OPERA
experimental results

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on behalf of OPERA Collaboration

2nd International Conference on Particle Physics
in Memoriam Engin Arık and Her Colleagues
Doğuş University, İstanbul, Turkey
20 - 25 June 2011

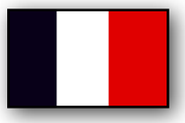
The OPERA Collaboration

180 physicists, 32 institutions in 12 countries

Belgium
IIHE-ULB Brussels

Croatia
IRB Zagreb

France
LAPP Annecy
IPHC Strasbourg
IPNL Lyon

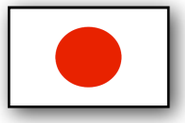


Germany
Hamburg
Münster

Israel
Technion Haifa

Italy
Bari
Bologna
LNF Frascati
L'Aquila,
LNGS
Naples
Padova
Rome
Salerno

Japan
Aichi
Toho
Kobe
Nagoya
Utsunomiya



Korea
Jinju

Russia
INR RAS Moscow
LPI RAS Moscow
ITEP Moscow
SINP MSU Moscow
JINR Dubna

Switzerland
Bern
ETH Zurich

Tunisia
CNSTN Tunis

Turkey
METU Ankara

http://operaweb.web.cern.ch/operaweb/index.shtml

Outline

- Introduction
- The OPERA experiment
  - Requirements
  - The CNGS neutrino beam
  - The OPERA detector
- Detector performances
- Physics results
- Conclusions and outlook

Neutrino oscillations

$$(\nu_e, \nu_\mu, \nu_\tau)^T = U\,(\nu_1, \nu_2, \nu_3)^T$$

3 eigestates of flavor

Unitary matrix: 3 Eulero rotation angles + 1 CP phase

3 eigestates of mass

Neutrino oscillations

$$(\nu_e, \nu_\mu, \nu_\tau)^T = U\,(\nu_1, \nu_2, \nu_3)^T$$

3 eigestates of flavor

Unitary matrix: 3 Eulero rotation angles + 1 CP phase

3 eigestates of mass

PMNS (Pontecorvo-Maki-Nakagawa-Sakata) Matrix

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}\,e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}\,e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$

$s^2_{23} \sim 0.5$ — Measured by atmospheric and accelerator ν experiments

$s^2_{13} <$ few % — Mainly constrained by reactor experiments

$s^2_{23} \sim 0.3$ — Measured by ν solar experiments

Neutrino oscillations

In the last decades several experiments provided evidence for neutrino oscillations (***disappearance mode***)

- **CHOOZ** (1997): The main oscillation channel responsible for atmospheric neutrino disappearance is not $\nu_\mu \rightarrow \nu_e$;

- **SK** (1998): The main oscillation channel responsible for atmospheric neutrino anomaly is not $\nu_\mu \rightarrow \nu_e$ and can be interpreted as $\nu_\mu \rightarrow \nu_\tau$ oscillation.

- (2004-2009) **K2K,MINOS**: precision measurements of ν_μ disappearance

The OPERA experiment

Oscillation Project with Emulsion-tRacking Apparatus

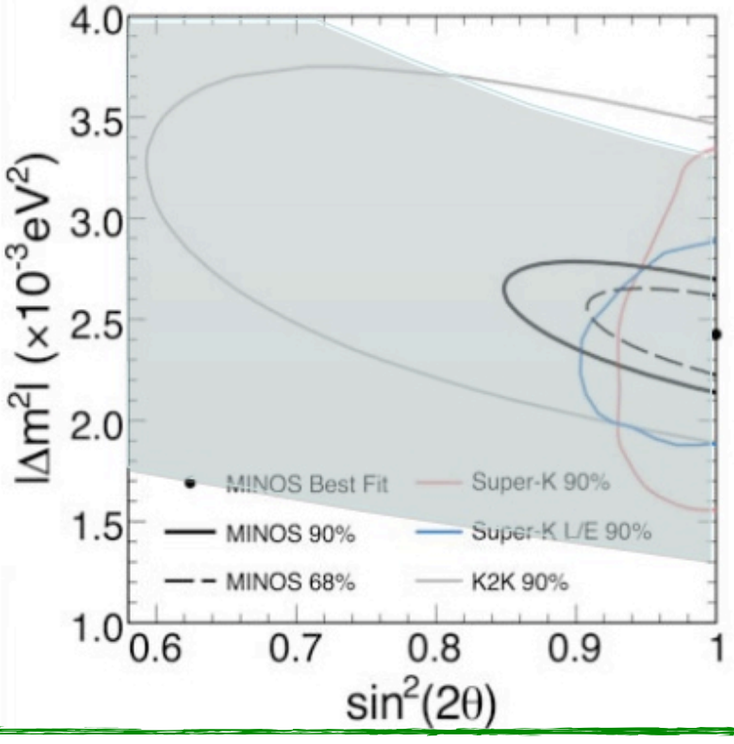
AIM: first direct detection of neutrino oscillations in
APPEARANCE mode in the $\nu_\mu \longrightarrow \nu_\tau$ channel

The OPERA experiment

Oscillation Project with Emulsion-tRacking Apparatus

AIM: first direct detection of neutrino oscillations in **APPEARANCE** mode in the $\nu_\mu \longrightarrow \nu_\tau$ channel

