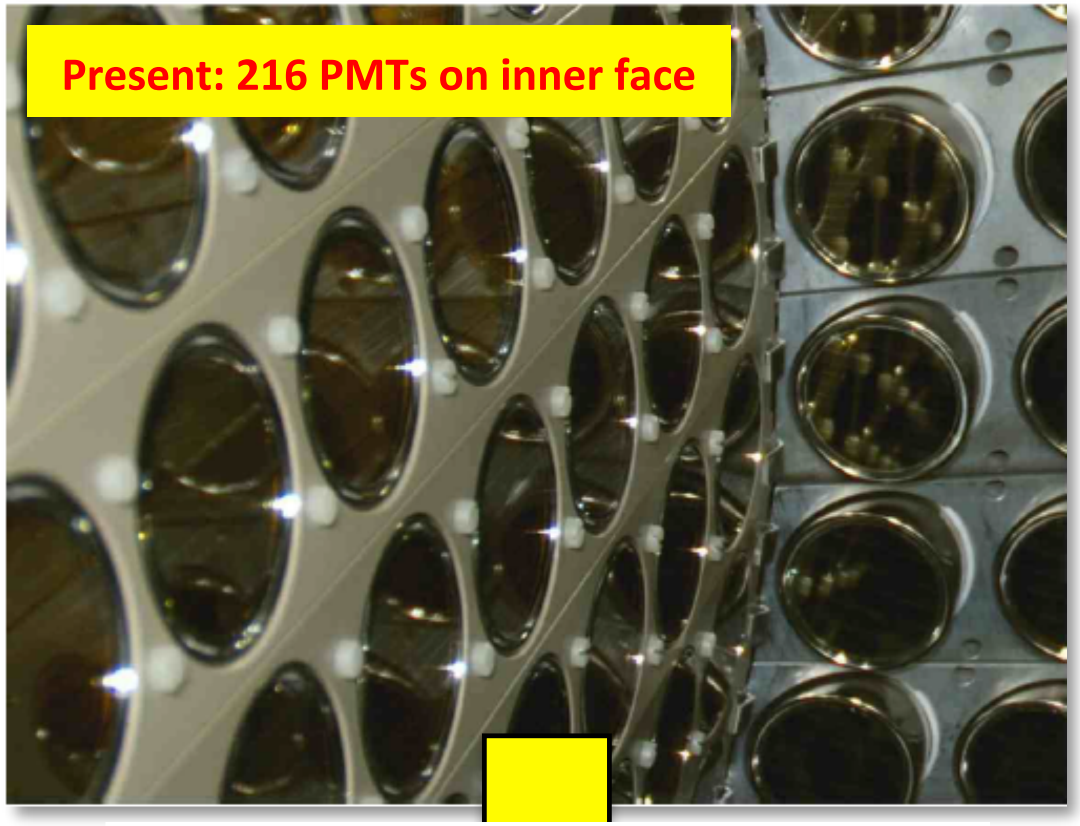


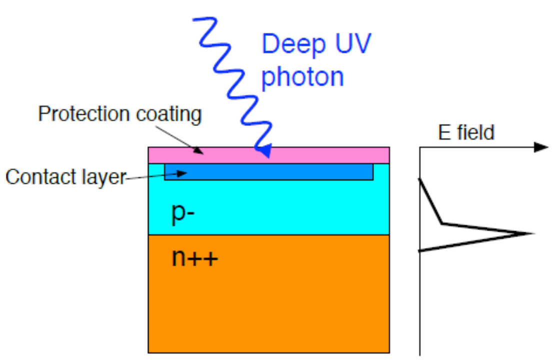


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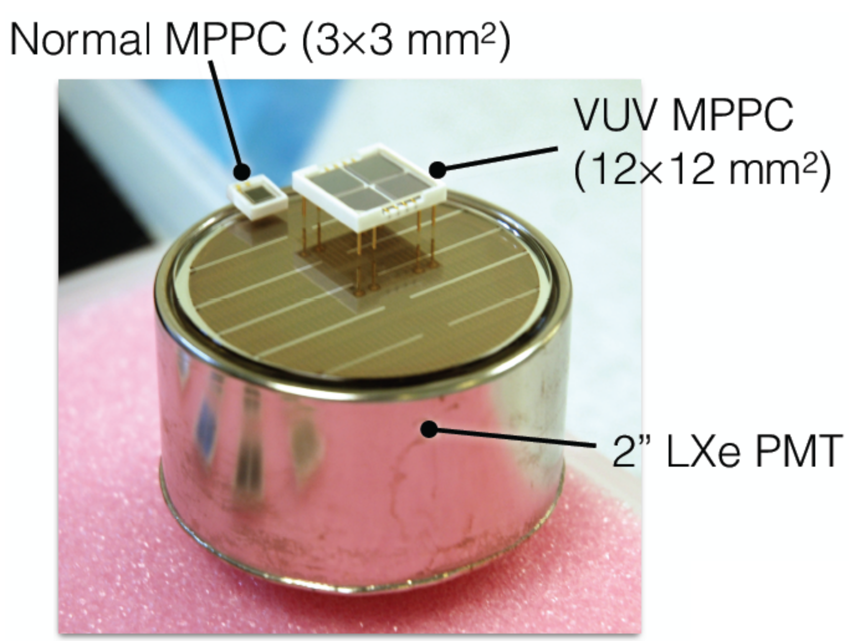


