Detecting ν_τs: the CHORUS and OPERA experience

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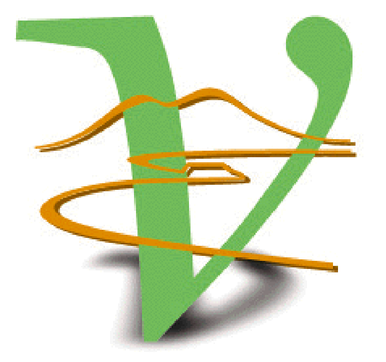
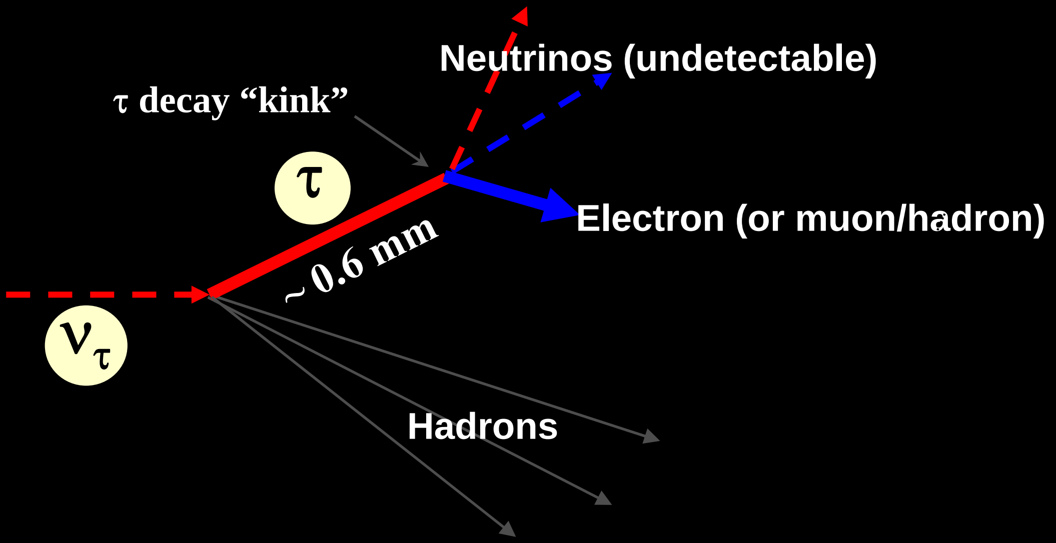


Outlook

- Experimental challanges in detecting ν_τs
- The CHORUS experiment
- The OPERA experiment
- Final considerations

How to detect τ s ?

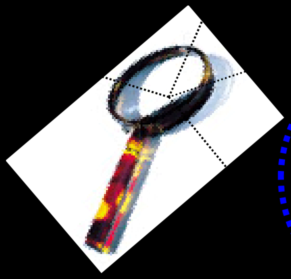
The τ is not a stable particle. At the typical energy it is created, it decays after a short path of about 1 mm in a well identifiable way:

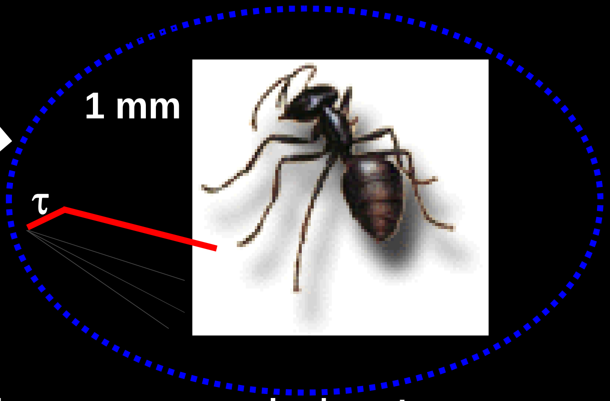


Charged particles can be seen in detectors as tracks.

A τ event can be identified as many tracks coming from the same point (neutrino interaction vertex) and one of them (τ) changing sharply direction after about 1 mm path (the kink)

How does this look like ?





→ Needs a detector with high space resolution !

Is τ detection easy ?

A neutrino experiment with τ identification is a big challange, due to a lot of practical difficulties:

Neutrinos interact weakly with matter.
Needs large target mass

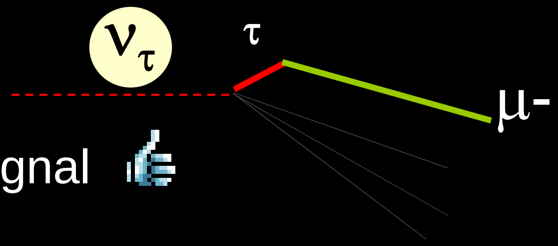
τ identification requires
very high space resolution

The τ is a heavy particle, to produce it high energy neutrinos are needed.
τ production threshold ≈4 GeV

Needs a detector which should be at the same time:

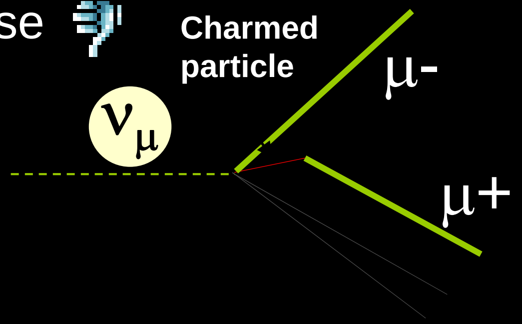
- Massive
- Accurate (micrometric resolution)
- Affordable !!

And it is not finished yet !
The signal should be separated from the noise.
This is one possible example:



Signal 👍

Noise 👎



Other rare particles (hadrons containing the charm quark) can be produced and decay almost like the tau

Looking for τ events is a « needle in the haystack » problem

Signal: tau event:
(depending on the real value of the parameters we are searching for)

Noise: from ν_μ interactions

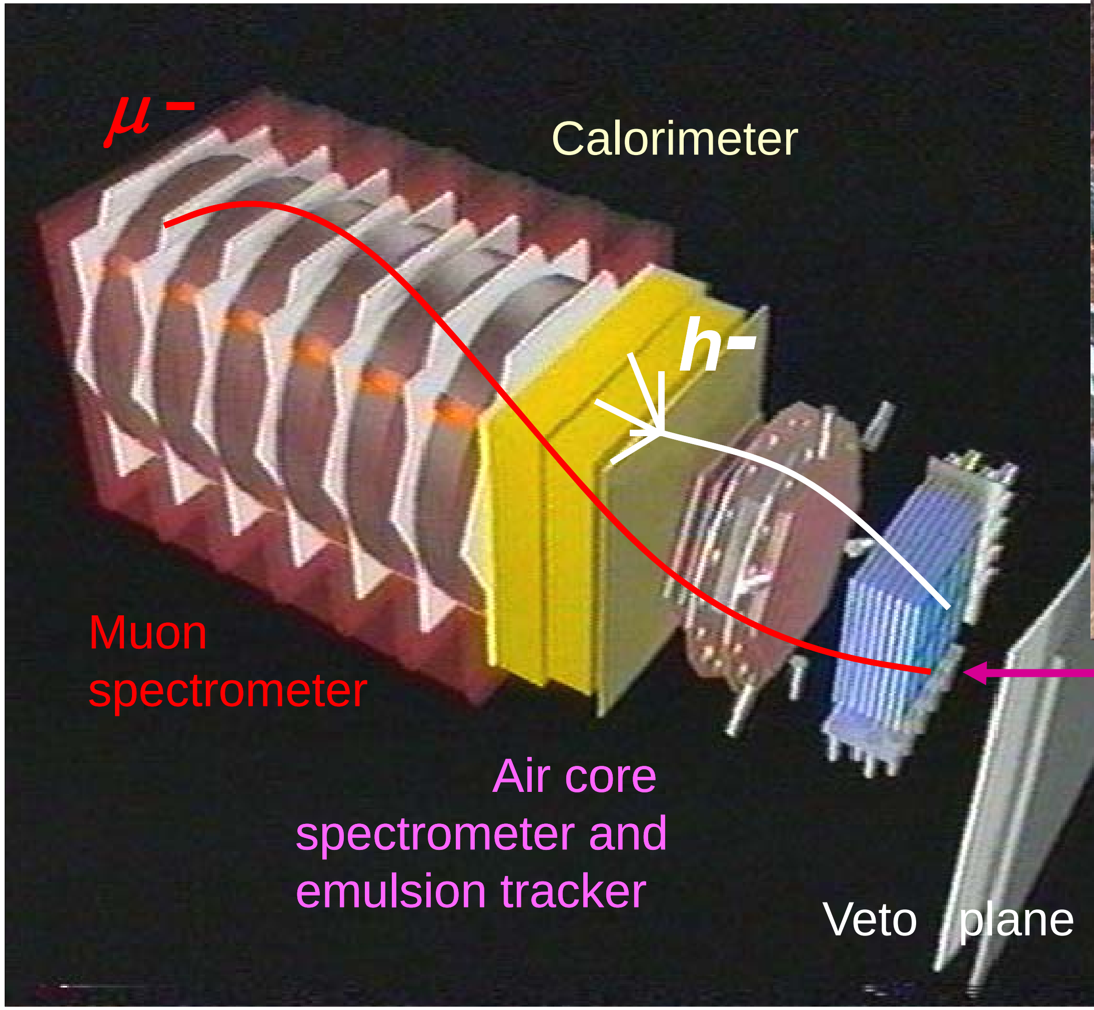
The detector should have some extra « handles » to kill the noise.
This is paied also by killing part of the signal which is closer to the noise.

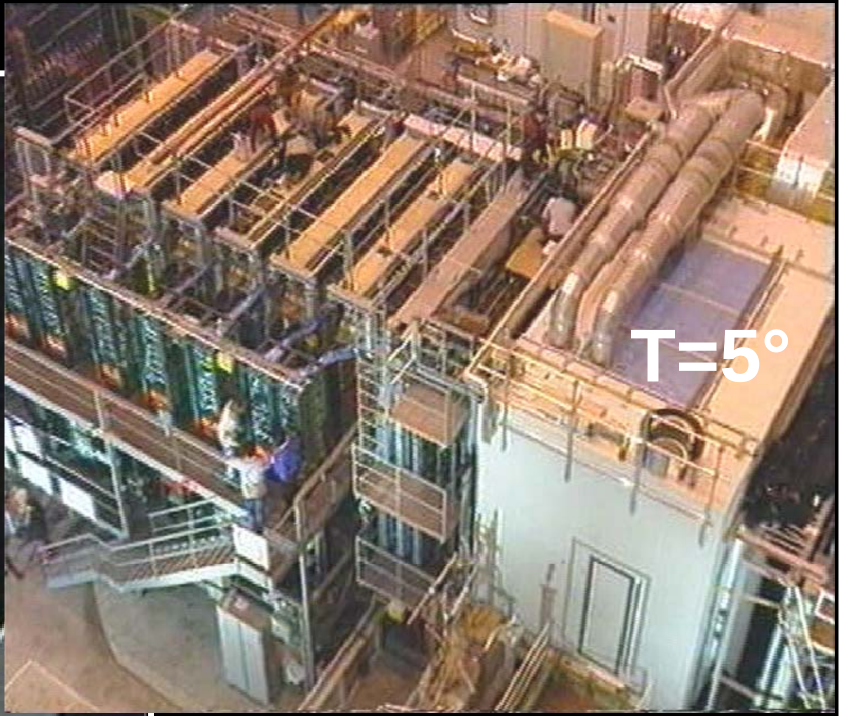
Possible approaches

- Electronic detectors: kinematical analysis and impact parameter techniques
- Nuclear emulsion based detectors:
  - CHORUS (pure emulsion target)
  - OPERA (ECC target)

