University of Zurich[UZH]
Physik–Institut

Search for the decay

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

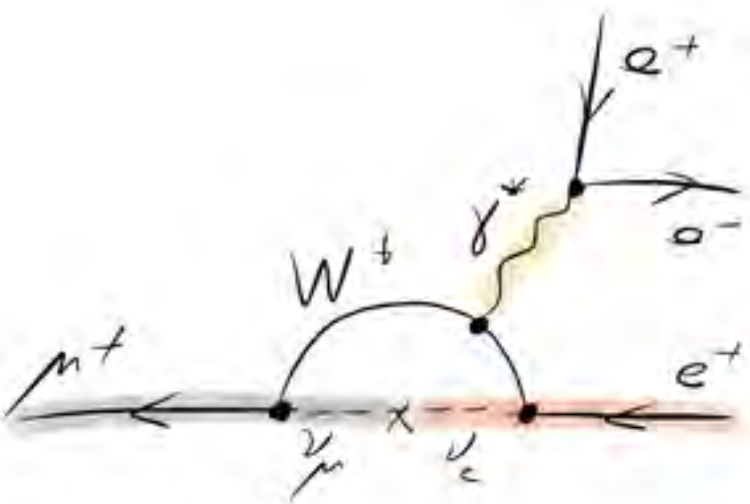
XVII International Workshop
on Neutrino Factories and Future Neutrino Facilities

Roman Gredig on behalf of the Mu3e Collaboration

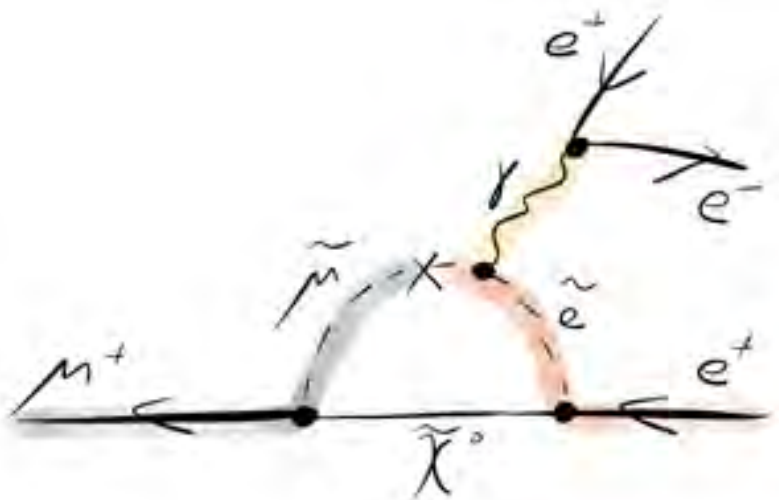
Lepton Flavor Violating Decay

Search for the lepton flavor violating decay $\mu^+ \to e^+e^-e^+$

- lepton flavor not conserved
- we know it from neutrino oscillation
- but the charged leptons?



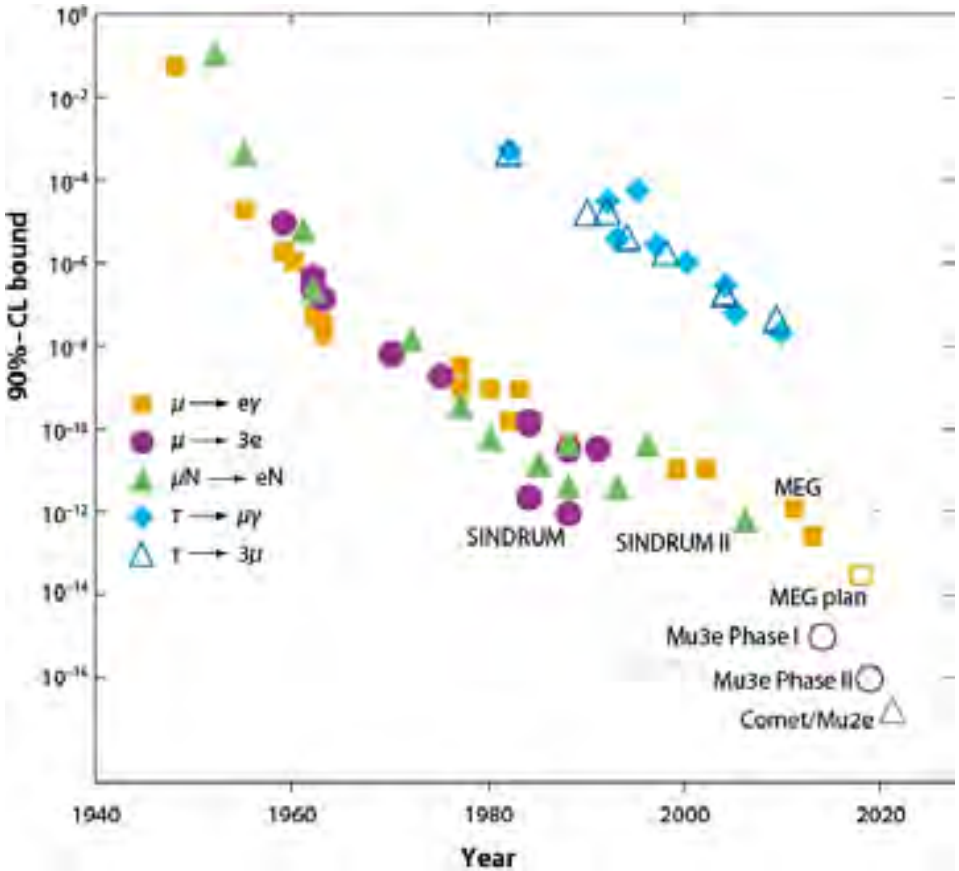
$\mathcal{B} < 10^{-54}$



$\Rightarrow$ sensitive to new physics

CLFV Experiments

long history at the Paul Scherrer Institute



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

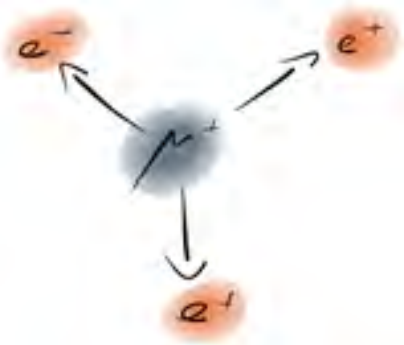
- SINDRUM (1988)
  $\mathcal{B}(\mu \to eee) < 1 \cdot 10^{-12}$
- SINDRUM II (2006)
  $\mathcal{B}(\mu^- \mathrm{Au} \to e^- \mathrm{Au}) < 7 \cdot 10^{-13}$
- MEG (2013)
  $\mathcal{B}(\mu^+ \to e^+ \gamma) < 5.7 \cdot 10^{-13}$

