The µ3e Experiment:

How to design an experiment searching for 10^{-16}?

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Overview

How
is an experiment conceived?

- **Where**
  to look for new physics?
- **What**
  constrains the experiment?
- **How**
  to get the required performance?

Caveat

μ3e
is work in progress

- No
  guarantee that it will work out
- No
  unique solution to the problem
- Questions
  often more important than answers

The Standard Model of particle physics
works almost too well...

...but it can't be all there is

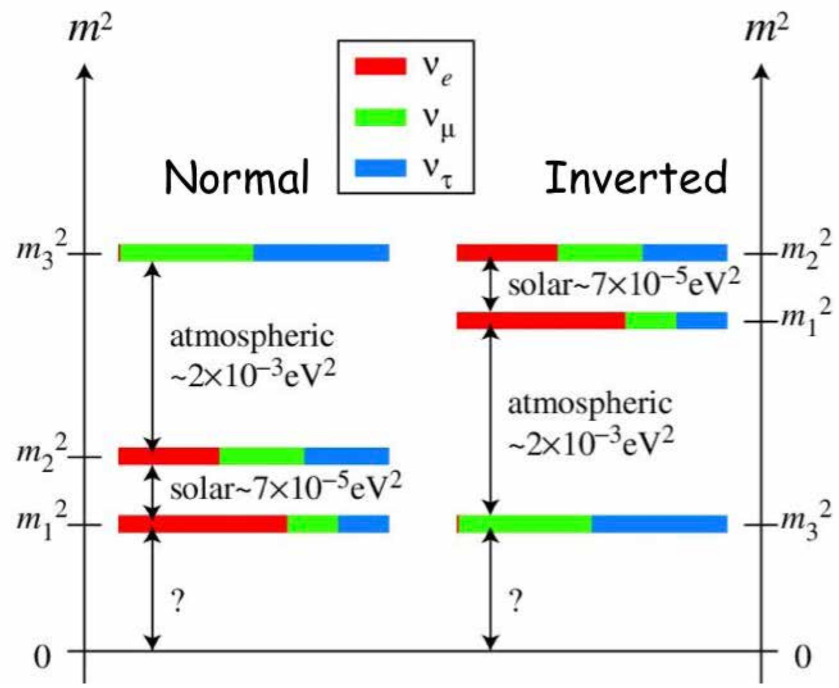
Search for new physics!

Where?

Hints?

Neutrino Oscillations!

Neutrinos



Neutrinos always seem good for a surprise

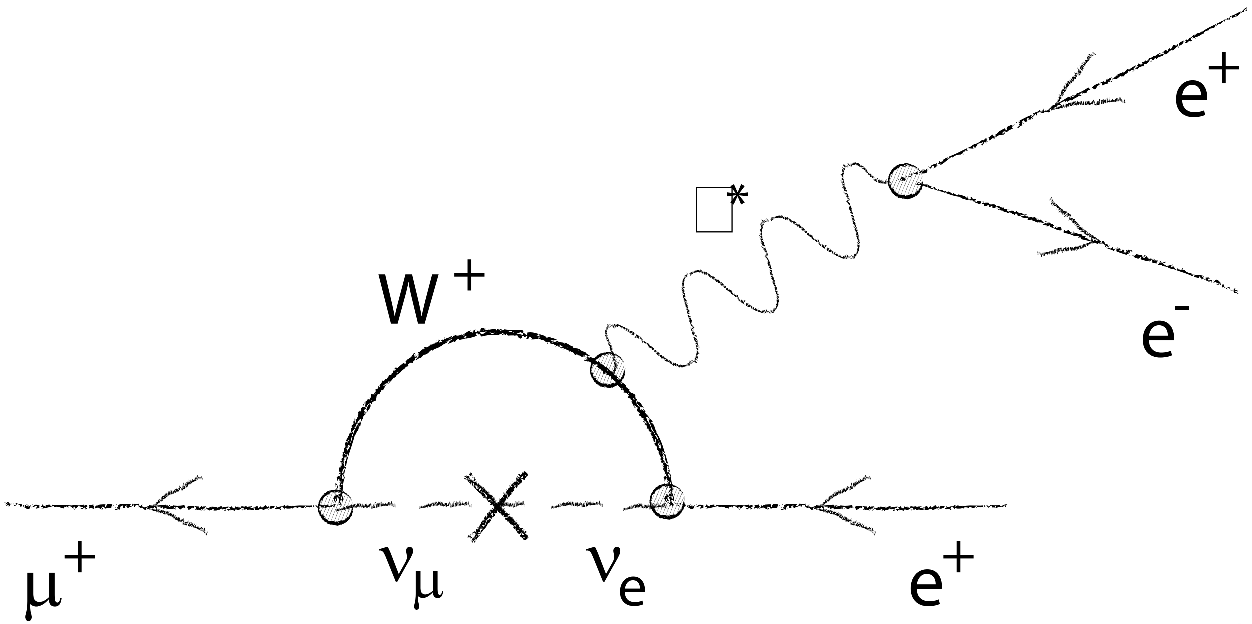
- They have mass
- They mix maximally
- What next?

What to do about it?

- Do more neutrino experiments: CP-Violation, sterile neutrinos etc. (However: Big and low rates)
- Look in the vicinity...

Charged leptons?

- What about charged leptons?
- Charged lepton-flavour violation through neutrino oscillations heavily suppressed (BR < 10^{-50})
- Observation clear sign for new physics
- No observation so far...



Where to search for LFV?

Lepton decays

- $\mu \to e\gamma$
- **$\mu \to eee$**
- $\tau \to l\gamma$
- $\tau \to lll$ $\quad l = \mu, e$
- $\tau \to lh$

Meson decays

- $\phi, K \to ll'$
- $J/\psi, D \to ll'$
- $\Upsilon, B \to ll'$

LFV

Conversion on Nucleus

- $\mu N \to eN$

Fixed target experiments (proposed)

- $eN \to \mu N$
- $eN \to \tau N$
- $\mu N \to \tau N$

Collider experiments

- $ep \to \mu(\tau) X$ (HERA)
- $Z' \to ll'$ (LHC)
- $\chi^{0,\pm} \to ll' X$ (LHC)

Experimental Status

Purely leptonic LFV

- BR($\mu \rightarrow e\gamma$) < 2.4×10^{-12} (MEG 2011)
- BR($\tau \rightarrow e(\mu)\gamma$) <~ 4×10^{-8} (B-Factories)
- BR($\mu \rightarrow eee$) < 10^{-12} (SINDRUM)
- BR($Z \rightarrow e\mu$) < 10^{-6} (LEP)

Semi-hadronic LFV

- BR($K \rightarrow \pi e \mu$) <~ 10^{-11}
- BR($\mu N \rightarrow eN$) <~ 10^{-12} (SINDRUM 2)

We want discovery potential:

Push significantly beyond these limits

But there are constraints...

Constraints

Technology

(Rates, resolution)

Money

(Accelerator, experiment)

Expertise

(Why can we do it better than others?)

Which lepton?

Electrons are stable...

Muons or Taus?

Which lepton?

Electrons are stable...

Muons or Taus?

B-factories and super B-factories are
hard to beat for taus - potential of one order of magnitude

Which channel?

$\mu \rightarrow e\gamma$

(being measured, hitting limitations)

$\mu \rightarrow eee$

(last measured 25 years ago)

$\mu N \rightarrow eN$

(last measured 20 years ago, new plans)

When is a μ→eee experiment competitive?

Compare with other limits...

10^{-15} a must,

10^{-16} as a goal

What does this mean for the experiment?

Observe several 10^{16} muon decays:

High rate

Suppress background to less than 10^{-16}

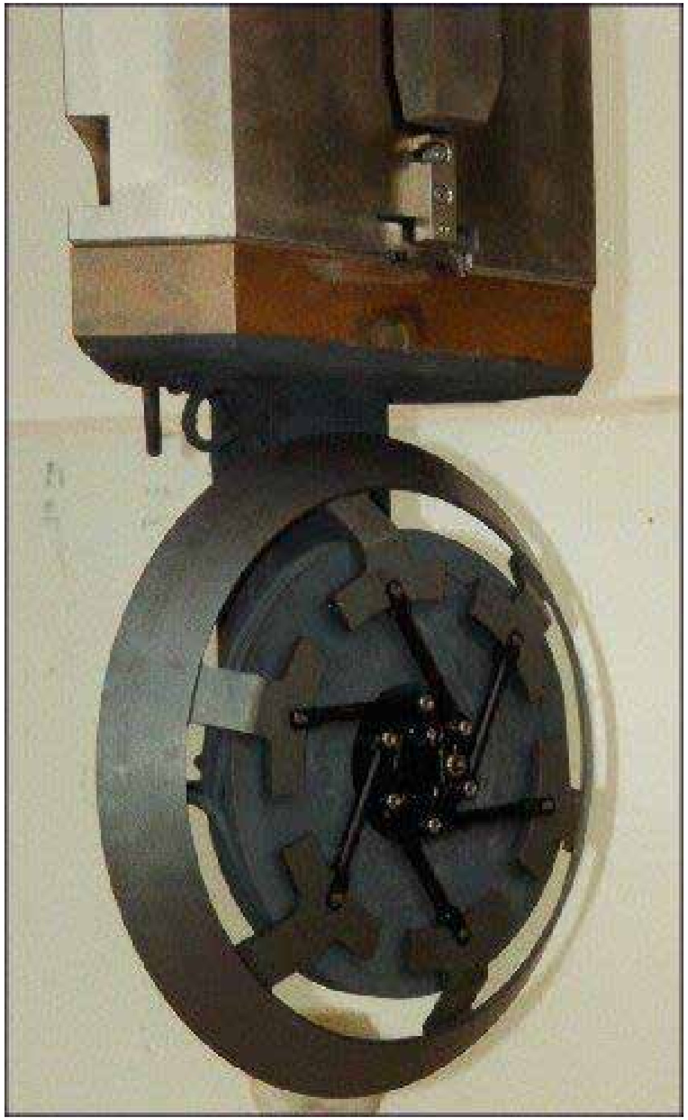
High precision

Muons: What rate is needed?

$$10^{16} / 100 \text{ days} = 1 \text{ GHz}$$

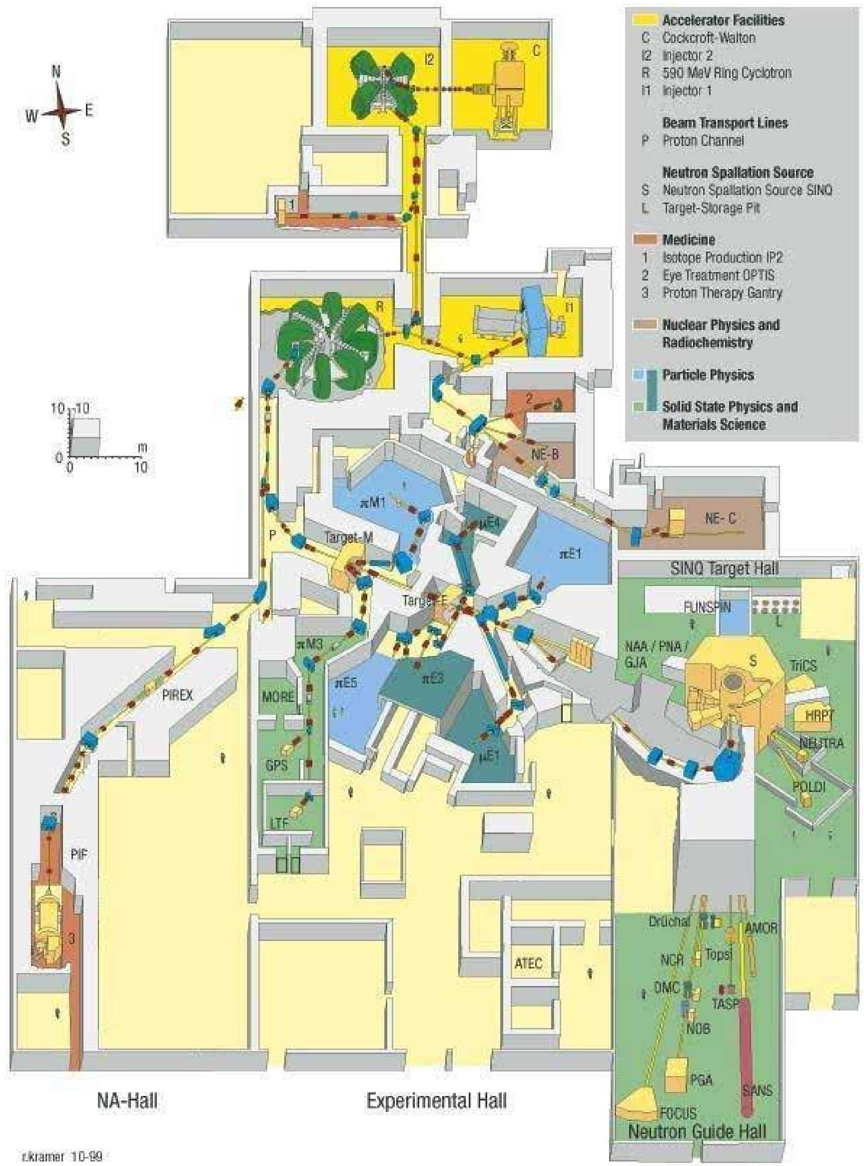
Billions of muons per second...

High rate: Muons from PSI



- The Paul Scherrer Institut (PSI) in Villigen, Switzerland has the world's most powerful DC proton beam (2.2 mA at 590 MeV)
- Pions and then muons are produced in rotating carbon targets

Muons from PSI



DC muon beams at PSI:

- μE1 beamline: ~ 5×10^8 muons/s
- πE5 beamline: ~ 10^8 muons/s
  (MEG experiment)
- μE4 beamline: ~ 10^9 muons/s

- SINQ (spallation neutron source) target could even provide
  ~ 5×10^{10} muons/s

- Requires investment from PSI: Need to demonstrate that the experiment works...

And now for the hard part...

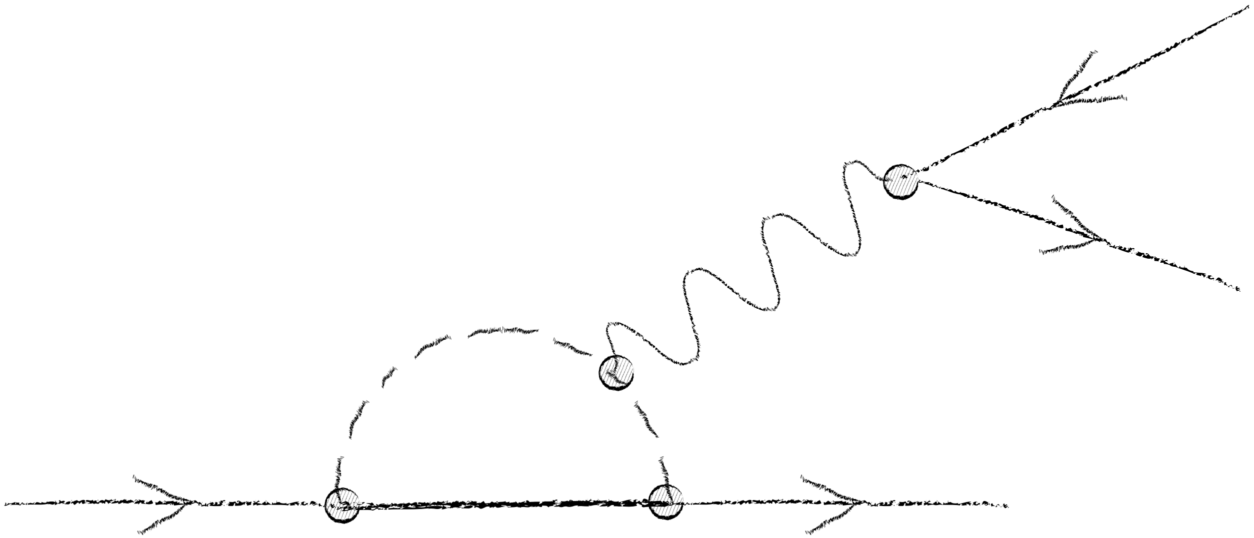
Suppress background by 16 orders of magnitude...

...at several GHz muon rate...

...and not miss the signal

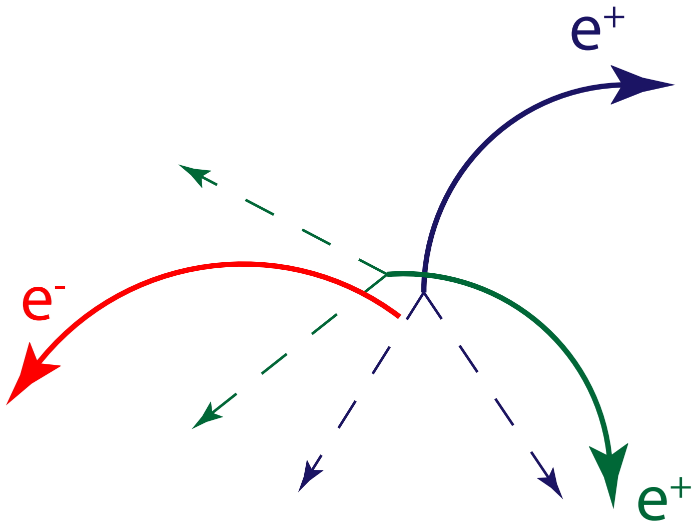
The Signal

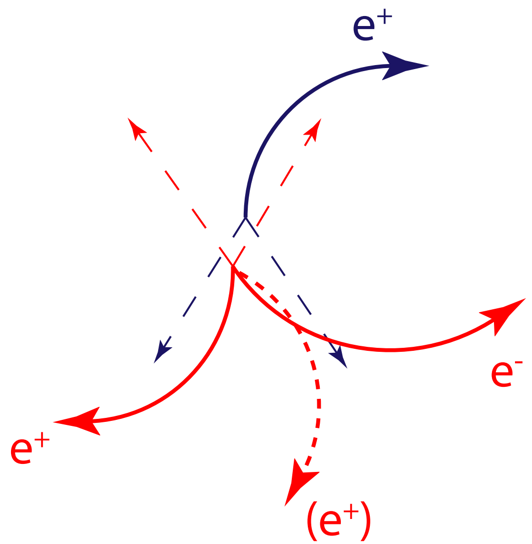
- Two positrons and one electron
- Coincident in time and vertex
- In a plane
- Energies sum up to muon mass



Need a precise, efficient tracker

Background: Accidental





- Overlays of two normal muon decays with an electron
- Electrons from Bhabha-scattering, photon conversion, mis-reconstruction

