

# Eksperyment ICARUS: neutrino i rozpad protonu

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seminarium Zakładów Cząstek, 23.04.2002

*W oparciu o następujące materiały:*

The ICARUS experiment, A Second-Generation Proton Decay Experiment and Neutrino Observatory at the Gran Sasso Laboratory, Initial Physics Program, LNGS-P28/2001, March 1, 2001

A Second-Generation Proton Decay Experiment and Neutrino Observatory at the Gran Sasso Laboratory, LNGS-EXP 13/89 add.2/01, November 26, 2001

C.Rubbia: Liquid Argon Imaging: A Novel Detection Technology, Particle Physics Seminar, CERN, February 26, 2002

<http://pcnometh4.cern.ch>, <http://www.lngs.infn.it>

# Współpraca ICARUS

F. Amadio, B. Babussinov, B. Badelek, A. Badertscher, M. Baldo-Ceolin, G. Battistoni, B. Bekman, P. Benetti, E. Bernardini, A. Bortolotto, M. Bischofberger, R. Brunetti, A. Bruno, E. Calligarich, D. Cavalli, F. Cavanna, P. Cennini, S. Centro, A. Cesana, C. Chen, Y. Chen, D. Cline, P. Crivelli, A. Dabrowska, M. Daszkiewicz, C. De Vecchi, R. Dell'Antoni, M. Felcini, A. Ferrari, F. Feri, A. Gigli Berzolari, I. Gil-Botella, K. Graczyk, L. Grandi, K. He, J. Holeczek, X. Huang, C. Juszczyk, D. Kielczewska, J. Kisiel, L. Knecht, T. Kozłowski, H. Kuna-Cisnal, M. Laffranchi, J. Lagoda, Z. Li, B. Lisowski, F. Lu, J. Ma, M. Marikiewicz, F. Mauri, G. Matthey, G. Meng, C. Montanari, S. Muraro, G. Natterer, B. Navas-Concha, G. Nurzia, B. Obwinowski, O. Palamara, D. Pascoli, L. Periale, G. Piano Mortari, A. Piazzoli, P. Picochi, F. Pietropaolo, W. Polchlopek, T. Rancati, A. Rappoldi, G.L. Raselli, J. Rico, E. Rondio, M. Rossella, A. Rubbia, C. Rubbia, P. Sala, D. Scannicchio, E. Segreto, Y. Seo, F. Bergiamperi, J. Sobczyk, J. Stepaniak, M. Stodulski, M. Szarska, M. Szepczyka, M. Terrani, S. Ventura, C. Vignoli, H. Wang, M. Wojcik, G. Xu, X. Yang, A. Zalawska, J. Zalipska, C. Zhang, Q. Zhang, S. Zhen, W. Zipper.

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Wroclaw University, Wroclaw - Poland

*This is an "open" collaboration: new teams welcome!*

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# Plan referatu

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Detektor:

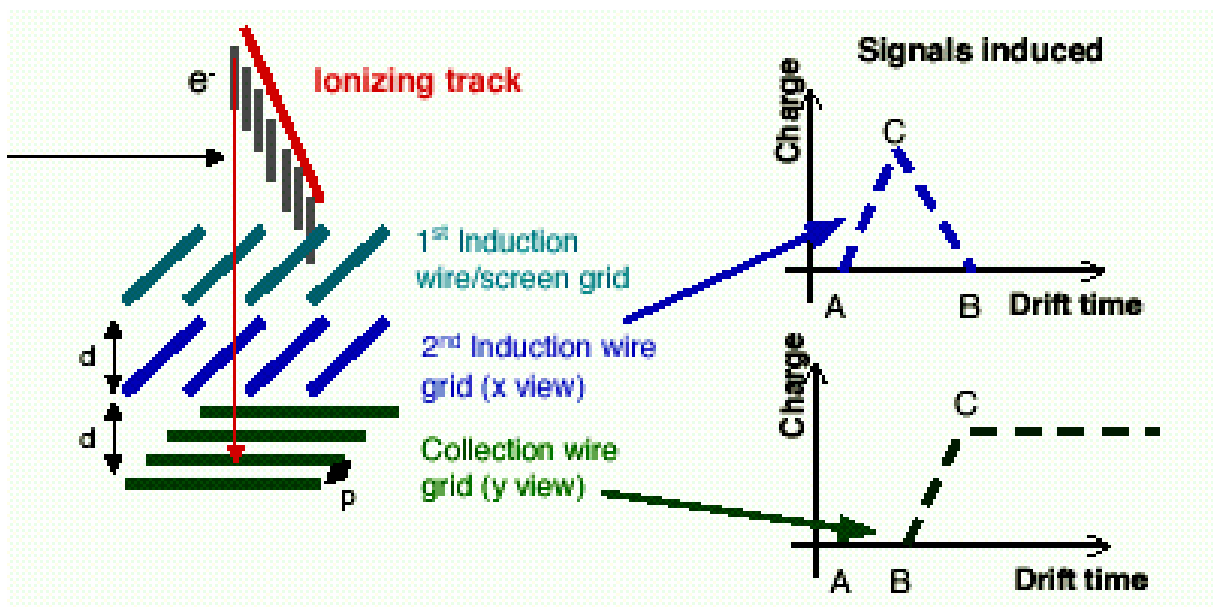
- zasada działania
- stan obecny i przyszła rozbudowa
- analiza danych z testów naziemnych

Fizyka:

- neutrina atmosferyczne i słoneczne
- neutrina z wiązki CNGS
- poszukiwania rozpadu protonu
- „Icarusiątko” w KEK-u?

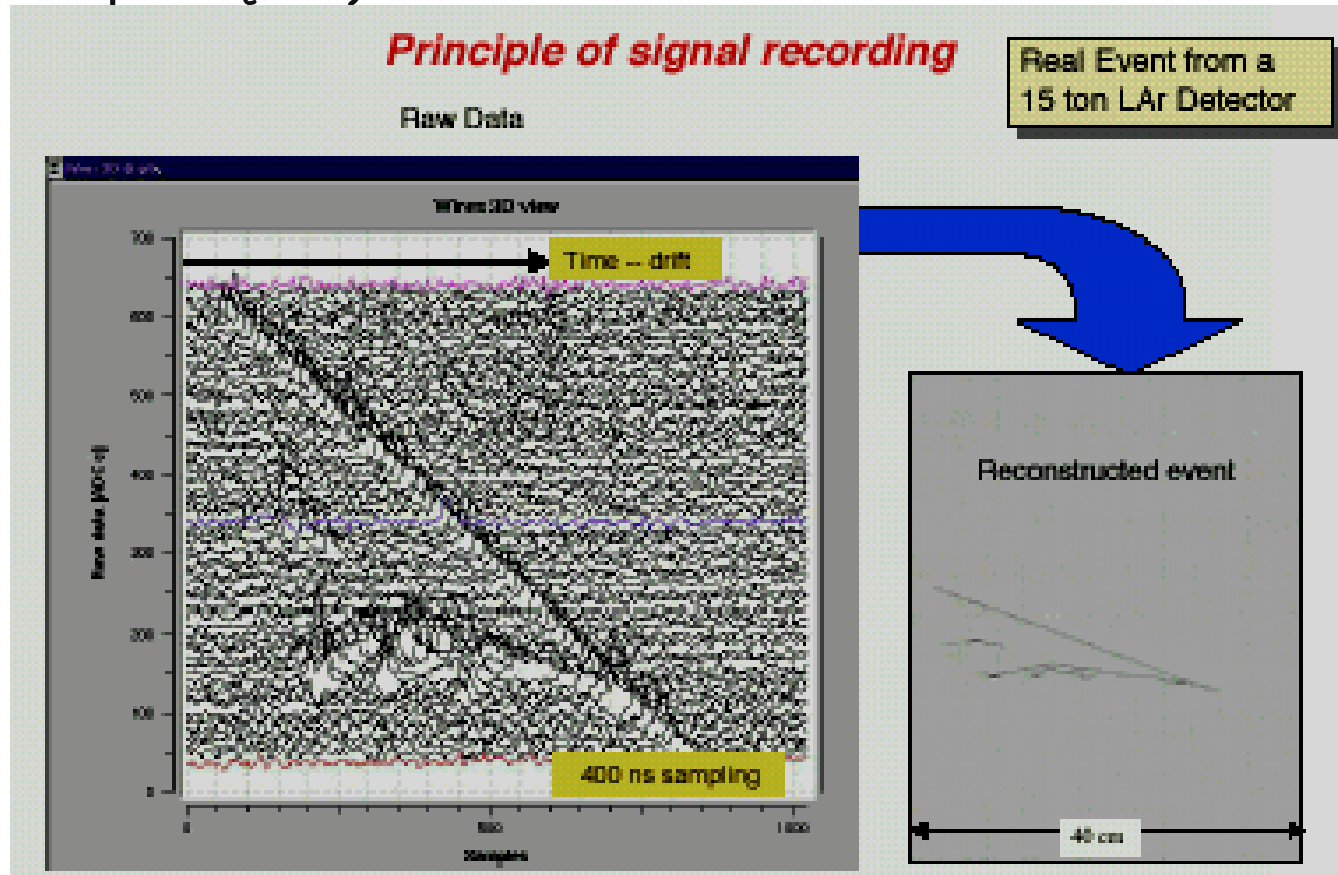
# Detektor - wielkie komory TPC wypełnione ciekłym argonem (300t/komorę)

- Wykorzystywane zjawisko jonizacji w ciekłym argonie przy przejściu cząstek naładowanych (5500 par e-jon/mm),
- Pod wpływem pola elektrycznego (typowo 500 V/cm) elektrony jonizacji dryfują do drutów anodowych



# Elektroniczne obrazowanie

Trójwymiarowy obraz torów i oddziaływań w oparciu o pomiar sygnałów na drutach (dwie współrzędne) i o pomiar czasu dryfu (trzecia współrzędna)



# „Elektroniczna komora pęcherzykowa”

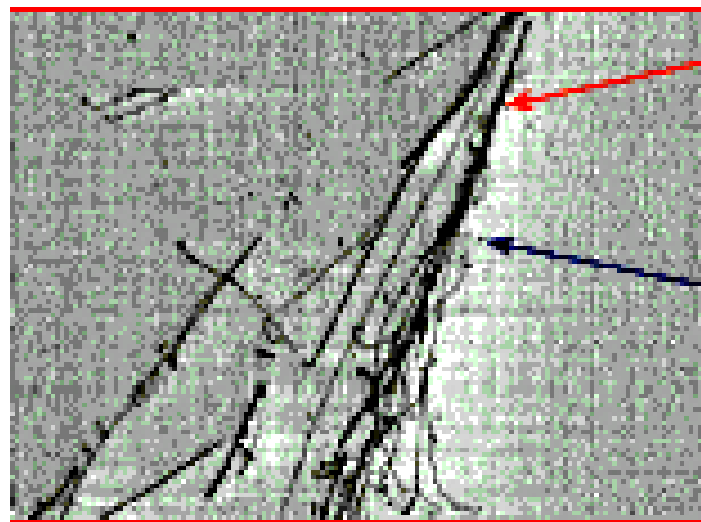
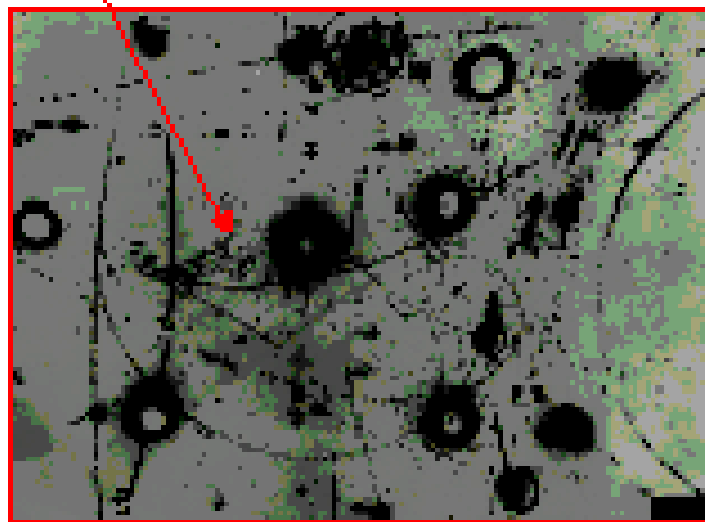
Thirty years later.....

