# Searching for Lepton Flavour Violation with the

# Mu3e Experiment


Niklaus Berger

Institut für Kernphysik, Johannes-Gutenberg Universität Mainz


Physics Colloquium

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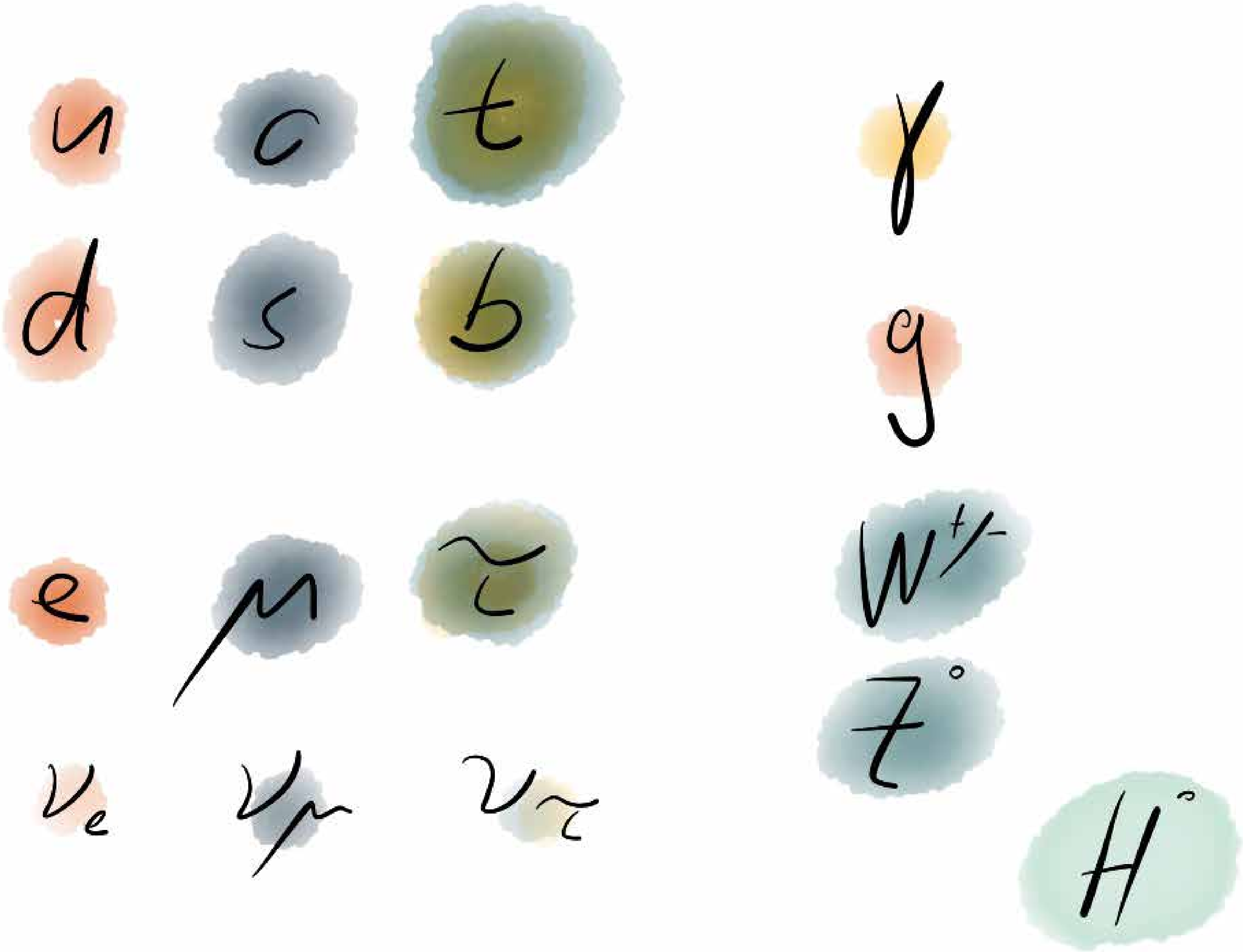
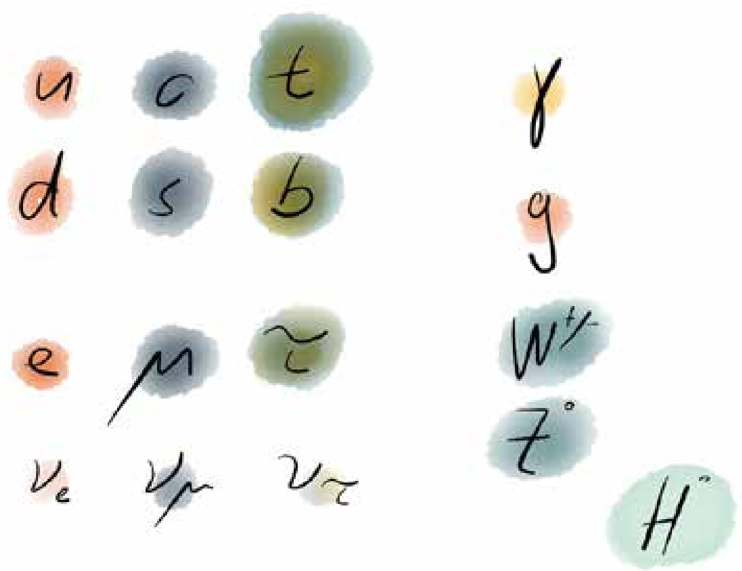
# Particle Physics:
## What are the fundamental constituents of matter and how do they interact?

# The Standard Model of Elementary Particles



# Hugely successful




Magnetic moment of the electron:

- Theory:

  $g_e$ = -2.002 319 304 363 56 (154)

  (Aoyama et al., PRL 109, 111807 (2012))

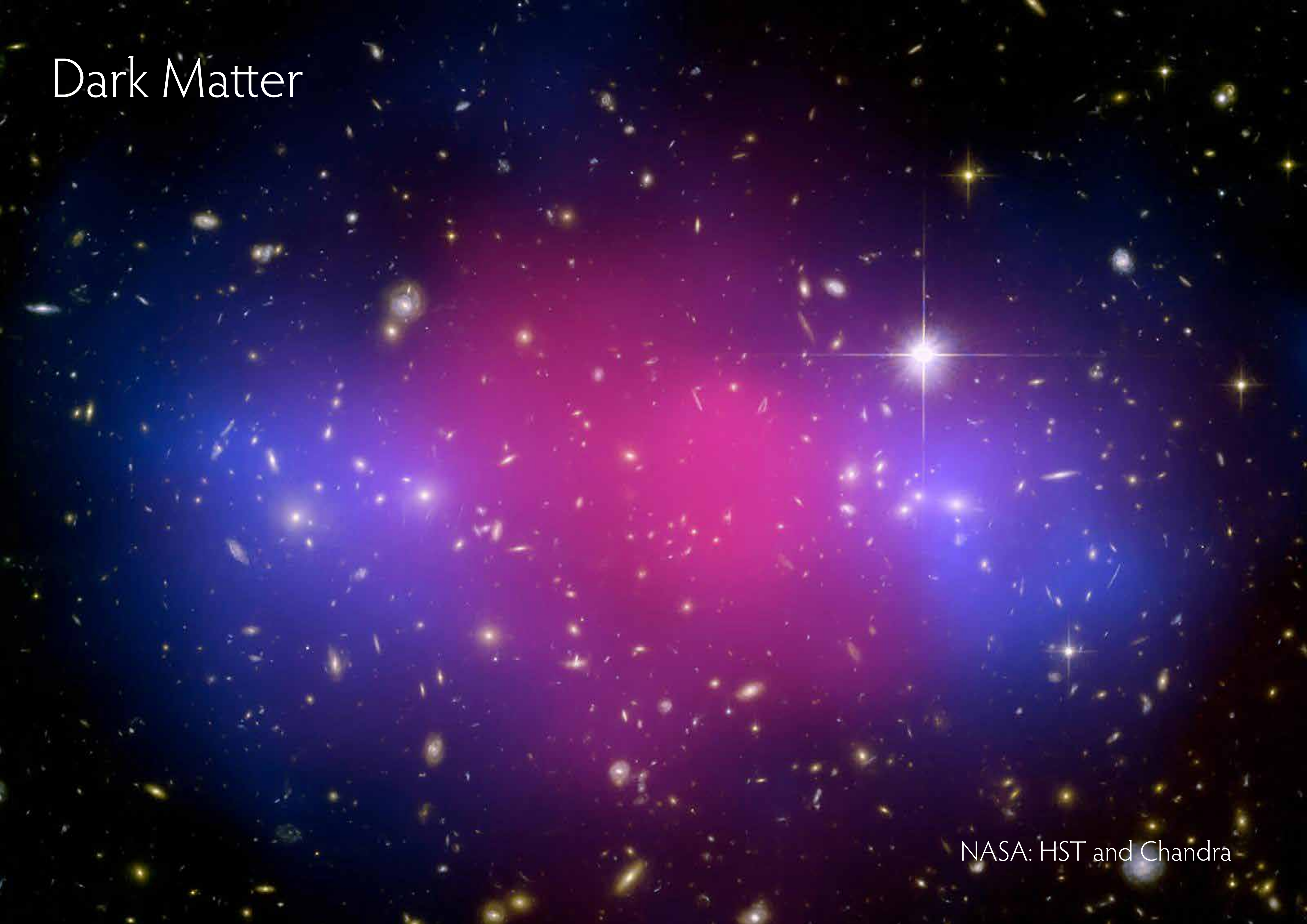
- Experiment:

  $g_e$ = - 2.002 319 304 361 53 (53)

  (Hanneke et al. PRL 100, 120801 (2008))

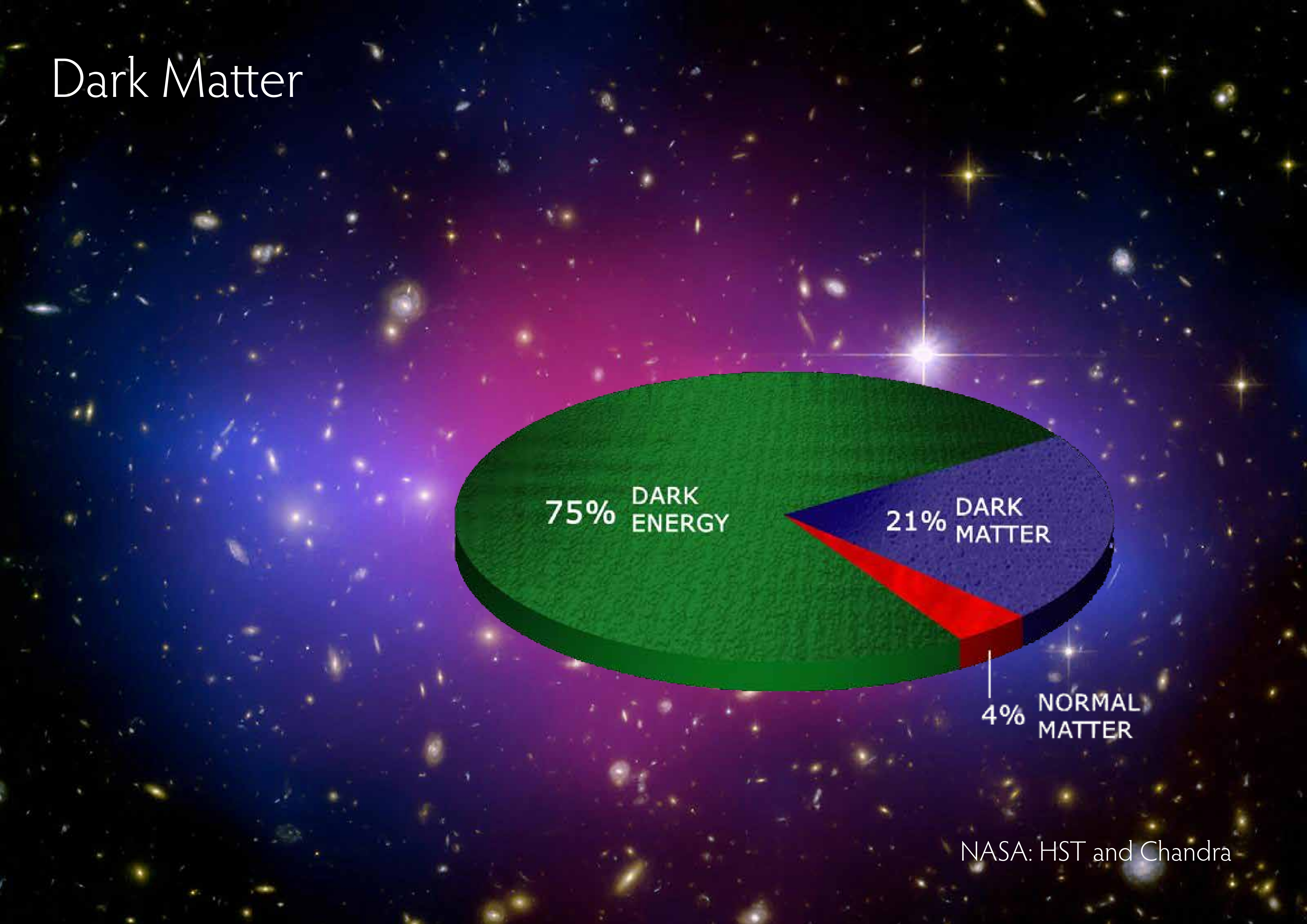
# Open Questions?

# Dark Matter



NASA: HST and Chandra

# Dark Matter




NASA: HST and Chandra

# Matter-Antimatter Asymmetry

| Antimatter | Matter |
|---|---|
| 10'000'000'000 | 10'000'000'001 |

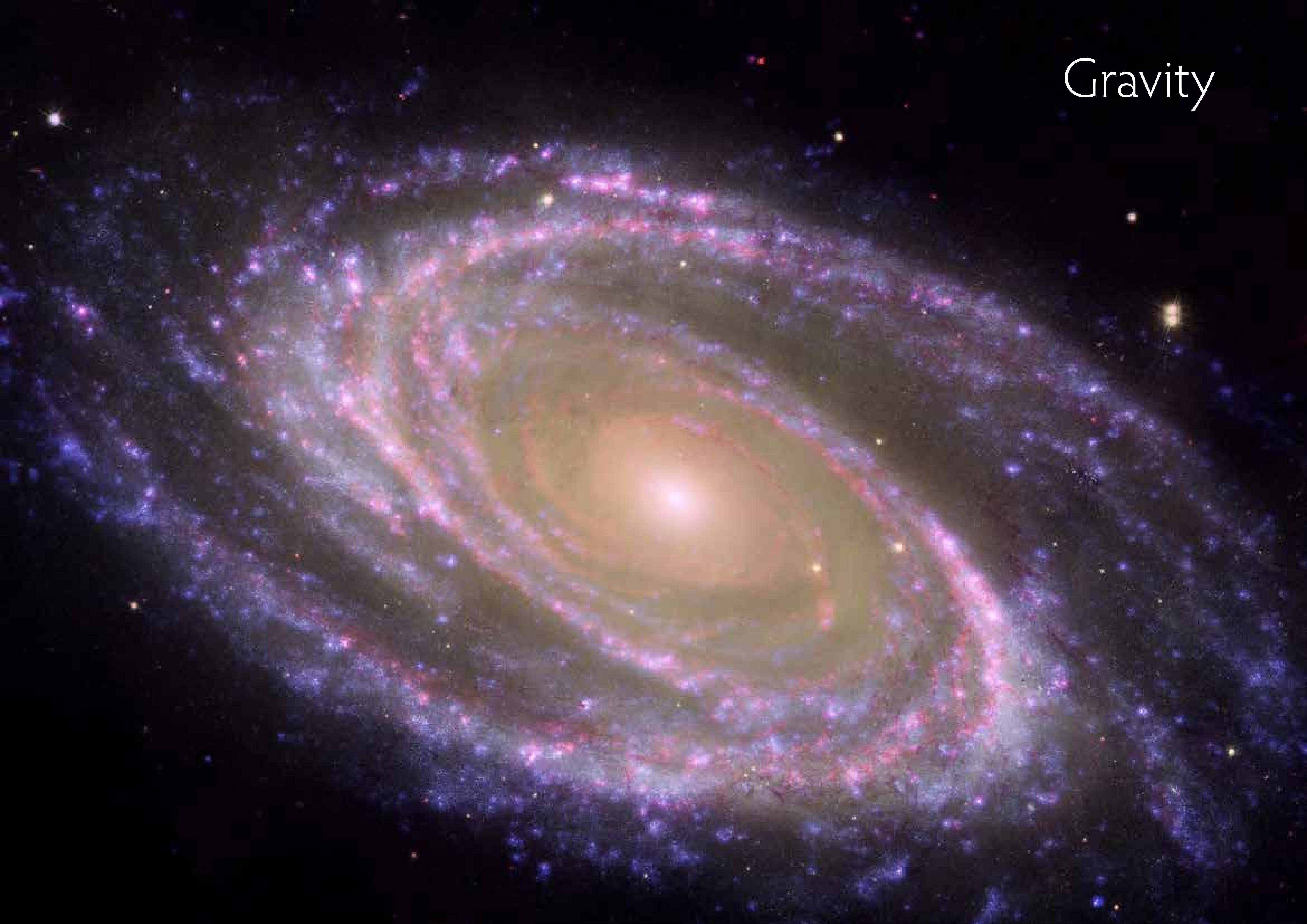
# Matter-Antimatter Asymmetry

Radiation

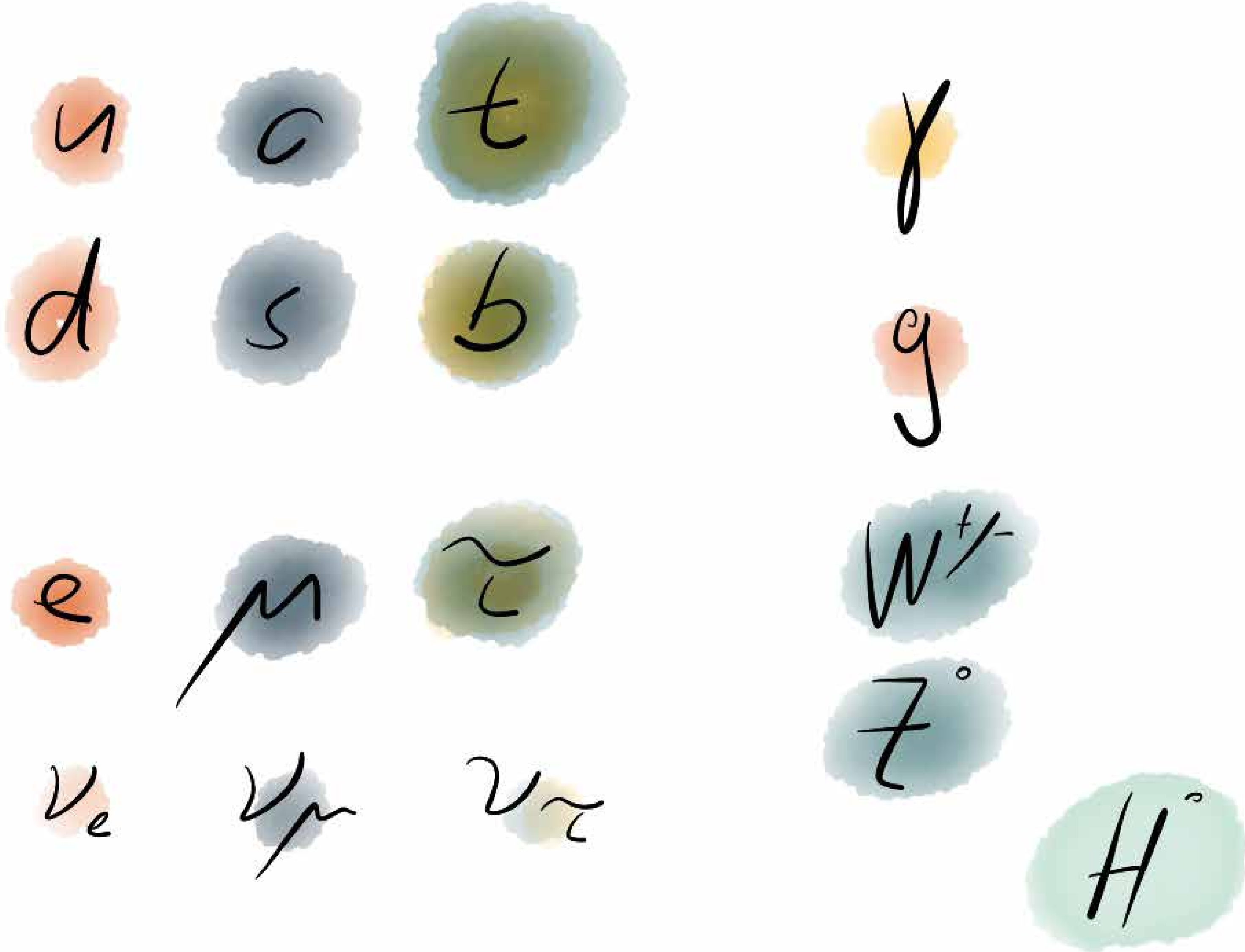
1

Us

# Gravity



# The Structure of the Standard Model



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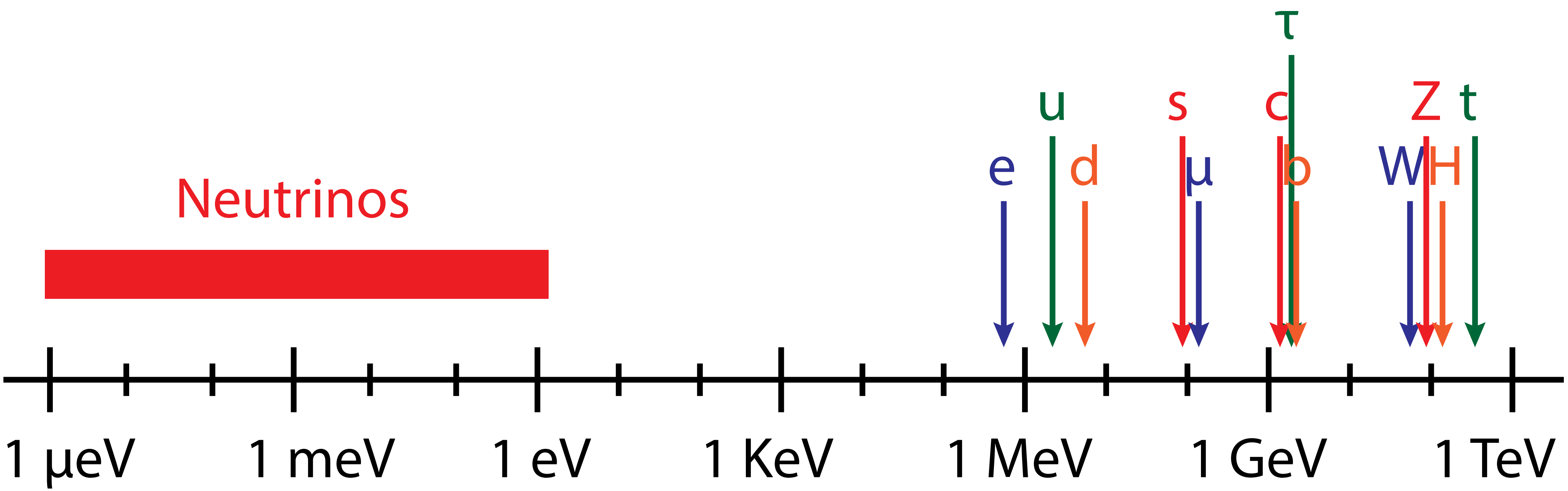

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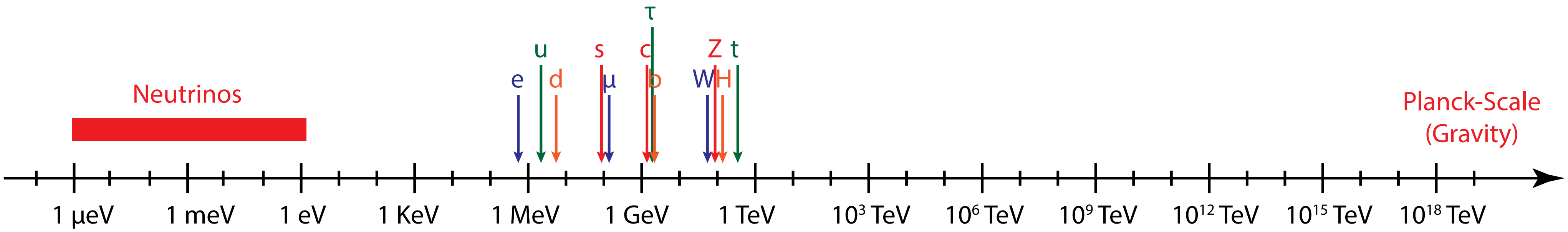

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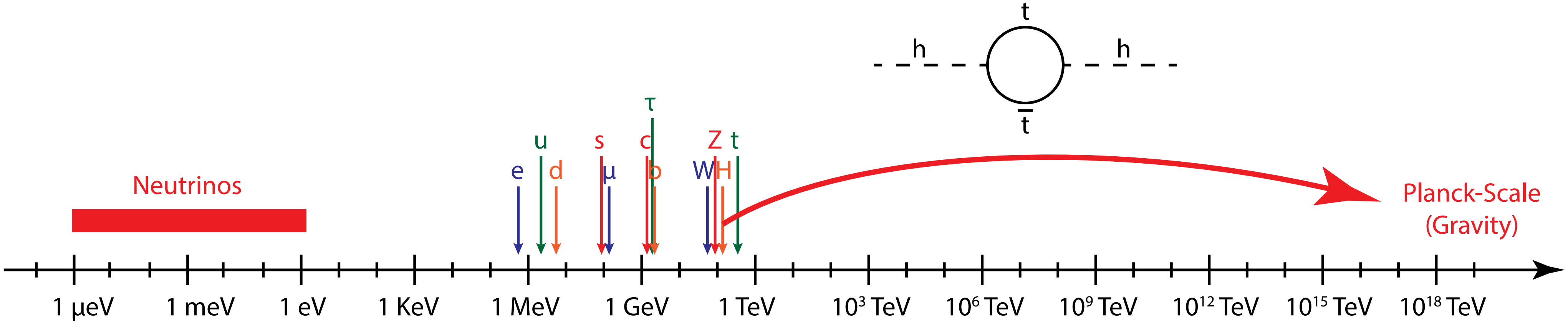

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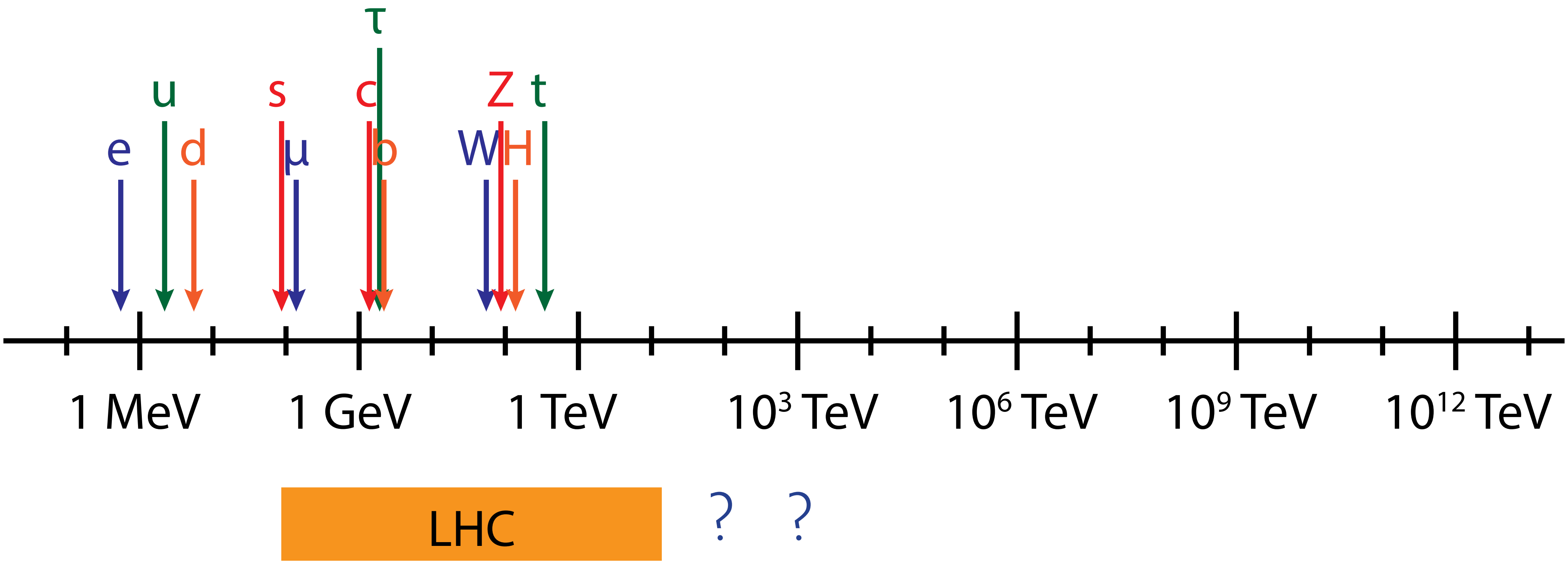
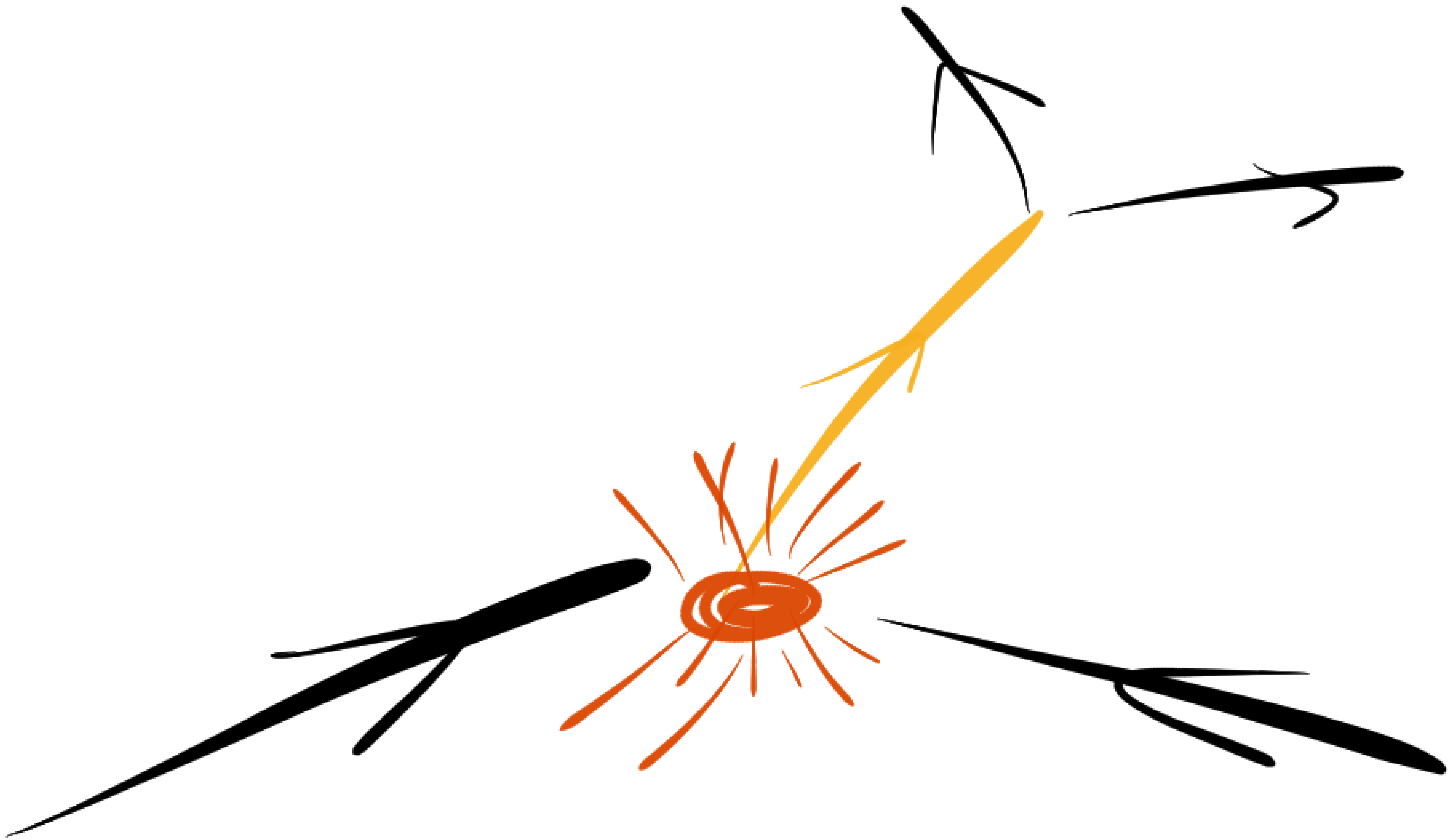
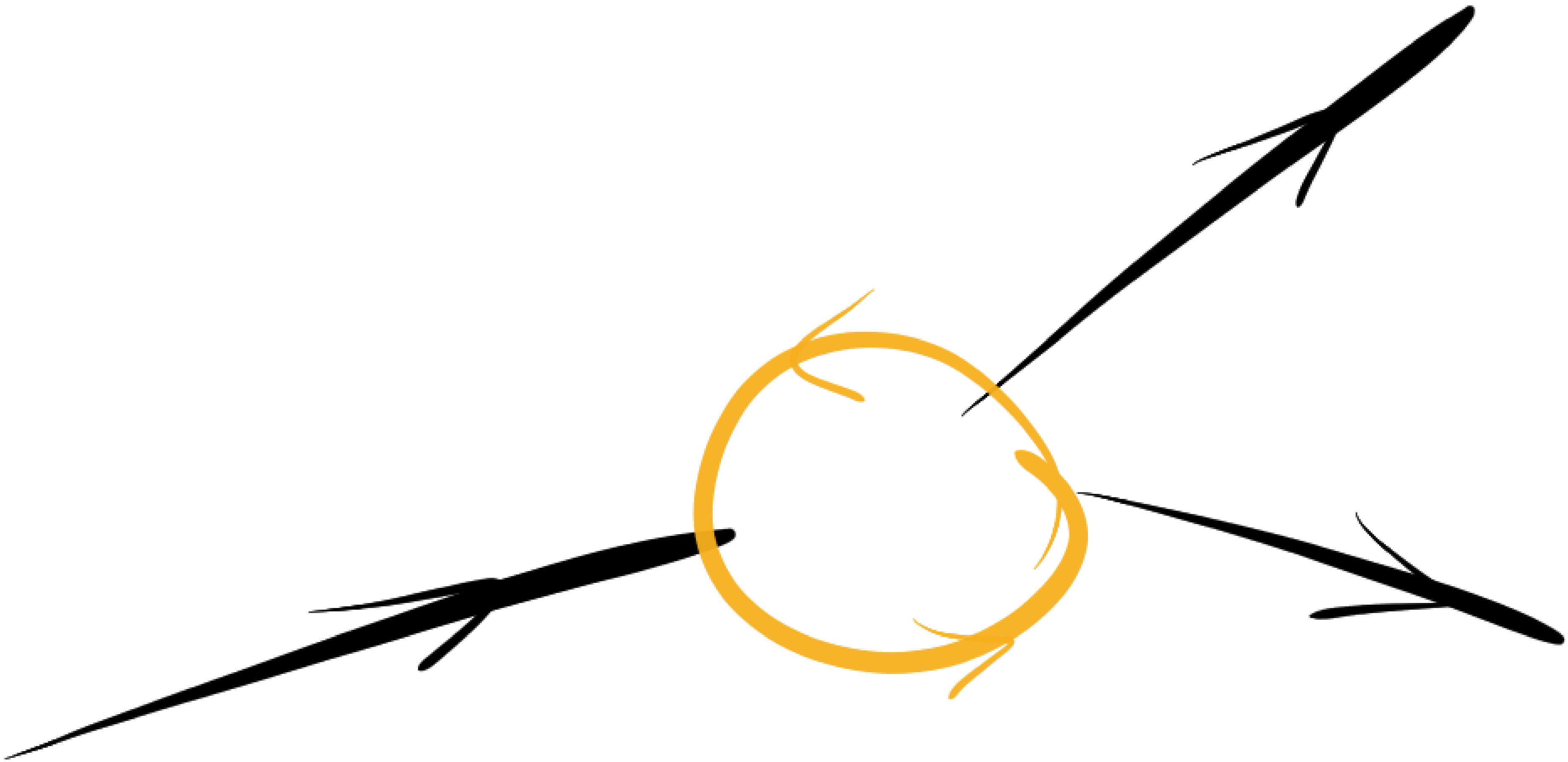


