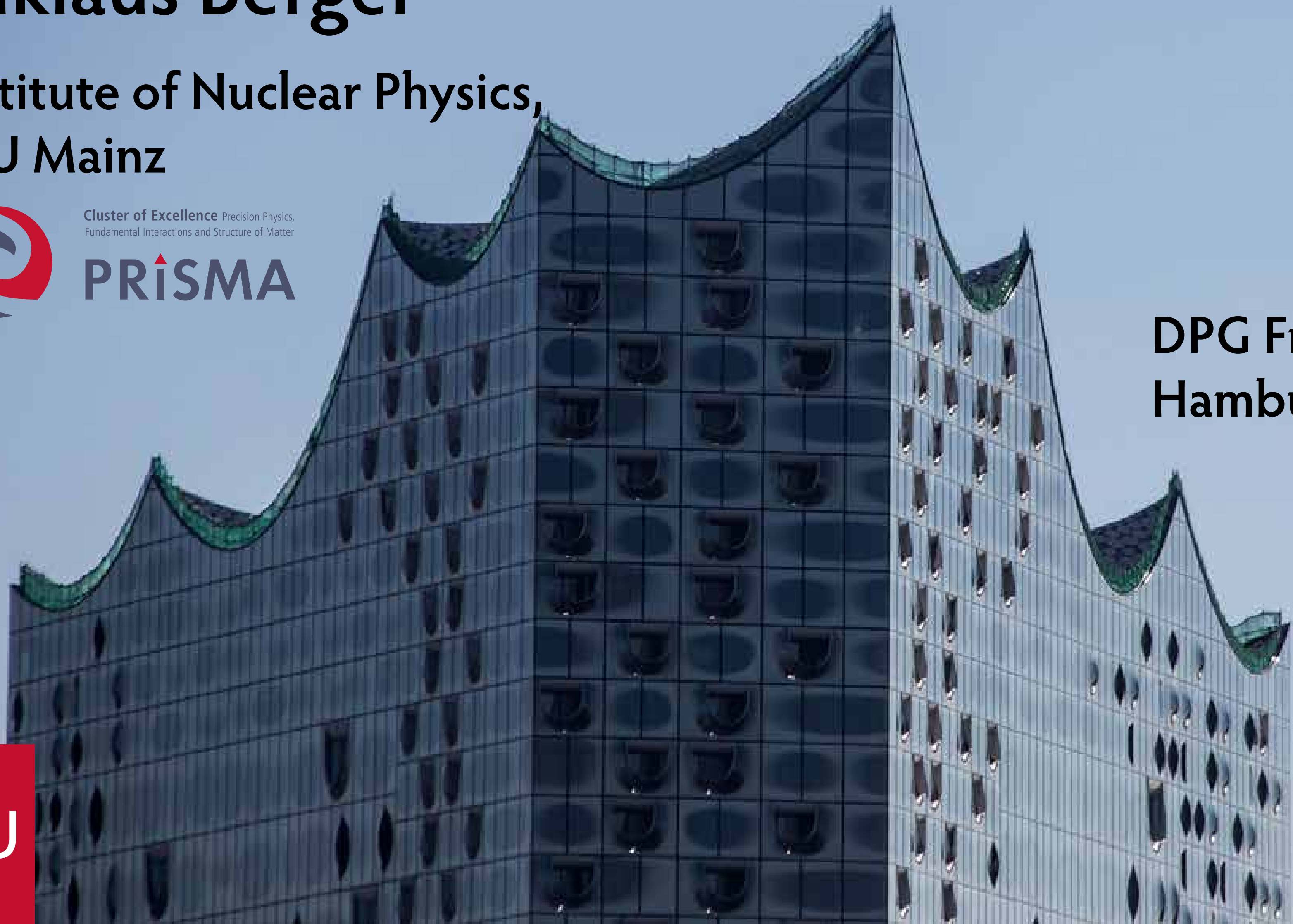
Low-Energy Precision Experiments with Muons

Niklaus Berger

Institute of Nuclear Physics,
JGU Mainz

Cluster of Excellence Precision Physics, Fundamental Interactions and Structure of Matter
PRISMA



DPG Frühjahrstagung
Hamburg 2016

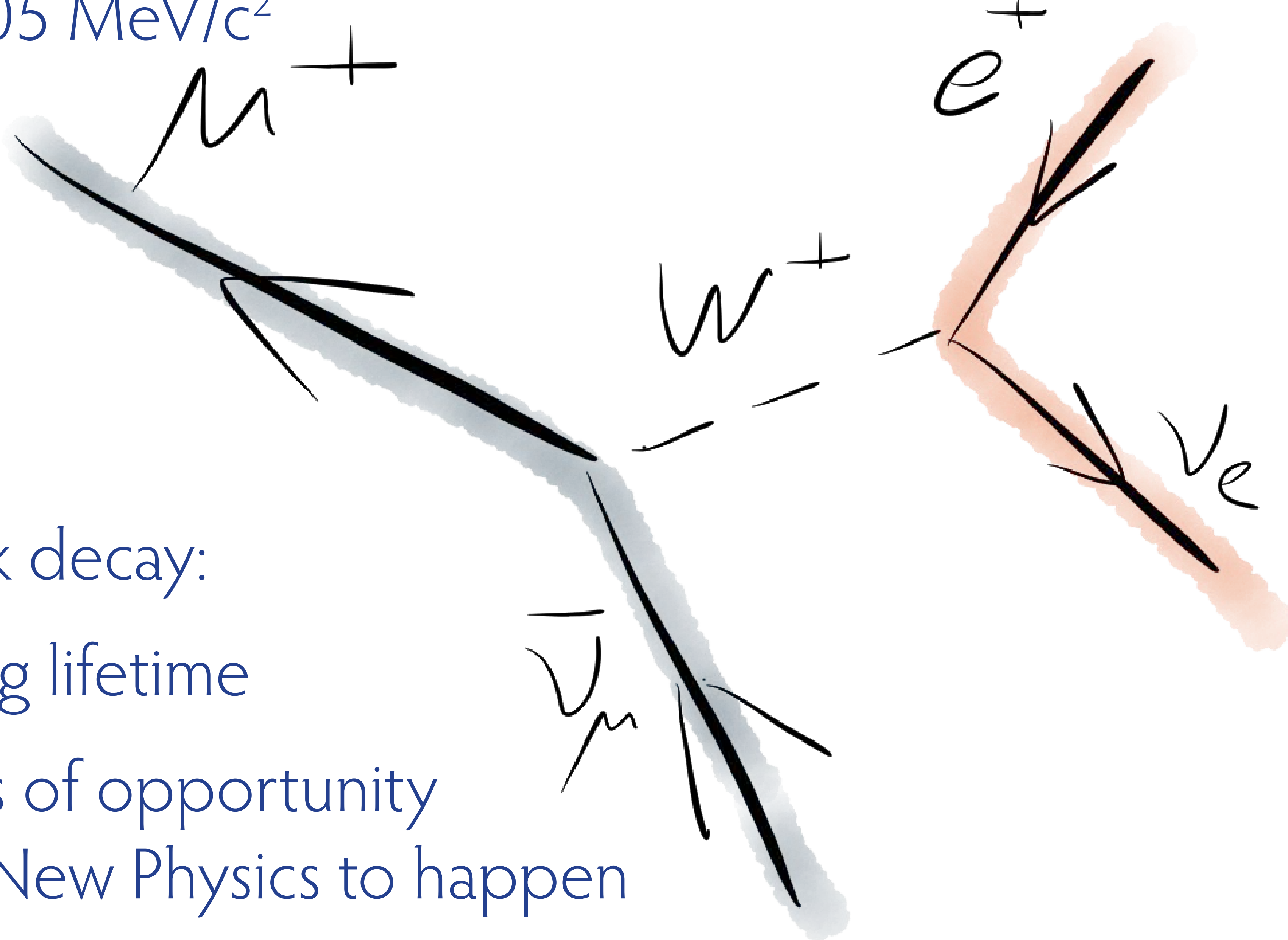
JG|U

Emmy Noether-Programm
Deutsche Forschungsgemeinschaft
DFG

Testing the Standard Model
Searching for New Physics

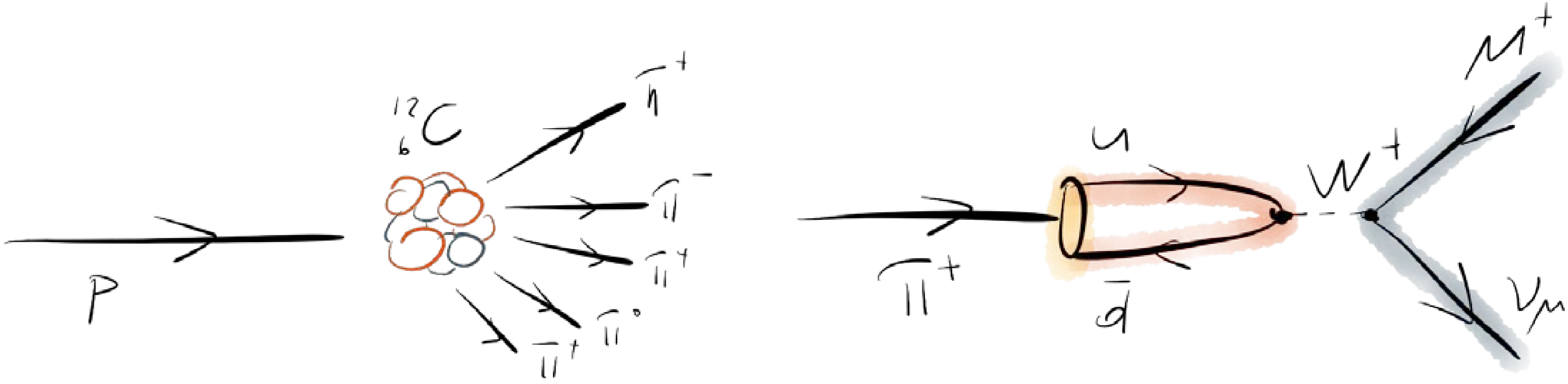
Why low energy muons?

$m_\mu = 105\ \mathrm{MeV}/c^2$



Weak decay:

- Long lifetime
- Lots of opportunity for New Physics to happen
- Theory well under control



Easy to produce with intense proton beams:

10^8 μ/s available

> 10^{10} μ/s planned

Polarized

Muons from PSI

Paul Scherrer Institute in Villigen, Switzerland

World's most intensive proton beam
2.2 mA at 590 MeV: 1.3 MW of beam power

Continuous beam

10^8 μ/s available
options for 10^{10} μ/s under study

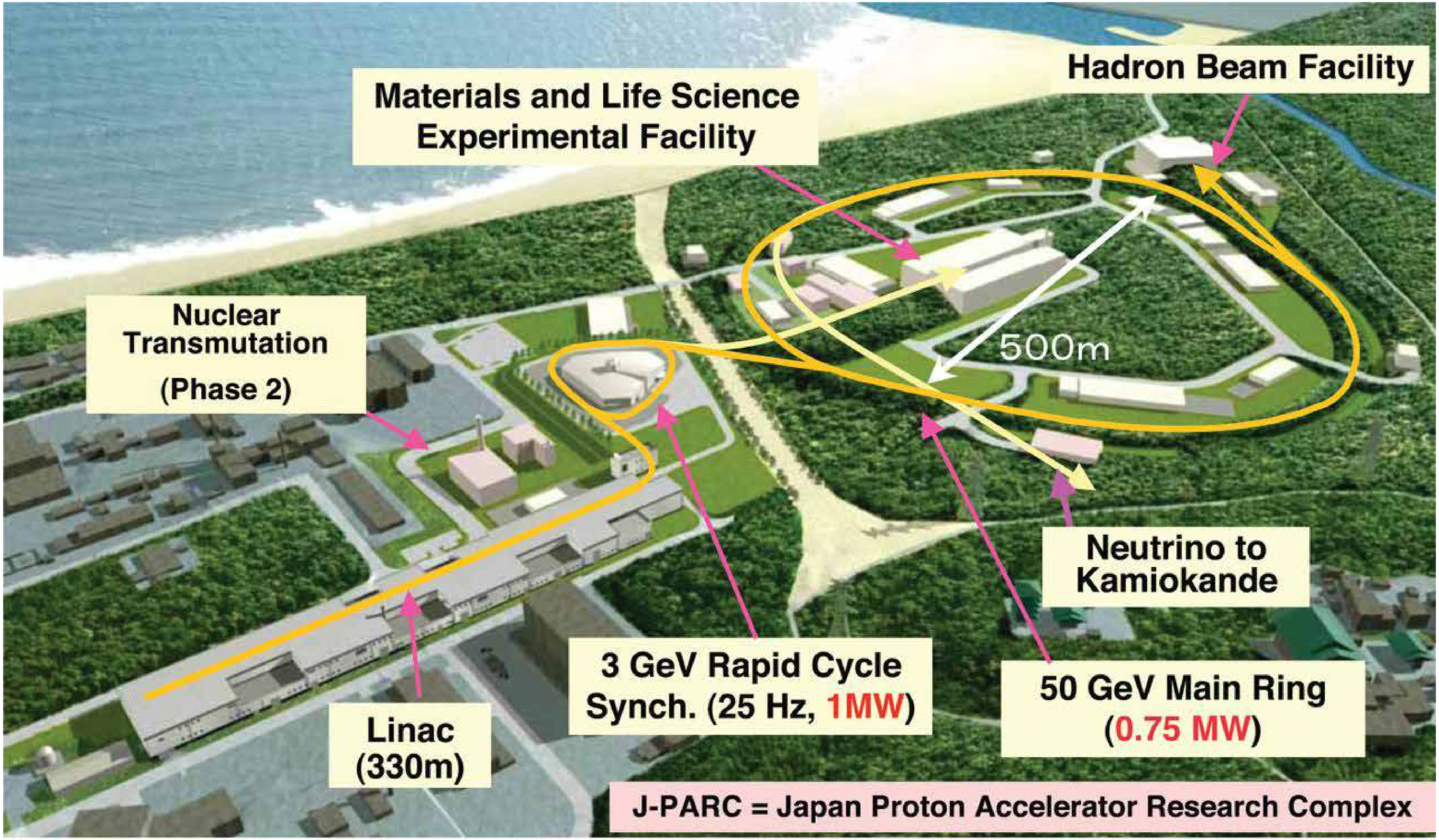
Muons from Fermilab ...

fnal.gov

- Re-use part of the Tevatron infrastructure
- Proton pulses every 1700 ns
- > 10^{10} μ/s

- Project X
(now Proton Improvement Plan-II)
would give another
2 orders of magnitude with a
new powerful proton linac

... and J-PARC



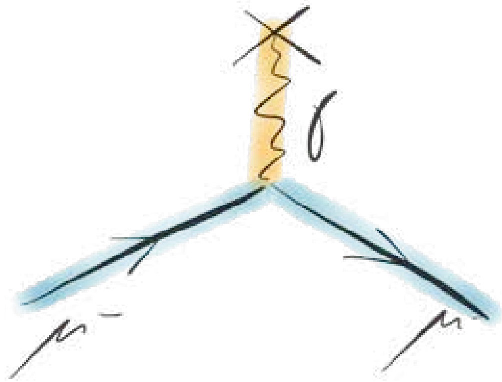
10^{11} μ/s from 8 GeV/c protons, pulsed

S. Nagamiya, Prog. Theor. Exp. Phys. (2012) 02B001

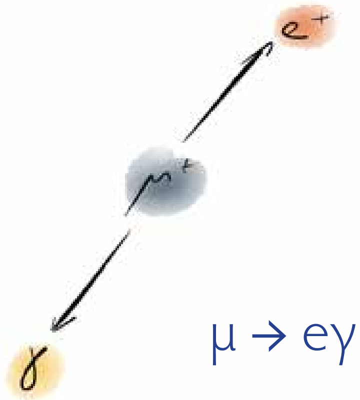
Outline:

Selection of muon precision experiments:

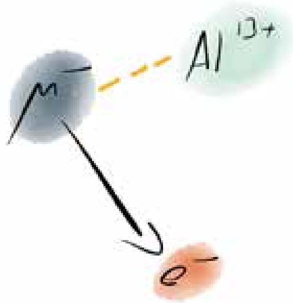
- The magnetic moment of the muon



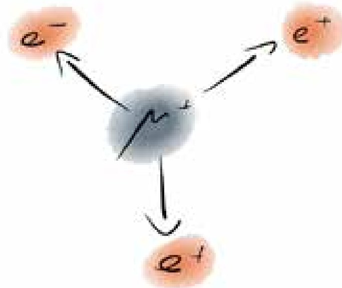
- Searches for lepton flavour violation in muon decays



μ → eγ



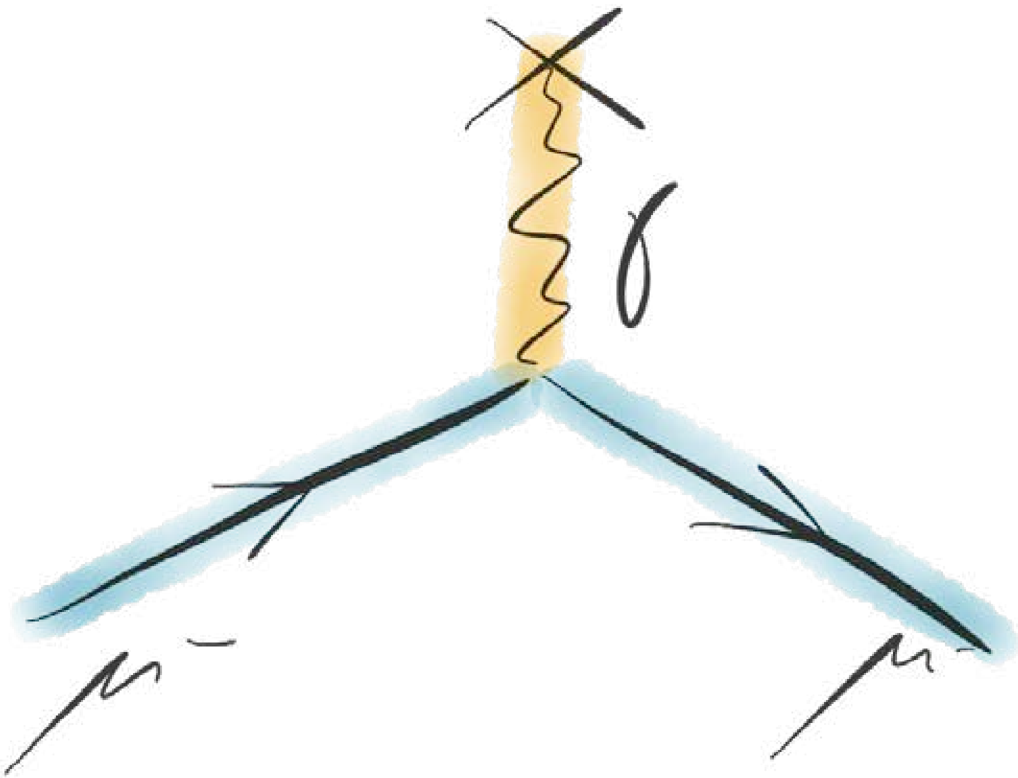
μ → e conversion in field of nucleus



μ → eee

Some results and many upcoming measurements

The magnetic moment of the muon



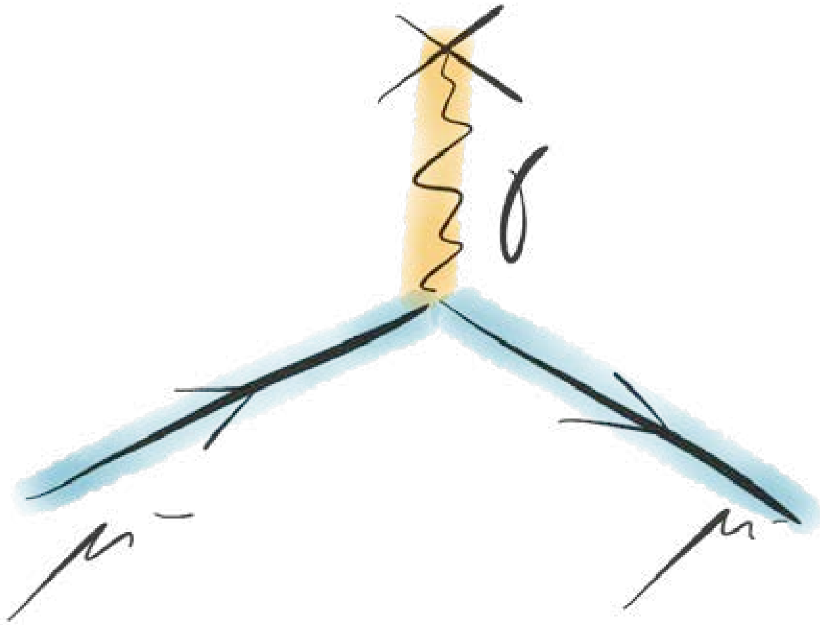
Magnetic moment of the muon

Spin precession in magnetic field:

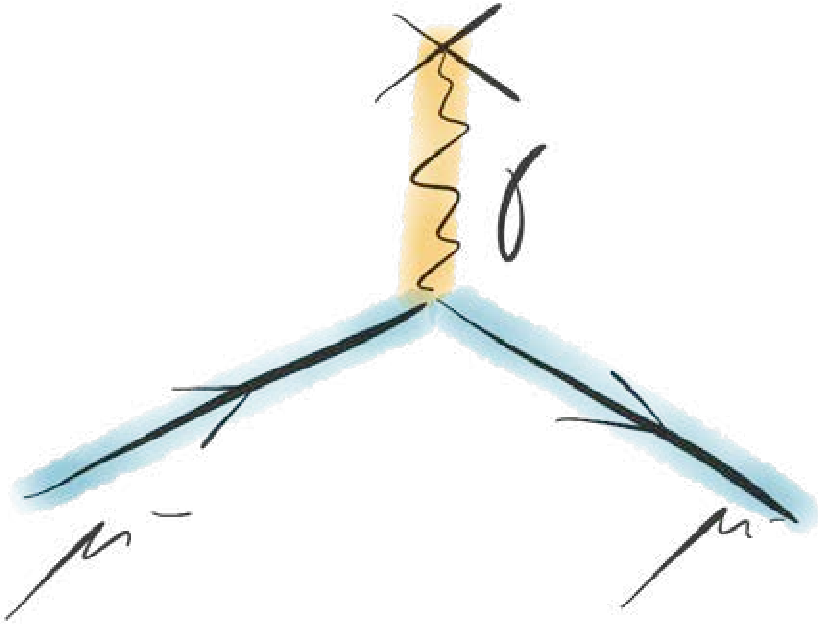
$$\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} = \vec{\mu} \times \vec{B}$$

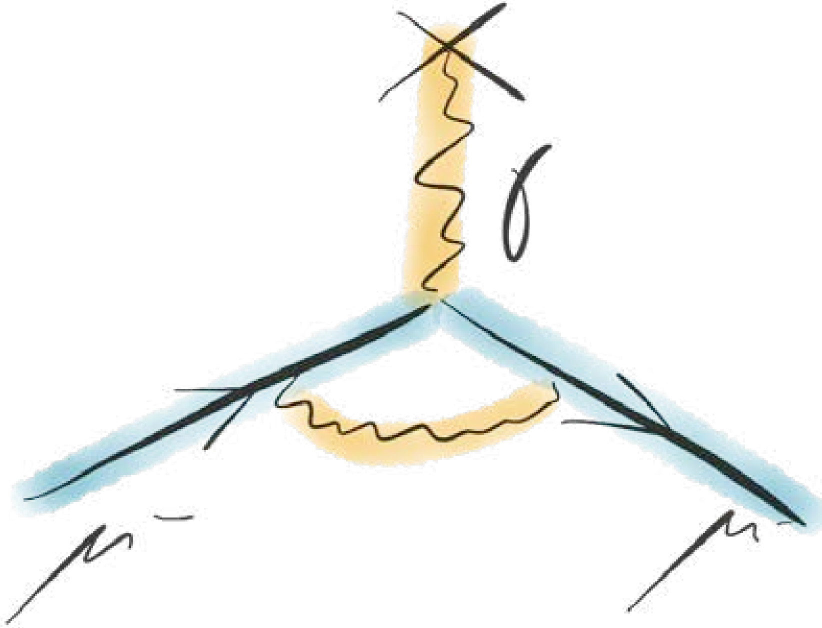
$$\vec{\mu} = g\frac{e}{2m}\vec{s}$$

Dirac: $g = 2$



Magnetic moment of the muon





Dirac:

$$g = 2$$

Schwinger:

$$a = \frac{g-2}{2} = \frac{\alpha}{2\pi}$$

J. S. Schwinger, Phys. Rev. 73, 416 (1948)

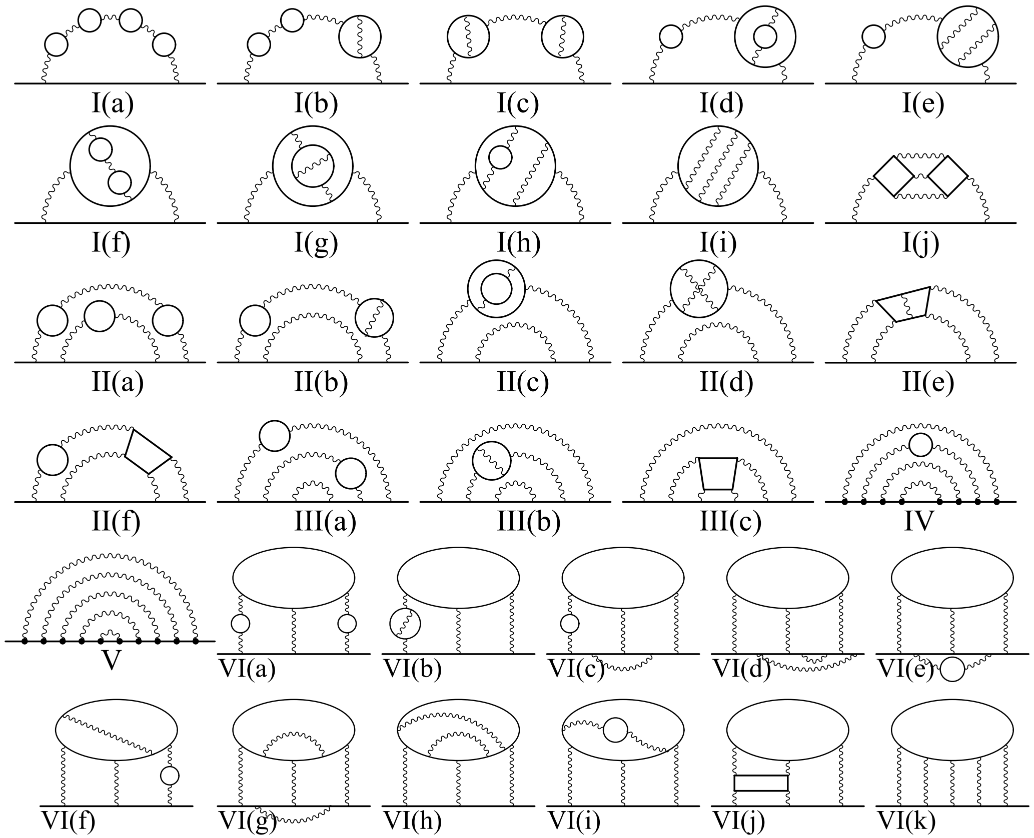
$$a_{SM} = a_{QED} + a_{EW} + a_{had}$$

$$a_{SM} = a_{QED} + a_{EW} + a_{had}$$

Known analytically to 3 loops

numerically to 5 loops

12672 diagrams



A. Petermann, Helv. Phys. Acta 30, 407 (1957)

C. M. Sommerfield, Ann. Phys. (N.Y.) 5, 26 (1958)

S. Laporta and E. Remiddi, Phys. Lett. B379, 283 (1996)

S. Laporta, Phys. Lett. B312, 495 (1993).

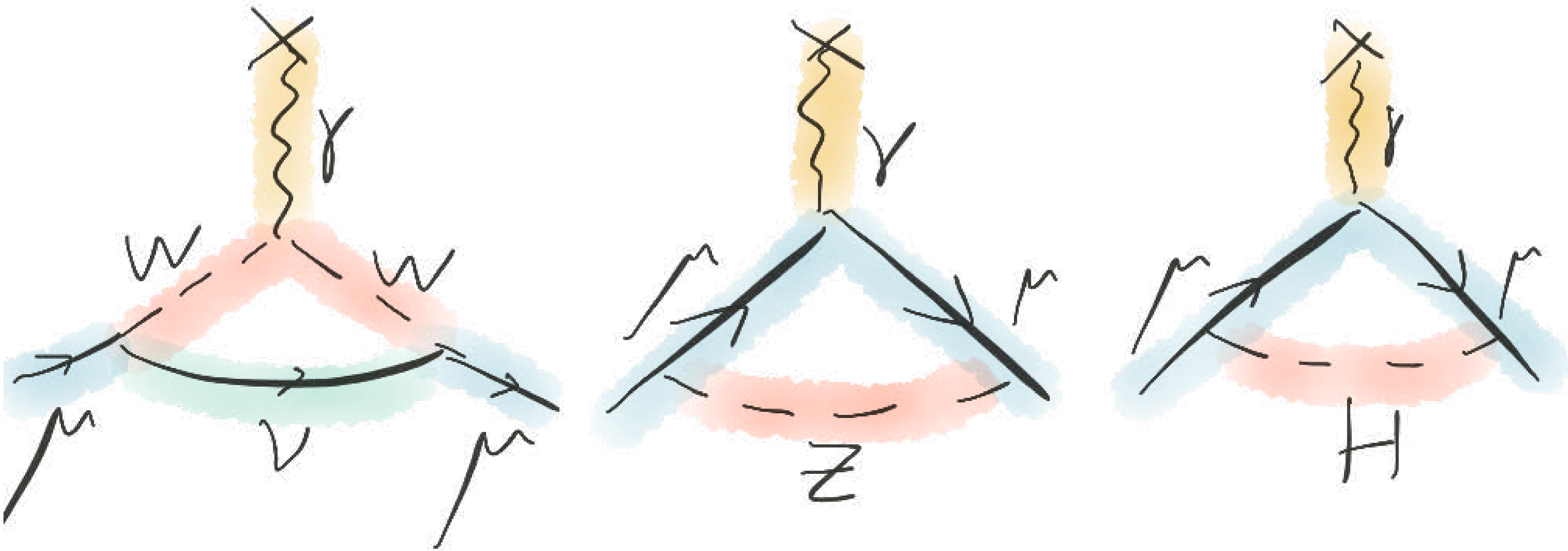
T. Kinoshita and M. Nio, Phys. Rev. D73, 013003 (2006).

