The Mu3e experiment to search for Charged Lepton Flavour Violation in $\mu^+ \to e^+e^+e^-$

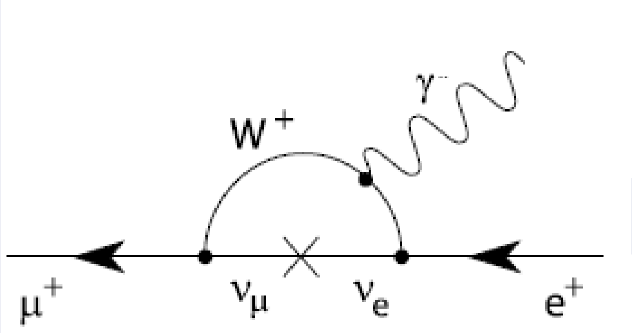
Joost Vossebeld

Charged Lepton Flavour Violation

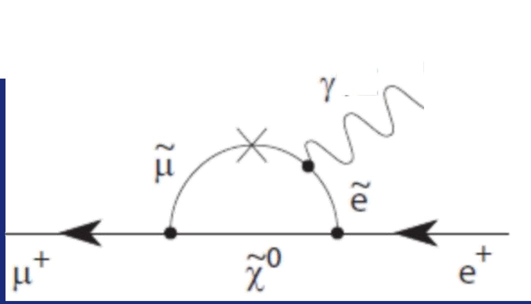
We see flavour violations in the quark and neutrino sectors, but not for charge leptons

SM (with m_ν) does allow for CLFV, but is heavily suppressed.

$$\mathrm{Br}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{i1}}{M^2_W}\right|^2 < 10^{-54}$$



Any observation of CLFV is evidence of NP.



CLFV appears naturally in NP theories: E.g new interactions coupling to mixed lepton eigenstates, or new particles with lepton number and a mixing matrix.

Some hints NP may show up in the lepton sector: muon g-2, lepton universality.

Muon decays

PDG 2018

μ^- DECAY MODES

μ^+ modes are charge conjugates of the modes below.

	Mode		Fraction (Γ_i/Γ)	Confidence level
Γ_1	$e^- \overline{\nu}_e \nu_\mu$		$\approx 100\%$	
Γ_2	$e^- \overline{\nu}_e \nu_\mu \gamma$	[a]	$(6.0 \pm 0.5) \times 10^{-8}$	
Γ_3	$e^- \overline{\nu}_e \nu_\mu e^+ e^-$	[b]	$(3.4 \pm 0.4) \times 10^{-5}$	

If charged lepton flavour is not conserved we also expect neutrinoless decays:

$\mu \to e\gamma$

$\mu \to eee$

and

$\mu N \to eN$

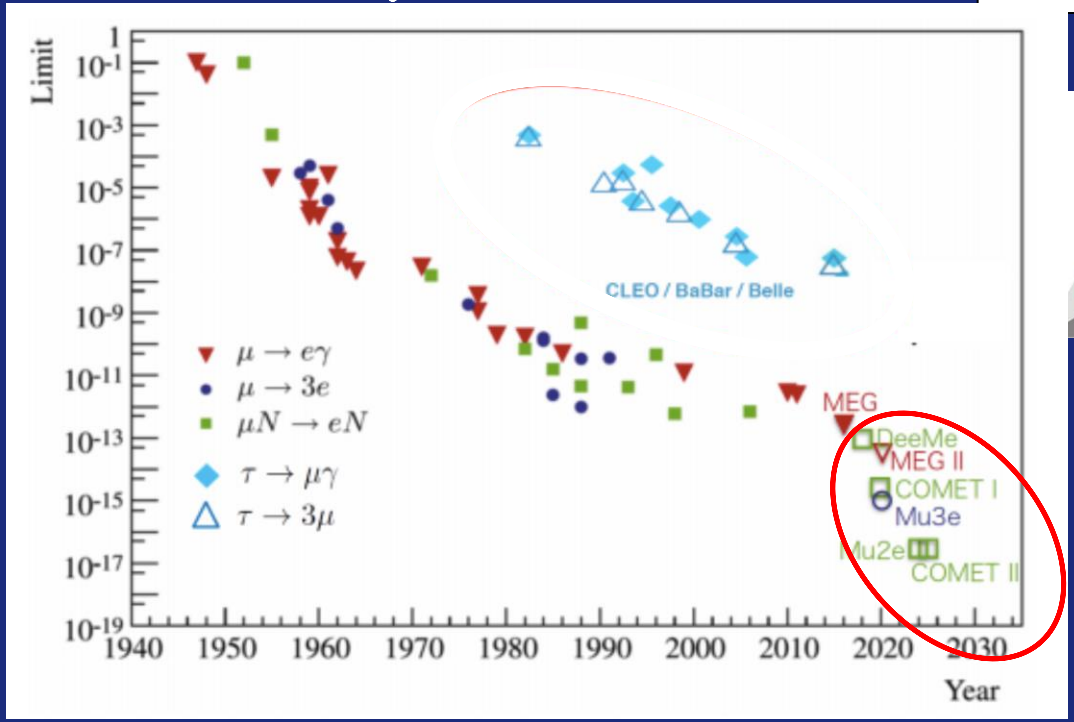
Lepton Family number (*LF*) violating modes

	Mode		Fraction		Confidence level
Γ_4	$e^- \nu_e \overline{\nu}_\mu$	*LF*	[c] < 1.2	%	90%
Γ_5	$e^- \gamma$	*LF*	< 4.2	$\times 10^{-13}$	90%
Γ_6	$e^- e^+ e^-$	*LF*	< 1.0	$\times 10^{-12}$	90%
Γ_7	$e^- 2\gamma$	*LF*	< 7.2	$\times 10^{-11}$	90%

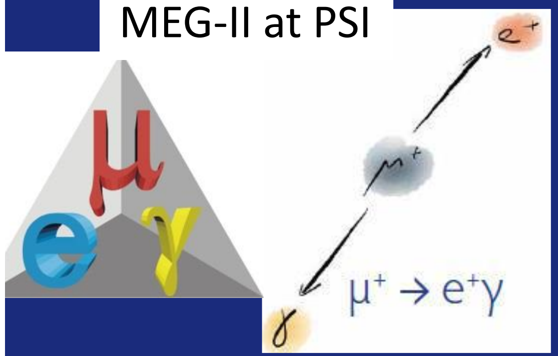
The long lifetime and the limited number of very clean SM decay modes make muon decays ideal to look for rare NP!

CLVF μ-decays

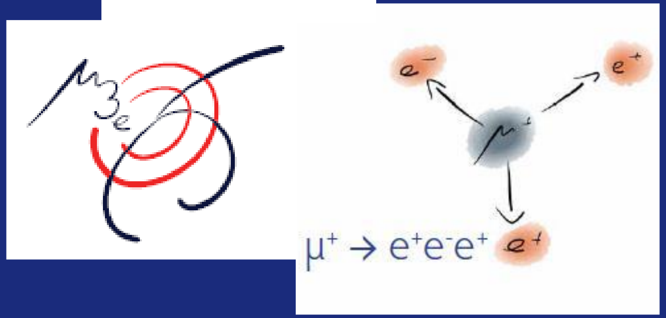
	Best limits	Projected sensitivities (90%CL)
$\mu \to e\gamma$	$< 4.3\times10^{-13}$ MEG (PSI)	4×10^{-14} MEG II (PSI)
$\mu \to eee$	$< 1.0\times10^{-12}$ SINDRUM (PSI)	4×10^{-15} Mu3e I (PSI) 1×10^{-16} Mu3e II (PSI)
$\mu N \to eN$	$< 7.0\times10^{-13}$ SINDRUM II (PSI) μ Au$\to$e Au	6×10^{-17} Mu2e (FNAL) 7×10^{-15} COMET I (J-PARC) 6×10^{-17} COMET II (J-PARC)



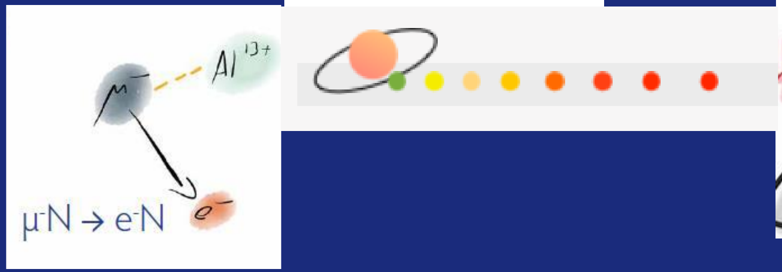
MEG-II at PSI



Mu3e at PSI



COMET at KEK



Mu2e at FNAL

New experiment will push $\mu \to e$ sensitivity by up to four orders of magnitude over the next 5-10 years.

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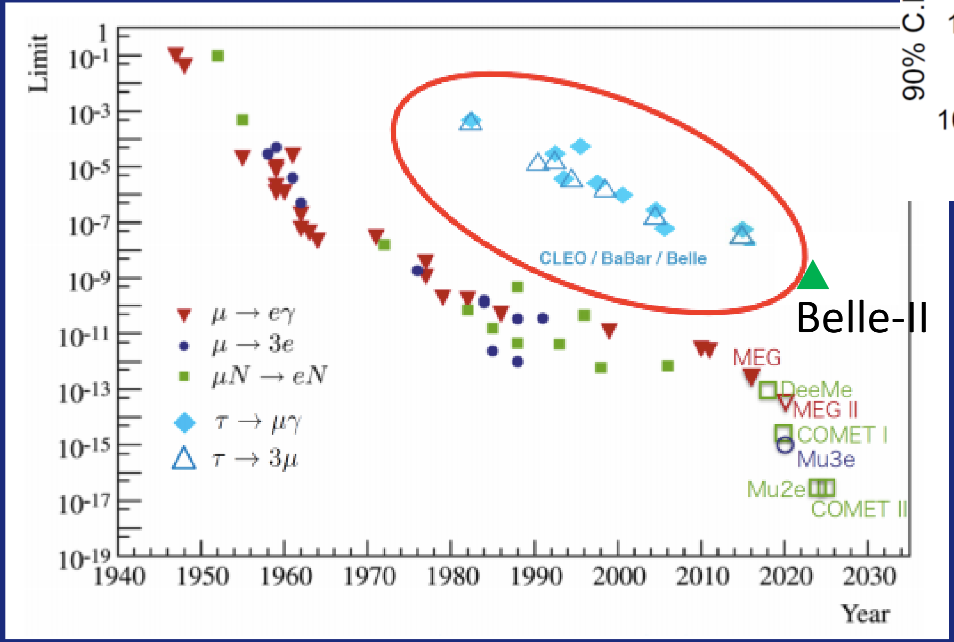
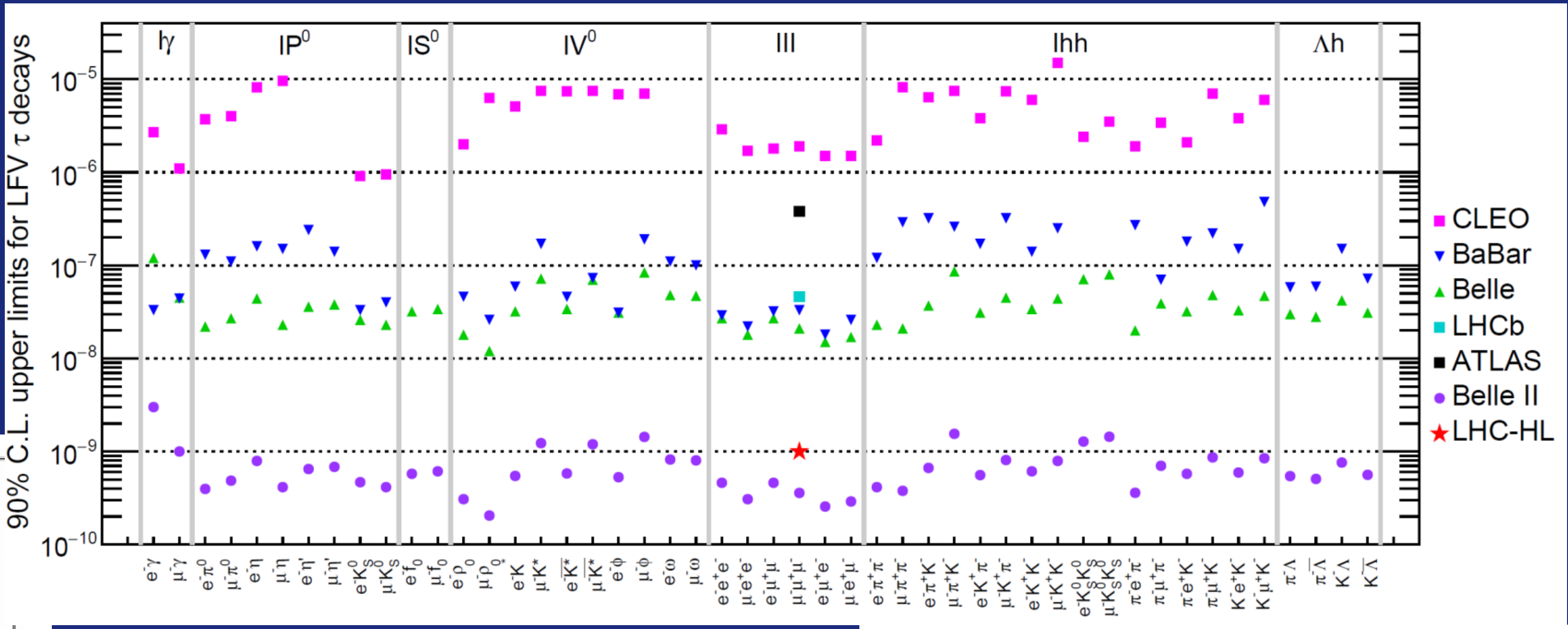
CLFV τ-decays





PDG 2019, “Tests of Conservation Laws”

Best τ limits from Belle and Babar, with improvements from Belle-II expected in coming years.

Compared to muons:

Shorter τ lifetime and higher BR limits means tau results are less sensitive to NP.

This is not compensated by higher tau mass unless NP has unexpected high power dependence on mass or is generation specific

Other CLFV searches (PDG 2019):

$\text{Br}(K_L^0 \to e^\pm \mu^\mp) < 4.7 \times 10^{-12}$ BNL E871

$\text{Br}(K^+ \to \pi^+ \mu^+ e^-) < 1.3 \times 10^{-11}$ BNL E865

$\text{Br}(B^0 \to e^\pm \mu^\mp) < 1.0 \times 10^{-9}$ **LHCb**

$\text{Br}(D^0 \to e^\pm \mu^\mp) < 1.3 \times 10^{-8}$ LHCb

ATLAS

$\text{Br}(Z \to e^\pm \mu^\mp) < 7.5 \times 10^{-7}, \quad \text{Br}(Z \to e^\pm \tau^\mp) < 9.8 \times 10^{-6}, \quad \text{Br}(Z \to \mu^\pm \tau^\mp) < 1.2 \times 10^{-5}$

ATLAS + CMS

$\text{Br}(H^0 \to e^\pm \mu^\mp) < 6.1 \times 10^{-5}, \quad \text{Br}(H^0 \to e^\pm \tau^\mp) < 0.47\%, \quad \text{Br}(H^0 \to \mu^\pm \tau^\mp) < 0.25\%,$

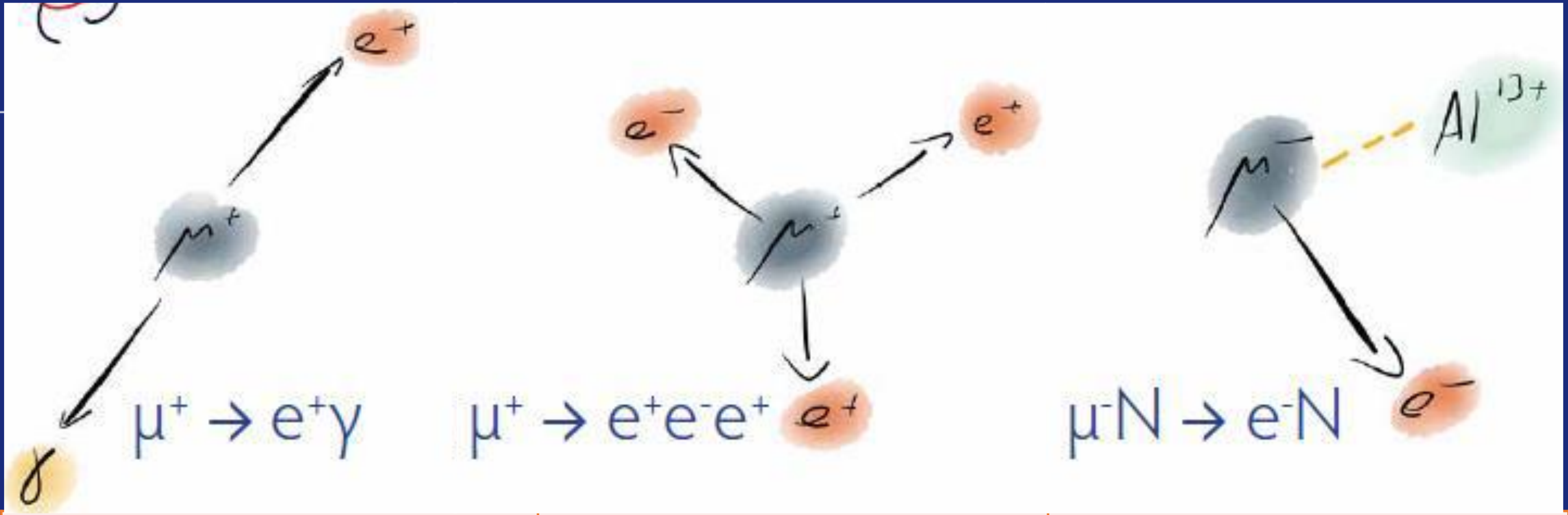
In general, again, the shorter lifetimes and higher BR limits compared to the muons means the results are less sensitive to (generic) NP.

CLFV Muon decay channels

In all cases muons are stopped on a target and decay at rest.

$E_{observed} = m_\mu$

(no neutrinos!)



back-to-back electron and photon $E_\gamma = E_e = ½ m_\mu$	3 co-planar electrons $\Sigma P_e = 0,\ \Sigma E_e = m_\mu$	Muon decay from muonic atom. Monochromatic electron $E_e = m_\mu - E_{binding} - E_{recoil}$
Radiative decay: $\mu \rightarrow e\nu\nu\gamma$ Accidental backgrounds: $\mu \rightarrow e\nu\nu$ + radiative photon	Radiative decay ($\mu \rightarrow ee e\nu\nu$); Accidental backgrounds $\mu \rightarrow e\nu\nu$ + conversion or Bhabha pairs	Non-LFV muon decay in orbit, beam related: prompt antiprotons, pions,..