# Direct production



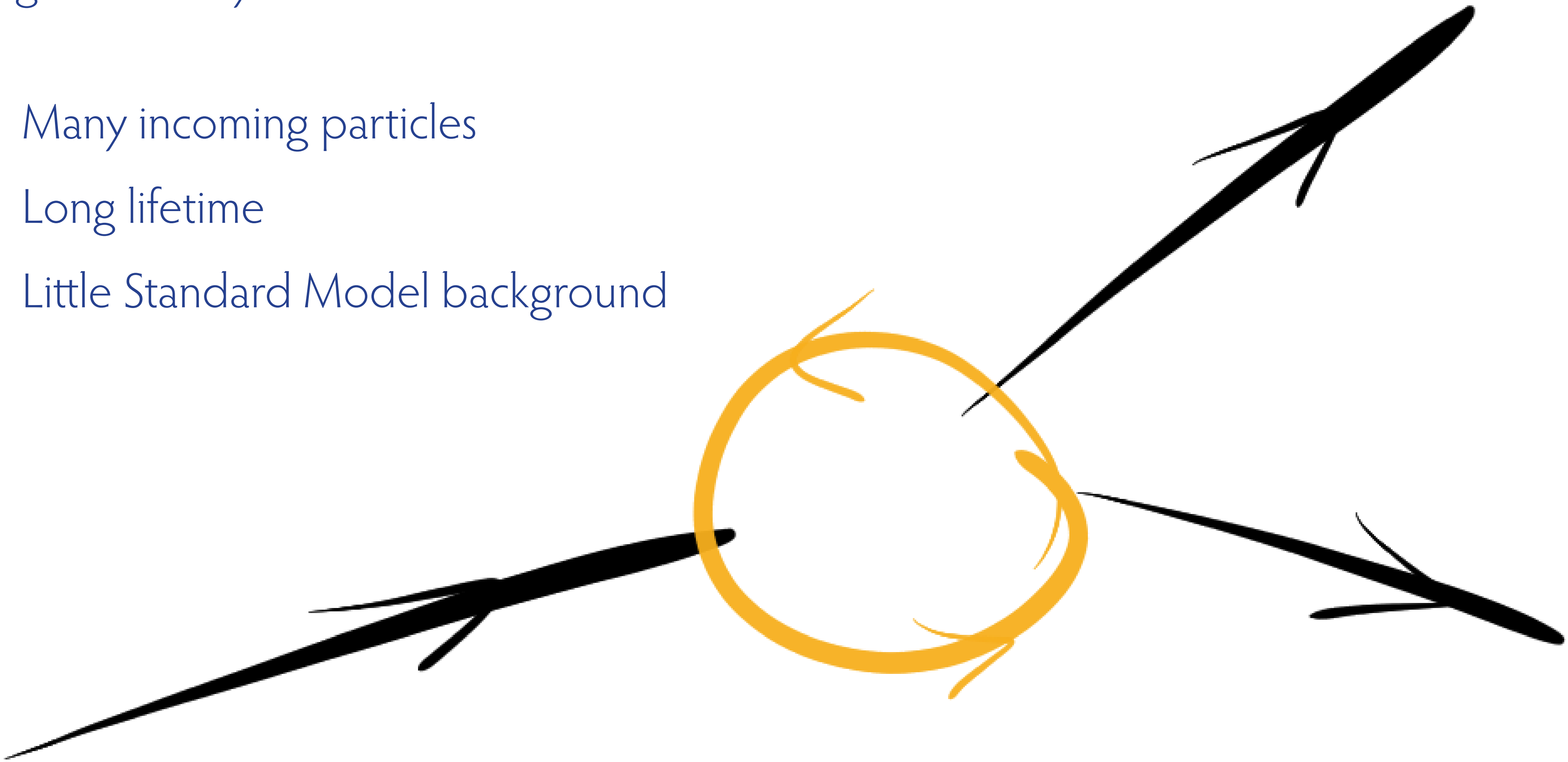
# Indirect effects in quantum loops



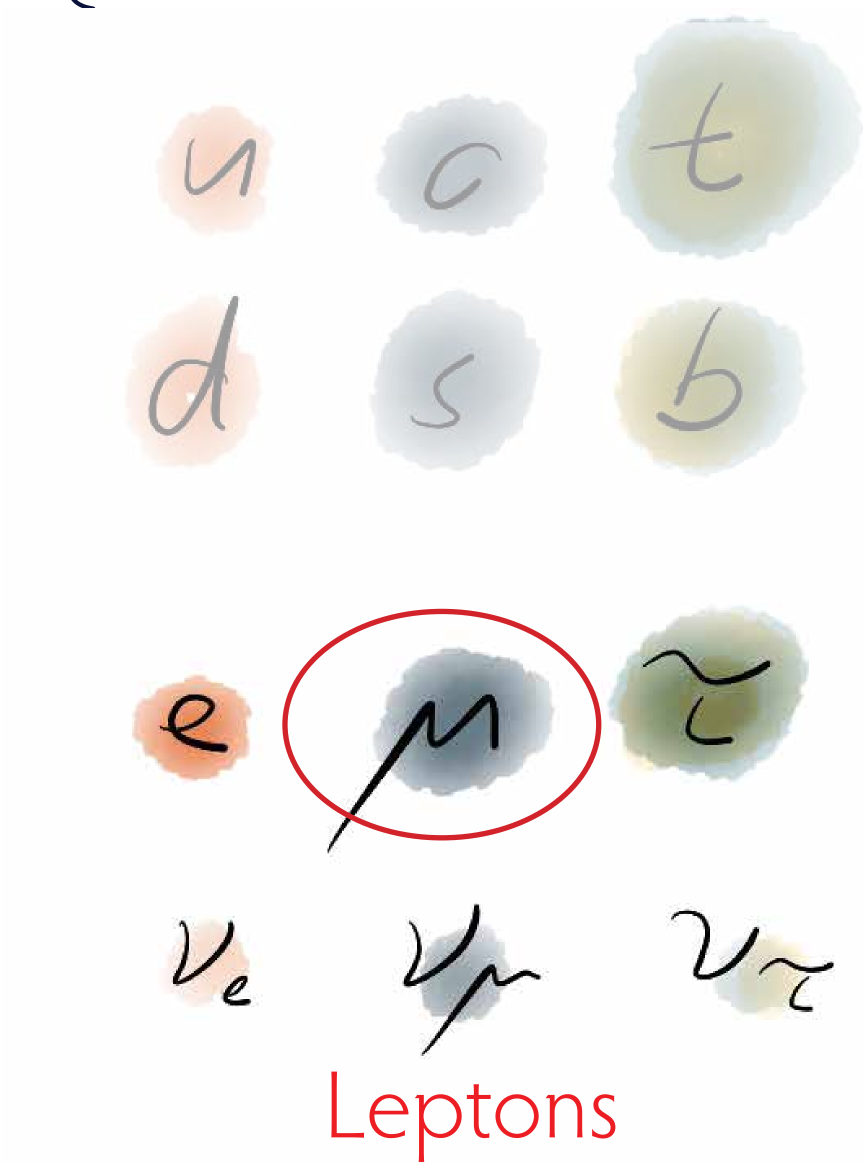
# Indirect effects in quantum loops

Large discovery reach if:

- Many incoming particles
- Long lifetime
- Little Standard Model background



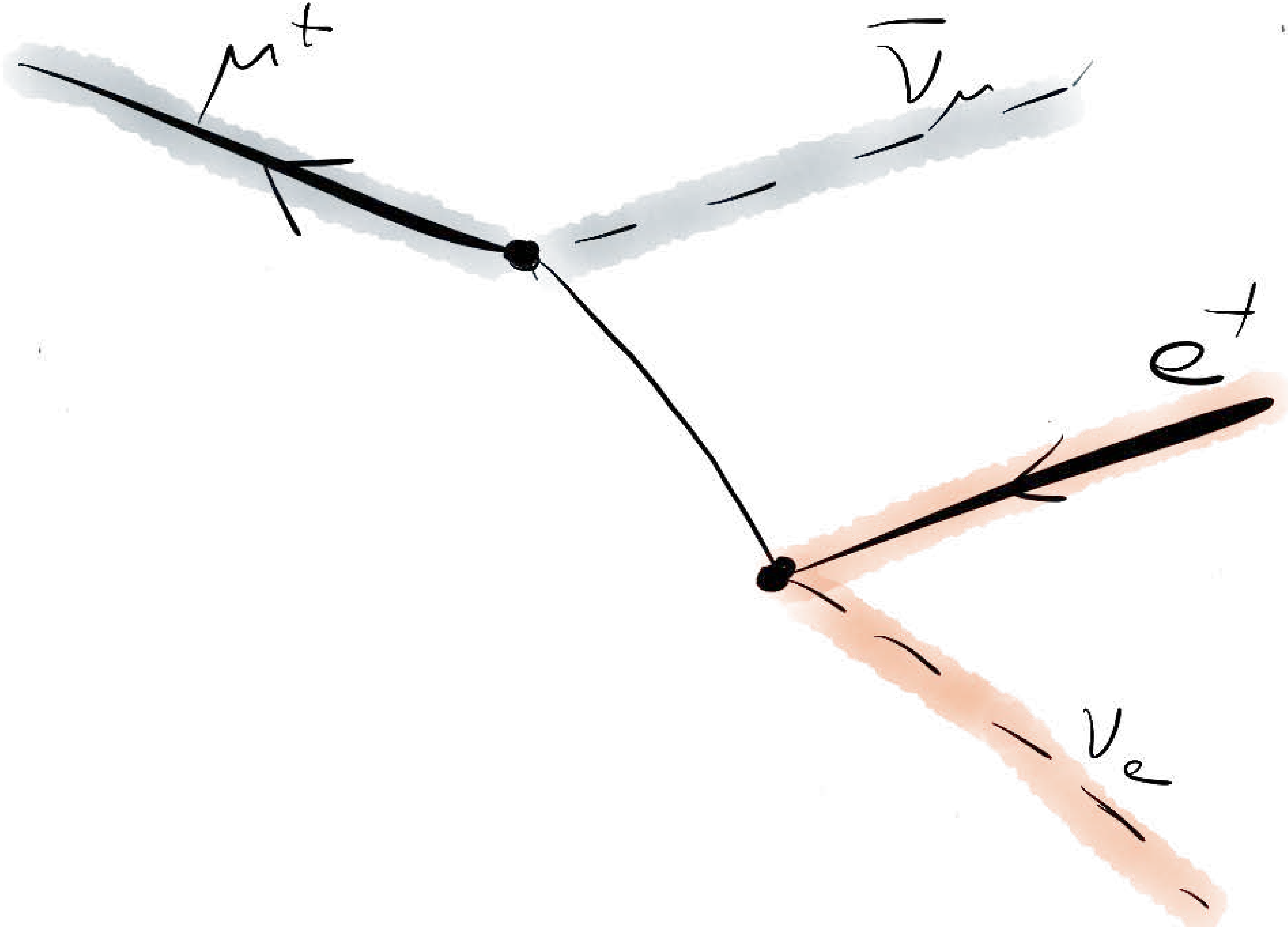
# Look at muons



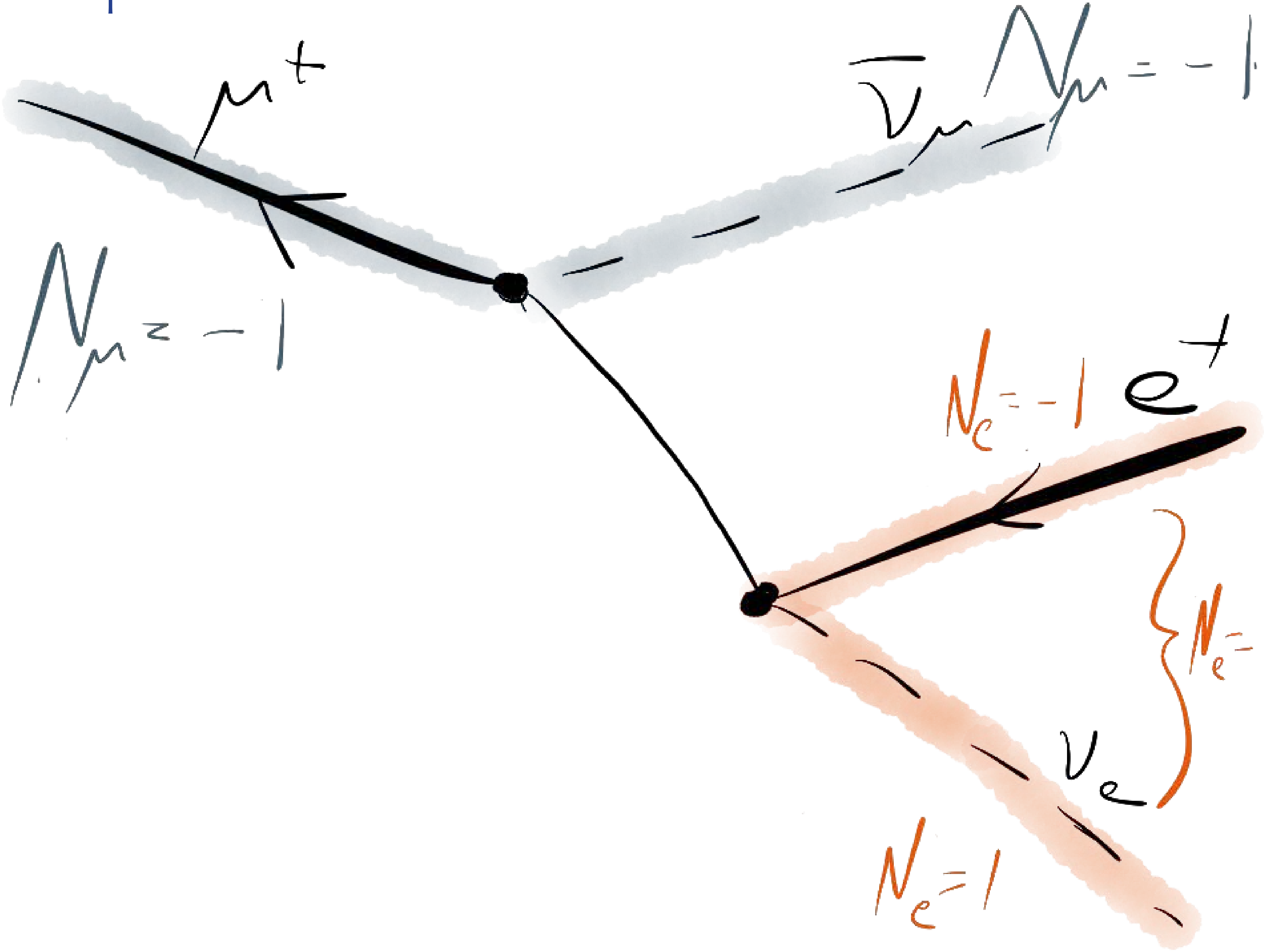

Large discovery reach if:

- Many incoming particles ($10^8$/s)
- Long lifetime (2.2 µs)
- Little Standard Model background

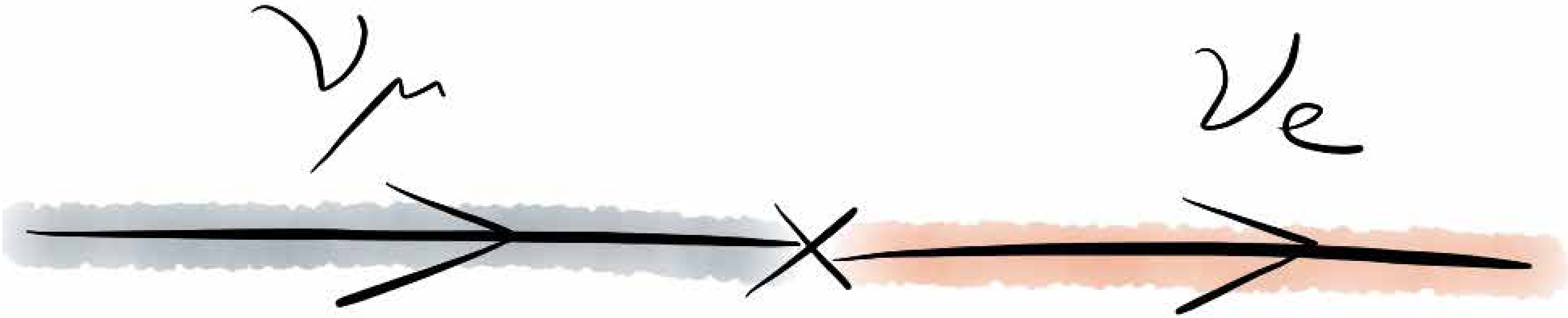
# Lepton Flavour



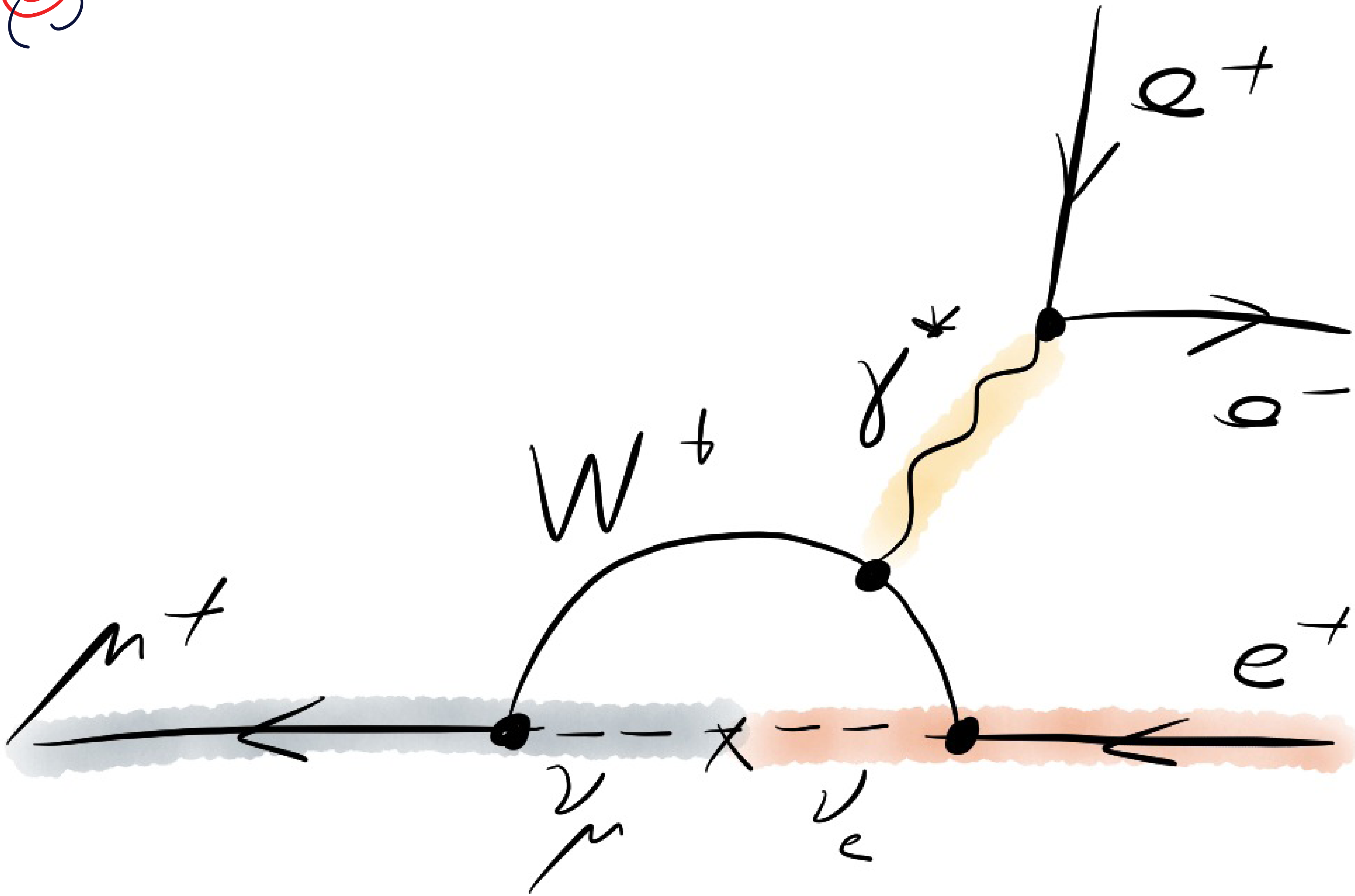
# Lepton Flavour



# Lepton Flavour Violation!



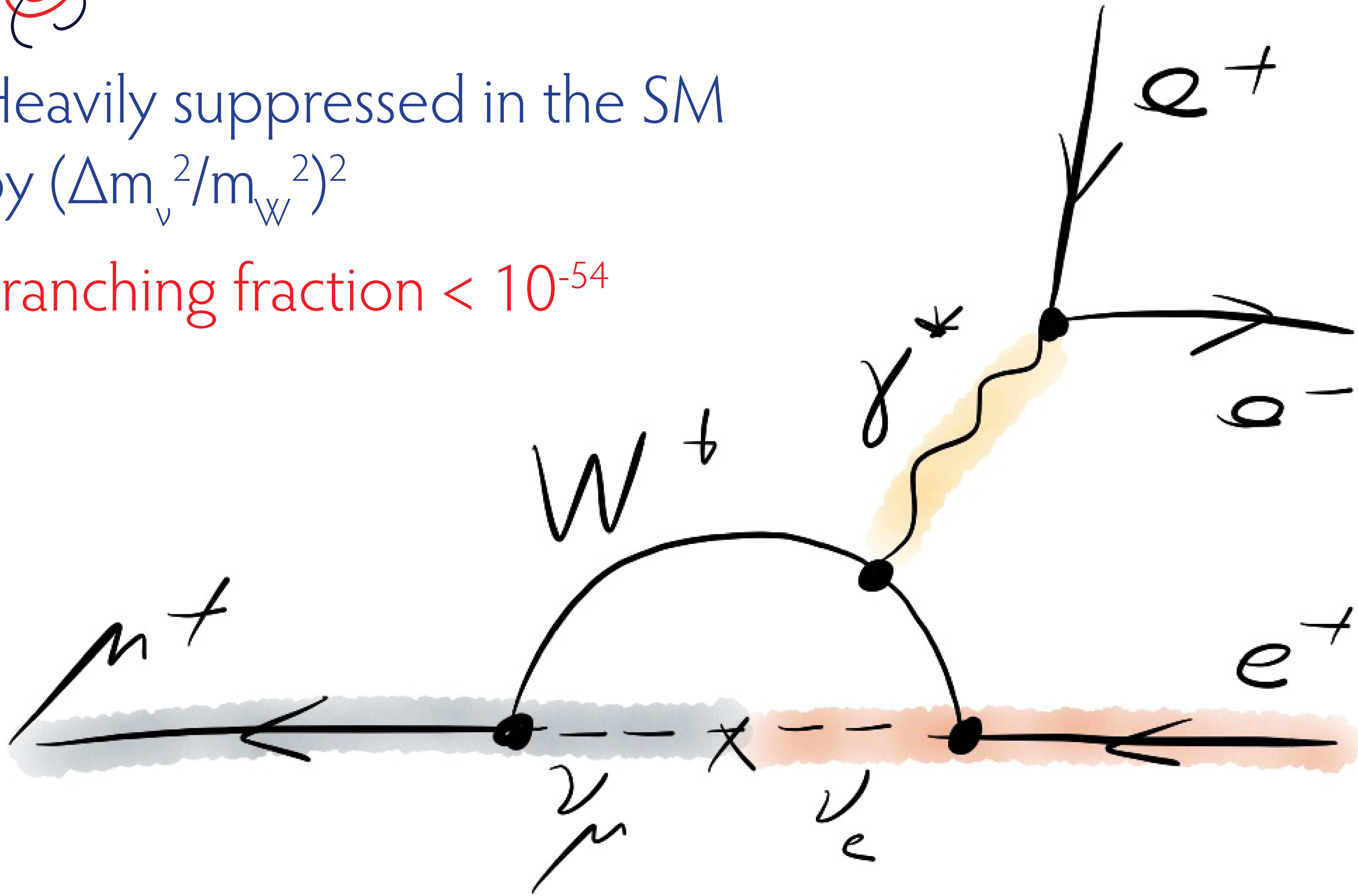
# Charged Lepton Flavour Violation?



# Charged Lepton Flavour Violation?

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

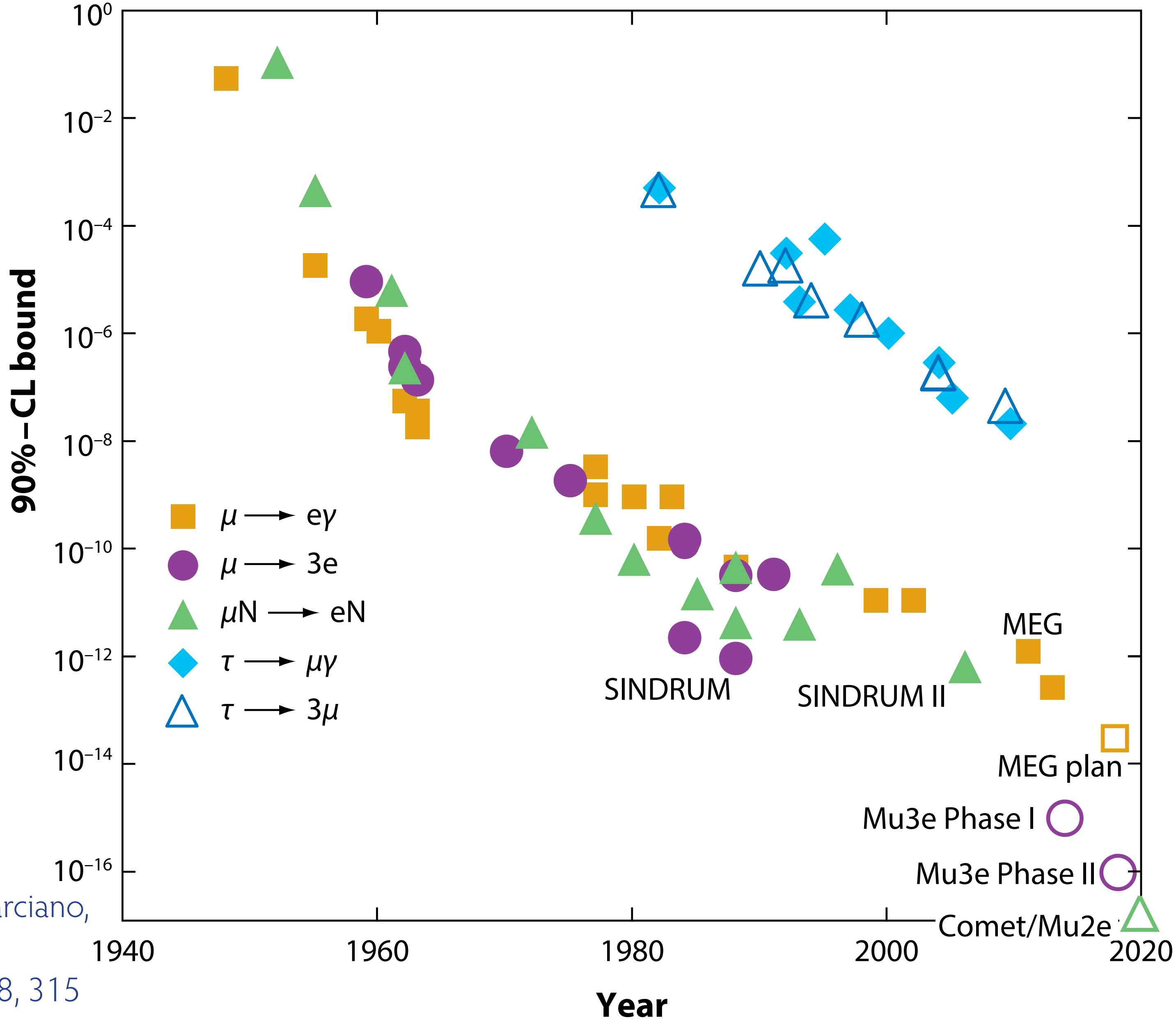
Branching fraction $< 10^{-54}$



This
(charged lepton flavour violation)
has never been seen

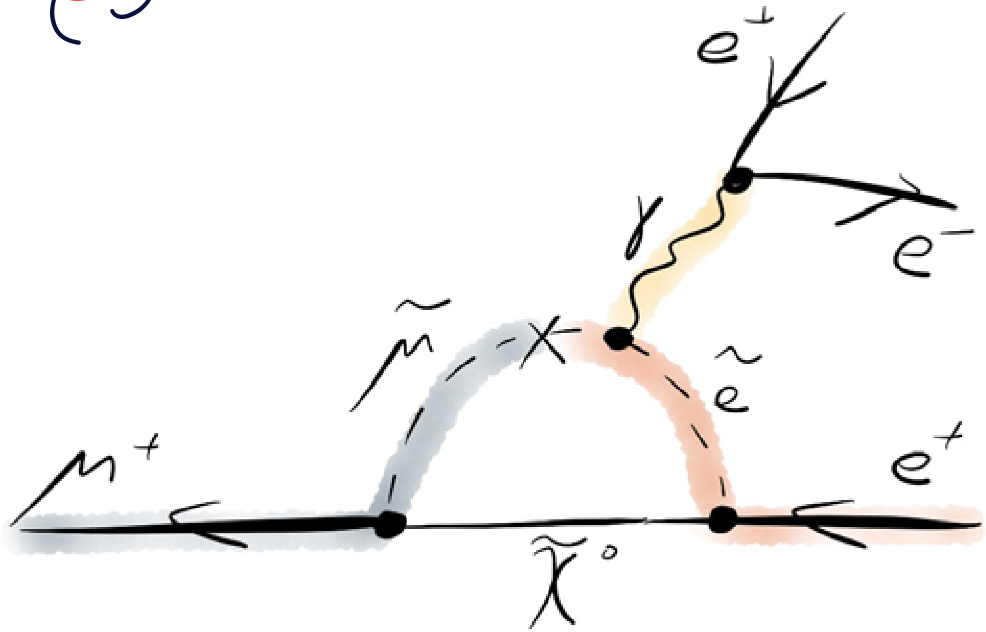
and not because we have not looked

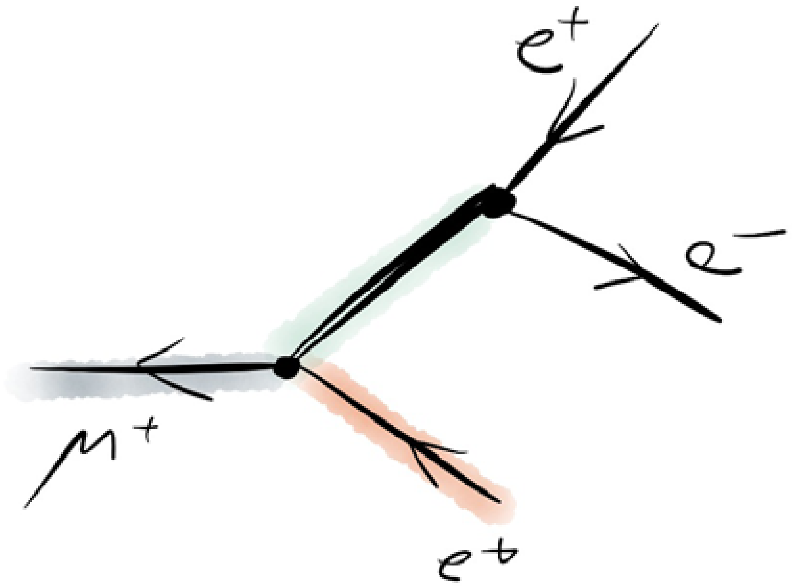
# History of LFV experiments




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

# New physics in $\mu^+ \rightarrow e^+e^-e^+$



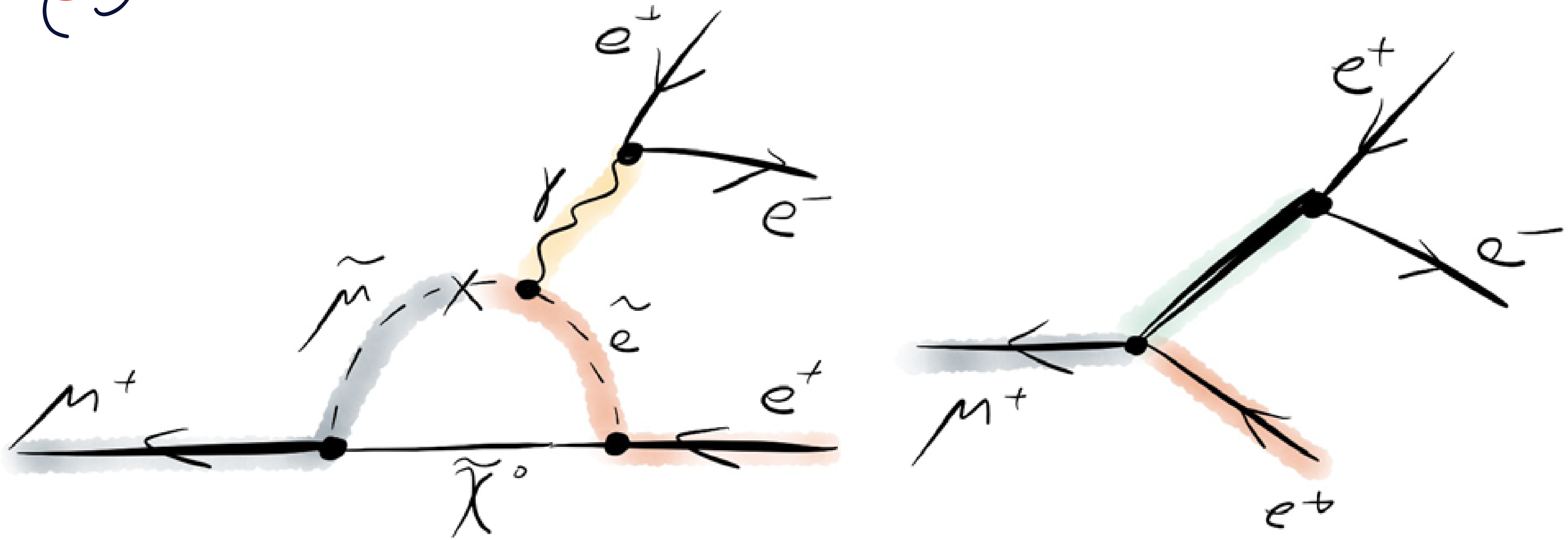

Loop diagrams

- Supersymmetry
- Little Higgs models
- Seesaw models
- GUT models (leptoquarks)
- and much more...

Tree diagrams

- Higgs triplet model
- Extra heavy vector bosons (Z')
- Extra dimensions (Kaluza-Klein tower)

# New physics in $\mu^+ \rightarrow e^+e^-e^+$



Muon decays at the $10^{-16}$ level sensitive to new physics at $\mathcal{O}$(1000 TeV) scale for $\mathcal{O}$(1) couplings!

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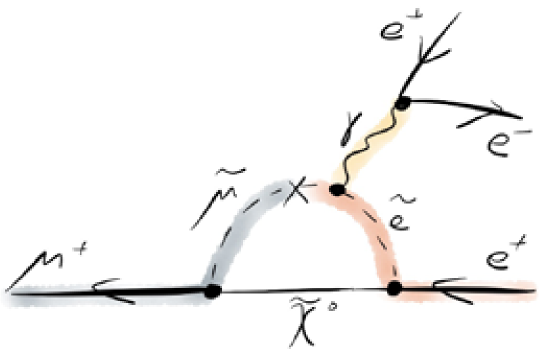
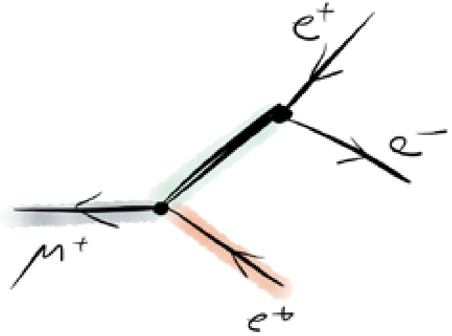
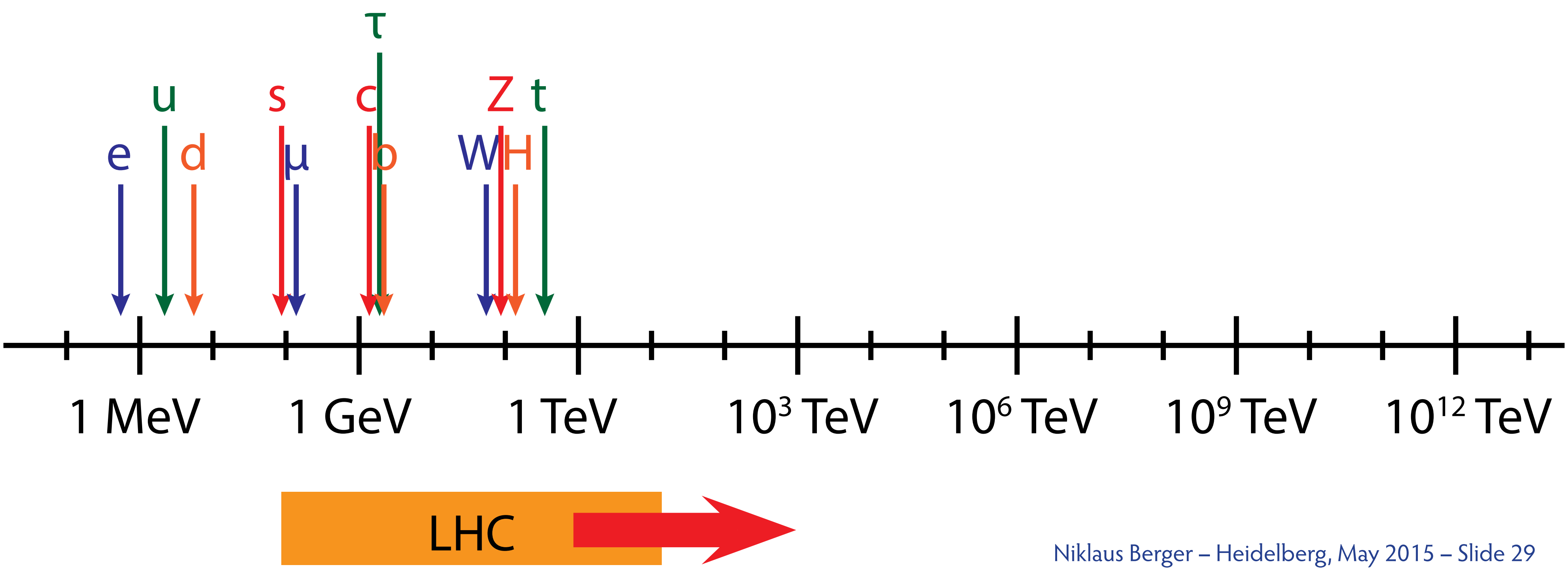




Muon decays at the $10^{-16}$ level sensitive to new physics at $\mathcal{O}$(1000 TeV) scale for $\mathcal{O}$(1) couplings!



