### The MuPix Telescope

### Tracking Low Momentum Particles at High Rate

Lennart Huth for the Mu3e Collaboration Physikalisches Institut Heidelberg DPG Spring Meeting Hamburg 03 March 2016

INTERNATIONAL MAX PLANCK RESEARCH SCHOOL



FOR PRECISION TESTS OF FUNDAMENTAL SYMMETRIES



## Motivation

#### MOTIVATION

#### What's beyond the SM?

- Charged Lepton Flavour Violation?
- Introduced by BSM theories
- Measurable branching ratios predicted



#### Lennart Huth - huth@physi.uni-heidelberg.de (PI HD)

#### The decay $\mu^+ \rightarrow e^+e^-e^+$

- SM BR <  $10^{-54}$
- $\cdot \sum \vec{p} = 0$
- Coincident in space and time
- $E_{max} < 53$  MeV

#### Background

 Radiative decay with internal conversion:  $\sum \vec{p} \neq 0$ 



### The Mu3e Experiment - Searching for $\mu^+ \to {\rm e^+e^-e^+}$ with a sensitivity of BR< $10^{-16}$



### Multiple scattering regime and high rate $\rightarrow$ Fast and thin pixel sensor

#### HIGHVOLTAGE - MONOLITHICACTIVEPIXELSENSORS (HV-MAPS)



Design Goals

- Binary readout
- Pixel size: 80 x 80 µm<sup>2</sup>
- 256 x 256 pixel
- 8 ns time stamps

- Time resolution < 20 ns
- Efficiency > 99 %
- $\cdot$  50  $\mu m$  thin  $\approx$  0,05 % radiation length

#### THE MUPIX 7

- Latest prototype
- Fully integrated readout on the chip
- On chip PLL & VCO
- 1.25 GBit/s data  $\approx$  33 MHits/s
- Details: T 72.1/2/3





### The MuPix Telescope

#### THE MUPIX TELESCOPE

**Idea:** Build a tracking detector out of Mu3e parts as integration test and fill a gap in the choice of existing beam telescopes:





Tiles



Test PCB



MuPix

 $\cdot$  Custom PCB holder with 10  $\mu m$  precision



- $\cdot$  Custom PCB holder with 10  $\mu m$  precision
- Commercial mechanical support



- Custom PCB holder with 10 μm precision
- Commercial mechanical support
- Differential high speed links: 1.25 GBit/s
- Online time sorting (T 22.4)



- Custom PCB holder with 10 μm precision
- Commercial mechanical support
- Differential high speed links:
  1.25 GBit/s
- Online time sorting (T 22.4)
- GByte/s data transfer to PC



- Custom PCB holder with 10 μm precision
- Commercial mechanical support
- Differential high speed links:
  1.25 GBit/s
- Online time sorting (T 22.4)
- GByte/s data transfer to PC
- Up to 60 MByte/s final data storage



- Custom PCB holder with 10 μm precision
- Commercial mechanical support
- Differential high speed links: 1.25 GBit/s
- Online time sorting (T 22.4)
- GByte/s data transfer to PC
- Up to 60 MByte/s final data storage
- User friendly control interface

FPGA DACs Honope									
Resets	DACE	Pleador	<u>د</u>	Fet Generator			syscool 1		ection x
Reset Event Counter	ant AL DA	Ck () ()	idant Readout; ad Once				5656		m
Global Report	Set Chip Di	MS C B	ad Continuously	Stat Grones	5		1000		3000
Frend Mitsure	Set Board D	ACI D T	iggered Readout	Second Lines.	Enviroide Events		hject	41	Inject ALI
Farm Person	Set Pixel D	ACL					TOP FF	ONT	TOP FRONT
OH SHIT BUTTON	Thresholds			Wattine			TOP 5	LCK .	TOP IMCK
	set sensor 1		www.hitesa				NOTTOM	TONT	DOTTOM FROM
🗆 san Téger	set sensor 2			Hits per Event			807704		BOTTOMBAC
	set sensor 3						-	Der Ca	DOMONUME
	set sensor 4						POL	T SYNOID	2.1
	set AL	lost default.	Over Riendly To	rotheam Control an	s ReasOut				PAD, INC
wite conits to fie			Get Ready	1	1 8	ert flux		HtTining	Drawitites
nath and Rename	and the second se				-			IS Control	
Choose Directory Printer, Bud In Text				ALM NUMBER		Friend Park		V enable	
								Clock at	e la
monitoring file same, monitoring, file as		-head-berr	0		0		0 4	5	
			Support Event	All hom.	904		0 2	T3 Broks	
			0				0 3		60
			Tripper Kill process	ned All-press	week .				
							0 4		
			0		0 14	er sala 708 pe	о <sup>4</sup> тол		
			0 RP to overi	Altered	0 tria	per nele 709° pe	0 4 7 TDA 0 5.0	n Fare (ii	
			0 89 to moni	12 month	O trip ver Xigger ra	ur nele 709 pe	0 1 104 0 1.0	Pane ()	Ten Ten
			0 RP to-moni 0 Reset value (Fed	Altered	0 Dig viel Xigger ra	ur un 707 pu u 8017097 pu	0 * 704 0 % 8	h Files () stime ()	Tane Save Ta
			0 KB to moni Depent rate (Fig 0	All and	O Dig wel Rigger ra	per radio 700° (Pel na BOTTOW (Pel) Degene radio (	о <sup>4</sup> 704. О 5 О М	Pare (g stars (j	Ture Save Ta Load Ta
			0 RP to next 0 Dent sets (Md 0 Dent sets 709 (M	2	0 big wwf Nigger ra	per sala 709 (PA ta BOTSON (PA) Degger sala (	о́тон с тон с м	h Flate (j) stites (j)	T Save Tar Save Tar Load Tar
			0 RB to next 0 Reset was (Hig 0 Event was 70% (h 0 0 0	At south	O trip viel Xigger ra	per radio 703° (Pil na 80373099 (Pil) Diggar radio (	of TDA	Flate () Witers () Tor	T Save Ta Save Ta Load Ta e Services
			0 HB to noni Deset rate (Hd 0 Event rate 709 (H 0 Event rate 82772	Alternat N	O trip wet Kigger re	per sala 753° (Pi na BOTTOR (Pig Diggar cola (		Flane () where () The	Sove Tar Sove Tar Load Tar Services
			0 HB to noni Deset rate (Hd 0 Event rate 709 (h 0 Event rate 80770	X2 mont	O trip vivel Xigger / v Pla Dave O /	per nate 70% (Pe to BOTTOM (Peg Dogger rate (	0 * 104 0 % 0 % 0 %	Flate 0 store 1 To	Save Tare Save Ta Load Ta e Servors
GerealBuffer States	244	WMO	0 EF to-mont 0 Encost-naire (Hdg 0 Encost-naire (HDF (Hdg 0 Encost-naire (HDF (Hdg 0 Encost-naire (HDF (Hdg 0 Encost-naire (HDF (Hdg 0 Encost-naire (Hdg)	All month	O trip Nigger 19 Pite Day O 7	per sale 70° (Pi to BOTTOM Pig Digger role ( BOS		Da Plate () utions () Tor	Save Ta Save Ta Lond Ta e Servers
GeneralBuffer States 240 TPO FF 240 TPO 400	245	W MO T RO-PR	0 R7 to novi 0 Boart outs (htt 0 Boart outs (htt 0 Breat outs (htt) 2 Breat outs (htt)	Readout Settingo	O Dig Viel Xigger / I Pla Dire O /	per rate 30° pe na BOTTOM pag Deggar rate ( BOC		Da Flane (d) whiteo (t) The	Save Ta Save Ta Load Ta e Servors
Gerraelfte-Ffee States 245 TED-Ffe 246 TED-Ffe 246 TEP-F0	244	W MO T RO-PR IT RO-PR	O R7 to need Description Great and 70P (P O Description R2772	River Njej Readout Settings Readout Settings	O Den Wer Kipper II Pla Der O I 100	per rate 30% per ra BOTTOM pag Degaer rate ( BOS		Plane (g vetero (g Ter	Tore Save Tor Load Tor a Services Exit
OccustiBuffer Status 2007 TSO FR 2007 TFO FR 2007 TF0 FR 2007 BFF-FR 2007 BFF-FR	244 244 244 244	W MO T RO-PR IT RO-PR featuring	C R2 to need Descrit and J6d C Descrit and 70P (P O Descrit and R2772	Altranit Njeg Readout Settinge Santout Settinge Readout Settinge	O Dag wer Kigger in Pla Bee O Z 300	per nele XXP (Pic na BOTTOM (Pic) Delgaer role ( BOC	0 4 7 TOA 0 5m 0 10 10 10	Plane () vities () Ter	Save Tare Save Ta Lead Ta e Service Exit

- $\cdot$  Custom PCB holder with 10  $\mu m$  precision
- Commercial mechanical support
- Differential high speed links: 1.25 GBit/s
- Online time sorting (T 22.4)
- GByte/s data transfer to PC
- Up to 60 MByte/s final data storage
- User friendly control interface
- Online monitoring, tracking and efficiency calculation
- GPU Online Tracking and direct memory access (T 42.5/6)



## **Testbeam Results**



#### COMPARISON OF POWER SETTINGS

#### Maximal cooling power: 400 mW/cm<sup>2</sup>



#### **EFFICIENCY SUMMARY**

### Larger rotation $\rightarrow$ more signal $\rightarrow$ Higher efficiency at higher thresholds



#### **CROSSTALK** I

#### Selection Criteria

- Single track
- Count hits on DUT
- Select events with only 2/3 hits
- Same column, row +/-2



triple\_hit\_row

#### **CROSSTALK II**



#### CROSSTALK III



#### CROSSTALK III



#### CONCLUSION

- First running integrated HV-MAPS system
- High Rate capabilities  $\mathcal{O}(1MHz)$
- Important tool to test scalability
- High system efficiency > 99 %
- Time resolution < 11 ns</li>
- Cross talk and clustering analysis ongoing
   → cross talk issue, should be fixed in
   MuPix8





The measurements leading to the rotated DUT results have been performed at the Test bEam Facility at DESY Hamburg (Germany), a member of the Helmholtz Association (HGF).

We would like to thank the PSI for providing high rate test beams under excellent conditions.

We owe our SPS test beam time to the SPS team and our LHCb colleagues, especially Heinrich, Kazu and Martin.

We thank the Institut für Kernphysik at the JGU Mainz for giving us the opportunity to take data at MAMI.

# Backup

il-stA

Trackmodel: Straight track without scattering

 $\vec{x}(z) = \vec{x_0} + \vec{a} \cdot z$ 

 $\rightarrow \mathcal{X}^2$  can be analytically minimized

$$\mathcal{X}^{2} = \sum_{i=1}^{n} \left( \frac{(x_{i} - (x_{0} + a_{x} \cdot z_{i}))^{2}}{\sigma_{x_{m_{i}}}^{2}} + \frac{(y_{i} - (y_{0} + a_{y} \cdot z_{i}))^{2}}{\sigma_{y_{m_{i}}}^{2}} \right)$$
  
assuming  $\sigma_{x/y_{m_{i}}} = \text{pixel resolution} = \frac{\text{pixel size}}{\sqrt{12}}$ 

ightarrow Fast and robust track model!

#### Alignment @ DESY





#### **TELESCOPE TIMING @ DESY**



#### Time Resolution

#### **MUPIX7 SPATIAL RESOLUTION**



- Resolution is dominated by the pixel size!
- Multiple Scattering small enough for 4 GeV/c electrons
- Resolution in x slightly worse than in y: Feature of pixel size

# Analysis Concept

#### ANALYSIS PROCEDURE

- Align the system
- Extrapolate track and check hits on DUT
- Match DUT hits
- Analyze cut-effects
- Extract the relevant parameters



#### **EFFICIENCY ANALYSIS**



#### **EFFICIENCY ANALYSIS**



#### **EFFICIENCY ANALYSIS**