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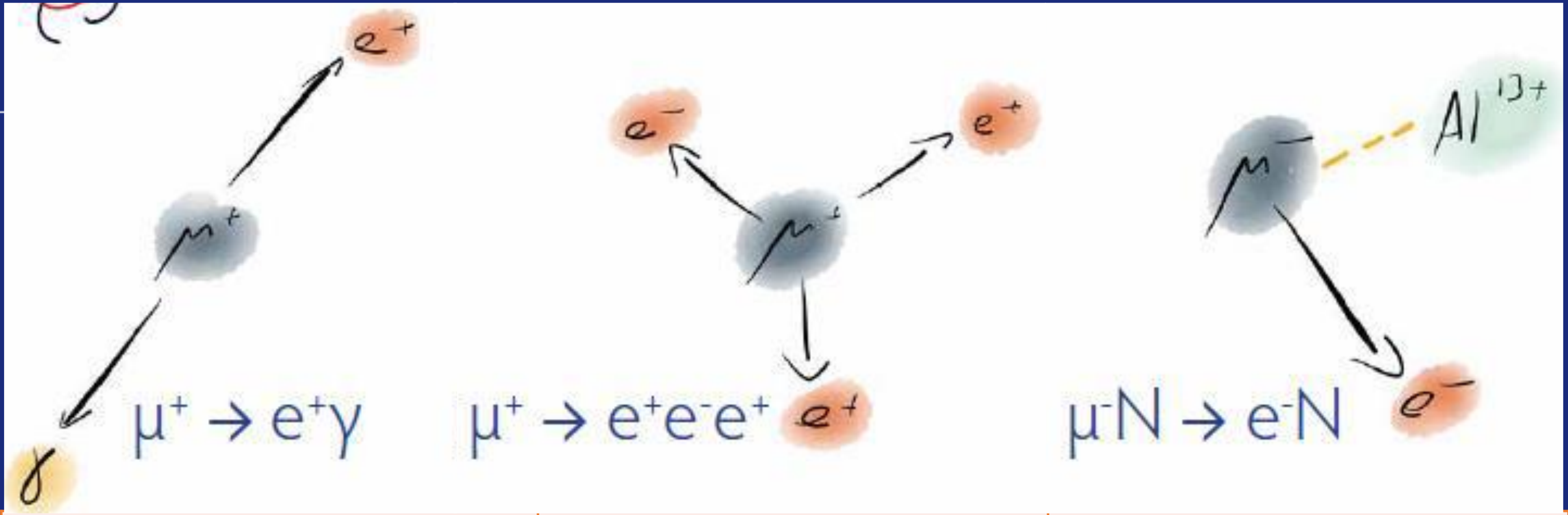

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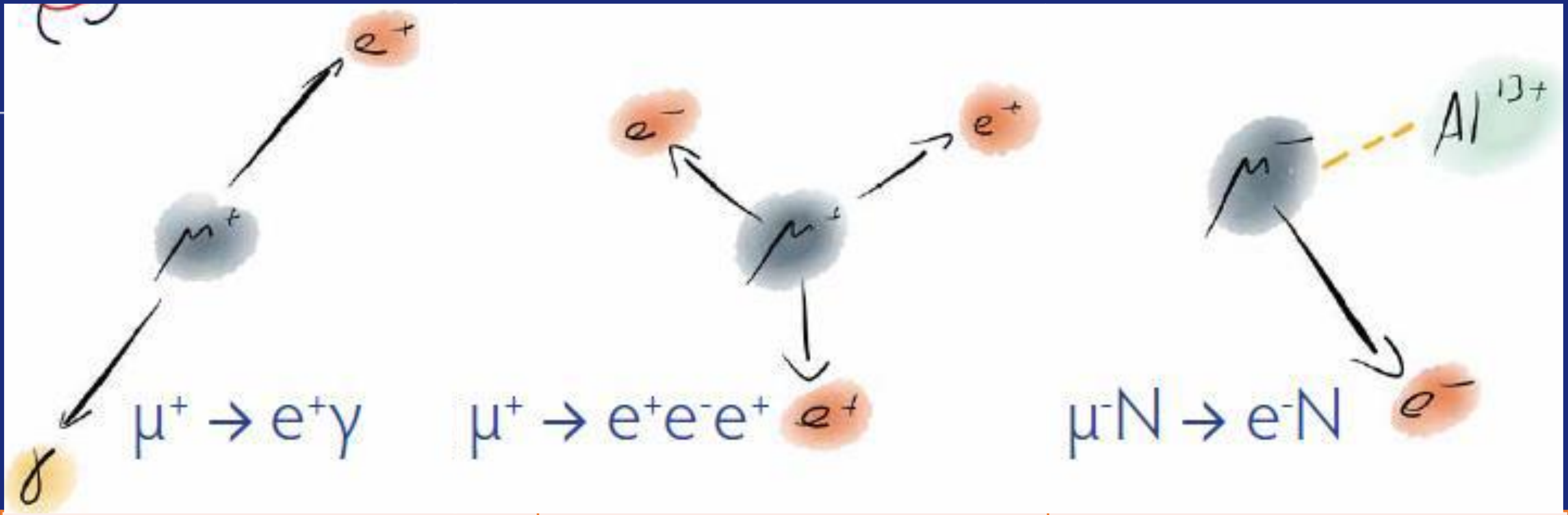
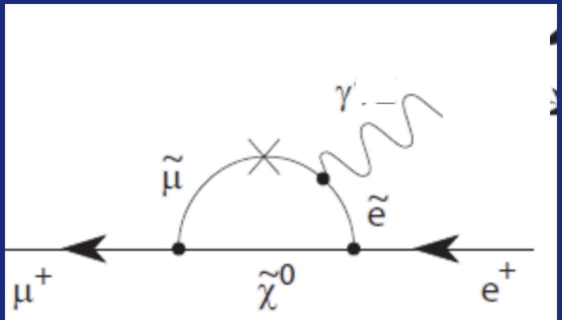
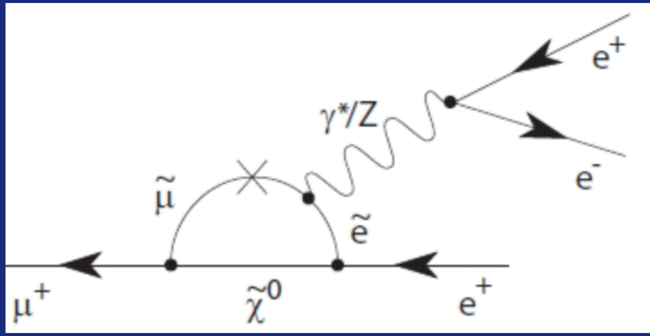
Radiative decay: $\mu \to e\nu\nu\gamma$ Accidental backgrounds: $\mu \to e\nu\nu$ + radiative photon DC beam	Radiative decay ($\mu \to eee\nu\nu$); Accidental backgrounds $\mu \to e\nu\nu$ + conversion or Bhabha pairs DC beam	Non-LFV muon decay in orbit, beam related: prompt antiprotons, pions,.. Pulsed beam

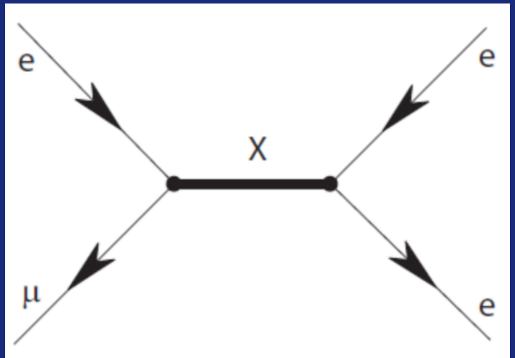


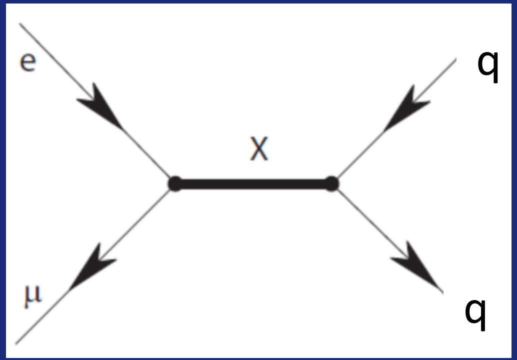
CLFV Muon decay channels

Sensitive to loop diagrams (coupling to γ)	Sensitive to loop (coupling to γ^*/Z, Z',..) and tree diagrams (eeeμ)	Sensitive to loop (coupling to γ^*/Z, Z',..) and tree diagrams (qqeμ)









Physics reach

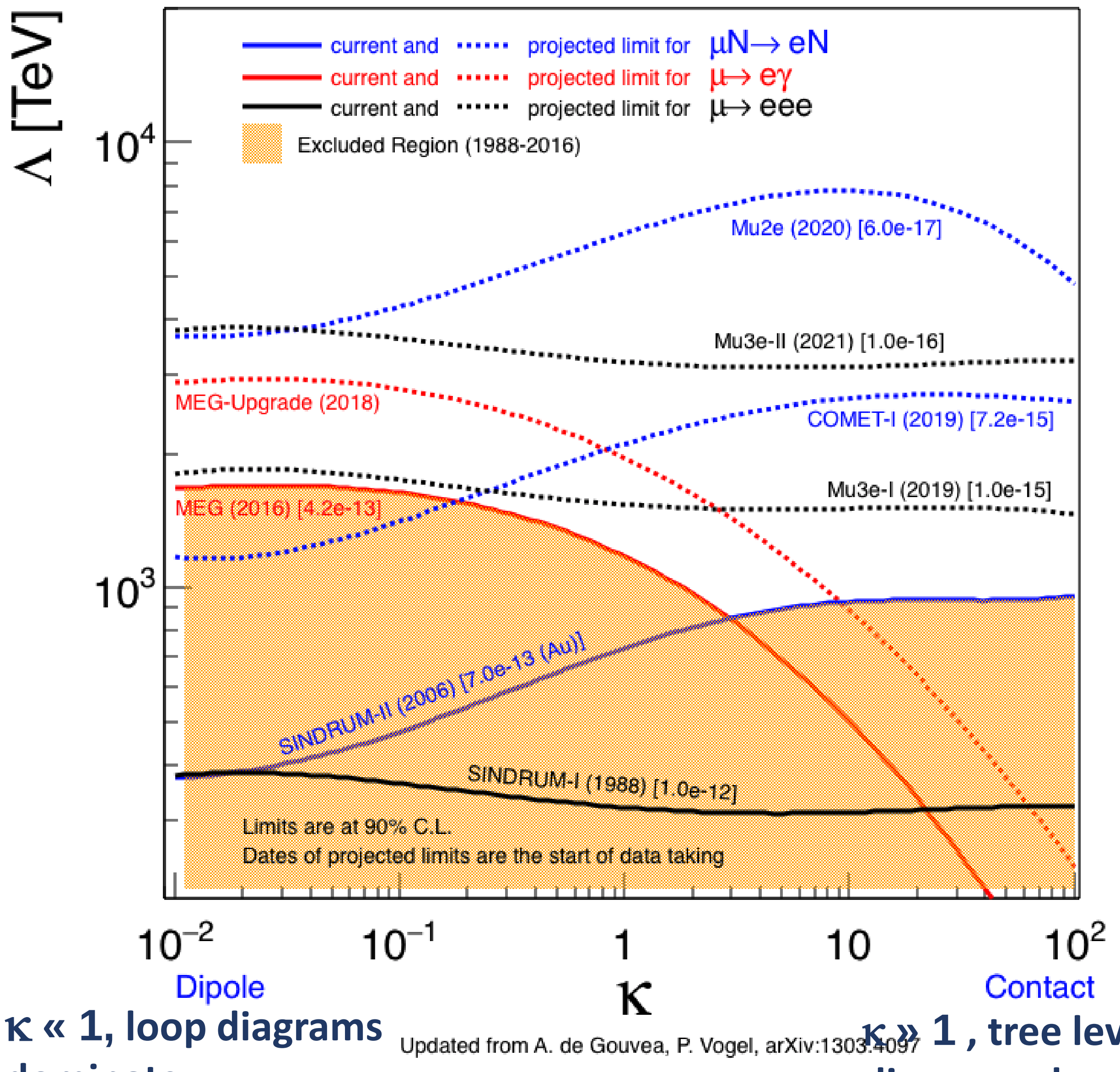
Highly model dependent. Different channels have varying sensitivity to different NP modes.

A comparison is possible with a generic Lagrangian model:

$$\mathcal{L}_{\rm CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + h.c. + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L\left(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L\right) + h.c.\,.$$

CLFV experiments have sensitivity up to several PeV effective scale.

Update from de Gouvea & Vogel, Prog. in Part. and Nucl. Phys. 71 (2013).



Dipole

κ « 1, loop diagrams dominate

Contact

κ » 1 , tree level diagrams dominate

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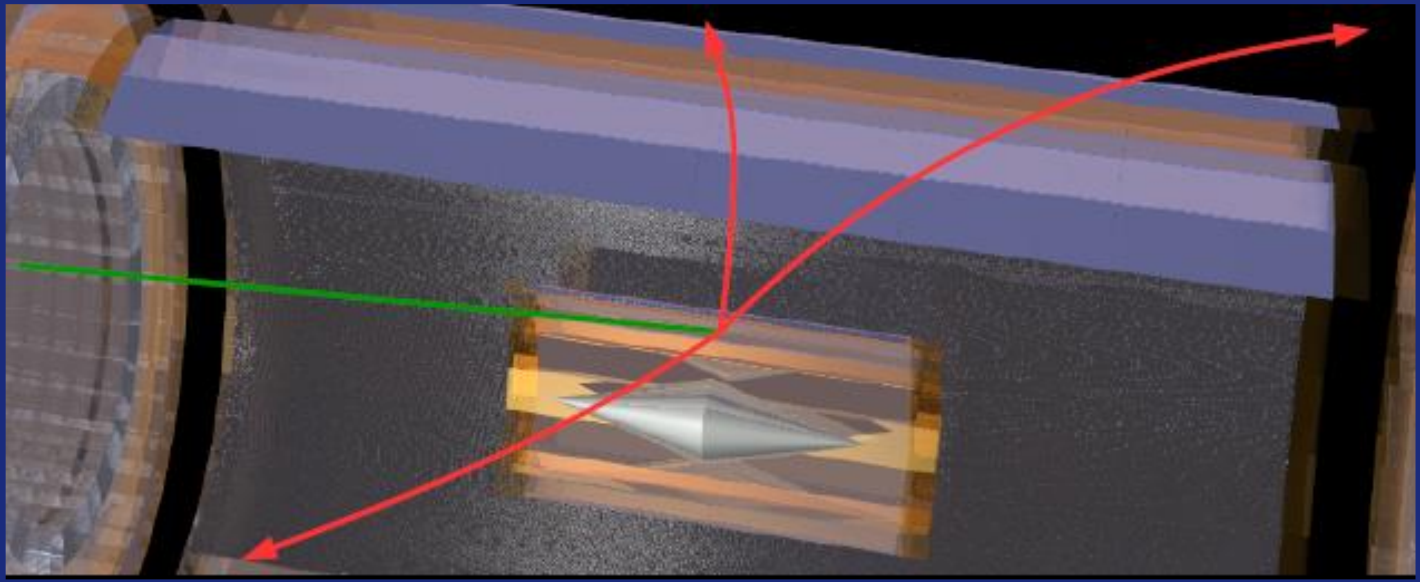
The μ3e experiment at PSI

Search for $\mu \rightarrow eee$ with sensitivity for BR > 10^{-16} using muon beam lines at PSI.



PAUL SCHERRER INSTITUT PSI

ETH Eidgenössische Technische Hochschule Zürich Swiss Federal Institute of Technology Zurich

UNIVERSITÉ DE GENÈVE

Universität Zürich[UZH]

n|w University of Applied Sciences and Arts Northwestern Switzerland

UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

KIT Karlsruher Institut für Technologie

KIRCHHOFF-INSTITUTE FOR PHYSICS

UCL

University of BRISTOL

UNIVERSITY OF OXFORD

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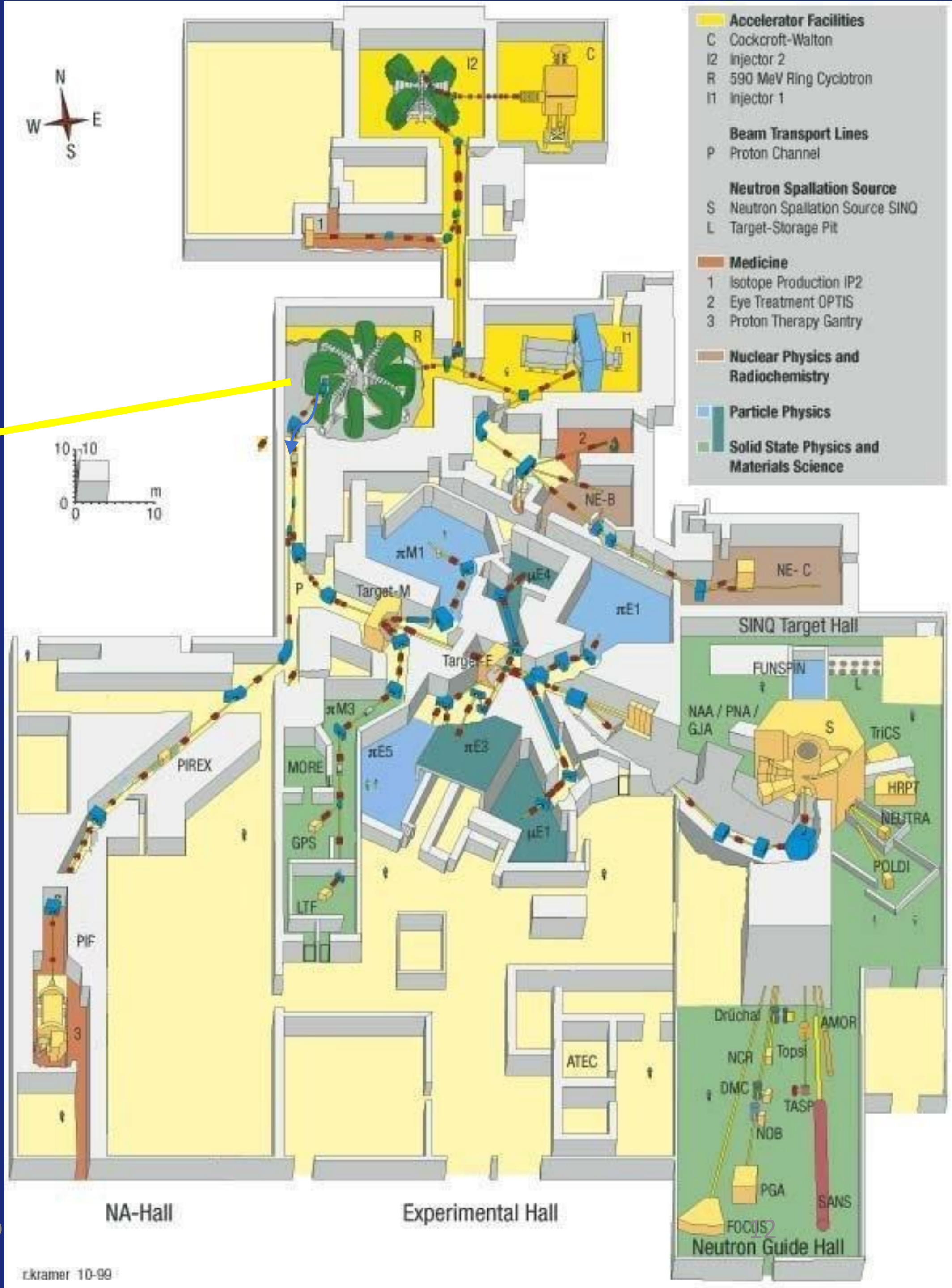
Muon production at PSI