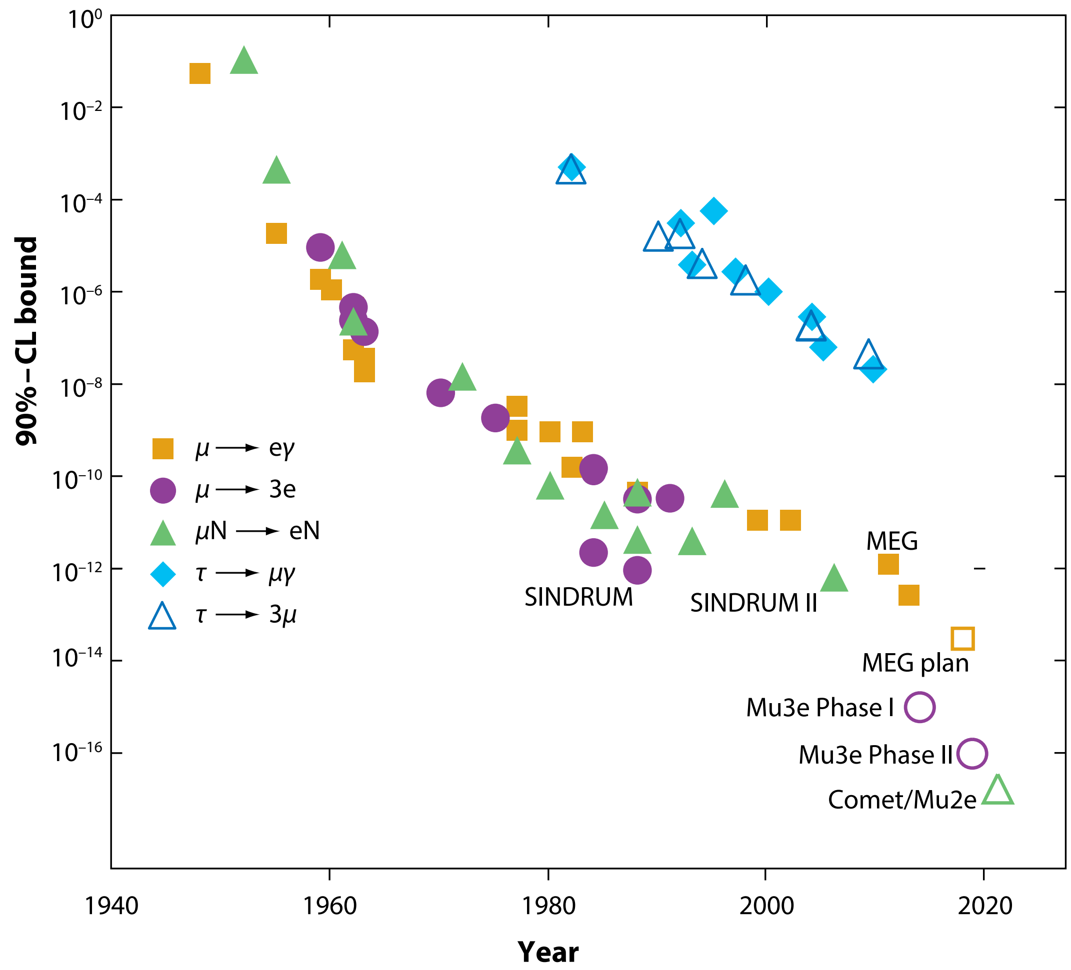
# Searching for
# $\mu^+ \rightarrow e^+e^-e^+$ at the $10^{-16}$ level

# The Goal: $10^{-16}$

- We want to find or exclude $\mu \rightarrow eee$ at the $10^{-16}$ level

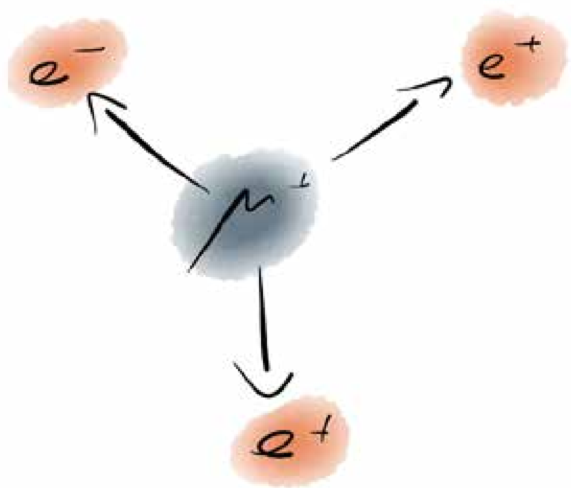
- $10^{-15}$ in phase I (existing beamline)
- $10^{-16}$ in phase II (new beamline)

- 4 orders of magnitude over previous experiment (SINDRUM 1988 - $10^{-12}$)




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

# The Challenges




- Observe more than $10^{16}$ muon decays:
  2 Billion muons per second

- Suppress backgrounds by more than 16 orders of magnitude

- Be sensitive for the signal

# Muons from PSI

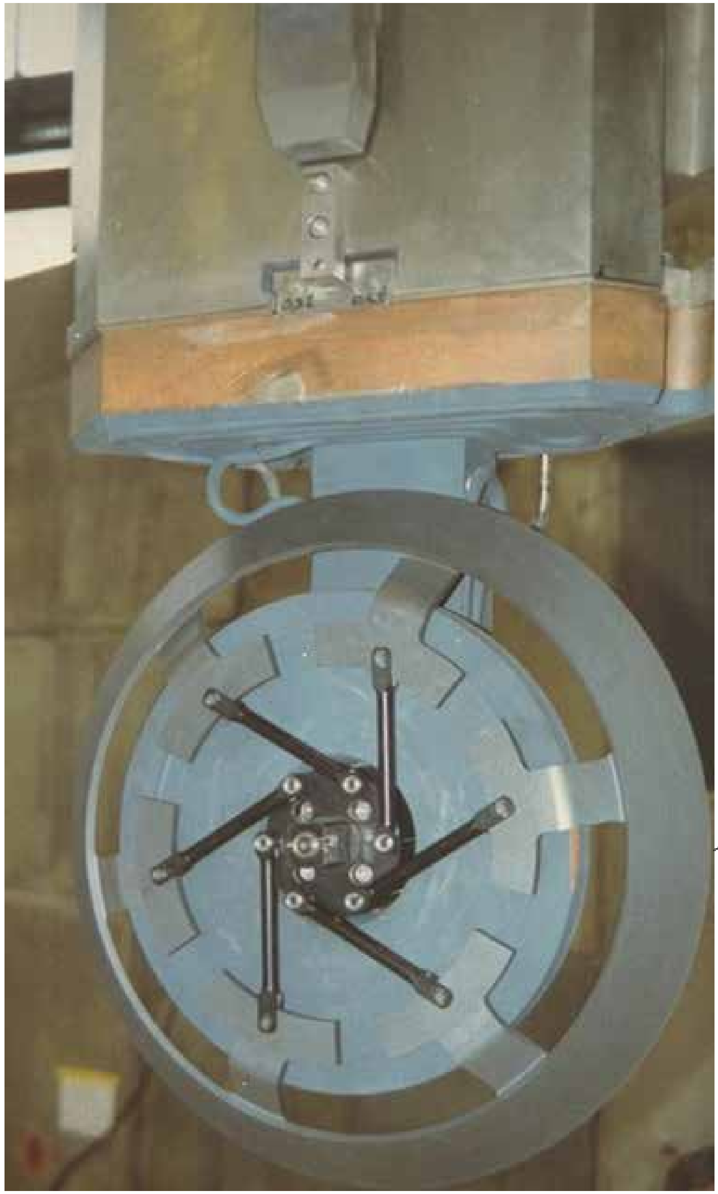
Paul Scherrer Institute in Villigen, Switzerland

# Muons from PSI

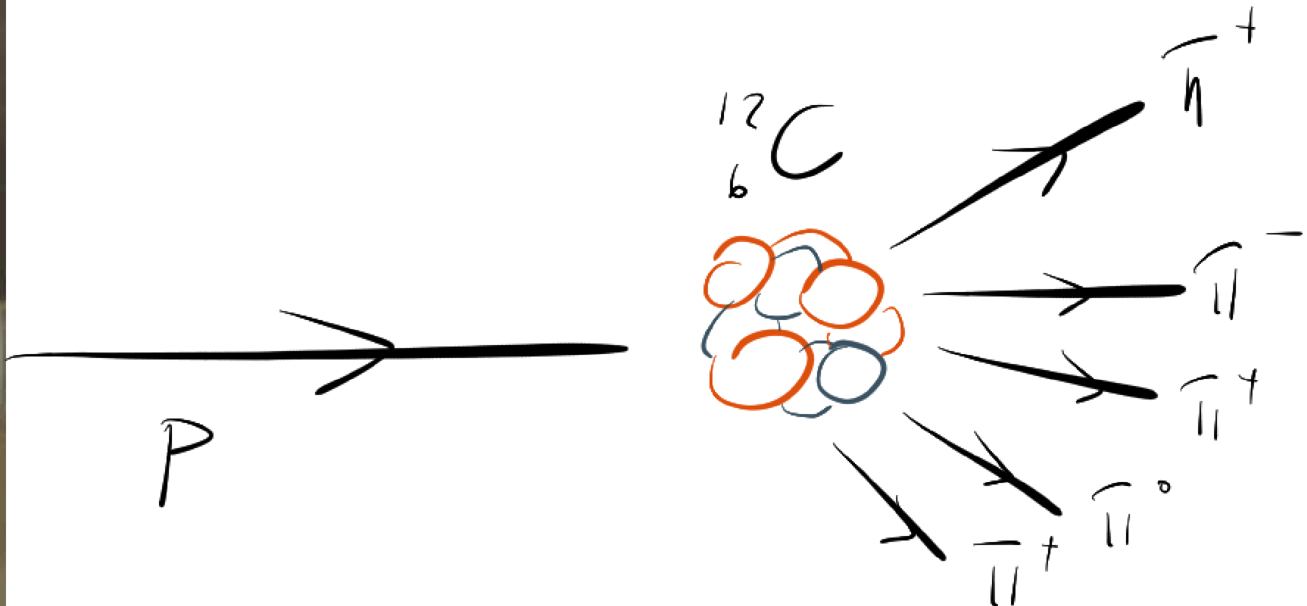
Paul Scherrer Institute in Villigen, Switzerland

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

# Pion production

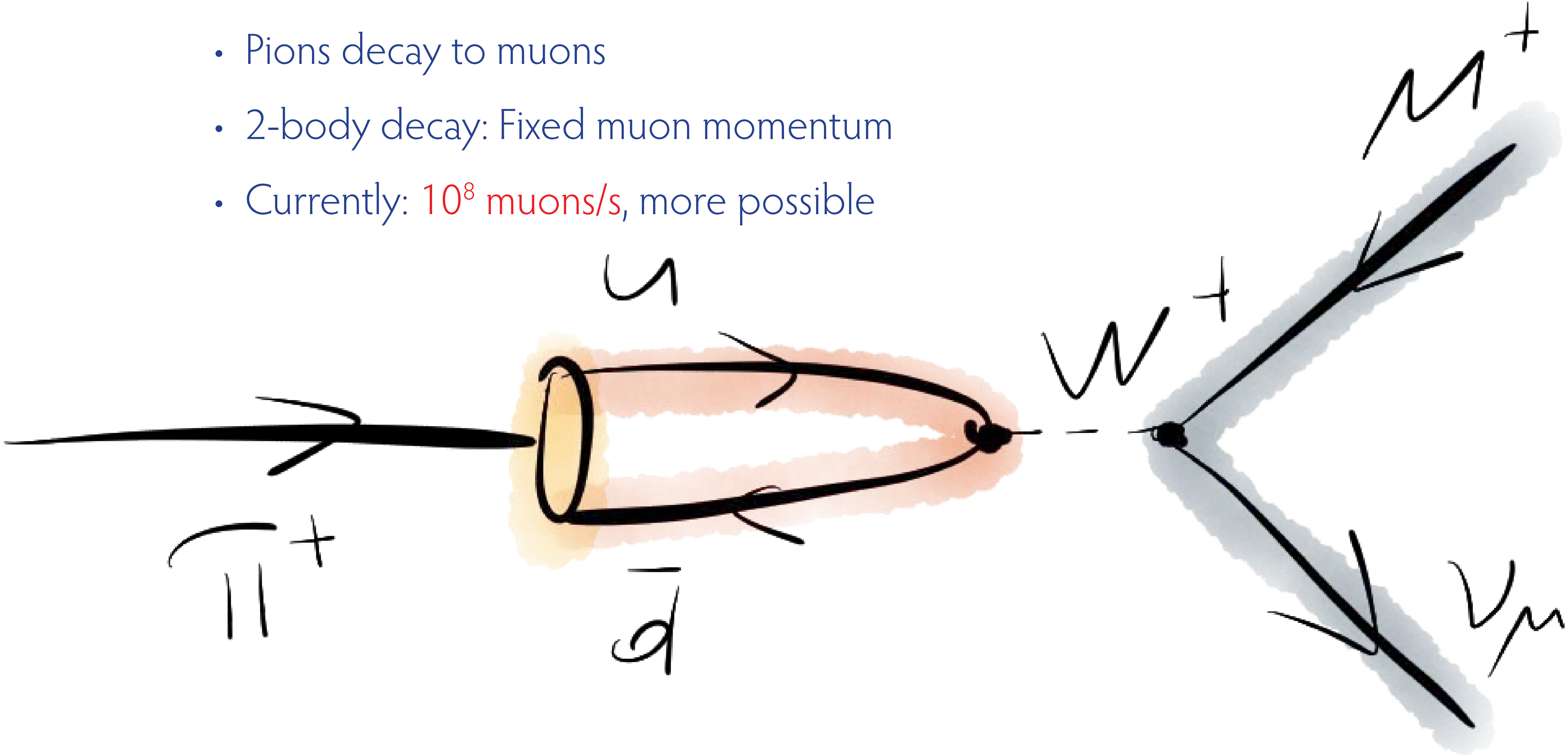


- Rotating carbon wheel as target
- Hit with proton beam
- Produce pions



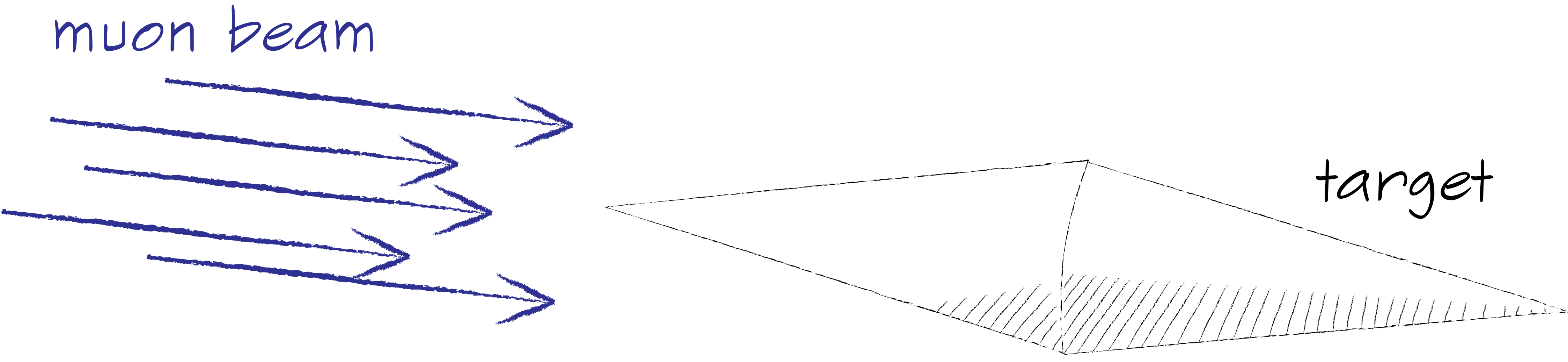
# Pion decay

- Pions decay to muons
- 2-body decay: Fixed muon momentum
- Currently: $10^8$ muons/s, more possible

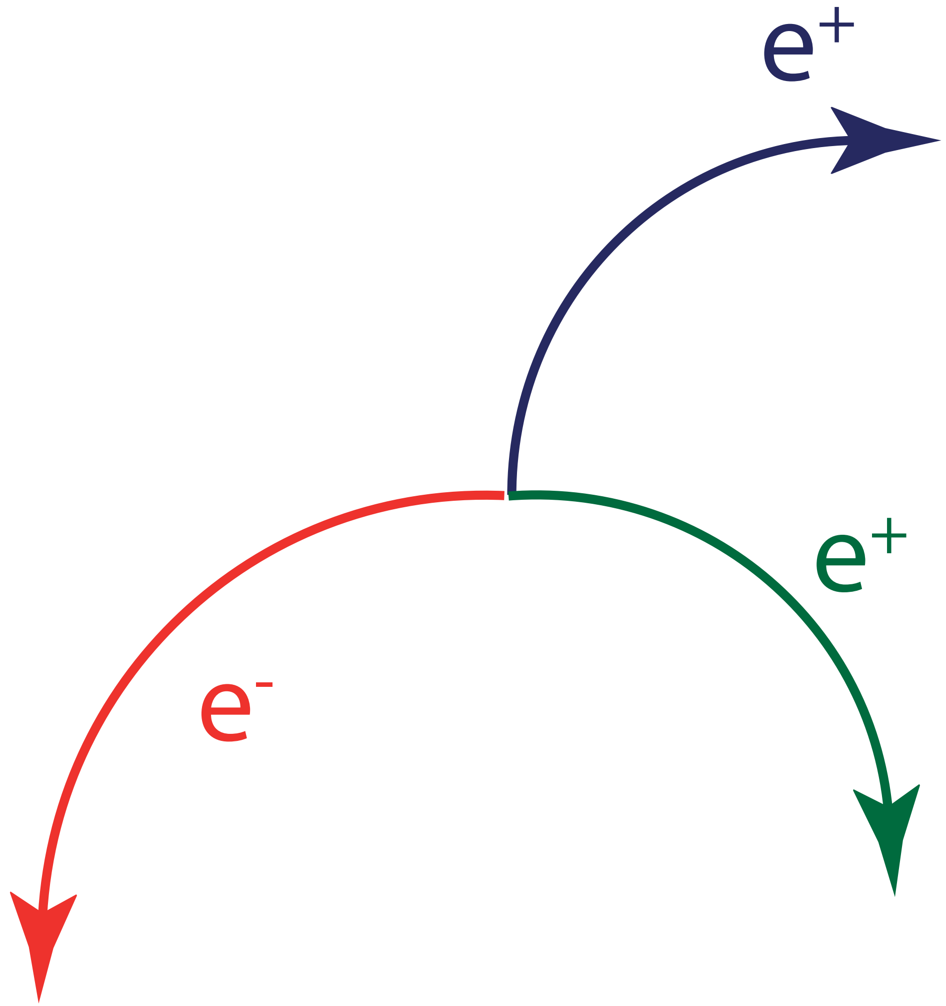


# Building the
# Mu3e Experiment

# Stop muons, let them decay

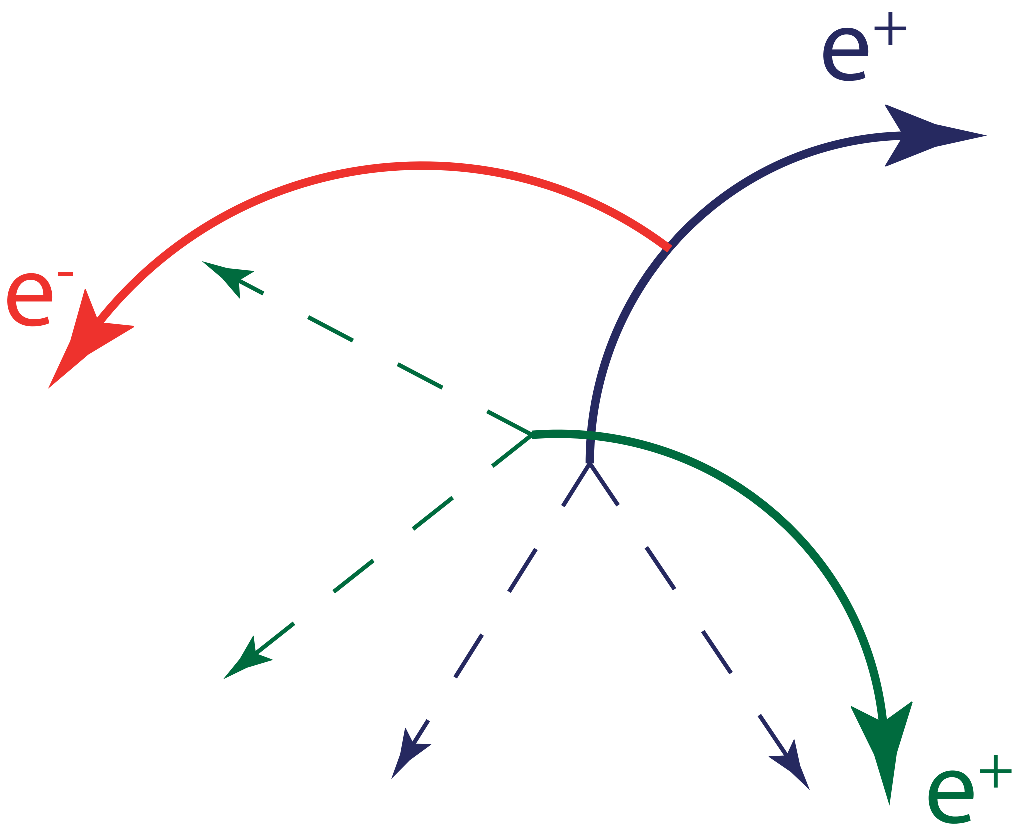


# The signal




- $\mu^+ \rightarrow e^+e^-e^+$
- Two positrons, one electron
- From same vertex
- Same time
- Sum of 4-momenta corresponds to muon at rest
- Maximum momentum: ½ $m_\mu$ = 53 MeV/c

# Accidental Background




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

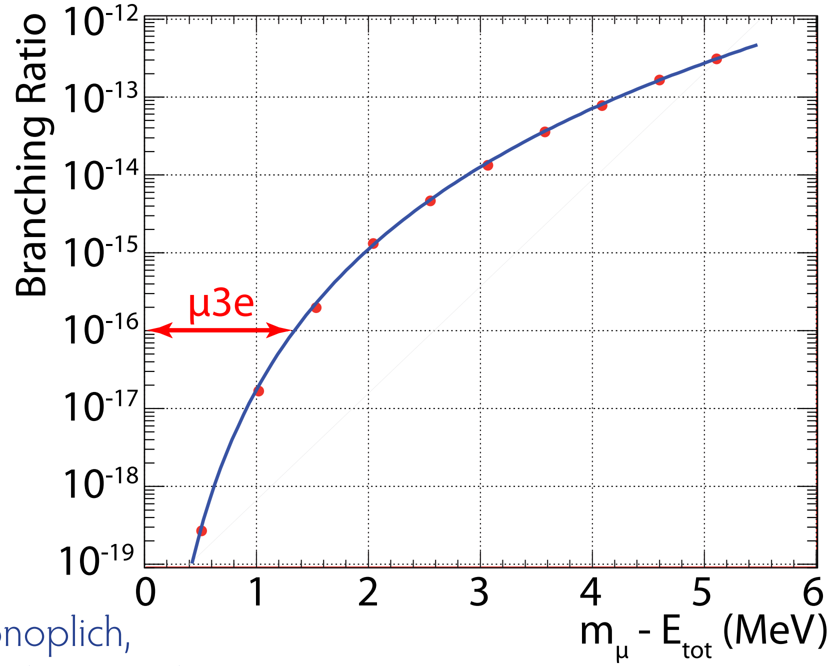
- Need very good timing, vertex and momentum resolution

# 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

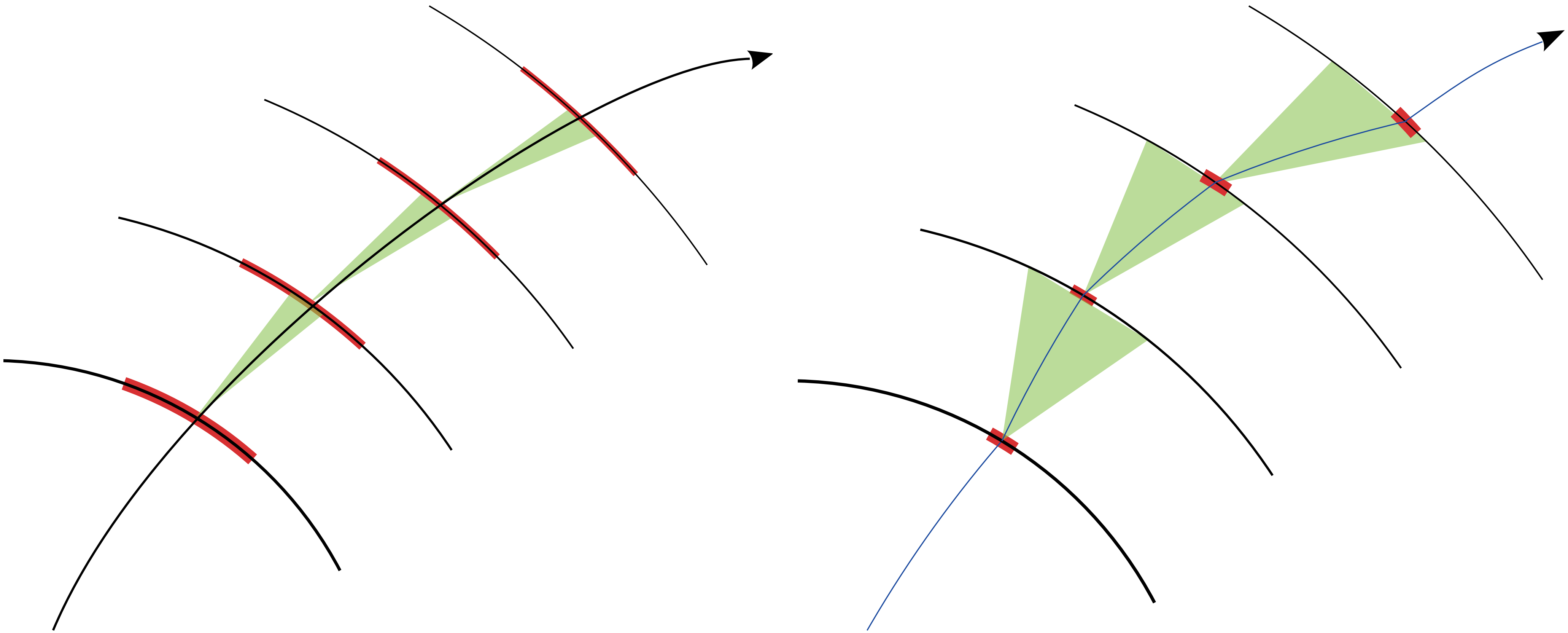



(R. M. Djilkibaev, R. V. Konoplich, Phys.Rev. D79 (2009) 073004)

- Need excellent momentum resolution

# Momentum measurement

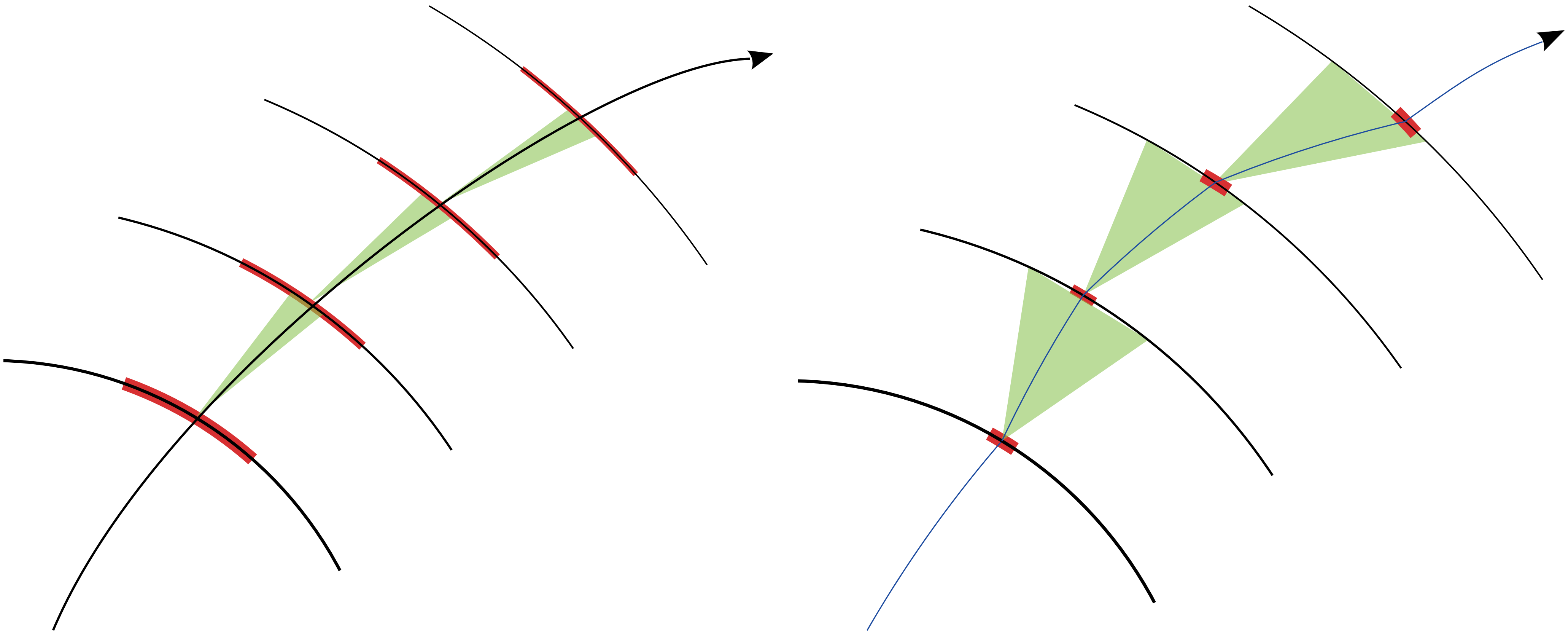
- Apply magnetic field (e.g. 1 Tesla)
- Measure curvature of particles in field
- Limited by detector resolution and scattering in detector



# Momentum measurement

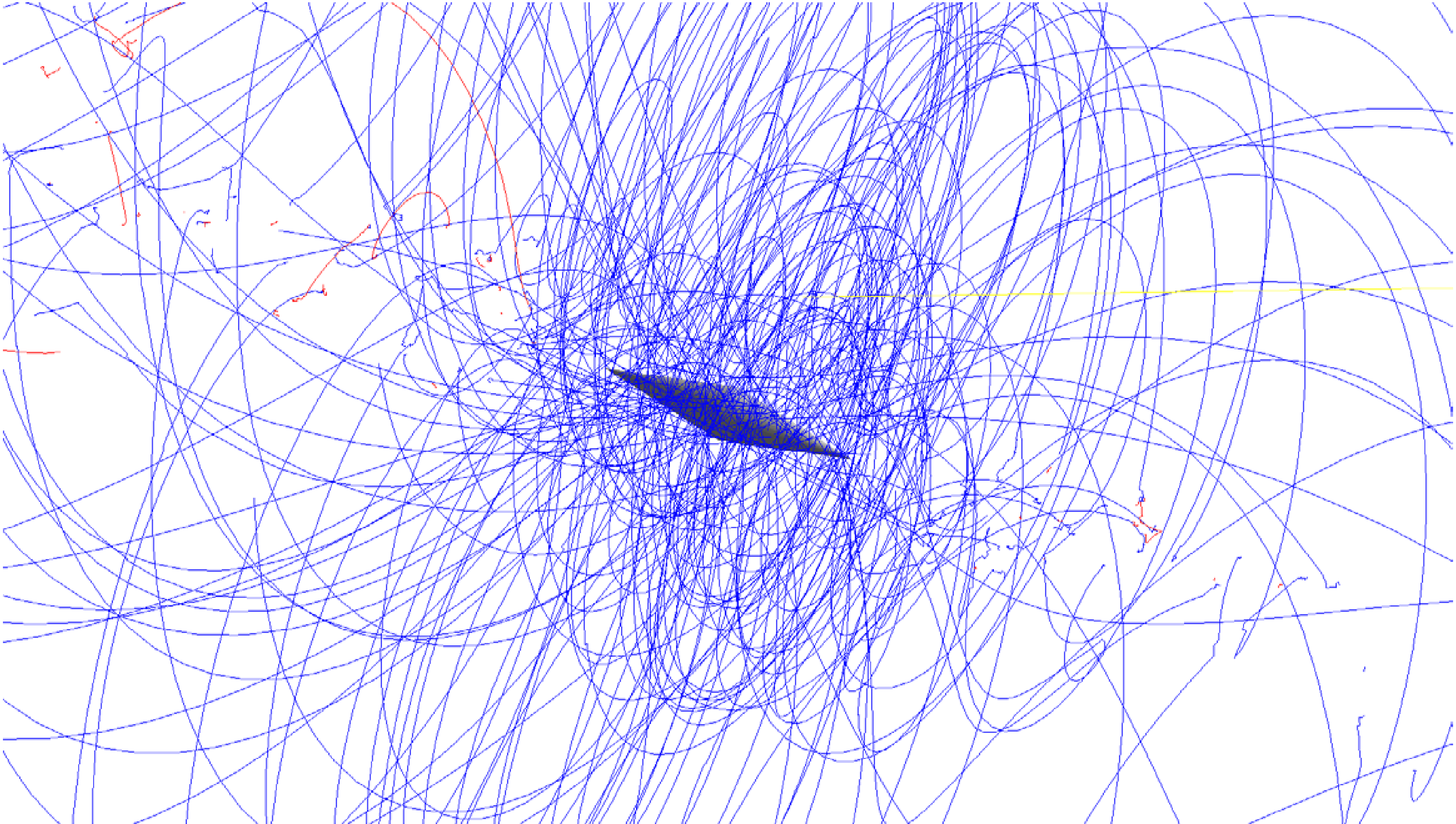
- Limited by detector resolution and scattering in detector

$$\theta_0 = \frac{13.6\ \mathrm{MeV}}{\beta c p}\, z \sqrt{x/X_0}\Big[1 + 0.038 \ln(x/X_0)\Big]$$



# 2 Billion Muon Decays/s

50 ns, 1 Tesla field



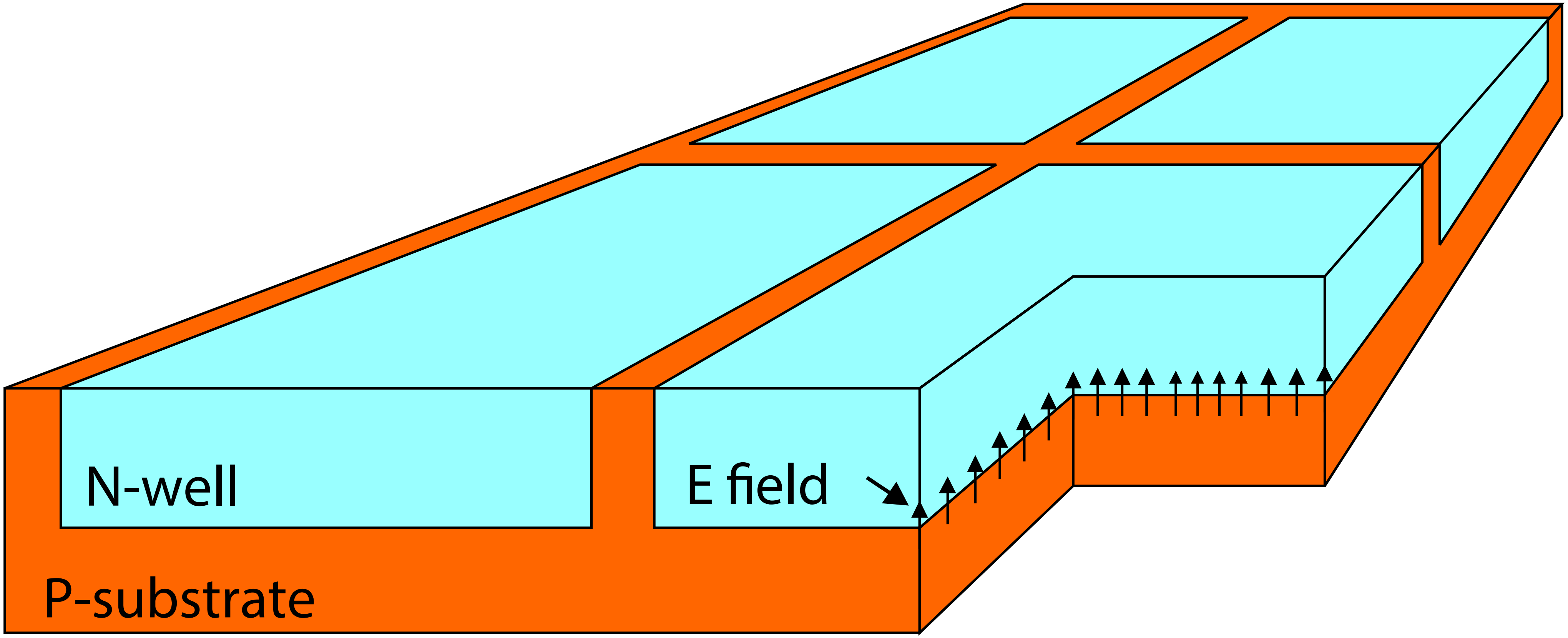
# Detector Technology

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

# 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

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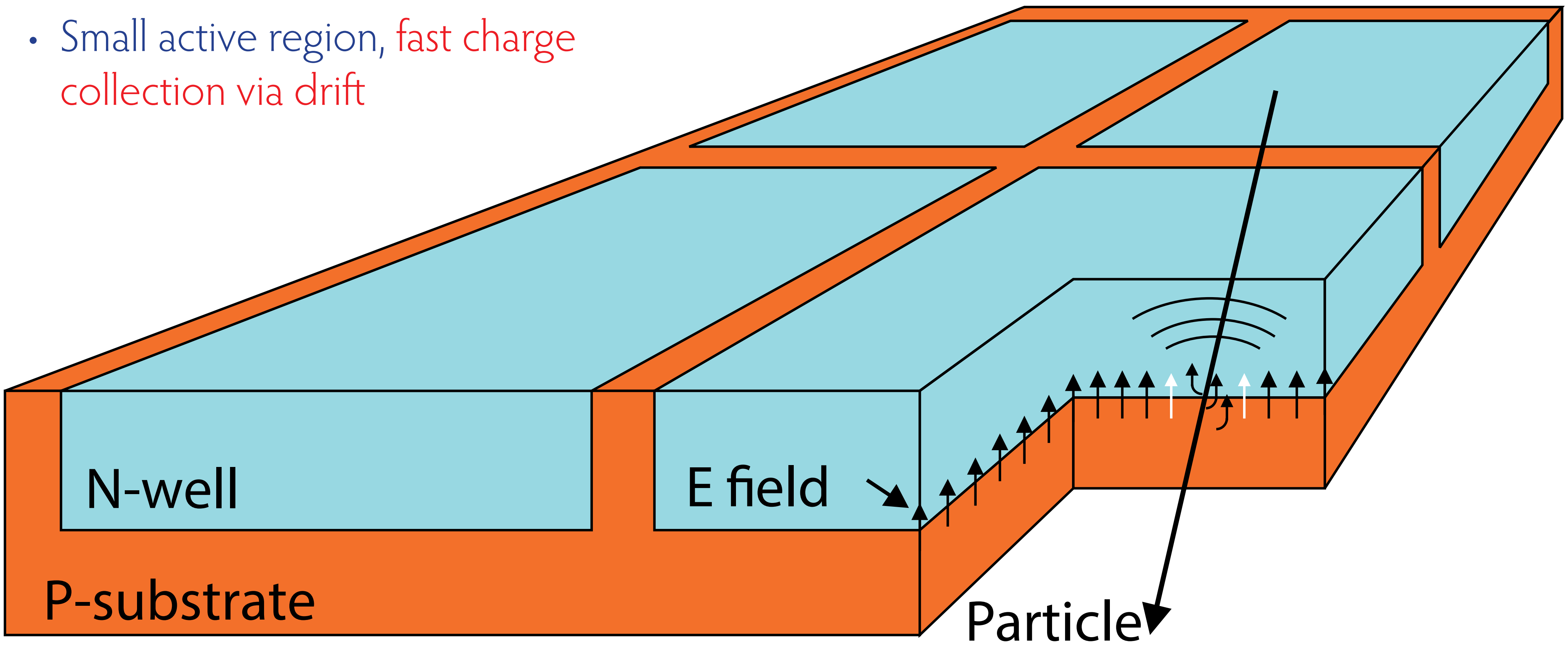
- Small active region, fast charge collection via drift



