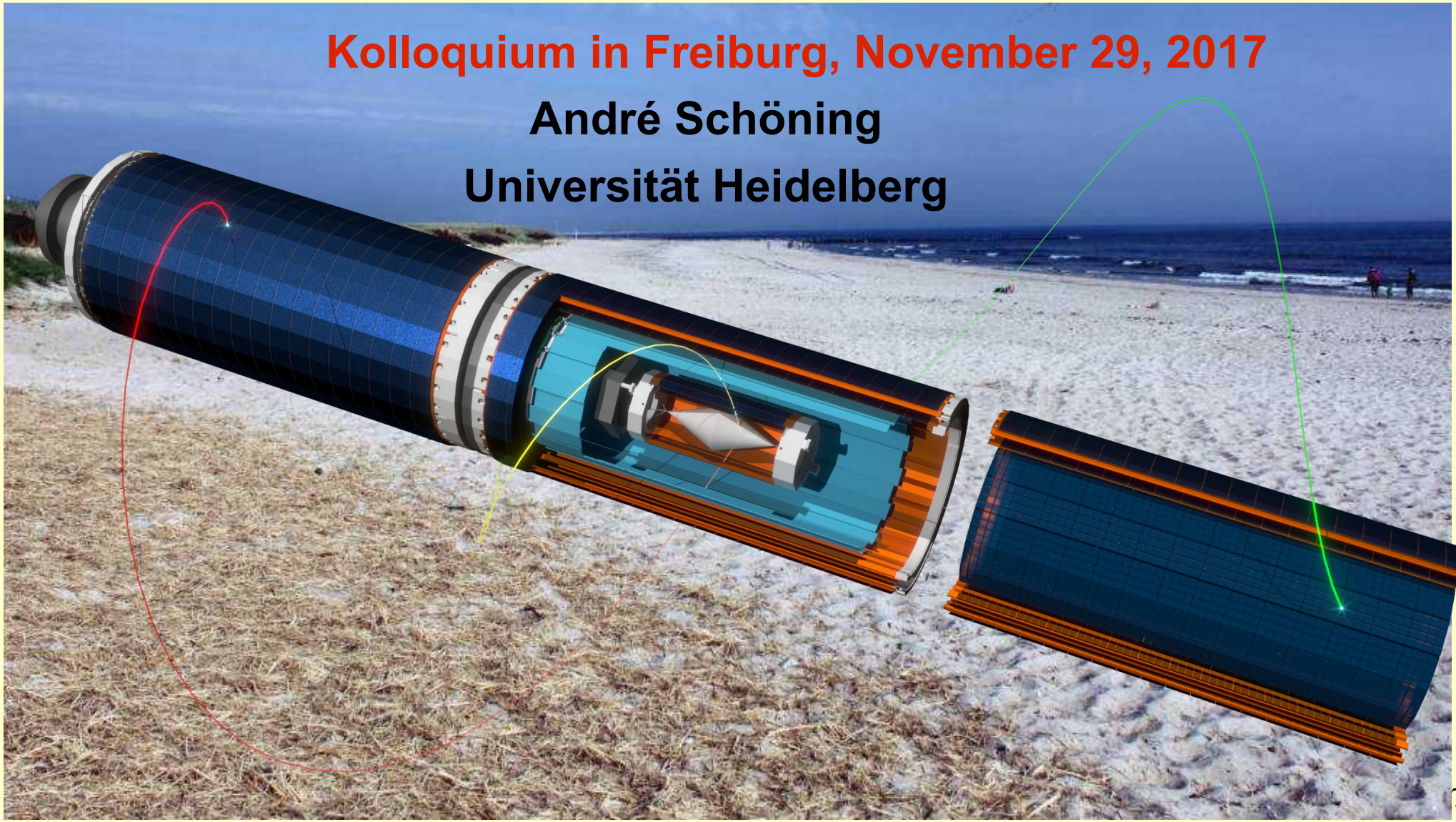
The Mu3e Experiment

A new search for μ → eee with unprecedented sensitivity

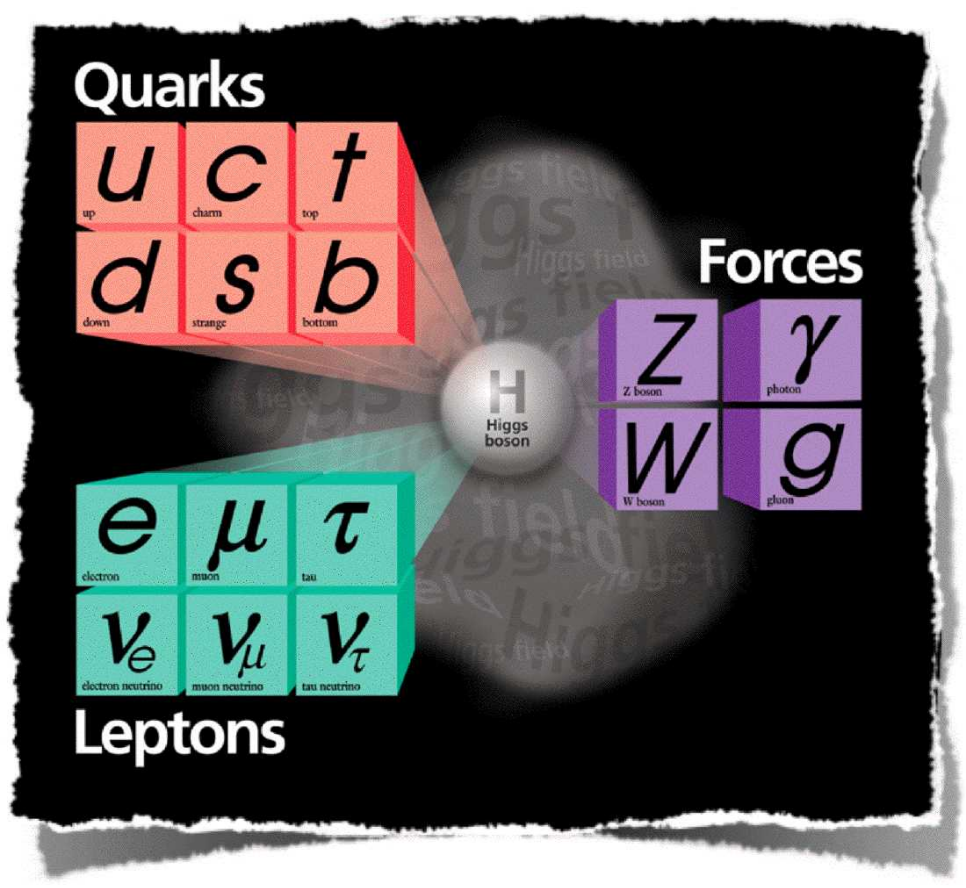


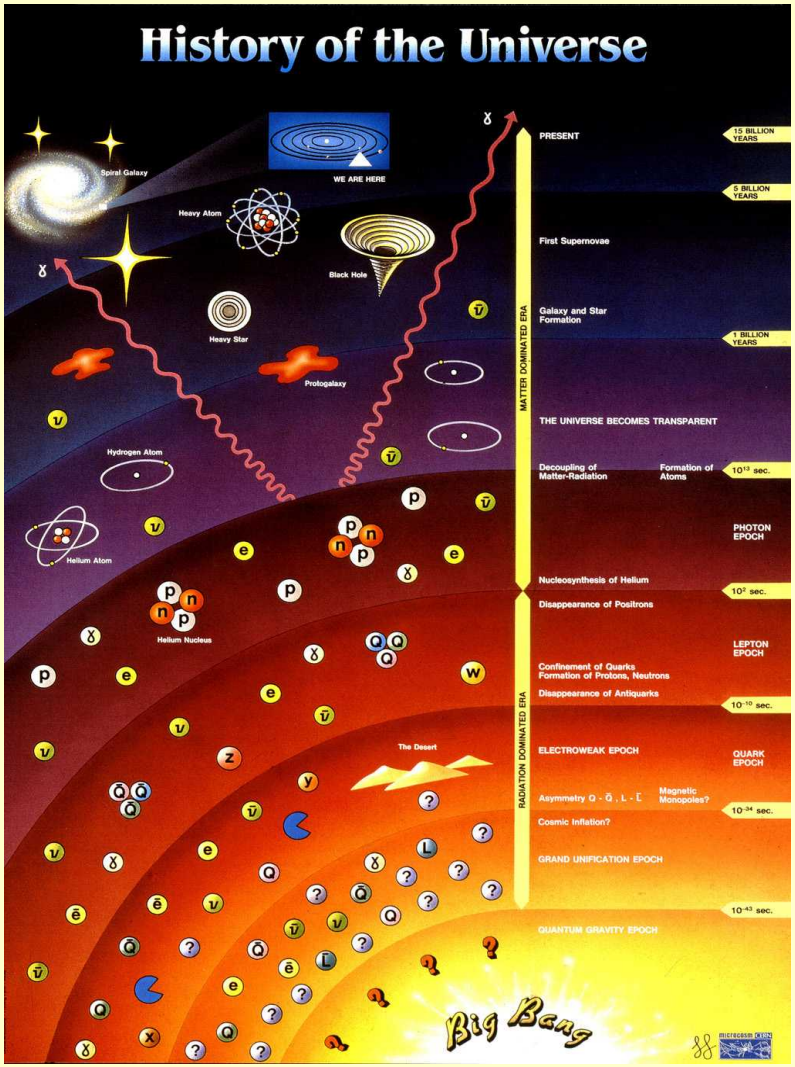
Kolloquium in Freiburg, November 29, 2017

André Schöning

Universität Heidelberg

SM of Particle Physics





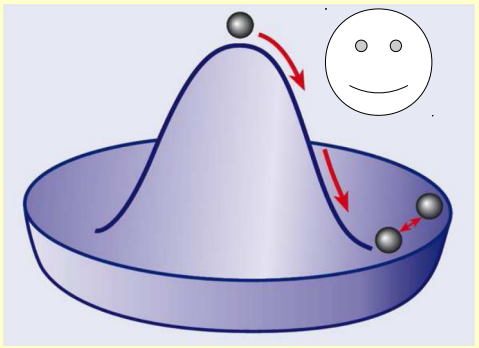
Physics after the electroweak epoch is described by the SM

Questions in (Particle) Physics

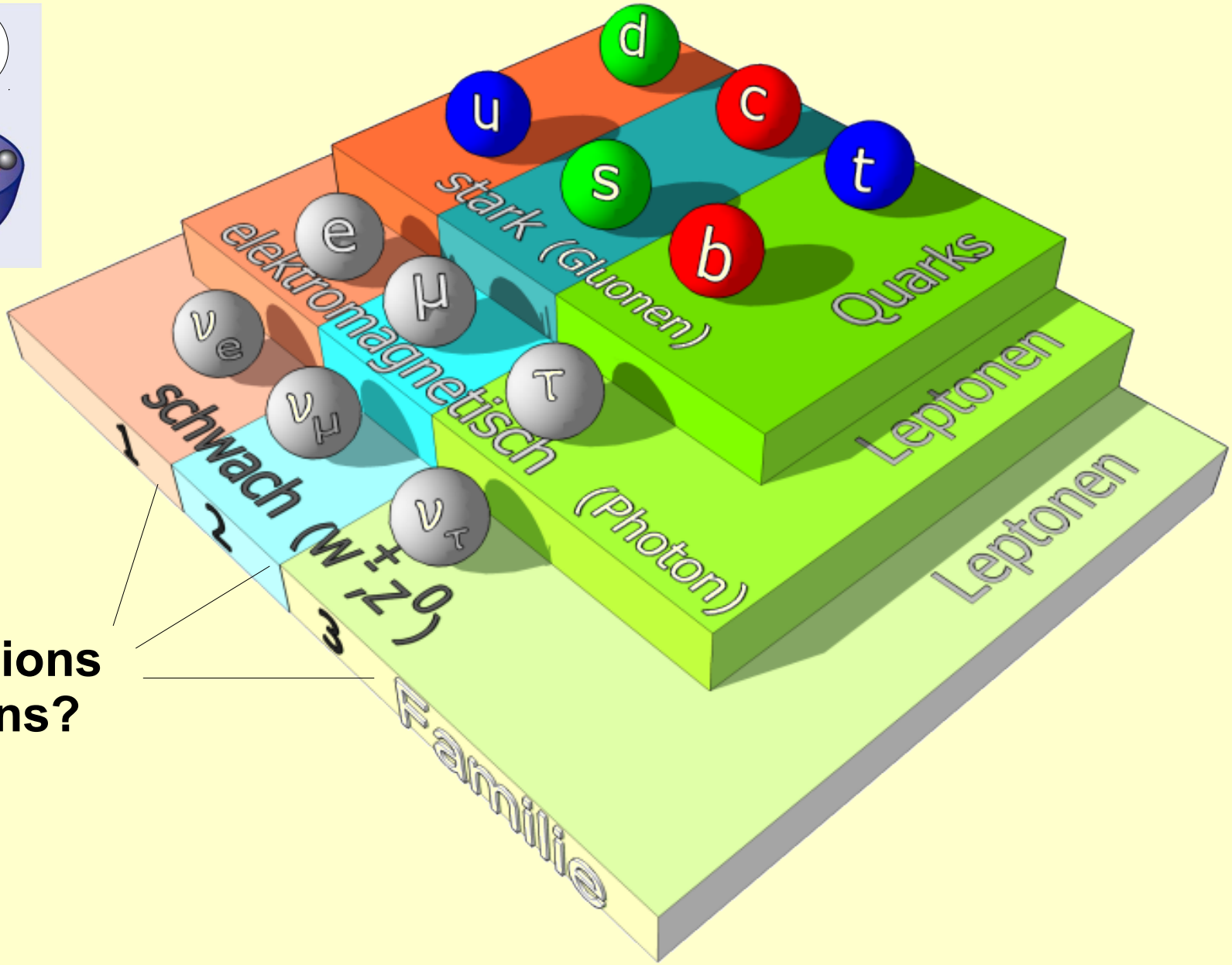
Neither we understand the “observation” of ordinary **matter** nor the observation of **dark matter**.

Must be understood!

Fermions in the Standard Model



Higgs field

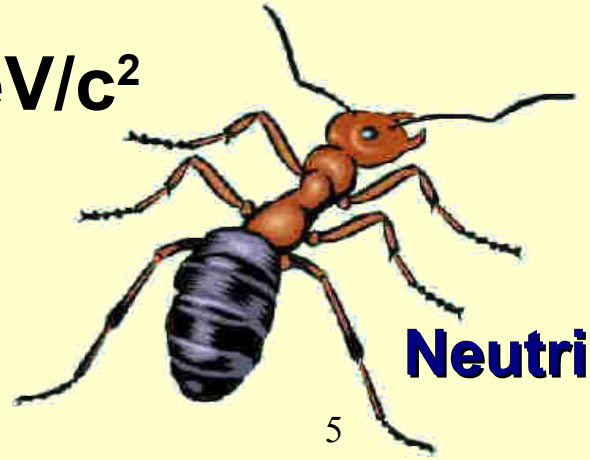


Why
3 generations
of fermions?

Fermion Masses in the SM

Proton: m ≈ 1 GeV/c²

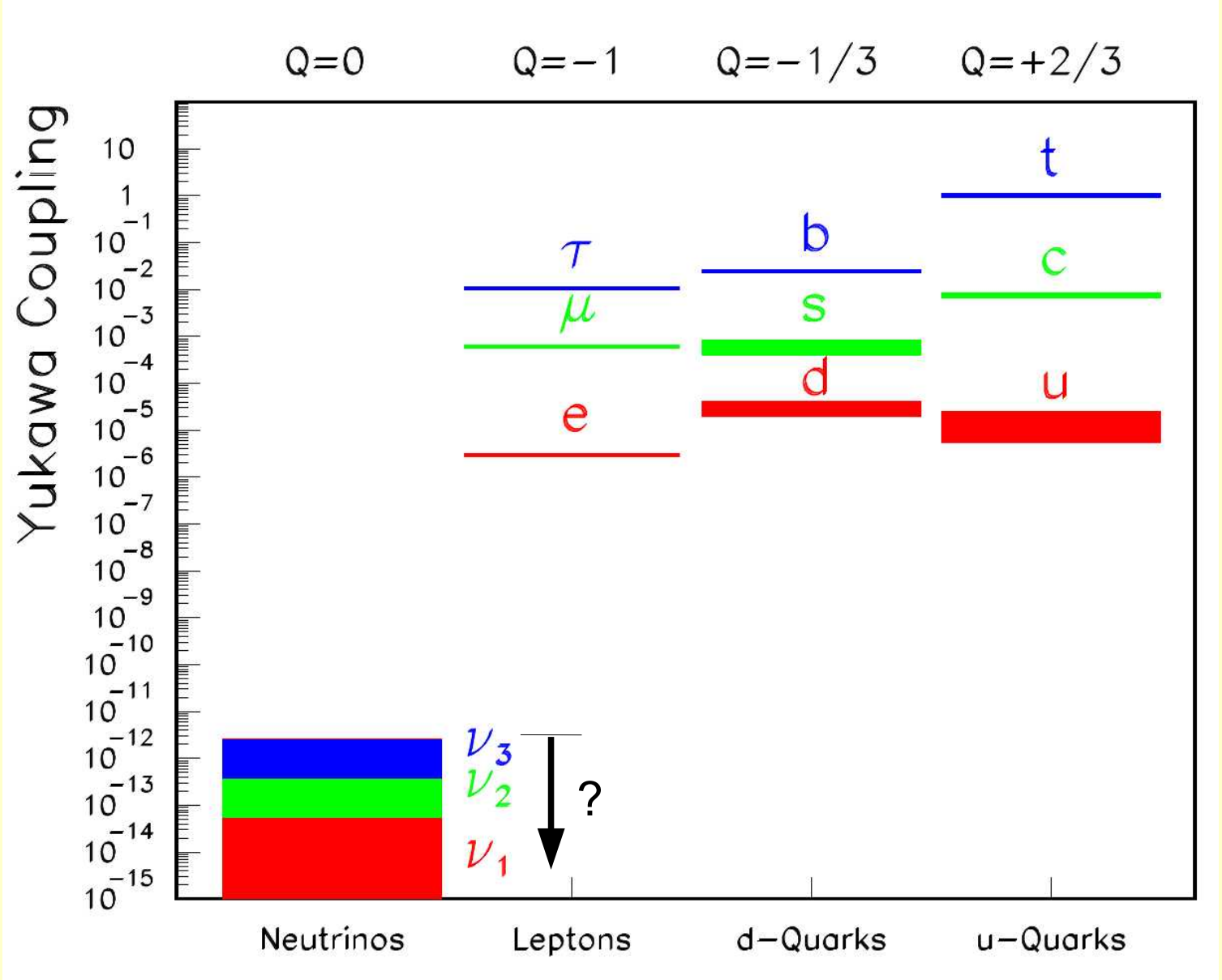
Elektron:
m ≈ 0.5 MeV/c²



Why Higgs couplings so different?

Neutrinos: m ≈ 0.01 - 0.1 eV/c²

Fermion Masses in the SM



$y_t \sim 1$ (within 1%)

Physics Beyond the SM (BSM)

Experimental Observations

- Matter-antimatter asymmetry in universe → **CP-Violation**
- Observation **Dark matter**

→ require new particles or interactions beyond the SM

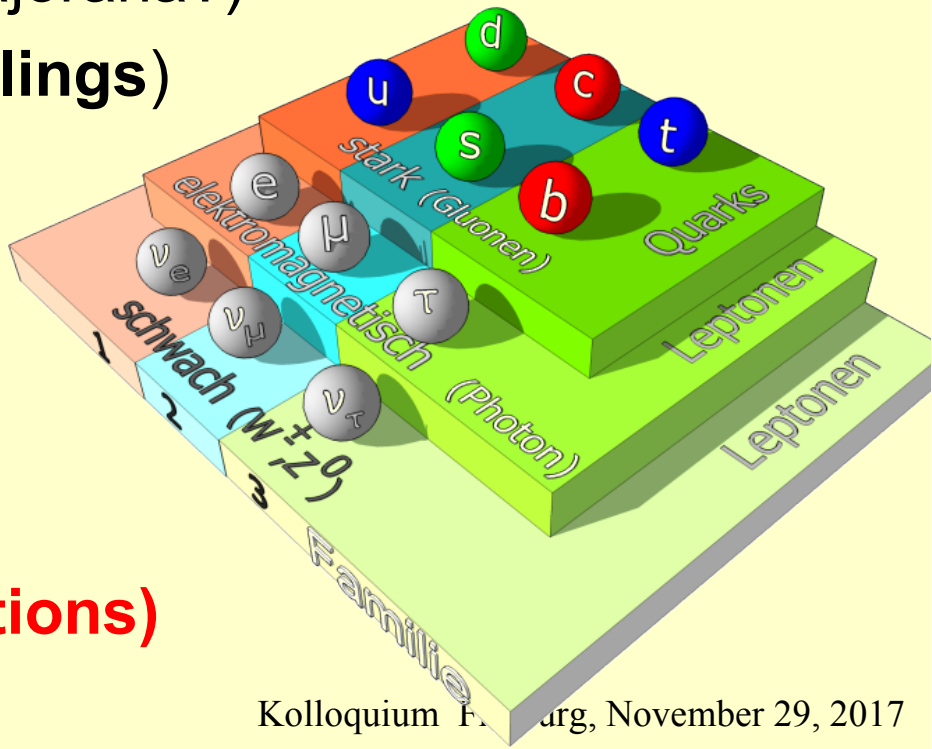
Unknowns

- Fermion **generations**
- nature of **neutrinos** (Dirac or Majorana?)
- Fermion masses (**Yukawa couplings**)

→ no explanation yet

Problems

… hierarchy “problem”, etc. ...

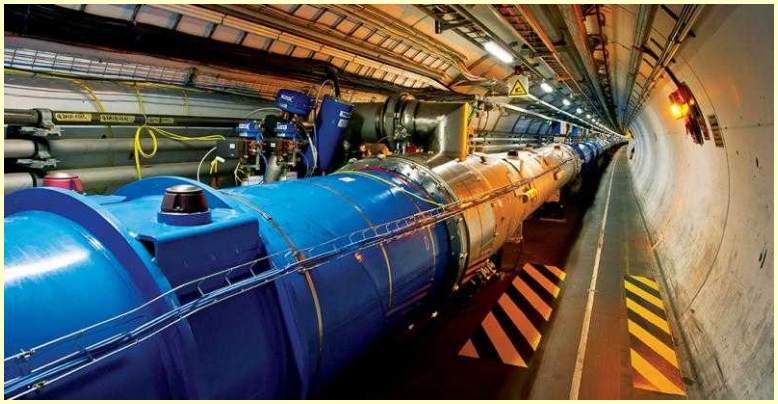


→ **requires new particles (interactions)**

Search Strategies

High Energy Frontier

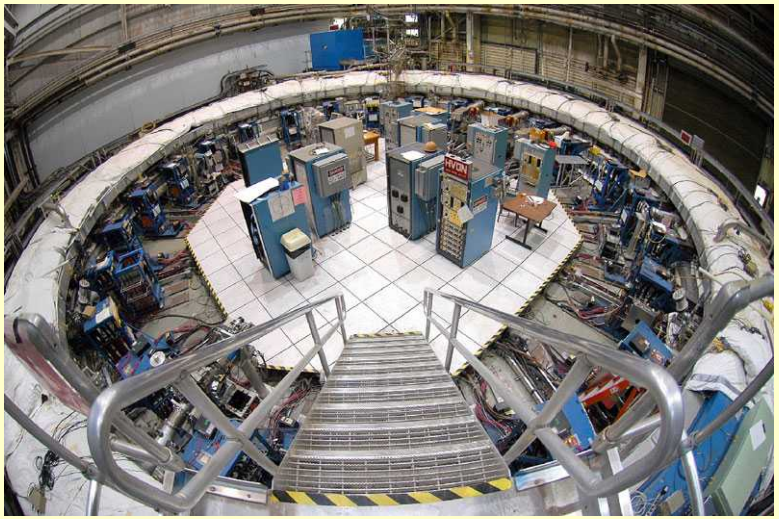
- Direct searches of new resonances or interactions in the mass reach of colliders
  - LHC, Future Circular Colliders, ...



LHC accelerator (Geneva)

High Intensity and Precision Frontier

- Indirect searches via precision measurements and searches for rare processes
  - Electric Dipole Moments (EDM)
  - Anomalous magnetic moments (g-2) →
  - Flavor Changing Neutral Current (FCNC)
  - **Charged Lepton Flavor Violation (cLFV)**

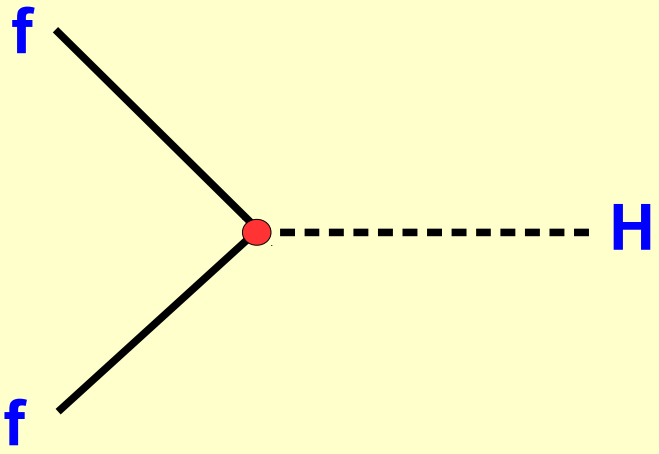


Muon g-2 @ Fermilab

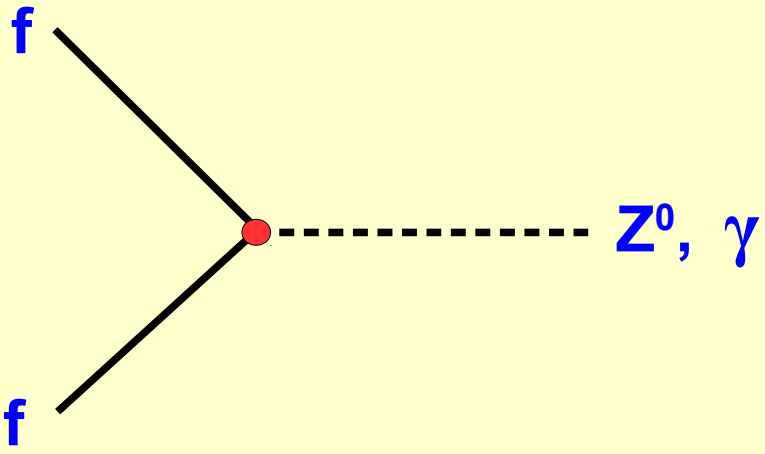
Overview

- Standard Model and Lepton Physics
- (charged) Lepton Flavor Violation (cLFV)
- Mu3e experiment
  - tracking concept
  - detector systems
- Sensitivity studies

Flavor Physics

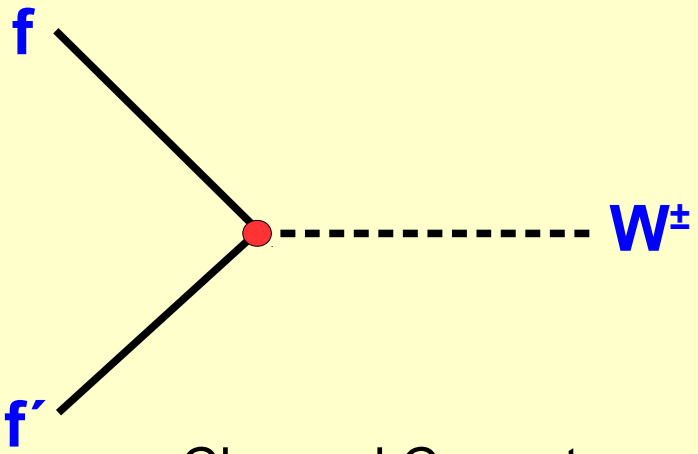


Higgs-Yukawa coupling



Neutral Current

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix} \qquad \begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$



Charged Current

Flavor Mixing Matrices

Quarks

Leptons

Cabibbo Kobayashi Maskawa (CKM)

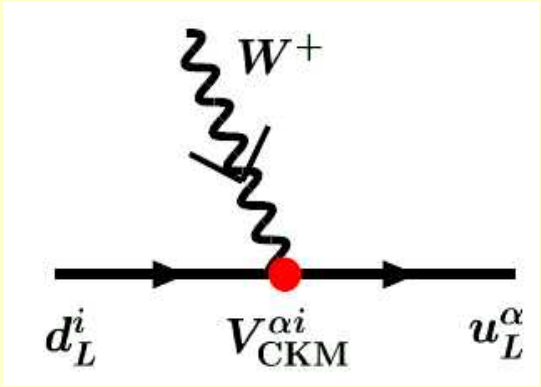
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} v_{ud} & v_{us} & v_{ub} \\ v_{cd} & v_{cs} & v_{cb} \\ v_{td} & v_{ts} & v_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

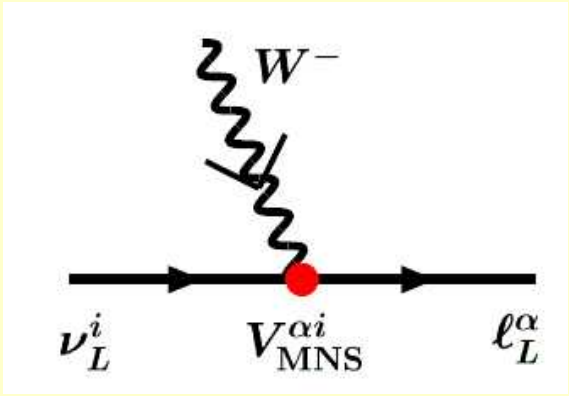
weak mass

Pontecorvo Maki Nakagawa Sakata (PMNS)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} v_{e1} & v_{e2} & v_{e3} \\ v_{\mu 1} & v_{\mu 2} & v_{\mu 3} \\ v_{\tau 1} & v_{\tau 2} & v_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

weak mass





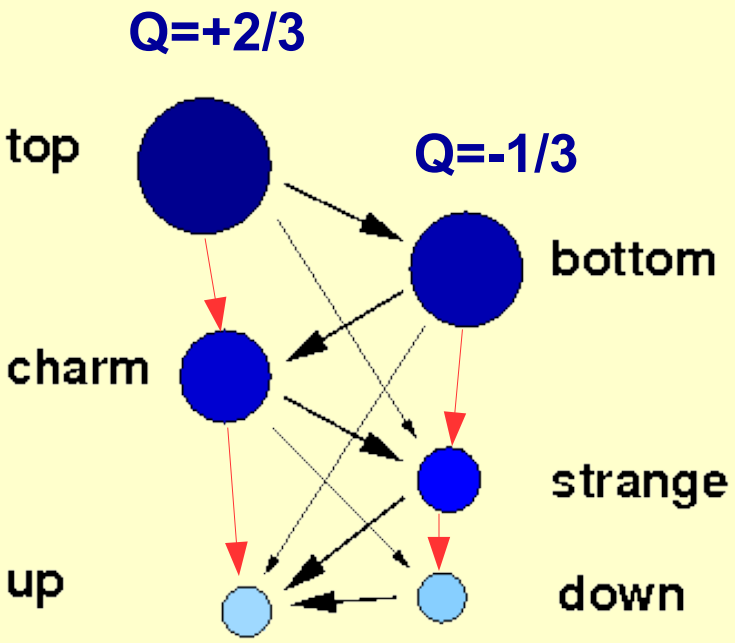
Q=-1/3 **Q=+2/3**

Q=0 **Q=-1**

Flavor Changing Processes

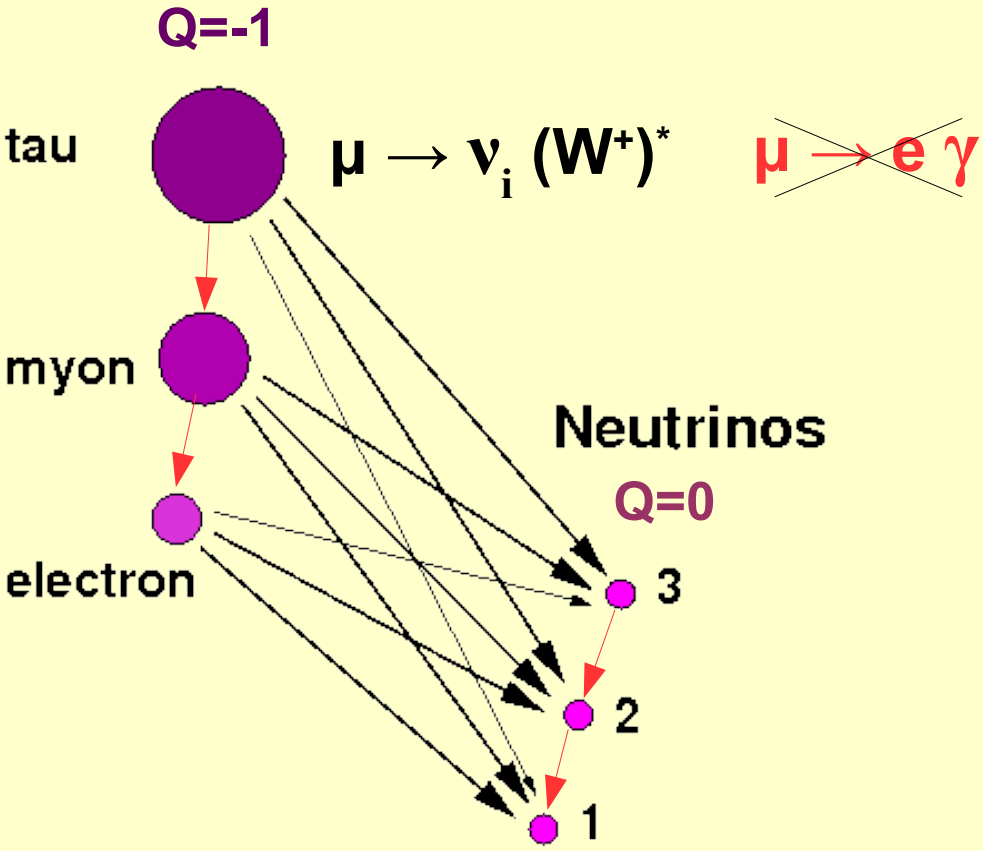
- Flavor Changing Charged Currents are allowed.
- Flavor Changing Neutral Currents (FCNC) are forbidden! (on tree level)

