Lepton Flavour Violation Experiments

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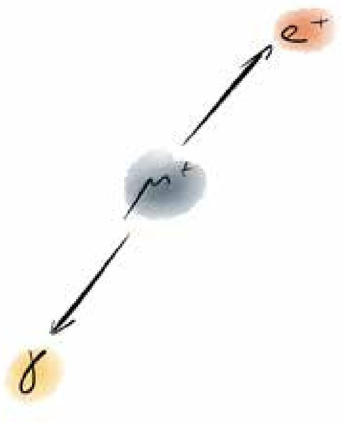
PRISMA

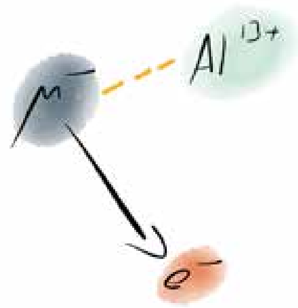
Heidelberg,
25.7.2016

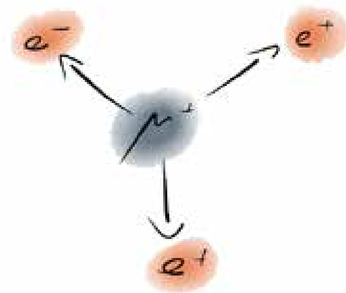
JG|U

Emmy Noether-Programm
Deutsche Forschungsgemeinschaft
DFG

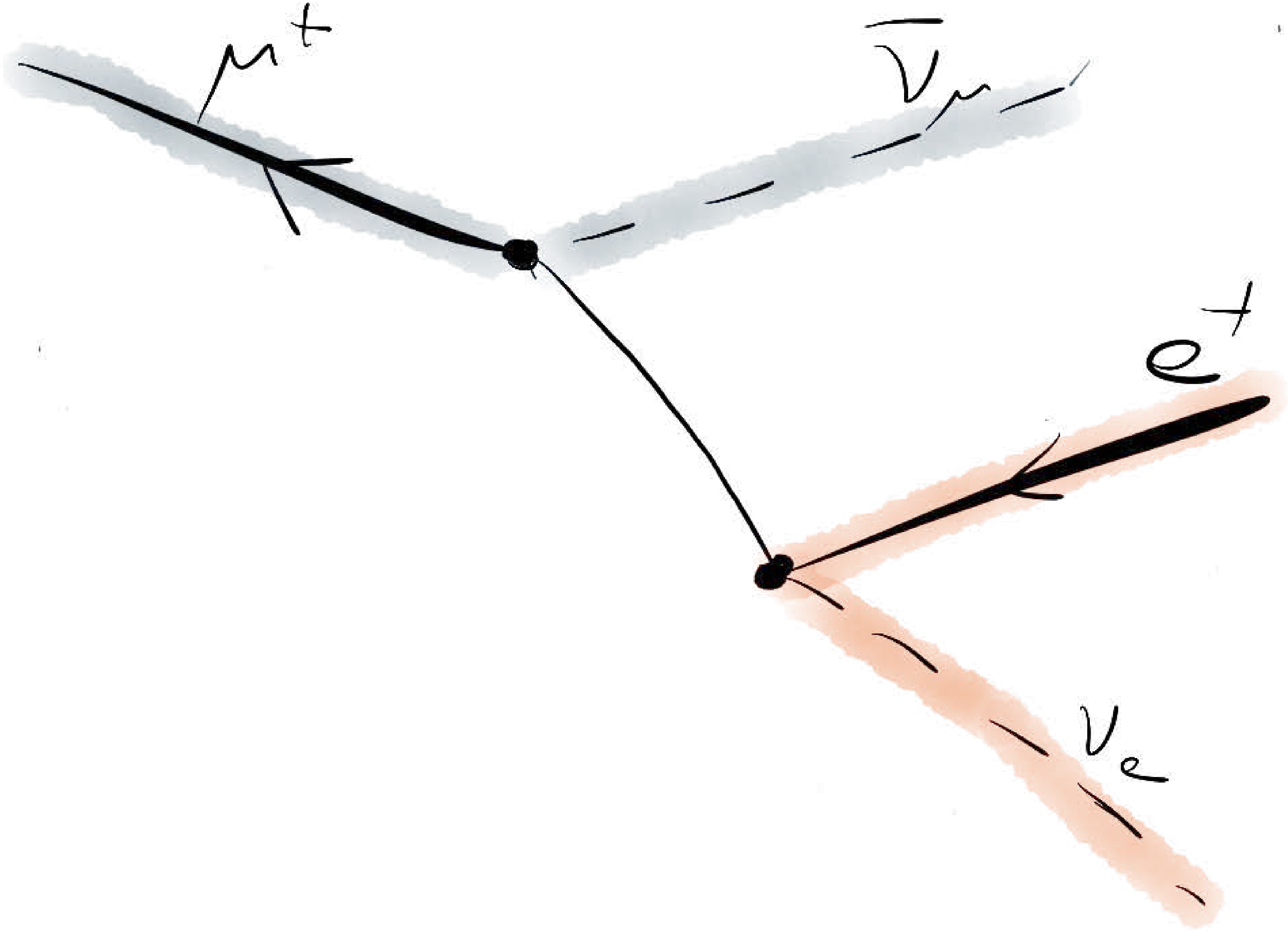
Charged Lepton Flavour Violation



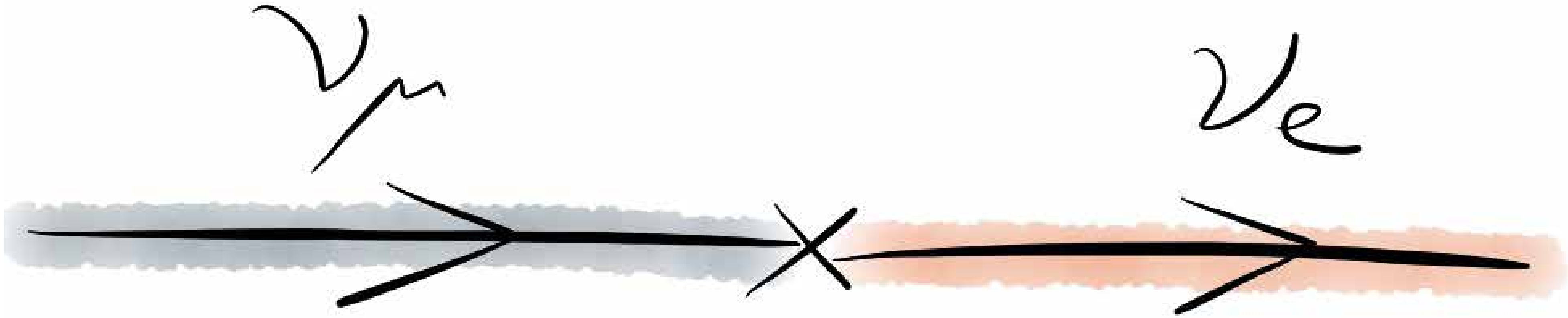




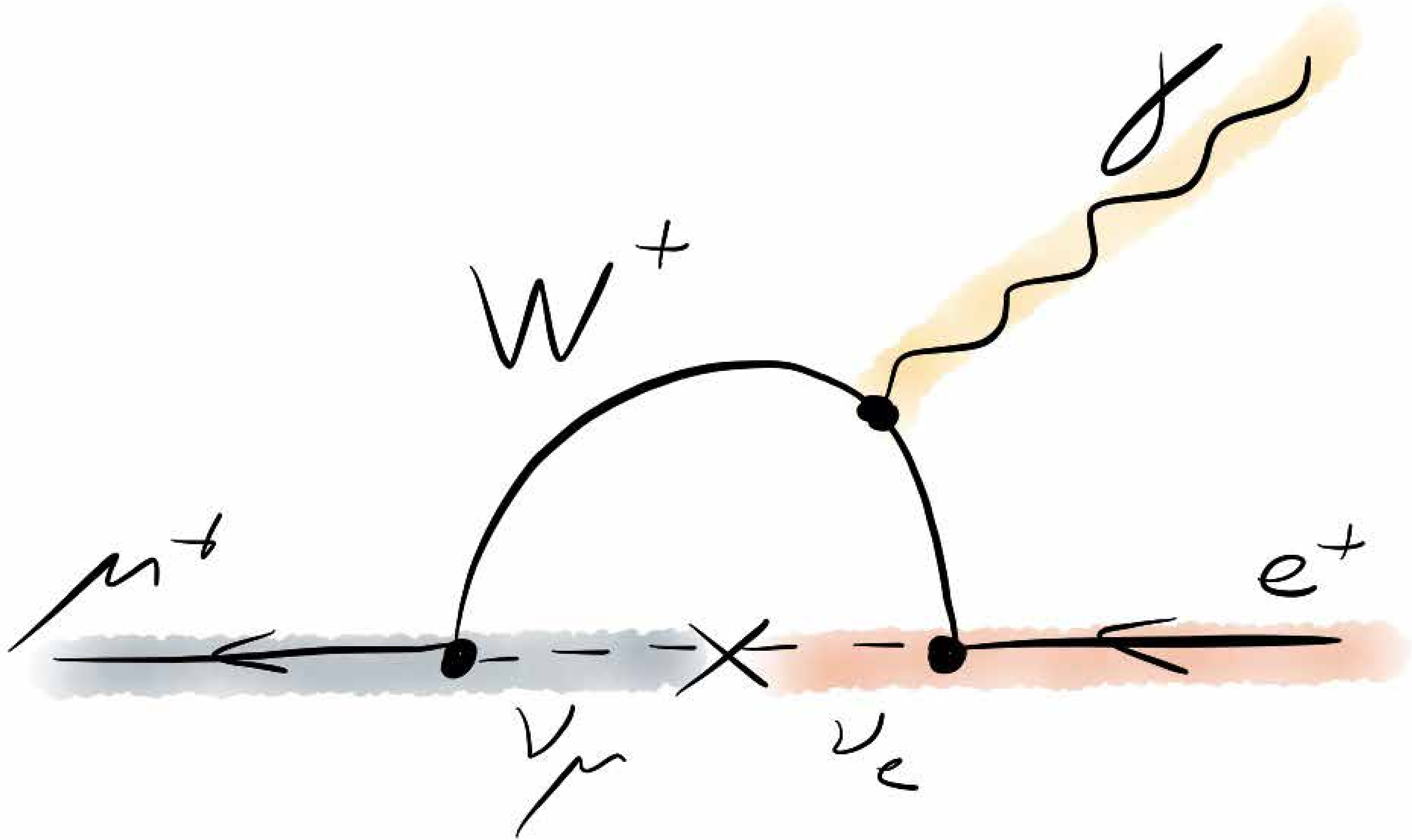
Lepton Flavour



Lepton Flavour Violation!



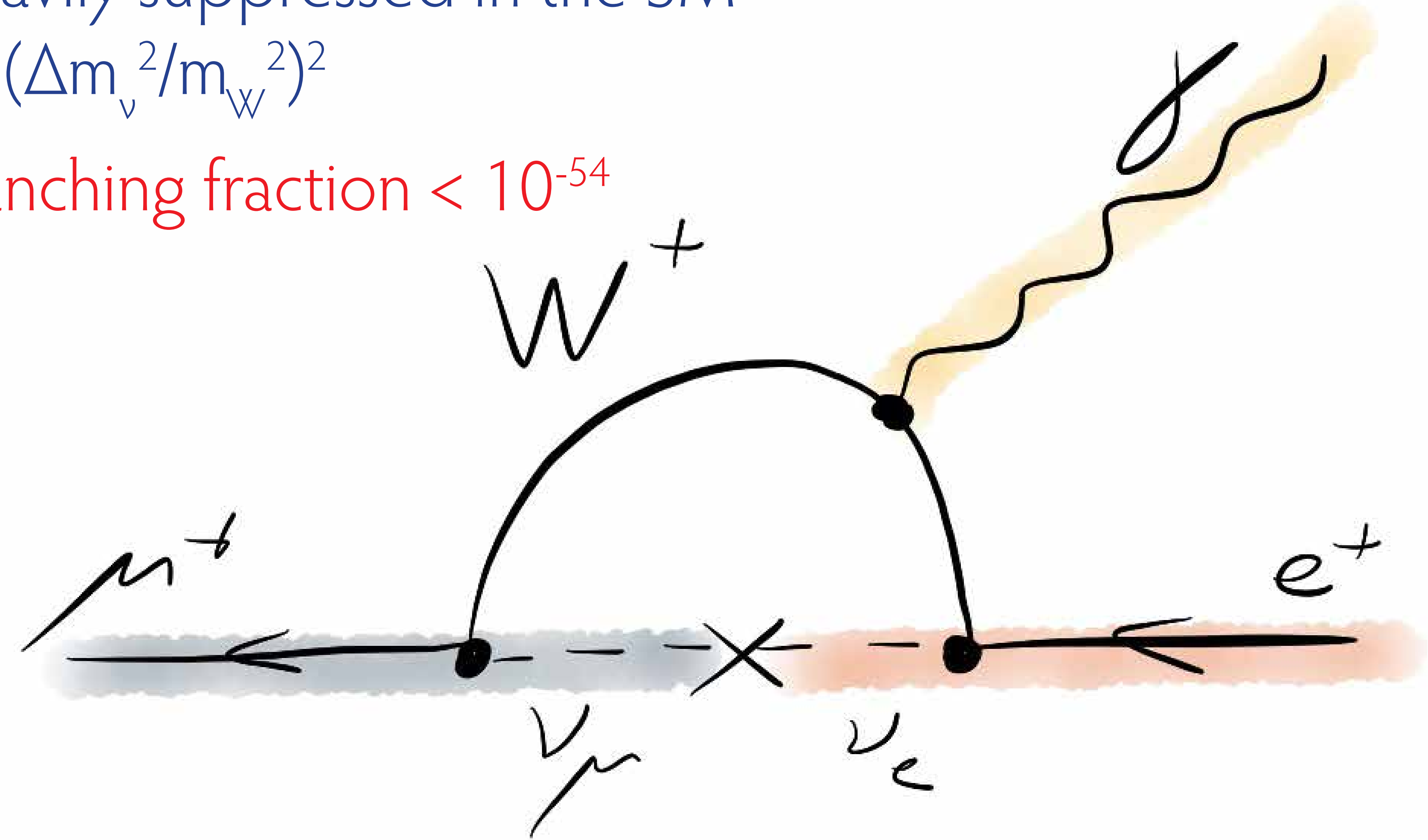
Charged Lepton Flavour Violation?



Charged Lepton Flavour Violation?

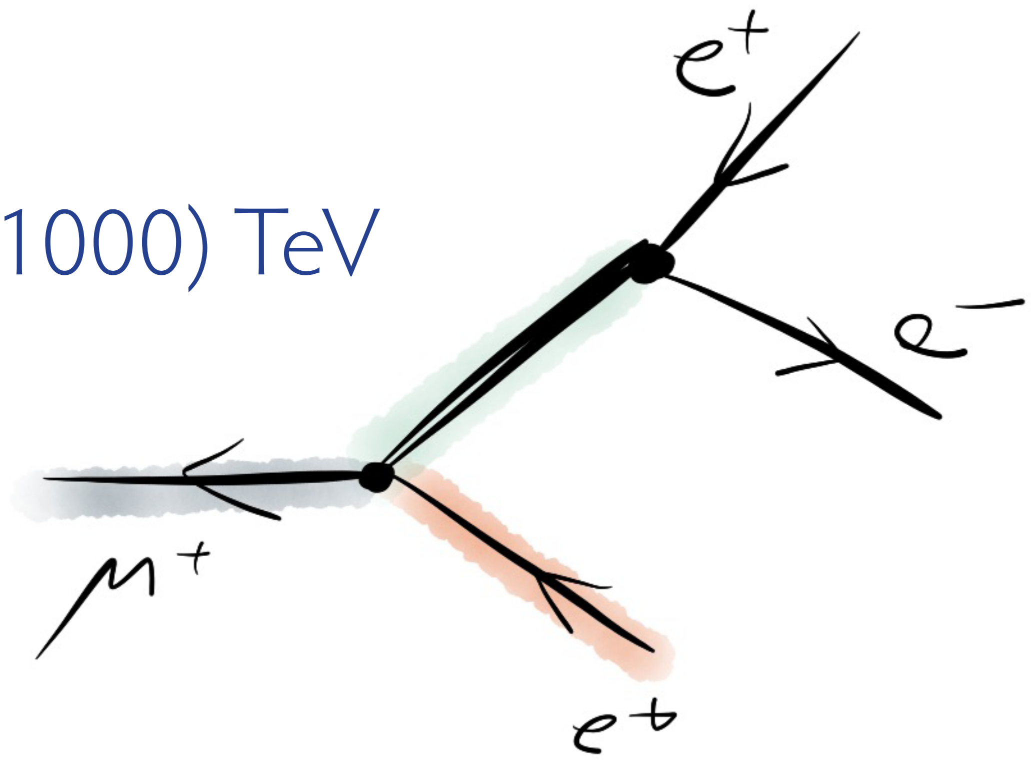
Heavily suppressed in the SM
by $(\Delta m_{\nu}^{2}/m_{W}^{2})^{2}$

Branching fraction $< 10^{-54}$



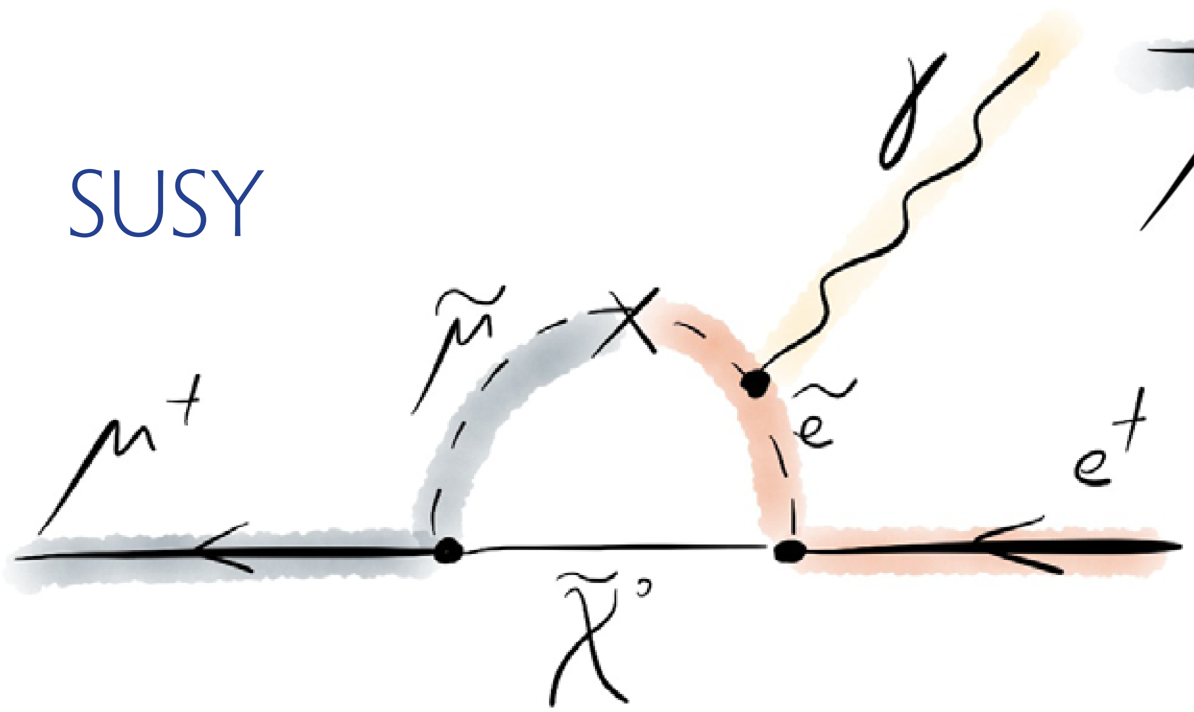
Charged Lepton Flavour Violation?

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

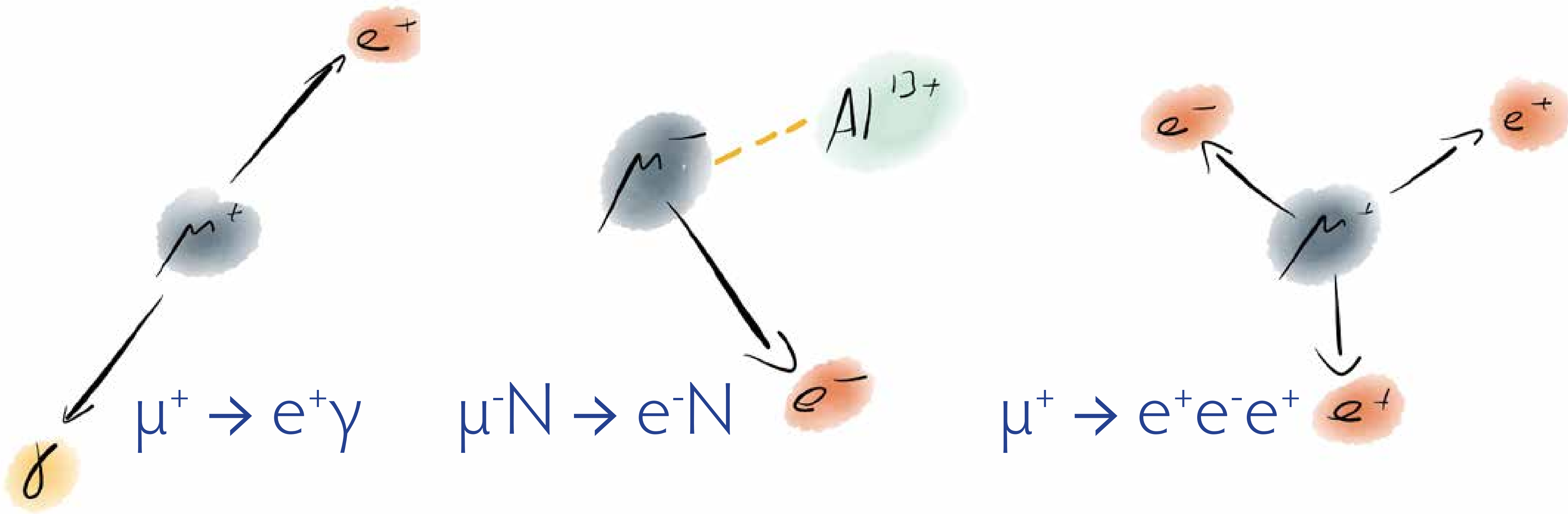


New bosons

SUSY

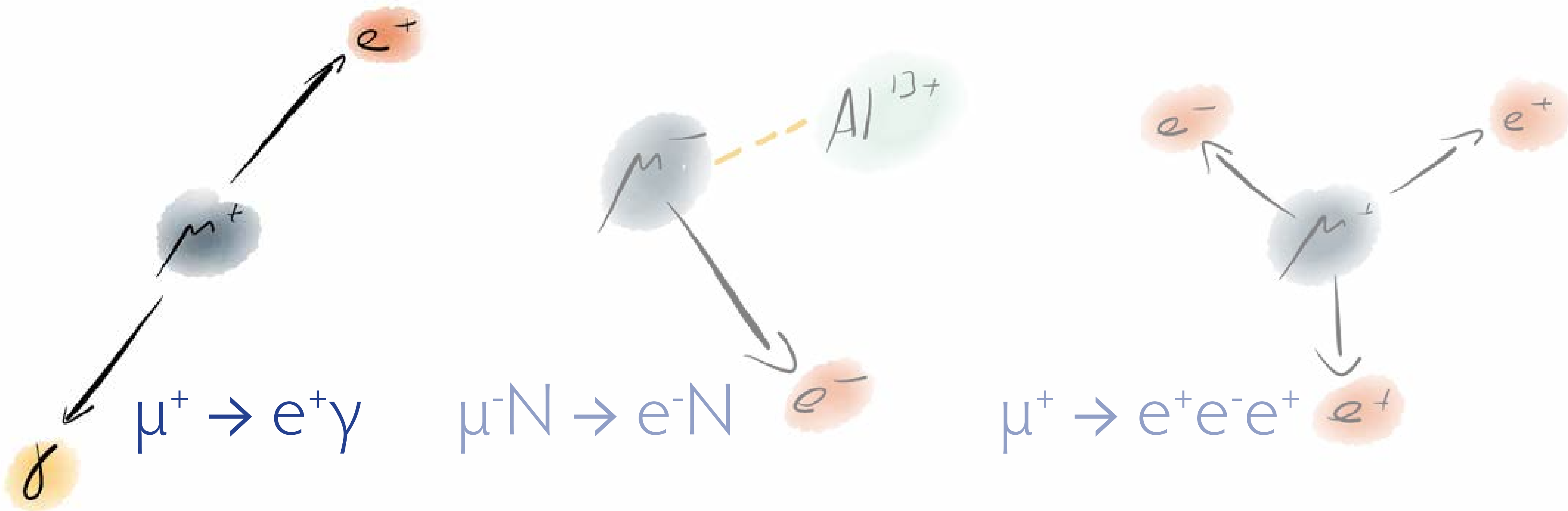


LFV Muon Decays



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

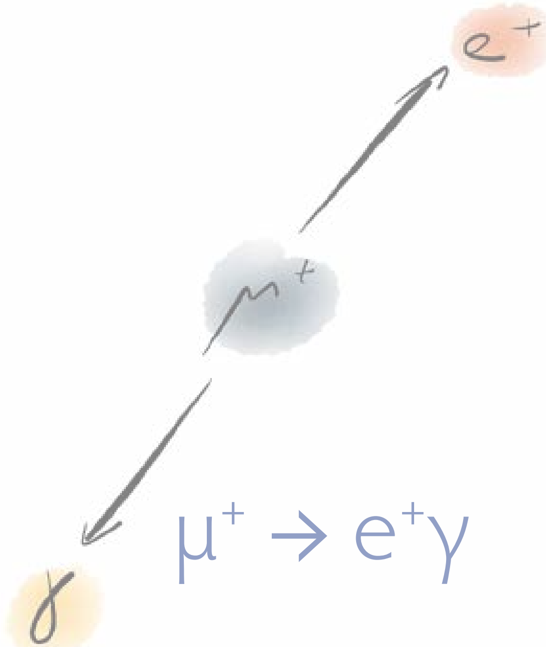
LFV Muon Decays: Experimental signatures



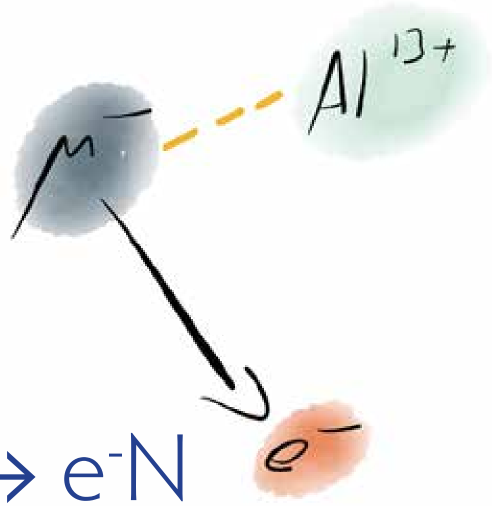
Kinematics

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

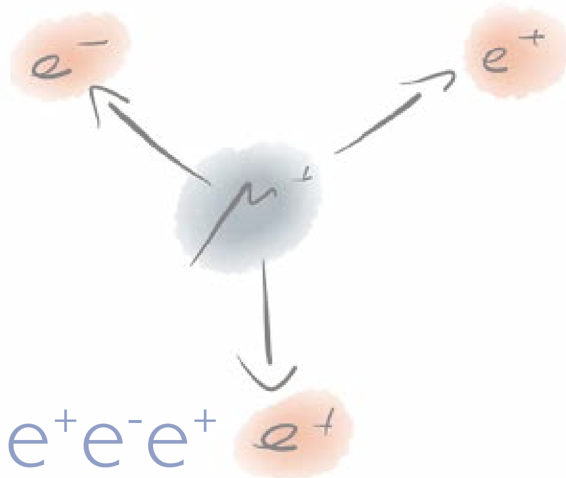
LFV Muon Decays: Experimental signatures



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



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



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

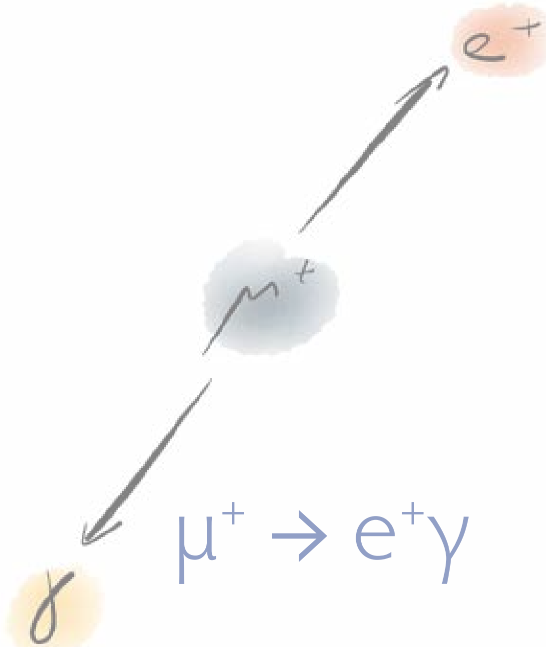
Kinematics

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

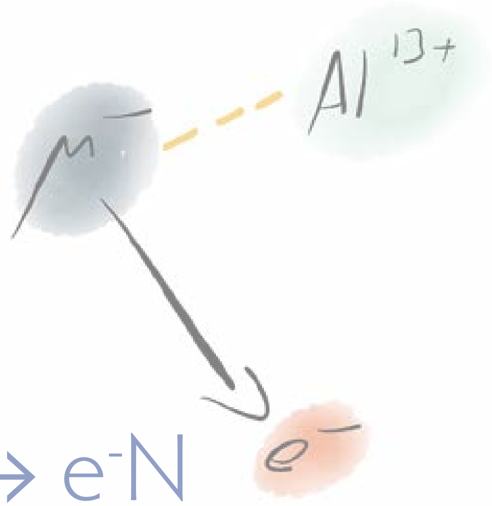
Kinematics

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

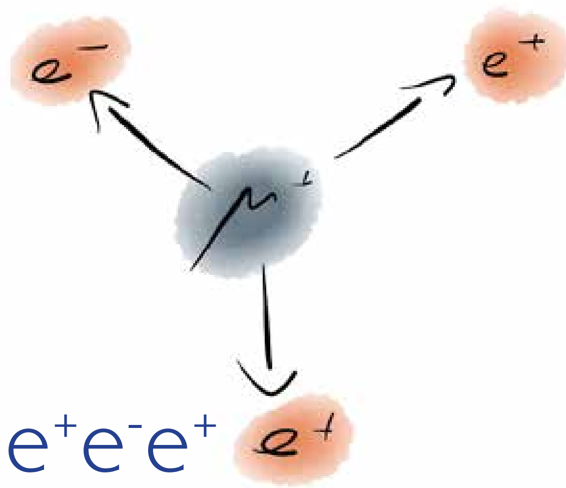
LFV Muon Decays: Experimental signatures



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



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



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

Kinematics

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

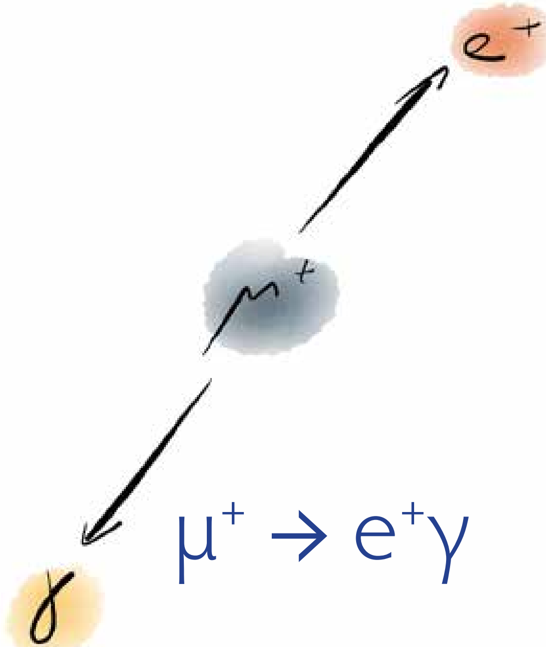
Kinematics

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

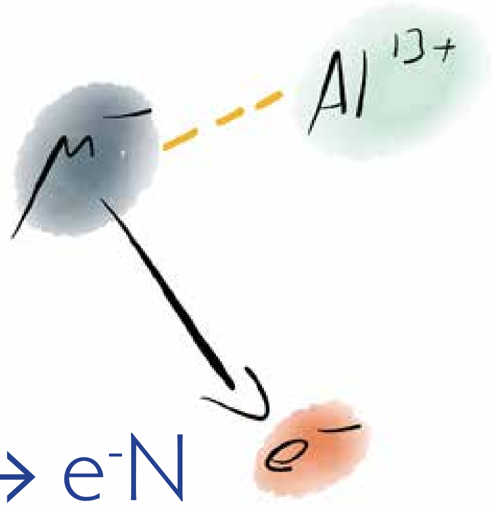
Kinematics

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

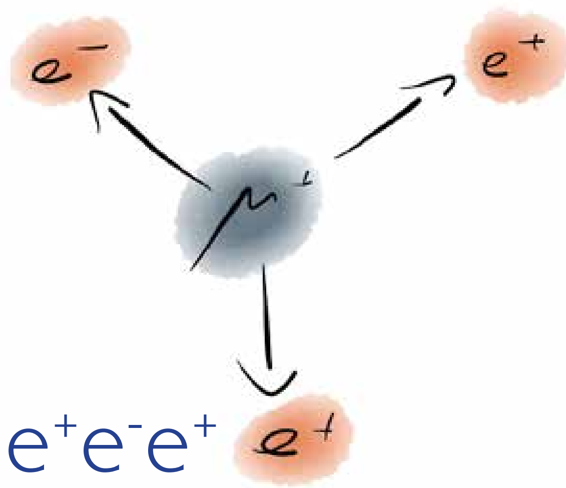
LFV Muon Decays: Experimental signatures



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



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



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

Kinematics

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

Background

- Accidental background
- Radiative decay

Kinematics

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

Background

- Decay in orbit
- Antiprotons, pions, cosmics

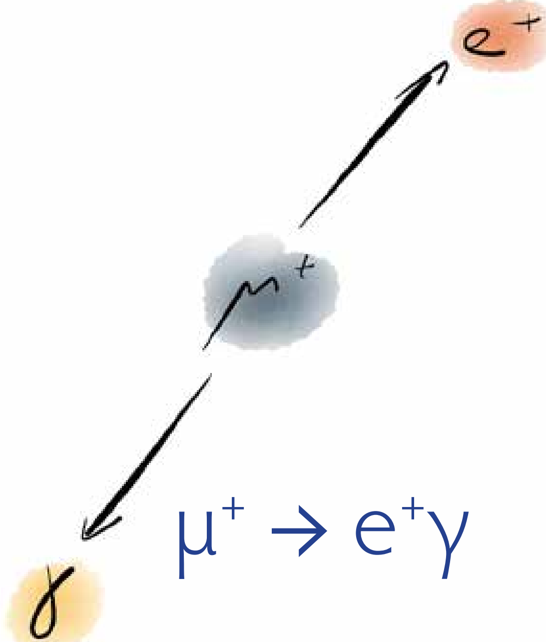
Kinematics

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

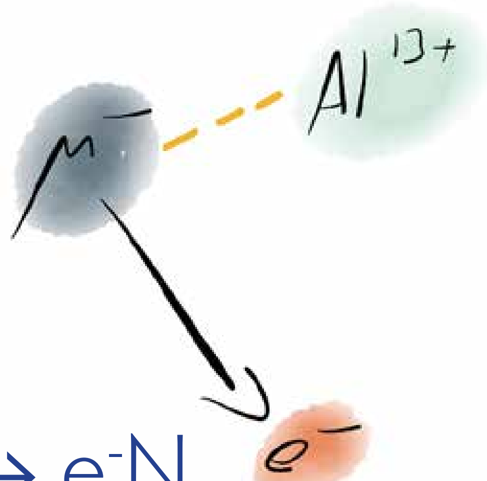
Background

- Internal conversion decay
- Accidental background

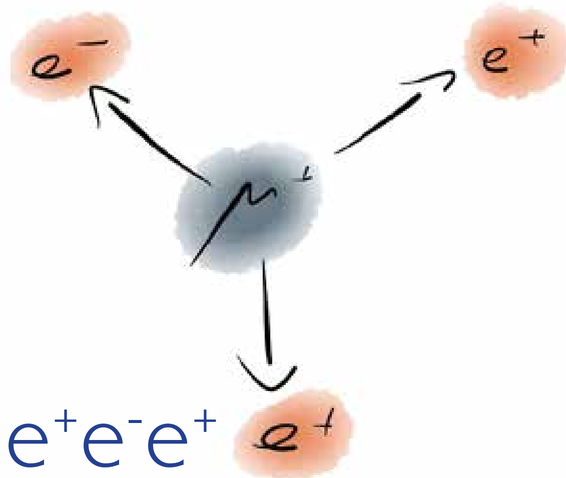
LFV Muon Decays: Experimental signatures



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



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



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

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

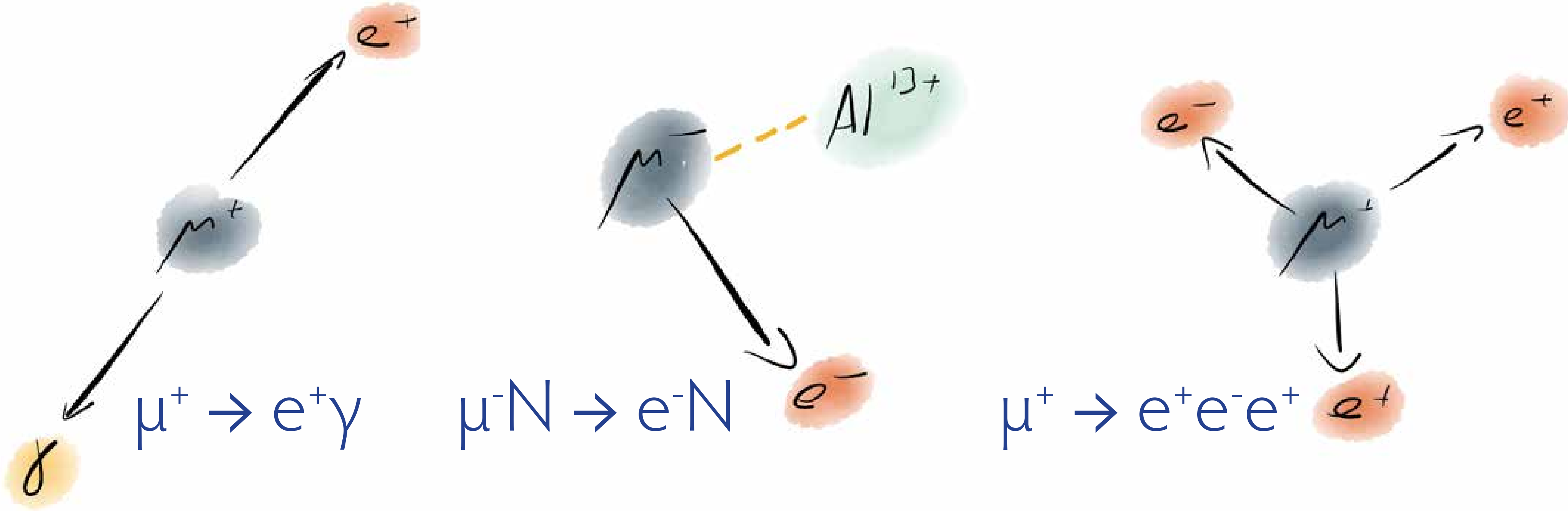
- 3-body decay
- Invariant ma… …aint
- $\Sigma p_i = 0$

Backgro…

- R… … decay
- Ac… …ental background

Continuous Beam

LFV Muon Decays: Experimental Situation



MEG (PSI)

$B(\mu^+ \to e^+\gamma) < 4.2 \cdot 10^{-13}$

(2016)

upgrading

SINDRUM II (PSI)

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

(2006)

relative to nuclear capture

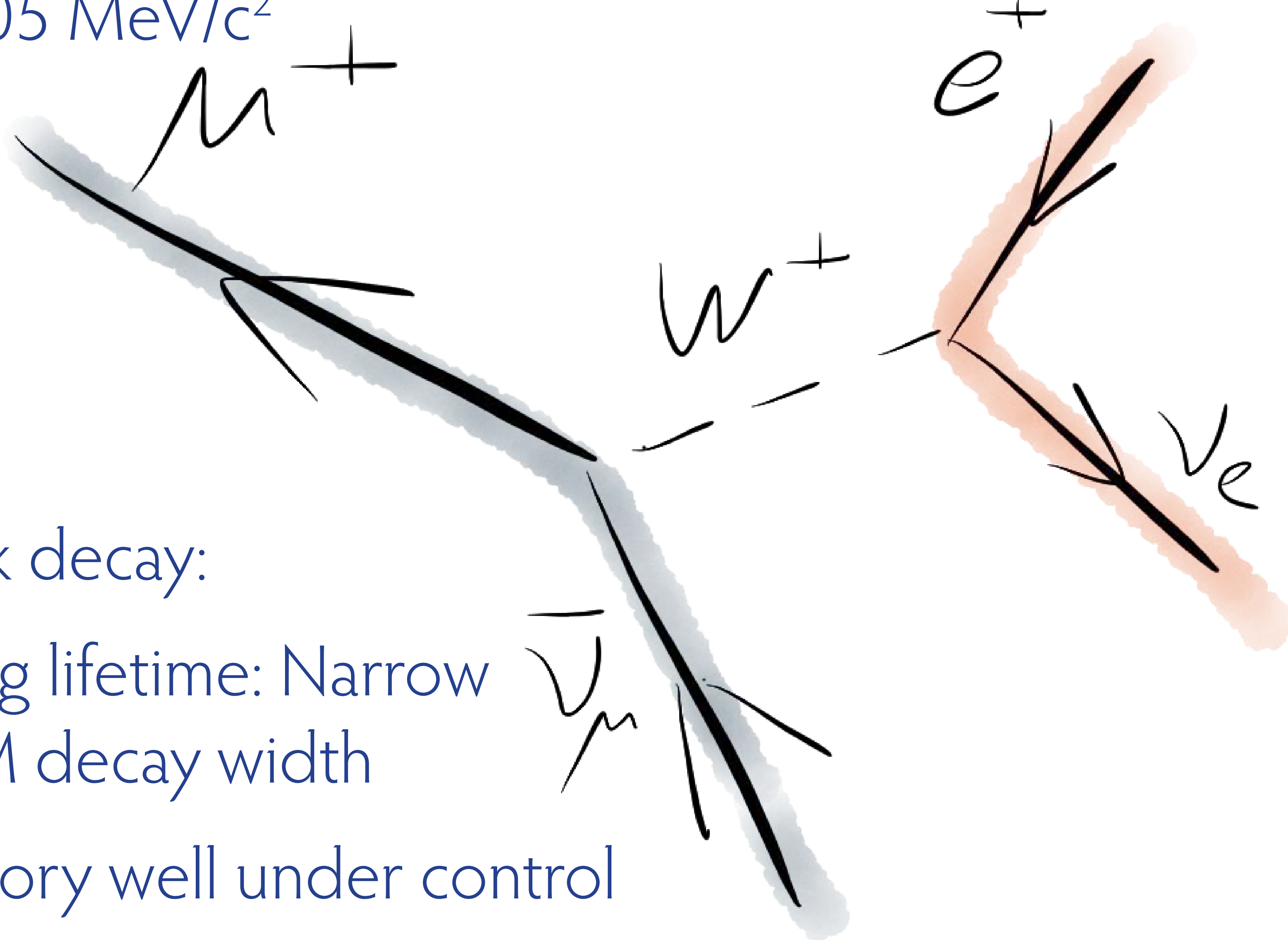
SINDRUM (PSI)

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

(1988)

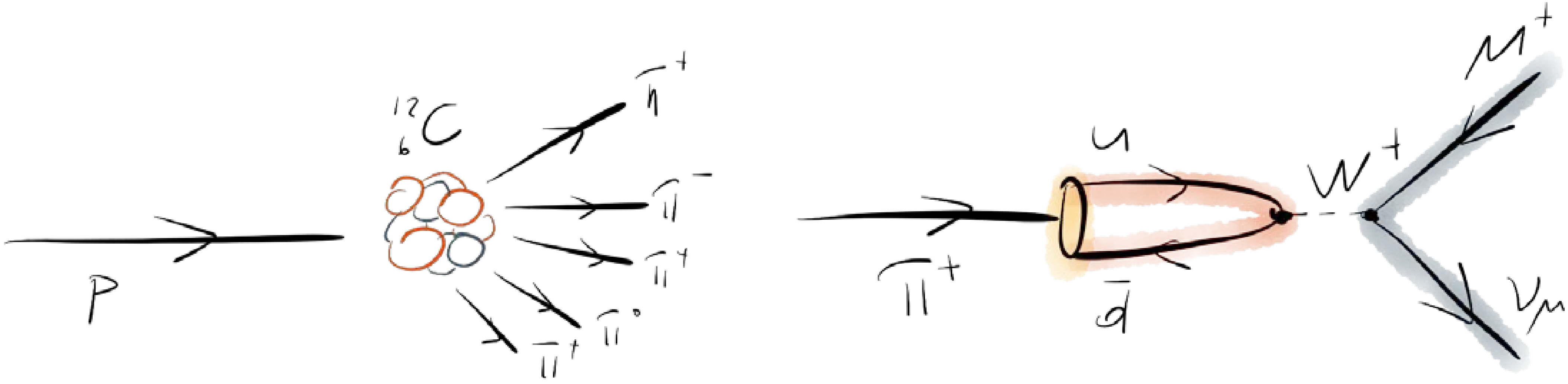
Why muons?

$m_\mu = 105\ MeV/c^2$



Weak decay:

- Long lifetime: Narrow SM decay width
- 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

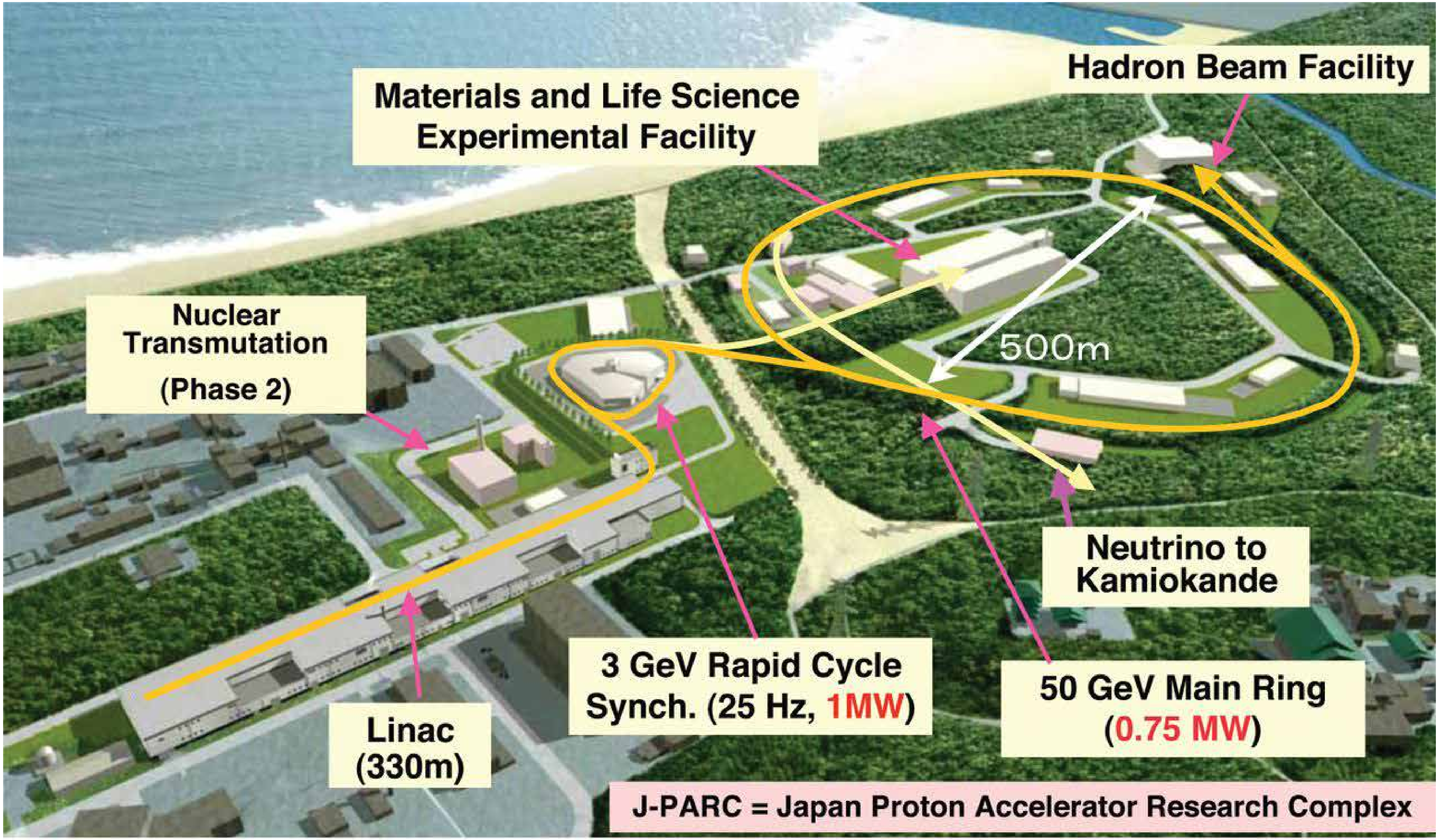
Muons from Fermilab ...

