The Mu3e experiment
Charged Lepton Flavour Violation in $\mu^+ \rightarrow e^+e^+e^-$

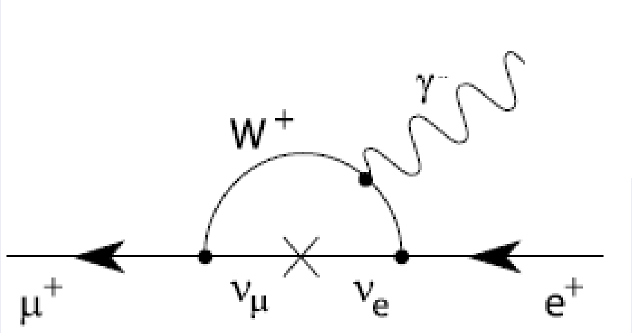
Joost Vossebeld

Charged Lepton Flavour Violation

We see flavour violations in the quark sector and since the observation of neutrino oscillations we know lepton flavour is not conserved.

In SM (with m_ν) CLFV can occur, but is heavily suppressed.

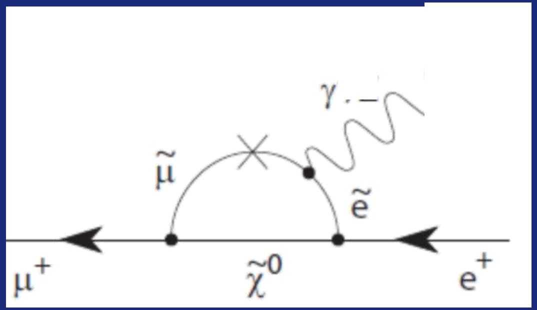
$$\mathrm{Br}(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{i1}}{M^2_W} \right|^2 < 10^{-54}$$



Any observation of CLFV is evidence of NP,

… and CLFV appears naturally in many NP theories.

E.g. in SUSY one can get CLFV through a slepton mixing matrix if NP couples to mixed eigenstates.



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Muon decays

μ^- DECAY MODES

PDG 2018

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]	$(6.0\pm0.5) \times 10^{-8}$	
Γ_3	$e^- \overline{\nu}_e \nu_\mu e^+ e^-$	[b]	$(3.4\pm0.4) \times 10^{-5}$	

If charged lepton flavour were not conserved we should also expect to see:

$\mu \rightarrow e\gamma$

$\mu \rightarrow eee$

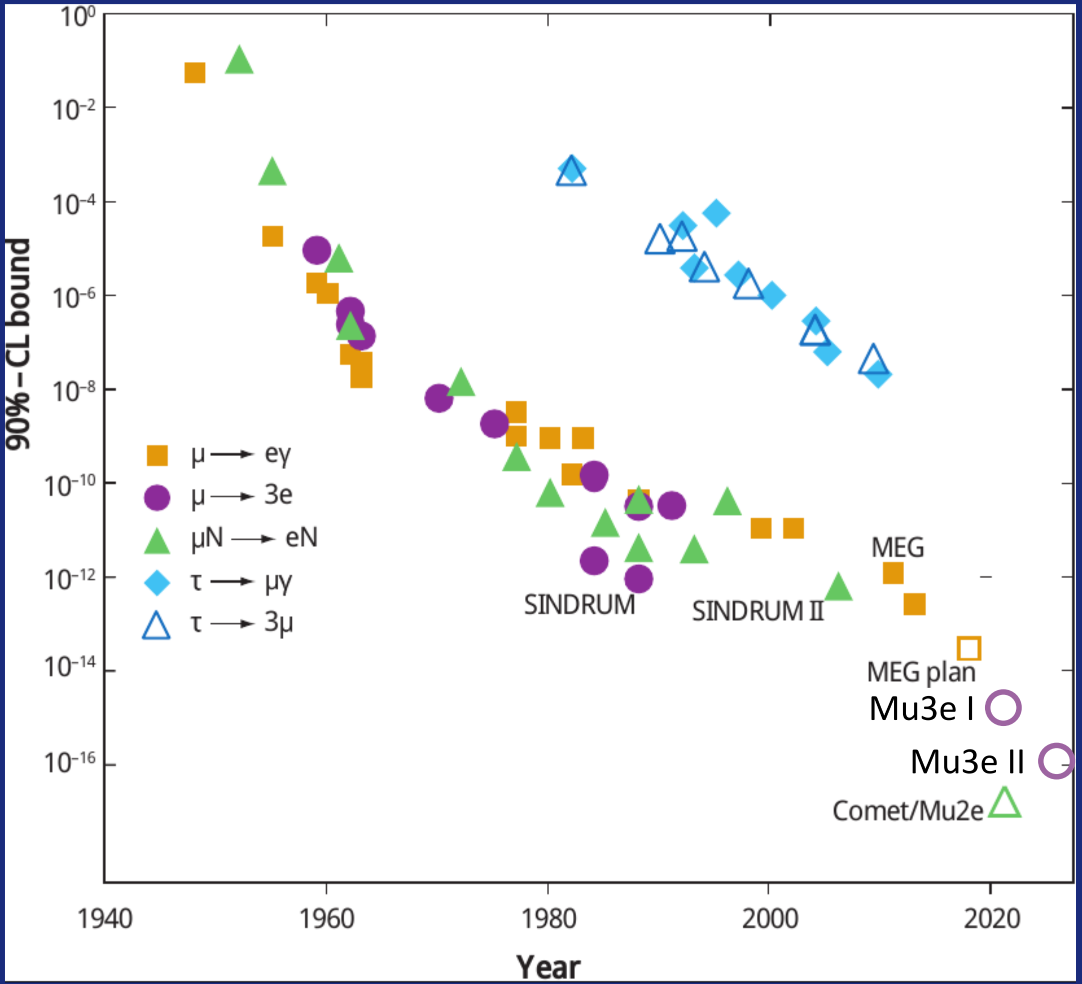
$\mu N \rightarrow eN$

Lepton Family number (*LF*) violating modes

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%

First search or $\mu \rightarrow e\gamma$ in using cosmic data in1948.

CLFV muon and tau decay searches



Best τ limits: Belle and Babbar

Best μ limits: SINDRUM (II) and MEG

Muon channels achieve 5 to 6 orders of magnitude smaller upper bounds on branching ratios than tau channels.

Long lifetime and few and simple SM decay modes also make muon decays ideal place to look for rarest effects due to NP.

Other CLFV searches

At e+e- or pp GPDs:

- Z → eμ, τμ, eτ,
- H → eμ, τμ, eτ

In flavour experiments:

- LFV in hadron decays

Generally, best reach for NP reach comes from muon decay searches.

Letter of Intent COMET phase 2013

Reaction	Present limit
$\mu^+ \to e^+\gamma$	< 4.3x10^{-13}
$\mu^+ \to e^+e^+e^-$	$< 1.0 \times 10^{-12}$
$\mu^- Ti \to e^- Ti$	$< 6.1 \times 10^{-13}$
$\mu^- Au \to e^- Au$	$< 7 \times 10^{-13}$
$\mu^+e^- \to \mu^-e^+$	$< 8.3 \times 10^{-11}$
$\tau \to e\gamma$	$< 3.9 \times 10^{-7}$
$\tau \to \mu\gamma$	$< 3.1 \times 10^{-7}$
$\tau \to \mu\mu\mu$	$< 1.9 \times 10^{-7}$
$\tau \to eee$	$< 2.0 \times 10^{-7}$
$\pi^0 \to \mu e$	$< 8.6 \times 10^{-9}$
$K_L^0 \to \mu e$	$< 4.7 \times 10^{-12}$
$K^+ \to \pi^+\mu^+e^-$	$< 2.1 \times 10^{-10}$
$K_L^0 \to \pi^0\mu^+e^-$	$< 3.1 \times 10^{-9}$
$Z^0 \to \mu e$	$< 1.7 \times 10^{-6}$
$Z^0 \to \tau e$	$< 9.8 \times 10^{-6}$
$Z^0 \to \tau\mu$	$< 1.2 \times 10^{-5}$

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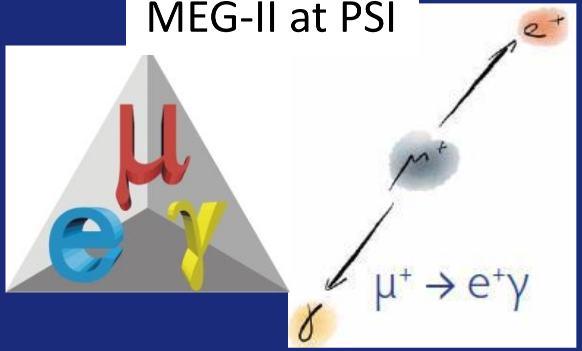
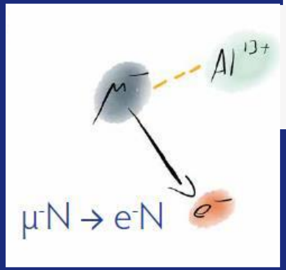
Upcoming CLVF muon decay searches

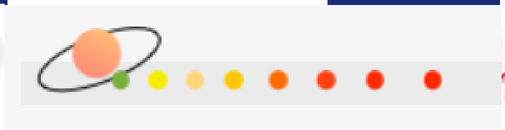
	Best limits	Projected sensitivities (90%CL)
$\mu \to e\gamma$	**< 4.3×10^{-13} MEG (PSI)**	**4×10^{-14} MEG II (PSI)**
$\mu \to eee$	**< 1.0×10^{-12} SINDRUM (PSI)**	**4×10^{-15} Mu3e I (PSI) 1×10^{-16} Mu3e II (PSI)**
$\mu N \to eN$	**< 7.0×10^{-13} SINDRUM II (PSI) μ Au $\to$ e Au**	**6×10^{-17} Mu2e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

MEG-II at PSI



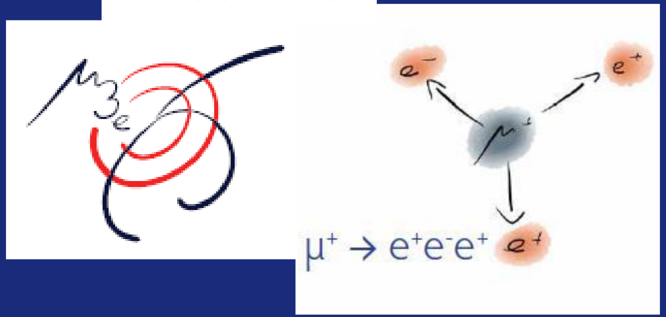


COMET at KEK



Mu2e at FNAL

Mu3e at PSI



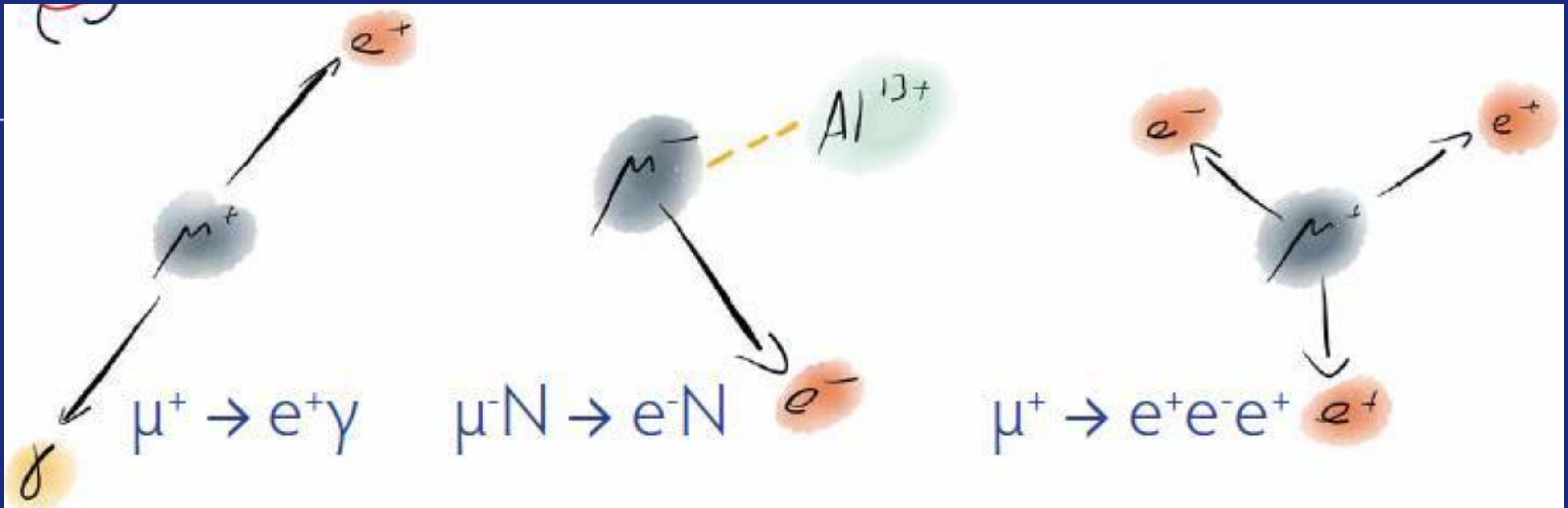
MEG-II, Mu3e, COMET and Mu2e will push $\mu \to e$ sensitivity by up to <u>four orders of magnitude</u> over the next 5-10 years.

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

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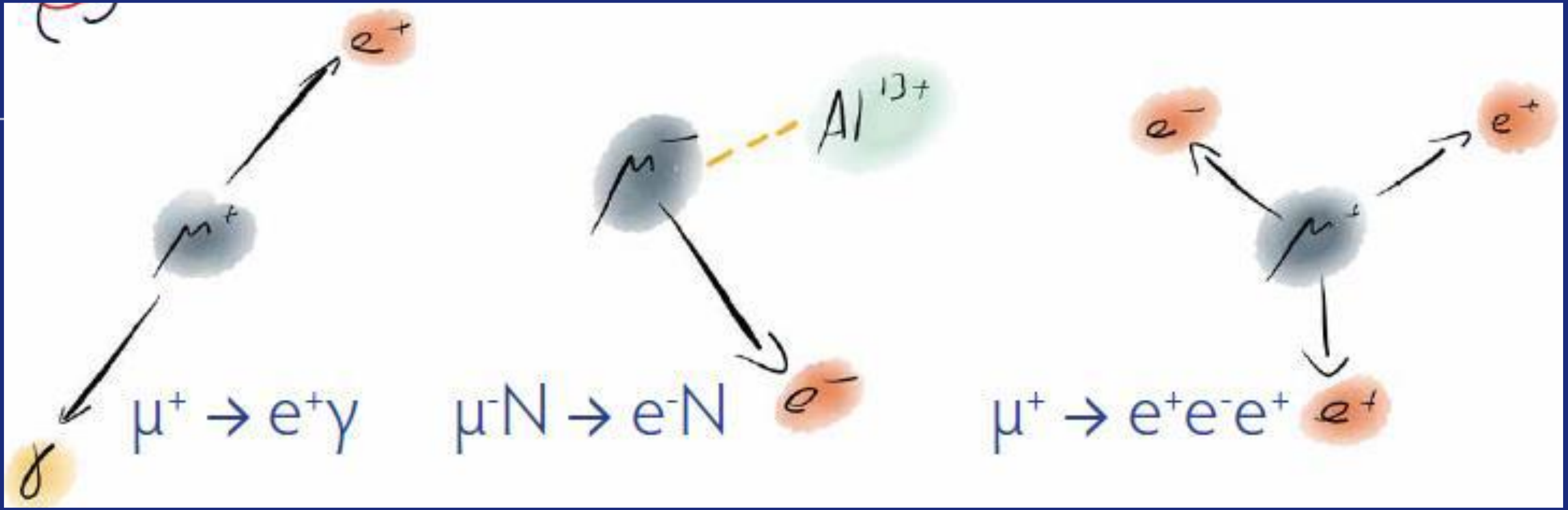

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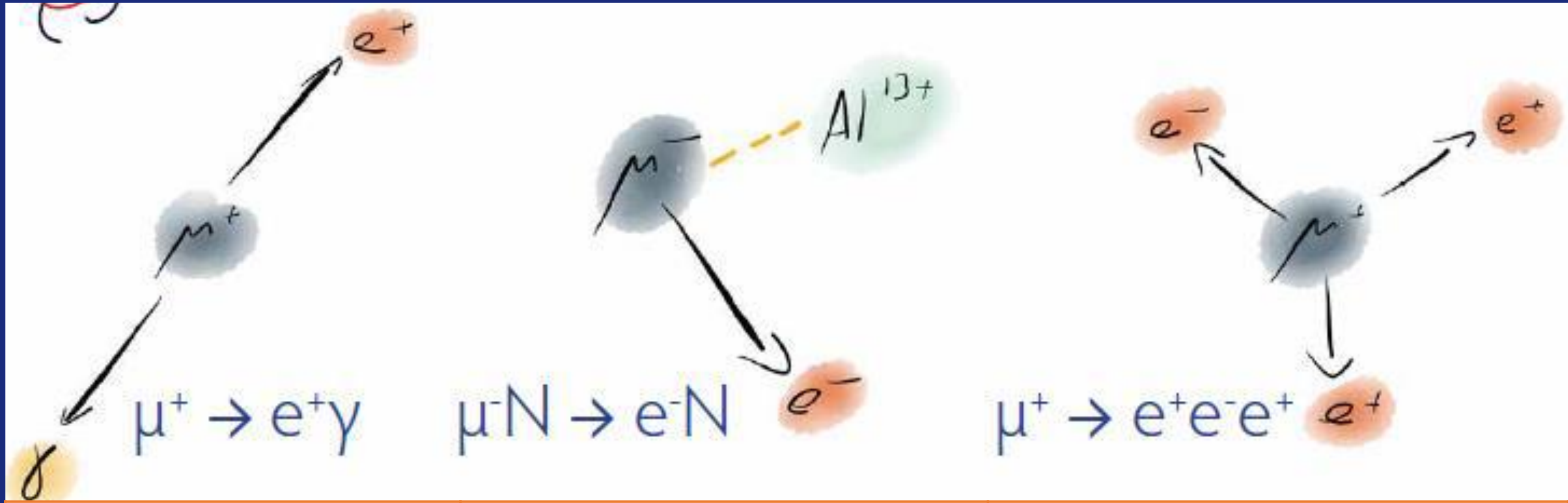
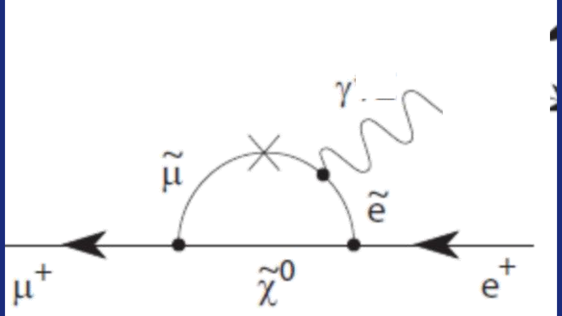
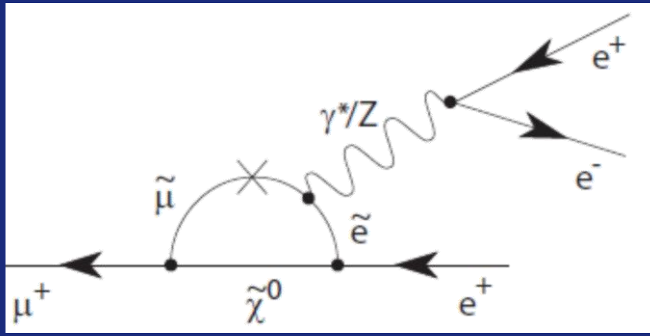
Radiative decay: DC beam $\mu \to e\nu\nu\gamma$ Accidental backgrounds: $\mu \to e\nu\nu$ + radiative photon	Muon Decay in orbit beam related: prompt antiprotons, pions,.. Pulsed beam	Radiative decay DC beam ($\mu \to ee e\nu\nu$); Accidental backgrounds $\mu \to e\nu\nu$ + conversion or Bhabha pairs

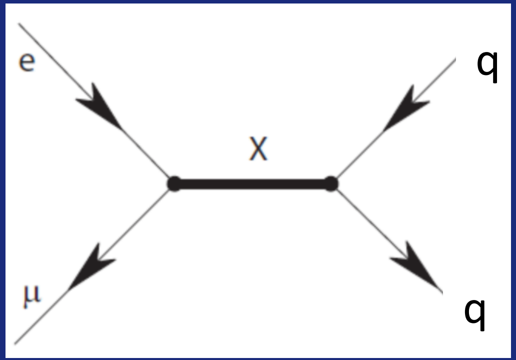
CLFV Muon decay channels

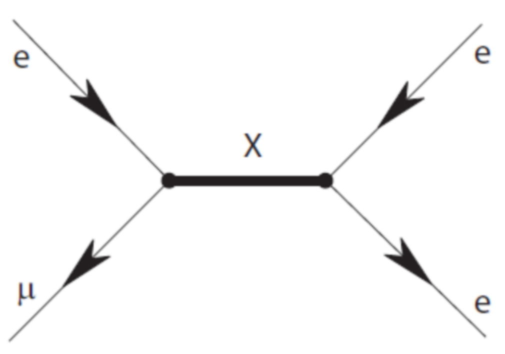


Sensitive to loop diagrams (coupling to γ)	Sensitive to loops (coupling to γ*/Z, Z',..) and tree diagrams (qqeμ)	Sensitive to loops(coupling to γ*/Z, Z',..) and tree diagrams (eeeμ)









