A novel experiment searching for the lepton flavour violating decay μ→eee

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Abstract

Since the discovery of neutrino oscillations it is known that lepton flavour is not conserved. Lepton flavour violating processes in the charged lepton sector have so far however eluded detection. An observation would be a clear signal for new physics.

We propose a novel experiment searching for the decay $\mu \to eee$ with the aim of ultimately reaching a sensitivity of 10^{-16}. The technologies enabling this are thin high-voltage monolithic active pixel sensors for precise tracking at high rates and scintillating fibres and tiles for high resolution time measurements plus a filter farm based on graphics processing units capable of reconstructing more than a billion tracks per second.

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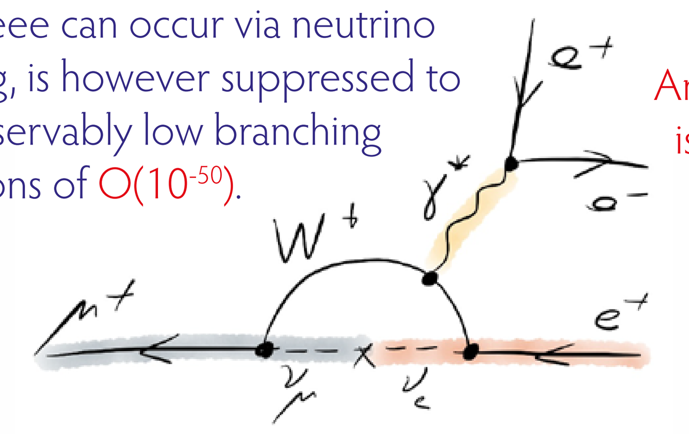
Motivation

In the Standard Model (SM) of elementary particle physics, $\mu \to eee$ can occur via neutrino mixing, is however suppressed to unobservably low branching fractions of $O(10^{-50})$.



An observation of $\mu \to eee$ is an unambiguous sign for new physics

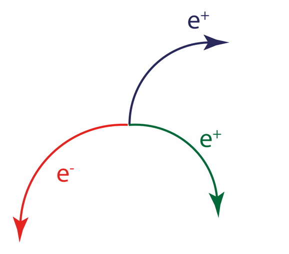
Indeed many models for physics beyond the standard model such as supersymmetry, grand unified theories, left-right symmetric models etc. predict enhanced lepton flavour violation.

$\mu \to eee$ occurs in less than 1 in 10^{12} muon decays (SINDRUM, 1988)

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

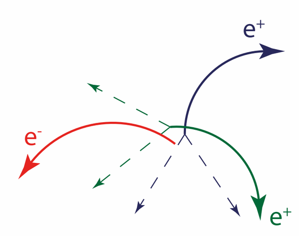
Observe 2×10^9 μ decays/s over a year

Signal & Background

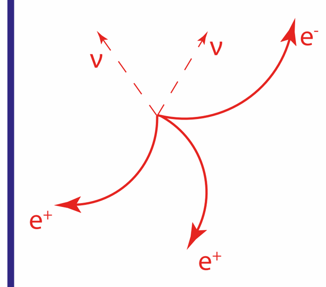


Signal $\mu^+ \to e^+e^-e^+$:
2 Positrons, 1 Electron
One vertex, same time
4-Momenta add to μ mass

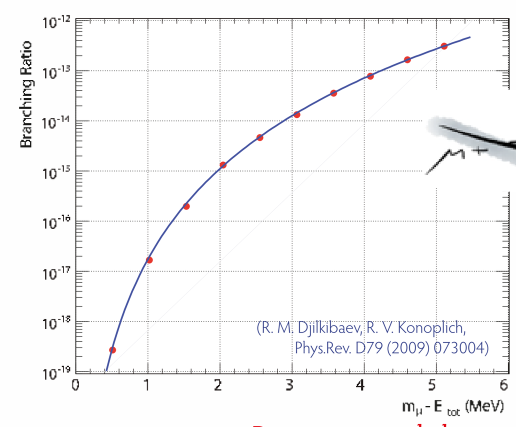
Combinatorial background:
Positrons from ordinary muon decay plus electron from photon conversion, Bhaba scattering, etc.