Quarks

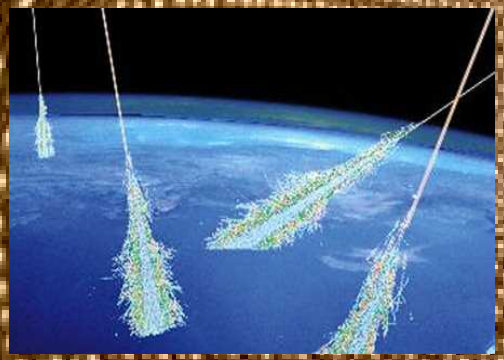


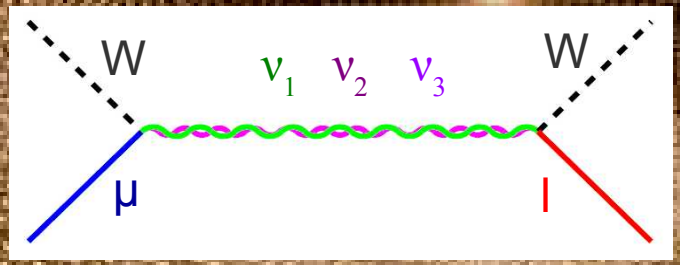
$t \rightarrow b$ $\quad$ ~~$t \rightarrow c$~~

Leptons



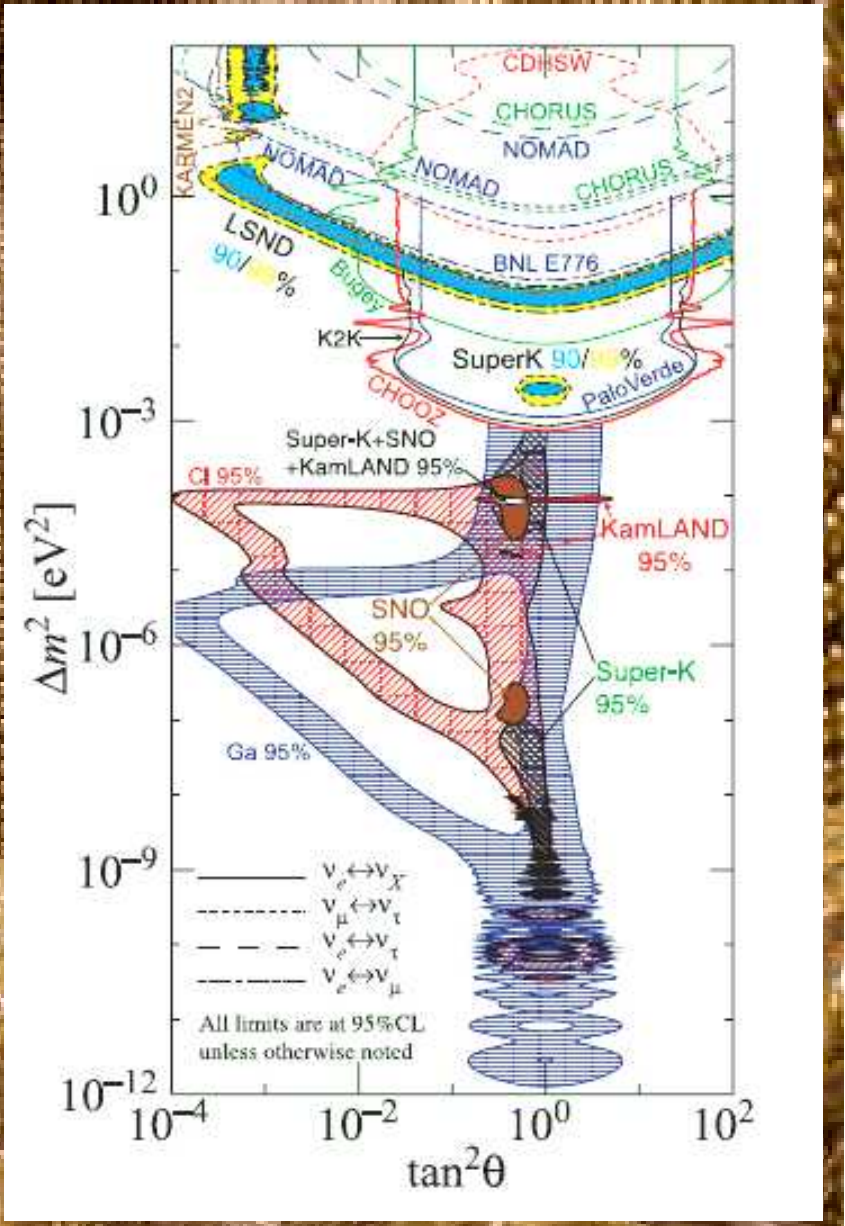
Discovery of Neutrino Oscillations



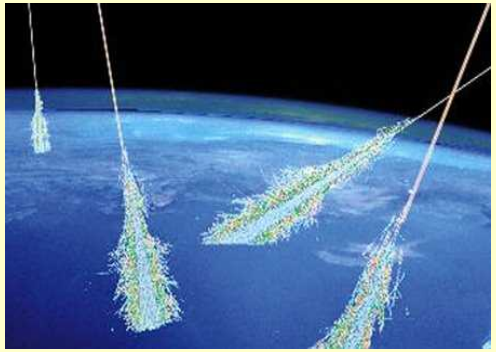


$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\Theta)\sin^2\left(\Delta m^2_{\alpha\beta}\frac{L}{E_\nu}\right)$$

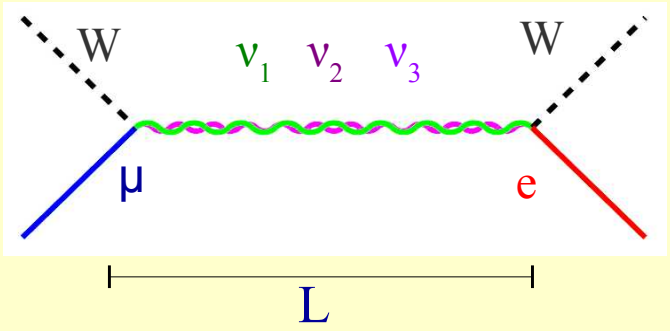
- Neutrino Oscillations:
  - solar neutrinos
  - reactor neutrinos
  - atmospheric neutrinos
  - neutrino beams



FCNC via Quantum Loops



$\mu \rightarrow e$ via ν-oscillation



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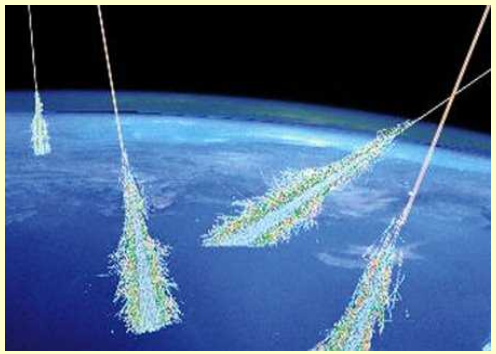
FCNC via Quantum Loops



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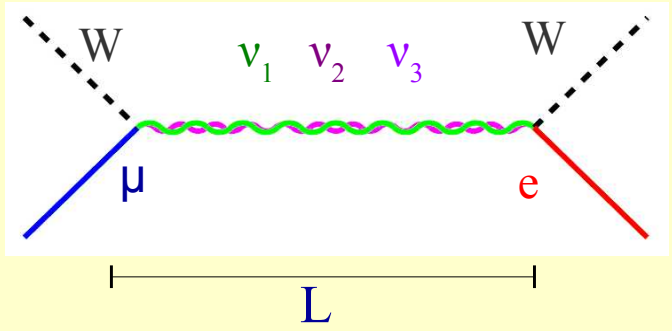
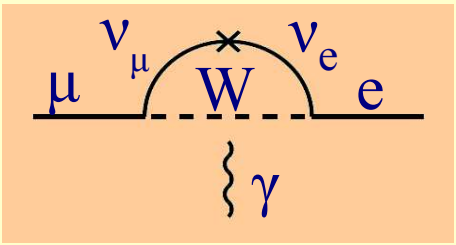
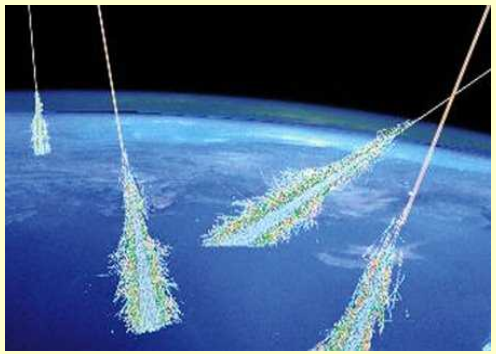


$\mu \rightarrow e\,\gamma$ via loop



$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\Theta)\,\sin^2\left(\Delta m^2_{\alpha\beta}\,\frac{L}{E_\nu}\right)$$

FCNC via Quantum Loops



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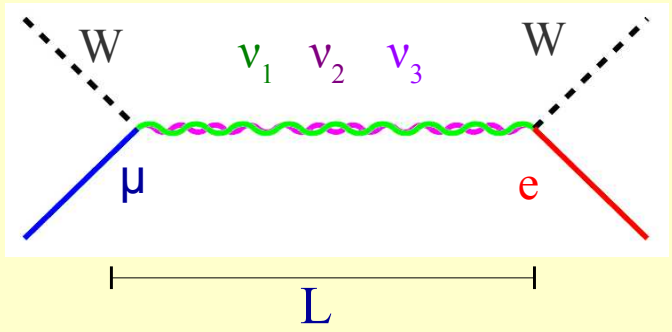
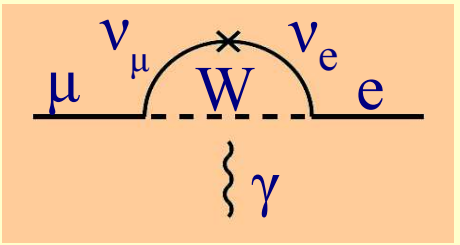


$\mu \rightarrow e\,\gamma$ via loop



$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\Theta)\,\sin^2\left(\Delta m^2_{\alpha\beta}\,\frac{L}{E_\nu}\right)$$

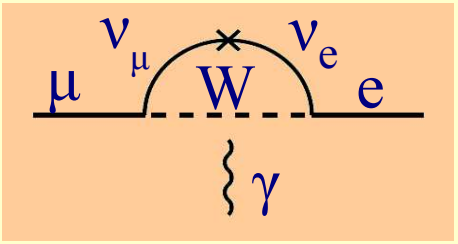
$$B(\mu \rightarrow e\,\gamma) \propto \sin^2(2\Theta)\,\left(\Delta m^2_{\alpha\beta}/m^2_W\right)^2$$

$$L \rightarrow 1/m_W$$

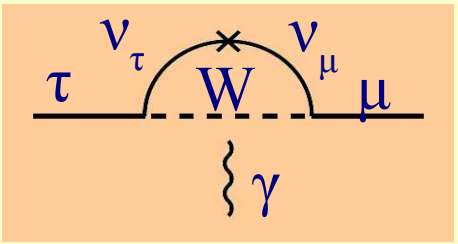
$$E_\nu \rightarrow m_W$$

Lepton Flavor Violation in the SM

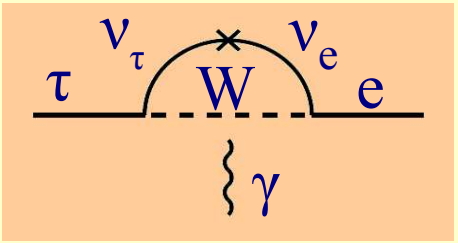
Higher Order!



$\mu \rightarrow e\,\gamma$



$\tau \rightarrow \mu\,\gamma$



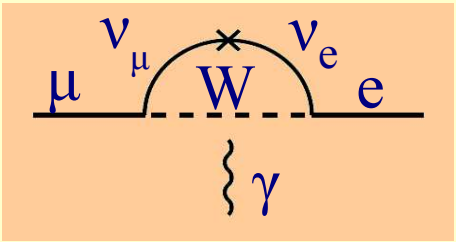
$\tau \rightarrow e\,\gamma$

LFV in generated from lepton mixing:

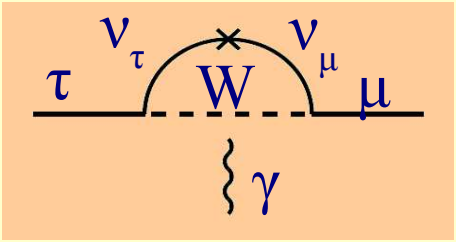
$$BR(l_j \rightarrow l_k \gamma) \propto \left| \sum_i V_{ij} (V_{jk})^* \frac{m^2_{\nu_i}}{M^2_W} \right|^2 \sim \left| \frac{\Delta m^2_{\nu_{jk}}}{M^2_W} \right|^2 \sim y^4_\nu$$

Lepton Flavor Violation in the SM

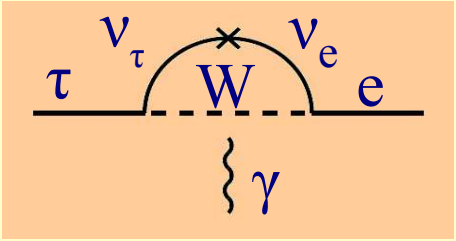
Higher Order!



$\mu \rightarrow e\,\gamma$



$\tau \rightarrow \mu\,\gamma$



$\tau \rightarrow e\,\gamma$

LFV in generated from lepton mixing:

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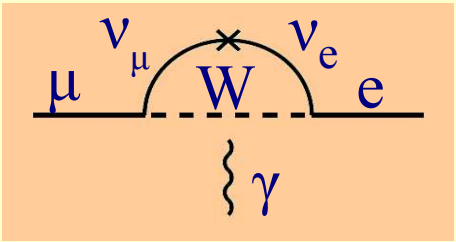
suppression factor for $\mu \rightarrow e$: **$\sim 10^{-50}$**

→ unobservable

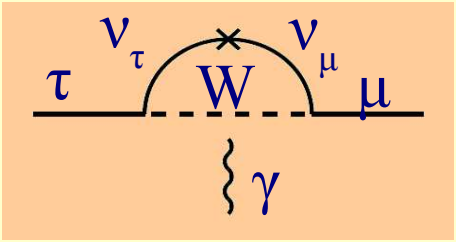
→ high sensitivity to new physics!!!

Lepton Flavor Violation in the SM

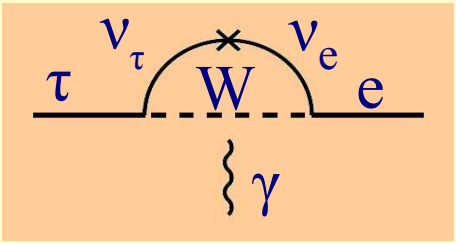
Higher Order!



$\mu \rightarrow e\,\gamma$



$\tau \rightarrow \mu\,\gamma$



$\tau \rightarrow e\,\gamma$

LFV in generated from lepton mixing:

$$BR(l_j \rightarrow l_k \gamma) \propto \left| \sum_i V_{ij} (V_{jk})^* \frac{m^2_{\nu_i}}{M^2_W} \right|^2 \sim \left| \frac{\Delta m^2_{\nu_{jk}}}{M^2_W} \right|^2 \sim y^4_\nu$$

suppression factor for μ → e: **~ 10^{-50}**

→ **unobservable**

→ **high sensitivity to new physics!!!**

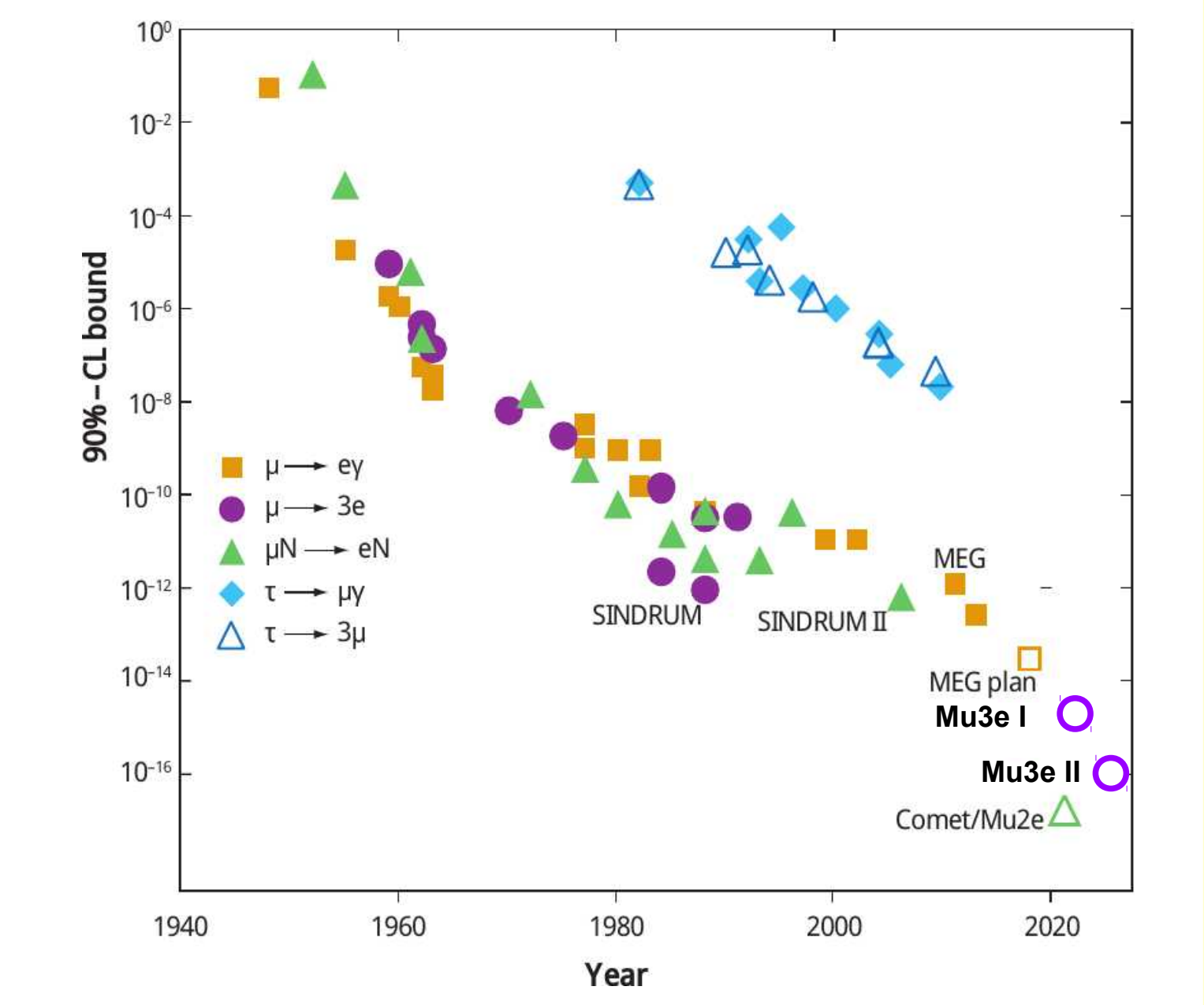
c.t. quark mixing:

→ FCNC in SM ~ 10^{-10}

$$\left(\frac{\Delta m^2_{c-u}}{M^2_W} \right)^2 \sim 10^{-7}$$

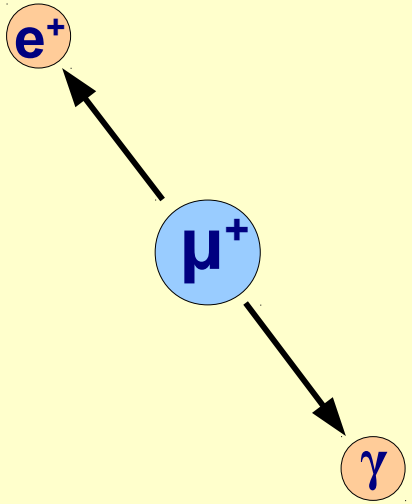

Lepton Flavor Conservation is an Accidental Symmetry!

History of LFV Decay experiments



LFV Muon Decays

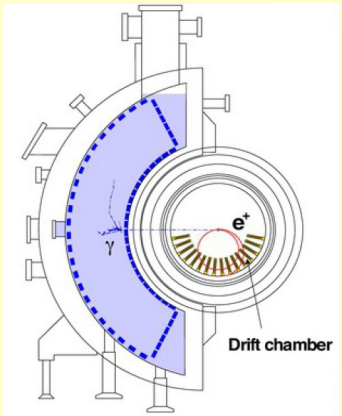
$\mu^+ \rightarrow e^+ \gamma$



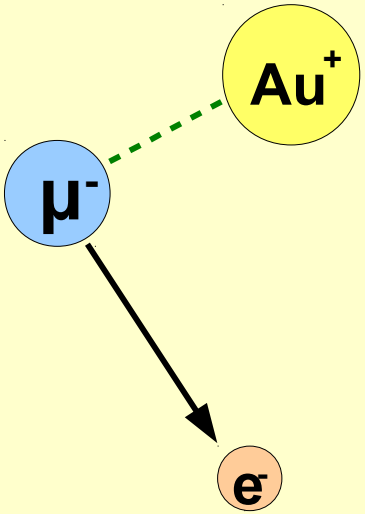
MEG (PSI)

$B(\mu^+ \rightarrow e^+\gamma) \leq 4.2 \cdot 10^{-13}$ (2016)

being upgraded

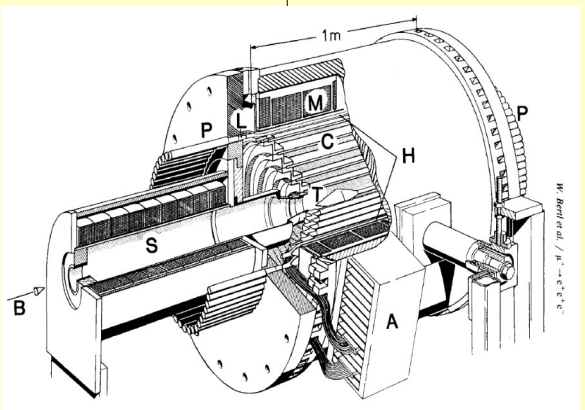


$\mu^- N \rightarrow e^- N$

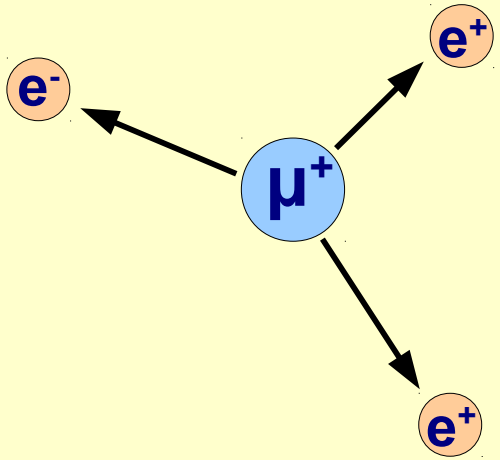


SINDRUM II (PSI)

$B(\mu\ Au \rightarrow e\ Au) \leq 7 \cdot 10^{-13}$ (2006)



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

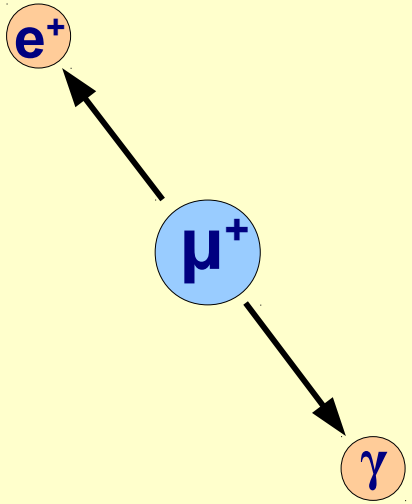


SINDRUM (PSI)

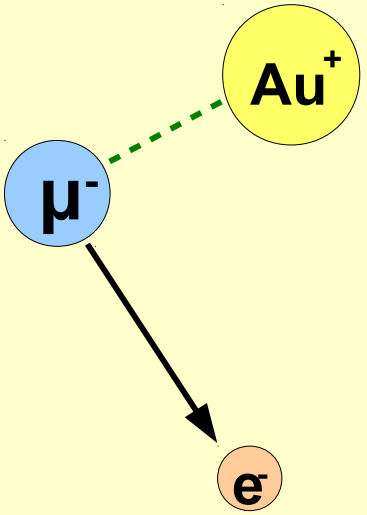
$B(\mu^+ \rightarrow e^+e^+e^-) \leq 10^{-12}$ (1988)

SM Loop Diagrams

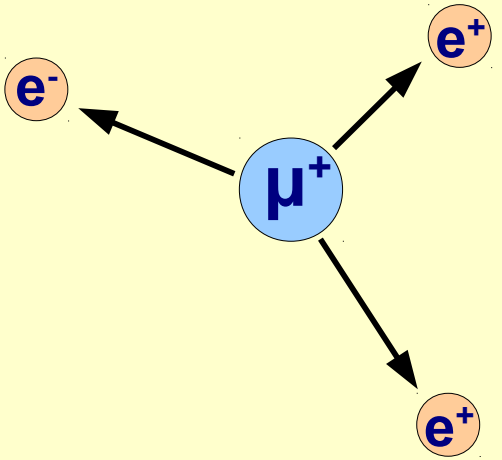
$\mu^+ \rightarrow e^+ \gamma$



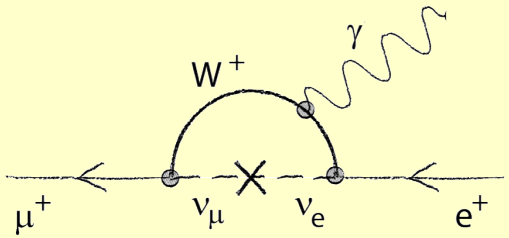
$\mu^- N \rightarrow e^- N$

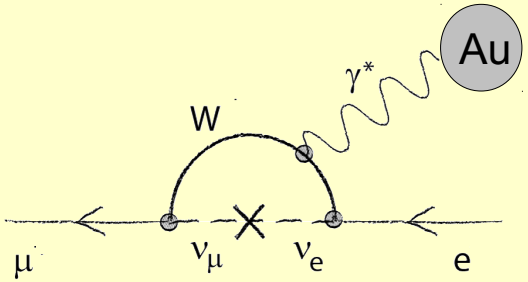


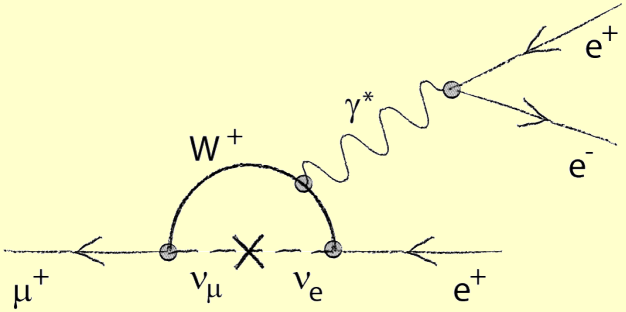
$\mu^+ \rightarrow e^+ e^+ e^-$



SM: LFV loops



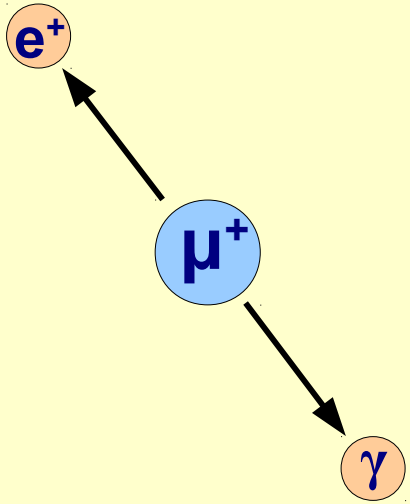




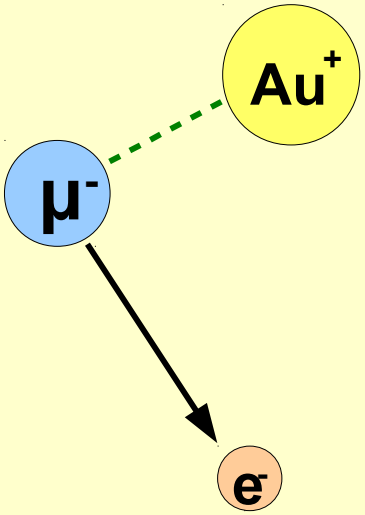
branching ratios suppressed by $\propto \frac{(\Delta m_\nu^2)^2}{m_W^4} \approx 10^{-50}$

LFV Muon Decays and SUSY Loops

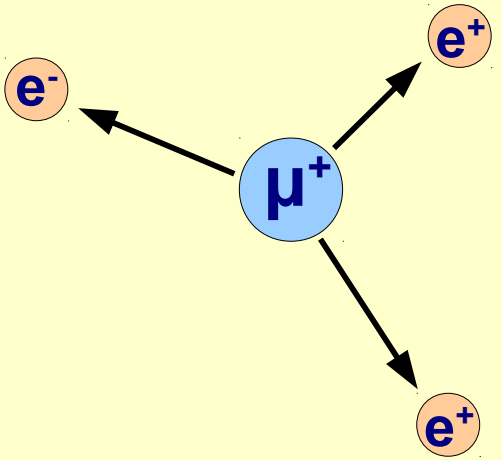
$\mu^+ \rightarrow e^+ \gamma$



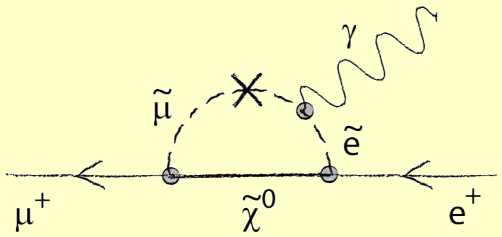
$\mu^- N \rightarrow e^- N$

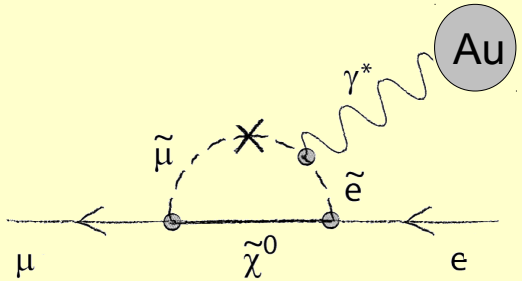


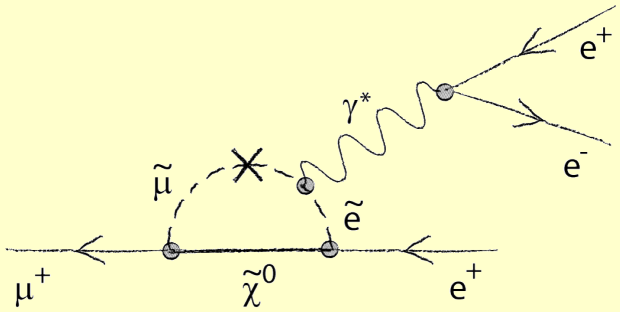
$\mu^+ \rightarrow e^+ e^+ e^-$



SUSY loops



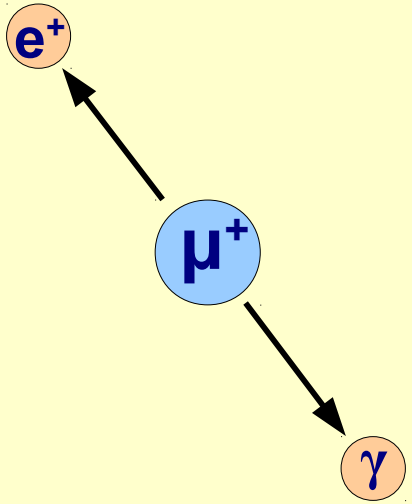




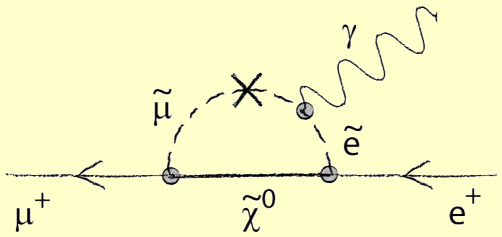
Most BSM models (e.g. SUSY) induce naturally LFV