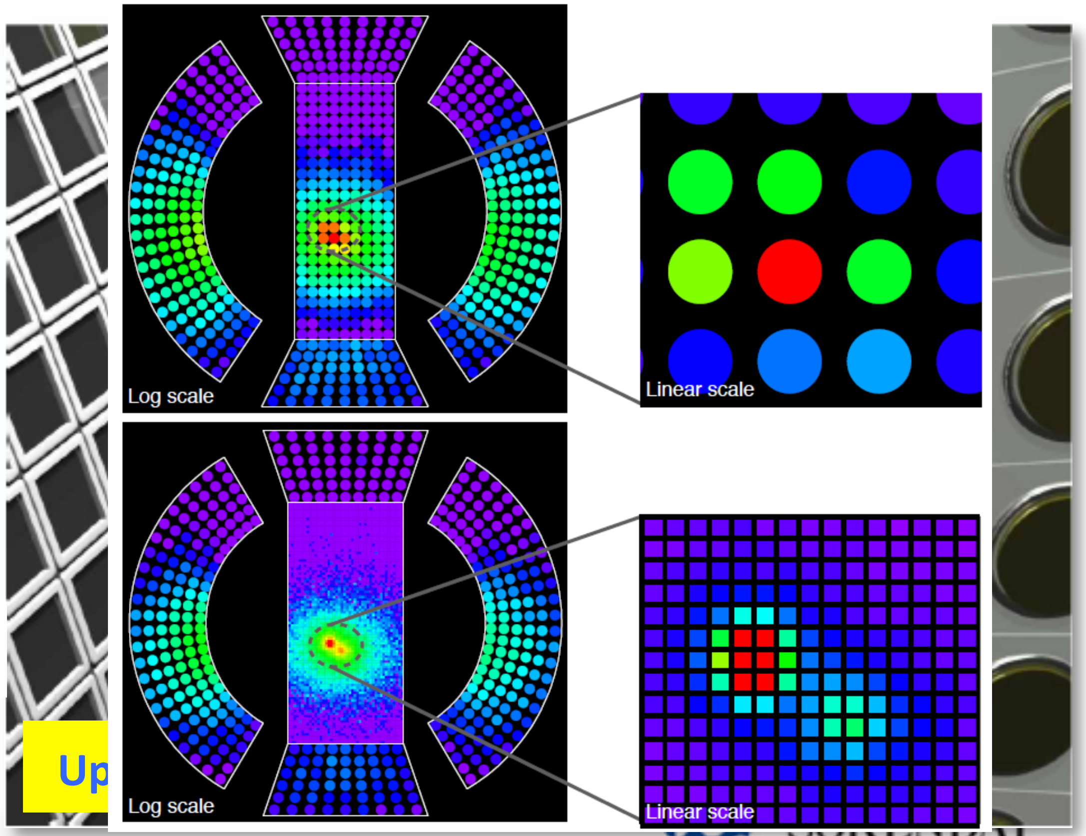


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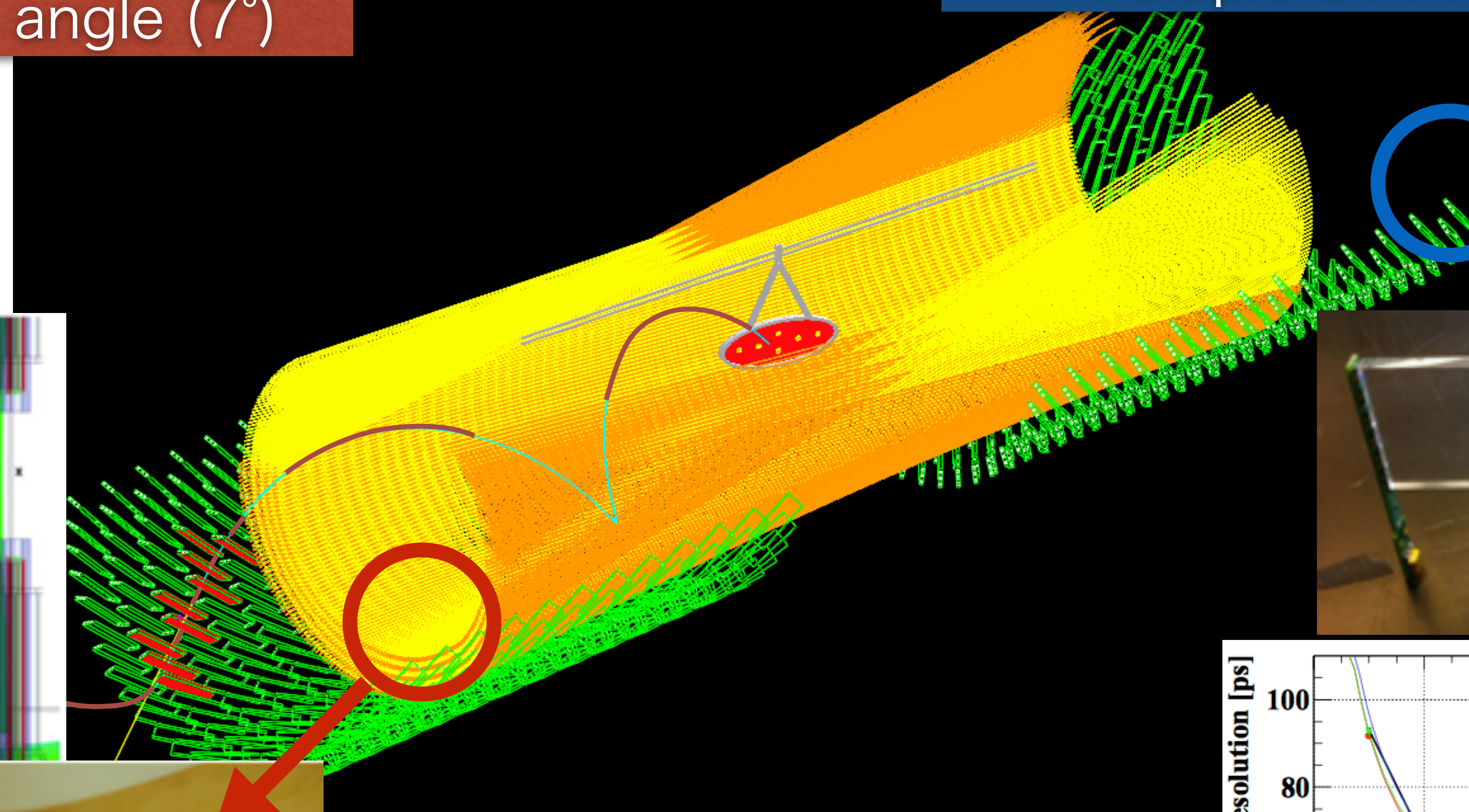
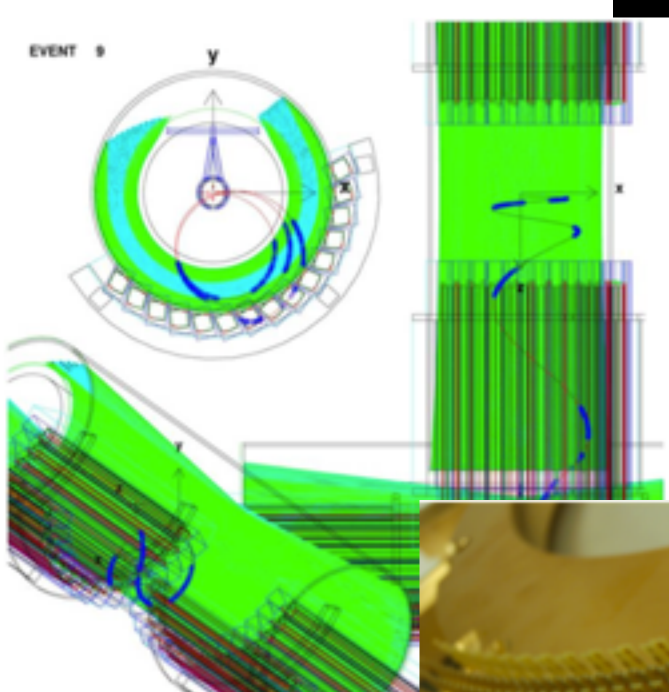
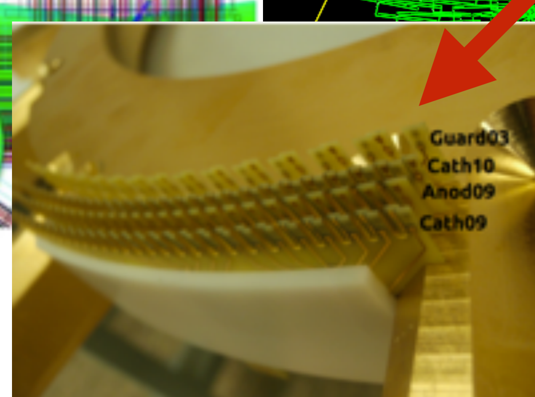
# Positron Detector Upgrade

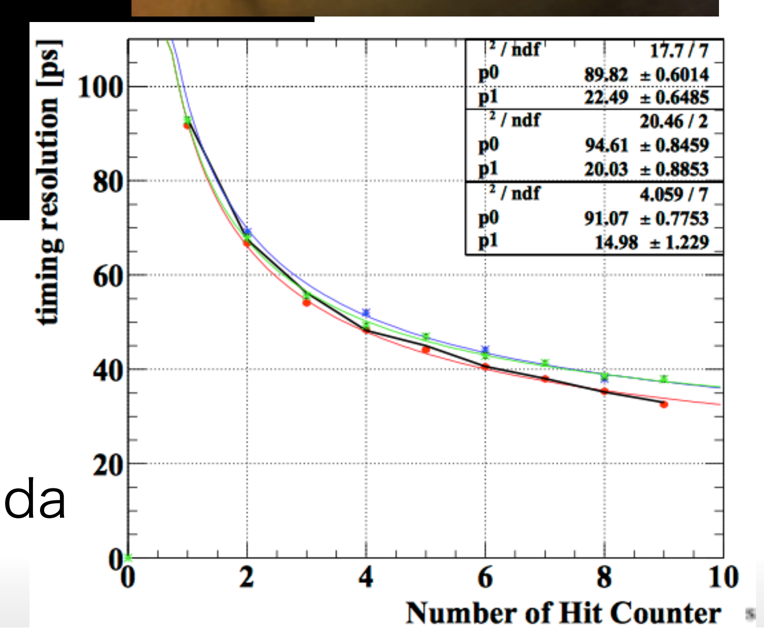
- DC Upgrade
- Single-volume, low-Z gas mixture ($He:iC_4H_{10}$ = 85:15)
- 1200 sense wires (2mL, 20 μm) with stereo angle (7°)