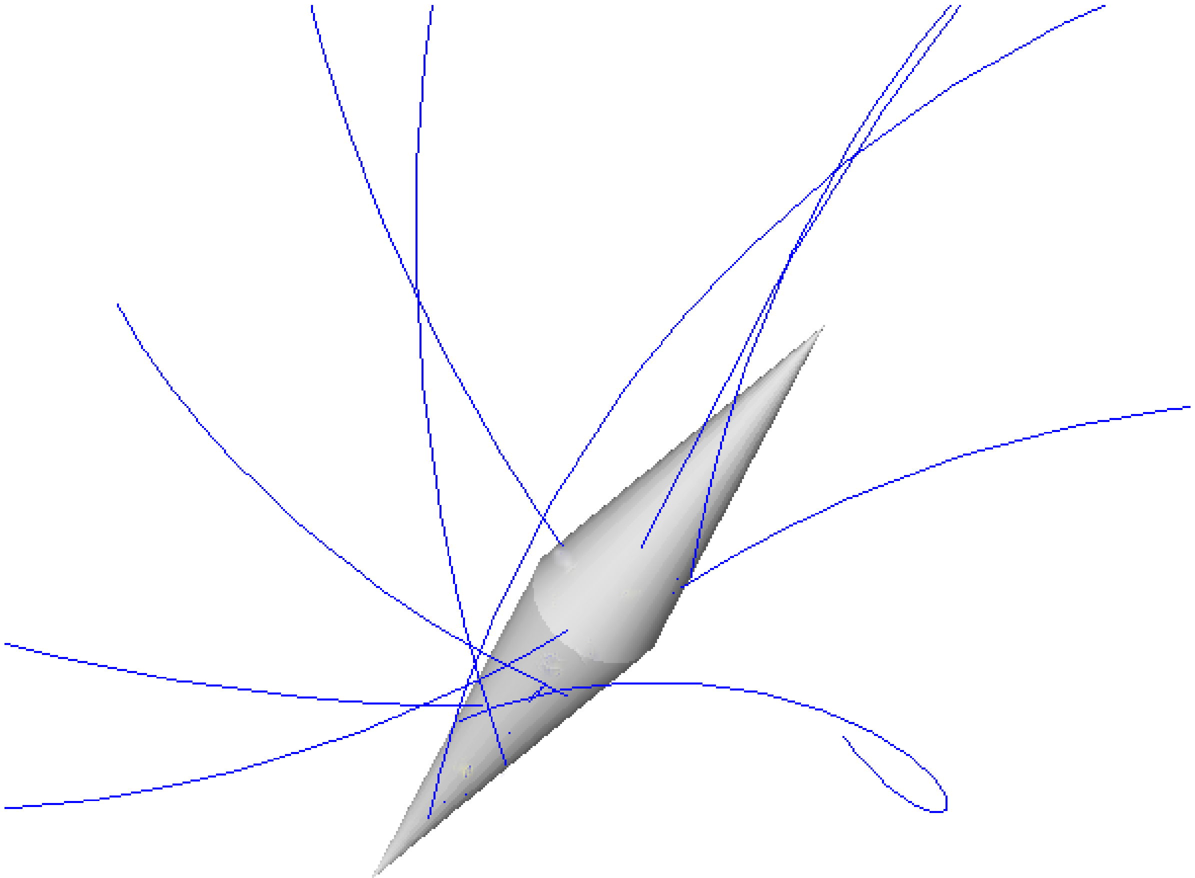
Need excellent:

- Vertex resolution
- Timing resolution
- Kinematics reconstruction

Spread events as much as possible in space and time:

Large stopping target

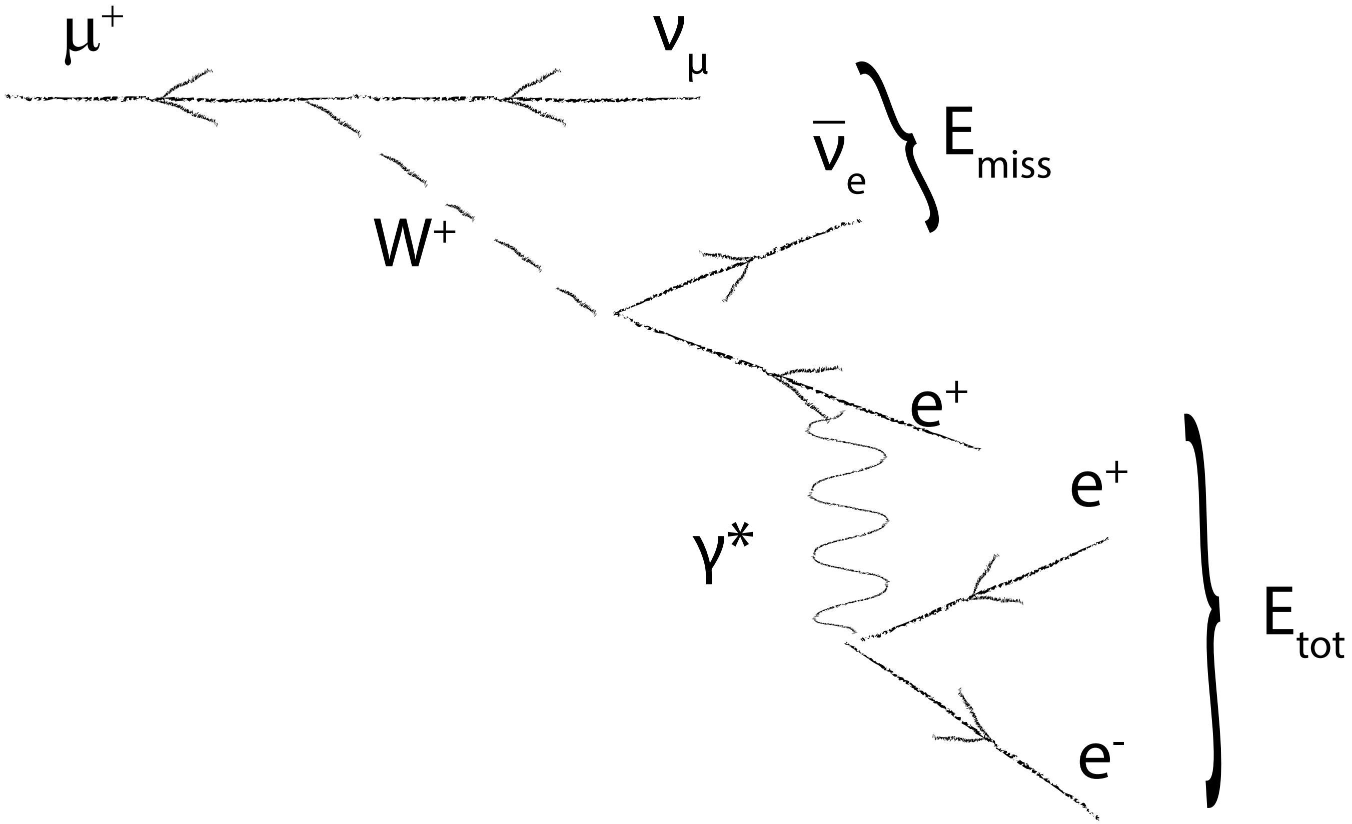
DC muon beam (PSI!)



Internal Conversion Background

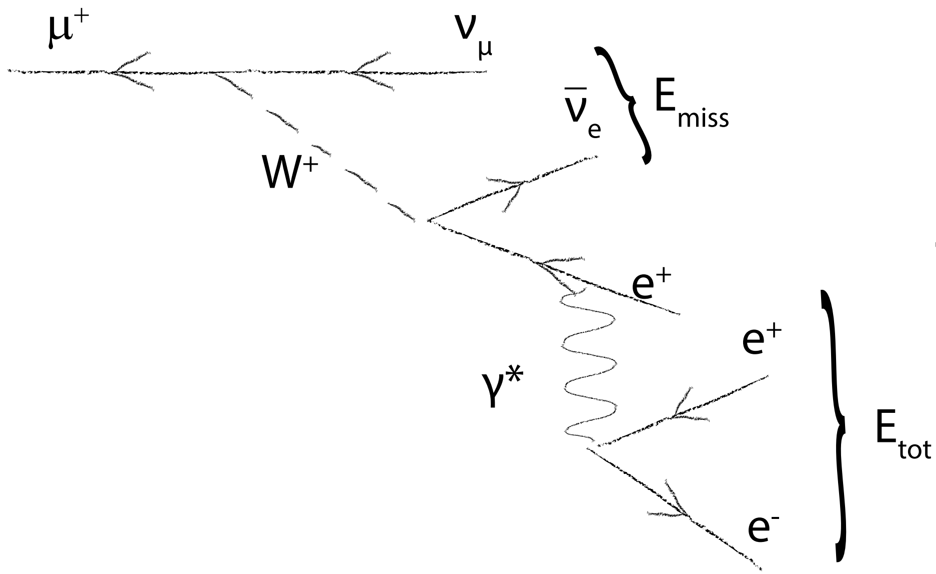
Radiative muon decay with internal conversion

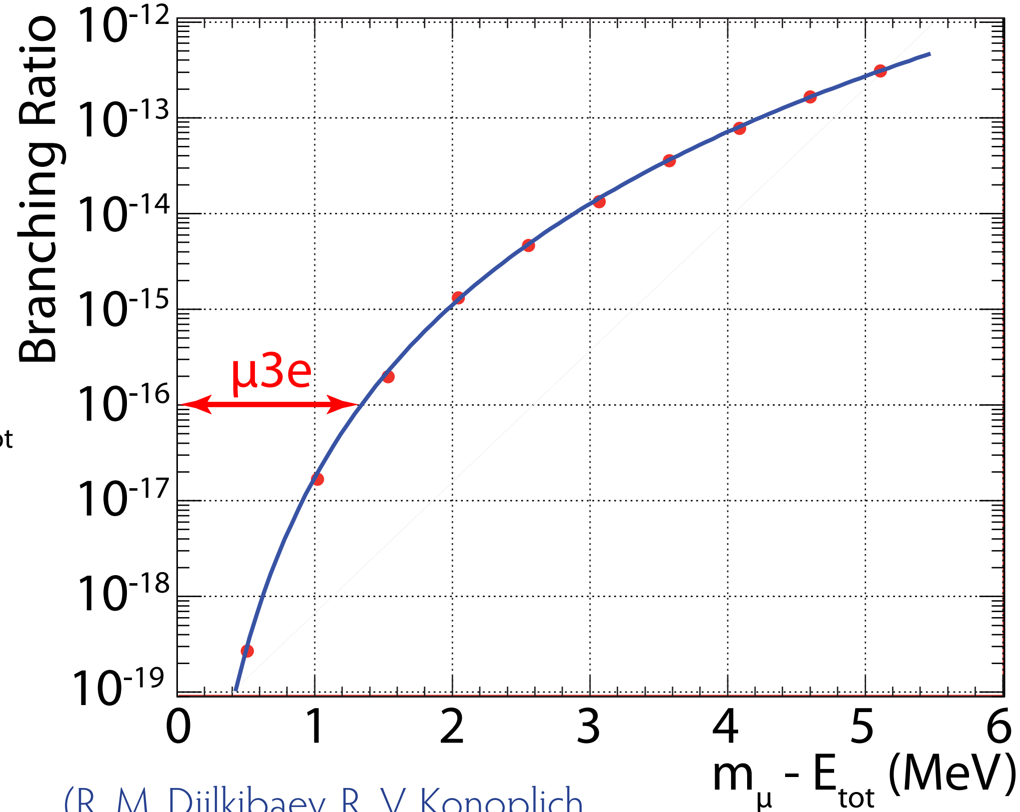
- Looks like signal
- Except for missing energy



Internal Conversion Background

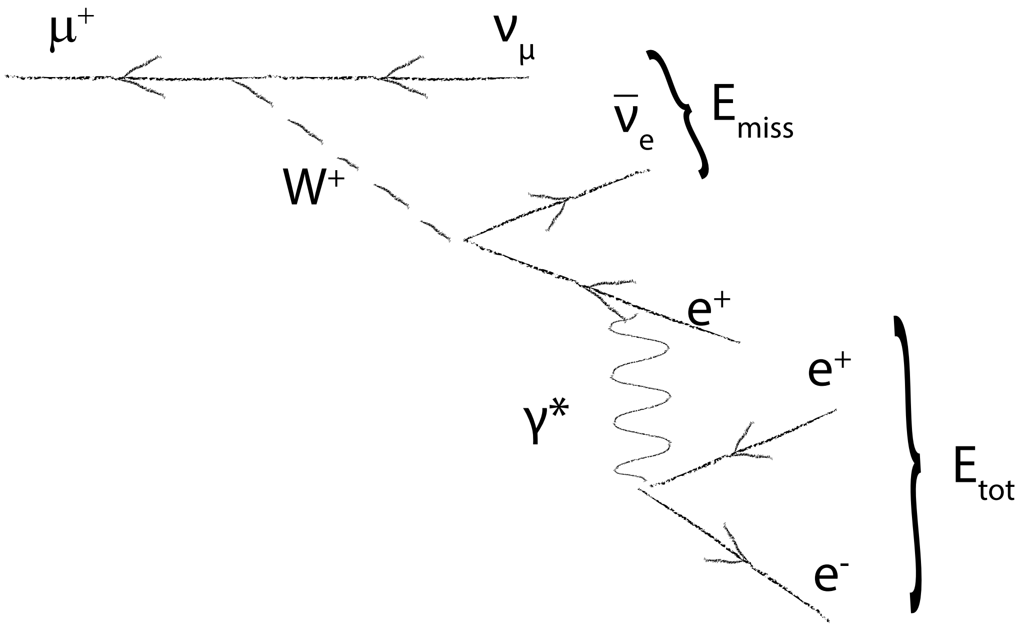
- Branching fraction 3.4×10^{-5}
- Need excellent momentum resolution to reject this background





(R. M. Djilkibaev, R. V. Konoplich, Phys.Rev. D79 (2009) 073004)

Statistical aside: Hit and miss generator



Aside on internal conversion simulation

- 5-particle final state…
  … 11-dimensional phase space
- Have to generate events equi-distributed in phase space (RAMBO)
- Calculate matrix element (a few 100 lines of ugly FORTRAN)
- Then perform hit-and-miss
- With a matrix element varying by 16 orders of magnitude over phase space

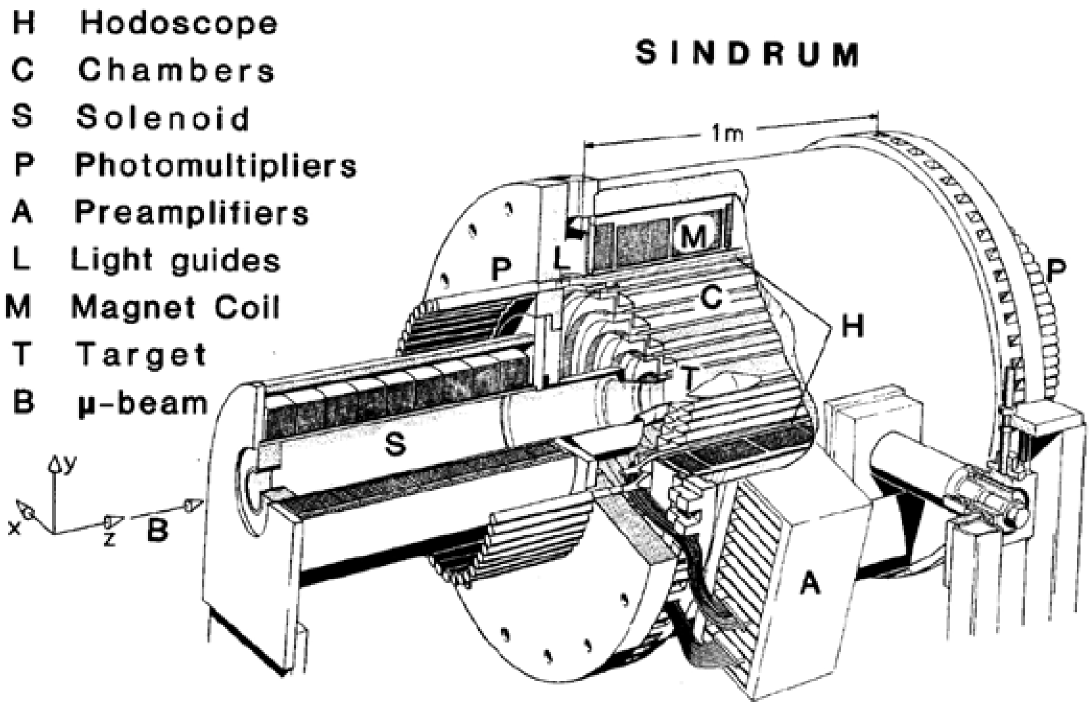
We need the best possible tracker for low momentum electrons

(and it should be fast and cheap...)

Last Experiment: SINDRUM

SINDRUM (1988)

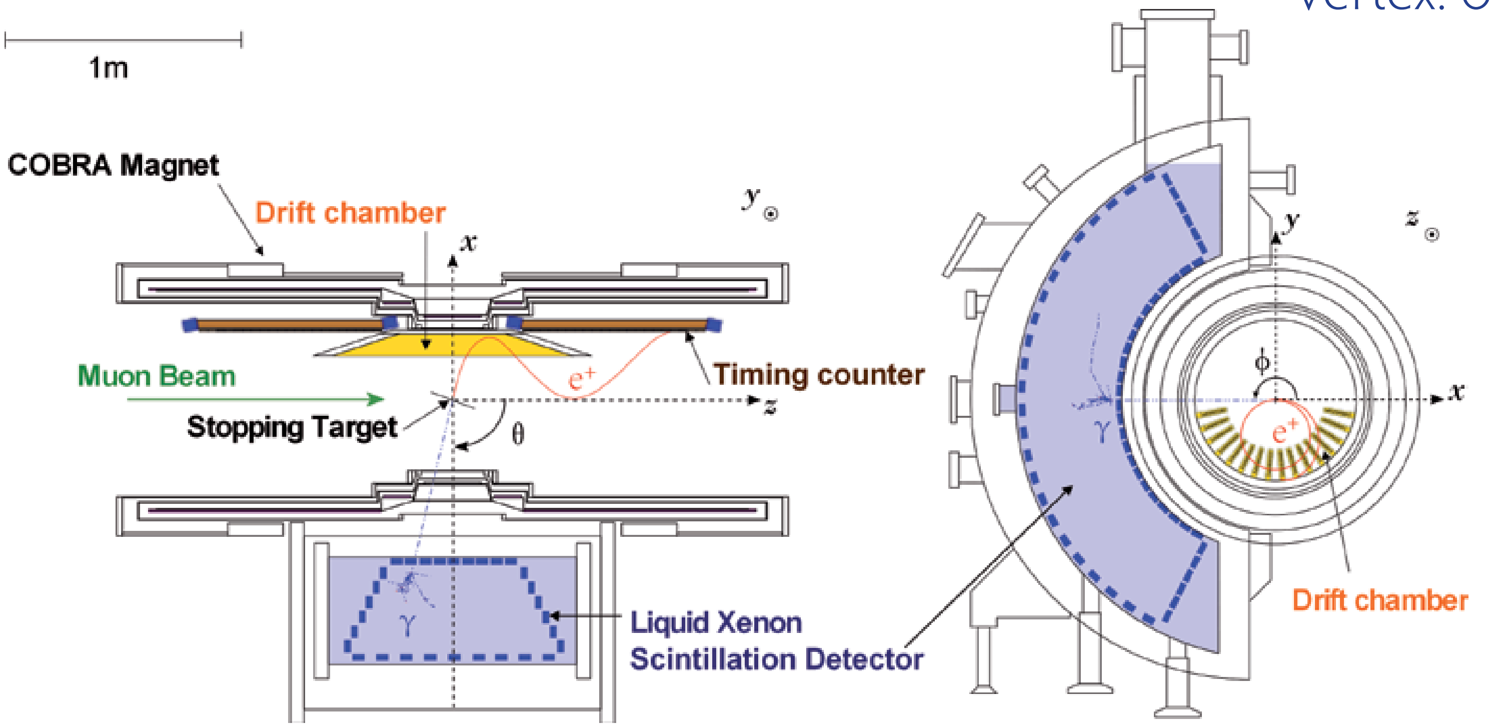
- σ_p/p (50 MeV/c) = 5.1%
- σ_p/p (20 MeV/c) = 3.6%
- σ_θ (20 MeV/c) = 28 mrad
- Vertex: $\sigma_d \approx 1$ mm
- X_0 (MWPC) =0.08 - 0.17% per layer