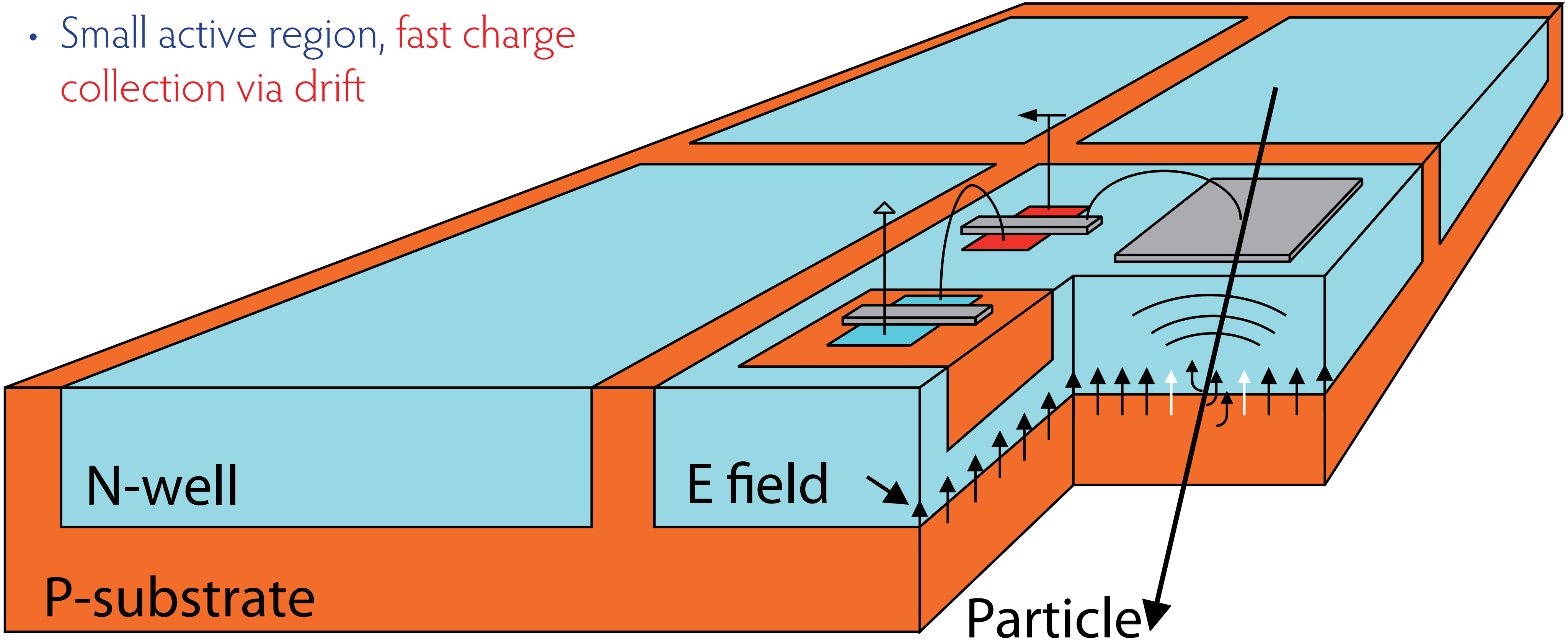
# Fast and thin sensors: HV-MAPS

High voltage monolithic active pixel sensors - Ivan Perić

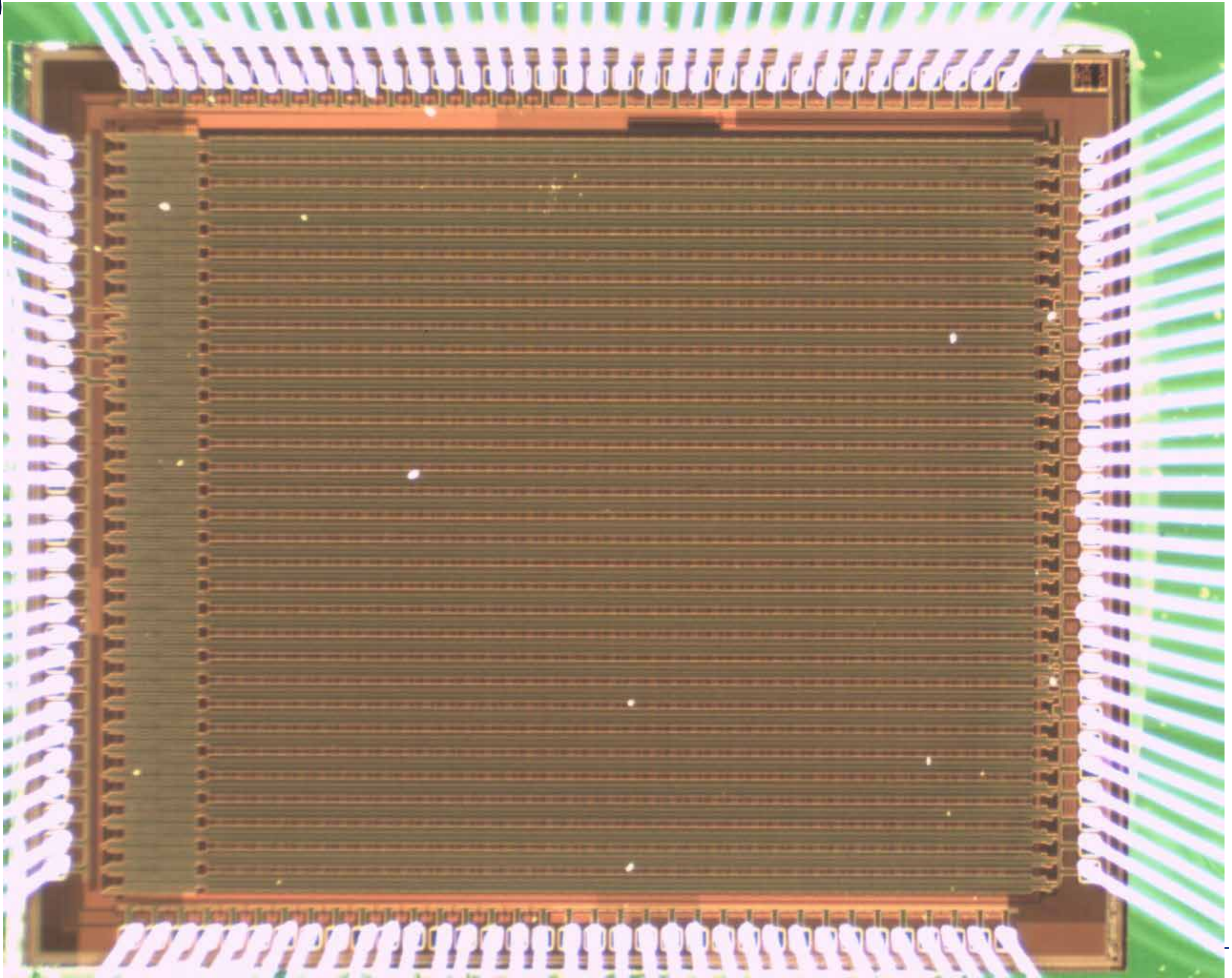
- Use a high voltage commercial process (automotive industry)
- Small active region, fast charge collection via drift

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

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



# HV-MAPS



3 mm

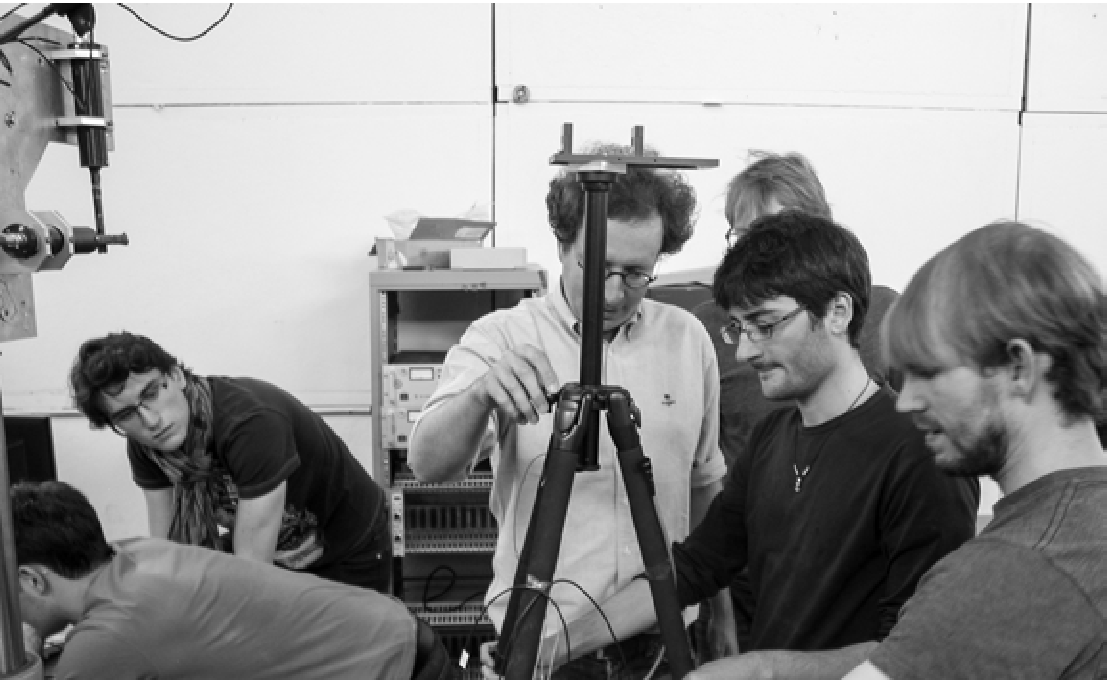
# HV-MAPS

Pixels with amplifier
40 x 32 pixels
80 x 103 µm pixel size
3 mm

# HV-MAPS

Comparator and digital pixel logic
Pixels with amplifier
40 x 32 pixels
80 x 103 µm pixel size
3 mm

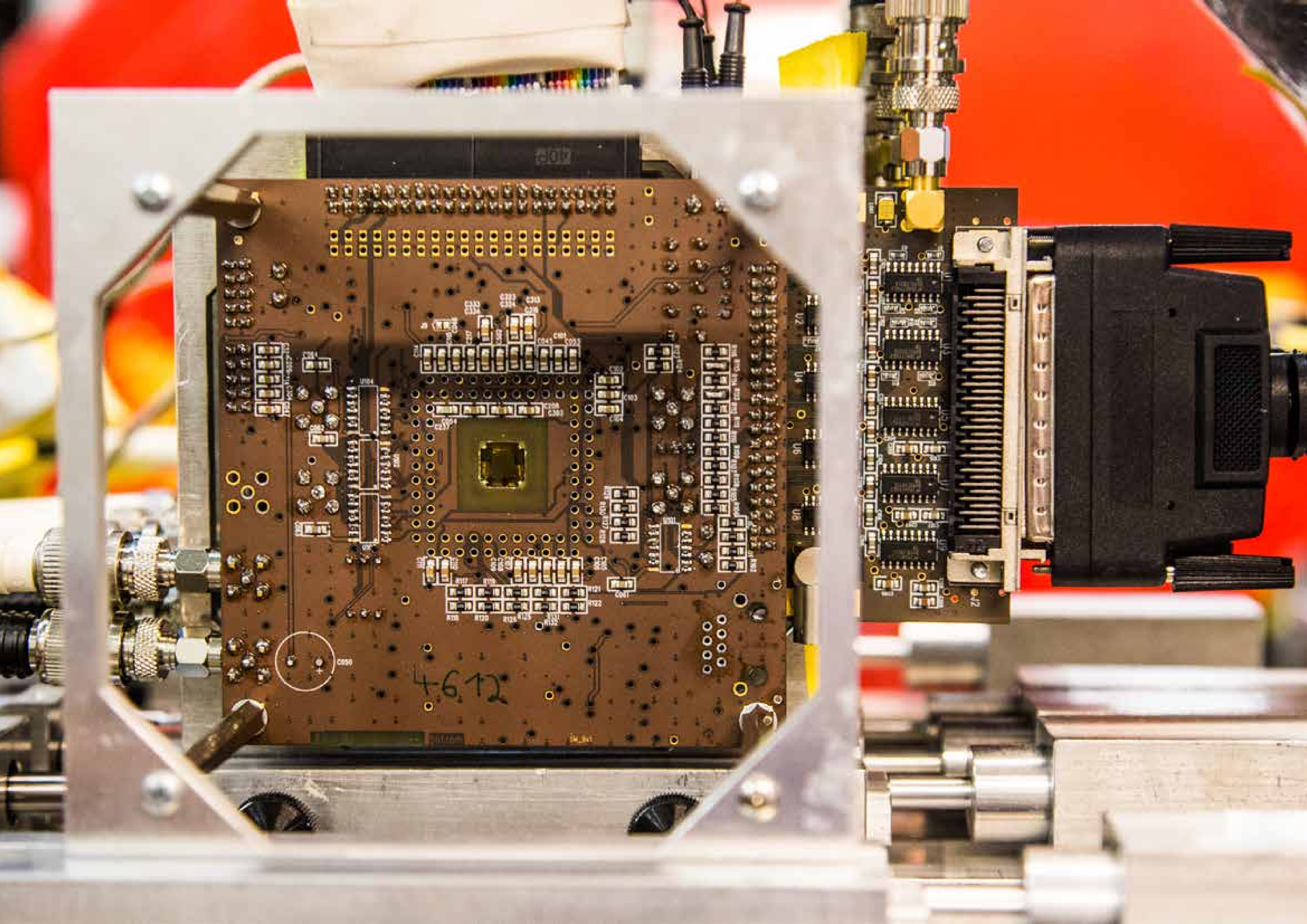
# Beam tests

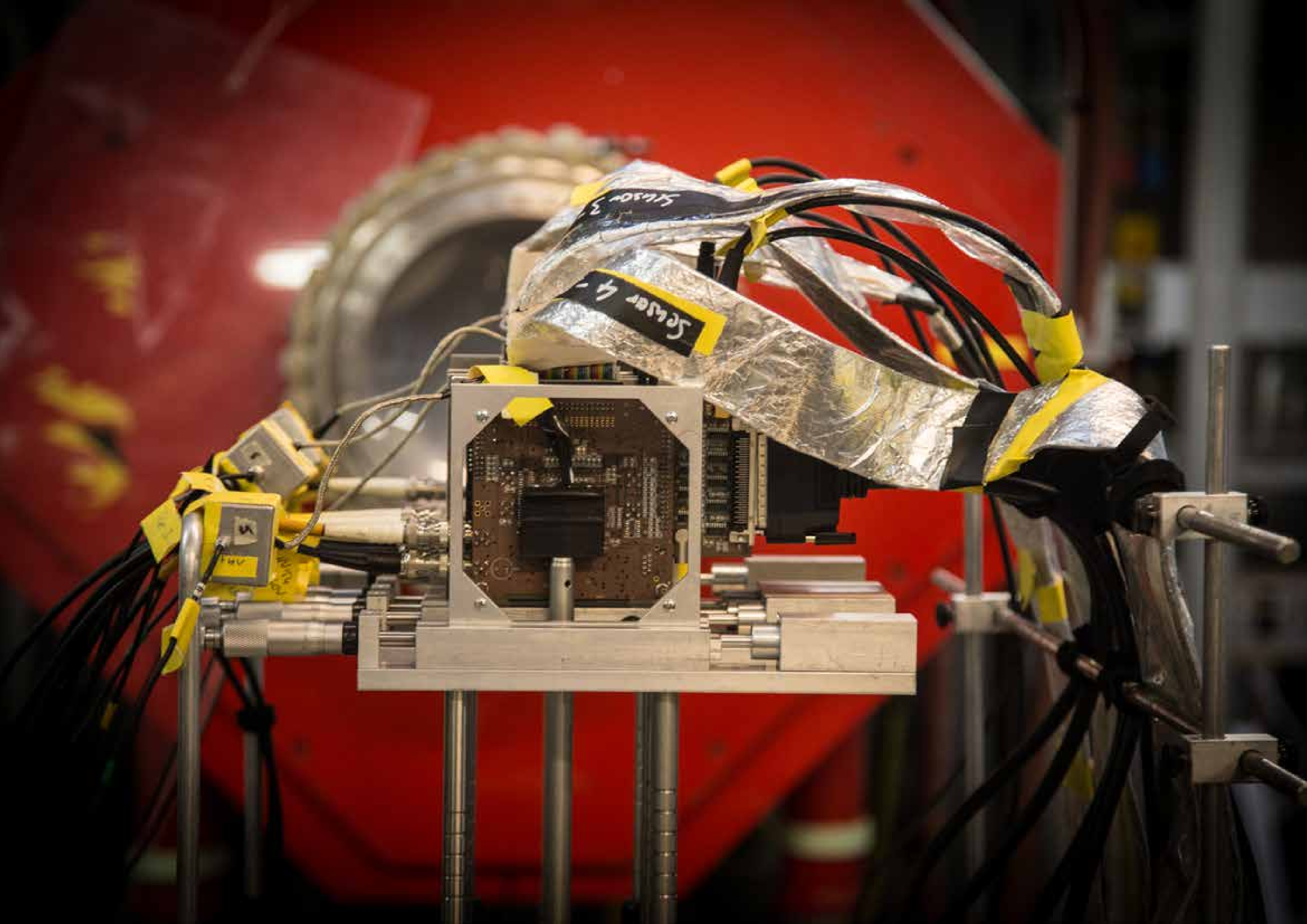


Tests done at

- CERN 250 GeV pions
- DESY 5 GeV electrons
- PSI 250 MeV pions
- Mainz 1.5 GeV electrons

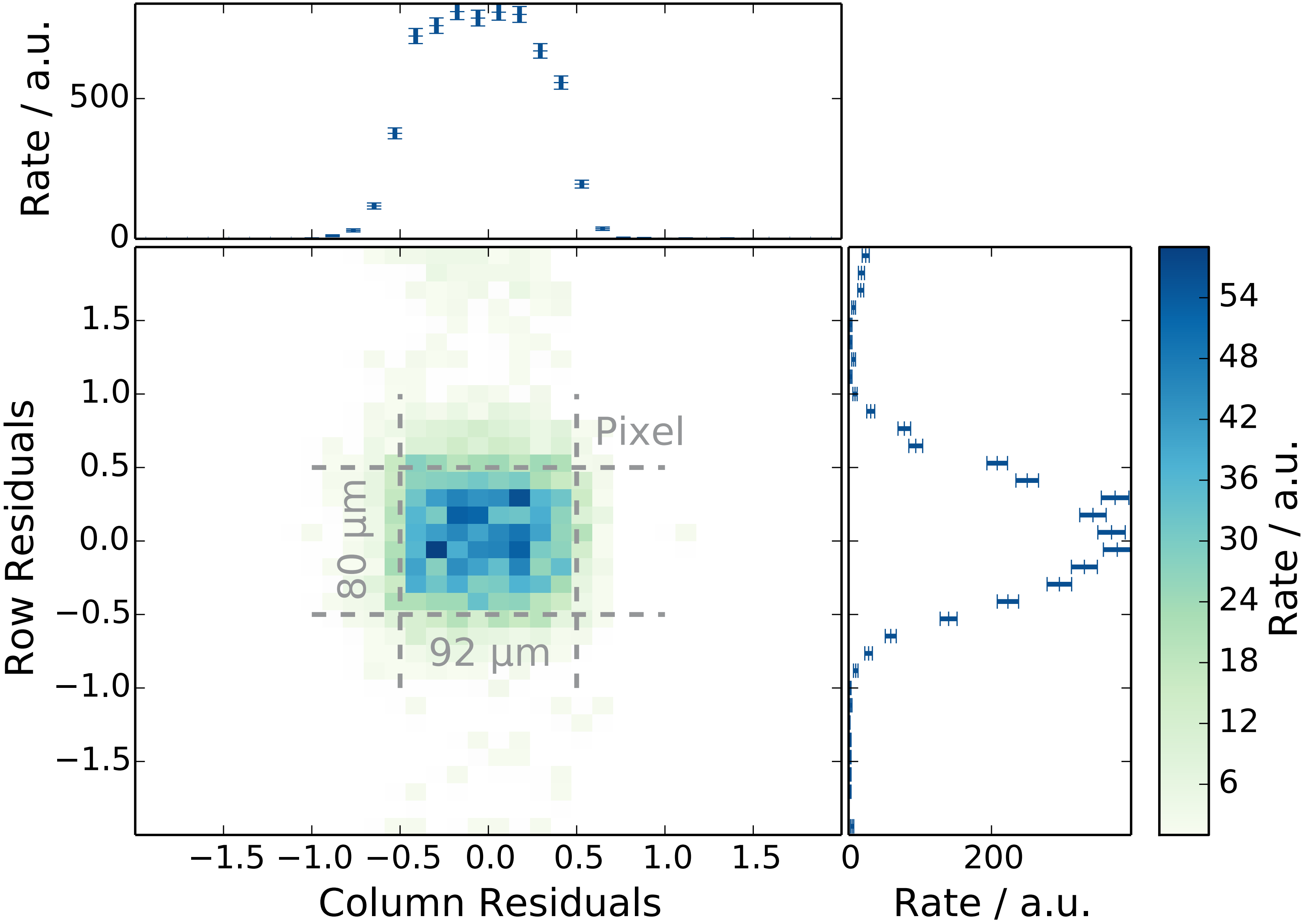
- Thanks for all the beam time and support!


4612



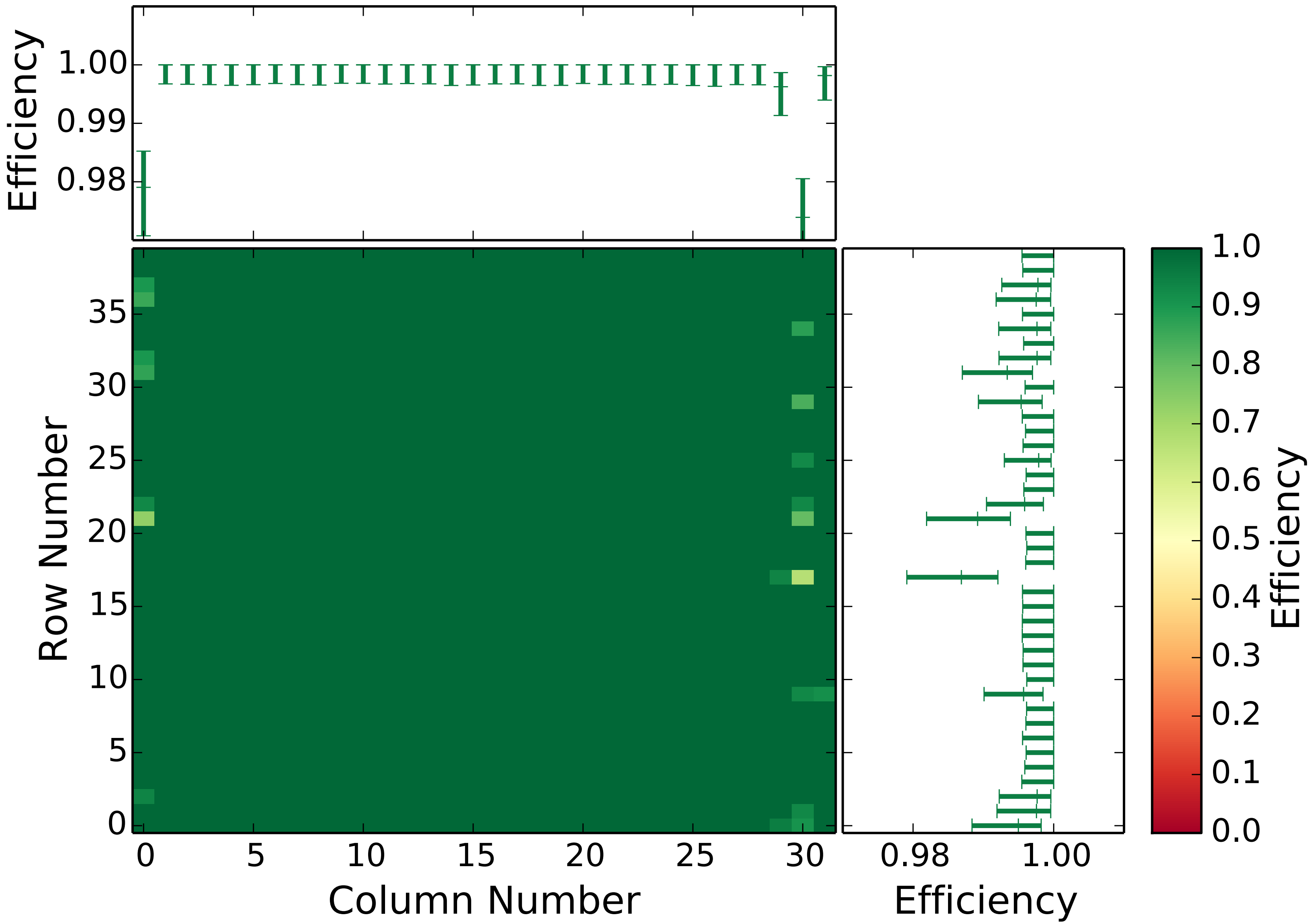
# Position Resolution

Position resolution given by pixel size

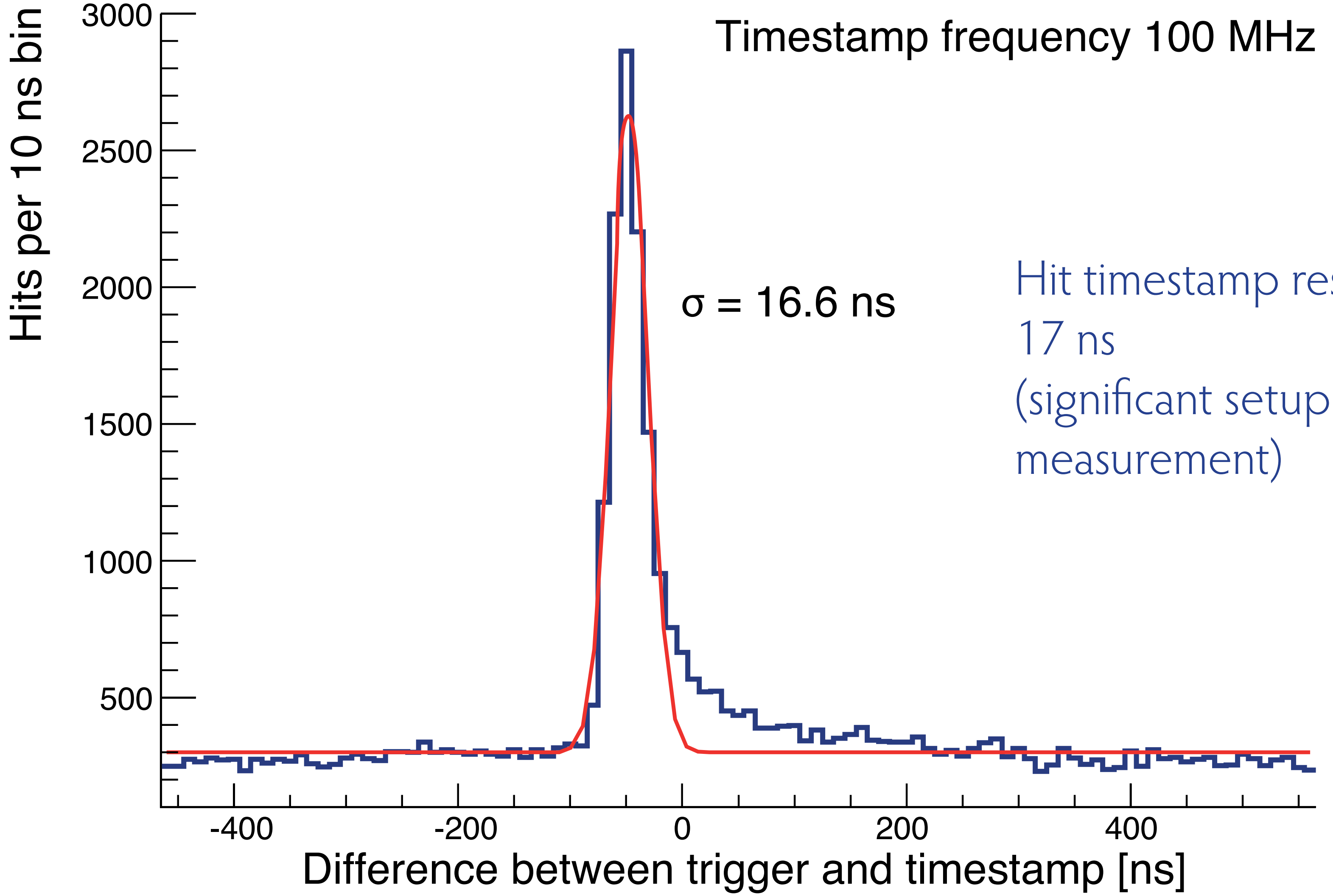


# Efficiency

Hit efficiency above 99% without tuning

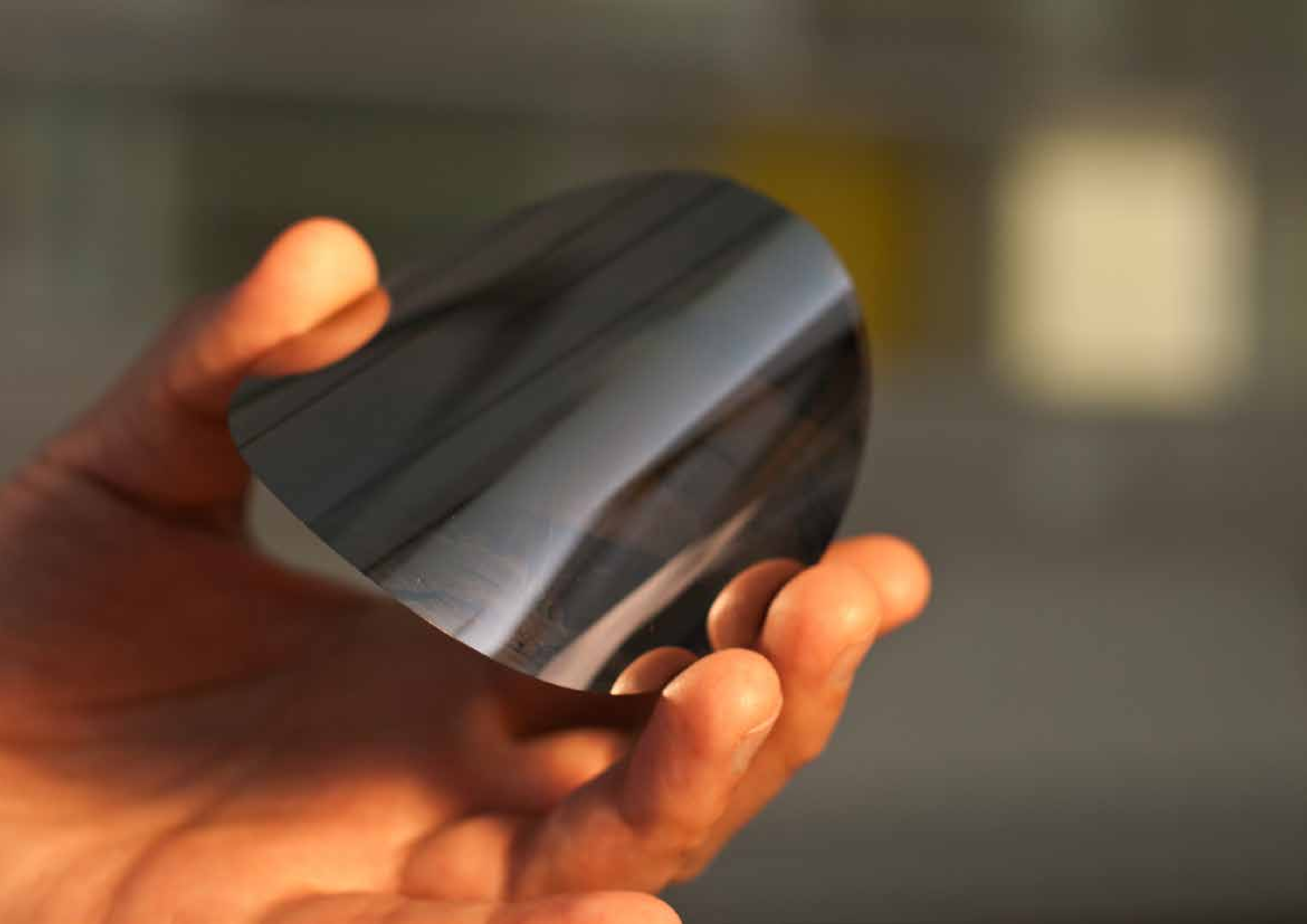


# Time resolution

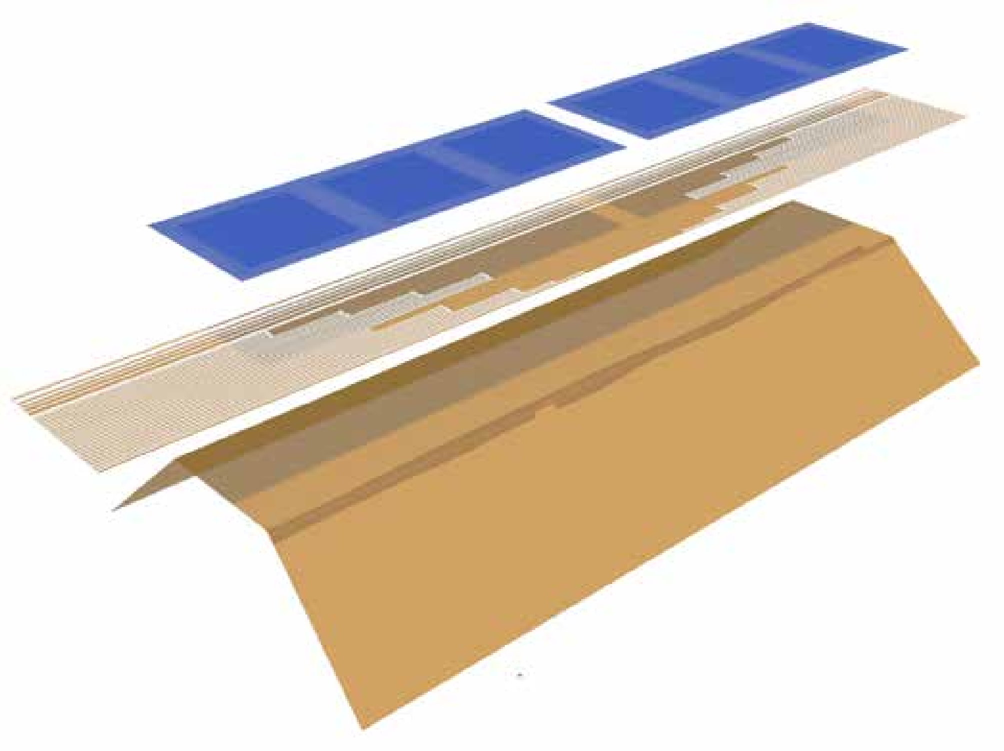



Hit timestamp resolution better than 17 ns
(significant setup contribution in the measurement)