- TC Upgrade
- Pixelated fast plastic scintillator
- Multiple-SiPM readout



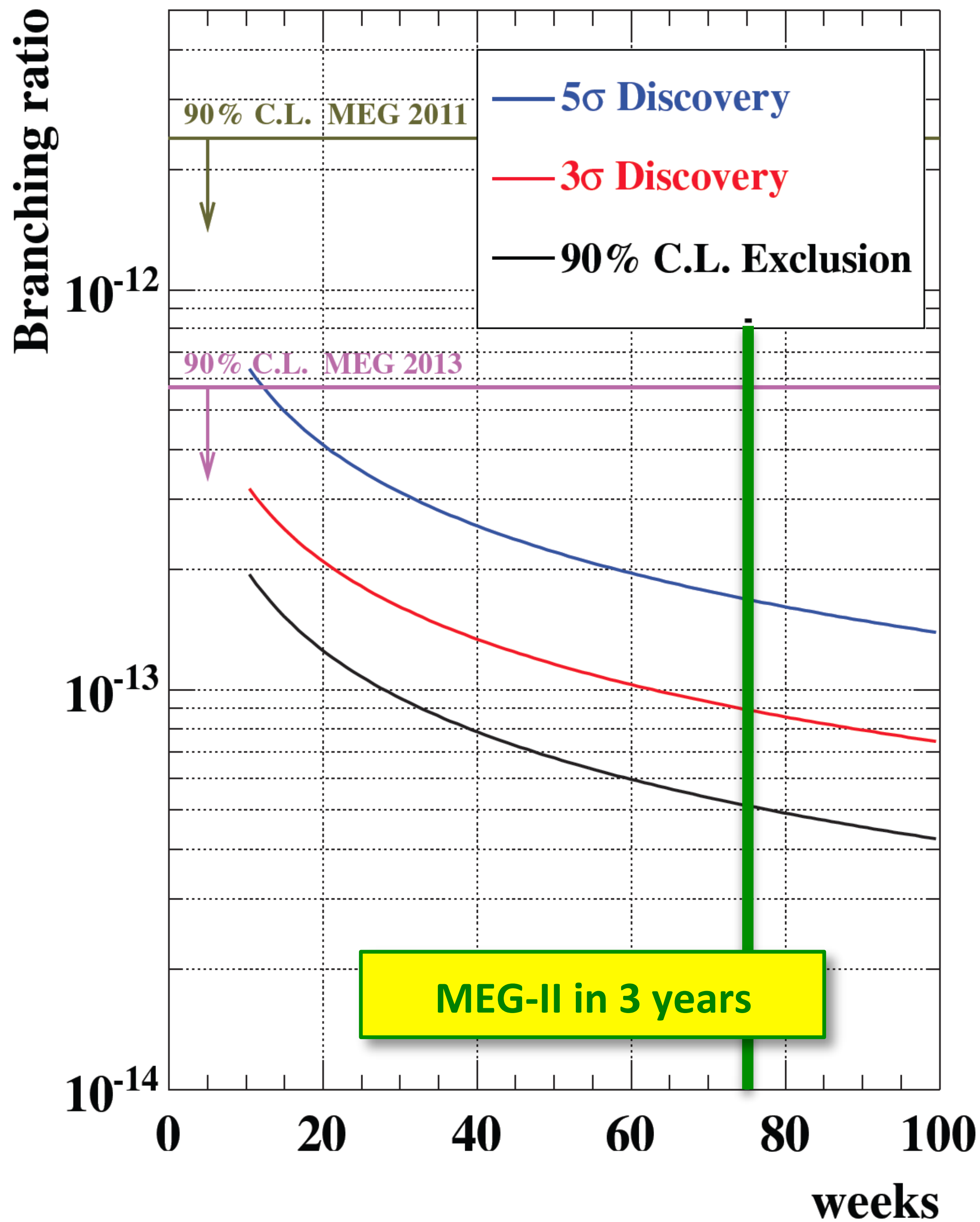


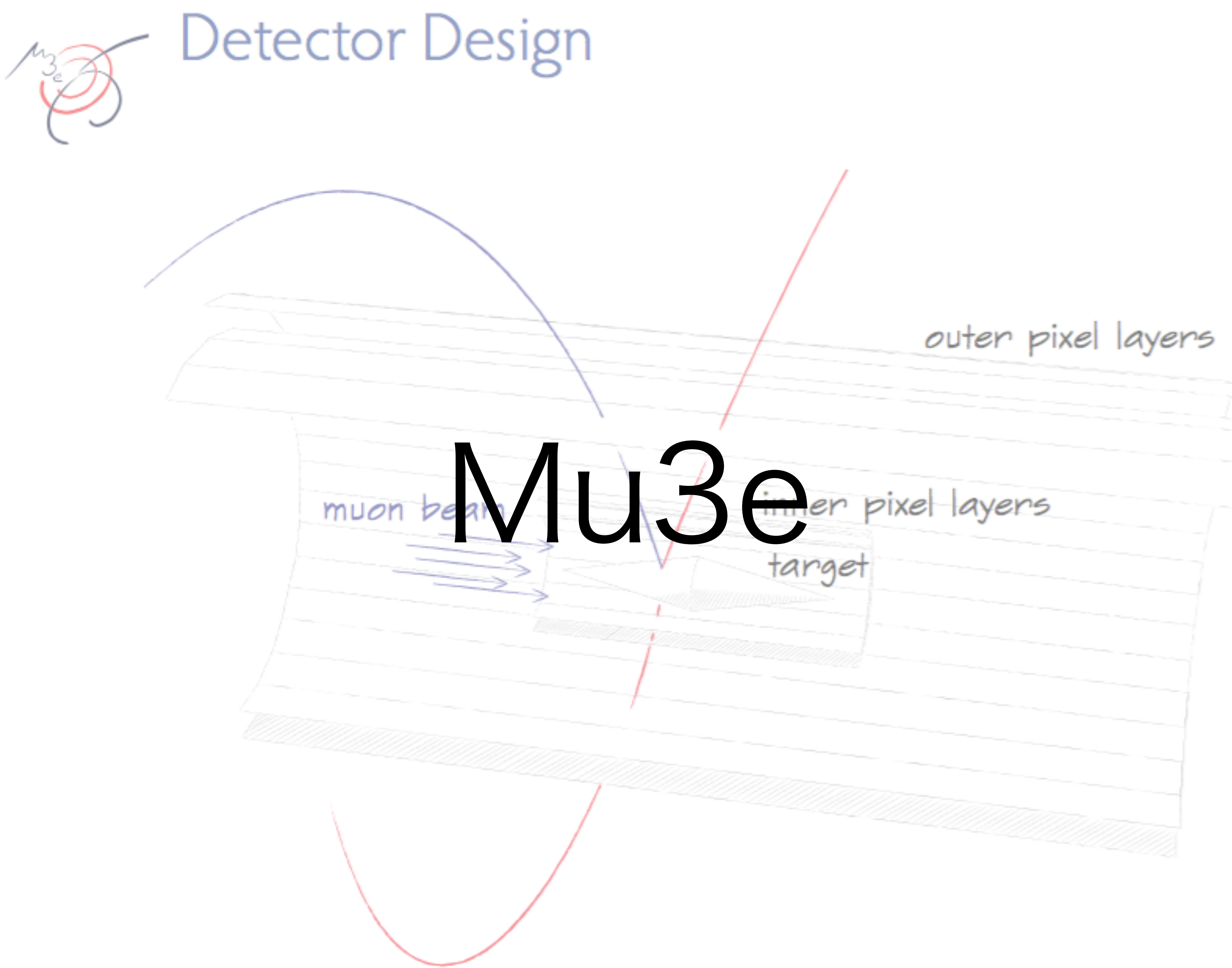




Poster 13 K.Yoshida

# MEG II Sensitivity

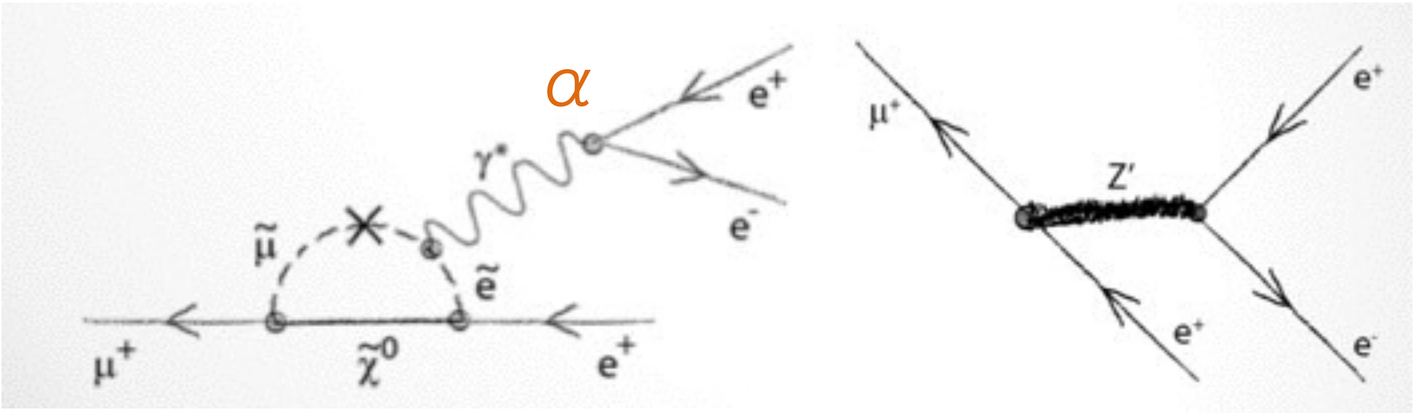


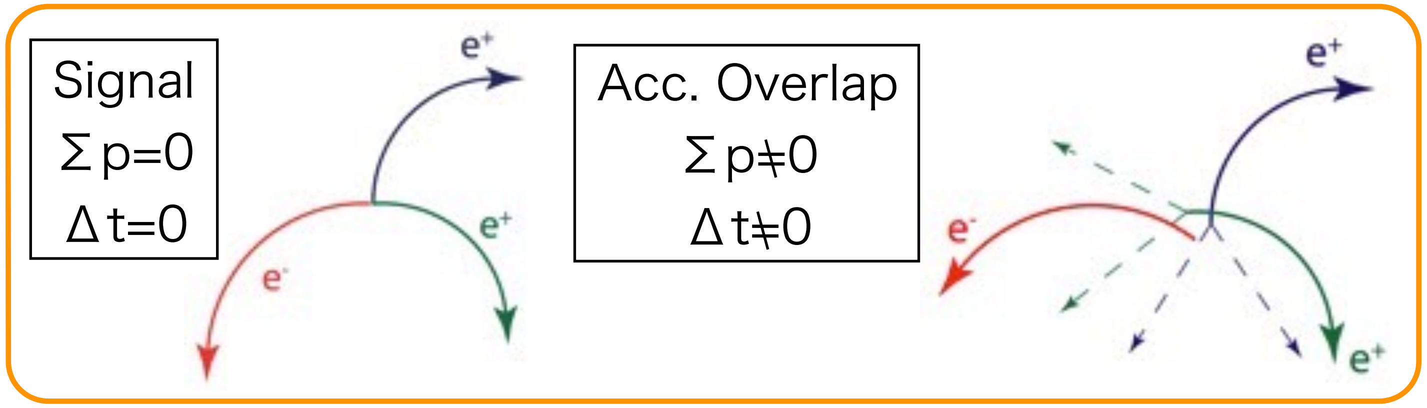

Detector Design
outer pixel layers
muon beam
inner pixel layers
target

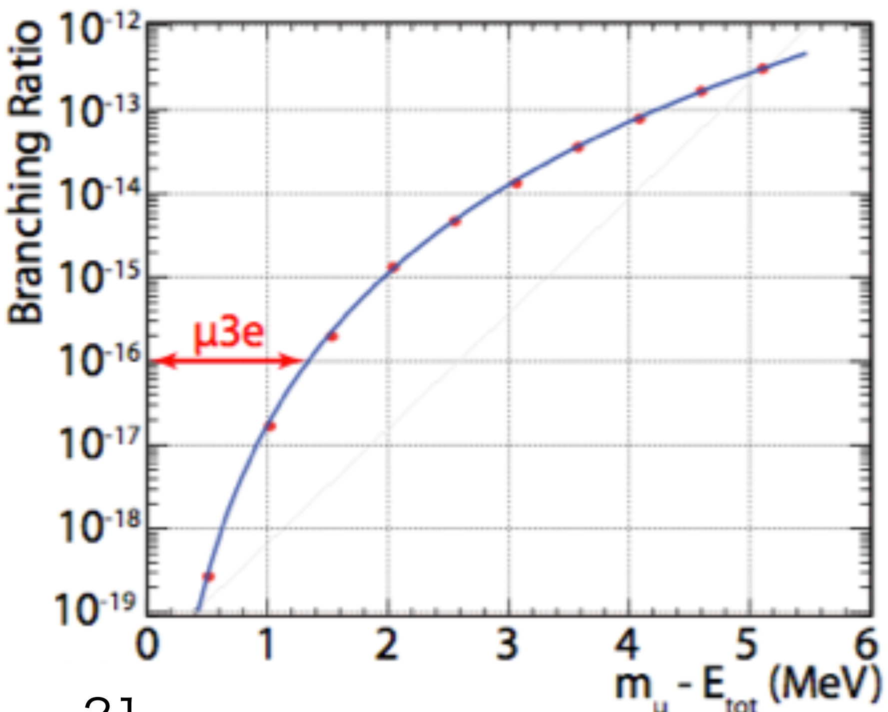
# Mu3e

# $\mu \to eee$ Search using DC Muon Beam

- Another channel sensitive to cLFV with DC muon beam
  - $1.0 \times 10^{-12}$ (90% C.L.) by SINDRUM
  - **Goal : $10^{-16}$ in 3 steps**
- Measure all electron tracks precisely
- most severe BG
  - $\mu^+ \to e^+ e^+ e^- \bar{\nu} \nu$