T. Aoyama et al., Phys. Rev. Lett. 99, 110406 (2007); Phys. Rev. D77, 053012 (2008)

T. Aoyama et al., Phys.Rev.Lett. 109, 111808 (2012)

$$a_{SM} = a_{QED} + a_{EW} + a_{had}$$

Known analytically to 2 loops



K. Fujikawa, B. Lee, and A. Sanda, Phys. Rev. D 6, 2923 (1972)

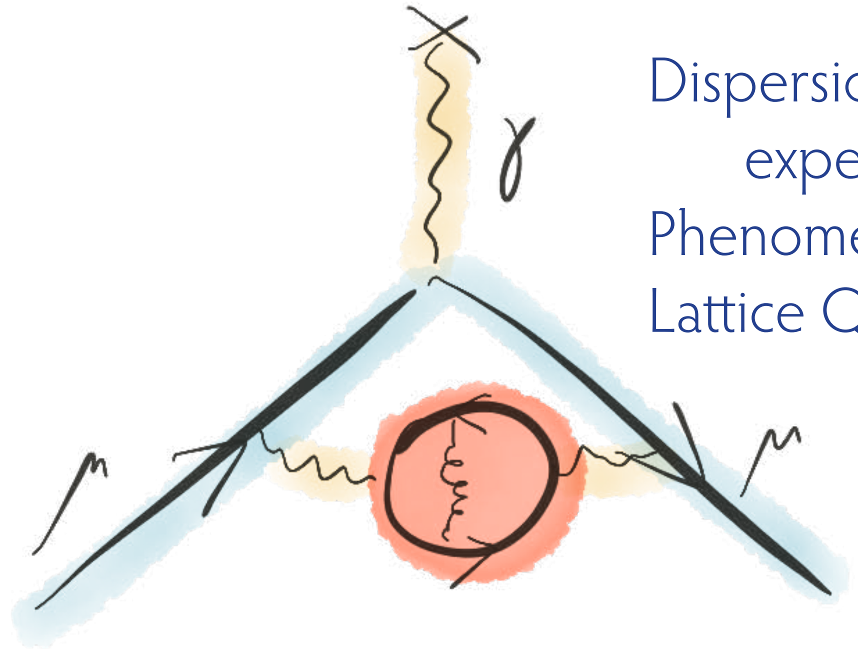
A. Czarnecki, B. Krause, and W. J. Marciano, Phys. Rev. Lett. 76, 3267 (1996)

M. Knecht, S. Peris, M. Perrottet, and E. De Rafael, J.High Energy Phys. 11, 003 (2002)

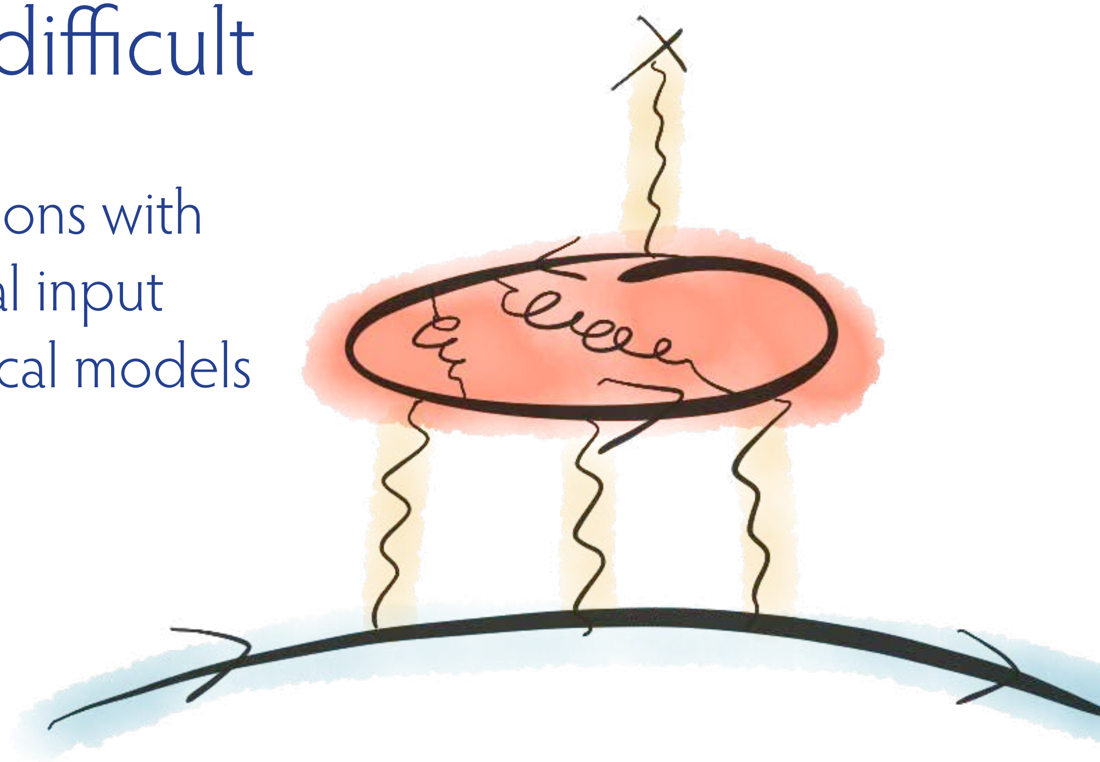
A. Czarnecki, W. J. Marciano, and A. Vainshtein, Phys. Rev. D 67, 073006 (2003)

$$a_{SM} = a_{QED} + a_{EW} + a_{had}$$

Hadronic contribution most difficult



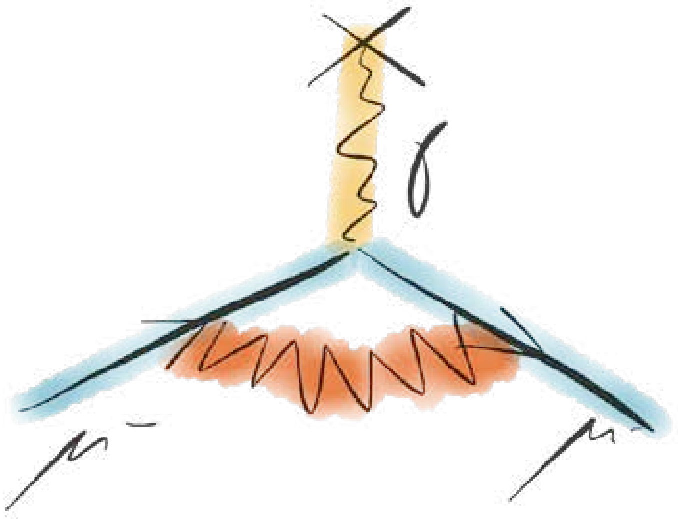
Dispersion relations with
experimental input
Phenomenological models
Lattice QCD

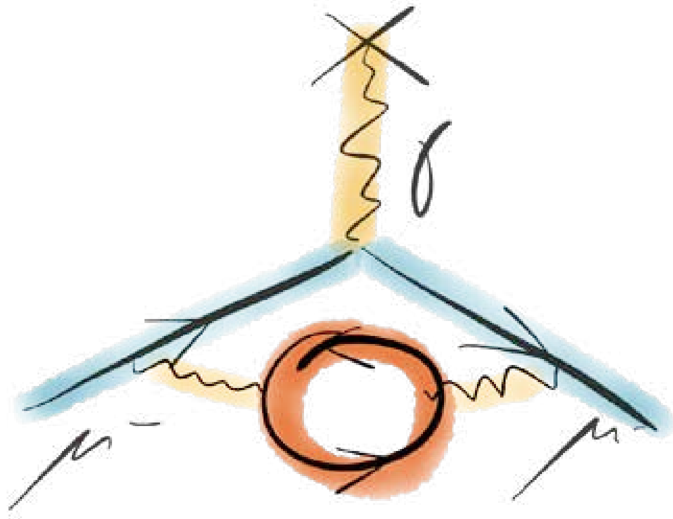


M. Davier, A. Hoecker, B. Malaescu, and Z. Zhang, Eur. Phys. J. C71, 1515 (2011).
F. Jegerlehner and R. Szafron, Eur. Phys. J. C71, 1632 (2011).
K. Hagiwara, R. Liao, A. D. Martin, D. Nomura, and T. Teubner, J. Phys. G38, 085003 (2011).
K. Melnikov and A. Vainshtein, Phys. Rev. D70, 113006 (2004).
J. Bijnens and J. Prades, Mod. Phys. Lett. A22, 767 (2007).
J. Prades, E. de Rafael, and A. Vainshtein, in Lepton Dipole Moments pp. 303–319 (2009).
A. Nyffeler, Phys. Rev. D79, 073012 (2009)
...

$$a_{SM} = 11\,659\,182.8(4.9) \times 10^{-10}$$

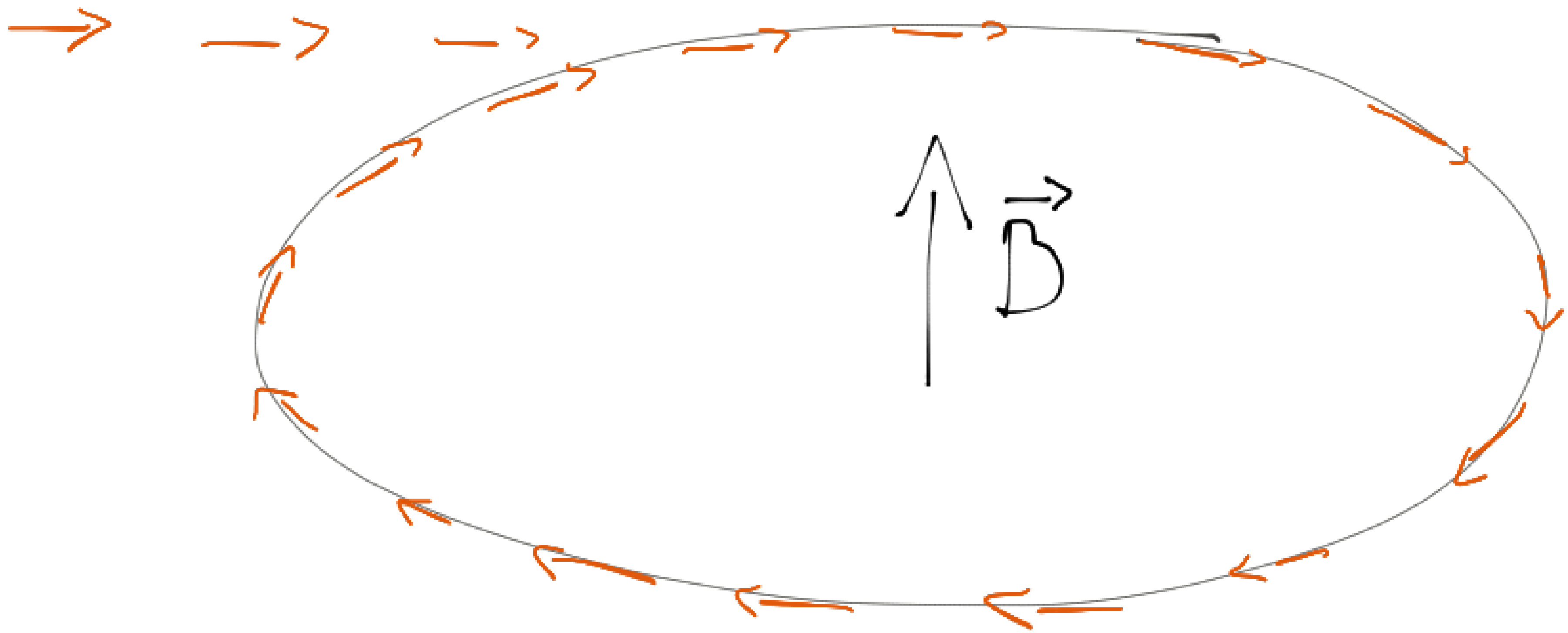
$$+a_{\text{New Physics}}?$$



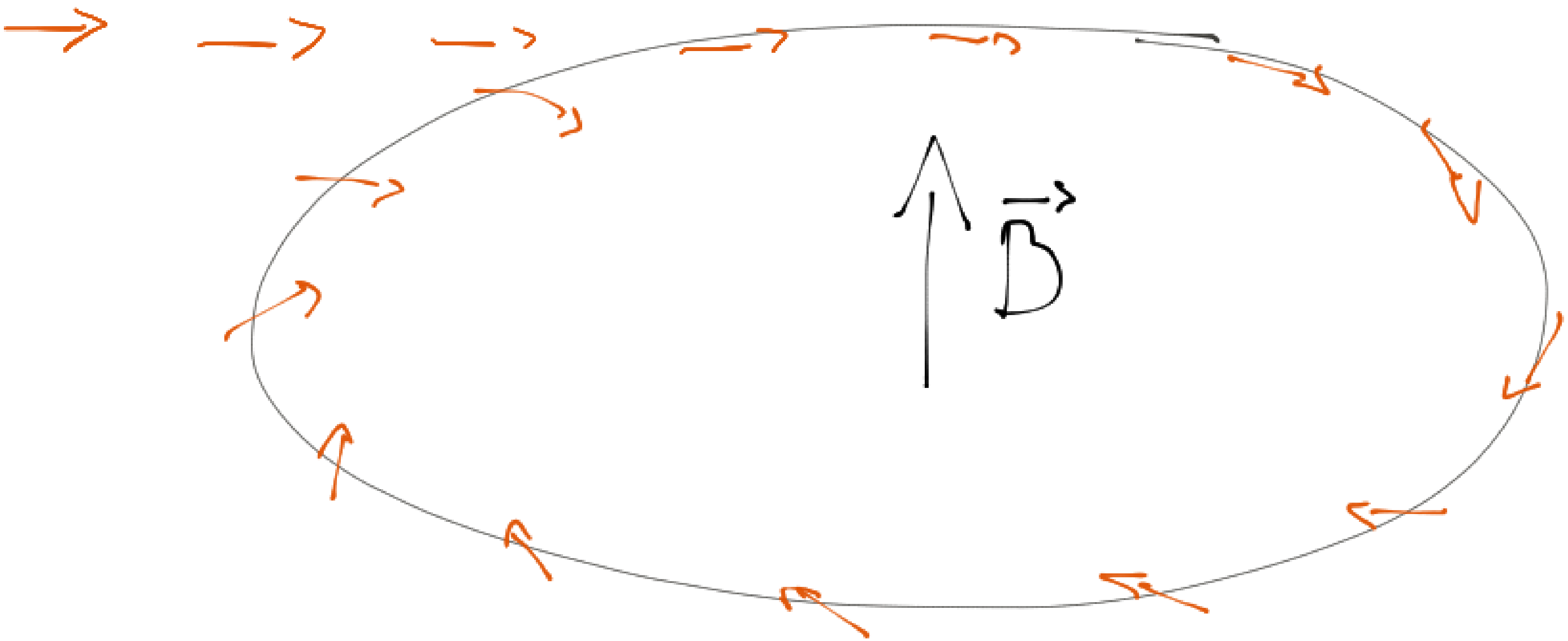


How about experiment?

g = 2



g > 2



Electrical focusing

- Use electric quadrupole fields for focusing

In muon rest frame: $$\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} = \vec{\mu} \times \vec{B}$$

In lab frame (all fields perpendicular to motion):

$$\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} = \frac{q}{m}\left(a\vec{B} + (a - \frac{1}{1-\gamma^2})(\vec{v} \times \vec{E})\right) \times \vec{s}$$

Electrical focusing

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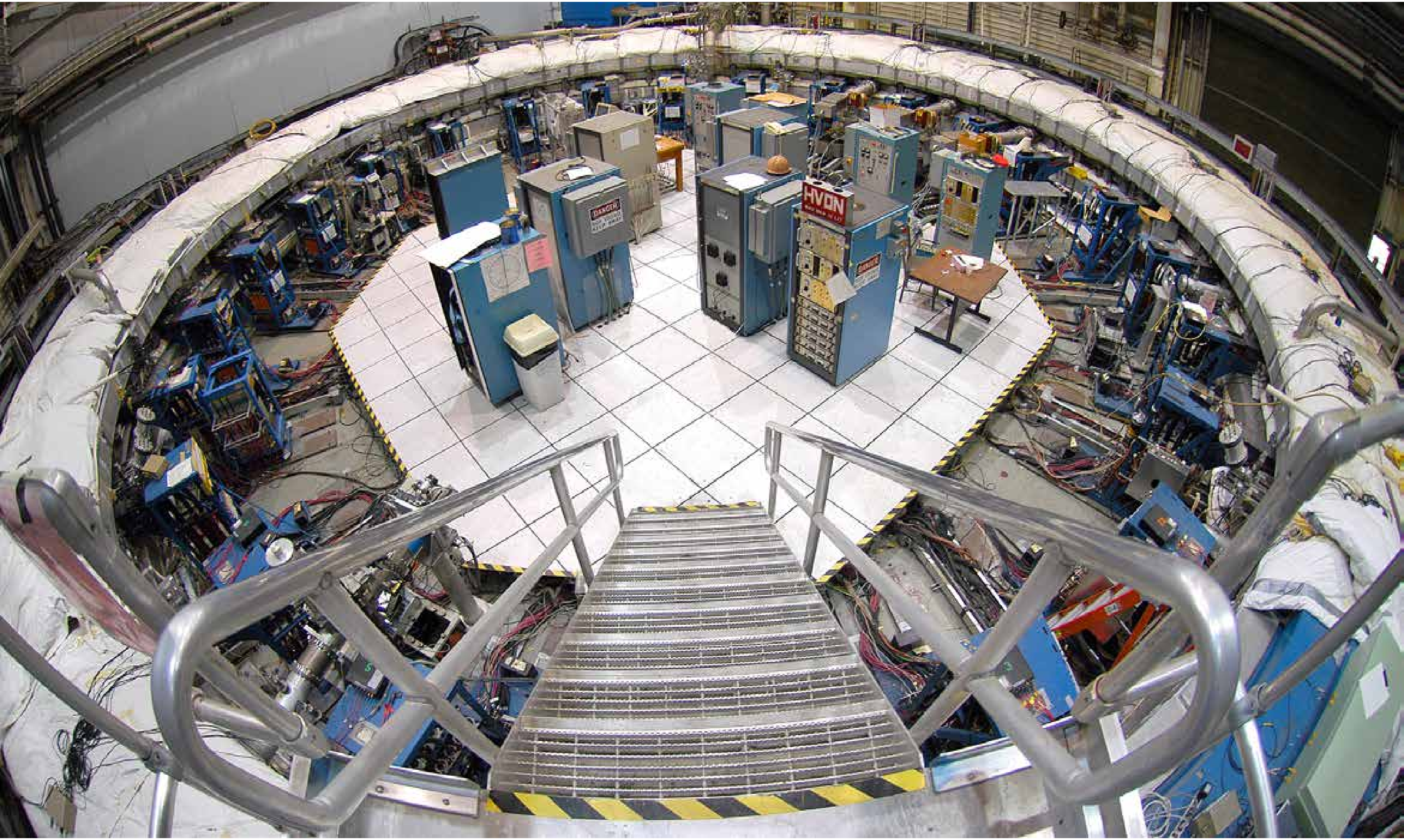
In lab frame (all fields perpendicular to motion):

$$\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} = \frac{q}{m}\left(a\vec{B} + \left(a - \frac{1}{1-\gamma^2}\right)(\vec{v} \times \vec{E})\right) \times \vec{s}$$

$= 0$

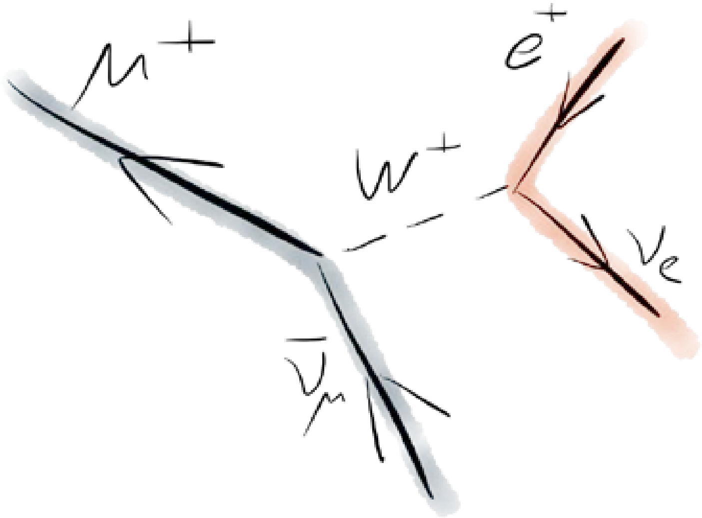
Run at the "magic momentum" of 3.1 GeV/c

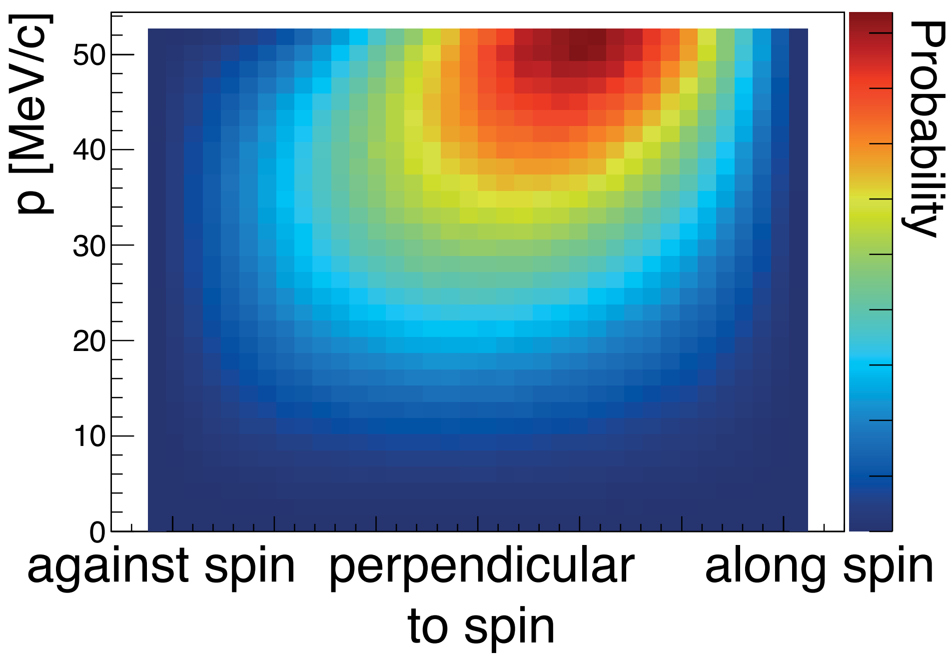
g-2 ring at Brookhaven National Lab



www.bnl.gov

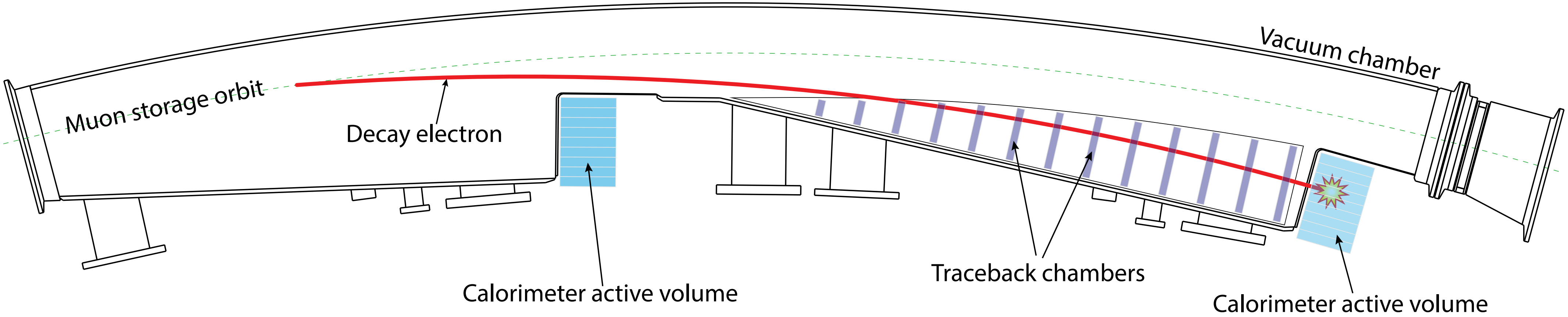
Where does the spin point?





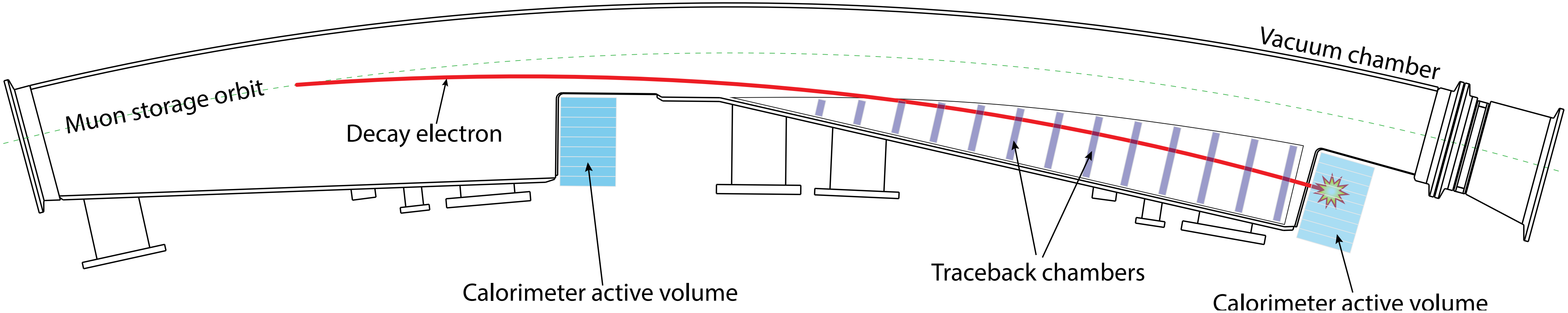
- 3-body muon decay ("Michel"-decay)
- Only electron/positron visible
- High energy e-/e+ preferentially parallel/ antiparallel to spin

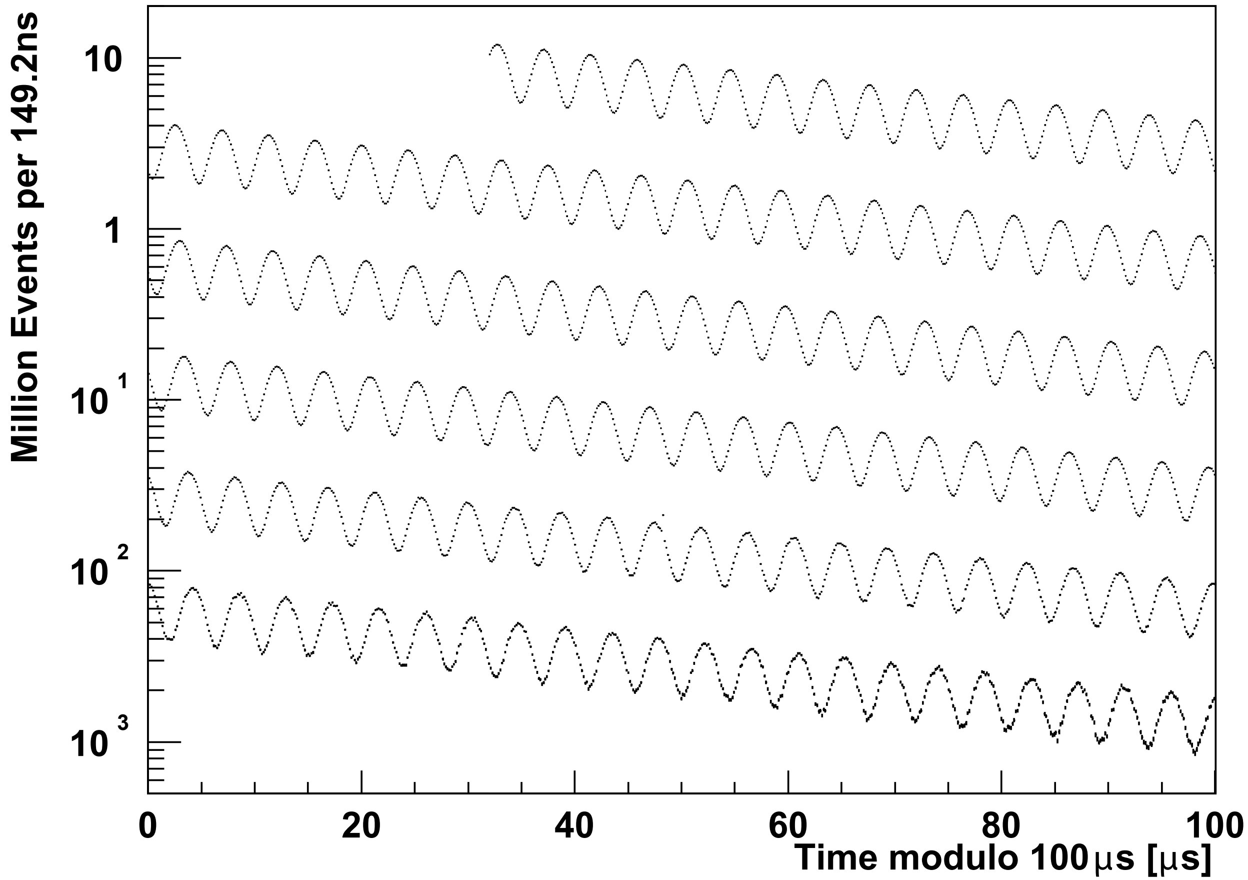
Detecting electrons



Fermilab g-2 TDR

Detecting electrons

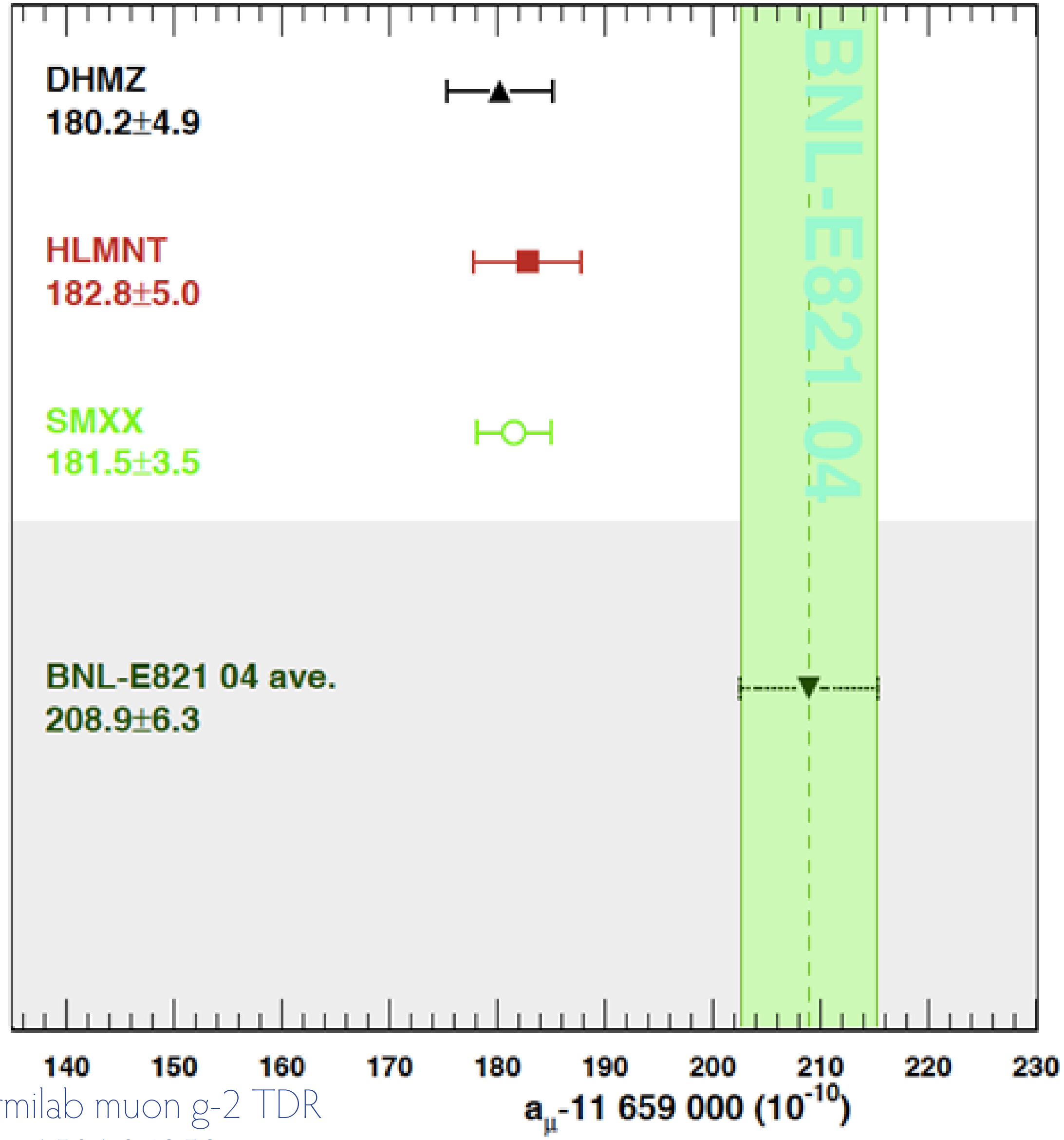




G. Bennett, et al.,
(Muon (g - 2) Collaboration),
Phys. Rev. D73, 072003 (2006).

Putting it all together...