CHORUS detector

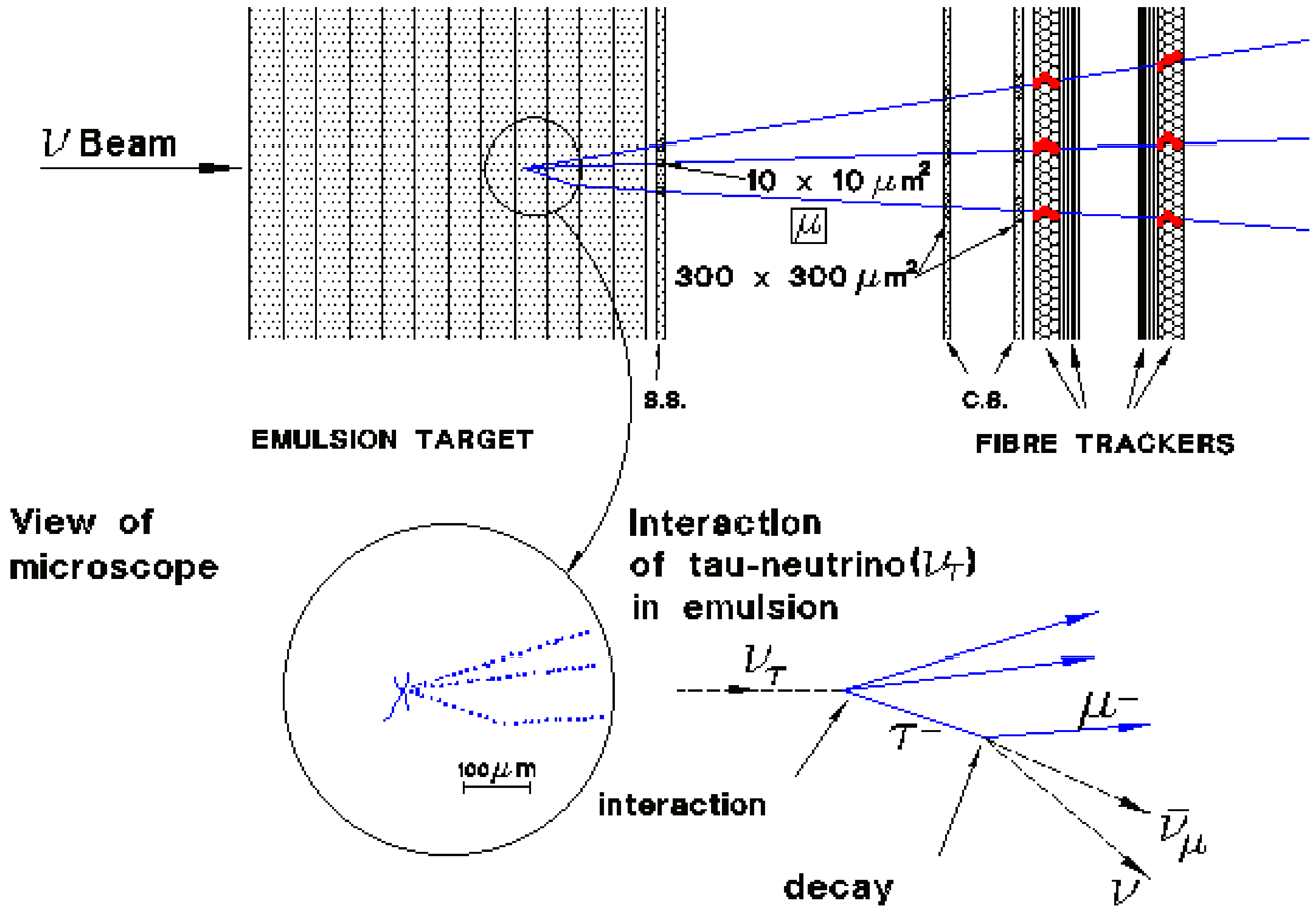
E.Eskut et al., Nucl. Instr. Meth. A 401 (1997) 7-44



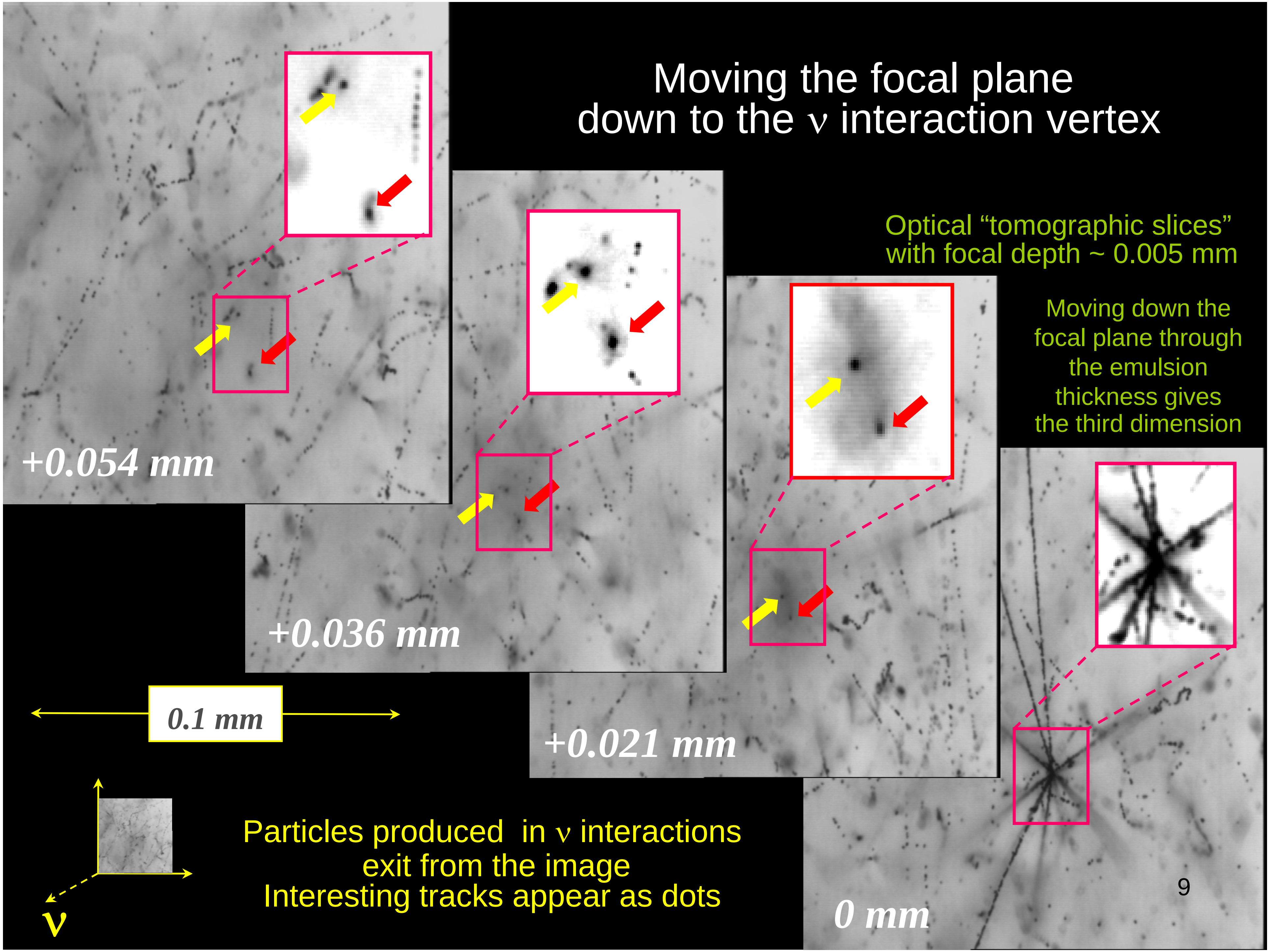


770 kg emulsion target and scintillating fibre tracker

The target region



Moving the focal plane down to the ν interaction vertex



Optical “tomographic slices”
with focal depth ~ 0.005 mm

Moving down the
focal plane through
the emulsion
thickness gives
the third dimension

Particles produced in ν interactions
exit from the image
Interesting tracks appear as dots

Diffractive D_s production

Phys. Lett. B 435 (1998) 458, CHORUS Coll.

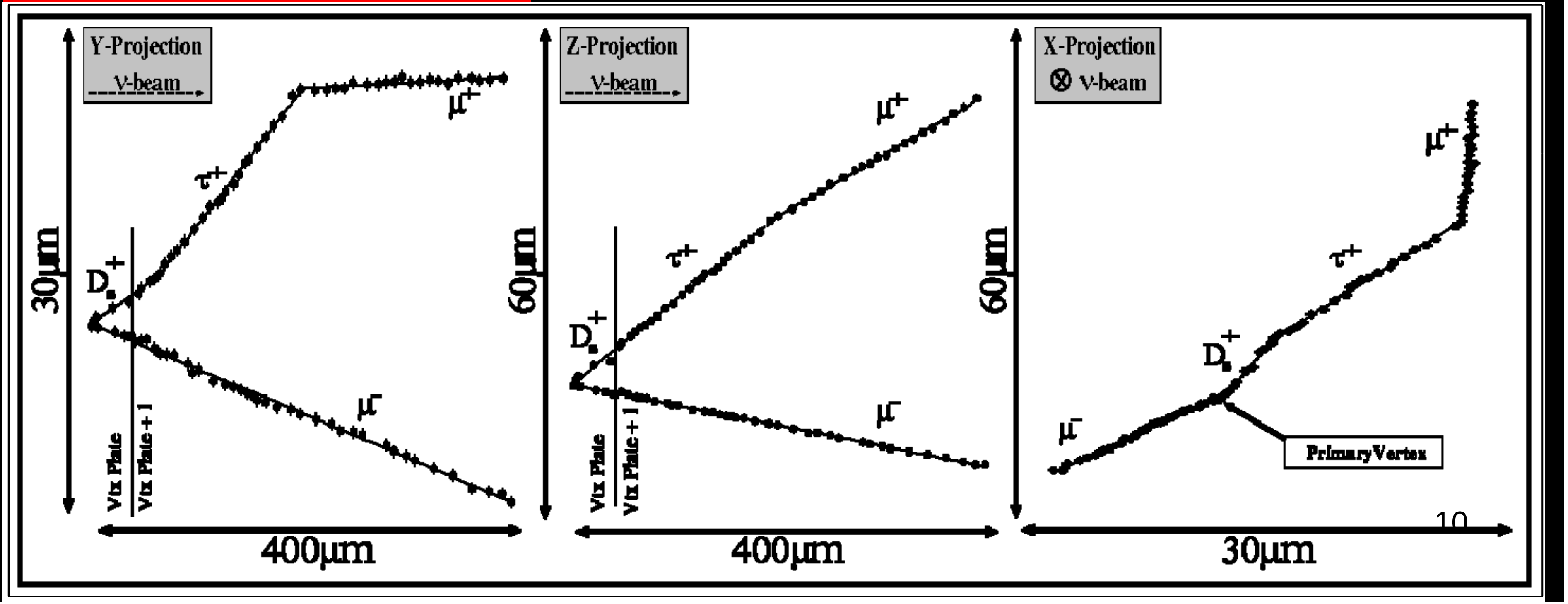
$$\nu_\mu N \to D_s^* \mu^- N'$$

$$\hookrightarrow D_s^+ \gamma$$

$$\hookrightarrow \tau^+ \nu_\tau$$

$$\hookrightarrow \mu^+ \nu_\mu \nu_\tau$$

Not a single grain is detected at the primary vertex!