State of the art: MEG

MEG (2010)

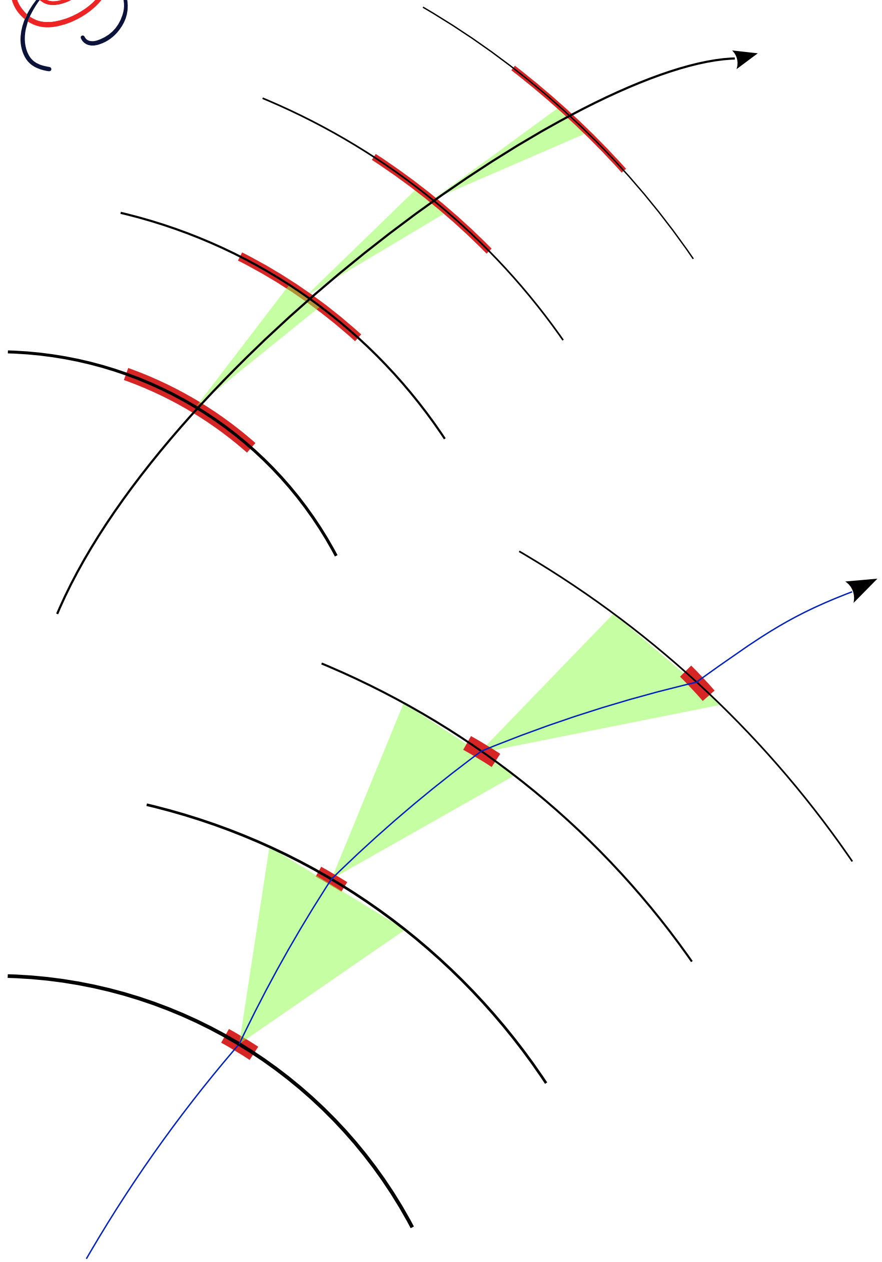
- σ_p/p (53 MeV/c) = 0.6 %
- σ_θ (53 MeV/c) = 11 mrad
- σ_ϕ (53 MeV/c) = 7 mrad
- Vertex: $\sigma_r \approx 1.1$ mm, $\sigma_z \approx 2.0$ mm



Experiment limited by accidentals

At the limit of drift chamber technology

Limiting resolution: Multiple scattering



- Decay particles are electrons with momenta < 53 MeV/c
- Strong multiple scattering

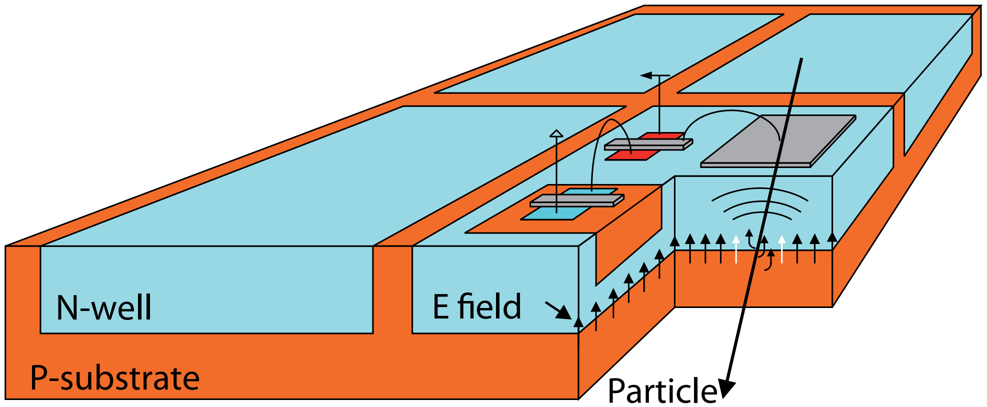
$$\propto \sqrt{X/X_0} \times 1/p$$

- Need a thin, fast, high resolution detector
- Rates and aging speak against a gaseous detector
- Silicon is heavy - or is it?

Silicon detector technologies

Technology	Thickness	Speed	Readout
ATLAS pixel	260 μm	25 ns	extra RO chip
DEPFET (Belle II)	50 μm	slow (frames)	extra RO chip
MAPS	50 μm	slow (diffusion)	fully integrated
HV-MAPS	> 30 μm	O(100 ns)	fully integrated

HV-MAPS

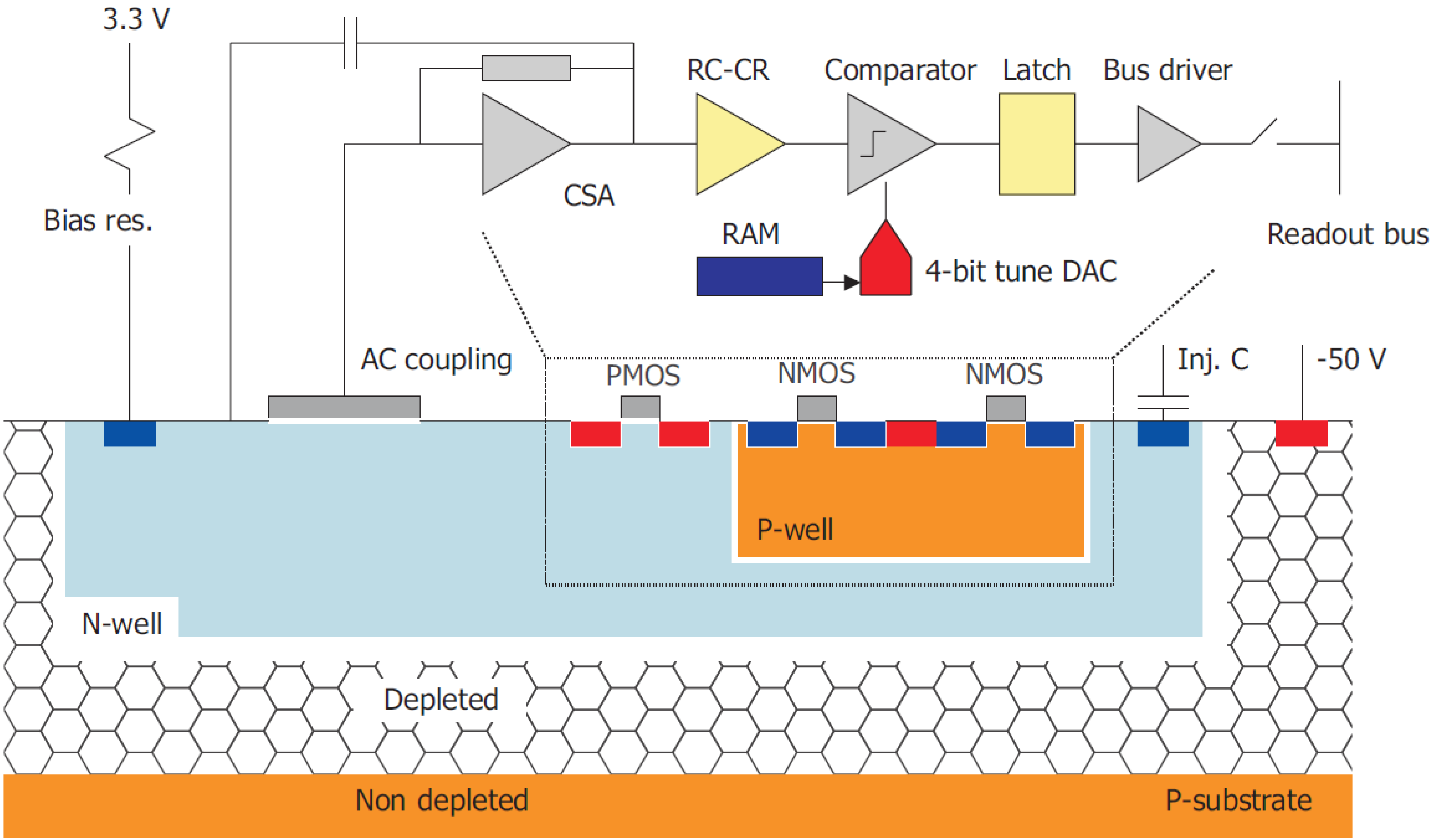


High voltage monolithic active pixel sensors

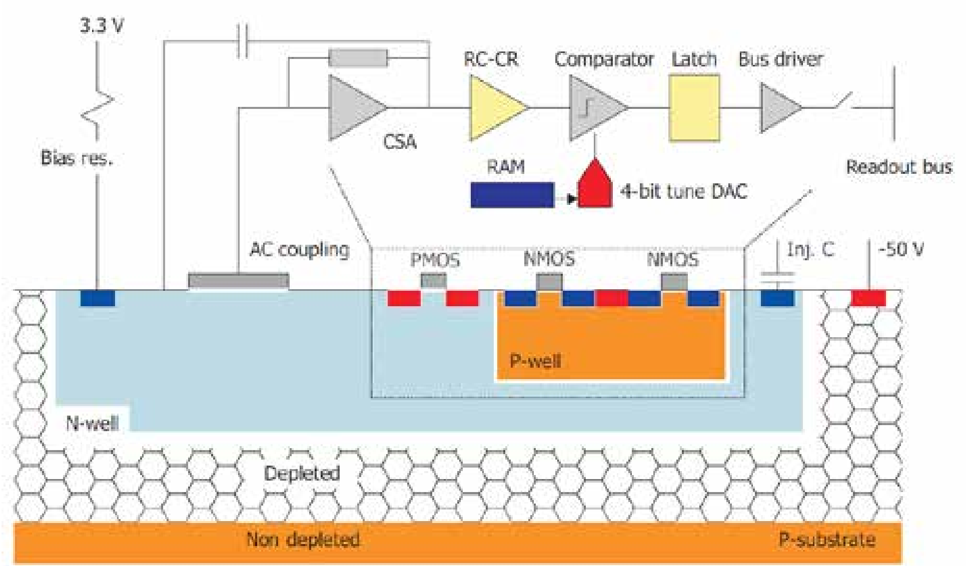
- Implement logic directly in N-well in the pixel - smart diode array
- Use a high voltage commercial process (automotive industry)
- Small active region, fast charge collection via drift
- Can be thinned down to < 50 μm
- Low power consumption

(I.Peric, P. Fischer et al., NIM A 582 (2007) 876 (ZITI Mannheim, Uni Heidelberg))

HV-Maps

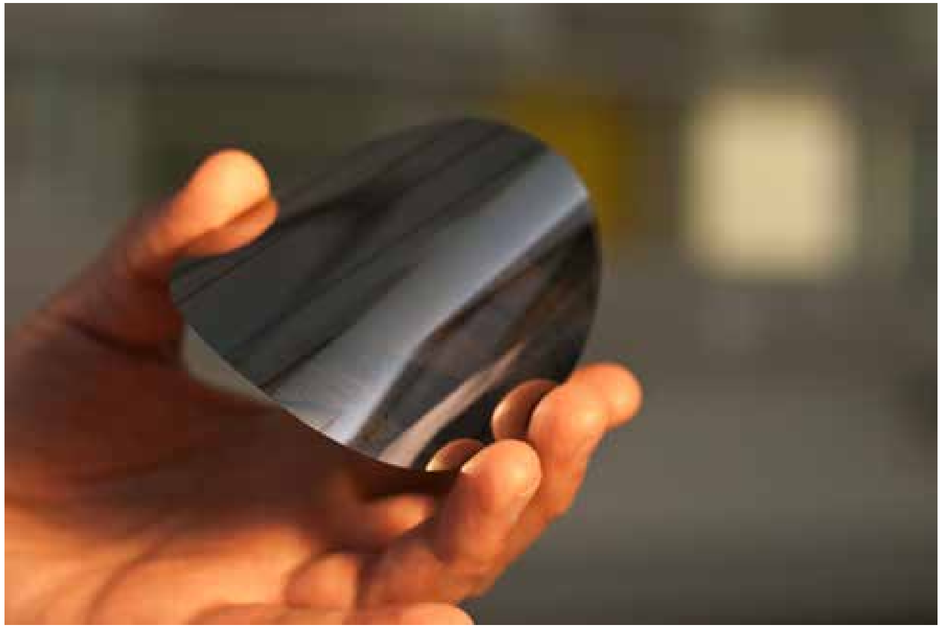

3.3 V
Bias res.
RC-CR
Comparator
Latch
Bus driver
CSA
RAM
4-bit tune DAC
Readout bus
AC coupling
PMOS
NMOS
NMOS
Inj. C
-50 V
P-well
N-well
Depleted
Non depleted
P-substrate

Sensor Specs



- Module size 6 × 1 cm (inner layers)
  6 × 2 cm (outer layers)
- Pixel size 80 × 80 μm
- Goal for thickness: 50 μm
- 1 bit per pixel, zero suppression on chip
- Power: 150 mW/cm^2
- Data output up to 3.2 Gbit/s
- Time stamps every 50 ns (20 MHz clock)

Can we use this to build a detector?



- 50 μm silicon is not self-supporting
  Need support structure
- Cooling?
  Liquids and pipes to heavy - gas
  Limit sensor power consumption
- Signals and Power?
  No big cables possible
  High rate links needed

Our idea: Kapton flexprint

Use 25 µm Kapton for support

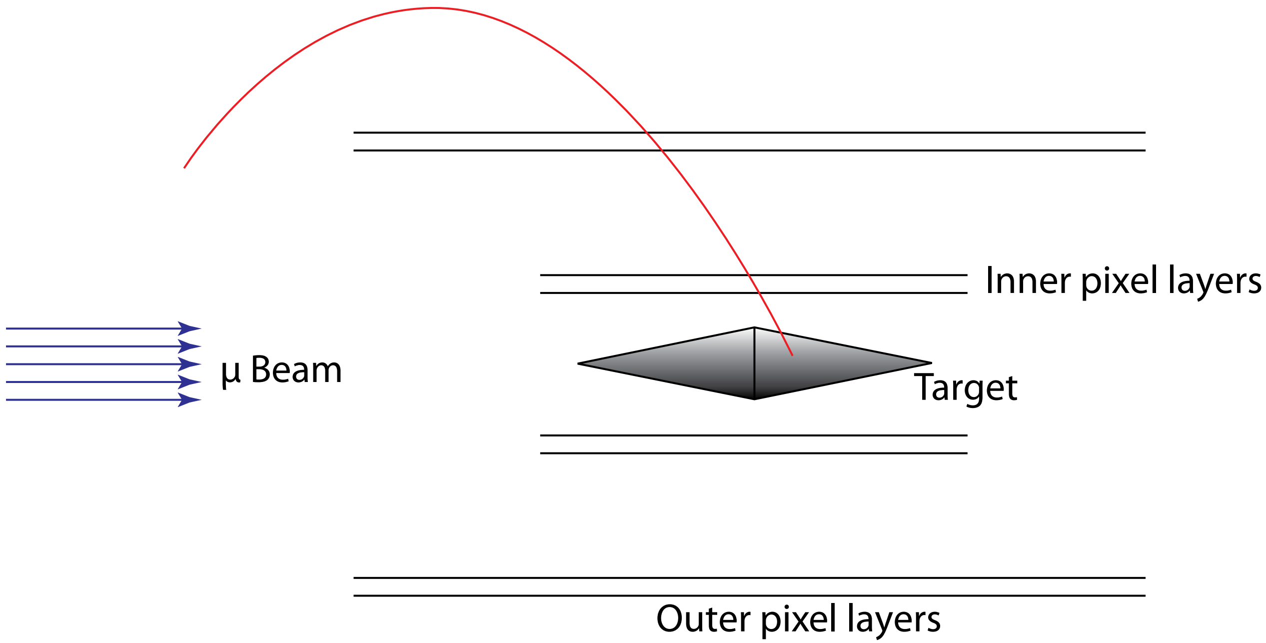
- Very light
- Can print signal and power lines (in Al)
- First prototypes very promising

Cooling

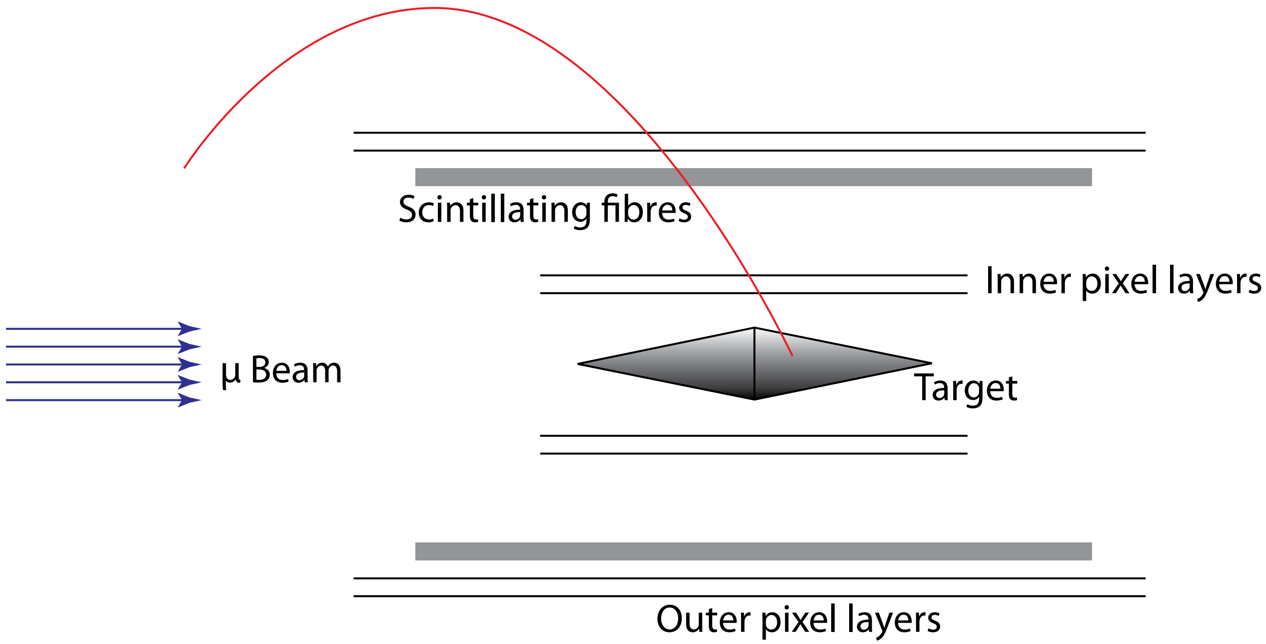
- No fluid coolant
- Put detector in helium atmosphere (high mobility, low multiple scattering)
- Reduce clock frequency of chips to 10 or 20 MHz
- Will need an additional timing detector