LFV Muon Decays and SUSY Loops

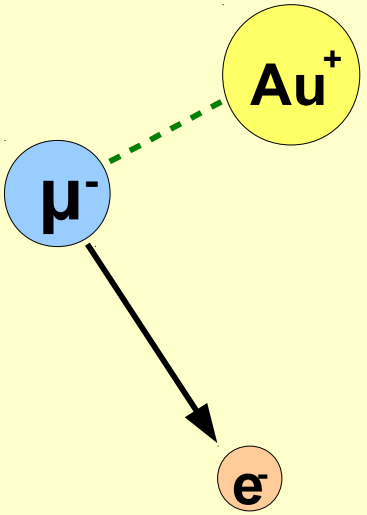
$\mu^+ \rightarrow e^+ \gamma$

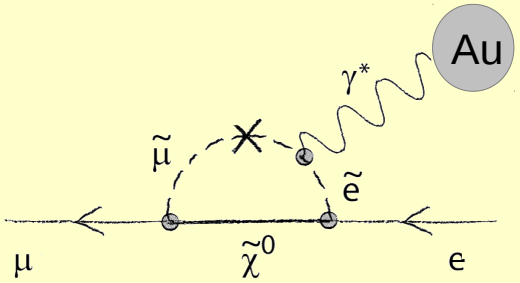


SUSY loops



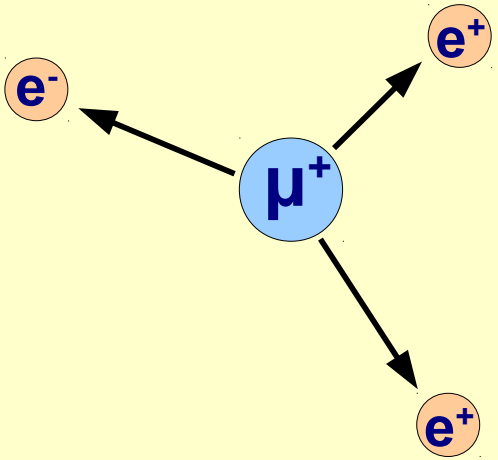
$\mu^- N \rightarrow e^- N$

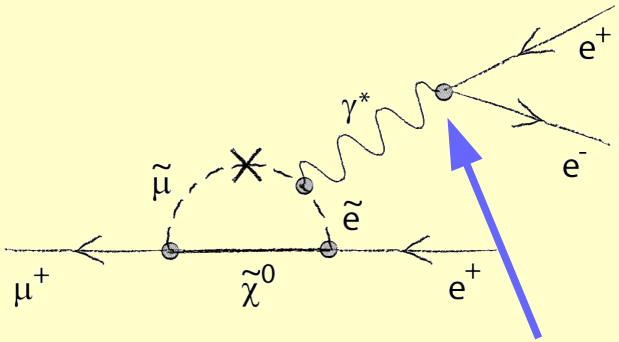




<u>enhanced</u> by
coherent conversion in
nucleus field for $Q^2(\gamma^*) \sim 0$

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

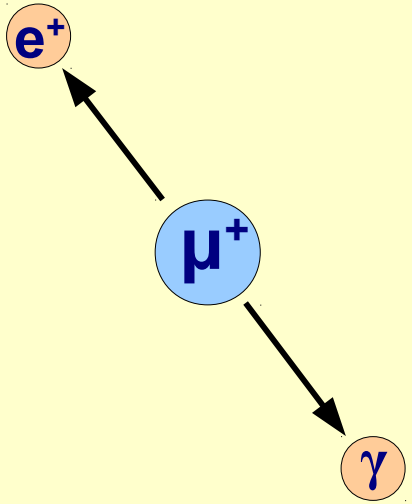


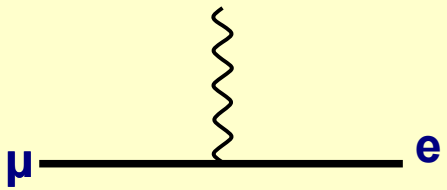


<u>suppressed</u> by extra vertex
with respect to $\mu^+ \rightarrow e^+ \gamma$

LFV Tree Diagrams

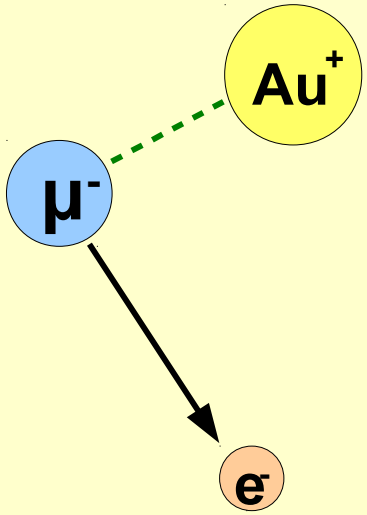
$\mu^+ \rightarrow e^+ \gamma$

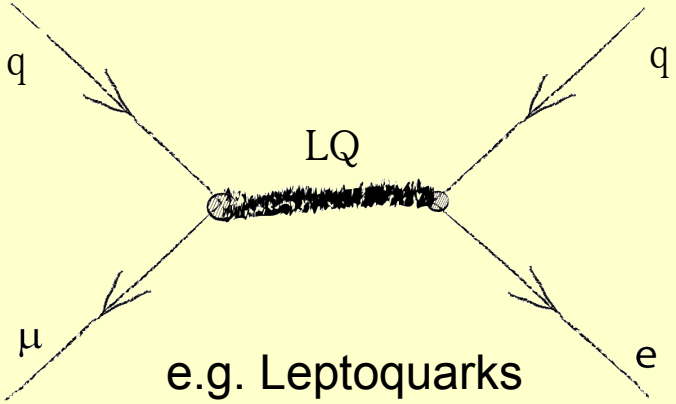




not allowed

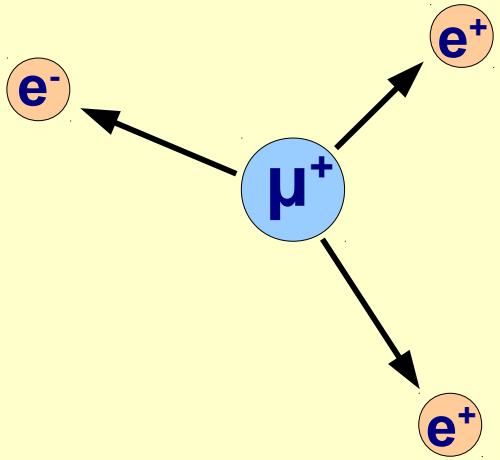
$\mu^- N \rightarrow e^- N$

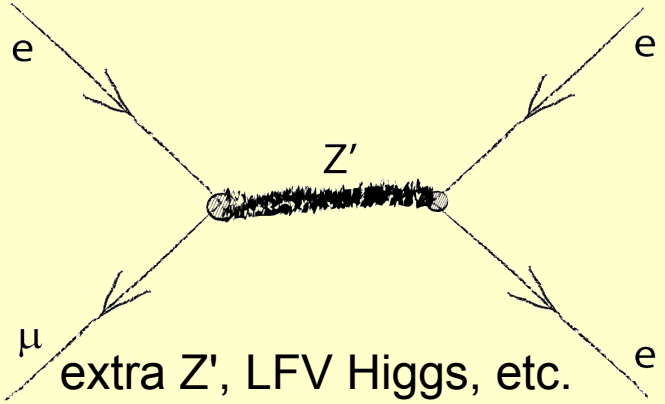




e.g. Leptoquarks

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



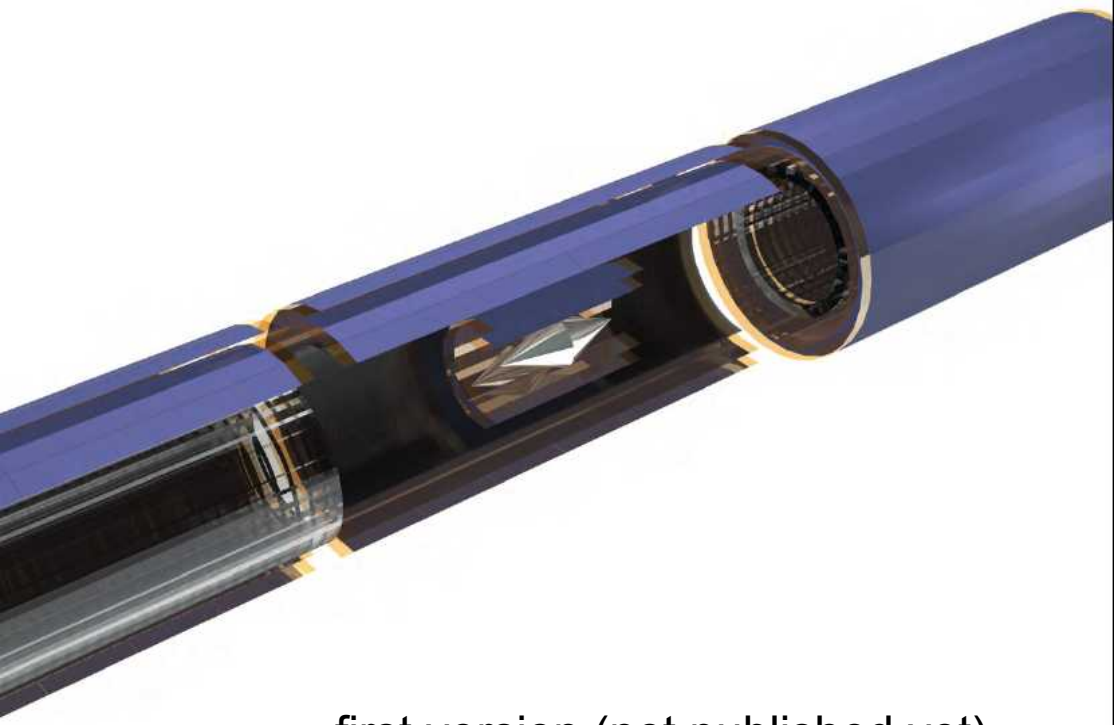


extra Z', LFV Higgs, etc.

Additional BSM tree diagrams in $\mu N \rightarrow eN$ and $\mu N \rightarrow eee$

Technical design of the Phase I

Mu3e Experiment



first version (not published yet)

Technical Design of the Phase I

Mu3e Experiment

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December 2016

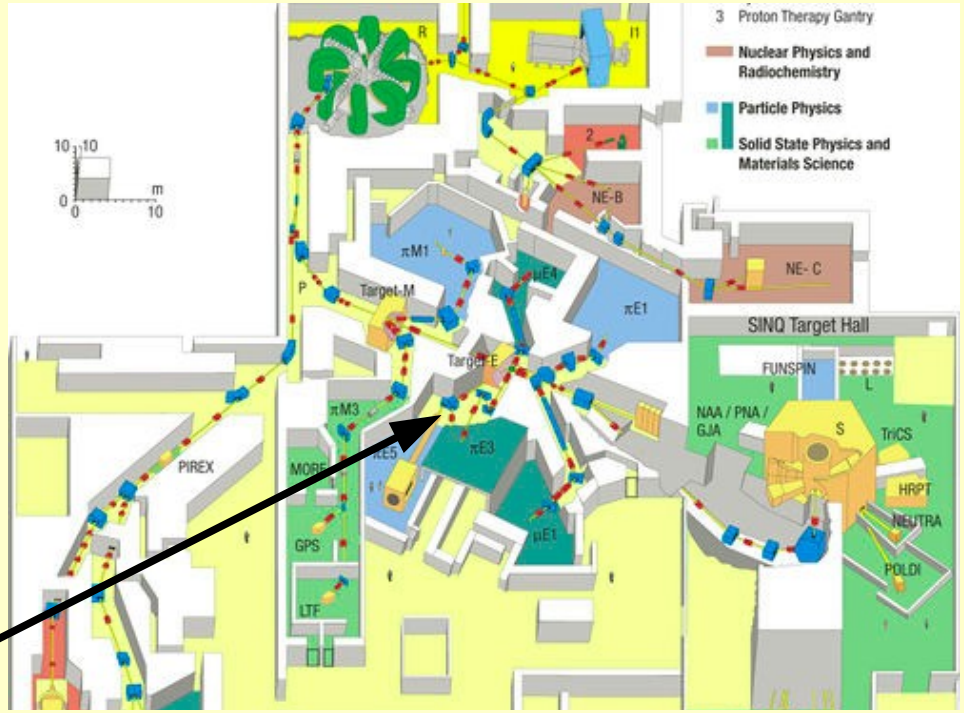
Search for $\mu^+ \rightarrow e^+e^+e^-$ at PSI

project approved in Jan 2013

proton cyclotron

I_p=2.4 mA @ 590 MeV

world-highest intensity beam!



Aiming for a sensitivity of

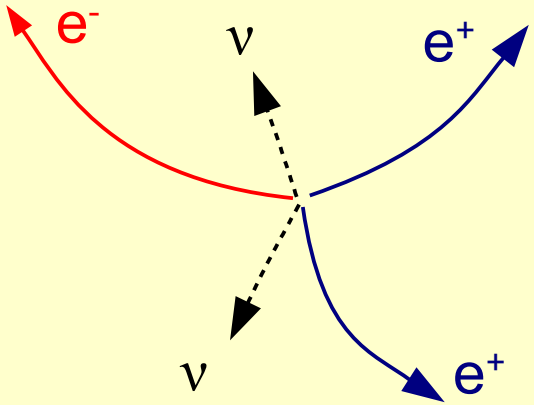
$BR(\mu \rightarrow eee) \sim 2 \cdot 10^{-15}$ (phase I)

$BR(\mu \rightarrow eee) < 10^{-16}$ (phase II)

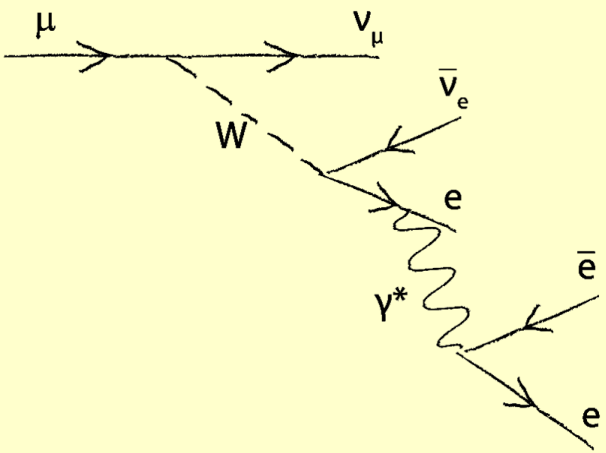
How Big is 10^{-16} ?

Backgrounds for Mu3e

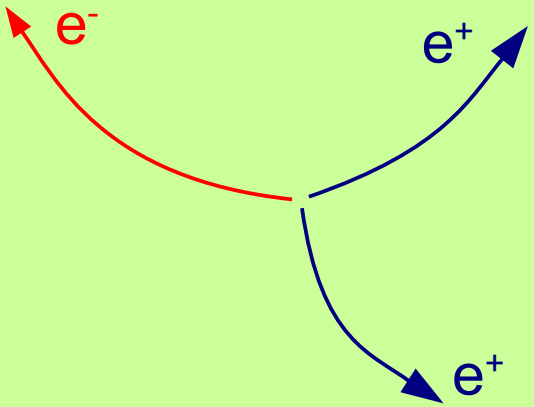
Irreducible BG: radiative decay with internal conversion (IC)



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



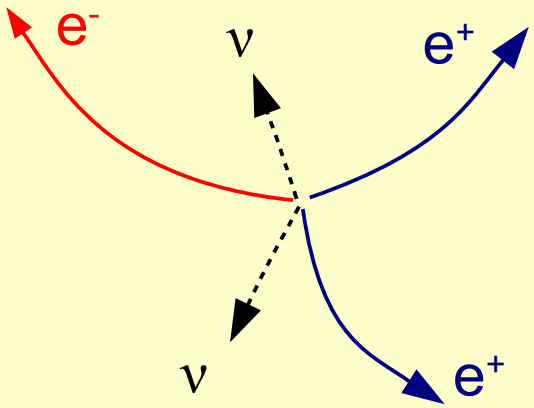
signal: $B(\mu^+ \rightarrow e^+e^+e^-)$



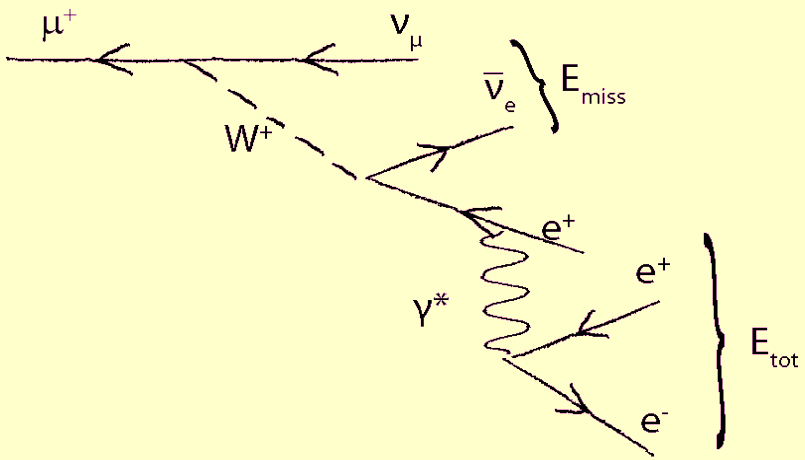
$$\sum_i E_i = m_\mu$$
$$\sum_i \vec{p}_i = 0$$

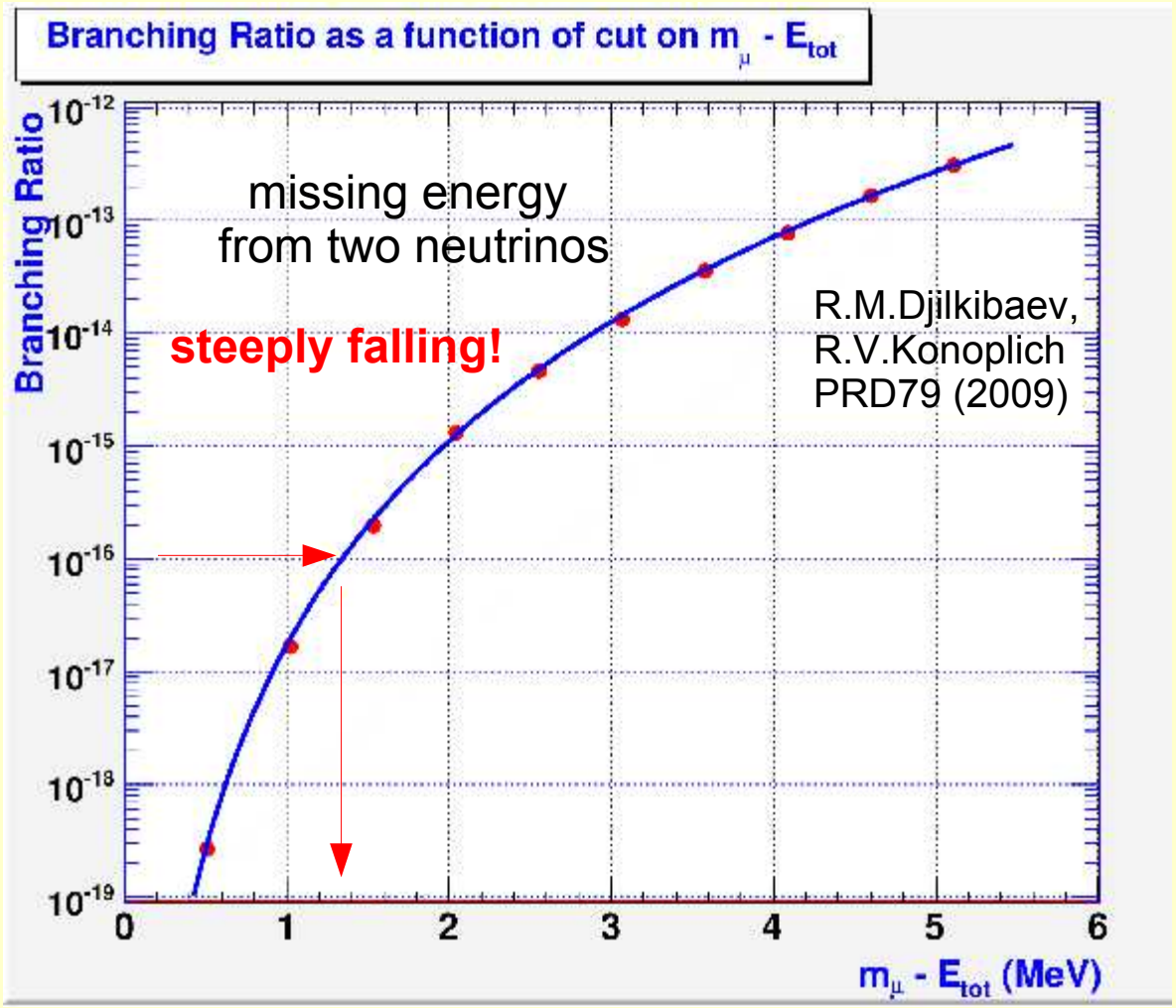
Backgrounds

Irreducible BG: radiative decay with internal conversion (IC)



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

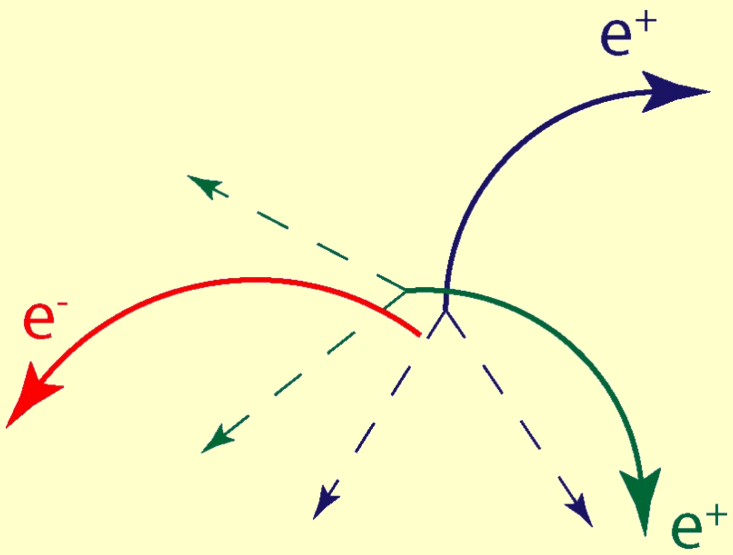


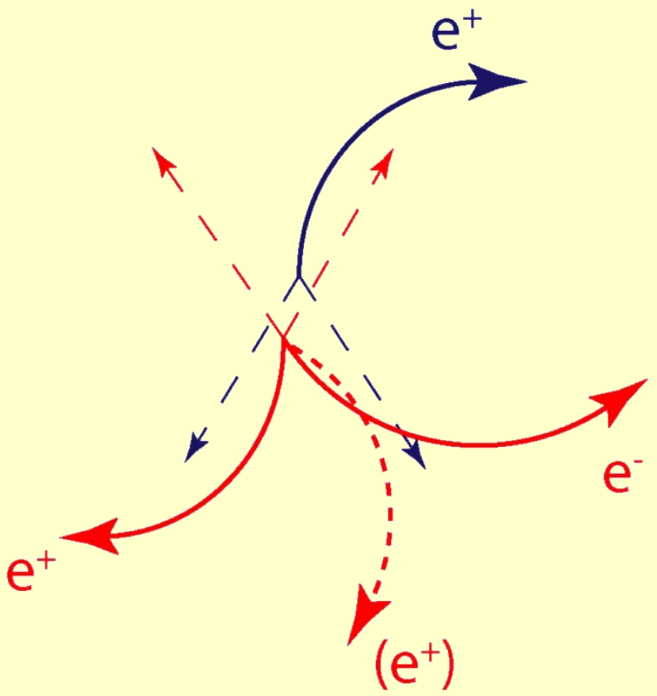


very good momentum +
total energy resolution required!

Accidental Backgrounds

- **Overlays** of two ordinary **μ^+ decays** with a (fake) **electron (e^-)**
- Electrons from: **Bhabha** scattering, photon conversion, mis-reconstruction

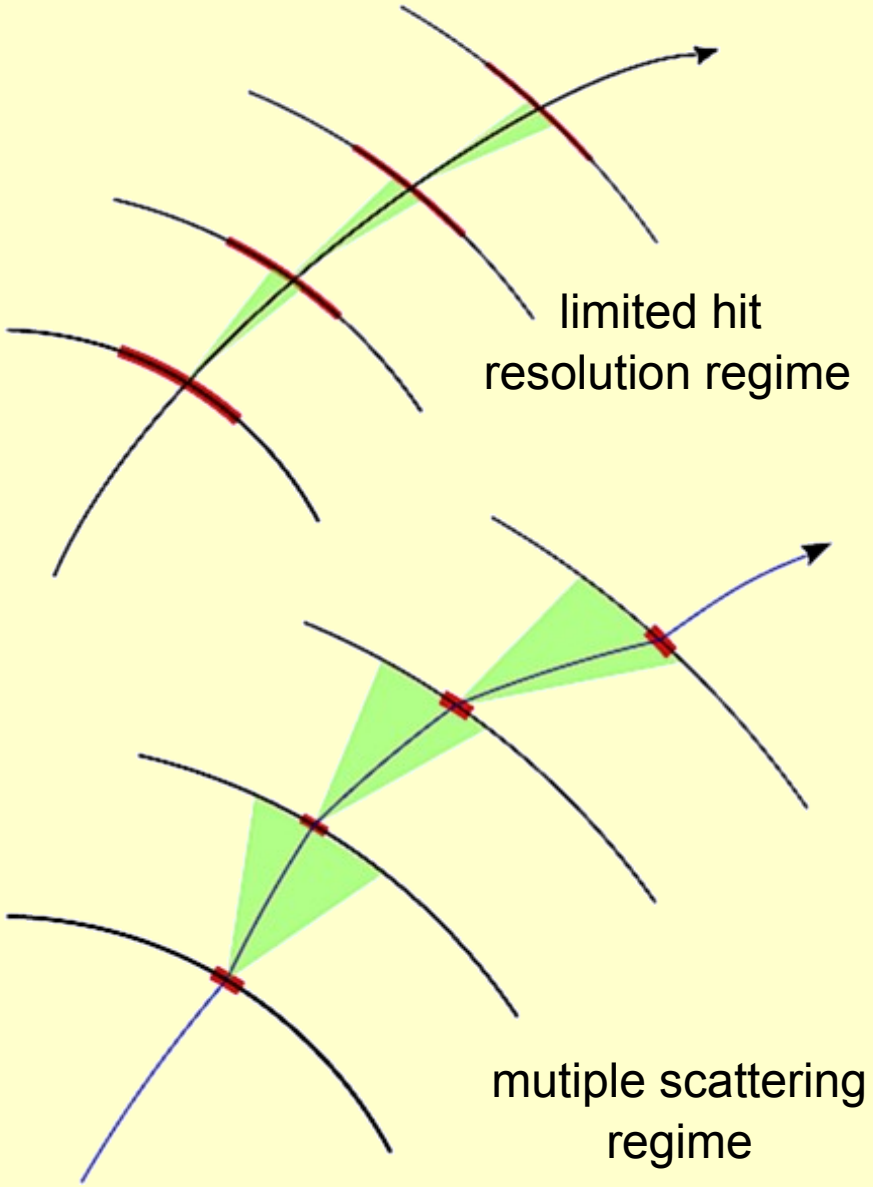




Detector requirements:

- **Vertex resolution**
- **Timing resolution**
- **Kinematic reconstruction**

Tracking Resolution + Multiple Scattering



- Muon decay (m=105.6 MeV):

  → electrons in low momentum range

  p < 53 MeV/c

- Multiple scattering is dominant!

