Charged Lepton Flavour Violation Experiments

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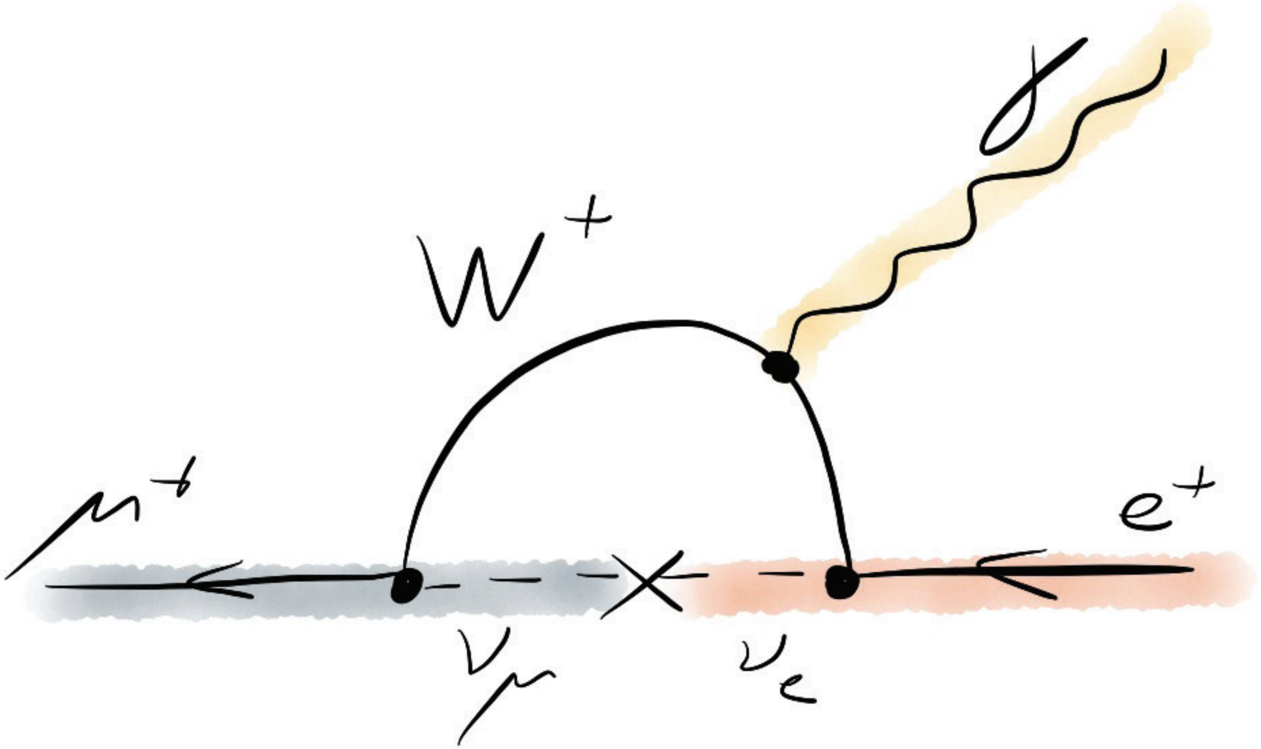
Zürich Phenomenology Workshop,
January 2015

JG|U

Emmy Noether-Programm
Deutsche Forschungsgemeinschaft
DFG

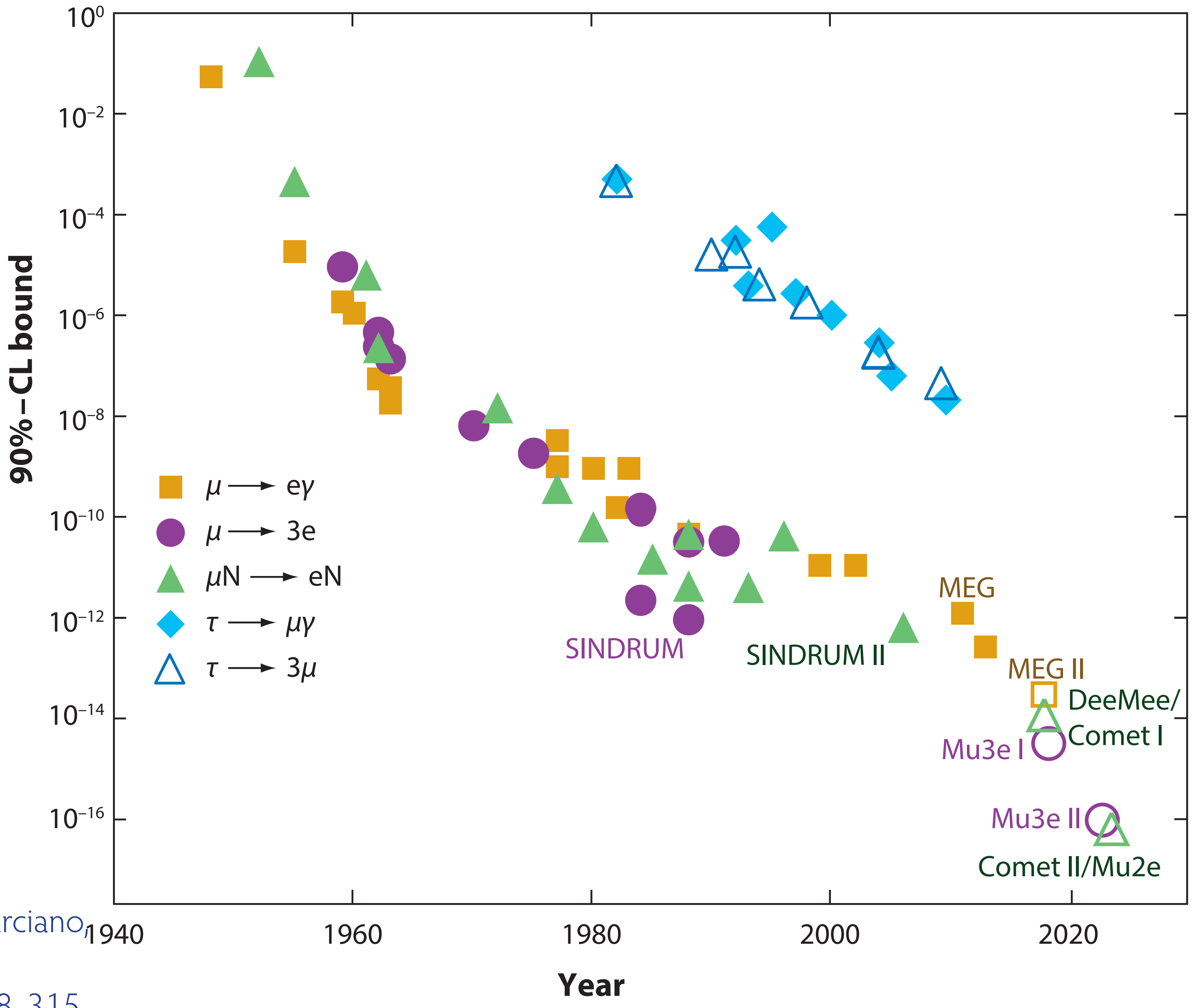


Standard Model branching fractions of

$10^{-50\text{ish}}$

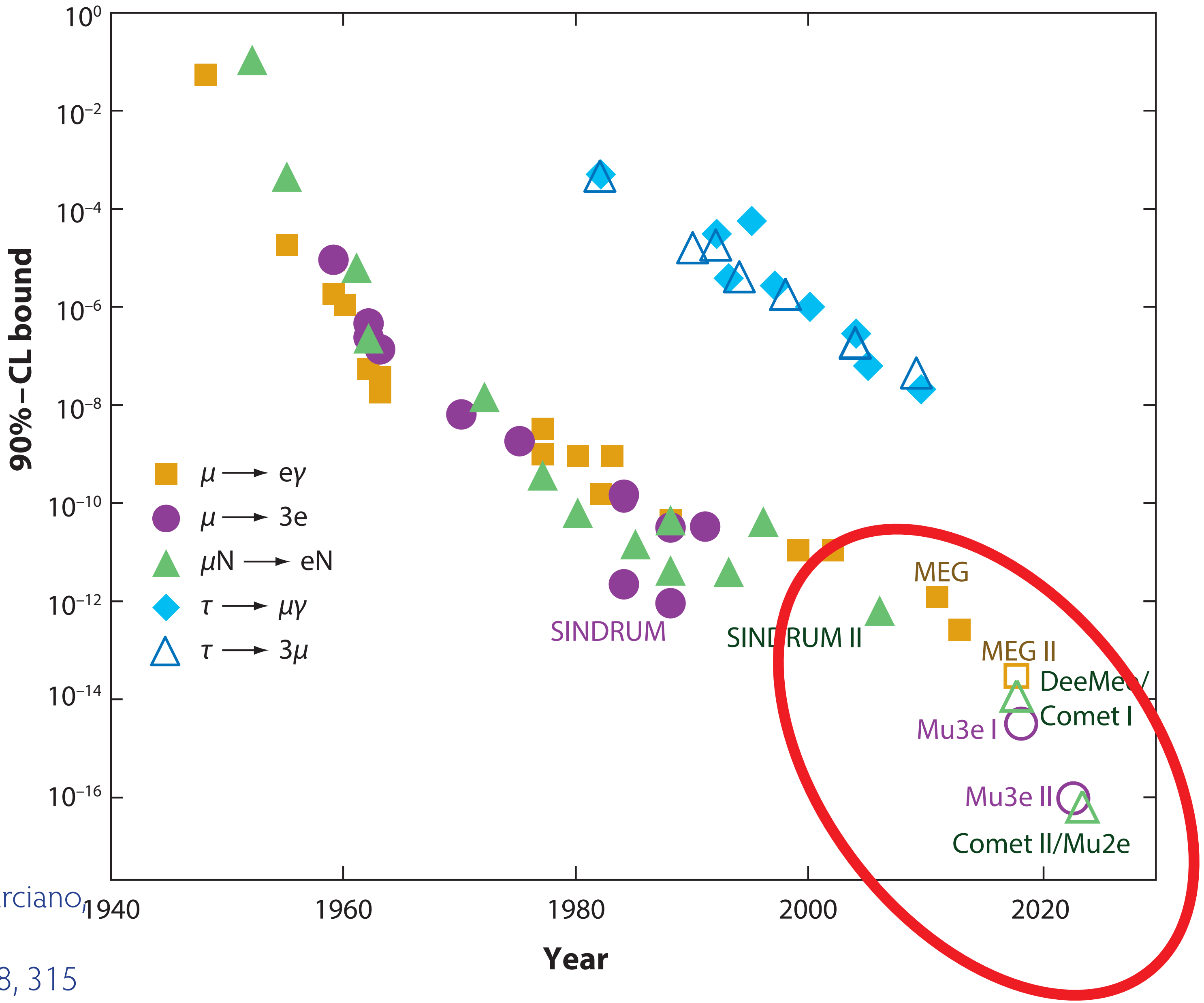
Only limited by number of muons (taus)
and background suppression

History of LFV experiments



(Updated from W.J. Marciano,
T. Mori and J.M. Roney,
Ann.Rev.Nucl.Part.Sci. 58, 315
(2008))

History of LFV experiments



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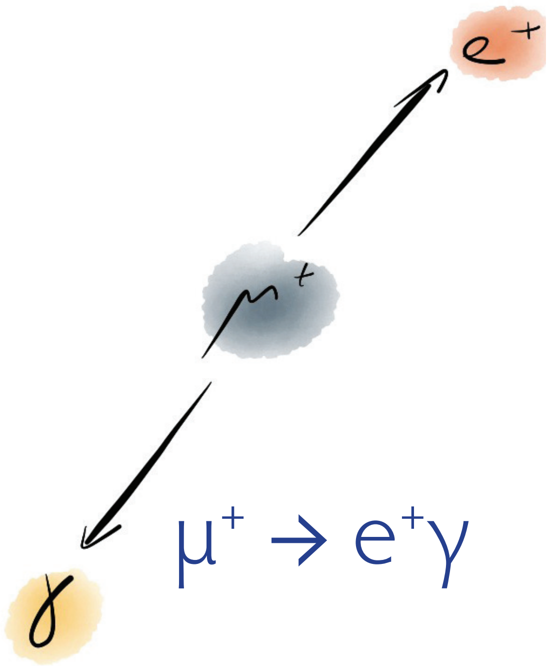
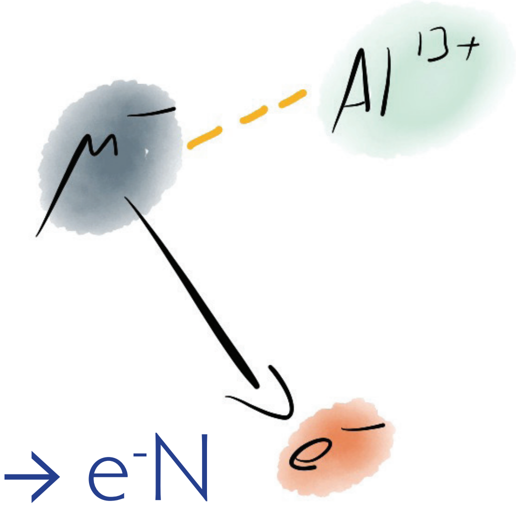
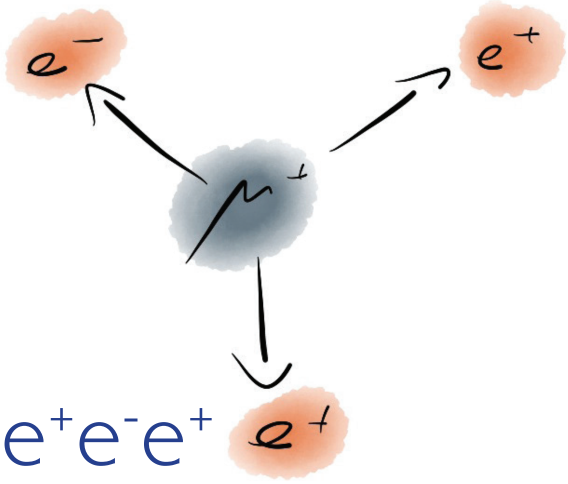
LFV Muon Decays



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

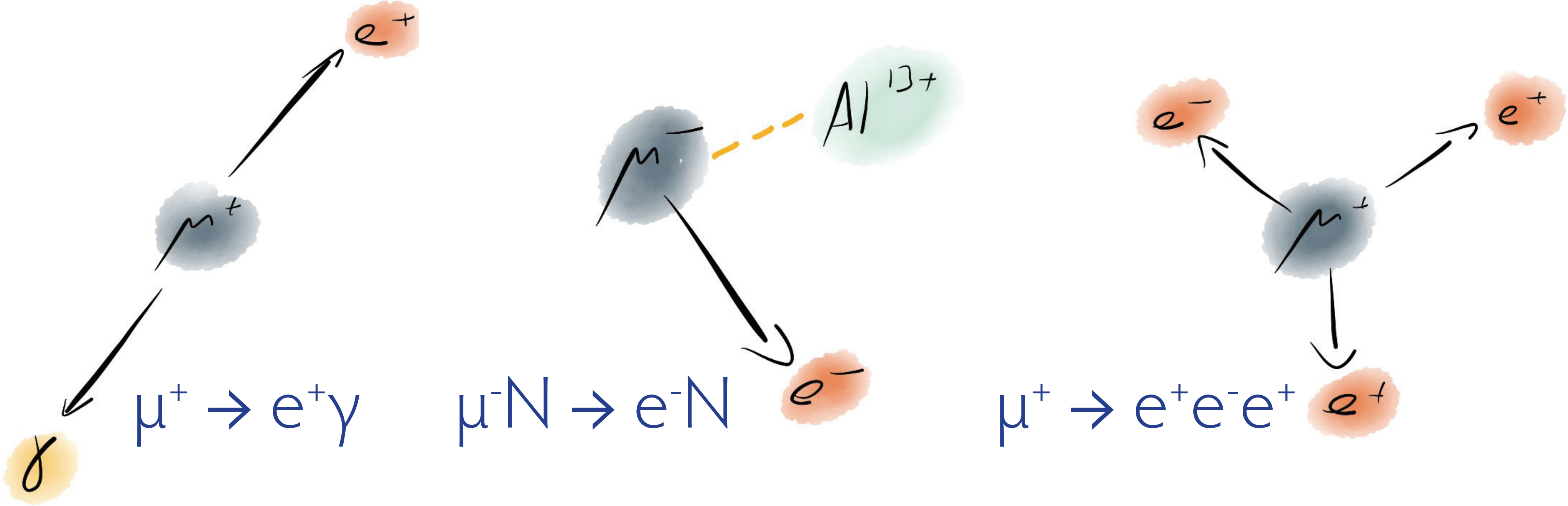


$\mu^- N \rightarrow e^- N$



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

LFV Muon Decays: Experimental Situation



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

MEG (PSI)

$B(\mu^+ \rightarrow e^+\gamma) < 5.7 \cdot 10^{-13}$
(2013)

upgrading

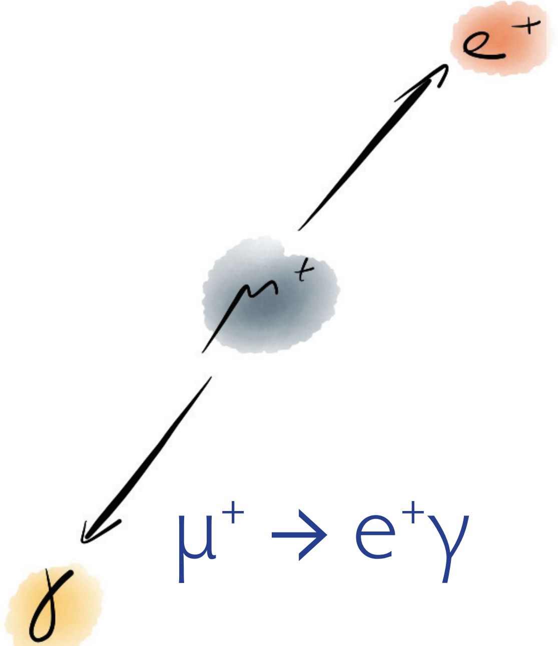
SINDRUM II (PSI)

$B(\mu^- Au \rightarrow e^- Au) < 7 \cdot 10^{-13}$
(2006)
relative to nuclear capture

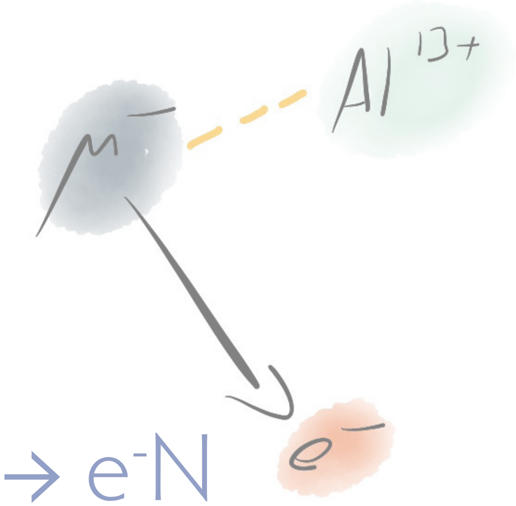
SINDRUM (PSI)

$B(\mu^+ \rightarrow e^+e^-e^+) < 1.0 \cdot 10^{-12}$
(1988)

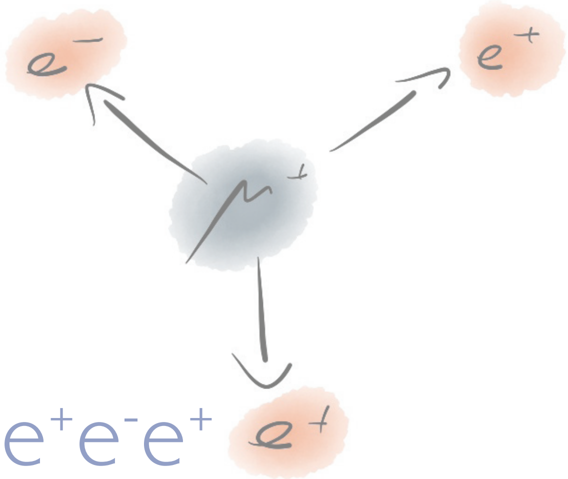
LFV Muon Decays: Experimental signatures



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



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

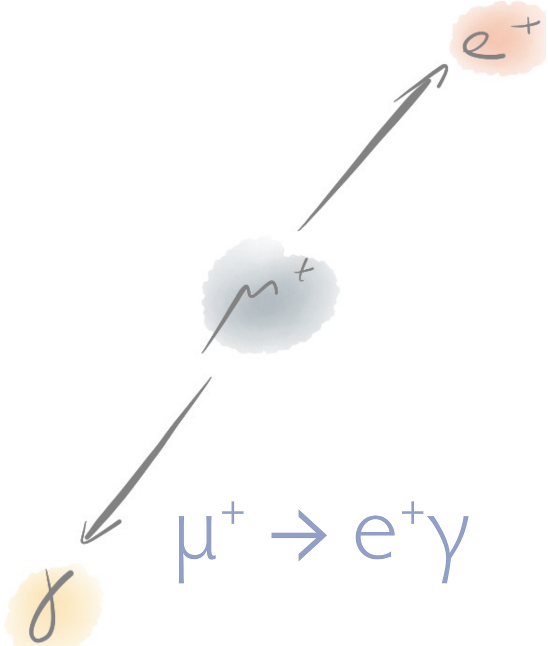


$\mu^+ \rightarrow e^+e^-e^+$

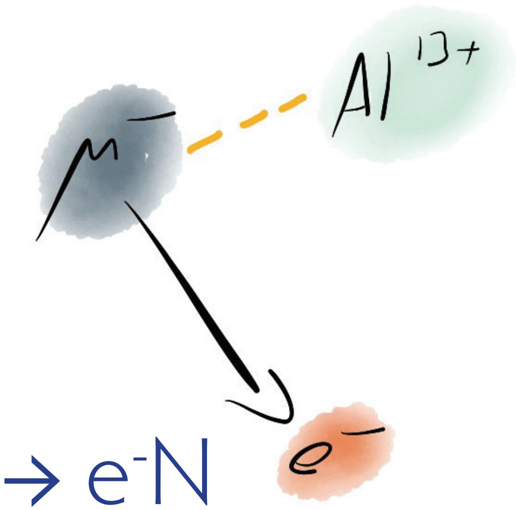
Kinematics

- 2-body decay
- Monoenergetic e^+, γ
- Back-to-back

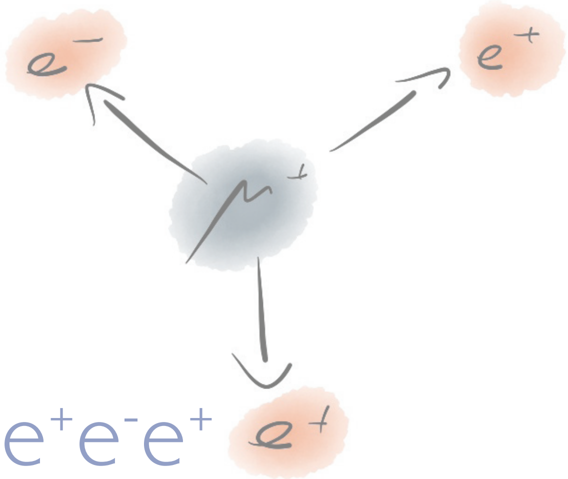
LFV Muon Decays: Experimental signatures



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



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



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

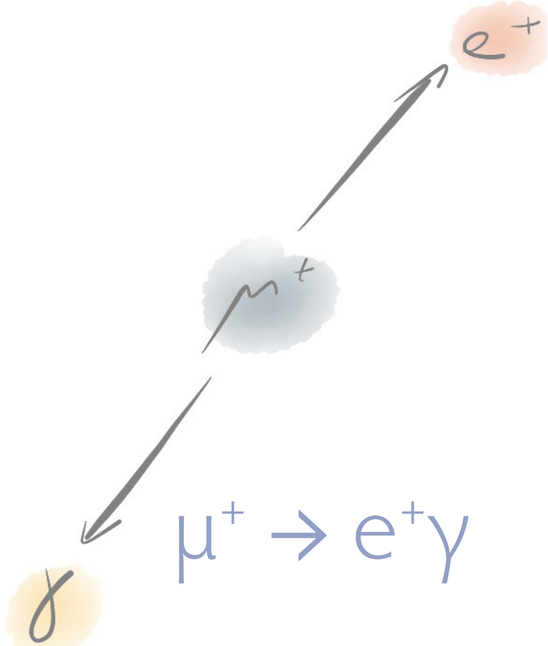
Kinematics

- 2-body decay
- Monoenergetic e^+, γ
- Back-to-back

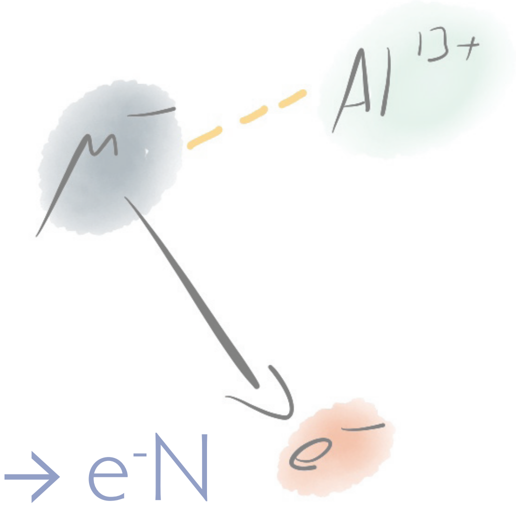
Kinematics

- Quasi 2-body decay
- Monoenergetic e^-
- Single particle detected

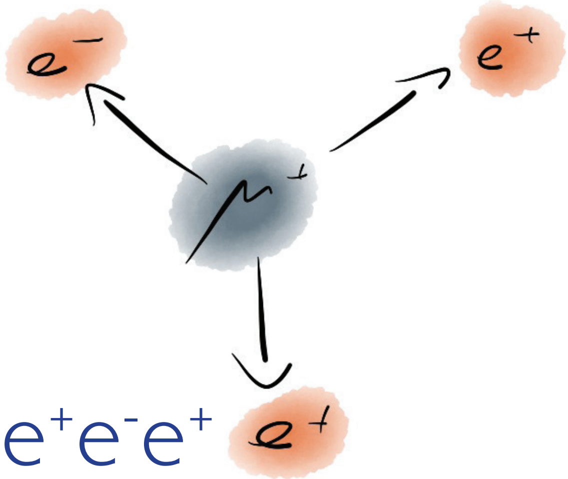
LFV Muon Decays: Experimental signatures



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



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



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

Kinematics

- 2-body decay
- Monoenergetic e^+, γ
- Back-to-back

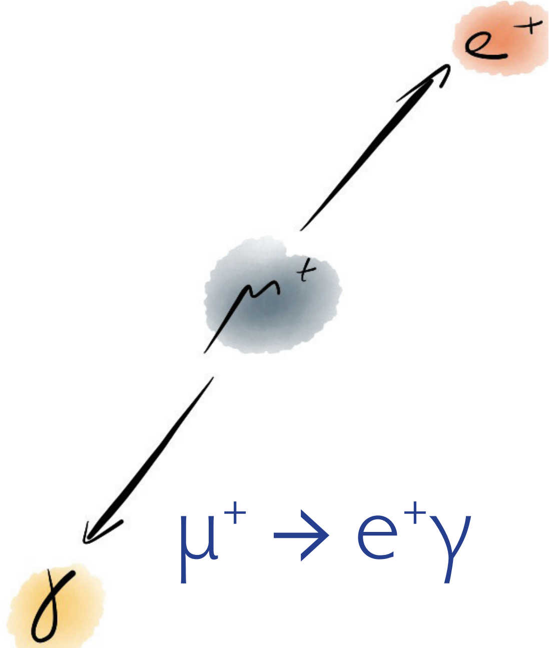
Kinematics

- Quasi 2-body decay
- Monoenergetic e^-
- Single particle detected

Kinematics

- 3-body decay
- Invariant mass constraint
- $\Sigma p_i = 0$

LFV Muon Decays: Experimental signatures



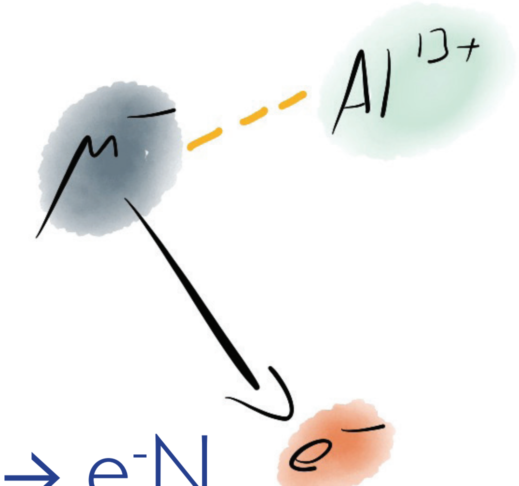
$\mu^+ \rightarrow e^+\gamma$

Kinematics

- 2-body decay
- Monoenergetic e^+, γ
- Back-to-back

Background

- Accidental background
- Radiative decay



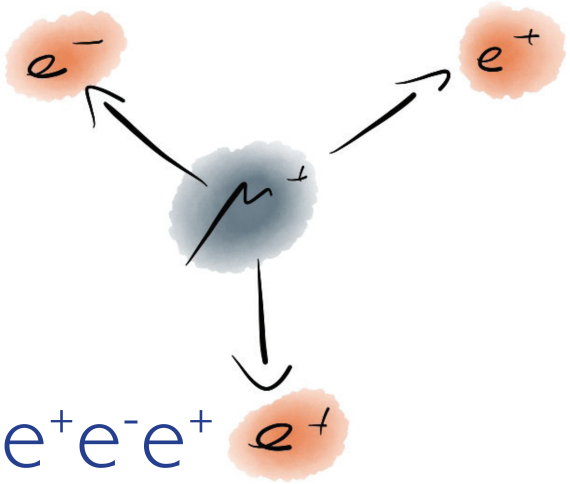
$\mu^- N \rightarrow e^- N$

Kinematics

- Quasi 2-body decay
- Monoenergetic e^-
- Single particle detected

Background

- Decay in orbit
- Antiprotons, pions, cosmics



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

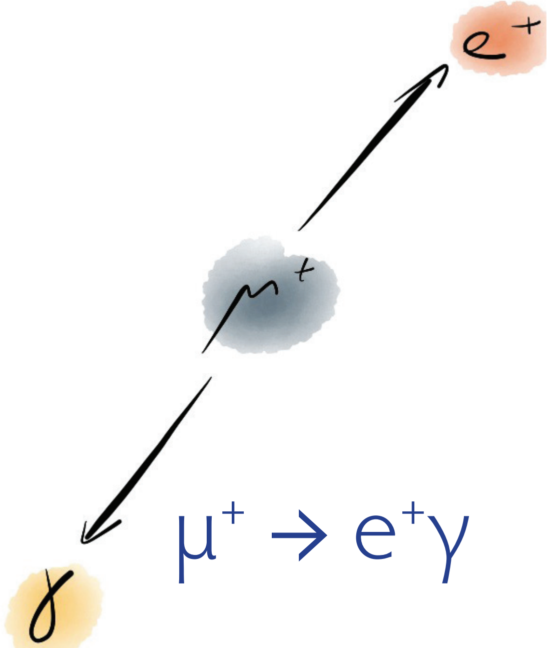
Kinematics

- 3-body decay
- Invariant mass constraint
- $\Sigma\, p_i = 0$

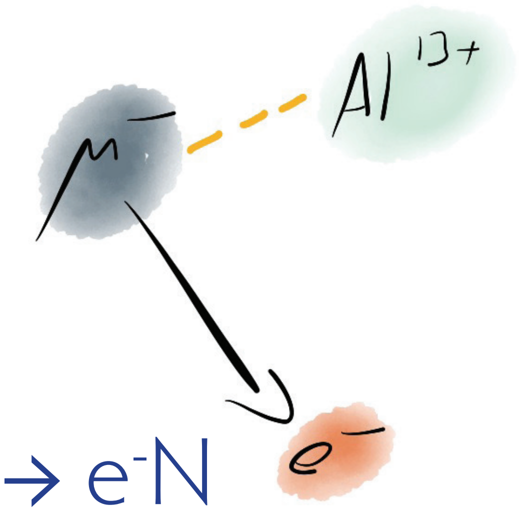
Background

- Internal conversion decay
- Accidental background

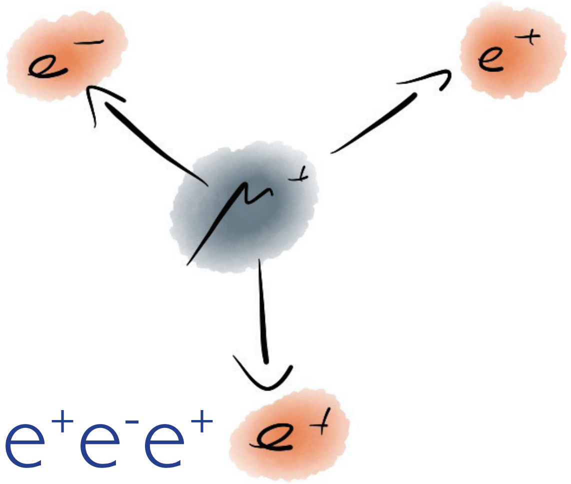
LFV Muon Decays: Experimental signatures