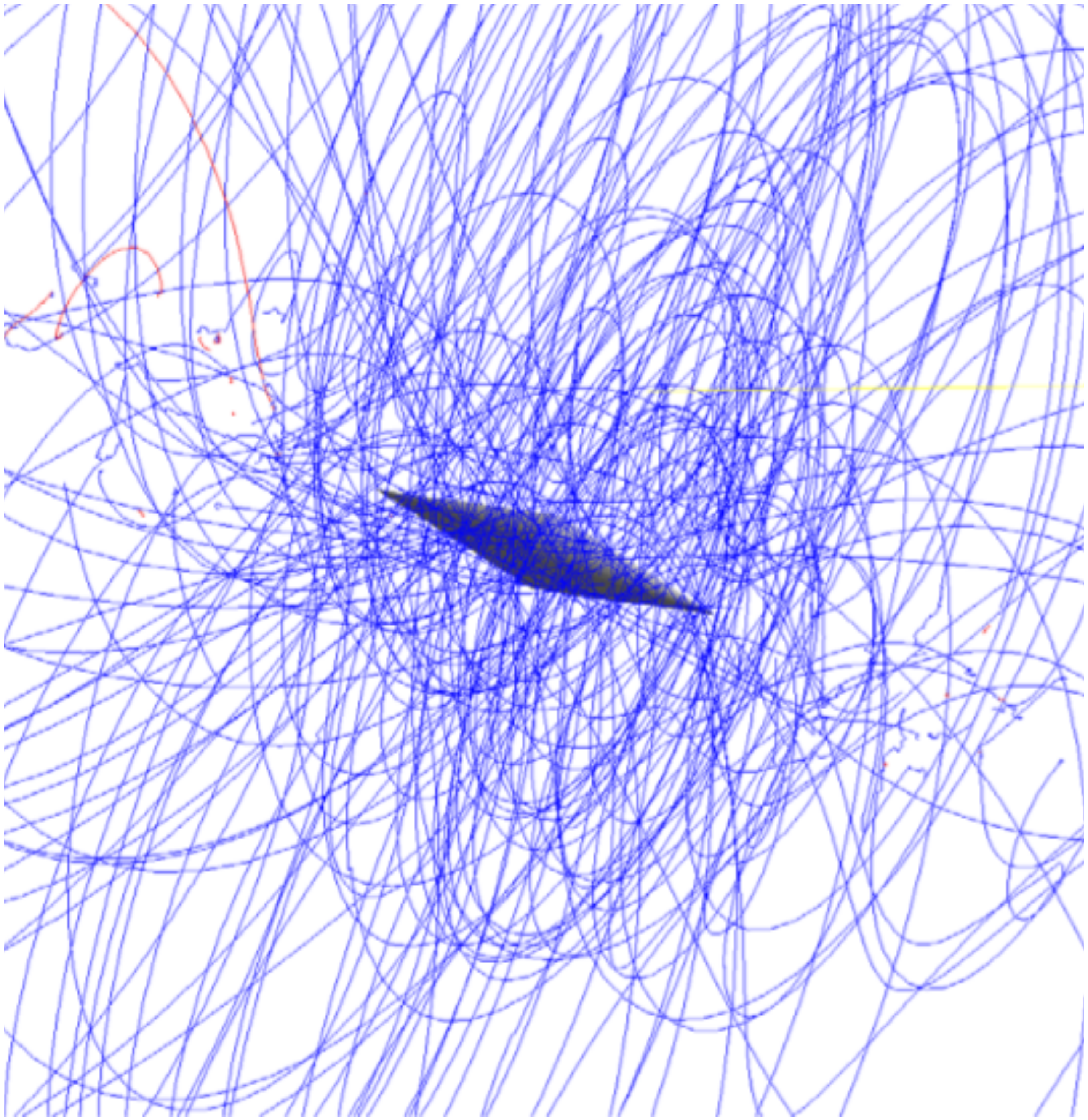



Suppress BG by more than 16 orders of magnitudes

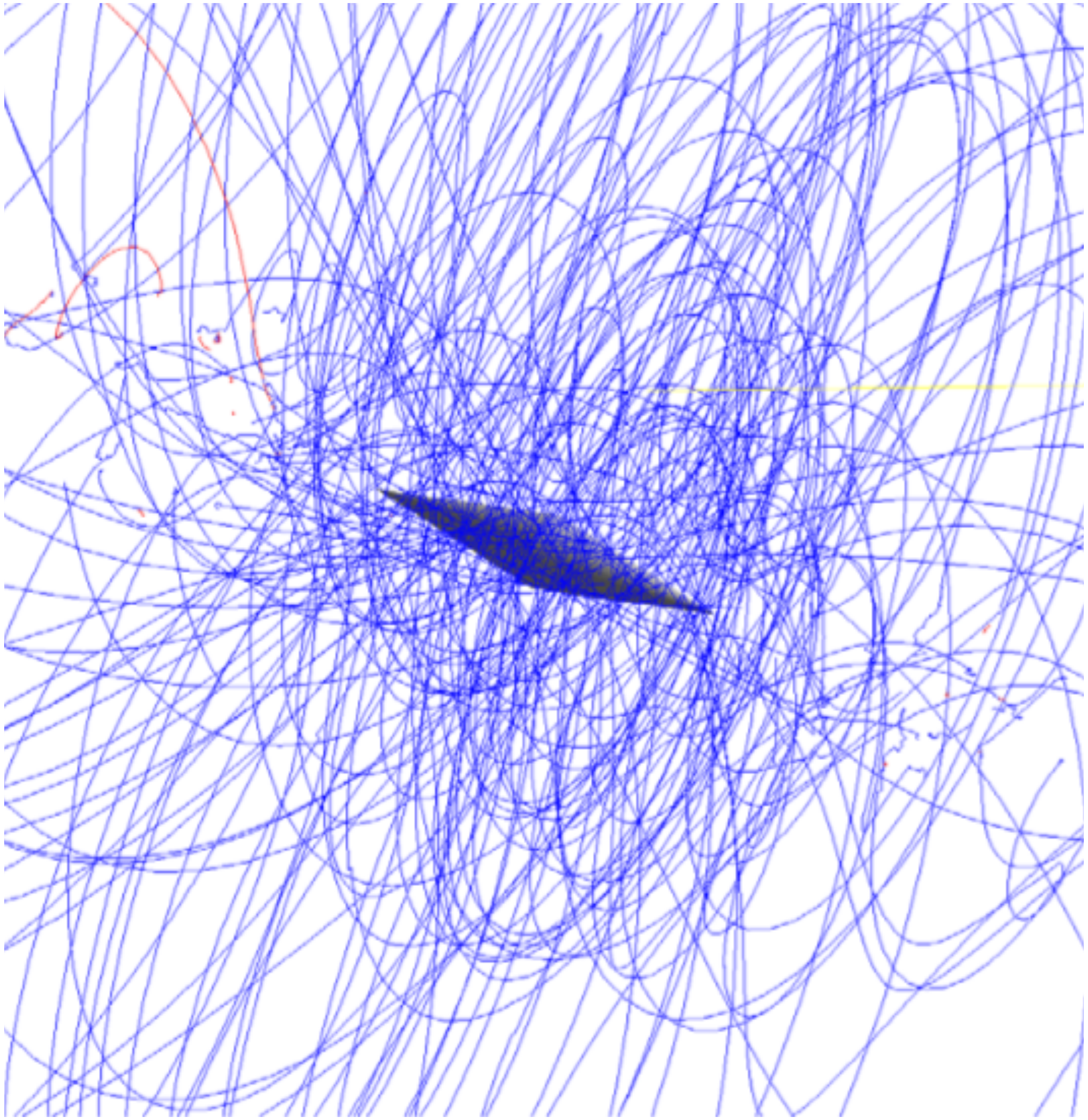
# Detector Technology



50 nsec, 1Tesla

- High granularity (occupancy)
- Close to target (vertex resolution)
- 3D space points (reconstruction)
- Minimum material (momenta below 53 MeV/c)

# Detector Technology



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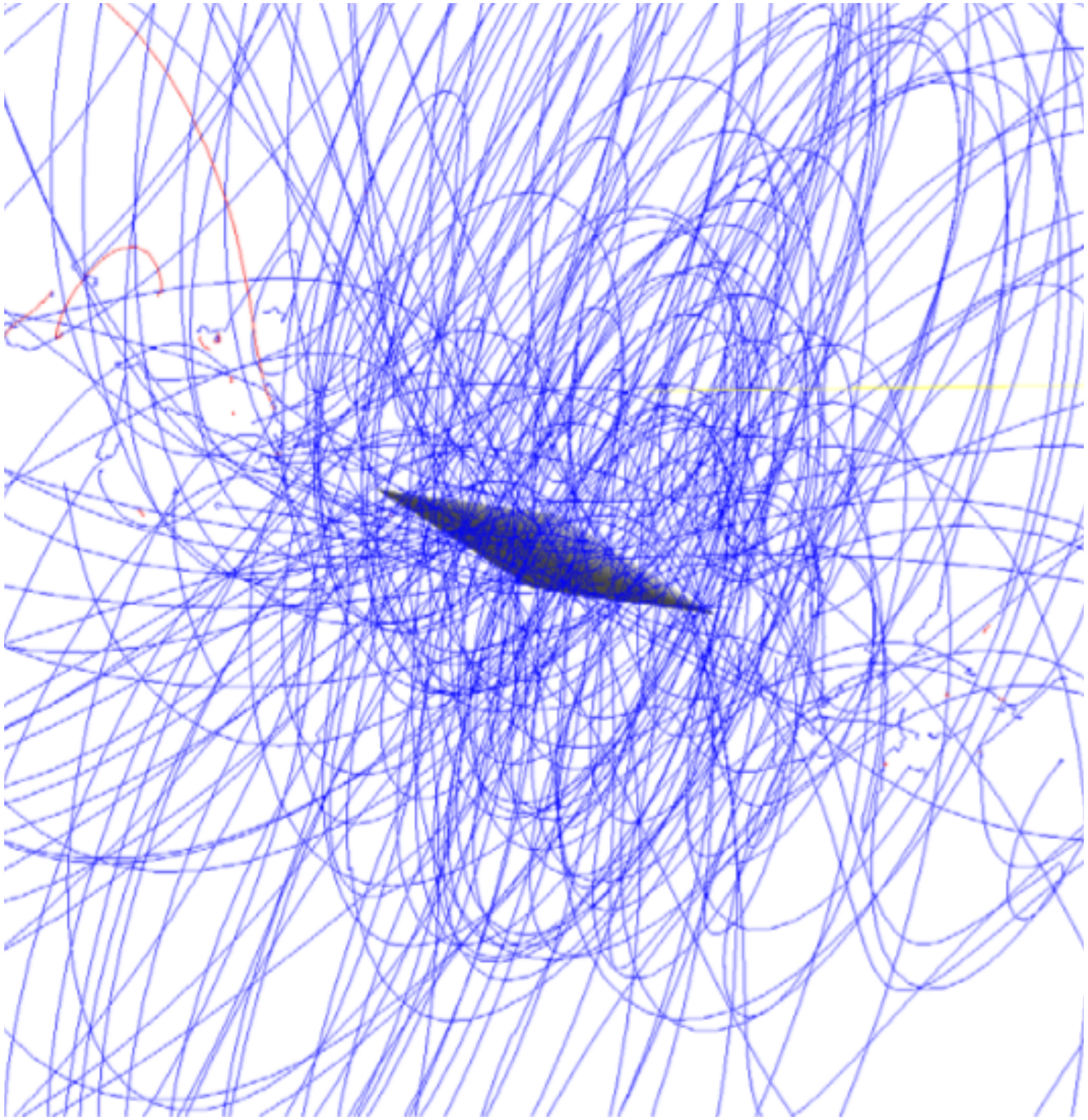
- 3D space points (reconstruction)
- Minimum material (momenta below 53 MeV/c)
- Gas detectors do not work (space charge, aging, 3D)