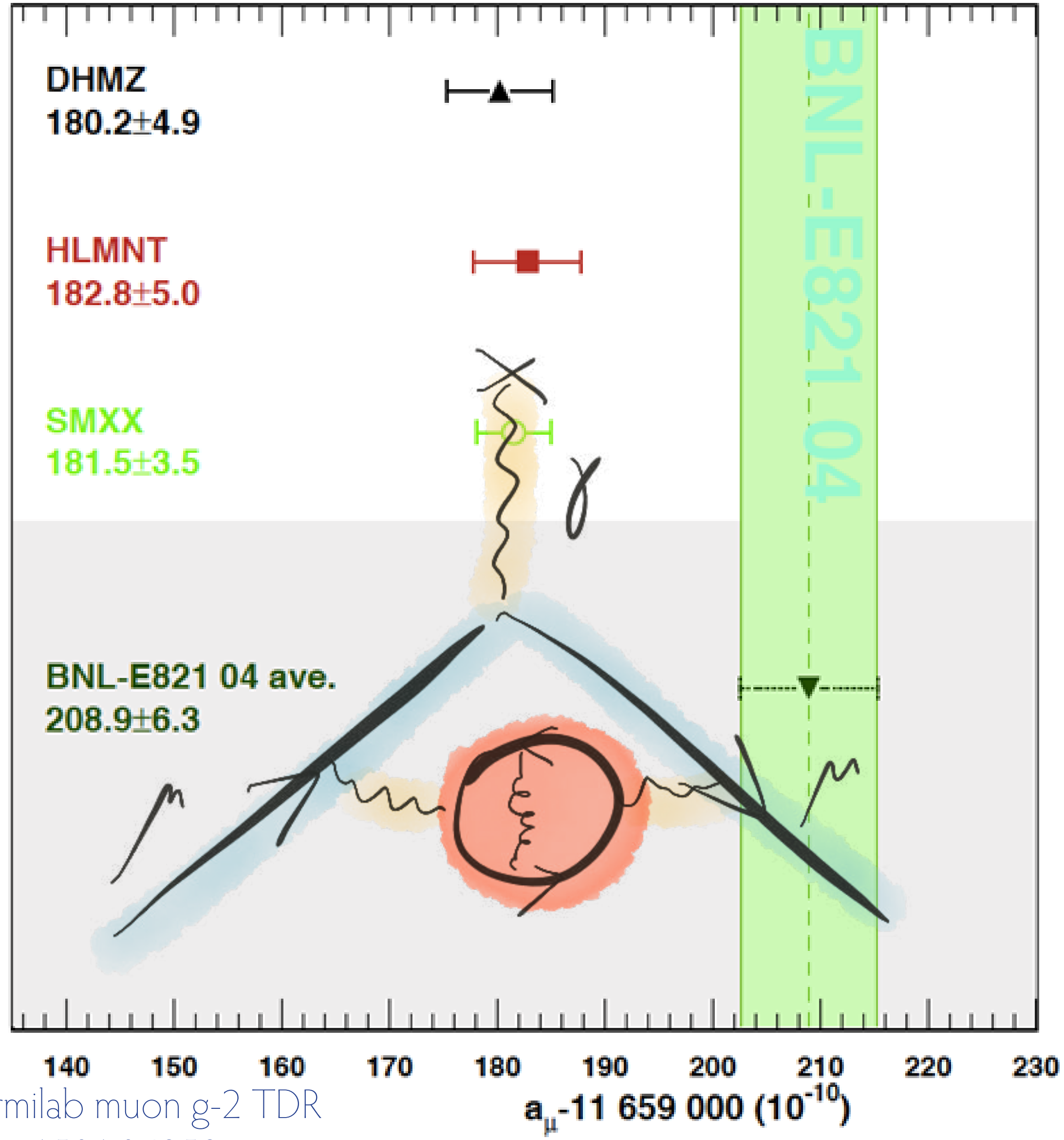
$$a_{SM} = 11\,659\,182.8(4.9) \times 10^{-10}$$
$$a_{exp} = 11\,659\,208.9(4.4)(3.3) \times 10^{-10}$$



Fermilab muon g-2 TDR
arxiv:1501.06858

- SM prediction and measurement differ by 3 - 4 σ

Putting it all together...



Fermilab muon g-2 TDR
arxiv:1501.06858

- Statistical fluctuation?
- Problem with theory?
- Lots of work ongoing
- Problem with experiment?
- New physics?
- New measurements planned

The big move …

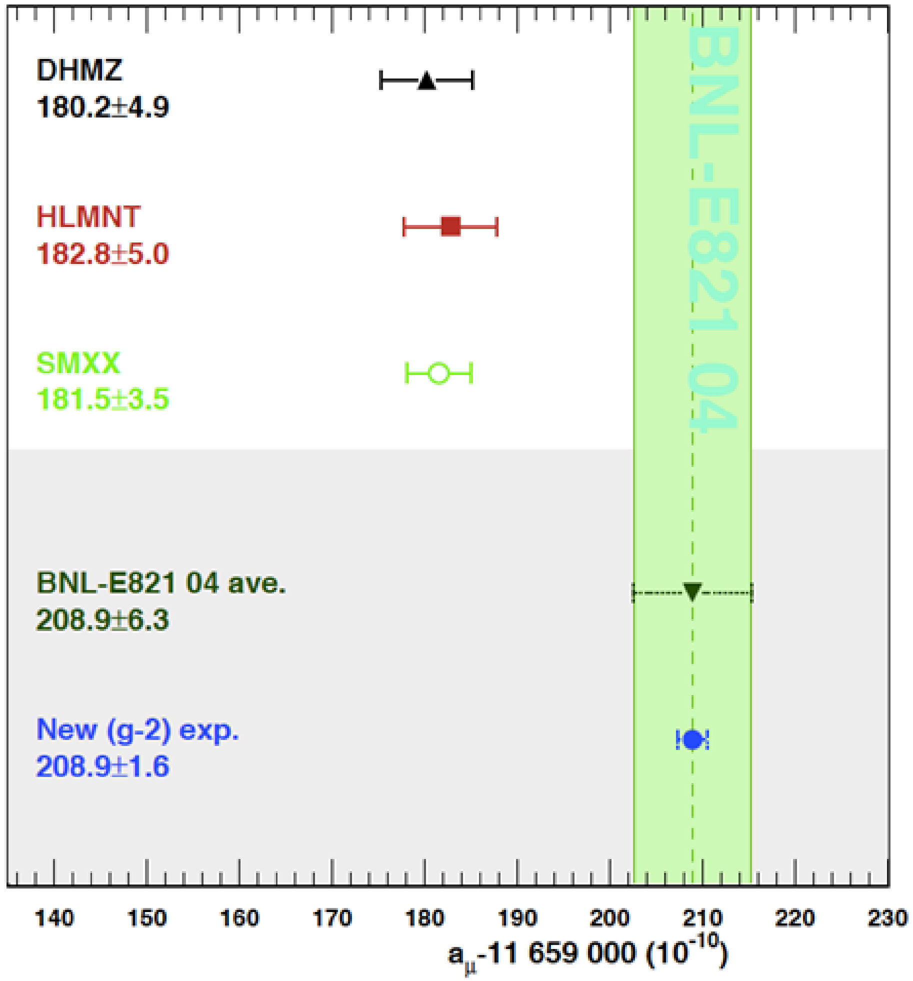
- Bring ring from Brookhaven to Fermilab

Fermilab g-2

Improve over Brookhaven with:

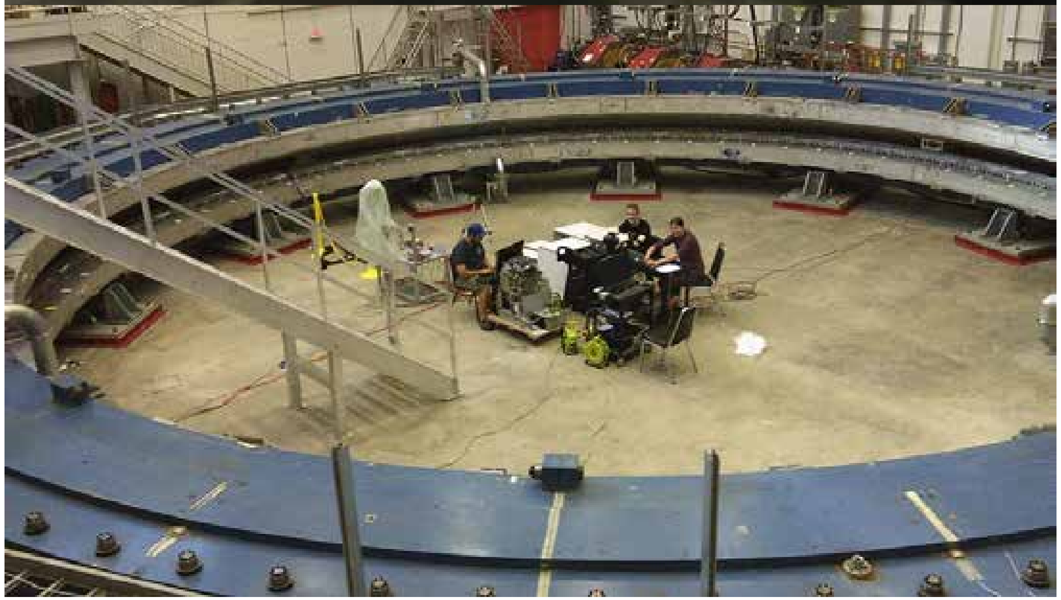
- 20 x more muons
- Cleaner beam
- Better calorimeters, trackers
- More field probes
- Better environment control

- Goal: 4 times smaller error



Fermilab g-2 status

- Magnet arrived safely
- Cold and powered
- Shimming ongoing
- Data taking could start next year



https://www.facebook.com/The-new-g-2-experiment-at-Fermilab-76812692423/

Can we do a different experiment for g-2?

New idea: Use cold muons

$$\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} = \frac{q}{m}\left(a\vec{B} + \left(a - \frac{1}{1-\gamma^2}\right)\left(\vec{v} \times \vec{E}\right)\right) \times \vec{s}$$

No vertical focusing - no electric field

New idea: Use cold muons

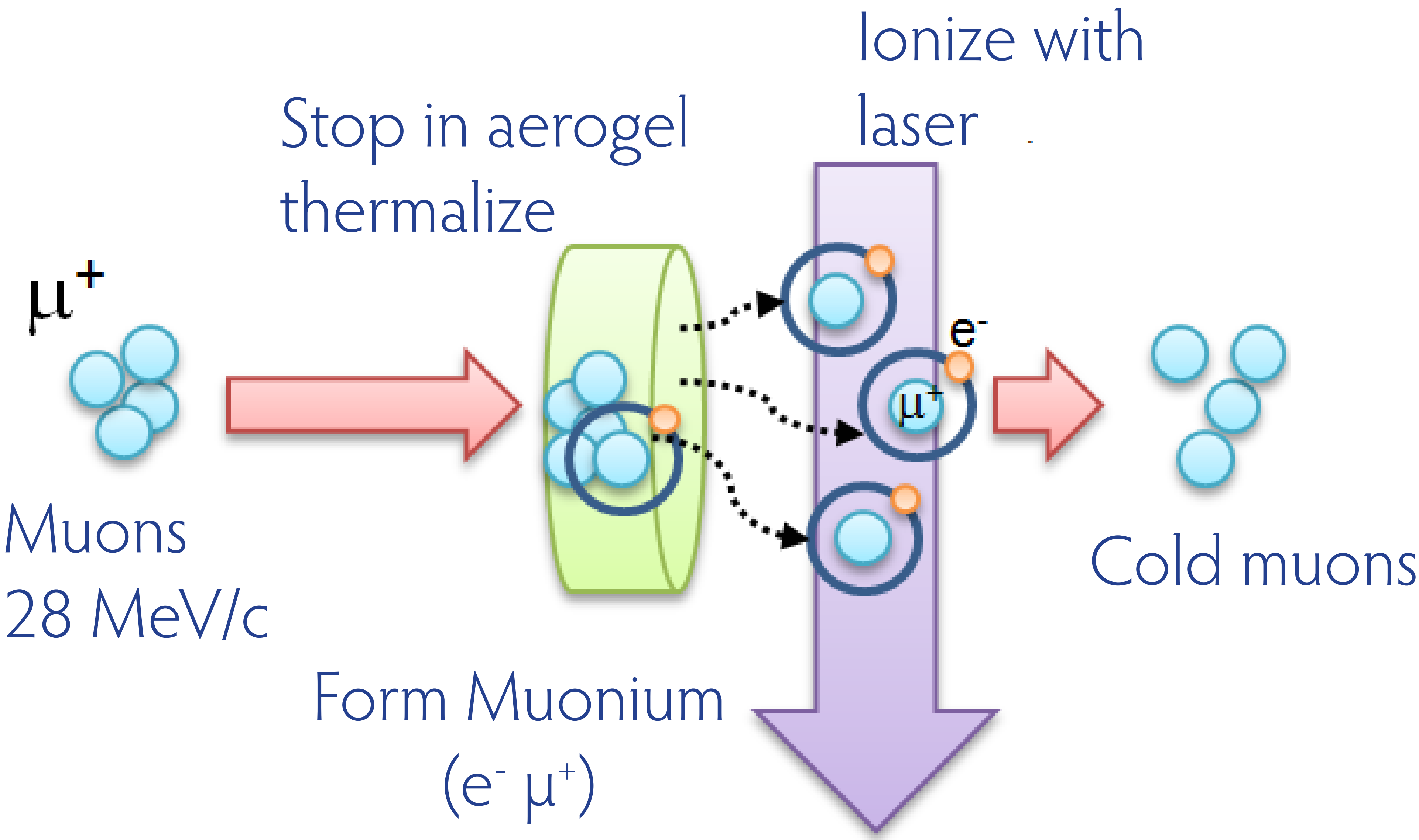
$$\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} = \frac{q}{m}\left(a\vec{B} + (a - \frac{1}{1-\gamma^2})(\vec{v} \times \underbrace{\vec{E}}_{= 0})\right) \times \vec{s}$$

No vertical focusing - no electric field

Can run at lower momentum - smaller magnet

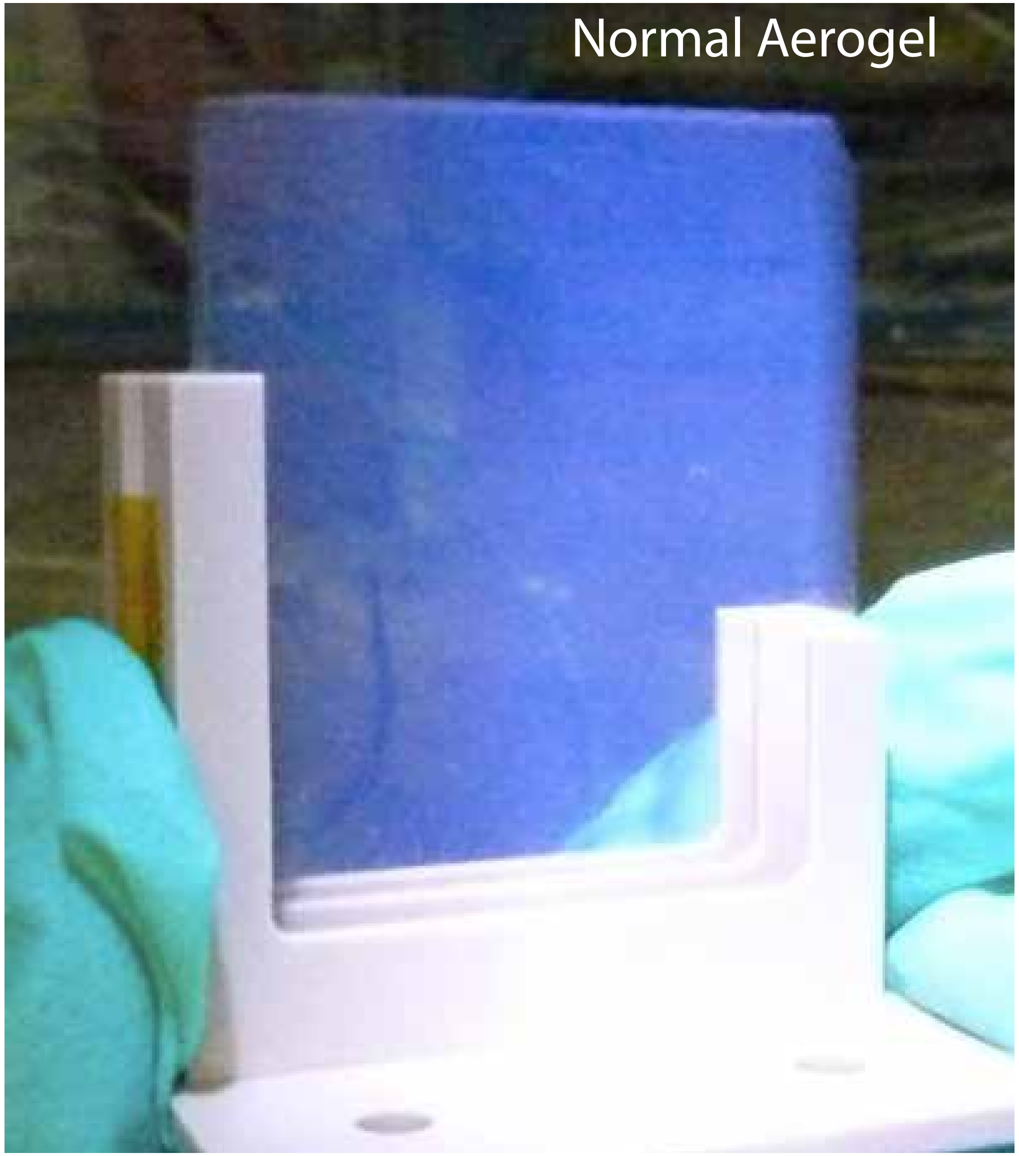
Cold muons from muonium

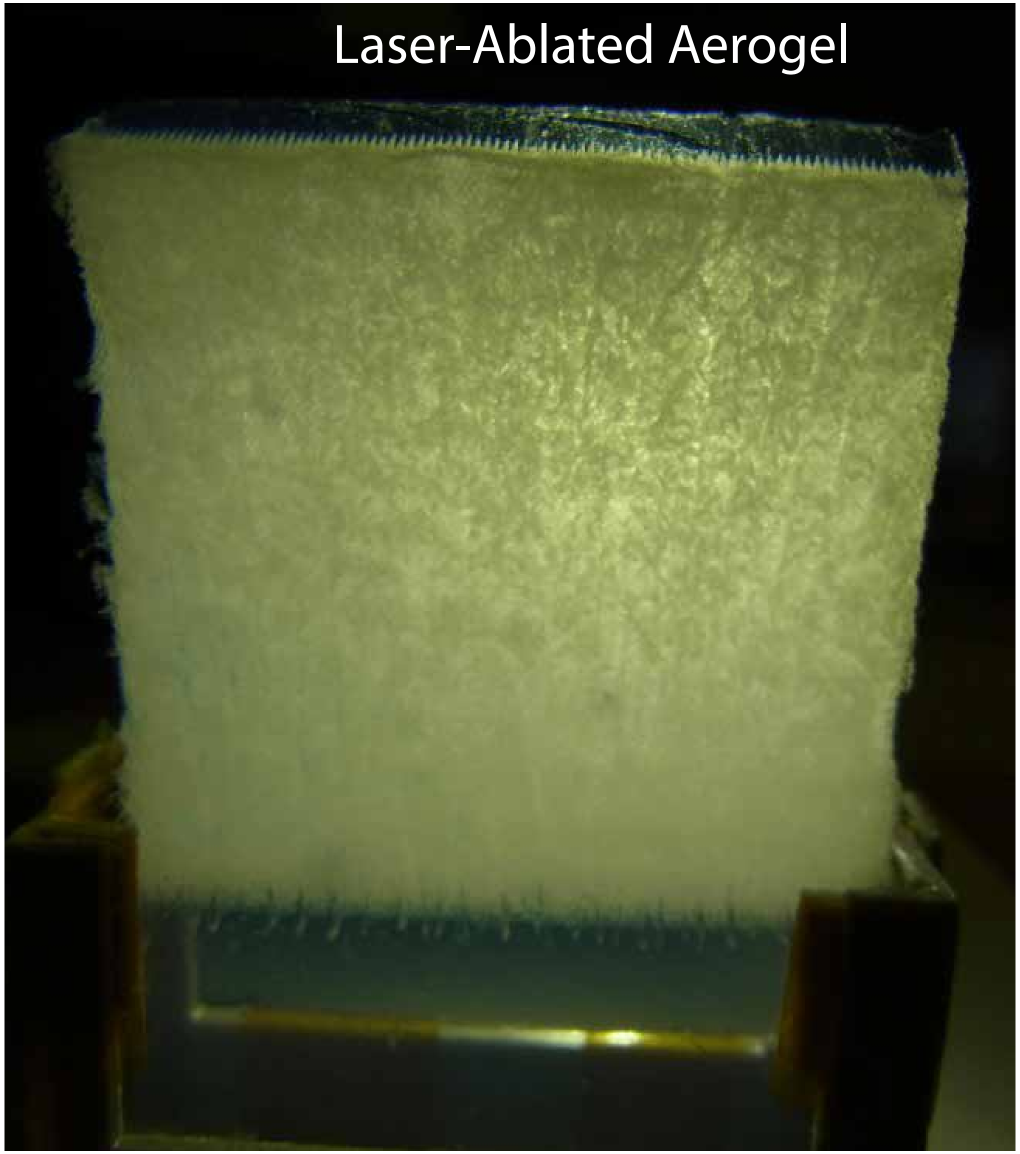
T. Mibe



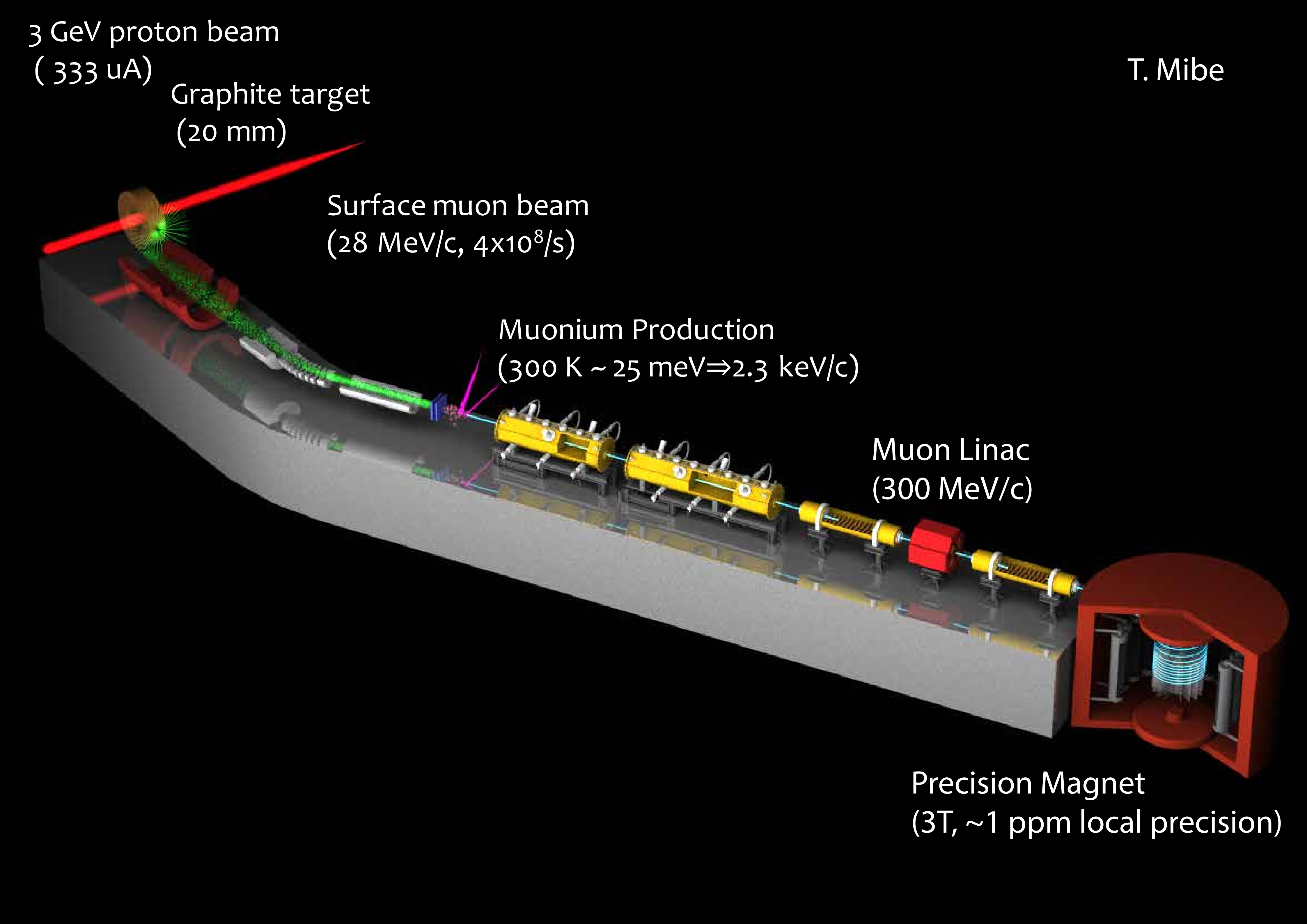
Muonium production in aerogel

T. Mibe

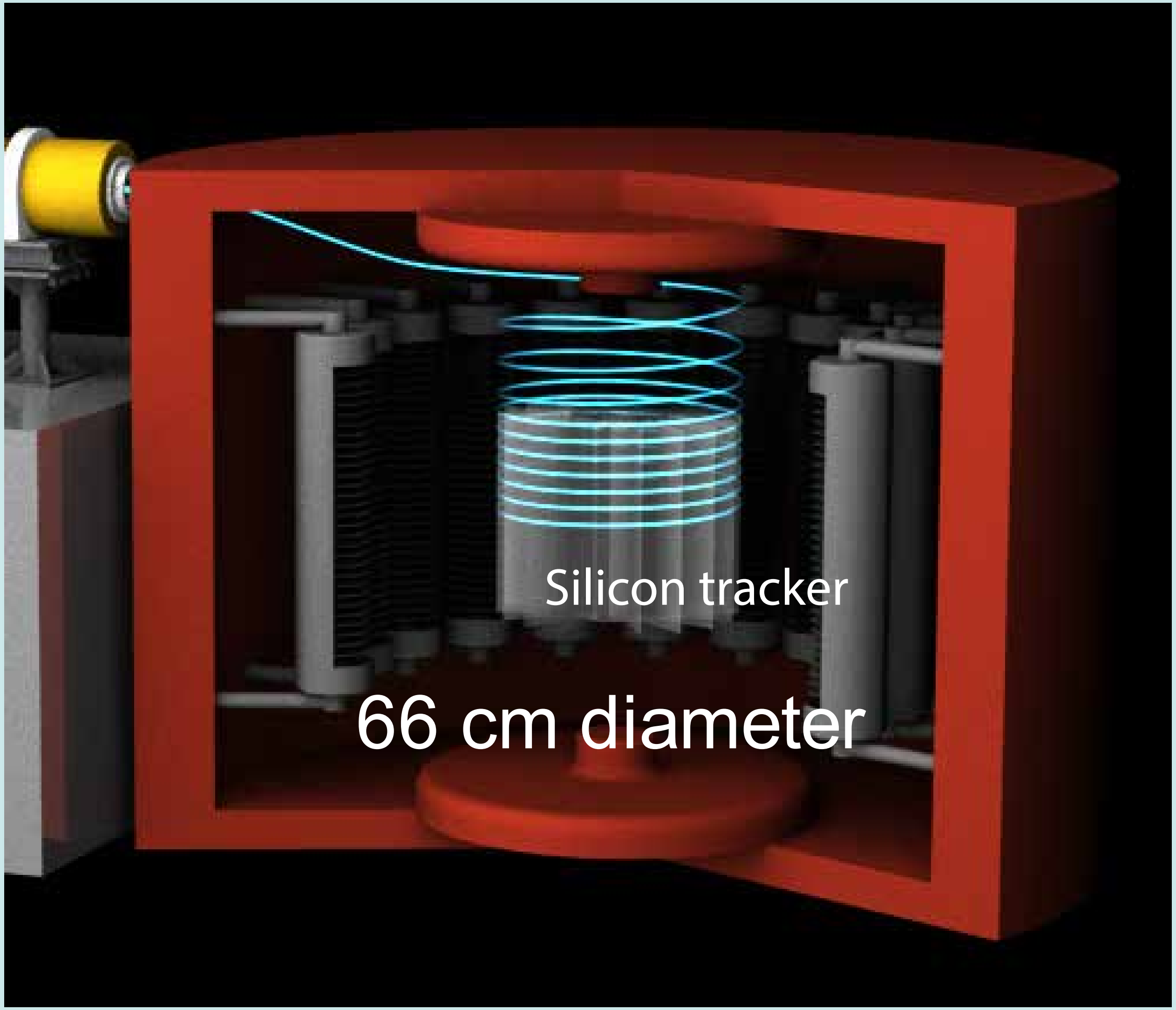




1 Muonium in vacuum per 14 muon stops


3 GeV proton beam
(333 uA)
Graphite target
(20 mm)
Surface muon beam
(28 MeV/c, 4x10^8/s)
Muonium Production
(300 K ~ 25 meV⇒2.3 keV/c)
Muon Linac
(300 MeV/c)
Precision Magnet
(3T, ~1 ppm local precision)
T. Mibe