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



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



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

Kinematics

- 2-body decay
- Monoenerge ,
- Back-to-b

Backgro

- A al background

Continuous Beam

Kinematics

- Quasi 2-body d
- Monoenerge
- Single p etected

Backgro

- D orbit
- A protons, pions

Pulsed Beam

Kinematics

- 3-body decay
- Invariant mas aint
- $\Sigma p_i = 0$

Backgro

- R decay
- Ac dental background

Continuous Beam

Searching for μ → eγ with

MEG

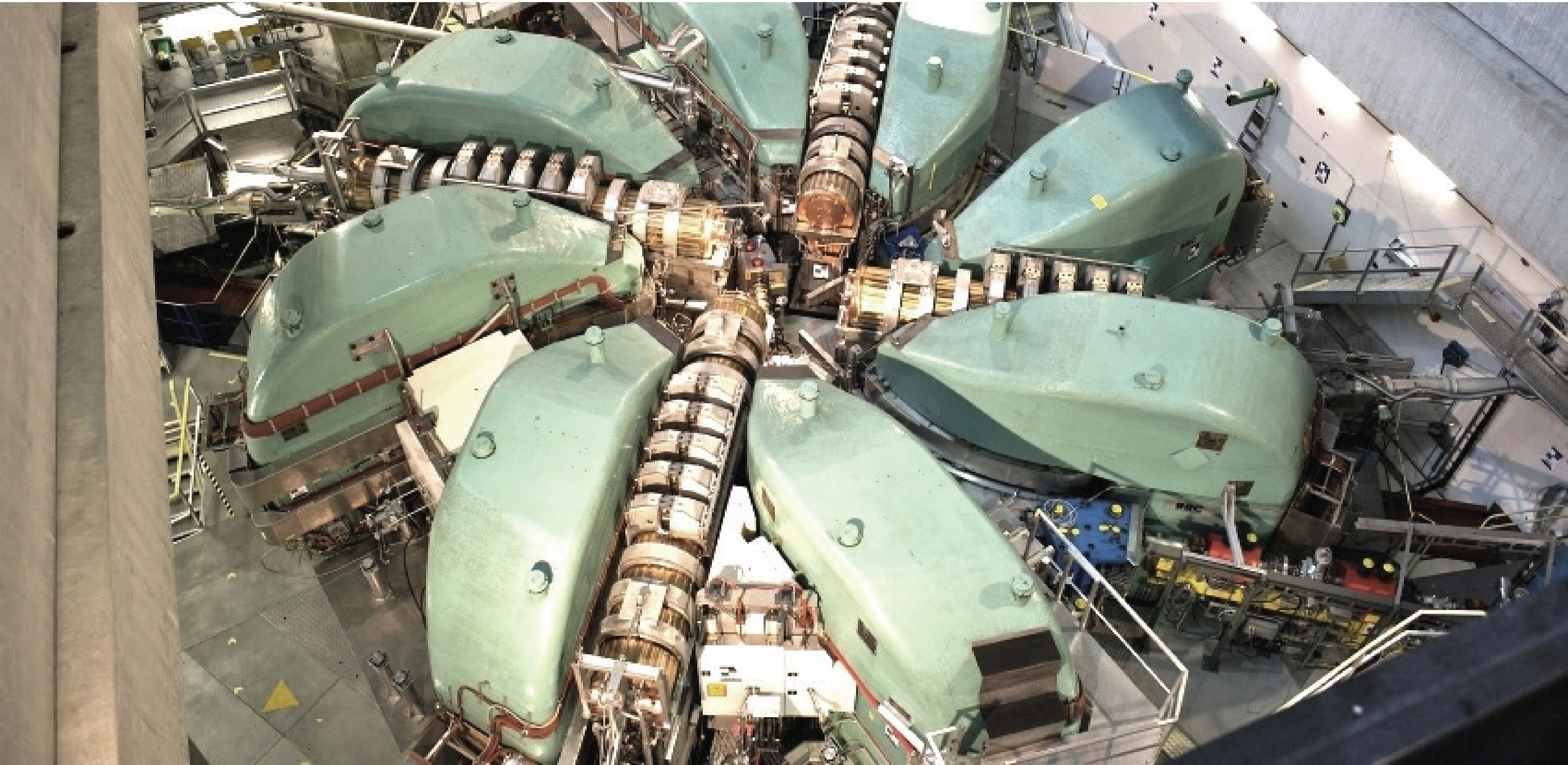
Muons from PSI

Paul Scherrer Institute in Villigen, Switzerland

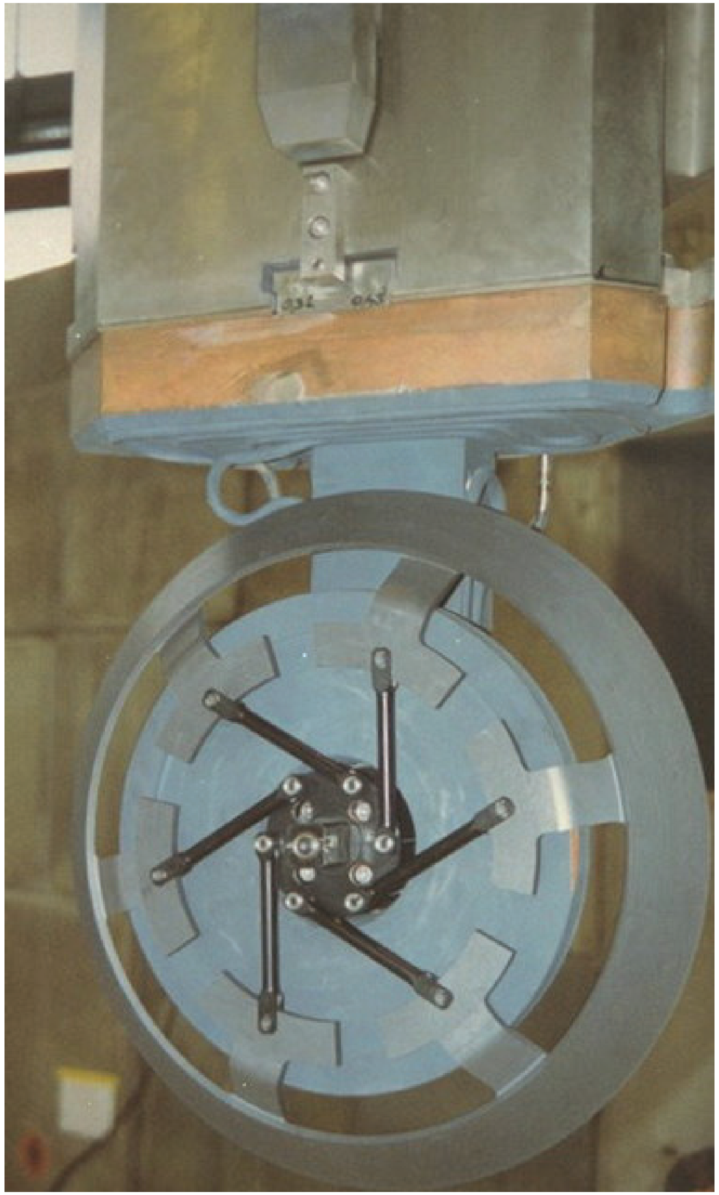
Muons from PSI

Paul Scherrer Institute in Villigen, Switzerland

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



Muons from PSI



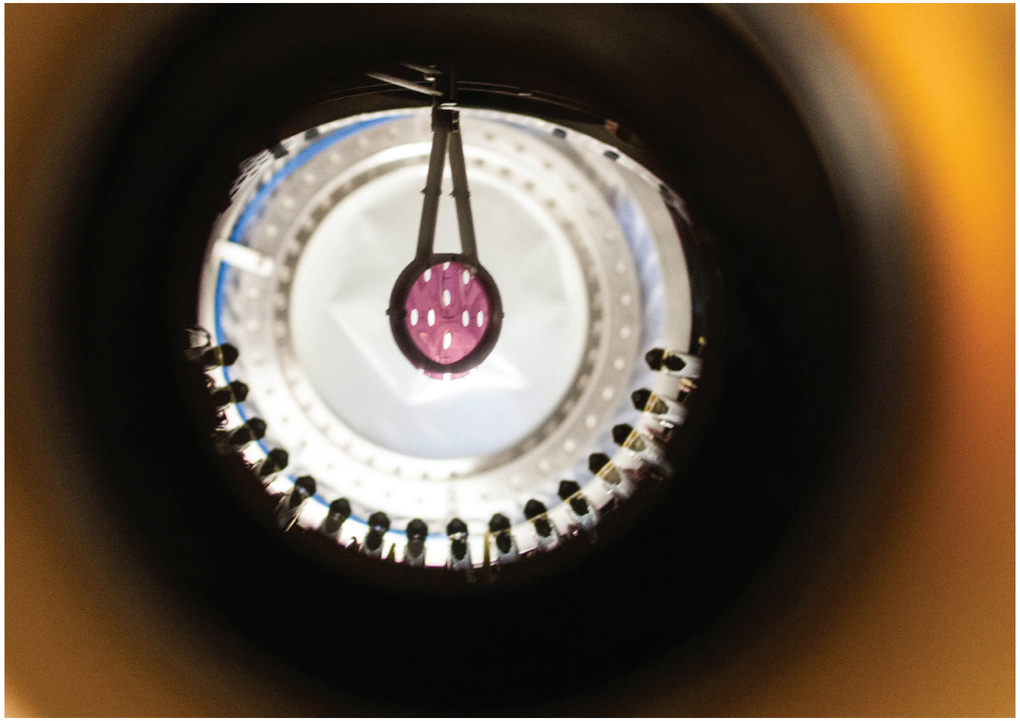
DC muon beams at PSI:

- πE5 beamline: ~ 10^8 muons/s
  (MEG experiment, Mu3e phase I)

- Surface muons with about 27 MeV/c

- Higher rates, need magnetic elements closer to production target

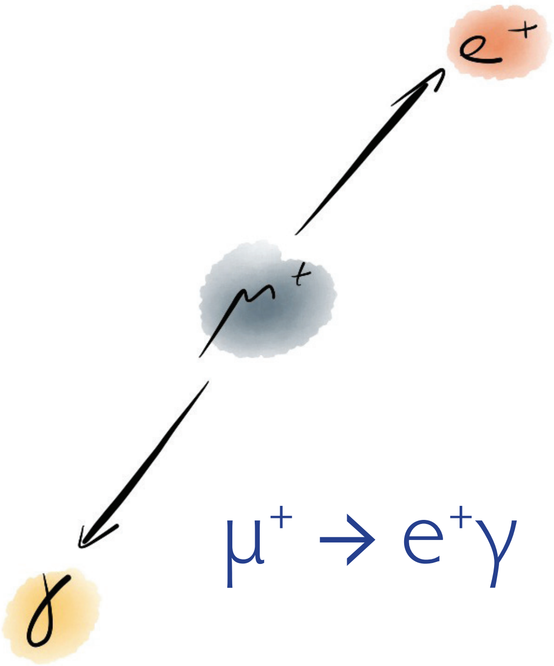
Rates and accidentals



- Muon lifetime 2.2 μs
- Single muon in target experiments limited to < 450'000 μ/s
- Corresponds to few 10^{12} μ decays a year

- New experiments operate at 10^{7}++ μ/s
- Many muons on target at any time
- Accidental background

MEG Signal and background



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

Kinematics

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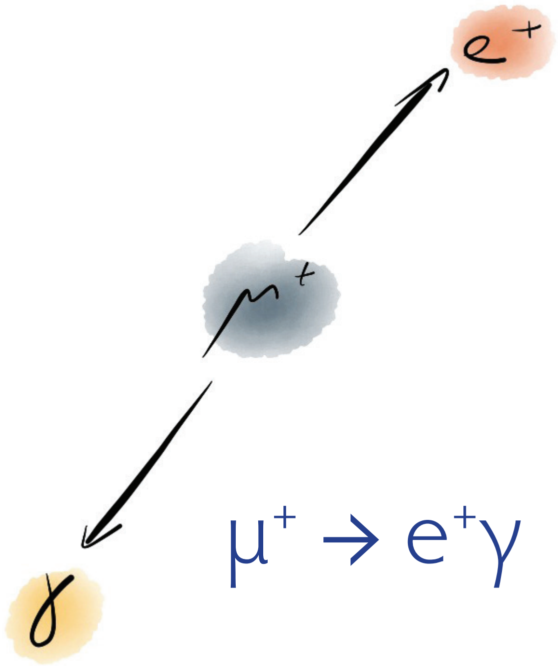
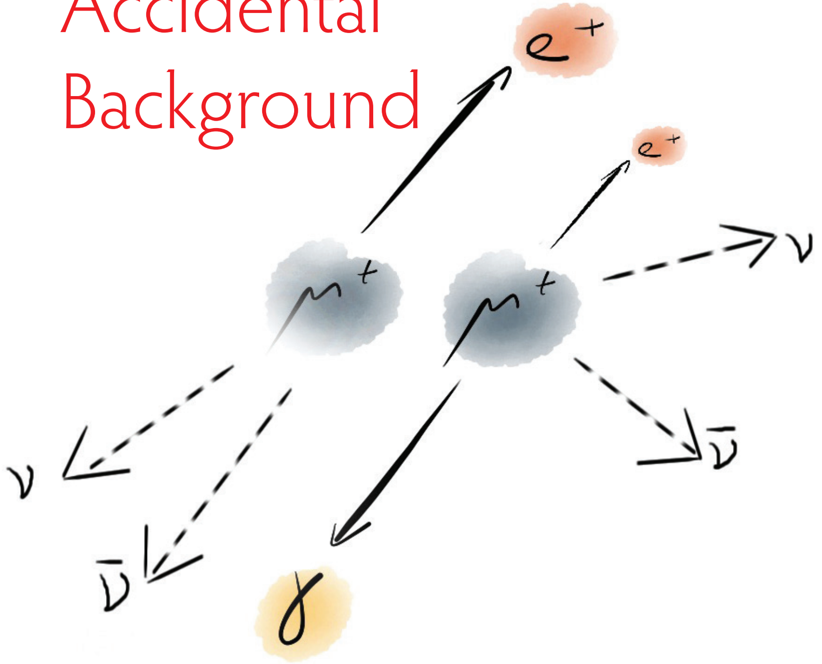
MEG Signal and background



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

Accidental Background

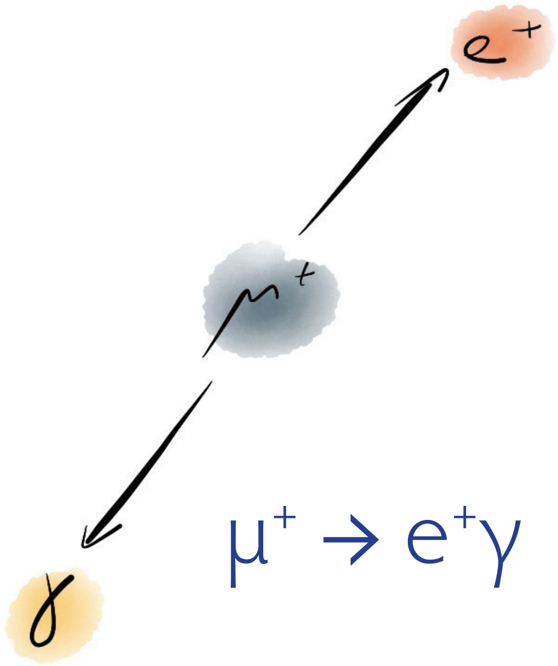


Kinematics

- 2-body decay
- Monoenergetic e^+, γ
- Back-to-back

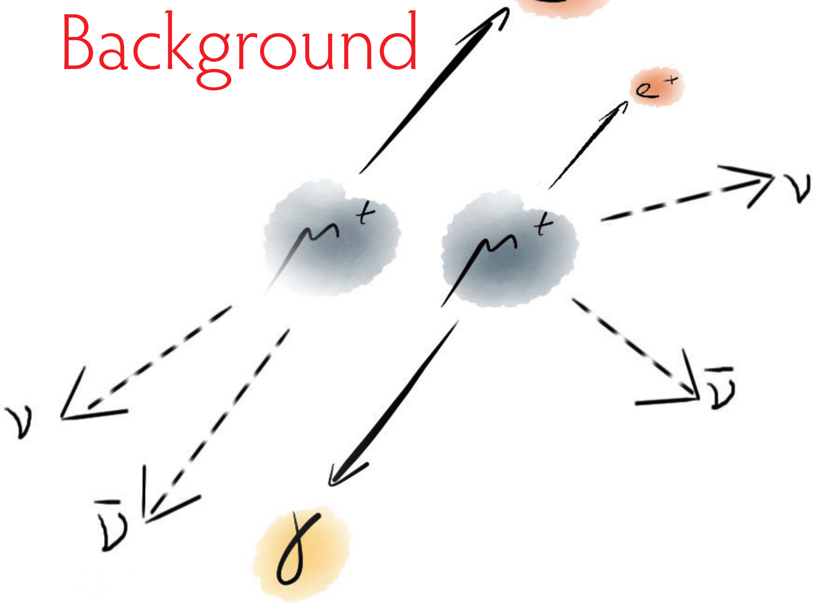
- Not exactly in time
- Not exactly same vertex
- e^+, γ energies somewhat off
- Not exactly back-to-back

MEG Signal and background

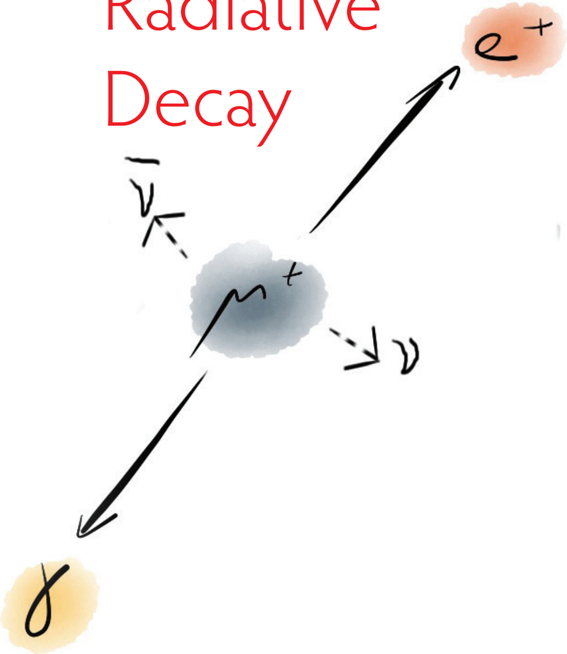


$\mu^+ \rightarrow e^+\gamma$

Accidental Background



Radiative Decay



Kinematics

- 2-body decay
- Monoenergetic e^+, γ
- Back-to-back

- Not exactly in time
- Not exactly same vertex
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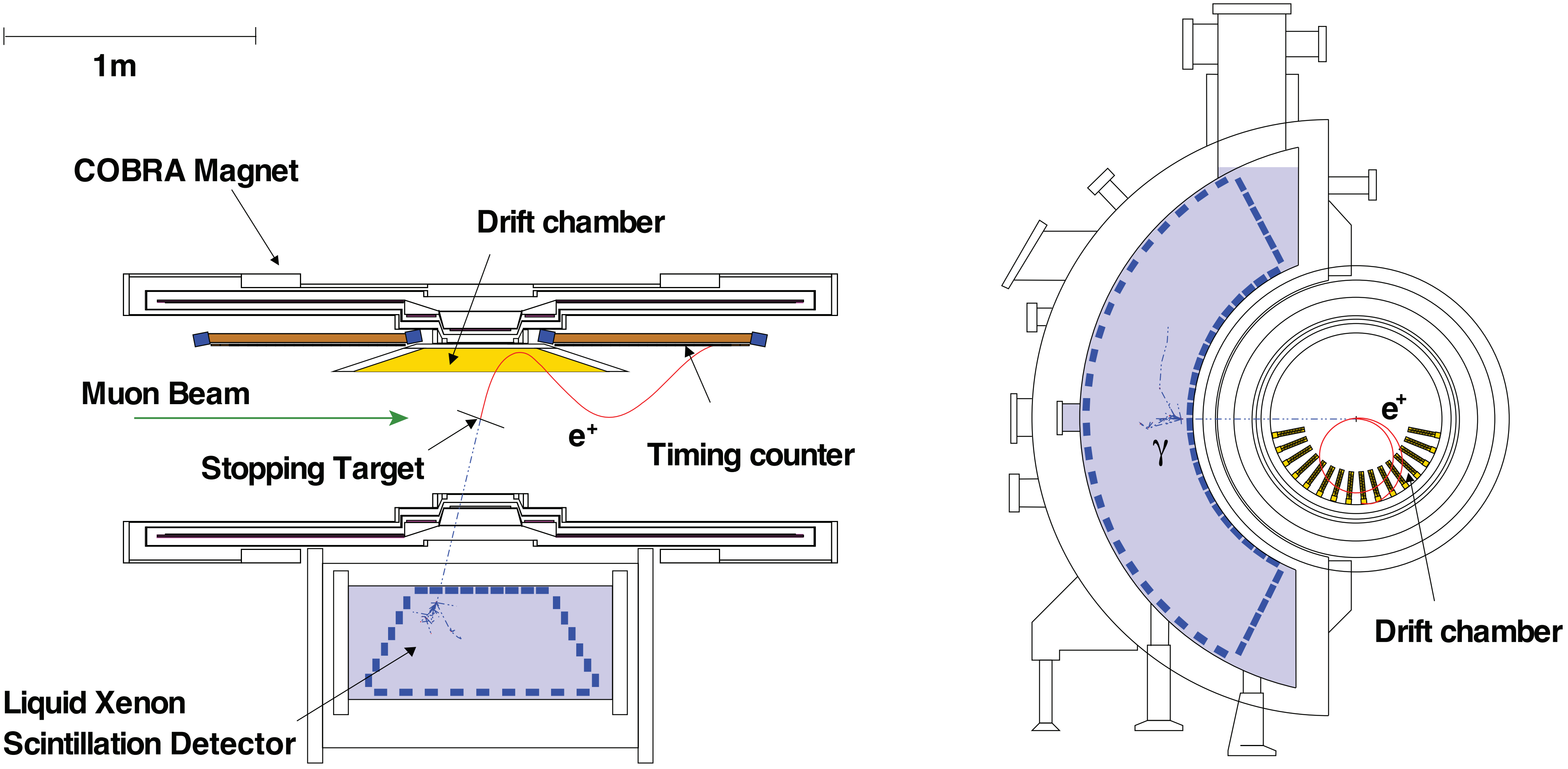
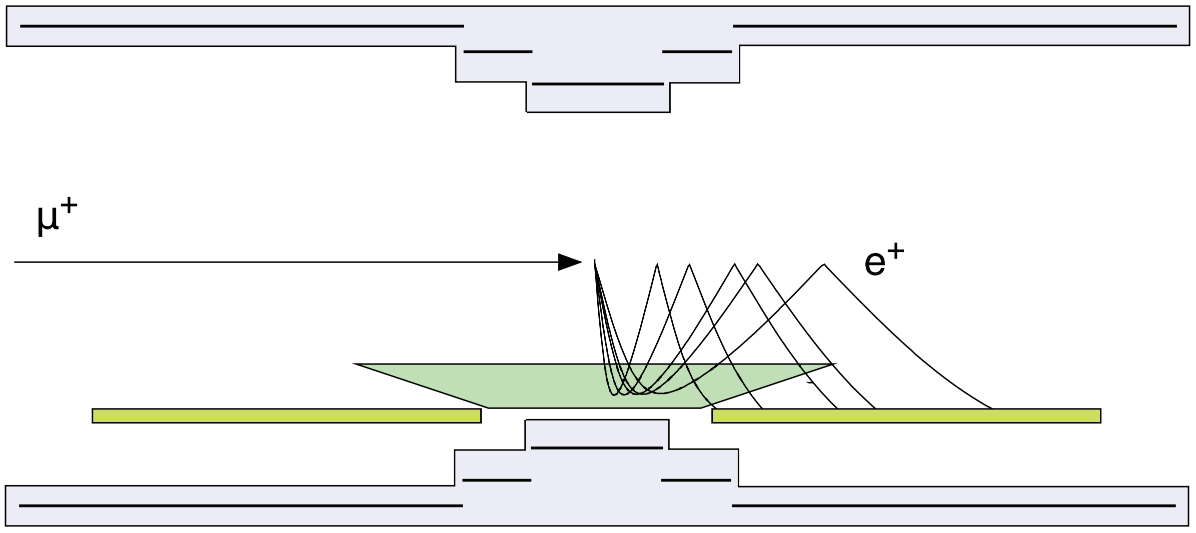
The MEG Detector

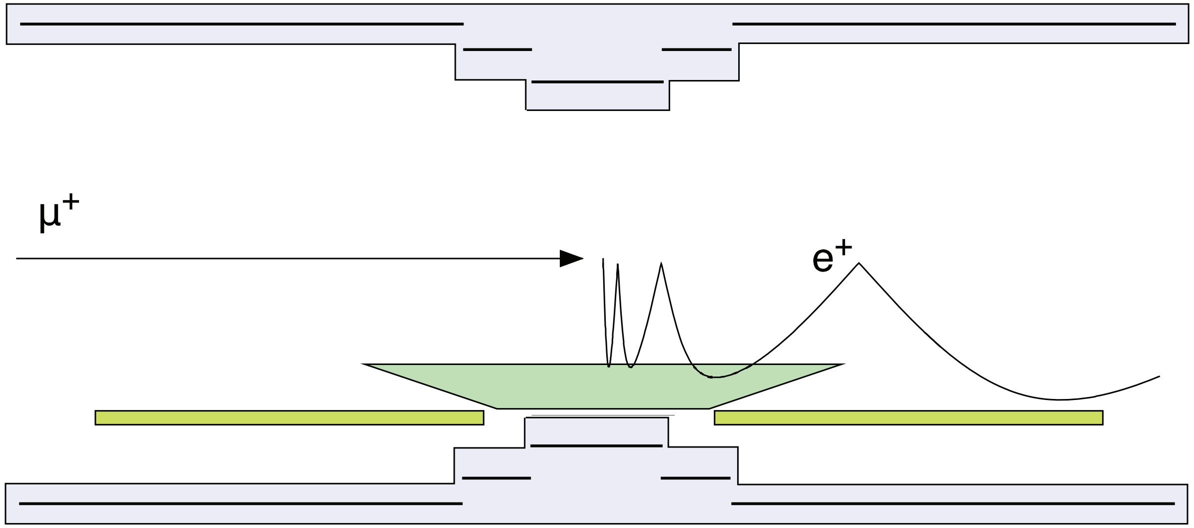


J. Adam et al. EPJ C 73, 2365 (2013)

COBRA Magnet



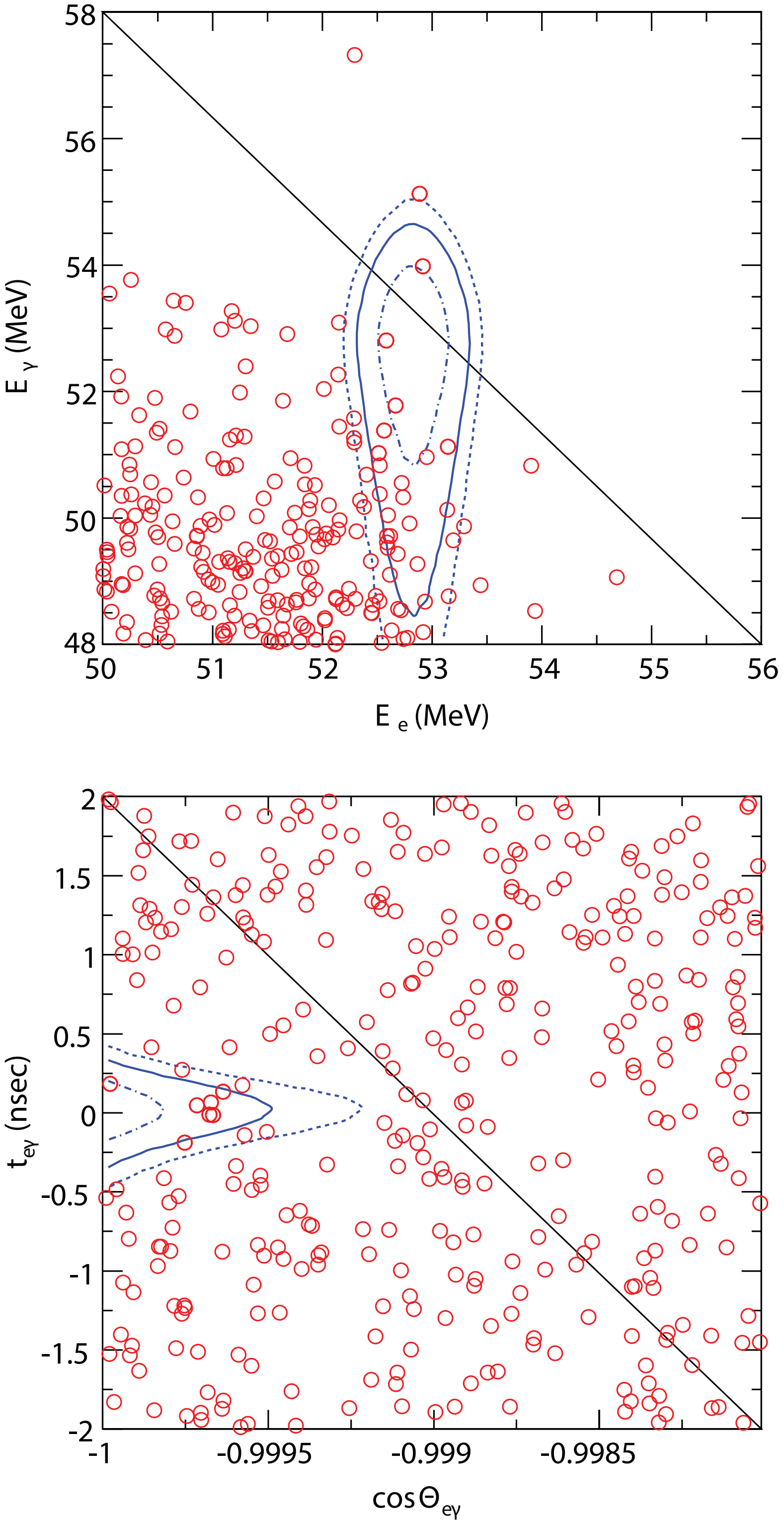
Gradient field gives constant bending radius independent of angle



Fast sweep of curlers

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

MEG Results

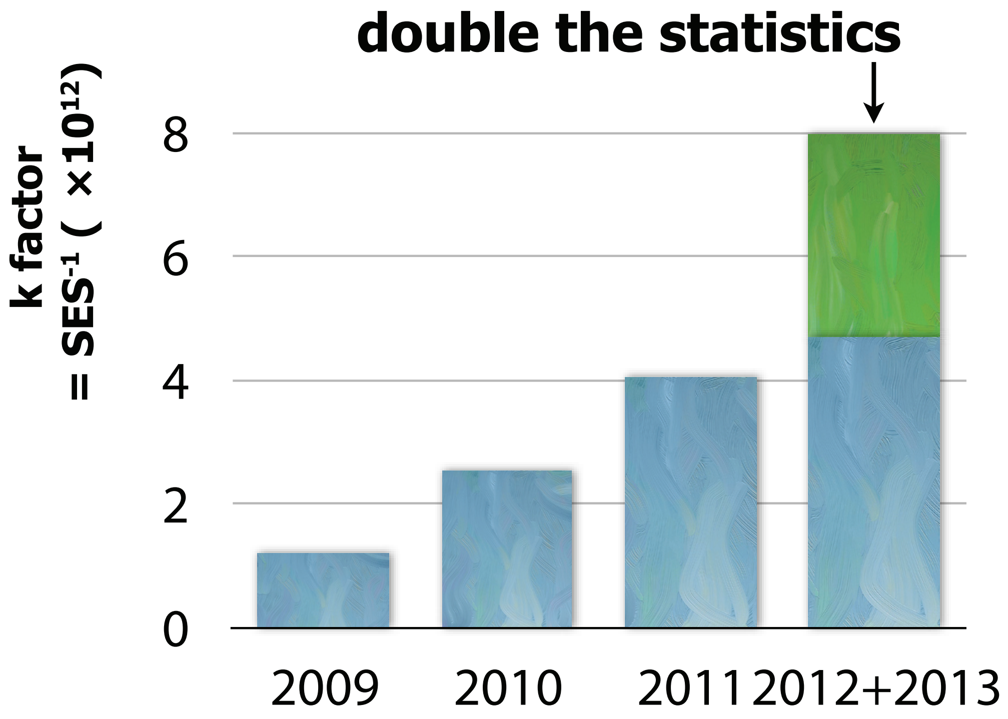


- 2009-2011 data
- Blue: Signal PDF, given by detector resolution
- No signal seen
- Upper limit at 90% CL:

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

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

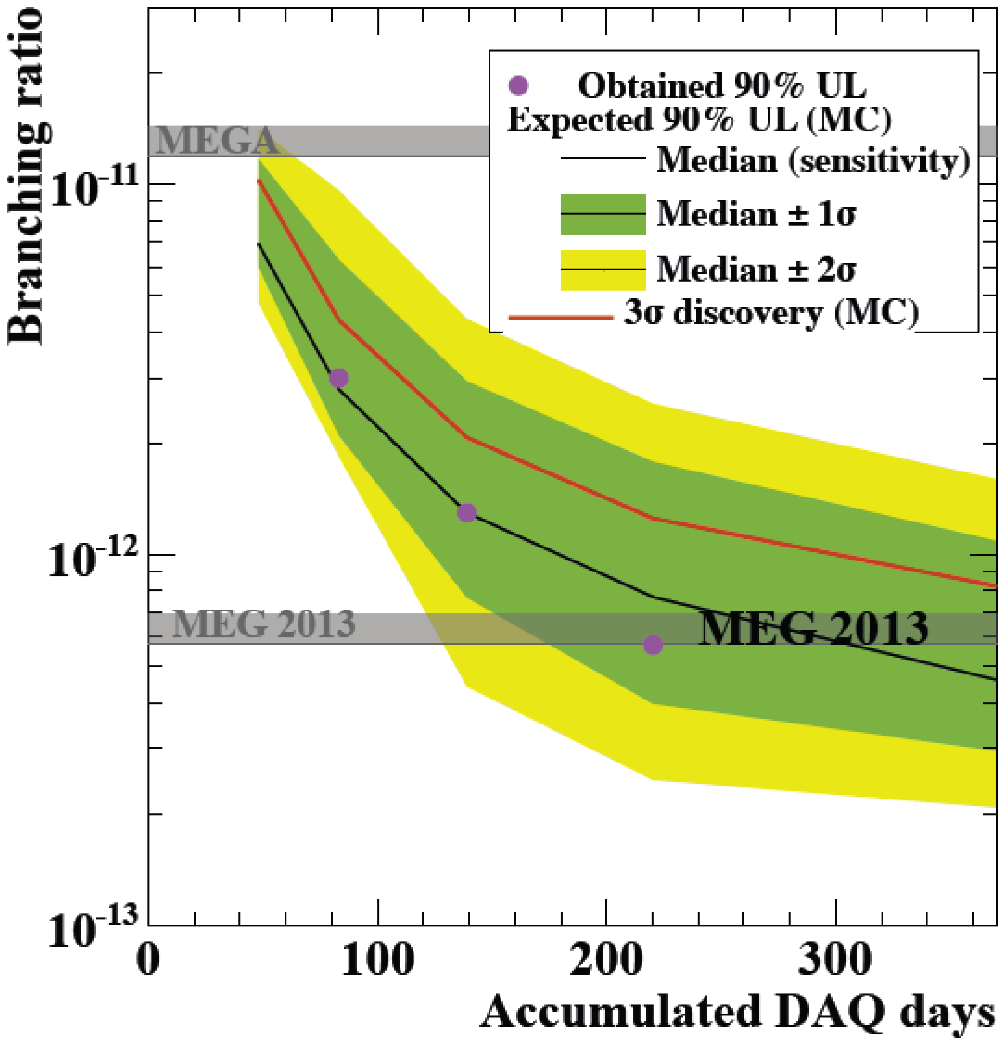
MEG - Data

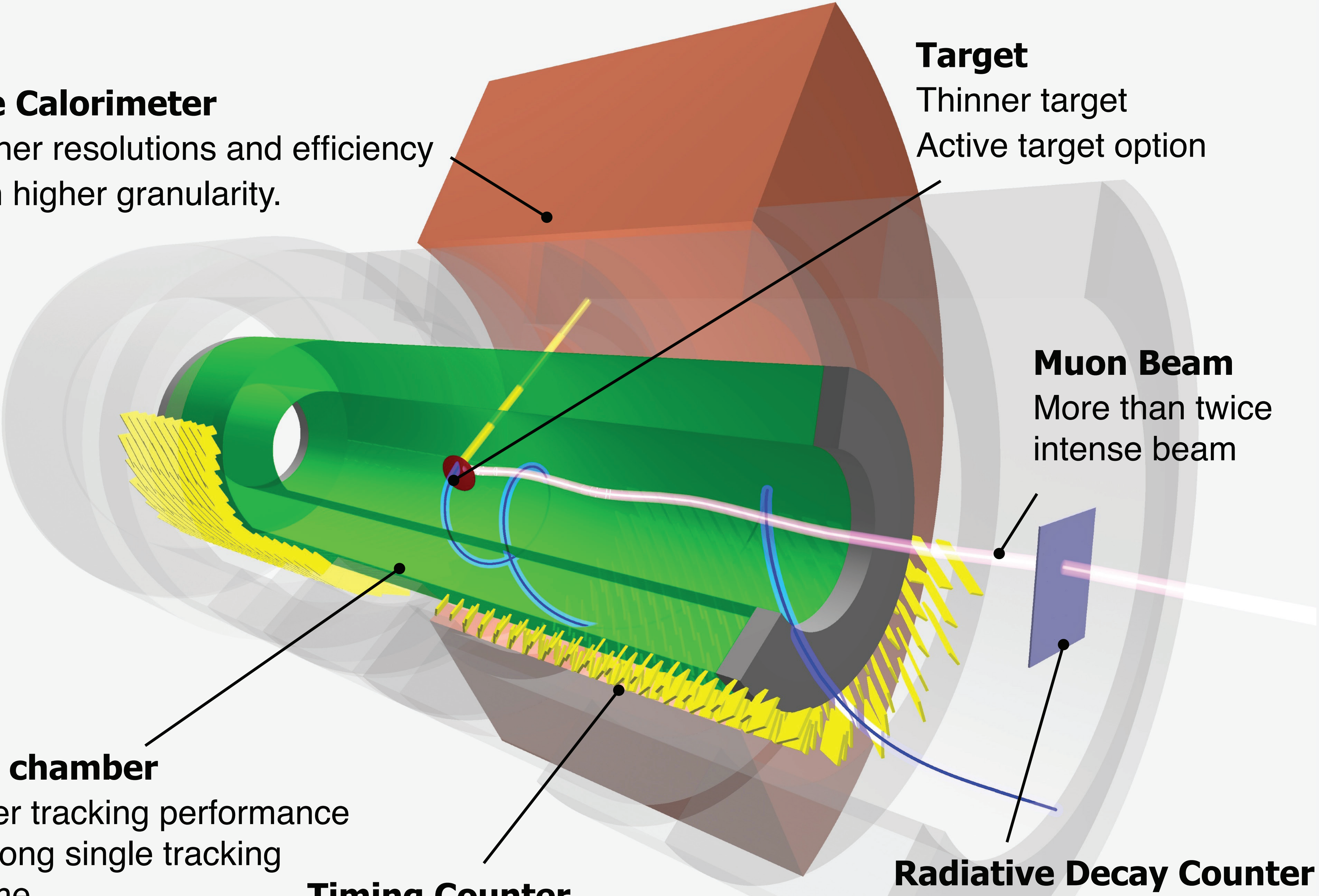


- Further improvements need detector improvements - upgrade ongoing

- 2012 & 2013 data are being analysed

Observed limits and sensitivity





LXe Calorimeter
Higher resolutions and efficiency
with higher granularity.