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



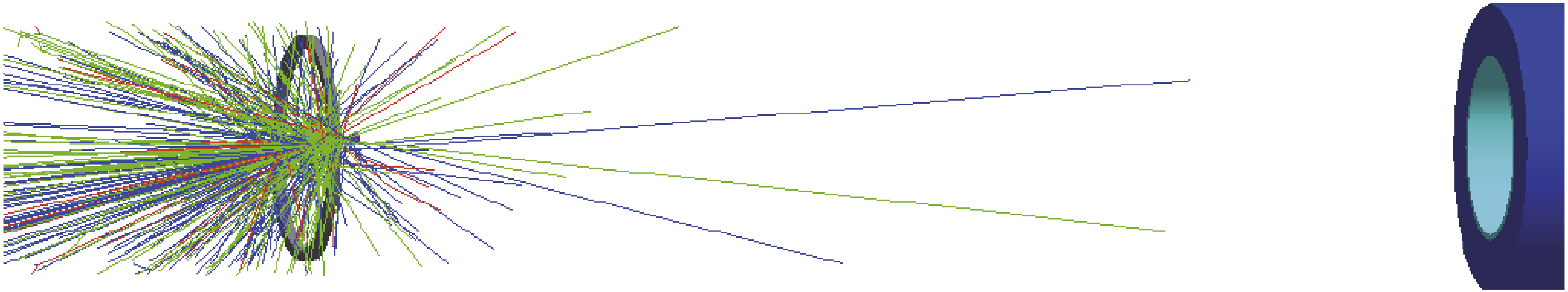
10^{11} μ/s from 8 GeV/c protons, pulsed

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

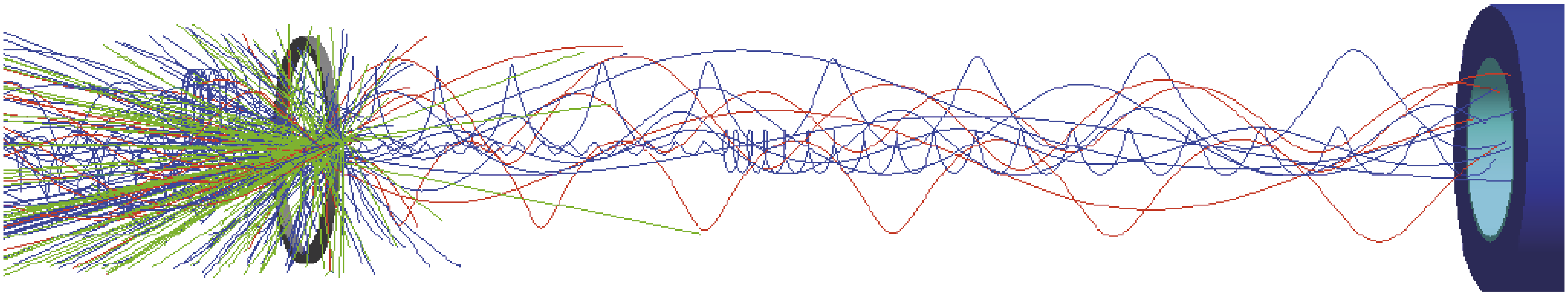
Very high intensity muon beams

A. Gaponenko, cLFV 2016

Instead of this



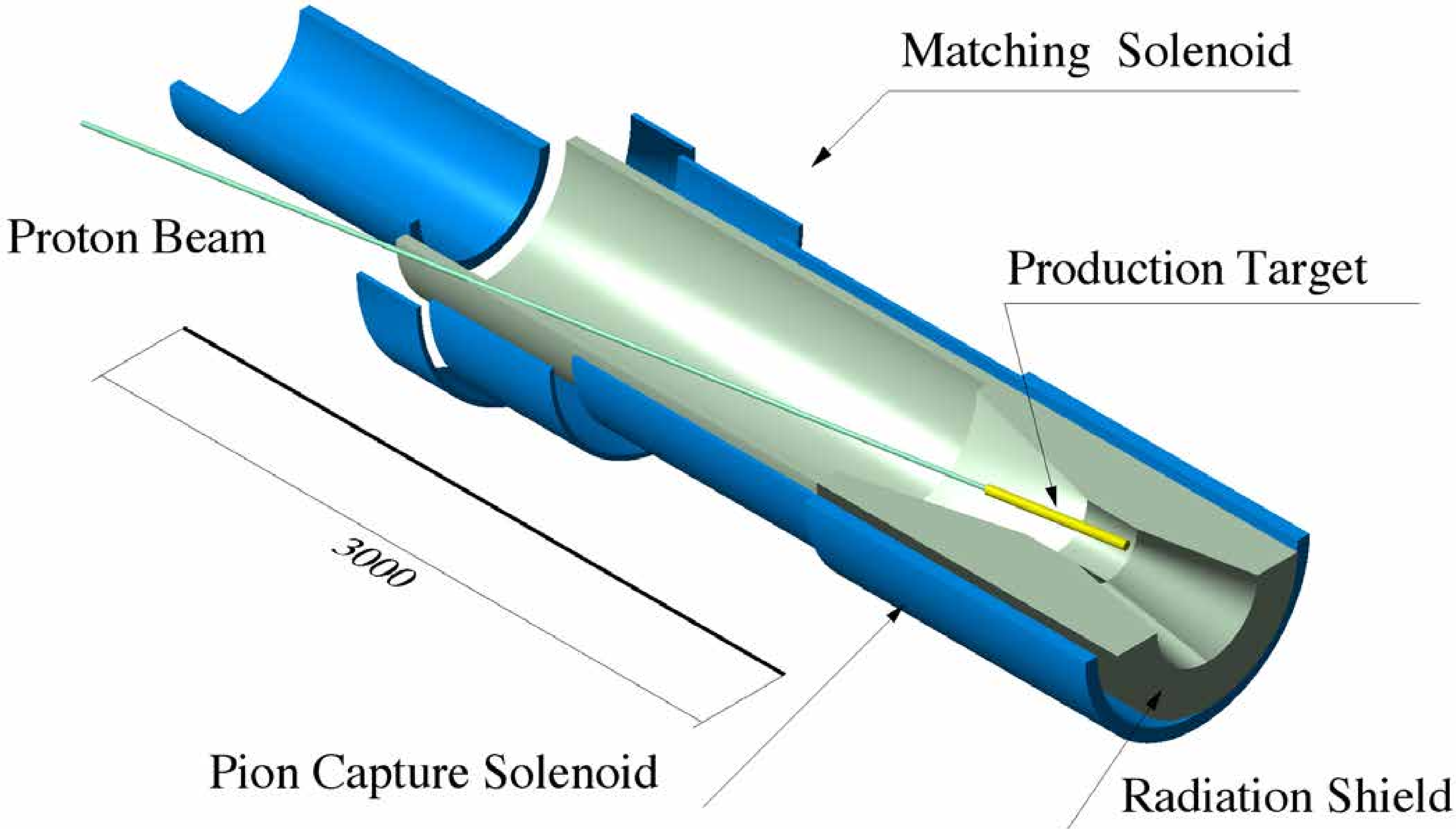
Do this



Solenoidal *B* field confines soft pions. Collect their muons.

Mu2e: $> 10^{10}$ μ^-/s from only 8 kW of protons!

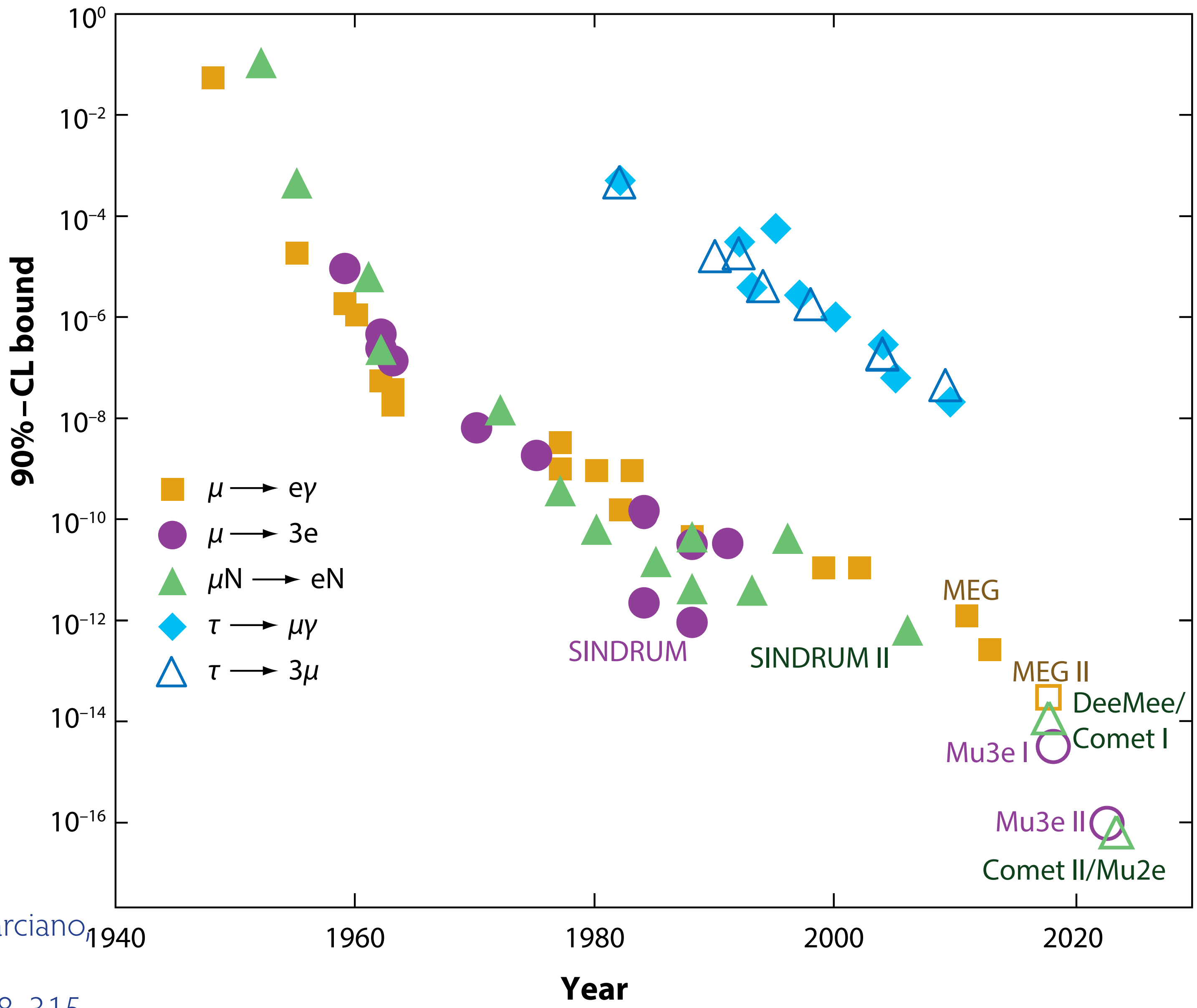
Production target inside a solenoid



Capture most pions produced in target

Shielding of superconducting magnet very challenging

History of LFV experiments

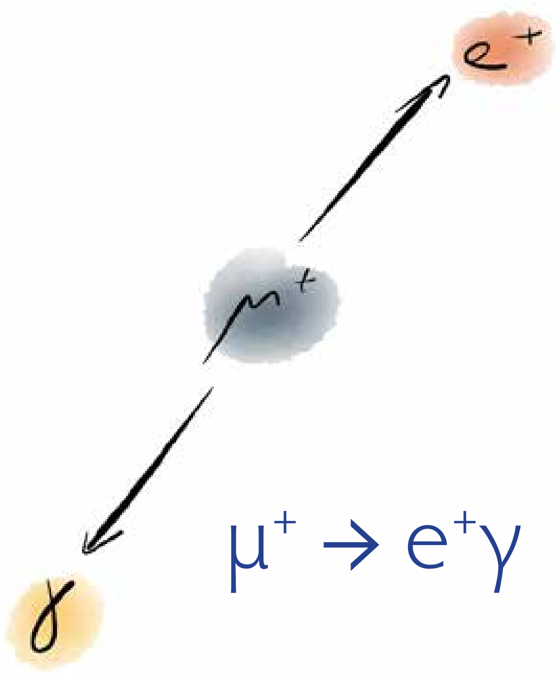


(Updated from W.J. Marciano, T. Mori and J.M. Roney, Ann.Rev.Nucl.Part.Sci. 58, 315 (2008))

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

MEG

MEG Signal and background

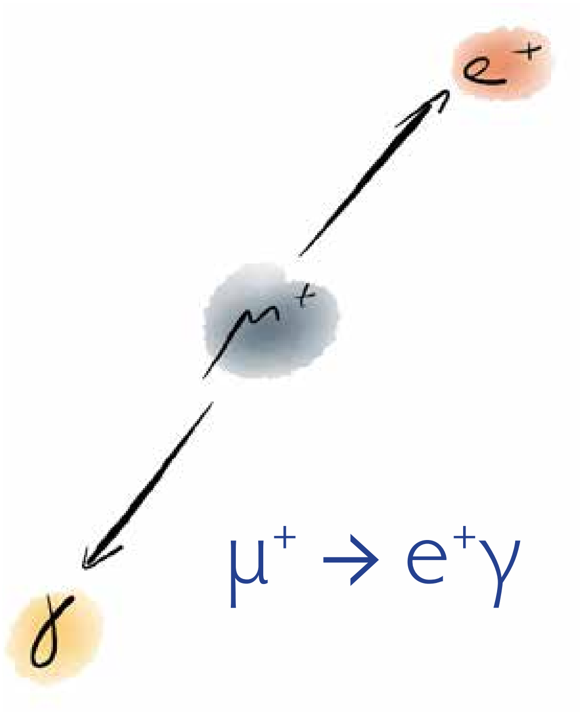


$$\mu^+ \rightarrow e^+\gamma$$

Kinematics

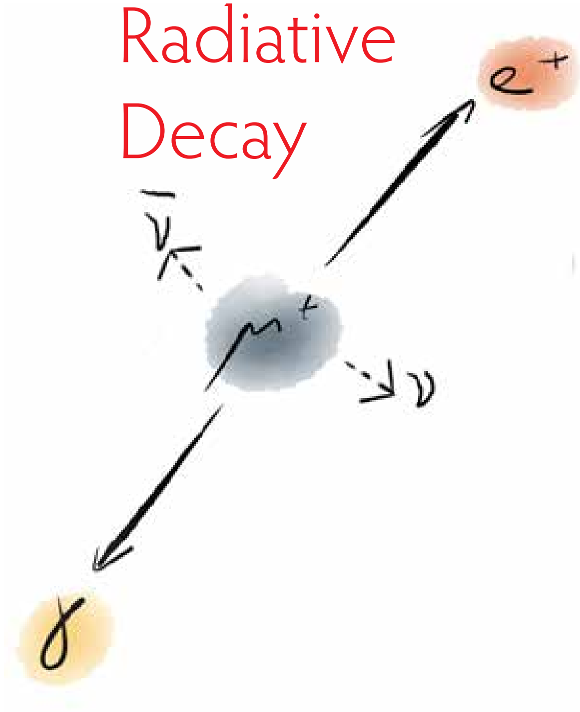
- 2-body decay
- Monoenergetic e^+, γ (53 MeV = $m_\mu/2$)
- Back-to-back
- Same time

MEG Signal and background



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

Radiative Decay

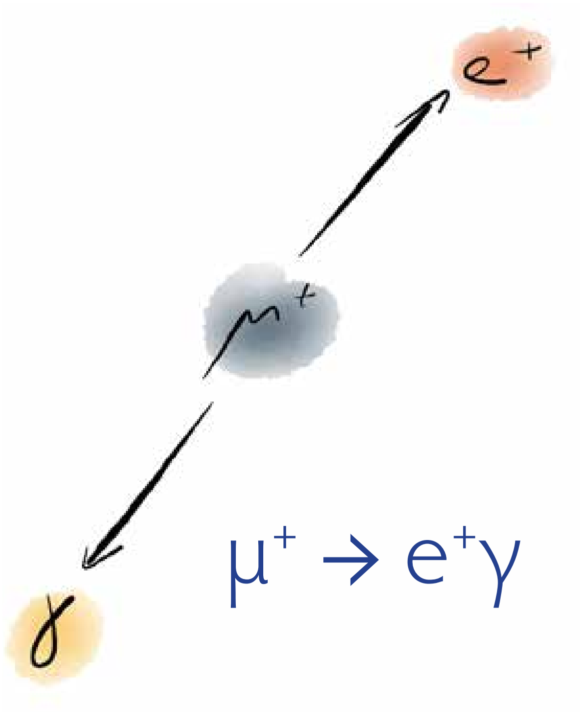


Kinematics

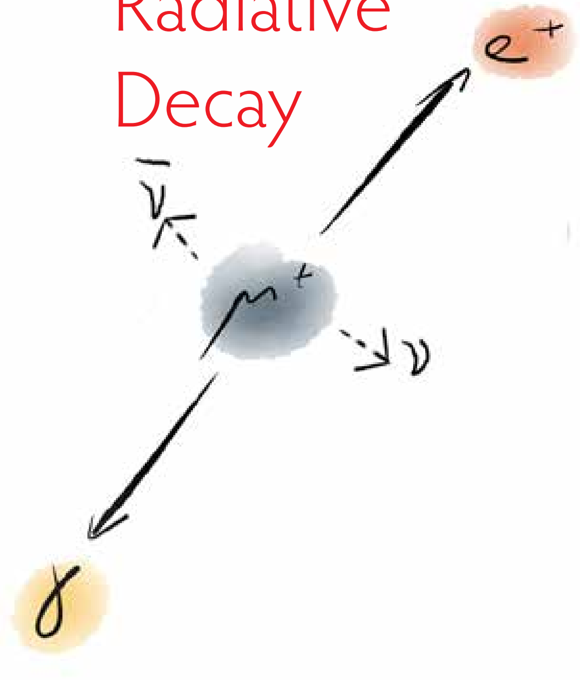
- 2-body decay
- Monoenergetic e^+, γ (53 MeV = $m_\mu/2$)
- Back-to-back
- Same time

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

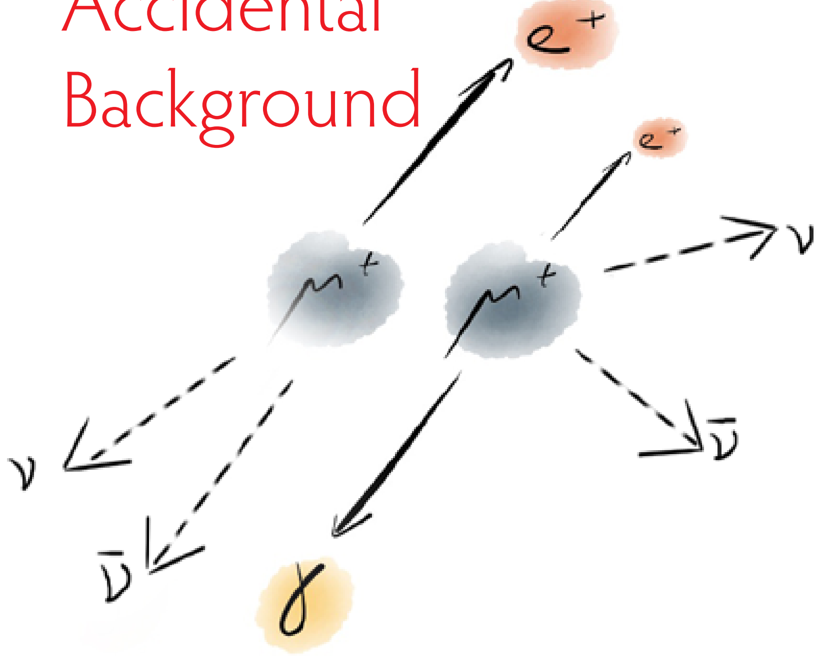
MEG Signal and background



Radiative Decay



Accidental Background



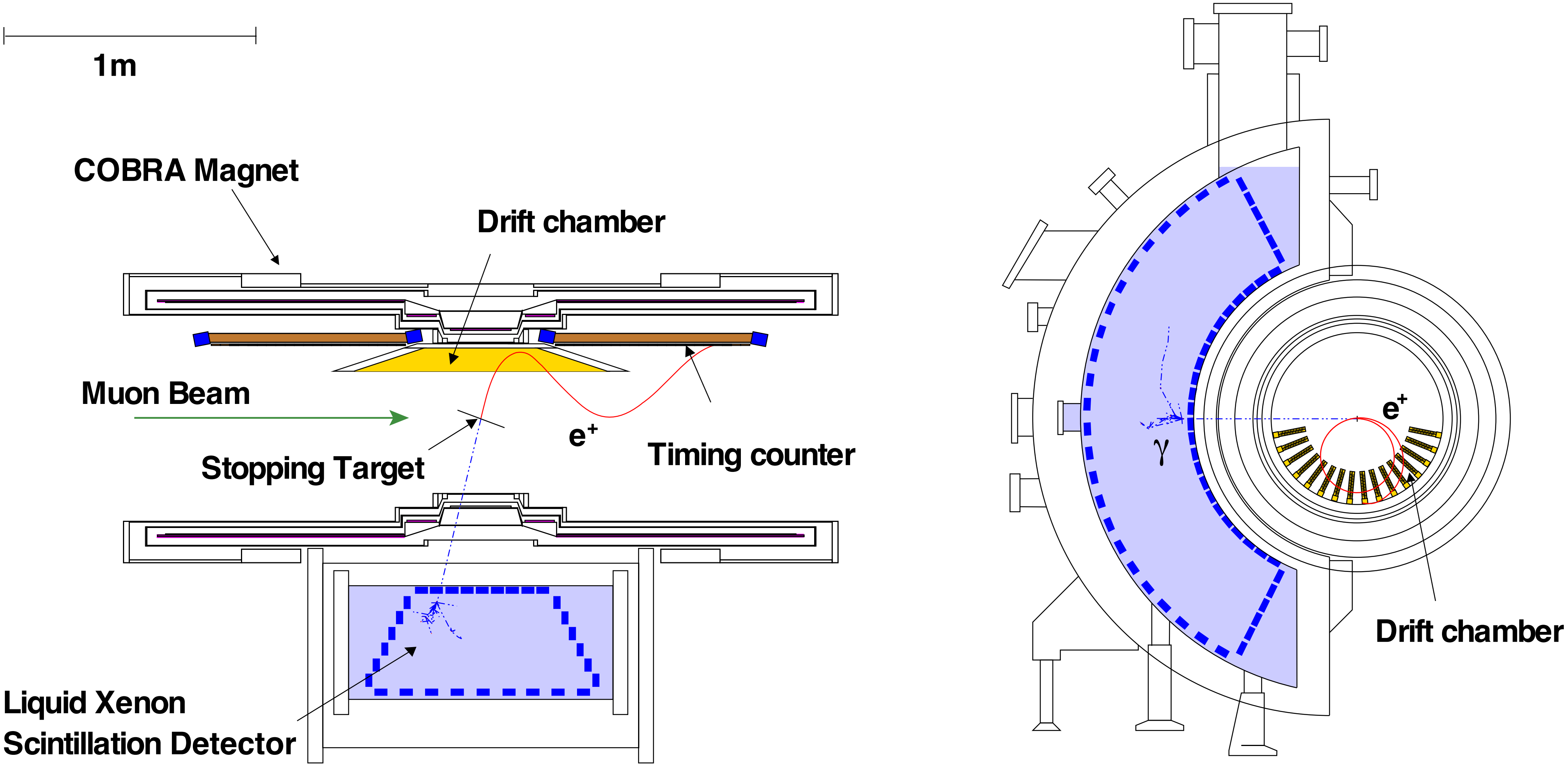
Kinematics

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

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

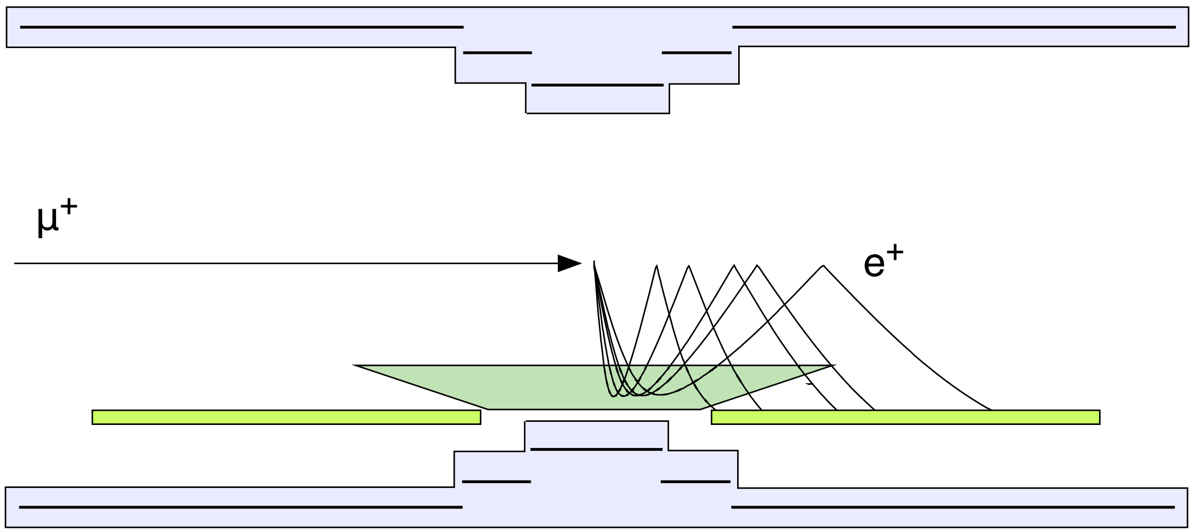
- Not exactly in time
- Not exactly same vertex
- e^+, γ energies somewhat off
- Not exactly back-to-back

The MEG Detector

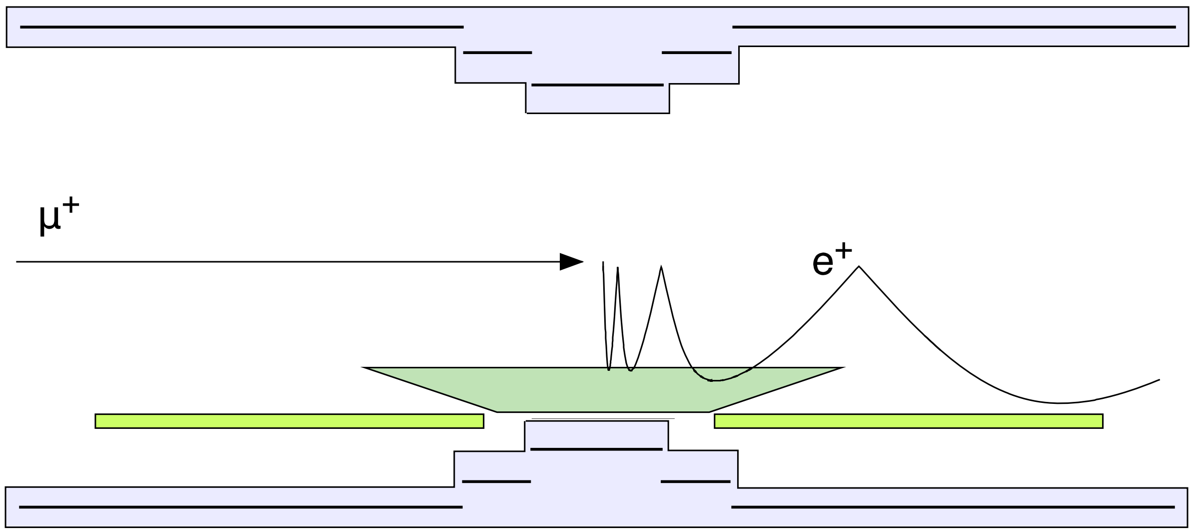


J. Adam et al. EPJ C 73, 2365 (2013)

COBRA Magnet

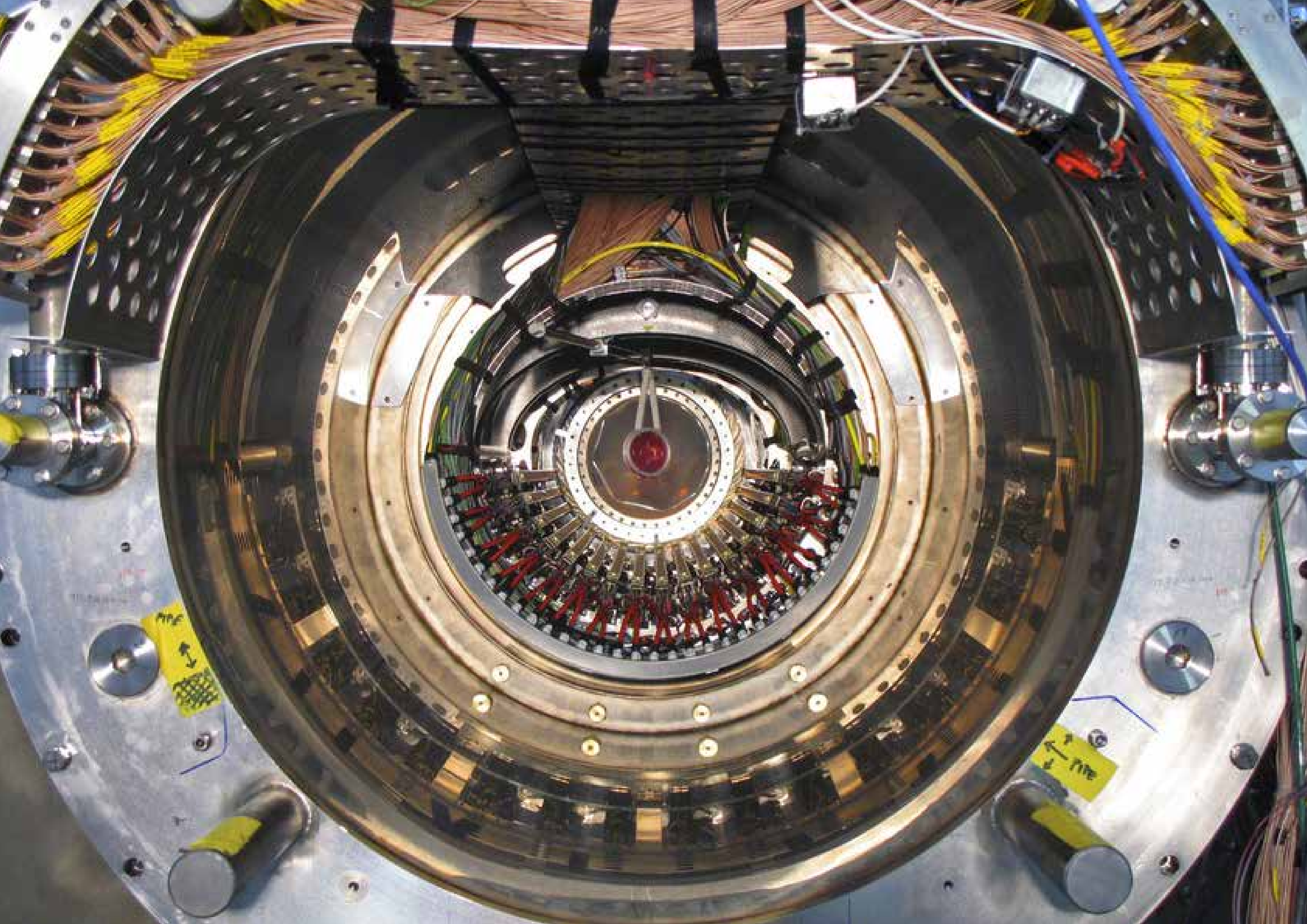


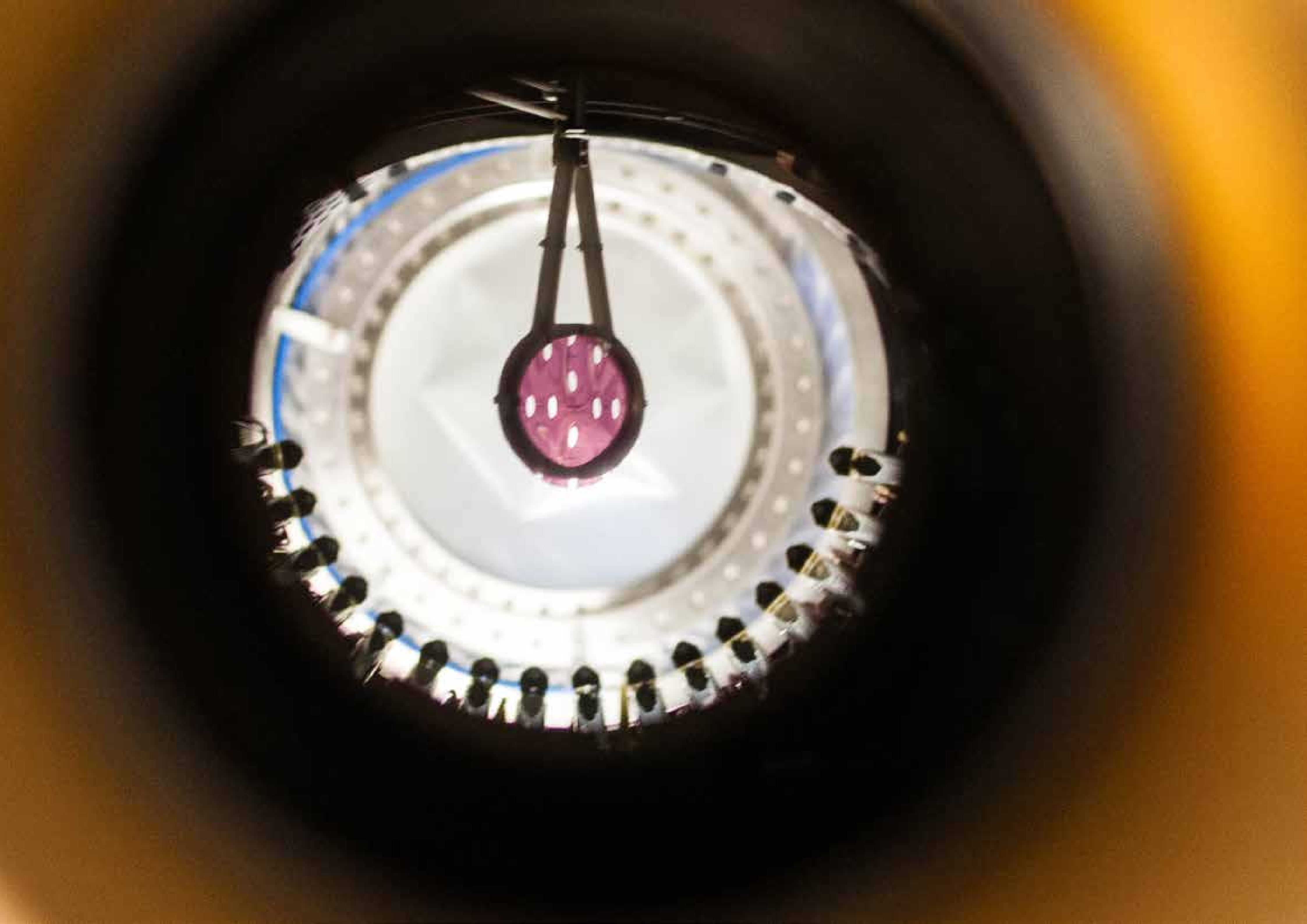
Gradient field gives constant bending radius independent of angle

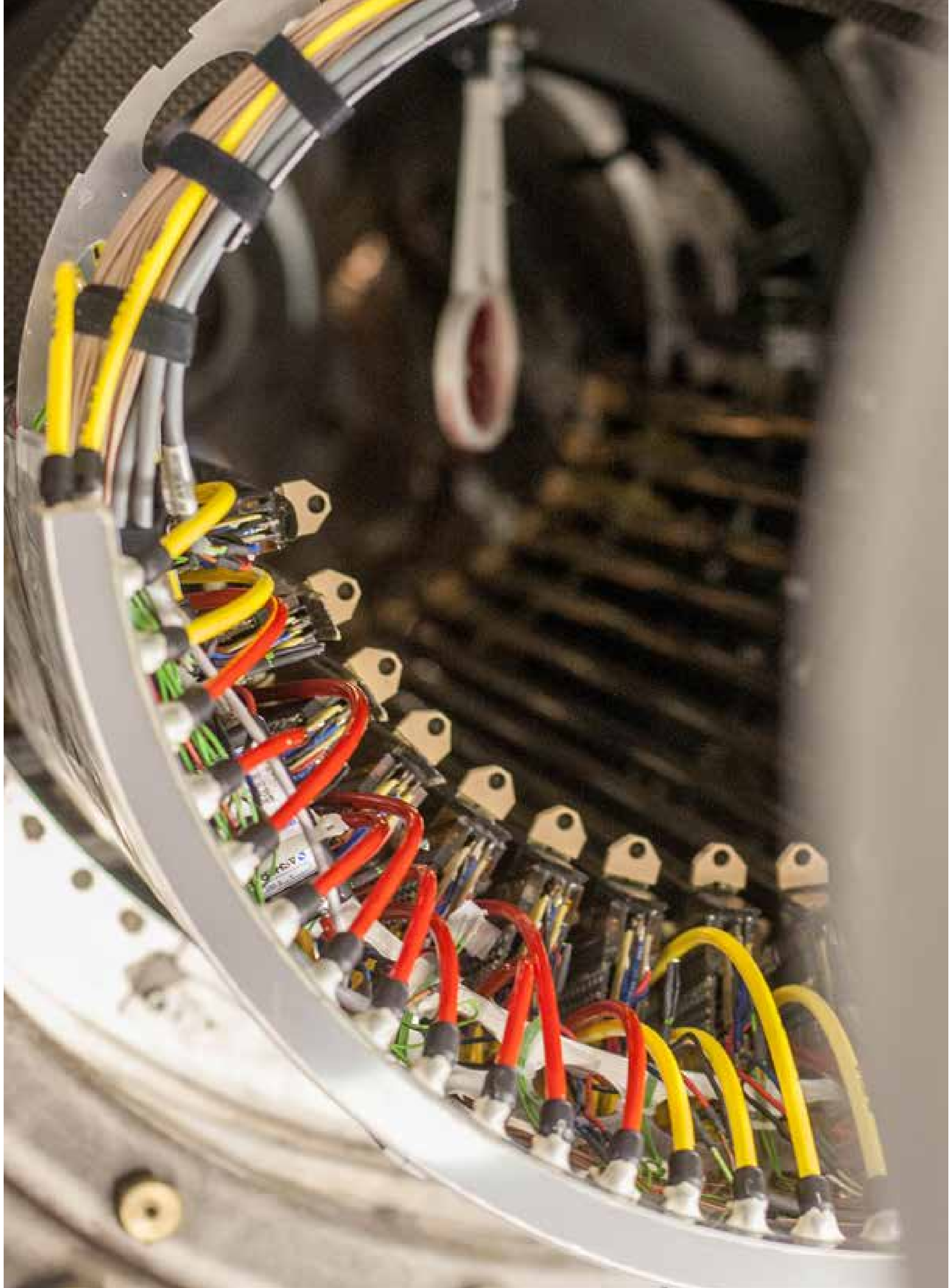


Fast sweep of curlers

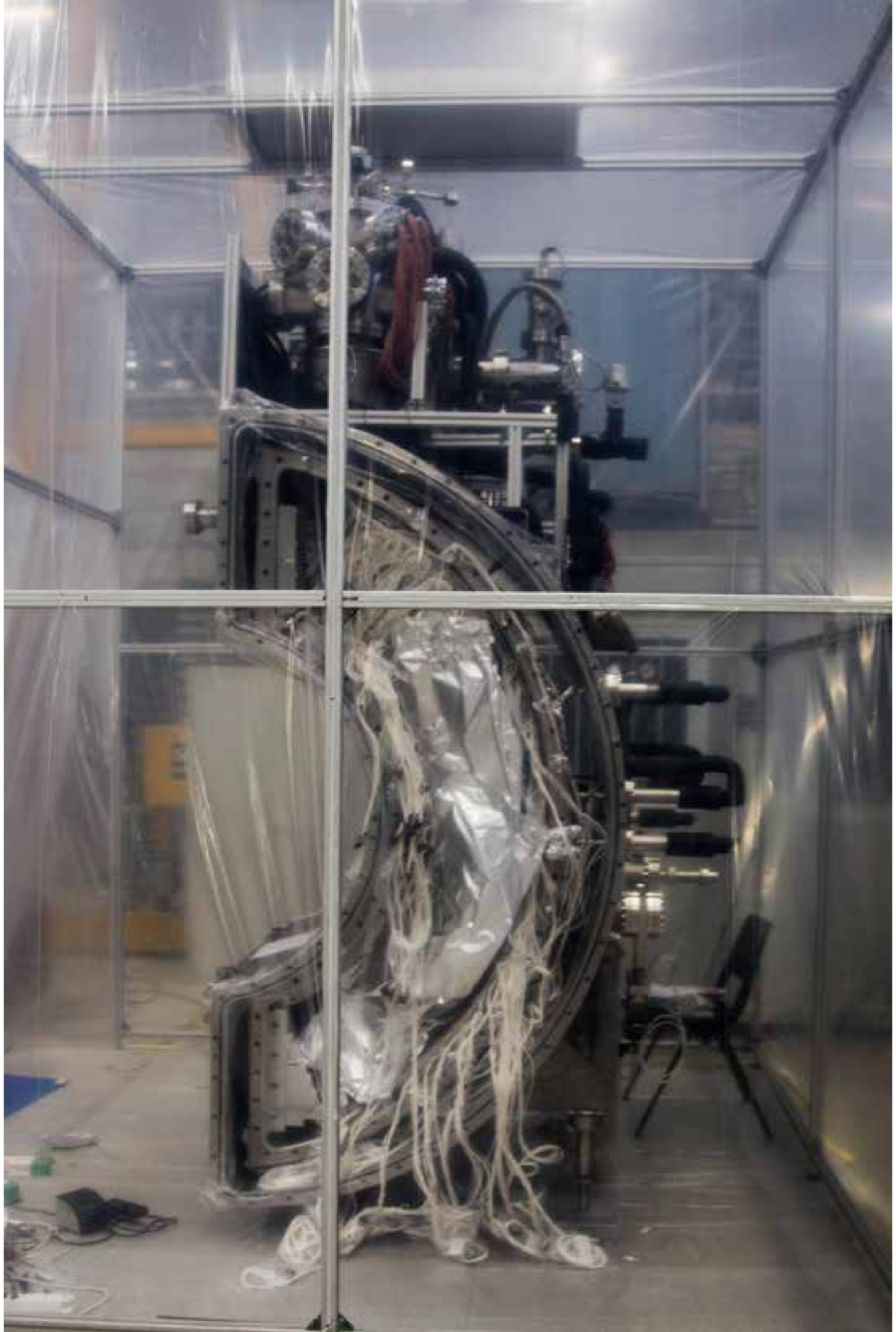
J. Adam et al. EPJ C 73, 2365 (2013)


PIPE
PIPE






1039
RA 1397
RA 1029



How to know your detector works,
if you (almost) never see a signal?

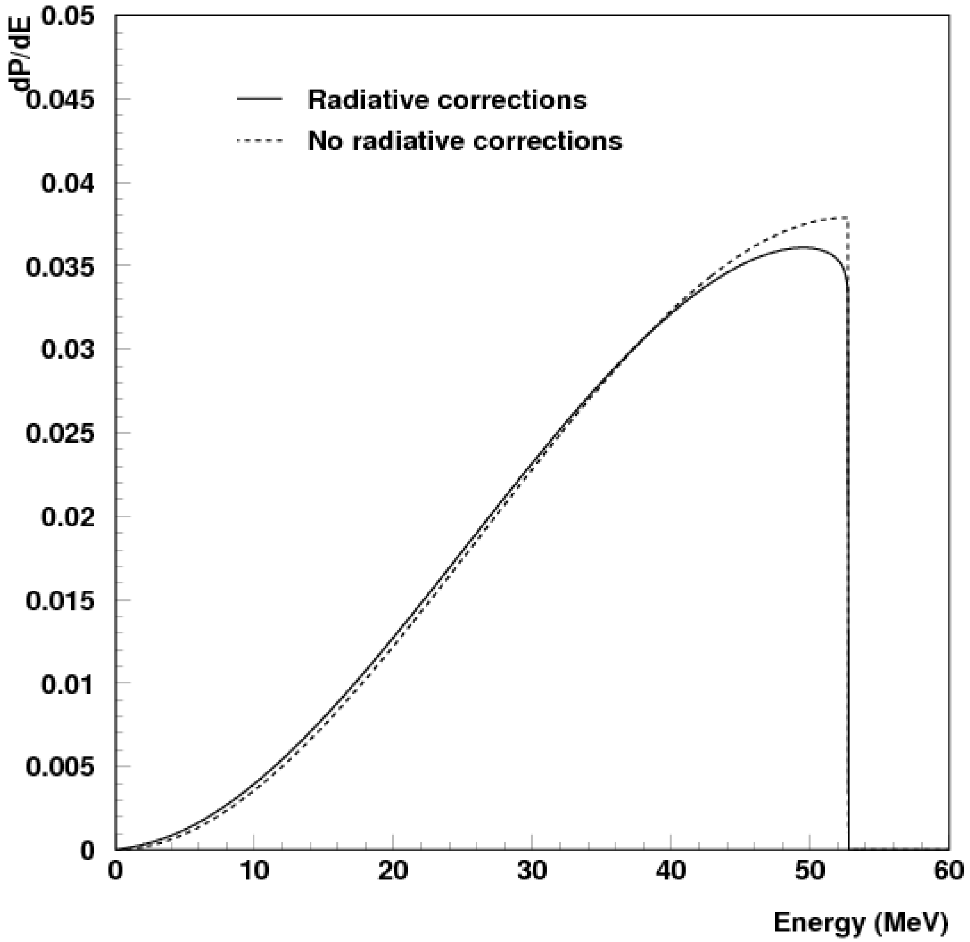
How to know your detector works,
if you (almost) never see a signal?