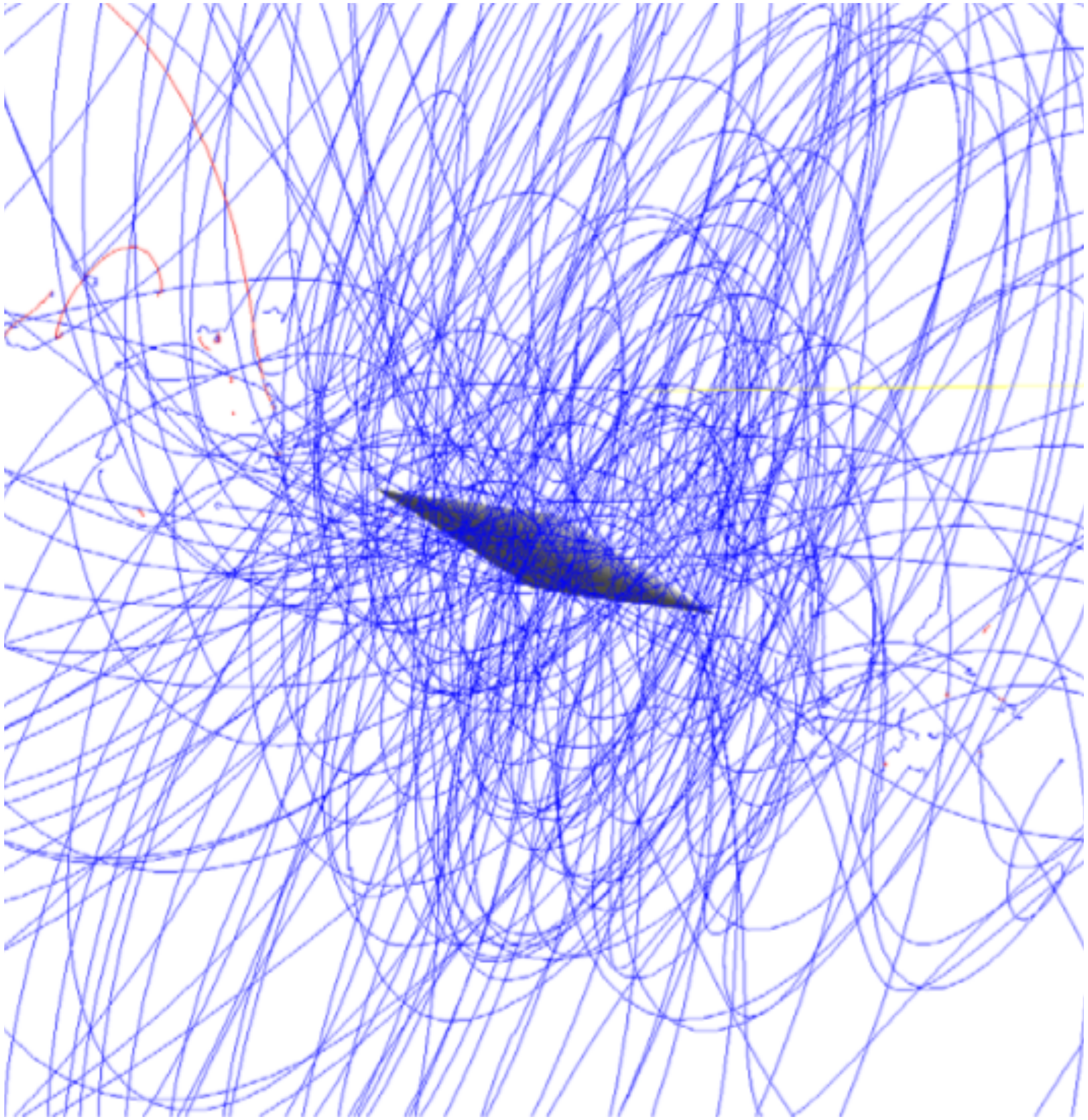
# Detector Technology



50 nsec, 1Tesla

- High granularity (occupancy)
- Close to target (vertex resolution)
- 3D space points (reconstruction)
- Minimum material (momenta below 53 MeV/c)
- Gas detectors do not work (space charge, aging, 3D)
- Silicon strips do not work (material budget, 3D)

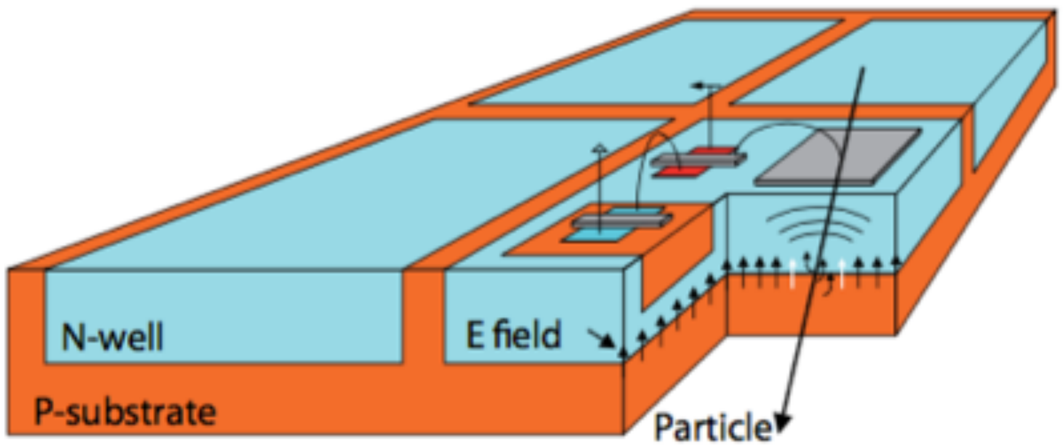
# Detector Technology



50 nsec, 1Tesla

- High granularity (occupancy)
- Close to target (vertex resolution)
- 3D space points (reconstruction)
- Minimum material (momenta below 53 MeV/c)
- Gas detectors do not work (space charge, aging, 3D)
- Silicon strips do not work (material budget, 3D)
- Hybrid pixels (as in LHC) do not work (material budget)

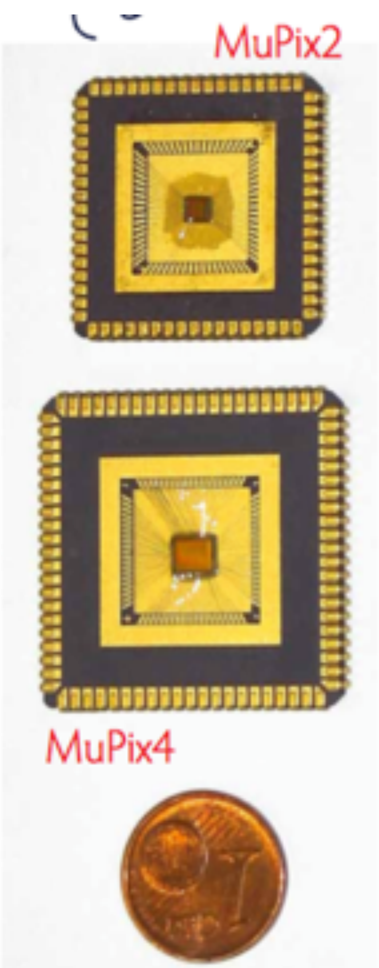
# Detector Technology

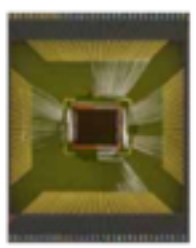



NIM A 582 (2007) 876

High voltage monolithic active pixel sensors - Ivan Perić

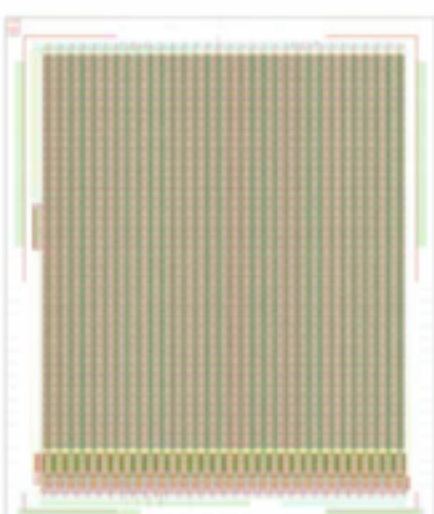
- thinned down to < 50 $\mu$m
- Logic on chip: Output zero suppressed hit addresses and timestamps

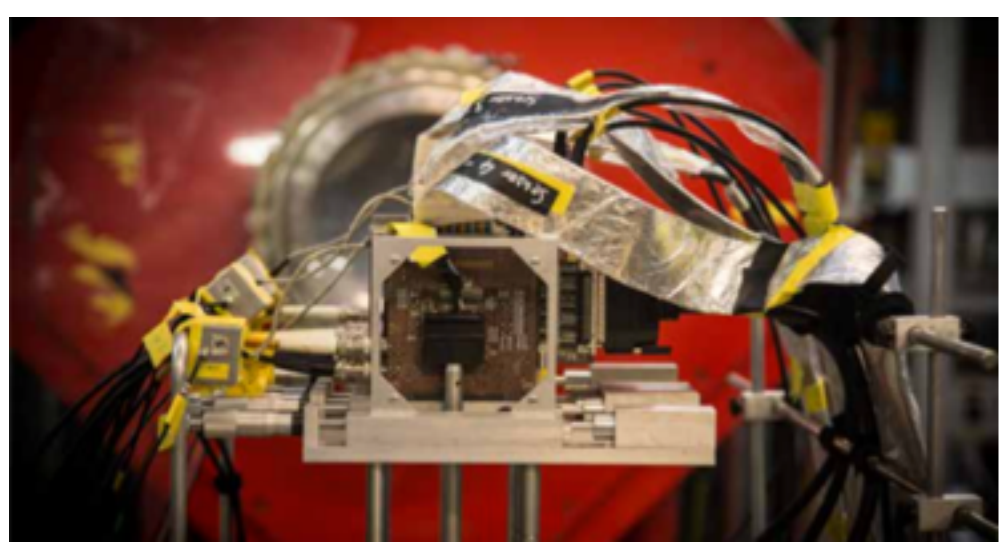


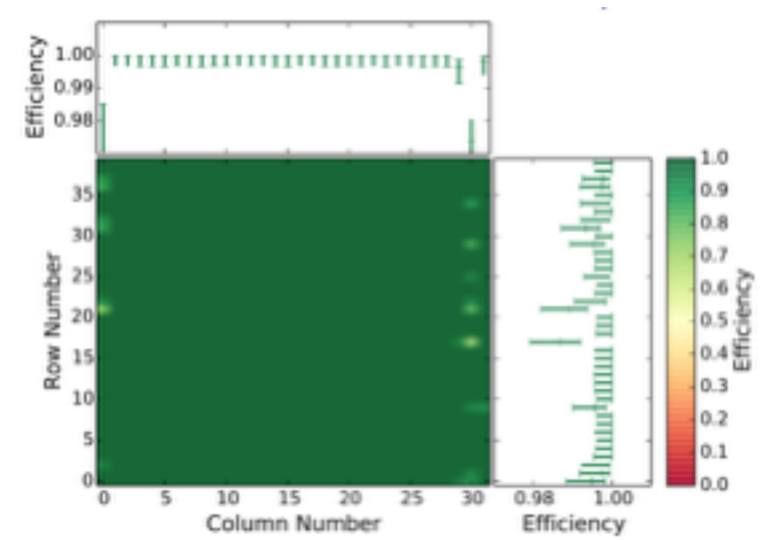
MuPix6

5 generations of prototypes, MuPix7 is current generation with all features of final sensors