Target
Thinner target
Active target option

Muon Beam
More than twice
intense beam

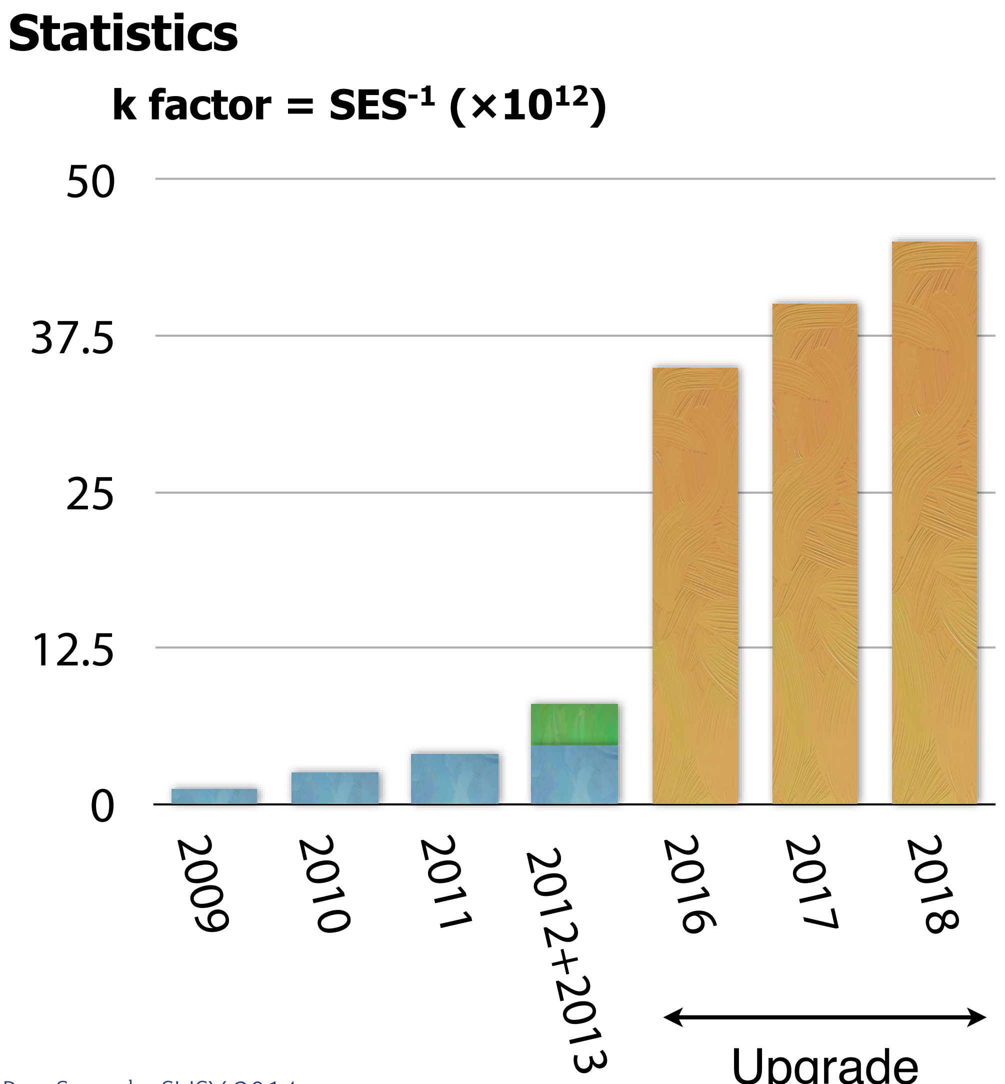
Drift chamber
Higher tracking performance
with long single tracking
volume

Timing Counter
Higher time resolution with
highly segmented detector

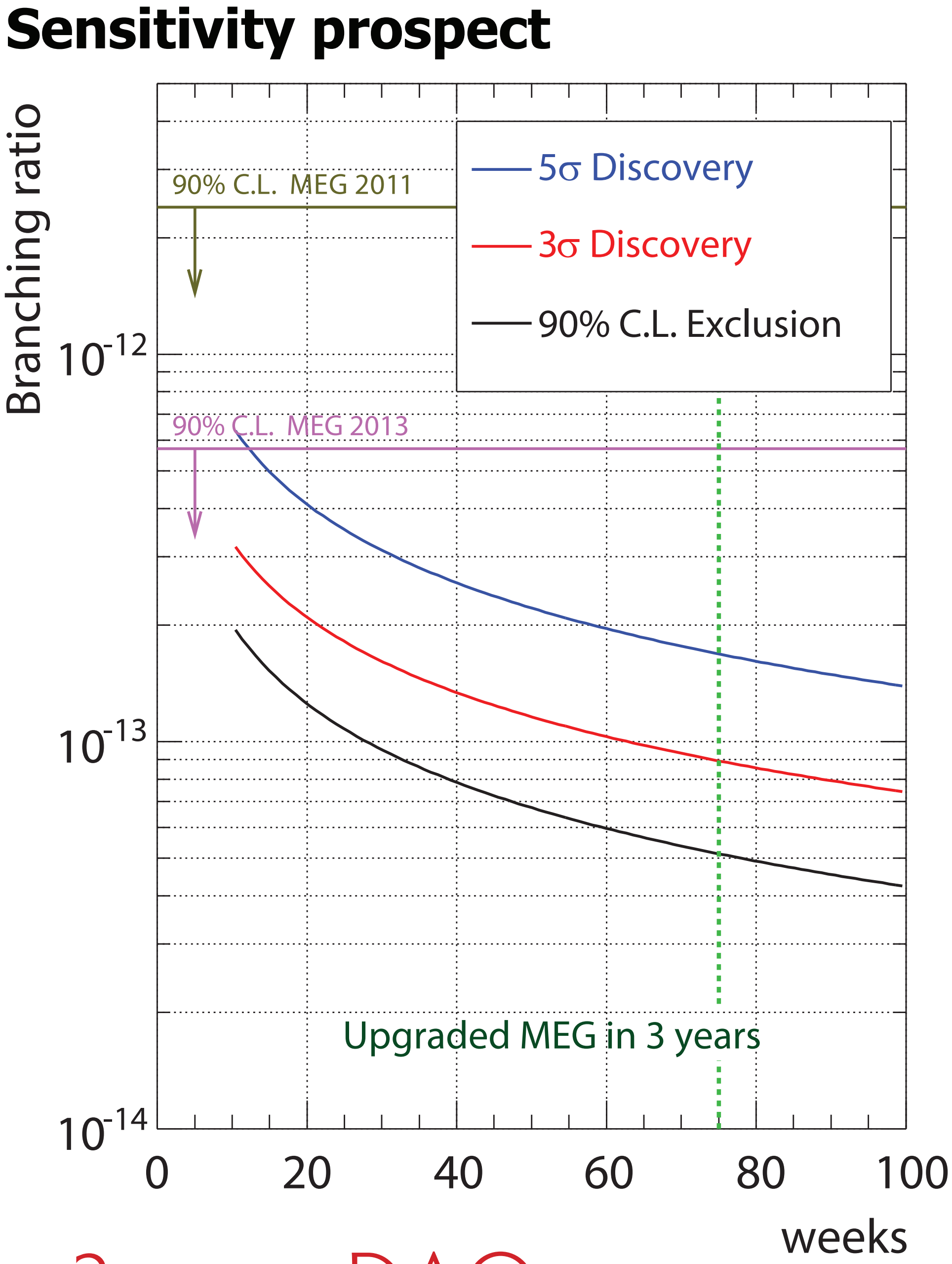
Radiative Decay Counter
Identify gammas from muon
radiative-decays
(optional)

Ryu Sawada, SUSY 2014

MEG II sensitivity projection



Ryu Sawada, SUSY 2014

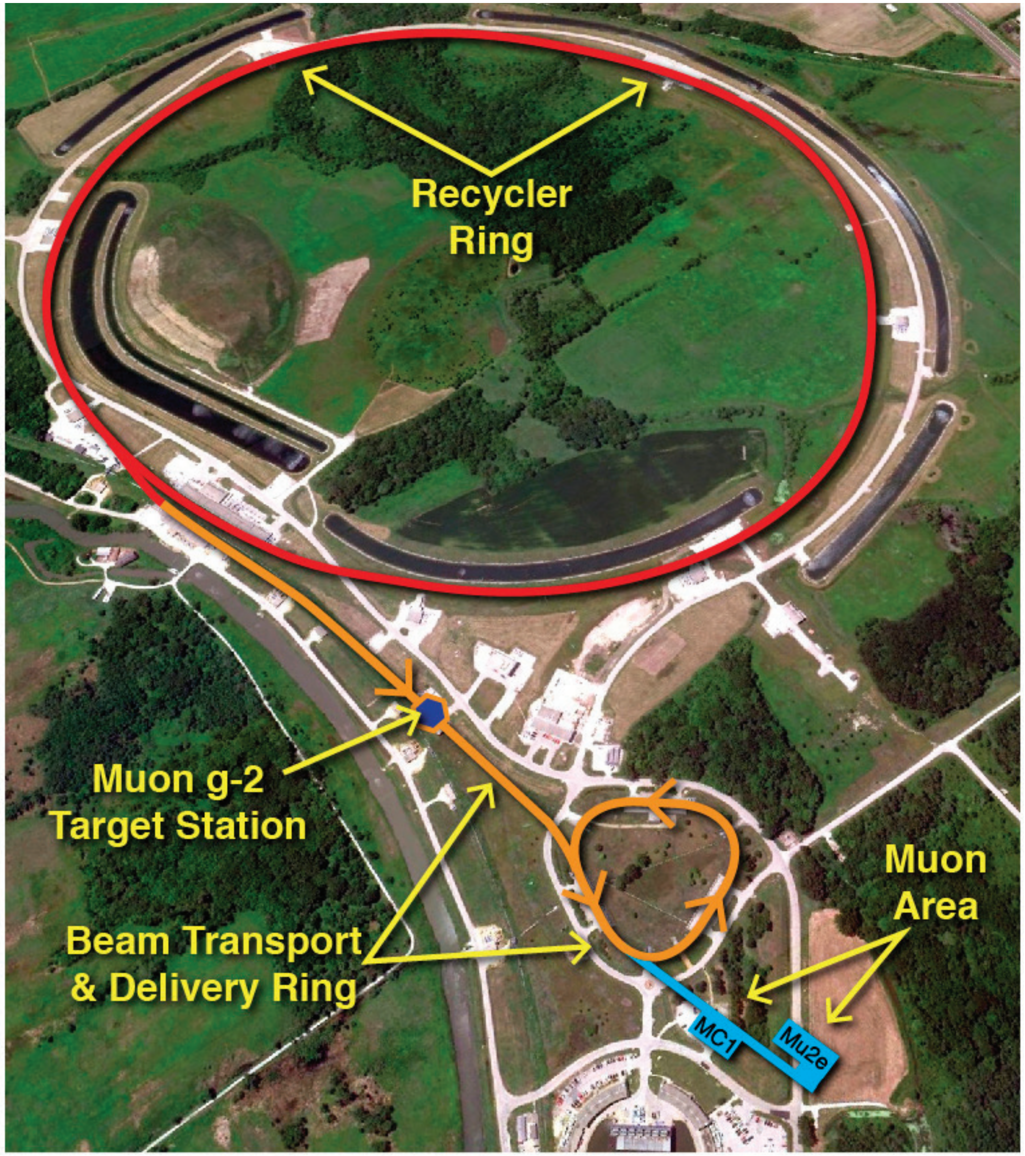


5×10^{-14} sensitivity in 3 years DAQ

Searching for μ → e conversion with

Mu2e, DeeMee, COMET, PRISM

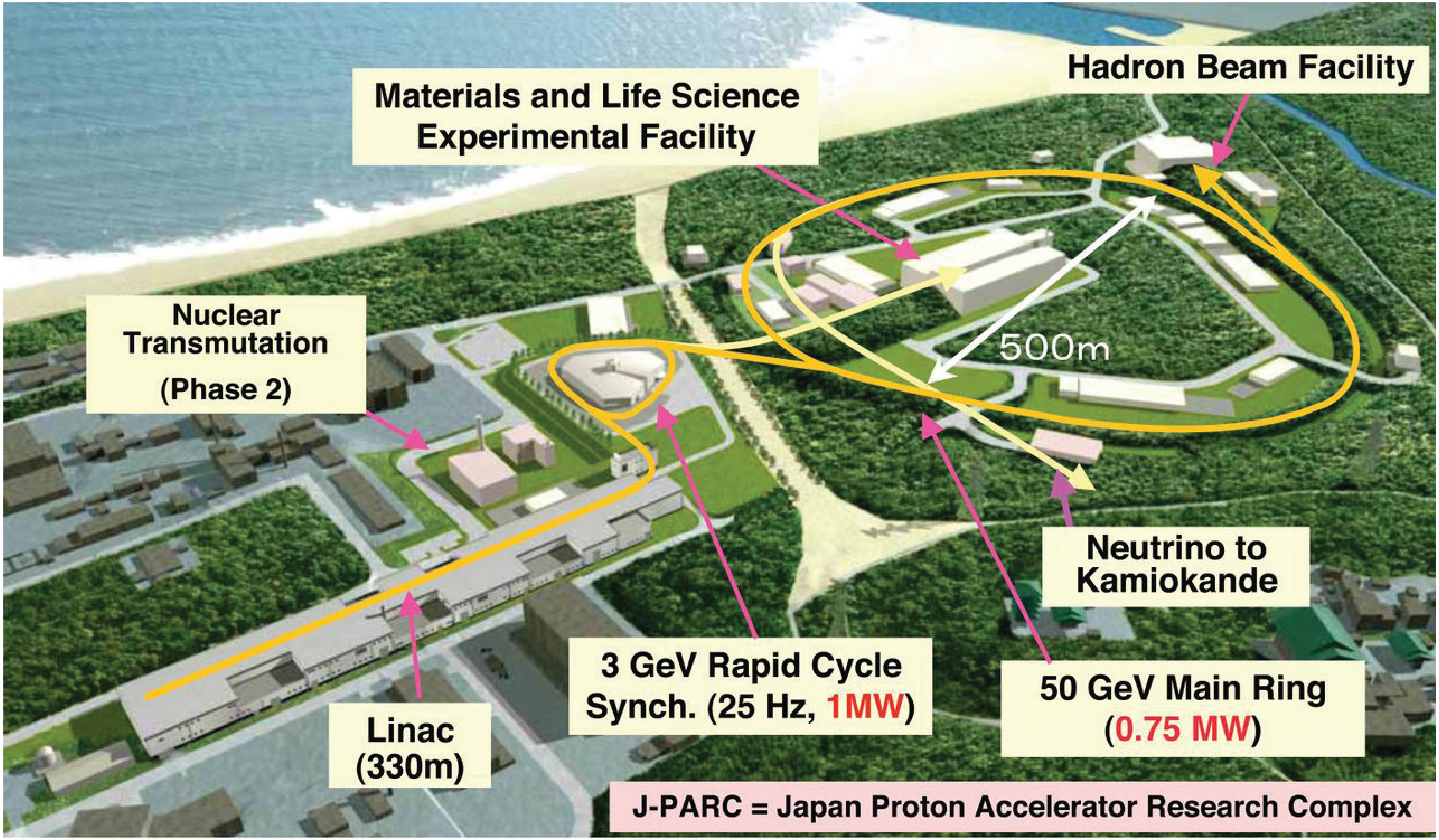
Muons from Fermilab...



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

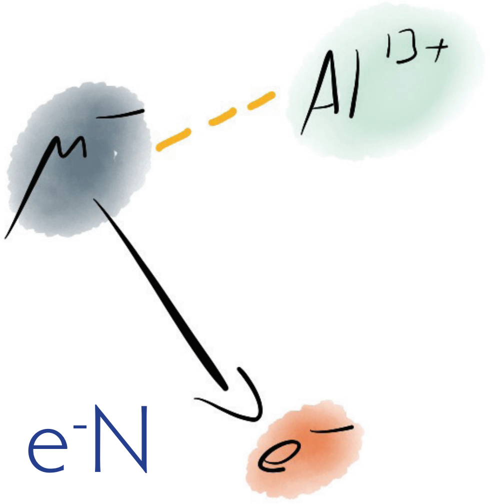
- Project X would give another 2 orders of magnitude at an energy below the antiproton threshold

… and J-PARC



- 10^{11} μ/s from 8 GeV/c protons

Conversion Signal and Background



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

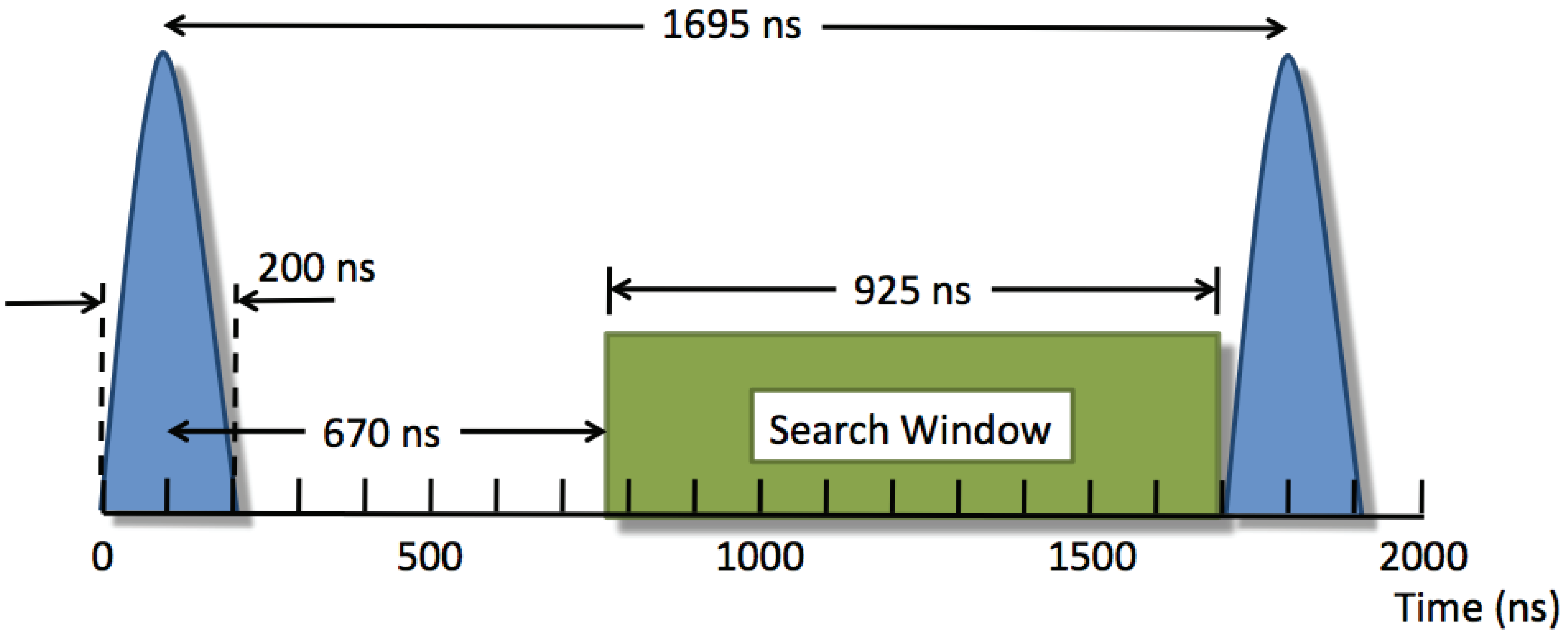
- Single 105 MeV/c electron observed

Backgrounds:

Anything that can produce a 105 MeV/c electron

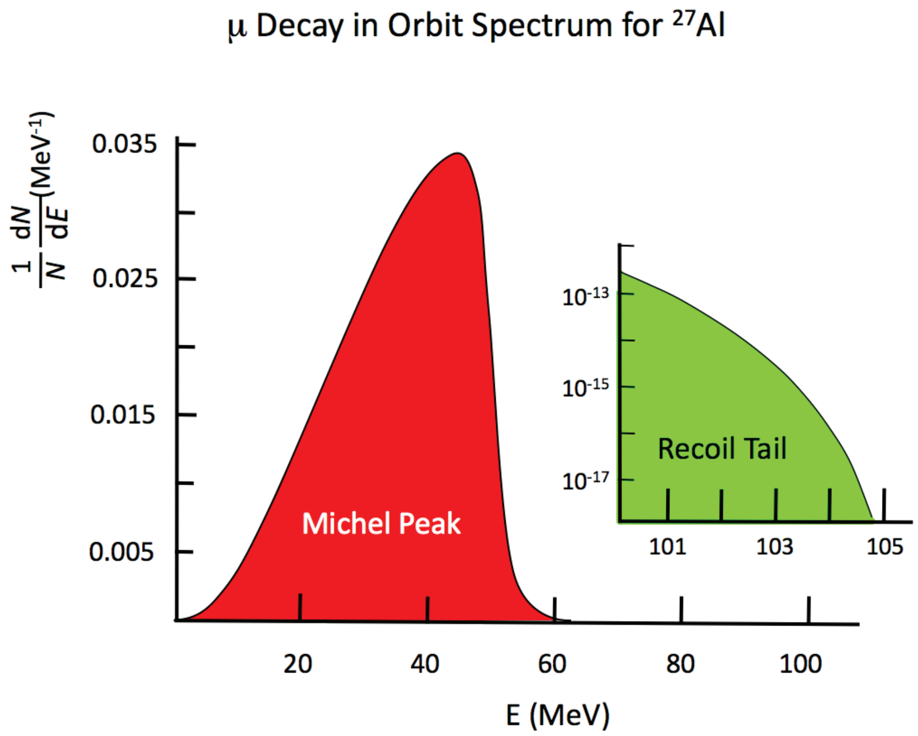
- Primary proton beam
- Decay in Orbit (DIO)
- Nuclear capture (AlCap effort at PSI)
- Cosmics

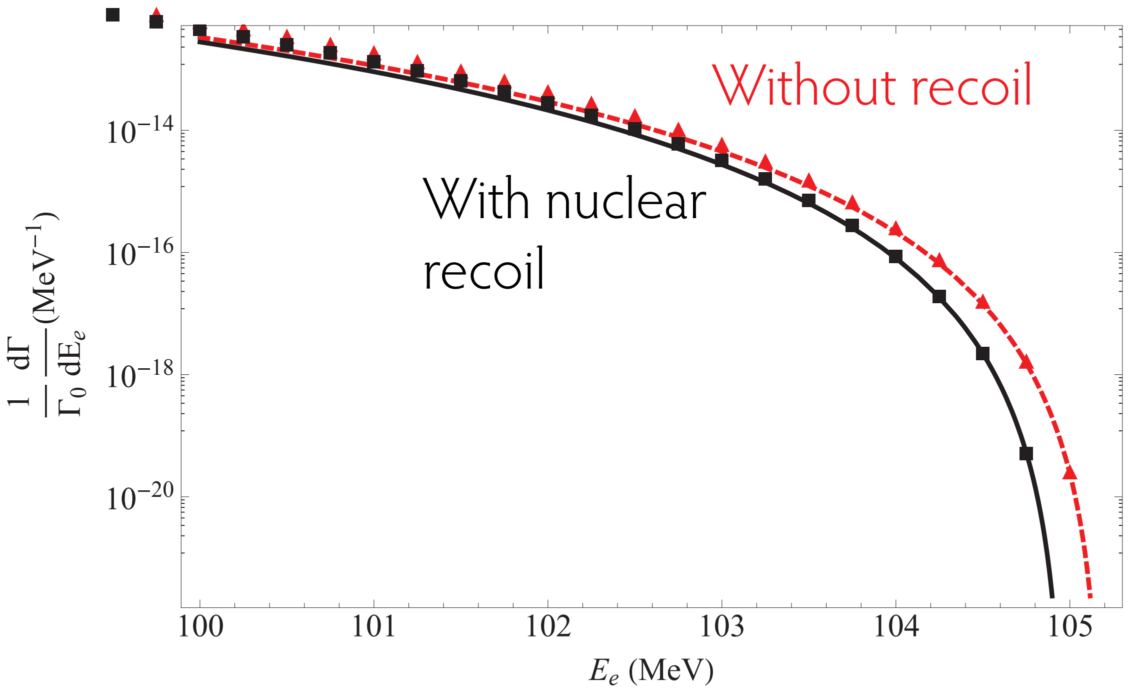
Beam induced background



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

Deacy-in-orbit background



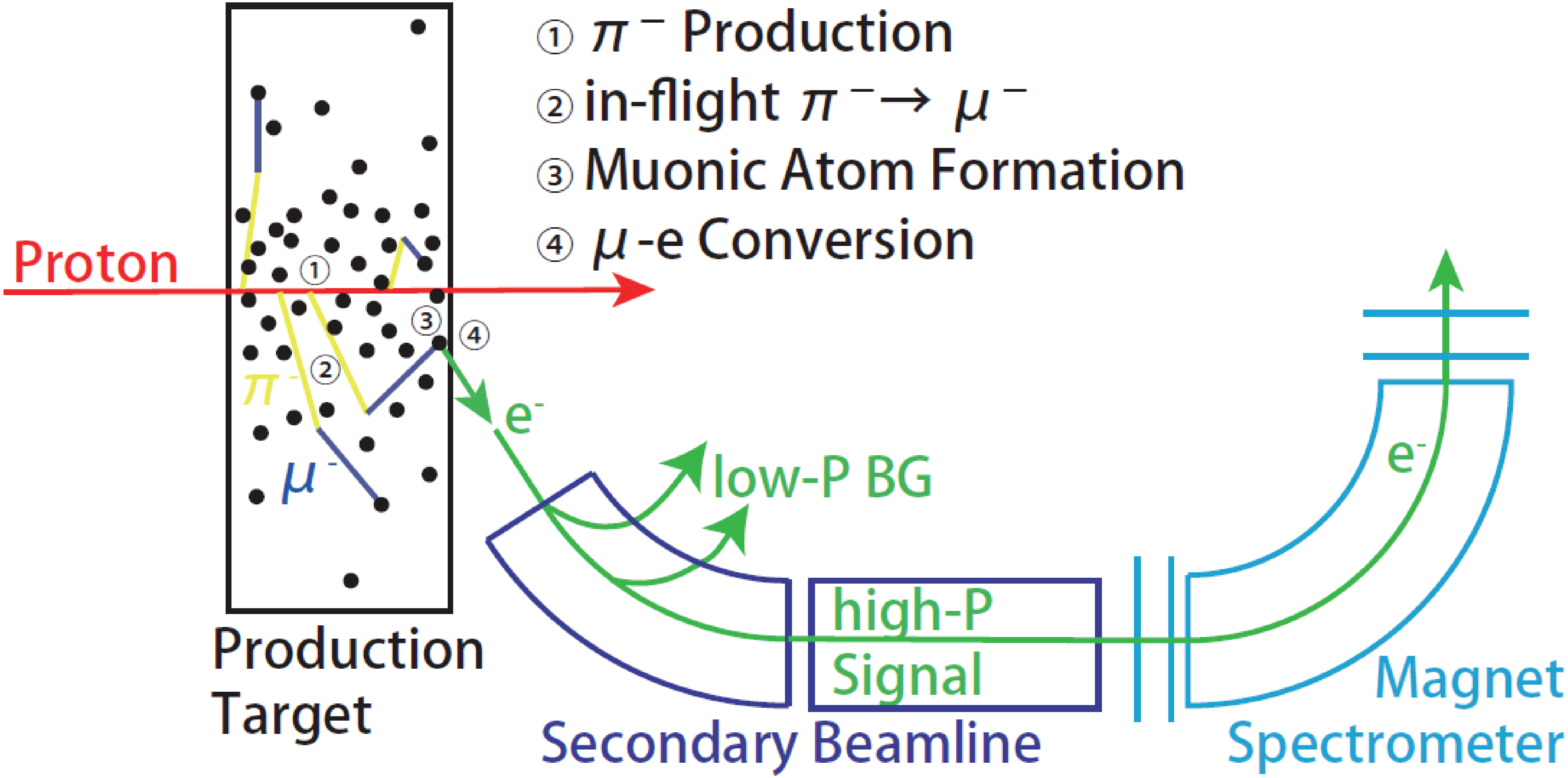


- Nuclear recoil allows for electron energies above $m_\mu/2$

- Calculation by Czarnecki, Garcia i Tormo and Marciano, Phys. Rev. D84 (2011)