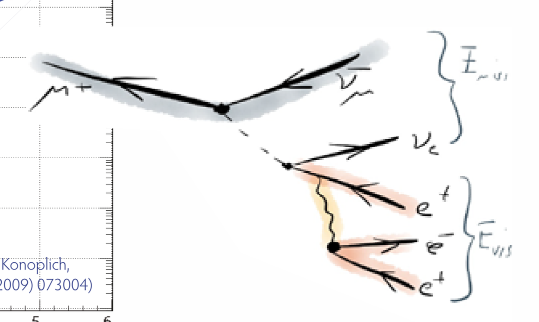


→ Good vertex, time and momentum resolution



Radiative decay with internal conversion:
Allowed muon decay
Only difference from signal:
Momentum carried by neutrinos





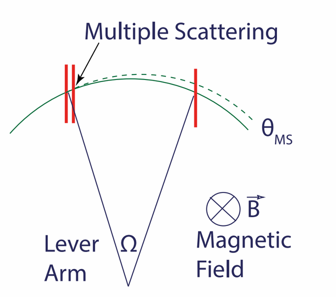
→ Best possible momentum resolution

Challenges

- High rates
- Excellent momentum resolution
- Great vertex resolution
- Good timing resolution
- Extremely low material budget

Momentum measurement

For low momentum electrons, momentum resolution dominated by multiple Coulomb scattering in detector material



$$\sigma_P/_P \sim \theta_{MS}/_\Omega$$

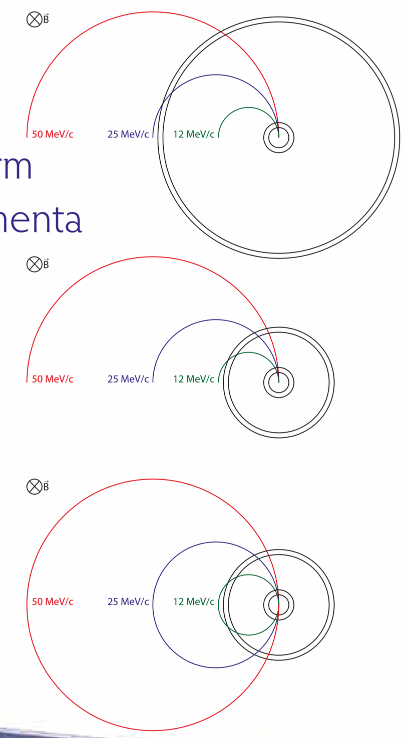
Minimize material
Maximize lever arm

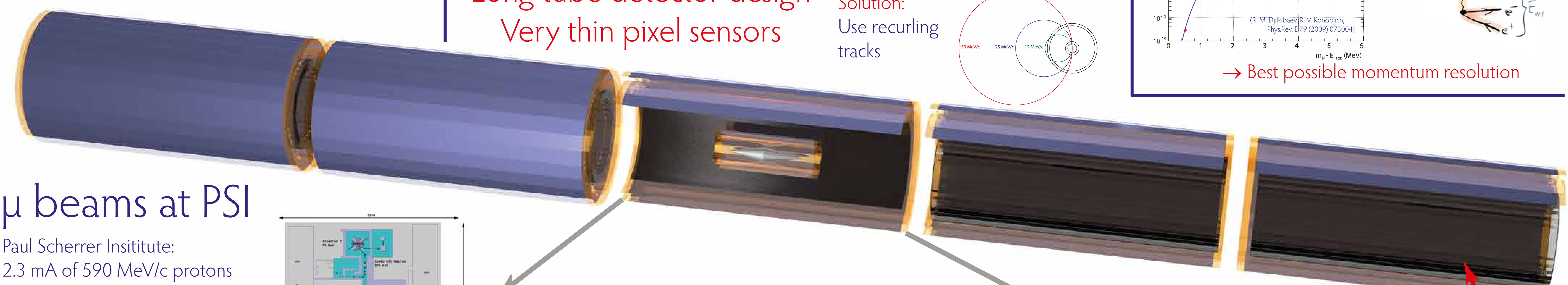
Long tube detector design
Very thin pixel sensors