J-PARC g-2 magnet

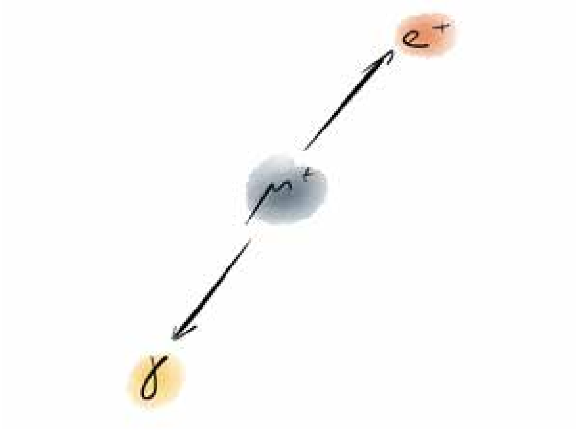


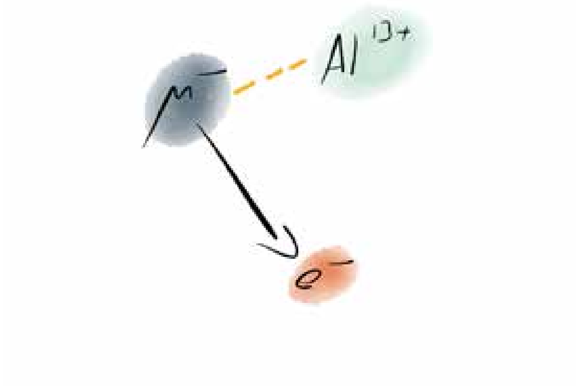
Development ongoing

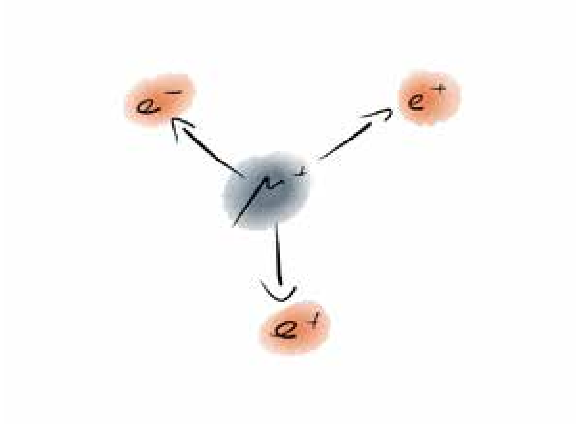
Potential to match or exceed Fermilab precision

N. Saito

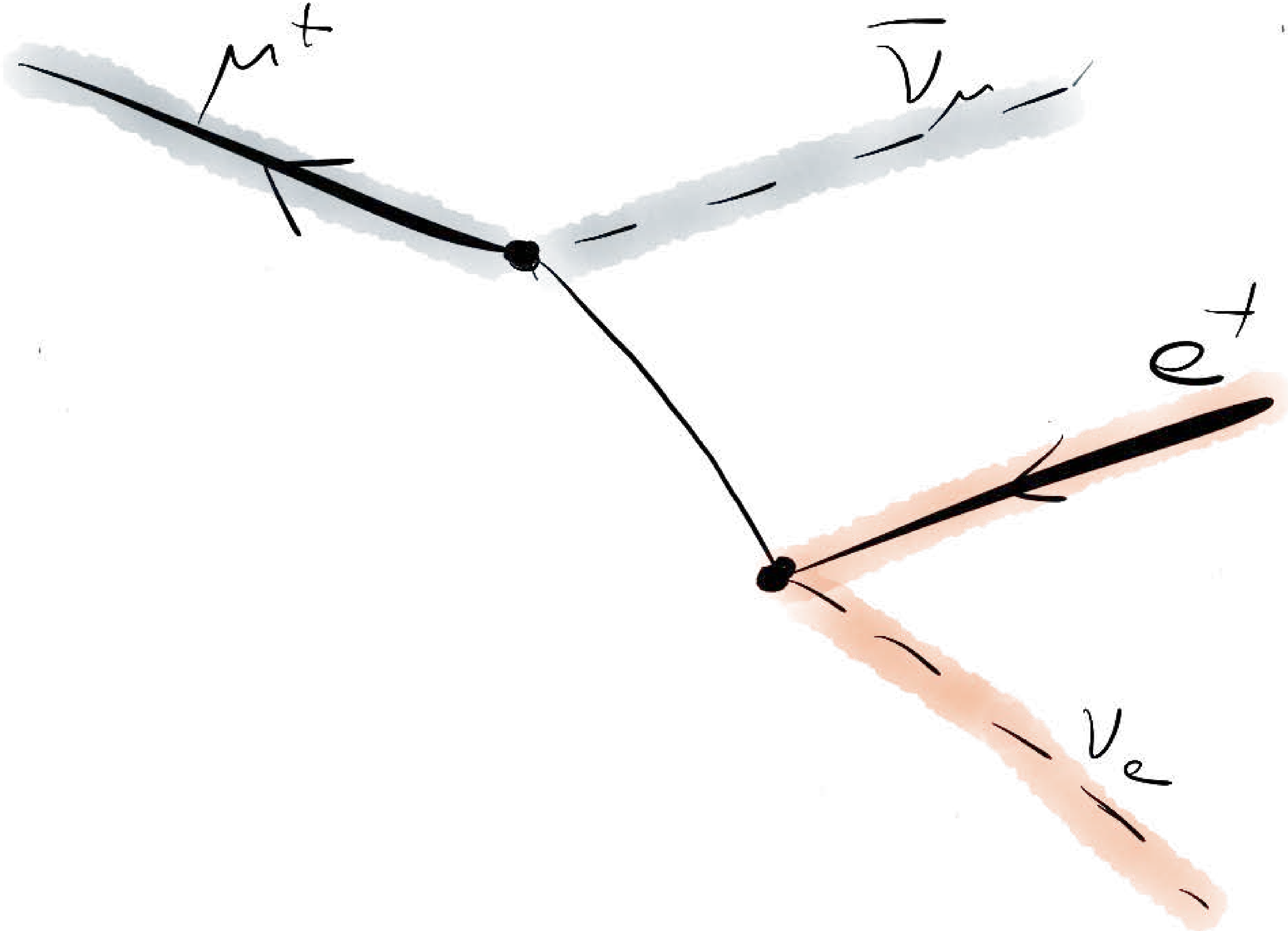
Charged Lepton Flavour Violation



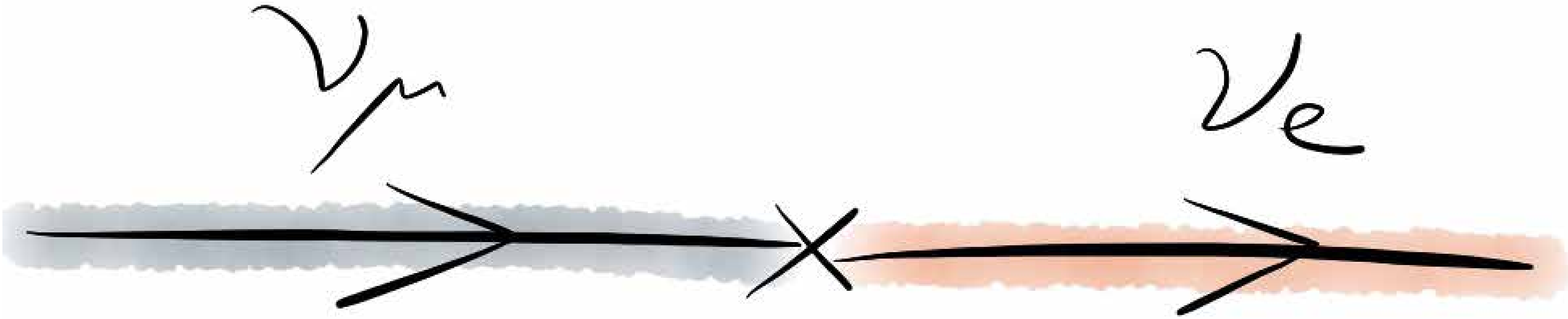




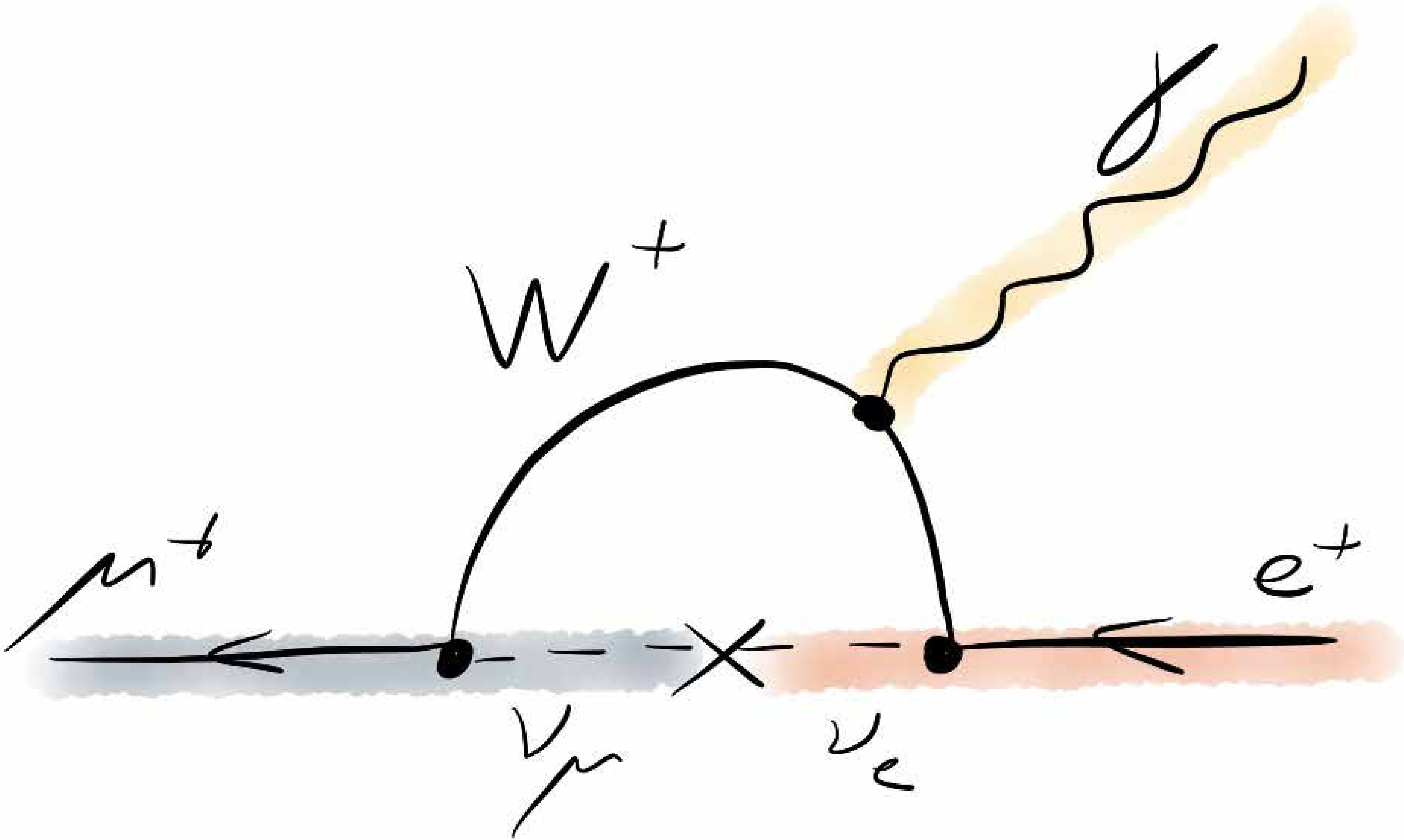
Lepton Flavour



Lepton Flavour Violation!



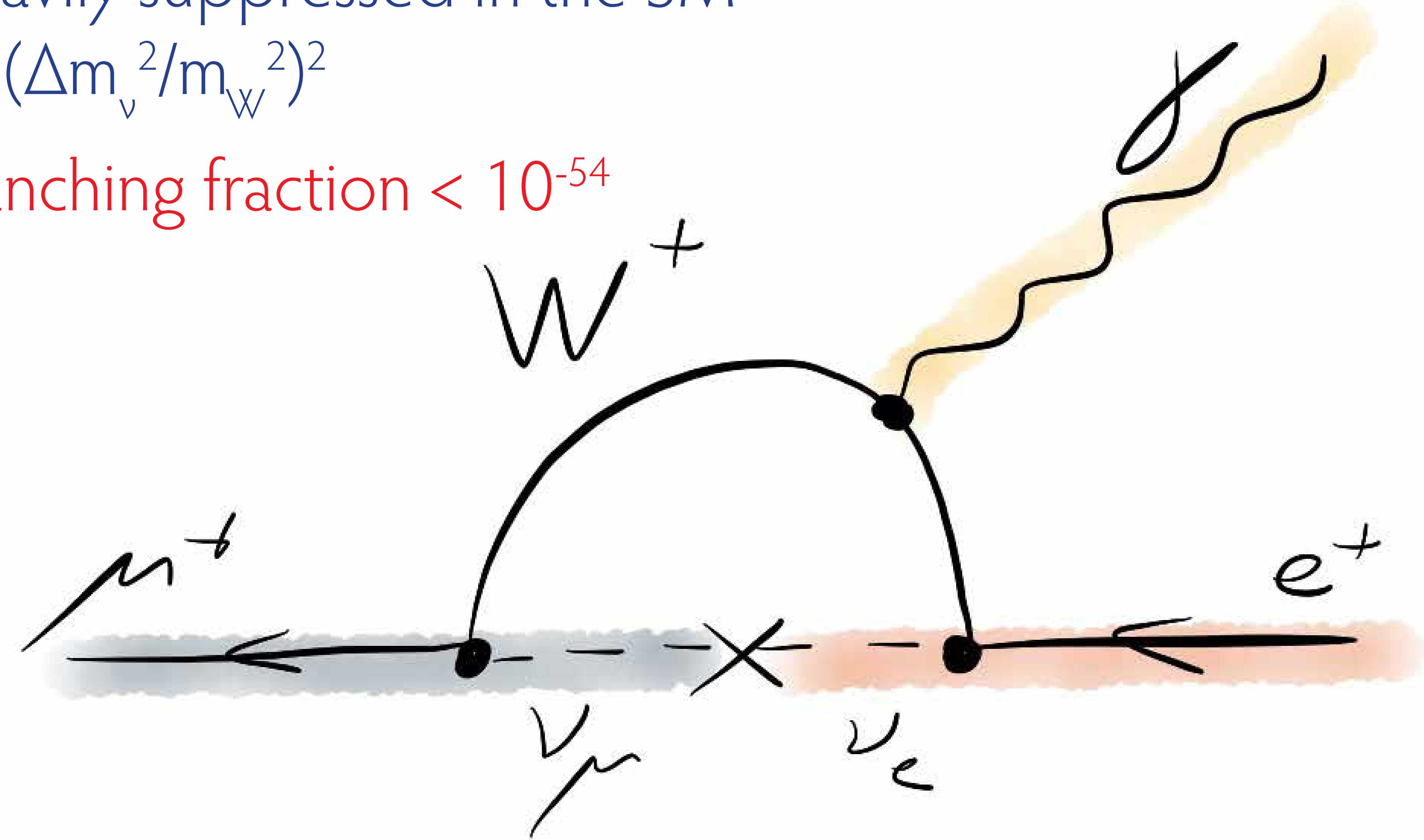
Charged Lepton Flavour Violation?



Charged Lepton Flavour Violation?

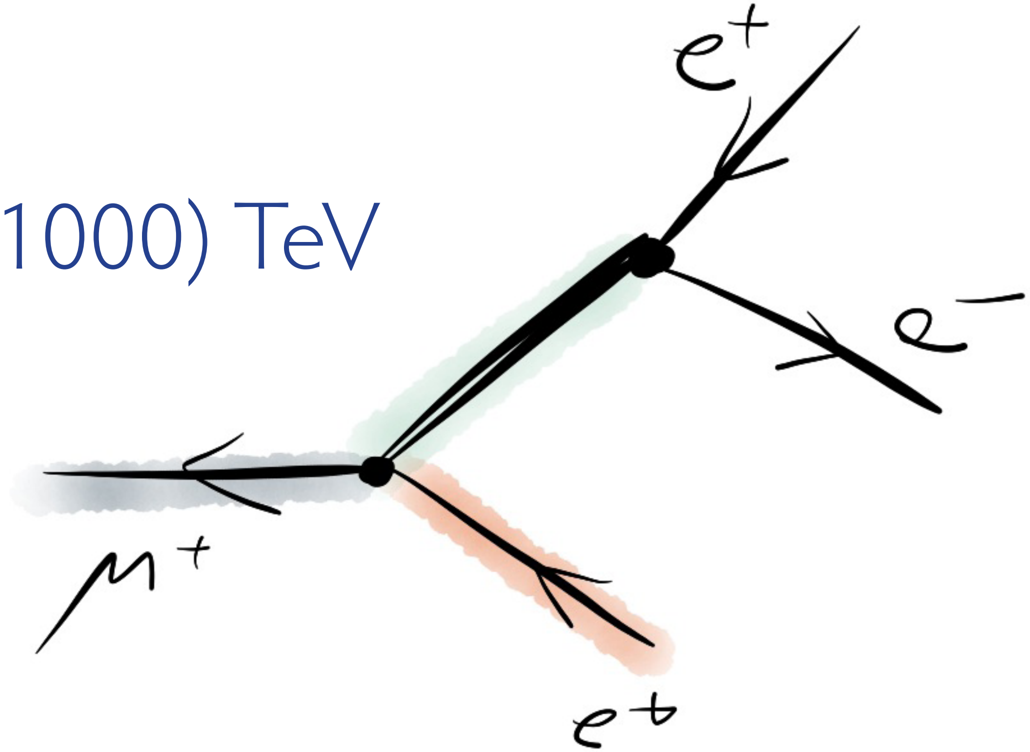
Heavily suppressed in the SM
by $(\Delta m_{\nu}^{2}/m_{W}^{2})^{2}$

Branching fraction < 10^{-54}



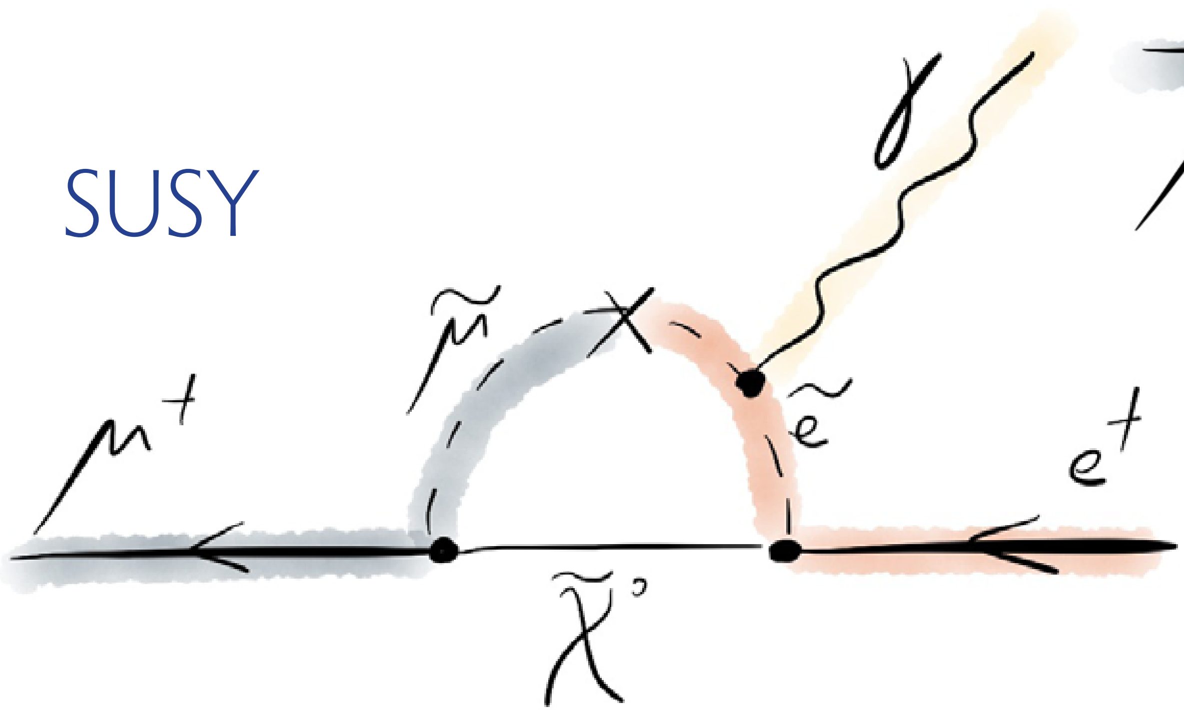
Charged Lepton Flavour Violation?

Enhanced in many models of
New Physics
Mass reach often O(100) - O(1000) TeV

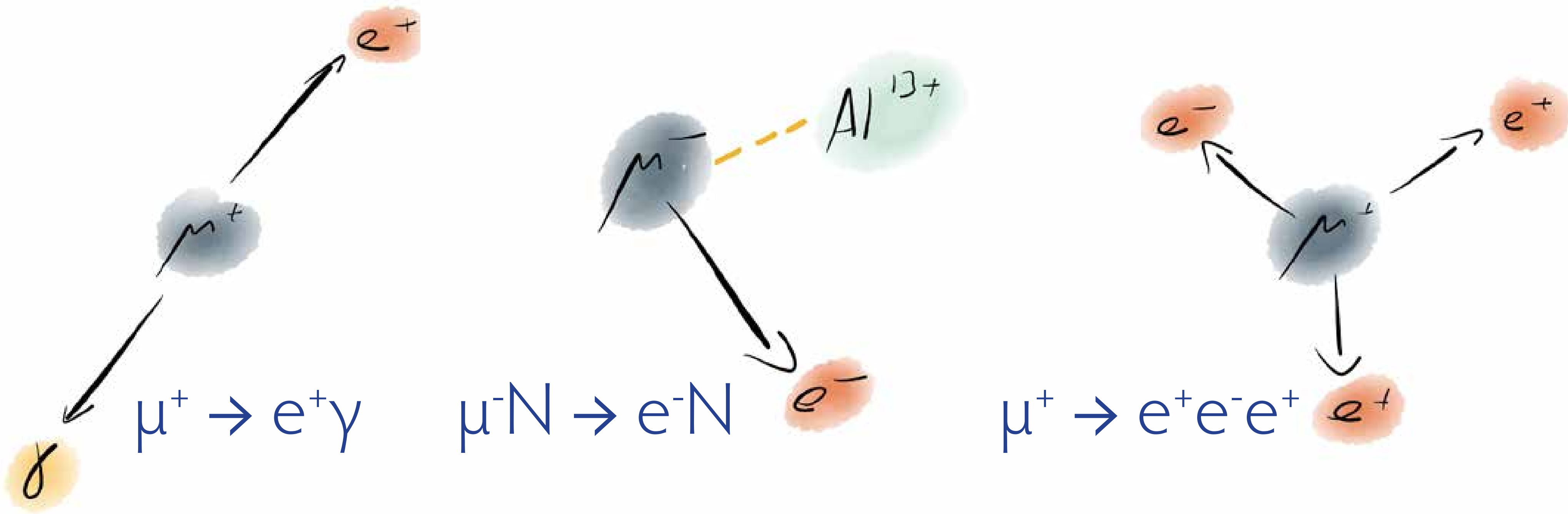


New bosons

SUSY

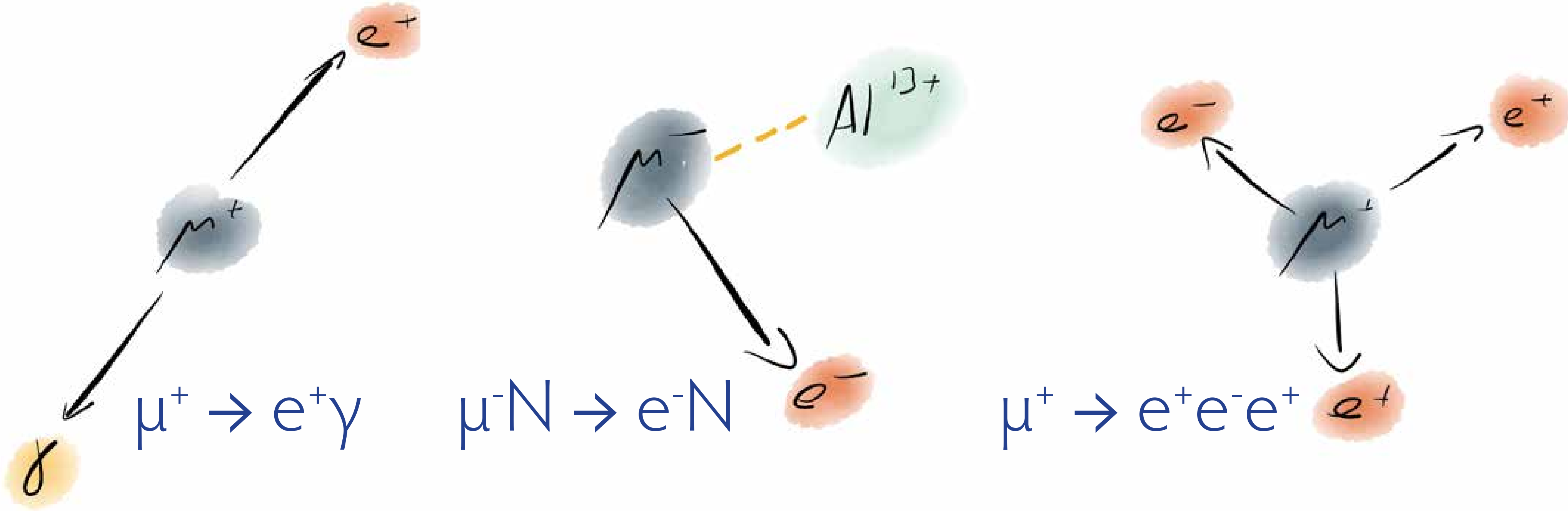


LFV Muon Decays



$\mu^+ \to e^+\gamma$ $\quad$ $\mu^-N \to e^-N$ $\quad$ $\mu^+ \to e^+e^-e^+$

LFV Muon Decays: Experimental Situation



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

MEG (PSI)

$B(\mu^+ \to e^+\gamma) < 5.7 \cdot 10^{-13}$

(2013)

upgrading

SINDRUM II (PSI)

$B(\mu^- Au \to e^- Au) < 7 \cdot 10^{-13}$

(2006)

relative to nuclear capture

SINDRUM (PSI)