- Requires excellent momentum resolution

Experimental concept - DeeMee



① π^- Production

② in-flight $\pi^- \rightarrow \mu^-$

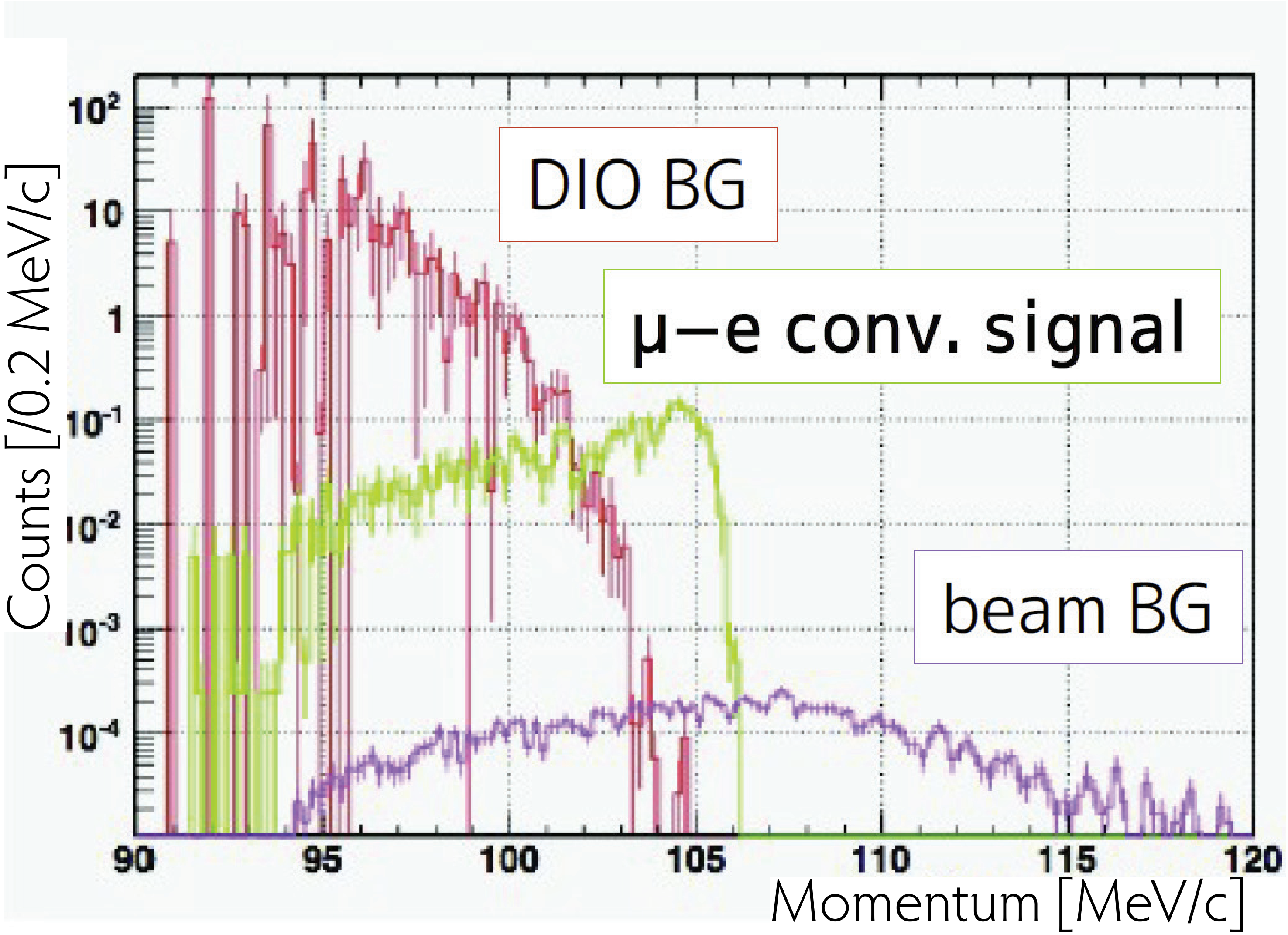
③ Muonic Atom Formation

④ μ-e Conversion

Yohei Nakatsugawa, NuFACT2014

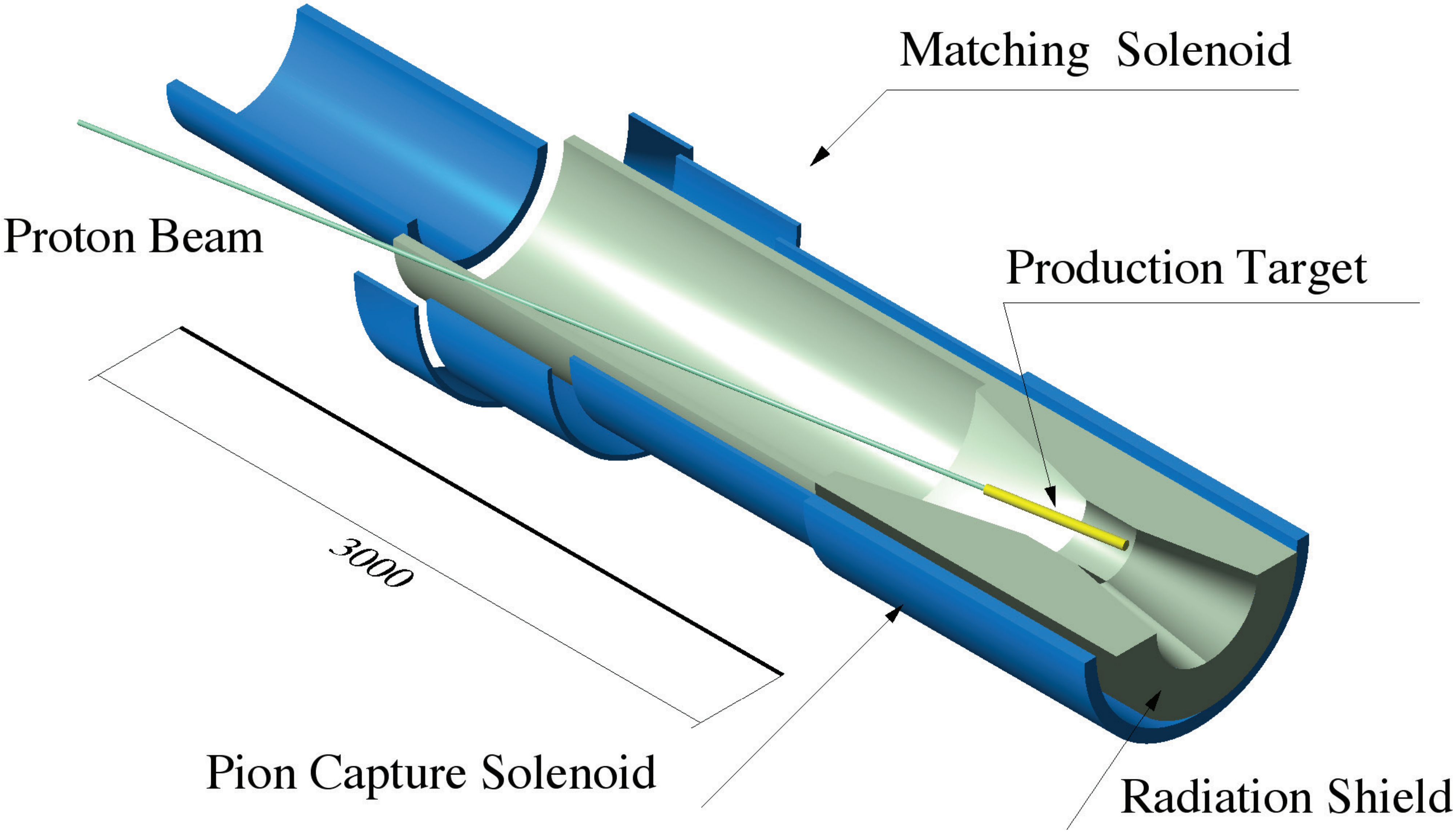
Sensitivity - DeeMee

- Expect 2.1×10^{-14} single event sensitivity for one year running



Yohei Nakatsugawa,
NuFACT2014

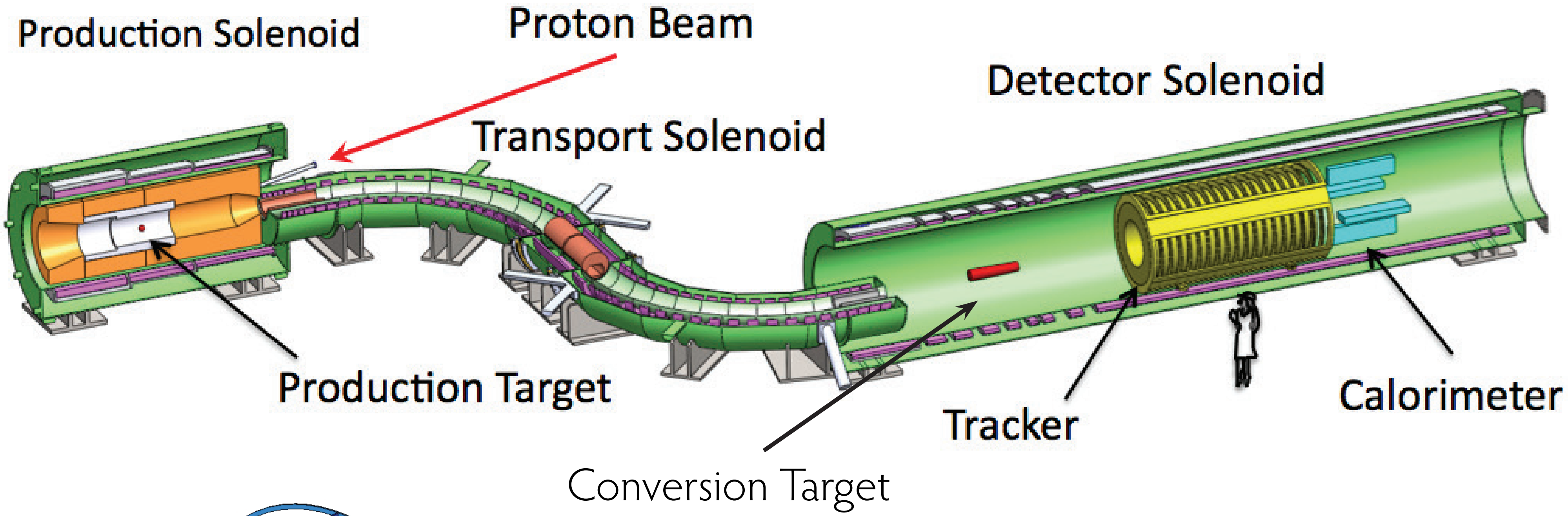
Production target inside a solenoid

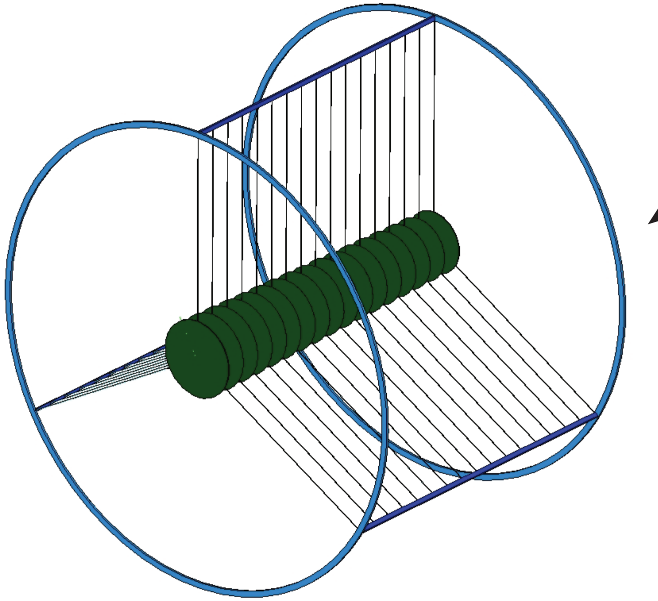


Capture most pions produced in target

Shielding of superconducting magnet very challenging

Experimental layout - Mu2e

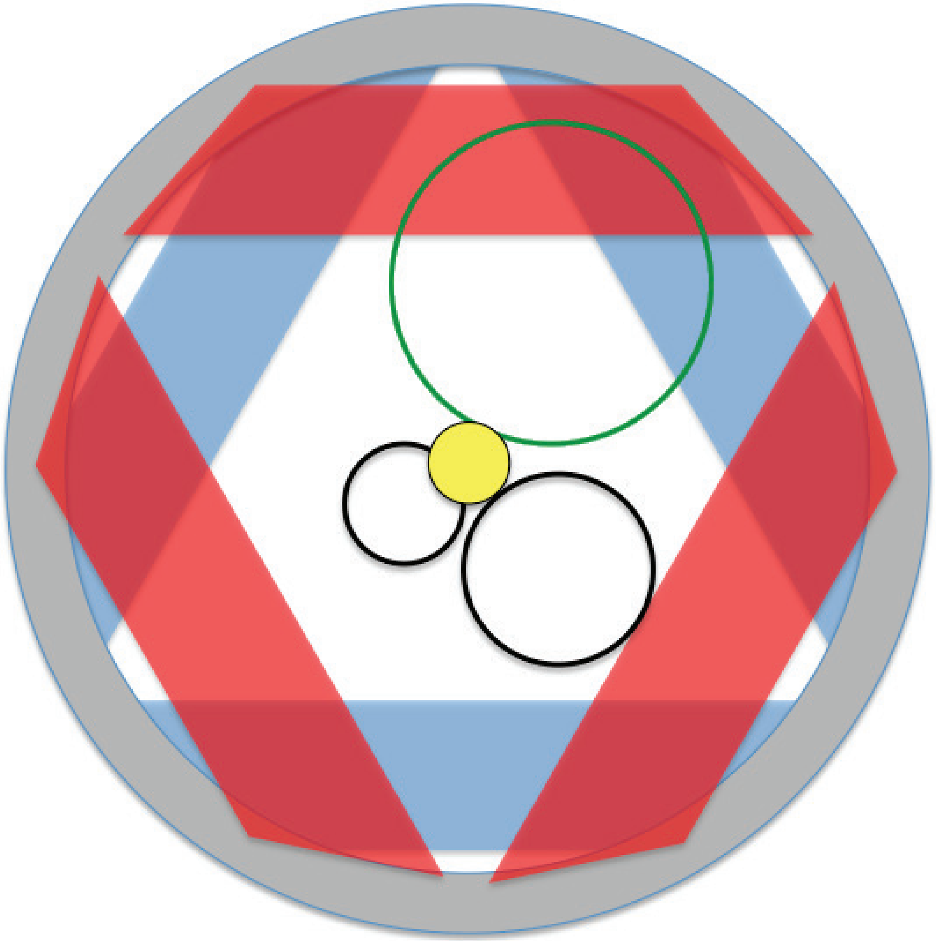


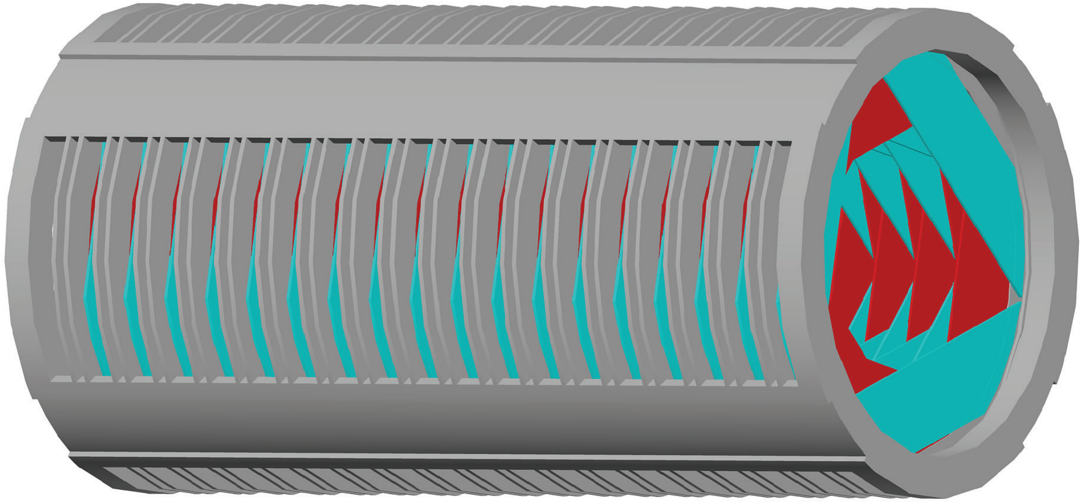


Mu2e CDR

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

Mu2e Tracker

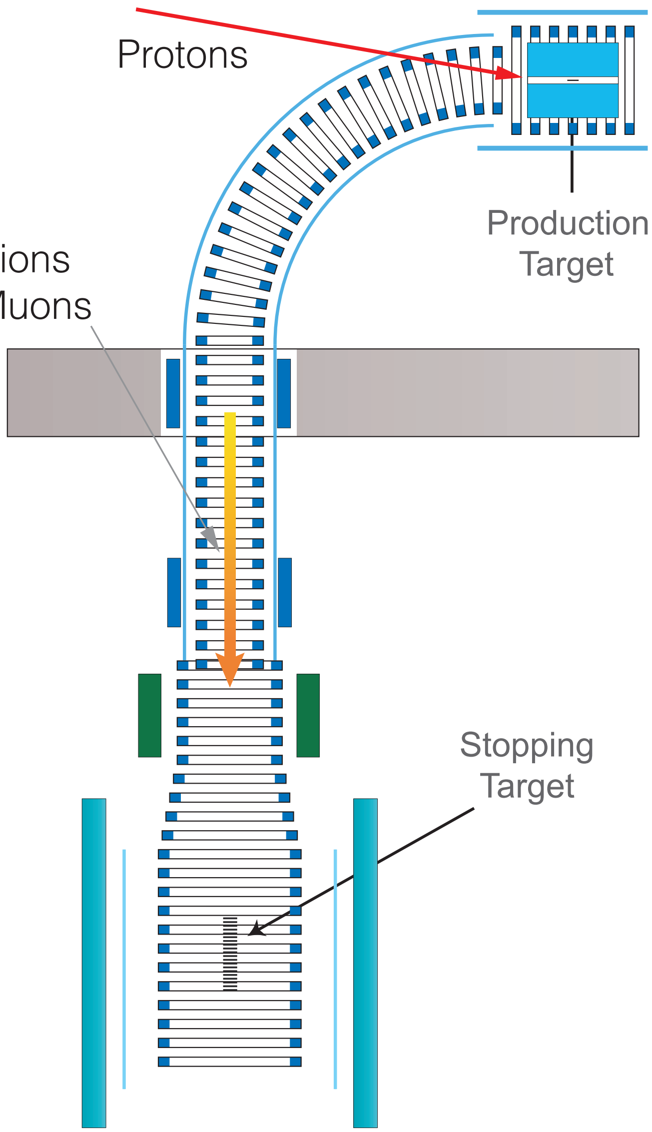




- Straw tubes in vacuum
- Outside of radius of Michel electrons

Mu2e CDR

Experimental layout - COMET Phase I



Pion Capture Section

High solenoidal field

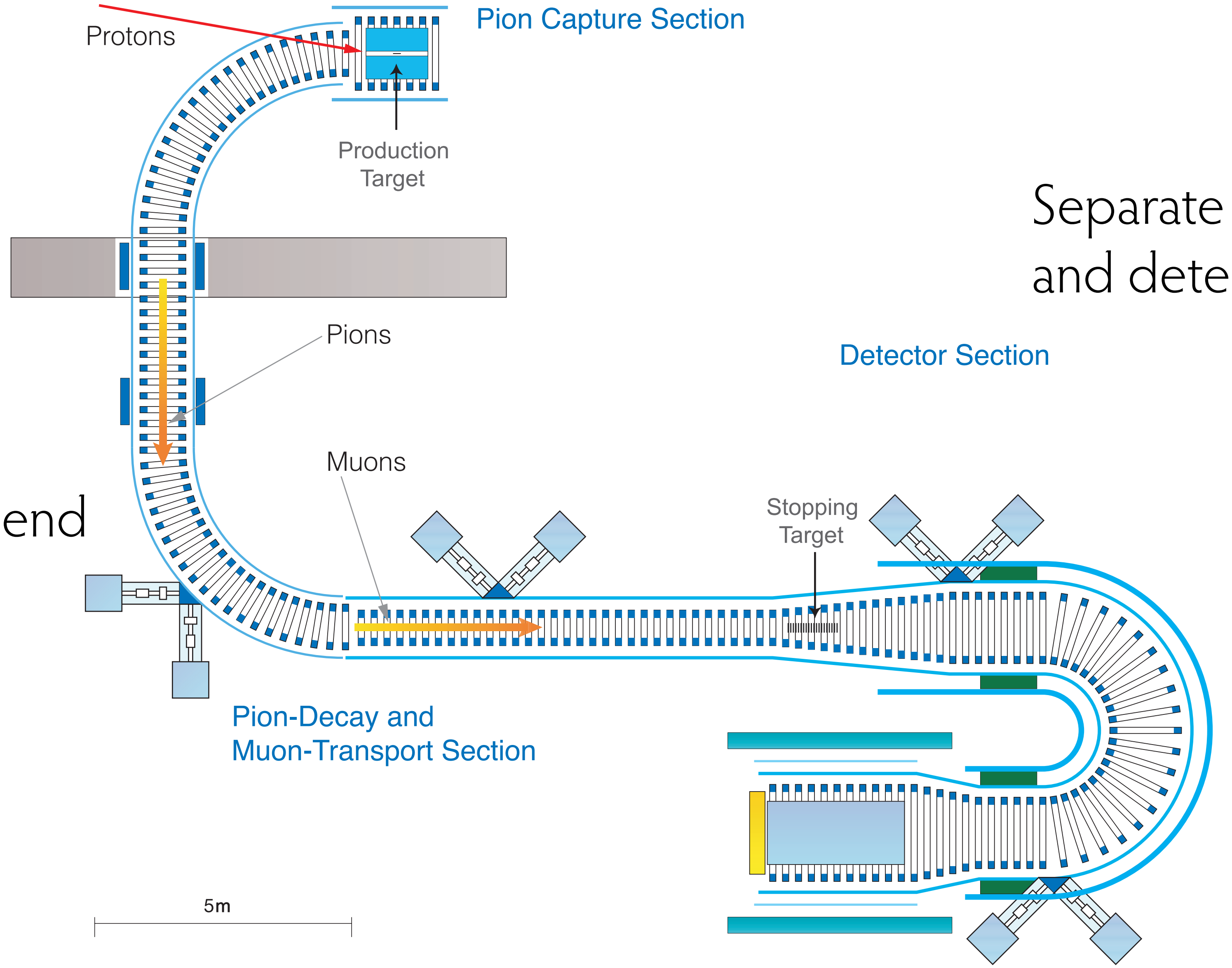
Capture pions with large solid angle

Pion-Decay and Muon-Transport Section

Detector Section

Comet CDR

Experimental layout - COMET Phase II



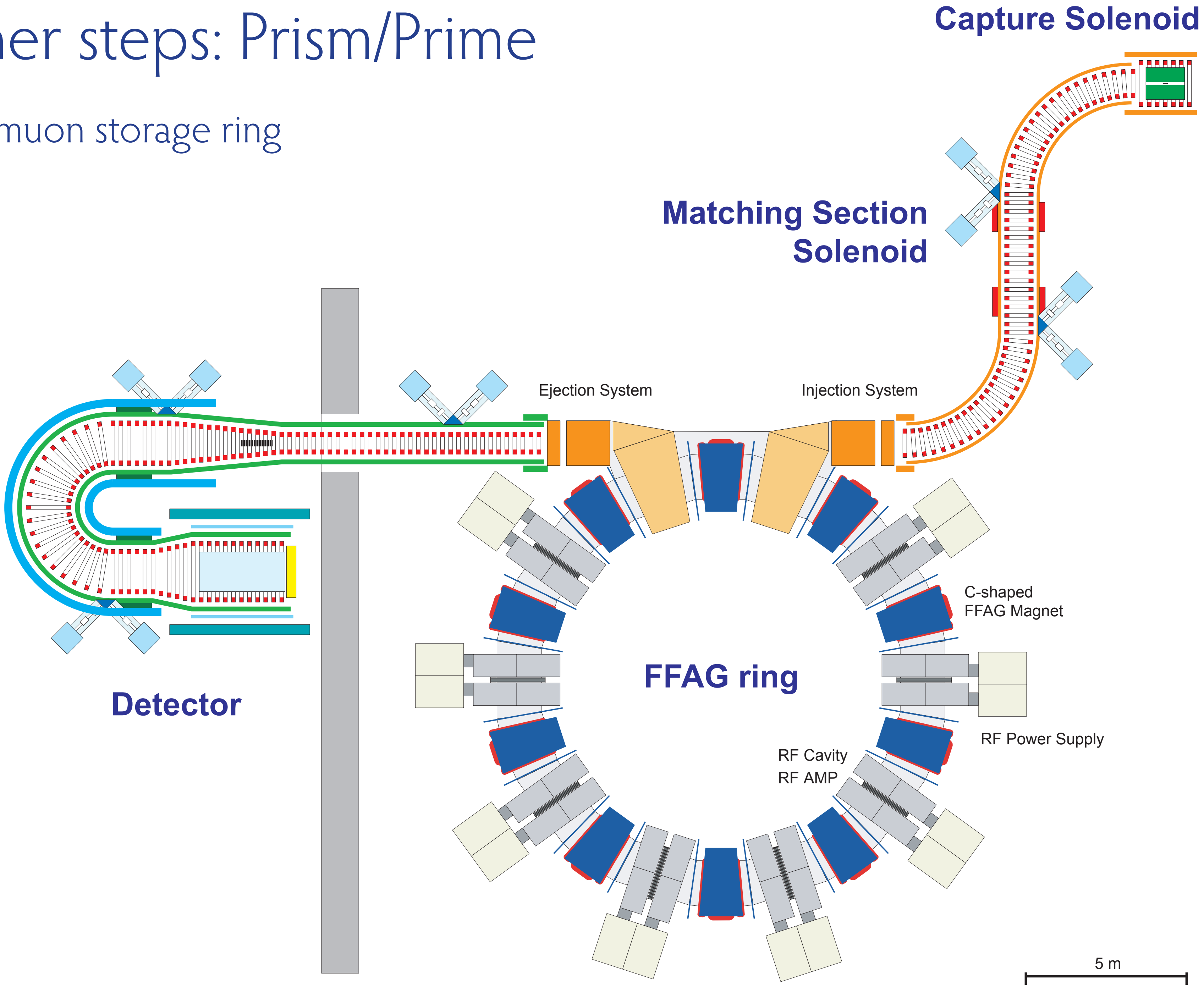
Separate muon decay and detector region

One more bend

Comet CDR

Further steps: Prism/Prime

Add a muon storage ring



Conversion: Expected sensitivities

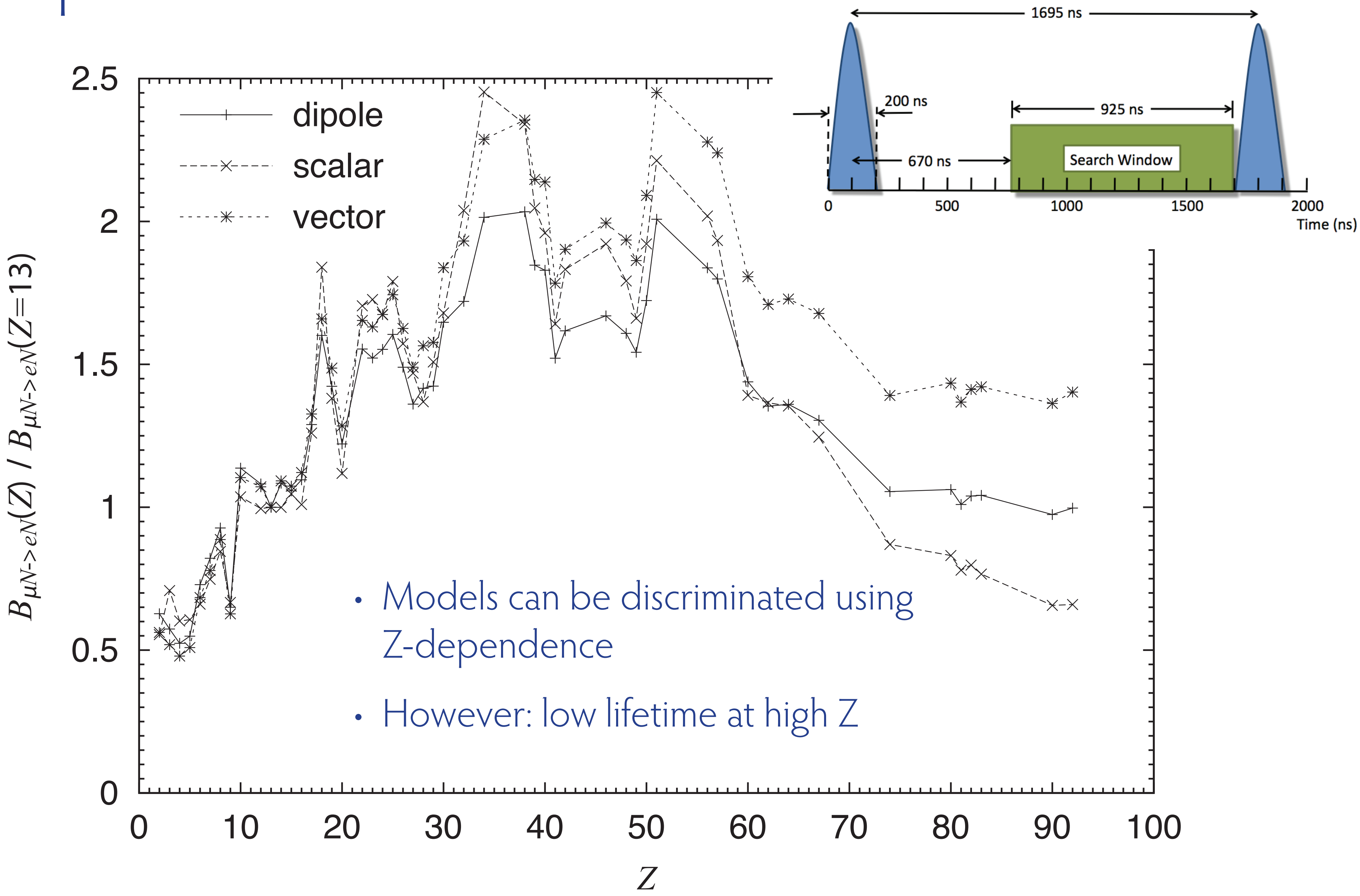
- Comet Phase I and DeeMee might get to $\sim 10^{-14}$ as early as 2016

- Both Comet Phase II and Mu2e will start around 2020

- Should get single event sensitivities well below 10^{-16}

- Prism/Prime and Mu2e with Project X explore paths to 10^{-18}

Z-dependence

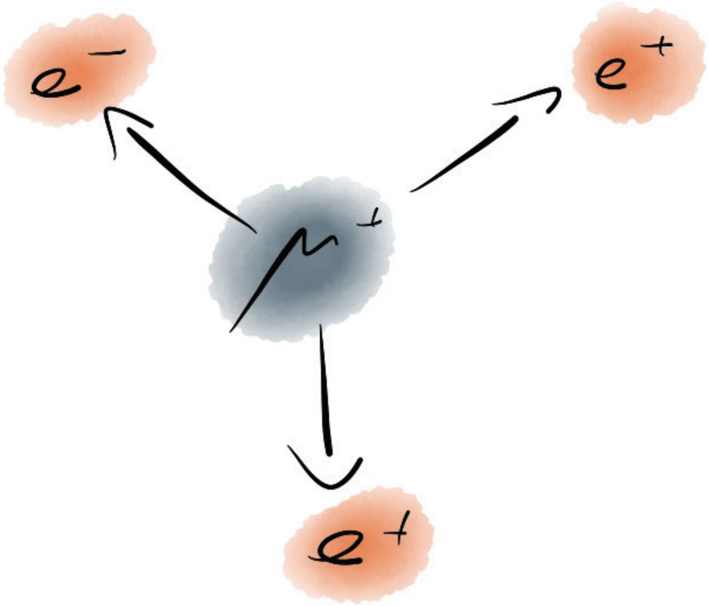


- Models can be discriminated using Z-dependence
- However: low lifetime at high Z

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

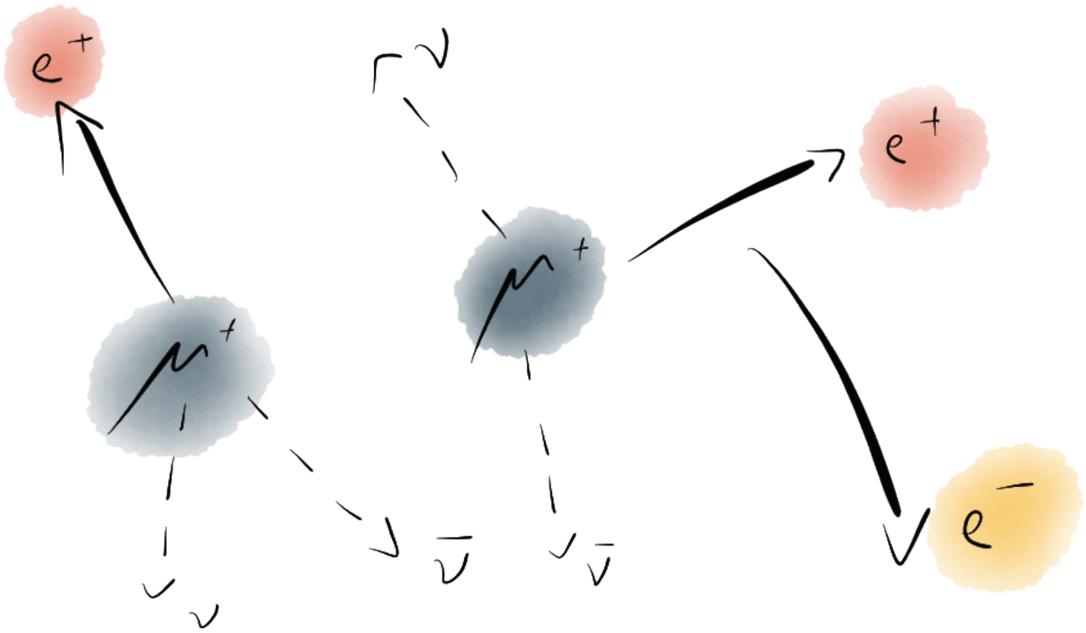
Mu3e

The signal



- $\mu^+ \rightarrow e^+e^-e^+$
- Two positrons, one electron
- From same vertex
- Same time
- $\Sigma p_e = m_\mu$
- Maximum momentum: $\frac{1}{2} m_\mu = 53$ 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

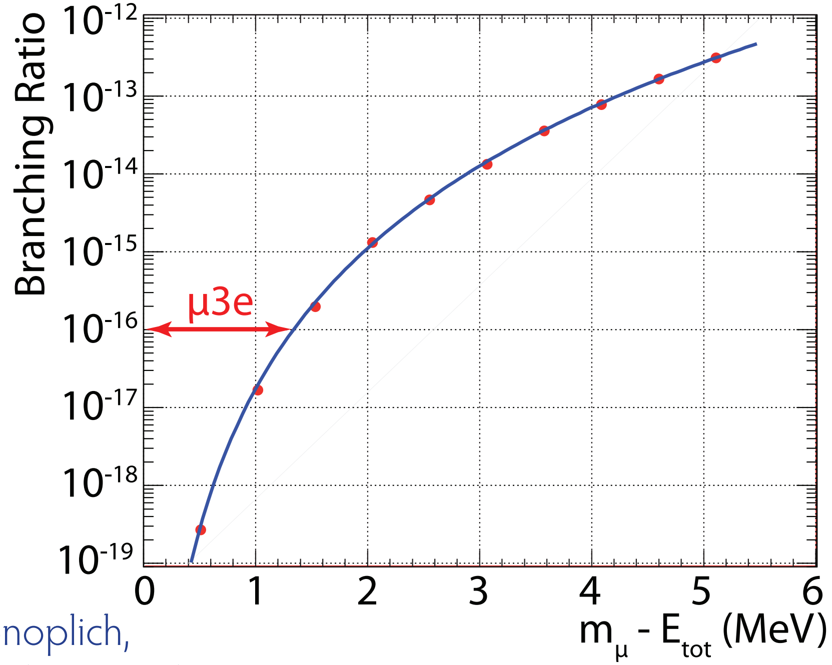
- Allowed radiative decay with internal conversion:

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

- Only distinguishing feature: Missing momentum carried by neutrinos

- Need excellent momentum resolution

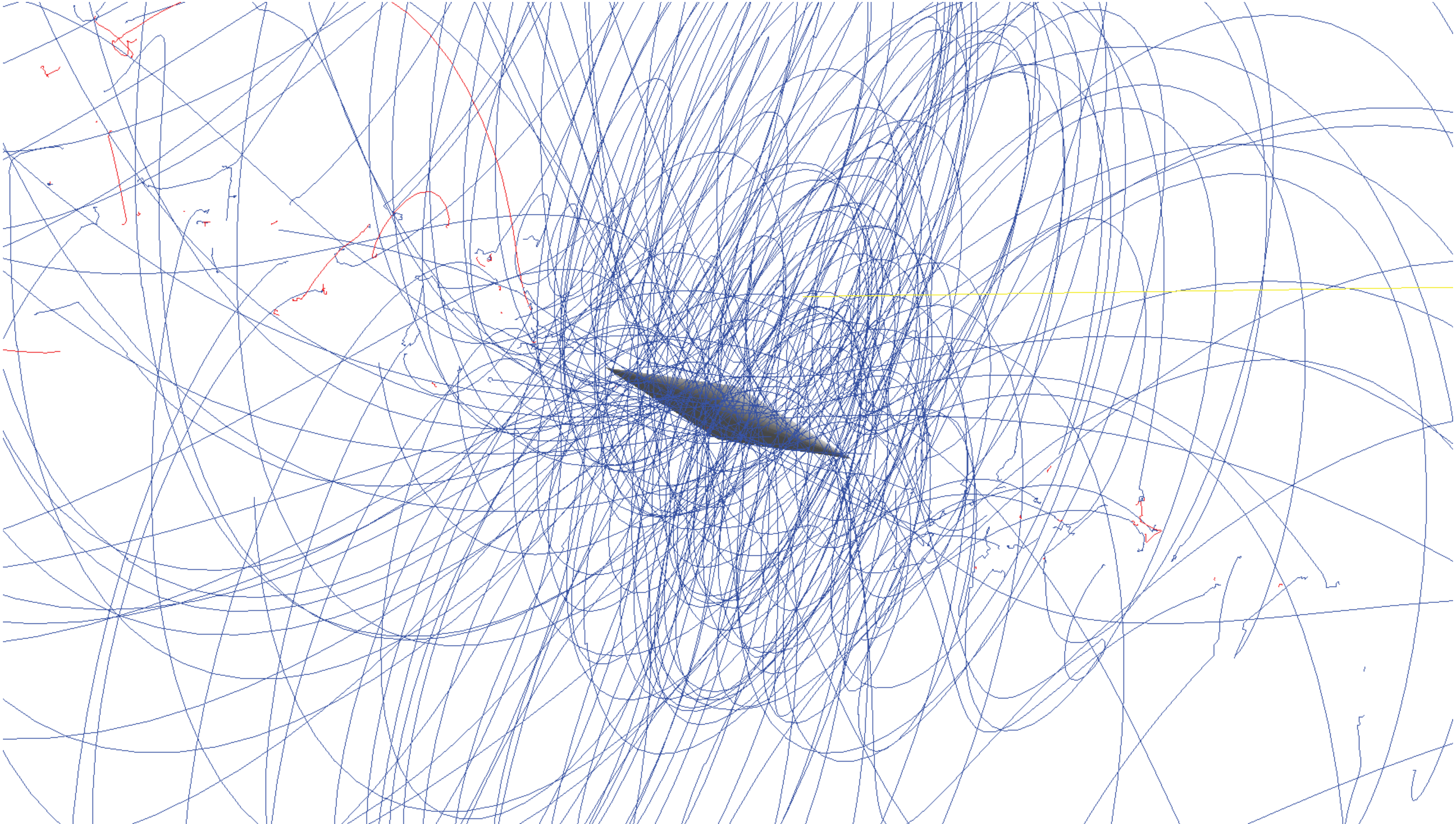
- Tree-level calculation; could one loop corrections be big?