LAr is a cheap liquid ( $\approx 1$  CHF/litre), vastly produced by industry

Bubble diameter  $\approx 3$  mm  
(diffraction limited)

Gargamelle bubble chamber

ICARUS electronic chamber



"Bubble" size  
 $\approx 3 \times 0.5 \times 0.2 \text{ mm}^3$

Energy depositor  
measured for each  
point

Medium	Heavy freon
Sensitive mass	3.0 ton
Density	1.5 g/cm <sup>3</sup>
Radiation length	11.0 cm
Collision length	48.5 cm
dE/dx	2.3 MeV/cm

Medium	Liquid Argon
Sensitive mass	Many kilons
Density	1.4 g/cm <sup>3</sup>
Radiation length	14.0 cm
Collision length	54.8 cm
dE/dx	2.1 MeV/cm

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# ICARUS - stan obecny

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- ◆ 2 komory TPC po 300 ton ciekłego argonu każda,
- ◆ pierwsza komora gotowa i w pełni przetestowana w 2001 roku w Pawii, m.in. dwa miesiące zbierania danych dla promieni kosmicznych
- ◆ montaż drugiej komory aktualnie na ukończeniu,
- ◆ instalacja obu komór w Gran Sasso na przełomie 2002/2003,
- ◆ do 2006 roku badania neutrin atmosferycznych, słonecznych i poszukiwania rozpadów protonu.

# ICARUS - obecny detektor

Under construction

Number of independent containers = 2

Single container Internal Dimensions: Length = 19.6 m , Width = 3.9 m , Height = 4.2 m

Total (cold) Internal Volume = 534 m<sup>3</sup>

Sensitive LAr mass = 476 ton

Number of wires chambers = 4

Readout planes / chamber = 3 at 0° , ± 60° from horizontal

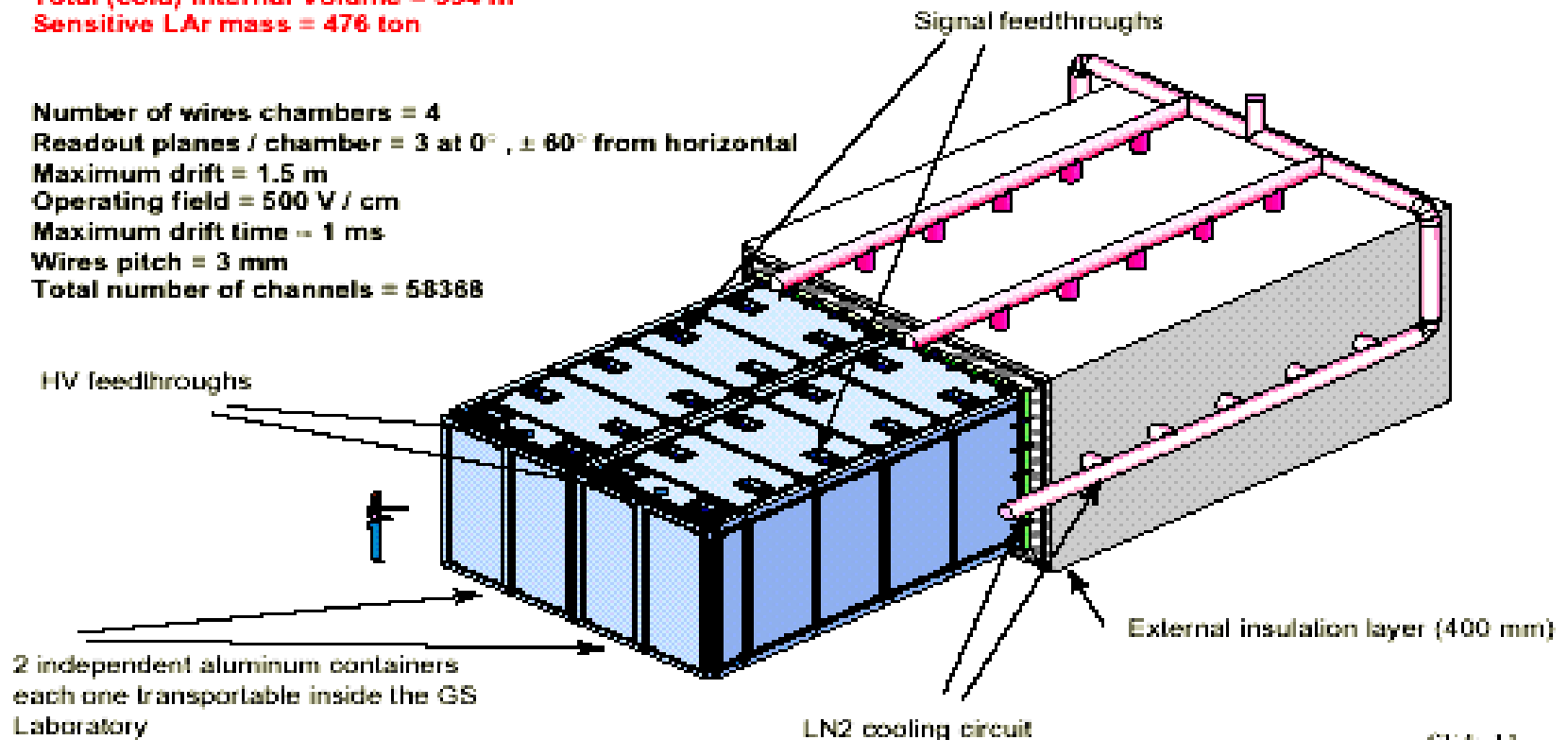
Maximum drift = 1.5 m

Operating field = 500 V / cm

Maximum drift time = 1 ms

Wires pitch = 3 mm

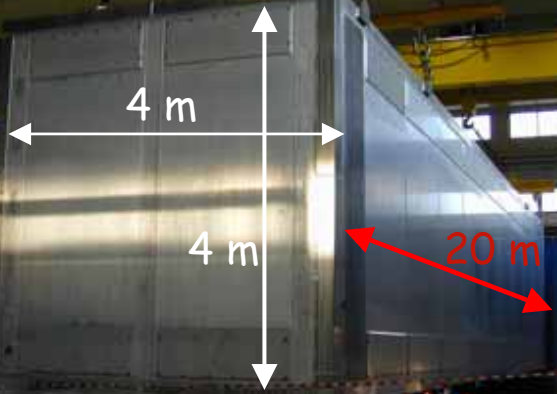
Total number of channels = 58368



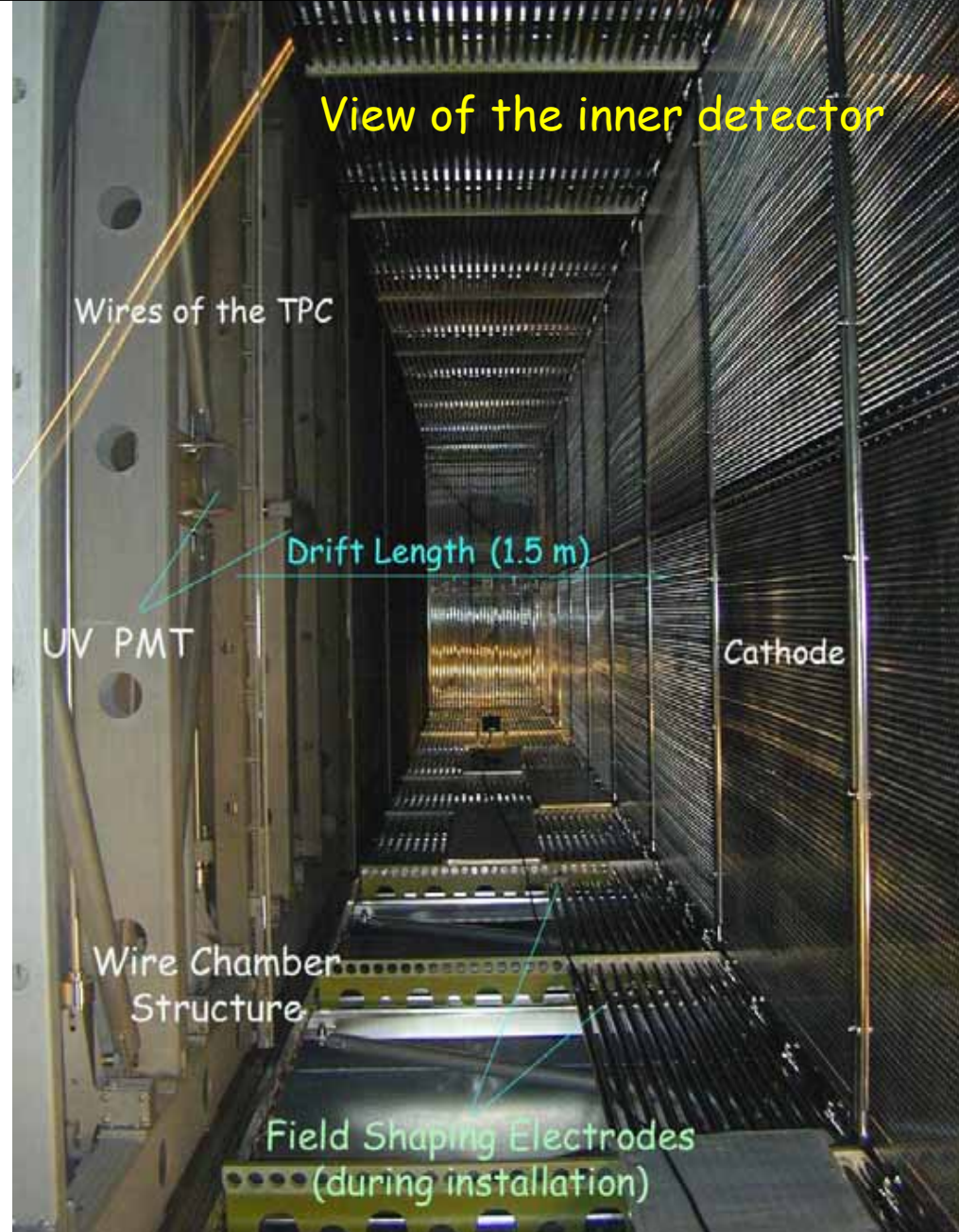


# Obecny detektor w fazie konstrukcji

## LAr Cryostat (half-module)



## View of the inner detector



## Electronic Racks

## Signal Flanges and feed-throughs



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# Naziemne testy w Pawii w 2001 roku

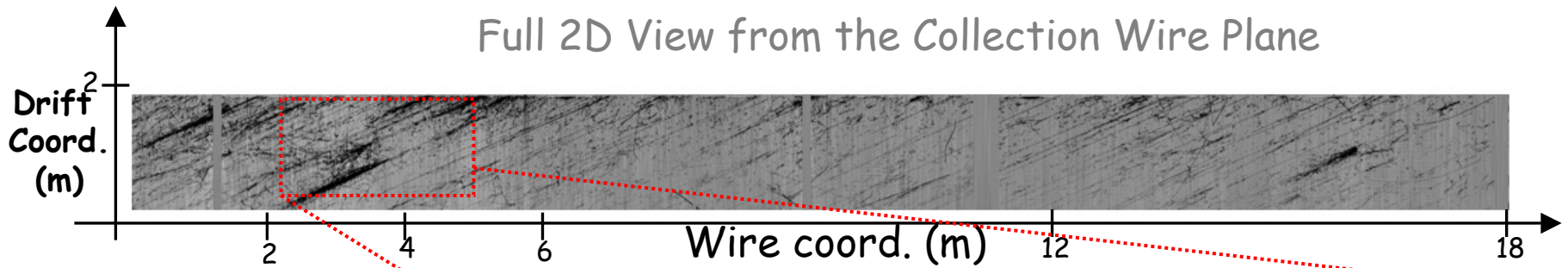
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W pełni udane testy pierwszej docelowej komory TPC eksperymentu ICARUS - kwiecień-lipiec 2001

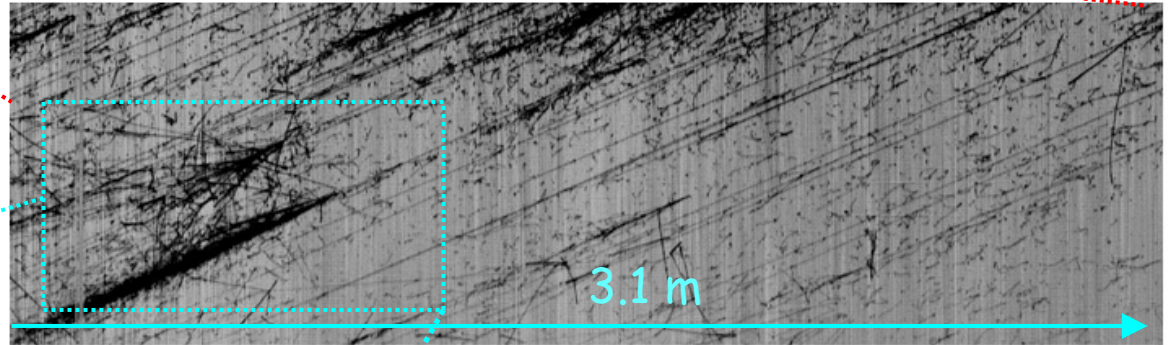
- ◆ test konstrukcji mechanicznej i kriogeniki
- ◆ test komory i jej wyposażenia: fotopowielaczy, monitorów czystości argonu, mierników poziomu itp..
- ◆ test elektroniki odczytu i systemu zbierania danych (kompletny przypadek ma objętość 200 Mbytes)
- ◆ zebranych zostało 28000 przypadków dla różnych konfiguracji trygera zewnętrznego (w oparciu o scyntylatory) i trygera wewnętrznego (w oparciu o fotopowielacze)