- Mu3e Phase I
  $\mathcal{B}(\mu \to eee) < 10^{-15}$
- Mu3e Phase II
  $\mathcal{B}(\mu \to eee) < 10^{-16}$

The Mu3e Experiment

- Mu3e is a dedicated experiment searching for $\mu^+ \to e^+e^-e^+$
- aimed sensitivity $\mathcal{B}(\mu \to eee) < 10^{-16}$
- stopped muons per second: 10^9
- main background: $\mu \to eee\nu_e\nu_\mu$, with $\mathcal{B} = 3.4 \cdot 10^{-5}$ and accidentals

Signal:



- $\Sigma\vec{p}_i = 0$
- common vertex
- $p < 53\,\text{MeV}$

BG: Internal Conversion

- $\Sigma\vec{p}_i \neq 0$
- common vertex

BG: Accidental

- non common vertex
- not in coincidence

The Mu3e Experiment

Requirements

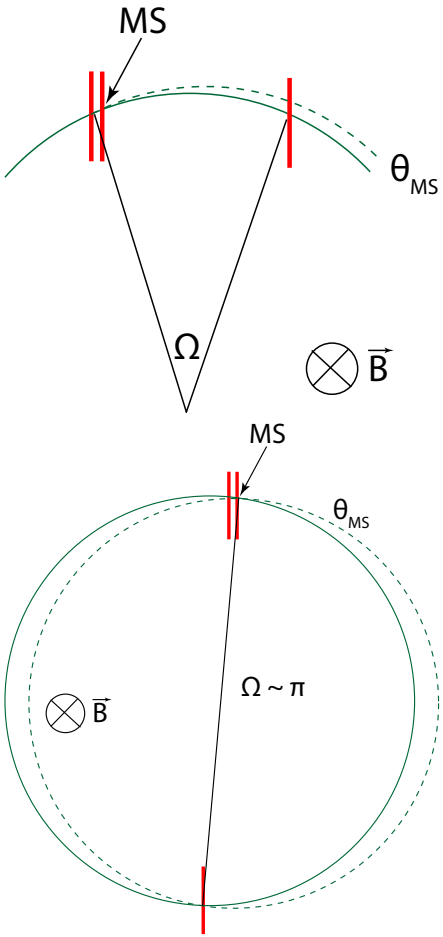
- combinatorial background
  $\Rightarrow$ high vertex and time resolution: $\mathcal{O}(100\,\mu m)$, $\mathcal{O}(\text{several}100\,ps)$

- $\mu \rightarrow eee\nu_e\nu_\mu$ background
  $\Rightarrow$ precise measurement of momentum: $\sim 0.5\,MeV/c$

- multiple scattering
  $\Rightarrow$ thin detectors

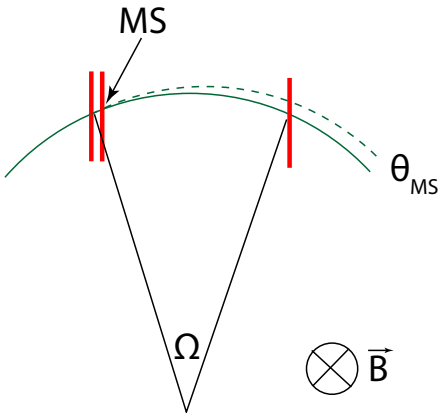
- modular structure: 3 phase construction concept
  $\Rightarrow$ several intermediate steps until the final rate of $\sim 10^9\ \mu^+/s$

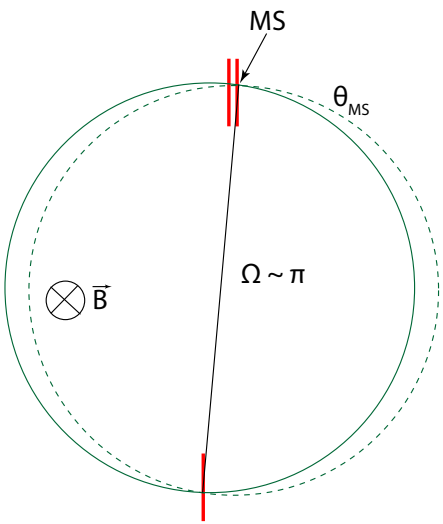
Momentum Measurement



- $p = 15 - 53\text{MeV}/c$
- resolution dominated by multiple scattering (and not by the sensor resolution)
- 1st order momentum resolution: $\frac{\sigma_p}{p} \sim \frac{\Theta_{MS}}{\Omega}$
- multiple scattering effects cancel out after half turn
- Mu3e designed for measuring *re-curlers*

Momentum Measurement





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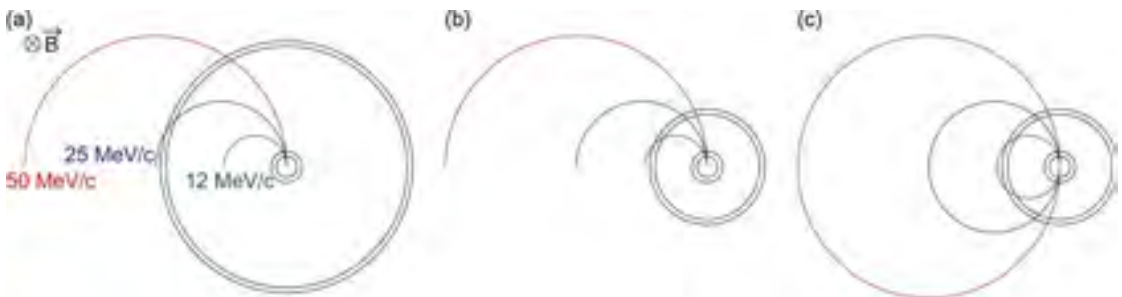
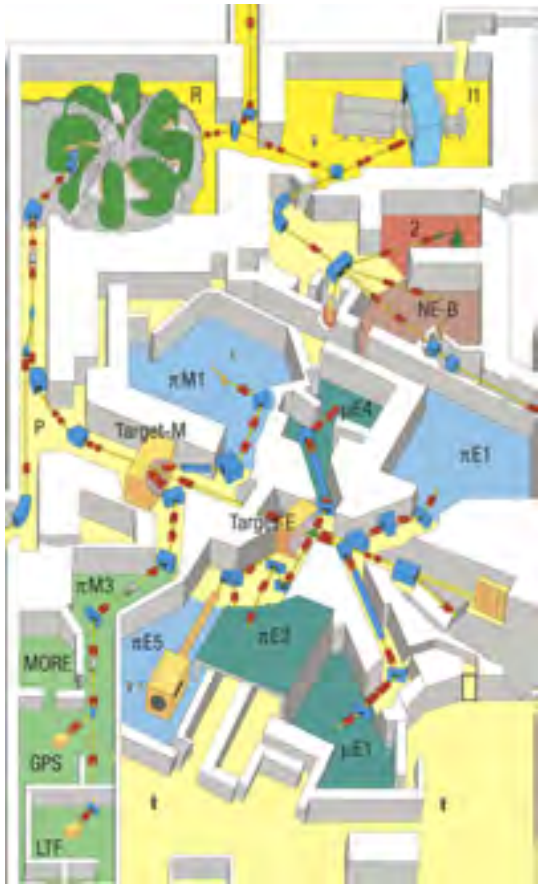