(R. M. Djilkibaev, R. V. Konoplich,
Phys.Rev. D79 (2009) 073004)

2 Billion Muon Decays/s

50 ns, 1 Tesla field



Detector Technology

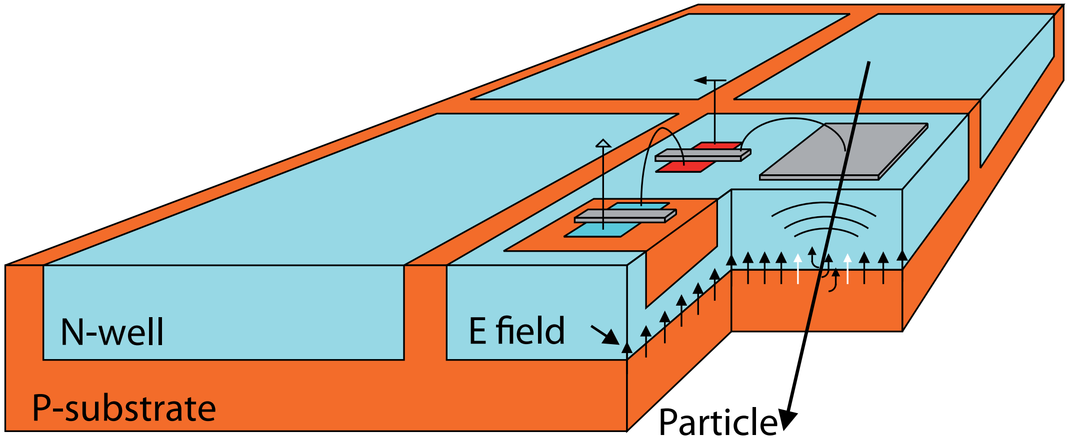
- High granularity (occupancy)
- Close to target (vertex resolution)
- 3D space points (reconstruction)
- Minimum material (momenta below 53 MeV/c)

Detector Technology

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

- 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)

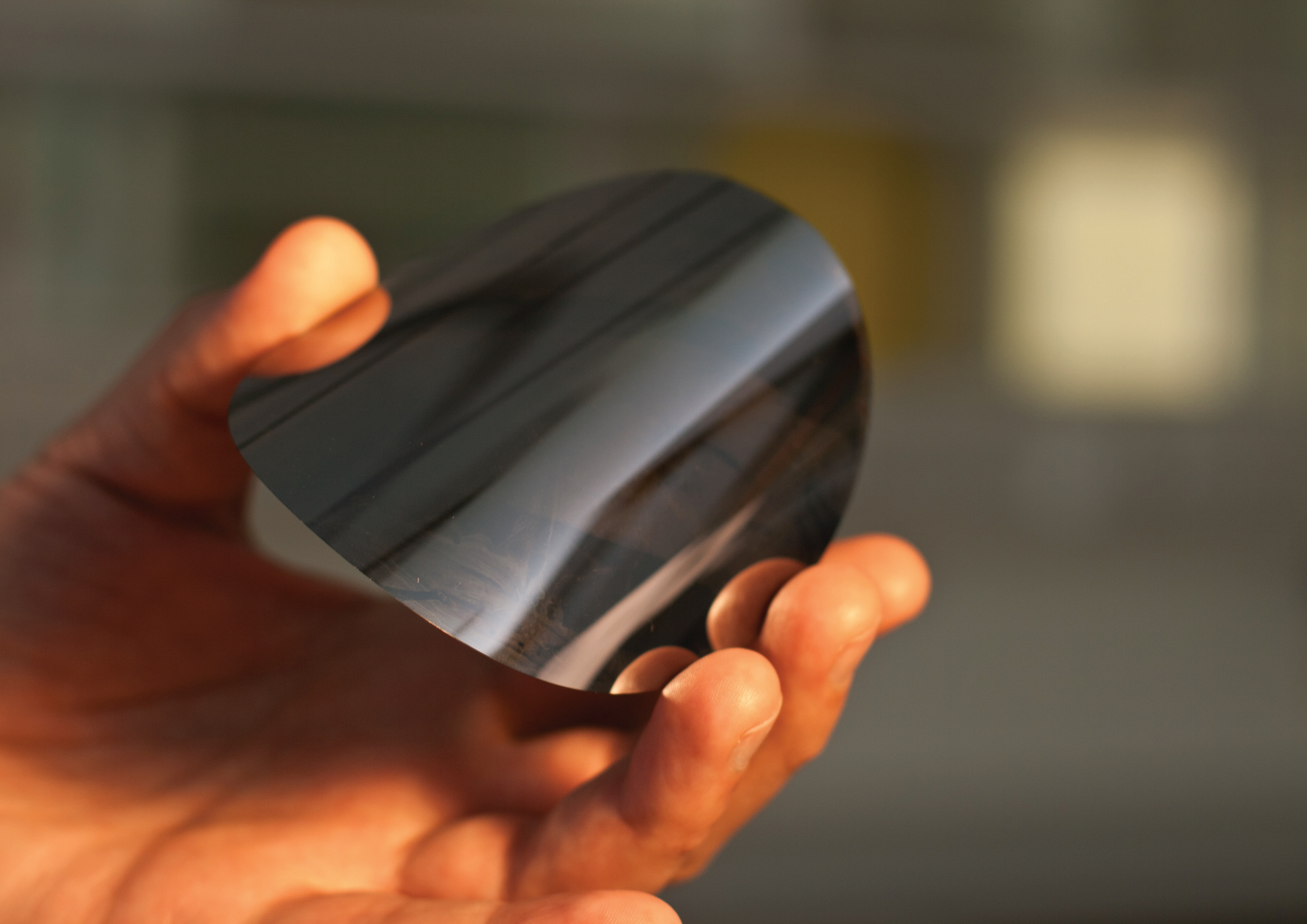
Fast and thin sensors: HV-MAPS



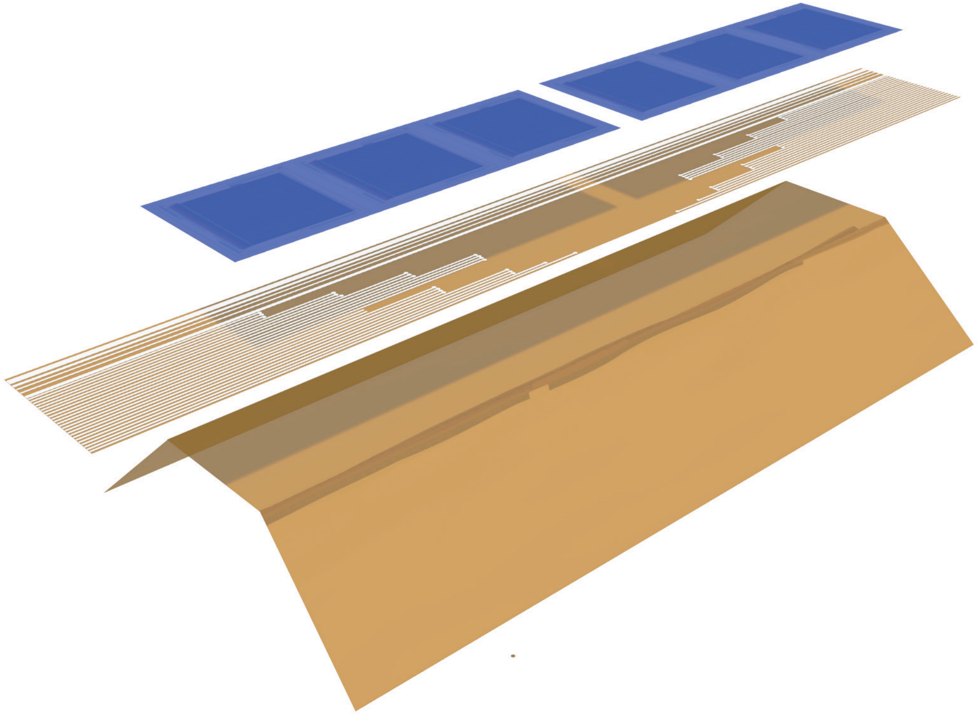
High voltage monolithic active pixel sensors - Ivan Perić

- Use a high voltage commercial process (automotive industry)
- Small active region, fast charge collection via drift
- Can be thinned down to < 50 µm
- Implement logic directly in N-well in the pixel - smart diode array
- Logic on chip: Output are zero-suppressed hit addresses and timestamps

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

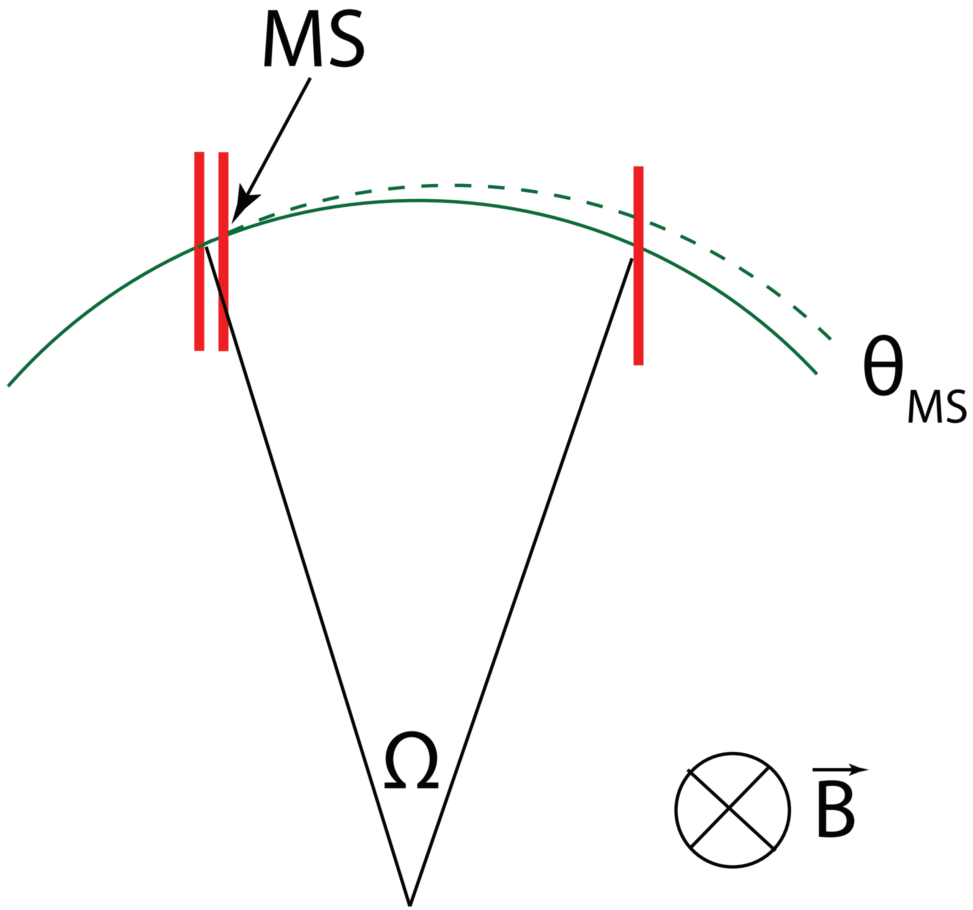


Mechanics



- 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

Momentum measurement

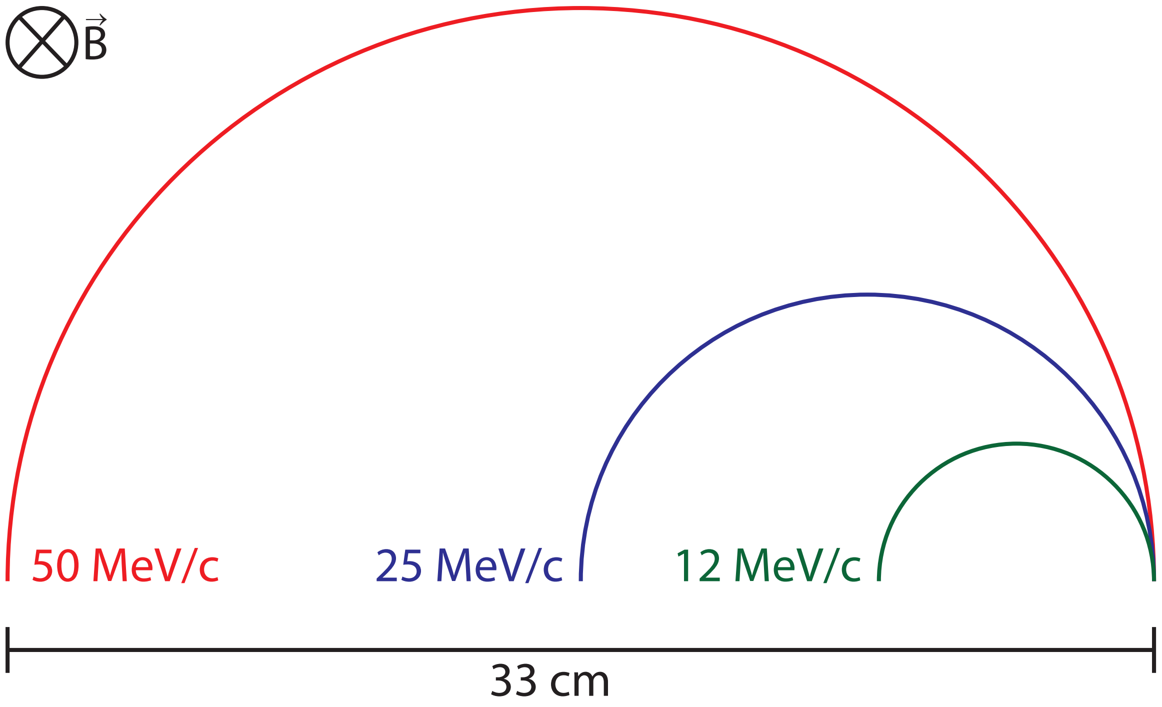


- 1 T magnetic field
- Resolution dominated by multiple scattering
- Momentum resolution to first order:

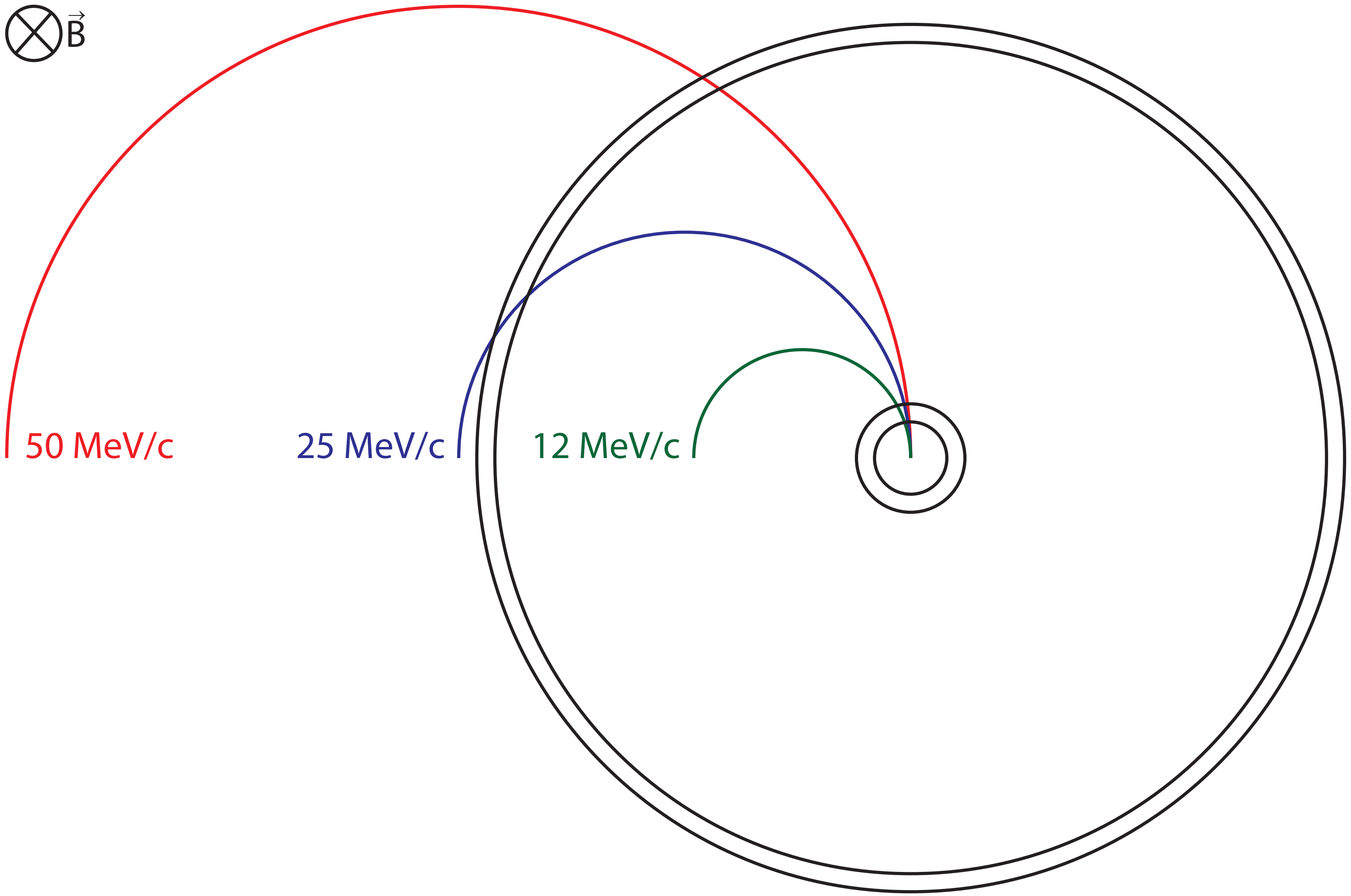
$$\sigma_P/P \sim \theta_{MS}/\Omega$$

- Precision requires large lever arm (large bending angle Ω) and low multiple scattering θ_{MS}