Detector concept

Detector concept

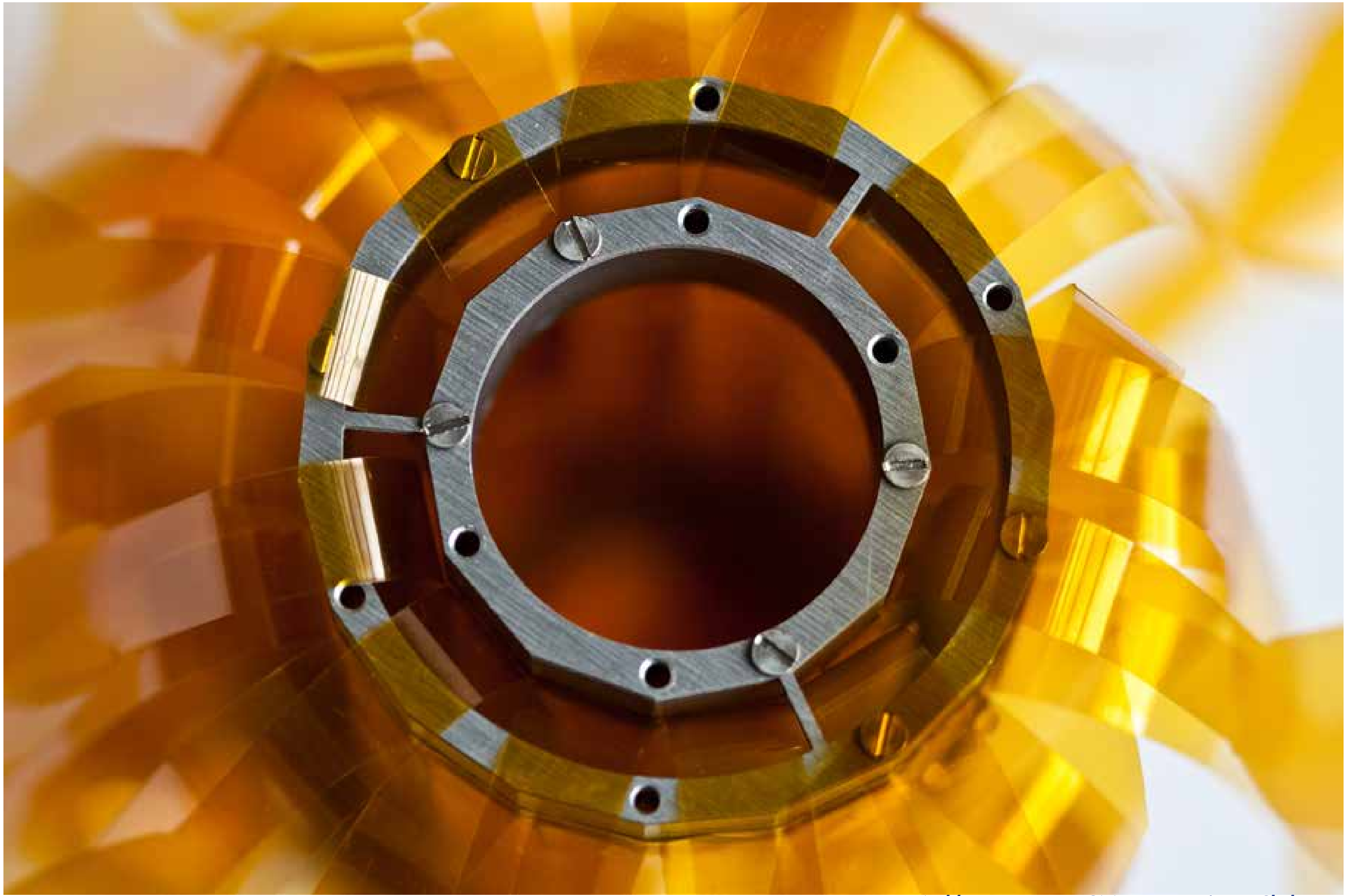


Detector concept



Mechanics

Mechanics



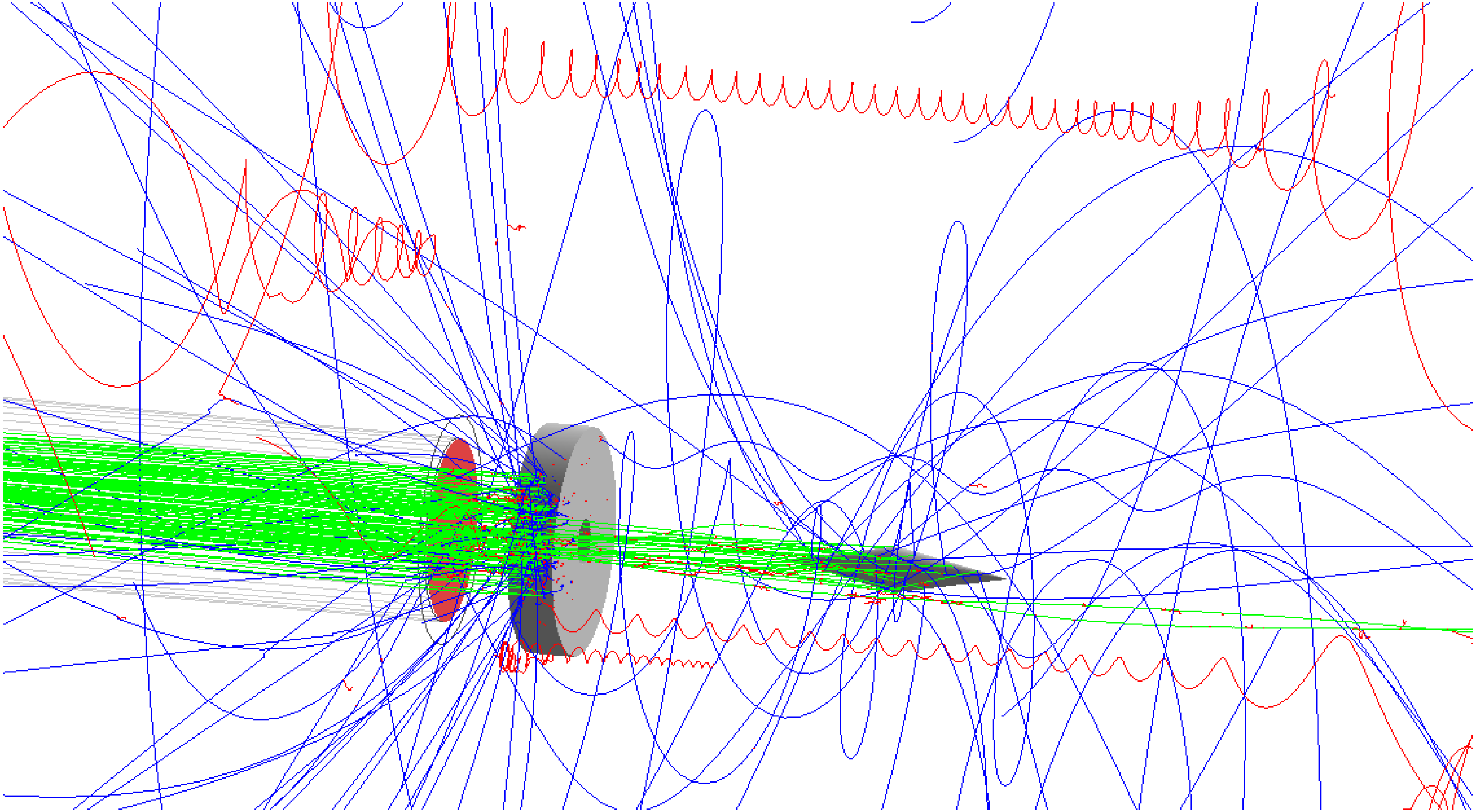
Does this work?

Where to put the layers? What magnetic field?

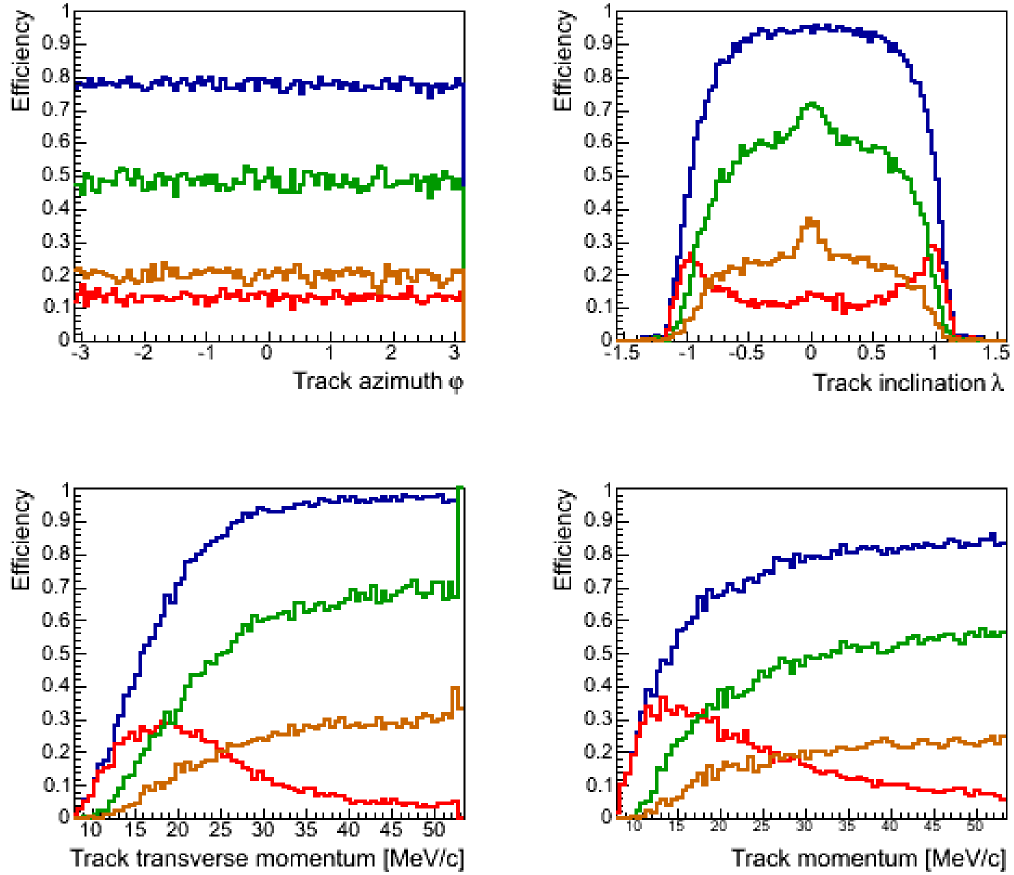
How about track finding?

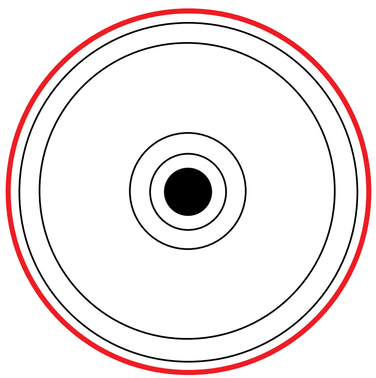
Simulation!

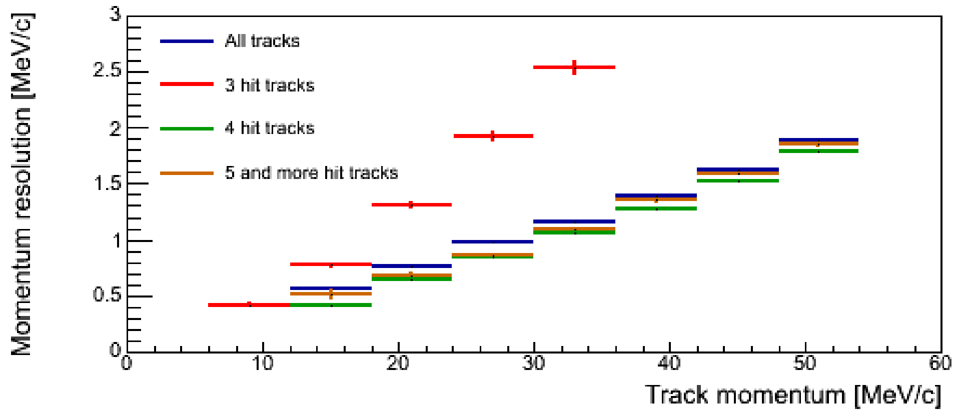
Write a few 10'000 lines of code using Geant4



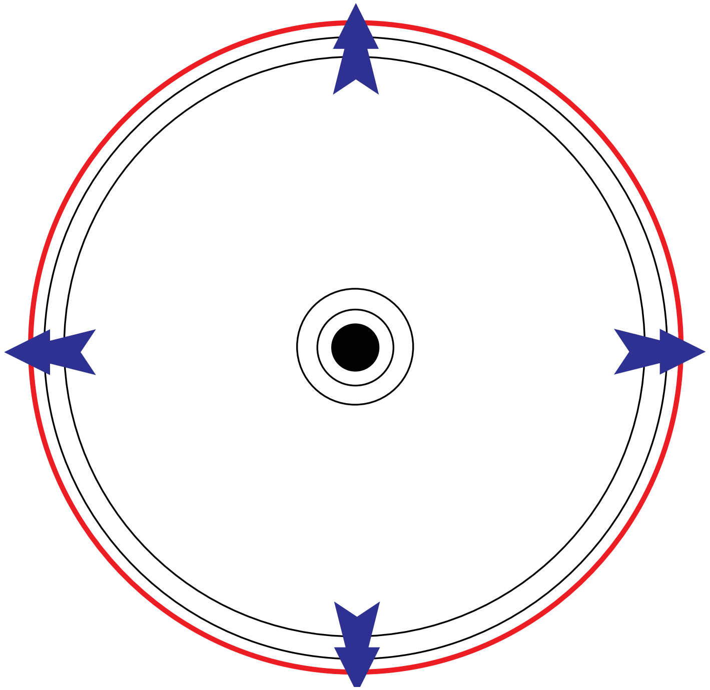
- Minimal detector, outer layers at r = 6.14 and 7.03cm, 24 cm long
- Fibres just outside last layer
- Very high acceptance
- Very limited resolution due to small lever arm

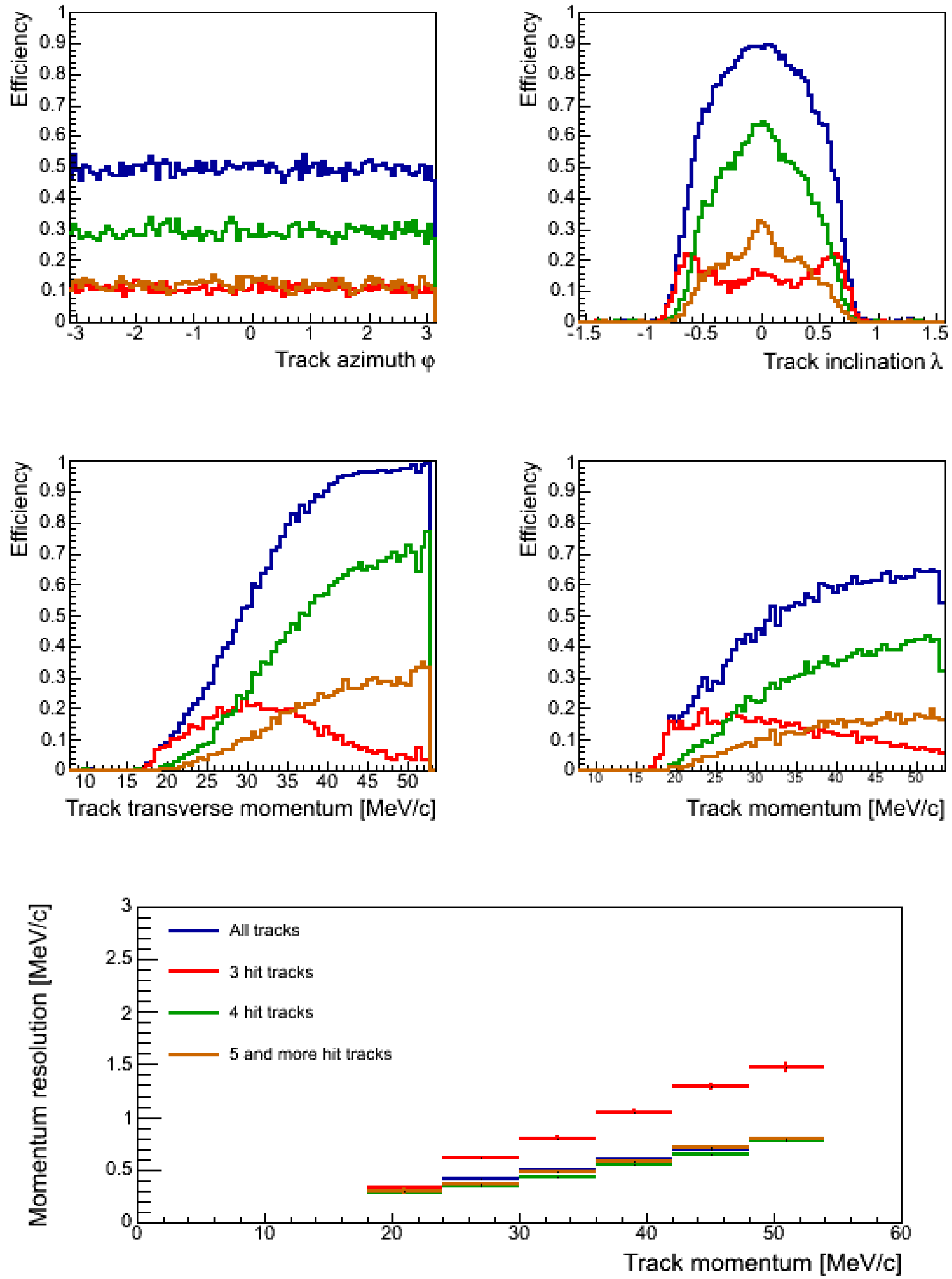


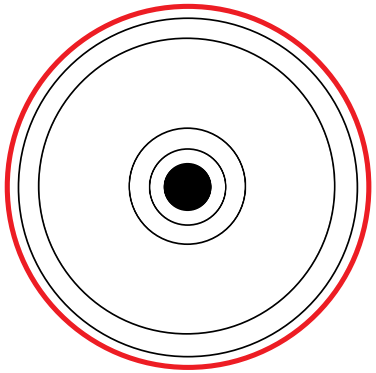




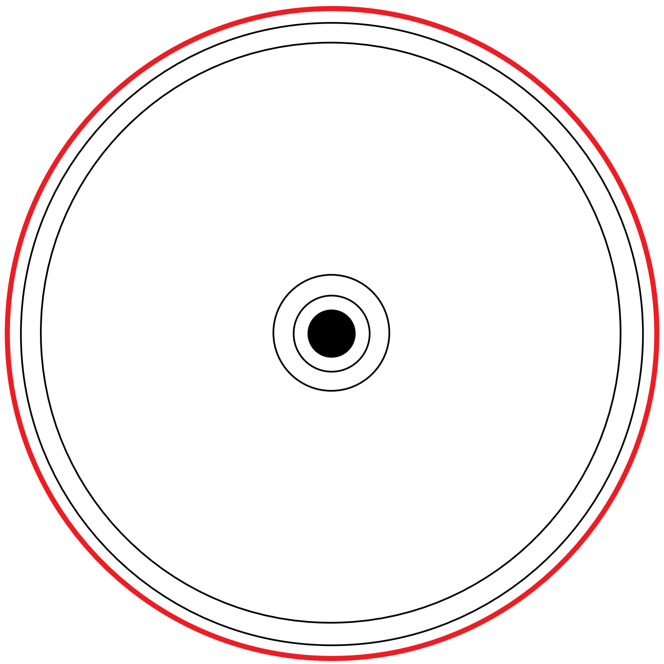
- Outer layers now at r = 12.1 and 12.9 cm, 24 cm long
- Fibres just outside last layer
- Detector too short, blind at low p_T
- Improved resolution, but still not sufficient

