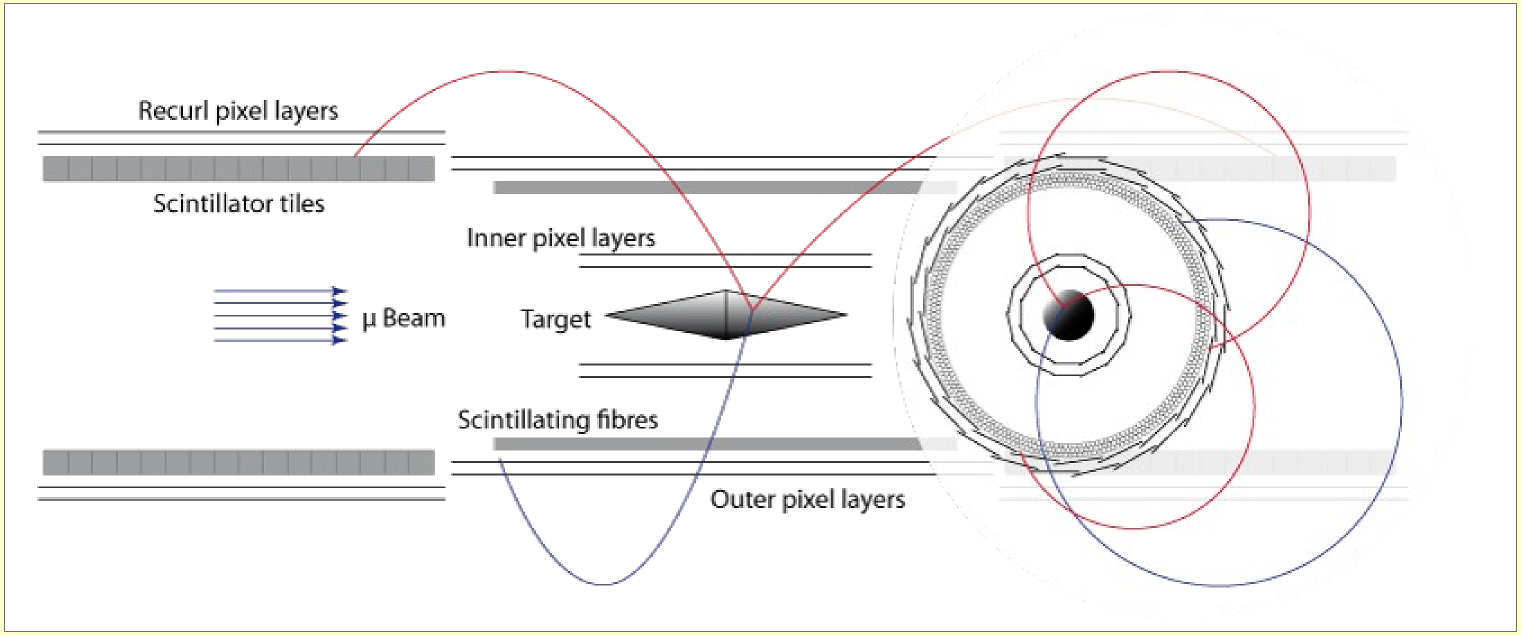
New Experimental Search for μ→eee

Paul Scherrer Institut

Open Users Meeting BV43

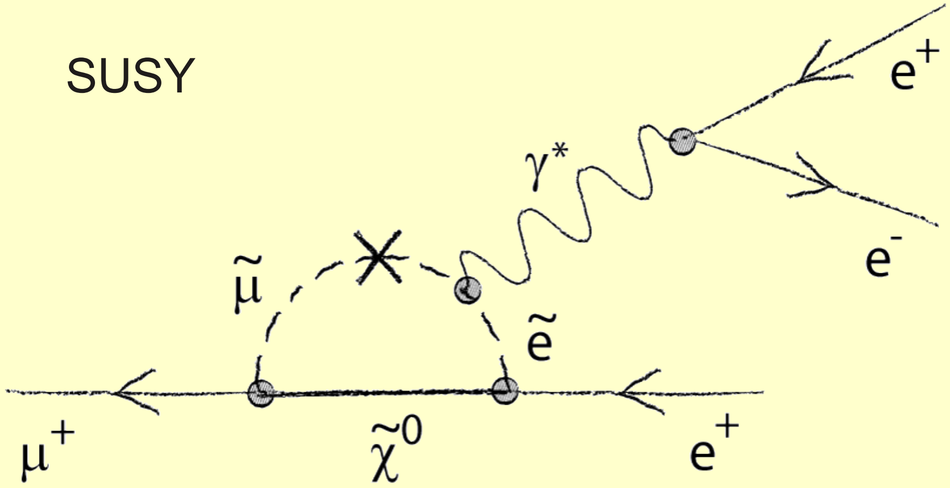
February 22, 2012

André Schöning for the **Mu3e Collaboration**

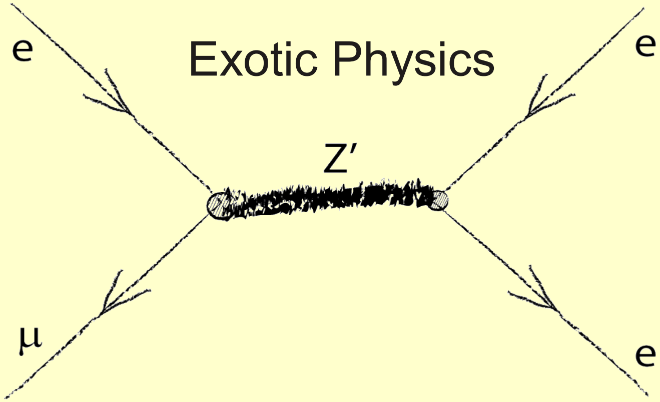


Lepton Flavor Violating Decay $\mu^+ \rightarrow e^+e^+e^-$

SUSY



Exotic Physics



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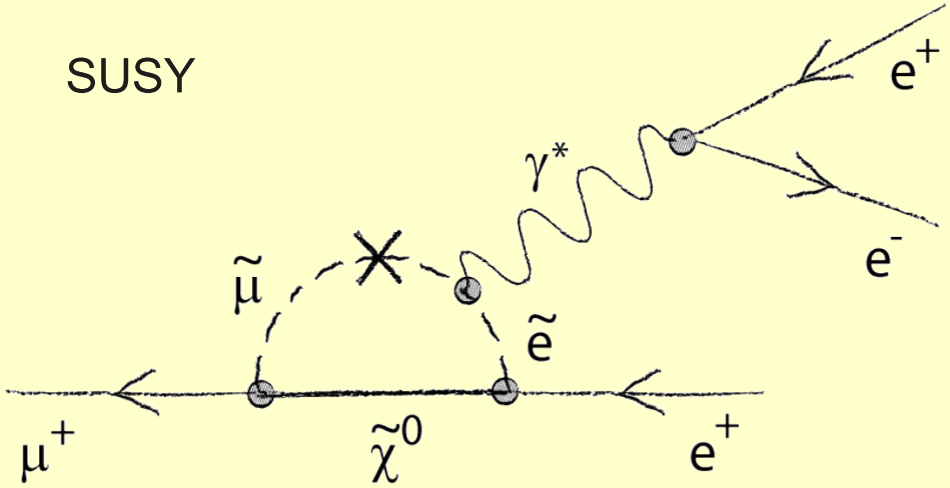
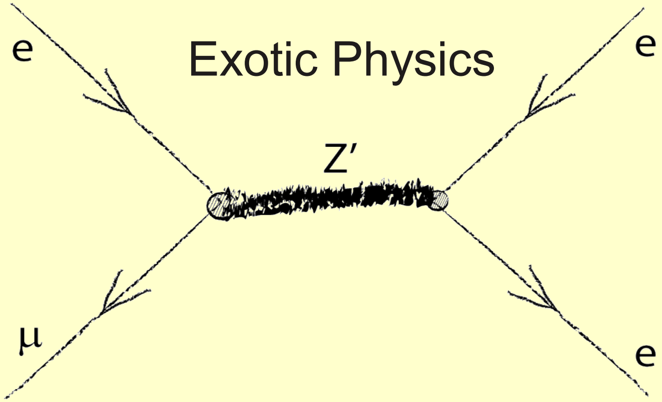

SUSY


Exotic Physics

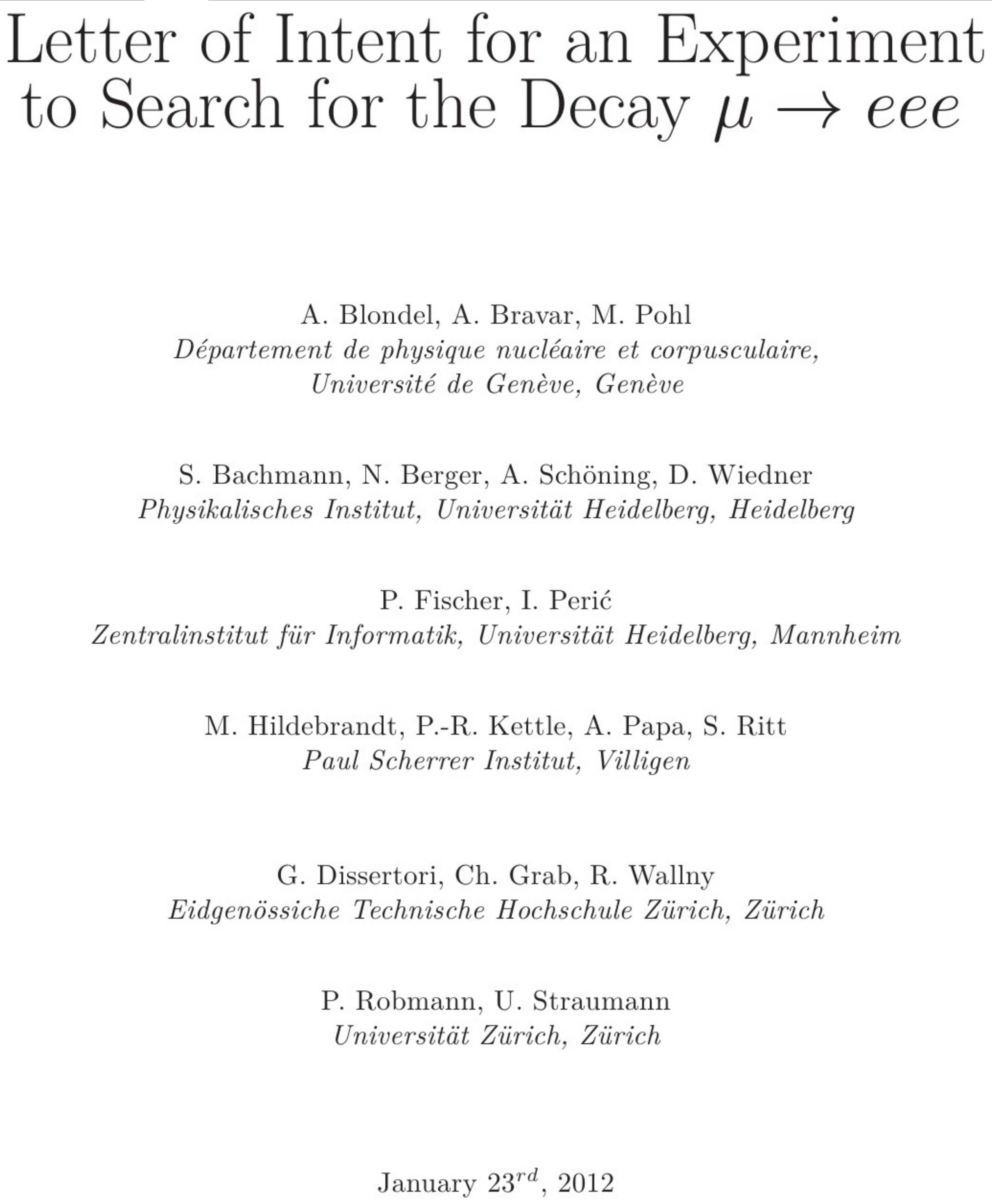
Current experimental limit:

$B(\mu^+ \to e^+e^+e^-) < 10^{-12}$ (90%CL, SINDRUM 1988)

Our ultimate Goal:

$B(\mu^+ \to e^+e^+e^-) < 10^{-16}$ (90% CL exclusion)

$B(\mu^+ \to e^+e^+e^-) \sim 2.5 \cdot 10^{-16}$ (5 sigma discovery)



Letter of Intent for an Experiment to Search for the Decay $\mu \rightarrow eee$

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M. Hildebrandt, P.-R. Kettle, A. Papa, S. Ritt
Paul Scherrer Institut, Villigen

G. Dissertori, Ch. Grab, R. Wallny
Eidgenössiche Technische Hochschule Zürich, Zürich

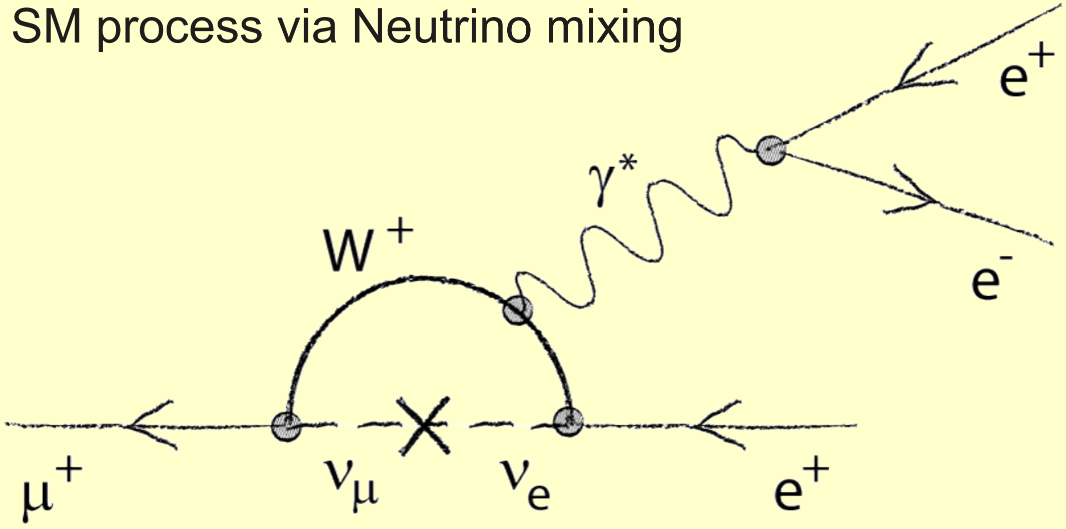
P. Robmann, U. Straumann
Universität Zürich, Zürich

January 23^{rd}, 2012

1. Motivation
2. Theory
3. Experimental Situation
4. The decay μ→eee
5. The novel experiment
6. Timetable + Costs

LFV in the Standard Model

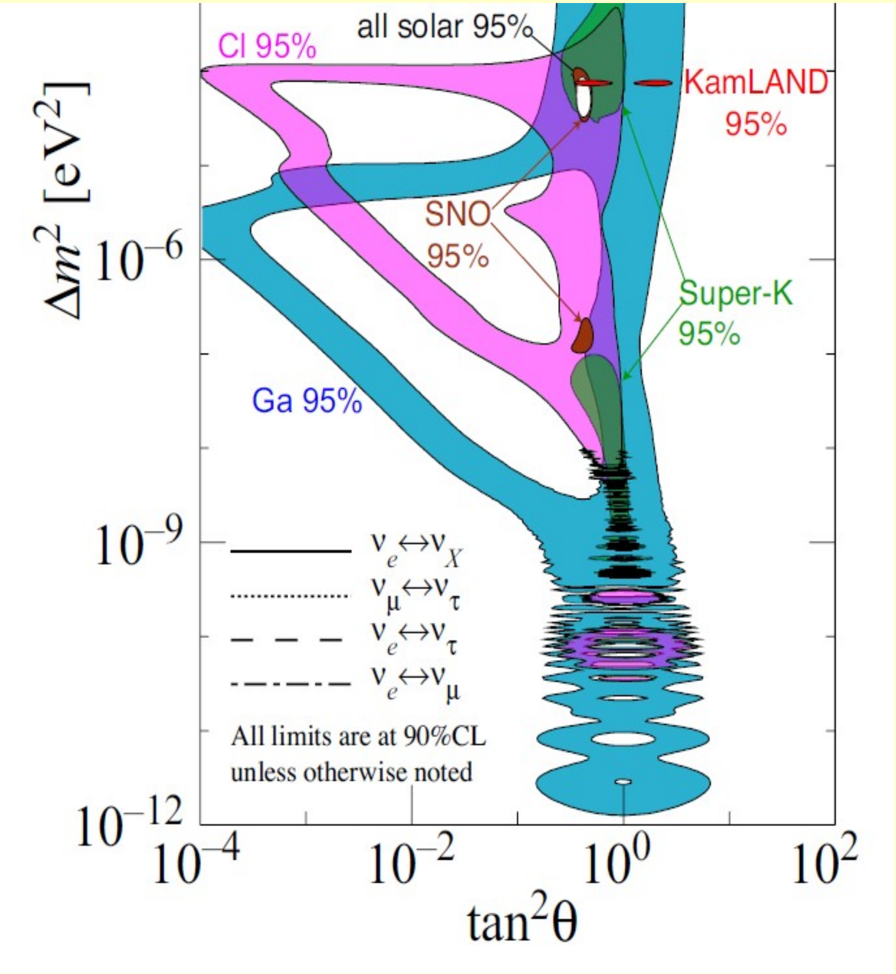
SM process via Neutrino mixing



process is heavily suppressed due to small mass difference of neutrinos!

$$B(\mu^+ \to e^+e^+e^-) \ll 10^{-50}$$

Neutrino Oscillation Summary Plot

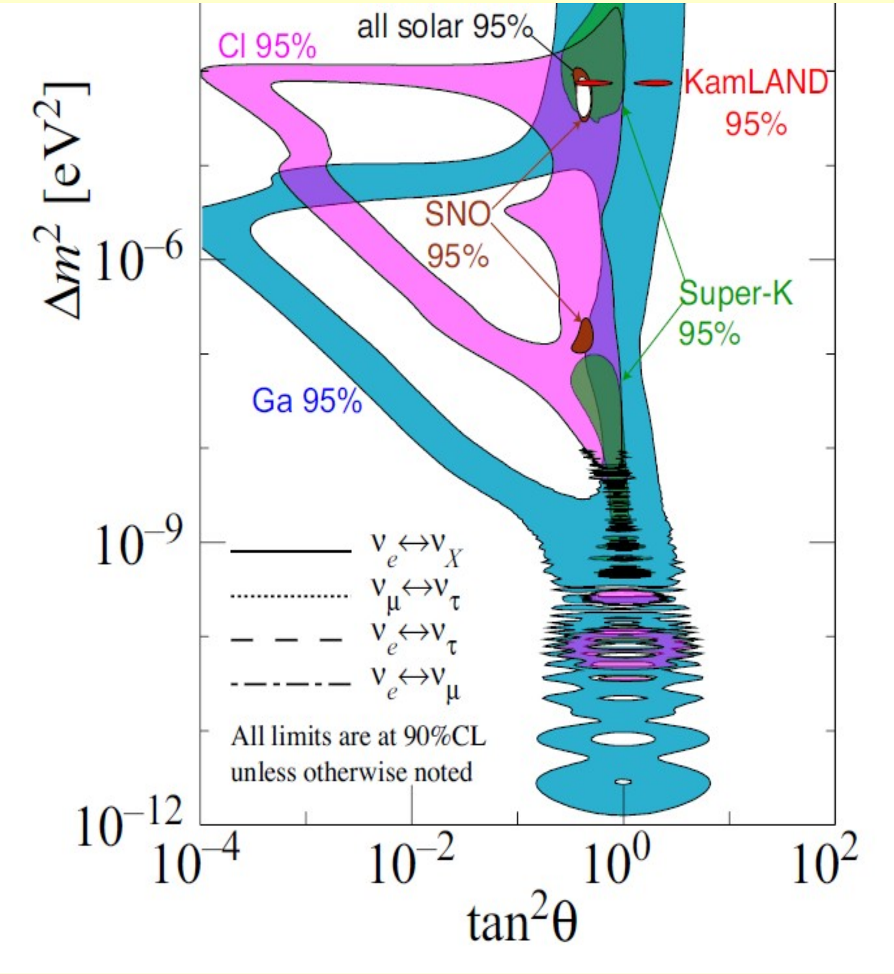


Beyond the Standard Model

Lepton Flavor Violation predicted by many New Physics models:

- **Supersymmetry**
- **Higgs Triplet Models**
- **Little Higgs Models**
- **New Heavy Vector bosons (Z')**
- **Leptoquarks (GUT models)**
- **Extra Dimensions (KK towers)**

Neutrino Oscillation Summary Plot



In many models obervable LFV effects are expected, related to the mixing large observed in lepton sector

B($\mu^+ \rightarrow e^+e^+e^-$) ~ 10^{-12} possible

Effective cLFV Lagrangian

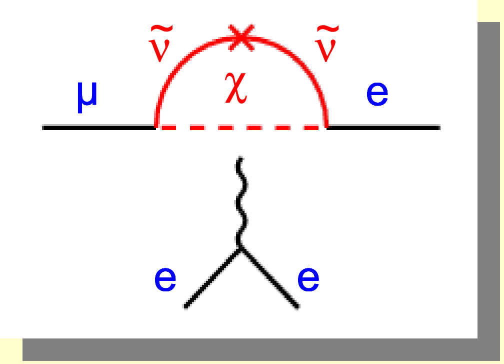
Effective charged LFV Lagrangian (Y. Kuno and Y Okada):