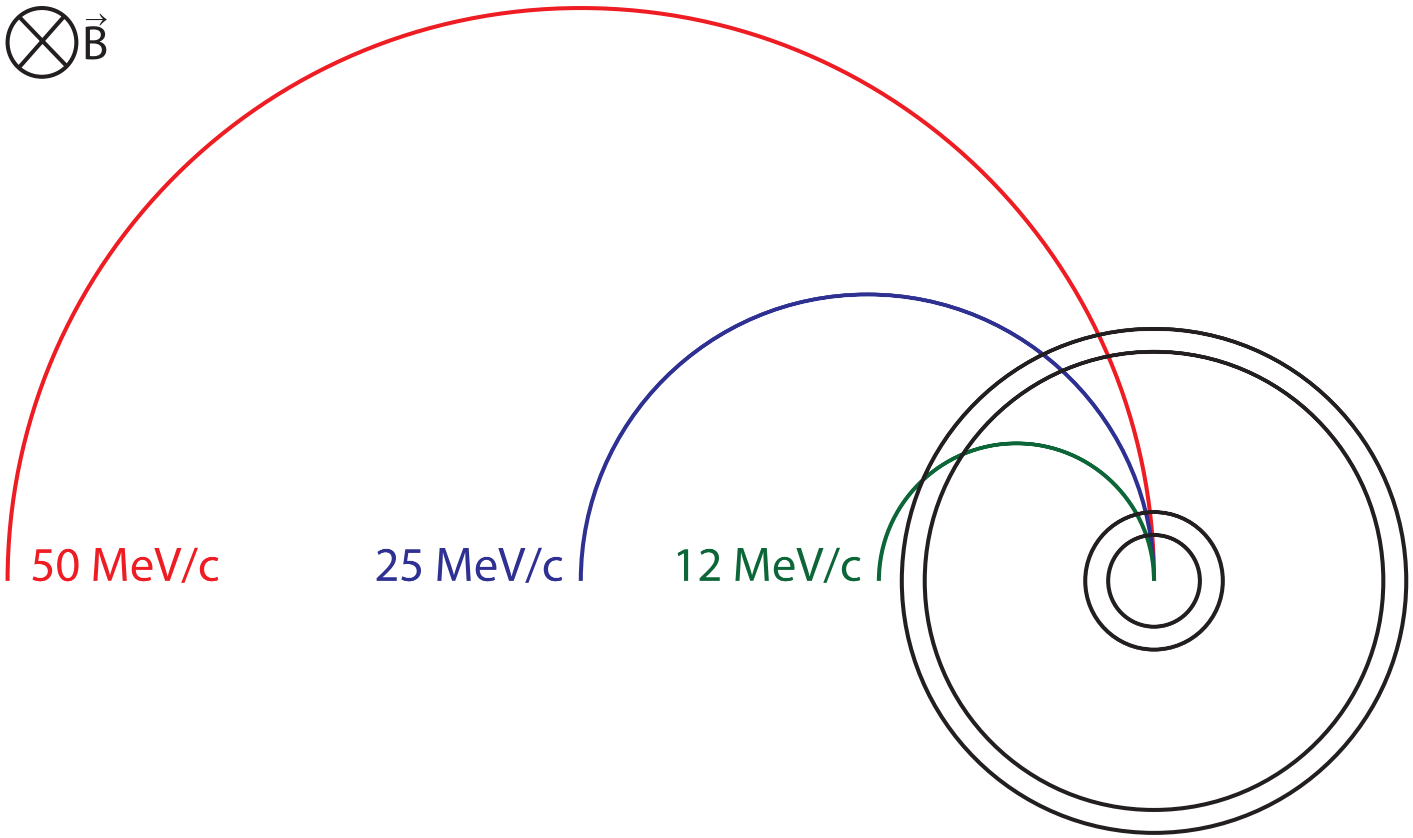
Precision vs. Acceptance



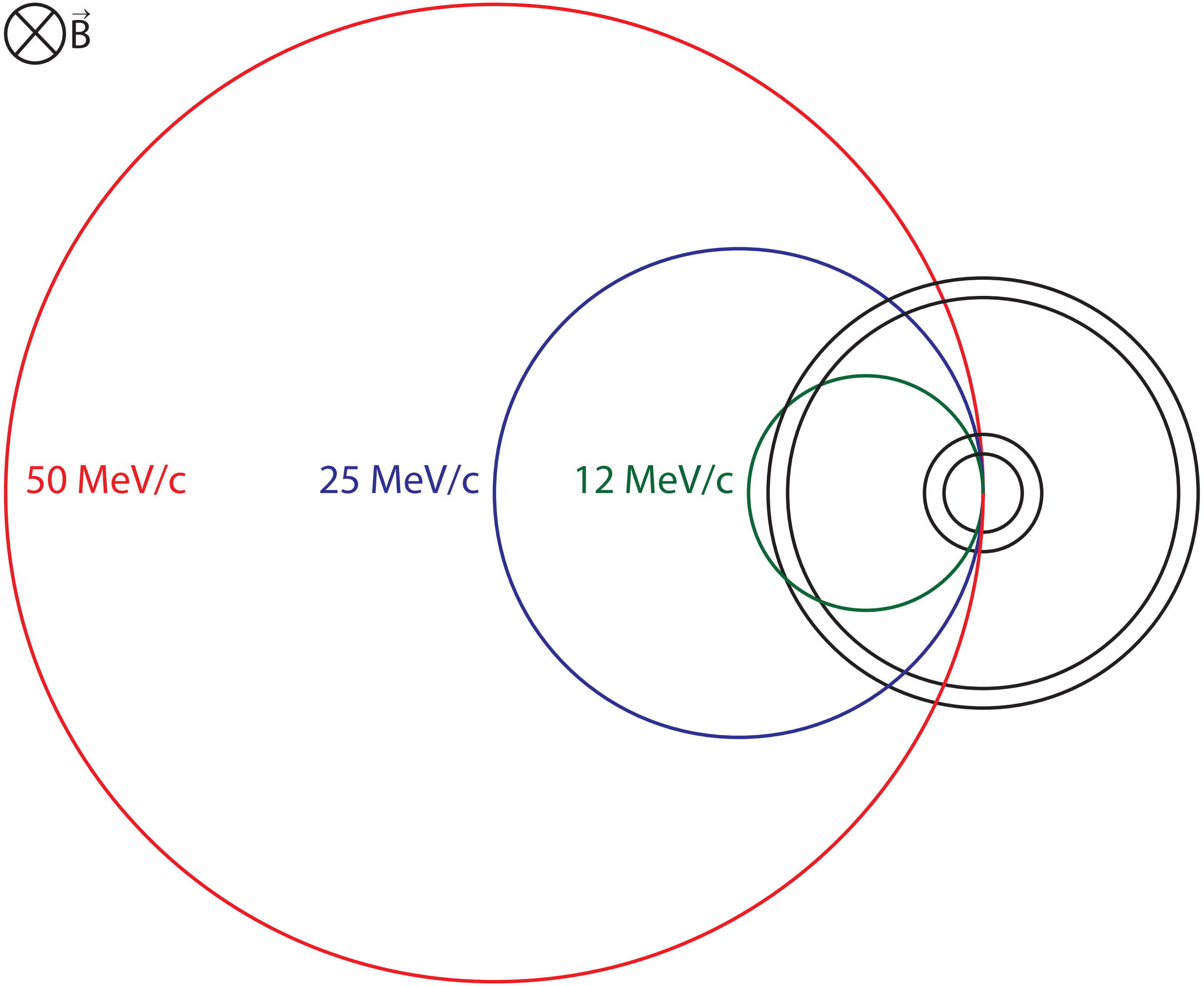
Precision vs. Acceptance



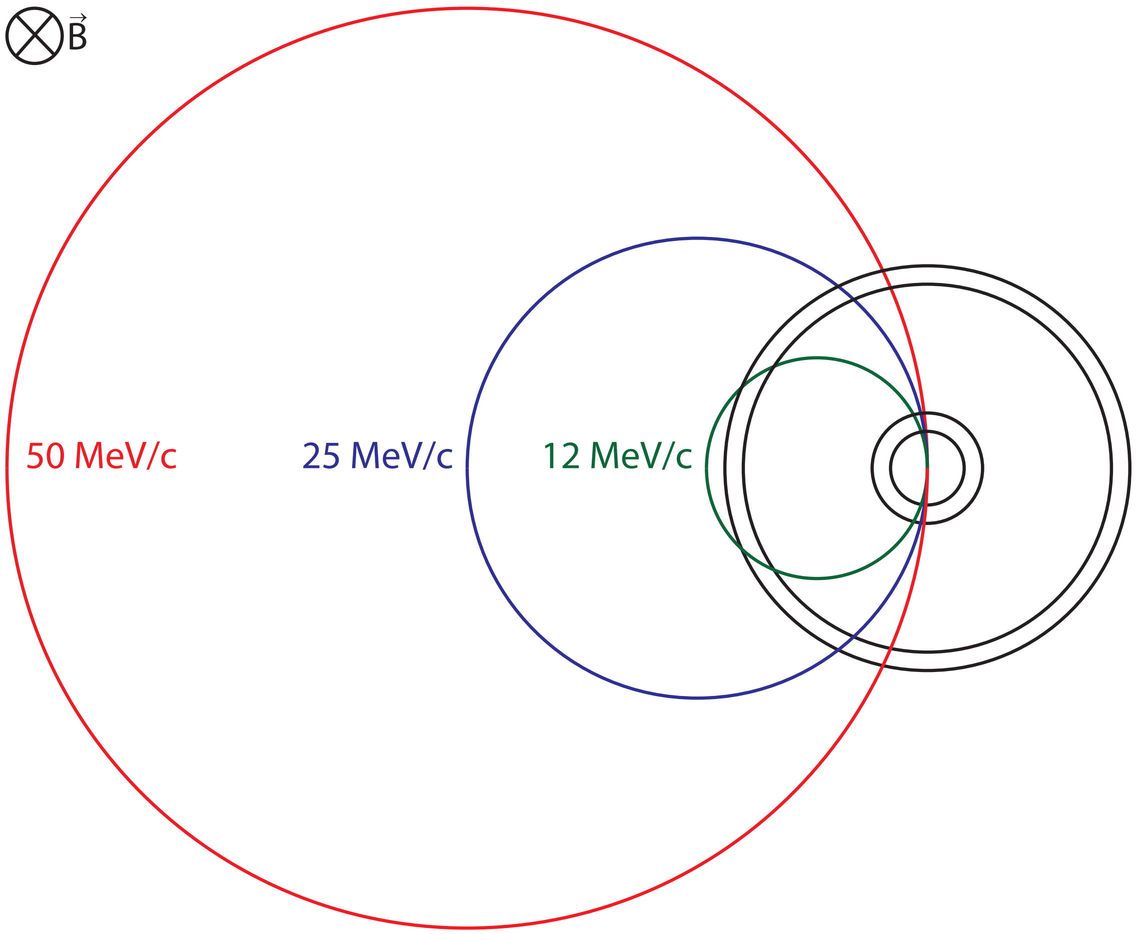
Precision vs. Acceptance

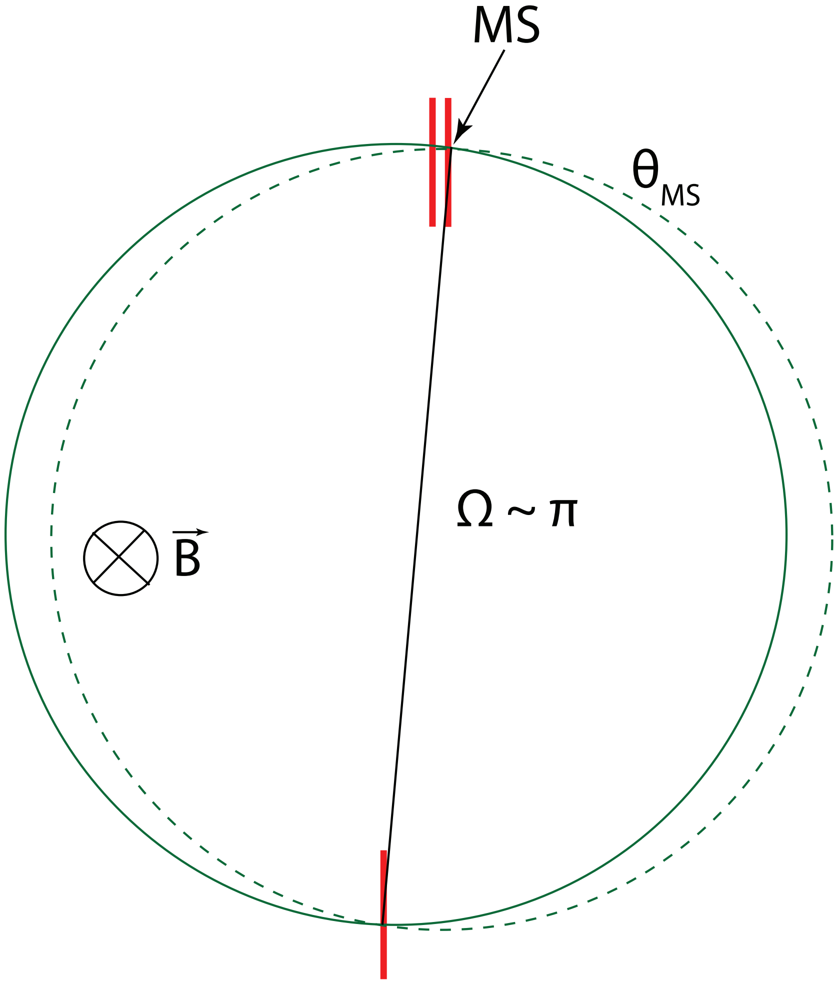


Precision vs. Acceptance

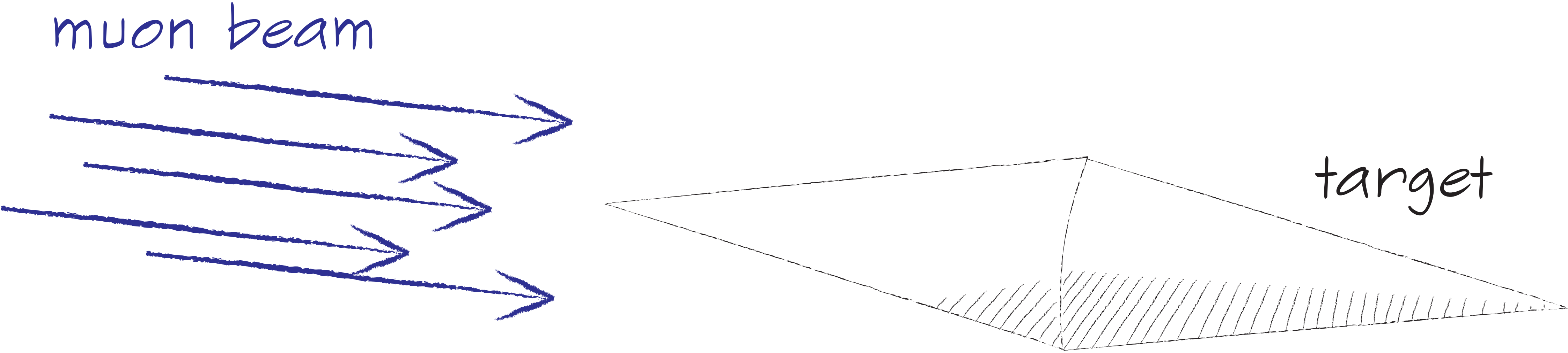


Precision vs. Acceptance

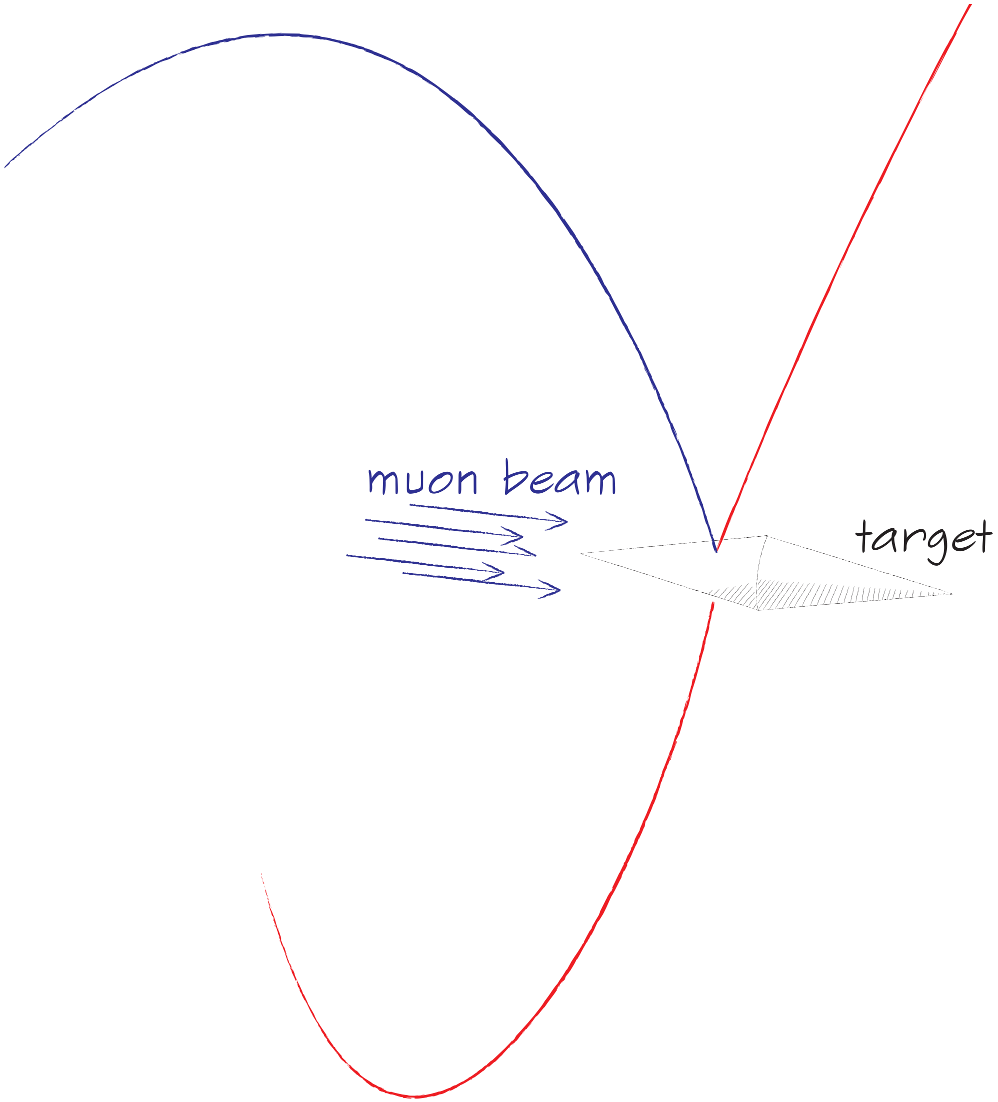




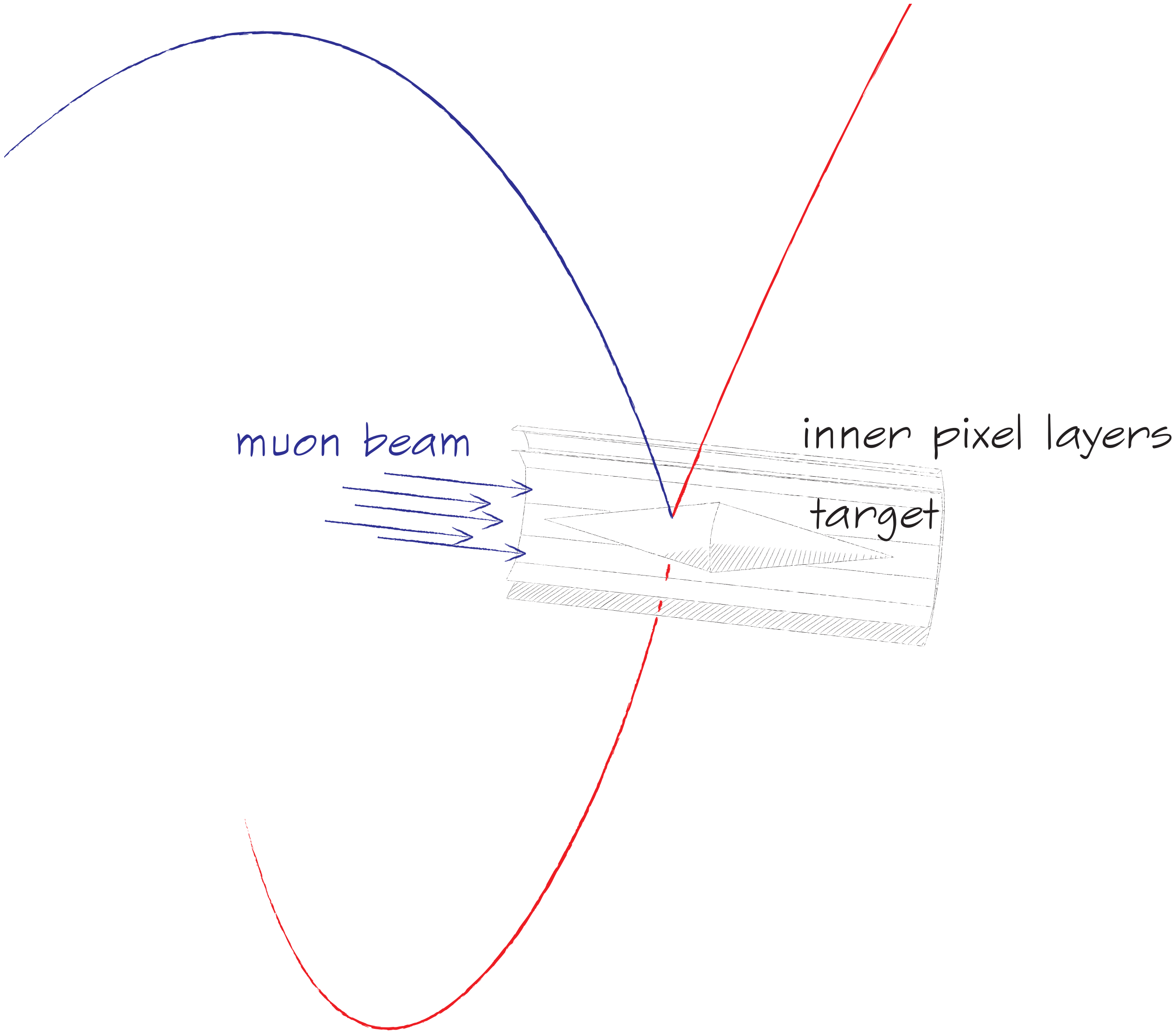
Detector Design



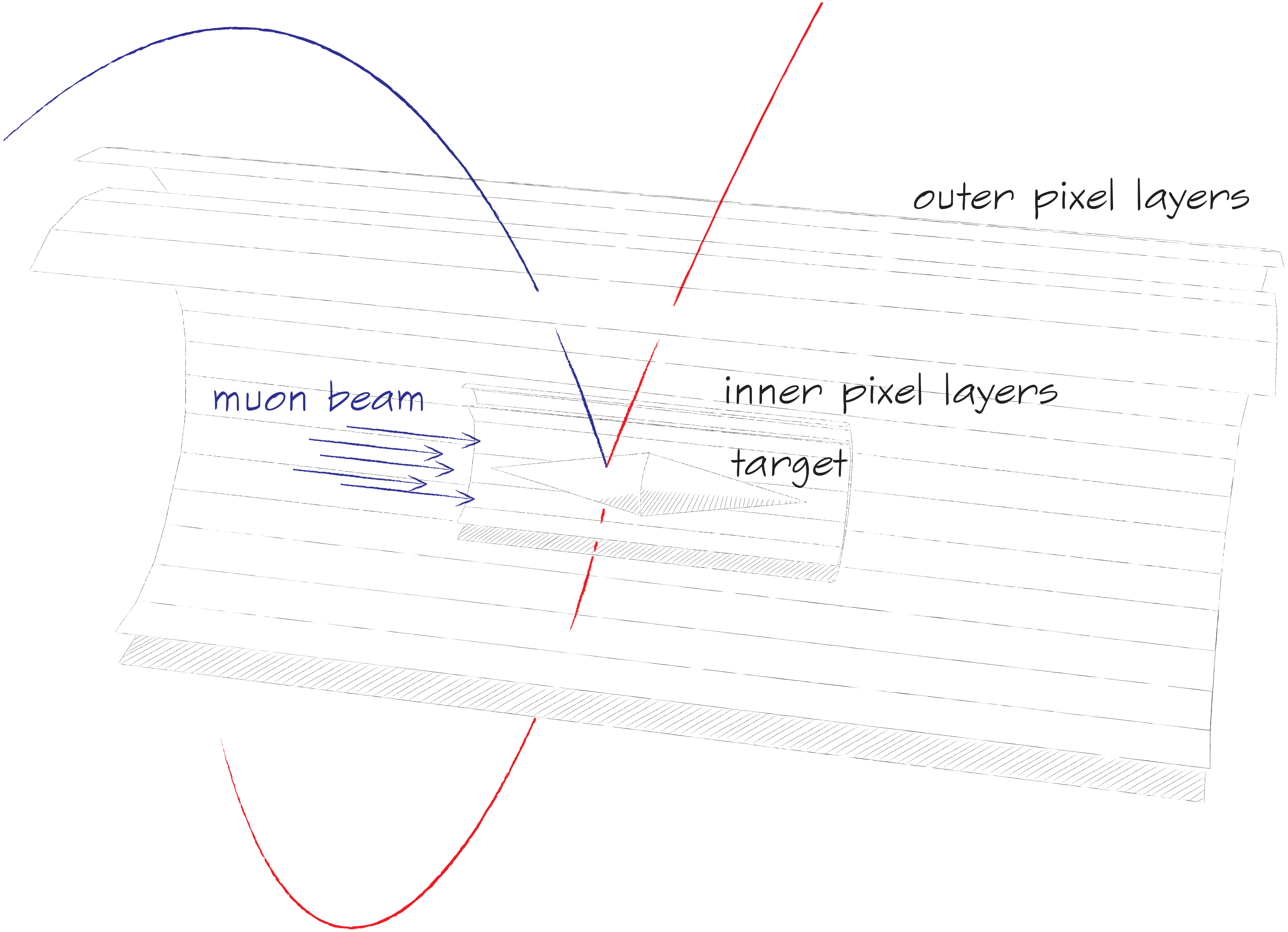
Detector Design



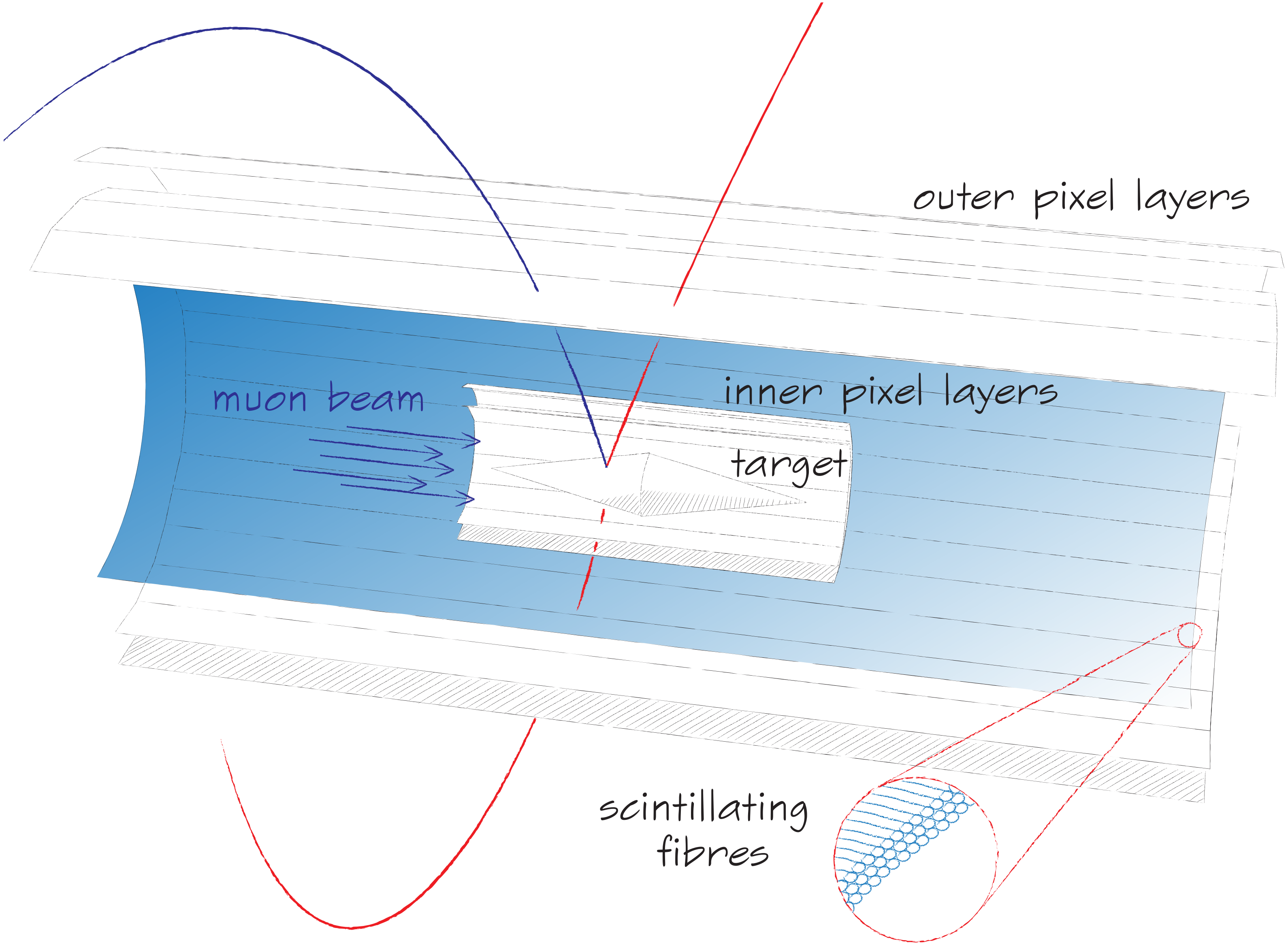
Detector Design



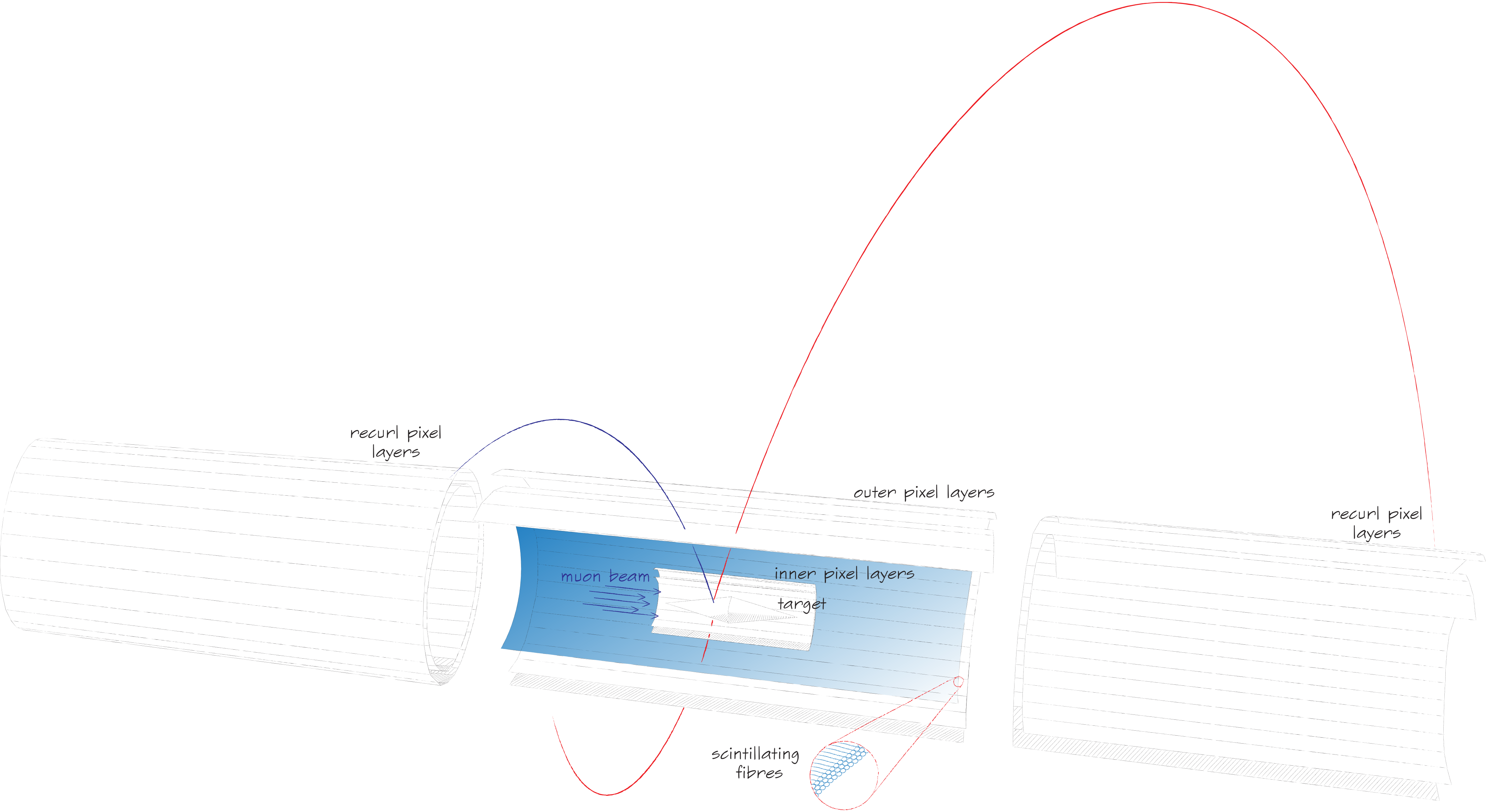
Detector Design



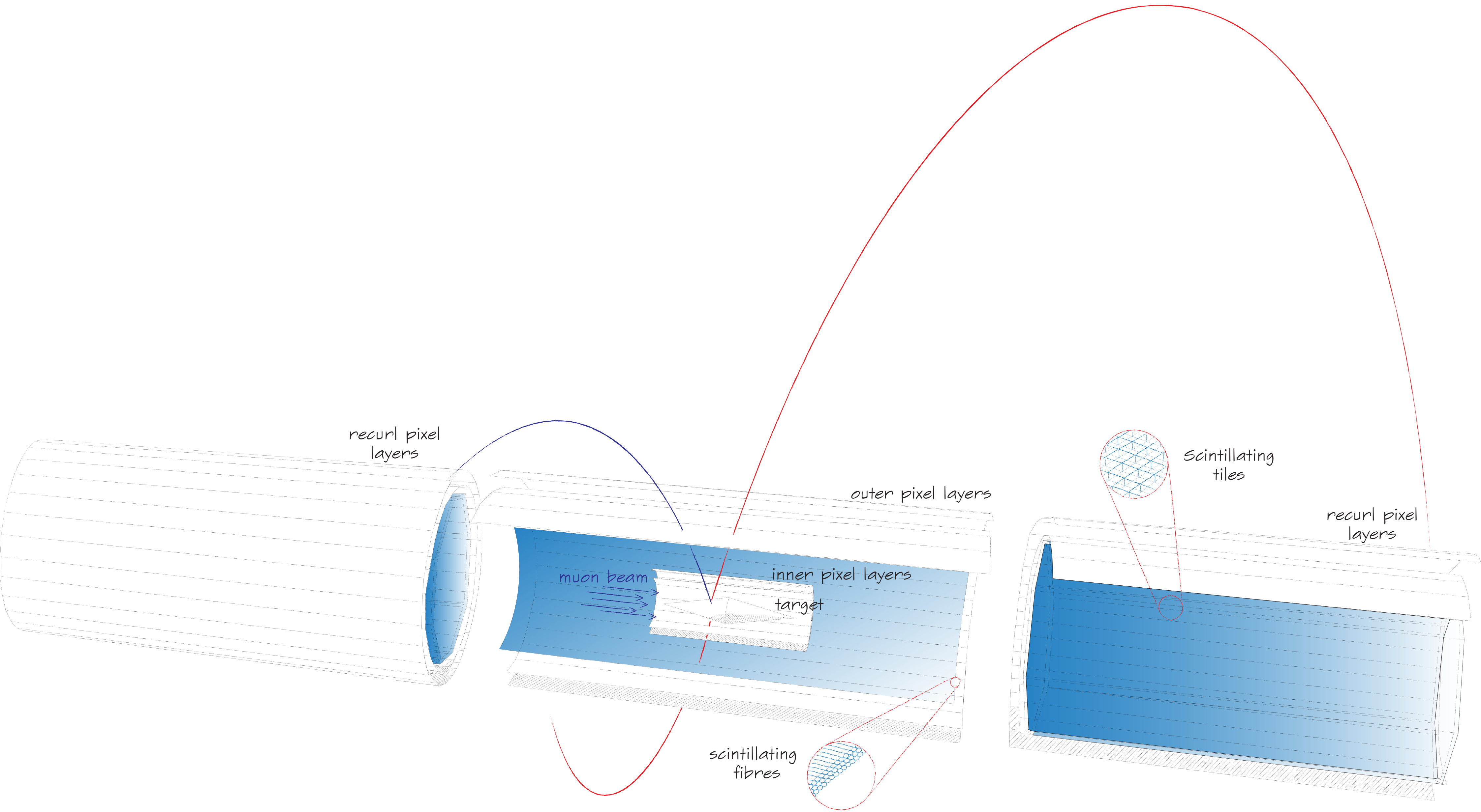
Detector Design



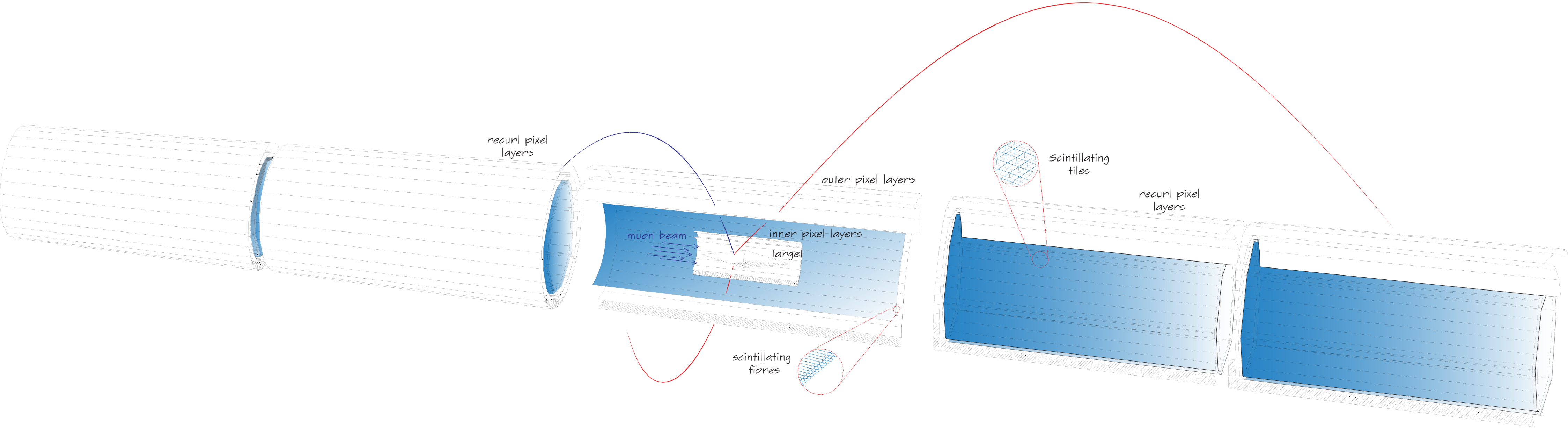
Detector Design



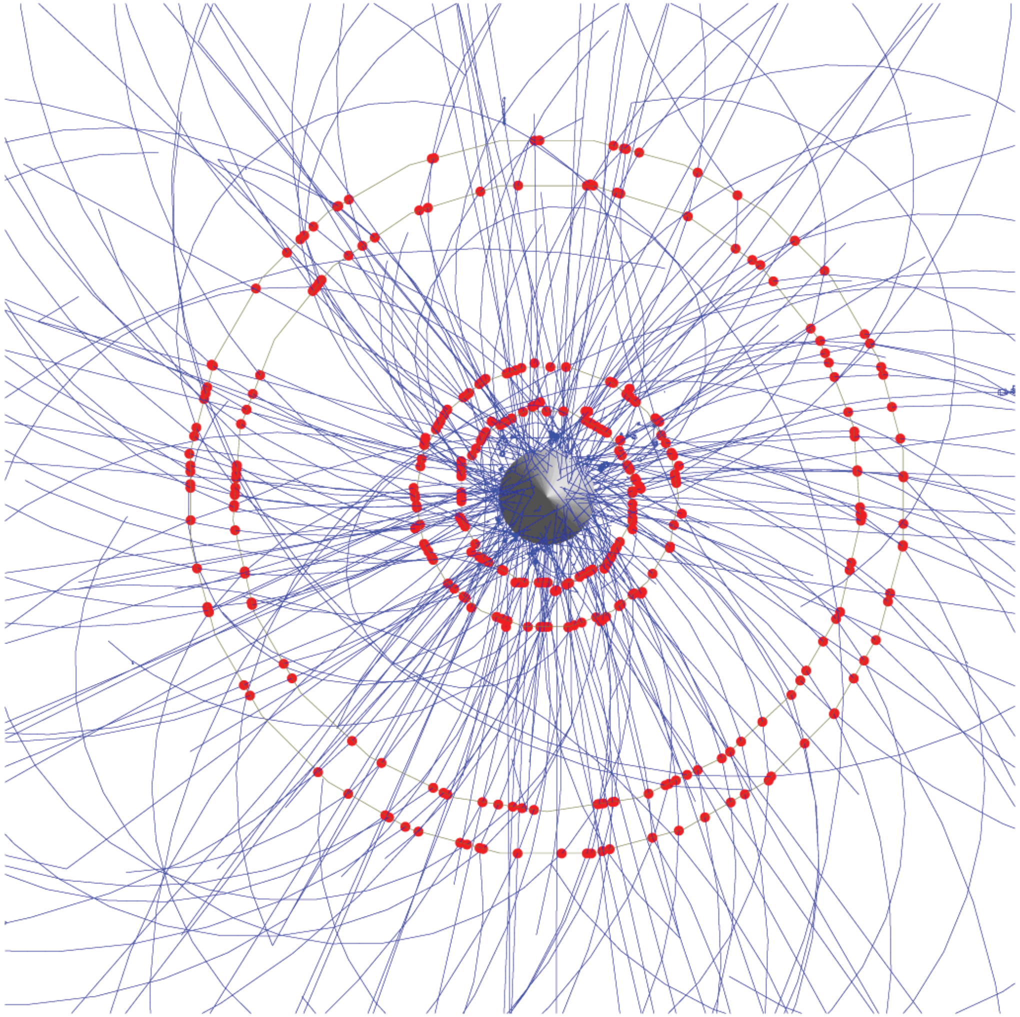
Detector Design



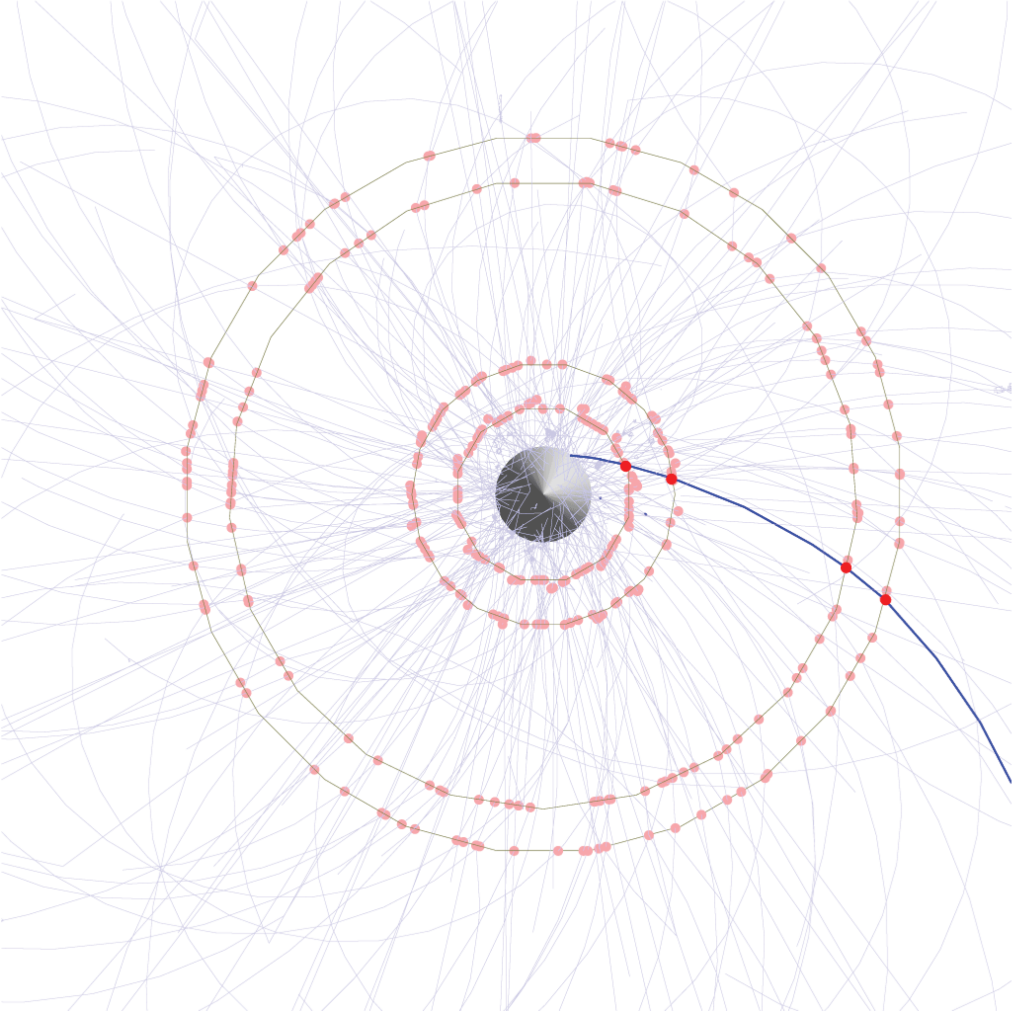
Detector Design



Timing measurements

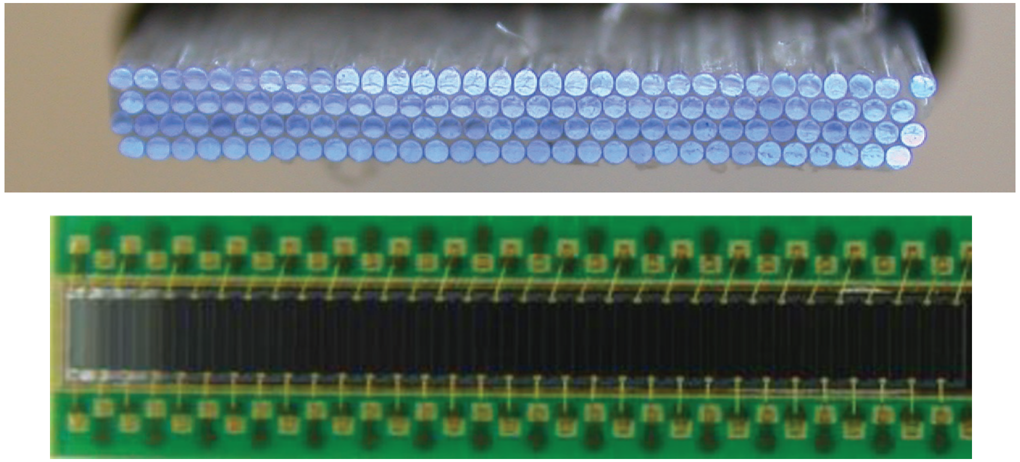


Pixels: O(50 ns)