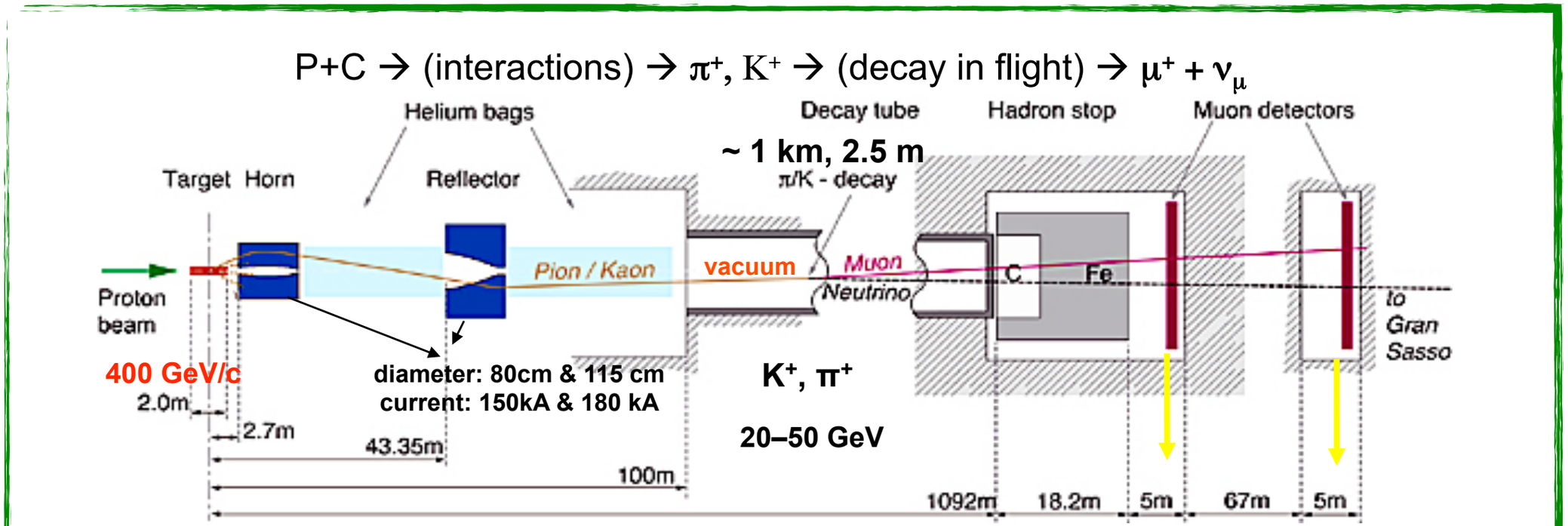
Oscillation parameters in the atmospheric neutrino sector



Full mixing and $\Delta m^2_{23} \sim 2.4 \times 10^{-3}$ eV^2

The light blue band indicates the OPERA allowed region (90% CL) for the above parameter values for 22.5×10^{19} pot

The CNGS neutrino beam



- 400 GeV/c proton from the CERN SPS on graphite target, producing pions and kaons
- Helium tubes are placed in the free space of the target in order to reduce the interaction probability for secondary hadrons
- Pions and kaons are directed towards the decay tunnel to produce ν_μ beam
- Muon detectors are used for online monitoring and tuning of the beam

The CNGS neutrino beam

Conventional ν beam

$\langle E\nu_\mu \rangle$ (GeV)	17
$(\nu_e+\overline{\nu}_e)/\nu_\mu$	0.87% *
$\overline{\nu}_\mu/\nu_\mu$	2.1% *
ν_τ prompt	Negligible *

* Interaction rate at LNGS

Expected interactions for 22.5×10^{19} pot (nominal pot in 5 years for 1.25 kton target)