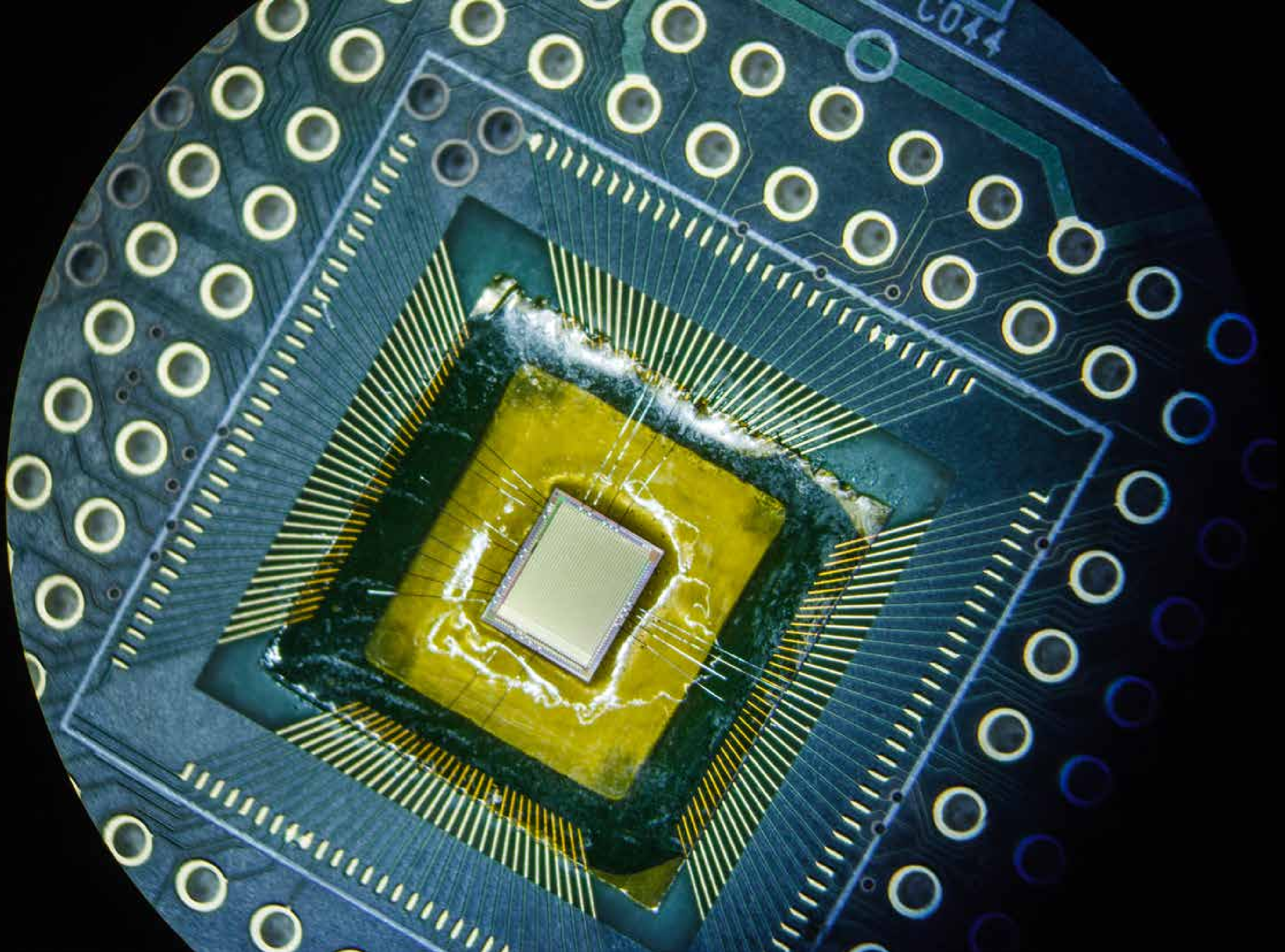
# Building a detector thinner than a hair



# Mechanics



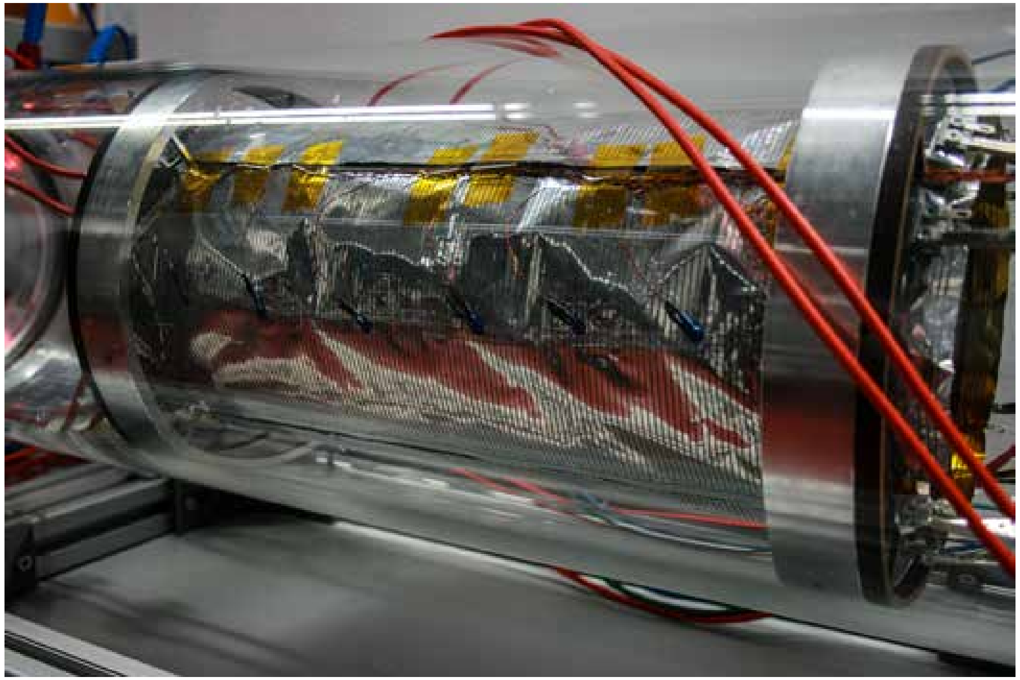
- 50 μm silicon
- 25 μm Kapton™ flexprint with aluminium traces
- 25 μm Kapton™ frame as support
- Less than 1‰ of a radiation length per layer

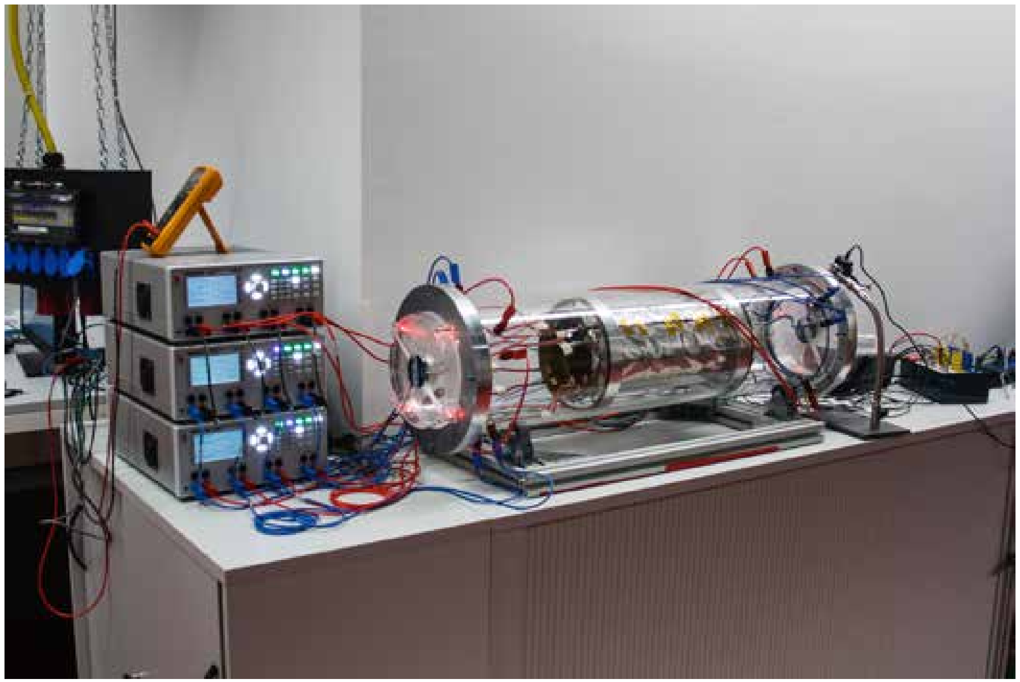

C044

# Cooling

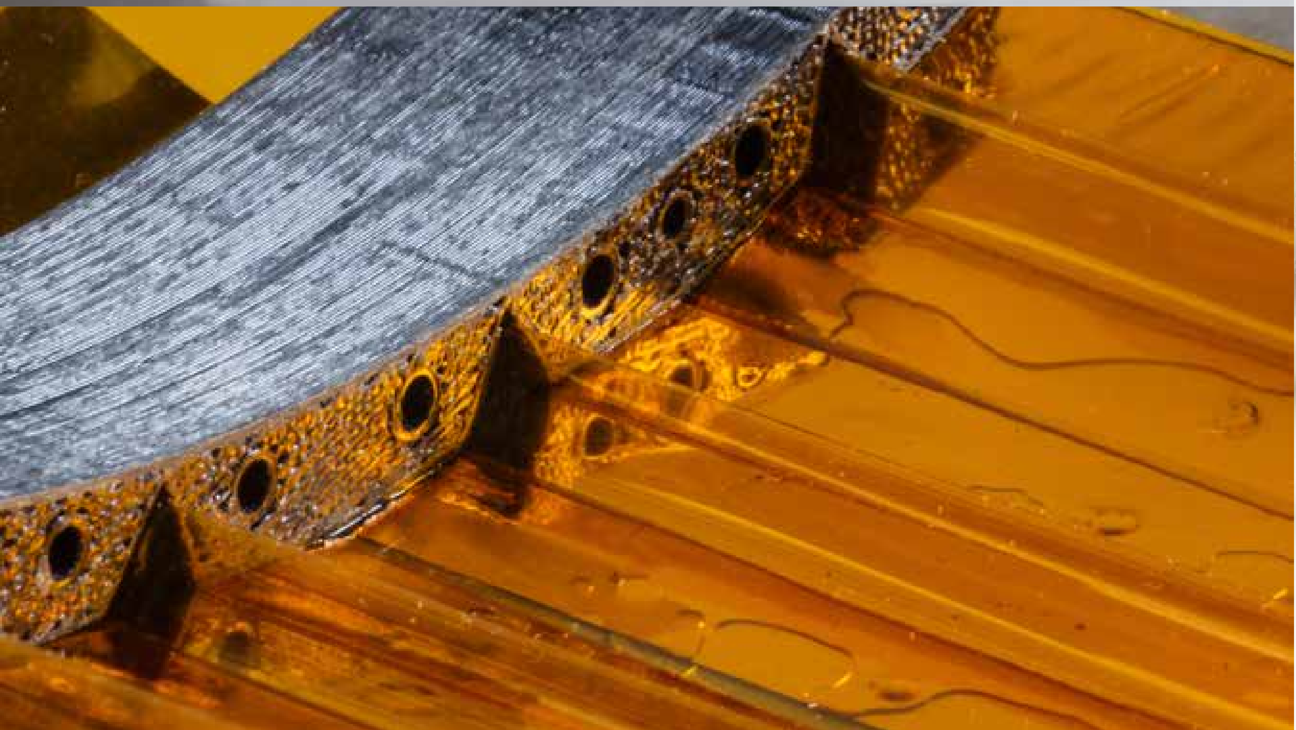
- Add no material:
  Cool with gaseous Helium
  (low scattering, high mobility)
- ~ 150 mW/cm$^2$ - total 2 kW
- Simulations: Need ~ several m/s flow

- Full scale heatable prototype built
- 36 cm active length
- No visible vibrations
- Can add local cooling

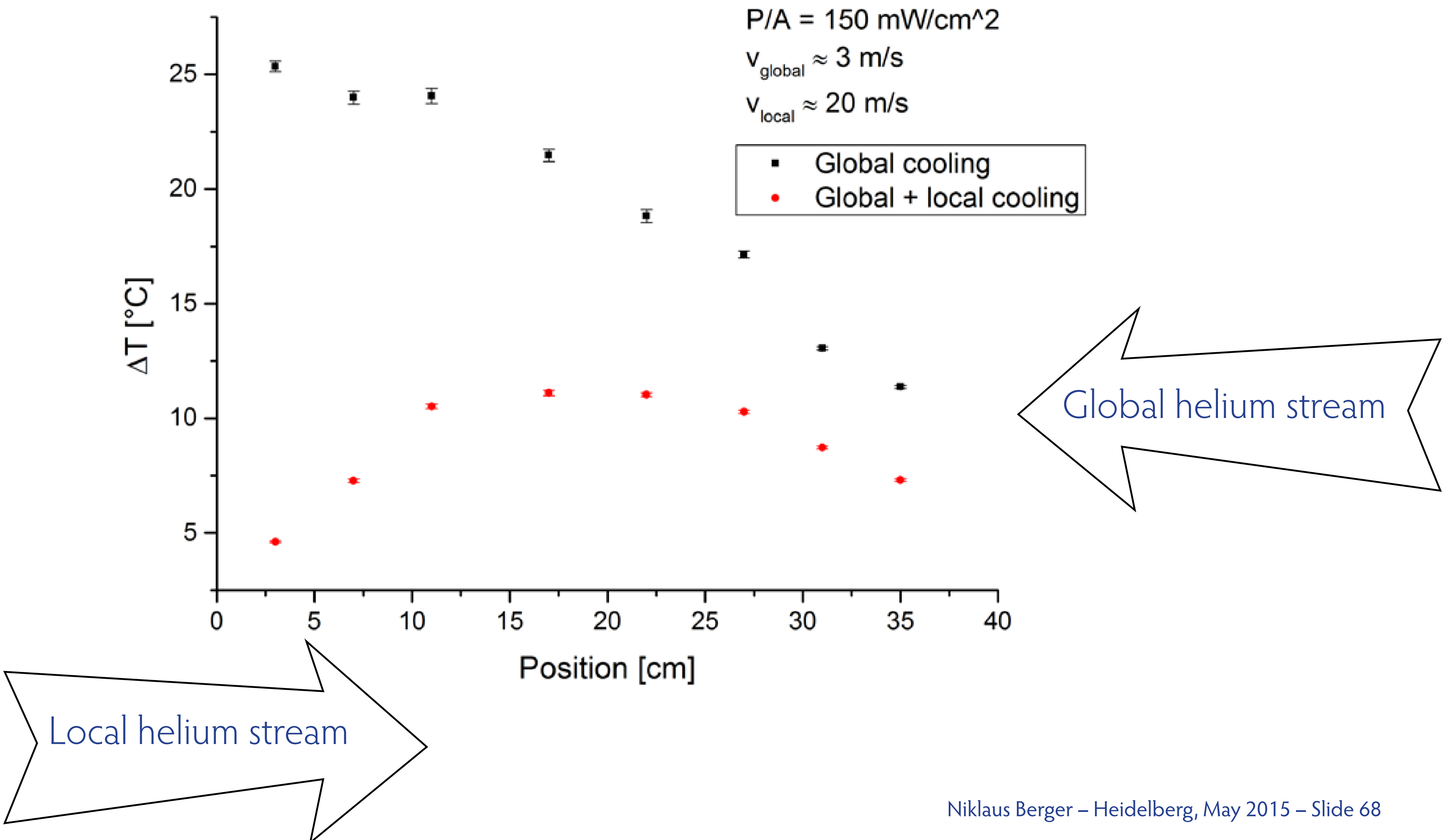




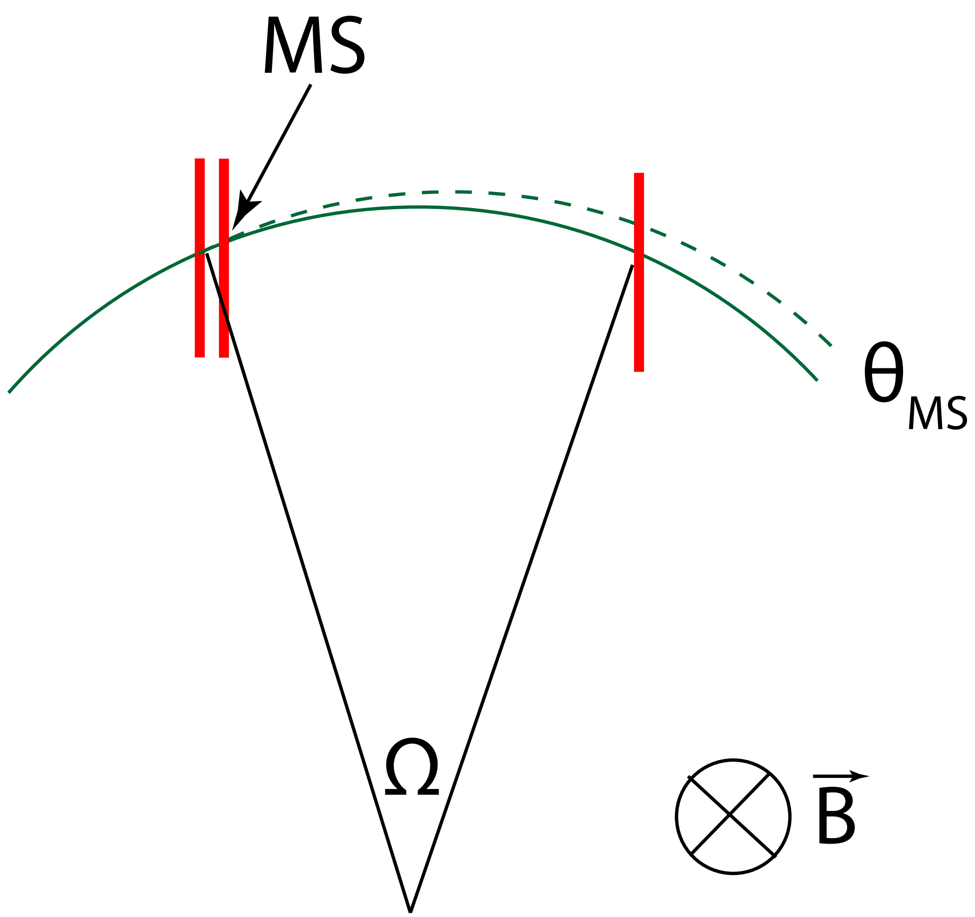

Ring 4
vorne



# Cooling tests



# Momentum measurement

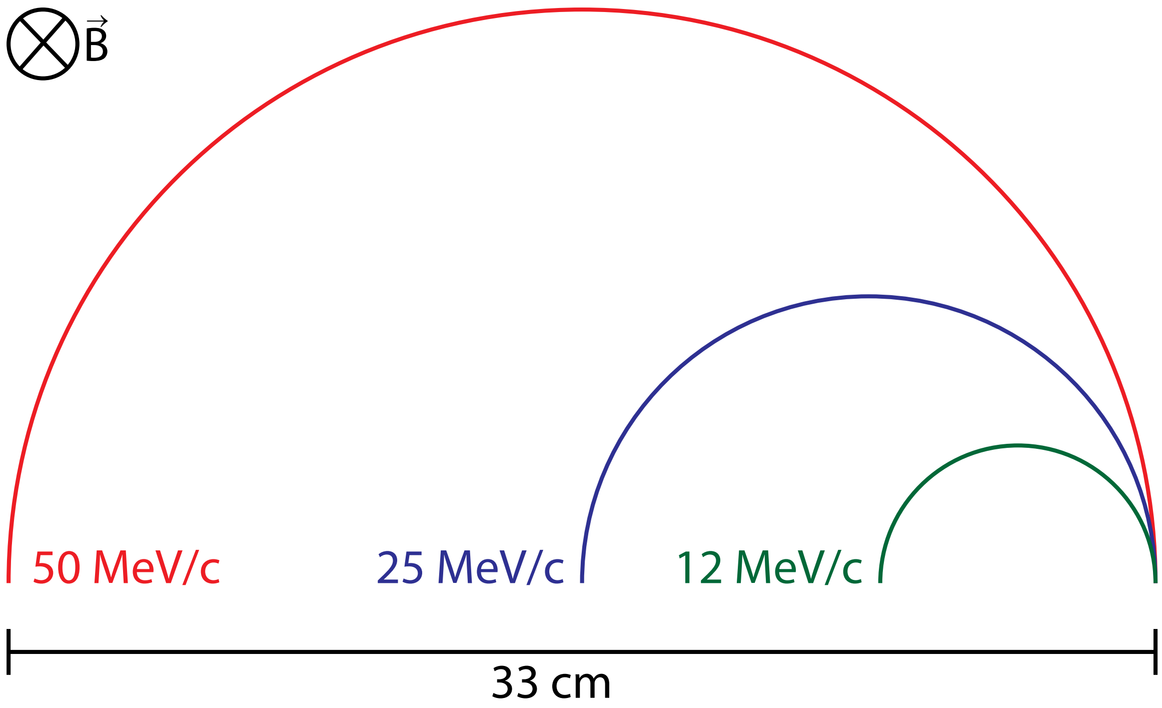



- 1 T magnetic field
- Resolution dominated by multiple scattering
- Momentum resolution to first order:

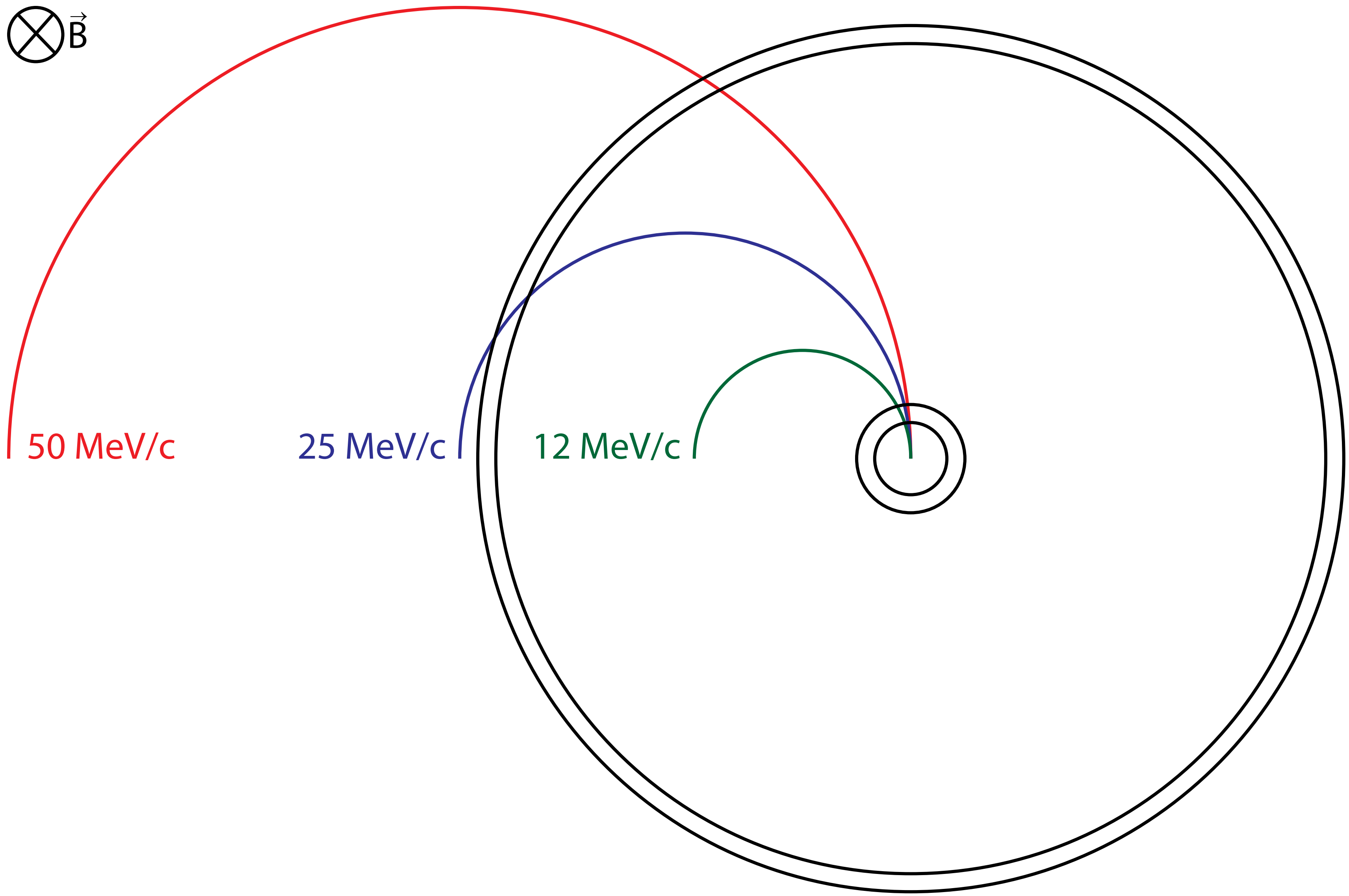
$$\sigma_P/P \sim \theta_{MS}/\Omega$$

- Precision requires large lever arm (large bending angle $\Omega$) and low multiple scattering $\theta_{MS}$