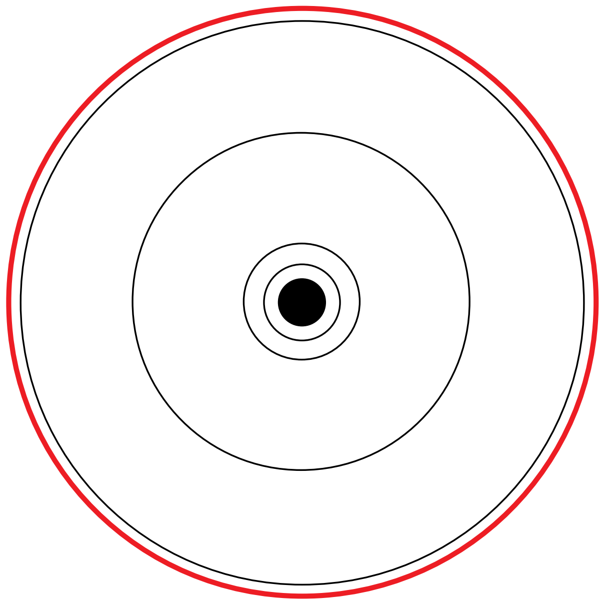




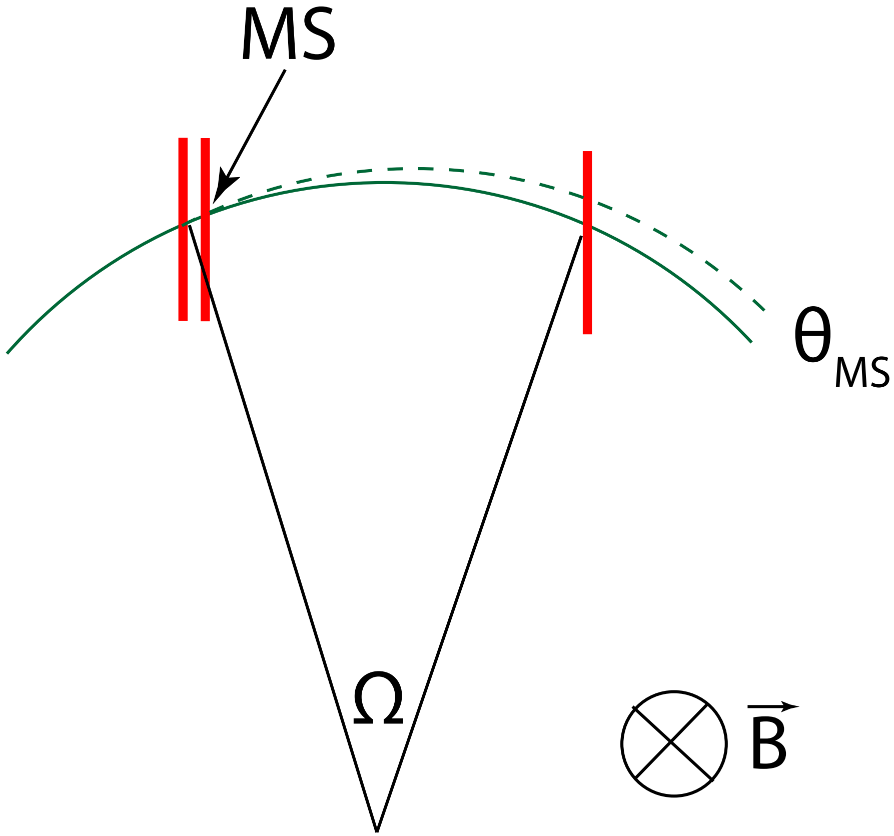


- Trade-off between lever arm and acceptance
- Due to large angle scatters, “lonely layers” very difficult for reconstruction with multiple tracks
- Fibres are heavy - bad for scattering, good for stopping curlers





Momentum measurement

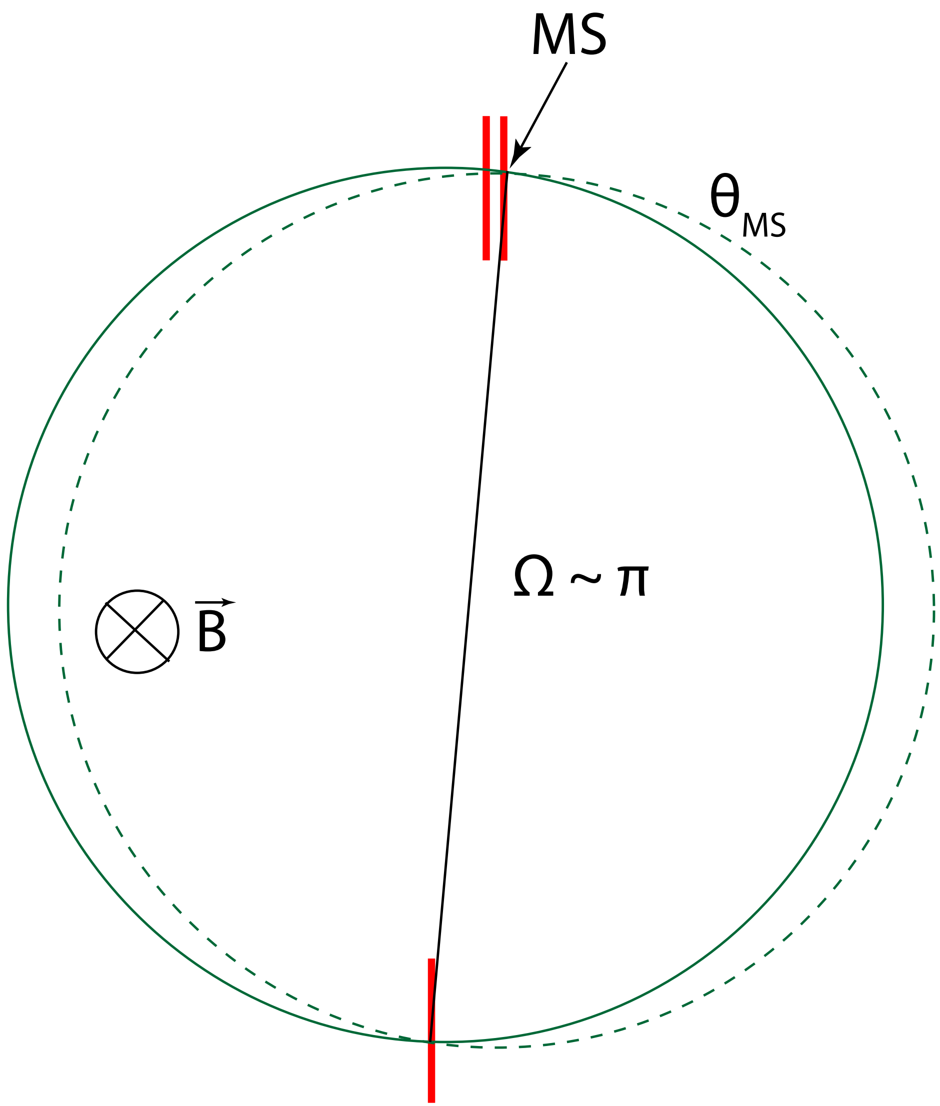


Momentum resolution given by (linearised):

$$\sigma_P / P \sim \theta_{MS} / \Omega$$

- Precision requires large lever arm (large bending angle Ω)

Momentum measurement

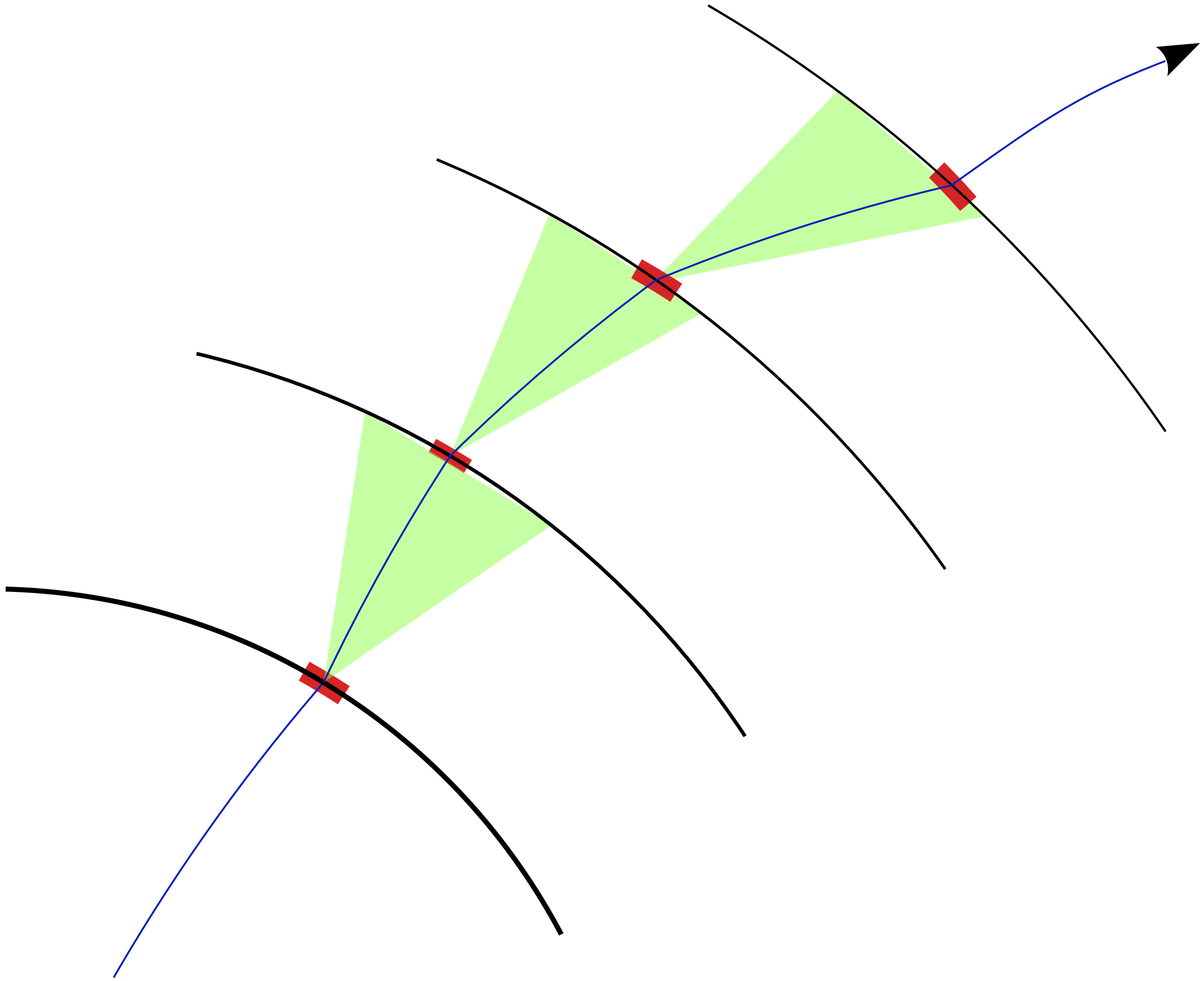


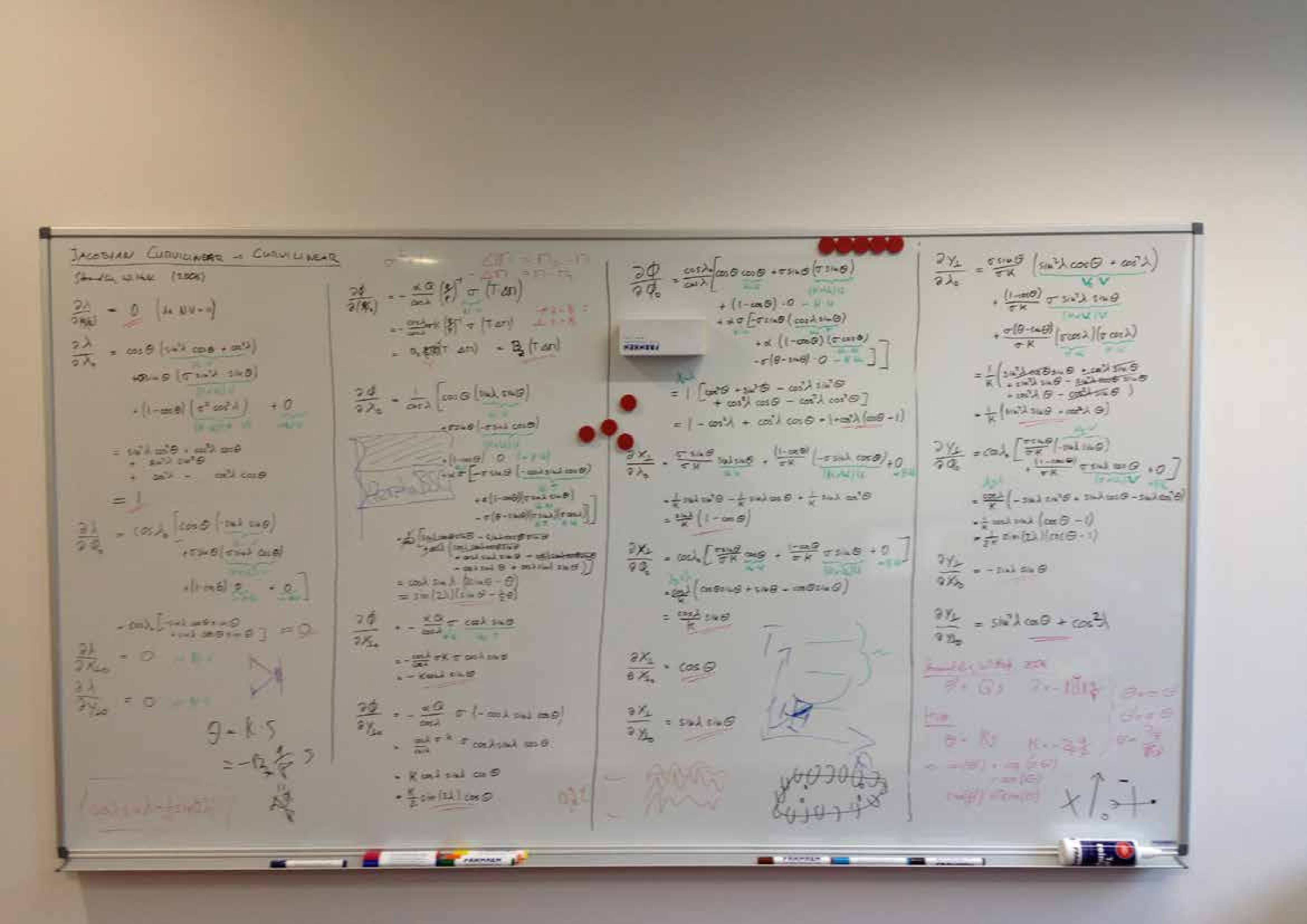
Momentum resolution for half turns given by