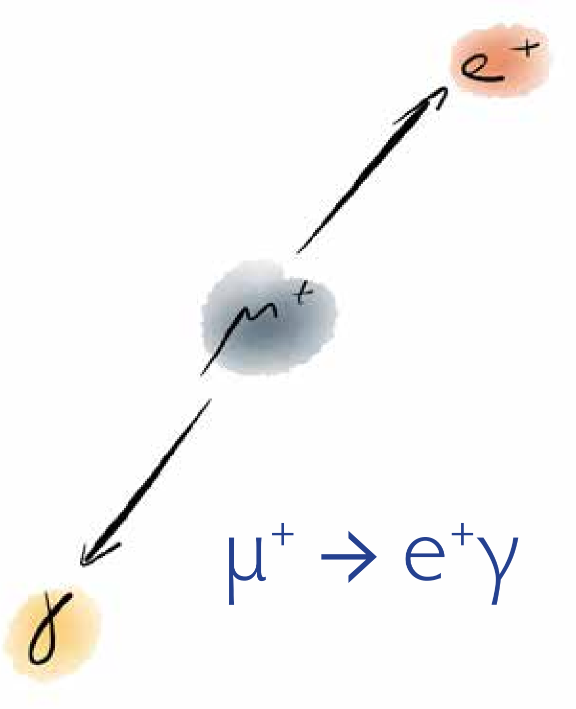
$B(\mu^+ \to e^+e^-e^+) < 1.0 \cdot 10^{-12}$

(1988)

Searching for $\mu \rightarrow e\gamma$ with

MEG

MEG Signal and background

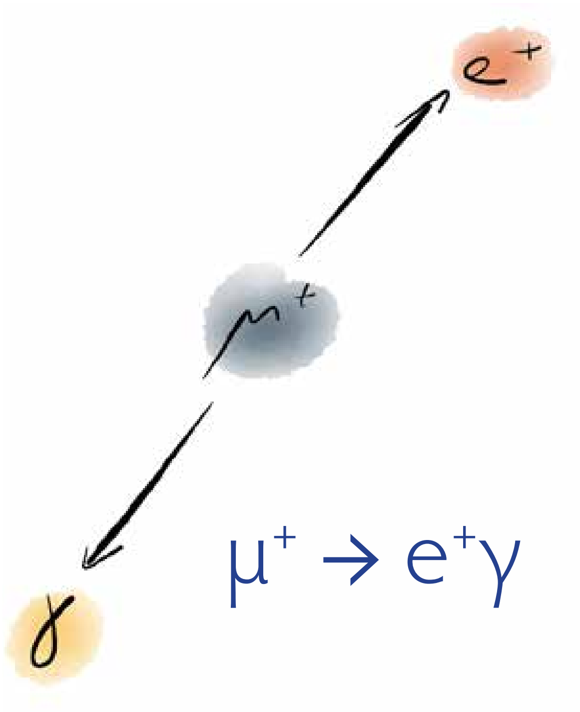


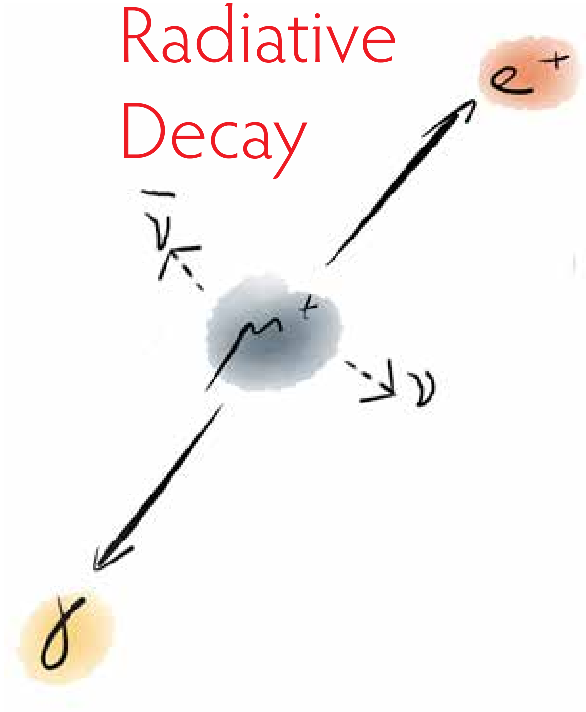
$\mu^+ \rightarrow e^+\gamma$

Kinematics

- 2-body decay
- Monoenergetic e^+, γ (53 MeV = $m_\mu/2$)
- Back-to-back
- Same time

MEG Signal and background



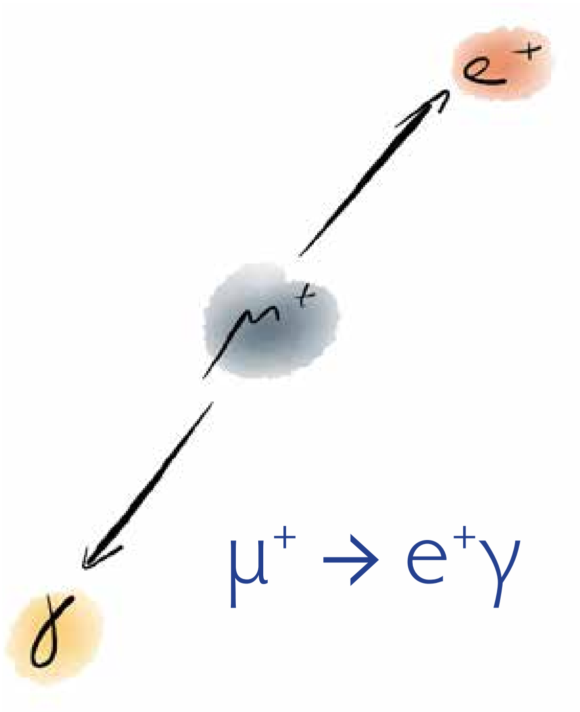


Kinematics

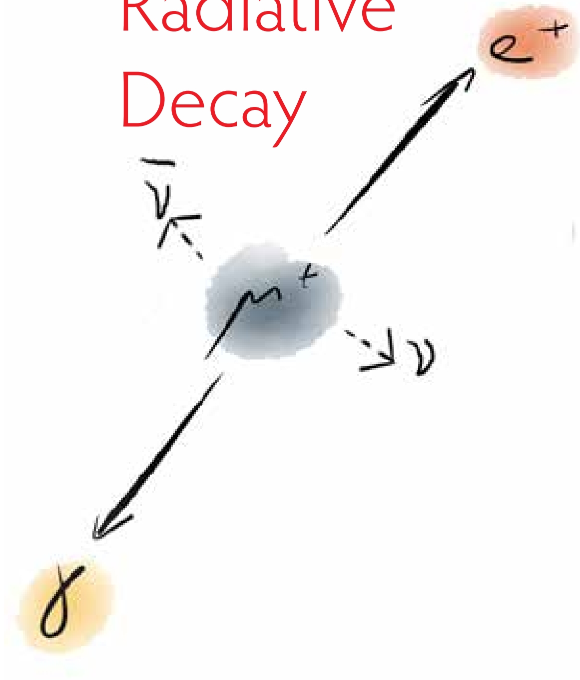
- 2-body decay
- Monoenergetic e^+, γ (53 MeV $= m_\mu/2$)
- Back-to-back
- Same time

- e^+, γ energies somewhat off
- Not exactly back-to-back

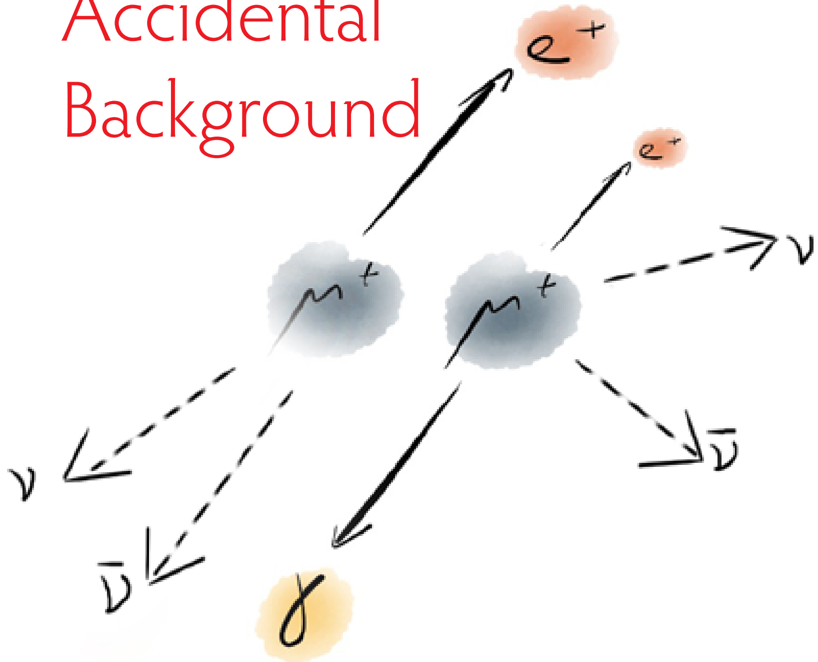
MEG Signal and background



Radiative Decay



Accidental Background



Kinematics

- 2-body decay
- Monoenergetic e^+, γ (53 MeV = $m_\mu/2$)
- Back-to-back
- Same time

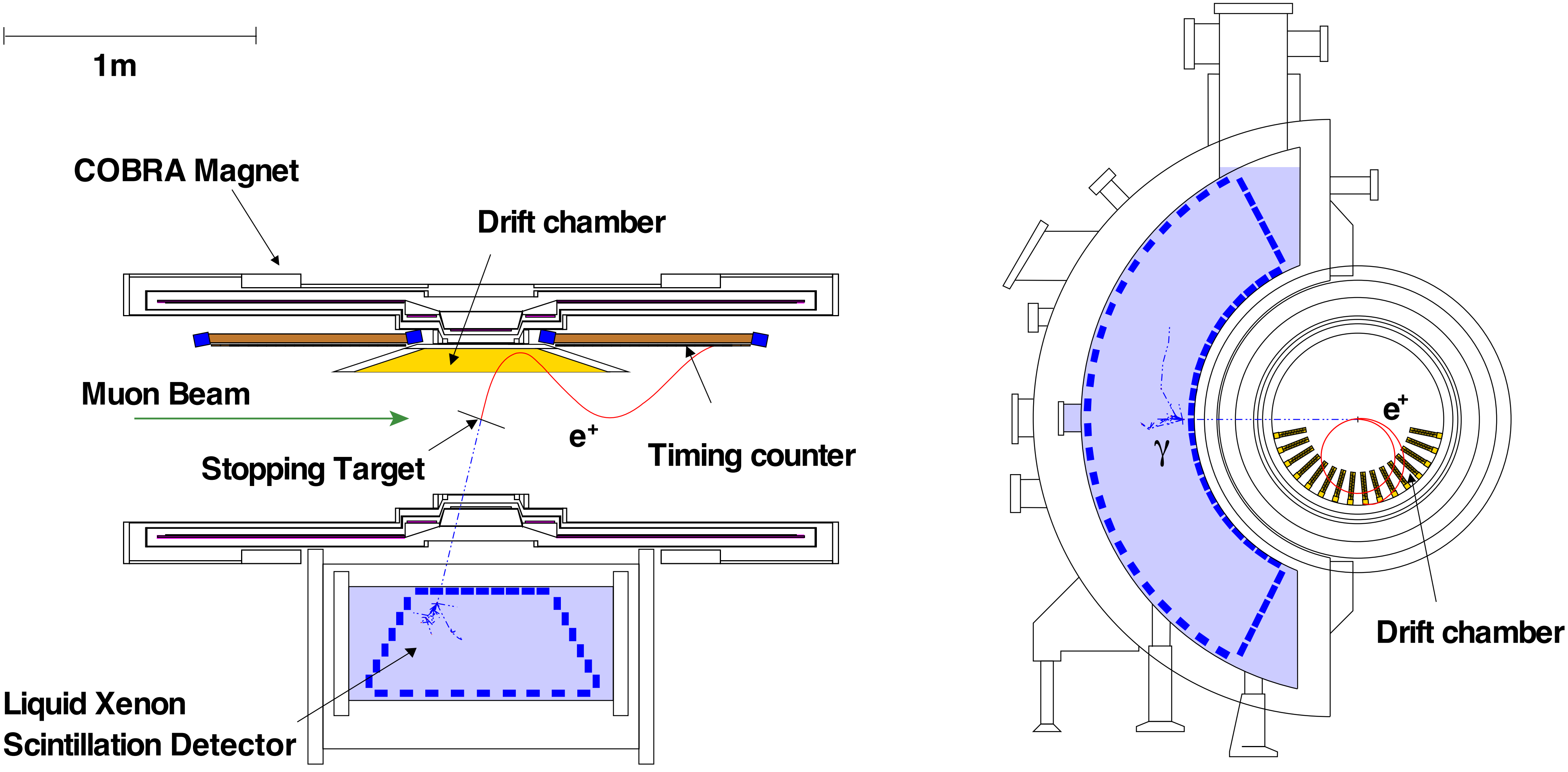
Radiative Decay:

- e^+, γ energies somewhat off
- Not exactly back-to-back

Accidental Background:

- Not exactly in time
- Not exactly same vertex
- e^+, γ energies somewhat off
- Not exactly back-to-back

The MEG Detector



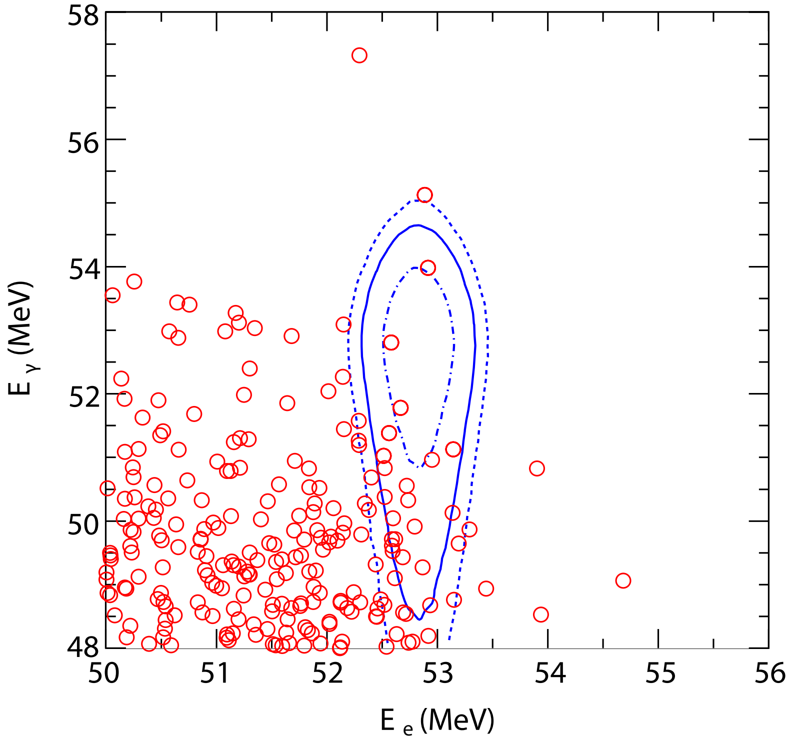
J. Adam et al. EPJ C 73, 2365 (2013)

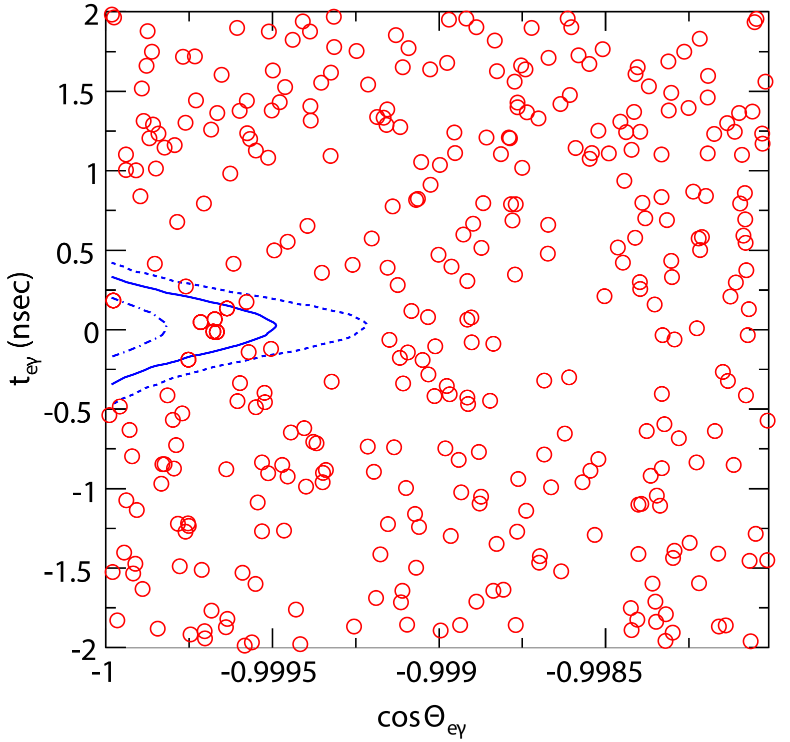
MEG Results

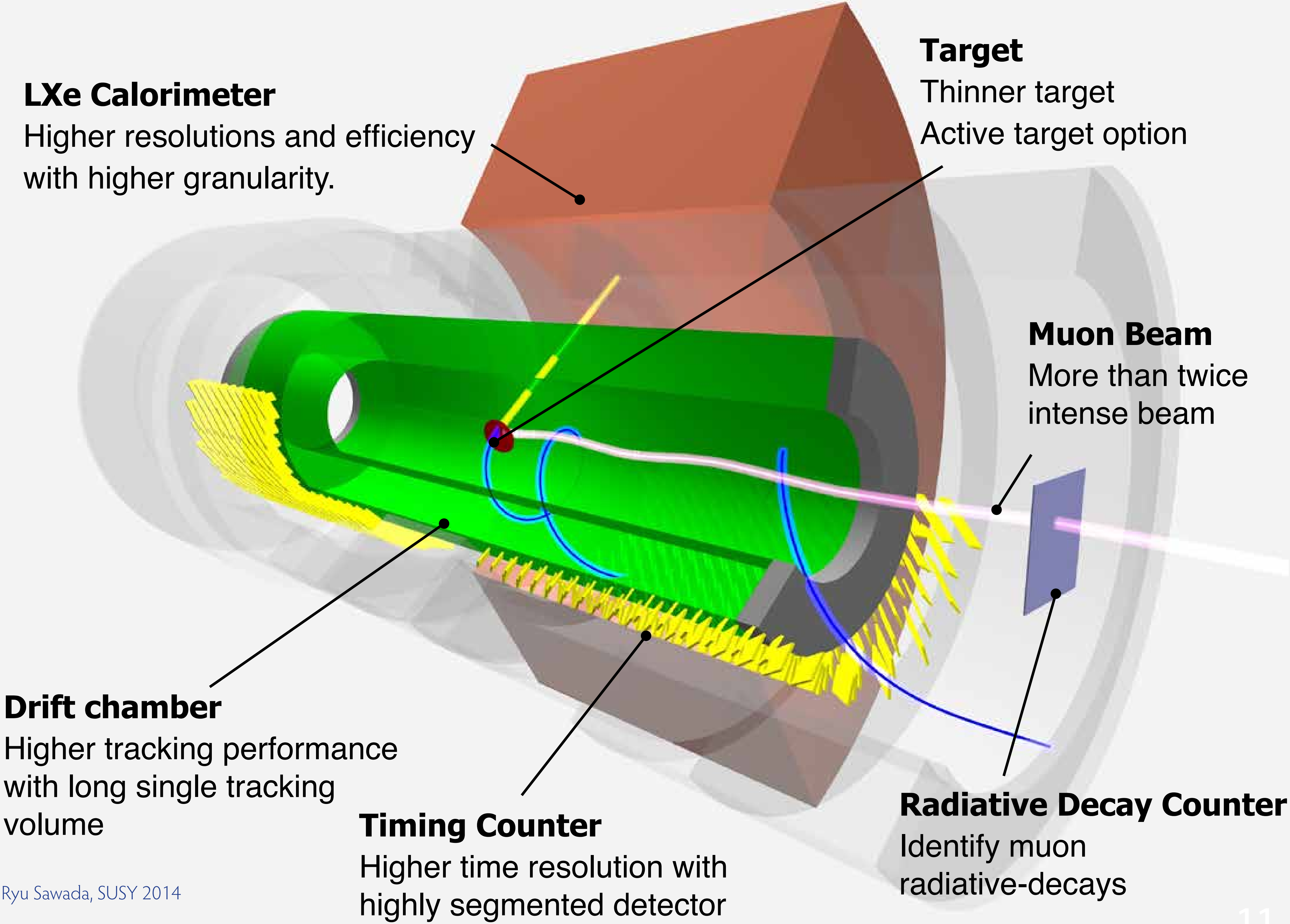
- 2009-2011 data
- Blue: Signal PDF, given by detector resolution
- No signal seen
- Upper limit at 90% CL:

$BR(\mu \rightarrow e\gamma) < 5.7 \times 10^{-13}$

J. Adam et al. PRL 110, 201801 (2013)



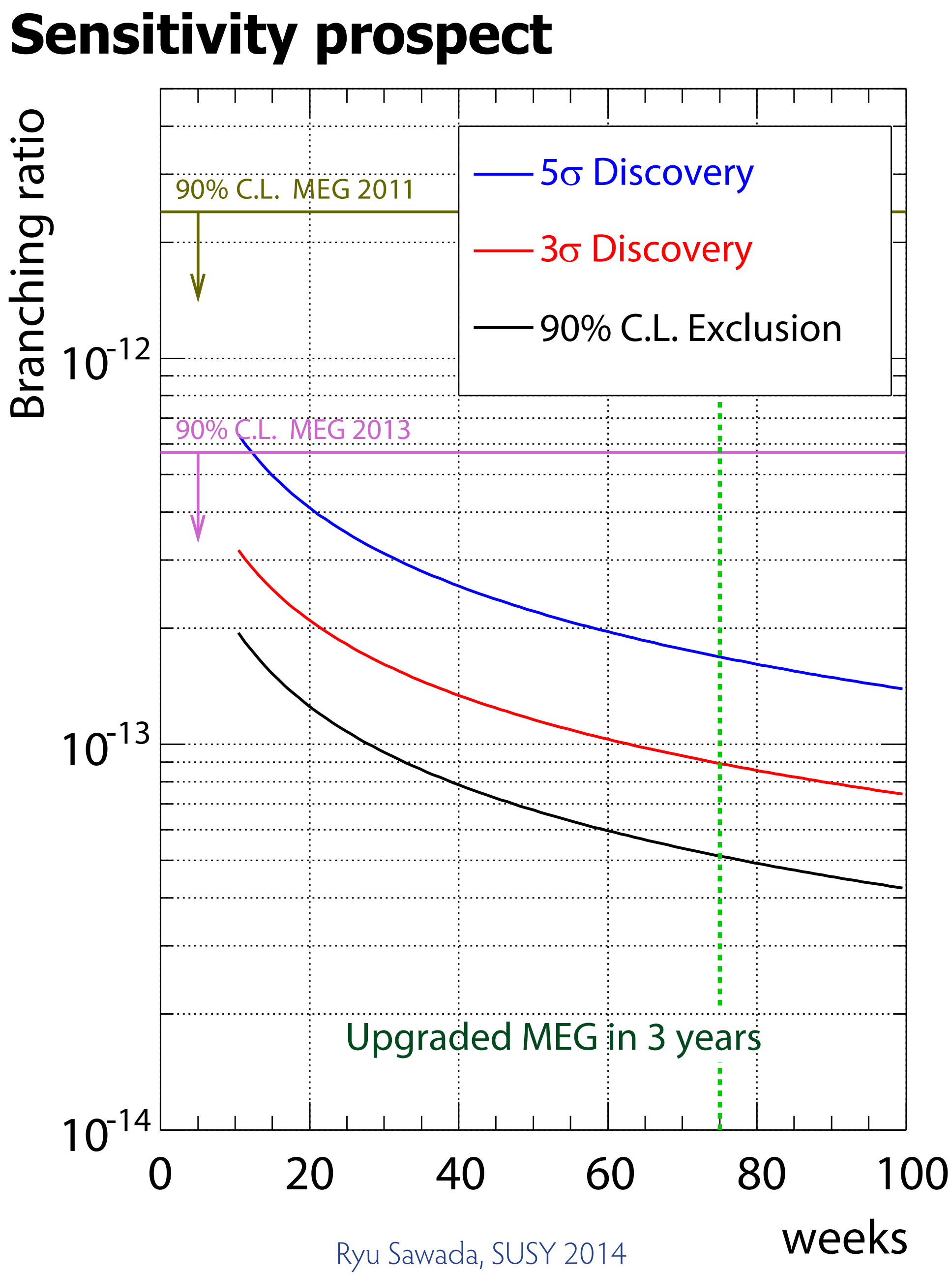



LXe Calorimeter
Higher resolutions and efficiency
with higher granularity.
Target
Thinner target
Active target option
Muon Beam
More than twice
intense beam
Drift chamber
Higher tracking performance
with long single tracking
volume
Timing Counter
Higher time resolution with
highly segmented detector
Radiative Decay Counter
Identify muon
radiative-decays

MEG II sensitivity projection

5×10^{-14} sensitivity in
3 years data taking

Starting 2017

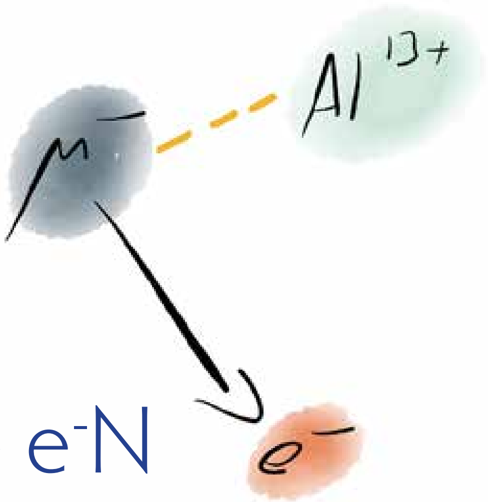


Ryu Sawada, SUSY 2014

Searching for $\mu \rightarrow e$ conversion with

Mu2e, COMET

Conversion Signal and Background



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

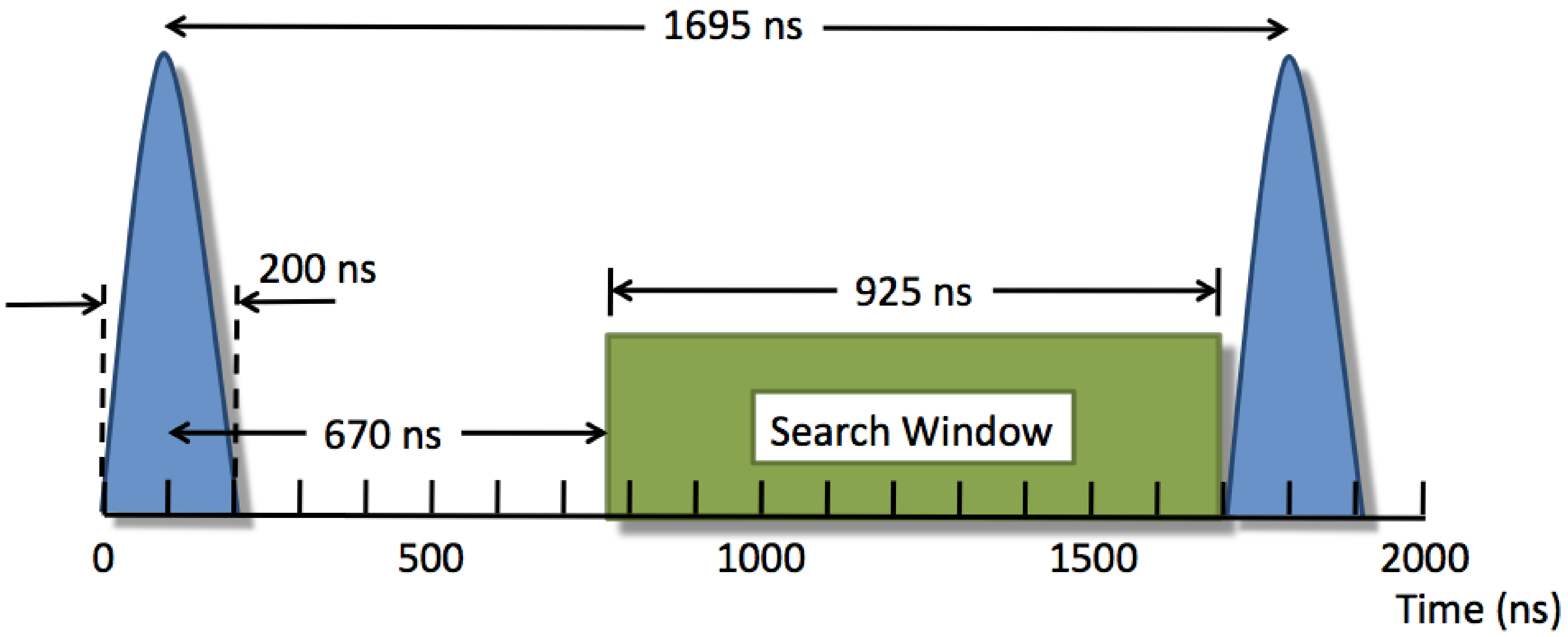
- Single 105 MeV/c electron observed

Backgrounds:

Anything that can produce a 105 MeV/c electron

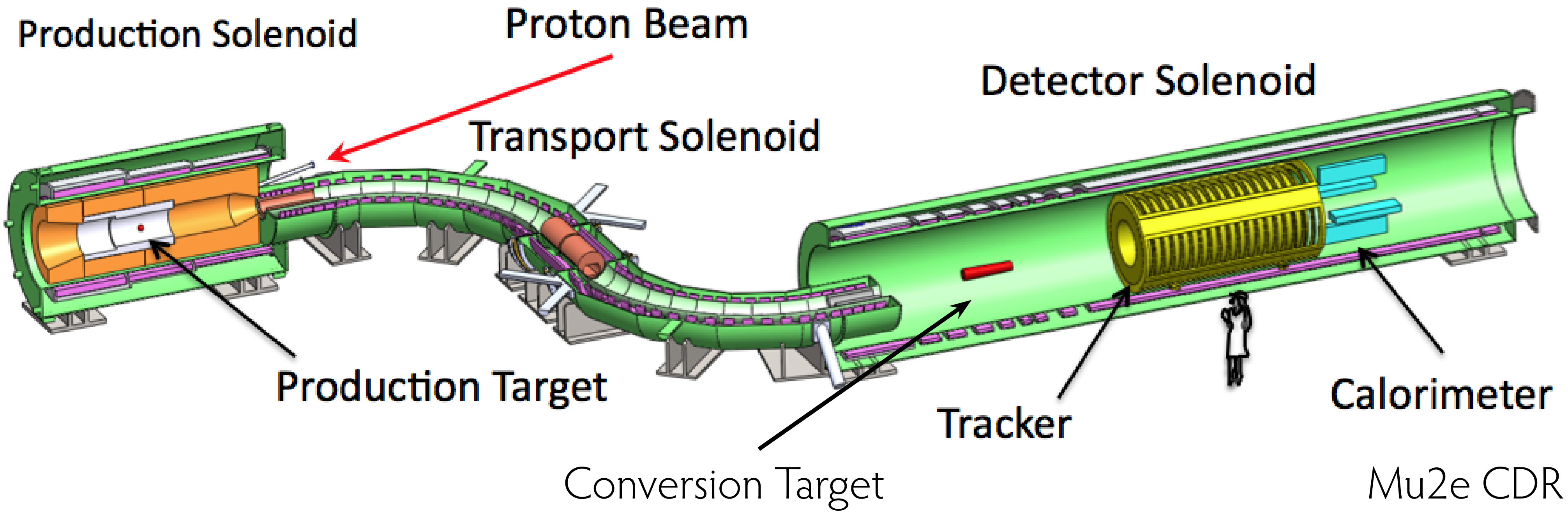
- Primary proton beam
- Decay in Orbit (DIO)
- Nuclear capture
- Cosmics

Beam induced background



- Proton beam produces pions, photons, (antiprotons) etc.
- Wait until things become better...