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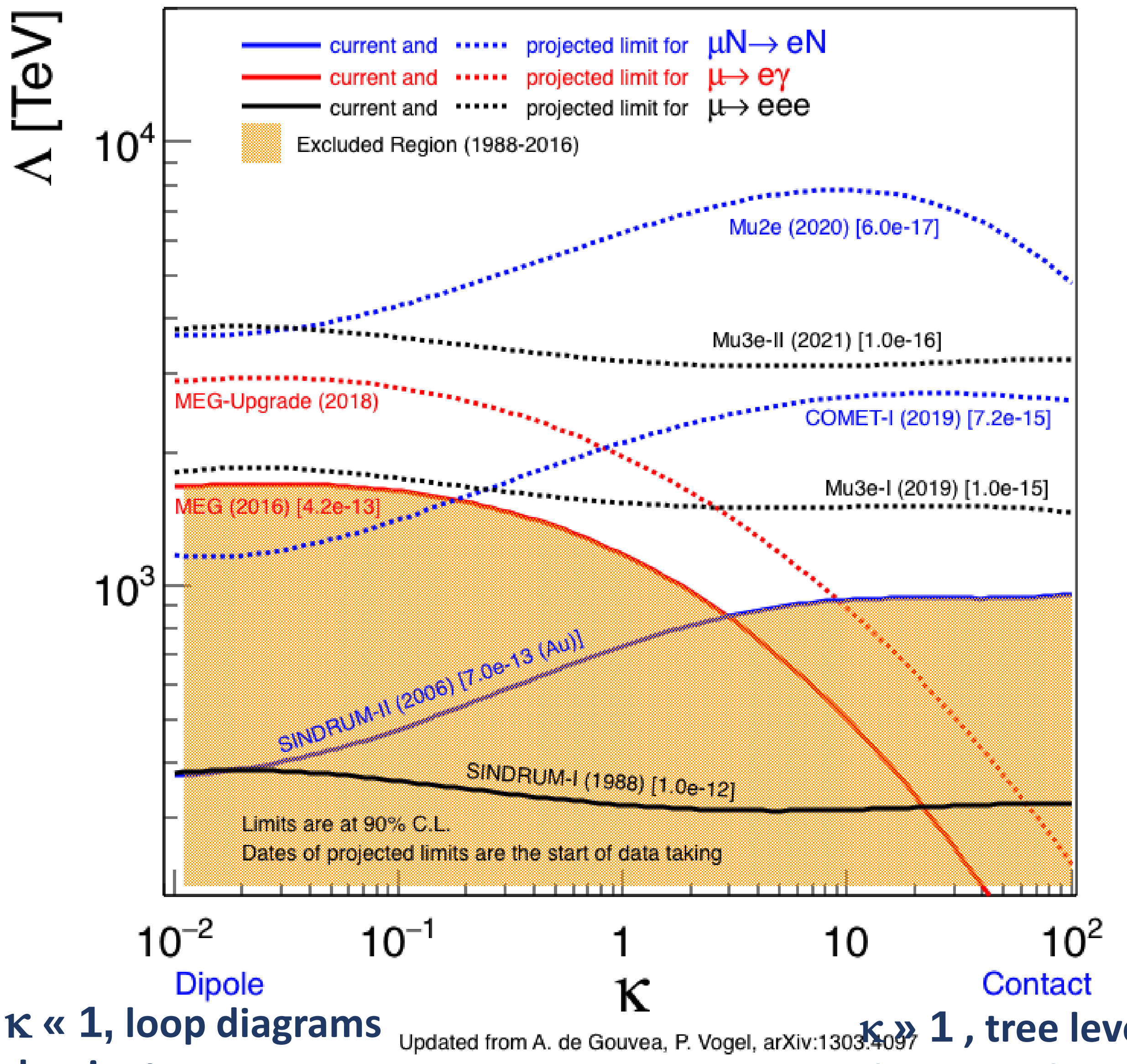
Physics reach

Highly model dependent. Comparison possible with a generic Lagrangian model:

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

CLFV experiments have sensitivity up to 10 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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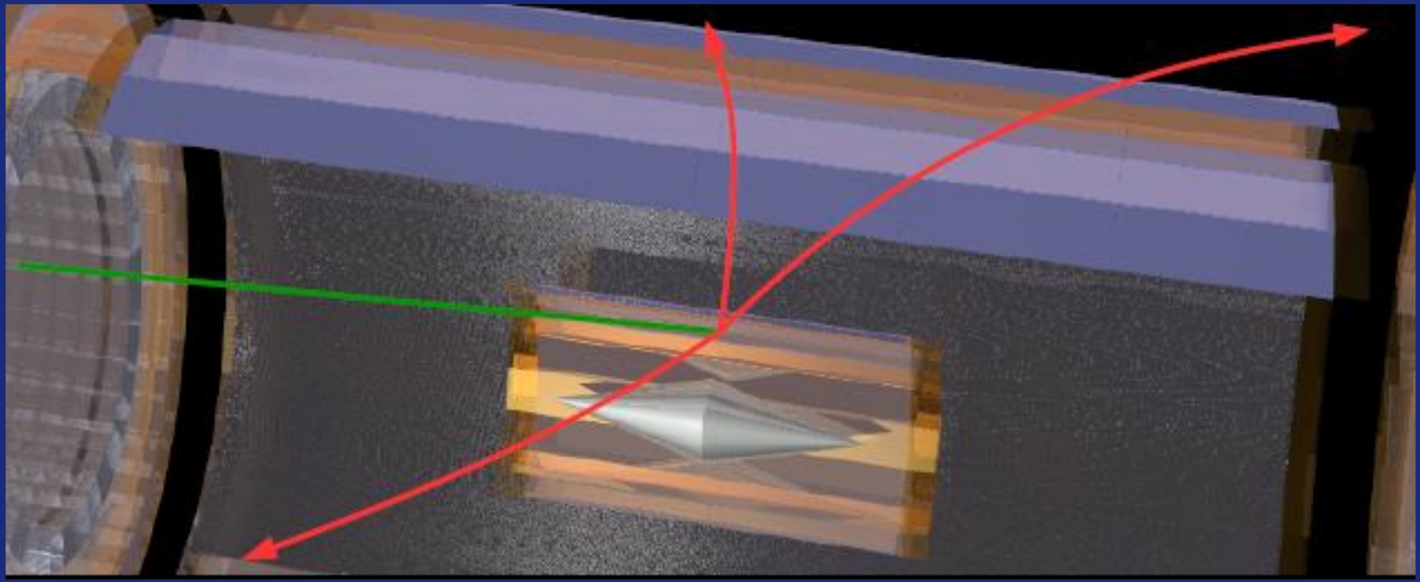
The μ3e experiment at PSI

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

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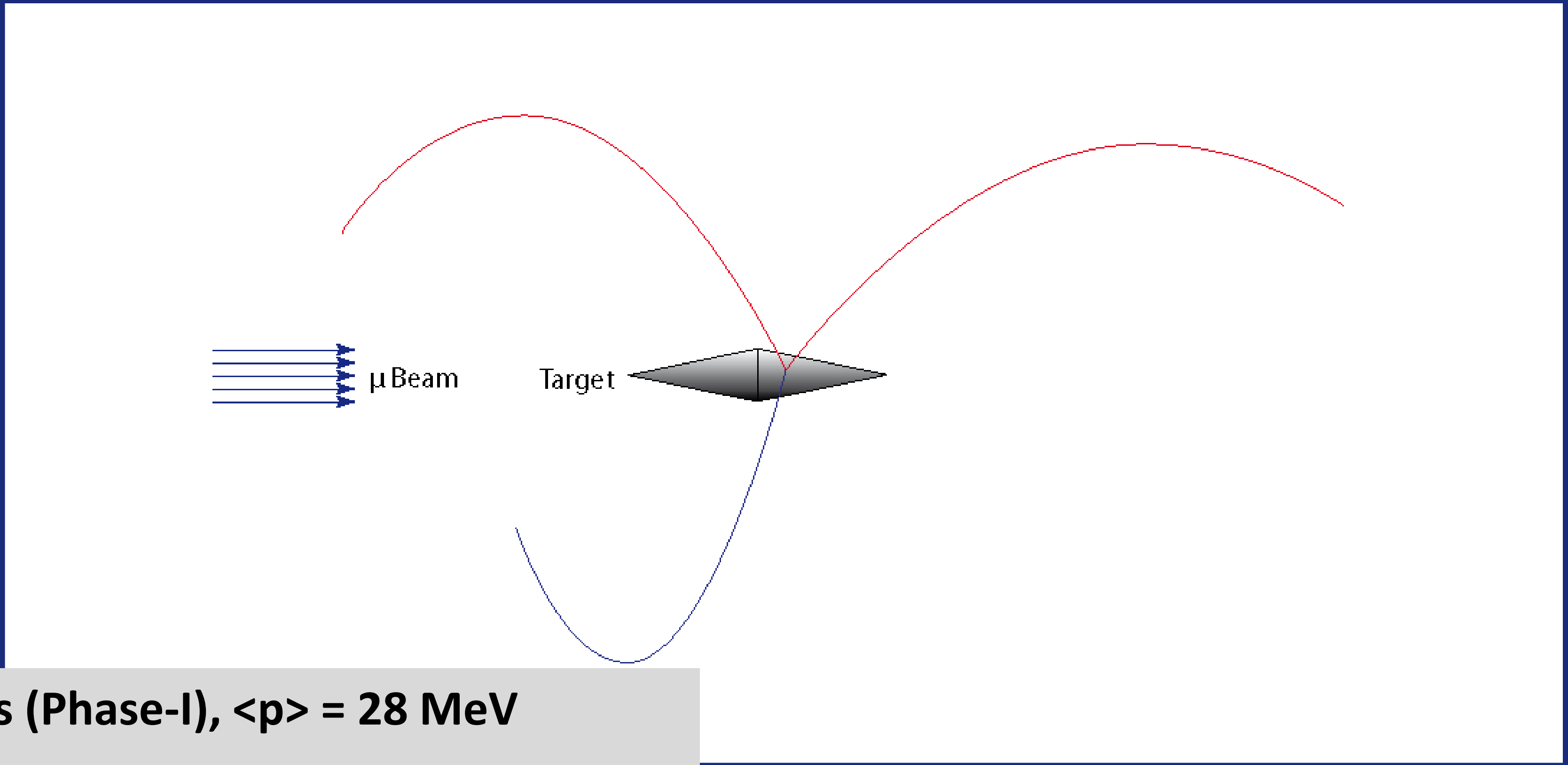
Mu3e experiment: the main components

DC beam 10^8 μ/s (Phase-I), <p> = 28 MeV

Thin mylar target (75 μm front, 85 μm back)

Mu3e experiment: the main components



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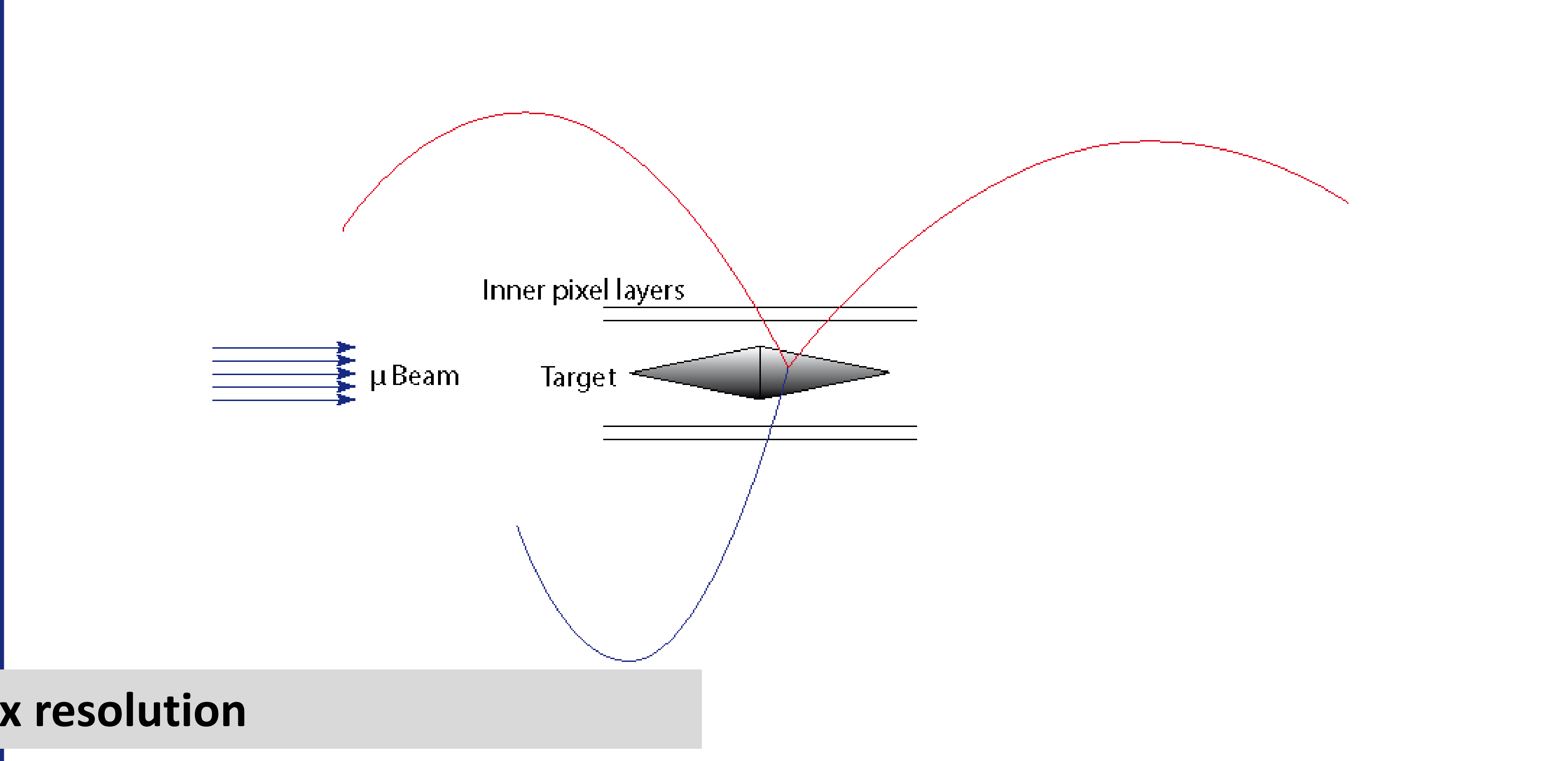
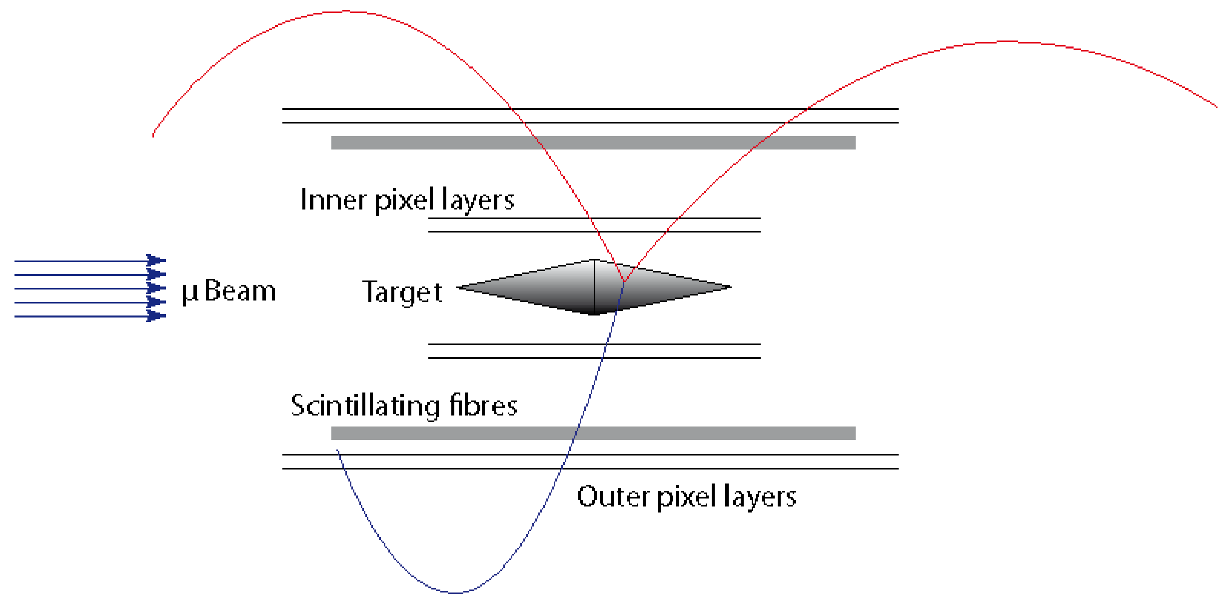


