Flexprint Design Studies for the Mu3e Experiment

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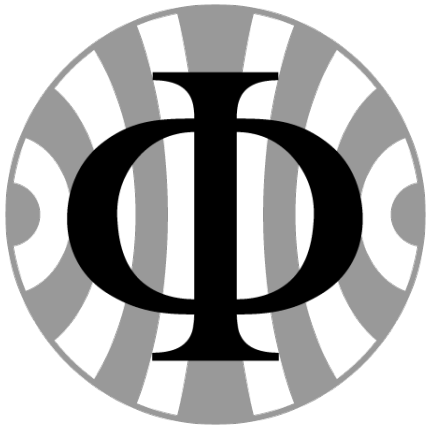
on behalf of the Mu3e collaboration

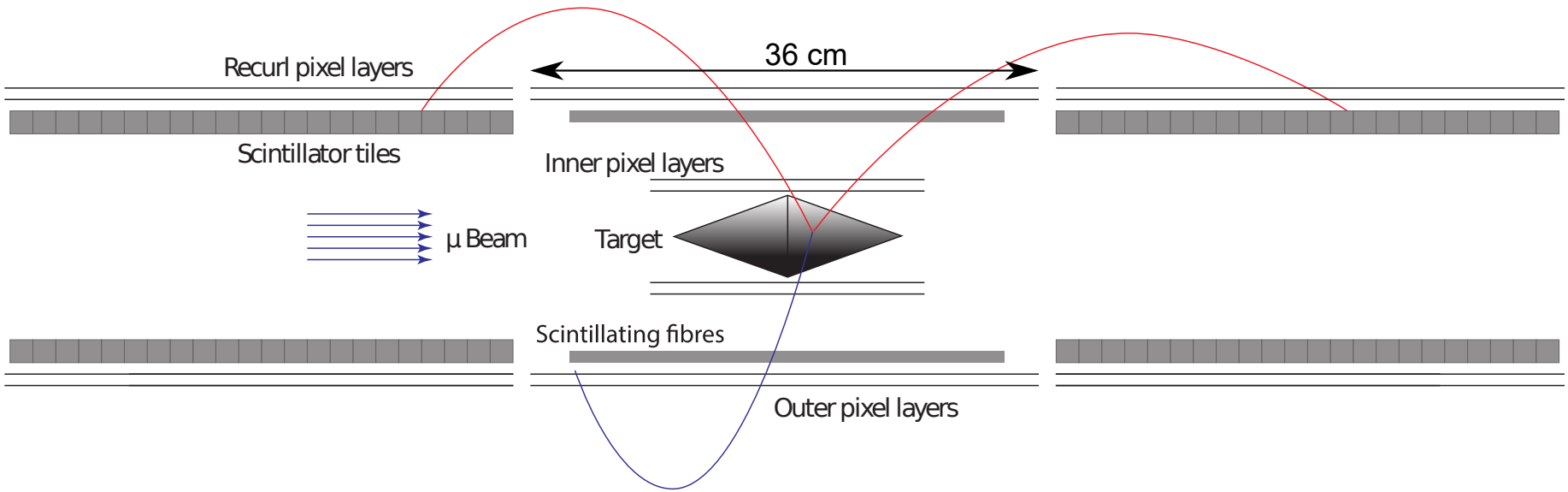
DPG Frühjahrstagung Münster 2017

March 28, 2017



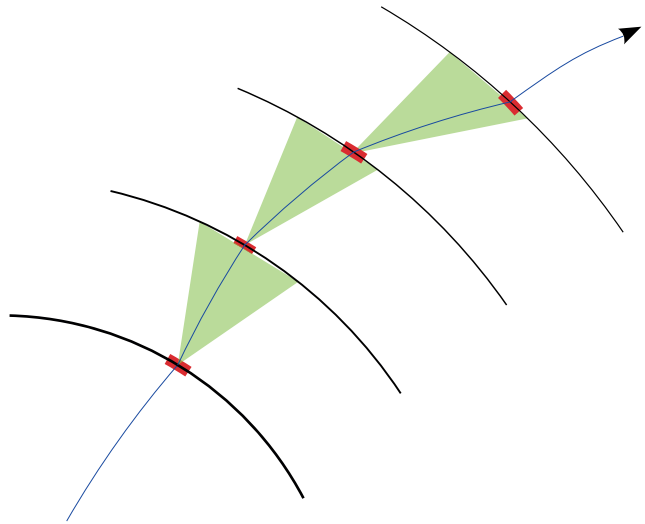
The Mu3e Experiment - Detector Concept

- μ^+ are stopped
- decay at rest
  $\rightarrow$ low momentum electrons $p_e \leq 53\ MeV/c$
- 1 T magnetic field



The Mu3e Experiment - Detector Concept

- low momentum electrons
  $p_e \leq 53\ MeV/c$
- **multiple Coulomb scattering**
  dominates momentum
  resolution



$$\Theta_{rms} \propto \sqrt{\frac{x}{X_0}}$$

tracking in scattering dominated regime

$\rightarrow$ **consequence:** minimize material budget

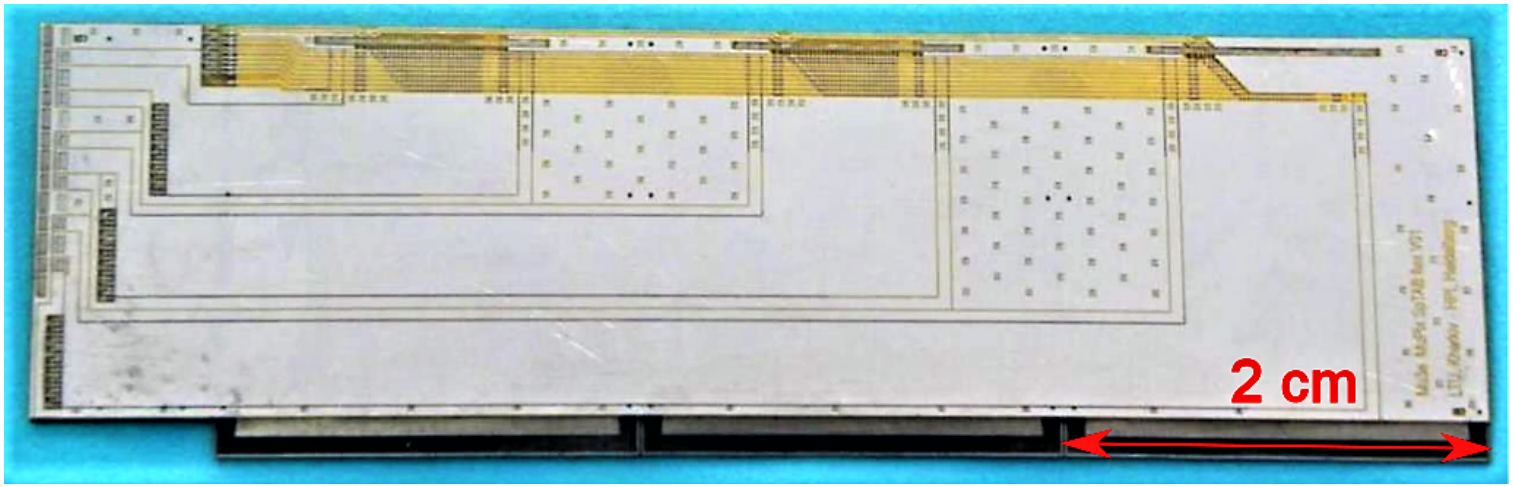
Flexprints for the Mu3e Detector

Challenge: minimize material budget

Solution: thinned pixel chips and flexprints

- dielectric layers:
  polyimide film (Kapton)
- electric layers: copper or aluminium

thinned wafer

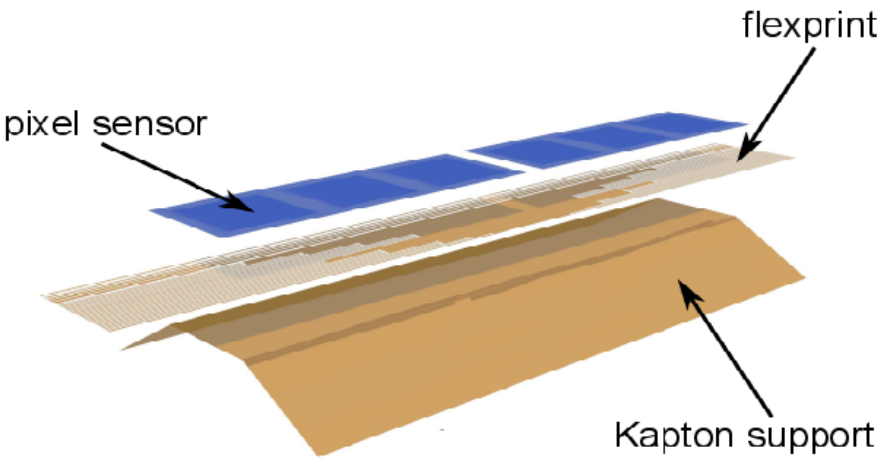


flexprint prototype

Flexprints for the Mu3e Detector

- desired material budget:
  $x/X_0 \leq 0.1\%$ per layer

	x/X_0
pixel chip (50 µm)	~ 0.05 %
flexprint	~ 0.05 %
support + glue (35 µm)	~ 0.01 %
per layer	~ 0.11 %



Flexprints for the Mu3e Detector

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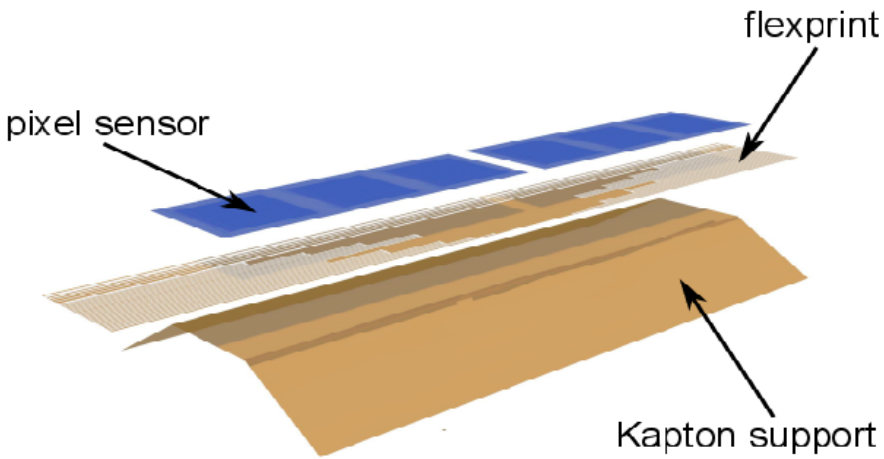


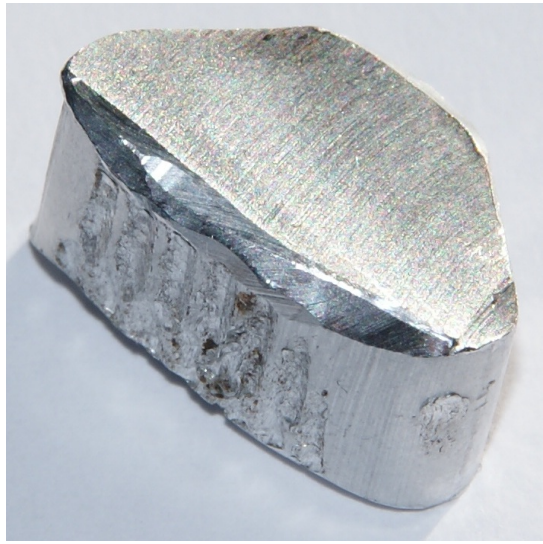
	x/X_0
pixel chip (50 µm)	$\sim$ 0.05 %
flexprint	$\sim$ 0.05 %
support + glue (35 µm)	$\sim$ 0.01 %
per layer	$\sim$ 0.11 %

Experiment	x/X_0 **per layer**
ATLAS IBL [1]	1.9 %
CMS (upgrade) [2]	$\sim$1.1 %
ALICE (upgrade) [3]	0.3 %
STAR [4]	0.4 %
BELLE II IBL [5]	0.2 %
Mu3e	$\sim$**0.1** %

Aluminium vs. Copper

	conductivity	radiation length
Cu	$59.6 \times 10^6\,\mathrm{S\,m^{-1}}$	1.436 cm
Al	$36.9 \times 10^6\,\mathrm{S\,m^{-1}}$	8.897 cm

from wikipedia [6]



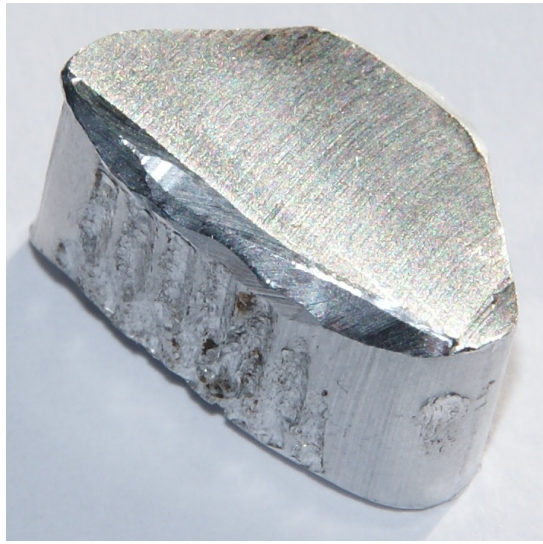
from wikipedia [7]

Aluminium vs. Copper

	conductivity	radiation length
Cu	1.5× higher	
Al		6× longer

⇒ Aluminium saves us a **factor of 4** in material!

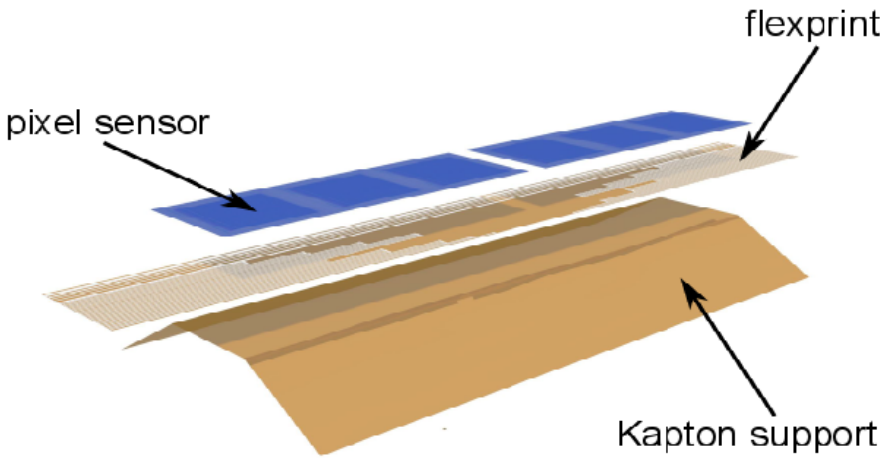
from wikipedia [6]



from wikipedia [7]

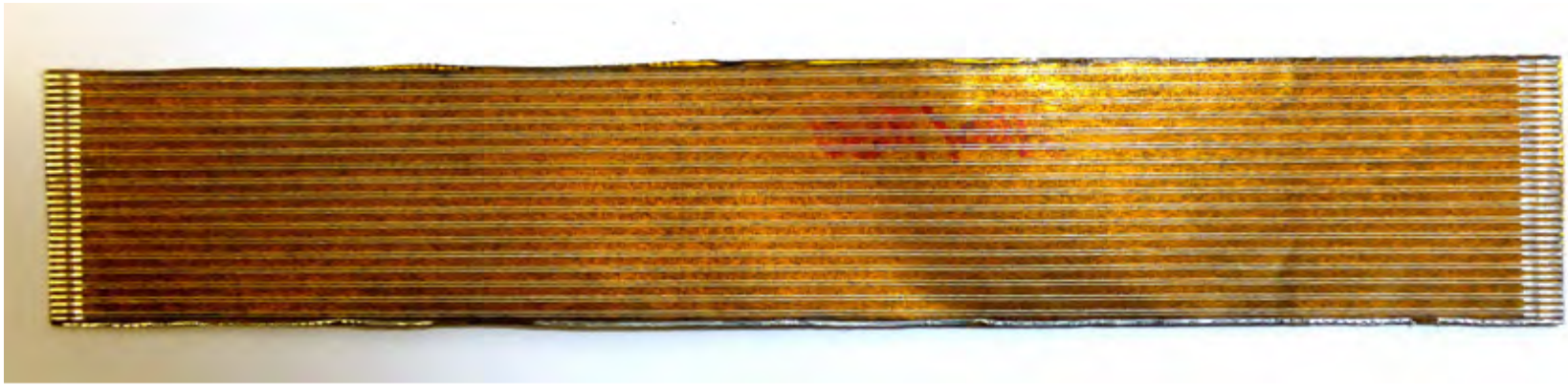
The Mu3e Experiment - Flexprint Requirements

- fast data transmission (1.25 Gb/s LVDS)
- power supply and slow control
  - power $\leq 400\,\mathrm{mW/cm^2}$
  - high voltage $\mathcal{O}(-100\,\mathrm{V})$
  - clock, reset, configuration signals



Flexprint Prototypes - First Steps

In-house production with laser platform

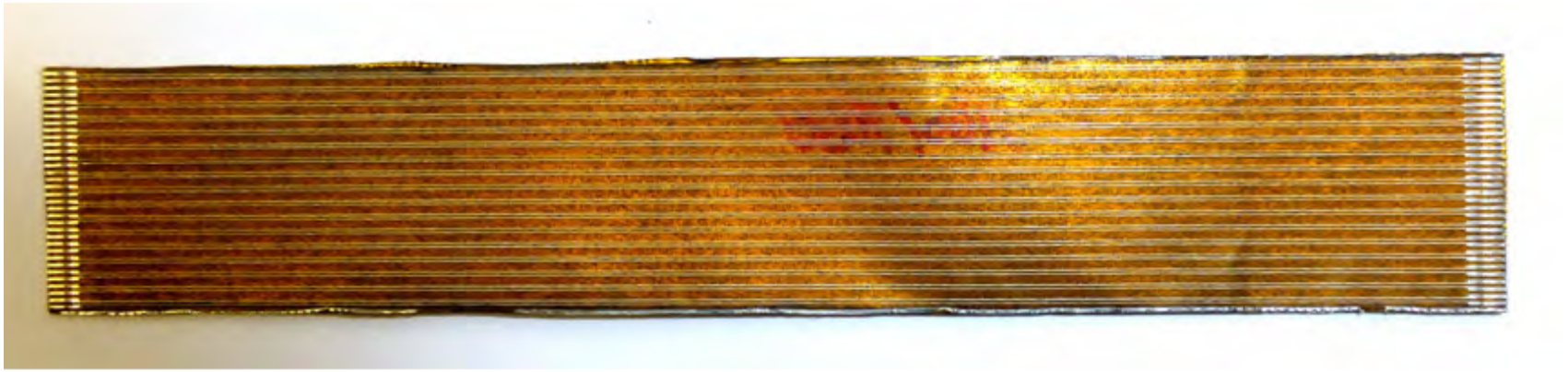


First flexprint: $10 \times 1.8\,\mathrm{cm}^2$

- 25 µm Kapton + 25 µm Al + glue
- trace width $\geq$ 120 µm,
  trace separation $\geq$ 120 µm
- different lengths up to 1 m

Flexprint Prototypes - First Steps

In-house production with laser platform



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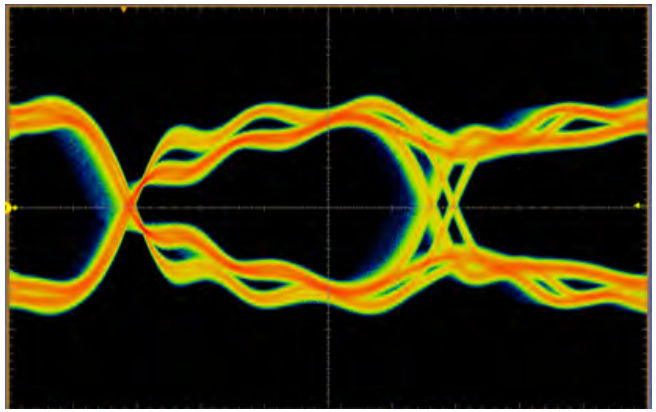
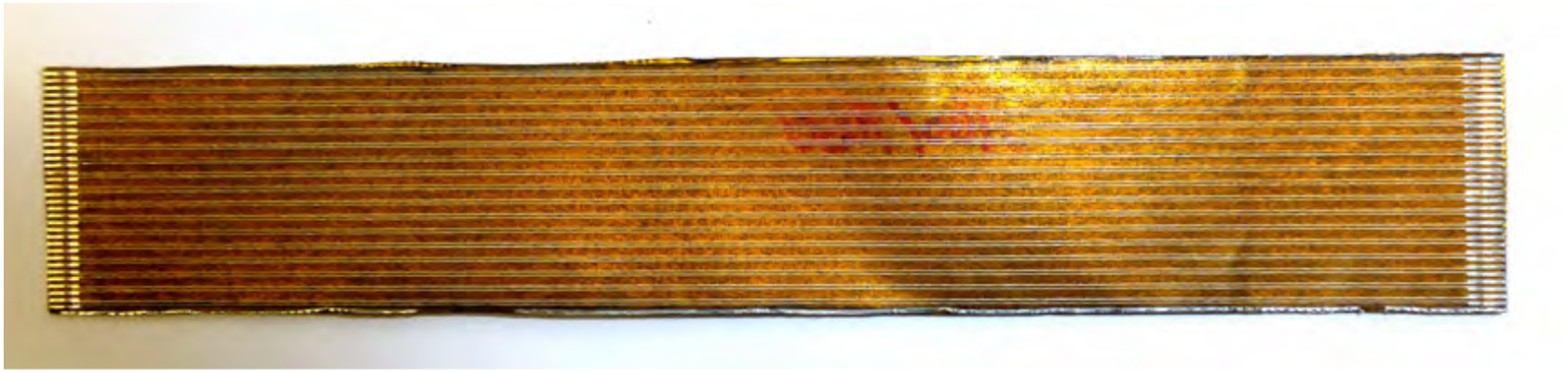


Eye diagram at 800 Mb/s,
length: 10 cm

Flexprint Prototypes - First Steps

In-house production with laser platform



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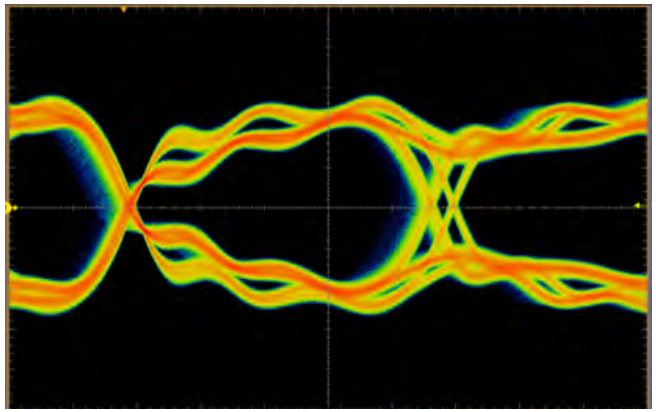
Problem:
structures not small enough!



Eye diagram at 800 Mb/s,
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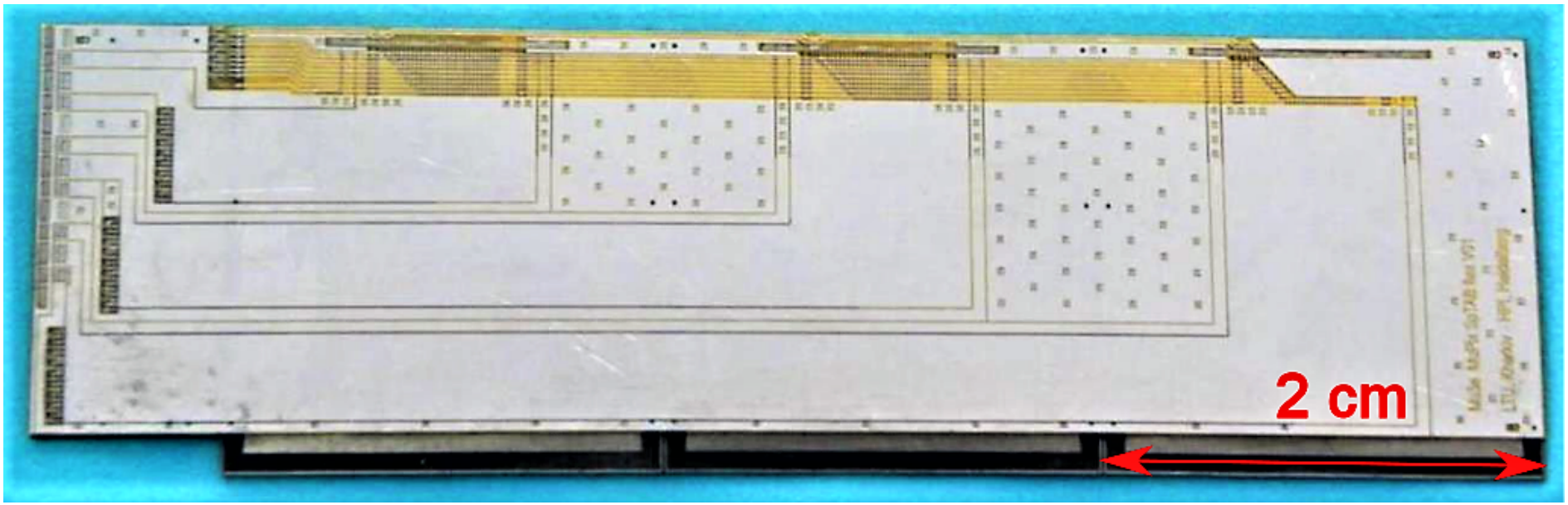
First LTU Flexprint Prototype

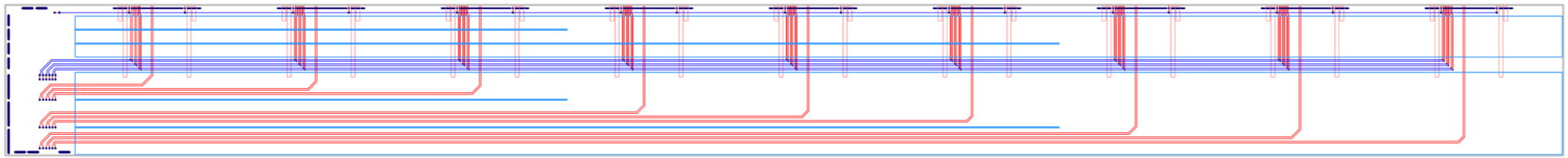
- manufactured by LTU
- smallest structure sizes: 63 µm $\rightarrow$ **sufficiently small**
- 3 dummy chips glued on flexprint
- only mechanical test



Flexprint Study for Outer Layers

Feasibility study (Bachelor Thesis by Lars Noehte, 2016 [8])

- 9 pixel chips over 18 cm
- min. number of signal traces
- power distribution critical

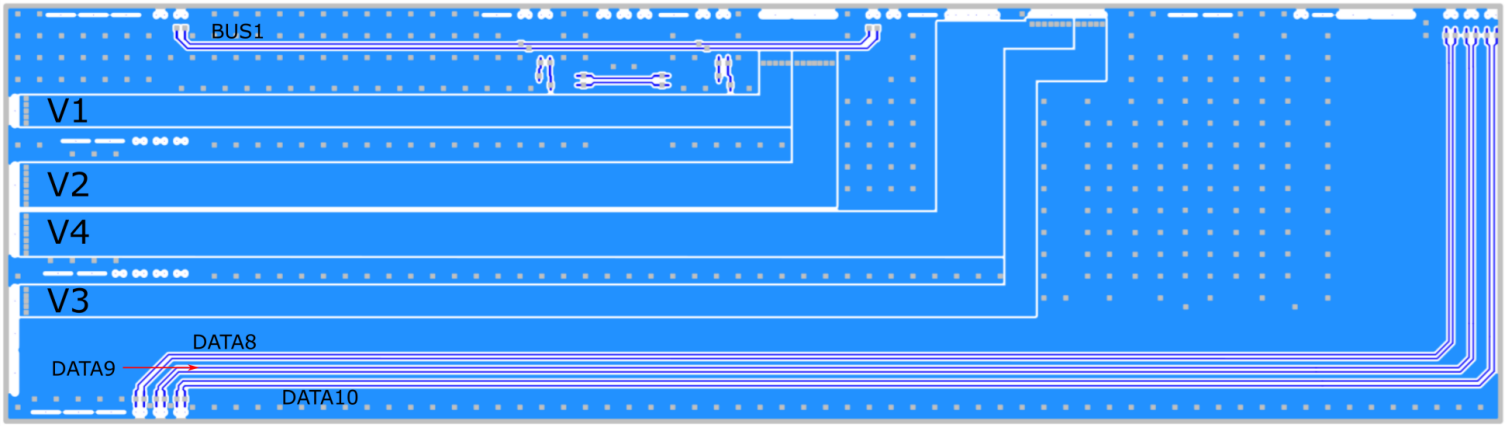


size: $1.8 \times 19.0\,\mathrm{cm}^2$

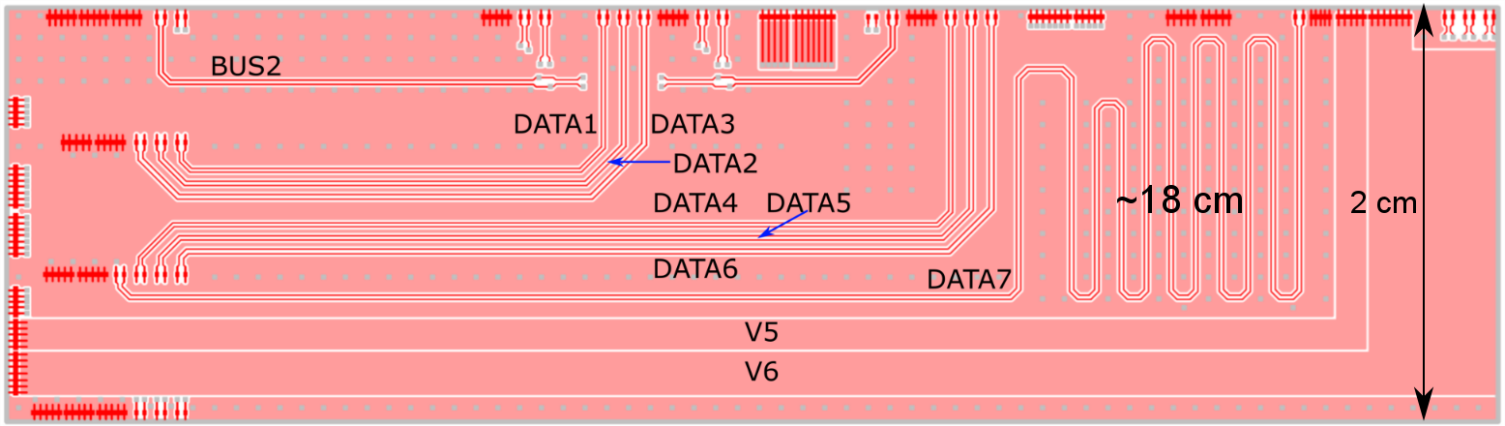
$\Rightarrow$ Next step: **Design test structure with all critical characteristics**

Flexprint Prototypes - Test Structure

Design containing all crucial characteristics for final design



top layer

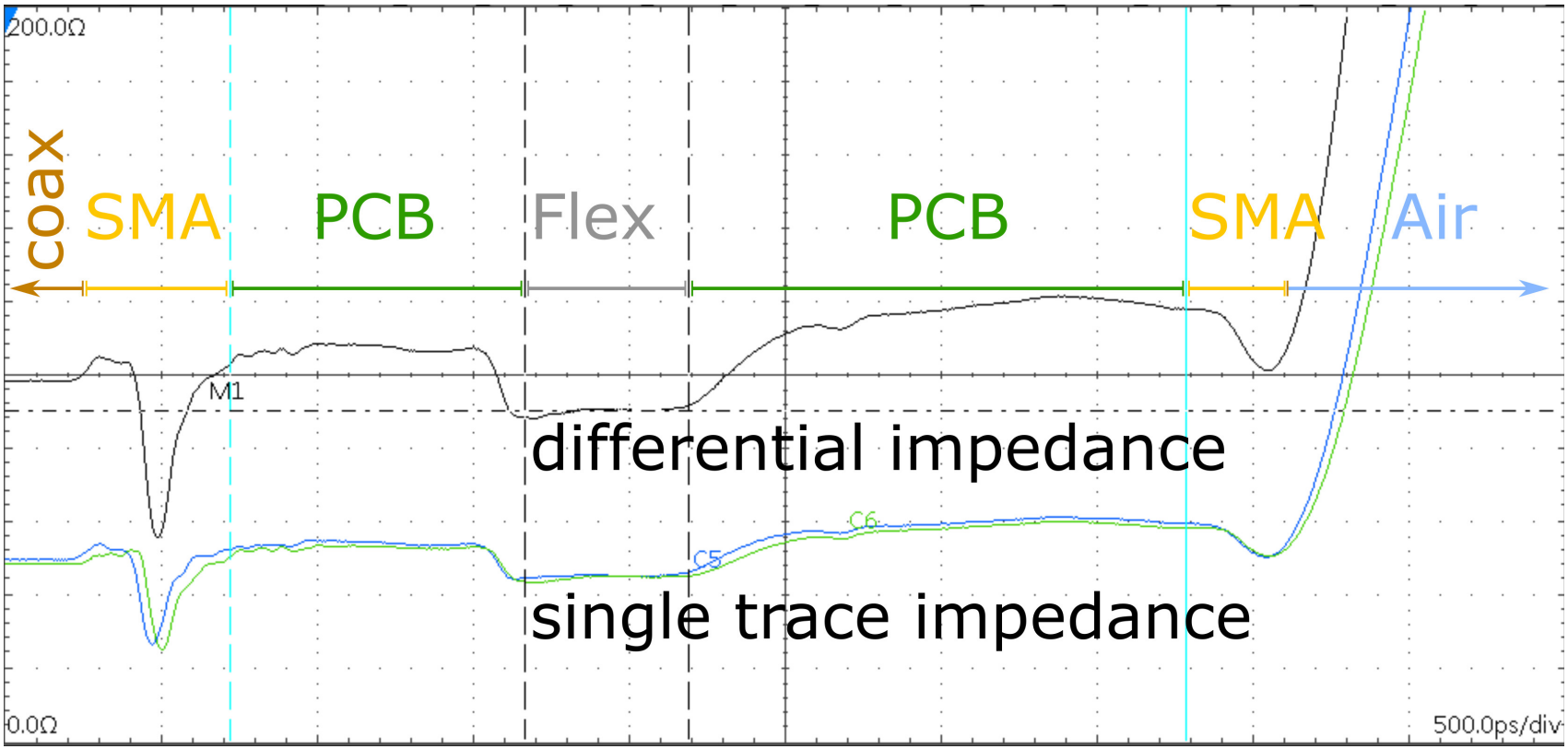


bottom layer

Flexprint Prototypes - Test Structure

Time Domain Reflectometry (TDR)

- measure impedance via reflection of input pulse
- essential for fast data transmission: $Z_0 = 50\,\Omega$, $Z_{diff} = 100\,\Omega$



Flexprint Prototypes - Test Structure

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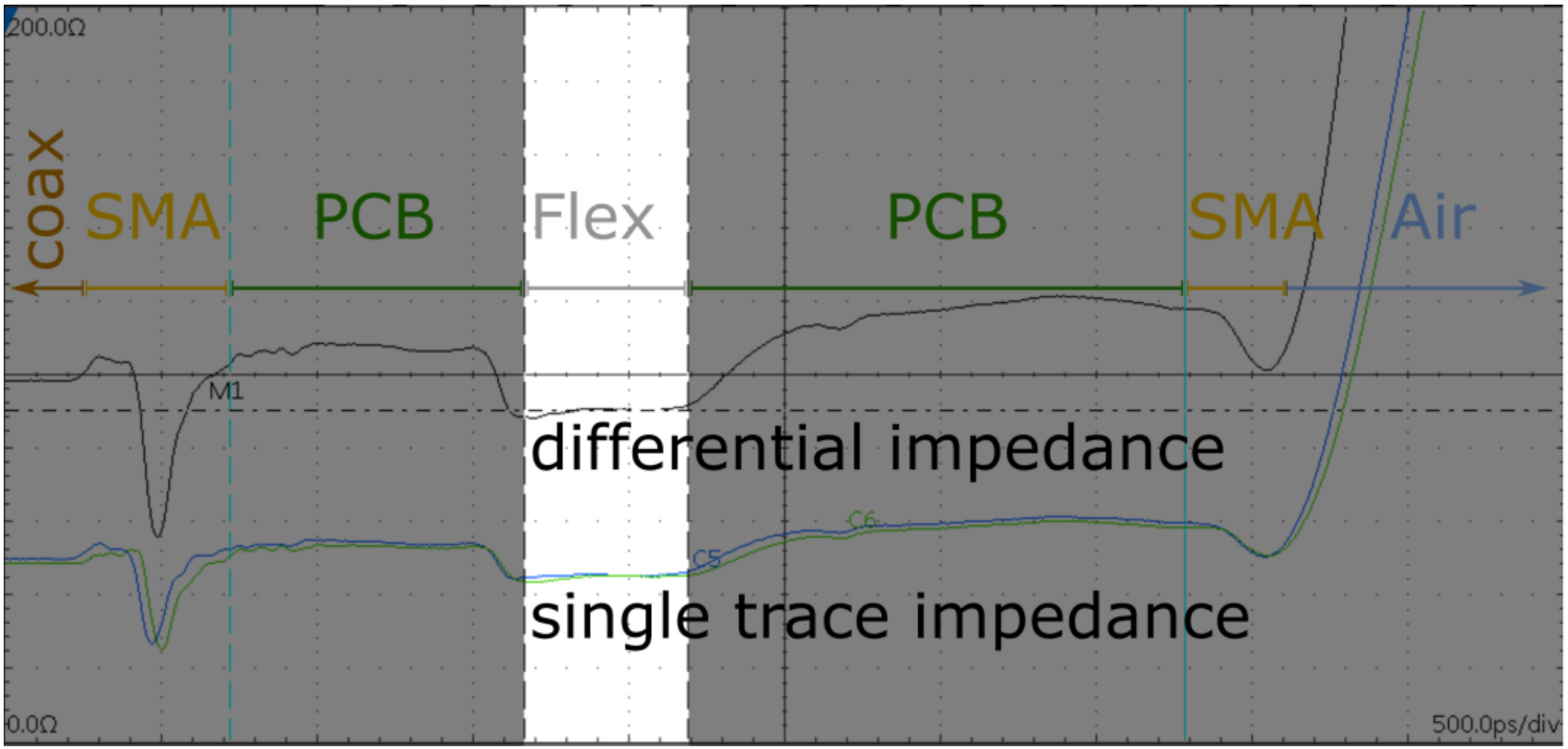

Flexprint Prototype - Test Structure

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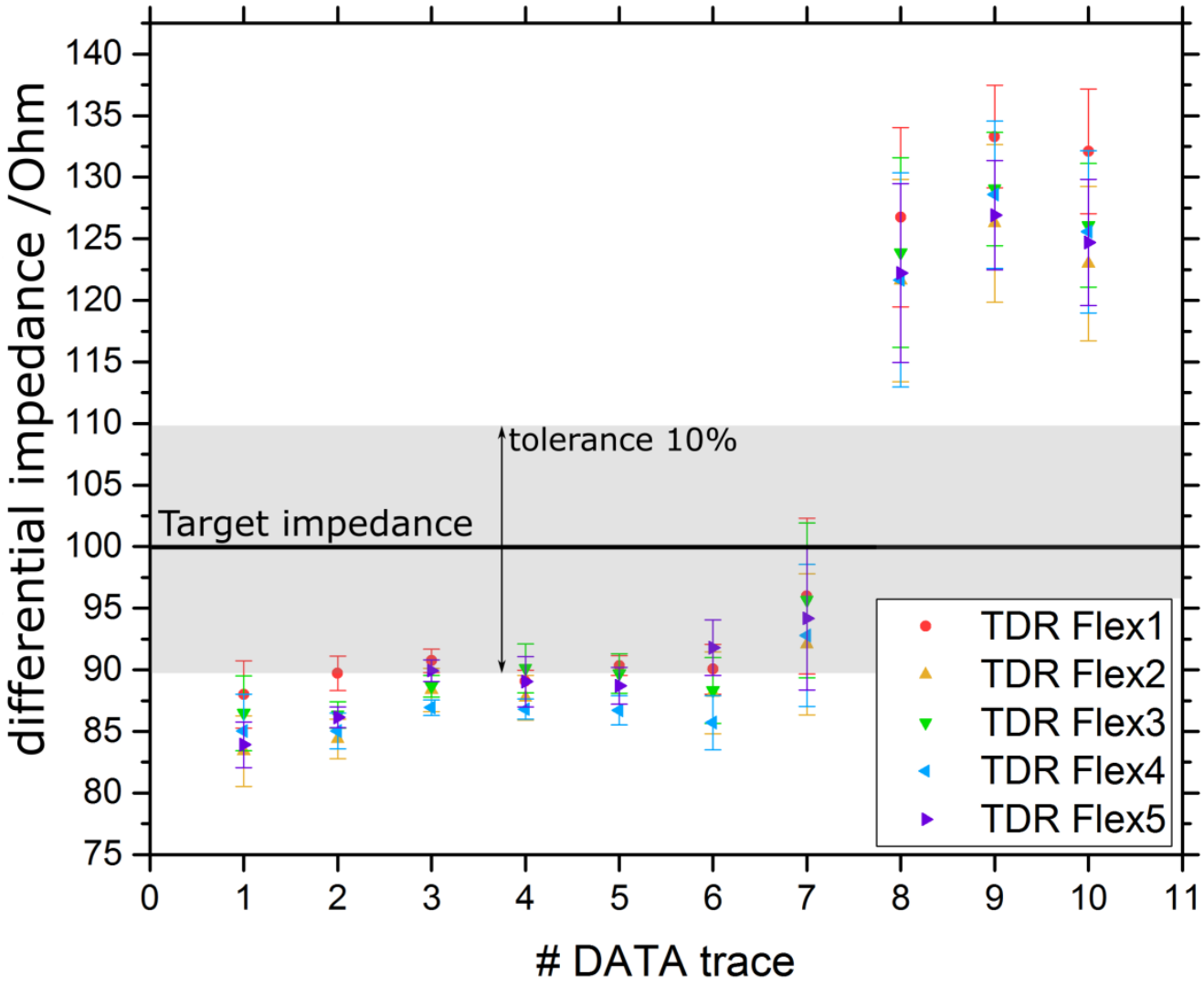
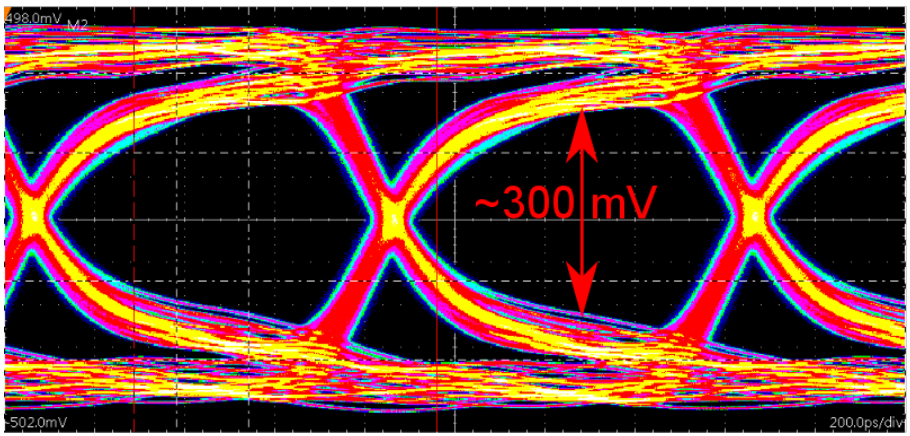


Flexprint Prototypes - Test Structure

Data Transmission Studies

- eye diagram analysis



Eye diagram at 1.25 Gb/s

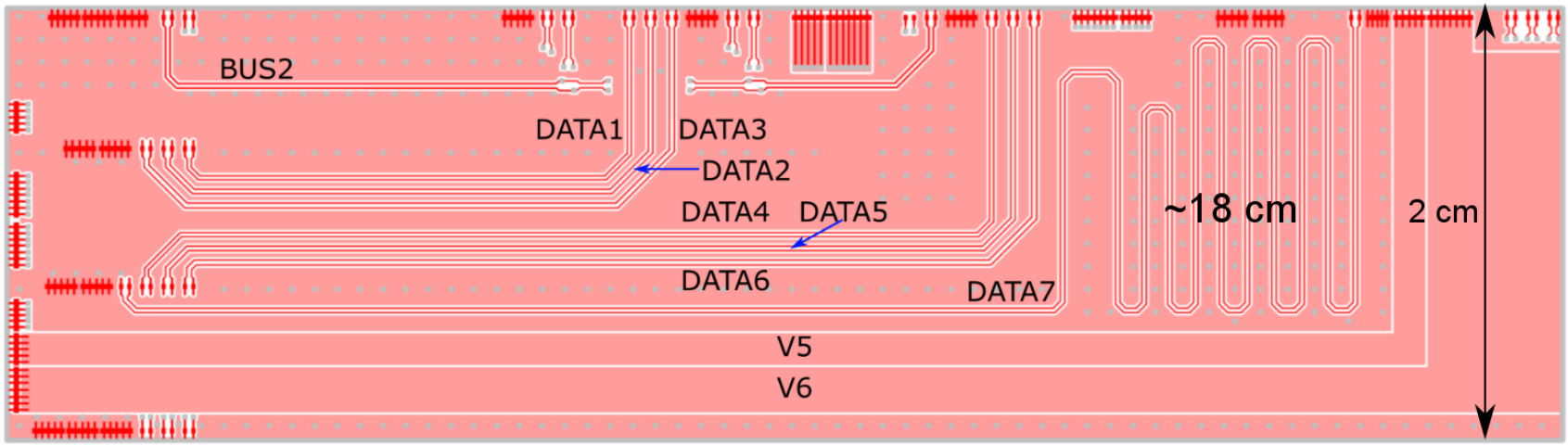
- bit error rate test
  $\rightarrow$ transmit pseudo random bit stream

$$BER = \frac{\#\text{ error bits}}{\#\text{ transmitted bits}}$$

Flexprint Prototypes - Test Structure

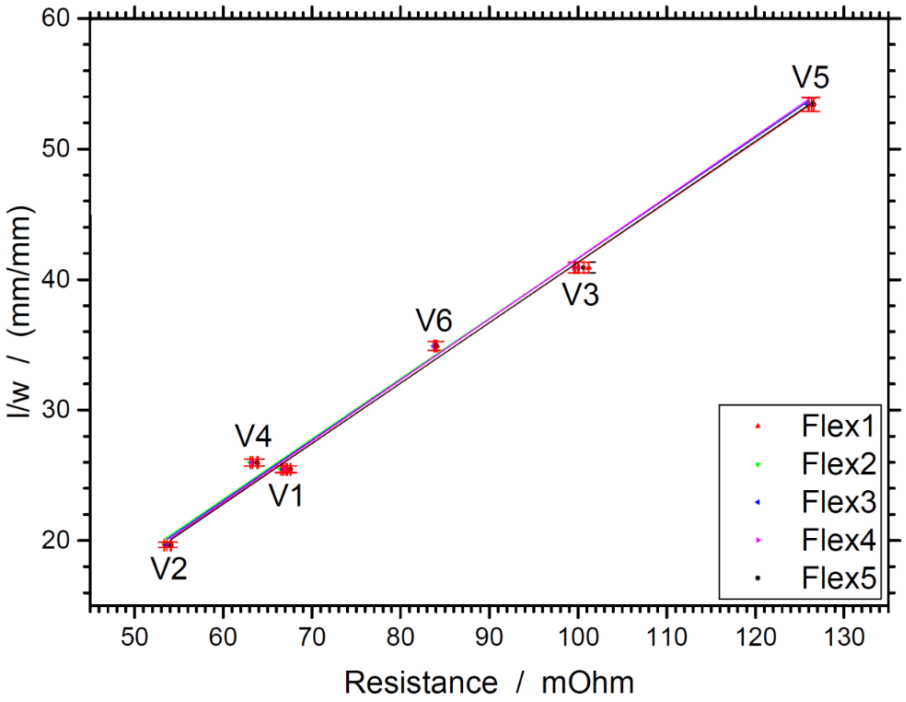
Bit Error Rate Test

data rate [Gb/s]	line	BER upper limit at 95% CL
1.25 Gb/s	**all**	$\leq 5.5 \times 10^{-13}$
2.5 Gb/s	all	$\leq 5.9 \times 10^{-13}$
3.2 Gb/s	all short	$\leq 4.1 \times 10^{-13}$
	18 cm	fail
4.0 Gb/s	all	fail

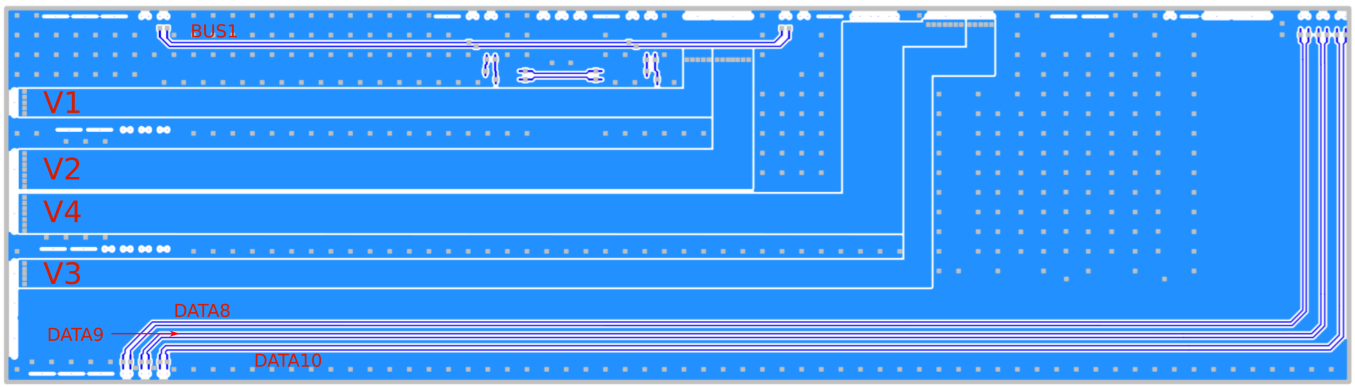


Flexprint Prototype - Test Structure

Power Planes



- manufacturer:
  Al thickness $\sim 14\,\mu m$
- $R = R_0 + \rho_{Al} \frac{1}{t} \frac{l}{w}$
- thickness from resistance measurement:
  $t = 12.3 \pm 0.3\,\mu m$
- no significant deviations between flexprints



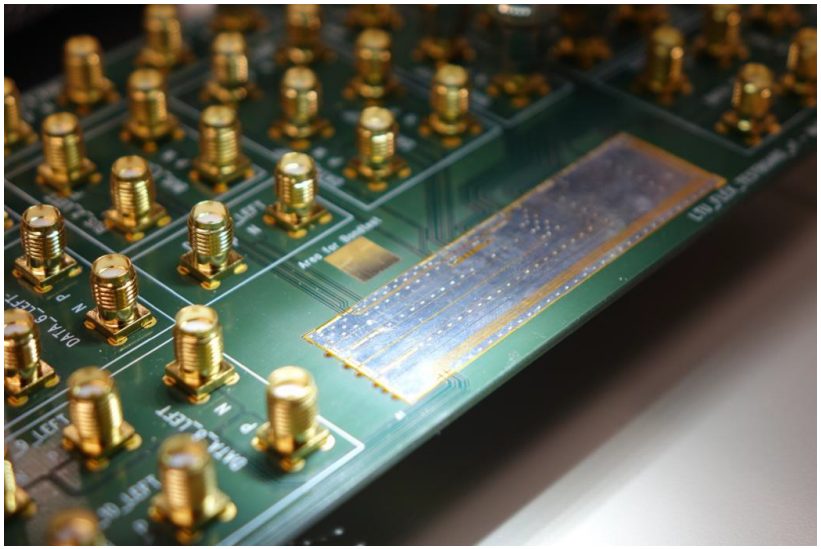
Flexprint Prototypes - Summary and Next Steps

Summary

- Mu3e: search for cLFV
- **ultra-low material** detector
- flexprints for readout and power supply of pixel tracker
- very promissing
  - **bit error rate tests** and
  - **power tests**

Next Steps

- improve trace parameters
- operate **one** pixel chip on a flexprint
- operate **multiple** pixel chips on a flexprint



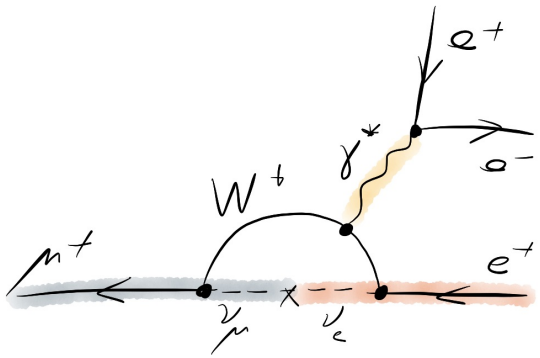
References

[1] ATL-INDET-PROC-2015-001
[2] CERN-LHCC-2012-016, CMS-TDR-11
[3] arXiv:1211.4494v1
[4] talk by G. Contin at PIXEL 2016
[5] talk by C. Koffmane at PIXEL 2016
[6] `https://upload.wikimedia.org/wikipedia/commons/f/f0/NatCopper.jpg`
[7] `https://upload.wikimedia.org/wikipedia/commons/5/5d/Aluminium-4.jpg`
[8] L. Noehte, *Flexprint design and characterization for the Mu3e experiment*, Bachelor thesis, Heidelberg University, 2016, `https://www.psi.ch/mu3e/ThesesEN/BachelorNoehte.pdf`

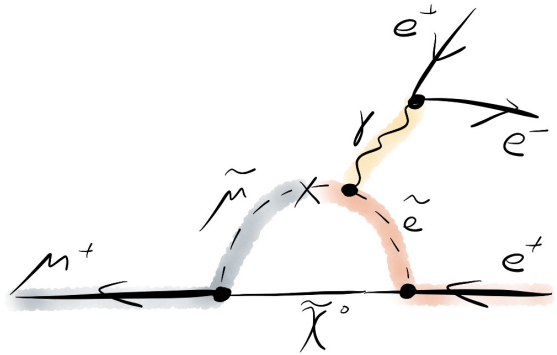
Backup

The Mu3e Experiment - Motivation

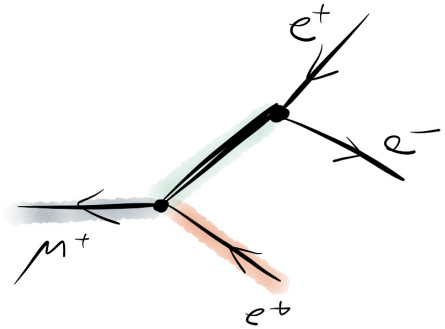
- search for lepton-flavour violating decay $\mu^+ \rightarrow e^+e^-e^+$
- sensitivity: 1 in 10^{16} decays
- νSM branching ratio $\leq 10^{-54}$
- signal would be clear sign for BSM physics



SM process

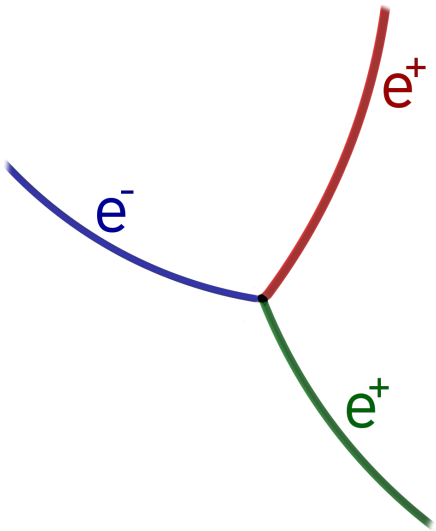


SUSY process

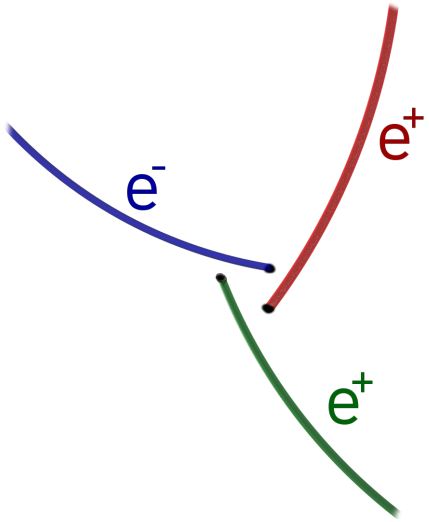


tree-level LFV process

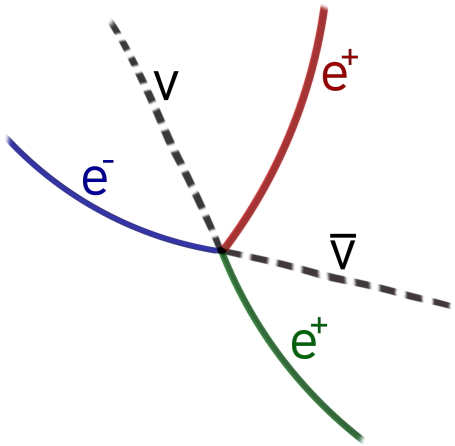
The Mu3e Experiment - Signal and Backgrounds



signal



combinatorial background

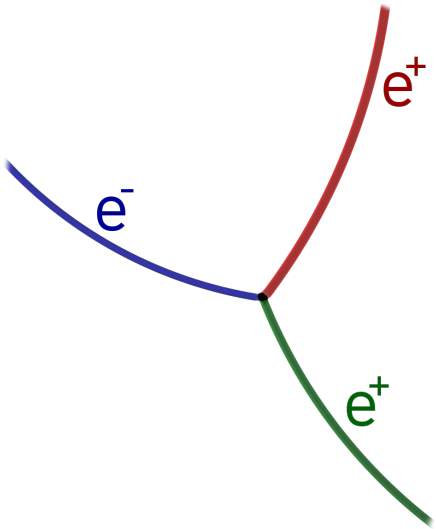


internal conversion background

→ **Detector Requirements:**

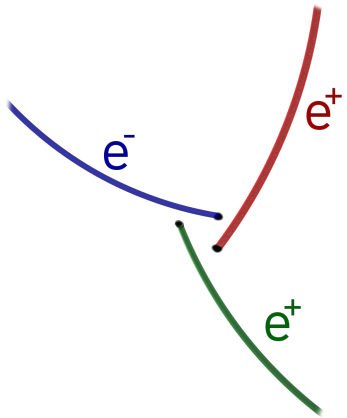
- very high vertex resolution
- excellent momentum reconstruction

The Mu3e Experiment - Signal and Background Topologies



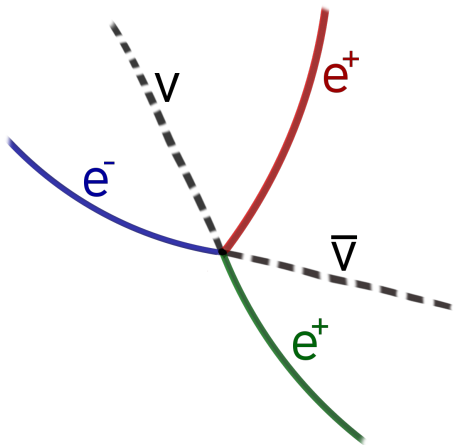
signal

- commom vertex
- coincident (in time)
- $\Sigma \vec{p} = 0$
- $\Sigma E = m_\mu$



combinatorial background

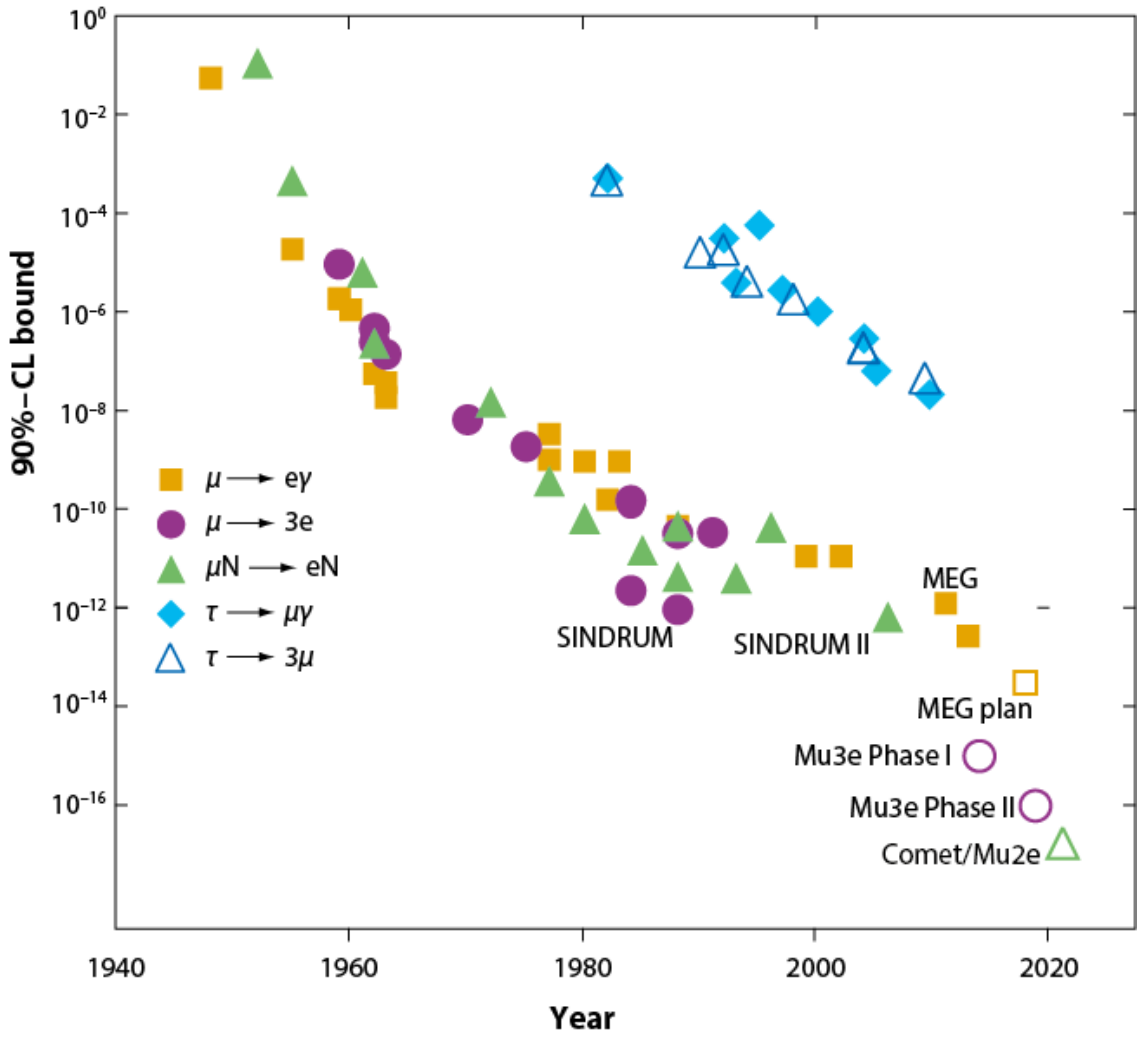
- no commom vertex
- not coincident (in time)
- $\Sigma \vec{p} = 0$
- $\Sigma E = m_\mu$



internal conversion background

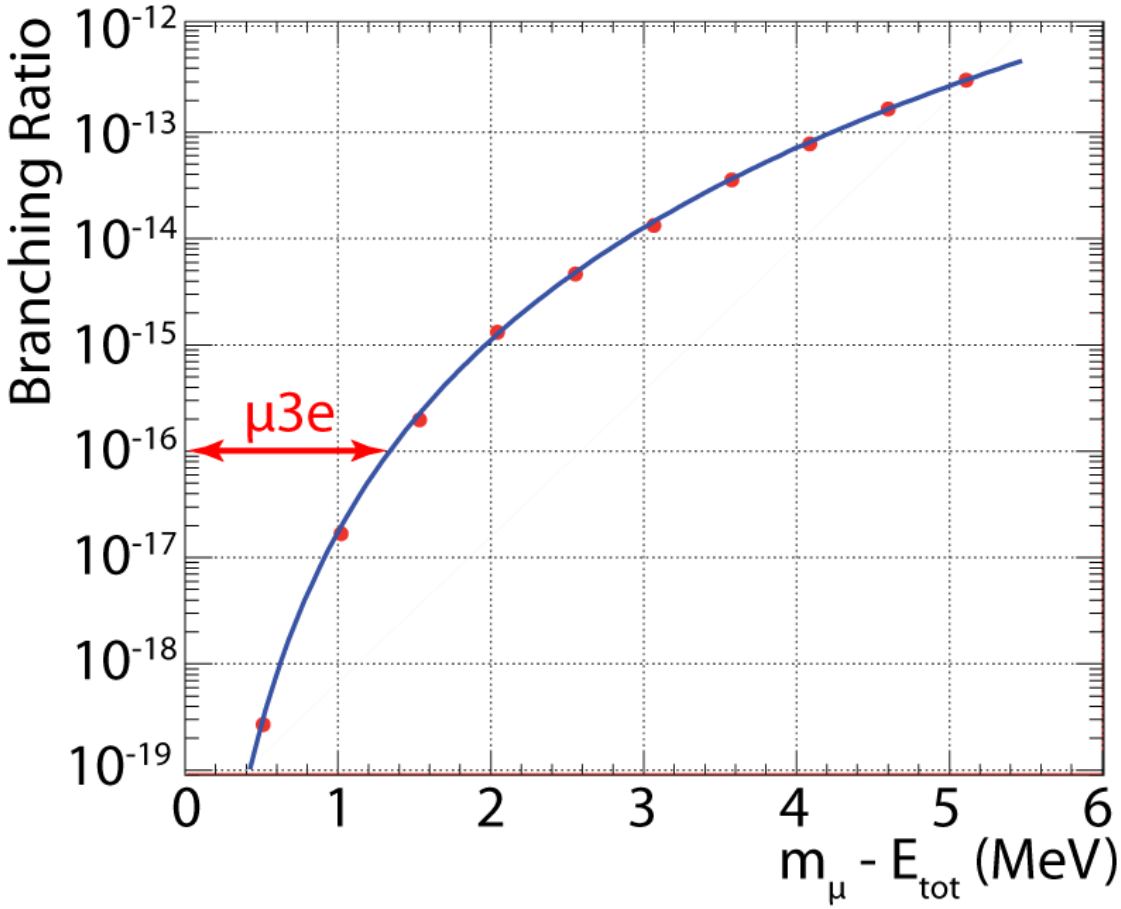
- commom vertex
- coincident (in time)
- $\Sigma \vec{p} \neq 0$
- $\Sigma E \neq m_\mu$

History of LVF Experiments



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

E_{miss} Resolution Requirement for Mu3e



R.M. Djilkibaev and R.V. Konoplich, Rphzs.Rev., D79 073004, 2009