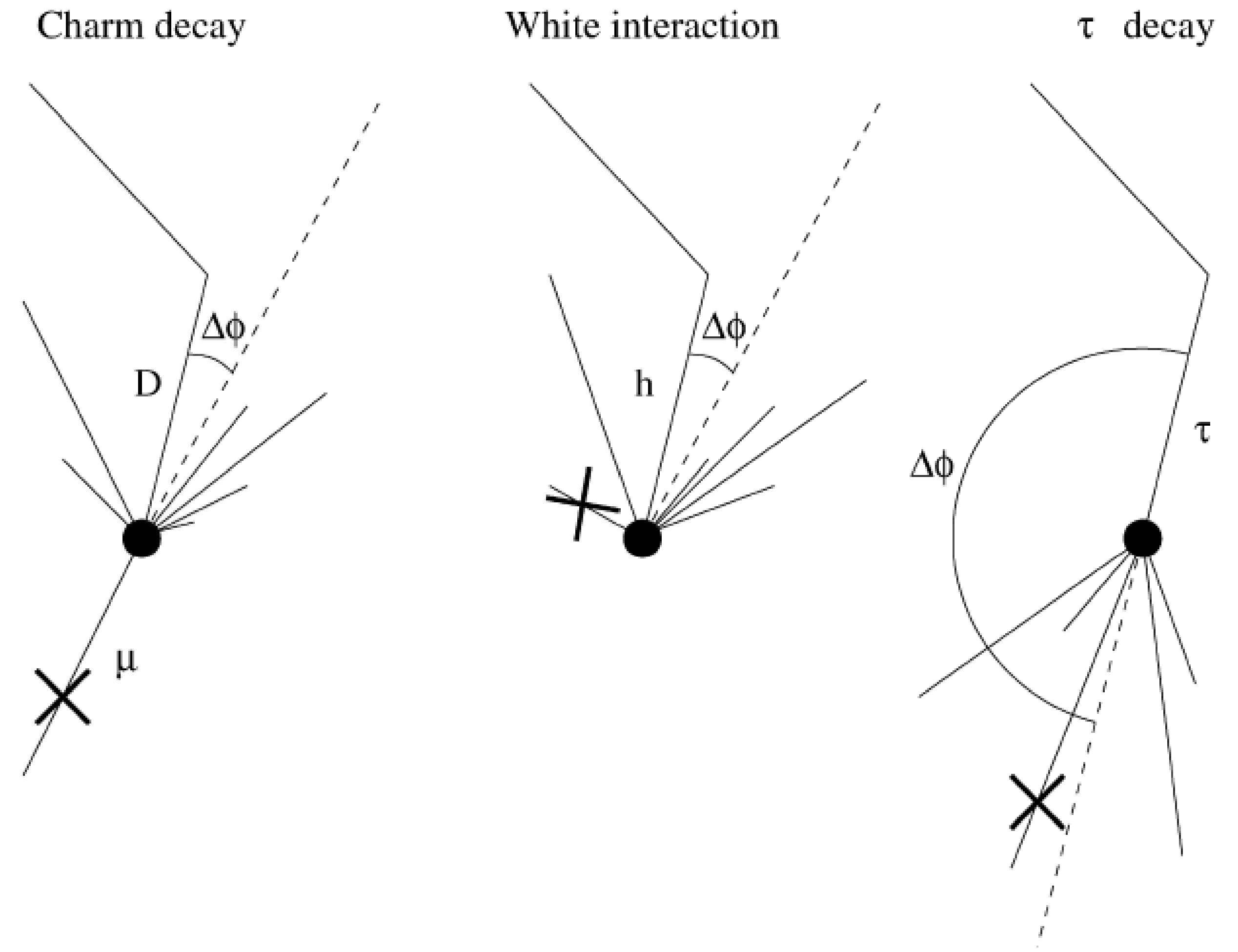


Fig. 3. Definition of the angle $\Delta\phi$. The dashed line is the mean direction of the primary tracks, with the exclusion of the one which has the largest ϕ angle relative to the parent particle. The $\Delta\phi$ distribution is different for charm, white interaction or τ events.

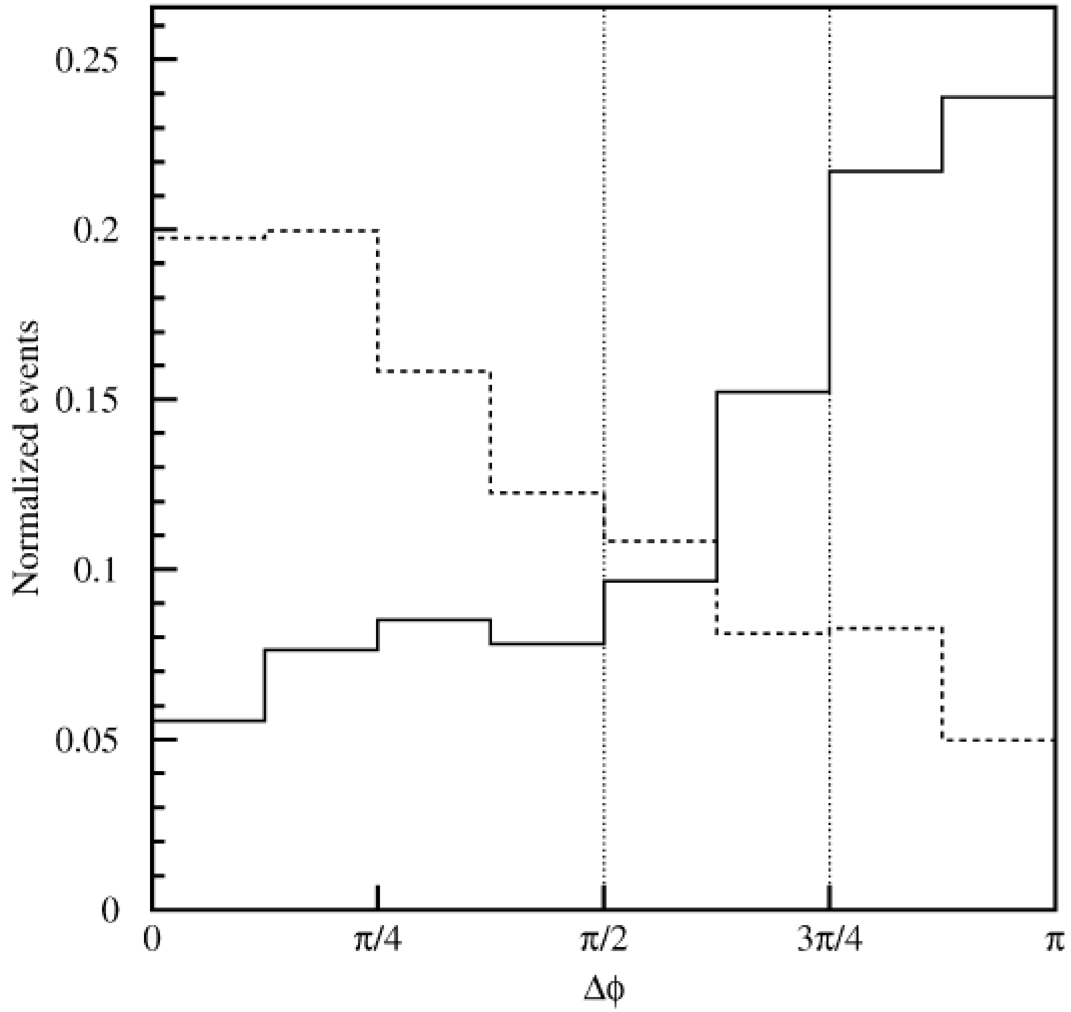


Fig. 4. $\Delta\phi$ distributions for simulated 0μ C1 events: comparison between ν_τ (solid line) and charmed events (dashed line). The area is normalized to 1. The vertical lines show the applied cut dividing the events in three subsamples.

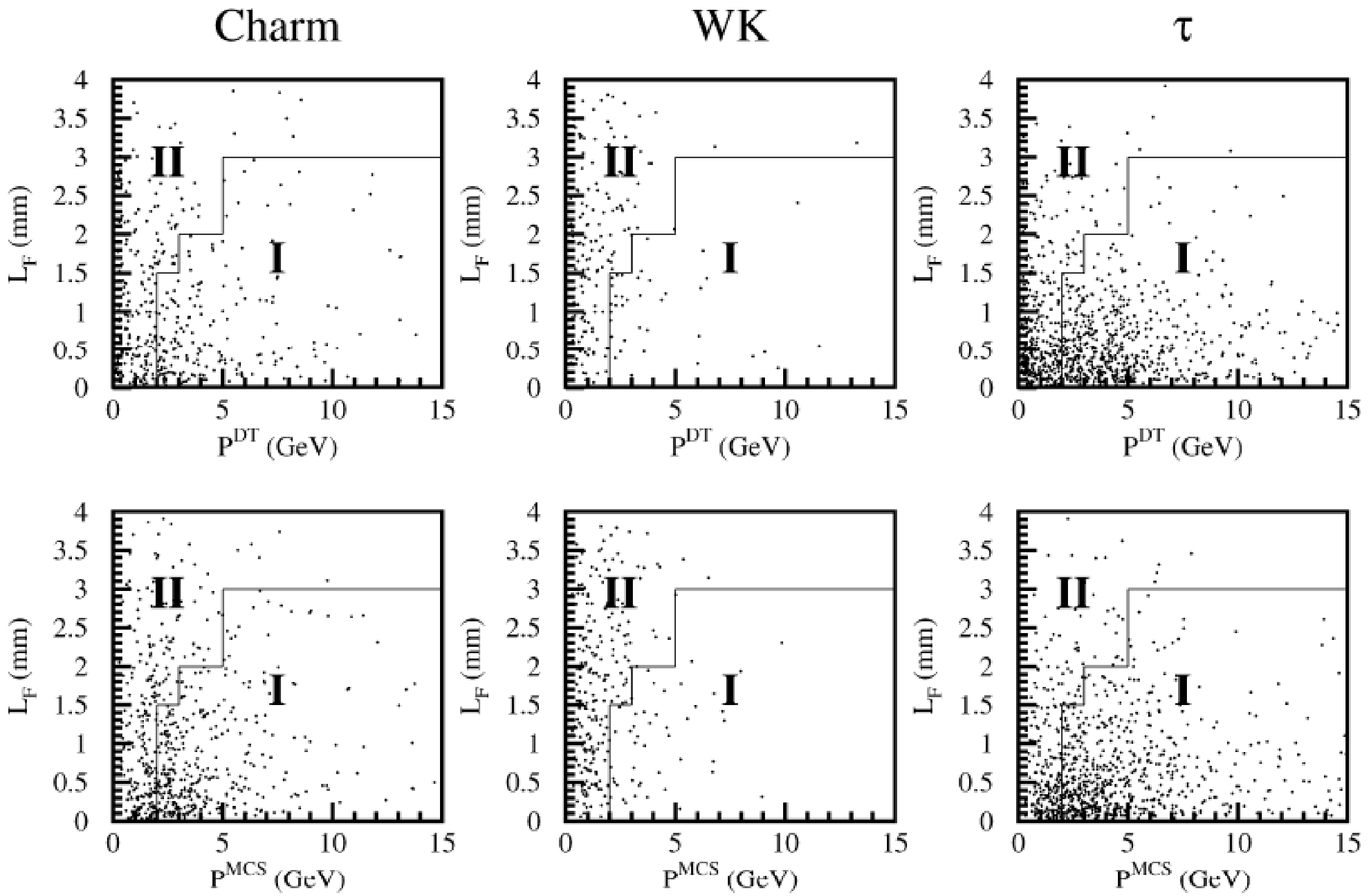


Fig. 2. The flight length L_F versus daughter particle momentum computed for charm (left), white kink (centre) and τ events (right). The momentum is evaluated by DT (top) or MCS (bottom). Only events in region I are selected.