Start from PSI proton cyclotron

590 MeV protons at up to 2.3 mA

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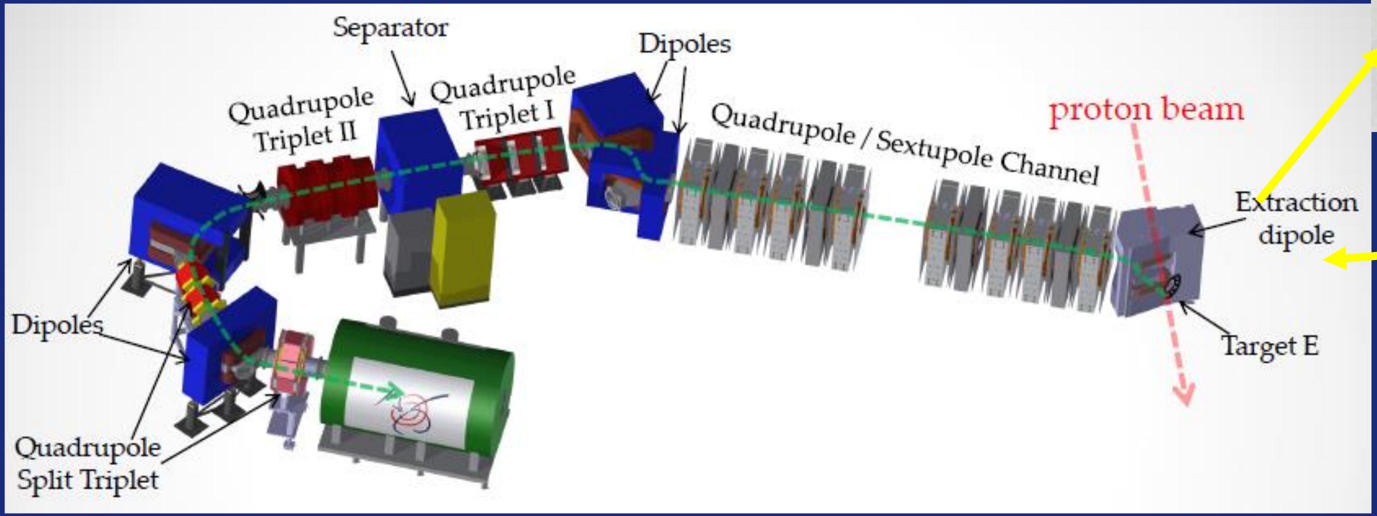
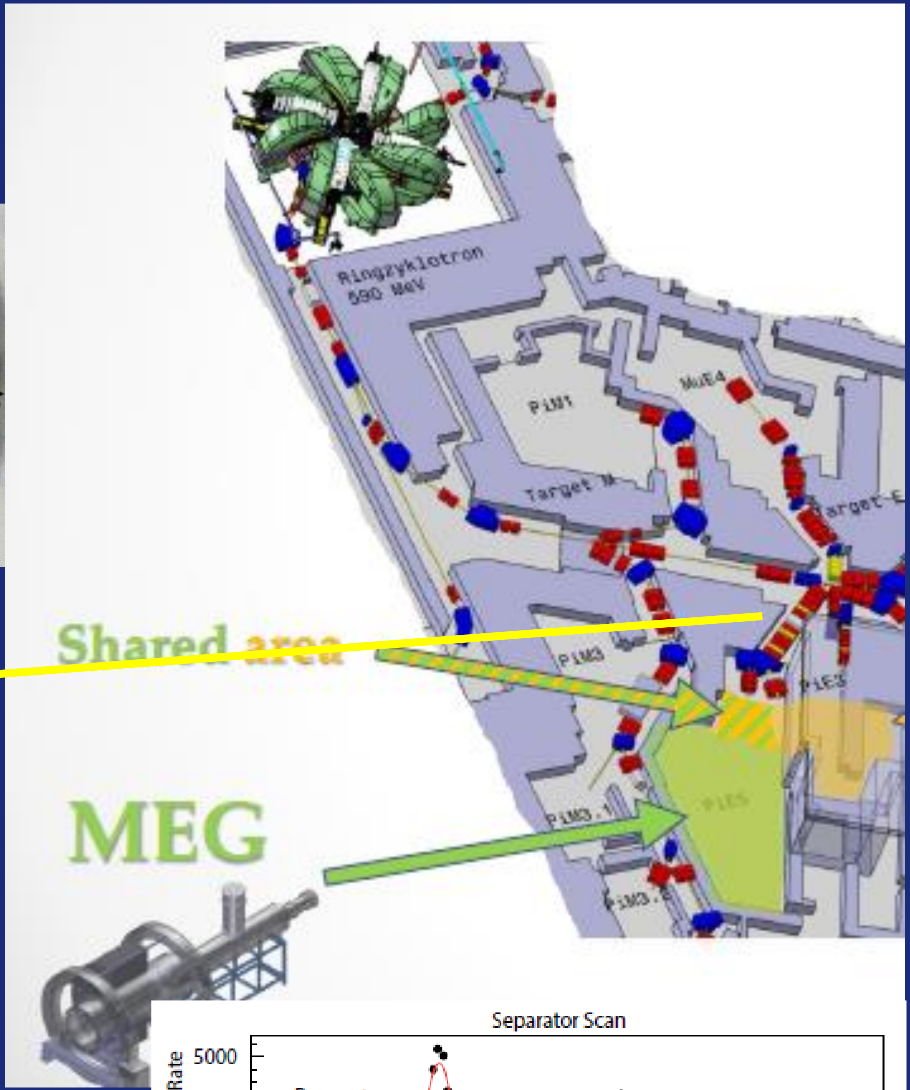
Target-E and the πe5 / Compact Muon Beam Line



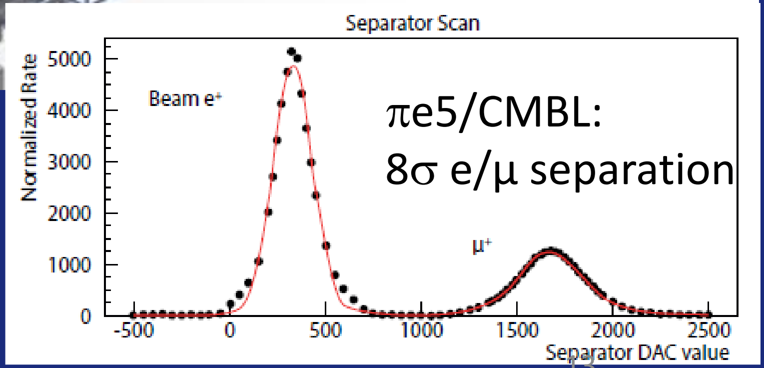


Protons hit fast spinning carbon target.

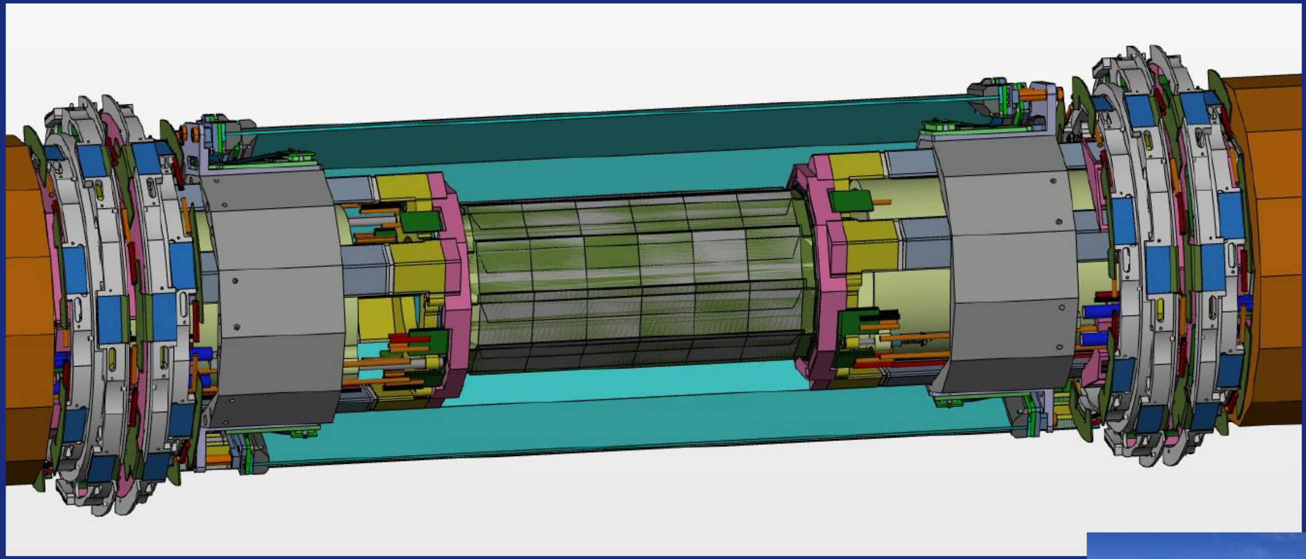
Muons from pion decays near surface peak around p = 29 MeV.

πe5/combined muon beamline (CMBL) captures muons from target, delivering 10^8 μ/s in a narrow momentum bite stopped on target.

Effective removal e^+ from Michel or π_0 decays near target.



The detector



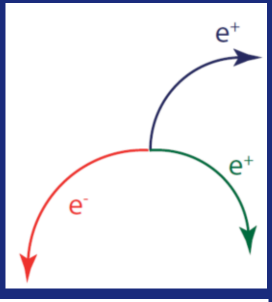
Mu3e targets BR($\mu^+ \rightarrow e^+e^+e^-$) with a sensitivity of 10^{-16}.

This requires:

- a fast detector with high bandwidth read-out to cope with up to record up to $2x10^9$ muon decays per second.
- excellent timing and tracking to separate the signal from background processes

Equivalent to searching for one grain of sand on all of the Germany's beaches.

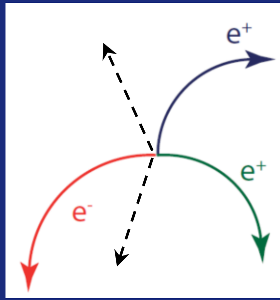
The $\mu^+ \to e^+e^+e^-$ search: physics constraints



The signal:

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

$E_{total} = m_\mu$

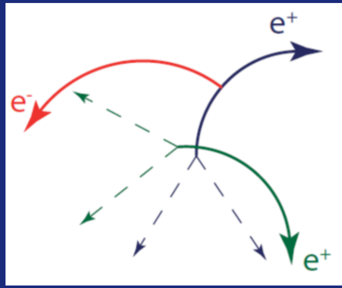


Michel decays with internal conversion:

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

Irreducible background a part from missing E_T

$E_{total} < m_\mu$

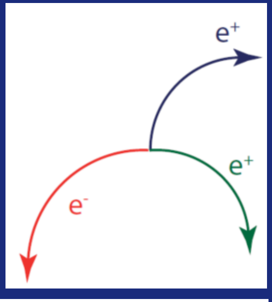


Accidental backgrounds:

Michel positron(s) & electron or e^+e^- pair from photon conversion or Bhabha scattering.

Electrons not (all) from a common vertex

The $\mu^+ \to e^+e^+e^-$ search: physics constraints



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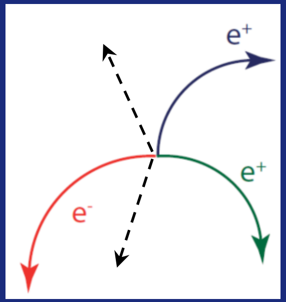

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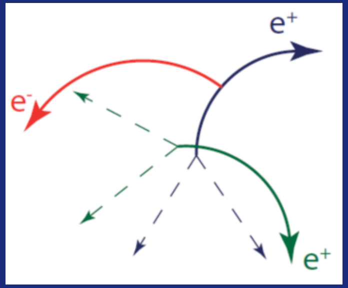
Irreducible background a part from missing E_T

$E_{total} < m_\mu$

Need good resolution on E_{total}



Accidental backgrounds:

Michel positron(s) & electron or e^+e^- pair from p ersion or Bhabha scattering.

Electrons not (all) from a common verte

Need good resolution on timing and vertex position

Irreducible background: $\mu^+ \to e^+e^+e^-\nu\nu$

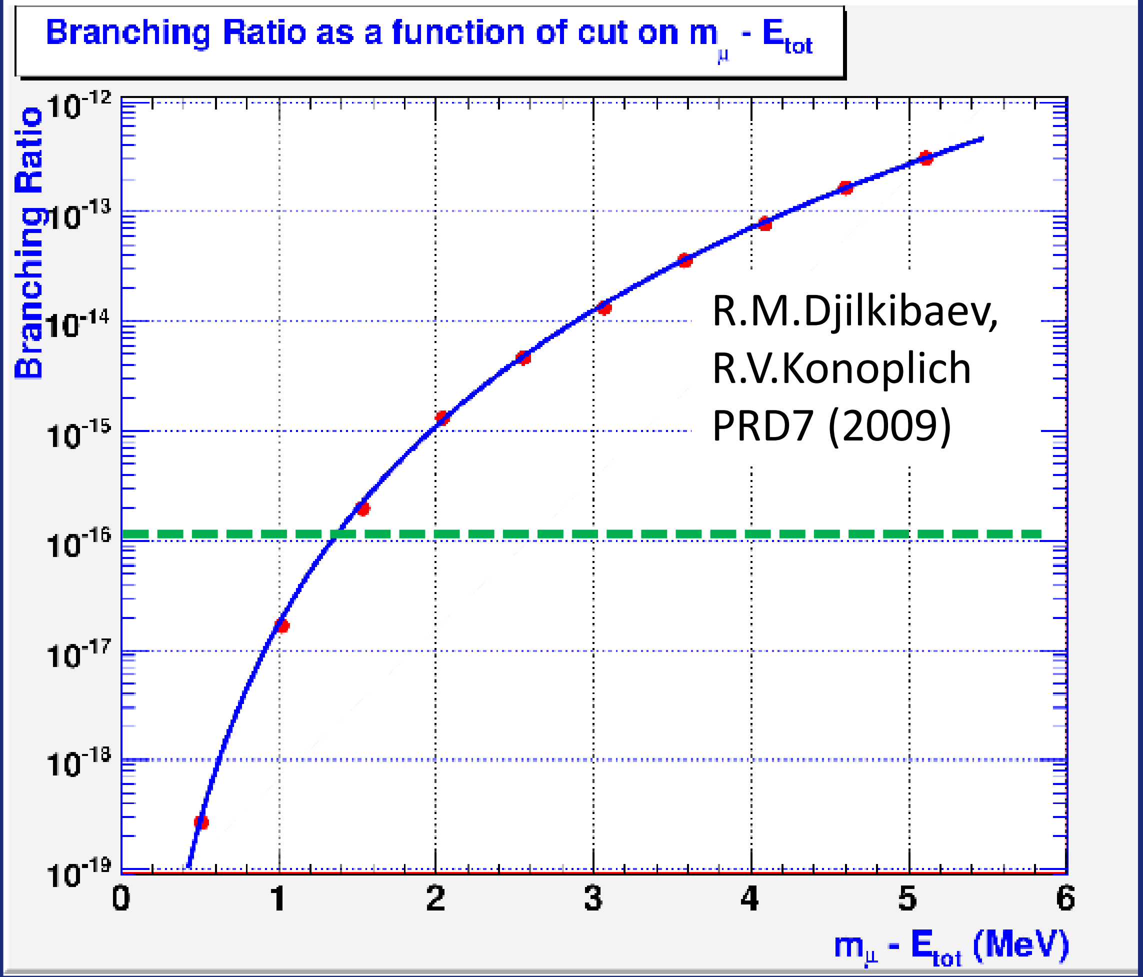
BR (3.4×10^{-5}) is 11 orders of magnitude greater than targeted signal sensitivity for $\mu\to$ eee,

but this drops steeply towards kinematic endpoint.

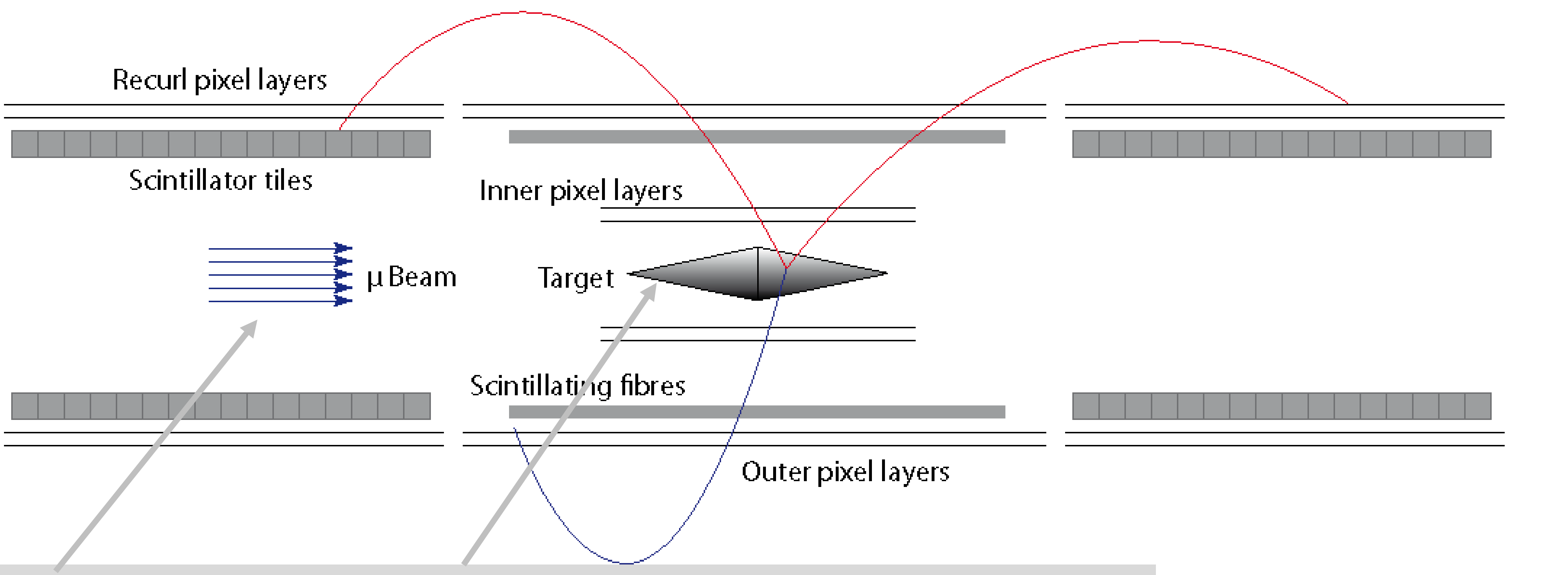
Need: $\sigma(E_{tot})$ < 1 MeV

Very challenging to achieve for low energy electrons (E_e < 53 MeV) and up to 2×10^9 muon decays per second.