Tensor terms (dipole)

$$L_{\mu\rightarrow eee} \quad = \quad \frac{4G_F}{2}\left[m_\mu A_R \overline{\mu_R}\sigma^{\mu\nu} e_L F_{\mu\nu} + m_\mu A_L \overline{\mu_L}\sigma^{\mu\nu} e_R F_{\mu\nu}\right.$$

e.g. Supersymmetry

dipole coupling

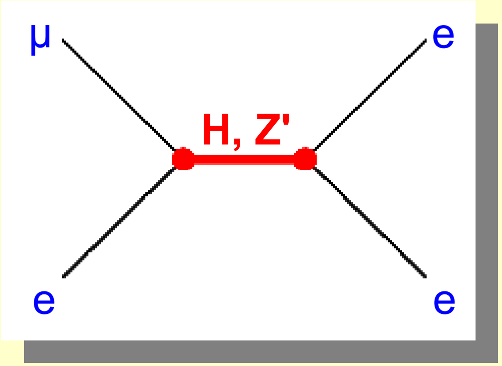


Four-fermion terms

$$\begin{aligned} &+ g_1 \left(\overline{\mu_R} e_L\right)\left(\overline{e_R} e_L\right) + g_2 \left(\overline{\mu_L} e_R\right)\left(\overline{e_L} e_R\right) && \text{(scalar)} \\ &+ g_3 \left(\overline{\mu_R}\gamma e_R\right)\left(\overline{e_R}\gamma_\mu e_R\right) + g_4 \left(\overline{\mu_L}\gamma e_L\right)\left(\overline{e_L}\gamma_\mu e_L\right) && \text{(vector)} \\ &+ g_5 \;\left(\overline{\mu_R}\gamma e_R\right)\left(\overline{e_L}\gamma_\mu e_L\right) + g_6 \left(\overline{\mu_L}\gamma e_L\right)\left(\overline{e_R}\gamma_\mu e_R\right) \; + \; H.c. \left.\right] \end{aligned}$$

e.g. Higgs, Z'

tree diagram



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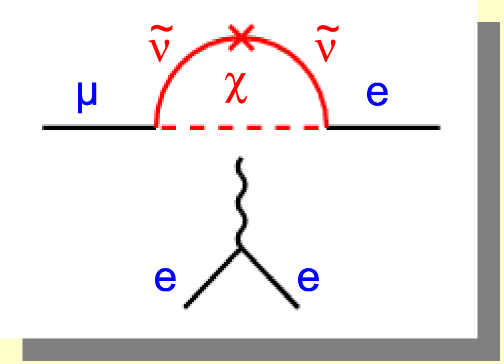

Four-fermion terms

$$\begin{aligned}
&+ g_1 (\overline{\mu_R} e_L)(\overline{e_R} e_L) + g_2 (\overline{\mu_L} e_R)(\overline{e_L} e_R) && \text{(scalar)}\\
&+ g_3 (\overline{\mu_R}\gamma e_R)(\overline{e_R}\gamma_\mu e_R) + \boxed{g_4 (\overline{\mu_L}\gamma e_L)(\overline{e_L}\gamma_\mu e_L)} && \text{(vector)}\\
&+ g_5 (\overline{\mu_R}\gamma e_R)(\overline{e_L}\gamma_\mu e_L) + g_6 (\overline{\mu_L}\gamma e_L)(\overline{e_R}\gamma_\mu e_R) + H.c.\left.\right]
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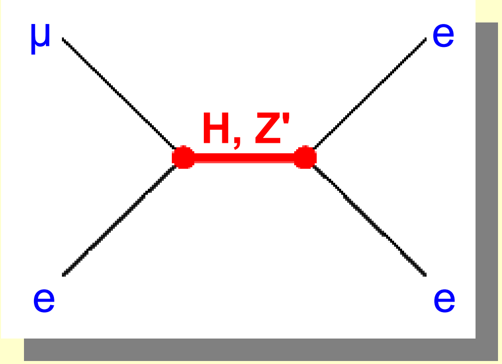

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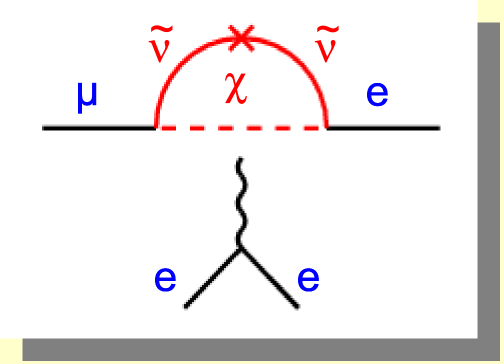
e.g. Supersymmetry

$$\boxed{\frac{m_\mu}{\Lambda^2(1+\kappa)} H^{dipole}}$$

dipole coupling



Four-fermion terms

$$+ g_1 (\overline{\mu_R} e_L)(\overline{e_R} e_L) + g_2 (\overline{\mu_L} e_R)(\overline{e_L} e_R) \quad \text{(scalar)}$$

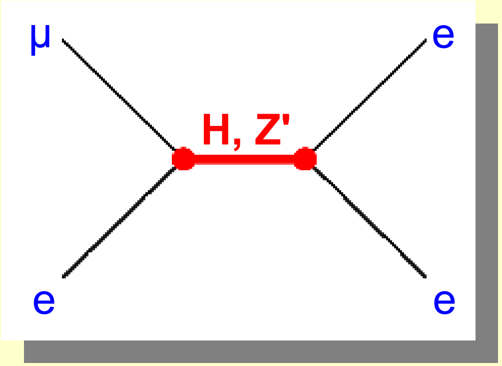
$$+ g_3 (\overline{\mu_R}\gamma e_R)(\overline{e_R}\gamma_\mu e_R) + \boxed{g_4 (\overline{\mu_L}\gamma e_L)(\overline{e_L}\gamma_\mu e_L)} \quad \text{(vector)}$$

$$\left. + g_5 (\overline{\mu_R}\gamma e_R)(\overline{e_L}\gamma_\mu e_L) + g_6 (\overline{\mu_L}\gamma e_L)(\overline{e_R}\gamma_\mu e_R) + H.c.\right]$$

e.g. Higgs, Z'

$$\boxed{\frac{\kappa}{\Lambda^2(1+\kappa)} J^{e\mu}_{\nu} J^{\nu,ee}}$$

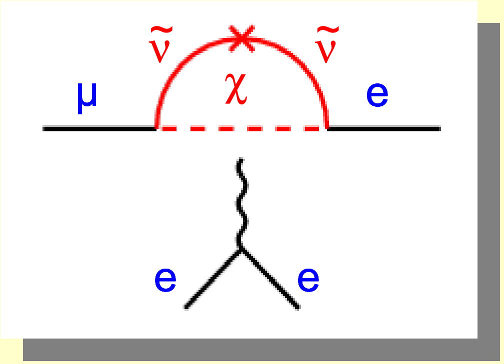
tree diagram



Effective Model Comparison

Effective cLFV Lagrangian:

$$L = \frac{m_\mu}{\Lambda^2 (1+\kappa)} H^{dipole} + \frac{\kappa}{\Lambda^2 (1+\kappa)} J_\nu^{e\mu} J^{\nu,ee}$$



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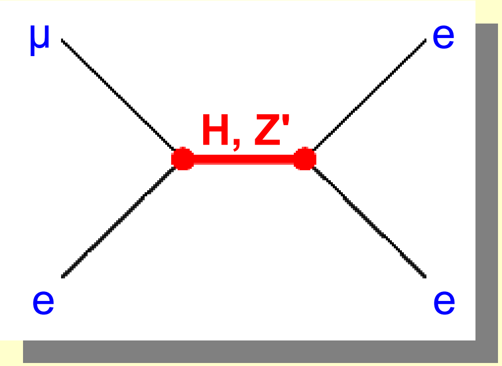


$$= 1/\kappa$$

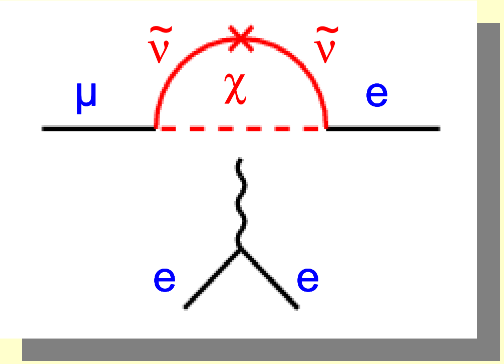
$\kappa = 0$ $\kappa = \infty$

Λ = effective mass scale (including coupling)

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

Effective cLFV Lagrangian:

$$L = \frac{m_\mu}{\Lambda^2(1+\kappa)} H^{dipole} + \frac{\kappa}{\Lambda^2(1+\kappa)} J_\nu^{e\mu} J^{\nu,ee}$$



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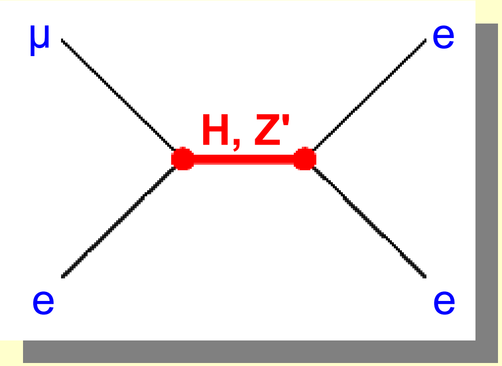
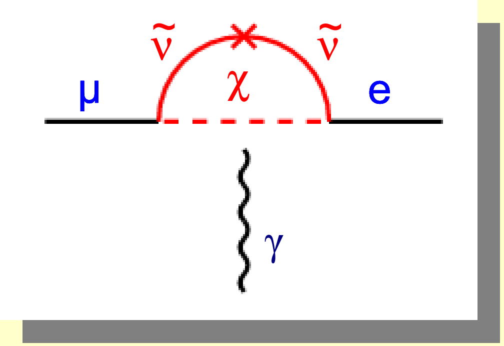


$$= 1/\kappa$$

$\kappa = 0$

$\kappa = \infty$



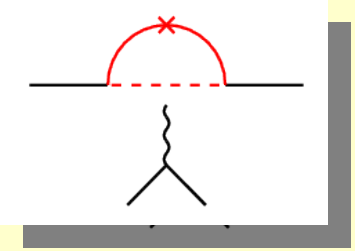
-

Mu3e sensitive
to additional diagrams!

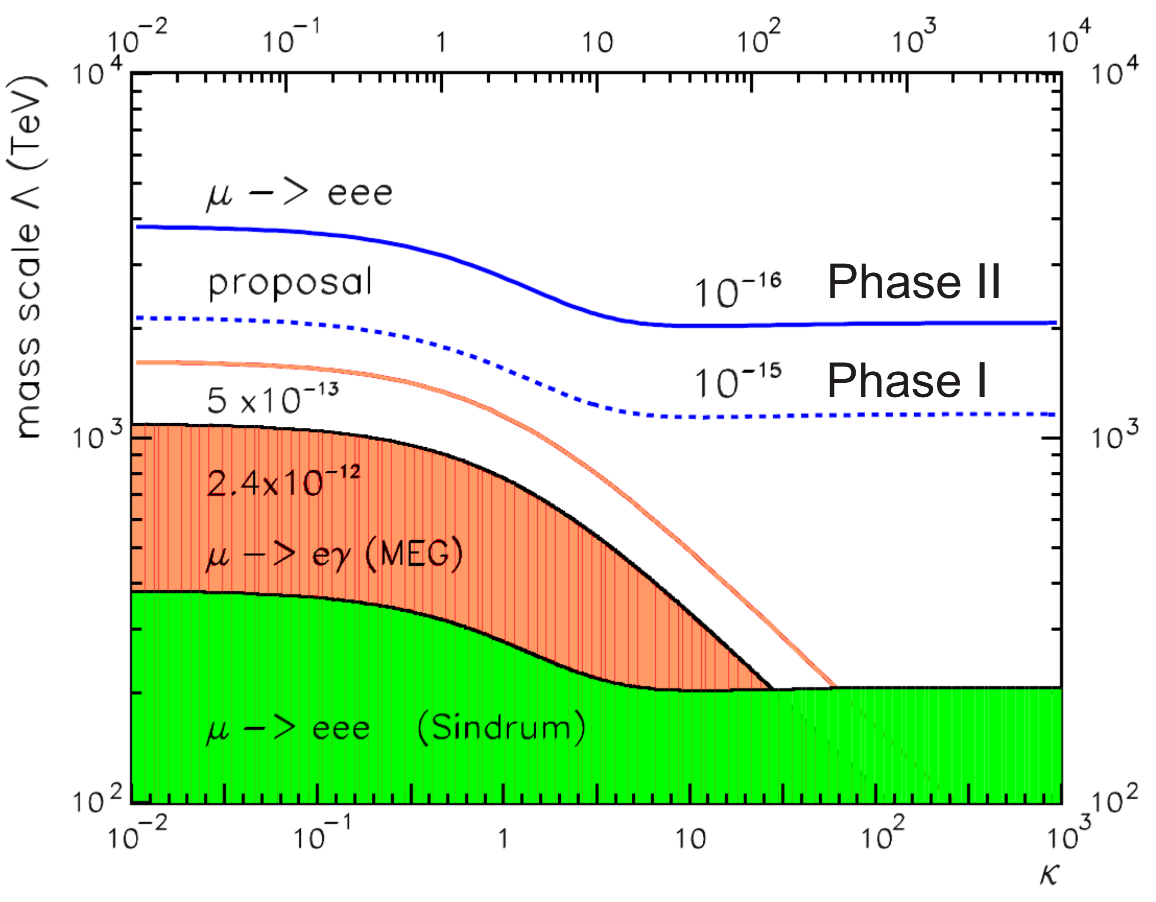
$\mu^+ \to e^+e^+e^-$ versus $\mu^+ \to e^+\gamma$

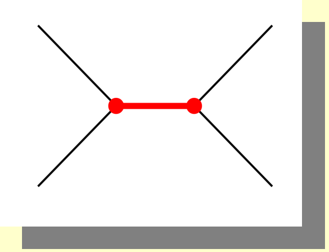
Effective cLFV Lagrangian:

$$L = \frac{m_\mu}{\Lambda^2 (1+\kappa)} H^{dipole} + \frac{\kappa}{\Lambda^2 (1+\kappa)} J_\nu^{e\mu} J^{\nu,ee}$$



$\kappa = 0$

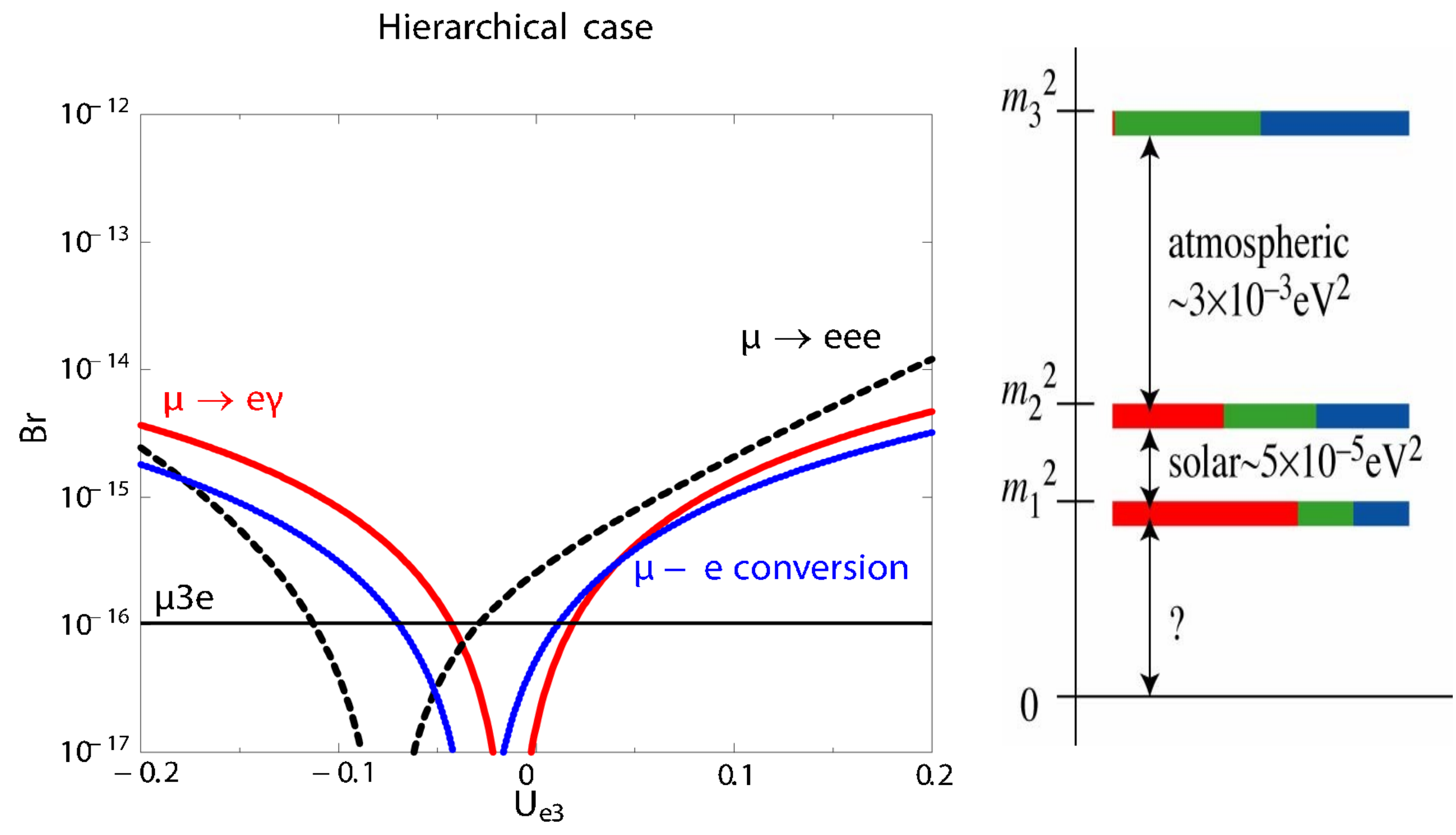




$\kappa = \infty$

Example: Higgs Triplet Models

M.Kakizaki et al., Phys.Lett. **B566** 210, 2003



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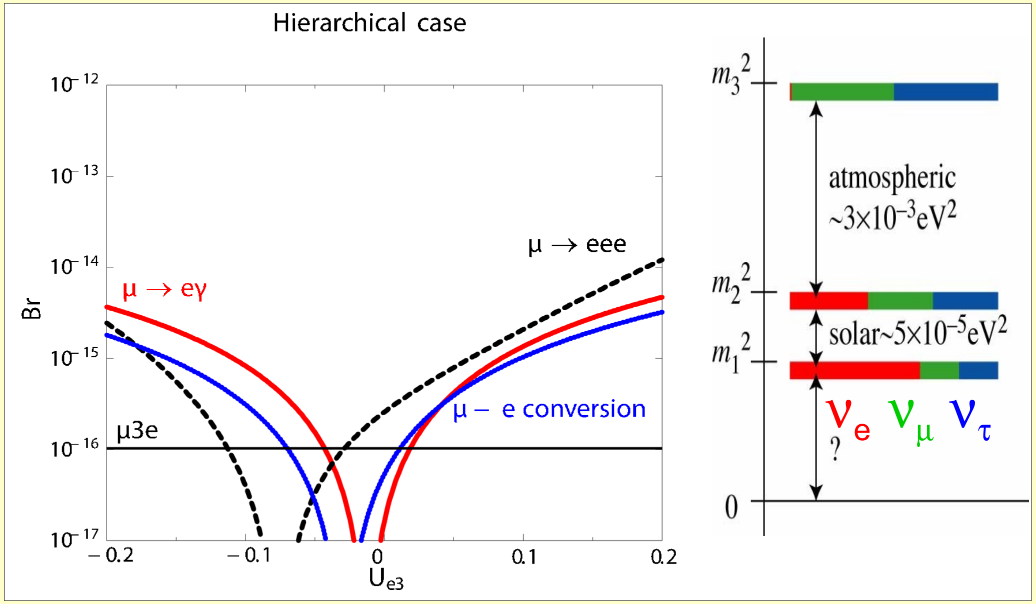
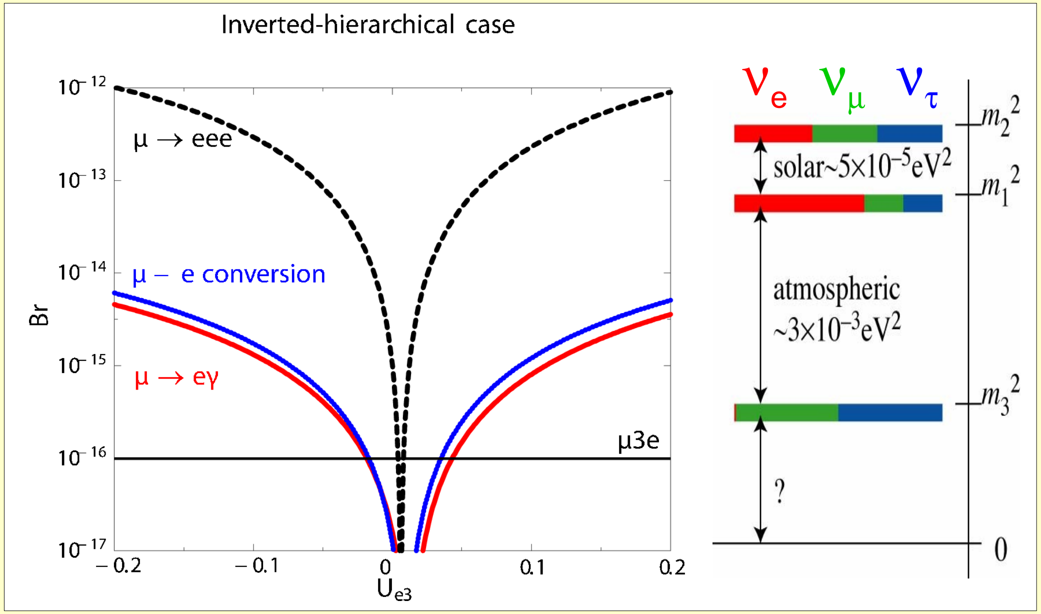
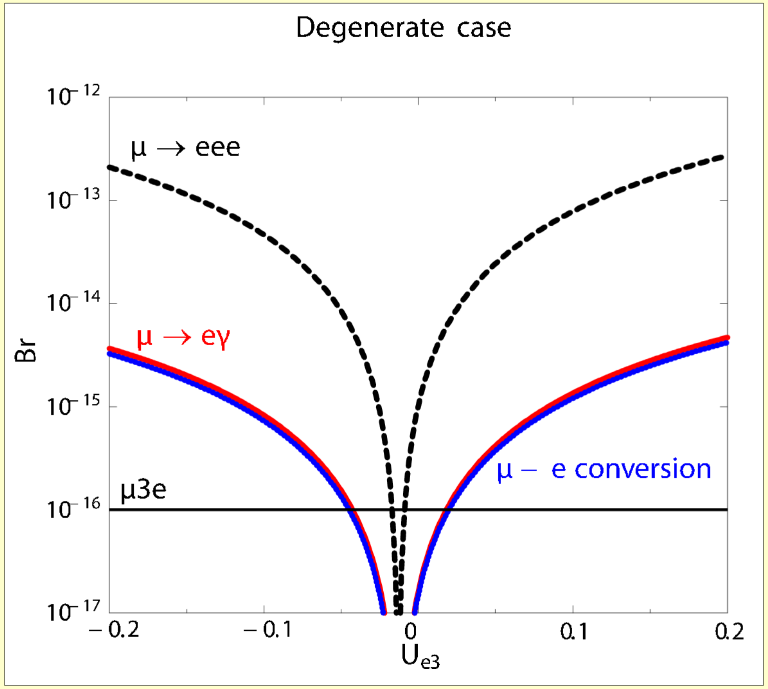


