Università degli Studi di Torino
Scuola di Dottorato in Scienza ed Alta Tecnologia

Indirizzo in Fisica ed Astrofisica XXVI ciclo

Triggerless hybrid pixel detector for the $\overline{\text{P}}$ANDA experiment and benchmark study of a $\psi(4040)$ decay

Candidate: Laura Zotti

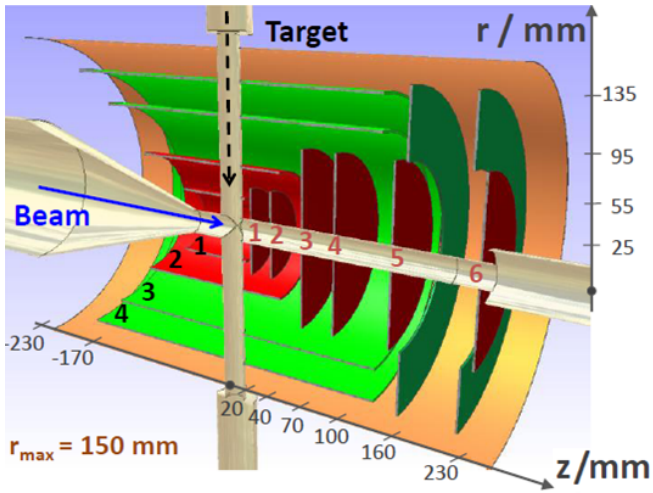
Tutor: Prof. Simonetta Marcello

2010/2013

Outlines

- The Micro Vertex Detector
- Hybrid Pixel Prototype Performance
- The $\psi(4040) \rightarrow D^{*+}D^{*-}$

The Micro-Vertex Detector



Geometrical Constraints

- Maximum Radius: 15cm
- Dimension along z: $\pm$ 23cm

Layout

- 6 Forward Disks
- 4 Barrels

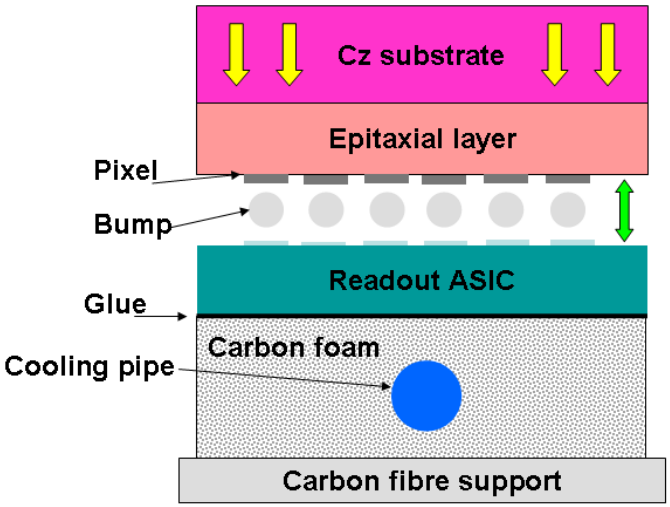
Readout Channels

- $\sim 10^7$ Hybrid Pixels
- $\sim 2 \cdot 10^5$ Double-Side Microstrips

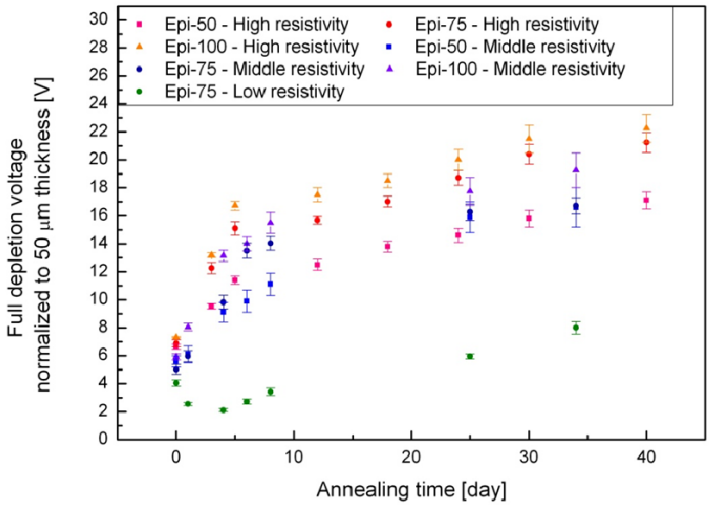
Requirements & Features

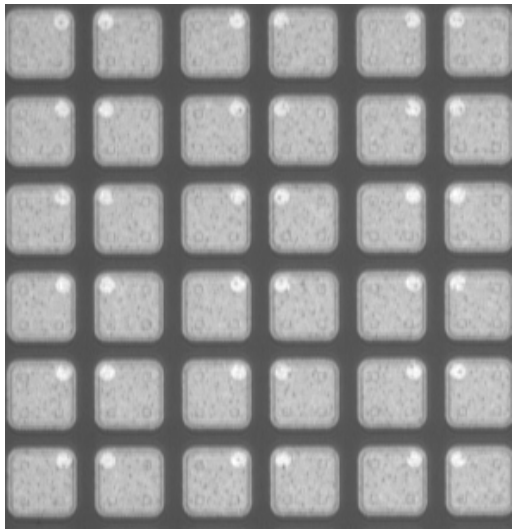
- Spatial resolution < 100μm
- Momentum resolution $\delta p/p < 2\%$
- Time resolution $<$ 10ns
- High rate capability
- No hardware trigger
- Radiation tolerance $\sim 10^{14}$ $n_{1MeV\ eq}cm^{-2}$
- Low material budget
- PID by dE/dx

MVD Hybrid Pixels

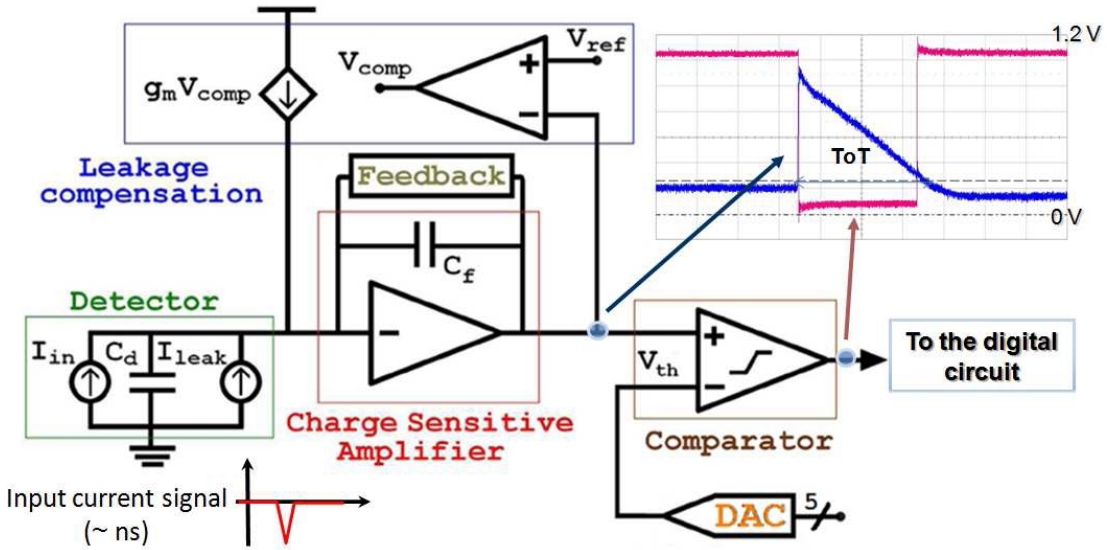


- Epitaxial Silicon Material
- 100μmx100μmx100μm
- $\rho_{epi} \sim$ k Ω·cm
- $\rho_{Cz} \sim$ 20-50 m Ω·cm





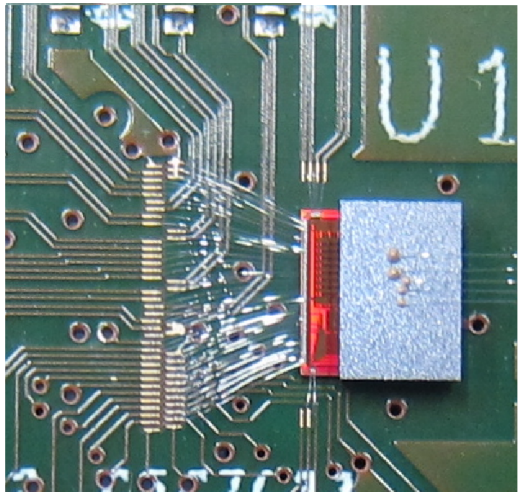
MVD Hybrid Pixels

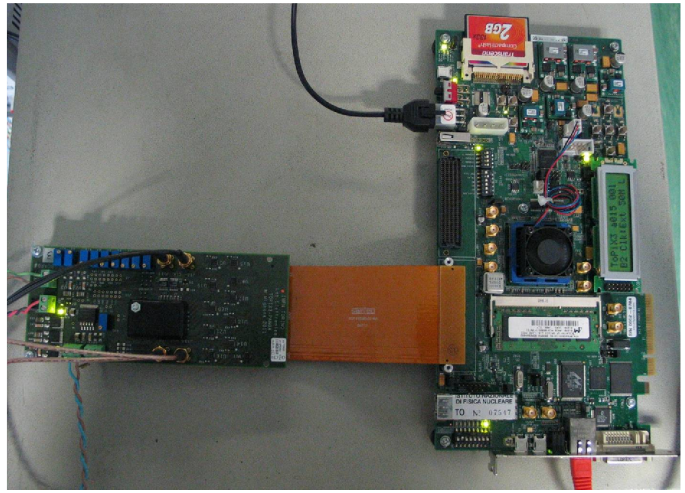


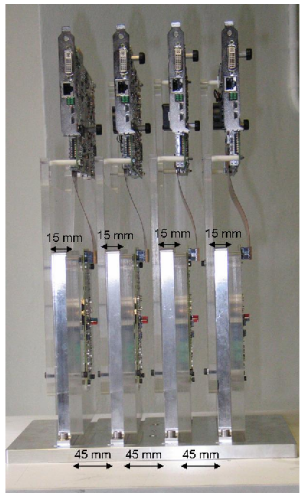
- Pixel Size: 100µmx100µm
- Self Trigger Capability
- Chip Size: 11.6 mm x 14.8 mm
- ToT for dE/dx Measurement
- Input Range: up to 50 fC
- Noise Floor: $\leq$ 0.032 fC

- Clock Frequency: 155.52 MHz
- Time Resolution: 6.45 ns
- Power Budget: < 800 mW/cm^2
- Max Rate cm^{-2}: 6·10^6 Hits/s
- TID: $\leq$ 100 kGy
- Serial Output

Hybrid Pixel Prototypes







Sensors

- Produced @ FBK (Trento)
- Bump Bonding @ IZM (Berlin)
- 100μm Active Epitaxial Layer

Setup

- 640 pixels (matrix of 3.2x2 mm^2)
- 4 Pixel Planes - Total length $\sim$20 cm
- 50 MHz clock

Electronics

- ToPix3 Prototype
- Testing Board
- Xilinx Evaluation board + Virtex 6FPGA

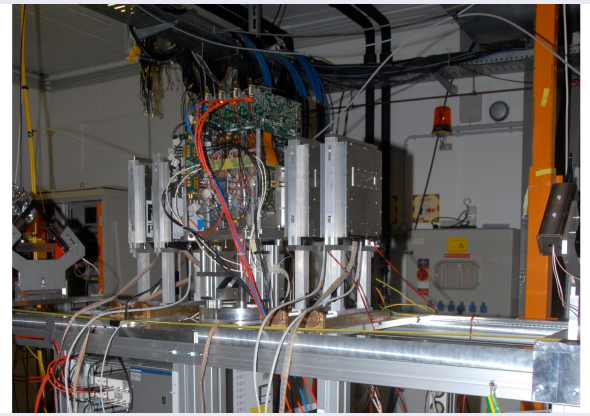
Raw Data

- Column & Row Information
- 12 bits Leading & Trailing Edge (Gray Encoded)
- 44 bits TimeStamp

Hybrid Pixel Beam Tests

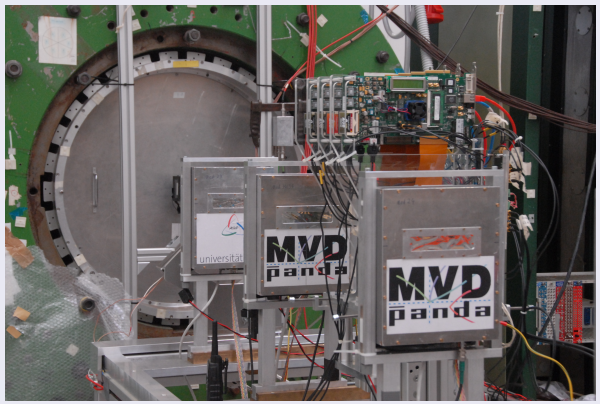
Jülich Beam Test

- p @ 2.7 GeV/c
- 525μm Passive CZ Substrate

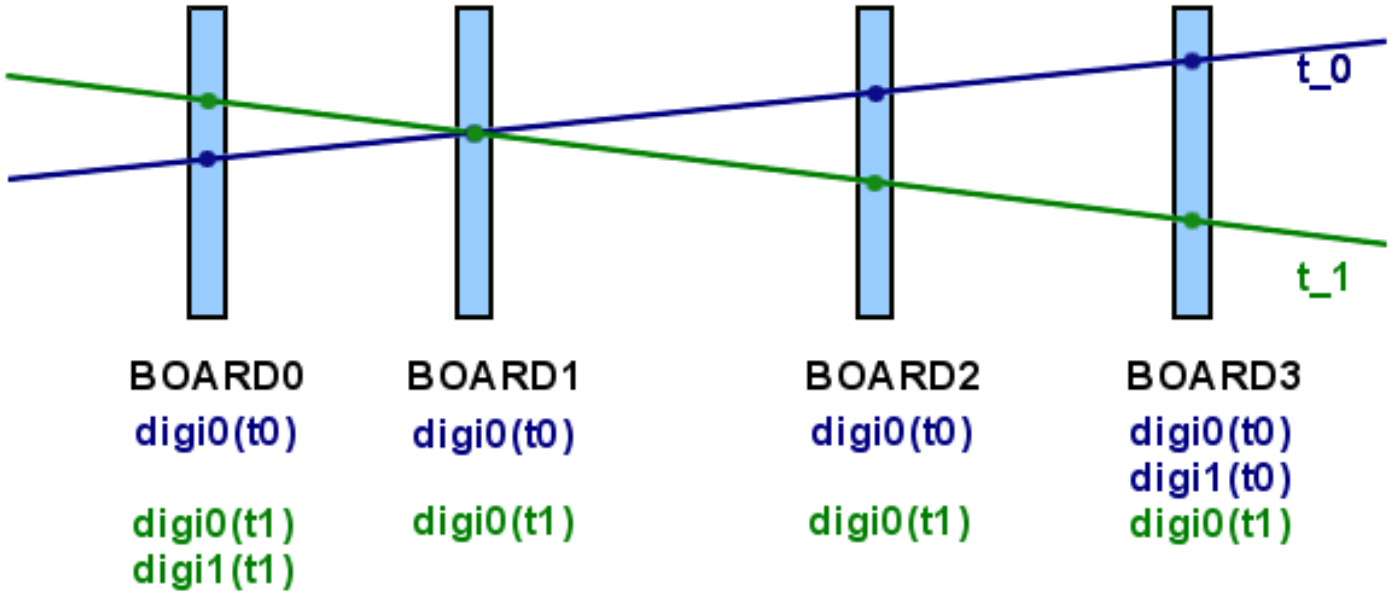


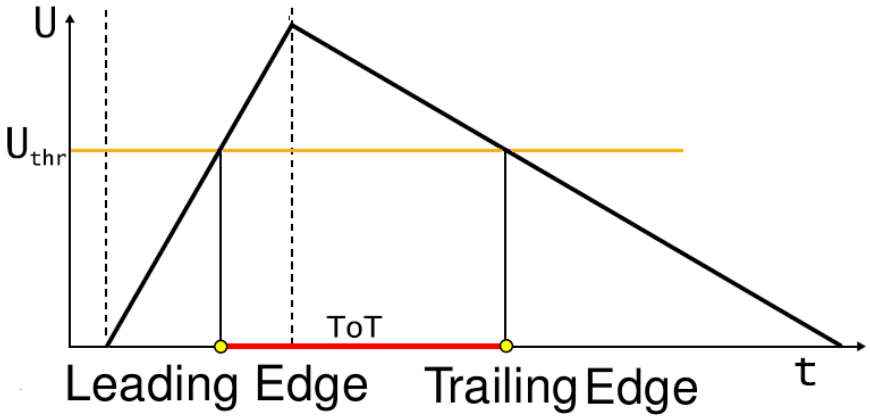
CERN Beam Test

- π @ 10 GeV/c
- 20μm Passive CZ Substrate



Handling Triggerless Data...