m_μ - E_{Total} distribution $\mu^+\to e^+e^+e^-\nu\nu$

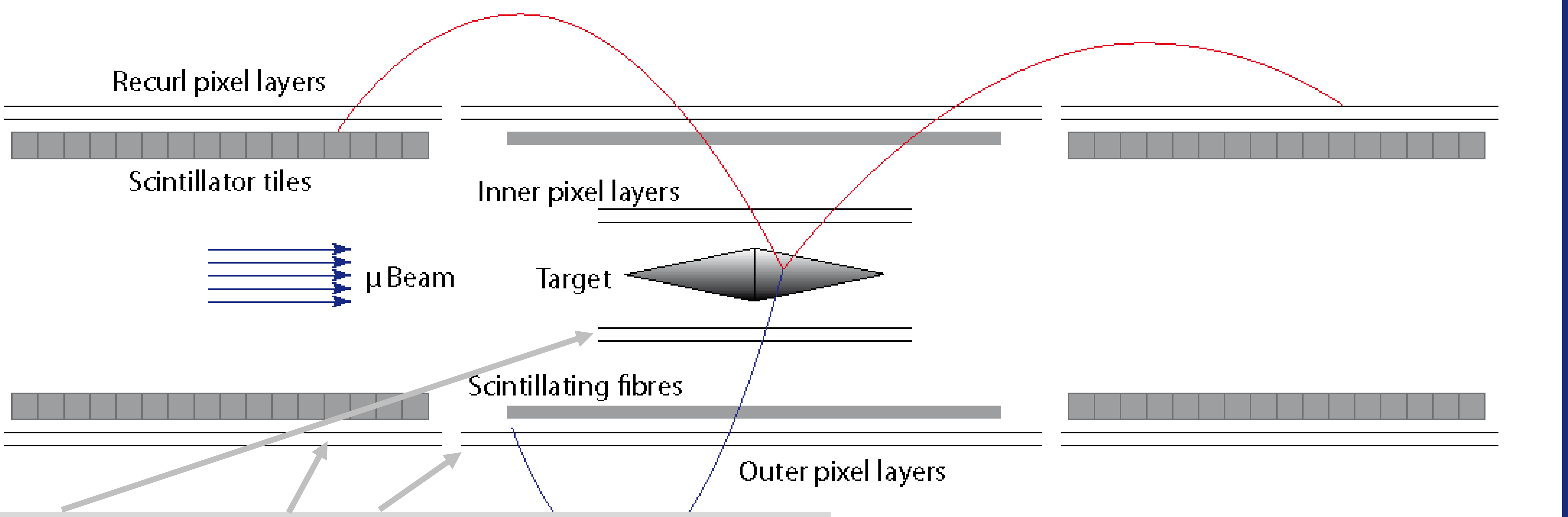


The Mu3e detector (Phase 1)



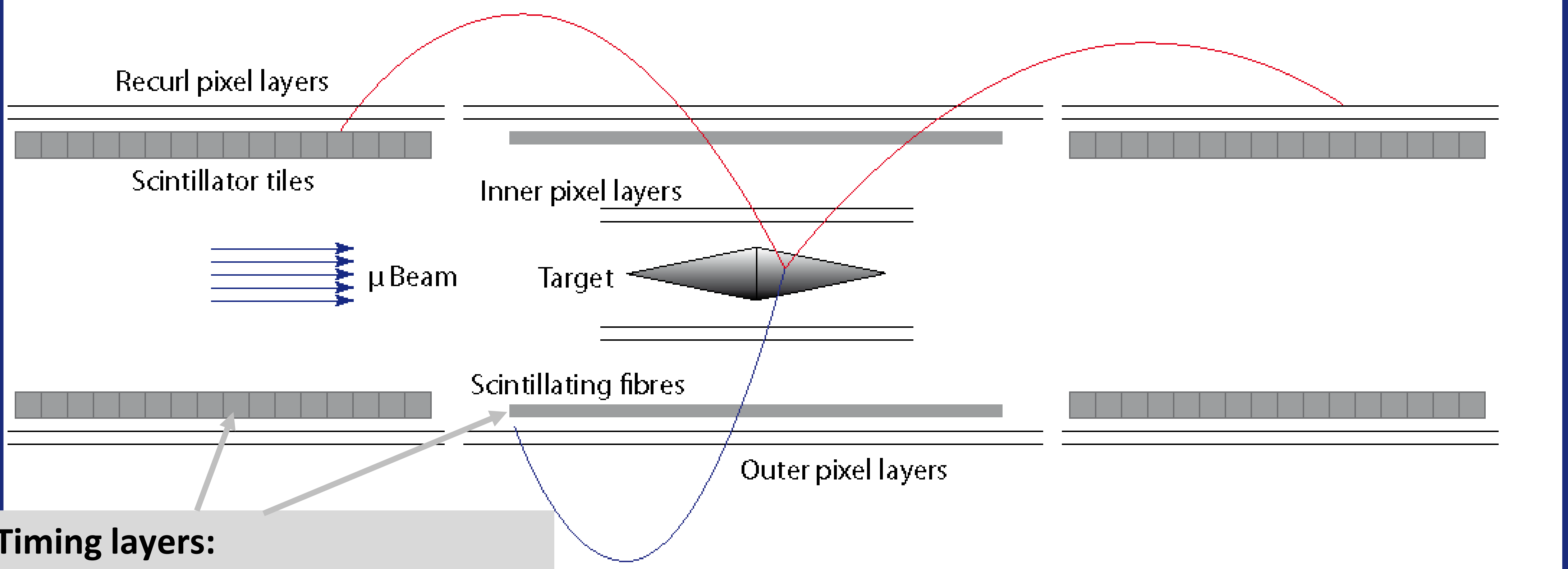
DC beam 10^8 μ/s (Phase-I), <p> = 28 MeV
Muons are stopped in double-cone mylar target (75 μm front, 85 μm back)

The Mu3e detector (Phase 1)



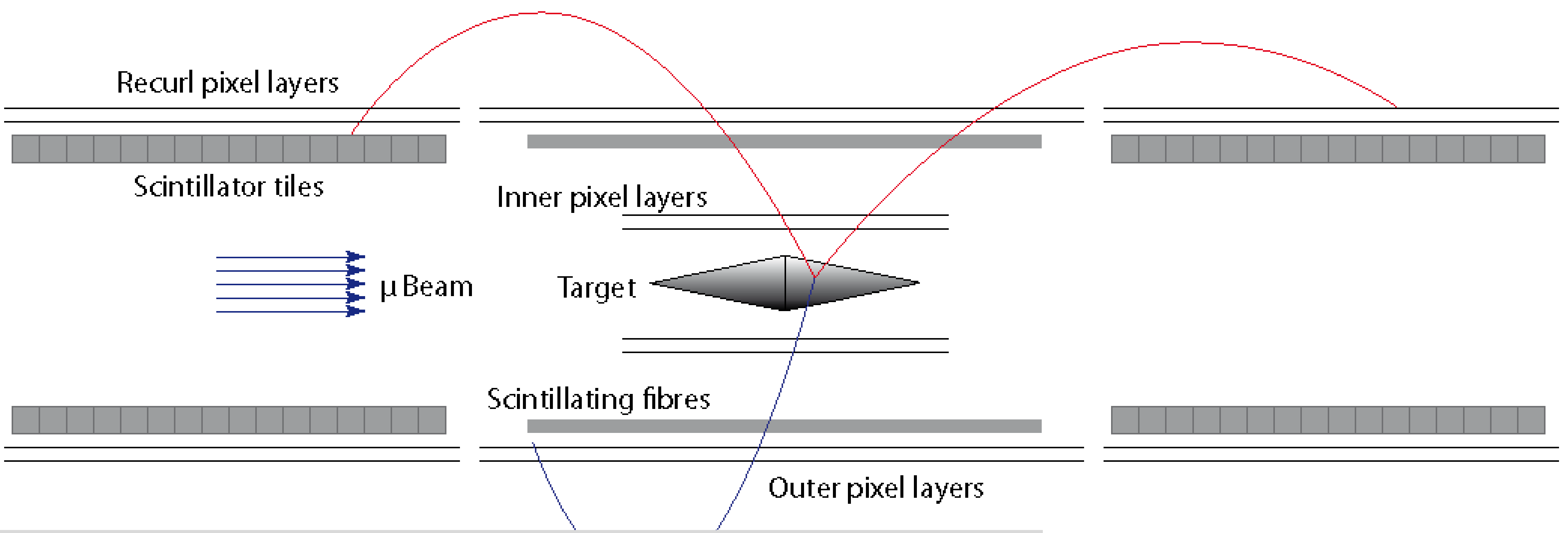
Low mass (0.1% X_0) HV-CMOS pixel tracker
Critical for vertex position and momentum resolution.
Inside 1 T solenoidal field

The Mu3e detector (Phase 1)



Timing layers:
Scintillating fibres: σ(t) <500 ps
Scintillator tiles: σ(t) <100 ps

The Mu3e detector (Phase 1)



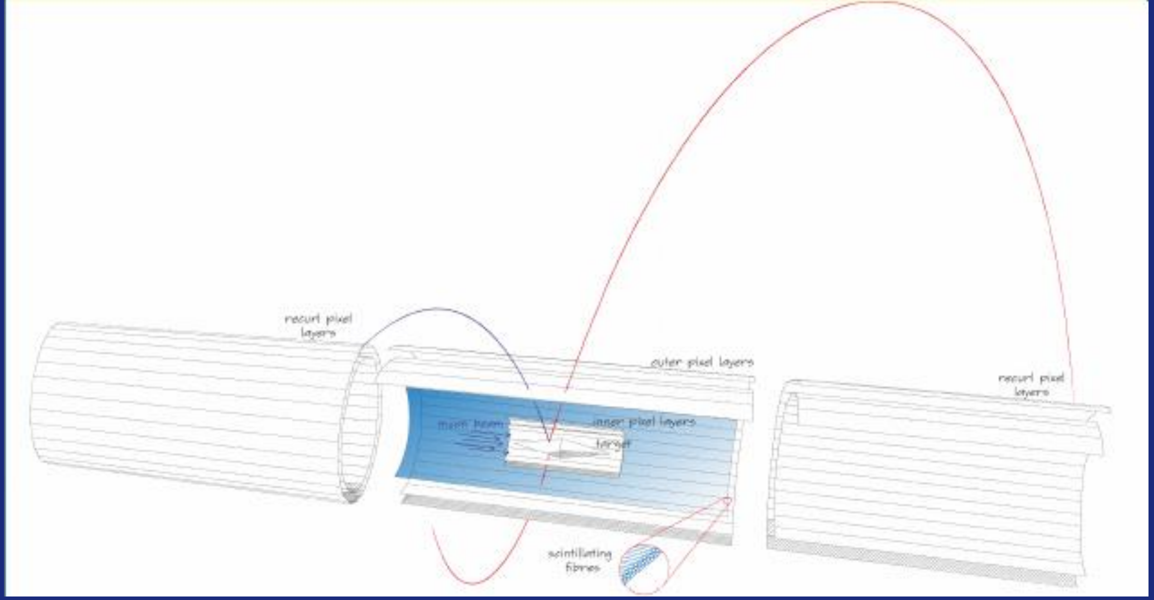
UK contribution Phase 1 detector:

- **Clock and reset distribution system (UCL)**
- **Outer and recurl pixel layers (Bristol, Liverpool, Oxford)**

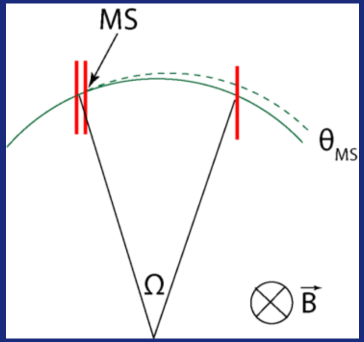
Tracking concept

At $p_e < 53$ MeV multiple coulomb scattering dominates track errors.

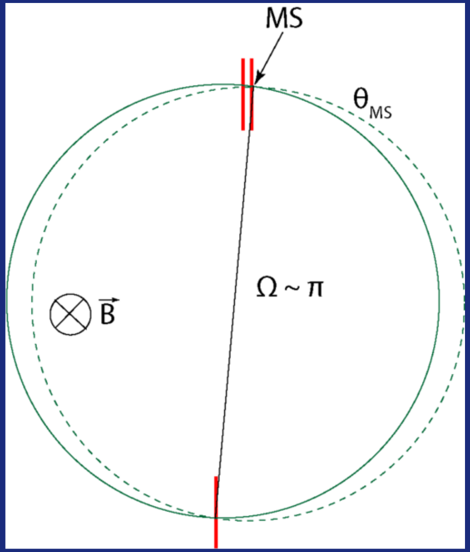
$\theta_{MS} \sim \sqrt{X/X_0}$ (reduce material, 0.1% X_0 per Silicon layer)

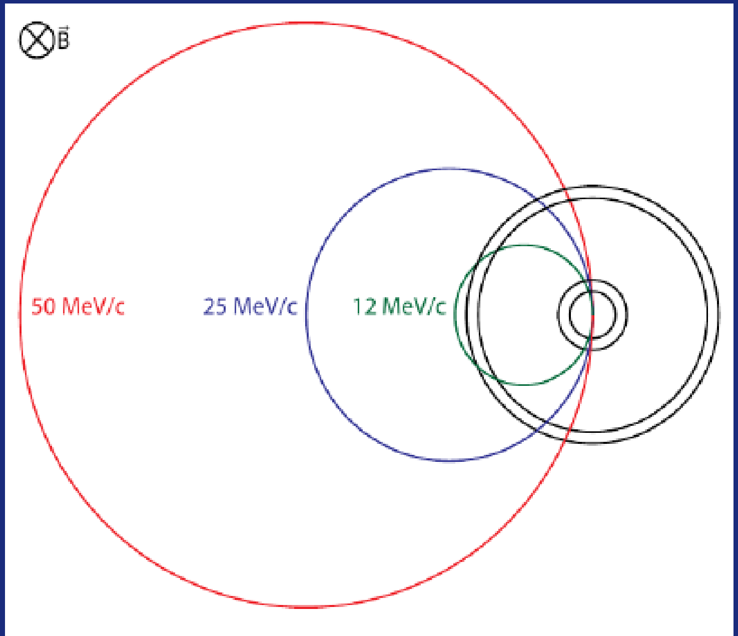


$\frac{\sigma(p)}{p} \sim \frac{\theta_{MS}}{\Omega}$ (for small Ω)



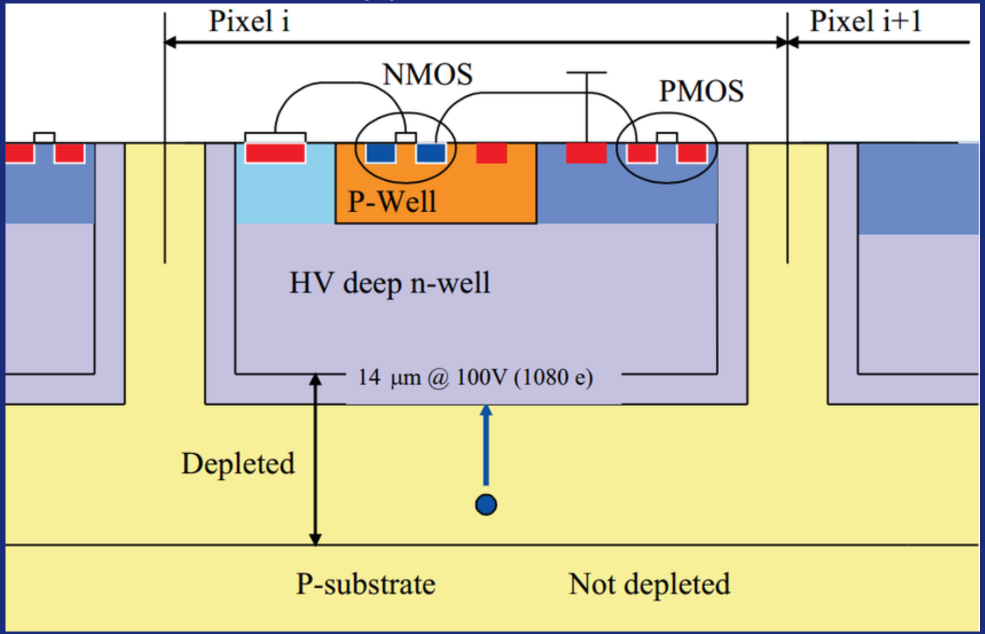
But, for very large lever arm (Ω ~ π) first order effects of θ_{MS} cancel out.





Layer radii are optimised for momentum resolution and acceptance.

I. Peric, NIMA 650 pp. 158-162, 2011



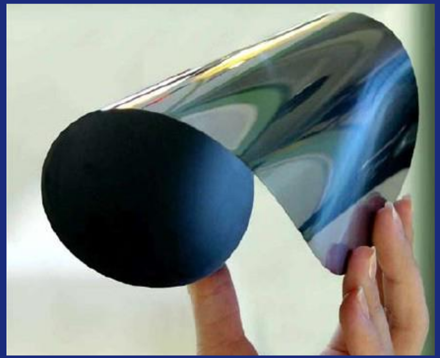
HV-MAPS sensors

Adaptation from CMOS-MAPS using high-voltage compliant CMOS processes.

- Specific is deep N-well that collects charge and includes analogue and digital circuits. (no parasitic collection)
- N-well is biased to > 80 – 200 V giving 10 - 30 µm depletion in bulk.
- High signal and fast charge collection, *combining compactness of CMOS with performance of hybrid planar silicon sensors.*

<u>*Critical properties for Mu3e:*</u>

- Sensors can be thinned to 50 µm without signal loss.
- Sensors can operate in a high rate environment ($\sigma(t)$ < 15 ns)



Mu3e is the first PP experiment to employ HV-MAPS in a tracker

Mu3e would not be possible without this new technology! (sensitivity ~ $(X/X_0)^3$

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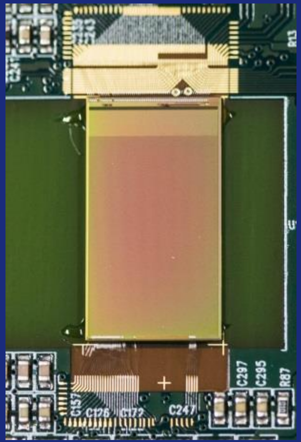
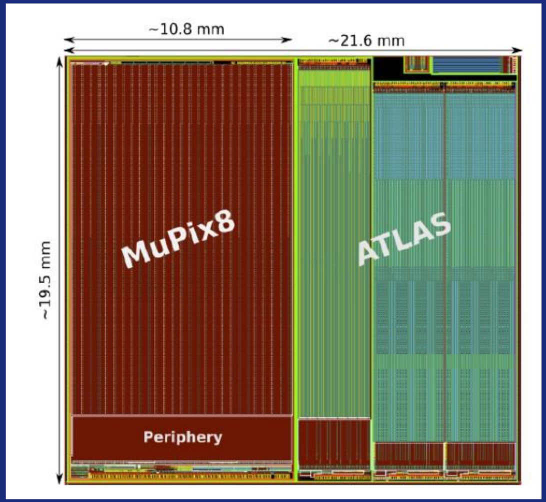
MuPix HV-MAPS



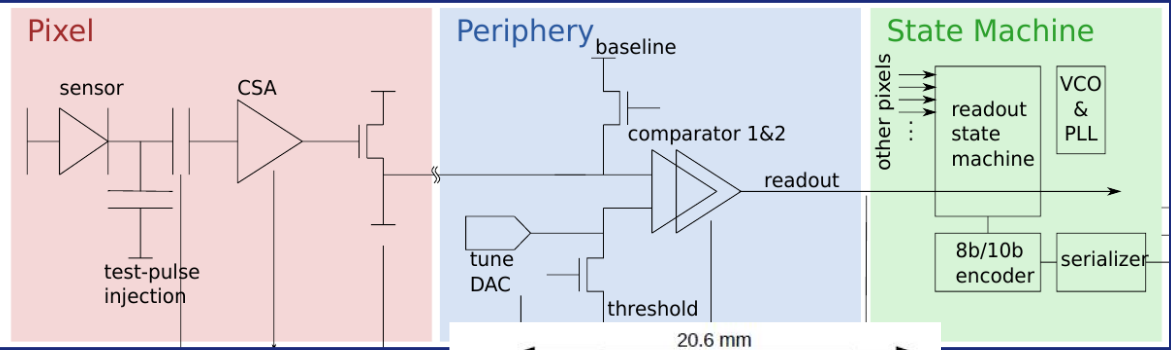


HV-MAPS development in AMS 360 nm and 180 nm HV-CMOS process, now moved to TSI 180 nm process.