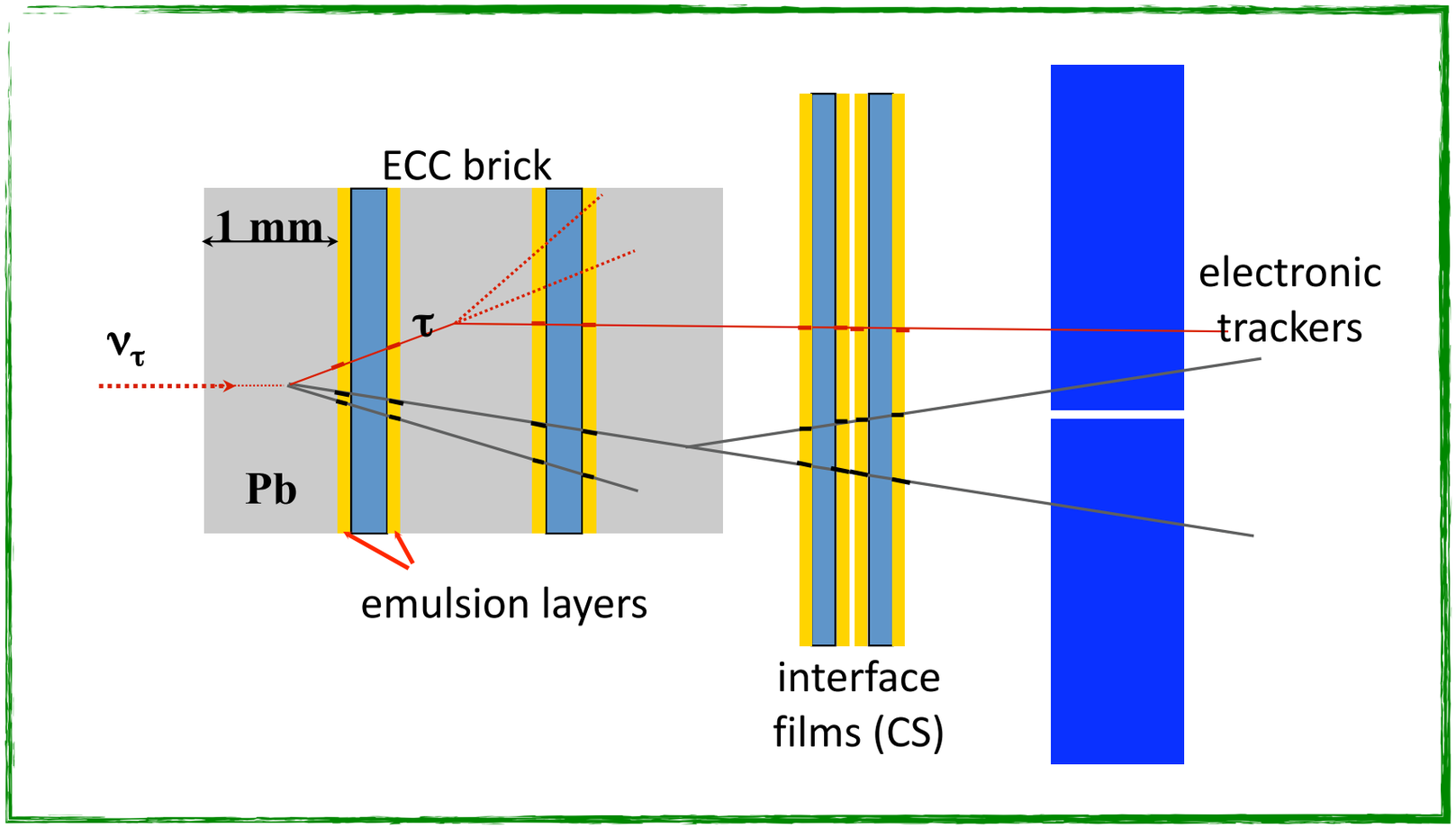
~ 23600 ν_μ CC+NC

~ 160 $\nu_e+\overline{\nu}_e$ CC

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

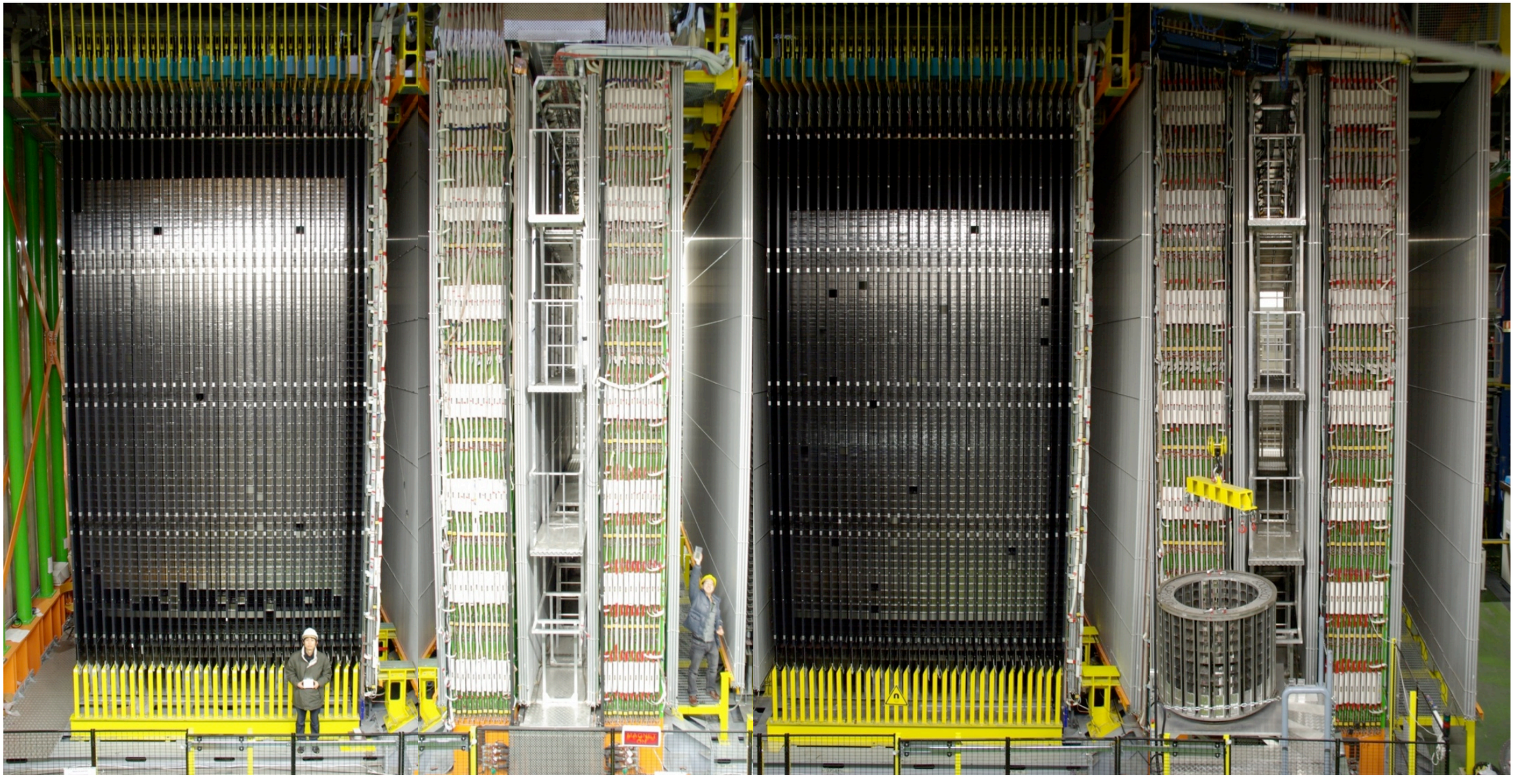
~ 10 ν_τ CC identified (BG<1)

