Precision Muon Physics

and

101 How to build a Fast, Thin, Segmented Timing Detector

Simon Corrodi, YSSS, 4th December 2018

What I tell my friends

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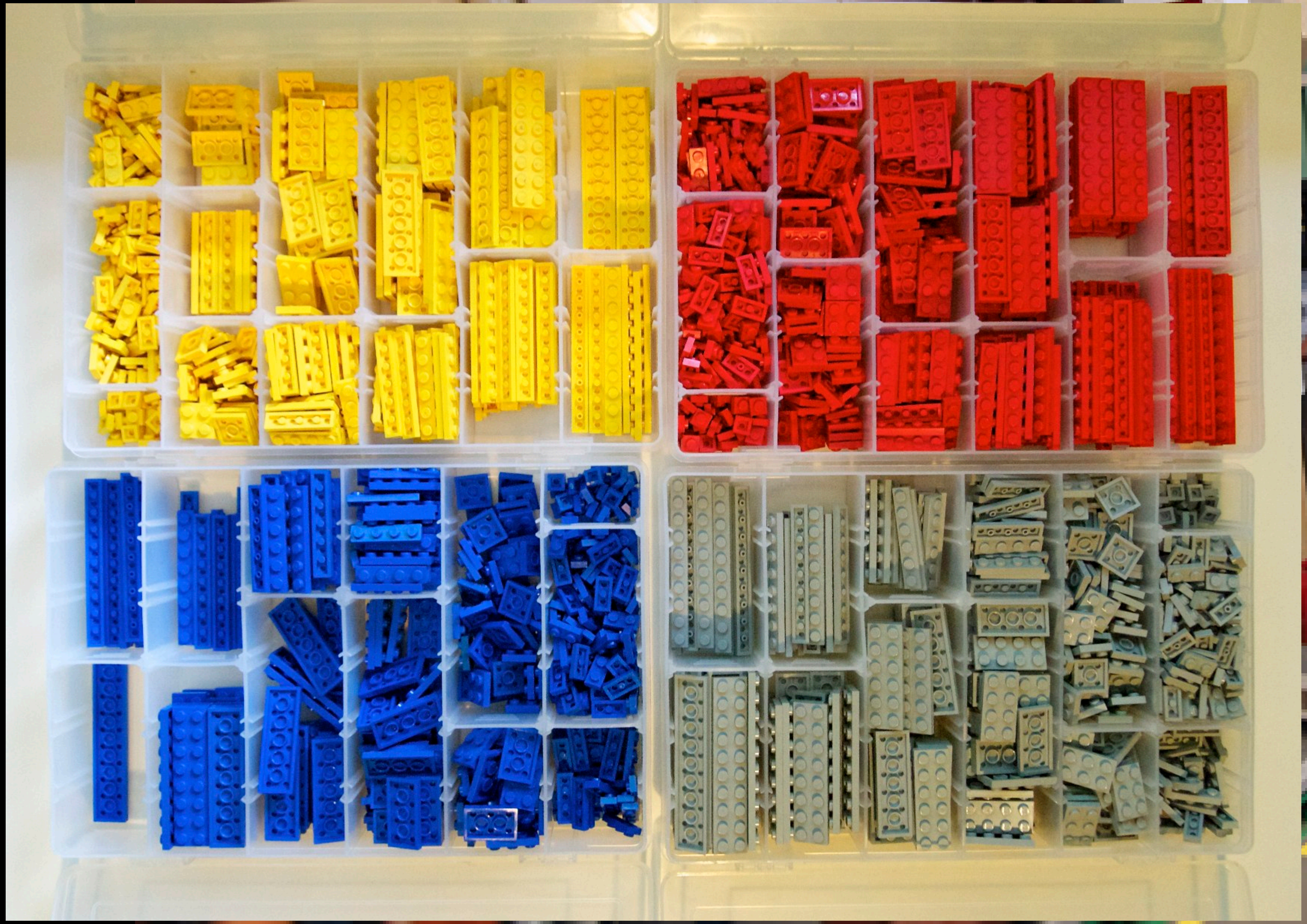
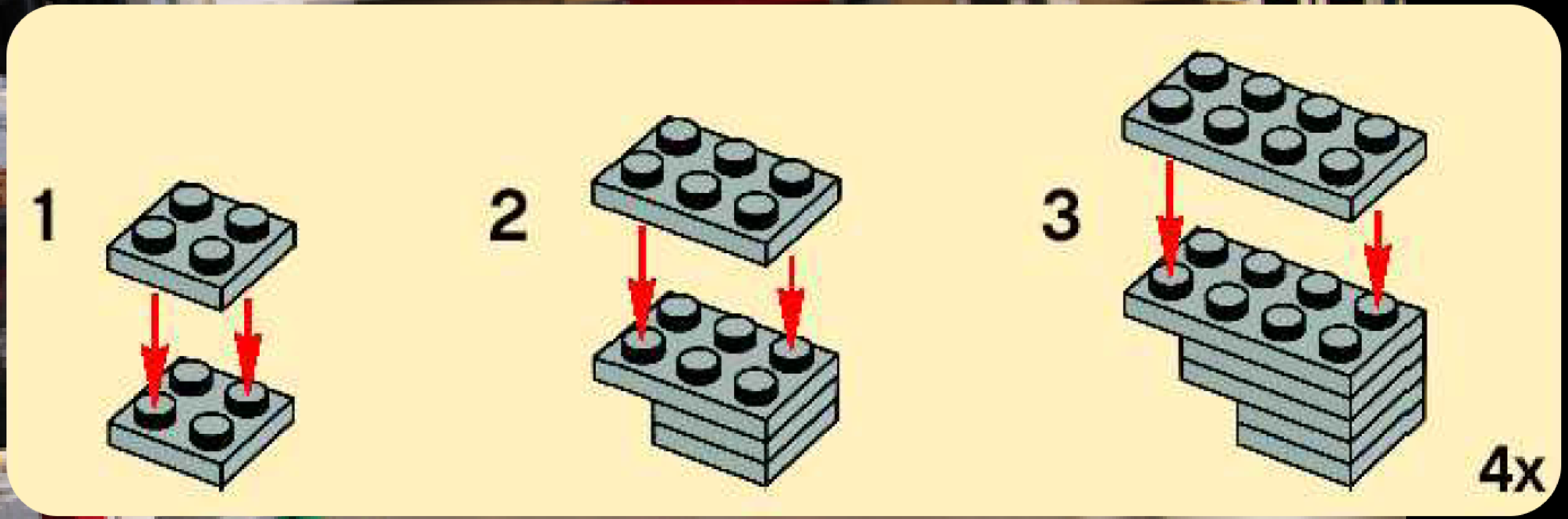


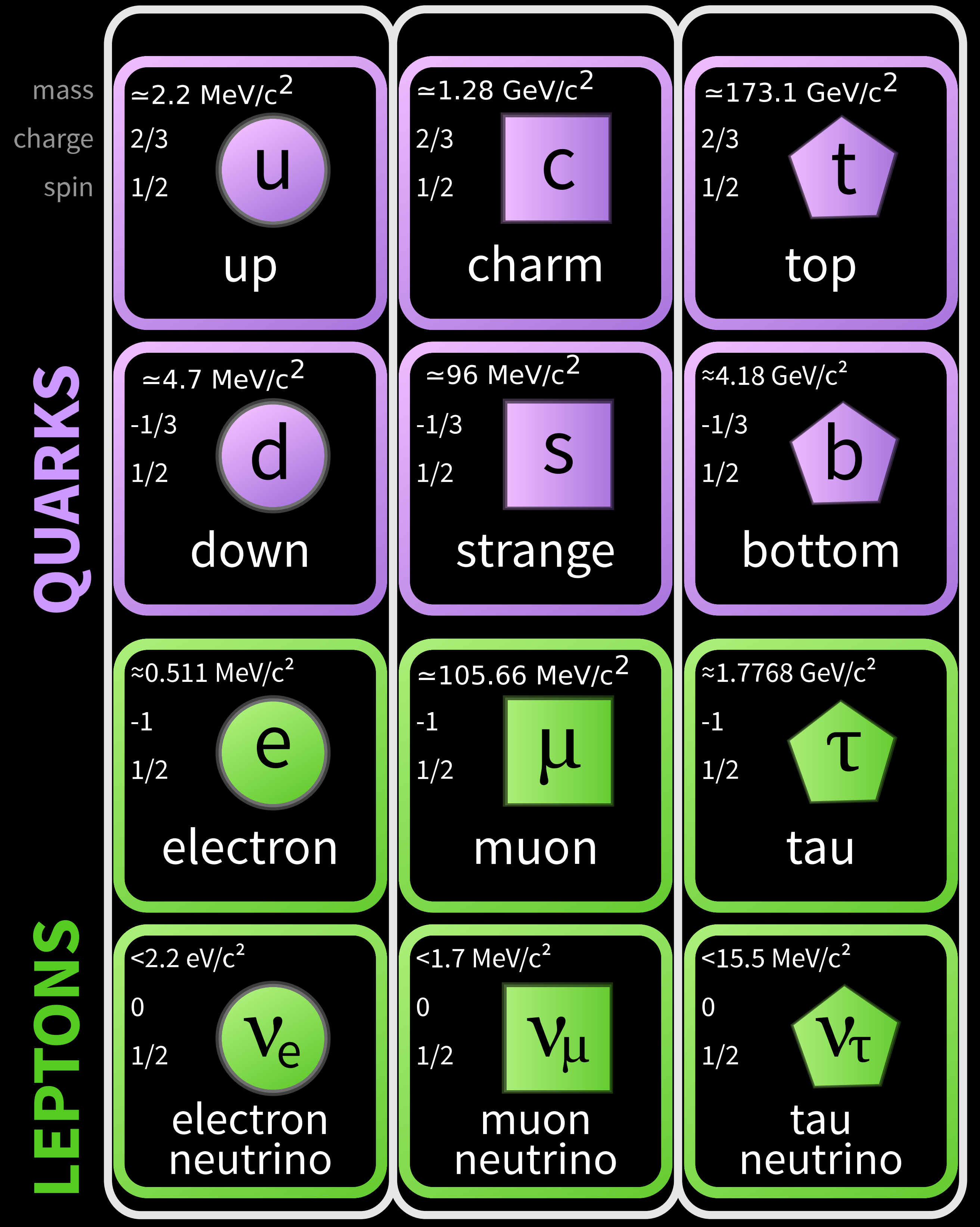
Constituents

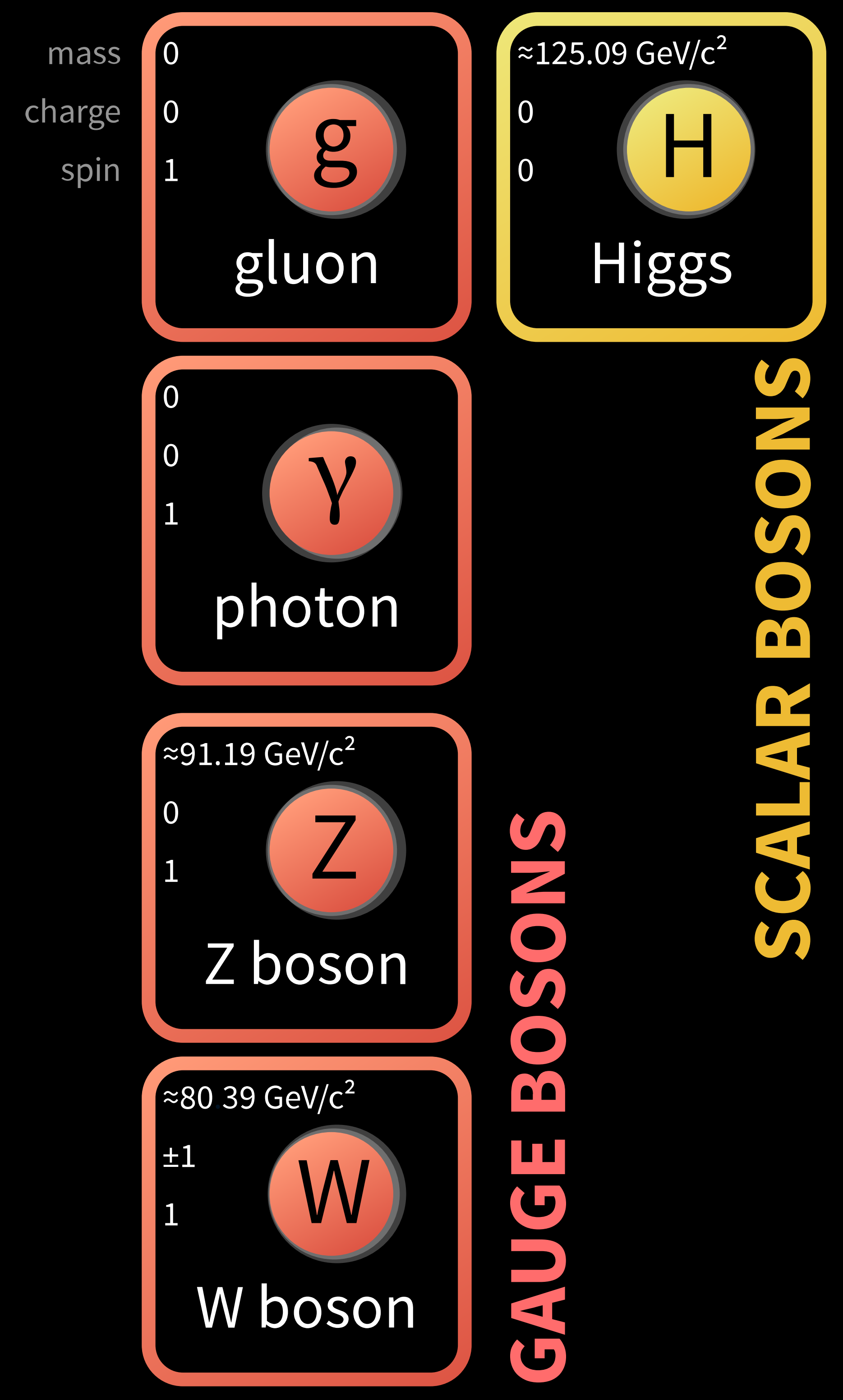


Interactions

The Standard Model of Particle Physics

3 x Families

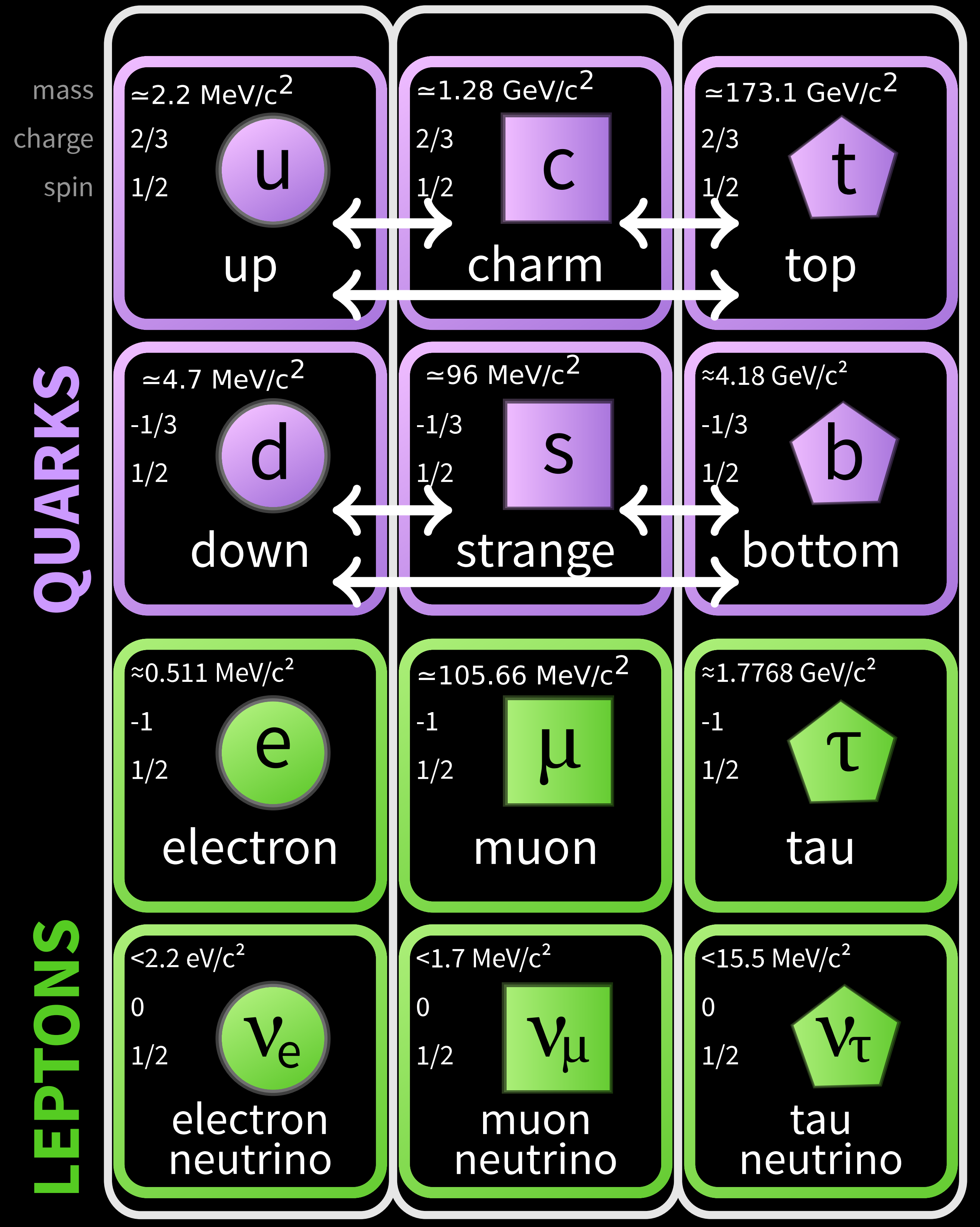




Constituents/Matter **Interactions/Forces**

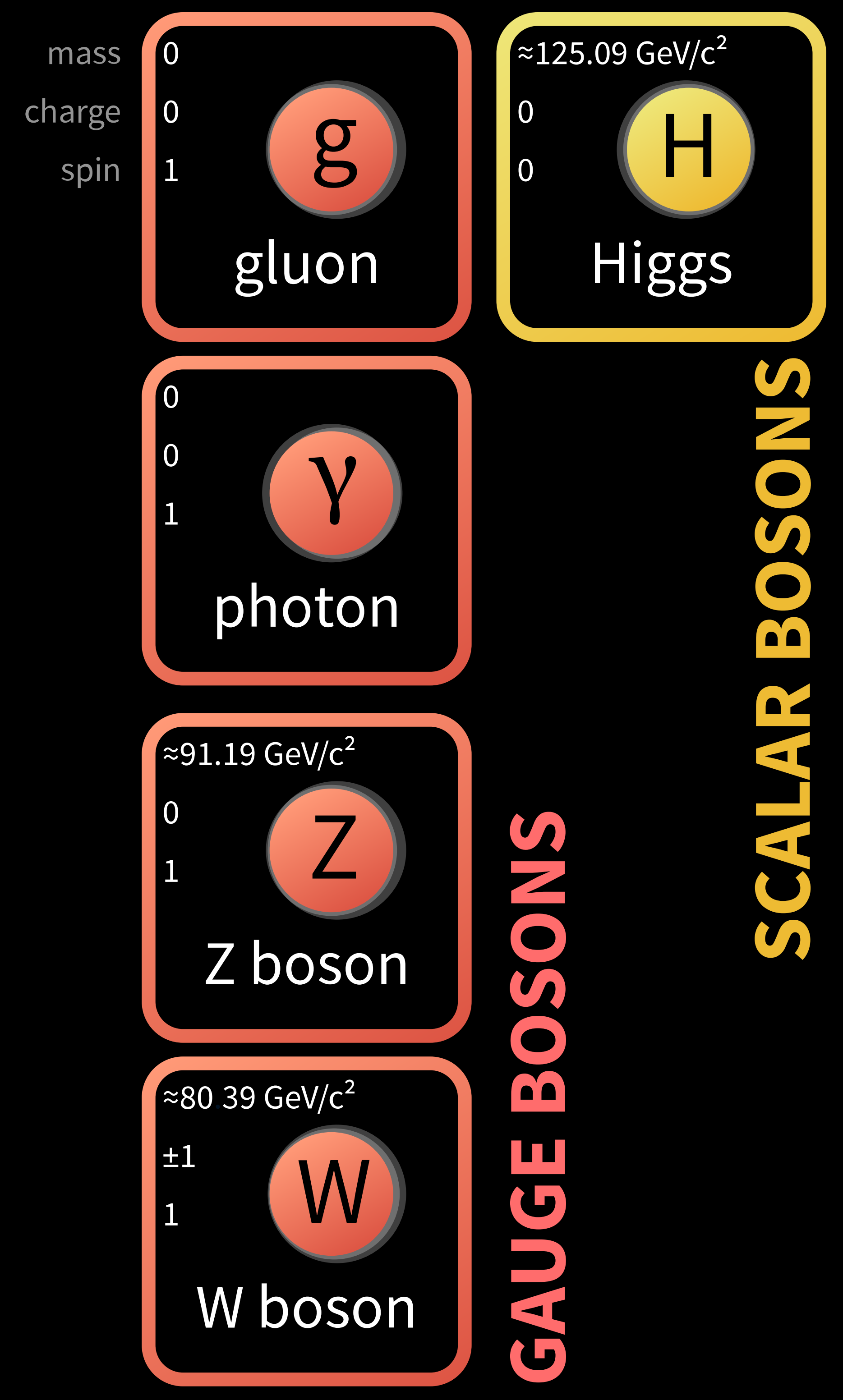
The Standard Model of Particle Physics

3 x Families



quark mixing

$$d' = V_{ud}\, d + V_{us}\, s + V_{ub}\, b$$



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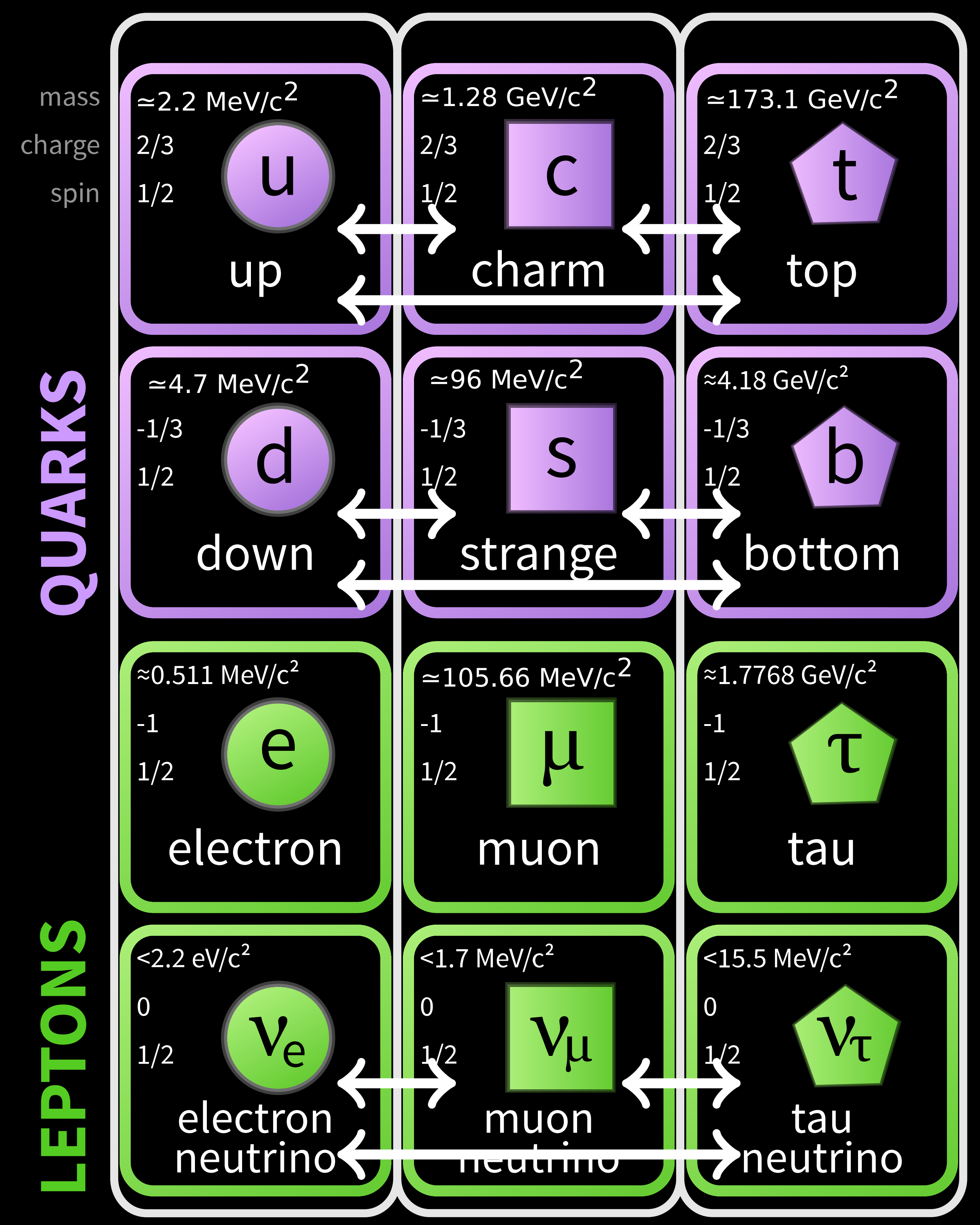
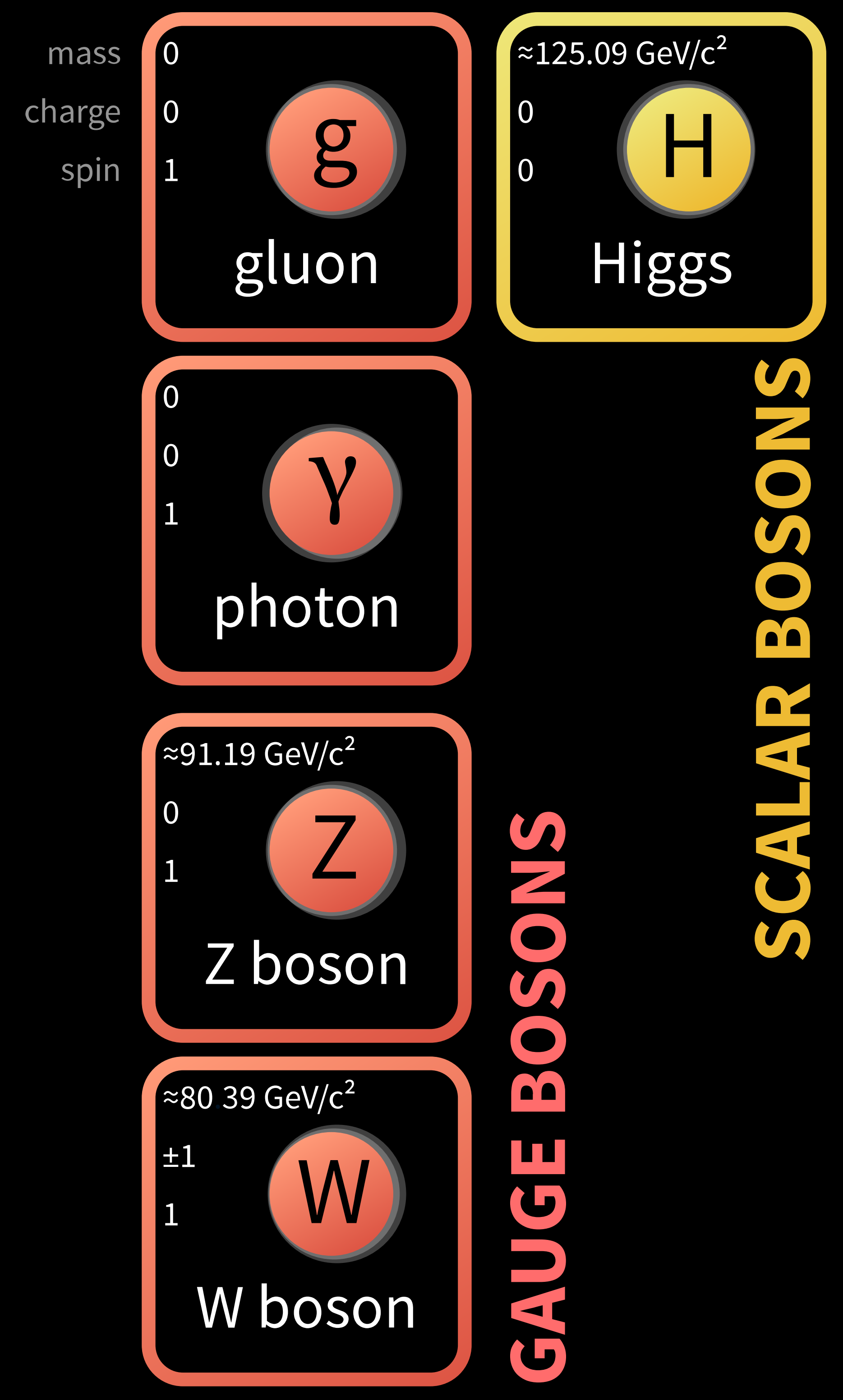


quark mixing

$$d' = V_{ud}\, d + V_{us}\, s + V_{ub}\, b$$

$$\nu_e = U_{e1}\, \nu_1 + U_{e2}\, \nu_2 + U_{e3}\, \nu_3$$

neutrino oscillation



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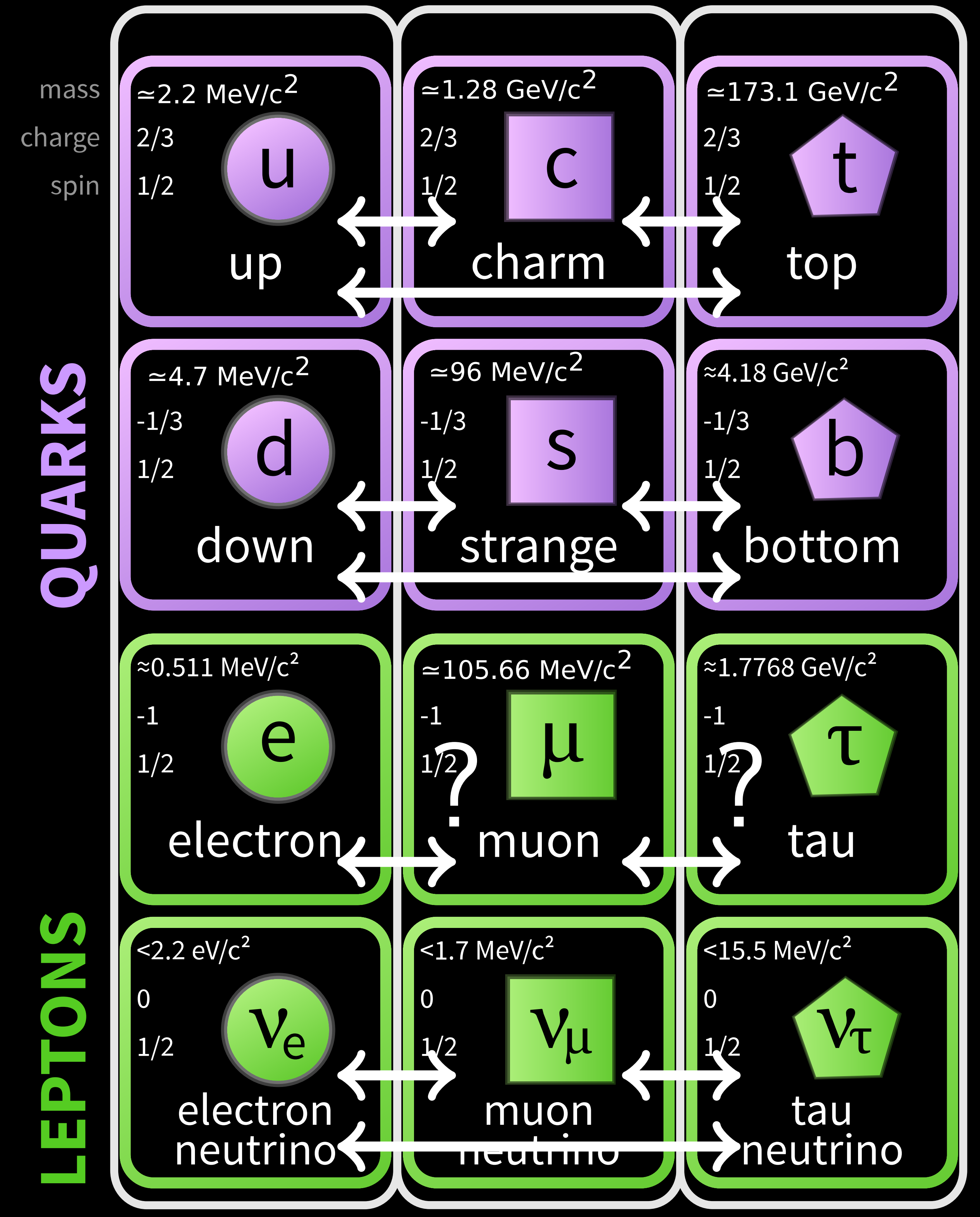


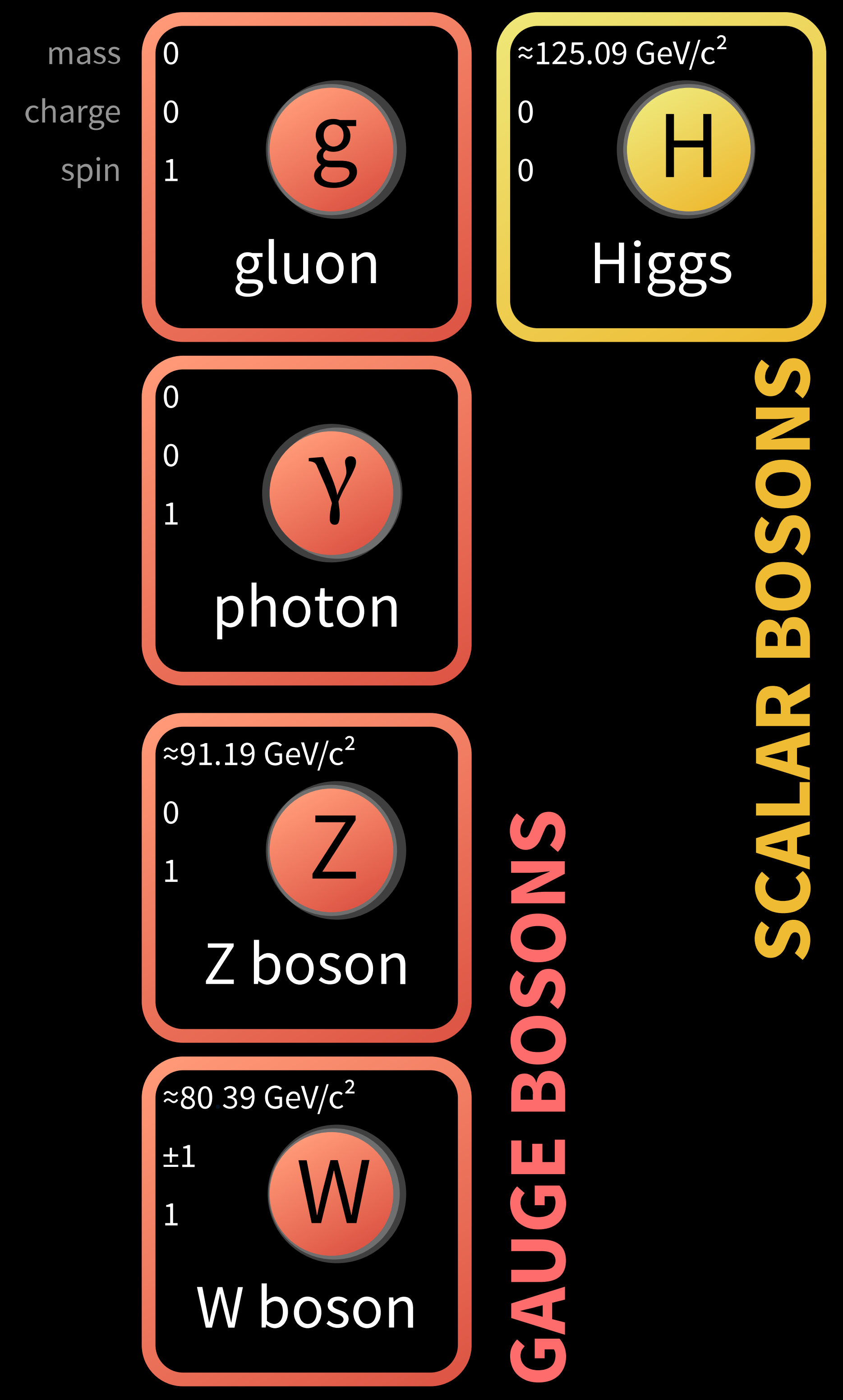
quark mixing

$d' = V_{ud}\, d + V_{us}\, s + V_{ub}\, b$

Charged Lepton Flavour Violation?

$\nu_e = U_{e1}\, \nu_1 + U_{e2}\, \nu_2 + U_{e3}\, \nu_3$

neutrino oscillation



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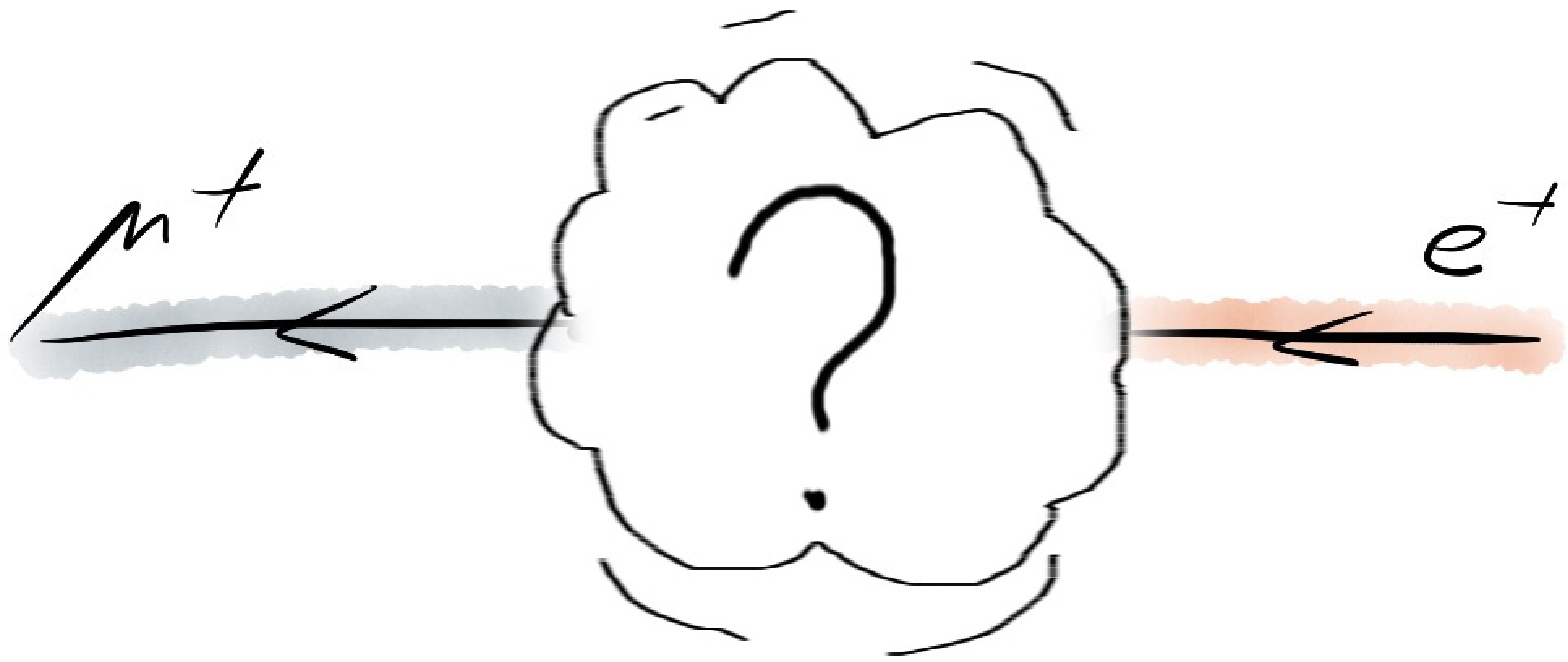

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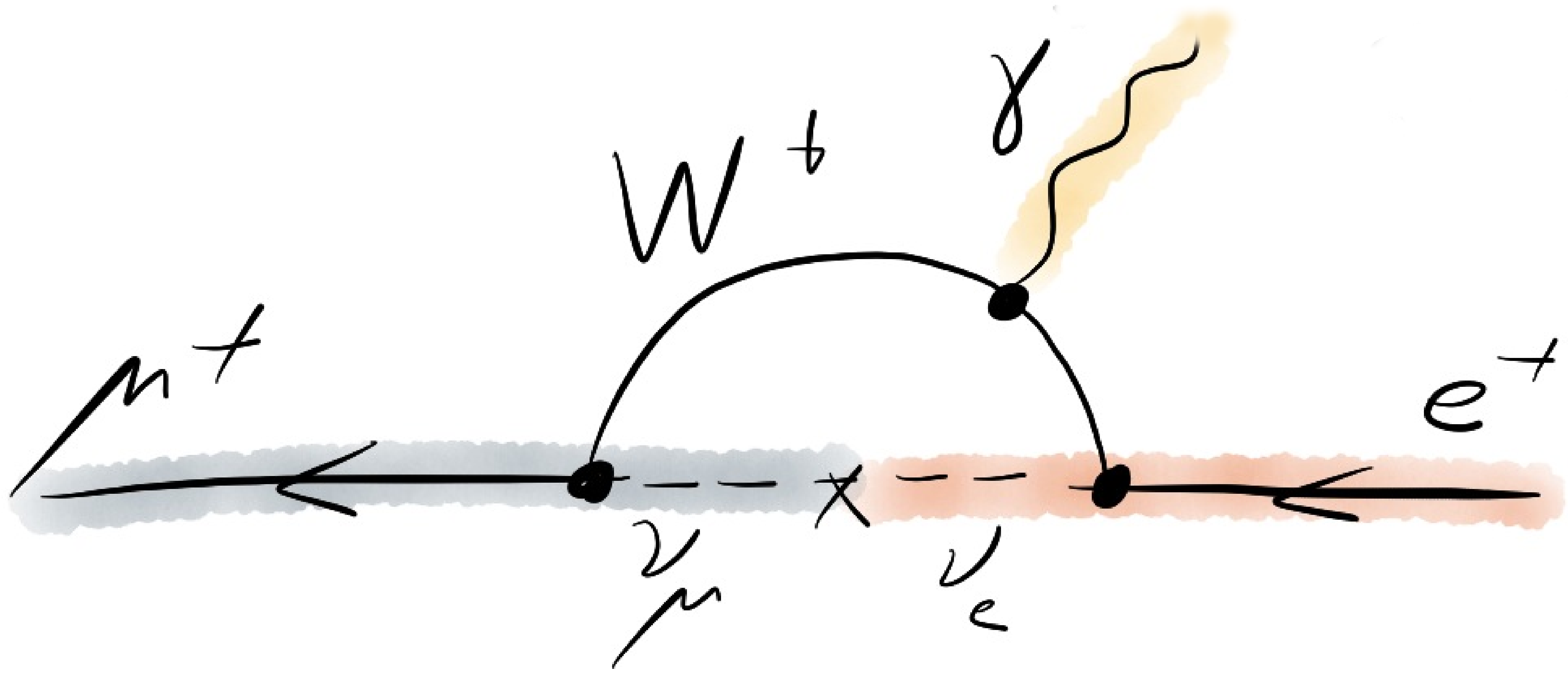