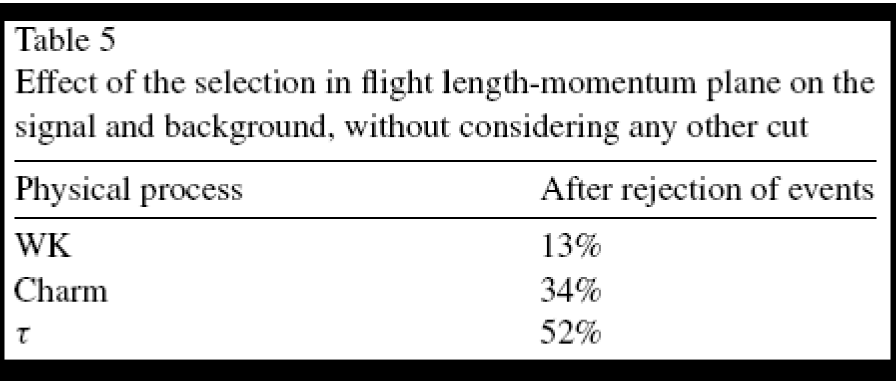


Table 5
Effect of the selection in flight length-momentum plane on the signal and background, without considering any other cut

Physical process	After rejection of events
WK	13%
Charm	34%
τ	52%

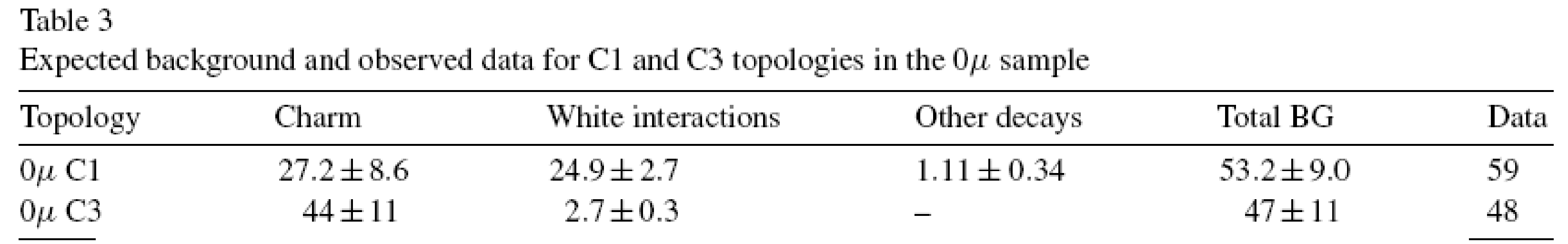


Table 3
Expected background and observed data for C1 and C3 topologies in the 0μ sample

Topology	Charm	White interactions	Other decays	Total BG	Data
0μ C1	27.2 ± 8.6	24.9 ± 2.7	1.11 ± 0.34	53.2 ± 9.0	59
0μ C3	44 ± 11	2.7 ± 0.3	–	47 ± 11	48

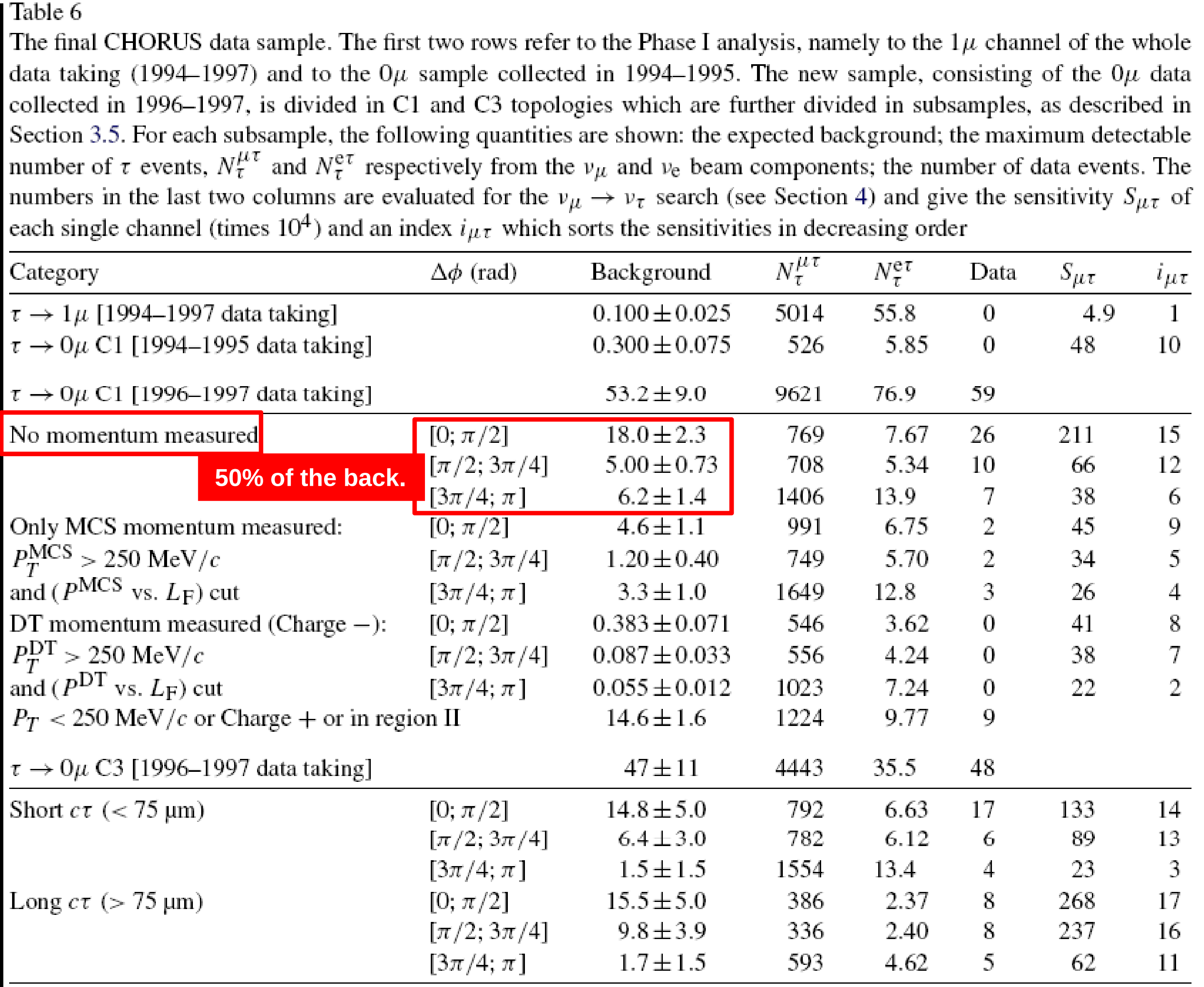
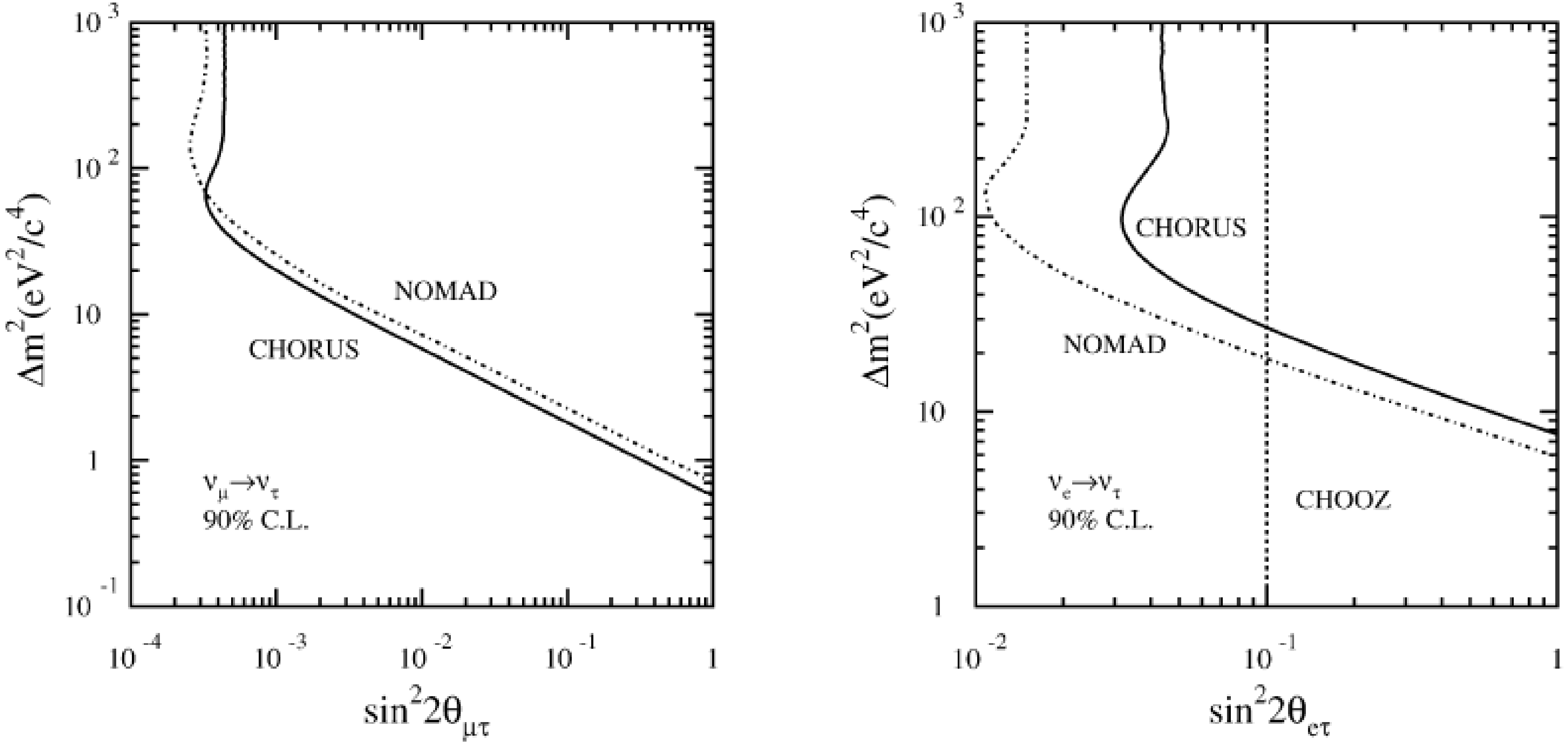


Table 6
The final CHORUS data sample. The first two rows refer to the Phase I analysis, namely to the 1μ channel of the whole data taking (1994–1997) and to the 0μ sample collected in 1994–1995. The new sample, consisting of the 0μ data collected in 1996–1997, is divided in C1 and C3 topologies which are further divided in subsamples, as described in Section 3.5. For each subsample, the following quantities are shown: the expected background; the maximum detectable number of τ events, $N_\tau^{\mu\tau}$ and $N_\tau^{e\tau}$ respectively from the ν_μ and ν_e beam components; the number of data events. The numbers in the last two columns are evaluated for the $\nu_\mu\to\nu_\tau$ search (see Section 4) and give the sensitivity $S_{\mu\tau}$ of each single channel (times 10^4) and an index $i_{\mu\tau}$ which sorts the sensitivities in decreasing order

Category	$\Delta\phi$ (rad)	Background	$N_\tau^{\mu\tau}$	$N_\tau^{e\tau}$	Data	$S_{\mu\tau}$	$i_{\mu\tau}$
$\tau\to1\mu$ [1994–1997 data taking]		0.100 ± 0.025	5014	55.8	0	4.9	1
$\tau\to0\mu$ C1 [1994–1995 data taking]		0.300 ± 0.075	526	5.85	0	48	10
$\tau\to0\mu$ C1 [1996–1997 data taking]		53.2 ± 9.0	9621	76.9	59		
No momentum measured	$[0;\pi/2]$	18.0 ± 2.3	769	7.67	26	211	15
	$[\pi/2;3\pi/4]$	5.00 ± 0.73	708	5.34	10	66	12
	$[3\pi/4;\pi]$	6.2 ± 1.4	1406	13.9	7	38	6
Only MCS momentum measured:	$[0;\pi/2]$	4.6 ± 1.1	991	6.75	2	45	9
$P_T^{\text{MCS}}>250$ MeV$/c$	$[\pi/2;3\pi/4]$	1.20 ± 0.40	749	5.70	2	34	5
and (P^{MCS} vs. L_{F}) cut	$[3\pi/4;\pi]$	3.3 ± 1.0	1649	12.8	3	26	4
DT momentum measured (Charge $-$):	$[0;\pi/2]$	0.383 ± 0.071	546	3.62	0	41	8
$P_T^{\text{DT}}>250$ MeV$/c$	$[\pi/2;3\pi/4]$	0.087 ± 0.033	556	4.24	0	38	7
and (P^{DT} vs. L_{F}) cut	$[3\pi/4;\pi]$	0.055 ± 0.012	1023	7.24	0	22	2
$P_T<250$ MeV$/c$ or Charge $+$ or in region II		14.6 ± 1.6	1224	9.77	9		
$\tau\to0\mu$ C3 [1996–1997 data taking]		47 ± 11	4443	35.5	48		
Short $c\tau$ (<75 µm)	$[0;\pi/2]$	14.8 ± 5.0	792	6.63	17	133	14
	$[\pi/2;3\pi/4]$	6.4 ± 3.0	782	6.12	6	89	13
	$[3\pi/4;\pi]$	1.5 ± 1.5	1554	13.4	4	23	3
Long $c\tau$ (>75 µm)	$[0;\pi/2]$	15.5 ± 5.0	386	2.37	8	268	17
	$[\pi/2;3\pi/4]$	9.8 ± 3.9	336	2.40	8	237	16
	$[3\pi/4;\pi]$	1.7 ± 1.5	593	4.62	5	62	11

50% of the back.