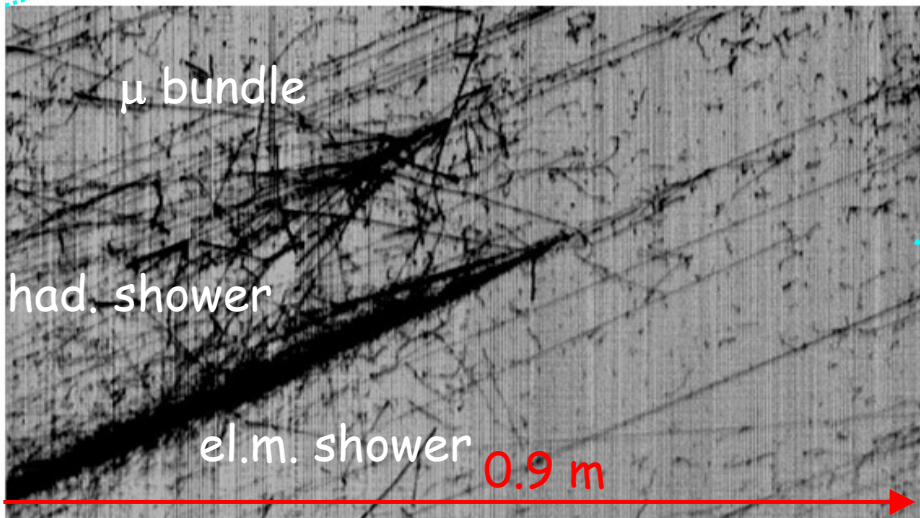
# Full 2D View from the Collection Wire Plane



Zoom View

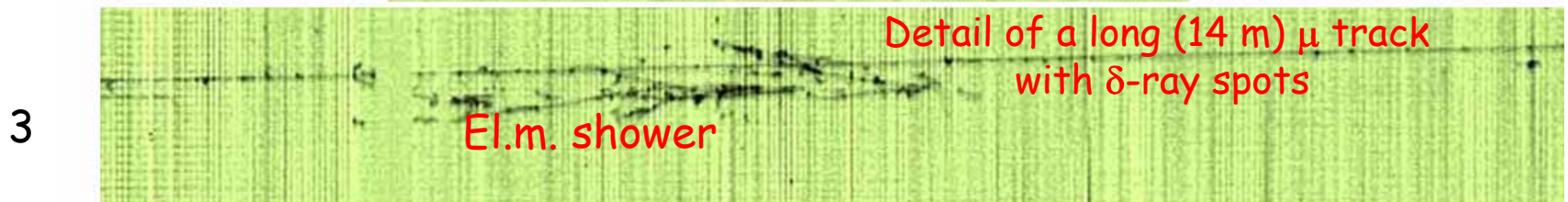
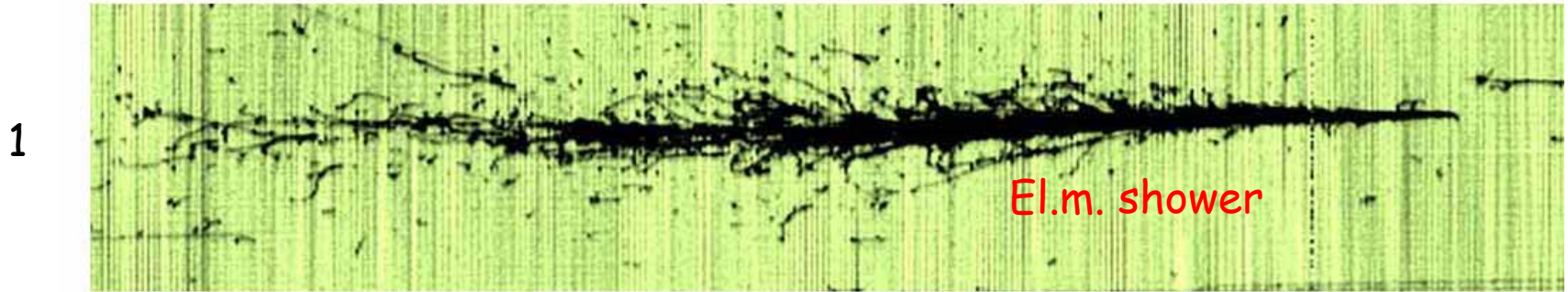
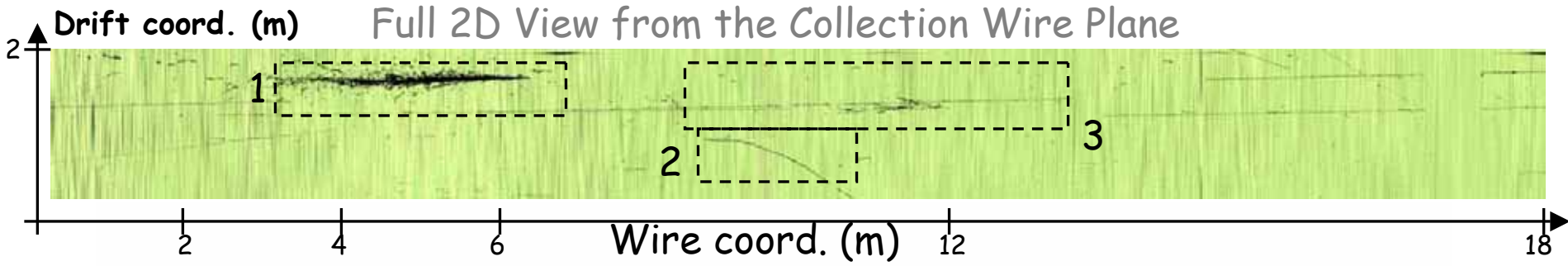


Zoom View



Przypadek pęku kosmicznego  
tworzonego przez setki śladów  
( $\mu$  i  $\pi$ ) i konwertujące  
niskoenergetyczne  $\gamma$ .  
Pokazane też są kaskady:  
hadronowa i elektromagnetyczna

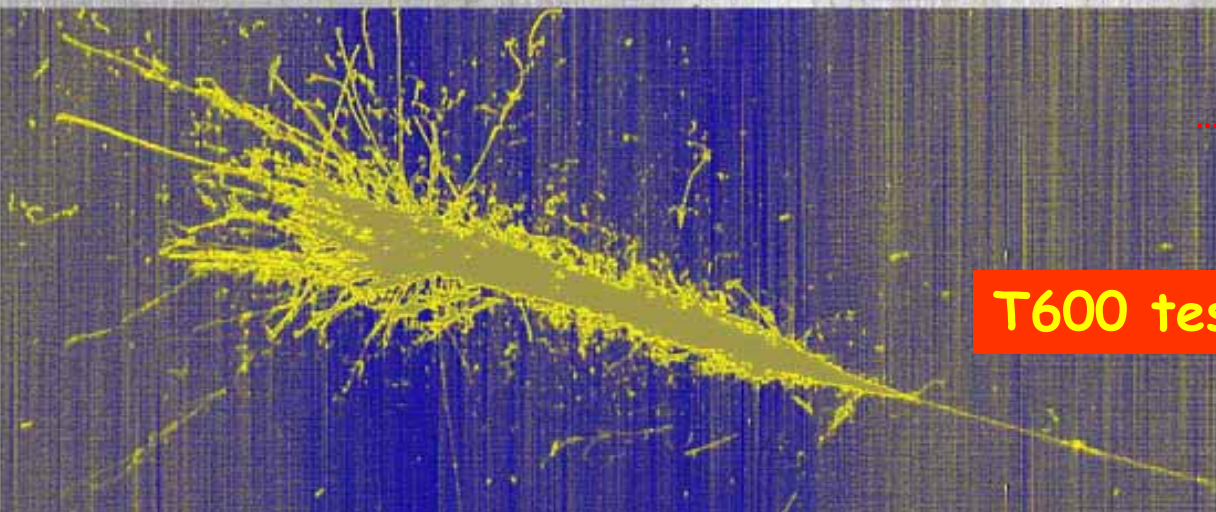
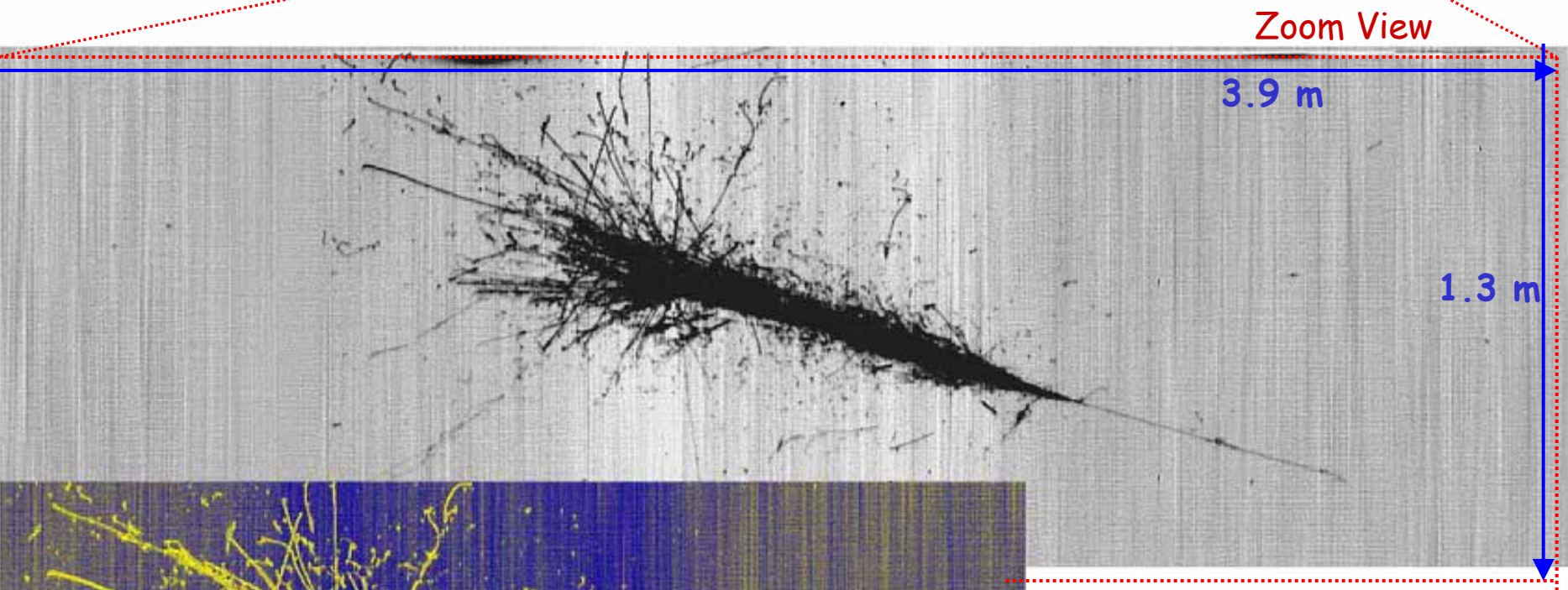
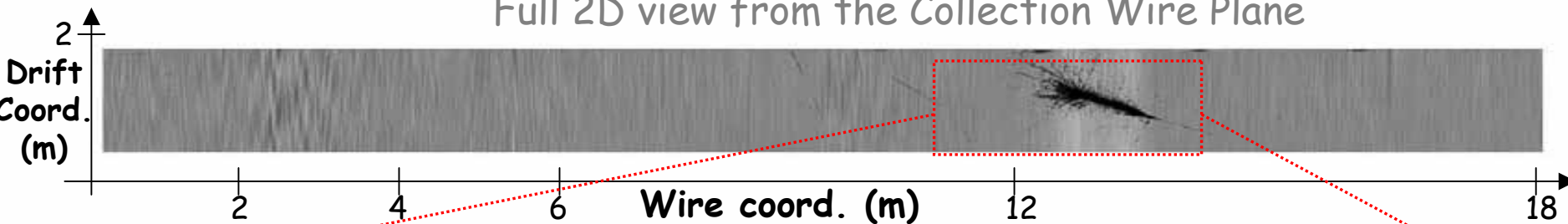
T600 test @ Pv: Run 308 - Evt 4 (July 2nd, 2001)