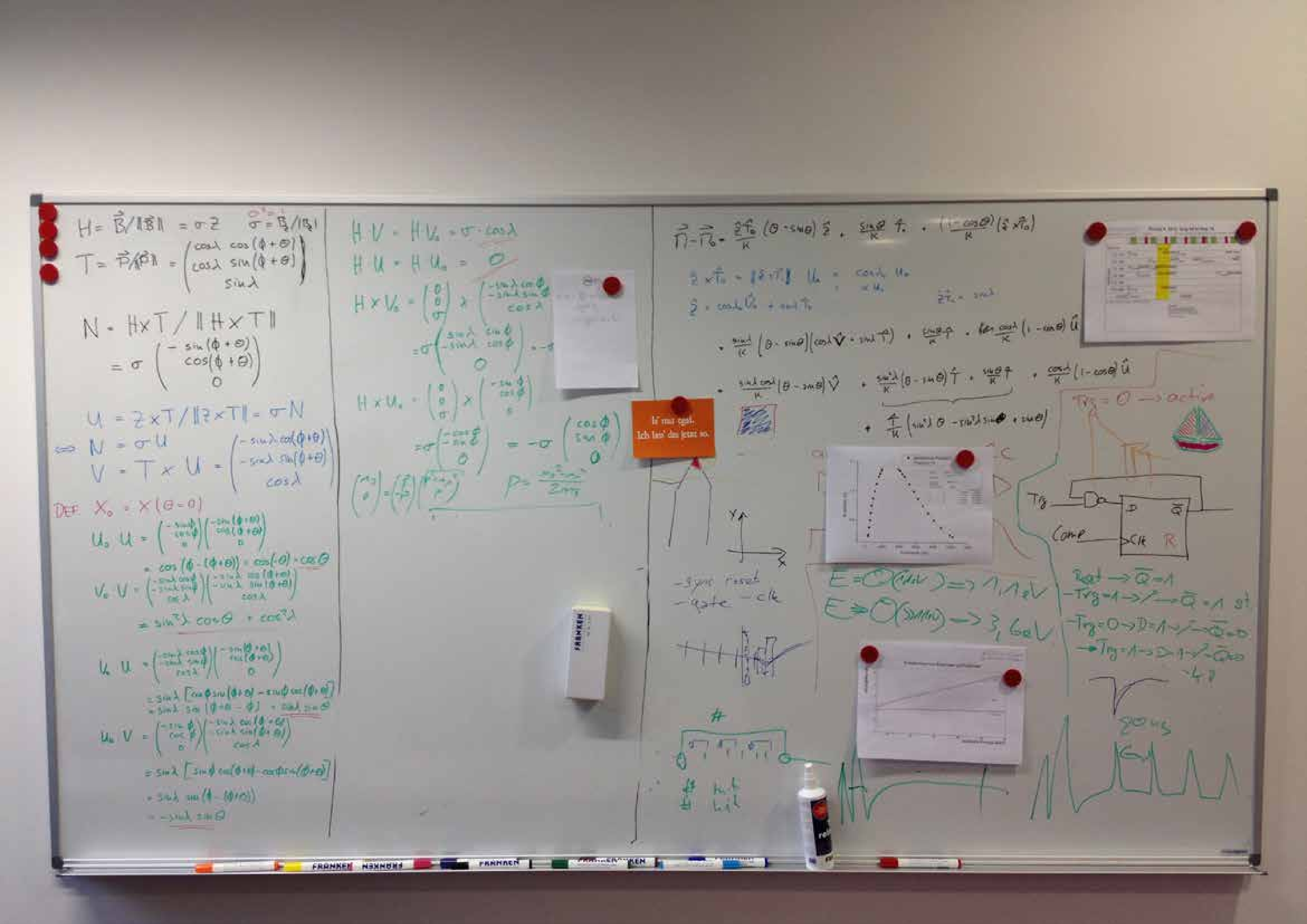
$$\sigma_P/P \sim O(\theta^2_{MS})$$

- Best precision for half turns
- Design tracker to measure recurlers

Advanced error propagation

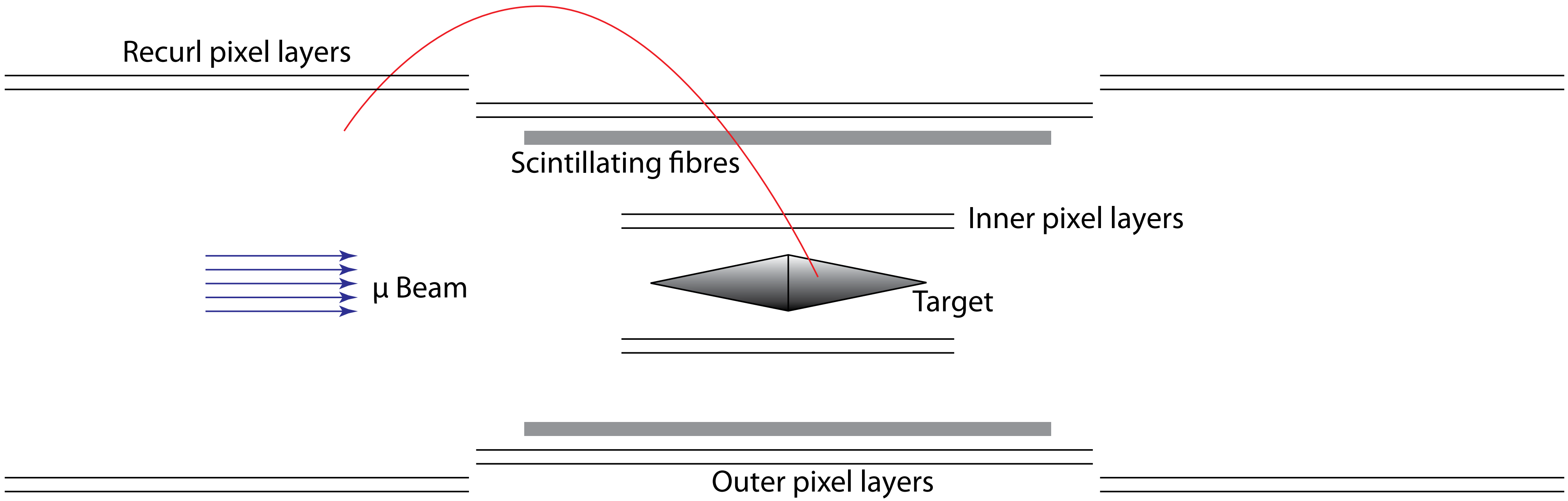



JACOBIAN CURVILINEAR → CURVILINEAR

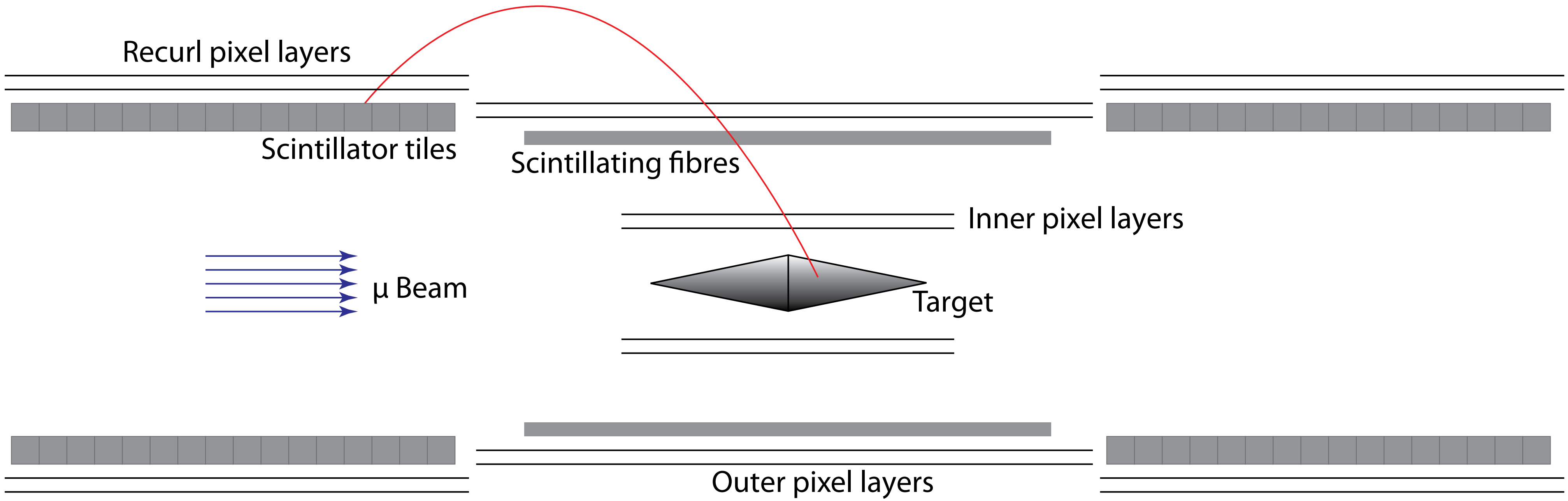


N = H×T / ‖H×T‖
U = Z×T / ‖Z×T‖ = σ·N
V = T × U
DEF X₀ = X(θ=0)
Is' mir egal.
Ich lass' das jetzt so.
Trg
Comp
D
Clk
R
Reset
sync reset
clk

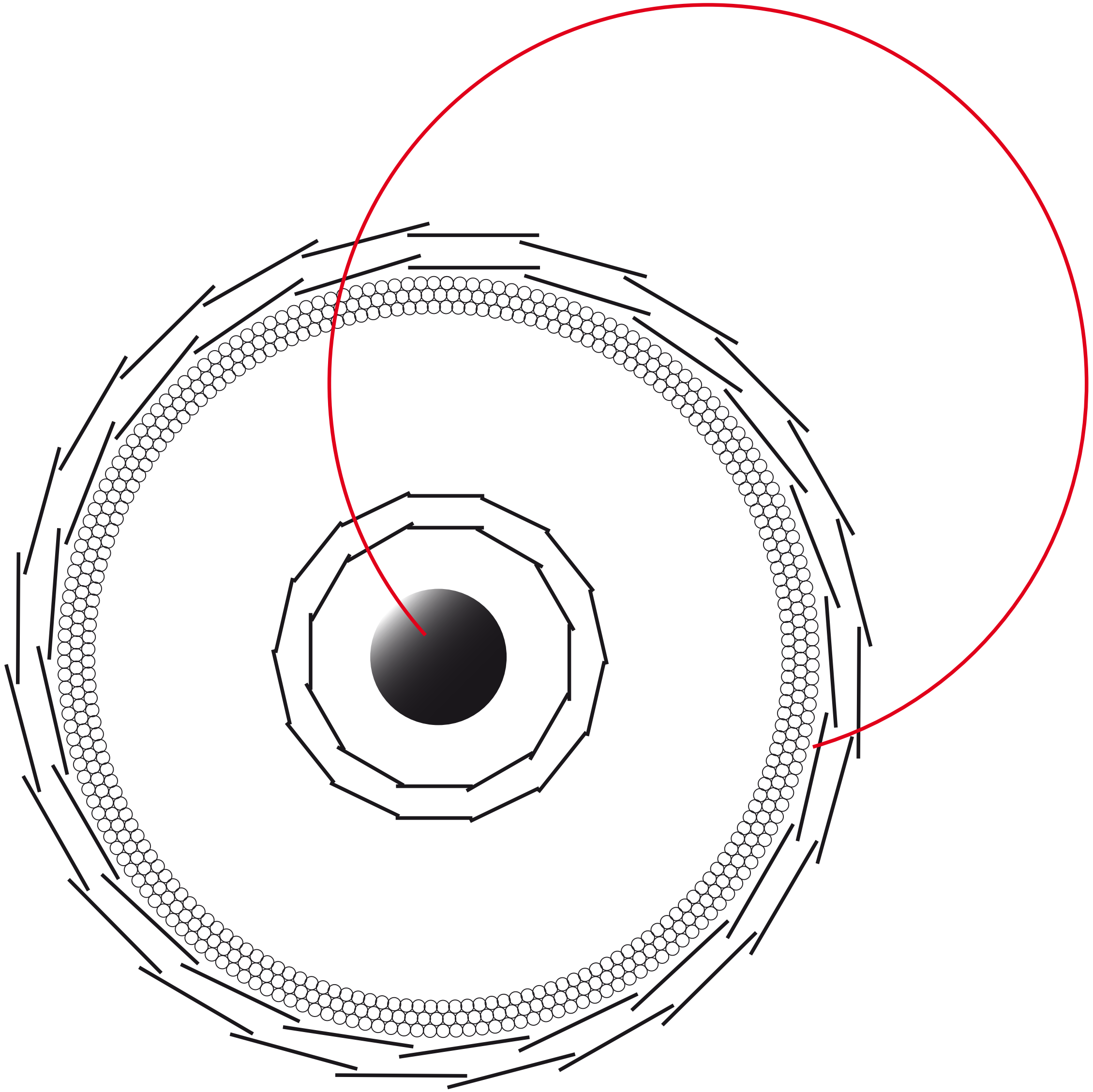
Detector concept



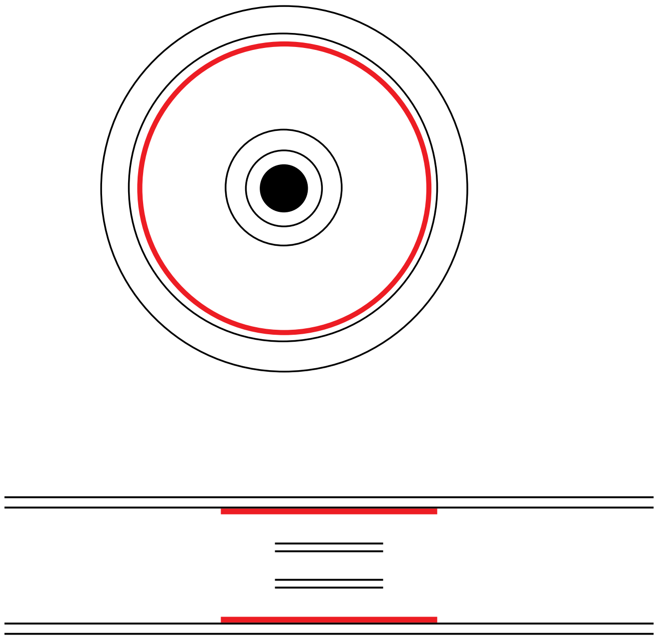
Detector concept

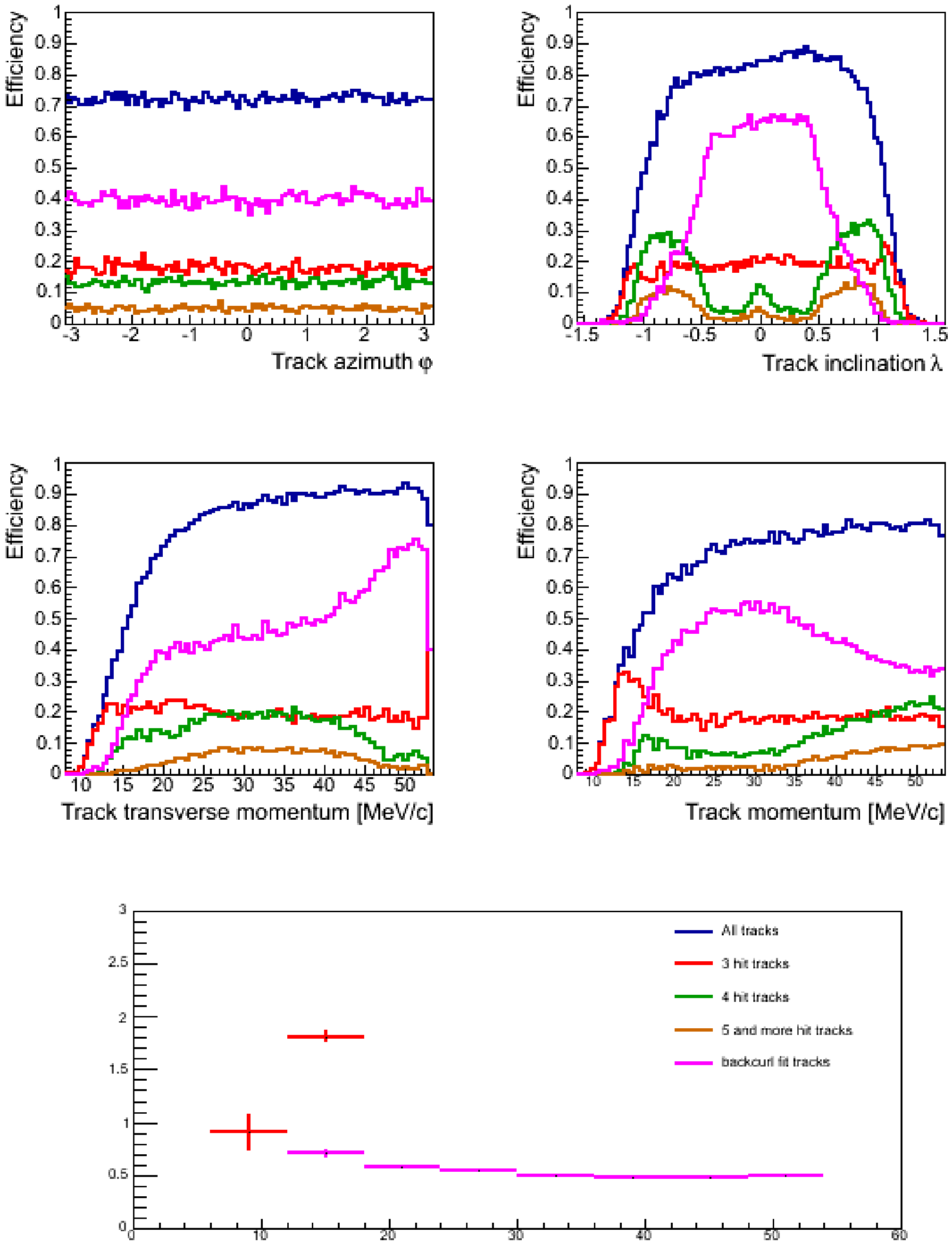


Detector Concept

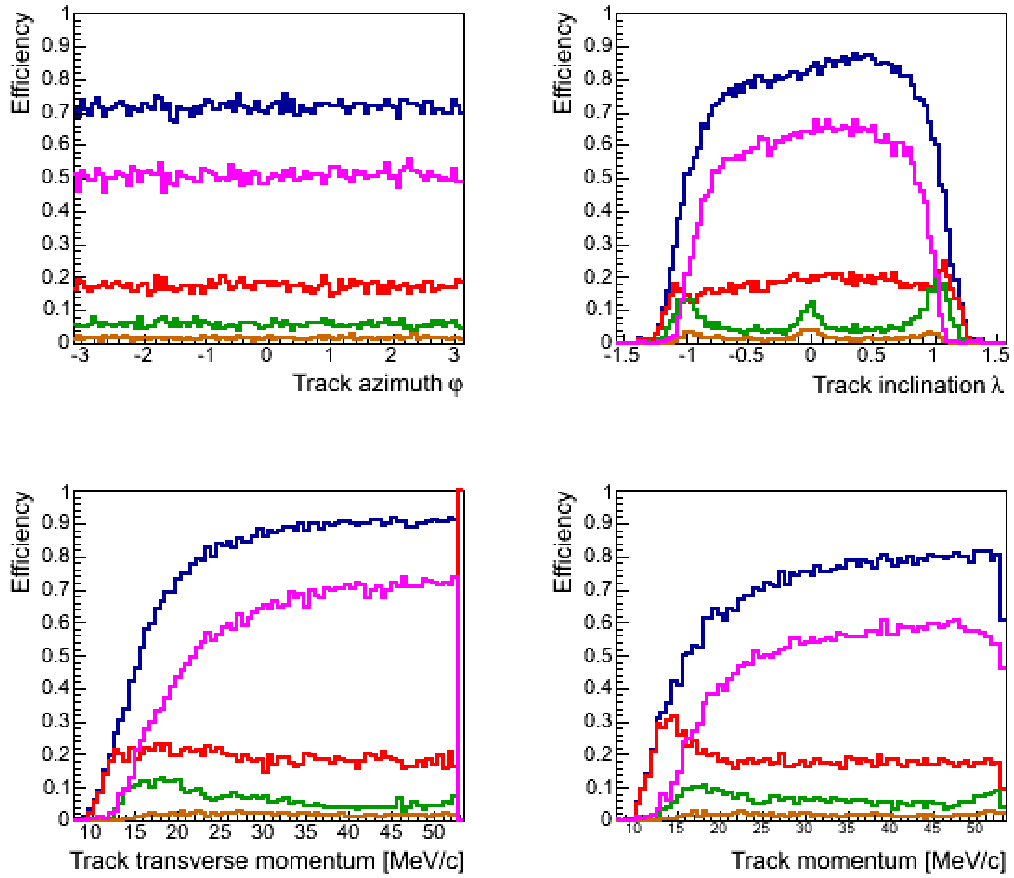


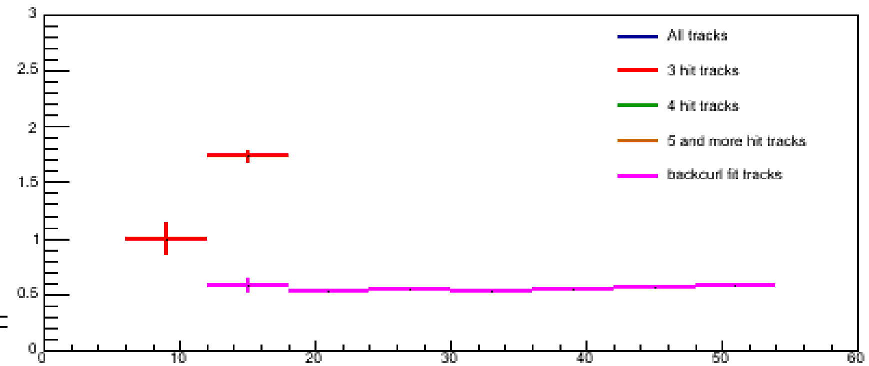
- Use recurlers
- Resolution and momentum reach look very promising
- Here:
  Using 72 cm outer layers: too short