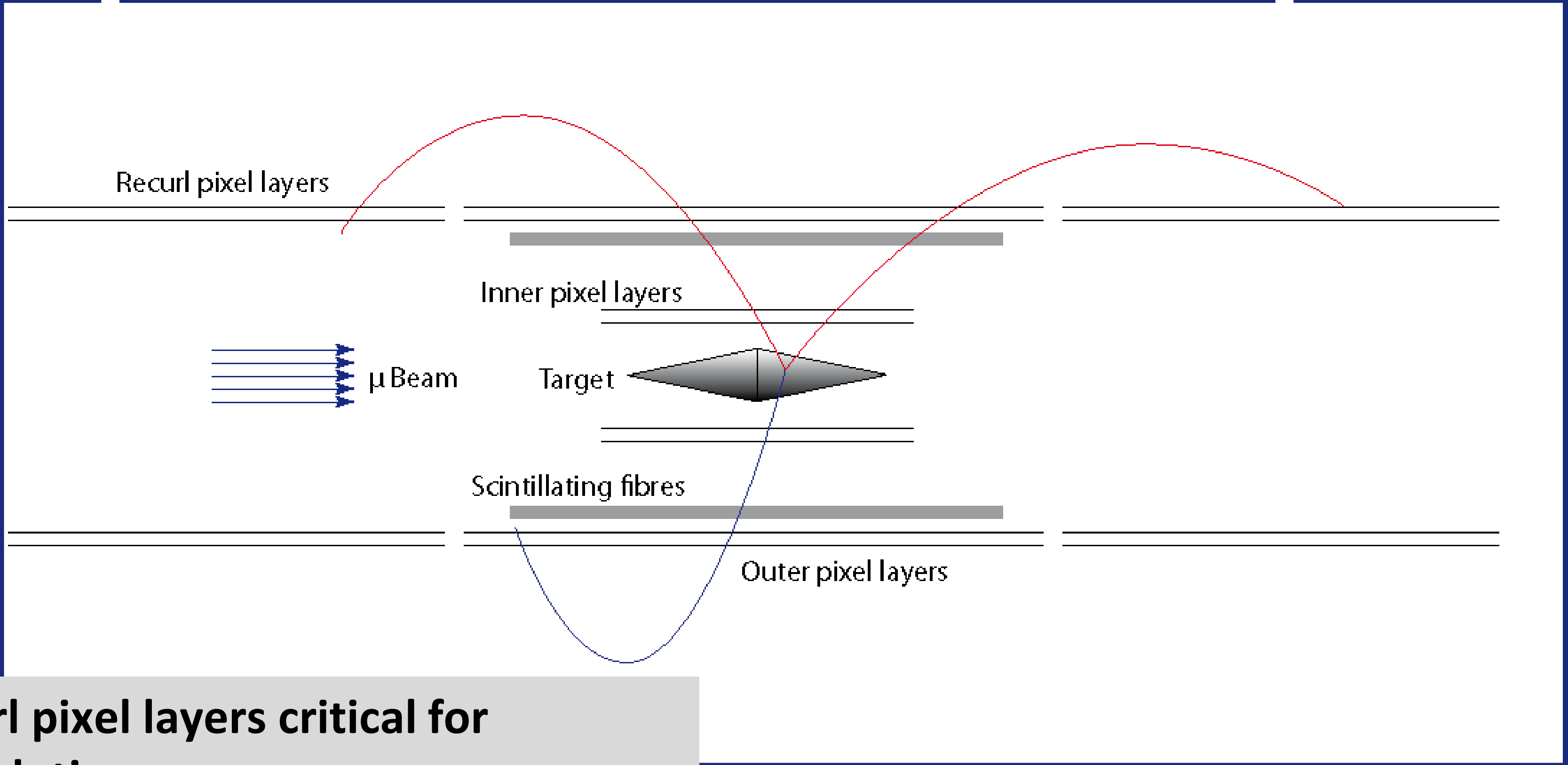
Critical for vertex resolution

Mu3e experiment: the main components



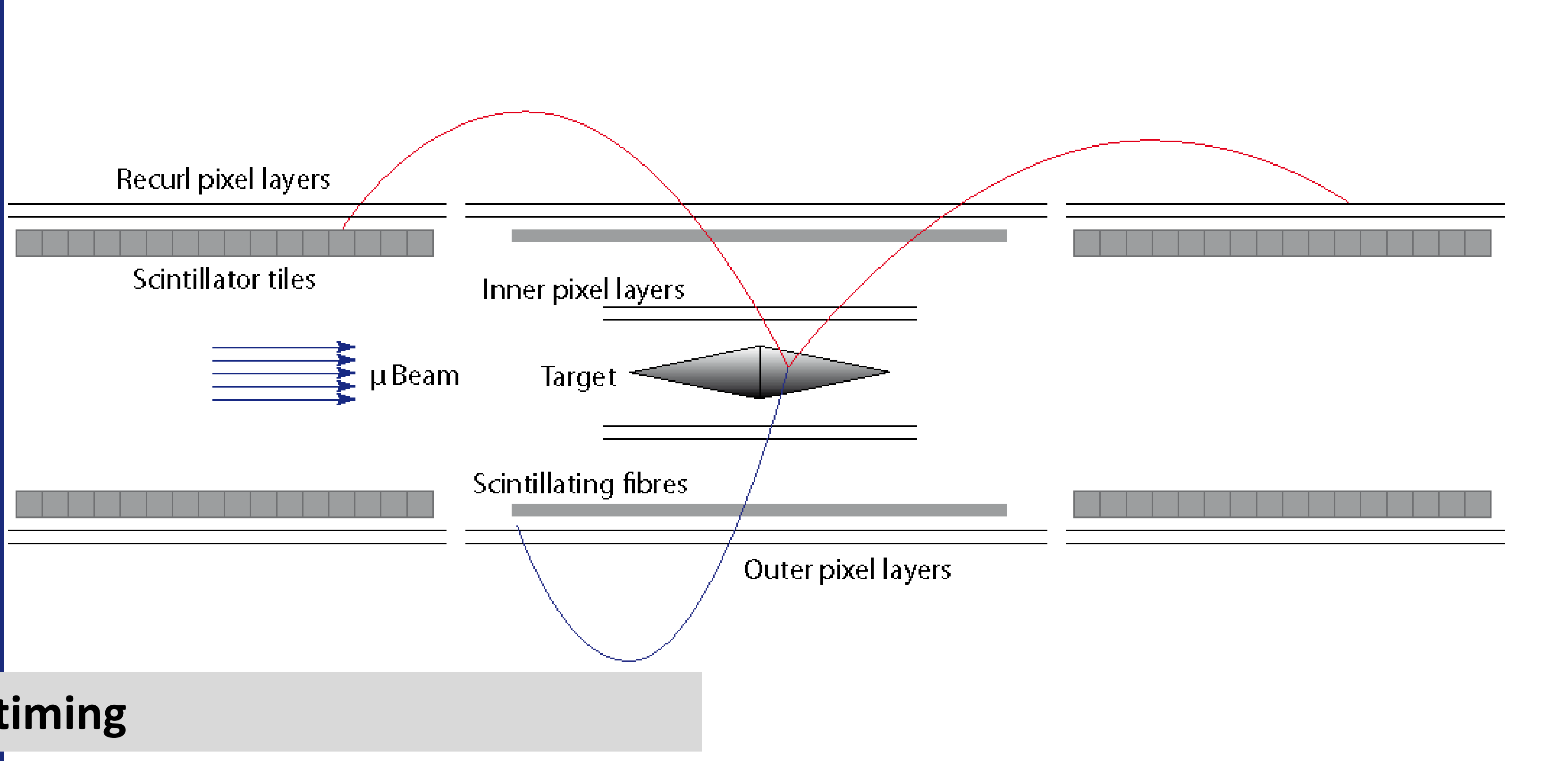
Fibres critical for timing

Mu3e experiment: the main components



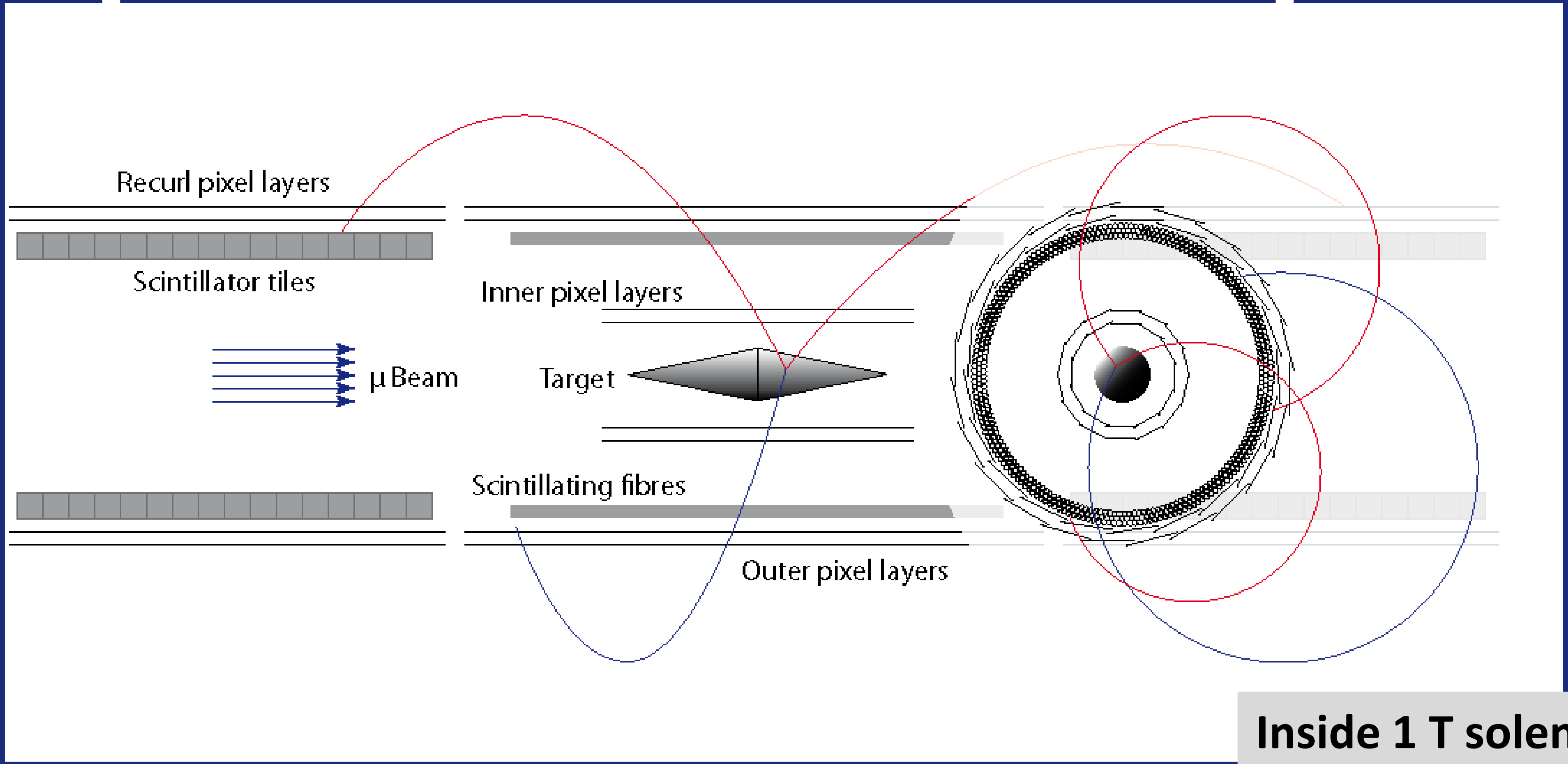
Outer and recurl pixel layers critical for momentum resolution

Mu3e experiment: the main components



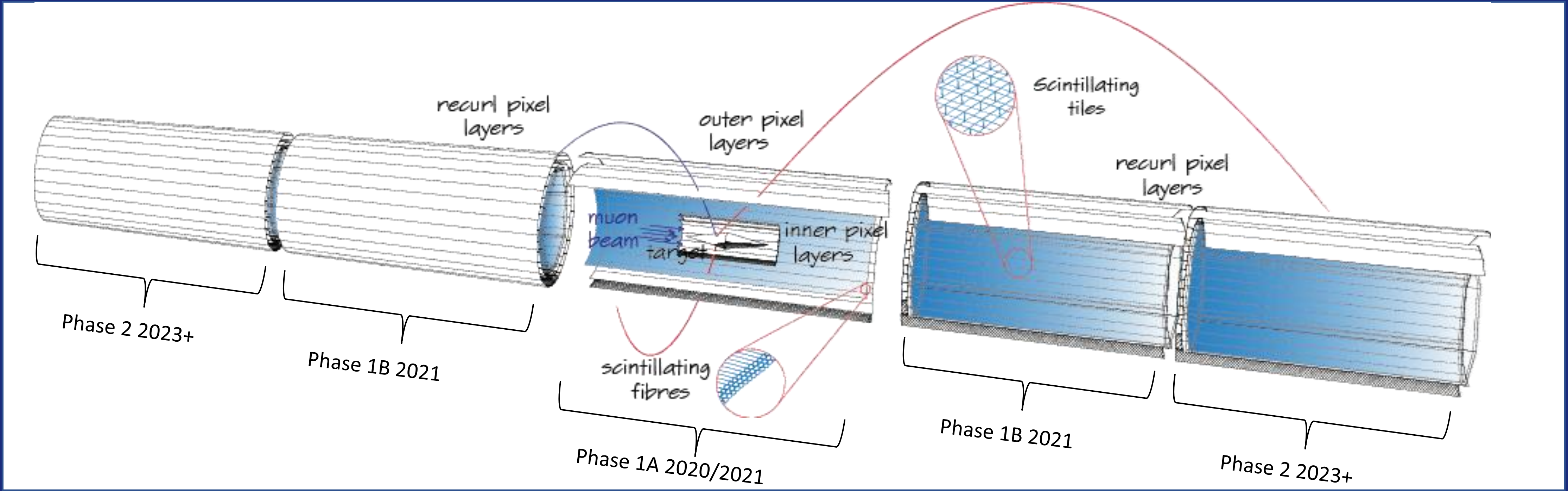
Tiles critical for timing

Mu3e experiment: the main components



Inside 1 T solenoid
In Helium atmosphere

Expected schedule



Phase 1A/1B: BR ($\mu \rightarrow eee$) < 4×10^{-15} , ~3 years running at 10^8 μ/s from PSI πe5 Compact Muon Beam Line

Phase 2: BR ($\mu \rightarrow eee$) < 10^{-16} , ~3 years running with extended acceptance detector at 2×10^9 μ/s from planned High Intensity Muon Beam (HIMB)

UK deliverables (Phase 1)

- Assembly off all outer pixel layers of the MuPix tracker
- Mu3e clock-and-control system for the time-slice based DAQ

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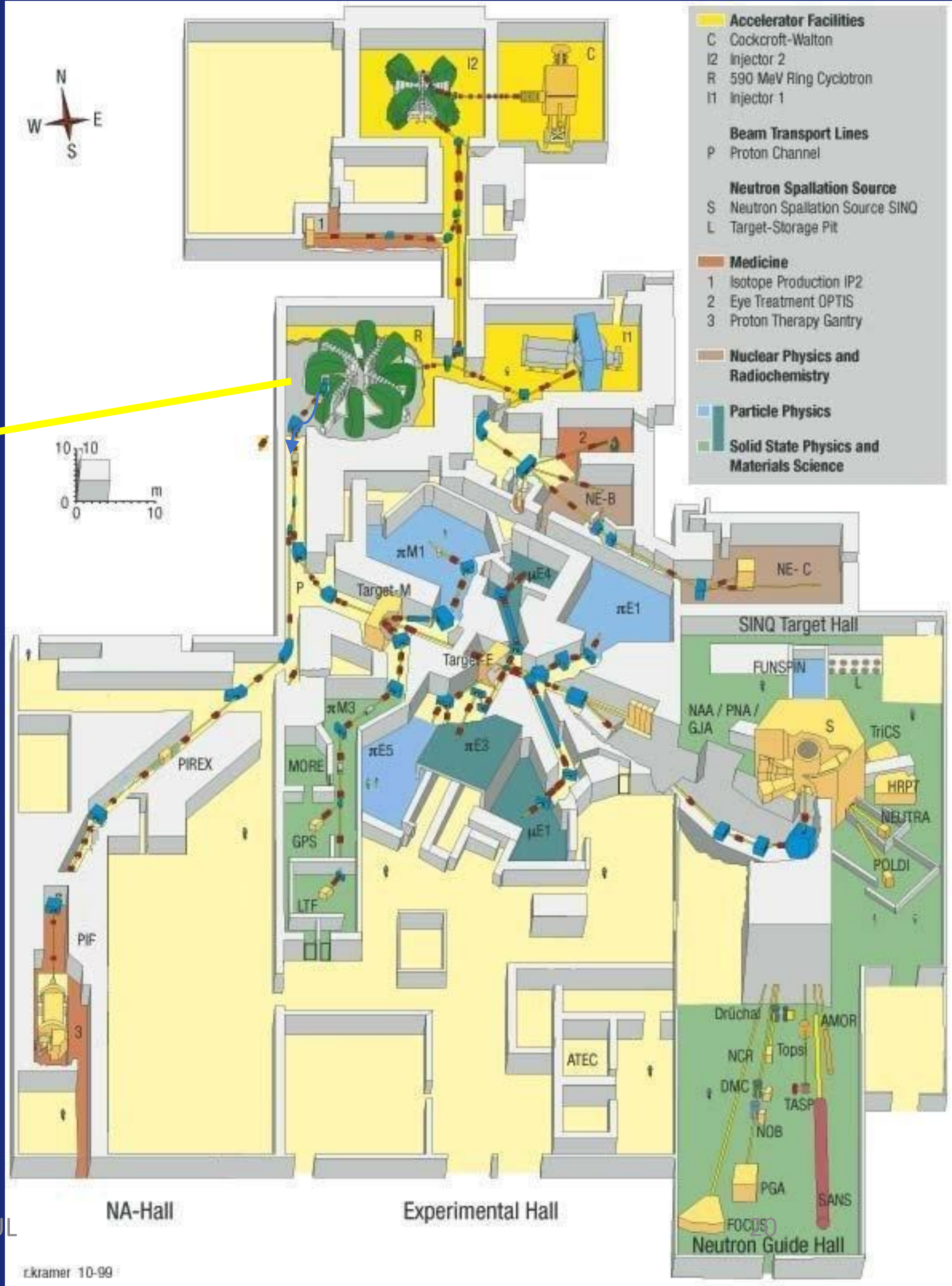
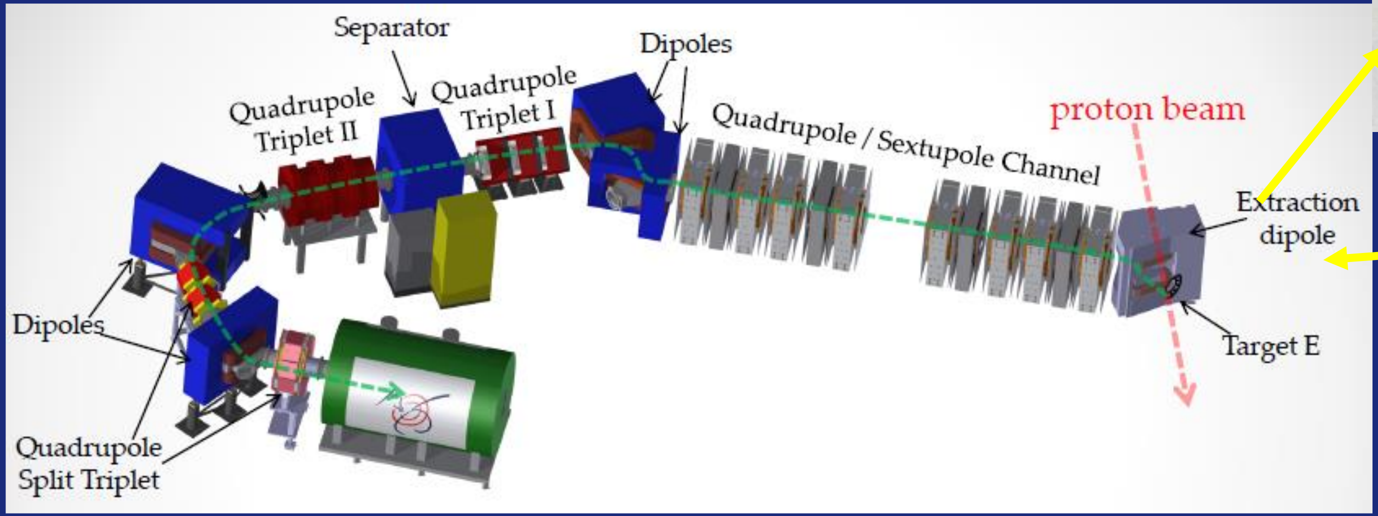
Muon production at PSI

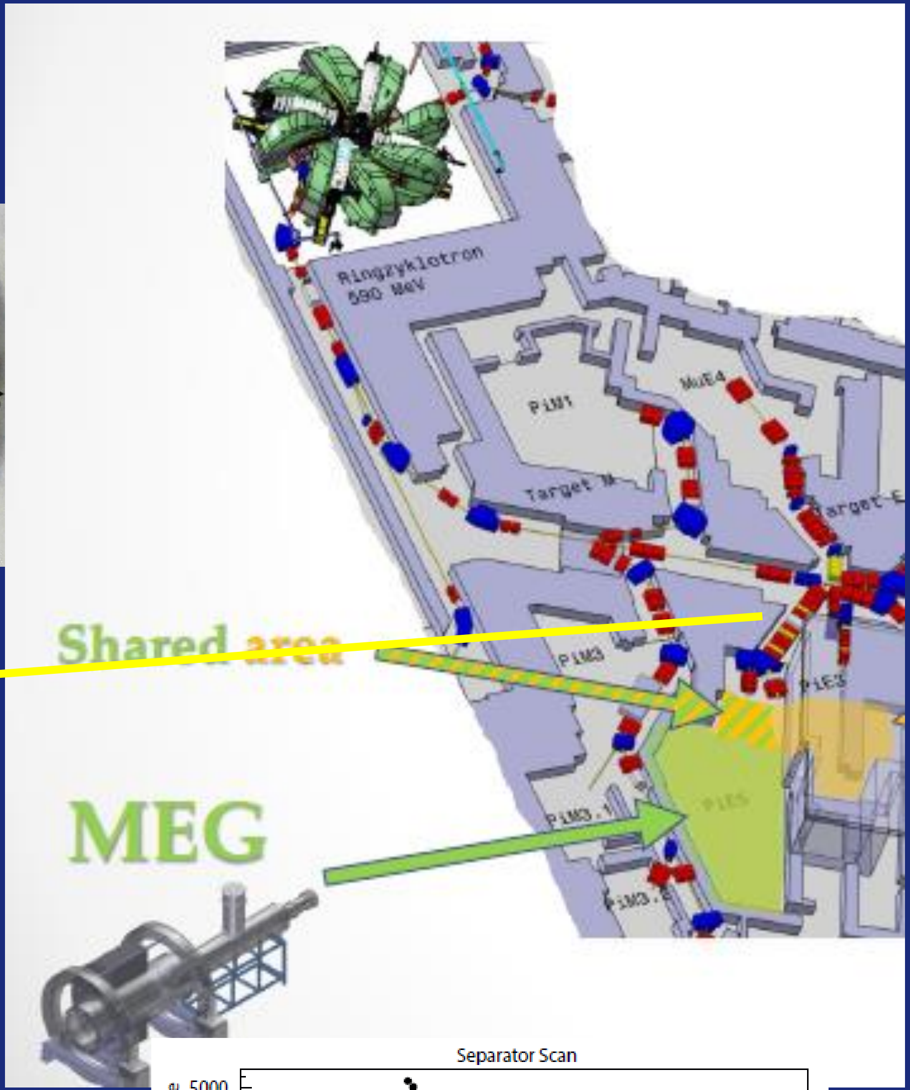


Start from PSI proton cyclotron

590 MeV protons at up to 2.3 mA

Target-E and the πe5 / Compact Muon Beam Line

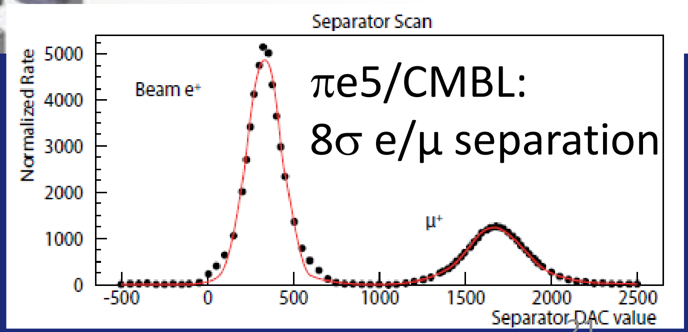




Protons hit fast spinning carbon target. Muons from pion decays near surface peak around p = 29 MeV.

πe5/CMBL beamline captures muons from target-E, delivering 10^8 μ/s in a narrow momentum bite (<p> = 28 MeV, stopped in < 1 mm of target).

πe5/CMBL: Effective removal e^+ from Michel or π_0 decays near target.



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Technological challenges

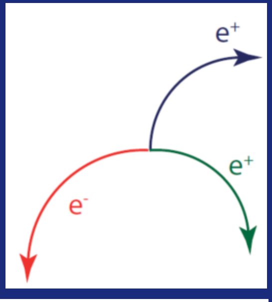
Mu3e targets BR($\mu^+ \rightarrow e^+e^+e^-$) with sensitivity of 10^{-16}, a factor 10,000 improvement on last $\mu^+ \rightarrow e^+e^+e^-$ search (SINDRUM).

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

(Almost exactly equivalent to1 grain of sugar in the entire world's annual sugar production, 166,000,000 metric tons in 2015).