Calibration

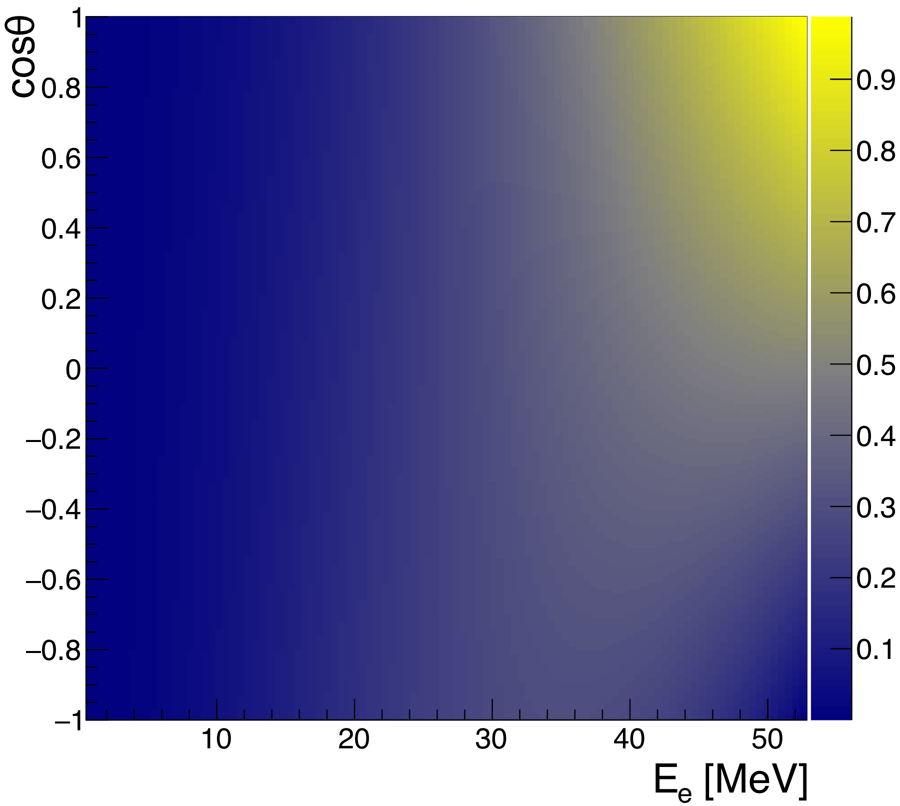
Table 1 The calibration tools of the MEG experiment.

Process		Energy	Main Purpose	Frequency
Cosmic rays	$\mu^{\pm}$ from atmospheric showers	Wide spectrum $\mathcal{O}$(GeV)	LXe-DCH relative position	annually
			DCH alignment	
			TC energy and time offset calibration	
			LXe purity	on demand
Charge exchange	$\pi^{-}p \rightarrow \pi^{0}n$ $\pi^{0} \rightarrow \gamma\gamma$	55, 83, 129 MeV photons	LXe energy scale/resolution	annually
Radiative μ−decay	$\mu^{+} \rightarrow e^{+}\gamma\nu\bar{\nu}$	photons > 40 MeV,	LXe-TC relative timing	continuously
		positrons > 45 MeV	Normalisation	
Normal μ−decay	$\mu^{+} \rightarrow e^{+}\nu\bar{\nu}$	52.83 MeV end-point positrons	DCH energy scale/resolution	continuously
			DCH and target alignment	
			Normalisation	
Mott positrons	e^{+} target $\rightarrow e^{+}$ target	≈ 50 MeV positrons	DCH energy scale/resolution	annually
			DCH alignment	
Proton accelerator	^{7}Li(p, γ)^{8}Be	14.8, 17.6 MeV photons	LXe uniformity/purity	weekly
	^{11}B(p, γ)^{12}C	4.4, 11.6, 16.1 MeV photons	TC interbar/ LXe–TC timing	weekly
Neutron generator	^{58}Ni(n, γ)^{59}Ni	9 MeV photons	LXe energy scale	weekly
Radioactive source	^{241}Am(α, γ)^{237}Np	5.5 MeV α's, 56 keV photons	LXe PMT calibration/purity	weekly
Radioactive source	^{9}Be($\alpha_{^{241}Am}$, n)^{12}C* ^{12}C*(γ)^{12}C	4.4 MeV photons	LXe energy scale	on demand
LED			LXe PMT calibration	continuously

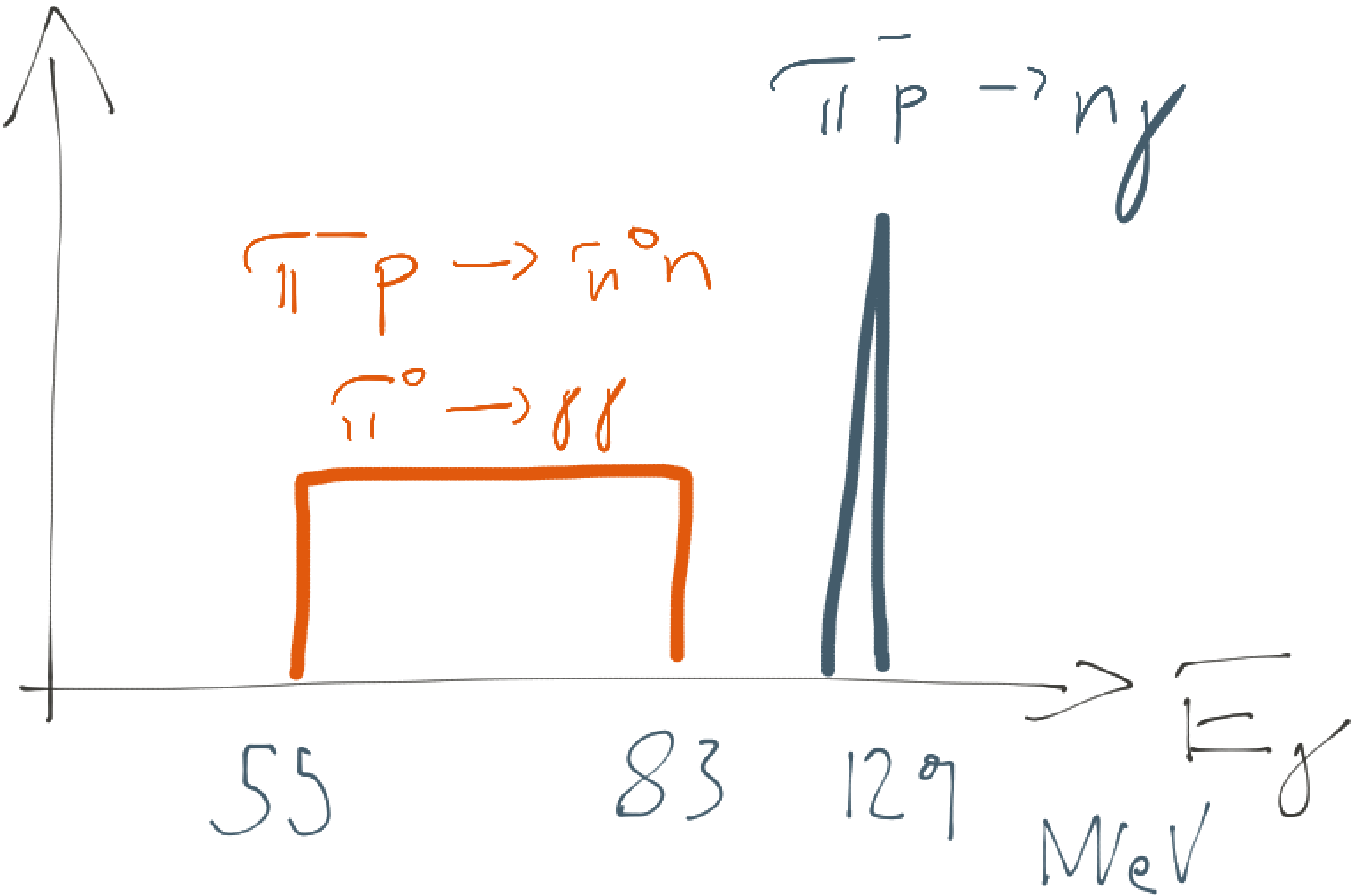
Muon decay as calibration tool



- Sharp edge in positron spectrum
- Strong angle-energy correlations



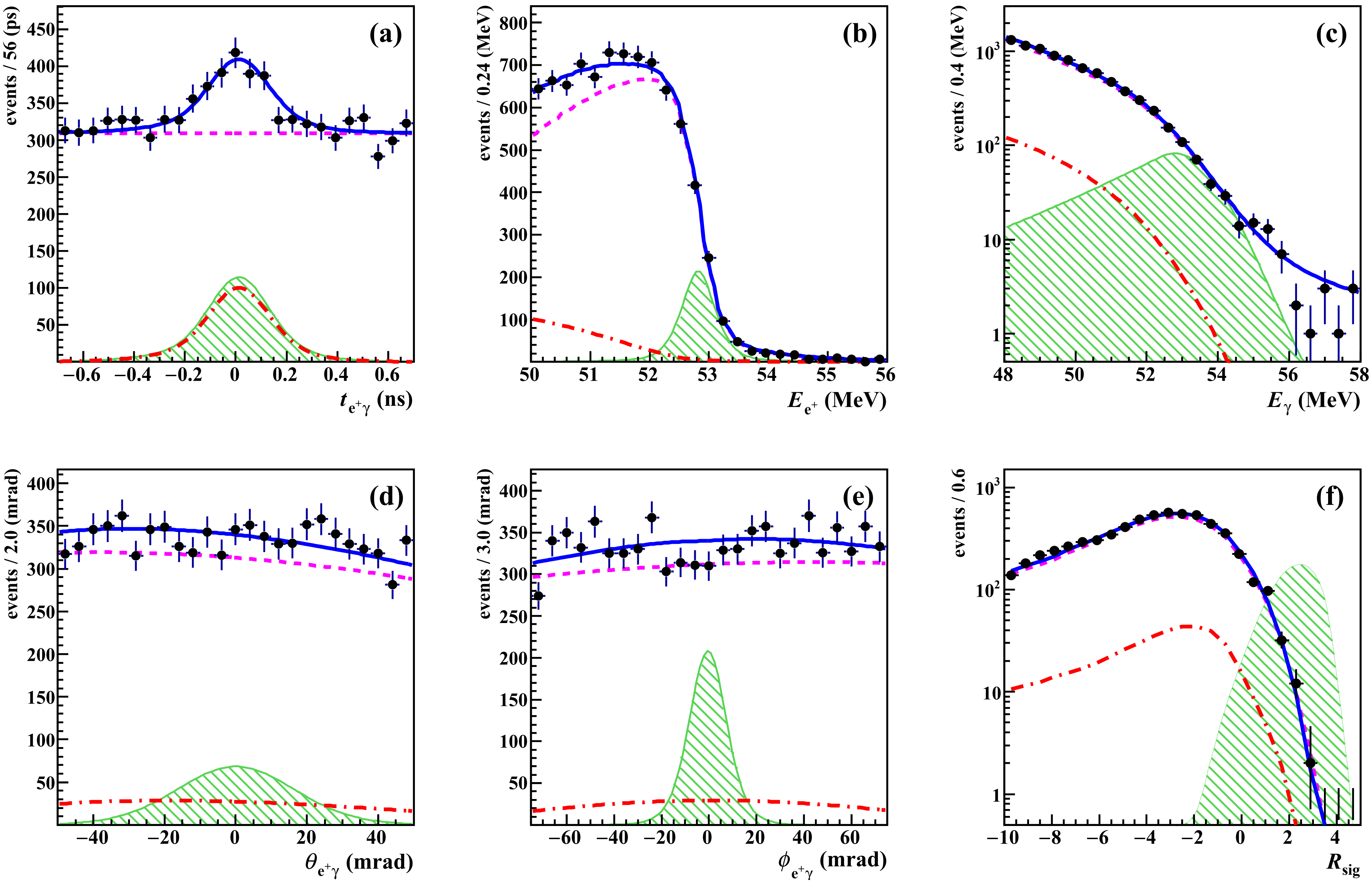
Pions as a calibration tool



Nuclear Reactions

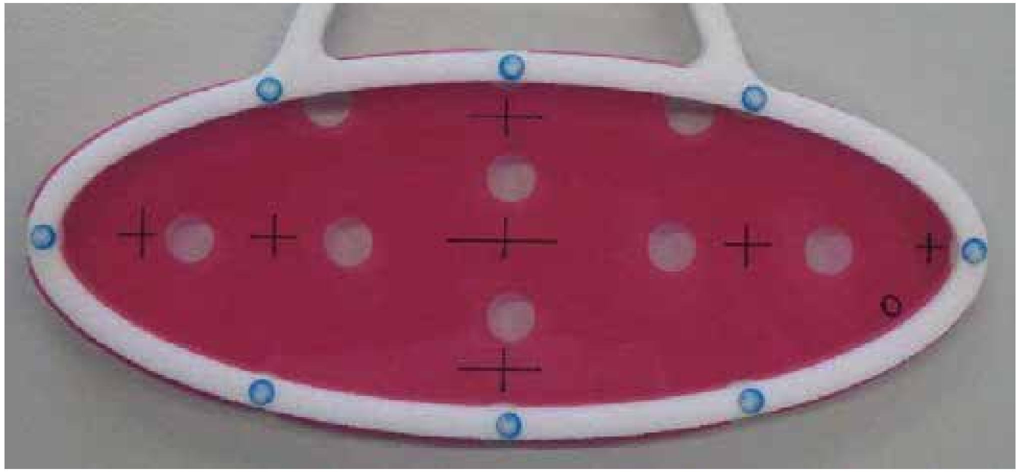
- Separate proton accelerator
- $^{7}Li(p,\gamma)^{8}Be$ gives 17.6 MeV photons
- $^{11}Be(p,\gamma_1)^{12}C^*$ and $^{12}C^* \rightarrow {}^{12}C\ \gamma_2$
  4.4 and 11.6 MeV photons
  for photon timing and photon separation

Results

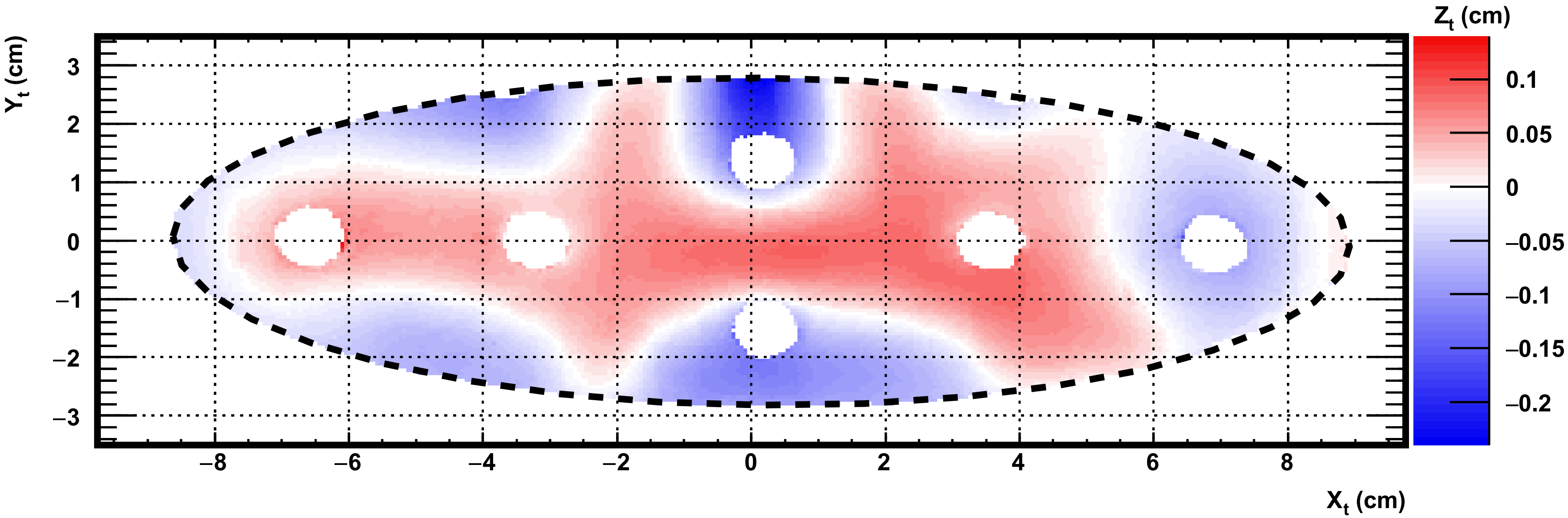

(a)
events / 56 (ps)
$t_{e^+\gamma}$ (ns)
(b)
events / 0.24 (MeV)
E_{e^+} (MeV)
(c)
events / 0.4 (MeV)
E_γ (MeV)
(d)
events / 2.0 (mrad)
$\theta_{e^+\gamma}$ (mrad)
(e)
events / 3.0 (mrad)
$\phi_{e^+\gamma}$ (mrad)
(f)
events / 0.6
R_{sig}

Guess the largest systematic...

Target deformation



- Simple plastic piece
- Position important for photon - positron angle

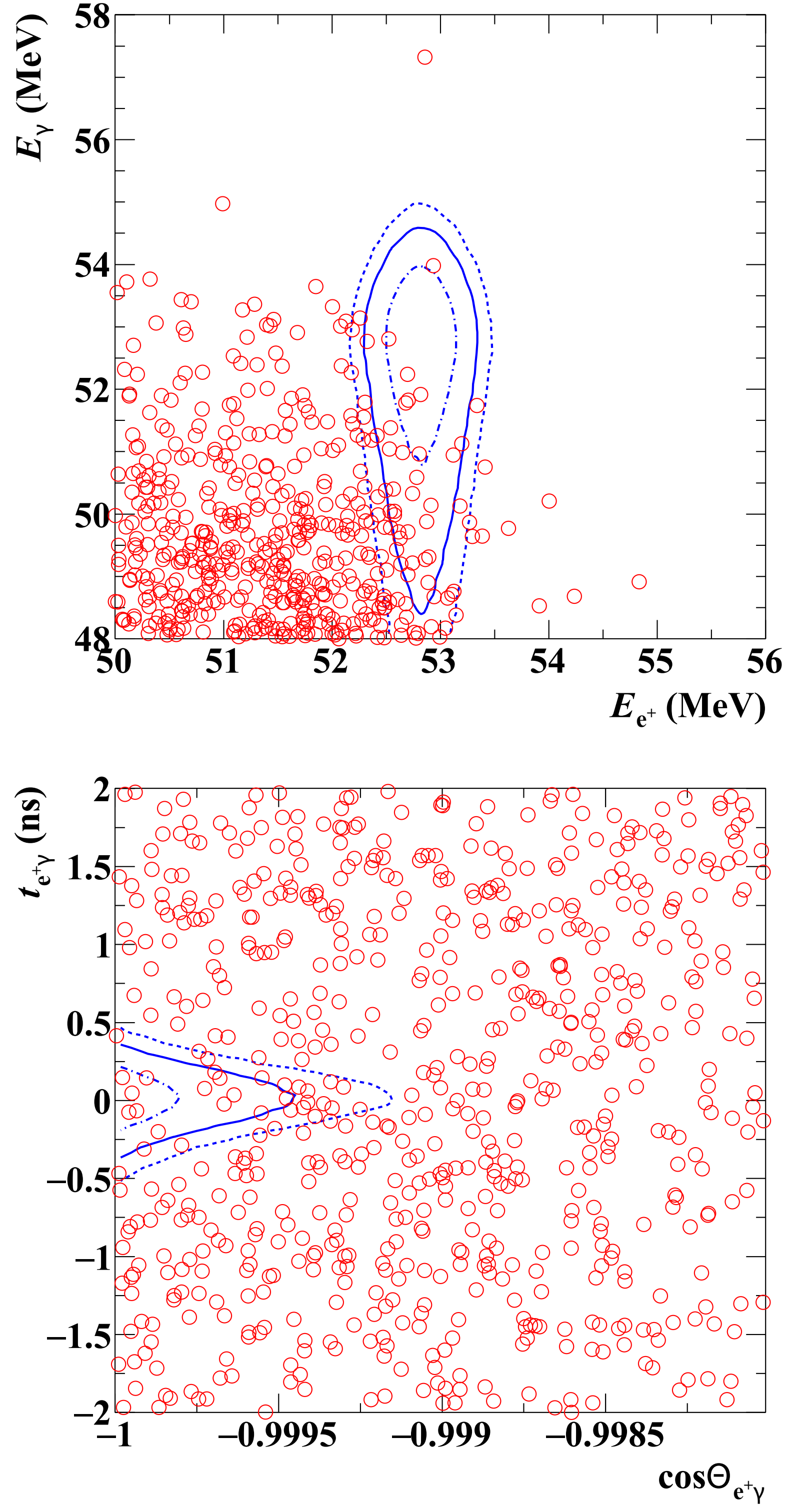


MEG Results

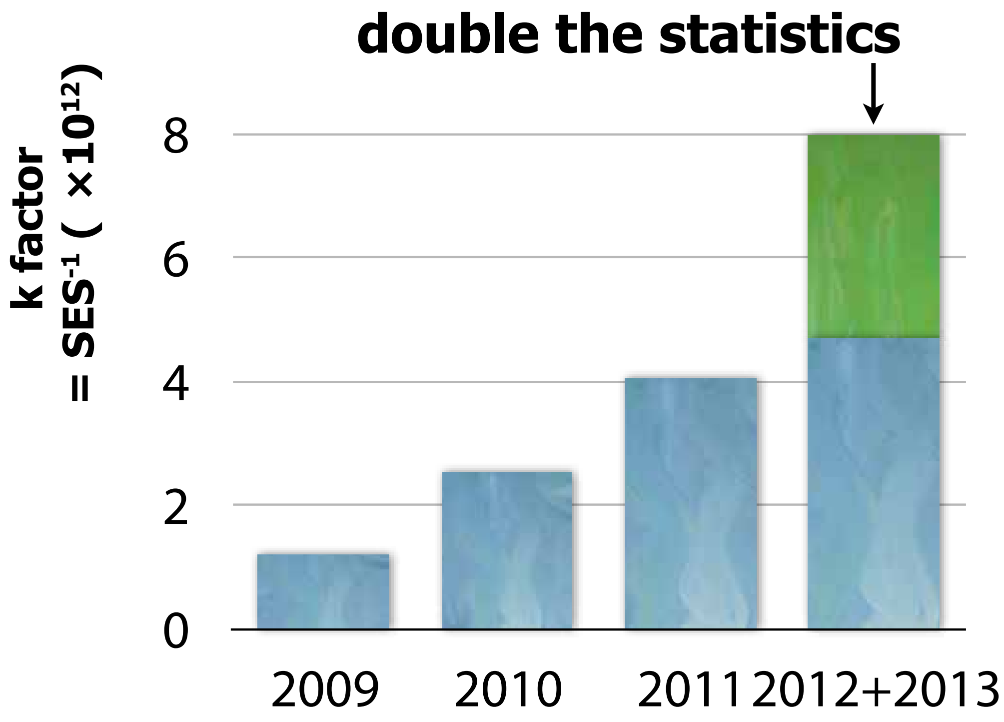
- 2009-2013 data
- Blue: Signal PDF, given by detector resolution
- No signal seen
- Upper limit at 90% CL:

$BR(\mu \to e\gamma) < 4.2 \times 10^{-13}$

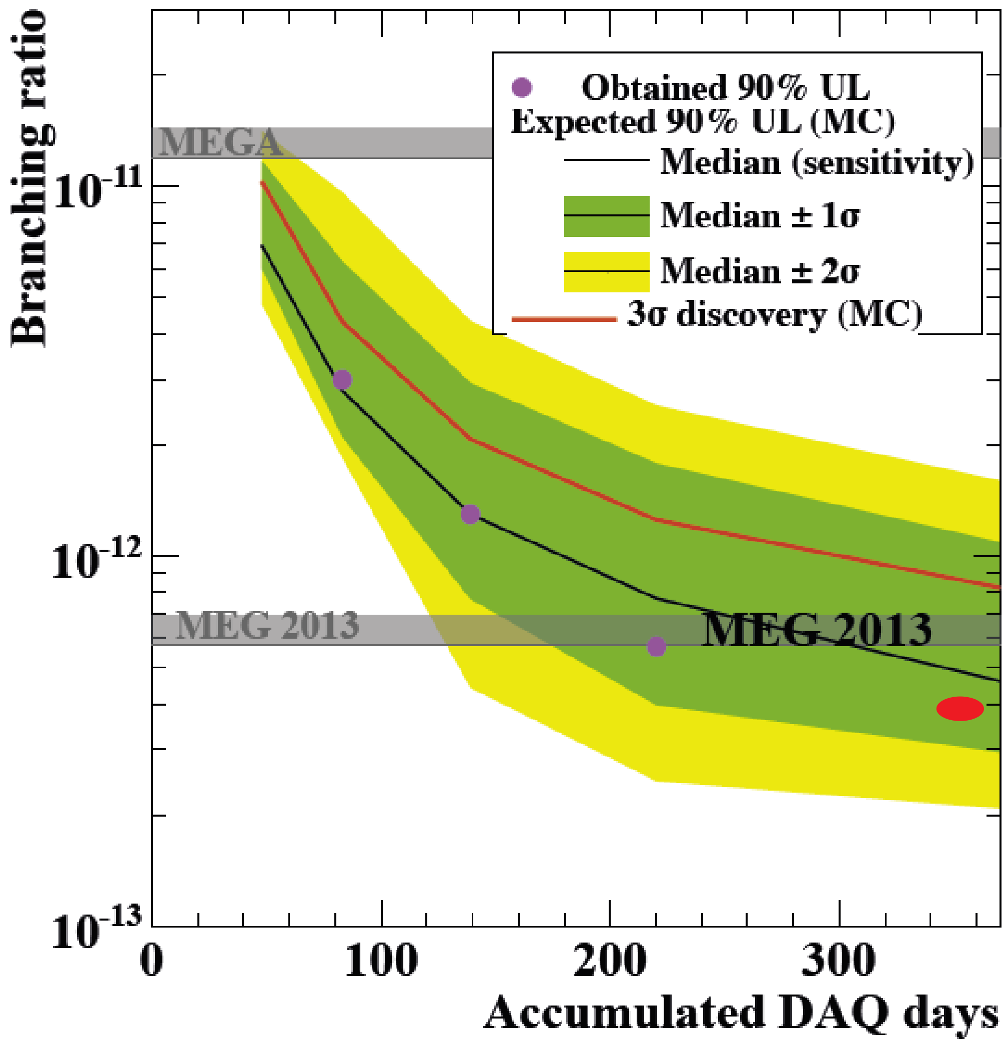
A. M. Baldini et al. arXiv:1605.05081 [hep-ex]



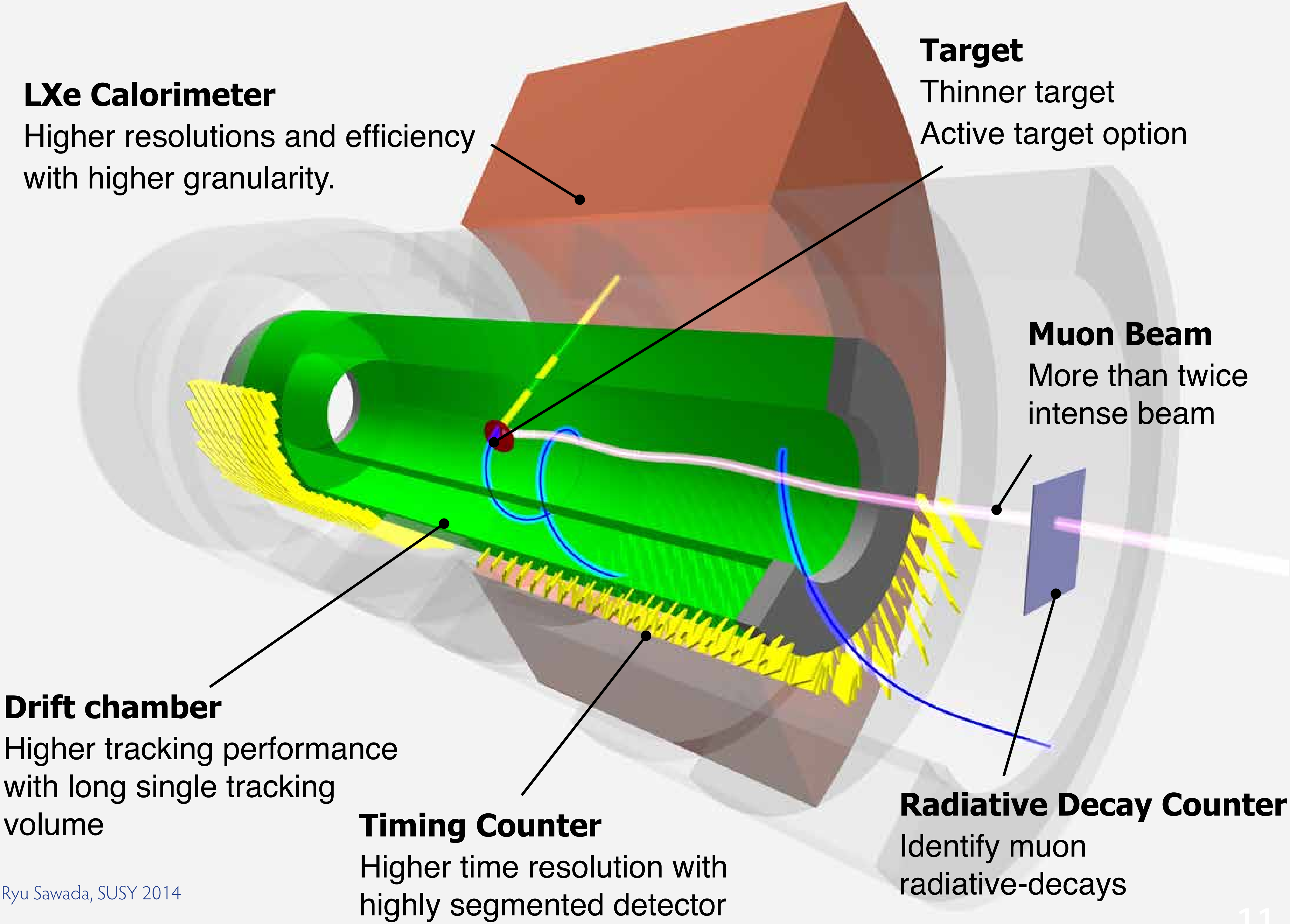
MEG - Data



Observed limits and sensitivity

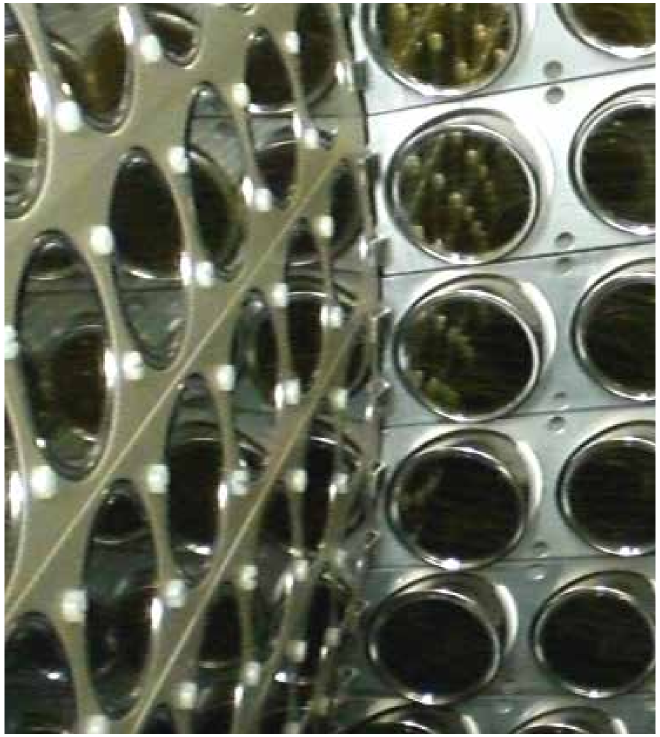


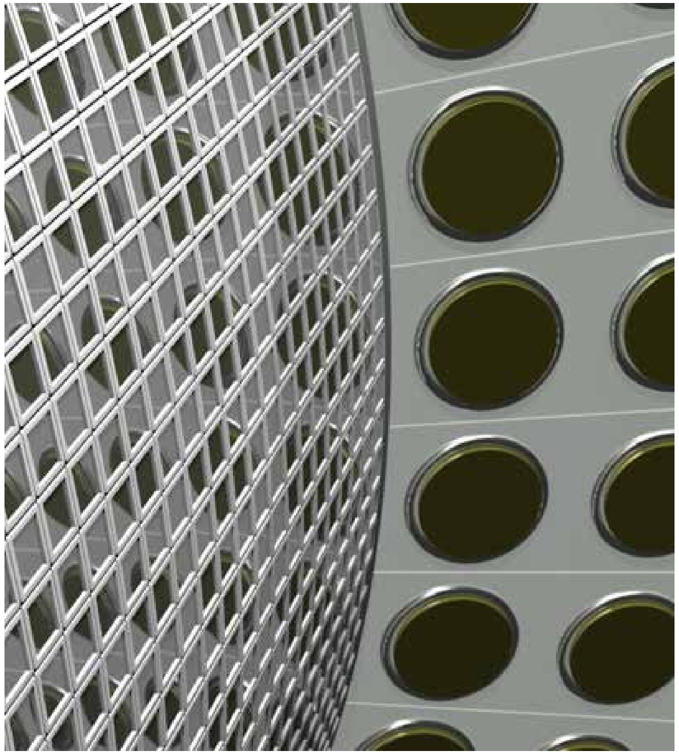
- Further improvements need detector improvements - upgrade ongoing


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

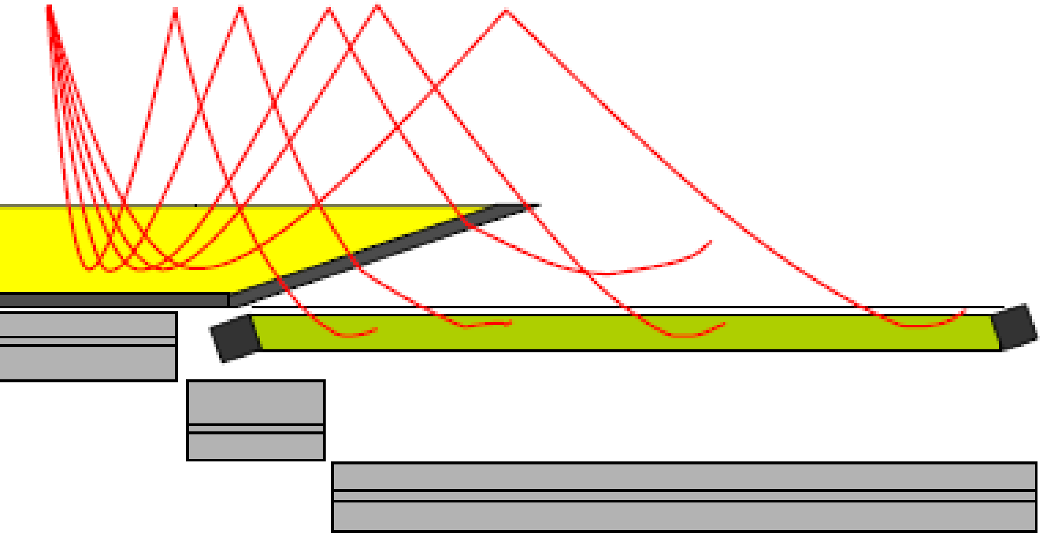
MEG Upgrade - Calorimeter

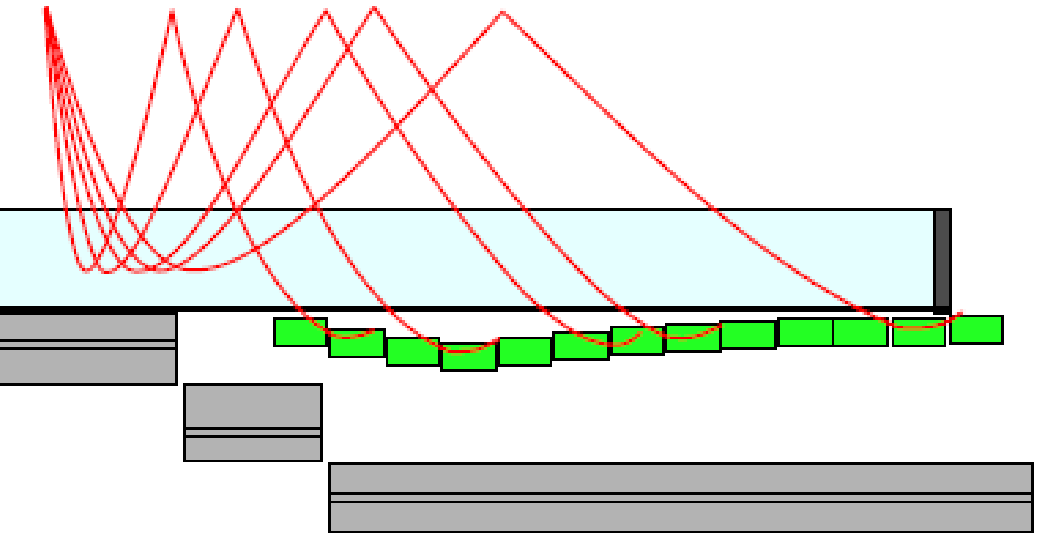
- ~4000 VUV sensitive SiliconPMs on entry face (new development with Hamamatsu)
- Better position and energy resolution
- Better efficiency

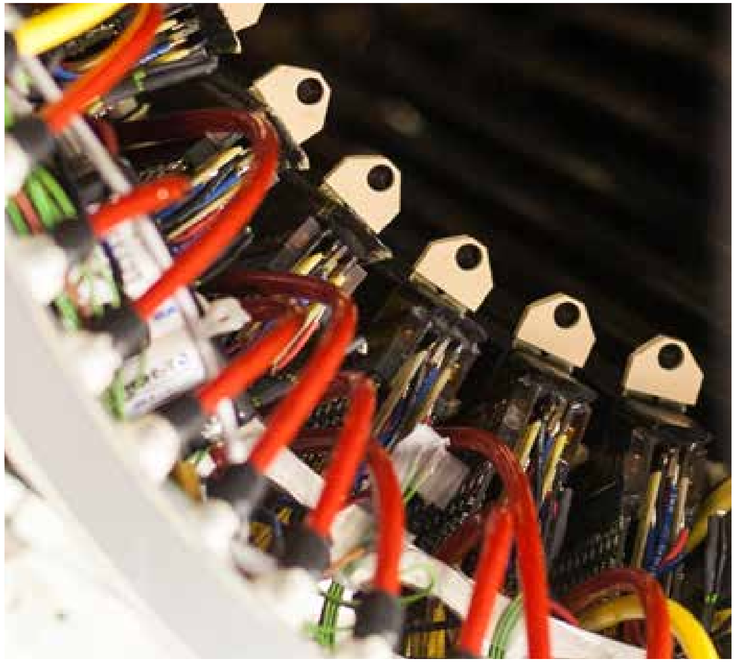




MEG Upgrade - Drift Chamber



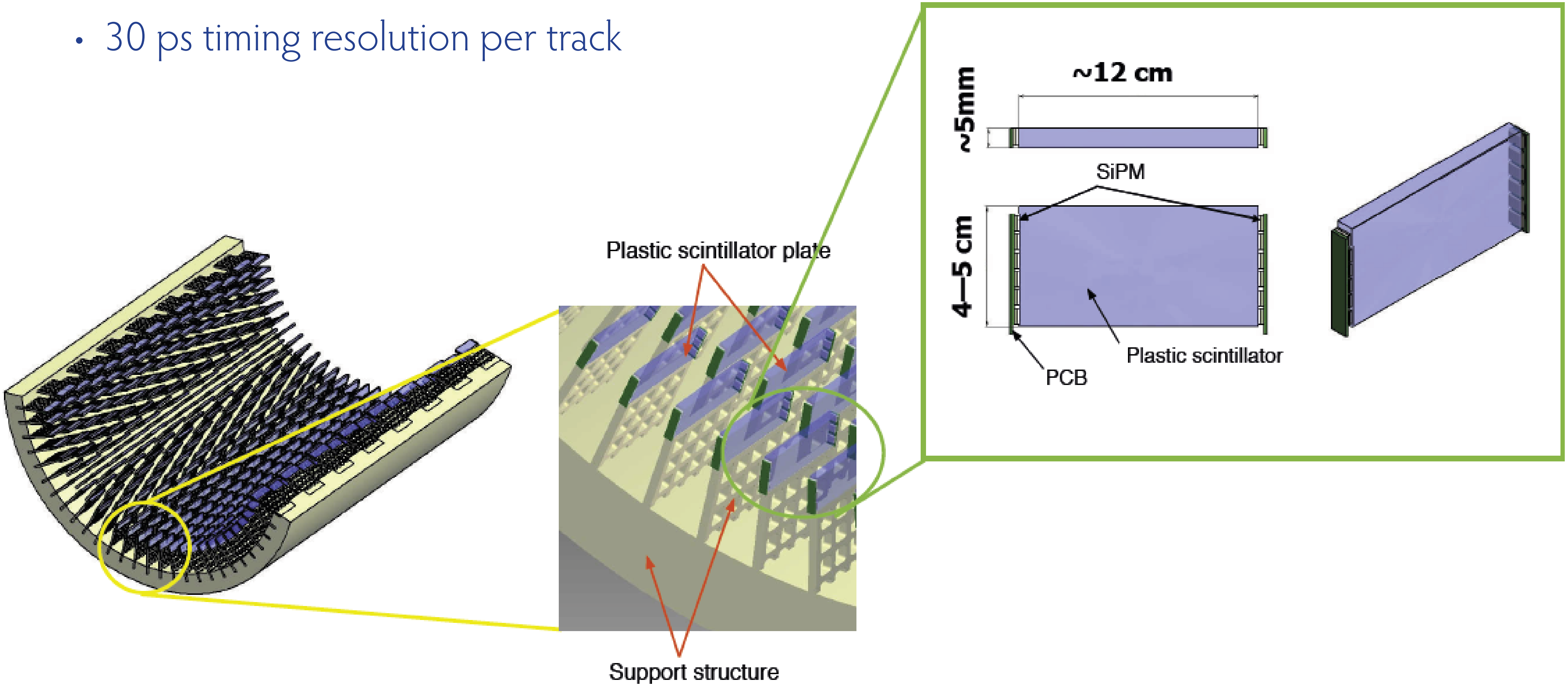




- New single volume drift chamber
- Lower Z gas mixture
- More space points per track
- Better rate capability
- Less material in front of timing counters

MEG Upgrade - Timing Counter

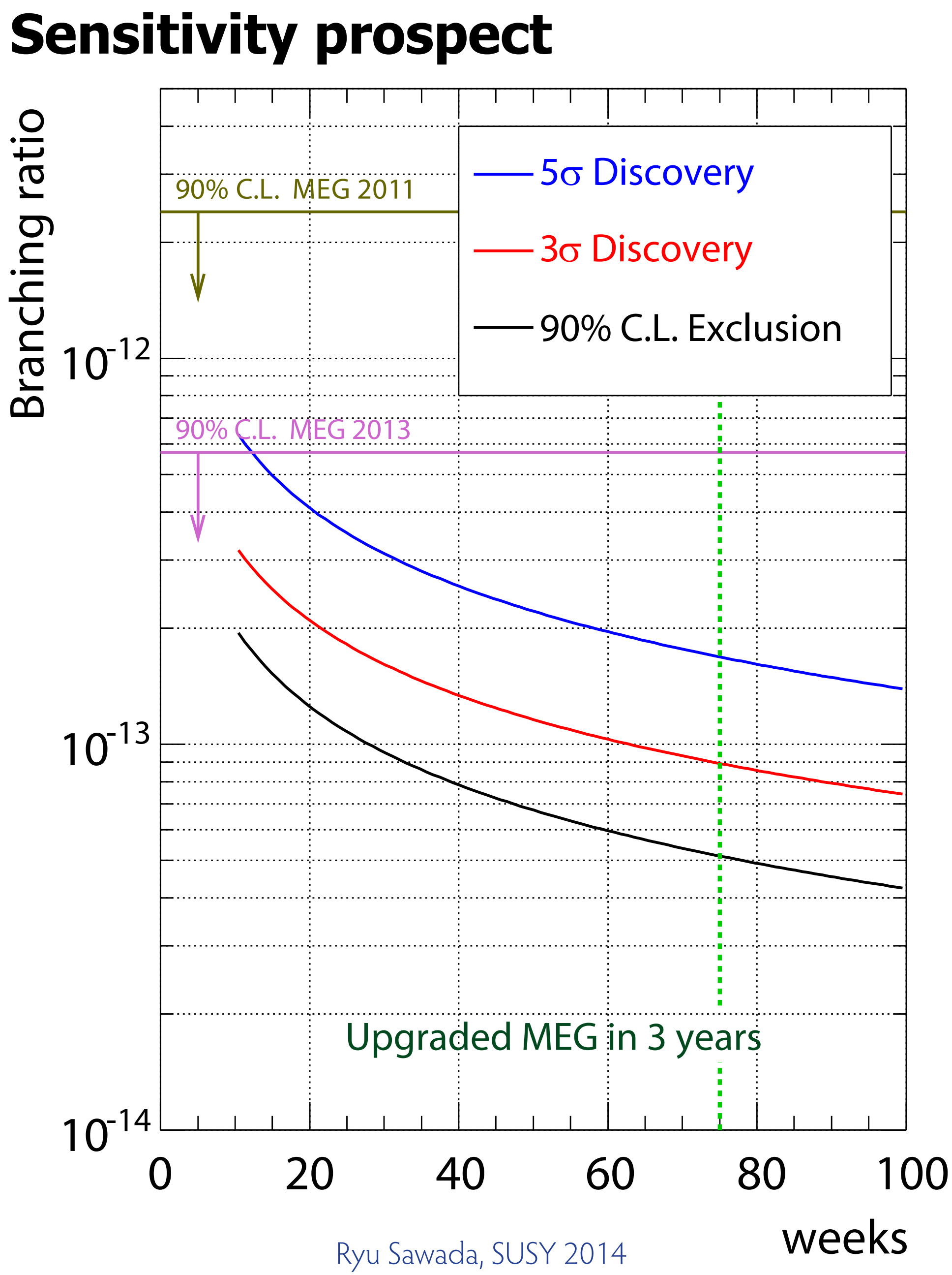
- Many small scintillators
- Read-out by SiliconPMs
- On average eight counters hit by track
- 30 ps timing resolution per track