The principle

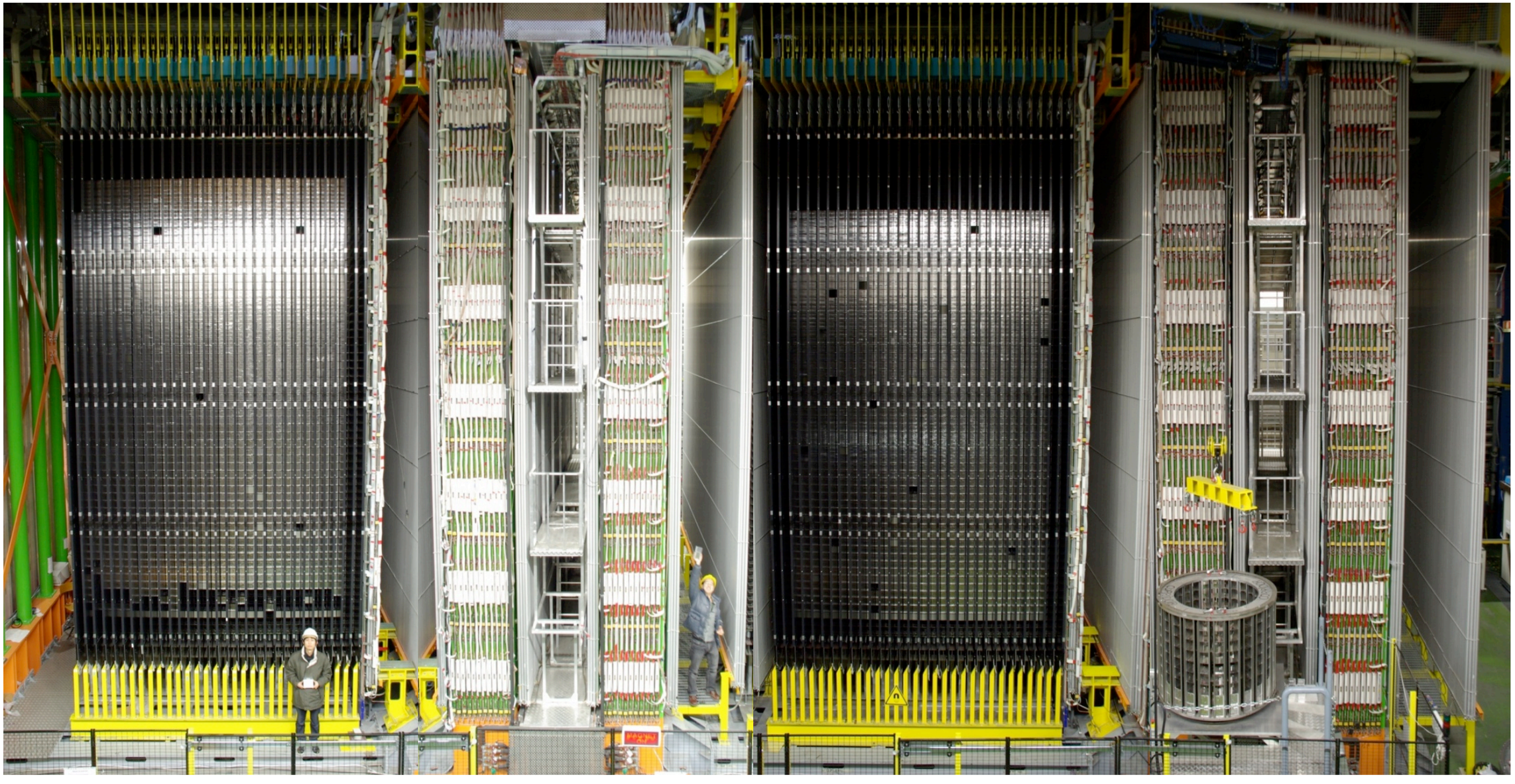


- Massive active target with micrometric space resolution
- Detect τ-lepton production and decay
- Underground location
- Usage of electonic detectors to provide “time resolution” to the emulsions and preselect the interaction region