- Fast High-Voltage Monolithic pixel sensors on low mass supports, to cope with high occupancy, ~0.1% X_0 per layer, achieving <u>$\sigma(p) < 1$ MeV</u> and <u>excellent vertex resolution</u>
- Gaseous Helium cooling
- Thin scintillating fibre detector (~0.3% X_0)
- Silicon PM readout of fibres and tiles to achieve <u>$\sigma(t) < 500$ ps</u> and <u>$\sigma(t) < 100$ ps</u>, respectively
- Online GPU filter farm for full reconstruction 10^8 -10^9 muon decays per second

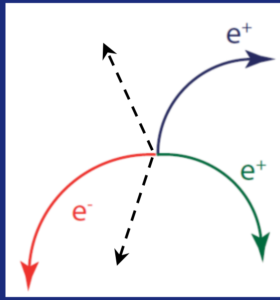
Mu3e experiment: physics constraints



The signal:

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

$E_{total} = m_\mu$

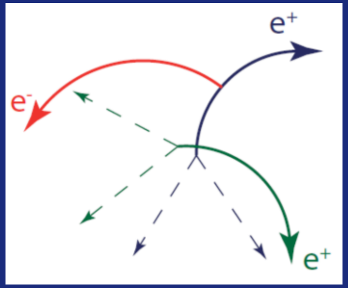


Michel decays with internal conversion:

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

Irreducible background a part from missing E_T

$E_{total} < m_\mu$

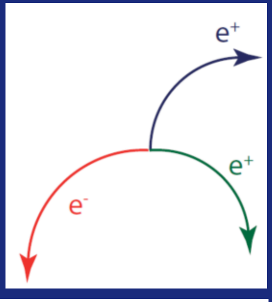


Accidental backgrounds:

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

Electrons not (all) from a common vertex

Mu3e experiment: physics constraints



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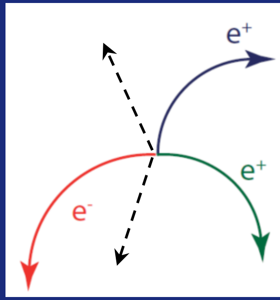

Michel decays with internal conversion:

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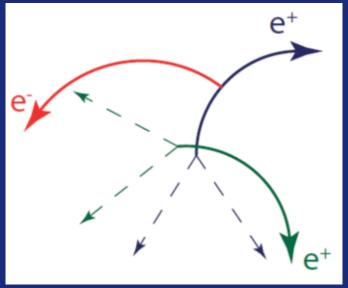
Irreducible background a part from missing E_T

$E_{total} < m_\mu$

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

The μ3e experiment

$\mu \to ee\nu\nu$ background is irreducible.

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

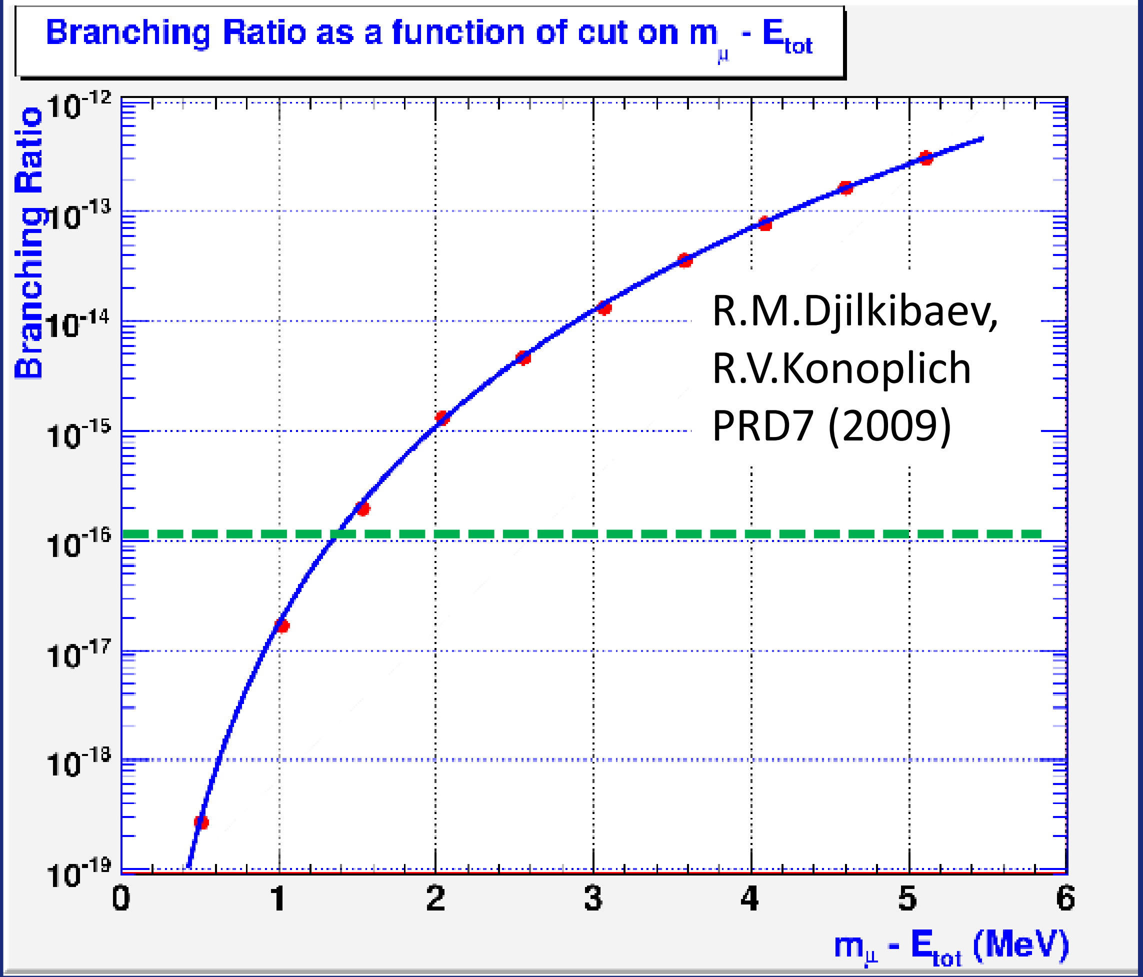
Drops steeply towards kinematic endpoint.

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

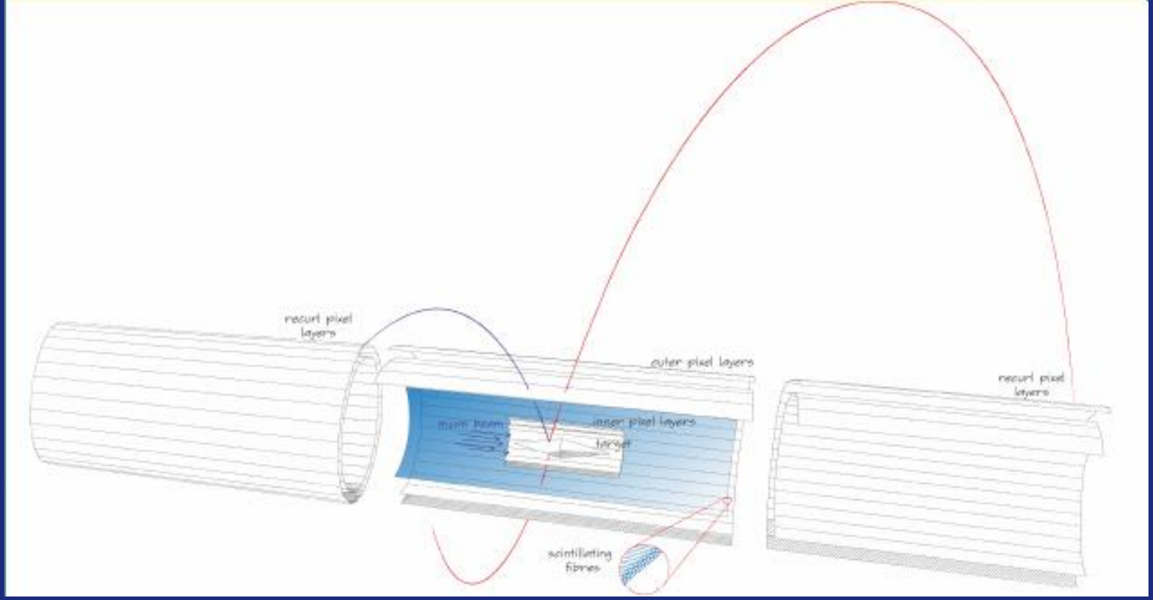
Very challenging:

- $E_e < 53$ MeV
- up to 2×10^9 μ/s

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



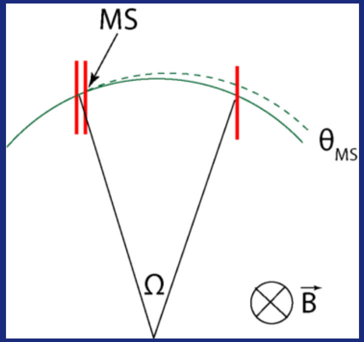
Tracking concept



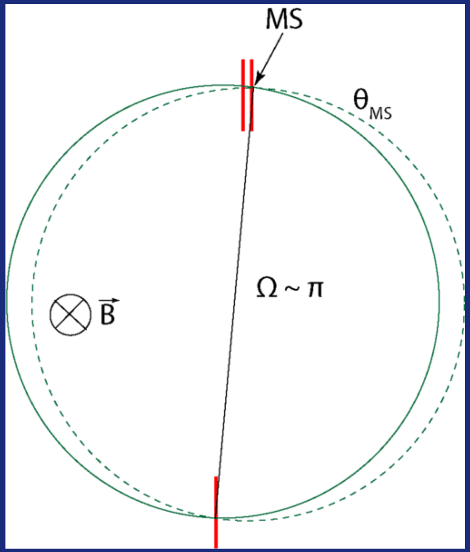
At $p_e < 53$ MeV multiple coulomb scattering dominates track errors.

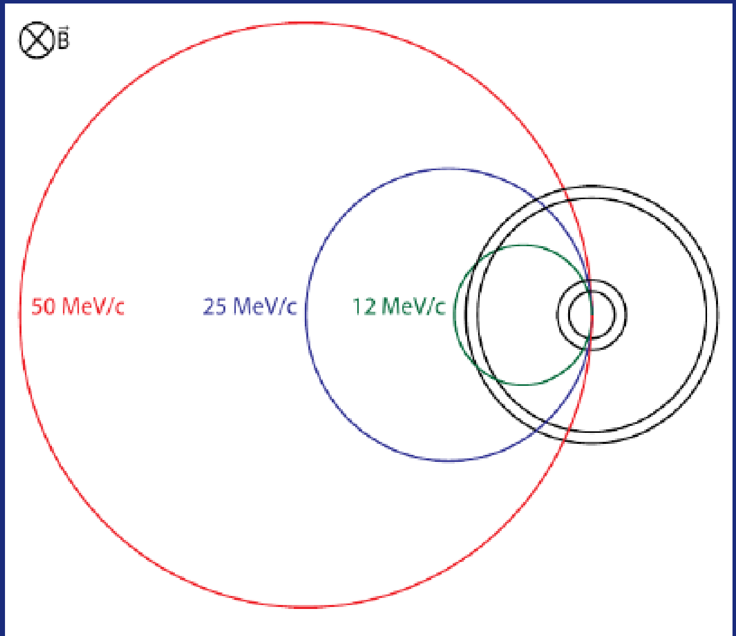
$\theta_{MS} \sim \sqrt{X/X_0}$ (reduce material, 0.1% X_0 per Silicon layer)

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



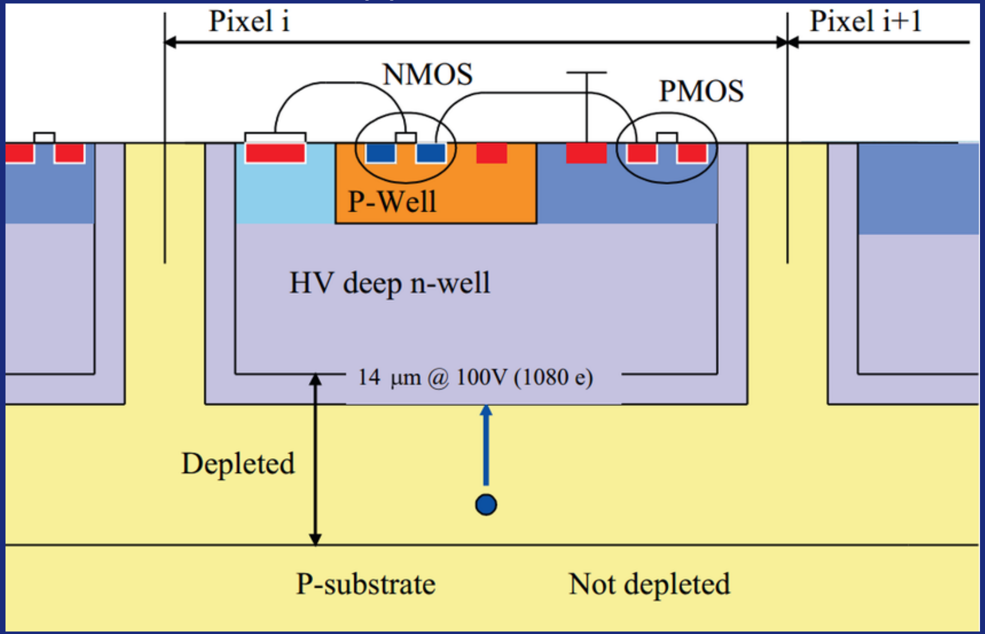
But, for very large lever arm ($\Omega \sim \pi$) first order effects of θ_{MS} cancel out.





Layer radii are optimised for momentum resolution and acceptance.

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



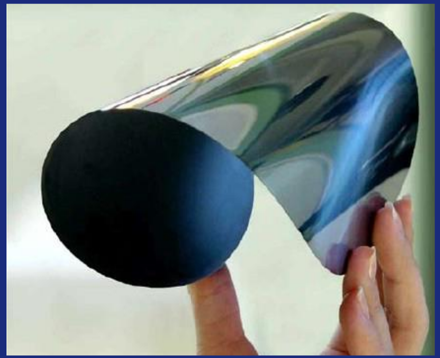
HV-MAPS sensors

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.*

Critical properties for Mu3e:

- Sensors can be thinned to 50 µm without signal loss.
- Sensors can operate in a high rate environment ($\sigma(t) < 25$ 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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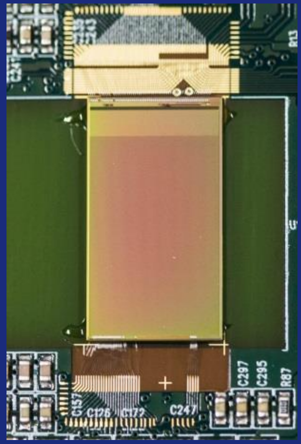
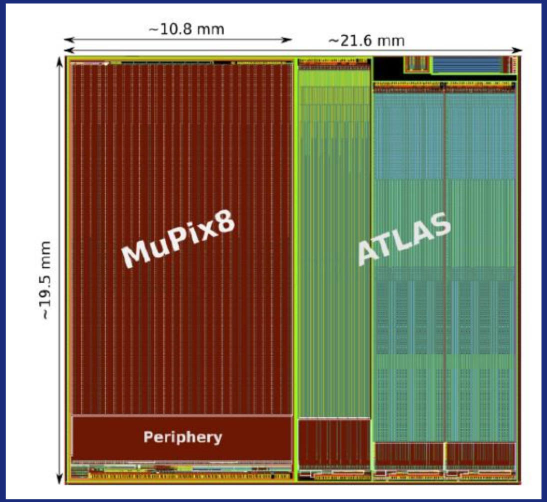
MuPix HV-MAPS

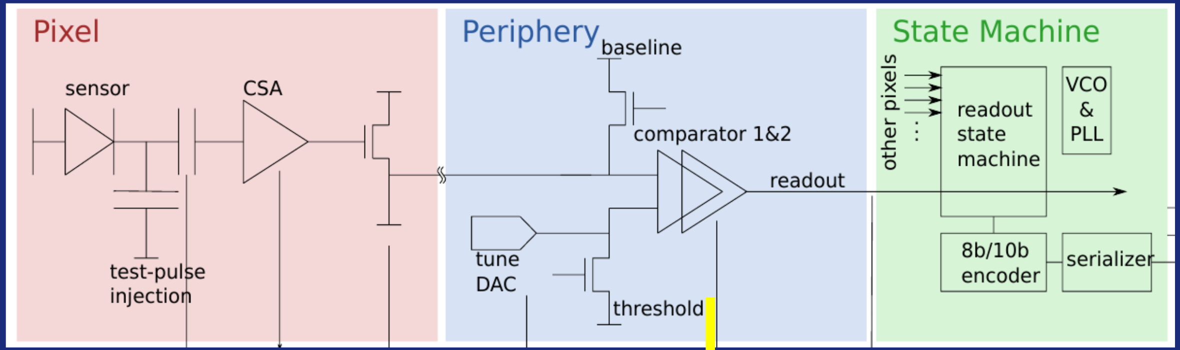
HV-MAPS development in AMS 360 nm and 180 nm HV-CMOS process, now moved to TSI 180 nm process.





MuPix8 (shared submission with ATLASPIX, different substrate resistivities)
First large area demonstrator: active area: 1×1.6cm^2

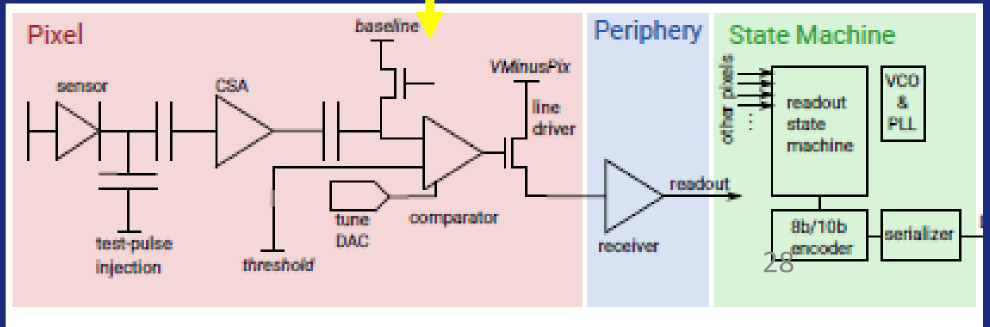
- 80 x 80 μm^2
- Amplifier in pixel,
- Comparator and digital logic in periphery.
- 3 (or 1) data outputs, 1.25 Gb/s each
- Power: ~300 mW/cm^2



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

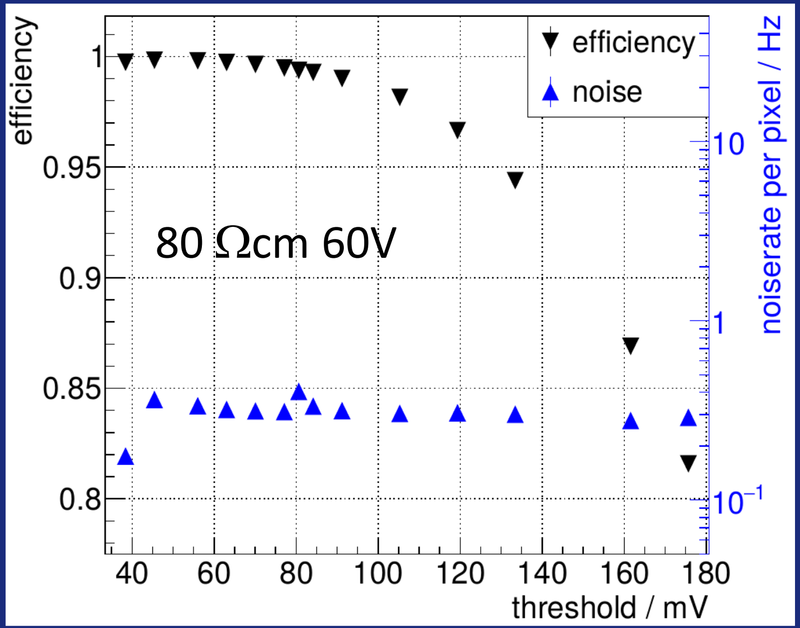
- Reduced number of pads per chip
- move comparator in to pixel (tested in ATLASPIX chip)
  - smaller periphery, reduced cross-talk

Submission Q4 2019
MuPix11 final detector chip, submission Q4 2020

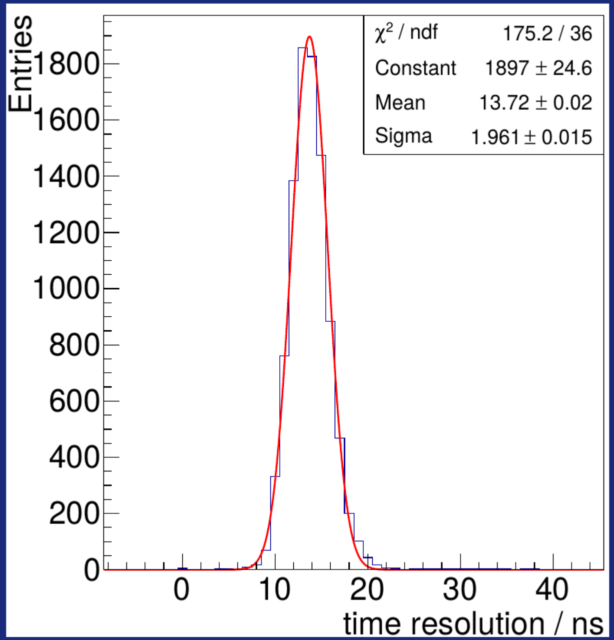


Results from testbeam: MuPix8

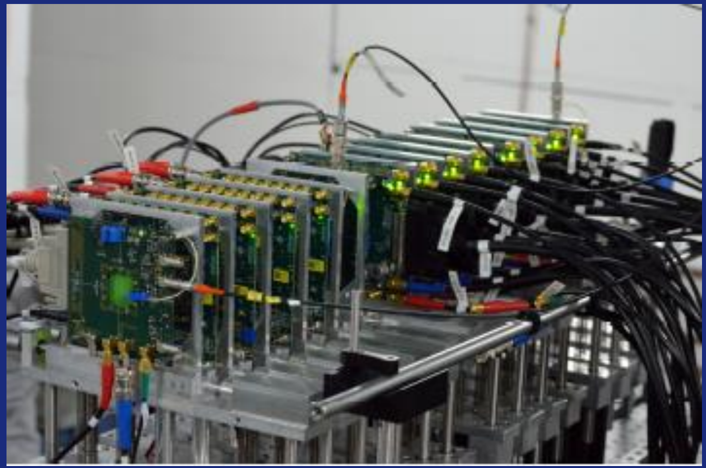
Testbeams with MuPix/FEI4 telescope mostly at DESY and PSI