Muon Beam at PSI



- muon beamline at PSI
- low energy DC beams
- πE5 beamline: $\sim 10^8$ 28 MeV/c surface muons
  - shared with MEG
  - works for Phase I
- HiMB:
  High intensity muon beam
  study ongoing
  needed for Phase II
  Mu3e: $\sim 10^9$ μ^+/s
  PSI Goal: $\sim 10^{10}$ μ^+/s

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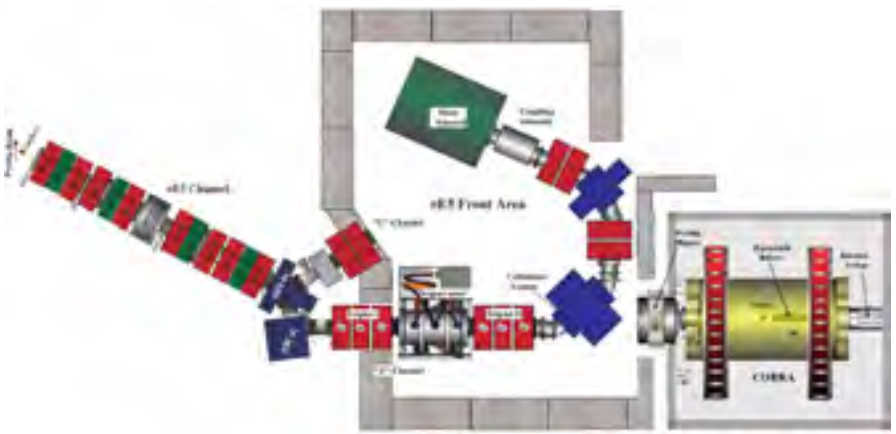

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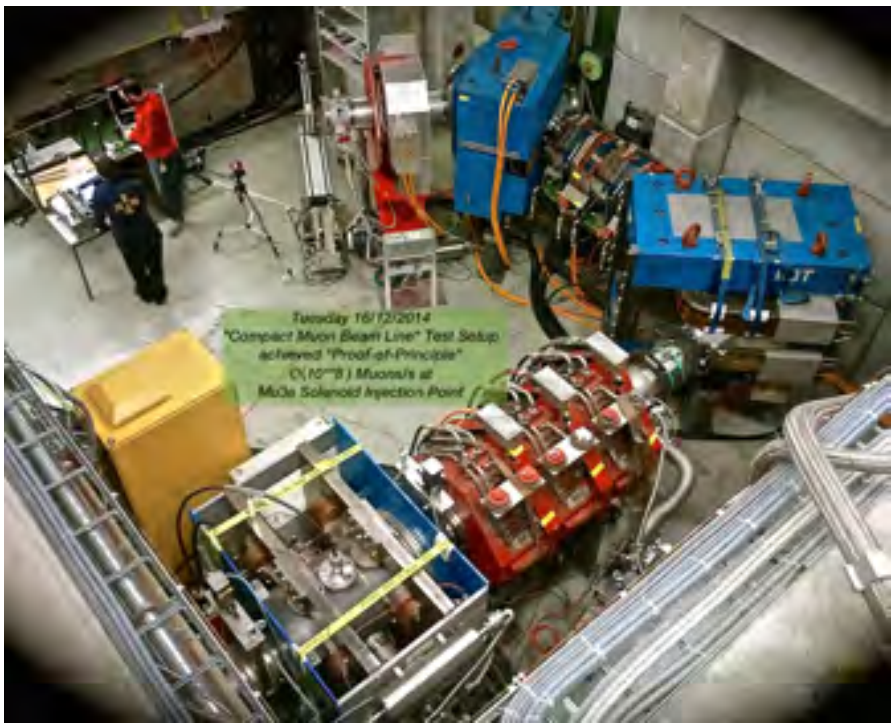