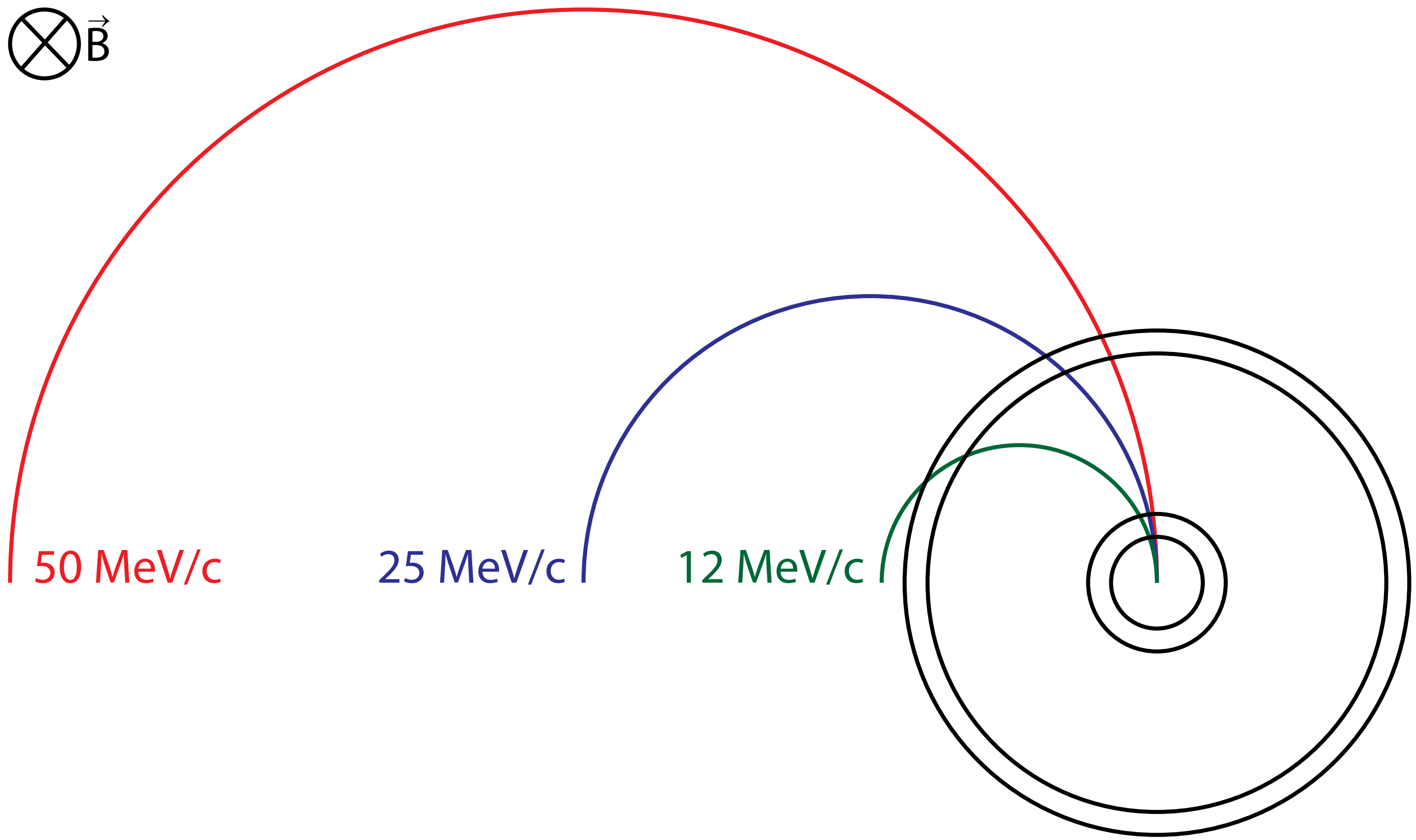
# Precision vs. Acceptance



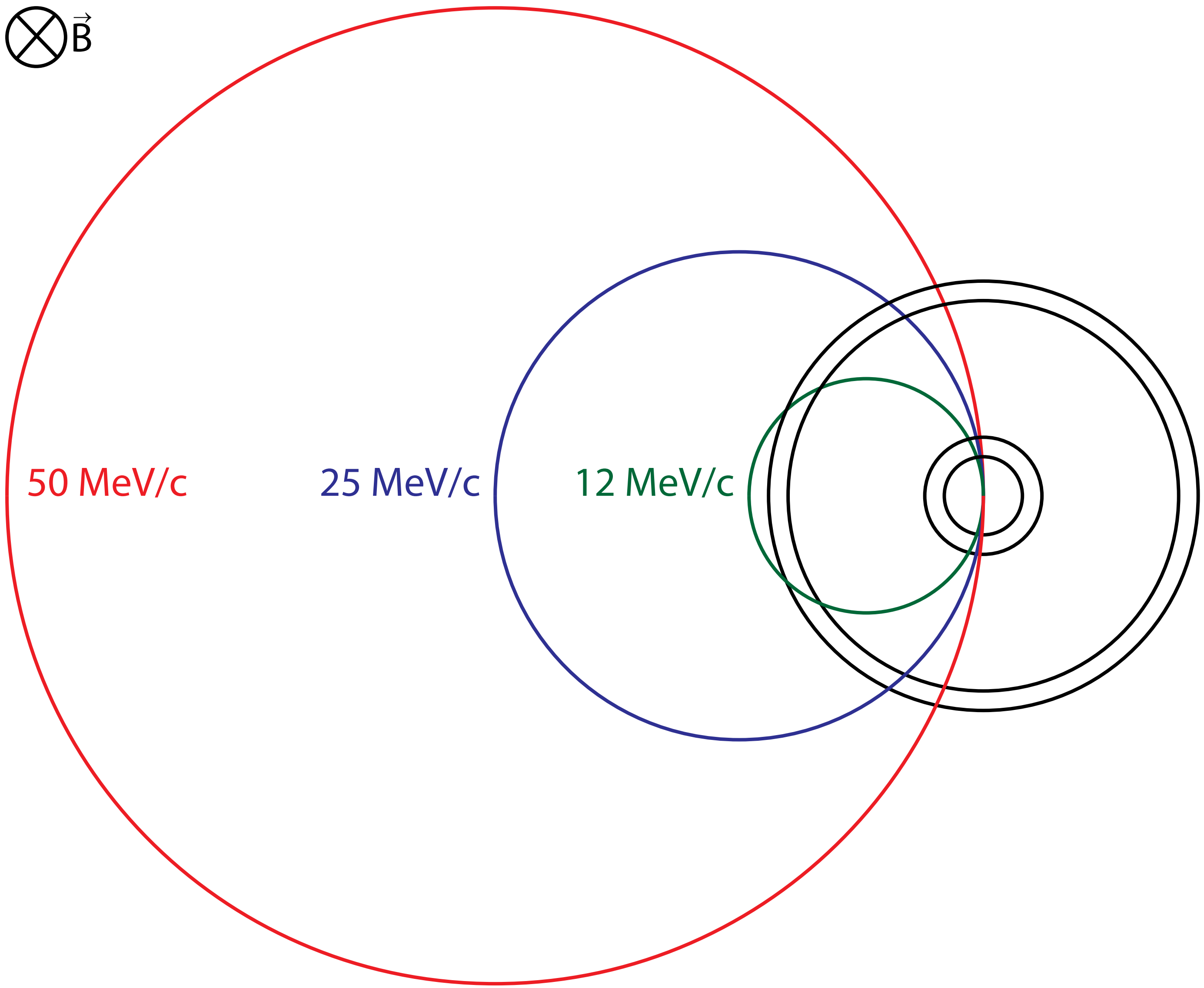
# Precision vs. Acceptance



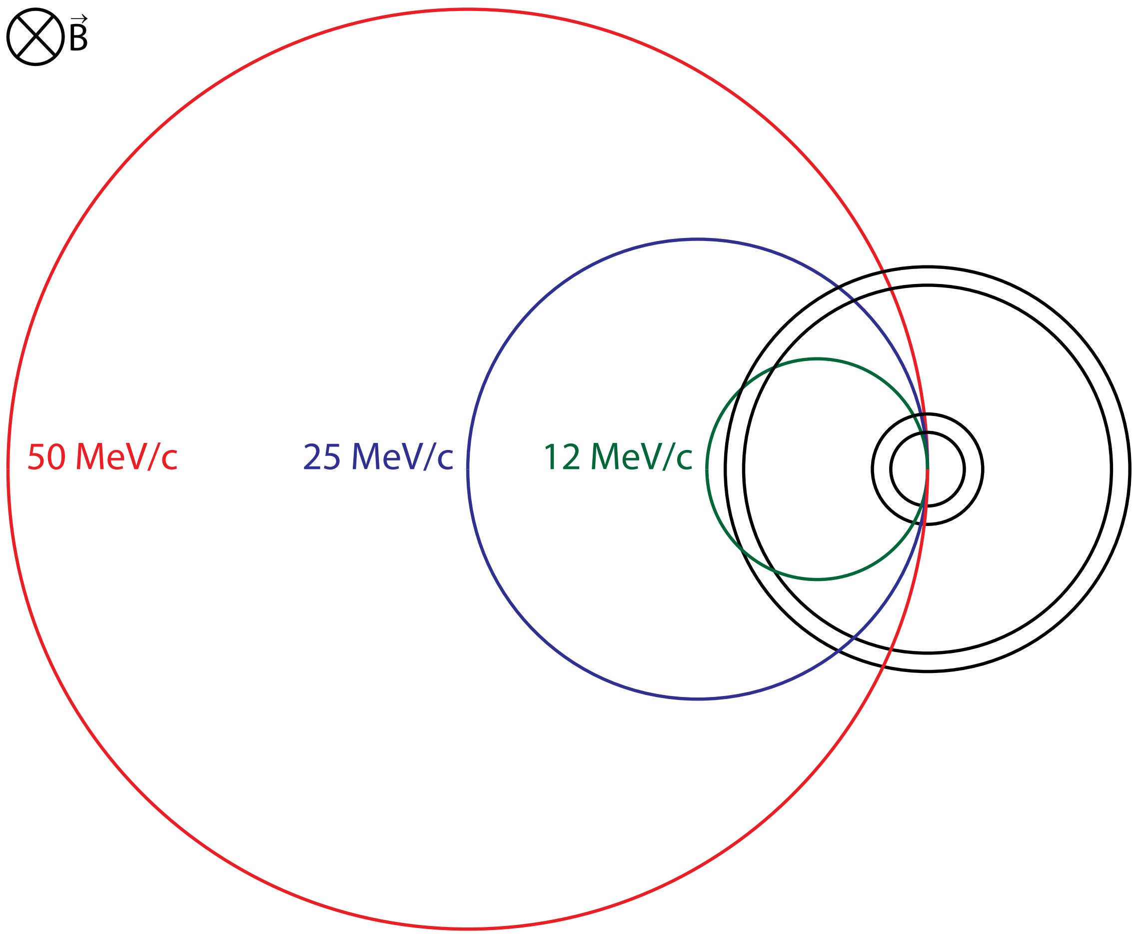
# Precision vs. Acceptance

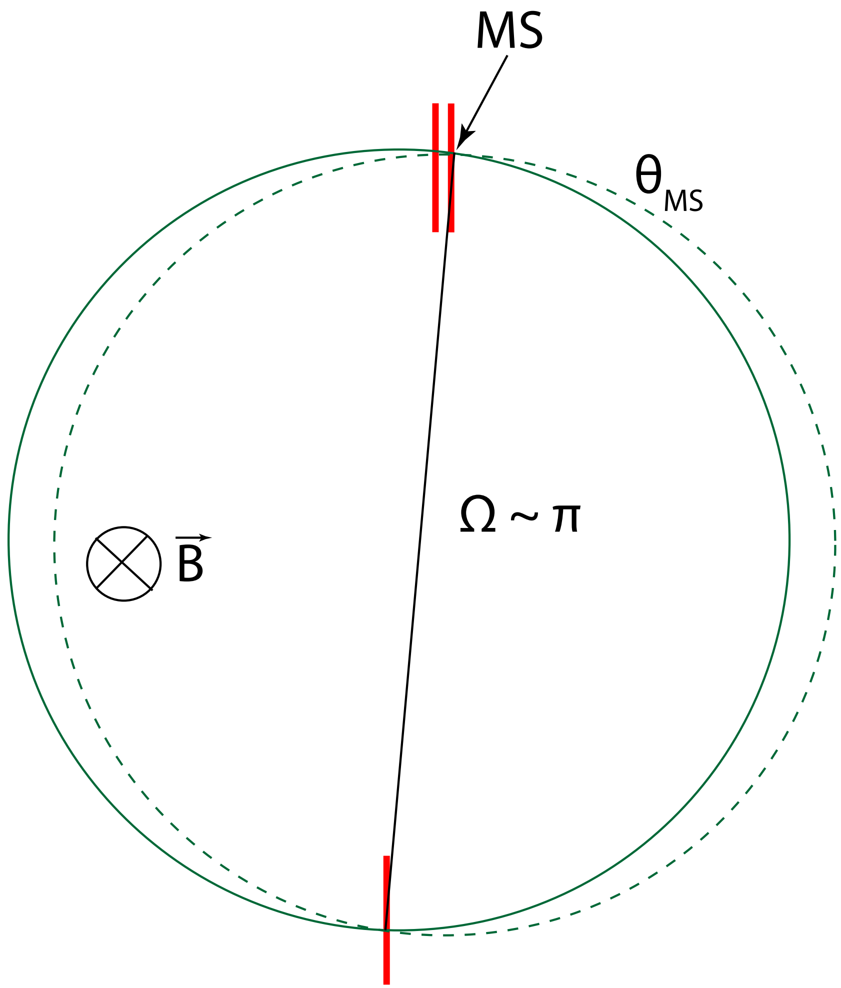


# Precision vs. Acceptance

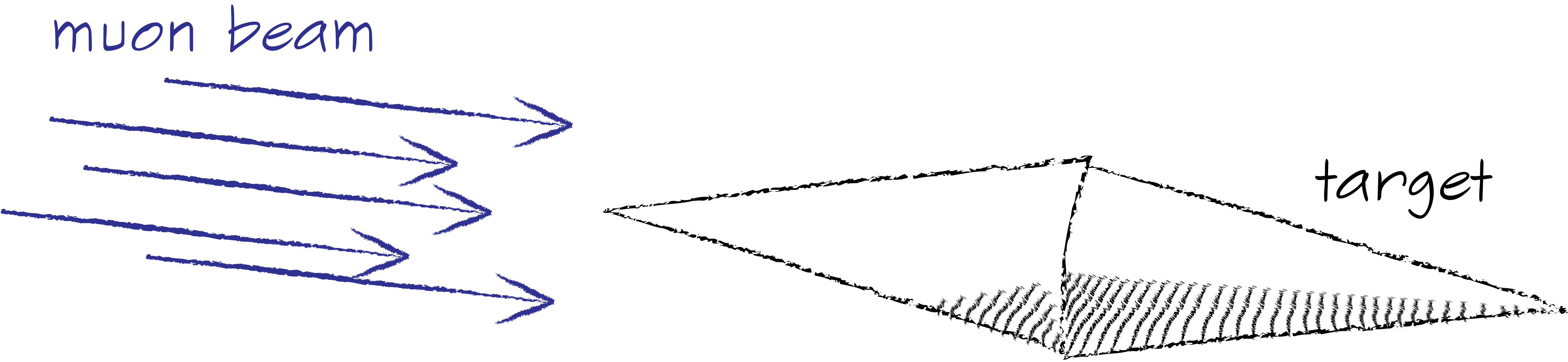


# Precision vs. Acceptance

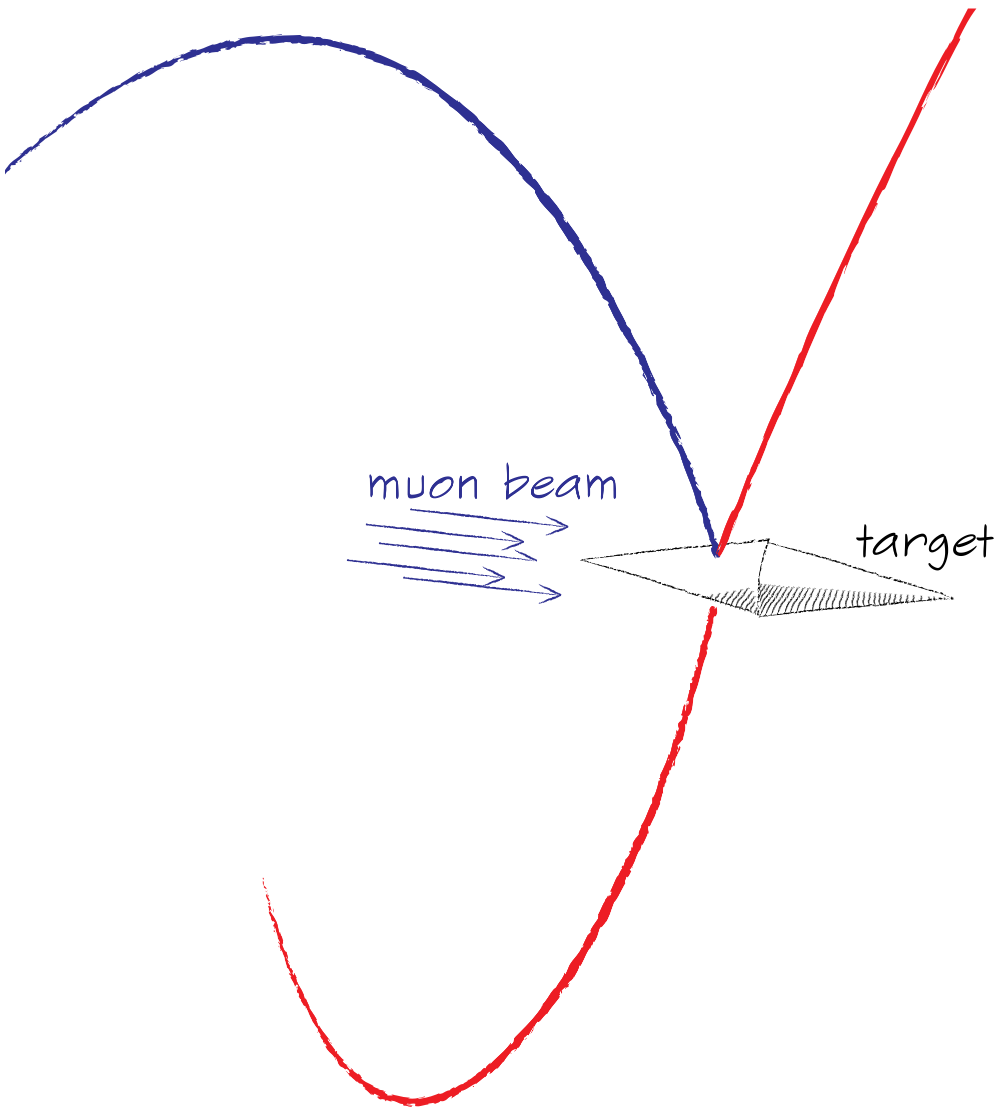


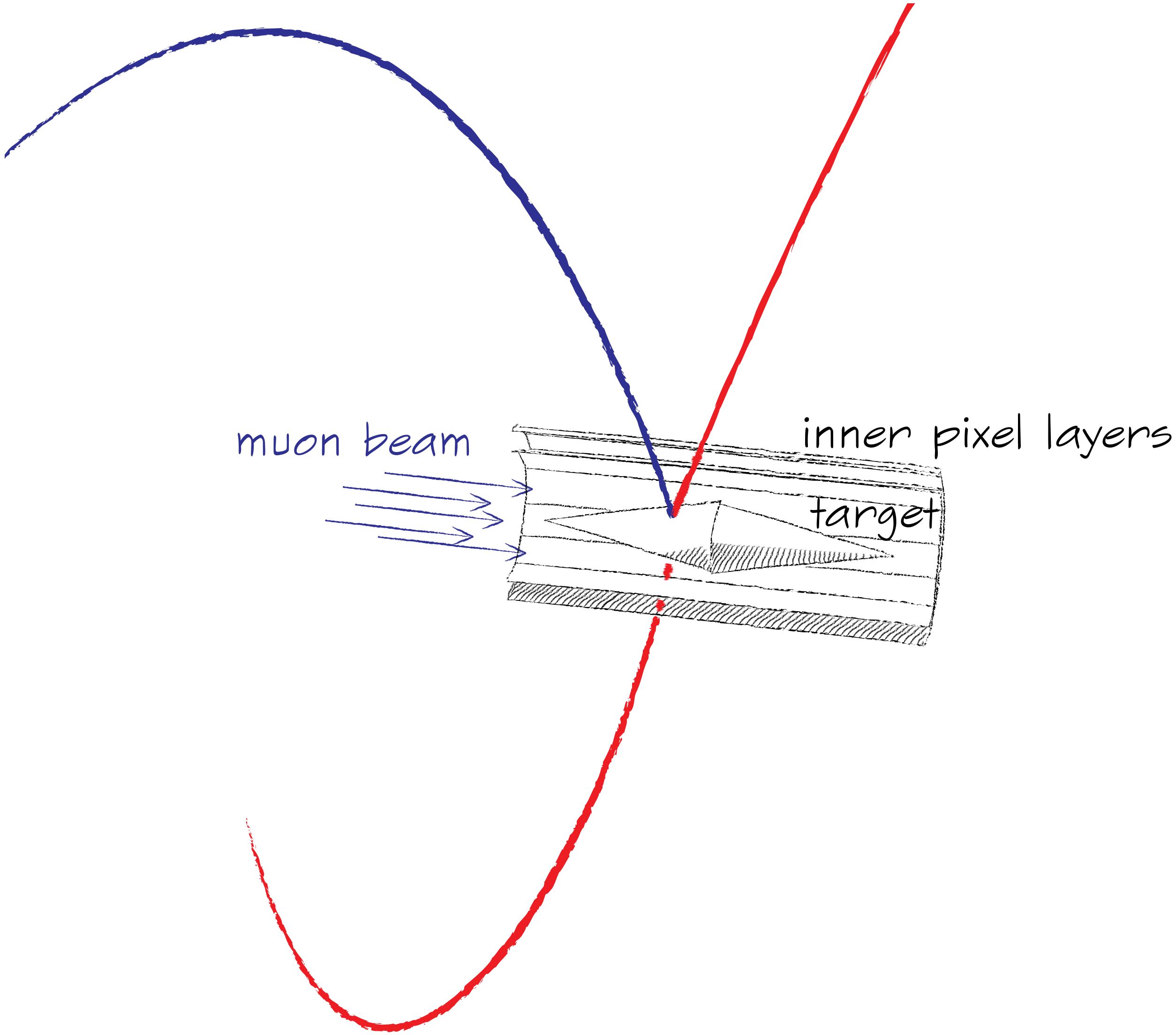
# Detector Design



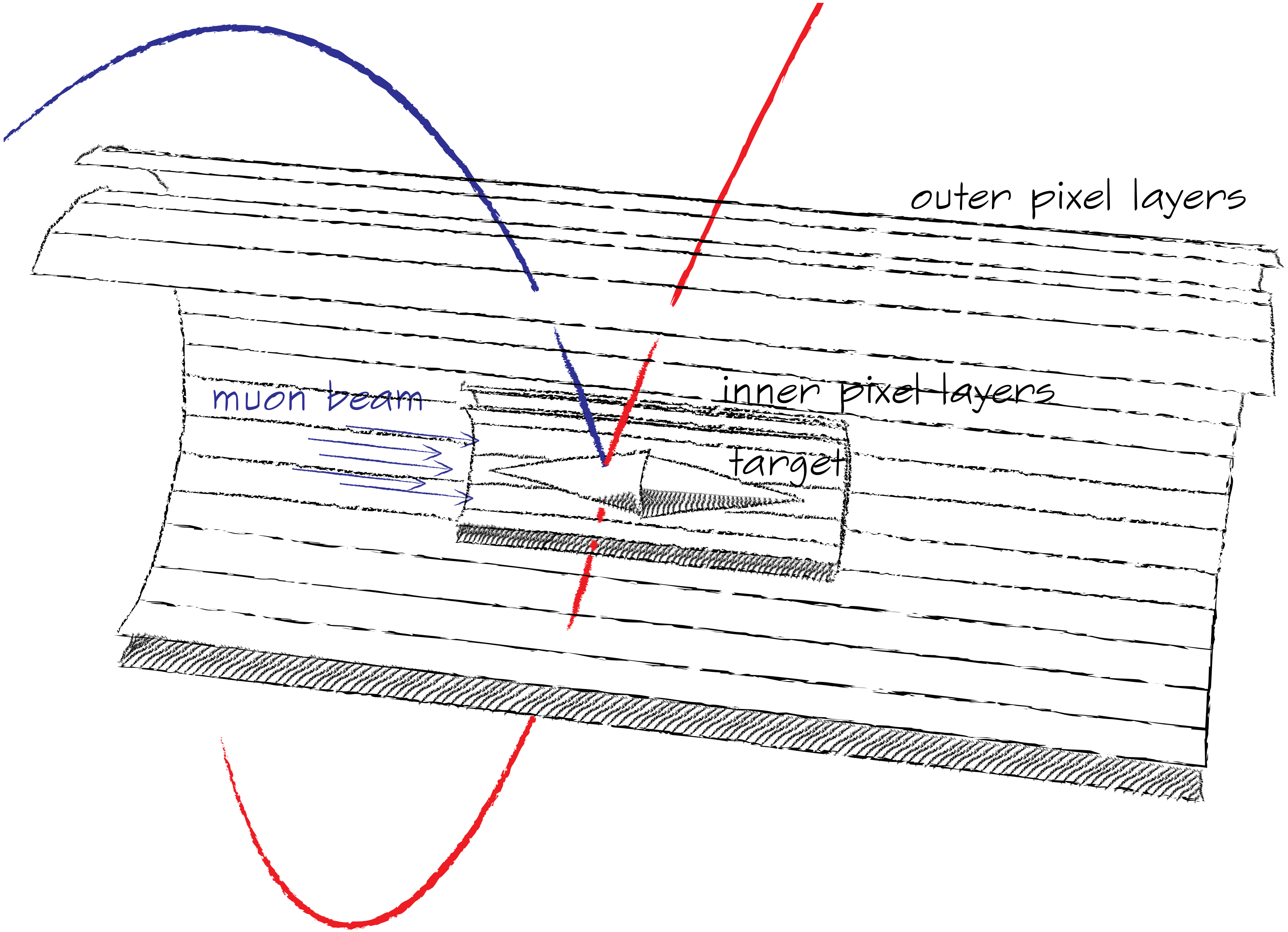
# Detector Design



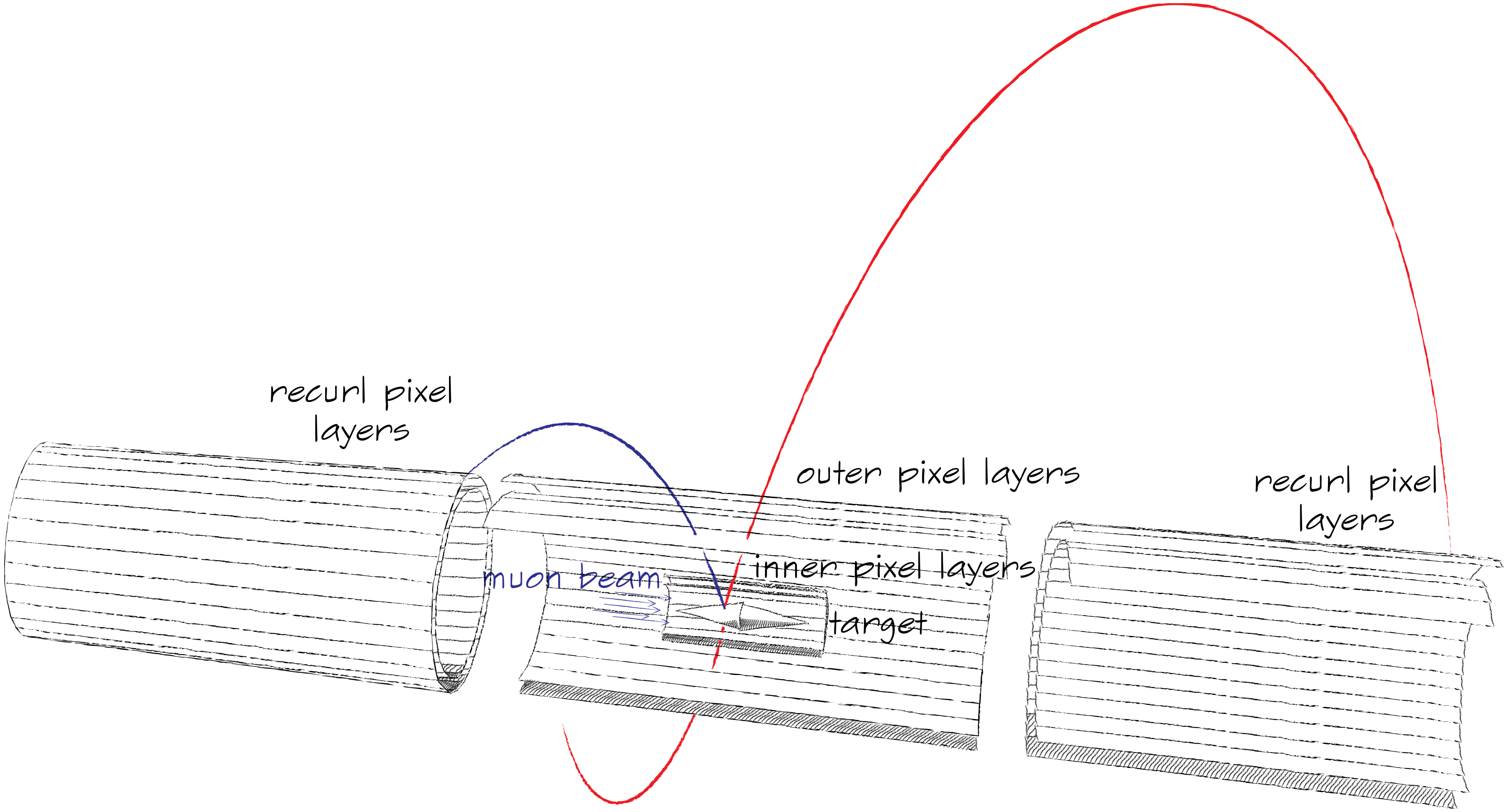
# Detector Design



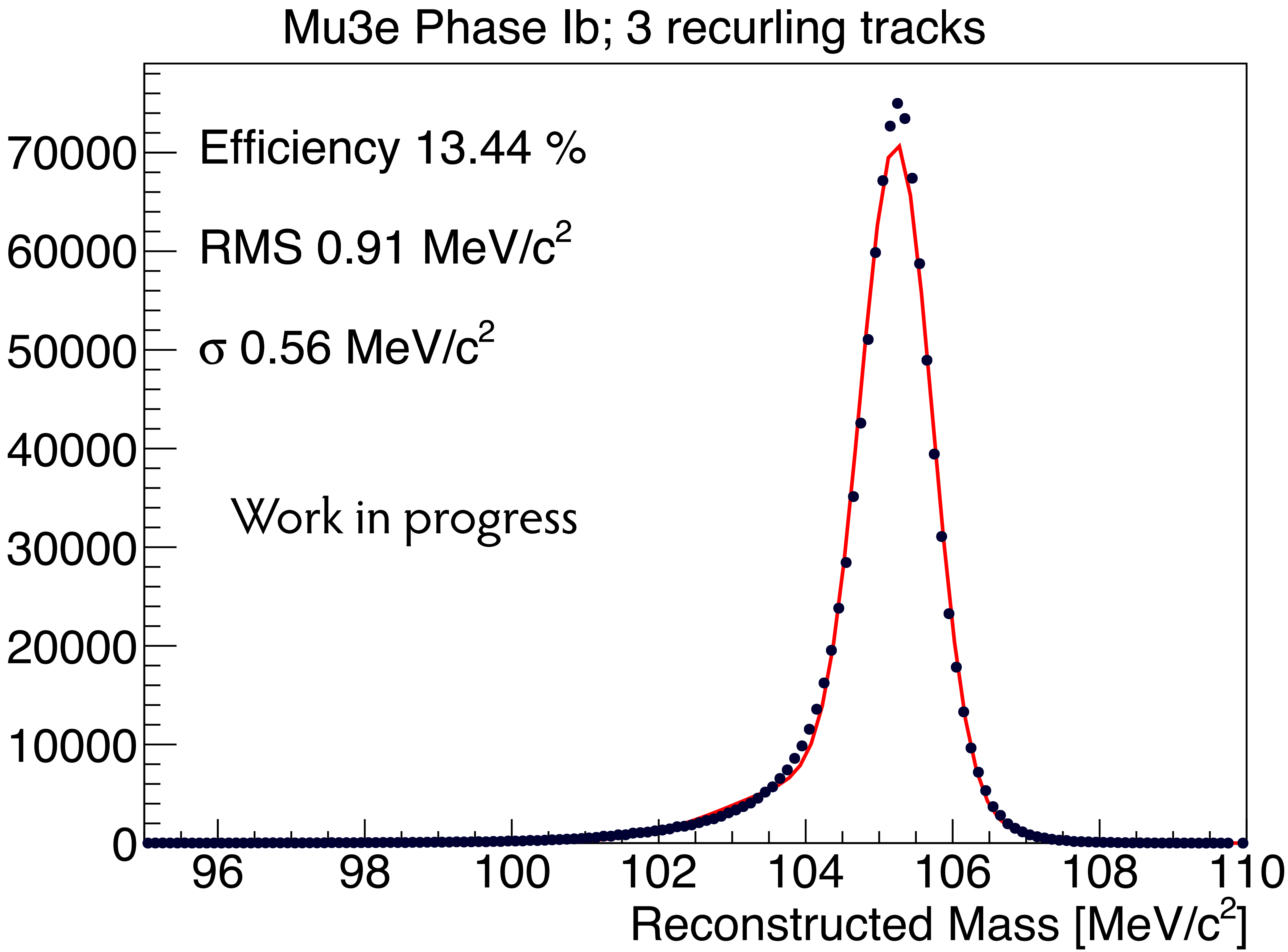
# Detector Design



# Detector Design



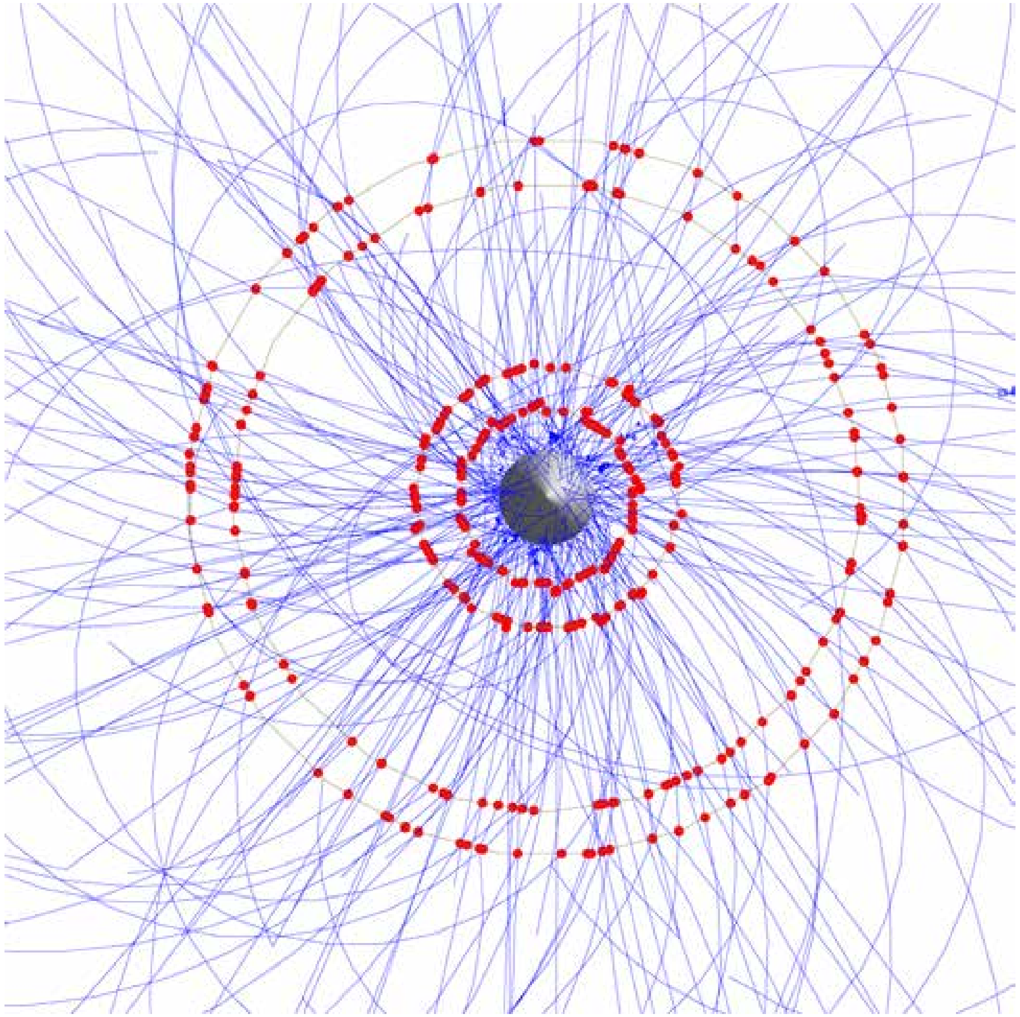
# Performance Simulations: Mass reconstruction



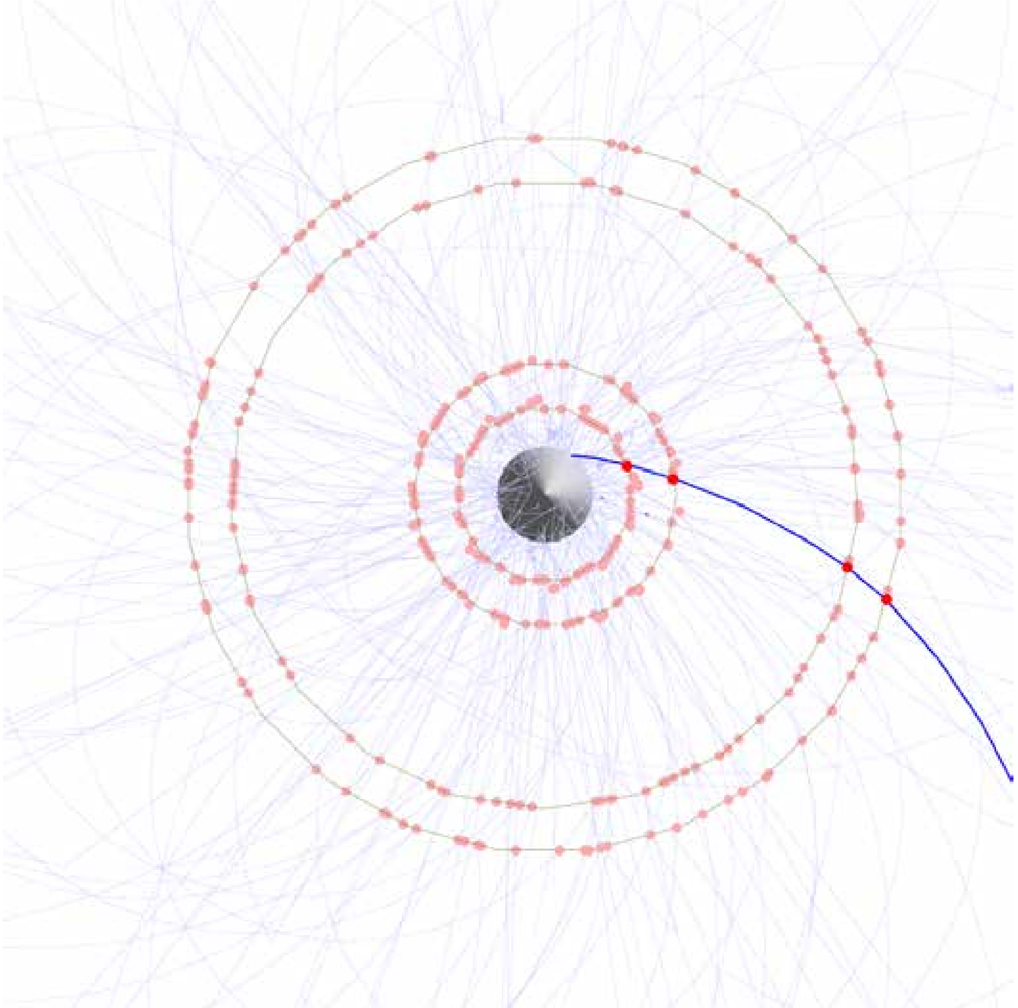
Need suppression of accidental background:

# Timing

# Timing measurements

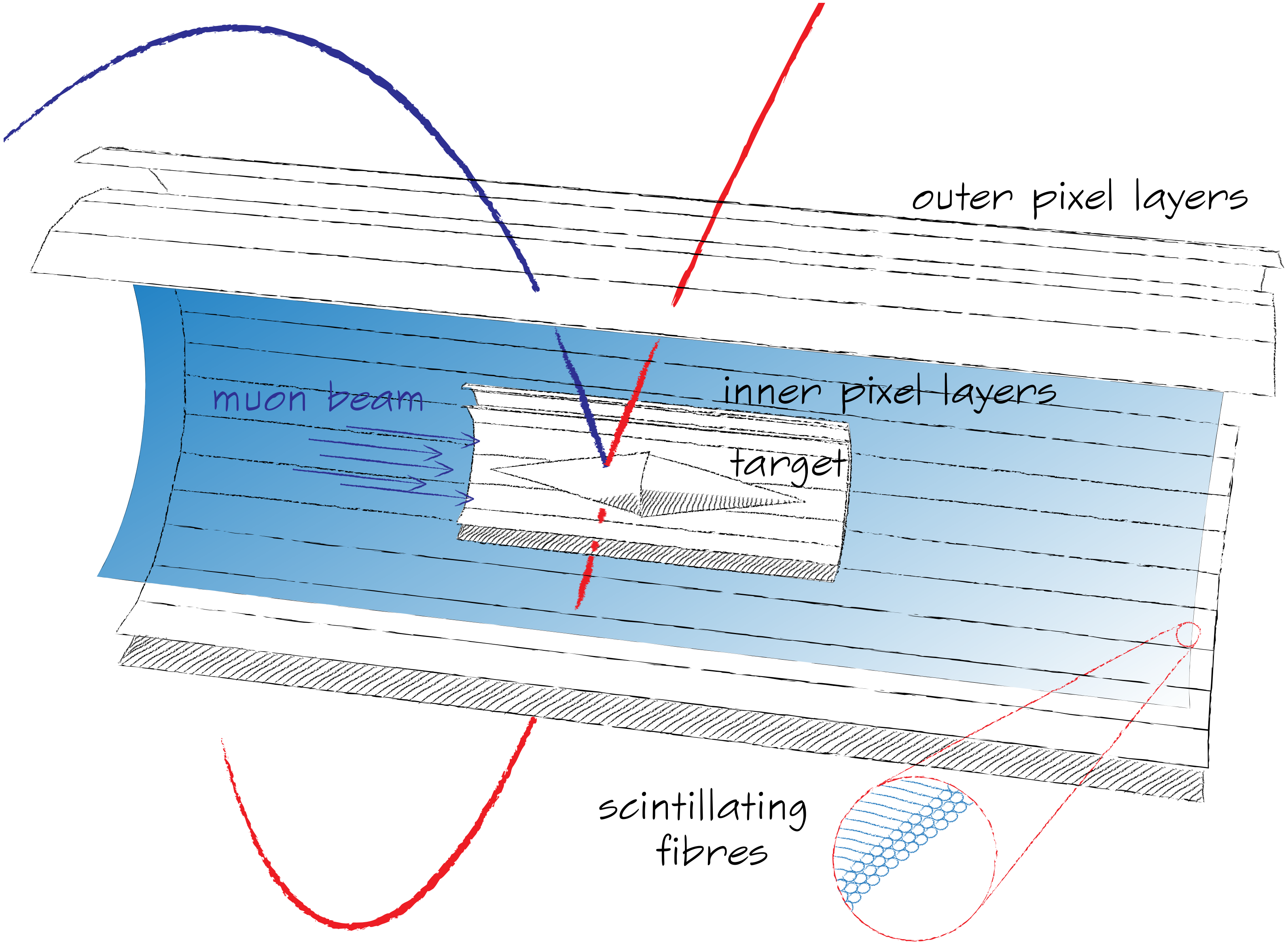


Pixels: O(50 ns)

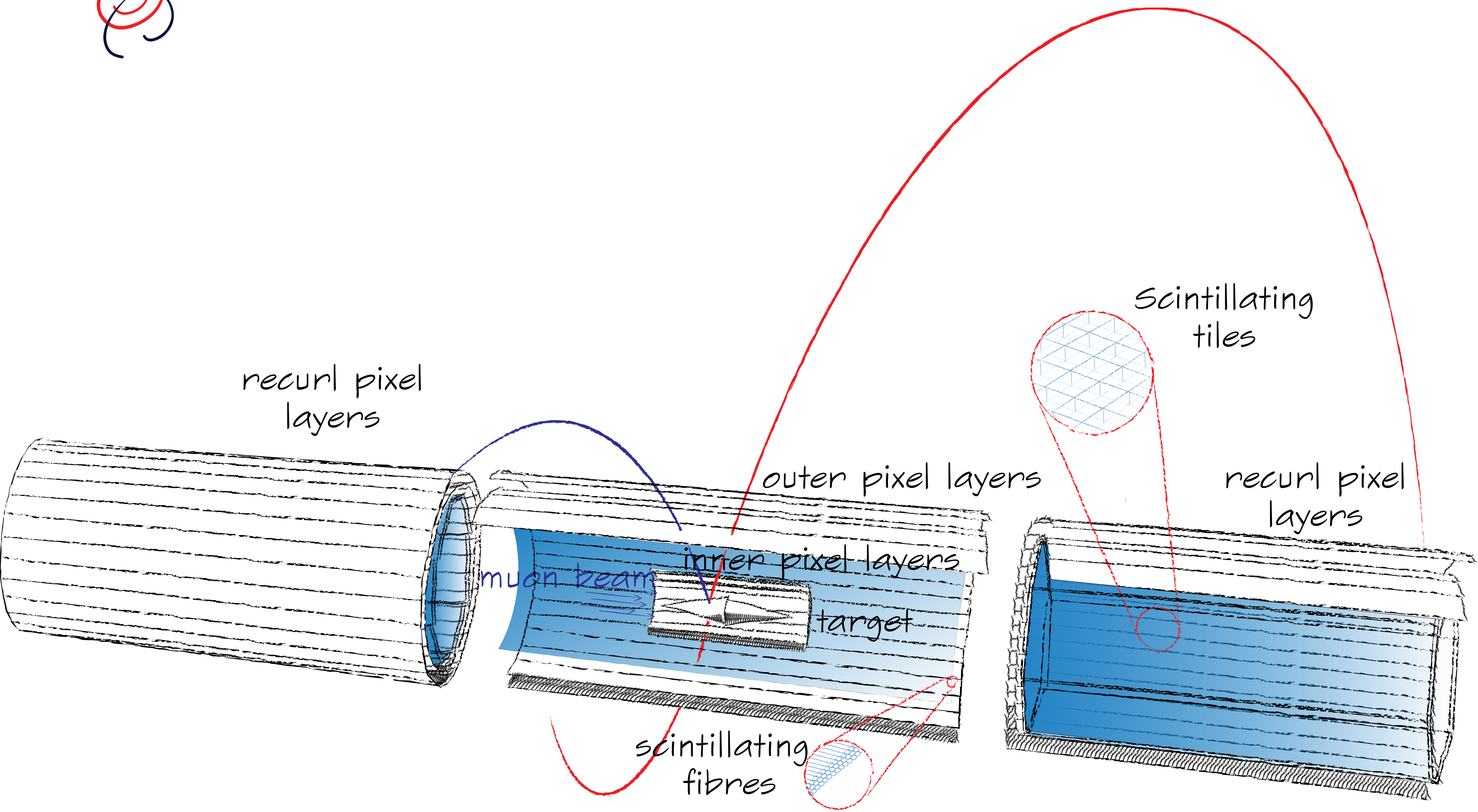


Scintillating fibres O(1 ns);
Scintillating tiles O(100 ps)

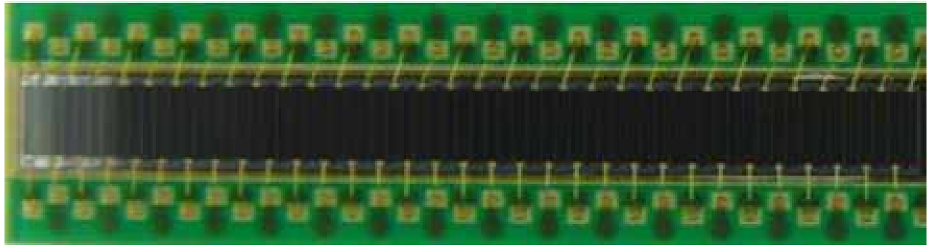
# Detector Design



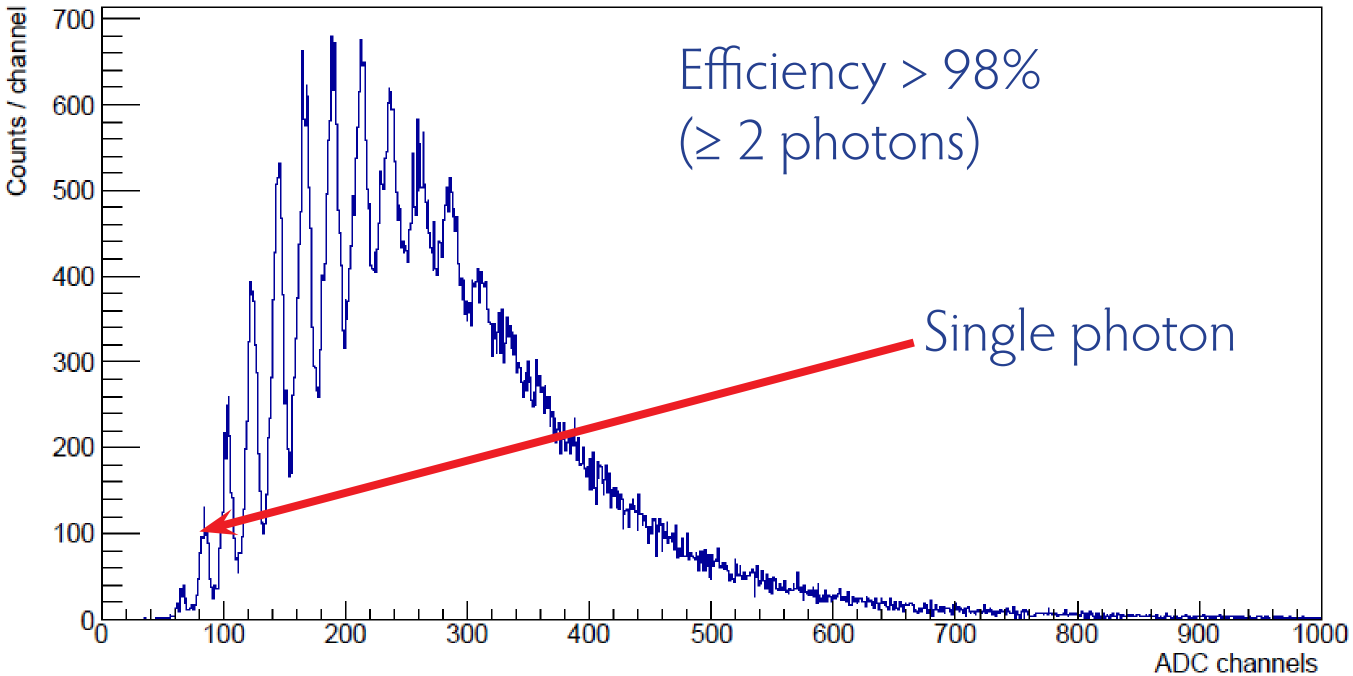
# Detector Design



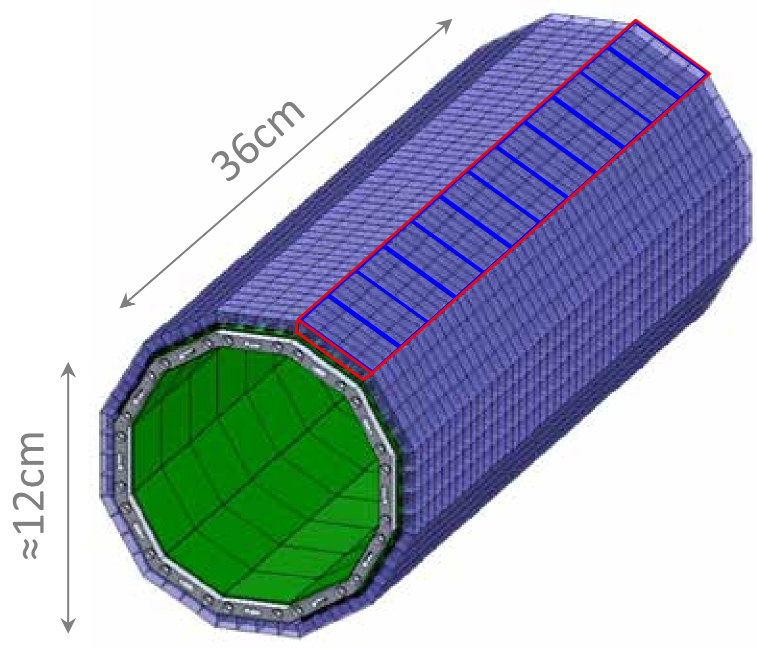
# Timing Detector: Scintillating Fibres

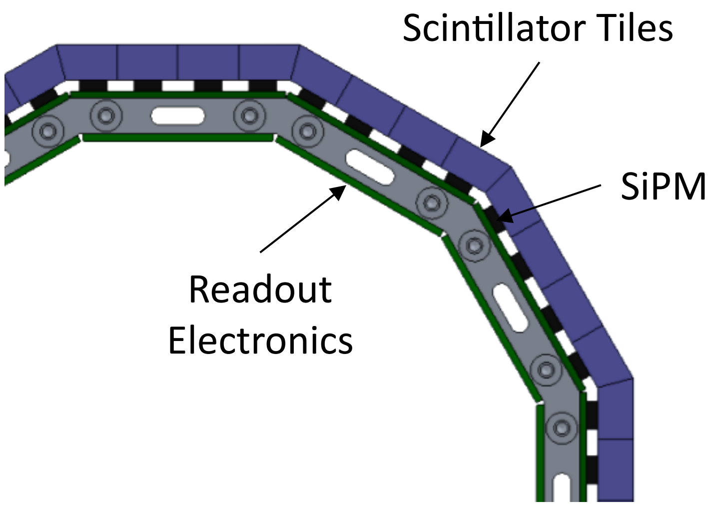


- 3-5 layers of 250 μm scintillating fibres
- Read-out by silicon photomultipliers (SiPMs) and custom ASIC (STiC)
- Timing resolution $\mathcal{O}$(1 ns) (measured with sodium source)