T600 test @ Pv: Run 201 - Evt 12



# Full 2D view from the Collection Wire Plane

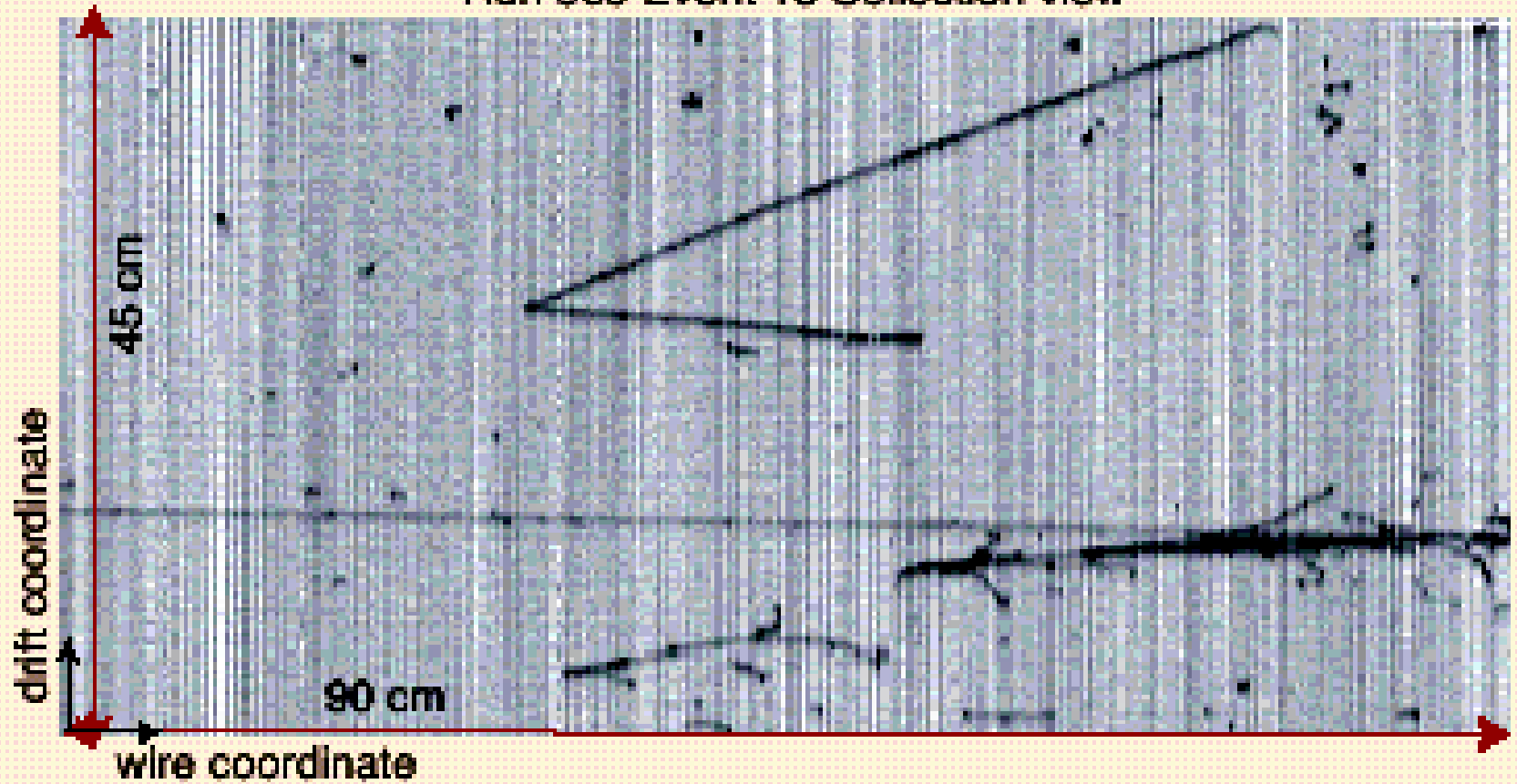


T600 test @ Pv: Run 308 - Evt 7

Large el.m. shower

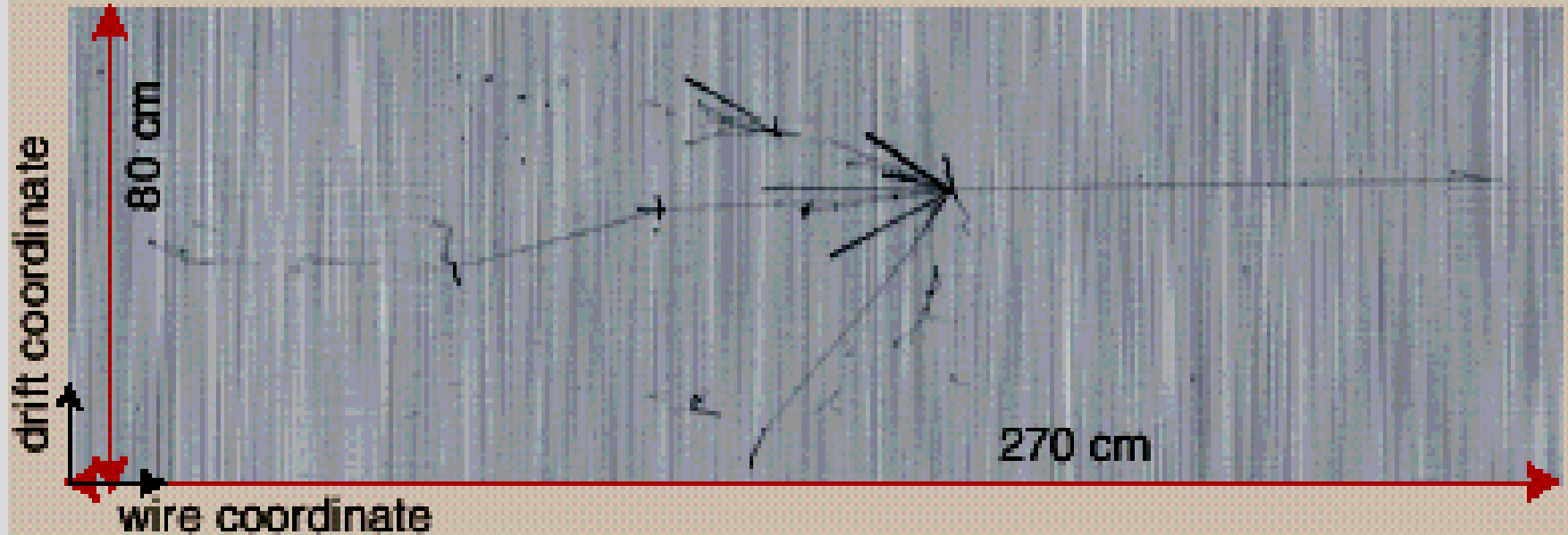
# Kandydat na $V^0$

Run 969 Event 18 Collection view

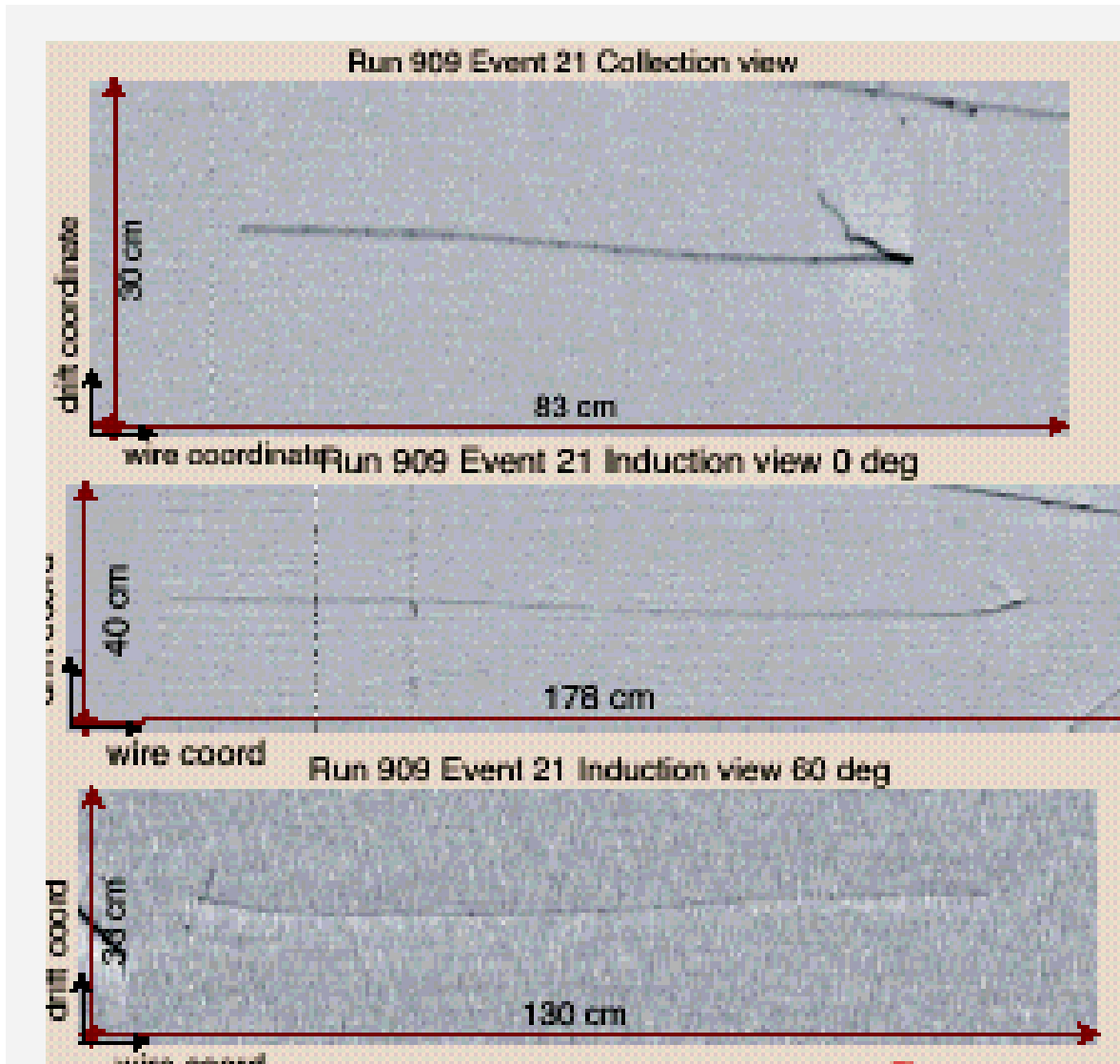


# Oddziaływanie hadronowe

Run 308 Event 160 Collection view



# Rozpad - widok w trzech projekcjach



← „Collection”

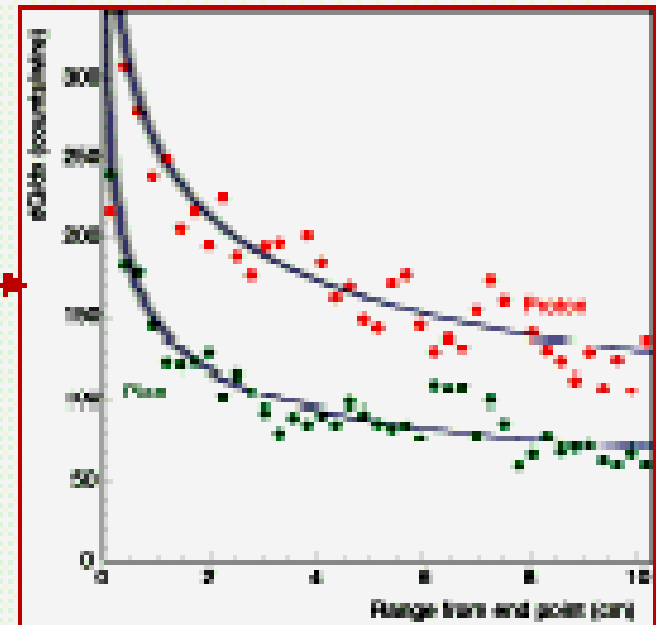
← „Induction 1”

← „Induction 2”



# Możliwości detektora

- Measurement of local energy deposition:
  - ↳ Electron / gamma separation (3mm)
  - ↳ Particle ID by means of  $dE/dx$  vs range measurement
- Total energy reconstruction of the events from charge integration → excellent calorimeter with high accuracy for contained events