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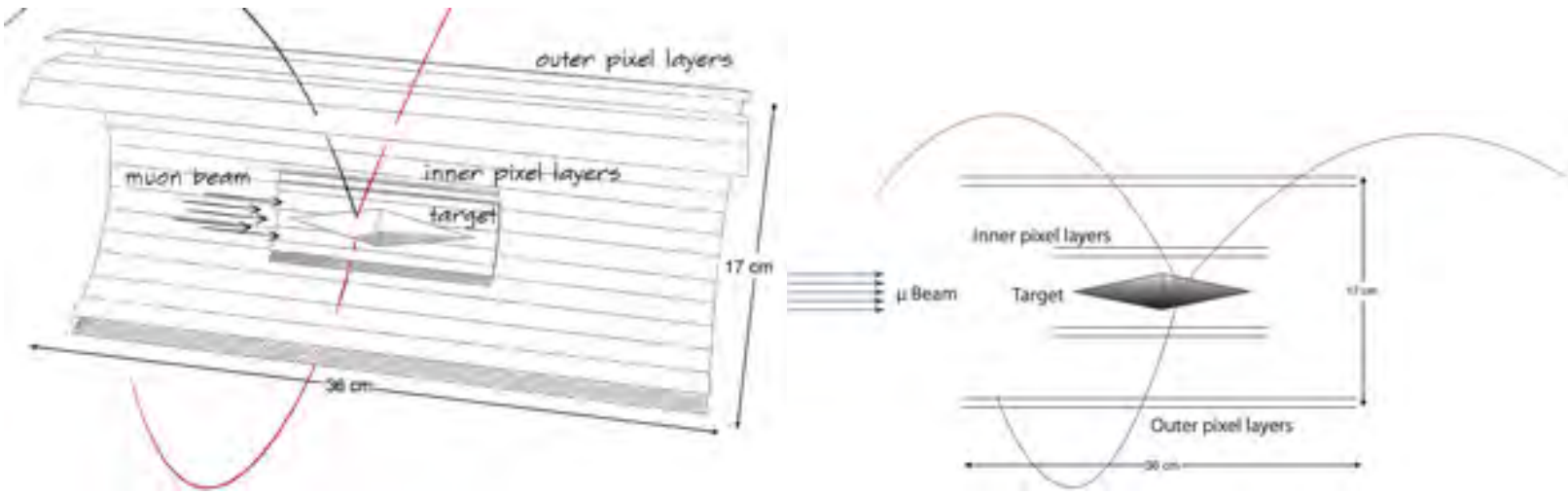
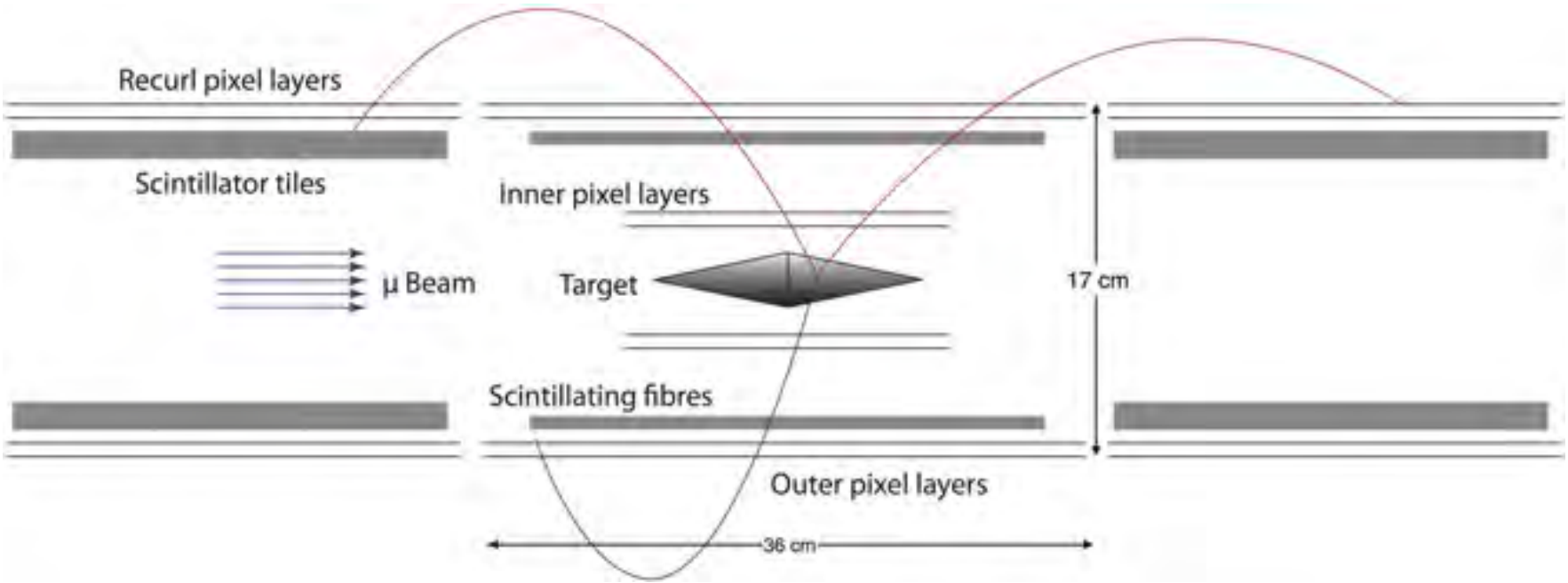
Detector Concept

- hollow Mylar double cone target 100 mm × 38 mm, thickness 50 − 150µm
- homogeneous magnetic field: ∼1 T and He atmosphere
- Phase Ia: muon stopping: ∼ 10^7 μ^+/s (2016)
- central module only
- four layers of Si pixel detectors
- module length 36 cm, diameter 17 cm



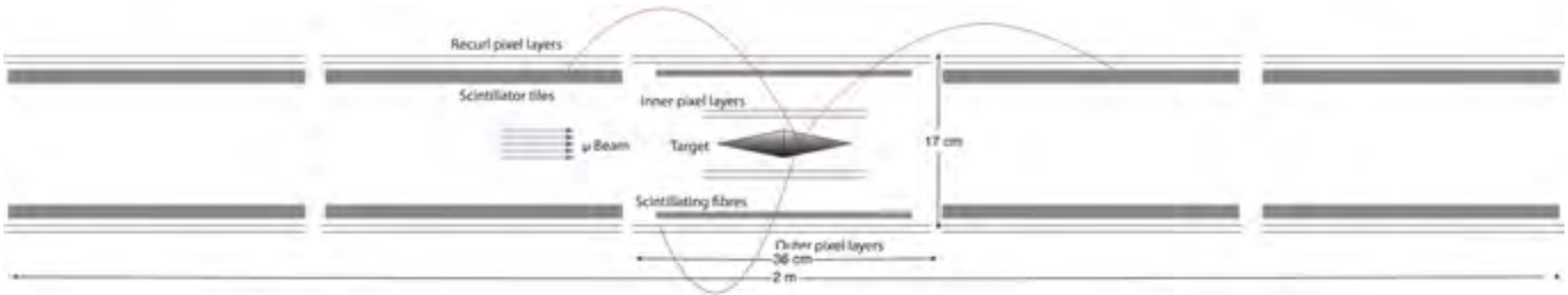
Detector Concept

- Phase Ib: muon stopping $\sim 10^8$ μ^+/s (2017)
- central module upgraded with 250 µm diameter scintillation fibres (three layers)
- two additional recurl modules including pixel and scintillation tiles
  $\Rightarrow$ better timing