12bit 1 1 1 1 1 1 1 1 1 1 1 1

4 0 9 5

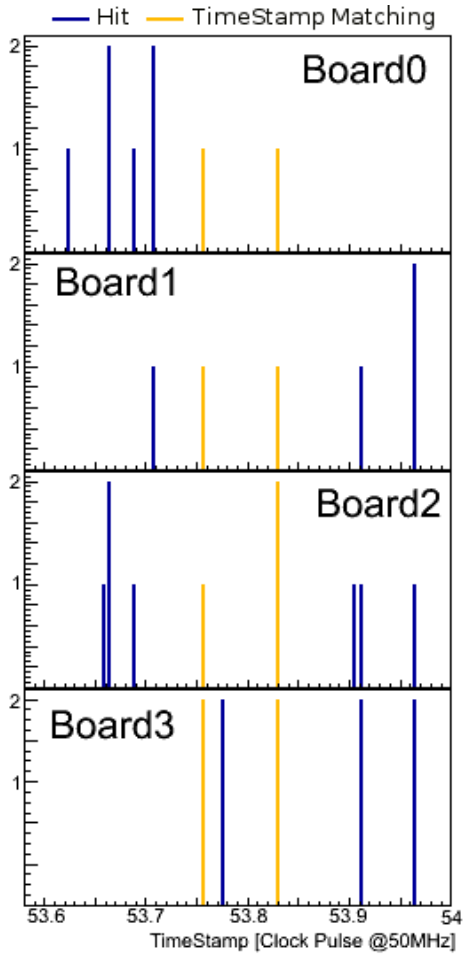
@ 50MHz $81.9 \cdot 10^{-6} s$

12bit + 32bit (EOC) = 44bit

@ 50MHz $\rightarrow$ $351.8 \cdot 10^{3} s$

Handling Triggerless Data...→ TimeStamp Matching

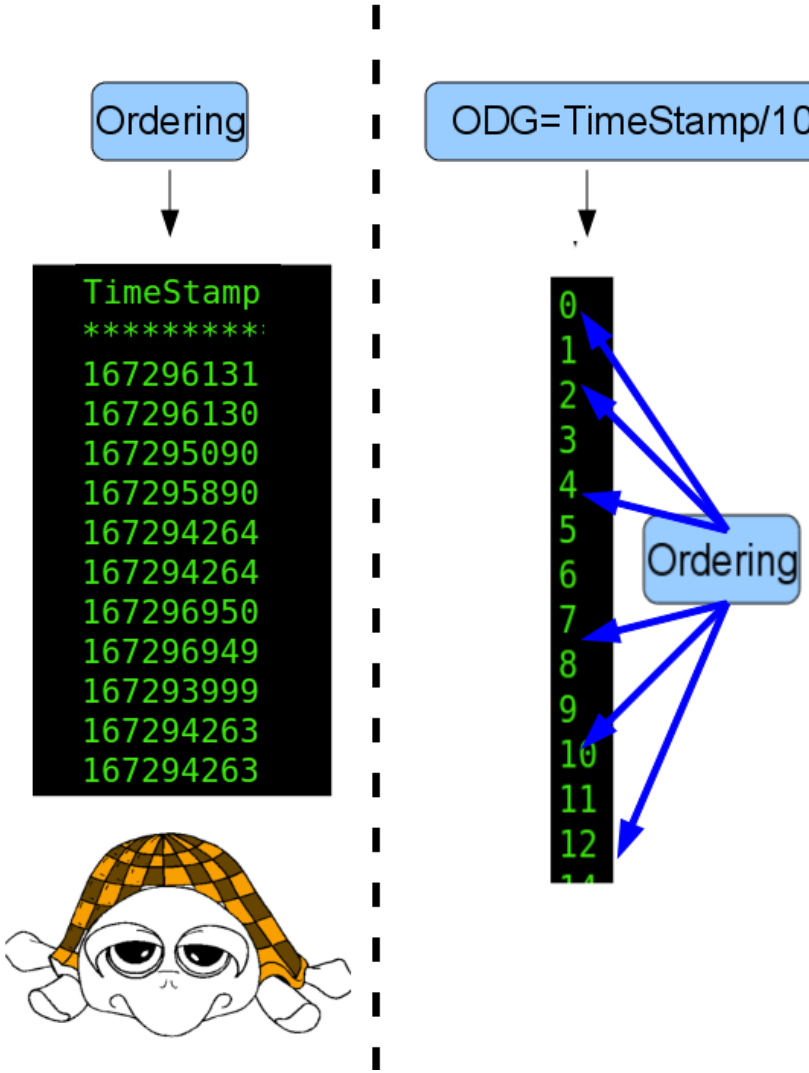
BOARD0		BOARD1		BOARD2		BOARD3	
Row	fTimeStam	Row	fTimeStam	Row	fTimeStam	Row	fTimeStam
210	537020249	150	558724657	190	546305718	155	558729325
211	546462082	151	558730152	191	546305718	156	558730152
212	558710073	152	558733717	192	546305718	157	558732955
213	558724656	153	558739485	193	558704130	158	558733716
214	558730152	154	558748899	194	558730151	159	558738431
215	558742175	155	558749613	195	558732954	160	558738432
216	558749612	156	558755429	196	558733718	161	558739485
217	558749615	157	558762802	197	558733720	162	558743179
218	558755430	158	558765330	198	558738431	163	558745417
219	558762802	159	558766188	199	558739485	164	558748900
220	558765330	160	558766254	200	558748900	165	558749612
221	558766189	161	558766528	201	558749612	166	558754553
222	558766253	162	558766529	202	558753162	167	558755429
223	558766674	163	558768586	203	558754310	168	558762802
224	558770175	164	558770174	204	558755429	169	558765330
225	558770402	165	558770174	205	558762802	170	558766188
226	558770904	166	558770402	206	558765330	171	558766254
227	558775489	167	558770903	207	558766188	172	558766419
228	558781647	168	558775489	208	558766253	173	558768586
229	558781648	169	558781647	209	558766528	174	558769056
230	558786946	170	558781649	210	558766531	175	558770174
231	559024129	171	558786945	211	558768586	176	558770904
232	559028535	172	559024127	212	558770174	177	558775489
233	559031646	173	559028535	213	558770904	178	558781015
234	559032975	174	559028891	214	558770904	179	558781225



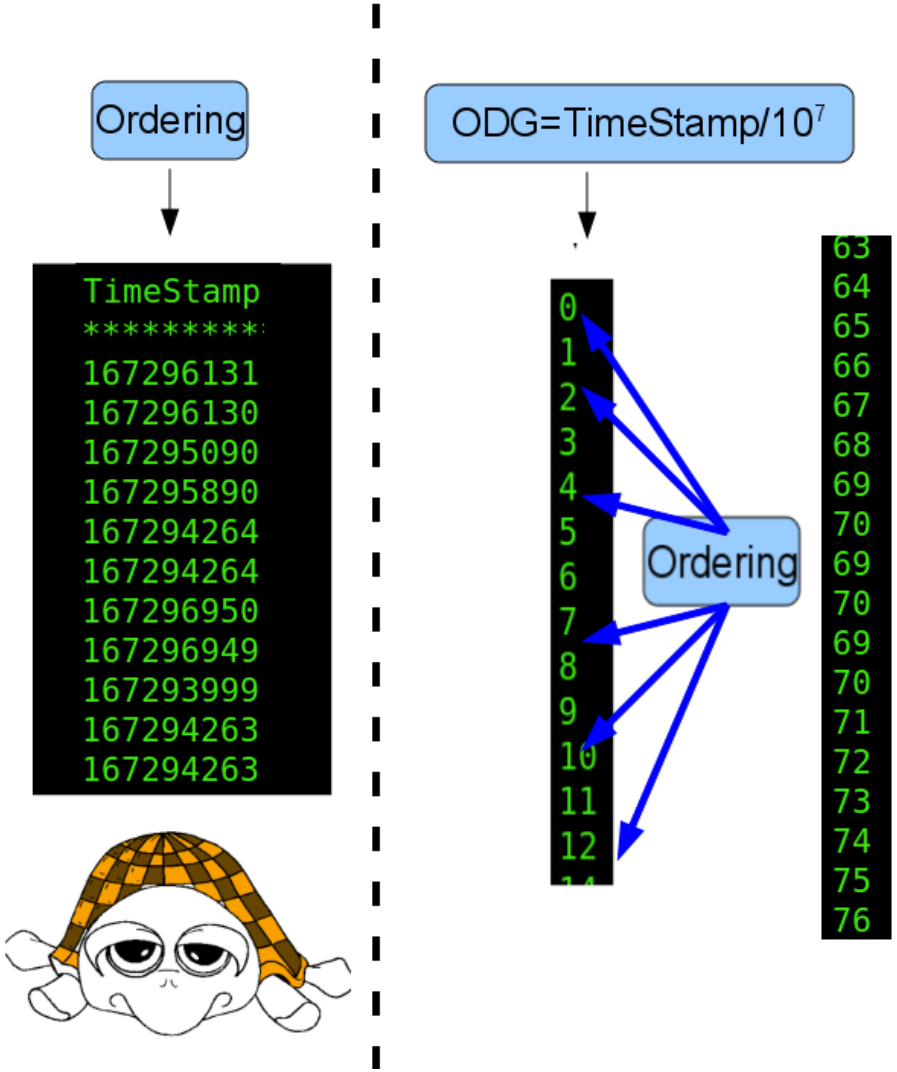
Handling Triggerless Data...→ Analysis Framework

Handling Triggerless Data...→ Analysis Framework

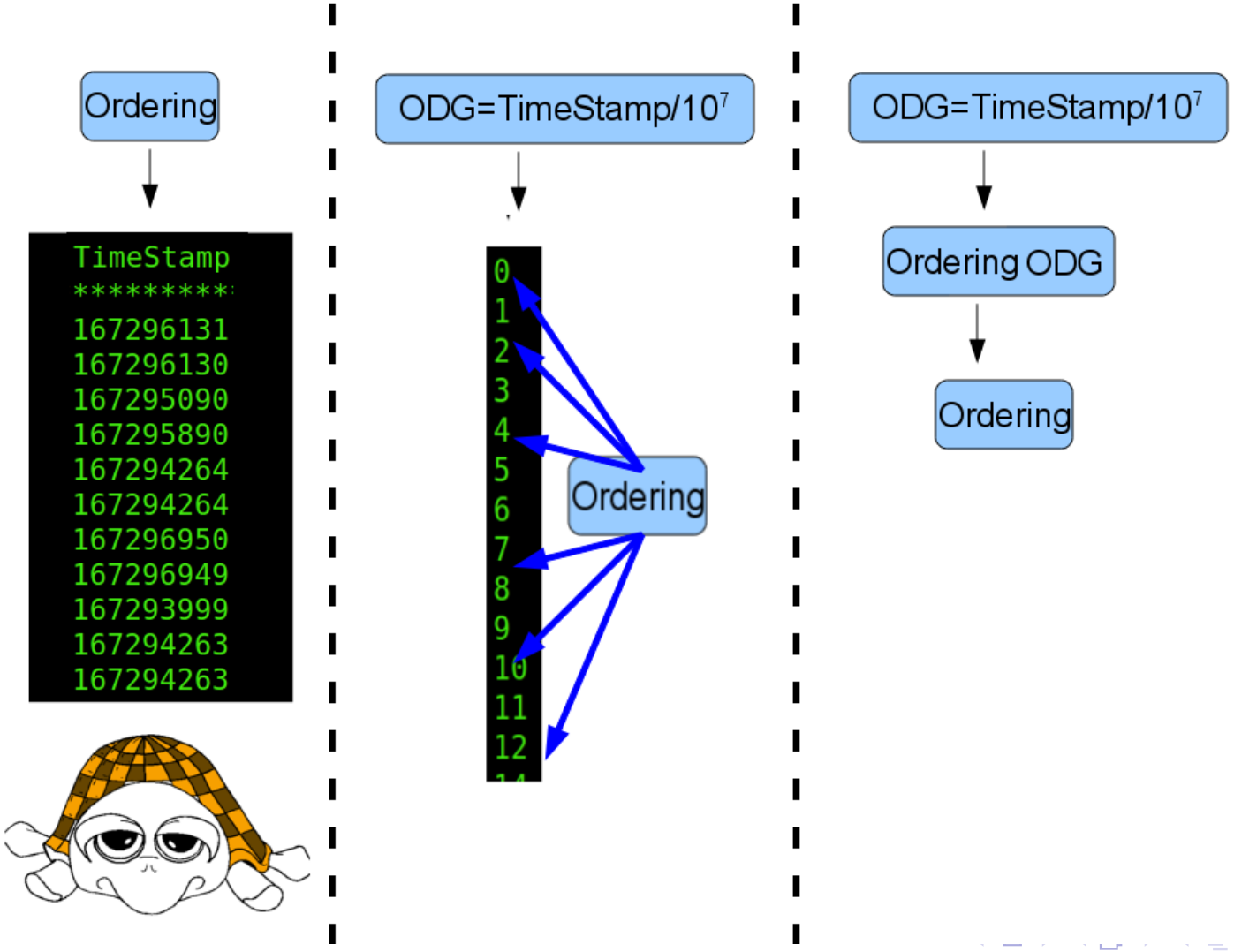
Handling Triggerless Data...→ Analysis Framework



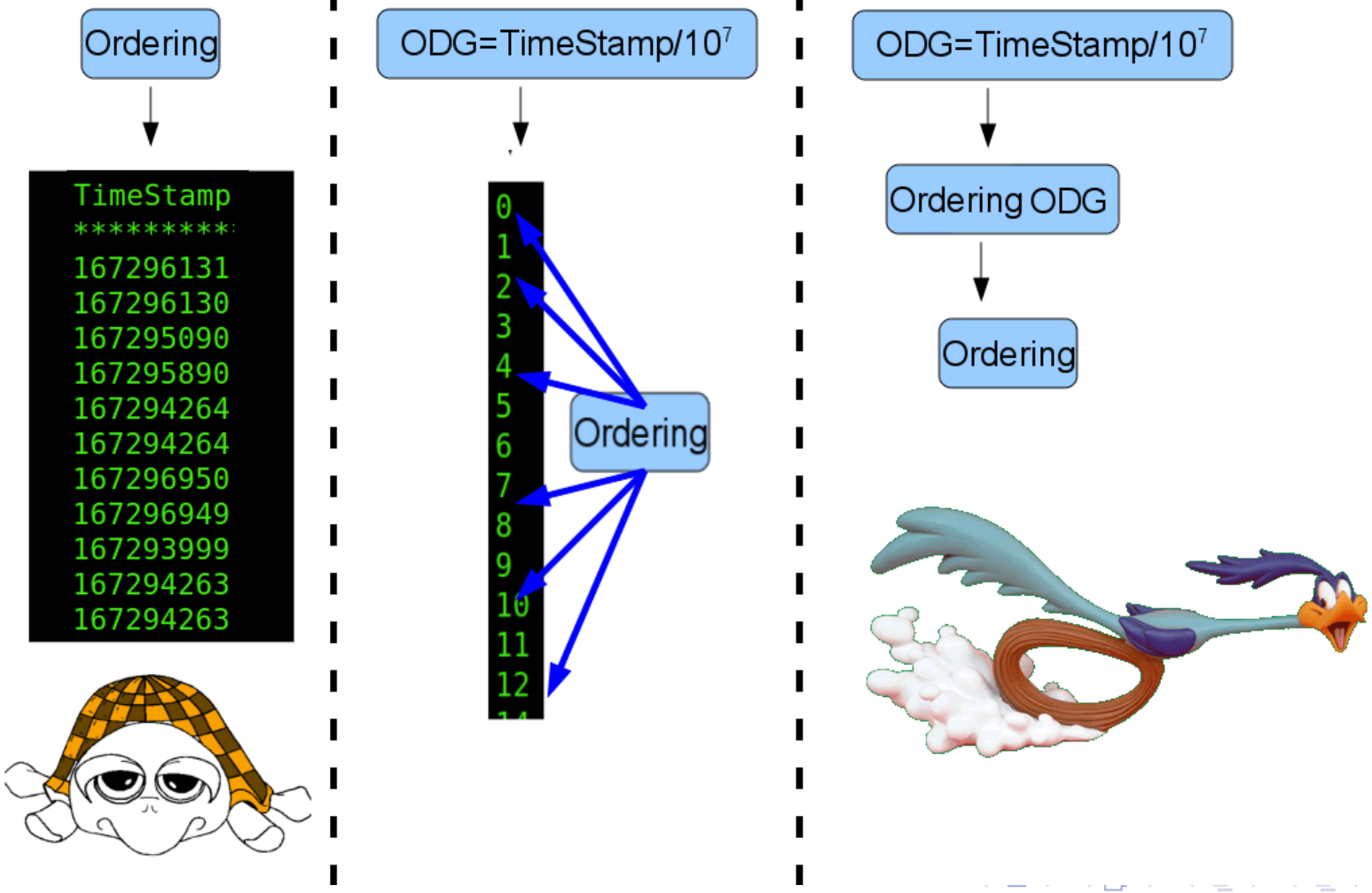
Handling Triggerless Data...→ Analysis Framework



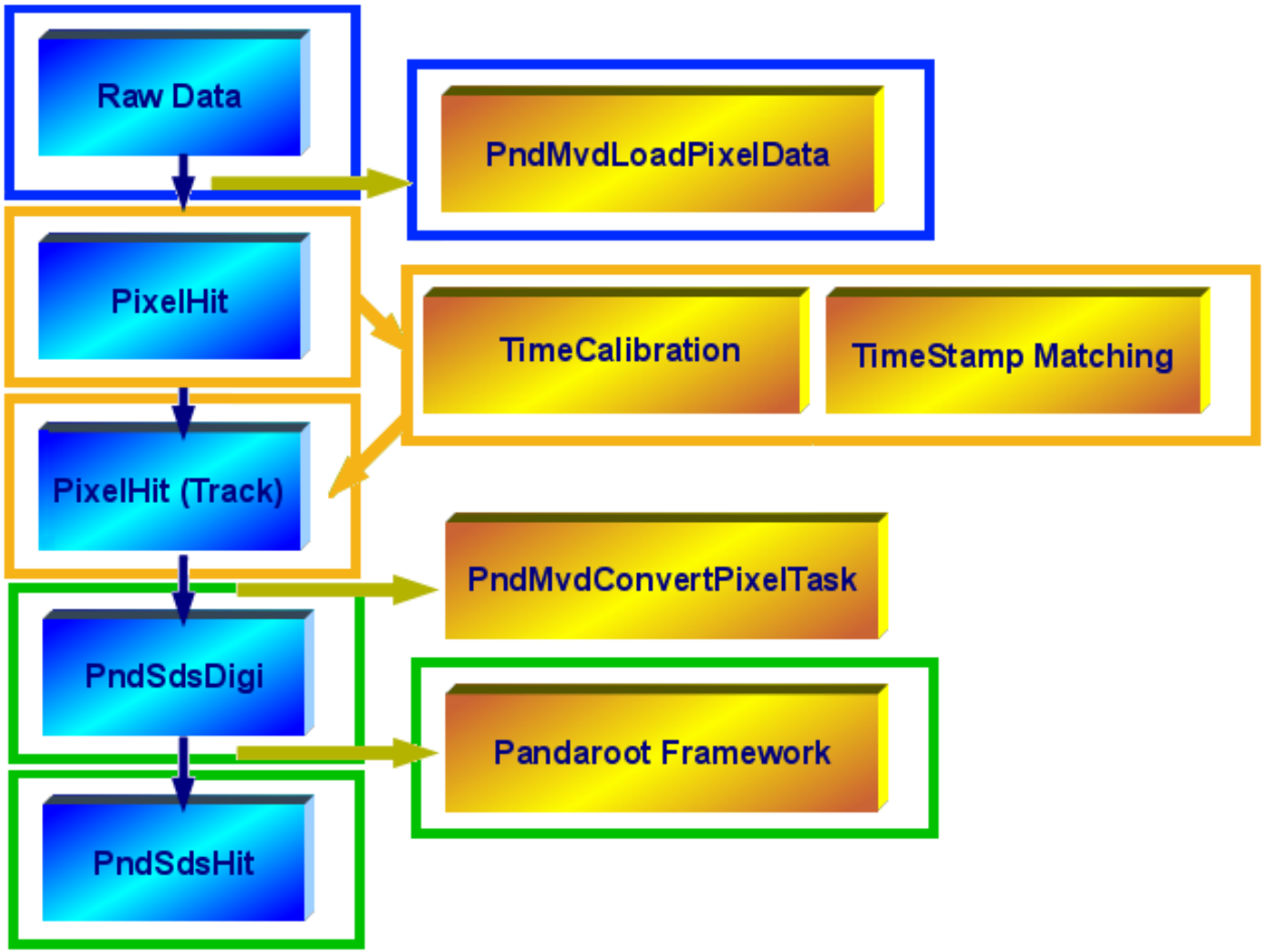
Handling Triggerless Data...→ Analysis Framework



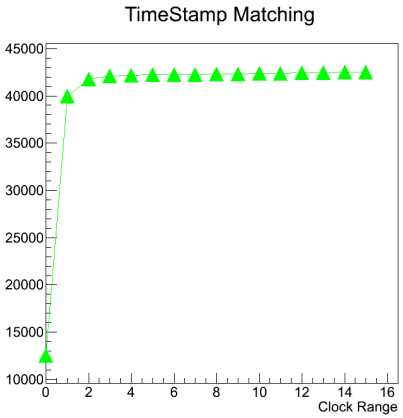
Handling Triggerless Data...$\rightarrow$ Analysis Framework

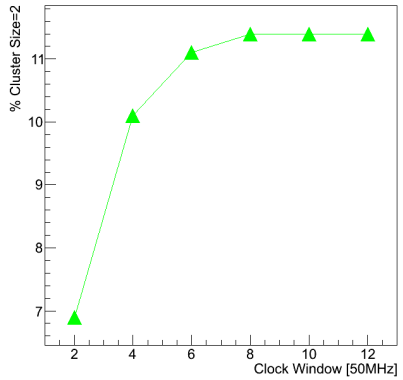


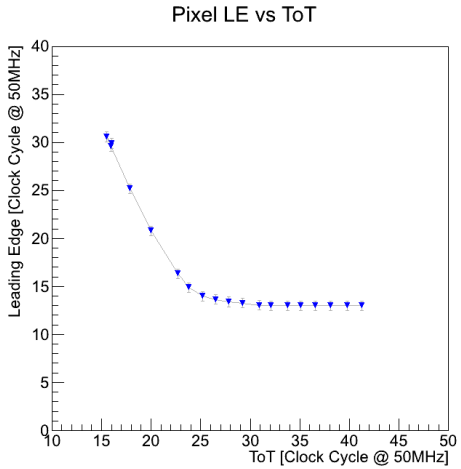
Handling Triggerless Data...→ Analysis Framework

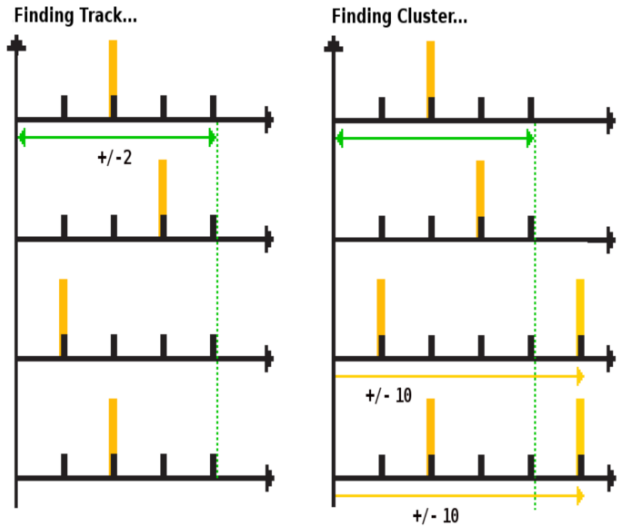


Handling Triggerless Data....$\rightarrow$ TimeStamp Matching



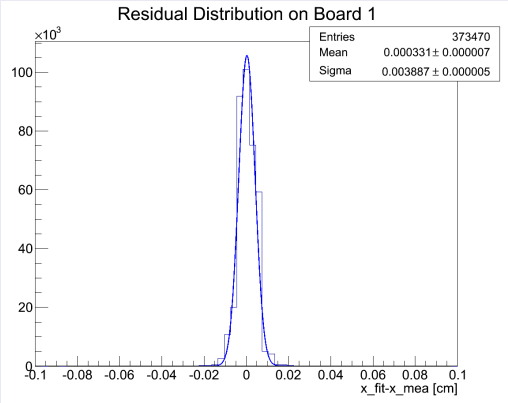






Alignment Study

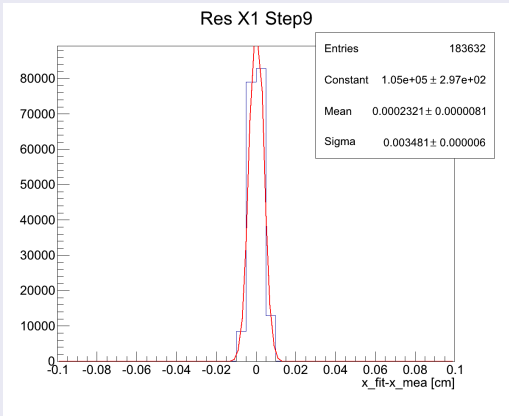
Julich Beam Test



Pixel Plane	σ_x [µm]	σ_y [µm]
0	65	62
1	39	42
2	45	45
3	73	53

$\sigma_{track_x} = \sigma_{track_y} \simeq 27\mu m$

CERN Beam Test

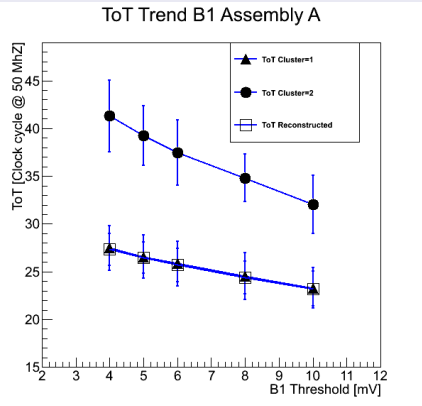


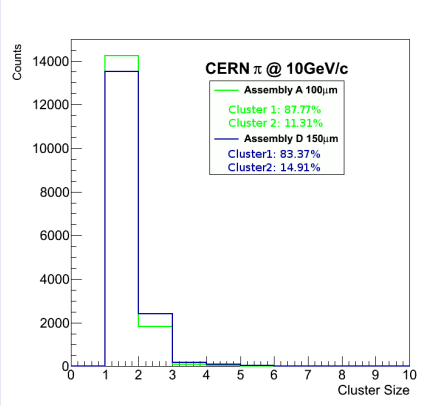
Pixel Plane	σ_x [µm]	σ_y [µm]
0	51	54
1	34	36
2	33	34
3	49	51

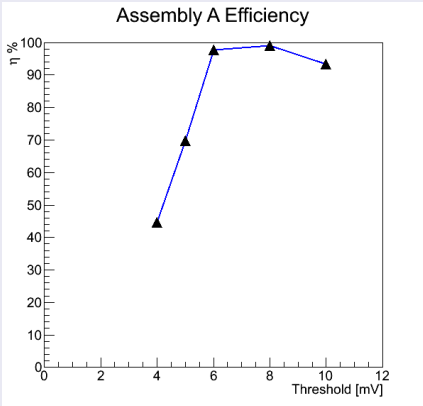
$\sigma_{track_x} = \sigma_{track_y} \simeq 21\mu m$

ToT Study → Scan @ CERN

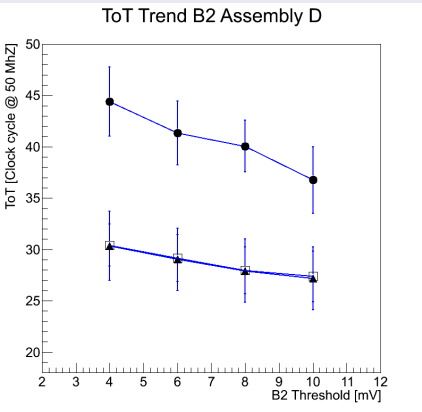
Assembly A 100µm

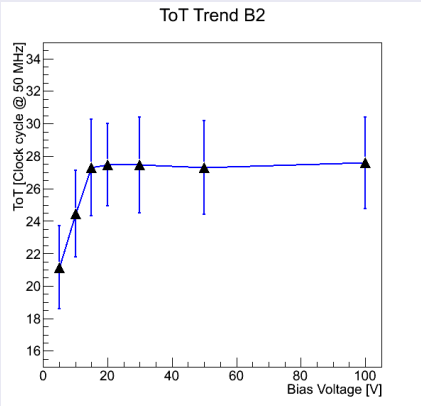


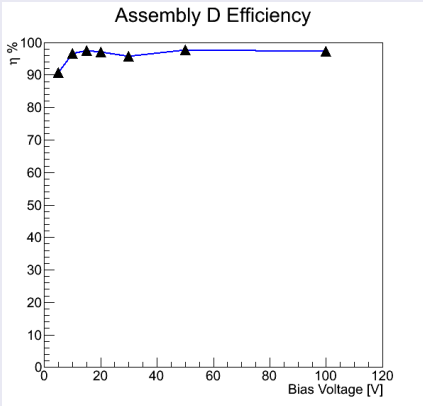




Assembly D 150µm







$\psi(4040)$

$\psi(4040)$

$I^G(J^{PC}) = 0^-(1^{--})$

$\psi(4040)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
4039 ± 1 OUR ESTIMATE				
4039.6± 4.3	[1] ABLIKIM	08D	BES2	$e^+e^- \rightarrow$ hadrons
• • • We do not use the following data for averages, fits, limits, etc. • • •				
4034 ± 6	[2] MO	10	RVUE	$e^+e^- \rightarrow$ hadrons
4037 ± 2	[3] SETH	05A	RVUE	$e^+e^- \rightarrow$ hadrons
4040 ± 1	[4] SETH	05A	RVUE	$e^+e^- \rightarrow$ hadrons
4040 ±10	BRANDELIK	78C	DASP	e^+e^-

$\psi(4040)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
80 ±10 OUR ESTIMATE				
84.5±12.3	[5] ABLIKIM	08D	BES2	$e^+e^- \rightarrow$ hadrons
• • • We do not use the following data for averages, fits, limits, etc. • • •				
87 ±11	[6] MO	10	RVUE	$e^+e^- \rightarrow$ hadrons
85 ±10	[7] SETH	05A	RVUE	$e^+e^- \rightarrow$ hadrons
89 ± 6	[8] SETH	05A	RVUE	$e^+e^- \rightarrow$ hadrons
52 ±10	BRANDELIK	78C	DASP	e^+e^-

PDG-2012

$\psi(4040)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)		Confidence level
Γ_1	e^+e^-	$(1.07\pm0.16)\times10^{-5}$		
Γ_2	$D\overline{D}$	seen		
Γ_3	$D^0\overline{D}^0$	seen		
Γ_4	D^+D^-	seen		
Γ_5	$D^*\overline{D}$ + c.c.	seen		
Γ_6	$D^*(2007)^0\overline{D}^0$ + c.c.	seen		
Γ_7	$D^*(2010)^+D^-$ + c.c.	seen		
Γ_8	$D^*\overline{D}^*$	seen		
Γ_9	$D^*(2007)^0\overline{D}^*(2007)^0$	seen		
Γ_{10}	$D^*(2010)^+D^*(2010)^-$	seen		
Γ_{11}	$D\overline{D}\pi$ (excl. $D^*\overline{D}$)			
Γ_{12}	$D^0D^-\pi^+$ +c.c. (excl. $D^*(2007)^0\overline{D}^0$ +c.c., $D^*(2010)^+D^-$ +c.c.)	not seen		
Γ_{13}	$D\overline{D}^*\pi$ (excl. $D^*\overline{D}^*$)	not seen		
Γ_{14}	$D^0\overline{D}^{*-}\pi^+$ +c.c. (excl. $D^*(2010)^+D^*(2010)^-$)	seen		
Γ_{15}	$D_s^+D_s^-$	seen		
Γ_{16}	$J/\psi(1S)$ hadrons			
Γ_{17}	$J/\psi\pi^+\pi^-$	< 4	$\times10^{-3}$	90%
Γ_{18}	$J/\psi\pi^0\pi^0$	< 2	$\times10^{-3}$	90%
Γ_{19}	$J/\psi\eta$	< 7	$\times10^{-3}$	90%
Γ_{20}	$J/\psi\pi^0$	< 2	$\times10^{-3}$	90%
Γ_{21}	$J/\psi\pi^+\pi^-\pi^0$	< 2	$\times10^{-3}$	90%
Γ_{22}	$\chi_{c1}\gamma$	< 1.1	%	90%
Γ_{23}	$\chi_{c2}\gamma$	< 1.7	%	90%
Γ_{24}	$\chi_{c1}\pi^+\pi^-\pi^0$	< 1.1	%	90%
Γ_{25}	$\chi_{c2}\pi^+\pi^-\pi^0$	< 3.2	%	90%
Γ_{26}	$h_c(1P)\pi^+\pi^-$	< 3	$\times10^{-3}$	90%
Γ_{27}	$\phi\pi^+\pi^-$	< 3	$\times10^{-3}$	90%
Γ_{28}	$\mu^+\mu^-$			

Cross Section of $\psi(4040) \rightarrow D^{*+}D^{*-}$

$$p\bar{p} \rightarrow \psi(4040) \rightarrow D^{*+}D^{*-} \text{ @ } p_{\bar{p}}=7.71 \text{ GeV/c}$$
$$D^{*+/-} \rightarrow D^0\pi^{+/-} \quad \text{BR: 67.7 \%}$$
$$D^0 \rightarrow K^-\pi^+ \quad \text{BR: 3.88 \%}$$

$$\sigma_R(s) = \frac{4\pi\hbar^2c^2}{(E/2)^2} \frac{2J+1}{(2S_1+1)(2S_2+1)} \frac{B_{in}B_{out}\Gamma^2/4}{(E-E_r)^2+\Gamma^2/4}$$

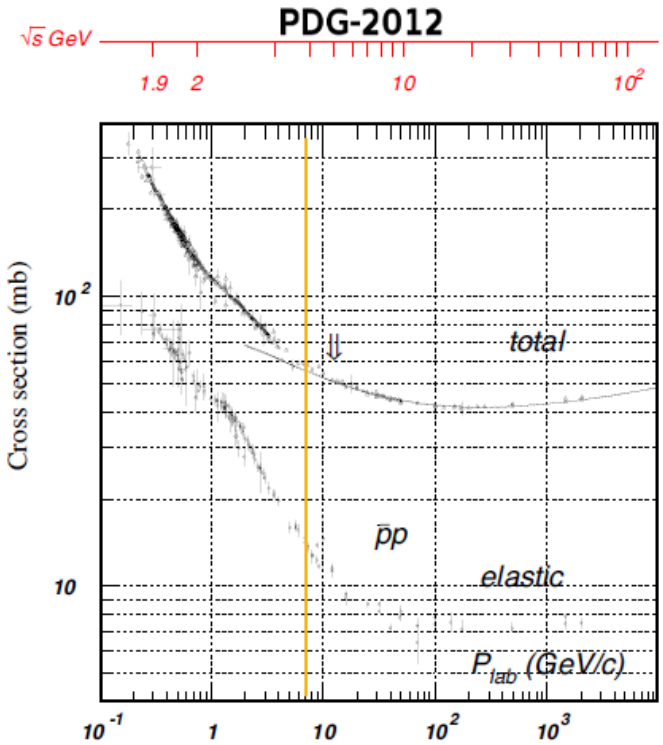
- Bin: BR $\psi(4040) \rightarrow \bar{p}p$
  $B_{in} = B[J/\psi \rightarrow p\bar{p}] \frac{\Gamma_{J/\psi}}{\Gamma_{\psi(4040)}} = 2.17 \cdot 10^{-3} \frac{92.2keV}{80MeV} = 2.5 \cdot 10^{-6}$
- Bout: BR $[\psi(4040) \rightarrow D^{*+}D^{*-}]$ = 33% [1]
- M_r=4039 $\pm$ 1 MeV, Γ_r=80 $\pm$ 10 MeV

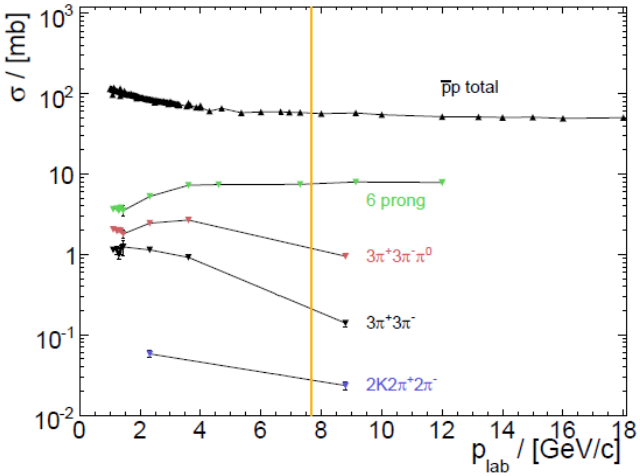
$$\sigma(\bar{p}p \rightarrow \psi(4040) \rightarrow D^{*+}D^{*-}) = 2.2 \text{ nb}$$

[1] G. Goldhaber and J.E. Wiss, Phys. Lett., 69B(4), August 1977.

Hadronic Background

$$R = \frac{\sigma(\bar{p}p \rightarrow D^{*+}D^{*-} \rightarrow 2D^0 2\pi \rightarrow 2K4\pi)}{\sigma(\bar{p}p \rightarrow X)} = \frac{1.5pb}{35mb} = 4.3 \cdot 10^{-11}$$

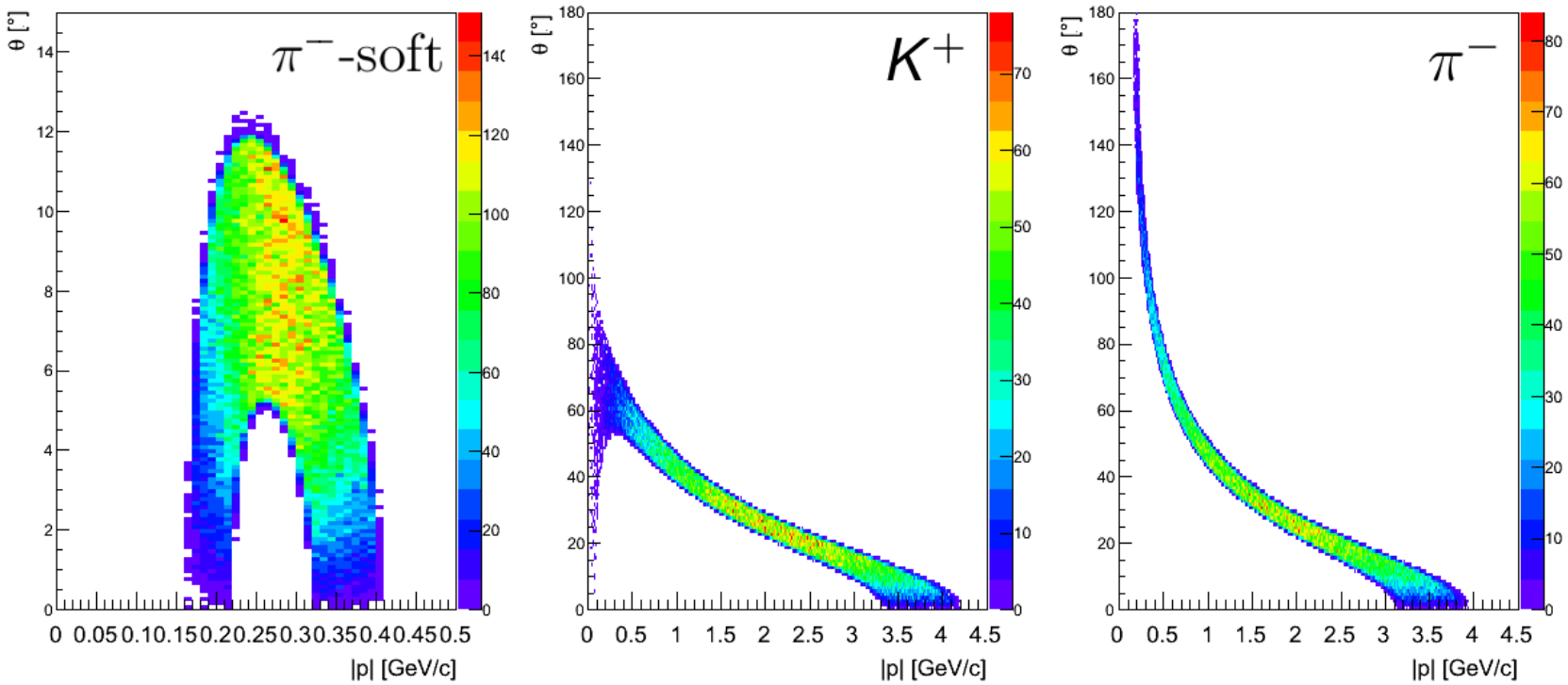




Reaction	σ [mb]	Fraction to $\bar{p}p$
$3\pi^+3\pi^-\pi^0$	1.3	$3.7\ 10^{-2}$
$3\pi^+3\pi^-$	0.21	$6.0\ 10^{-3}$
$2K4\pi$	0.029	$8.2\ 10^{-4}$

Final Particle Momentum Distributions

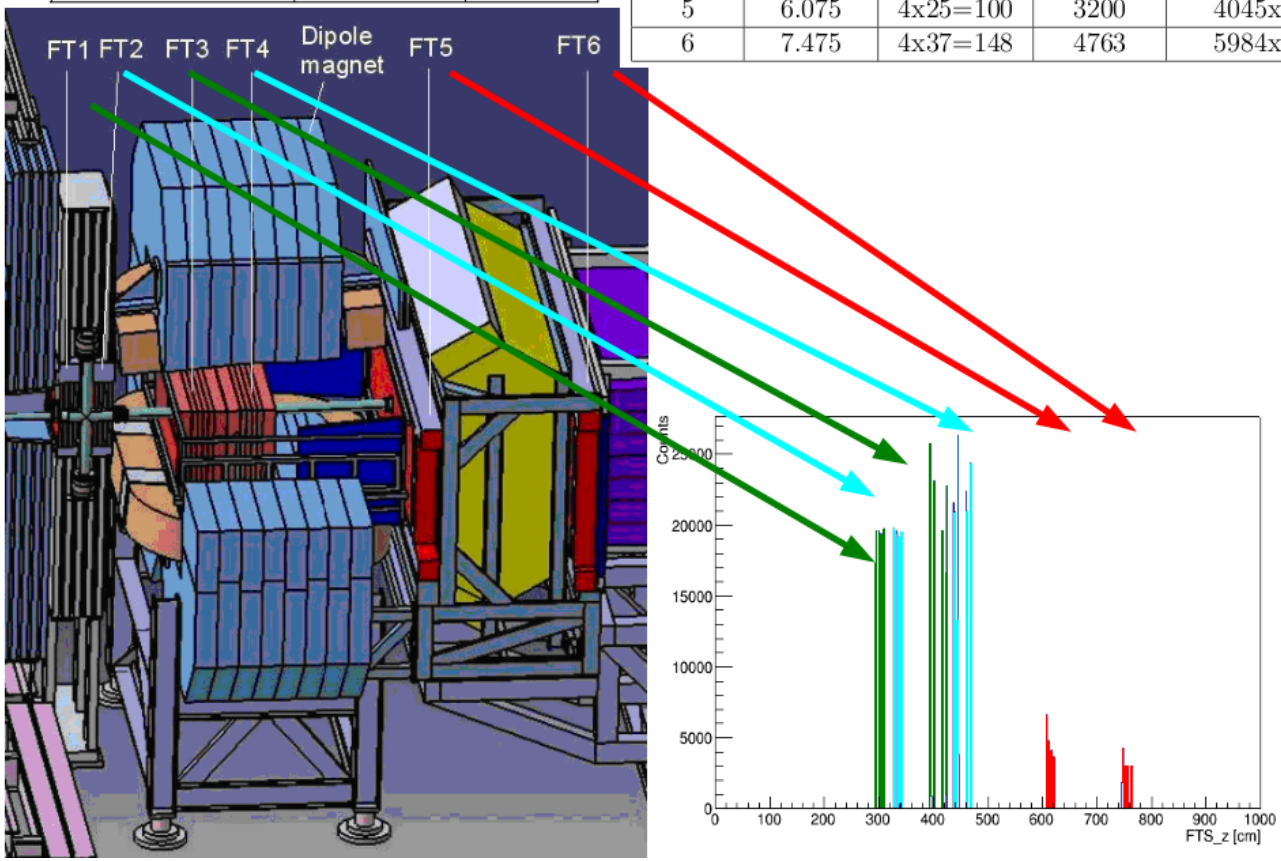
$$\psi(4040) \rightarrow D^{*+}D^{*-} \rightarrow D^0\pi^+\overline{D^0}\pi^- \rightarrow \pi^+K^-\pi^+\pi^-K^+\pi^-$$



MC-Matching Results & Acceptance Considerations

Charged Tracks	$\eta \pm 0.1$ %	$\delta p/p$ %
K^+	75.9	
K^-	71.5	1.8
π^+	75.2	
π^-	77.0	1.6
π^+-soft	41.1	
π^--soft	40.6	2.3

Station	z-pos [m]	# modules	# straws	Area x·y [mm^2]
1	2.954	4x8=32	1024	1298x640
2	3.274	4x8=32	1024	1298x640
3	3.945	4x12=48	1536	1944x690
4	4.385	4x12=48	1536	1944x767
5	6.075	4x25=100	3200	4045x1180
6	7.475	4x37=148	4763	5984x1480



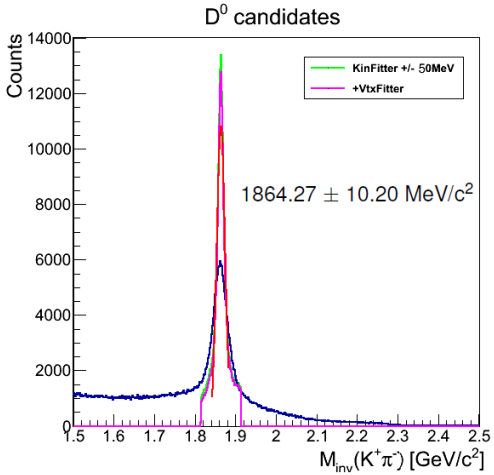
Analysis Strategy

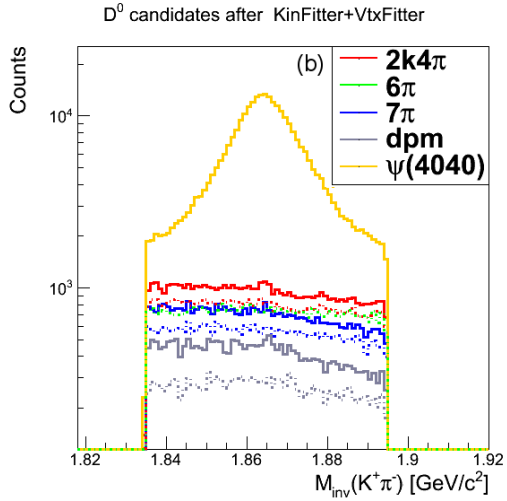
- 4/6 candidates: K^+, K^-, π^+, π^- (π^+, π^- hard-soft component separation)
  - Cut on the Momentum Distribution
- D^0 / $\overline{D}^0$ candidates
  - Kinematic Fit $\rightarrow$ Mass Constraint
  - Cut $\pm 3\sigma$ around the D^0 mass
  - Cut on the Momentum Distribution
  - Vertex Fit $\rightarrow$ $d_{IP} < 0.2$cm
- $D^{*+/-}$ candidates
  - Cut $\pm 3\sigma$ around the $D^{*+/-}$ mass
- $\psi(4040)$ candidates
  - Kinematic Fit $\rightarrow$ 4C (Beam Energy)

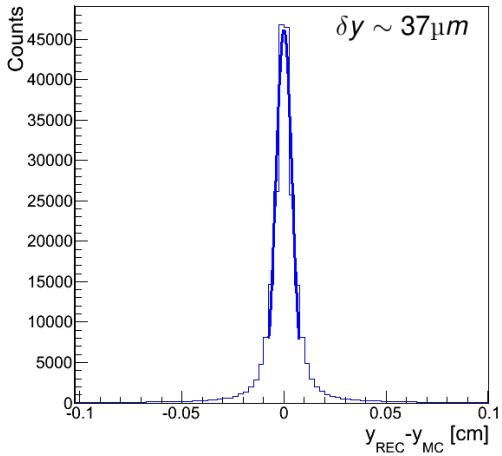
FairRoot April-2013, PandaRoot rev. 21574

$D^0 - \overline{D^0}$ Candidates

MC-Interval	$\pm 2\sigma$
$3.06 < \|p\| < 4.1$ GeV/c	$3.21 < \|p\| < 4.31$ GeV/c
$\|p_t\| < 0.21$ GeV/c	$\|p_t\| < 0.25$ GeV/c
$\theta(K) < 4^\circ$	



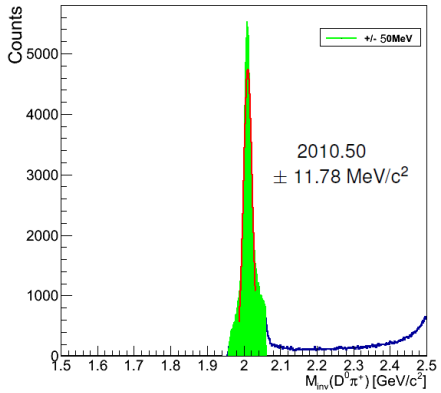


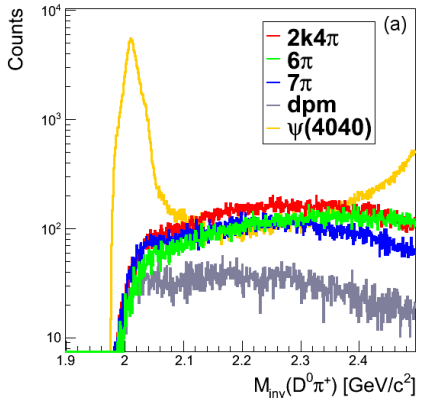


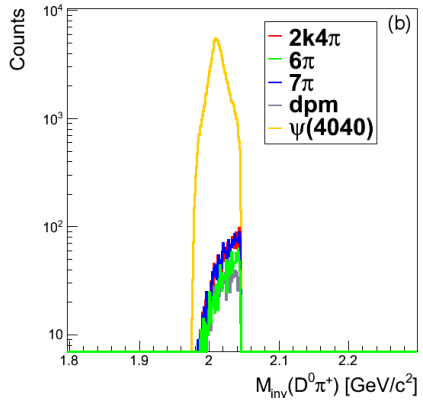
		Signal	2K4π	6π	7π	$\bar{p}p$
4Prong	KinFitter	86.1%	99.9%	99.9%	99.9%	99.9%
	VtxFitter	4.8%	17.7	18.9%	20.7%	37.8%
6Prong	KinFitter	81.1%	99.9	99.9%	99.9%	99.8%
	VtxFitter	4.9%	17.6	18.8%	20.5%	37.3%

Efficiency of combinatorials and background rejection.

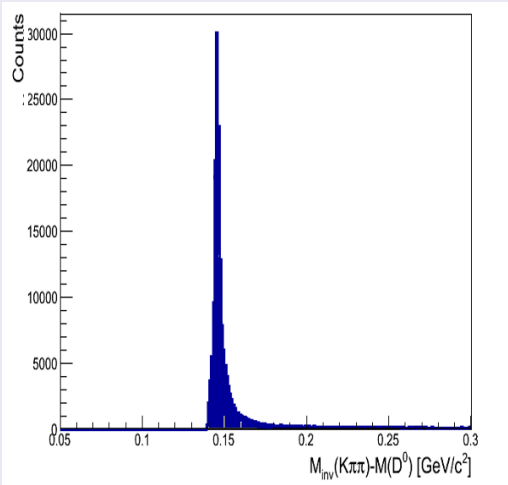
$D^{*+} - D^{*-}$ Candidates

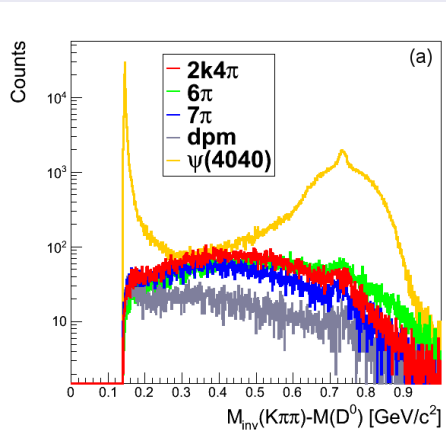


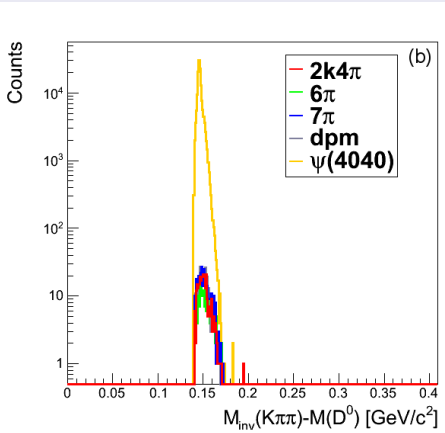




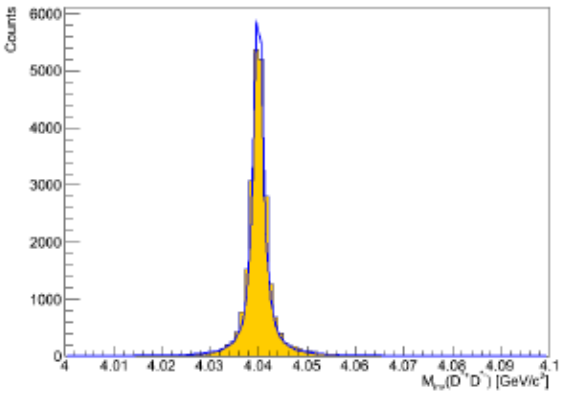
Alternative Method







$\psi(4040)$



	4Prong %	6Prong %
Mean	4039.9 MeV/c^2	
σ	1.4 MeV/c^2	1.4 MeV/c^2
η	4%	3.3 %

$N_{events} = \sigma \cdot L_{int}$
$(L_{int} = 3.1 \cdot 10^{39} cm^{-2})$
$\psi(4040) \rightarrow D^{*+}D^{*-}$ $6.84 \cdot 10^6$ events
Of these, ~4700 should decay into
$D^{*+}D^{*-} \rightarrow \pi^+ D^0 \pi^- \overline{D^0} \rightarrow 2\pi^+ 2\pi^- K^+ K^-$

Channel	σ [mb]	N_{events}	Sim. Evt	RP 4Prong	RP 6Prong	RP ΔM
2K4π	0.033	$9.0 \cdot 10^{10}$	$1.5 \cdot 10^7$	$\leq 1.3 \cdot 10^{-7}$	$< 6.7 \cdot 10^{-8}$	$< 6.7 \cdot 10^{-8}$
6π	0.32	$6.5 \cdot 10^{11}$	$2 \cdot 10^7$	$< 5 \cdot 10^{-8}$	$< 5 \cdot 10^{-8}$	$< 5 \cdot 10^{-8}$
7π	1.5	$4.0 \cdot 10^{12}$	$2 \cdot 10^7$	$\leq 5 \cdot 10^{-8}$	$\leq 5 \cdot 10^{-8}$	$< 5 \cdot 10^{-8}$
$p\bar{p}$	35	$1.1 \cdot 10^{14}$	$2.25 \cdot 10^7$	$\leq 8.9 \cdot 10^{-8}$	$< 4.4 \cdot 10^{-8}$	$< 4.4 \cdot 10^{-8}$

Rejection power for the main background sources.

Channel	4Prong	6Prong	ΔM
2K4π	$\geq 1.6 \cdot 10^{-2}$	$> 2.7 \cdot 10^{-2}$	$> 2.7 \cdot 10^{-2}$
6π	$> 5.8 \cdot 10^{-3}$	$> 4.9 \cdot 10^{-3}$	$> 4.9 \cdot 10^{-3}$
7π	$\geq 9.5 \cdot 10^{-4}$	$\geq 8 \cdot 10^{-4}$	$> 8 \cdot 10^{-4}$
$p\bar{p}$	$\geq 1.9 \cdot 10^{-5}$	$> 3.3 \cdot 10^{-5}$	$> 3.3 \cdot 10^{-5}$

Signal to background ratio for the main background sources.

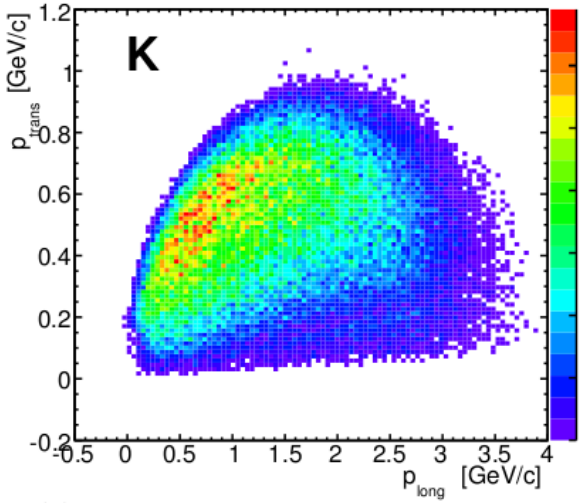
Conclusions

- An analysis framework for triggerless data has been developed.
- Different analysis on topic detector aspects have been carried out for 2 different beam test data.
- Detailed MonteCarlo study of the $\overline{p}p \rightarrow \psi(4040) \rightarrow D^{*+}D^{*-}$ decay chain were performed to test the potential reconstruction performance, the secondary vertices reconstruction capability and the hadronic background suppression.

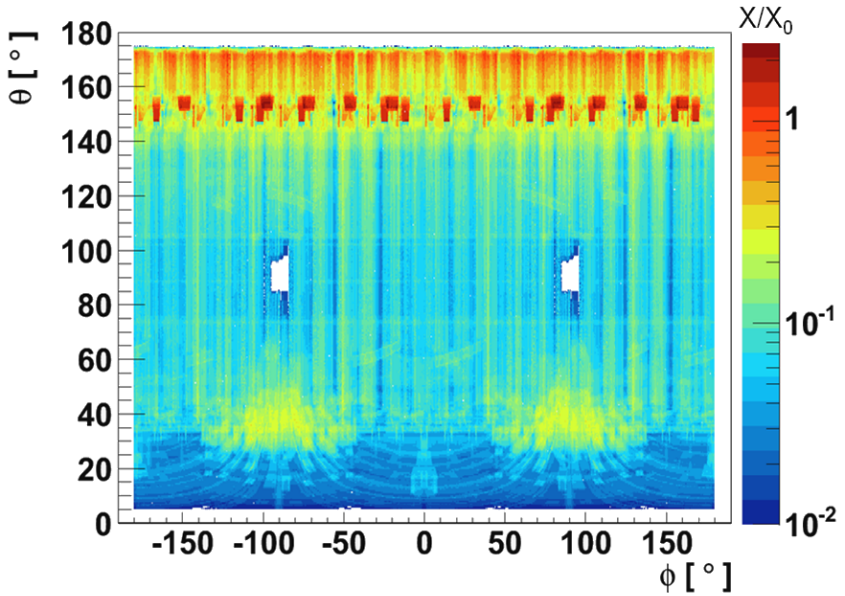
Backup Slides

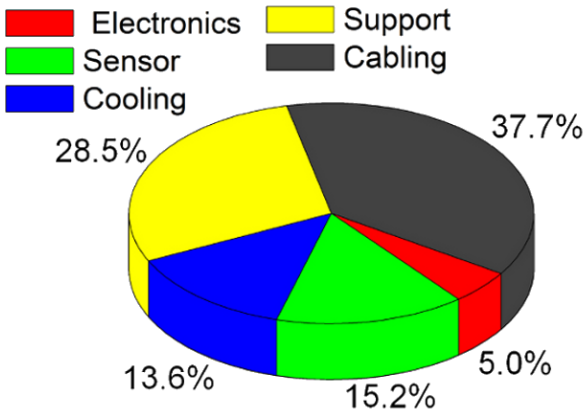
Material Budget

$\bar{p}p \rightarrow D^+D^- \rightarrow K^-\pi^+\pi^+K^+\pi^-\pi^-$

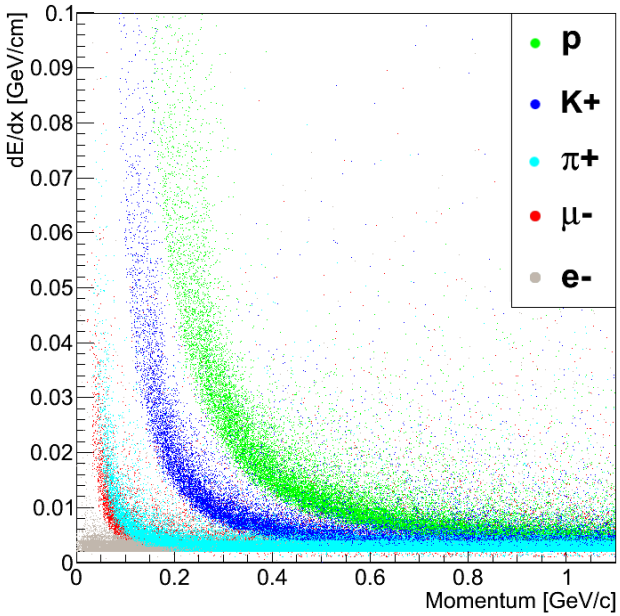


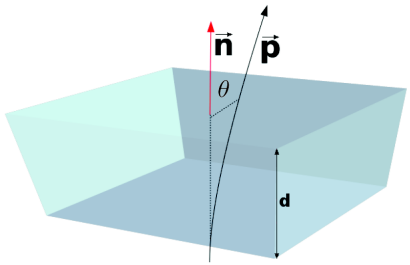
R. Jakel, PhD thesis, TU Dresden, 2009





PID Algorithm

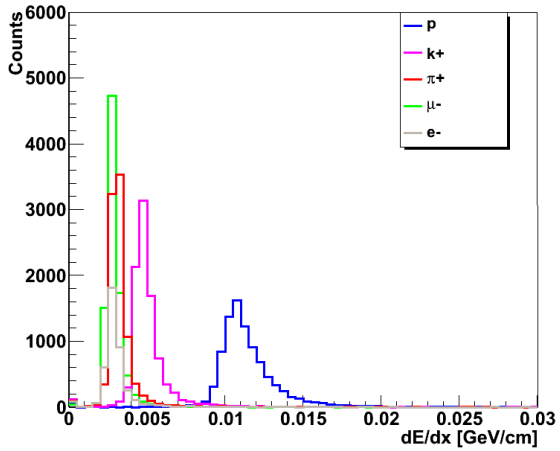




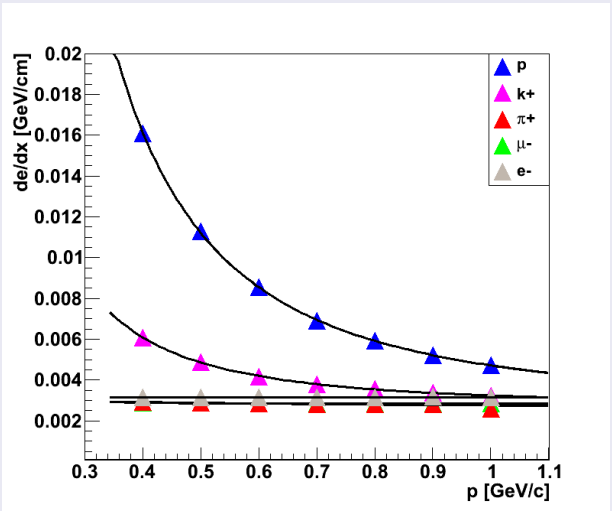
$$\frac{dE}{dx} \approx \frac{\Delta E}{d/\cos\theta}$$

Estimator

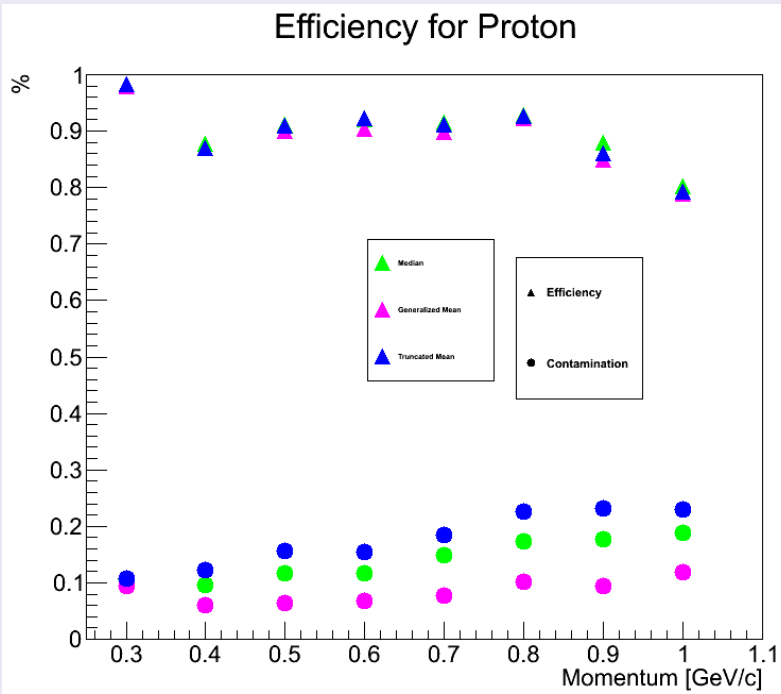
- Landau
- Generalized Mean
- Truncated Mean
- Median



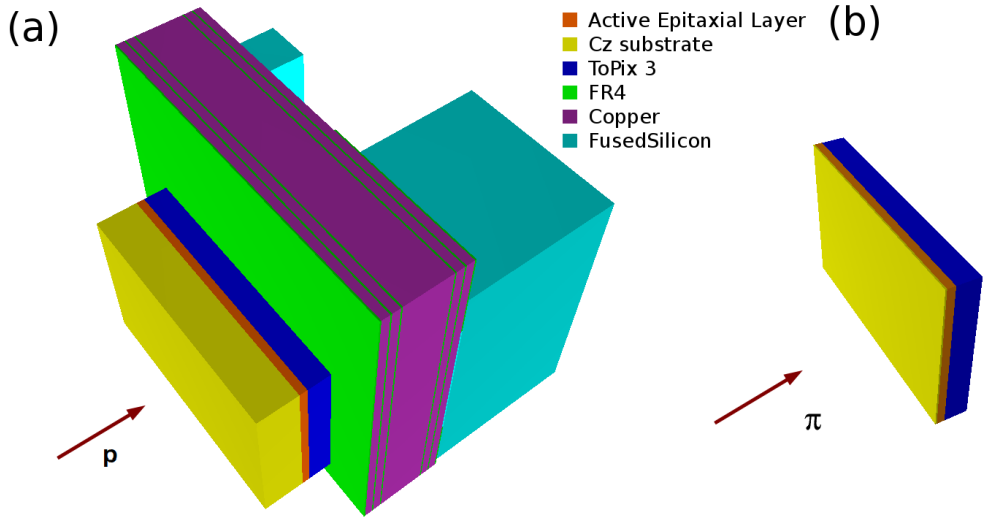
PID Algorithm



- Particle X: p, dE/dx
- Get dE/dx_{expe} from parametrization using p
- Get Probability from dE/dx_{meas}-dE/dx_{expe}



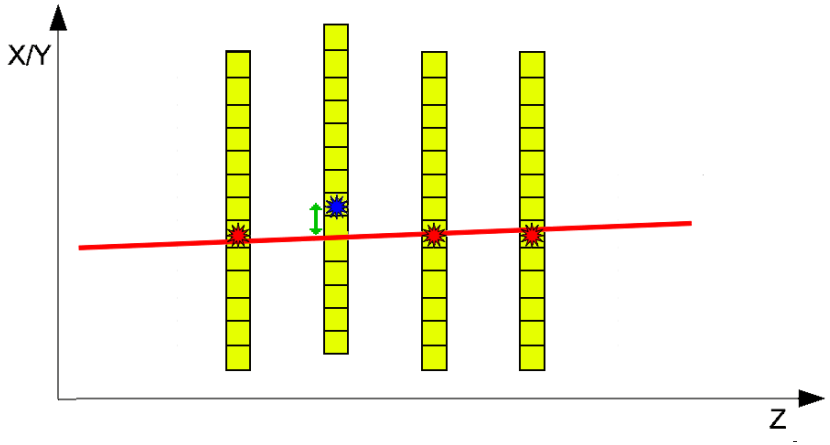
Sensor & Setup Considerations

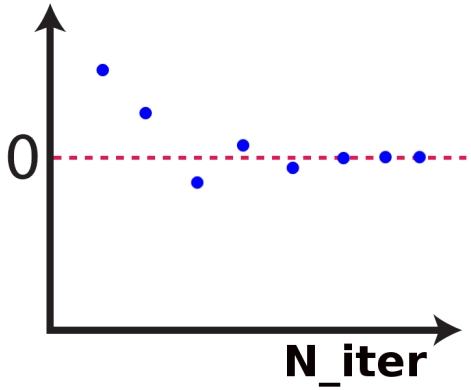


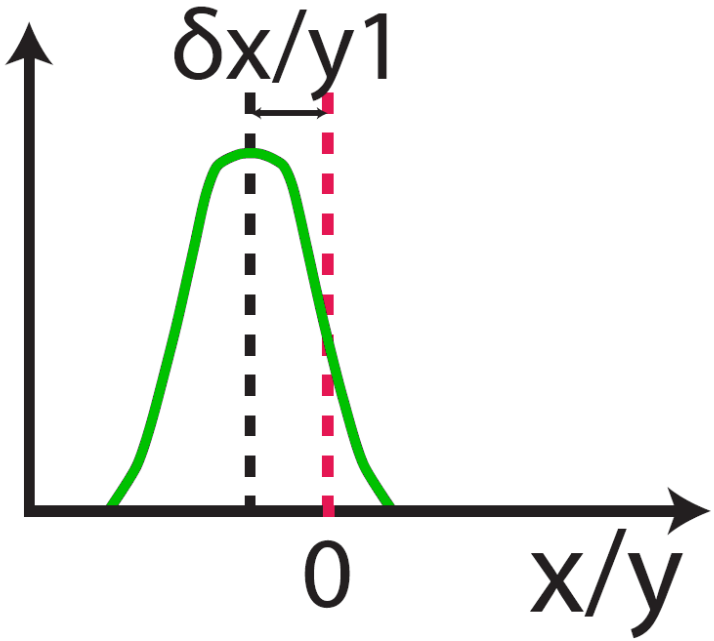
Jülich Beam Test			
Material	ρ/X_0	Thick [cm]	X/X_0 %
Silicon	9.3496	0.0925	0.99
Copper	1.4350	0.0474	3.30
FR4	16.7134	0.1200	0.72
FusedSilicon	12.2638	0.2000	1.63
1 Pixel plane	min=∼5% max=∼6.6%		
4 Pixel plane	min=∼20% max=∼26.6%		

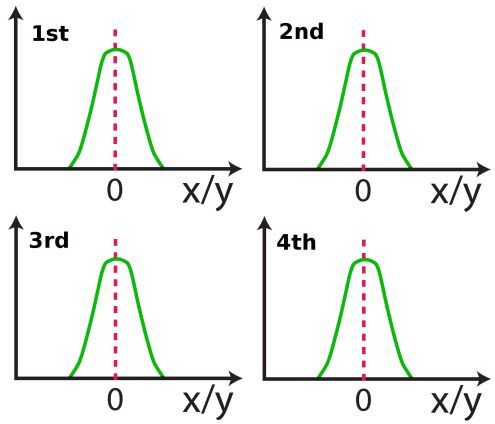
CERN Beam Test			
Material	ρ/X_0	Thick [cm]	X/X_0 %
Silicon	9.3496	0.0420	0.45
1 Pixel plane	∼0.45%		
4 Pixel plane	∼1.8%		

Alignment Study



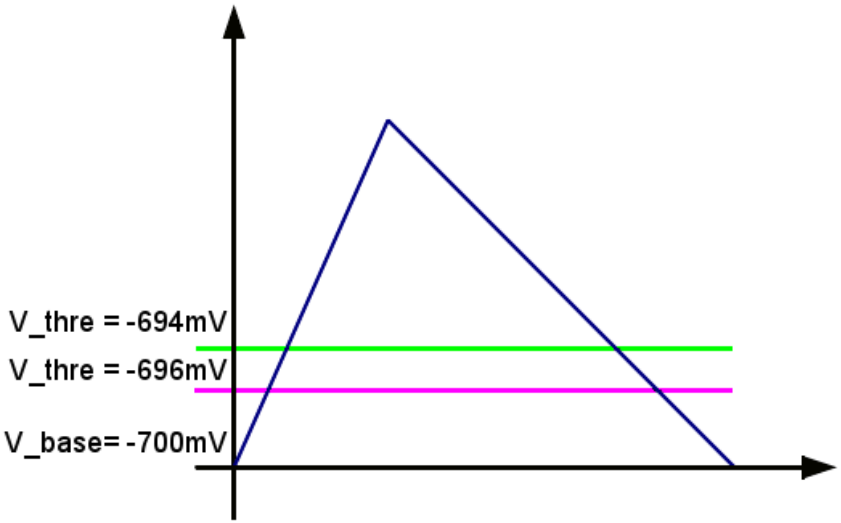




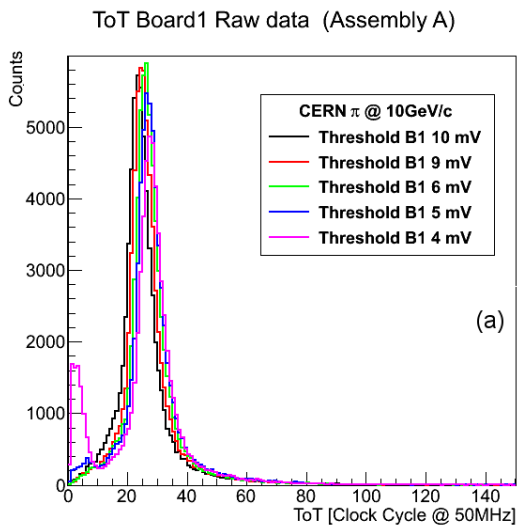


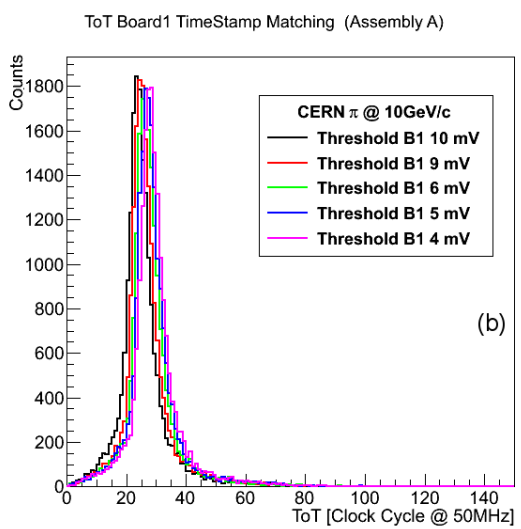
$$\sigma_{track} = \frac{\sqrt[4]{\sigma_0 * \sigma_1 * \sigma_2 * \sigma_3}}{\sqrt{4}}$$

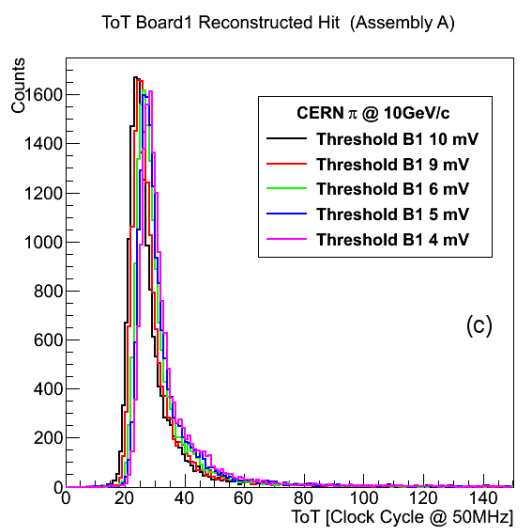
ToT Study



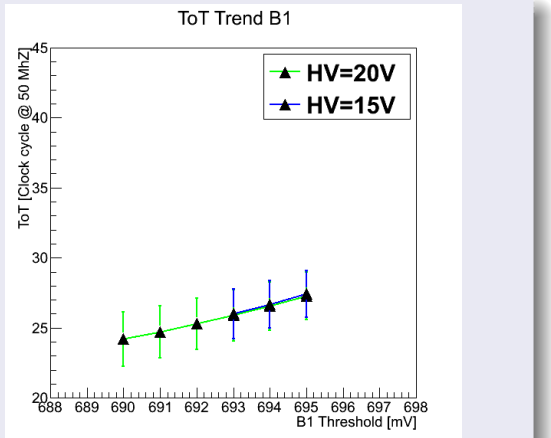
- ToT=Leading-Trailing
- Convolution Landau+Gaus

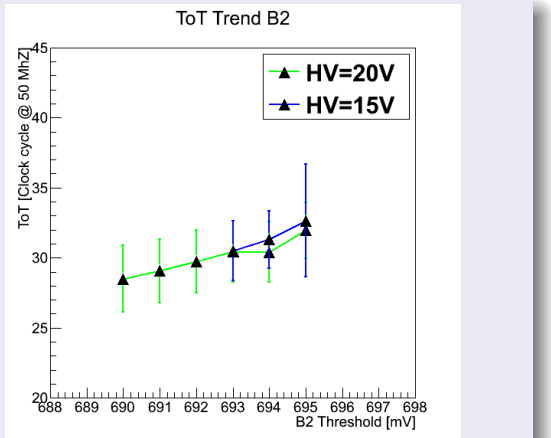


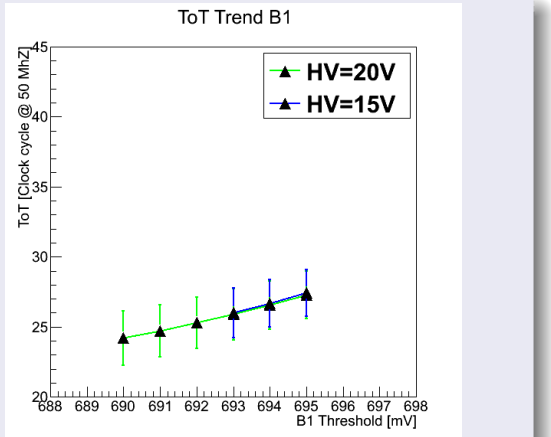


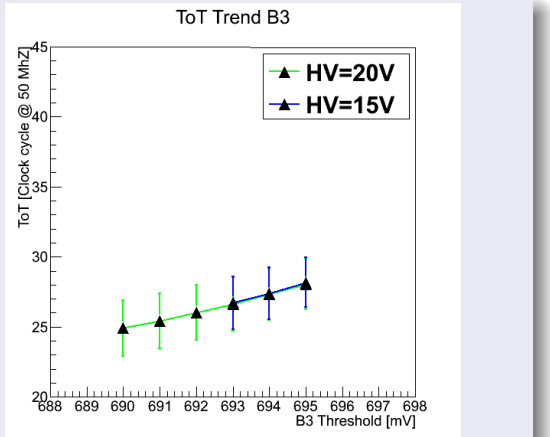


ToT Study → Scan @ Julich

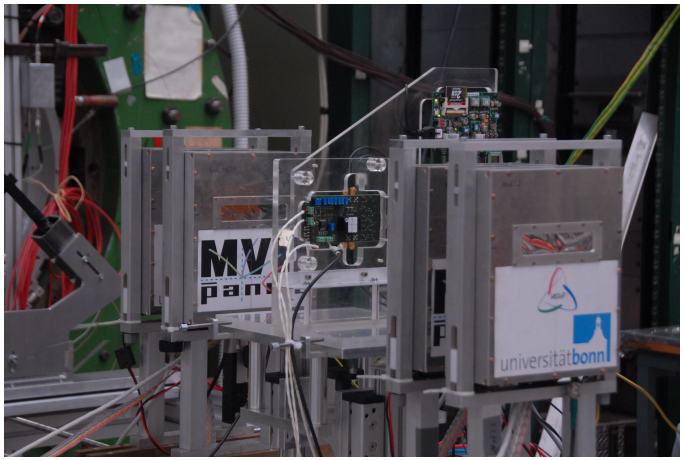


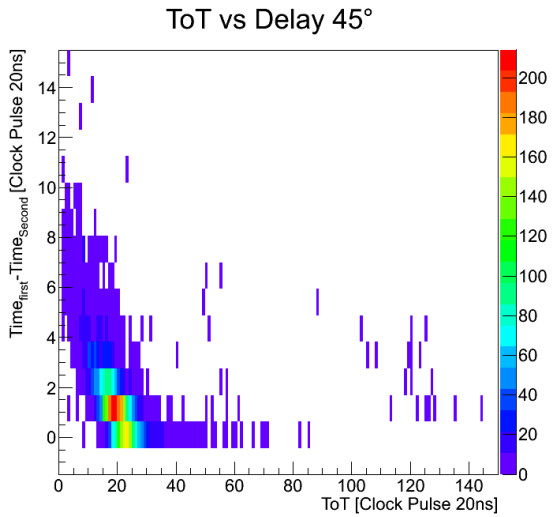


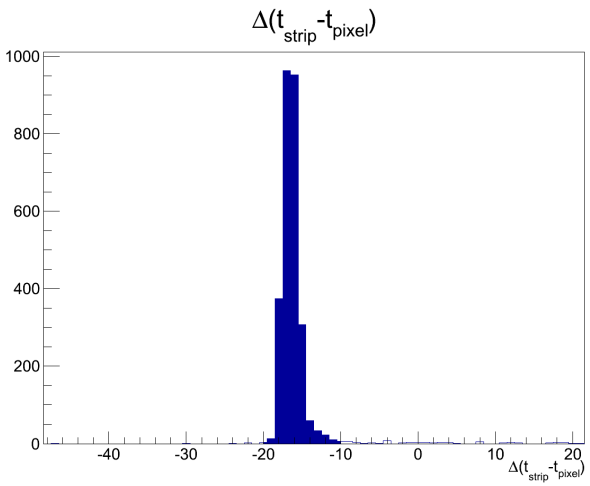


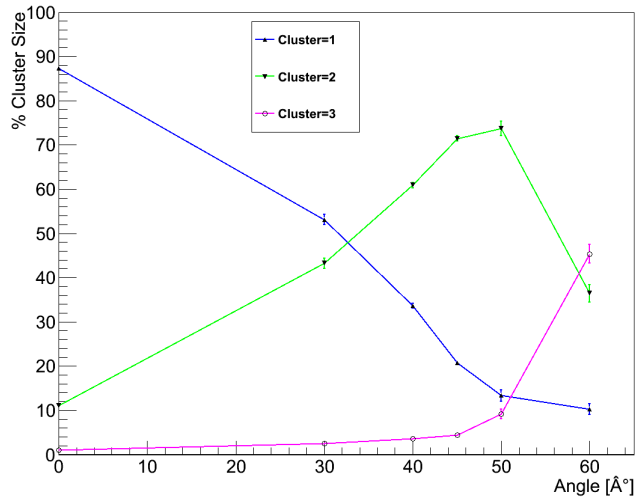


Cluster Size Study

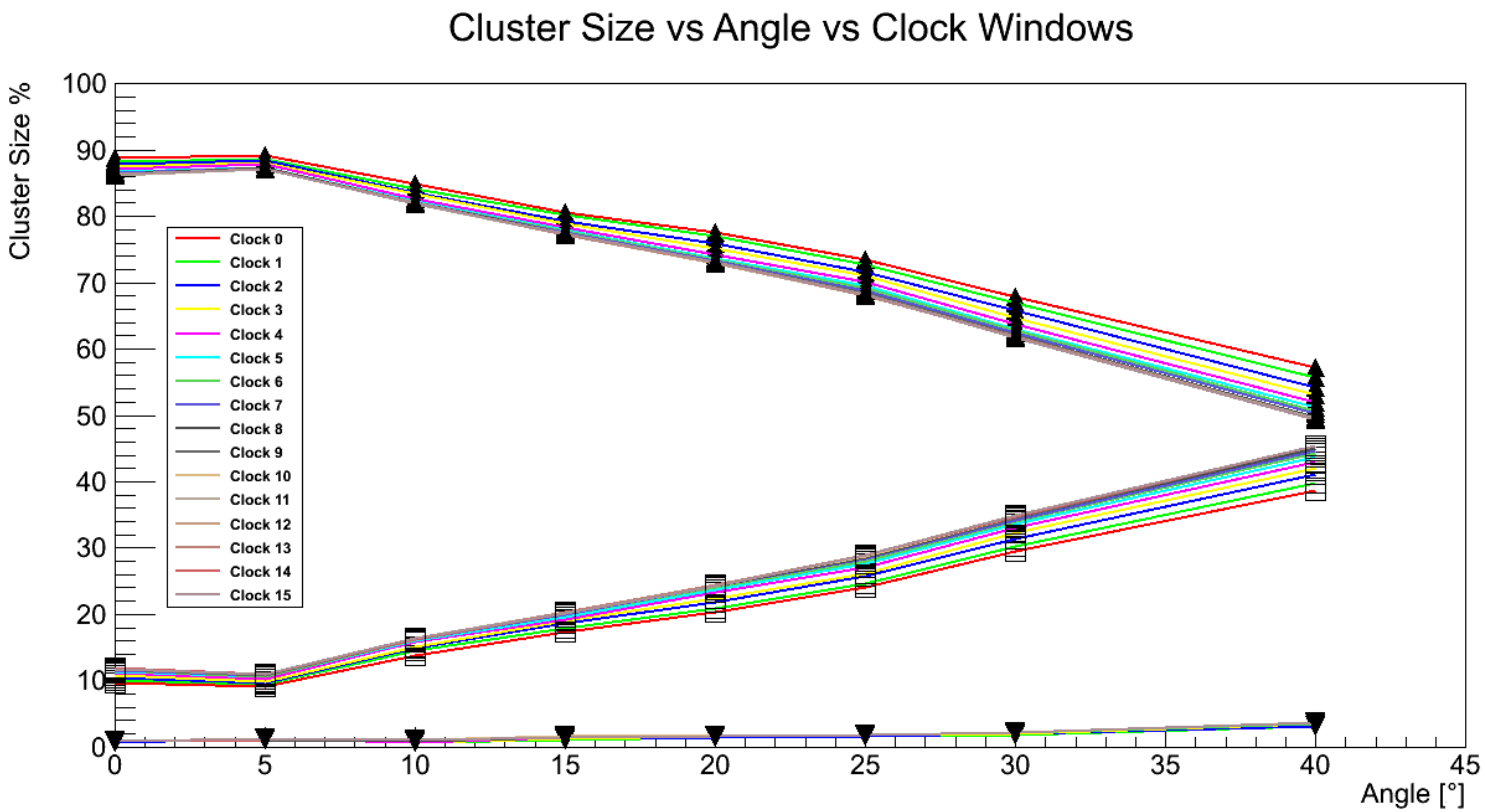




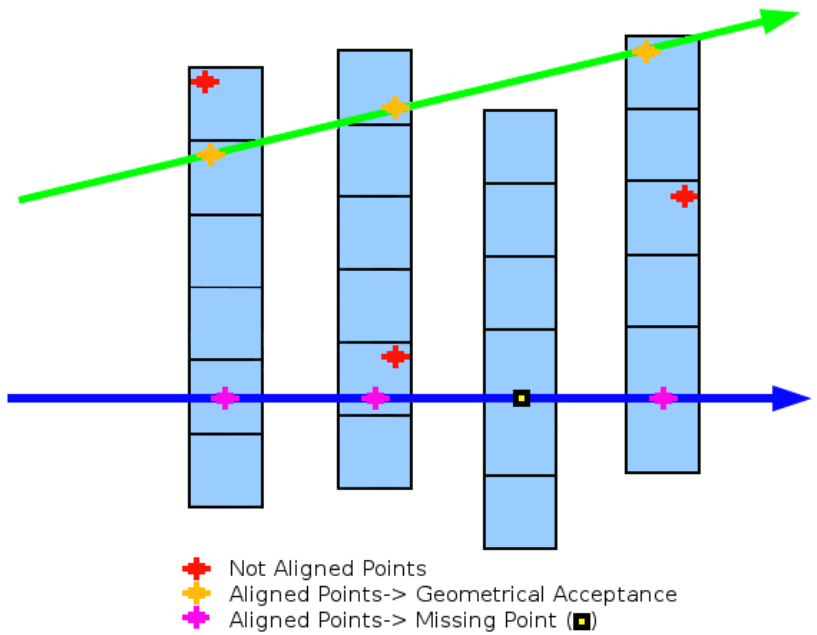




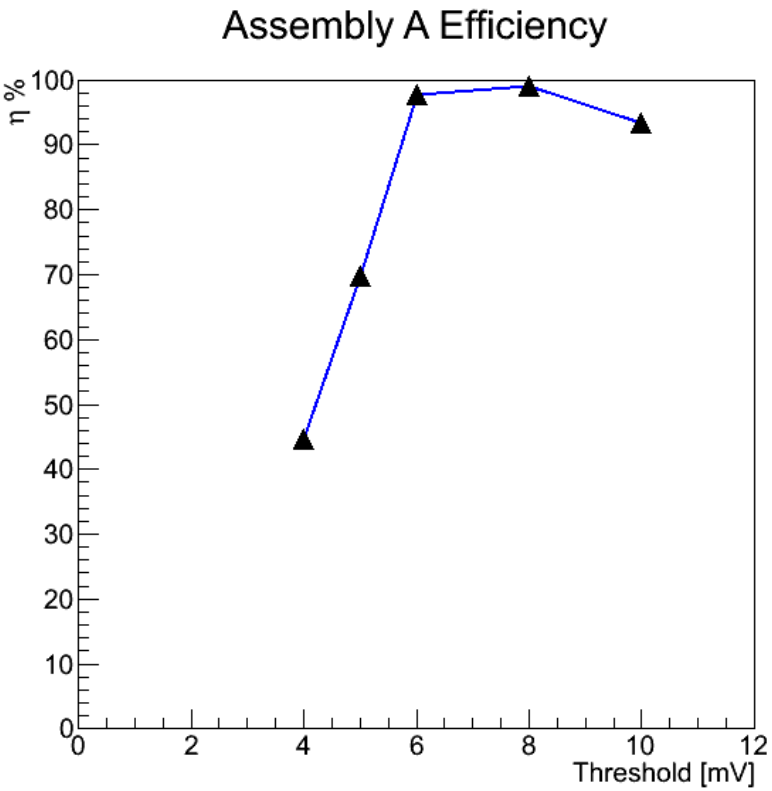
Cluster Size Study

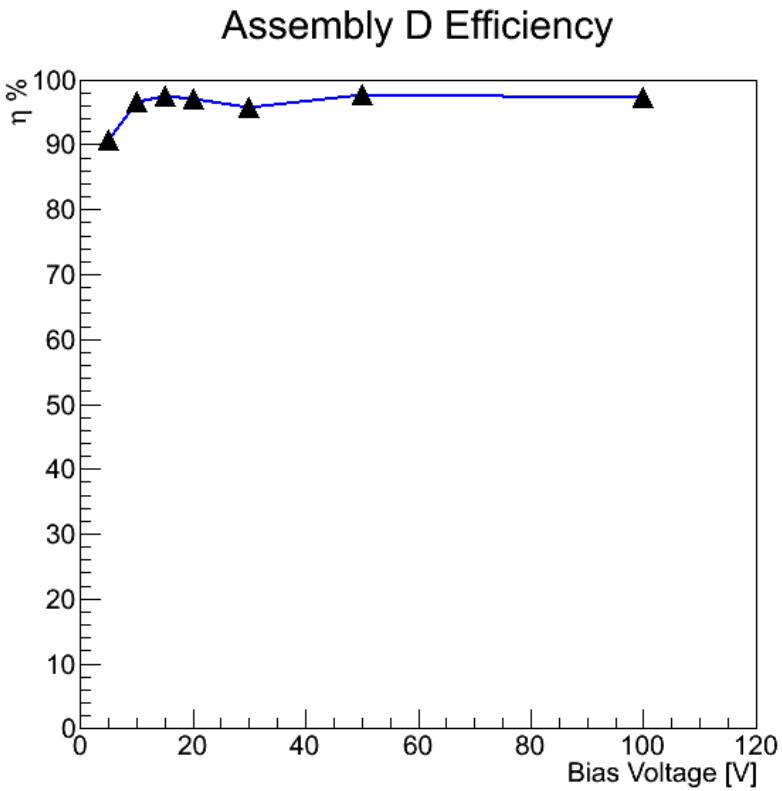


$$\epsilon = \frac{N_{det}}{N_{cross}} = \frac{N_4}{N_3}$$

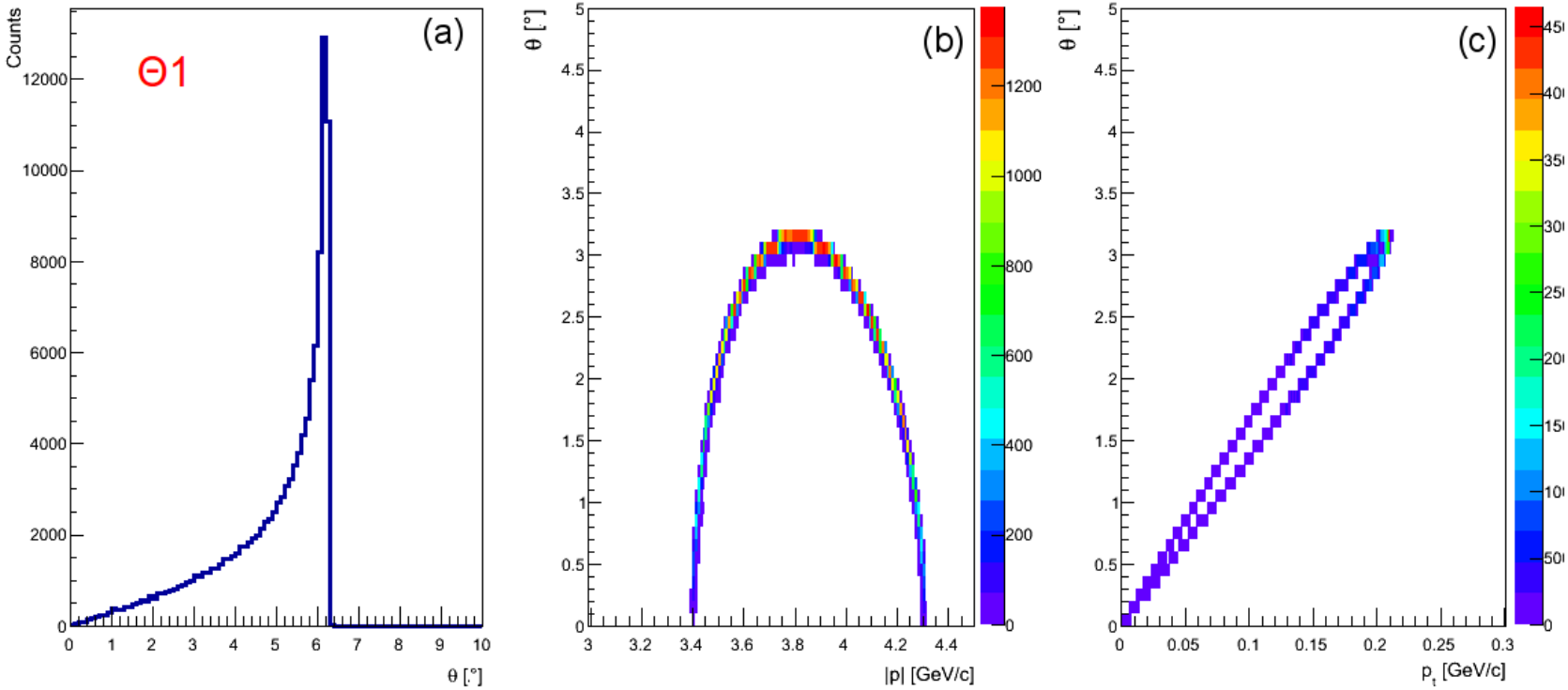


$$\rho = \frac{N\sum_{i=1}^{N} x_i \sum_{i=1}^{N} z_i - \sum_{i=1}^{N} z_i \sum_{i=1}^{N} z_i}{\sqrt{[N\sum_{i=1}^{N} x_i^2 - (\sum_{i=1}^{N} x_i)^2] \cdot [N\sum_{i=1}^{N} z_i^2 - (\sum_{i=1}^{N} z_i)^2]}} \quad (1)$$


Assembly A Efficiency
η %
100
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
Threshold [mV]

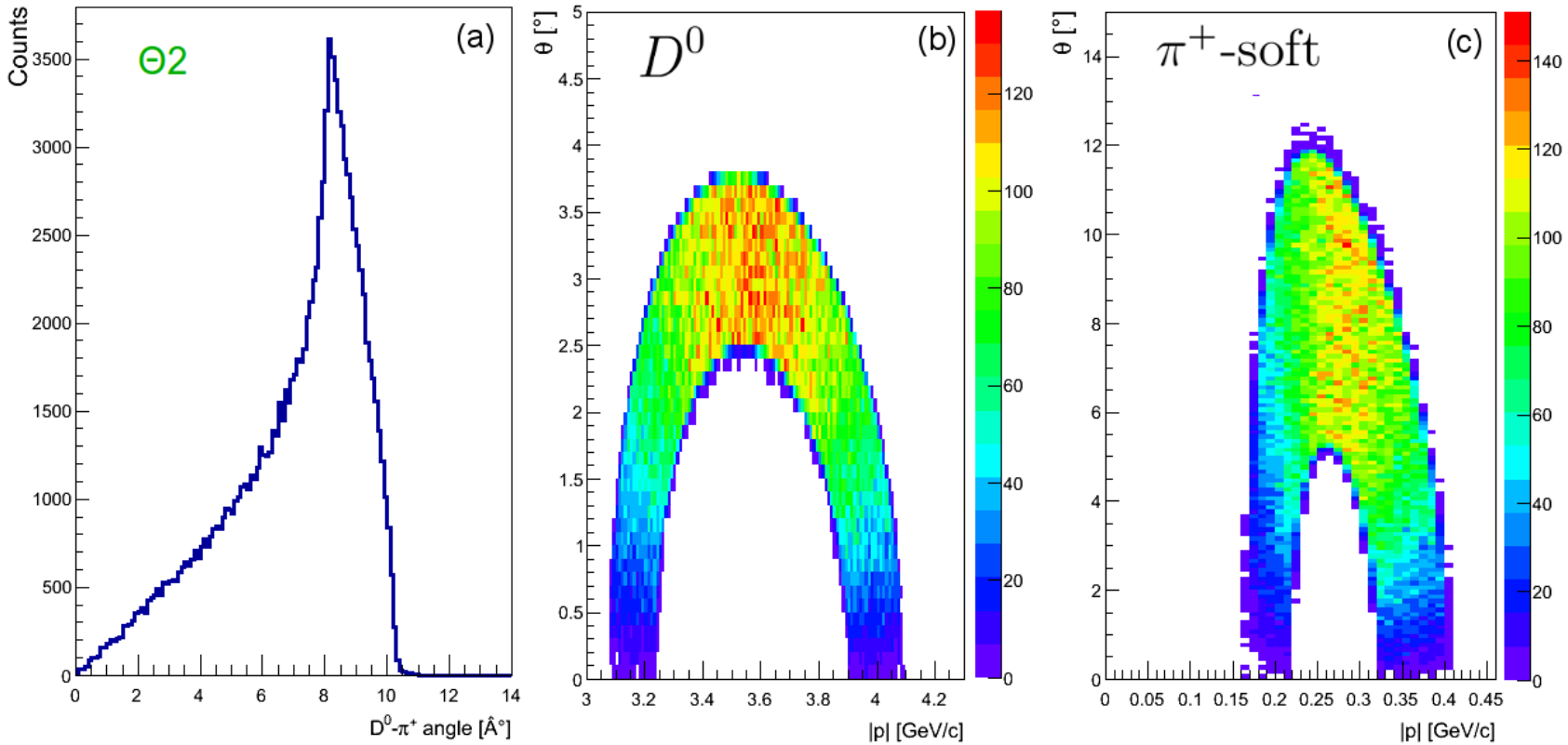

Assembly D Efficiency
η %
100
90
80
70
60
50
40
30
20
10
0
0
20
40
60
80
100
120
Bias Voltage [V]

Study of the momentum distributions



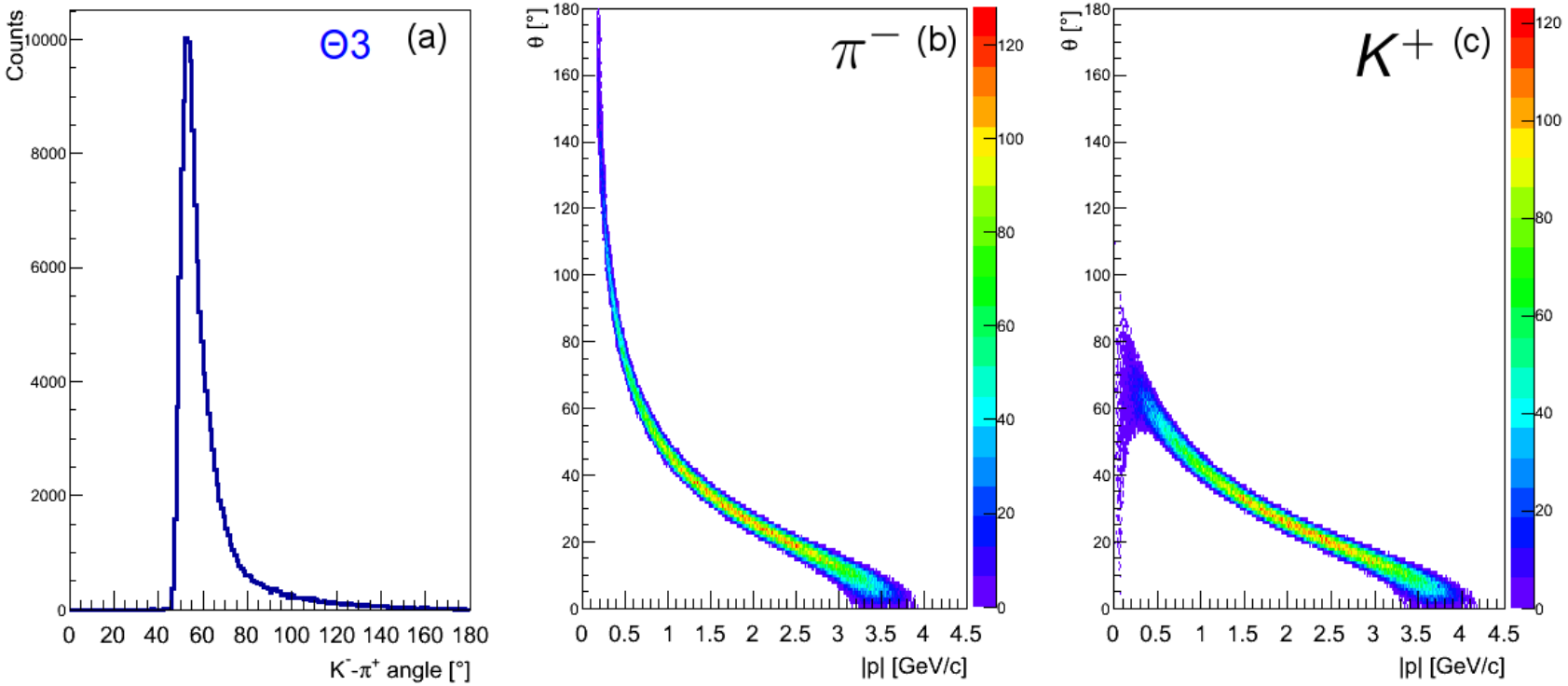
Study of the momentum distributions

Two-body decay of $D^{*+/-} \rightarrow$ the heavier D^0 carries most of the $D^{*+/-}$ boost.



Study of the momentum distributions

Two-body decay of D^0 -> $\theta_{max}(\pi)$ =180 $\theta_{max}(k)$ =90

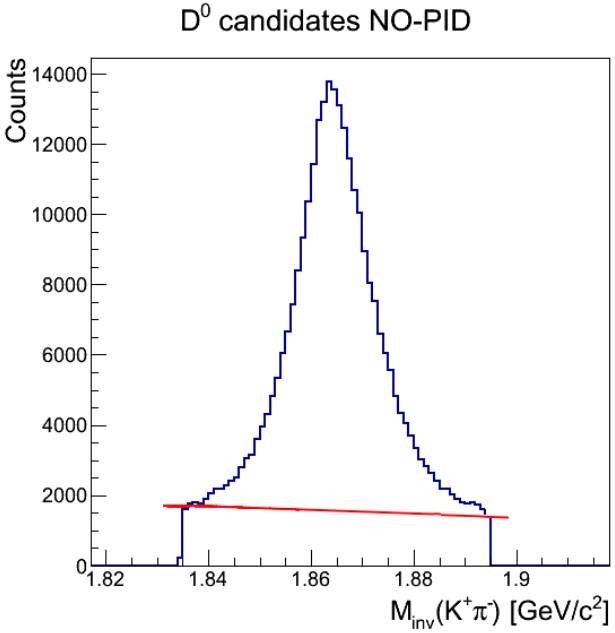


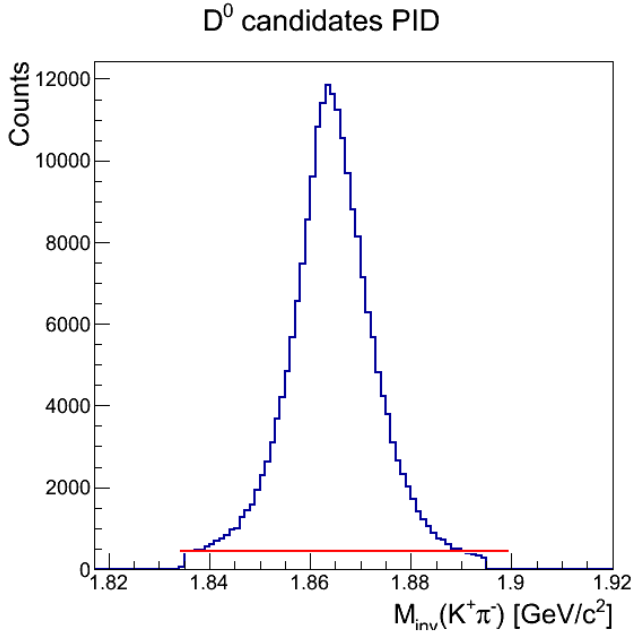
Charged Tracks

	Signal	2K4π	6π	7π	$\bar{p}p$
$K^{+/-}$	4.1%	8.5%	11.9%	7.2%	19.3%
$\pi^{+/-}$	2.8%	7.4%	10.7%	5.9%	17.9%
$\pi^{+/-}$-hard	28.8%	11.4%	22.9%	24.1%	28.0%
$\pi^{+/-}$-soft	80.1%	93.4%	94.4%	98.9%	97.9%

Efficiency of combinatorials and background rejection.

PID Considerations

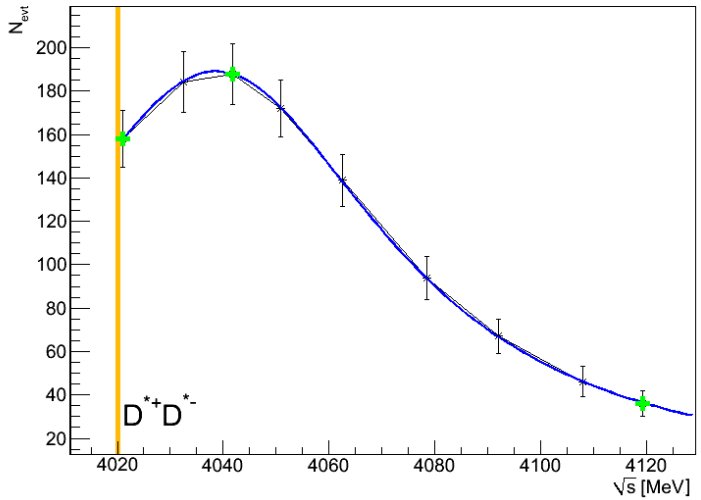




Candidates	Method	NO-PID	PID
D^0	4Prong	1.9	7.1
	6Prong	1.9	7.1
$\overline{D^0}$	4Prong	2.5	6.2
	6Prong	2.4	7.9

The $\psi(4040)$ Line Shape

$p_{\overline{p}}$ GeV/c	CM [MeV]	N_{evt}	$\delta N/N$ %
7.62	4021	158	8
7.67	4033	184	7
7.71	4042	188	7
7.75	4051	172	8
7.80	4062	139	8
7.87	4078	94	10
7.93	7092	67	12
8.00	7108	46	15
8.05	4119	36	17



- M = 4038.8 $\pm$ 2.4 MeV/c^2
- Γ=78.8 $\pm$ 21.1 MeV