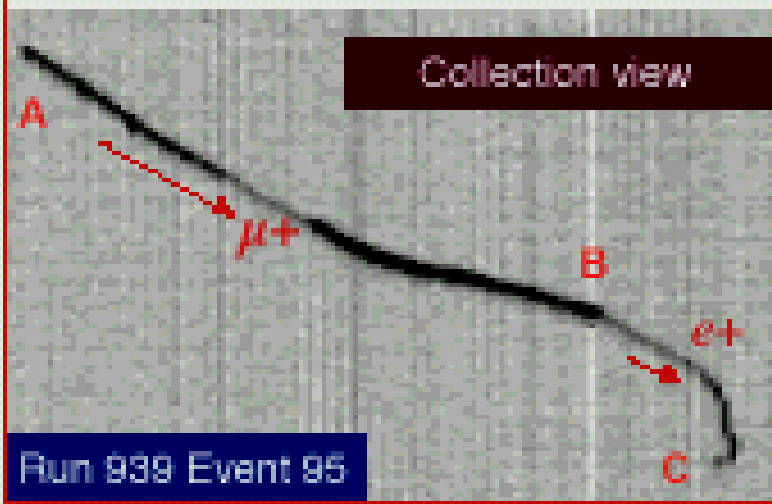
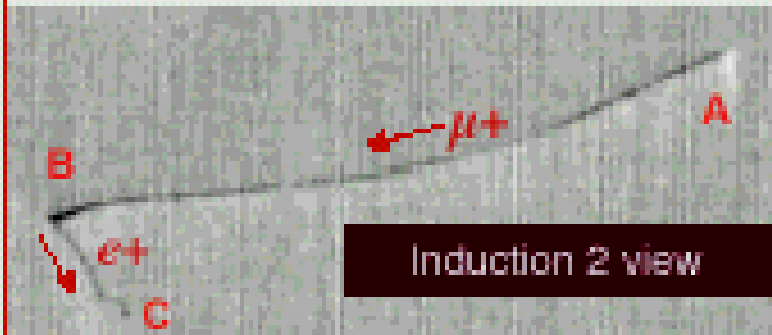


## RESOLUTIONS

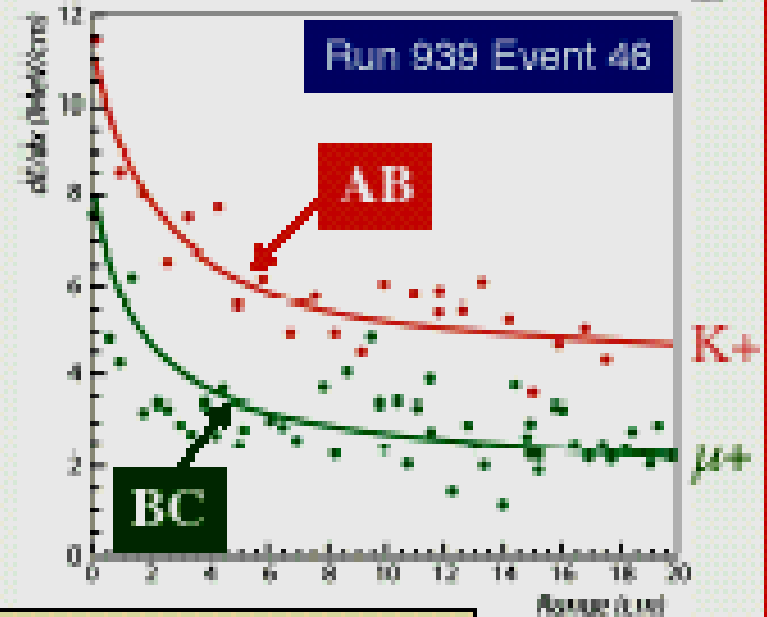
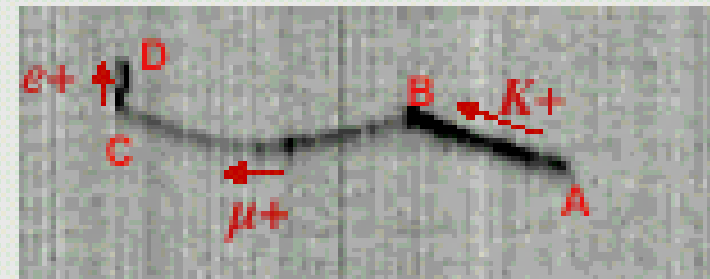
Low energy electrons:	$\sigma(E)/E = 7\% / \sqrt{E(\text{MeV})}$
Electromagn. showers:	$\sigma(E)/E = 3\% / \sqrt{E(\text{GeV})}$
Hadronic showers (pure LAr):	$\sigma(E)/E = 16\% / \sqrt{E(\text{GeV})} + 1\%$
Hadronic showers (+TMG):	$\sigma(E)/E = 12\% / \sqrt{E(\text{GeV})} + 0.2\%$

# Możliwości detektora

$$\mu^+[AB] \rightarrow e^+[BC]$$

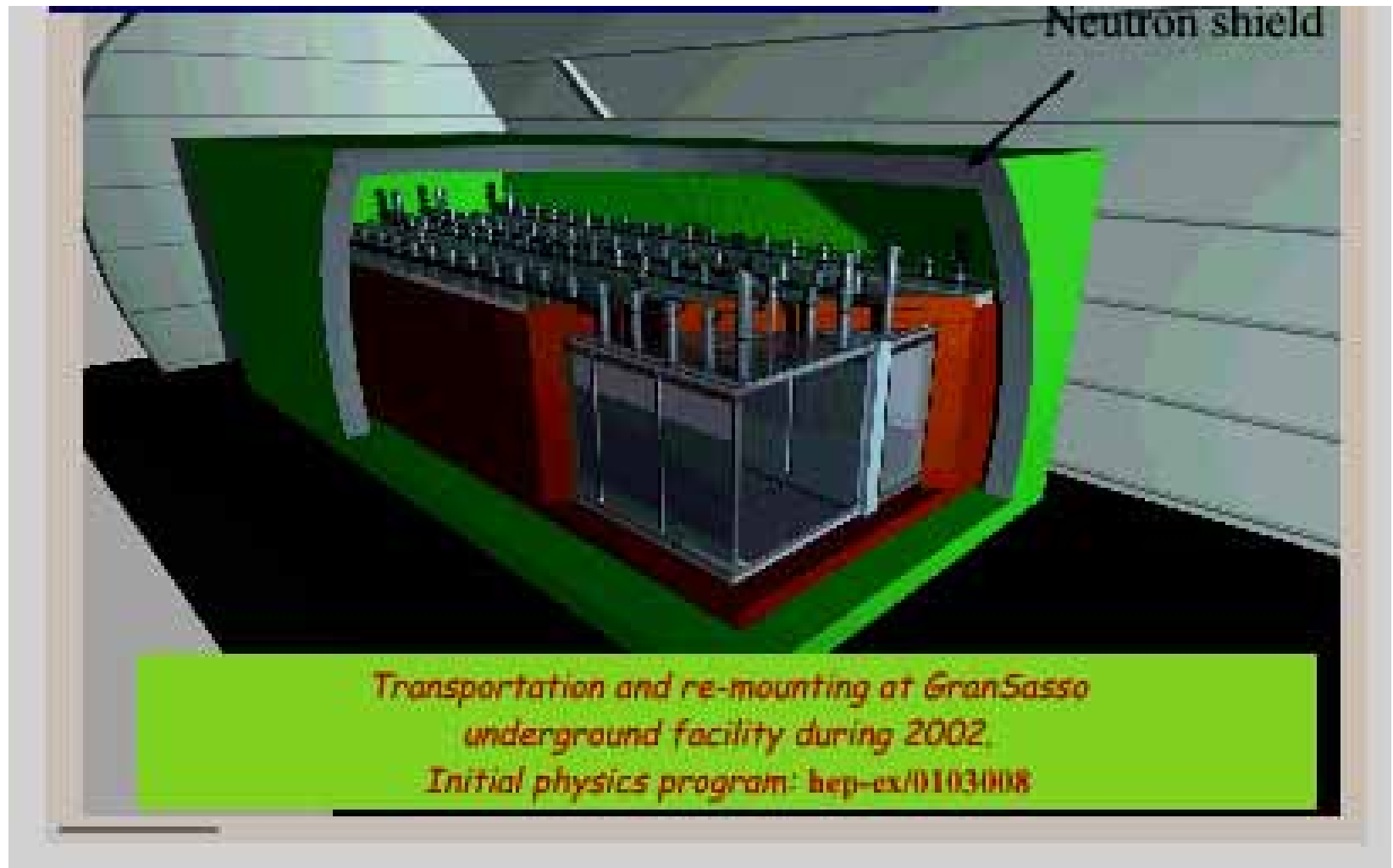


$$K^+[AB] \rightarrow \mu^+[BC] \rightarrow e^+[CD]$$



Particle identification by characteristic decay ( $\mu^+, \mu^-$ )

# Obecny detektor - instalacja w G.S.



# Rozbudowa detektora do 3 kton



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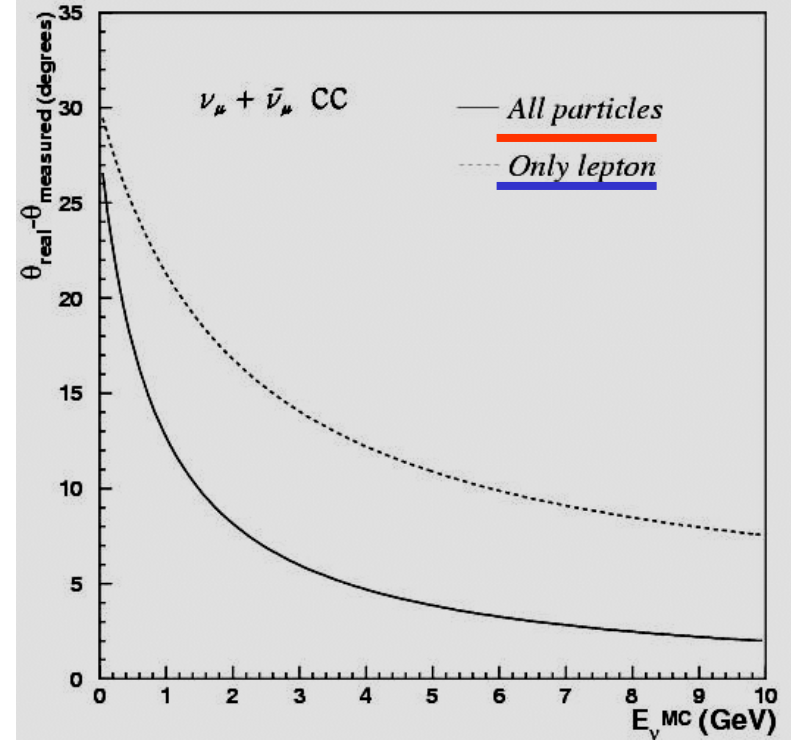
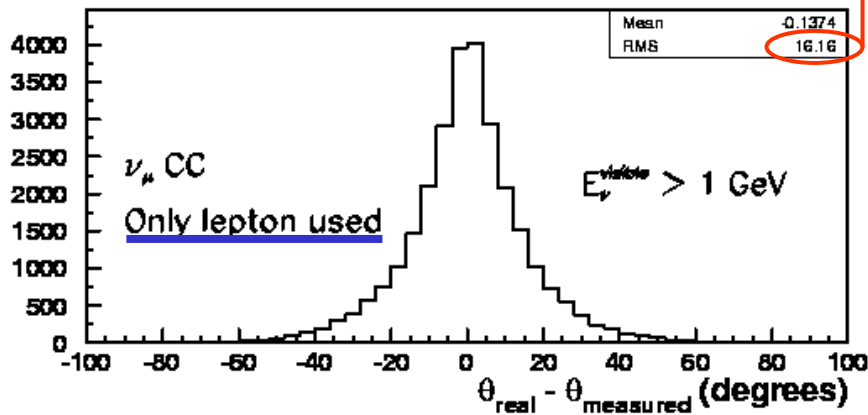
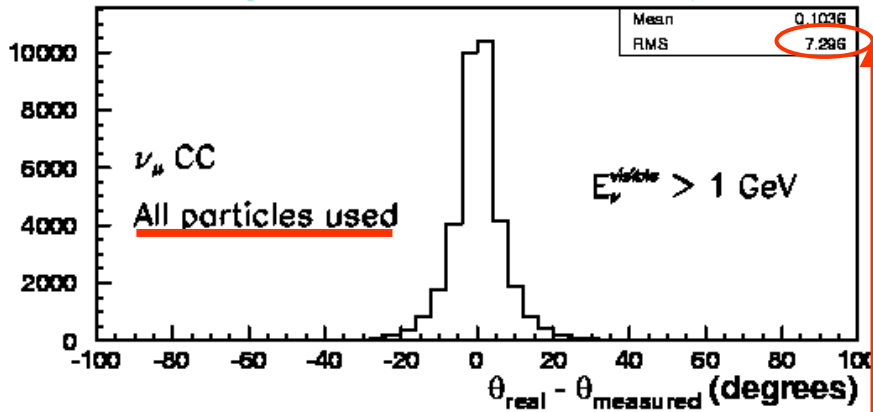
# Fizyka neutrin atmosferycznych