CHORUS results



$P(\nu_\mu \to \nu_\tau) < 2.2 \times 10^{-4}$

$P(\nu_e \to \nu_\tau) < 2.2 \times 10^{-2}$

CHORUS experience

PROS

- Pure emulsion target allows for the detection of very low energy particles/nuclear fragments (i.e. a single grain can be observed)
- The event topology can be easily and efficiently measured
- Light target minimizes the track interaction probability

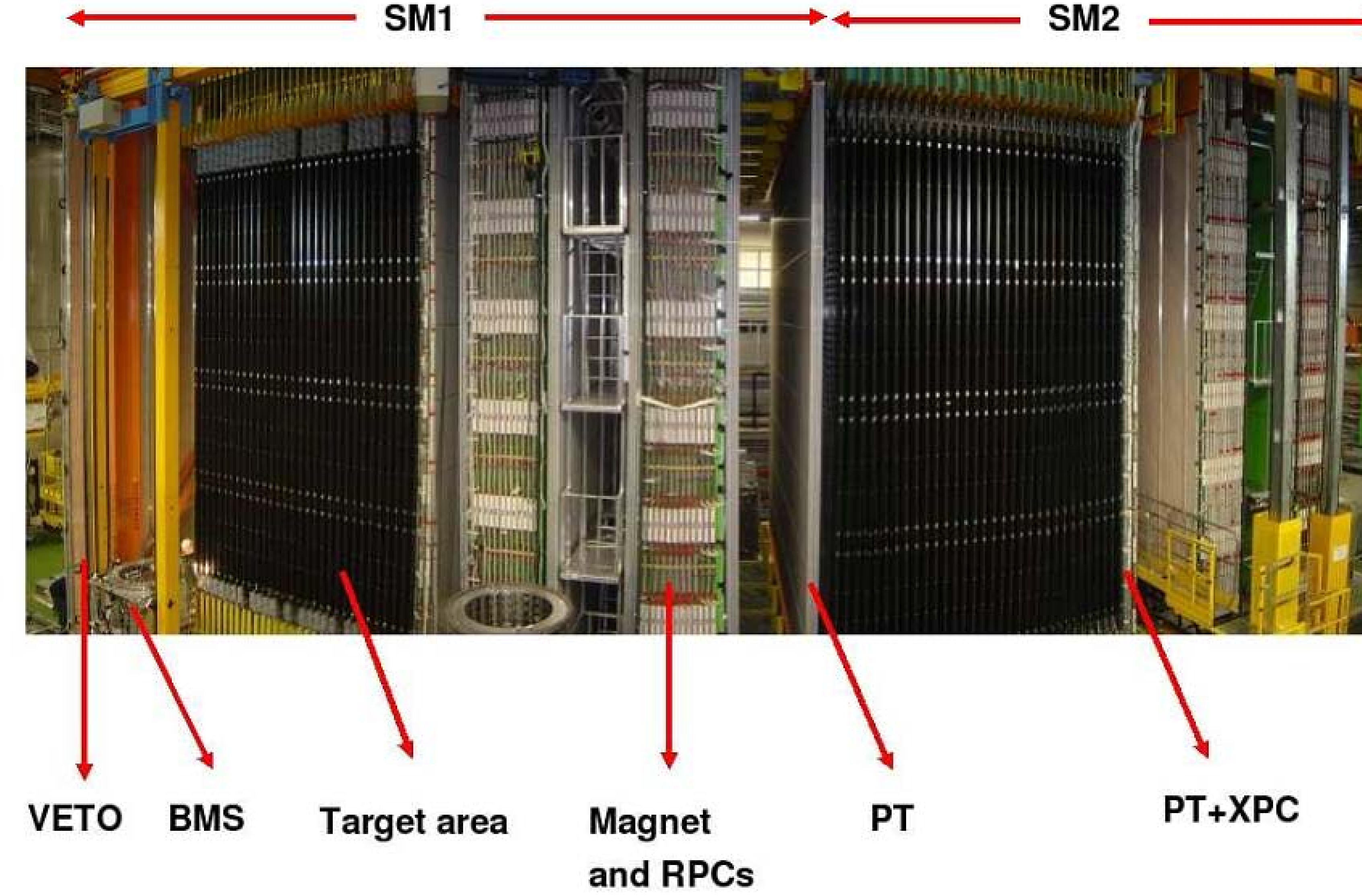
CONTRA

- The hadronic spectrometer measured the charge of the kink daughter only in about 30% of the events
- The emulsion target was too light to measure the particle momentum by MCS
- The distance between the target and the calorimeter was too large: small muon acceptance and pion/kaon decay in flight before the calorimeter
- The scanning speed was too slow to allow the analysis of bigger volumes (i.e. better efficiency)

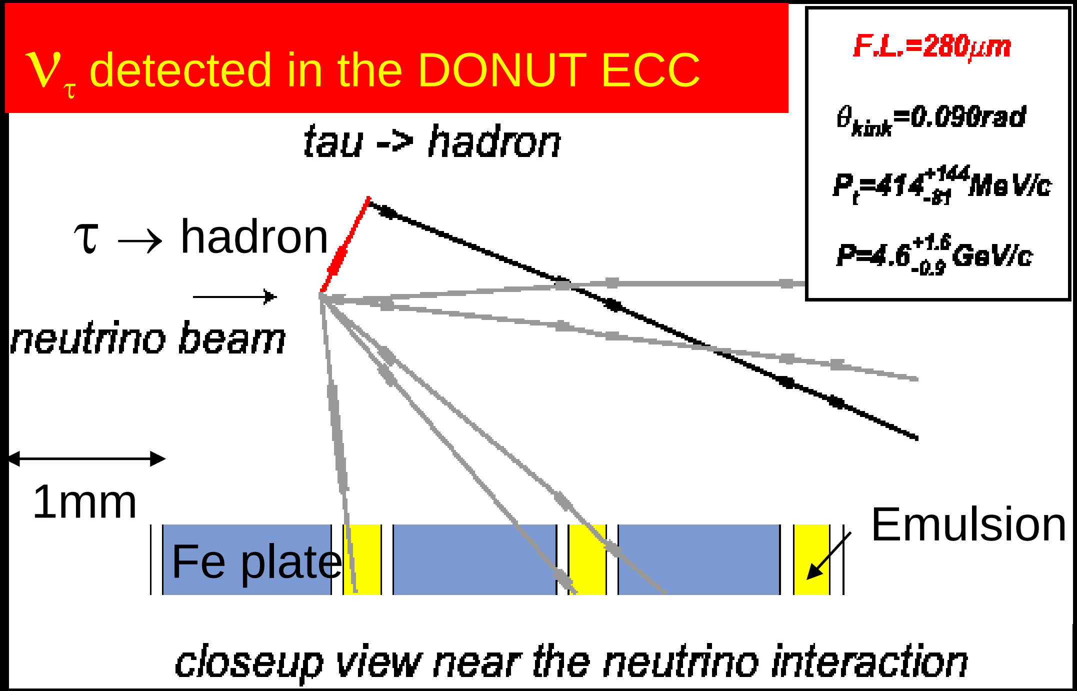
The bottleneck is the momentum measurement!

The OPERA experiment

(R. Acquafredda et al., JINST 4 (2009) 04018)



