Scintillating Fibre Detector for the Mu3e Experiment

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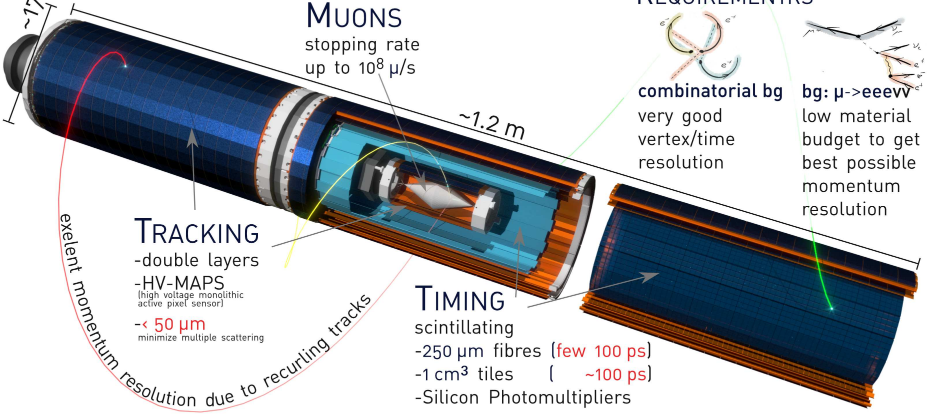
27th February, 2017, INSTR17, BINP

An Experiment Searching for the Lepton Flavour Violating Decay

$$\mu^+ \longrightarrow e^+ e^- e^+$$

$BR_{SM} \ll 10^{-50}$
Any observation is a sign for new physics.

$B(\mu\text{->}eee) < 1.0\ 10^{-12}$ (SINDRUM, 1988)
Mu3e: find or exclude μ->eee at a 10^{-16} level



Requirementrs

combinatorial bg
very good vertex/time resolution

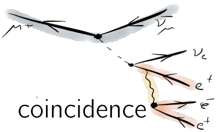
bg: μ->eeevv
low material budget to get best possible momentum resolution

more details: "Status of the Mu3e detector", D. Wiedner, Tu 28/2.

Timing Detector Motivation

Internal Conversion

$\mu \to eee\nu\nu$

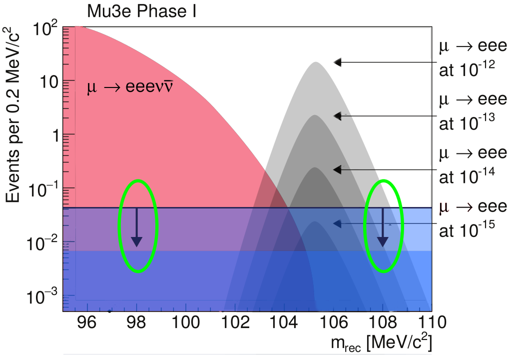


coincidence

same vertex

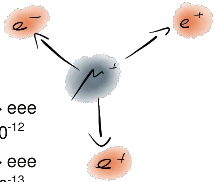
$|\sum P_e| \neq m_\mu^2$

BR $= 3.4 \cdot 10^{-5}$



Signal

$\mu \to eee$



coincidence

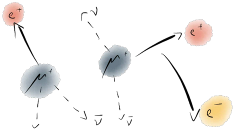
same vertex

$|\sum P_e| = m_\mu^2$

Combinatorial BG

$2 \times \mu^+ \to e^+\nu\nu$

$? \to e^-$



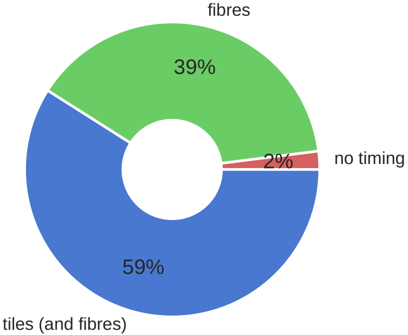
excellen momentum resolution

excellen vertex/timing resolution

Timing Detector Motivation

BG suppression

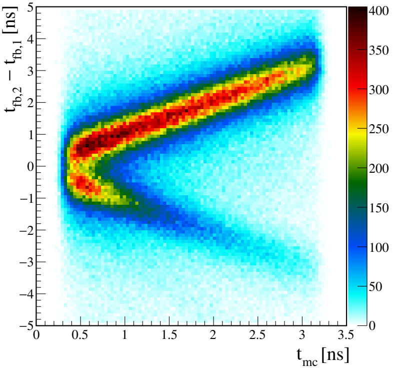
Fraction of reconstructed tracks (Michel decay, $\geq$6 hits) with **dominant** timing from corresponding detector.



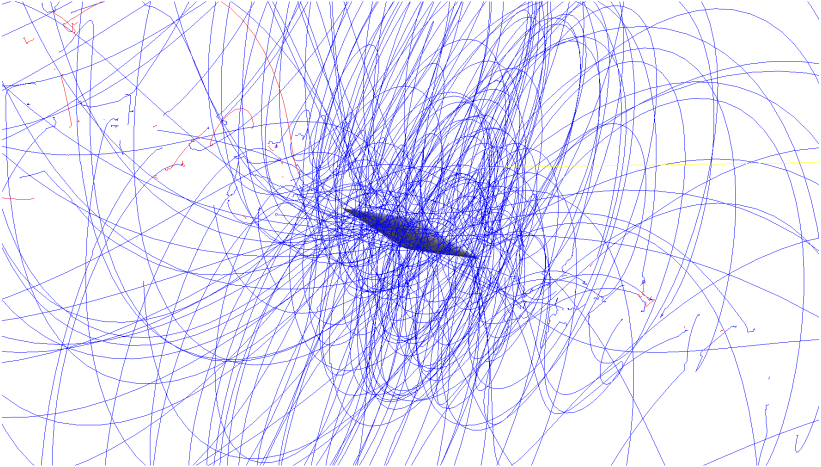
	suppression
only tiles	$\mathcal{O}(10)$
only fibres	$\mathcal{O}(30)$
combination	$\mathcal{O}(100)$

Charge Identification

Time resolution $\lesssim 0.5$ ns allows reliable charge identification for recurling ($\geq$8 hits) tracks.



Trigger-Less DAQ

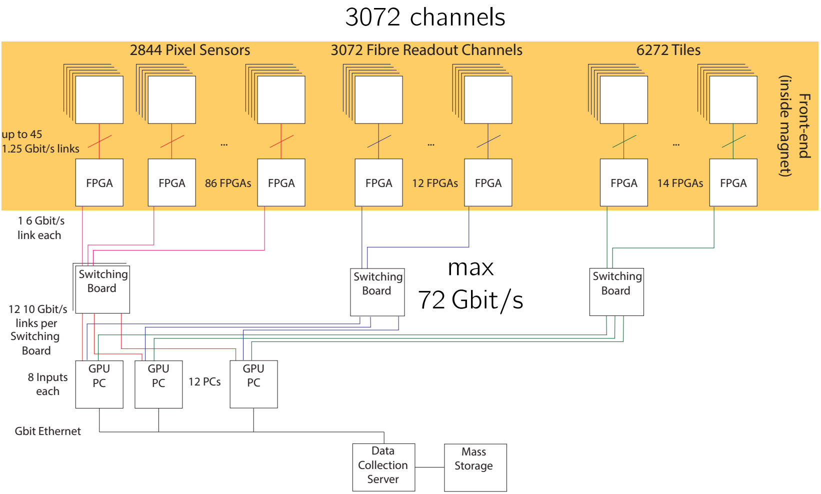


reasonable time $\rightarrow$ high μ rates required (PSI)

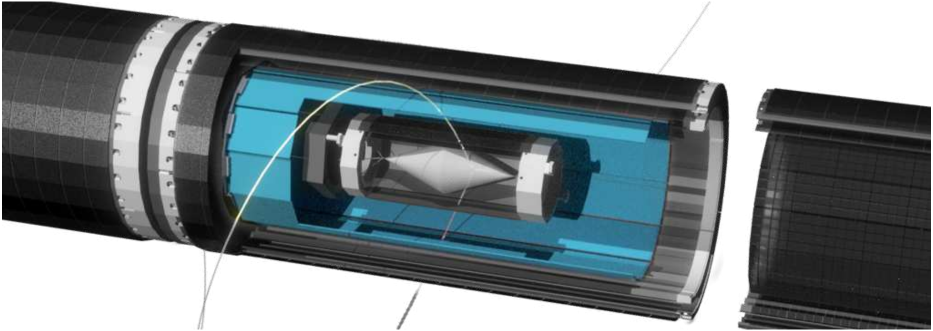
online reconstruction

trigger-less DAQ

Readout Concept



The Scintillating Fibre Detector



Components

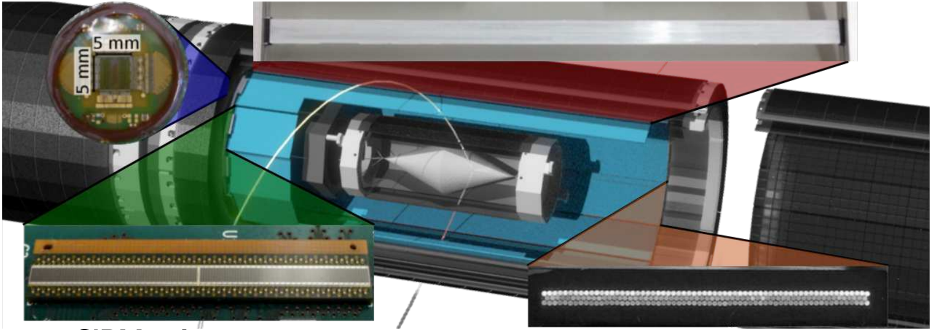
- cylindrical r $\sim$ 6 cm; l = 28-30 cm
- 12 ribbons of 3-4 layers of 250 μm fibres
- SiPM column arrays
- mixed mode ASIC: MuTRiG

Requirements

- as thin as possible; $\leq 0.5\,\%\ X/X_0$ (1 mm)
- as efficient as possible; $\sim 100\,\%$
- time resolution better than 500 ps
- up to 250 kHz/fibre;

The Scintillating Fibre Detector

STiC/**MuTRiG** 12: 28-30 cm long ribbons of 250 µm fibres



SiPM column arrays 3 layers, 32 mm width

Components

- cylindrical r $\sim$ 6 cm; l = 28-30 cm
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Requirements

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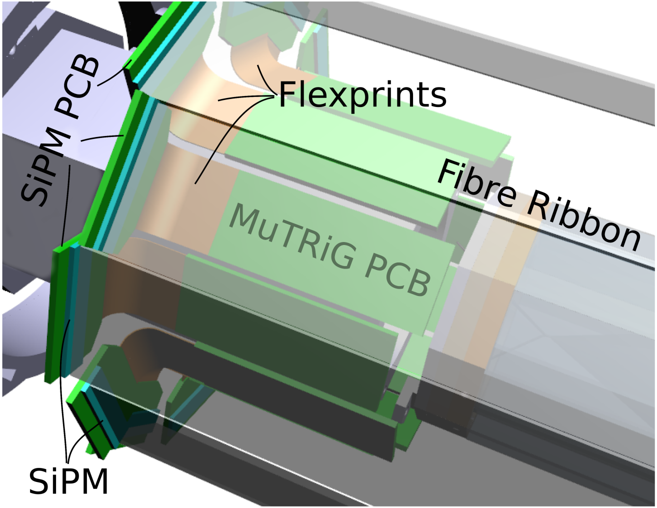
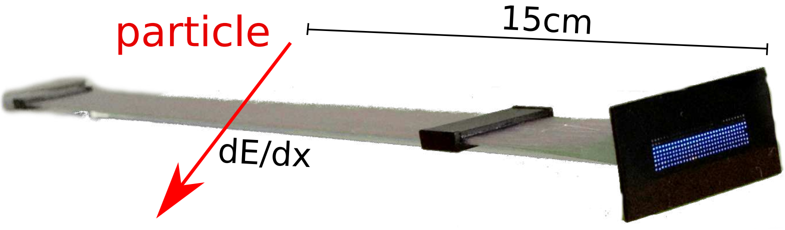
- up to 250 kHz/fibre;

Mechanical Design



bottom line: **very limited space**

Expected Number of Photons

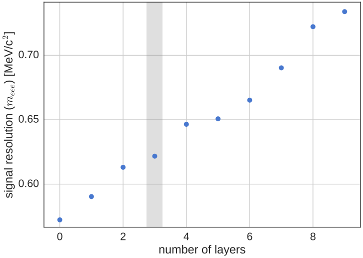


$\frac{dE}{dx}$ (160 MeV e^-)	d_{fibre}	yield	ε_{cap}	d_{att}	$\varepsilon_{\text{detection}}$	
$200\,\frac{\text{keV}}{\text{mm}}$	$210\,\mu\text{m}$	$\sim 8\,\frac{\text{ph}}{\text{keV}}$	5.4 %	95 %	30 %	$\approx$ **5**

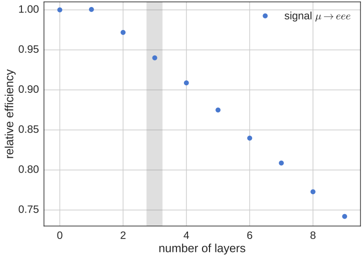
Scintillating Fibre Detector Optimization (Layers)

Implications on Tracking

invariant mass (m_{eee}) resolution

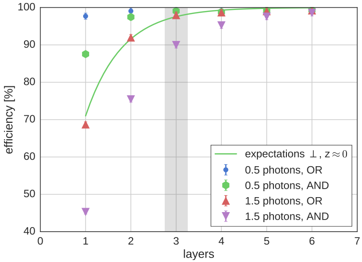


relative efficiency for $\mu \to eee$

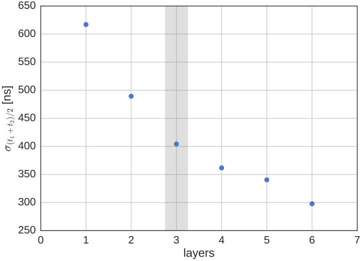


Impact on Timing

fibre detector efficiency



fibre detector time resolution



Prototypes

4 layers, 250 µm fibres, $\sim$ 45 cm long

in lab (^{90}Sr), at PSI (πM1) 115-215 MeV/c e, SP 190 GeV/c protons

Squared Fibres

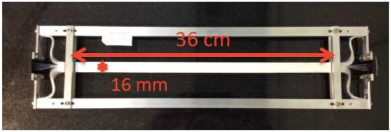
Saint Gobain BCF-12 ($\boldsymbol{\tau} \approx$ **3.2 ns**)

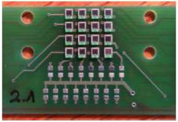
additional Al coating

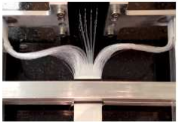
Hamamatsu S13360-1350CS

($1.3 \times 1.3\,\mathrm{mm}^2$, 50 µm pitch, trenches)

Round Fibres







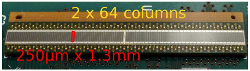
Kuraray SCSF-81M

($\boldsymbol{\tau} \approx$ **2.4 ns**, $y_{\mathrm{SCSF-81}} < y_{\mathrm{BCF-12}}$)

optional TiO_2 in glue

Hamamastu S12571-050P ($1 \times 1\,\mathrm{mm}^2$)

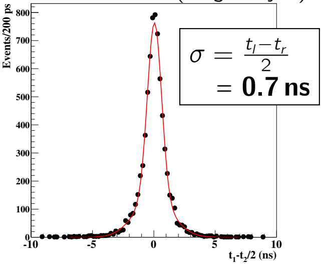
and SiPM columm array (same as LHCb)



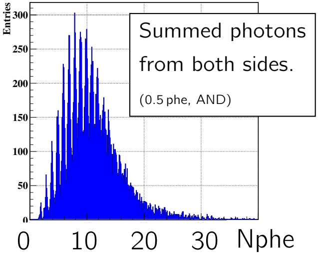
Results: Single Layer

Squared Fibres ($\varepsilon_{\mathrm{OR}}^{0.5\mathrm{p}} = 97\,\%$)

Time Resolution (single layer)

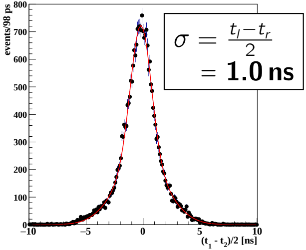


Number of Photons (single layer)

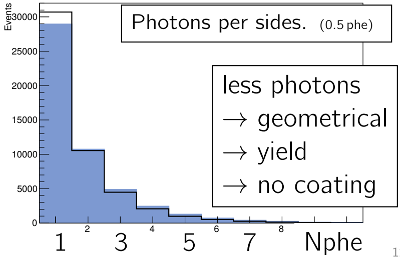


Round Fibres ($\varepsilon_{\mathrm{OR}}^{0.5\mathrm{p}} = 95\,\%$)

Time Resolution (single layer)



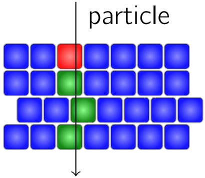
Number of Photons (single layer)



Results: Multiple Layers

Triple Layer Time Resolution

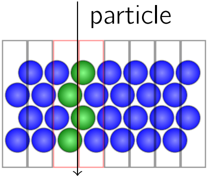
single fibre (fan-out), pre-amp/digitizer



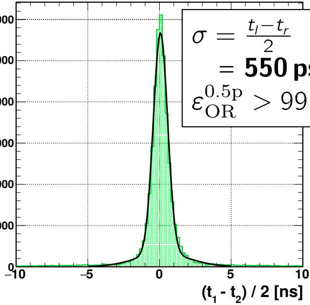
trigger
offline selection:
hits in 3 layers

SiPM column array readout

no fan-out, mixed-mode ASIC: STiC3.1



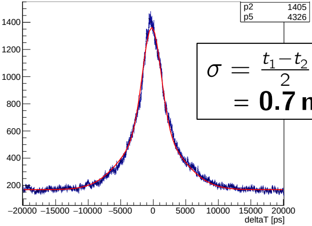
Time Resolution (triple layer)



$$\sigma = \frac{t_l - t_r}{2} = \mathbf{550\,ps}$$

$$\varepsilon^{0.5p}_{OR} > 99\,\%$$

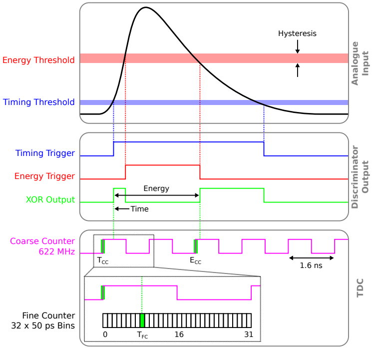
Time Resolution (column array)



$$\sigma = \frac{t_1 - t_2}{2} = \mathbf{0.7\,ns}$$

Readout Electronics: STiC3.1/MuTRiG

mixed mode, ≈ 50 ps t-stamps
high impedance, opt. differential



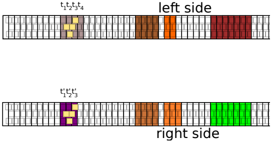
Tiles: both Thresholds
Fibres: only Timing-Threshold and Energy-Flag *"time mode"*

	STiC3.1 in use	**MuTRiG** received end Jan.
number of channels	64	32
LVDS speed [Mbit/s]	160	1250
event size [bit]	48	47
time mode	-	26
event rate / chip [MHz]	∼2.6	∼20
time mode	-	∼38
event rate / ch [kHz]	∼40	∼650
time mode	-	∼1200
power per channel [mW]	35	35
size [mm x mm]	5x5	5x5
number of PLLs	2	1

Data Rate and Clustering

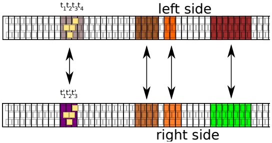
at 10^8 stopped μ/s	event rate [M/s]	data rate [Gbit/s]
SciFi detector	274	
Scintilating Fibres (235k/s/fibre)	1083	
SiPM columns signal (420 k/s/column)	1290	36.1
SiPM columns dark counts (∼300 k/s/column)	922	25.8
SiPM columns total	2211	**61.9**
clustering		**20.0**

clustering per side

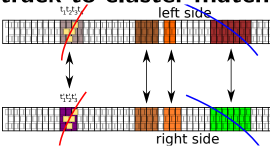


- on FPGA (FE)

match sides



track to cluster match

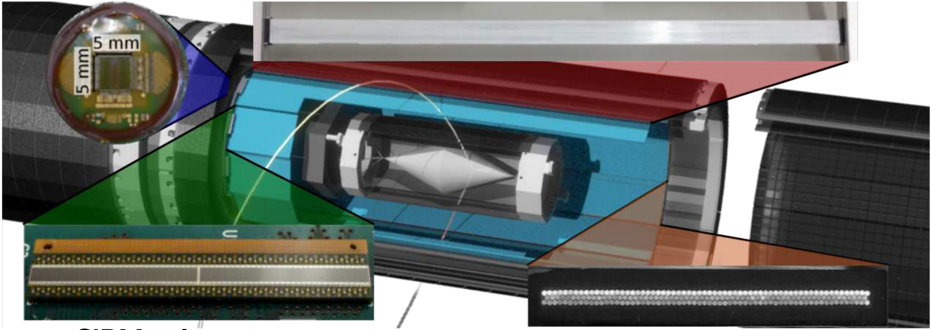


- best timing: use tracking

Summary and Outlook

STiC
MuTRiG

12: 28-30 cm long ribbons of 250 μm fibres



SiPM column arrays

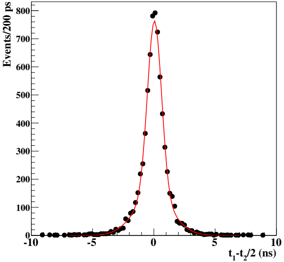
3 layers, 32 mm width

- R&D finished (baseline chosen)
- full prototypes expected early 2018
- Mu3e: first beam expected 2019

Appendix

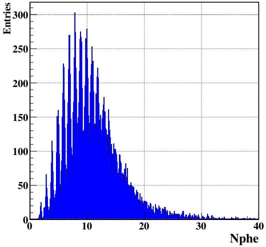
The Fibre Detector: Squared Results

Time Resolution (single layer)



$\sigma = (t_l - t_r)/2 = \mathbf{700\,ps}$

Number of Photons (single layer)



Summed photons from both sides. (0.5 phe, AND)

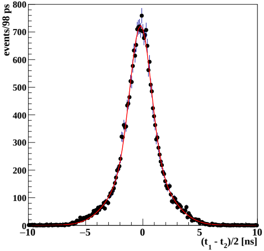
Efficiency

$\varepsilon_{\text{single}}$ [%]	OR	AND
0.5 phe	97	71
1.5 phe	79	34

$\varepsilon_{\text{triple}}$ [%]	OR	AND
0.5 phe	>99	**95**
1.5 phe	97	67

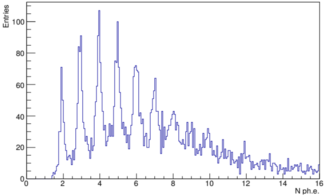
The Fibre Detector: Round Results

Time Resolution (single layer)



$\boldsymbol{\sigma} = (t_l - t_r)/2 = \mathbf{1.0\,ns}$

Number of Photons (single layer)



Summed photons from both sides.*(0.5 phe, AND)

Efficiency

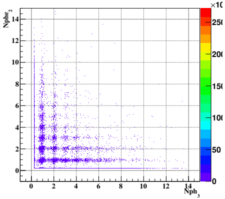
$\varepsilon_{\text{single}}$ [%]	OR
0.5 phe	95±9

$\varepsilon_{\text{triple}}$ [%]	OR	AND
0.5 phe	97±1	70*
1.5 phe	90*	

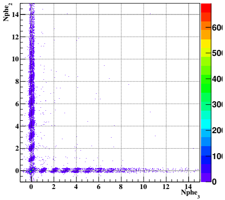
Crosstalk

Al coating

no additional Al



with additional Al

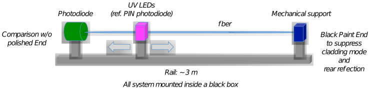


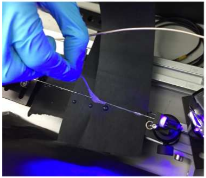
- significant cross-talk reduction
- $\sim$60 % yield increase (diffuse)

material	n	light loss	
		bare	Al
optical cement	1.56	$\sim$40 %	$\leq$1 %
Araldite rapid	$\sim$1.5	$\sim$30 %	$\leq$1 %
optical grease	1.465	$\sim$20 %	$\leq$1 %

TiO_2 in glue

- crosstalk-reduction (ribbon dependent)
- 10-20 % yield increase (diffuse)
- $\sim$10 % cluster size reduction





Radiation Damage

expectations:

- e^+/e^- flux: $0.9/1.7\,\mathrm{MHz\,mm^{-2}}$
- integrated flux per year: $0.8/1.4{\cdot}10^{10}$ $e^+/e^-\mathrm{mm}^{-2}$
- dose per year: 55/97 mJ; 24/42 Gy