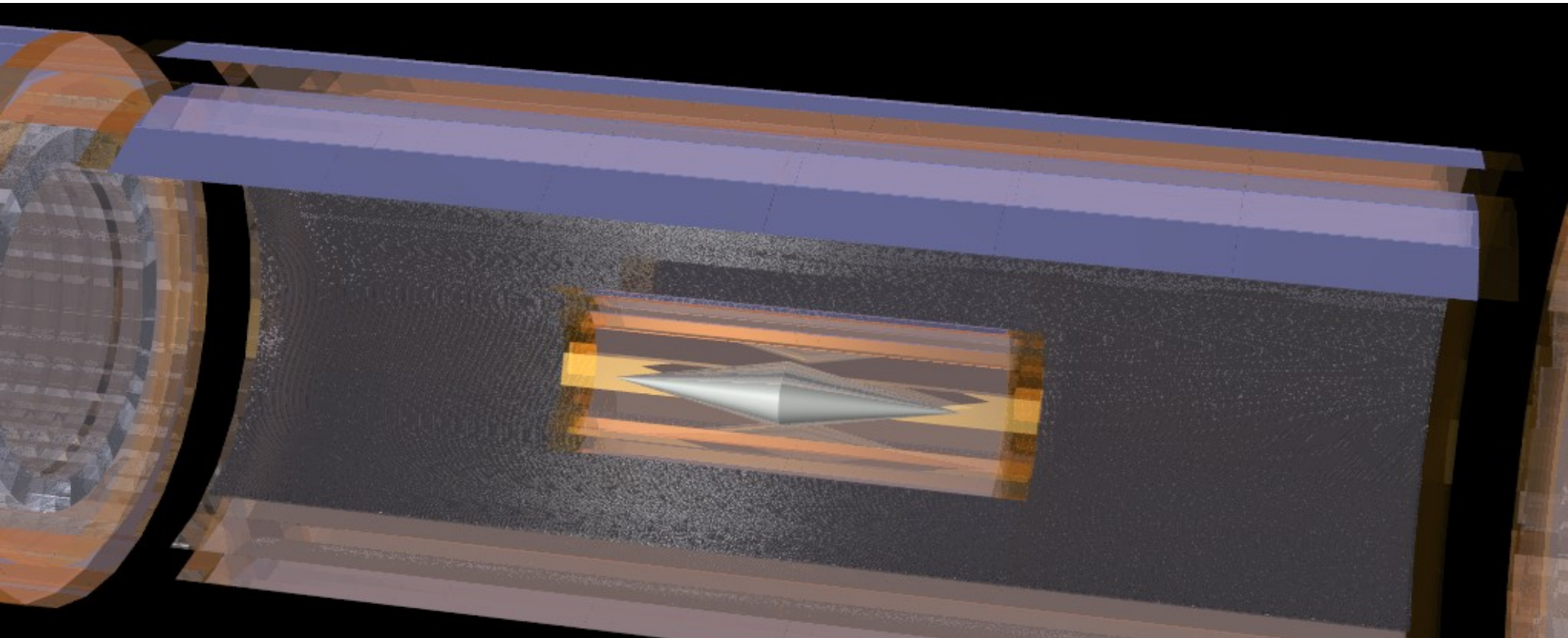
Status of the Mu3e Experiment

Open Users Meeting BVR49

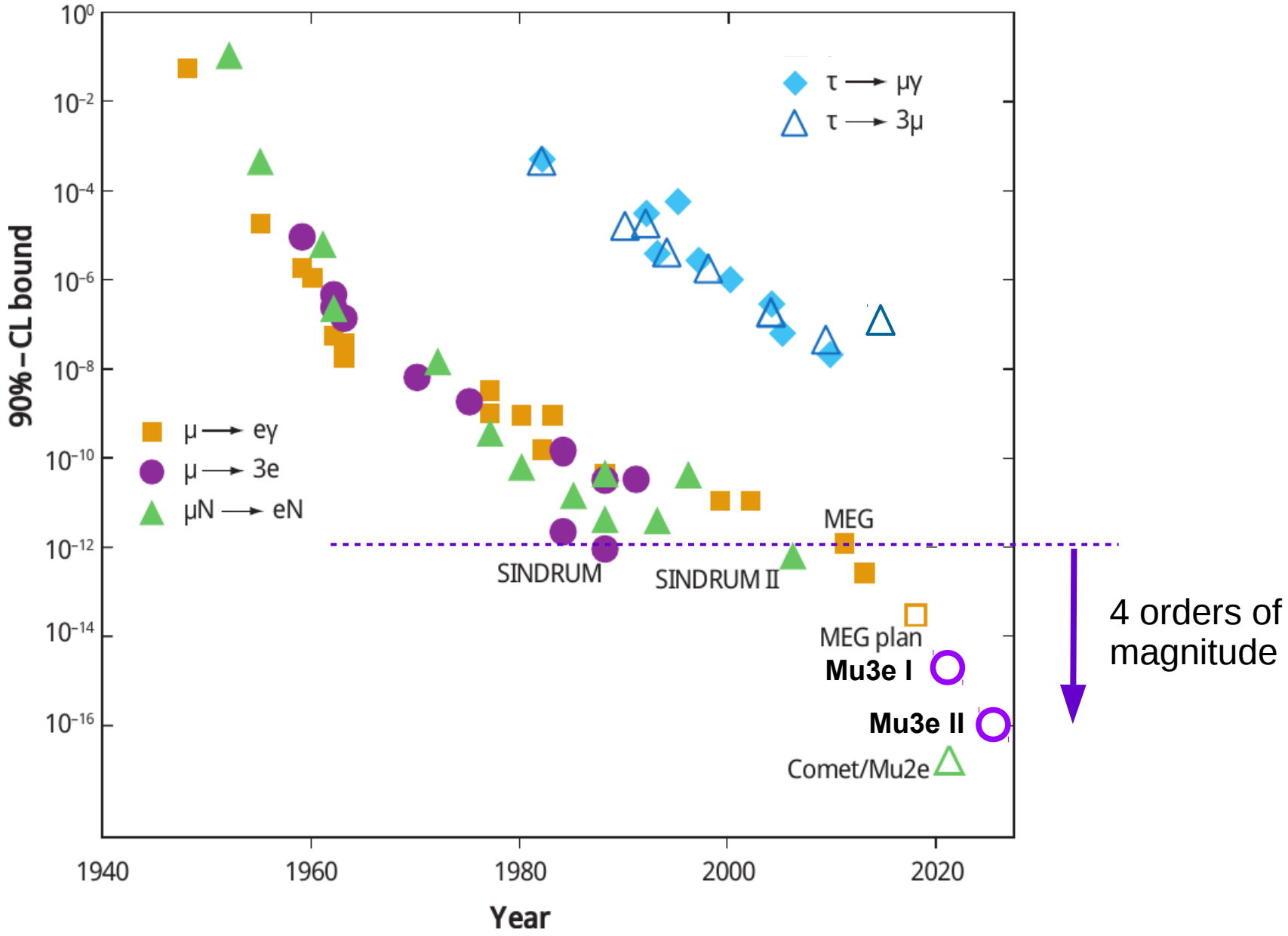
February 13, 2018

André Schöning

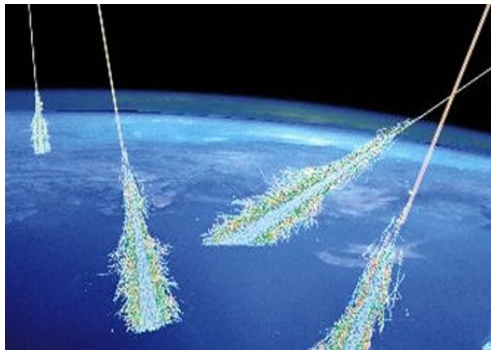
for the Mu3e Collaboration

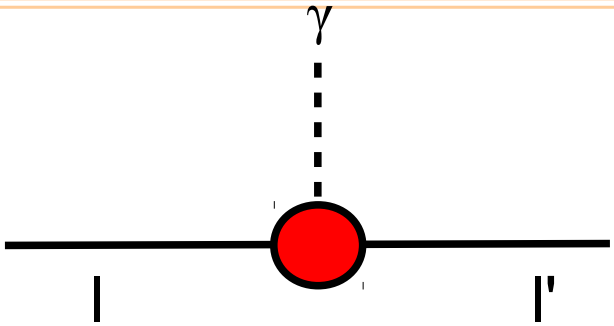


History of LFV Decay experiments



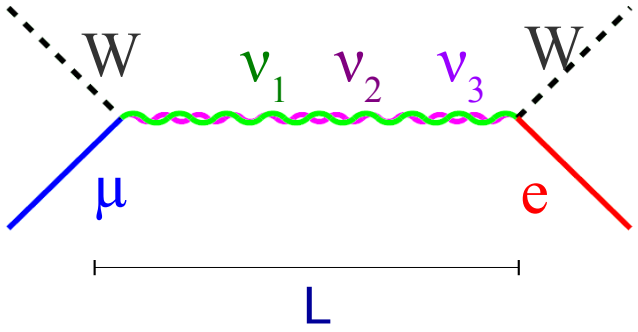
Lepton Mixing & Lepton Flavor Violation





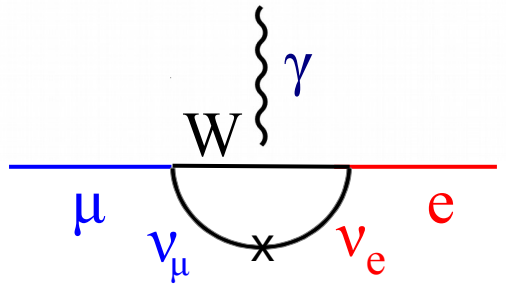
μ → e via ν-oscillation

μ → e γ via quantum loop



$L \to 1/m_W$

$E_\nu \to m_W$

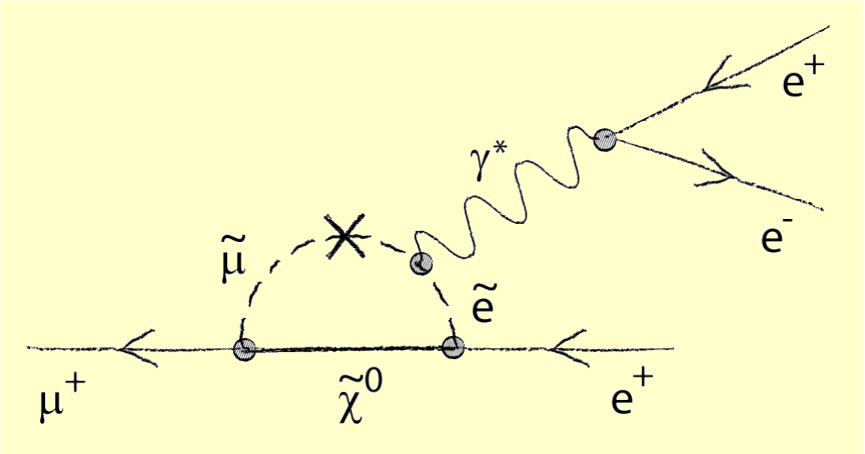


$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\Theta)\sin^2\left(\Delta m^2_{\alpha\beta}\frac{L}{E_\nu}\right)$$

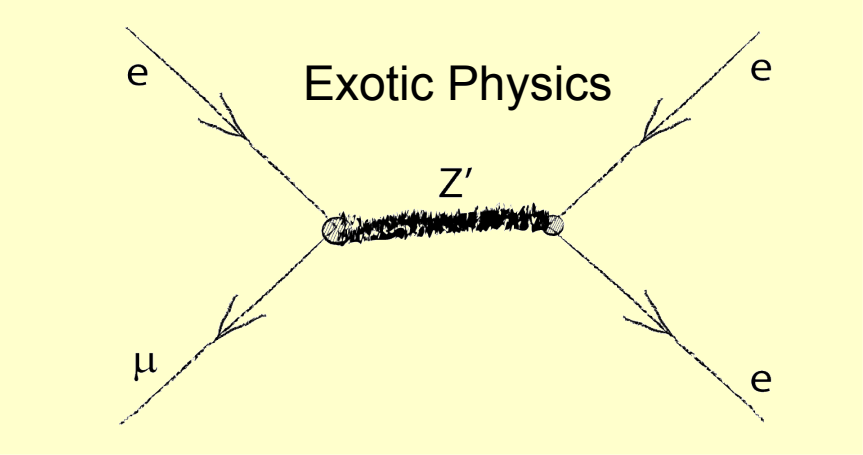
$$B(\mu \to e\gamma) \propto \sin^2(2\Theta)\left(\Delta m^2_{\alpha\beta}/m^2_W\right)^2$$

$$\propto \frac{(\Delta m^2_\nu)^2}{m^4_t} \approx y^4_\nu \approx 10^{-50}$$

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



loop diagrams



tree diagram

- **Supersymmetry**
- **Little Higgs Models**
- **Seesaw Models**
- **GUT models (Leptoquarks)**
- **many other models**

- **Higgs Triplet Model**
- **New Heavy Vector bosons (Z')**
- **Extra Dimensions (KK towers)**

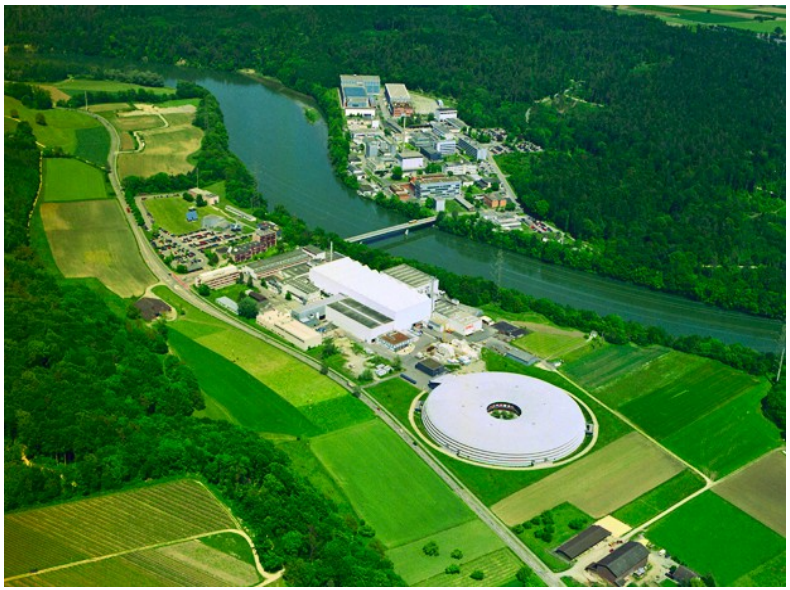
Many models "naturally" induce charged lepton flavor violation (cLFV)

Mu3e Experiment

Search for $\mu^+ \rightarrow e^+e^+e^-$ at the Paul Scherrer Institute

project approved in Jan 2013

PSI provides
high intensity
DC muon beam
of E_{kin}=29 MeV



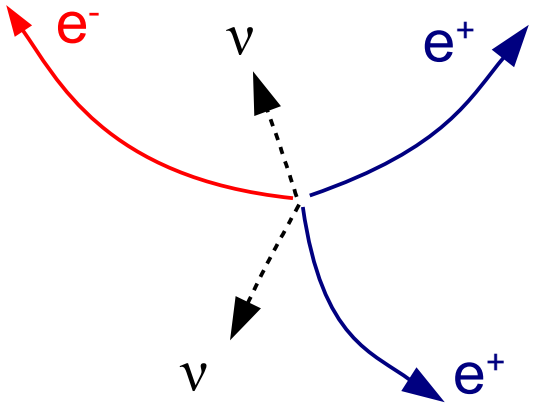
Aiming for a sensitivity of

$BR(\mu \rightarrow eee) < 10^{-15}$ (Phase I @ PiE5)

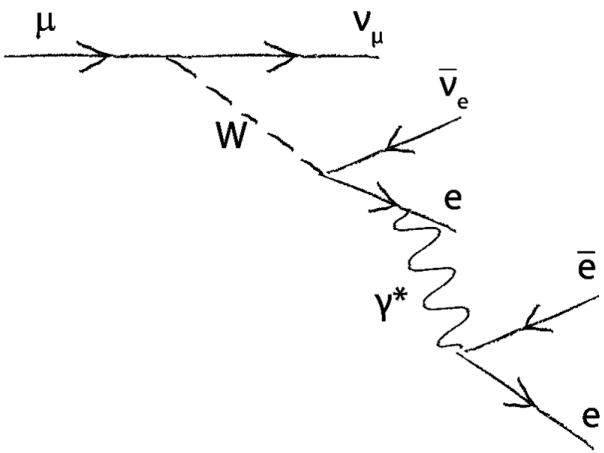
$BR(\mu \rightarrow eee) < 10^{-16}$ (Phase II @ HiMB - not approved)

Backgrounds

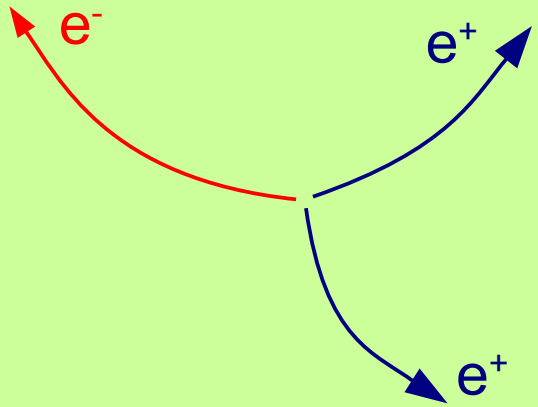
Irreducible BG: radiative decay with internal conversion



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



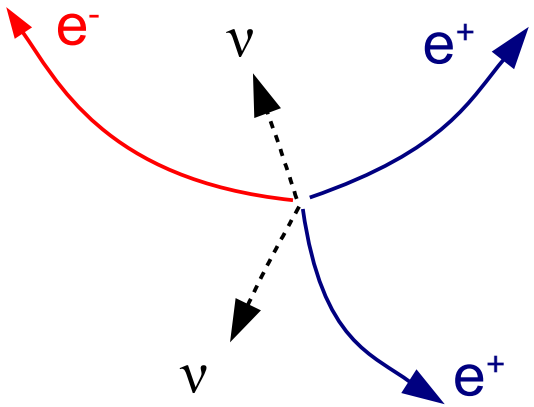
signal: $B(\mu^+ \rightarrow e^+e^+e^-)$



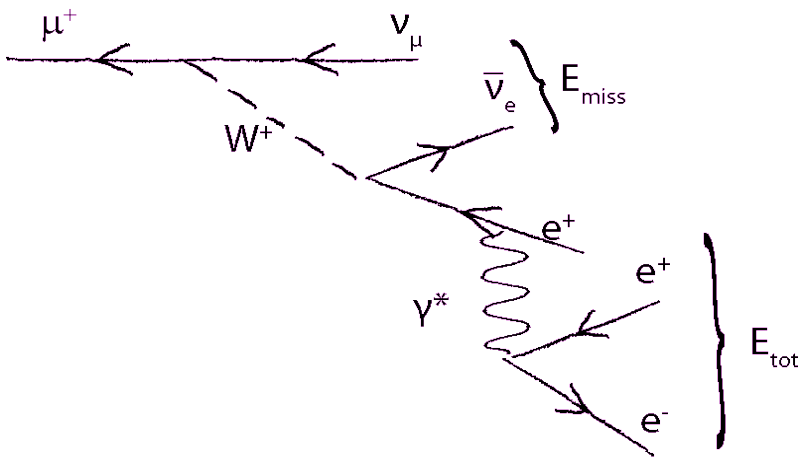
$$\sum_i E_i = m_\mu$$
$$\sum_i \vec{p}_i = 0$$

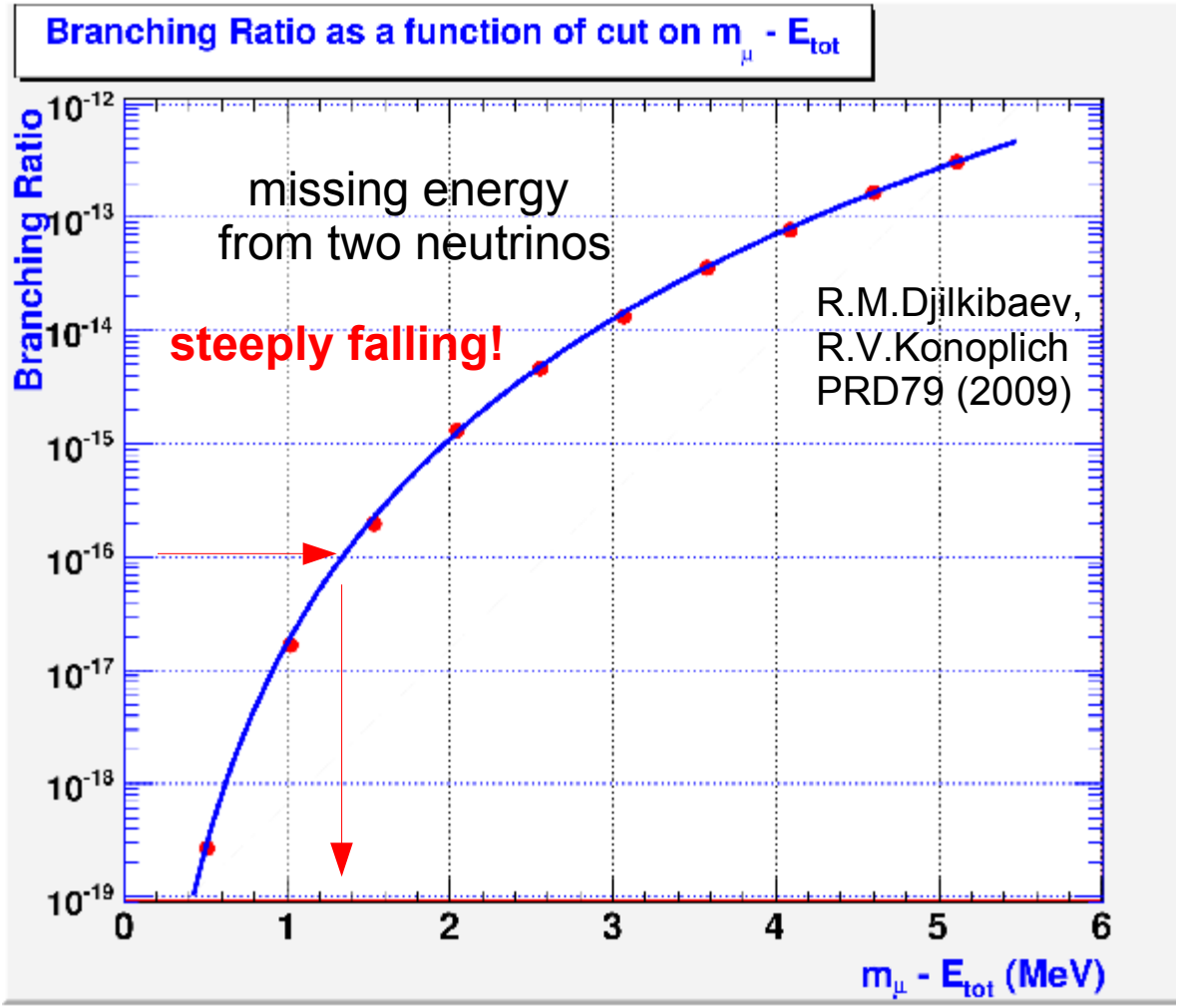
Backgrounds

Irreducible BG: radiative decay with internal conversion



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

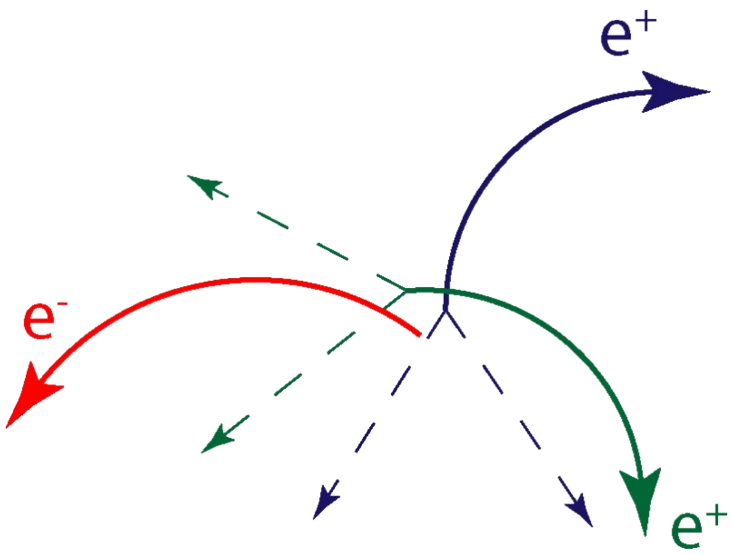


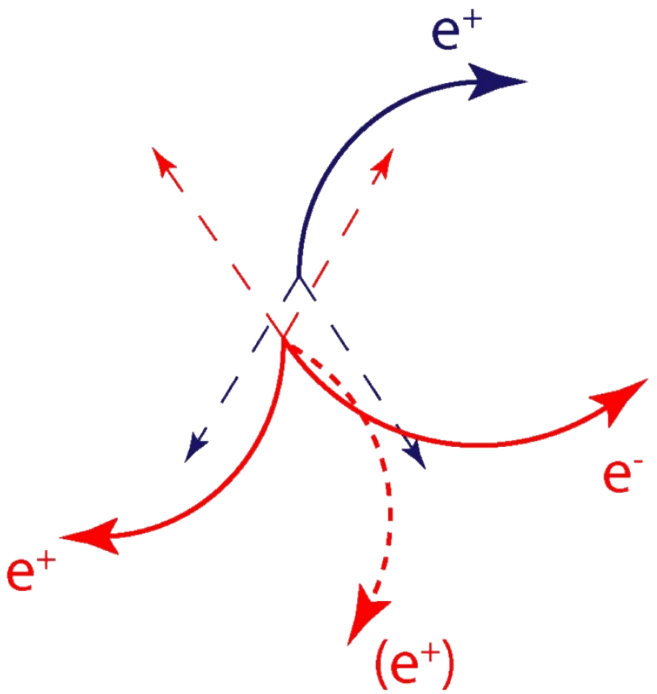


very good momentum +
total energy resolution required!

Accidental Backgrounds

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





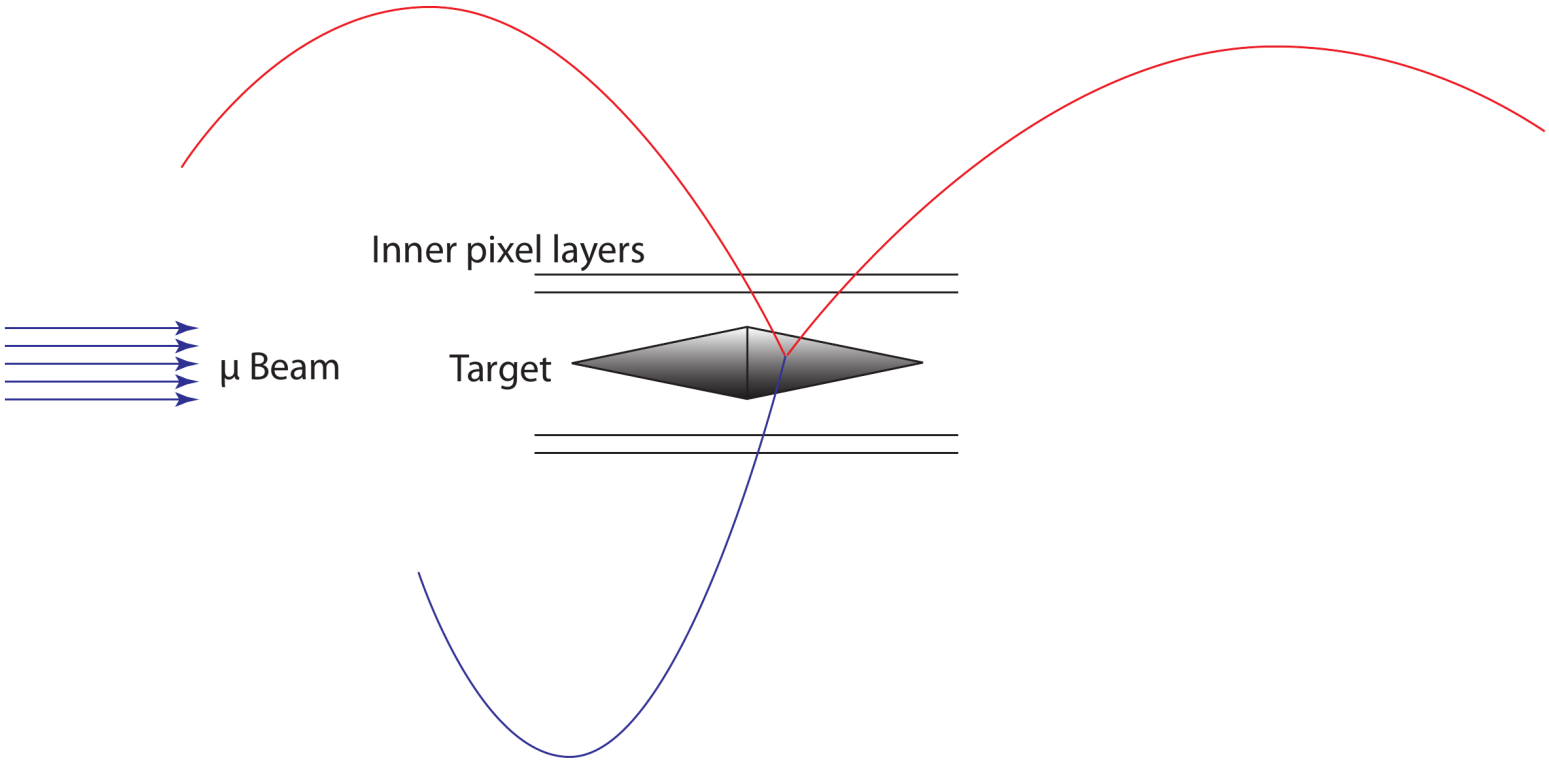
Need excellent:

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

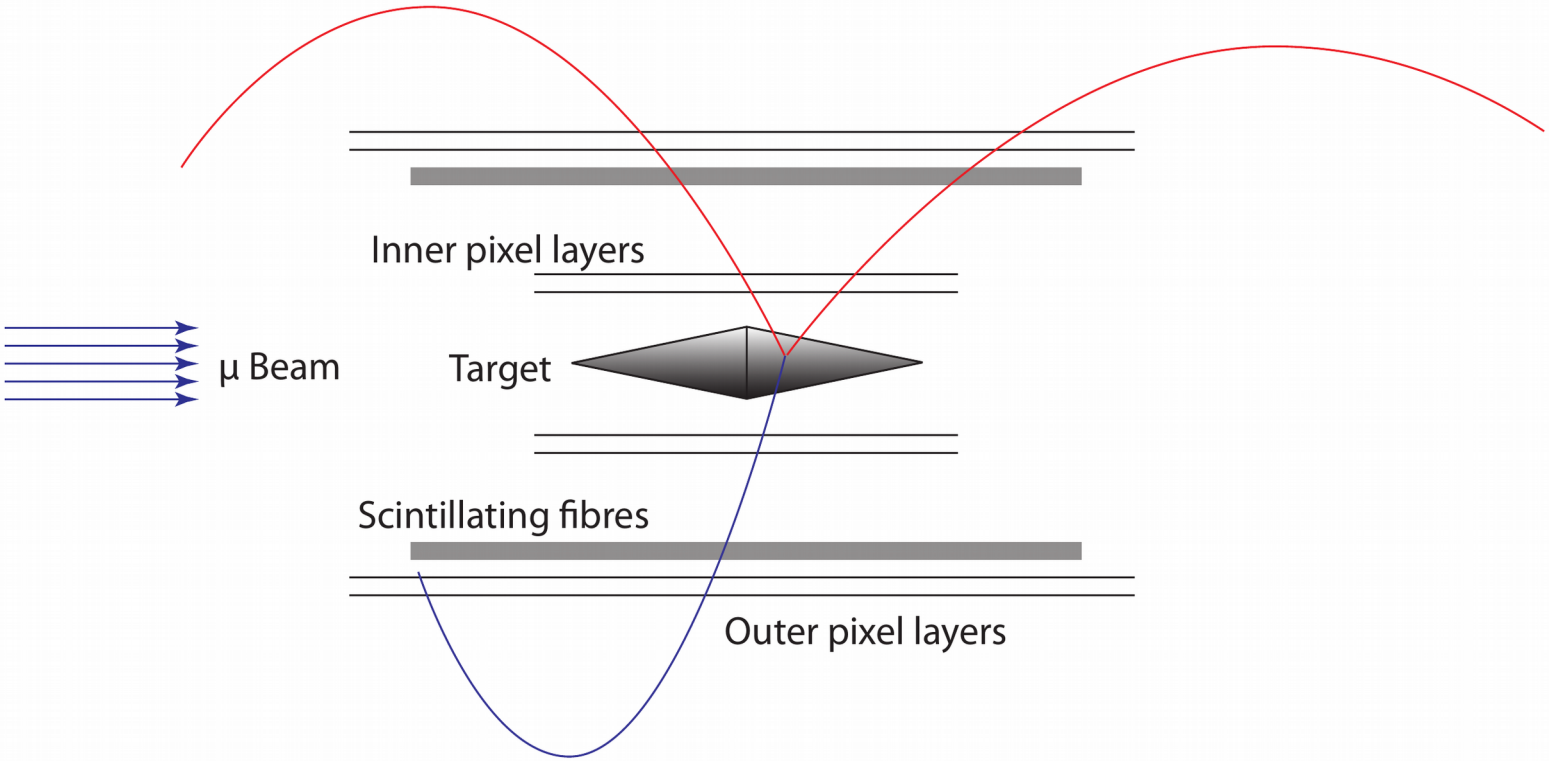
Mu3e Design Concept

Mu3e Baseline Design

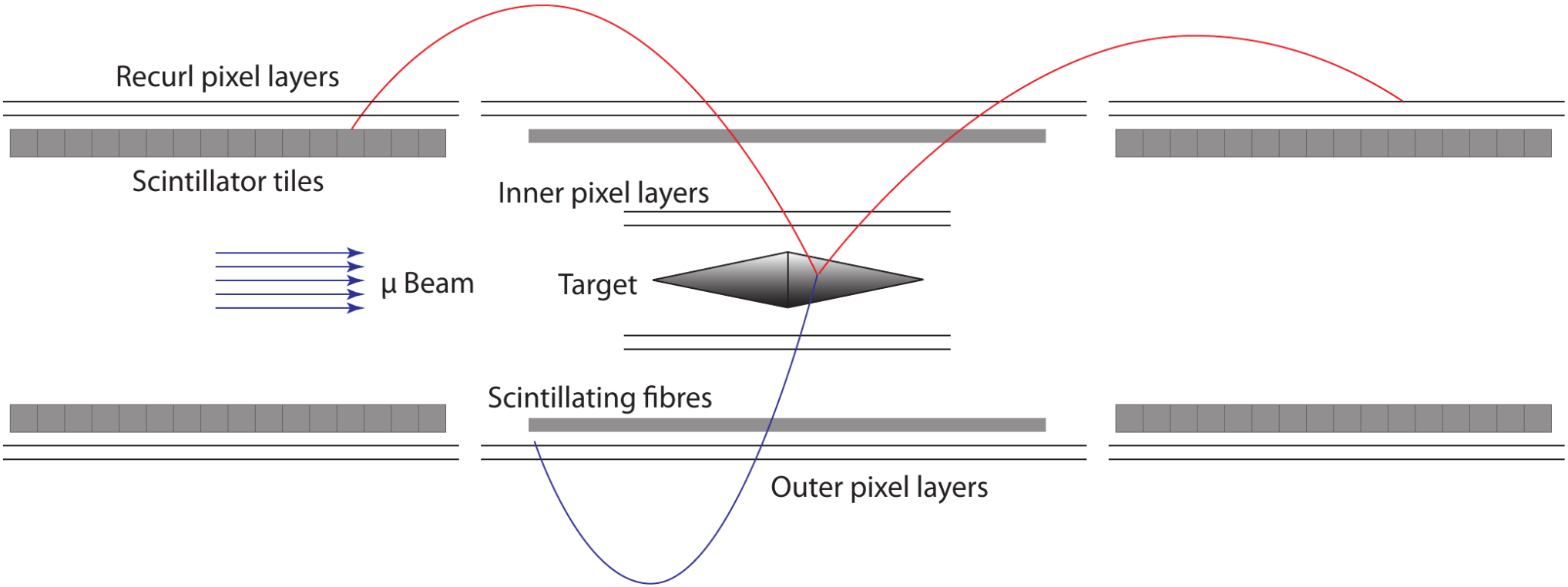
Mu3e Baseline Design



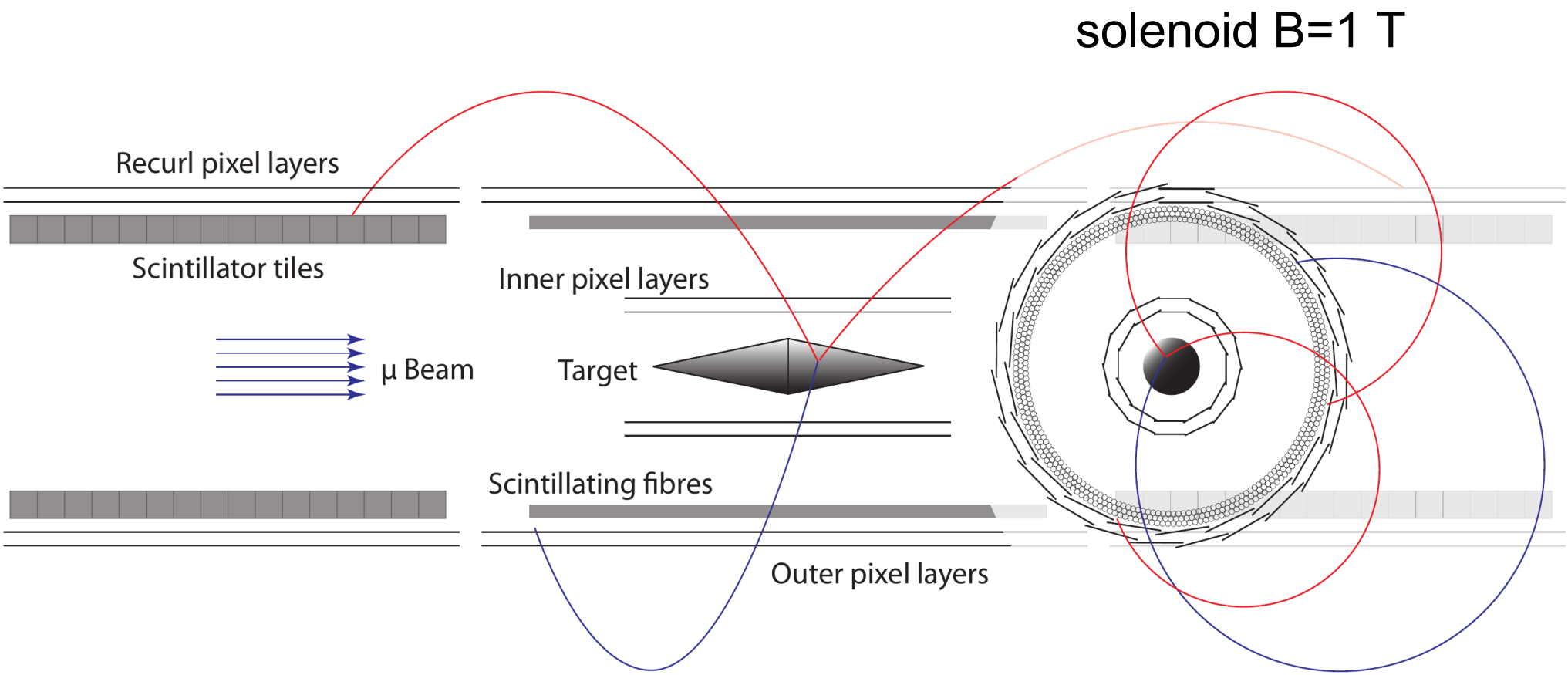
Mu3e Baseline Design



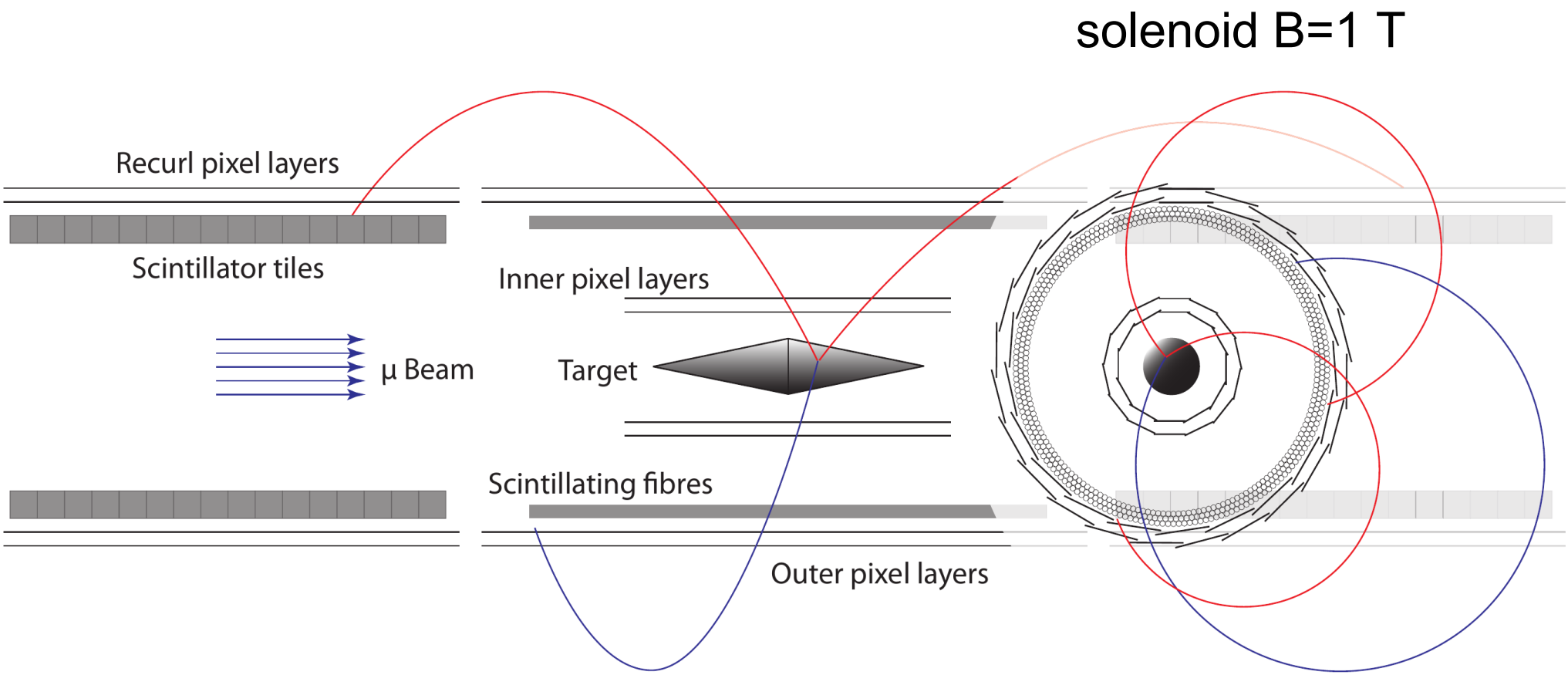
Mu3e Baseline Design



Mu3e Baseline Design



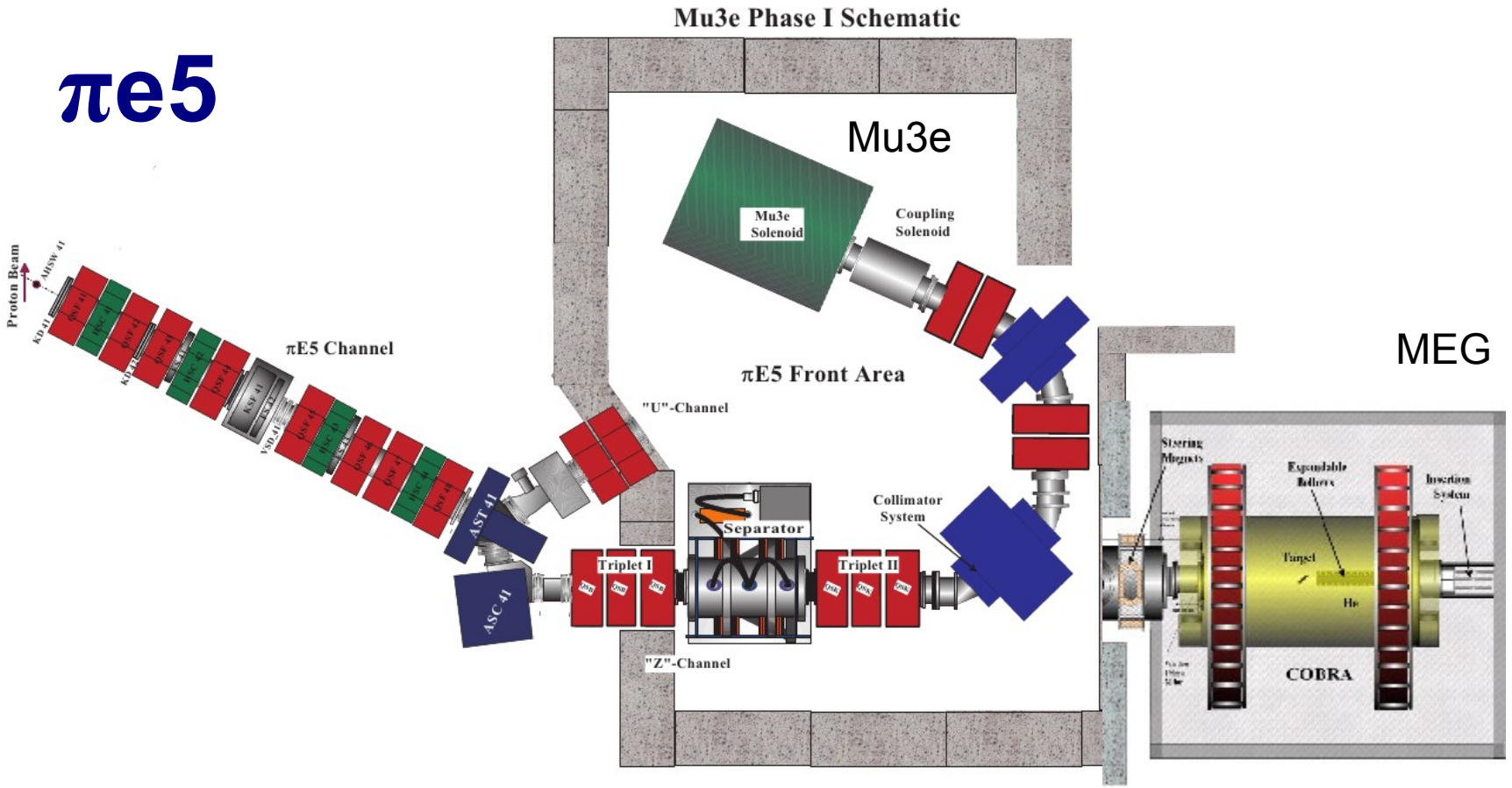
Mu3e Baseline Design



Momentum resolution dominated by multiple scattering!

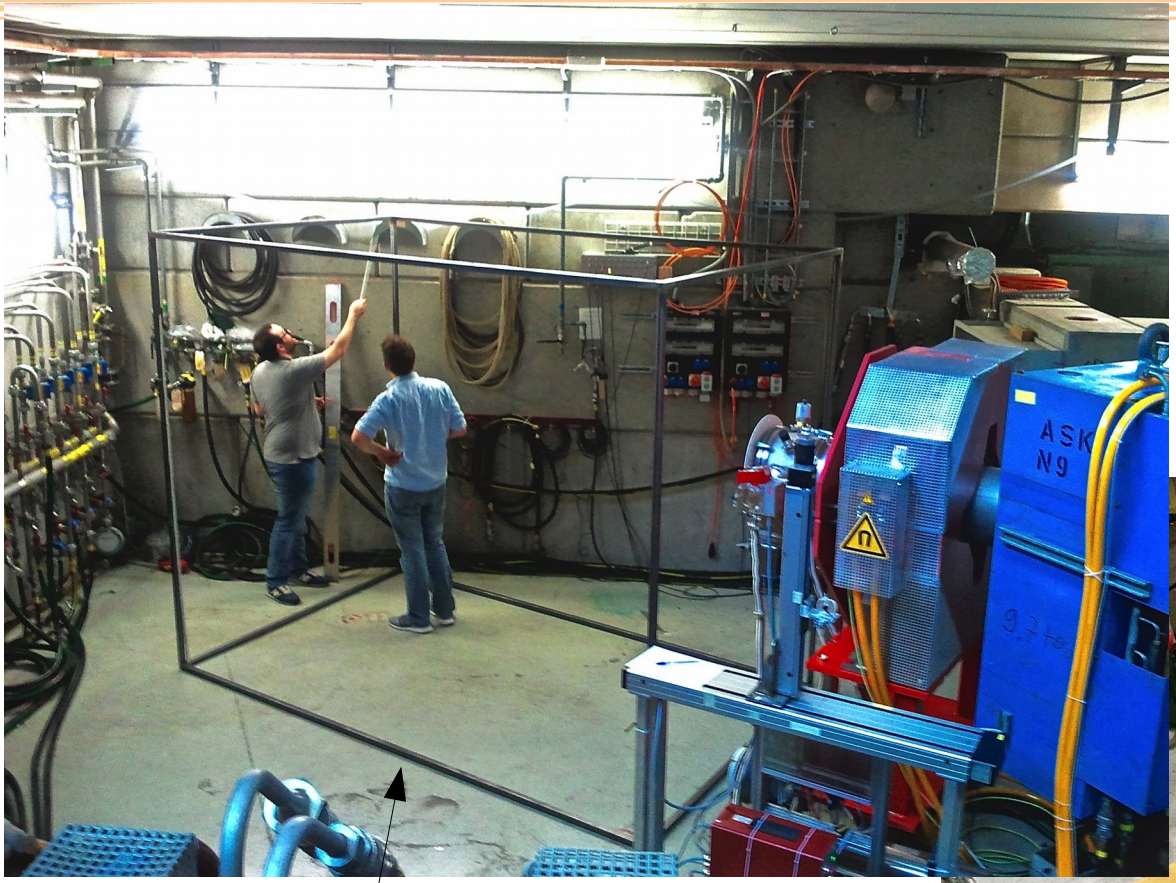
- **helium-gas atmosphere**
- **pixel tracking layer X/X_0 ~ 1 per mil!**

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**

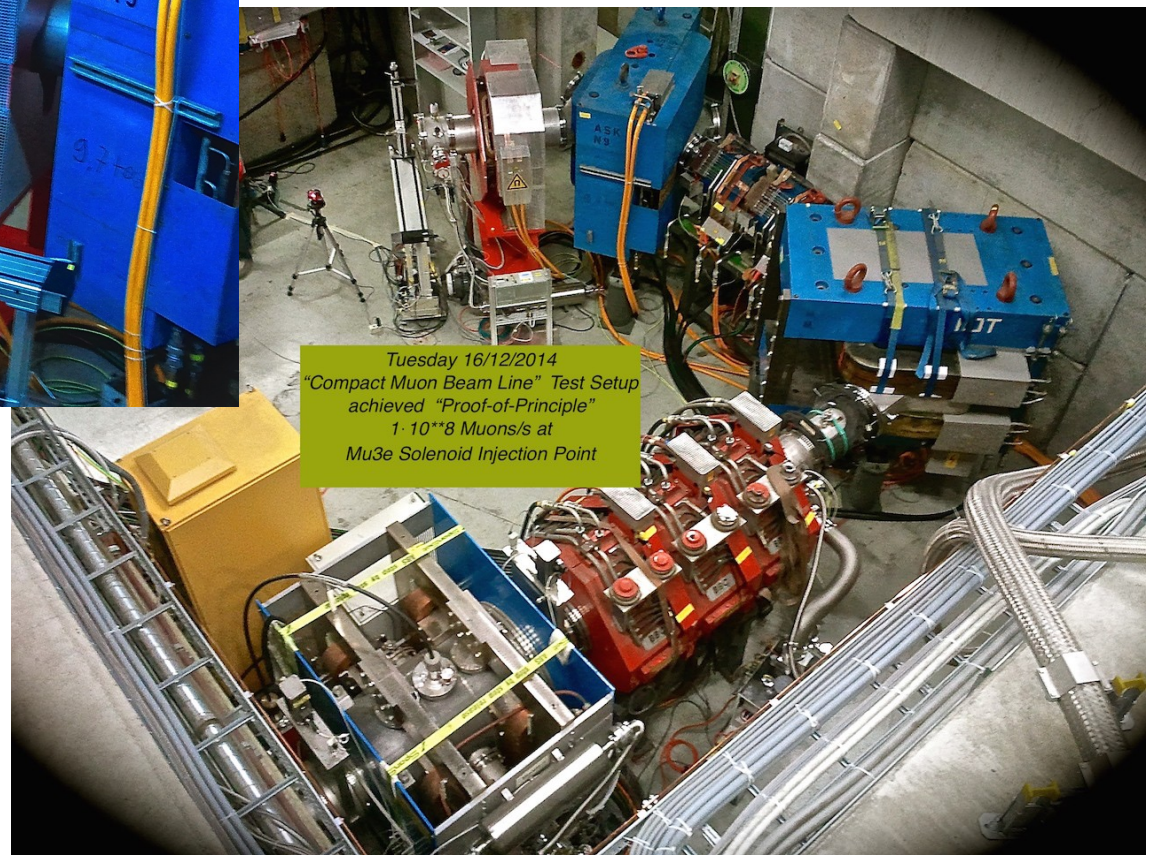
PiE5 Beamline + Experimental Region



mockup for Mu3e solenoid

Space is very tight!

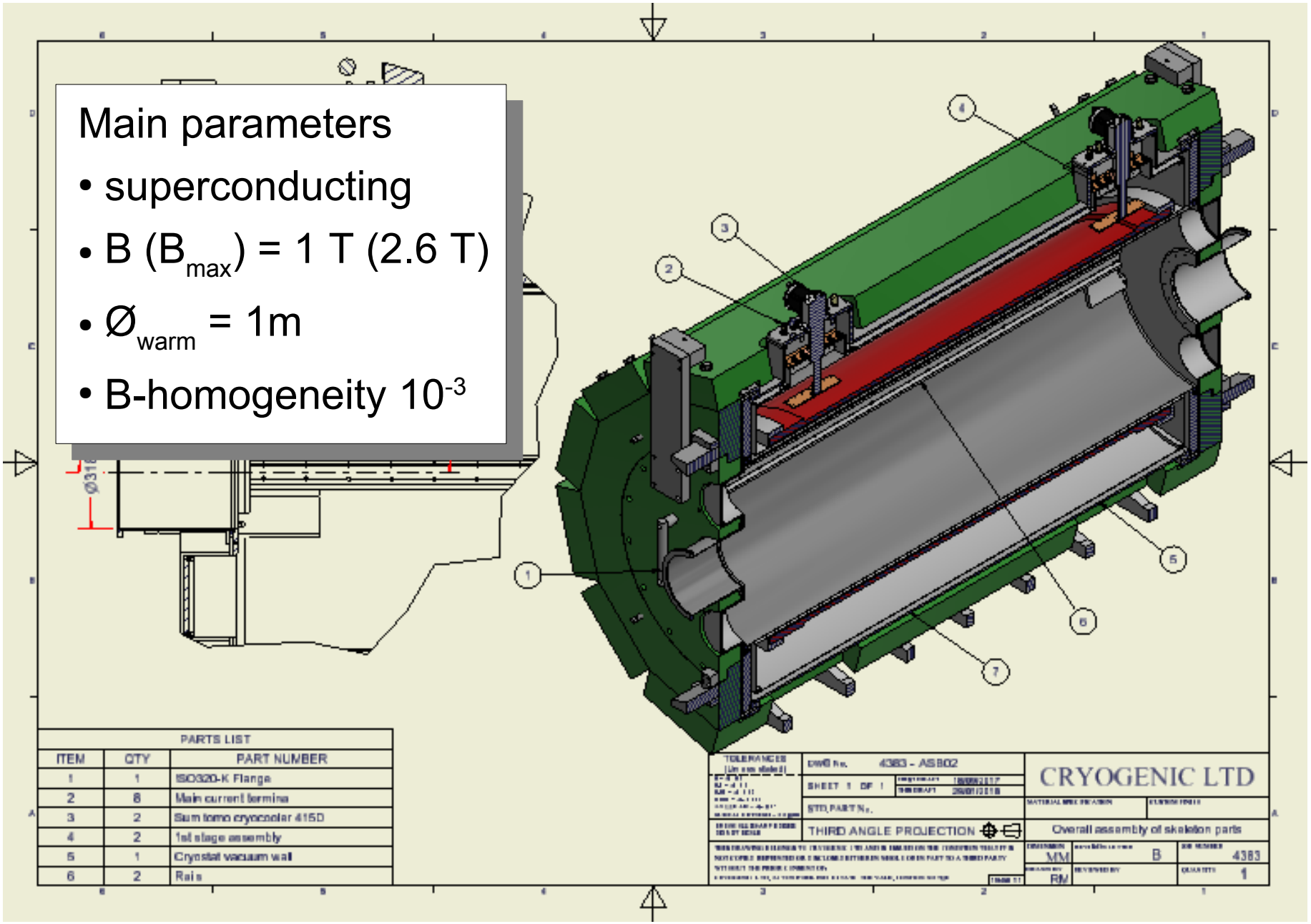
Compact Muon Beamline was successfully commissioned providing up to ~10^8 muons/s



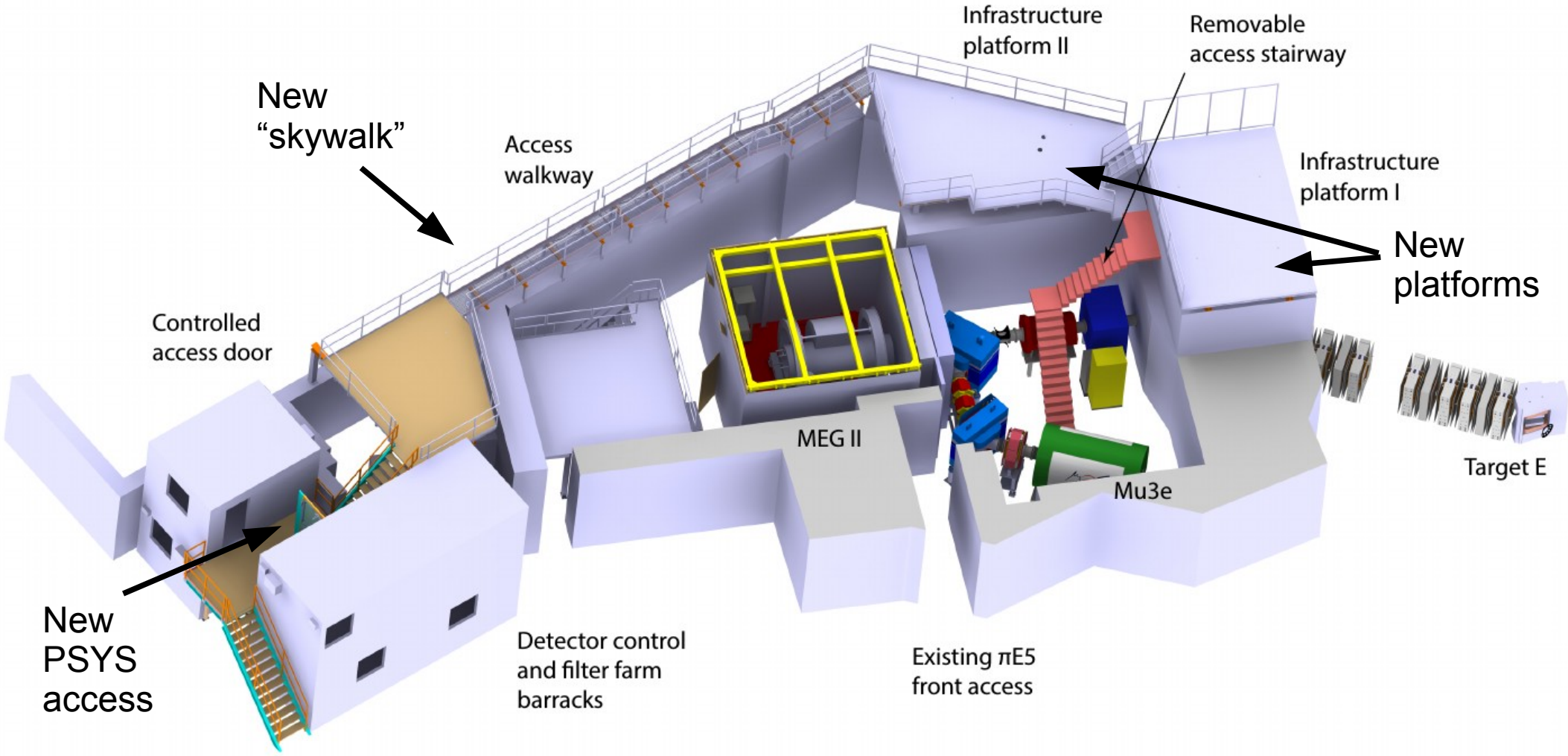
Prel. Design from Cryogenic Ltd.

Main parameters

- superconducting
- B (B_{max}) = 1 T (2.6 T)
- $Ø_{warm}$ = 1m
- B-homogeneity 10^{-3}



The Mu3e (MEG) PiE5 Area



New platforms needed for services

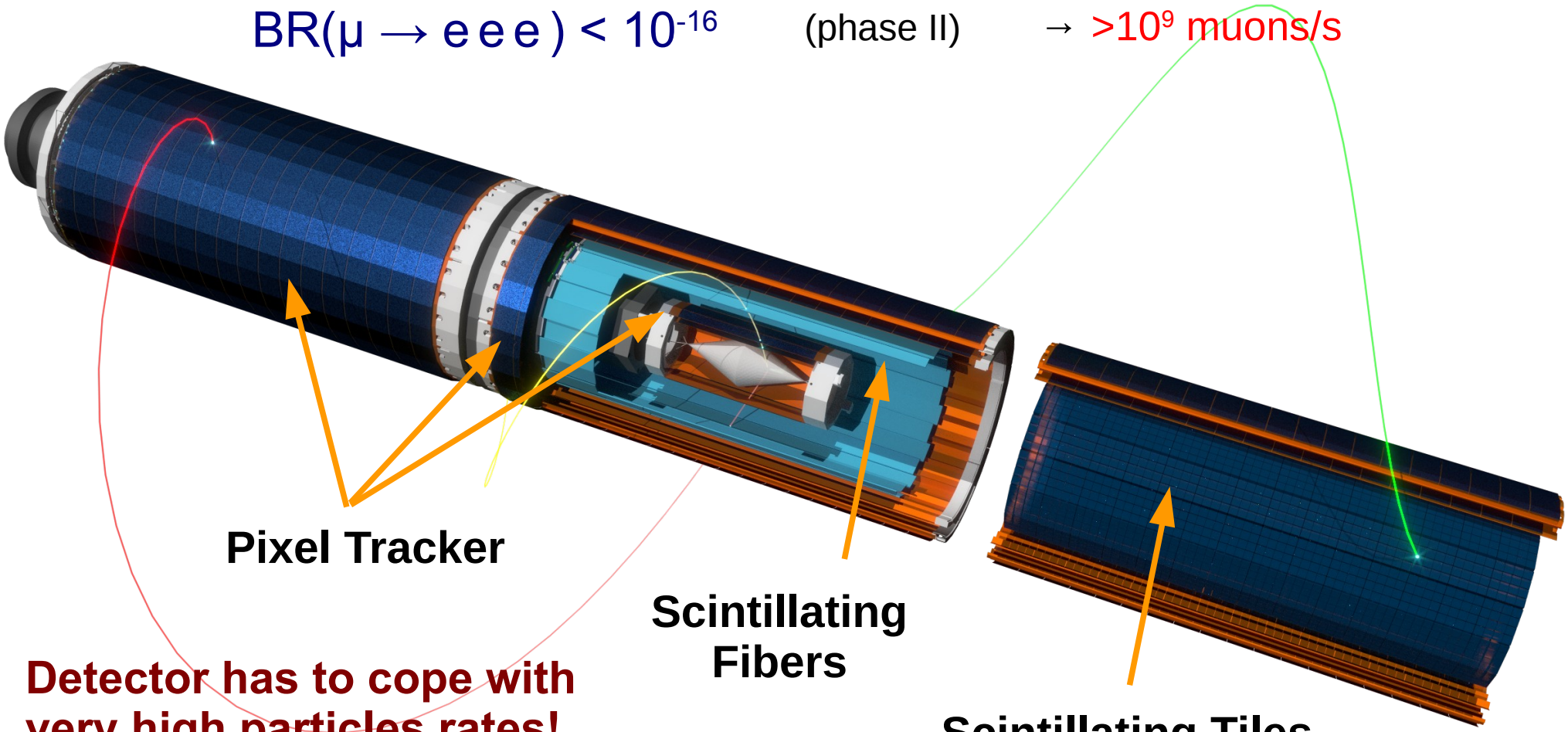
PiE5 Area
Mu3e skywalk constructed in 2017

Mu3e Experiment

Aiming for a sensitivity of

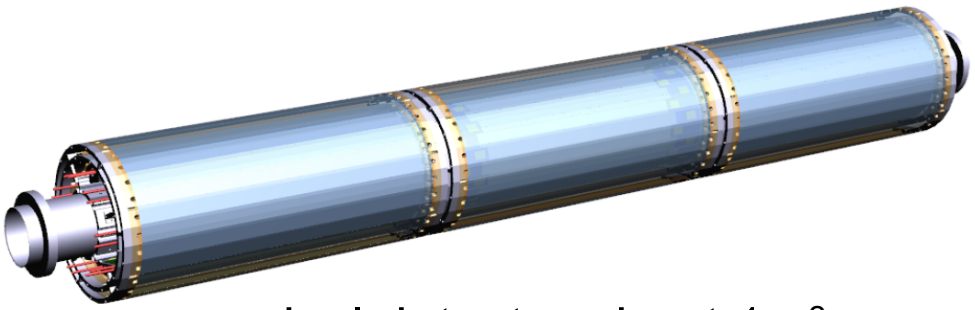
$BR(\mu \rightarrow eee) < 2 \cdot 10^{-15}$ (phase I) → 10^8 muons/s (existing)

$BR(\mu \rightarrow eee) < 10^{-16}$ (phase II) → $>10^9$ muons/s



Detector has to cope with very high particles rates!

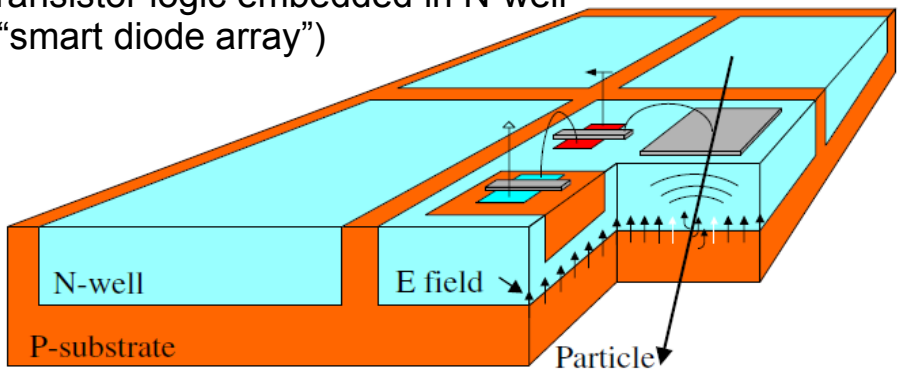
Pixel Detector Technology



- pixel detector about 1m^2
- very thin: X/X_0 ~ 1 per mil
- Helium gas cooling

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

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

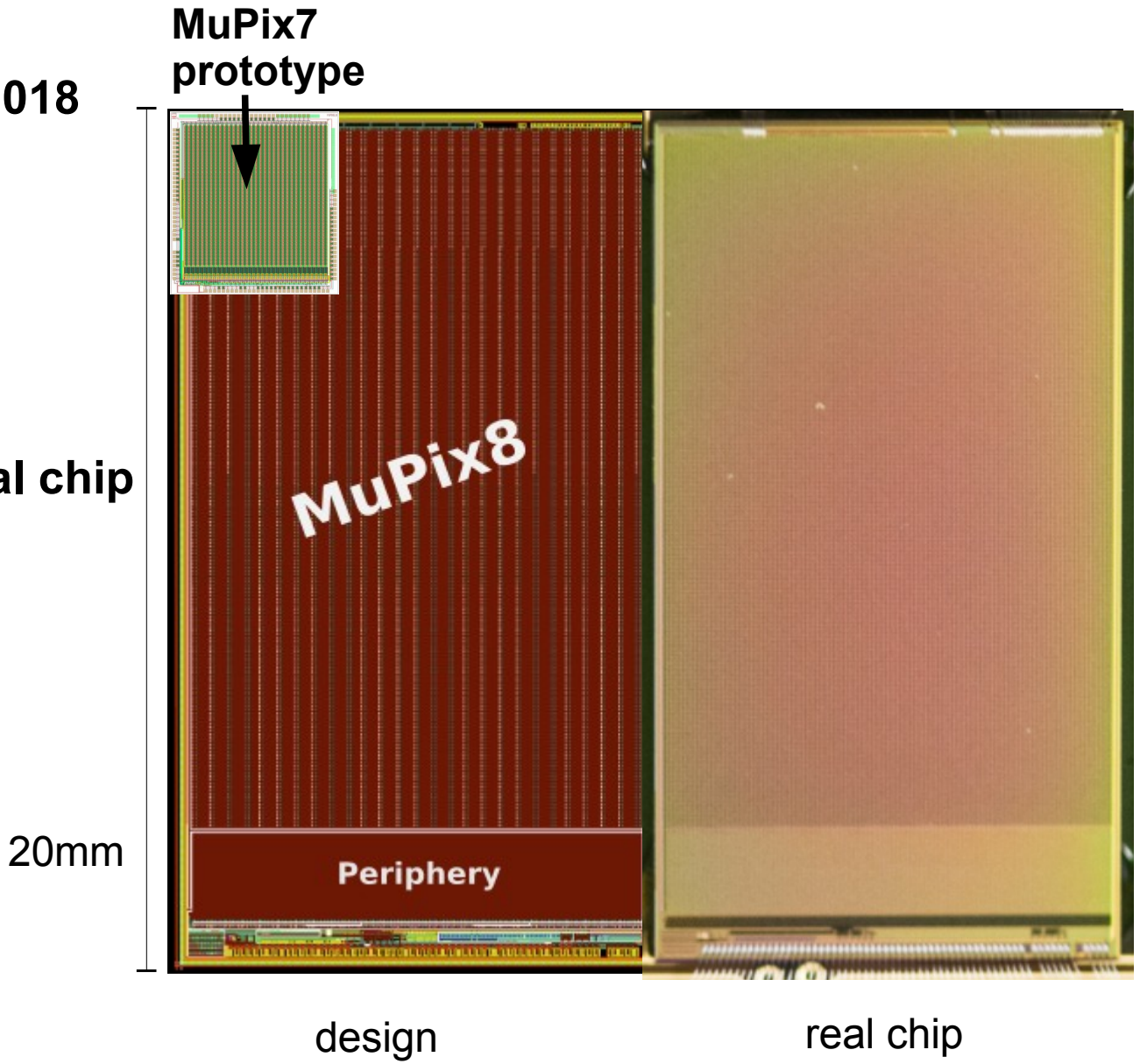


I.Peric, P. Fischer et al., NIM A 582 (2007) 876

- **Active sensor:**
  - **hit finding + digitization + readout**
- HV-CMOS: 60-80 V
- commercial process (Austria Microsystems)
- thinned to ~**50 µm** (~ 0.0005 X_0)
- fast timing **<20ns**
- continuous readout

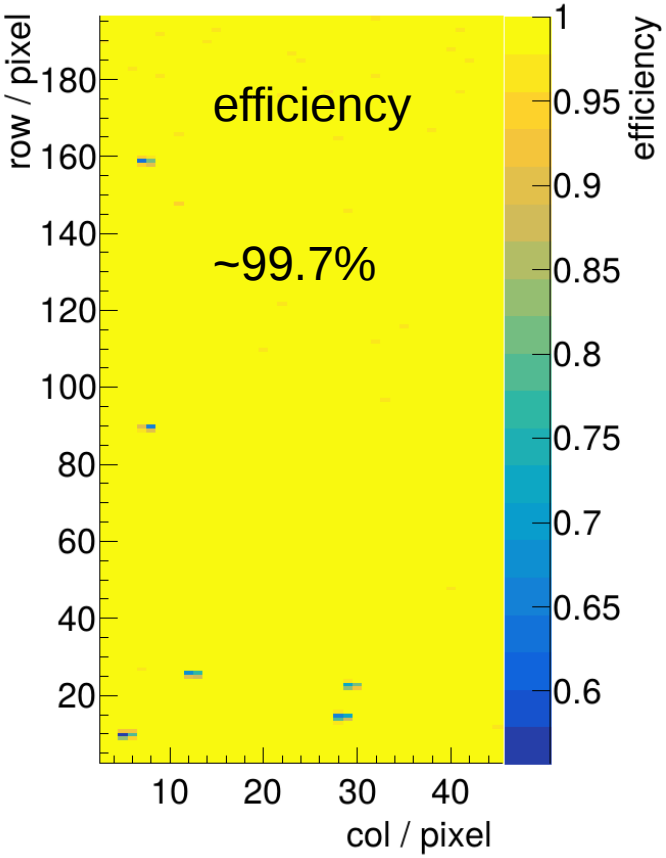
Monolithic HV-CMOS Sensor

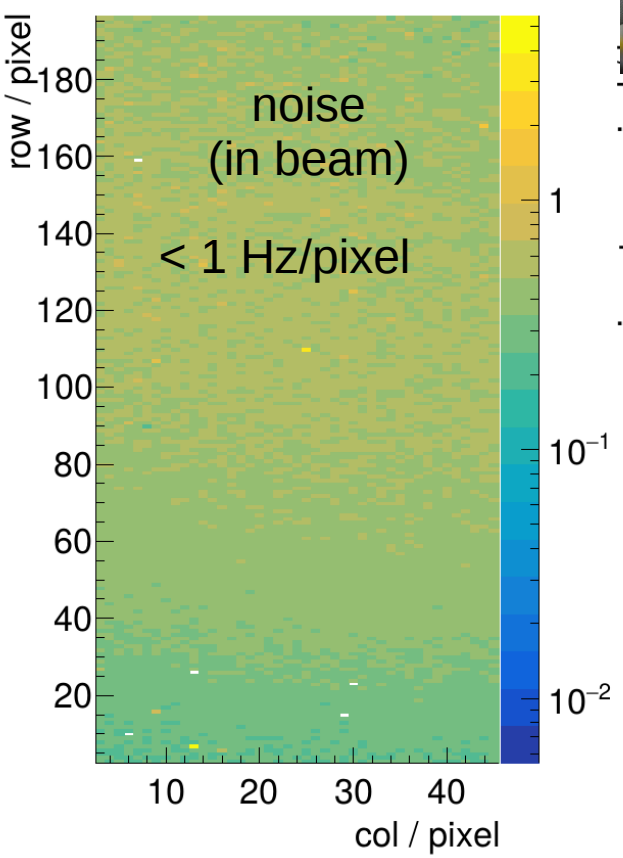
- **Mupix8 received in August 2018** (pre-production)
- **pixels size 80 x 80 µm²**
- **new substrate ~80 Ωcm**
  → larger depletion
- **design and area close to final chip**
  (→ 20 x 20 mm²)

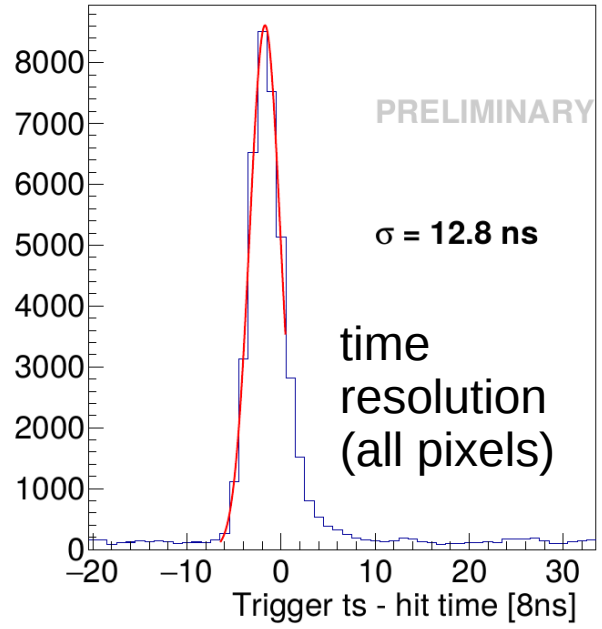


Recent Mupix Performance Plots

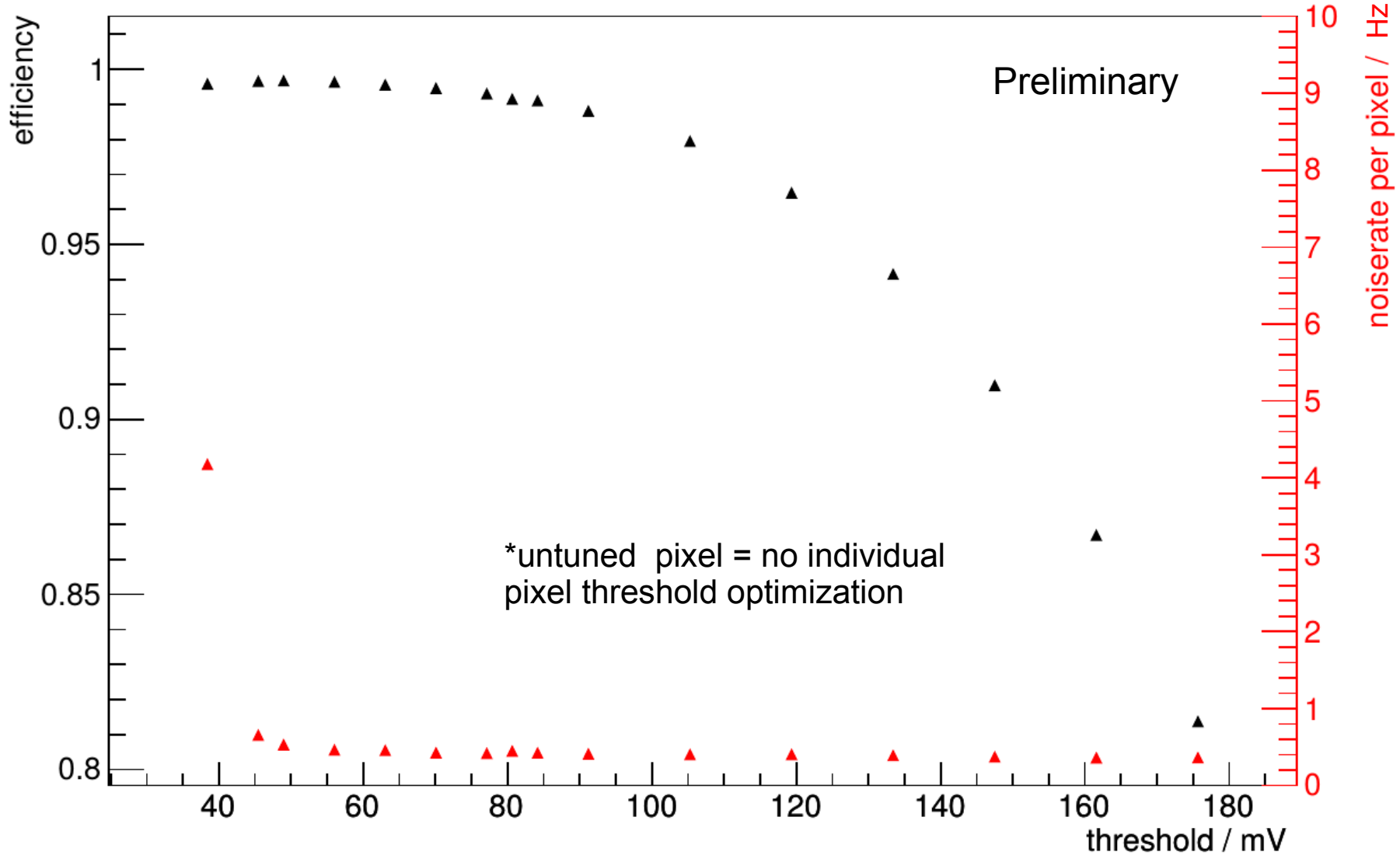
- Mupix8 characterized in lab
- test beams at DESY (x3) & CERN
- Mupix8 beam telescope (4 layers)







Threshold Scan Mupix8 (untuned*)



large region of operation → robustness

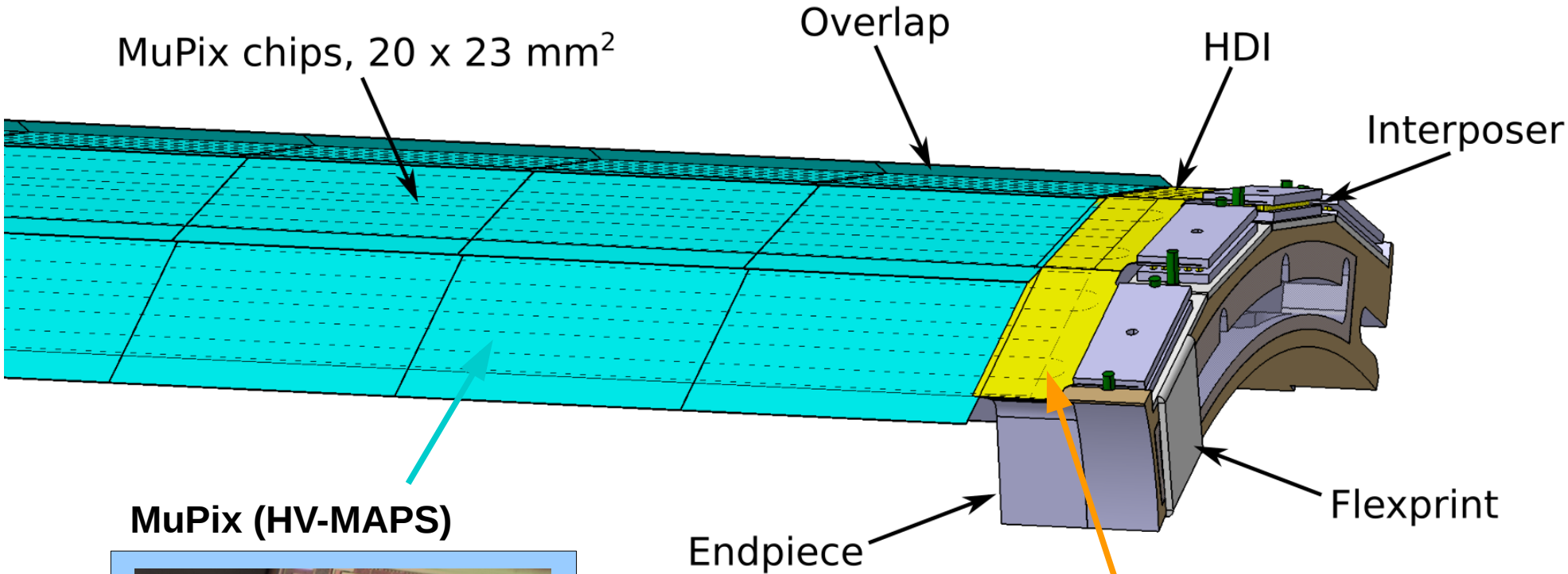
Status of Mu3e Pixel Detector

- TDR table updated with Mupix8 prel. results

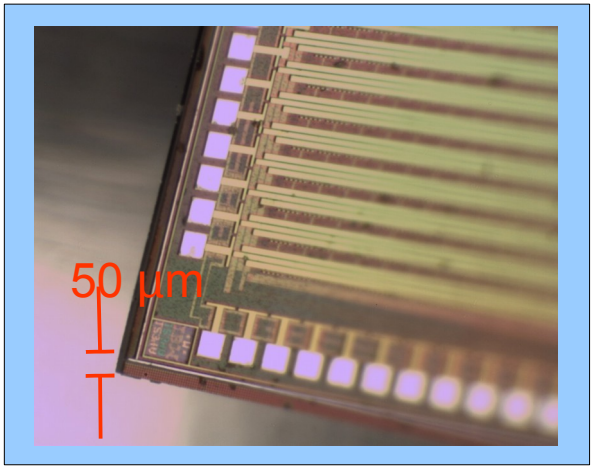
	Specification	MuPix7	**MuPix8 prel.**
Pixel size (μm^2)	80×80	103×80	**80 x 81**
Sensor size (mm^2)	20×20	3×3	**10 x 20**
Thickness (μm)	50	50	650
Bandwidth per chip (Gbit/s)	3×1.25	1×1.25	3 x 1.25
Hit rate (MHz/cm^2)	2.5	5.5	-
Spatial resolution (μ)	< 100	$103/\sqrt{12}$	80 / √12
Time resolution (ns)	< 20	11	12 (→ 5 -10)
Efficiency (%)	> 99	99.5	**~99.7 (99.9)**
Signal to noise	> 20	$10 \ldots 15$	~18 (untuned)
Power (mW/cm^2)	≤ 300	≤ 300	**~210**

- **so far only pre-produced Mupix8 characterized**
- **Mupix8 main production expected for March 2018**

(Outer) Pixel Tracker Module

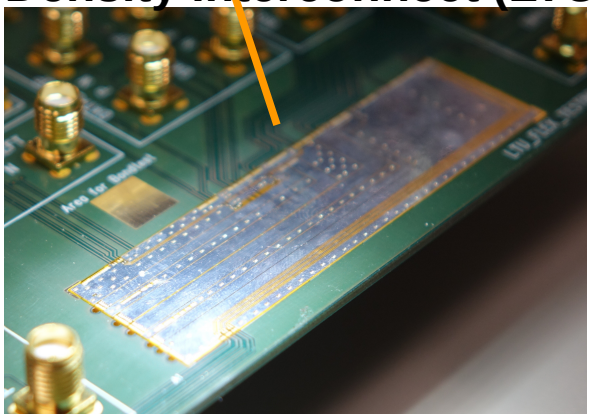


MuPix (HV-MAPS)

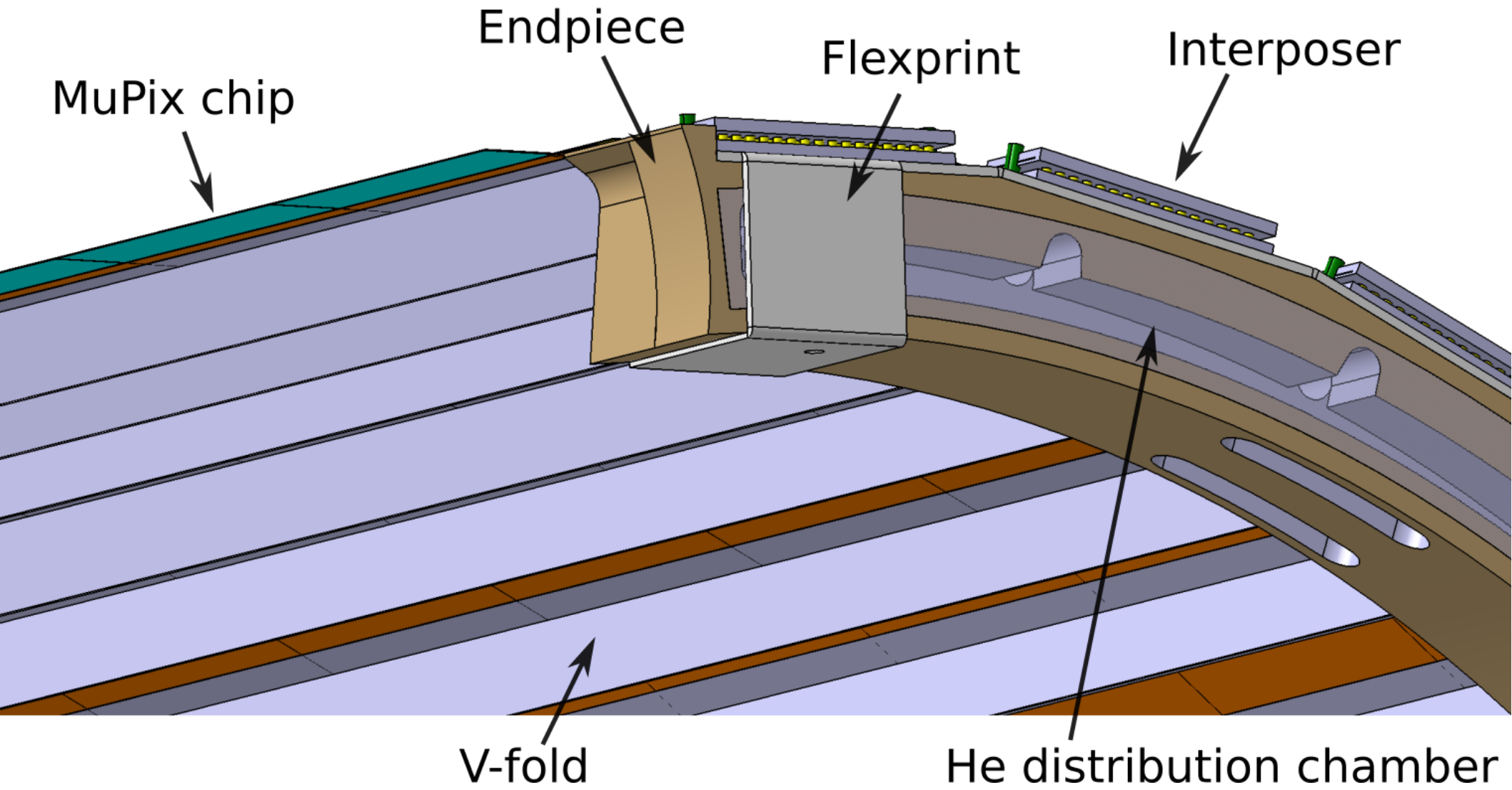


180 nm HV-CMOS (AMS)

High Density Interconnect (LTU, Ukraine)

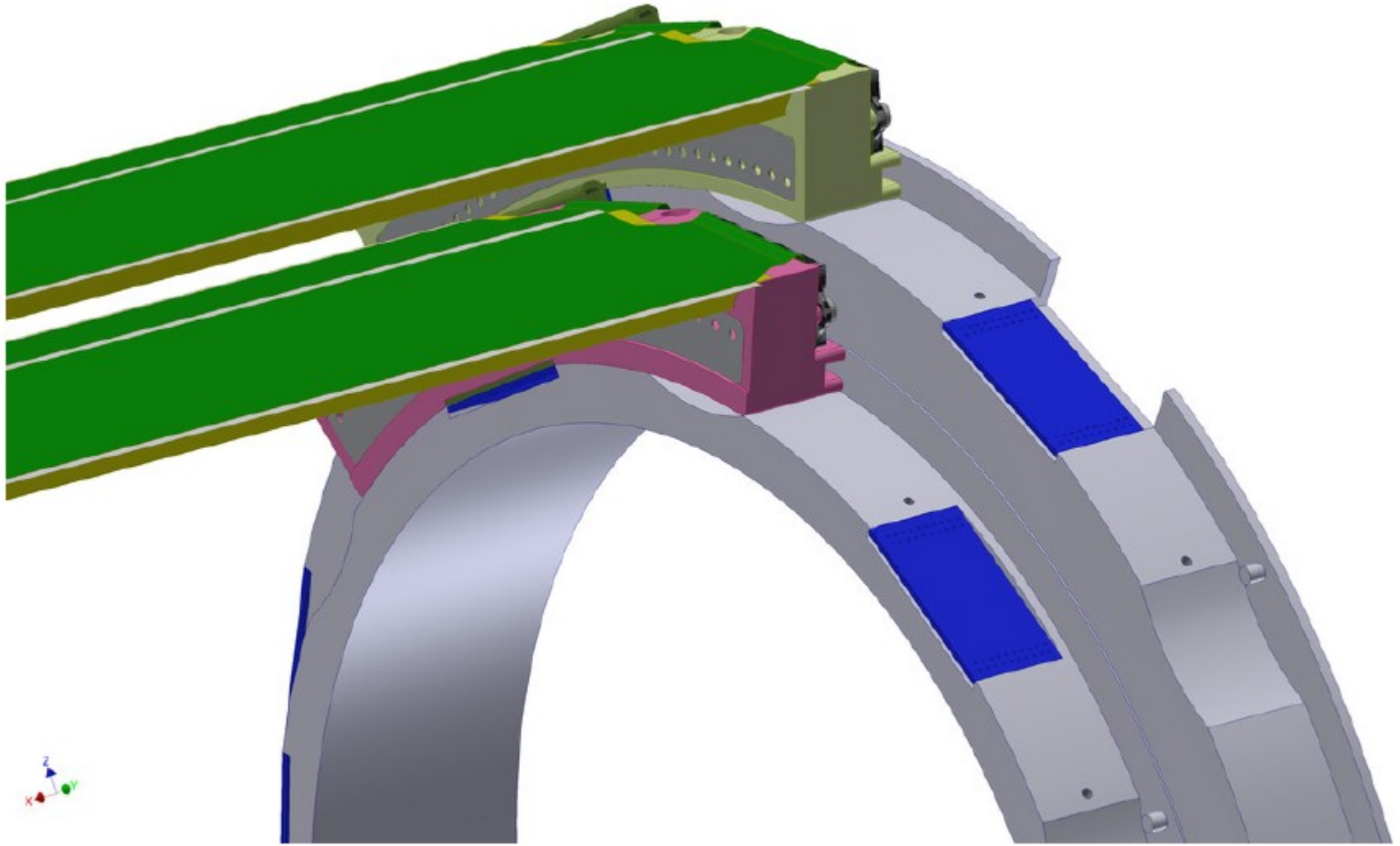


V-Fold Cooling Channels

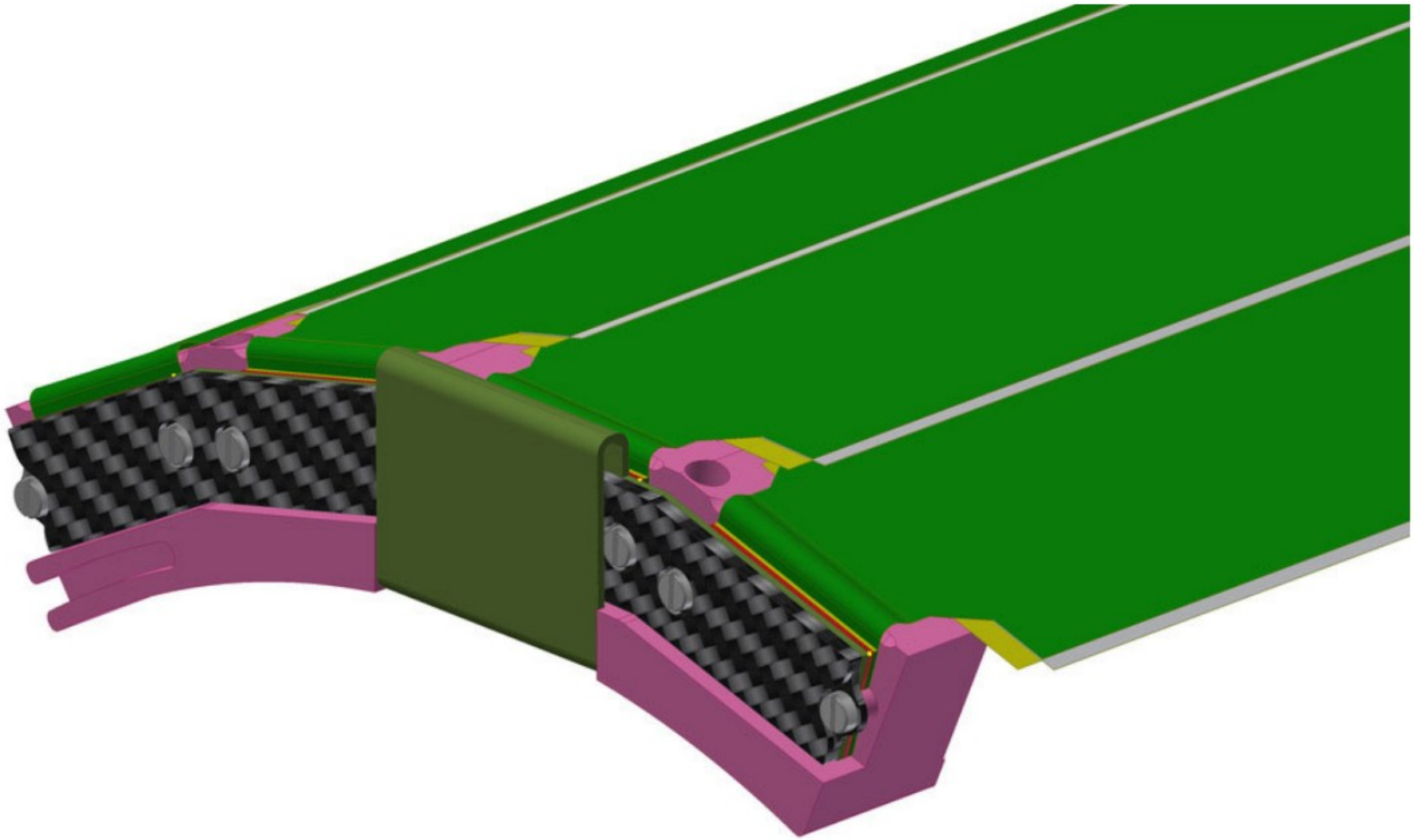


Outer Pixel Tracking Layers

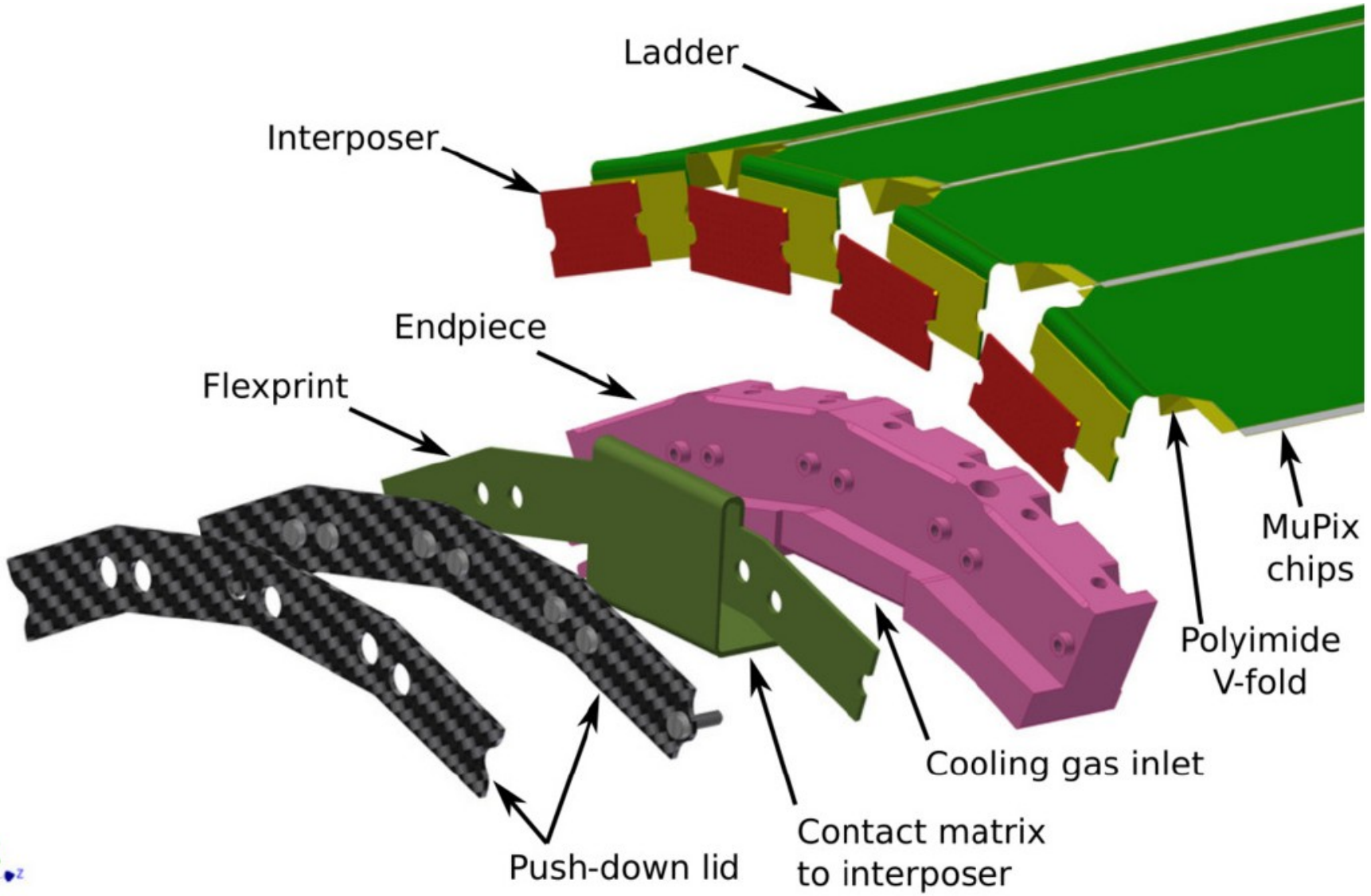
layer 3 and layer 4 modules:



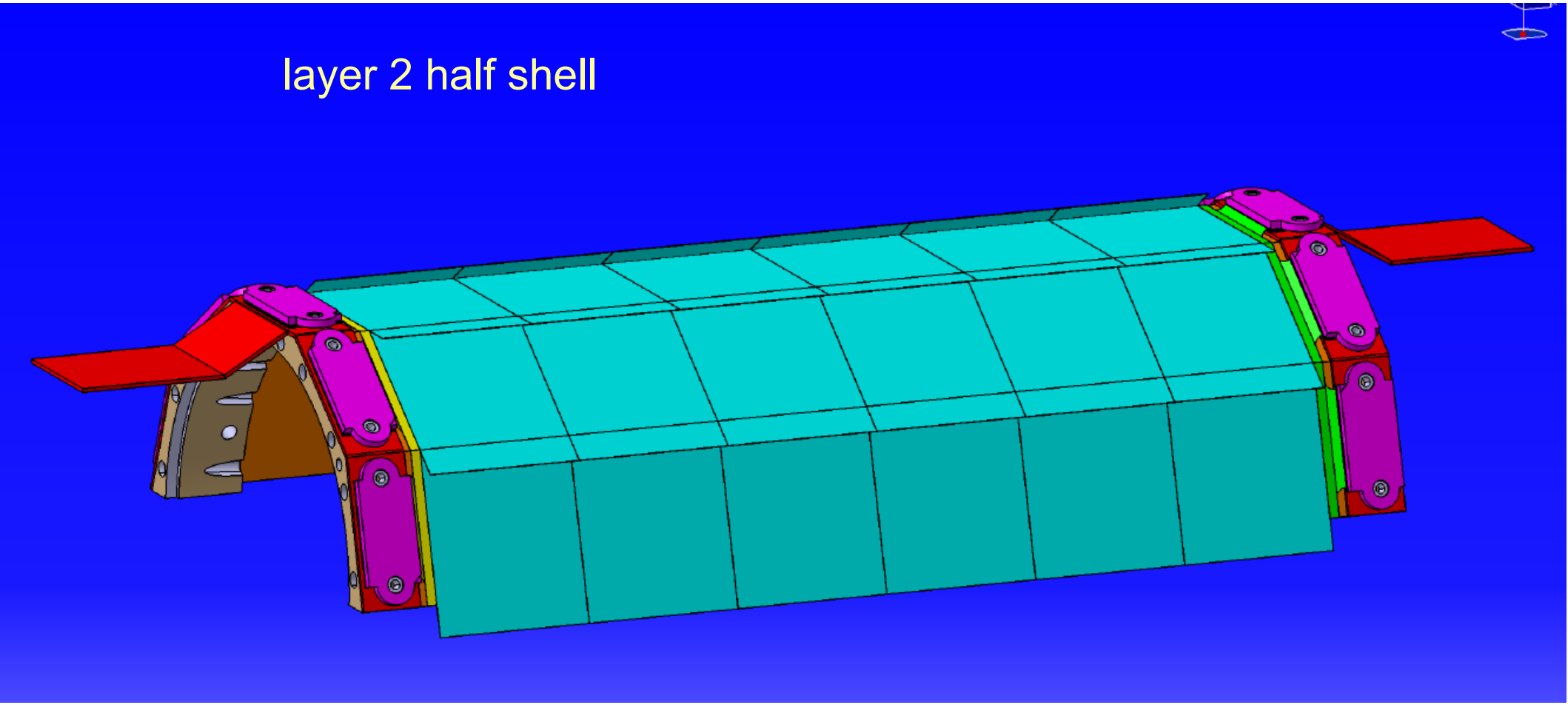
Outer Pixel Tracker Module



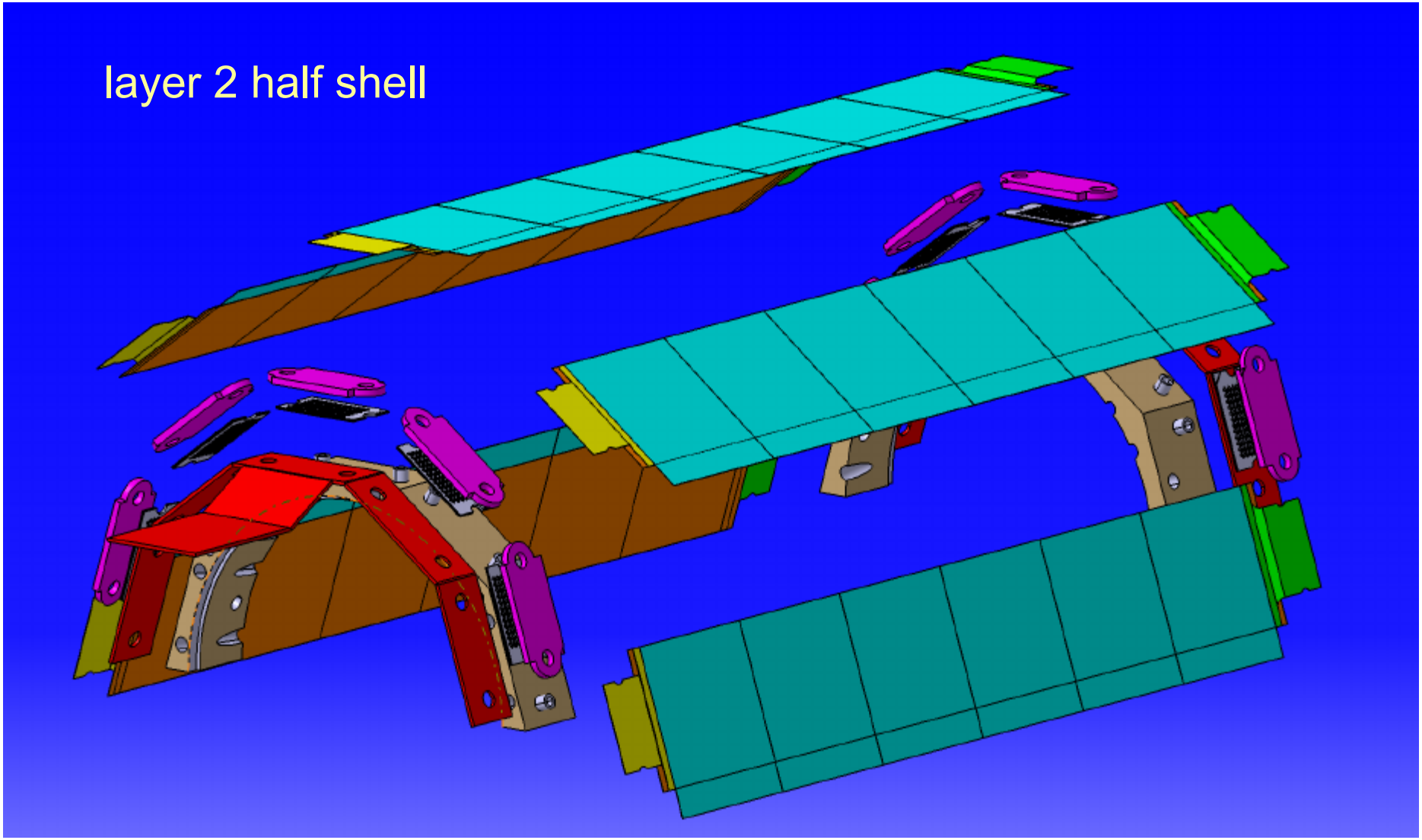
Outer Pixel Tracker Module



Inner Pixel Tracking Layer



Inner Pixel Tracking Layer



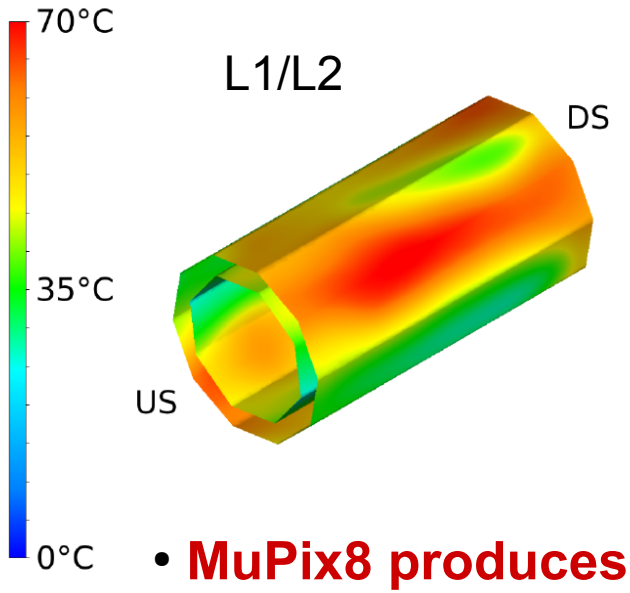
thermo-mechanical mockups were manufactured!

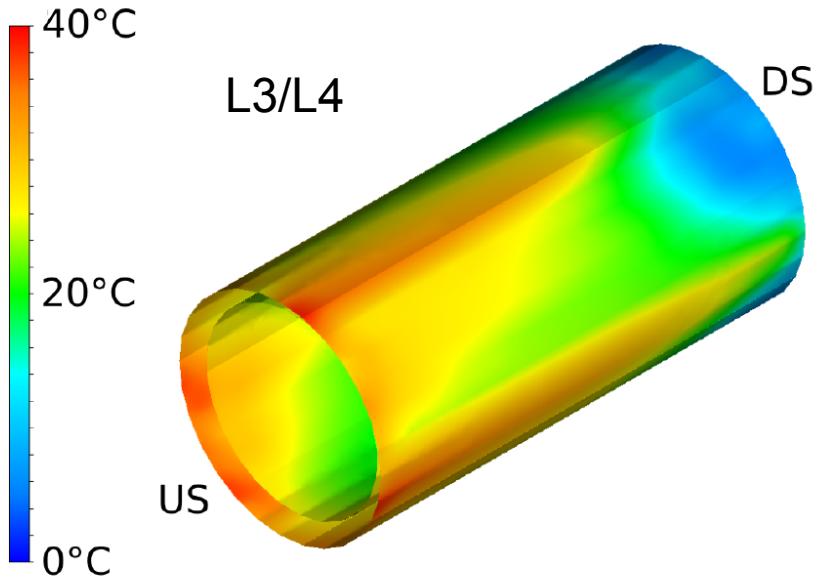
Helium Gas Cooling

3D computer simulations

- for power dissipation 400 mW / cm²
- gas flow with T_{in} = 0°C
- pressure drops
- design details considered

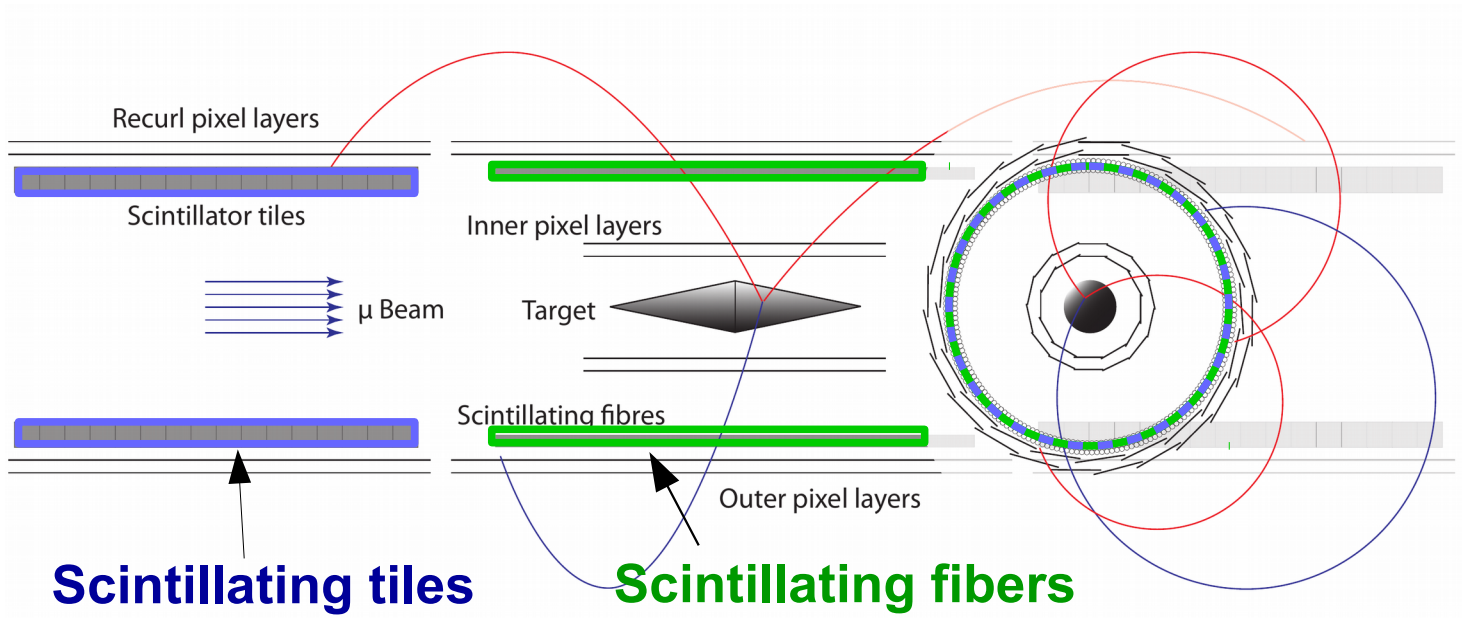
Volume	Flow speed (m/s)
Gap L1/L2	10
Gap SciFi/L3	5
V-folds L3/L4	20
Gap L3/L4	10
Global	0.5

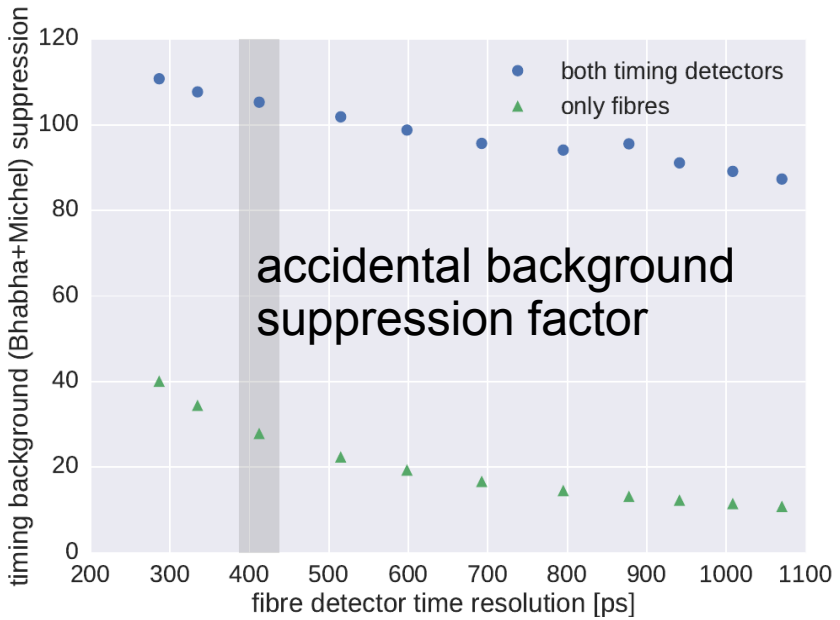


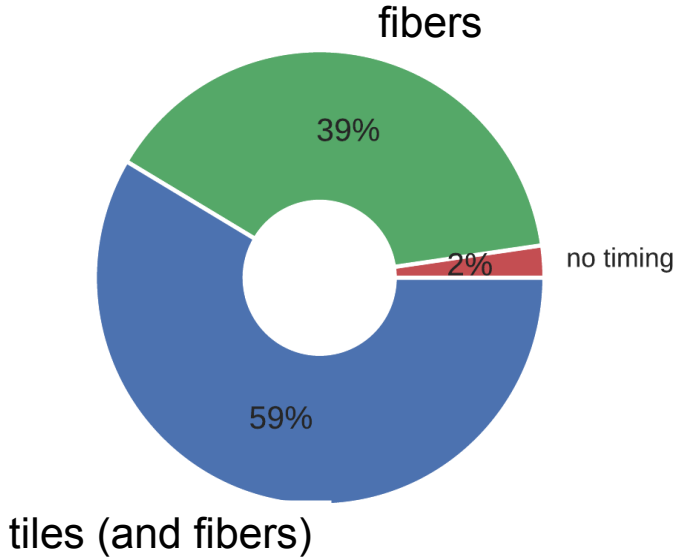


- **MuPix8 produces ~ 210 mW / cm²**
- **Further optimizations are possible!**

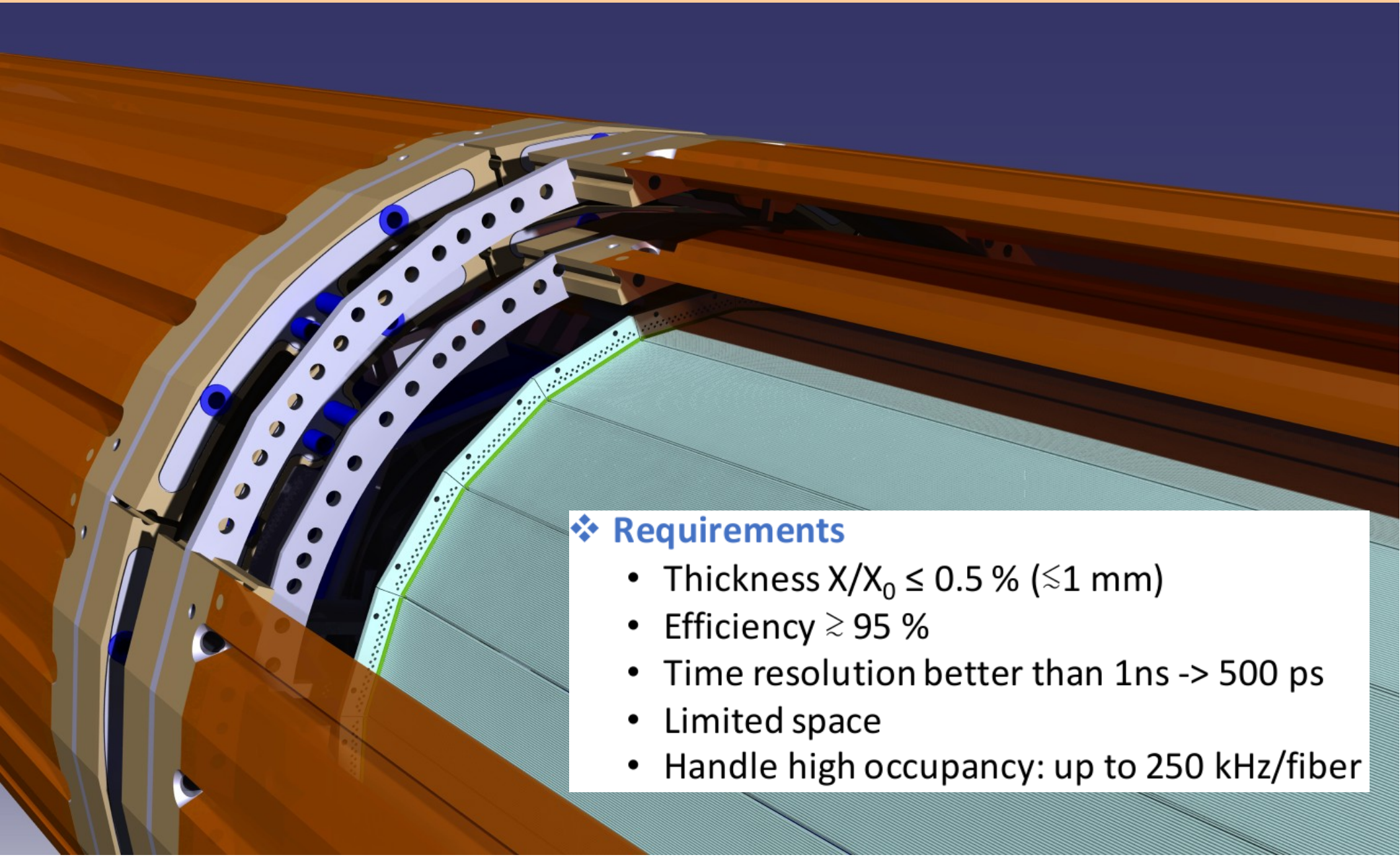
Mu3e Time Timing Detectors





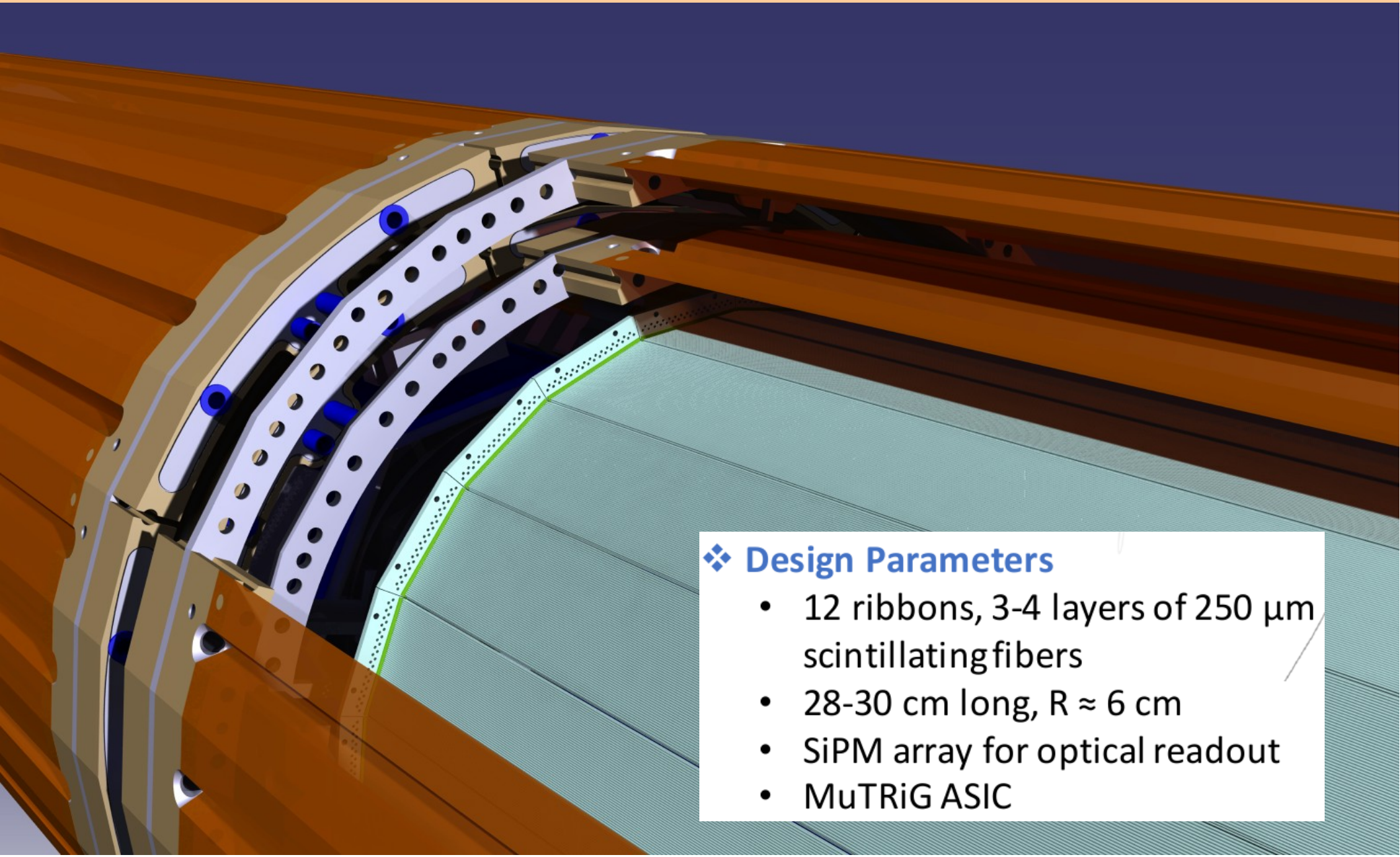


Scintillating Fiber Detector



- **Requirements**
  - Thickness $X/X_0 \leq 0.5\ \%$ ($\lesssim$1 mm)
  - Efficiency $\gtrsim 95\ \%$
  - Time resolution better than 1ns -> 500 ps
  - Limited space
  - Handle high occupancy: up to 250 kHz/fiber

Scintillating Fiber Detector

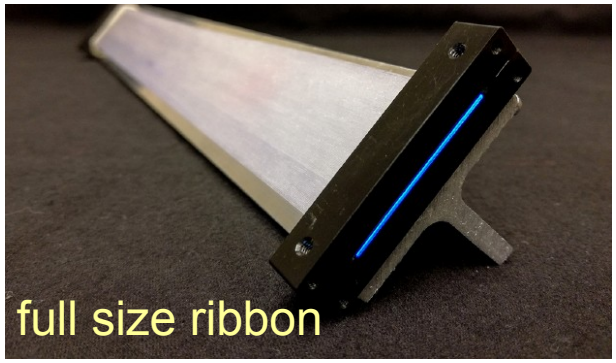


❖ **Design Parameters**

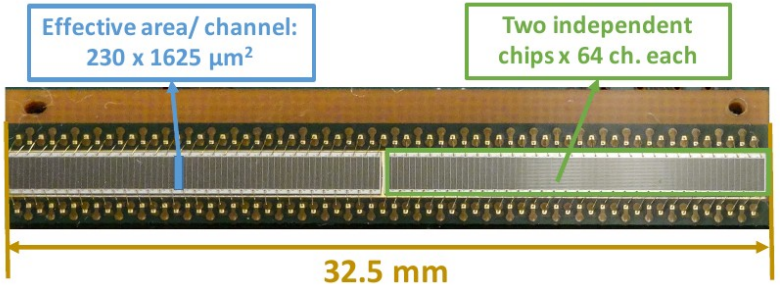
- 12 ribbons, 3-4 layers of 250 µm scintillating fibers
- 28-30 cm long, R ≈ 6 cm
- SiPM array for optical readout
- MuTRiG ASIC

Scintillating Fibers Tests & Prototyping

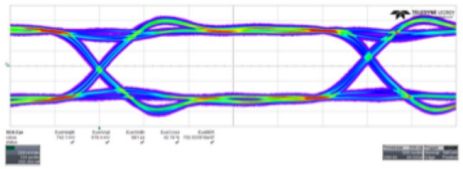
- Several types of scintillating 250µm fibres studied:
  - Kuraray: SCSF-81M, **78M**, NOL11
  - Saint Gobain: BC F12, BC 418
  - **round** & squared
  - different coatings (**no coating**, Al, TiO_2)

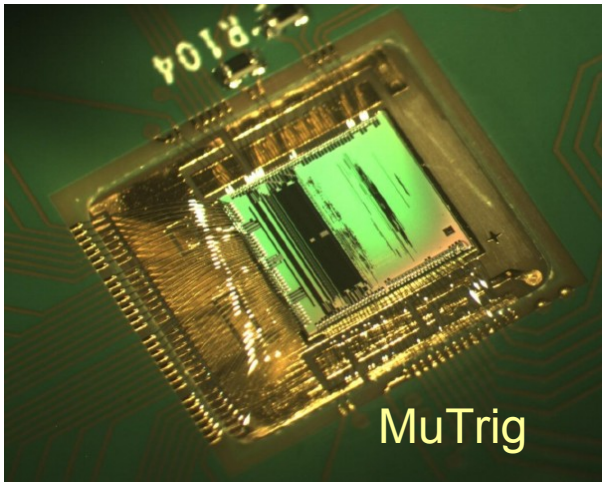


- SiPM: Hamatsu S13552-HQR (LHCb)
  - SiPM array
  - 128 channels

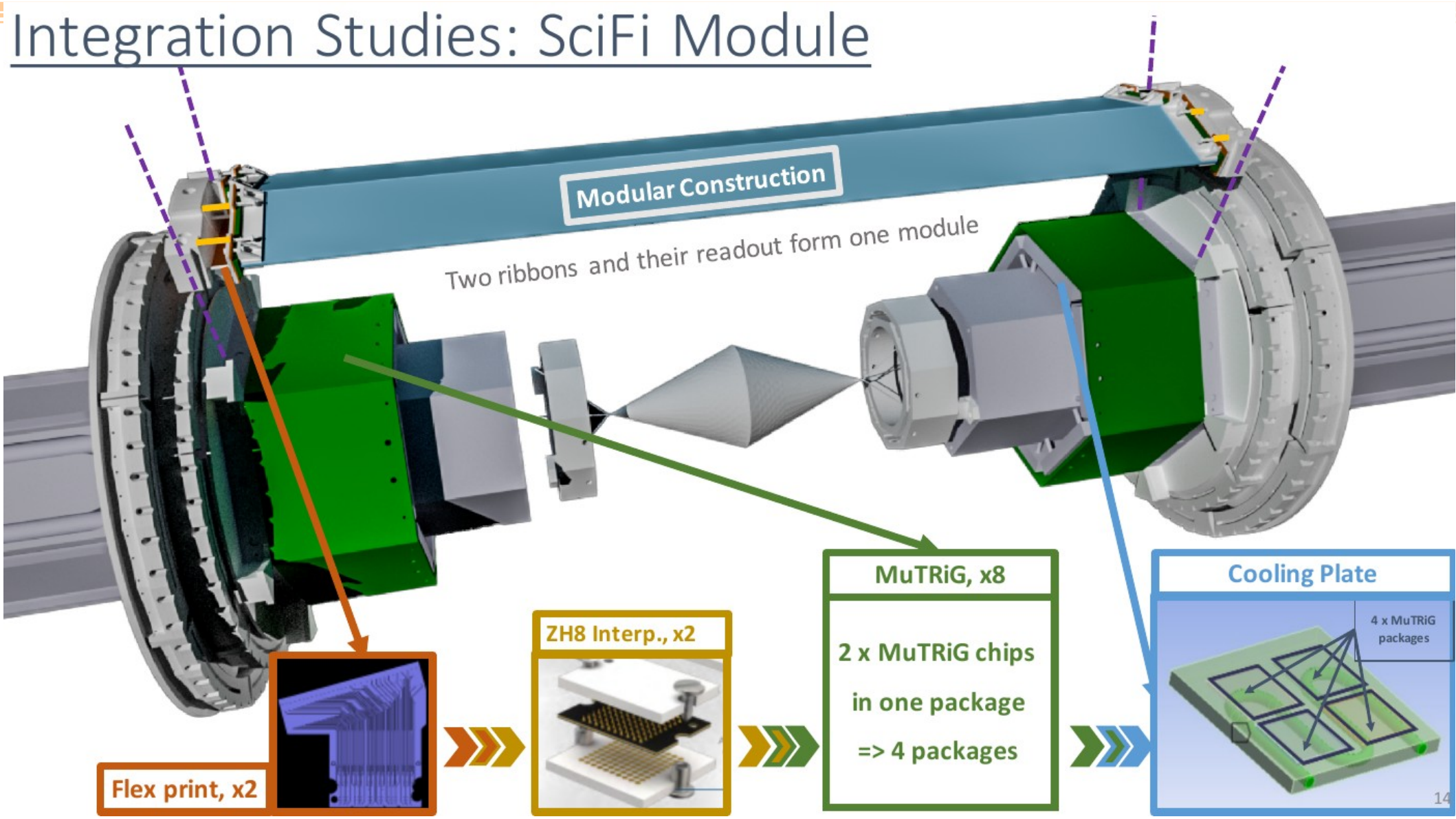


- New MuTrig readout chip (KIP, Heidelberg)
  - time resolution 50 ps
  - 32 channels
  - bandwidth 1.25 Gbit/s
  - chip successfully tested

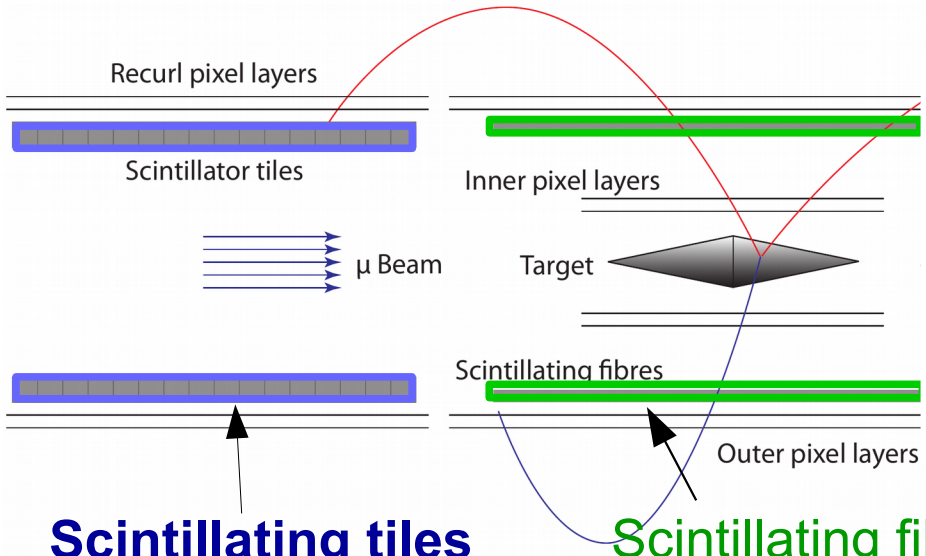




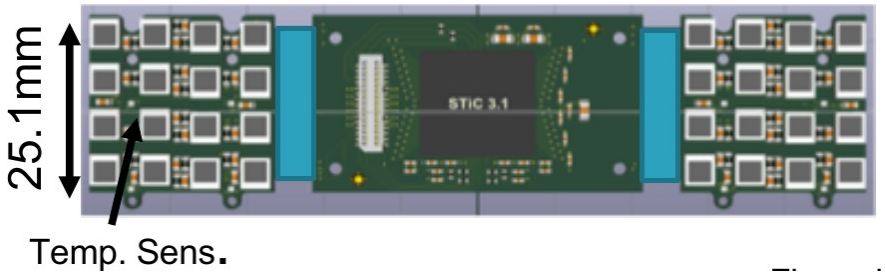
Integration Studies: SciFi Module

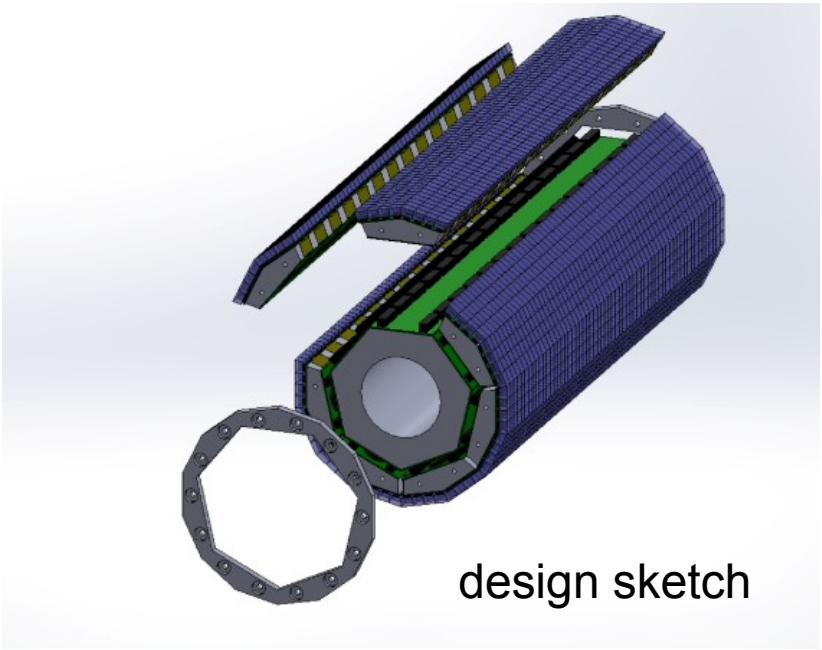


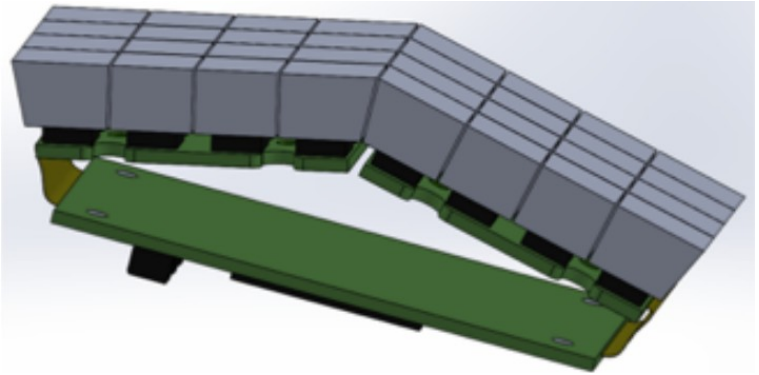
Scintillating Tile Detector



- 3 x 3 mm² single SiPM
- Hamamatsu S13360-3050PE
- timing resolution of <100 ps
  → measured in testbeams
- readout based on MuTrig

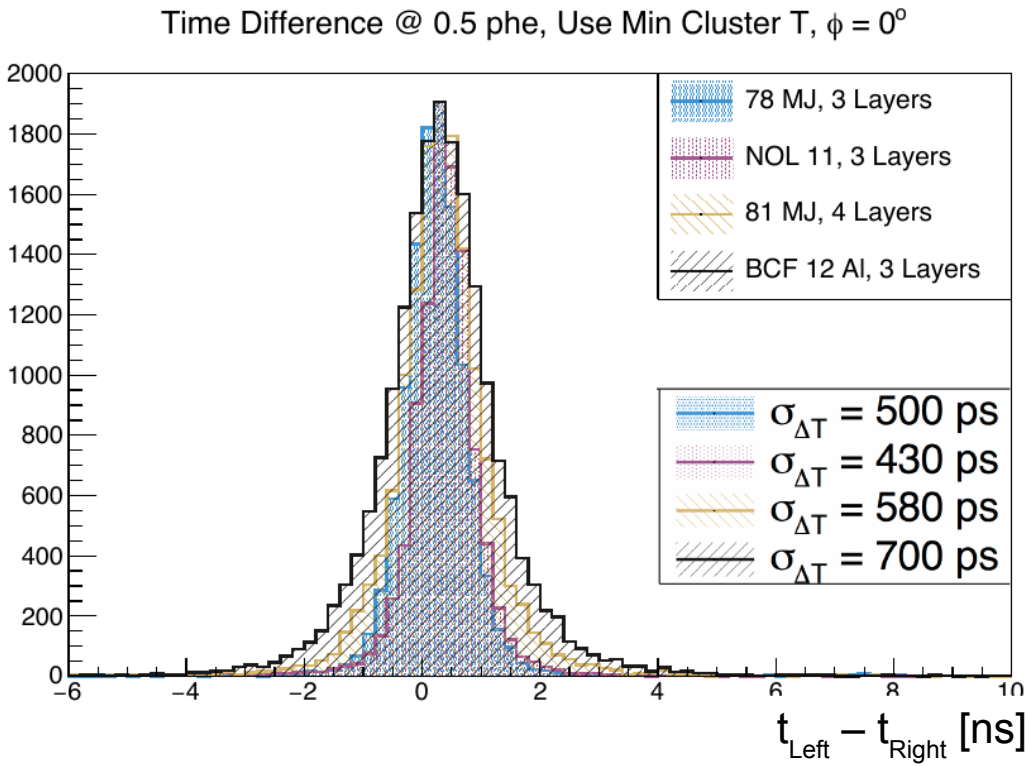






Performance & Status Timing Detectors

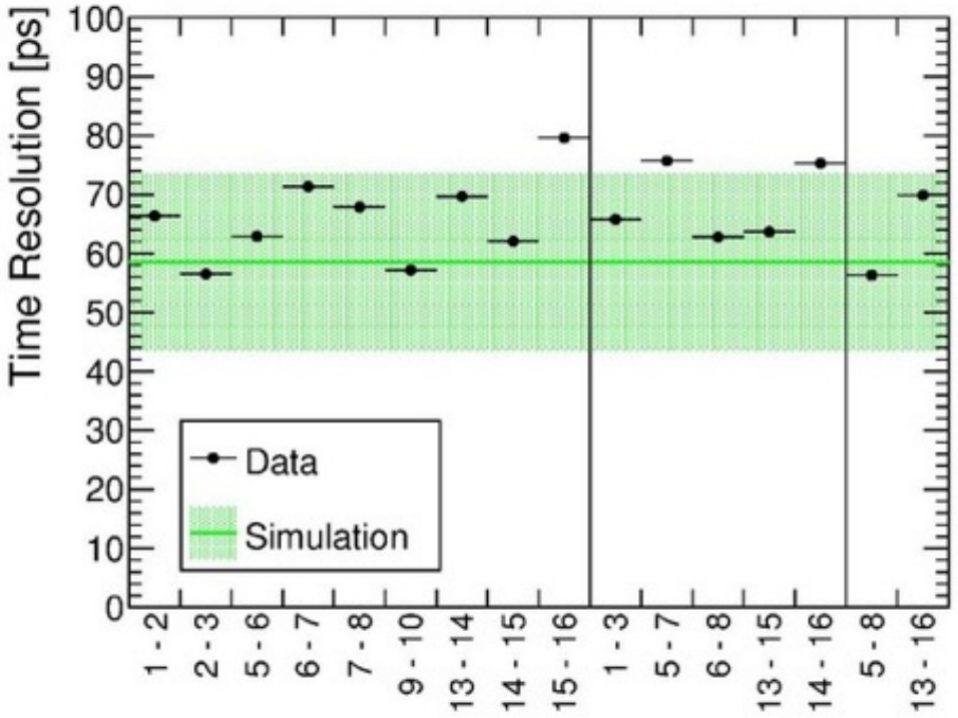
Fibers



better than specified:

σ_{dt} < 1400 ps → 700 ps

Tiles



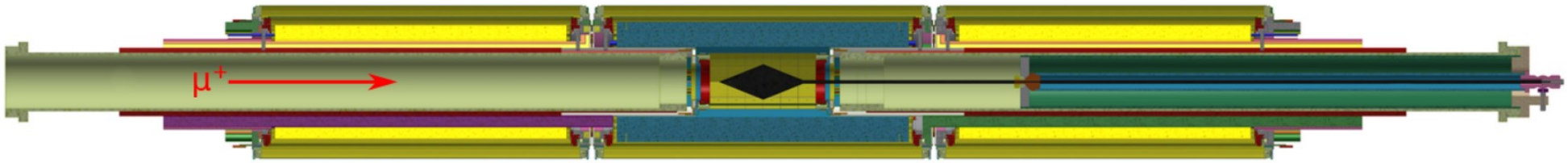
better than specified:

σ_t < 100 ps

Plan for 2018: Demonstrator modules to achieve production readiness

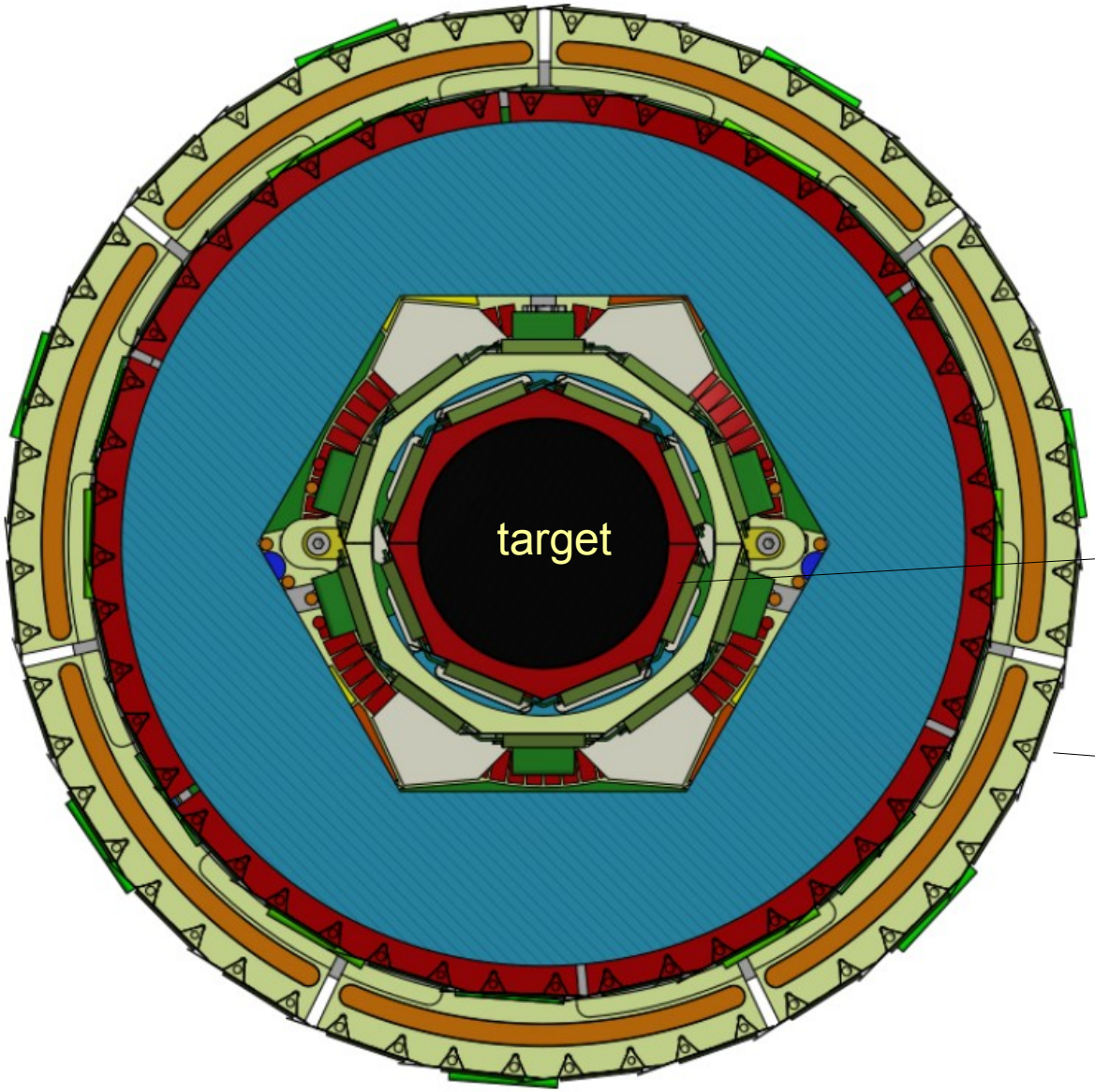
Detector Integration

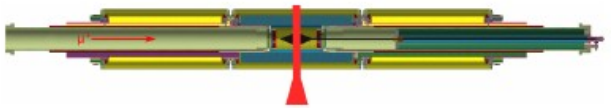
- 10 kW of power (Pixel Tracker, MuTrig readout chip, ...)
- helium-gas cooling with high flux 20-40 m^3 / min
- high number of readout channels and cables
- modular design required
- very limited space!



CAD drawings exist for almost all parts

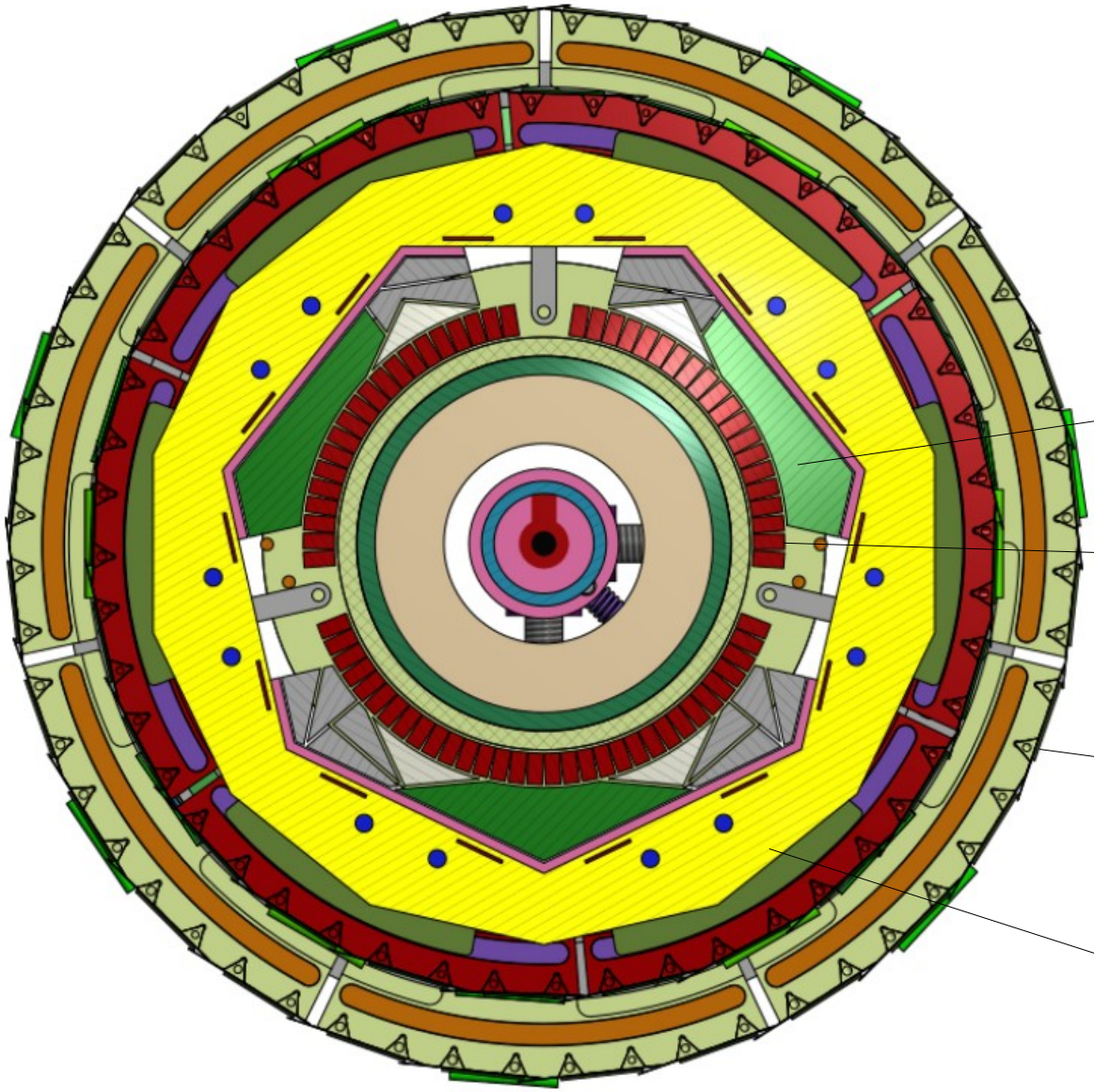
Cross Section at Target

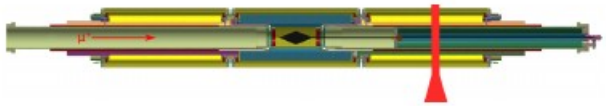




Cut through target.
Observe: SciFi not in here.

Cross Section at Recurl Station





Similar cut inside SciTile

Helium distribution

copper bars (power)

outer pixel layers

scintillating tile detector

Status of Detector and Plans

Status

- We have working prototypes for all sub-detectors & readout electronics
- We have detailed CAD drawings for most parts

Next Steps

- finalize overall design → next months (finalize TDR)
- build demonstrator modules & full vertical slice test → about 12-18 months
- achieve production readiness → a few more months
- production → 2019 -2020
- detector integration → second half of 2020

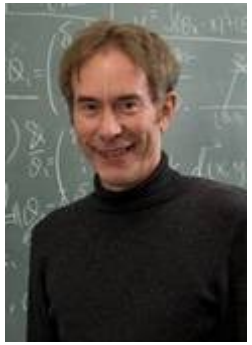
New Mu3e Institute and Groups

- **University of Bristol (BRI)**
- University Geneva (GVA)
- Kirchhoff Institute for Physics@Heidelberg (HD-KIP)
- Physics Institute@Heidelberg (HD-PI)
- Karlsruhe Institute of Technology (KIT)
- **University of Liverpool (LIV)**
- **University College London (UCL)**
- Universität Mainz (JGU)
- **University of Oxford (OXF)**
- **High Energy Group at PSI, Villigen**
- Muon Group at the PSI, Villigen
- ETH Zürich (ETHZ)
- **University Zürich (UZH)**

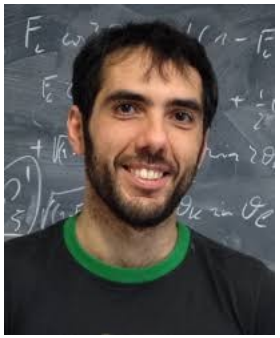
Joel Goldstein
(Bri)

Joost Vossebelt
(Liv)

Gavin Hesketh
(UCL)


Ian Shipsey
(Oxf)

Bohdan Kotlinski
(PSI-HE)


Nicola Serra
(UZH)

Σ ~ 60 authors

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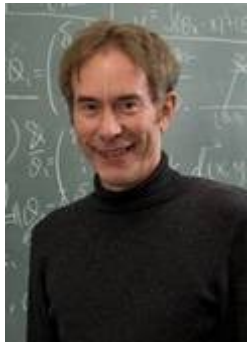
→ **Pixel Detector**

Joel Goldstein
(Bri)

Joost Vossebelt
(Liv)

Gavin Hesketh
(UCL)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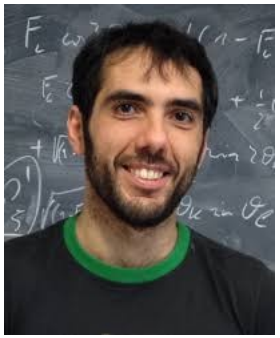
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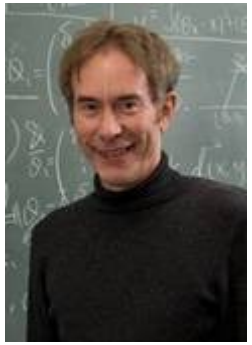
→ Clock Distribution

Joel Goldstein
(Bri)

Joost Vossebelt
(Liv)

Gavin Hesketh
(UCL)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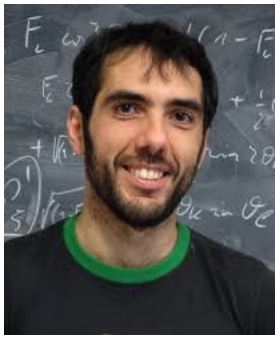
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→ Scintillating Fiber Detector

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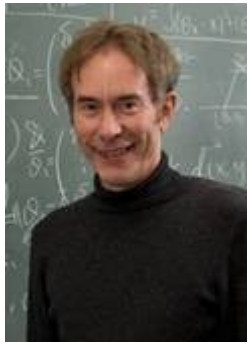
(UCL)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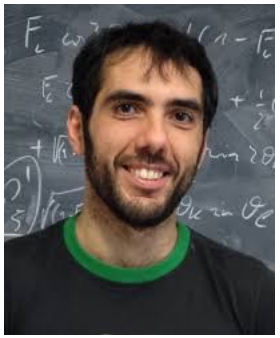
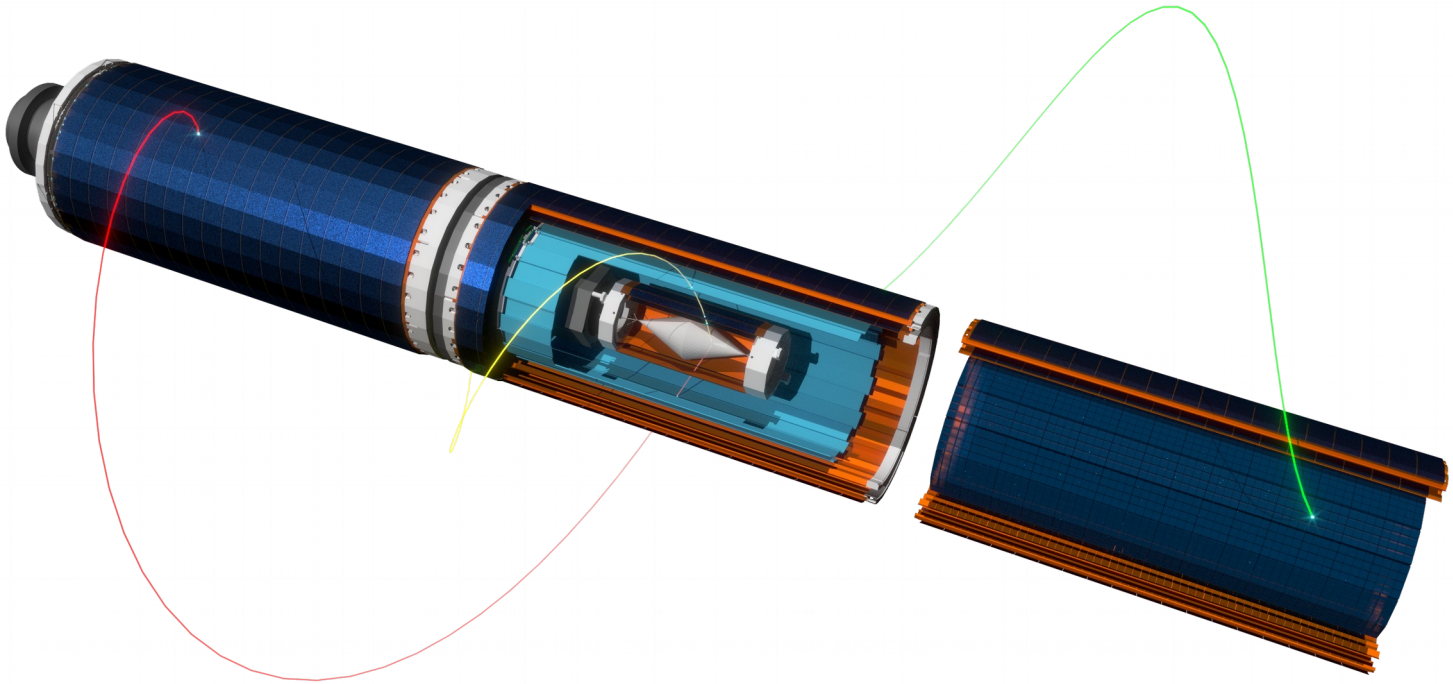

Nicola Serra
(UZH)

Last but not least...

Thank You!

- PSI for the hospitality and support
- PSI Research Committee and Mu3e Reviewers for a very constructive and helpful review process



Backup

Beam Requests for 2018

We would like to thank PSI for providing us so much support!

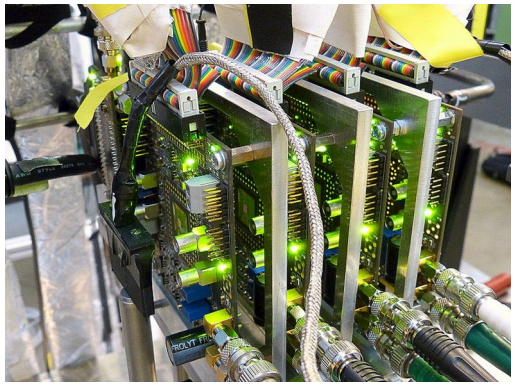
Test Beams in 2017:

- Delays in licensing new piE5 safety installations at the beginning of 2017 did not allow for testing the CMBL at piE5.
- Mu3e had one week of test beam in piM1 (SciFi)

Requests:

- **PiE5**: **4 weeks** CMBL tests
- **PiM1** (or equivalent) **week 41+42** for detector prototype tests:
  - one week SciFi
  - one week pixel detector

Mupix beam telecope
in Juli 2014 at PSI



Example: Low Scale Seesaw Model

"Inverted Seesaw Model"

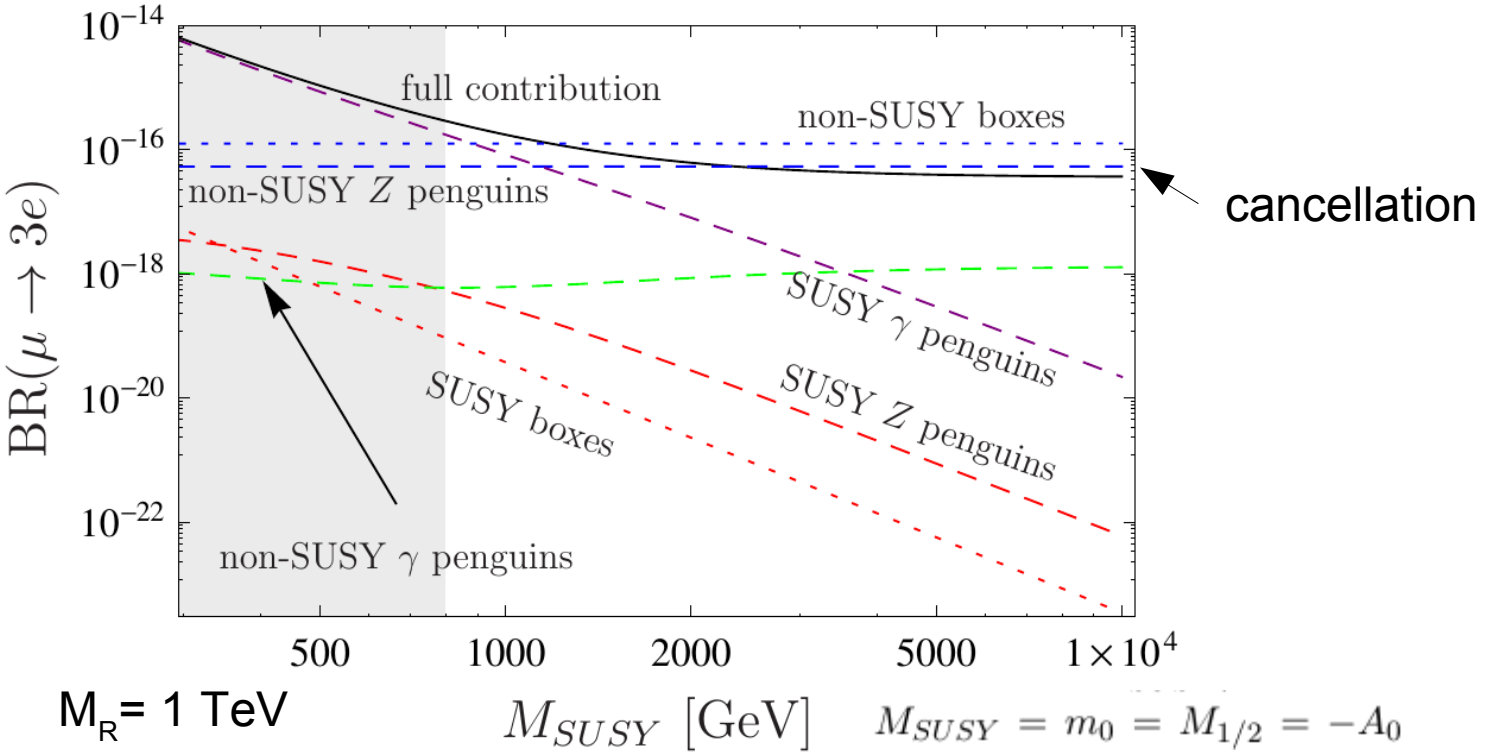
$$W_{IS} = W_{\rm MSSM} + Y_\nu \hat{\nu}^c \hat{L} \hat{H}_u + M_R \hat{\nu}^c \hat{N}_S + \frac{\mu_N}{2} \hat{N}_S \hat{N}_S$$

$$m_\nu \propto \mu_N$$

right-handed neutrinos

leptonic gauge singlets

M.E.Krauss, W. Porod et al., arXiv:1408:0138

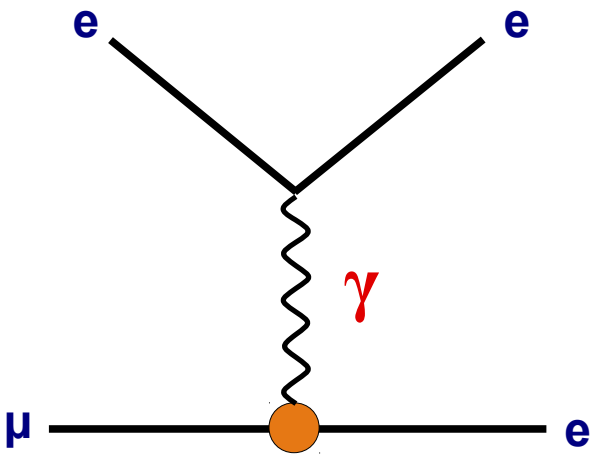


cancellation

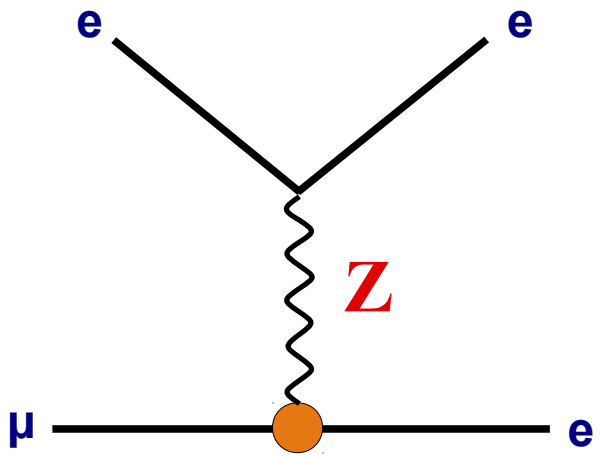
M_R= 1 TeV

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

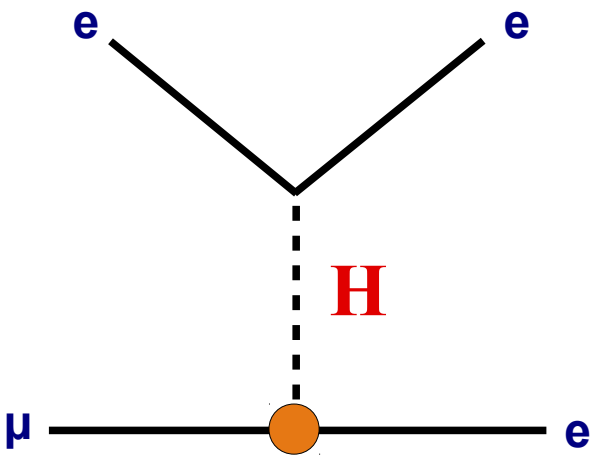
$\mu^+ \rightarrow e^+e^+e^-$



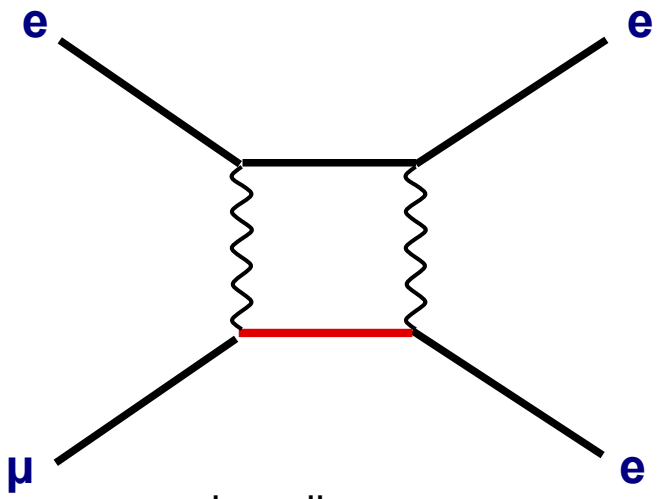
photon penguin



Z - penguin



Higgs-penguin



box diagram

Some CLFV Processes

D.Glenzinski

Process	Current Limit	Next Generation exp
$\tau \rightarrow \mu\eta$	BR < 6.5 E-8	
$\tau \rightarrow \mu\gamma$	BR < 6.8 E-8	10^{-9} - 10^{-10} (Belle II)
$\tau \rightarrow \mu\mu\mu$	BR < 3.2 E-8	
$\tau \rightarrow eee$	BR < 3.6 E-8	
$K_L \rightarrow e\mu$	BR < 4.7 E-12	
$K^+ \rightarrow \pi^+ e^- \mu^+$	BR < 1.3 E-11	
$B^0 \rightarrow e\mu$	BR < 7.8 E-8	
$B^+ \rightarrow K^+ e\mu$	BR < 9.1 E-8	
$\mu^+ \rightarrow e^+\gamma$	BR < ~~5.7~~ 4.2 E-13	10^{-14} (MEG)
$\mu^+ \rightarrow e^+e^+e^-$	BR < 1.0 E-12	10^{-16} (PSI)
$\mu N \rightarrow eN$	$R_{\mu e}$ < 7.0 E-13	10^{-17} (Mu2e, COMET)

(current limits from the PDG)

- Most promising CLFV measurements use μ

Complementarity of LFV Processes

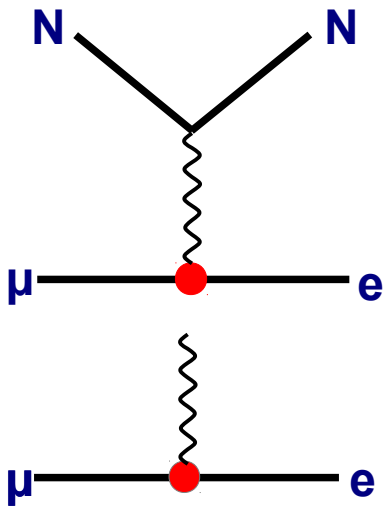
Blanke et al., Acta Phys.Polon. B41 (2010) 657-683

ratio	LHT	MSSM (dipole)	MSSM (Higgs)
$\frac{Br(\mu^- \to e^- e^+ e^-)}{Br(\mu \to e\gamma)}$	0.02...1	$\sim 6 \cdot 10^{-3}$	$\sim 6 \cdot 10^{-3}$
$\frac{Br(\tau^- \to e^- e^+ e^-)}{Br(\tau \to e\gamma)}$	0.04...0.4	$\sim 1 \cdot 10^{-2}$	$\sim 1 \cdot 10^{-2}$
$\frac{Br(\tau^- \to \mu^- \mu^+ \mu^-)}{Br(\tau \to \mu\gamma)}$	0.04...0.4	$\sim 2 \cdot 10^{-3}$	0.06...0.1
$\frac{Br(\tau^- \to e^- \mu^+ \mu^-)}{Br(\tau \to e\gamma)}$	0.04...0.3	$\sim 2 \cdot 10^{-3}$	0.02...0.04
$\frac{Br(\tau^- \to \mu^- e^+ e^-)}{Br(\tau \to \mu\gamma)}$	0.04...0.3	$\sim 1 \cdot 10^{-2}$	$\sim 1 \cdot 10^{-2}$
$\frac{Br(\tau^- \to e^- e^+ e^-)}{Br(\tau^- \to e^- \mu^+ \mu^-)}$	0.8...2.0	~ 5	0.3...0.5
$\frac{Br(\tau^- \to \mu^- \mu^+ \mu^-)}{Br(\tau^- \to \mu^- e^+ e^-)}$	0.7...1.6	~ 0.2	5...10
$\frac{R(\mu\mathrm{Ti} \to e\mathrm{Ti})}{Br(\mu \to e\gamma)}$	$10^{-3}...10^{2}$	$\sim 5 \cdot 10^{-3}$	0.08...0.15

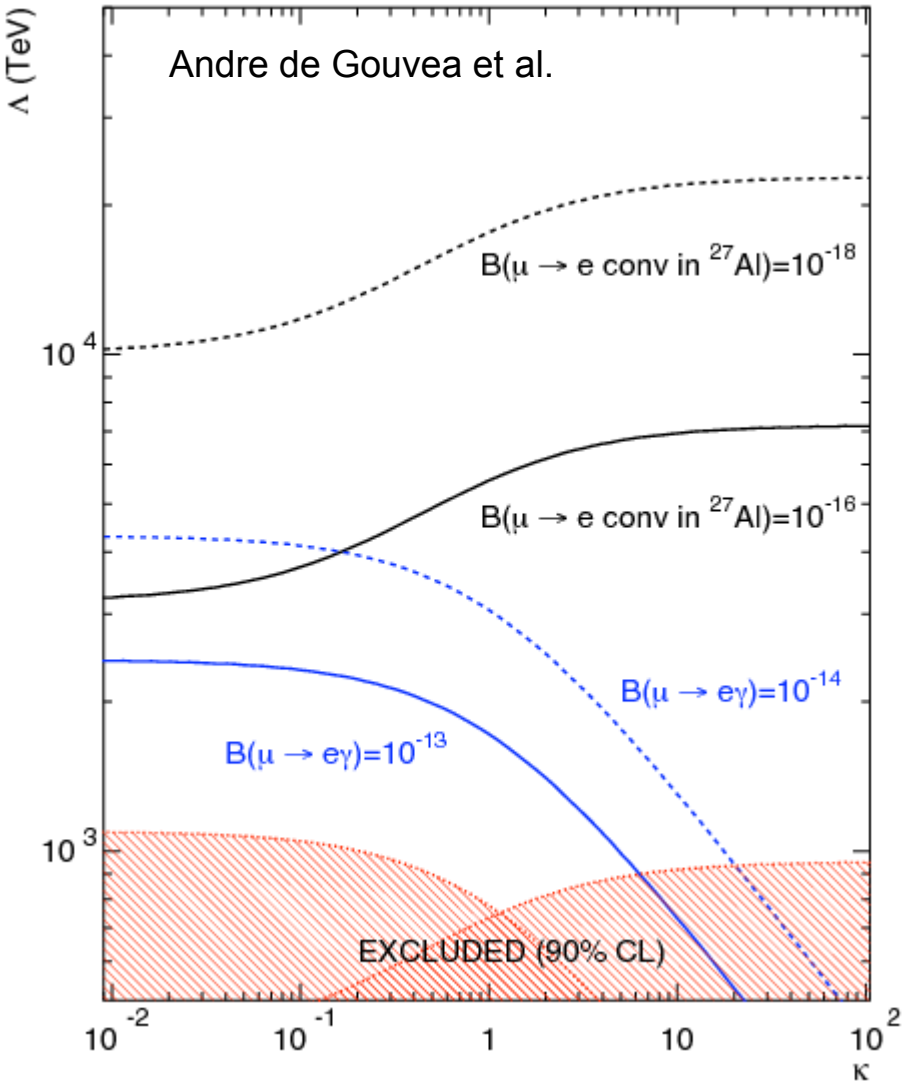
Table 3: *Comparison of various ratios of branching ratios in the LHT model ($f = 1\,\mathrm{TeV}$) and in the MSSM without [92, 93] and with [96, 97] significant Higgs contributions.*

Model Independent Comparison

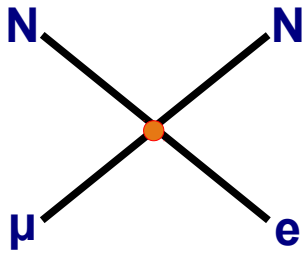
dipole



$\kappa \to 0$



μeNN contact IA



$\kappa \to \infty$

→ LFV processes are highly complementary!

LFV Higgs Couplings I

Framework

LFV

$$Y_{ij} = \frac{m_i}{v}\delta_{ij} + \frac{v^2}{\sqrt{2}\Lambda^2}\hat{\lambda}_{ij}$$

LFV decays of SM Higgs:

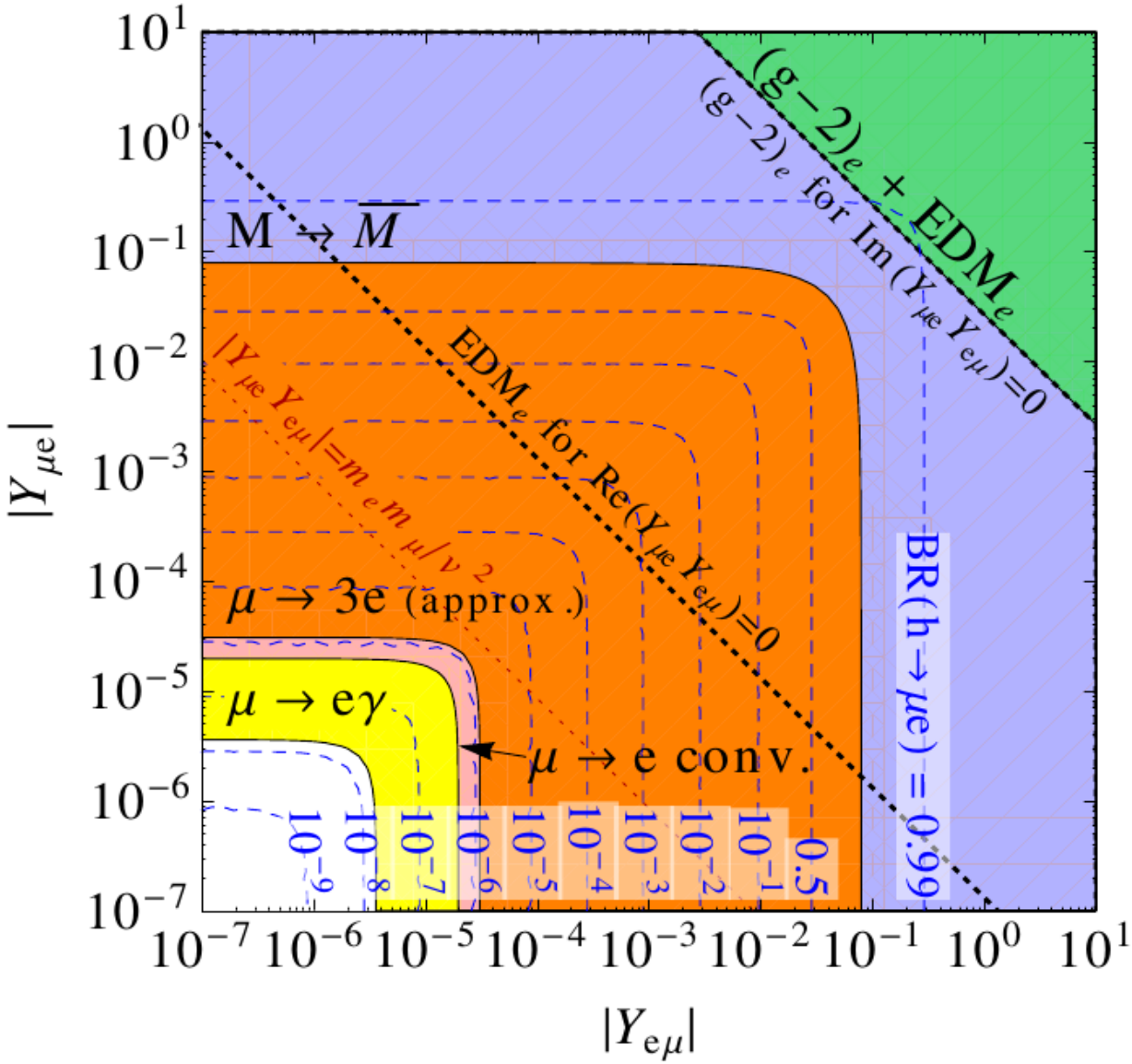
$$\mathrm{BR}(h \to \ell^\alpha \ell^\beta) = \frac{\Gamma(h \to \ell^\alpha \ell^\beta)}{\Gamma(h \to \ell^\alpha \ell^\beta) + \Gamma_{\mathrm{SM}}}$$

LFV muon decay:

$$\sim \sqrt{|Y_{\mu e}|^2 + |Y_{e\mu}|^2}$$

LHC not competitive with LFV muon decay searches!

R. Harnik, J. Kopp J, Zupan [arXiv:1206.6497]



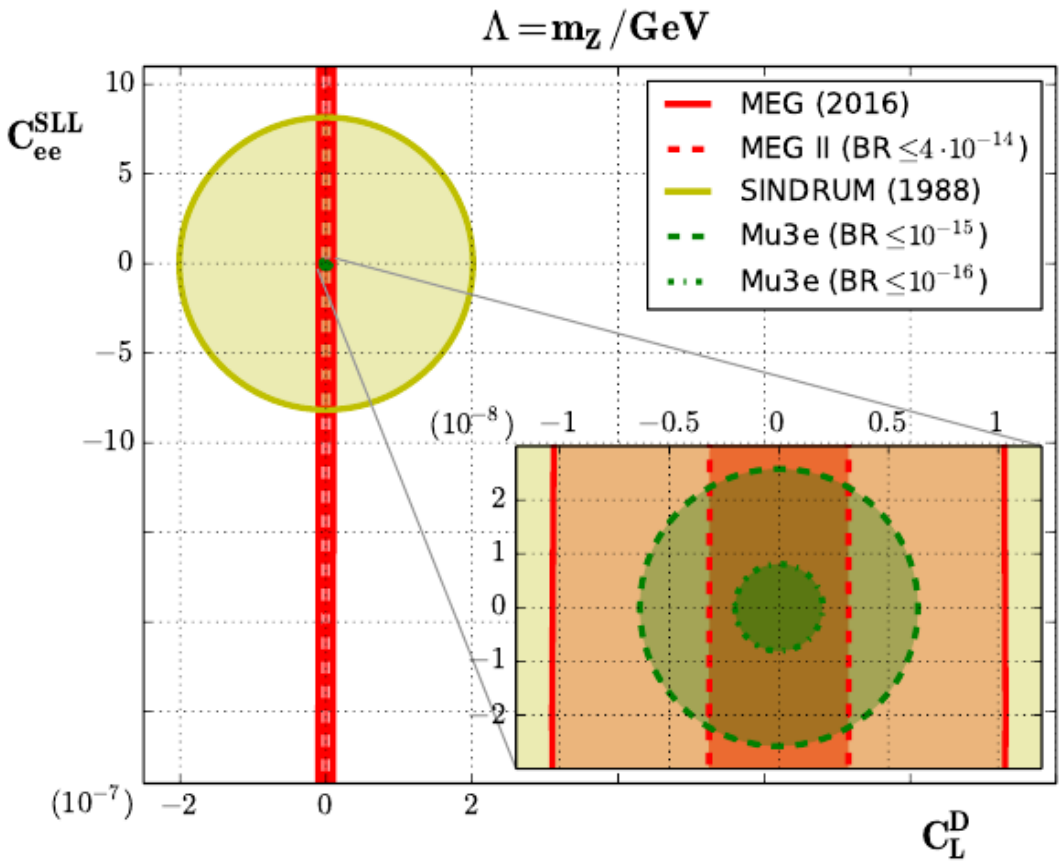
LFV-Effective Field Theory

A.Crivellin et al., PSI-PR-16-15

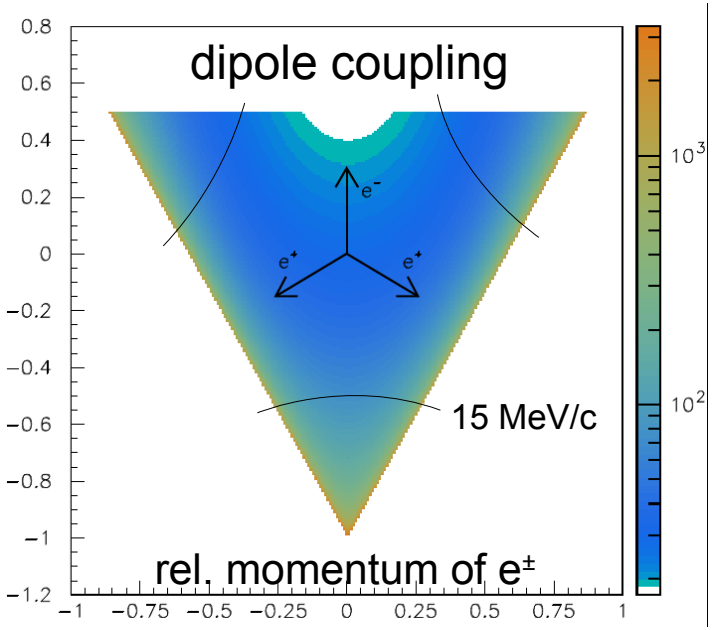
$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{QED+QCD}} + \frac{1}{\Lambda}\sum_k C_k^{(5)} Q_k^{(5)} + \frac{1}{\Lambda^2}\sum_k C_k^{(6)} Q_k^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda 3}\right)$$

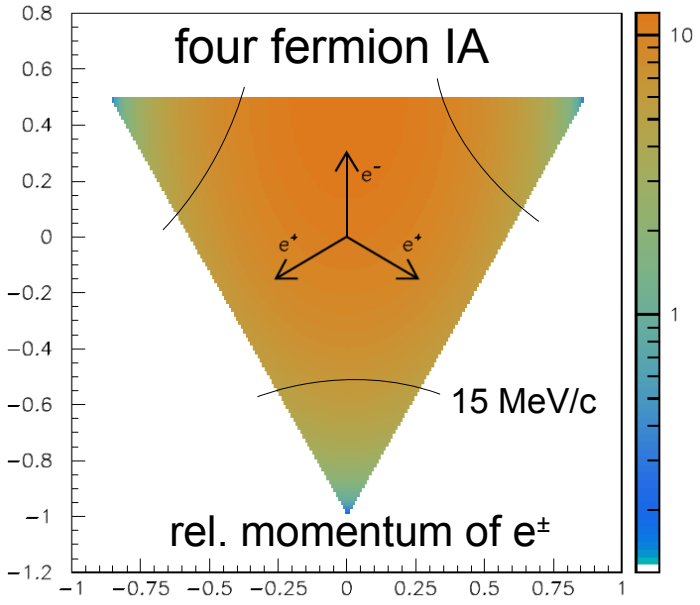
Representation by Wilson coefficients and higher-dimensional operators:

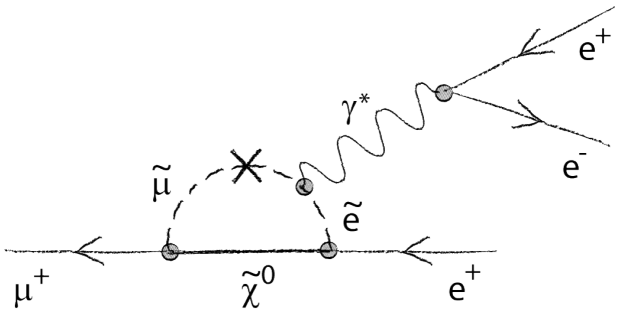
$$O_L^D = e\, m_\mu \left(\bar{e}\sigma^{\mu\nu} P_L \mu\right) F_{\mu\nu},$$
$$O_{ff}^{V\,LL} = \left(\bar{e}\gamma^\mu P_L \mu\right)\left(\bar{f}\gamma_\mu P_L f\right),$$
$$O_{ff}^{V\,LR} = \left(\bar{e}\gamma^\mu P_L \mu\right)\left(\bar{f}\gamma_\mu P_R f\right),$$
$$O_{ff}^{S\,LL} = \left(\bar{e} P_L \mu\right)\left(\bar{f} P_L f\right),$$
$$O_{ff}^{S\,LR} = \left(\bar{e} P_L \mu\right)\left(\bar{f} P_R f\right),$$
$$O_{ff}^{T\,LL} = \left(\bar{e}\sigma_{\mu\nu} P_L \mu\right)\left(\bar{f}\sigma^{\mu\nu} P_L f\right),$$

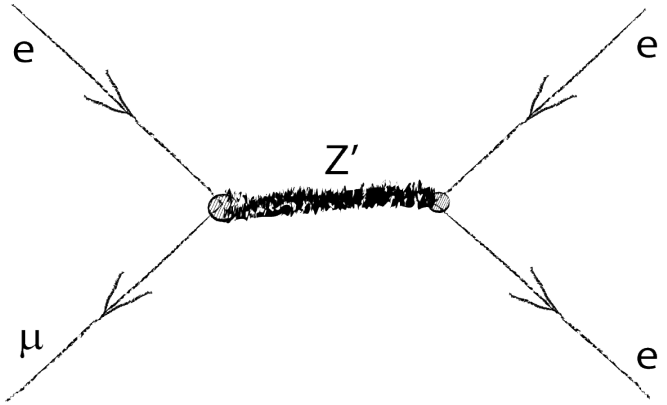


Mu3e Acceptance of BSM-Models

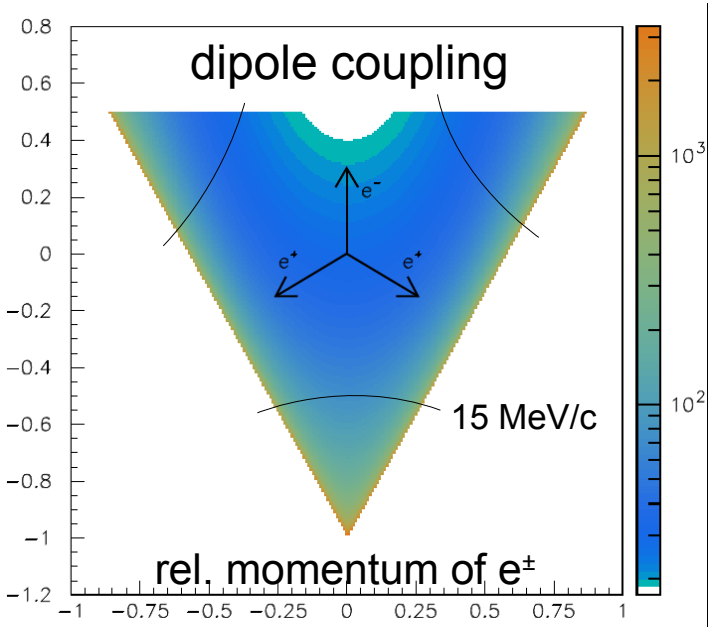


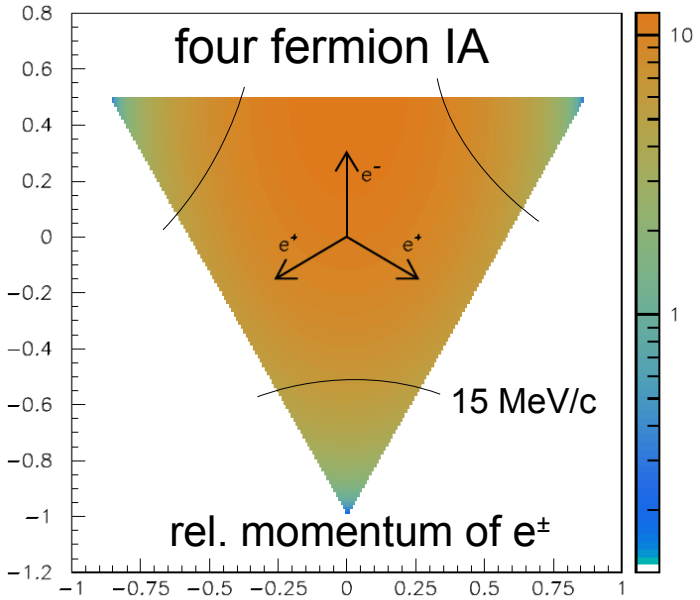


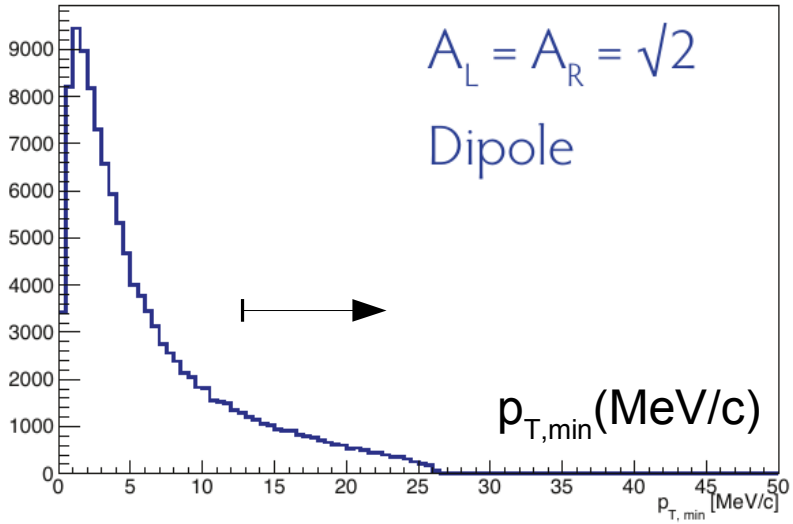


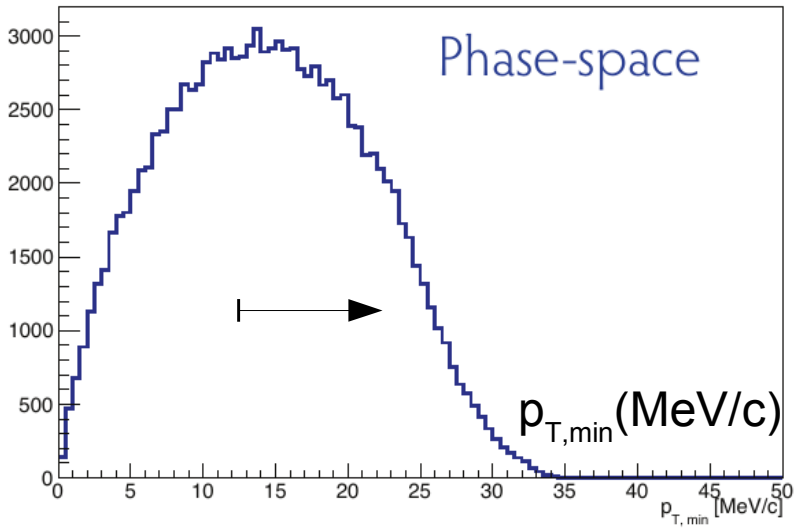


Mu3e Acceptance of BSM-Models

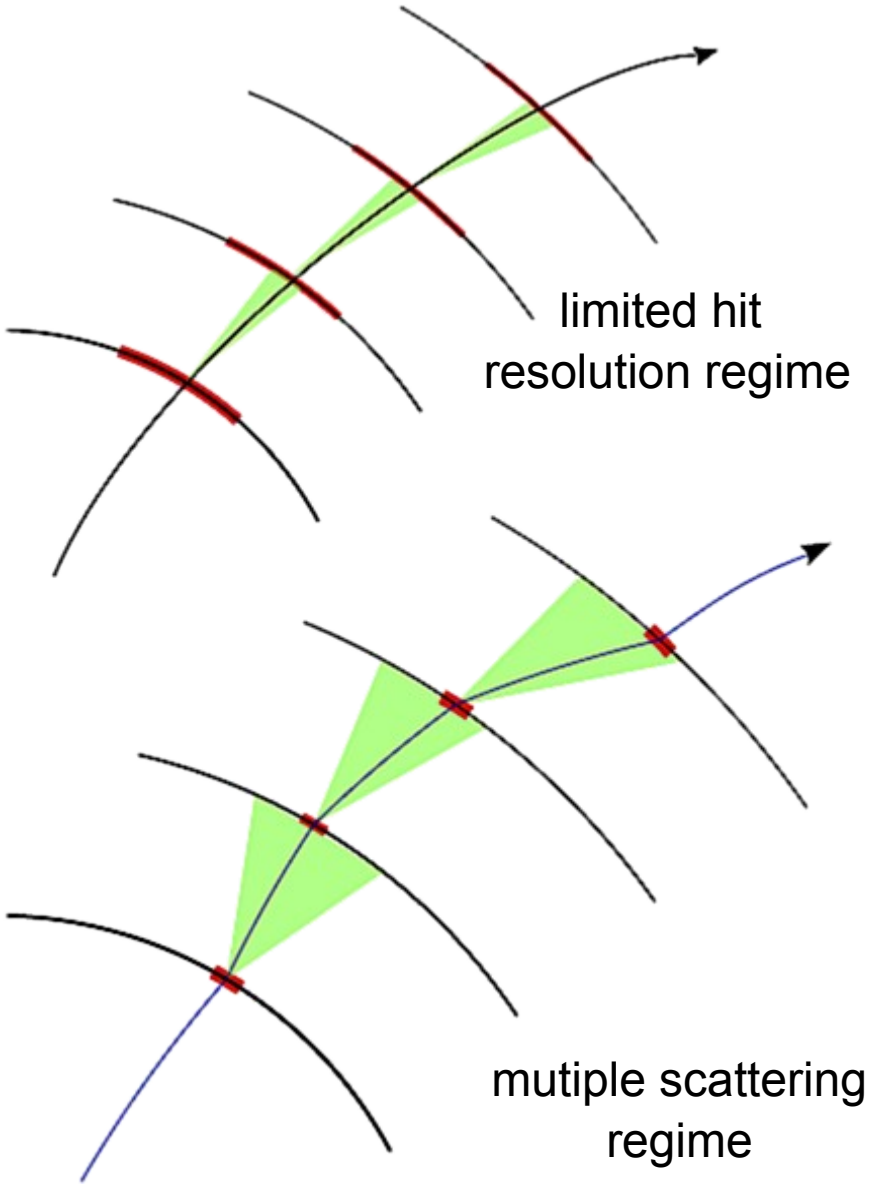








Kinematic Resolution + Multiple Scattering



- Muon decay:

  → electrons in low momentum range

  p < 53 MeV/c

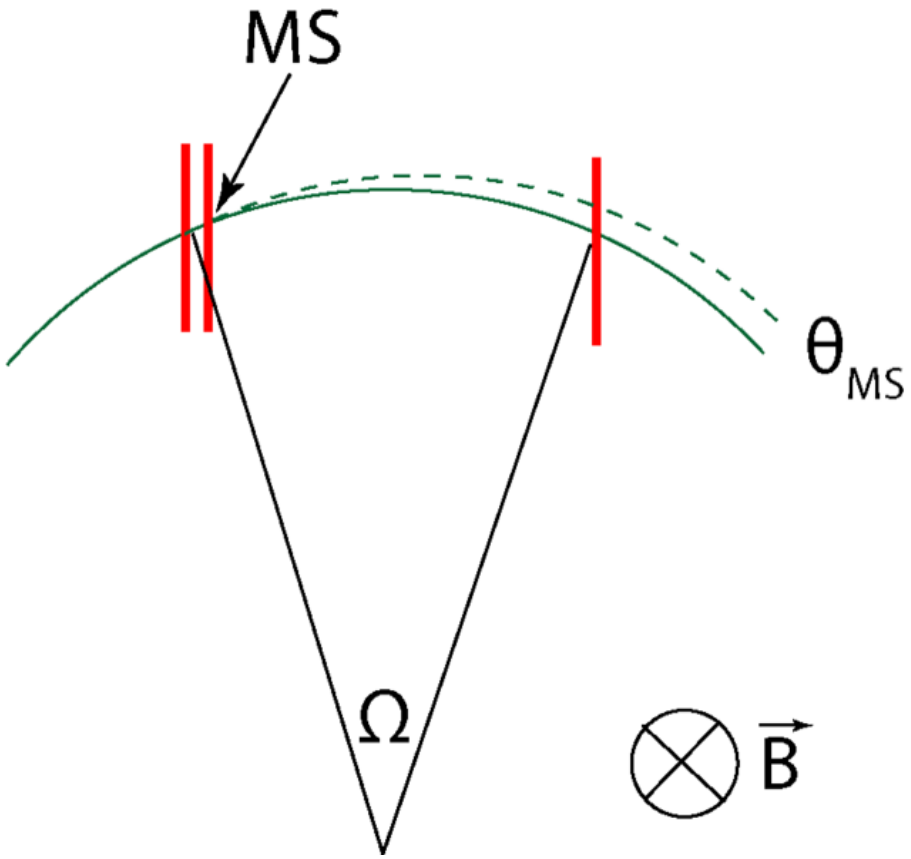
- Multiple scattering is dominant!

→ **Need thin, fast and high resolution tracking detectors operated at high rate of ~ 10^9 particles/s**

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

Momentum Resolution in MS Regime

- Standard spectrometer:

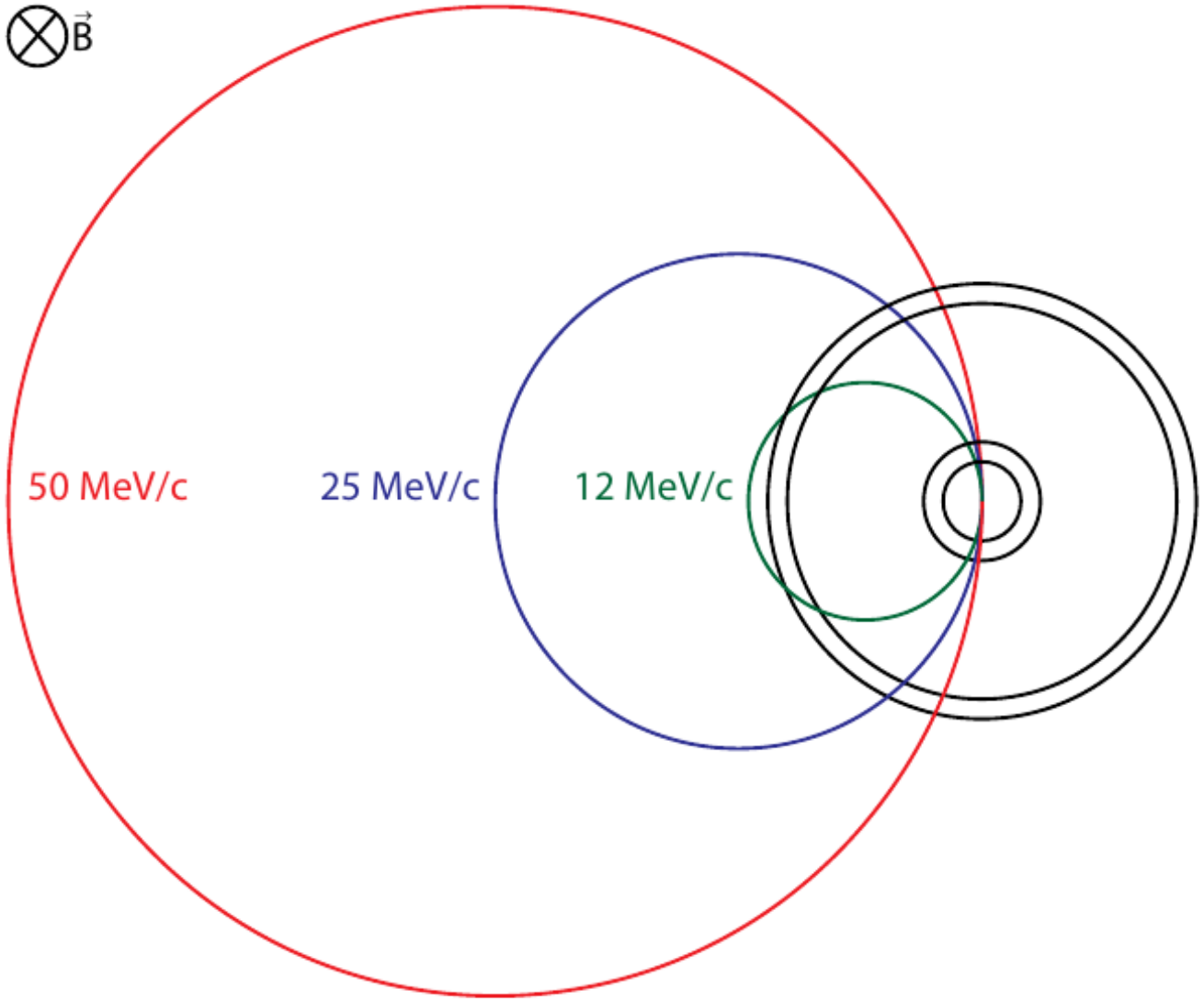


$$\frac{\sigma_p}{P} \sim \frac{\Theta_{MS}}{\Omega}$$ (linearised)

precision requires large lever arm

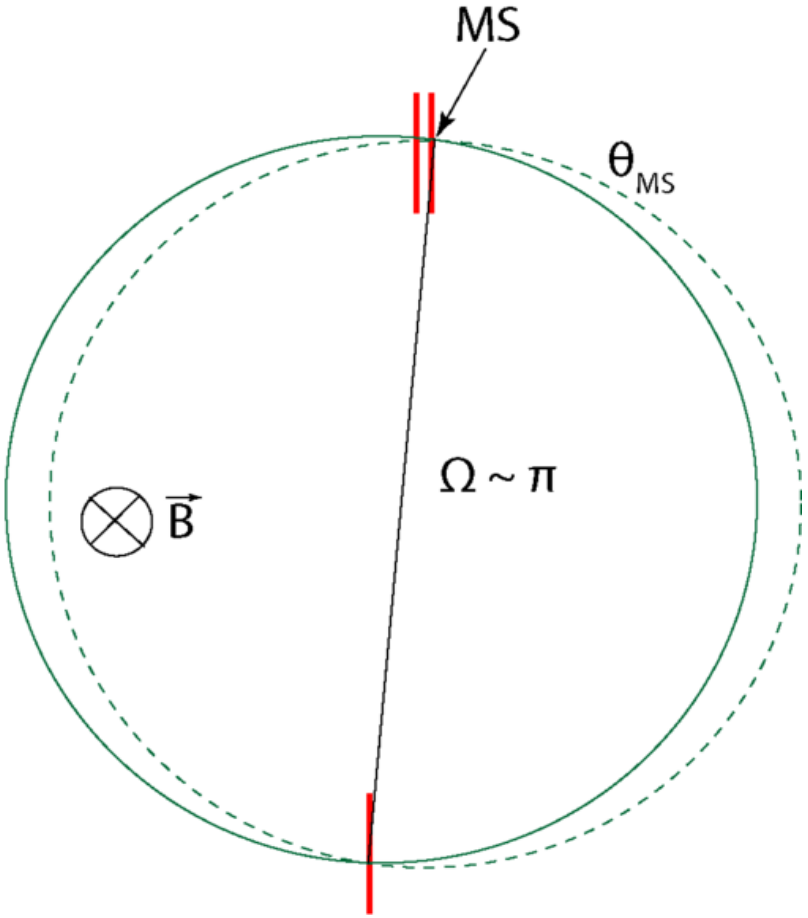
large bending angle Ω

Tracking Design Considerations



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**
- **have to measure recurlers**

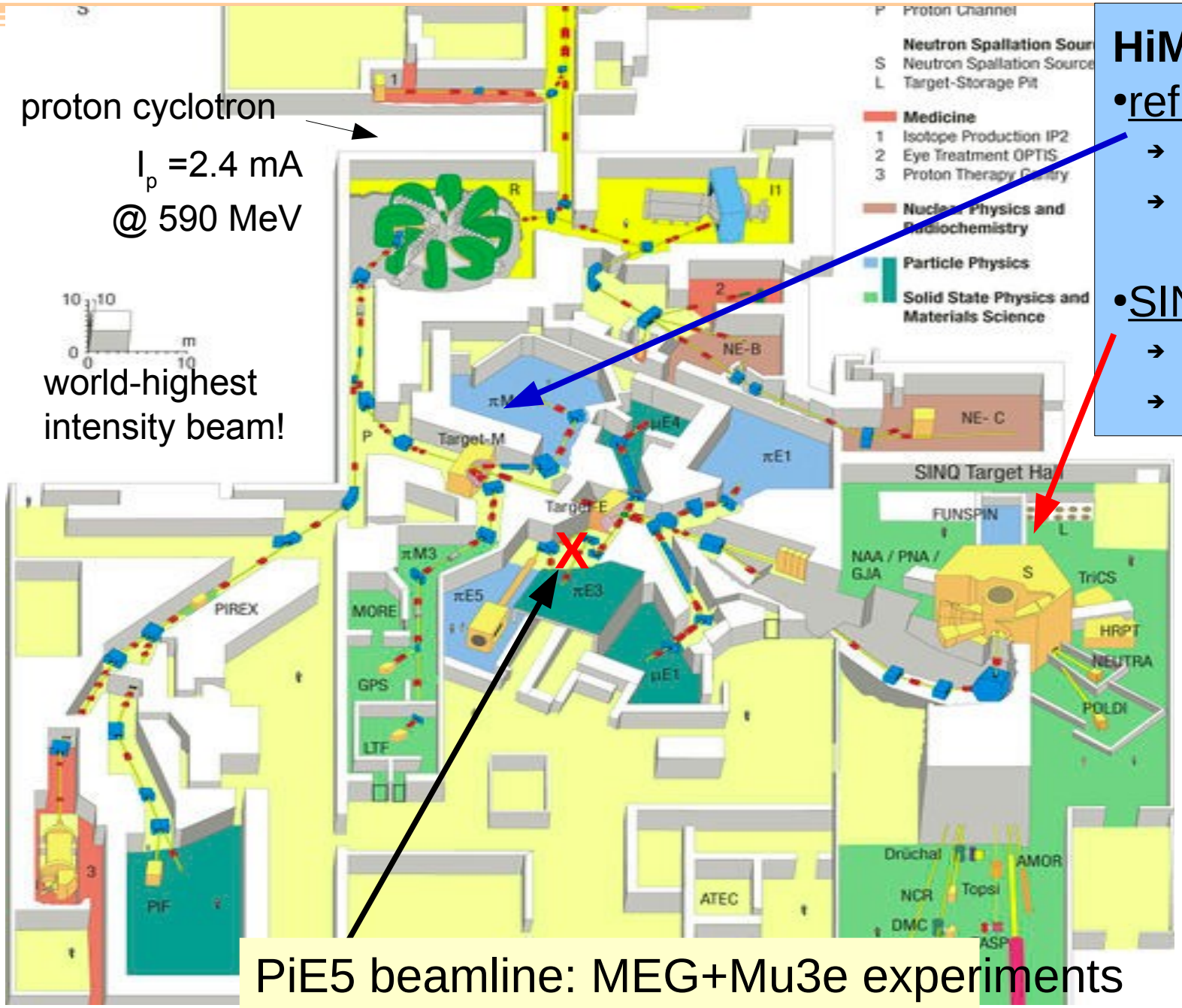
High Intensity Muon Beamline (HiMB)

proton cyclotron

I_p =2.4 mA

@ 590 MeV

world-highest intensity beam!



HiMB Studies:

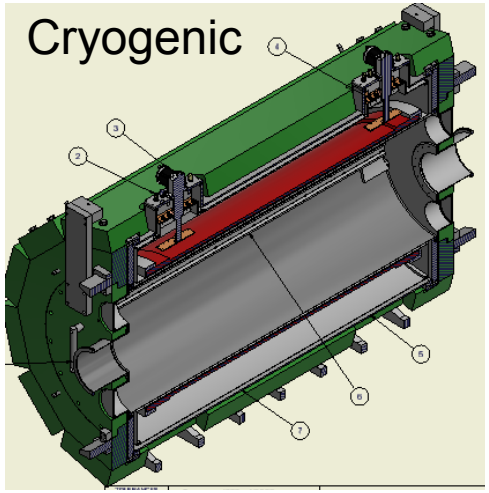
- refurbish target M
  - → μ rates >> 10^9/s
  - → **promising!**
- SINQ target:
  - → rates >10^{10}/s possible
  - → but extremely difficult

PiE5 beamline: MEG+Mu3e experiments

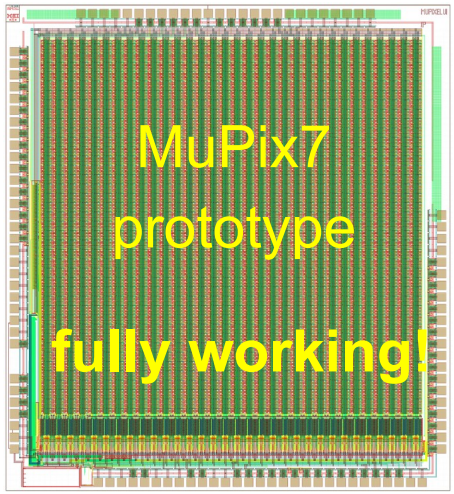
Mu3e Solenoid Magnet

- Contract with Danfysik canceled by Heidelberg University at January 25th 2017 because of non-fulfillment
  - ➔ Danfysik had underestimated technical risk and business hazard Q-BVR48
  - ➔ problem were not our specifications (B=2T, homogeneous)

- 2018 events…
  - tendering process started Easter 2017
  - specs almost unchanged; B → 2.6T
  - serious offers from Cryogenic Ltd and TESLA Ltd only
  - decision for Cryogenic (better price)
  - kick of meeting in September 2017
- Magnet TDR March 2018 (no show stopper so far)
- Magnet delivery expected for beginning 2019 (in accordance with out plans)



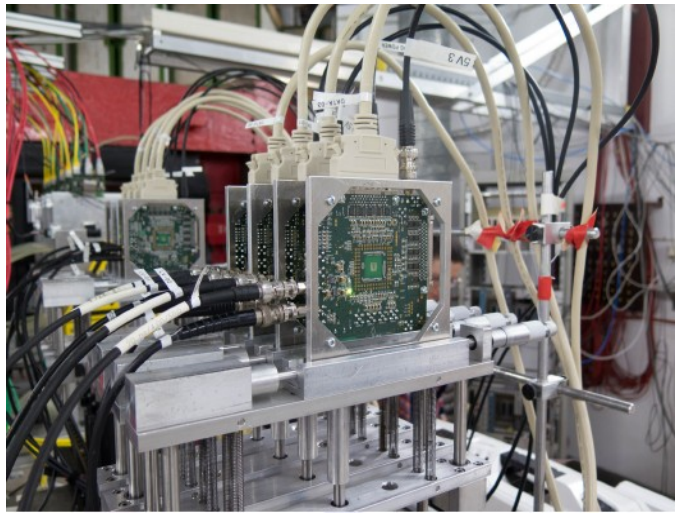
Mupix7 Results



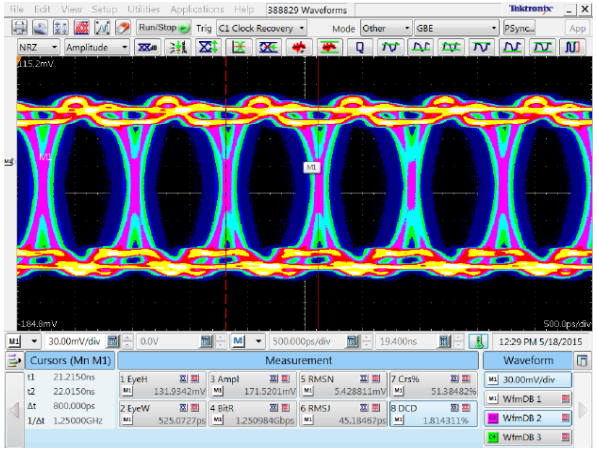
50 µm thickness

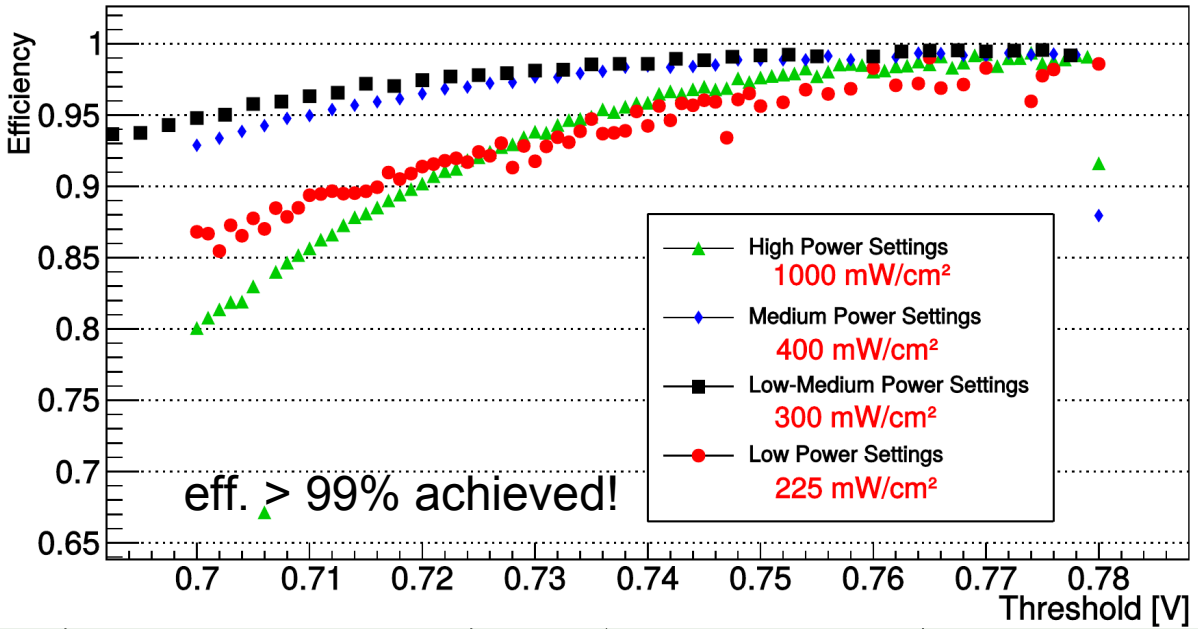
test beams performed at

- CERN
- PSI
- DESY
- MAMI

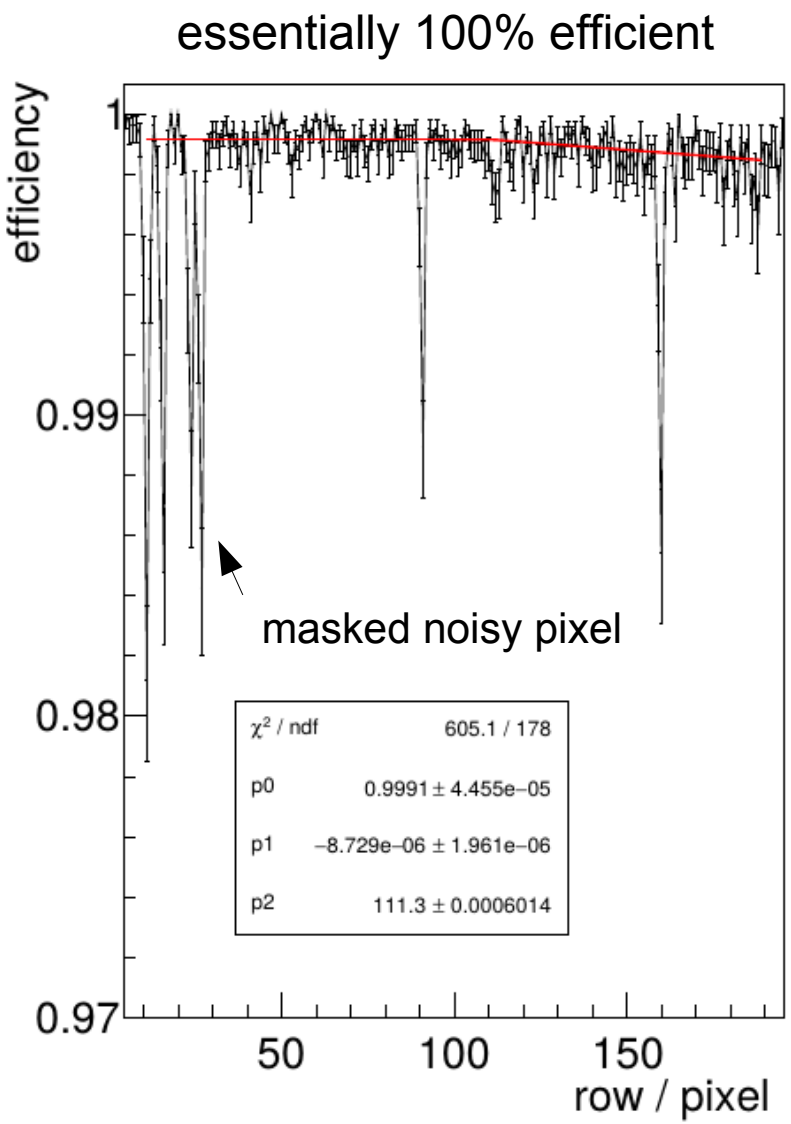


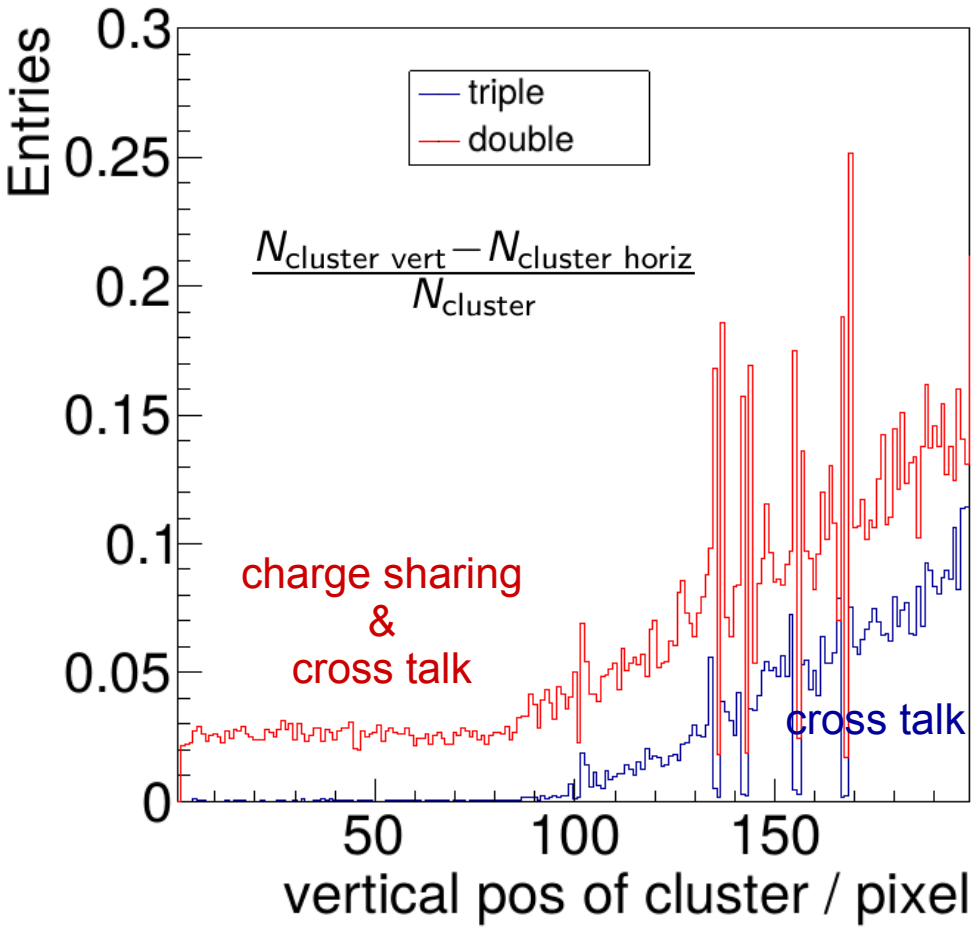
- continuous readout (zero suppressed)
- serial readout with 1.25 Gbit/s
- up to 33 Mhits/s





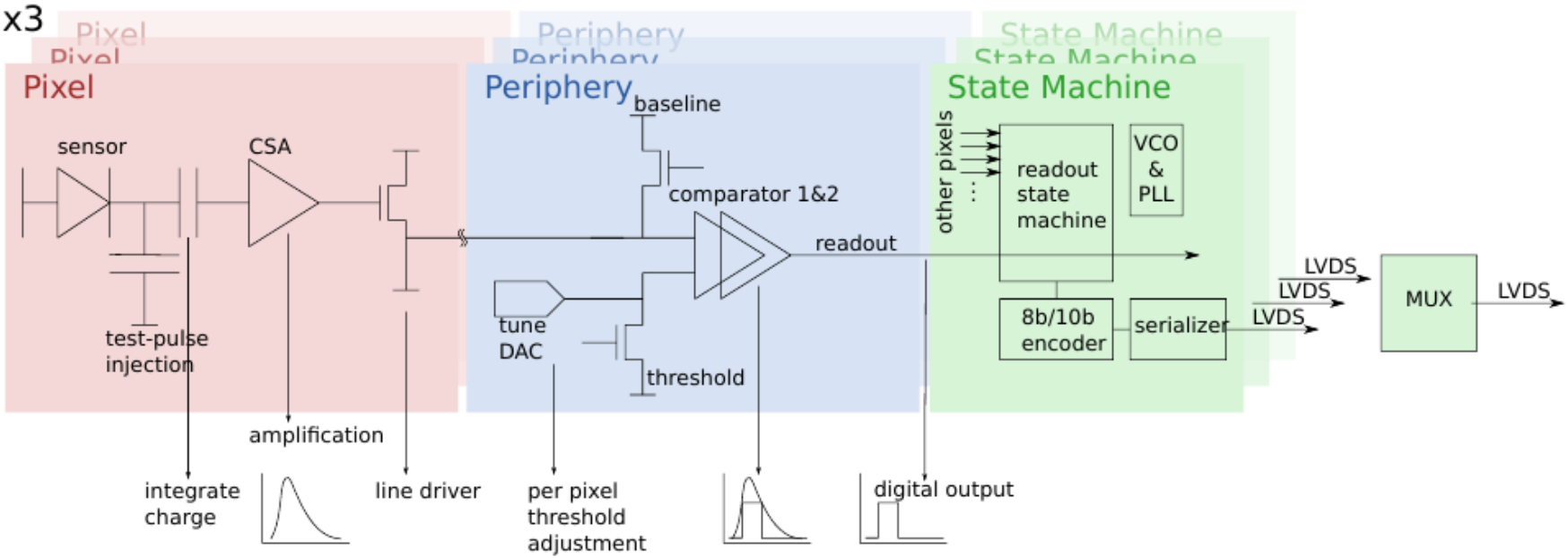
Mupix8 and Crosstalk



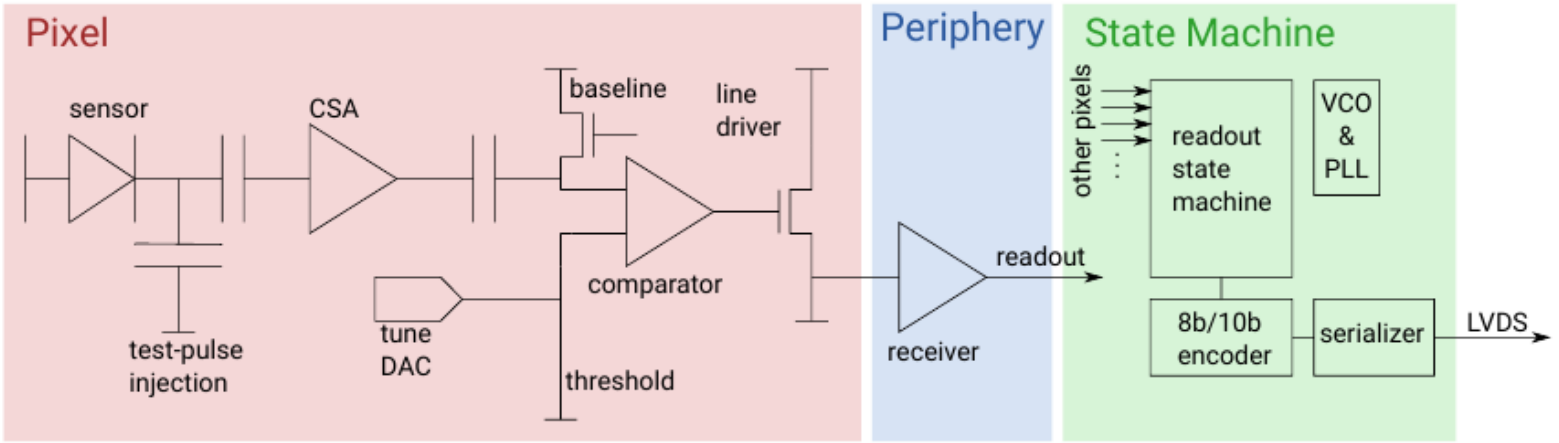


Mupix8 and ATLASpix Design

MuPix8

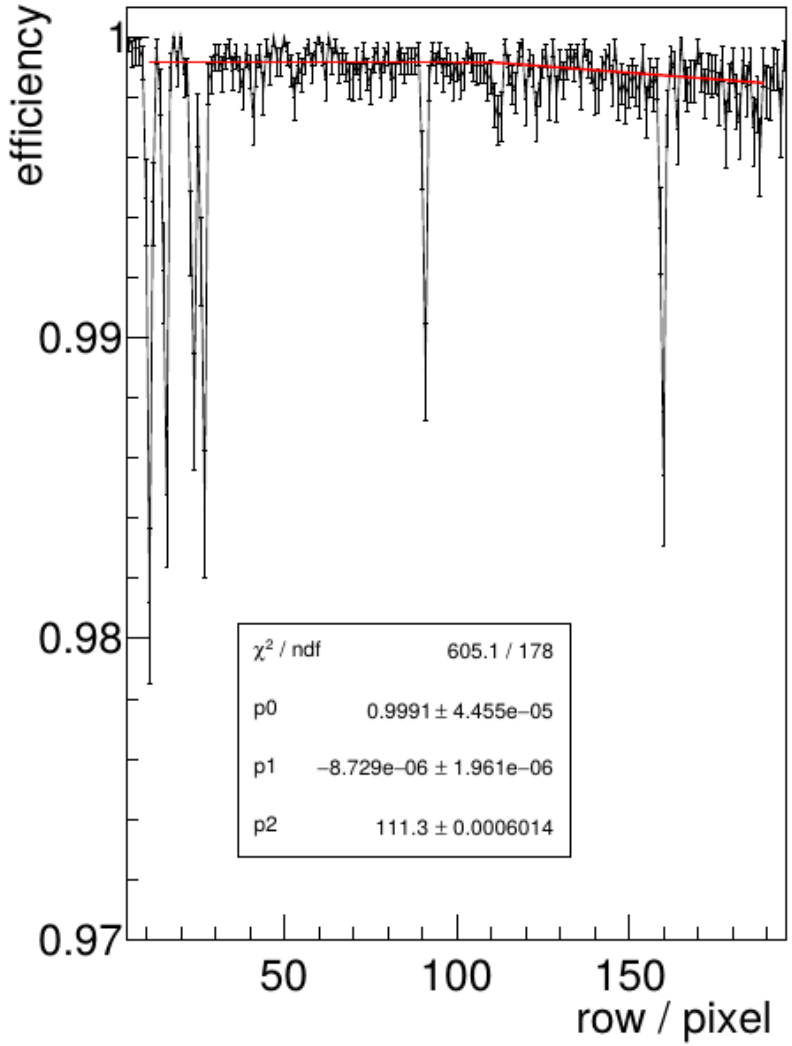


AtlasPix

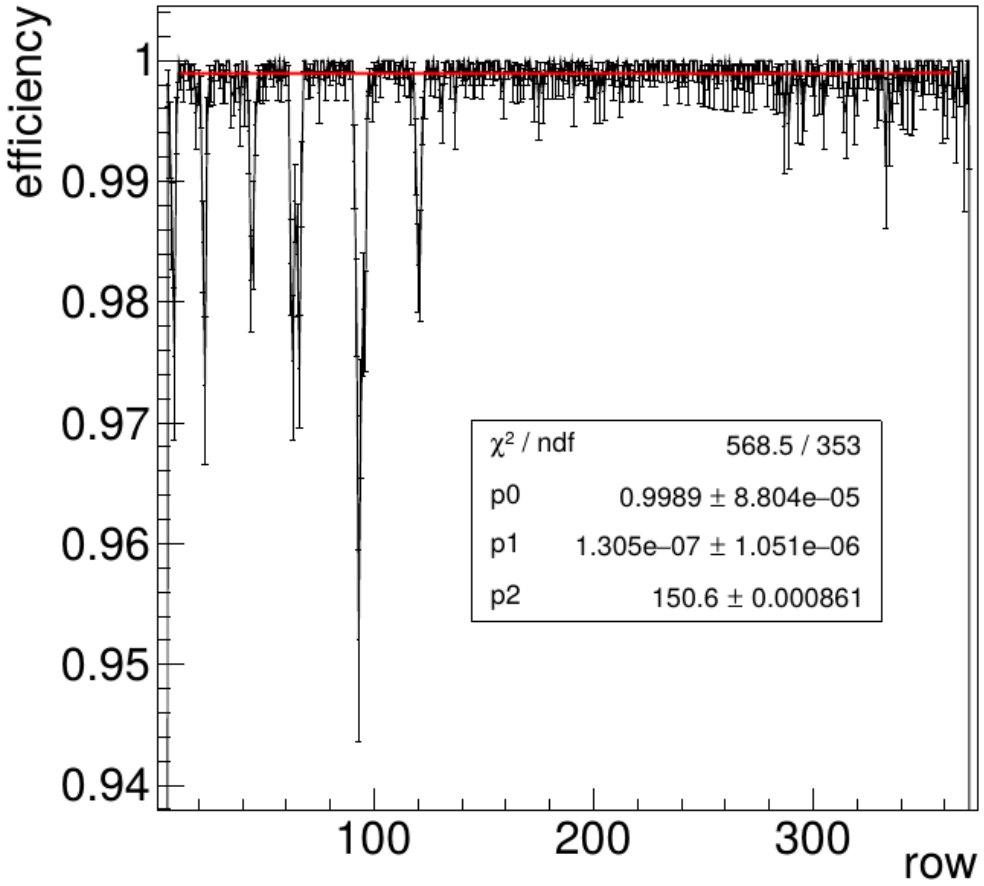


Efficiency Comparison

MuPix8

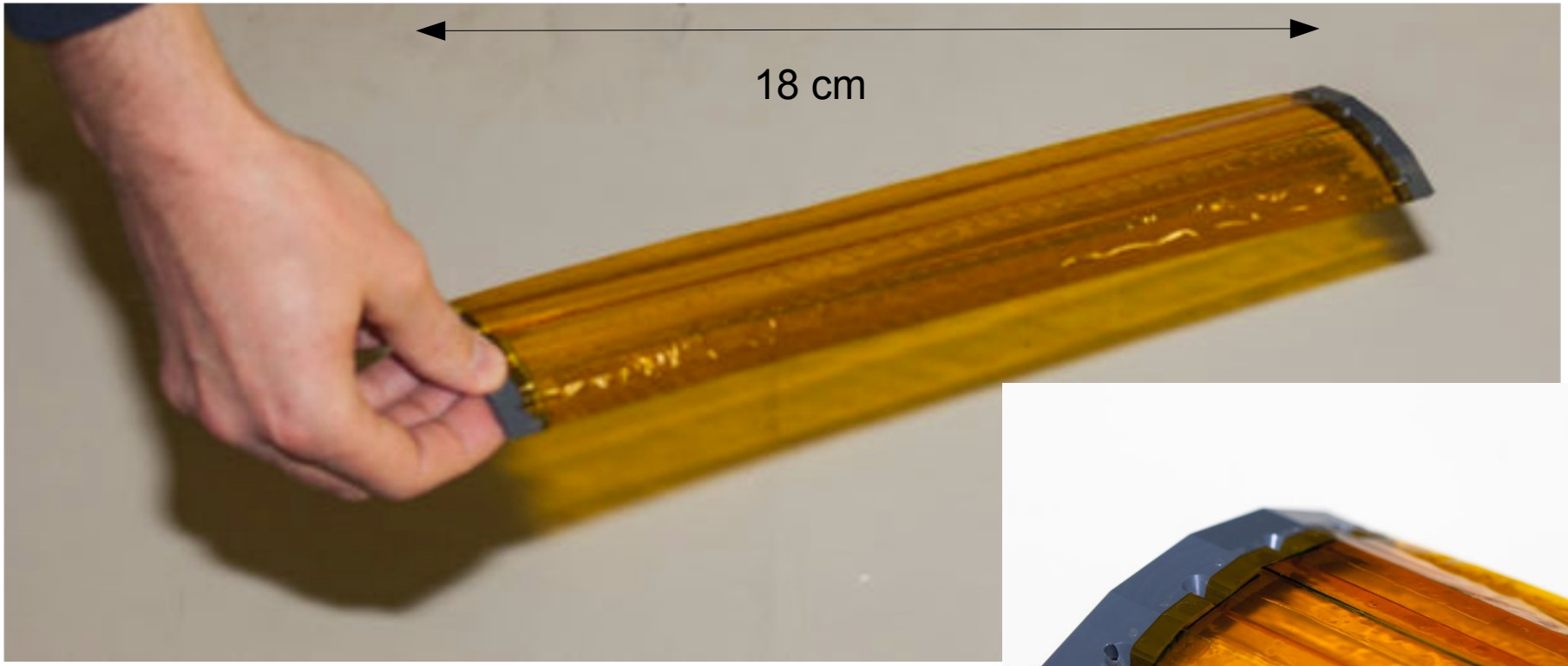


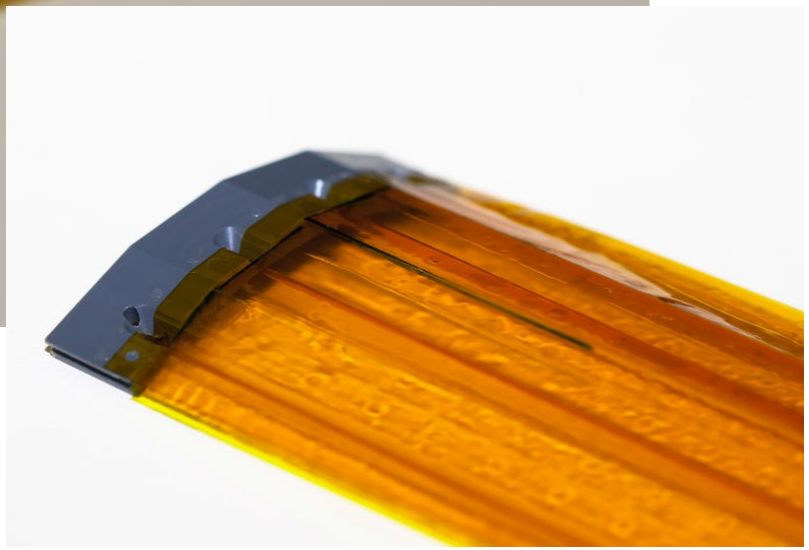
ATLASpix



Mechanical Prototypes for Pixel Tracker

even larger stable structures with 100 µm thickness possible



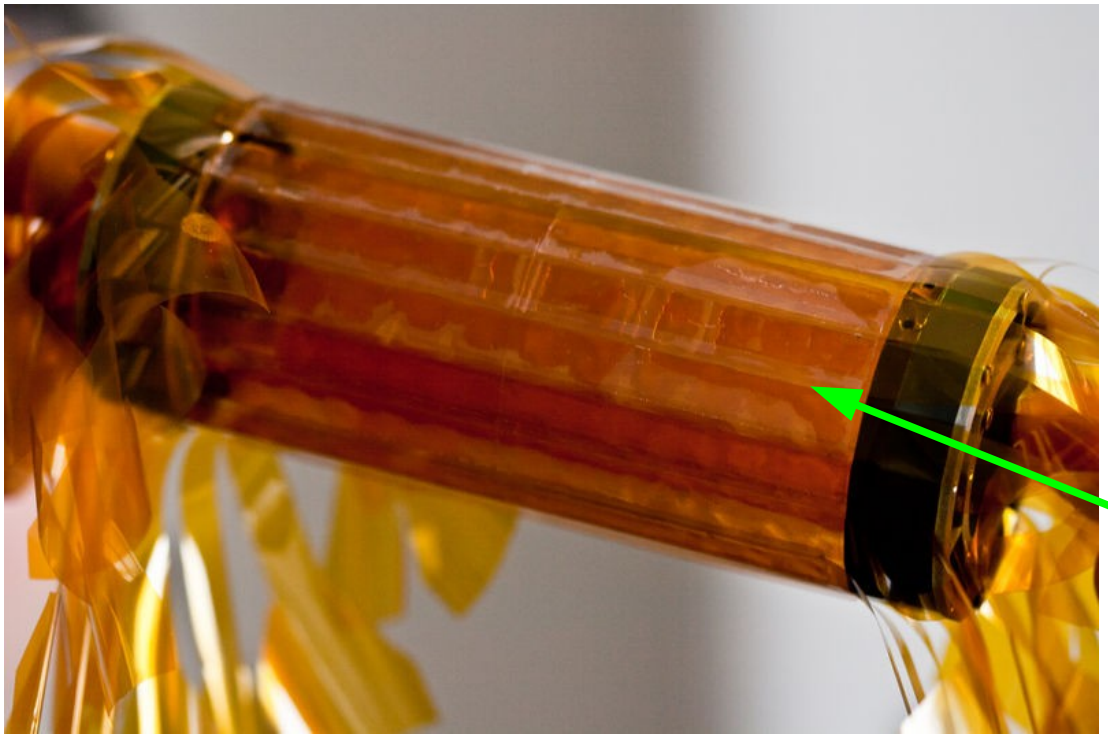


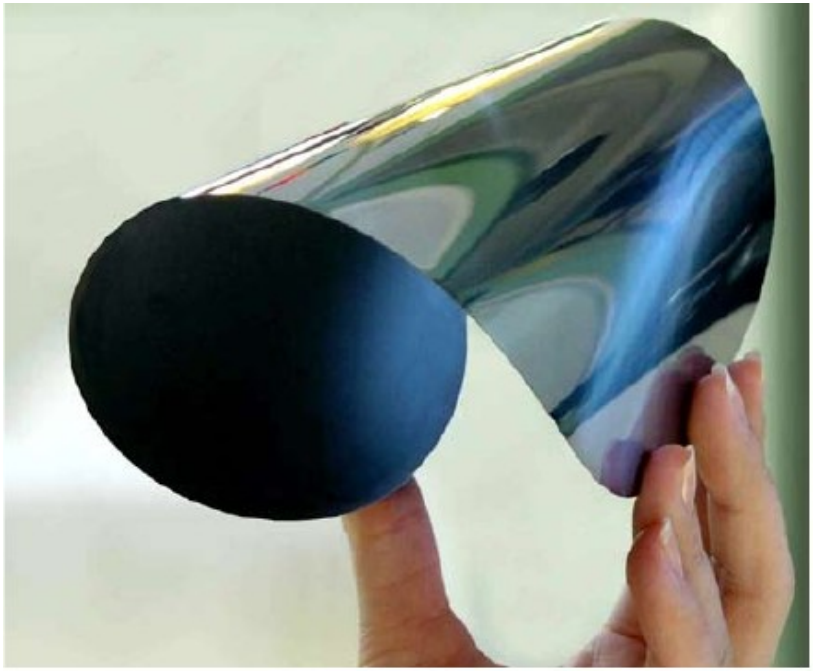
by using Kapton folds

Mechanical Prototypes for Pixel Tracker

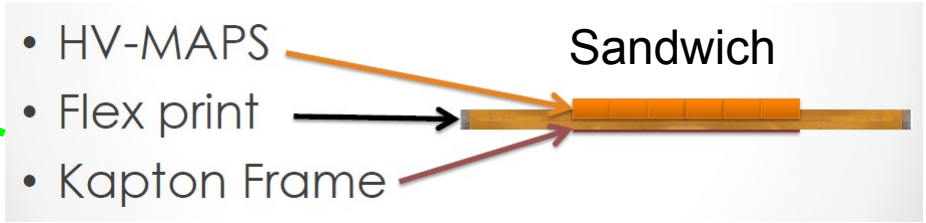
Ultra-thin detector mock-up:

- sandwich of 25 µm Kapton®
- here 50 µm glass (instead of Si)





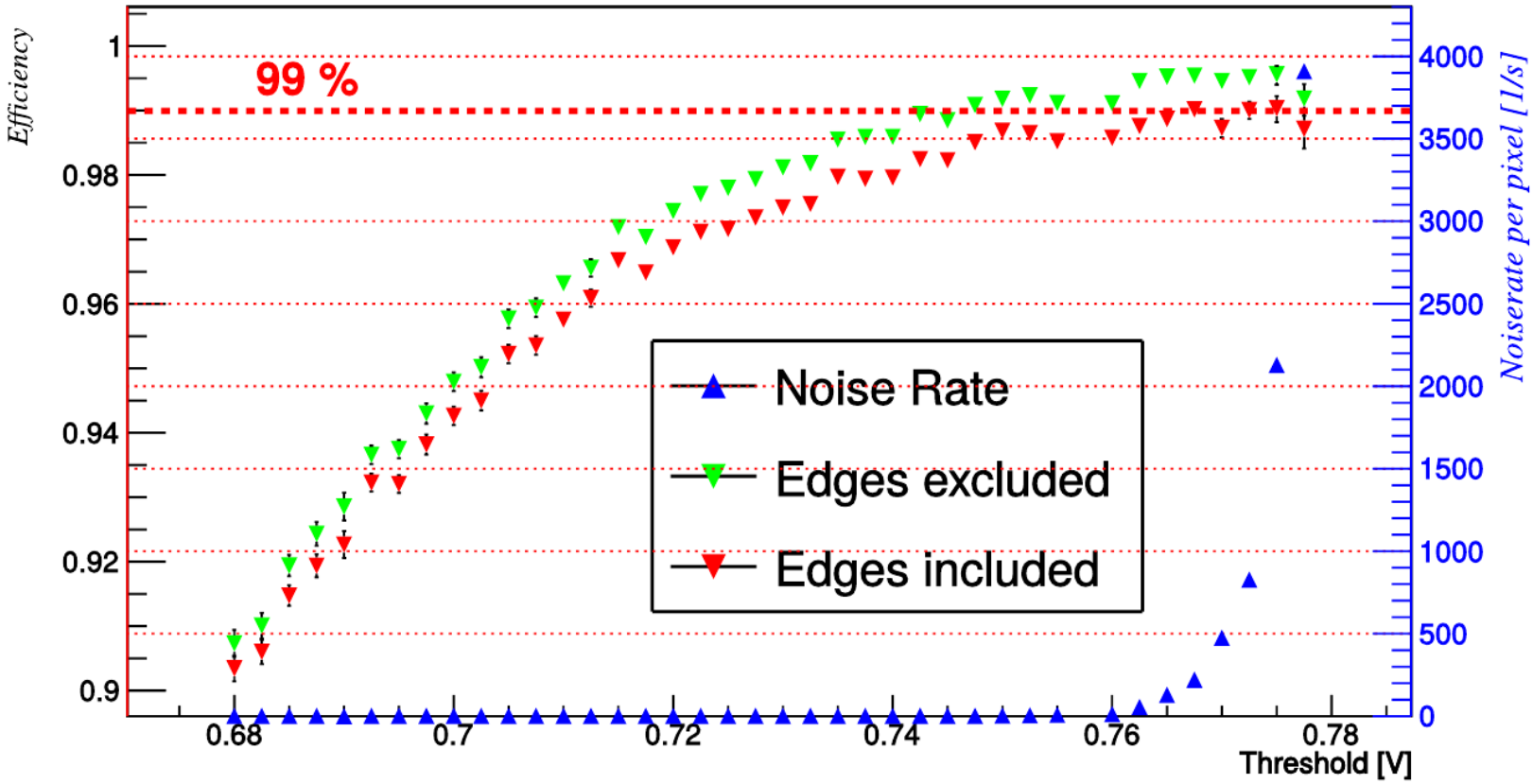
50 mu silicon wafer



X ≤ 0.1% X_0 per layer possible

MuPix7: Efficiency

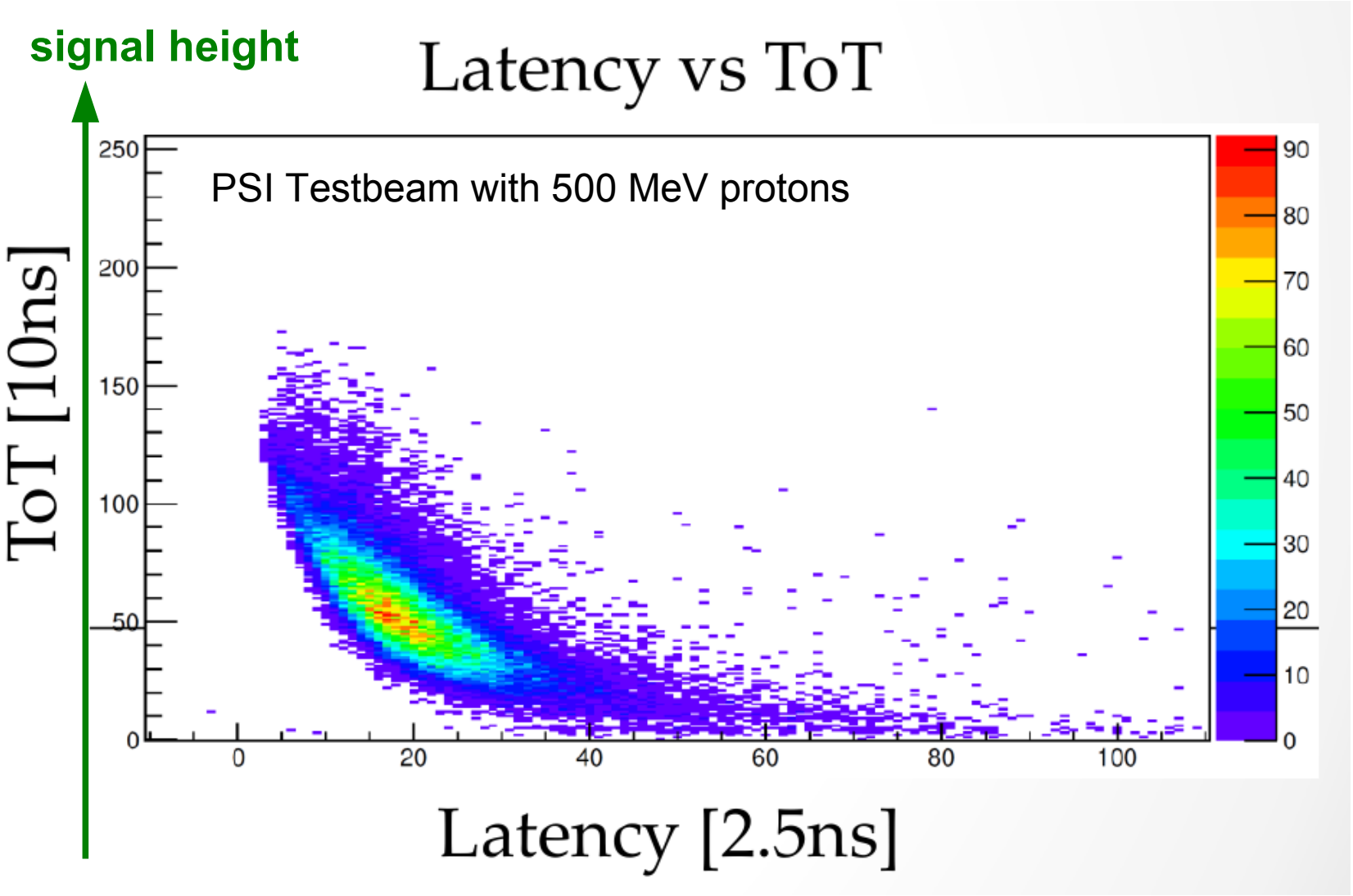
Efficiencies of DUT in a telescope:



One setting (intermediate power) as example with noise rate

Data taken at PSI

MuPix6 Time Resolution

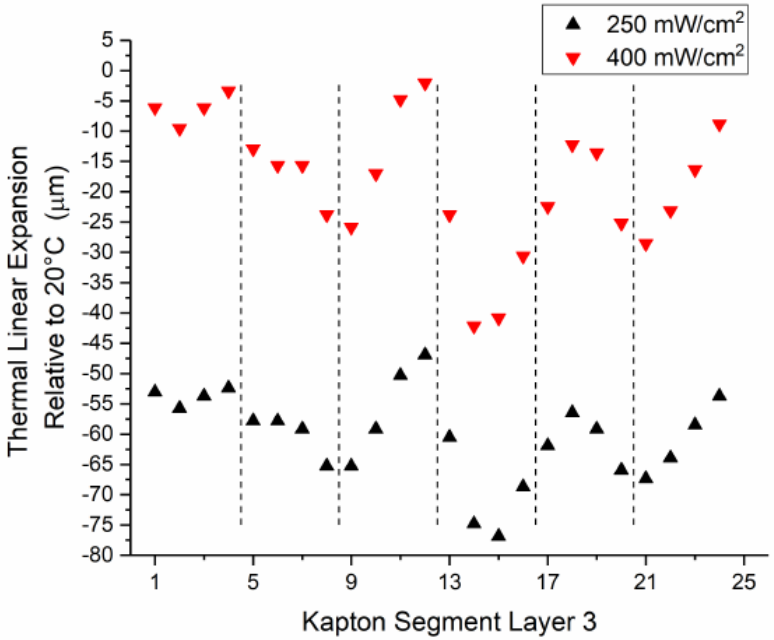


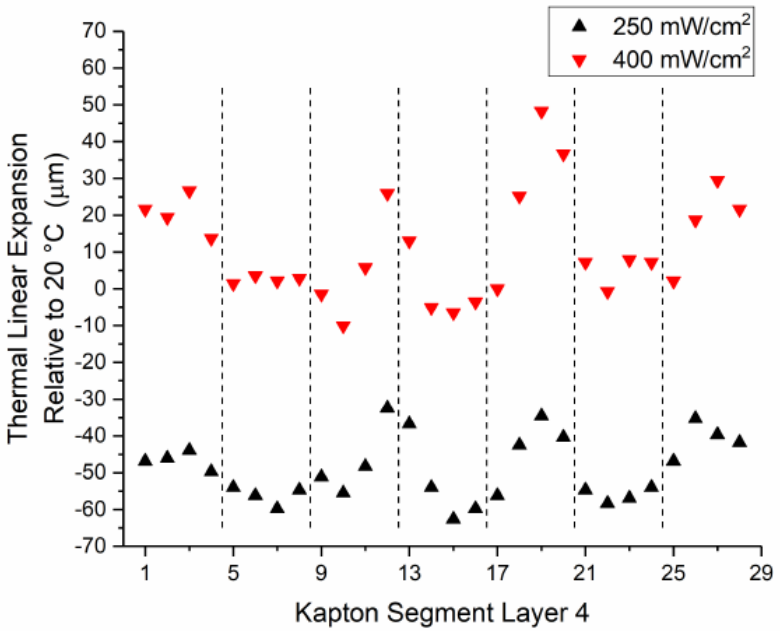
→ **timewalk correction possible**

Thermal Expansion of Pixel Layers

Cooling simulations

Average temperature of ladder translated into thermal expansion of polyimide:





Note: This is a result calling for more studies. Plan is to optimise gas inlets. Interplay with duct layout, hence non-trivial.

Ribbon Characterization: Summary

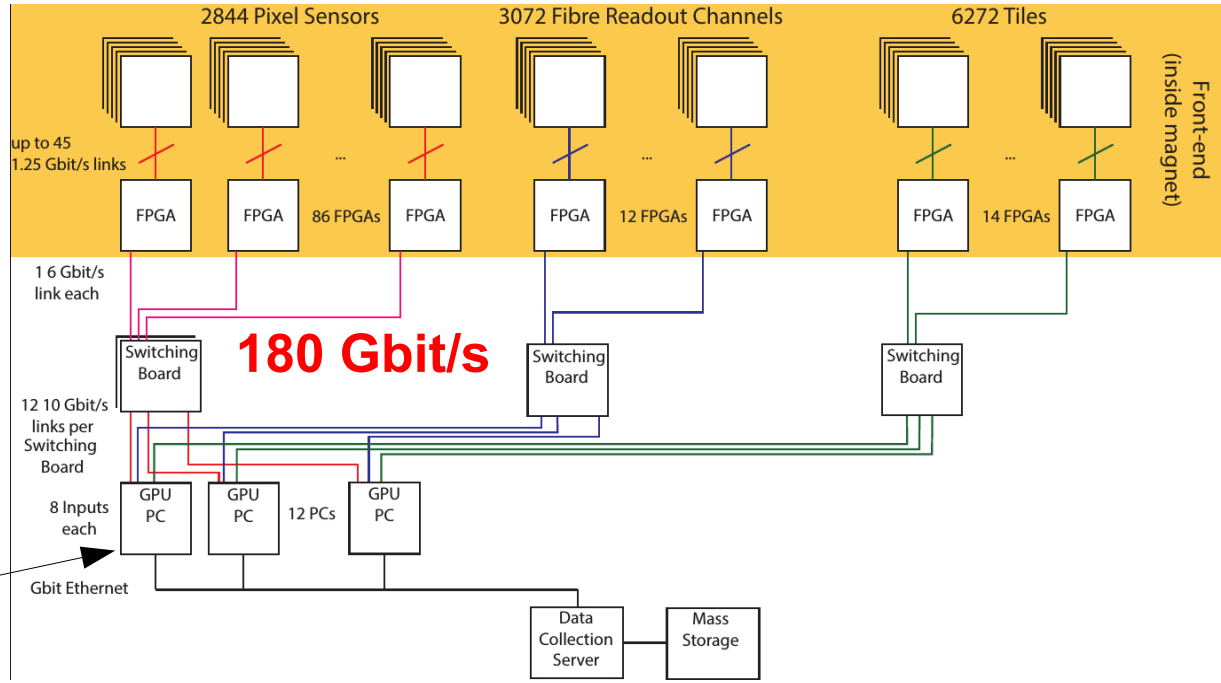
Fiber	Layers	Coating	$\sigma_{\Delta T}$ [ps]	Efficiency within ± 3σ [%]
SCSF 78 MJ	**3**	**Clear**	**500**	**92.3**
SCSF 78 MJ	**4**	**Clear**	**450**	**97.3**
SCSF 78 MJ	4	TiO2 20%	430	94.0
NOL 11	2	TiO2 Outside	510	88.7
NOL 11	3	TiO2 Outside	430	93.8
NOL 11	4	TiO2 20%	395	95.8
NOL 11	4	Clear	380	94.3
SCSF 81 MJ	4	TiO2 20%	580	91.1
BCF 12, square	3	Al 100 nm	700	68.5
Design requirement			**710**	**95.0**

➢ Ribbons will be produced with Kuraray **SCSF 78 MJ** using **Clear epoxy**

Online Filter Farm

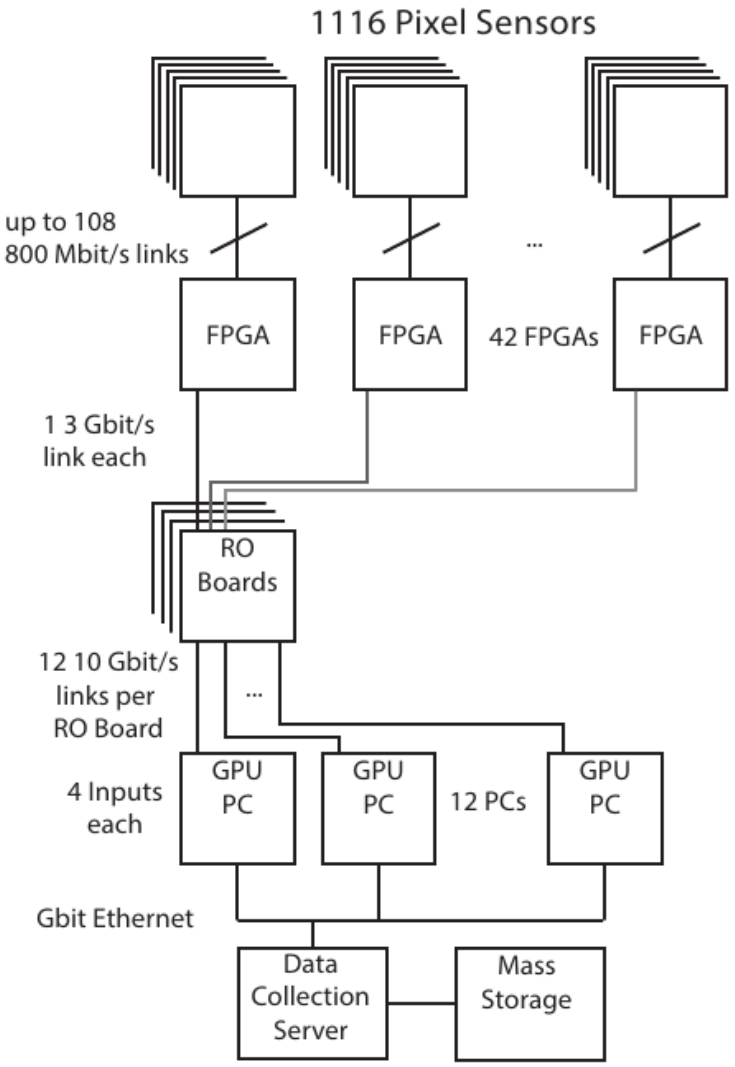
- Data reduction by **factor 100** required
- GPU Filter farm
  - reconstruction of **tracks** in central detector
  - simplified **vertex fit**
  - about 2 million 50ns-frames per second on GTX1080
  - 12 PC needed for farm

Mu3e Data Acquisition



Data Acquisition

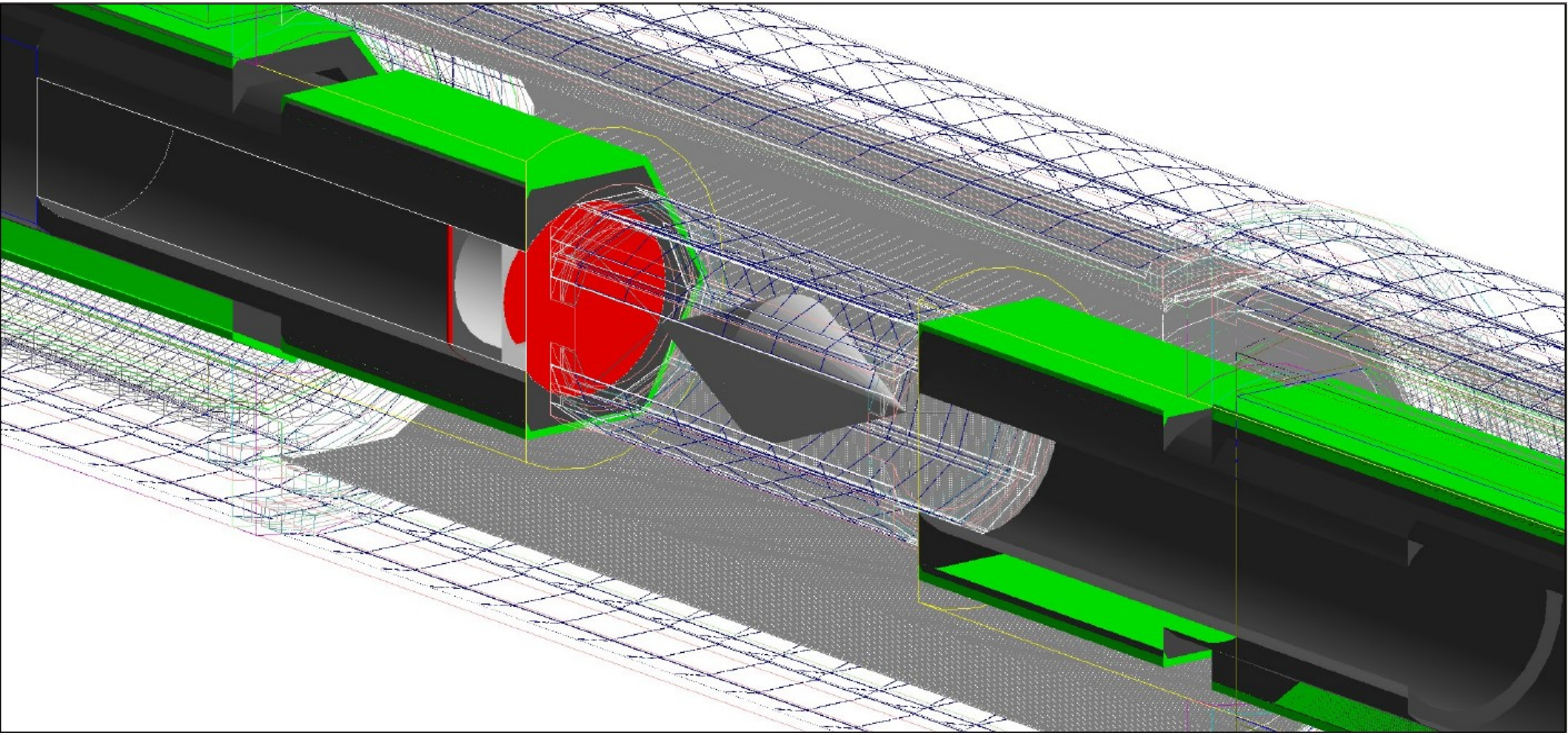
- Total number of pixels ~280 mill (+fibers+tiles)
- Frontend data rate of ~1 Tbit/s (Phase II)
- Online event reconstruction (no trigger)
- FPGA based switching network
- Graphics Processing Units (~50 GPUs)



plan to perform complete vertical slices test with existing prototypes in 2018

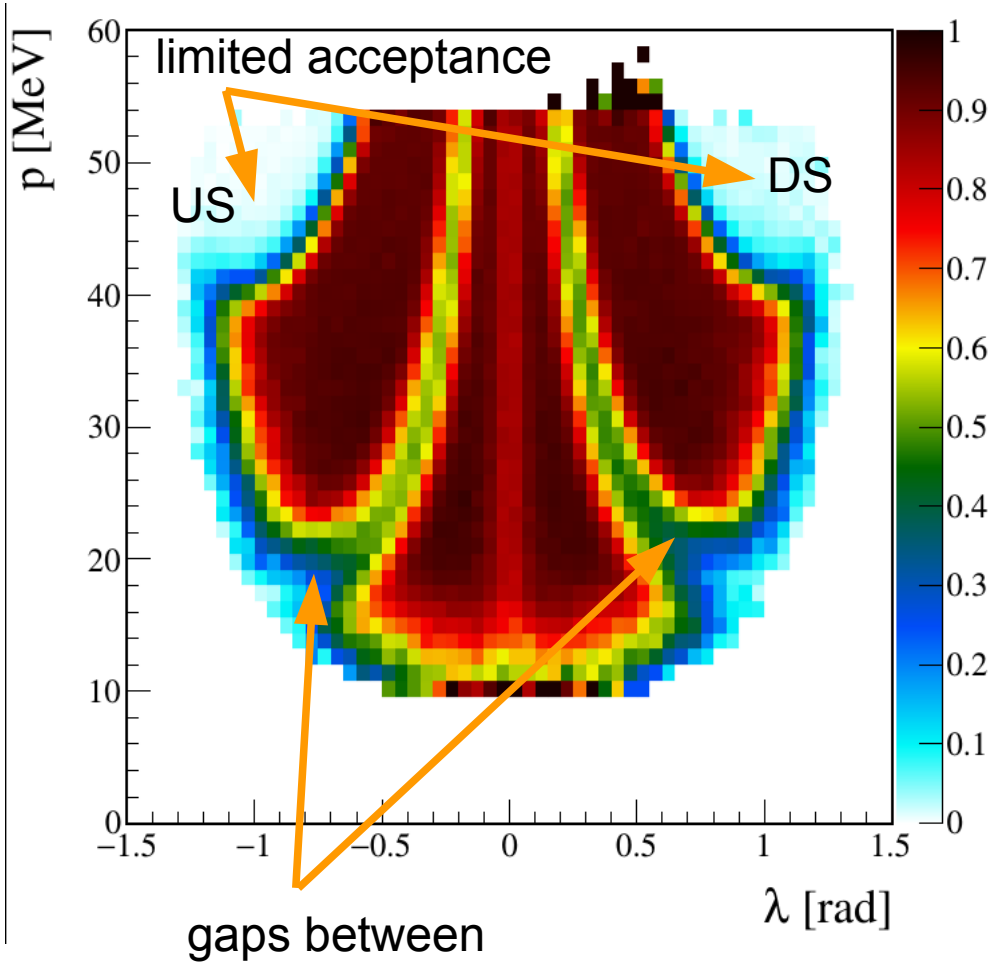
Logging rate ~50-100 MB/s

Simulation and Performance

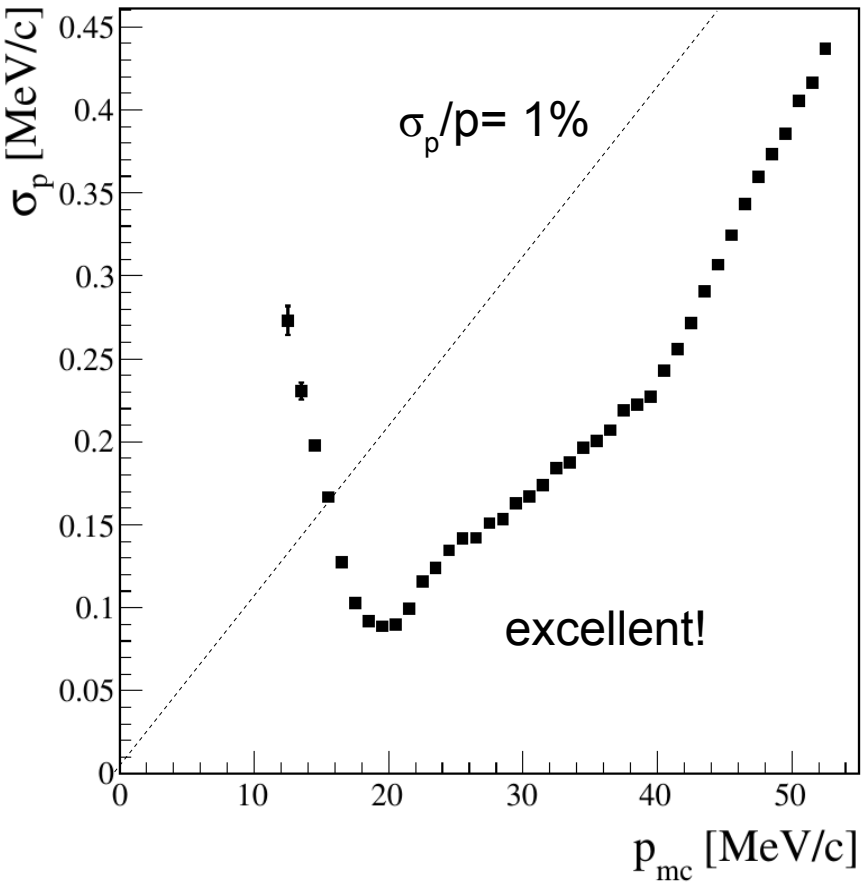


Simulation and Performance

Track Reconstruction Efficiency



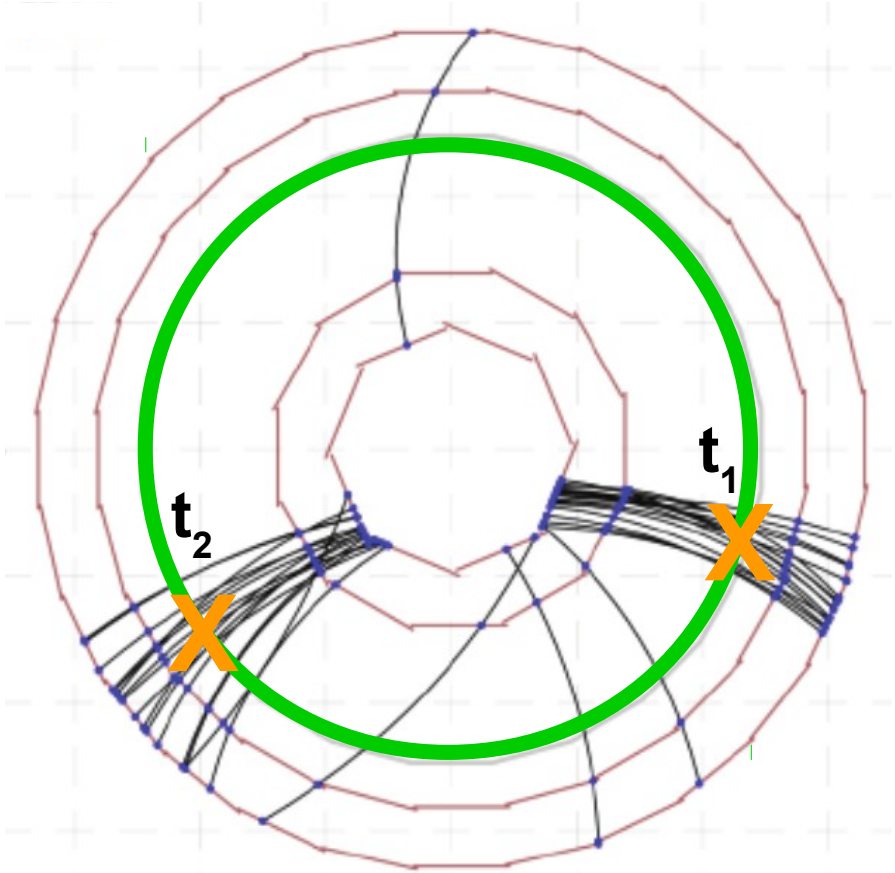
Track Momentum Resolution



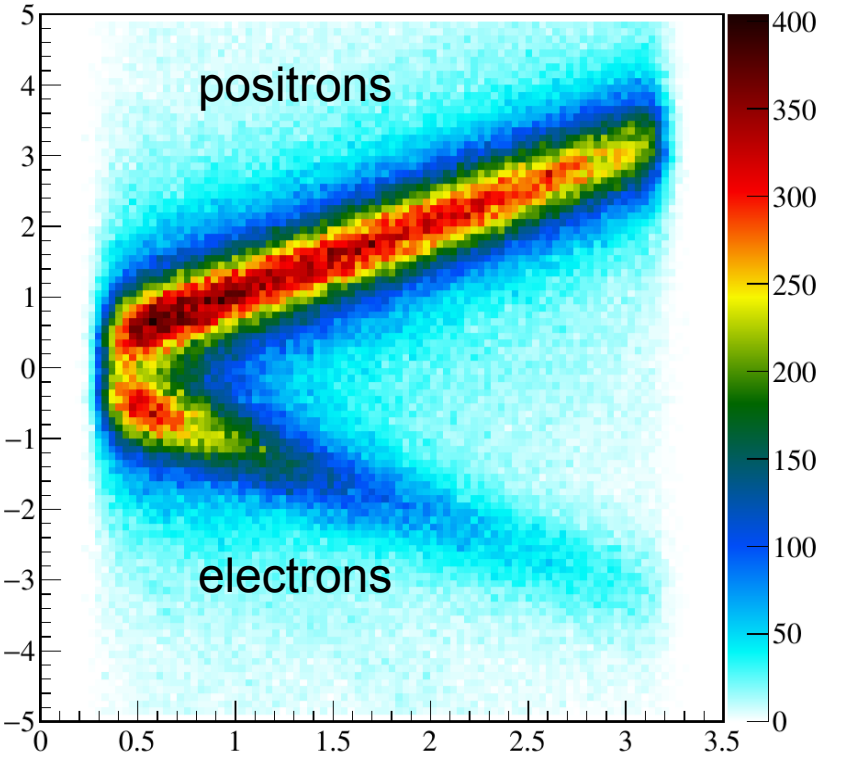
Charge Identification

Main process: $\mu^+ \rightarrow e^+ \nu\nu$

positron loopers → charge confusion

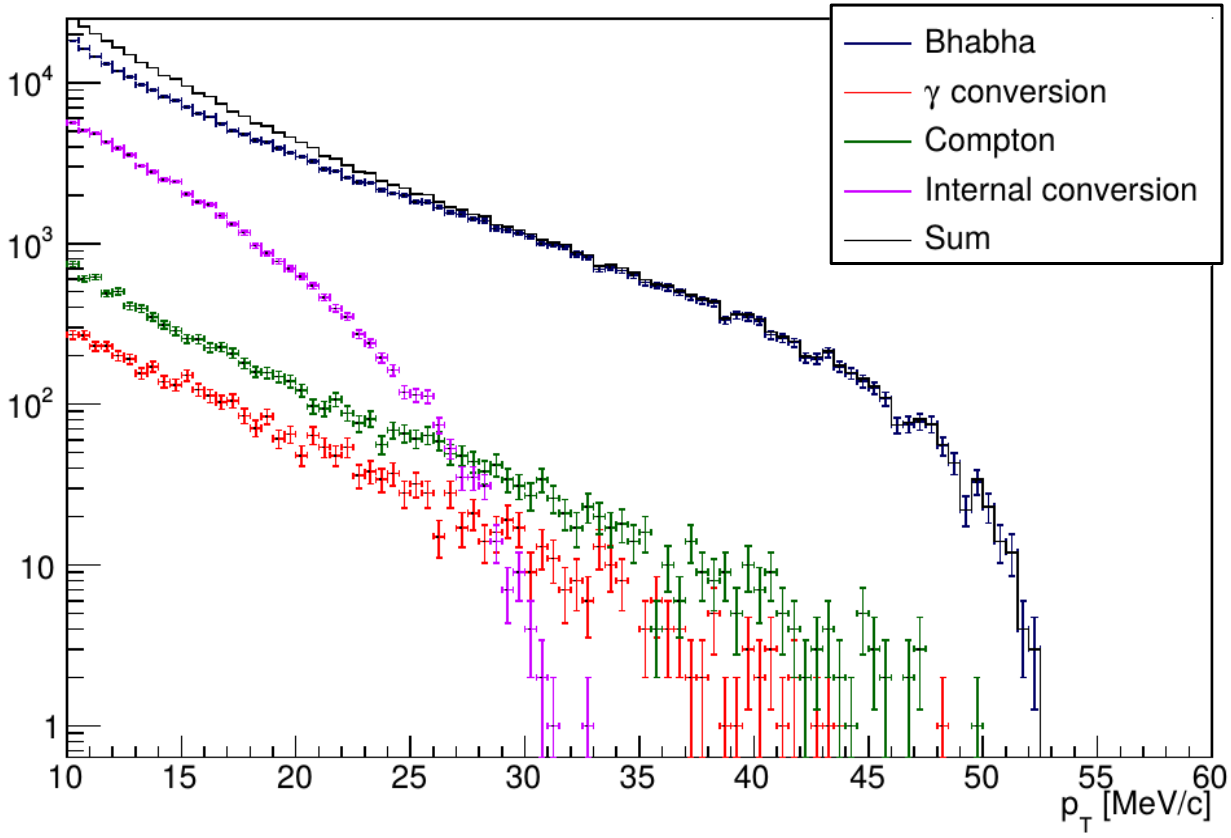


Time difference vs path length

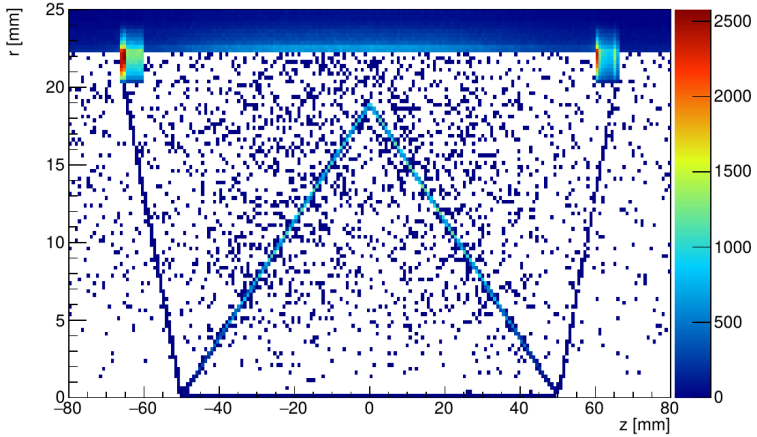


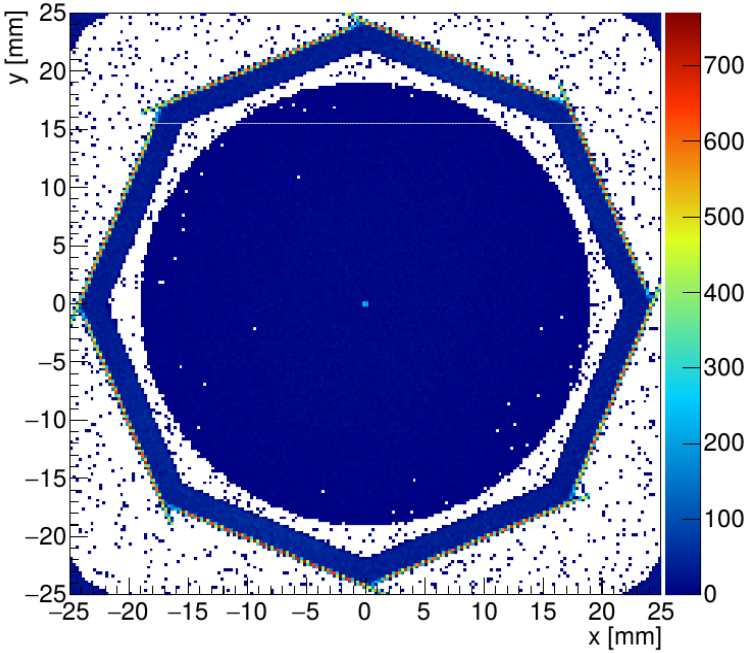
Significant reduction of BG for: $\mu^+ \rightarrow e^+ e^+ e^-$

Bhabha Scattering Background



Bhabha vertices target region



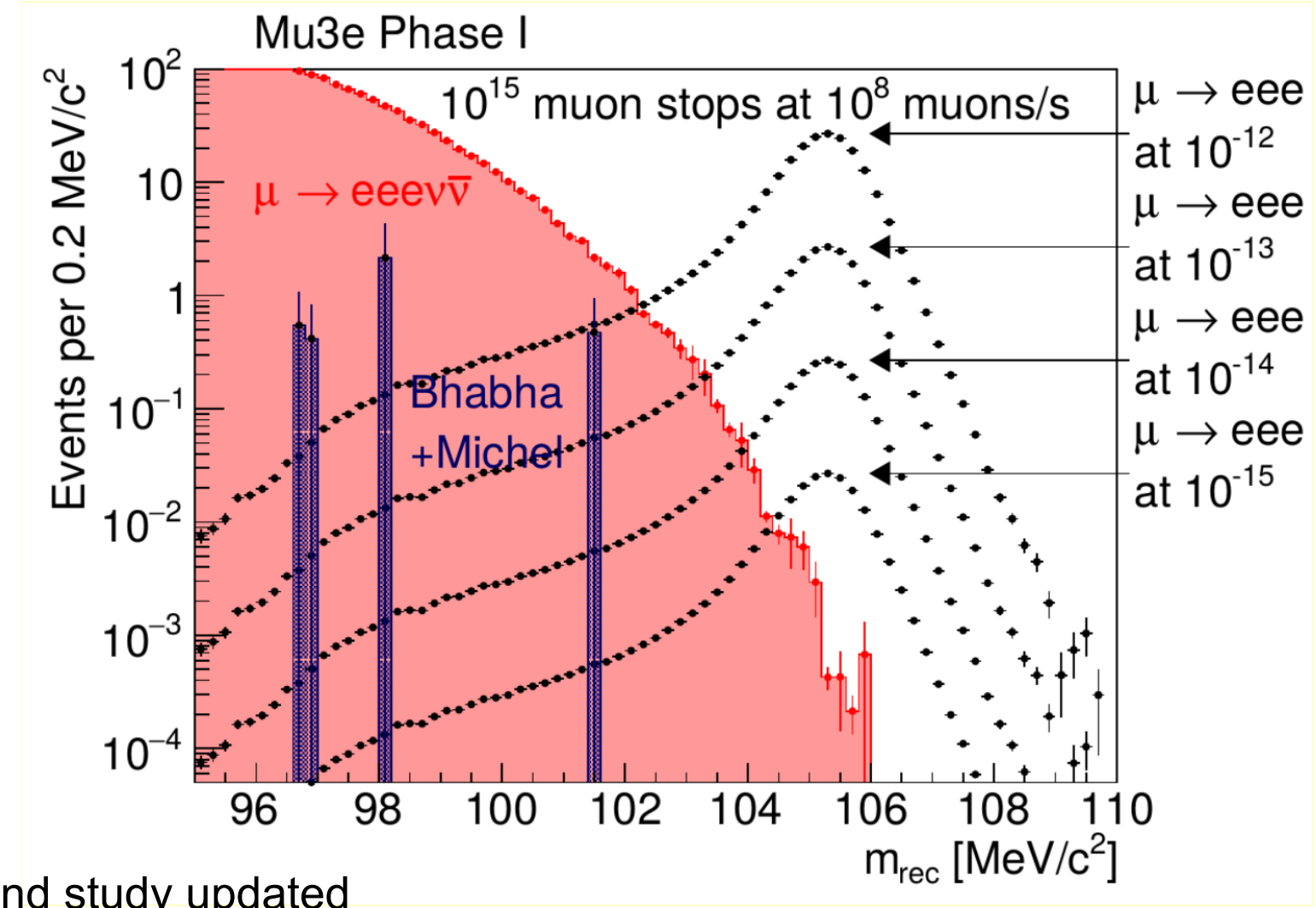


- Accidental background due to Bhabha scattering is difficult to simulated
- Bhabha's can be cut away with only small loss in signal efficiency

Event Selection

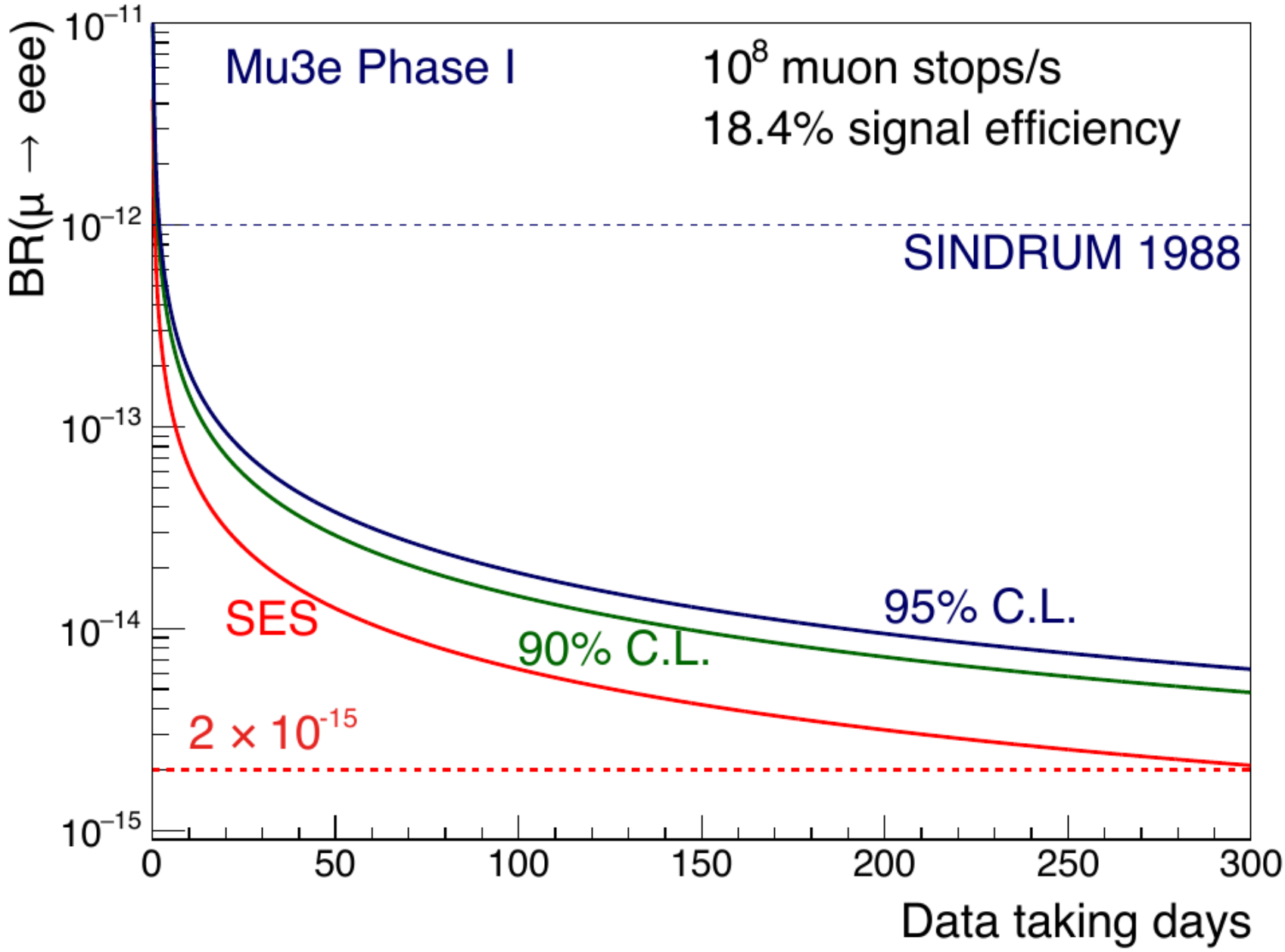
Step	Step efficiency	Total efficiency
Muon stops	100%	100%
Geometrical acceptance, short tracks	42.3%	42.3%
Geometrical acceptance, long tracks	65.1%	27.5%
Short track reconstruction	98.9%	41.9%
Long track reconstruction	87.3%	24.0%
Vertex fit	99.8%	24.0%
Vertex fit $\chi^2 < 30$	88.5%	21.3%
CMS momentum $< 8\,\mathrm{MeV/c}$	88.9%	18.9%
Timing	98.0%	18.4%

Simulation & Performance



- accidental background study updated
- MC statistics corresponds to to 3e15! muon decays
- background under control for Mu3e phase I

Sensitivity versus Time



Estimated Schedule (Optimistic)

	2018				2019				2020			
Pixel	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Mupix10 submission			X									
Mupix10 characterized						X						
demonstrator module							X					
production readiness								X				
sub-detector final										X		
SciTiles	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
demonstrator module				X								
production readiness					X							
sub-detector final								X				
SciFibers	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
demonstrator module					X							
production readiness						X						
sub-detector final								X				
Integration	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
magnet at PSI					X							
compl. vertical slice					X							
area & infrastr. ready								X				
sub-detectors mounted											X	

Q-BVR48

→ Retreat