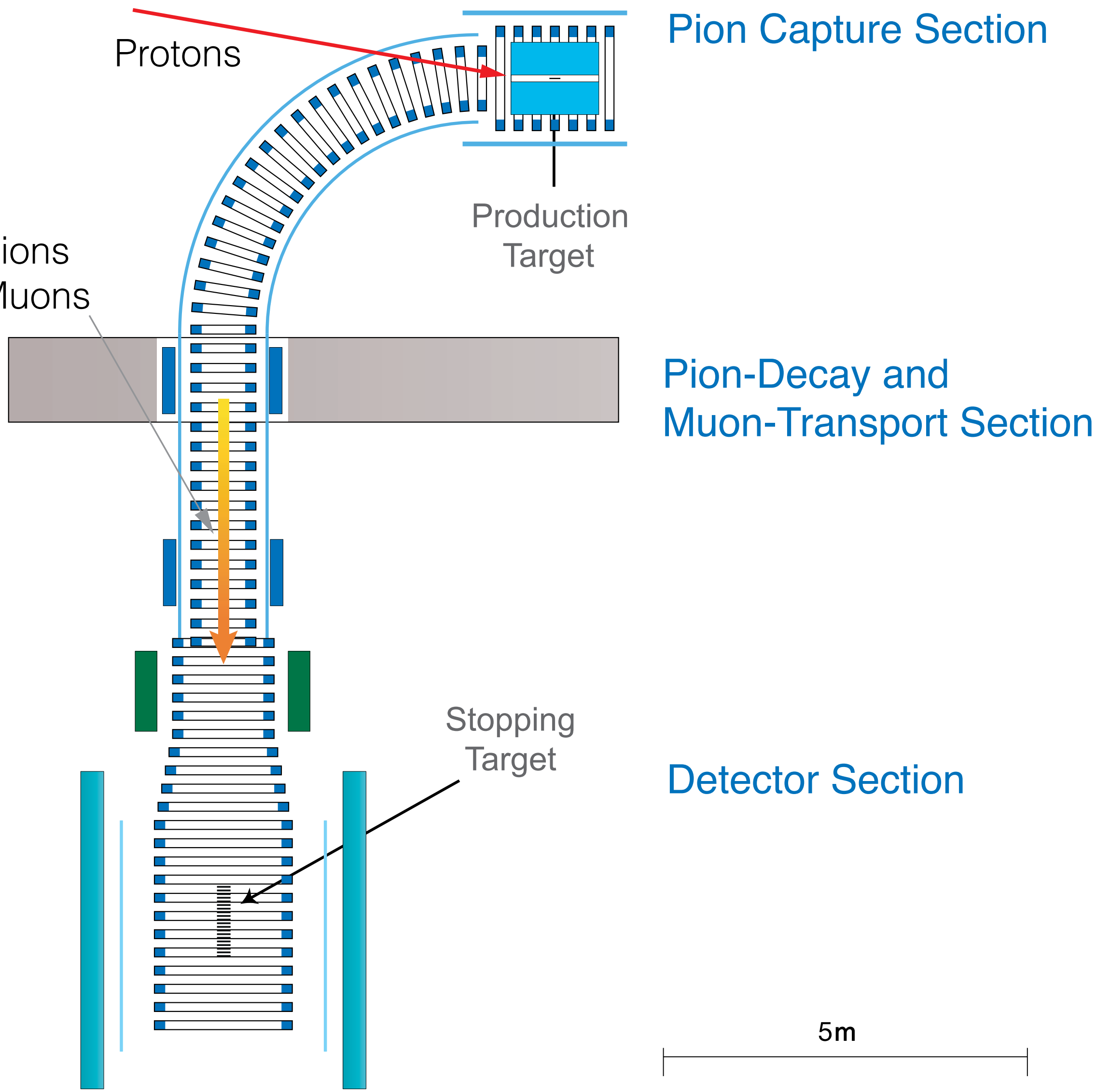
Experimental layout - Mu2e at Fermilab



Mu2e CDR

- Separate muon production and conversion target
- Not shown: cosmic ray veto and absorbers

Experimental layout - COMET Phase I at J-PARC



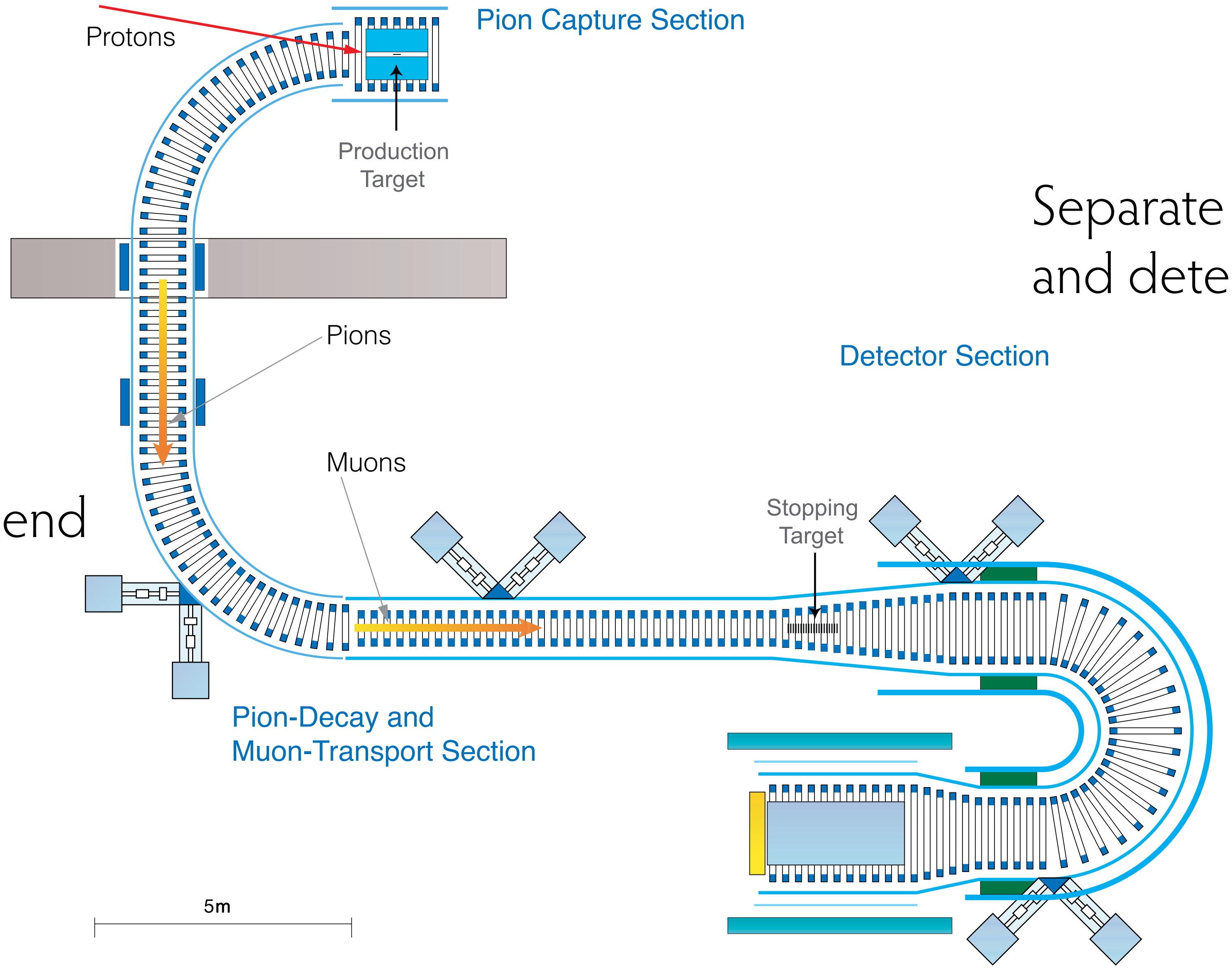
Comet CDR

Y. Kuno

Curved solenoid

Drift chamber

Experimental layout - COMET Phase II



Separate muon decay and detector region

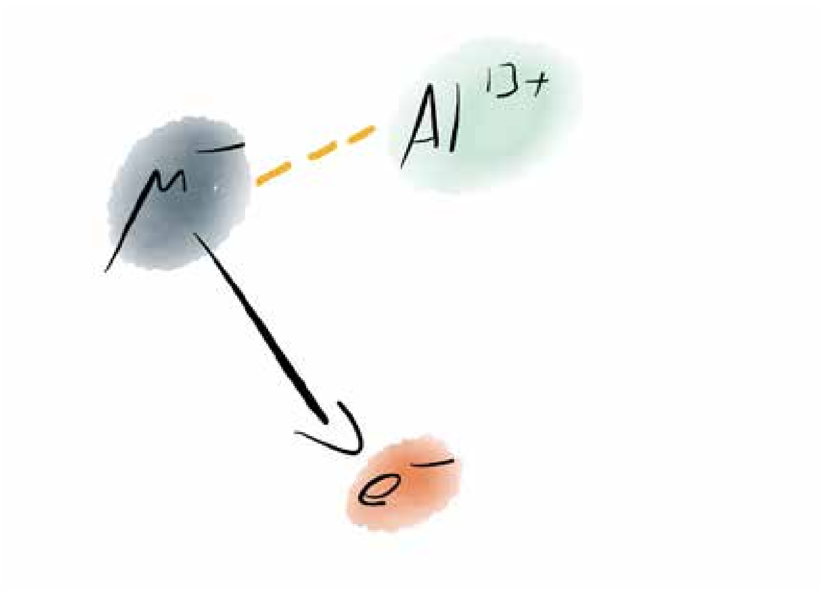
One more bend

Comet CDR

Conversion: Expected sensitivities

- Comet Phase I aims for $\sim 3\times10^{-15}$
  start data taking 2018

- Comet Phase II and Mu2e will start around 2020
  Sensitivities below 10^{-16}

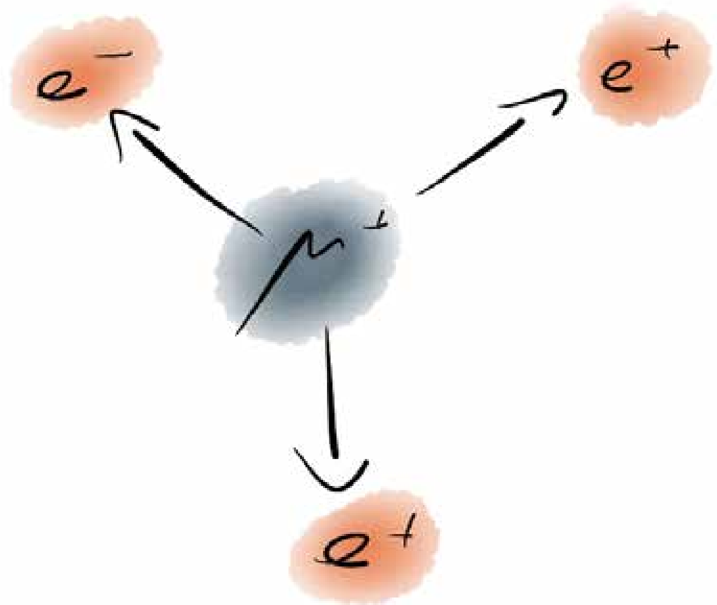


Searching for $\mu^+ \rightarrow e^+e^-e^+$ with

Mu3e

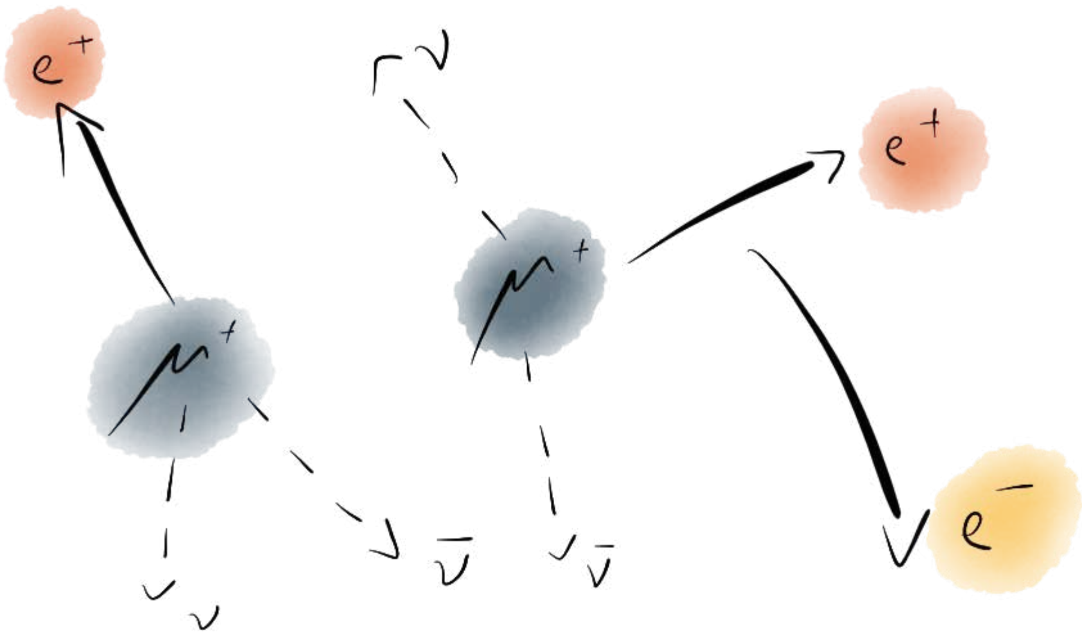
German participants:
Heidelberg, Karlsruhe, Mainz

The signal



- $\mu^+ \rightarrow e^+e^-e^+$
- Two positrons, one electron
- From same vertex
- Same time
- $\Sigma\, p_e = m_\mu$
- Maximum momentum: ½ m_μ = 53 MeV/c

Accidental Background



- Combination of positrons from ordinary muon decay with electrons from:
  - photon conversion,
  - Bhabha scattering,
  - Mis-reconstruction

- Need very good timing, vertex and momentum resolution

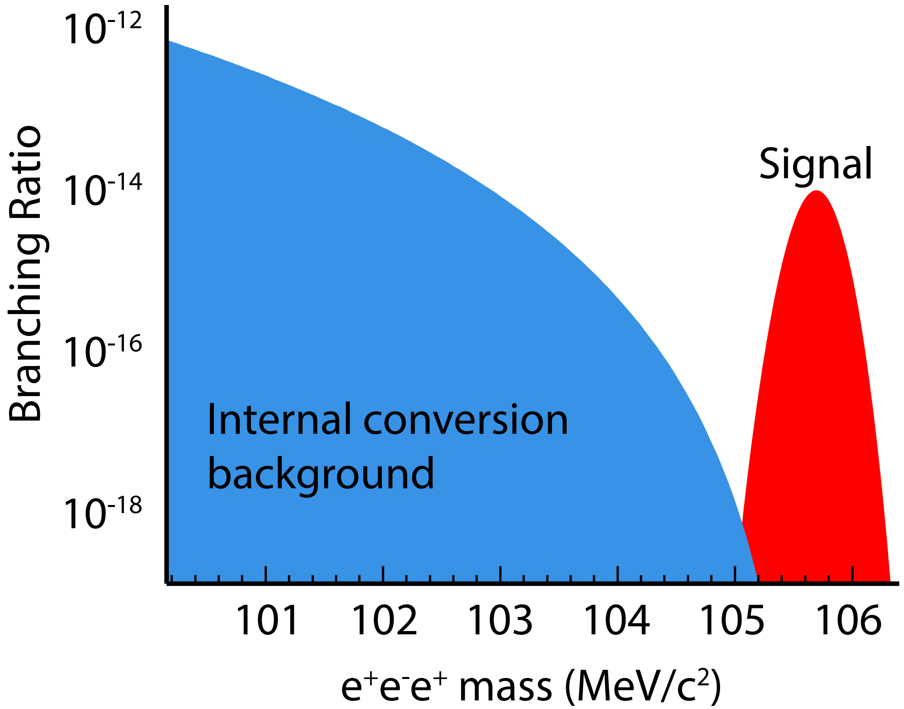
Internal conversion background

- Need excellent momentum resolution

- Allowed radiative decay with internal conversion:

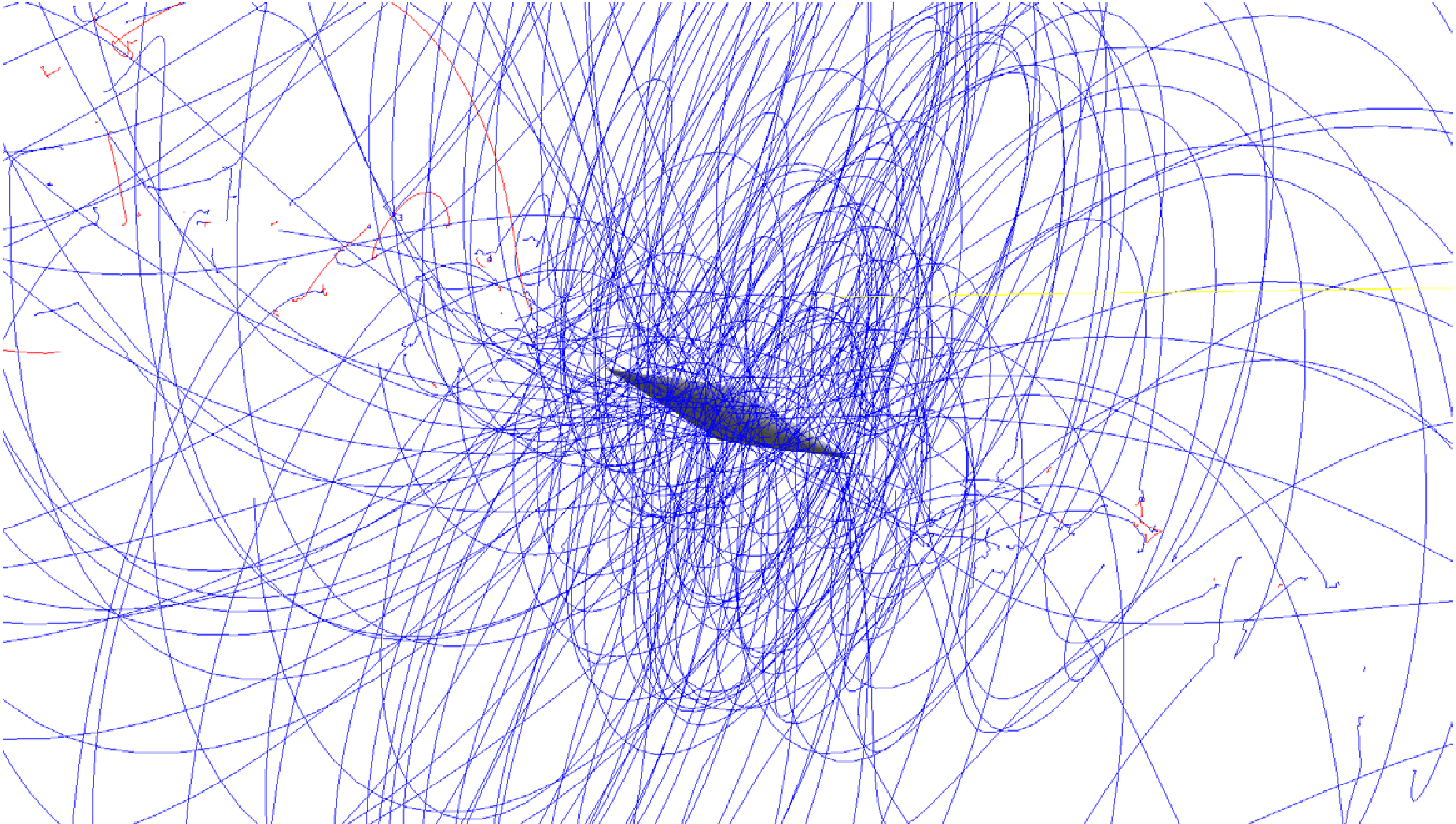
$$\mu^+ \rightarrow e^+e^-e^+\nu\bar{\nu}$$

- Only distinguishing feature: Missing momentum carried by neutrinos



2 Billion Muon Decays/s

50 ns, 1 Tesla field



Detector Technology

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

Detector Technology

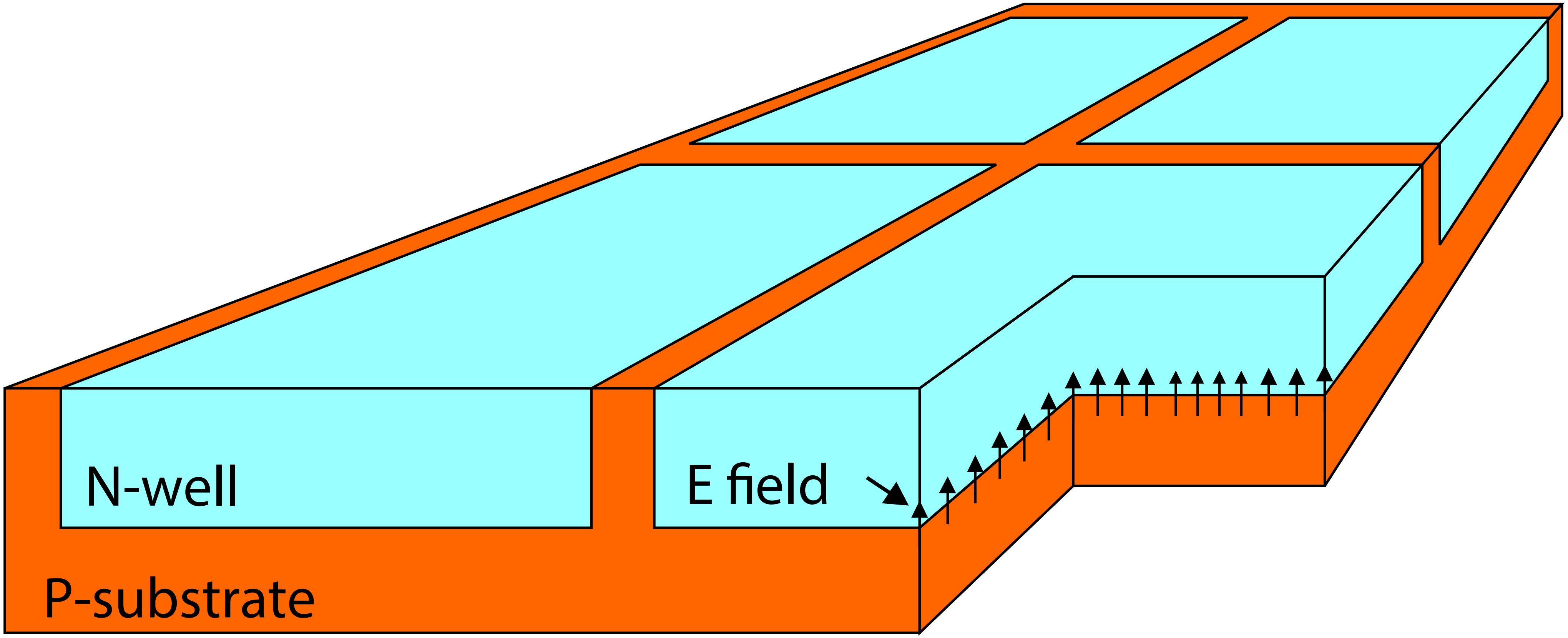
- High granularity (occupancy)
- Close to target (vertex resolution)
- 3D space points (reconstruction)
- Minimum material (momenta below 53 MeV/c)

- Conventional detectors cannot deal with rate or are too thick

Fast and thin sensors: HV-MAPS

High voltage monolithic active pixel sensors - Ivan Perić

- Use a high voltage commercial process (automotive industry)



Fast and thin sensors: HV-MAPS

High voltage monolithic active pixel sensors - Ivan Perić

- Use a high voltage commercial process (automotive industry)
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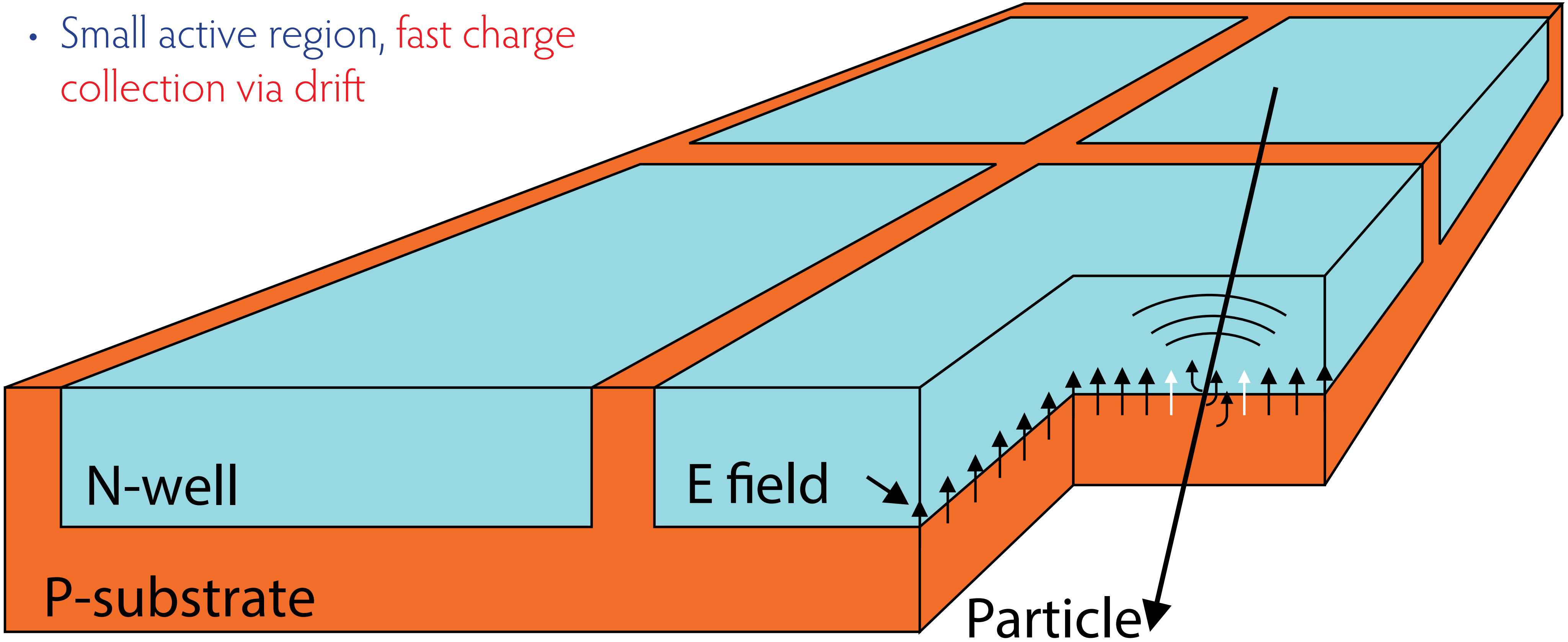


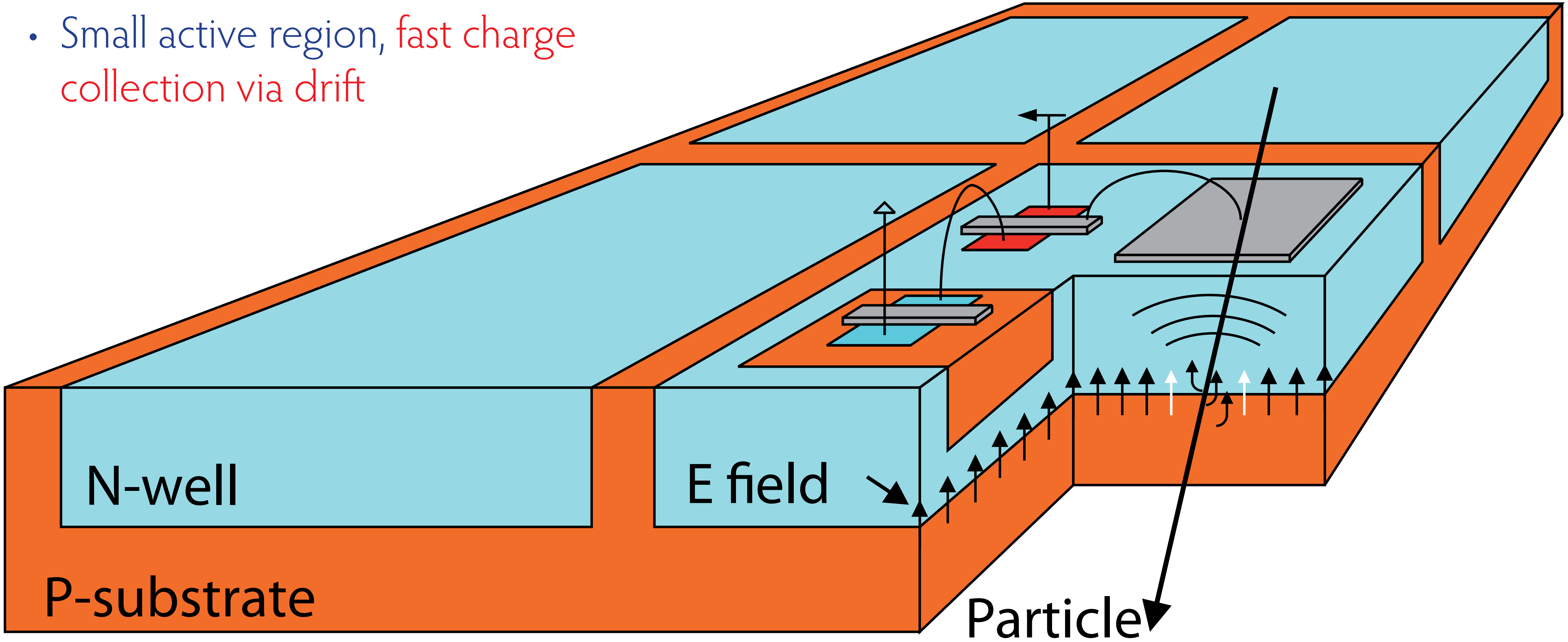
Fast and thin sensors: HV-MAPS

High voltage monolithic active pixel sensors - Ivan Perić

- Use a high voltage commercial process (automotive industry)
- Small active region, fast charge collection via drift