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- ◆ Możliwość badania oddziaływań neutrin mionowych i elektronowych (typu CC i NC) praktycznie aż do progu kinematycznego (prawie 50% neutrin atmosferycznych ma energię poniżej 400 MeV - próg w SuperK)
- ◆ Możliwy pomiar protonu odrzutu (w 60% przypadków) oraz analiza i rekonstrukcja skomplikowanych wielocząstkowych stanów końcowych
- ◆ Lepsza rekonstrukcja kierunku i energii neutrina (w oparciu o wszystkie cząstki w stanie końcowym, a nie tylko lepton)

## Zenith angle resolution as a function of the incoming neutrino energy

### Difference between real and reconstructed neutrino angle for events with $E_\nu > 1$ GeV



- $E_\nu < 500$  MeV: the resolution is dominated by the smearing introduced by the Fermi motion of the initial state nucleon and re-interaction of hadrons inside the nucleus
- $E_\nu > 500$  MeV: the improvement in resolution when all particles are detected is significant

## Difference in the rates of upward and downward going atm. neutrino events for a 2 Kton year exposure

	2 kton×year				
	No osci	$\Delta m_{23}^2$ (eV <sup>2</sup> )			
		$5 \times 10^{-4}$	$1 \times 10^{-3}$	$3.5 \times 10^{-3}$	$5 \times 10^{-3}$
<b>Muon-like</b>	$270 \pm 16$	$206 \pm 14$	$198 \pm 14$	$188 \pm 14$	$182 \pm 13$
Downward	$102 \pm 10$	$102 \pm 10$	$102 \pm 10$	$98 \pm 10$	$95 \pm 10$
Upward	$94 \pm 10$	$46 \pm 7$	$46 \pm 7$	$47 \pm 7$	$49 \pm 7$
<b>Electron-like</b>	$152 \pm 12$	$152 \pm 12$	$152 \pm 12$	$152 \pm 12$	$152 \pm 12$
Downward	$56 \pm 7$	$56 \pm 7$	$56 \pm 7$	$56 \pm 7$	$56 \pm 7$
Upward	$48 \pm 7$	$48 \pm 7$	$48 \pm 7$	$48 \pm 7$	$48 \pm 7$

Table 1: Predicted downward ( $\cos \theta_{zenith} > 0.2$ ) and upward ( $\cos \theta_{zenith} < -0.2$ ) atmospheric neutrino rates in case no oscillations occur and assuming  $\nu_\mu \rightarrow \nu_\tau$  oscillations take place with maximal mixing. Four different  $\Delta m^2$  values have been considered. Only statistical errors are quoted. As a reference, we also show the total expected rates for both muon and electron-like events.

Quite evident deficit of upward going “muon like” events, for the range of osc. parameters allowed by SK measurements

# Atmospheric $\nu$ events

(simulated  $\nu_\mu$  event)

90 cm

$p$   $\mu$   $e$

90 cm

$E_\nu = 370 \text{ MeV}$

$P_\mu = 250 \text{ MeV}$

$T_p = 90 \text{ MeV}$

(simulated  $\nu_e$  event)

90 cm

$p$   $e$

100 cm

$E_\nu = 450 \text{ MeV}$

$P_e = 200 \text{ MeV}$

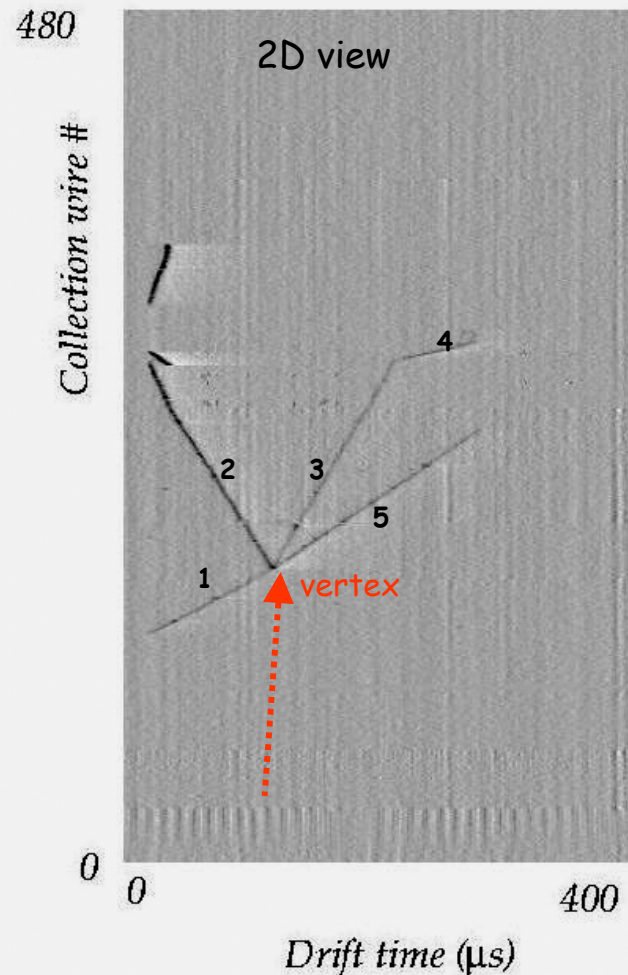
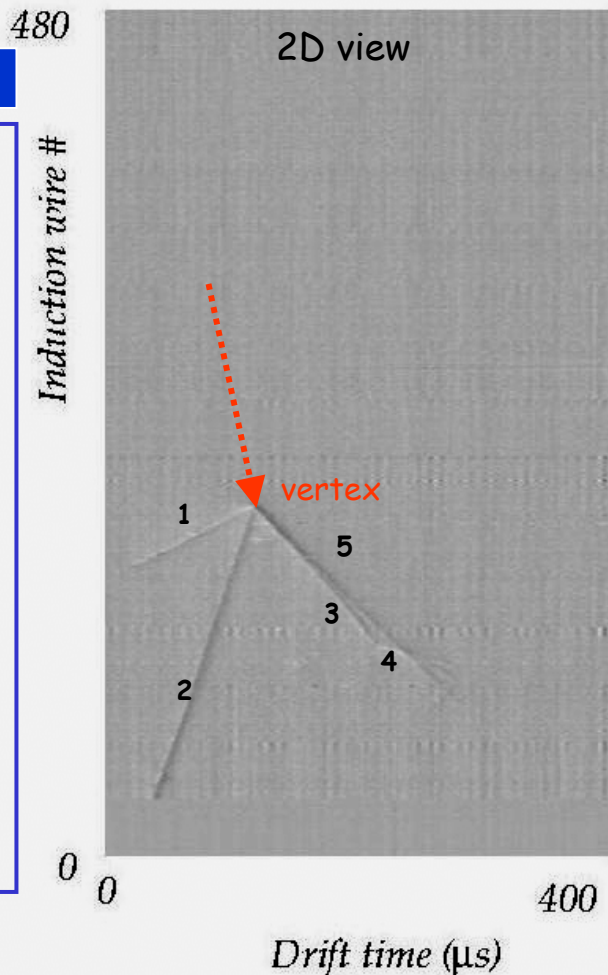
$T_p = 240 \text{ MeV}$



# Cosmic ray event containing a hadronic interaction vertex providing an "Atmospheric neutrino"-like topology

## Preliminary analysis

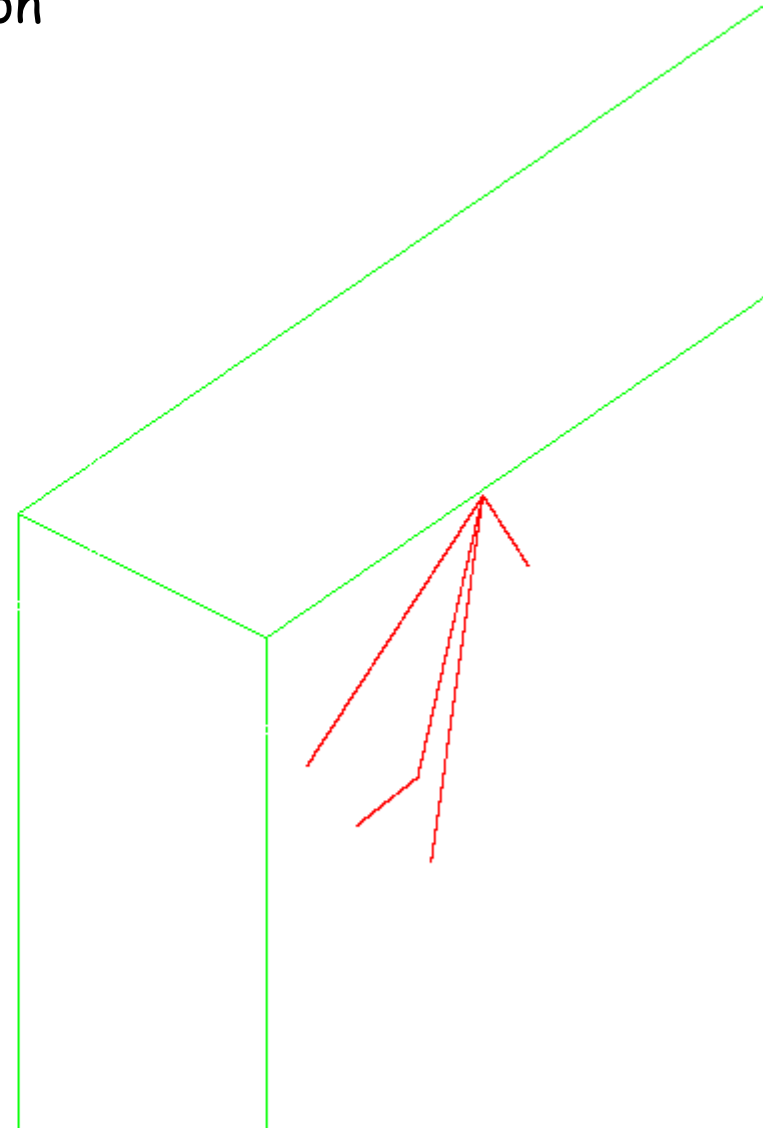
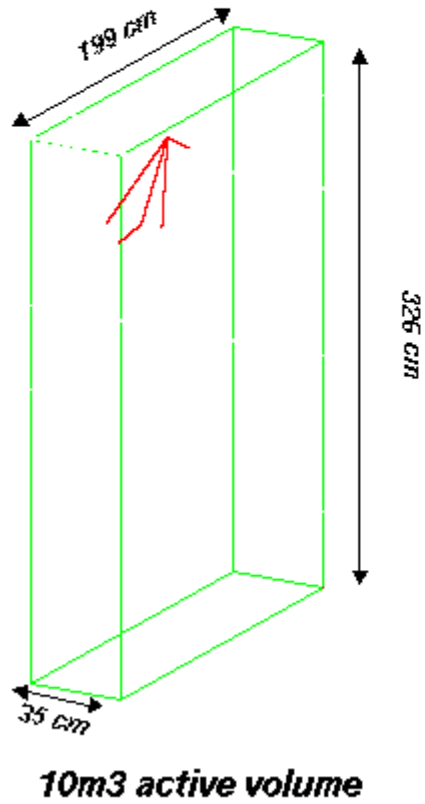
- Trk. 1 - m.i.p.  
 $E_{dep} = 31 \text{ MeV}$   
 $L_{trk} \sim 18 \text{ cm}$
- Trk. 2 - heavily i.p.  
 $E_{dep} = 191 \text{ MeV}$   
 $L_{trk} \sim 53 \text{ cm}$
- Trk. 3 - m.i.p.  
 $E_{dep} = 105 \text{ MeV}$   
 $L_{trk} \sim 60 \text{ cm}$
- Trk. 4 - heavily i.p.  
 $E_{dep} = 42 \text{ MeV}$   
 $L_{trk} \sim 16 \text{ cm}$
- Trk. 5 - m.i.p.  
 $E_{dep} = 111 \text{ MeV}$   
 $L_{trk} \sim 60 \text{ cm}$



10 m<sup>3</sup> test @ LNGS: Run 641 - Evt 14 (Apr. 14th, 2000)

# 10 m<sup>3</sup> test @ LNGS: Run 641 - Evt 14 (Apr. 14th, 2000)

## 3D reconstruction



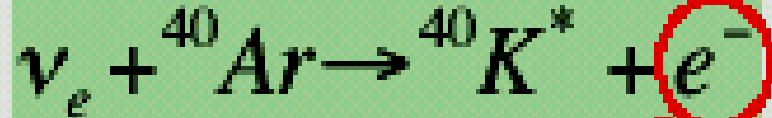
# Fizyka neutrin słonecznych i z SN

- Real-time detection of low energy i.e. solar and supernovae neutrinos through two independent reactions:

Elastic scattering on atomic electron

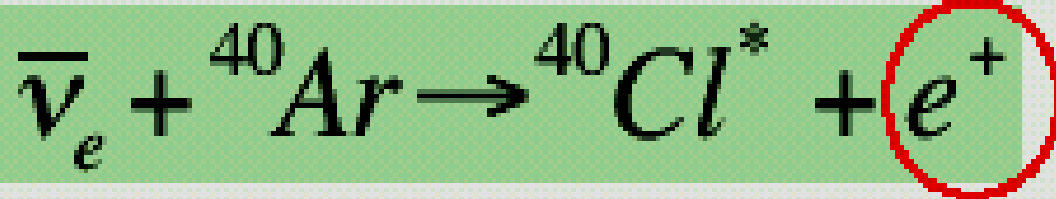


$\nu$  absorption on Argon nuclei (CC reaction)



- Double signature for CC events: **primary electron track** eventually surrounded by **low energy secondary tracks** ( ${}^{40}\text{K}^*$  de-excitation).
- Electron **detection threshold = 5 MeV** (needed to reduce background contribution and to establish the  $e^-$  direction in elastic scattering).
- Sensitive to  ${}^{\text{8B}}$  and **hep** components of the solar neutrino spectrum.