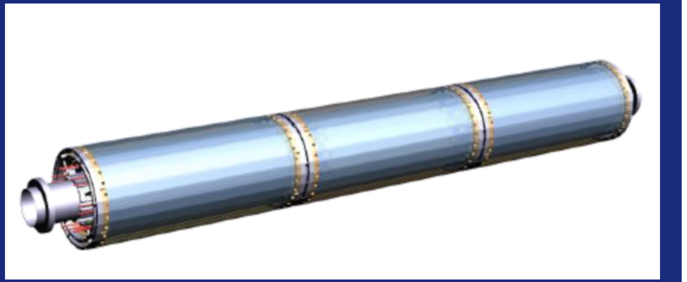
Eff. ~ 99.8%
higher over larger range of thresholds with 200 Ωcm

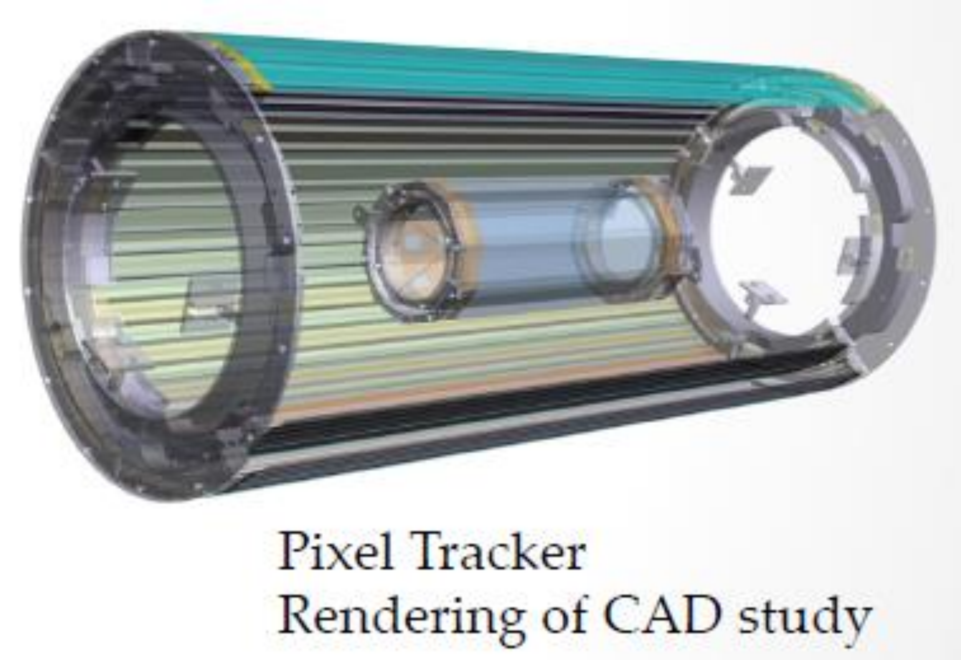


σ(t) ~ 14 ns
Tuning the threshold we can improve to 6-7 ns

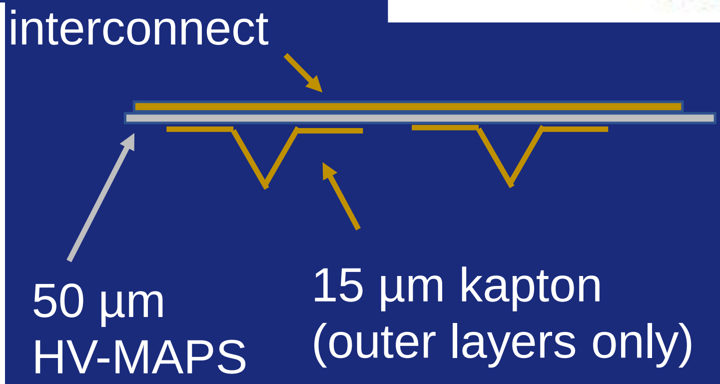


MuPix mechanics





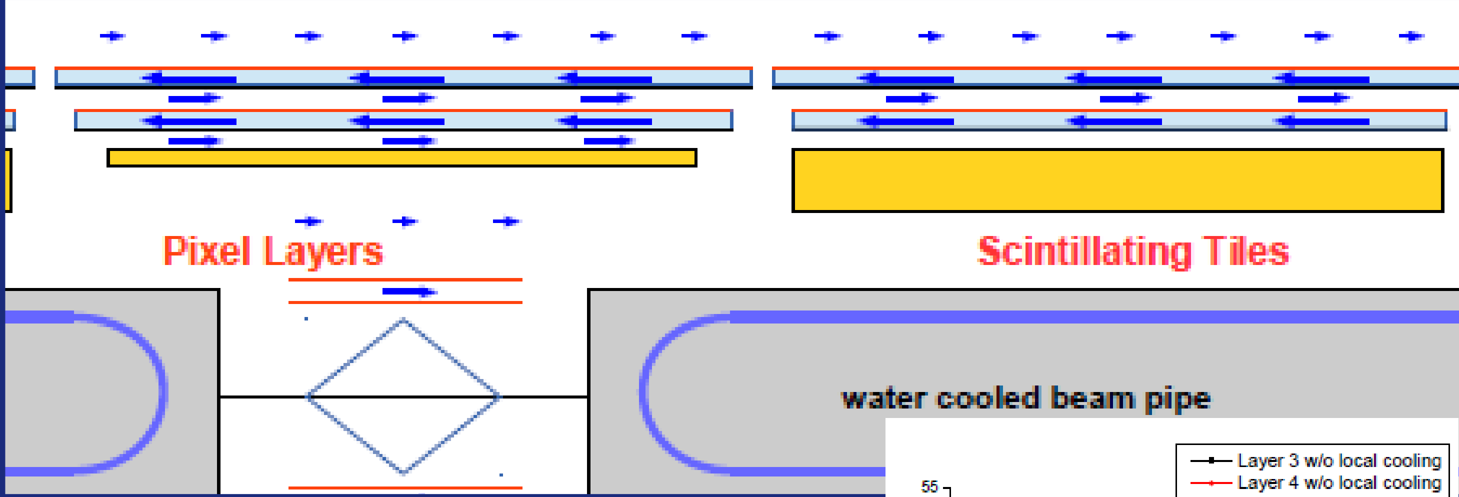
In total for Phase-1 2808 HV-MAPS chips will be mounted to 170 high density interconnect flex circuits to produce the inner and outer layers
(1.1. m^2 of HV-MAPS sensors)



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)

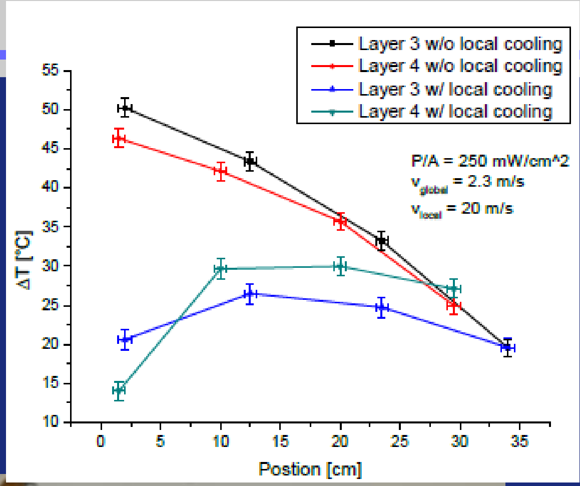
Resulting in approximately <u>0.1% X_0 per tracking layer</u>



MuPix 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

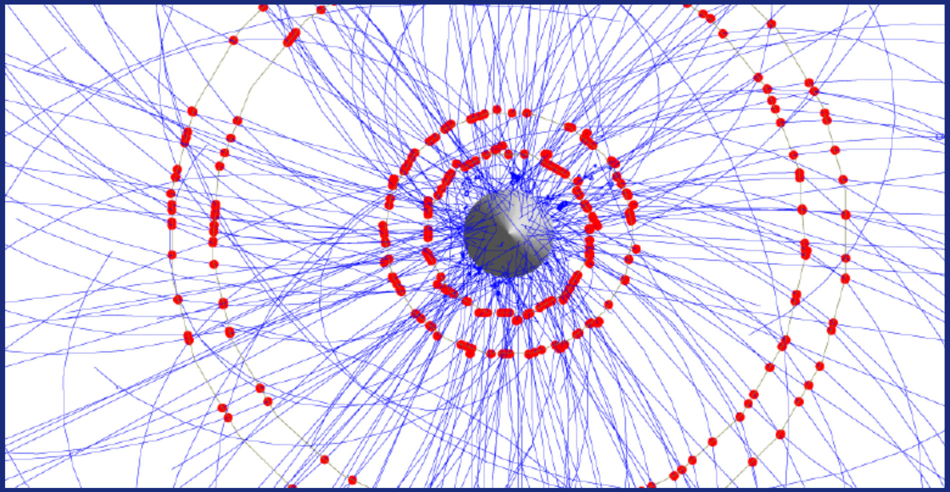
Since Mu3e uses a DC beam accidental backgrounds can be reduced by improved timing.

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

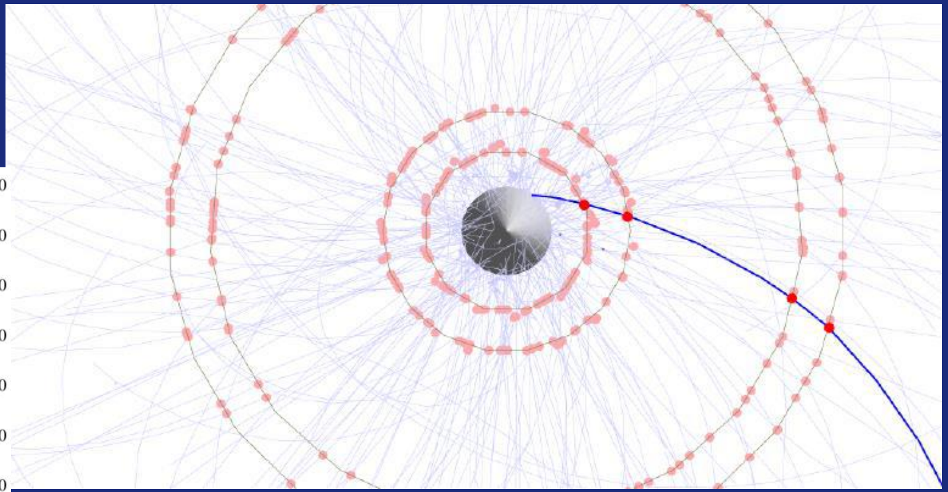
Note HV-MAPS are slower, so for track-finding still need longer window (spec: $\sigma(t) < 20$ ns)

Timing also important to prevent charge mis-identification for ~90° tracks that circle back to target

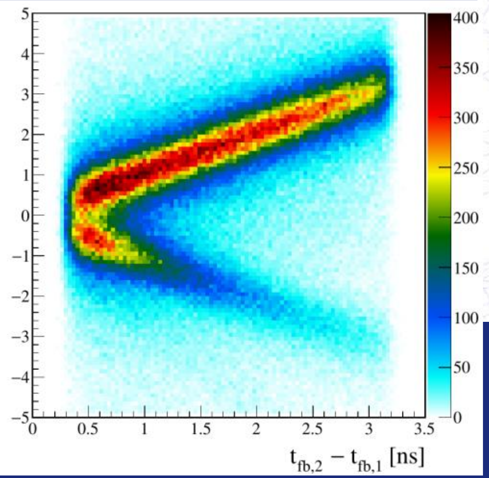
50 ns time slice at 2×10^9 μ/s



with < 500 ps time resolution:

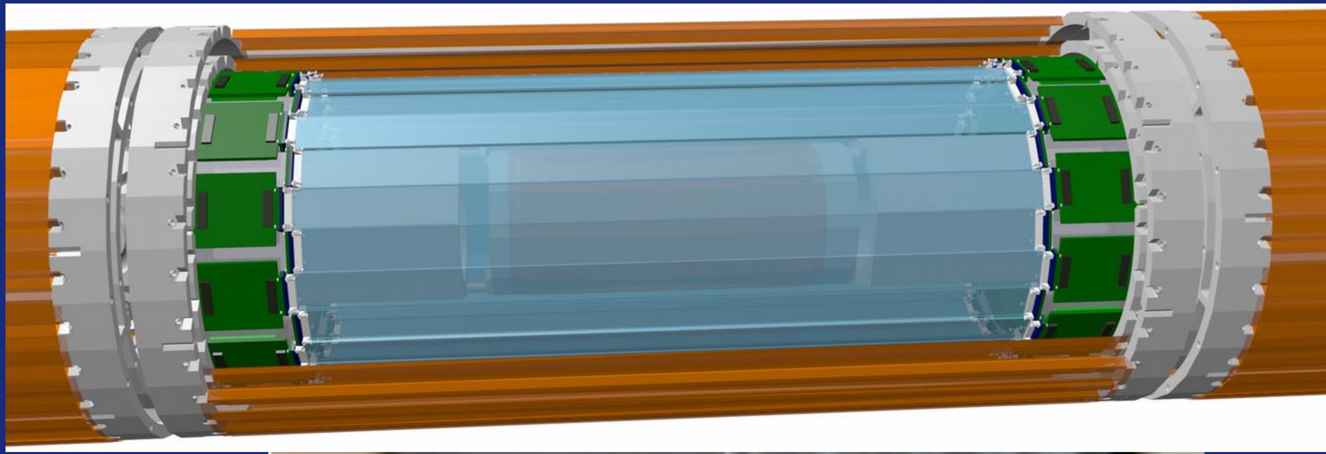


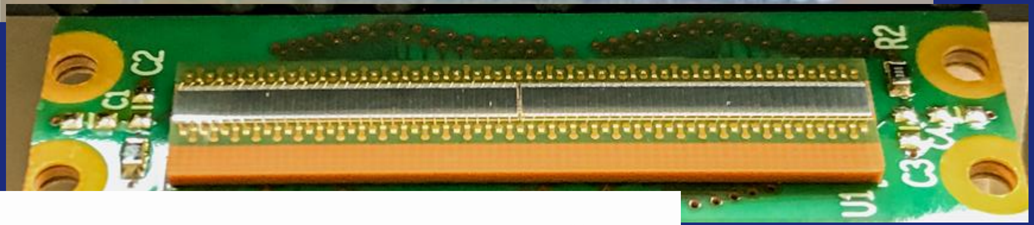
Measured Δ(t) track



Expected Δ(t) for positron

Scintillating fibre detector





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

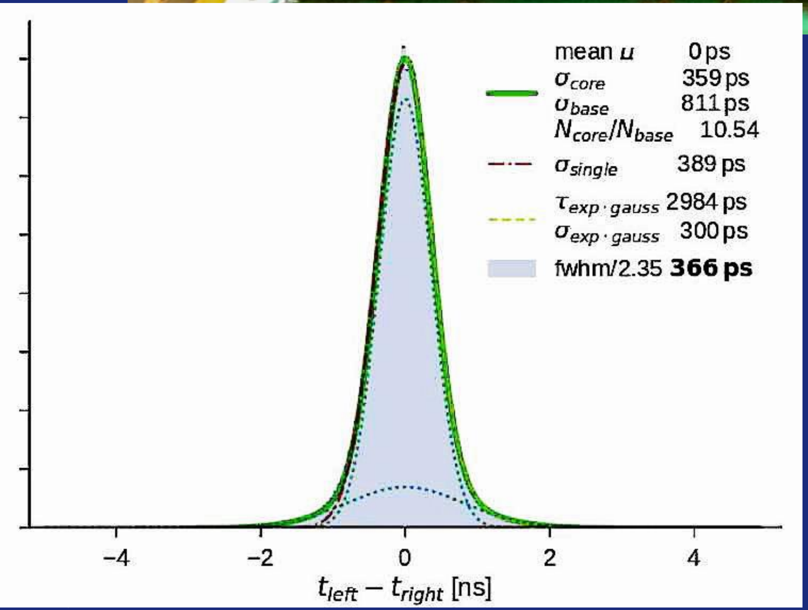
~0.3% X_0

2 x 64 channel Si PM arrays (Hamamatsu)

MuTRig readout chip

Test beam results:

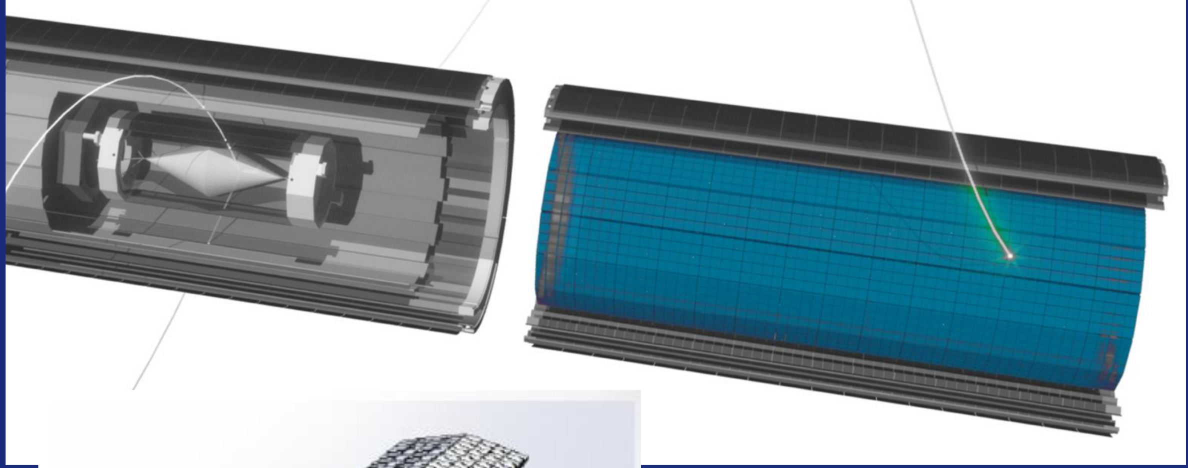
- time resolution ~370 ps

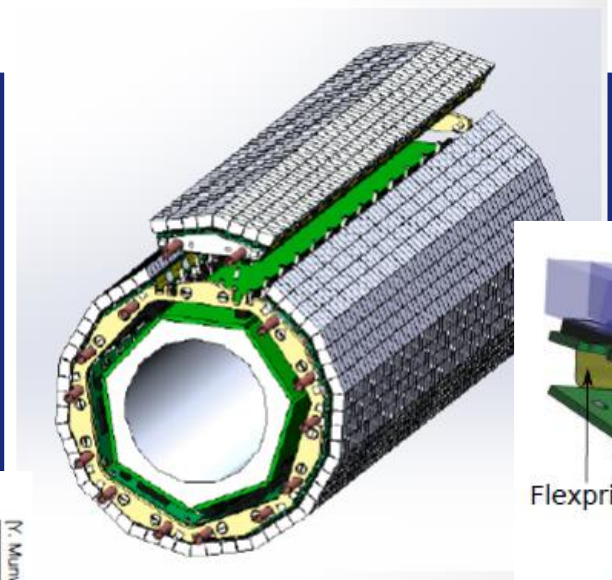


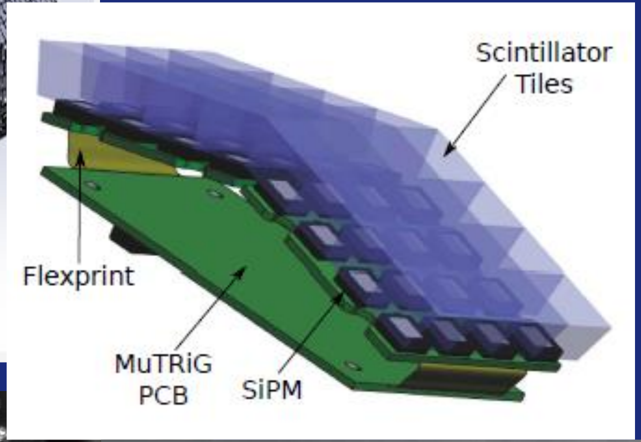
Scintillating Tile detector

- ~0.5 cm^3 scintillating tiles, arranged in 4x4 arrays
- mounted on a cylinder for each re-curl station
- timing resolution <100 ps (varying with energy)

Readout: single channel SiPM, MuTrig ASIC





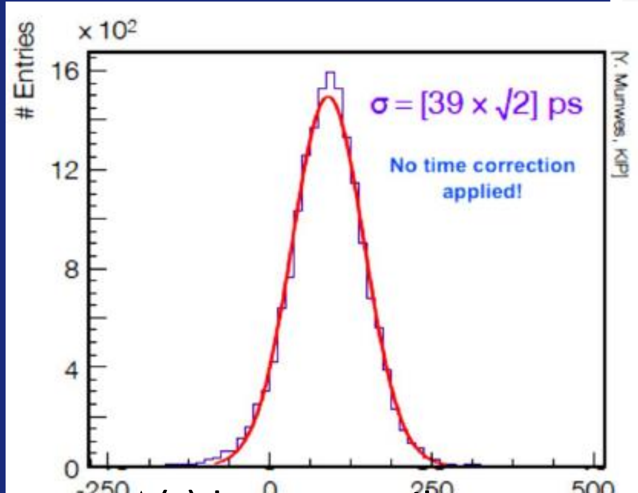


DESY test-beam:

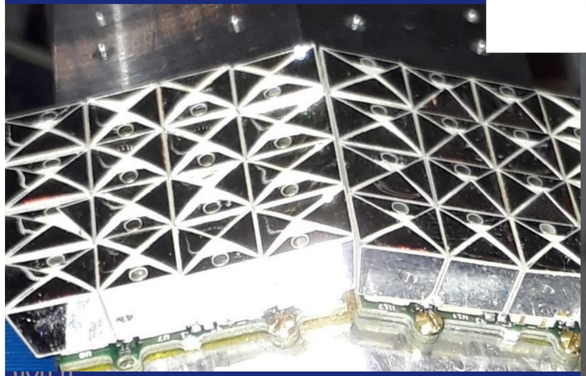
time resolution 40 ps

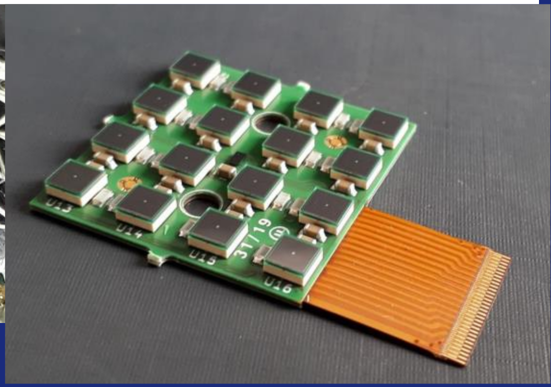
(for high energy electrons)