MuPix8 (shared submission with ATLASPIX, different substrate resistivities)

First large area demonstrator: active area: 1×1.6cm^2

- 80 x 80 μm^2
- Amplifier in pixel,
- Comparator and digital logic in periphery.
- 3 (or 1) data outputs, 1.25 Gb/s each
- Power: ~250 mW/cm^2

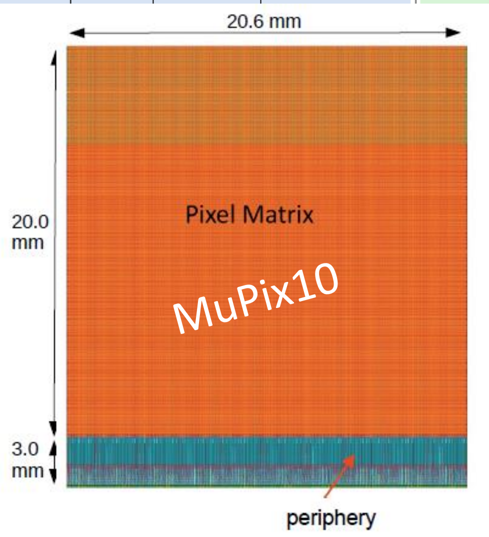


MuPix10 first full size chip for detector: active area: 2 × 2 cm^2

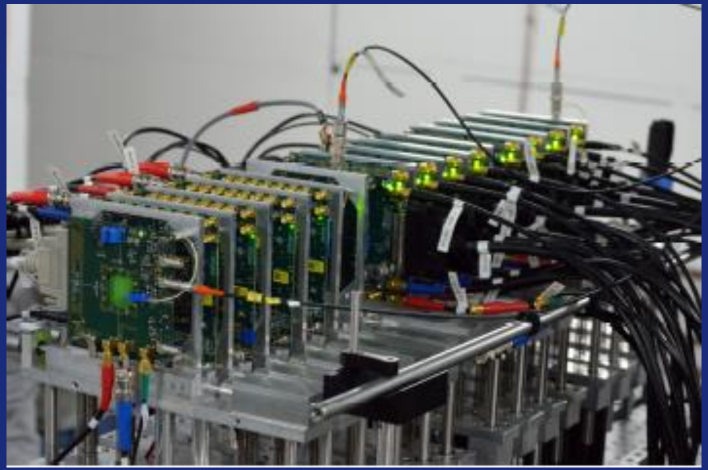
- Optimised pad layout for module construction
- Optimisation power distribution
- Some rerouting of signal lines to reduce cross talk
- Smaller periphery,
- 80 → 200 Ωcm

Submitted Nov 2019, received March 2020 (just before lock down)

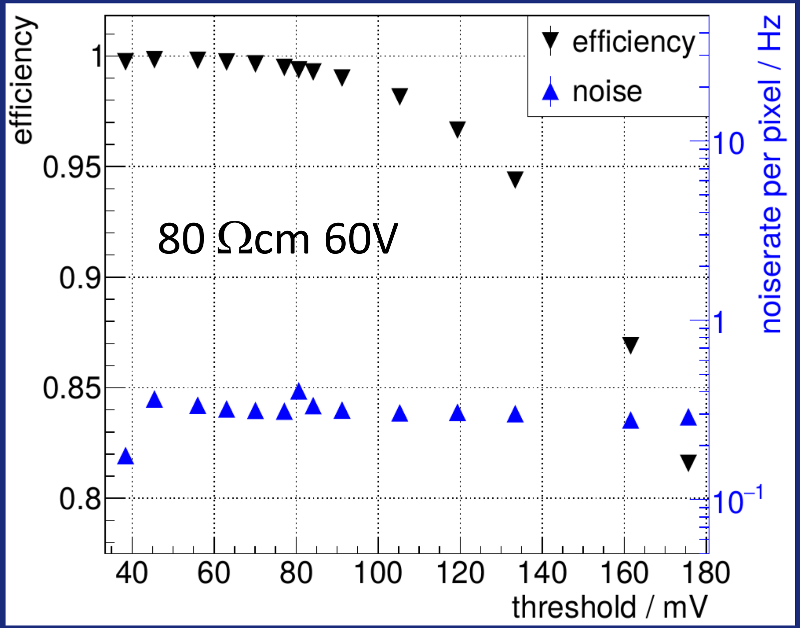
MuPix11, if necessary, submission Q4 2020 → Pixel tracker assembly in 2021

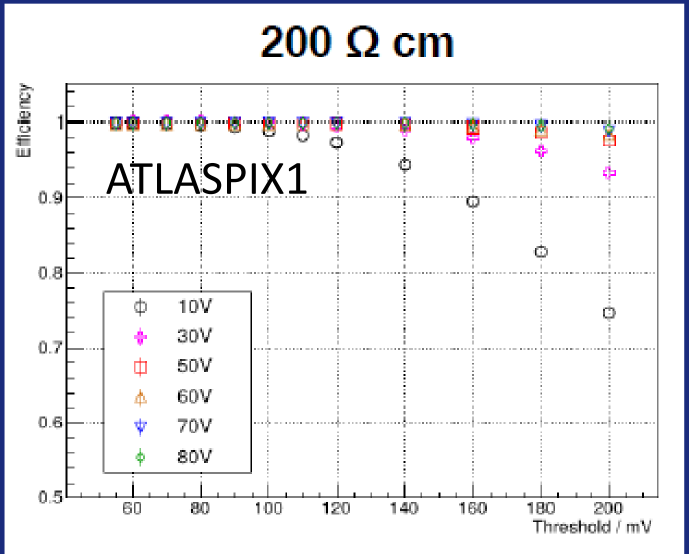


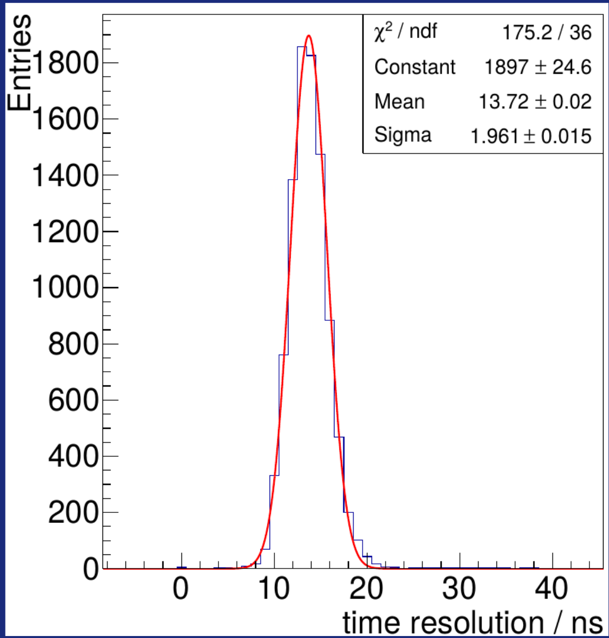
Results from testbeam: MuPix8



Testbeams with MuPix/FEI4 telescope mostly at DESY and PSI







Eff. ~ 99.8%
higher over larger range of thresholds with 200 Ωcm

σ(t) ~ 14 ns
Tuning the threshold we think we can improve this to 6-7 ns

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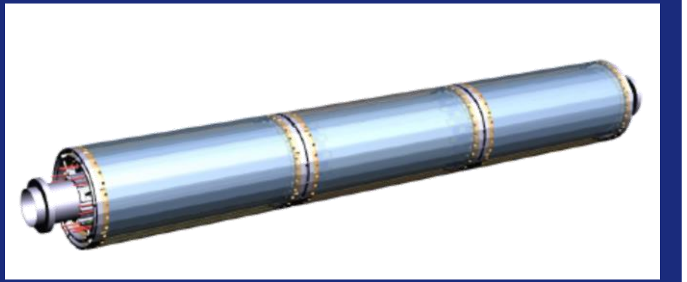
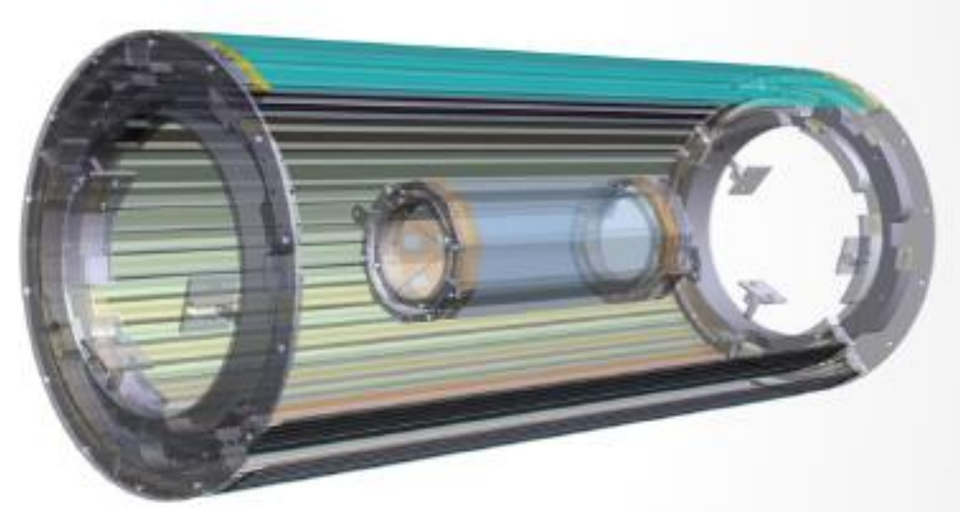
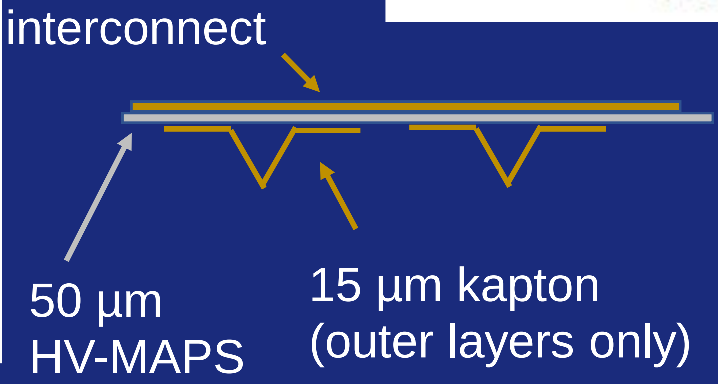




Pixel Tracker
Rendering of CAD study

MuPix mechanics

In total for Phase-1 2808 HV-MAPS chips will be mounted to 170 high density interconnect flex circuits to produce the inner and outer layers
(1.1 m^2 of HV-MAPS sensors)

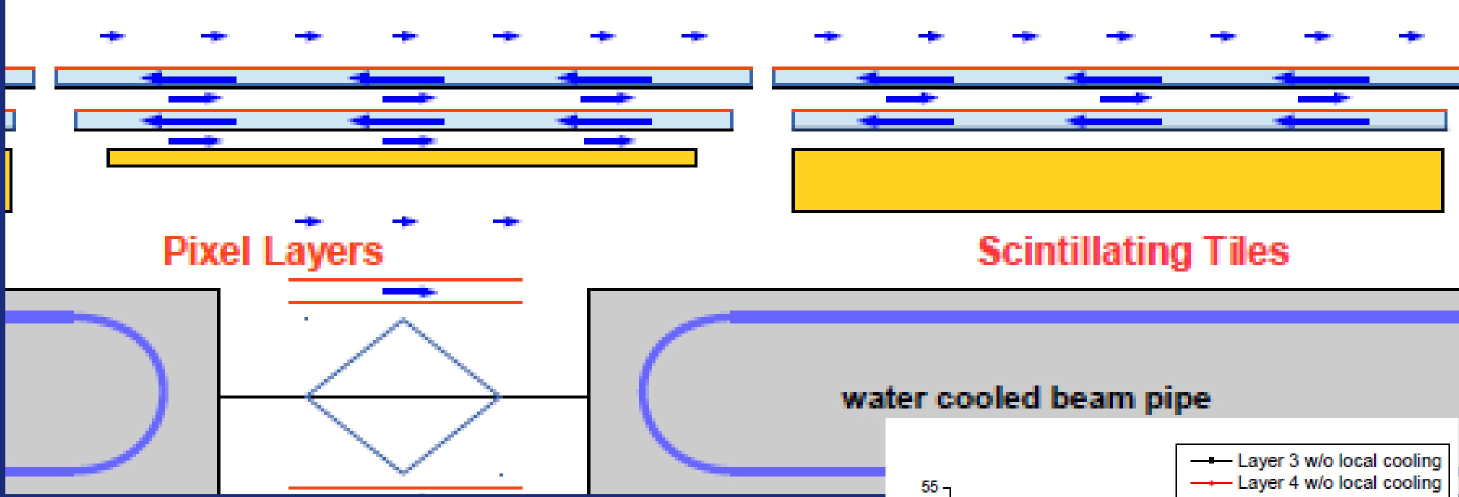


Material budget is critical

- 50 µm HV-MAPS (~0.05% X_0)
- Ultra thin interconnect flex (~0.05% X_0)
- 15 µm kapton v-fold strengthening spines (also He-channel)

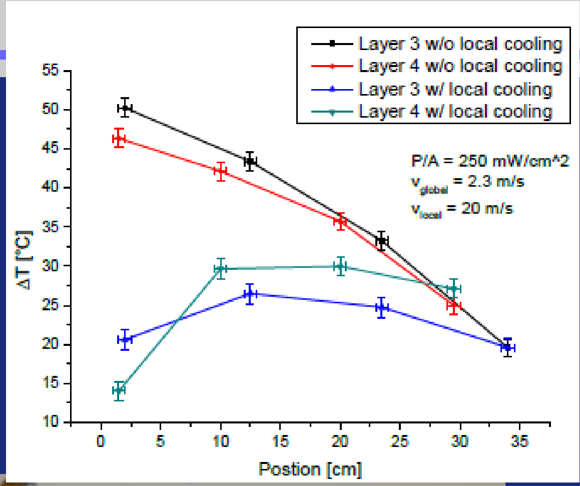
Resulting in approximately <u>0.1% X_0 per tracking layer</u>

Gaseous Helium cooling



~4.5 kW power dissipation in very low mass structure.

Must life with relatively high thermal gradient (0°C - 55°C)



Counter-flow cooling system with gaseous Helium flowing through v-channels and between pixel layers.

- High gas velocity Helium flow (up to 20 m/s).
- Multiple parallel flow paths.
- Detector structure does not tolerate substantial pressure differentials.

Simulations and lab test confirm satisfactory cooling performance.

Development cooling control system, advanced simulations and tests ongoing.

Thermo-mechanical mock-up pixel layer 1

Timing

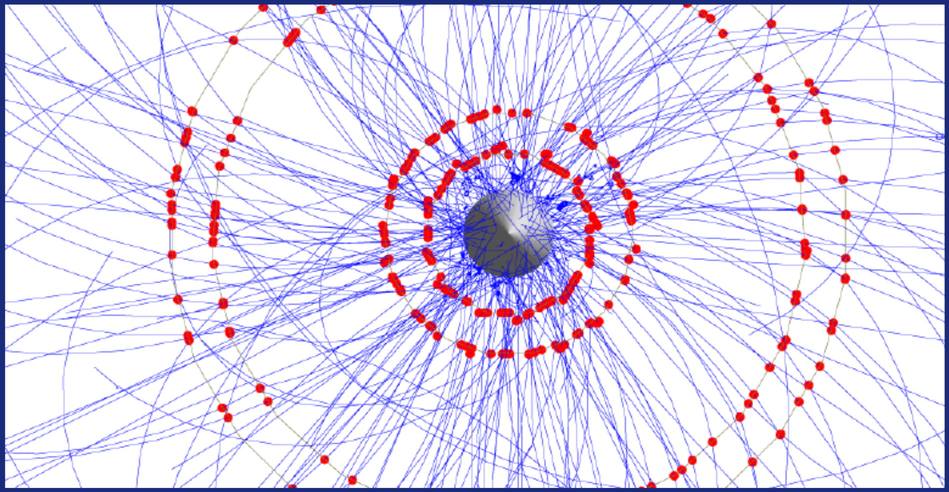
Accidental combinatorial backgrounds can be reduced by accurate timing resolution.

Scintillating Fibres ($\sigma(t) < 500$ ps) and Tiles ($\sigma(t) \sim 100$ ps) provide high resolution time stamp for tracks.

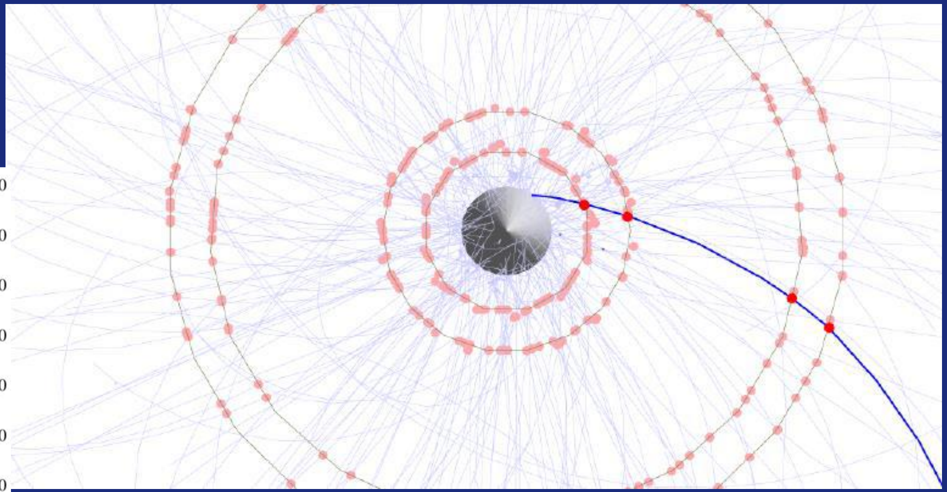
Note HV-MAPS are slower, so for track-finding still need longer window (spec: $\sigma(t) < 20$ ns)

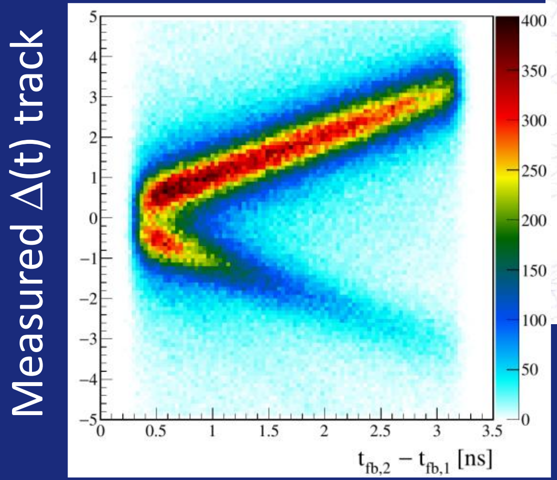
Timing also critical in preventing charge mis-identification for tracks that circle back in to target.