Emulsion Cloud Chamber for ν_τ detection



ν_τ detected in the DONUT ECC

closeup view near the neutrino interaction

Structure: OPERA ECC = DONUT ECC

Material : Lead ≠ Iron

Better performance for physics analysis

“Compact” brick as a baseline option for OPERA

The brick structure

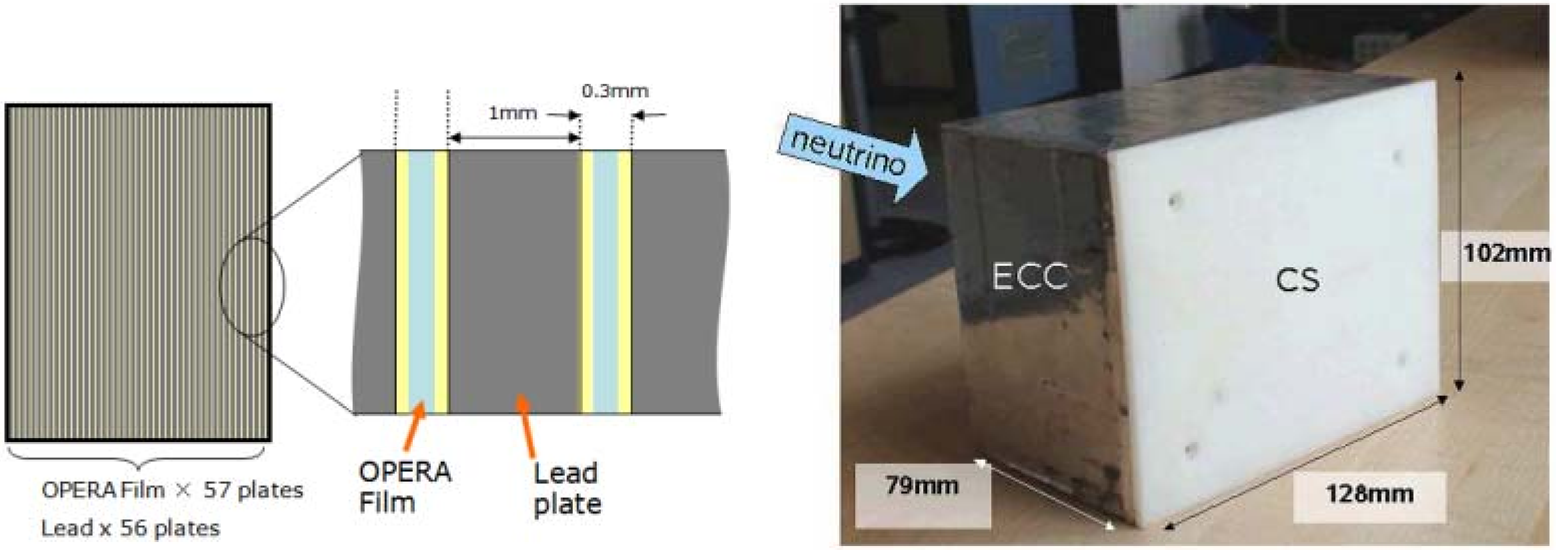
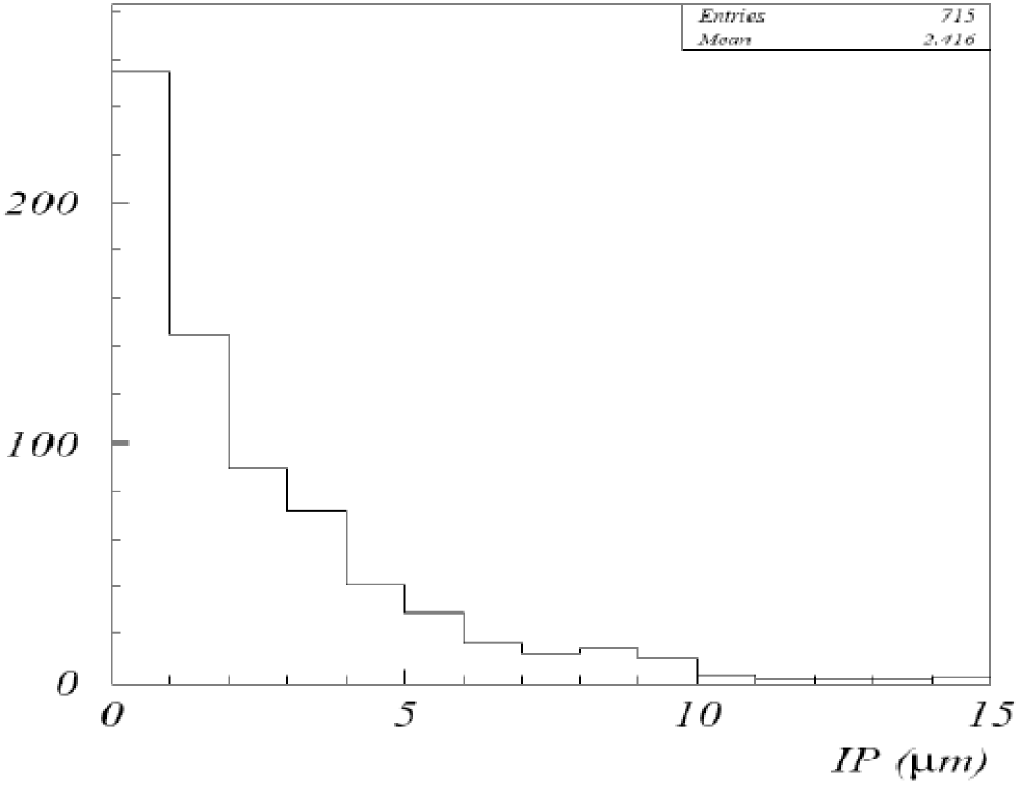
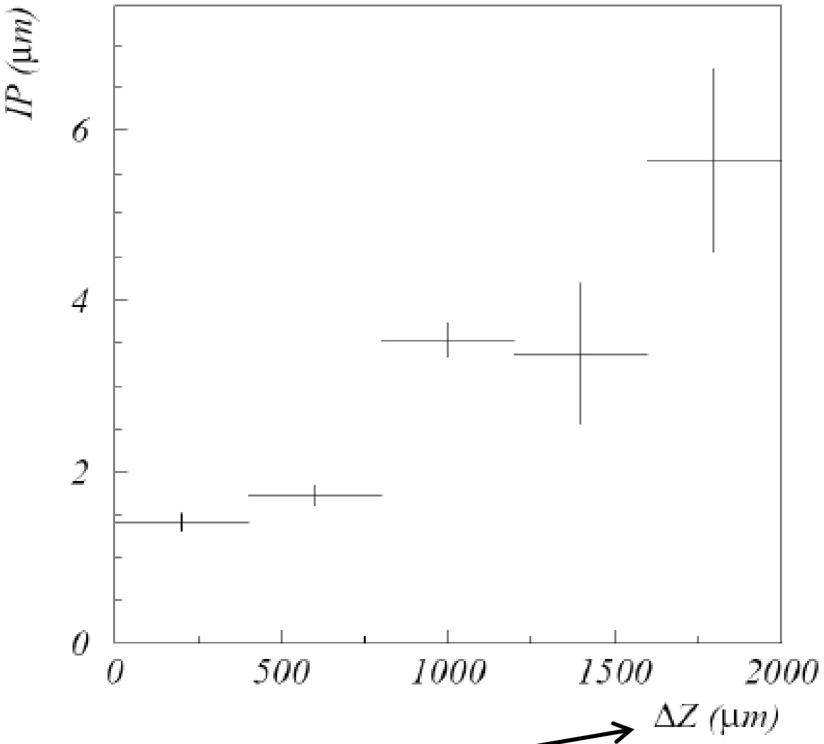
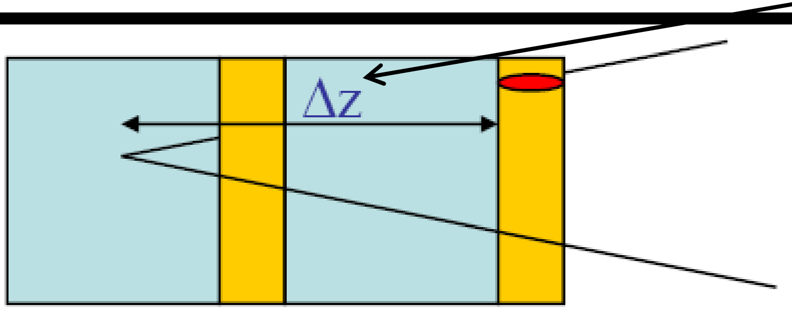


Figure 9. Left: schematic view of a brick in the target. Middle: blow-up insert showing two emulsion films and one lead plate. Right: photograph of a real brick as produced and inserted in the OPERA walls; CS is the box containing the two Changeable Sheets.

Impact parameter distribution

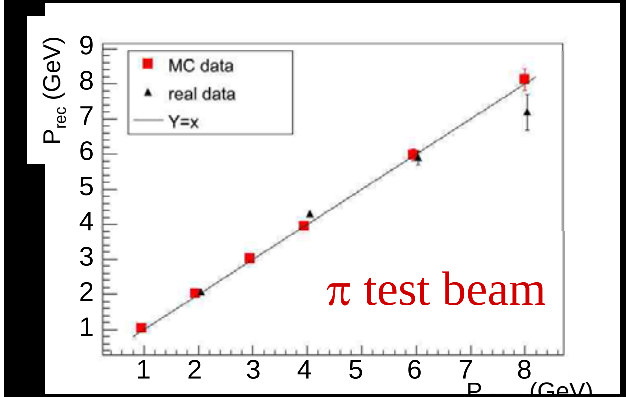


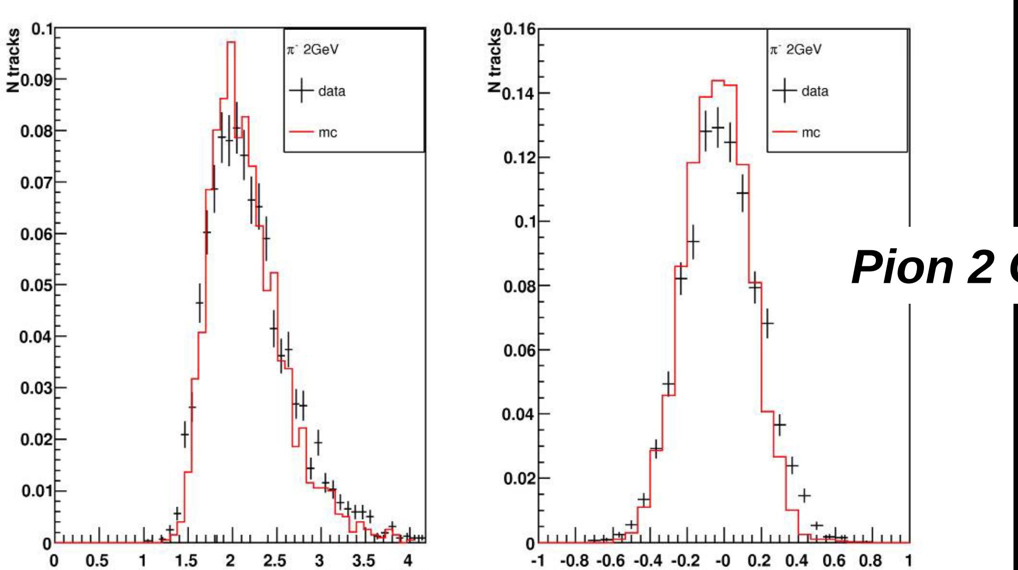




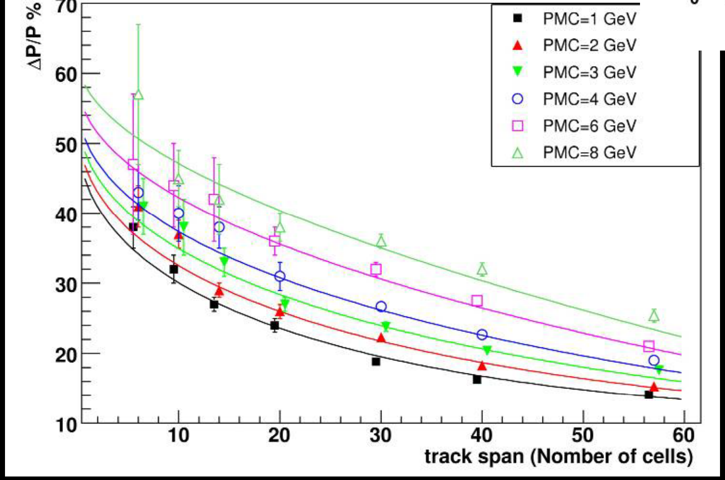
Distance between the vertex and the base-track used to compute the IP

Test beam data samples of pions and several MC samples were produced and used for the development of the method.