MEG II sensitivity projection

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

Starting 2017

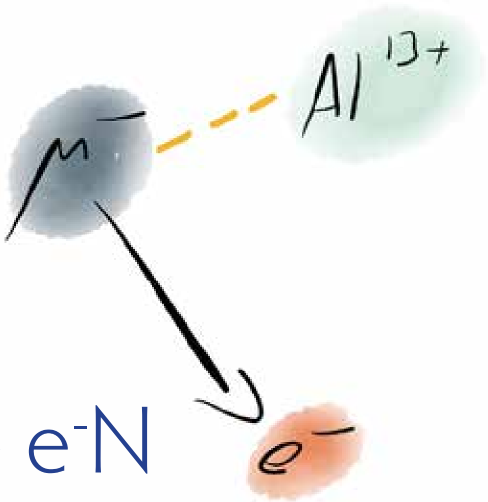


Ryu Sawada, SUSY 2014

Searching for $\mu \rightarrow e$ conversion with

DeeMee, Mu2e, COMET

Conversion Signal and Background



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

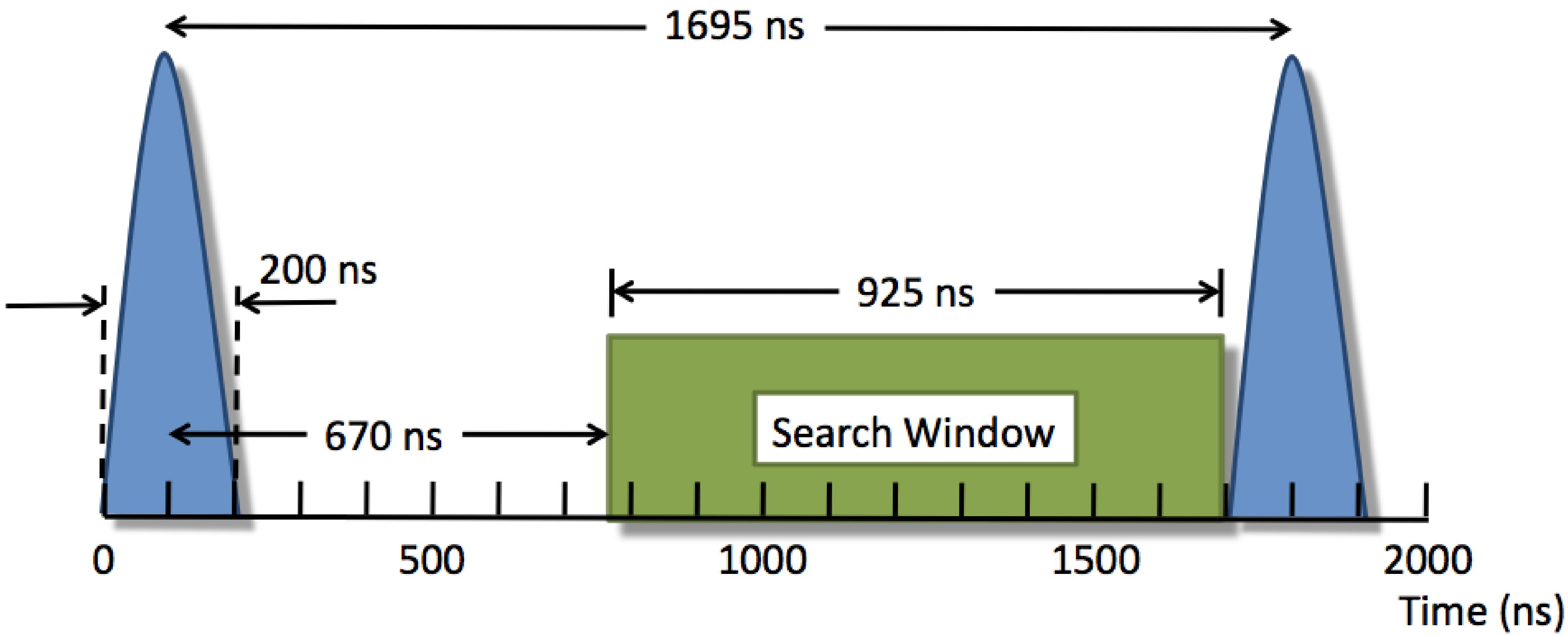
- Single 105 MeV/c electron observed

Backgrounds:

Anything that can produce a 105 MeV/c electron

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

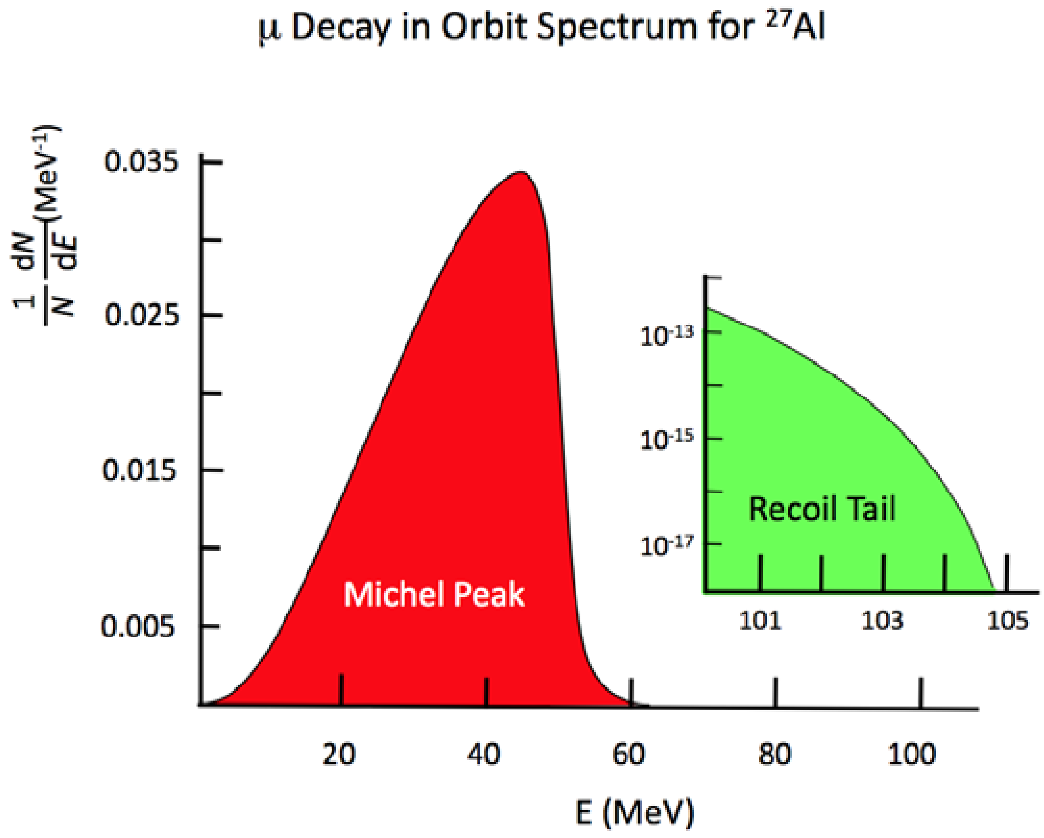
Beam induced background



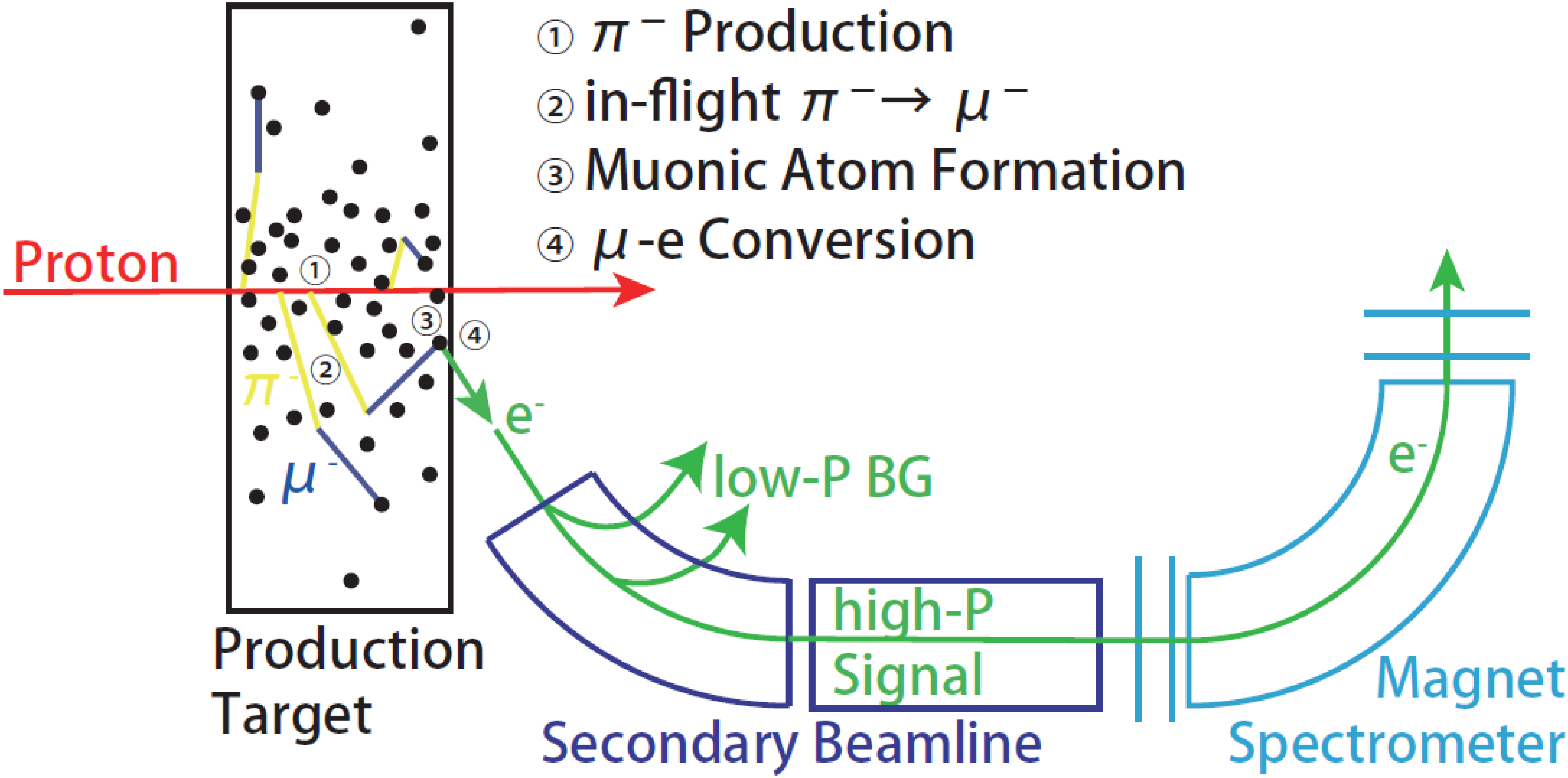
- Proton beam produces pions, photons, (antiprotons) etc.
- Wait until things become better...

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



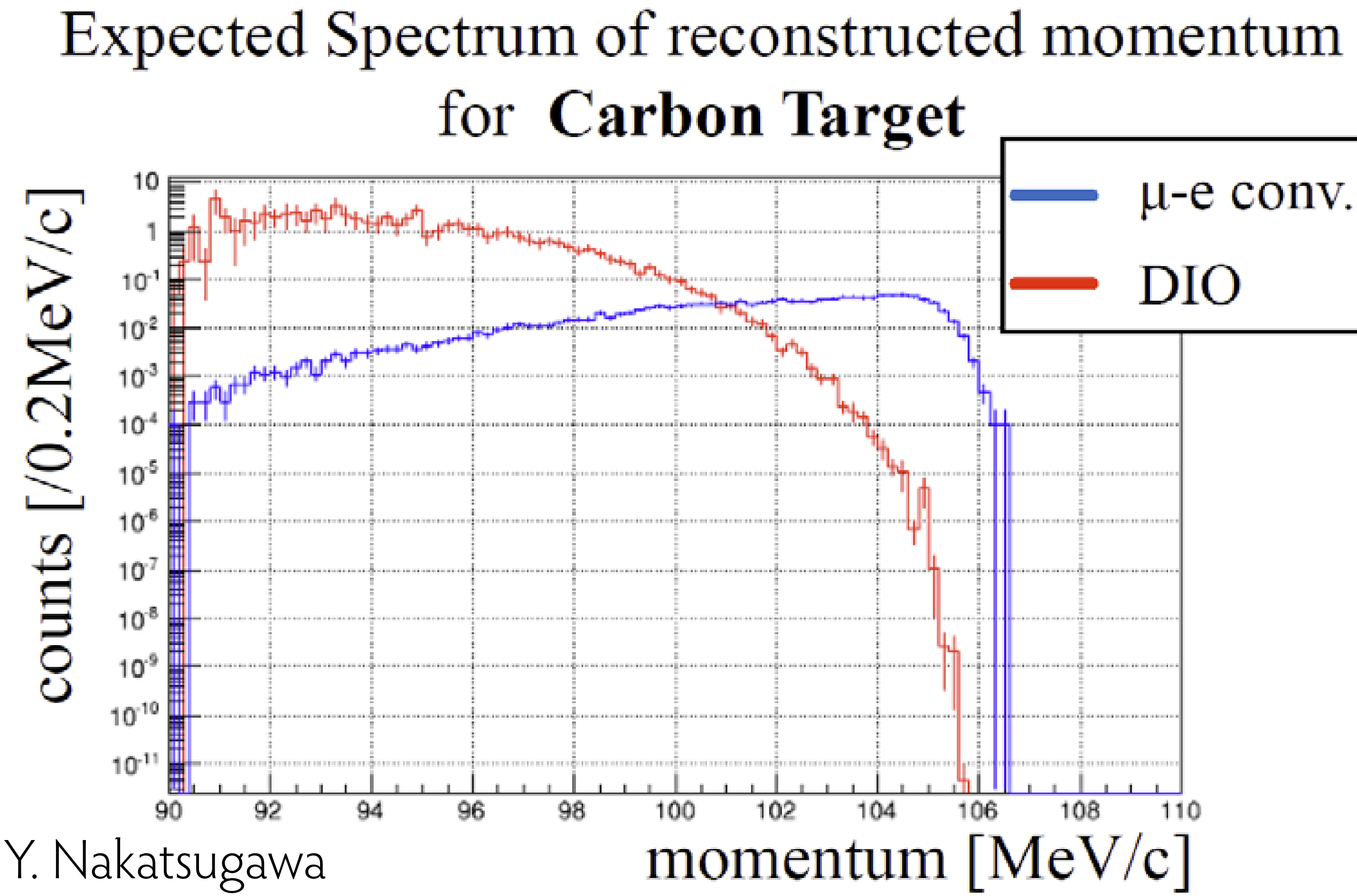
Experimental concept - DeeMee at J-PARC



Yohei Nakatsugawa, NuFACT2014

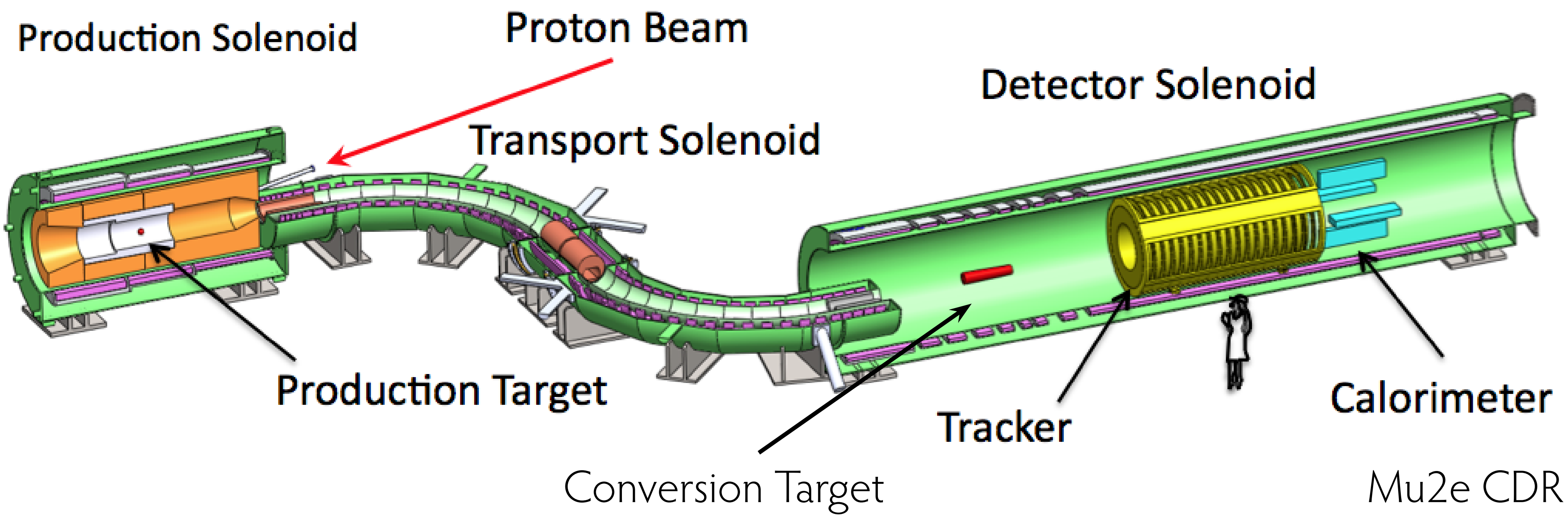
Sensitivity - DeeMee

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



Y. Nakatsugawa

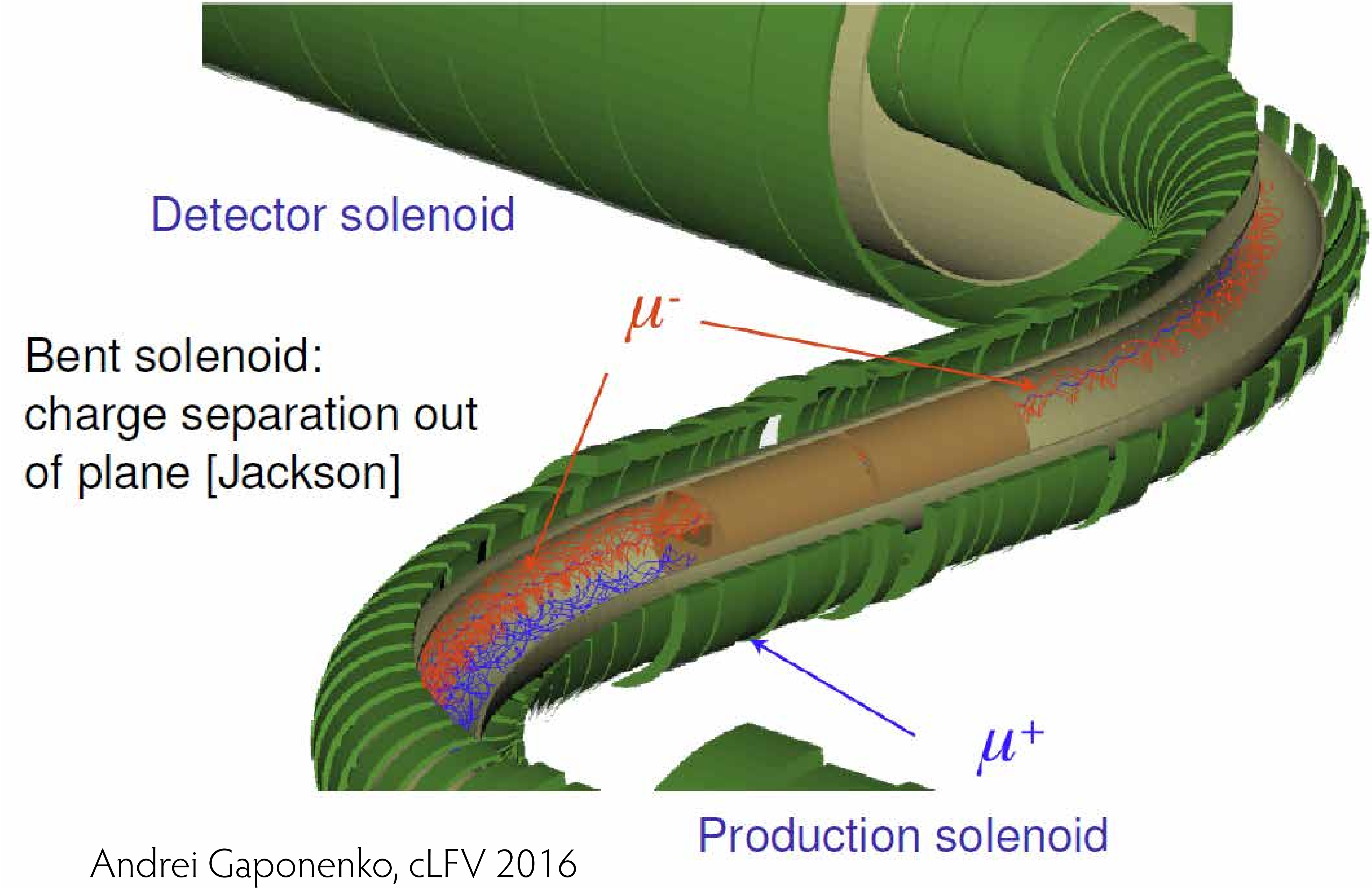
Experimental layout - Mu2e at Fermilab



Mu2e CDR

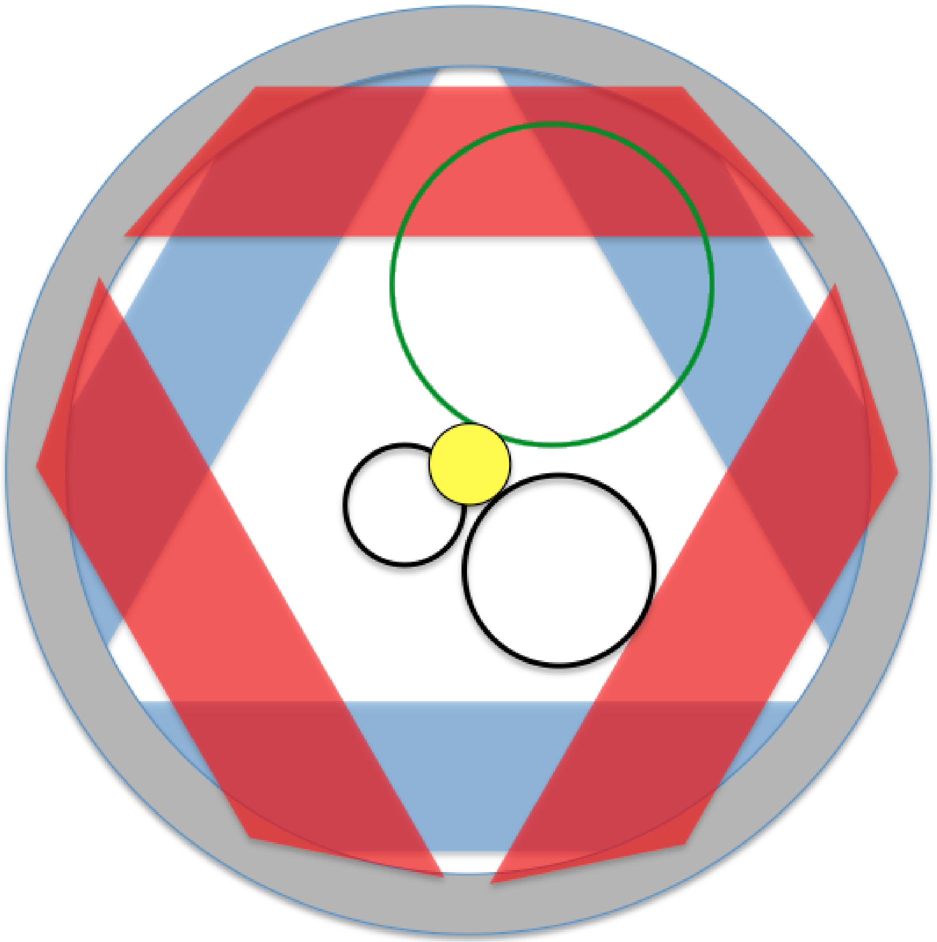
- Separate muon production and conversion target
- Not shown: cosmic ray veto and absorbers

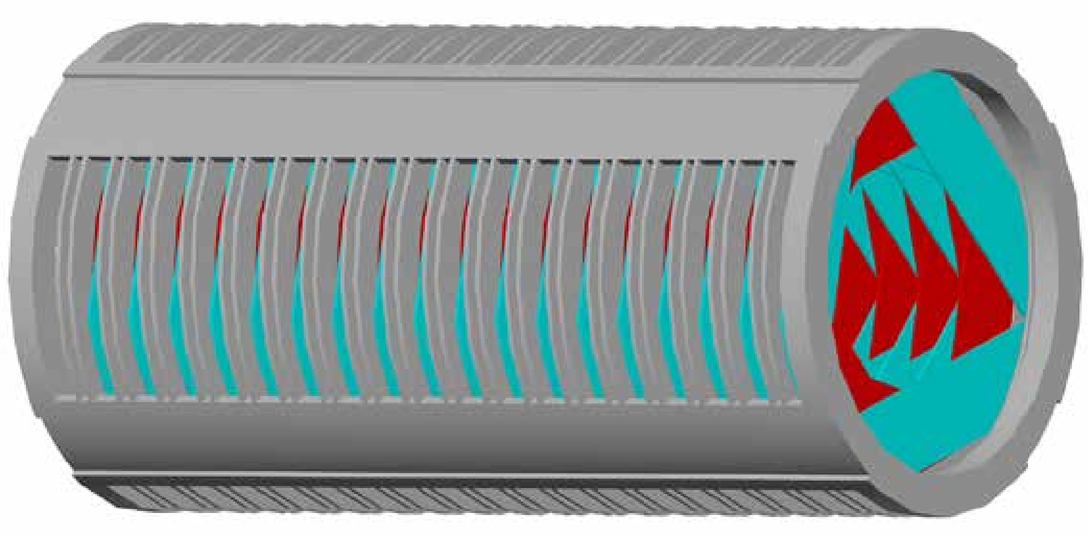
Charge selection



Andrei Gaponenko, cLFV 2016

Mu2e Tracker



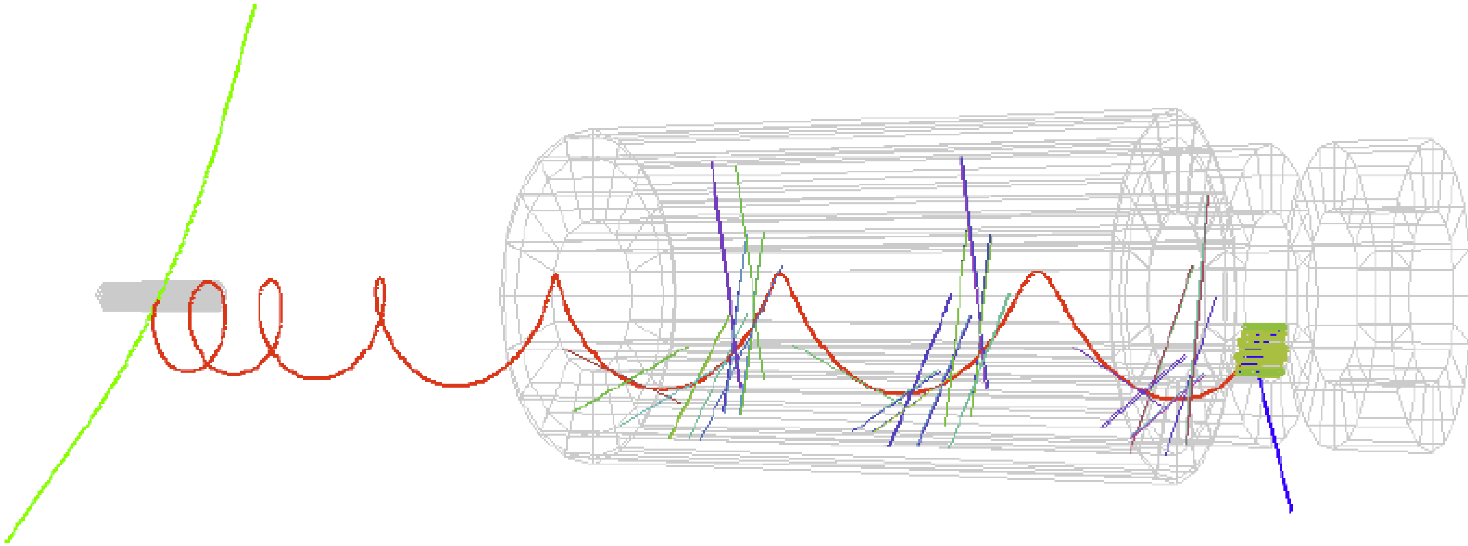


- Straw tubes in vacuum
- Outside of radius of Michel electrons

Mu2e CDR

Mu2e Cosmic Ray Background

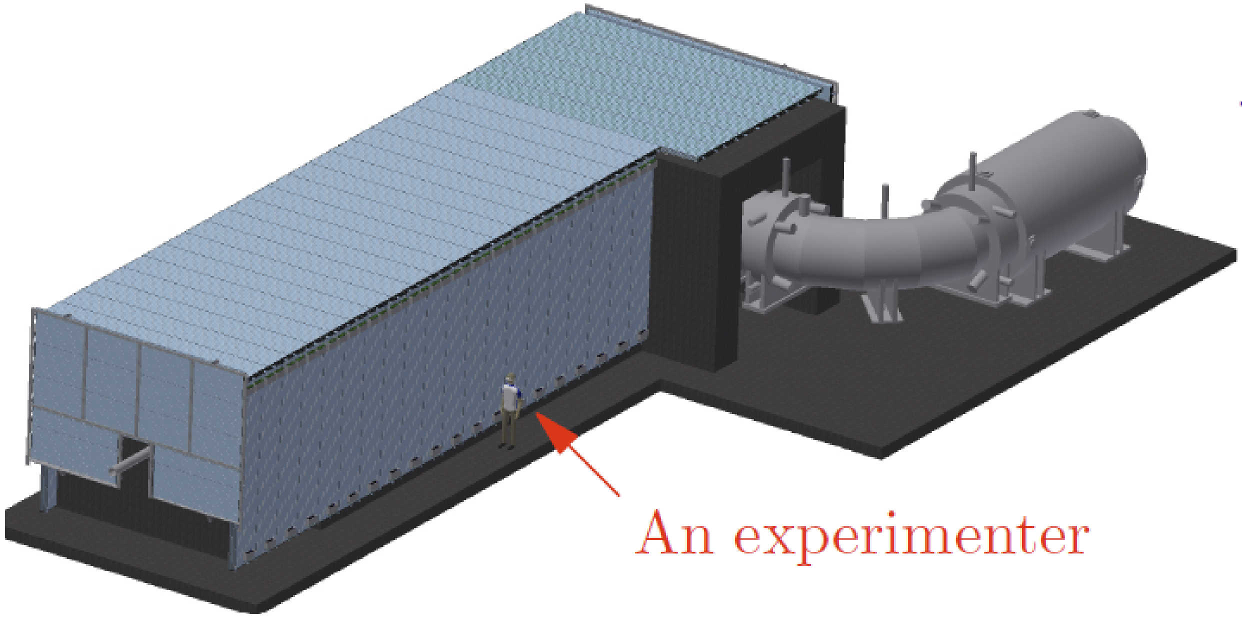
- A cosmic muon track can look like a 105 MeV/c electron track
- A cosmic muon can decay, or knock out an electron from detector material



- 1 event per day without counter-measures
- Vetoing cosmic muons is crucial
- Aim for as much coverage as possible

Andrei Gaponenko, cLFV 2016

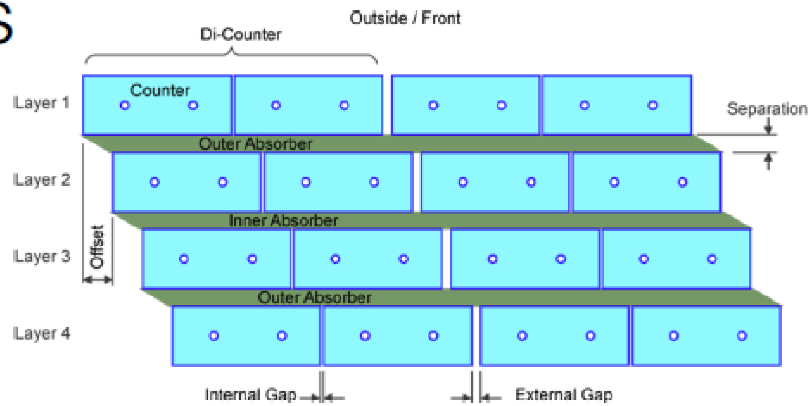
Mu2e Cosmic Ray Veto



Intense radiation field

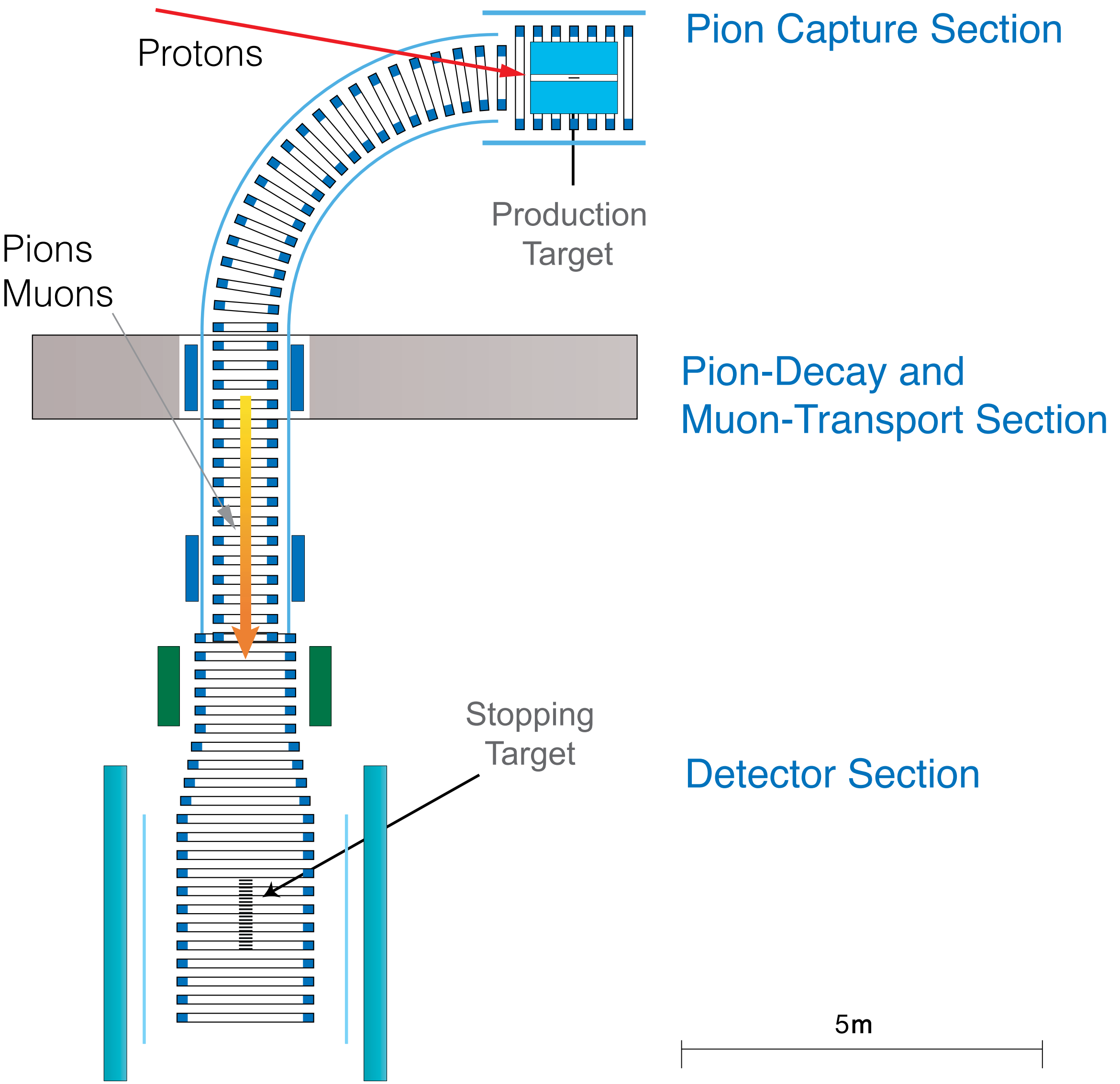
- proton target
- $\mathcal{O}(10^{10})$ muon captures per second: n, γ, . . .
- false vetoes (dead time)

- Optimized counter and shielding design using massive G4 and MARS simulations
- Four layers of scintillator counters
- Aluminum absorbers
- Veto will be applied offline

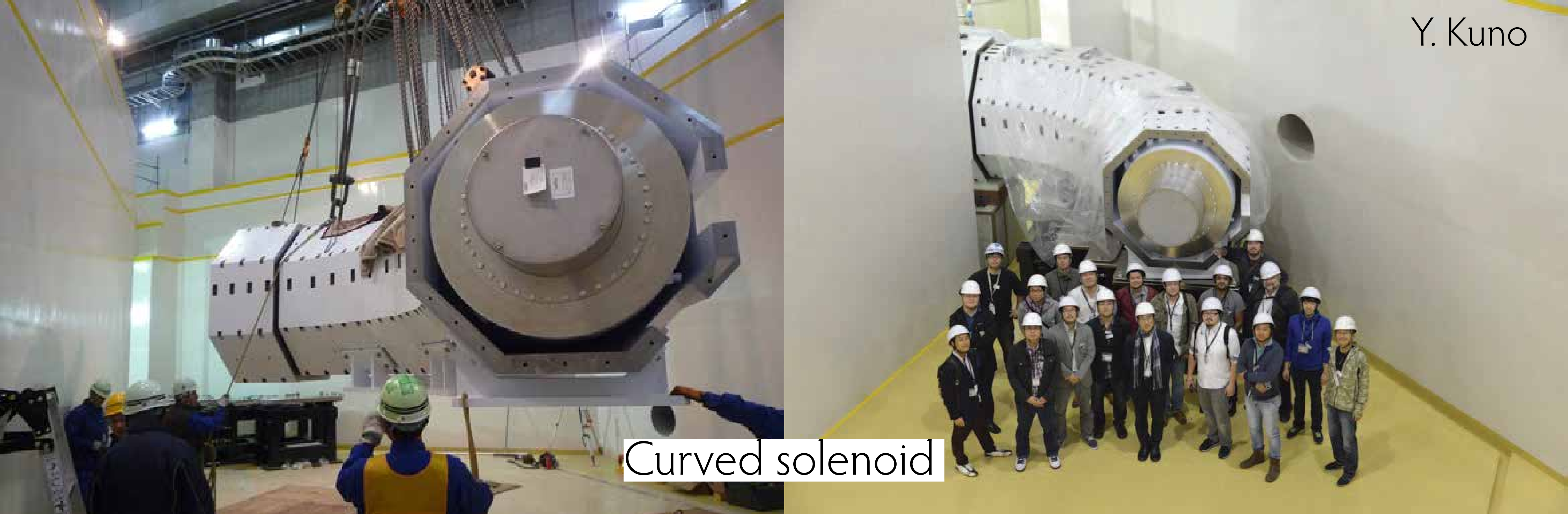


Andrei Gaponenko, cLFV 2016

Experimental layout - COMET Phase I at J-PARC

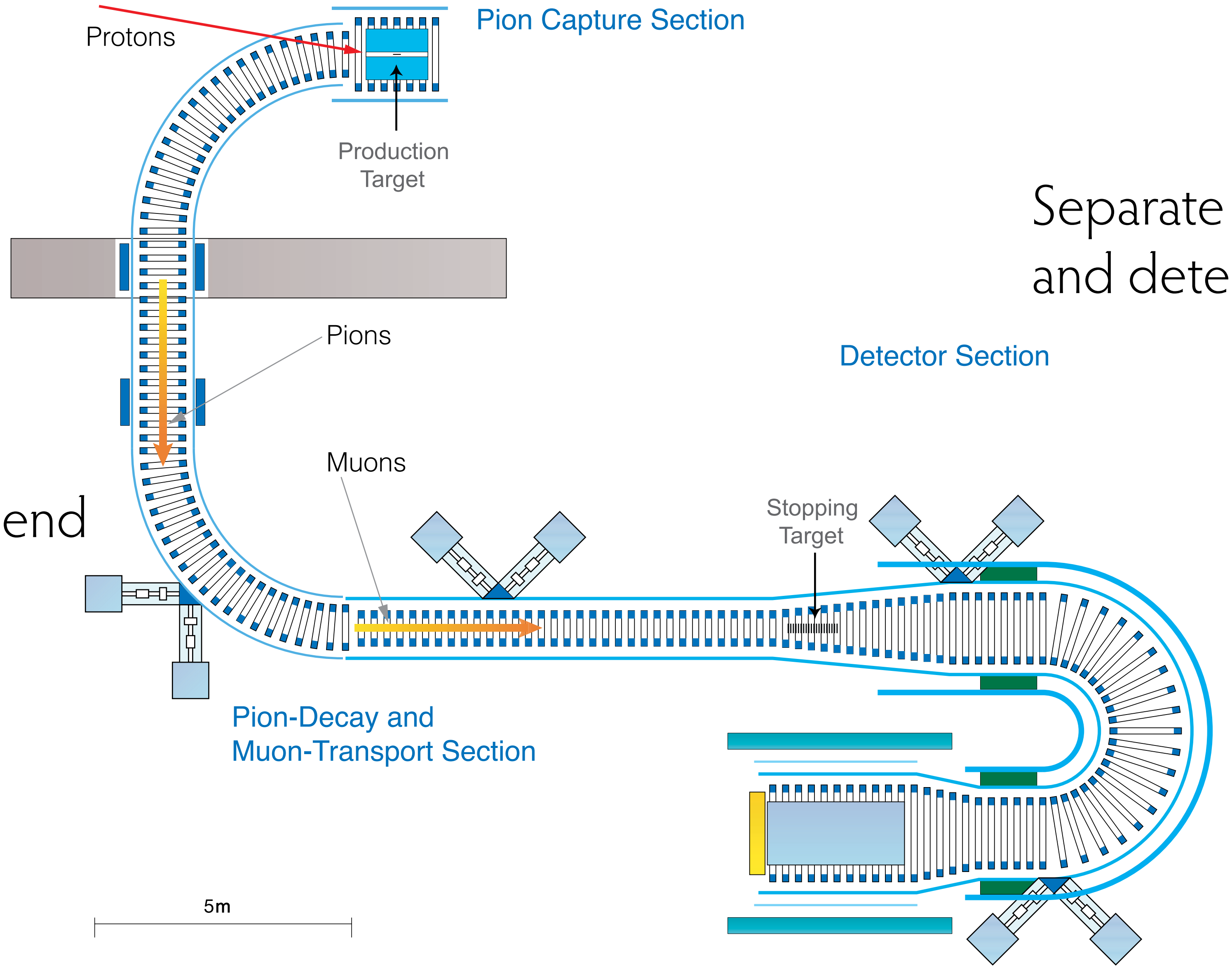


Comet CDR


Y. Kuno
Curved solenoid


Drift chamber

Experimental layout - COMET Phase II



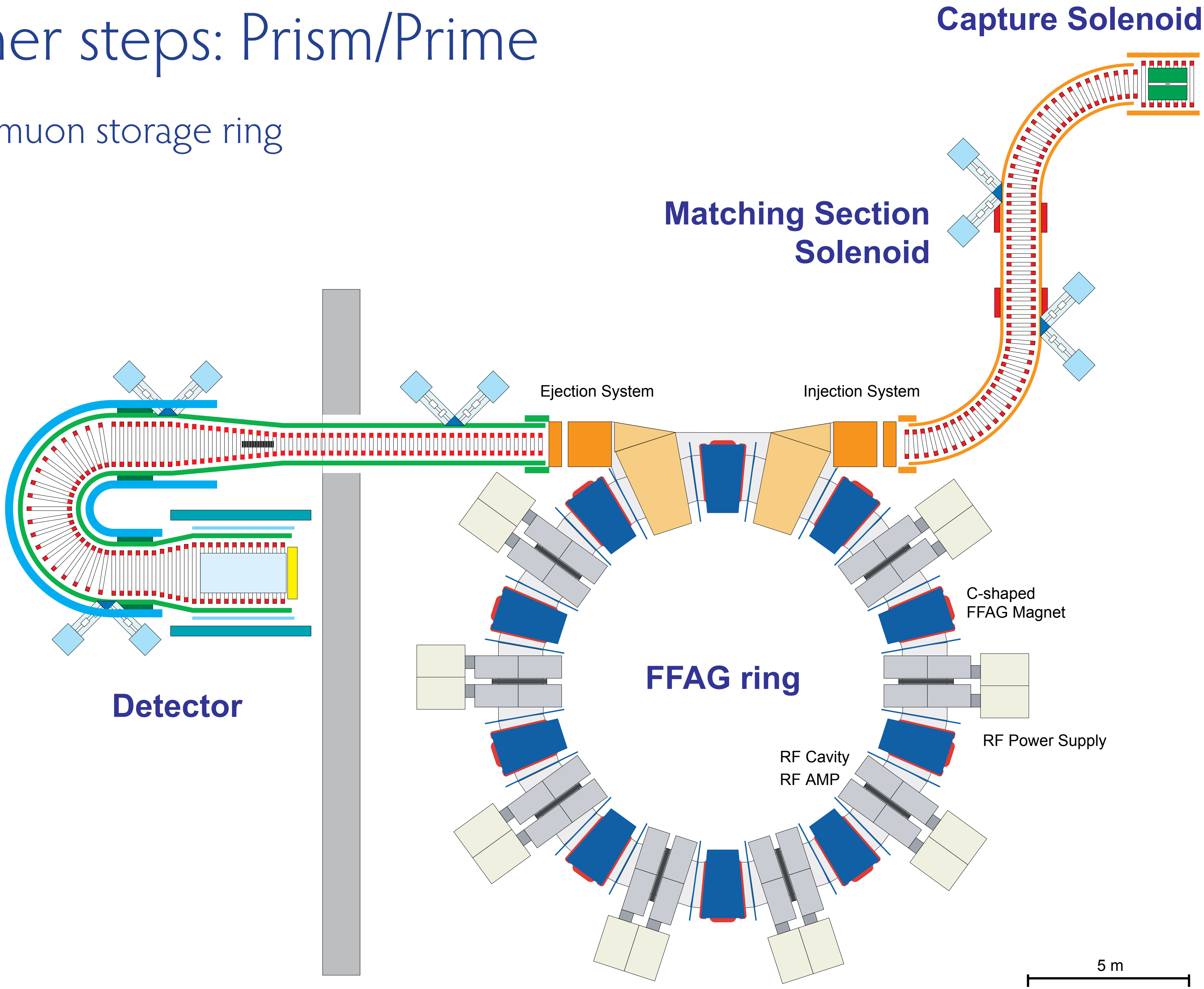
Separate muon decay and detector region

One more bend

Comet CDR

Further steps: Prism/Prime

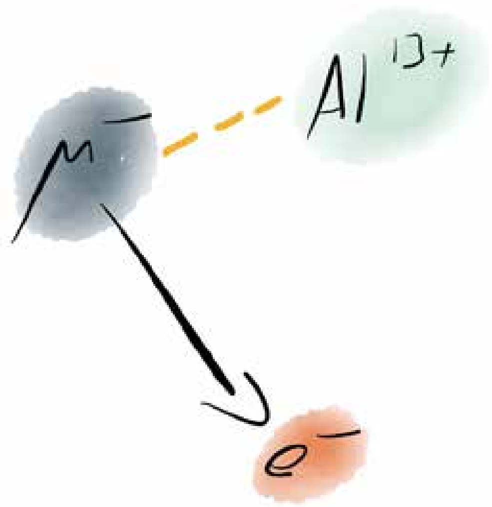
Add a muon storage ring



Conversion: Expected sensitivities

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

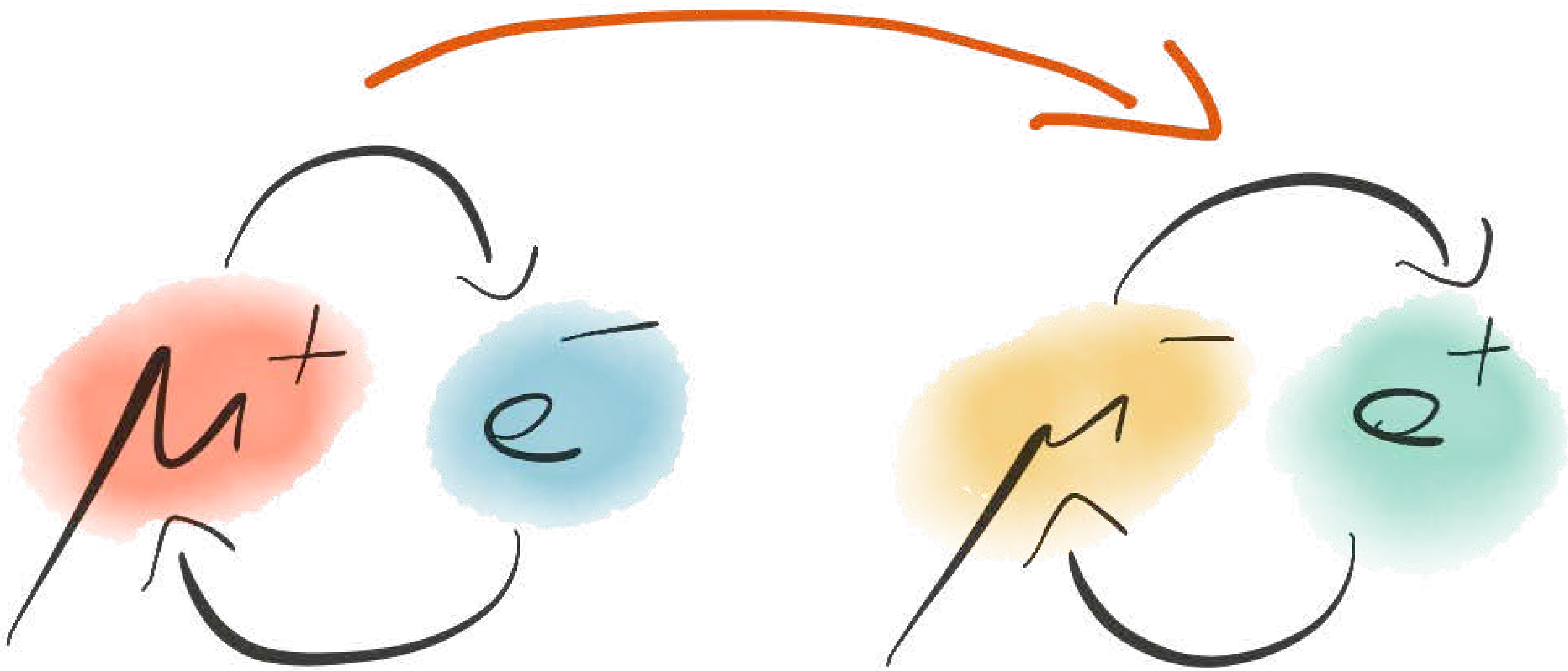
- Comet Phase II and Mu2e will start around 2020
  Sensitivities below 10^{-16}



Other things to do...