50 ns time slice at 2×10^9 μ/s

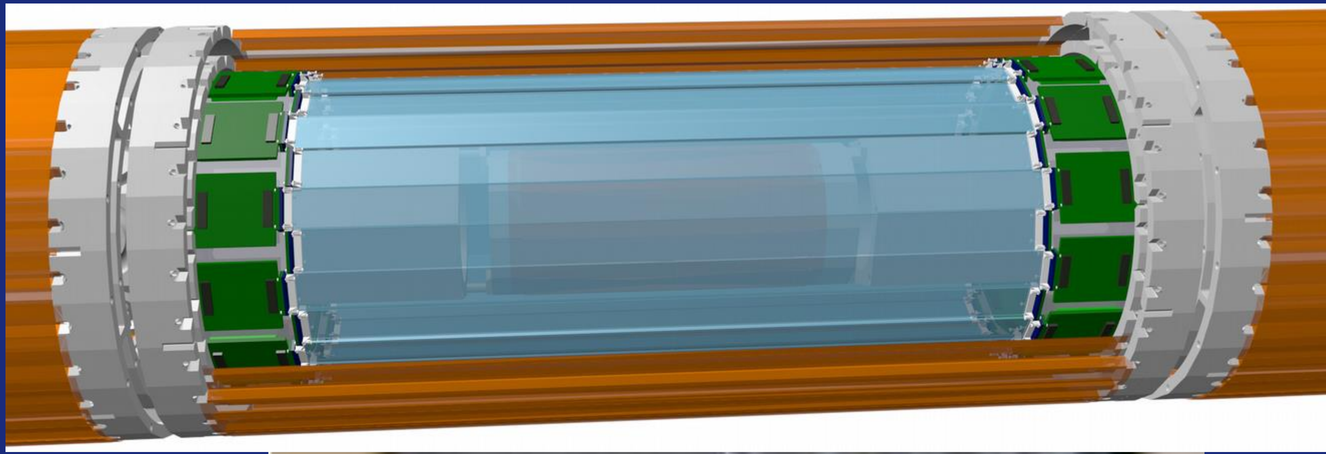


with < 500 ps time resolution:





Expected Δ(t) for positron



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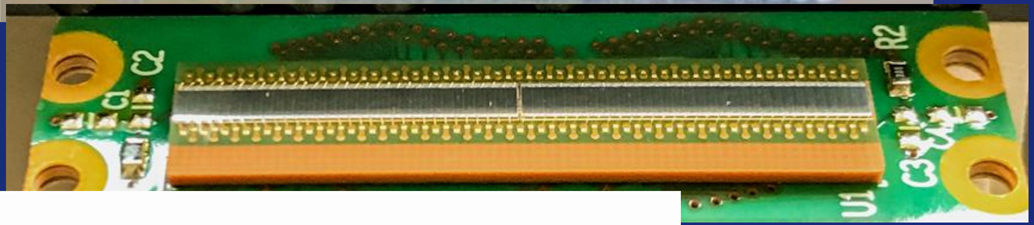
Scintillating fibre detector

250 µm diameter scintillating fibres stacked in to 1 cm wide ribbons of 3 staggered layers, set in clear epoxy.

~0.3% X_0

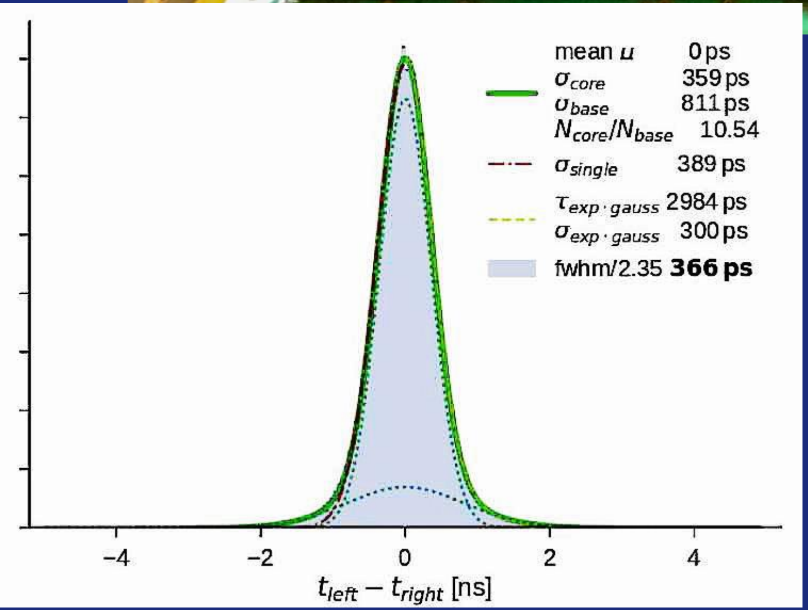


2 x 64 channel Si PM arrays (Hamamatsu)

MuTRig readout chip

Test beam results:

- time resolution ~370 ps



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Scintillating Tile detector

- ~0.5x0.5x0.5 cm^3 scintillating tiles, arranged in 4x4 arrays, wrapped in metal foil
- mounted on a cylinder for each re-curl station

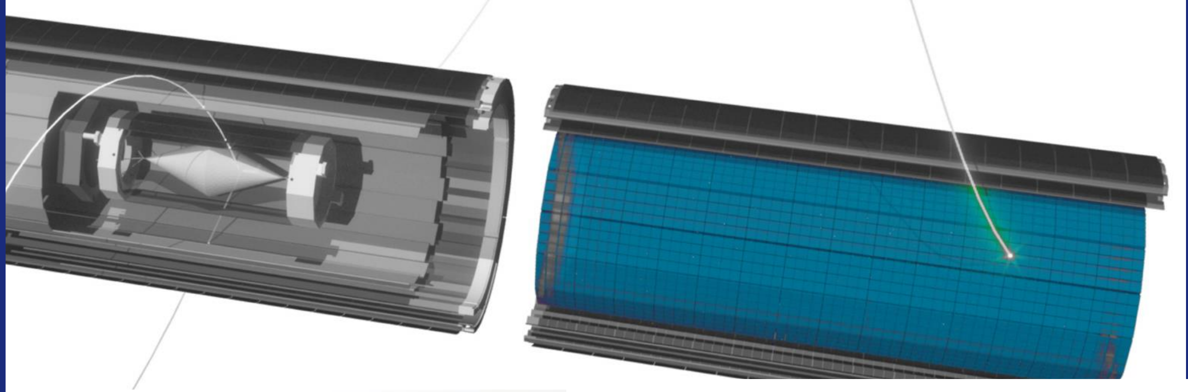
Readout: single channel SiPM, MuTrig ASIC

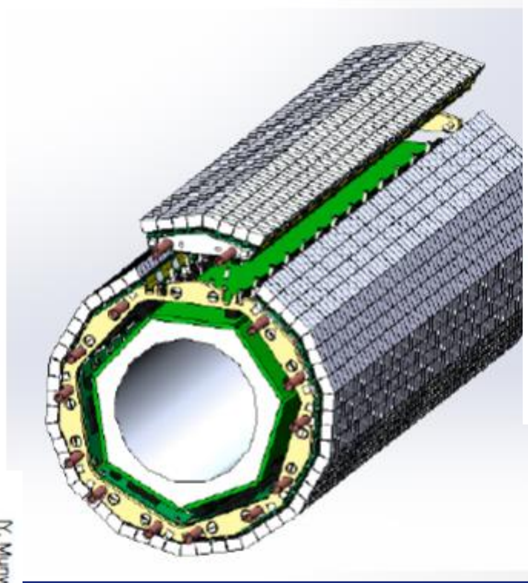
DESY test-beam:

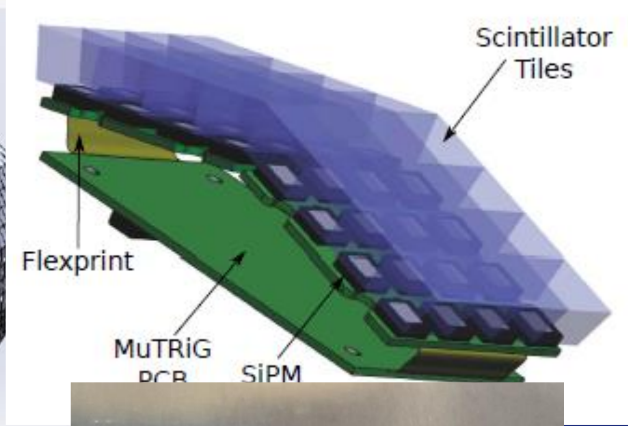
time resolution 40 ps

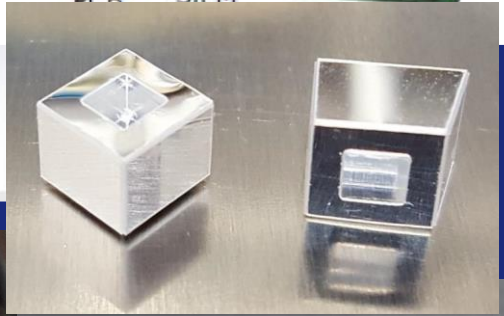
(for high energy electrons)

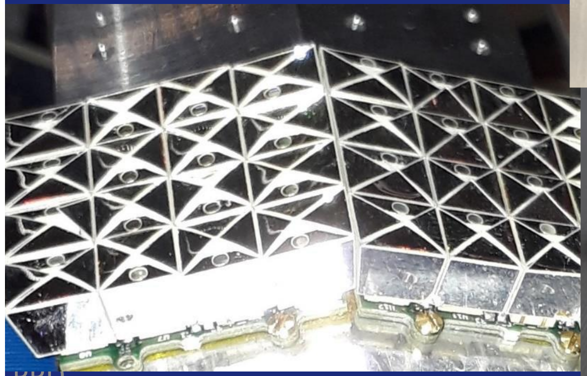
<100 ps for all energies

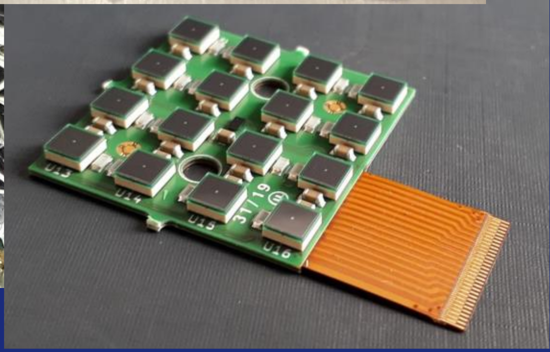


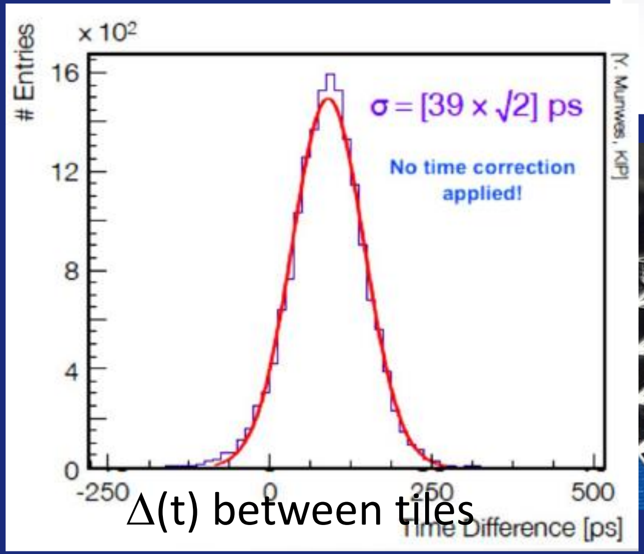












Δ(t) between tiles

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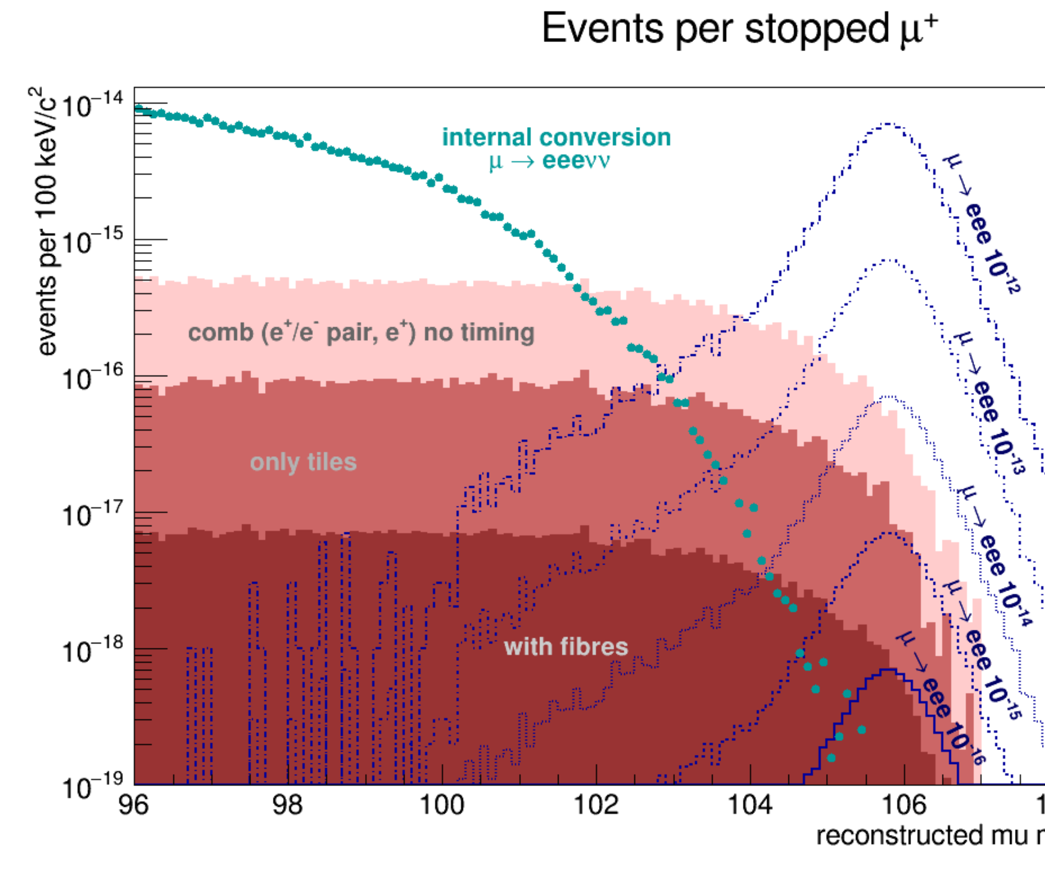
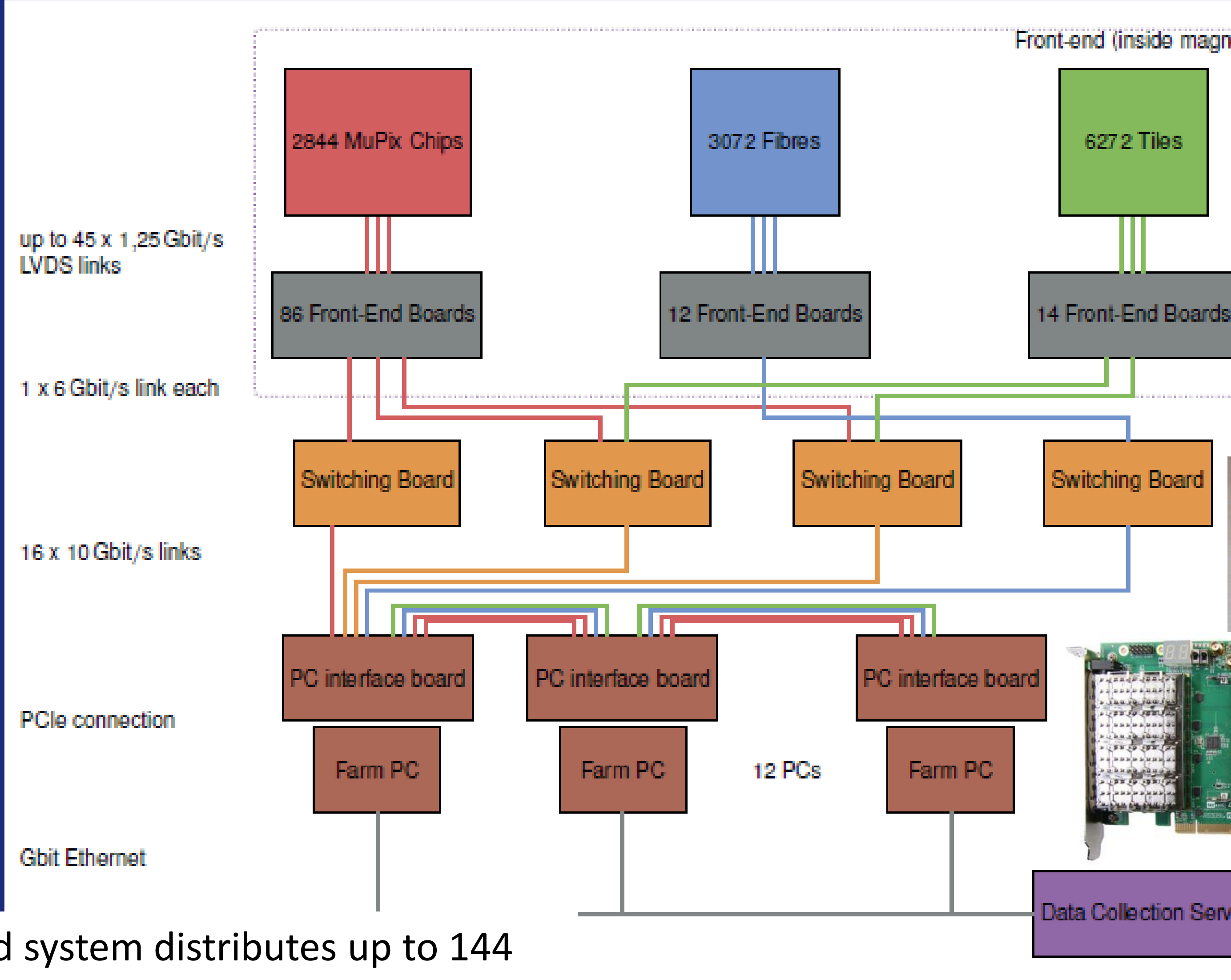
Reduction of accidental backgrounds

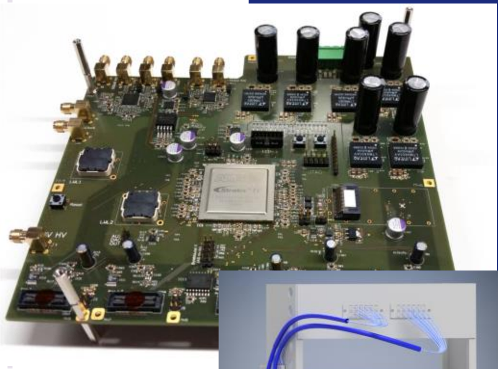


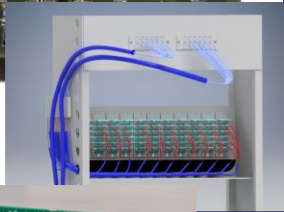
For 1×10⁸ muon decays per second.