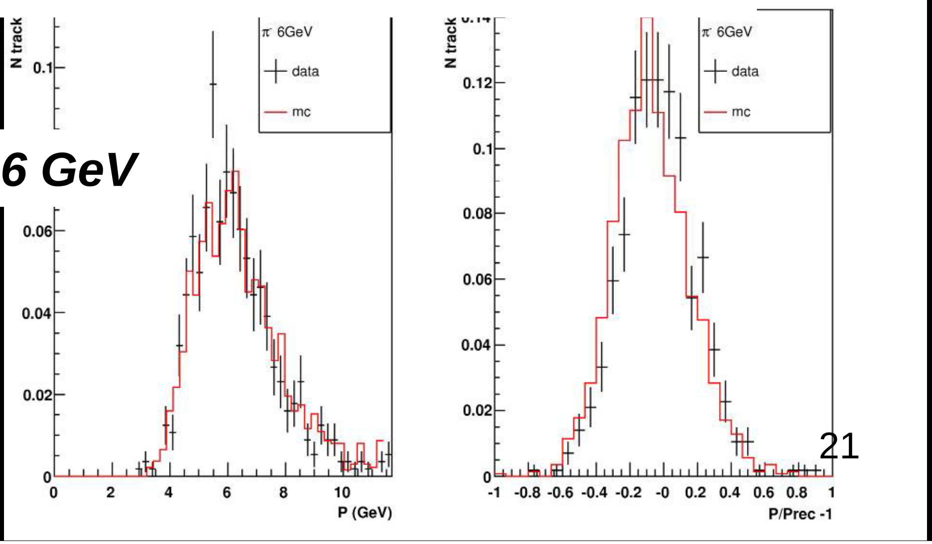




Pion 2 GeV

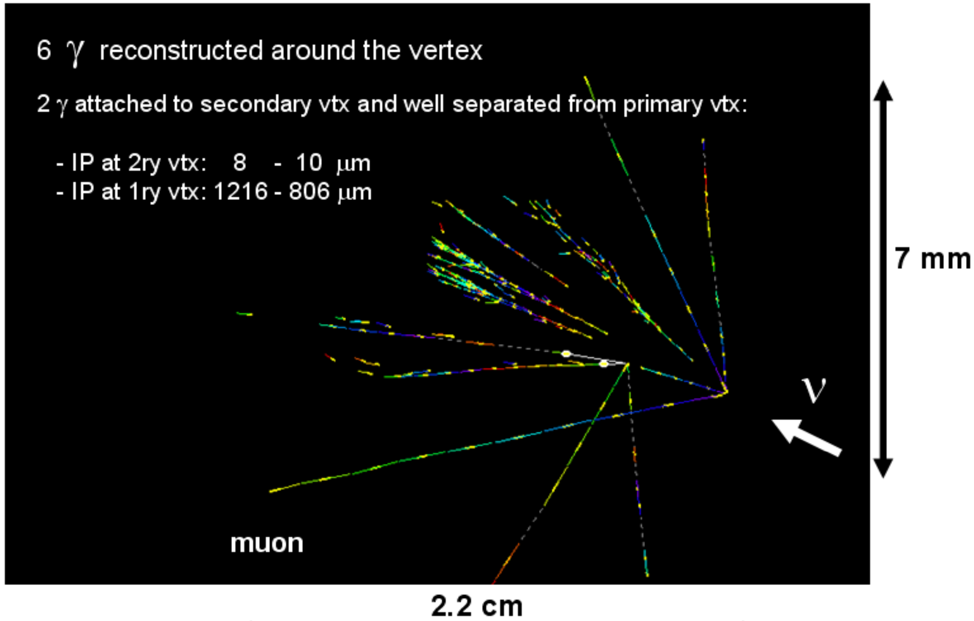


Pion 6 GeV



Example of reconstructed γ's in real neutrino interactions

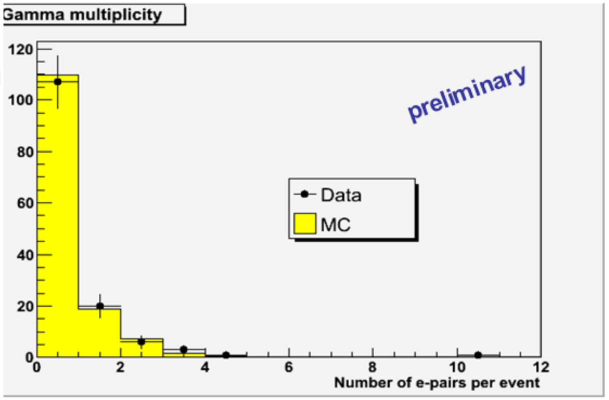
Example of Gamma to vertex attachment



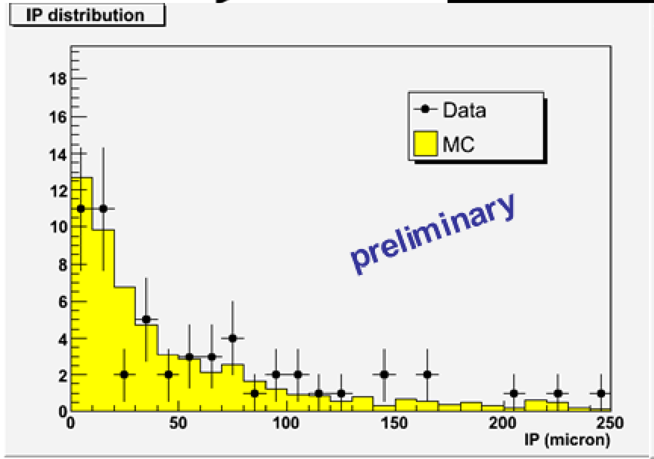
6 γ reconstructed around the vertex

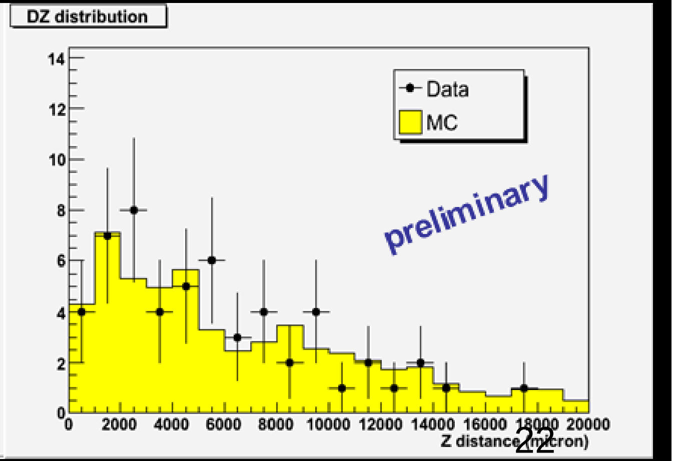
2 γ attached to secondary vtx and well separated from primary vtx:

- IP at 2ry vtx: 8 - 10 μm
- IP at 1ry vtx: 1216 - 806 μm



Comparison data/MC for the Gamma multiplicity in ν_μ CC+NC events



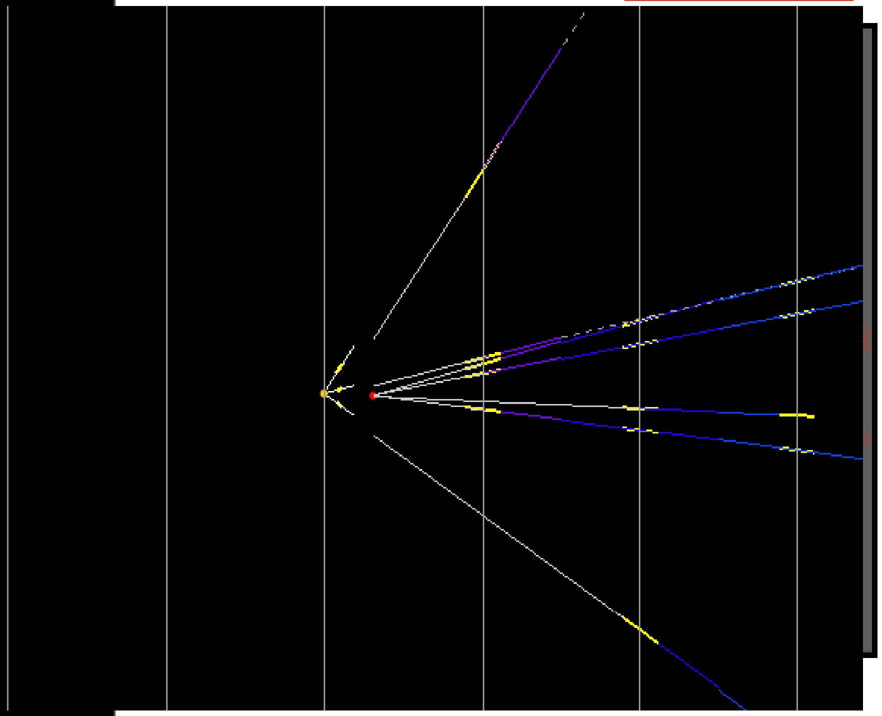


Important for τ hadronic decay channels (signal vs background discrimination)

Topological identification and kinematical confirmation

Event 234654975

Brick 85405



VERTEX 1

	Impact Parameter
Track 1	1,36
Track 2	0,88
Track 7	0,51

X	66716,60
Y	49892,8
Z	90,9

Primary vertex

VERTEX 2

	Impact Parameter
Track 3	1,13
Track 4	1,81
Track 5	1,99
Track 6	1,39

X	66710,10
Y	49899
Z	403,9

Decay vertex

D^0

Tx	Ty	Flight Length (μm)	phi	minimum mass (GeV/c^2)
-0,0207	0,0198	313,1	173,2°	1,7

OLD NUMBERS!!!!

Expected number of background events

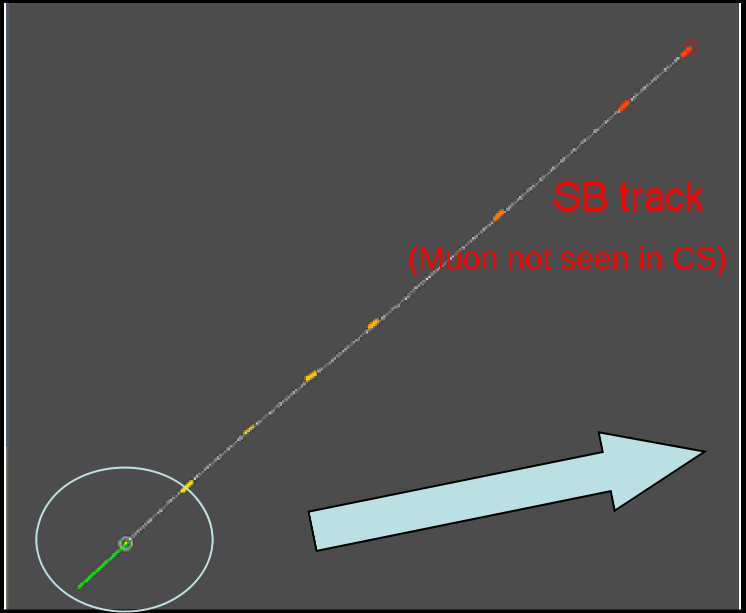
(5 years run, nominal intensity)

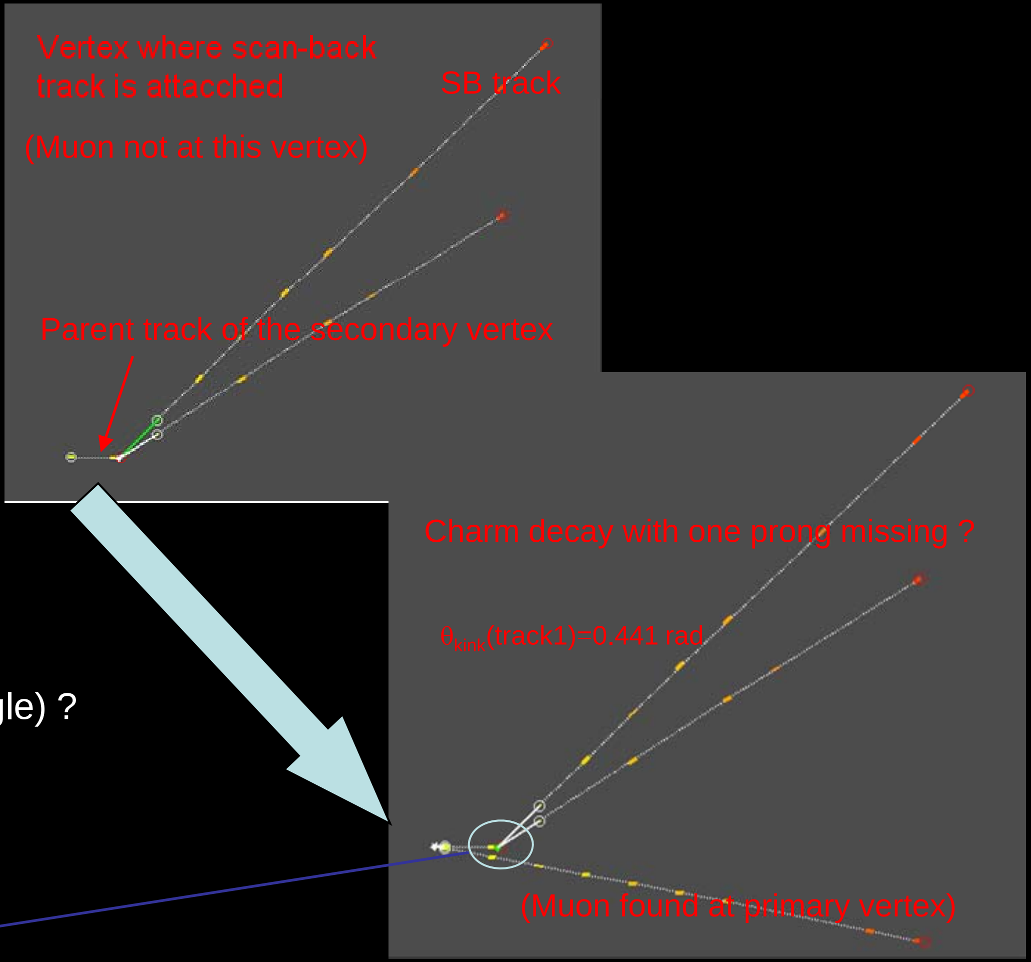
	τ→e	τ→μ	τ→h	total
Charm background	.210	.010	.162	.382
Large angle μ scattering		.116		.116
Hadronic background		.093	.116	.209
Total per channel	.210	.219	.278	.707

1. Charm background :
   - Based on CHORUS cross-section measurements
2. Large angle μ scattering :
   - Upper limit from past measurements used so far
   - Calculations including nuclear form factors give a factor 5 less
3. Hadronic background :
   - Estimates based on Fluka standalone : 50% uncertainty

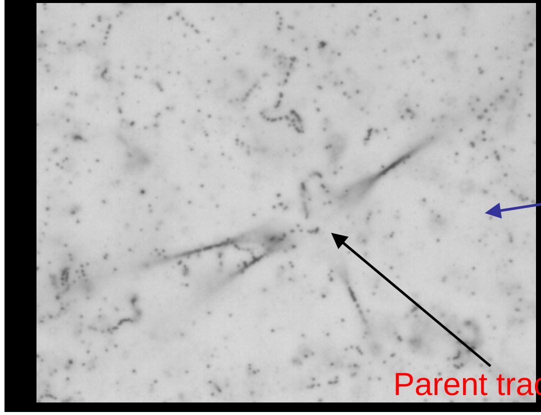
Hadronic background is suppressed by applying severe kinematical cuts
→ the τ detection efficiency is strongly affected
Charm background could be reduced to the one of the muonic channel if the charge of the daughter particles is measured

A lucky event!