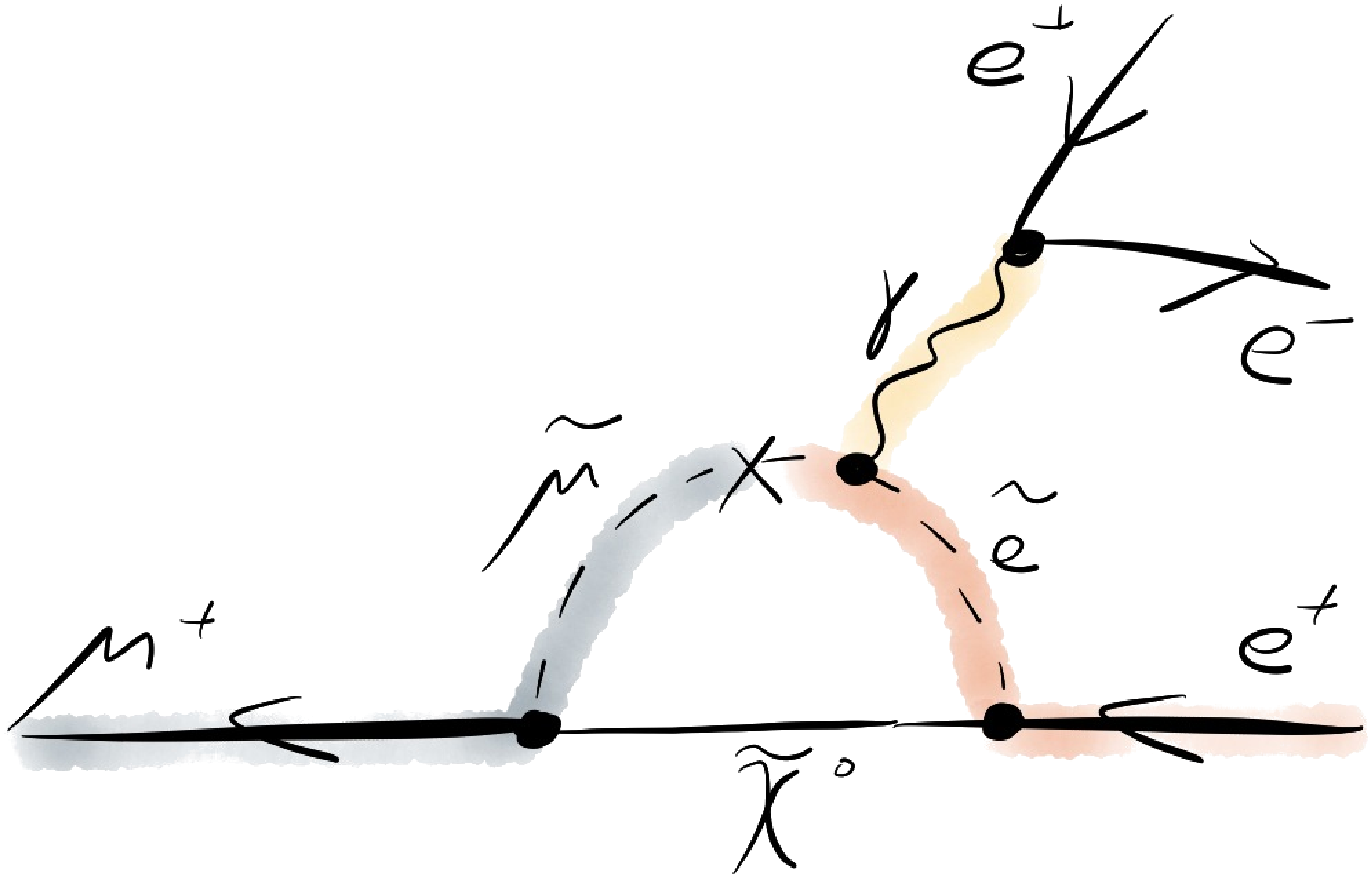
Standard Model branching fractions

$< 10^{-54}$

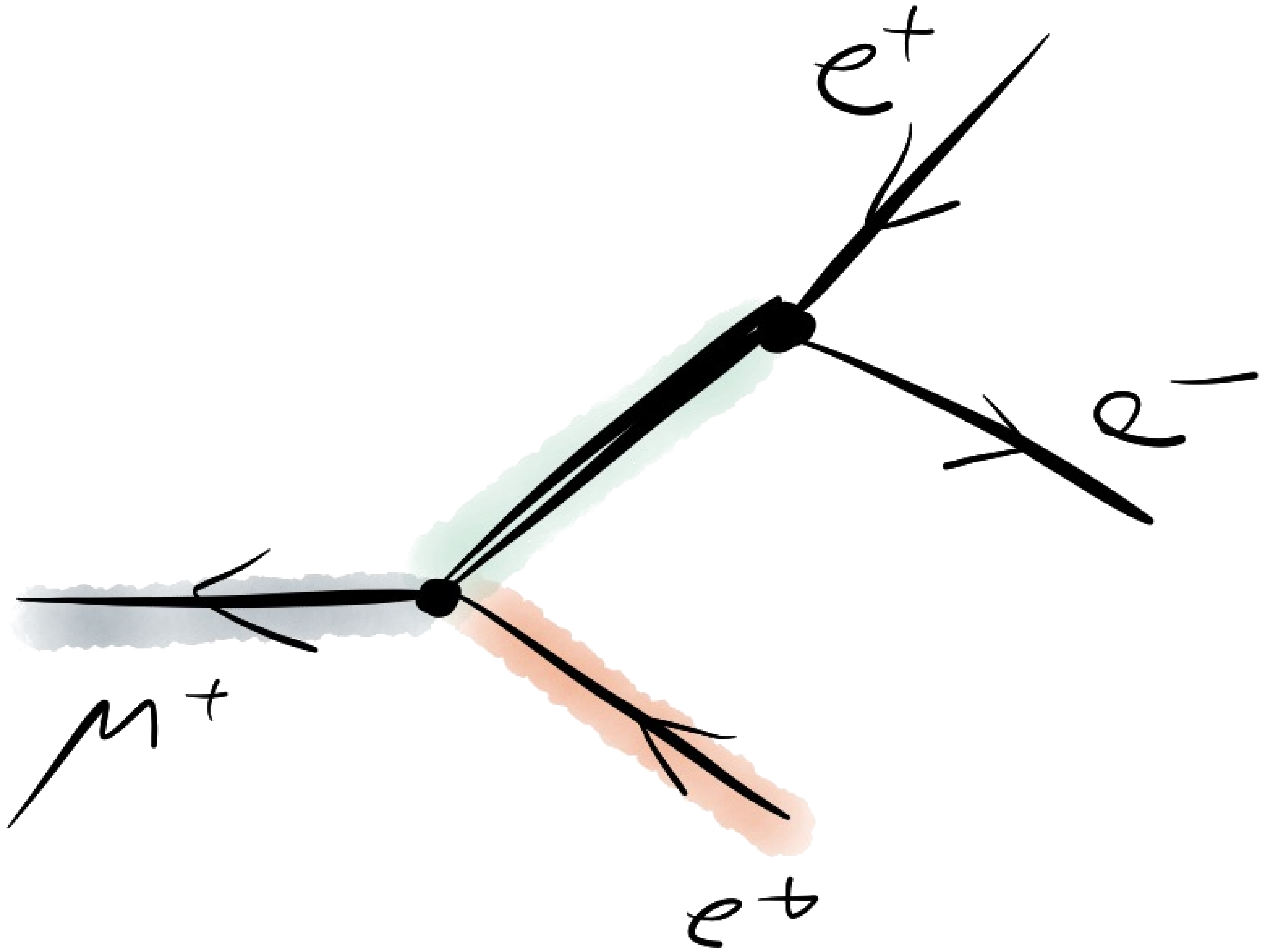
any observation is **new physics**

$\sim \left(\frac{\Delta m_\nu^2}{m_W^2}\right)^2$

Charged Lepton Flavour Violation

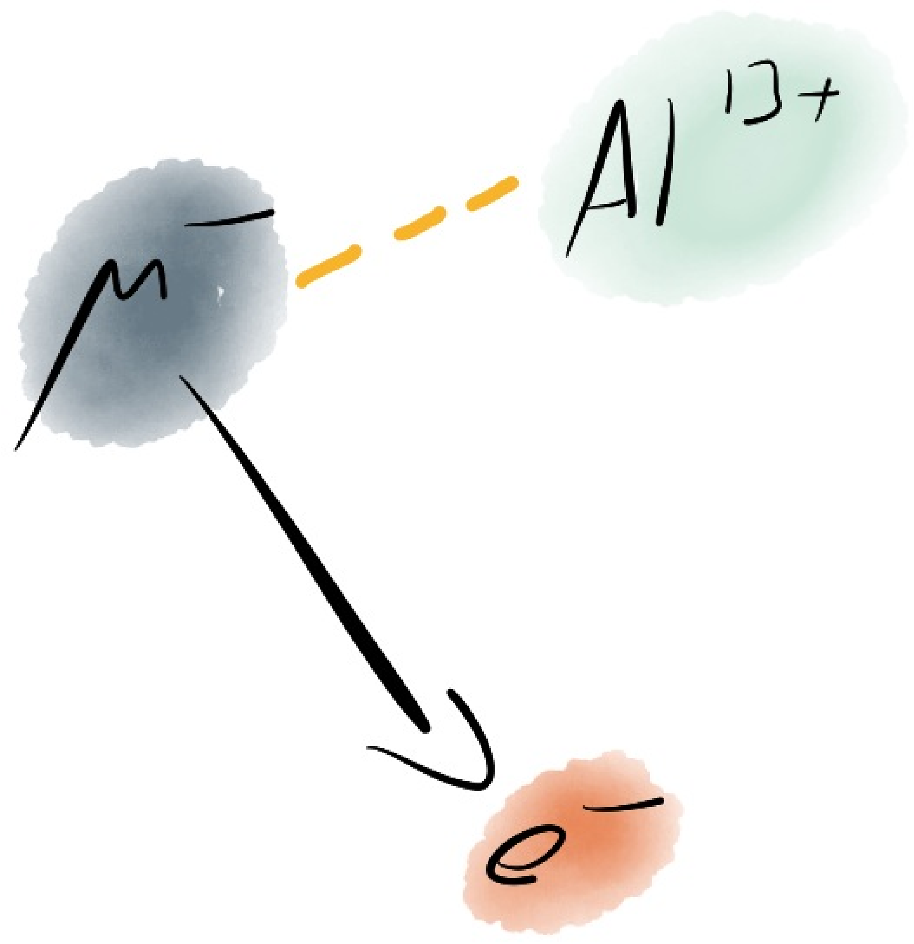


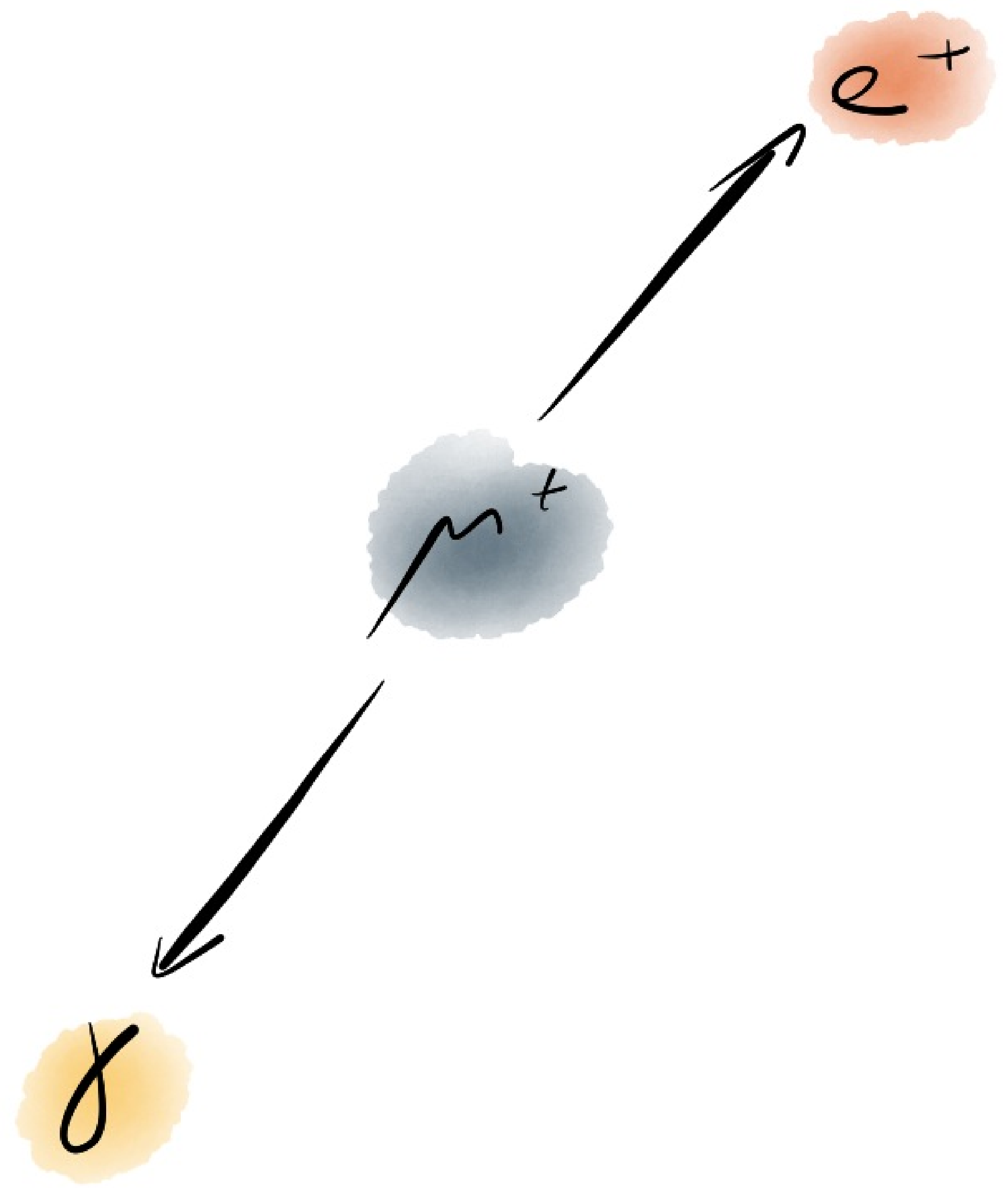
loop (SUSY) scenario

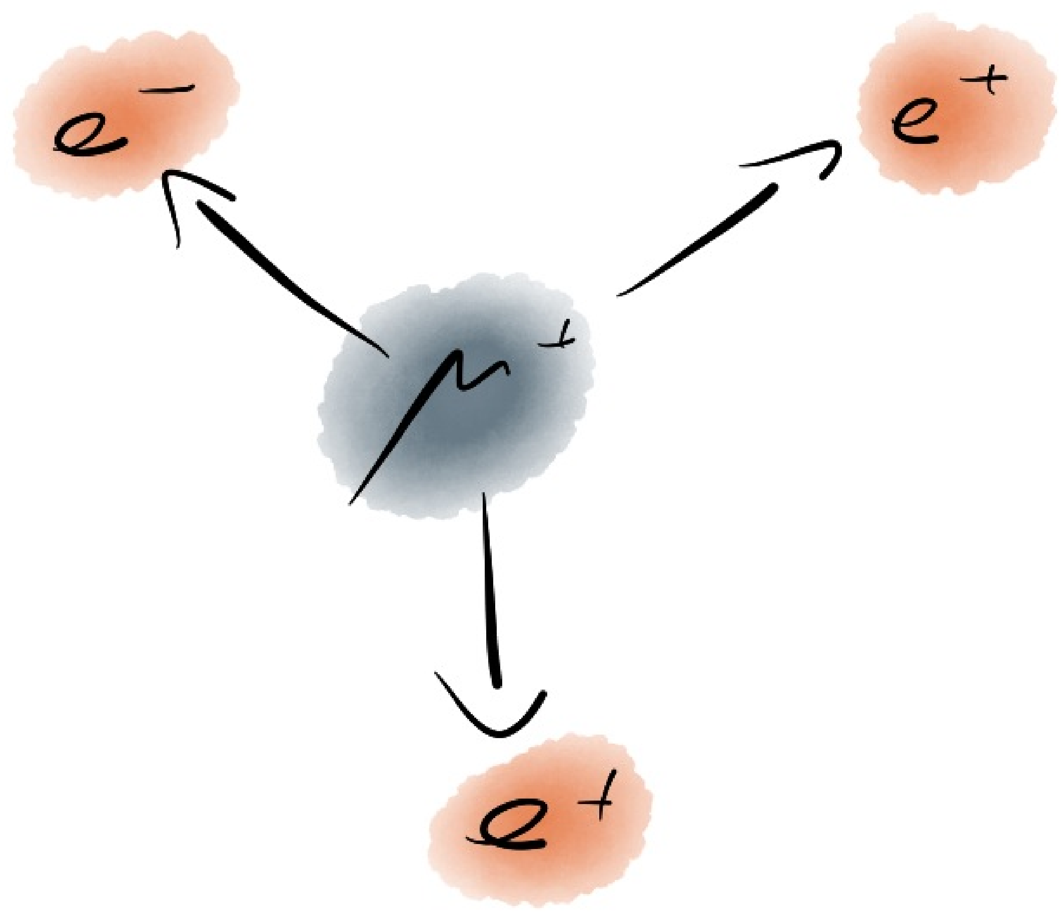


tree-level scenario

Charged Lepton (Muon) Flavour Violating **Decays**

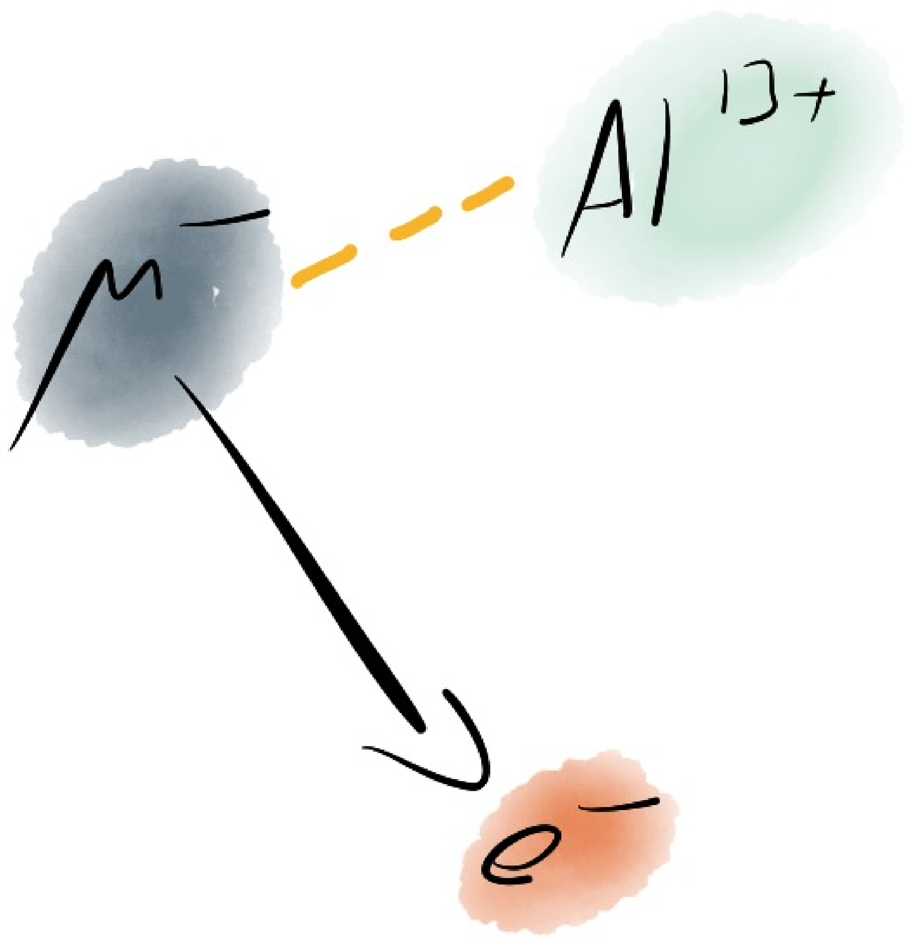


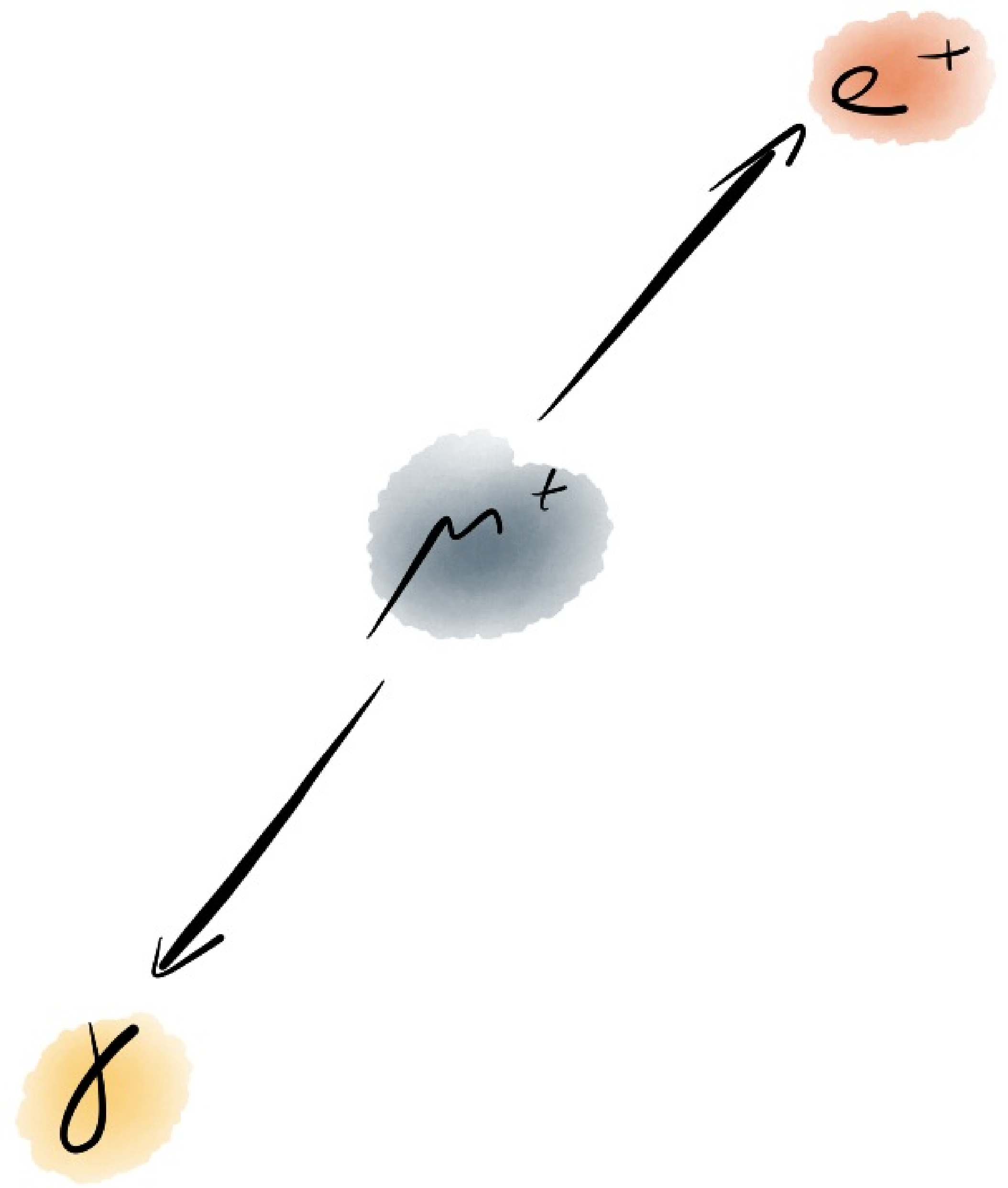


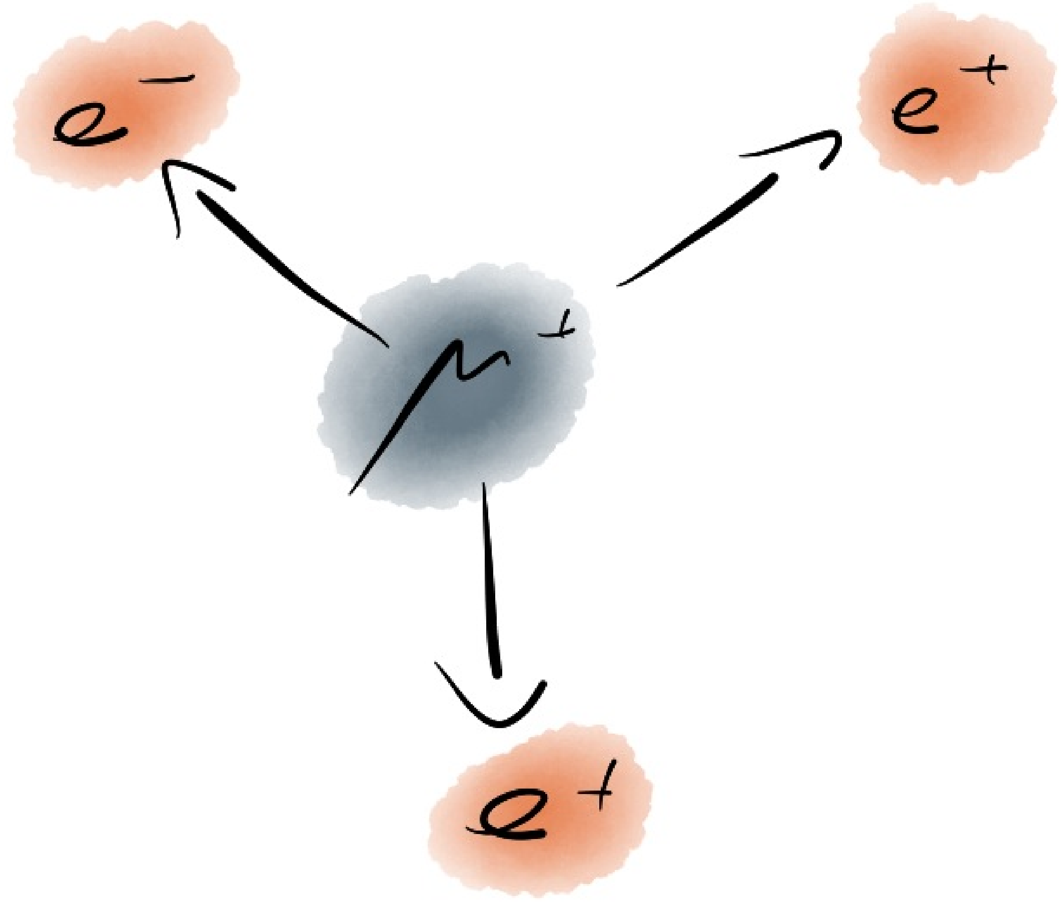


$\mu^- N \to e^- N$	$\mu^+ \to e^+ \gamma$	$\mu^+ \to e^+ e^- e^+$
SINDRUM II (PSI, 2006) $Br < 7 \cdot 10^{-13}$ $(N = Au)$	**MEG** (PSI, 2016) $Br < 4.2 \cdot 10^{-13}$	**SINDRUM** (PSI, 1988) $Br < 1.0 \cdot 10^{-12}$
DeeMe, COMET, Mu2e (J-PARC/FNAL) $Br \lesssim 3 \cdot 10^{-15} - 2.6 \cdot 10^{-17}$	**MEG II** (PSI) $Br \lesssim 5 \cdot 10^{-14}$	**Mu3e** (PSI) $Br \lesssim 2.0 \cdot 10^{-15} - 1.0 \cdot 10^{-16}$

Charged Lepton (Muon) Flavour Violating **Decays**







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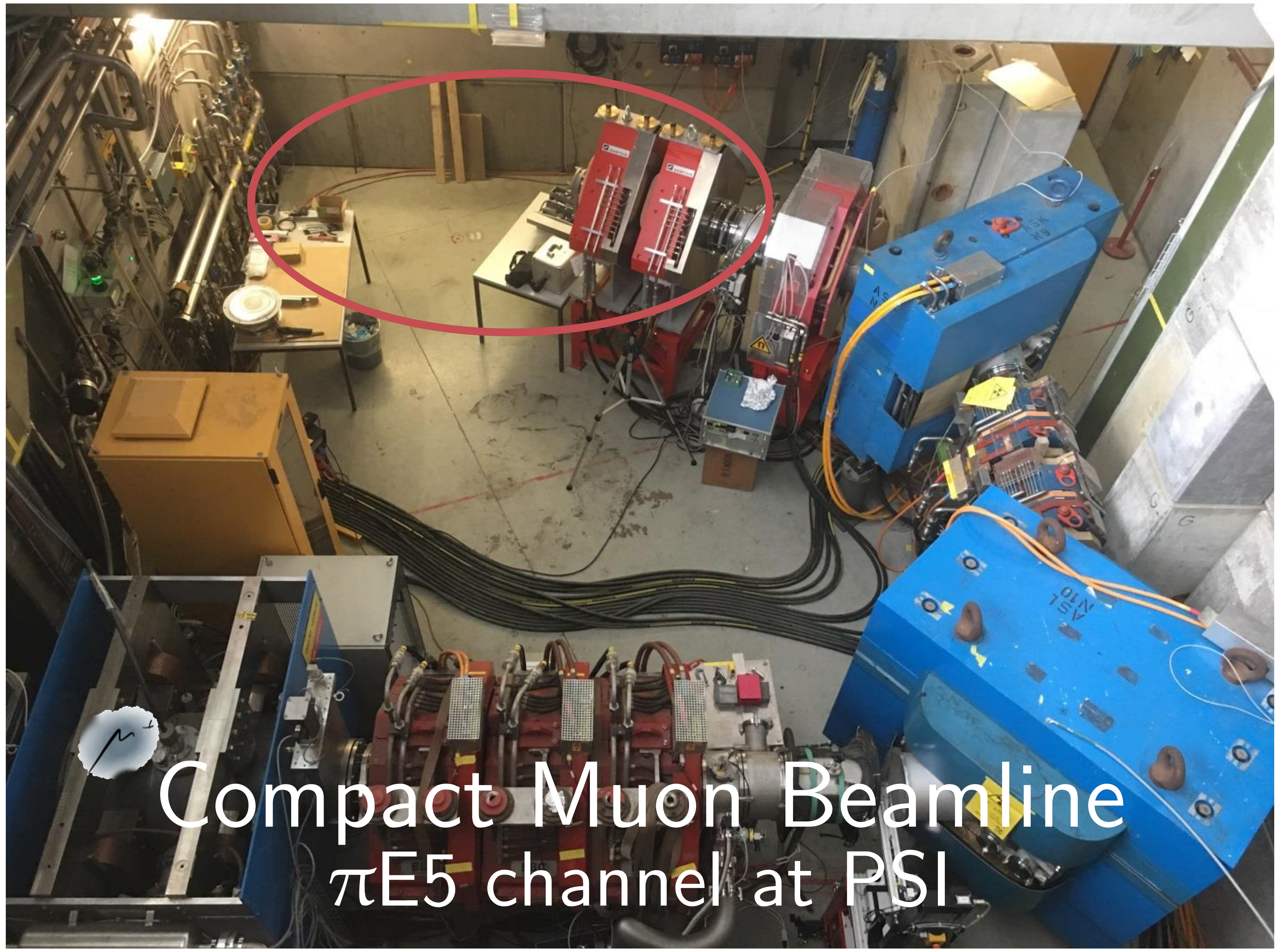
The Mu3e Experiment

Mu3e is a **dedicated** experiment for the search of the charged **lepton flavour violating** decay

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

that aims at a sensitivity better than $\mathbf{10^{-16}}$.



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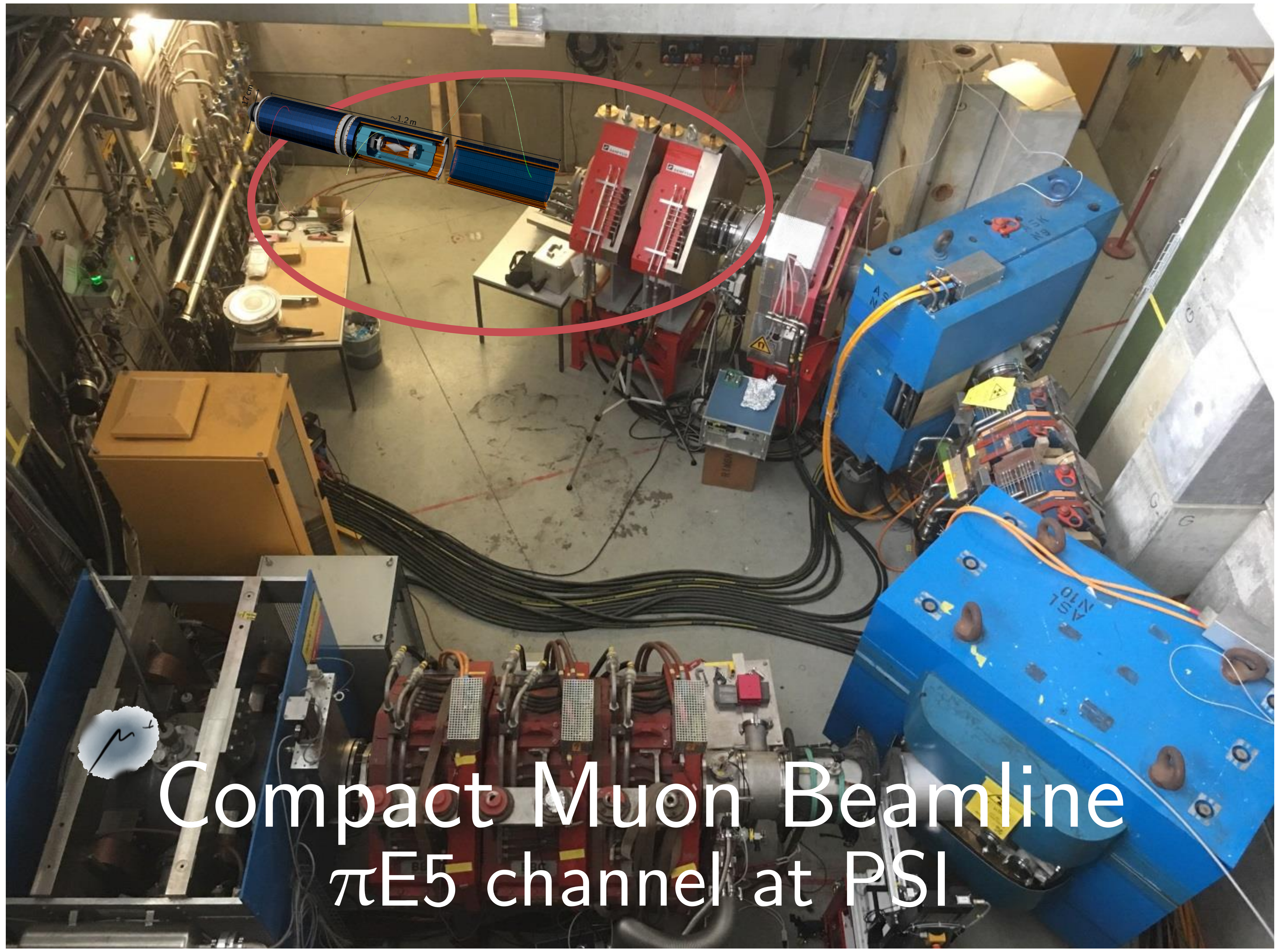

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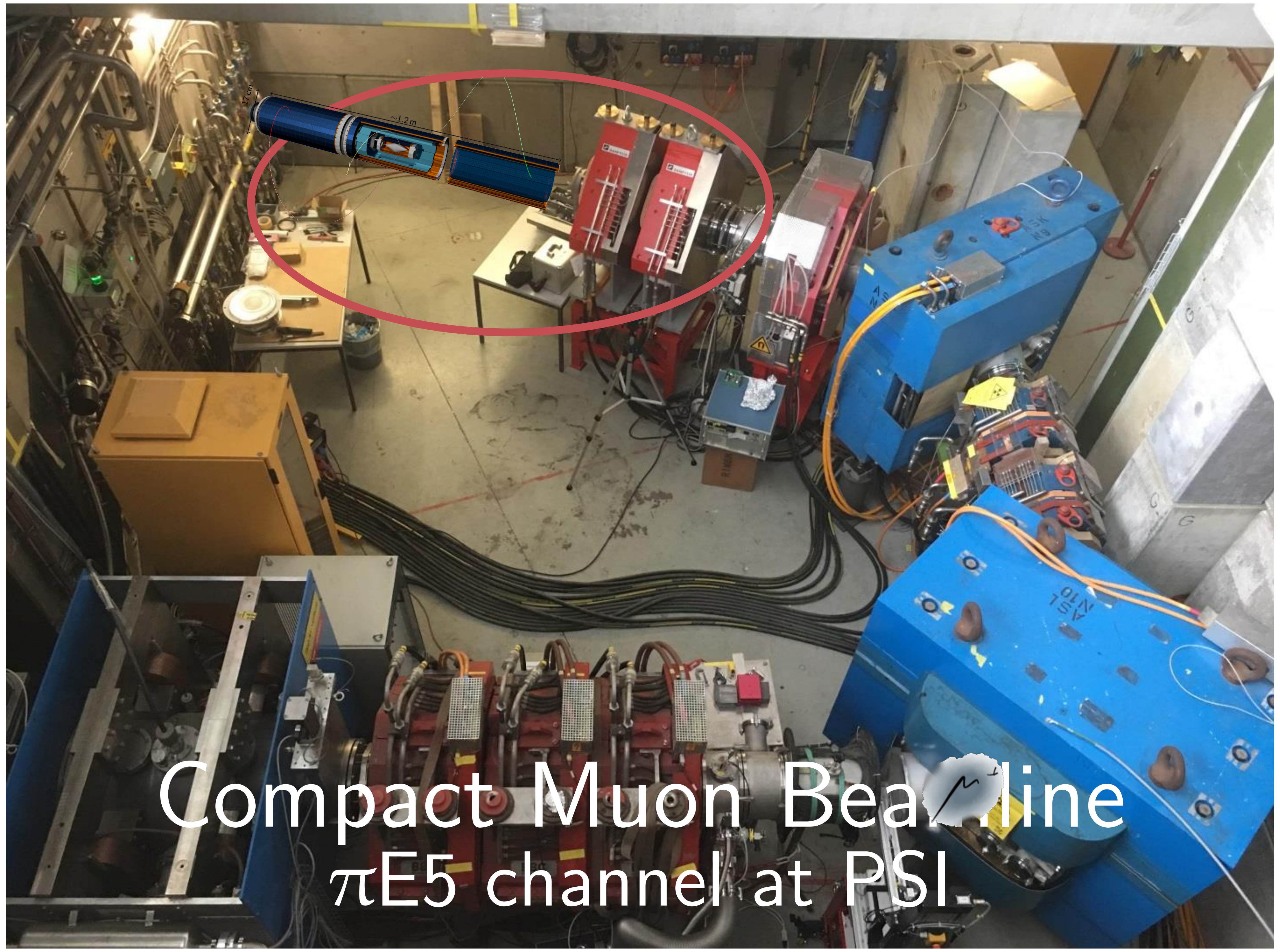

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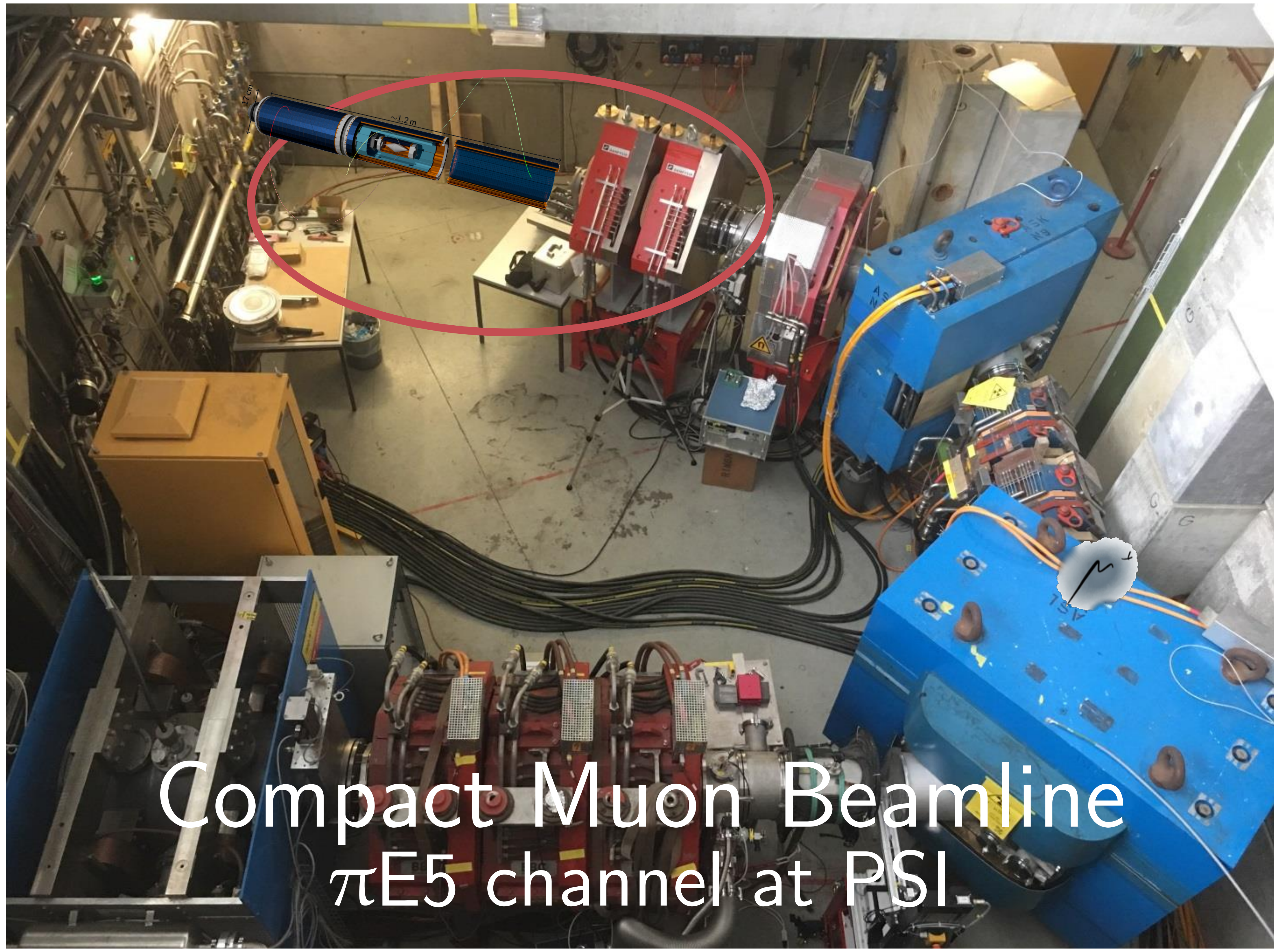

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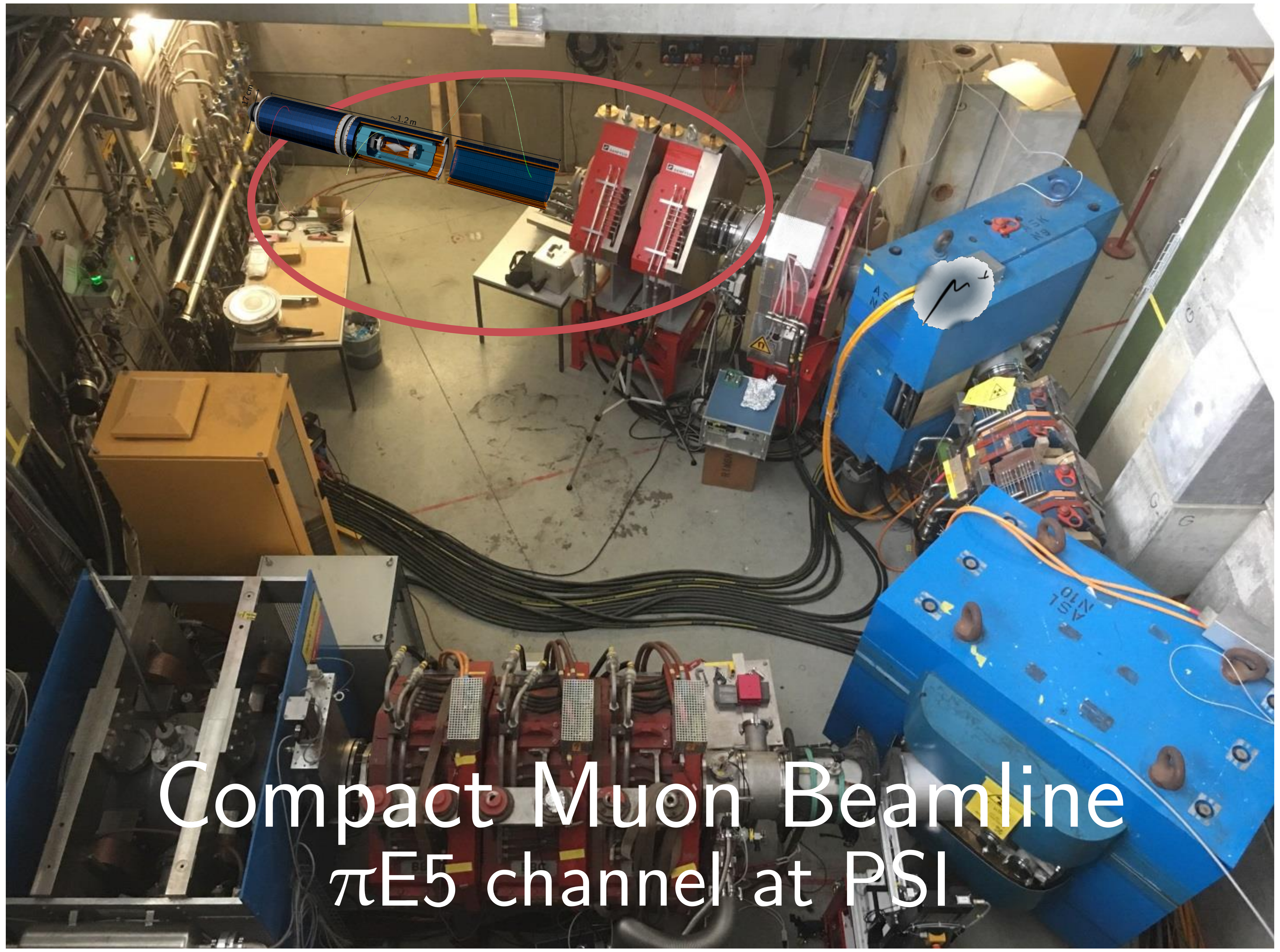

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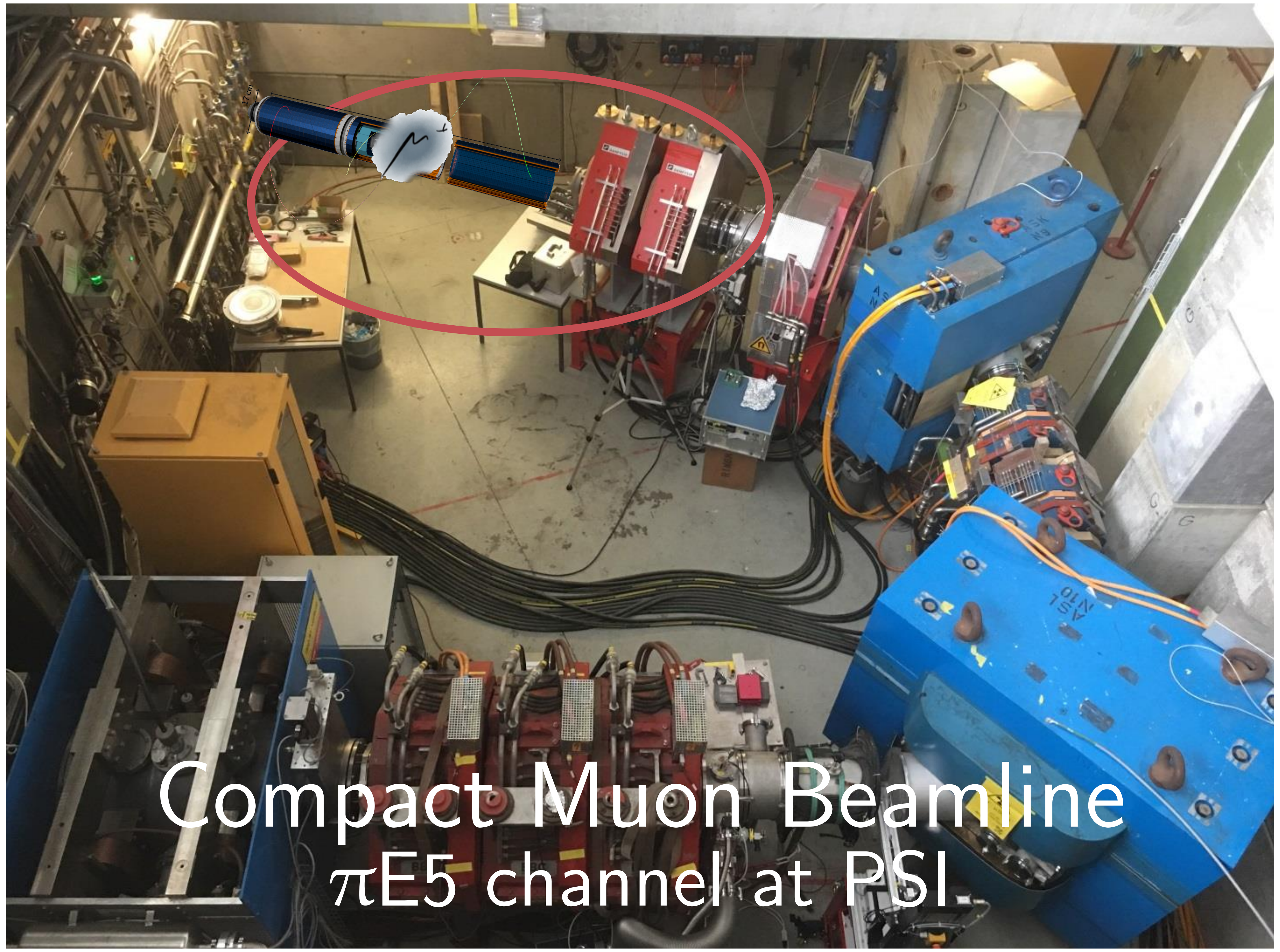
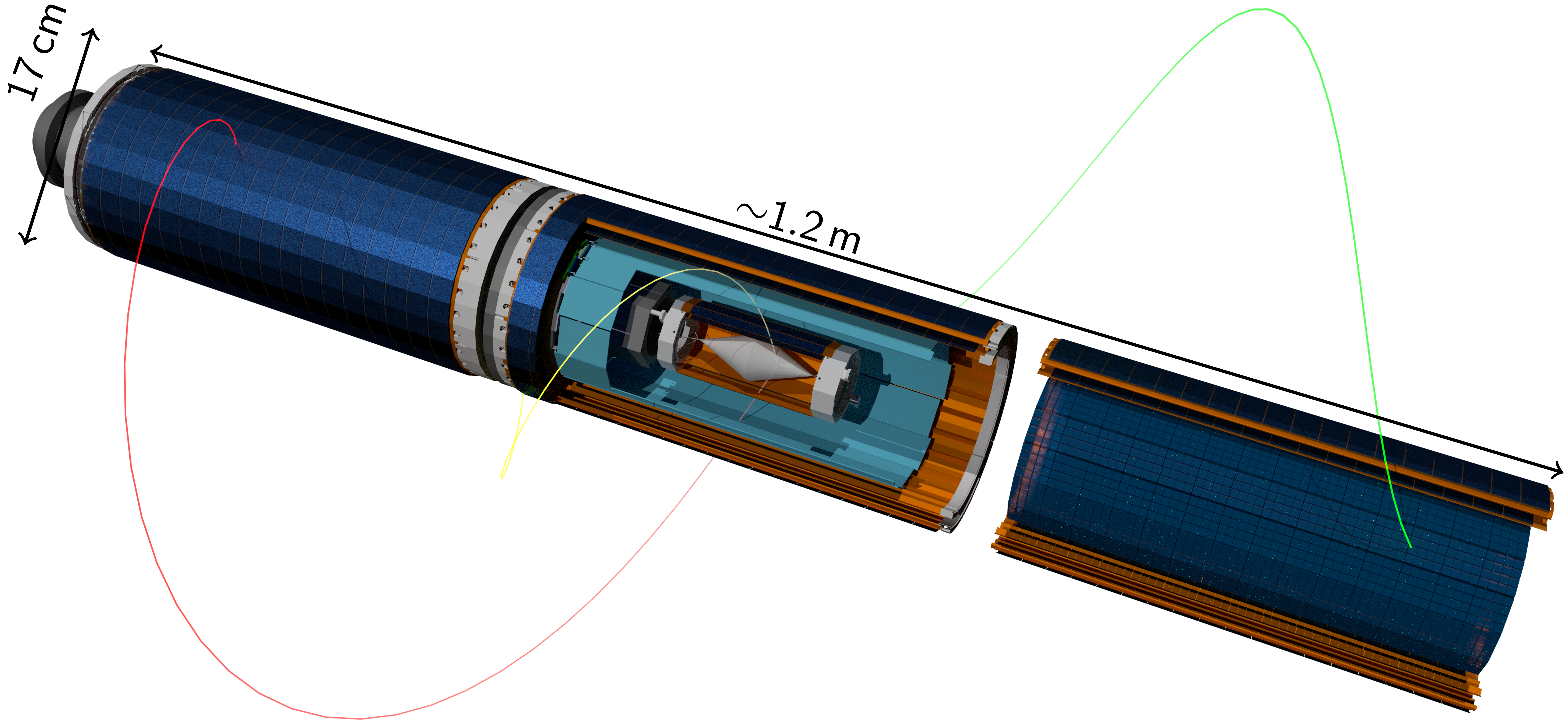