The detector

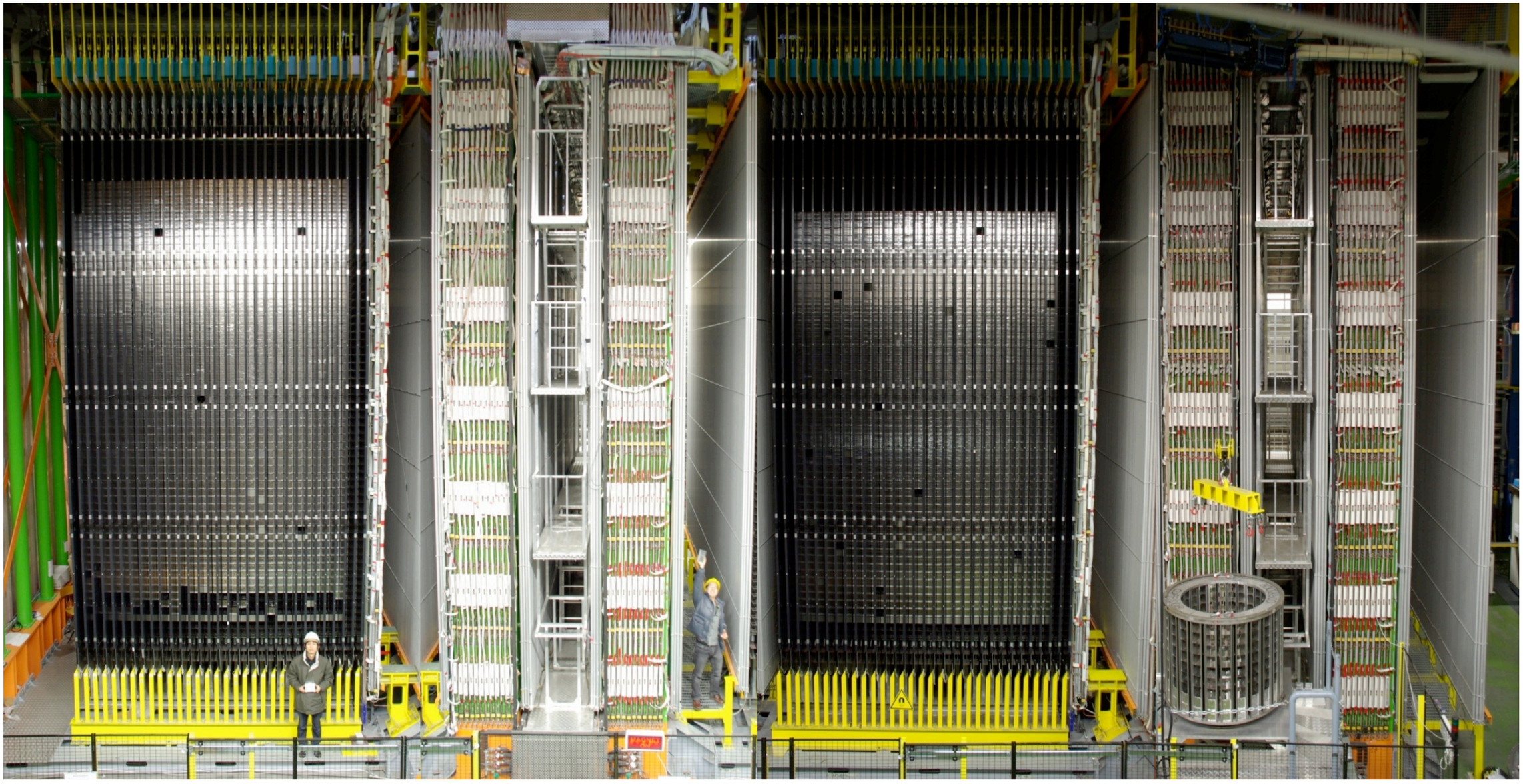


The detector



SM-1 **SM-2**

The detector



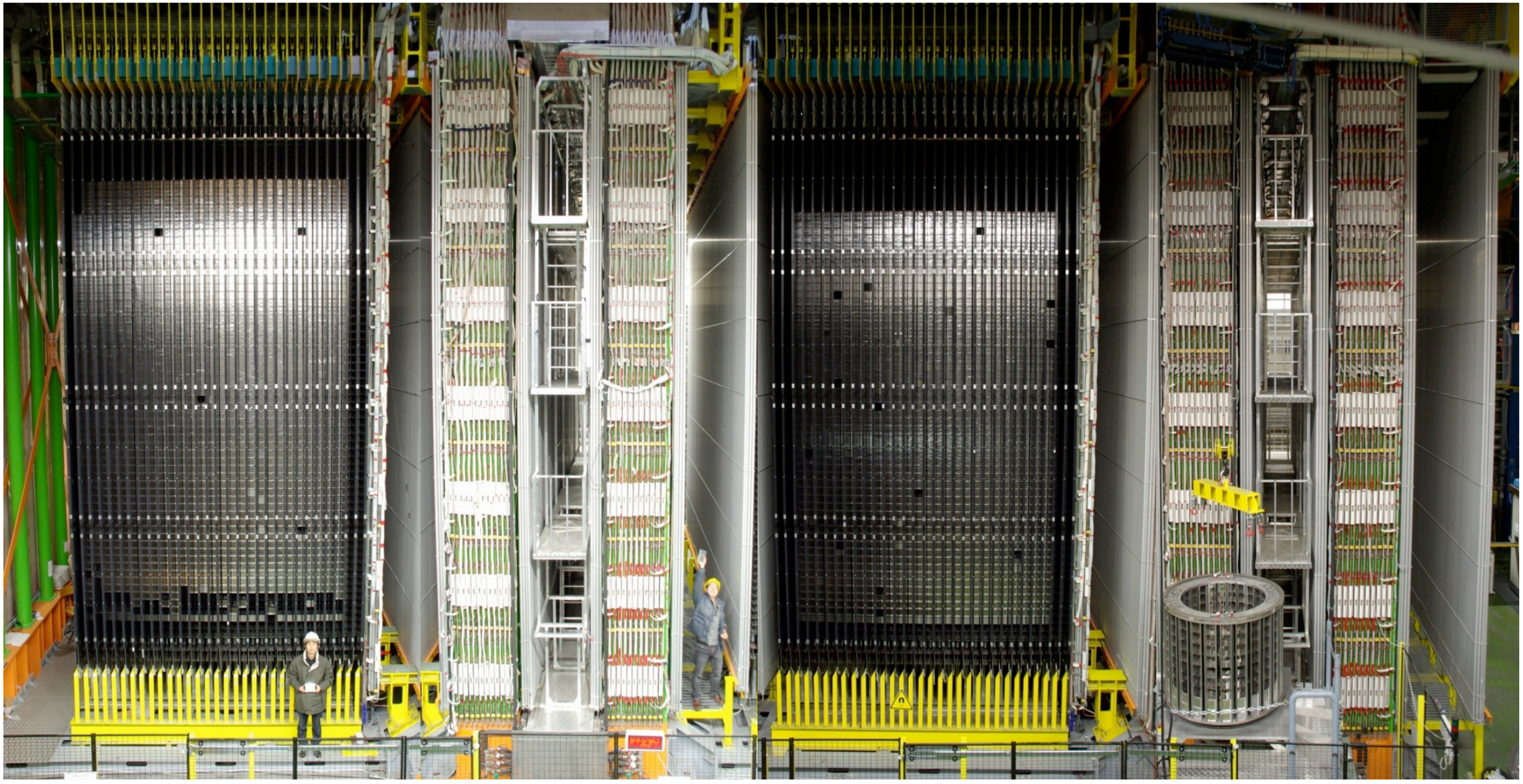
Target

Target

SM-1

SM-2

The detector

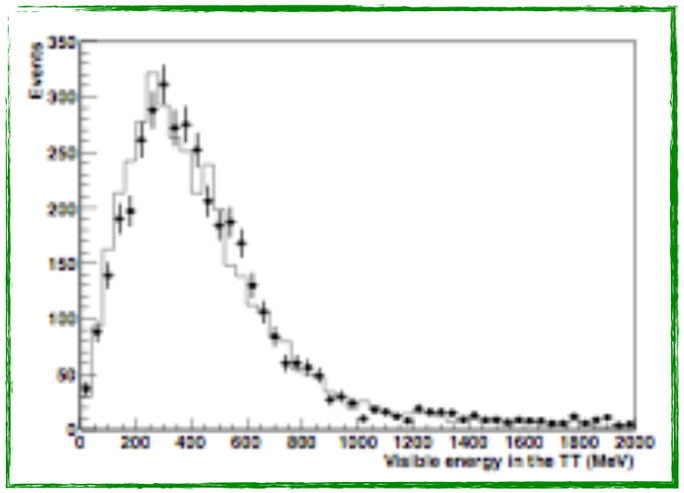


Target | Spectrometer | Target | Spectrometer

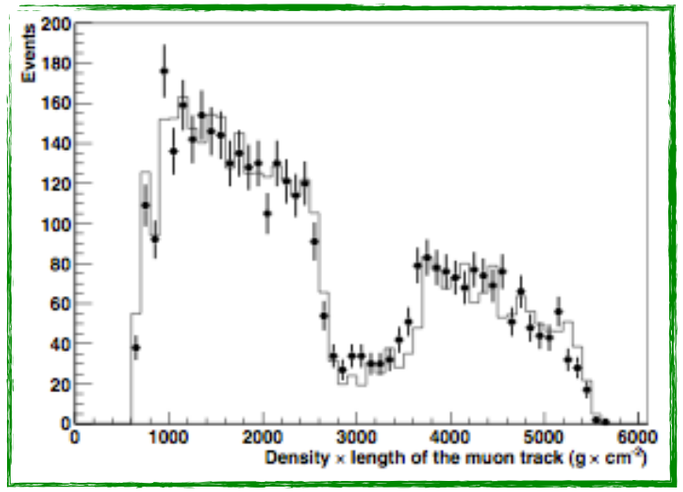
SM-1 | SM-2

Electronic Detector Performances

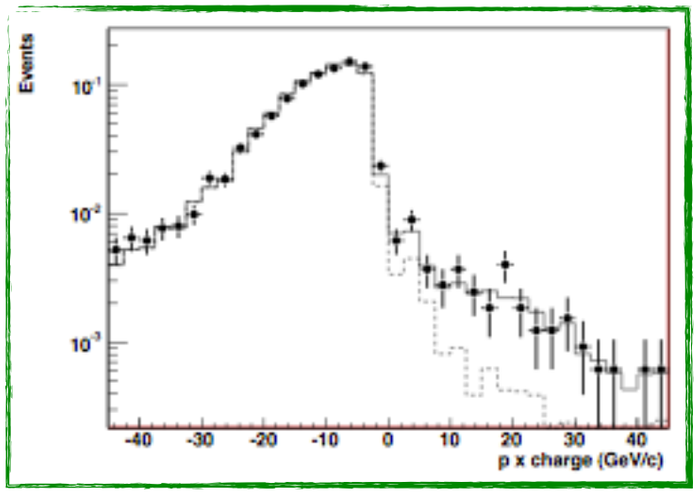