<100 ps for all energies

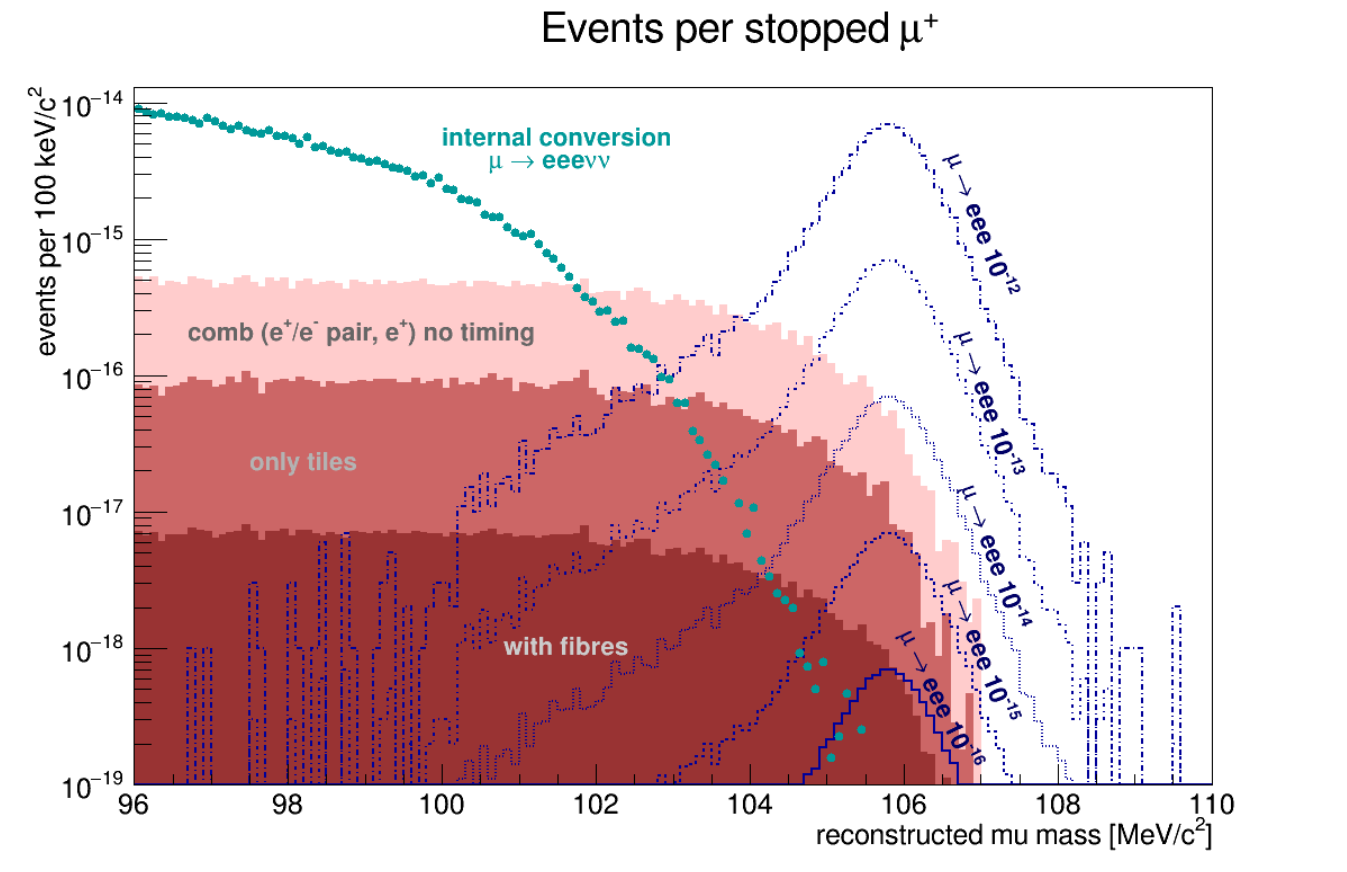


Δ(t) between tiles



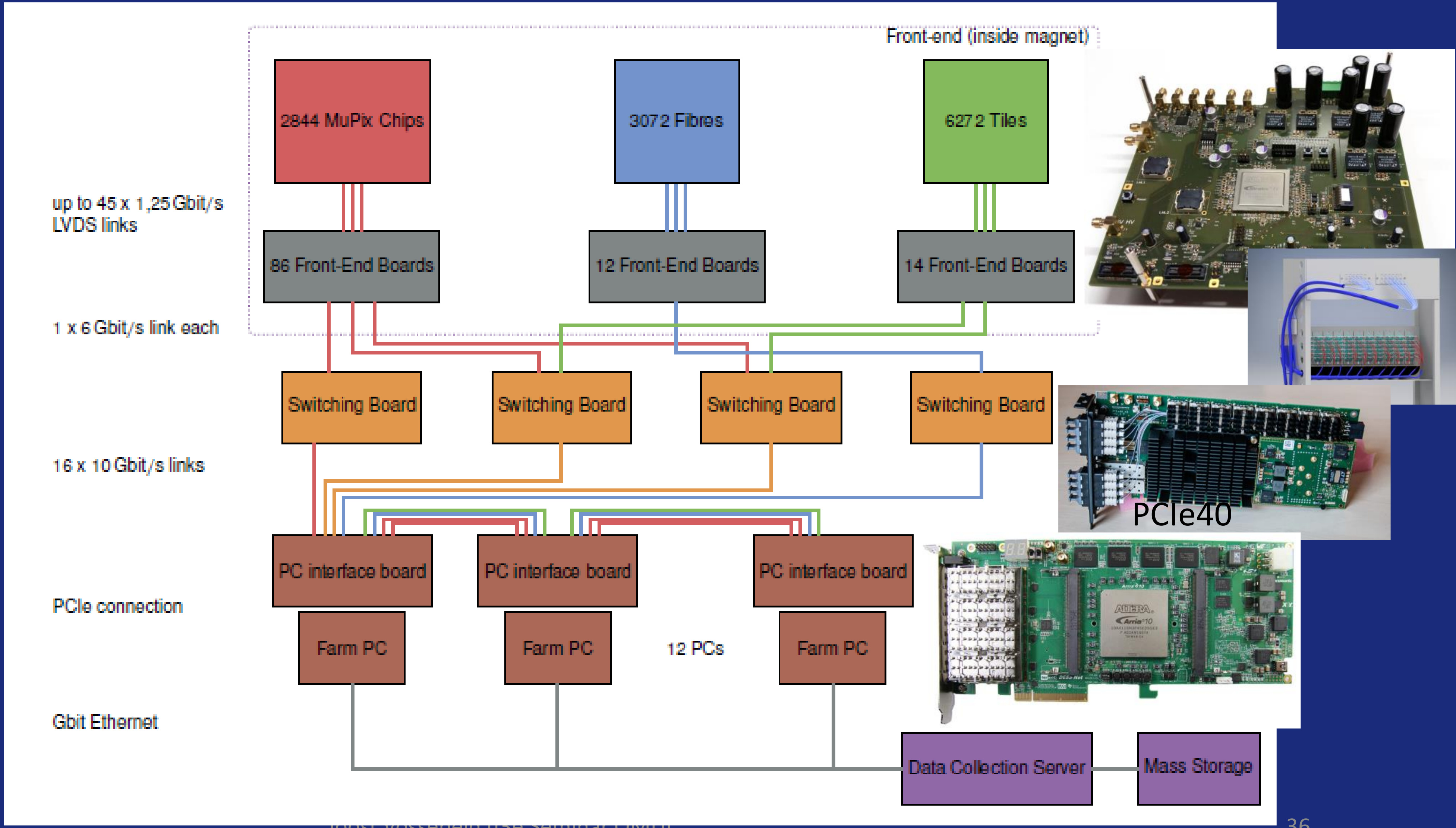


Reduction of accidental backgrounds

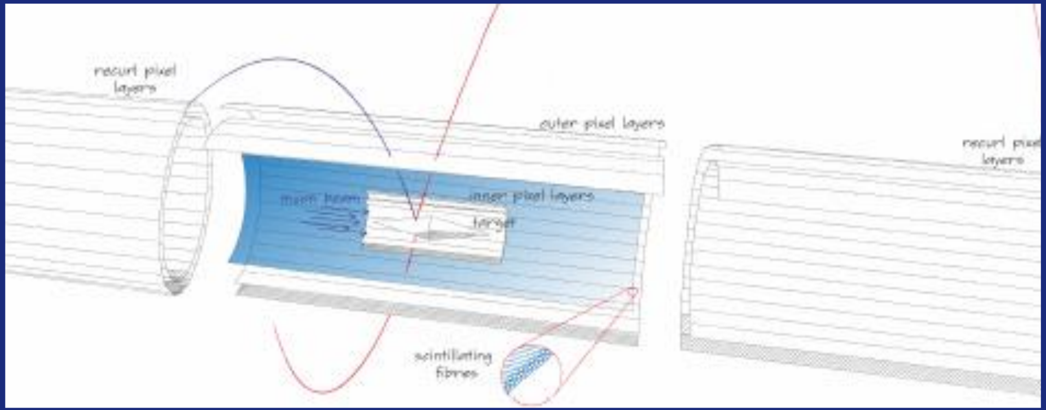


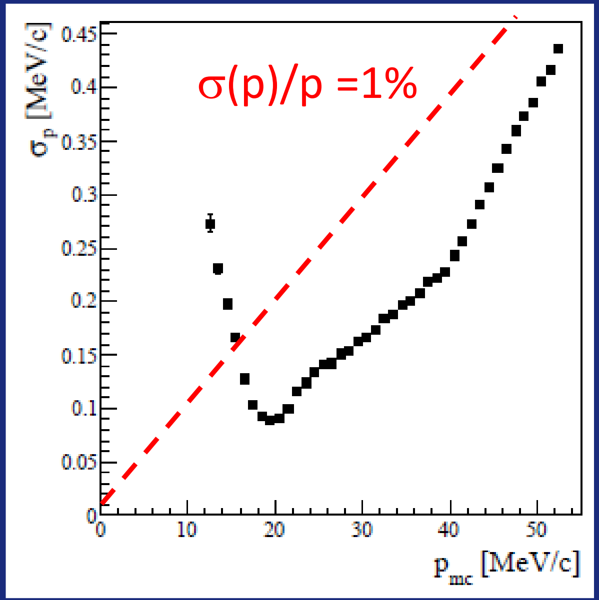
Readout concept

- 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).

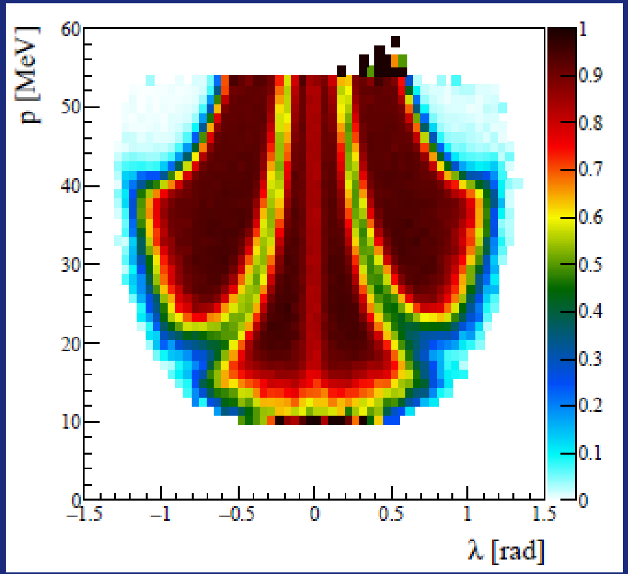


Tracking performance





Excellent momentum resolution for long tracks (“recurlers”)



Efficiency and geometric acceptance for long tracks

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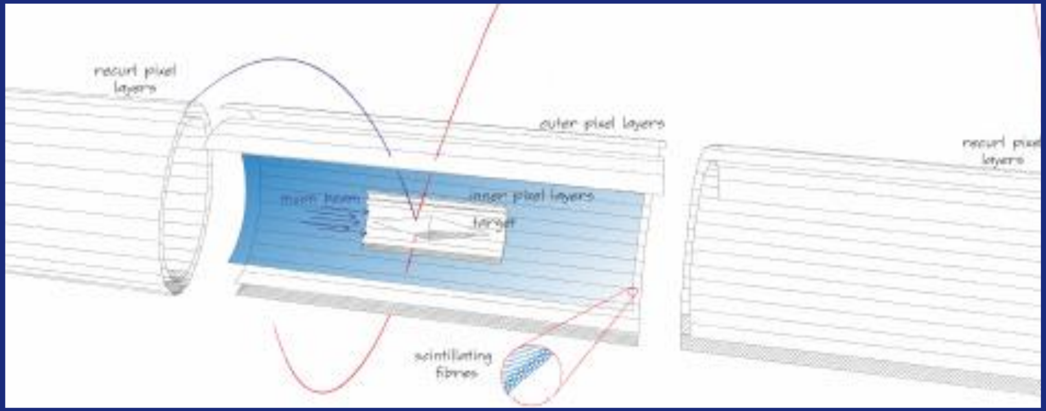
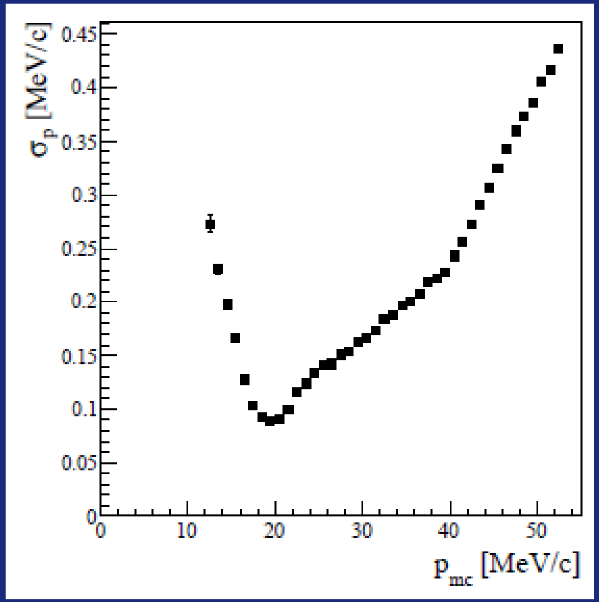
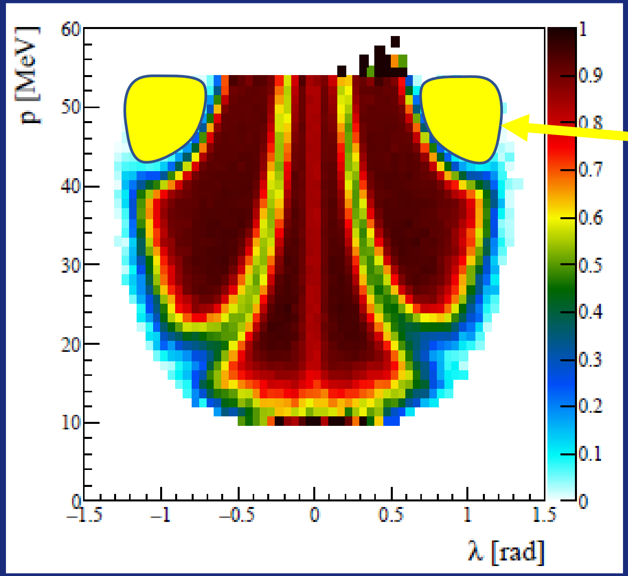
Tracking performance





Excellent momentum resolution for long tracks (“recurlers”)



Efficiency and geometric acceptance for long tracks

Phase-II extended re-curl stations

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Physics performance

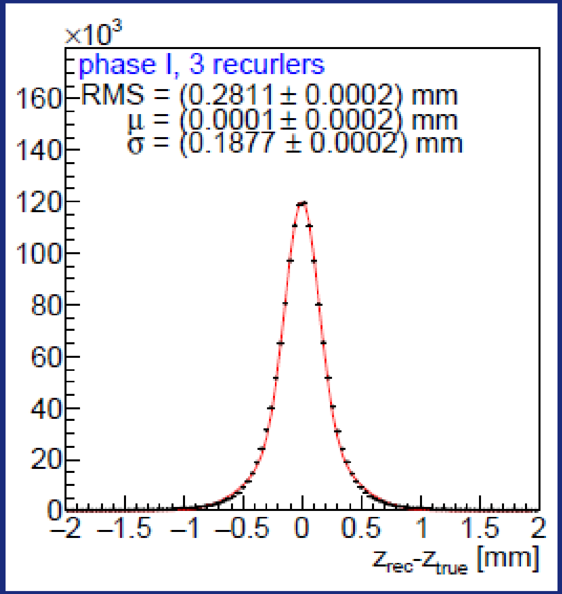
Step	Step efficiency	Total efficiency
Muon stops	100%	100%
Geometrical acceptance, short tracks	43.2%	43.2%
Geometrical acceptance, long tracks	60.6%	26.2%
Short track reconstruction	89.9%	38.8%
Long track reconstruction	80.4%	21.0%
Vertex fit	98.6%	20.8%
Vertex fit $\chi^2 < 30$	98.1%	20.4%
CMS momentum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

Signal reconstruction efficiency

19.7%: 3 long tracks from good vertex.

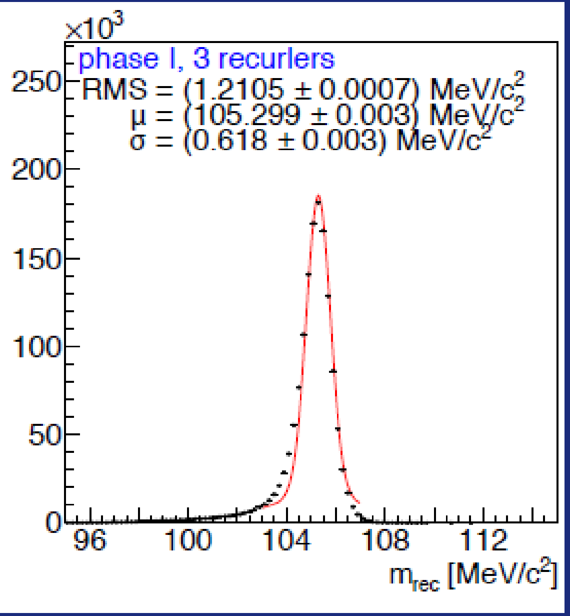
Geometric acceptance dominates

Note this is somewhat model dependent!



vertex z resolution
3 long tracks

< 200 μm

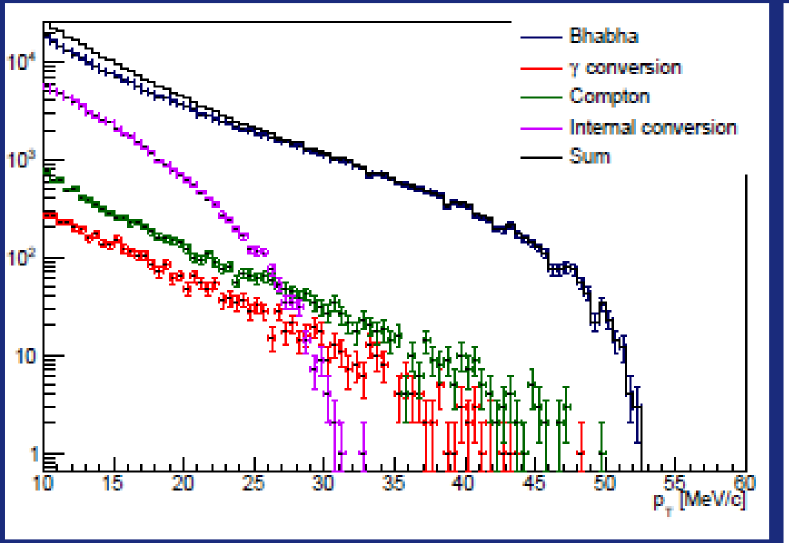


m_{eee} resolution

3 long tracks

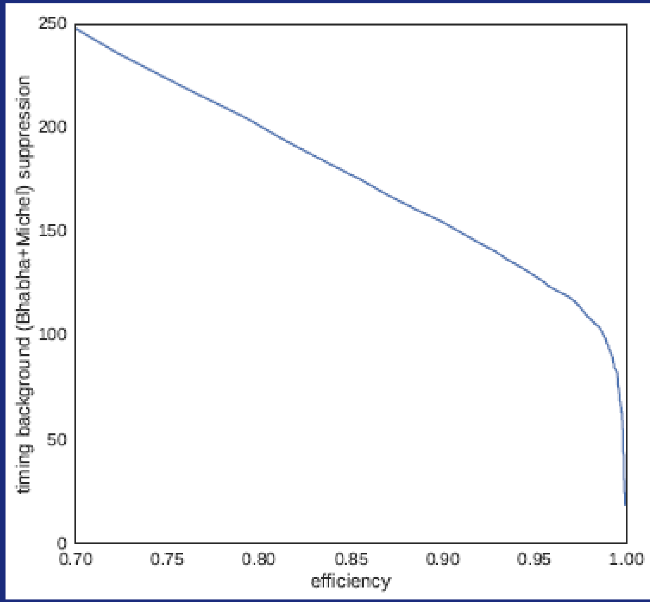
$\sigma(m_{eee}) \sim 0.6$ MeV

Accidental backgrounds



P_T spectrum of electrons:

Dominant source are Bhabha electrons, ~7.8×10^{-5} per muon decay produced in the target region.