Large Radius:
Good lever arm
Lose low momenta

Small Radius:
Bad lever arm

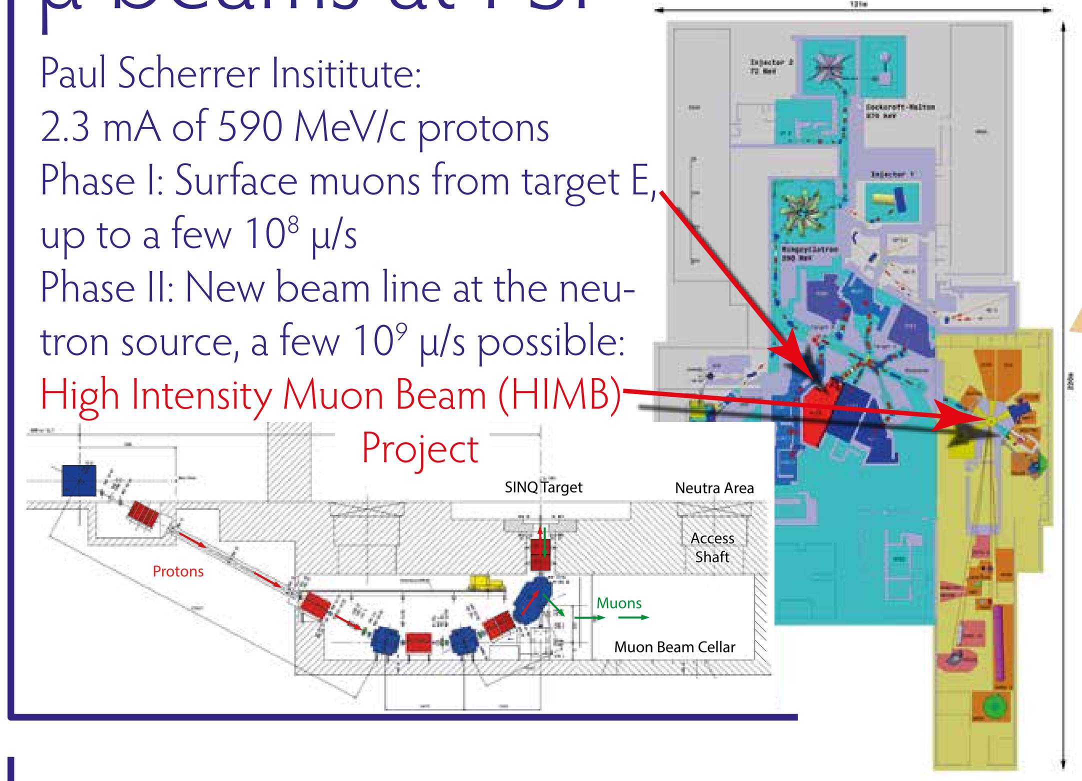
Solution:
Use recurling tracks

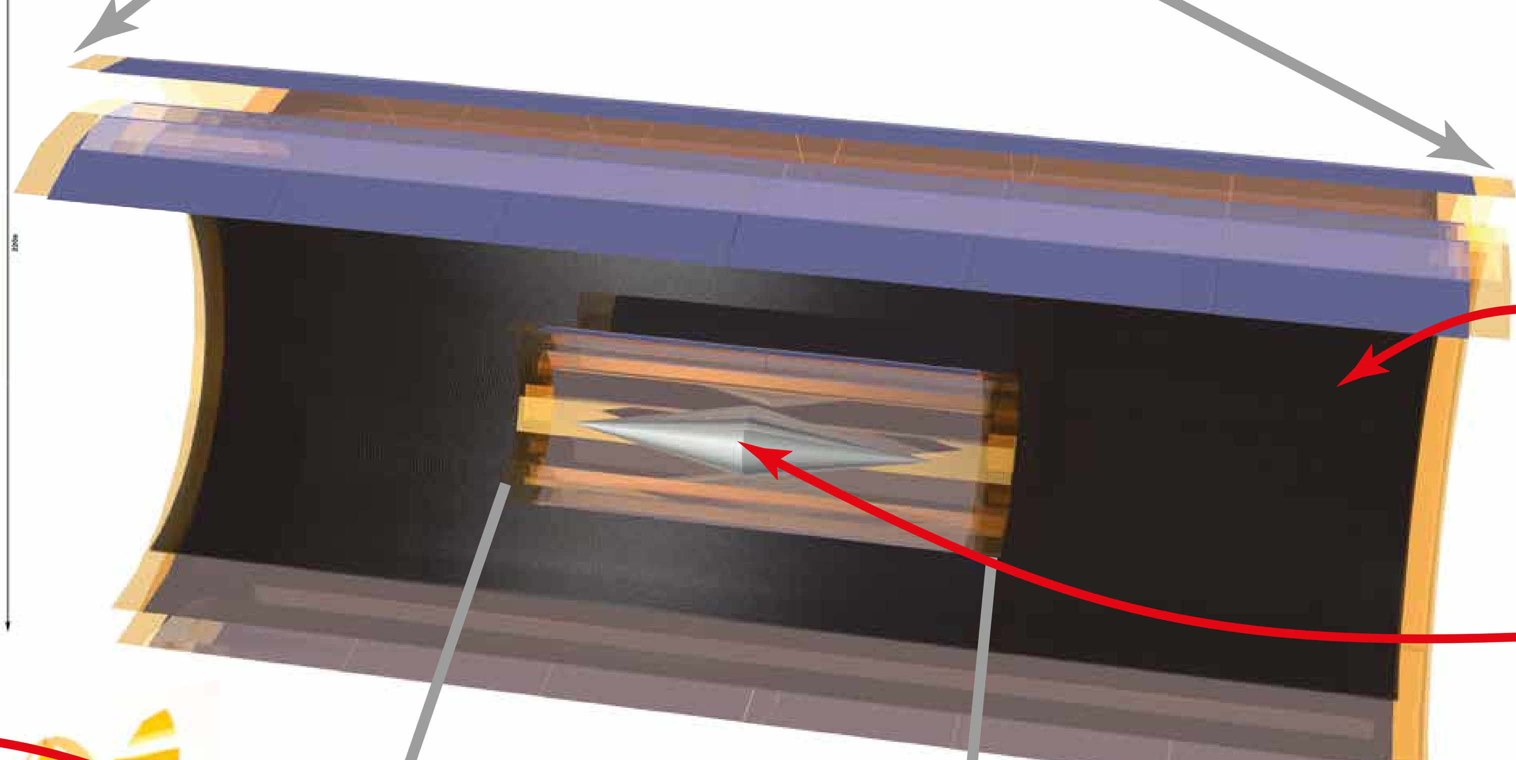




μ beams at PSI

Paul Scherrer Insititute:
2.3 mA of 590 MeV/c protons
Phase I: Surface muons from target E, up to a few 10^8 μ/s