- Implement logic directly in N-well in the pixel - smart diode array

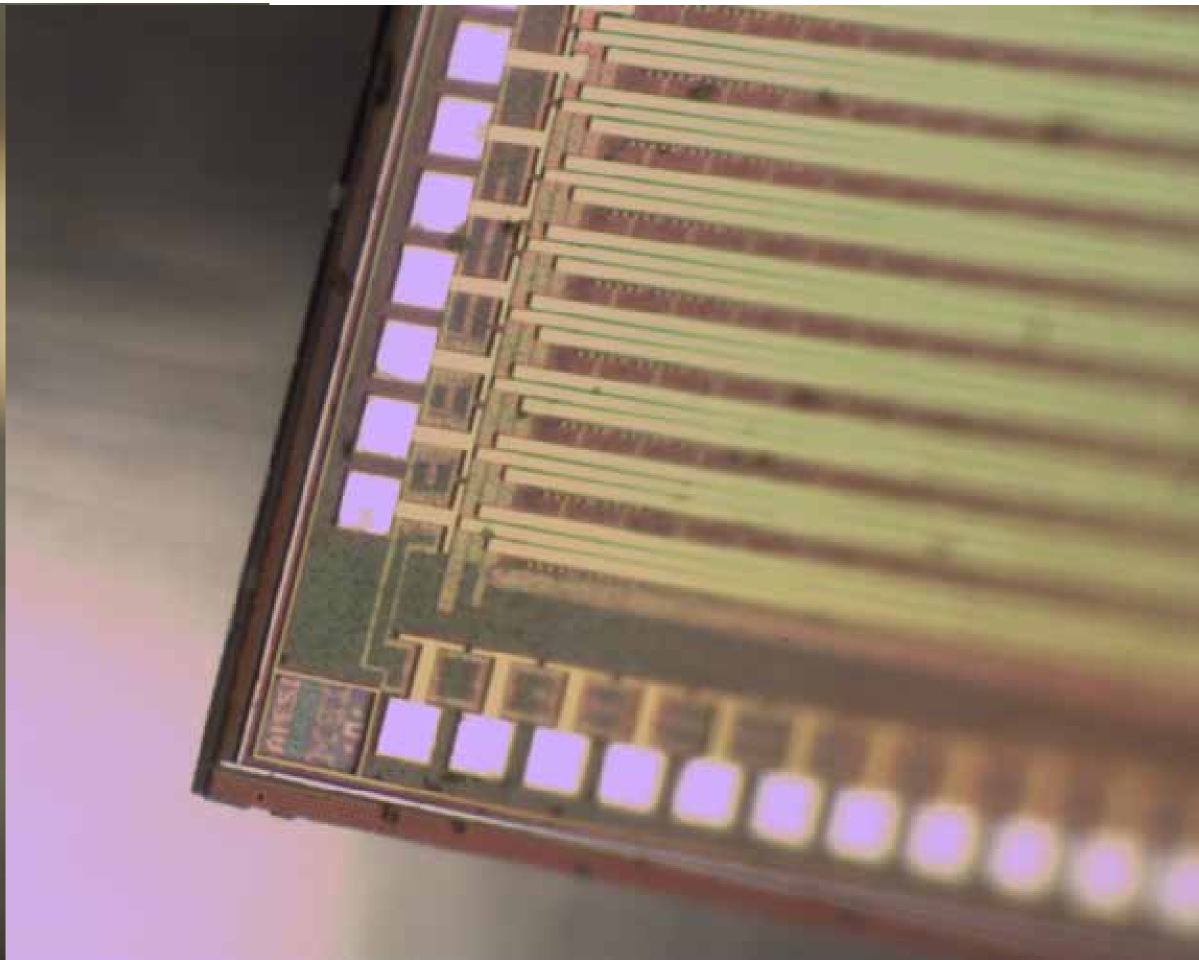
(I.Perić, P. Fischer et al., NIM A 582 (2007) 876)



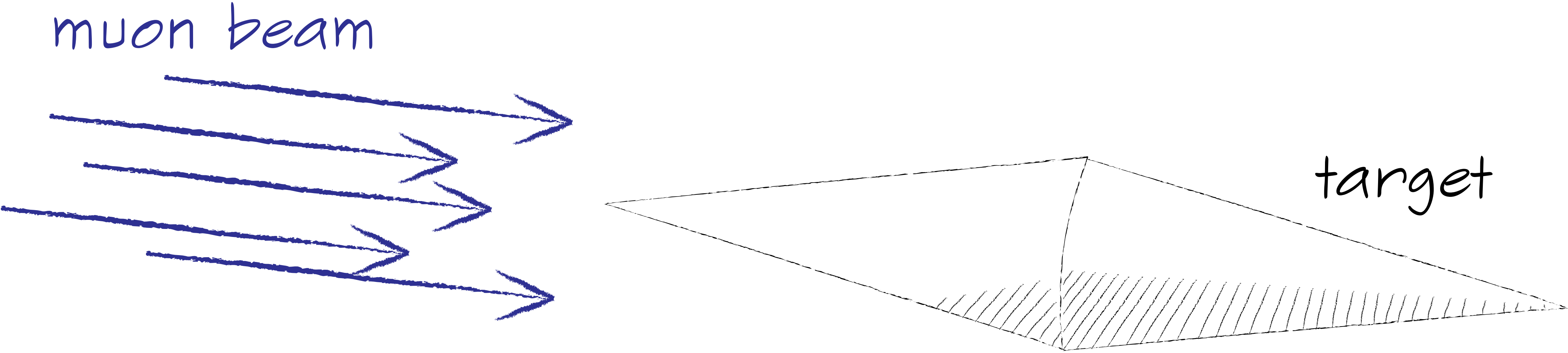
Fast and thin sensors: HV-MAPS

High voltage monolithic active pixel sensors - Ivan Perić

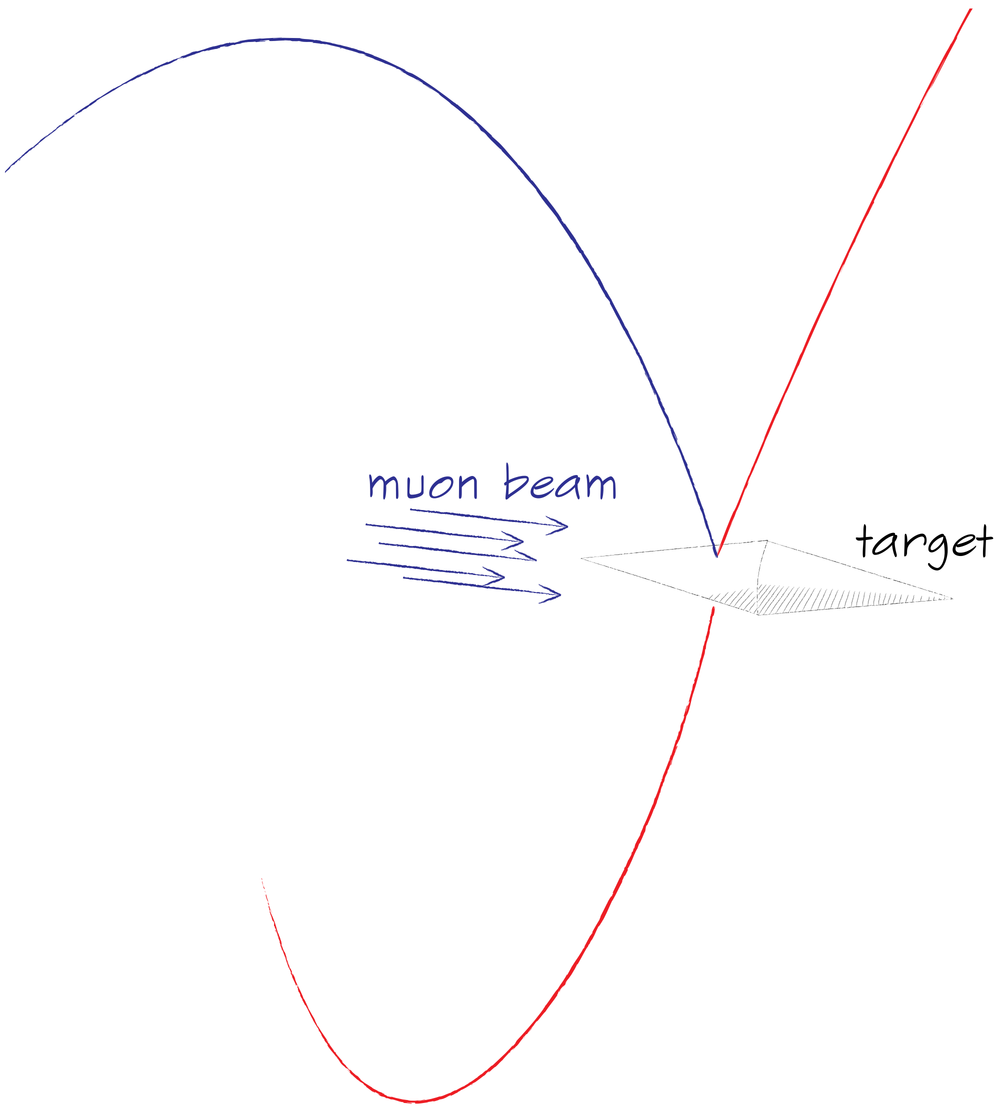
- Use a high voltage commercial process (automotive industry)
- Implement logic directly in N-well in the pixel - smart diode array
- Can be thinned down to < 50 µm