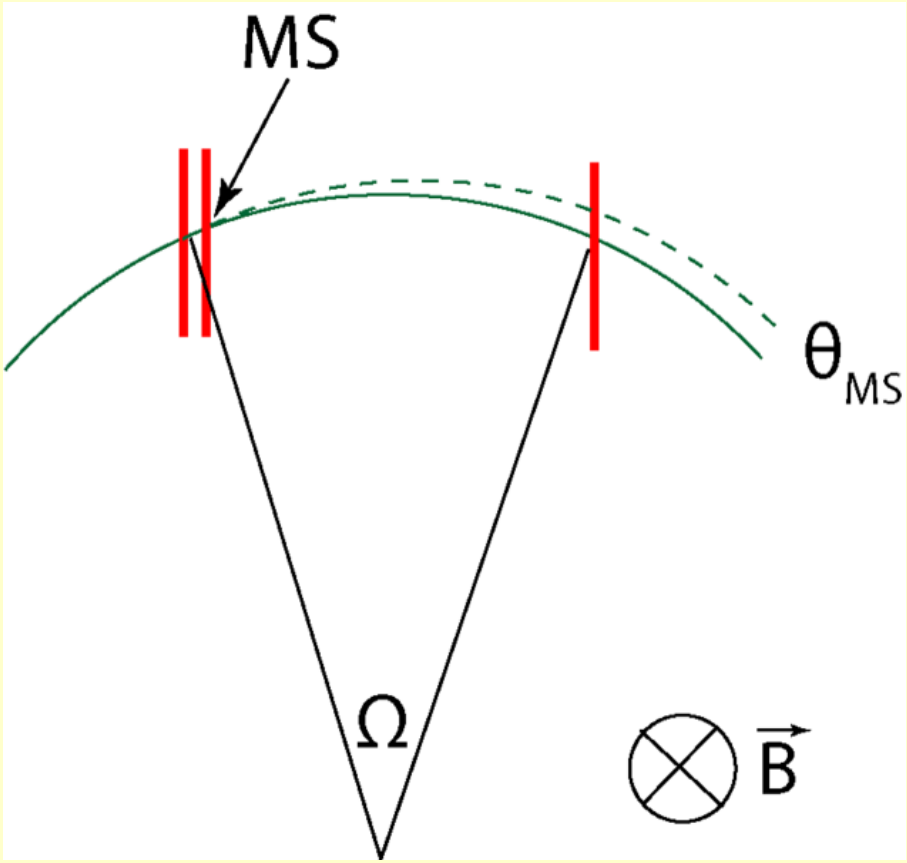
→ **Need thin, fast and high resolution tracking detectors operated at high rate (>10^9 particles/s @ phase II)**

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

Mu3e Design Concept

Momentum Resolution in MS Regime

- Standard spectrometer:



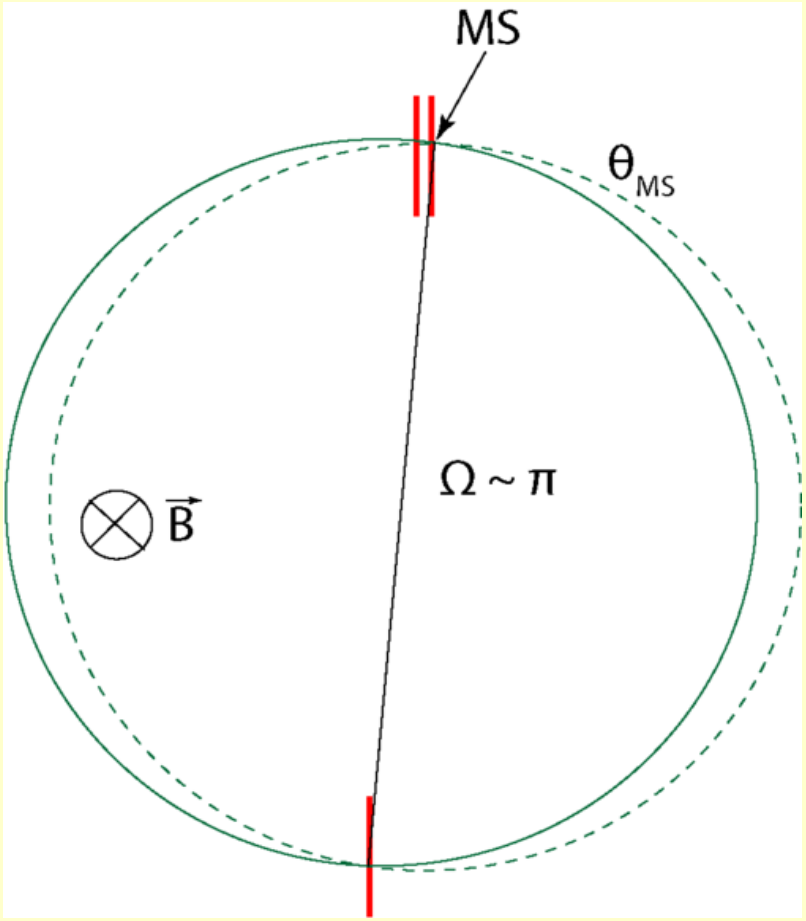
$$\frac{\sigma_p}{P} \sim \frac{\Theta_{MS}}{\Omega}$$ (linearised)

precision requires large lever arm

large bending angle Ω

Momentum Resolution in MS Regime

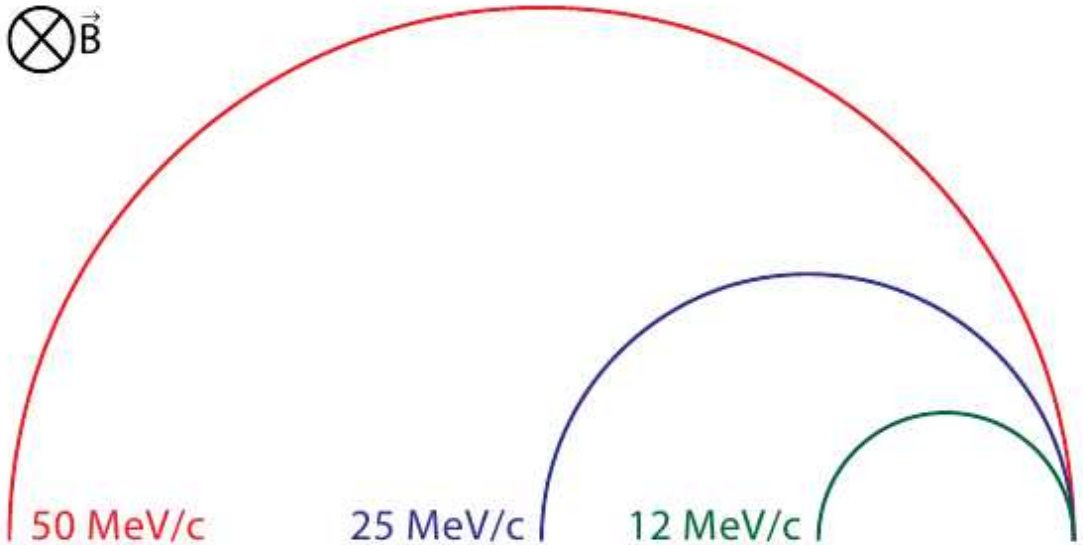
- "Half turn" spectrometer:



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

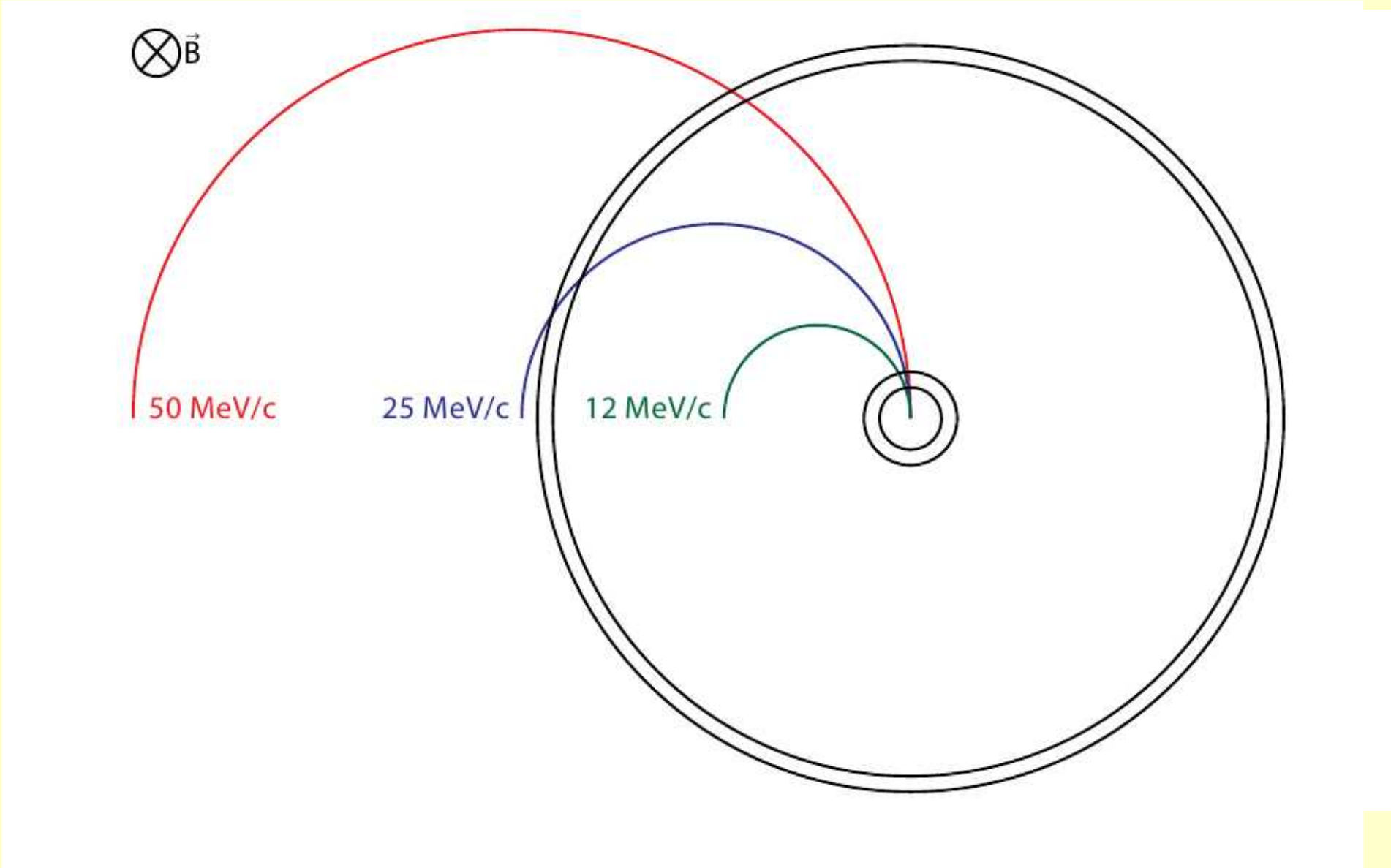
- **best precision for half turn tracks**
- **measure recurlers**

Tracking Design Considerations

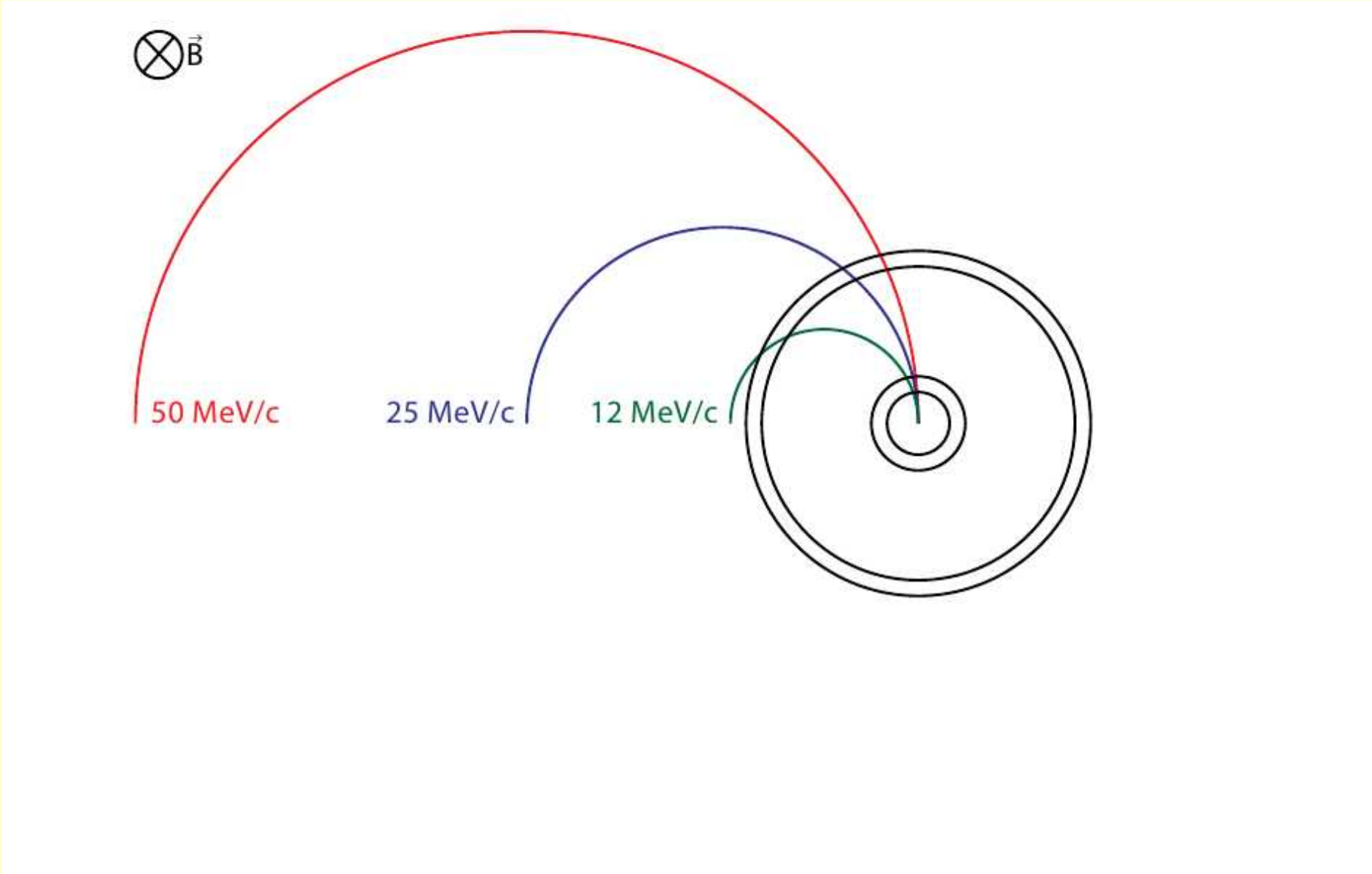


muon mass ~ 105 MeV/c^2

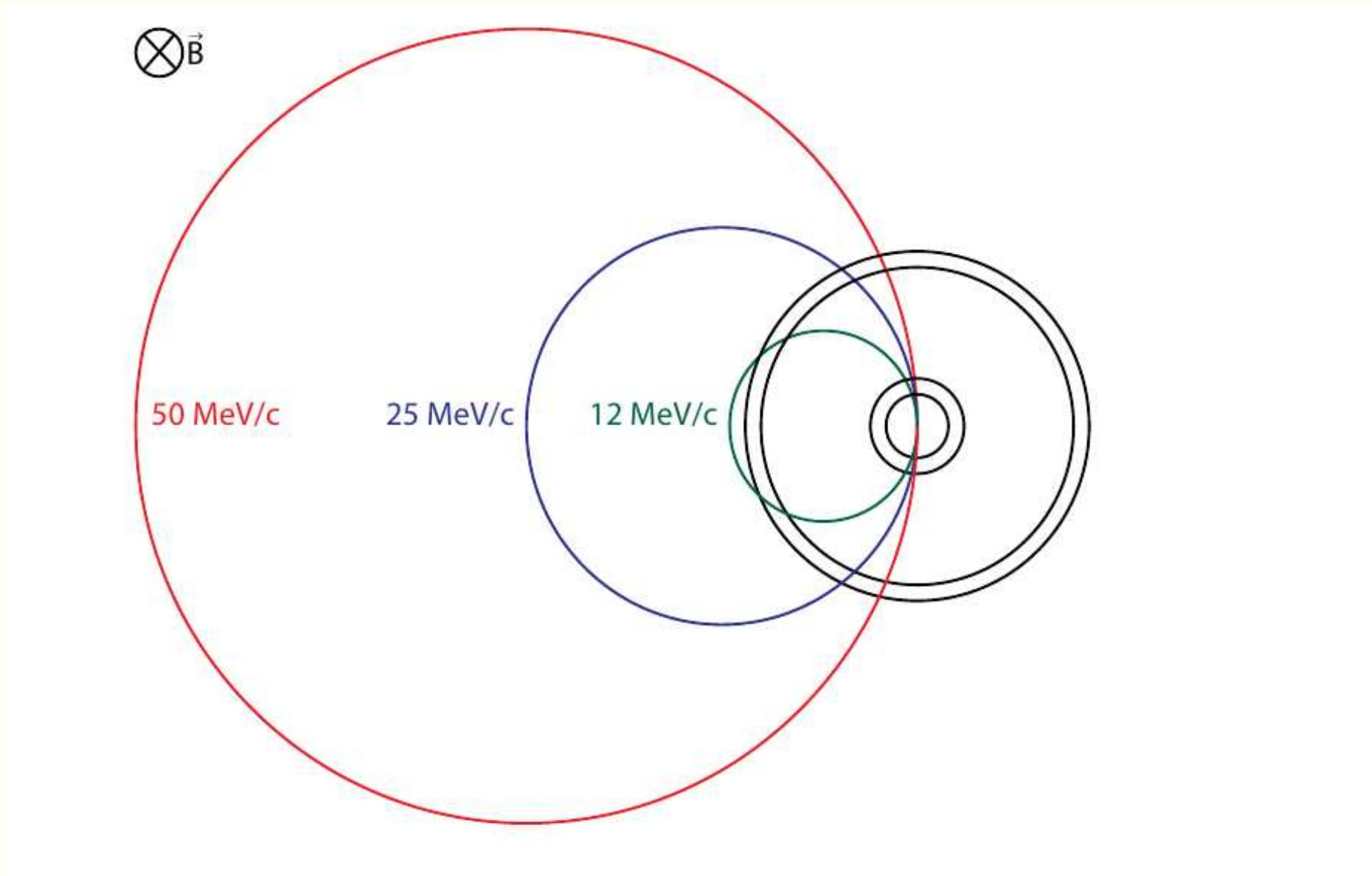
Tracking Design Considerations



Tracking Design Considerations



Tracking Design Considerations

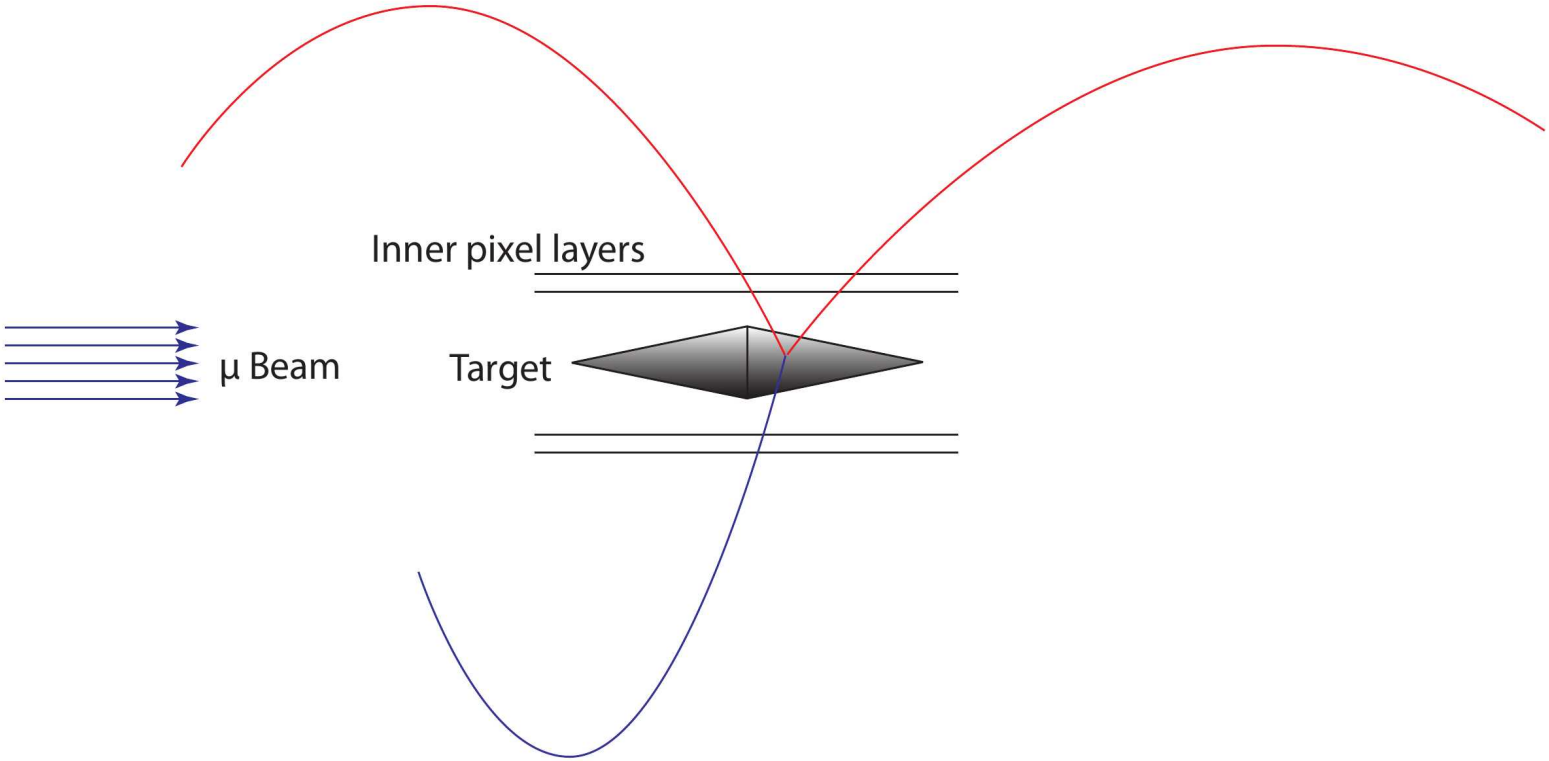


Mu3e Baseline Design

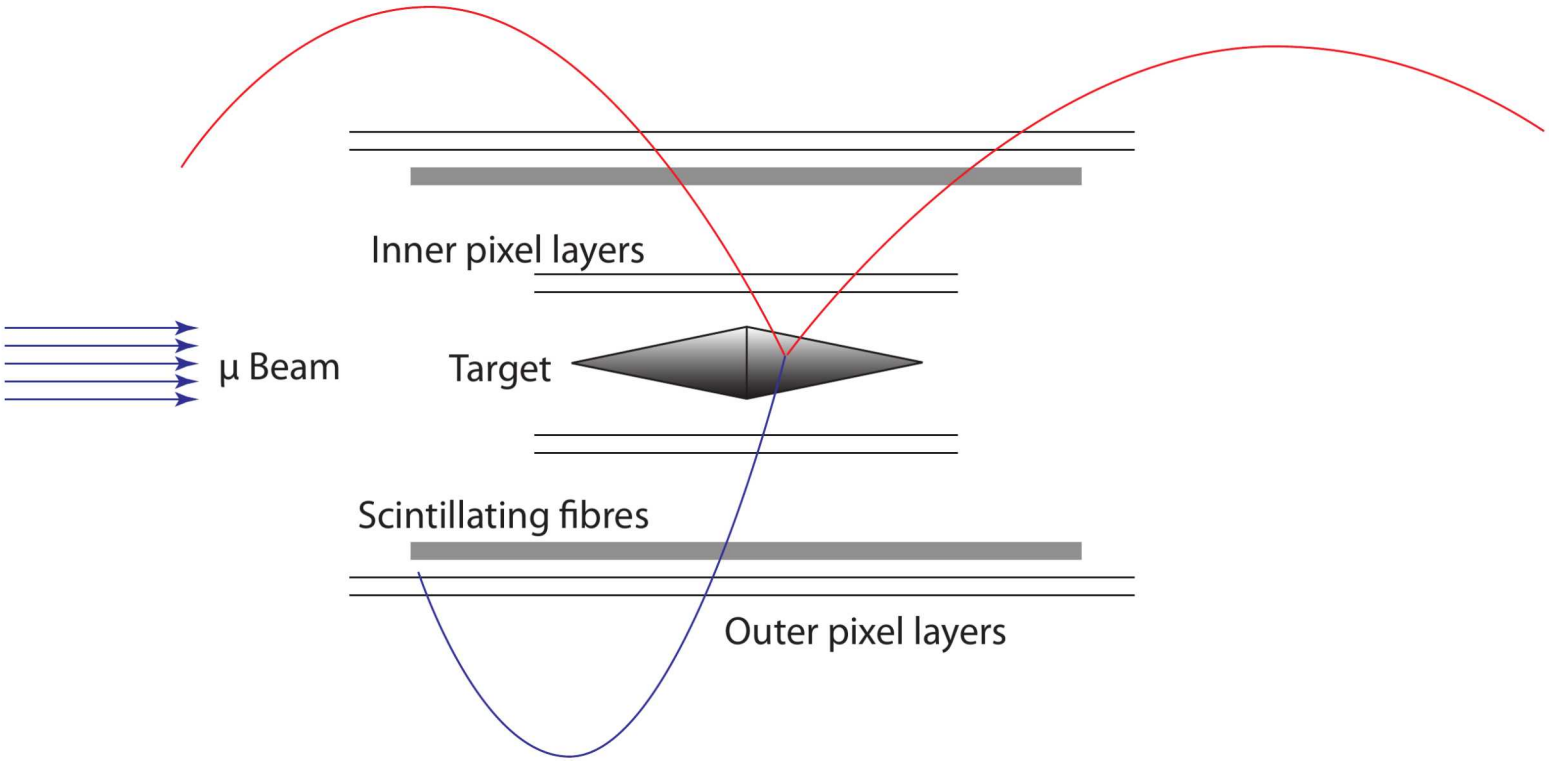
10^8 muons per second (phase I)

p=28 MeV/c

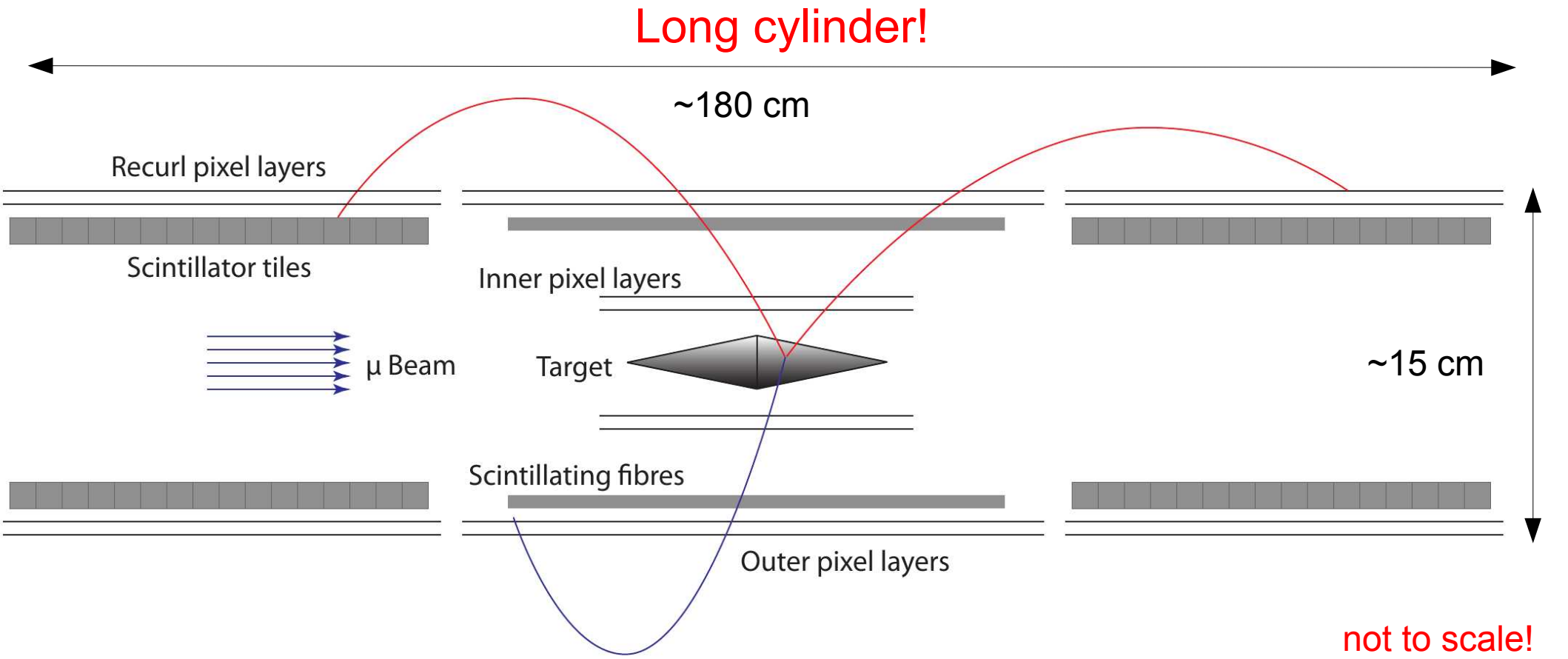
Mu3e Baseline Design



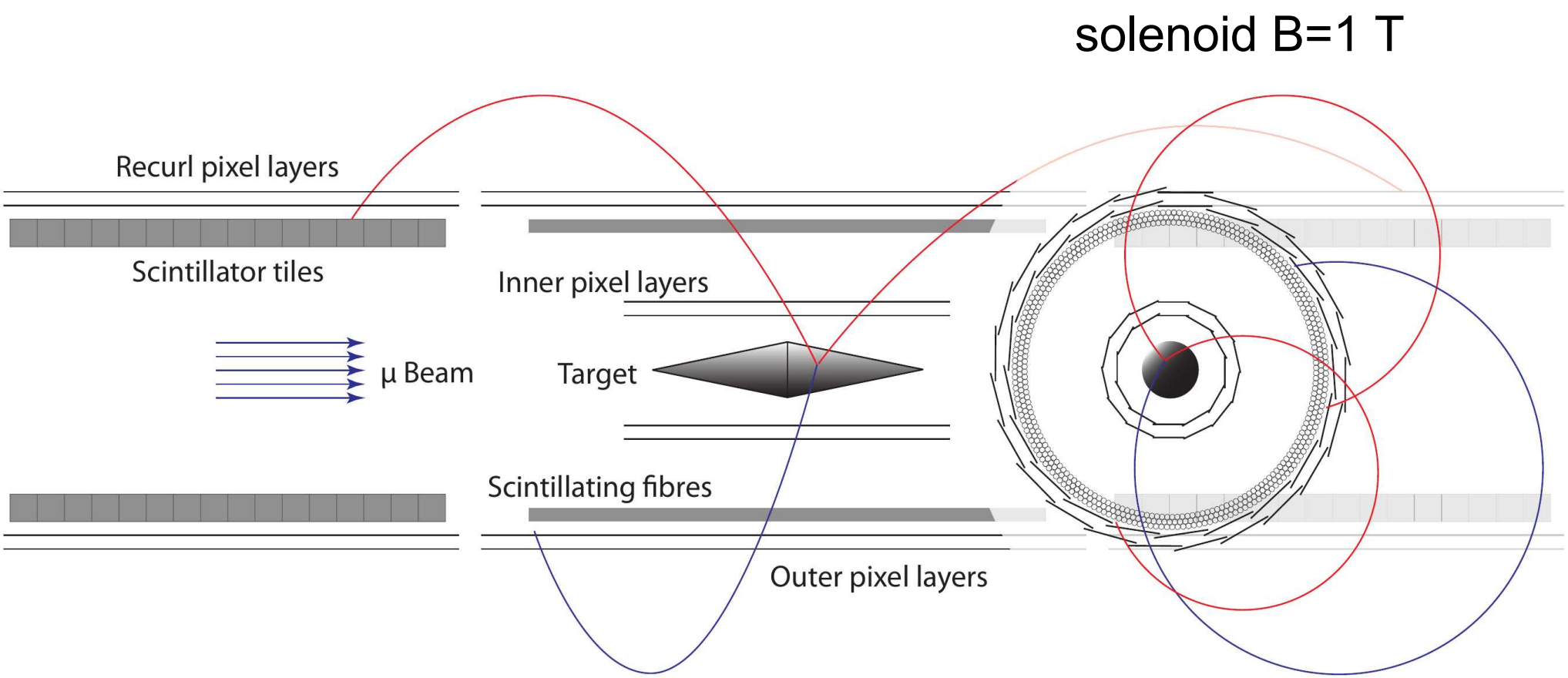
Mu3e Baseline Design



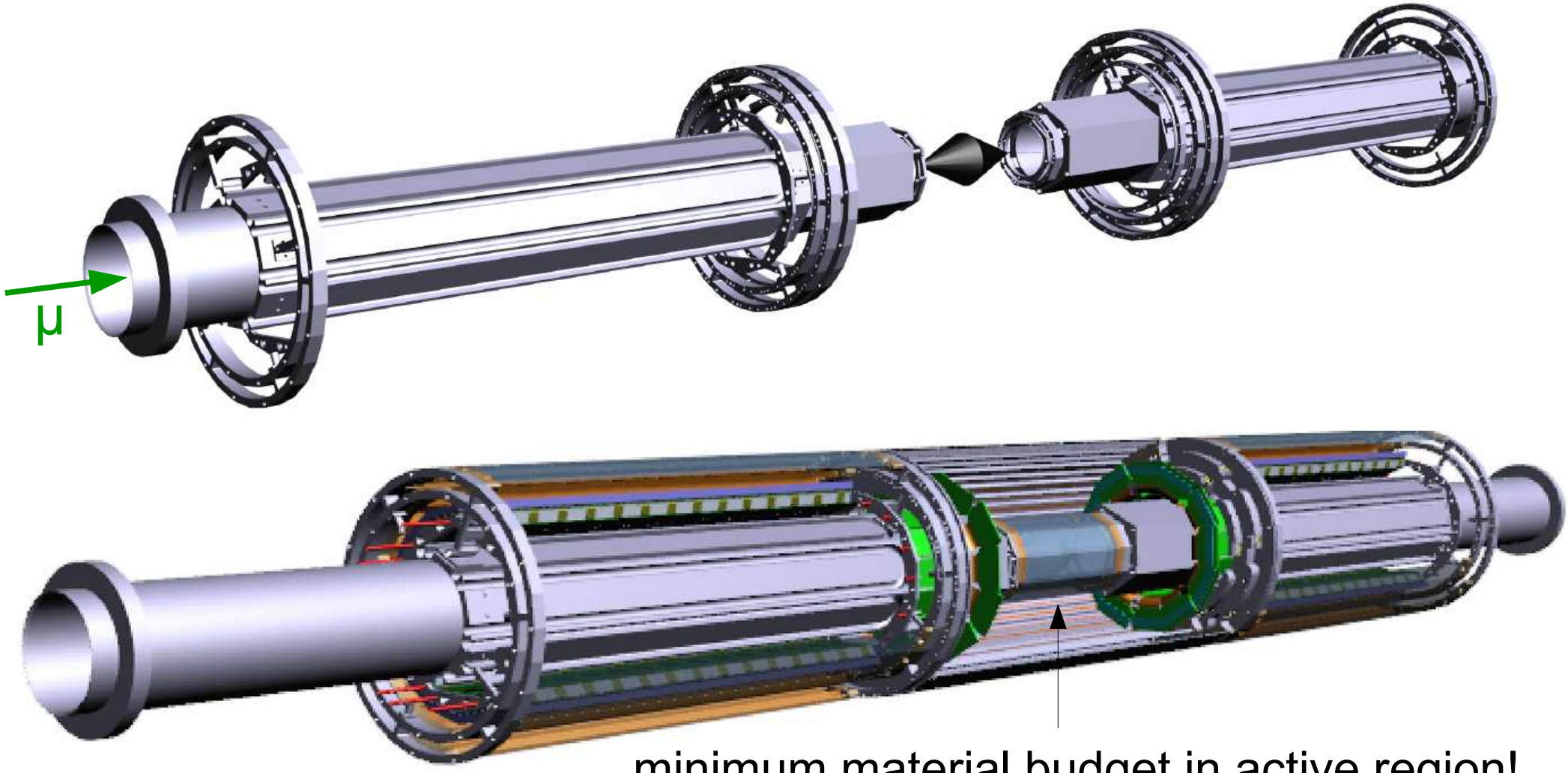
Mu3e Baseline Design



Mu3e Baseline Design



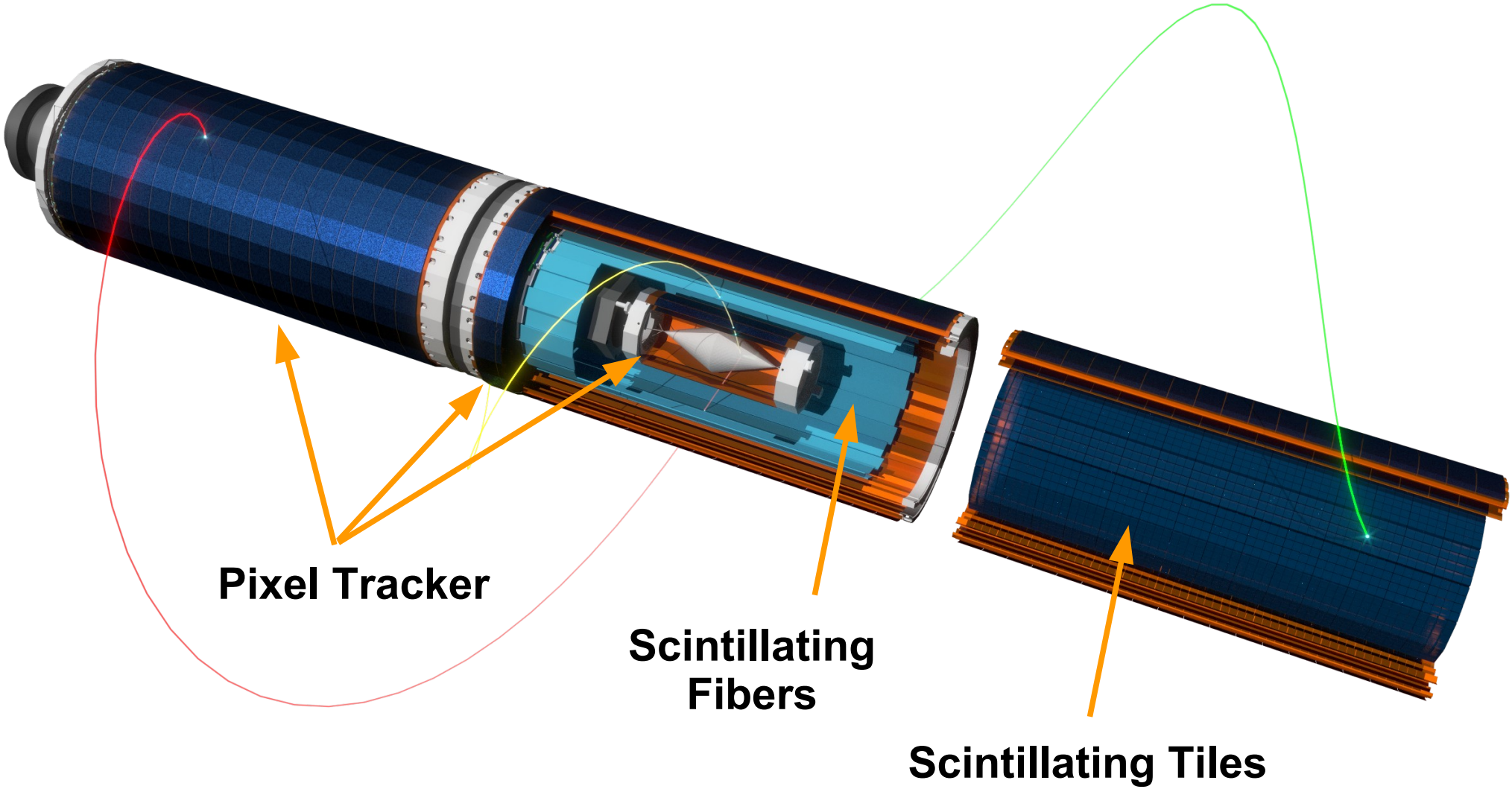
Mu3e CAD Drawings



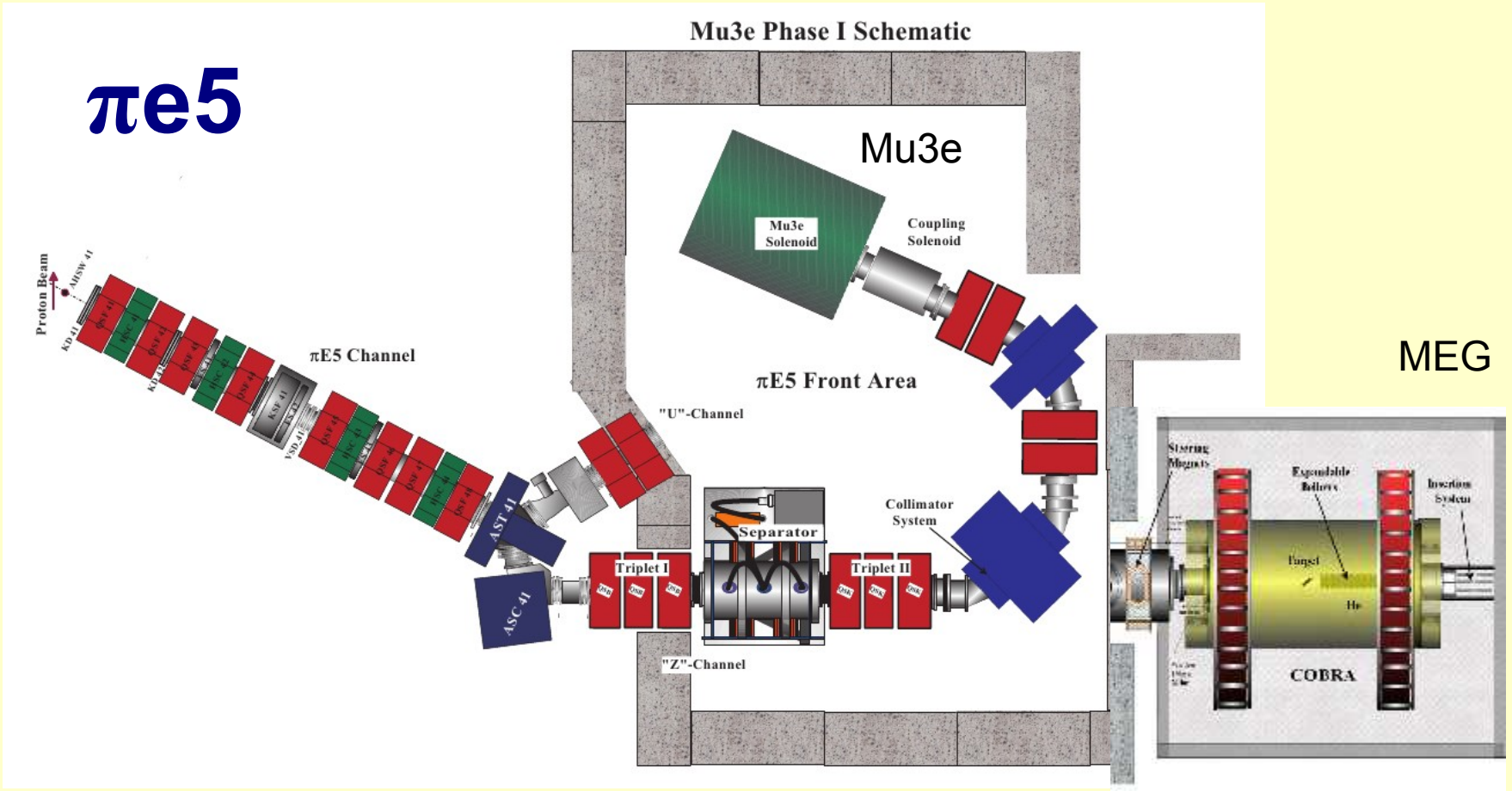
minimum material budget in active region!

multiple scattering is the enemy!

Mu3e Detector



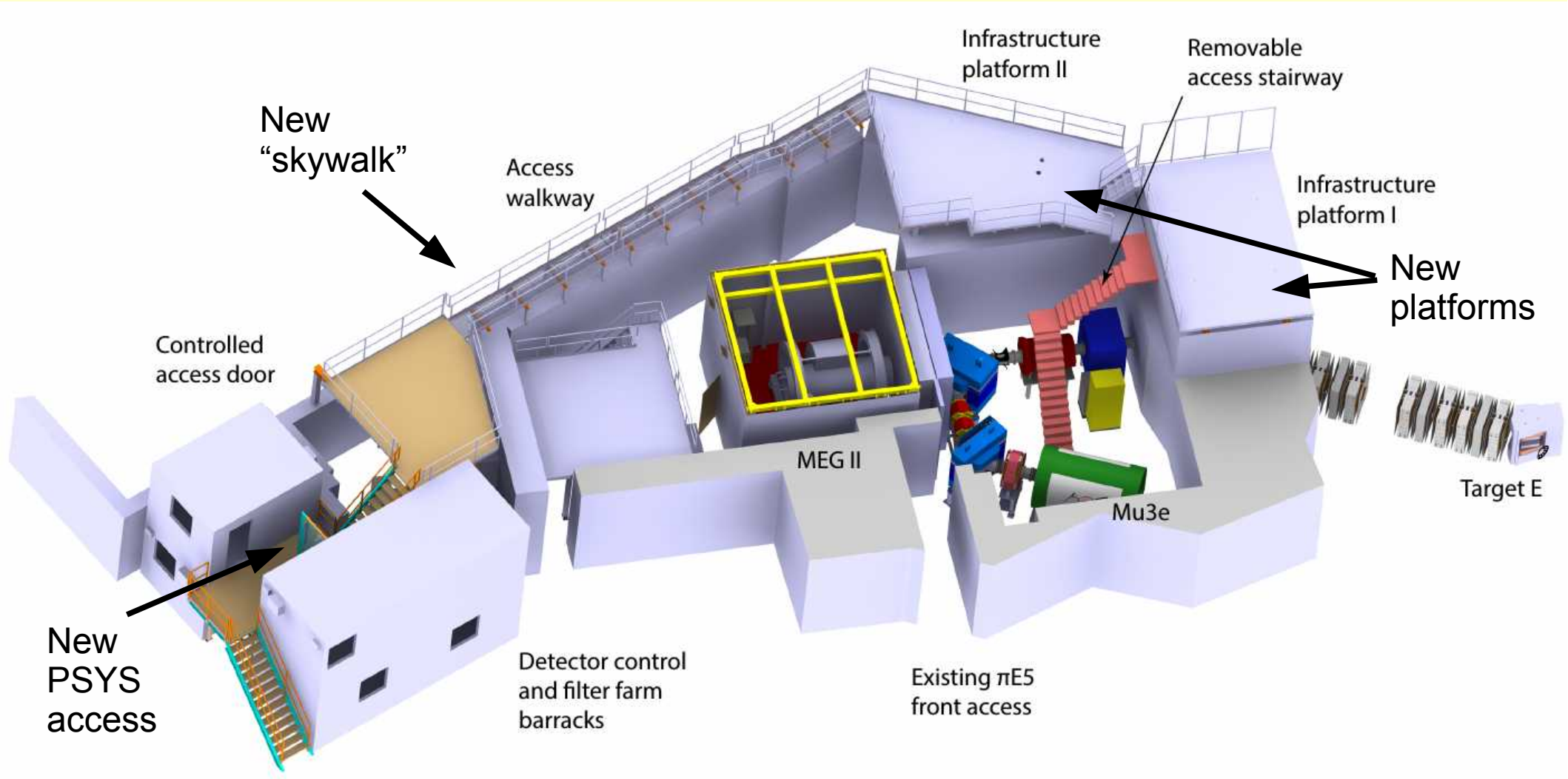
Compact Muon Beamline (Phase I)



- muon rates of up to **$8.4 \cdot 10^7$/s** at **solenoid entrance** achieved in 2016
- further optimizations might be possible
- aiming for: → **10^8/s muons on target**

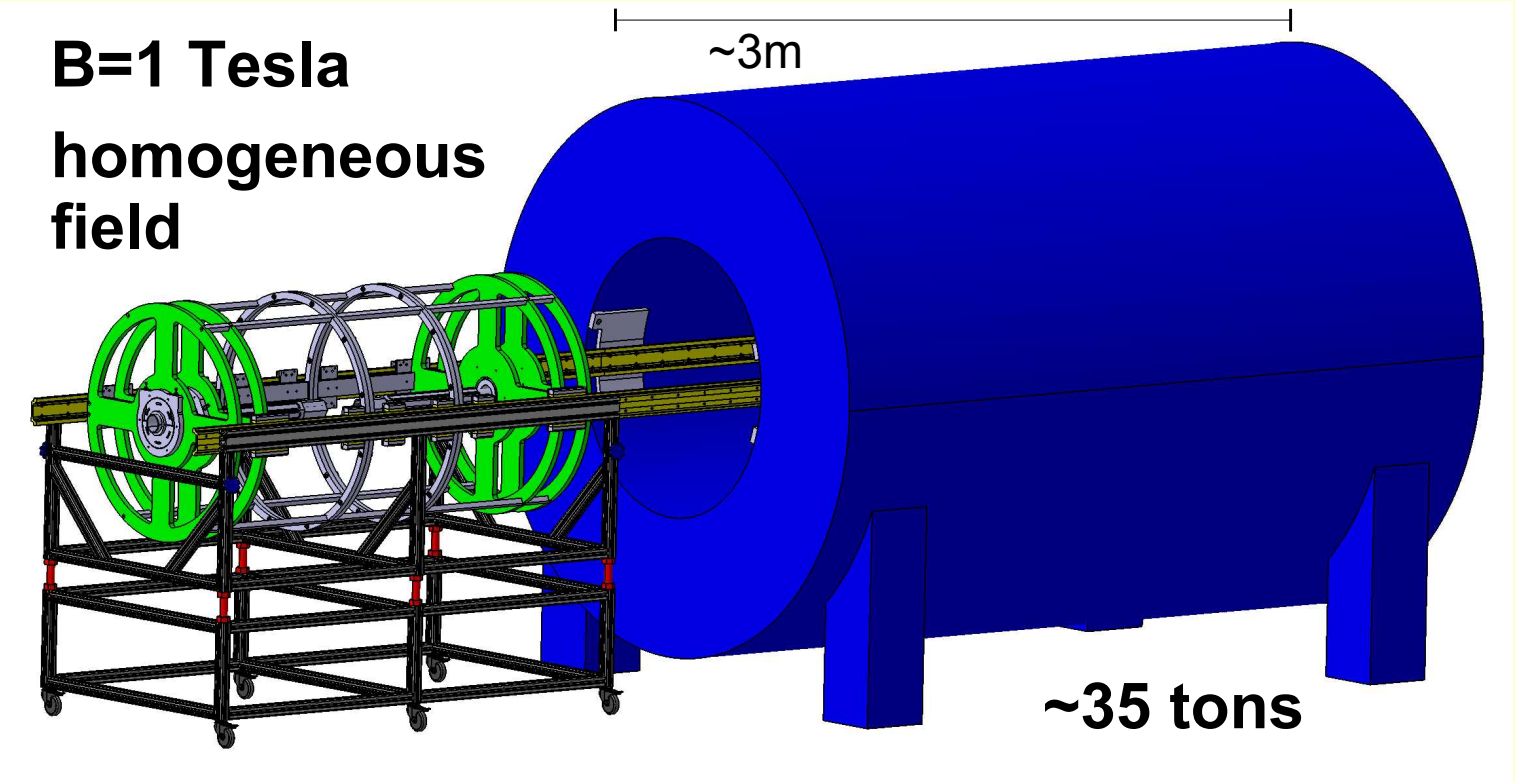
Compact Muon Beamline (CMB)

The Mu3e (MEG) PiE5 Area



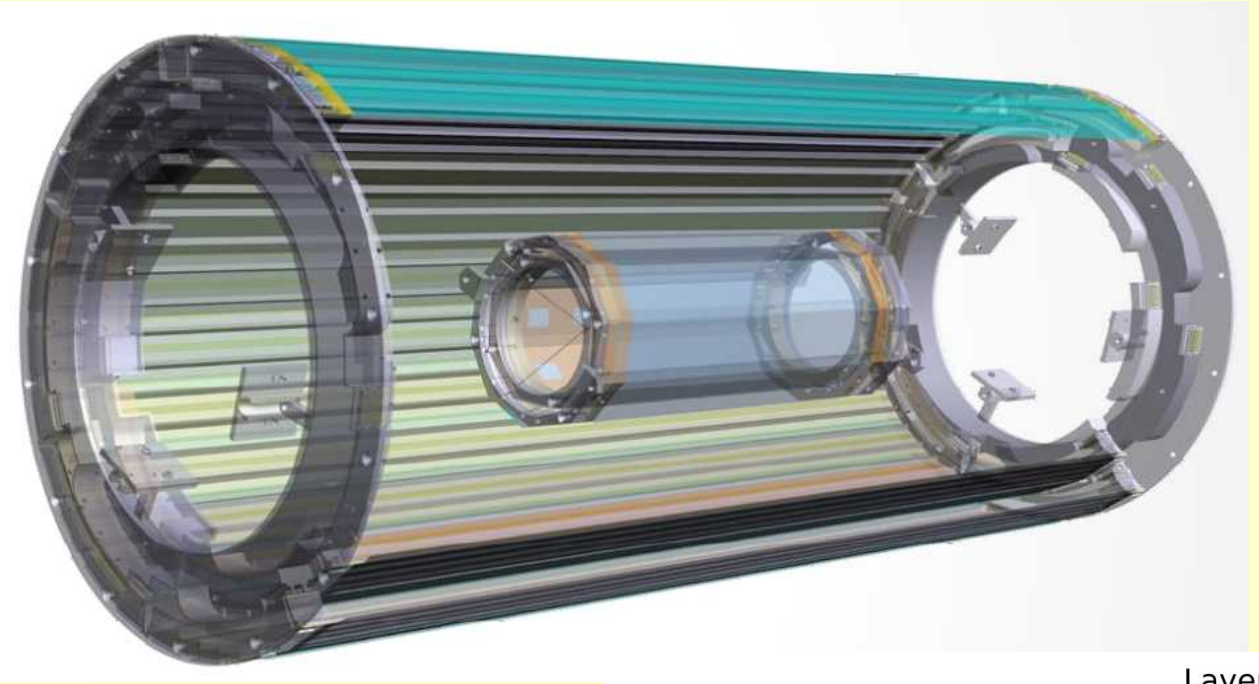
Area Proposal

Mu3e Magnet

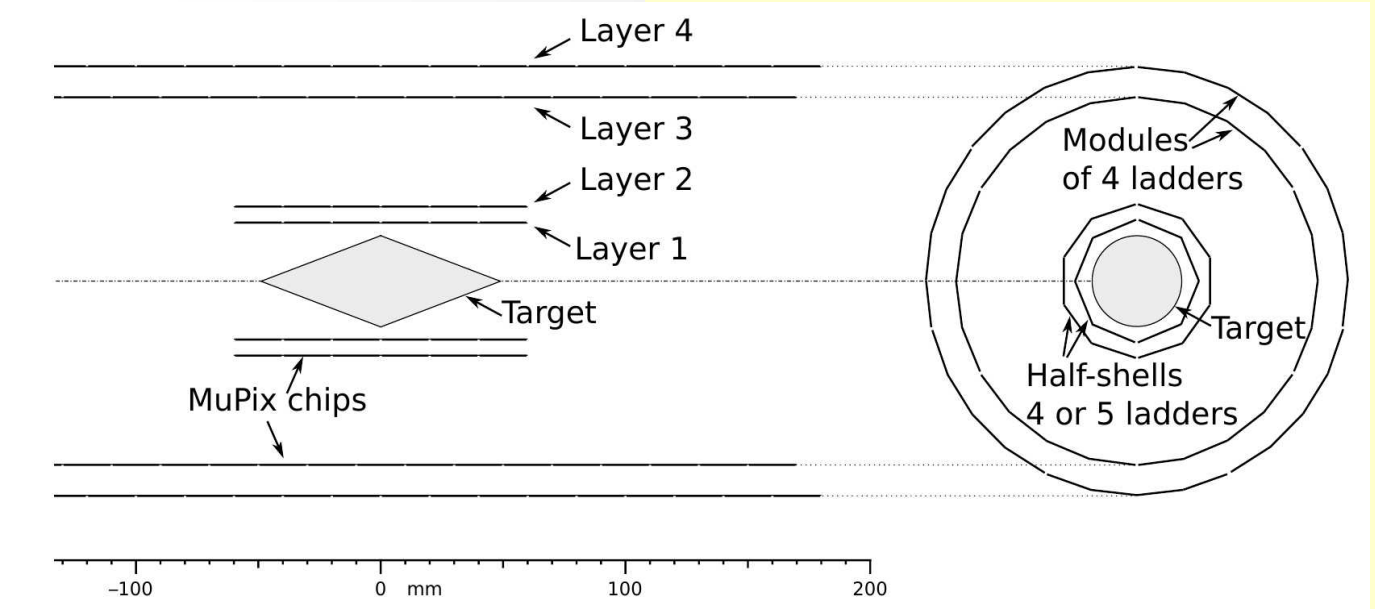


Magnet (up to 2.6T) expected beginning of 2019

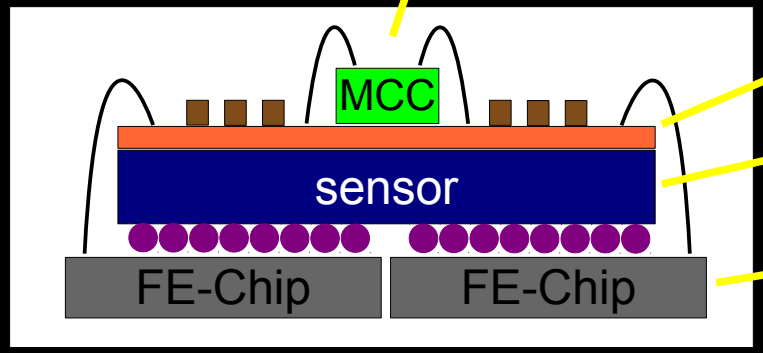
Pixel Tracker



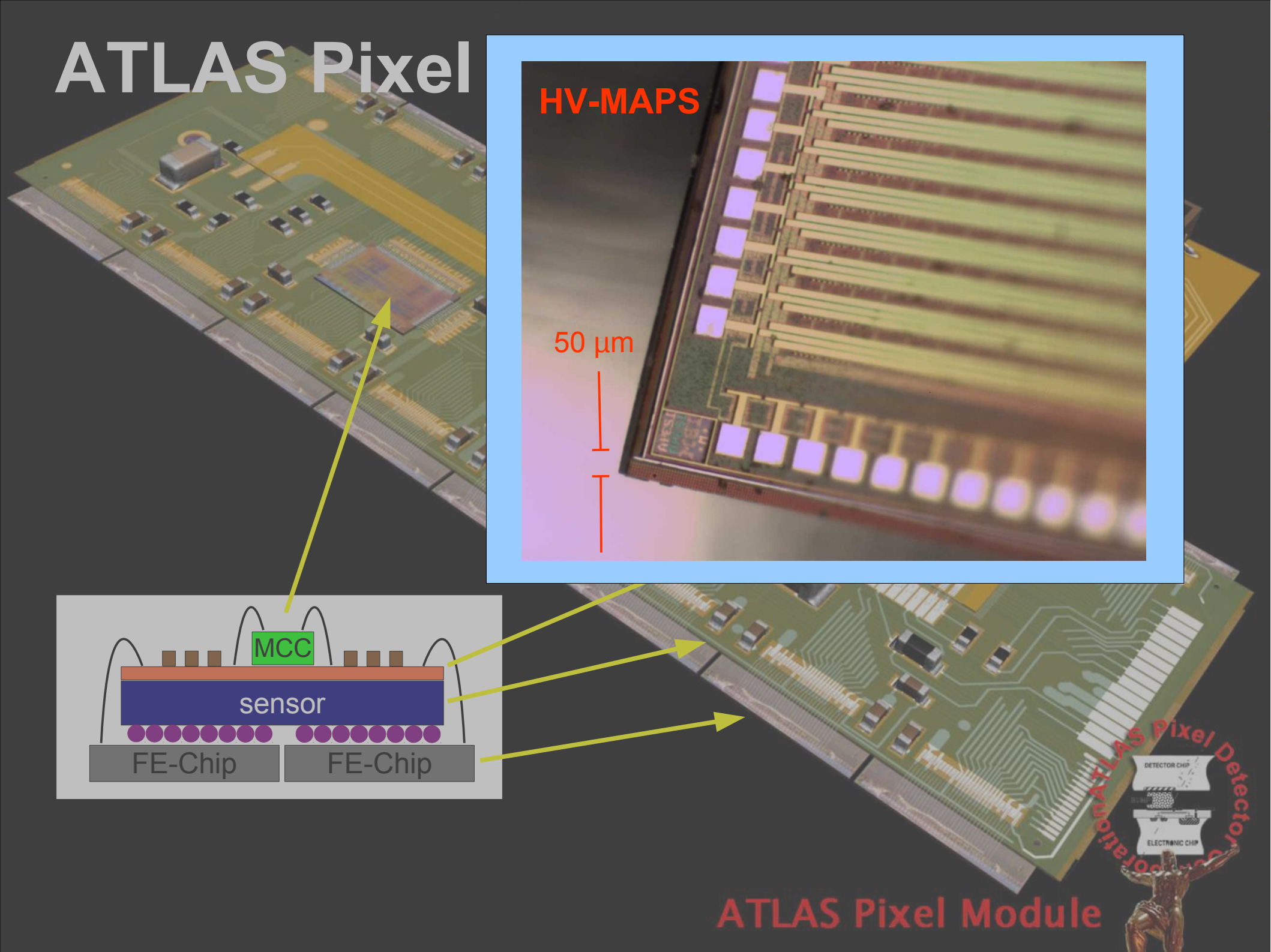
TRACKING LAYERS
MUST BE THIN!



ATLAS Pixel Module

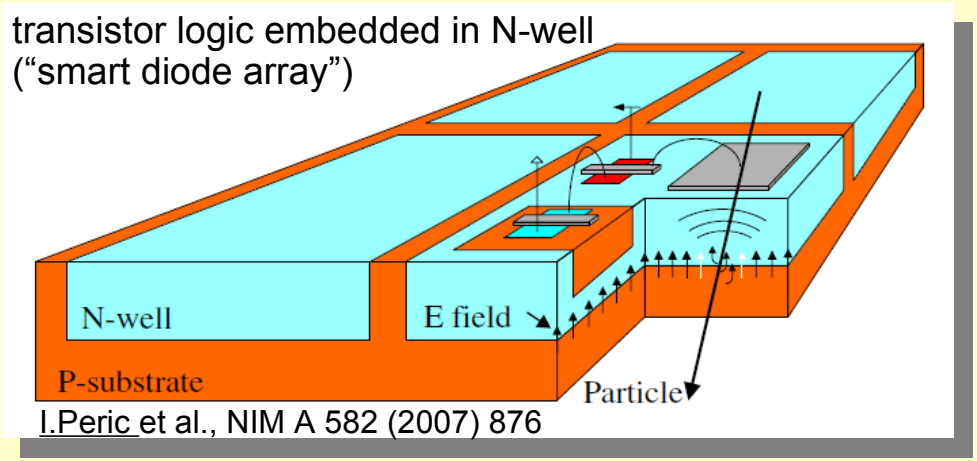


ATLAS Pixel



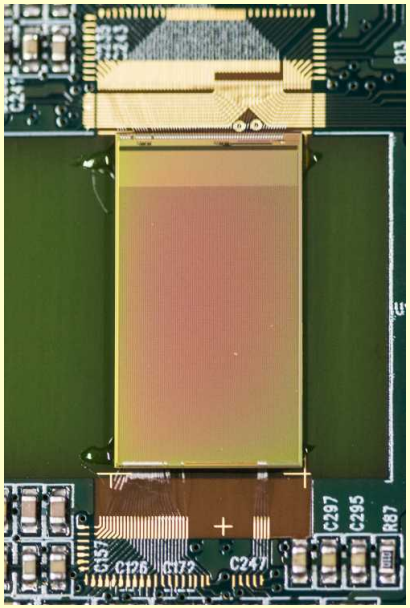
Pixel Detector Technology

High Voltage-Monolithic Active Pixel Sensor (HV-MAPS)



- **active sensors**
  → hit finding + digitisation + readout
- HV-CMOS: 60-85 V
- low cost process (Austria-Micro-Systems)
- "thinned" to ~**50 µm** (~ 0.0005 X_0)

MuPix8 prototype

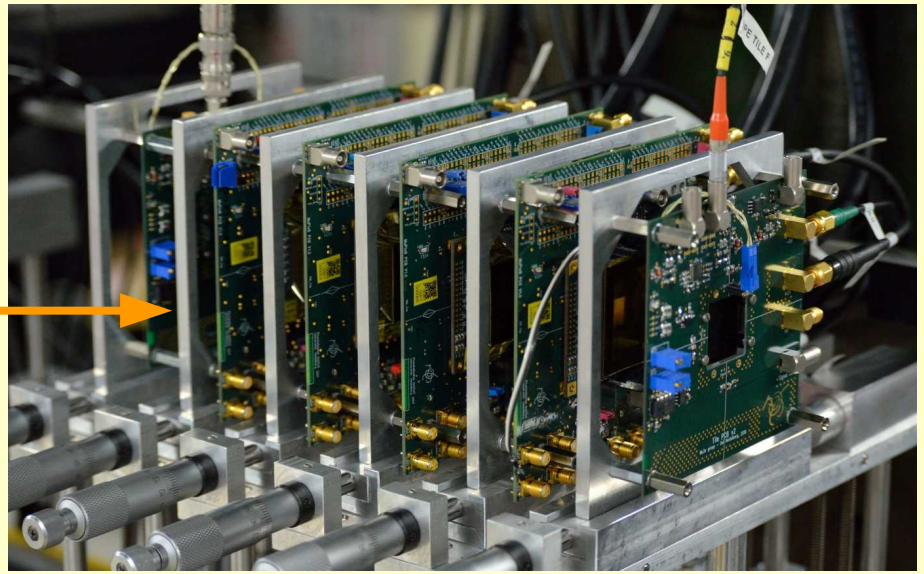


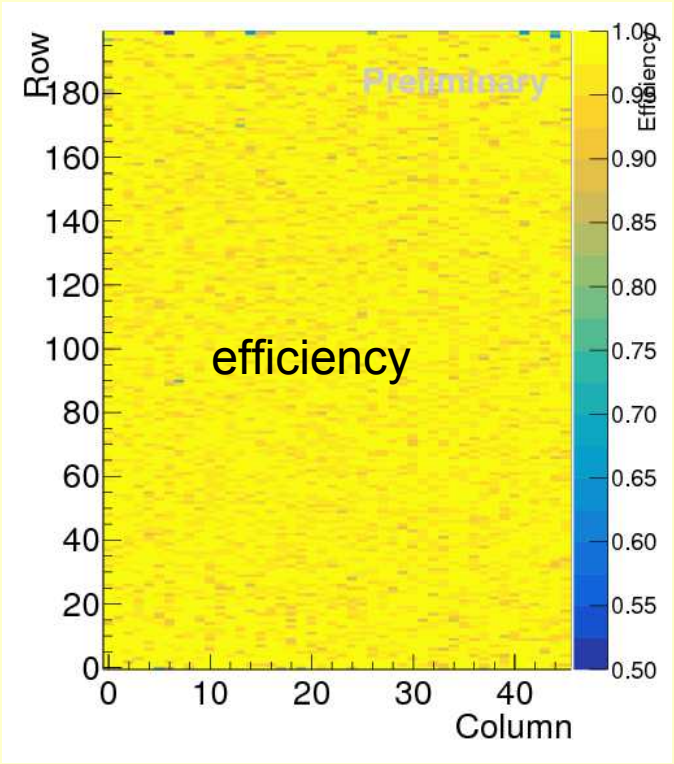
MuPix has been fully characterized in the lab and in several test beams

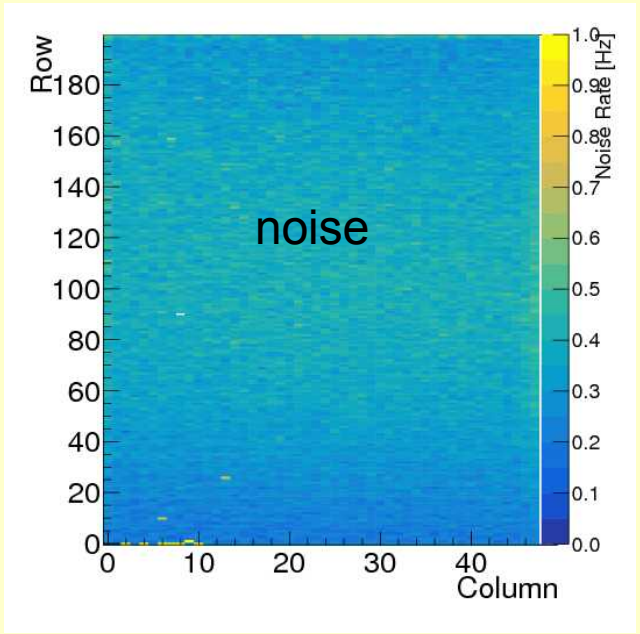
- efficiency
- noise
- rate
- (radiation hardness)
- temperature-dependence

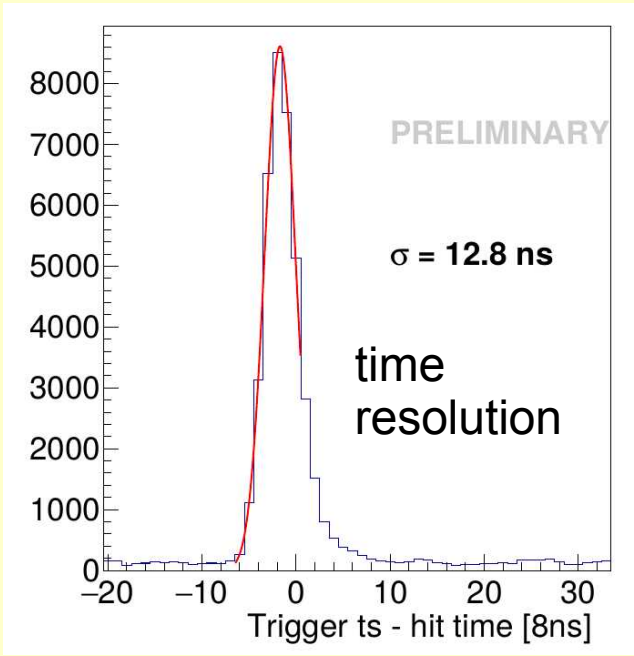
Recent Mupix8 Performance Plots

- Mupix8 delivered end of August
- test beams ad DESY x2, CERN
- Mupix 8 beam telescope (4 layers)

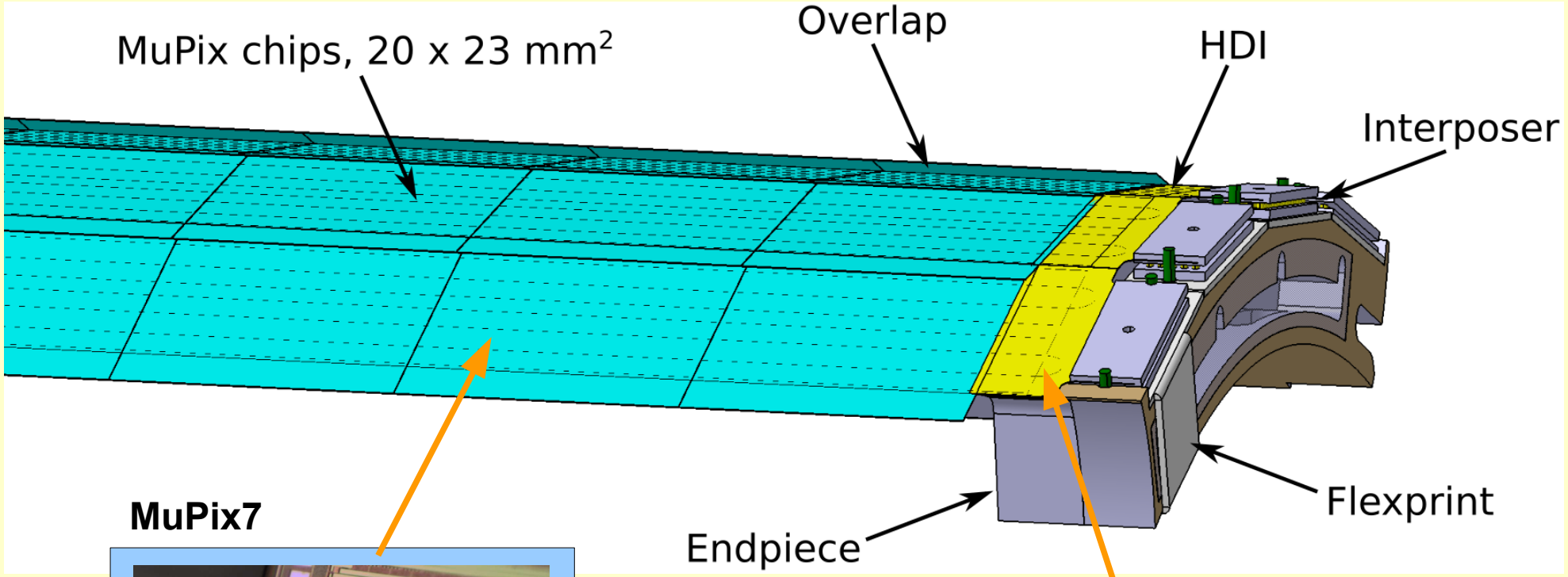




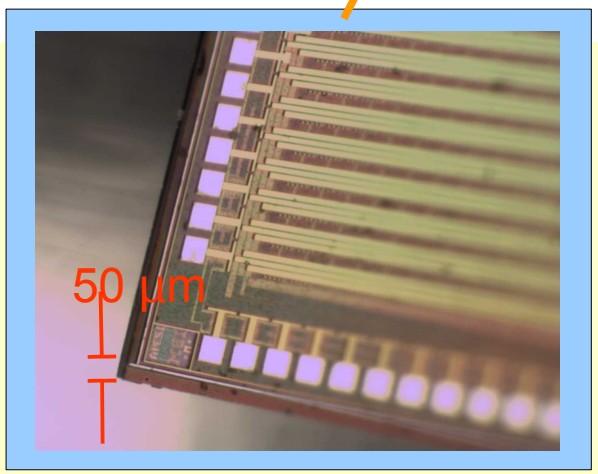




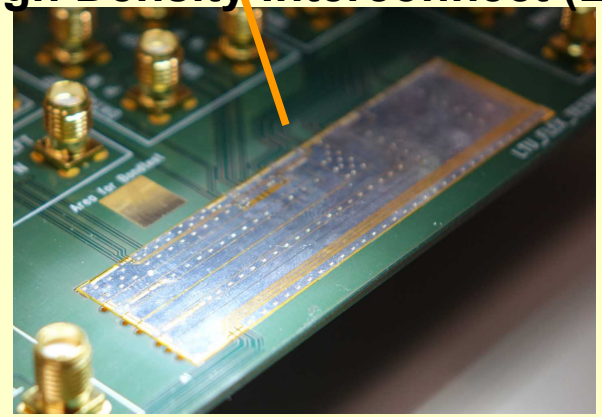
(Outer) Pixel Tracker Module



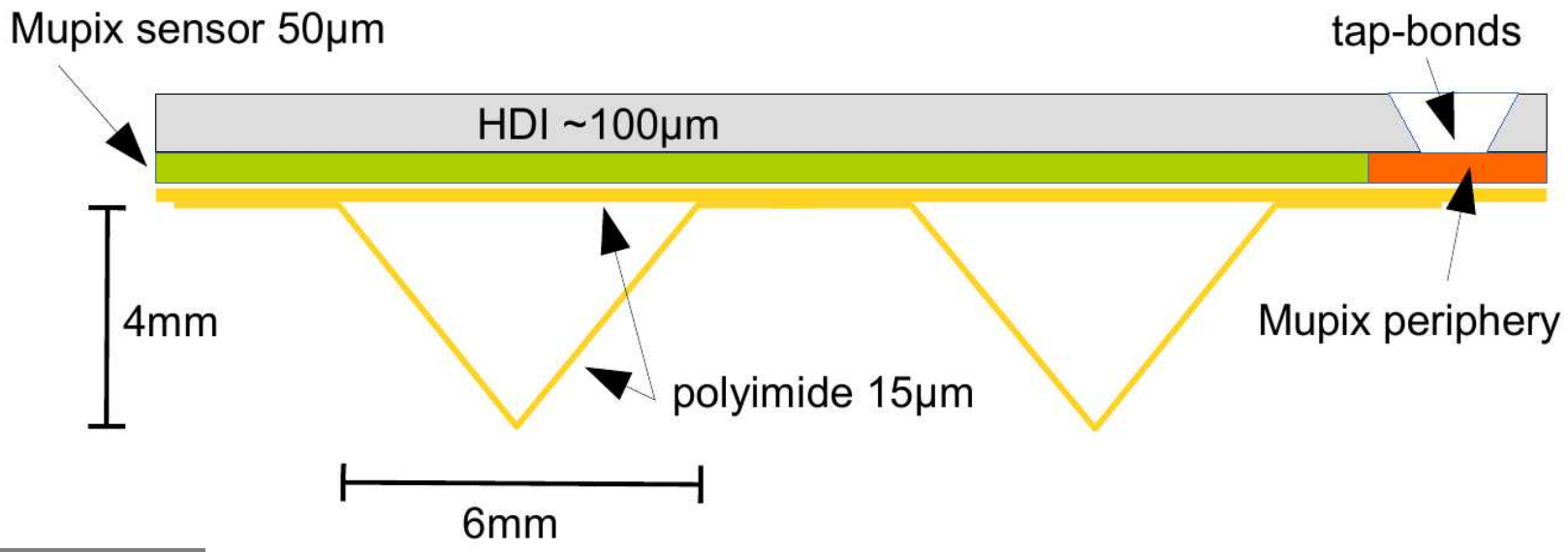
MuPix7



High Density Interconnect (LTU)



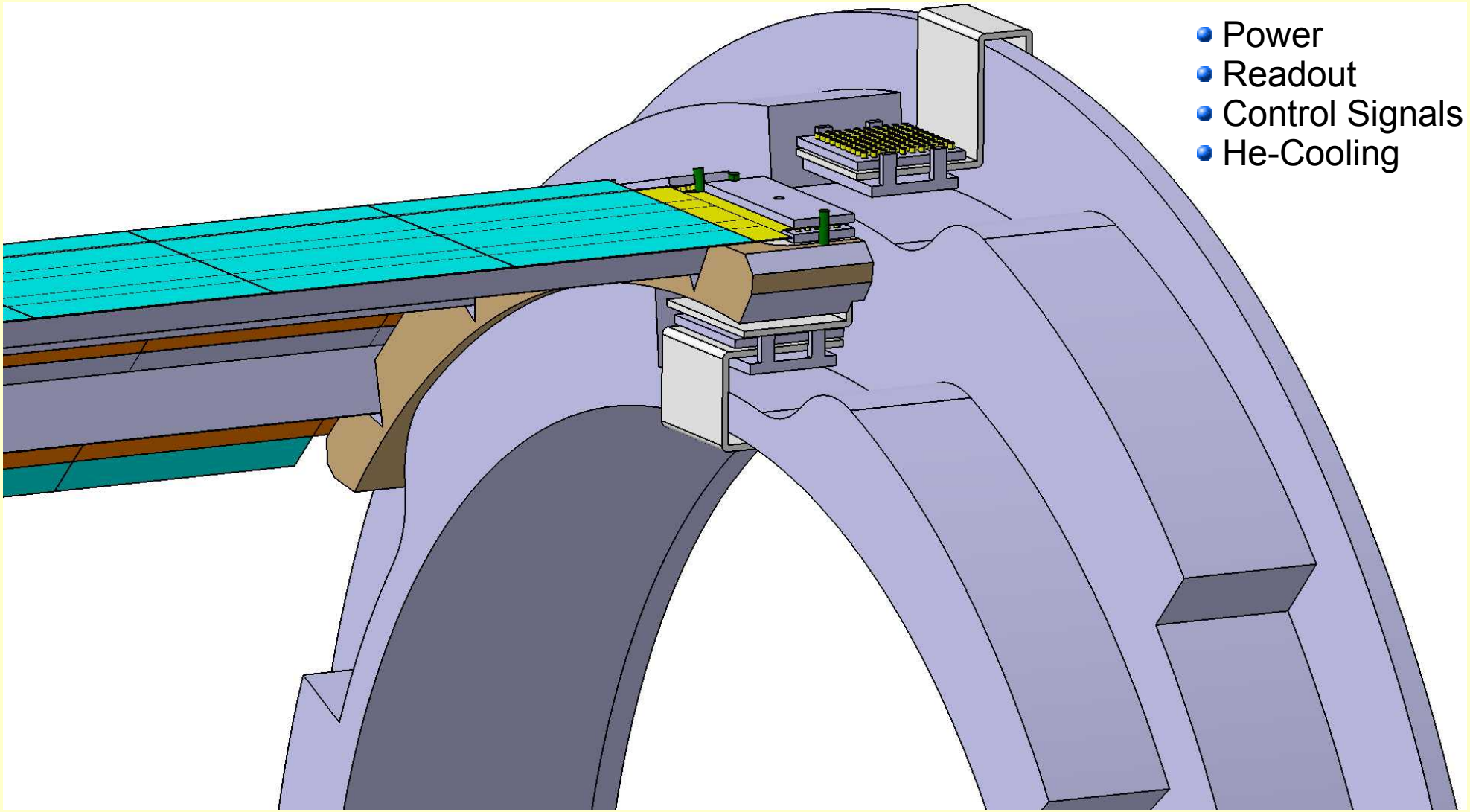
Ultralight Pixel Ladder



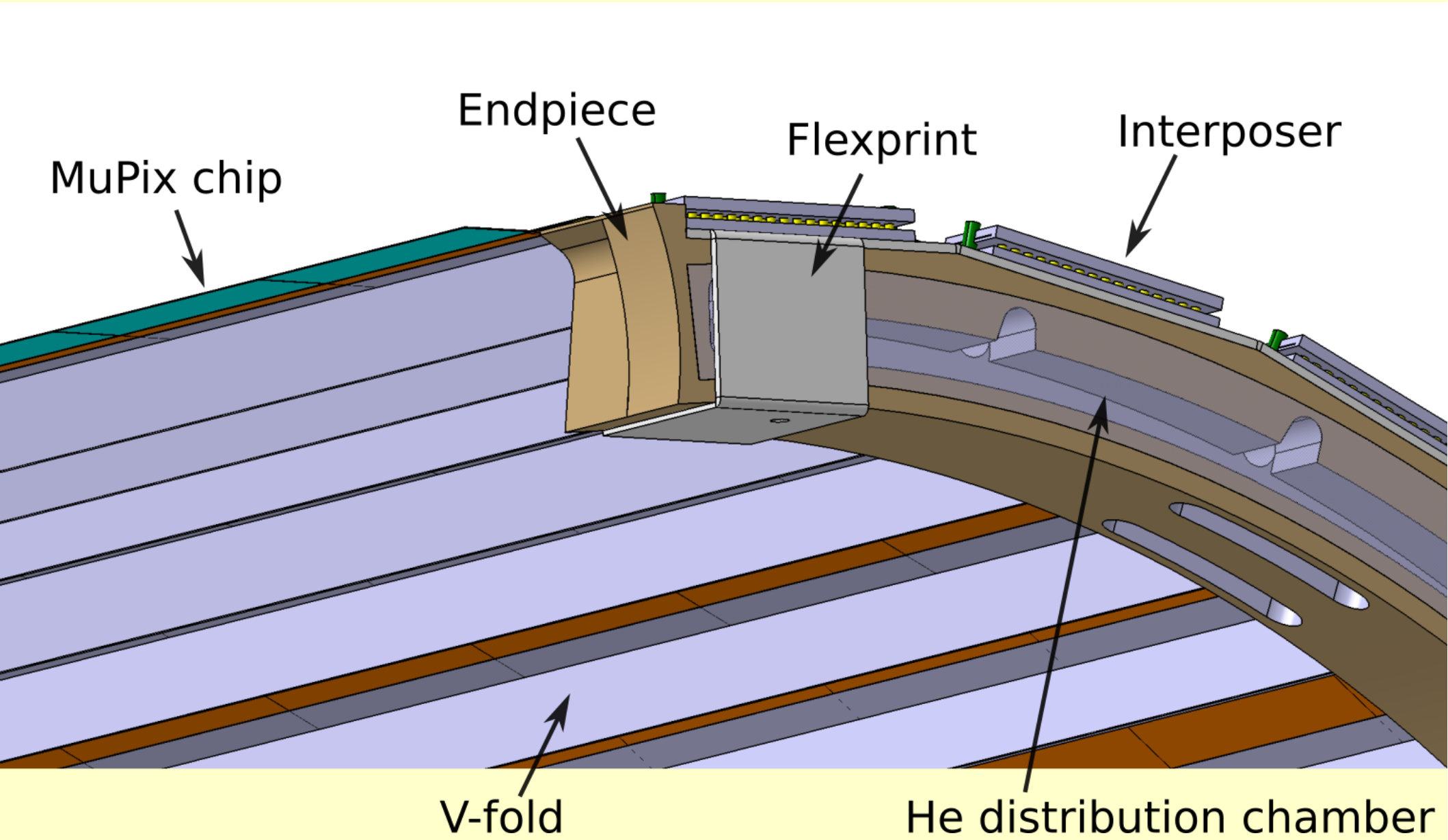
	Layer 1-2		Layer 3-4	
	thickness [µm]	X/X_0	thickness [µm]	X/X_0
MuPix Si	45	$0.48 \cdot 10^{-3}$	45	$0.48 \cdot 10^{-3}$
MuPix Al	5	$0.06 \cdot 10^{-3}$	5	$0.06 \cdot 10^{-3}$
HDI polyimide & glue	45	$0.18 \cdot 10^{-3}$	45	$0.18 \cdot 10^{-3}$
HDI Al	28	$0.31 \cdot 10^{-3}$	28	$0.31 \cdot 10^{-3}$
polyimide support	25	$0.09 \cdot 10^{-3}$	≈ 30	$0.10 \cdot 10^{-3}$
adhesives	10	$0.03 \cdot 10^{-3}$	10	$0.03 \cdot 10^{-3}$
total	158	$1.15 \cdot 10^{-3}$	163	$1.16 \cdot 10^{-3}$

module: ~ 1 per mille radiation length

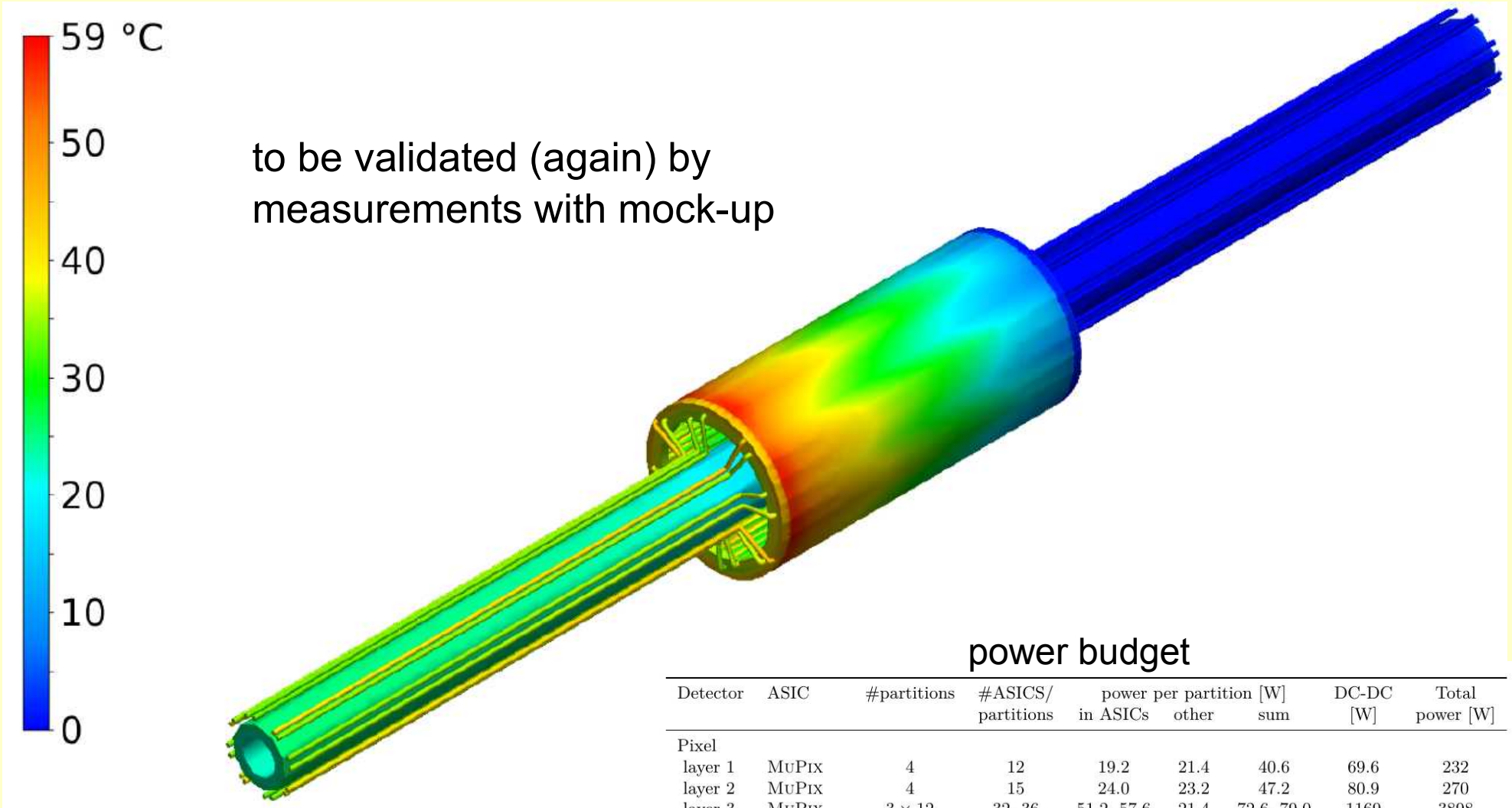
Pixel Tracker Endrings



V-Fold Cooling Channels



Simulation of Helium Cooling



to be validated (again) by measurements with mock-up

power budget

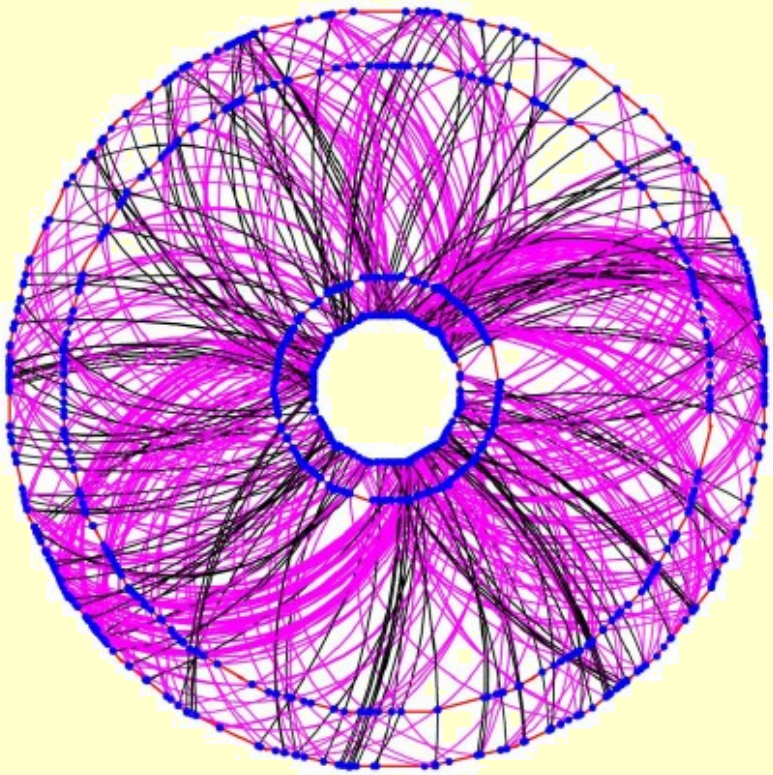
Detector	ASIC	#partitions	#ASICS/ partitions	power per partition [W] in ASICs	other	sum	DC-DC [W]	Total power [W]
Pixel								
layer 1	MuPix	4	12	19.2	21.4	40.6	69.6	232
layer 2	MuPix	4	15	24.0	23.2	47.2	80.9	270
layer 3	MuPix	3×12	32, 36	51.2, 57.6	21.4	72.6, 79.0	1169	3898
layer 4	MuPix	3×14	36	57.6	21.4	79.0	1422	4740
Fibre	MuTRiG	12	16	17.6	18.4	36.0	185.1	617
Tile	MuTRiG	14	14	15.4	18.4	33.8	202.8	676
Total		112						**10433**

Timing

Pileup

10^9 muon stops/second (phase II)

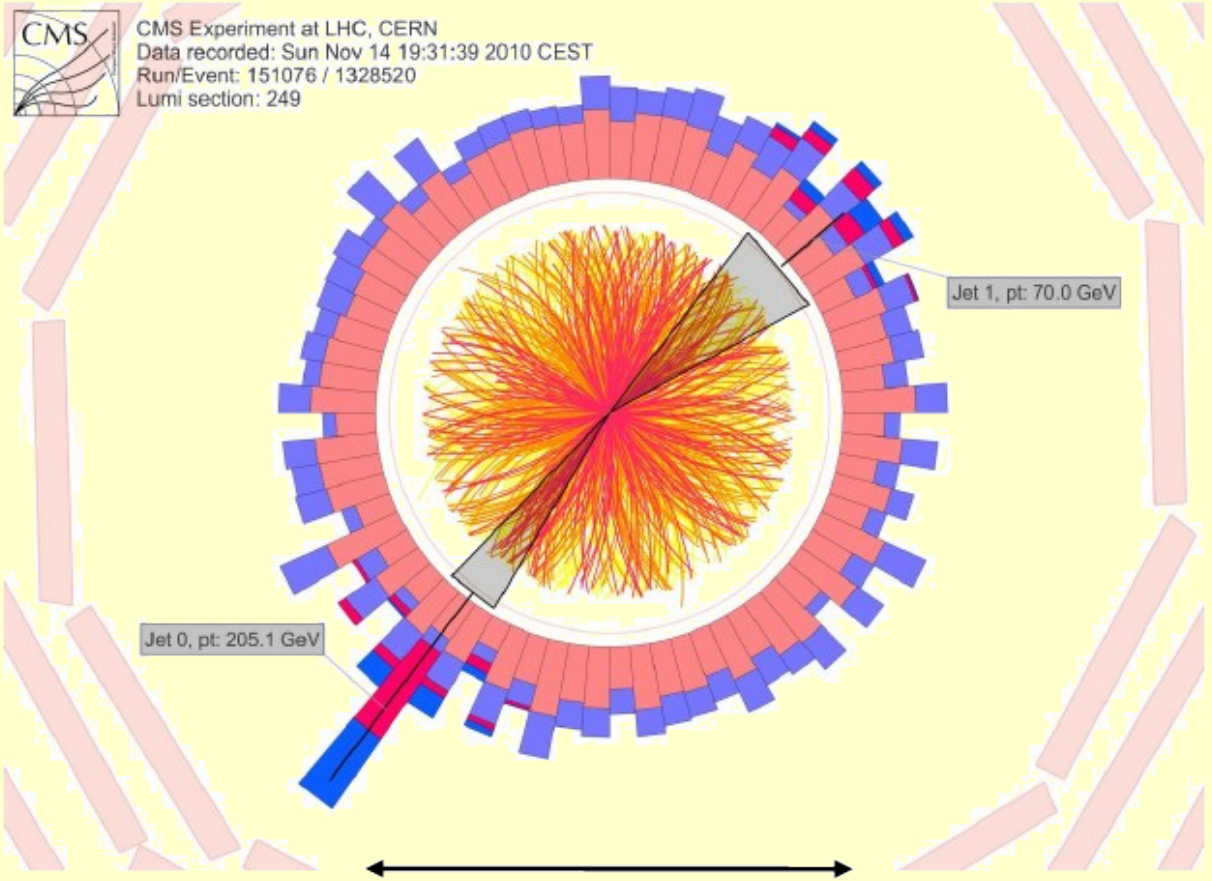
Mu3e: reconstructed 4-hit tracks



≈16 cm

Readout in frames of 50 ns

E ~ 10-50 MeV

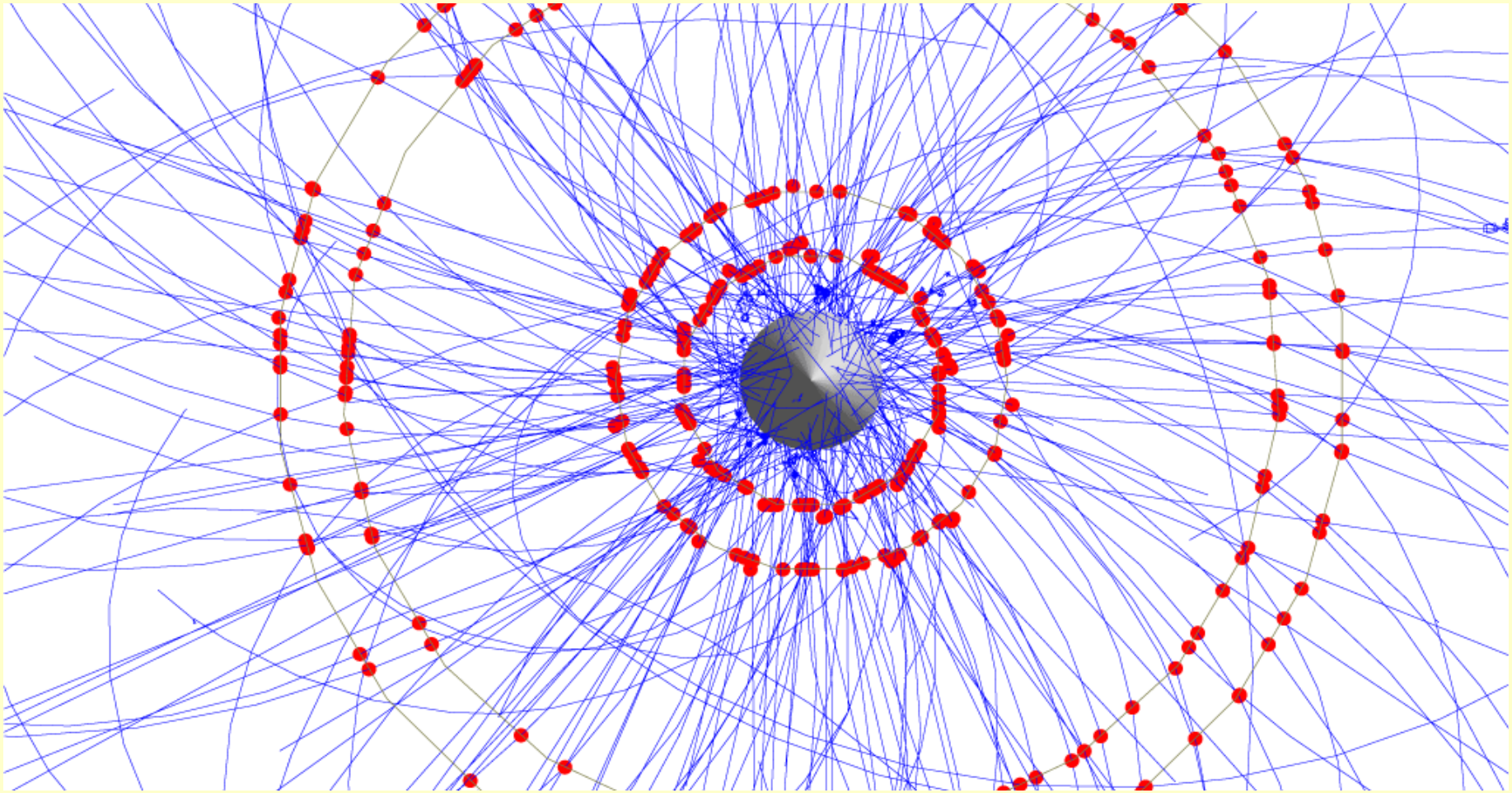


≈2.5 m

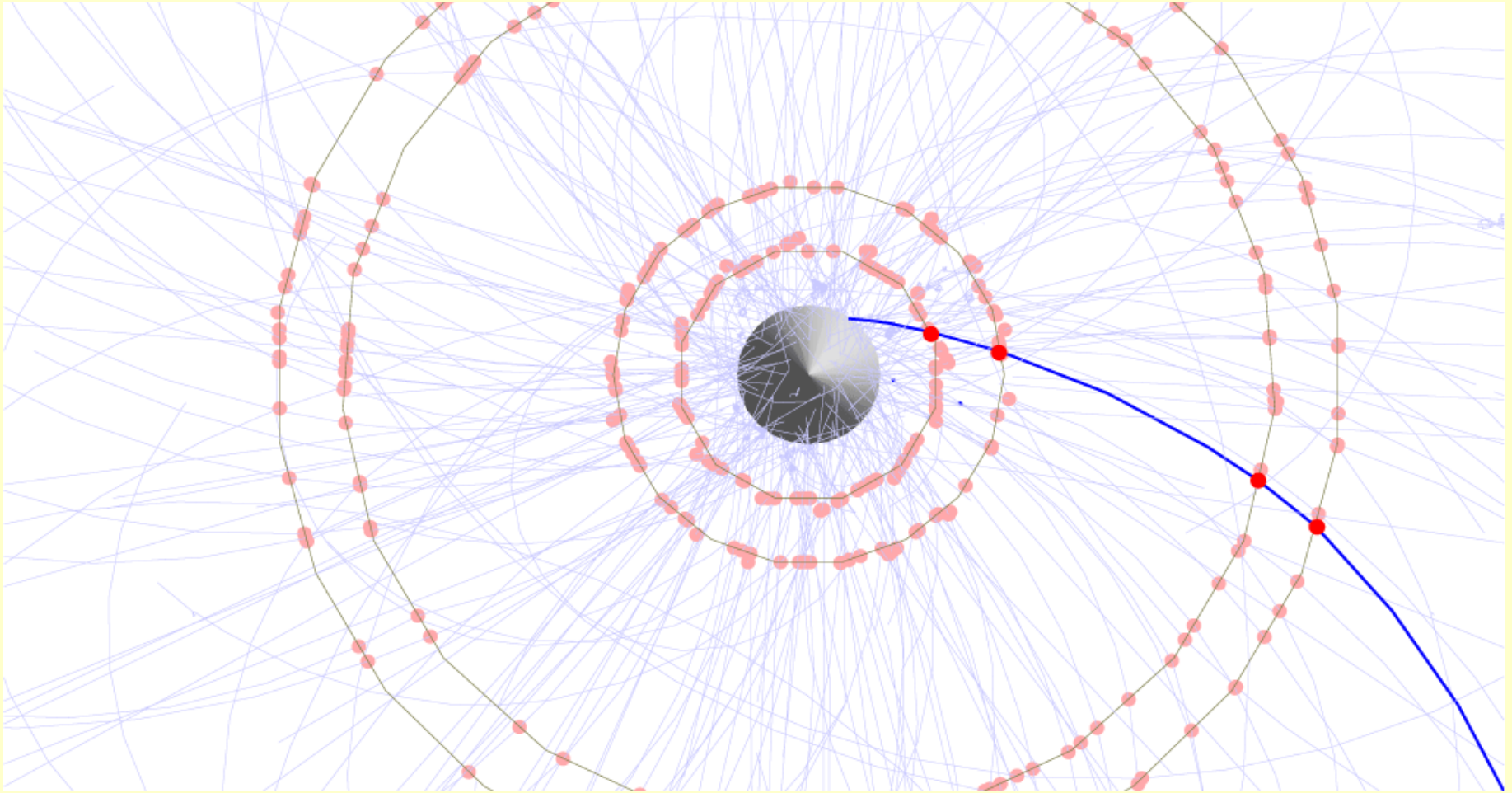
Collision every 25 ns

E ~ 200 GeV

Tracks in Pixel Detector

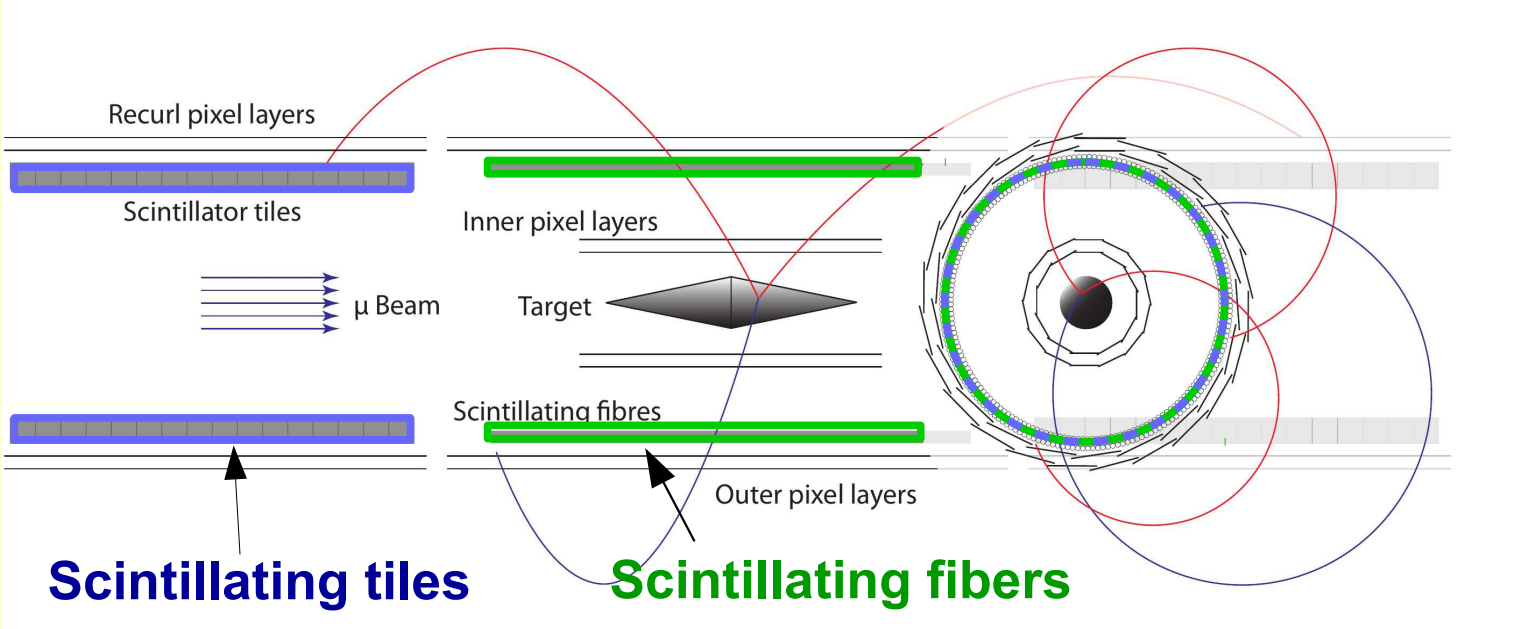


Tracks in Pixel Detector

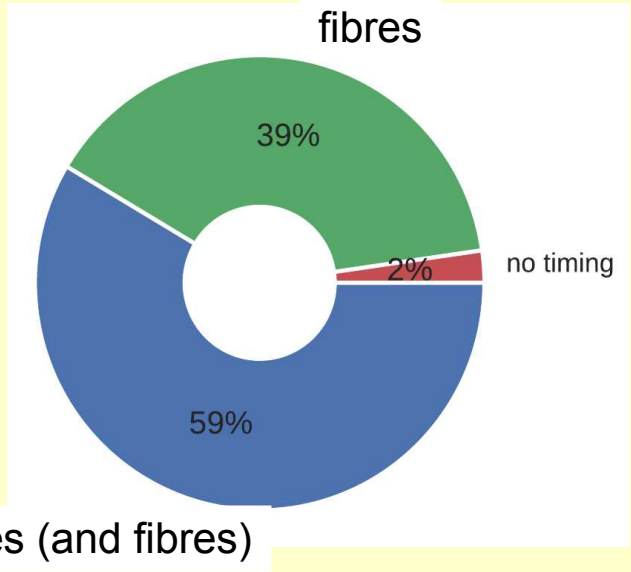


- additional timing detectors needed < 1ns

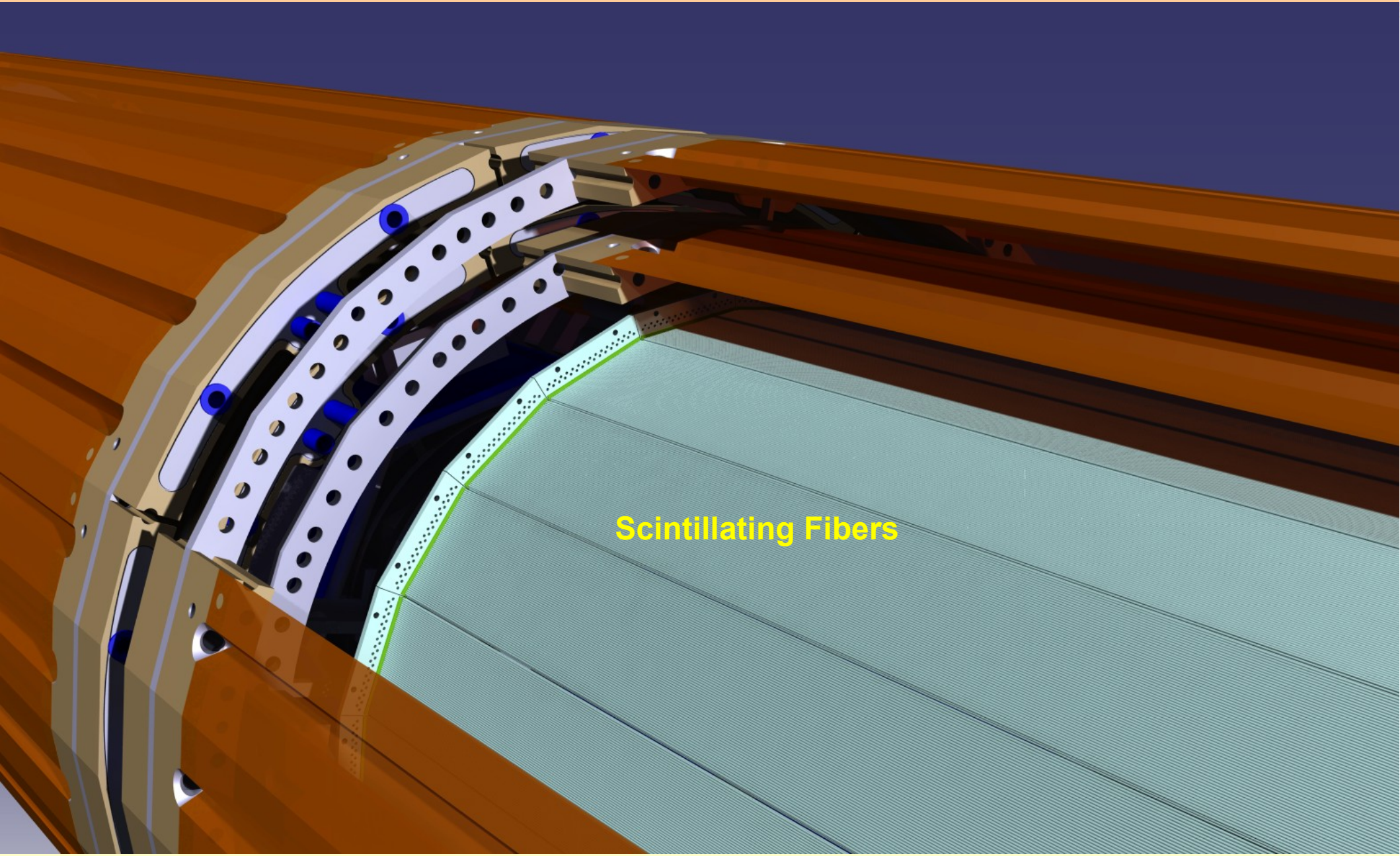
Mu3e Time Timing Detector



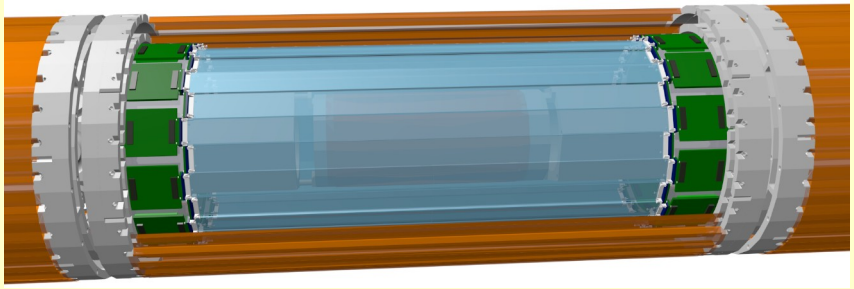
→ **background suppression factor of 100!**



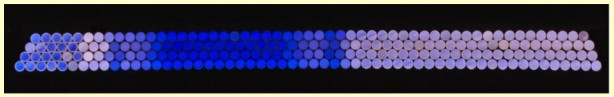
Scintillating Fibre Detector



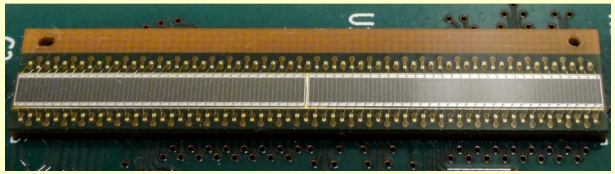
Scintillating Fibres



- Two types of scintillating 250µm fibres studied:
  - round (Kuraray SCSF-81M)
  - squared (Saint Gobain BC 418) (coated with Al)

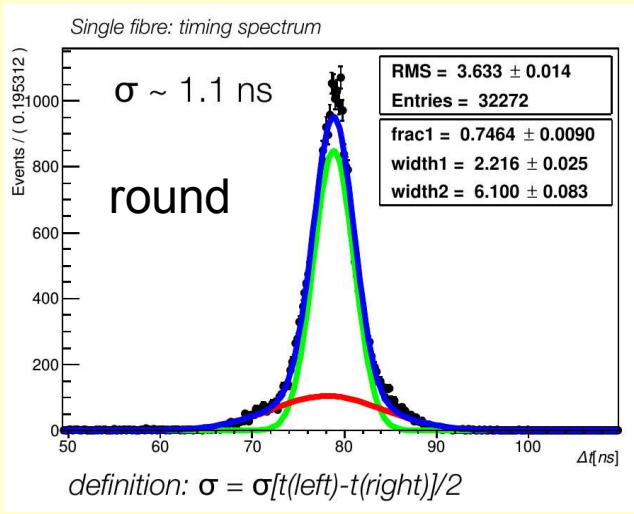


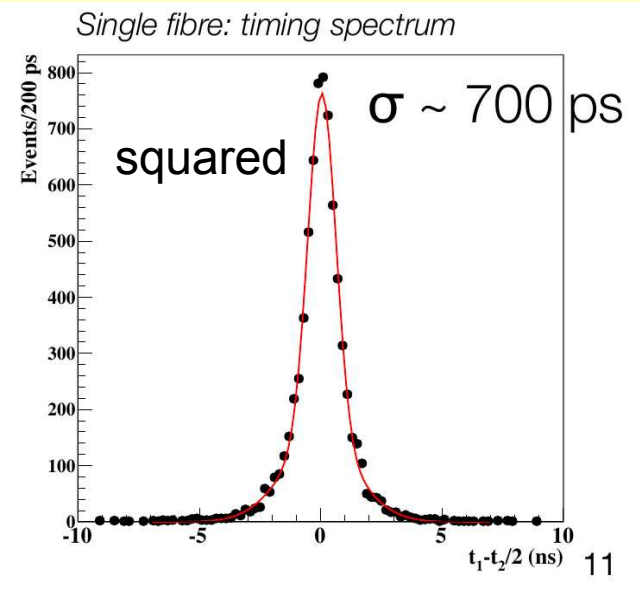
- SiPM: Hamatsu S12571-050P (LHCb)
  - SiPM array
  - 1 x 1 mm^2, 50 µm pitch



- MuTRig readout chip
  - time resolution 50 ps
  - 32 channels
  - bandwidth 1.25 Gbit/s
  - chip received January 2017

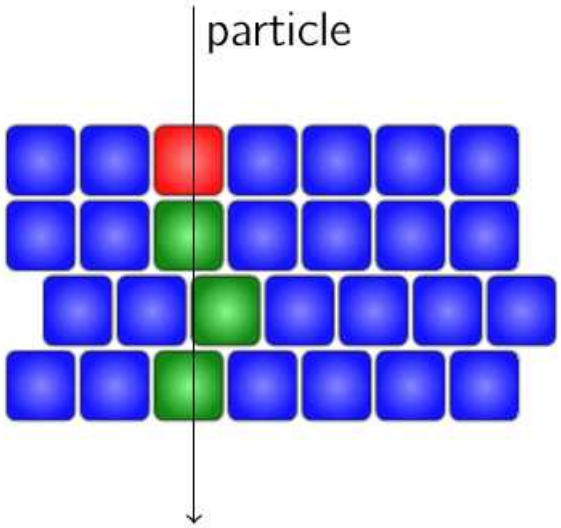
Single fibre time resolutions



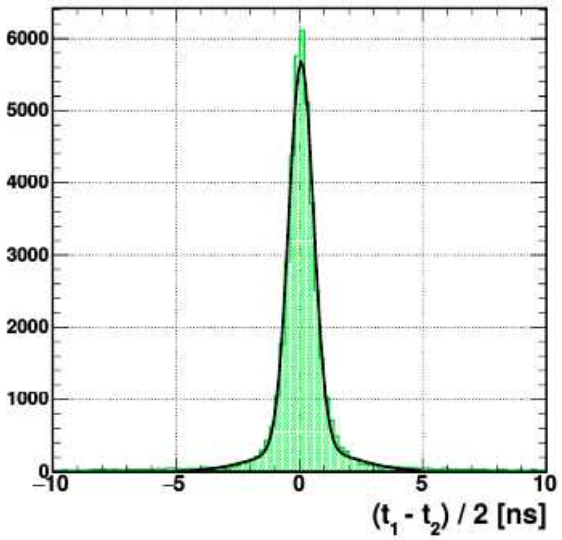


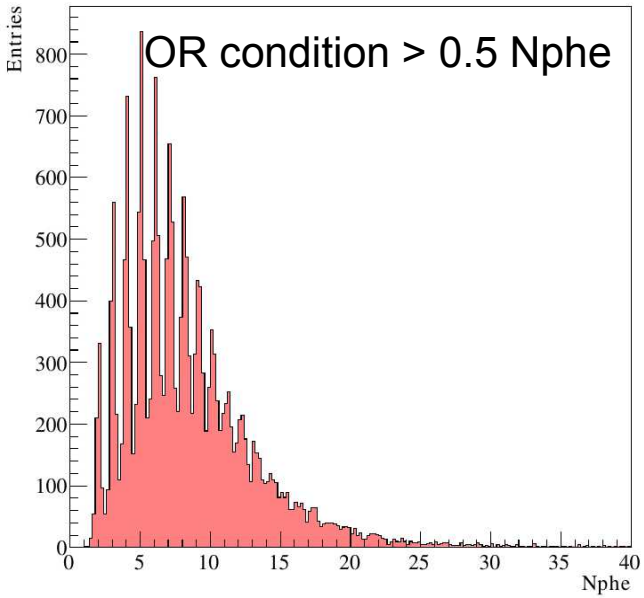
Scintillating Fibre Test Beams

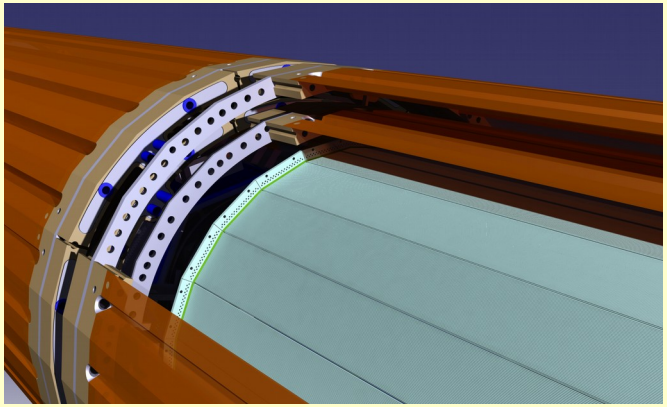
trigger
offline selection:
hits in 3 layers



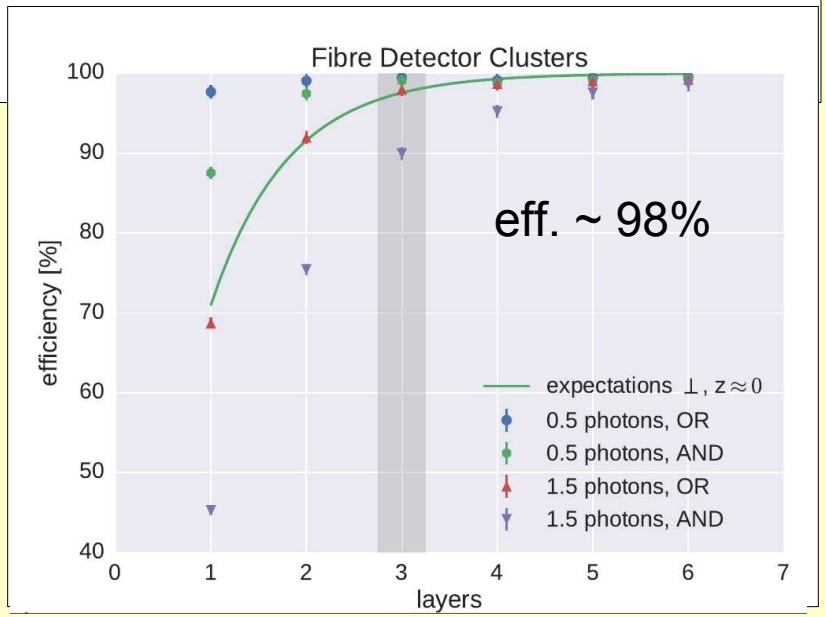
lab: $\mathcal{O}(520\,\text{ps})$
testbeam $\mathcal{O}(\mathbf{550\,ps})$



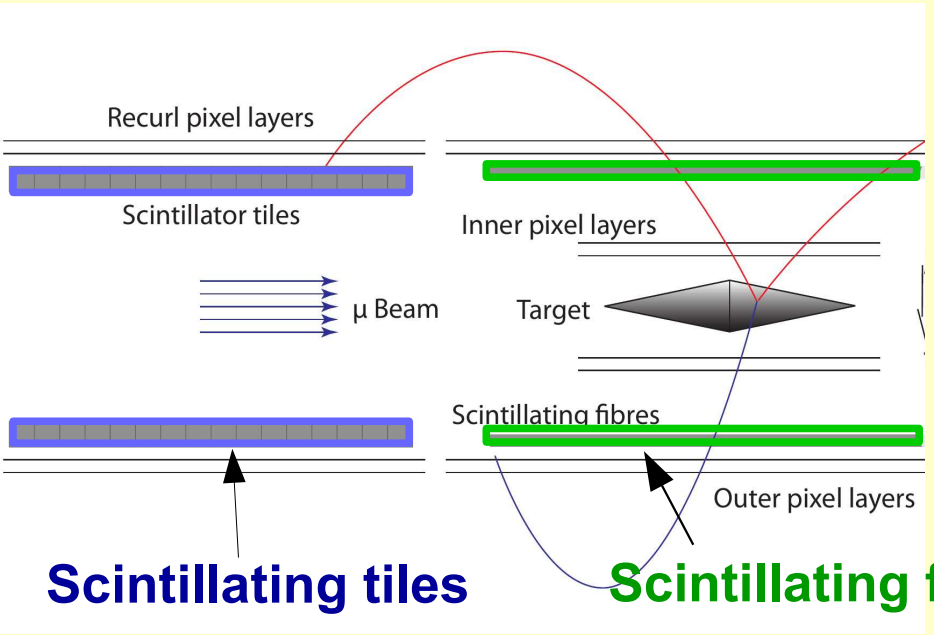


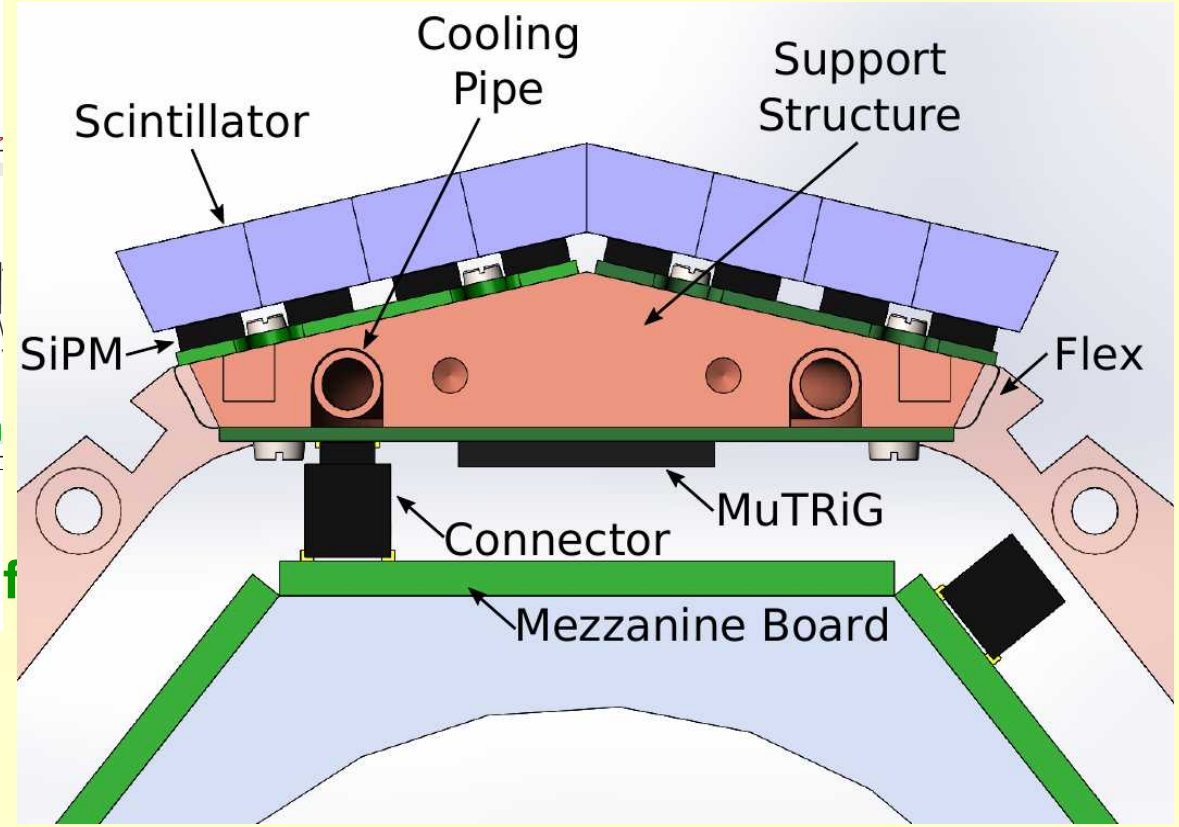


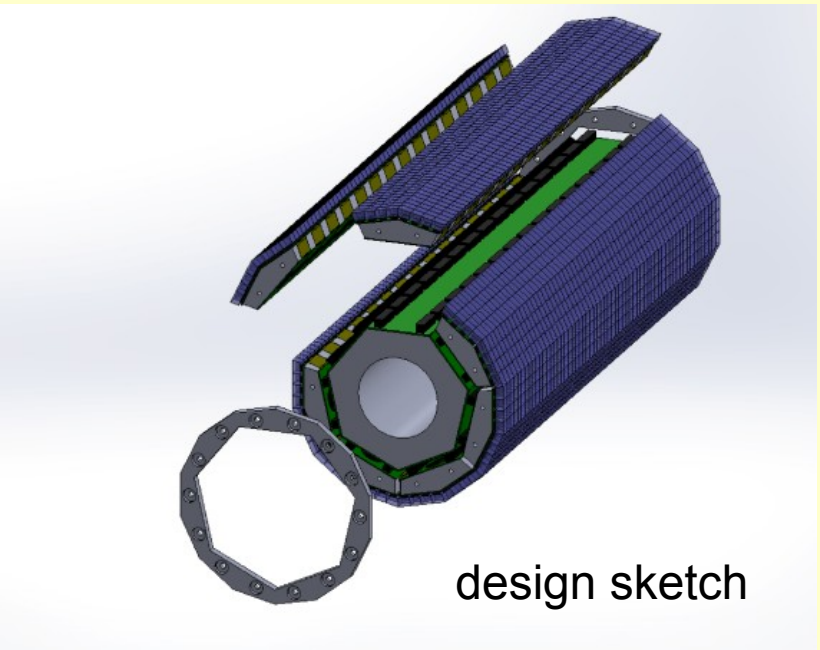
Requirements and expectations fulfilled in test beams!



Scintillating Tile Detector



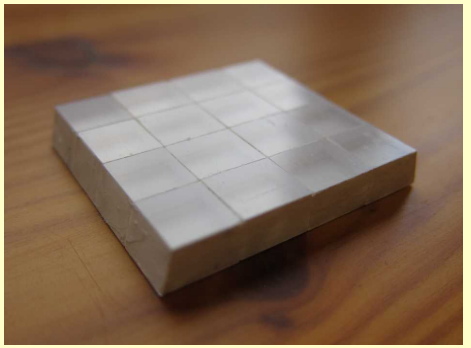


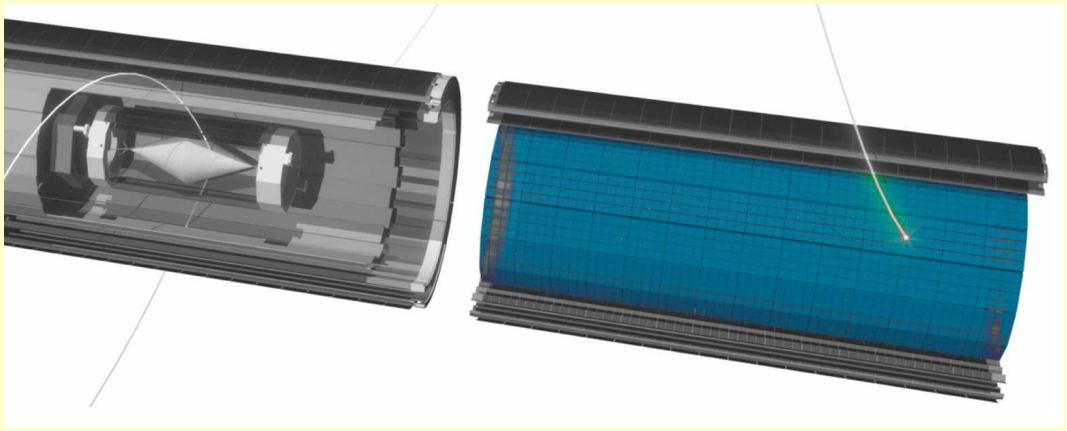


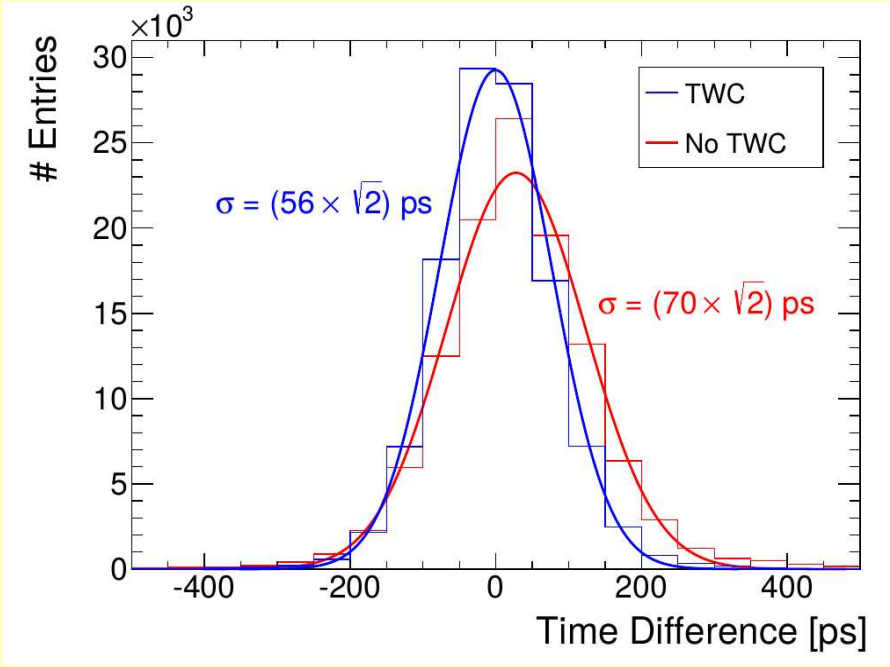
- 56 x 56 tiles (6.5 x 6.5 x 5.0 mm^3)
- 3 x 3 mm^2 single SiPM
- timing resolution of 100 ps
- mixed mode ASIC (MuTRig)

Scintillating Tile Detector

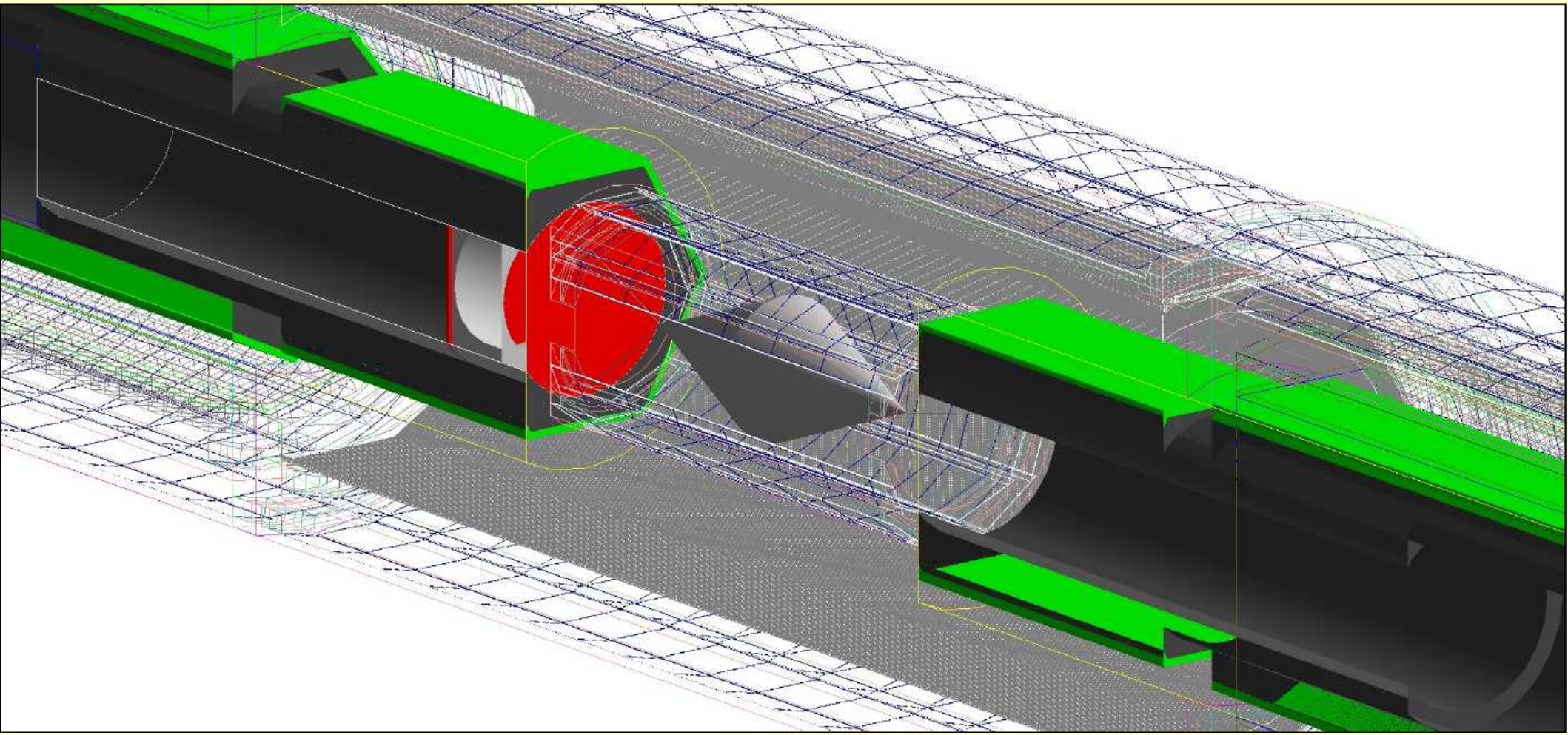
- Very promising results from test beam measurements (4 x 4 array)
- Time resolution < 100 ps
- Now testing new MuTRig readout ASIC





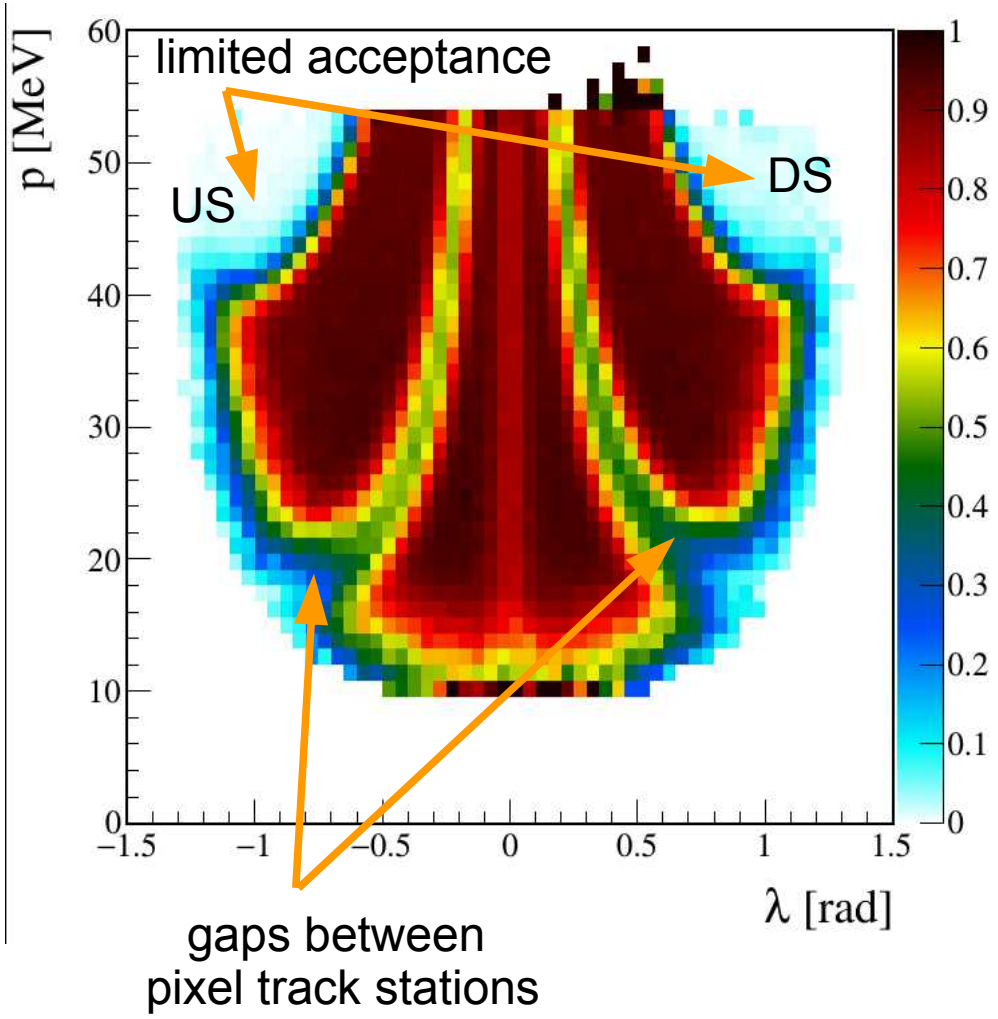


Simulation and Performance

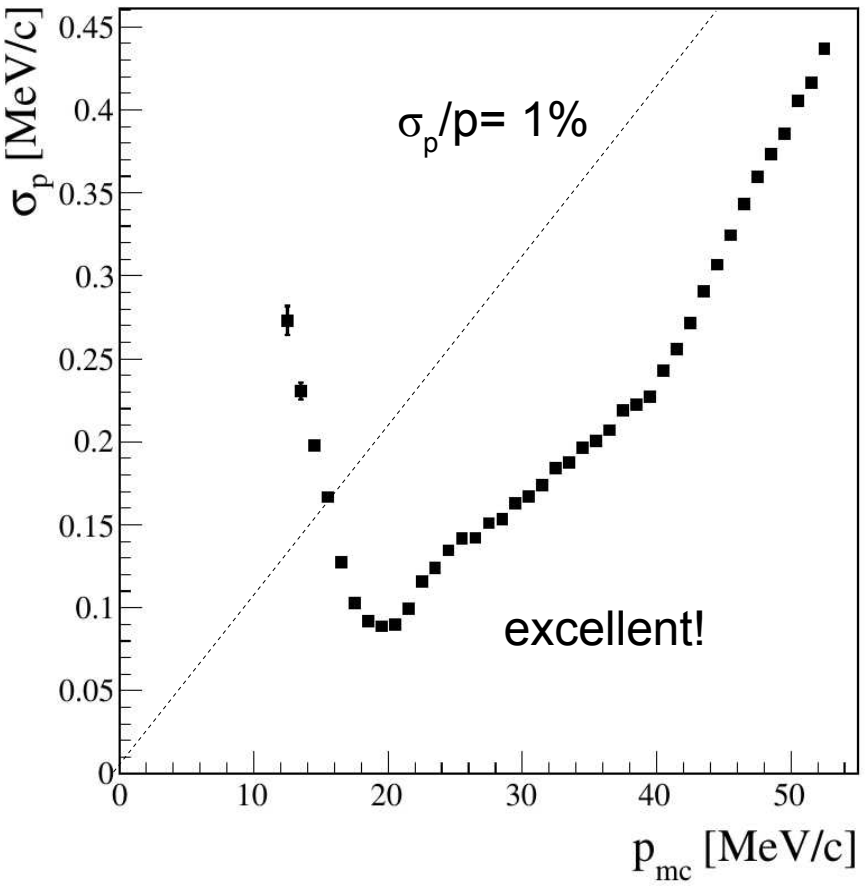


Simulation and Performance

Track Reconstruction Efficiency



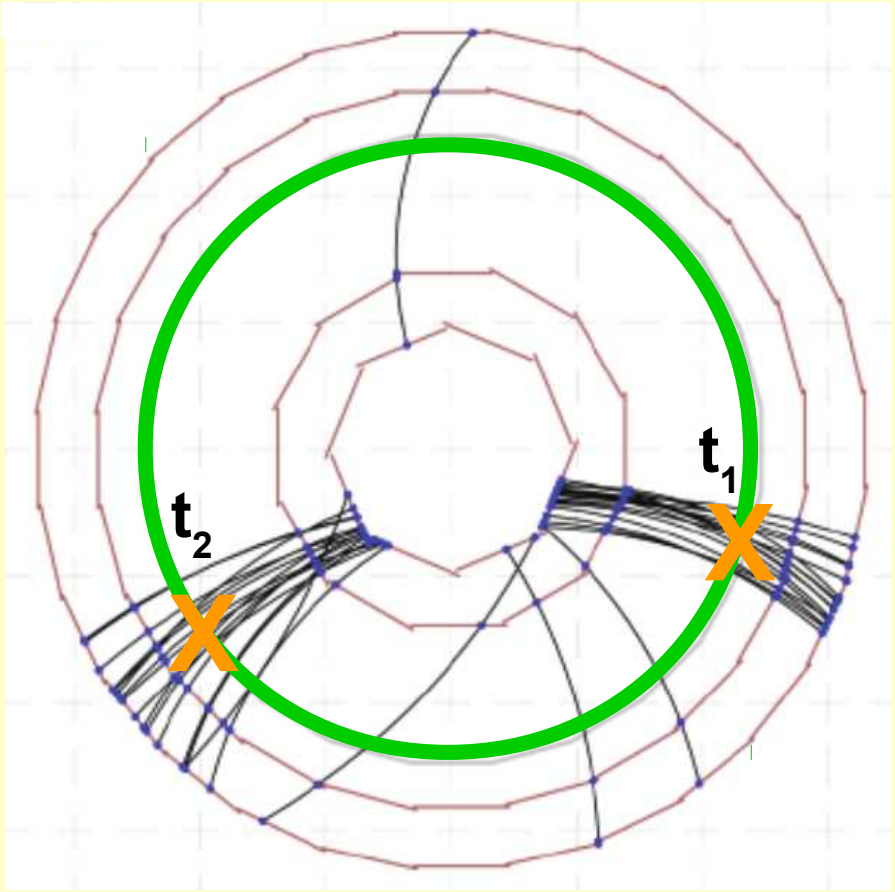
Track Momentum Resolution



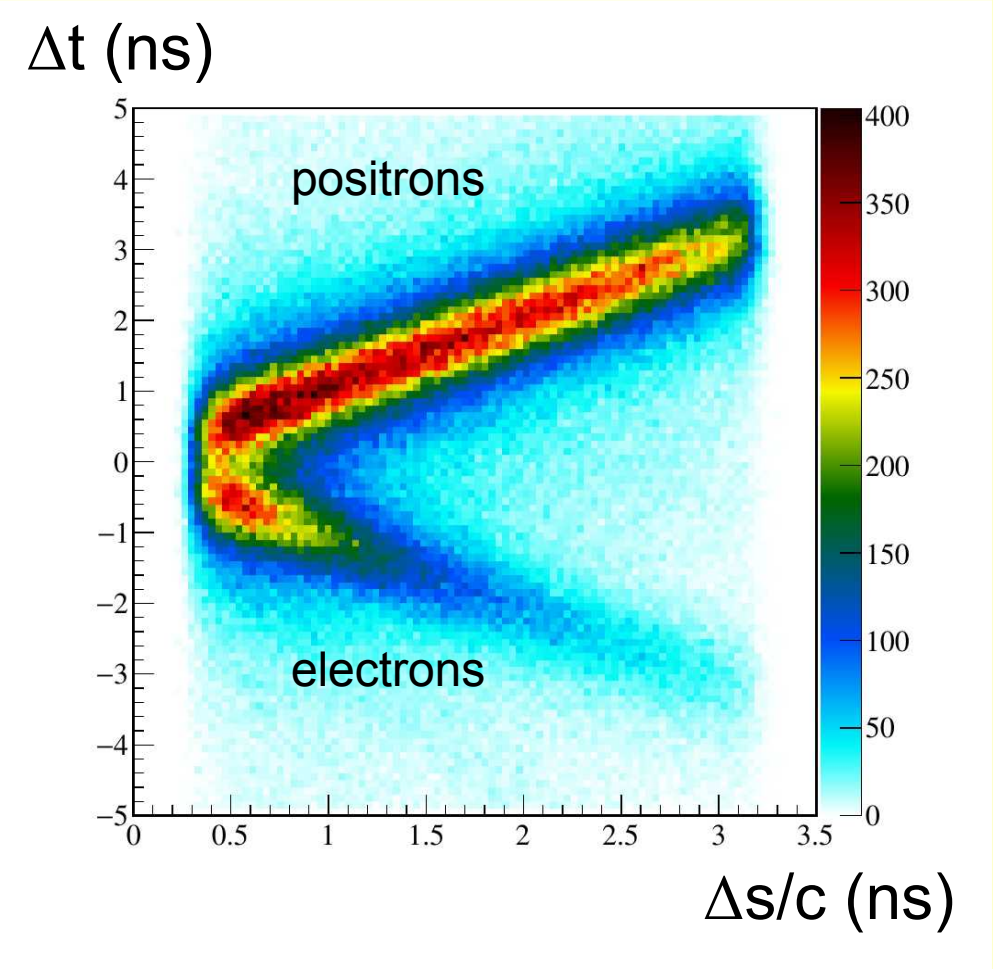
Charge Identification

Main process: $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$

positron loopers → charge confusion

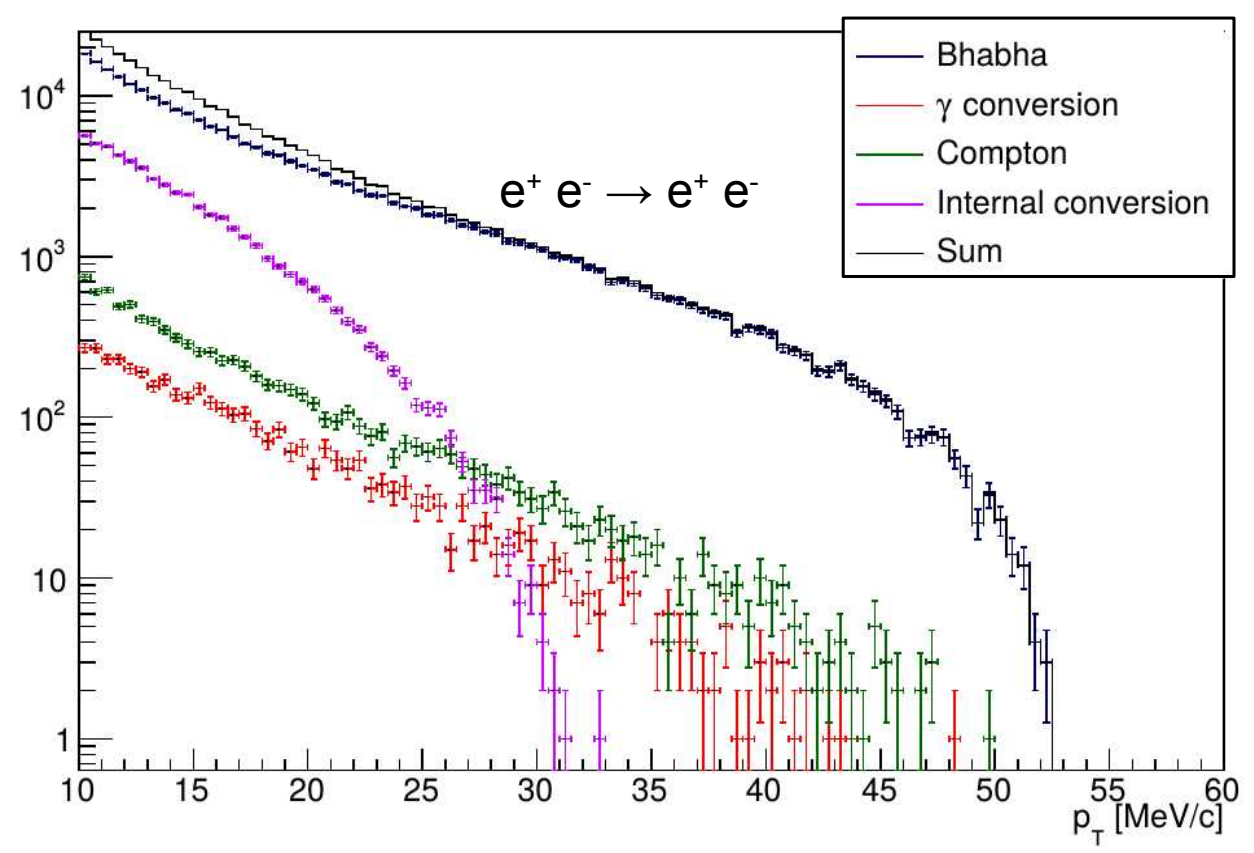


Time difference vs path length

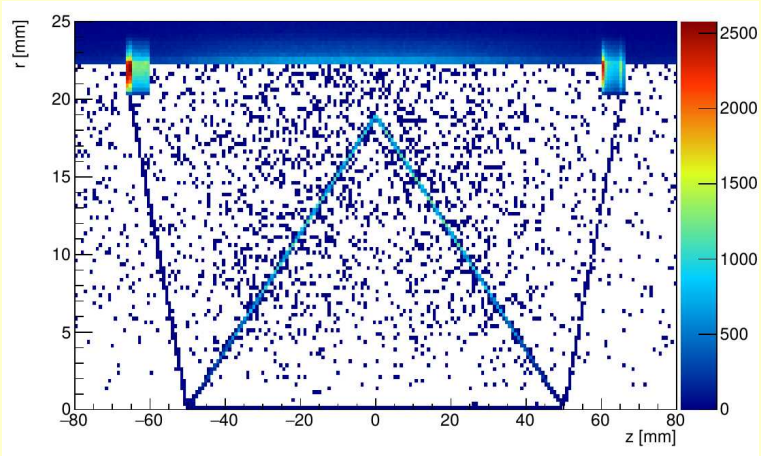


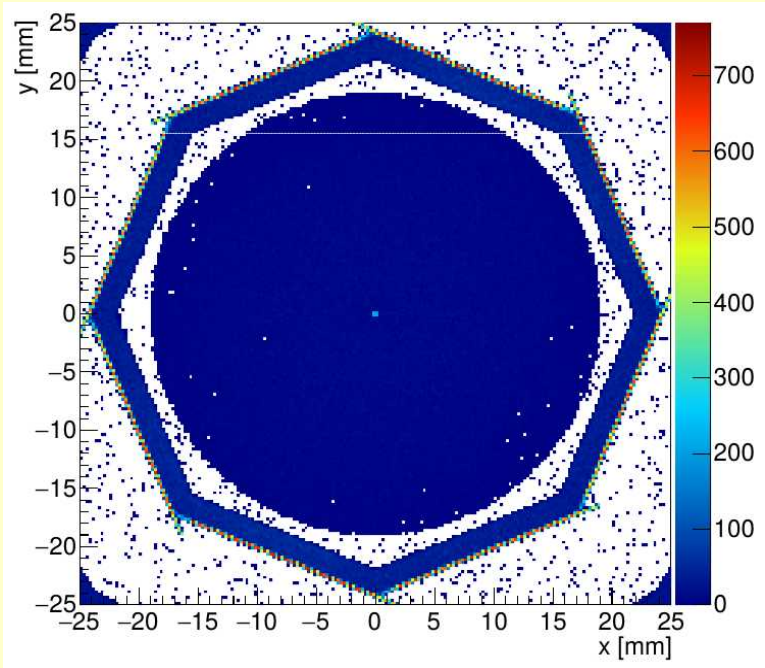
Significant reduction of BG for: $\mu^+ \rightarrow e^+ e^+ e^-$

Bhabha Scattering Background



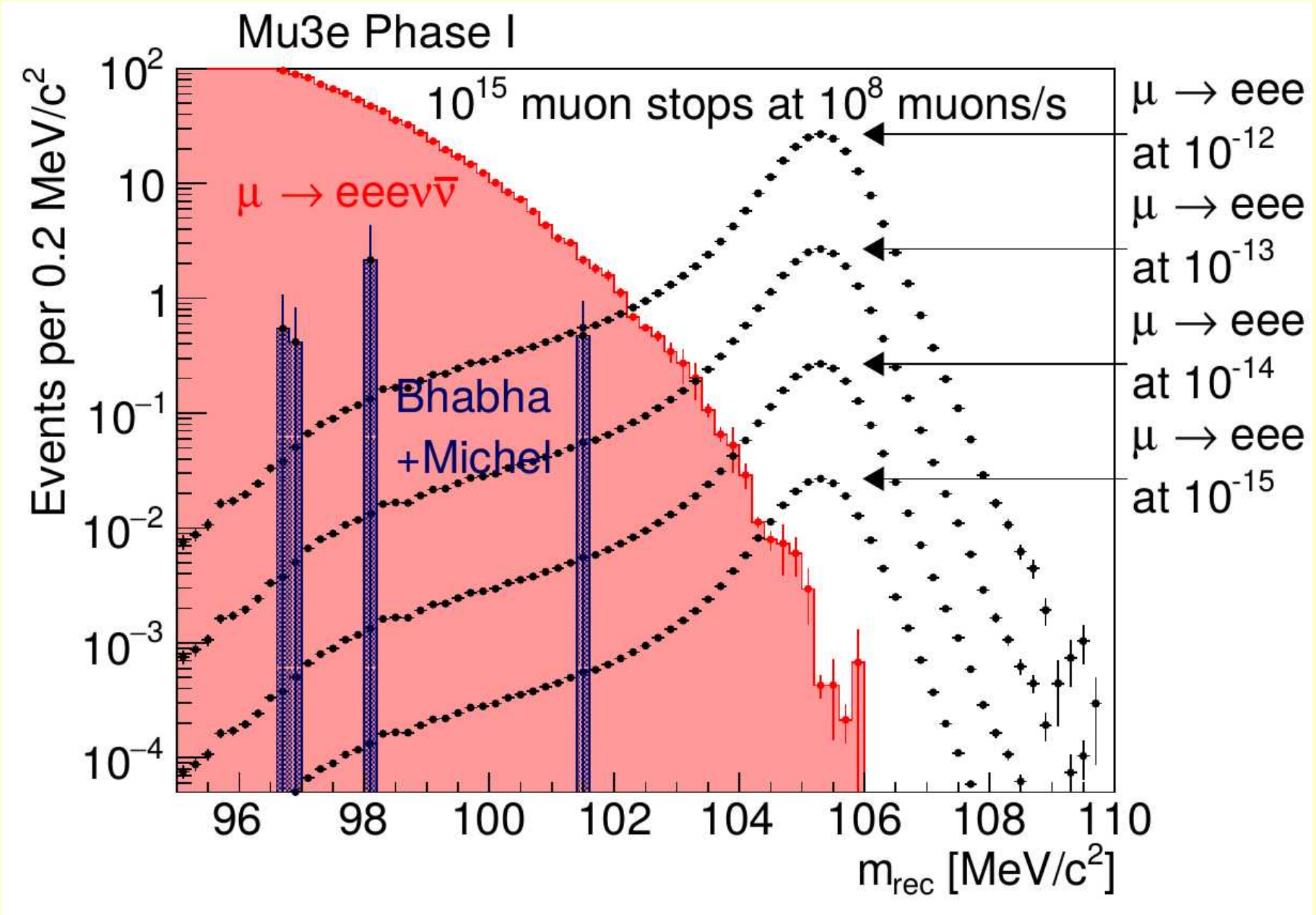
Bhabha vertices target region



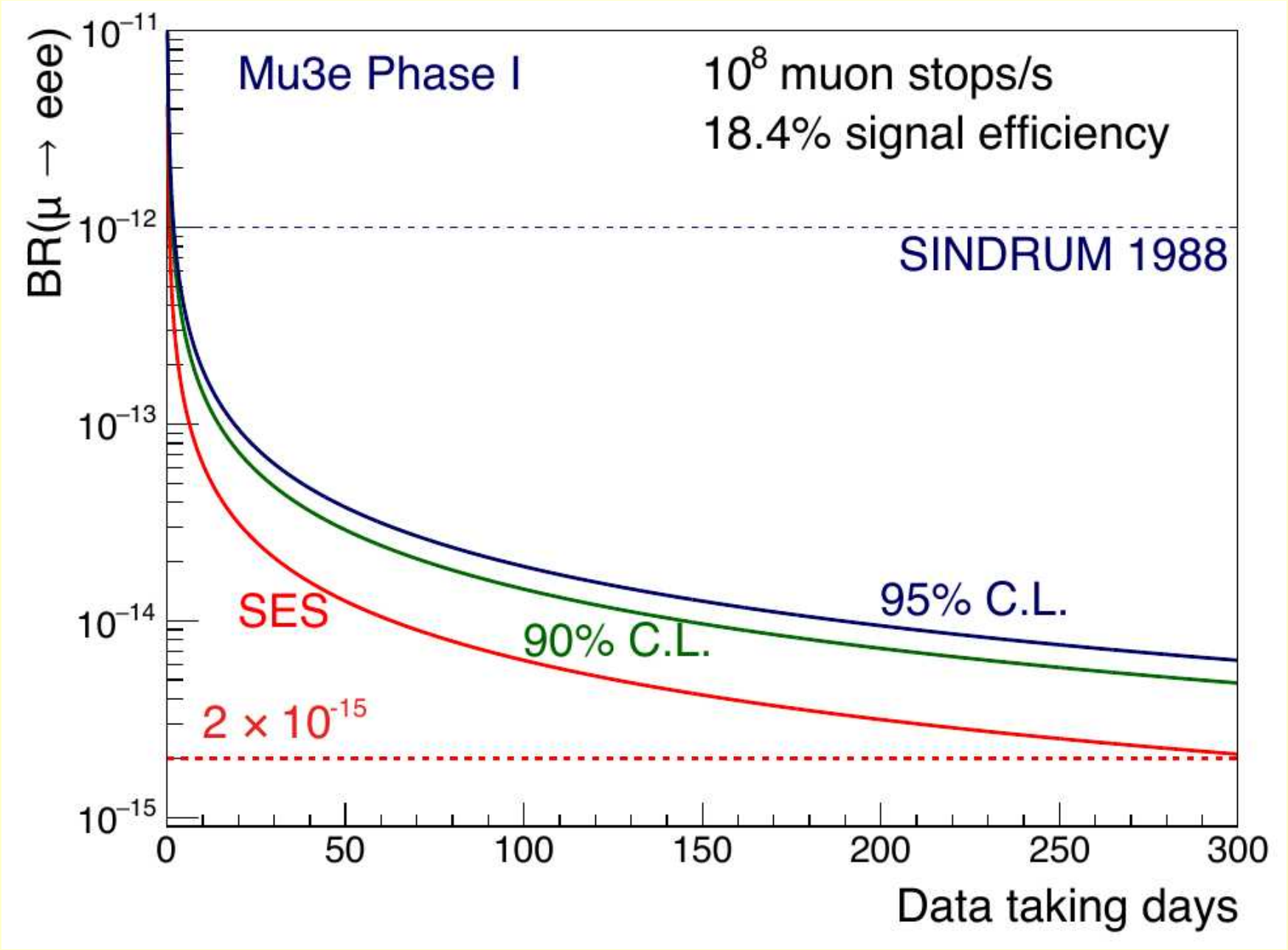


- Accidental background due to Bhabha scattering is difficult to simulate
- Bhabha's can be cut away with only small loss in signal efficiency

Mu3e Mass Plot



Sensitivity versus Time

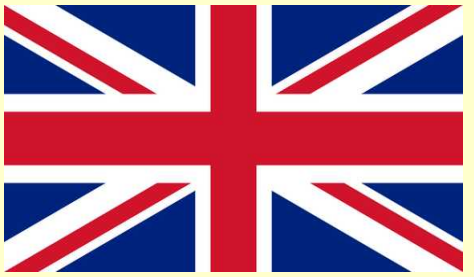


Mu3e Collaboration

Germany
- University Heidelberg
- Karlsruhe Institute of Technology
- University Mainz

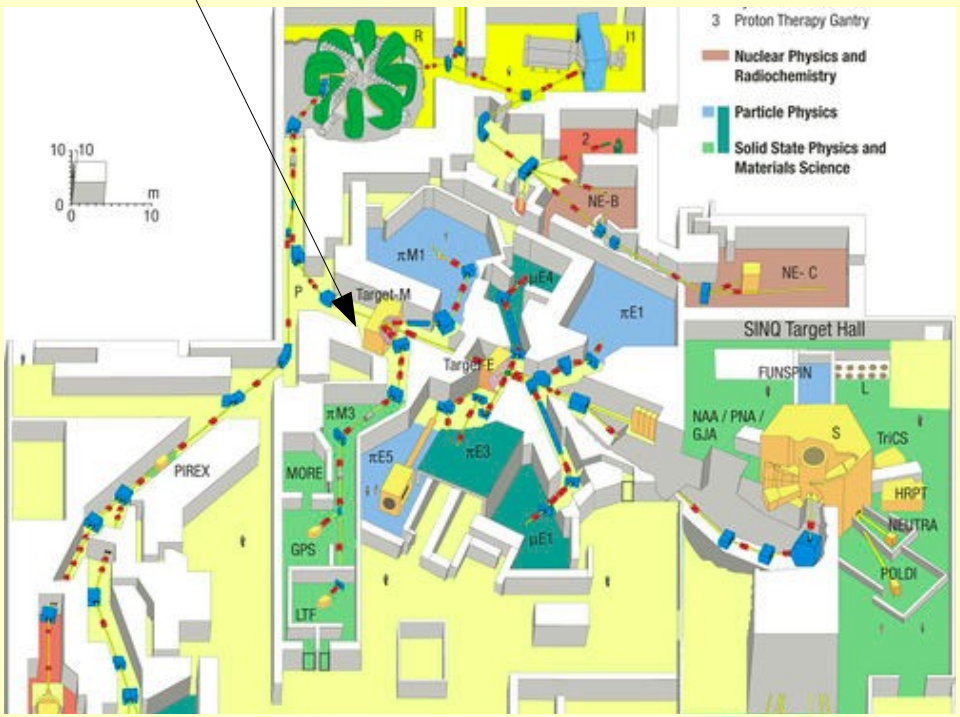
Switzerland
- University of Geneva
- Paul Scherrer Institute
- ETH Zurich
- University Zurich

United Kingdom
- Bristol
- Liverpool
- Oxford
- UC London



Mu3e Summary

- Technical Design Report
- Detector R&D is concluding → pre production is starting
- First beam in 2019/20 (Phase I)
- More muons with High Intensity Muon Beamline (HiMB Project)
  Aim: $B(\mu^+ \rightarrow e^+e^+e^-) \leq 10^{-16}$ (90% CL)



- Unique discovery potential for New Physics