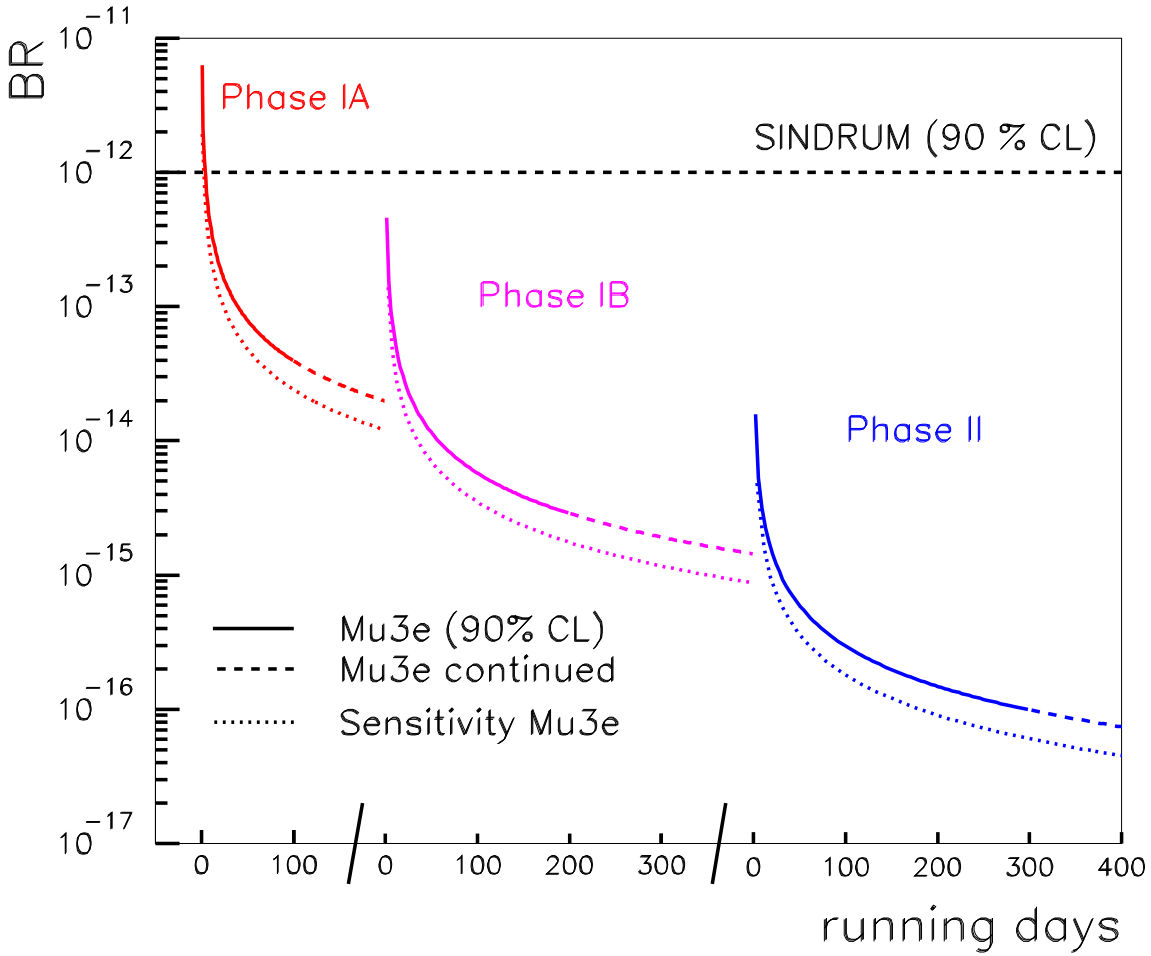


Detector Concept

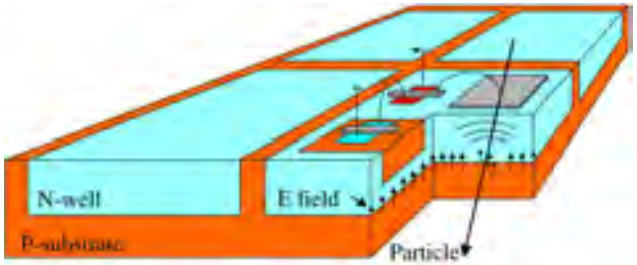
- Phase II: muon stopping $\sim 10^9$ μ^+/s (2019)
- add two identical recurl modules (with pixel and tiles)
  $\Rightarrow$ increased acceptance
- new muon beamline



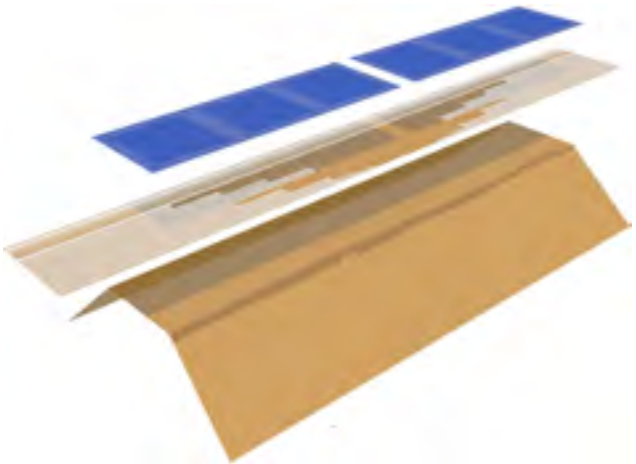
Expected Sensitivity



Monolithic Active Pixel Sensors

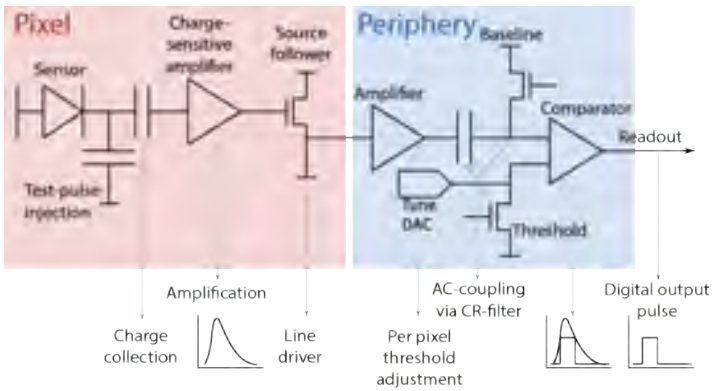


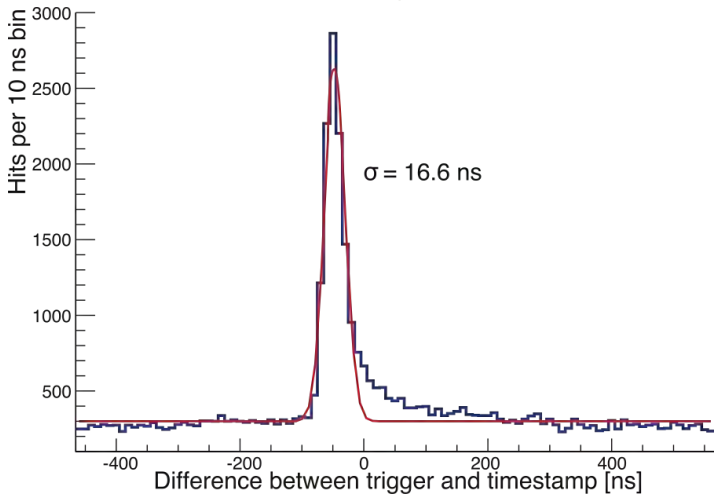
I. Peric, P. Fischer et al. NIM A 582 (2007) 876



- HV-MAPS: High Voltage Monolithic Active Pixel Sensors ($\sim$ 70 V)
- HV-CMOS technology
- fast charge collection by drift $\mathcal{O}$(1 ns)
- thickness: $<$50 µm
- pixel size: 80 µm $\times$ 80 µm
- active area: 2 cm $\times$ 2 cm
- zero-suppressed data: addresses and timestamps via LVDS link
- with capton support structure thickness $\sim$ 1 ‰ radiation length per layer