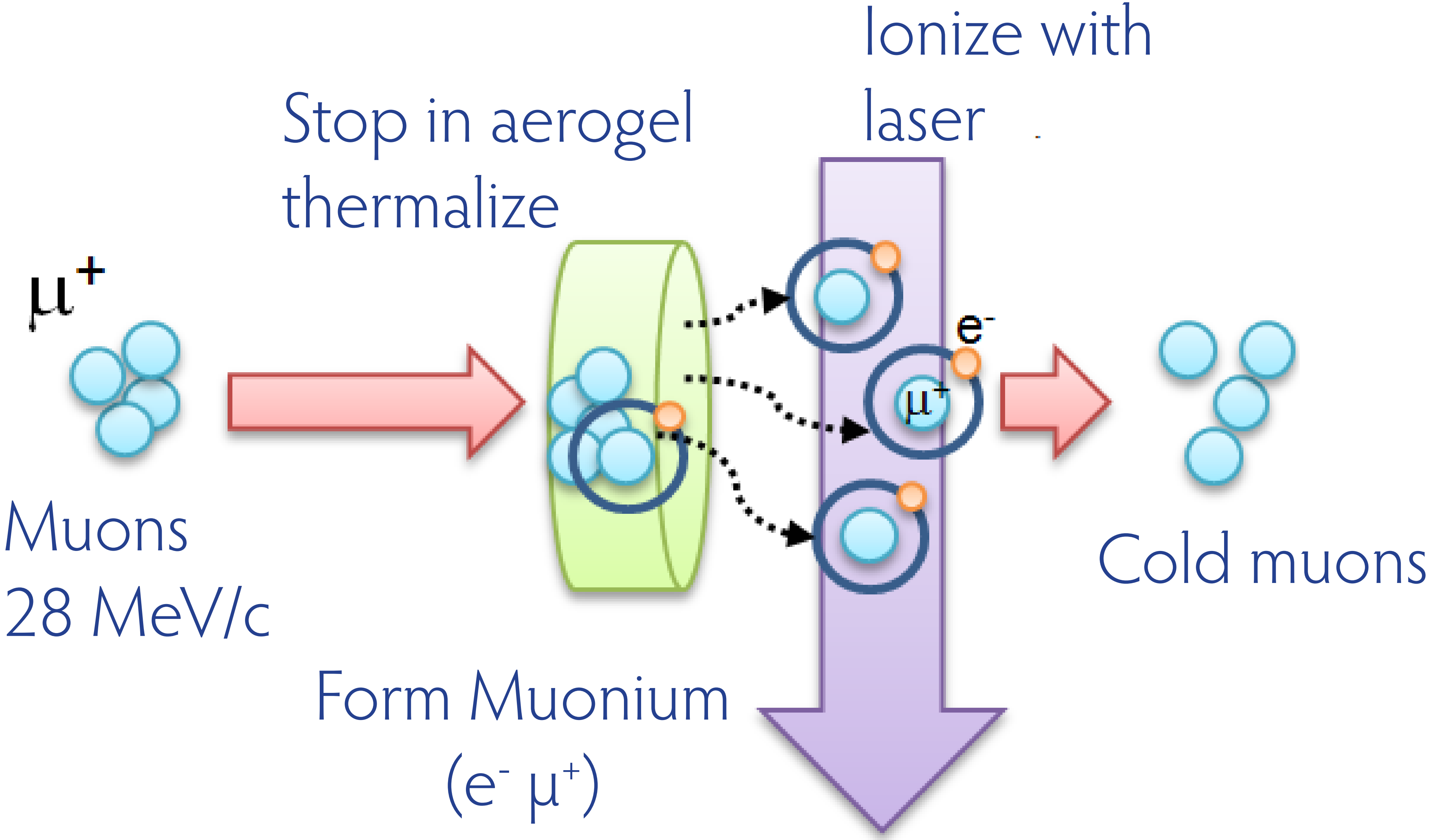
Muonium-antimuonium oscillations

- Lepton flavour changes by two units...
- Need a controlled muonium beam



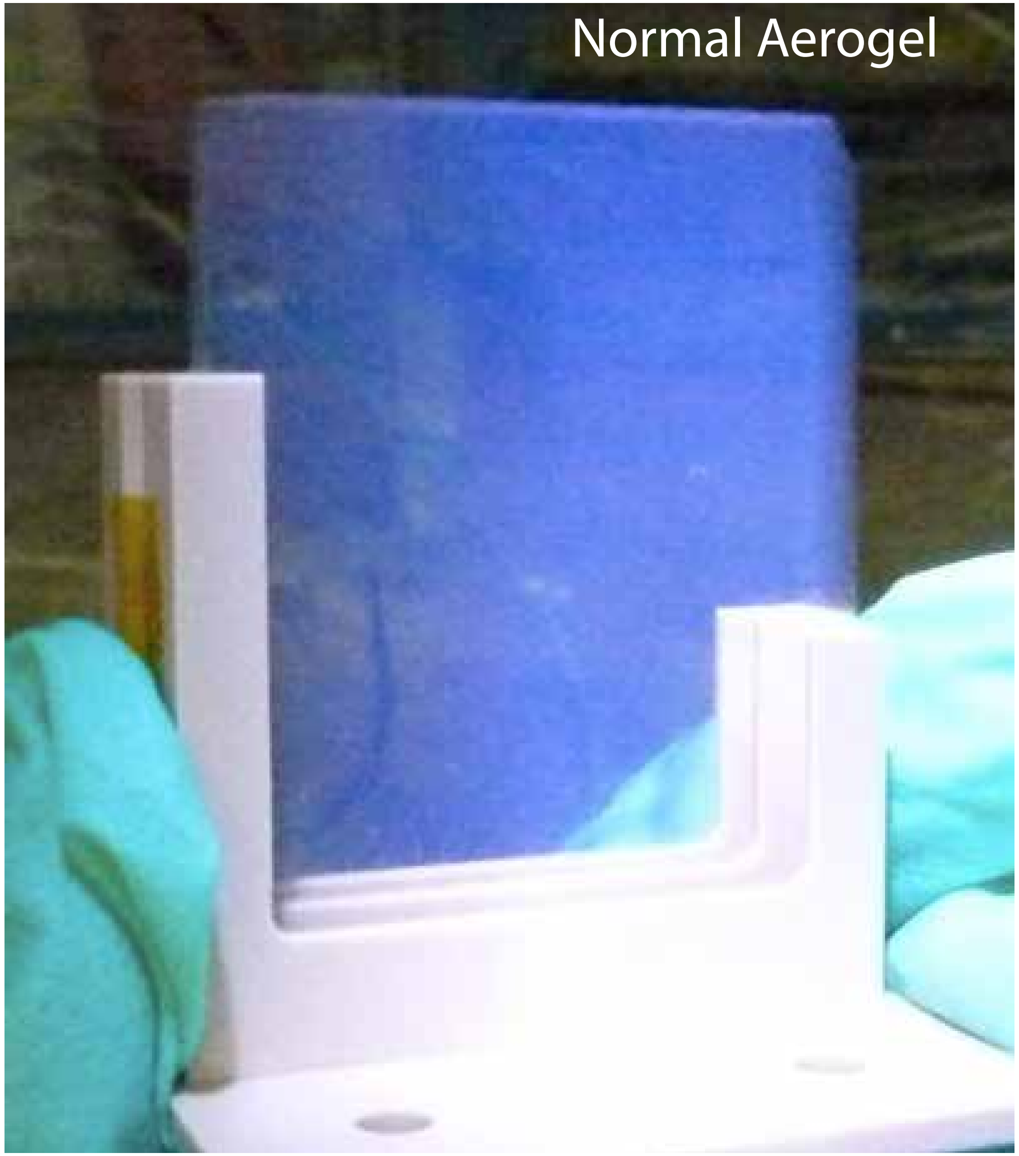
Cold muons from muonium

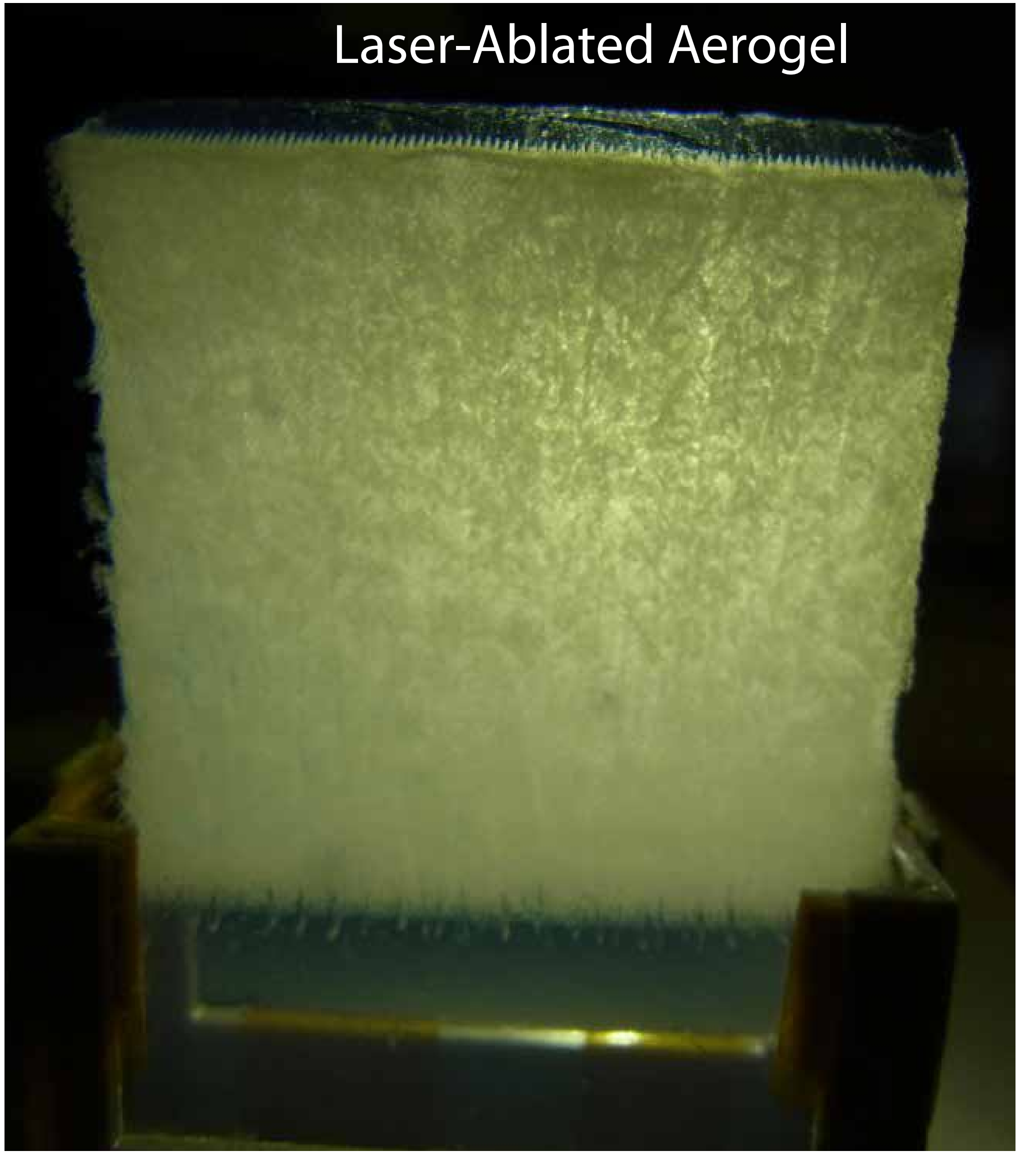
T. Mibe



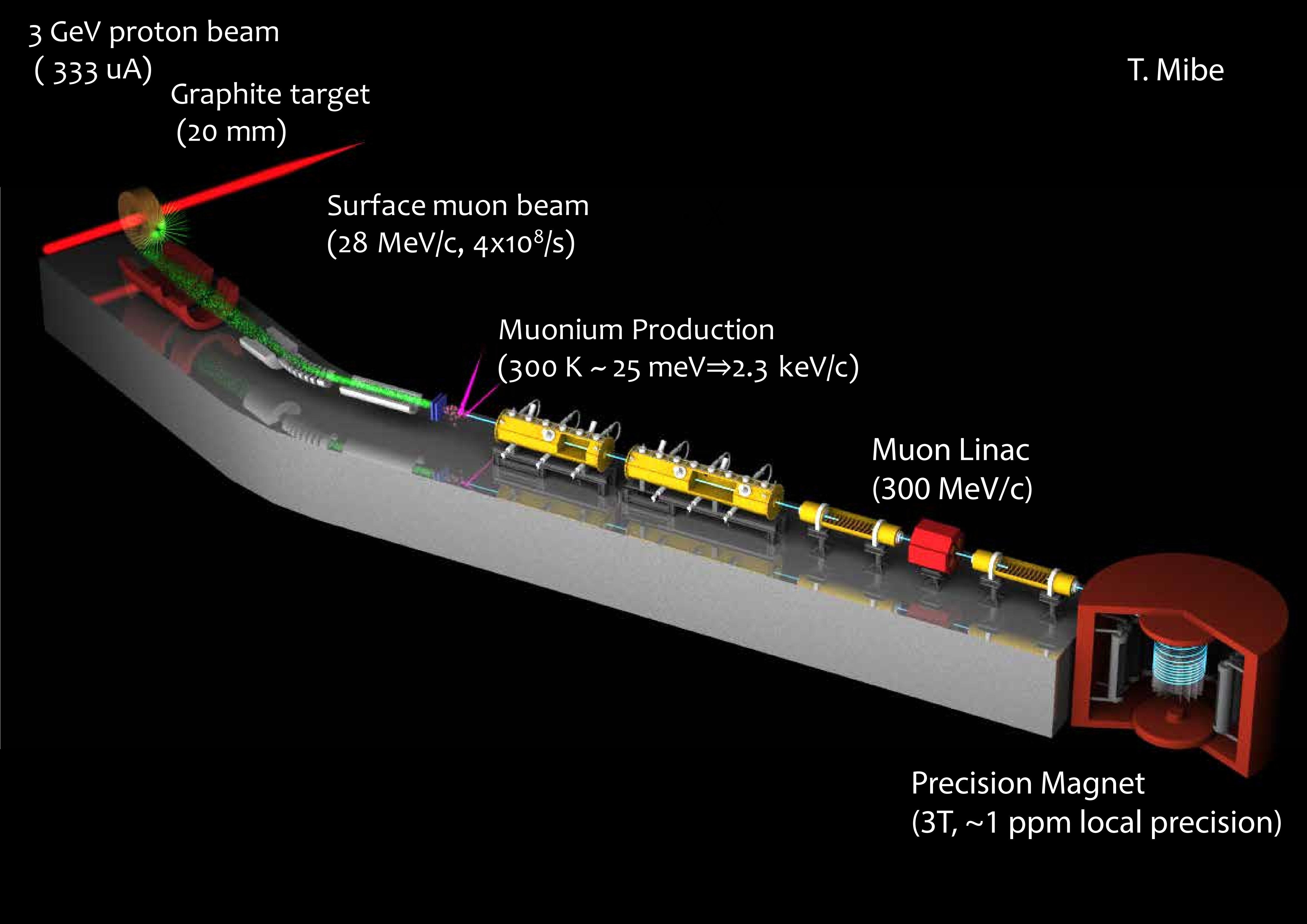
Muonium production in aerogel

T. Mibe

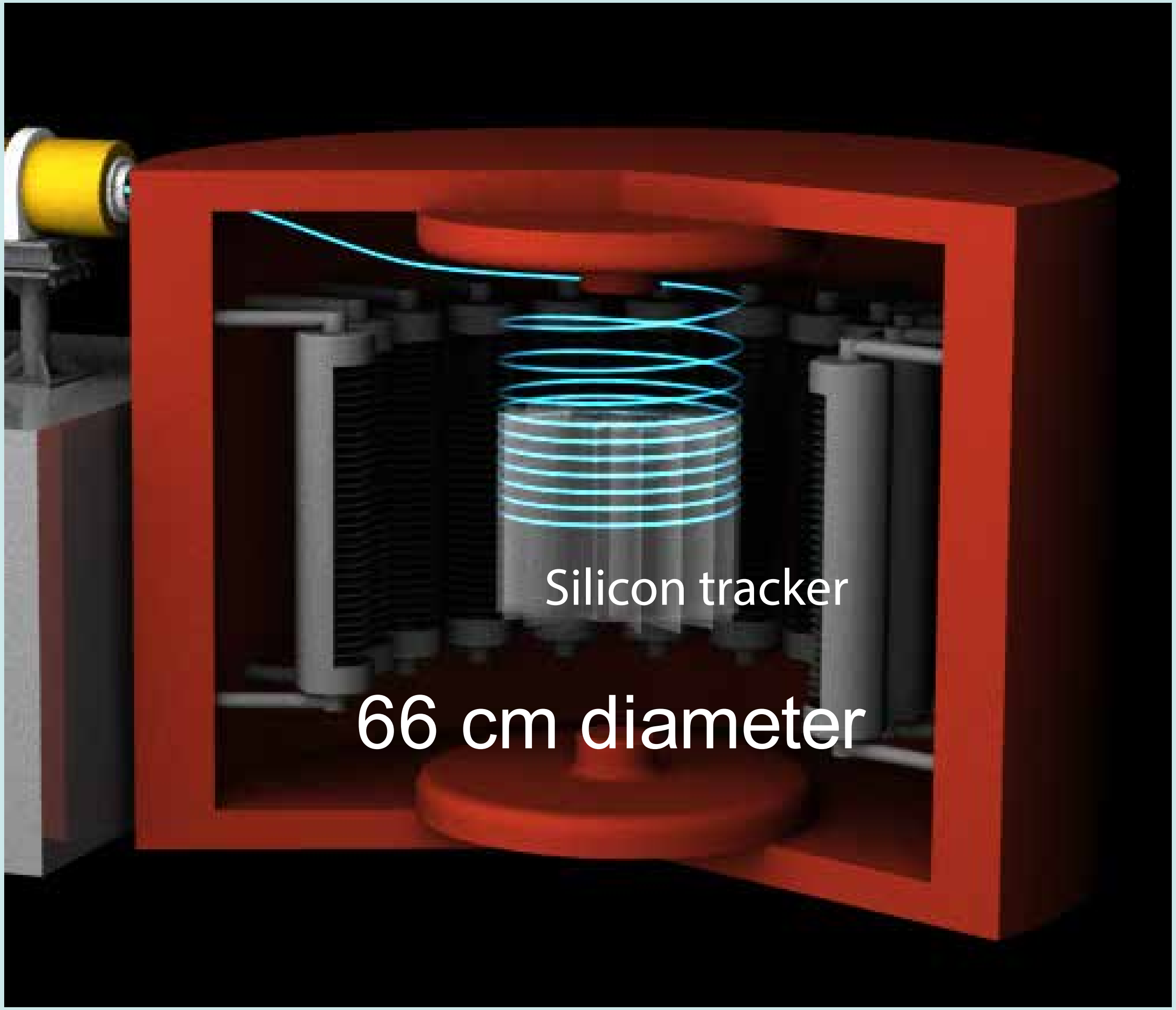




1 Muonium in vacuum per 14 muon stops


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



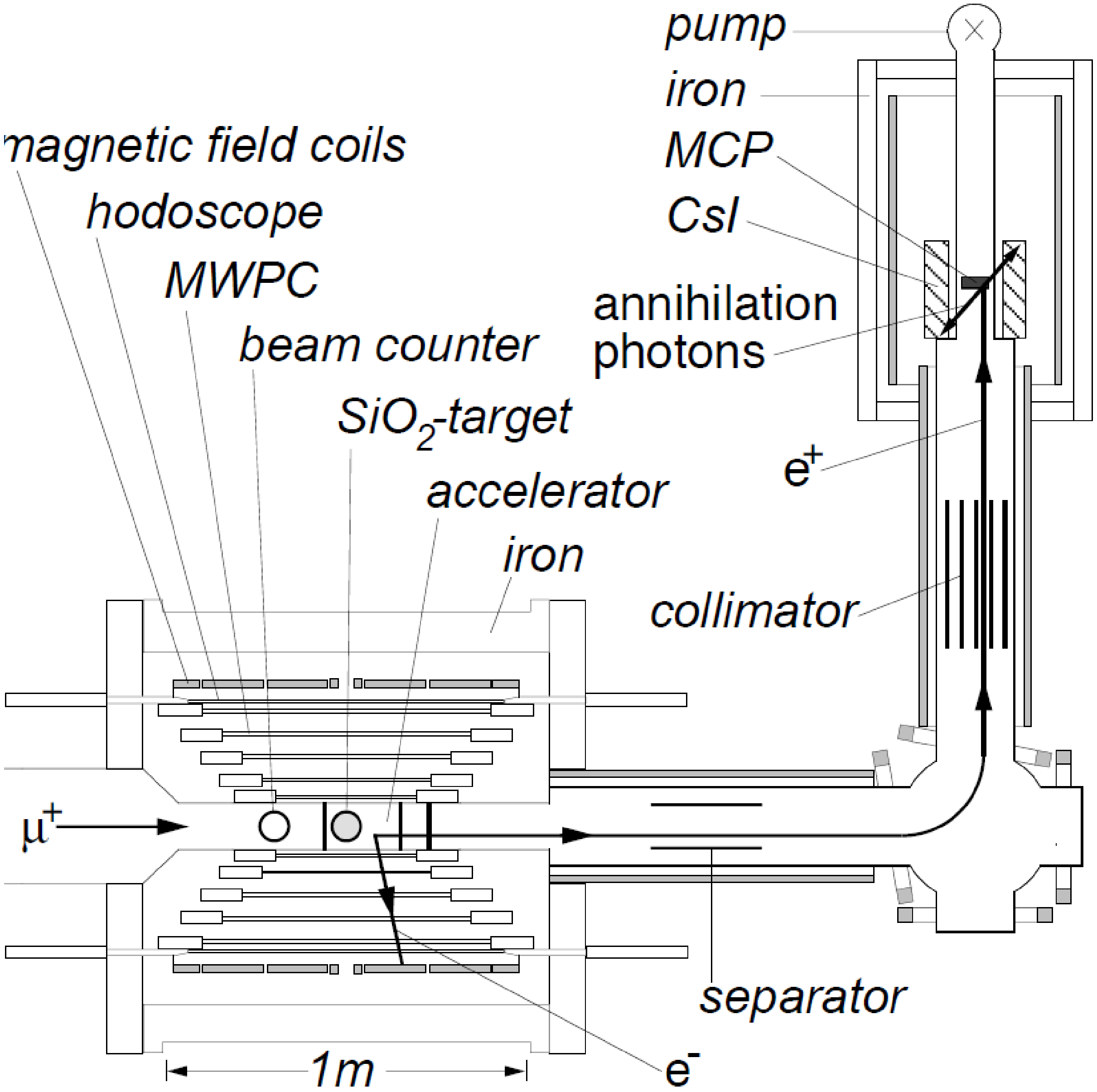
Development ongoing

Potential to match or exceed Fermilab precision

N. Saito

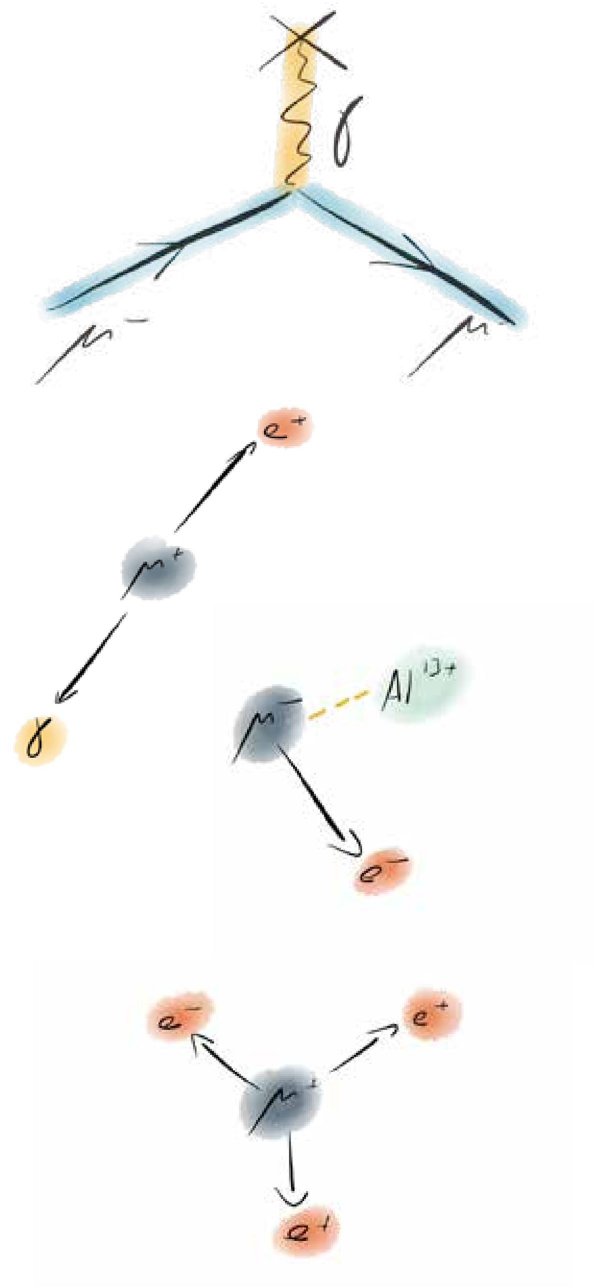
How to build a muonium oscillation experiment?

MACS at PSI



Willmann et al.
Phys.Rev.Lett. 82 (1999) 49-52

Summary

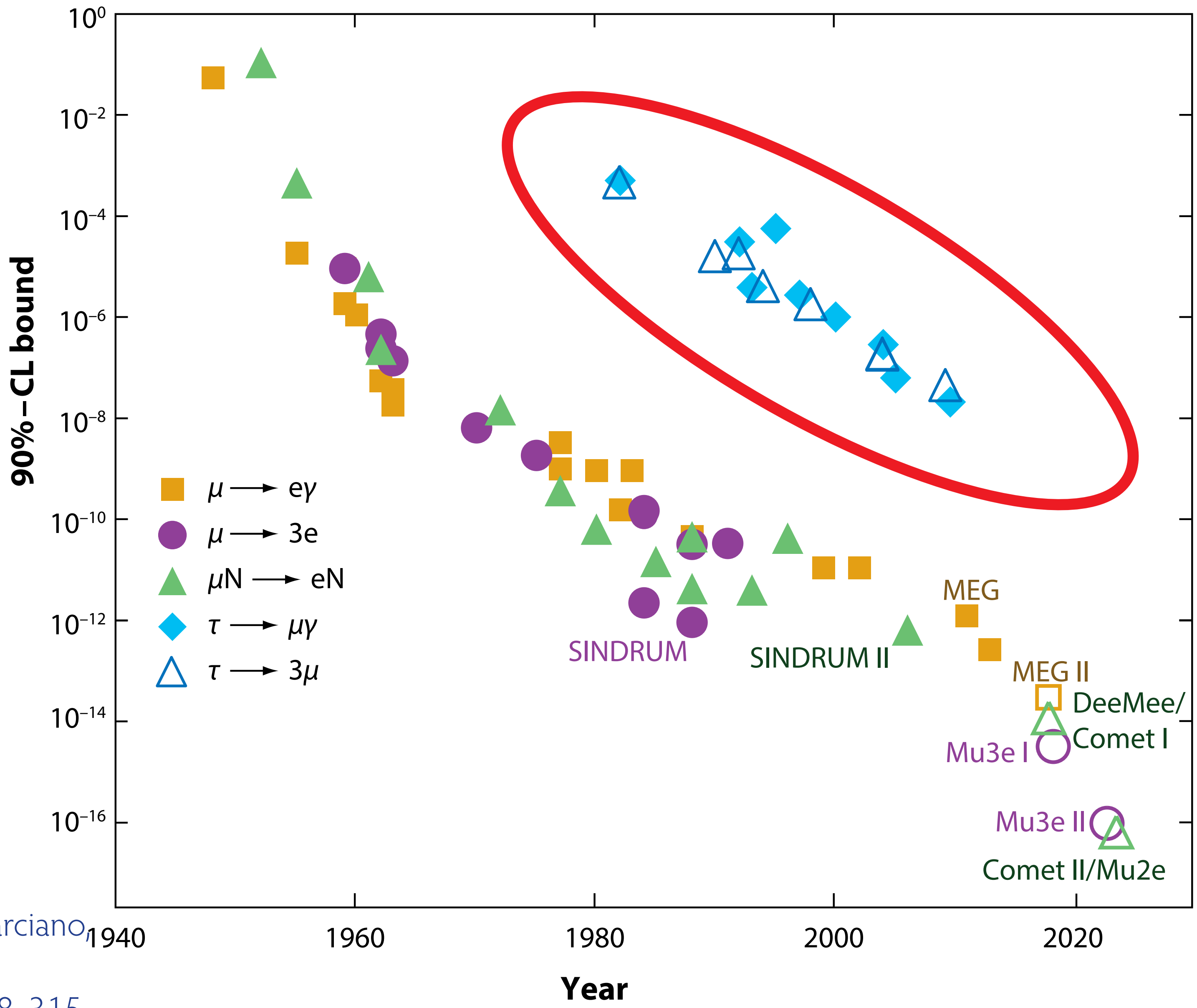


- Exciting times ahead in lepton flavour violation physics
- MEG aims for another order of magnitude for $\mu \rightarrow e\gamma$
- Comet I aims for two orders on $\mu \rightarrow e$ conversion
- Mu3e Phase I aims for two orders on $\mu \rightarrow eee$
- Mu2e/Comet II aim for $< 10^{-16}$ for $\mu \rightarrow e$ conversion and Mu3e Phase II for $< 10^{-16}$ for $\mu \rightarrow eee$
- Ideas for 10^{-18} are around

Backup Material

Tau decays

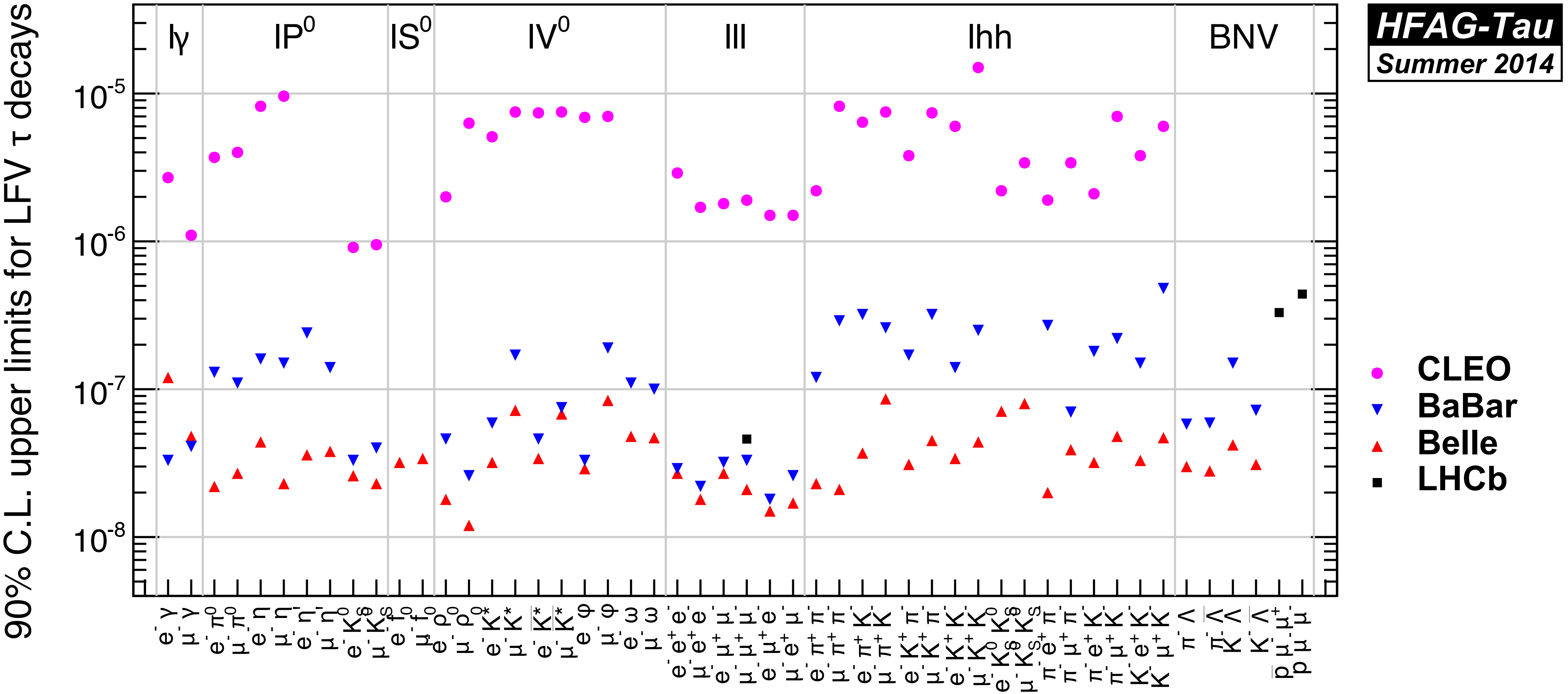
History of LFV experiments



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

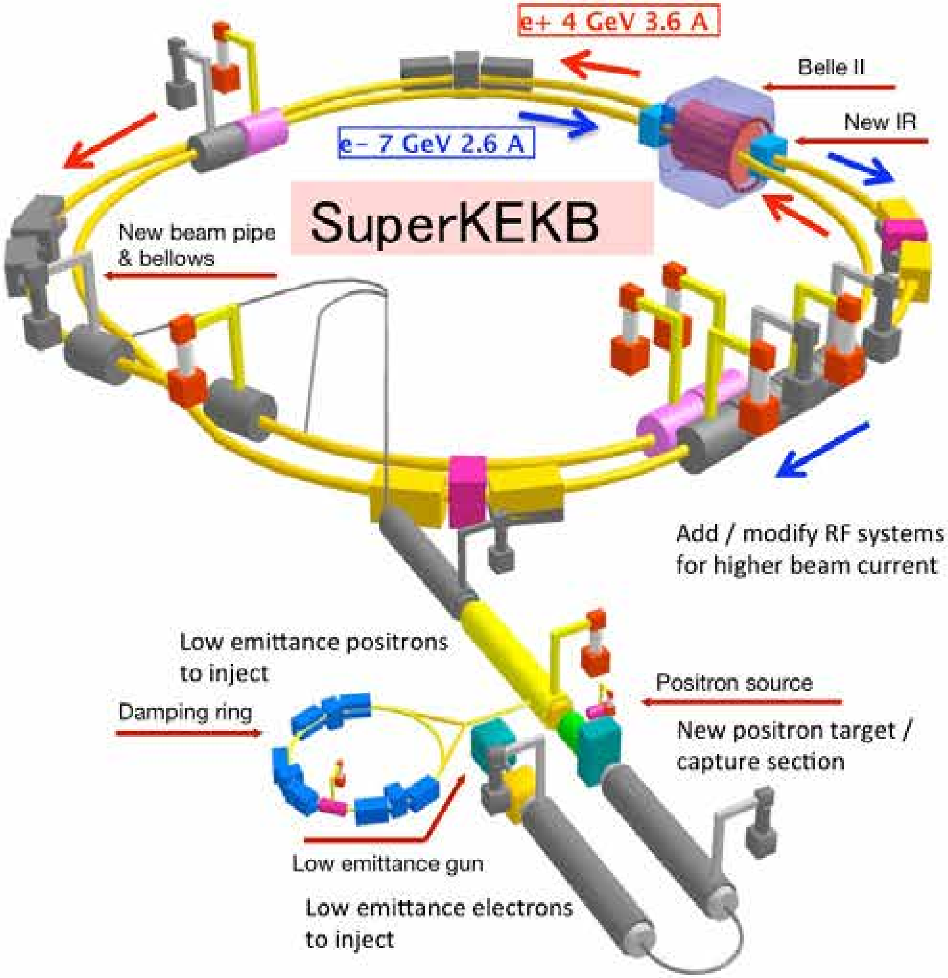
Lepton flavour violating τ-decays

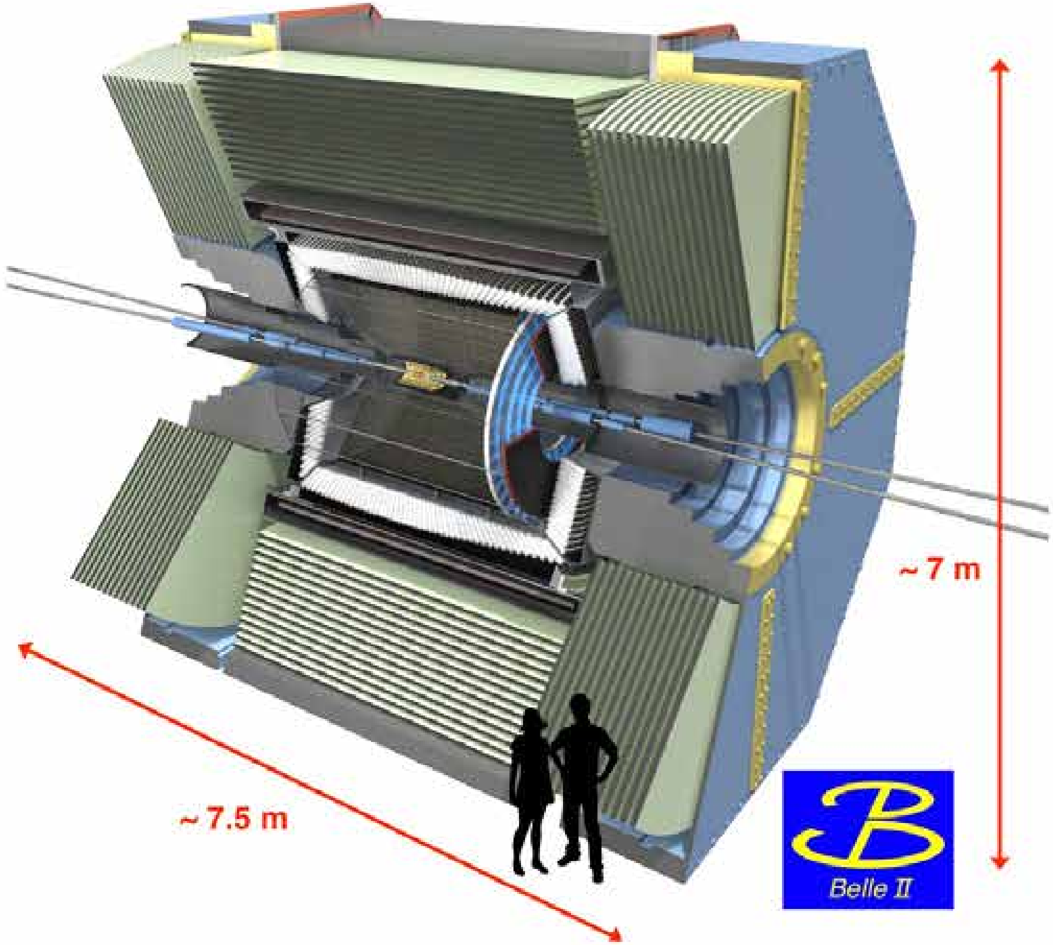
Y



HFAG 2014
arXiv:1412.7515 [hep-ex], Y. Amhis et al., "Averages of b-hadron, c-hadron, and tau-lepton properties as of Summer 2014"

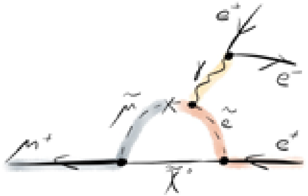
Belle II at Super KEKB





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

A general effective Lagrangian for μ → eee



Tensor terms (dipole) e.g. supersymmetry

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

Four-fermion terms e.g. Z'

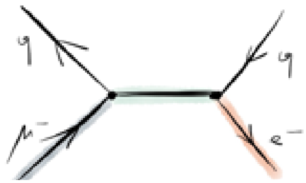
$$+ g_1 (\overline{\mu}_R e_L)(\overline{e}_R e_L) \quad + g_2 (\overline{\mu}_L e_R)(\overline{e}_L e_R)$$

scalar

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

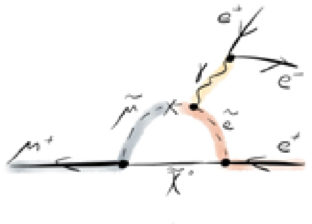
$$+ g_5 (\overline{\mu}_R \gamma^\mu e_R)(\overline{e}_L \gamma^\mu e_L) \quad + g_6 (\overline{\mu}_L \gamma^\mu e_L)(\overline{e}_R \gamma^\mu e_R) \;\; + H.\,C.\,)$$

vector

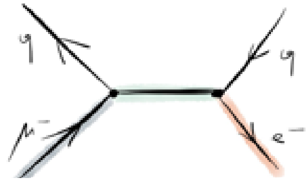


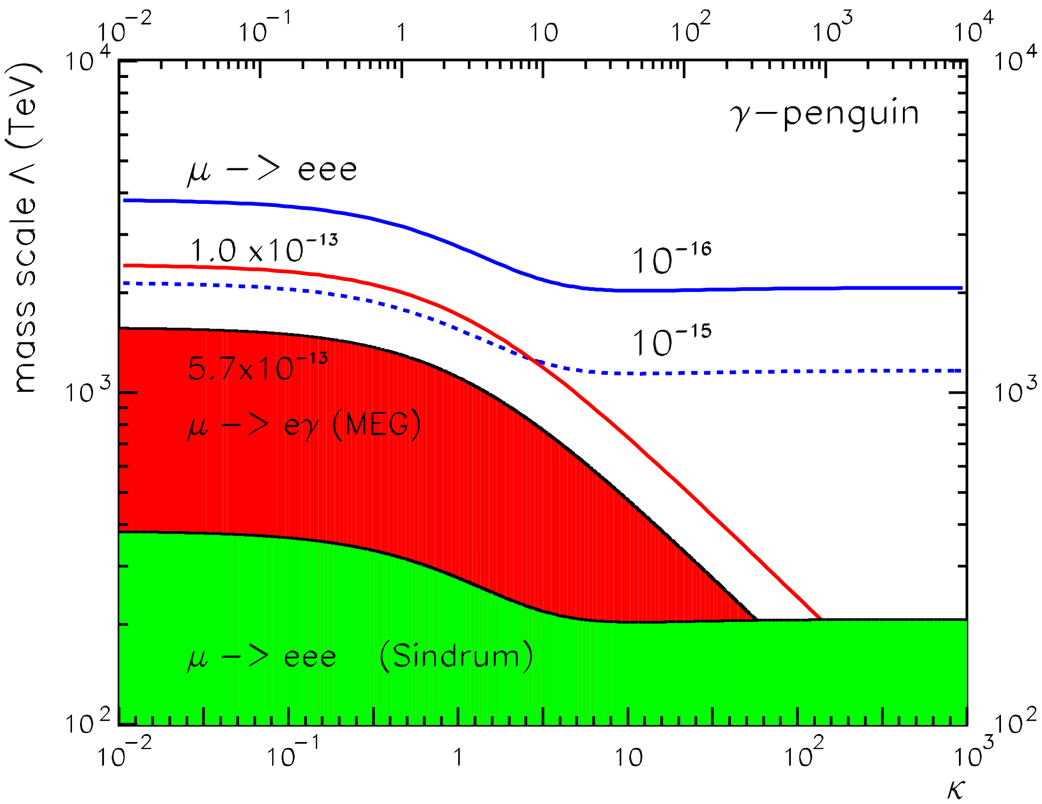
(Y. Kuno, Y. Okada,
Rev.Mod.Phys. 73 (2001) 151)

Comparison between $\mu^+ \rightarrow e^+\gamma$ and $\mu \rightarrow eee$



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



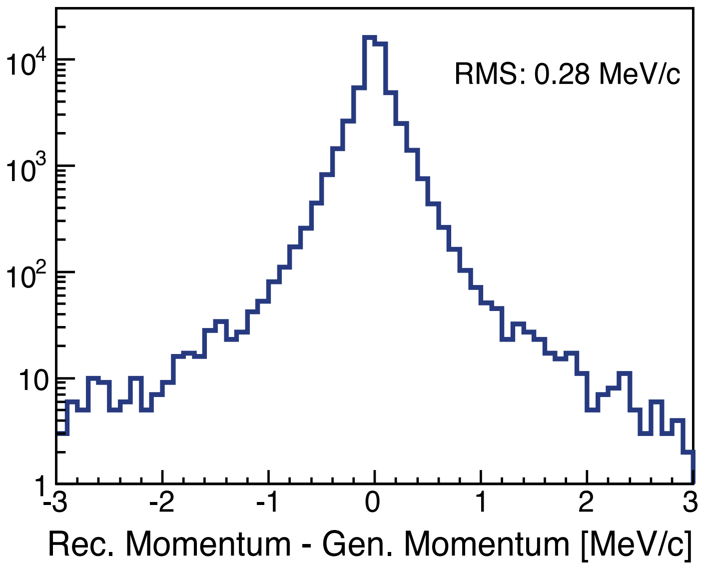


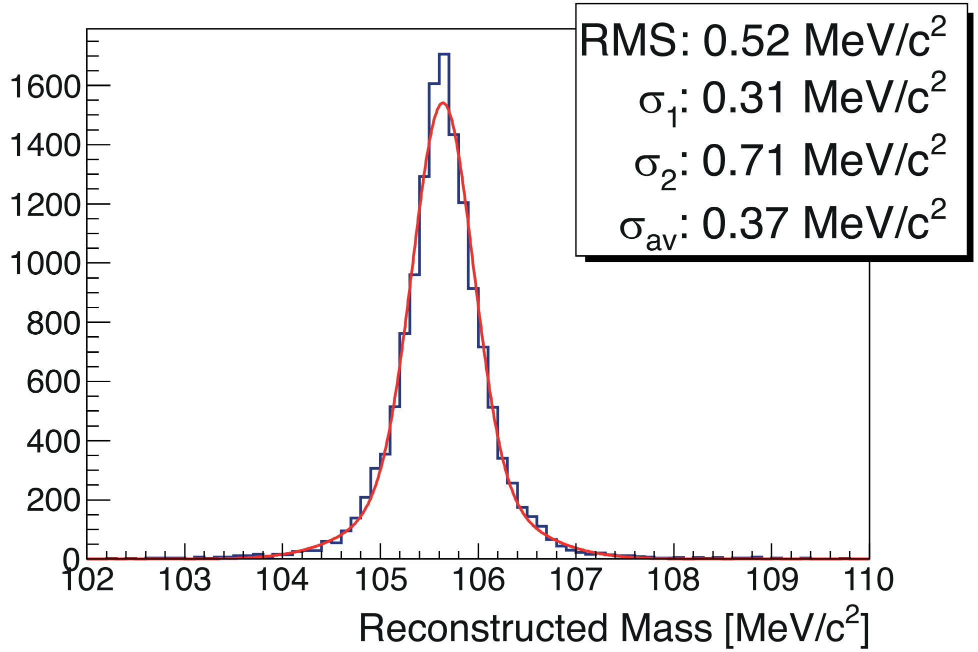
- One loop term and one contact term
- Ratio κ between them
- Common mass scale Λ
- Allows for sensitivity comparisons between $\mu \rightarrow eee$ and $\mu \rightarrow e\gamma$
- In case of dominating dipole couplings ($\kappa = 0$):