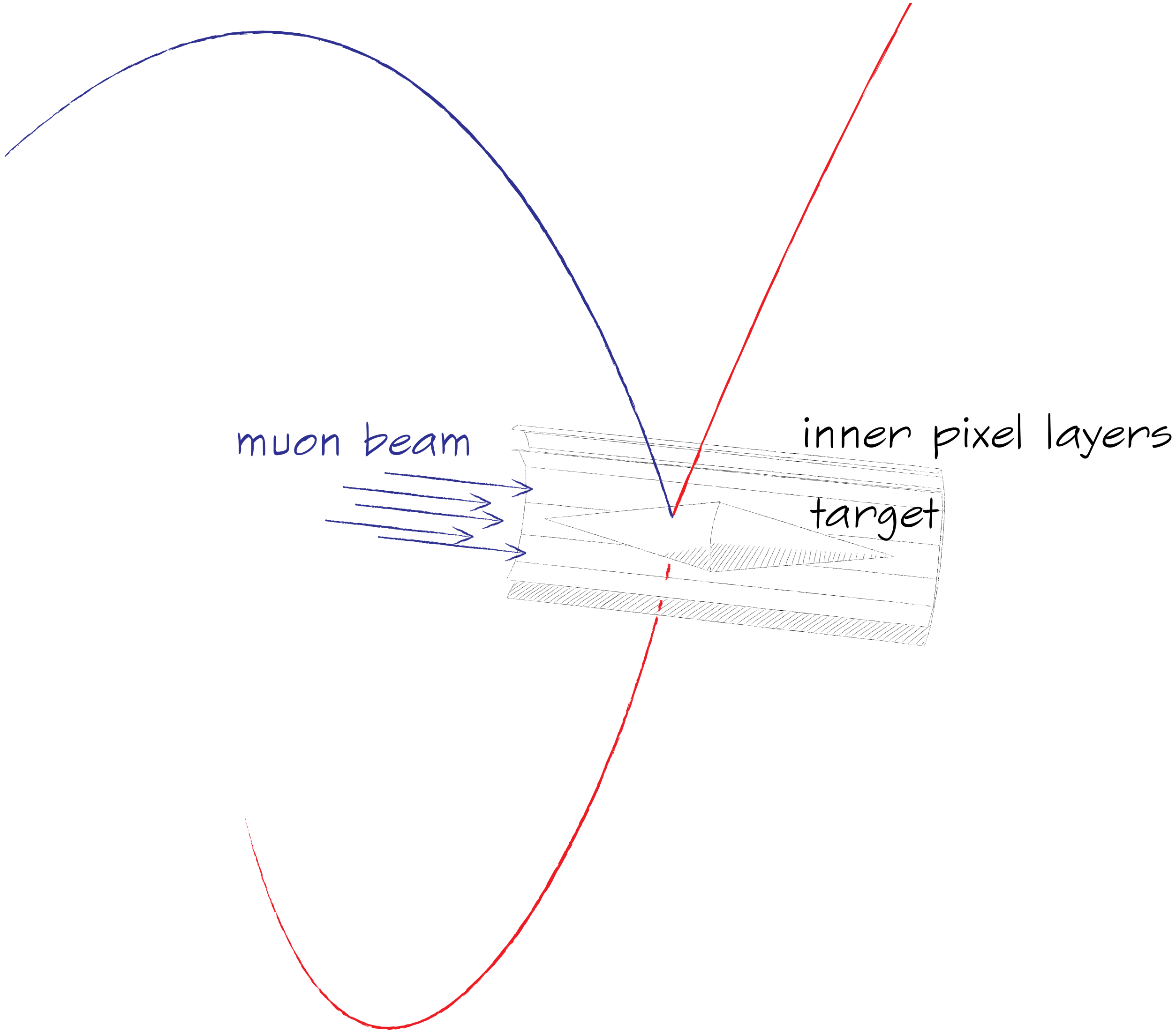
Detector Design



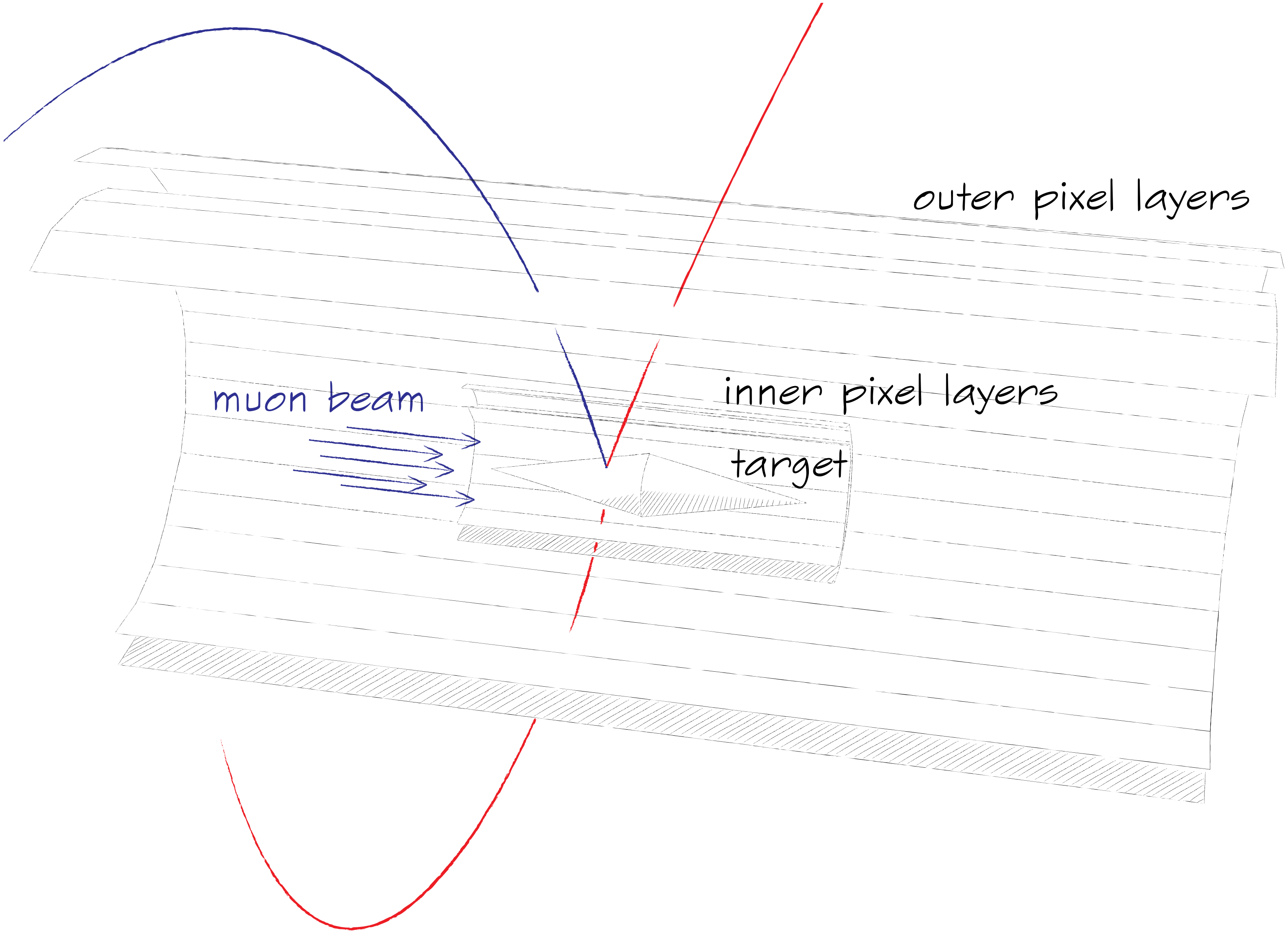
Detector Design



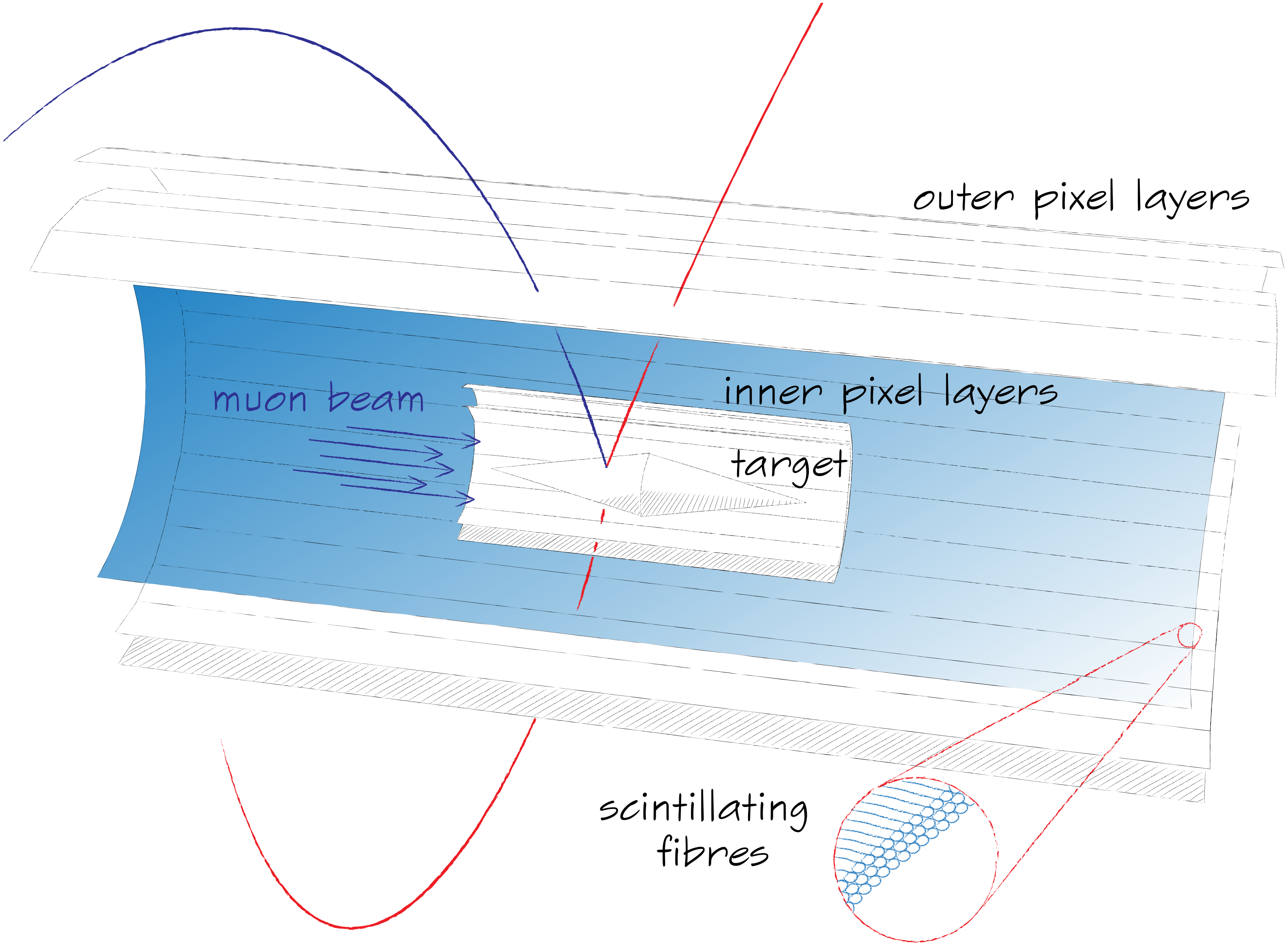
Detector Design



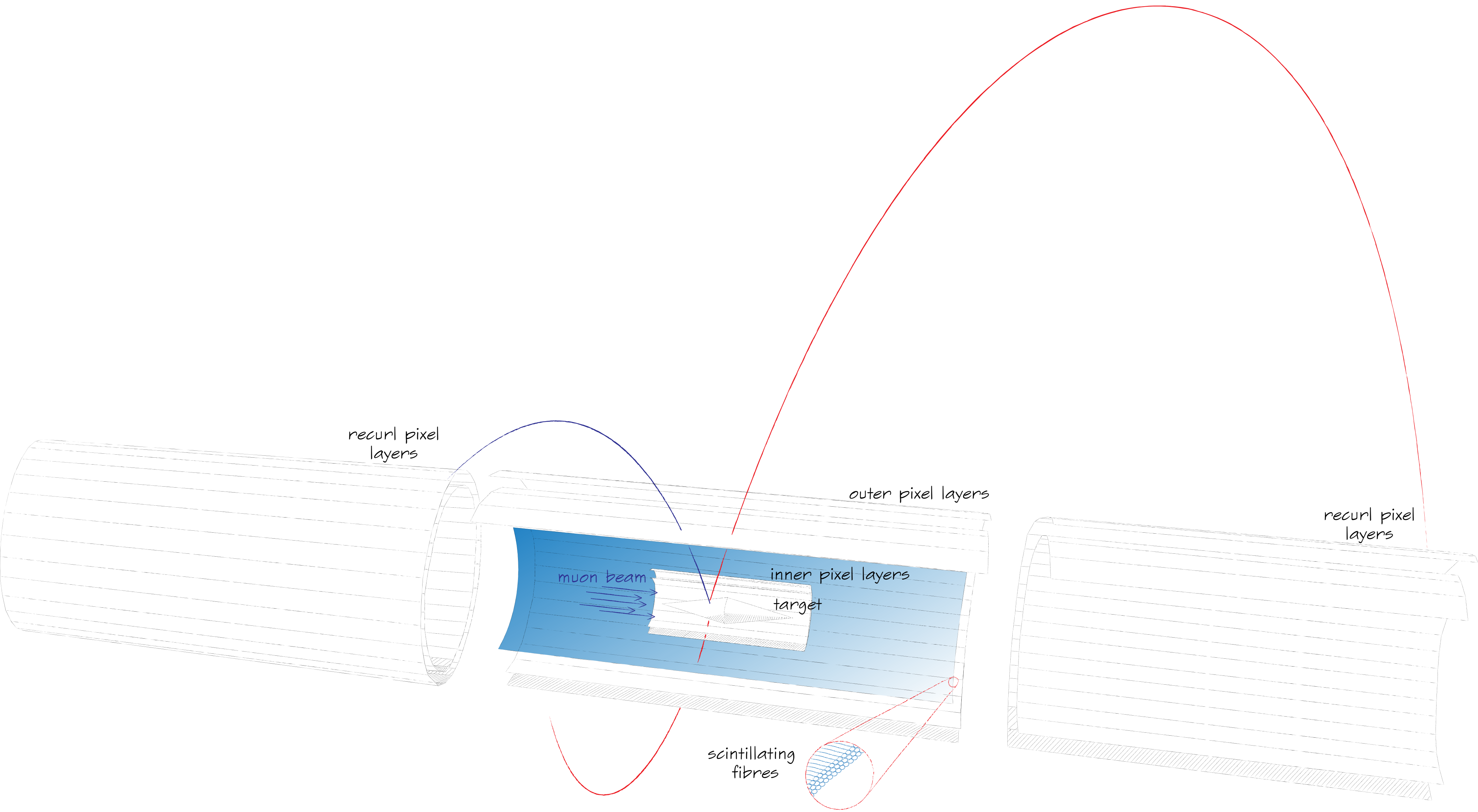
Detector Design



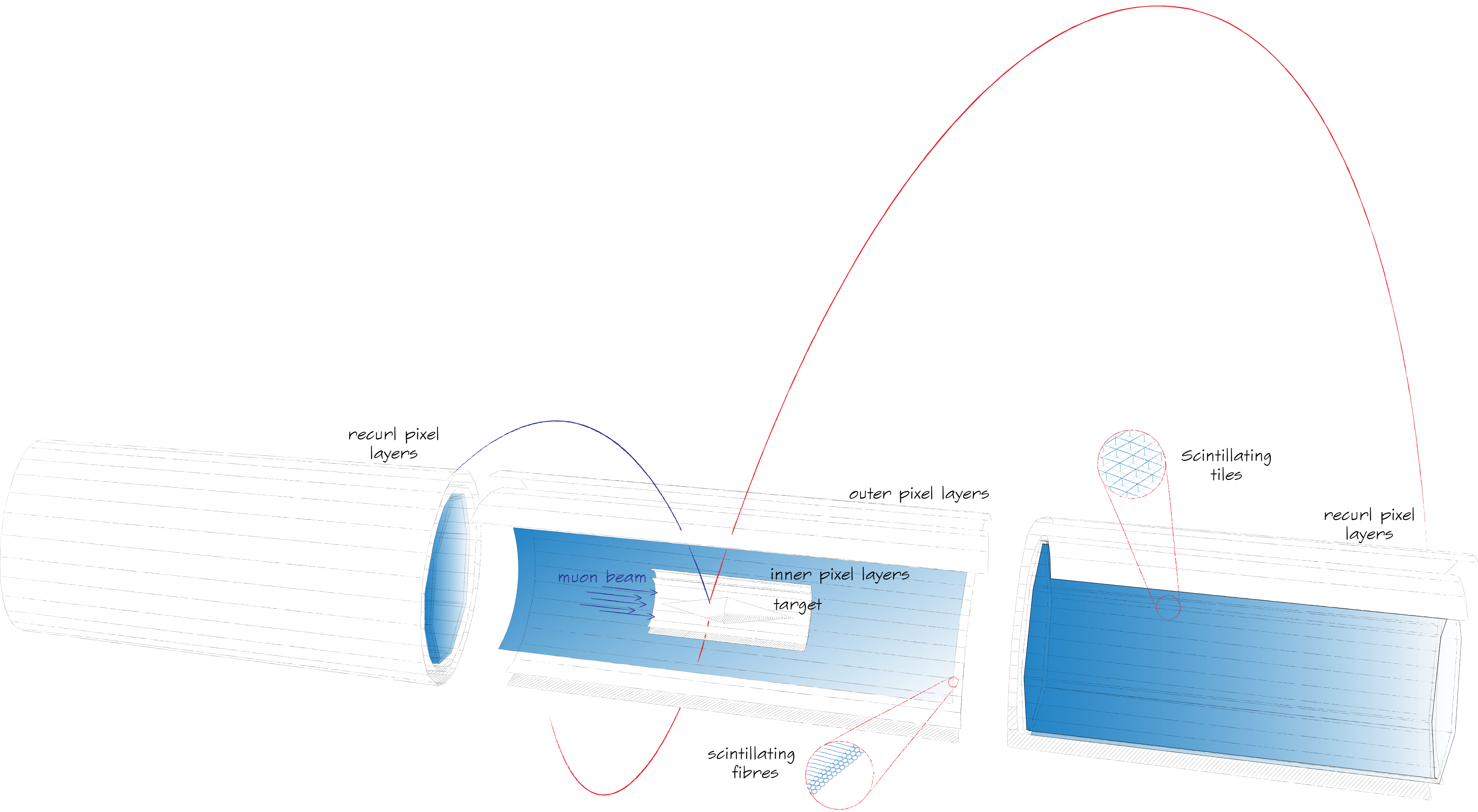
Detector Design

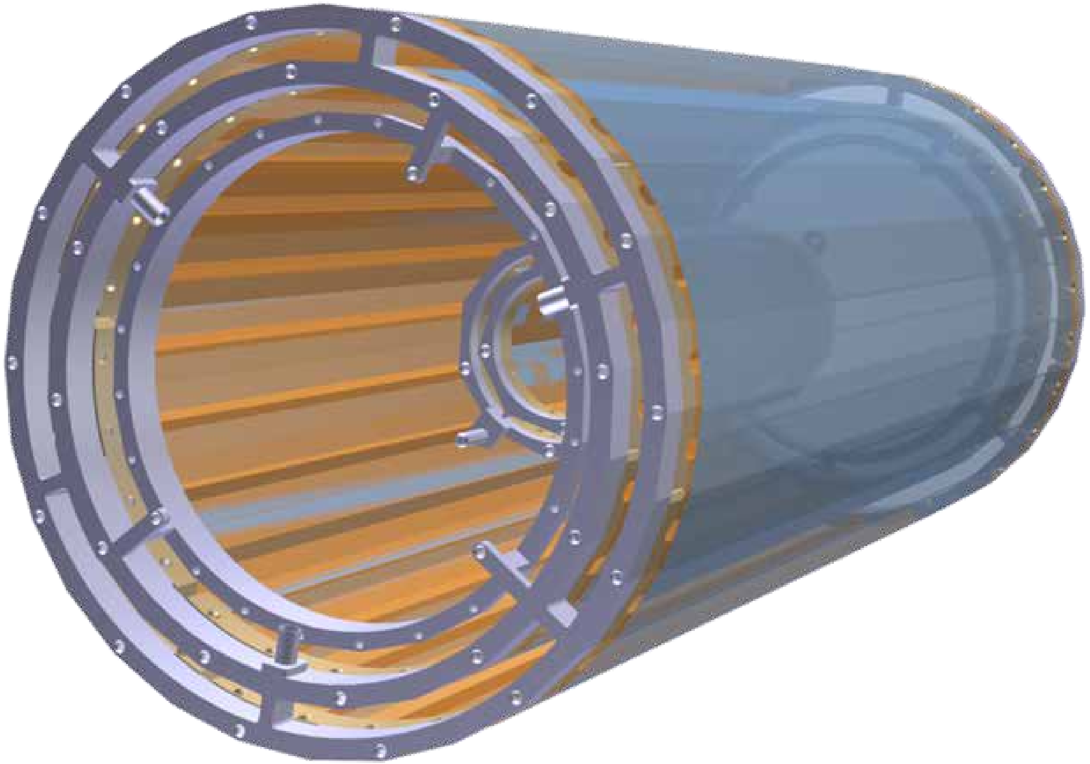


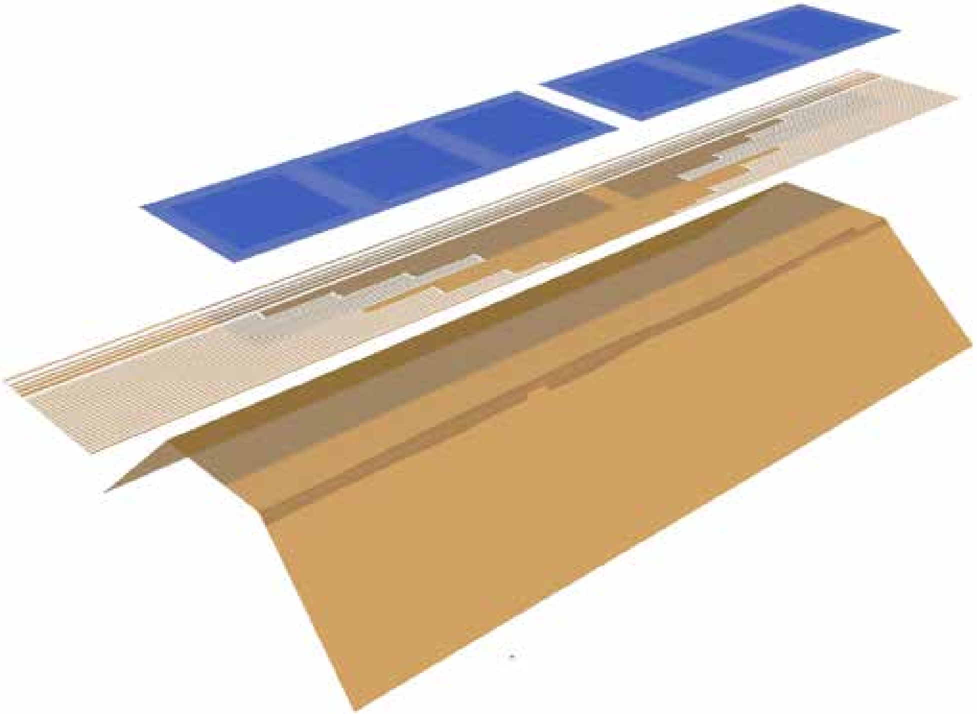
Detector Design



Detector Design

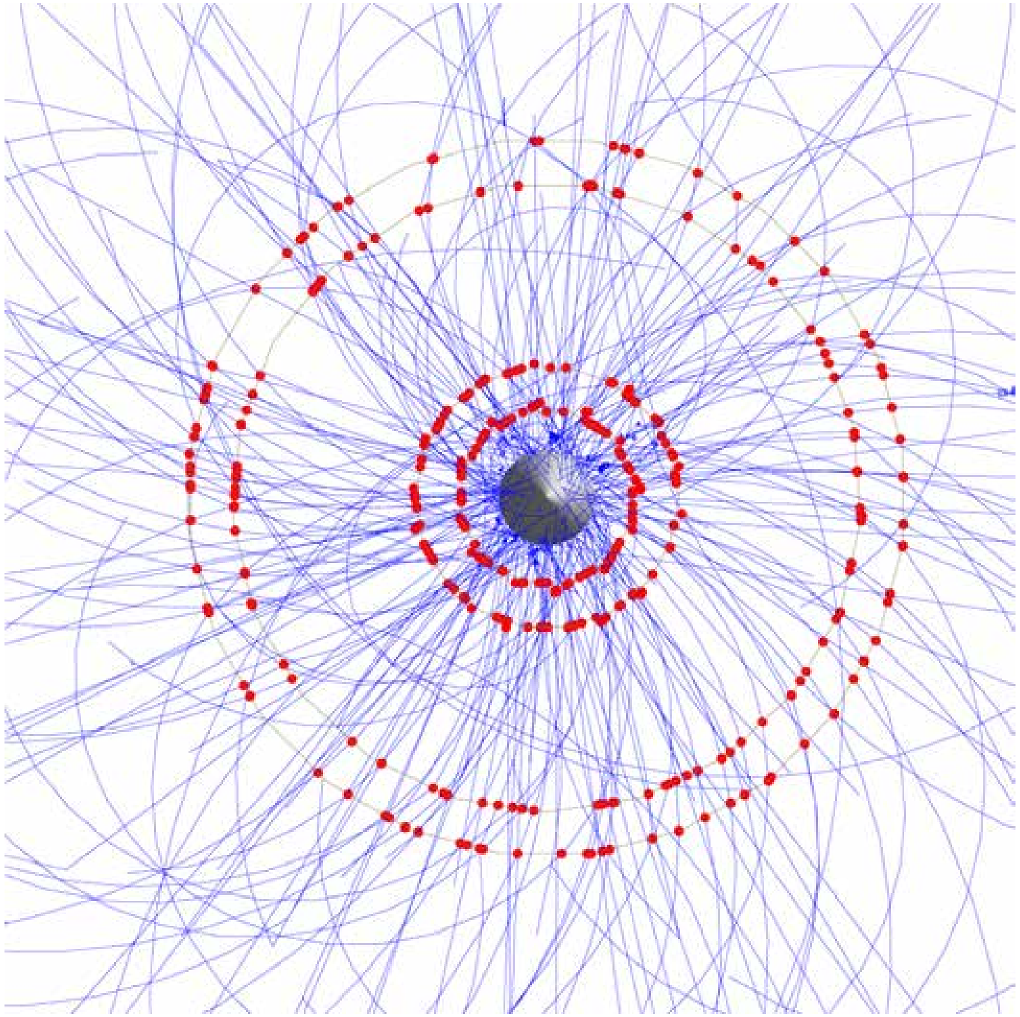




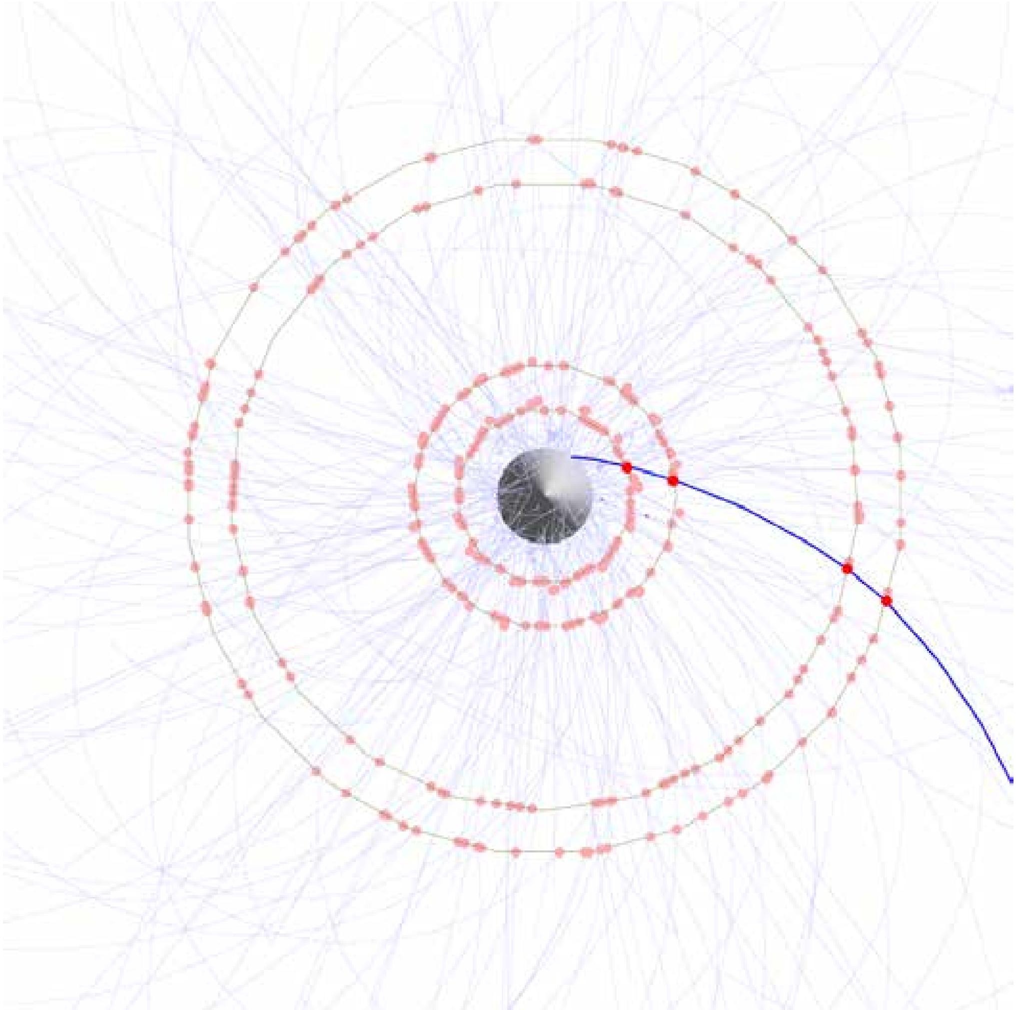


- 50 µm silicon
- 25 µm Kapton™ flexprint with aluminium traces
- 25 µm Kapton™ frame as support
- Less than 1‰ of a radiation length per layer

Timing measurements

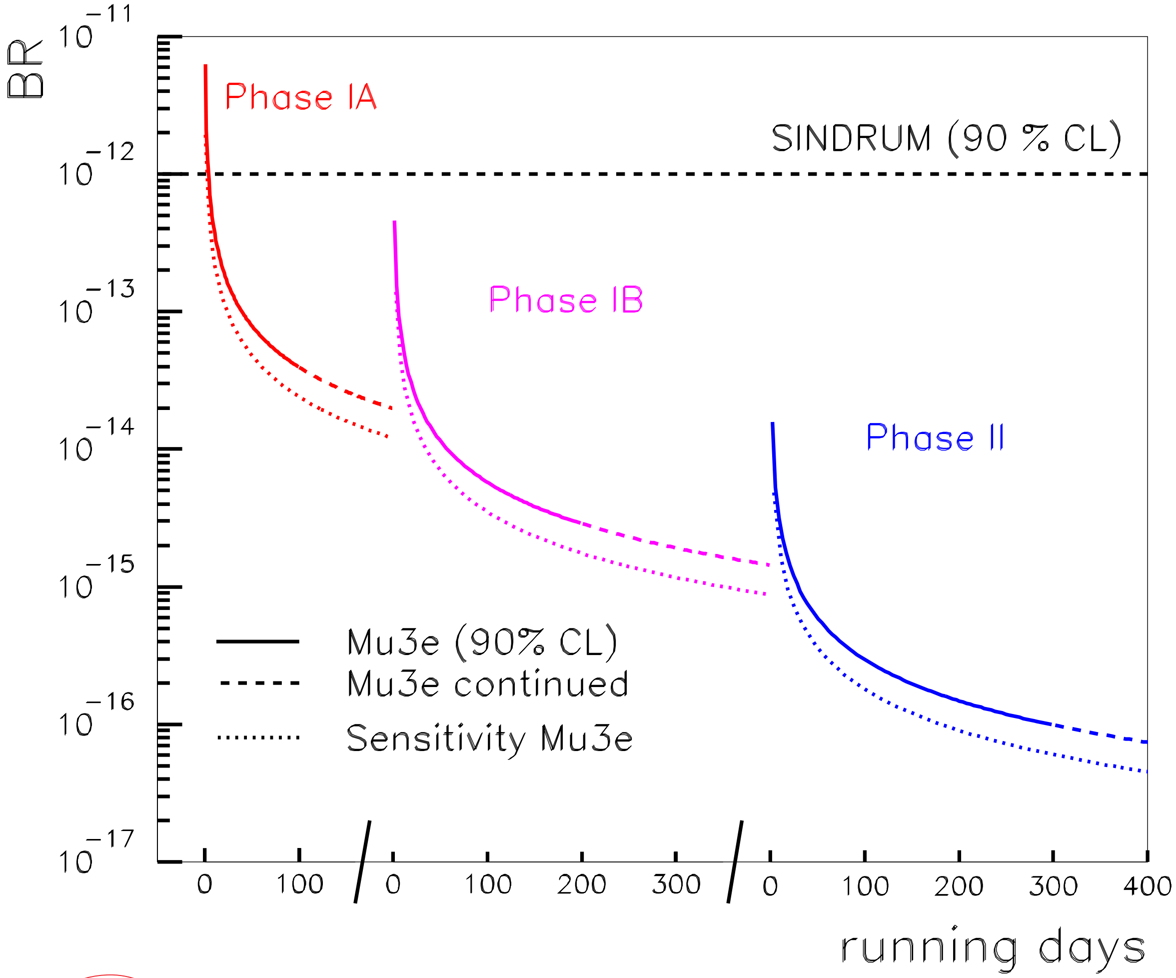


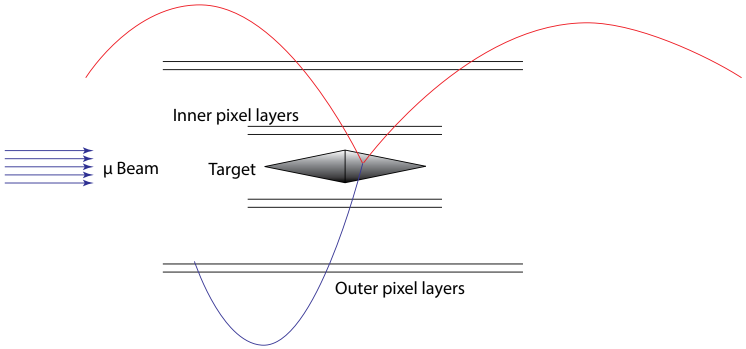
Pixels: O(50 ns)



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

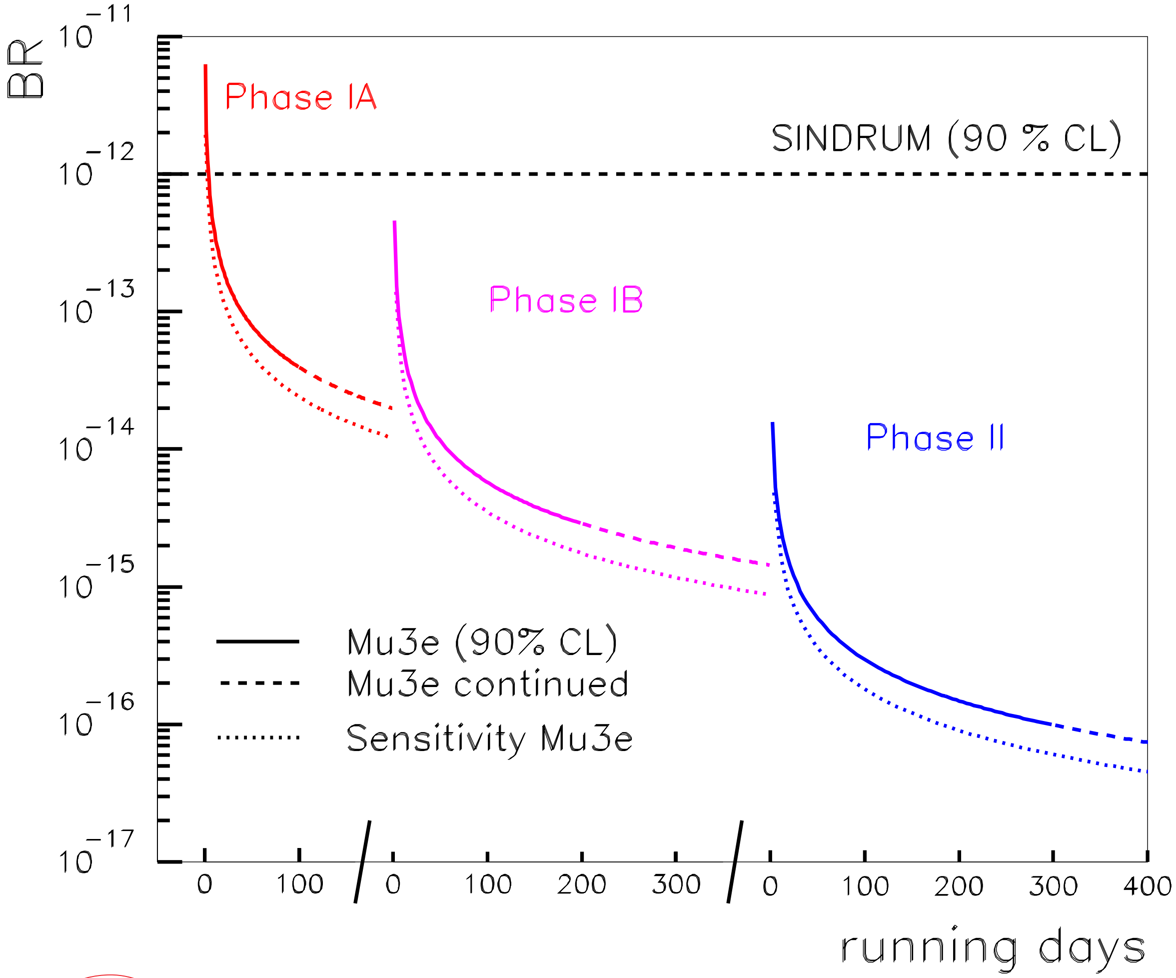
Sensitivity

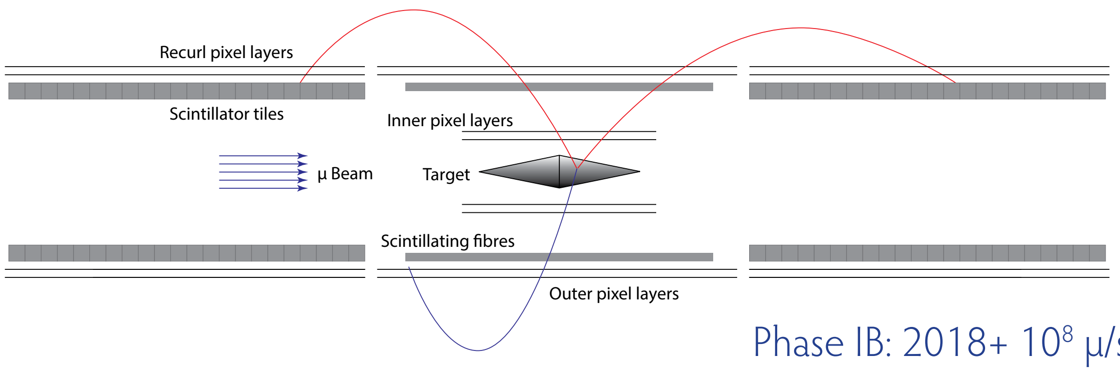




Phase IA: Starting 2017 10^7 μ/s

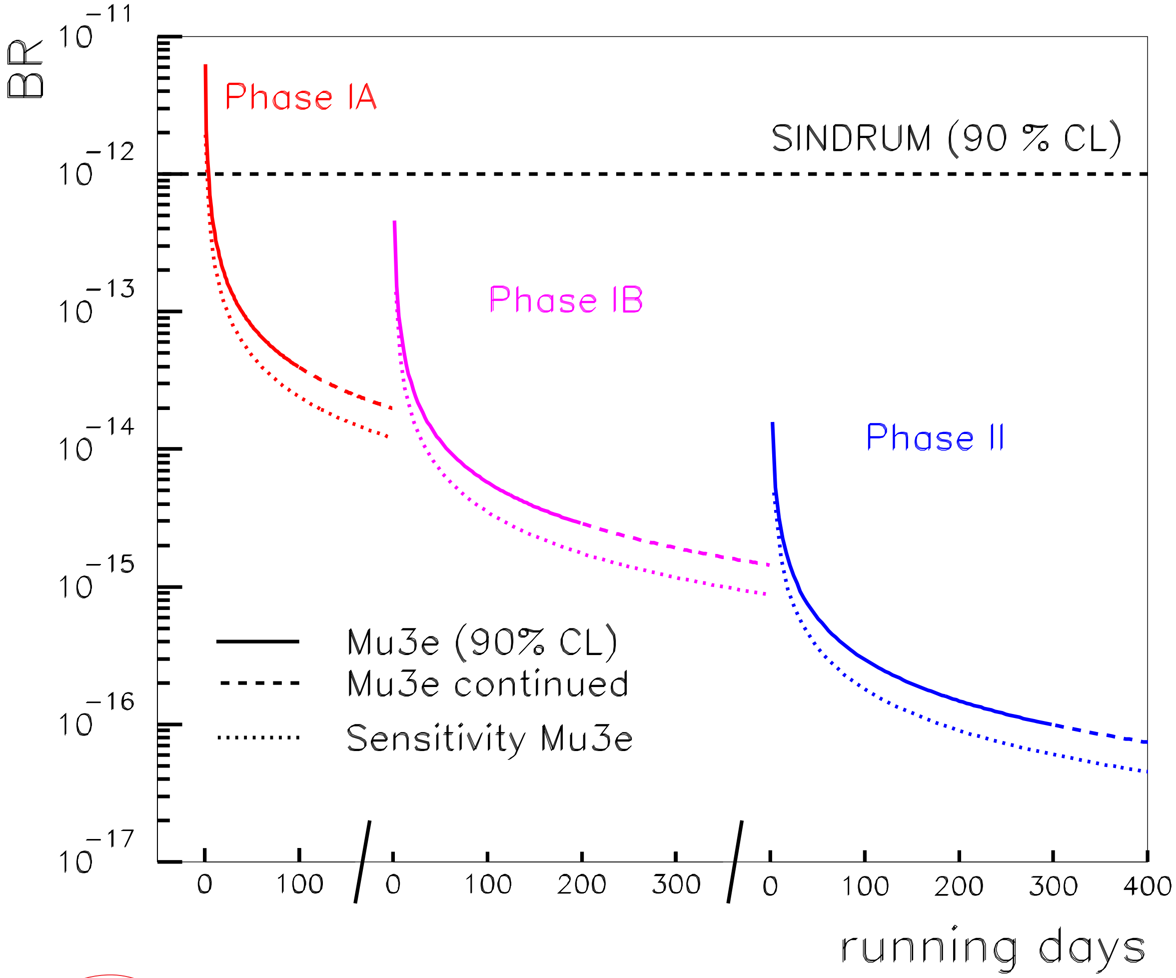
Sensitivity

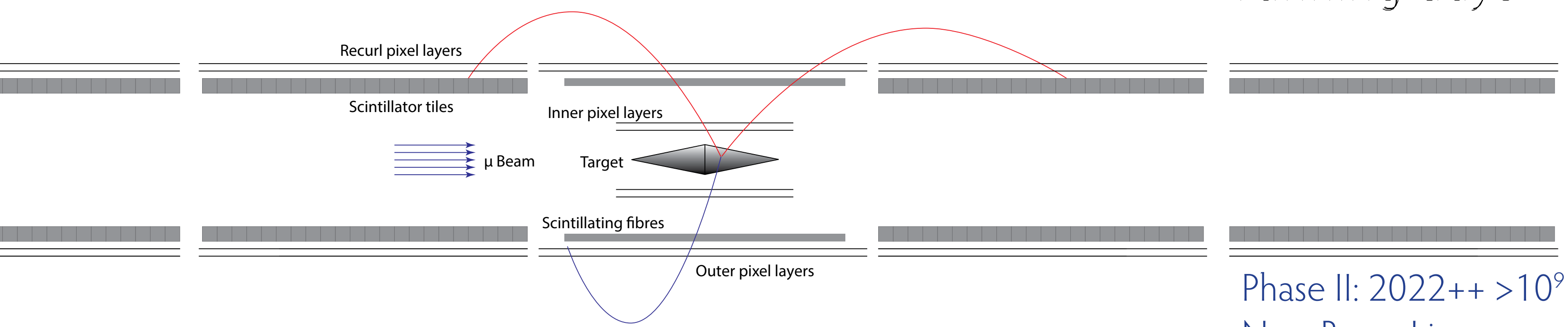




Phase IB: 2018+ 10^8 μ/s

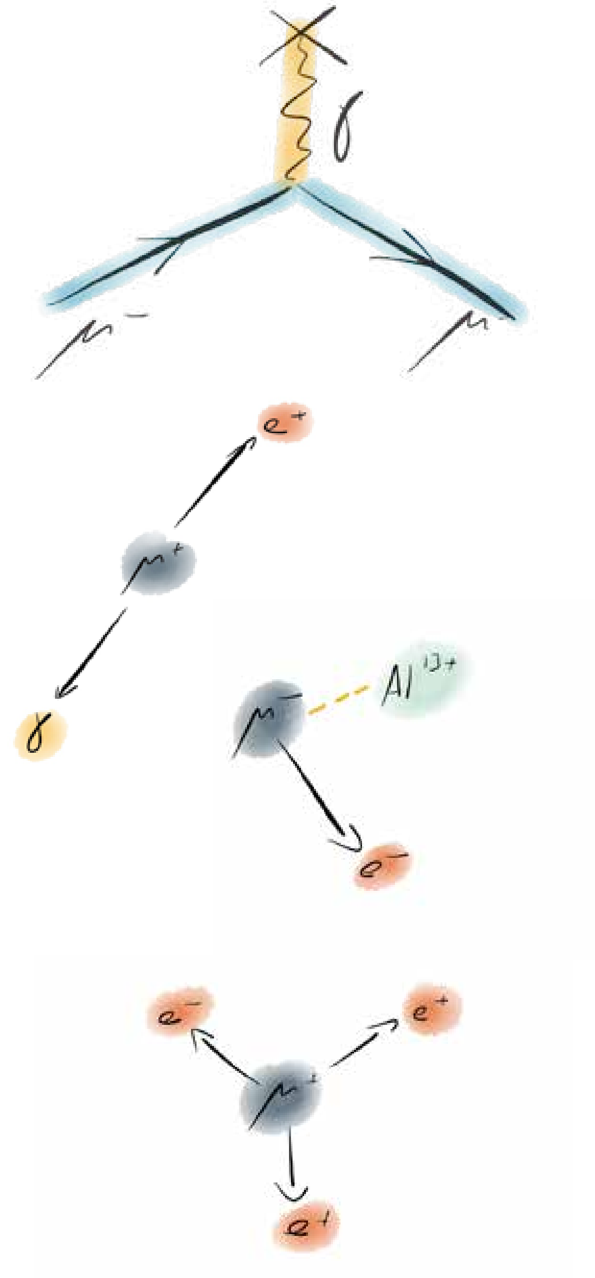
Sensitivity





Phase II: 2022++ $>10^9$ μ/s
New Beam Line

Summary



- Exciting times ahead in muon physics
- New g-2 at Fermilab soon, J-PARC with cold muons
- MEG aims for another order of magnitude for μ→eγ
- Comet I aim for two orders on μ→e conversion
- Mu3e Phase I aims for two orders on μ→eee
- Mu2e/Comet II aim for $< 10^{-16}$ for μ→e conversion and Mu3e Phase II for $< 10^{-16}$ for μ→eee
- Ideas for 10^{-18} are around

More on Mu3e

- T22.4 Ann-Kathrin Perrevoort: Data Acquisition at the Front-End of the Mu3e Pixel Detector
- T22.5: Qinhua Huang: Fast optical readout for Mu3e experiment
- T42.5: Dorothea vom Bruch: Online Track and Vertex Reconstruction on GPUs for the Mu3e Experiment
- T42.6: Carsten Grzesik: GPU-based online track reconstruction for the MuPix-telescope
- T42.7: Sebastian Dittmeier: Flex-prints for the Mu3e experiment

- T72.1: Heiko Augustin: A pixel tracker in HV-MAPS technology for the Mu3e experiment
- T72.2: David Immig: Temperaturabhängigkeit von HV-MAPS am Beispiel des MuPix7
- T72.3: Jan Hammerich: HV-MAPS Ergebnisse für Energieauflösung und Schwellenkalibration
- T75.7: Adrian Herkert: Mechanics and Cooling of the Mu3e Detector
- T98.1: Alexandr Kozlinskiy: Track reconstruction for the Mu3e experiment
- T98.5: Ulrich Hartenstein: Track Based Alignment of the Mu3e Detector
- T99.5: Lennart Huth: The MuPix Telescope - Tracking Low Momentum Particles at High Rates