Monolithic Active Pixel Sensors





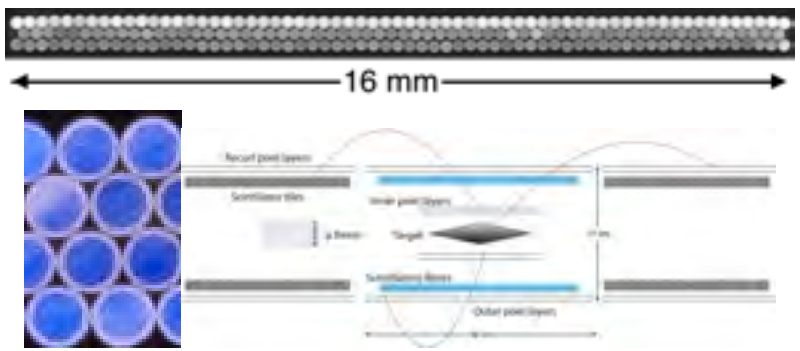
MuPix currently in its 7th generation:

- MuPix 2
  - $30 \times 39\,\mu m^2$ pixel size
  - $1.8 \times 1.2\,mm^2$ active area
  - proof of concept
- MuPix 3 and 4
  - $80 \times 92\,\mu m^2$ pixel size
  - $2.9 \times 3.2\,mm^2$ active area
- MuPix 6
  - same geometry
  - second amplifier added

  MuPix 7
  - still small scale prototype
  - full digital readout + fast serial link

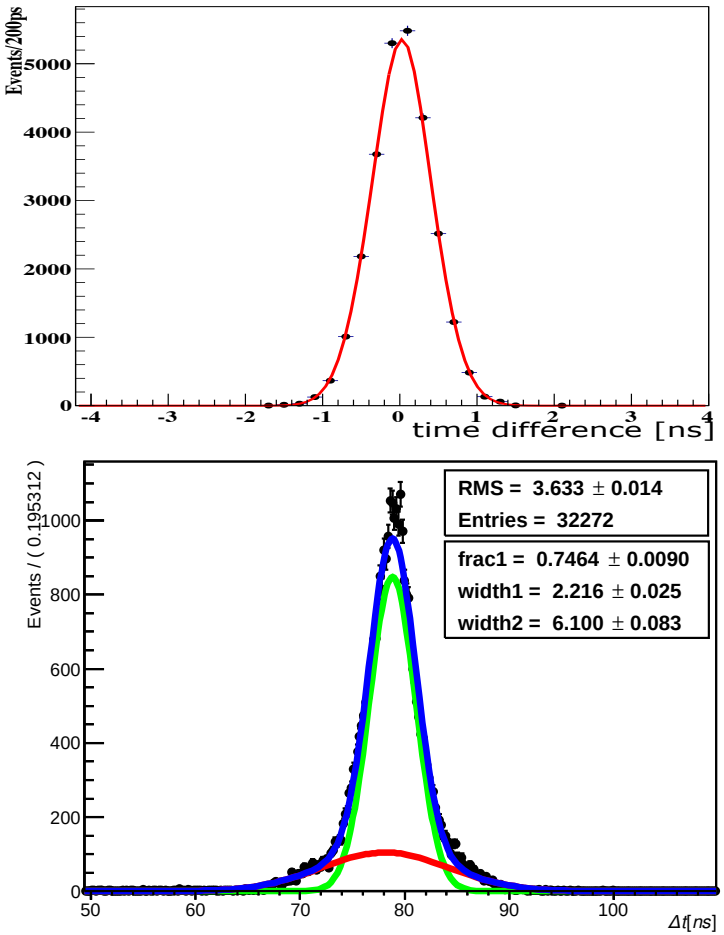
Scintillating Fibres

- three layers of $\sim$ 1500 fibres with a diameter of 250 µm
- produced as 16 mm wide modules with a length of 30 cm
- read out on both ends with silicon photomultiplier arrays and custom ASIC (STiC chip)
  (either columns wise or individual with fanout)
- time resolution goal: $<$1 ns
- two fibre types under investigation:
  - round double cladding fibres
  - squared double cladding fibres



Scintillating Fibres

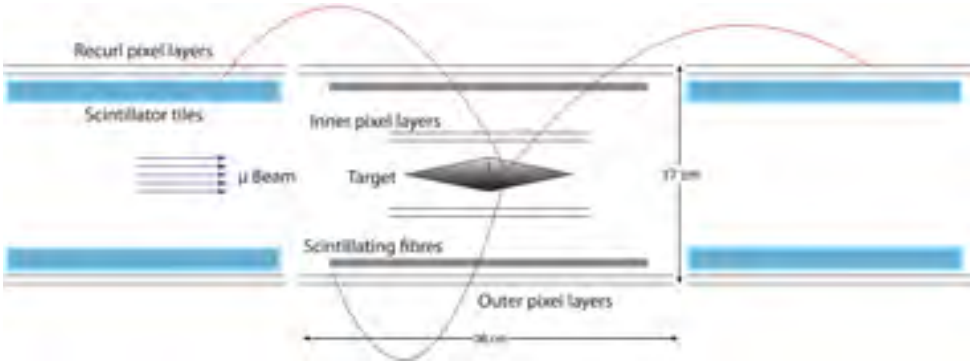
Fibre prototyping

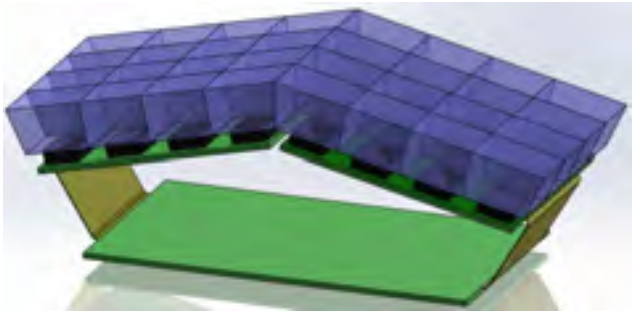


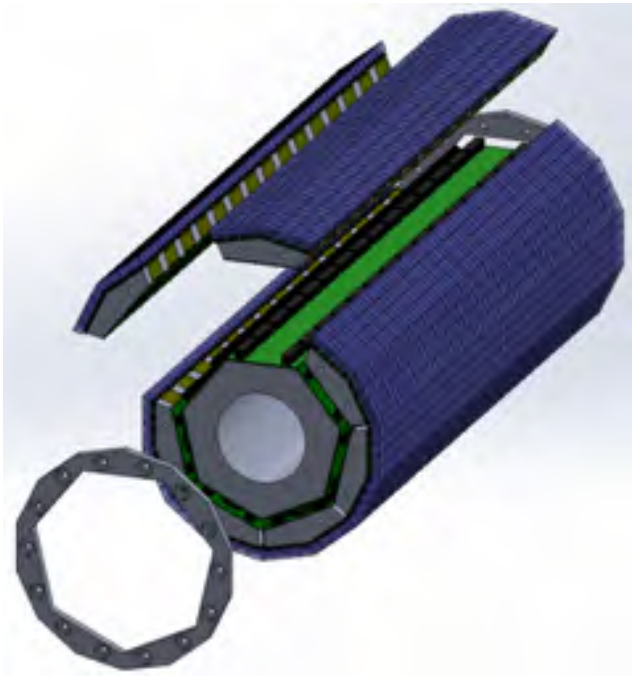
fibre end time difference: top: squared fibres, bottom: round fibres