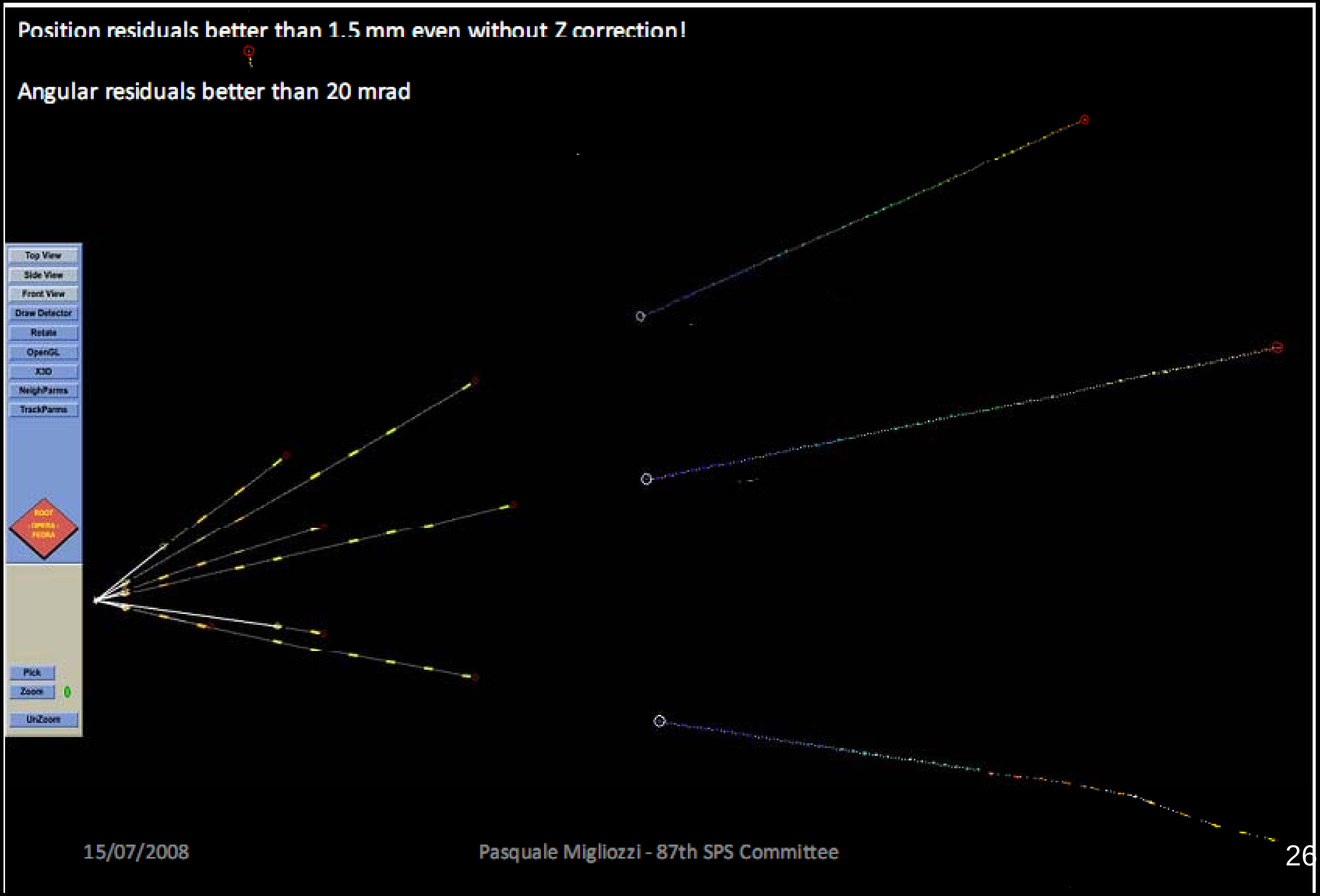


Charged charm candidate with one prong not reconstructed or hadronic interaction (large angle) ?



For this particular event an unforeseen extra handle allows to clarify its nature: the decay vertex is just at the surface of the downstream lead plate, nuclear fragments backscattered are visible in the emulsion upstream
→ It is an hadronic interaction and not a charm

Brick to brick connection



Position residuals better than 1.5 mm even without Z correction!

Angular residuals better than 20 mrad

OPERA experience

PROS

- Large mass easily available
- Both the topology and the kinematics of the event can be efficiently measured
- Previous achievements are possible thanks to the available scanning power and the ECC technology

CONTRA

- The charge of the daughter particles is not measured

I see no bottleneck!

ν_τ prompt background

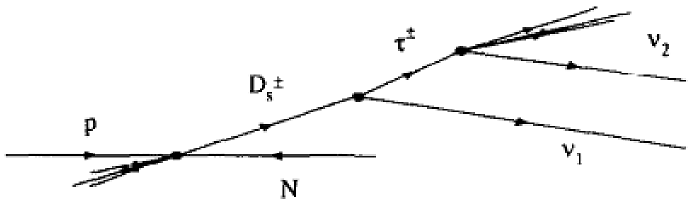


Fig. 3. $D_s^\pm$ production and decay.

TABLE I. $N_{\nu_\tau}CC/N_{\nu_\mu}CC$ for 450 GeV protons on Be and Fe for the CHORUS experiment.

α_ψ	$\frac{\sigma(pA\to D_s^-)}{\sigma_{\rm in}(pA)}$	$\langle E_{\nu_\tau 1}\rangle$	$\mathrm{Acc}_{\nu_\tau 1}$	$\langle E_{\nu_\tau 2}\rangle$	$\mathrm{Acc}_{\nu_\tau 2}$	$\frac{N_{\nu_\tau}CC1}{N_{\nu_\mu}CC}$	$\frac{N_{\nu_\tau}CC2}{N_{\nu_\mu}CC}$
		pBe					
0	$1.\times 10^{-4}$	20	8.2×10^{-4}	52	1.8×10^{-3}	2.6×10^{-7}	2.1×10^{-6}
-2.2	1.7×10^{-4}	17	6.7×10^{-4}	45	1.4×10^{-3}	2.7×10^{-7}	2.3×10^{-6}
		pFe					
0	1.7×10^{-4}	21	3.2×10^{-3}	51	6.8×10^{-3}	1.2×10^{-7}	$1.\times 10^{-6}$
-2.2	3×10^{-4}	17	2.5×10^{-3}	44	5.5×10^{-3}	1.2×10^{-7}	1.1×10^{-6}

TABLE III. $N_{\nu_\tau}CC/N_{\nu_\mu}CC$ for a future experiment running at the SPS beam at 350 GeV and 120 GeV.

$E_{\rm lab}$	$\frac{\sigma(pA\to D_s^-)}{\sigma_{\rm in}(pA)}$	$\langle E_{\nu_\tau 1}\rangle$	$\mathrm{Acc}_{\nu_\tau 1}$	$\langle E_{\nu_\tau 2}\rangle$	$\mathrm{Acc}_{\nu_\tau 2}$	$\frac{N_{\nu_\tau}CC1}{N_{\nu_\mu}CC}$	$\frac{N_{\nu_\tau}CC2}{N_{\nu_\mu}CC}$
		pBe					
350	1.1×10^{-4}	13.	3.7×10^{-4}	36.	7.4×10^{-4}	7.4×10^{-8}	8.1×10^{-7}
120	1.8×10^{-5}	5.3	8.6×10^{-5}	18.	1.1×10^{-4}	2.8×10^{-9}	6.1×10^{-8}
		pFe					
350	1.9×10^{-4}	13	1.5×10^{-3}	35.	2.9×10^{-3}	3.8×10^{-8}	3.8×10^{-7}
120	3.2×10^{-5}	5.2	3.3×10^{-4}	18	4.5×10^{-4}	1.4×10^{-9}	3.1×10^{-8}

Which strategy?

CHORUS

- About 100000 ν_μCC events collected in the emulsion target
- Expected background about 100 event
- Back/Signal $\approx 10^{-3}$

OPERA

- About 30000 ν_μCC events collected in the emulsion target
- Expected background about 1 event
- Back/Signal $\approx 10^{-5}$

Charm background

	τ→e	τ→μ	τ→h	total
Charm background	.210	.010	.162	.382

If one could measure the electron and hadron charge
→ the background for e and h channels could be brought to the μ one

	τ→e	τ→μ	τ→h	total
Charm background	.010	.010	0.010	0.03

In the optimistic case a reduction factor of about 10 could be achieved

Note that I'm assuming a muon acceptance as the OPERA one. Maybe some improvement is still possible

Muon scattering background

	τ→e	τ→μ	τ→h	**total**
Large angle μ scattering		.116		.116

Tricky background and difficult to estimante:

- GEANT gives a larger value (about a factor 10). Upper limit from past measurements used so far
- Calculations including nuclear form factors give a factor 5 less

	τ→e	τ→μ	τ→h	**total**
Large angle μ scattering		.020		.020

In the optimistic case a reduction factor of about 5 could be achieved

Hadronic background

	$\tau \to e$	$\tau \to \mu$	$\tau \to h$	total
Hadronic background		.093	.116	.209

In an experiment à la OPERA the main limitation comes from the impossibility to detect nuclear recoils

$$\lambda_{WKCHORUS} \approx 20\text{ m} \qquad \lambda_{WKOPERA} \approx 1\text{ m}$$

	$\tau \to e$	$\tau \to \mu$	$\tau \to h$	total
Hadronic background		.005	.006	.01

In the ideal that nuclear recoils are detected in an experiment à la OPERA, a reduction factor of about 20 could be achieved

Summarizing

- In the ideal case the background rate we could expect in an experiment à la OPERA, but with “lead having” micrometric resolution is $\approx 1\mathrm{x}10^{-6}$
- Remember that with 120 GeV protons the background from prompt ν_τ is $\approx 10^{-(8\div 9)}$
- Note that the previous estimates do not include a possible optimization of the analysis

Emulsion gel

(from M. Nakamura talk)

	CHORUS	OPERA	Current exp.
Target Mass	800kg	1300ton	10ton?
Gel Mass	800kg	30ton	1~10 ton?
# of Films	600	9.3M	100K~10K

- Price: \200M \2G

- Current Emulsion supplier:

  Fuji (Japan)

  Slavich (Russia)

Scanning technique

(from M. Nakamura talk)

	CHORUS	OPERA	Planning exp.
Scan Area	1 m^2/4year	100m^2/year	20m^2???
# of events	500K/4year	4K/year	10M
# of Films	600	9.3M	100K~10K
System	NTS / UTS	SUTS	SUTS
Speed	~1cm2/h	100cm2/h	100cm2/h
LOAD	5 Years	1 Year	3 months

The European Scanning System has a speed of 20cm2/h, but the number of available microscopes is larger than in Japan (about a factor 5)

Conclusion

To be written!