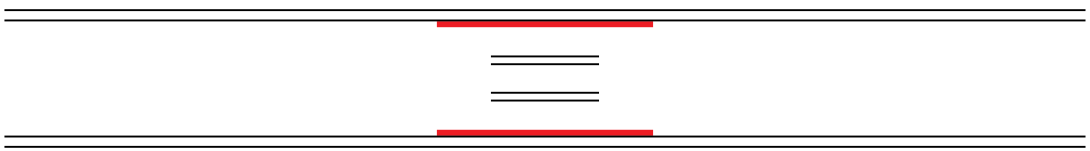


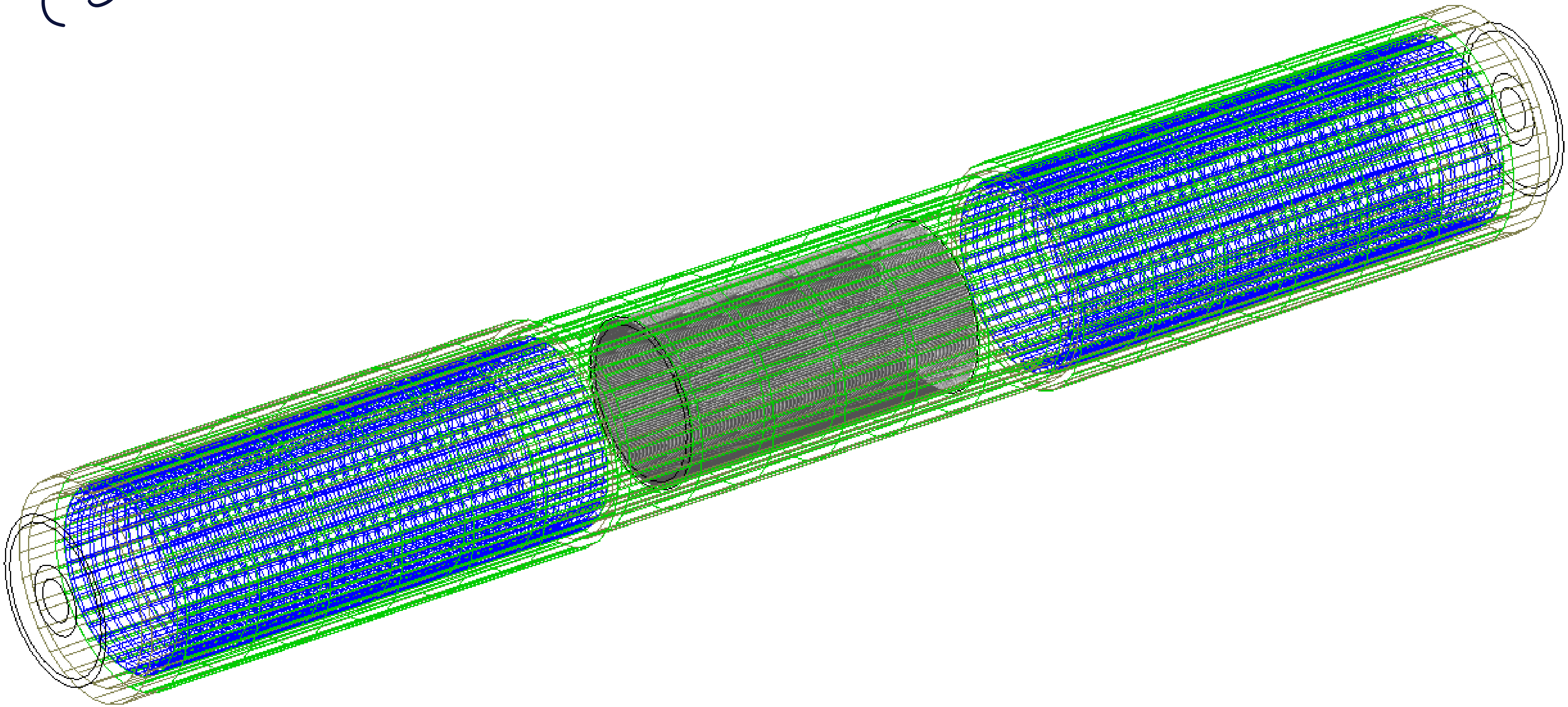


- 120 cm outer layer: long enough
- About 0.5 MeV/c momentum resolution, flat in momentum as expected from calculation
- Seem to have a working concept…

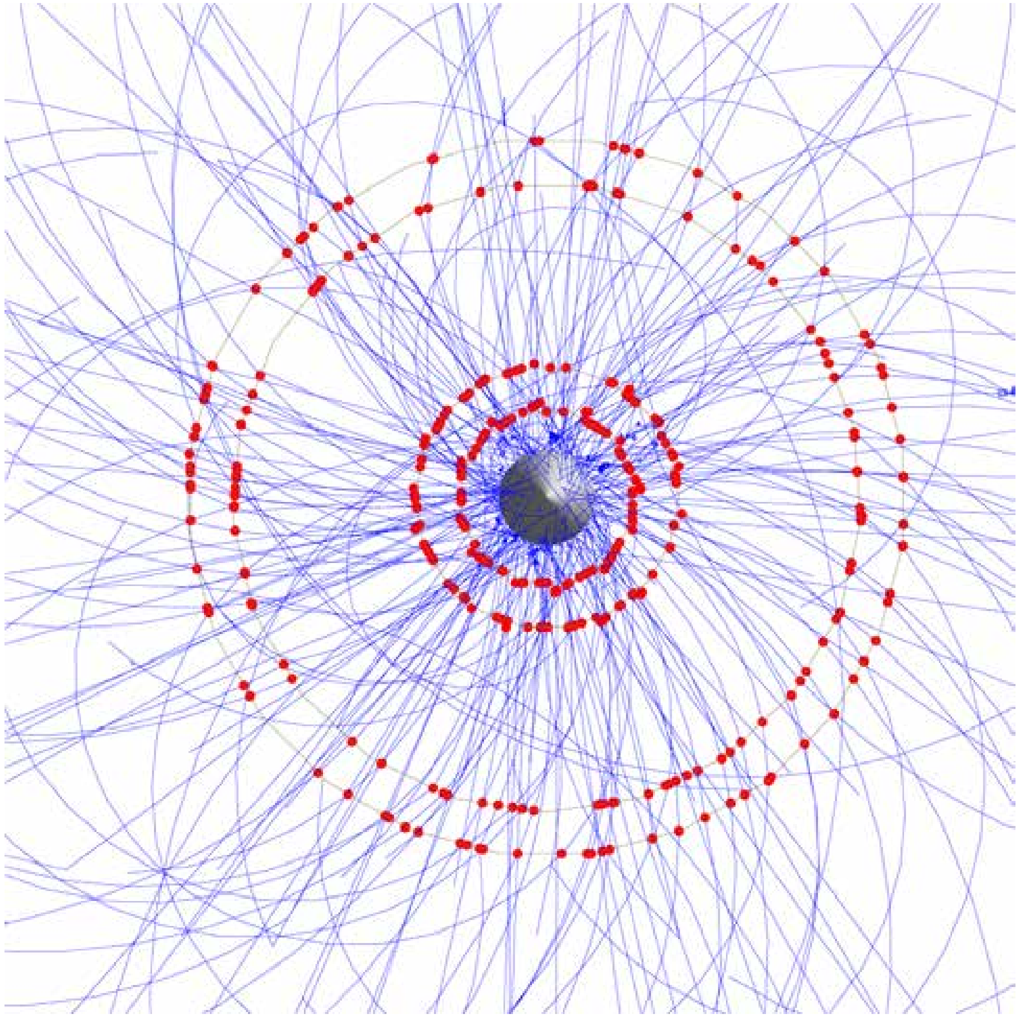






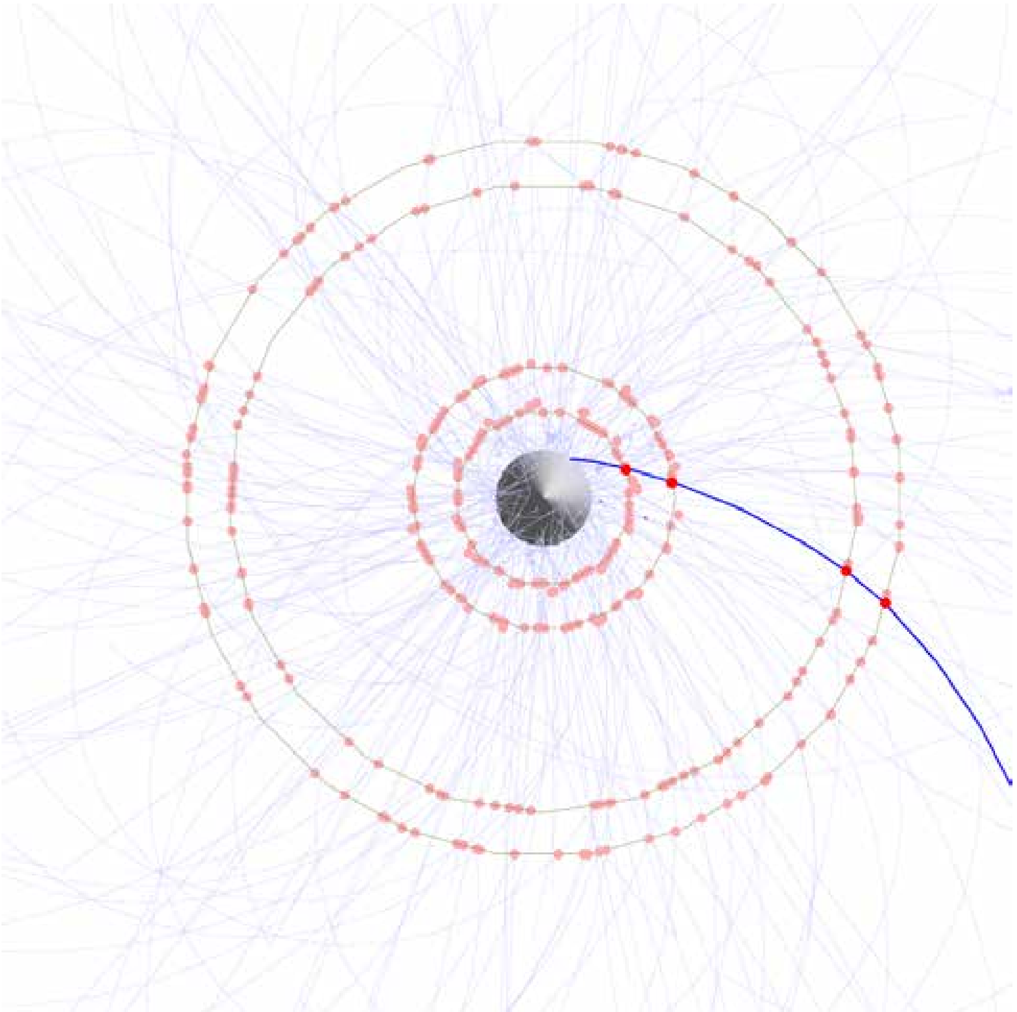


Timing



- The silicon detector is read out with 20 MHz (power consumption)
- Hundred electron tracks in one frame
- Can be resolved by hodoscope
- Scintillating fibres in central part ~ 1 ns
- Scintillating tiles in extensions ~ 100 ps
- Resolution ~ 100 ps - on average one electron

Timing



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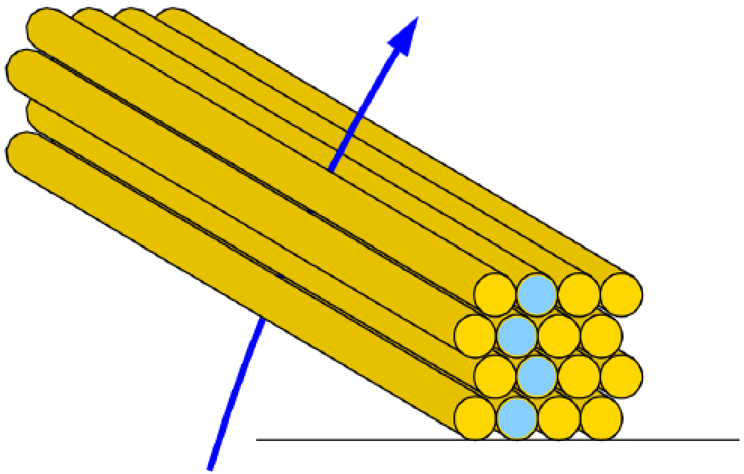
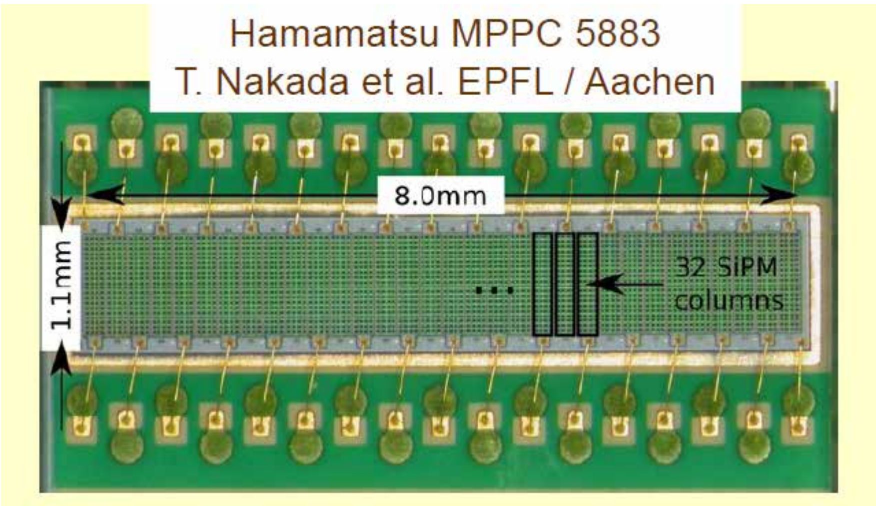
- Resolution ~ 100 ps - on average one electron

Scintillating fibres





- High spatial resolution for matching with pixels
- 200-250 μm fibres
- Photosensor: SiPM array;
  high gain, high frequency
- Readout via switched capacitor array
  (PSI developed DRS5 chip)

And suddenly, we have something rather big...

250 Million Pixels

10'000s of Fibres

What to do with the data?

Can we build a trigger?

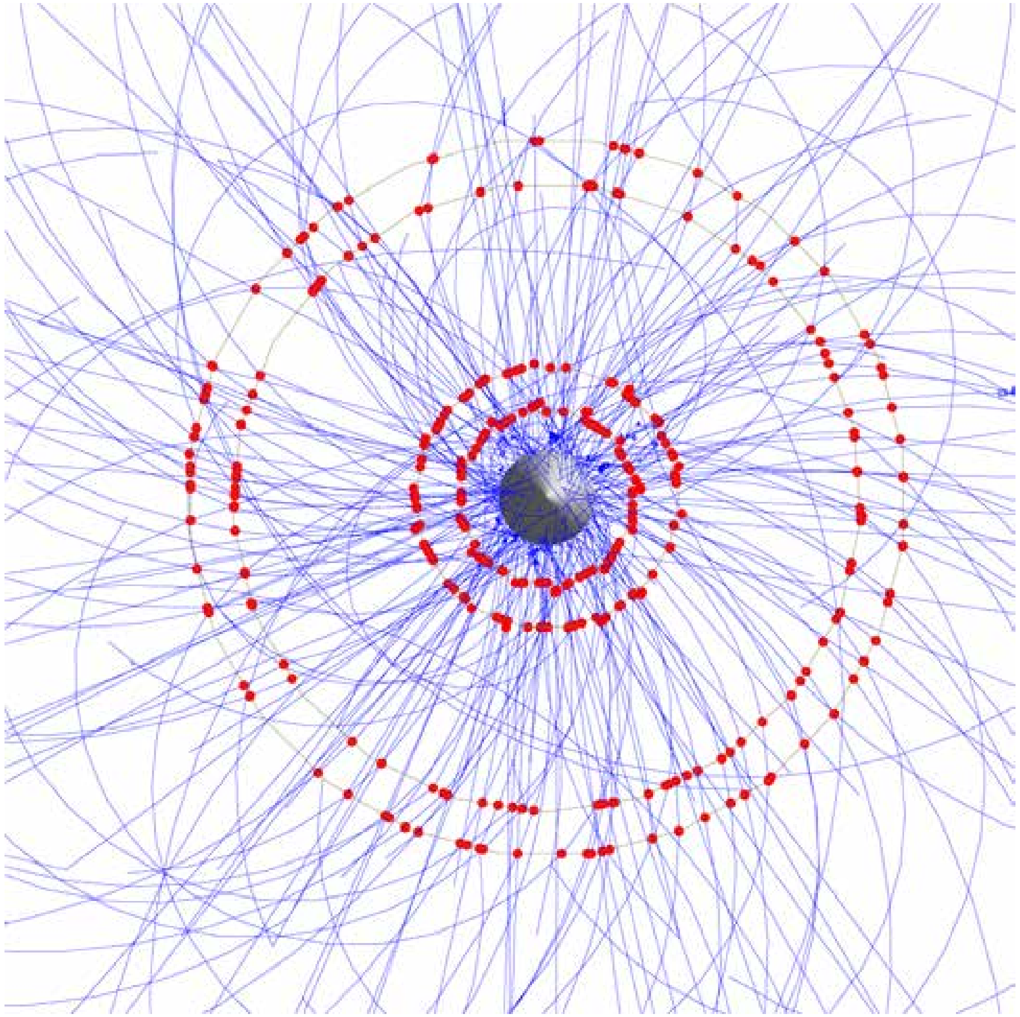
Triple coincidence from timing detectors?

Buffering of silicon hit data? Where?

No trigger - push everything out!