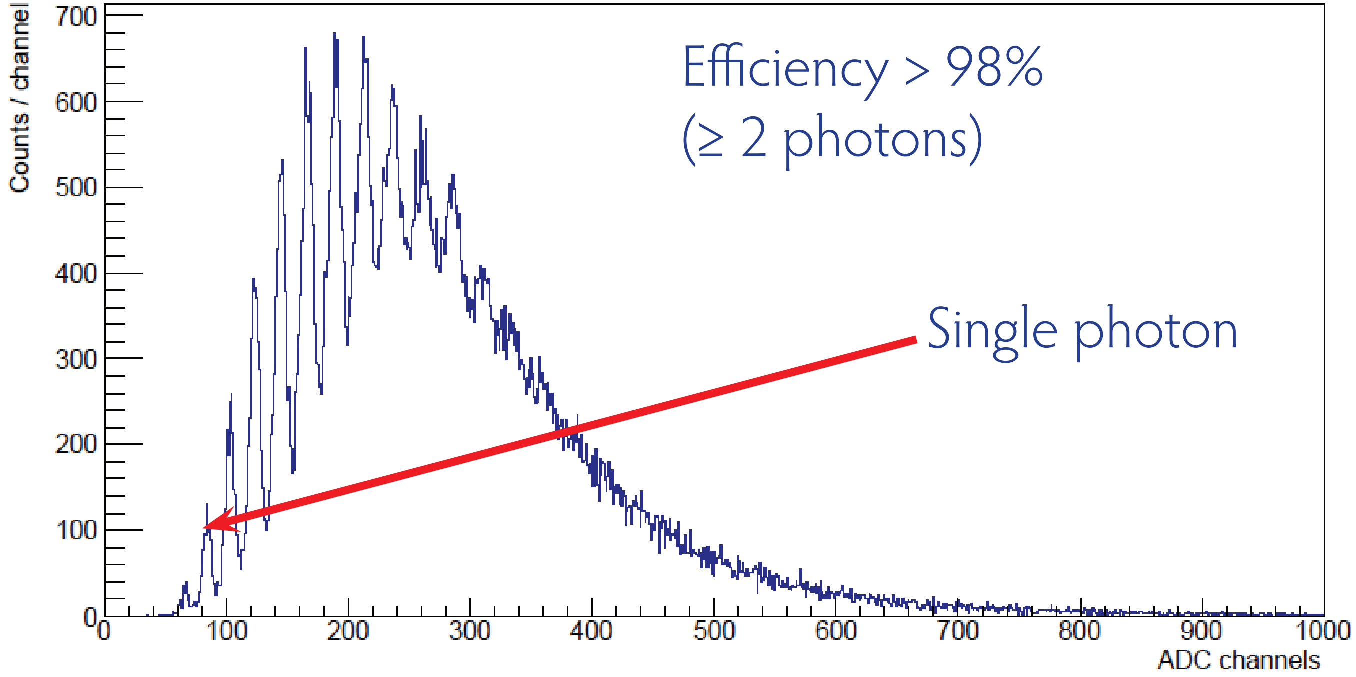


Scintillating fibres O(1 ns);
Scintillating tiles O(100 ps)

Timing Detector: Scintillating Fibres



- 3 layers of 250 µm scintillating fibres
- Read-out by silicon photomultipliers (SiPMs) and custom ASIC (STiC)
- Timing resolution $\mathcal{O}(1\ \mathrm{ns})$ (measured with sodium source)

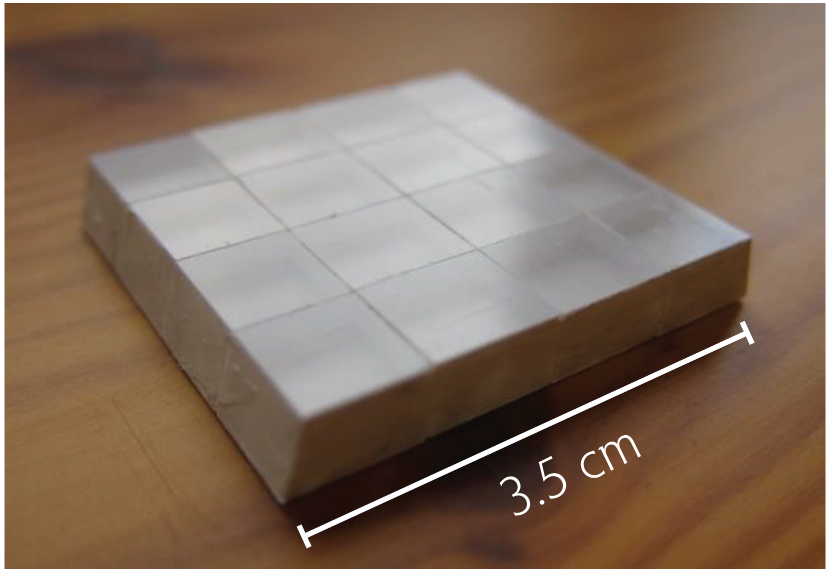


Efficiency > 98% (≥ 2 photons)

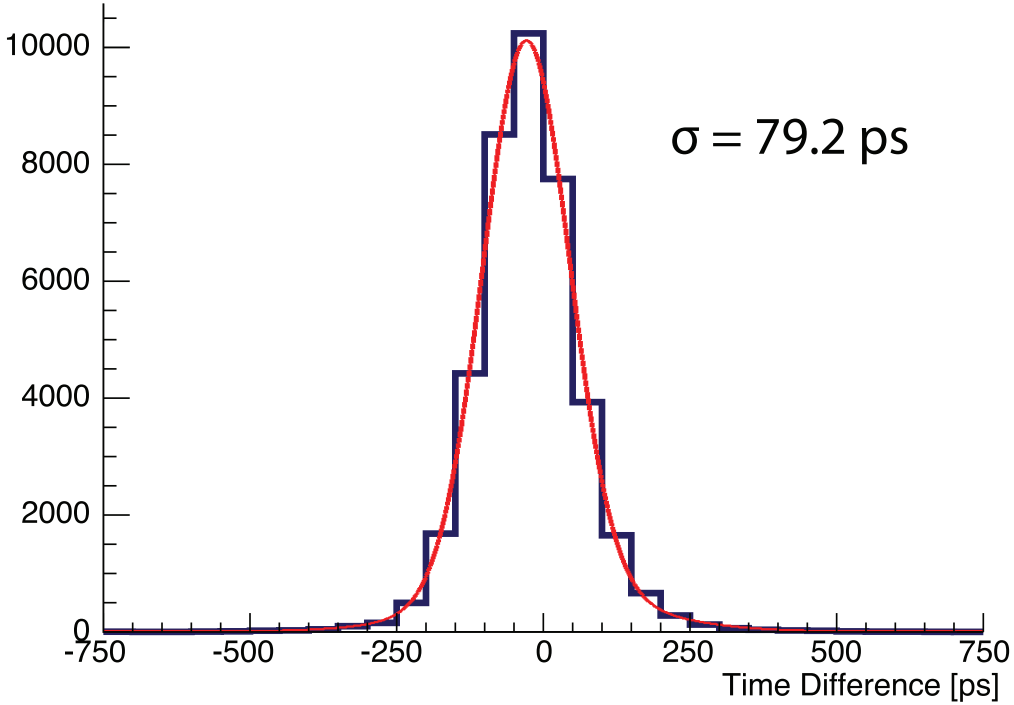
Single photon

Timing Detector: Scintillating tiles

Front

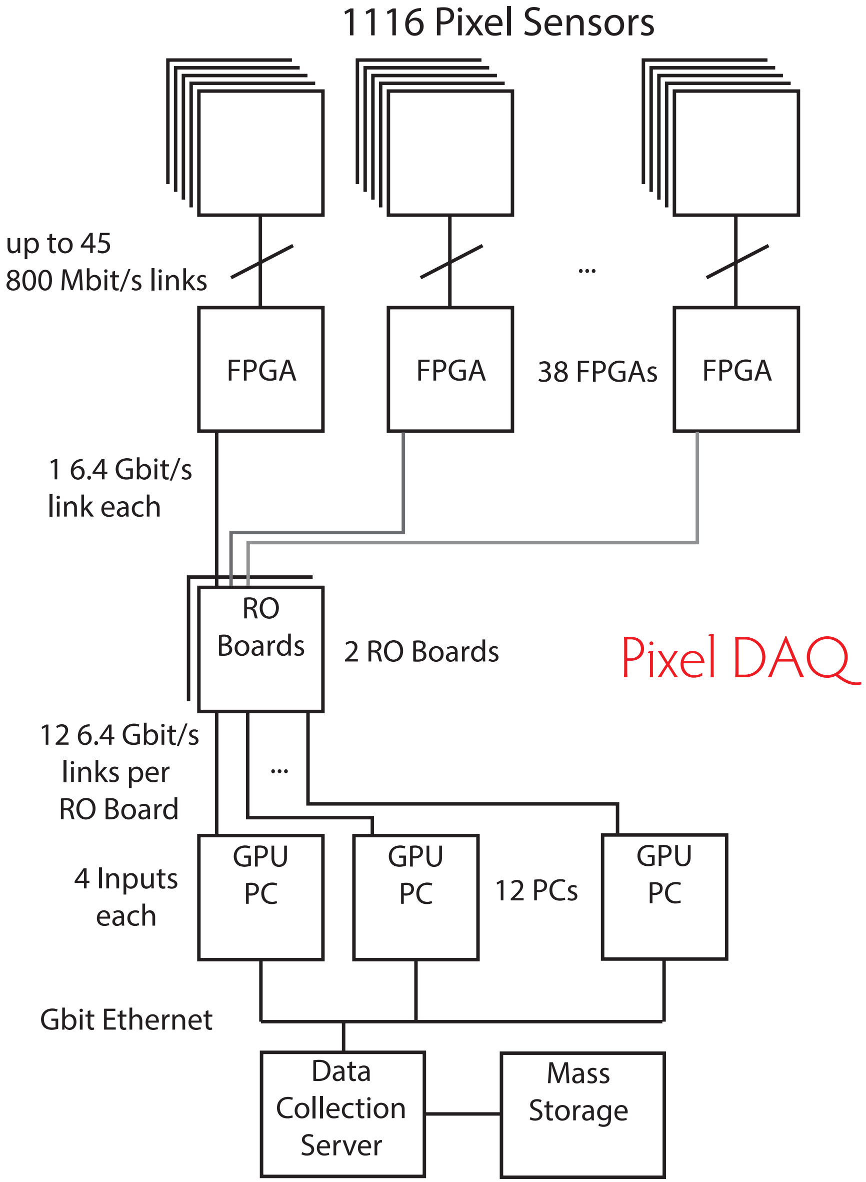


Back



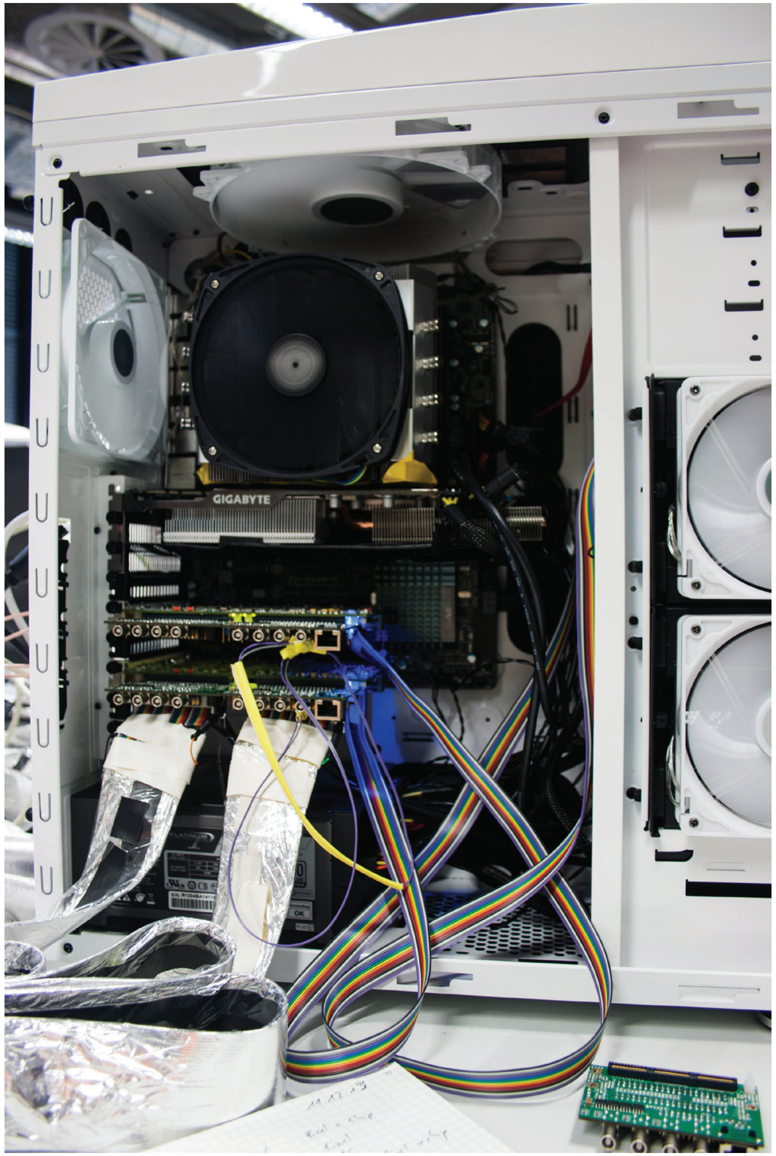
- Test beam with tiles, SiPMs and readout ASIC
- Timing resolution ~ 80 ps

Data Acquisition



- 280 Million pixels (+ fibres and tiles)
- No trigger
- ~ 1 Tbit/s
- FPGA-based switching network
- O(50) PCs with GPUs

Online filter farm

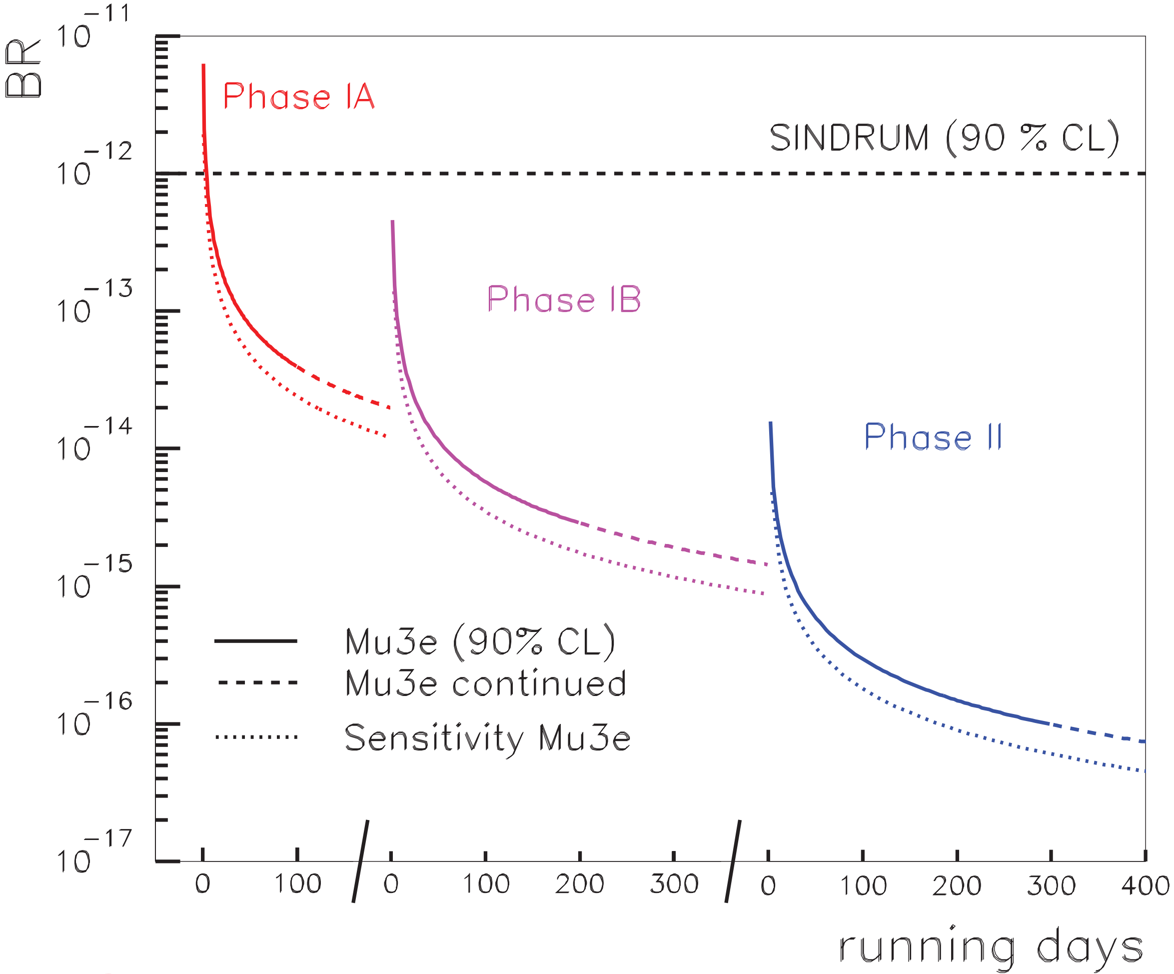


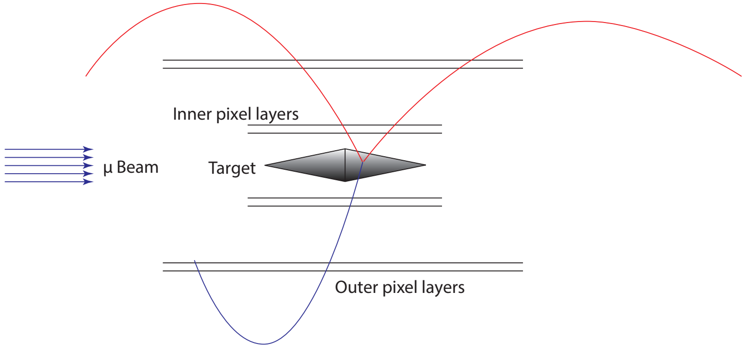
Online software filter farm

- PCs with FPGAs and Graphics Processing Units (GPUs)
- Online track and event reconstruction
- 10^9 3D track fits/s achieved
- Data reduction by factor ~1000
- Data to tape < 100 Mbyte/s

- What to save?
  Events with three tracks from one vertex
  Histogram of all tracks

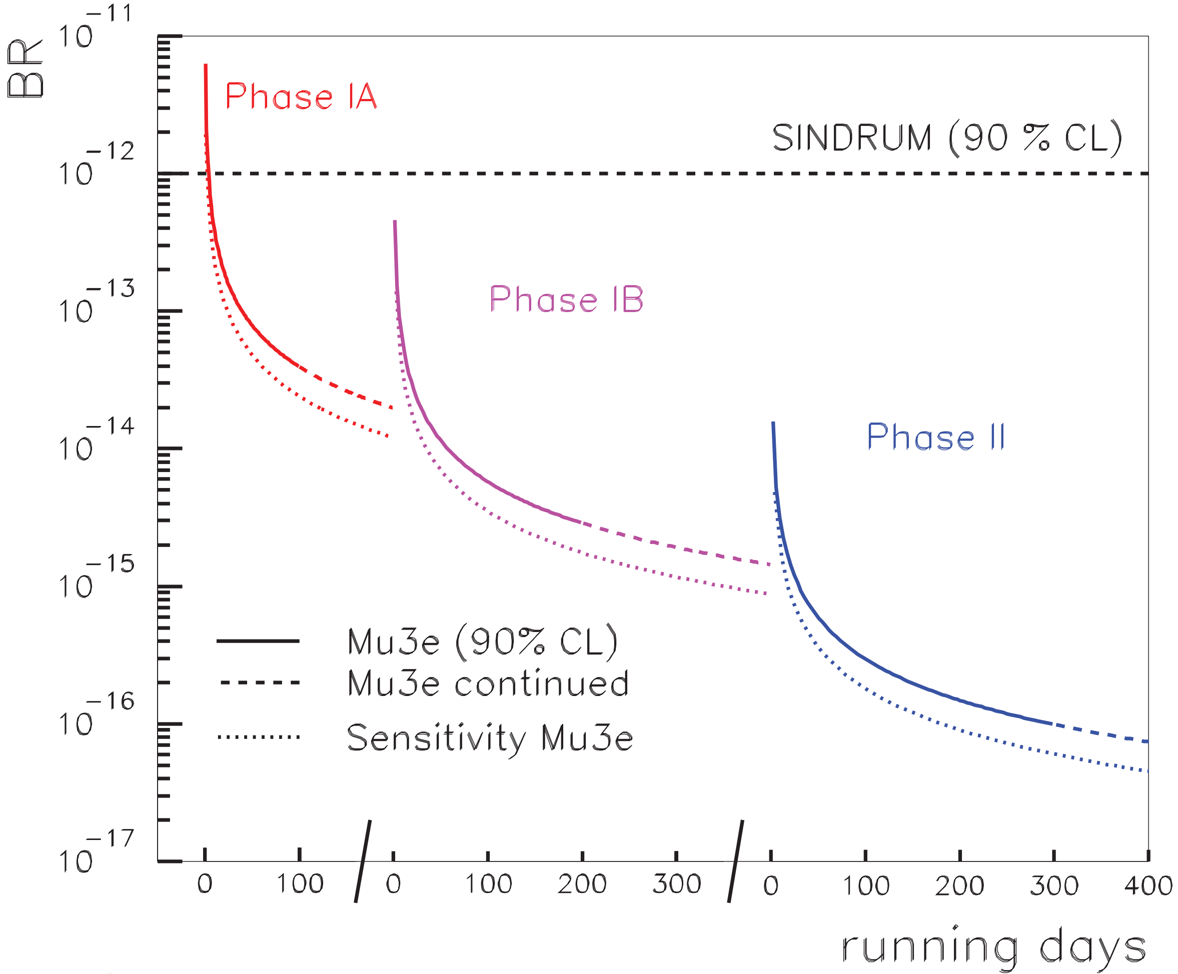
Sensitivity

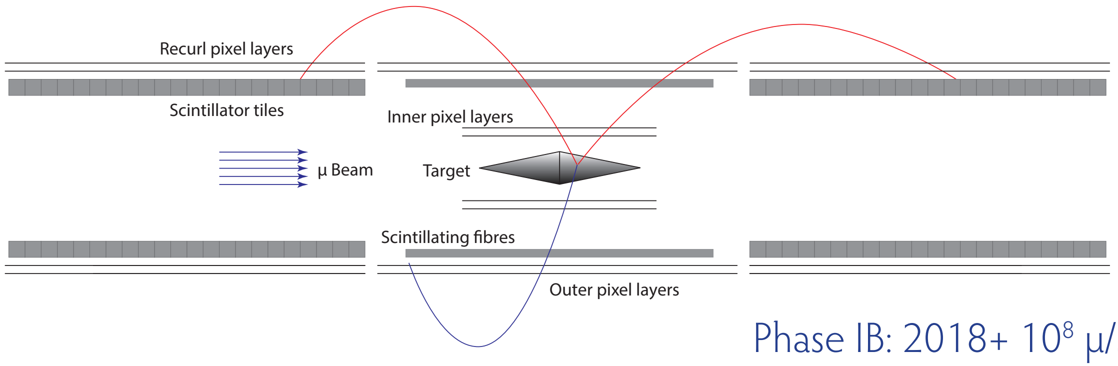




Phase IA: Starting 2017 10^7 μ/s

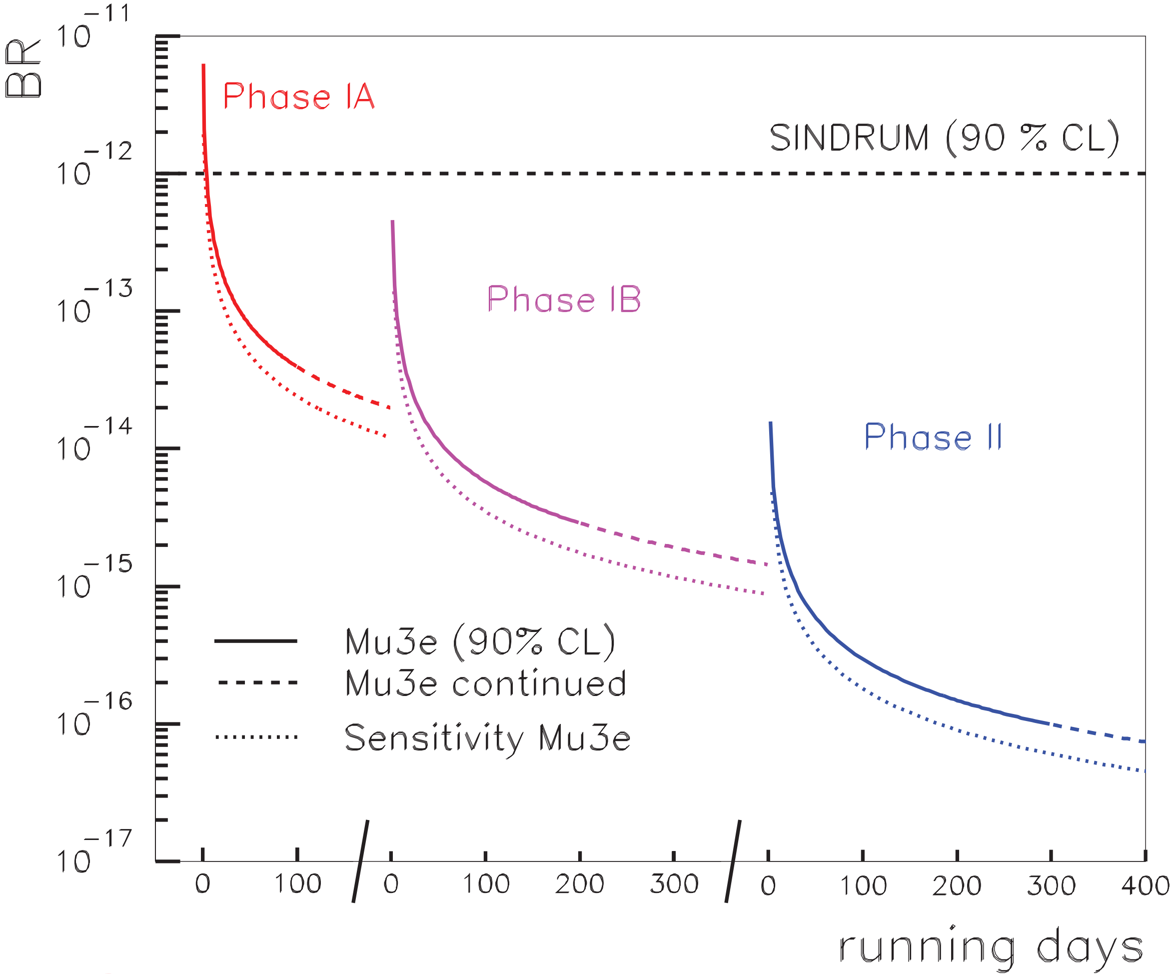
Sensitivity

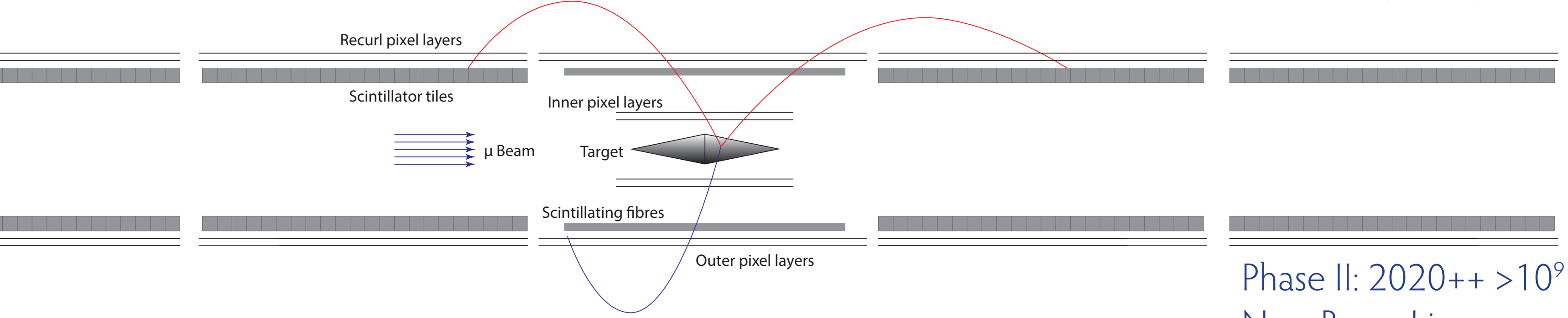




Phase IB: 2018+ 10^8 μ/s

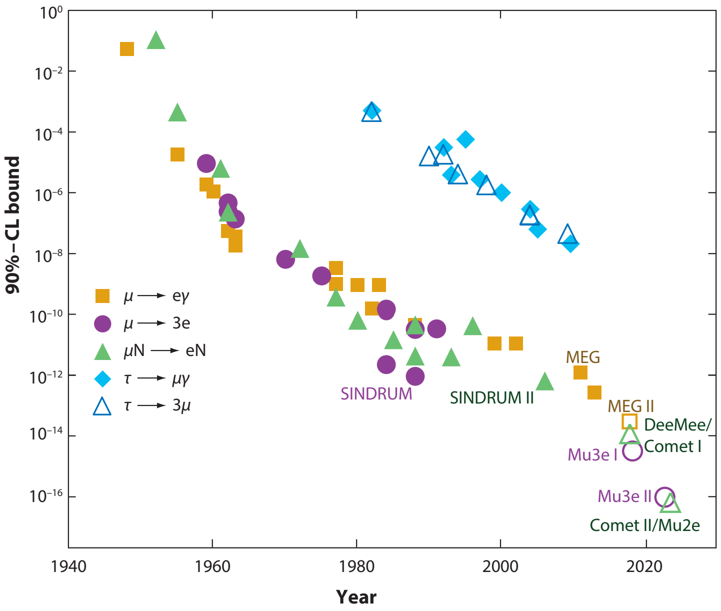
Sensitivity





Phase II: 2020++ >10^9 μ/s
New Beam Line

Summary



- Exciting times ahead in searches for LFV muon decays
- MEG aims for another order of magnitude for μ→eγ
- DeeMee/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

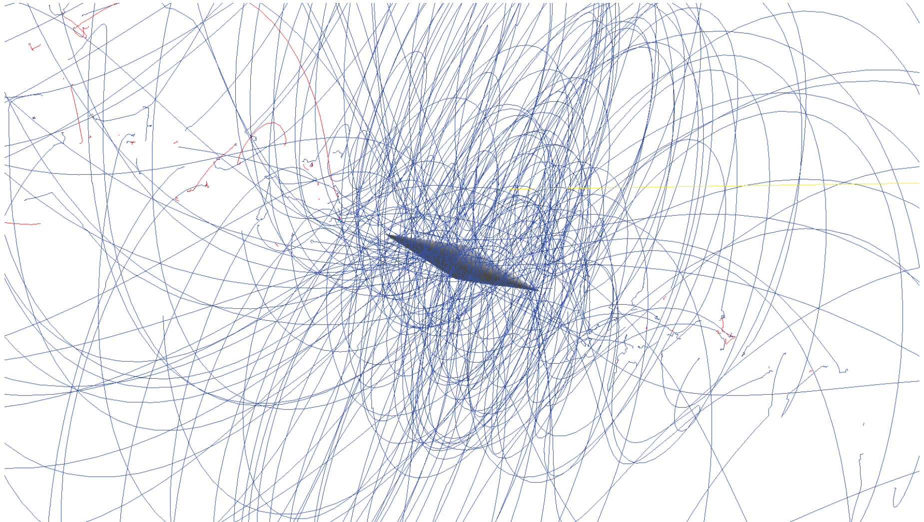
Wish list

- Many models with BR predictions for all three processes

- Bonus points for conversion Z-dependence and μ → eee Dalitz plot

- One-loop calculation of μ → eeeνν

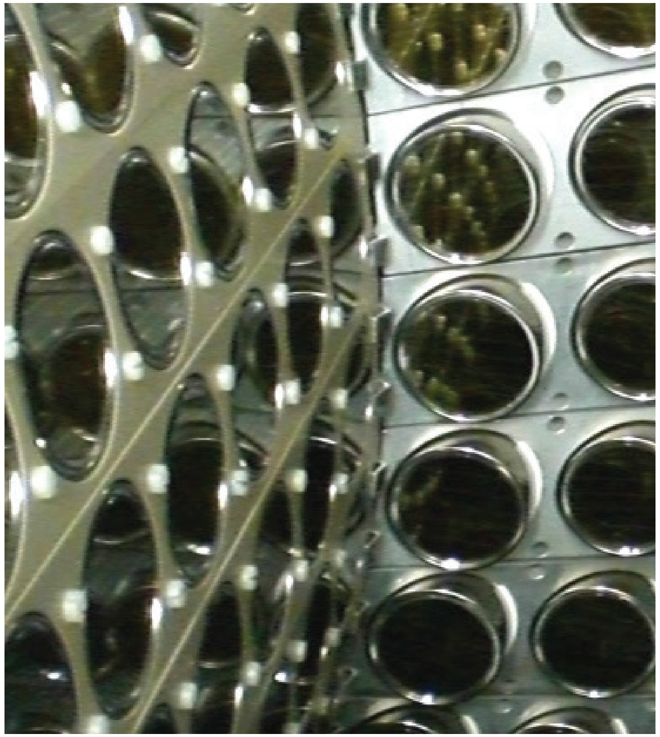
- Other ideas for what to do with 10^{16}+ muon decays