Phase II: New beam line at the neutron source, a few 10^9 μ/s possible:
High Intensity Muon Beam (HIMB) Project





Timing

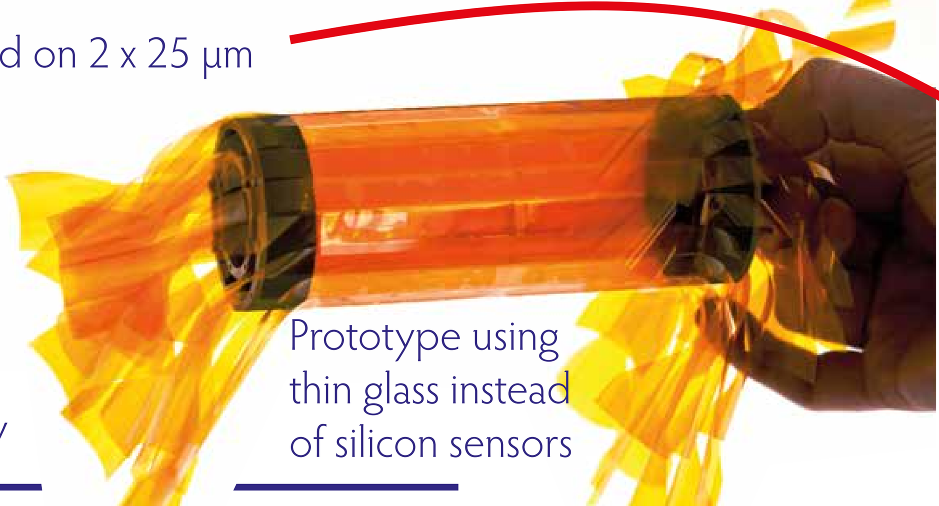
- 250 μm scintillating fibres in the central region for first timing measurement ~ 1 ns
- Precise timing (~ 100 ps) from ~1 cm thick scintillating tiles in the recurl tubes