Hadronic energy deposite in TT



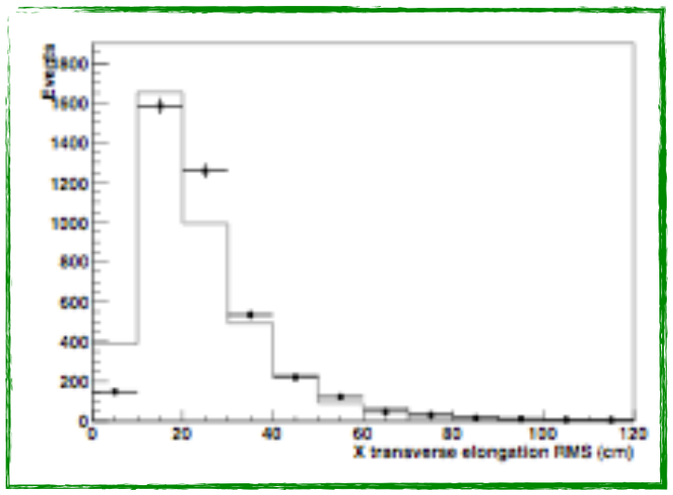
Density x length of the muon track



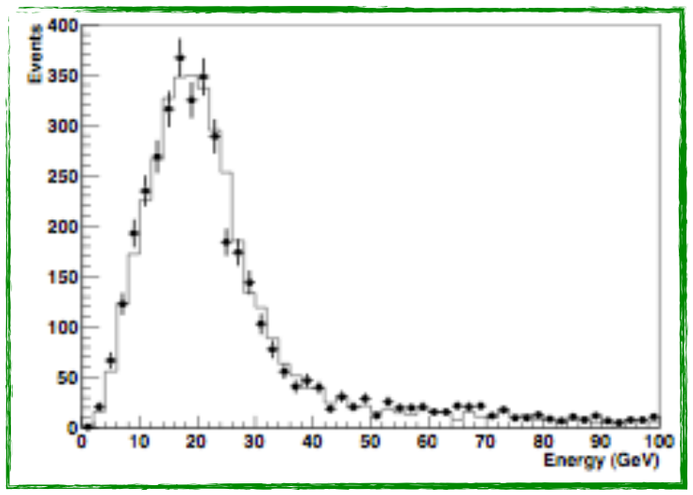
Momentum x charge of the muon



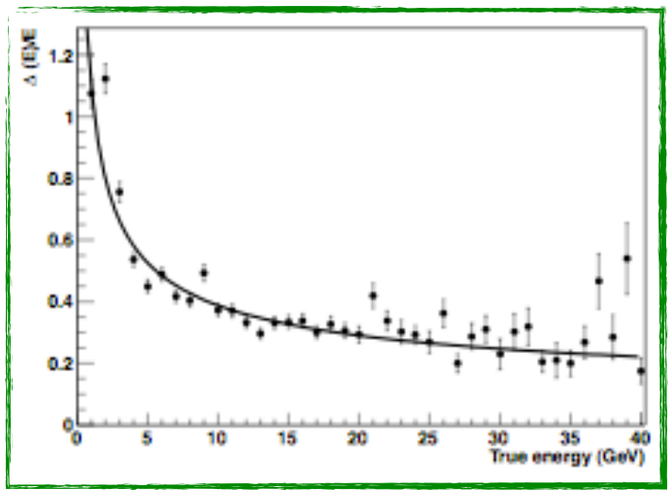
Transverse profile of hadronic showers



Total reconstructed energy in events with at least one identified muon



Energy resolution