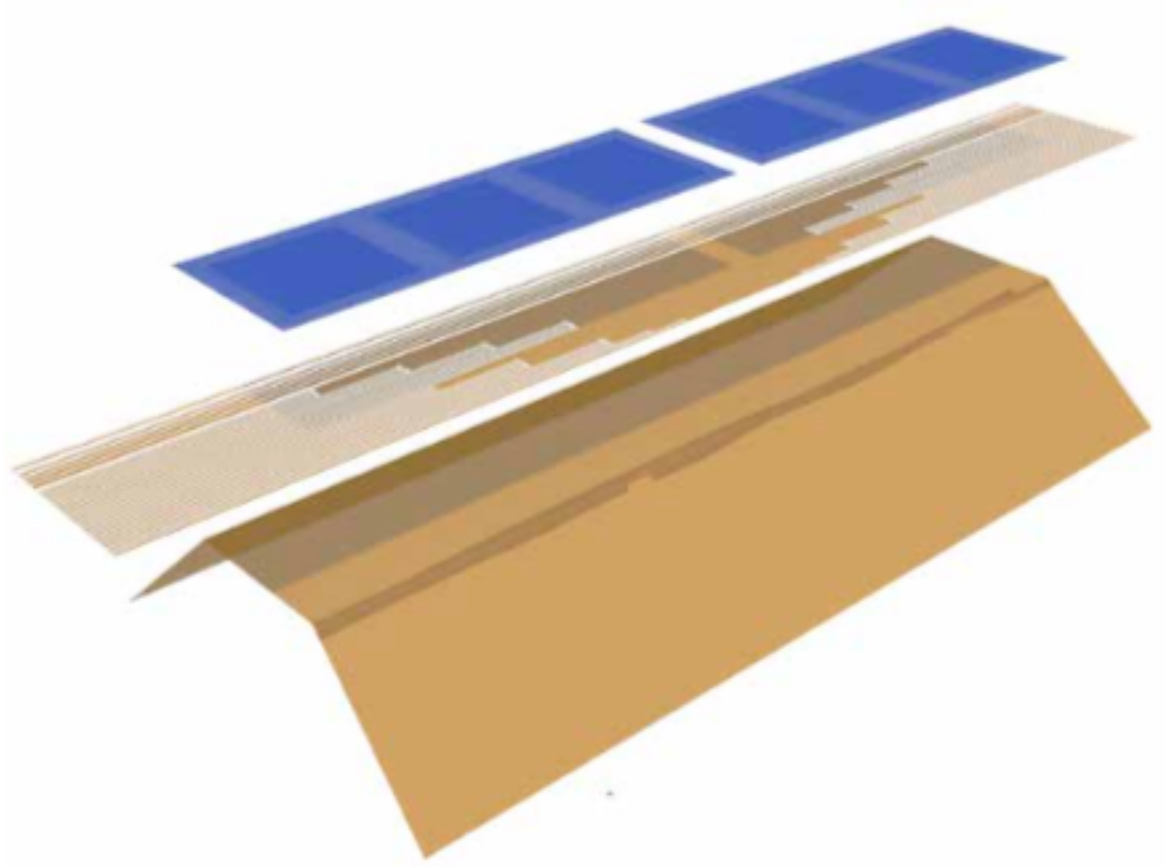


Test beam at DESY and PSI

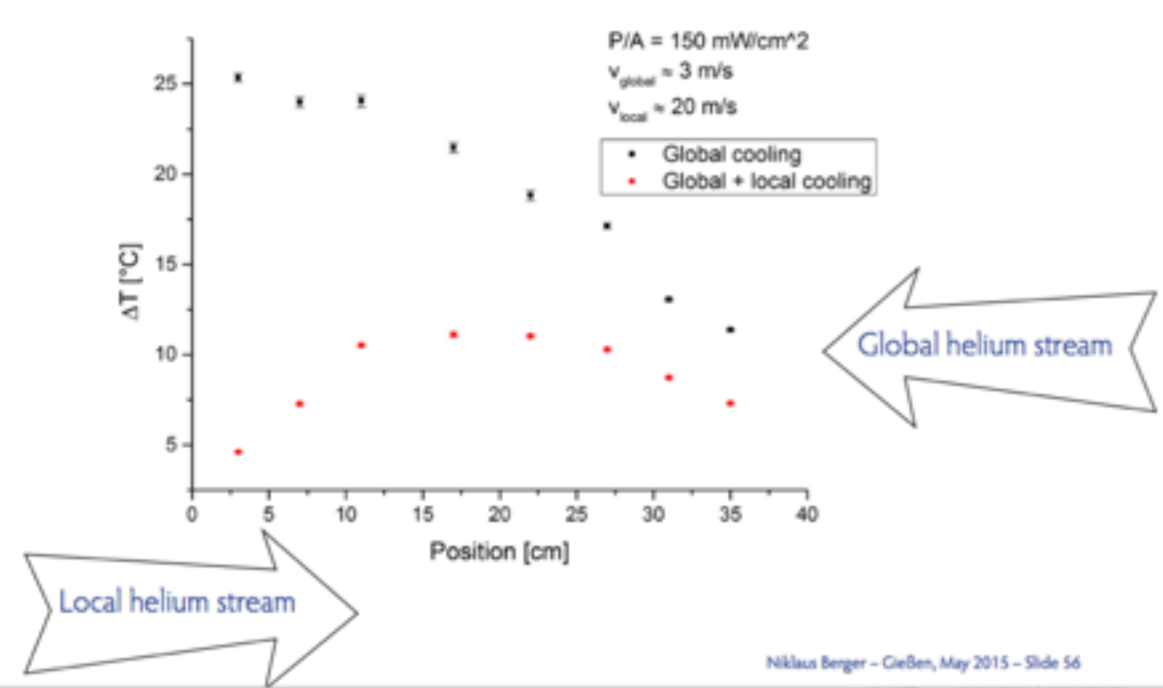



Efficiency above 99%

# Detector Building

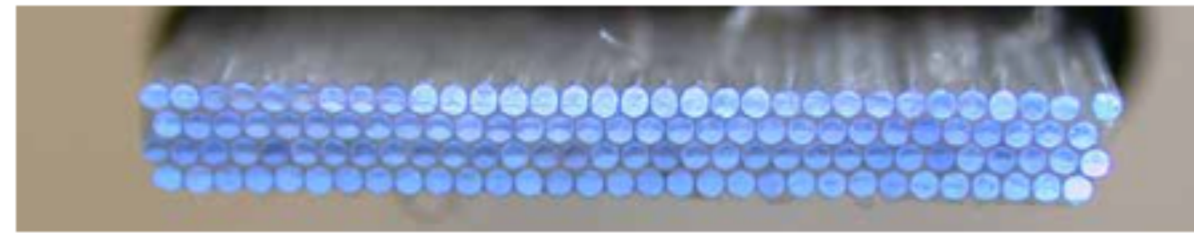


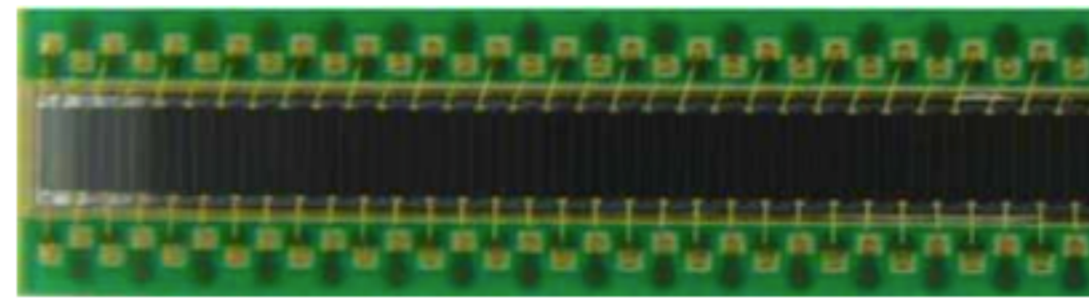
- 50$\mu$m silicon
- 25$\mu$m Kapton™ flexprint with Al traces
- 25$\mu$m Kapton™ frame
- Less than 1% R.L. per layer
- He cooling for 2kW heat generation from the chips

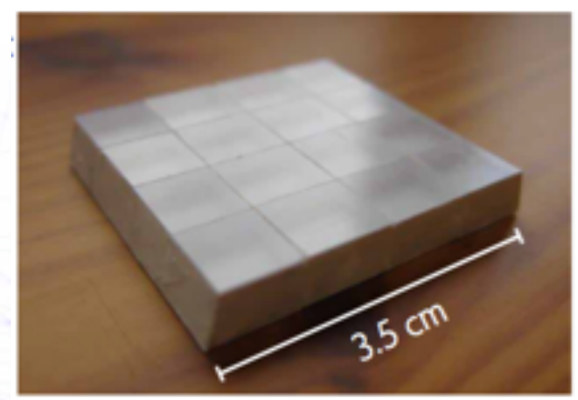


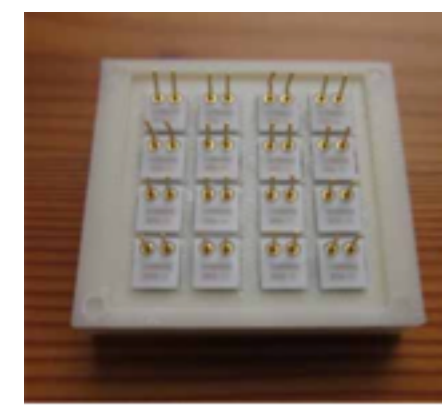
# Timing Measurement

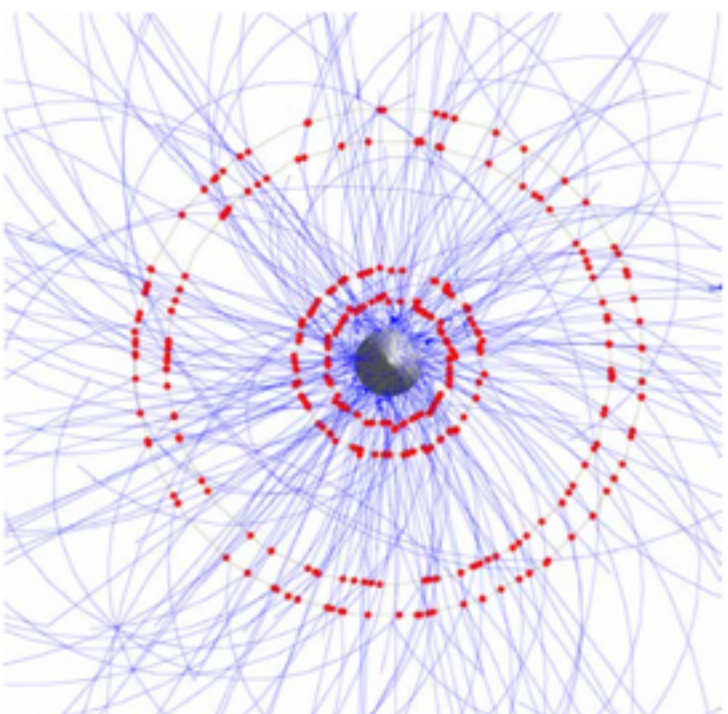
- Precise timing measurement is critical to reduce accidental BGs
  - Scintillating fibers O(1nsec)
  - Scintillating tiles O(100psec)