- fibre prototyping ongoing
- several testbeam campaigns
- time resolution:
  - squared fibres: $\frac{\sigma_{\Delta t}}{\sqrt{2}} = <500\,\text{ps}$
  - round fibres: $\frac{\sigma_{\Delta t}}{\sqrt{2}} = \sim 1.5\,\text{ns}$

Scintillating Tiles

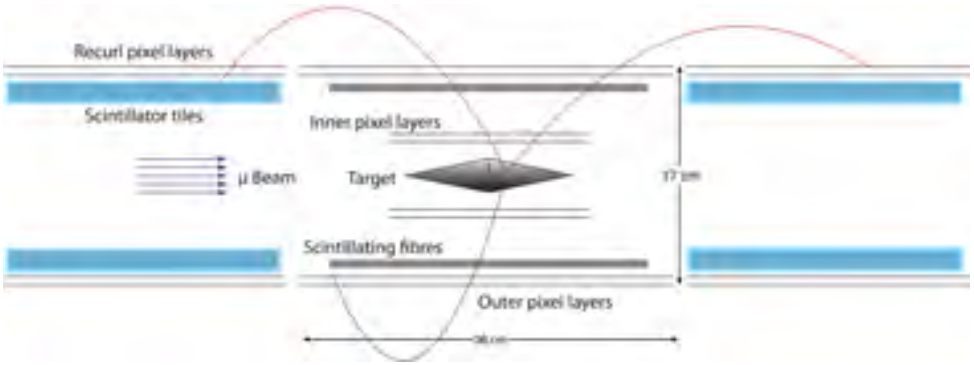


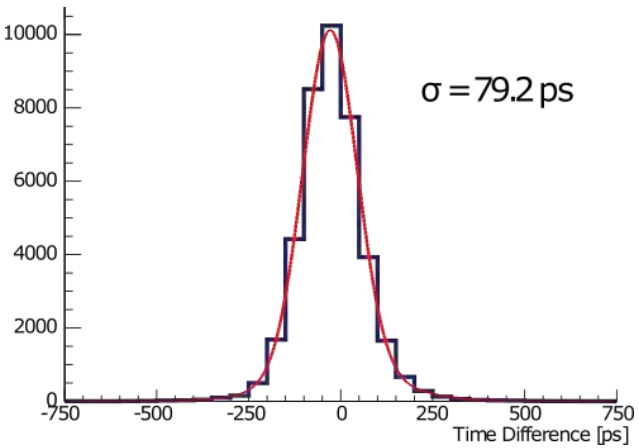




- 3360 scintillation tiles per station with $\sim 1 \times 1 \times 1\,\mathrm{cm}^3$
- individual readout with single SiPMs
- readout with same ASIC as fibres (STiC chip)
- time resolution $<100\,\mathrm{ps}$
- baseline design finished

Scintillating Tiles





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- time resolution $<100\,\mathrm{ps}$
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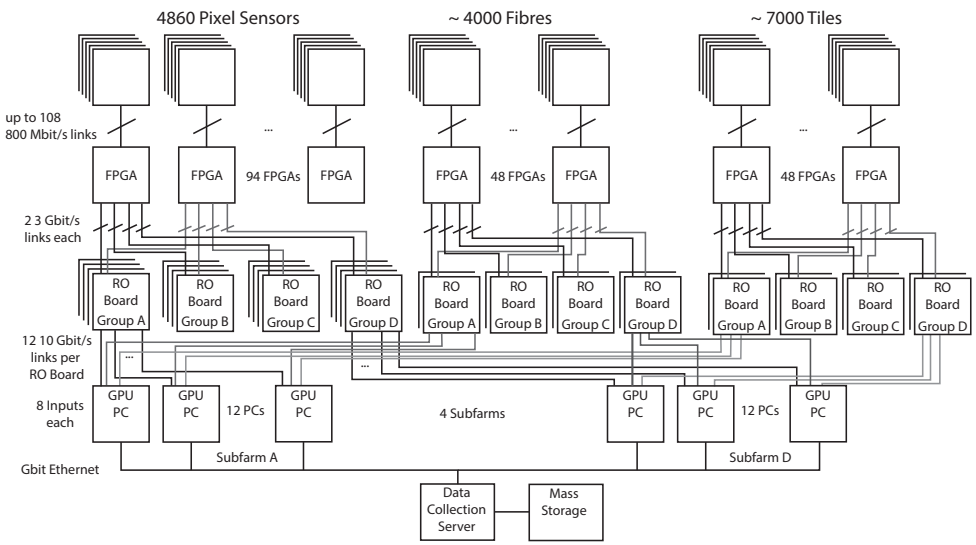
Data Acquisition

- 280 Million pixels (+ fibres and tiles)
- continuous triggerless front-end readout $\sim$1 Tbit s^{-1}
- FPGA-based switching network
- PCs with FPGAs and Graphics Processing Units (GPUs)
- online track and event reconstruction
- data reduction by factor $\sim$1000
- data to tape $<$100 MB s^{-1}



Summary and Outlook

- new experiment for the search of $\mu \to eee$ with sensitivitiy $< 10^{-16}$
- staged approach and modular principle
  - Phase Ia: Sensitivity $\mathcal{B}(\mu \to eee) < 10^{-14}$ (2016)
  - Phase Ib: Sensitivity $\mathcal{B}(\mu \to eee) < 10^{-15}$ (2017)
  - Phase II : Sensitivity $\mathcal{B}(\mu \to eee) < 10^{-16}$ (2019)
- thin active pixel sensors: HV-MAPS
- precise timing: $\mathcal{O}(100\,\text{ps})$
- high momentum resolution: $\sim 0.5\,\text{MeV}/c$
- triggerless readout

Questions ?