Target

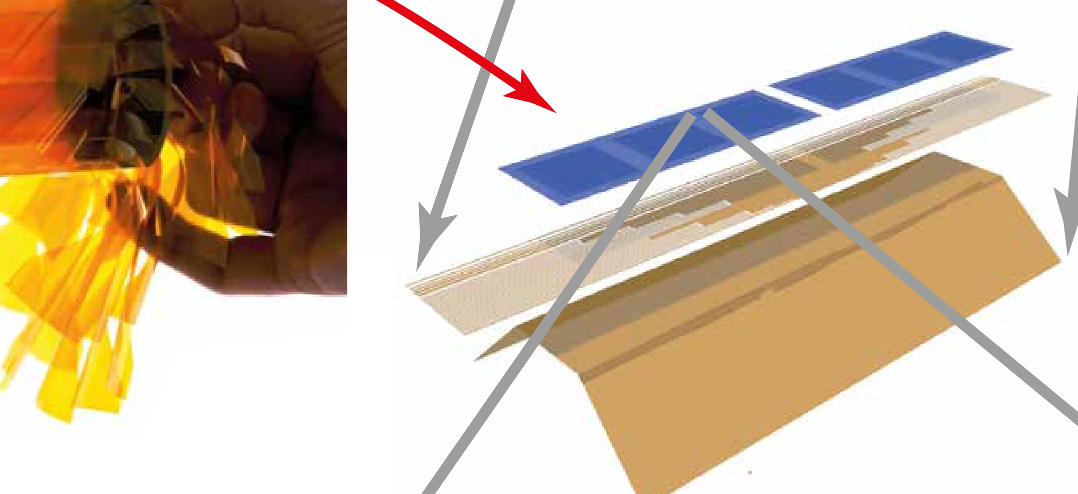
Double cone muon stopping target made from 70 μm Aluminium – large area for good vertex separation

Mechanics

Sensors supported on 2 x 25 μm Kapton™ strips with signal and power traces printed in Aluminium – extremely light and surprisingly sturdy