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

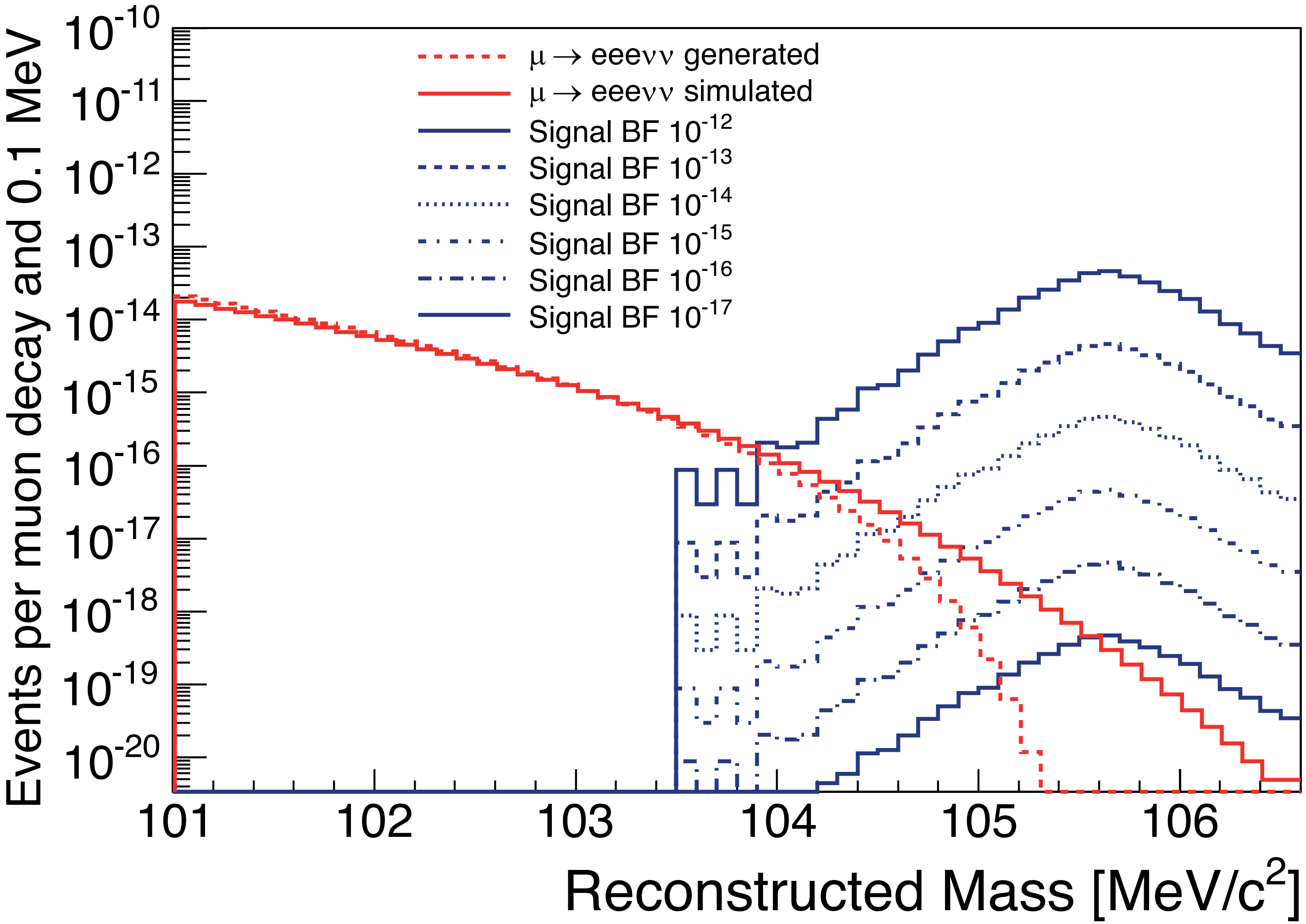
Simulated Performance - Mu3e Phase II

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

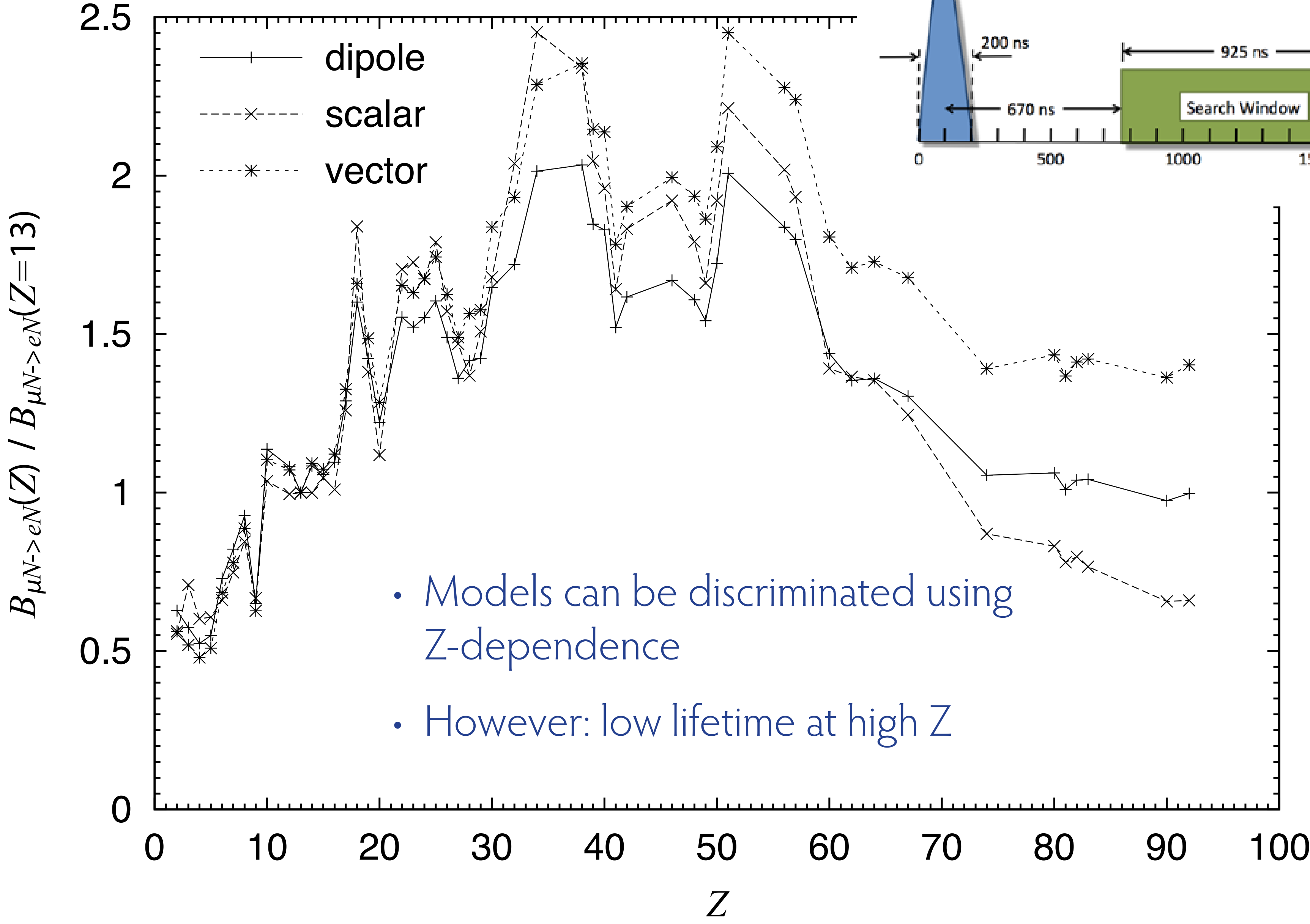


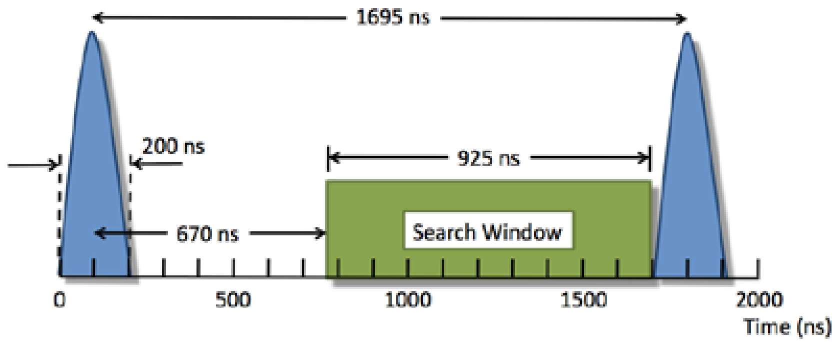


Simulated Performance - Mu3e Phase II



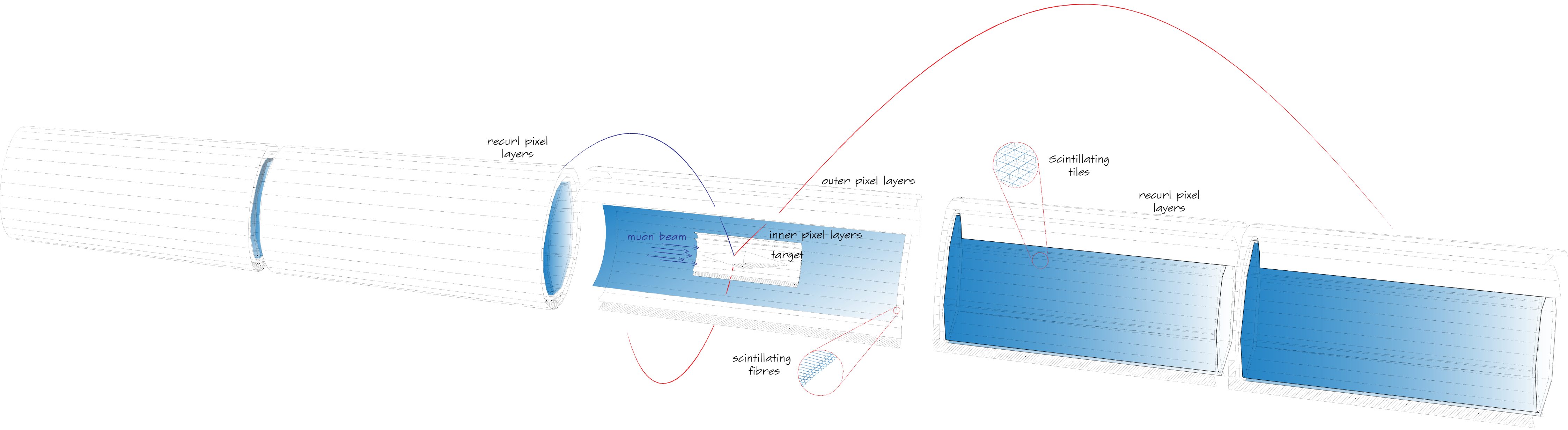
Z-dependence



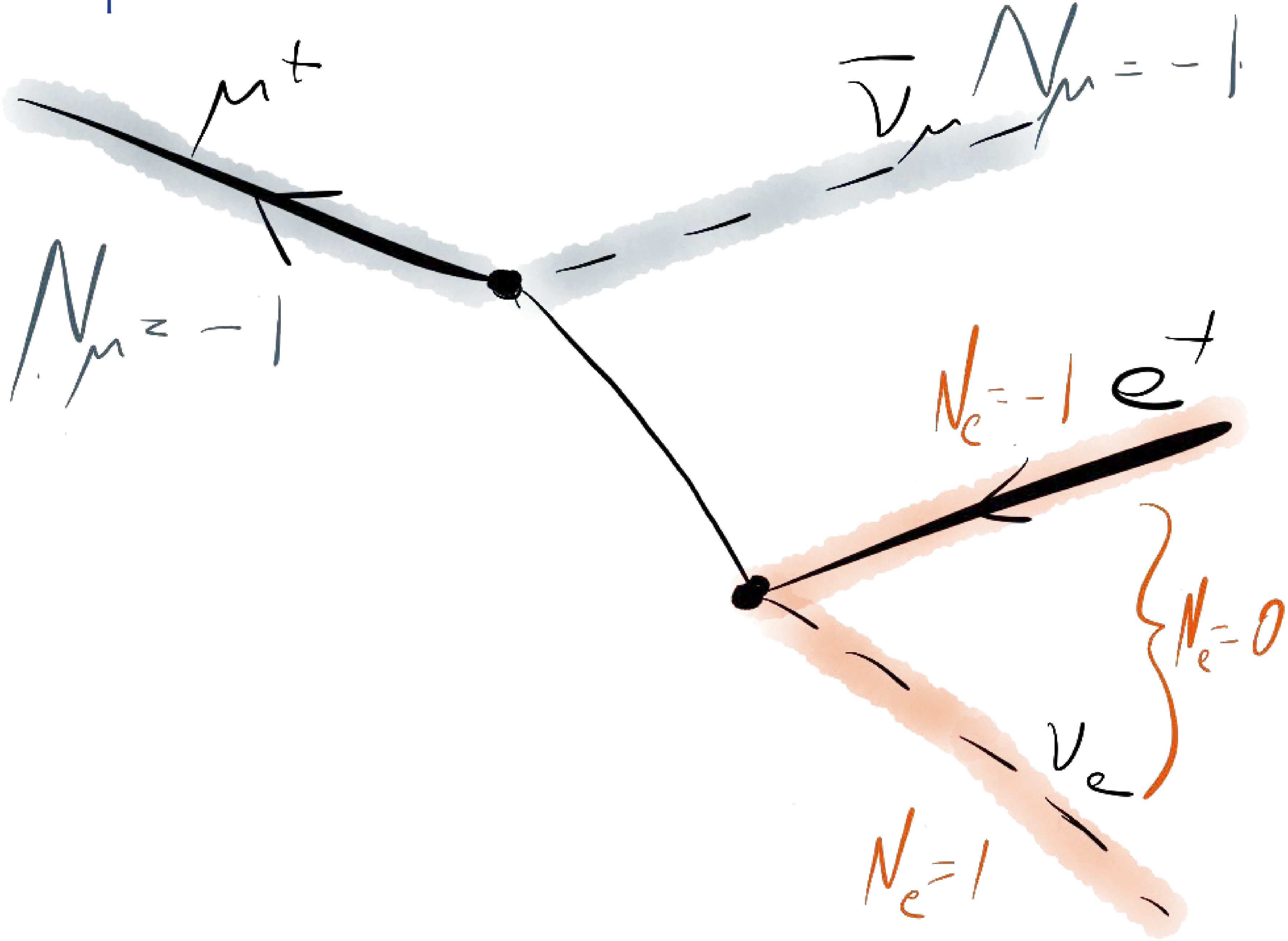


- Models can be discriminated using Z-dependence
- However: low lifetime at high Z

Detector Design



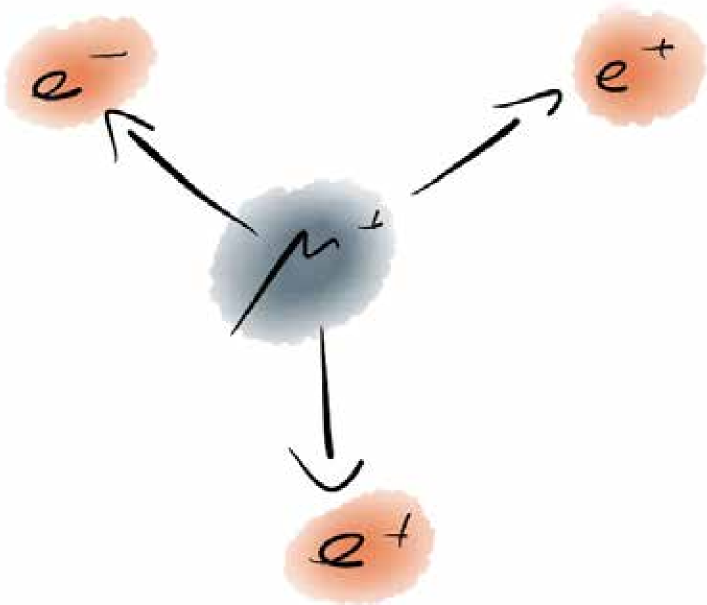
Lepton Flavour



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

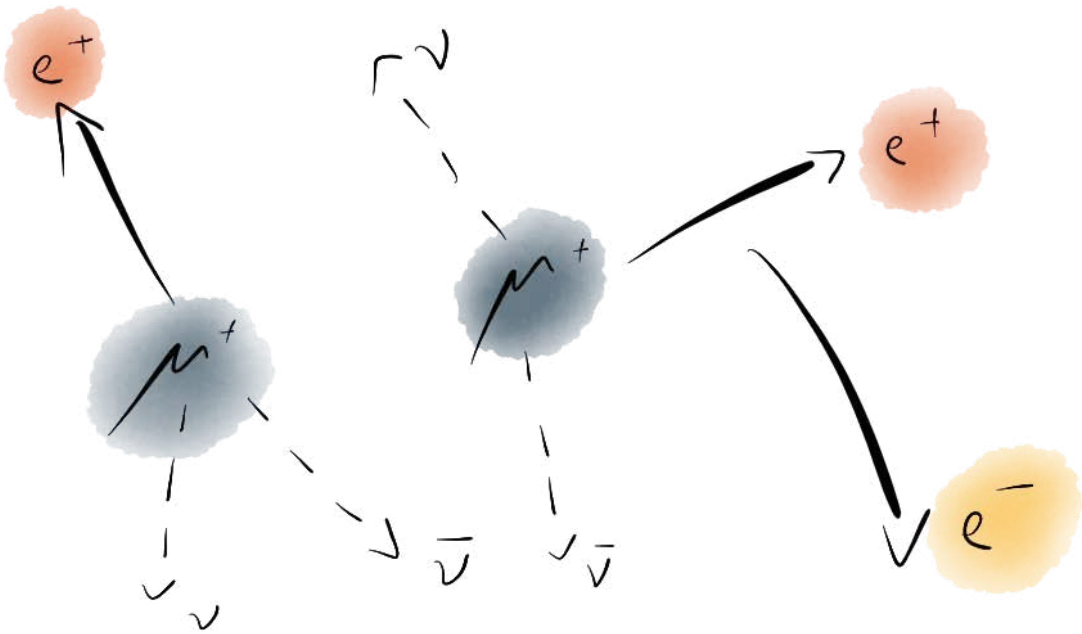
Mu3e

The signal



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

Accidental Background



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

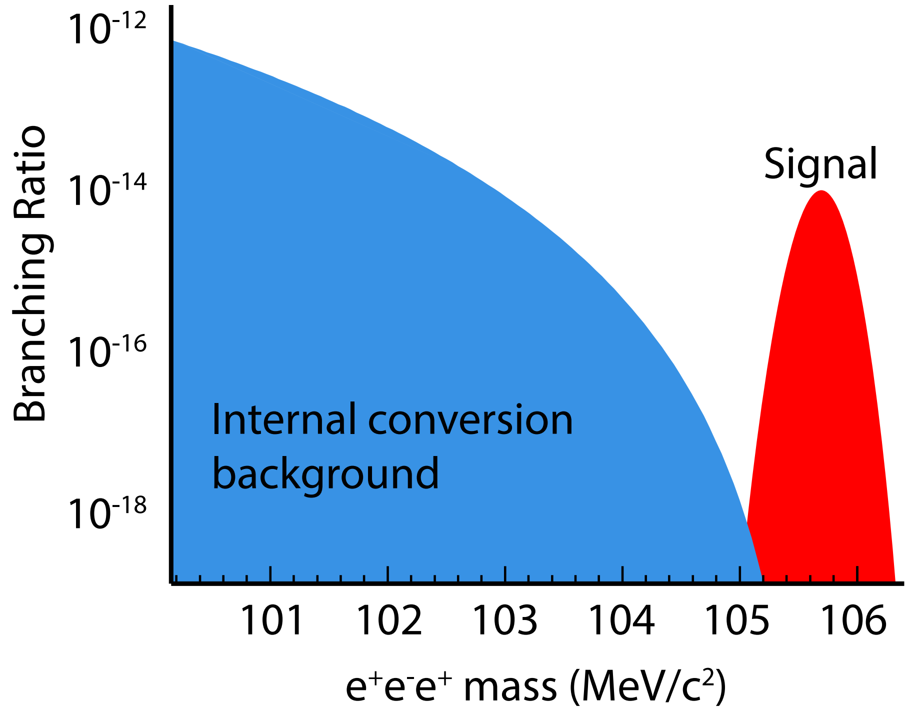
- Need very good timing, vertex and momentum resolution

Internal conversion background

- Allowed radiative decay with internal conversion:

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

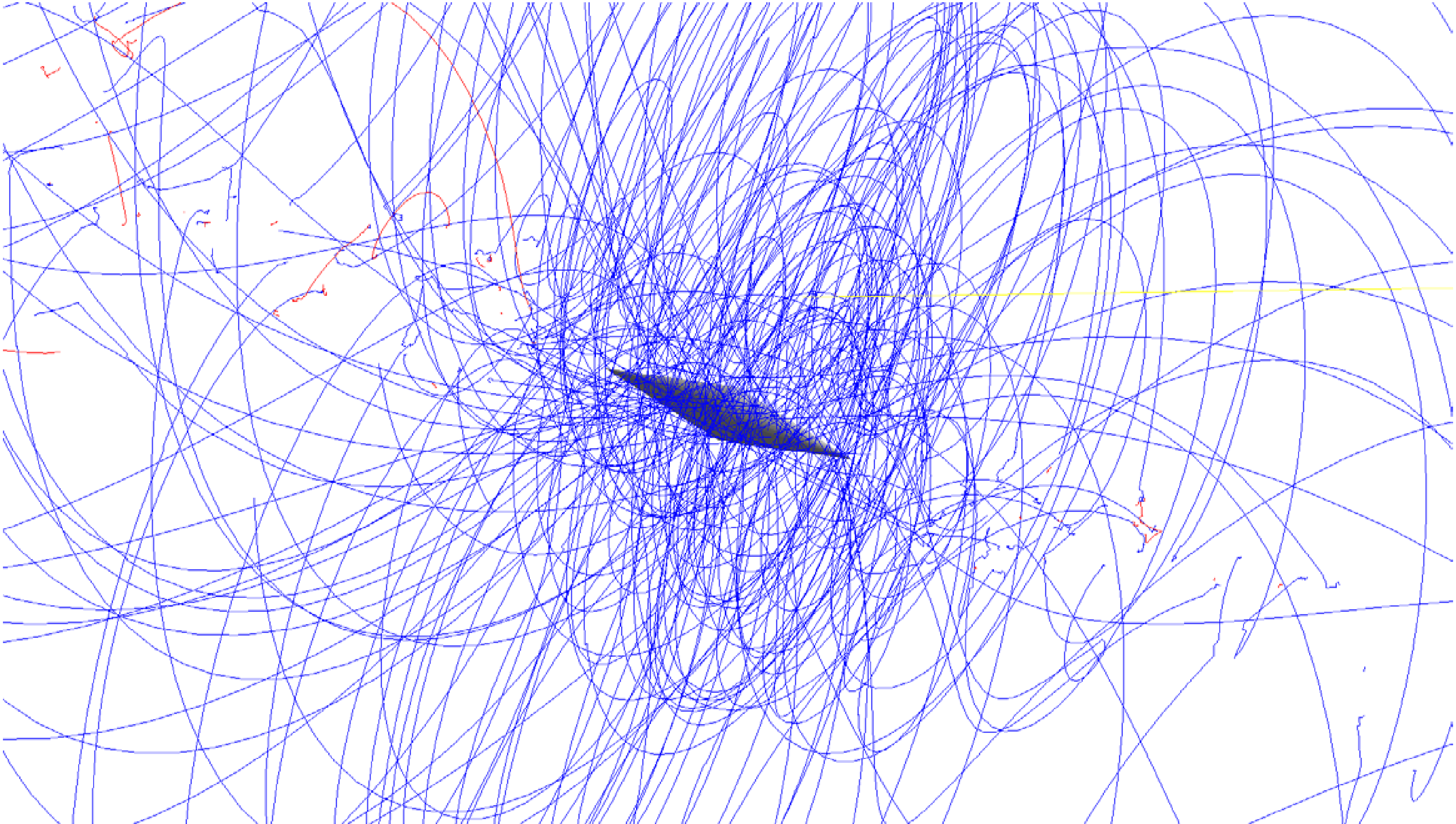
- Only distinguishing feature:
  Missing momentum carried by neutrinos



- Need excellent momentum resolution

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

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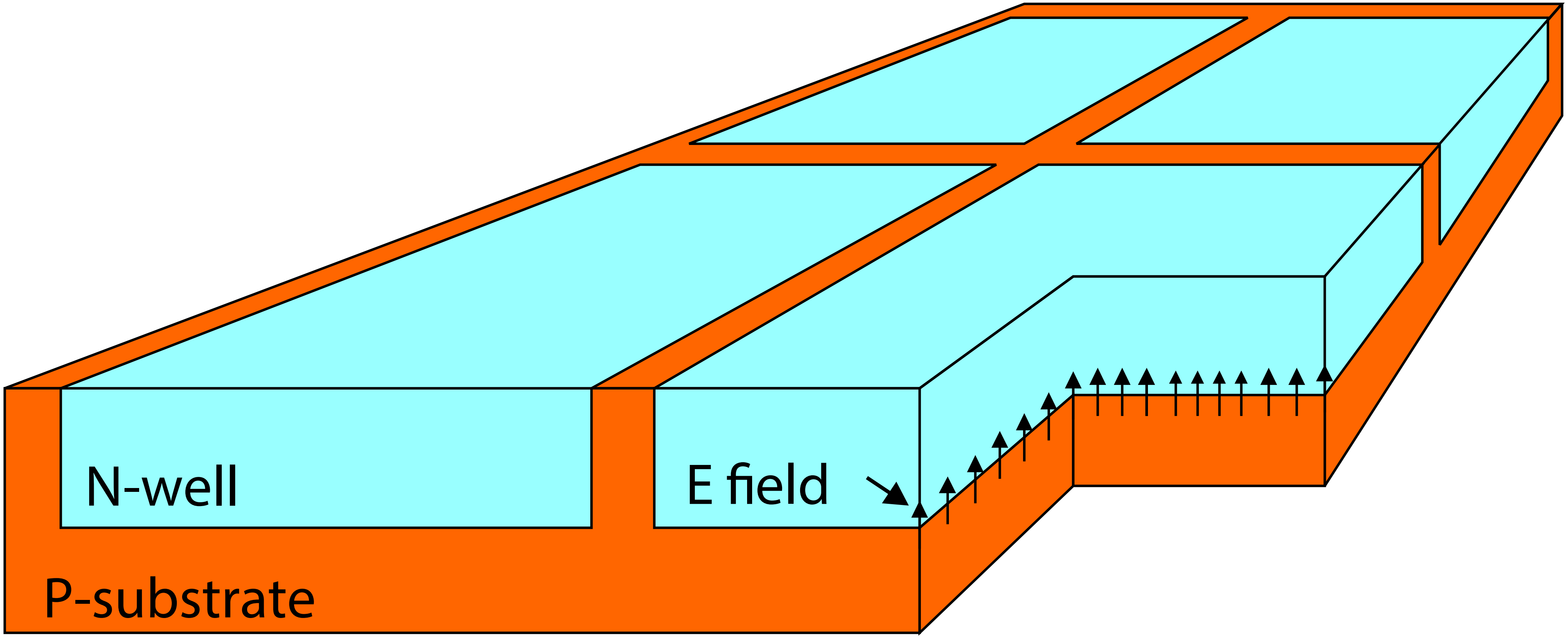
- Close to target (vertex resolution)
- 3D space points (reconstruction)
- Minimum material (momenta below 53 MeV/c)

- 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)



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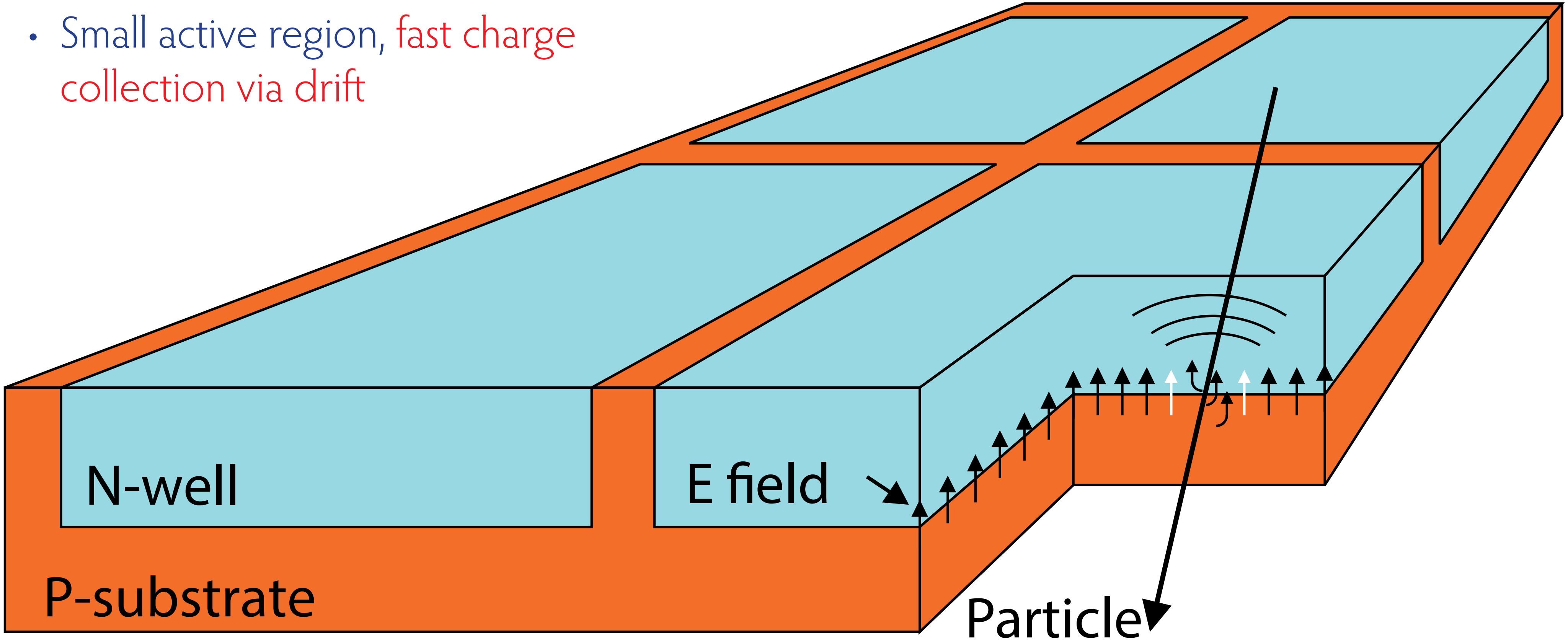

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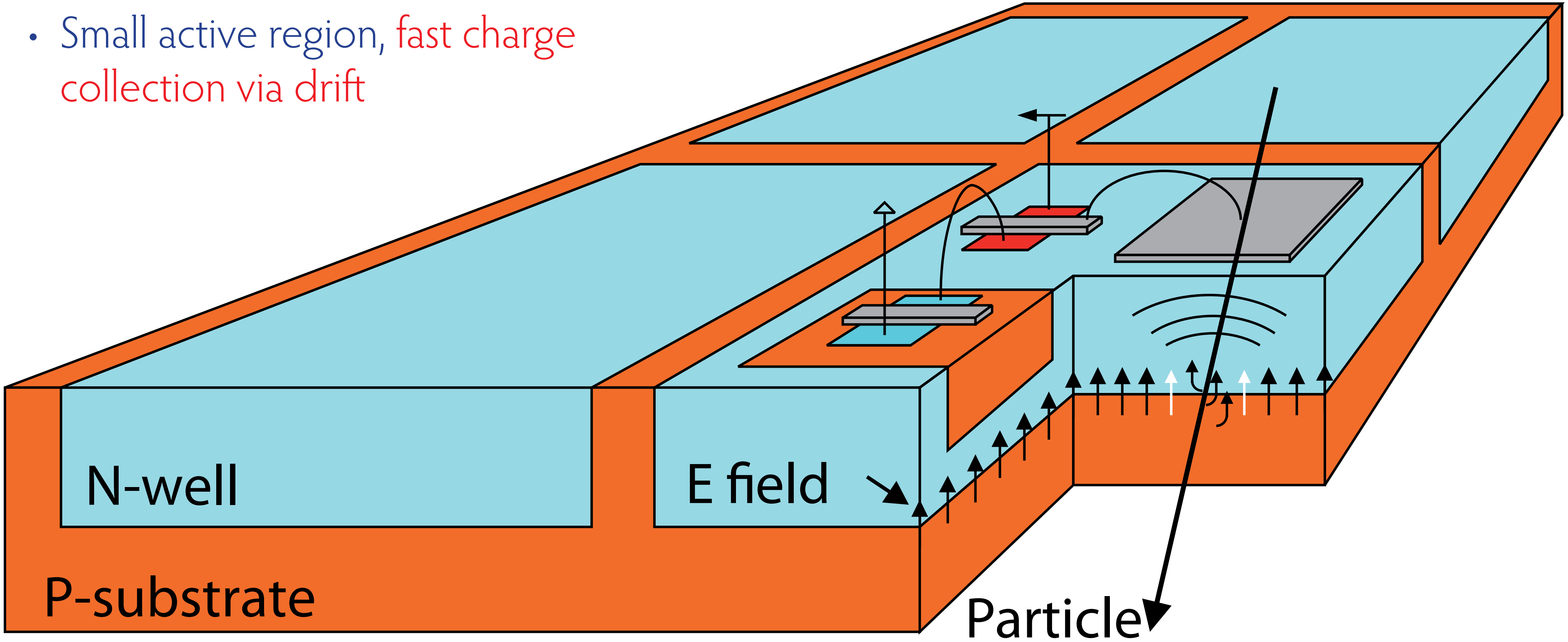
- Implement logic directly in N-well in the pixel - smart diode array

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

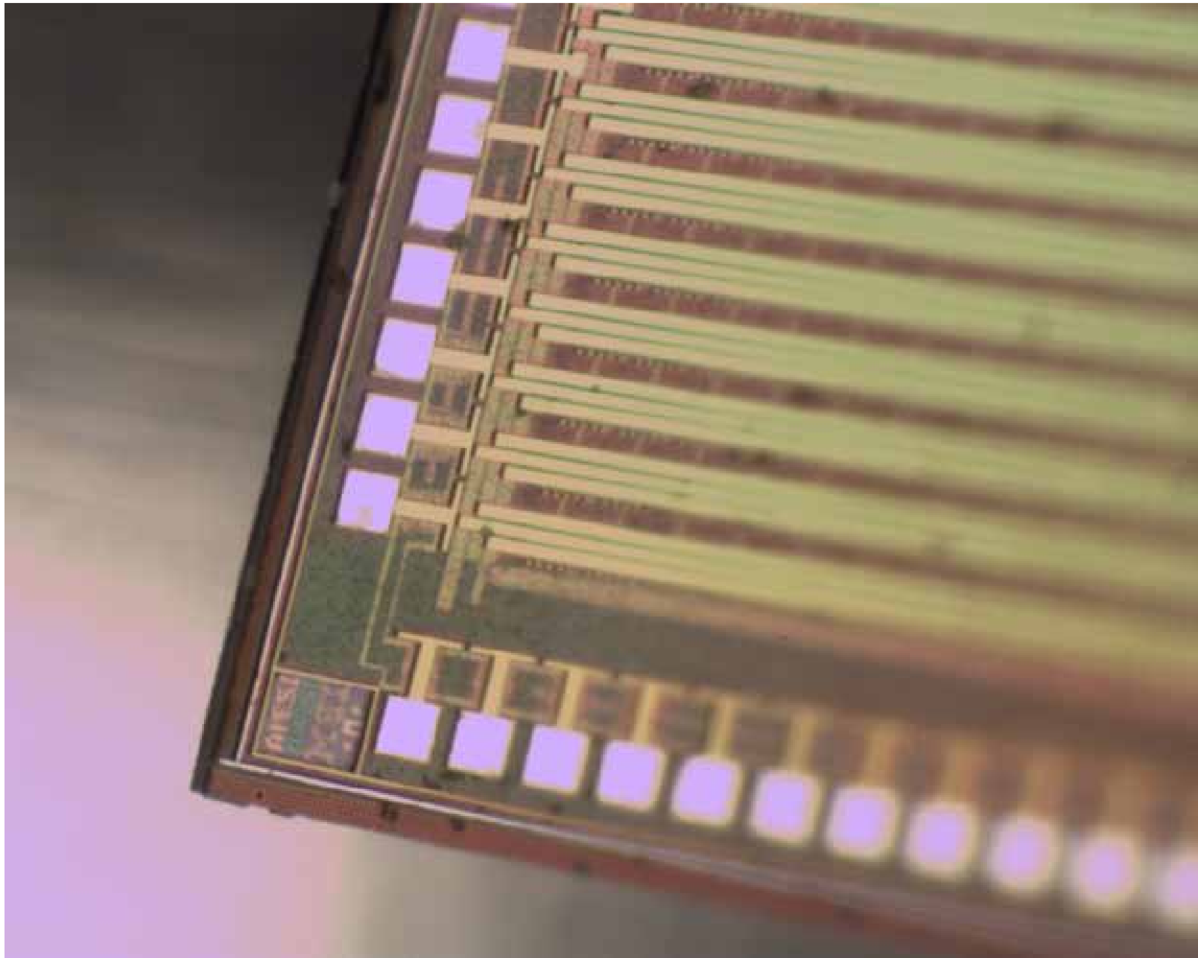


Fast and thin sensors: HV-MAPS

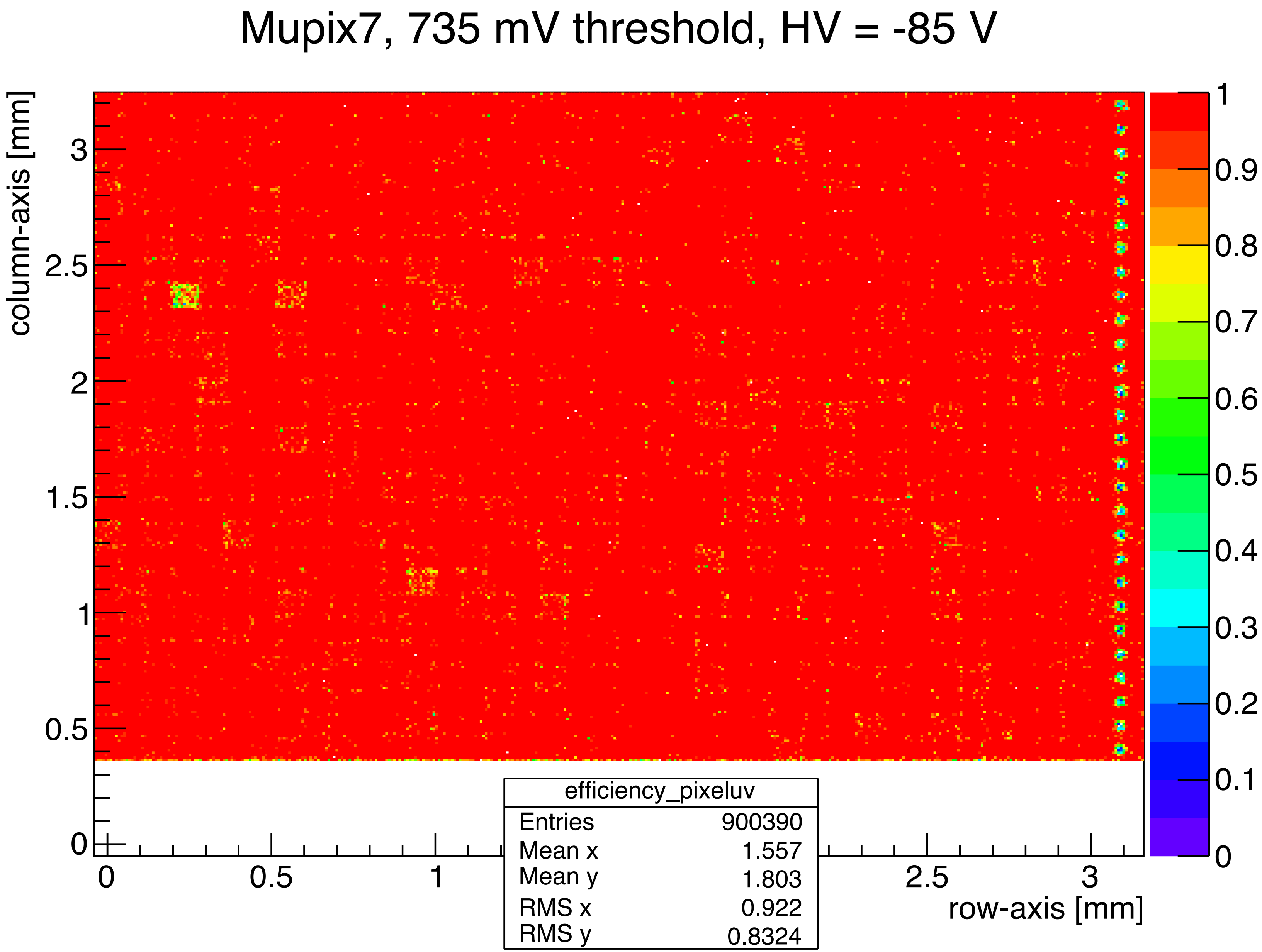
High voltage monolithic active pixel sensors - Ivan Perić

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

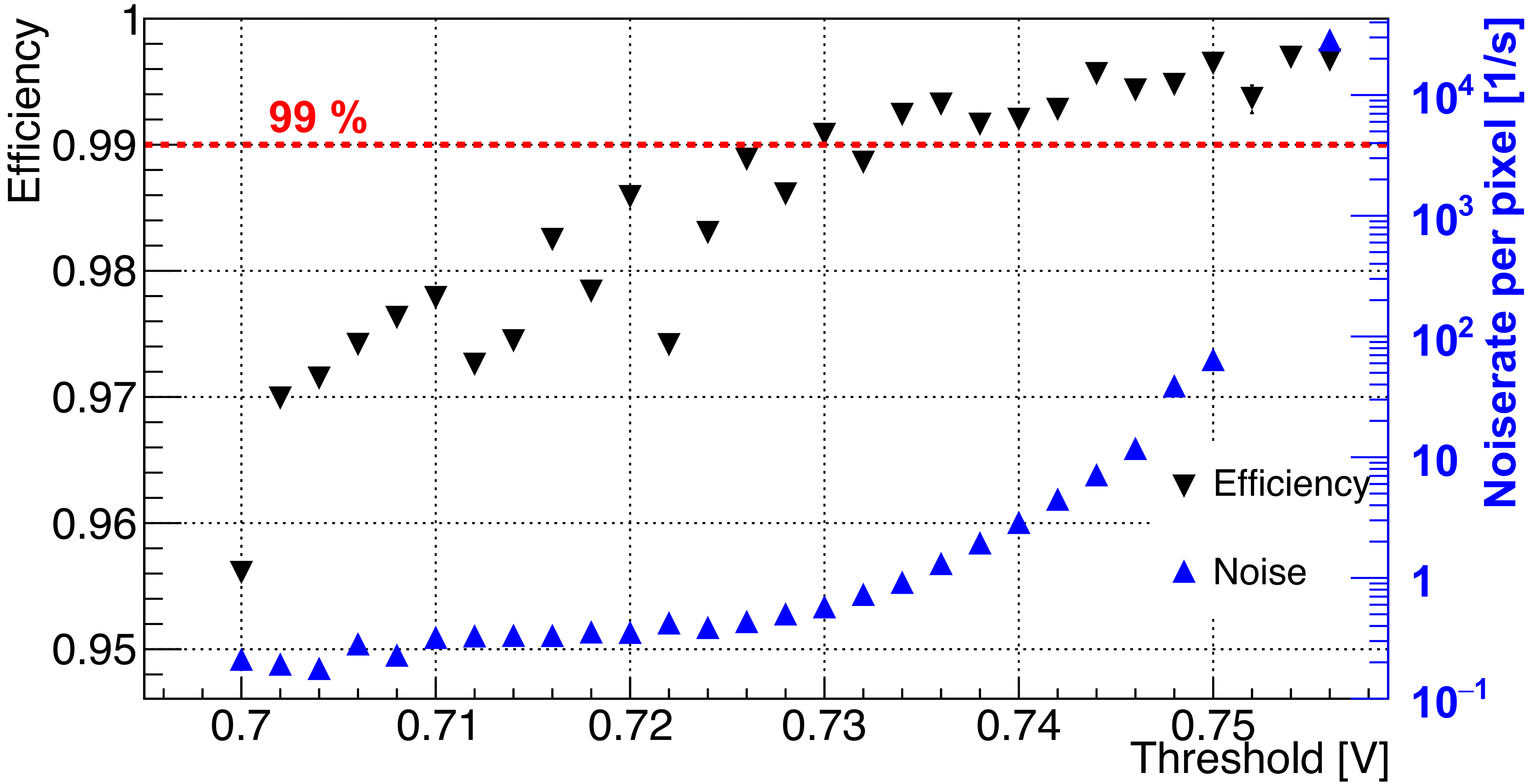
- Implement logic directly in N-well in the pixel - smart diode array
- Can be thinned down to < 50 μm