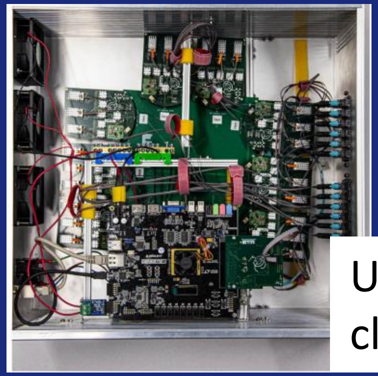
Mu3e readout chain

- Asynchronous readout of time-stamped data from ~180M channels.
- Sorting and event building done on FPGA boards. (event ≡ time-slice)
- Full event reconstruction and selection on online GPU farm. (only signal candidates can be kept).
- Full chain demonstrated in vertical slice test









UCL developed system distributes up to 144 clock/reset lines with ~ 5ps time jitter.

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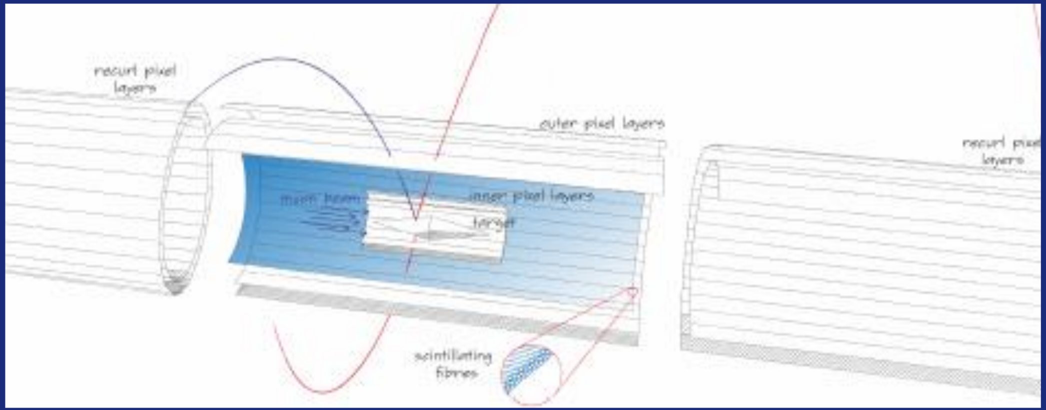
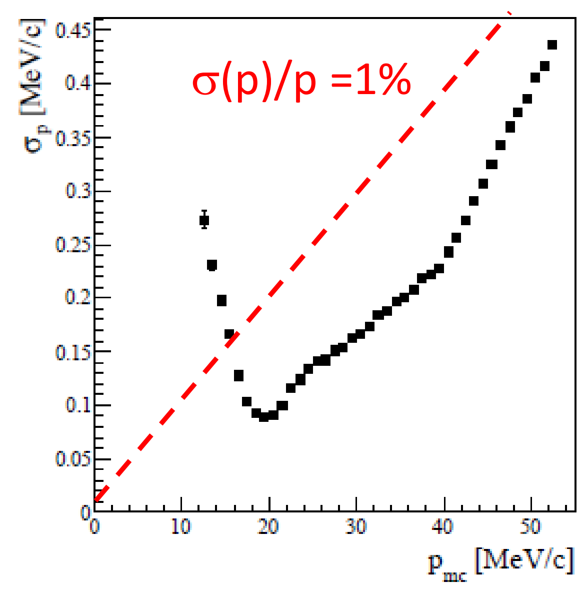
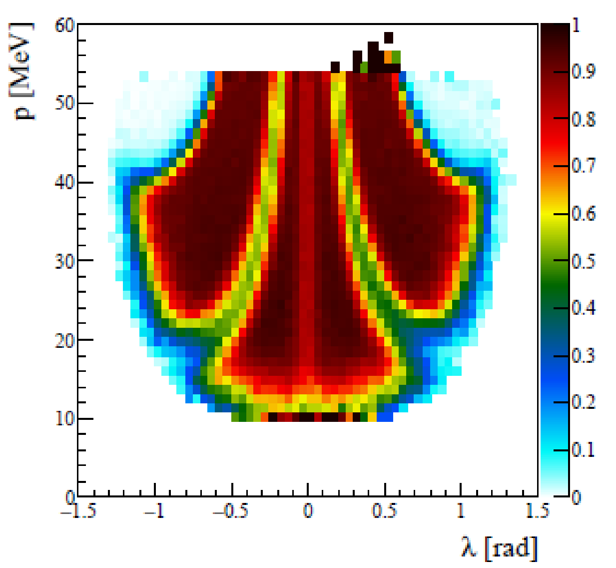
Tracking performance





Excellent momentum resolution for long tracks (“recurlers”)



Efficiency and geometric acceptance for long tracks

Physics performance

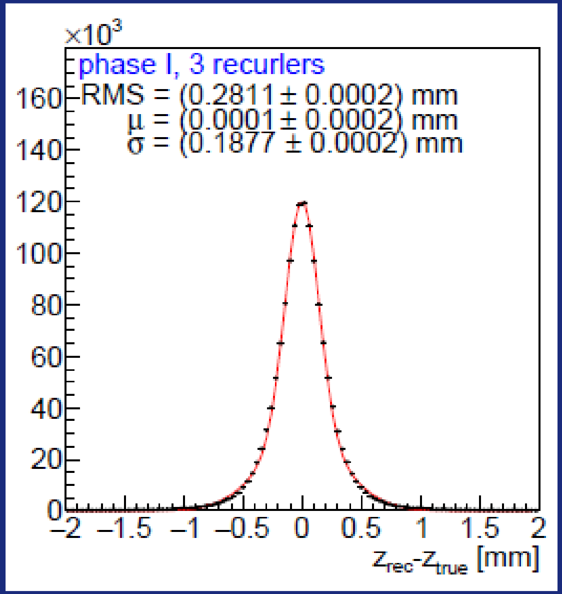
Step	Step efficiency	Total efficiency
Muon stops	100%	100%
Geometrical acceptance, short tracks	43.2%	43.2%
Geometrical acceptance, long tracks	60.6%	26.2%
Short track reconstruction	89.9%	38.8%
Long track reconstruction	80.4%	21.0%
Vertex fit	98.6%	20.8%
Vertex fit $\chi^2 < 30$	98.1%	20.4%
CMS momentum < 8 MeV/c	98.7%	20.1%
Timing	98.0%	19.7%

Signal reconstruction efficiency

19.7%: 3 long tracks from good vertex.

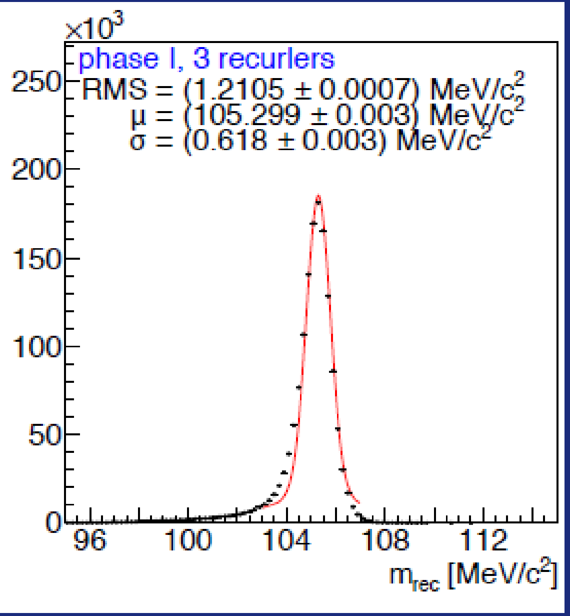
Geometric acceptance dominates

Note this is somewhat model dependent!



vertex z resolution
3 long tracks

< 200 μm

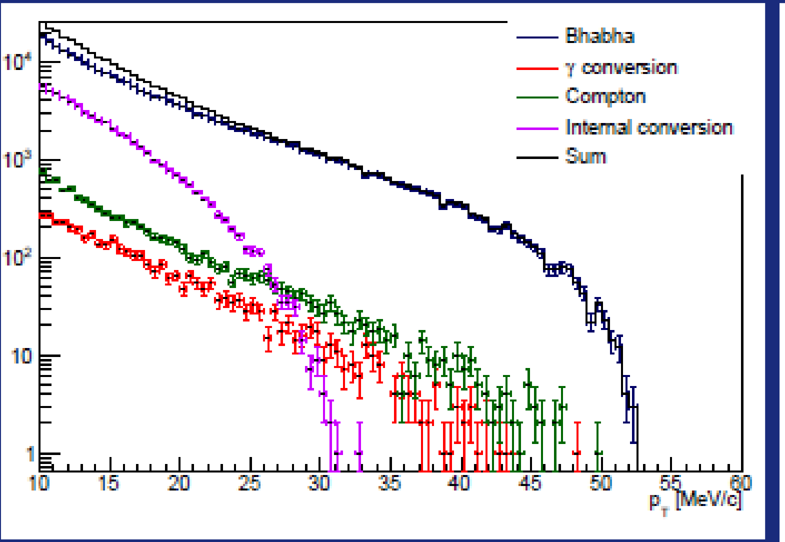


m_{eee} resolution

3 long tracks

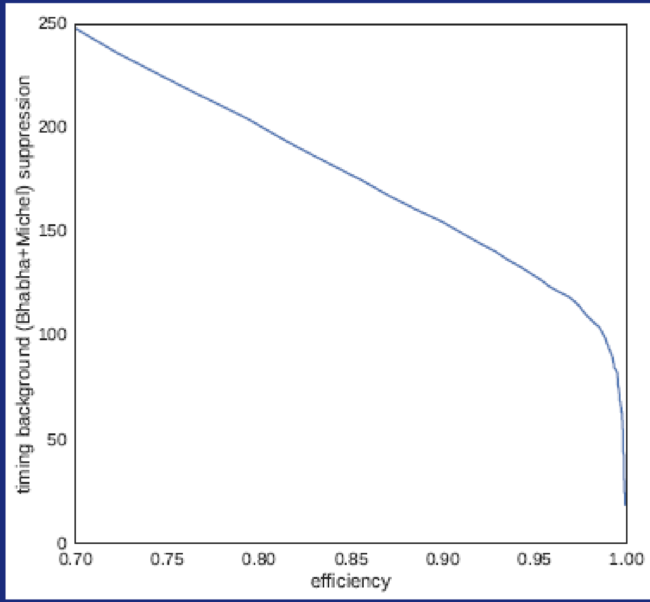
$\sigma(m_{eee})$ ~ 0.6 MeV

Accidental backgrounds



P_T spectrum of electrons:

Dominant source are Bhabha electrons, ~7.8x10^{-5} per muon decay produced in the target region.



BG rejection vs signal efficiency for timing cuts.

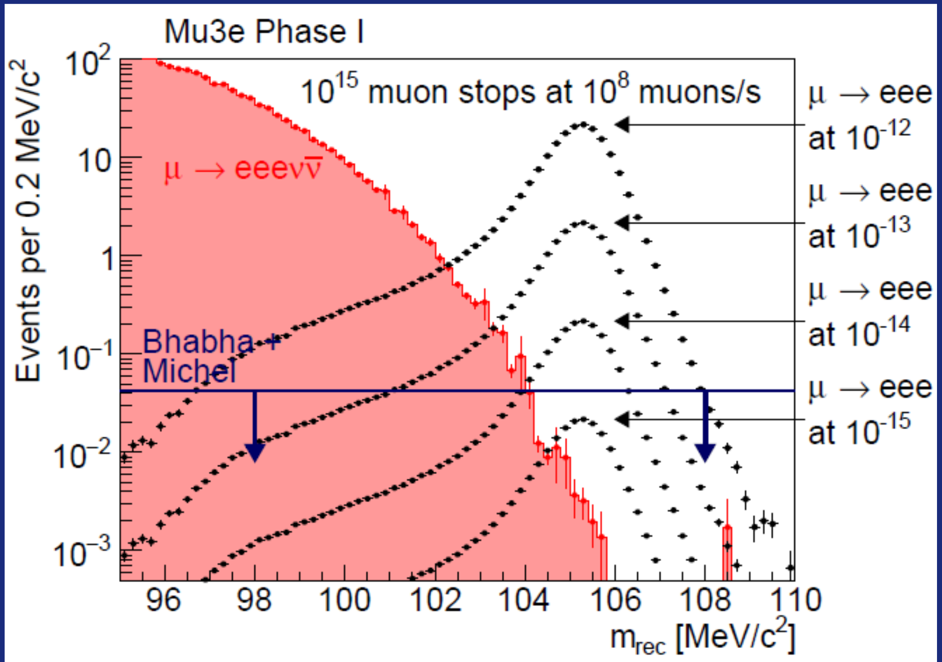
Factor 100 reduction achievable without substantial efficiency loss

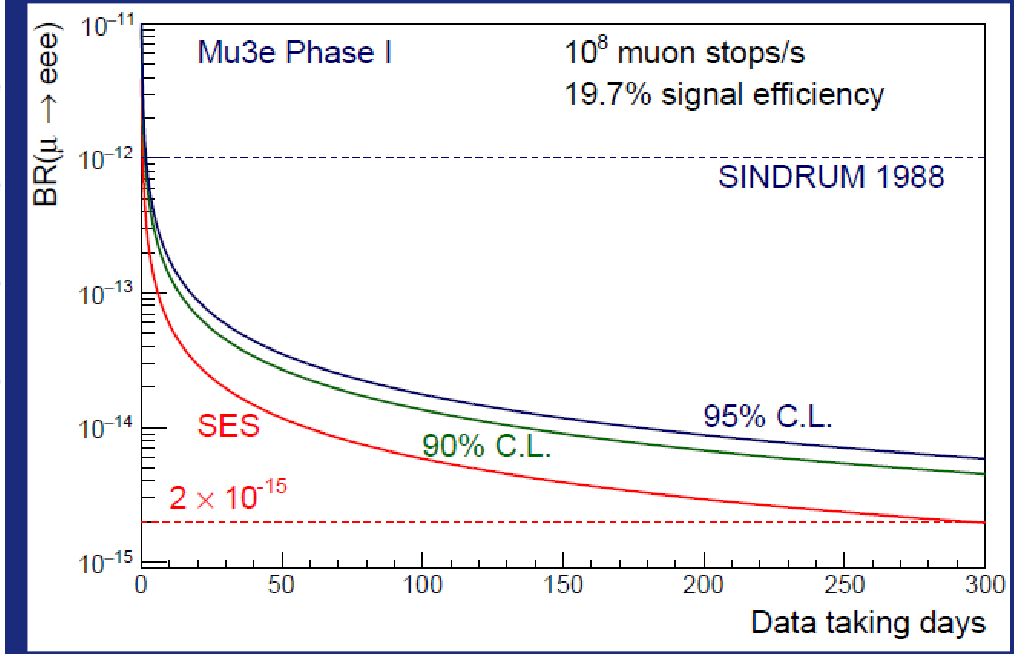
Procedure to estimate accidental background Bhabha-Michel overlaps:

- Overlay Bhabha events with 5.25x10^{8} simulated frames (normal Michel decays).
- Scaled with Bhabha rate and rejection factor this corresponds to ~7x10^{14} muon decays.
- No events pass the selection cuts!
- This allows to set an **upper limit** of 3.2x10^{-15} Bhabha-Michel overlap events per stopped muon.

We know we can further cut Bhabha events with more strict timing and m_{ee} cuts.

Physics sensitivity Phase-I





Challenges for Phase II.

- 2×10^9 μ/s, accidental backgrounds increase faster than the signal
- Timing performance of all detectors is better than the specifications we set.
- Increased detector acceptance means more re-curling tracks (superior momentum resolution)

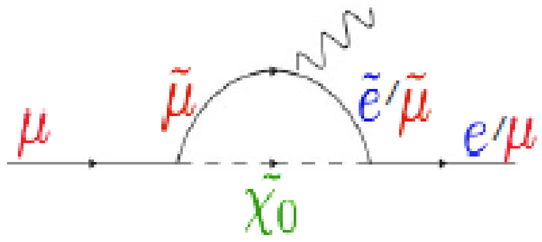
g-2

CLFV muon decay experiments have higher reach in terms of the effective mass scale.

Synergy with g-2

$$\text{Rate (CLFV)} \sim g^2 \times \theta_{e\mu}^2 \times \left(\frac{m_\mu}{\Lambda}\right)^2$$

$$a_\mu \sim g^2 \times \left(\frac{m_\mu}{\Lambda}\right)^2$$



If BNL discrepancy is confirmed by new FNAL g-2 experiment, CLFV muon decay experiments can probe whether potential NP includes a lepton mixing angle or set very strong constraints on the eμ mixing angle associated with such NP.