Supernova:



(Relatively) High Statistics available and reduced background, depending on the actual energy threshold:

$T_{thr}(e) = 5 \text{ MeV}$   
(limited by background)

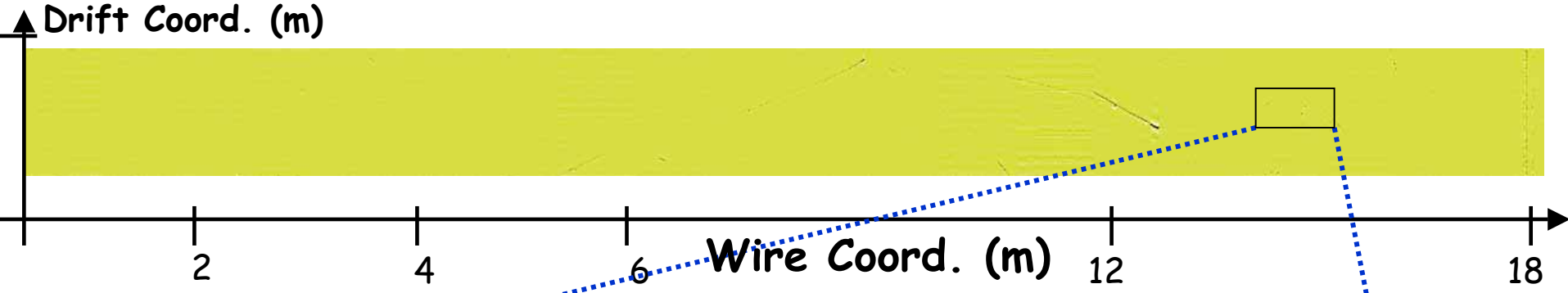
Event rates for  
an exposure of  
1 Kton year

$T_{th}$	Events				
	(MeV)	Elastic	Fermi	Gamow-Teller	Photons
0.0000	2674	1964	1902	$1.40 \times 10^8$	15745
1.0000	2238	1928	1902	$3.83 \times 10^7$	7243
2.0000	1826	1792	1868	$2.14 \times 10^6$	3306
3.0000	1438	1530	1832		1481
4.0000	1092	1151	1702		677
<b>5.0000</b>	<b>792</b>	<b>730</b>	<b>1453</b>		<b>306</b>
5.5000		530	1094		
6.0000	540	355	694		140
6.5000		213	504		
7.0000	347	111	338		64
7.5000		47	204		
8.0000	204	15	106		28
8.5000		4	45		
9.0000	106		15		
9.5000			4		
10.000	49				

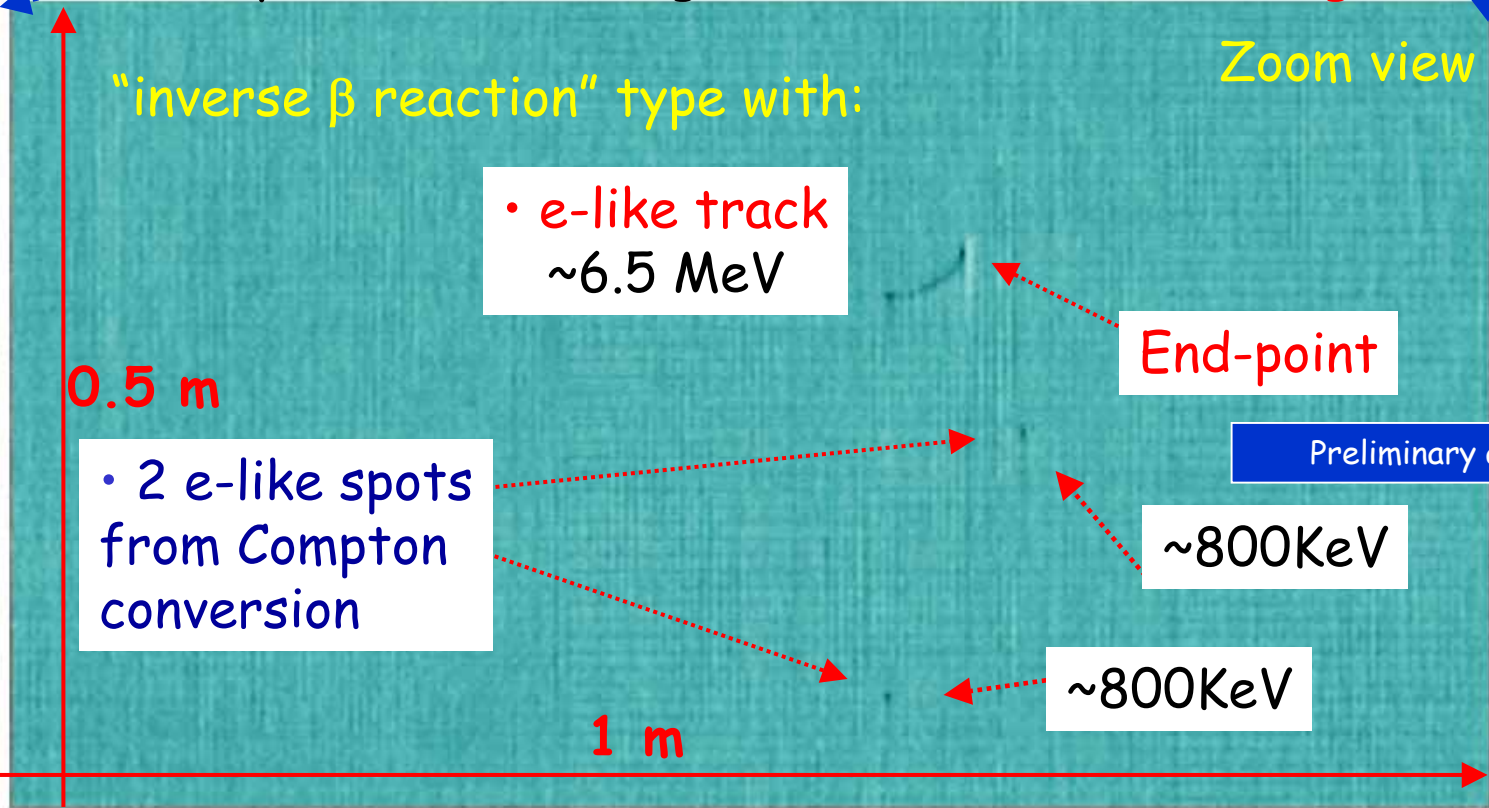
Table 1: Calculated solar neutrino reactions for an exposure of 1 kton  $\times$  year, as a function of the primary electron kinetic energy threshold  $T_{th}$ . **No oscillation hypothesis**

### Inputs:

- BP98  $\nu$  Flux ( $^8\text{B}$ )
- Ar nuclear shell model calculation and measures on mirror nucleus
- n meas. @ LNGS
- $\gamma$  meas. @ LNGS



Cosmic ray event containing a "Solar neutrino"-like signature



T600 test @ Pv: Run 785 - Evt 4 (July 22nd, 2001)

# Wiązka CNGS - poszukiwanie oscylacji $\nu_\mu \rightarrow \nu_\tau$

- Detector configuration
  - ↳ 5 T600 modules
  - ↳ Active LAr: **2.35 ktons**
- 5 years of CNGS running
  - ↳ Shared mode
  - ↳  $4.5 \times 10^{19}$  p.o.t./year
- **280  $\nu_\tau$  CC** expected for  $\Delta m^2_{23} = 3 \times 10^{-3} \text{ eV}^2$  and maximal mixing

Process	Expected Rates
$\nu_\mu$ CC	32600
$\nu_\mu$ CC	652
$\nu_\mu$ CC	262
$\nu_\mu$ CC	17
$\nu$ NC	10600
$\nu$ NC	243
$\nu_\tau$ CC, $\Delta m^2 \text{ (eV}^2\text{)}$	
$1 \times 10^{-3}$	31
$2 \times 10^{-3}$	125
$3 \times 10^{-3}$	280
$5 \times 10^{-3}$	750

## $\nu_\mu \rightarrow \nu_\tau$ appearance search summary

One half of  
full ICARUS

170000

T600+2 x T1200 modules

(2.35 kton active LAr)

5 year CNGS shared running

( $2.25 \times 10^{19}$  p.o.t.)

Super-Kamiokande:  $1.6 < \Delta m^2 < 4.0$  at 90% C.L.

$\tau$ decay mode	Signal $\Delta m^2 =$ $1.6 \times 10^{-3} \text{ eV}^2$	Signal $\Delta m^2 =$ $2.5 \times 10^{-3} \text{ eV}^2$	Signal $\Delta m^2 =$ $3.0 \times 10^{-3} \text{ eV}^2$	Signal $\Delta m^2 =$ $4.0 \times 10^{-3} \text{ eV}^2$	BG
$\tau \rightarrow e$	3.7	9	13	23	0.7
$\tau \rightarrow \rho$ DIS	0.6	1.5	2.2	3.9	< 0.1
$\tau \rightarrow \rho$ QE	0.6	1.4	2.0	3.6	< 0.1
Total	4.9	11.9	17.2	30.6	0.7

## $\tau \rightarrow e$ search: 3D likelihood

### A very simple analysis

~~1D analysis~~

- Analysis based on 3 dimensional likelihood

$$\Rightarrow E_{\text{visible}}, P_T^{\text{miss}}, \rho_1 = P_T^{\text{lep}} / (P_T^{\text{lep}} + P_T^{\text{miss}})$$

- Exploit correlation between variables

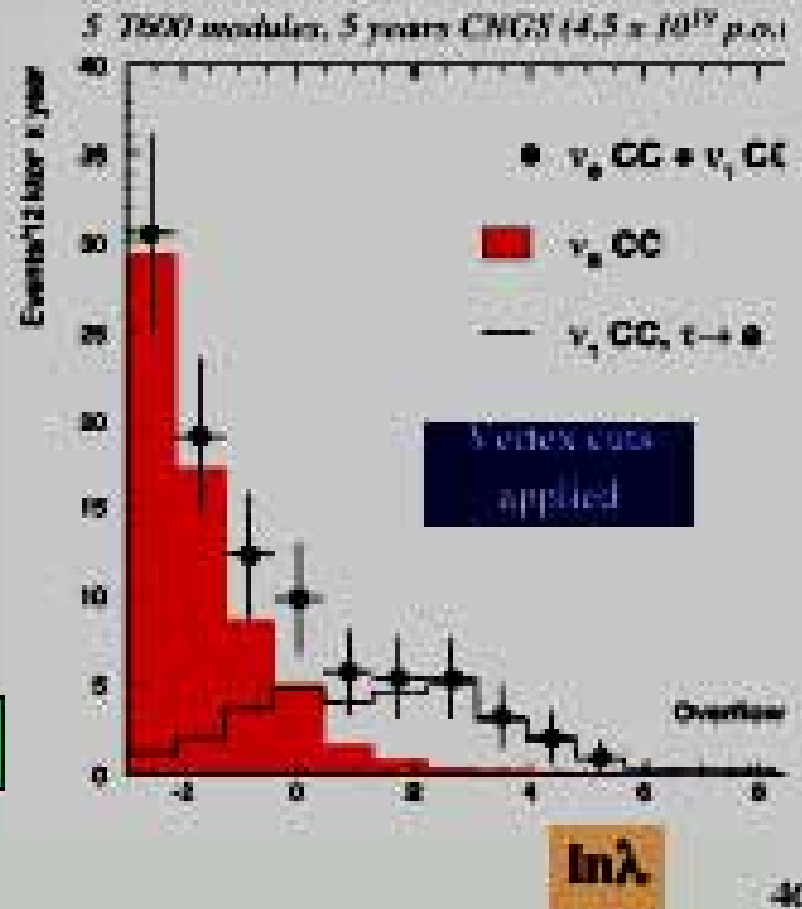
- Two functions built:

$$\Rightarrow L_s([E_{\text{visible}}, P_T^{\text{miss}}, \rho_1]) \text{ (signal)}$$

$$\Rightarrow L_b([E_{\text{visible}}, P_T^{\text{miss}}, \rho_1]) \text{ (} n_s \text{ CC background)}$$