BG rejection vs signal efficiency for timing cuts.

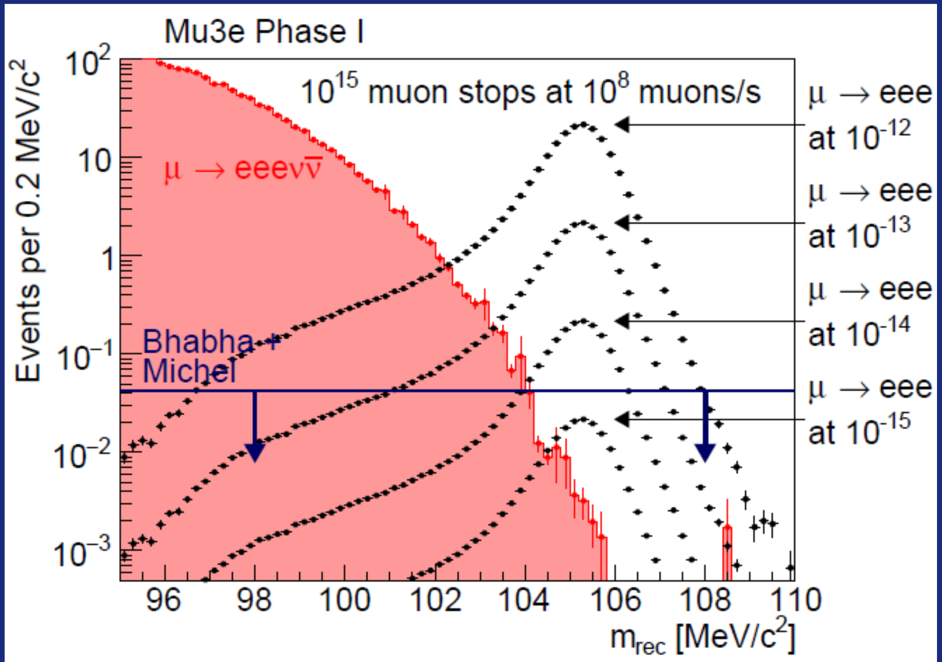
Factor 100 reduction achievable without substantial efficiency loss

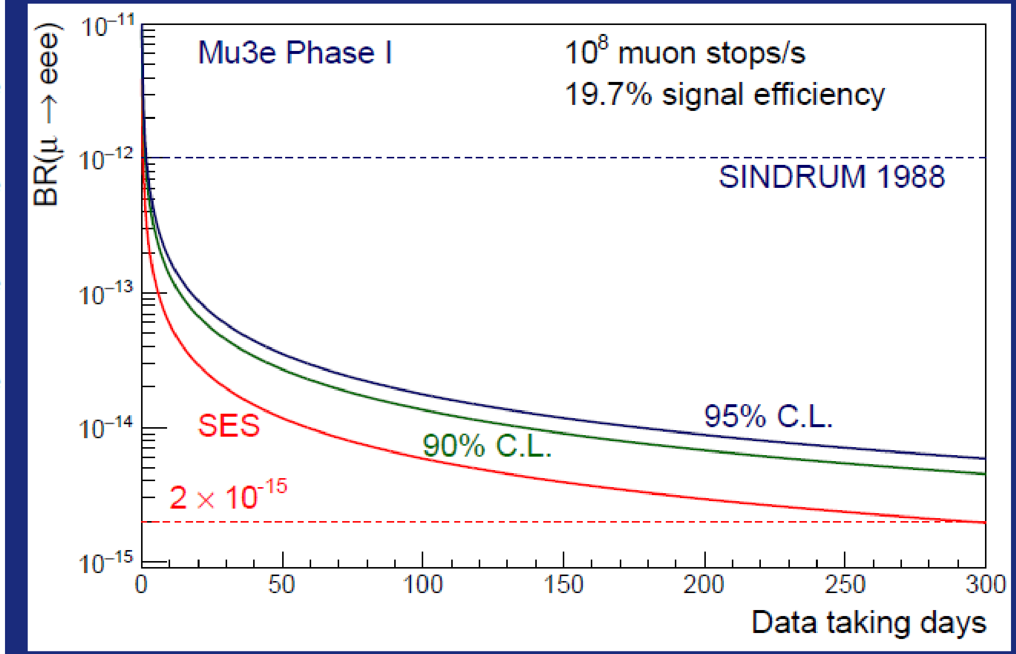
Procedure to estimate accidental background Bhabha-Michel overlaps:

- Overlay Bhabha events with 5.25×10^8 simulated frames (normal Michel decays).
- Scaled with Bhabha rate and rejection factor this corresponds to ~7×10^{14} muon decays.
- No events pass the selection cuts!
- This allows to set an **upper limit** of 3.2×10^{-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.

- $2x10^9$ 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)

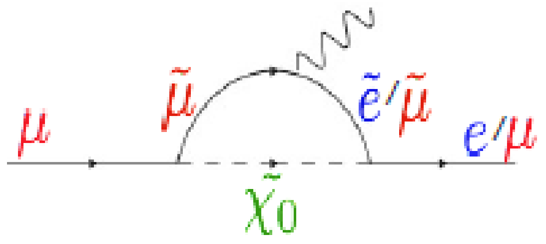
g-2

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 g-2 discrepancy is confirmed CLFV muon decay experiment can probe whether NP includes a lepton mixing angle or set very strong constraints on the eμ mixing angle associated with the NP.

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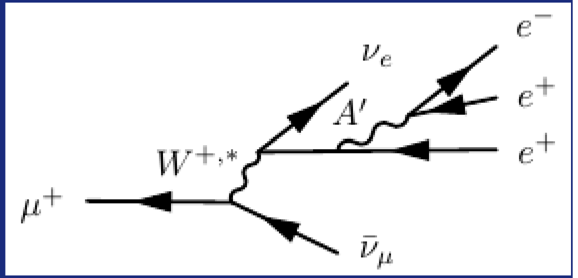
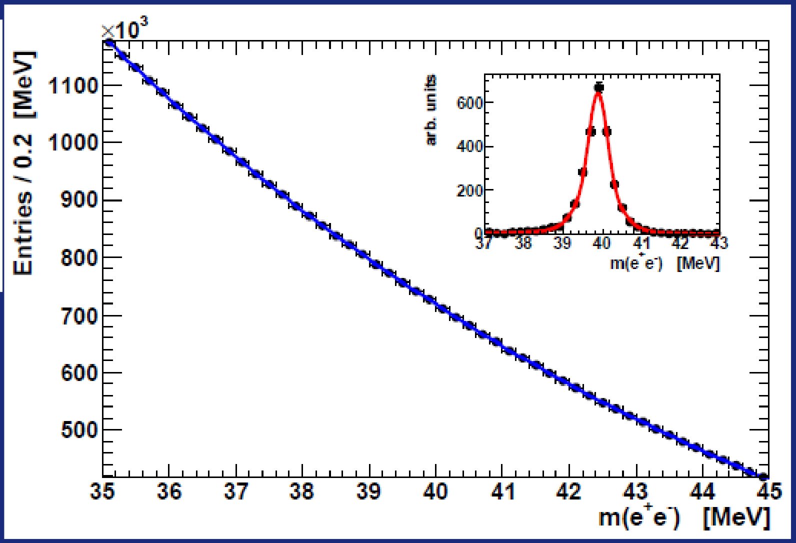
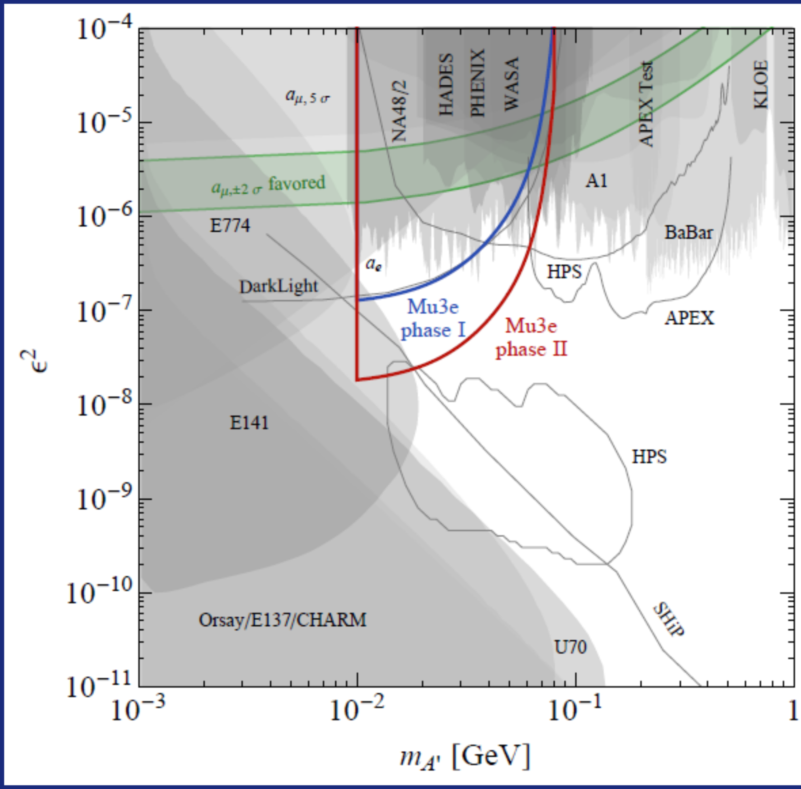
Other physics with Mu3e





Echenard, Essig, Zhong: arXiv:1411.1770v2



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)

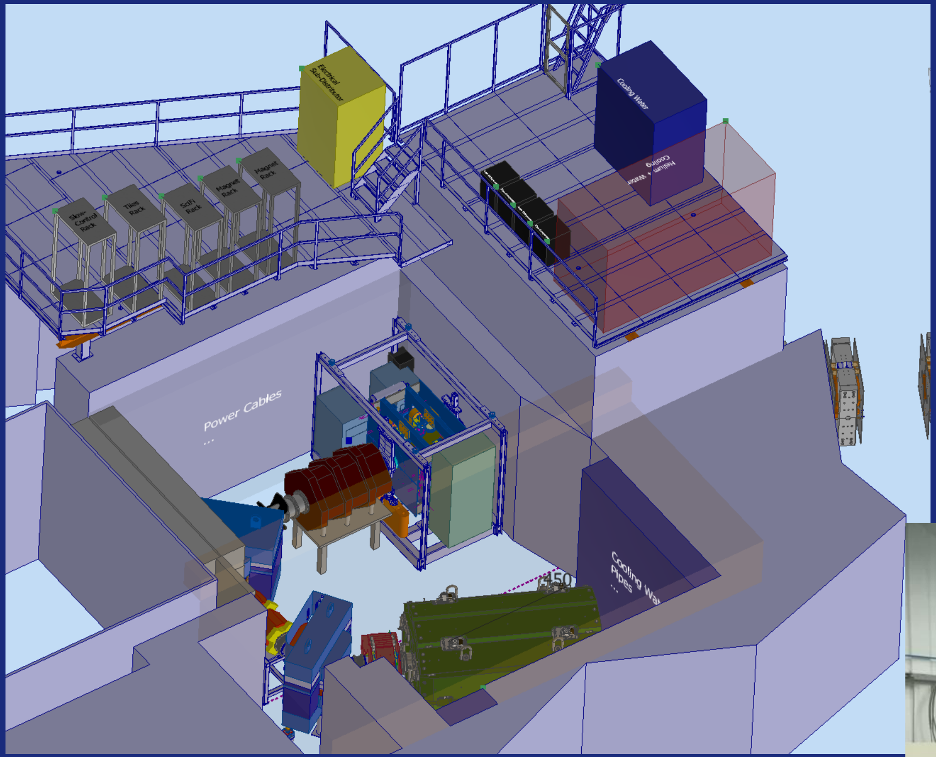
These also need to be performed online!

Preparations at PSI

Beamline in place since 2015

Services (power/cooling) ongoing.

Services platforms installed.

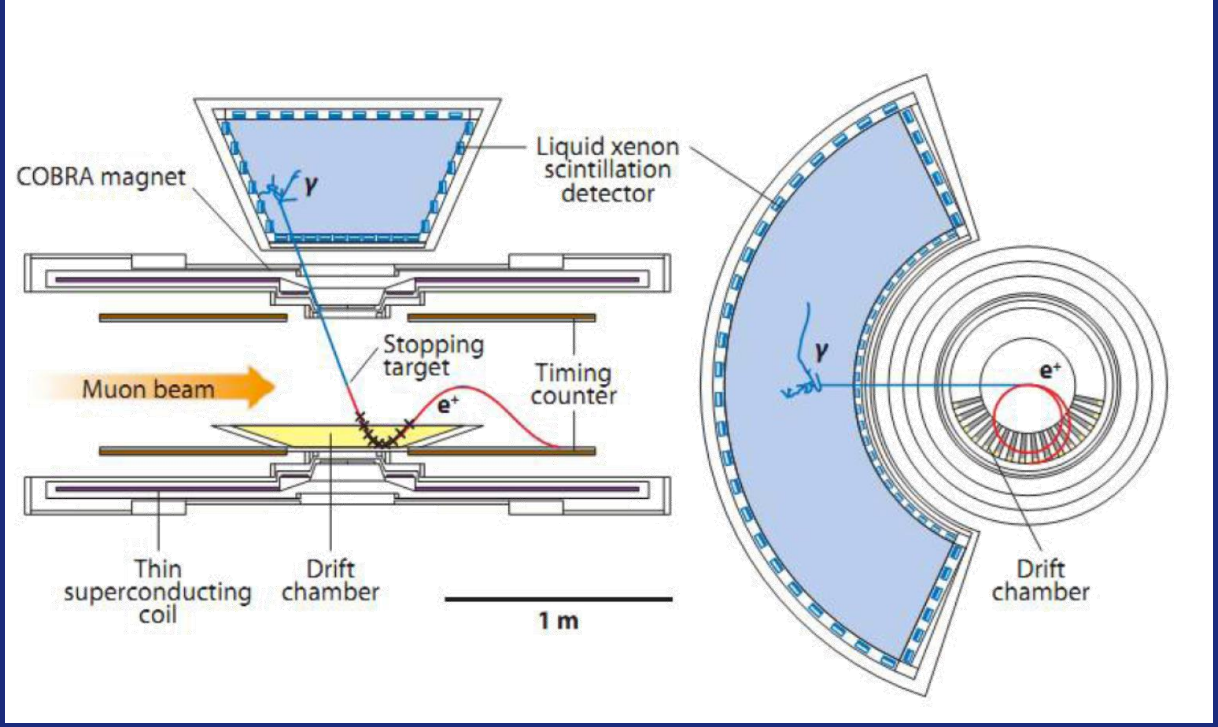


2T Superconducting Magnet, currently being wound. Arrival at PSI in Feb./Mar. 2020.

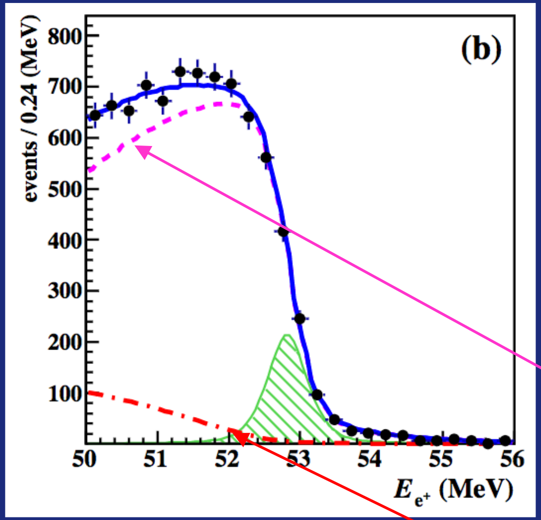
Summary

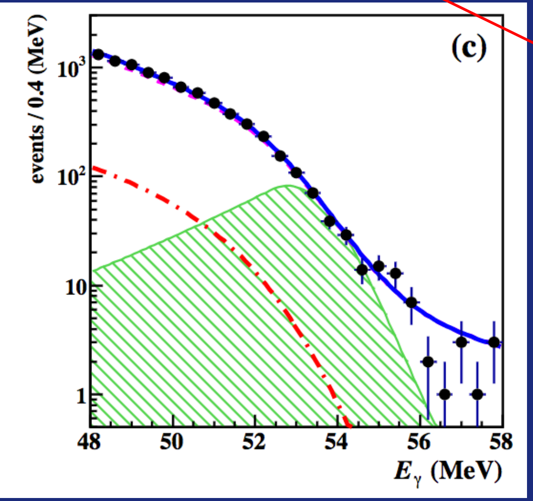
- Mu3e experiment is under construction to turn on in 2021 and will measure with sensitivity BR($\mu \rightarrow$ eee) ~10^{-16}
- Factor 10^4 improvement with SINDRUM-I achieved thanks to
  - Intense muon beams at PSI
  - Tracking of low momentum particles at high rates with thinned HV-CMOS, low mass 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 improvement on BR($\mu \rightarrow e\gamma$) and BR($\mu N \rightarrow$ eN).
- Many new results to look forward to over the next 5 years with sensitivity to NP at multi PeV scales.
- Continued (COMET-II, Mu3e-II, Mu3e-II, new possible eγ update of mu3e) programmes into the 2030's under development/consideration.

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



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





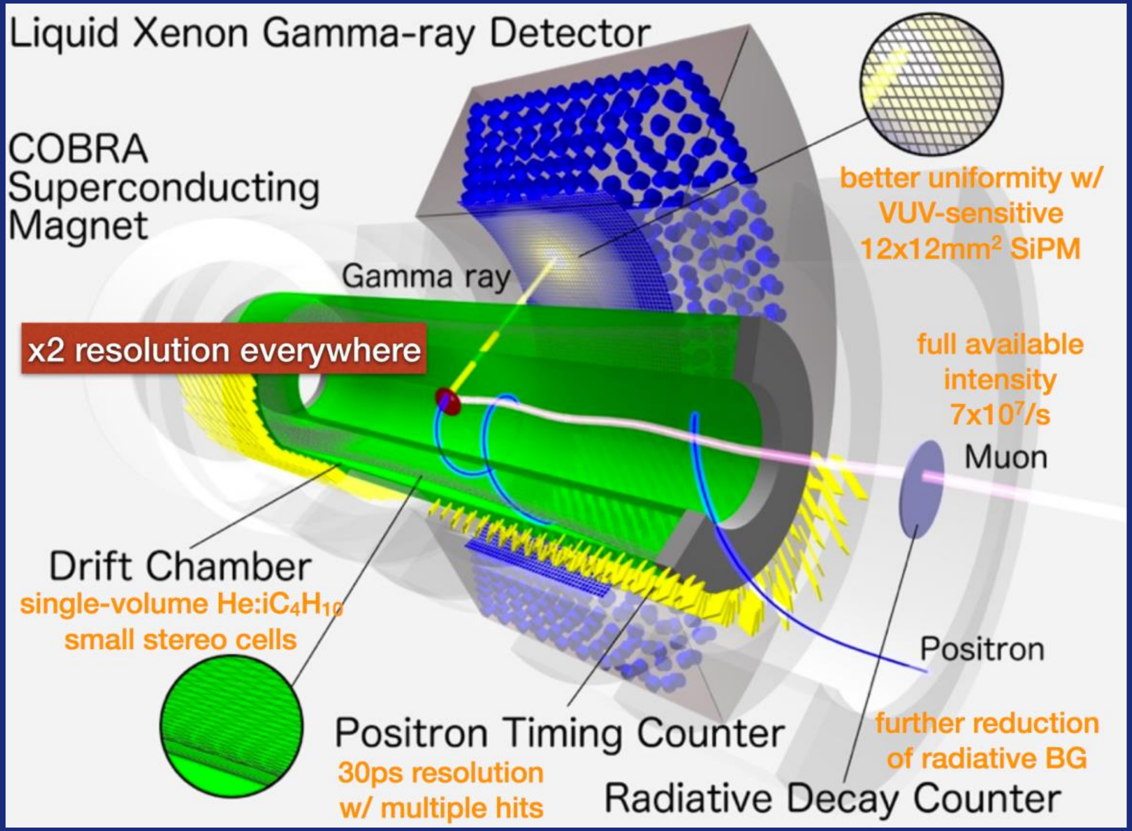
Main backgrounds:
Accidental:
e^+ from Michel decay + γ photon from e^+ annihilation or Bremsstrahlung or from radiative Michel decay .

Radiative Michel decays

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

MEG II

$\mu \rightarrow e\gamma$ (2017- …)

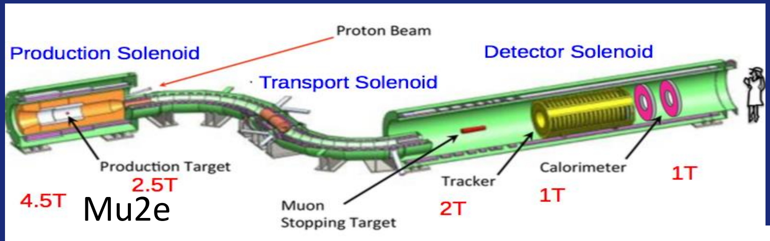


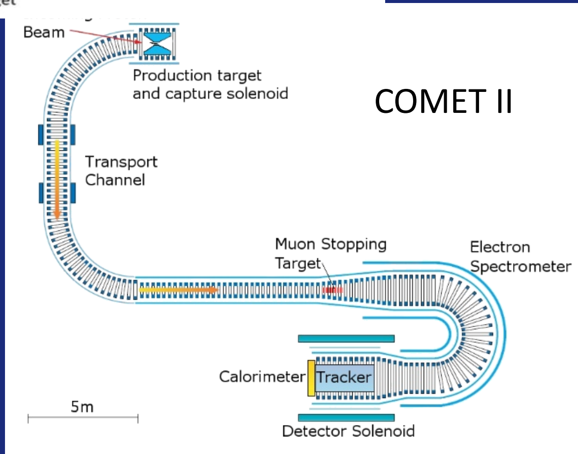
Beamline improvements approaching 10^8 μ/s
→ Higher accidental BG (Intensity^2)
→ Need better timing and momentum resolution.