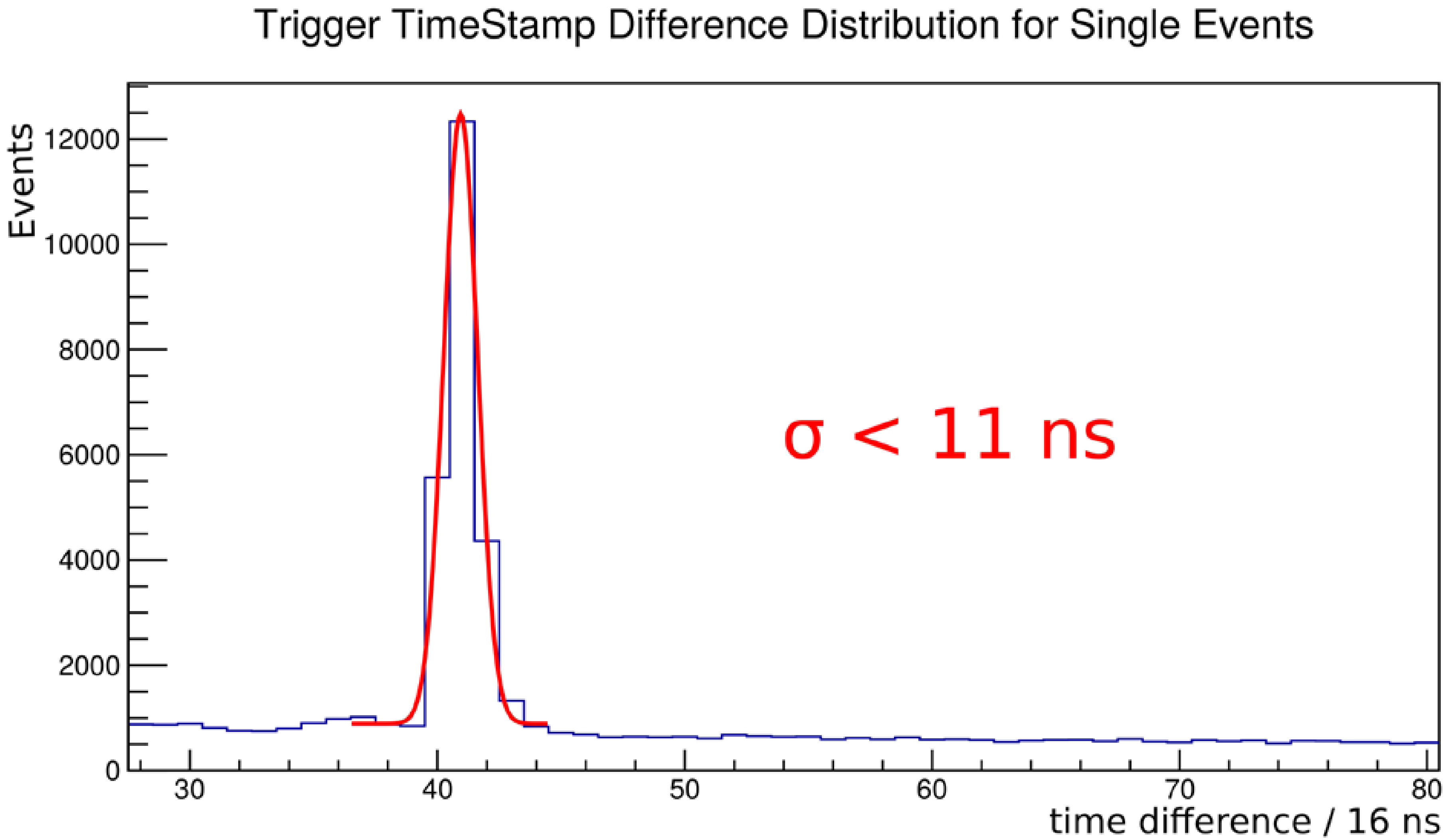
Performance: efficiency

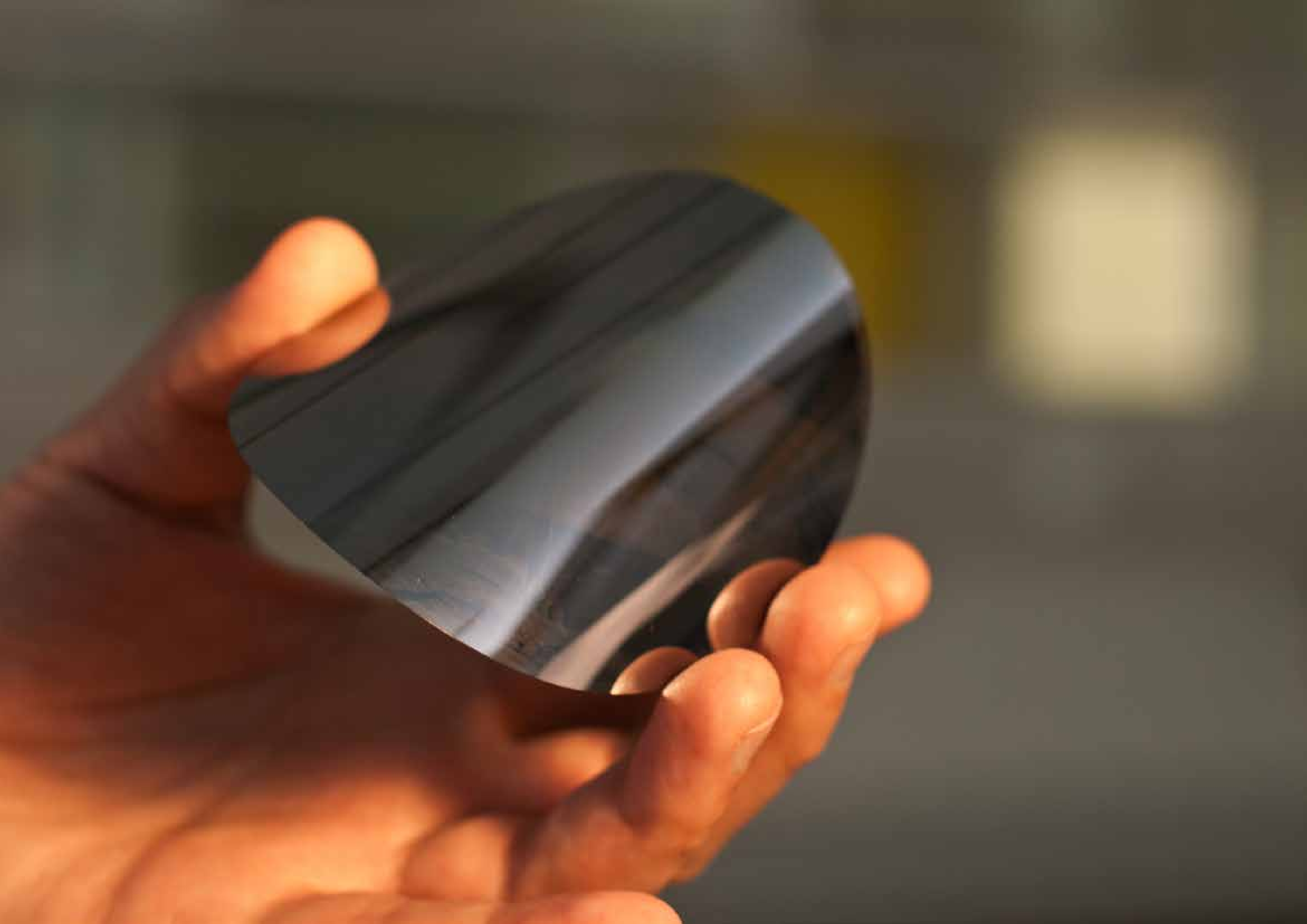


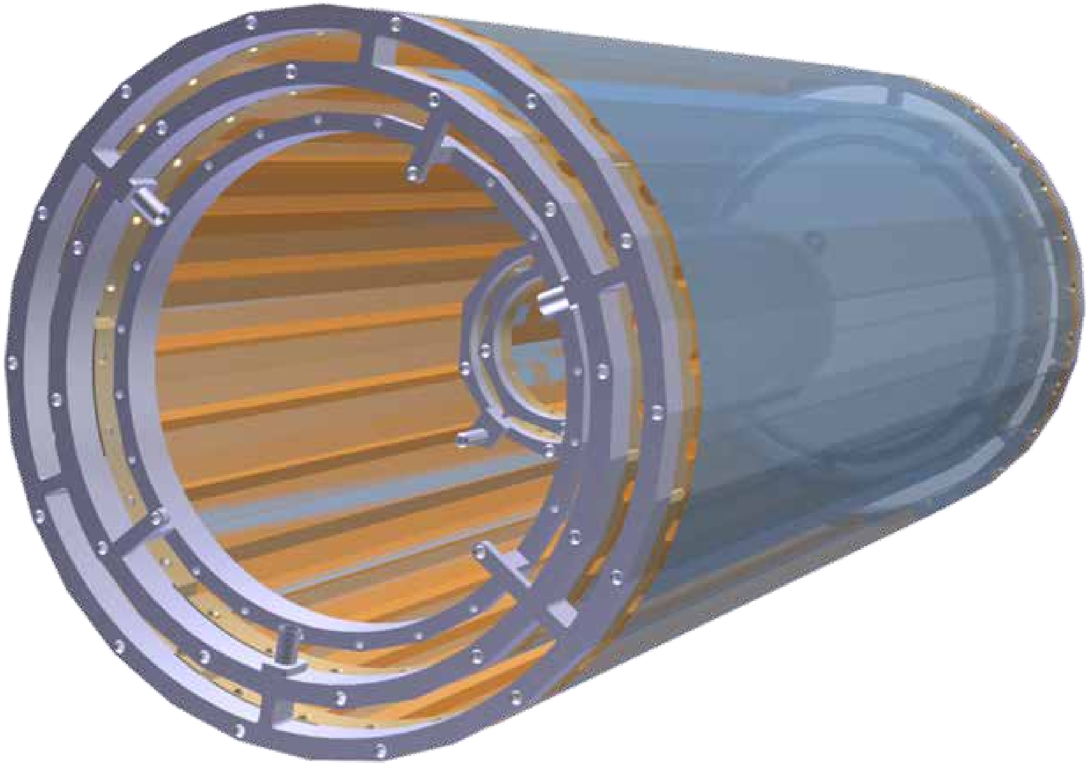
Performance: efficiency and noise

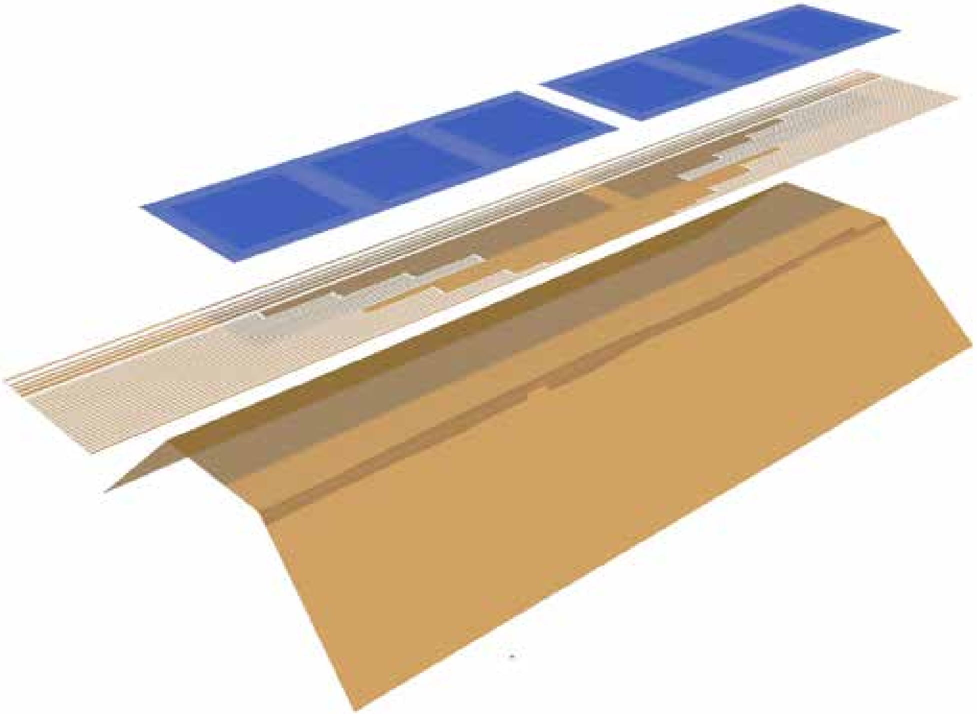


Performance: time resolution







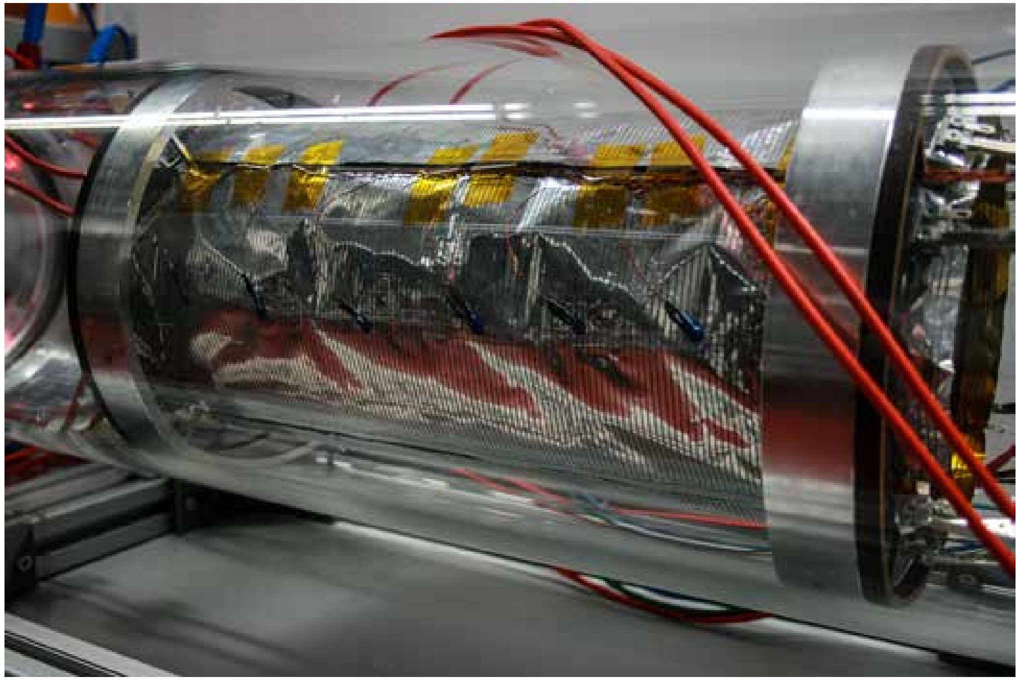


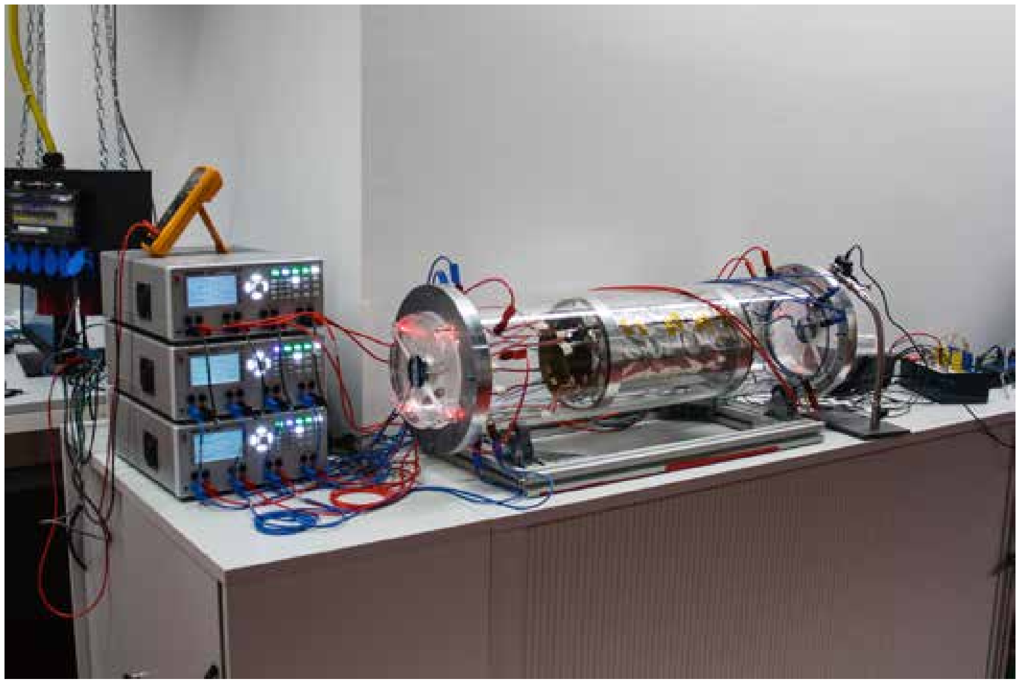
- 50 µm silicon
- 25 µm Kapton™ flexprint with aluminium traces
- 25 µm Kapton™ frame as support
- Less than 1‰ of a radiation length per layer

Cooling

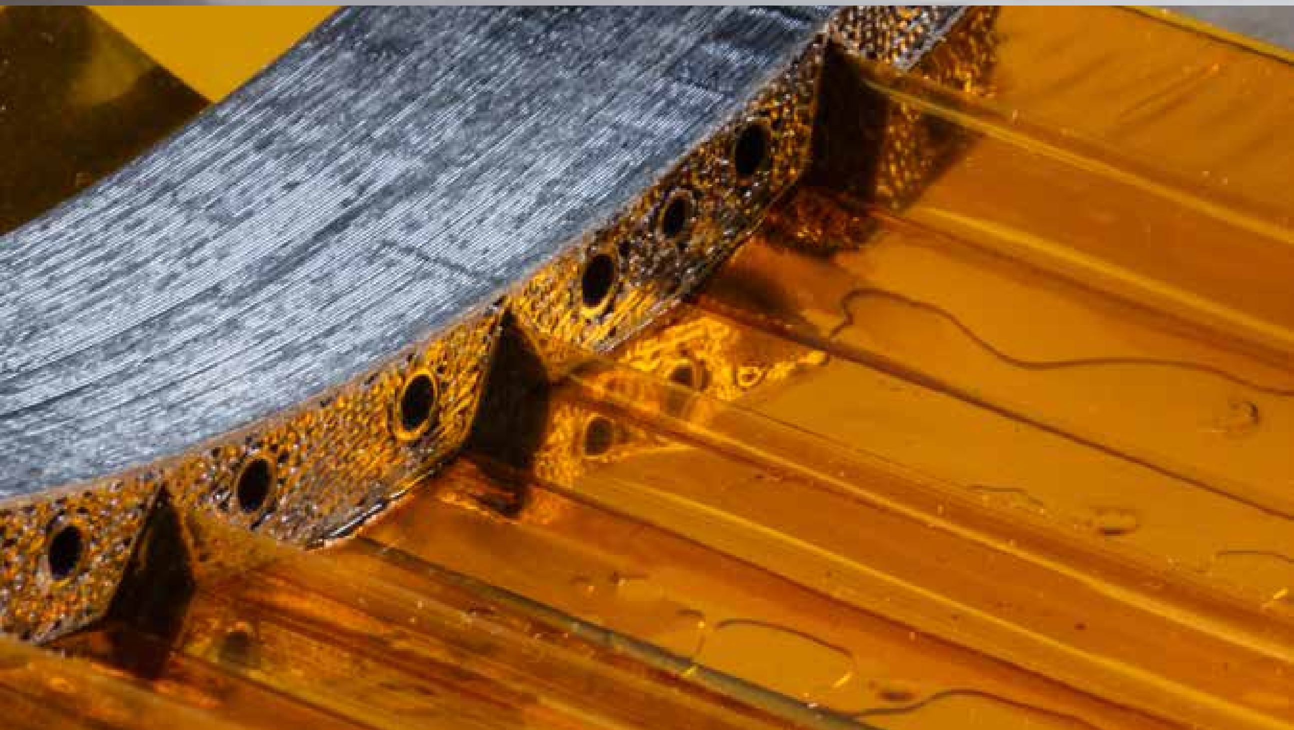
- Add no material:
  Cool with gaseous Helium
  (low scattering, high mobility)
- ~ 300 mW/cm^2 - total >2 kW
- Simulations: Need ~ several m/s flow

- Full scale heatable prototype built
- 36 cm active length
- Vibrations under control
  (Michelson interferometer)

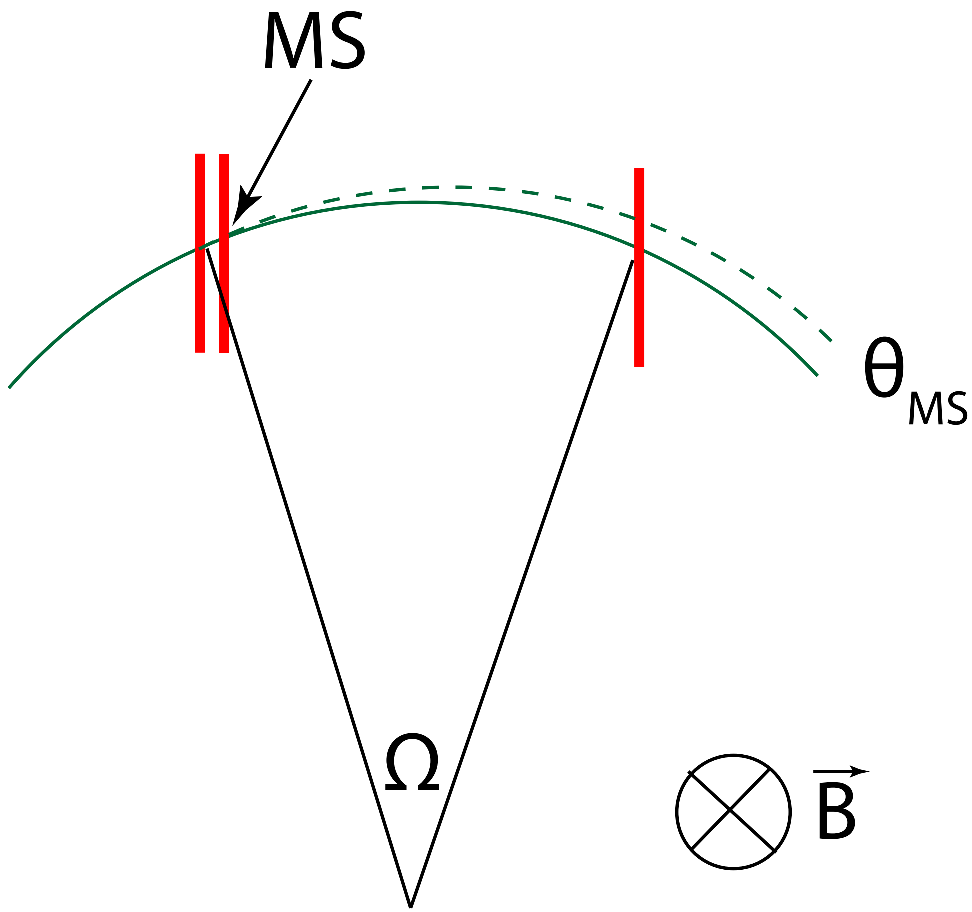





Ring 4
vorne



Momentum measurement

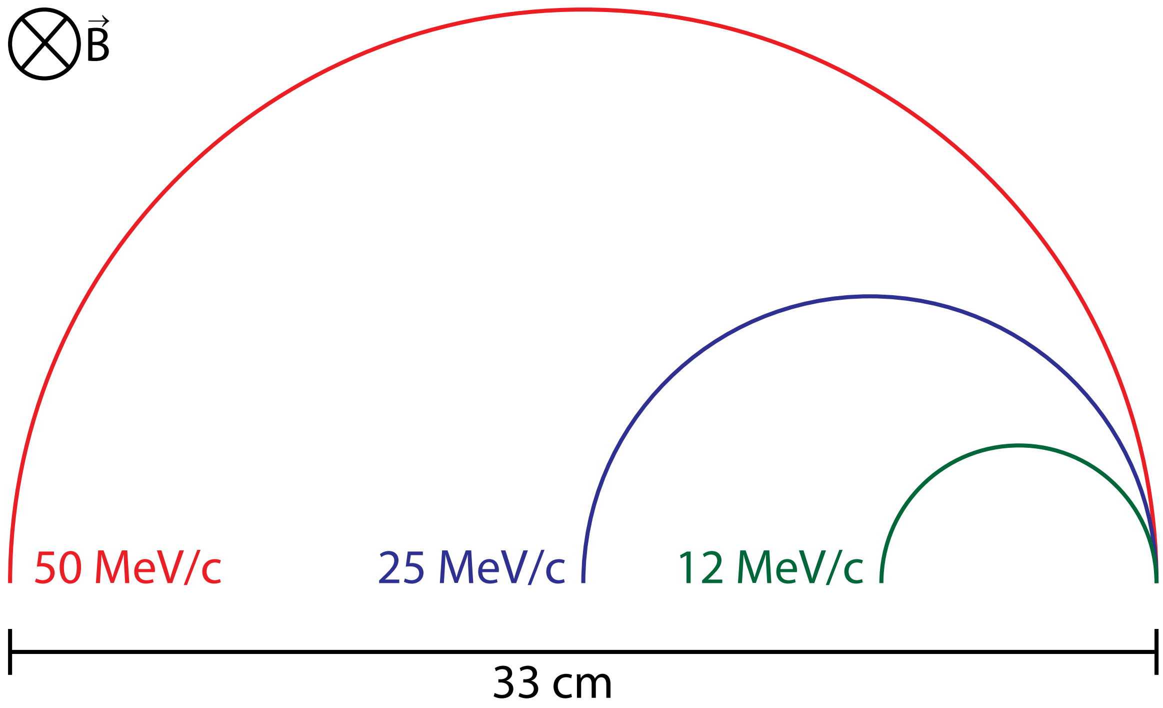


- 1 T magnetic field
- Resolution dominated by multiple scattering
- Momentum resolution to first order:

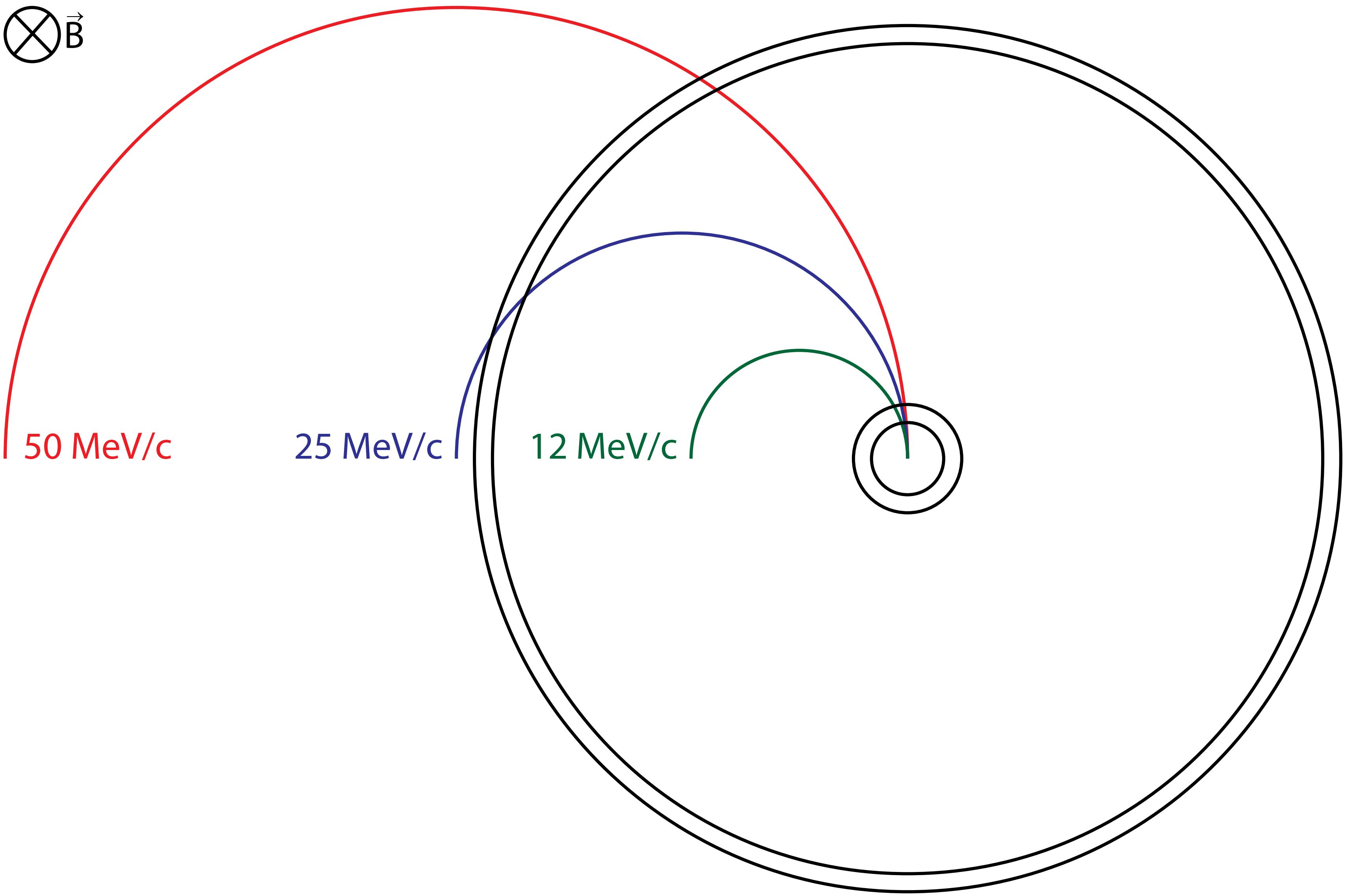
$$\sigma_P/P \sim \theta_{MS}/\Omega$$

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

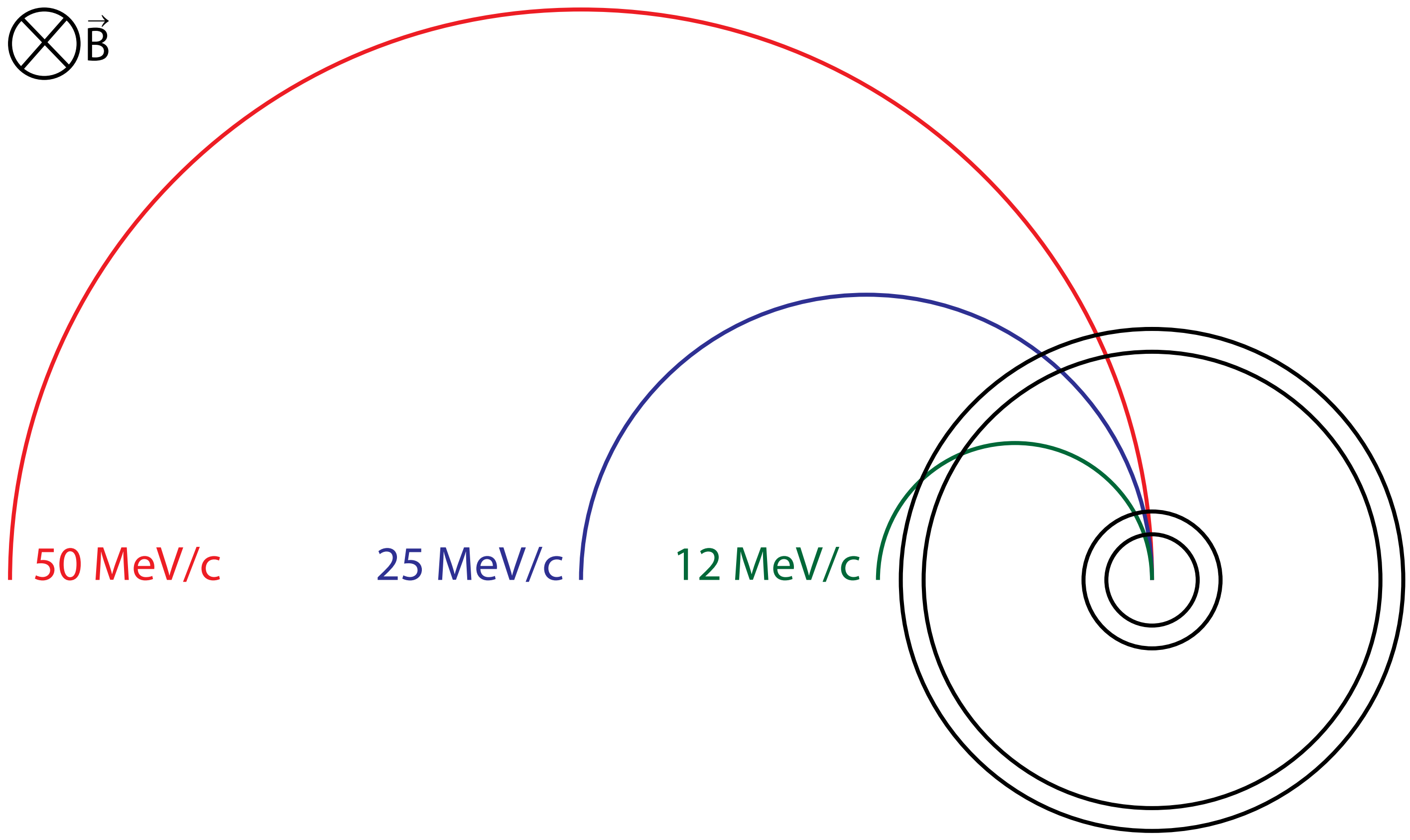
Precision vs. Acceptance



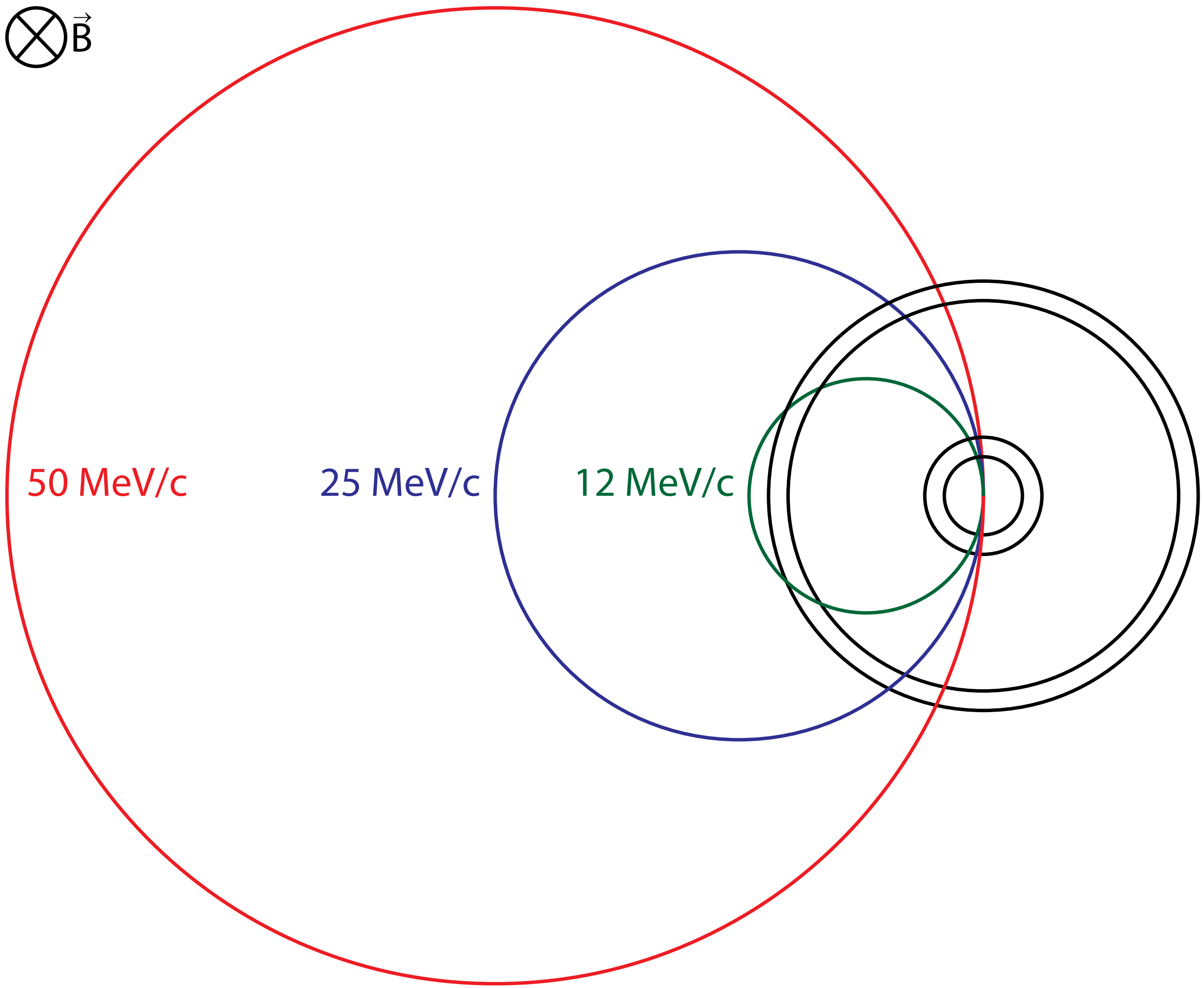
Precision vs. Acceptance



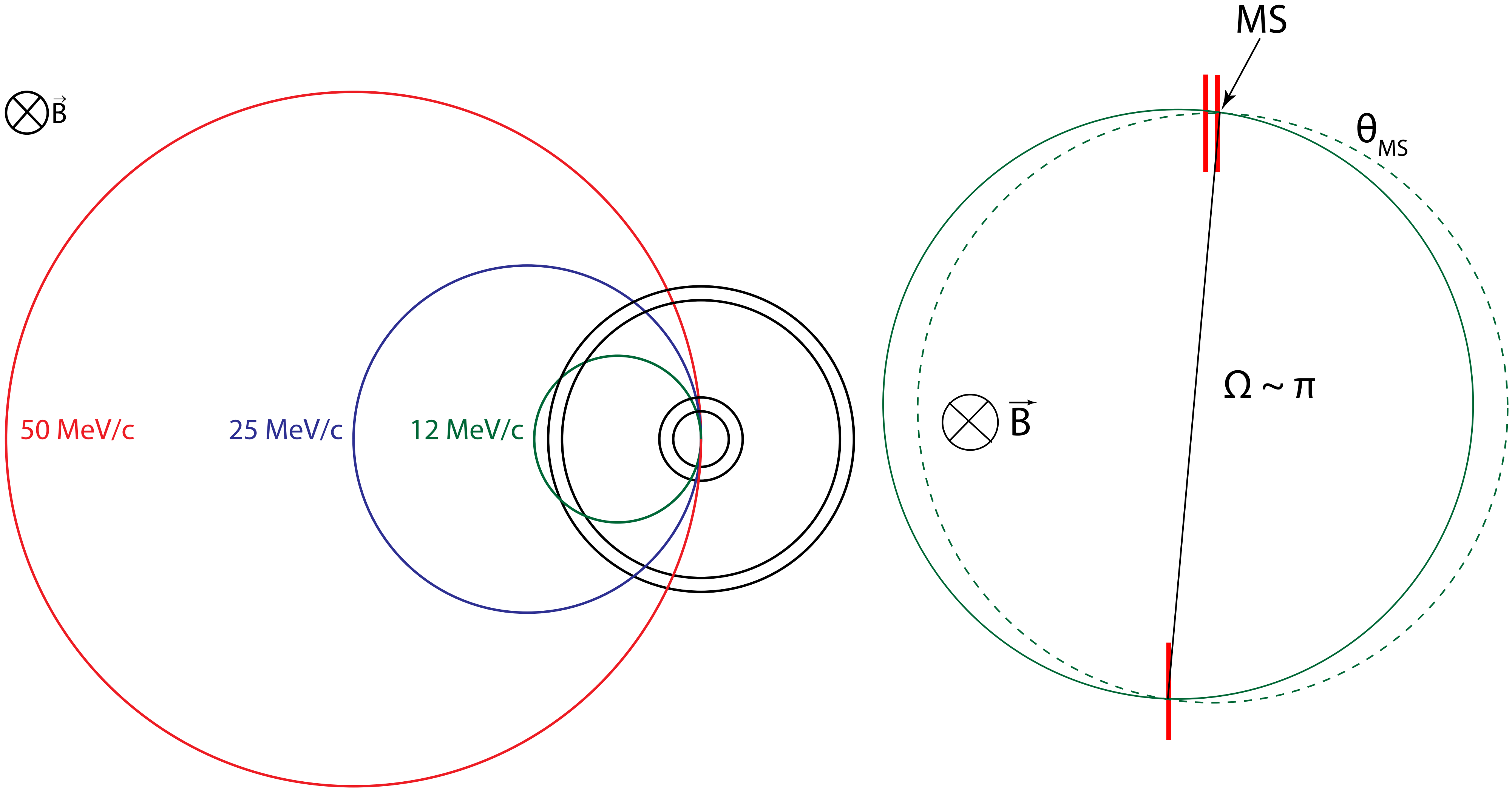
Precision vs. Acceptance



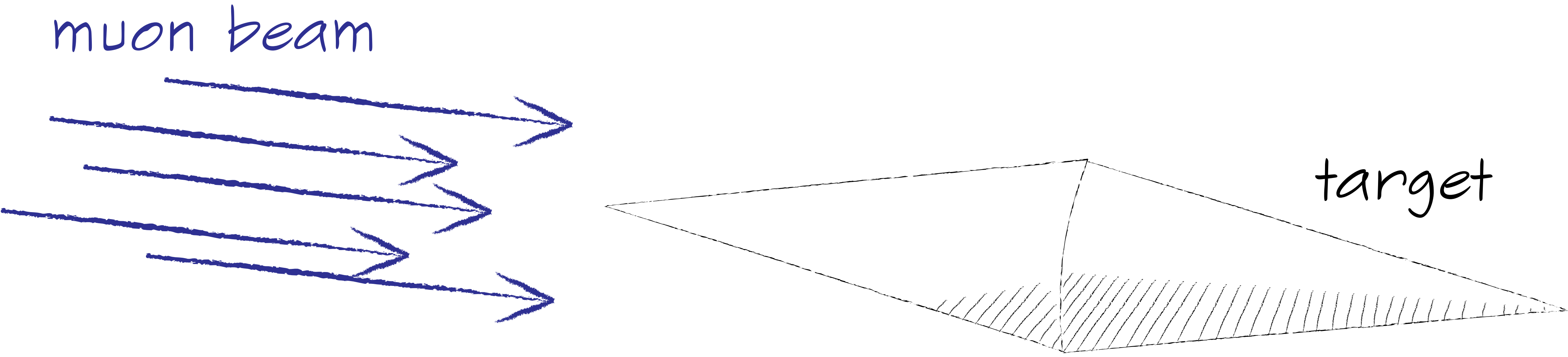
Precision vs. Acceptance



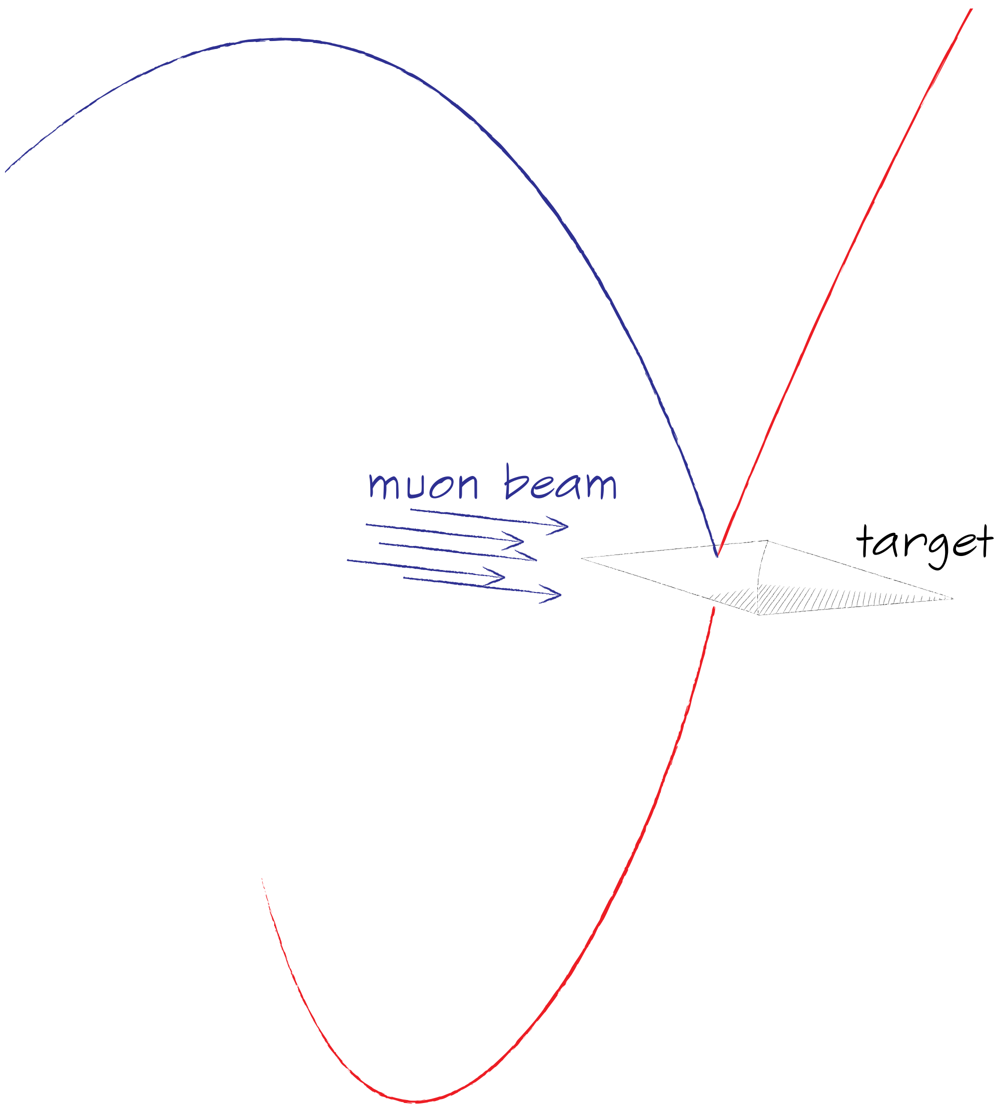
Precision vs. Acceptance



Detector Design



Detector Design



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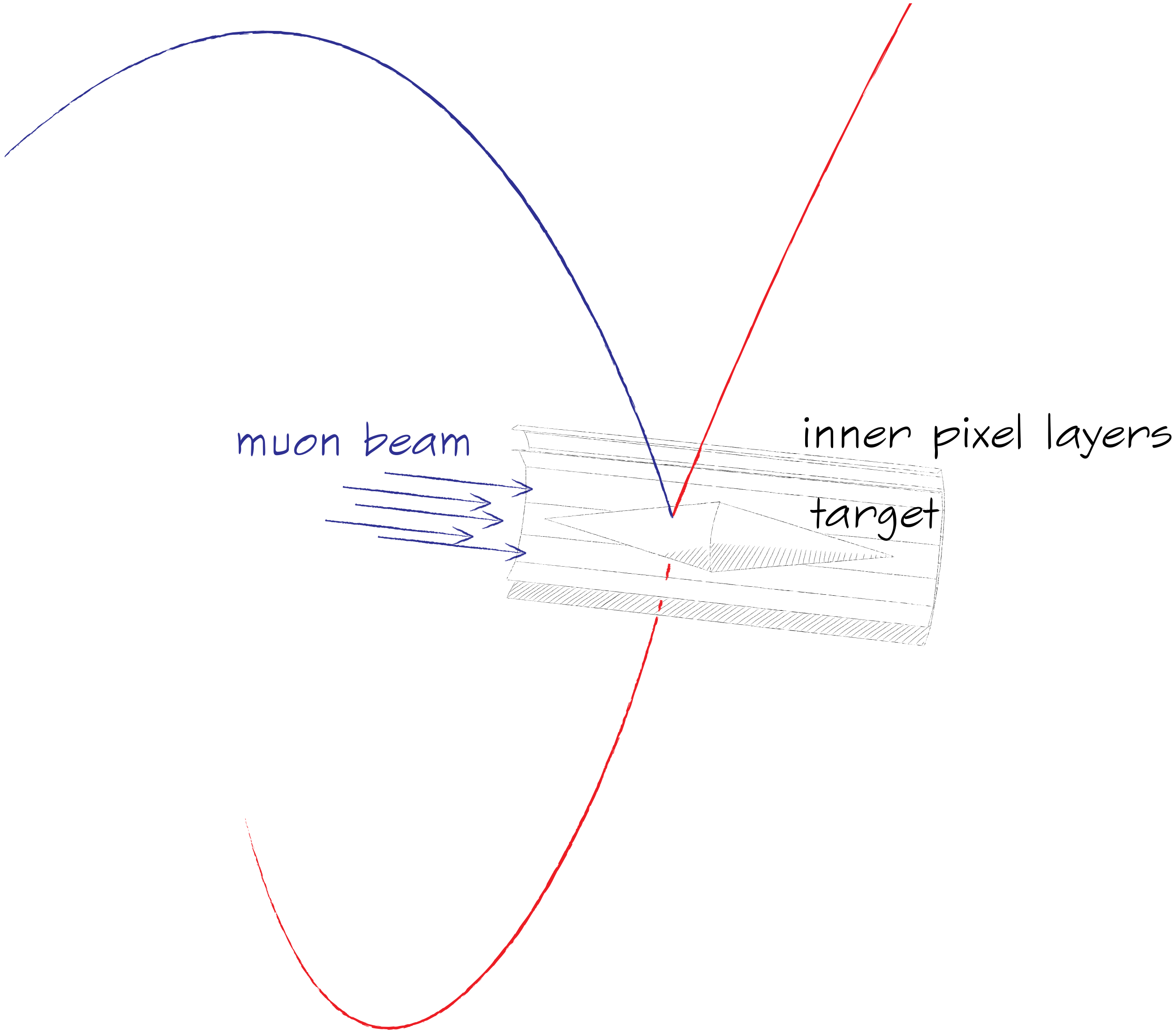
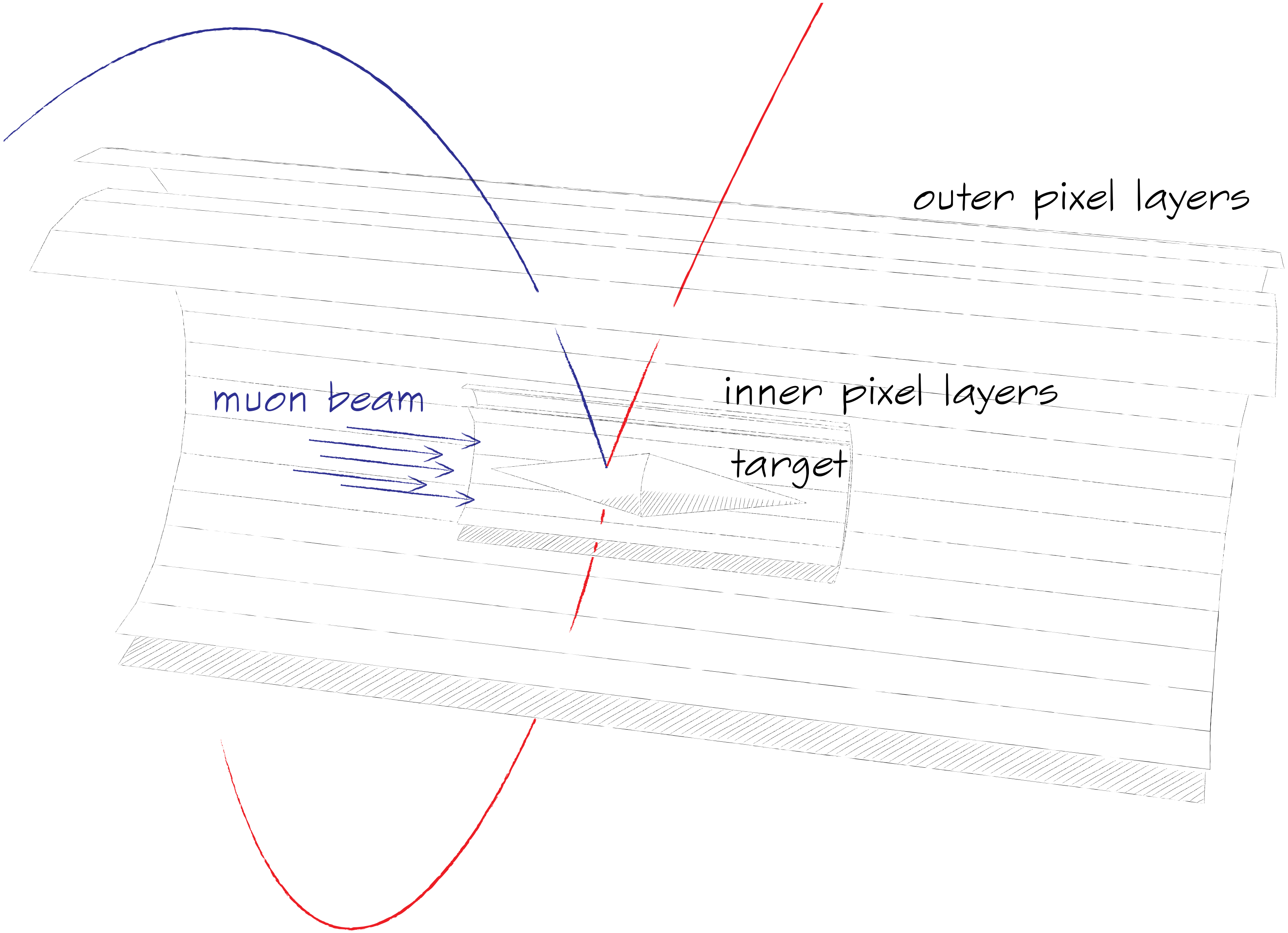
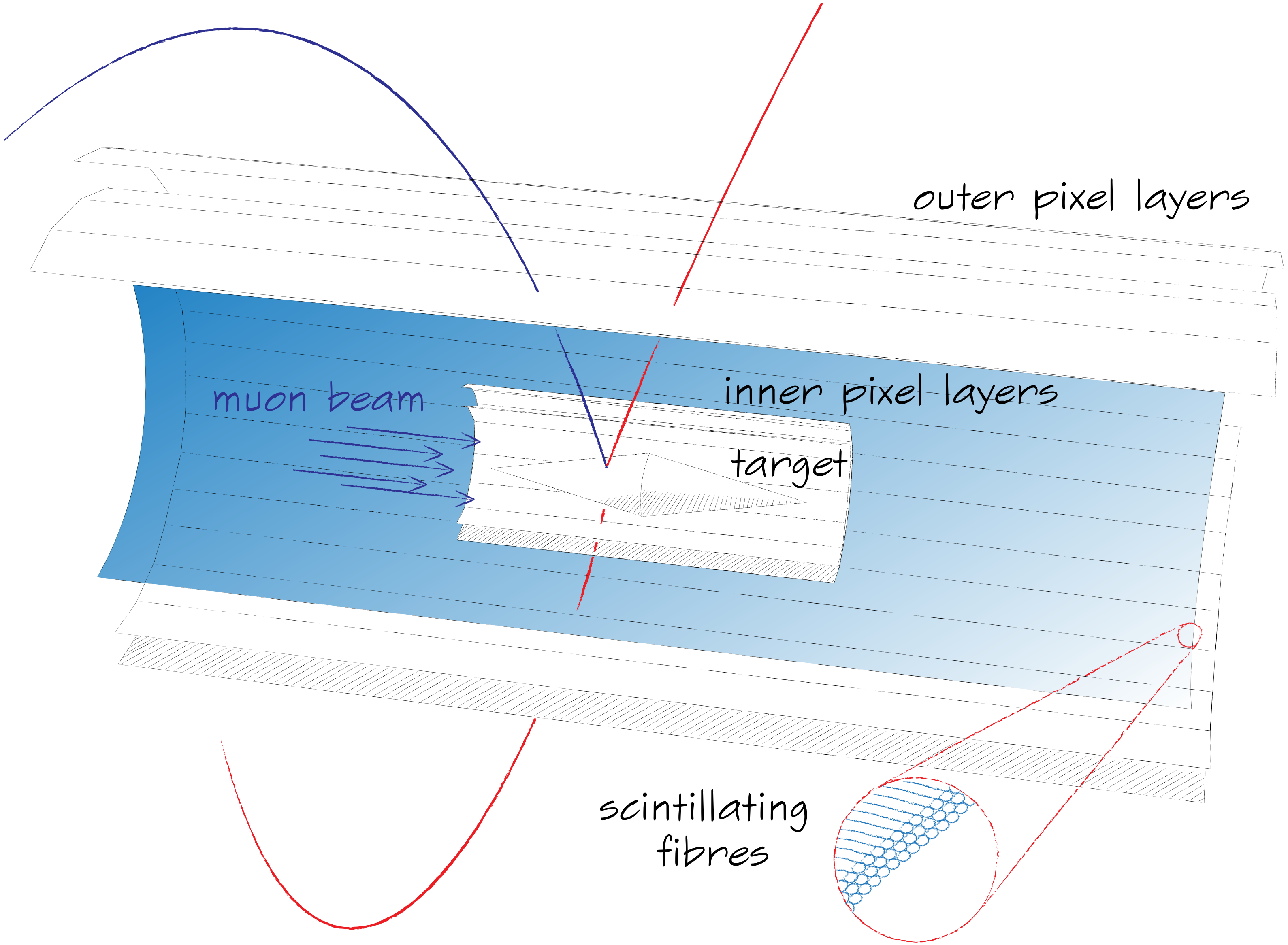


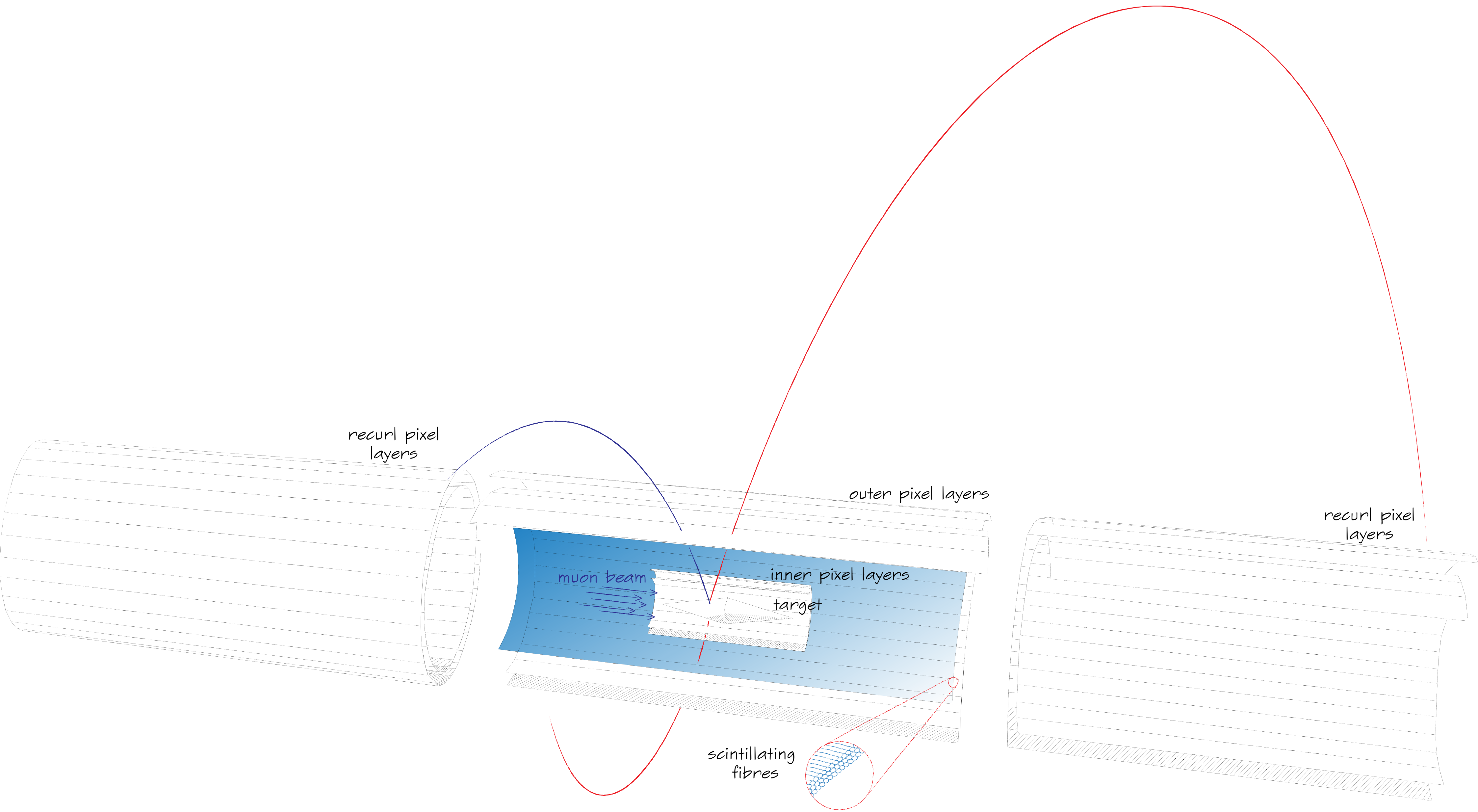
Detector Design



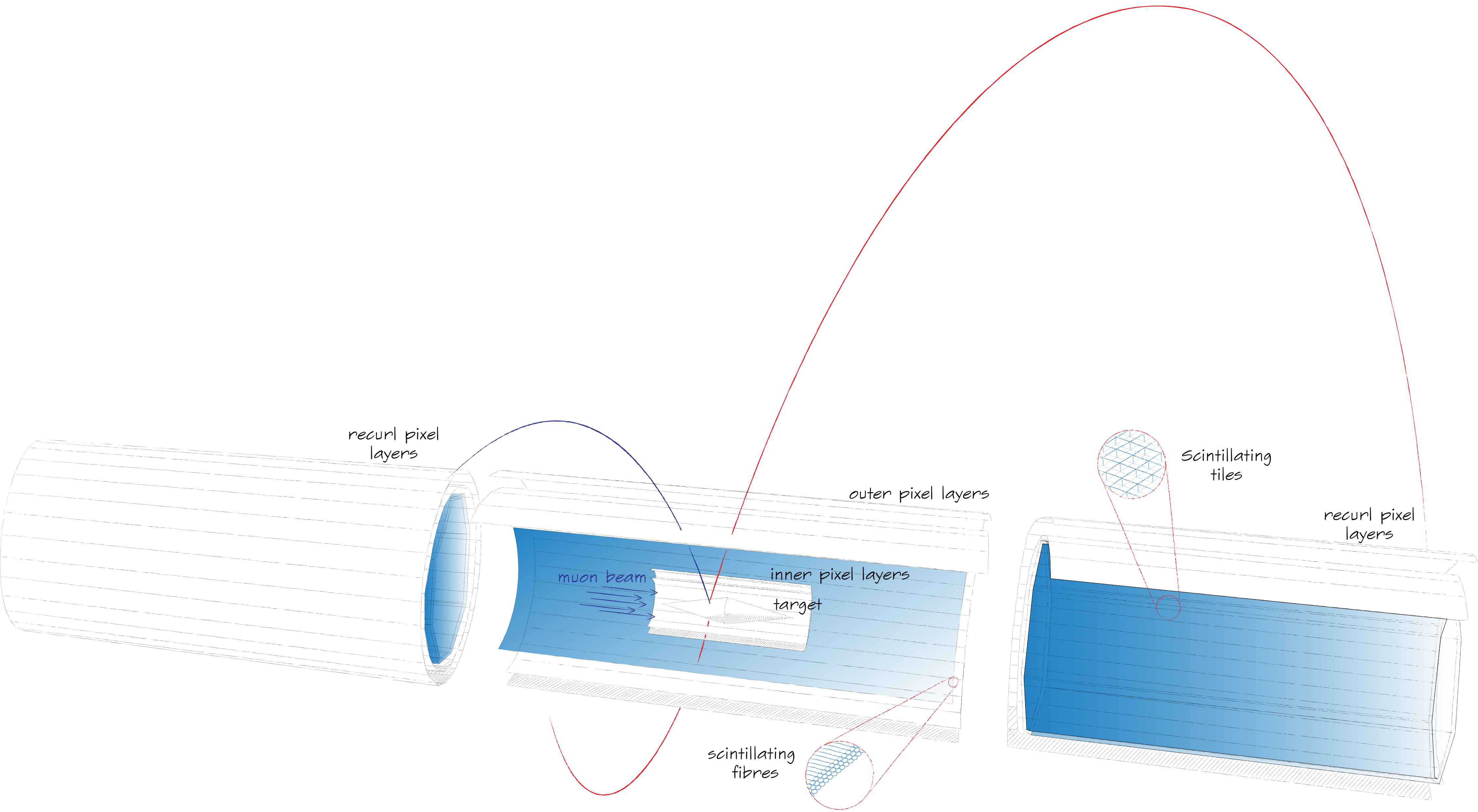
Detector Design



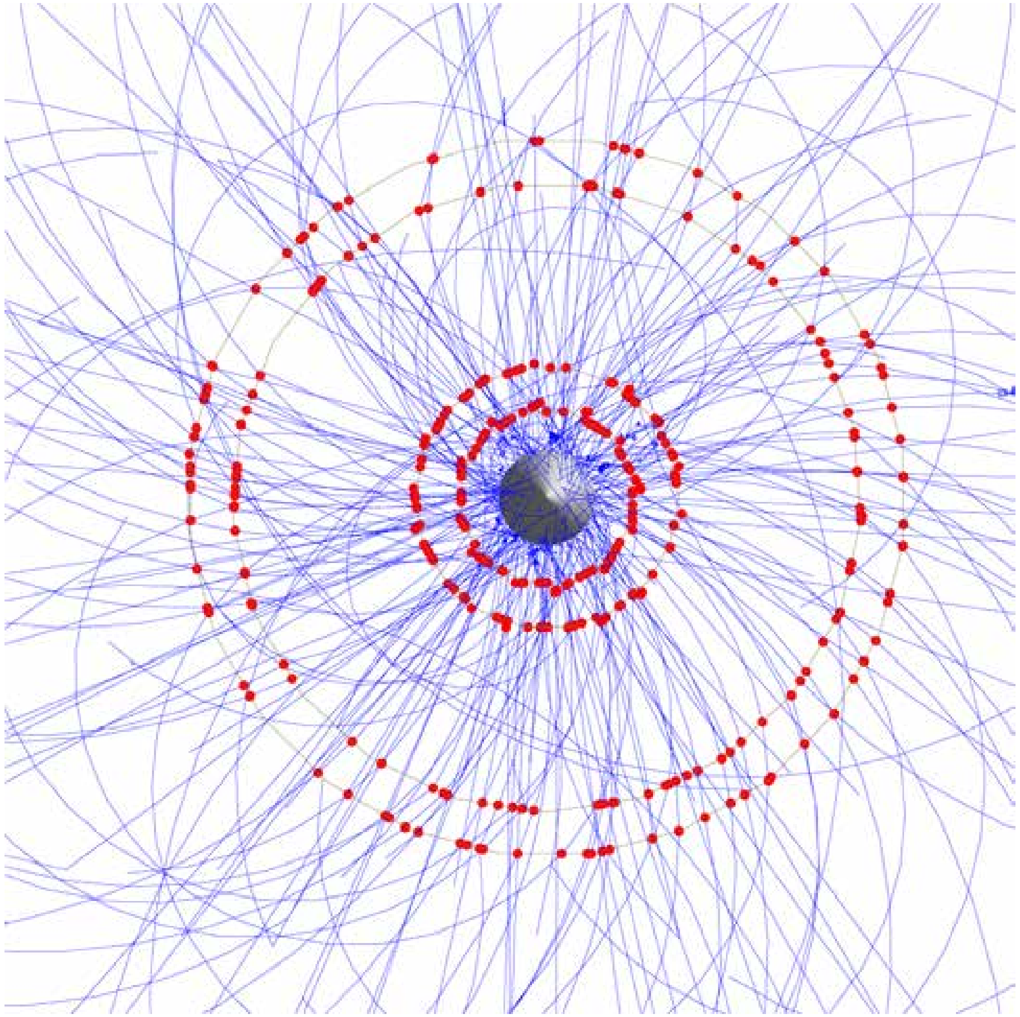
Detector Design



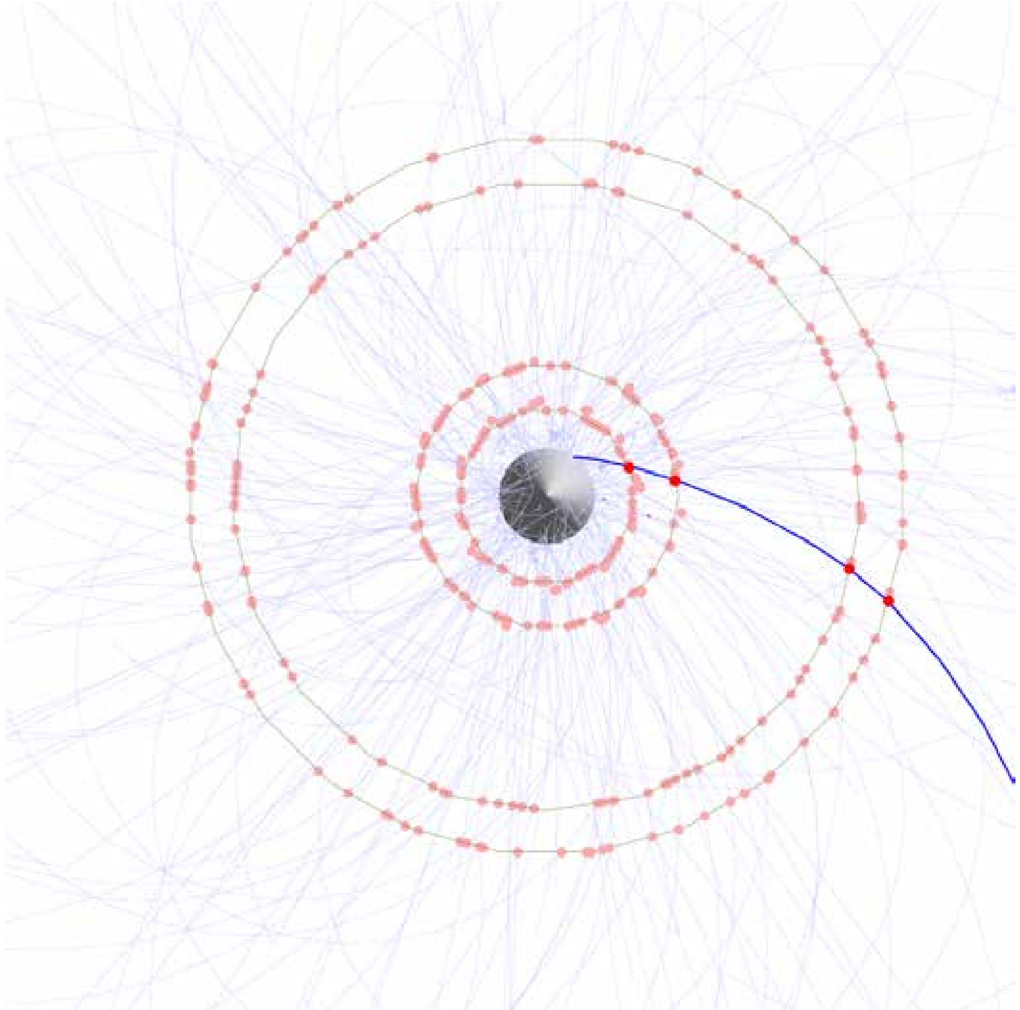
Detector Design



Timing measurements

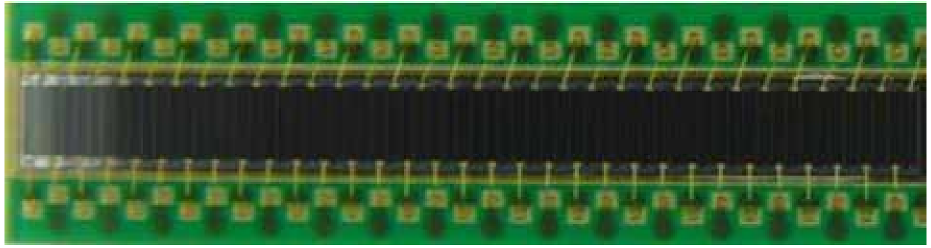


Pixels: O(50 ns)

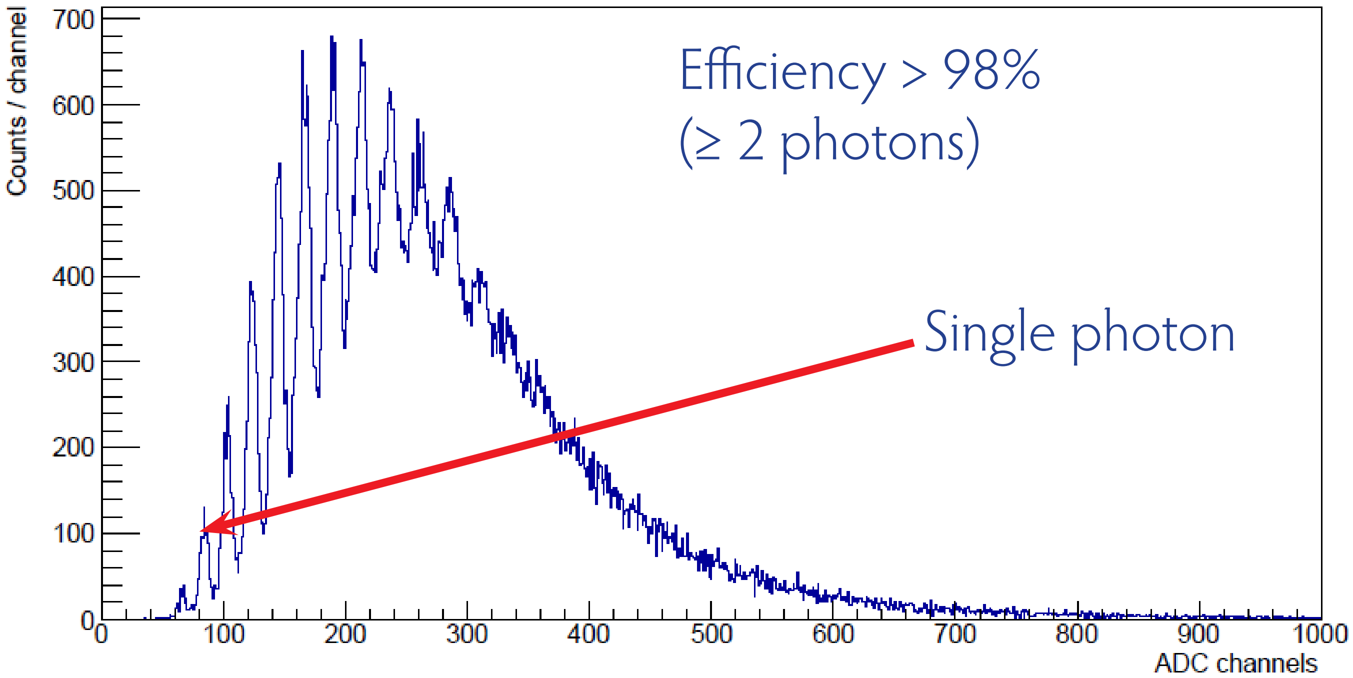


Scintillating fibres O(1 ns);
Scintillating tiles O(100 ps)

Timing Detector: Scintillating Fibres

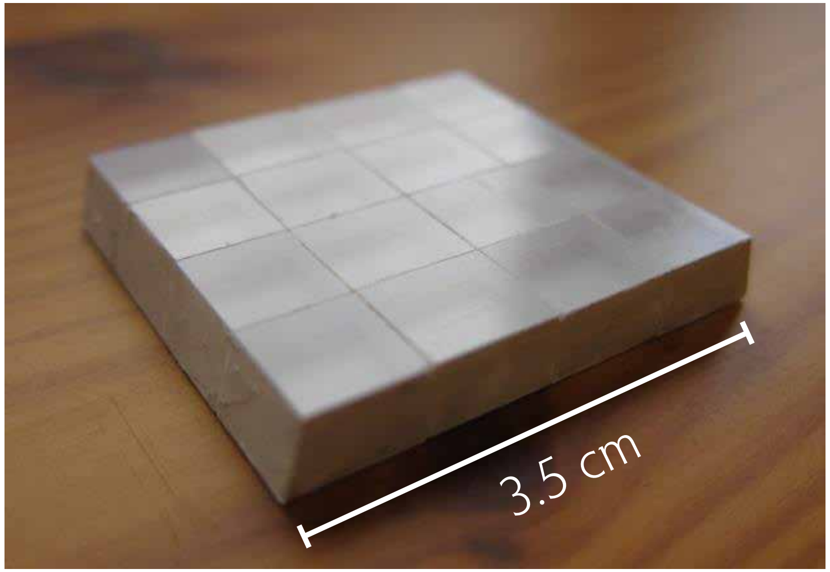


- 3 layers of 250 μm scintillating fibres
- Read-out by silicon photomultipliers (SiPMs) and custom ASIC (STiC)
- Timing resolution $\mathcal{O}$(1 ns) (measured with sodium source)

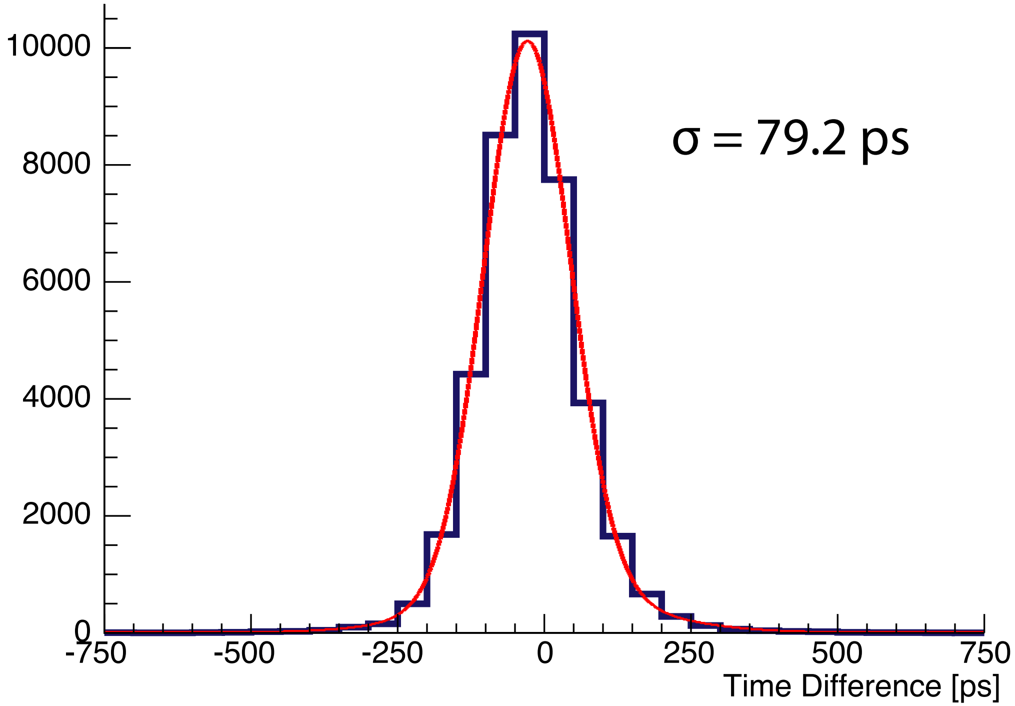


Timing Detector: Scintillating tiles

Front

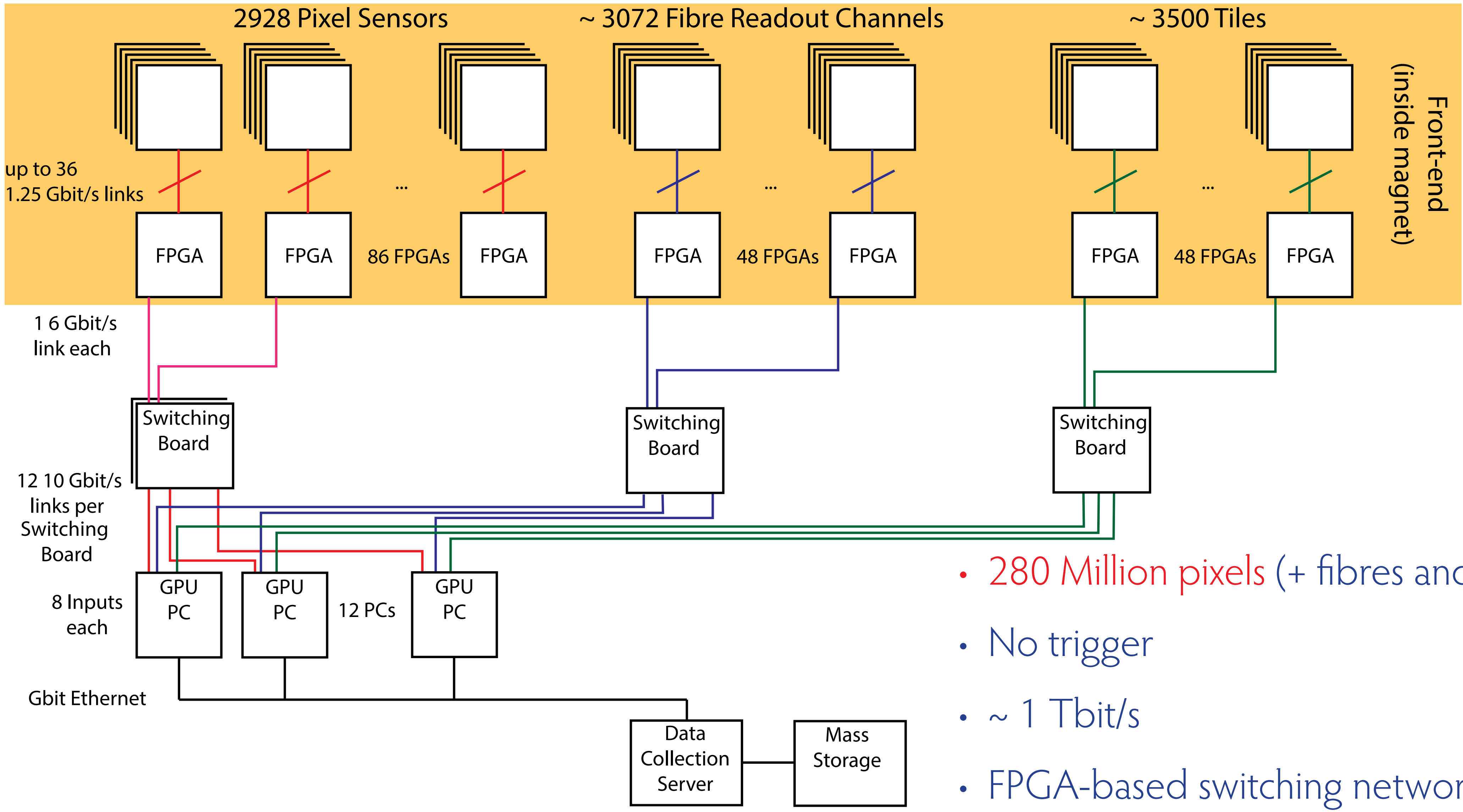


Back



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

Data Acquisition



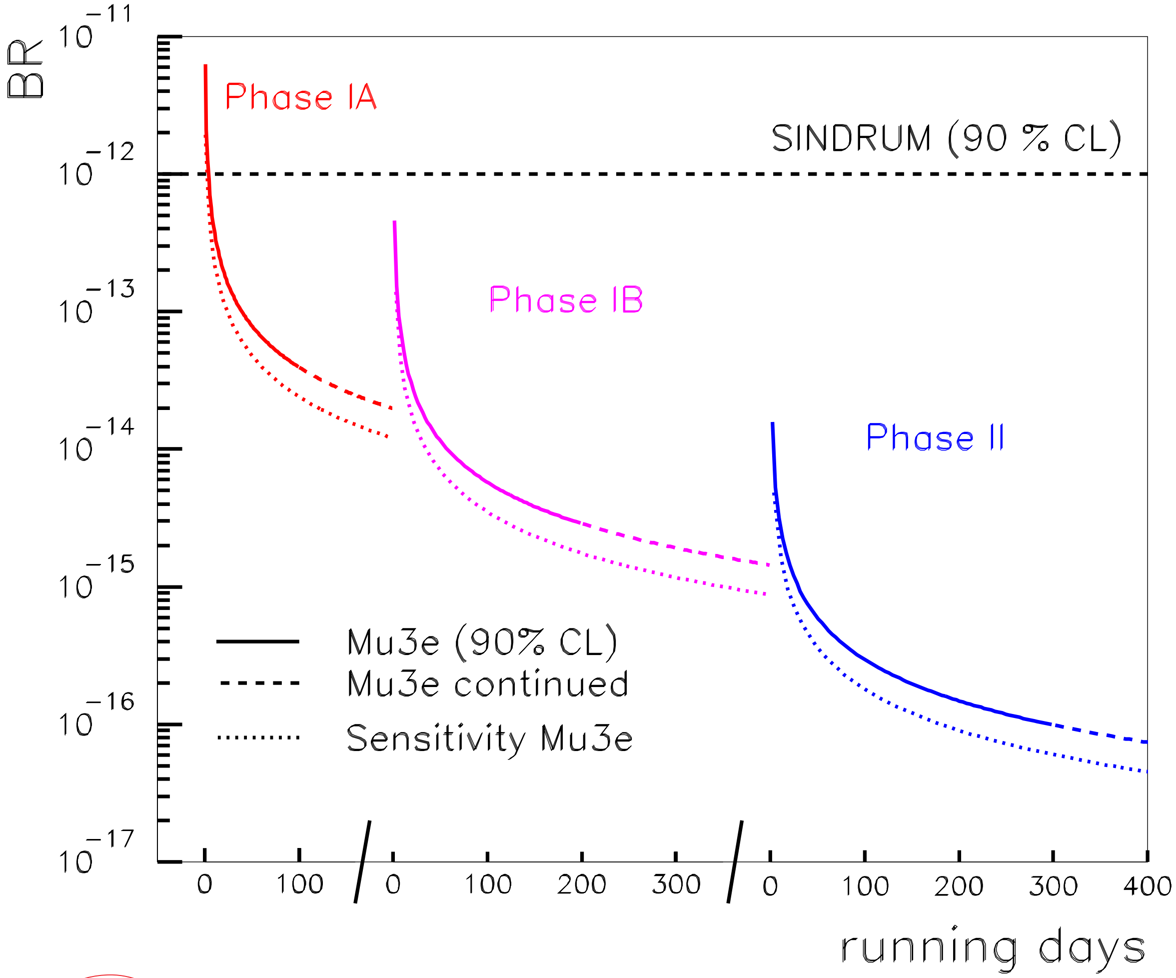
- 280 Million pixels (+ fibres and tiles)
- No trigger
- ~ 1 Tbit/s
- FPGA-based switching network
- O(50) PCs with GPUs

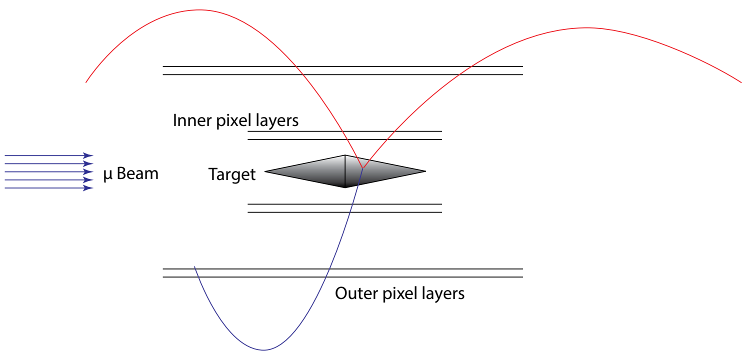
Online filter farm

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

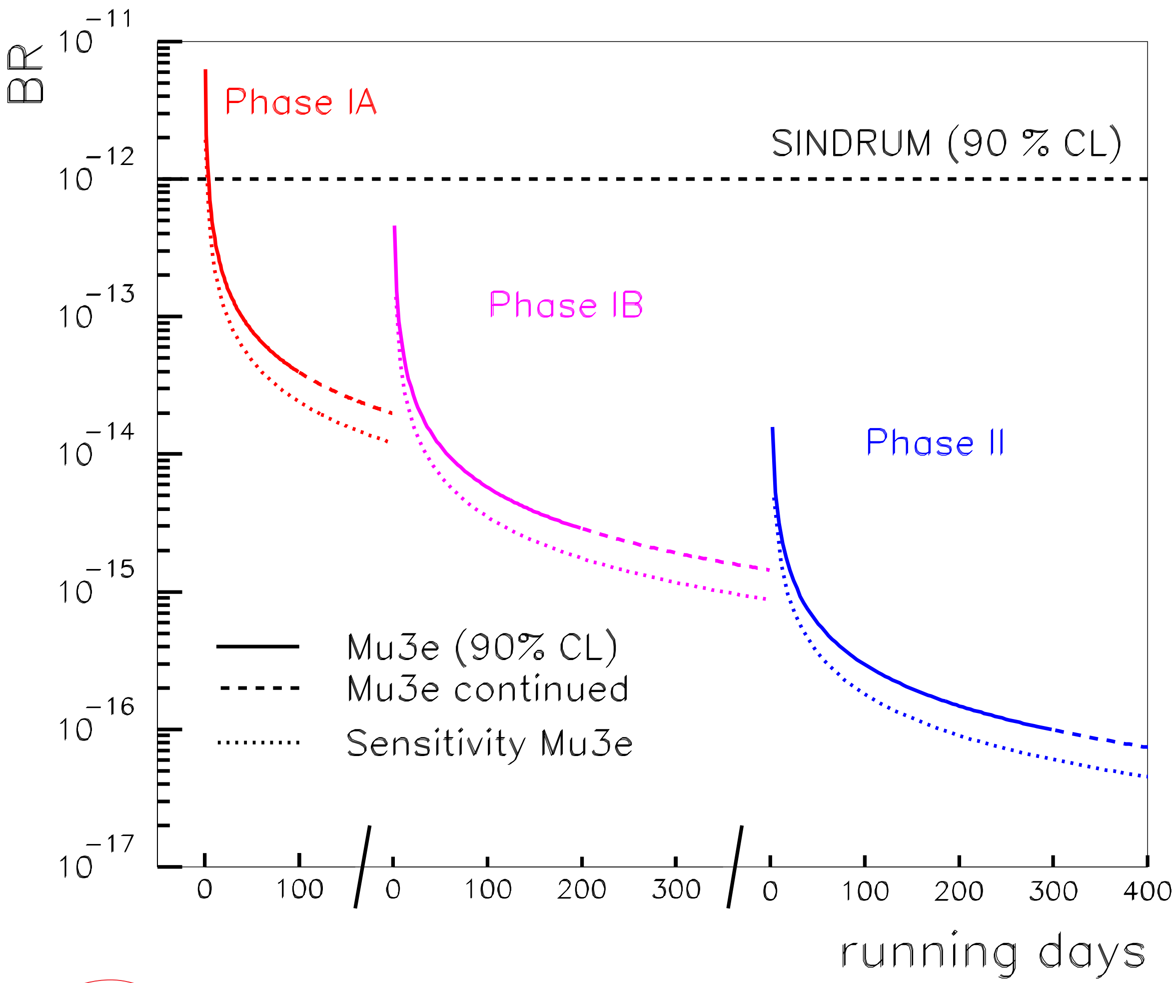
Sensitivity

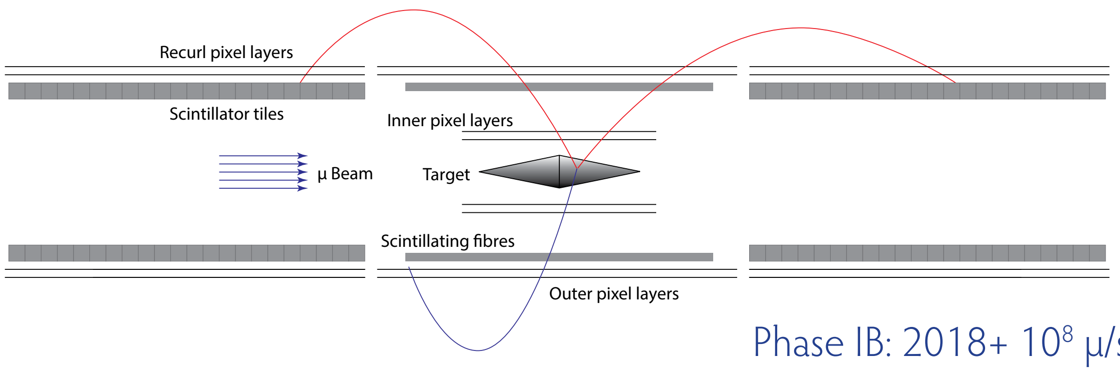




Phase IA: Starting 2017 10^7 μ/s

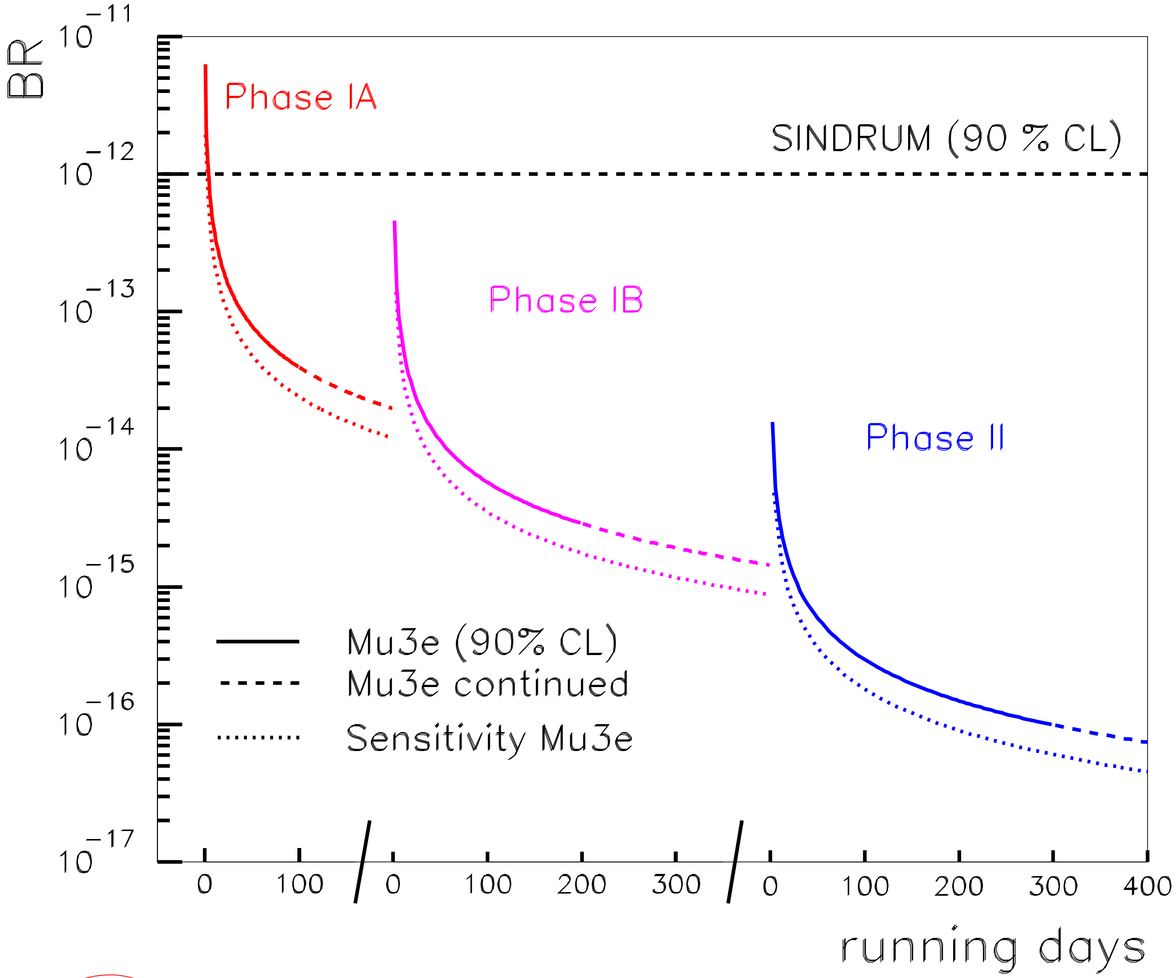
Sensitivity

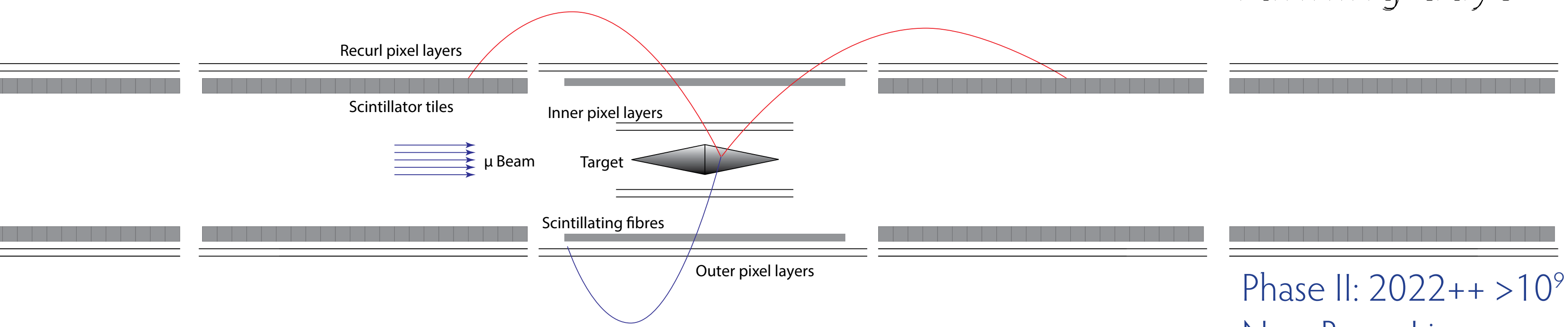




Phase IB: 2018+ 10^8 μ/s

Sensitivity





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