> 100 Gbyte/s

Data acquisition



Pixel detector:

- 250 million (zero suppressed) channels
- ~ 2000 hits per 50 ns frame

Fibre tracker:

- ~ 10'000 (zero suppressed) channels

For a muon stop rate of 2×10^9/s:

- Data rate ~ 150 Gbyte/s

Online filter farm

Online software filter farm

- Continuous front-end readout (no trigger)
- FPGAs and Graphics Processing Units (GPUs)
- Online track and event reconstruction
- Data reduction by factor ~1000
- Data to tape < 100 Mbyte/s

It could work...

we sent a letter of intent to PSI last January

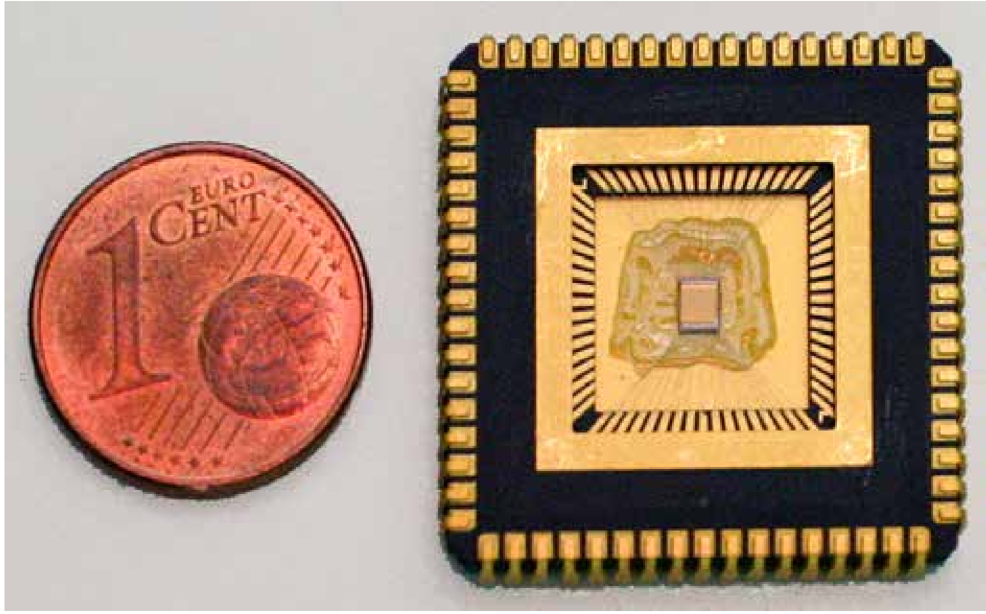
...the real work has started

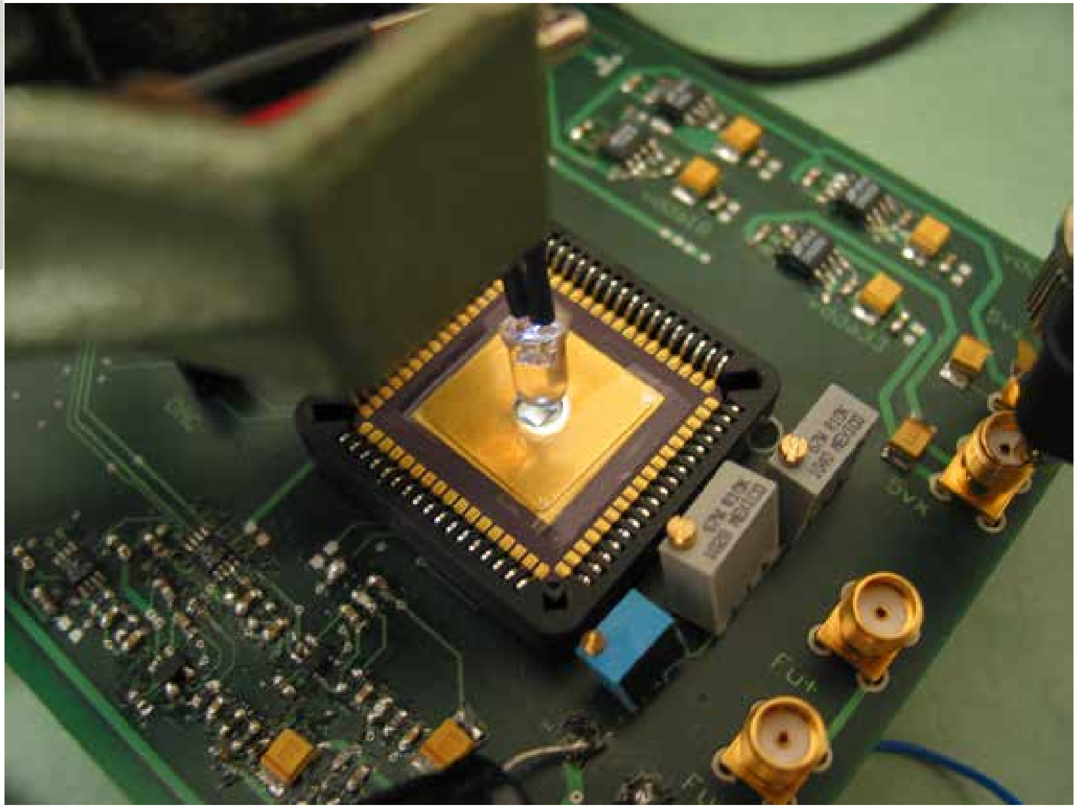
we want to hand in a full proposal in December

Sensor prototype tests

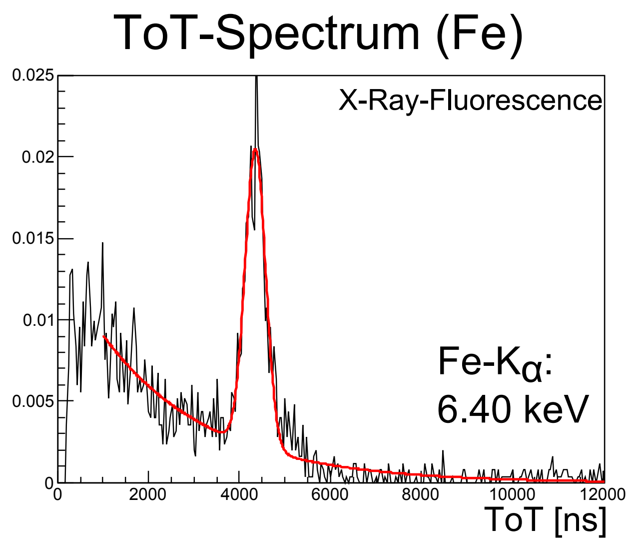
University of Heidelberg/ZITI Mannheim

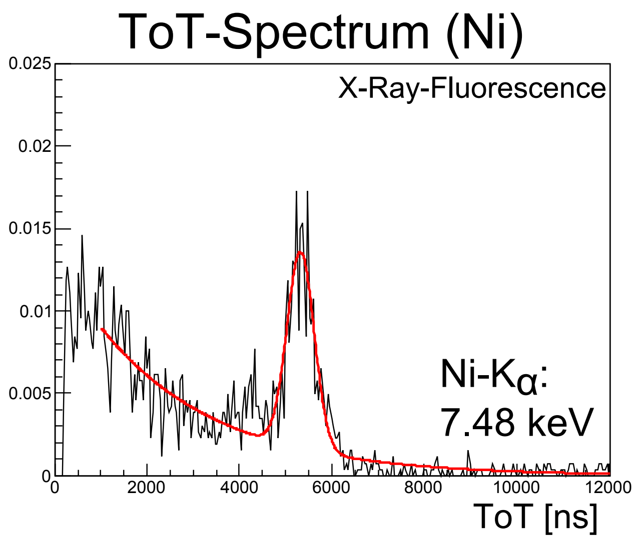
- Second generation prototype in IBM 180 nm process under test
- Next submission should come back soon





Sensor tests

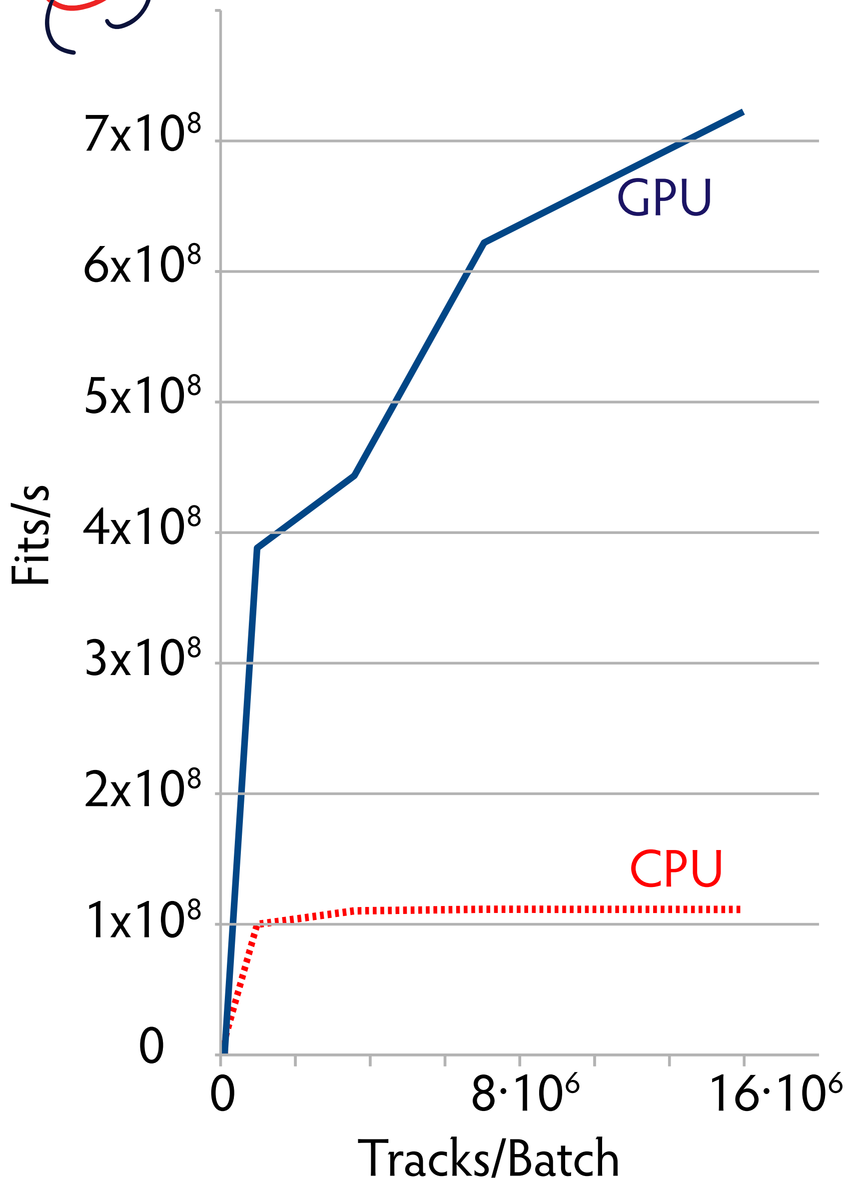




Prototype sensors perform well

- Signal/Noise > 40
- Nice time-over-threshold spectra (X-ray fluorescence)

Starting simple: GPU circle fits

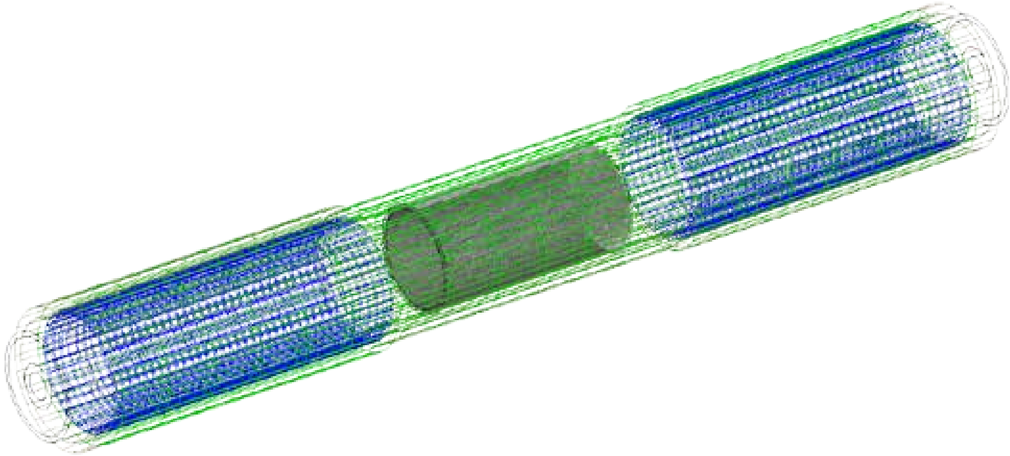


- Send data to GPU - process - return results (double buffered)
- Fit circle to four points
- Using non-iterative algorithm by V. Karimäki (~400 FLOPS/ 32 bytes input)
- OpenCL implementation on AMD Radeon HD 7990 (3 GB) on an AMD FX 8150 system
- Factor 7 faster than 8 core CPU
- Limited by bus speed

Lots to be done...

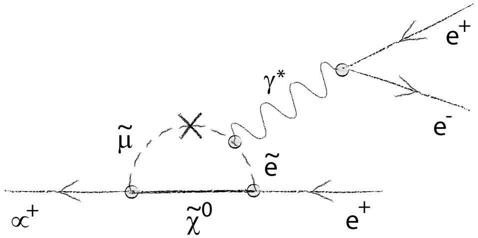
...a great team...

Summary



- Lepton flavour violation might be just around the corner
- Novel concept for an experiment searching for $\mu \rightarrow eee$
- Technologies: HV monolithic pixel sensor and fibre tracker
- Sensitivity of 10^{-16} feasible
- After more than 20 years, time has come to go beyond the very succesful SINDRUM experiment

A general effective Lagrangian



Tensor terms (dipole) e.g. supersymmetry

$$L_{\mu \rightarrow eee} = 2\, G_F \,(m_\mu A_R \, \overline{\mu}_R \, \sigma^{\mu\nu} e_L F_{\mu\nu} + m_\mu A_L \, \overline{\mu}_L \, \sigma^{\mu\nu} e_R F_{\mu\nu}$$

Four-fermion terms e.g. Higgs, Z', doubly charged Higgs....

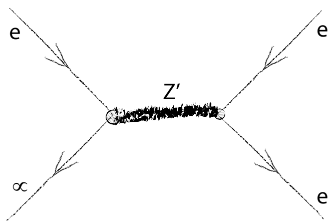
$$+ g_1 (\overline{\mu}_R e_L)(\overline{e}_R e_L) \qquad + g_2 (\overline{\mu}_L e_R)(\overline{e}_L e_R)$$

scalar

$$+ g_3 (\overline{\mu}_R \gamma^\mu e_R)(\overline{e}_R \gamma^\mu e_R) \qquad + g_4 (\overline{\mu}_L \gamma^\mu e_L)(\overline{e}_L \gamma^\mu e_L)$$

$$+ g_5 (\overline{\mu}_R \gamma^\mu e_R)(\overline{e}_L \gamma^\mu e_L) \qquad + g_6 (\overline{\mu}_L \gamma^\mu e_L)(\overline{e}_R \gamma^\mu e_R) \; + \text{H. C.} \,)$$

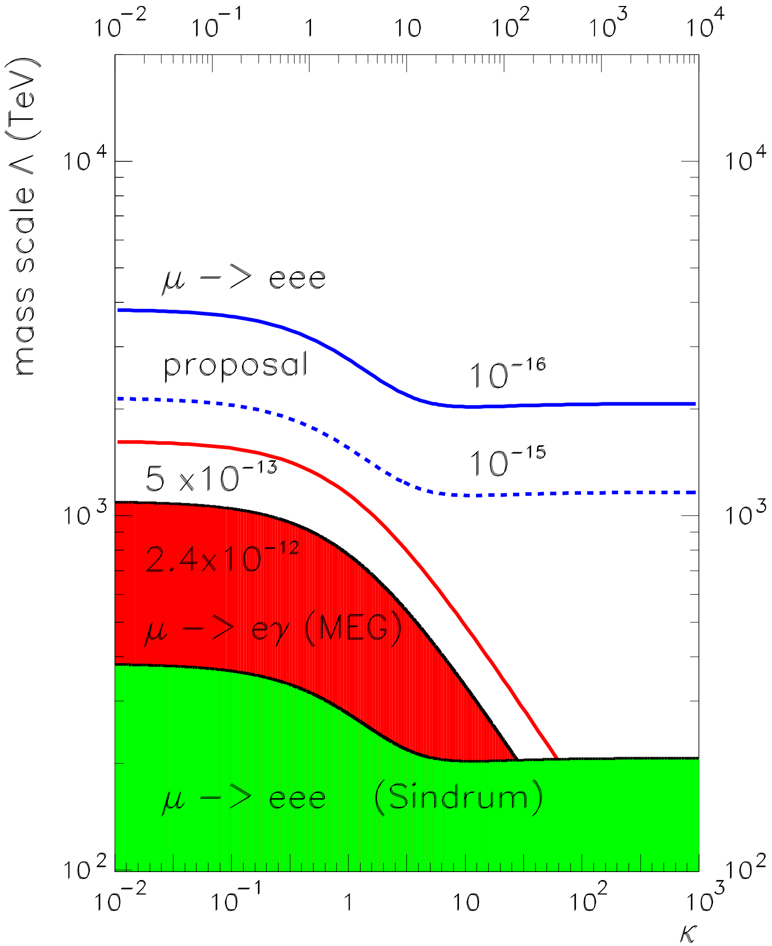
vector



(Y. Kuno, Y. Okada, Rev.Mod.Phys. 73 (2001) 151)

How good would we have to be?

$$L_{LFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2} A_R \bar{\mu}_R \sigma^{\mu\nu} e_L F_{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2} (\bar{\mu}_L \gamma^\mu e_L)(\bar{e}_L \gamma^\mu e_L)$$



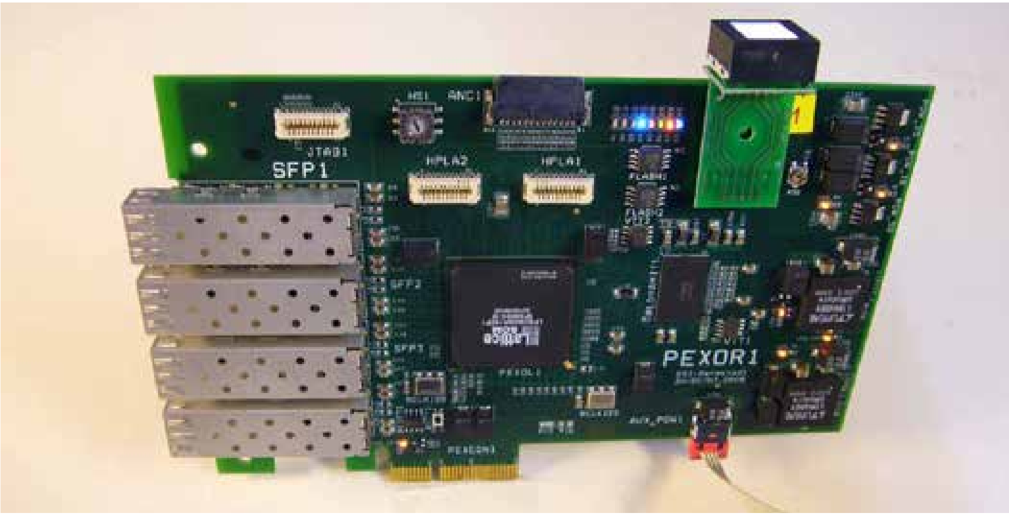
- Retain only one loop term and one contact term
- Ratio κ between them
- Common mass scale Λ
- Allows for sensitivity comparisons between $\mu \rightarrow eee$ and $\mu \rightarrow e\gamma$
- In case of dominating dipole couplings ($\kappa = 0$):

$$\frac{B(\mu \rightarrow eee)}{B(\mu \rightarrow e\gamma)} = 0.006 \quad (\text{essentially } \alpha_{em})$$

Onwards...

Technical challenge: Getting data into and out of GPU fast enough

- PCIe 3.0
- PCI cards with optical links will do DMA to GPU memory (PANDA development)



M. Turany et al., GSI/Giessen University

Floating point power sufficient to fit $O(10^{10})$ tracks on O(50) devices

Collaboration

A proto-collaboration has formed and submitted a letter of intent to PSI

- University of Geneva
- University of Heidelberg
- Paul Scherrer Institut (PSI)
- University of Zurich
- ETH Zurich

Also in contact with other interested groups

Goal: Detailed Research Proposal by 2013

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich