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SINP MSU Moscow
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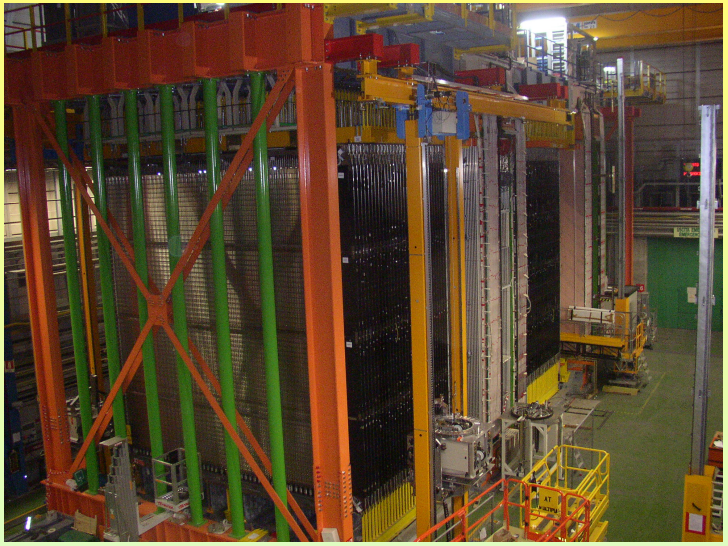


Updated results of the OPERA long baseline neutrino experiment

On behalf of the OPERA Collaboration

S.Dusini – INFN Padova

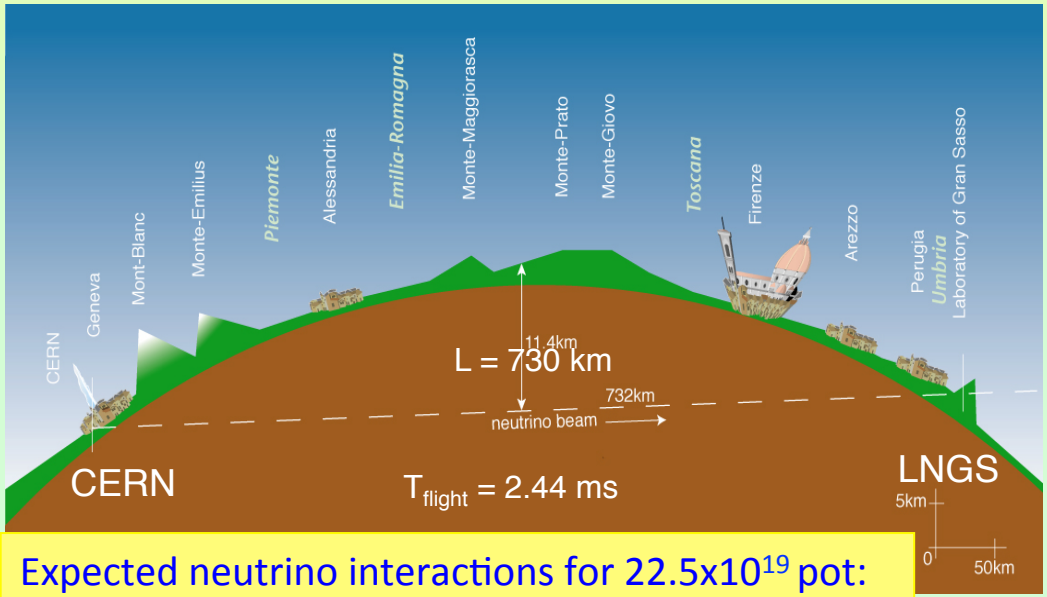
INFN Sezione di Padova

OPERA

OPERA experiment

The aim of OPERA experiment is the direct detection of neutrino oscillation in appearance mode in the $\nu_\mu \rightarrow \nu_\tau$ channel, an important missing tile in the neutrino oscillation physics.

Requirment: 1) long baseline, 2) high neutrino energy, 3) high beam intensity, 4) large mass, 5) detect short lived τ's



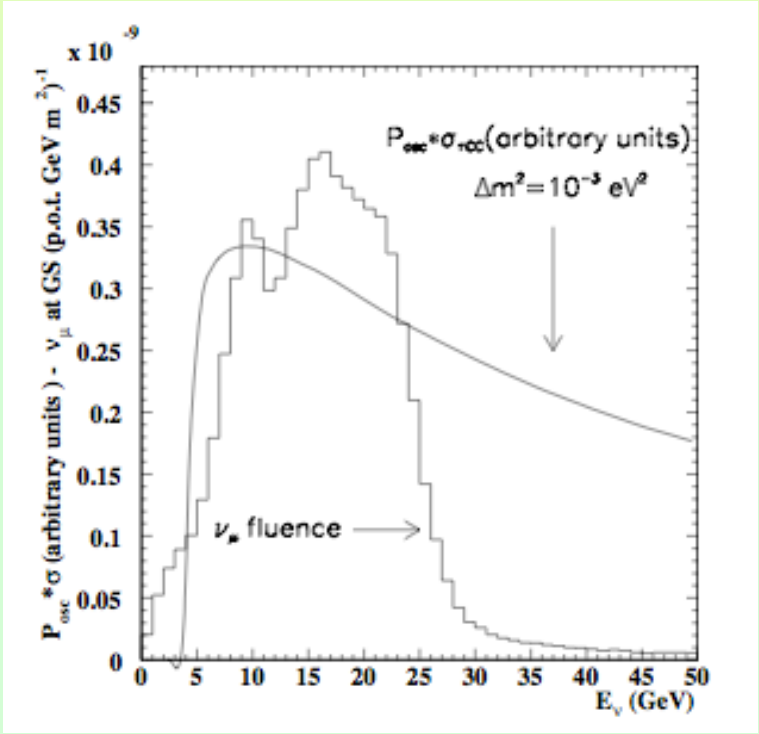
Expected neutrino interactions for 22.5×10^{19} pot:

~ 23600 ν_μ CC + NC

~ 520 anti-ν_μ CC + NC

~ 160 ν_e + anti-ν_e CC

~ 115 ν_τ CC ($\Delta m^2 = 2.5 \times 10^{-3}$ eV^2)

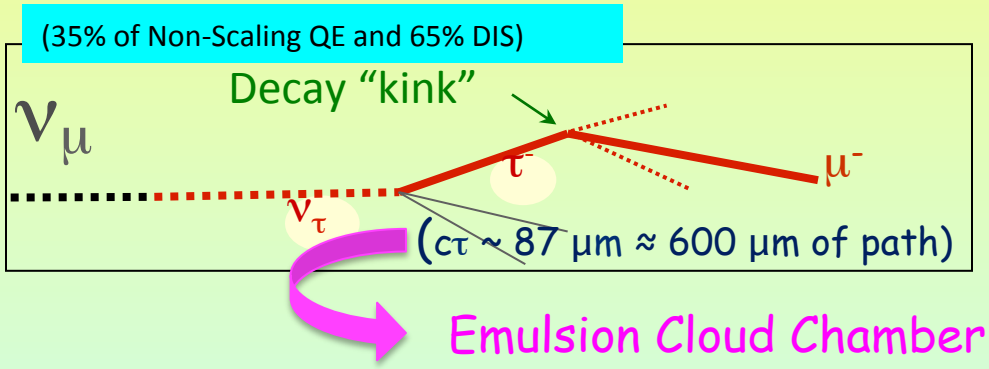


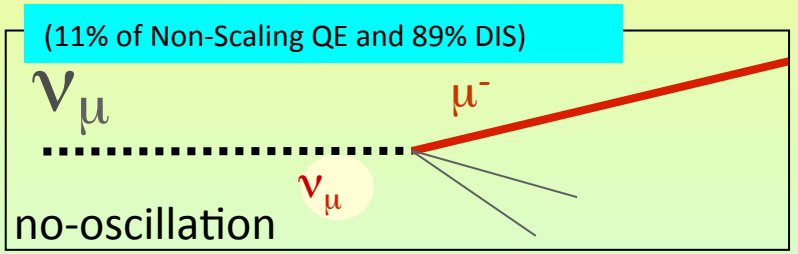
How to detect a tau

The separation of the $\nu_\tau CC$ from the dominant ν_μ interactions is based on the identification, event-by-event, of the peculiar decay topology of the τ.

oscillation

$$\nu_\mu \rightarrow \nu_\tau + N \rightarrow \tau^- + X$$

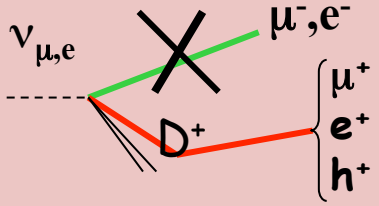




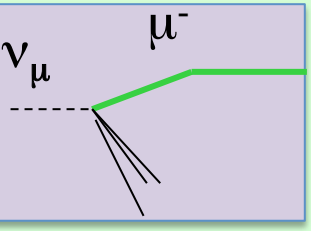
Emulsion Cloud Chamber = sandwich of lead plate and emulsion films

Background components:

Production of charmed particles in CC interactions (all decay channels)

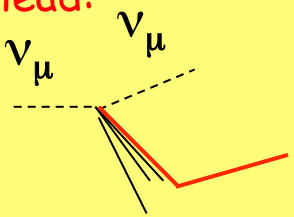


Coulomb large angle scattering of muons in lead
Bck. to $\tau \rightarrow \mu$

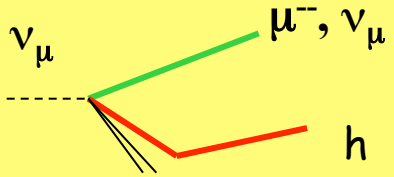


Hadronic interactions in lead:

Bck. to $\tau \rightarrow$ h



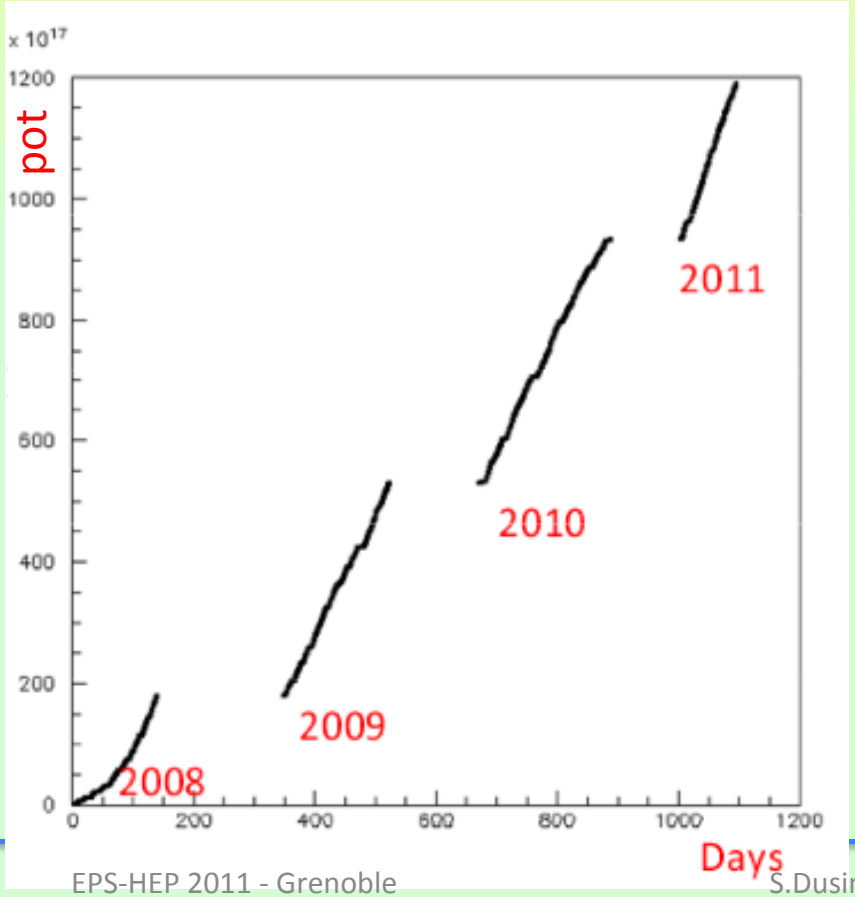
or to $\tau \rightarrow \mu$
(if hadron misid or mismatched with muon)



CNGS beam performance

Year	Beam days	Protons on target	SPS Eff.	Events in the bricks
2008	123	1.78×10^{19}	61%	1698
2009	155	3.52×10^{19}	70%	3693
2010	187	4.04×10^{19}	81%	4248
2011	Ongoing	2.86×10^{19}	79%	2858

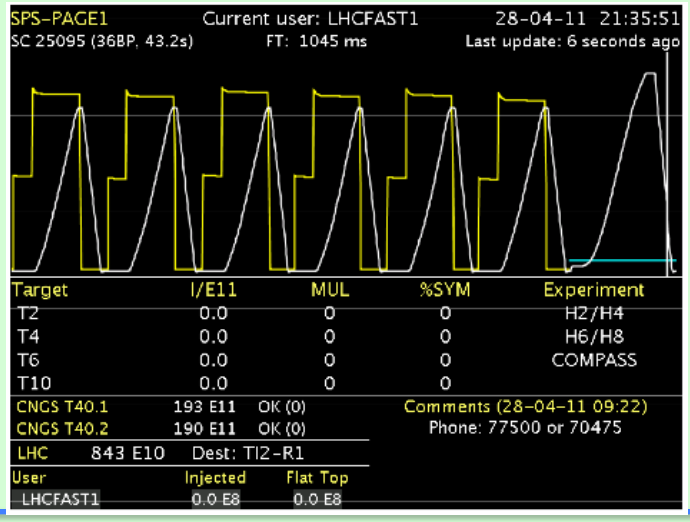
As 4/07/2011



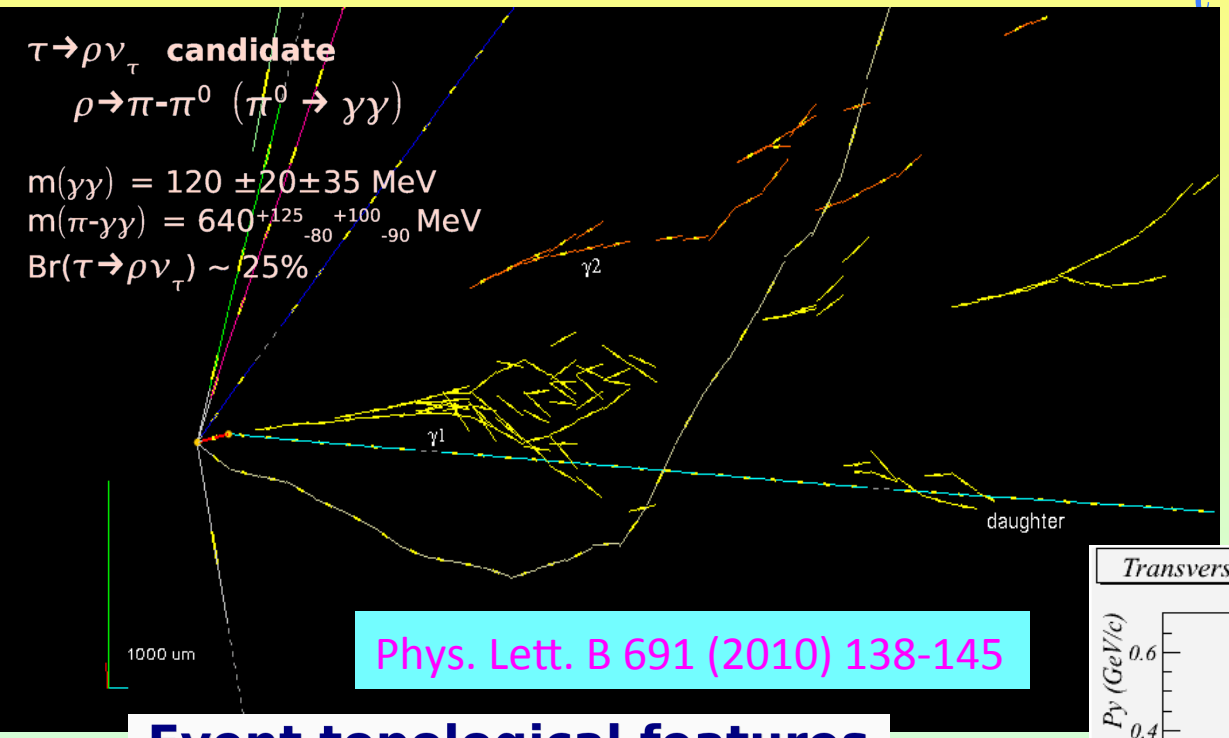
In 2011 in dedicated mode (no other fixed target exp.) from March 18th to June 7th

Expected to run for 223 days

➔ ≈5×10^{19} pot



Observation of first ν_τ candidate



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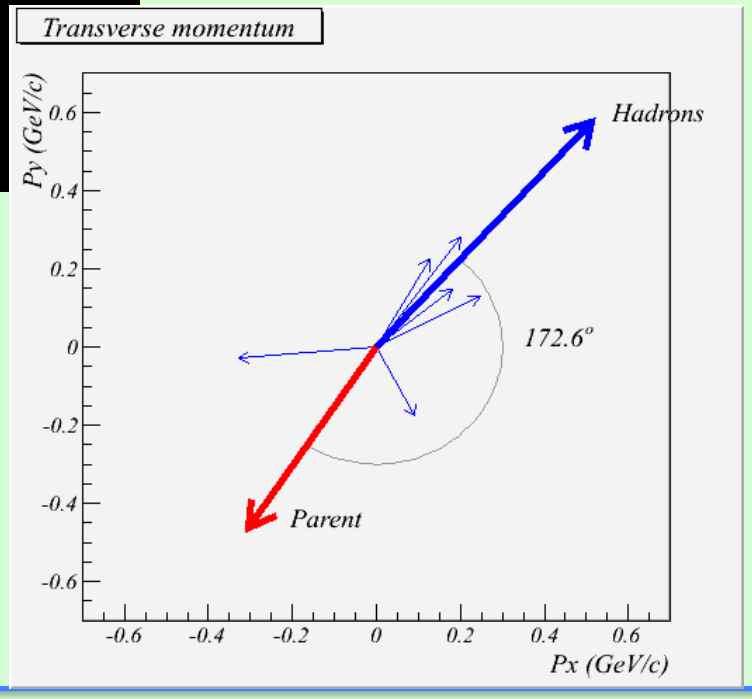
- In spring 2010 OPERA present the first ν_τ candidate base on the analysis of 35% of '08/'09 statistics.
- Data selection was done using the cuts defined at the time experimental proposal (2001)

Event topological features

Variable	Value	Selection criteria
kink (mrad)	**41±2**	**> 20**
decay lenght (μm)	**1335±35**	**≤ 2 Pb plates**
P daughter (GeV/c)	**12+6-3**	**> 2**
Pt (MeV/c)	**470+230-120**	**> 300**
missing Pt (MeV/c)	**570+320-170**	**< 1000**
Azimuth angle (deg)	**173±2**	**> 90**



Update and improvements of the analysis

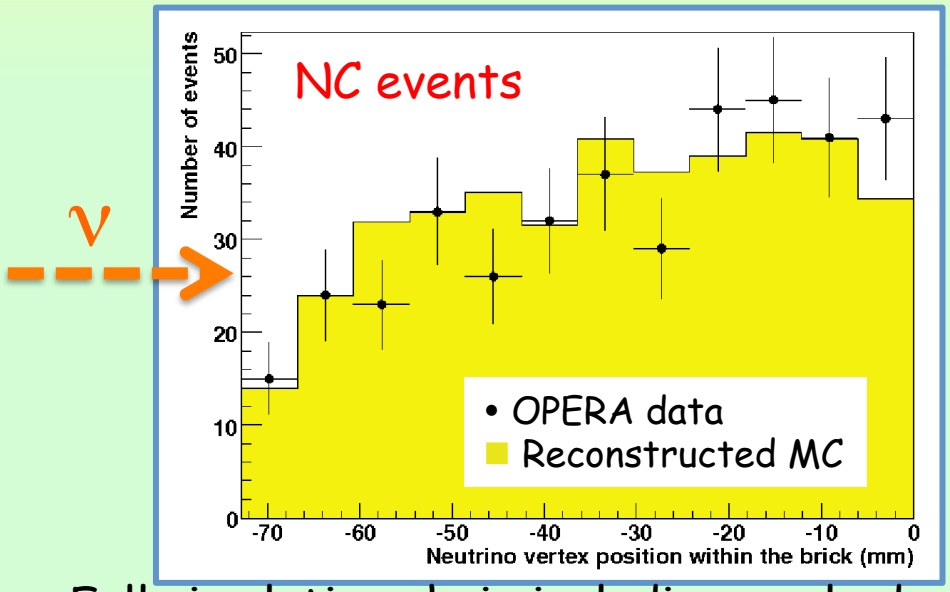
- Completed (92%) the 2008-2009 data analysis = 4.8 10^{19} pot
  - Statistic 2.6 larger then previous publication
- Improvements in signal and background based on:
  - Search of highly ionizing tracks in hadronic interactions
  - Follow down of the tracks in the emulsion to reduce
    - charm background searching for muons not observed by the Electronic Detector
    - Hadronic background due to muon mis-matched to hadrons
  - Full simulation chain with emulsion off-line reconstruction.
  - Better knowledge of Charm production cross section from CHORUS.

Paper submitted to Physics Letter B, (arXiv:1107.2594 [hep-ex]).

2008-2009 sample

85% are events induced by neutrino interaction outside OPERA target

	0 mu	1 mu	All
Trigger			31576
Events predicted by the electronic detector	1503	3752	5255
Located in dead material	54	245	299
Interactions located in the ECC	519	2280	2799
Decay search performed	494	2244	2738



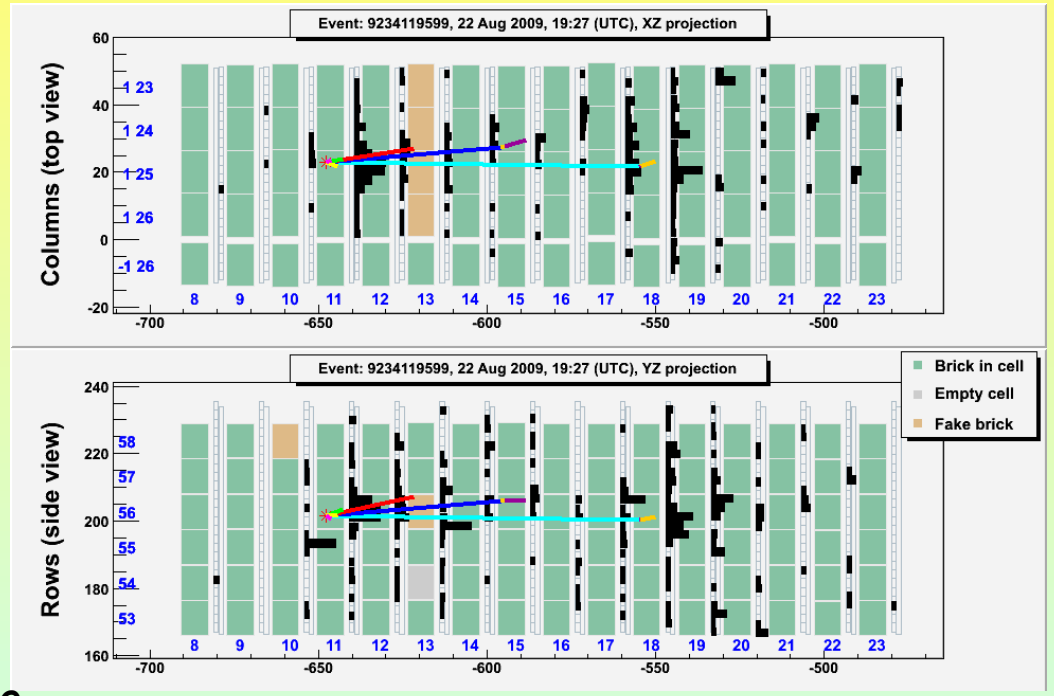
This corresponds to the 92% of the expected sample that could be decay searched: 2978±75

Location efficiency:
74% for CC
48% for NC

Full simulation chain including newly developed off-line emulsion reconstruction software

Track follow down

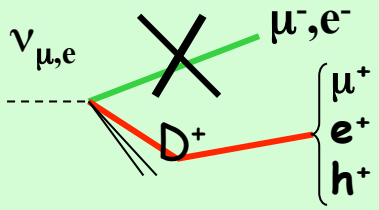
For the first ν_τ candidate we followed down all the tracks to search for possible muon not identified by
the Electronic Detector



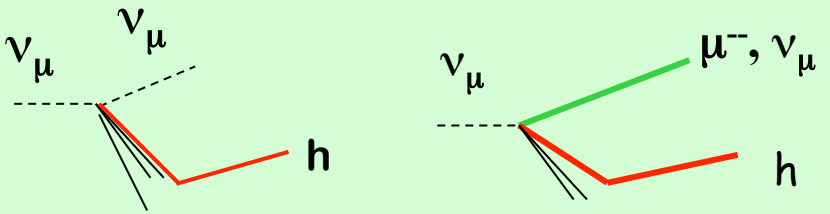
We can suppress backgrounds due to

- Charm
- Hadron interactions in ν_μ CC with misidentified μ ($\tau \to h$ channel)
- Hadron interactions in ν_μ CC and NC ($\tau \to \mu$ channel)

Charm background



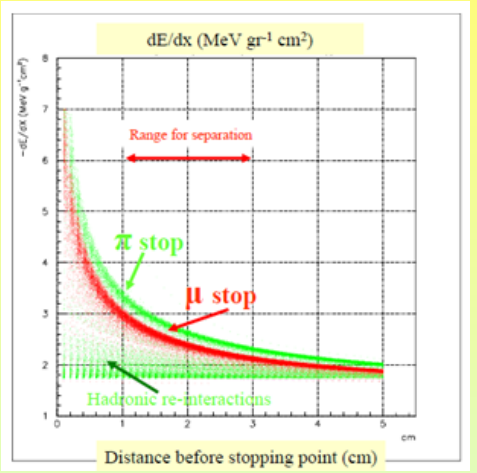
Hadron interactions background



Track Follow Down

Classification of the tracks:

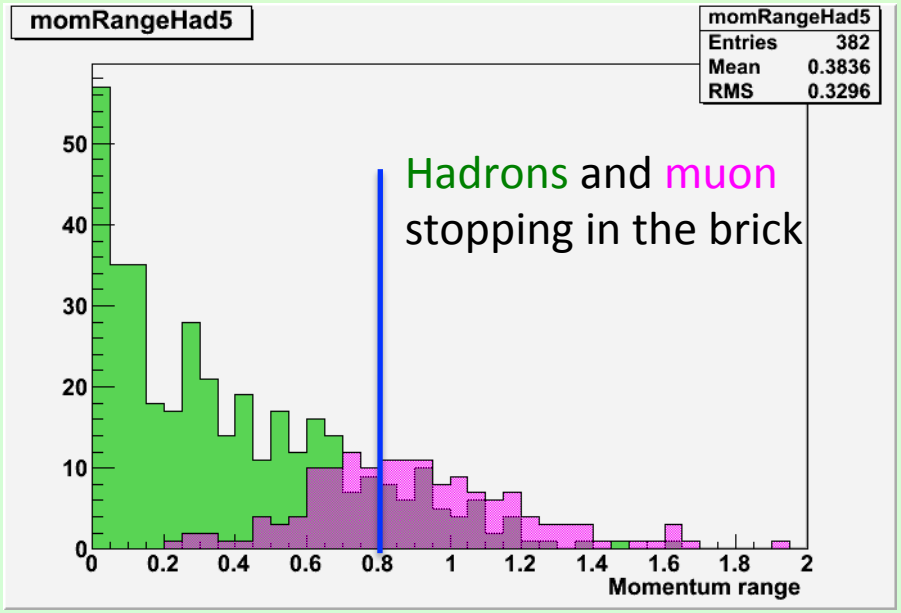
- Interaction visible in the brick
- dE/dx at end point of the track for π/μ separation
- Momentum/Range correlation



Discriminating variable

$$D = \frac{L}{R_{lead}(p)} \frac{\rho_{lead}}{\rho_{average}}$$

L = track length
R_{lead} = moun range in lead
$\rho_{average}$ = average density along the path
ρ_{lead} = lead density
p = momentum measured in the emulsion

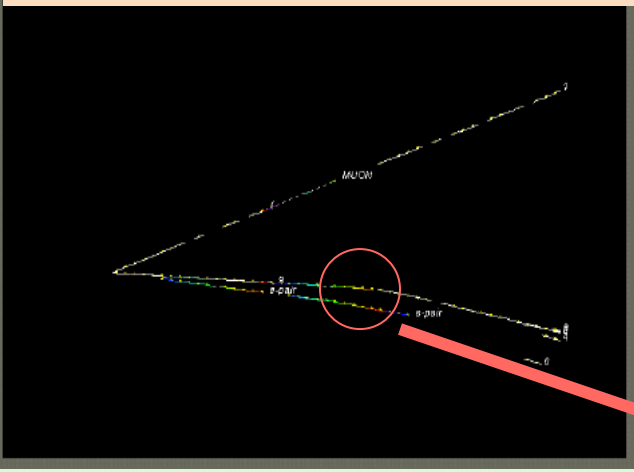


Results:

- Mis-ID muons in Charm events:
  3.28% (34% reduc.)
- 2 orders of magnitude reduction of hadronic background to $\tau \rightarrow \mu$ due to μ mismatch in CC and NC events

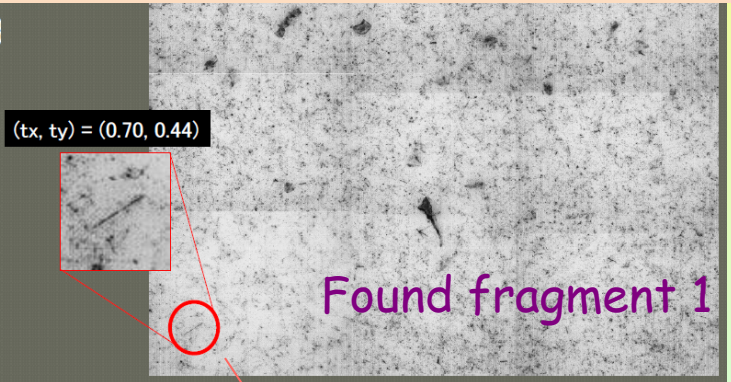
Search for highly ionizing particles in hadron interactions

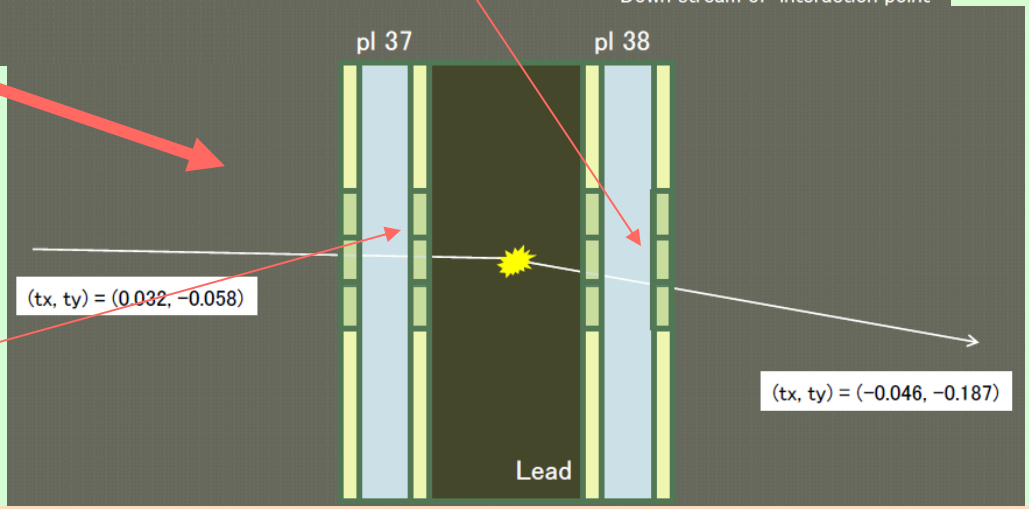
Hadron interactions background can be reduced by increasing the detection efficiency of protons and nuclear fragments emitted in the cascade of intra-nuclear interactions and in nuclear evaporation process

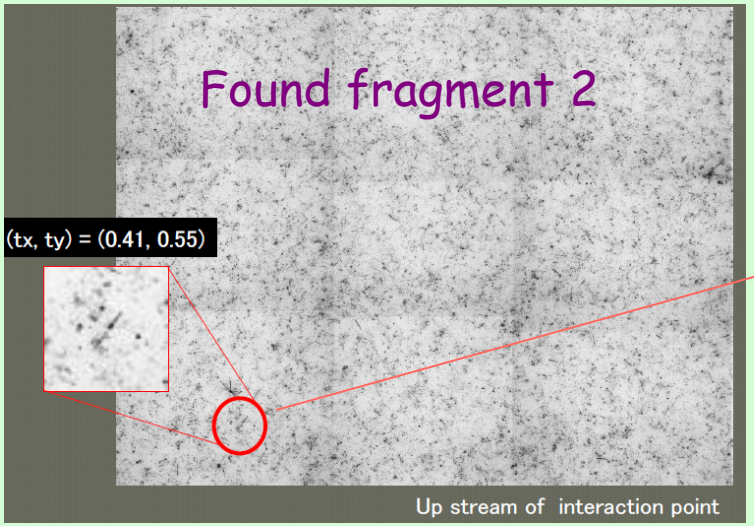


Hadron interaction at pl37 ⇔ pl3
Kink angle = 0.144 rad.
Pt = 0.265 GeV/c

Interaction position
z = 477micron







- Specific tool for scanning
- Validation on the test-beam sample of hadronic interactions
- No highly ionizing particle found in OPERA ν_τ candidate

Test beam for highly ionizing particles search

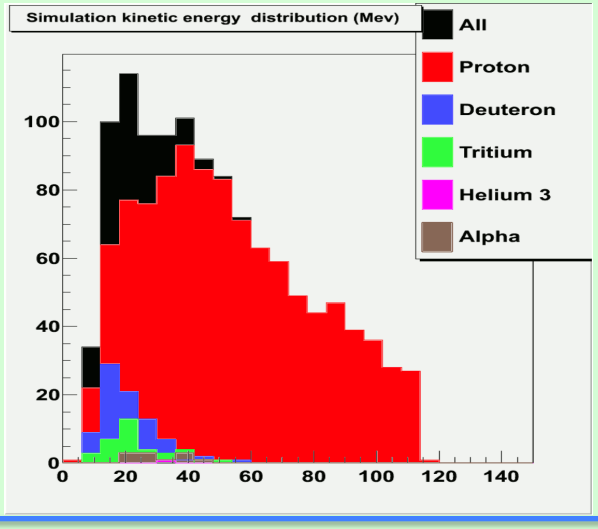
Study of 64 interactions of 8 GeV π^- beam

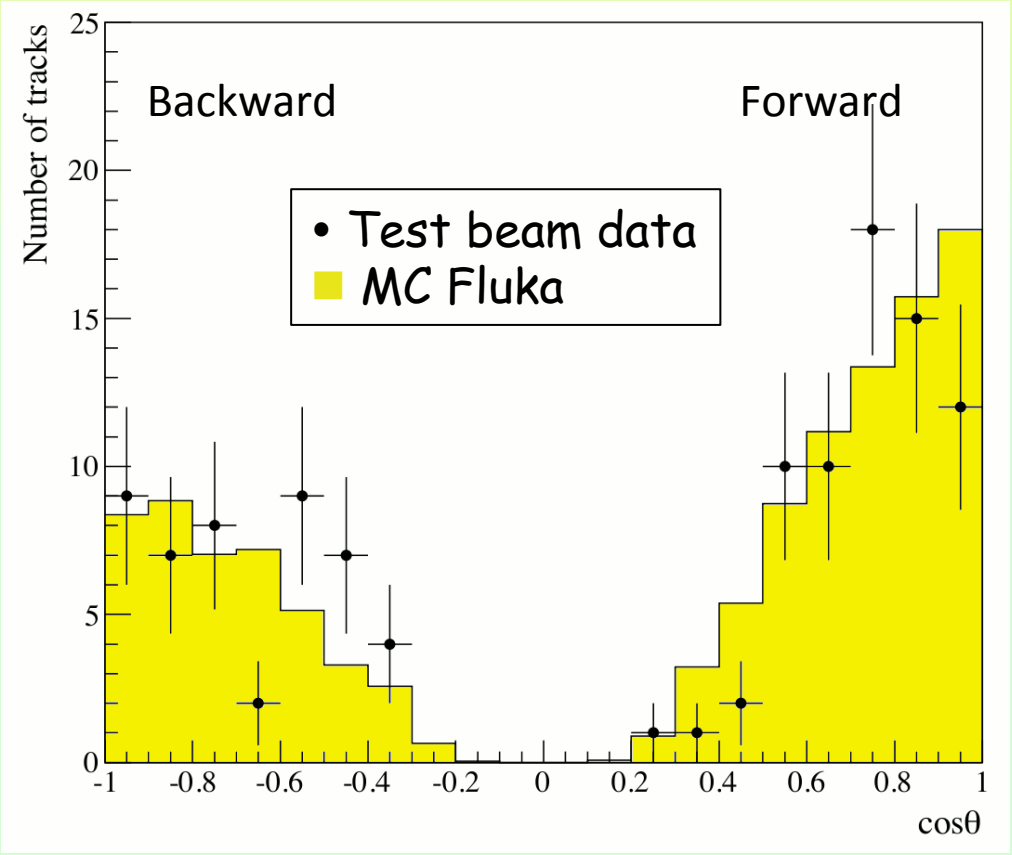
Search of "black" tracks ($\gamma\beta < 0.5$) in a large field of view 2.5x2.1 mm^2

→ Highly ionizing tracks detection in 57±7% of cases

Expected from Fluka : 53%

Forward-backward asymmetry:	0.75 ± 0.15
Expected from Fluka simulation:	0.71





Kink probability

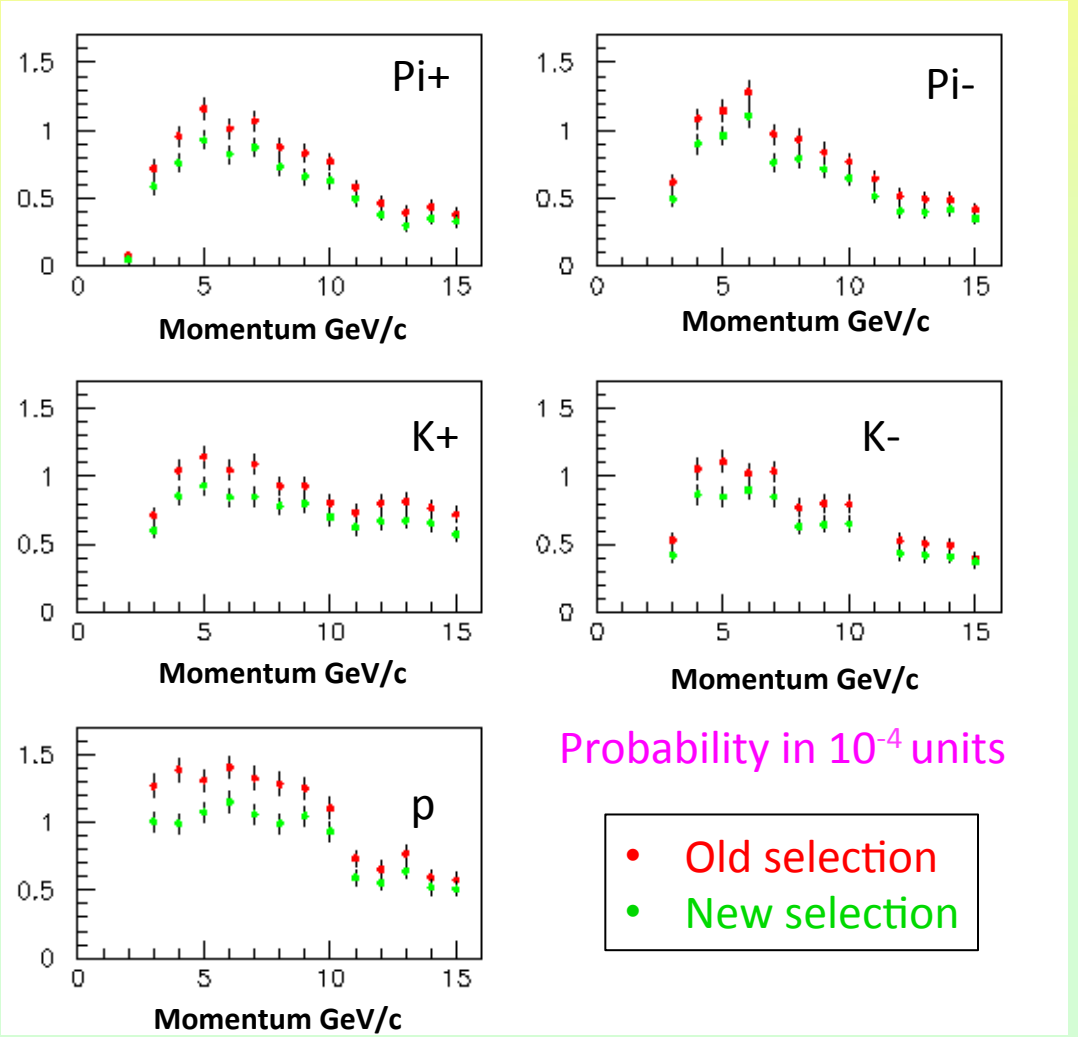
Fluka simulation

Taking into account the larger acceptance of the new scanning tool and the lower momentum threshold for additional protons and fragments the probability for a hadron to produce a single prong "kink" with

- P > 2 GeV
- (P_t > 0.6 GeV) or (P_t > 0.25 GeV + gamma)

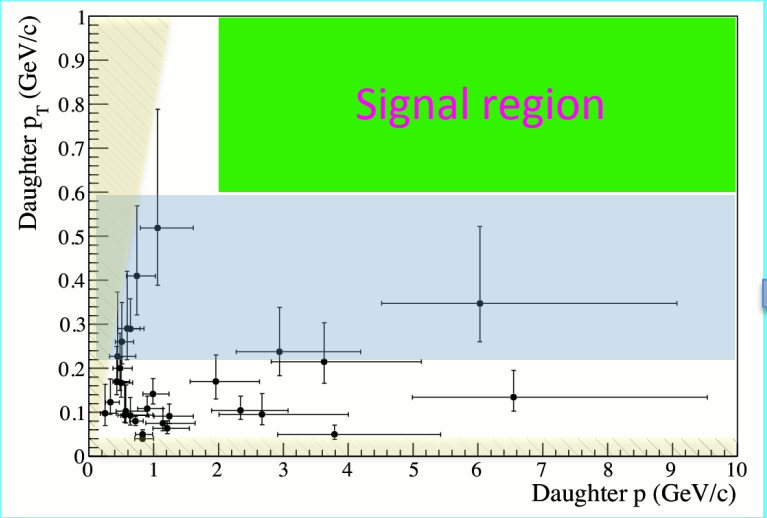
over 2 mm of lead

1.53 x 10^{-4} / NC
-20% previous estimation



Pion interaction studies

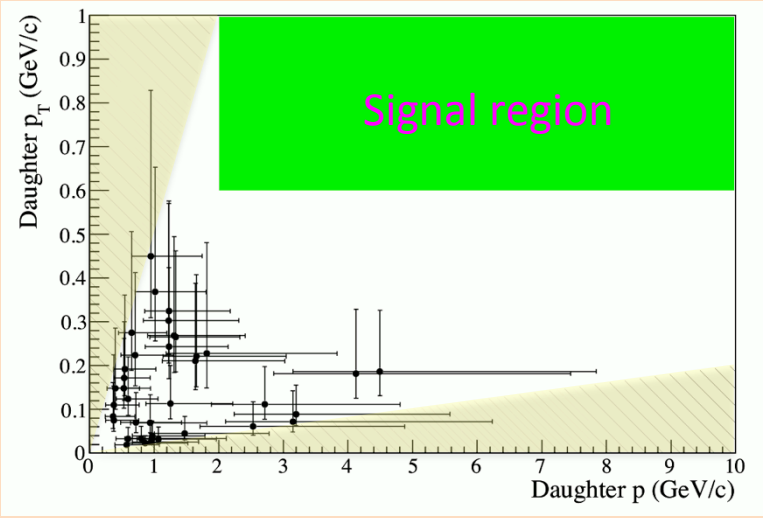
Hadron tracks in OPERA neutrino interactions with kink topology far from primary vertex

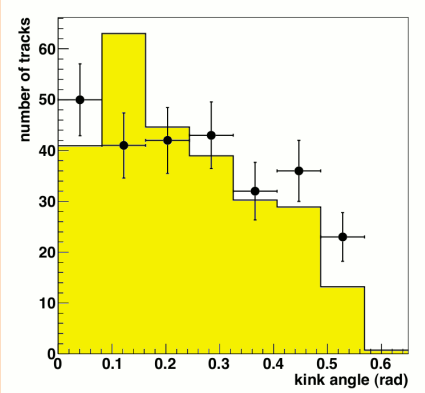


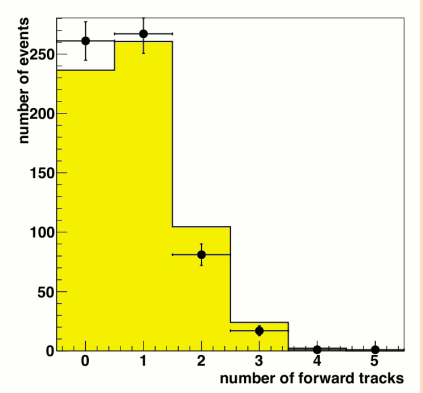
14 m, equivalent to 2300 NC events

No events found in signal region, signal boundary region (Pt>200 MeV/c):
→ 10 events observed (10.8 events expected by updated simulation including black tracks search)

Hadron interactions search in 4 GeV π test beam







Charm cross section and fragmentation

Results recently published by CHORUS - arXiv: 1107.0613 [hep-ex] scaled at OPERA energies

	CHORUS results [%]	@ OPERA [%]
$\sigma(\text{charm}) / \sigma(\nu_\mu CC)$	5.75 ± 0.32(stat) ± 0.30(sys)	4.46
$f(D^+)$	25.3 ± 4.2	21.7
$f(D^0)$	43.7 ± 4.5	43.8
f(L)	19.2 ± 4.2	25.3
$f(D_s)$	11.8 ± 4.7	9.2

Inclusive charm rate	OLD	NEW	Increase
$\sigma(charm) / \sigma(\nu_\mu CC)$	3.3	4.46	+35%

Fragmentation

	OLD	NEW
D^+	10%	21.7%
D_S^+	18%	9.2%
Λ_c^+	26%	25.3%

Muonic BR

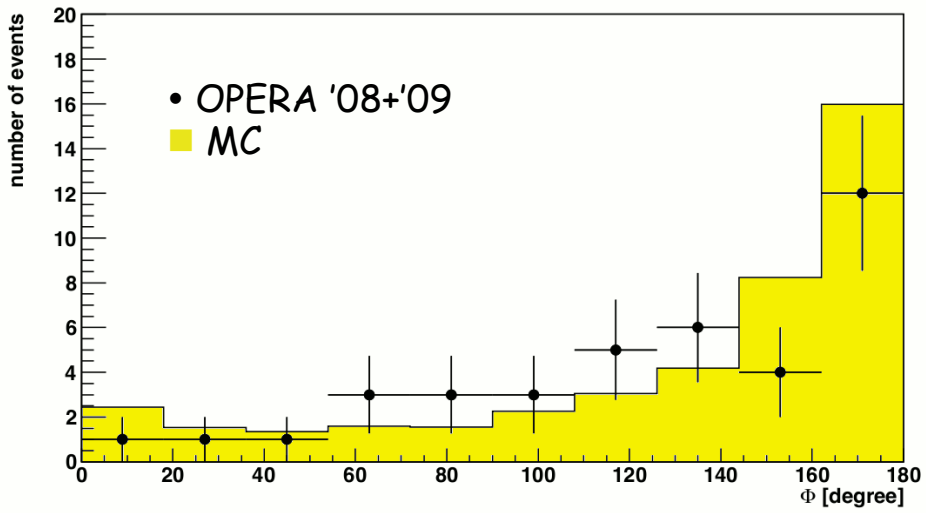
	OLD(1998)	NEW(2010)
D^+	$7\%^{3\%}_{2\%}$	$9.4\% \pm 0.8\%$
D_S^+	$3.4\% \pm 1\%$	$4.4\% \pm 0.7\%$
Λ_c^+	$2.0\% \pm 0.7\%$	$2.0\% \pm 0.7$

The D^+ has the main background contribution to all channels due to the higher efficiency for the kinematical cuts.
The charm background increase goes from x1.57 to x2.43 depending on channel (h-mu)

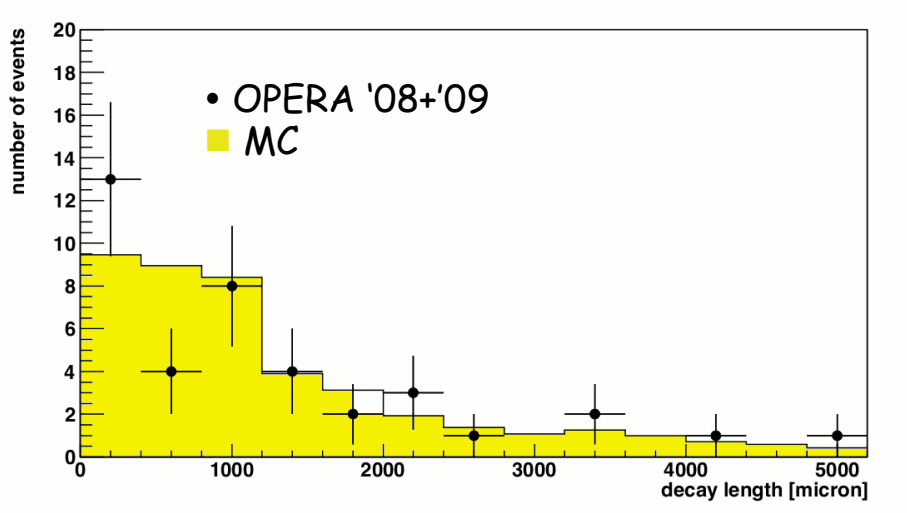
2008-2009 charm sample

Topology	Observed events	Expected events		
		Charm	Background	Total
Charged 1-prong	**13**	15.9	1.9	**17.8**
Neutral 2-prong	**18**	15.7	0.8	**16.5**
Charged 3-prong	**5**	5.5	0.3	**5.8**
Neutral 4-prong	**3**	2.0	<0.1	**2.1**
Total	**39**	39.1±7.5	3.0±0.9	**42.2±8.3**

Angle between the charmed particle and the primary μ in the transverse plane



Decay length of charmed particles



Updated OPERA sensitivity

Including all the improvements in the analysis

Decay channel	Number of signal events expected for $Dm^2 = 2.5\times10^{-3}\ eV^2$	
	22.5×10^{19} p.o.t.	Analysed sample
$\tau \rightarrow \mu$	1.79	0.39
$\tau \rightarrow e$	2.89	0.63
$\tau \rightarrow h$	2.25	0.49
$\tau \rightarrow 3h$	0.71	0.15
Total	7.63	1.65

In the analyzed sample (92% of '08+'09 data) one ν_τ observed in the $\tau \rightarrow h$ channel compatible with the expectation of 1.65 signal events.

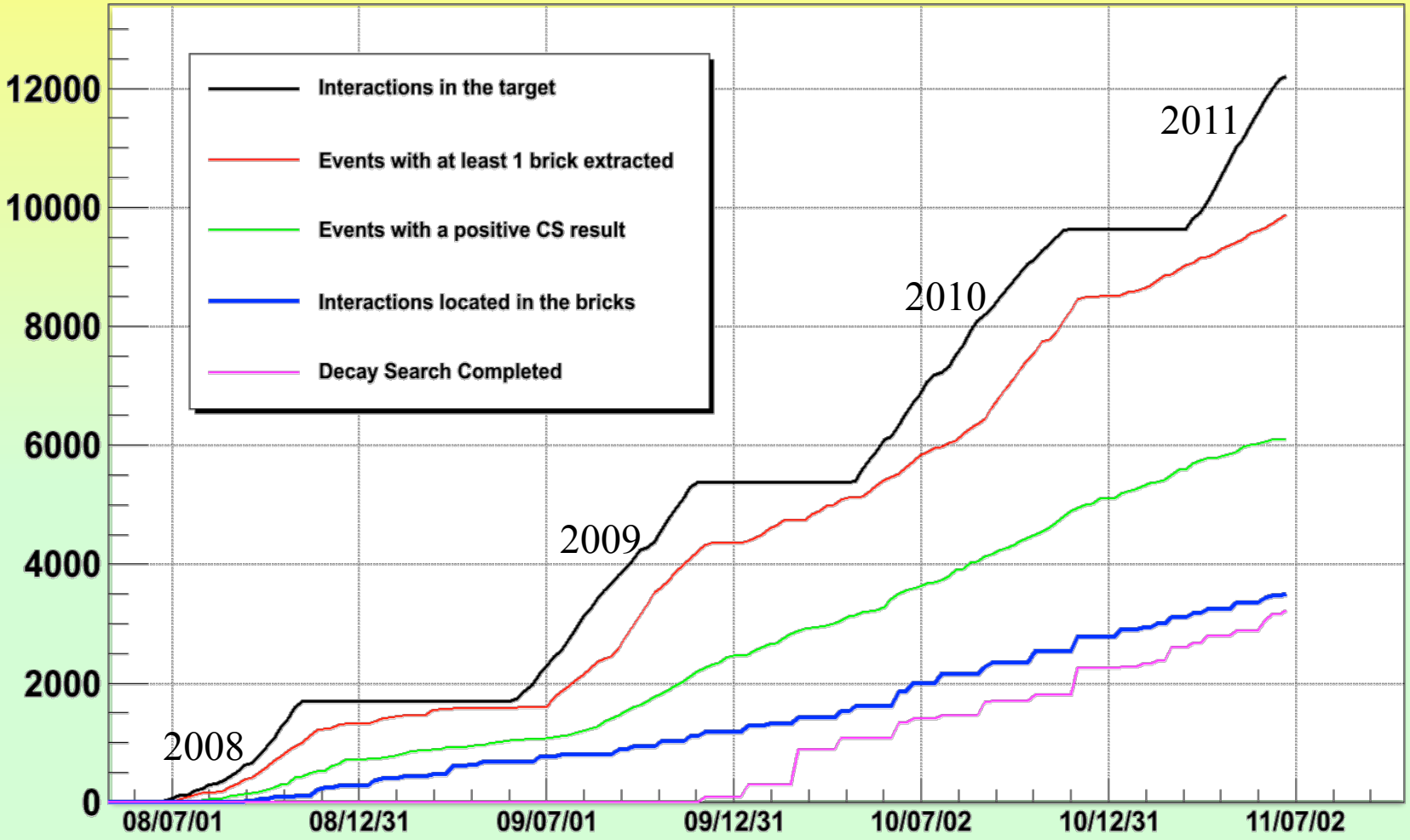
Summary of background

Very clean channel

Decay channel	Number of background events for:							
	22.5×10^{19} p.o.t.				Analysed sample			
	Charm	Hadron	Muon	Total	Charm	Hadron	Muon	Total
$\tau\rightarrow\mu$	0.025	0.00	0.07	0.09±0.04	0.00	0.00	0.02	0.02±0.01
$\tau\rightarrow e$	0.22	0	0	0.22±0.05	0.05	0	0	0.05±0.01
$\tau\rightarrow h$	0.14	0.11	0	0.24±0.06	0.03	0.02	0	0.05±0.01
$\tau\rightarrow 3h$	0.18	0	0	0.18±0.04	0.04	0	0	0.04±0.01
Total	0.55	0.11	0.07	0.73±0.15	0.12	0.02	0.02	0.16±0.03

The expected background in the $\tau \rightarrow h$ channel is 0.05 ± 0.01
The probability of a background fluctuation up to at least one event is 5%.
The total expected background is 0.16 ± 0.03 and the probability a background fluctuation is 15%.

Outlook



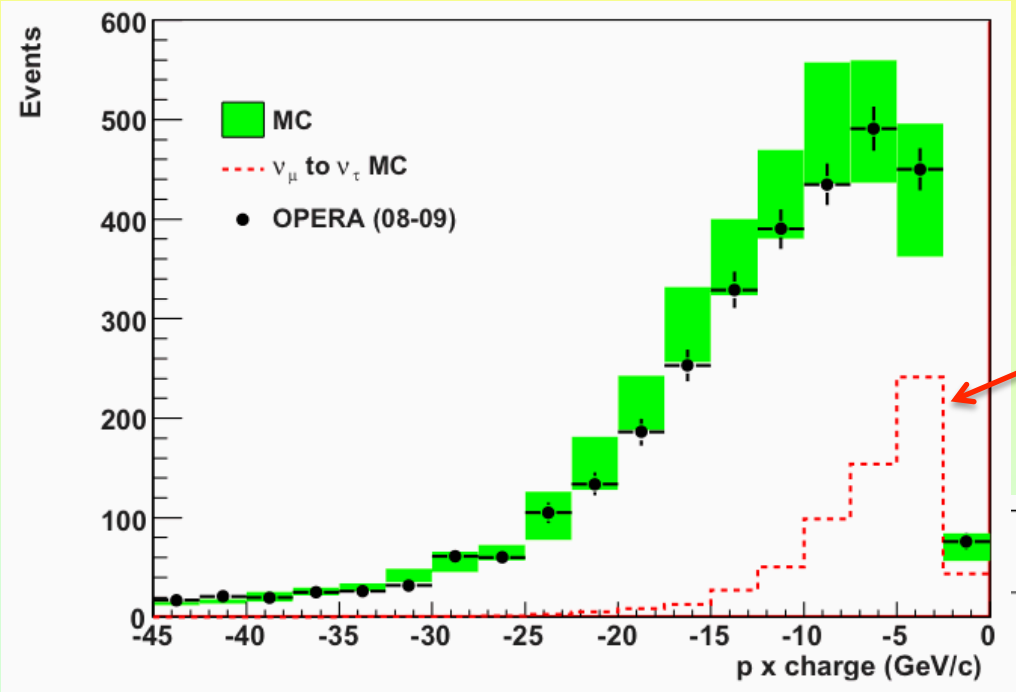
3513 interactions located in the bricks,
3232 "decay searched" events

Summary

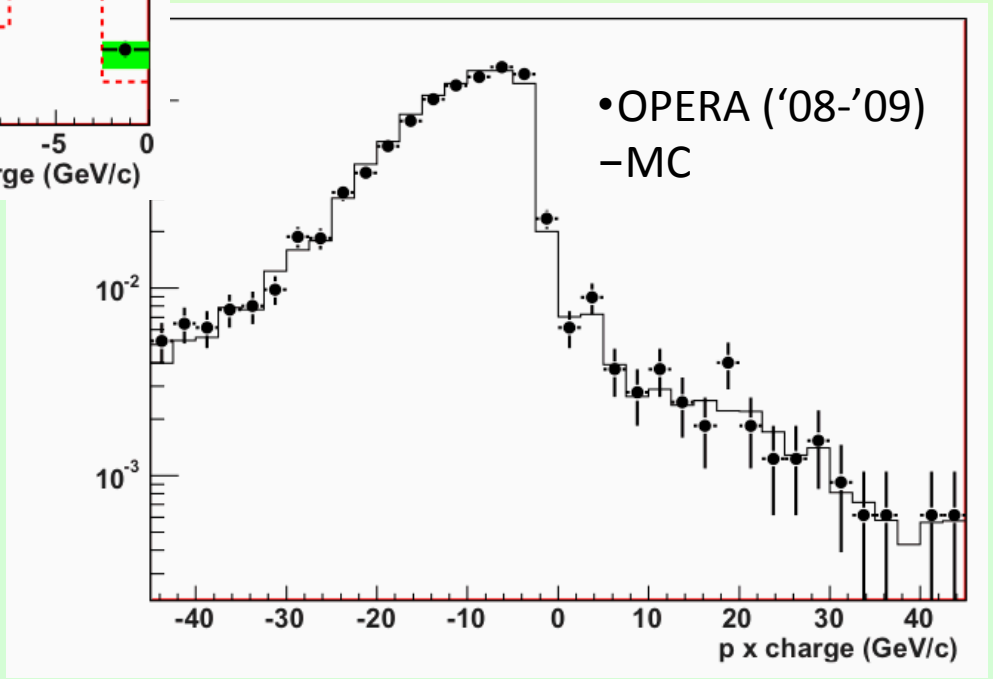
- The analysis **'08-'09** data sample has been **completed** (92%) and submitted to PLB, (arXiv:1107.2594 [hep-ex]).
- Analysed statistic **2.6 larger** then previous publication.
- The signal and background expectations have been updated
  - Full simulation chain with emulsion off-line reconstruction
  - Track Follow Down technique – hadronic background to $\tau \rightarrow \mu$ killed
  - Search for protons/fragments in hadronic interactions
  - New charm cross section (CHORUS paper)
- **One ν_τ observed** in the **$\tau \rightarrow h$ channel** compatible with the expectation of 1.65 signal events and a background of 0.05±0.01.
- Probability of a **background fluctuation is 5%**

Thank you

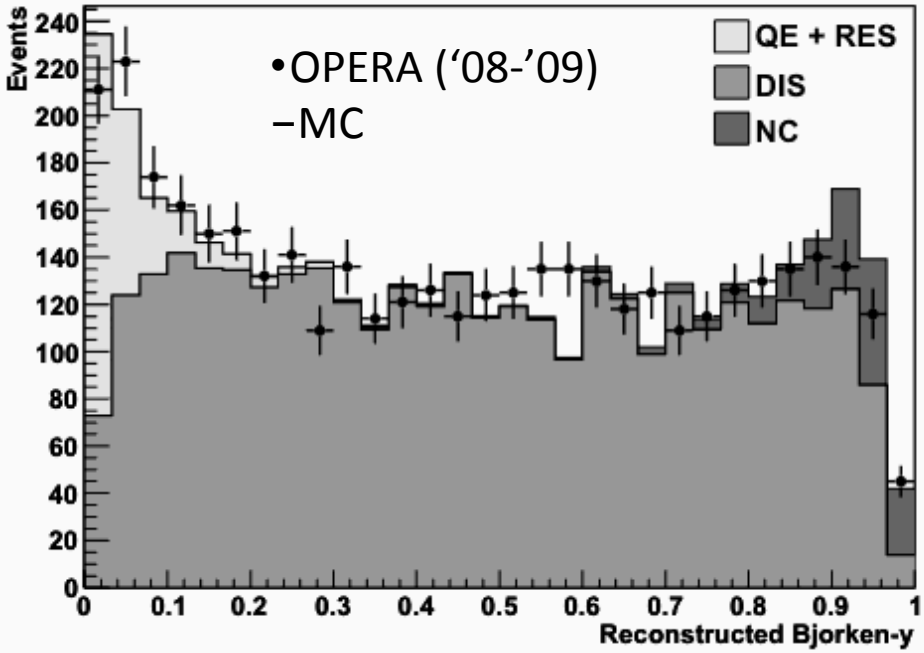
Muon reconstruction with ED

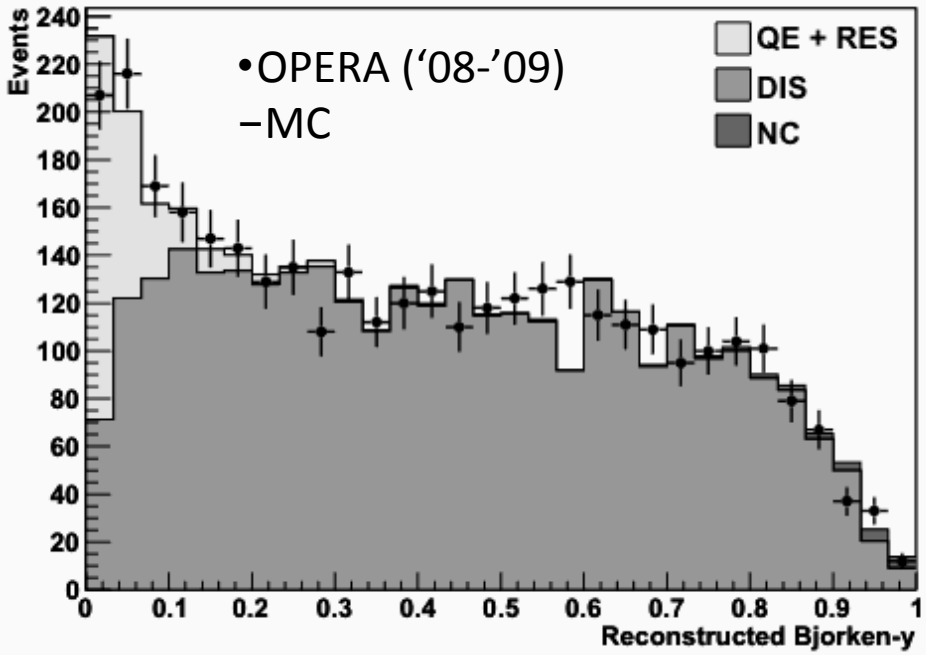


ν_τ signal in arbitrary units



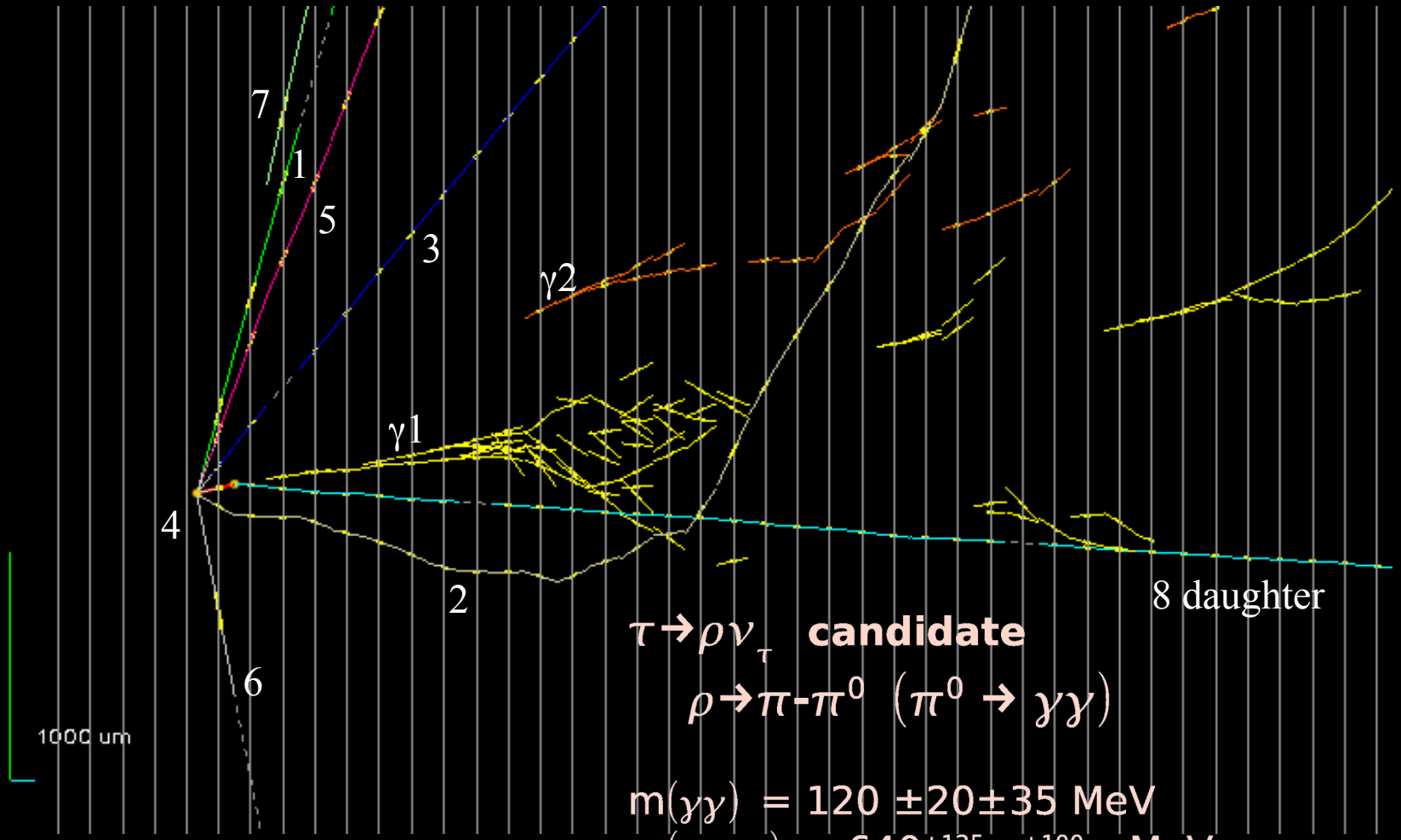
OPERA electronic detector performance





Side view

Event topological features



$\tau \rightarrow \rho \nu_\tau$ **candidate**

$\rho \rightarrow \pi\text{-}\pi^0 \quad (\pi^0 \rightarrow \gamma\gamma)$

$m(\gamma\gamma) = 120 \pm 20 \pm 35$ MeV

$m(\pi\text{-}\gamma\gamma) = 640^{+125}_{-80}{}^{+100}_{-90}$ MeV

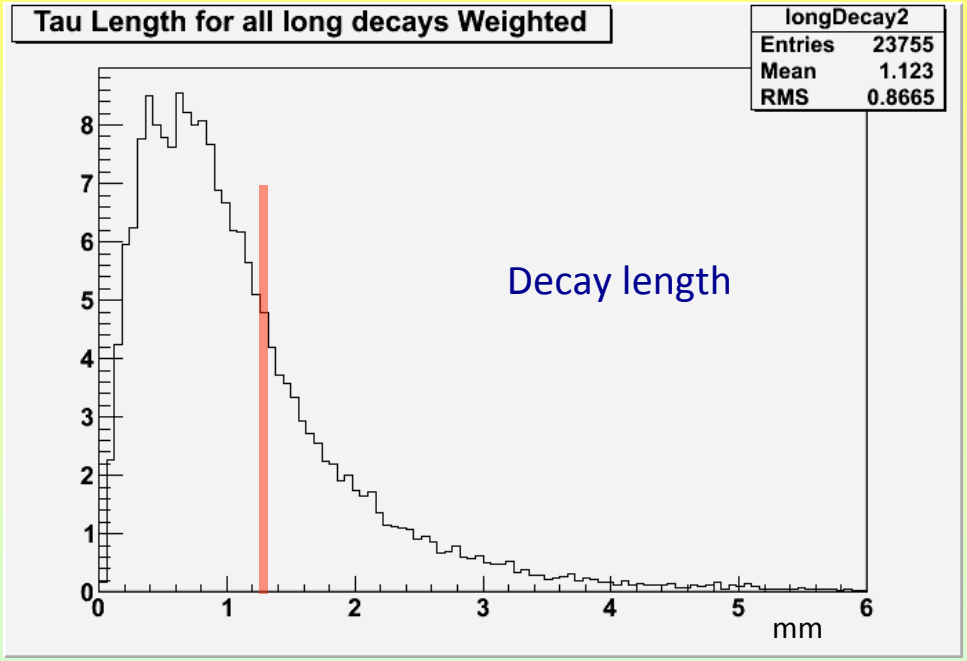
$Br(\tau \rightarrow \rho \nu_\tau) \sim 25\%$

Event tracks' features

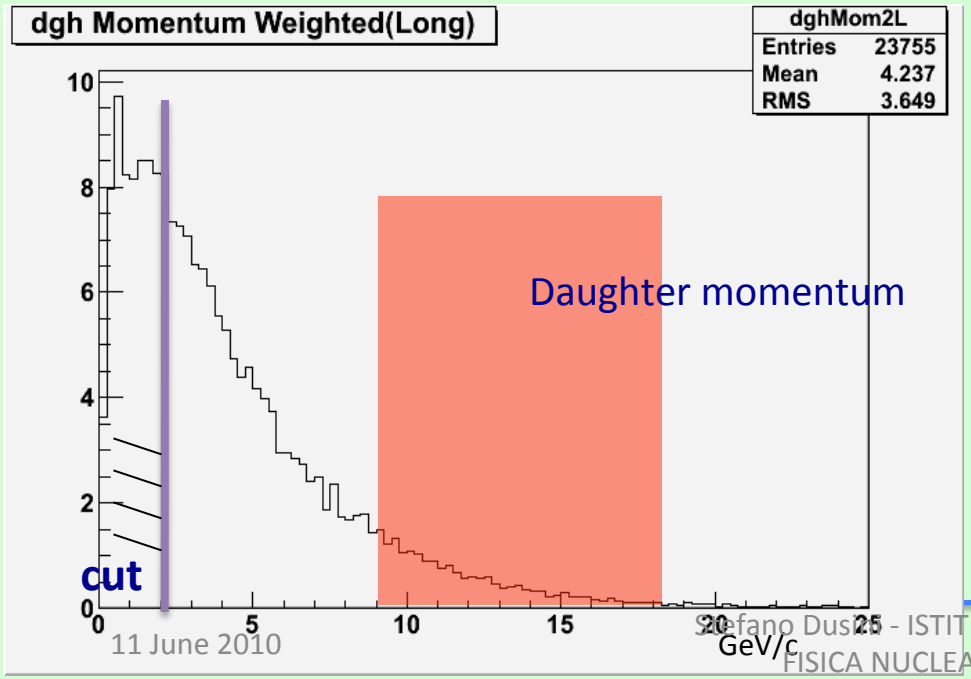
TRACK NUMBER	PID	Probability	MEASUREMENT 1			MEASUREMENT 2		
			tan Θ_X	tan Θ_Y	P (GeV/c)	tan Θ_X	tan Θ_Y	P (GeV/c)
1	HADRON range in Pb/ emul=4.1/1.2 cm	Prob(μ)≈10^{-3}	0.177	0.368	0.77 [0.66,0.93]	0.175	0.357	0.80 [0.65,1.05]
2	PROTON	range, scattering and dE/dx	-0.646	-0.001	0.60 [0.55,0.65]	-0.653	0.001	
3	HADRON	interaction seen	0.105	0.113	2.16 [1.80,2.69]	0.110	0.113	1.71 [1.42,2.15]
4 (PARENT)			-0.023	0.026		-0.030	0.018	
5	HADRON: range in Pb/ emul=9.5/2.8 cm	Prob(μ)≈10^{-3}	0.165	0.275	1.33 [1.13,1.61]	0.149	0.259	1.23 [0.98,1.64]
6	HADRON: range in Pb/ emul=1.6/0.5 cm	Prob(μ)≈10^{-3}				0.334	-0.584	0.36 [0.27,0.54]
7	From a prompt neutral particle		0.430	0.419	0.34 [0.22,0.69]	0.445	0.419	0.58 [0.39,1.16]
8 (DAUGHTER)	HADRON	interaction seen	-0.004	-0.008	12 [9,18]	-0.009	-0.020	

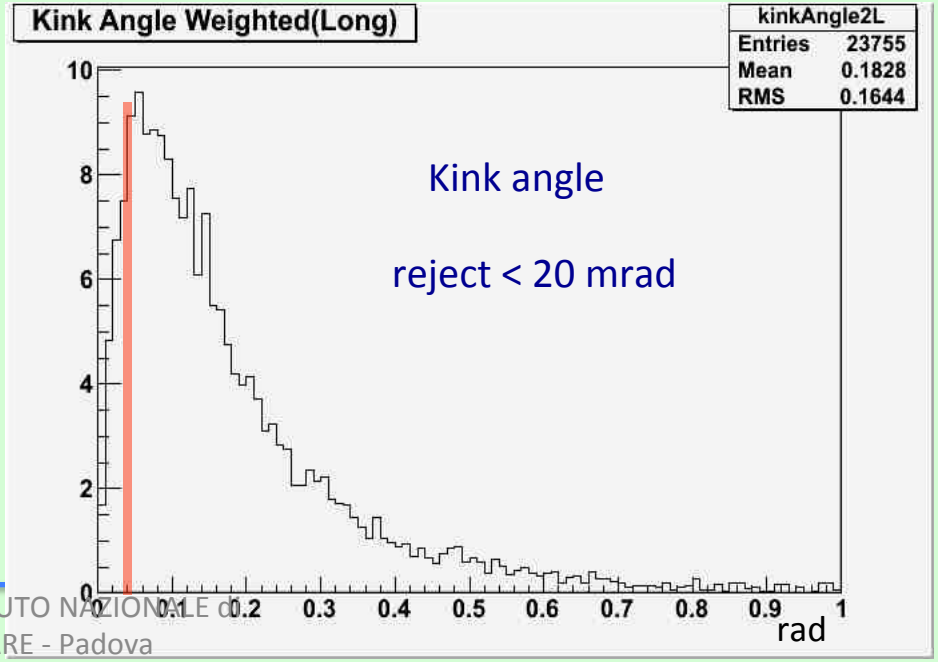
→ muonless event (favored hypothesis)

Features of the decay topology



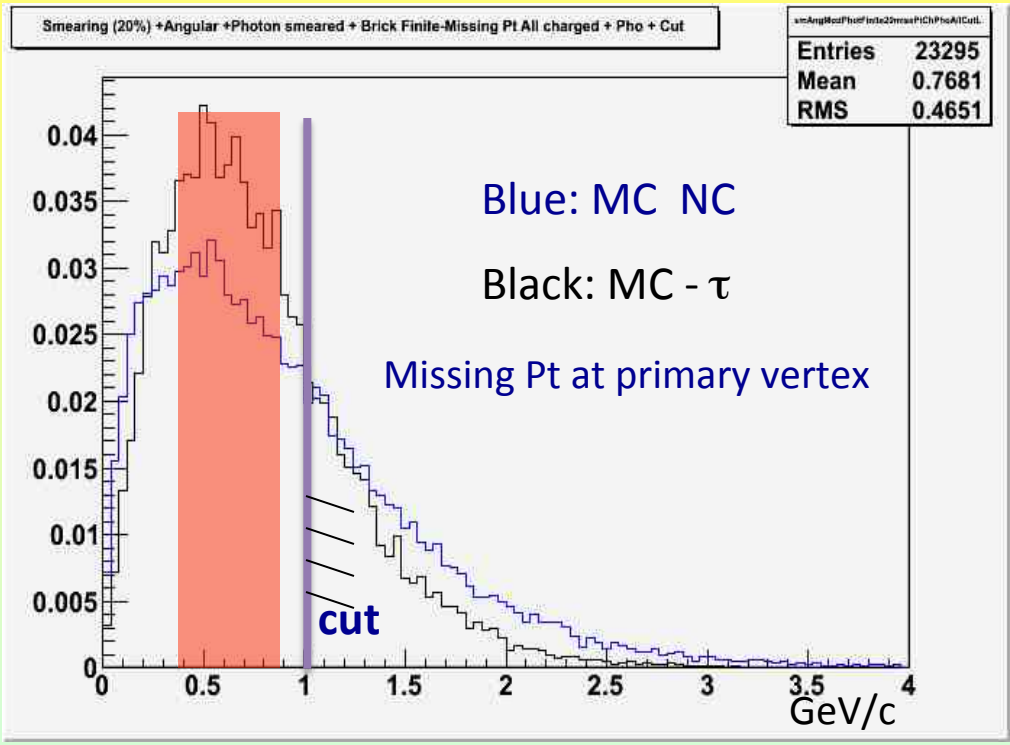
red bands: values for the "interesting" event with uncertainties



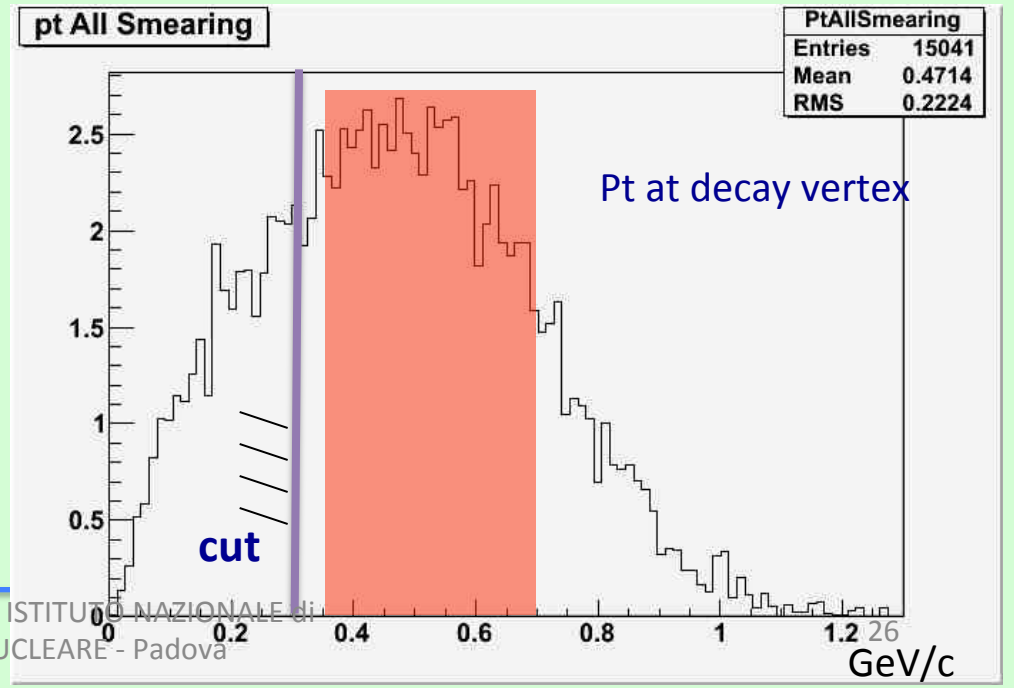


Kinematical cuts to be passed

Reject NC events with larger missing Pt (neutrino)



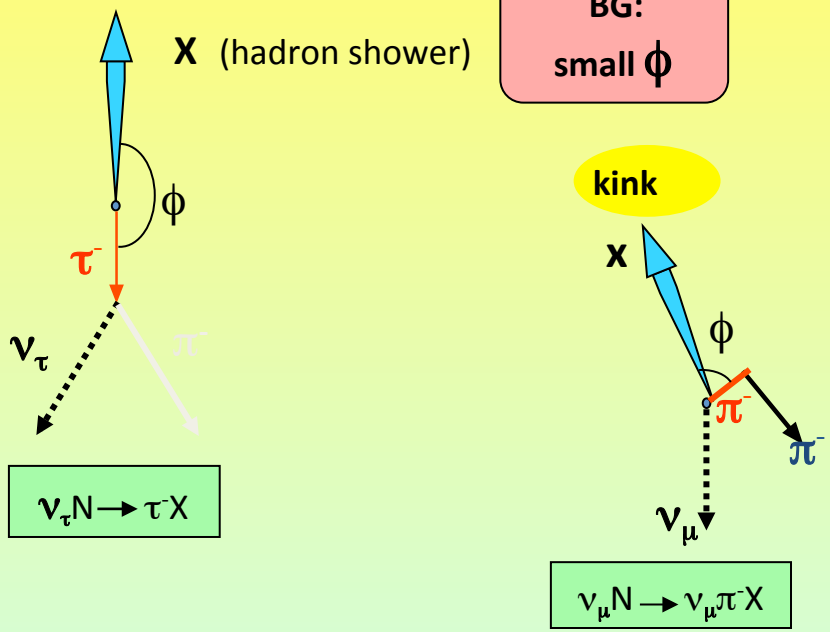
Reject hadron interactions

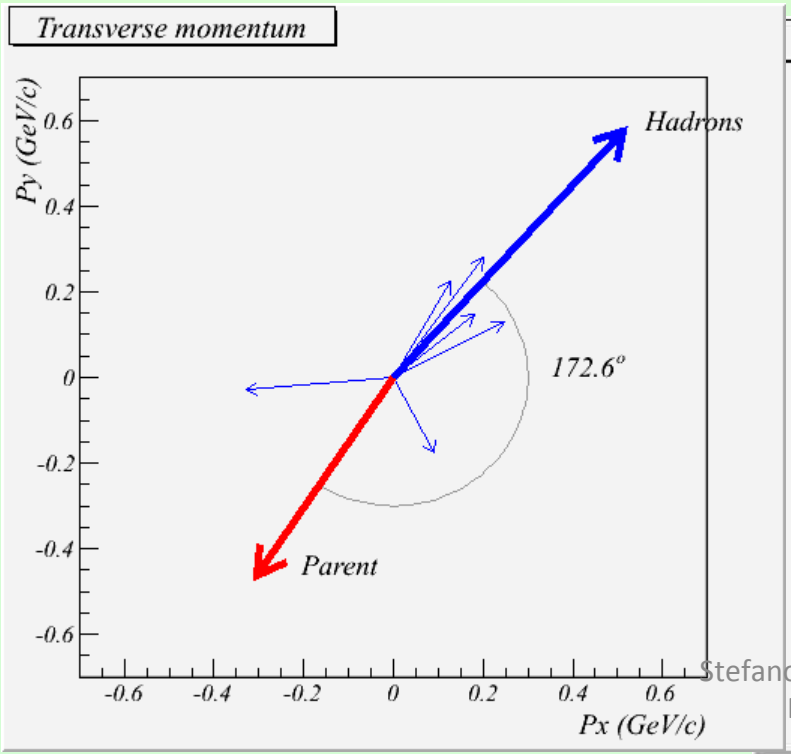


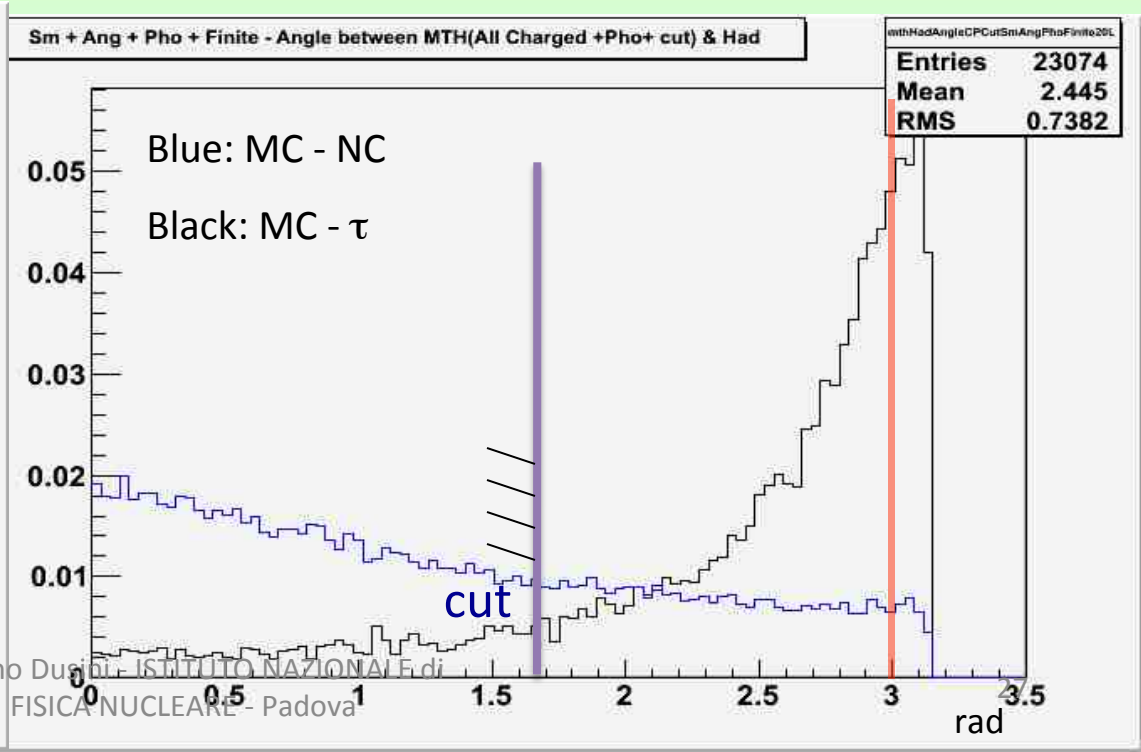
Azimuthal angle between the resulting hadron momentum direction and the parent track direction

Signal : $\phi = 180^o$

BG: small ϕ



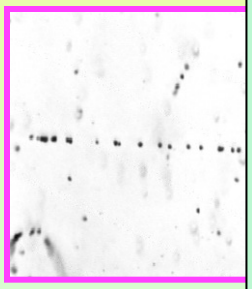




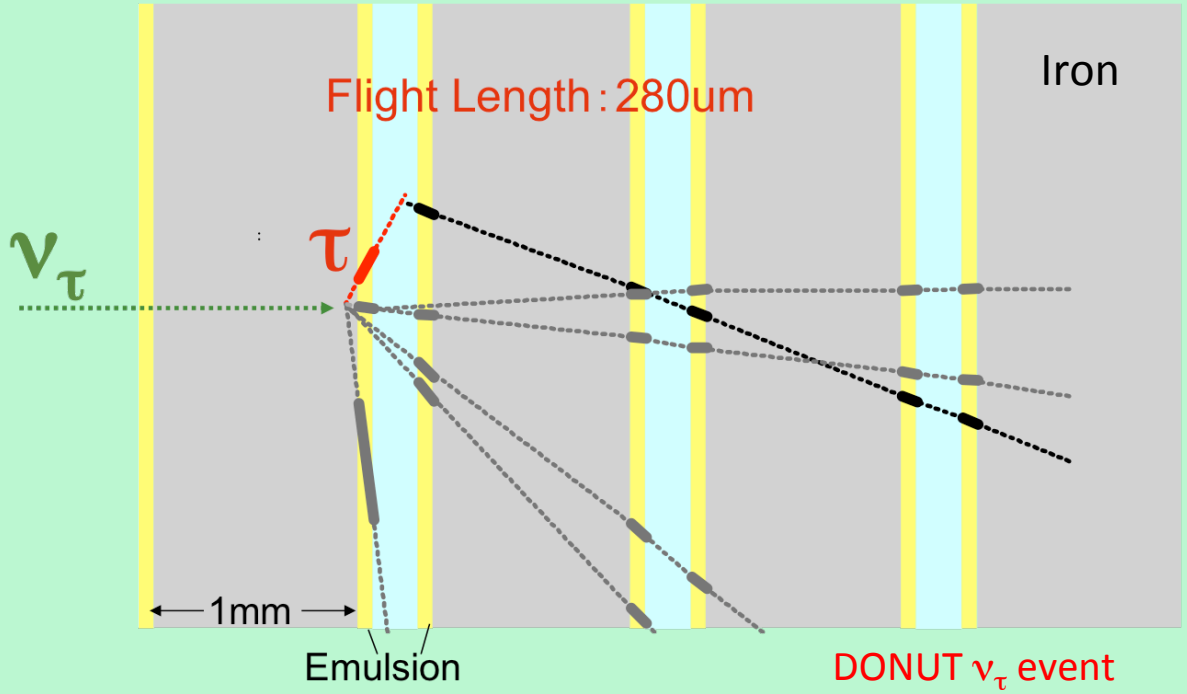
Detection of short lived particle with Emulsion Cloud Chamber (ECC)

To accommodate Large Mass – High Tracking Resolution we use thin metal plates (neutrino t

ECC technique successful applied in DONUT experiment for the discovery of ν_τ (2000)



3D tracking:
32 grains/100μm
0.3 μm accuracy



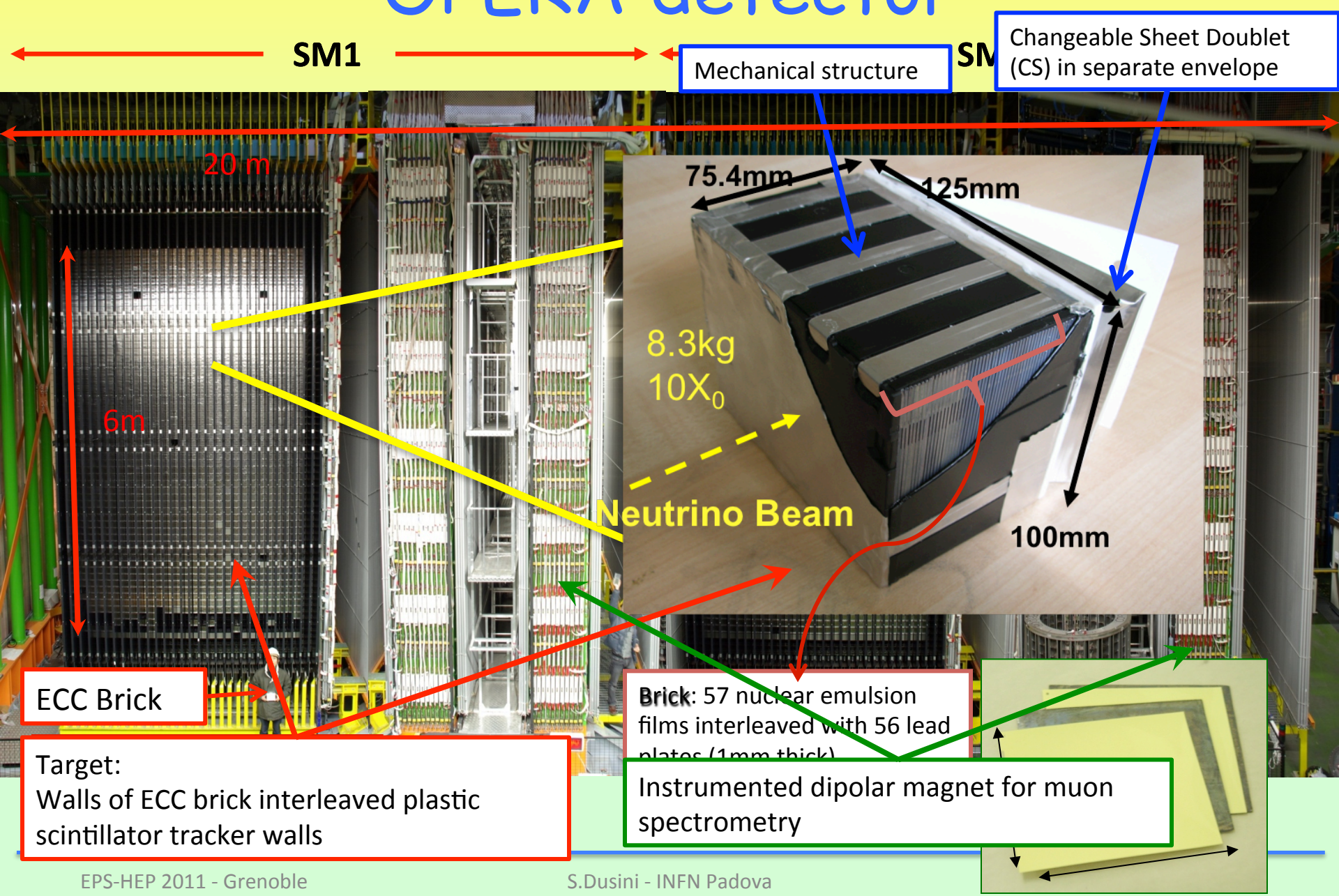
DONUT ν_τ event

lectronics
ackers

Changeable Sheet
removable emuls
detector O(mm) v

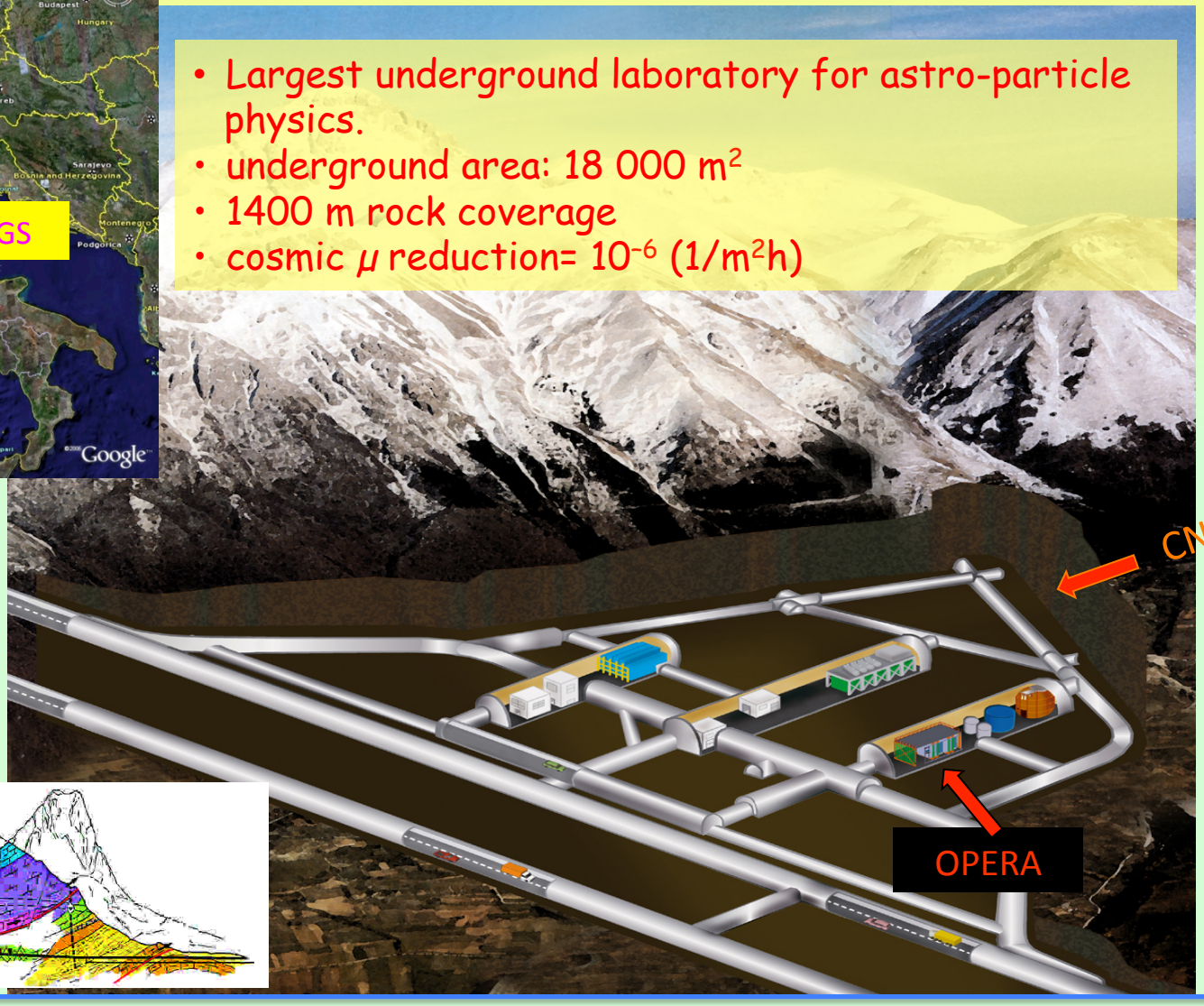
on" to the

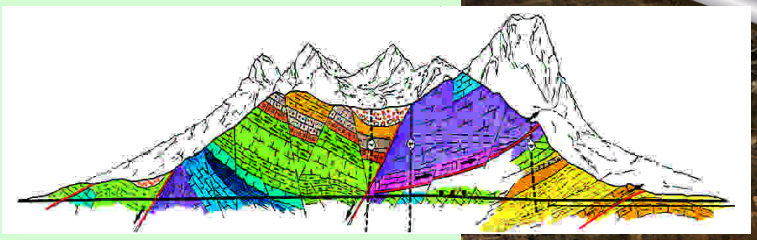
OPERA detector



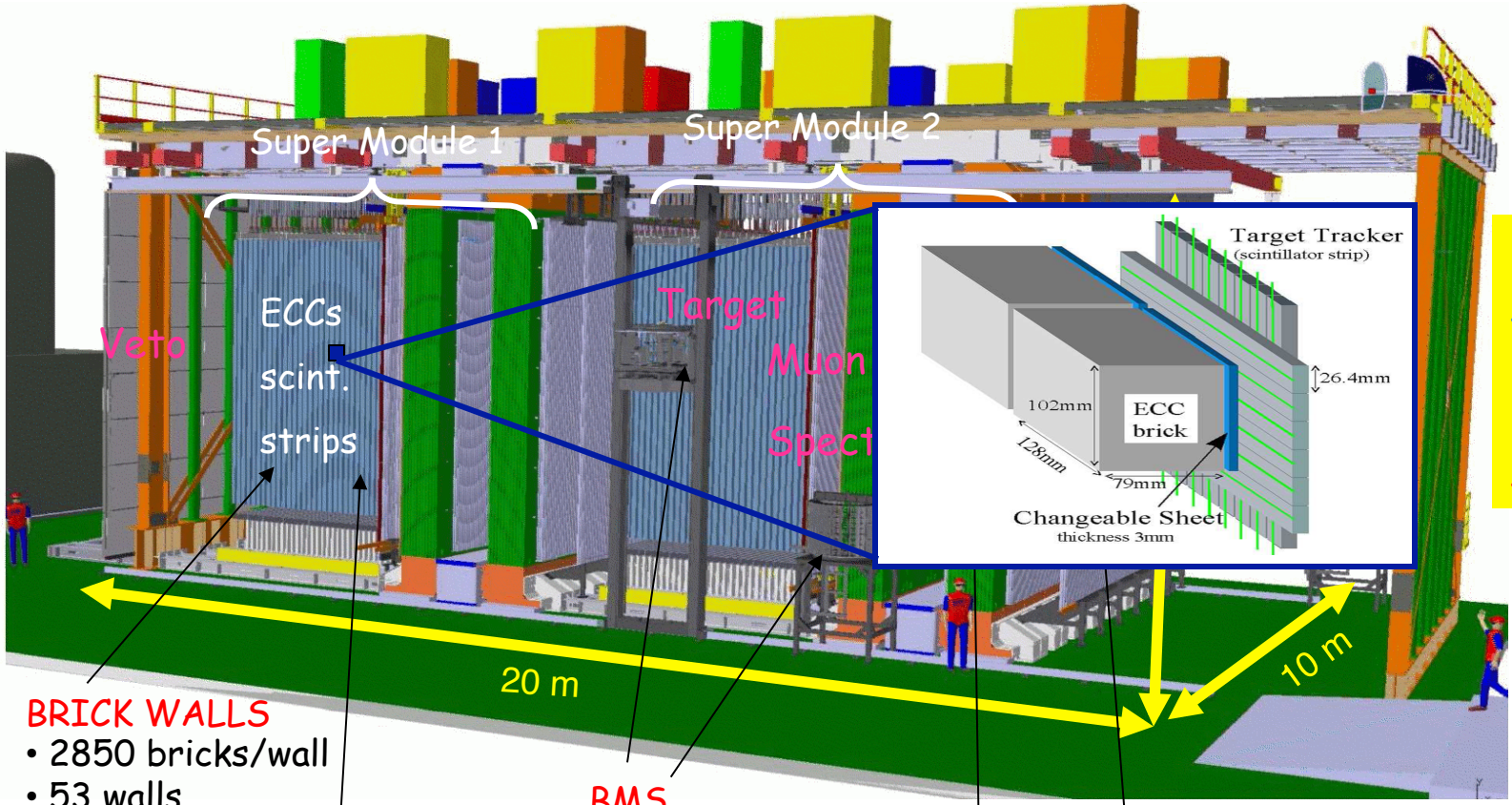
LNGS of INFN

- Largest underground laboratory for astro-particle physics.
- underground area: 18 000 m^2
- 1400 m rock coverage
- cosmic μ reduction= 10^{-6} ($1/m^2h$)





Oscillation Project with Emulsion tRacking Apparatus



Detector supermodules construction: Sept. 2003 - spring 2007

BRICK WALLS
- 2850 bricks/wall
- 53 walls

TARGET TRACKERS
- 2x31 scintill. strips walls
- 256+256 X-Y strips/wall
- WLS fiber readout
- 64-channel PMTs
- 63488 channels
- 0.8 cm resol., ε 99%
- rate 20 Hz/pixel @1 p.e.

Target Trackers
- neutrino trigger
- brick localization

BMS
Brick Manipulator system

HIGH PRECISION TRACKERS
6 drift-tube layers/spectrometer
spatial resolution < 0.5 mm

INNER TRACKERS
- 990-ton dipole magnets (B= 1.55 T) instrumented with 22 RPC planes
- 3050 m^2, ~1.3 cm res.

RPC + drift tubes in spectrometers:
- muon ID,
- momentum,
- charge