- Discrimination given by

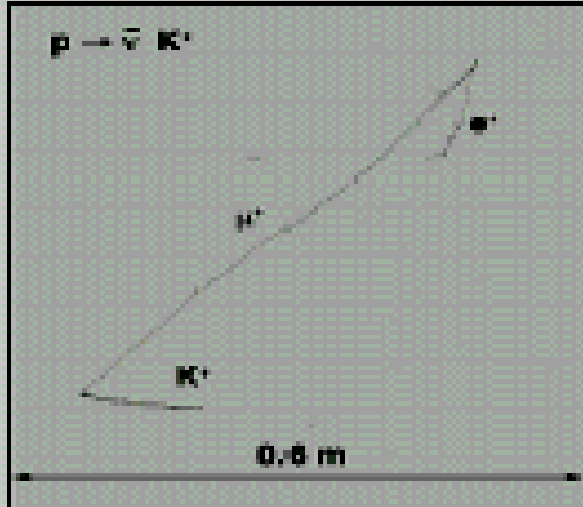
$$\ln \lambda = \mathcal{L}([E_{\text{visible}}, P_T^{\text{miss}}, \rho_1]) = L_s / L_b$$



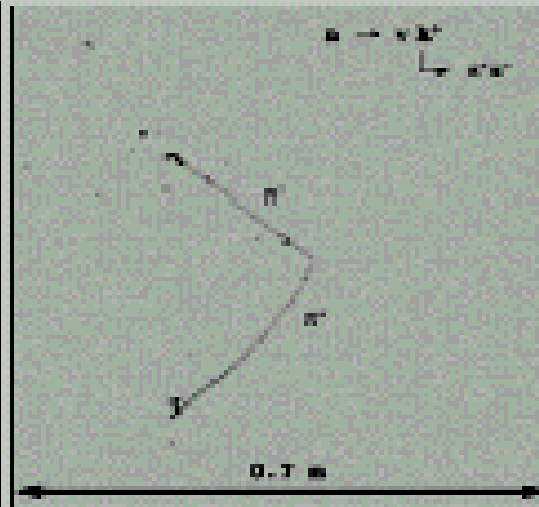


# Poszukiwanie rozpadów protonu

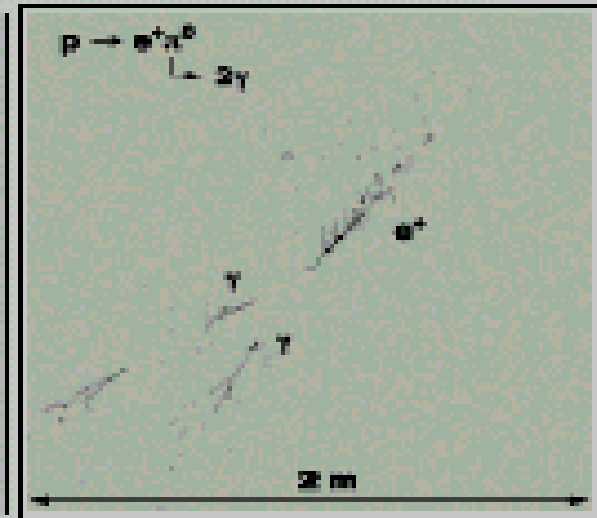
$p \rightarrow \bar{\nu} K^+$  decay



$n \rightarrow \bar{\nu} K^0$  decay



$p \rightarrow e^+ \pi^0$  decay



Thanks to excellent tracking and particle *id* capabilities

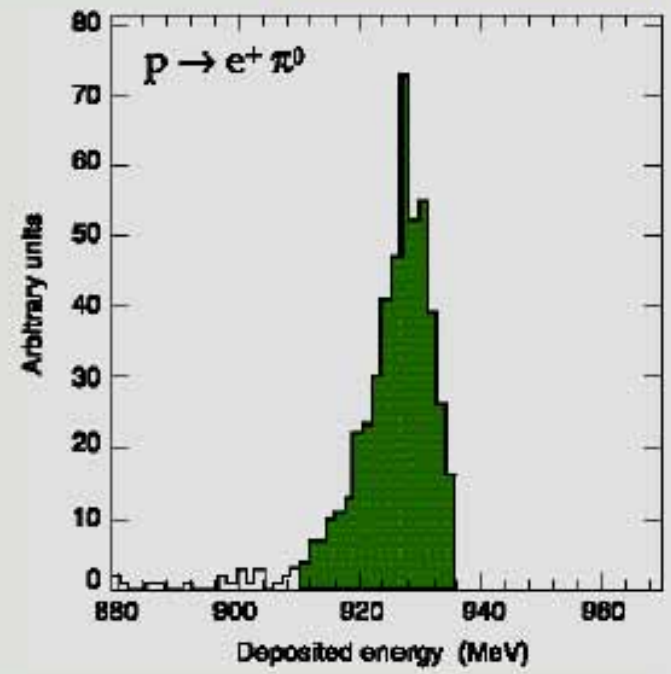
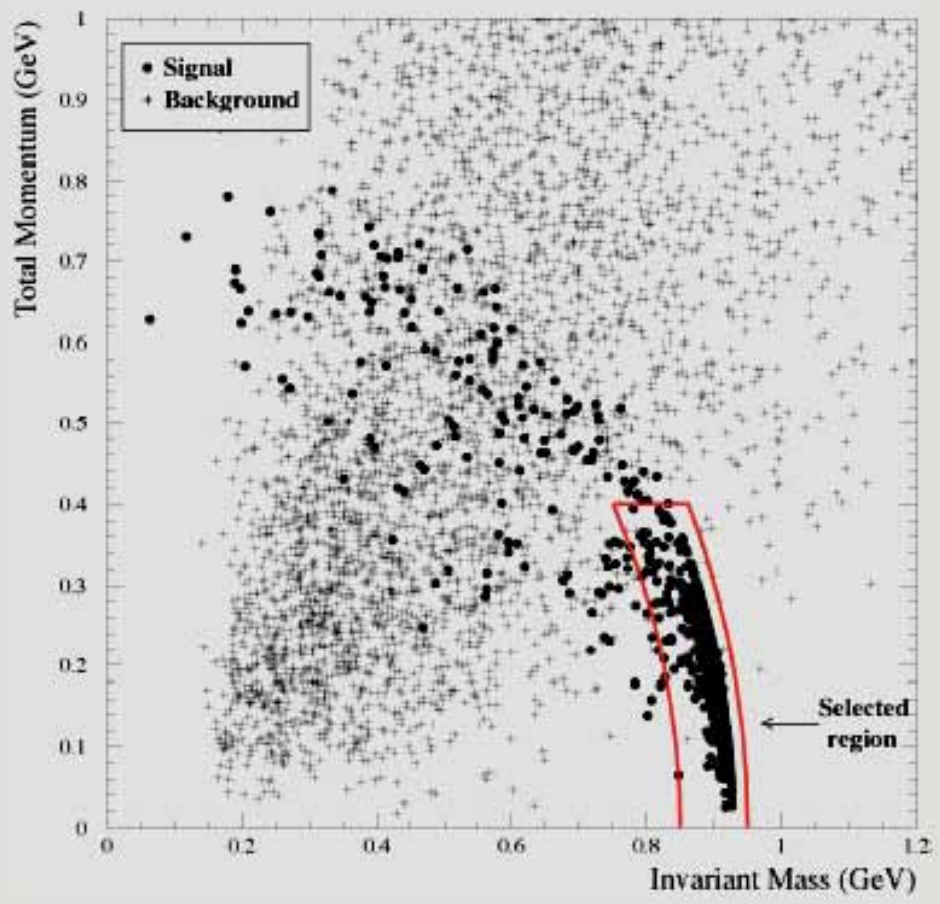
LAr unique tool for

Extremely efficient background rejection

High detection efficiency

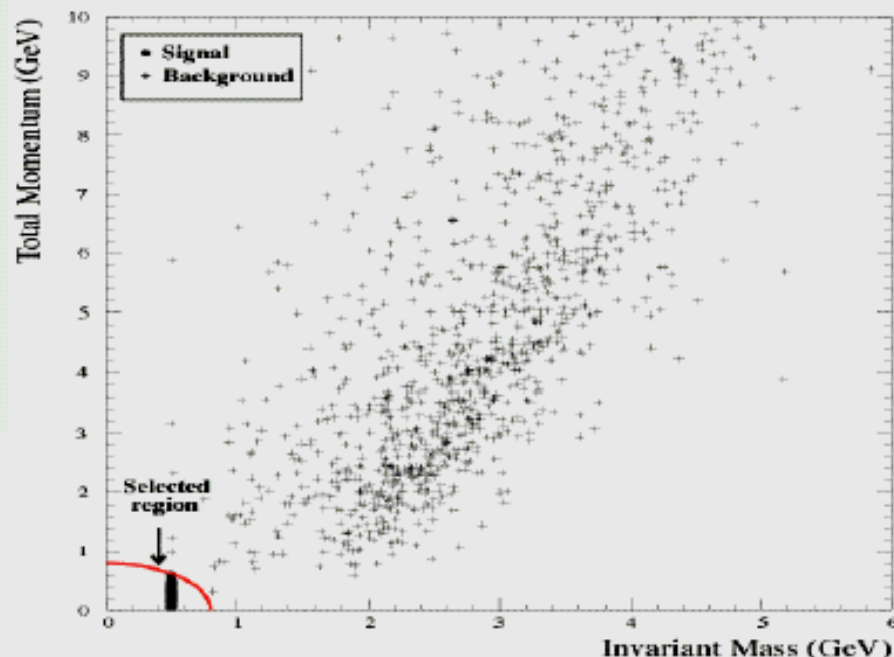
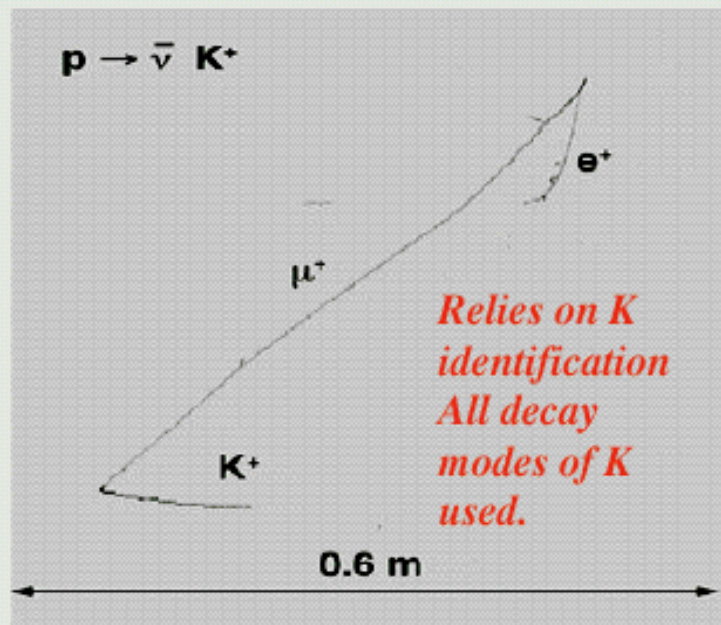
*Bias-free, fully exclusive channel searches!*

$p \rightarrow e^+ \pi^0$



95 % of the events  
in a 30 MeV wide  
window

## $p \rightarrow K^+ \bar{\nu}$ decay kinematics



Cuts	$p \rightarrow K^+ \bar{\nu}$	$\bar{\nu}_e$ CC	$\bar{\nu}_e$ CC	$\mu_\mu$ CC	$\bar{\nu}_\mu$ CC	$\nu$ NC	$\bar{\nu}$ NC
One Kaon	96.75%	308	36	871	146	282	77
No $\pi^0$	96.75%	143	14	404	56	138	25
No positrons	96.75%	0	0	404	56	138	25
No neutrinos	96.75%	0	0	0	0	138	25
No charged pions	96.75%	0	0	0	0	57	9
Total Energy < 0.8 GeV	96.75%	0	0	0	0	1	0