# Timing Detector: Scintillating tiles

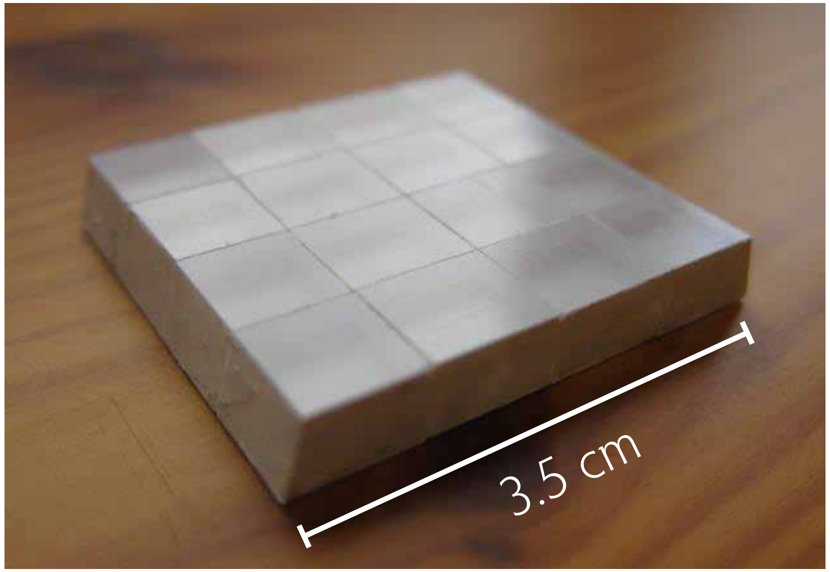


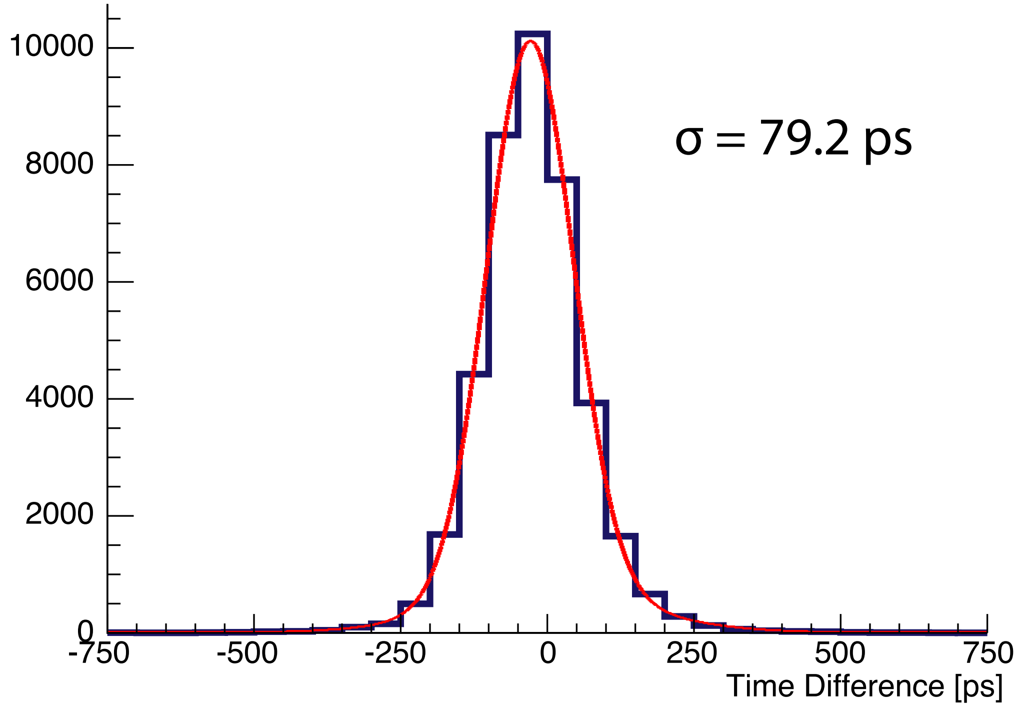

- ~ 0.5 $cm^3$ scintillating tiles
- Read-out by silicon photomultipliers (SiPMs) and custom ASIC (STiC)
- KIP Heidelberg

# Timing Detector: Scintillating tiles

Front

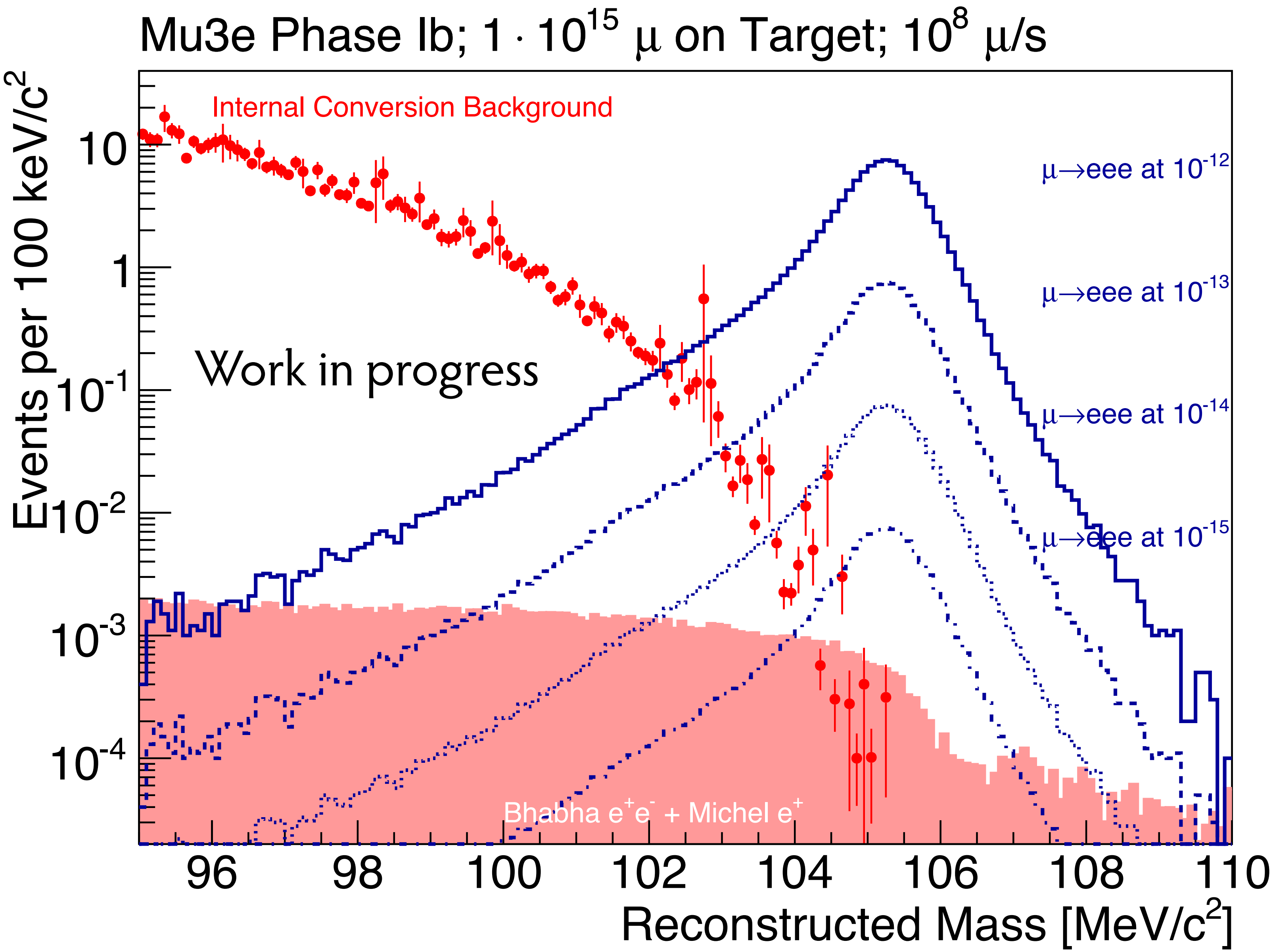



Back

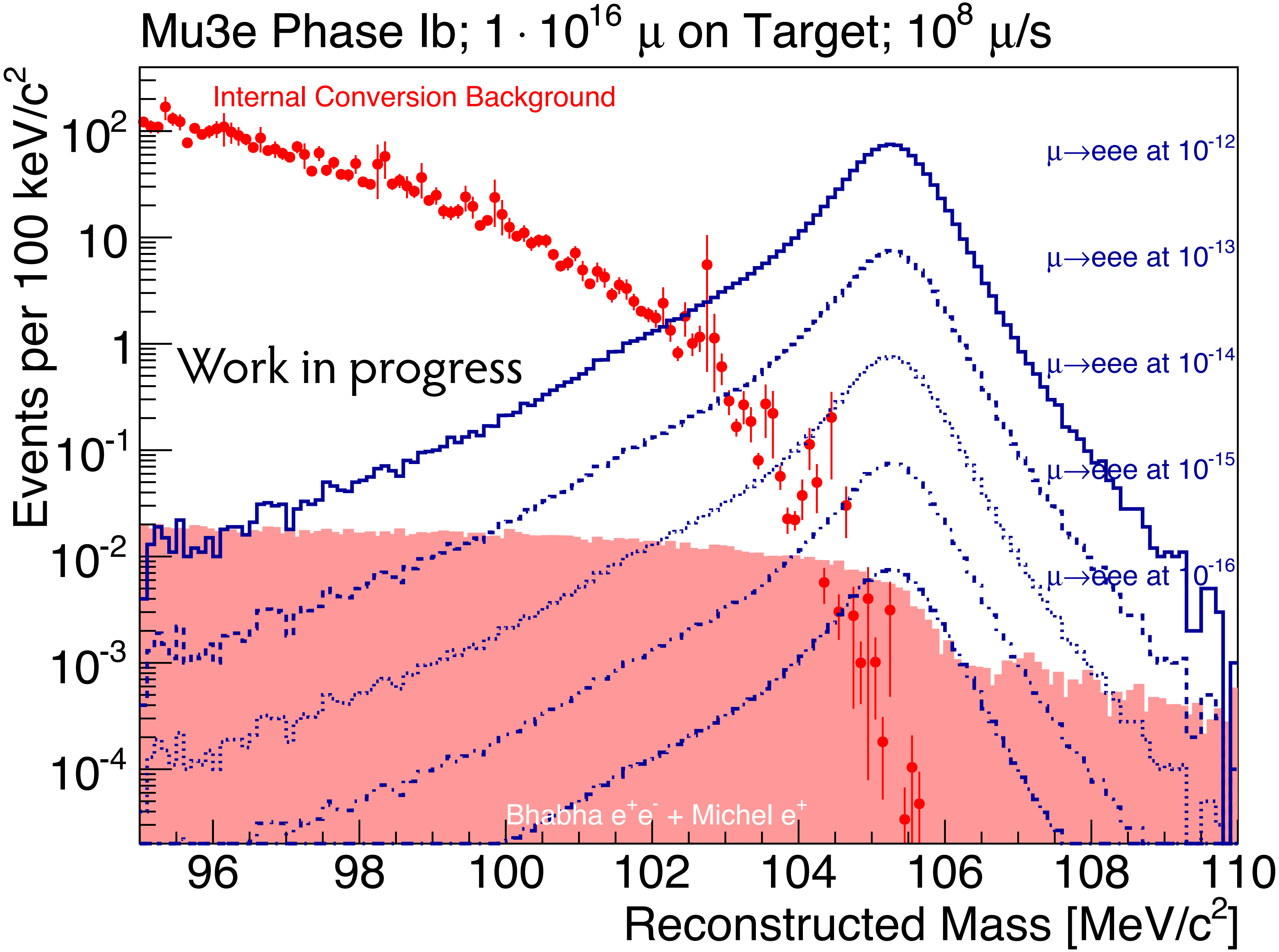



- Test beam with tiles, SiPMs and readout ASIC
- Timing resolution ~ 80 ps

# Performance Simulations: Signal & Background



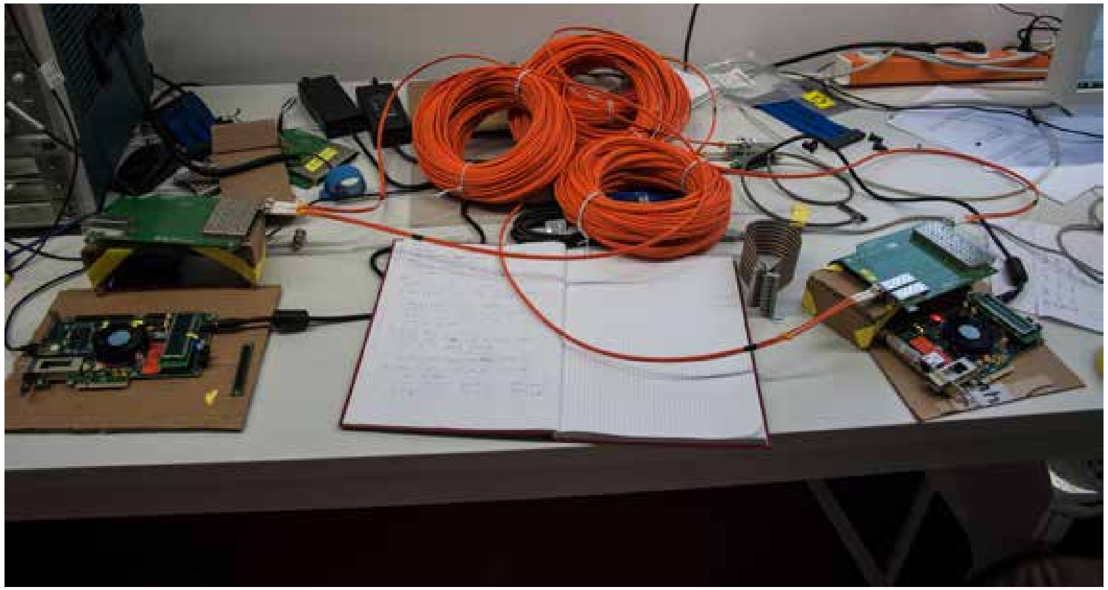
# Performance Simulations: Signal & Background



# Data Acquisition

# Data Acquisition

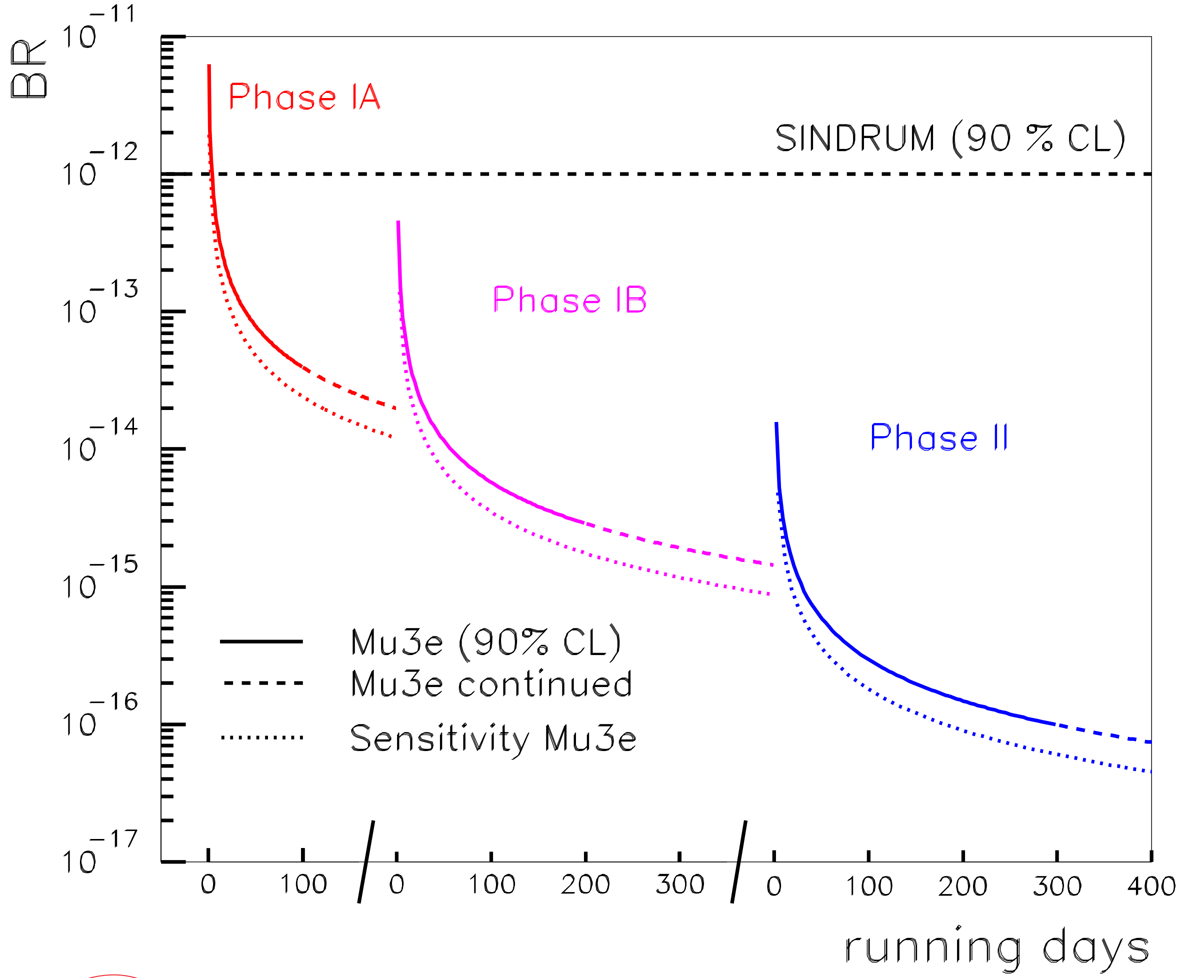

- 280 Million pixels (+ fibres and tiles)
- No trigger
- ~ 1 Tbit/s
- Need to find and fit billions of tracks/s

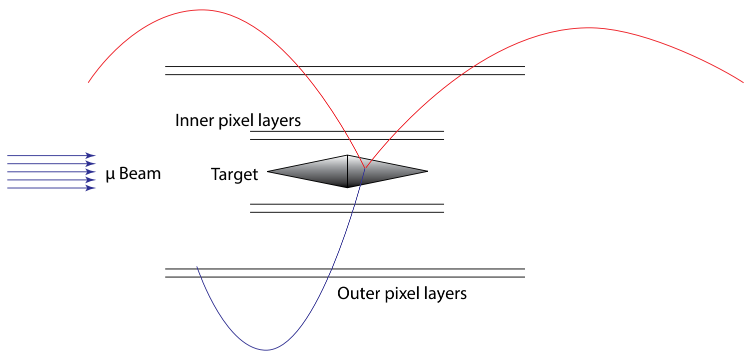


# Online filter farm


- PCs with 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

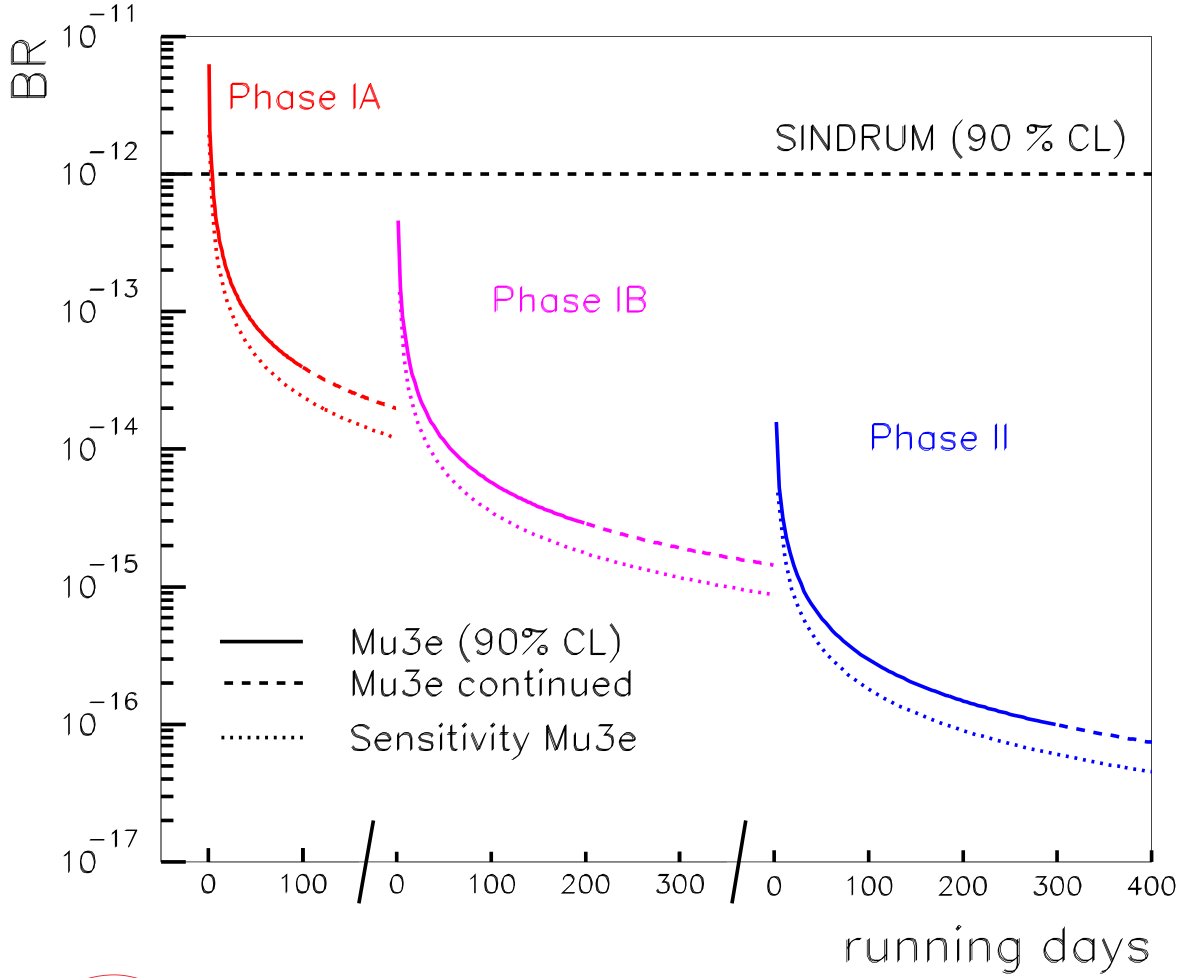
# Sensitivity

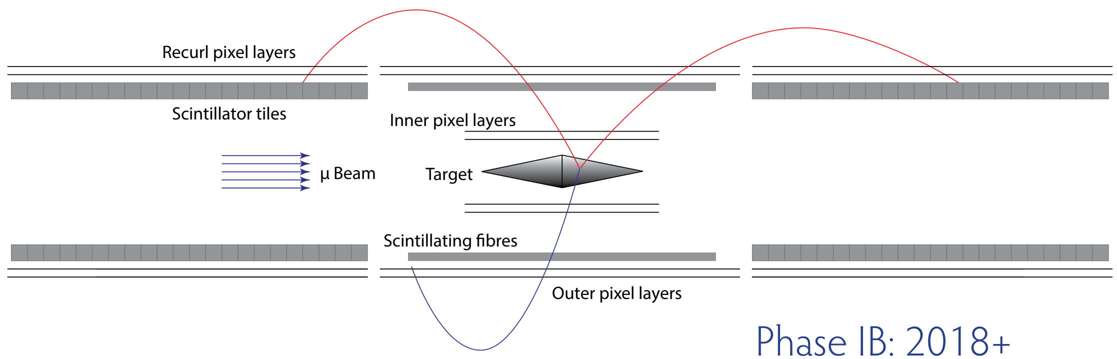



Phase IA: Starting 2017
$2 \cdot 10^7$ μ/s

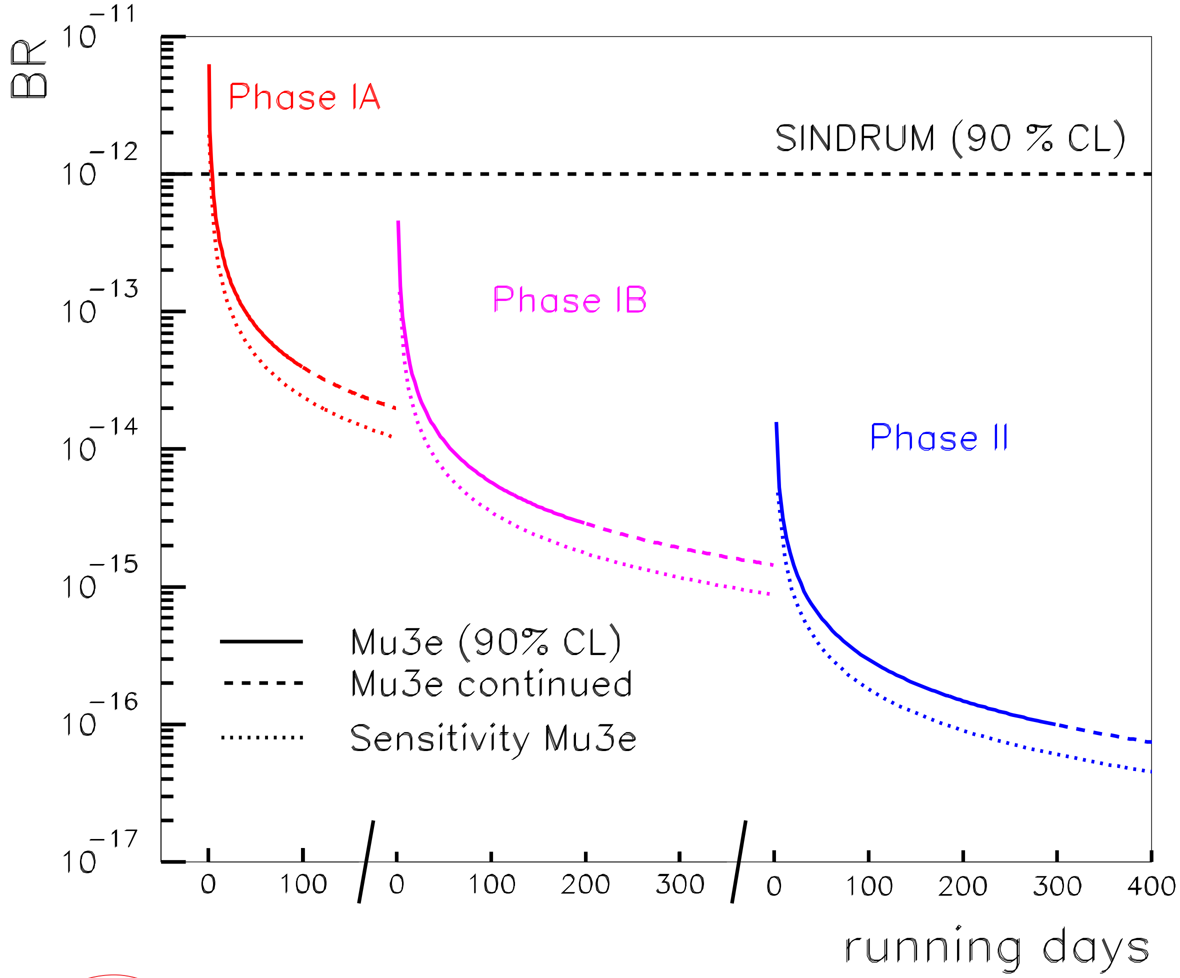
# Sensitivity

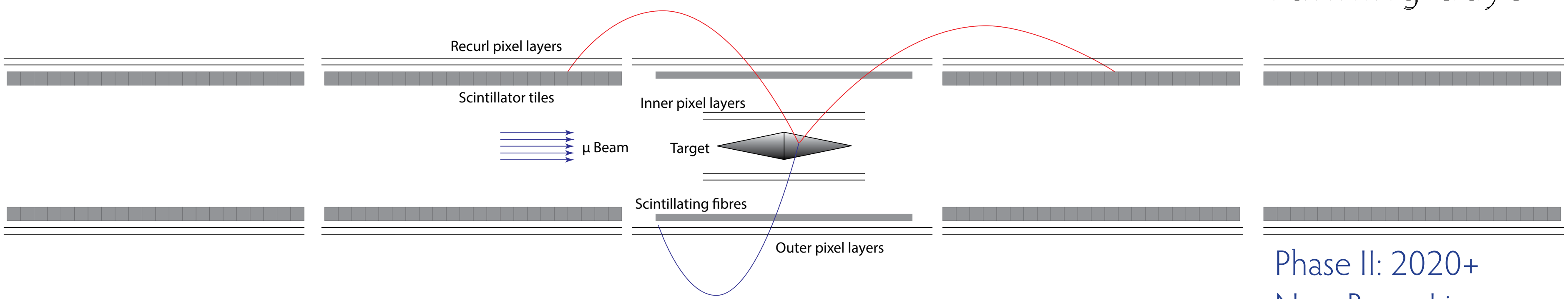



Phase IB: 2018+
$1 \cdot 10^8$ μ/s

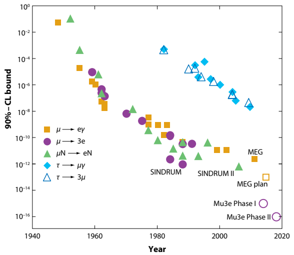
# Sensitivity



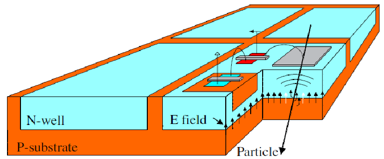




Phase II: 2020+
New Beam Line
$2 \cdot 10^9$ μ/s

# Conclusion




- Mu3e aims for $\mu \rightarrow eee$ at the $10^{-16}$ level




- First large scale use of HV-MAPS

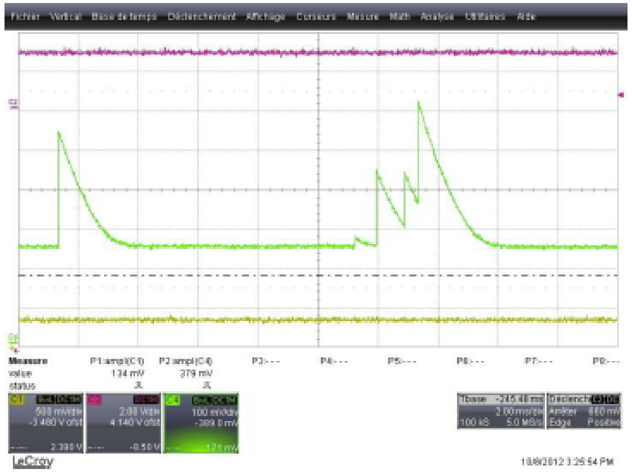
- Build detector layers thinner than a hair
- Timing at the 100 ps level
- Reconstruct 2 billion tracks/s in 1 Tbit/s on ~50 GPUs

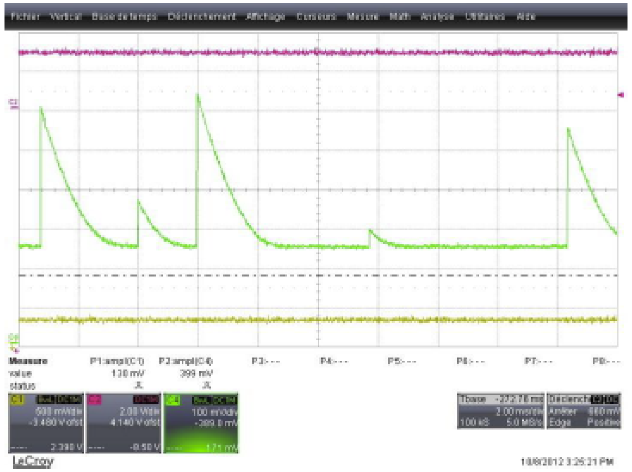
- Start data taking in 2017
- 2 billion muons/s not before 2020

# Backup Material

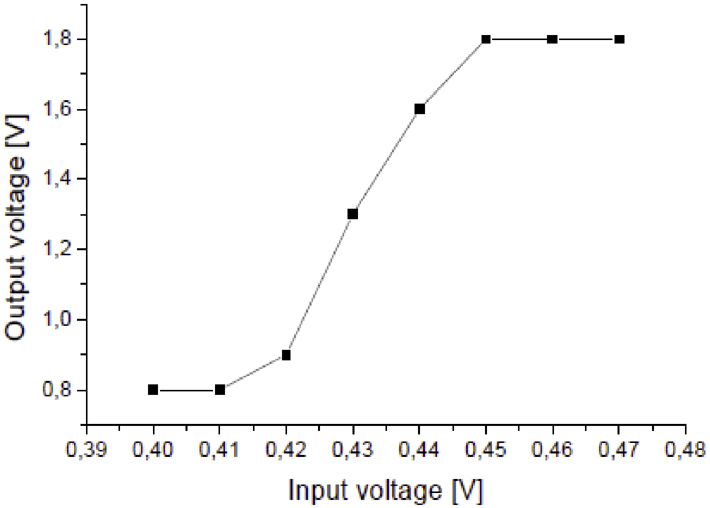
# Radiation Hardness

- Requirements not as strict as at LHC





The chip works, particles are measured when the chip is in the beam: Output of the amplifier

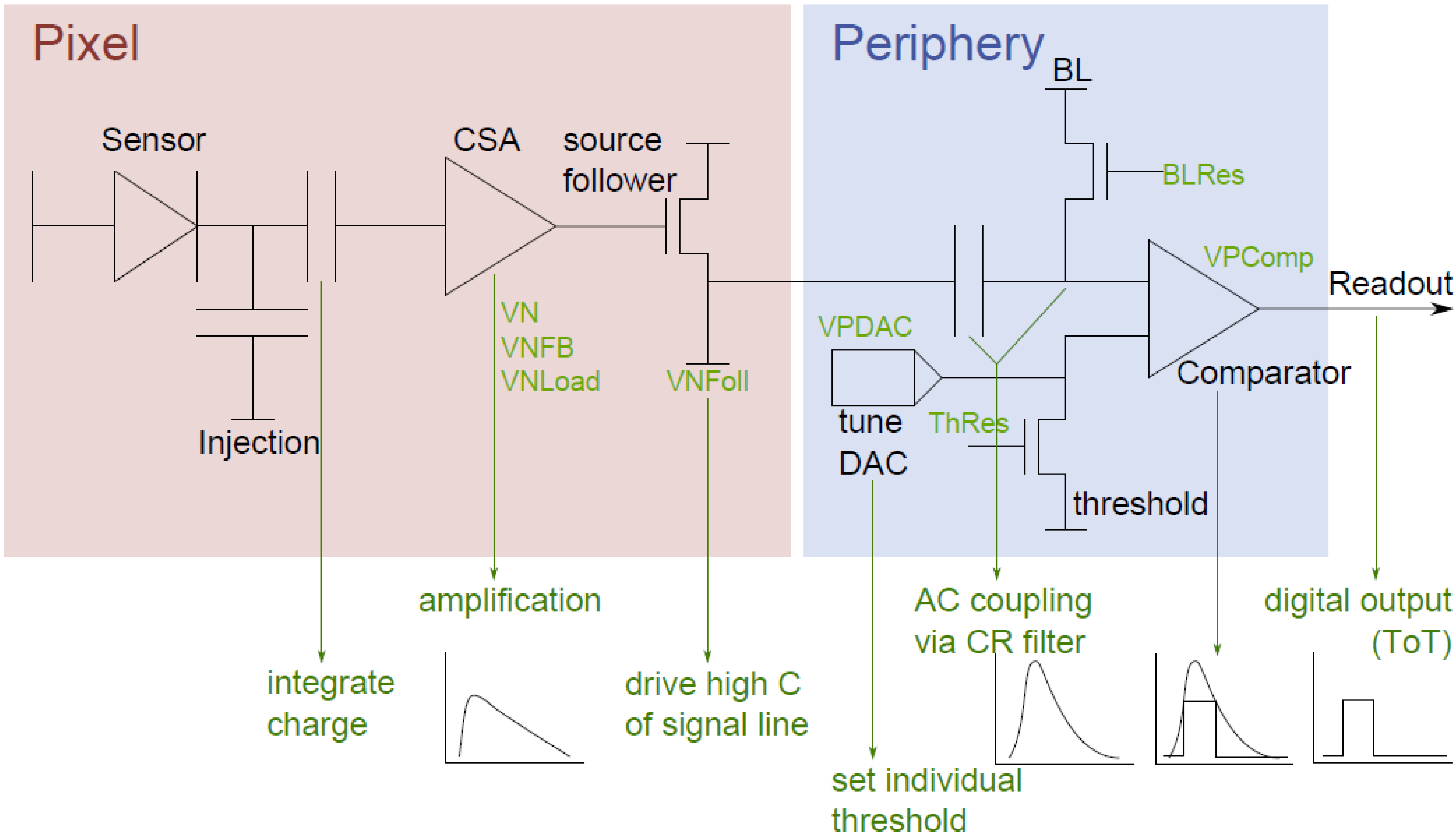



Comparator characteristics.