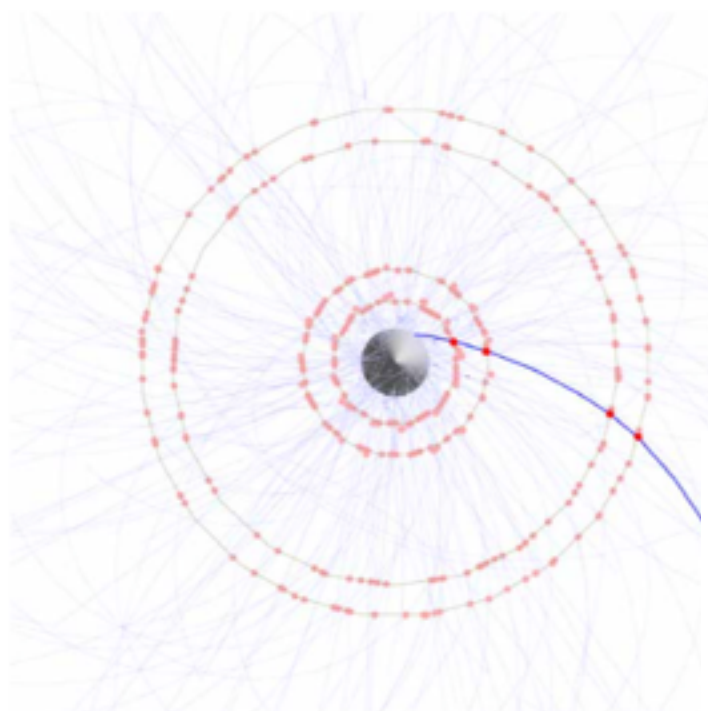




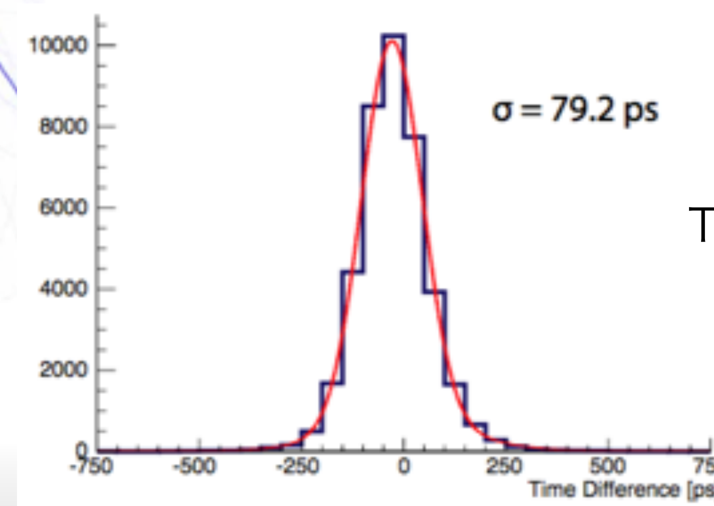





Pixels: O(50 ns)



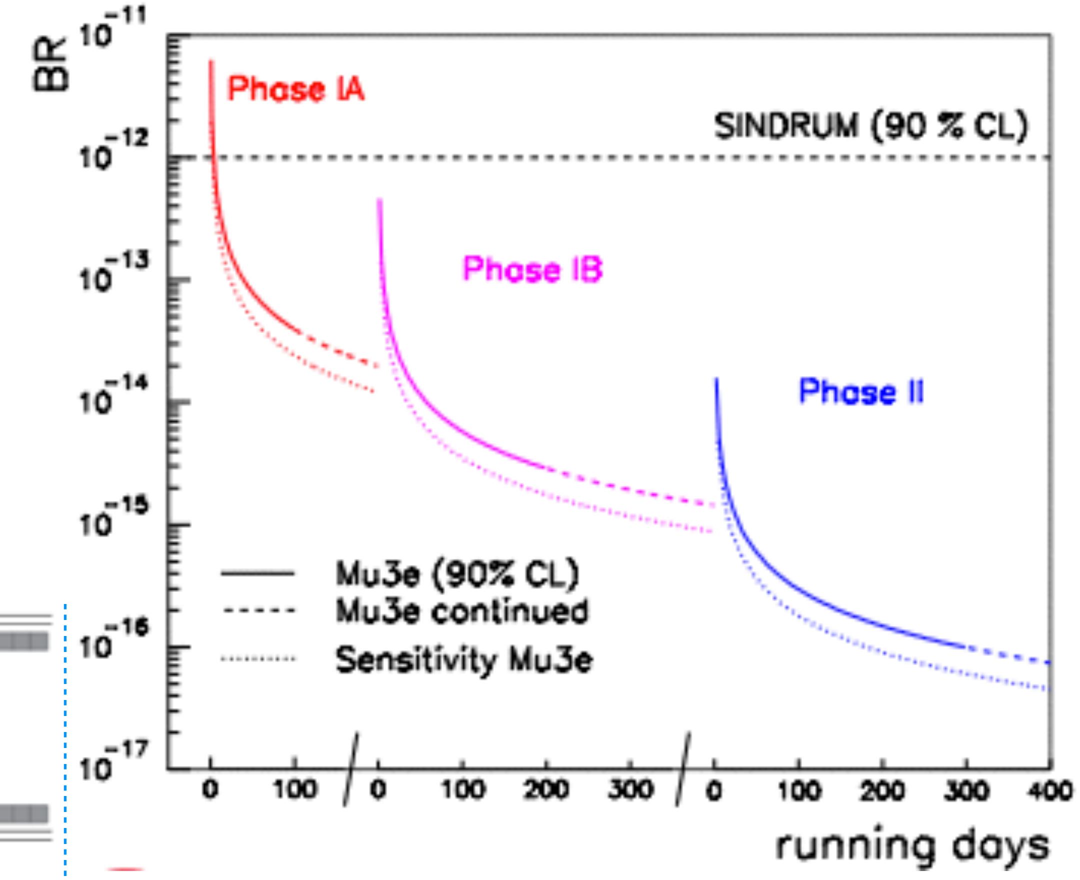
Scintillating fibres O(1 ns);
Scintillating tiles O(100 ps)

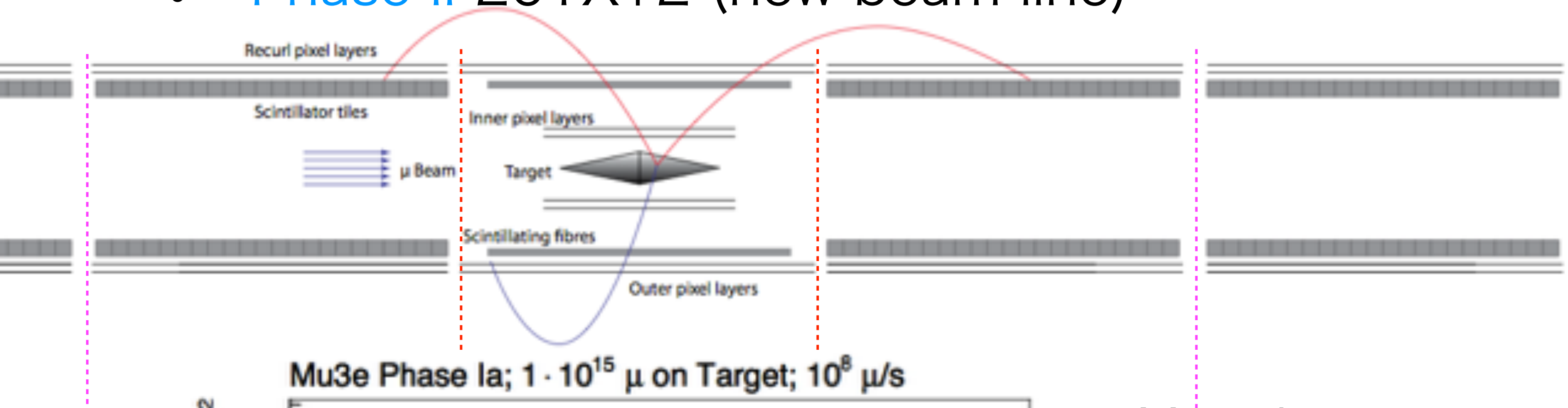


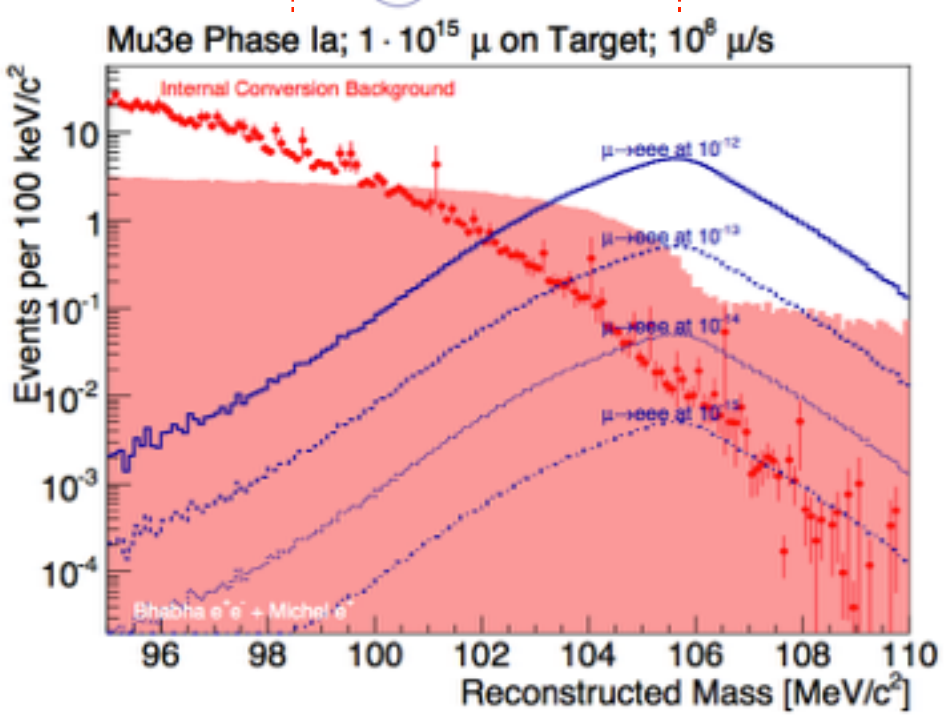

Test beam with Tiles
SiPM and ASIC

# Mu3e Staging Approach

- Mu3e staging approach
  - Phase IA 201X (PiE5 beam line)
  - Phase IB 201X+1 (PiE5 beam line)
  - Phase II 201X+2 (new beam line)