The target

Made of ~150000 ECC bricks

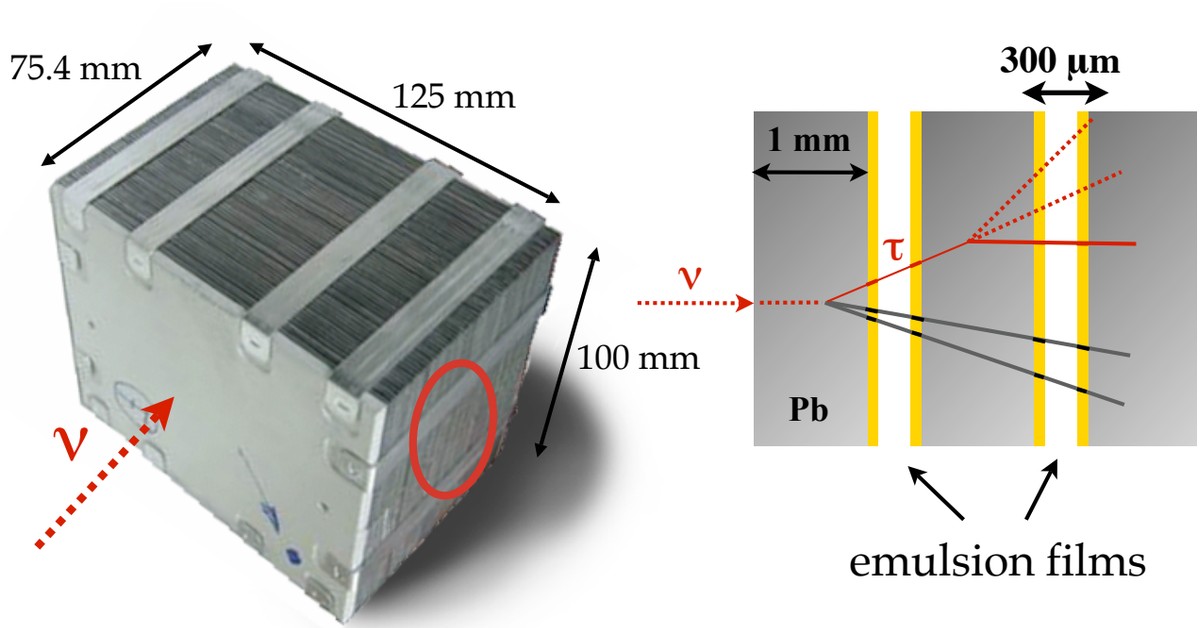
Emulsion Cloud Chamber

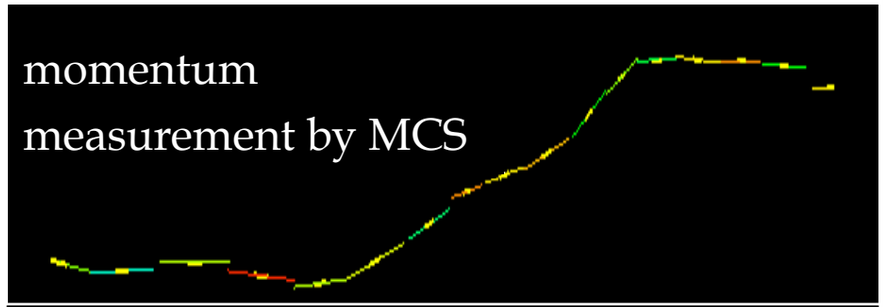
ECC

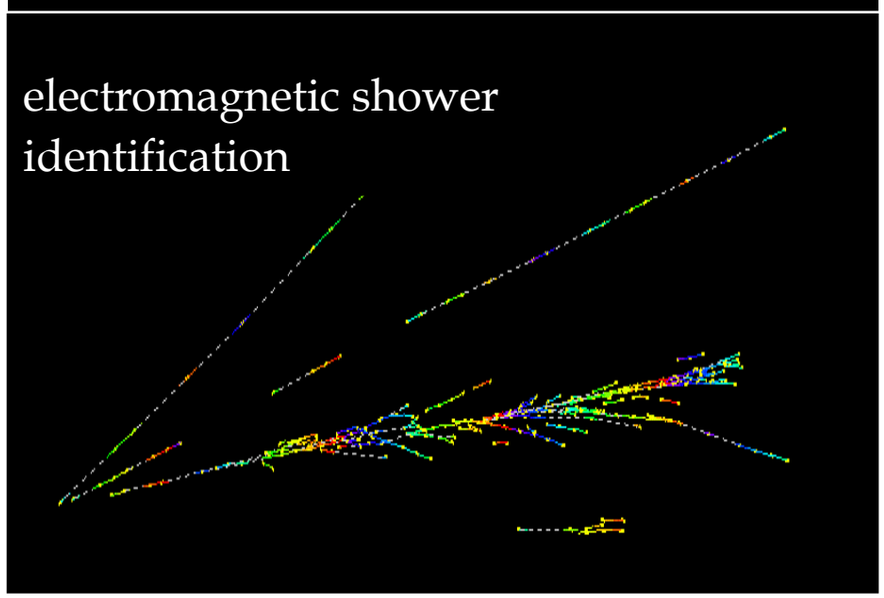
- passive material → lead (massive target)
- tracking device → nuclear emulsion (high resolution)

Brick

- 57 emulsion films
- 56 lead plates
- 1 Changeable Sheet doublet
- 10 X_0
- 8.3 kg