The Mu3e Collaboration:

- beam and target (PSI)
- solenoidal magnet (PI-HD)
- pixel detector (PI-HD, KIT, Mainz)
- scintillating fibre detector (ETHZ, PSI, UniGe, UZH)
- scintillating tile detector (KIP-HD)
- detector readout and filter farm (Mainz)
- mechanics and cooling (PSI, PI-HD)
- experimental infrastructure (PSI)
- slow control (PSI)

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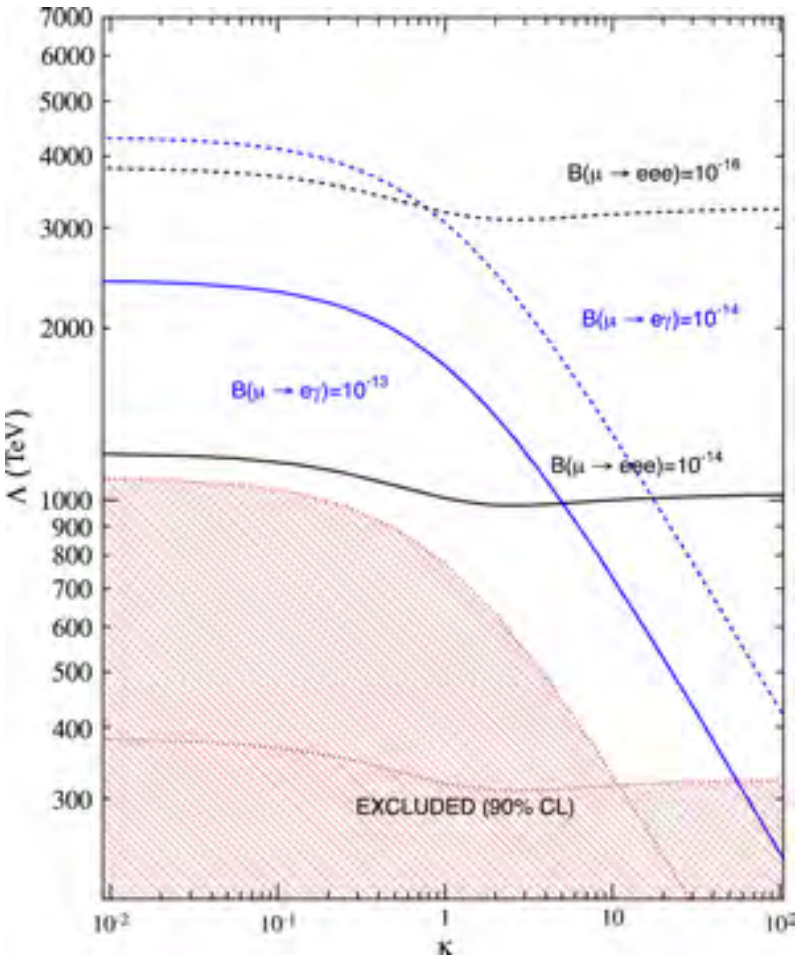
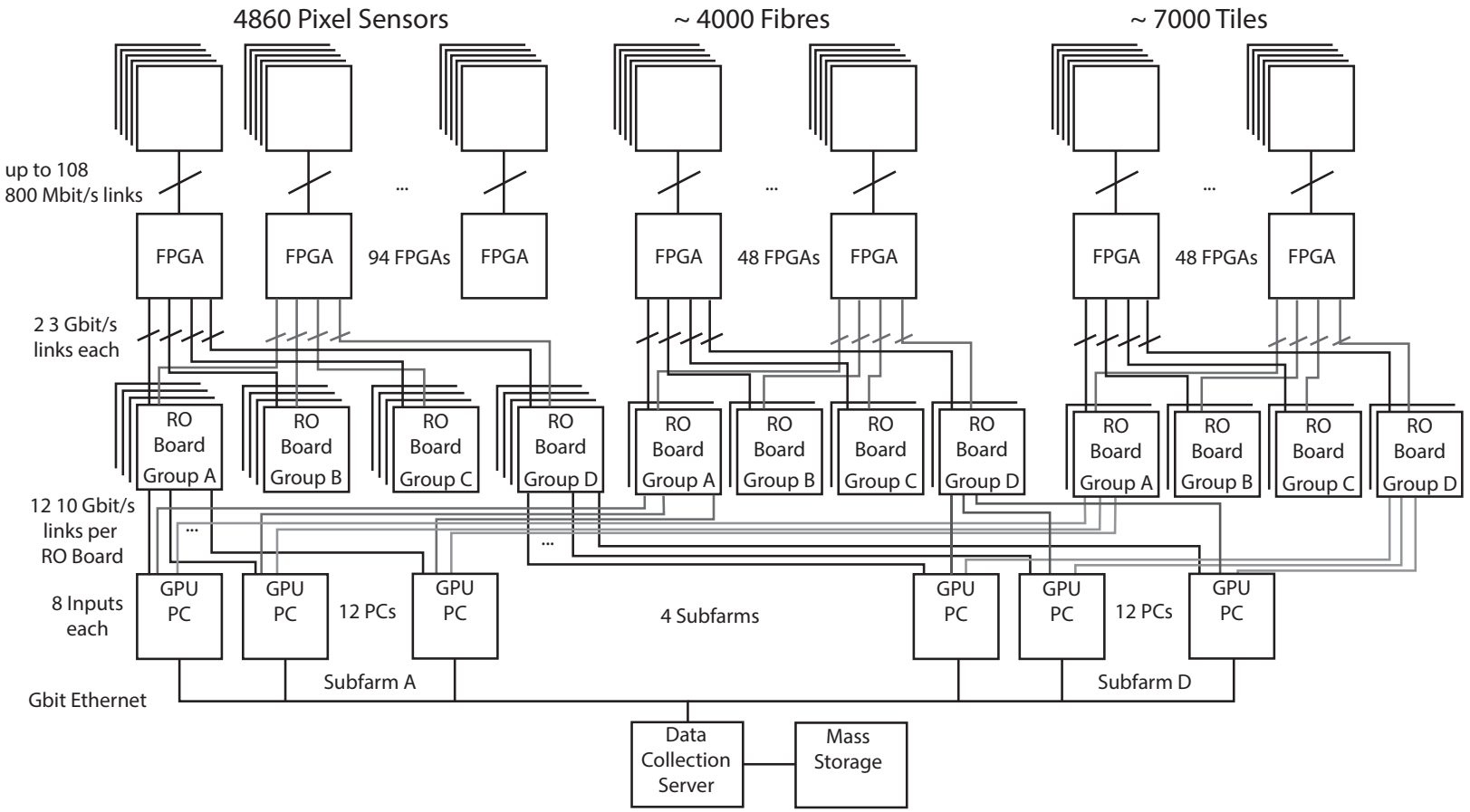
Backup



André de Gouvêa, Petr Vogel, Lepton flavor and number conservation, and physics beyond the standard model,
Progress in Particle and Nuclear Physics, 71 (2013) 75-92

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


4860 Pixel Sensors
~ 4000 Fibres
~ 7000 Tiles
up to 108
800 Mbit/s links
FPGA
94 FPGAs
48 FPGAs
2 3 Gbit/s
links each
RO Board Group A
RO Board Group B
RO Board Group C
RO Board Group D
12 10 Gbit/s
links per
RO Board
8 Inputs
each
GPU PC
12 PCs
4 Subfarms
Subfarm A
Subfarm D
Gbit Ethernet
Data Collection Server
Mass Storage