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($\mu \rightarrow e\gamma$) < 4×10^{-14} (90% C.L.)

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

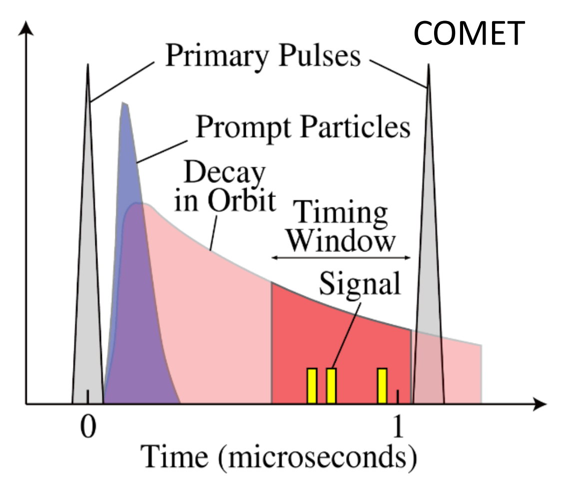




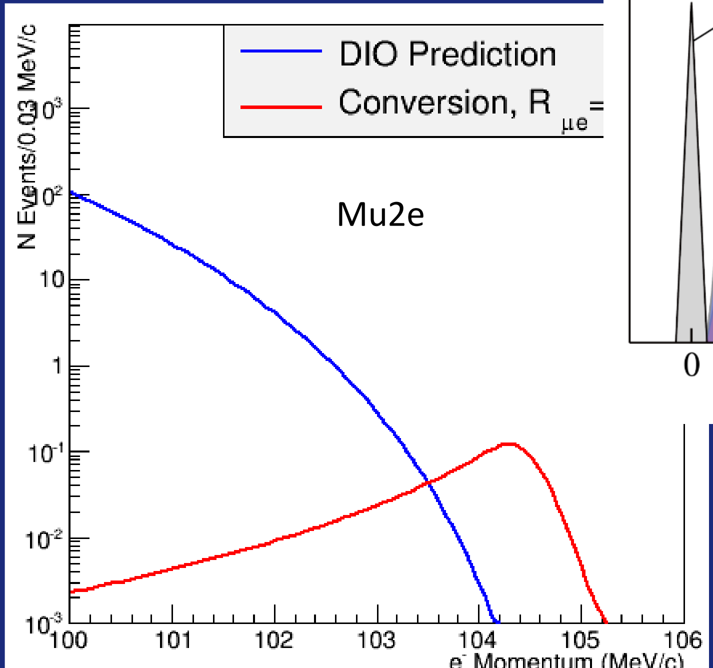
- Beam delivery systems optimised to achieve high intensity, very pure, muon beam on target.
- Stopped muons are trapped in orbit around the Al nucleus.
- Search for coherent decay $\mu N \rightarrow eN$

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

$\rightarrow$ 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})

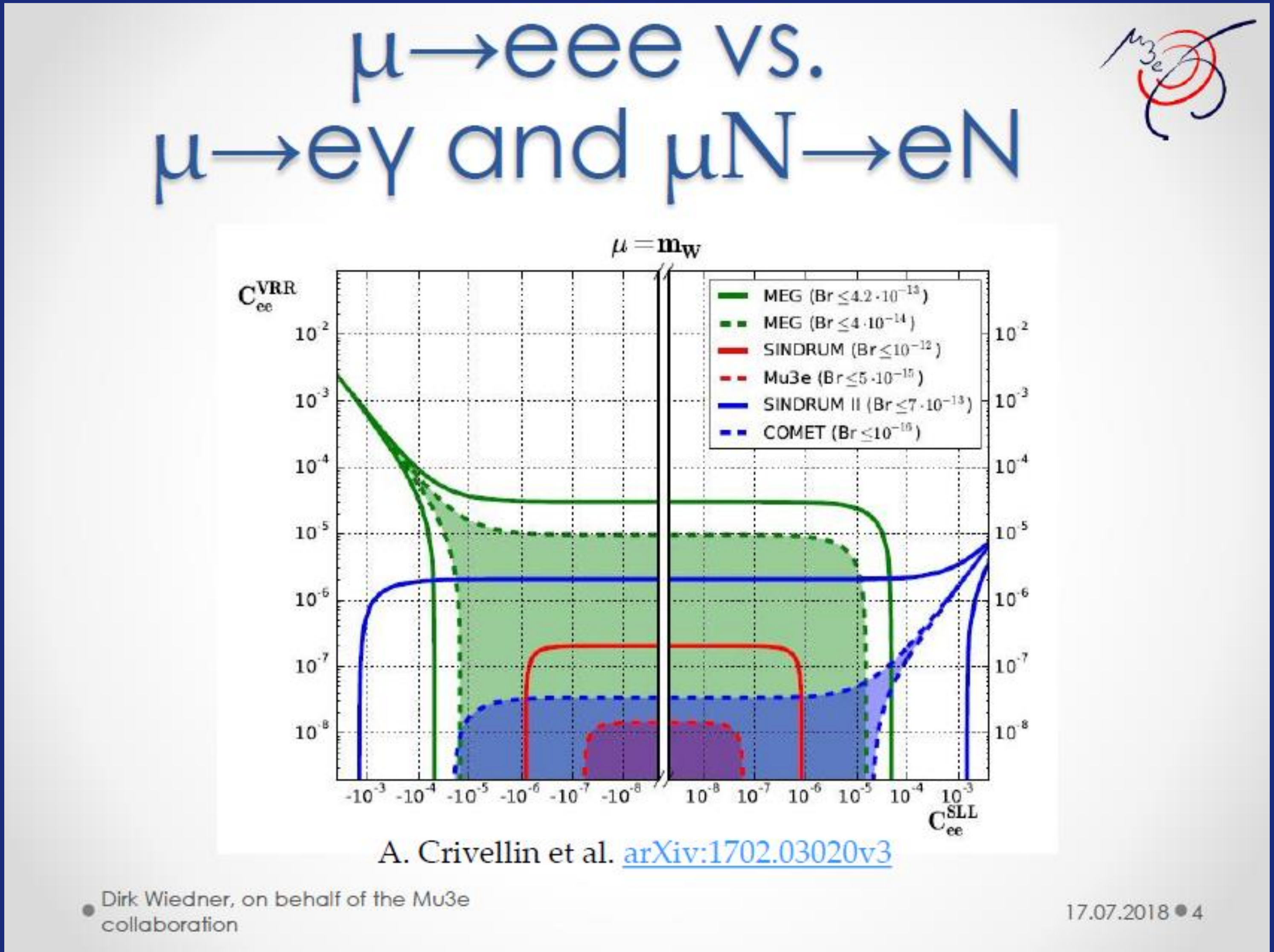


- **Muon decay in orbit** ($\mu N \rightarrow e\nu\nu N$)
- precise momentum resolution

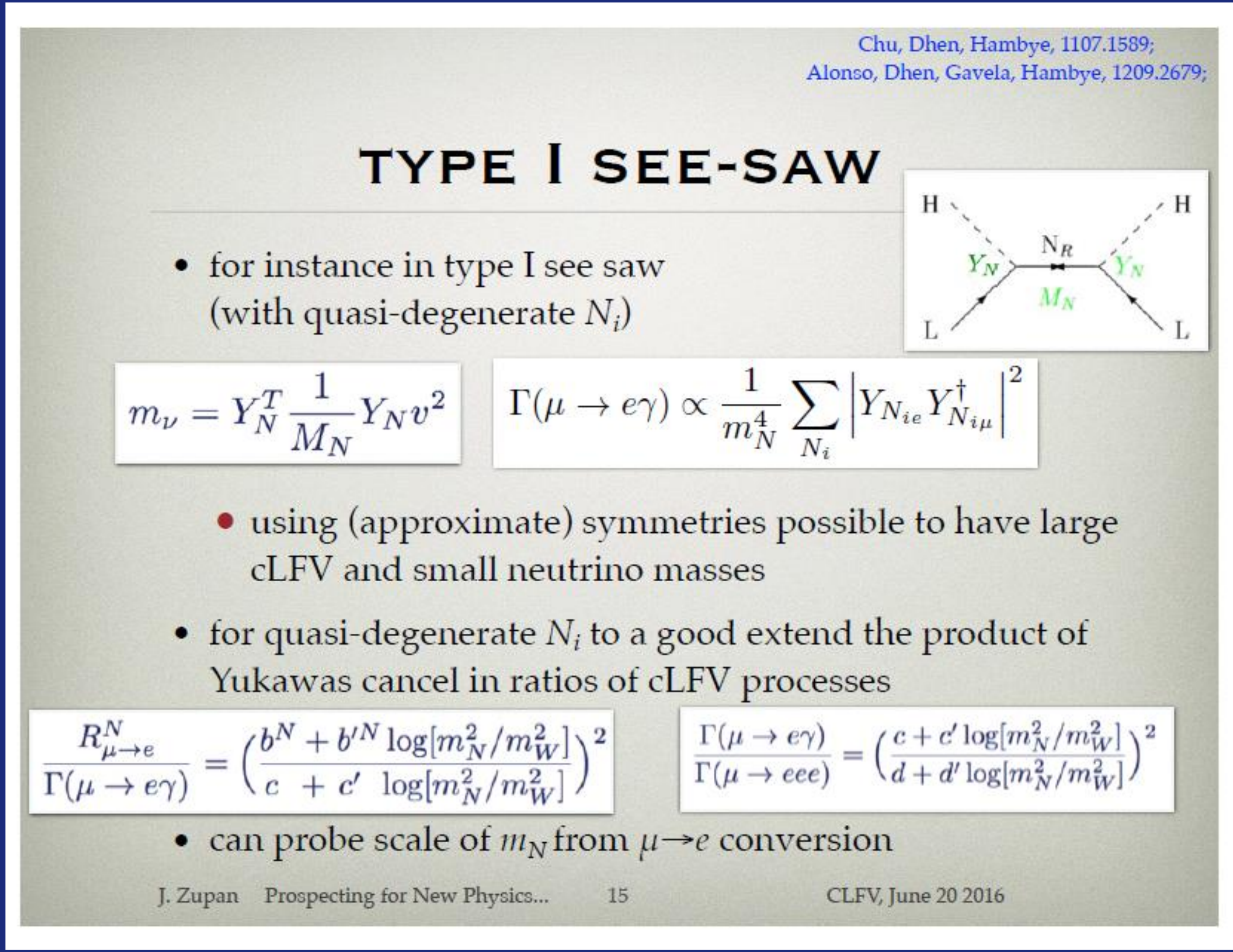
Mu3e specific CLFV sensitivity

Generic study comparing sensitivity to different Wilson coefficients.

Particular sensitivity to eμee 4 fermion contact terms



Importance of searching in all CLFV channels. Example



Chu, Dhen, Hambye, 1107.1589;
Alonso, Dhen, Gavela, Hambye, 1209.2679;

TYPE I SEE-SAW

- for instance in type I see saw (with quasi-degenerate N_i)

$$m_\nu = Y_N^T \frac{1}{M_N} Y_N v^2$$

$$\Gamma(\mu \to e\gamma) \propto \frac{1}{m_N^4} \sum_{N_i} \left| Y_{N_{ie}} Y^\dagger_{N_{i\mu}} \right|^2$$

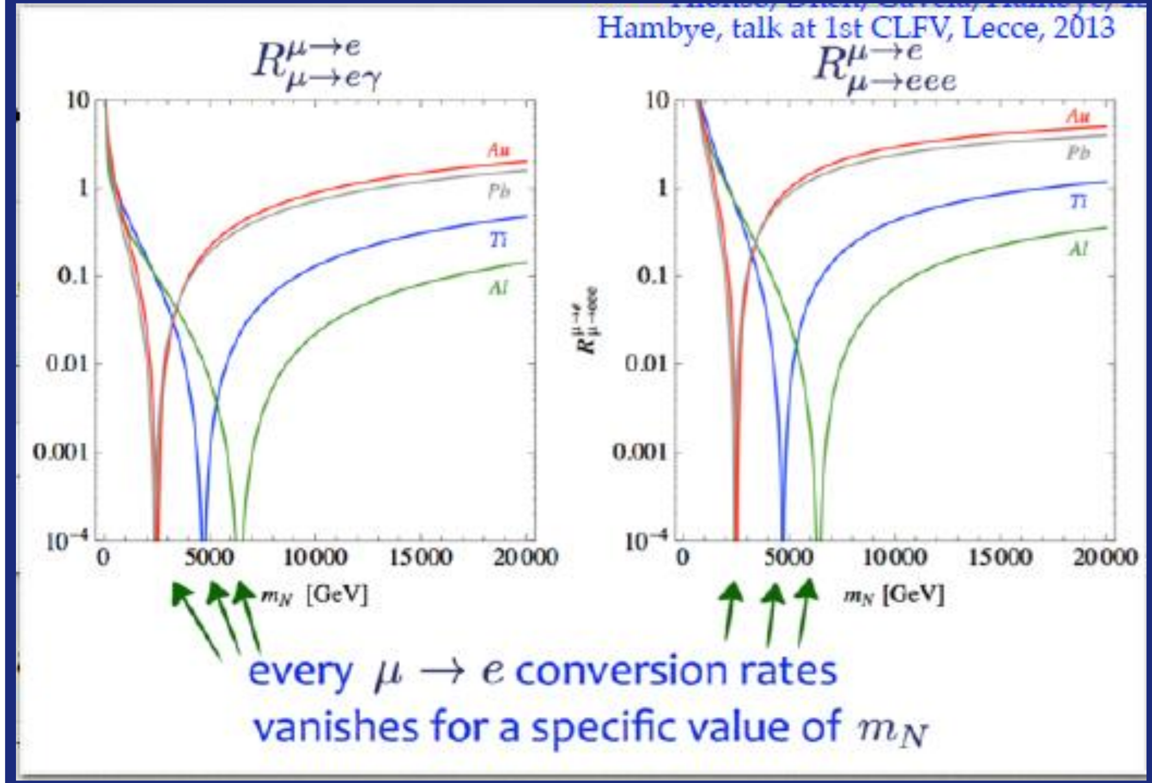
- using (approximate) symmetries possible to have large cLFV and small neutrino masses
- for quasi-degenerate N_i to a good extend the product of Yukawas cancel in ratios of cLFV processes

$$\frac{R^N_{\mu\to e}}{\Gamma(\mu \to e\gamma)} = \left(\frac{b^N + b'^N \log[m_N^2/m_W^2]}{c \ + c' \ \log[m_N^2/m_W^2]}\right)^2$$

$$\frac{\Gamma(\mu \to e\gamma)}{\Gamma(\mu \to eee)} = \left(\frac{c + c' \log[m_N^2/m_W^2]}{d + d' \log[m_N^2/m_W^2]}\right)^2$$

- can probe scale of m_N from $\mu\to e$ conversion

J. Zupan Prospecting for New Physics... 15 CLFV, June 20 2016



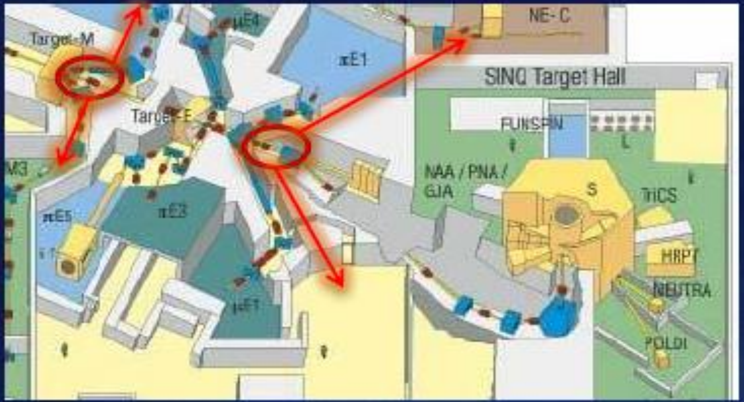
slide Jure Zupan, CLFV Charlottesville 2016

HIMB: Future high rate muon options at PSI

Alternative Possibilities

Constraints - any intervention to the proton beam line must:

- Not significantly increase the beam losses
- Preserve the proton footprint and energy on SINQ
- Preserve the total material budget seen by the beam

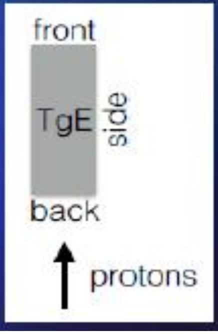


Just started to look at "conventional targets" in combination with solenoids
Possibilities under assessment

As a "conventional target", Target E is surprisingly efficient at producing surface muons: for I_p=2.3 mA

Polycrystalline Graphite, 1700K

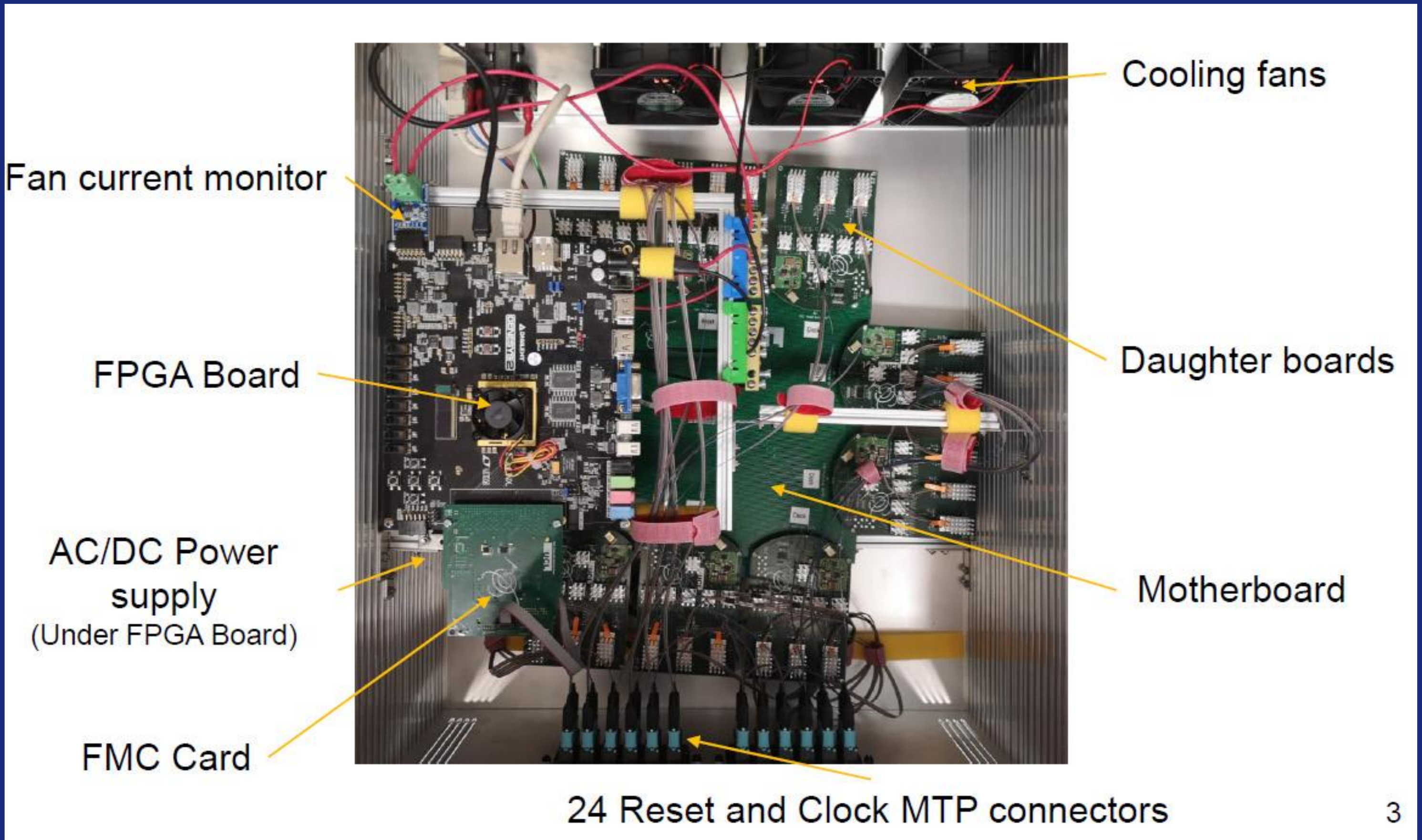
TgE length	Front	Back	Side
10 mm	9.6×10^{9}/s	1.5×10^{10}/s	1.9×10^{10}/s
20 mm	1.3×10^{10}/s	1.9×10^{10}/s	5.8×10^{10}/s
30 mm	1.6×10^{10}/s	1.7×10^{10}/s	9.5×10^{10}/s
40 mm	1.6×10^{10}/s	2.0×10^{10}/s	1.3×10^{11}/s
60 mm	1.6×10^{10}/s	2.1×10^{10}/s	2.2×10^{11}/s



- **Front/back surfaces saturate with L**
- **side surface viewing very efficient**

Peter-Raymond Kettle, 2015

Peter-Raymond Kettle *Future Muon Sources Workshop – Univ. of Huddersfield 2015* 16


Cooling fans
Fan current monitor
Daughter boards
FPGA Board
AC/DC Power supply
(Under FPGA Board)
Motherboard
FMC Card
24 Reset and Clock MTP connectors
3