Hierarchical case



Inverted-hierarchical case



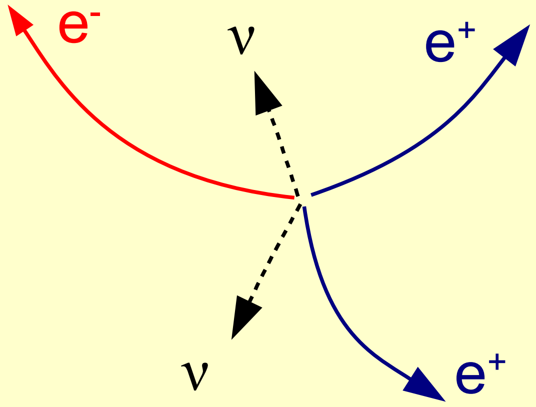
Degenerate case

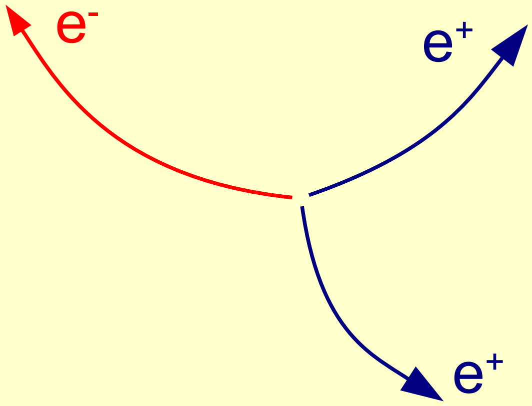
$\sin^2 2\theta_{13}$= 0.085±0.029(stat)±0.042(syst)
(accelerator and reactor)

Experimental Situation

Backgrounds

Irreducible BG: radiative decay with internal conversion



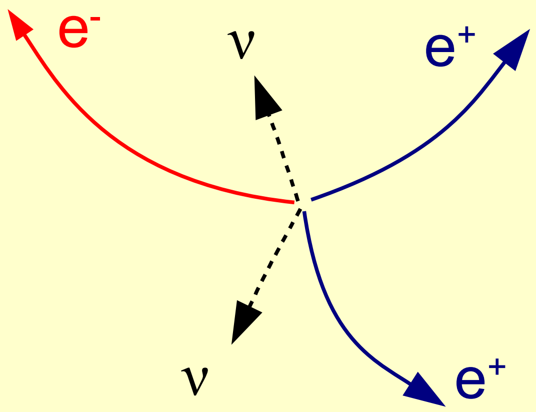


$B(\mu^+ \rightarrow e^+e^+e^- \nu\nu) = 3.4 \cdot 10^{-5}$

$$\sum_i E_i = m_\mu$$
$$\sum_i \vec{p}_i = 0$$

Backgrounds

Irreducible BG: radiative decay with internal conversion



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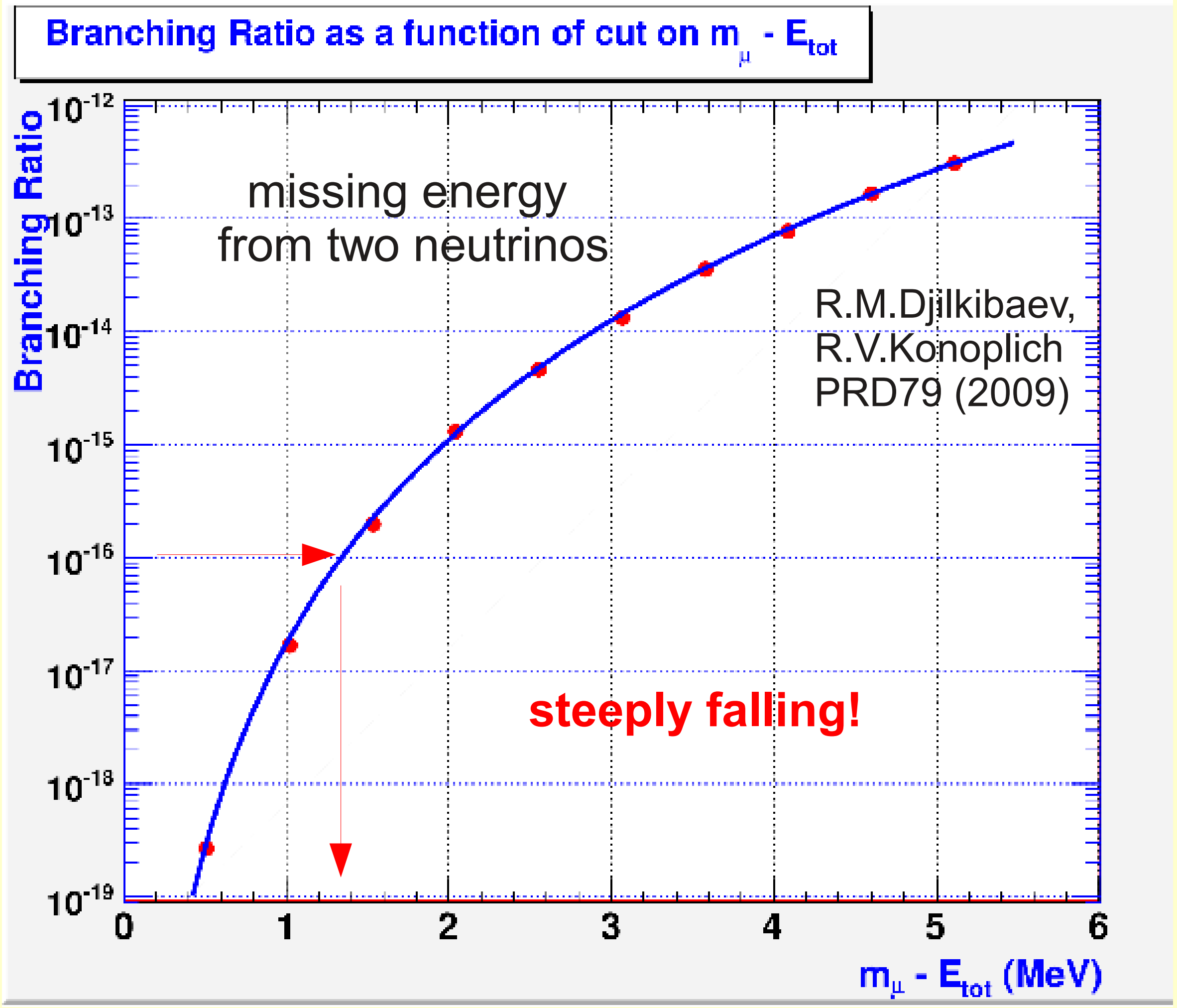
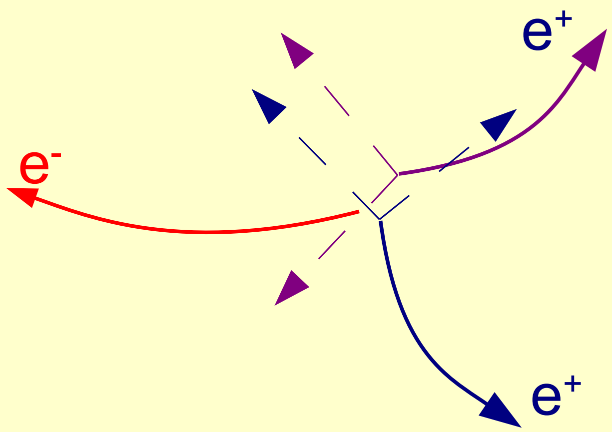


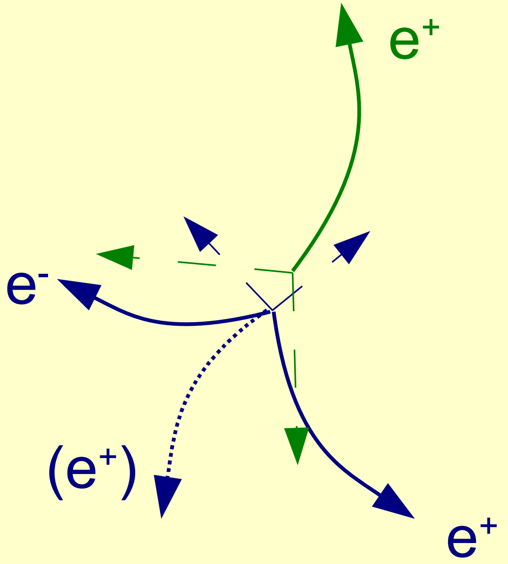
R.M.Djilkibaev,
R.V.Konoplich
PRD79 (2009)

➜ **very good momentum and total energy resolution required!**

Accidental Backgrounds

- **Combinatorial Background (Pile up):**
  - Two muon decays 2 x $(\mu^+ \to e^+ \nu\nu)$ and one fake e^- (wrong charge: reconstruction, Bhabha, back-curling $e^+ \to e^-$)
  - Radiative decay with internal conversion $\mu^+ \to (e^+)\ e^+e^-\ \nu\nu$ overlayed with muon decay $\mu^+ \to e^+\nu\nu$





Combinatorial BG can be largely reduced by imposing

- **precise timing (TOF)**
- **precise vertexing**
- **precise kinematics**

History

- **Sindrum (NP B299 1, 1988)**

  σ_p/p (50 MeV/c) = 5.1%

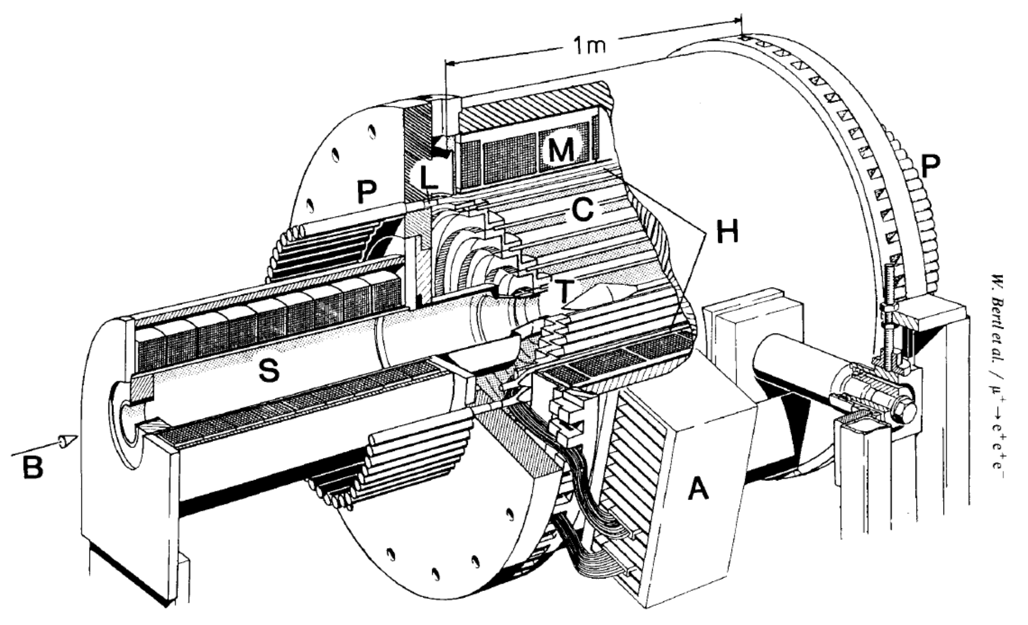
  σ_p/p (20 MeV/c) = 3.6%

  σ_θ (20 MeV/c) = 28 mrad

  VTX: $\sigma_d = \sim$ 1mm

  X_0(MWPC) = 0.08% - 0.17% per layer

  $B(\mu^+ \rightarrow e^+e^+e^-) < 10^{-12}$ (90%CL)



B = beam
S = solenoid
M = magnet
C = multiwire proportional chamber
H = hodoscope

- **Mu3e:**
  - factor **~10** better **spatial** and **kinematic** resolution
  - high rate of **$2 \cdot 10^8$ - $2 \cdot 10^9$ muons/s** on target
  - **$B(\mu^+ \rightarrow e^+e^+e^-) < 10^{-15} - 10^{-16}$**

Tracking - Technology Choice

Tracking detectors

- **High rates** and **aging effects** prohibitive for gaseous detectors
  - → **Solid state detectors**

- Precise spatial resolution for **vertexing** and **momentum** reconstruction
  - → **Silicon pixel sensor**

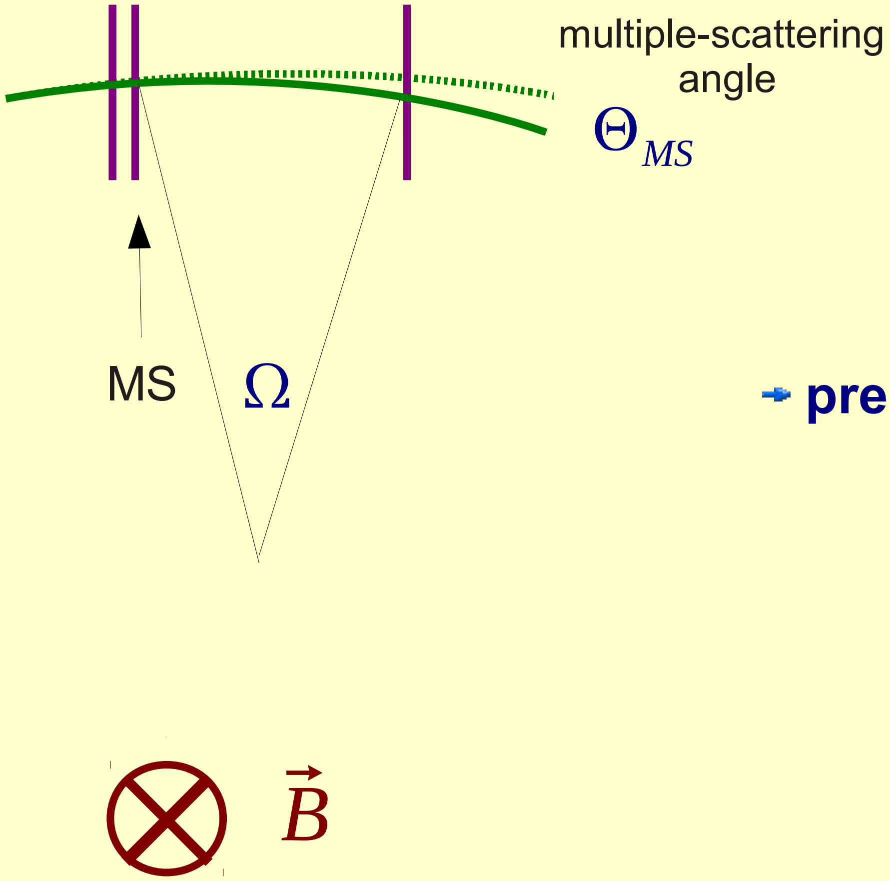
- Momentum resolution dominated by **multiple scattering** in range of interest (~**10-53 MeV**):

$$\Theta_{MS} \sim \frac{1}{P} \sqrt{X / X_0}$$

→ **Very thin silicon pixel sensor**

Momentum Resolution I

- Momentum resolution given by (linearised):

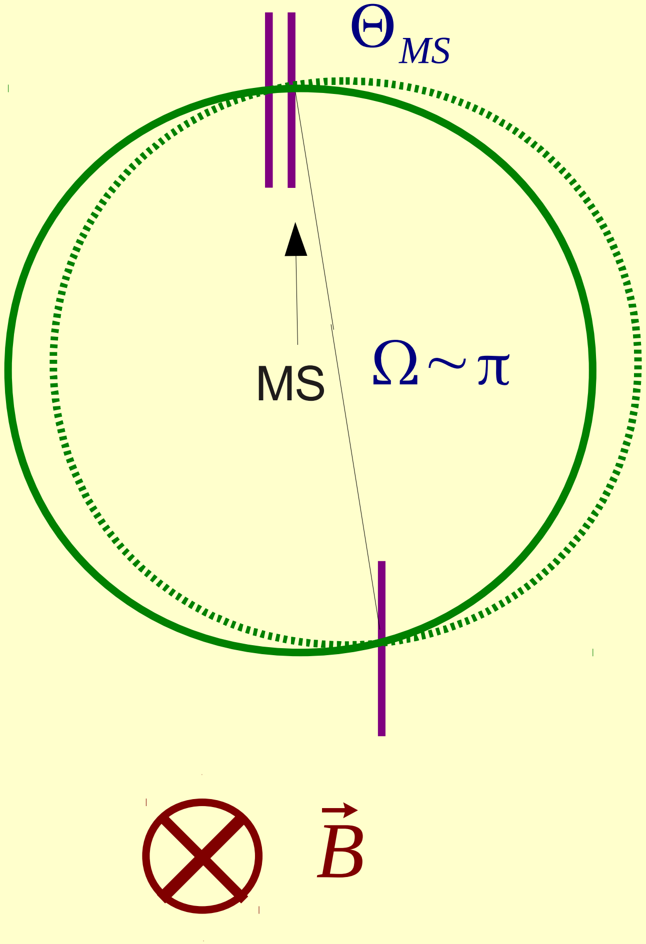


$$\frac{\sigma_p}{P} \sim \frac{\Theta_{MS}}{\Omega}$$

➔ **precision requires large lever arm (large bending angles Ω)**

Momentum Resolution II

- Momentum resolution for half turns given by:



$$\frac{\sigma_p}{P} \sim O\left(\Theta_{MS}^2\right)$$

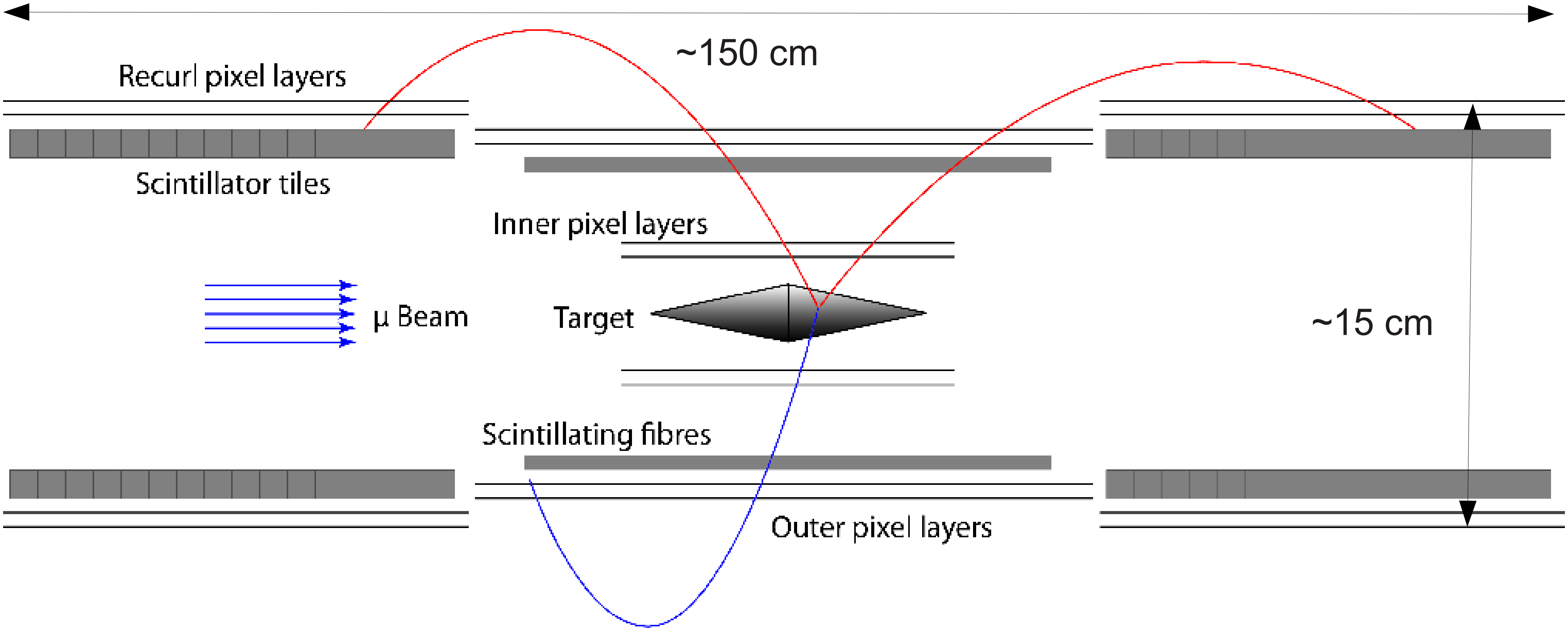
- **best precision for half turns**
- **design tracking detector for measuring recurlers**

Experimental Proposal

Mu3e Baseline Design

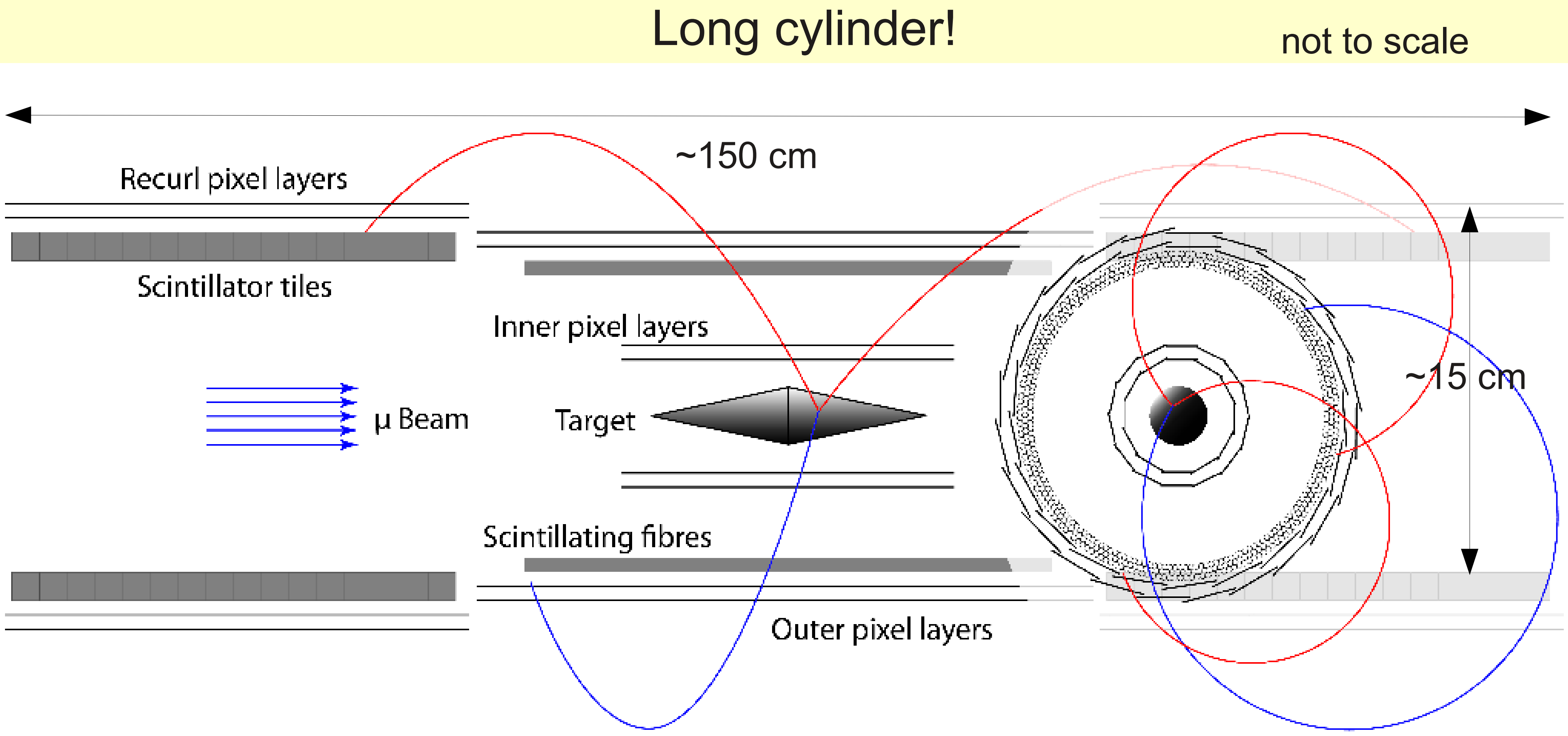
Long cylinder!

not to scale



Geometrical acceptance **~70 %** for **$\mu^+ \rightarrow e^+e^+e^-$** decay

Mu3e Baseline Design



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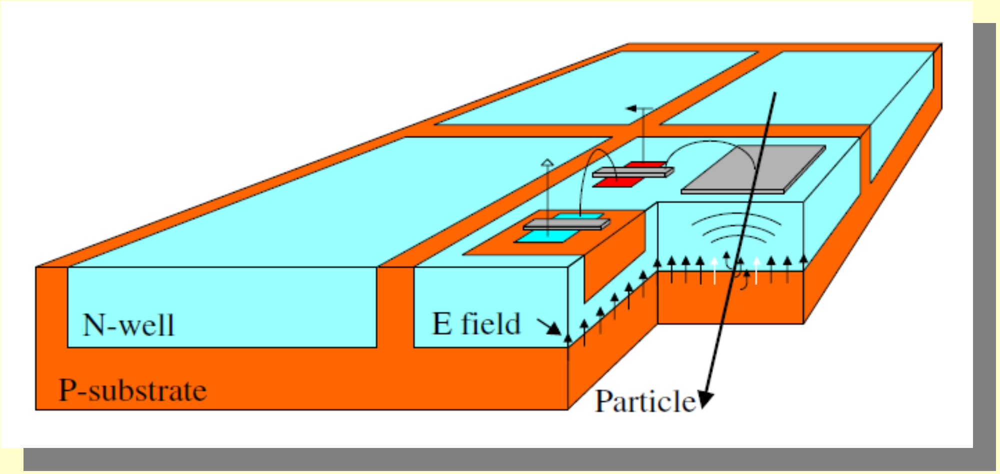
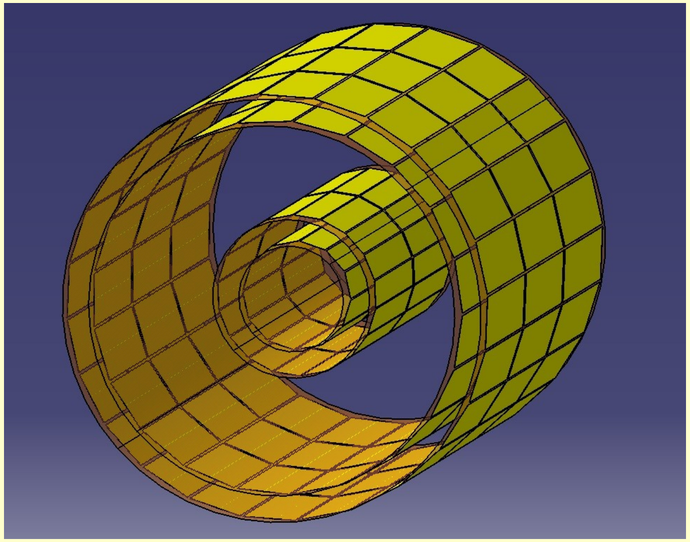
Silicon Pixel Detector



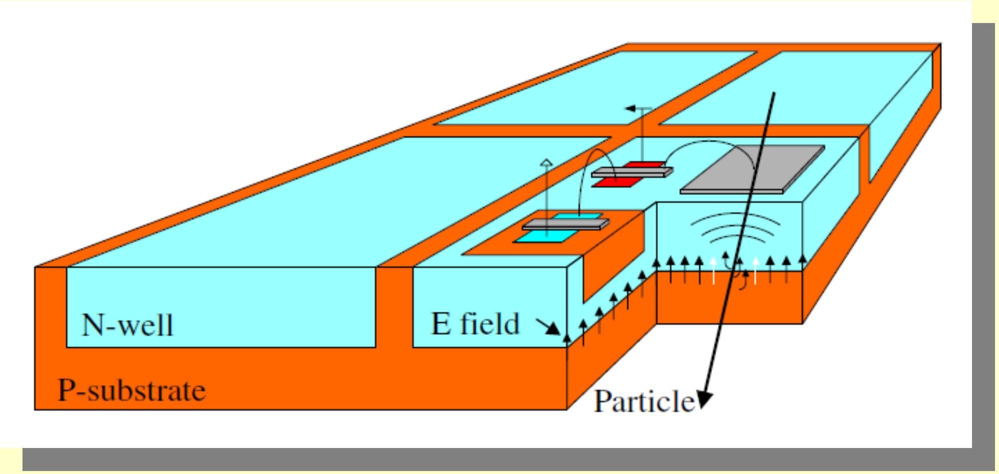


Technology Choice

High Voltage Monolithic Active Pixel Sensors (HV-MAPS)

- high precision → pixels 80 x 80 μm^2 (27 x 40 μm^2 currently in test)
- can be "thinned" down to **30 µm** (~ 0.0004 X_0)
- low production costs (standard HV-CMOS process, 60V)
- active sensors → small RO bandwidth, no bump bonding required
- triggerless and fast readout
- low power

High Voltage Monolithic CMOS Pixel



transistor logic embedded in N-well
(“smart diode array”)

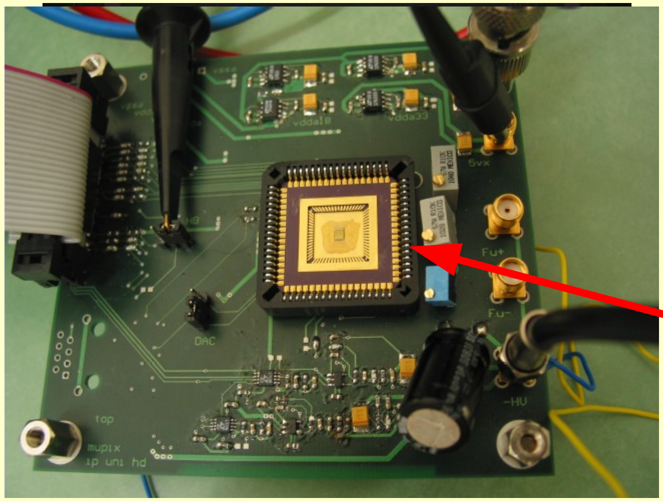
New Technology!

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

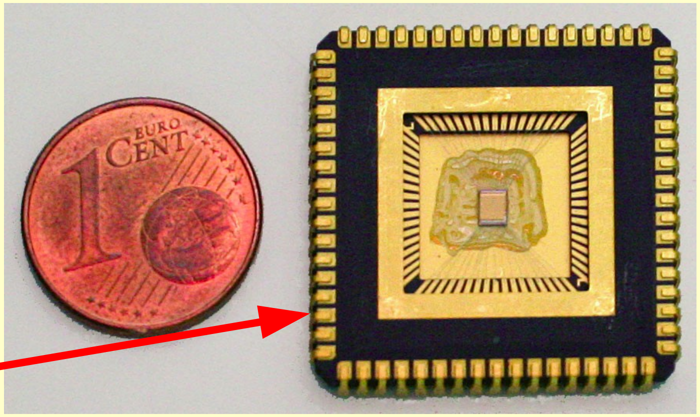
Sensors tested successfully:

- low noise: S/N = 30 – 50
- radiation tolerant
- high efficiency

Pixel Detector Hardware and Tests



University Heidelberg:
ZITI Mannheim /
Physikalisches Institut

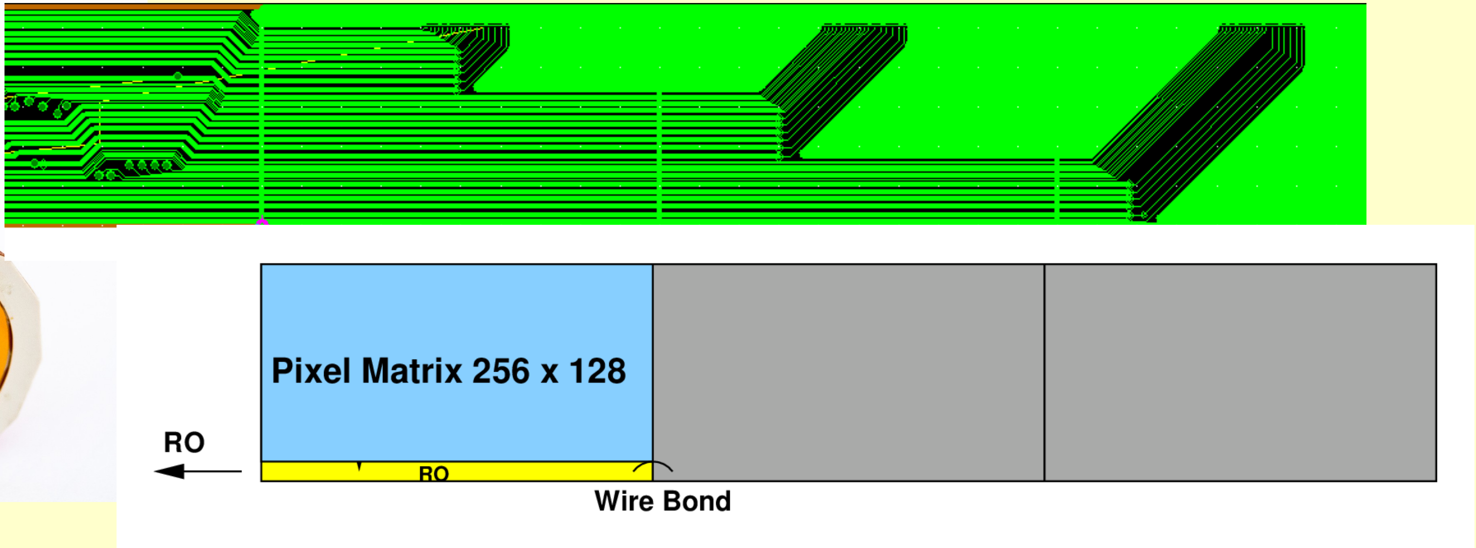


prototype 180 nm

Plan: construct barrel prototype in 2012

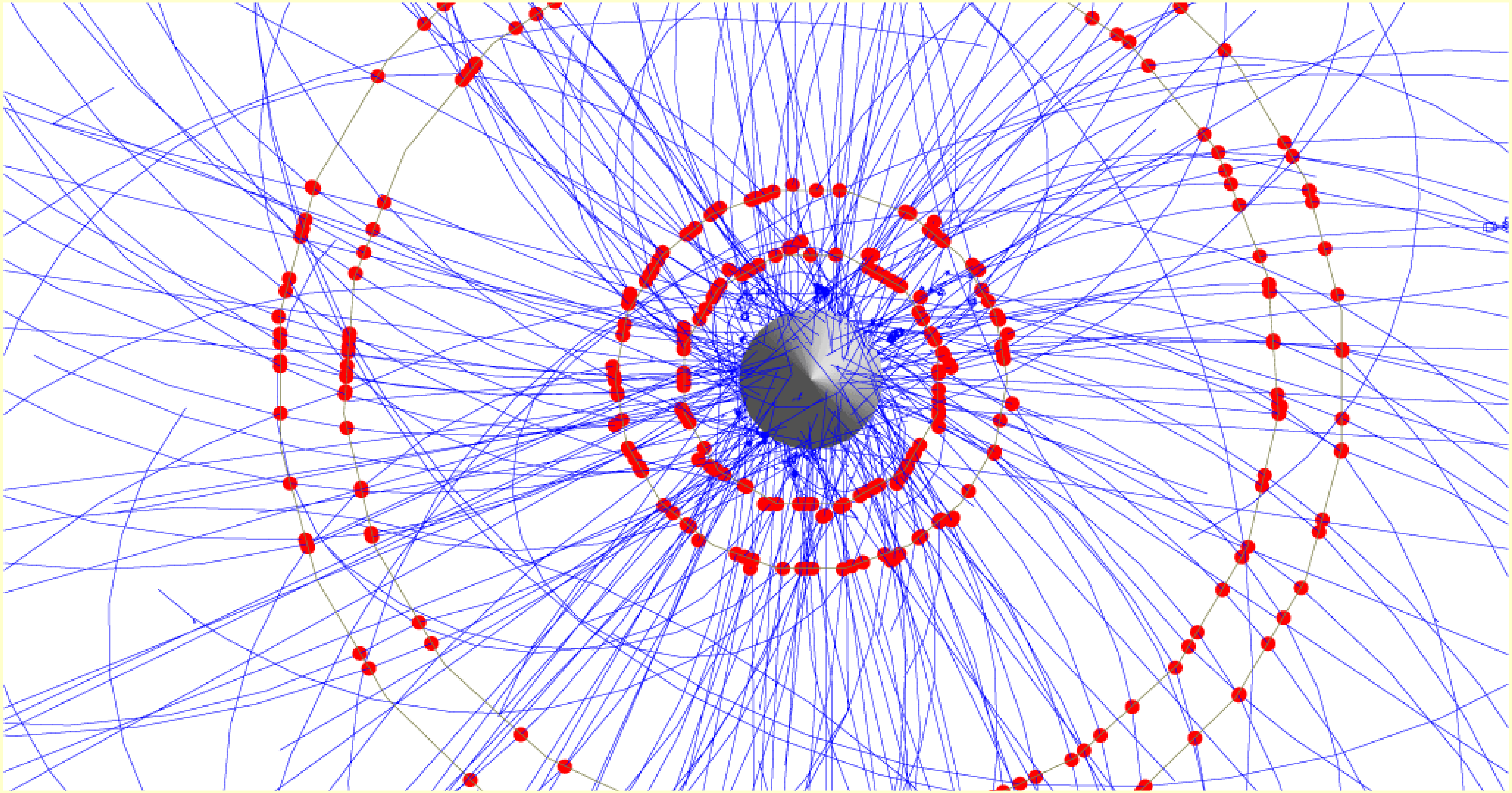
Support structure
25 mu Kapton

flexible kapton print 25 mu



Pixel: Readout Frames 50 ns

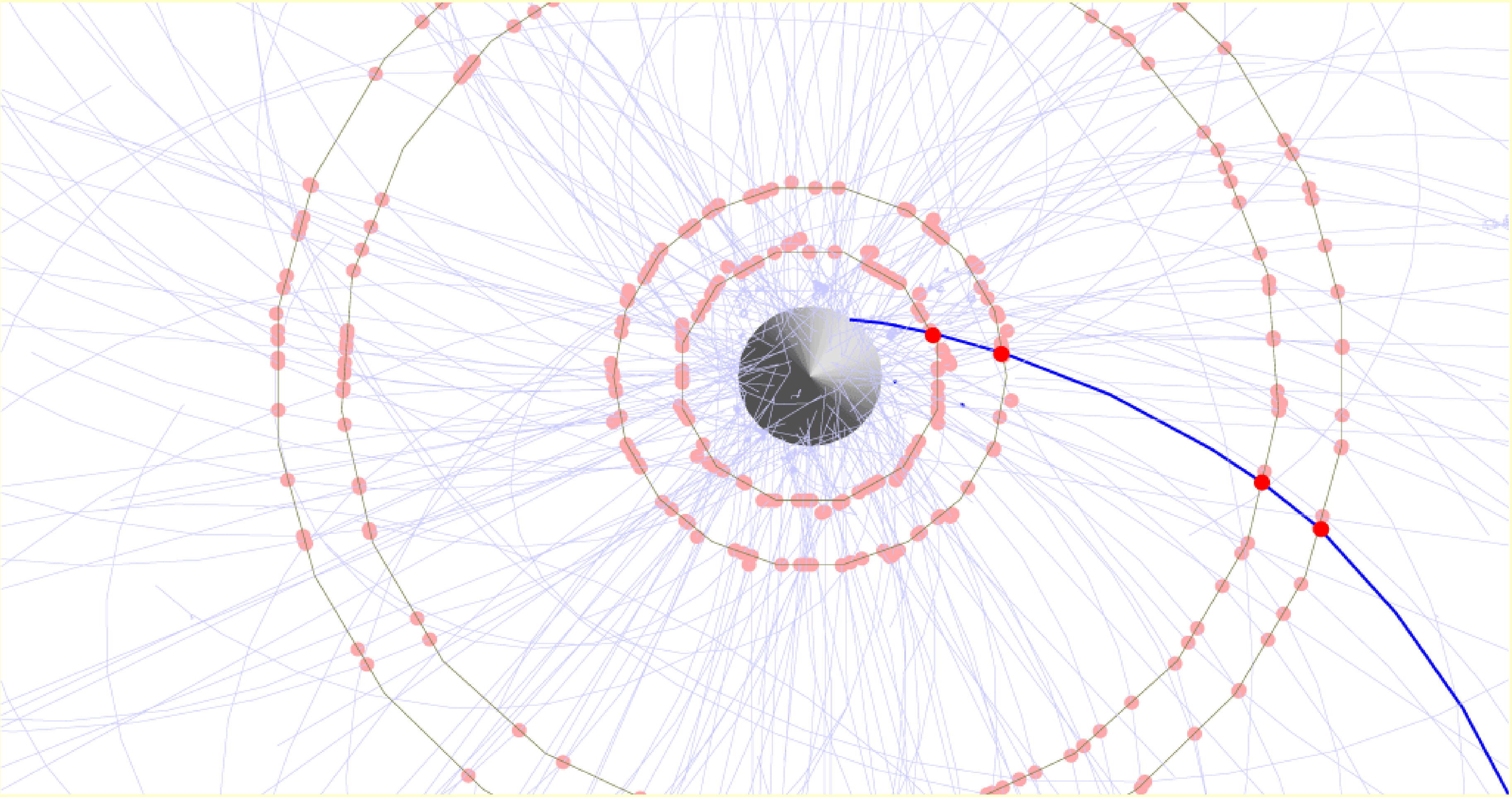
100 muon decays @ rate $2 \cdot 10^9$ muon stops/s



Intrinsic timing resolution of silicon pixel: <50 ns

Pixel: Readout Frames 50 ns

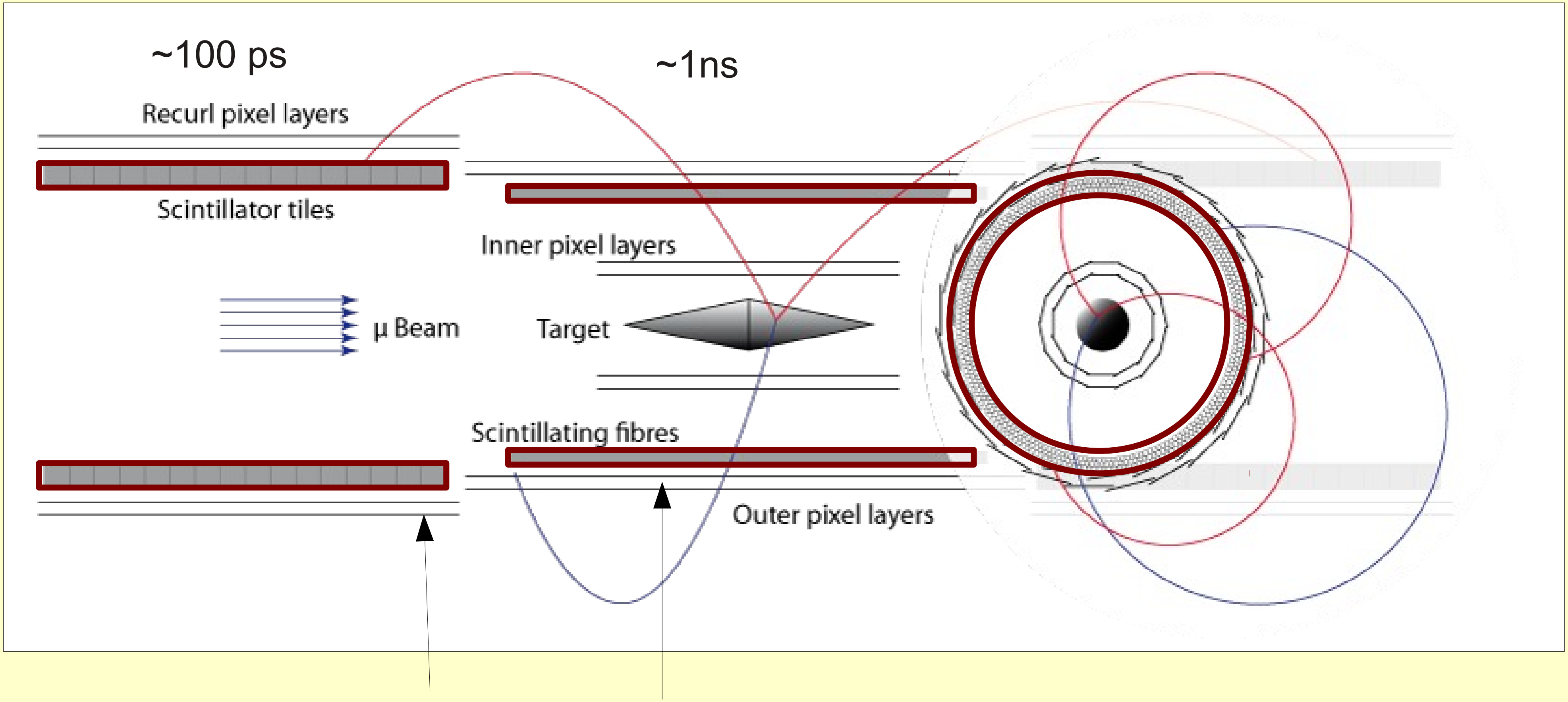
100 muon decays @ rate 2 · 10^9 muon stops/s



- **additional Time of Flight (ToF) detectors required < 1ns**

Mu3e Baseline Design

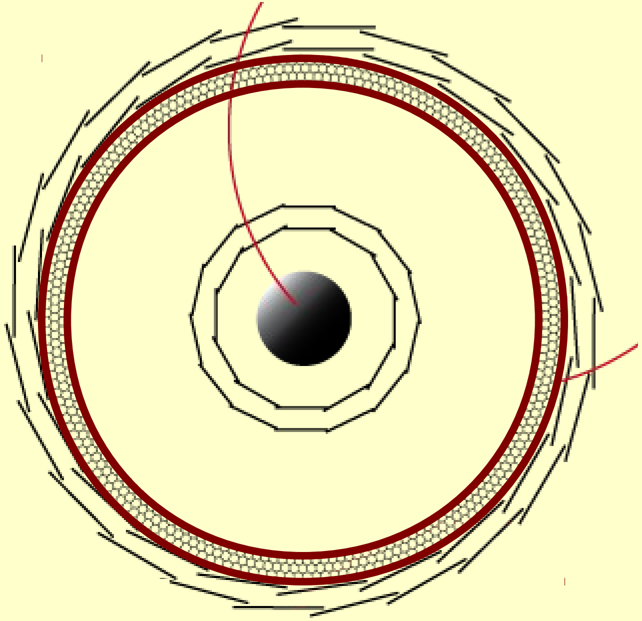
not to scale

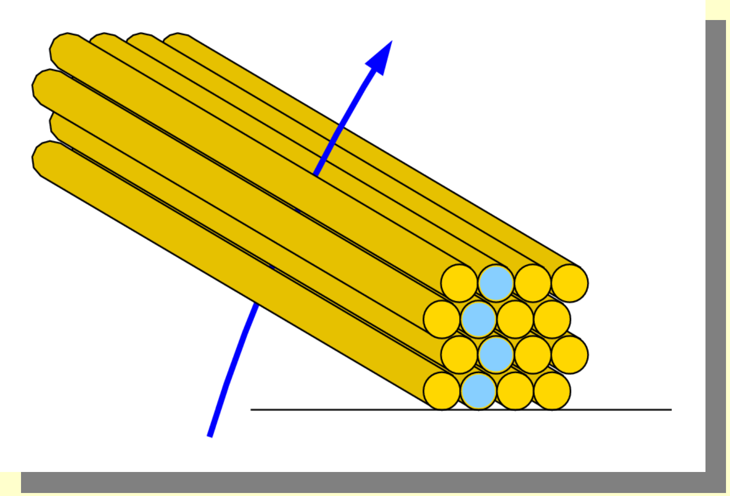


Scintillating tiles and fibers **(Universities Geneva + Zurich)**

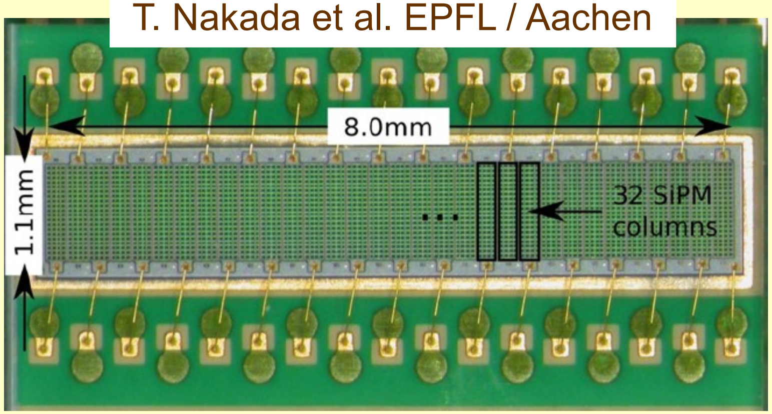
Scintillating Fiber Tracker

- high spatial resolution for unambiguous assignment of silicon hits:
- scintillating fibers:
  - x-y plane: Ø = 200-250 μm fibers
- photosensor
  - Hamamatsu MPPC arrrays (SiPM)
  - high gain $>10^5$, high frequency > 1MHz
- time resolution <1 ns
- prototype planned for summer 2012





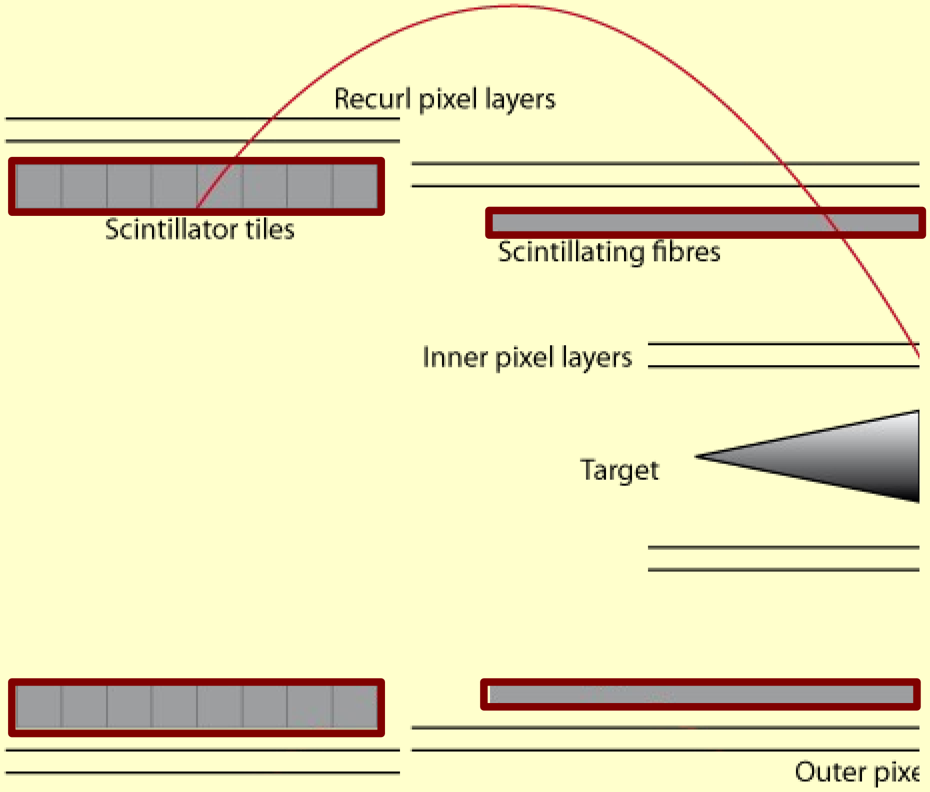
Hamamatsu MPPC 5883
T. Nakada et al. EPFL / Aachen



(in collaboration with EPFL (Nakada et al.))

Scintillating Tiles

- scintillating tiles of size ~ 1 cm^2
- timing resolution of ~100 ps
- light guides
- photosensor (SiPM)

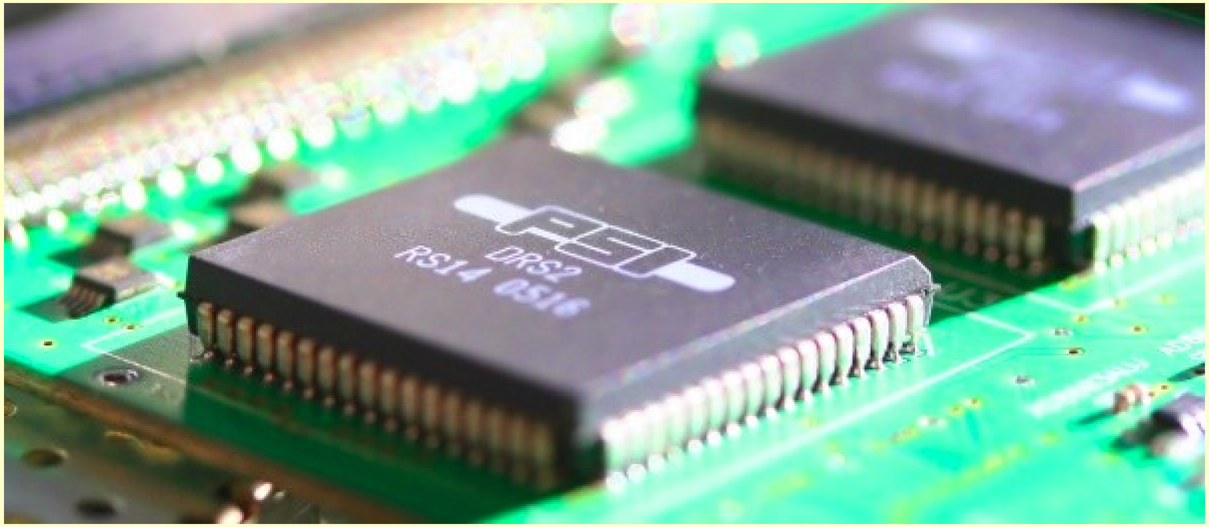


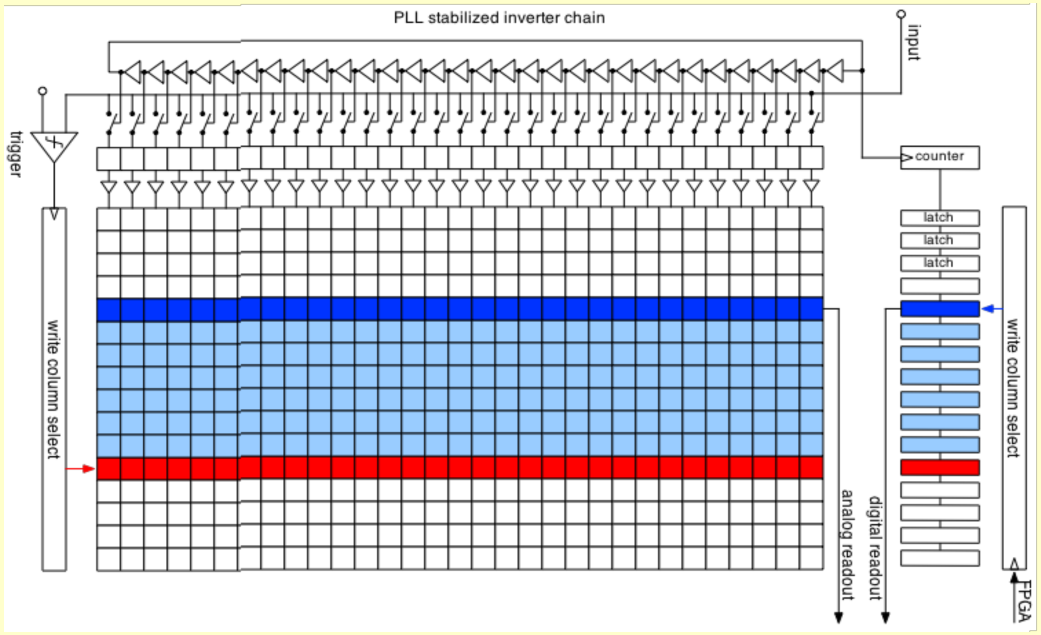
Timing information from tiles and scintillating fibers will help to reduce accidental backgrounds and ease track reconstruction

ToF Readout + New DRS5 Chip

<u>DRS4 chip (PSI)</u>

- switched capacitor chip
- 8+1 Channels
- 700 MS/s- 5 GS/s



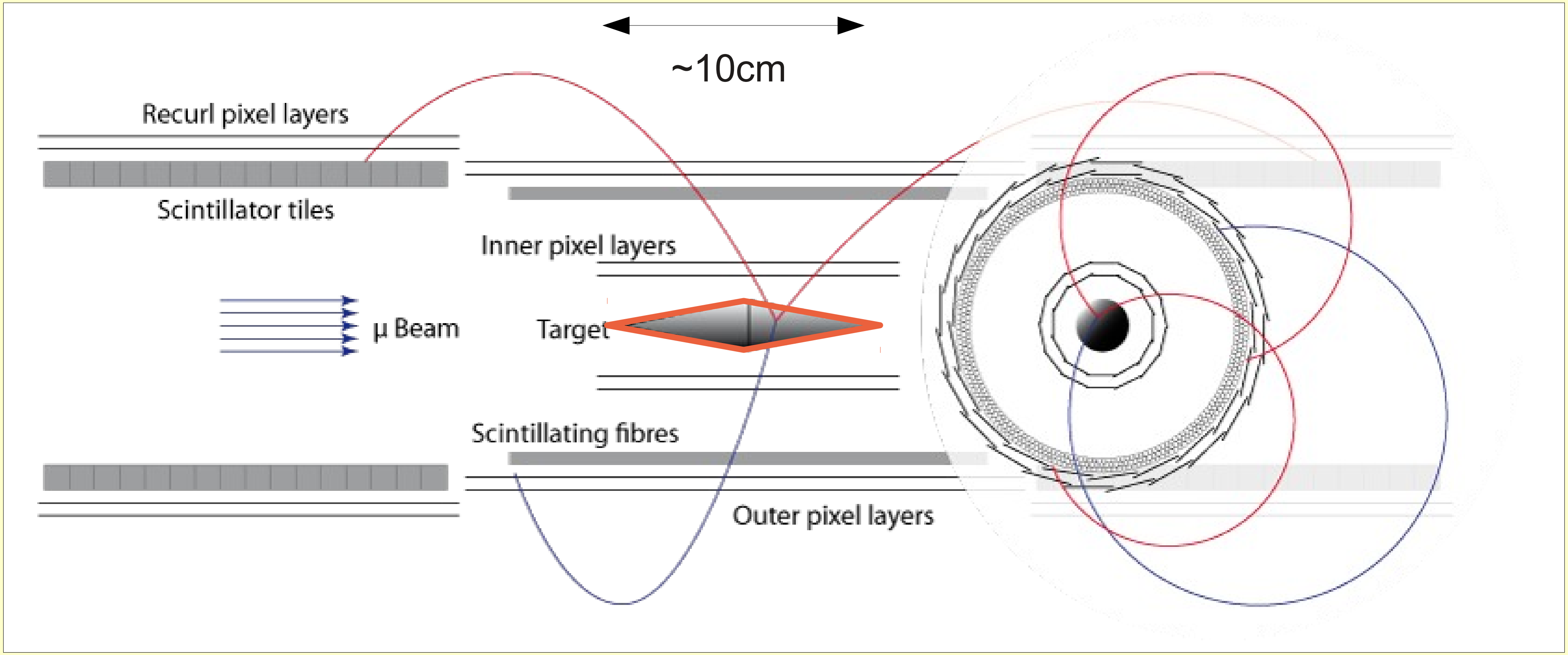


<u>New DRS5 chip (PSI)</u>

- first prototype mid 2012
- ≥ 2 MHz continuous hit rate
- considered for Mu3e - ToF readout

Muon Stopping Target

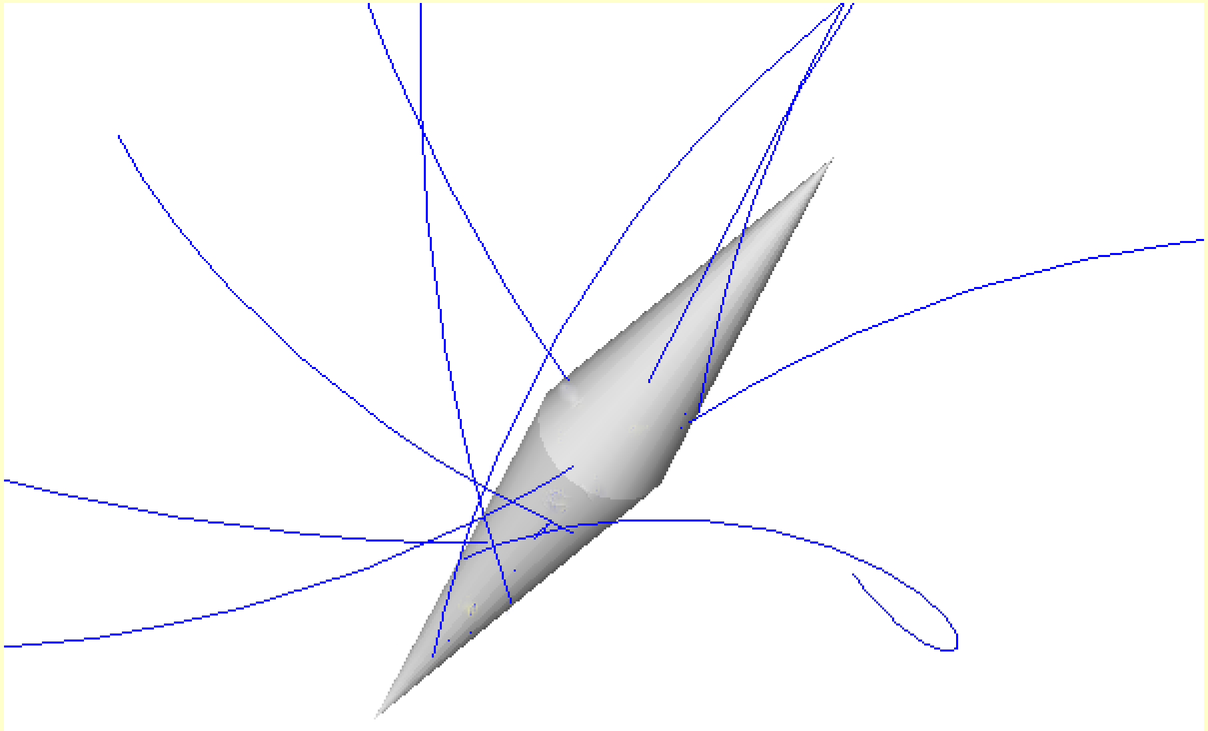
not to scale



- **Sindrum-like extended target**
- **hollow double cone target (e.g. 90 μm Al)**

Muon Stopping Target

Pixel detector: vertex resolution **~ 120 μm**



suppression of accidental BG 10^{-4} - 10^{-5}

- **Sindrum-like extended target**
- **hollow double cone target (e.g. 90 μm Al)**

DAQ and Online Filter Farm

Data Acquisition:

- **pixel detector:**
  - number of (zero suppressed) channels **250 million**
  - per **50 ns** readout frame **~2000** hits
- **fiber tracker:**
  - number of (zero suppressed) channels about **10k**
- **for muon stop rate of ~$2 \cdot 10^9$ ($2 \cdot 10^8$) muons per second**
  - raw data rate **~ 150 (15) Gbyte/s** (large but smaller than at LHC)

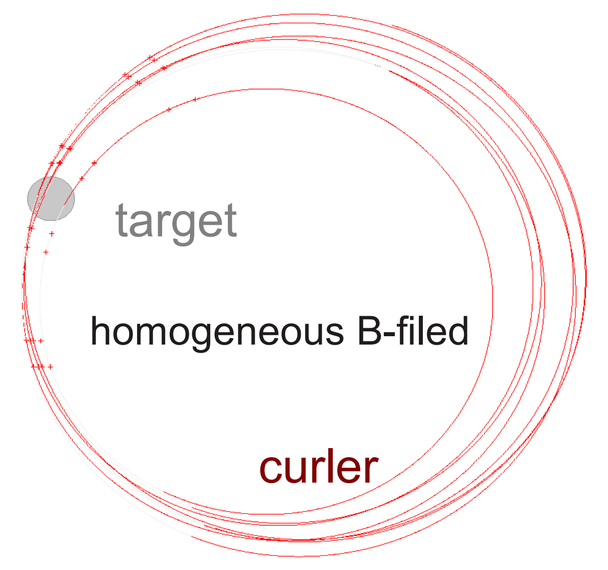
DAQ and Online Filter Farm

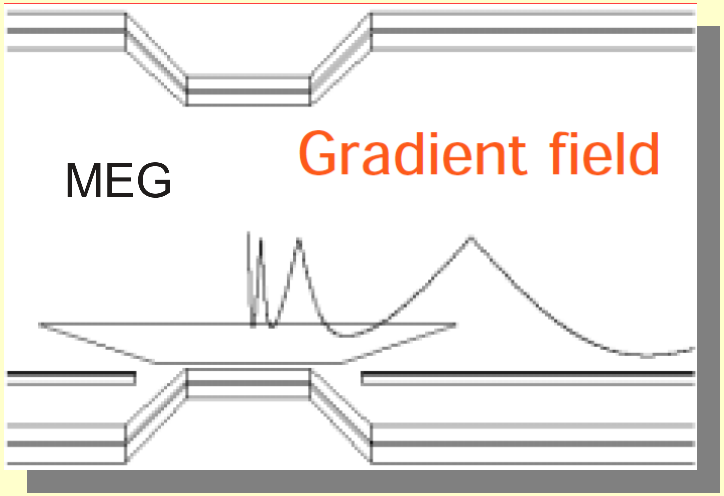
- **Online software filter farm**
  - continuous front-end readout (no trigger)
  - FPGAs and Graphical Processor Units (GPUs)
  - online track (event) reconstruction
  - data reduction by factor ~1000
  - on tape ~ 100 Mbyte/s

Magnet: gradient or no gradient?

Simulation Results for Baseline Design:

- 11 hits per electron gradient field
- 17 hits per electron homogeneous field





Speed of Track Reconstruction:

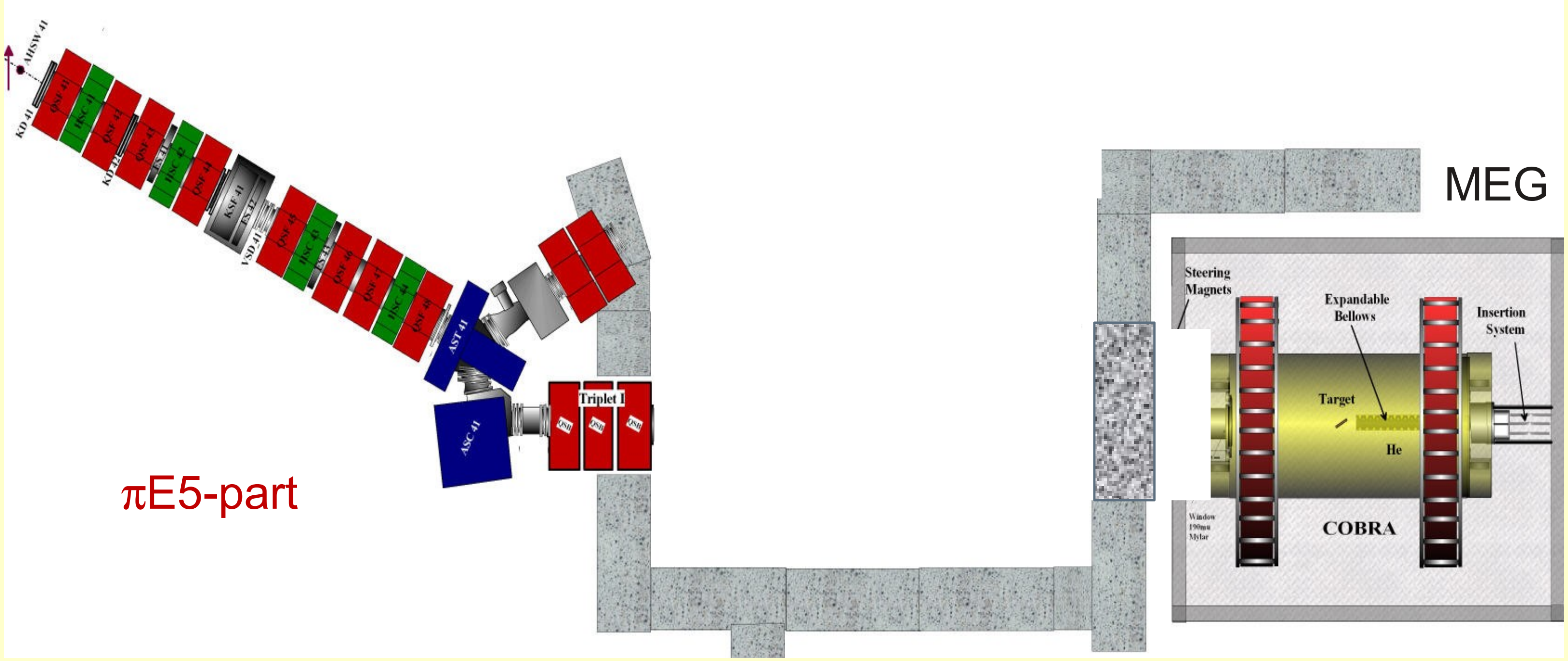
- homogeneous field allows for fast non-iterative analytical calculation
- reconstruction speed important for online filtering!

Homogeneous magnetic field of about 1-1.2 Tesla preferred

Beamline Phase I

Scenarios at beamline πe5

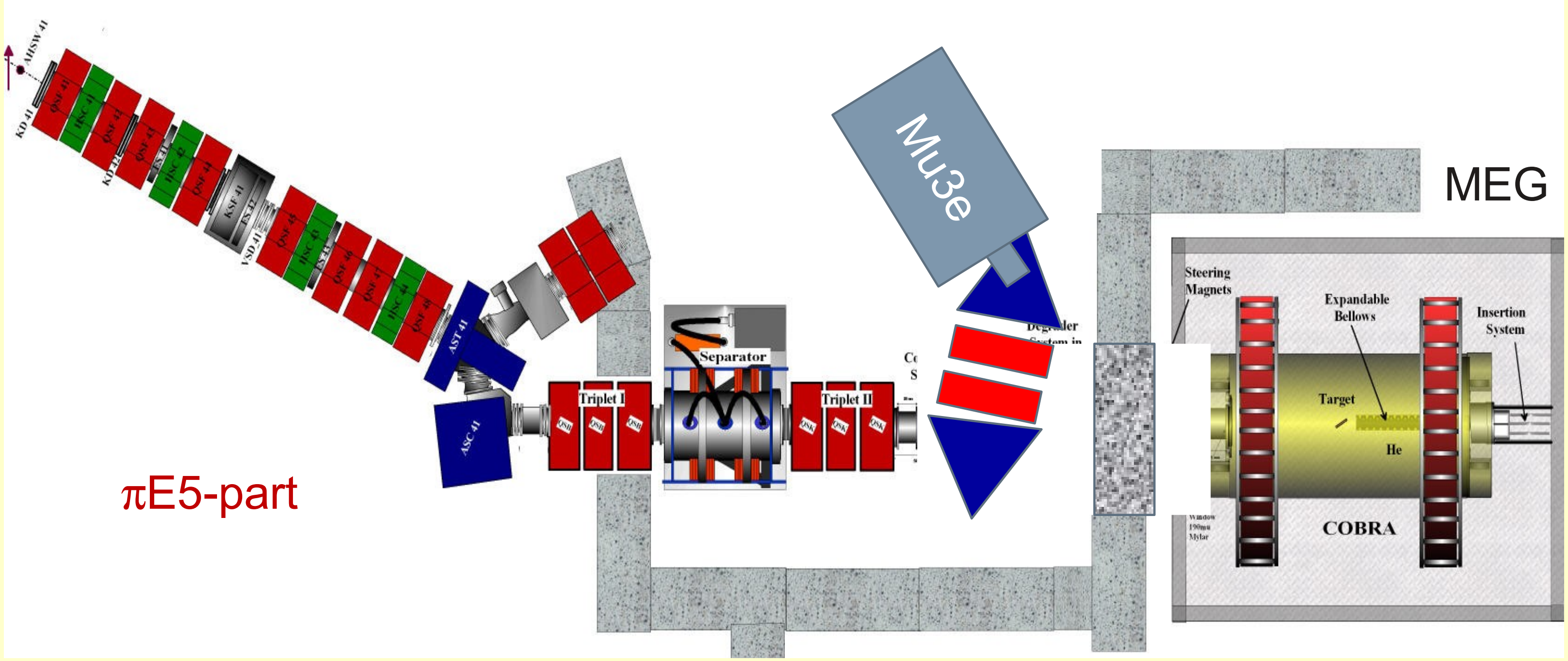
MEG and Mu3e could co-exist if MEG is to be upgraded



Beamline Phase I

Scenarios at beamline πe5

MEG and Mu3e could co-exist if MEG is to be upgraded

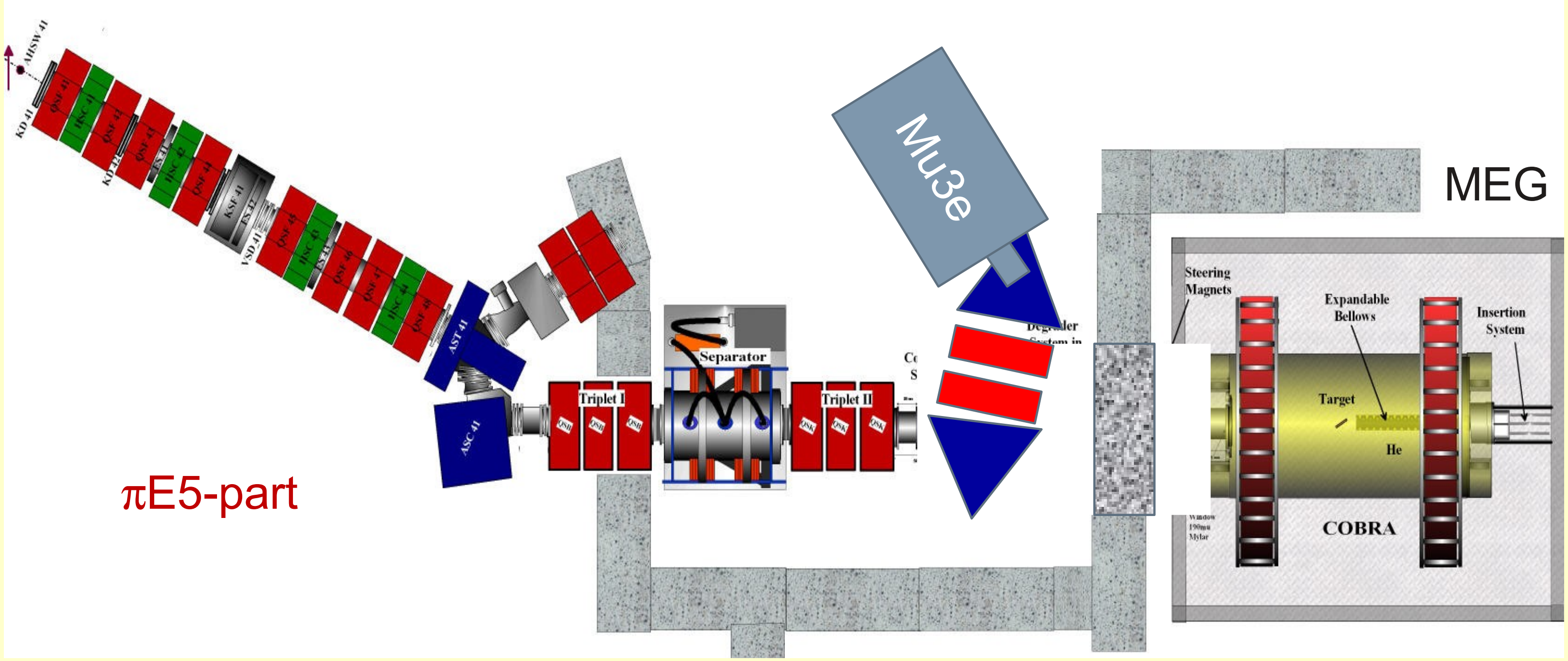


schematical sketch only!

Beamline Phase I

Scenarios at beamline πe5

MEG and Mu3e could co-exist if MEG is to be upgraded

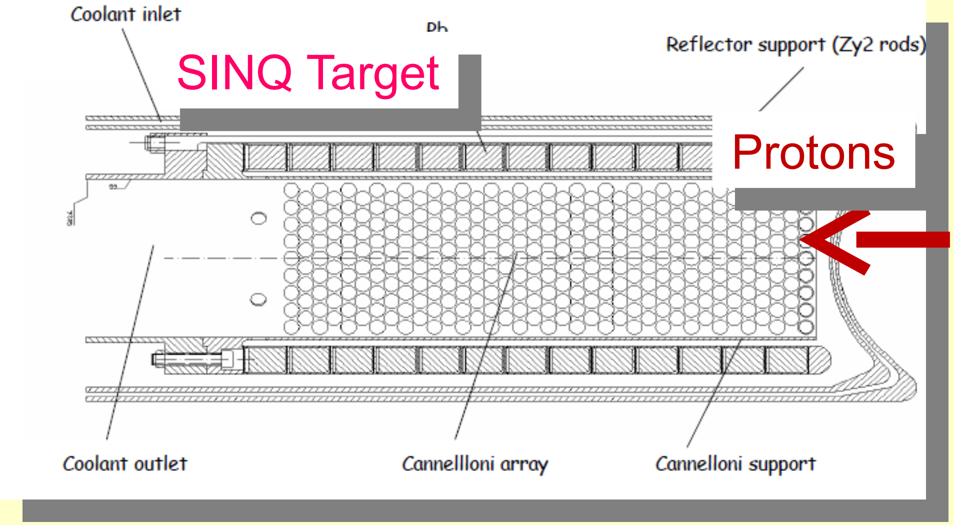


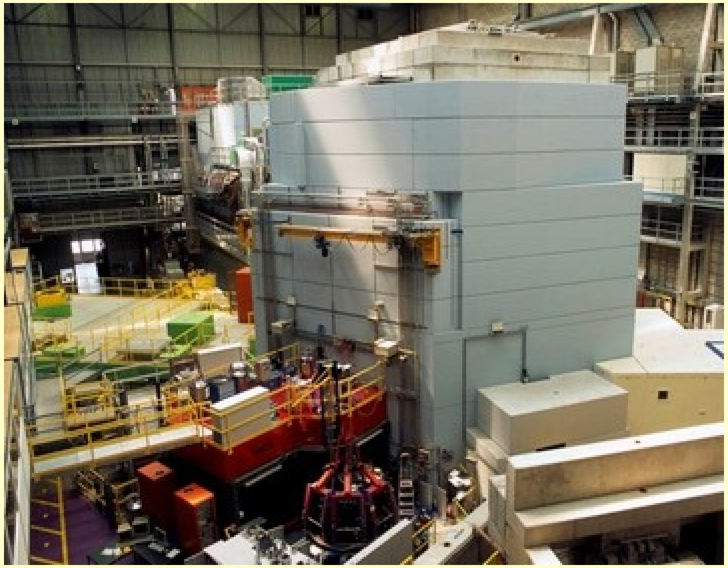
- muon rates of **1.4 · 10^8/s** achieved in past
- factor **~2** maybe possible by means of optimisations of "E" target → **3 · 10^8 muons/s**
- rate of **2 · 10^8/s** sufficient to reach **B($\mu^+ \rightarrow e^+e^+e^-$) < 10^{-15}** (90%CL) in 3 years

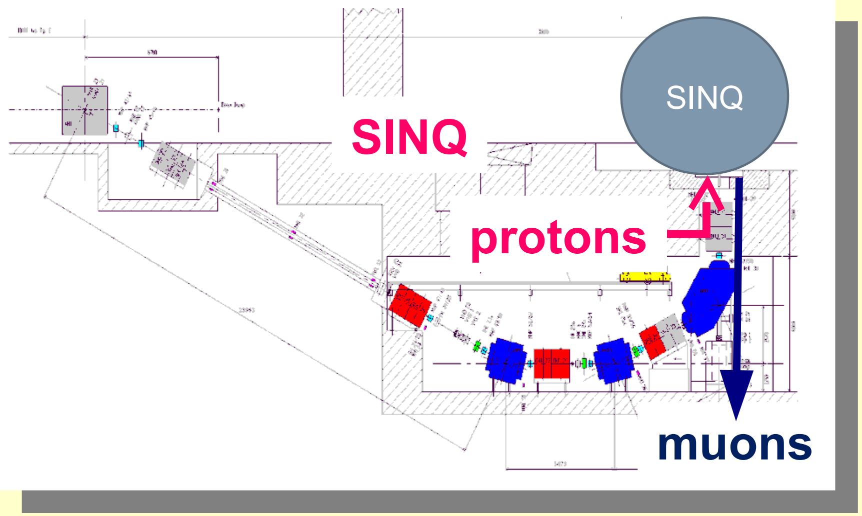
(→ corresponds to **~ B($\mu^+ \rightarrow e^+\gamma$) < 10^{-13}** (MEG))

Beamline Phase II

Neutron Source SINQ:



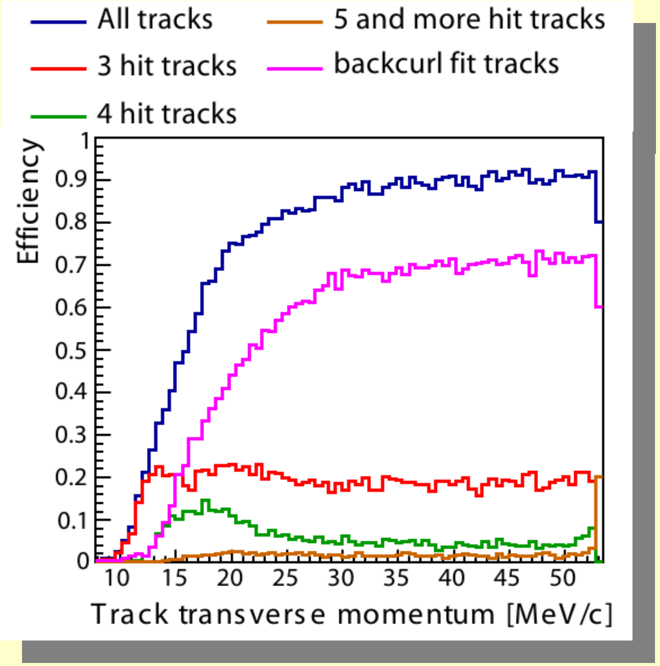




- Muon rates in excess of 10^{10} per second in beam phase acceptance possible
- First simulations confirmed calculations
- **$2 \cdot 10^{9}$** muons/s needed to reach ultimate goal of **$B(\mu^{+} \to e^{+}e^{+}e^{-}) < 10^{-16}$**
- **Not before 2017**

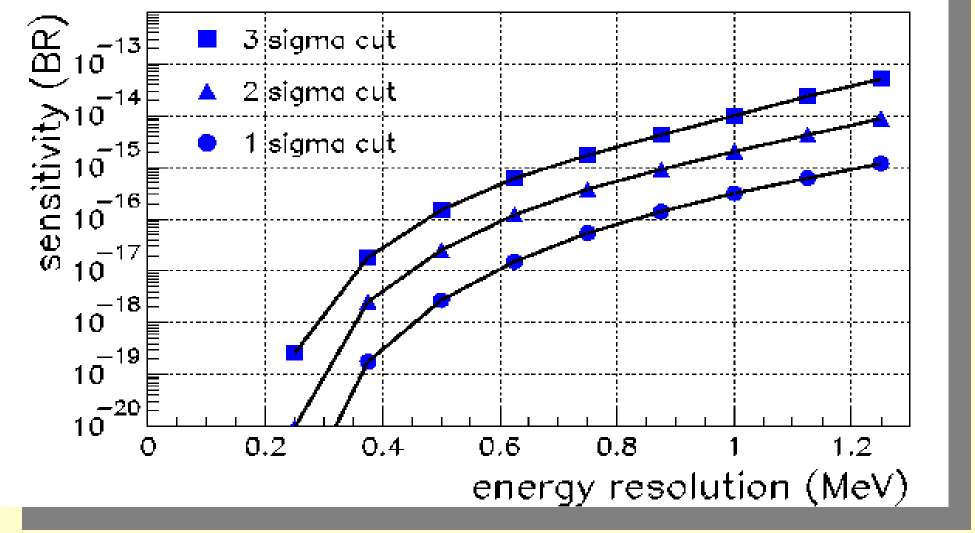
Status Simulations

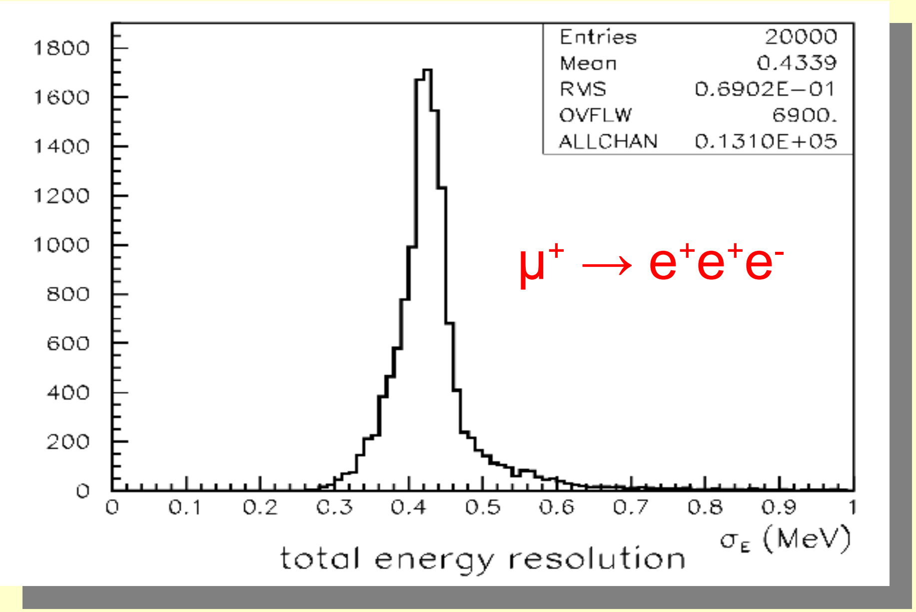
GEANT4 simulations, work in progress:
- determination of occupancies
- test track reconstruction eff. and resolution
- background studies



<u>Preliminary Results:</u>
- muon stop rate of **$2 \cdot 10^9$** experimentally possible
- most severe BG is $\mu^+ \rightarrow e^+e^+e^- \nu\nu$
- required resolutions can be achieved

Sensitivity limit from $\mu^+ \rightarrow e^+e^+e^- \nu\nu$



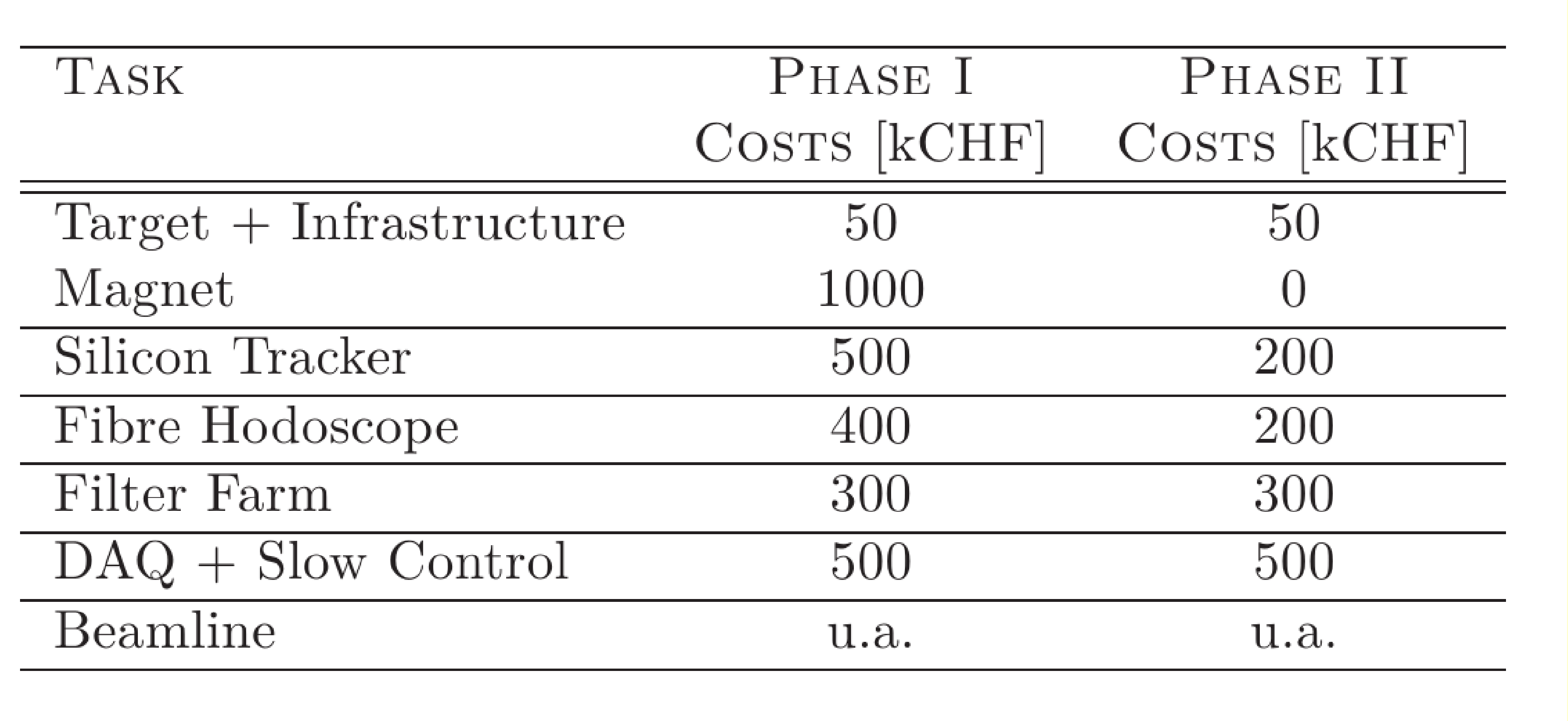


Mu3e Scenarios Phase I and II

	Phase I (2014-17)	**Phase II (>2017)**
operation	3 years	3 years
total time in seconds	3.0E+007	3.0E+007
muon rate [per second]	**2.0E+008**	**2.0E+009**
acceptance	0.7	0.7
track finding efficiency	0.9	0.9
3-prong efficiency	0.729	0.729
event selection eff.	0.75	0.75
total efficiency	0.38	0.38
#decays	2.3E+15	2.3E+16
single event sensitivity	4.3E-16	4.3E-17
90% exclusion limit	**0.7E-15**	**0.7E-16**

Preliminary Cost Estimates

from LOI



TASK	PHASE I COSTS [kCHF]	PHASE II COSTS [kCHF]
Target + Infrastructure	50	50
Magnet	1000	0
Silicon Tracker	500	200
Fibre Hodoscope	400	200
Filter Farm	300	300
DAQ + Slow Control	500	500
Beamline	u.a.	u.a.

u.a. = under assessment

Total cost estimate ~4 million CHF without beamlines

Proto-Collaboration

- **Uni Geneva**

UNIVERSITÉ
DE GENÈVE

- **Uni Heidelberg**
- **PSI**

PAUL SCHERRER INSTITUT
PSI

- **Uni Zurich**

Universität
Zürich^{UZH}

- **ETH Zurich**

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Also, in contact with other interested groups

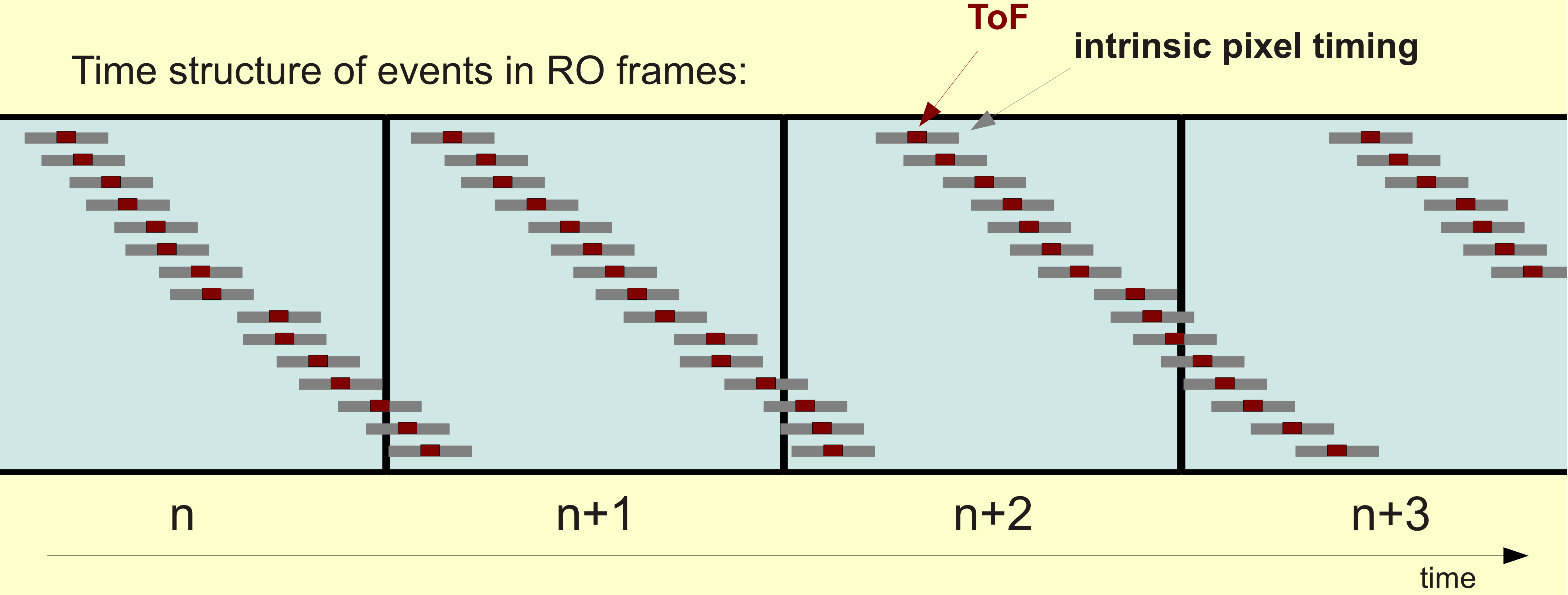
Plan: prepare a detailed Research Proposal within one year

Backup

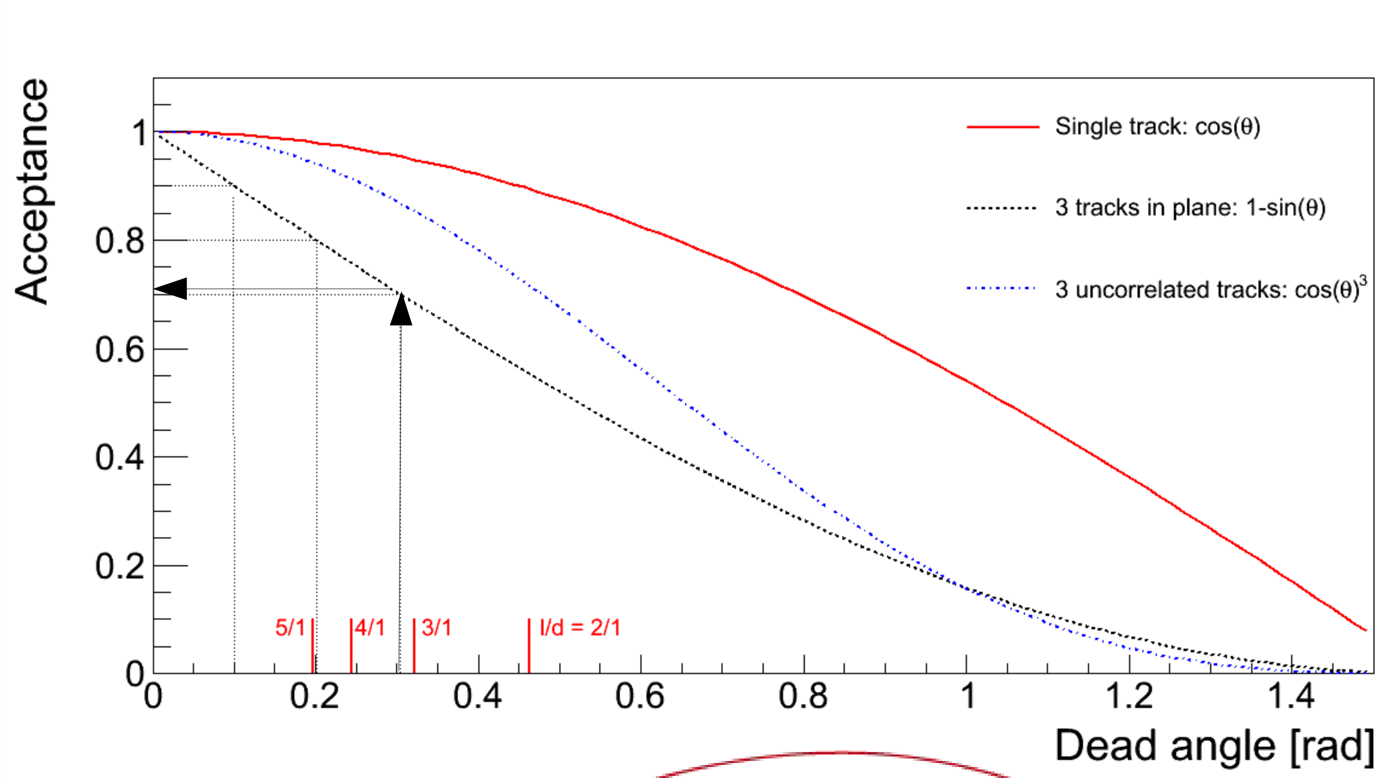
Readout Frames

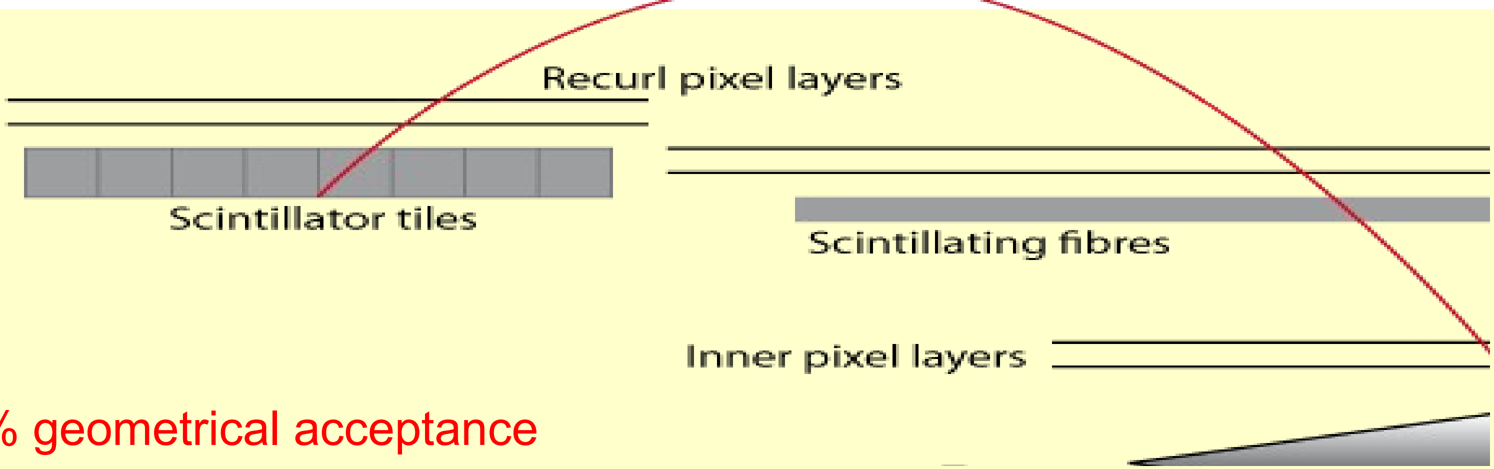
- The pixel detector readout is clocked at 20 MHz (50 ns)
- Intrinsic time resolution in silicon 10-20 ns (to be experimentally verified)
- Precise timing provided by ToF is 0.2-1ns
- Decay positrons spread over up to 3 ns (recurler)

Time structure of events in RO frames:



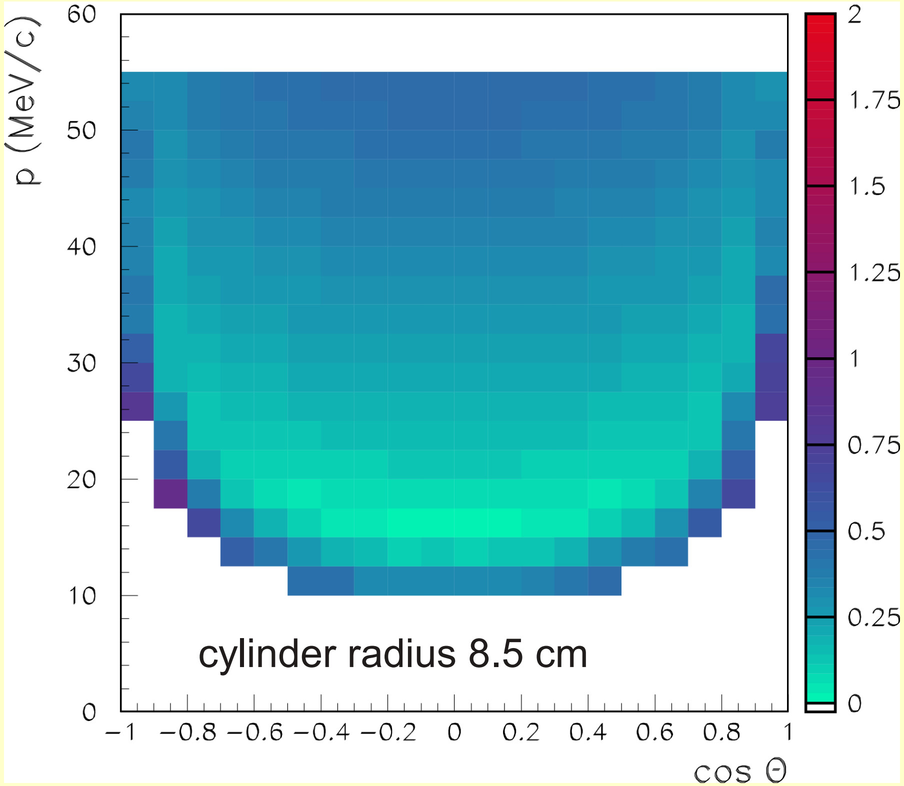
Geometrical Acceptance

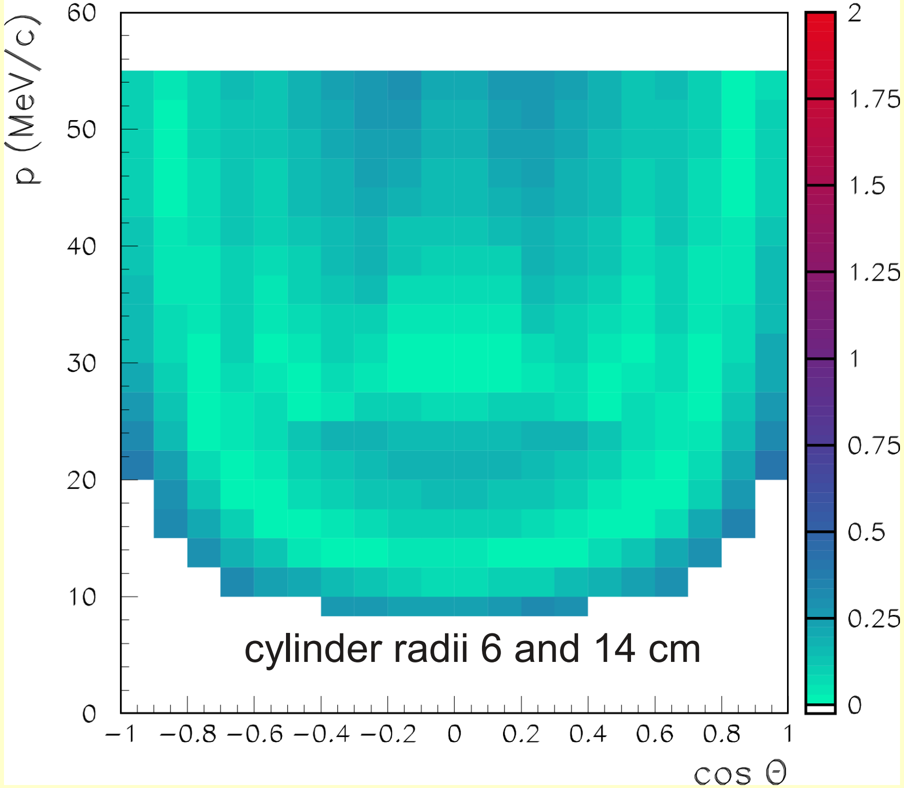


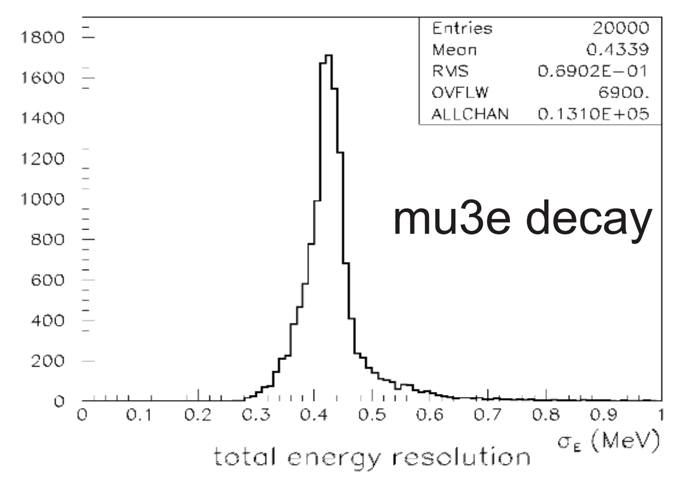


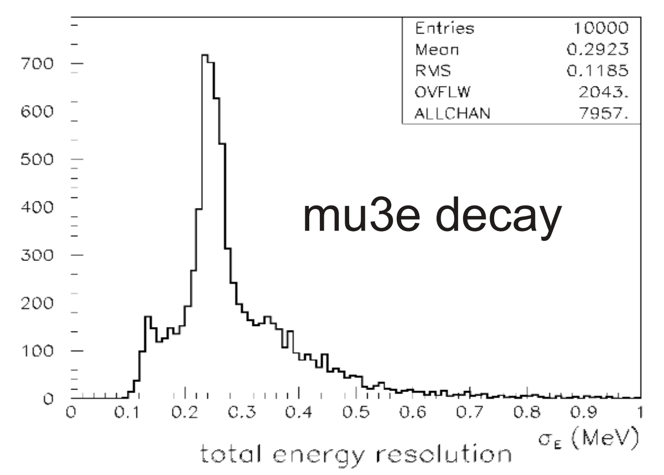
~ 70% geometrical acceptance

Two versus Three Double Layers

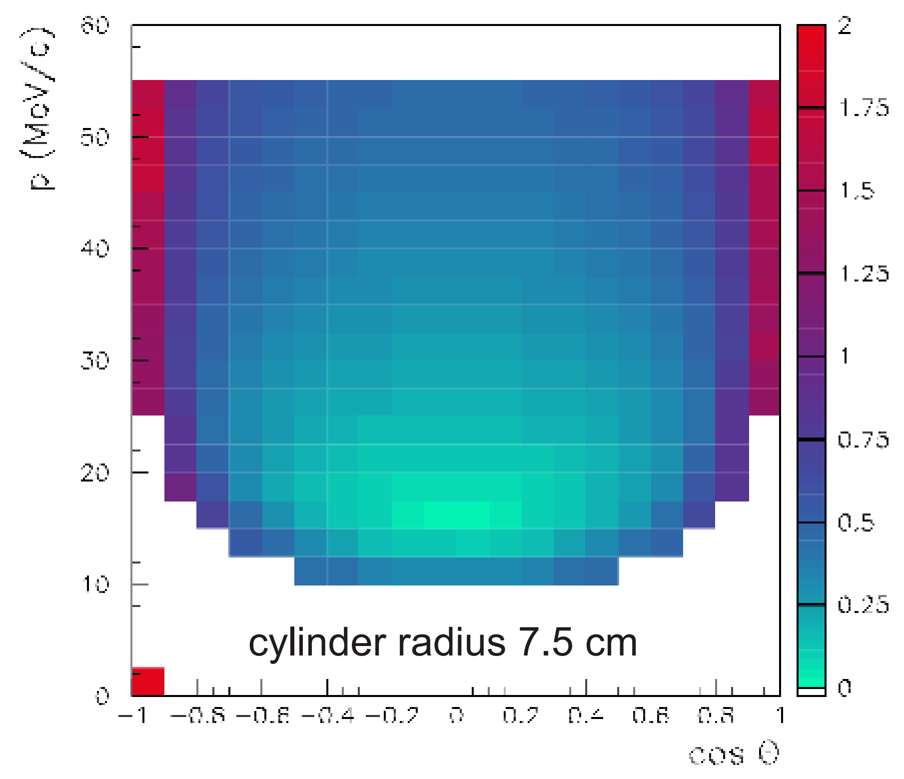


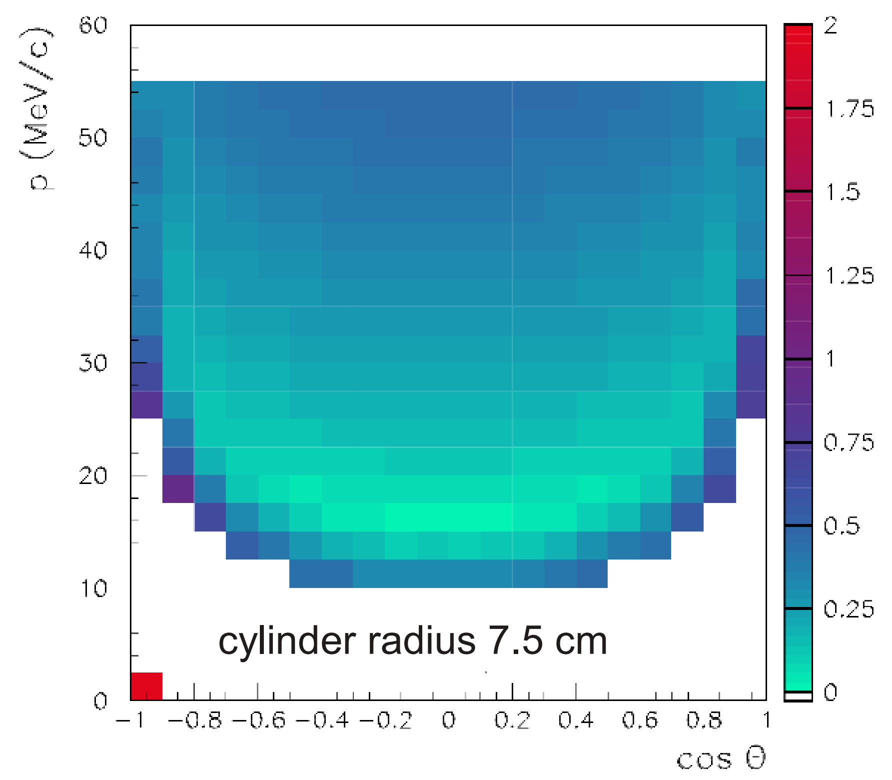


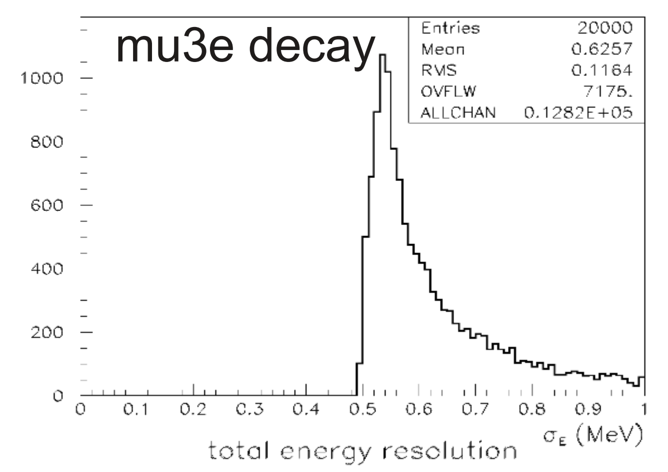


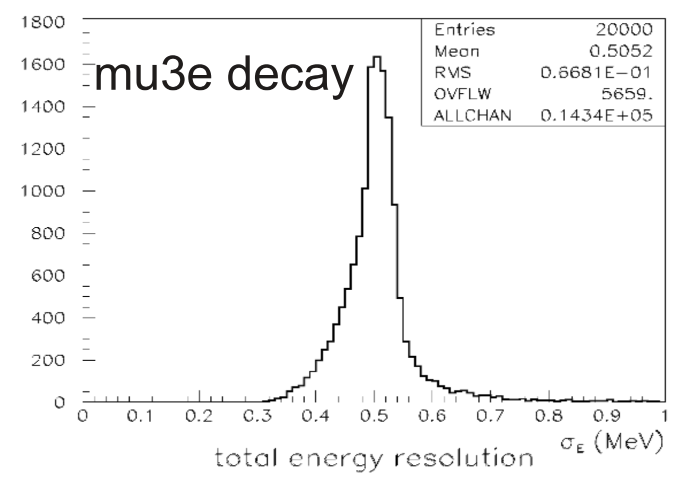


2D versus 3D tracking



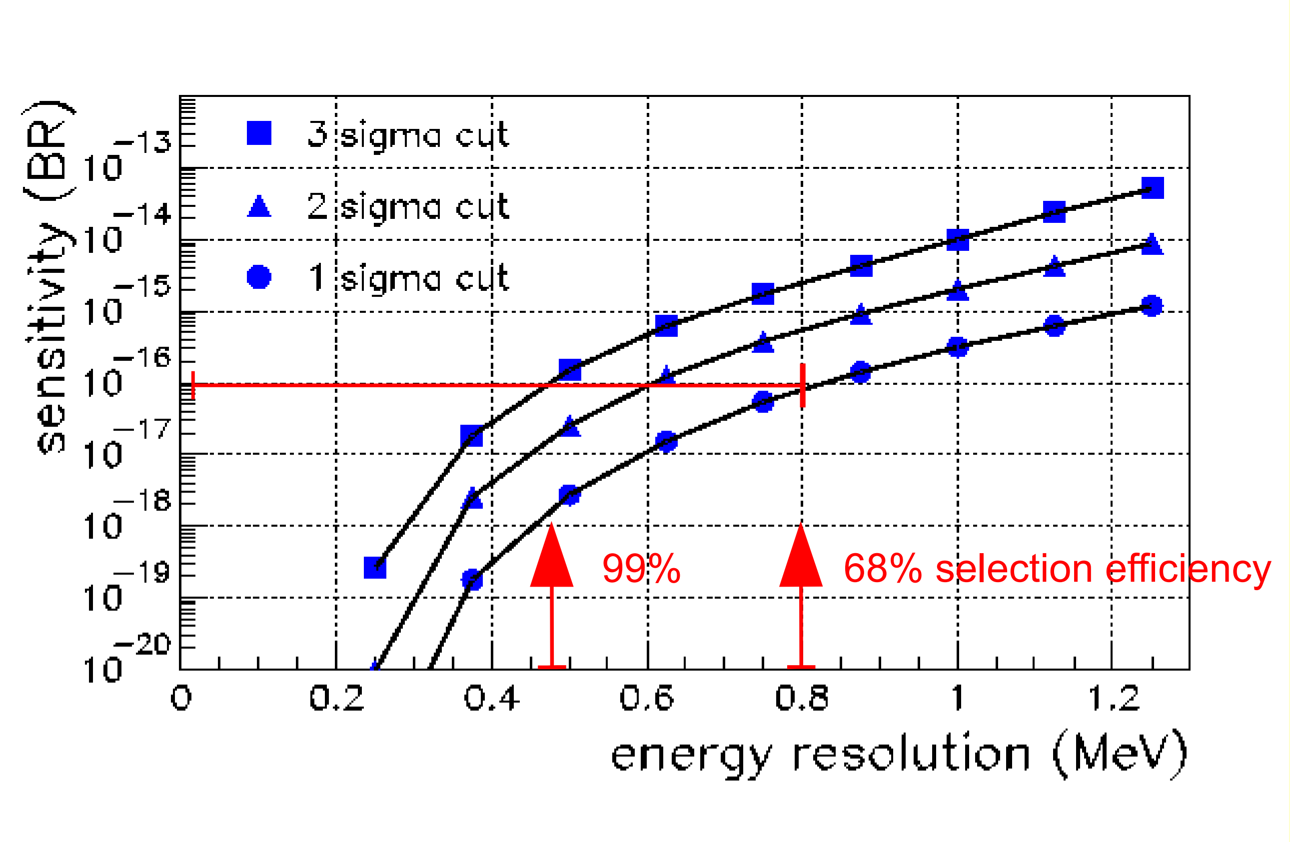






Sensitivity and Background Limitation

Rate of $\mu^+ \rightarrow e^+e^+e^- \nu\nu$ as function of the energy resolution:



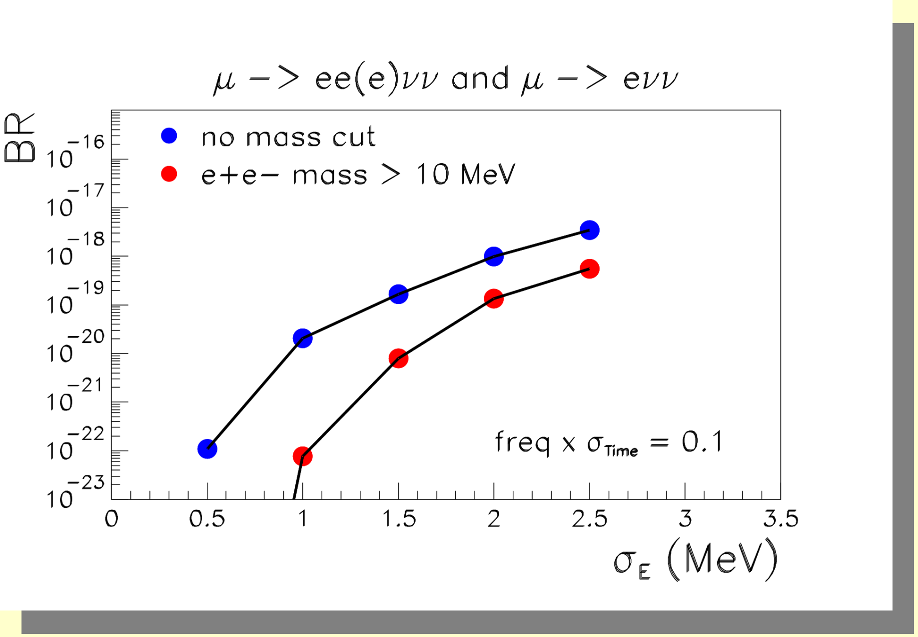
Combinatorial Background Study

Design Parameters:

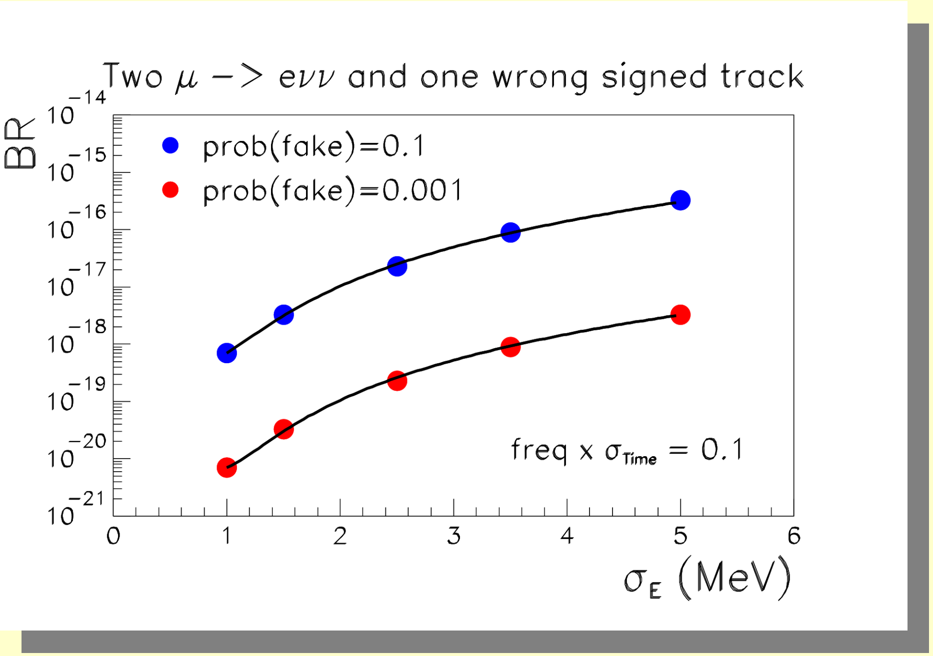
- prob (vertex coincidence) = $5 \cdot 10^{-5}$
- prob (time coincidence) = 0.1

  (100 ps @ 10^9 muons per second)

internal conversion and muon decay



fake track and two muon decays



combinatorial BG can be ignored already for moderate energy resolution σ_E < 3 MeV

vertex and timing constraints not severe

Comparison: μ-Decay Experiments

- **Sindrum 1988:**

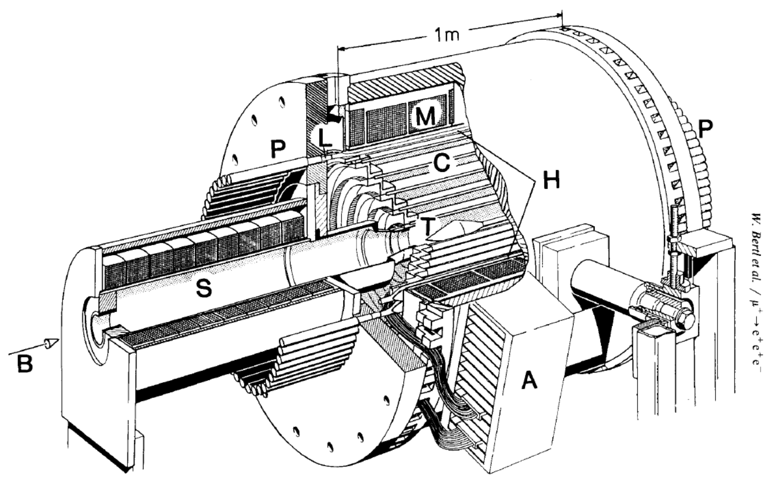
  σ_p/p (50 MeV/c) = 5.1%

  σ_p/p (20 MeV/c) = 3.6%

  σ_θ (20 MeV/c) = 28 mrad

  VTX: σ_d= ~ 1mm

  X0(MWPC) = 0.08% - 0.17% per layer



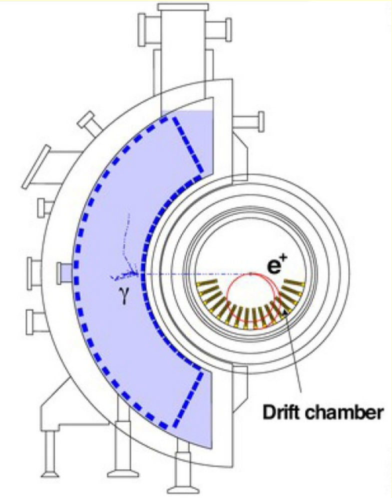
- **MEG 2010 (preliminary):**

  σ_p/p (53 MeV/c) = 0.7 %

  σ_Φ (53 MeV/c) = 8 mrad

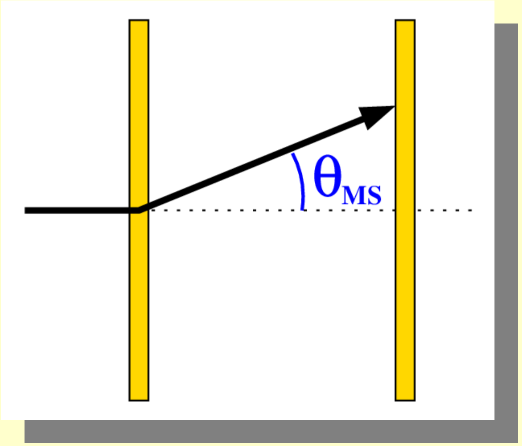
  σ_θ (53 MeV/c) = 8 mrad

  VTX: σ_R=1.4 mm, σ_z=2.5 mm



→ **Aim for similar or better angular and momentum resolutions, high rates and better vertex resolution ~ 150 μm (combinatorial BG)**

Multiple Scattering in Silicon



Momentum range p = 15-53 MeV

- multiple scattering!

Example: p = 53 MeV/c

- **MEG:** σ_{Θ}^{MS}= 8 mrad
  - multiple scatt. per layer X/X_0=0.1% → corresponds to 90 µm Silicon
- µ → eee: σ_{Θ}^{MS}= 5 mrad
  - multiple scatt. per layer X/X_0=0.044% → corresponds to 40 µm Silicon

Pixel sensors can be thinned down to 30-50 µm

(examples CMOS MAPS, DEPFET 50 µm)

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

Model Dependence:

$$\frac{dB(\mu \rightarrow eee)}{dx_1\, dx_2\, d\cos\theta\, d\phi} = \sum_{k=1}^{5} c_k\, \alpha_k(x_1, x_2)$$

four fermion

$$\begin{aligned} \boxed{c_1} &= \frac{g_1^2 + g_2^2}{16} + g_{34}^2 \\ \boxed{c_2} &= g_{56}^2 \end{aligned}$$

acc ~ 80%

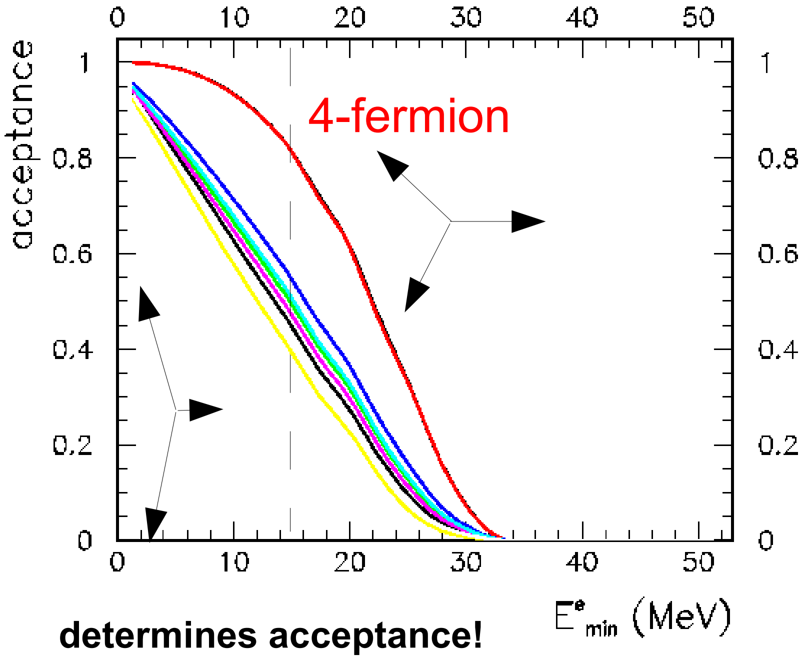
photon penguin

$$\begin{aligned} c_3 &= e\, A^2 \\ c_4 &= e\, A g_{34}\, \eta \\ c_5 &= e\, A g_{56}\, \eta' \end{aligned}$$

acc ~ 40%

T-odd

Minimum electron energy:



determines acceptance!

measure momenta
in range: p=15-53 MeV/c