The Mu3e Detector



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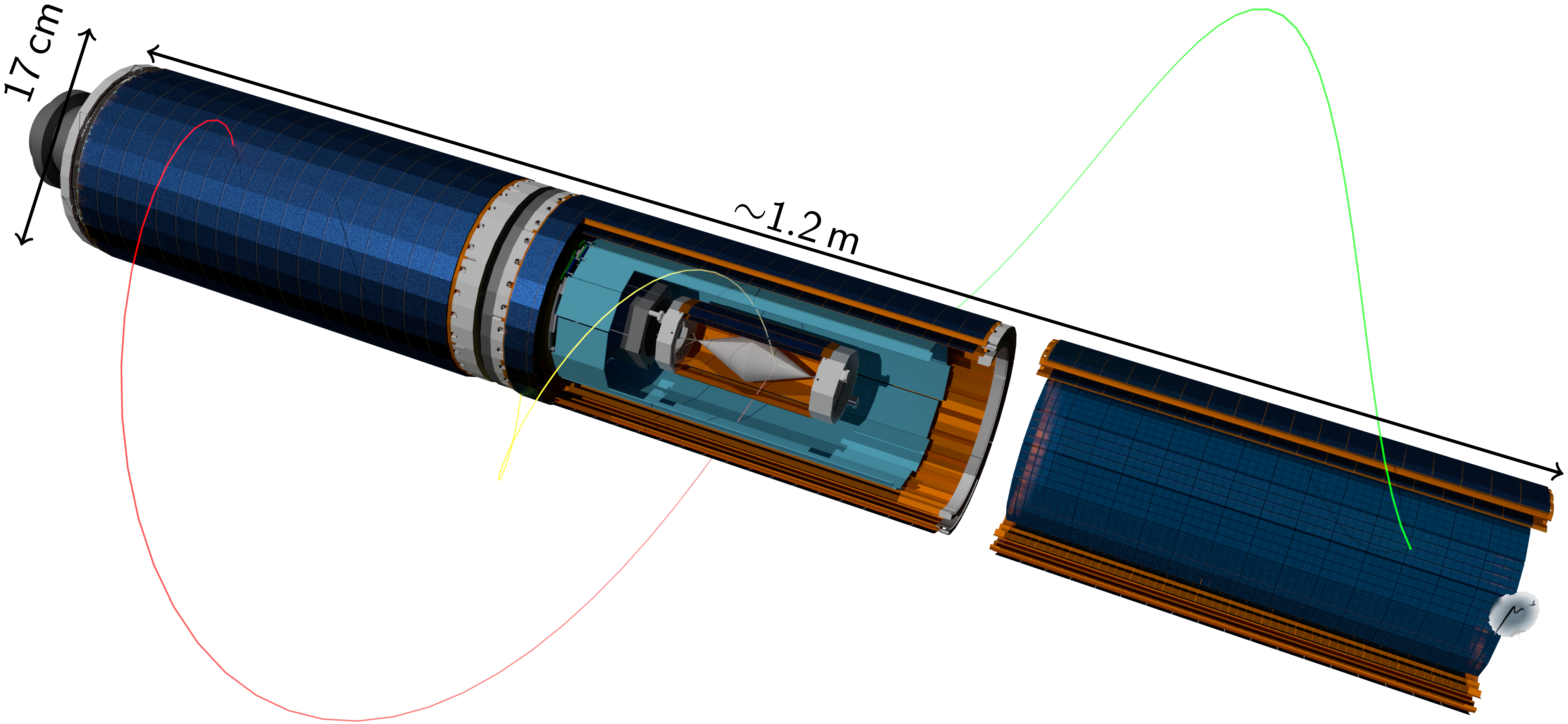

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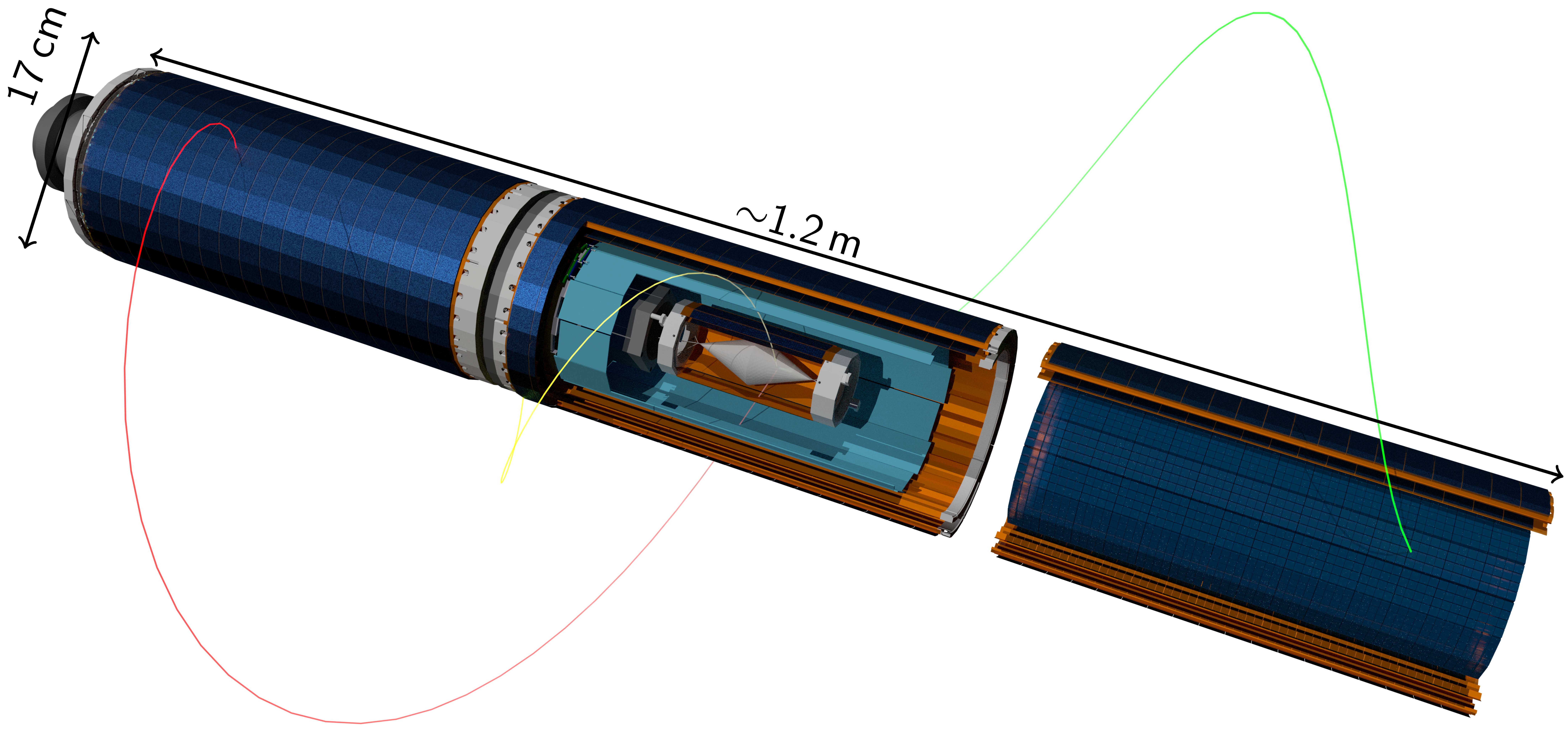

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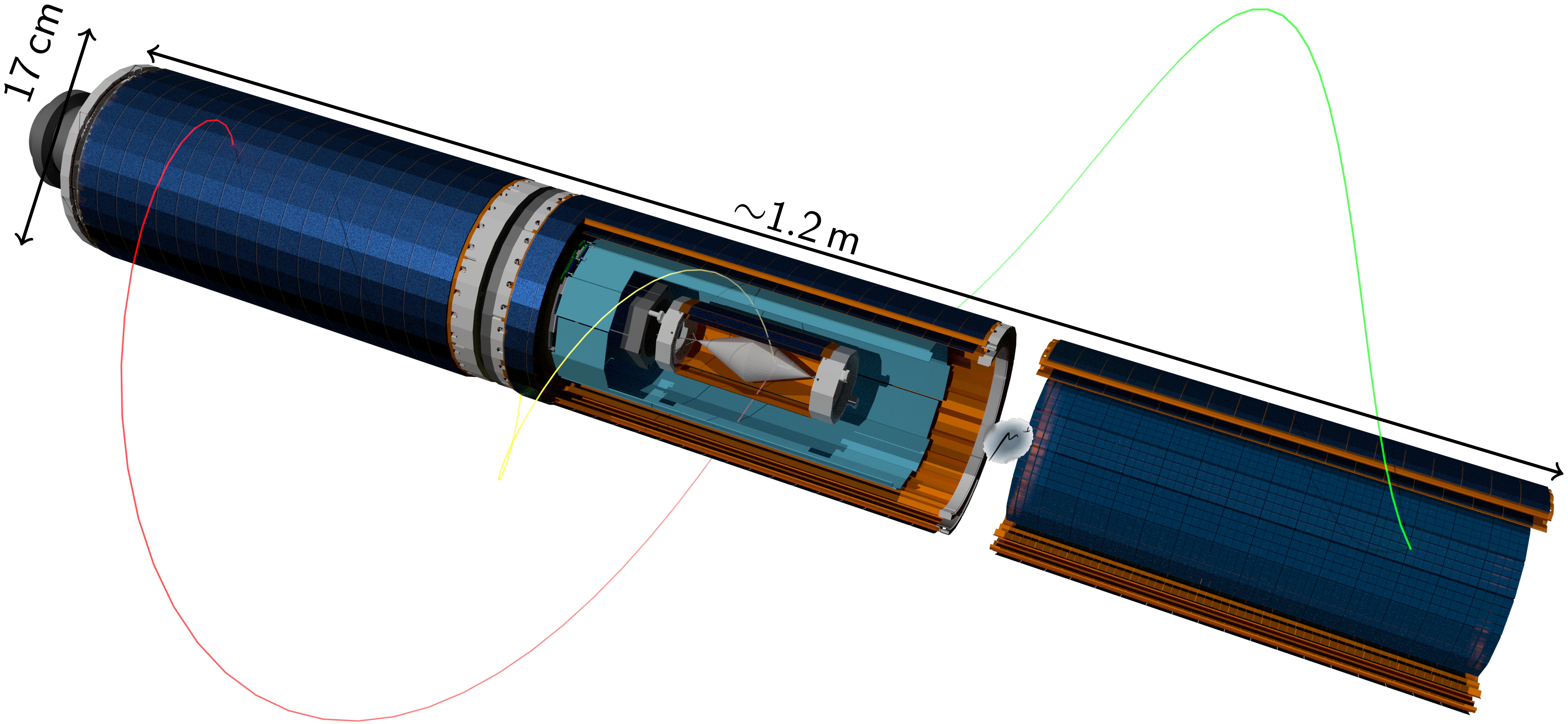

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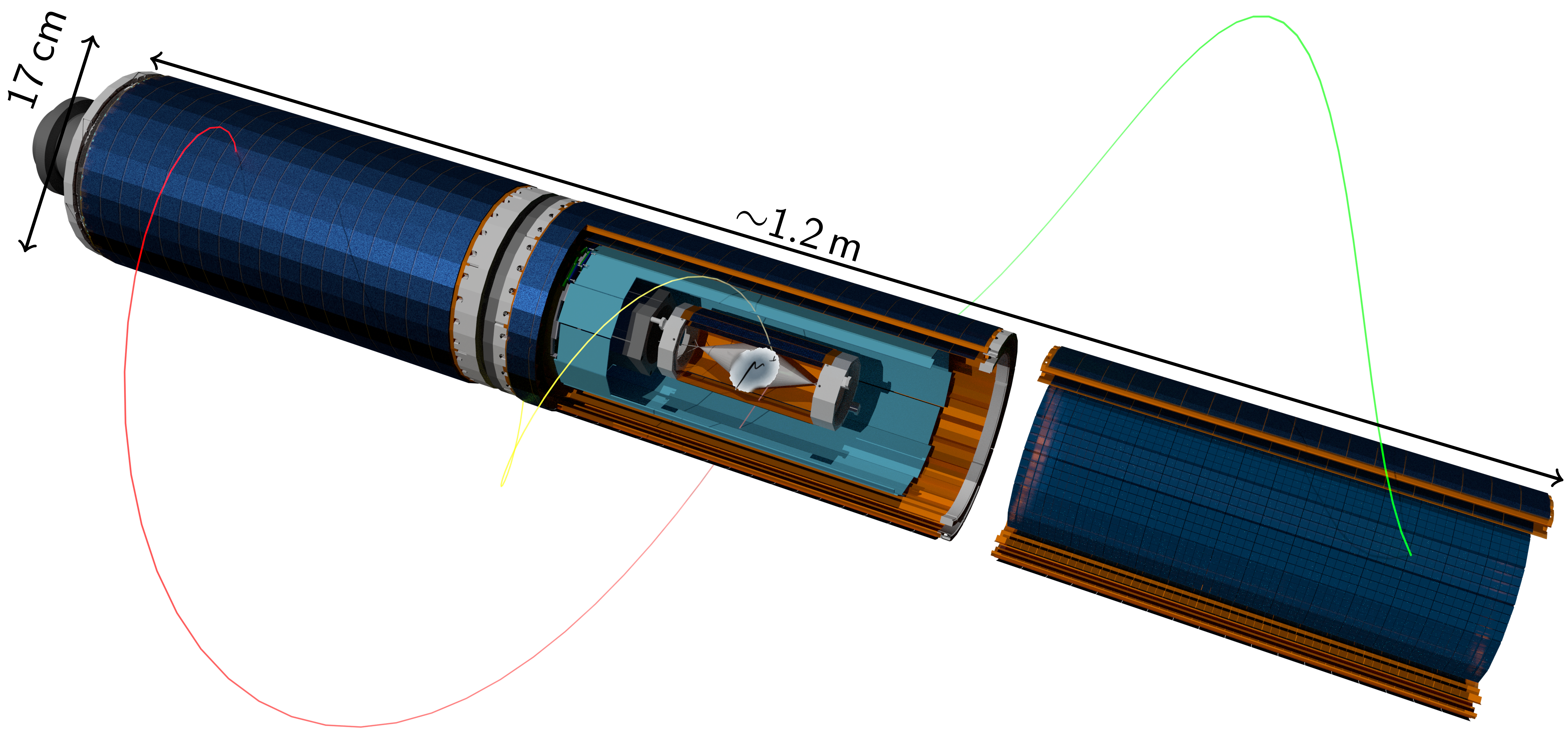


The Mu3e Detector

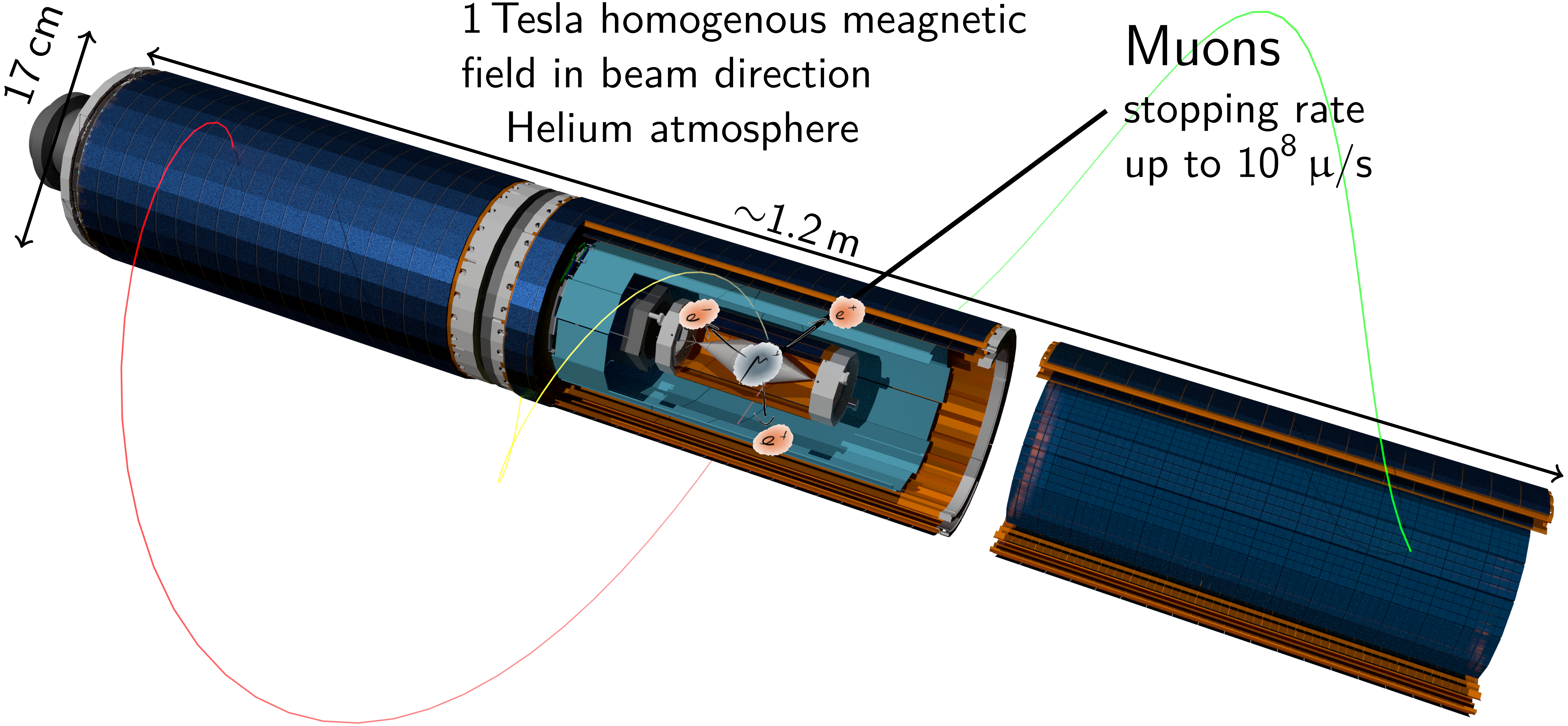
Environment

1 Tesla homogenous meagnetic field in beam direction

Helium atmosphere

Muons

stopping rate up to 10^8 μ/s



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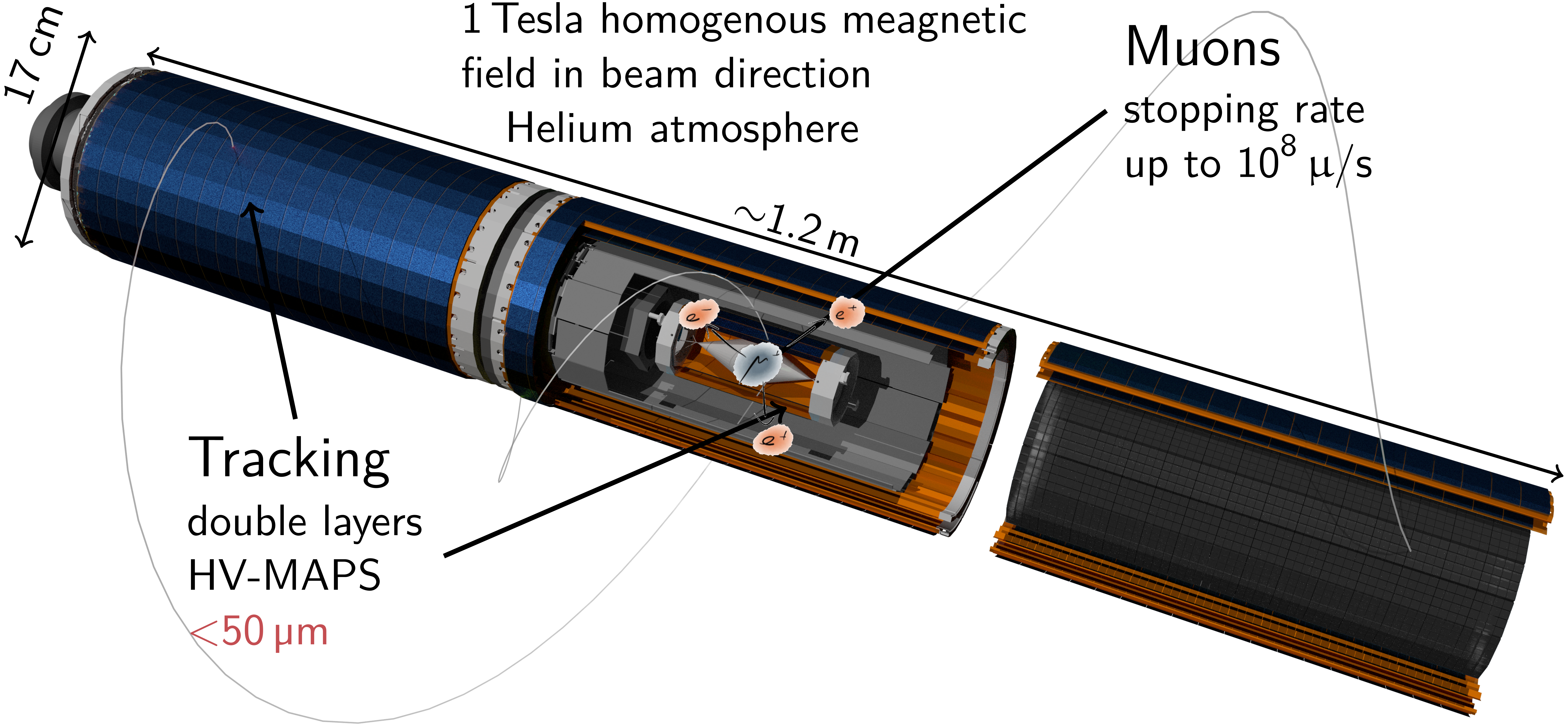

Environment

1 Tesla homogenous meagnetic field in beam direction

Helium atmosphere

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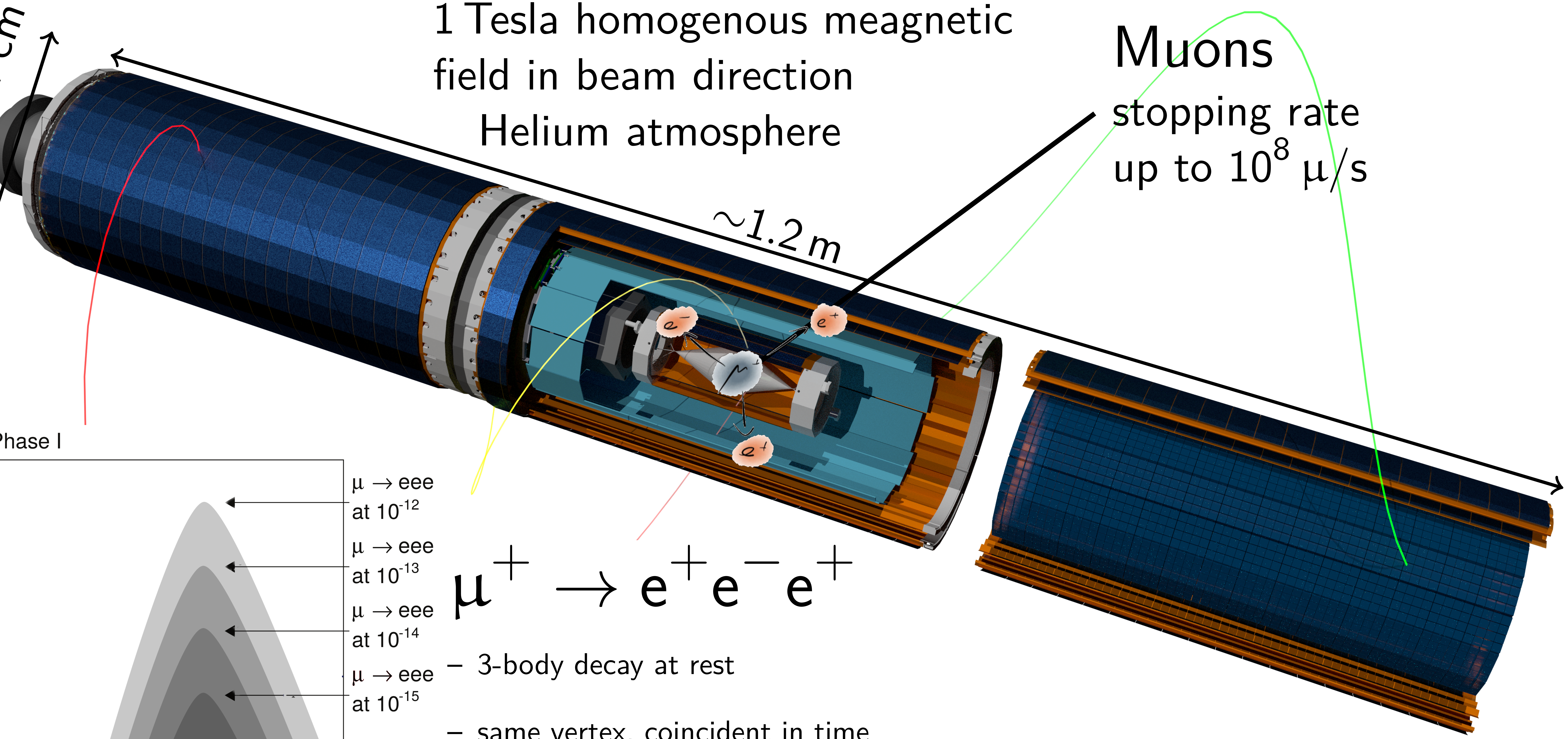
stopping rate up to 10^8 μ/s

Tracking

double layers HV-MAPS

<50 μm

The Mu3e Detector



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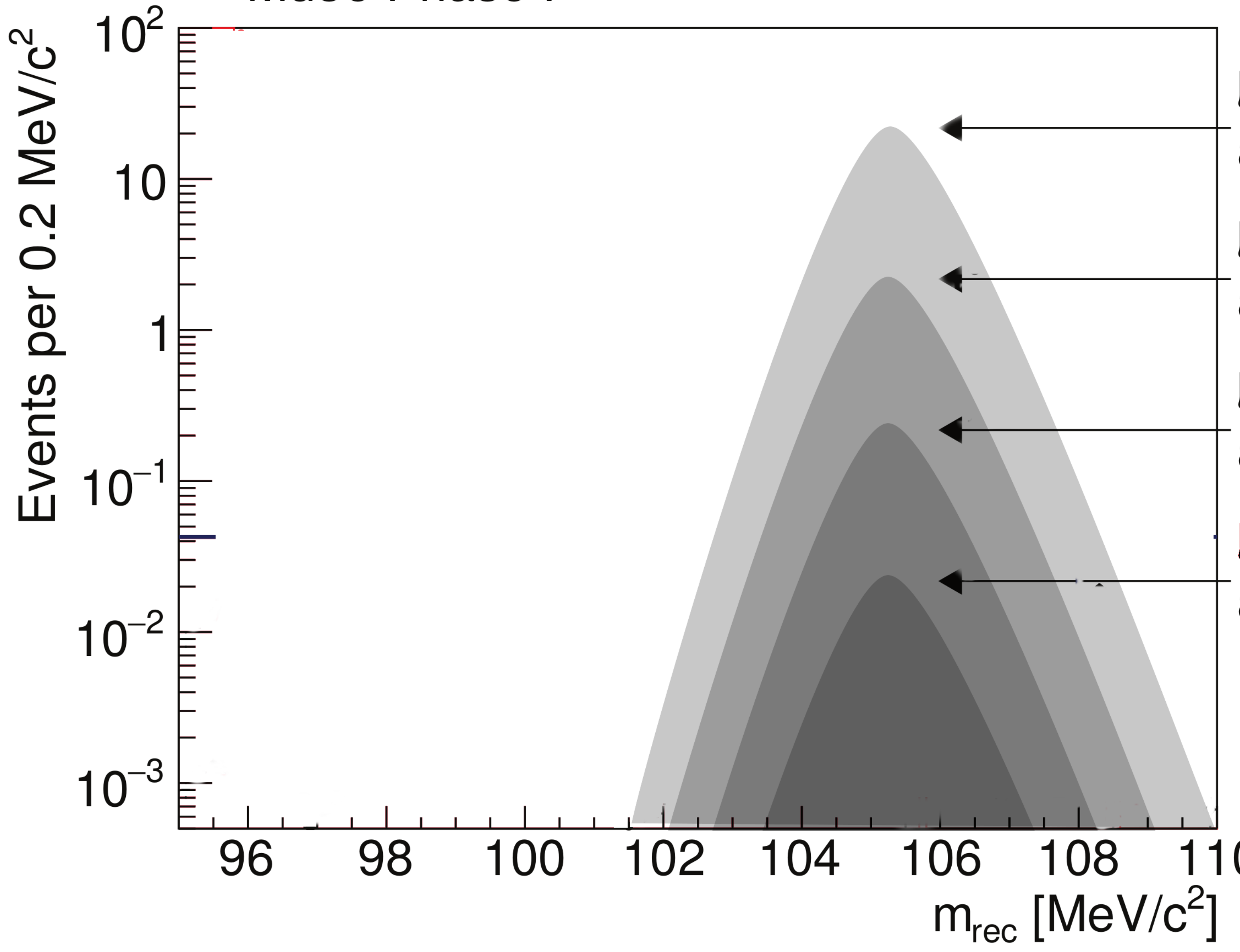
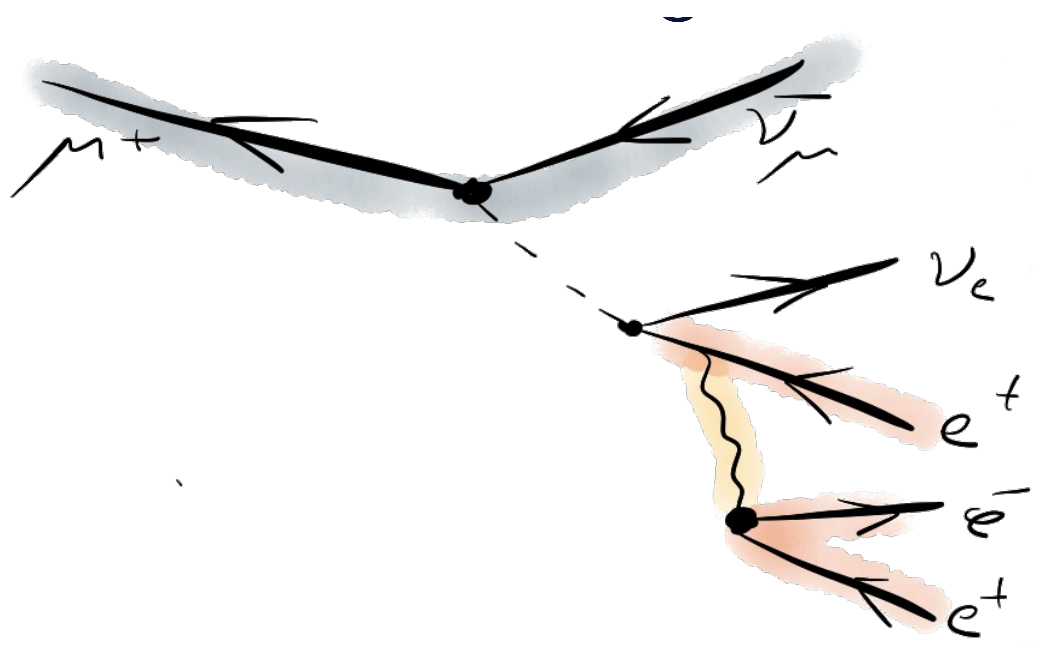


$$\mu^+ \rightarrow e^+ e^- e^+$$

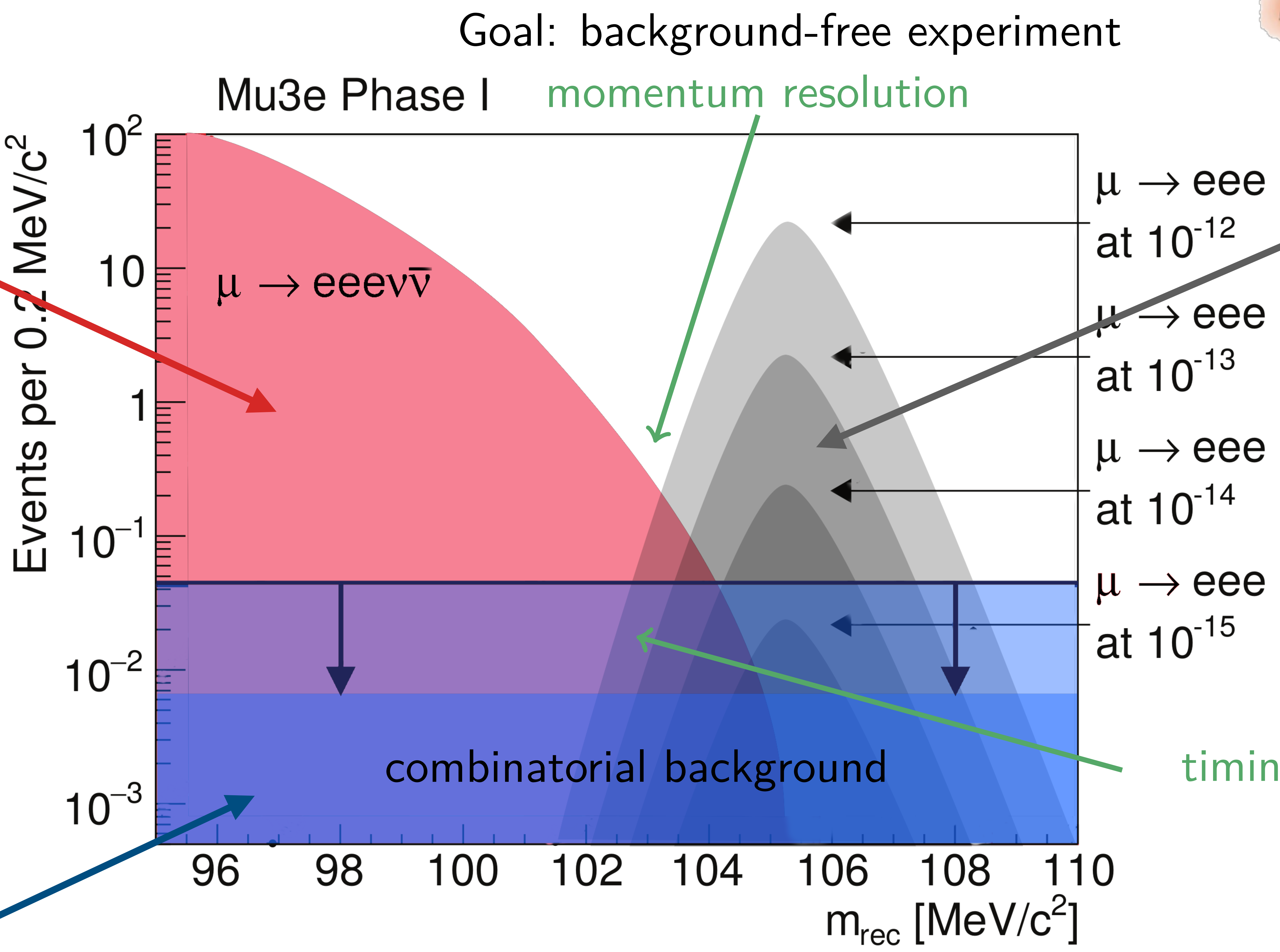
- 3-body decay at rest
- same vertex, coincident in time
- $\sum \vec{p}_e = 0, \quad \sum E_e = m_\mu$

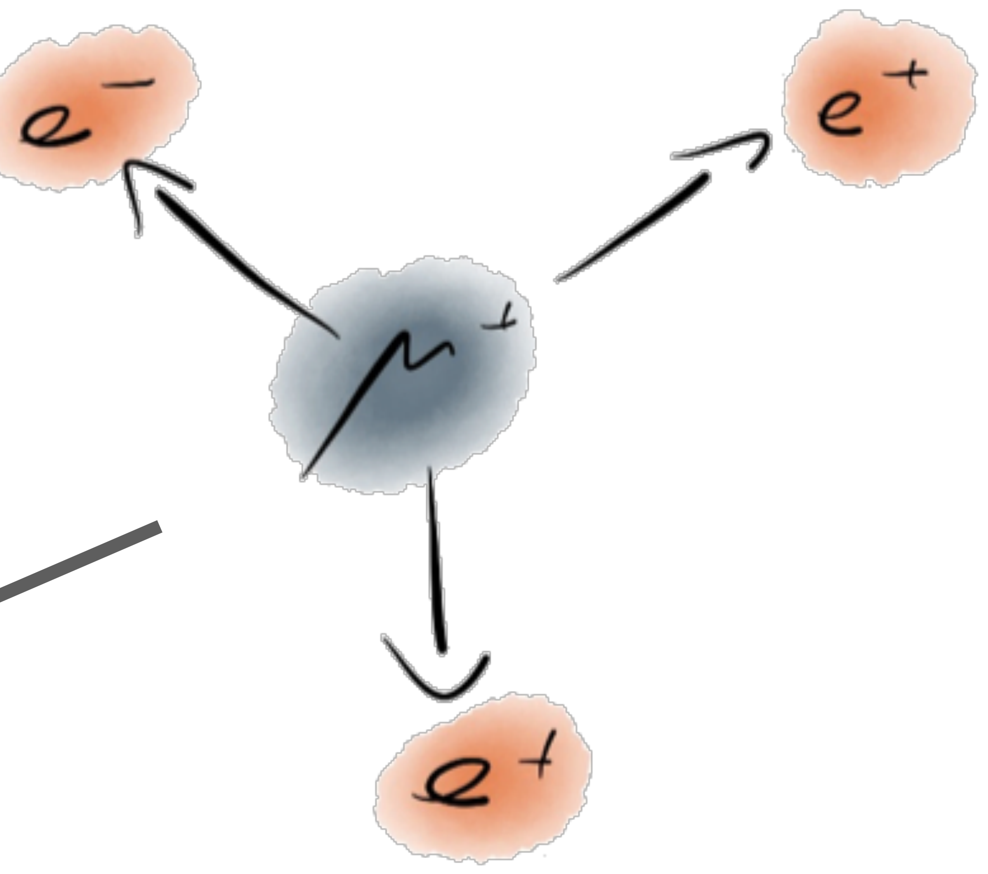
Recap: Signal + Backgrounds

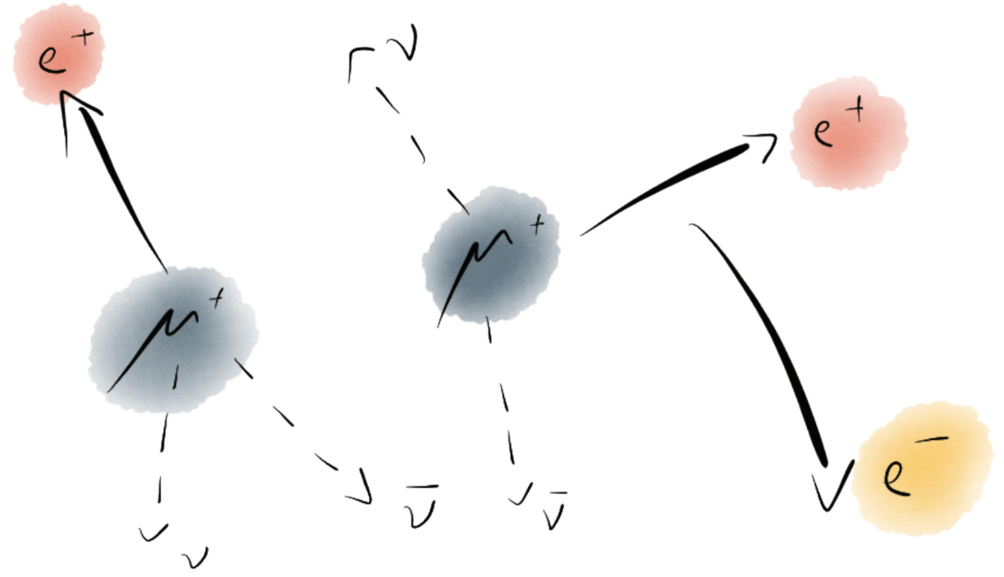


$$\mu^+ \to e^+e^-e^+\nu\bar{\nu}$$

$B = (3.4 \pm 0.4) \cdot 10^{-5}$



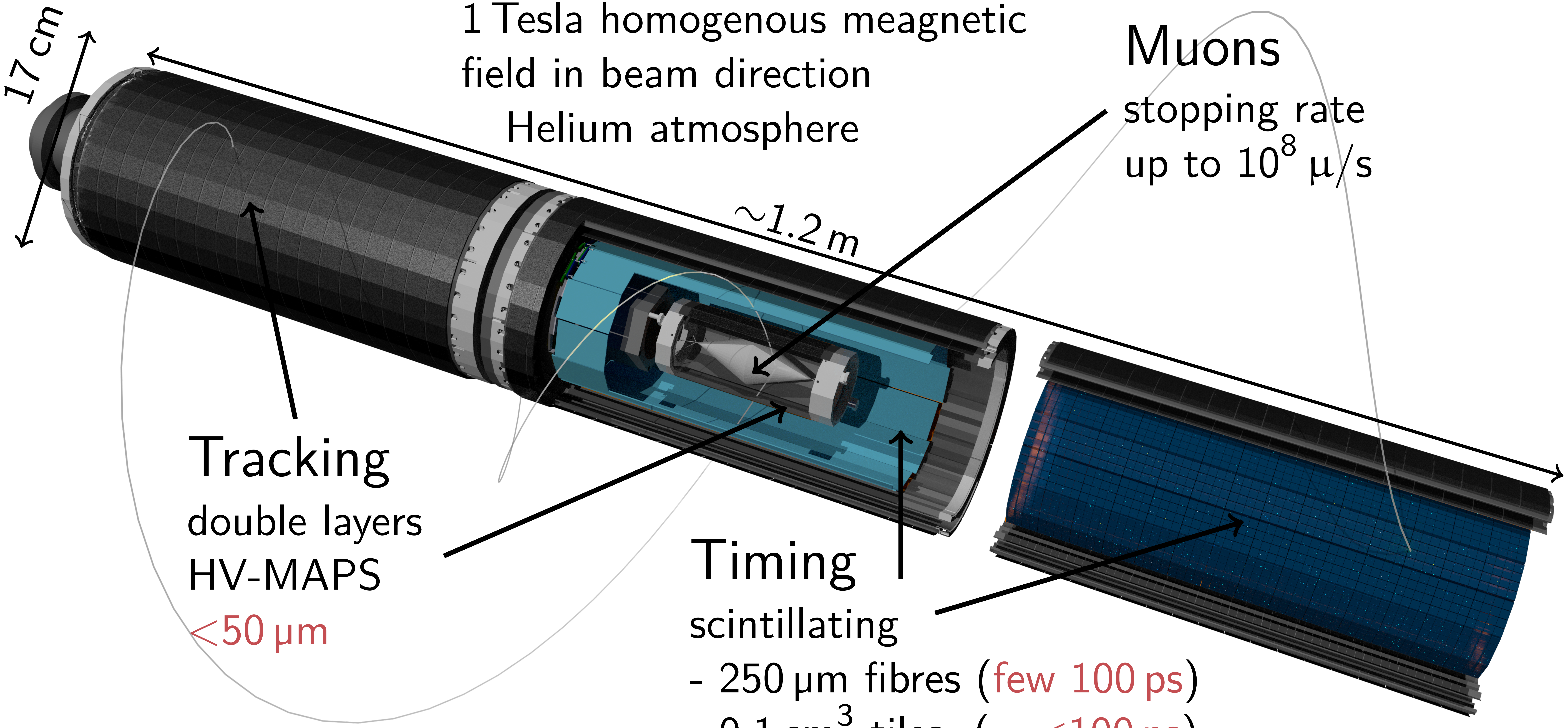




$$2 \text{ x } (\mu^+ \to e^+\nu\bar{\nu})$$

$$? \to e^- \; ?$$

The Mu3e Detector



Environment

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stopping rate up to 10^8 μ/s

Tracking

double layers HV-MAPS

<50 μm

Timing

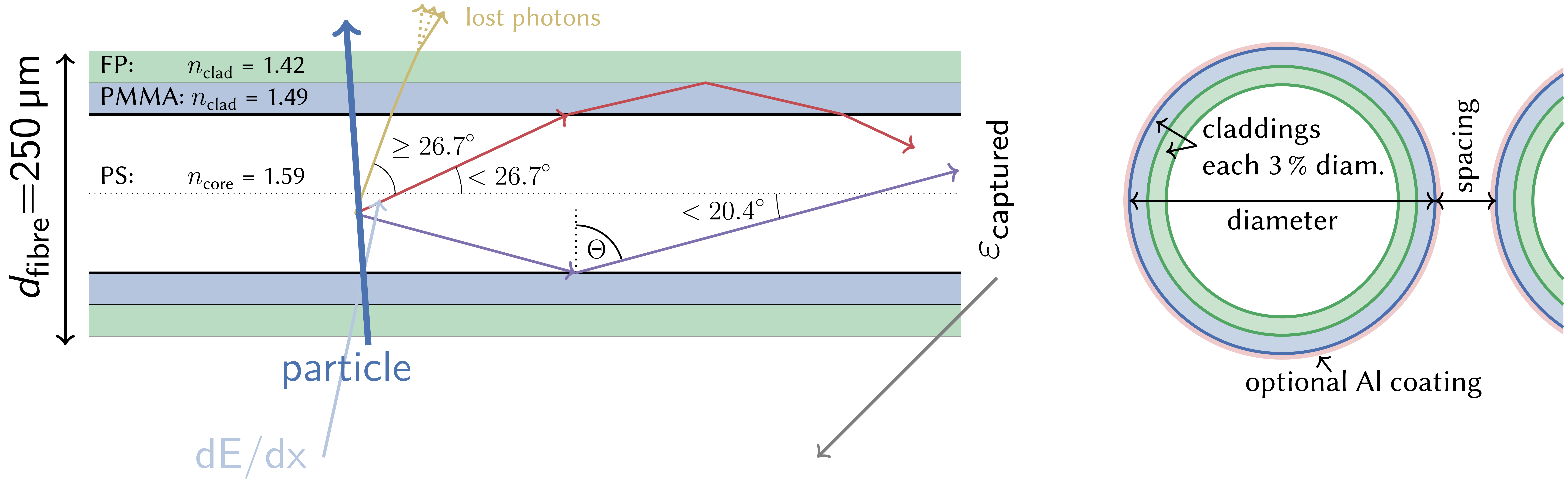
scintillating

- 250 μm fibres (few 100 ps)
- 0.1 cm^3 tiles (<100 ps)

Silicon Photomultipliers

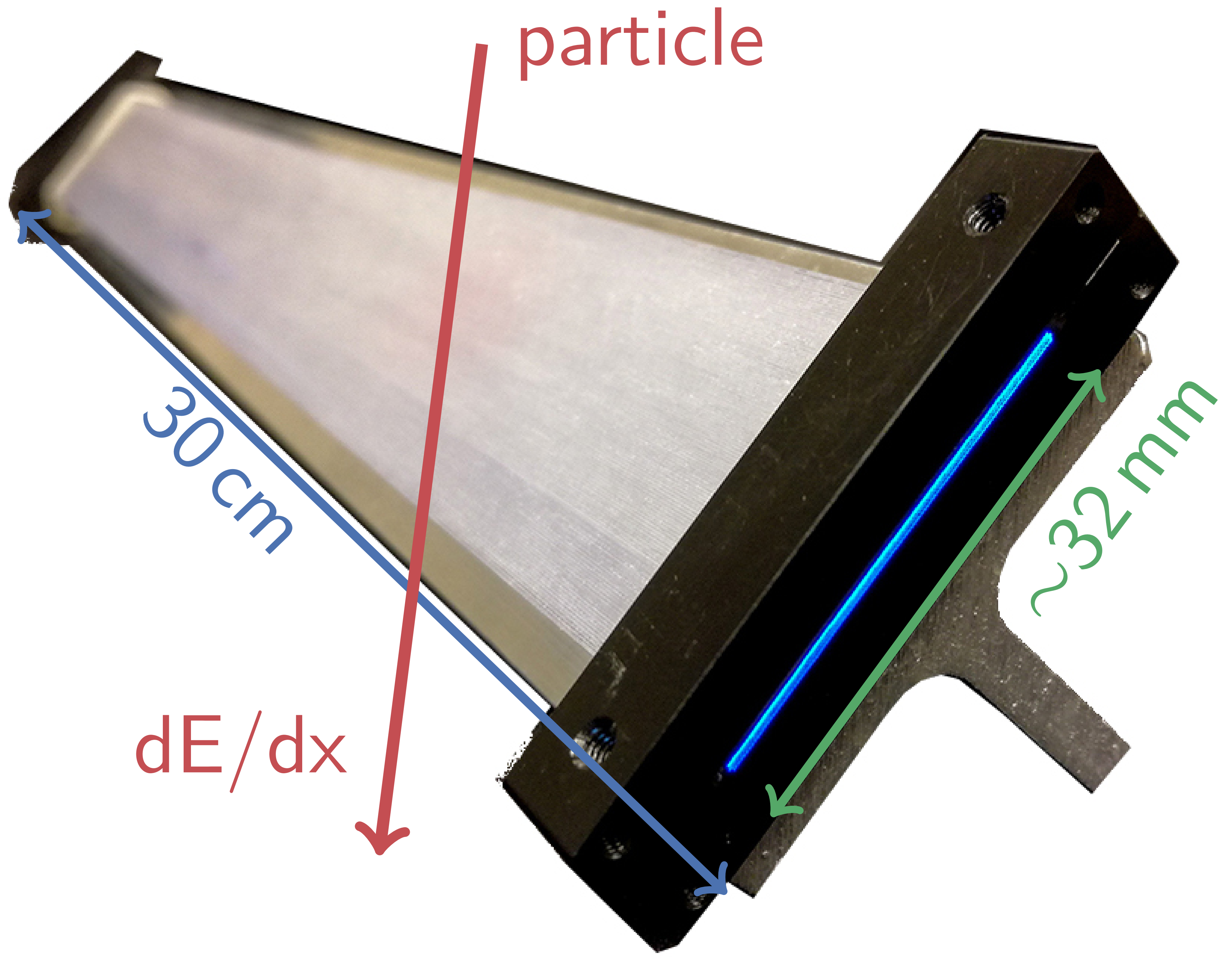
101 How to build a
Fast, Thin, Segmented Timing Detector

Sctintillating Fibres

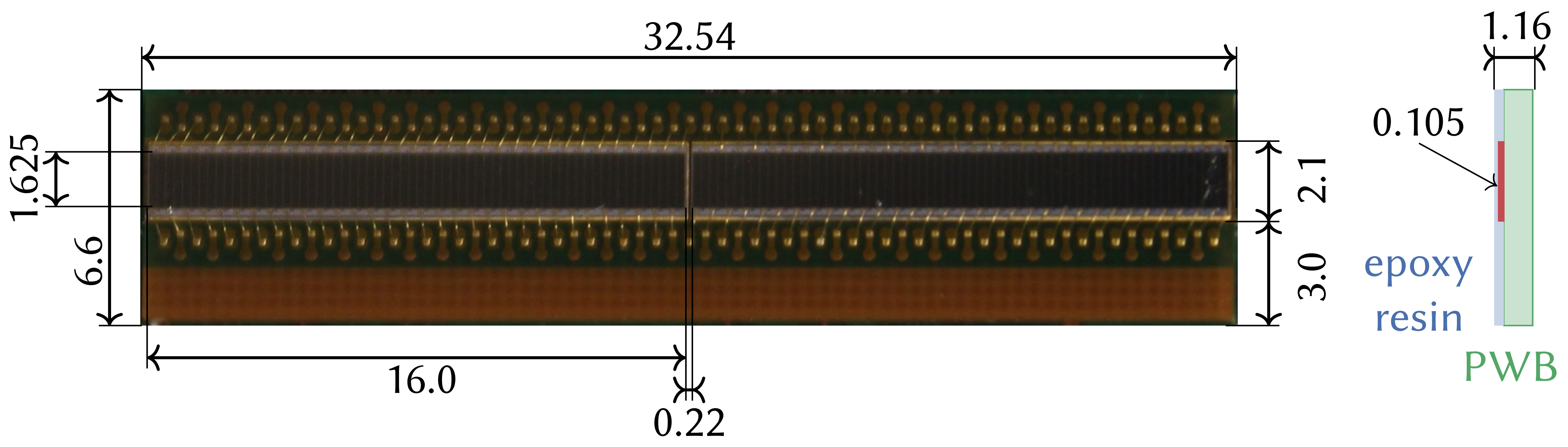


$\frac{dE}{dx}$ (40 MeV e^-)	$d_{\text{fibre core}}$	yield	ε_{cap}	d_{att}(15 cm)	$\varepsilon_{detection}$	
$200\,\frac{\text{keV}}{\text{mm}}$	× 0.21 mm	× $\sim 8\,\frac{\text{ph}}{\text{keV}}$	× 5.4 %	× 95 %	× 40 %	≈ **7** photons

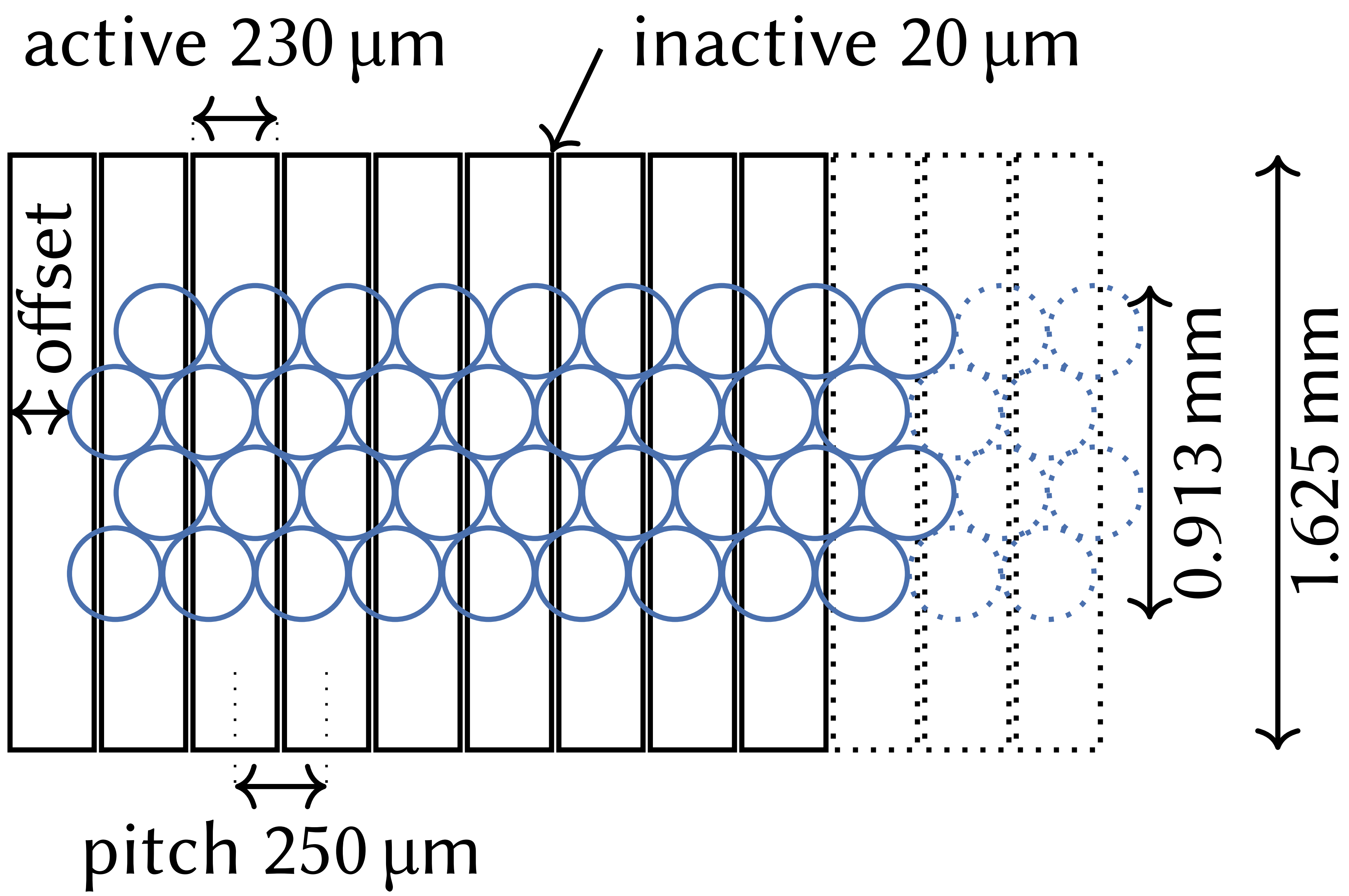
Sctintillating Fibre Ribbons & Silicon Photo Multipliers



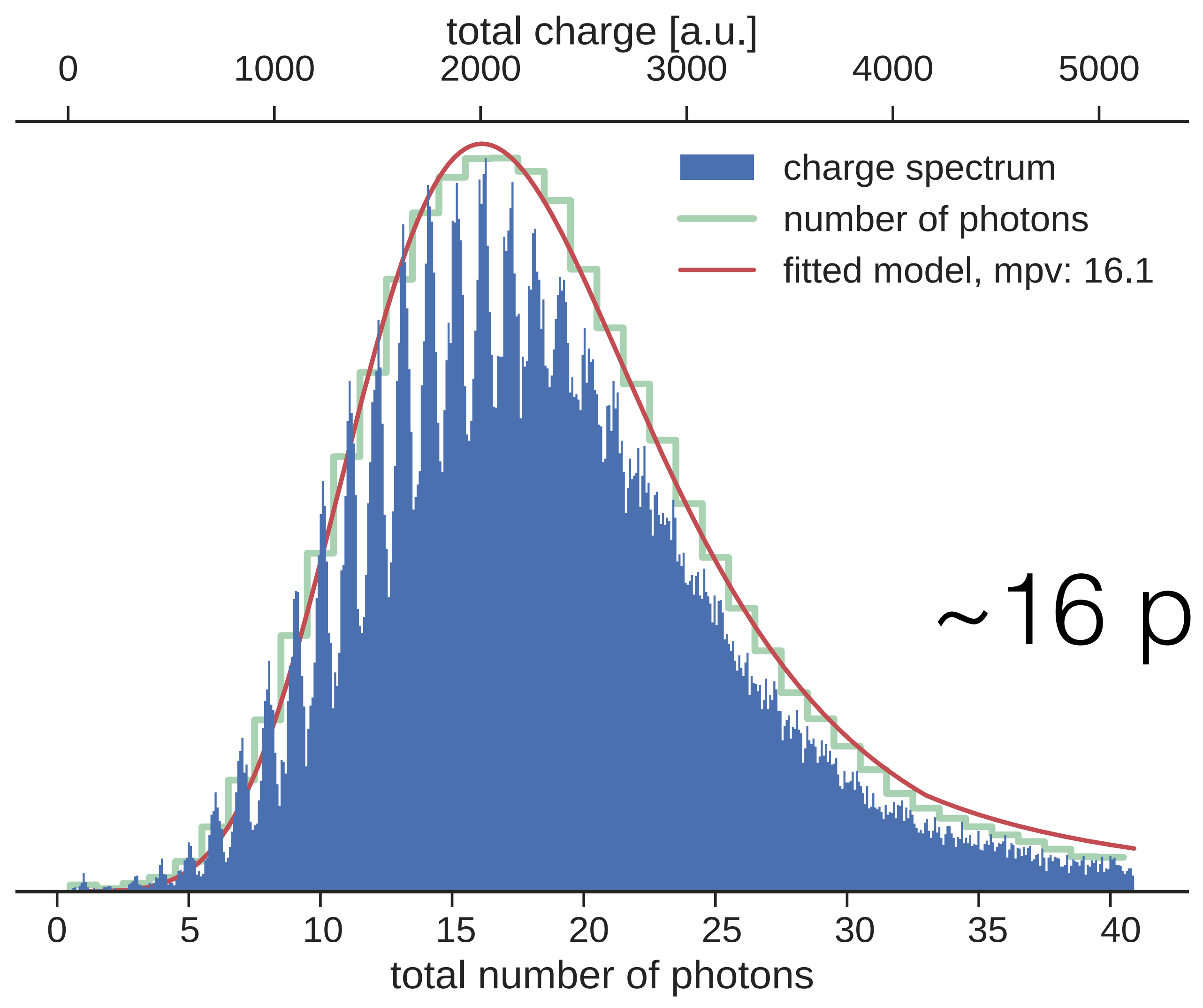
Silicon Photo Multiplier (SiPM) Array



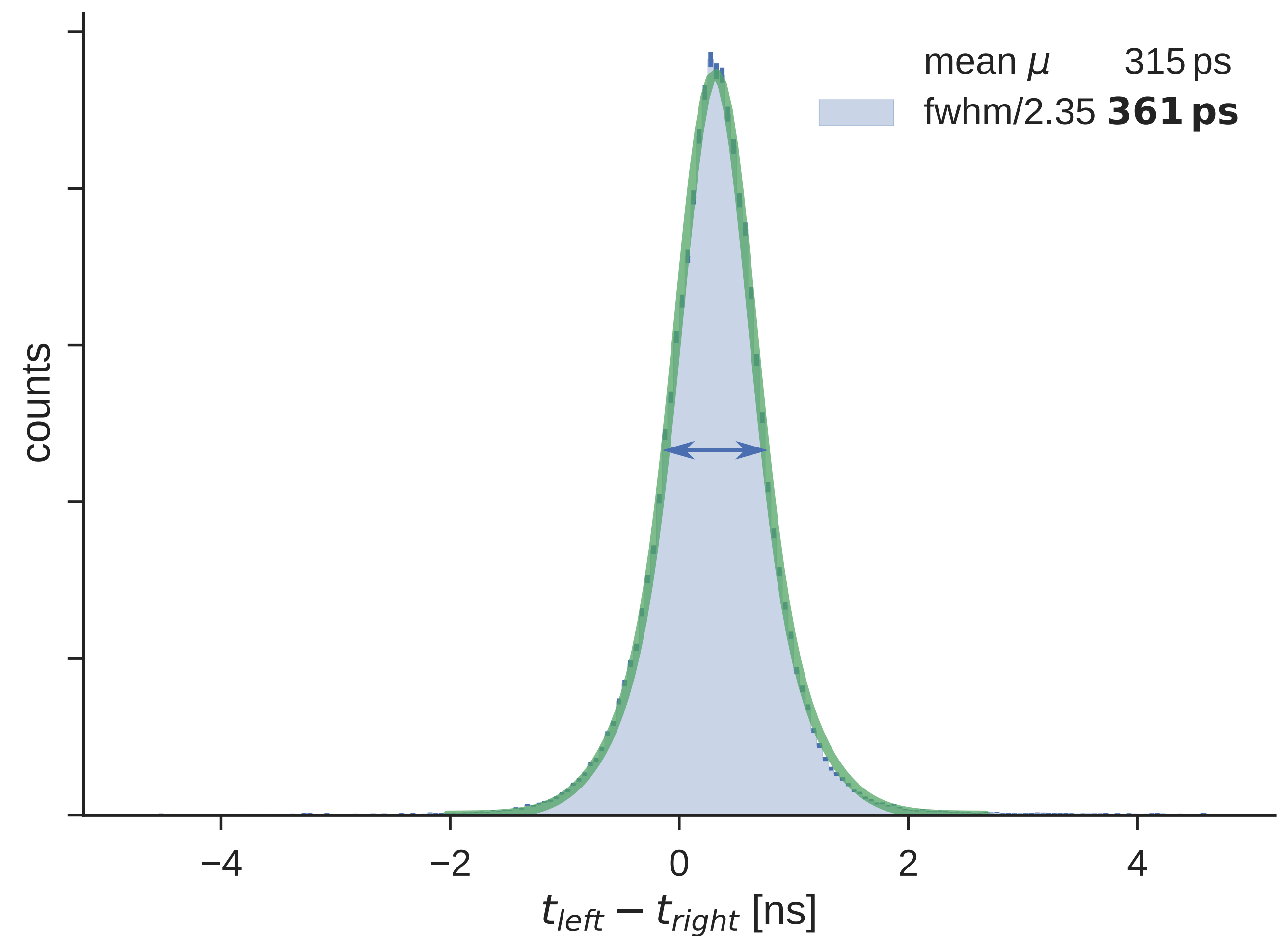
Hamamatsu SiPM array as used in LHCb



What you get: Overall



~16 photons per MIP



$$\sigma_{\text{fibre, waveform}} = \frac{\sigma(t_{left} - t_{right})}{\sqrt{2}} = 255(15)\,\text{ps}$$

fast: <300ps time resolution

thin: below 0.5% X_0

segmented: < 0.25mm

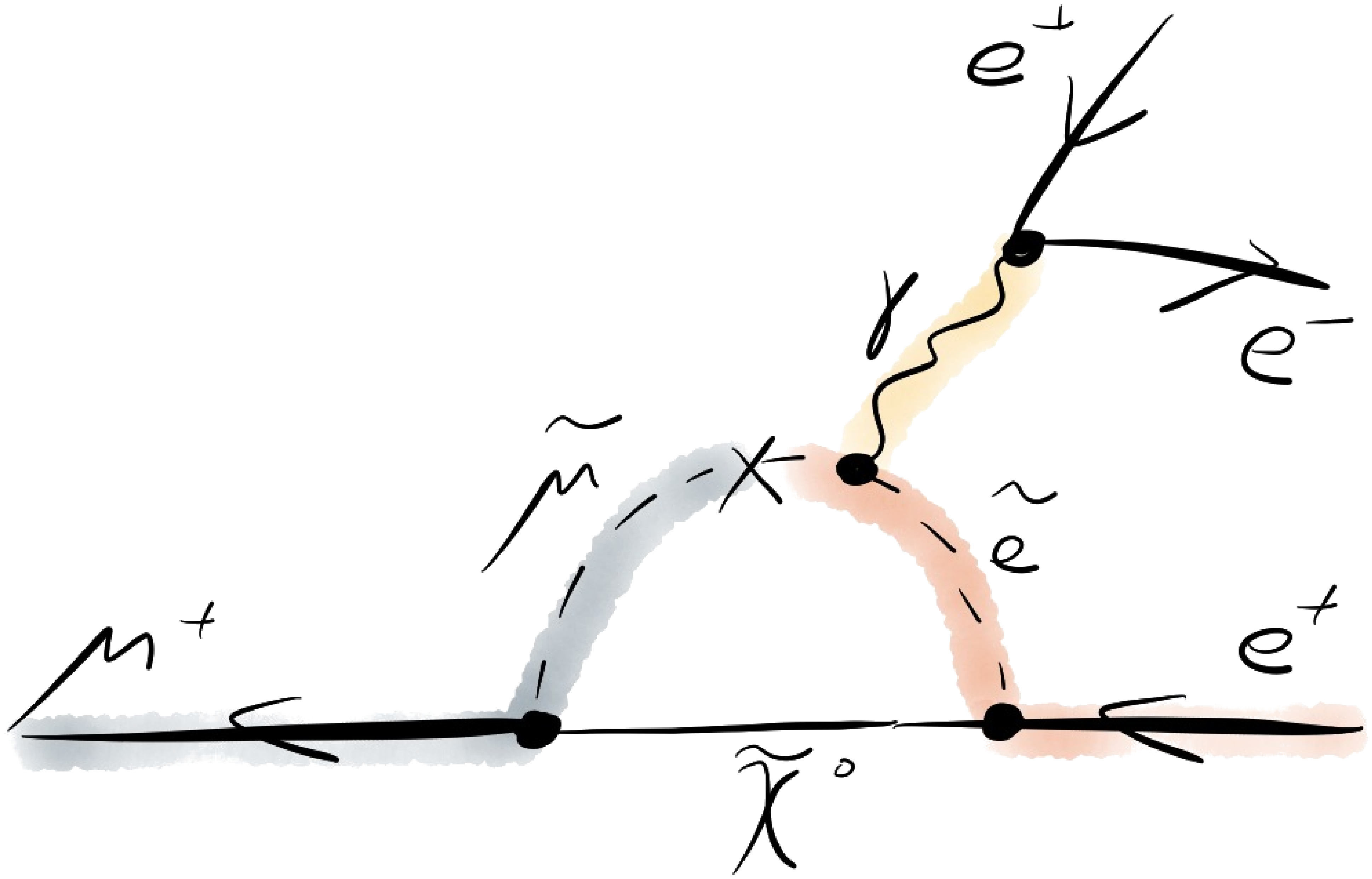
efficient Timing detector

easy to use **at room temperature**

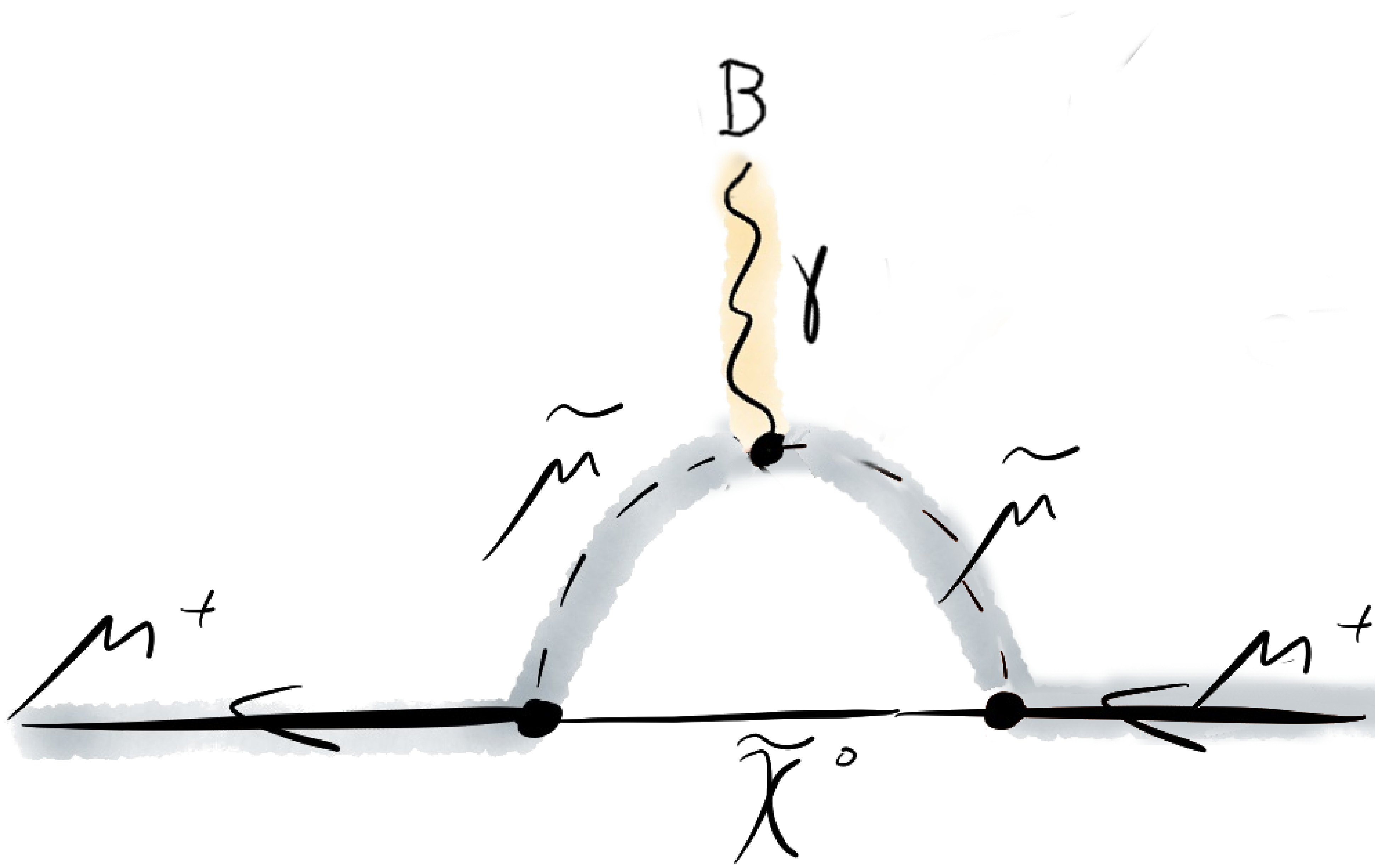
and **high rate**: up to 500 kHz per fibre

Back to New Physics
and
The Presence

Back to New Physics



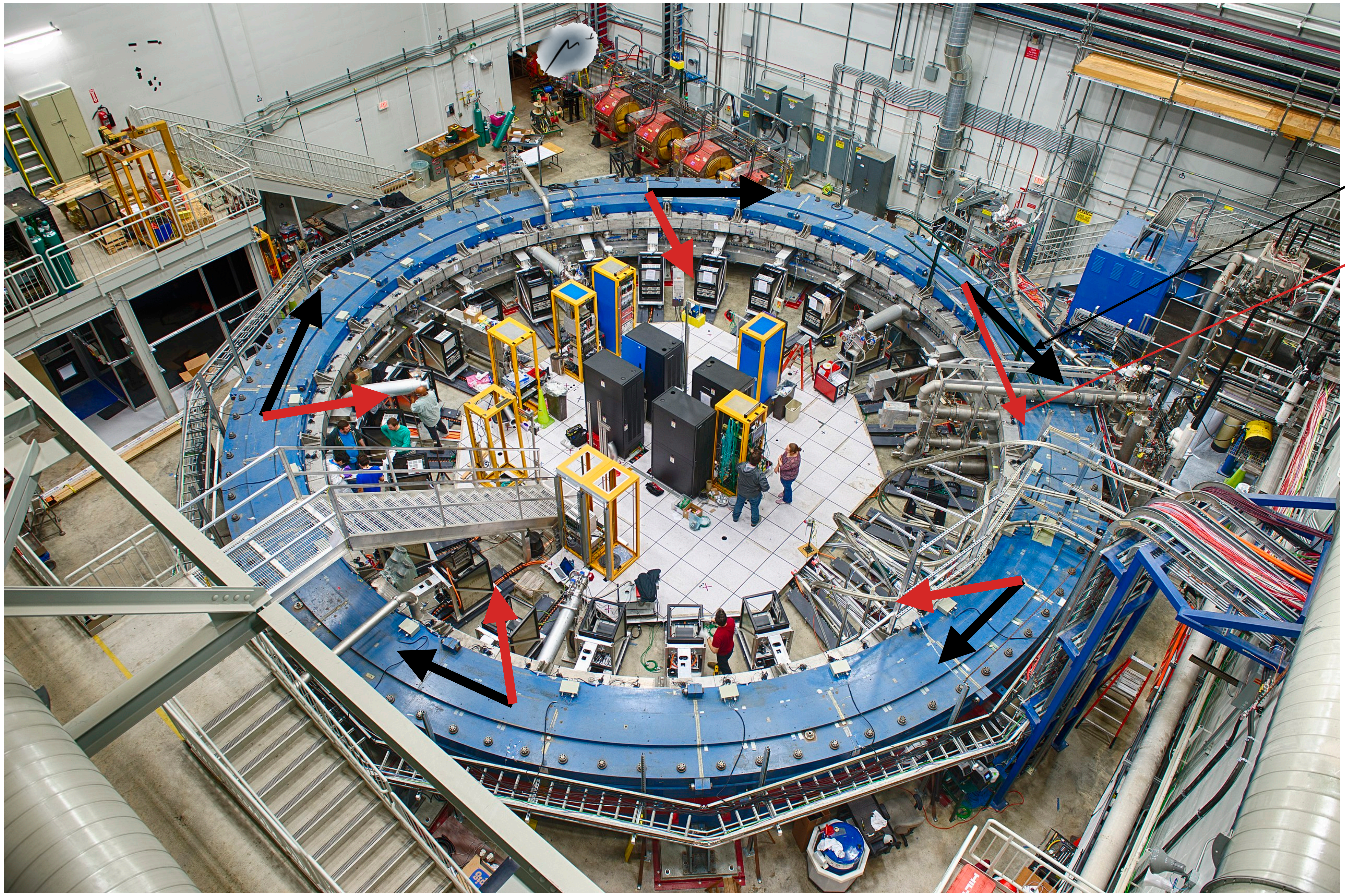
Charged Lepton Flavour Violation



modified magnetic dipole moment

$$a_\mu = \frac{g_\mu - 2}{2}$$

The Muon g-2 Experiment



Momentum

Spin

$$\vec{\omega_a} = -a\frac{e}{m}\vec{B}$$

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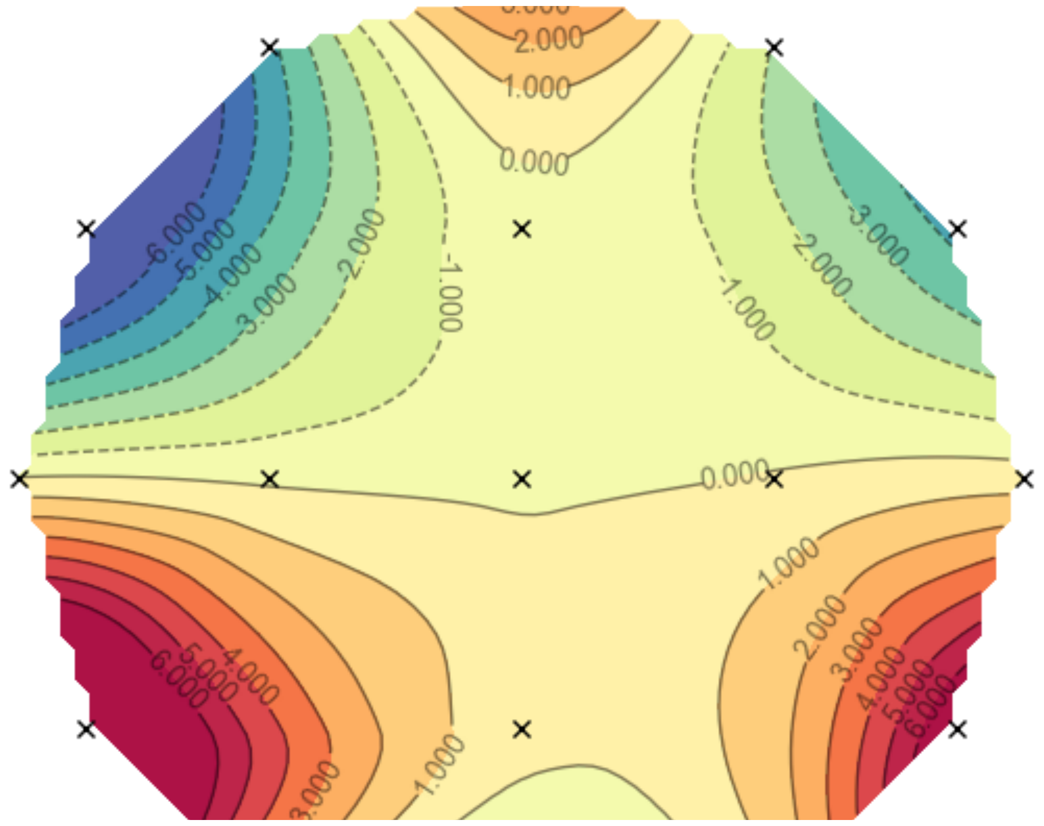

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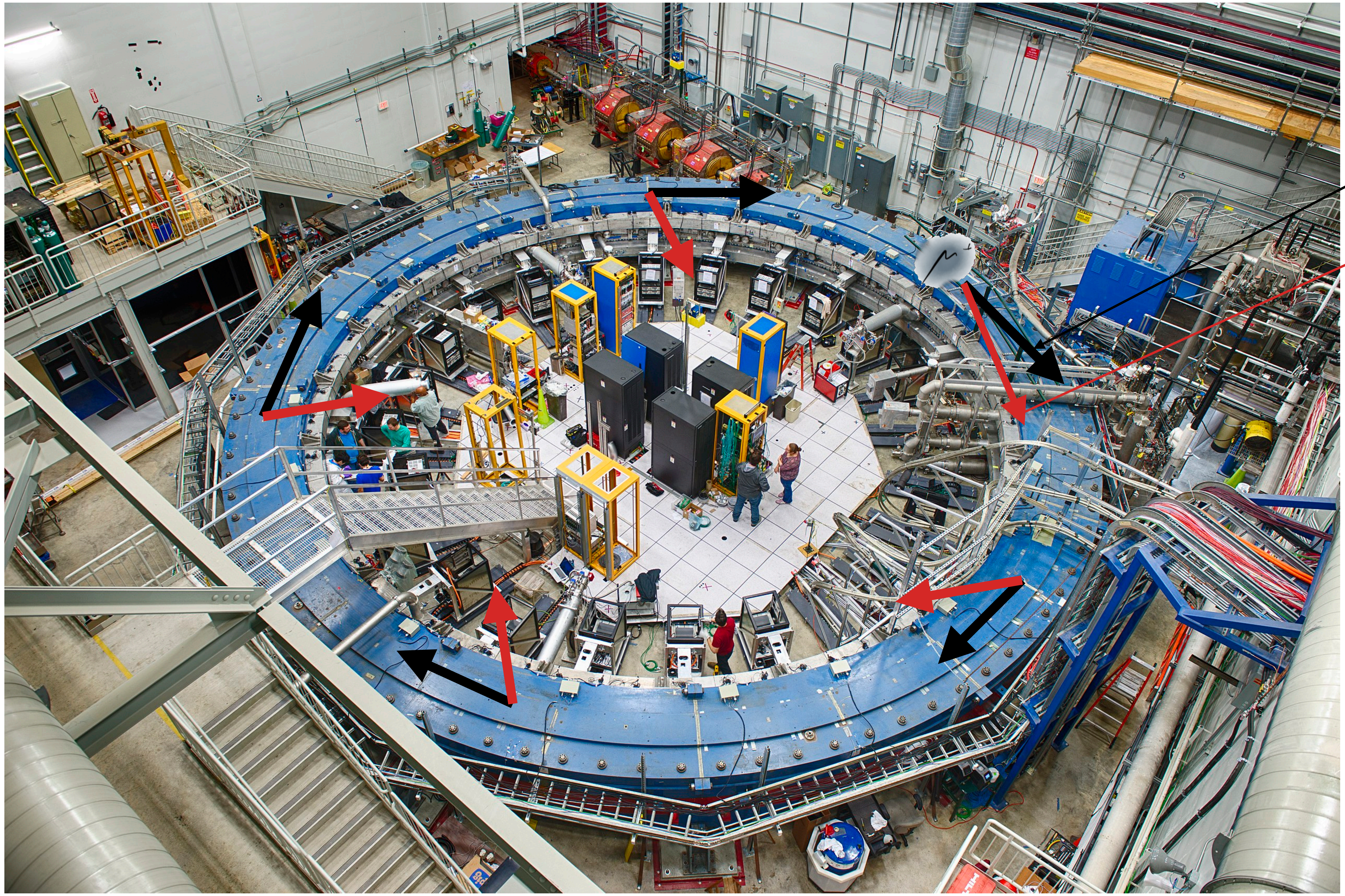

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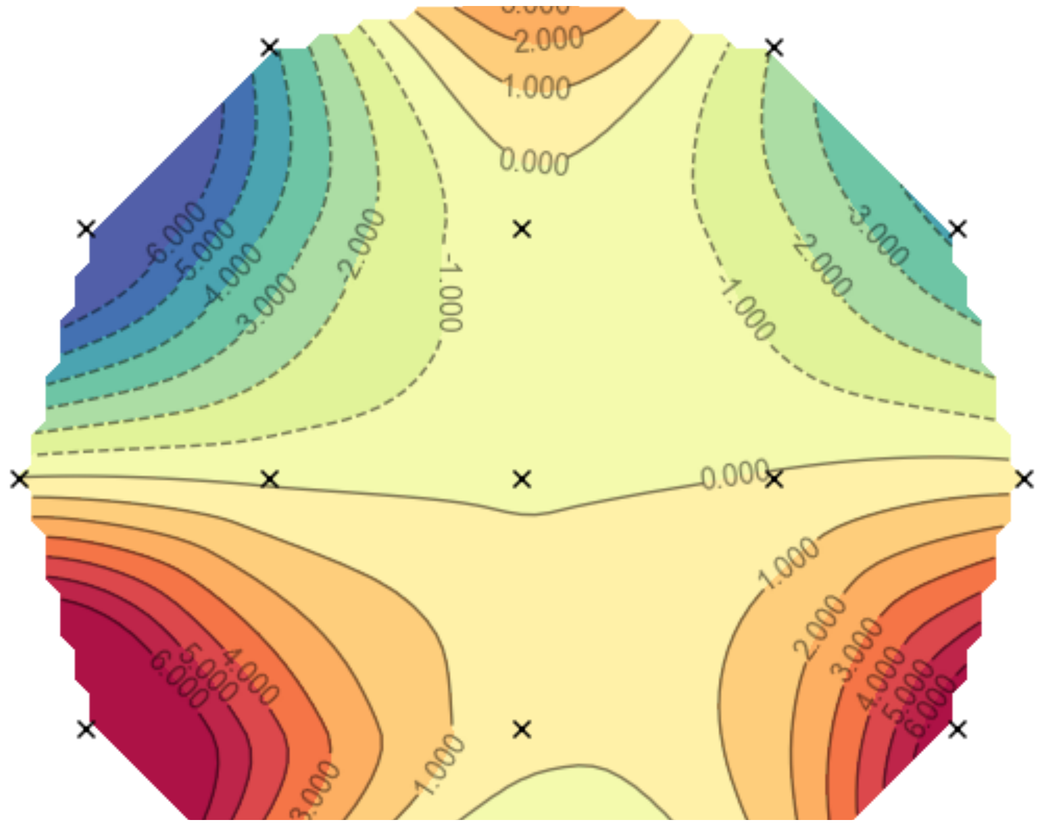

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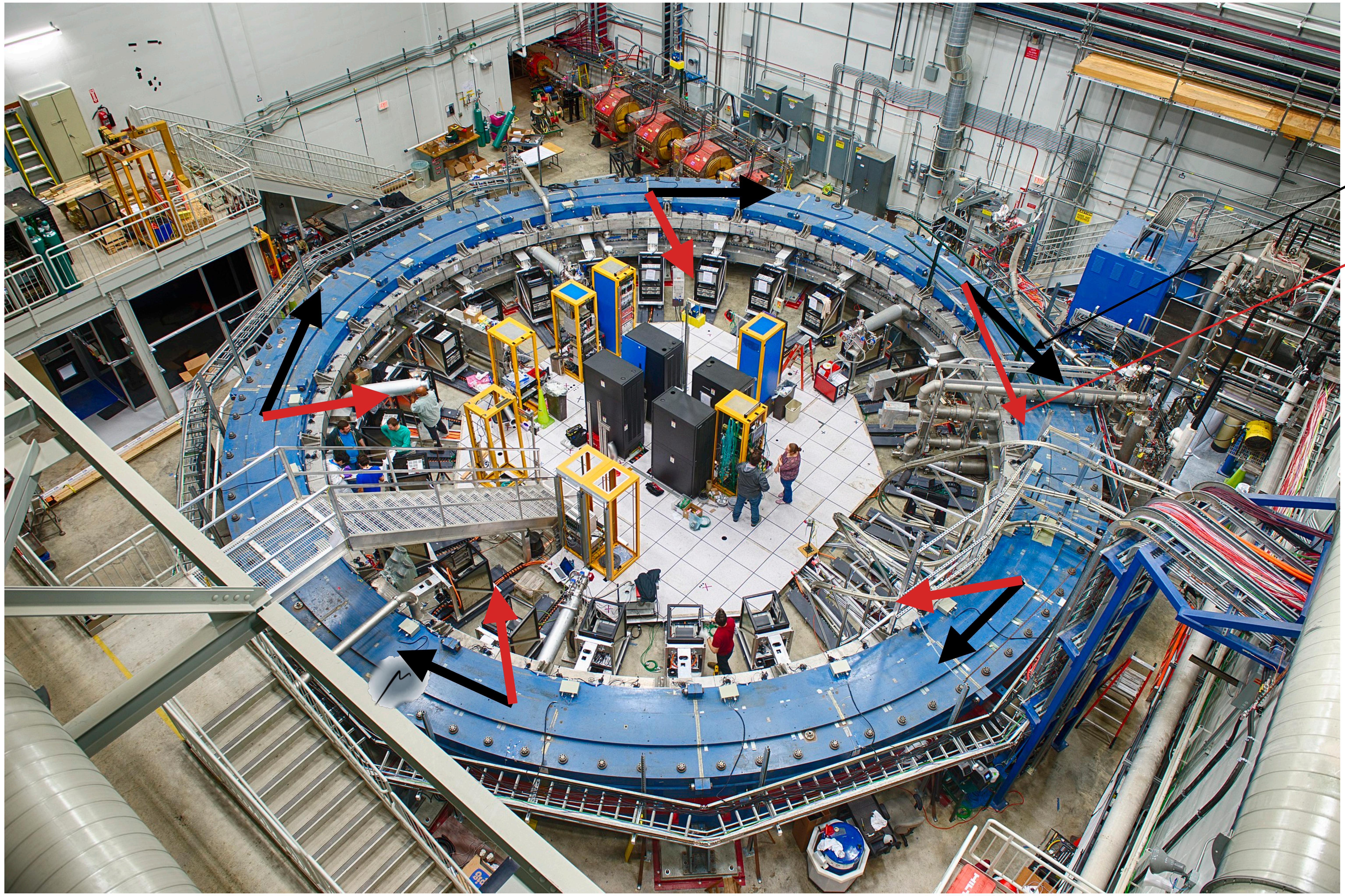

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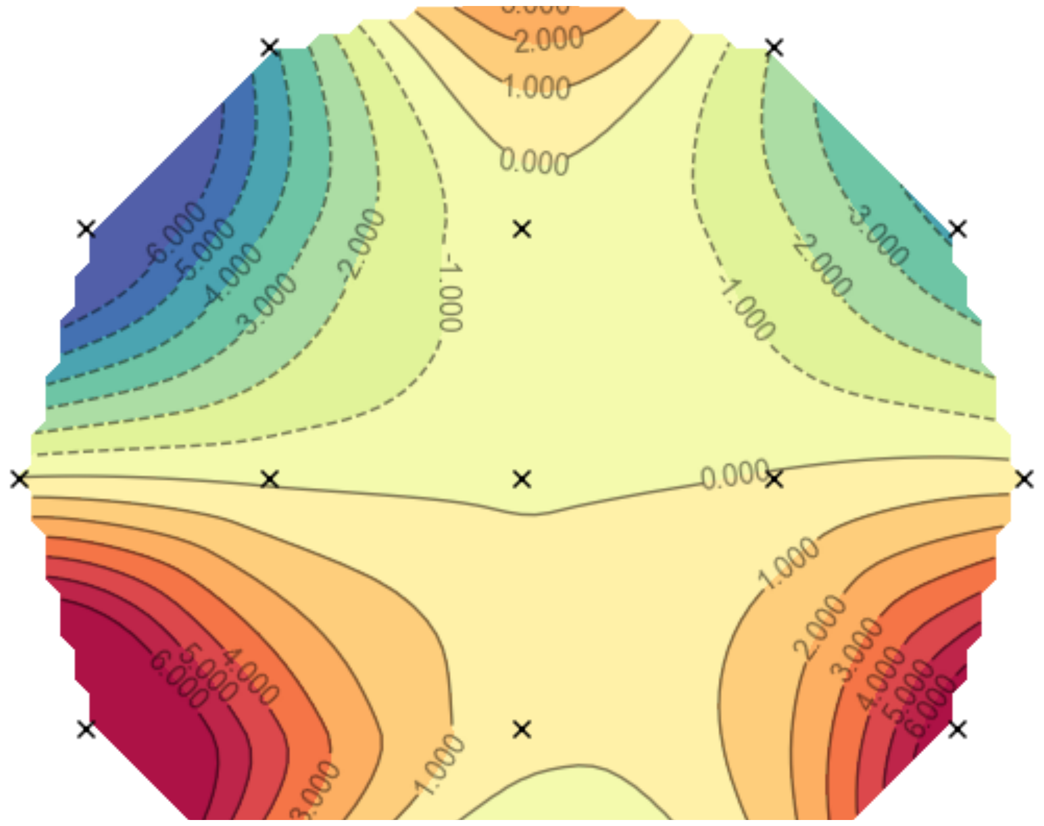

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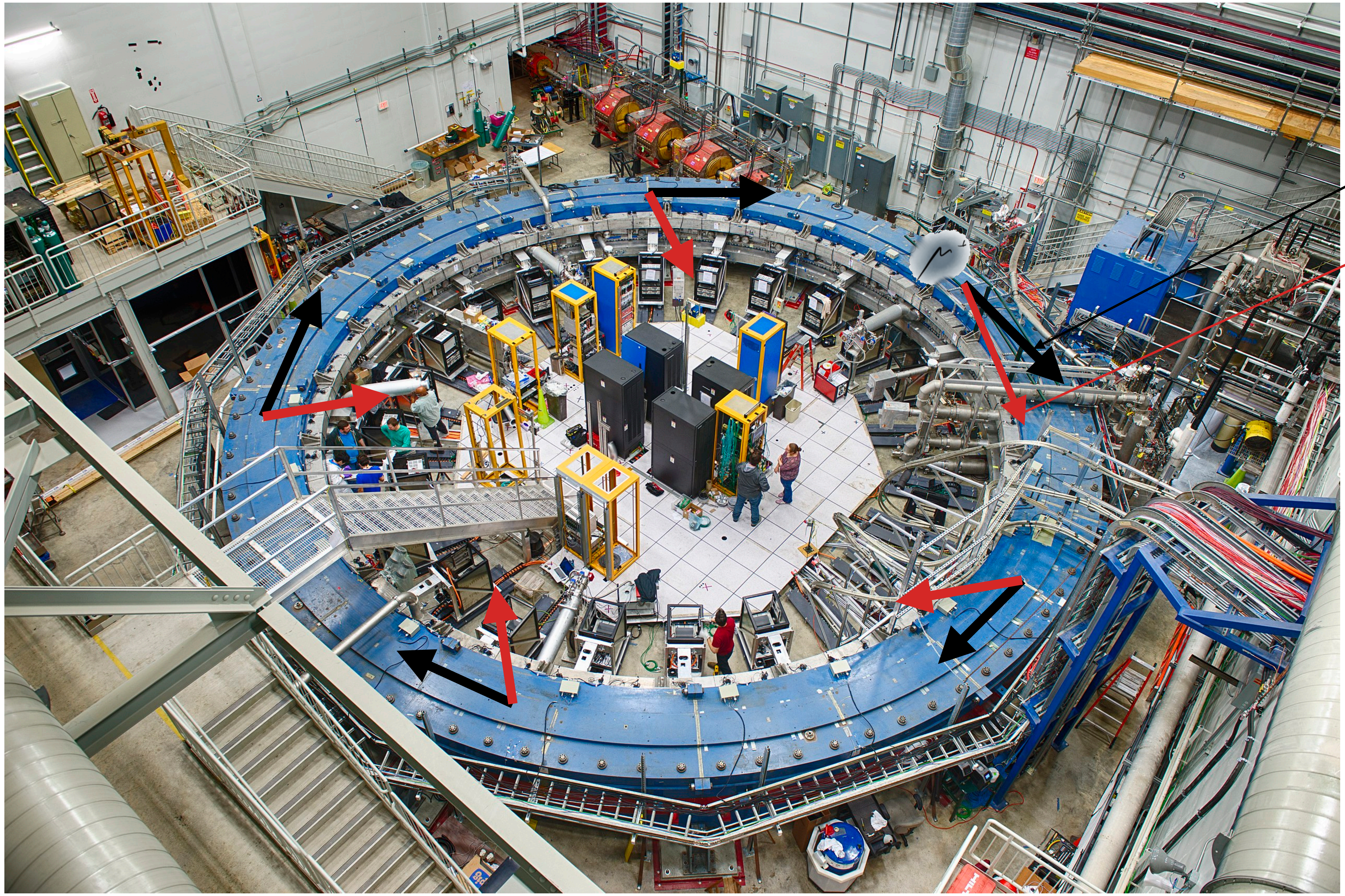

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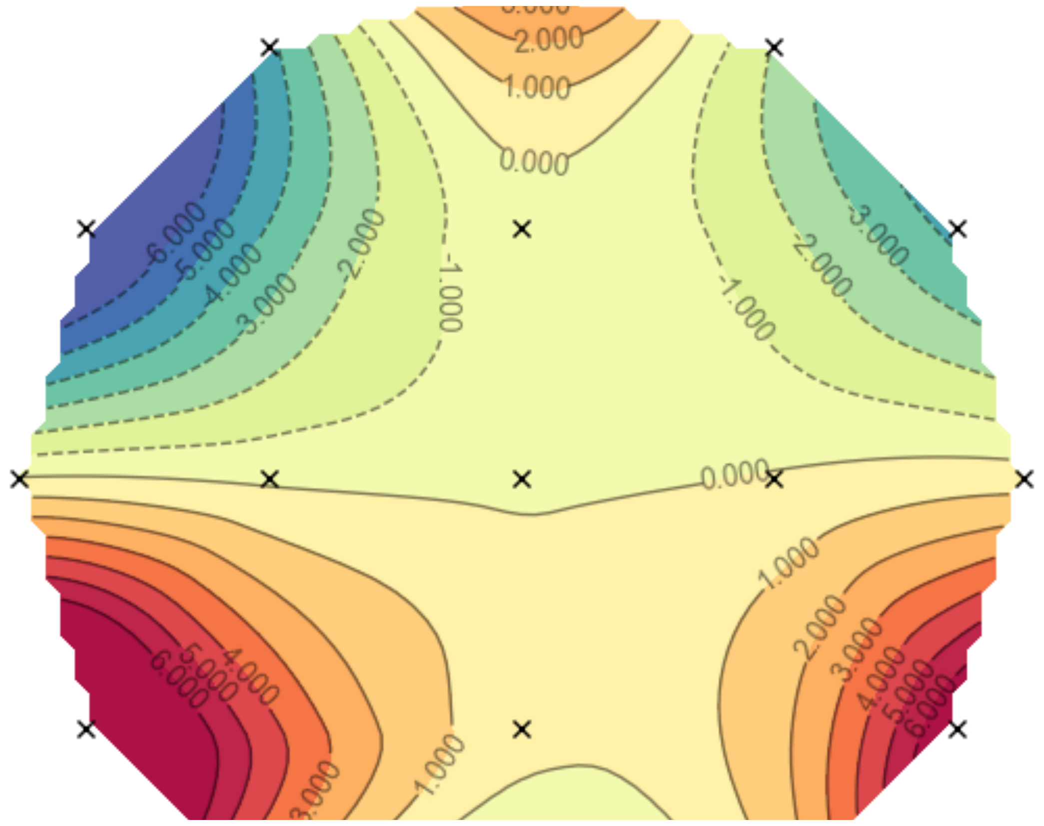
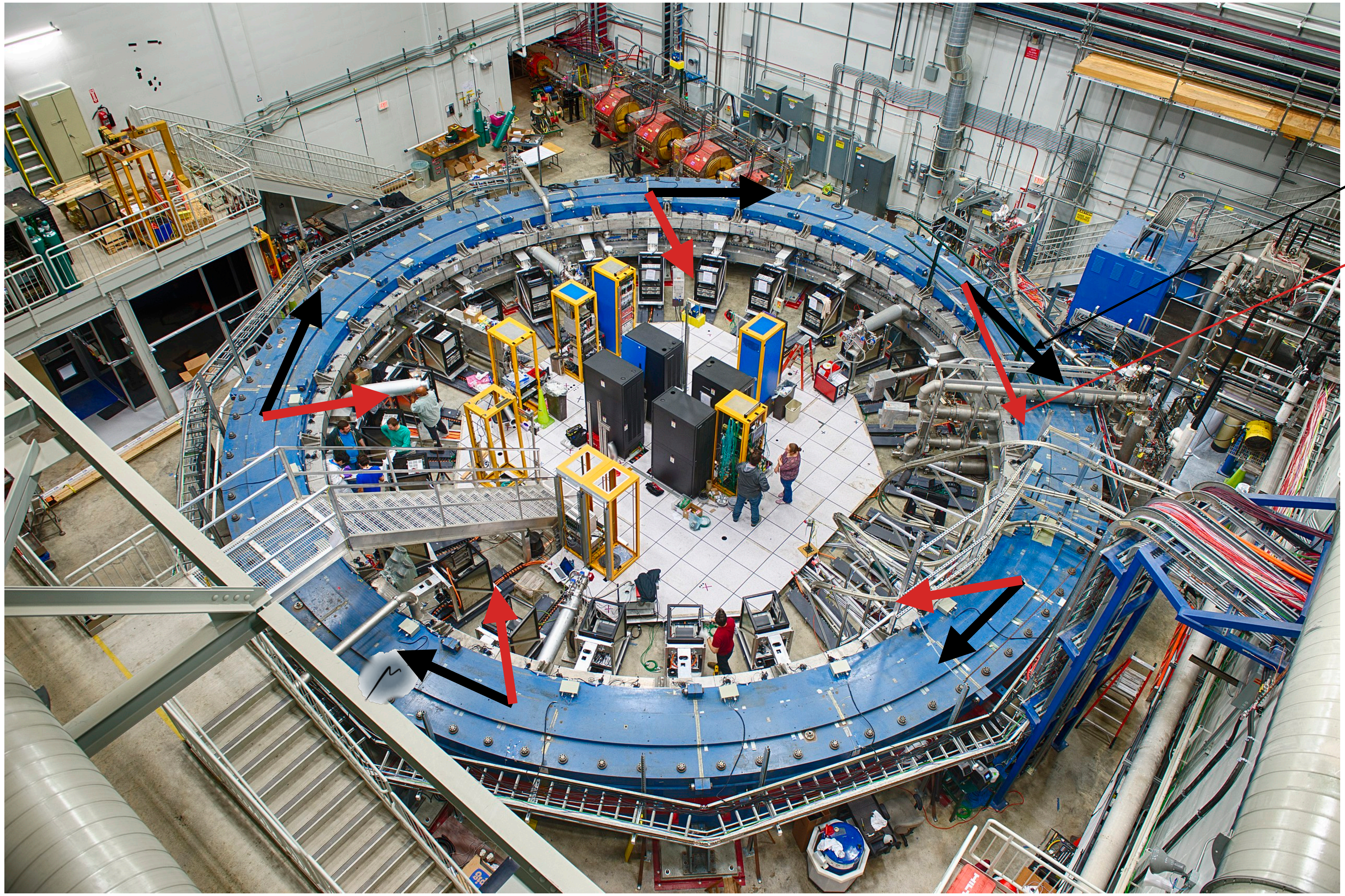


The Muon g-2 Experiment

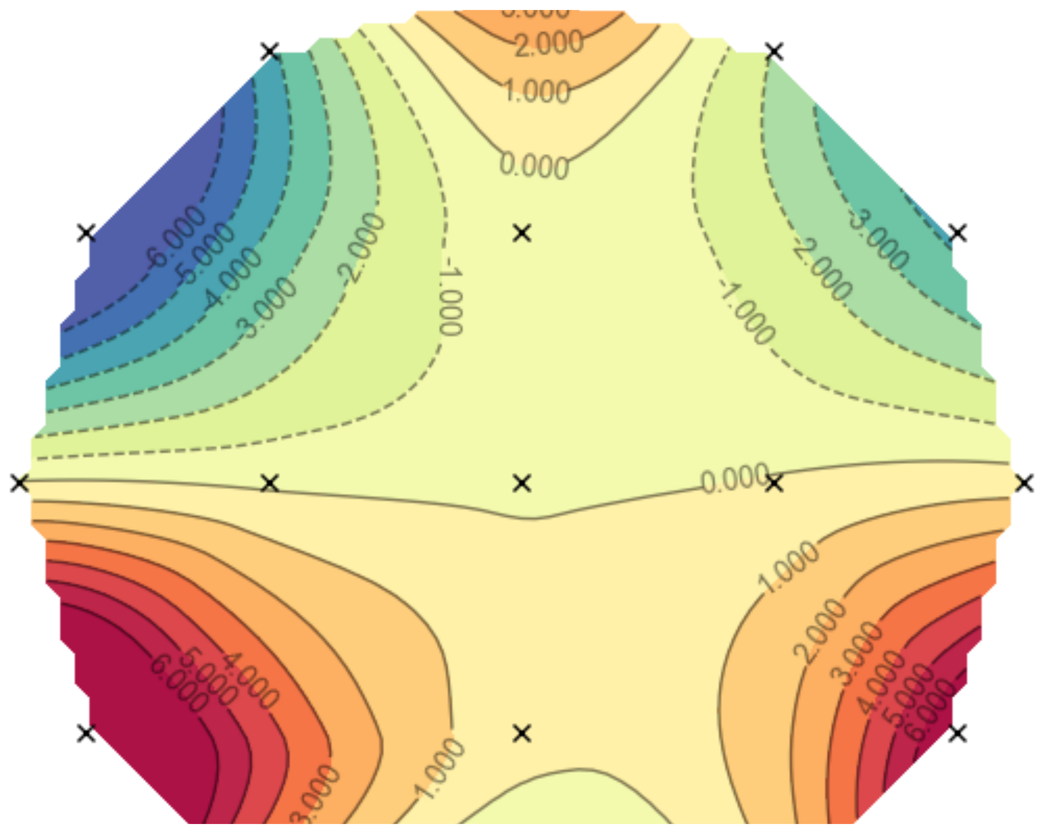


Momentum

Spin

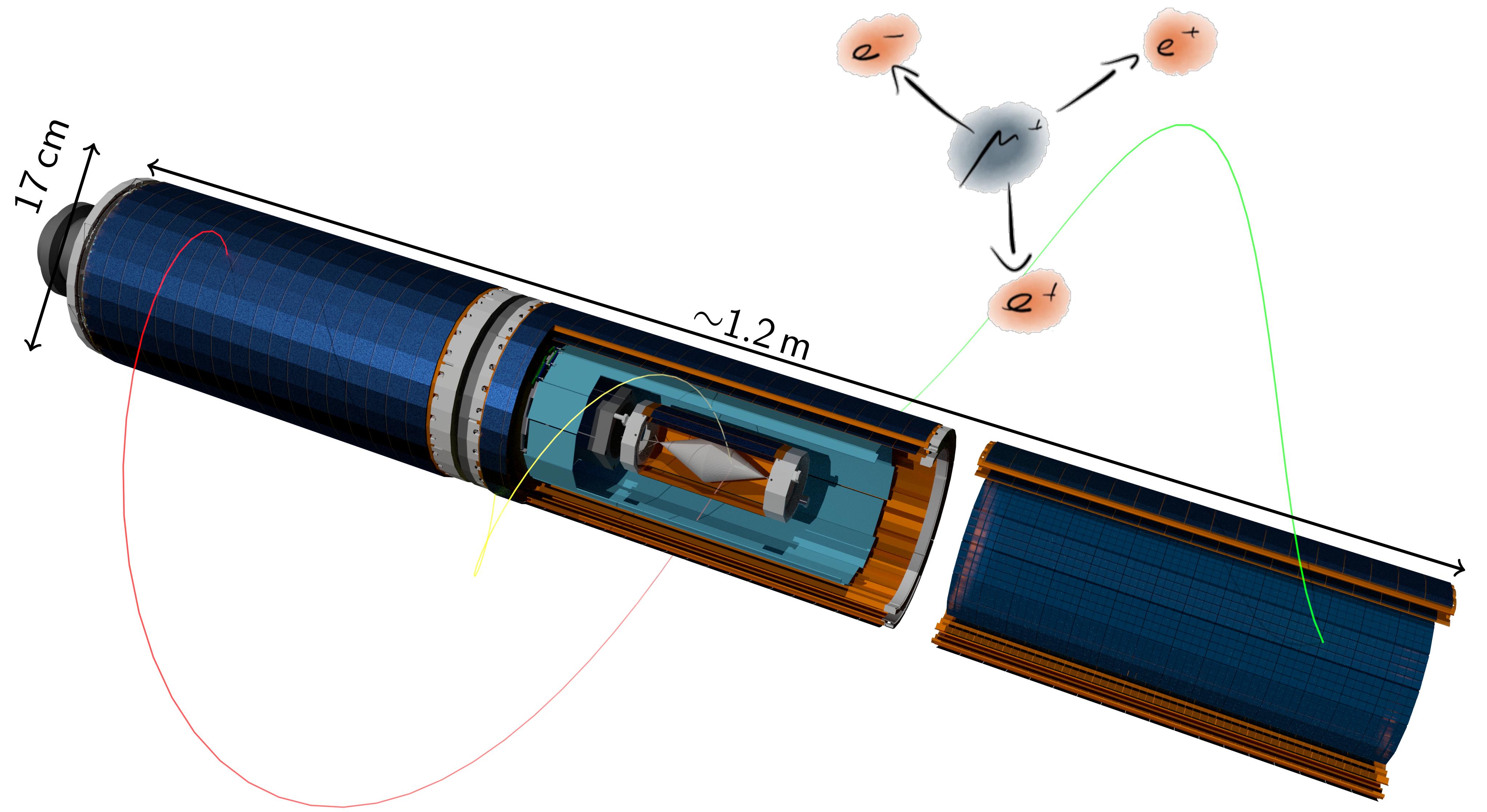
$$\overrightarrow{\omega_a} = -a\frac{e}{m}\overrightarrow{B}$$

Argonne NATIONAL LABORATORY



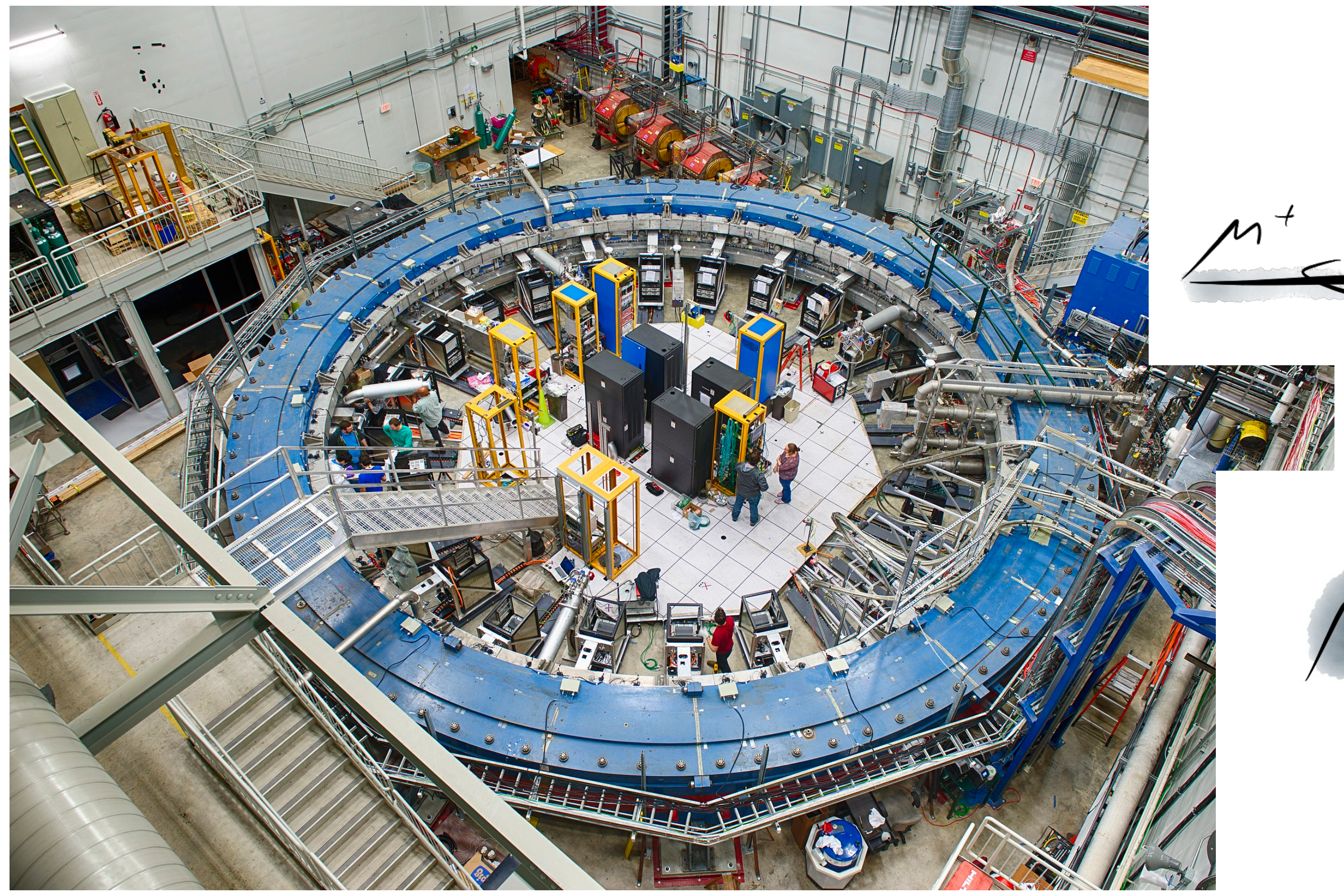
Before

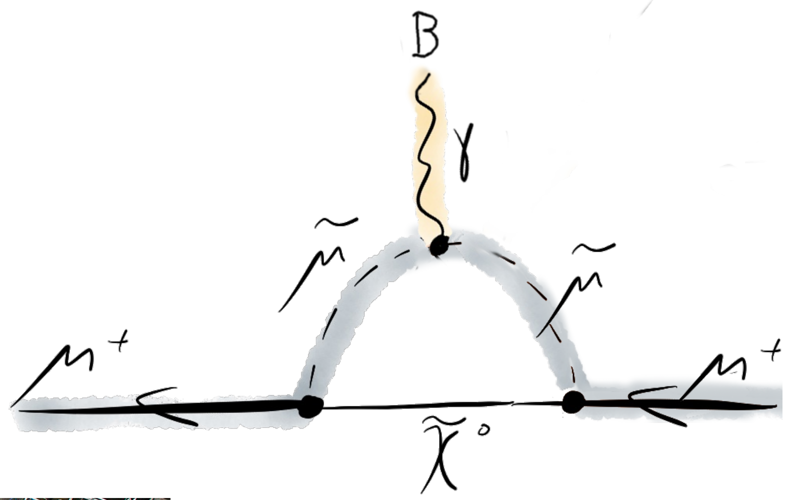
ETH zürich

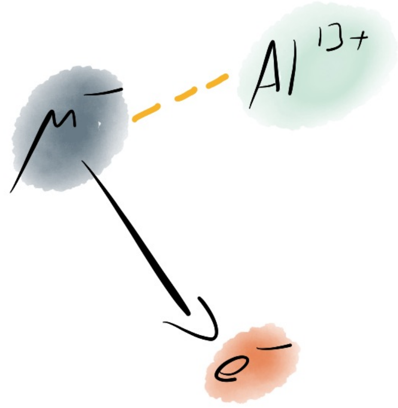


Now

Argonne
NATIONAL LABORATORY



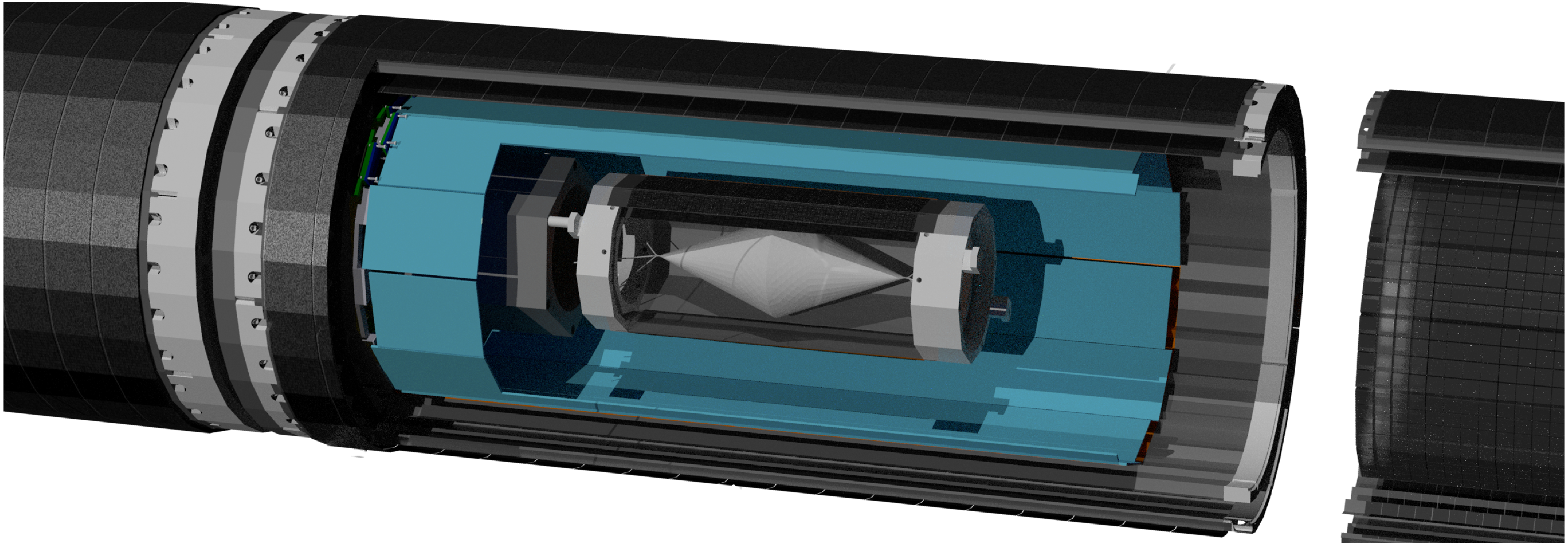




$\mu^- N \to e^- N$

Appendix

The Scintillating Fibre Detector: Overview



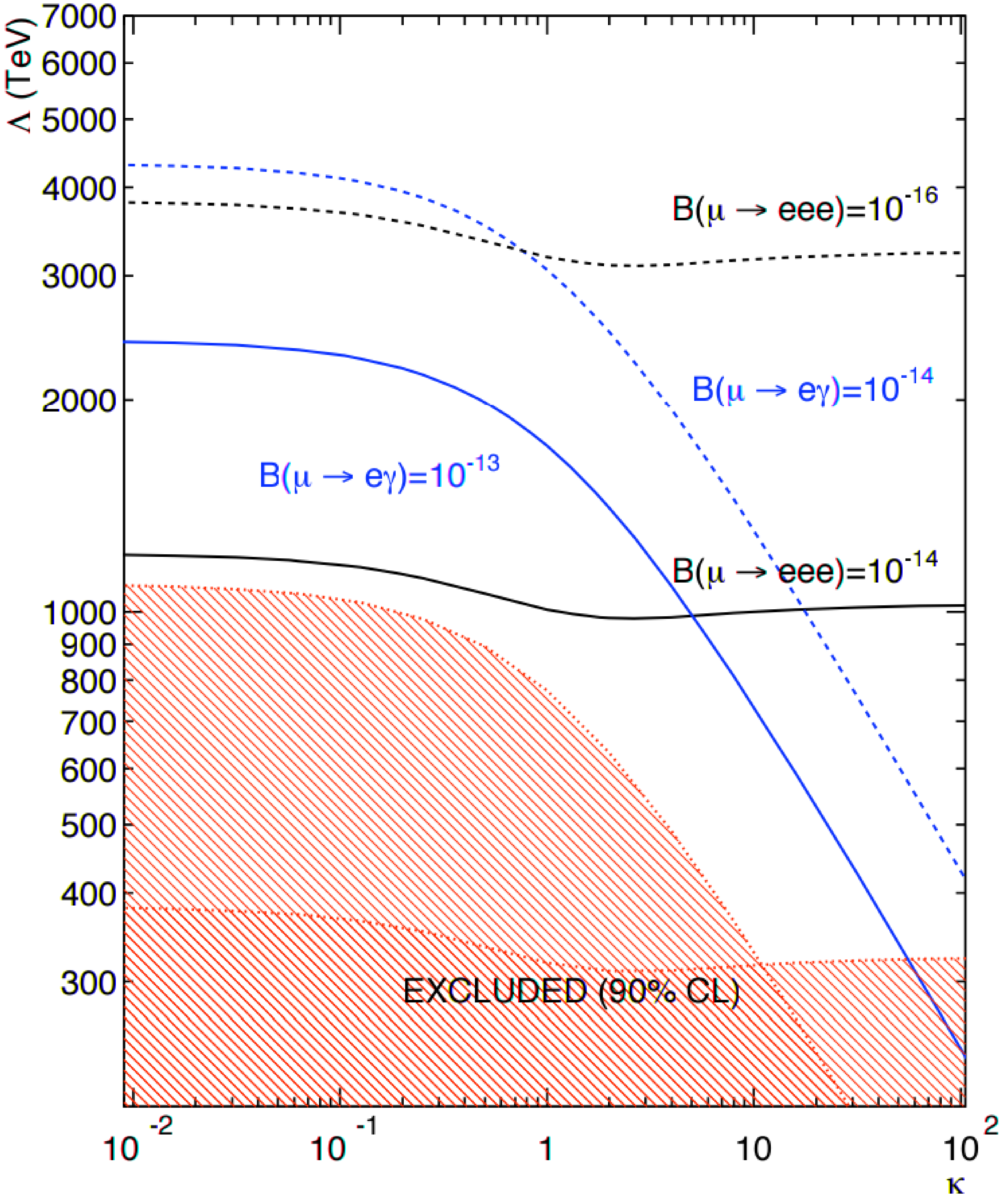
Components

- cylindrical at r $\sim$ 6 cm; 29 cm long
- 4 layers of 250 µm fibres in 12 ribbons
- SiPM column arrays
- mixed mode ASIC: MuTRiG

Requirements

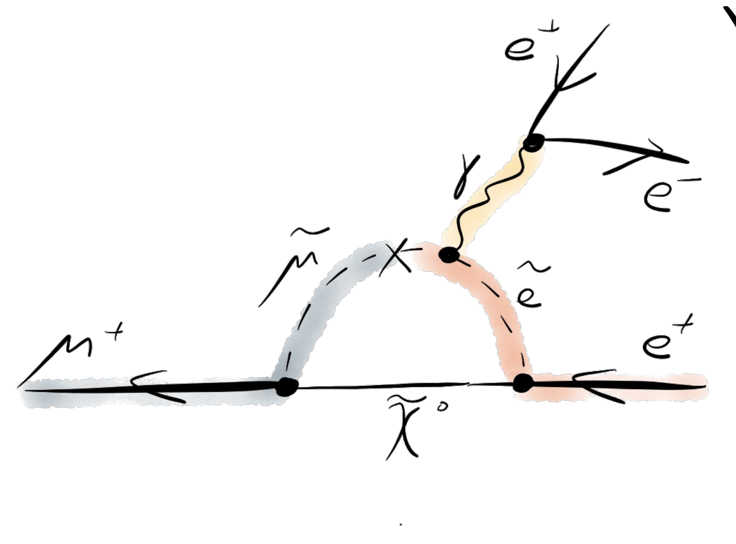
- as thin as possible; $\leq 0.5\,\% X_0$ (1 mm)
- as efficient as possible; close to 100 %
- time resolution better than 350 ps
- up to 250 kHz/fibre; 625 kHz/channel

Mu3e/MEG Processes

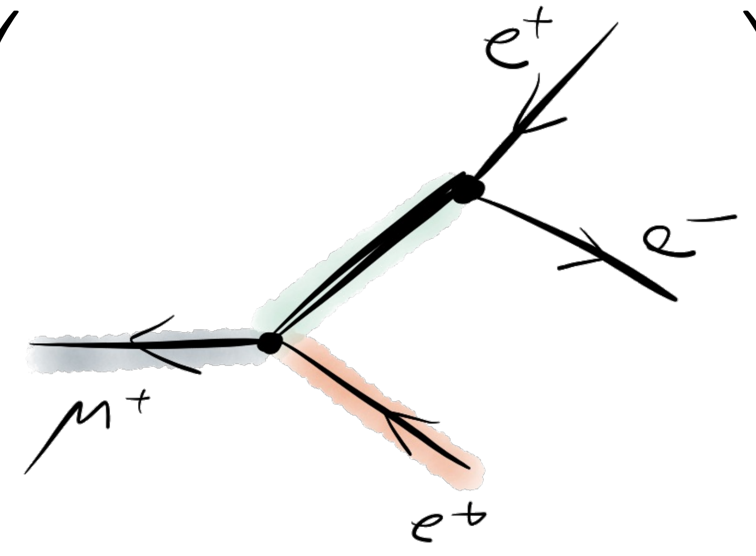


A. Gouvea1 and P. Vogle, Lepton Flavor and Number Conservation, and Physics Beyond the Standard Model, arXiv:1303.4097 (2013)

$$\frac{m_\mu}{1+\kappa}\Lambda^2 \left(\right.$$

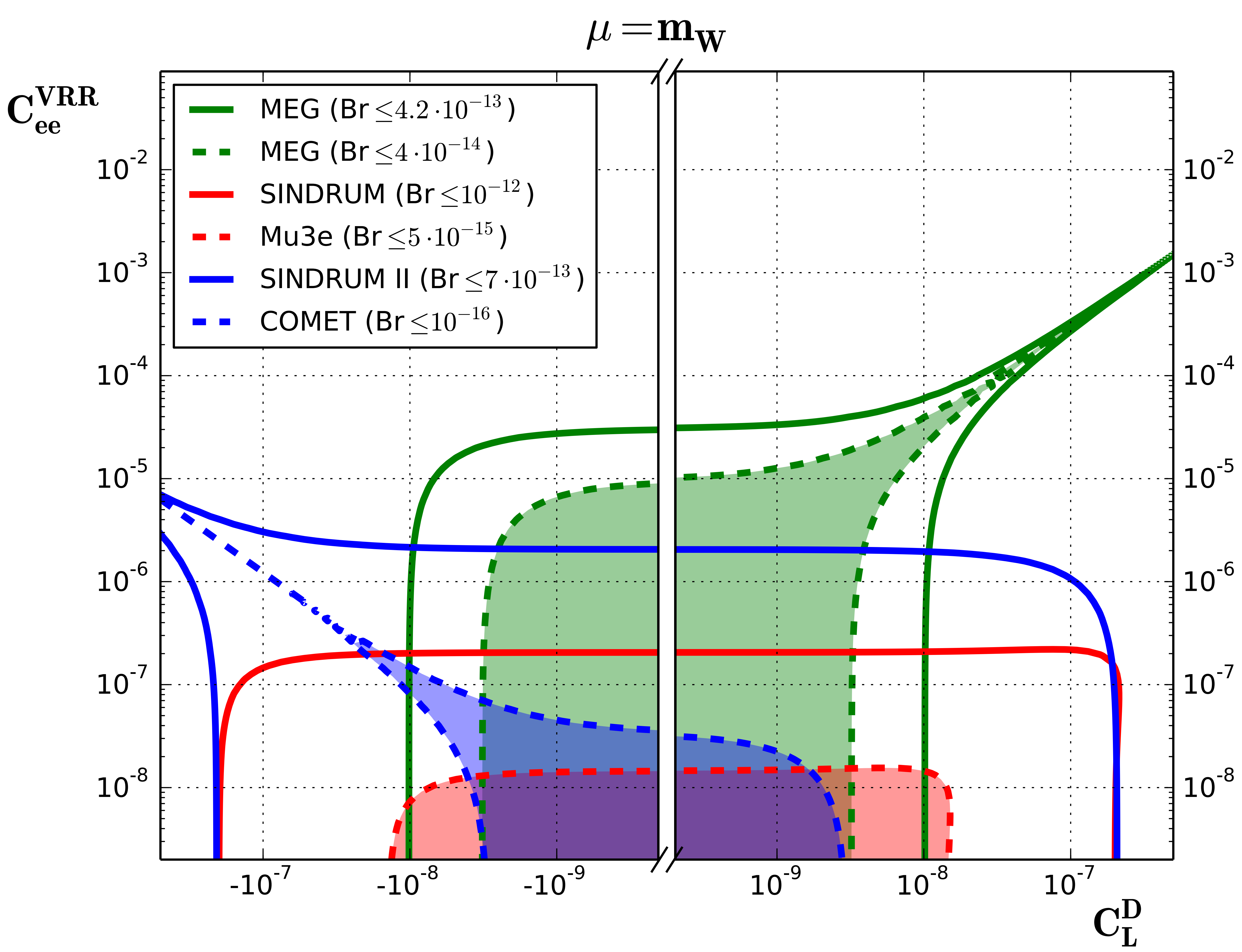


$$\left. \right) + \frac{\kappa}{1+\kappa}\Lambda^2 \left(\right.$$



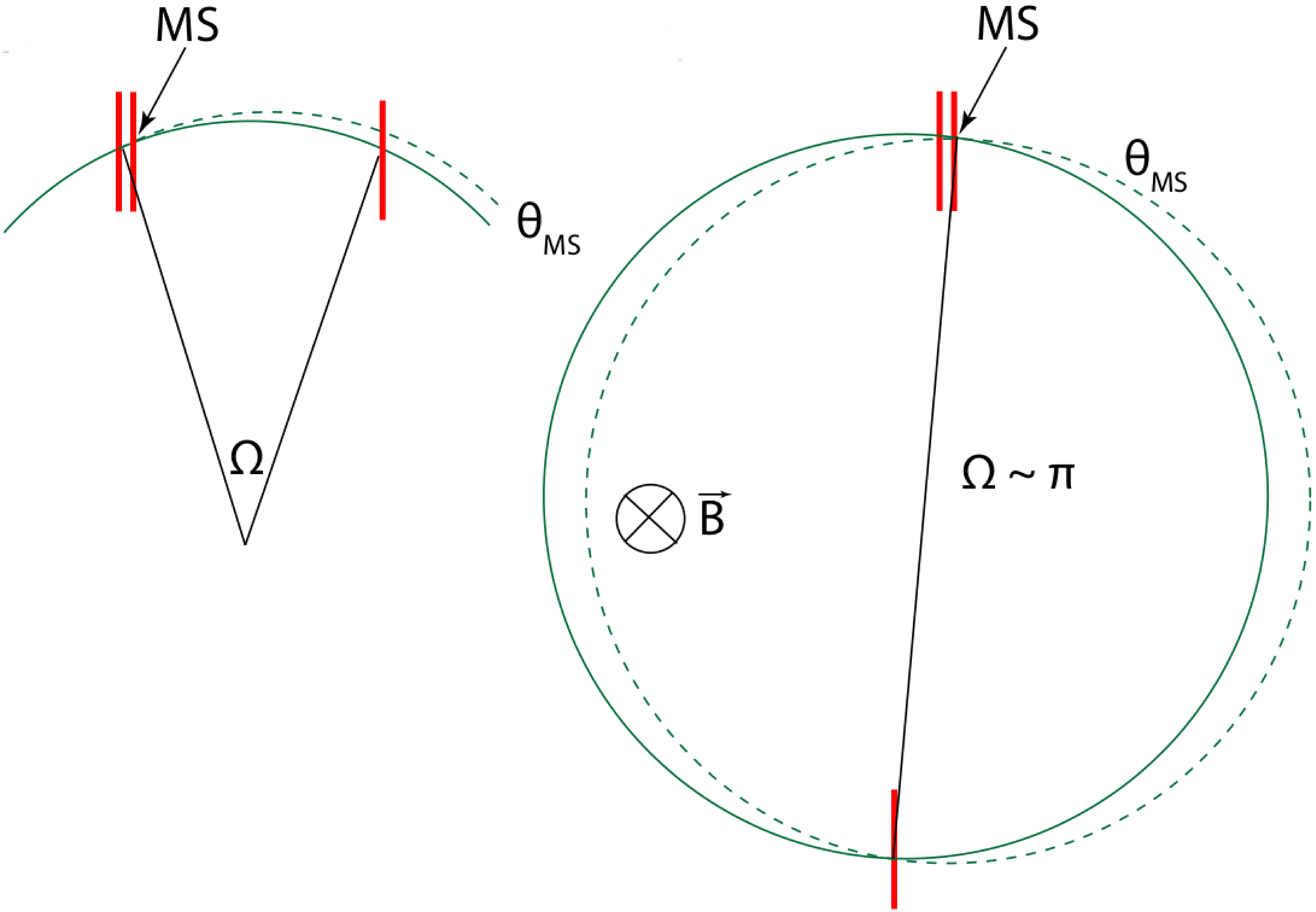
$$\left. \right)$$

Mu3e/Meg Comparison: Effective Field Theory



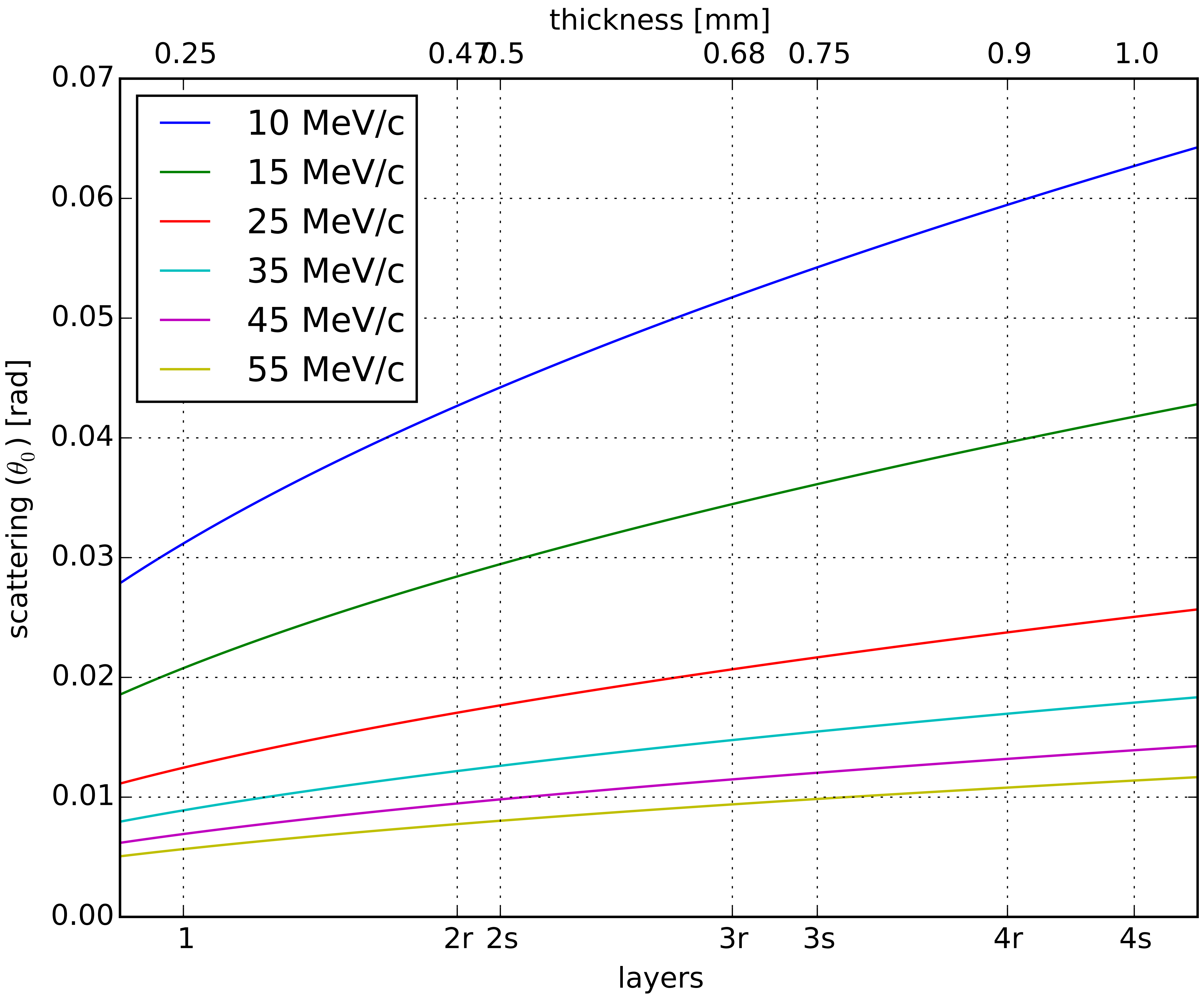
A. Crivellin, S. Davidson, G. M. Pruna, and A. Signer, "Renormalisation-grou improved analysis of $\mu \to e$ processes in a systematic effective-field-theory approach", JHEP, vol. 05, p. 117, 2017.

Multiple Scattering



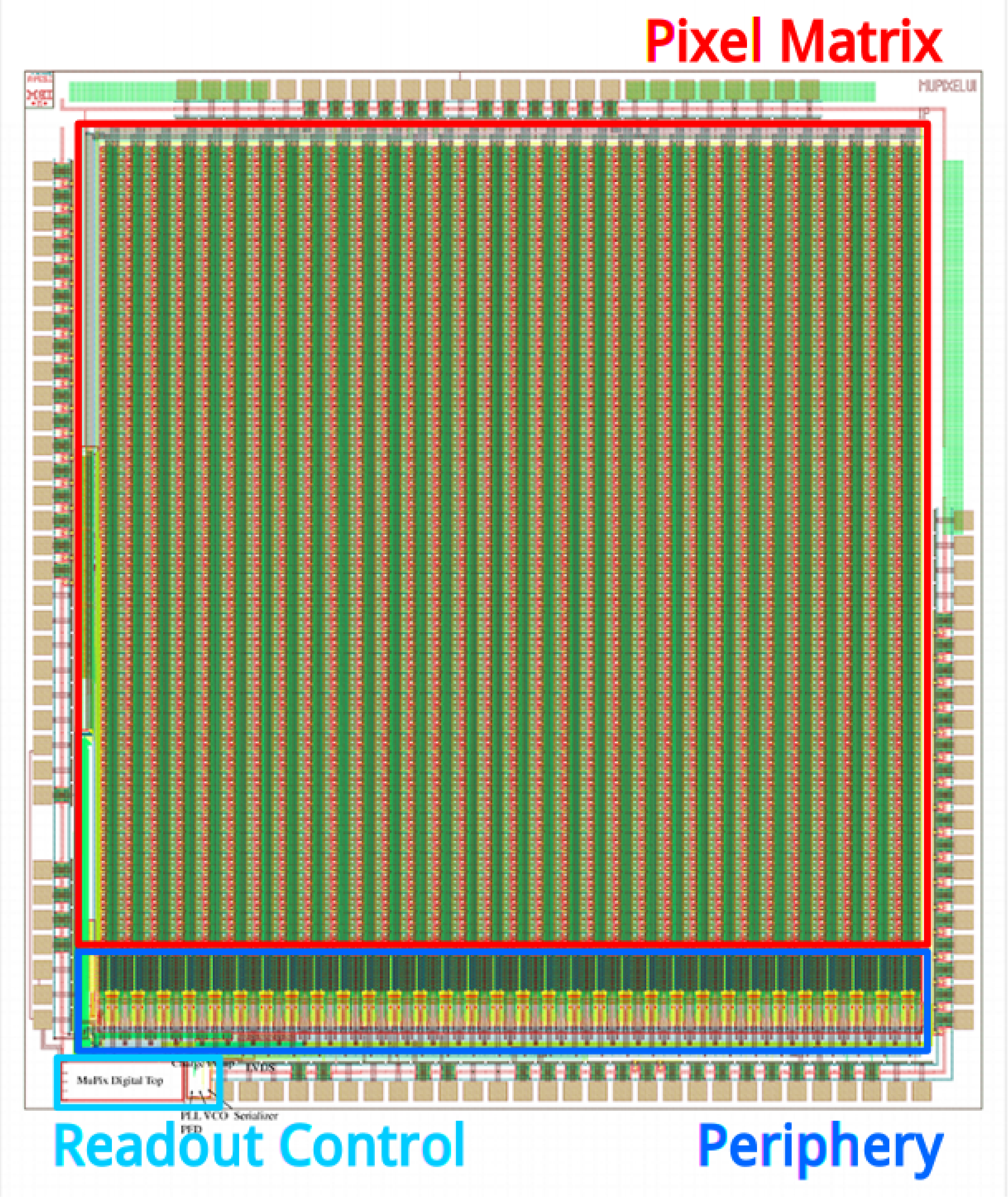
Multiple Coulomb Scattering

$$\theta_0 = \frac{13.6\,\text{MeV}}{\beta c p} z \sqrt{x/X_0}\left[1 + 0.038 \ln x/X_0\right]$$

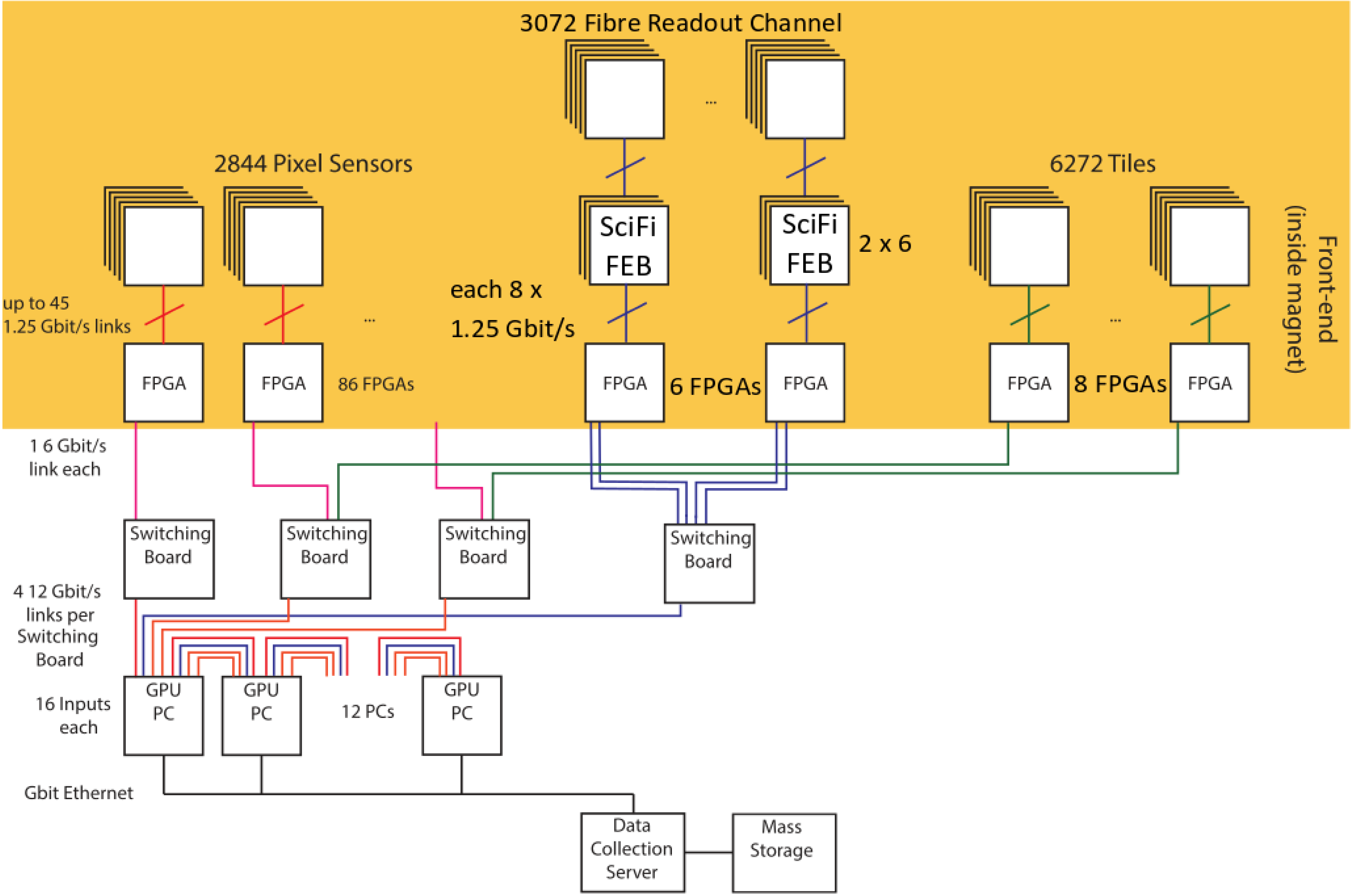


Caution: θ_0 with of Gaussian for central 98 %. The larger tails are not described with this.

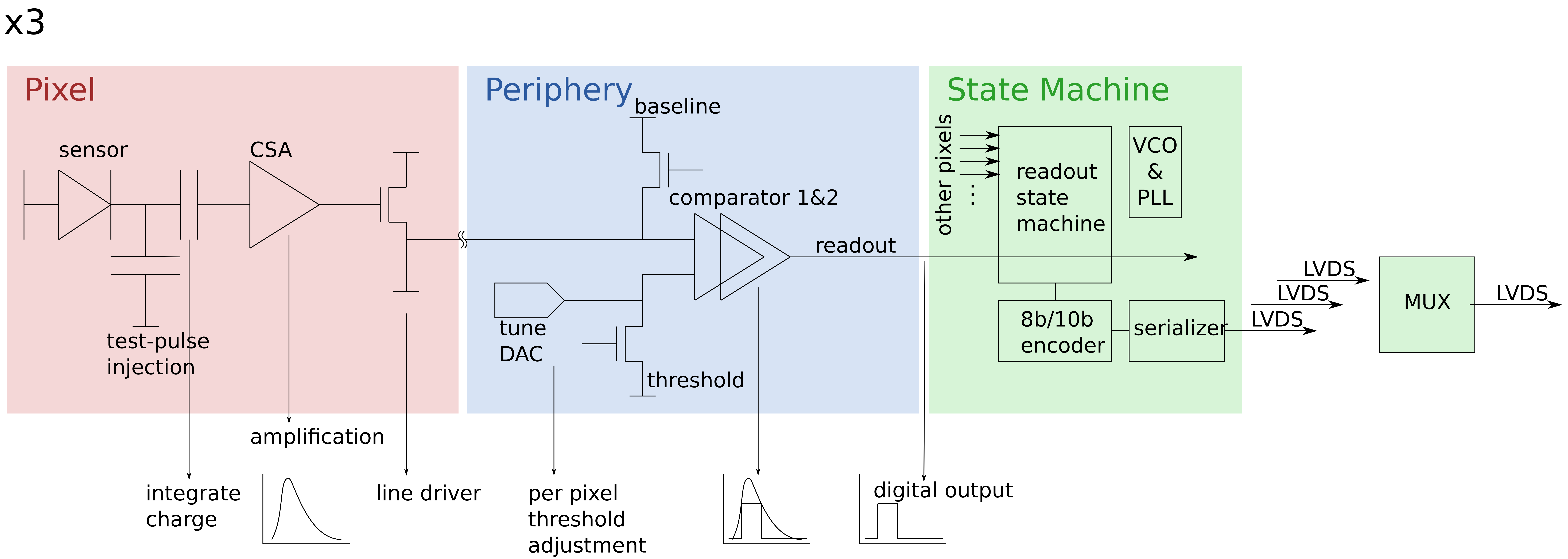
MuPix7


Pixel Matrix
MUPIXELUI
MuPix Digital Top
PLL VCO Serializer
Readout Control
Periphery

Readout Concept



Mupix Schematic

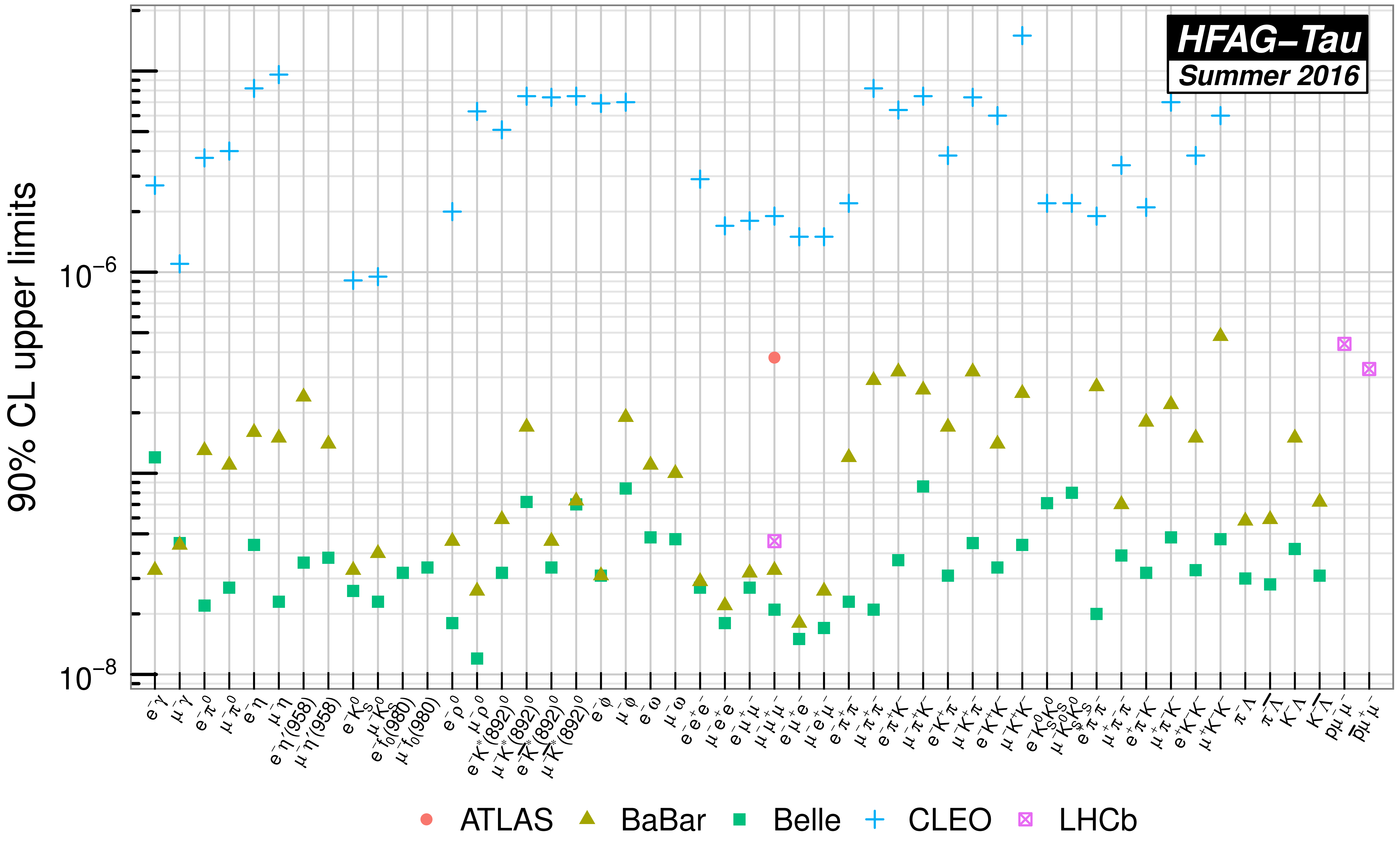


Lennart Huth (PI HD) July 2017.

The Collaboration

	involvement	Senior (incl. Prof)	PostDoc	PhDs
Paul Scherrer Institut PSI	infrastructure, scifi, target, pixel	8	1	1
Ruprecht-Karls-Universität Heidelberg PI	pixel, integration	2	1	4
Ruprecht-Karls-Universität Heidelberg KIP	tile detector, readout ASIC	2	1	3
JGU Johannes Gutenberg Universität Mainz	simulation, reconstruction, readout	1	2	1
KIT Karlsruher Institut für Technologie	sensor design	1	0	1
Université de Genève	scifi	1	0	2
ETH zürich	scifi	3	0	2
Universität Zürich UZH	simulation, scifi	2	2	0
University of Liverpool	pixel	6	1	0
University of Oxford	pixel	6	0	0
University of Bristol	pixel	3	1	0
UCL	clocking	2	0	0
total	**60**	**37**	**9**	**14**

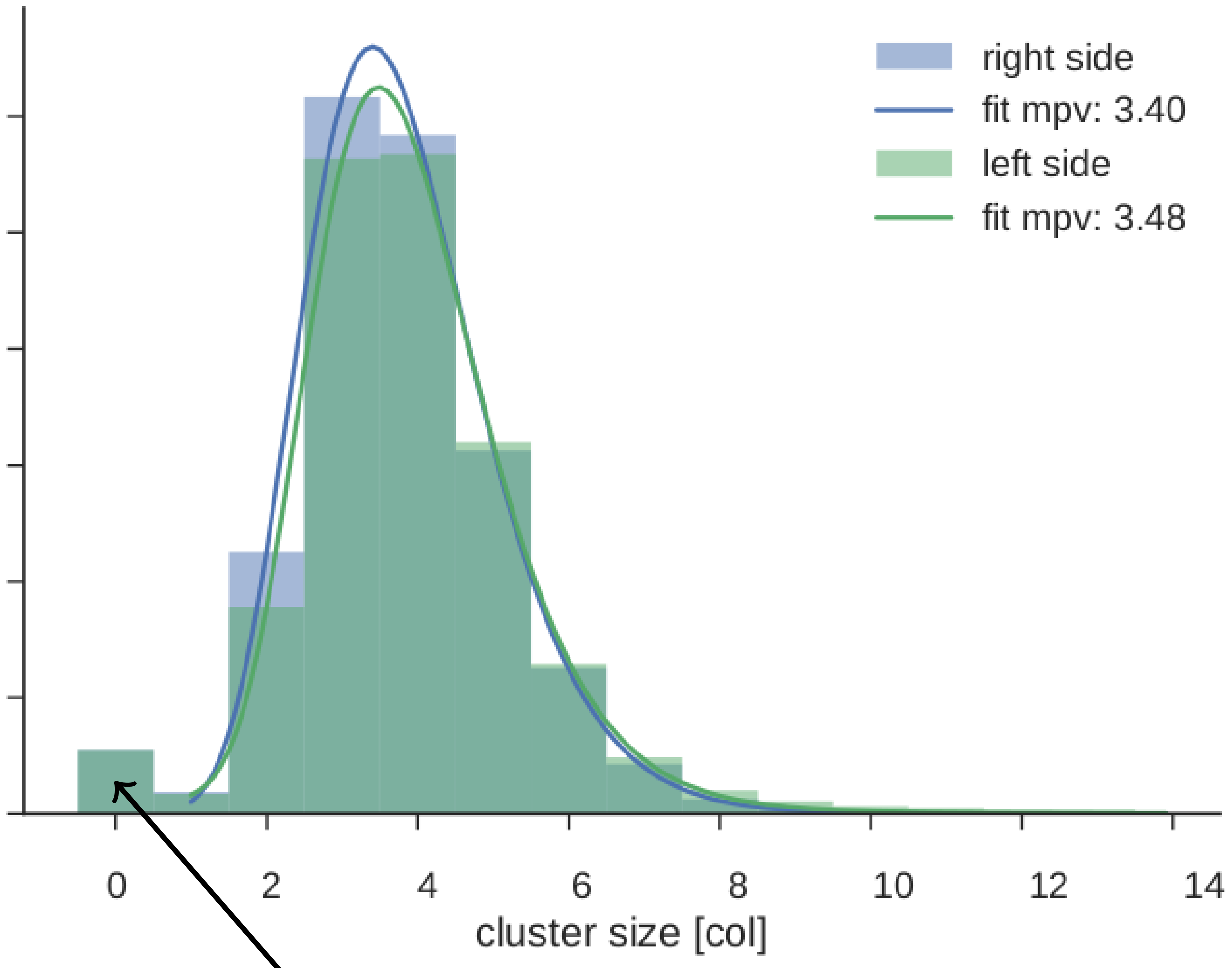
Charged Lepton (Tau) Flavour Violating **Decays**



from the HFAG working group from L. Calibbi and G. Signorelli, "Charged Lepton Flavour Violation: An Experimental and Theoretical Introduction"

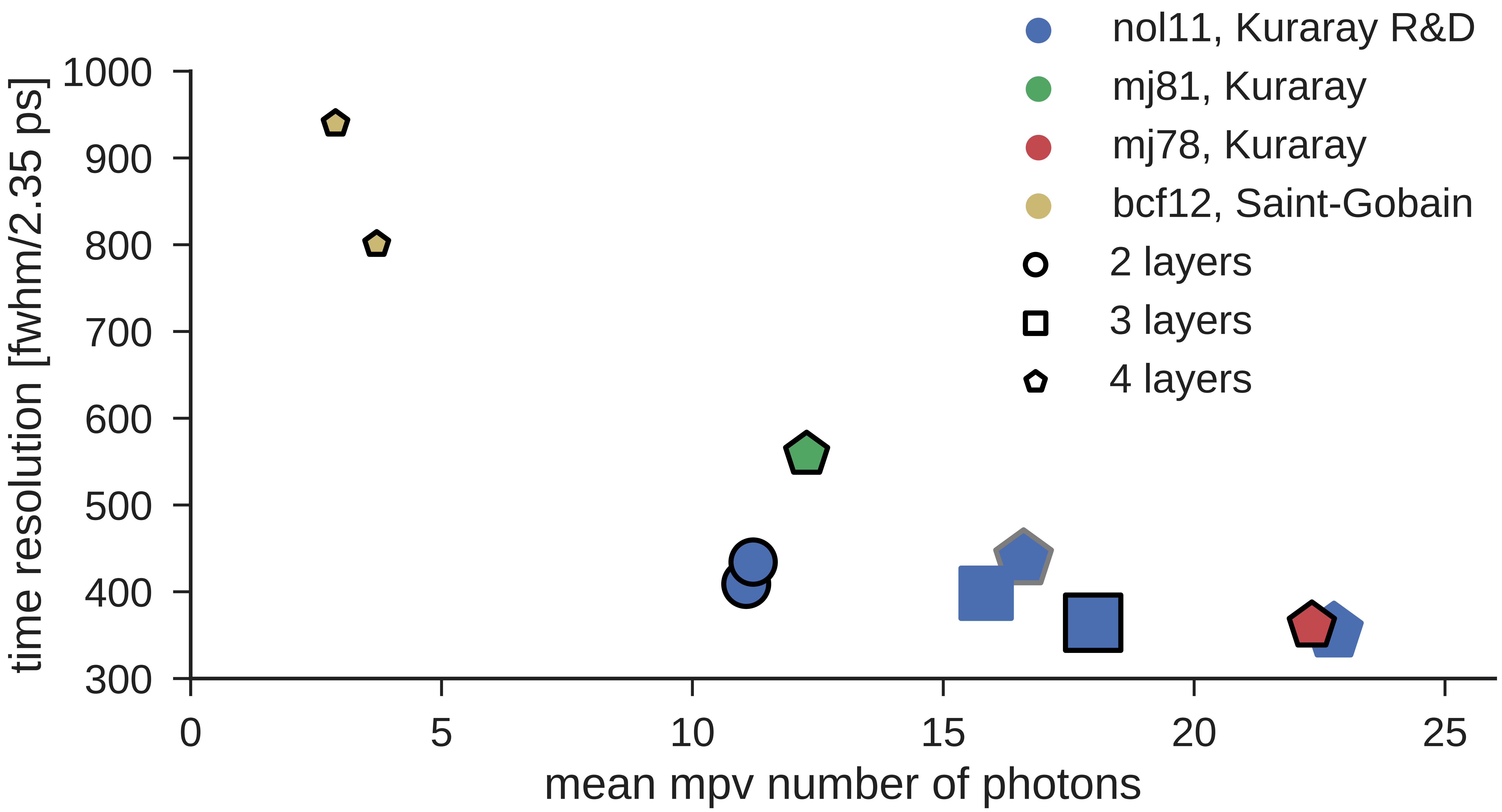
arXiv:1709.00294v2, 2017.

Scintillating Fibre Prototypes: Cluster Size



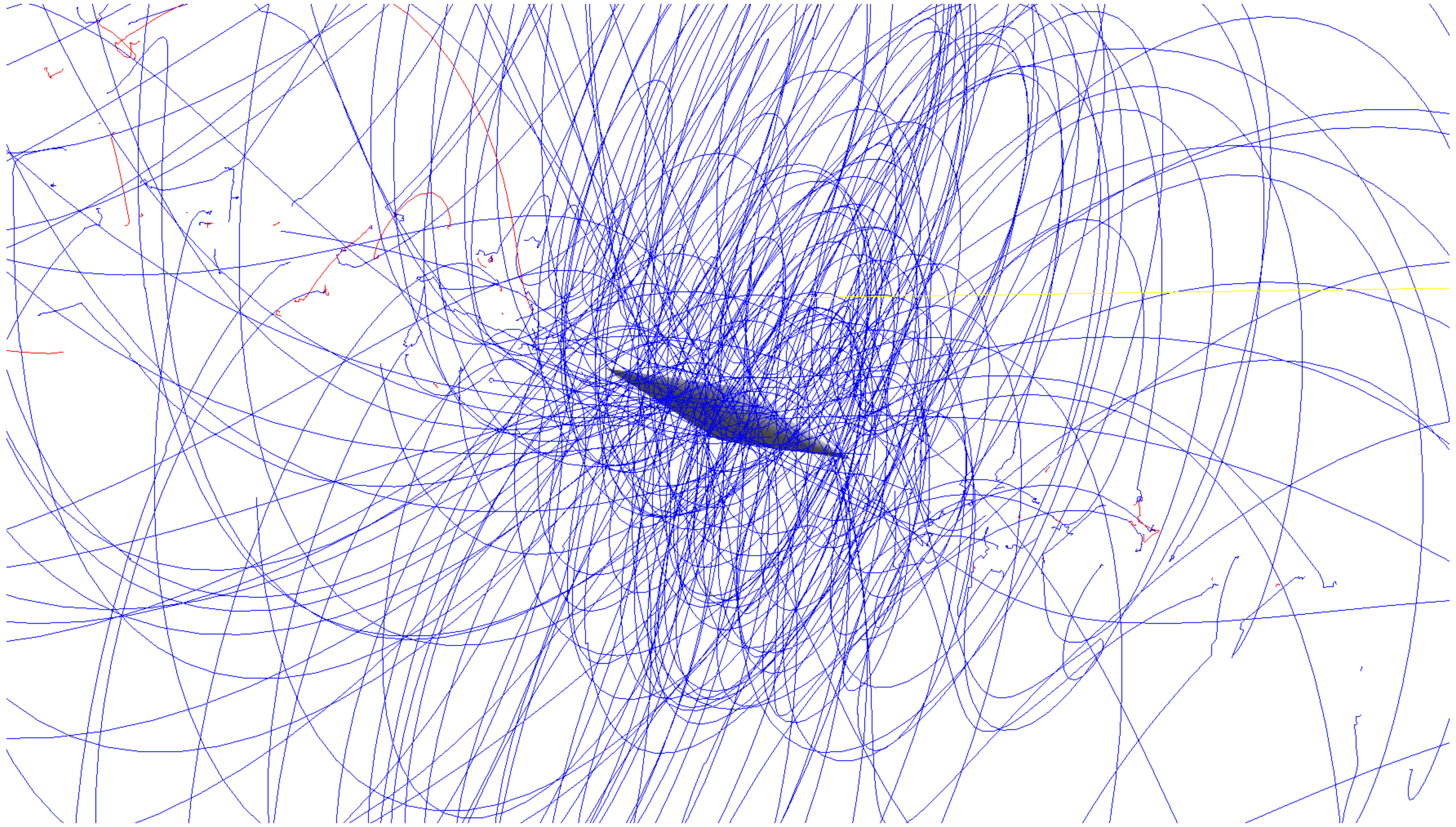
$\varepsilon > 97\,\%$

Prototype Comparison



Further Challenges

High Rates



Tracks within $\sim$10 µs.

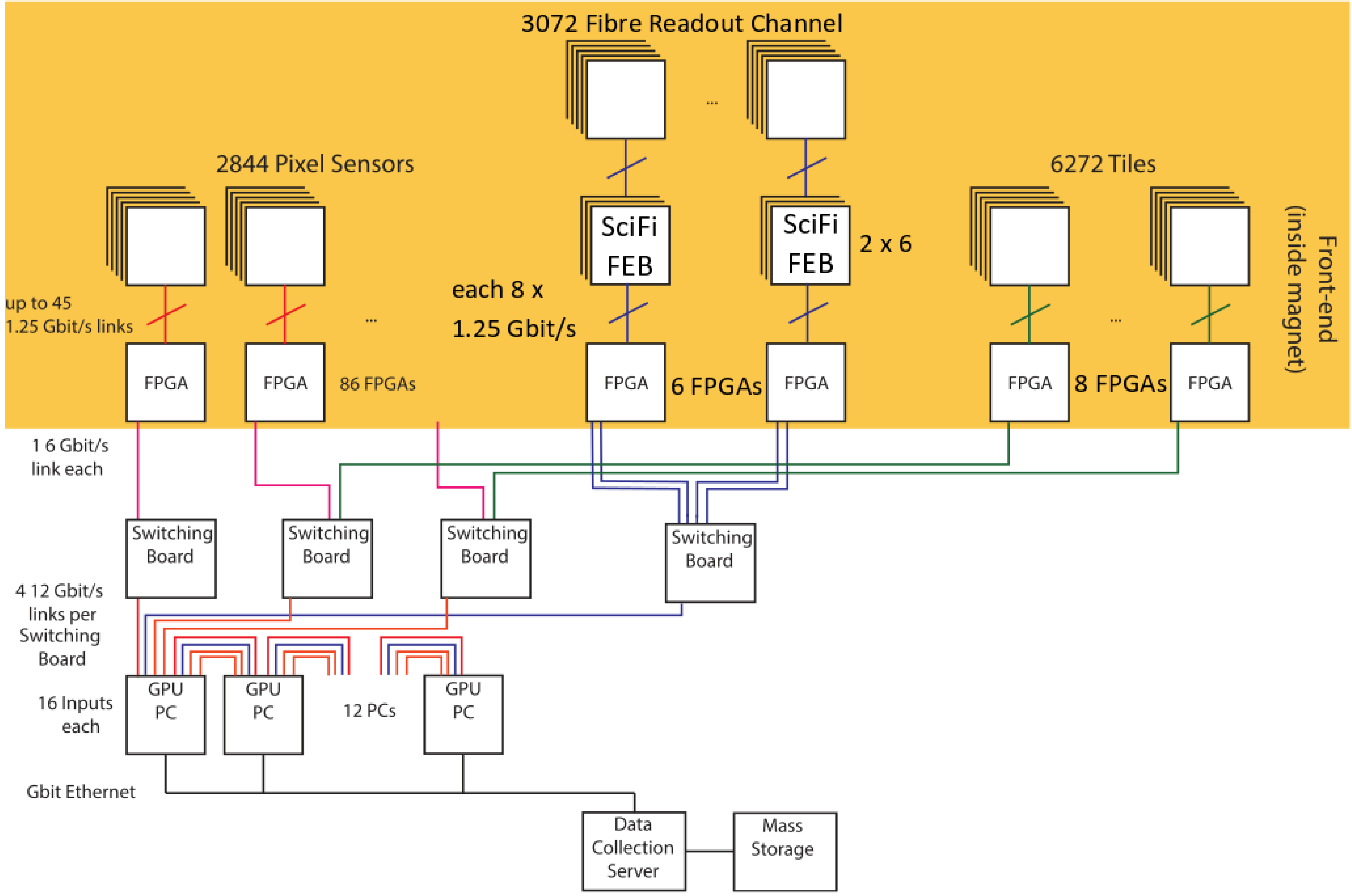
reasonable time → high rates required → MuE5 at PSI

continuous surface muon beam

Online Reconstruction

due to topology

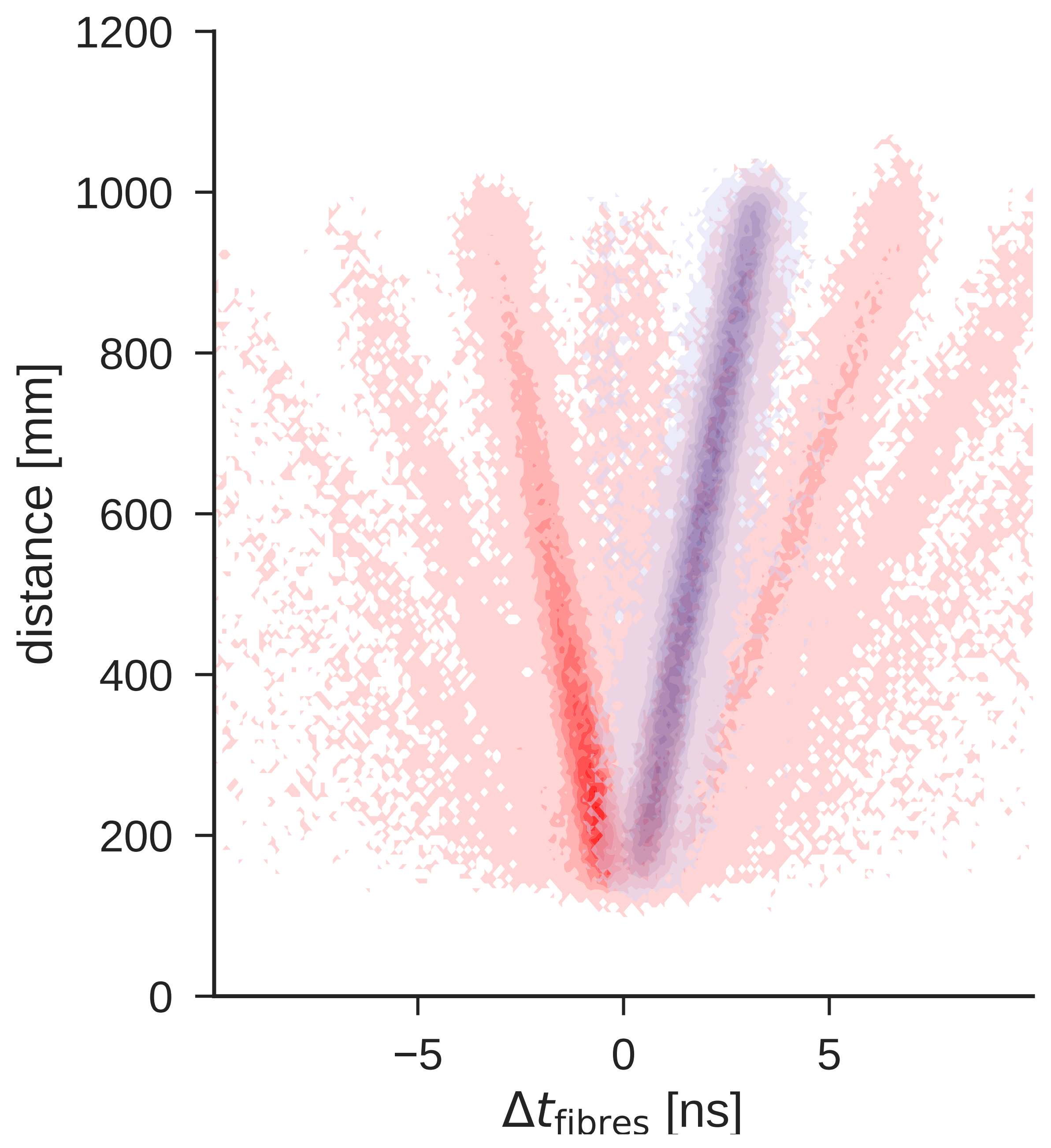
reconstruction farm: each **GPU** receives data from **the full detector** of a **time slice**

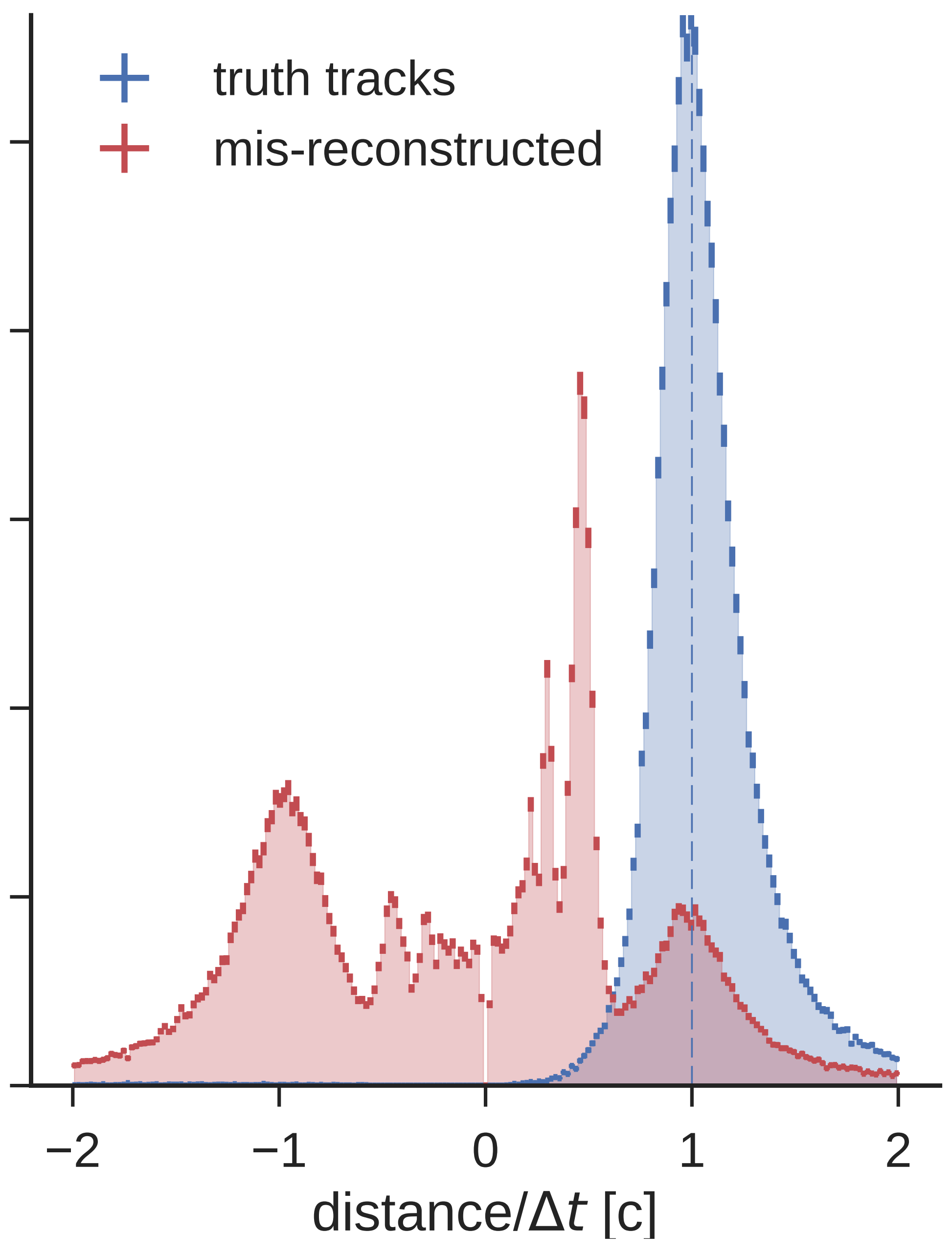


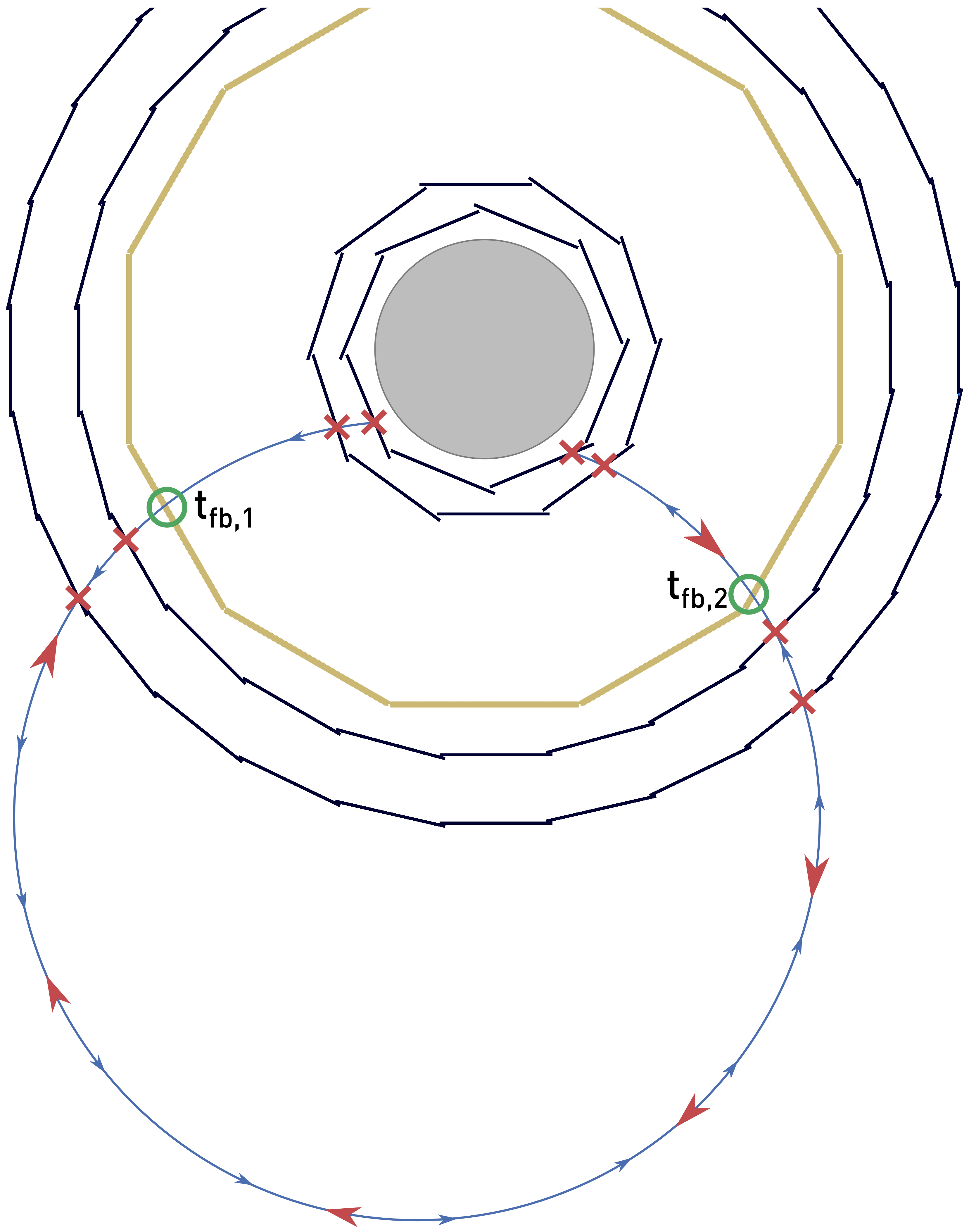
The Fibre Detector: Impacts

Rejection of Mis-Reconstructed Track Candidates

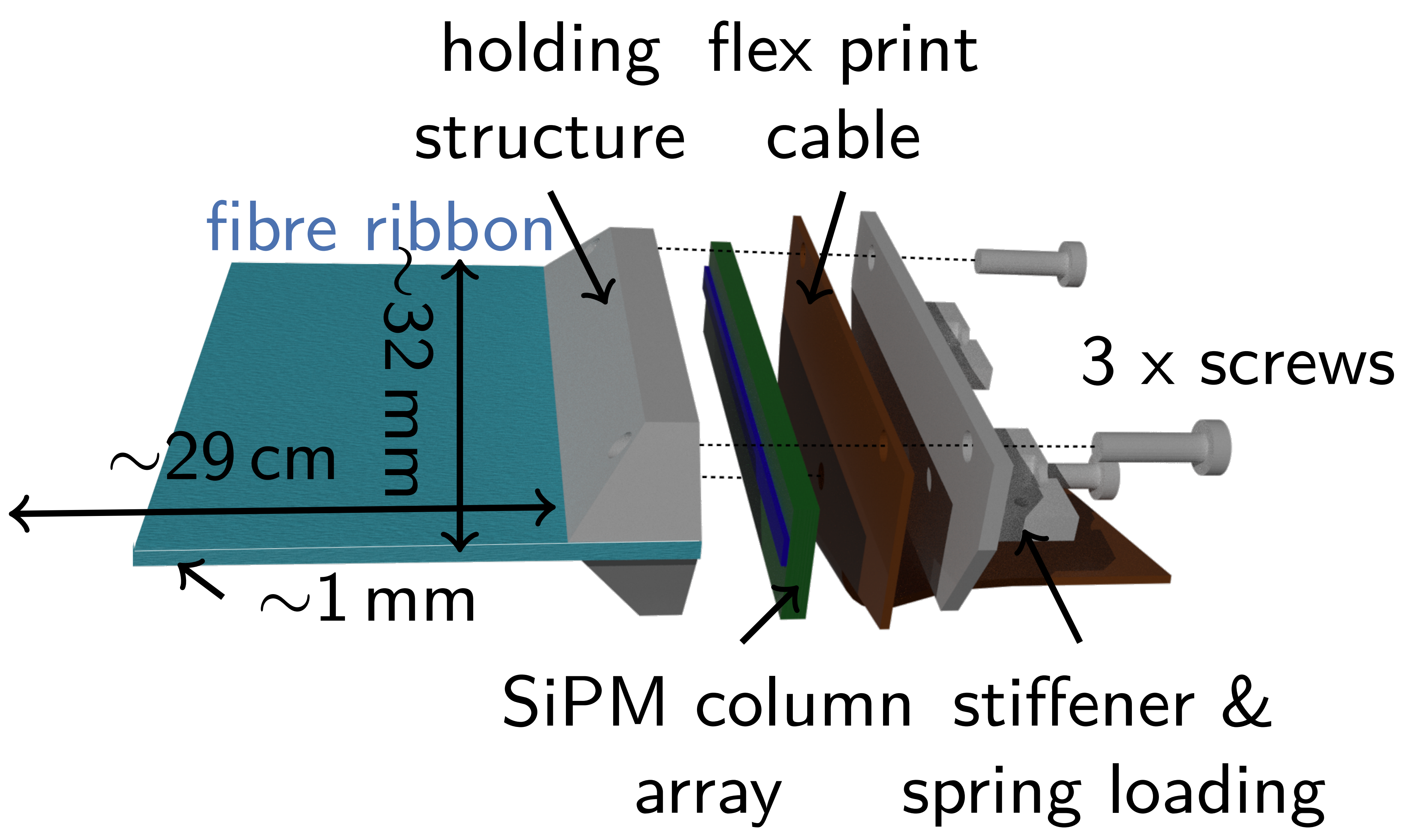
Time resolution ≤ 0.35 ns allows reliable charge identification for recurling tracks.

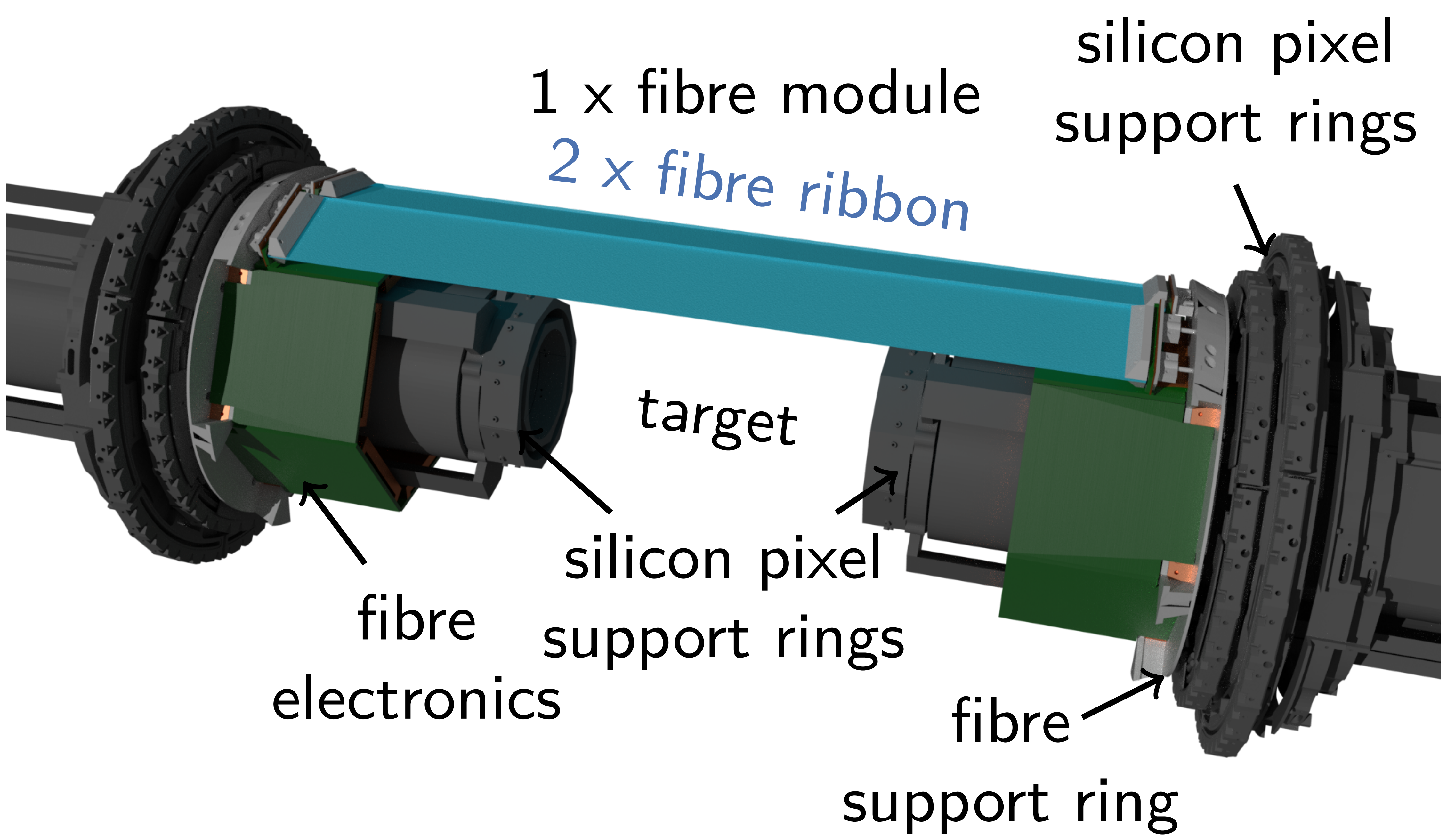






Mechanical and Electrical Integration



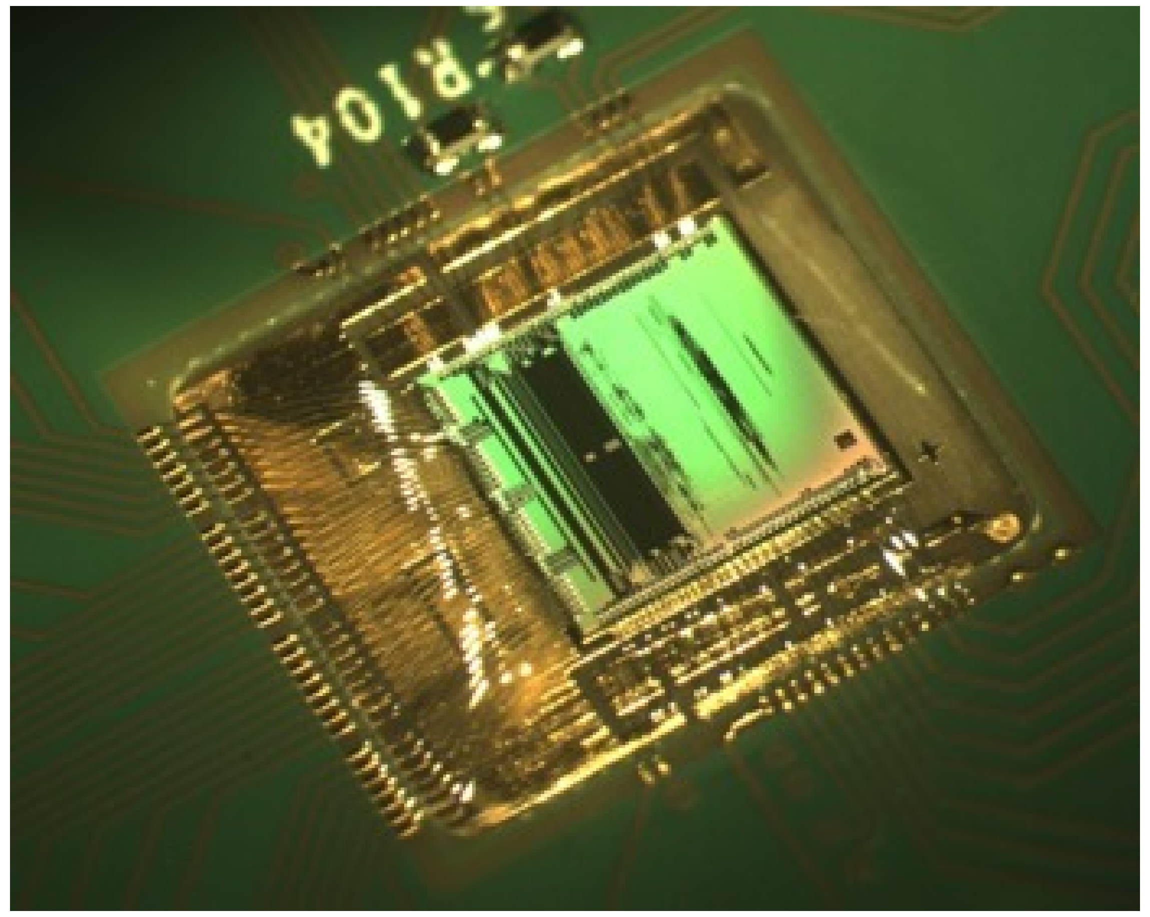


Design III: Mechanical Design

feasibility of mechanical integration of the sub-detector

Part II: Readout ASIC

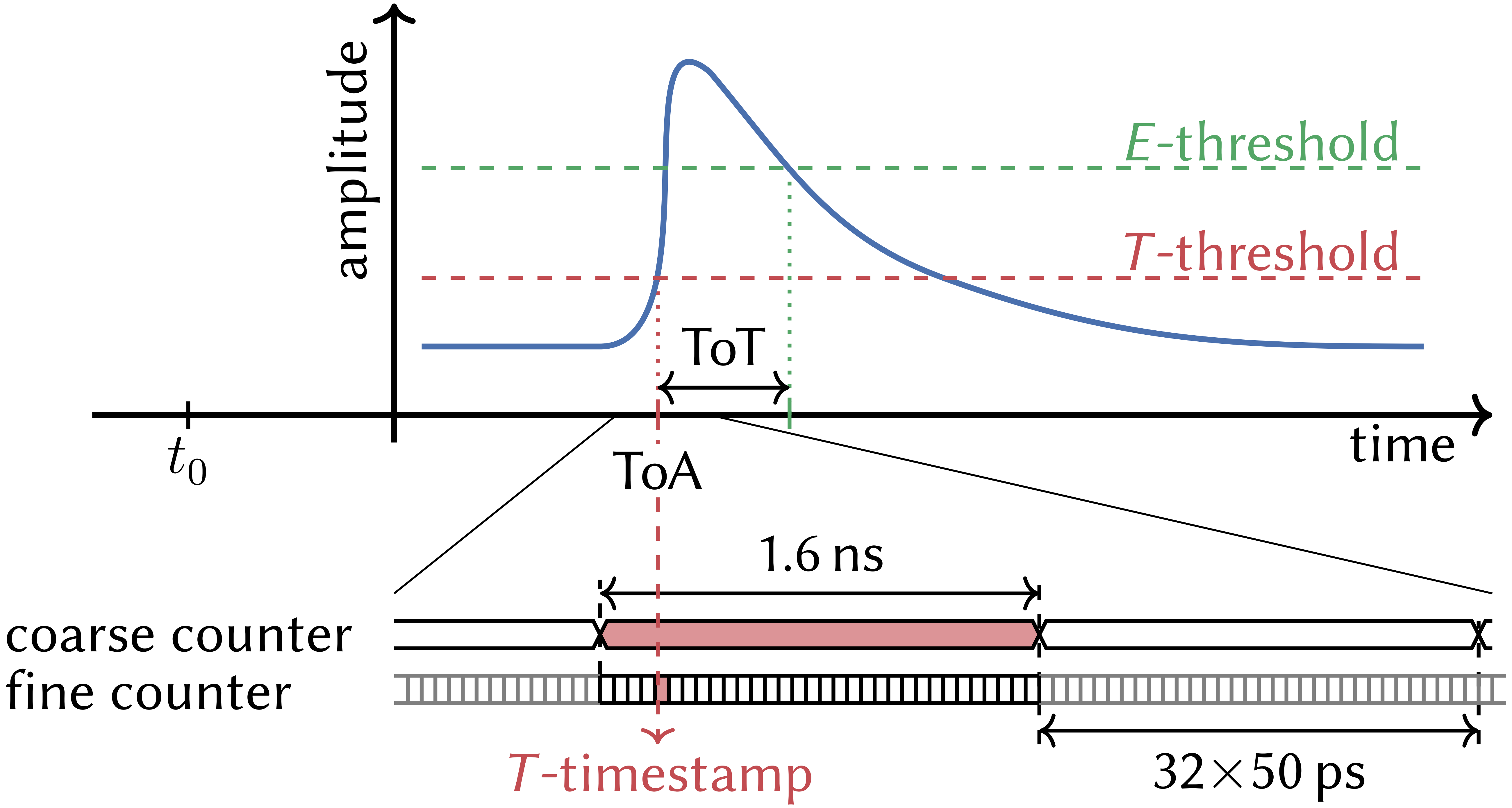
Time of Arrival (ToA) of 3072 channels each with a signal rate up to 1.0 MHz in very limited space



MuTRiG developed by KIP at University of Heidelberg

scope of this thesis: feedback to predecesors and fibre detector requirements, special "mode"

MuTRiG: mixed mode SiPM readout ASIC

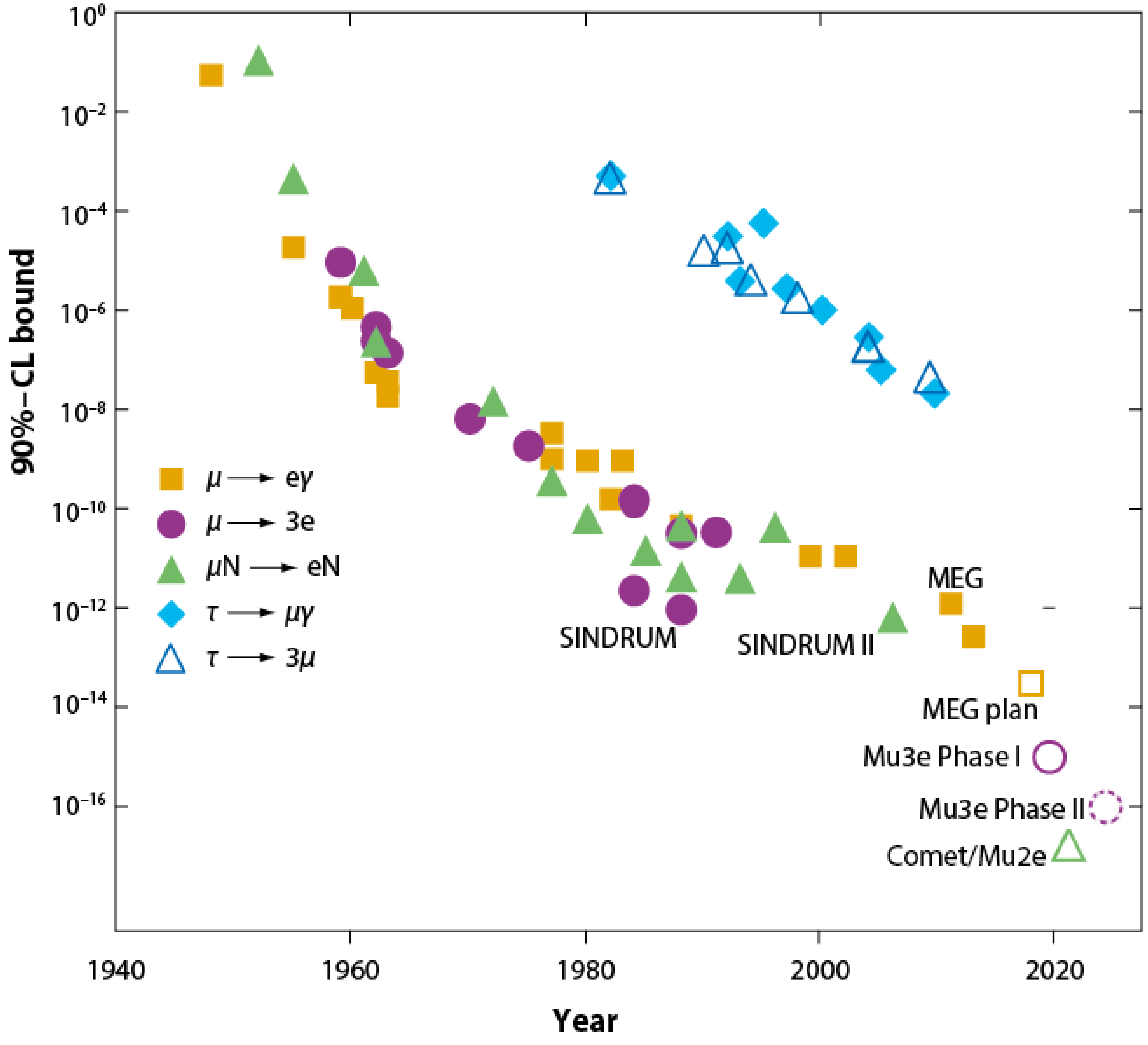


developed for PET: 100-1000 photons

tile detector: few 100 photons, (25 kHz/*ch*)

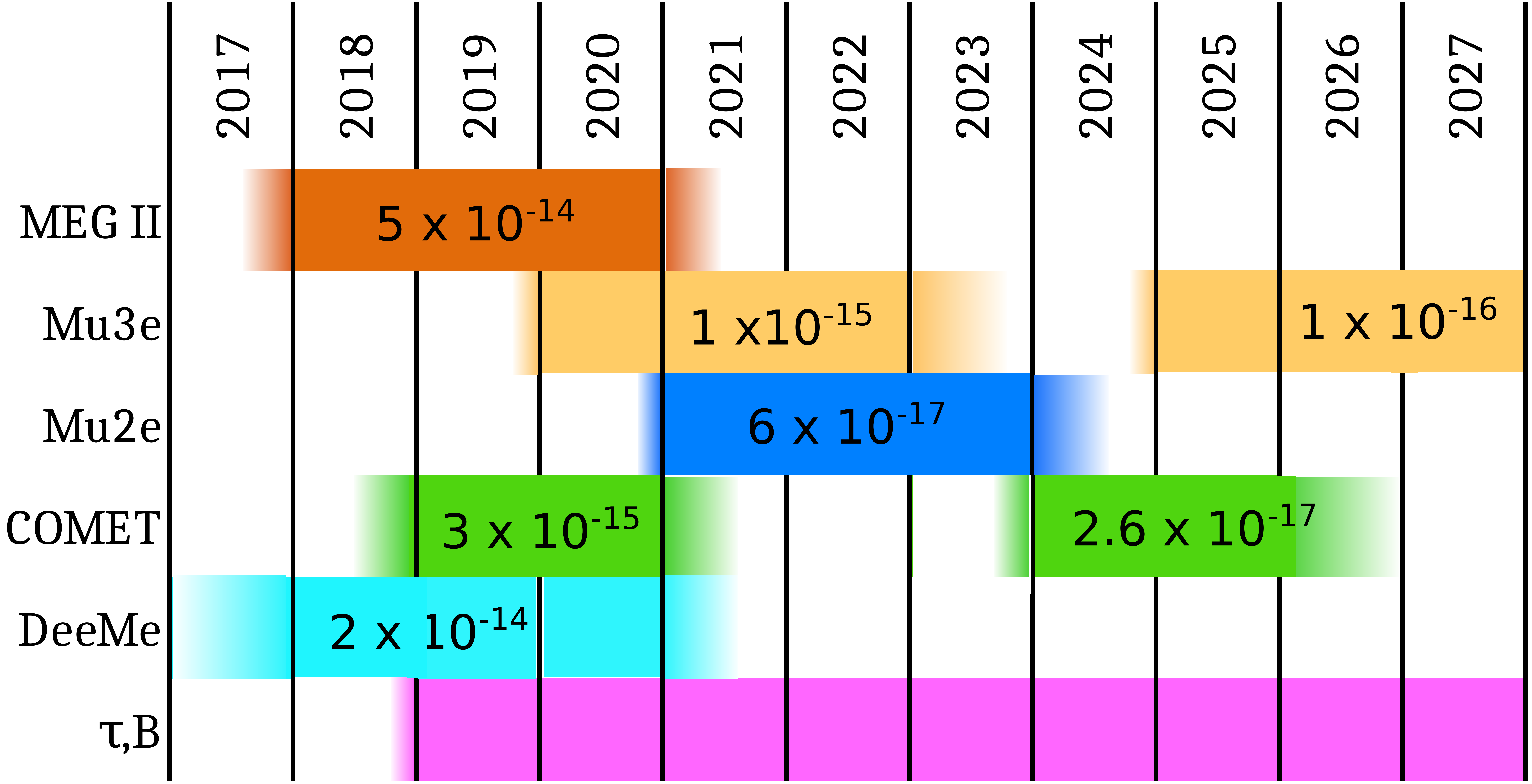
fibre detector: 1-7 photons, (1 MHz/*ch***)**

cLFV Decay **Experiments** History



Updated from W.J. Marciano et al., Ann.Rev.Nucl.Part.Sci. 58, 315 (2008).

cLFV Decay **Experiments** Future

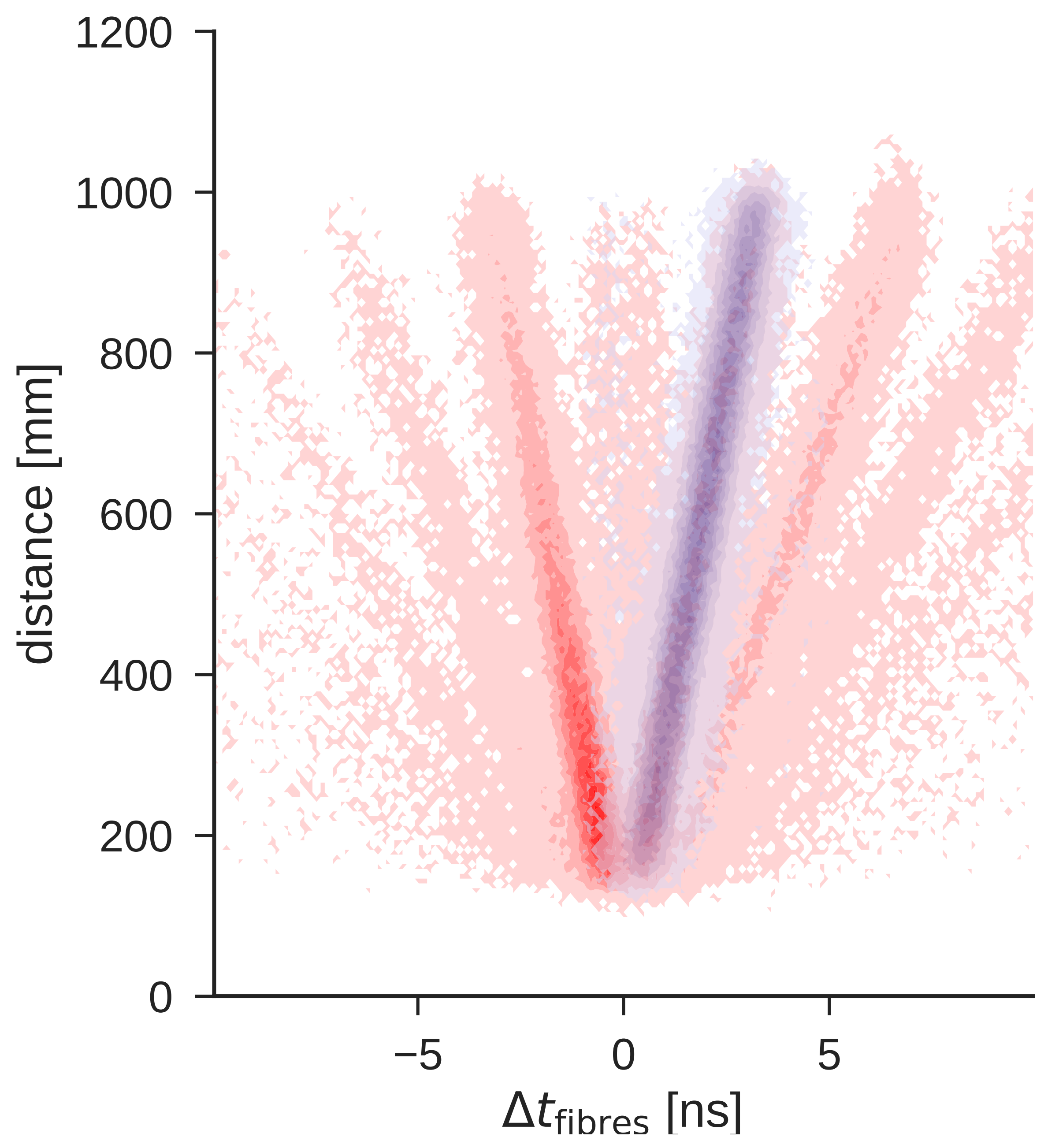


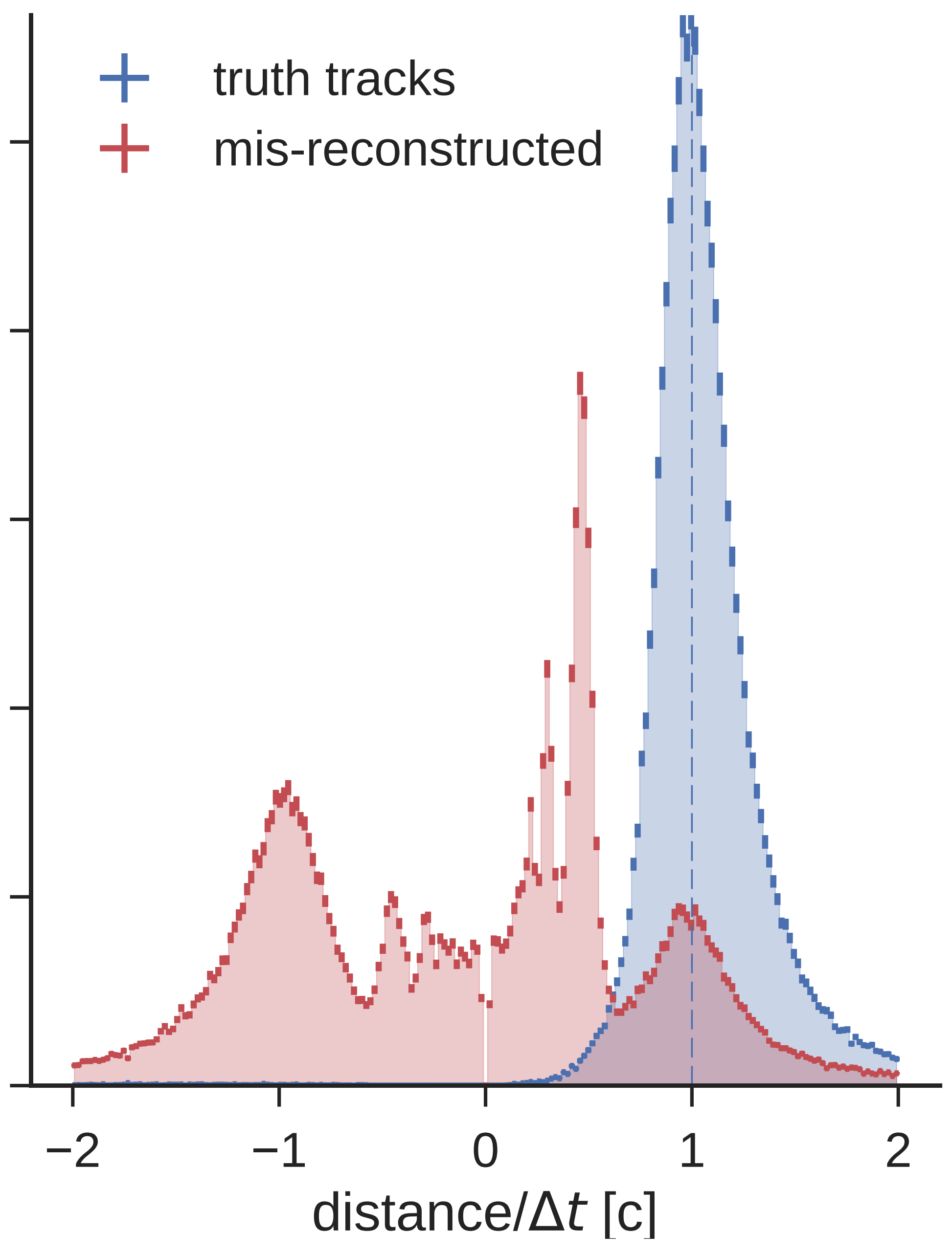
Modified from L. Calibbi and G. Signorelli, Charged Lepton Flavour Violation: An Experimental and Theoretical Introduction. arXiv:1709.00294v2, 2017.

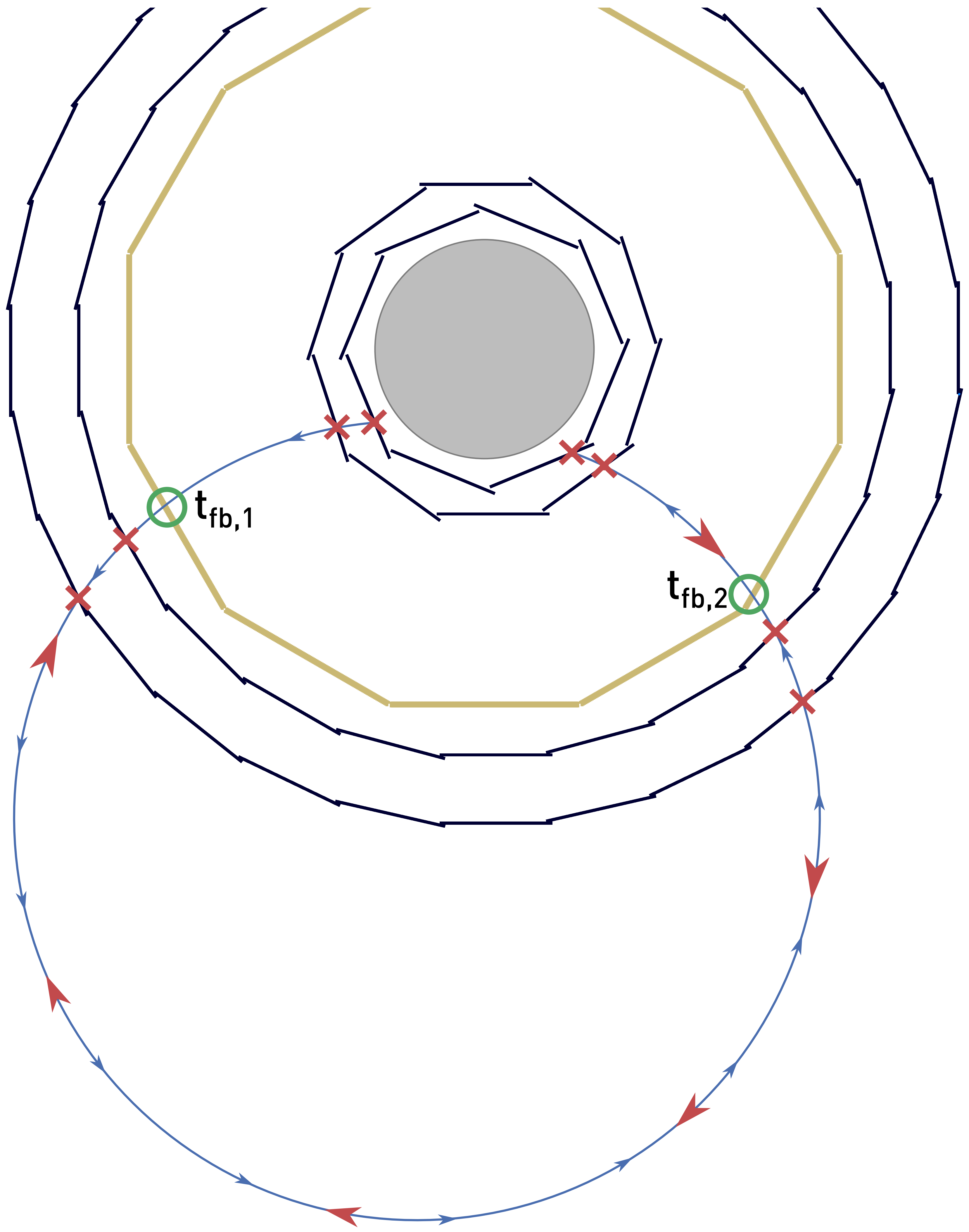
The Fibre Detector: Impacts

Rejection of Mis-Reconstructed Track Candidates

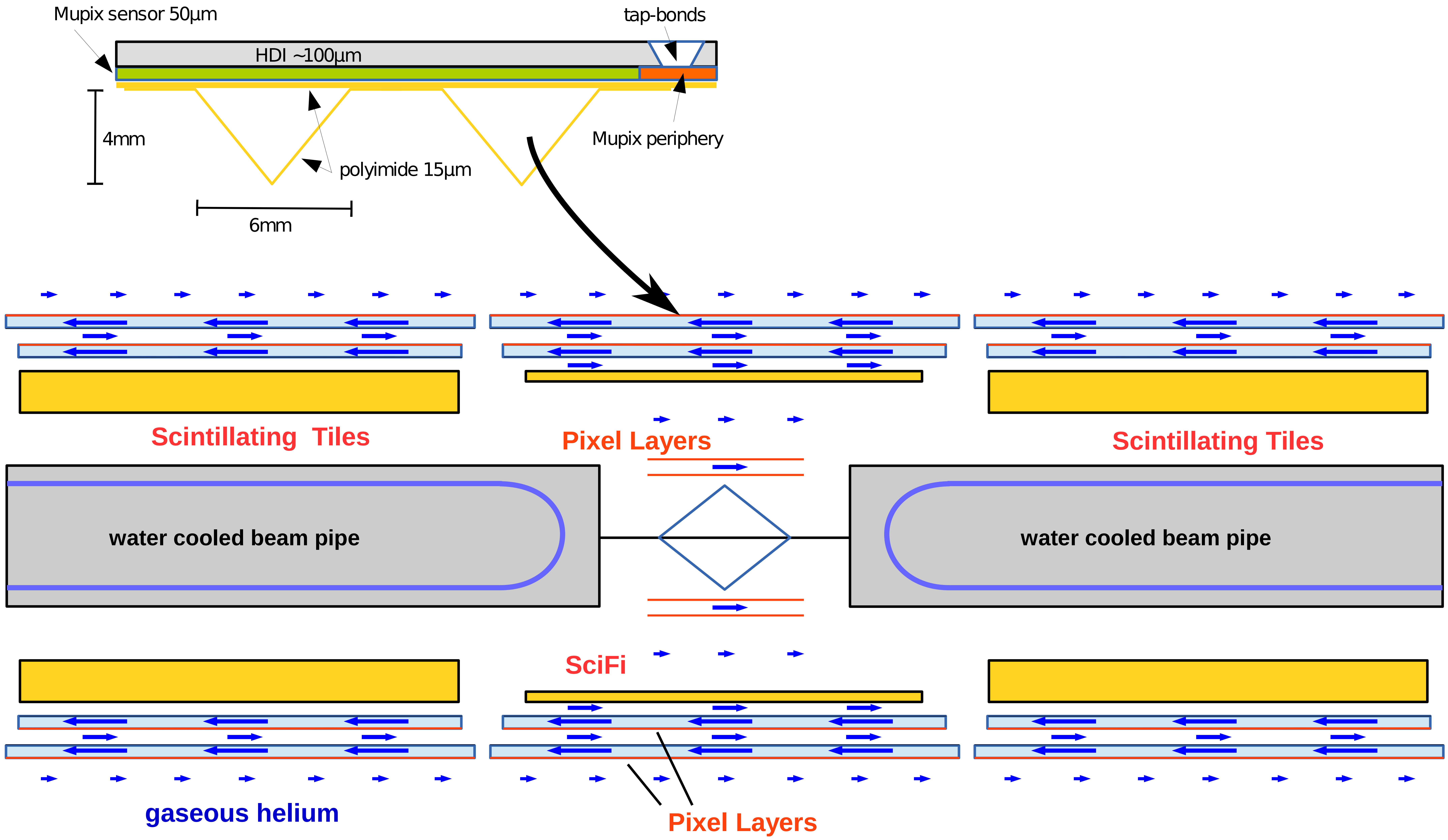
Time resolution $\leq 0.35\,\text{ns}$ allows reliable charge identification for recurling tracks.



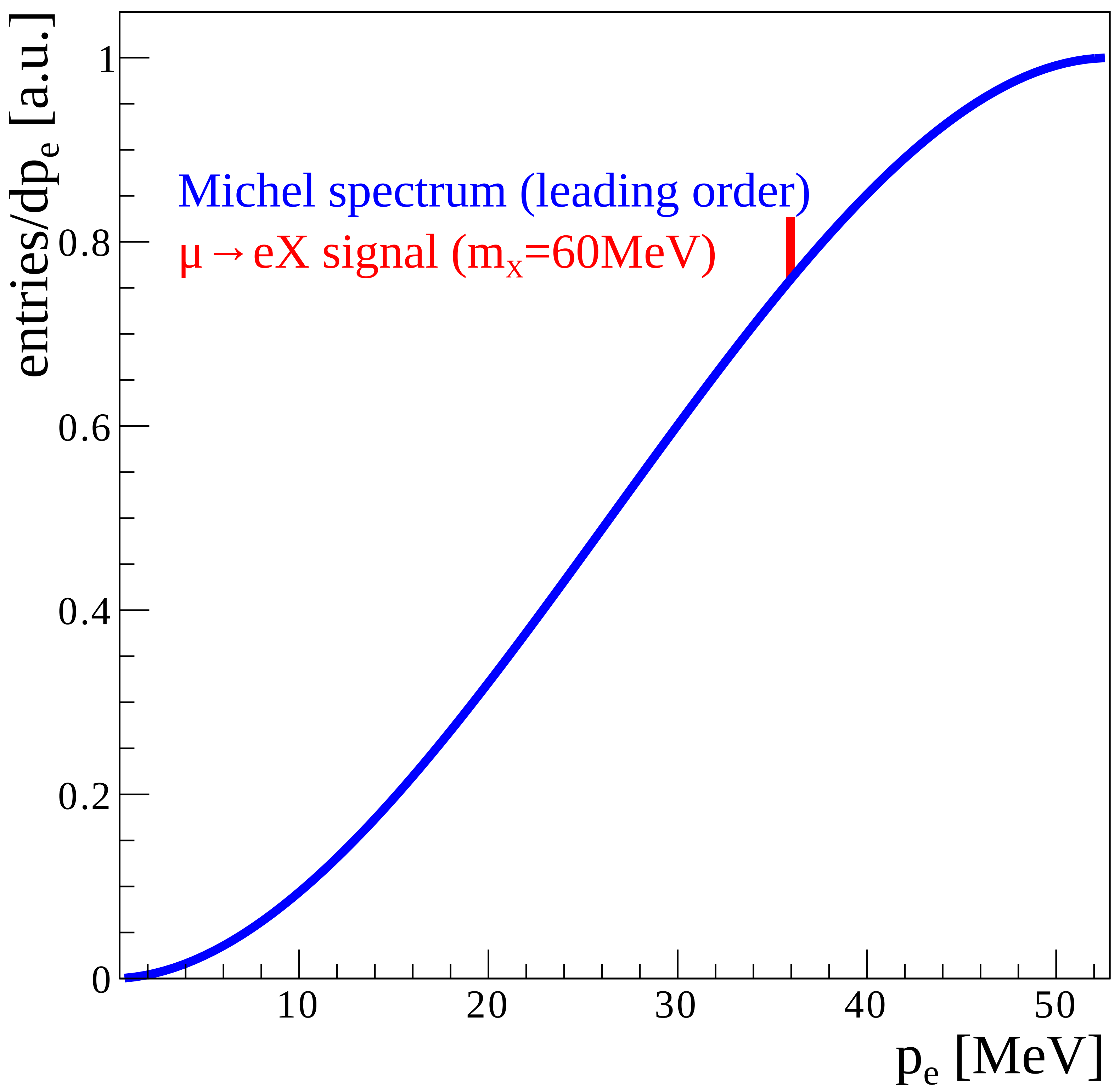


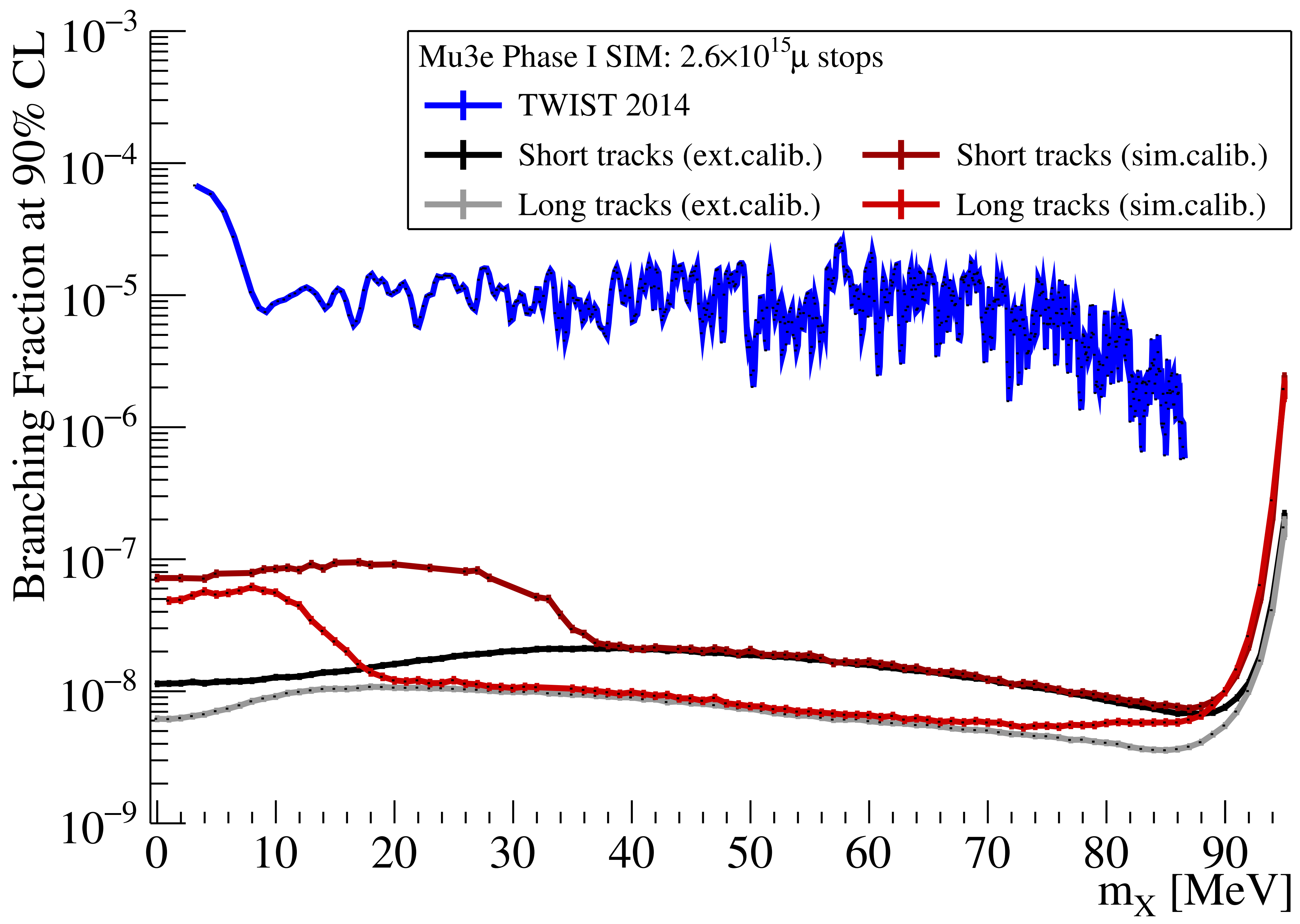


Cooling Concept



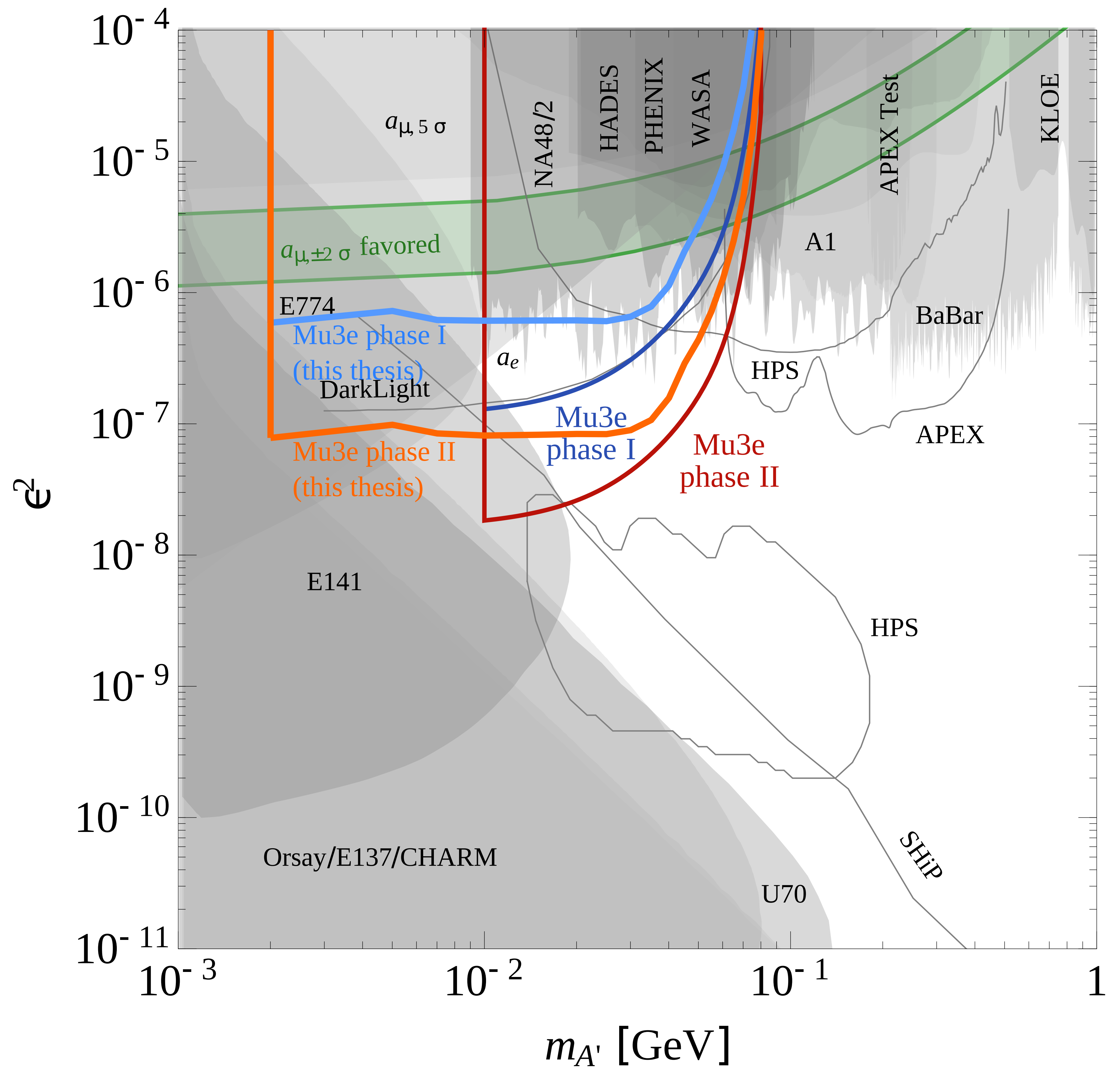
New Physics: $\mu^+ \rightarrow e^+X$





Ann-Kathrin Perrevoort, "Sensitivity Studies on New Physics in the Mu3e Experiment and Development of Firmware for the Front-End of the Mu3e Pixel Detector", University of Heidelberg, 2017.

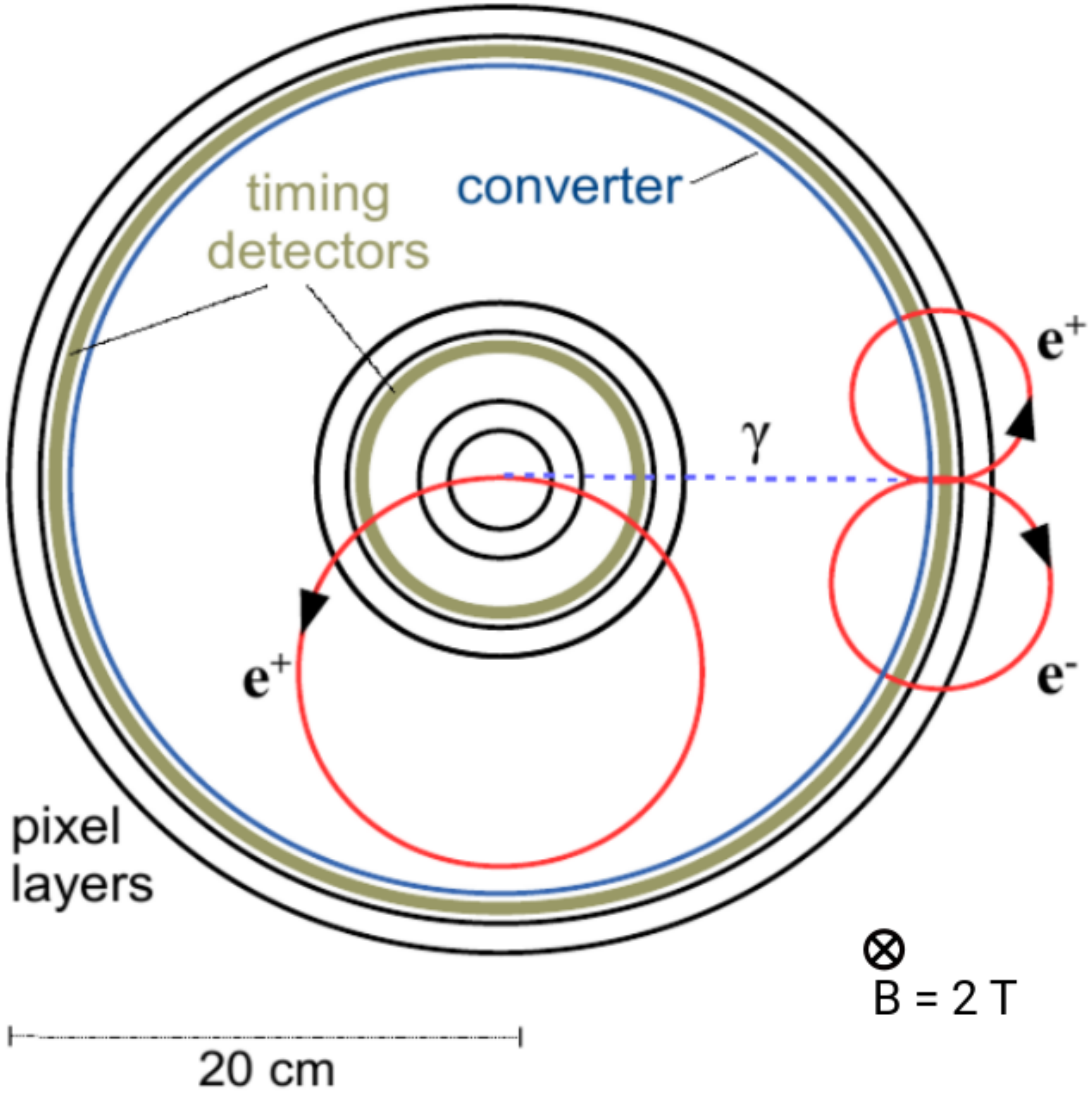
New Physics: $A' \to ee$



95 % CL on the kinetic mixing parameter ε^2 in $\mu \to e\nu\nu(A' \to ee)$

Ann-Kathrin Perrevoort, "Sensitivity Studies on New Physics in the Mu3e Experiment and Development of Firmware for the Front-End of the Mu3e Pixel Detector", University of Heidelberg, 2017.

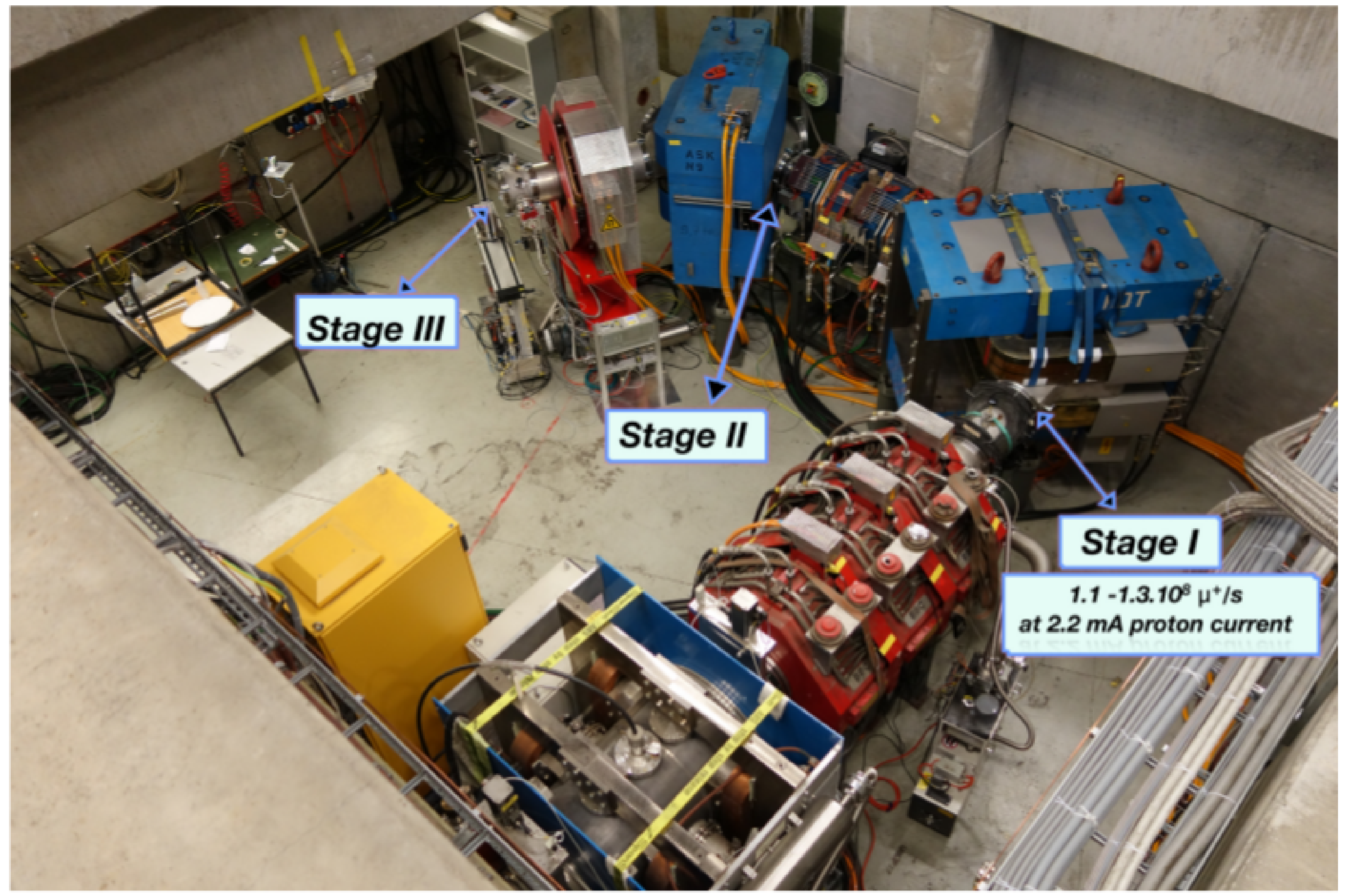
Potential Upgrades: Mu3e-Gamma



Status

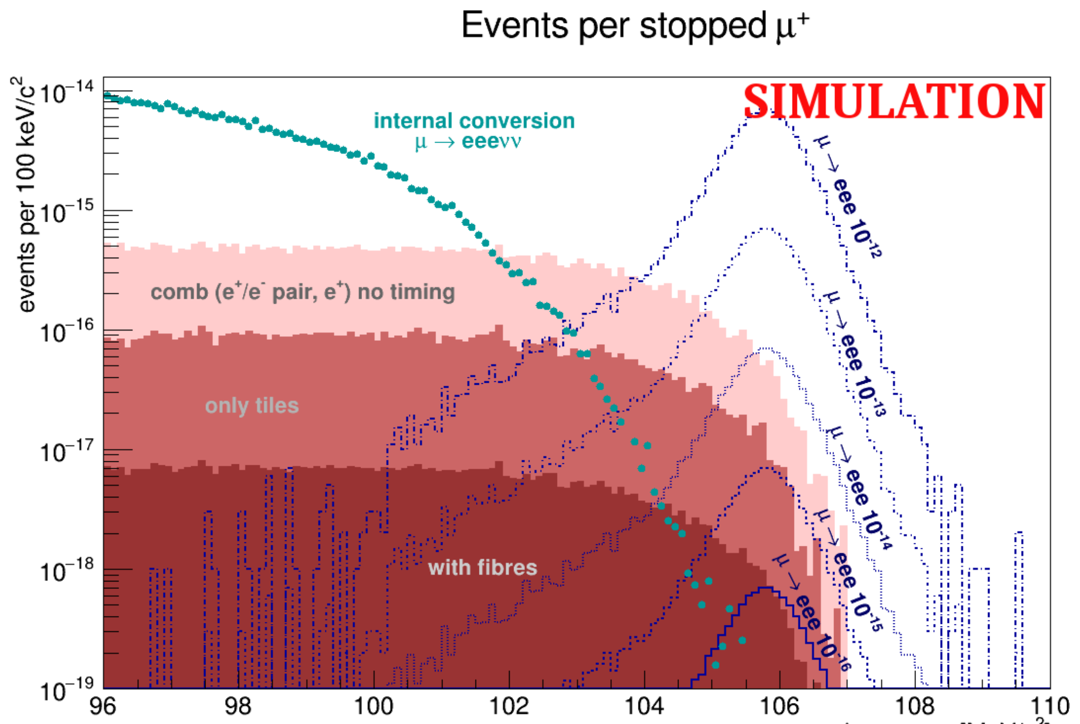
Beamline

achieved $10^8 \mu/s$ ✓



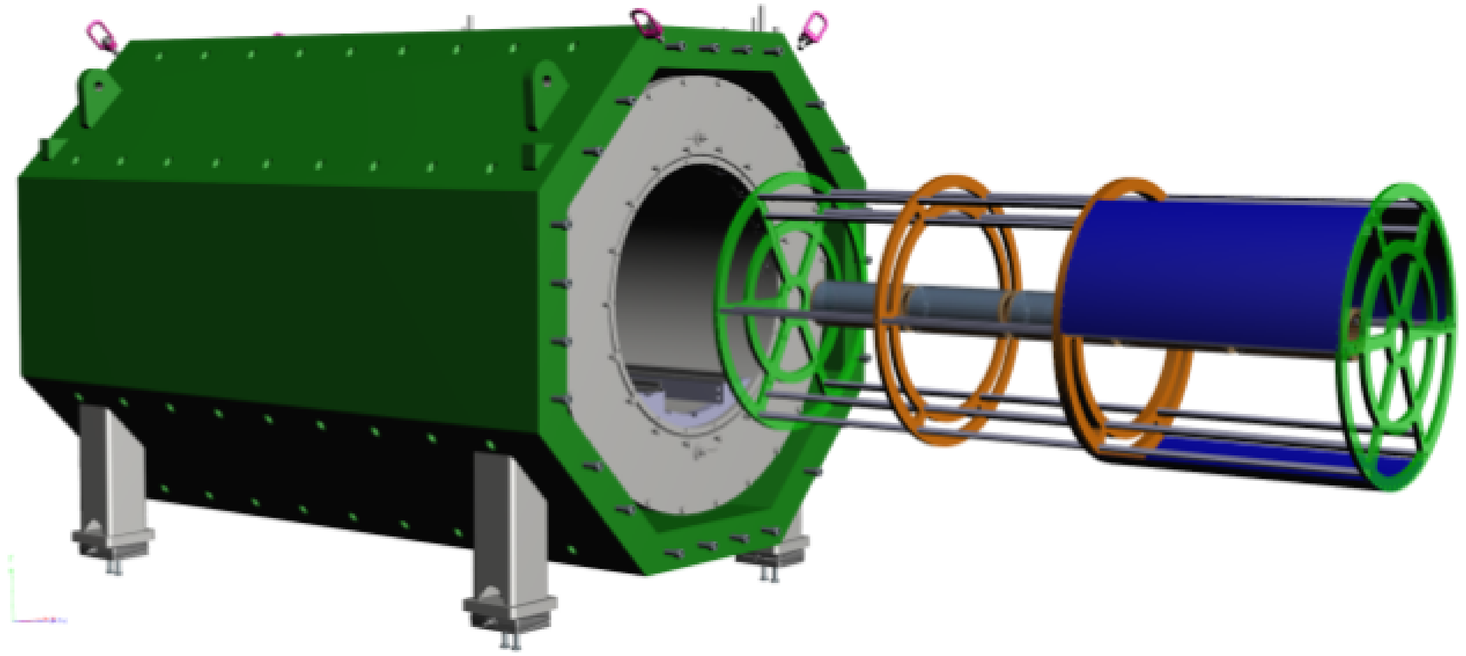
Simulation/Reconstruction

running framework ✓



Mechanics

Technical Design Report (phase I) ready, not published yet



Detector support inside magnet.

Magnet ordered, delivery is scheduled for early 2019.

Readout

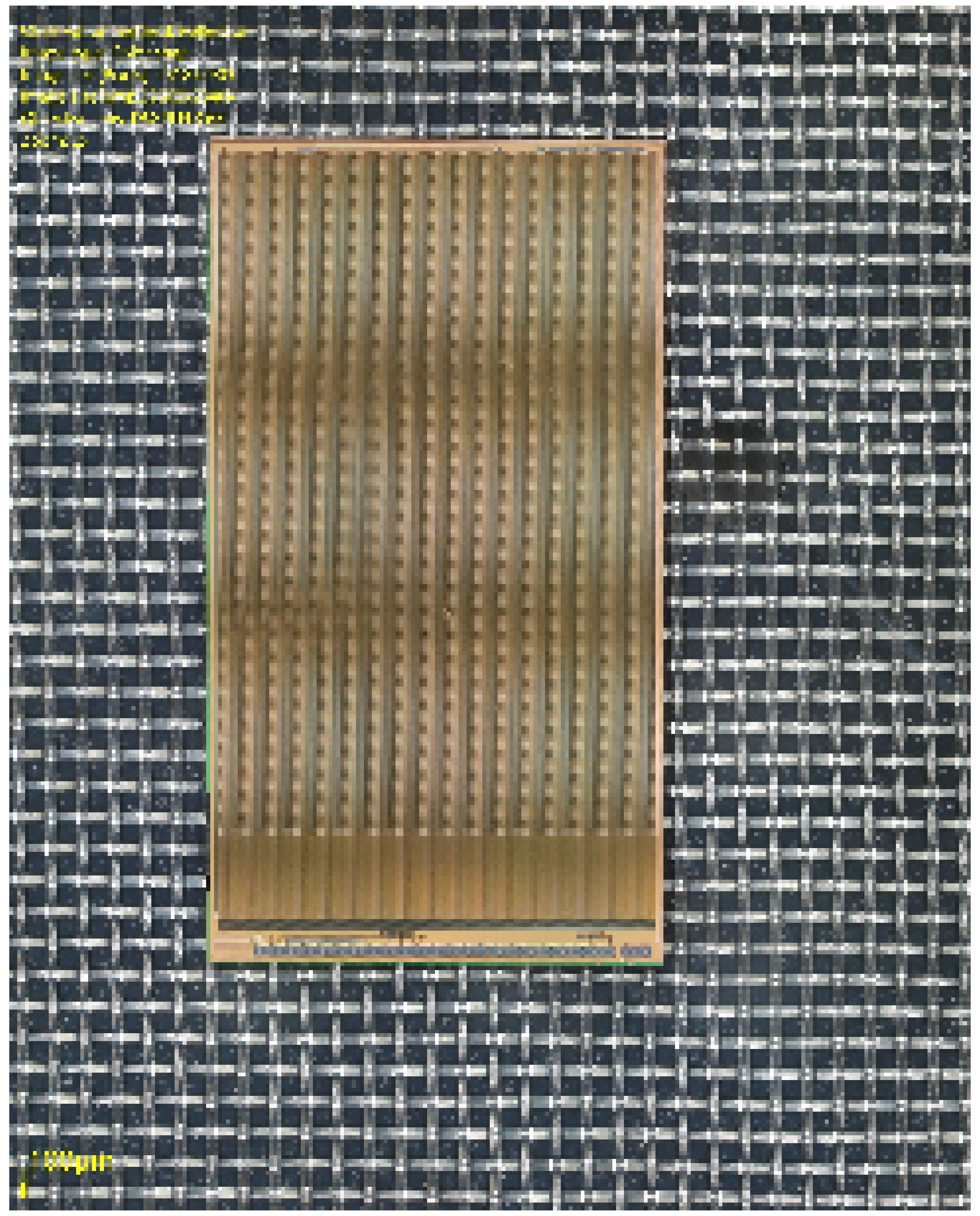
sub-systems come together

Pixel

up-scaling (MuPix8) ✓

switch from R&D to production runs

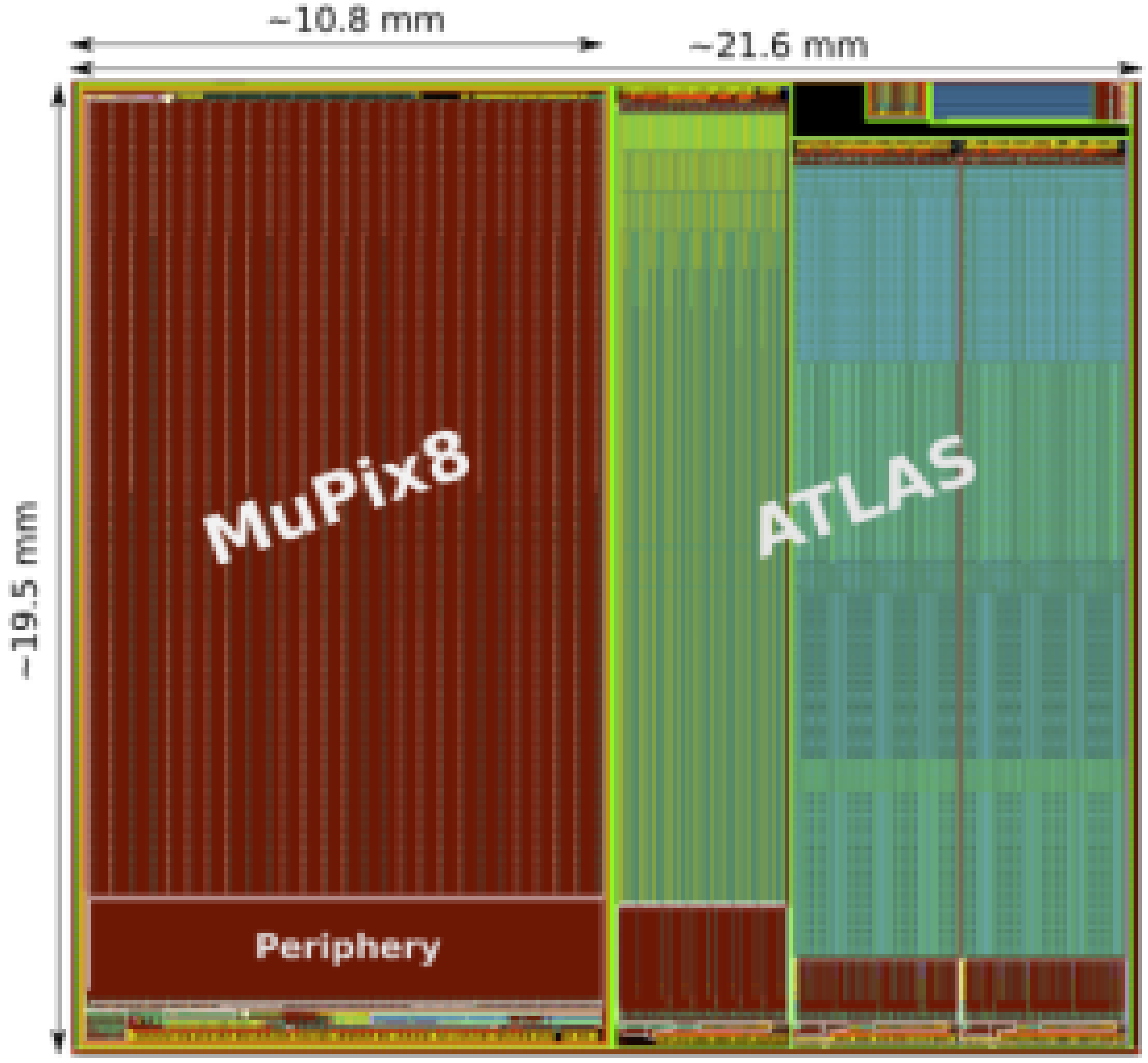
MuPixX ≥ 10



Mupix8: first "large" version

Pixel Sub-Detector: Status

MuPix8

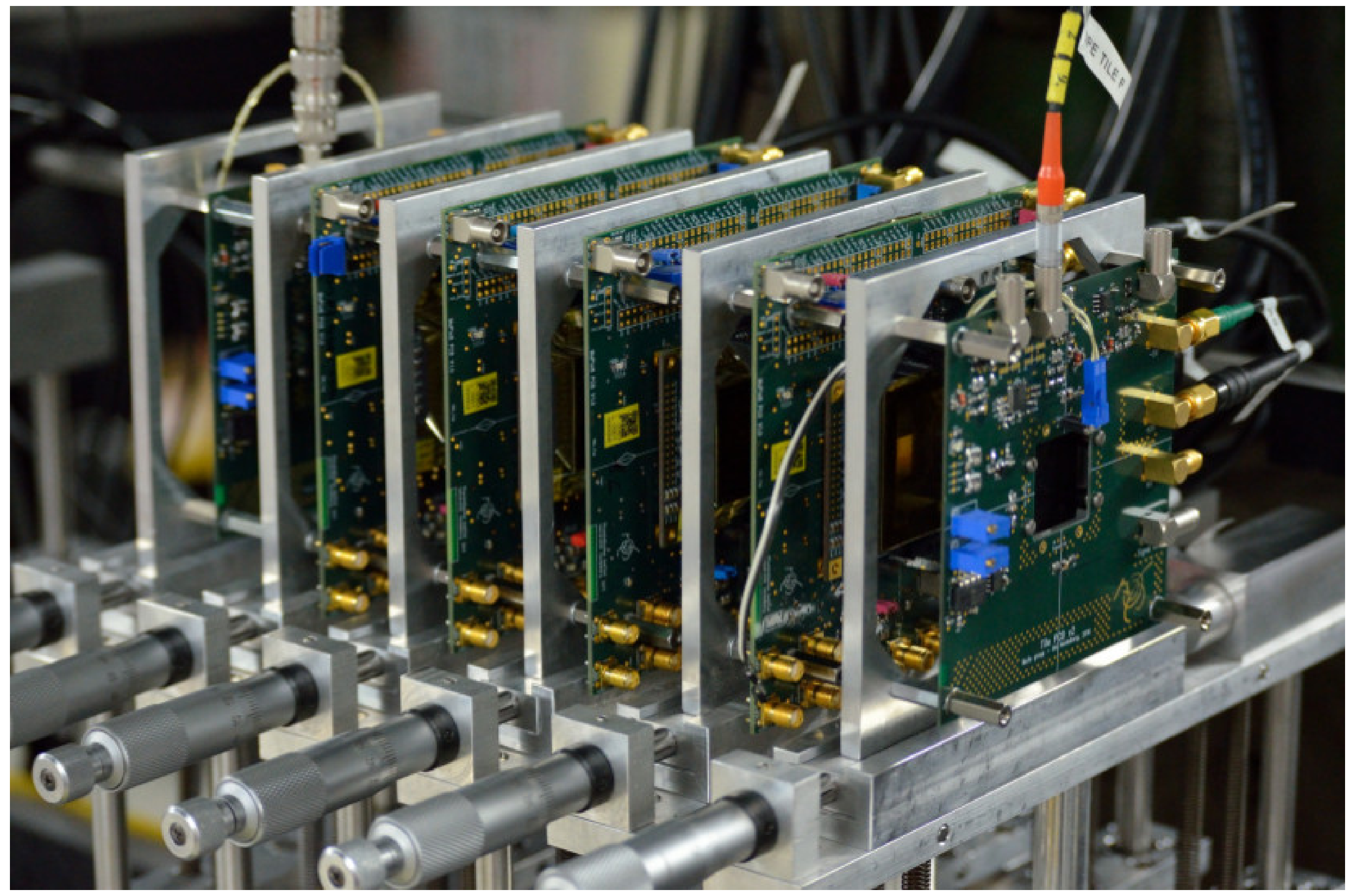


H. Augustin, S. Dittmeier, C. Grzesik, J. Hammerich, A. Herkert, L. Huth,

I. Sorokin, D. Immig, J. Kroeger, M. Zimmermann 2017

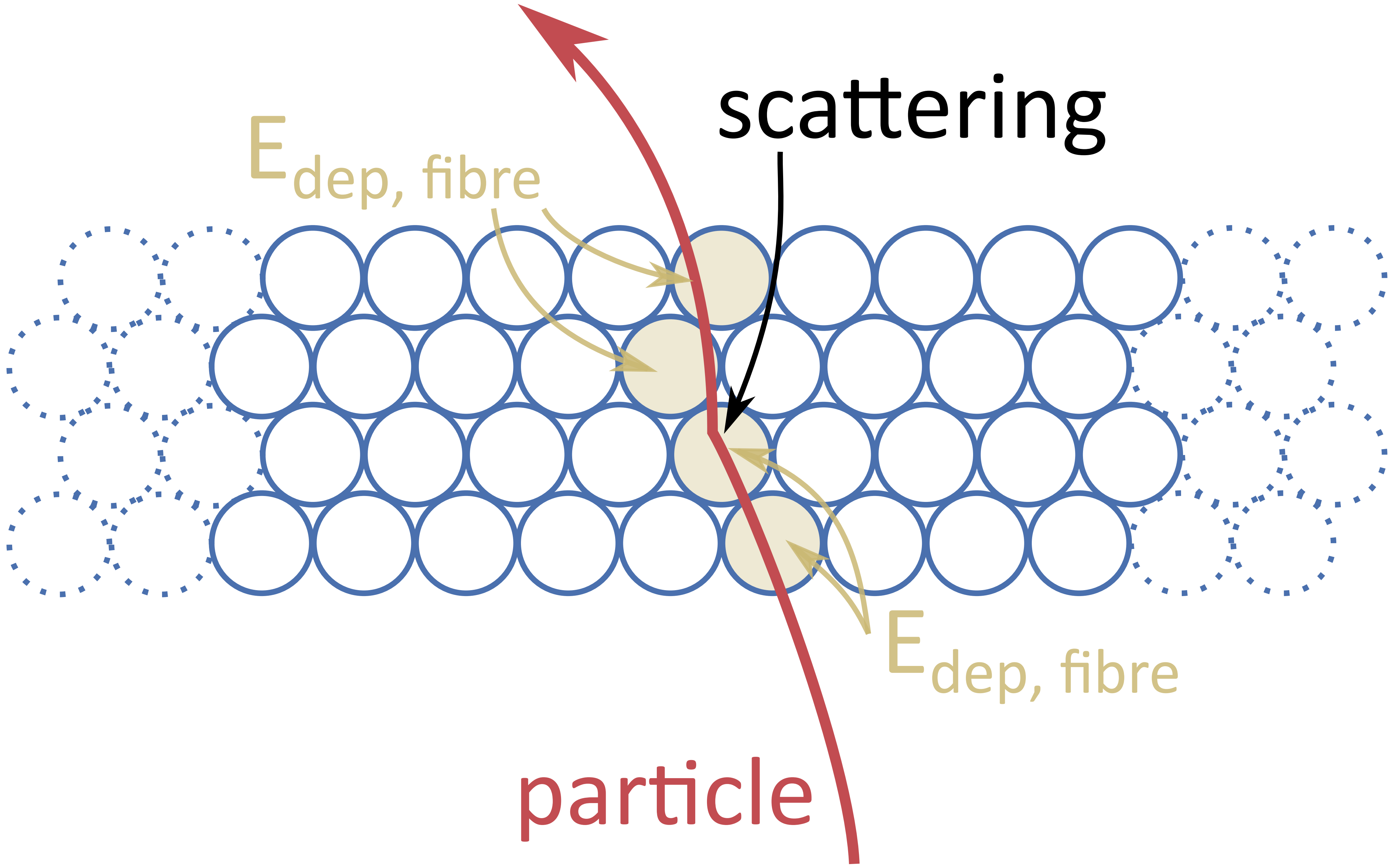
- 128×200 pixel
- $80 \times 81\,\mu m^2$
- 4 LVDS links each at 1.25 GBit/s
- **time resolution** $\boldsymbol{\sigma} \approx 13\,\text{ns}$
- efficiency above 0.98 at noise rate < 1 Hz/pixel

MuPix8 Telescope Configuration



Expected Performance

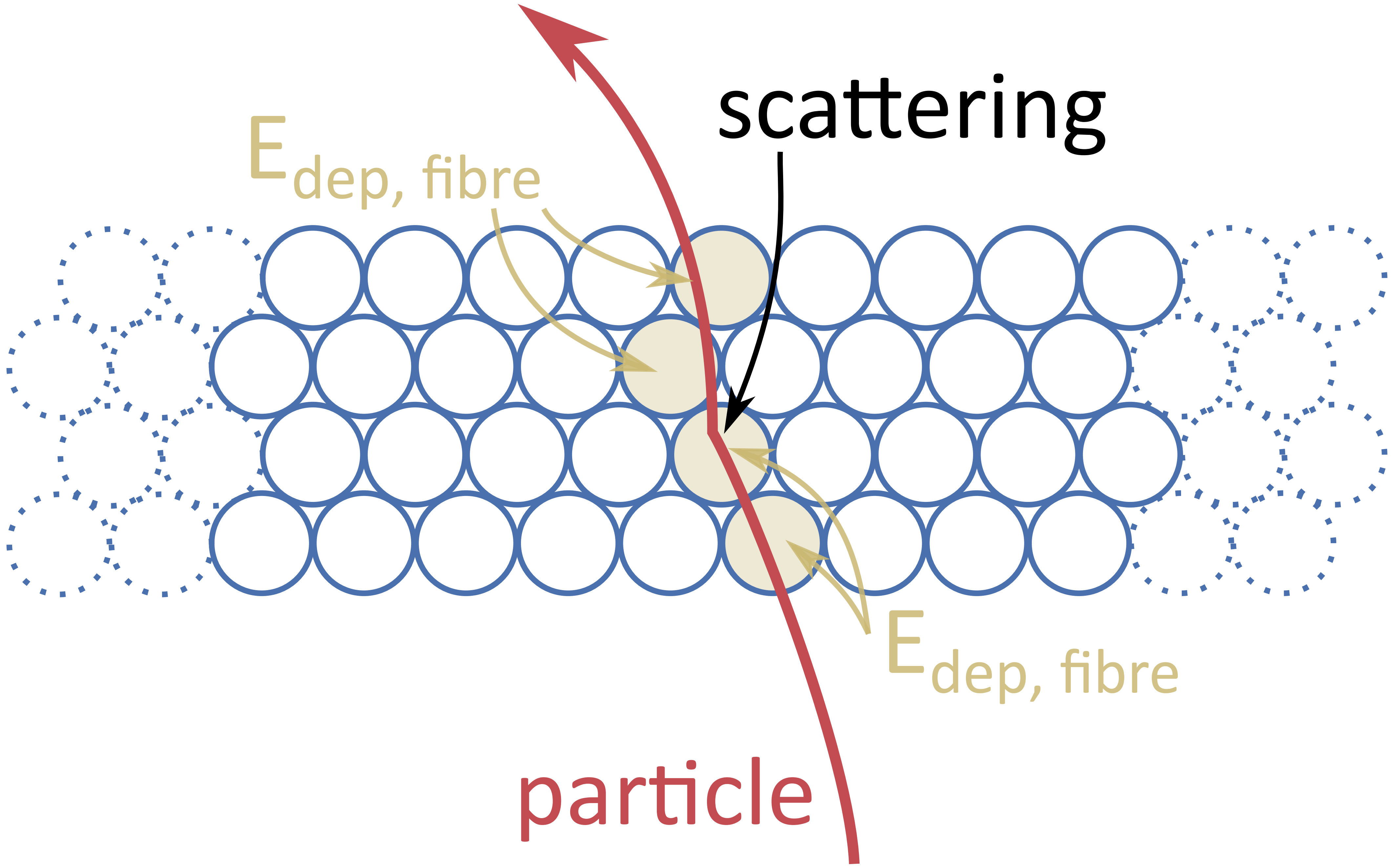
The integration of the fibre detector in the experiments Geant4 based simulation framework allows extrapolation from measurements to expected performance.

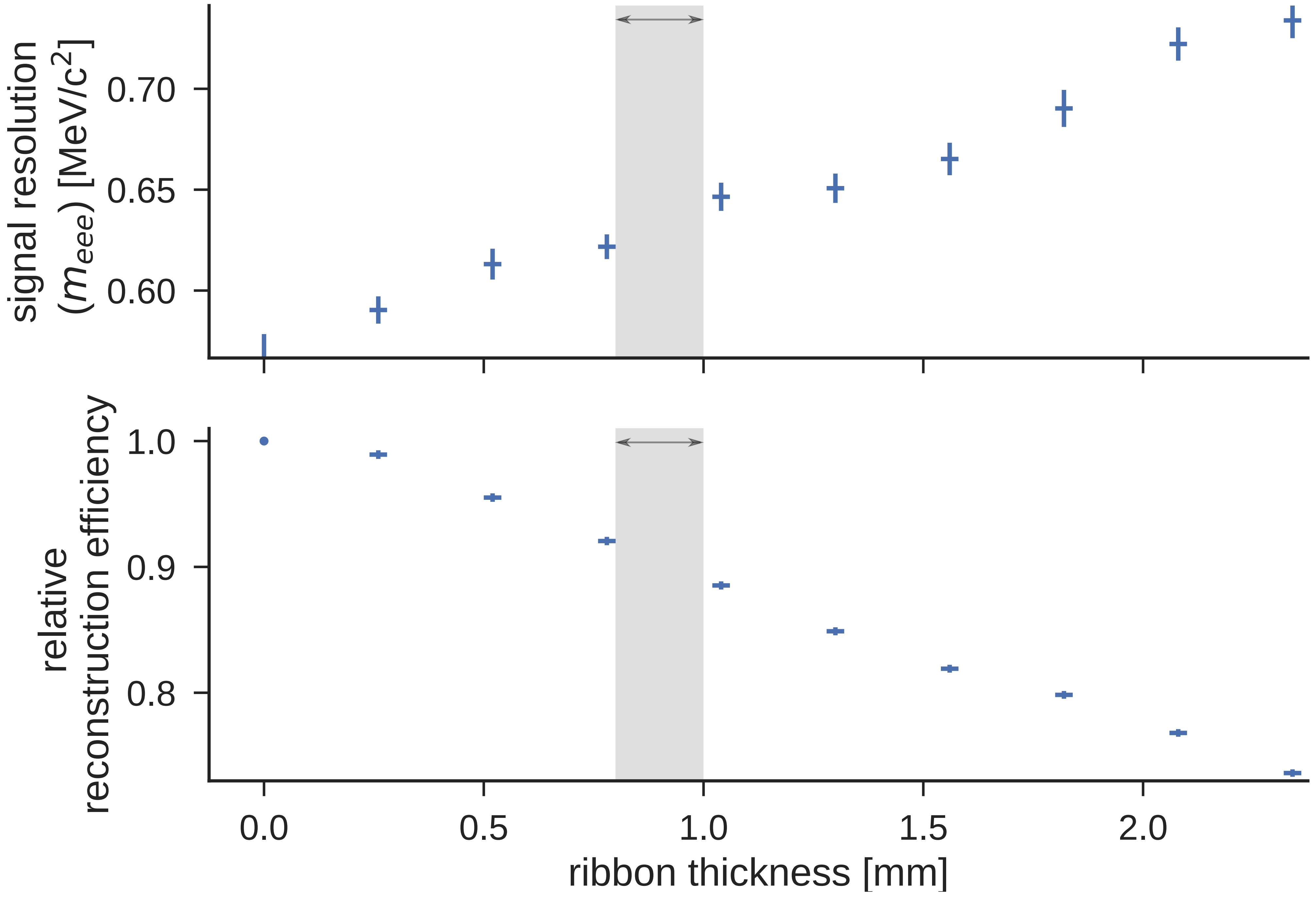


- particle propagation and $E_{\mathrm{dep}}^{\mathrm{fibre}}$ from Geant4 framework

Expected Performance

The integration of the fibre detector in the experiments Geant4 based simulation framework allows extrapolation from measurements to expected performance.

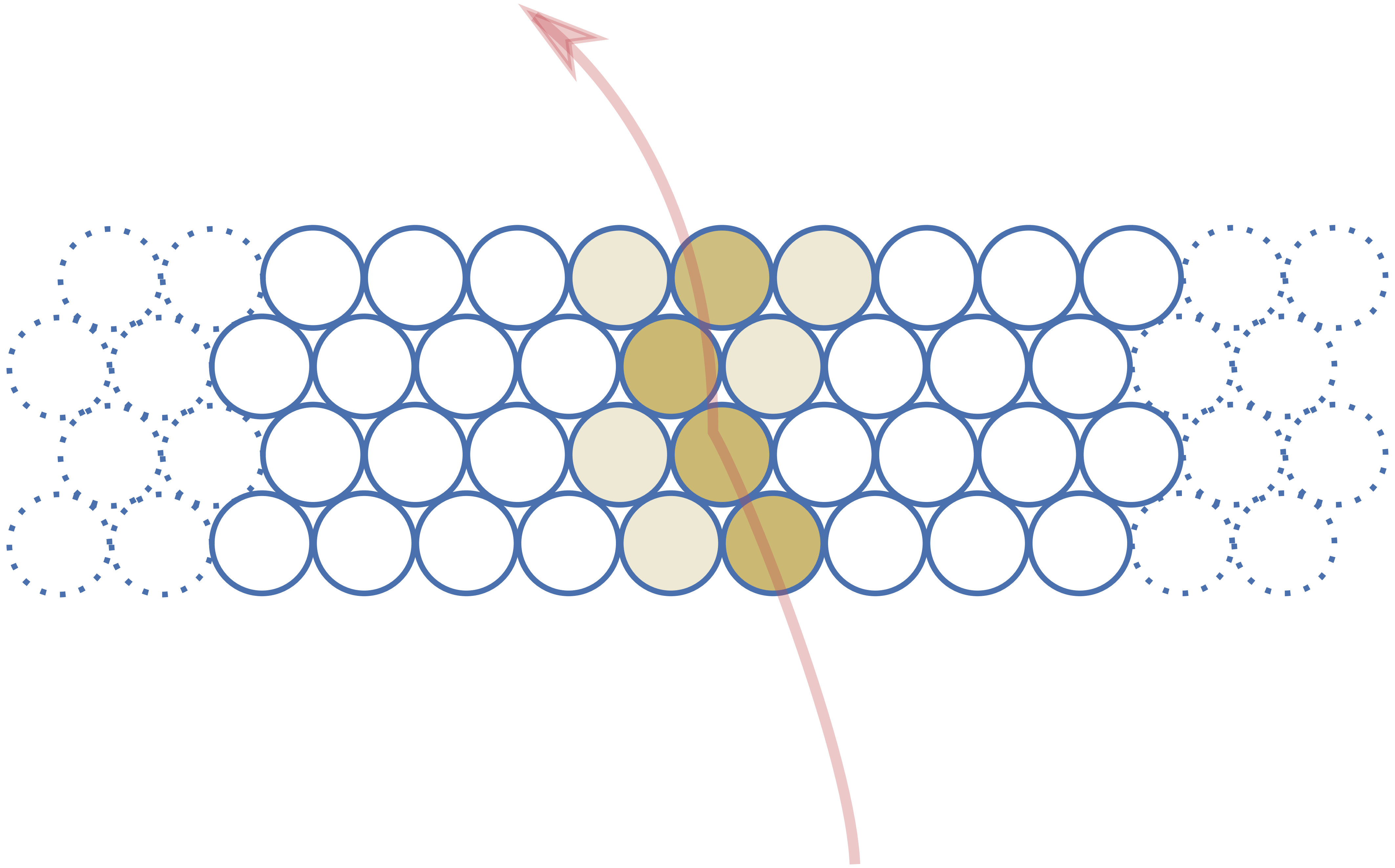




signal ($\mu \to eee$) degradation due to the fibre detector (scattering, E_{dep})

Expected Performance

The integration of the fibre detector in the experiments Geant4 based simulation framework allows extrapolation from measurements to expected performance.

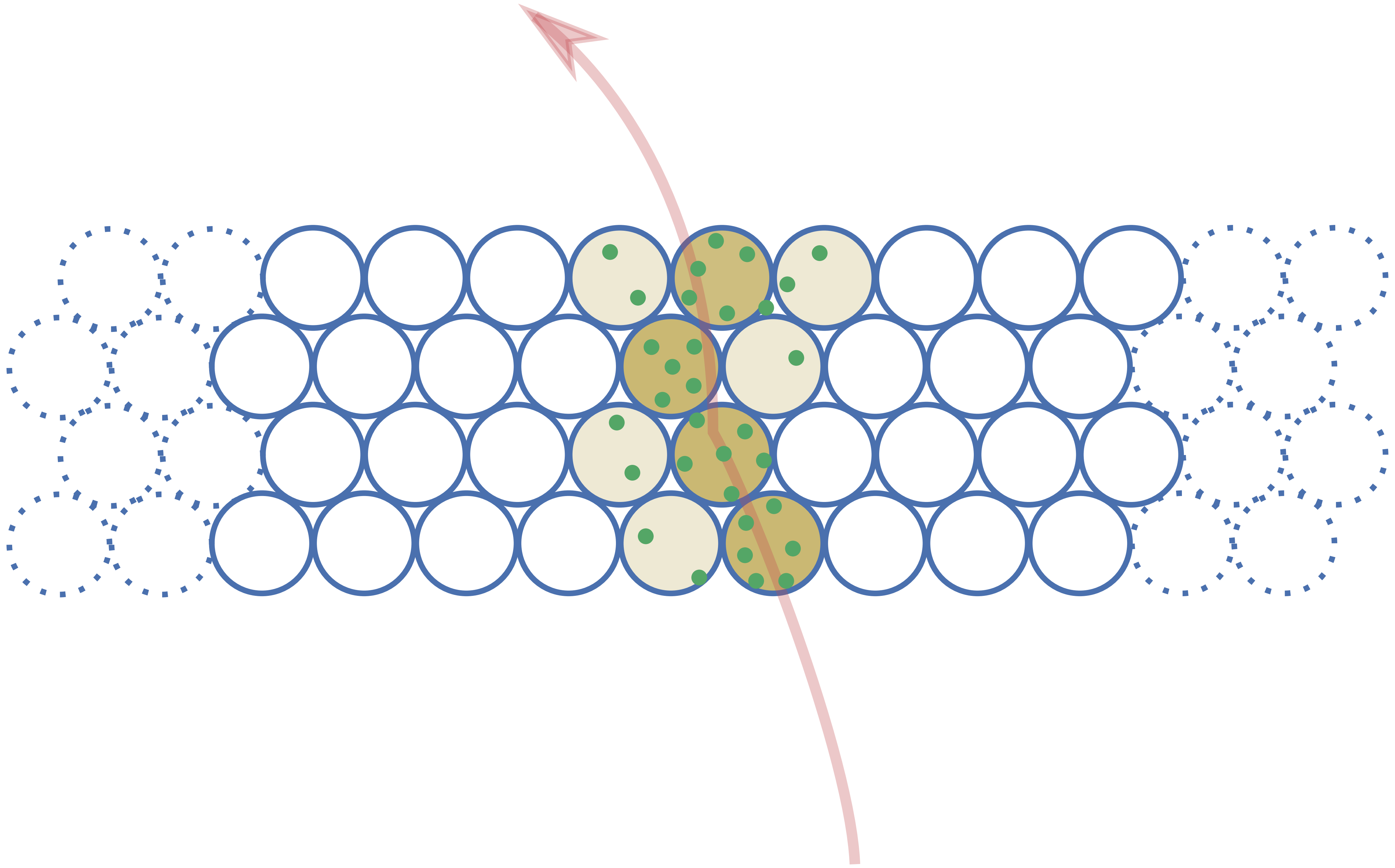


- particle propagation and $E_{\text{dep}}^{\text{fibre}}$ from Geant4 framework

- $n_{\text{scintillation}}^{\text{fibre}} \sim \mathcal{N}(E_{\text{dep}}^{\text{fibre}} \cdot Y)$ (Y: yield) including cross-talk

Expected Performance

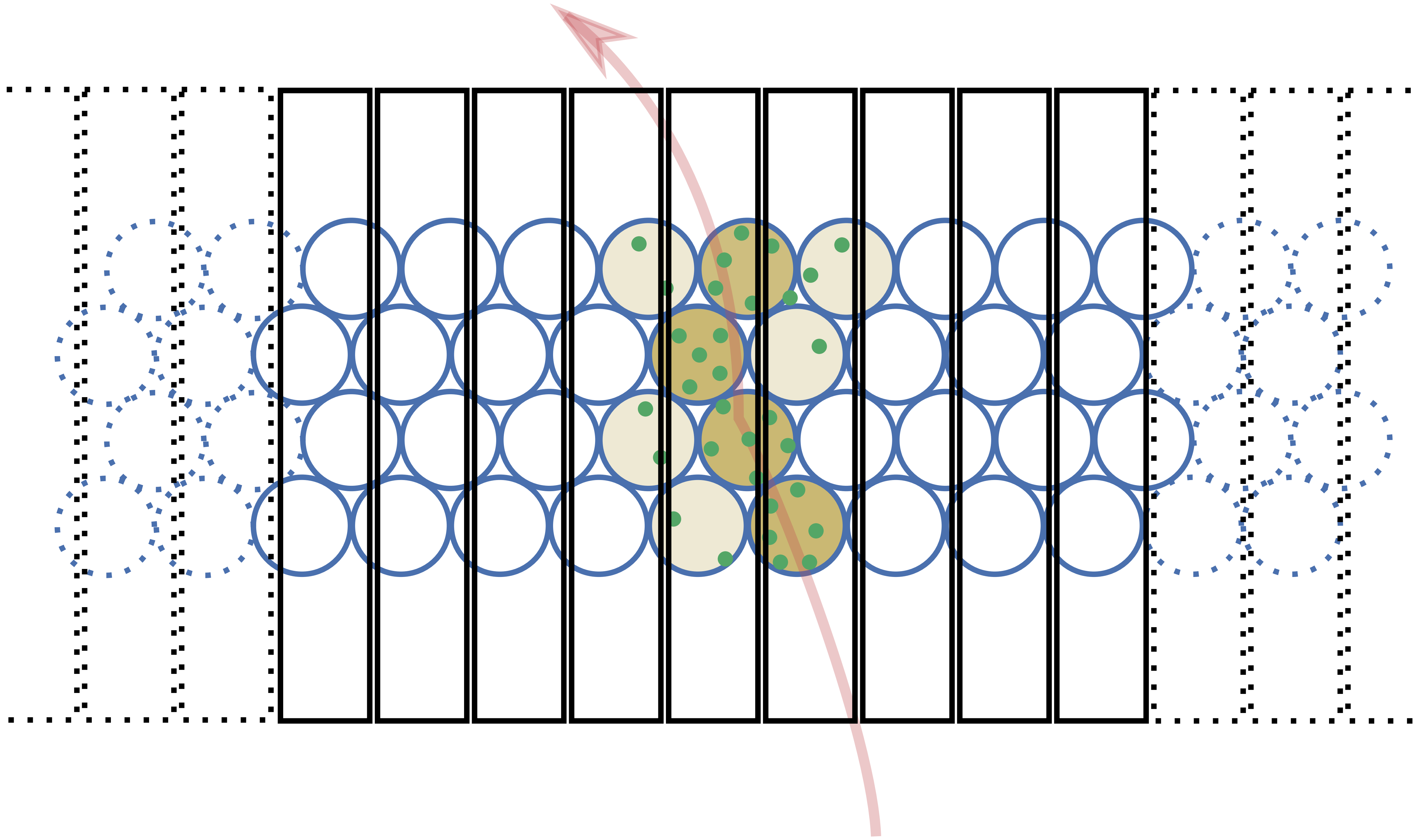
The integration of the fibre detector in the experiments Geant4 based simulation framework allows extrapolation from measurements to expected performance.



- particle propagation and $E_{\text{dep}}^{\text{fibre}}$ from Geant4 framework
- $n_{\text{scintillation}}^{\text{fibre}} \sim \mathcal{N}(E_{\text{dep}}^{\text{fibre}} \cdot Y)$ (Y: yield) including cross-talk
- $n_{\text{detected}}^{\text{fibre}} \sim \mathcal{P}(\mu)$
  $\mu = n_{\text{scint}}^{\text{fibre}} \cdot \varepsilon_{cap} \cdot \varepsilon_{det} \cdot exp\left(\frac{-d_{\text{side}}}{\Lambda_{\text{attenuation}}}\right)$

Expected Performance

The integration of the fibre detector in the experiments Geant4 based simulation framework allows extrapolation from measurements to expected performance.



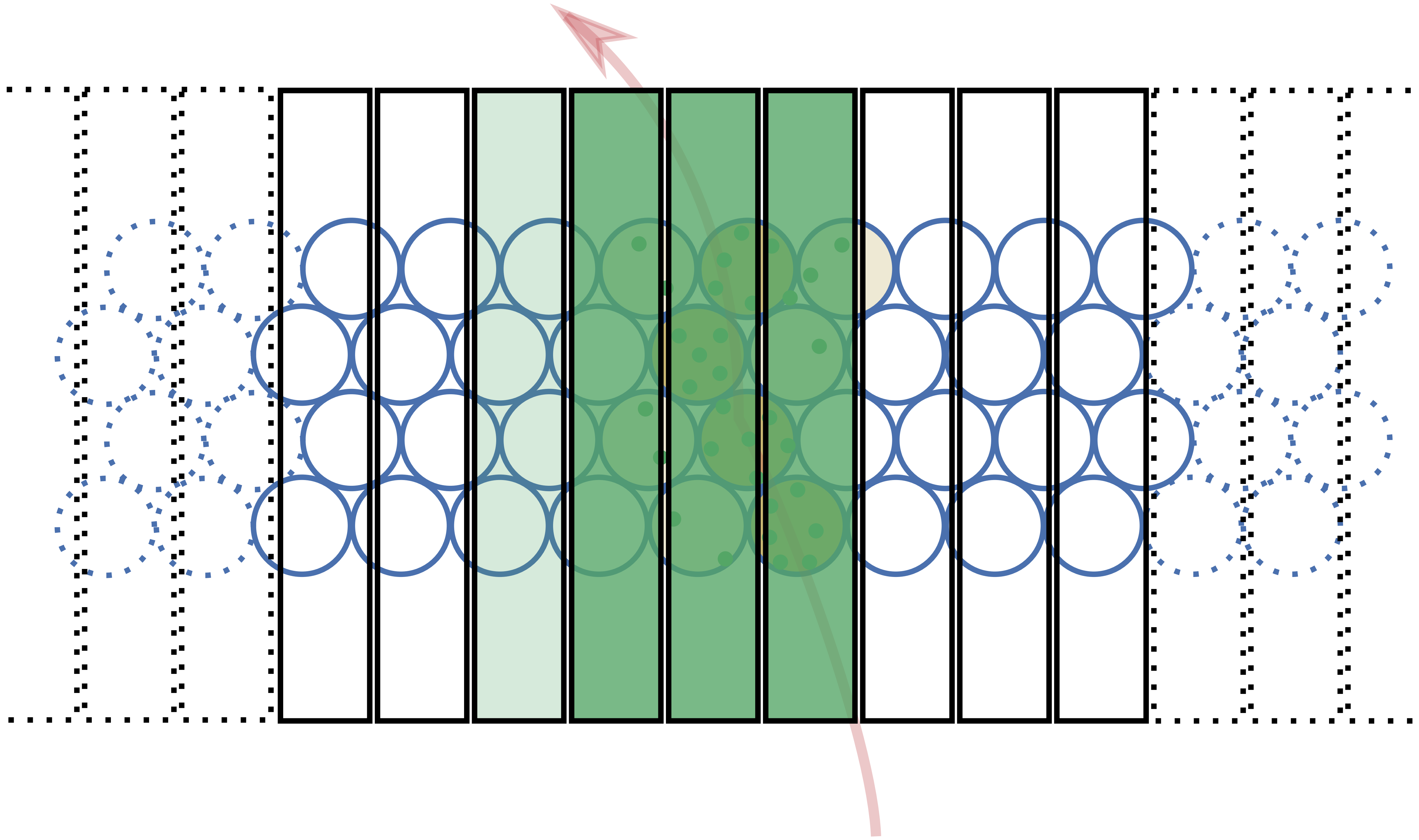
- particle propagation and E_{dep}^{fibre} from Geant4 framework

- $n_{scintillation}^{fibre} \sim \mathcal{N}(E_{dep}^{fibre} \cdot Y)$ (Y: yield) including cross-talk

- $n_{detected}^{fibre} \sim \mathcal{P}(\mu)$
  $\mu = n_{scint}^{fibre} \cdot \varepsilon_{cap} \cdot \varepsilon_{det} \cdot exp\left(\frac{-d_{side}}{\Lambda_{attenuation}}\right)$

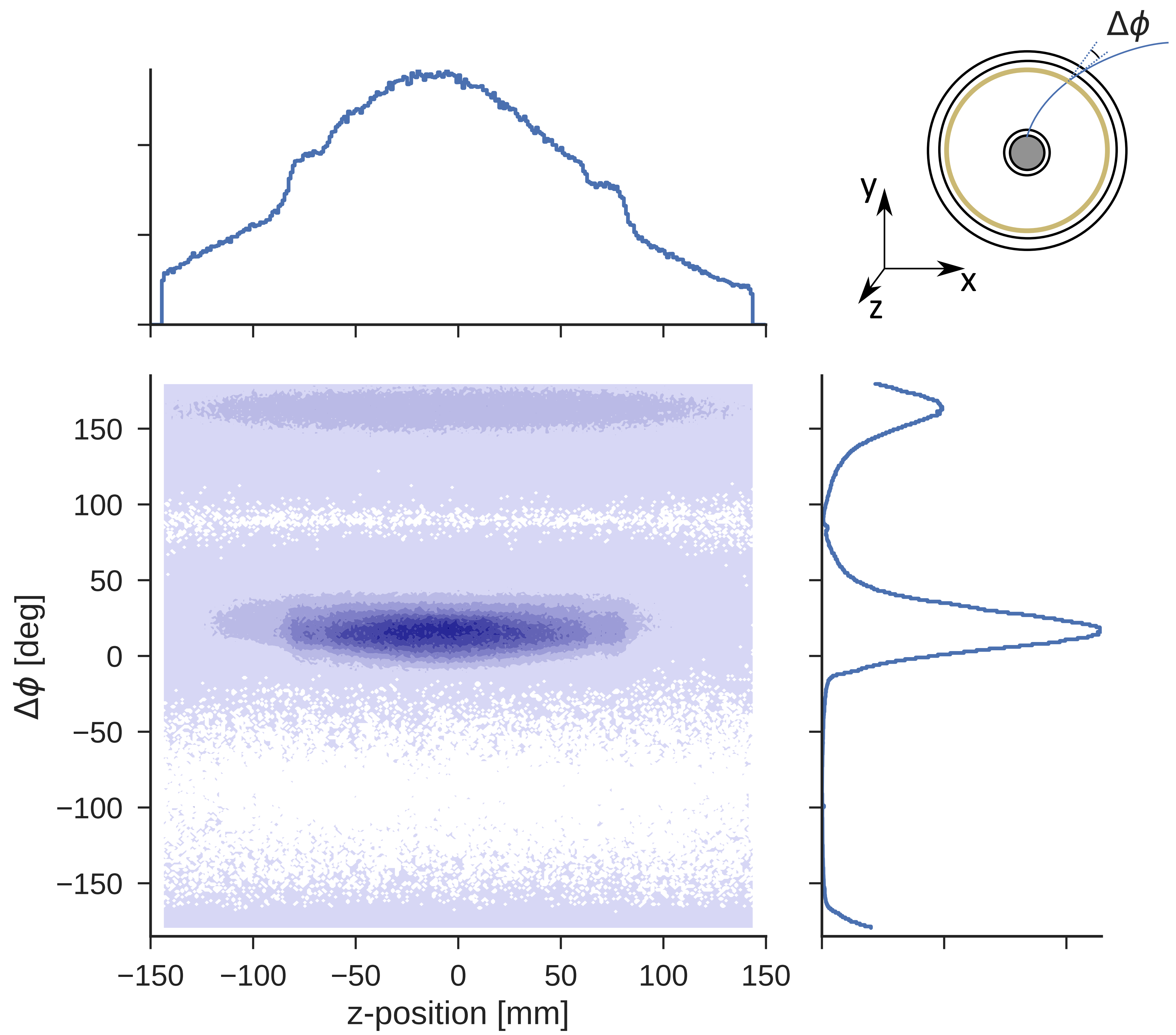
Expected Performance

The integration of the fibre detector in the experiments Geant4 based simulation framework allows extrapolation from measurements to expected performance.

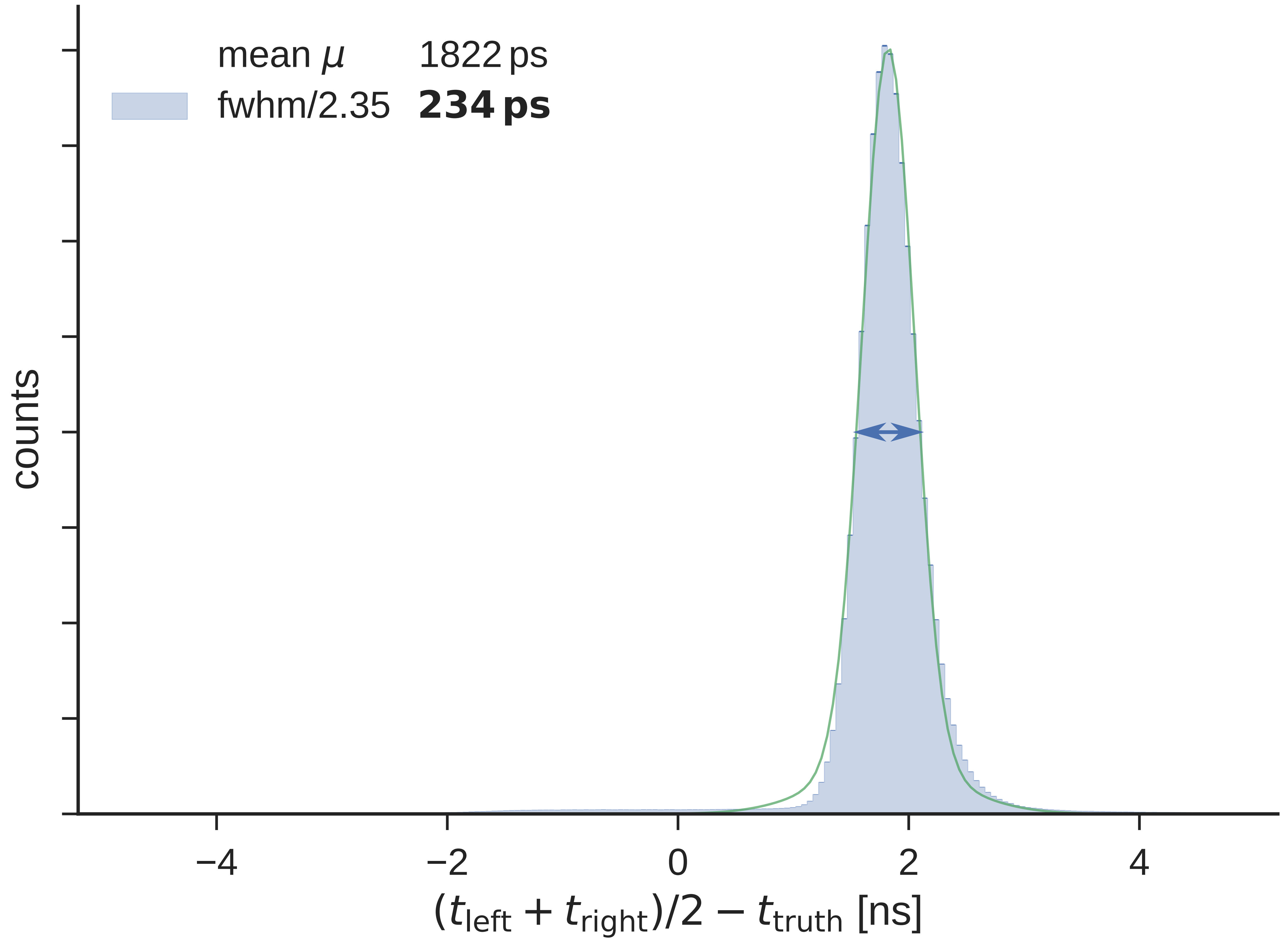


- particle propagation and E_{dep}^{fibre} from Geant4 framework
- $n_{scintillation}^{fibre} \sim \mathcal{N}(E_{dep}^{fibre} \cdot Y)$ (Y: yield) including cross-talk
- $n_{detected}^{fibre} \sim \mathcal{P}(\mu)$ $\mu = n_{scint}^{fibre} \cdot \varepsilon_{cap} \cdot \varepsilon_{det} \cdot exp\left(\frac{-d_{side}}{\Lambda_{attenuation}}\right)$
- $t_{detection}^{photon} = t_{interaction} + \Delta t_{decay} + \Delta t_{propagation} + \Delta t_{electronics}$

Expected Performance



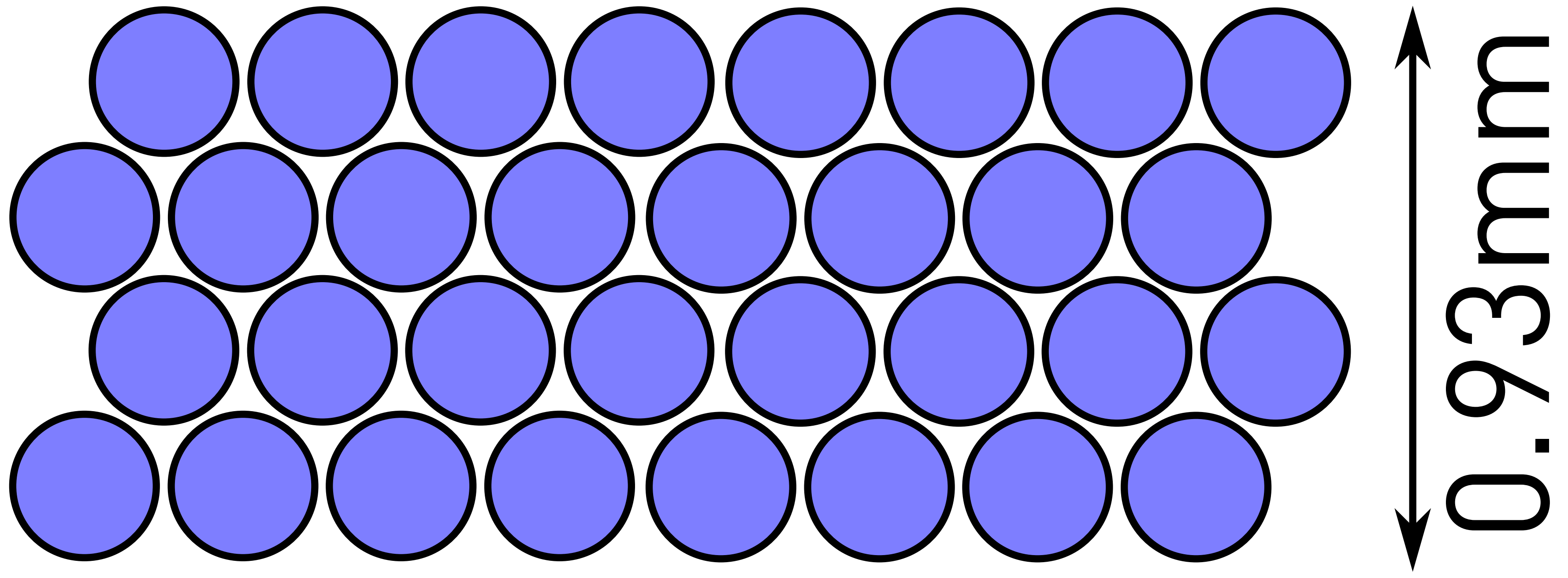
simulated position and angular distribution of **positrons** crossing the fibre detector



simulated fibre detector performance based on measurements with prototypes

Design II: Number of Layers

$\leq$ 4 layers round 250 µm fibres



The expected performance of such fibre ribbons (σ_{fibres}=234 ps) exceed the requirement of better than 350 ps.