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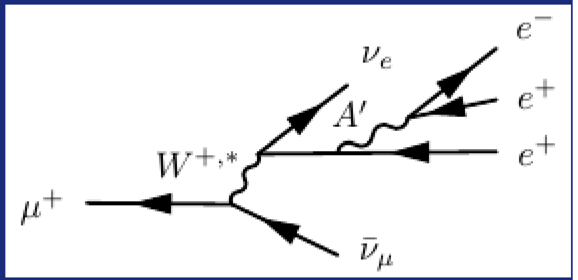
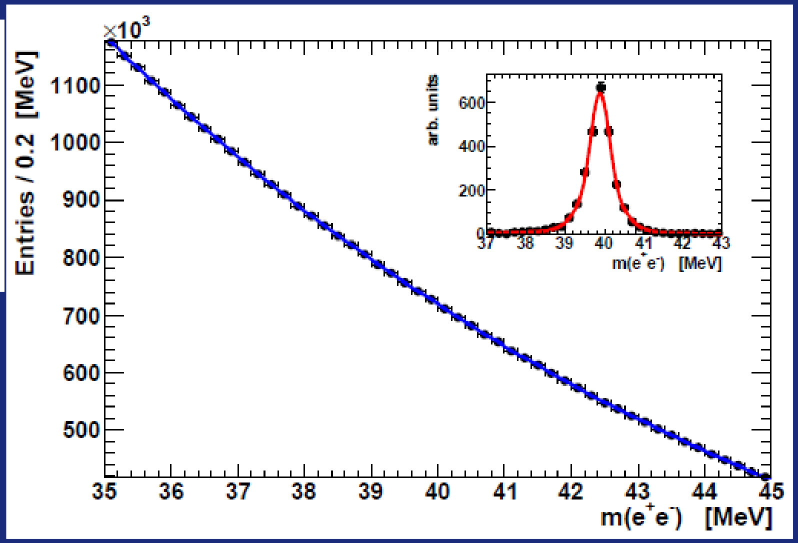
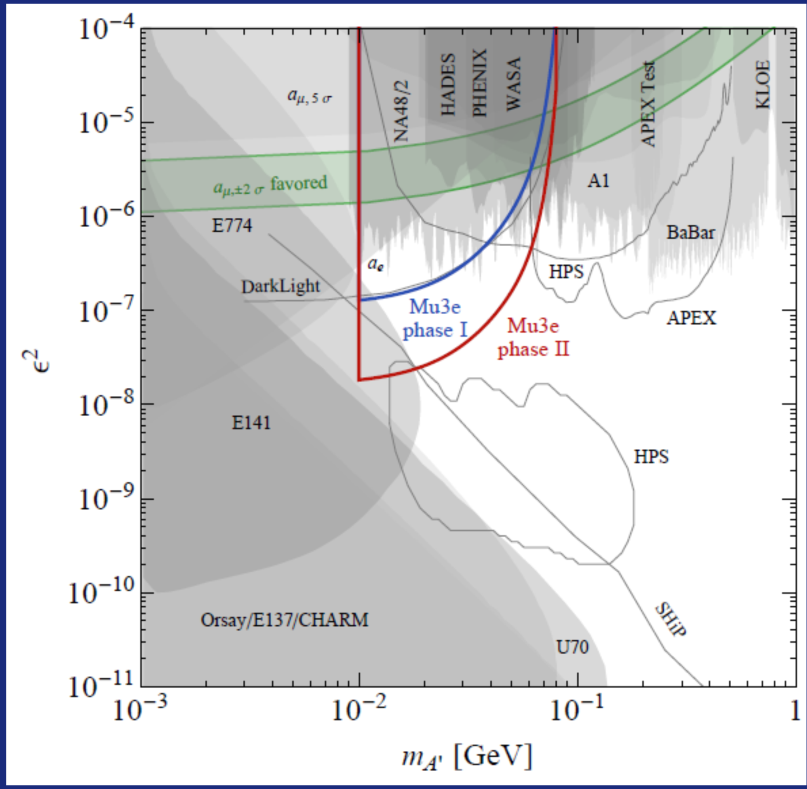




Echenard, Essig, Zhong: arXiv:1411.1770v2



Other physics with Mu3e

Unprecedented dataset of > 10^{16} fully reconstructed muon decays

Example: Search for dark photons

Look for resonance in e^+e^- spectrum in $\mu^+ \rightarrow e^+e^+e^- \nu\nu$ events.

Competitive with other experiments.

Note: This search needs to be performed online!

We cannot store the expected 10^{11} $\mu^+ \rightarrow e^+e^+e^- \nu\nu$ events.

Other ways to look for NP:

- E.g. mono energetic e^+ would indicate 2-body decay $\mu \rightarrow eX$, where X is unobserved.
- Precision measurements Michel parameters (based on ~10^{17} precisely measured muon decays)

These also need to be performed online!

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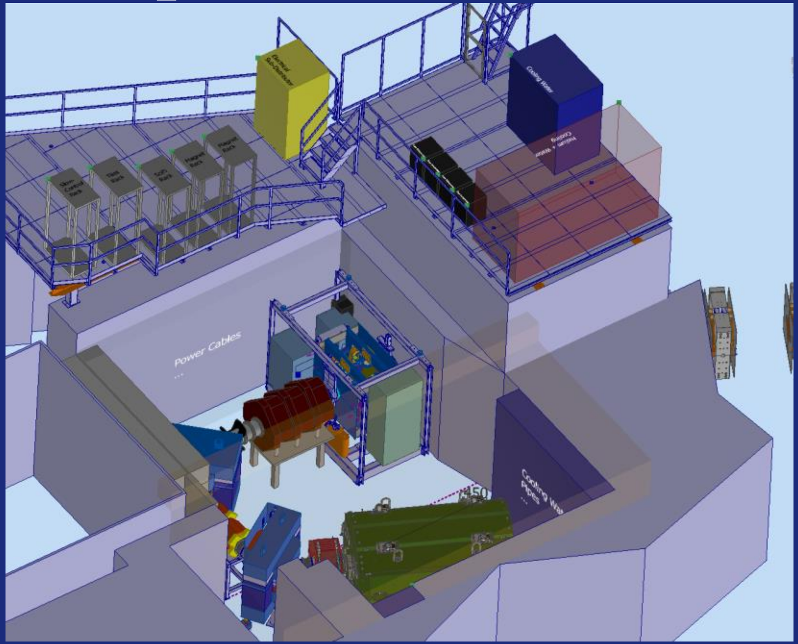
Experimental area at PSI

Beamline in place since 2015

Services (power/cooling) ongoing.

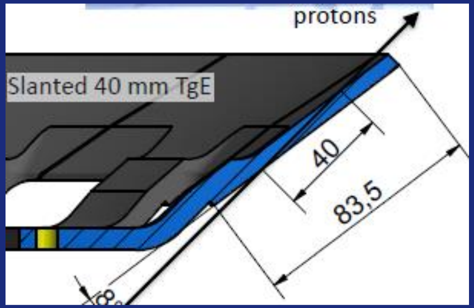


Services platforms installed.

2T Superconducting Magnet, currently being wound. Arrival at PSI in August 2020.

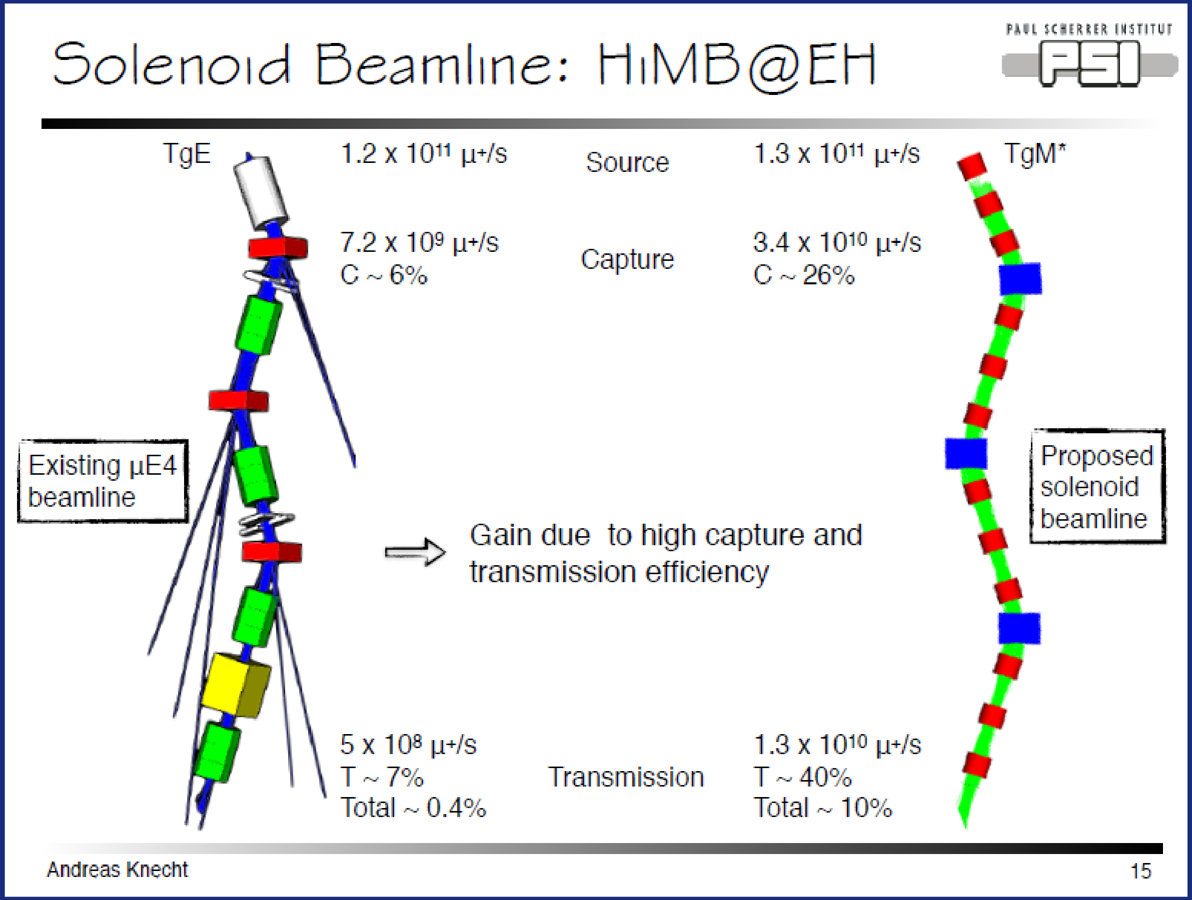
First commissioning run (with final prototype sensors) planned in Dec 2020.

Mu3 Phase II



HiMB programme at PSI develops increased intensity beams from muon experiments.

- optimization of target geometry
- capture solenoid and solenoid transport line
- Muon rate approaching 1×10^{10} may be feasible.



Mu3e adaptations for high rate:

- longer detector to increase acceptance
- faster silicon to reduce tracking ambiguities
- Larger beam emittance $\rightarrow$ larger target/detector
- smaller segmentation timing detectors

Alternative option is a $\mu \rightarrow e\gamma$ run:

Mu3e solenoid ability to go to 2T field allows for $e\gamma$ search using a conversion layer at larger radius.

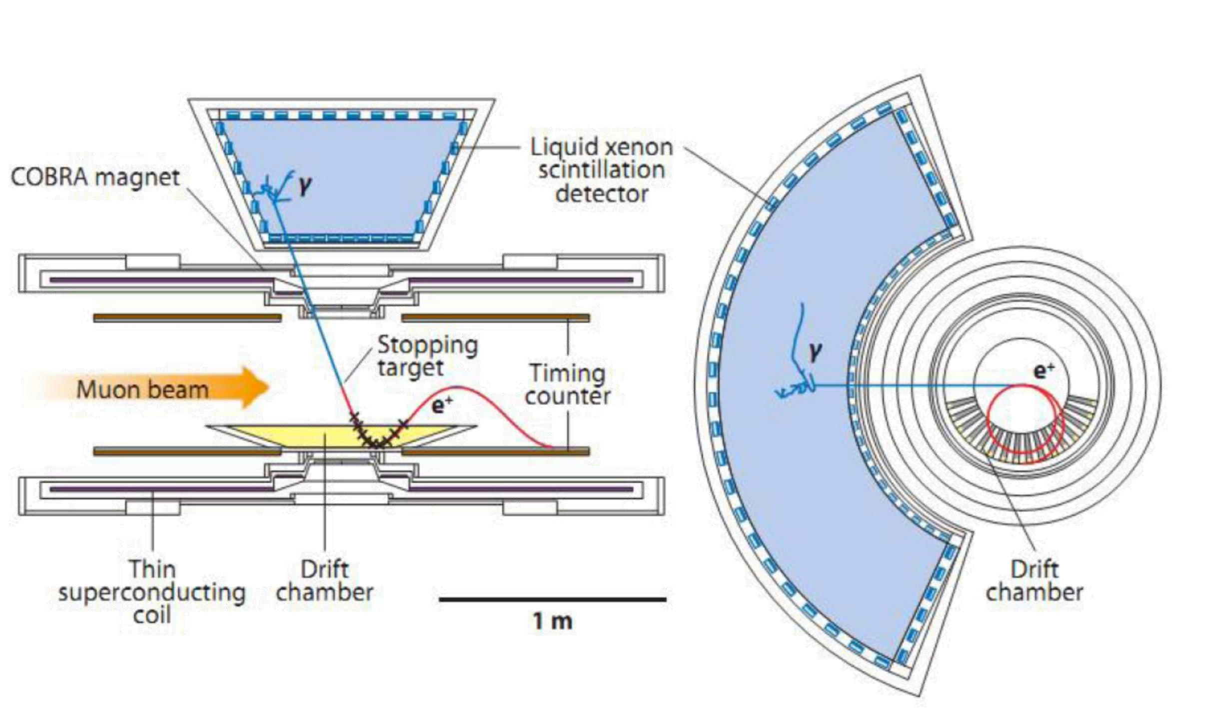
Summary

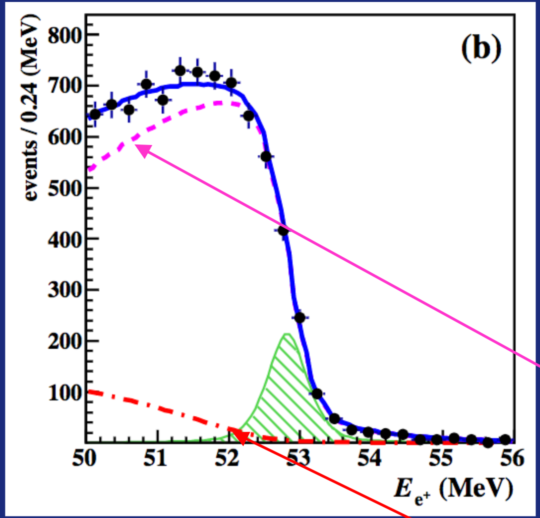
- Mu3e experiment progressing towards start-up

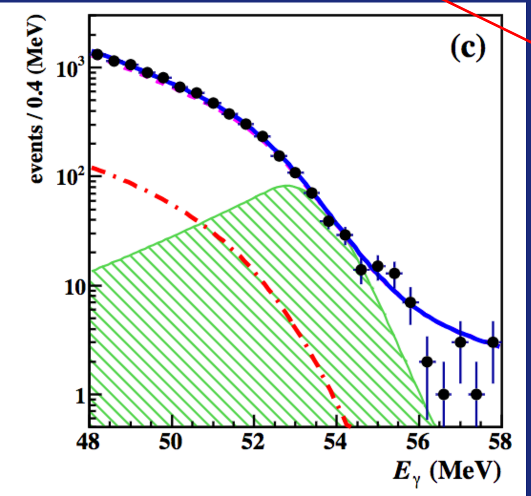
  Detector installation begins 2020
  - First prototype comissioing in expreirmental area, with beam December 2020
  - Completion detector cconstruction over 2021
  - Physics operation in 2022
- Start of programme to achieve 4 orders of magnitude improved sensitivity BR($\mu \to$ eee) compared to with SINDRUM-I. Thanks to:
  - Intense muon beams at PSI
  - Tracking of low momentum particles with fast and thin HV-MAPS, low mass supports and gaseous Helium cooling.
  - Accurate timing in highly compact fibre and tile detectors using Si-PMs.
- In parallel MEG-II, COMET and Mu2e will achieve major improvements on BR($\mu \to e\gamma$) and BR($\mu N \to$ eN).
- Many new results to look forward to over the next 5 to 10 years, with sensitivity to PeV-scale NP

MEG: $\mu \rightarrow e\gamma$ (2009-2013)

Search for $\mu \rightarrow e\gamma$
PSI πE5 beam (3×10^7 muons/s)







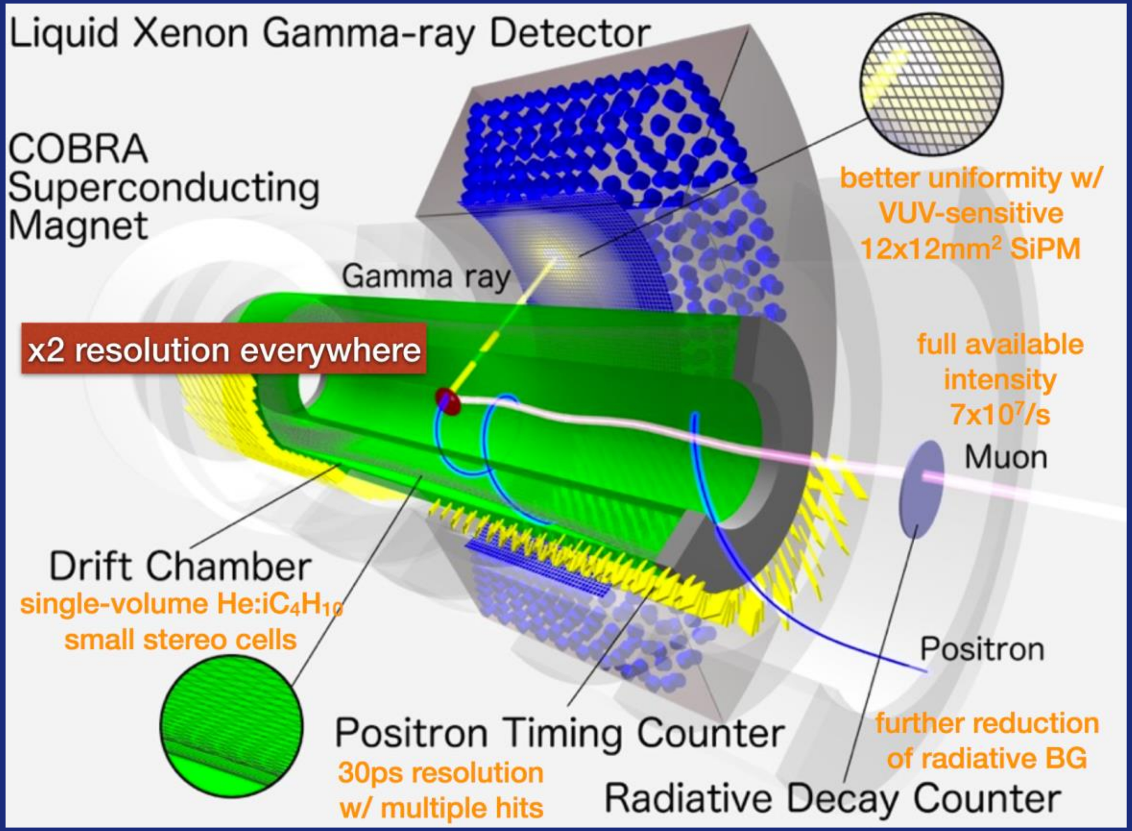
Main backgrounds:
Accidental:
e^+ from Michel decay + γ photon from e^+ annihilation or Bremsstrahlung or from radiative Michel decay .

Radiative Michel decays

Final result (2016)
BR($\mu \rightarrow e\gamma$) < 4.3×10^{-13} (90% C.L.)

MEG II

$\mu \to e\gamma$ (2017- …)



Beamline improvements approaching 10^8 μ/s
→ Higher accidental BG (Intensity^2)
→ Need better timing and momentum resolution.

Performance targets: $\Delta E(e^+)$ ~ 130 keV, $\Delta t\ (e^+)$ ~ 35 ps, $\Delta E(\gamma)$ ~ 1%, $\Delta t\ (\gamma)$ ~ 60 ps
Detector upgrades:

Projected MEG-II Sensitivity: BR($\mu \to e\gamma$) < 4×10^{-14} (90% C.L.)

$\mu N \to eN$ conversion (COMET/mu2e)

- Beam delivery systems optimised to achieve high intensity, very pure, muon beam on target.
- Stopped muons are trapped in orbit around the Al nucleus.
- Search for coherent decay $\mu N \to eN$

$\to$ mono-energetic electron (for aluminium: E_e=104.96 MeV)

$\to$ delayed w.r.t. prompt particles (τ_μ = 864 ns)

- **Prompt backgrounds** (radiative nuclear capture, muon
- decay in flight, pions, protons).
- Curved solenoid transport channel
- Pulsed beam with delayed time-window
- Strong extinction factor (less than 10^{-9})

•**Muon decay in orbit** ($\mu N \to e\nu\nu N$)

- precise momentum resolution