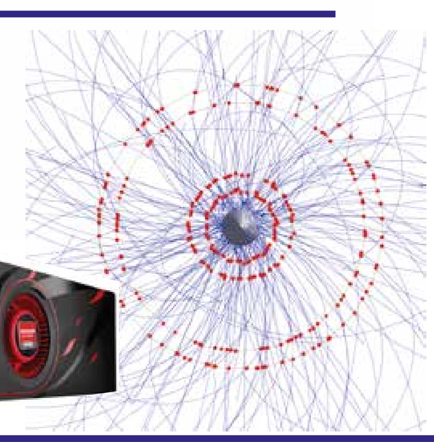


Prototype using thin glass instead of silicon sensors



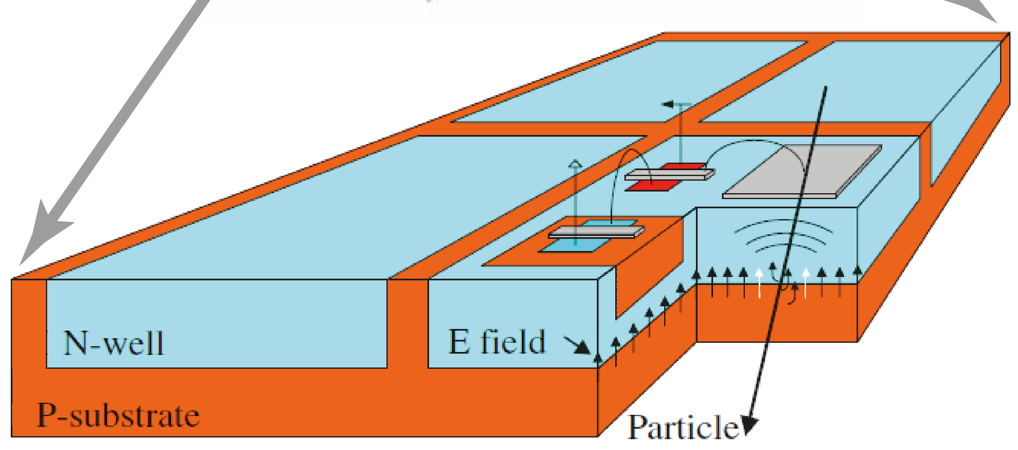
Readout & Reconstruction

- Triggerless readout of ~ 1 Tbit/s to an online farm
- Fast track finding and reconstruction on GPUs ($>10^9$ tracks/s)
- Reduction to ~ 100 Mbyte/s for offline storage and analysis.



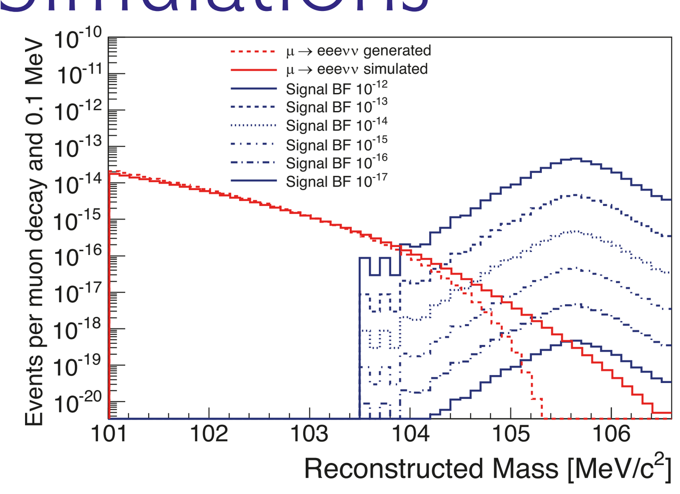
HV-MAPS

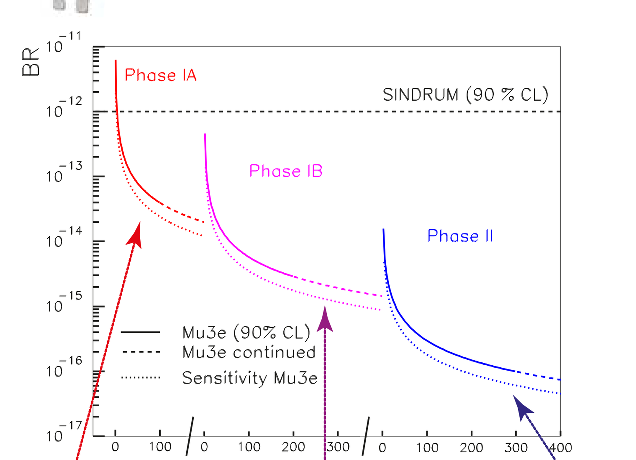
Using a commercial 180 nm CMOS process originating in the automotive industry, high voltage monolithic active pixel sensors housing the pixel electronics inside a deep N-well can be implemented. The high voltage (~70 V) leads to a thin depletion zone with fast charge collection. Most of the substrate is passive and can be thinned to < 50 μm thickness.
Mu3e uses 80 μm^2 pixels on 1x2 and 2x2 cm^2 sensors for a total of 280 Million pixels.



Ref.: I. Peric, A novel monolithic pixellated particle detector implemented in high-voltage CMOS technology Nucl.Instrum.Meth., 2007, A582, 876

Simulations





Central detector, no timing
Starting 2015

Extensions, fibres & tiles
Starting 2016

New beamline
Not before 2017