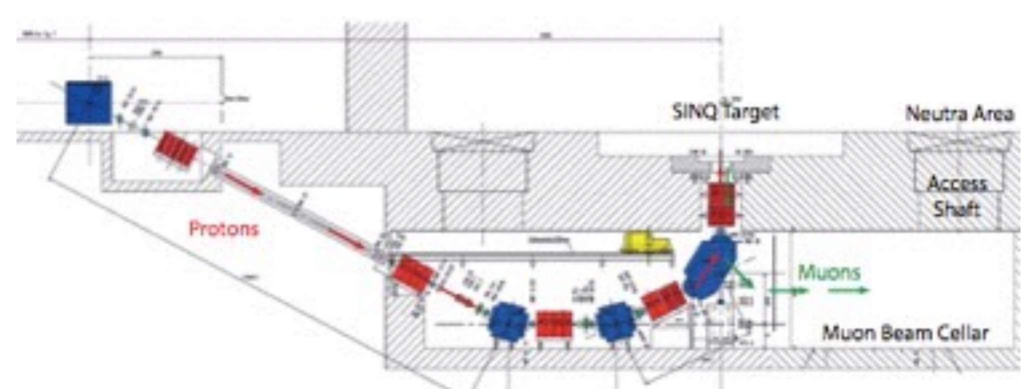


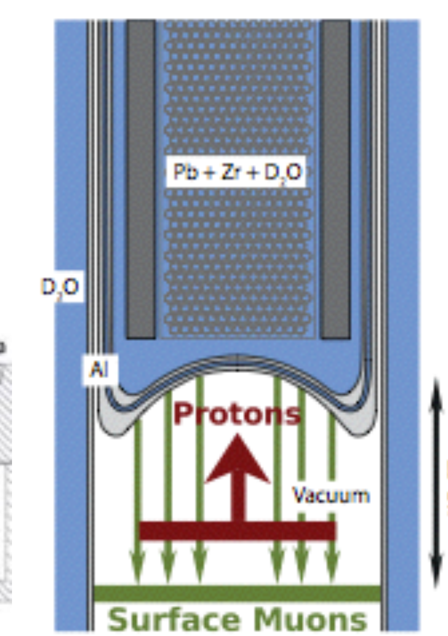




Muon beam

- $10^8$ muons/sec for Phase I
- $2 \times 10^9$ muons/s for Phase II

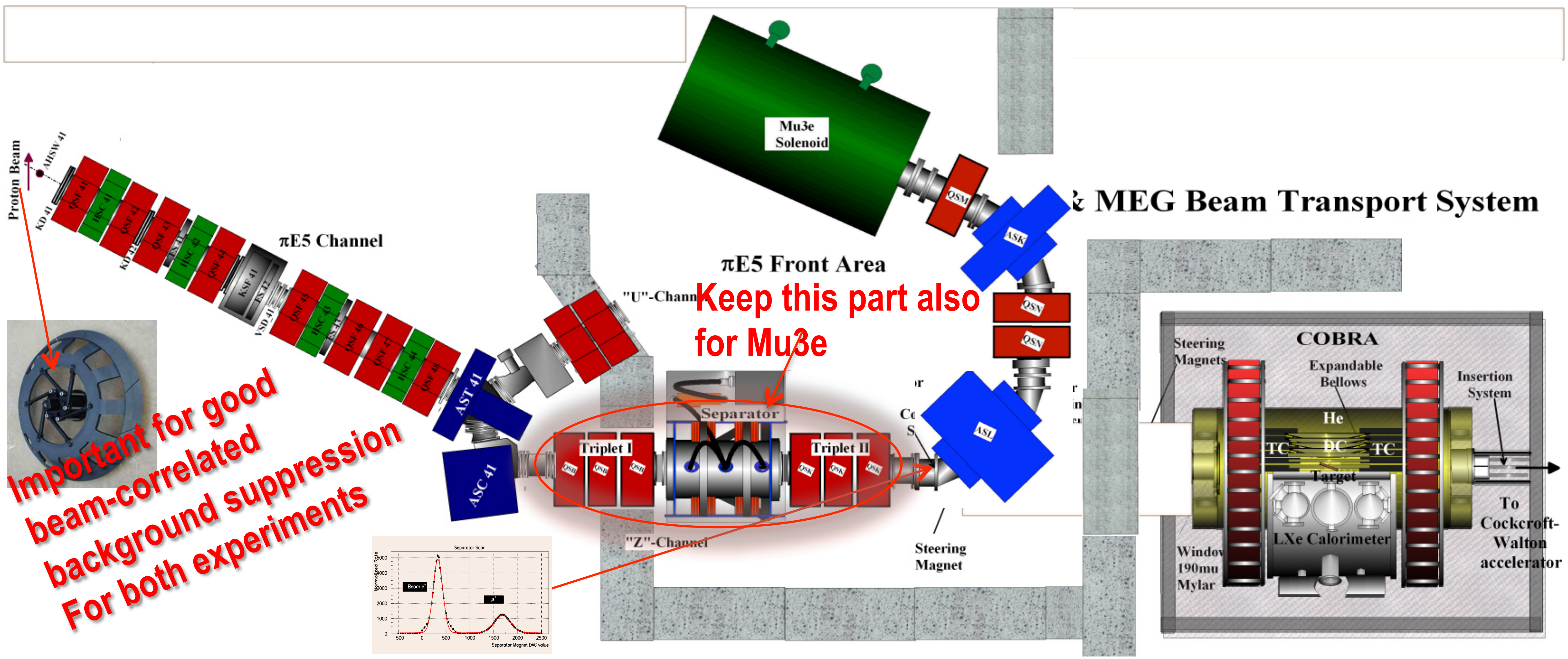


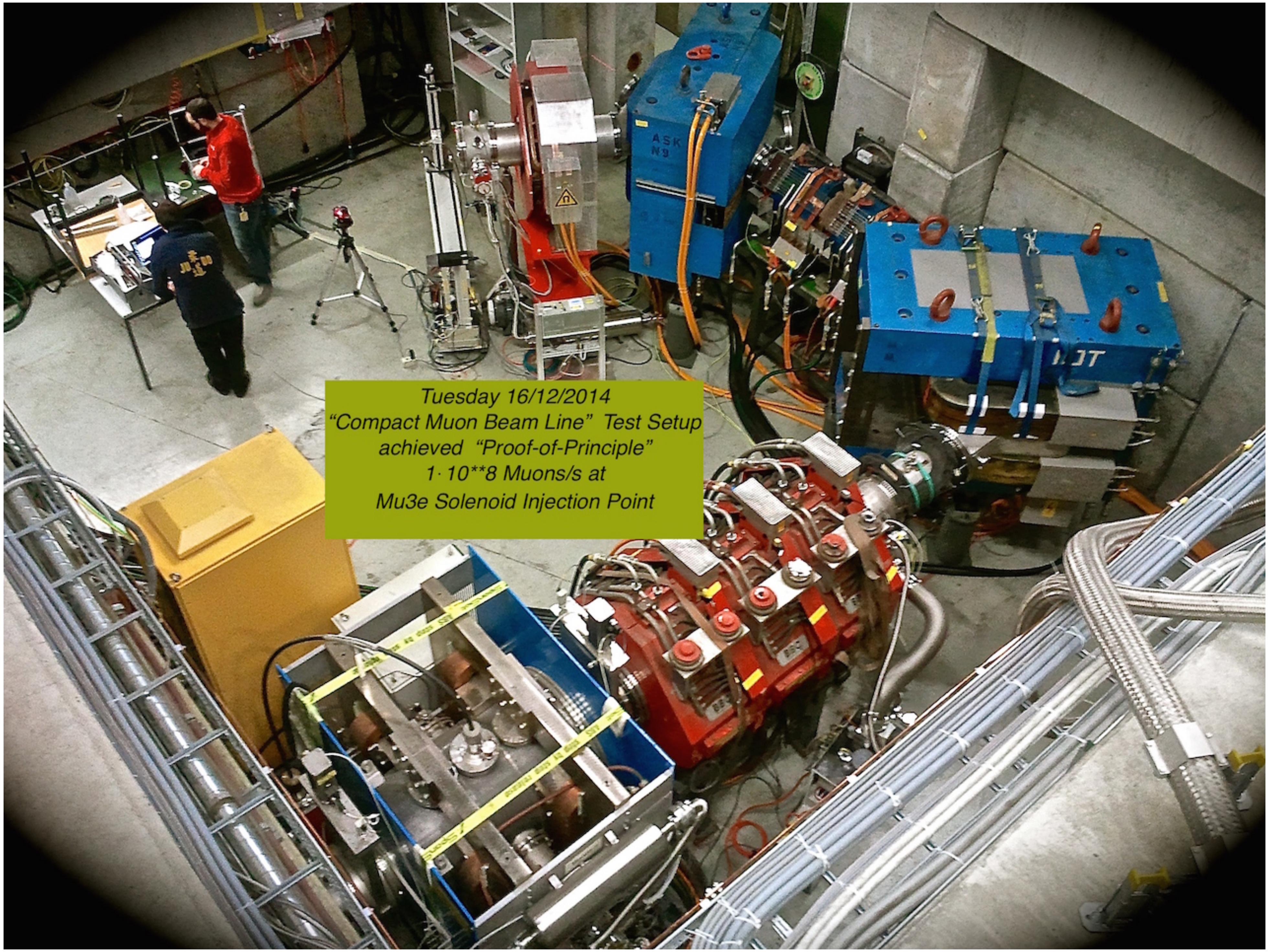

PSI new muon beam line (not before 2017)

# PiE5 Layout Scheme for MEG II & Mu3e I

- Both experiments have similar requirements O($10^8$) $\mu^+$/s, 28MeV/c
- Compact muon beam line for Mu3e allowing both to co-exist



# Mu3e CMBL Proof of Principle



# Summary

- Unique muon beam at PSI
  - High intensity O($10^8$) $\mu^+$/sec DC beam
  - R&D to improve by a factor of 20
- MEG completed successfully
  - The result is just around the corner
- MEG II preparation is in good shape
  - Improve the sensitivity by a factor of 10 to reach $5\times10^{-14}$
- Mu3e detector R&D in progress toward the start of a beautiful experiment using new technology

# Thanks to

- MEG & MEG II collaboration
- Nik Burger for Mu3e contents

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and FPCP2015 organizer