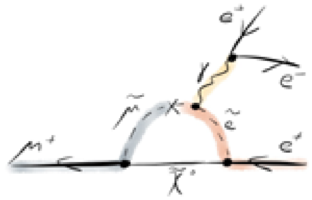
- Irradiation at PS
- After 380 MRad ($8 \times 10^{15}$ $n_{eq}/cm^2$)
- Chip still working

(Courtesy Ivan Perić, RESMDD 2012)

# MUPIX electronics



# 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'

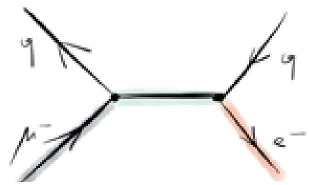
$$+ g_1 (\bar{\mu}_R e_L) (\bar{e}_R e_L) \qquad + g_2 (\bar{\mu}_L e_R) (\bar{e}_L e_R)$$

scalar

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

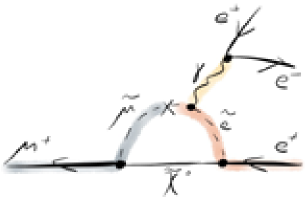
$$+ g_5 (\bar{\mu}_R \gamma^\mu e_R) (\bar{e}_L \gamma^\mu e_L) \qquad + g_6 (\bar{\mu}_L \gamma^\mu e_L) (\bar{e}_R \gamma^\mu e_R) \;\; + H.\,C.\,)$$

vector

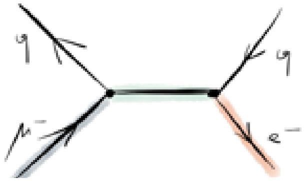


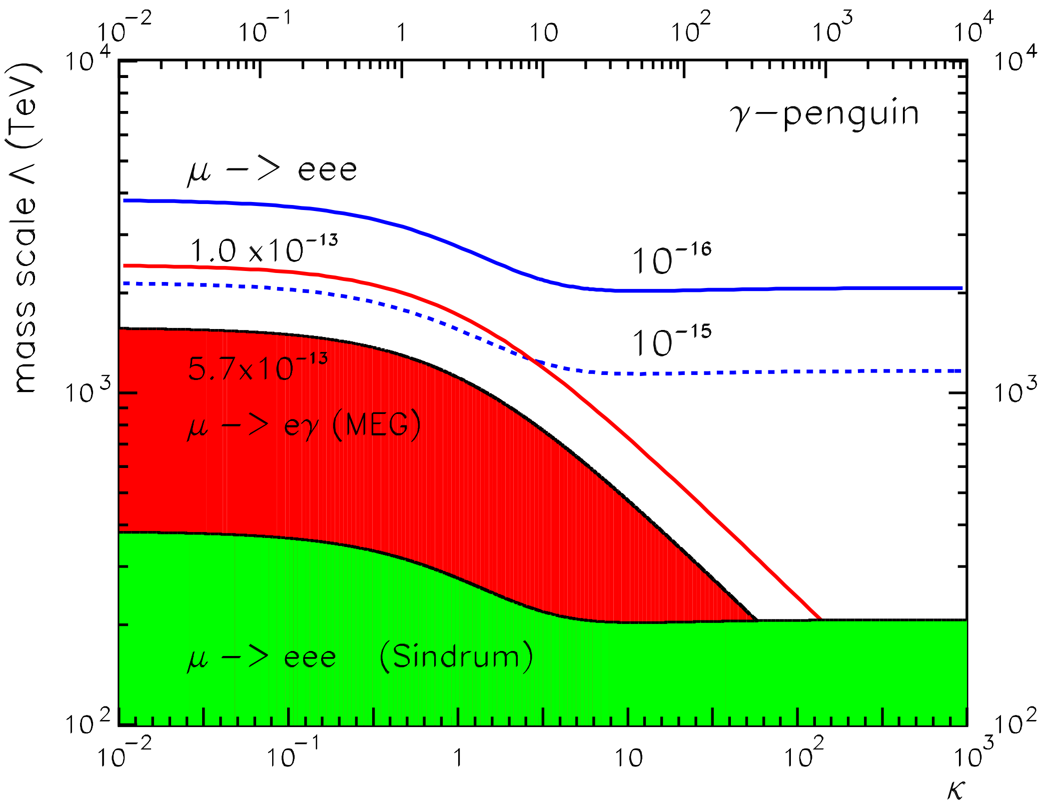
(Y. Kuno, Y. Okada,
Rev.Mod.Phys. 73 (2001) 151)

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



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

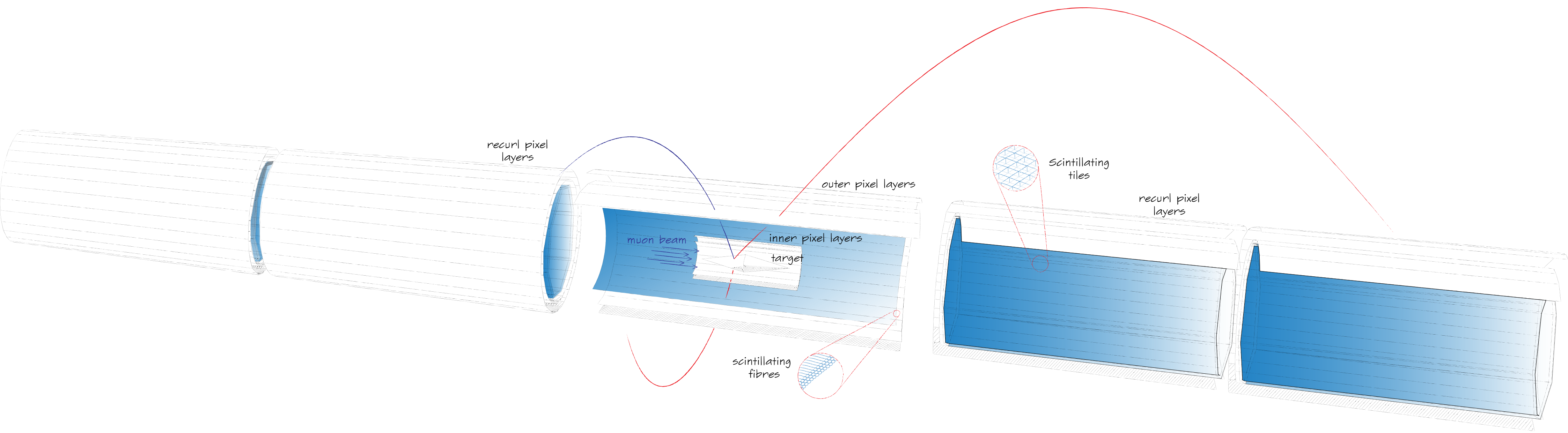





- One loop term and one contact term
- Ratio $\kappa$ between them
- Common mass scale $\Lambda$
- Allows for sensitivity comparisons between $\mu \to eee$ and $\mu \to e\gamma$
- In case of dominating dipole couplings ($\kappa = 0$):

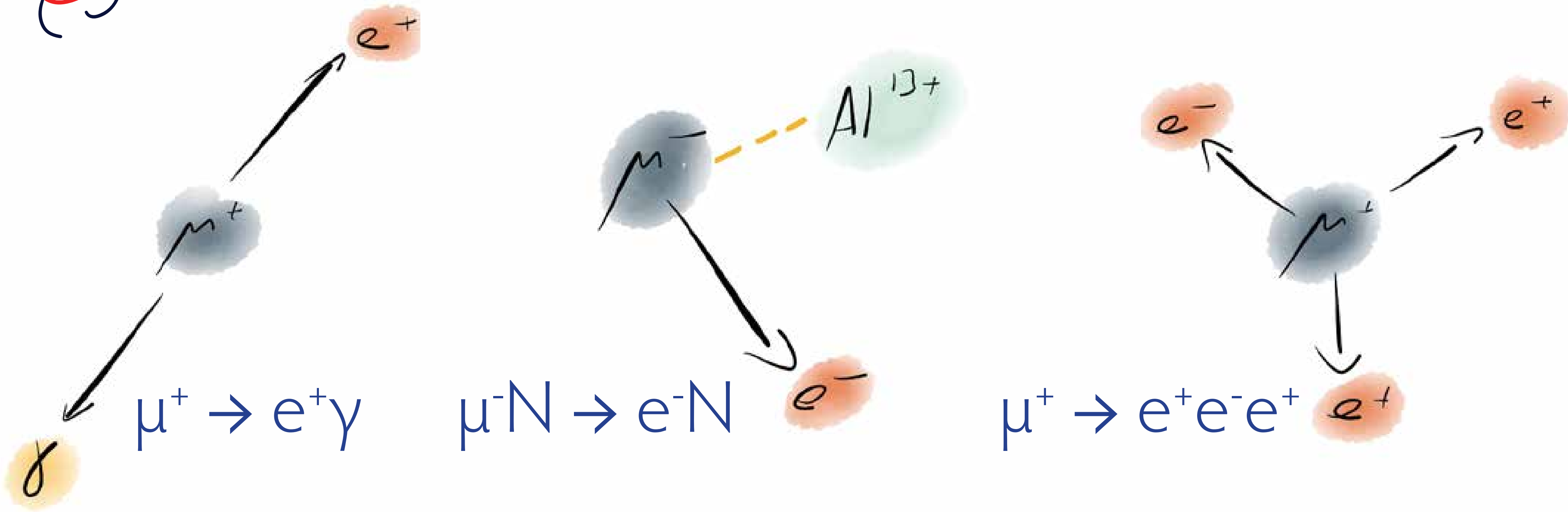
$$\frac{B(\mu \to eee)}{B(\mu \to e\gamma)} = 0.006 \quad (\text{essentially } \alpha_{em})$$

# Detector Design



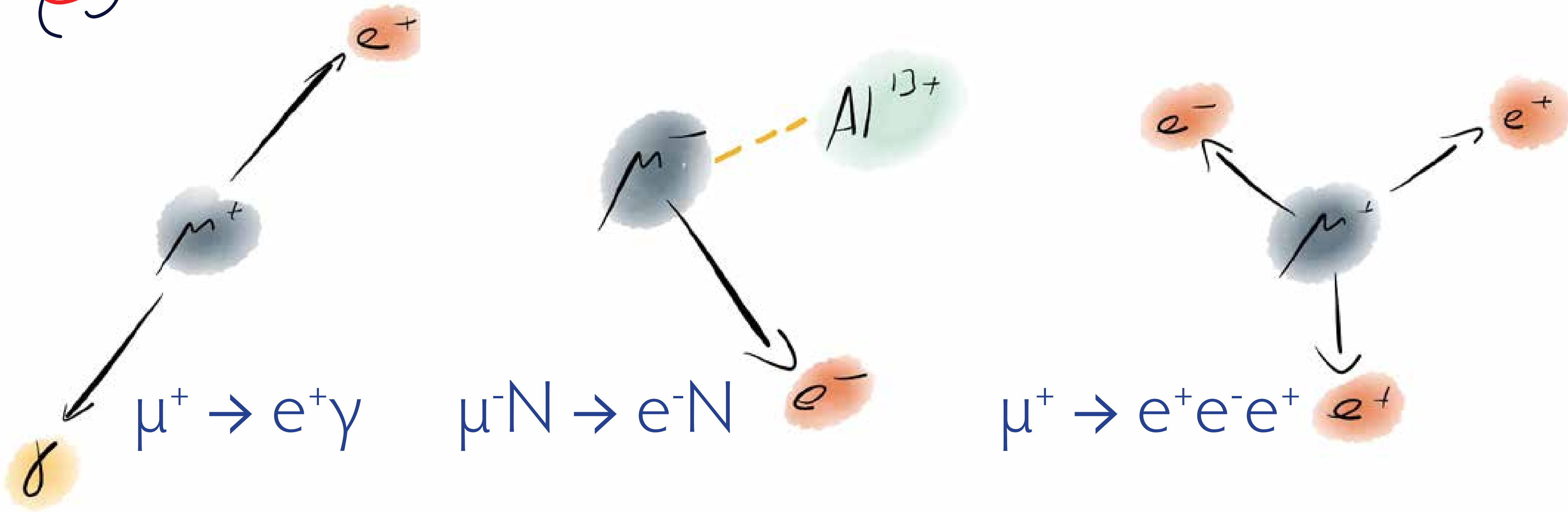
# The hunt for
# charged lepton flavour violation in μ-decays

# LFV Muon Decays: Experimental Situation




| | | |
|---|---|---|
| MEG (PSI) | SINDRUM II (PSI) | SINDRUM (PSI) |
| $B(\mu^+ \rightarrow e^+\gamma) < 5.7 \cdot 10^{-13}$ | $B(\mu^- Au \rightarrow e^- Au) < 7 \cdot 10^{-13}$ | $B(\mu^+ \rightarrow e^+e^-e^+) < 1.0 \cdot 10^{-12}$ |
| (2013) | (2006) | (1988) |

# LFV Muon Decays: Experimental Situation




## 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)

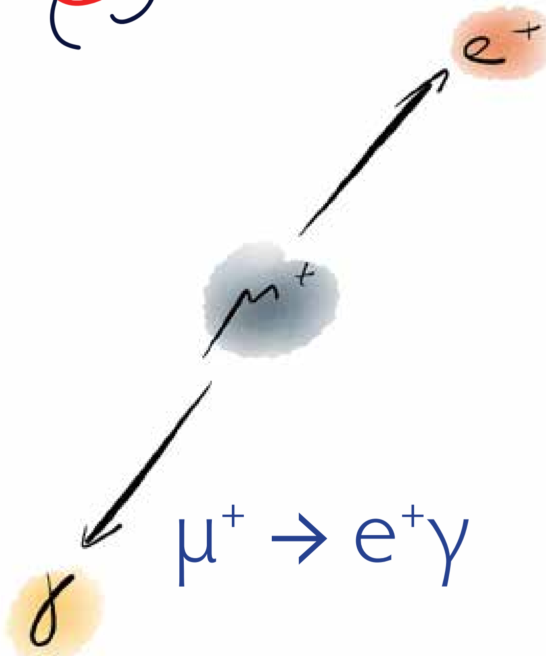
Mu2e/Comet

## SINDRUM (PSI)

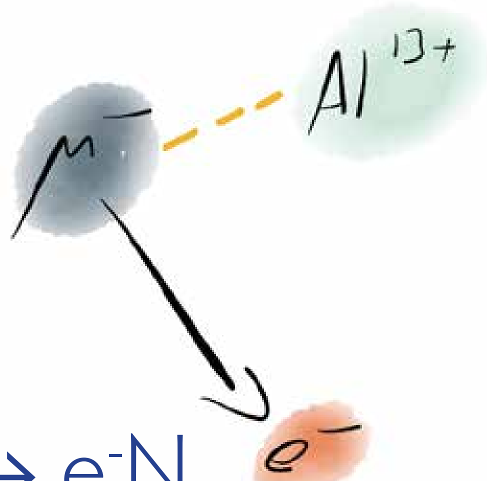
$B(\mu^+ \to e^+e^-e^+) < 1.0 \cdot 10^{-12}$
(1988)

Mu3e

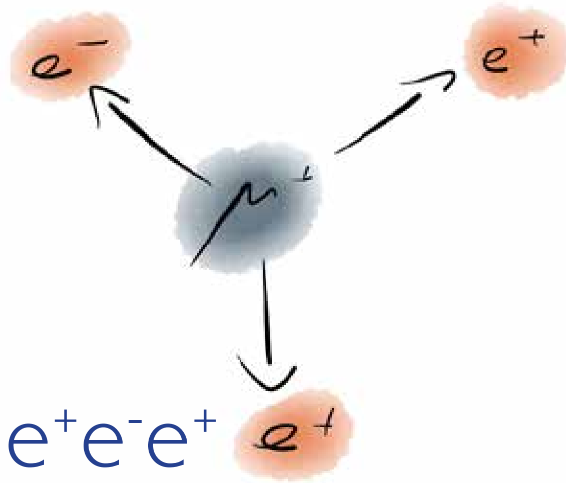
# LFV Muon Decays: Experimental signatures




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




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




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

Kinematics

- 2-body decay
- Monoenergetic $e^+$, $\gamma$
- Back-to-back

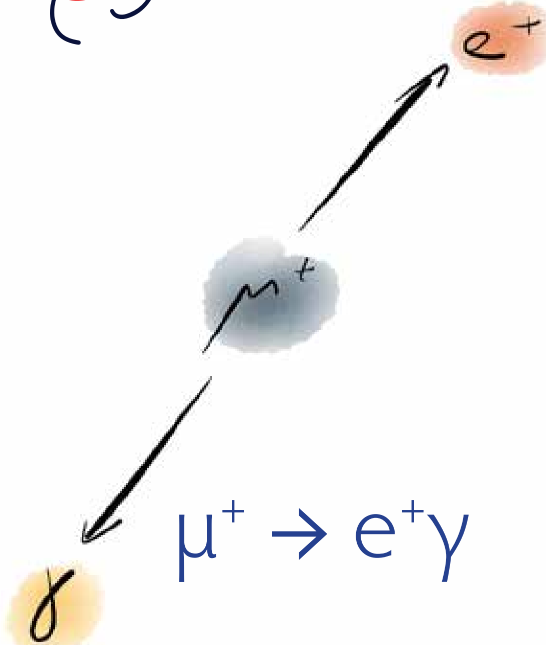
Kinematics

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

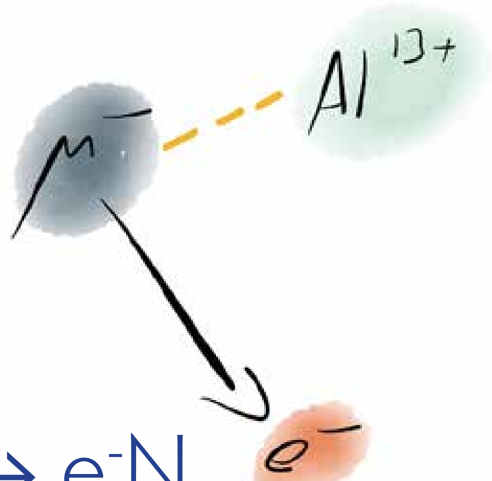
Kinematics

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

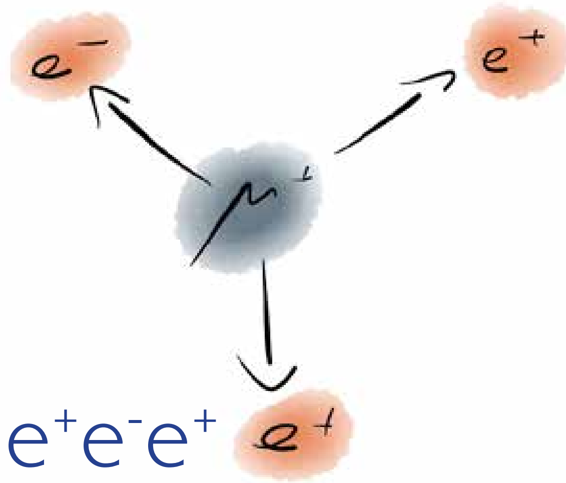
# LFV Muon Decays: Experimental signatures




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




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




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

Kinematics

- 2-body decay
- Monoenergetic $e^+$, $\gamma$
- Back-to-back

Background

- Accidental background

Kinematics

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

Background

- Decay in orbit
- Antiprotons, pions, cosmics

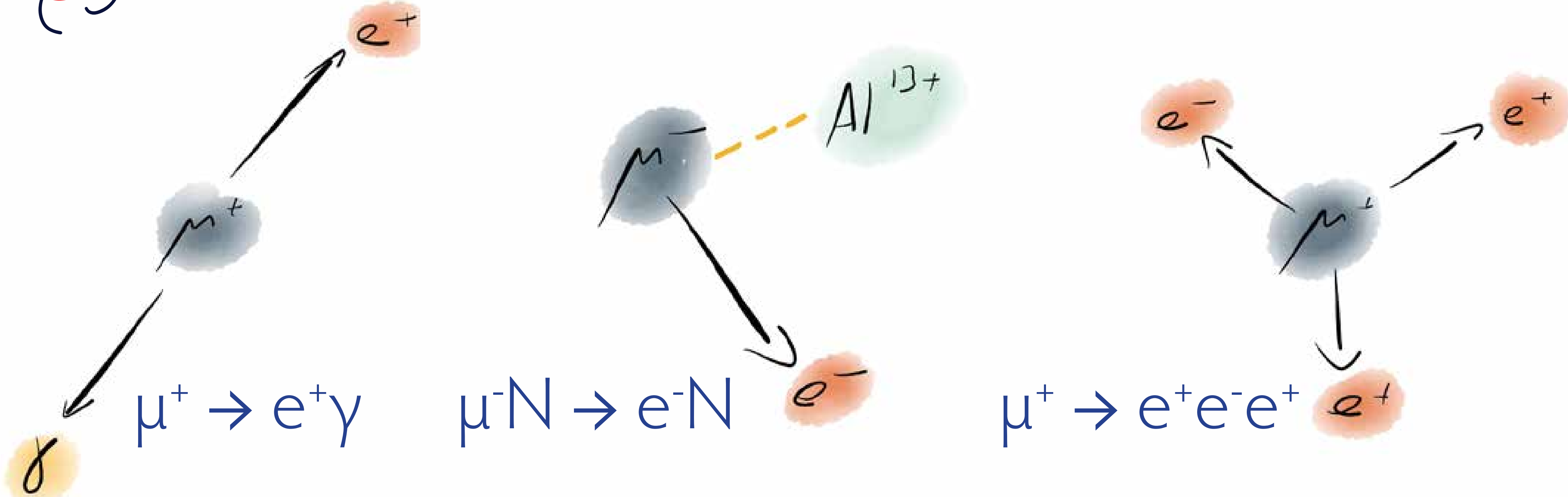
Kinematics

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

Background

- Radiative 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…

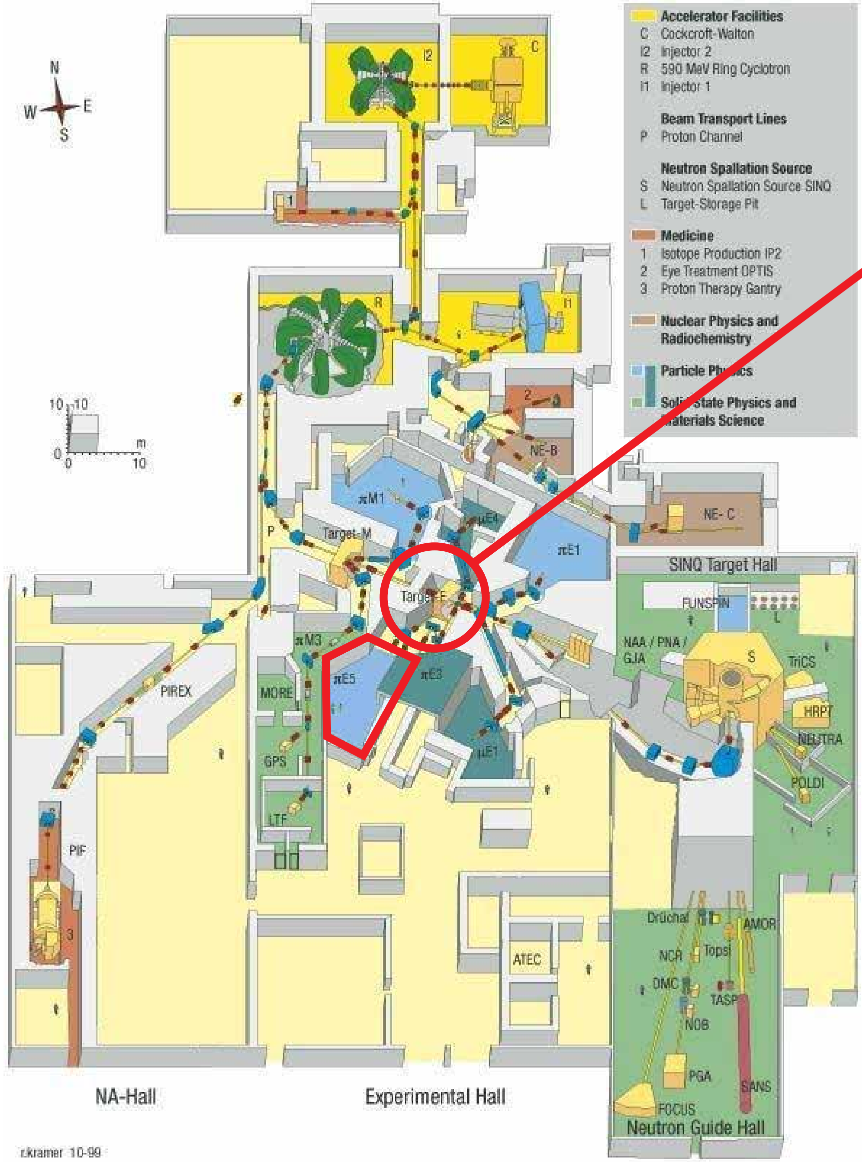
- R… … decay
- Ac… …dental background

Continuous Beam

# The Mu3e Collaboration

- DPNC, Geneva University
- Physics Institute, Heidelberg University
- KIP, Heidelberg University
- IPE, Karlsruhe Institute of Technology
- Paul Scherrer Institute
- Physics Institute, Zürich University
- Institute for Particle Physics, ETH Zürich
- Institute for Nuclear Physics, JGU Mainz

# Muons from PSI

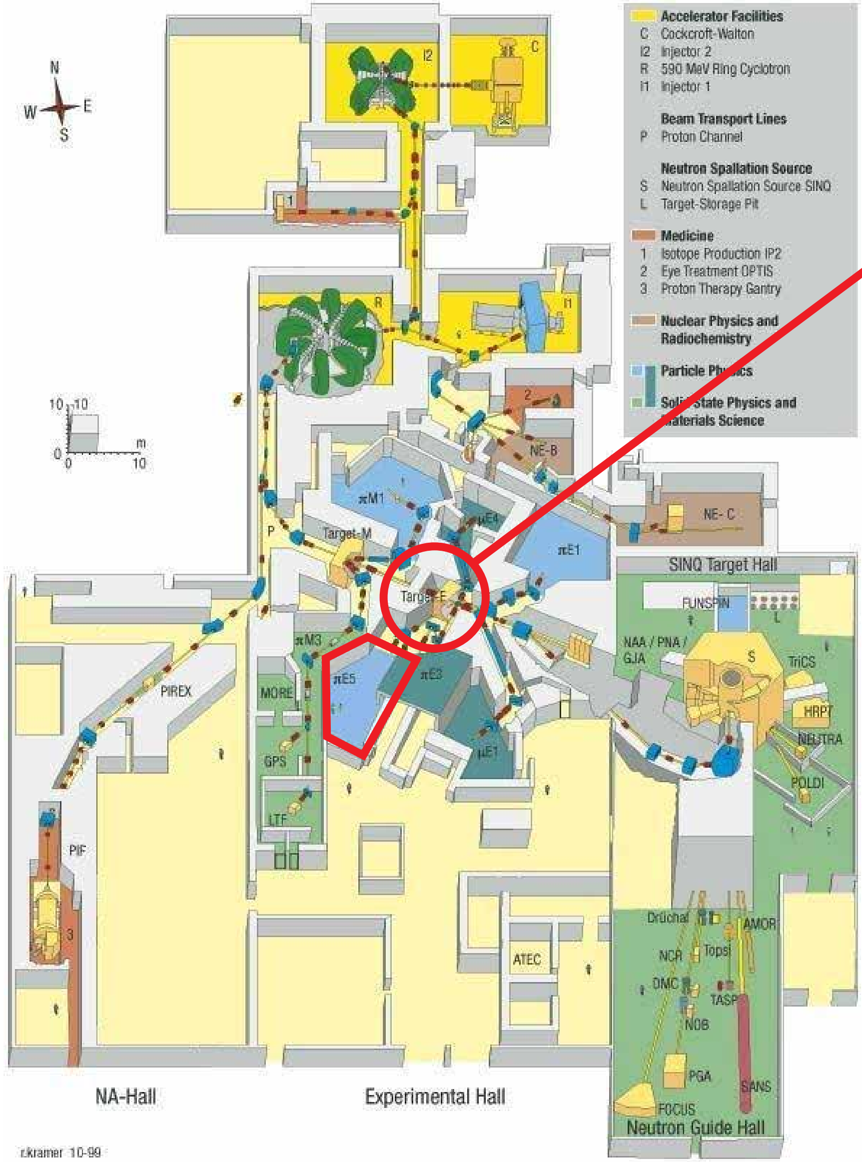



DC muon beams at PSI:

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

- Surface muons, p = 29.7 MeV/c
  Stopped in < 1 mm of plastic

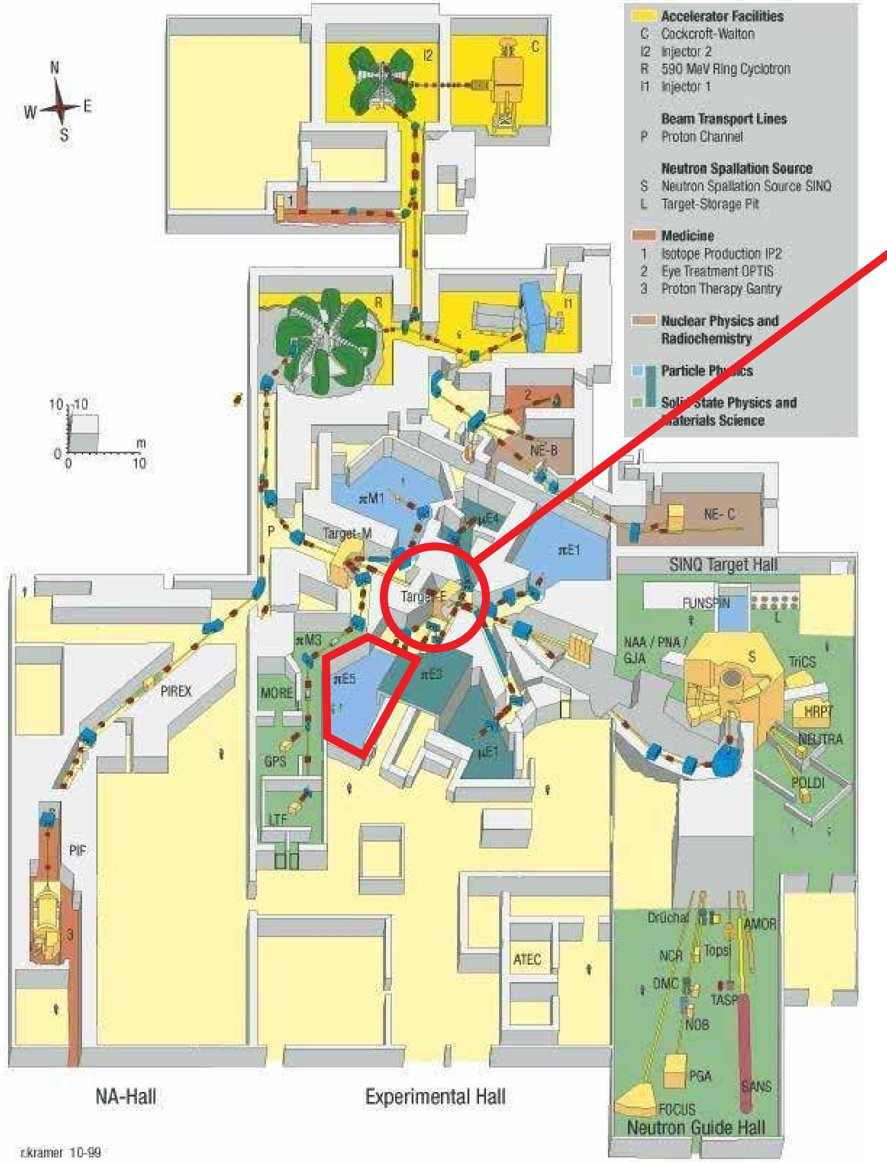
# Muons from PSI




DC muon beams at PSI:

- πE5 beamline: ~ $10^8$ muons/s
  (MEG experiment, Mu3e phase I)
- Surface muons, p = 29.7 MeV/c
  Stopped in < 1 mm of plastic
- The $\mu \to eee$ experiment (final stage) requires $2 \times 10^9$ muons/s focused and collimated on a ~2 cm spot

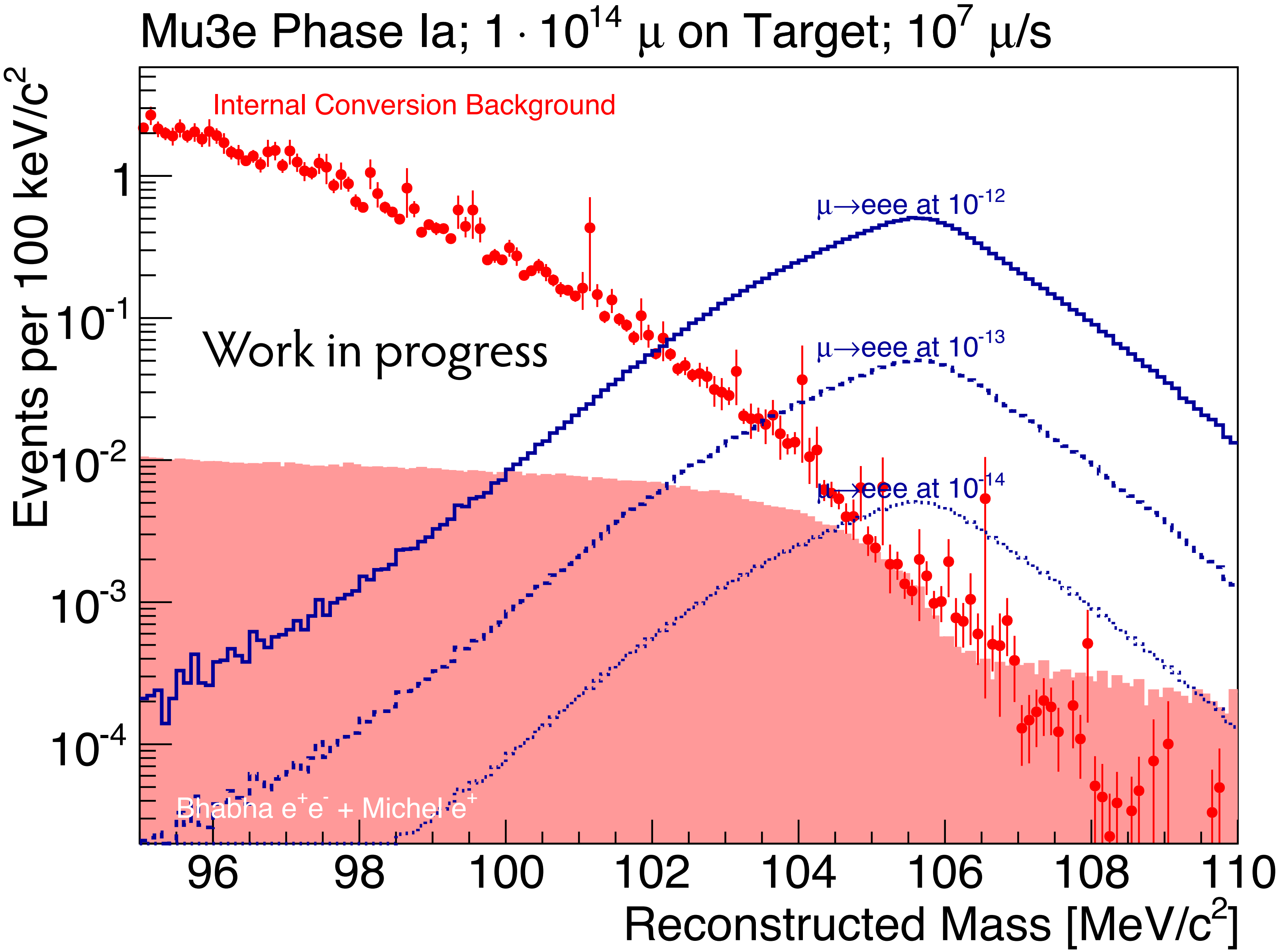
# Muons from PSI




DC muon beams at PSI:

- πE5 beamline: ~ $10^8$ muons/s
  (MEG experiment, Mu3e phase I)
- Surface muons, p = 29.7 MeV/c
  Stopped in < 1 mm of plastic
- The μ → eee experiment (final stage) requires 2 × $10^9$ muons/s focused and collimated on a ~2 cm spot
- More than ~ $10^{11}$ muons/s are produced; bring magnetic elements closer to capture them:
  High intensity muon beamline (HiMB) study currently ongoing

# Performance Simulations: Background



# Performance Simulations: Background