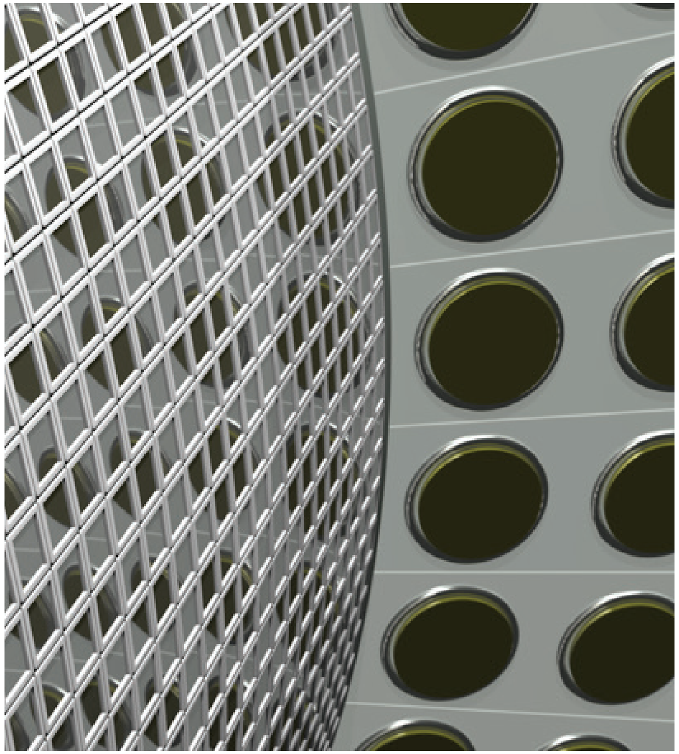


Backup Material

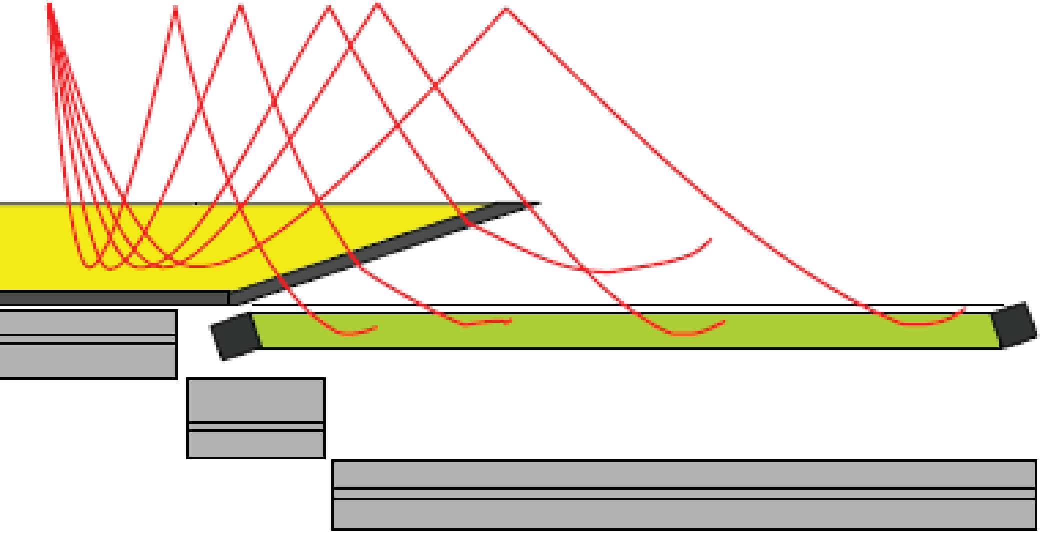
MEG Upgrade - Calorimeter

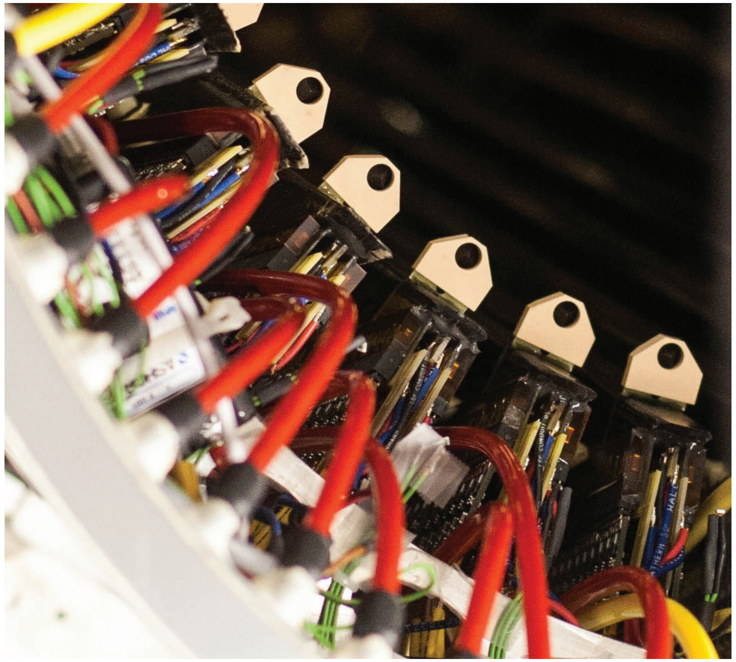
- ~4000 VUV sensitive SiliconPMs on entry face (new development with Hamamatsu)
- Better position and energy resolution
- Better efficiency

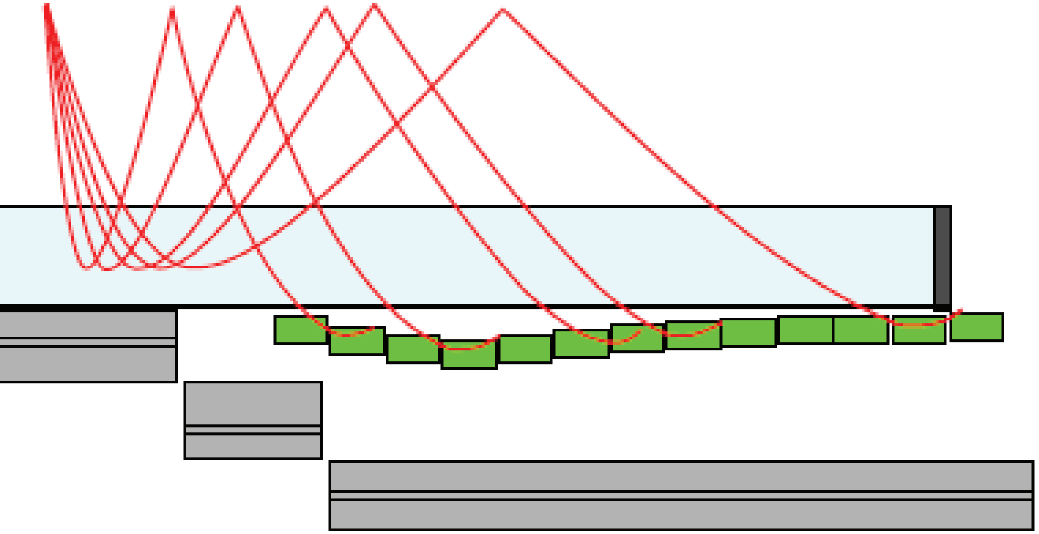




MEG Upgrade - Drift Chamber



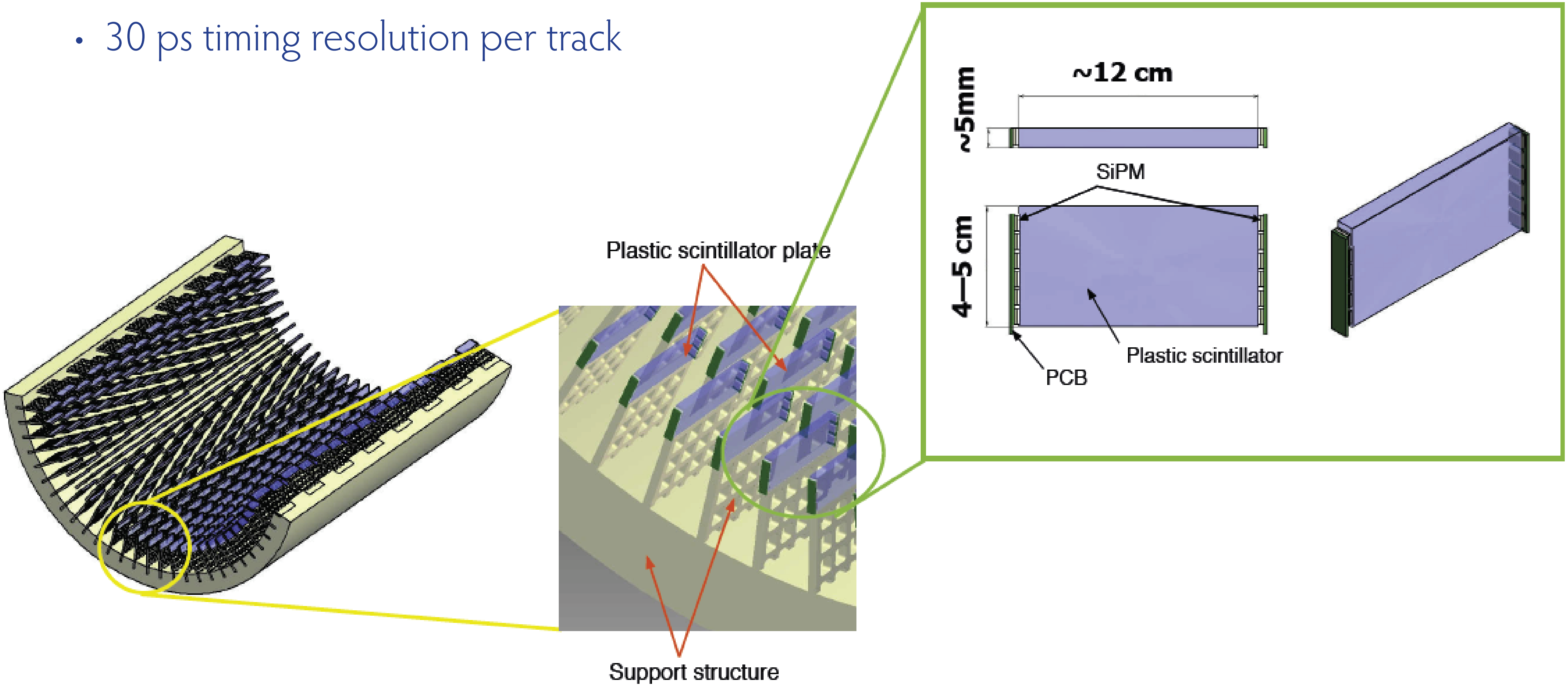




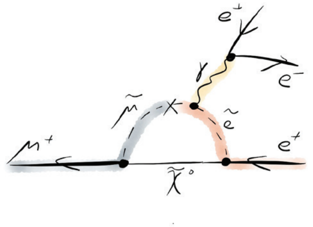
- New single volume drift chamber
- Lower Z gas mixture
- More space points per track
- Better rate capability
- Less material in front of timing counters

MEG Upgrade - Timing Counter

- Many small scintillators
- Read-out by SiliconPMs
- On average eight counters hit by track
- 30 ps timing resolution per track



A general effective Lagrangian



Tensor terms (dipole) e.g. supersymmetry

$$L_{\mu \to eee} = 2\, G_F \,(m_\mu A_R\, \bar{\mu}_R\, \sigma^{\mu\nu} e_L\, F_{\mu\nu} \qquad + m_\mu A_L\, \bar{\mu}_L\, \sigma^{\mu\nu} e_R\, F_{\mu\nu}$$

Four-fermion terms e.g. Z'

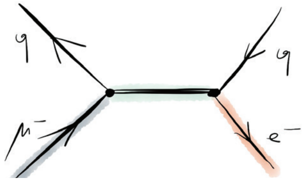
$$+ g_1 (\bar{\mu}_R e_L)(\bar{e}_R e_L) \qquad + g_2 (\bar{\mu}_L e_R)(\bar{e}_L e_R)$$

scalar

$$+ g_3 (\bar{\mu}_R \gamma^\mu e_R)(\bar{e}_R \gamma^\mu e_R) \qquad + g_4 (\bar{\mu}_L \gamma^\mu e_L)(\bar{e}_L \gamma^\mu e_L)$$

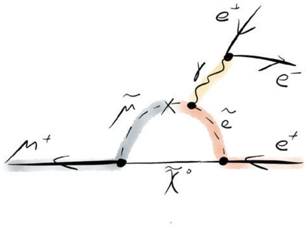
$$+ g_5 (\bar{\mu}_R \gamma^\mu e_R)(\bar{e}_L \gamma^\mu e_L) \qquad + g_6 (\bar{\mu}_L \gamma^\mu e_L)(\bar{e}_R \gamma^\mu e_R) \;\; + \text{H. C.} \,)$$

vector

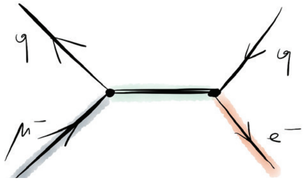


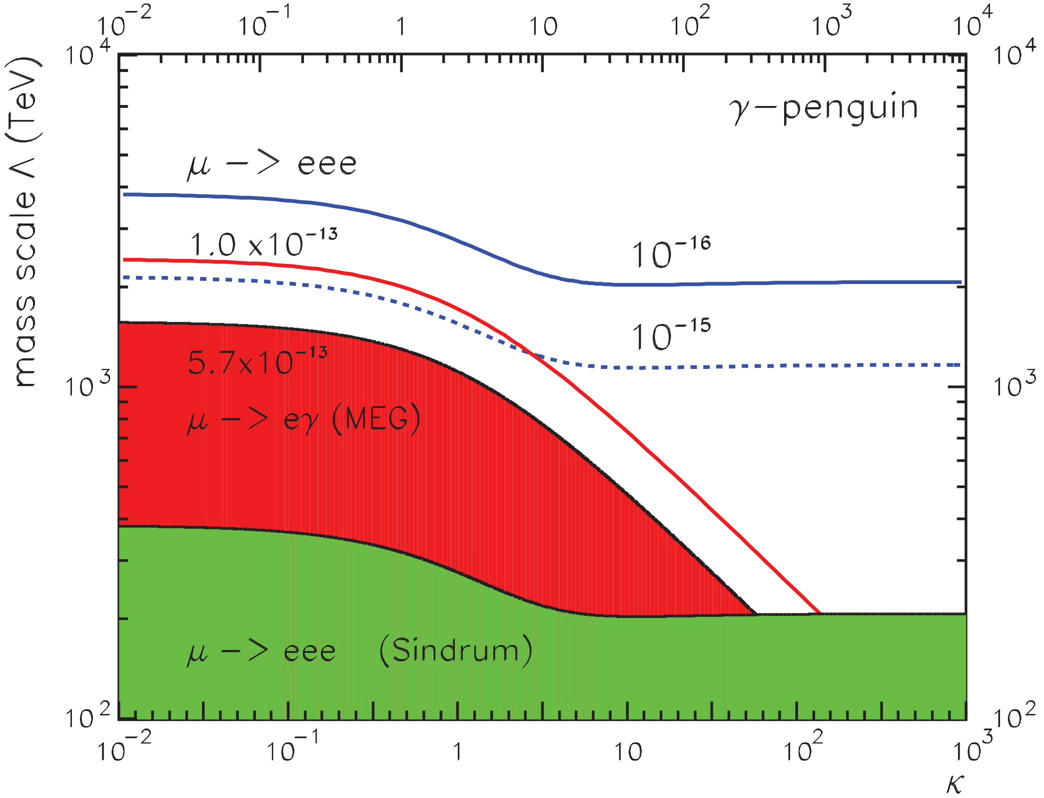
(Y. Kuno, Y. Okada,
Rev.Mod.Phys. 73 (2001) 151)

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



$$L_{LFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2} A_R \bar{\mu}_R \sigma^{\mu\nu} e_L F_{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2} (\bar{\mu}_L \gamma^\mu e_L)(\bar{e}_L \gamma^\mu e_L)$$

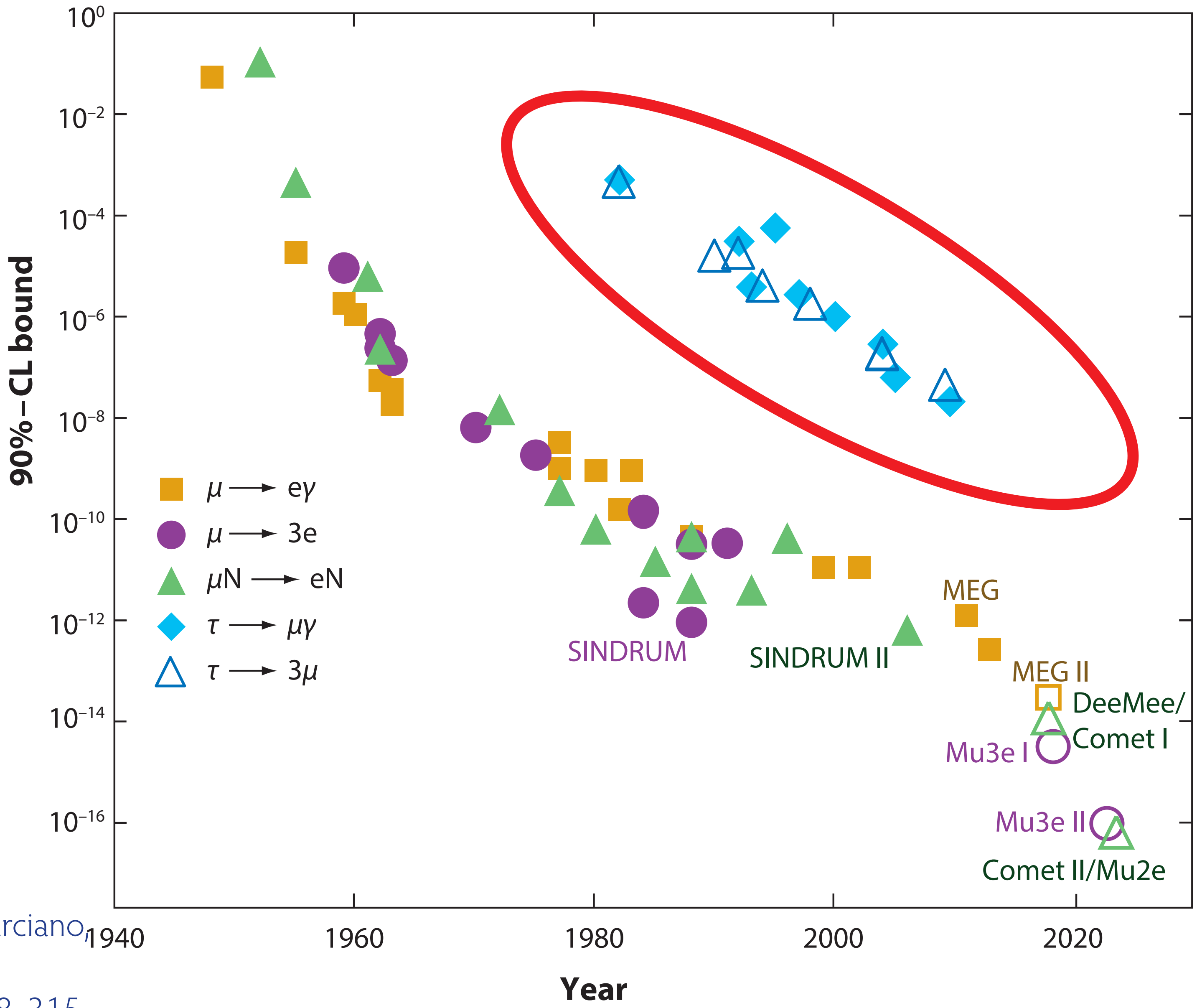




- One loop term and one contact term
- Ratio κ between them
- Common mass scale Λ
- Allows for sensitivity comparisons between μ → eee and μ → eγ
- In case of dominating dipole couplings (κ = 0):

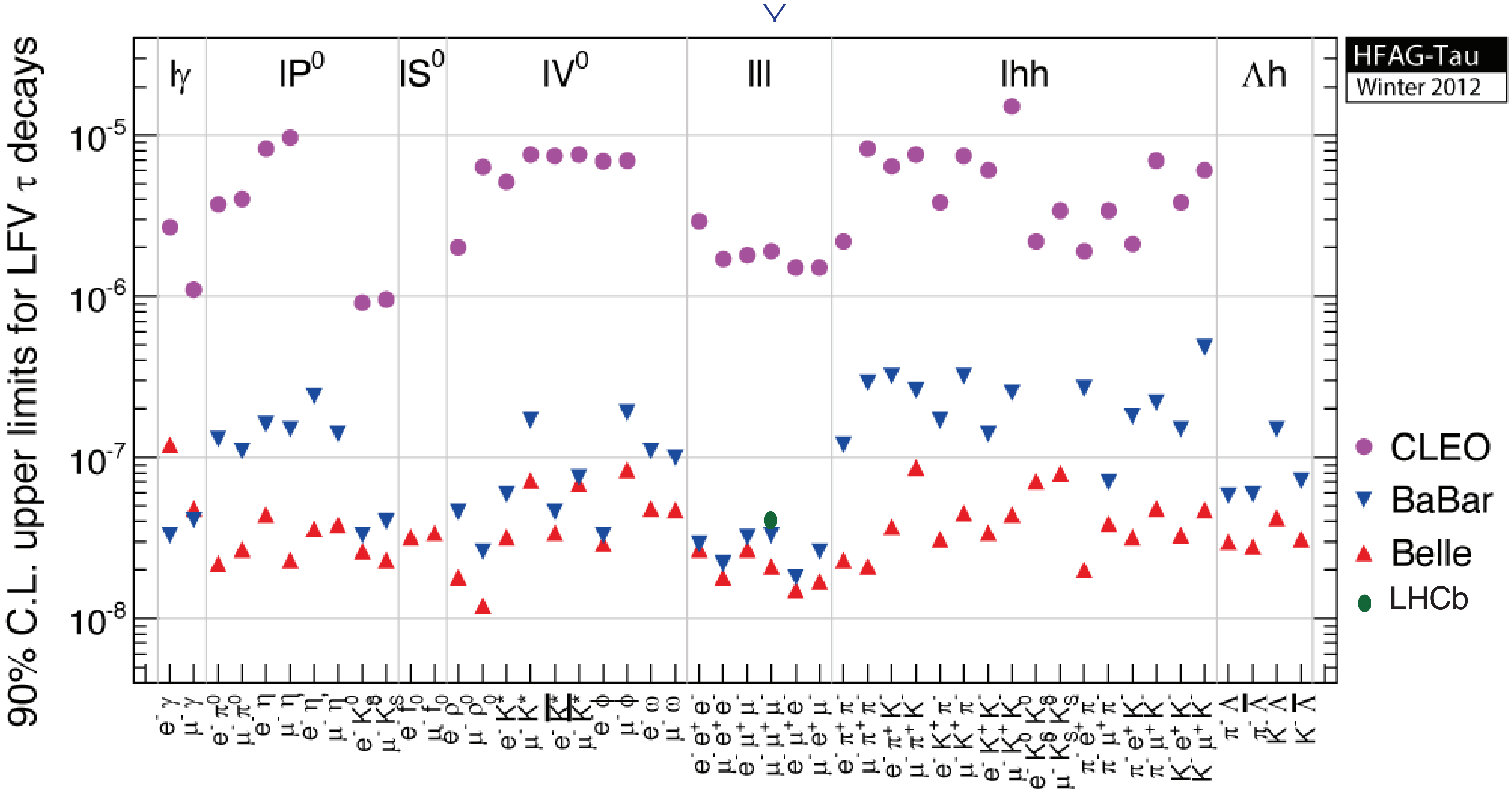
$$\frac{B(\mu \to eee)}{B(\mu \to e\gamma)} = 0.006 \quad (\text{essentially } \alpha_{em})$$

History of LFV experiments

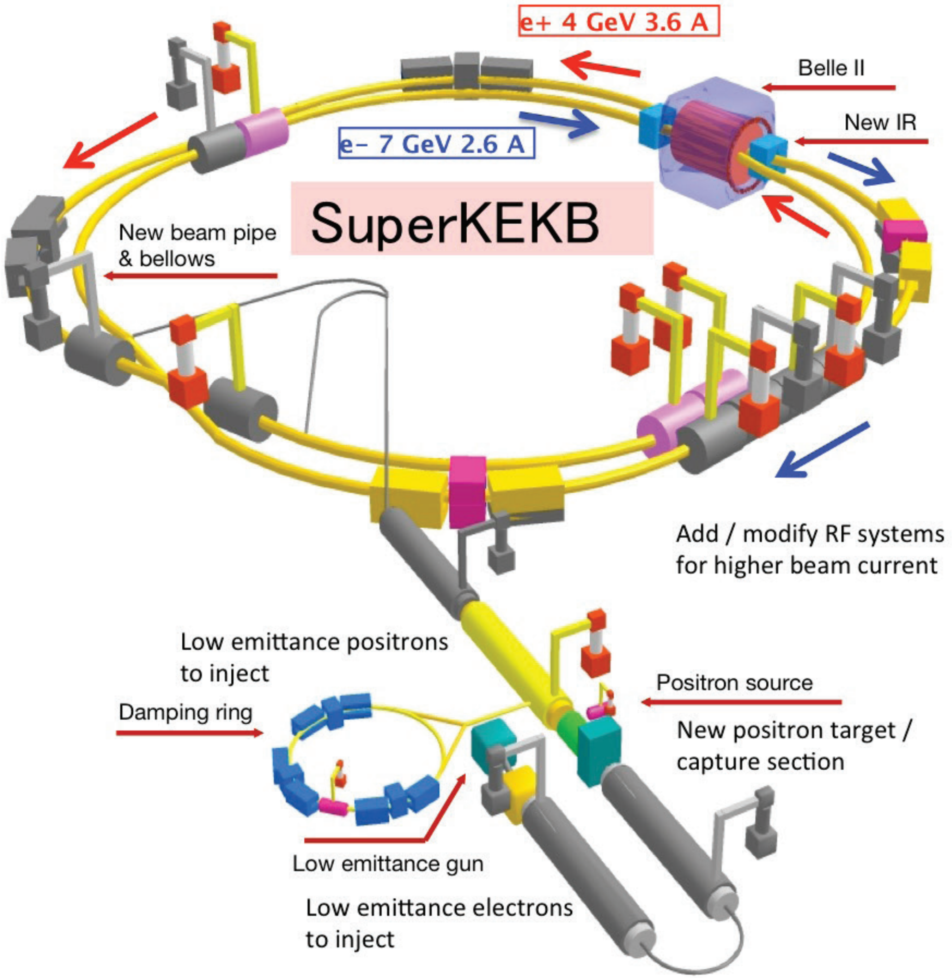


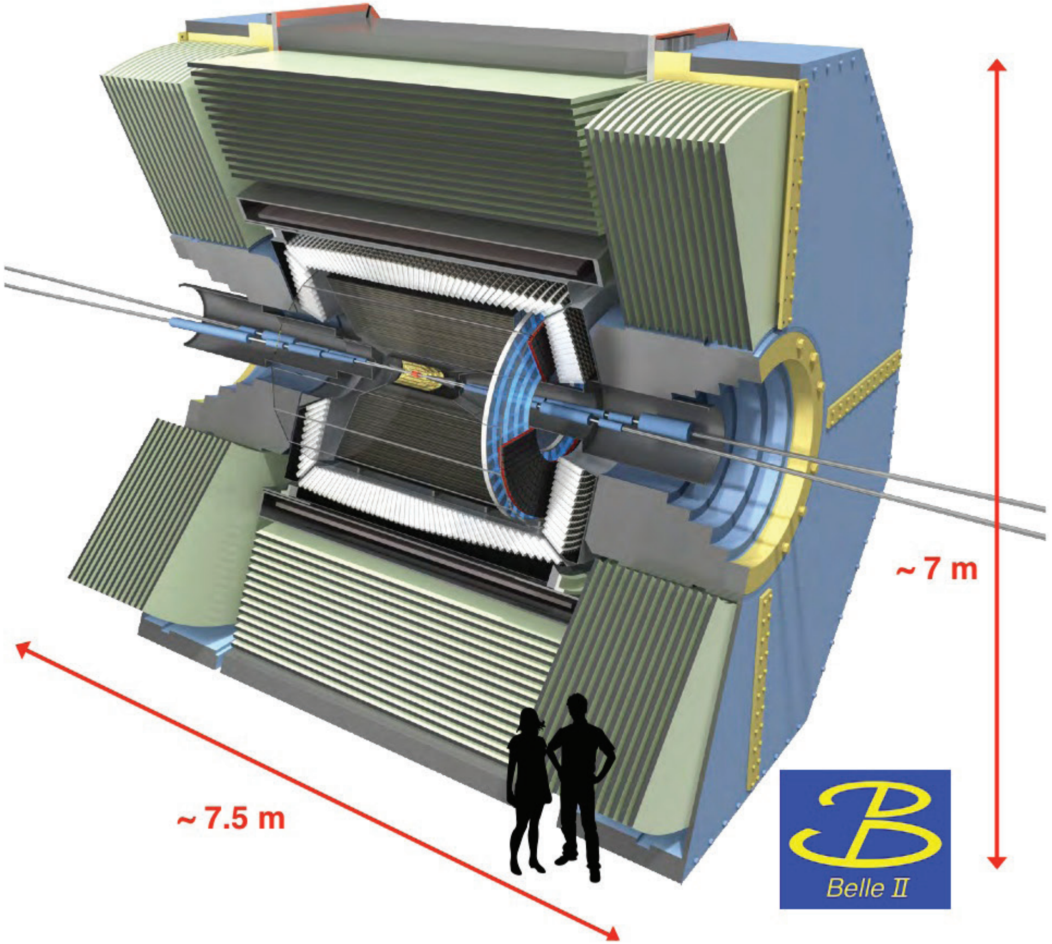
(Updated from W.J. Marciano, T. Mori and J.M. Roney, Ann.Rev.Nucl.Part.Sci. 58, 315 (2008))

Lepton flavour violating τ-decays



Belle II at Super KEKB

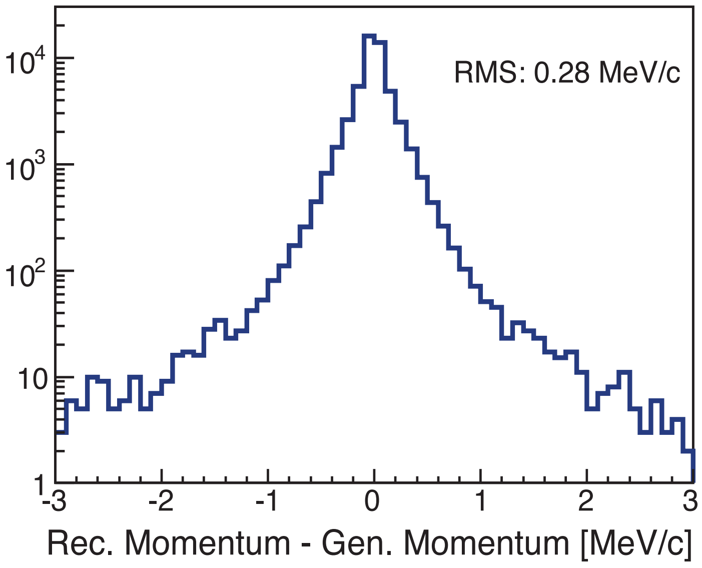


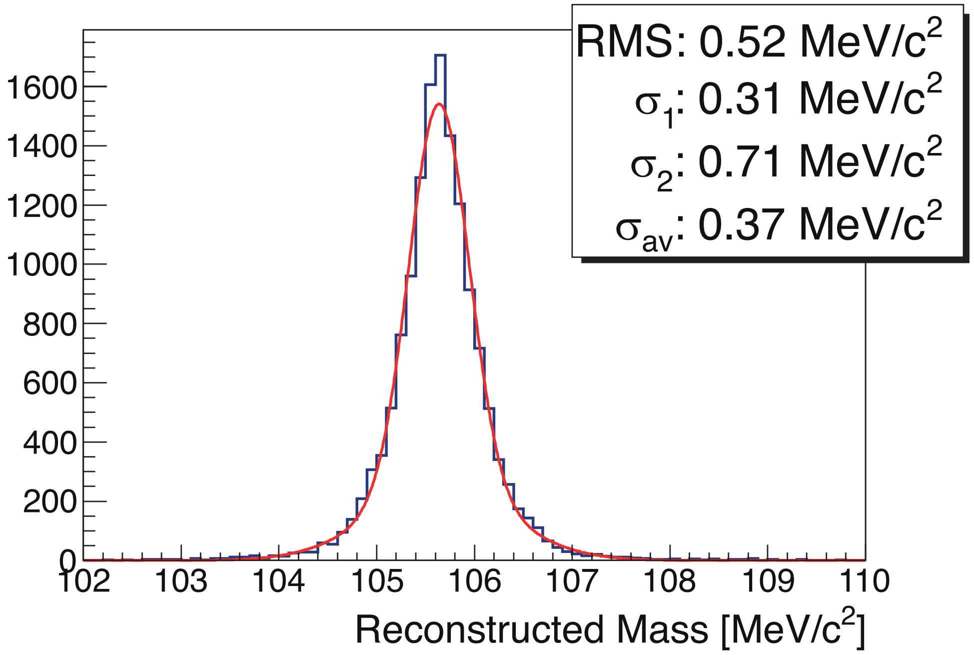


Expect 5× 10^{10} τ pairs - branching fractions of 10^{-9} achievable

Simulated Performance - Mu3e Phase II

- 3D multiple scattering track fit
- Simulation results:
  280 keV single track momentum
  520 keV total mass resolution





Simulated Performance - Mu3e Phase II