Event selection

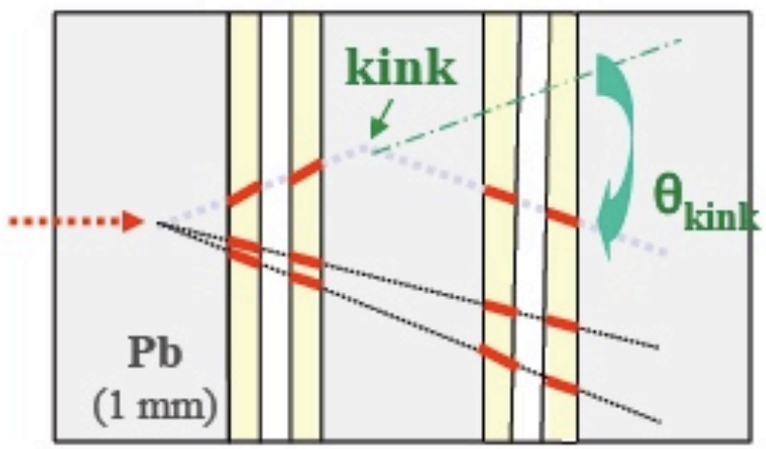
τ selection based on decay topology

Long decays

$\tau \rightarrow e\nu_\tau\nu_e$

$\tau \rightarrow \mu\nu_\tau\nu_\mu$

$\tau \rightarrow h\nu_\tau$



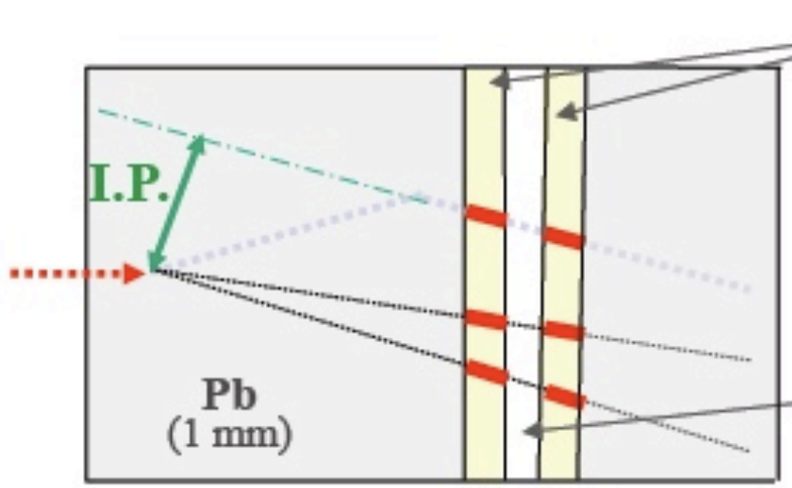
Kink angle

$\theta_{kink} > 20$ mrad

Short decays

$\tau \rightarrow e\nu_\tau\nu_e$

$\tau \rightarrow \mu\nu_\tau\nu_\mu$

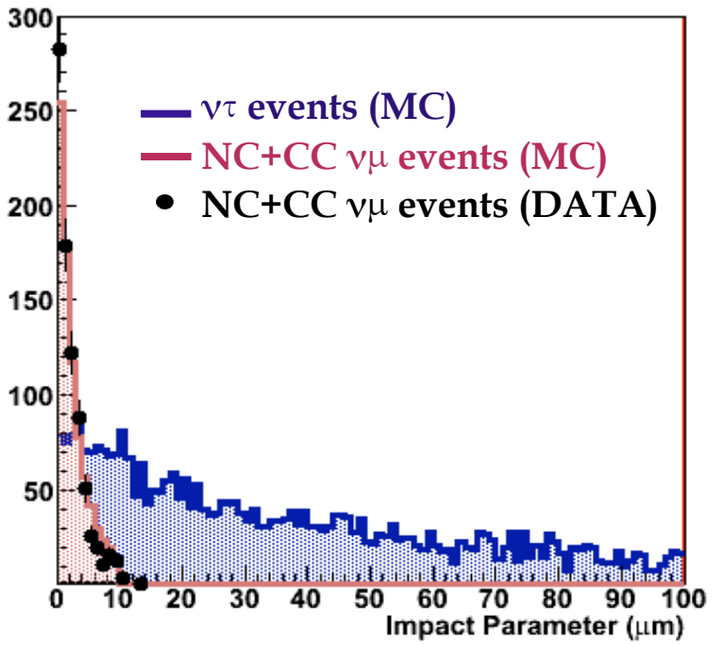


Impact parameter

I.P >10 to 500 μm

ECC Performance

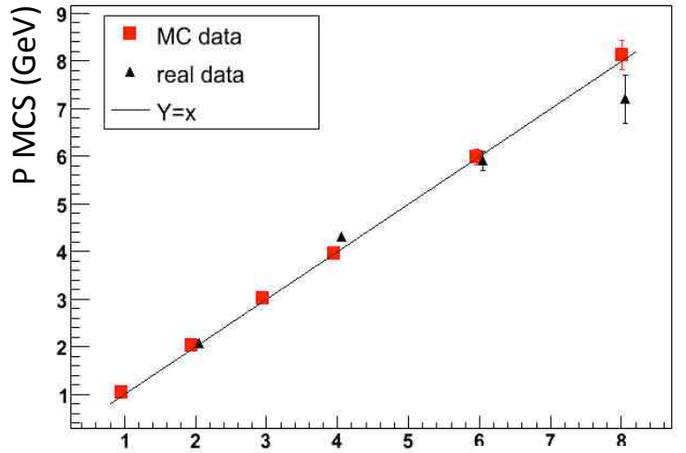
Impact parameter measurement



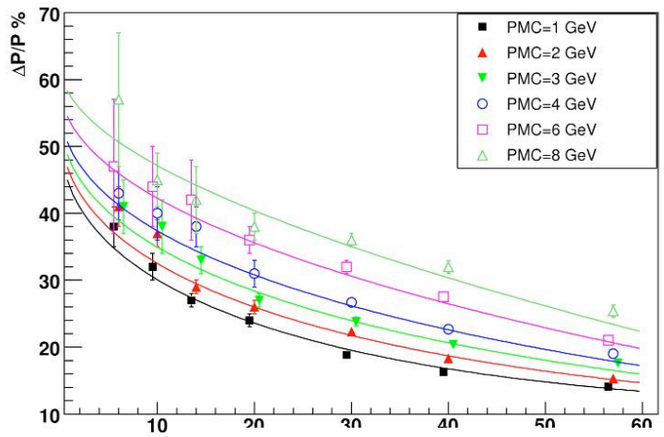
The detection of decay topologies is triggered by the observation of a track with large IP wrt the primary vertex, in addition to kink detection

Momentum measurement by MCS

Linearity of momentum center



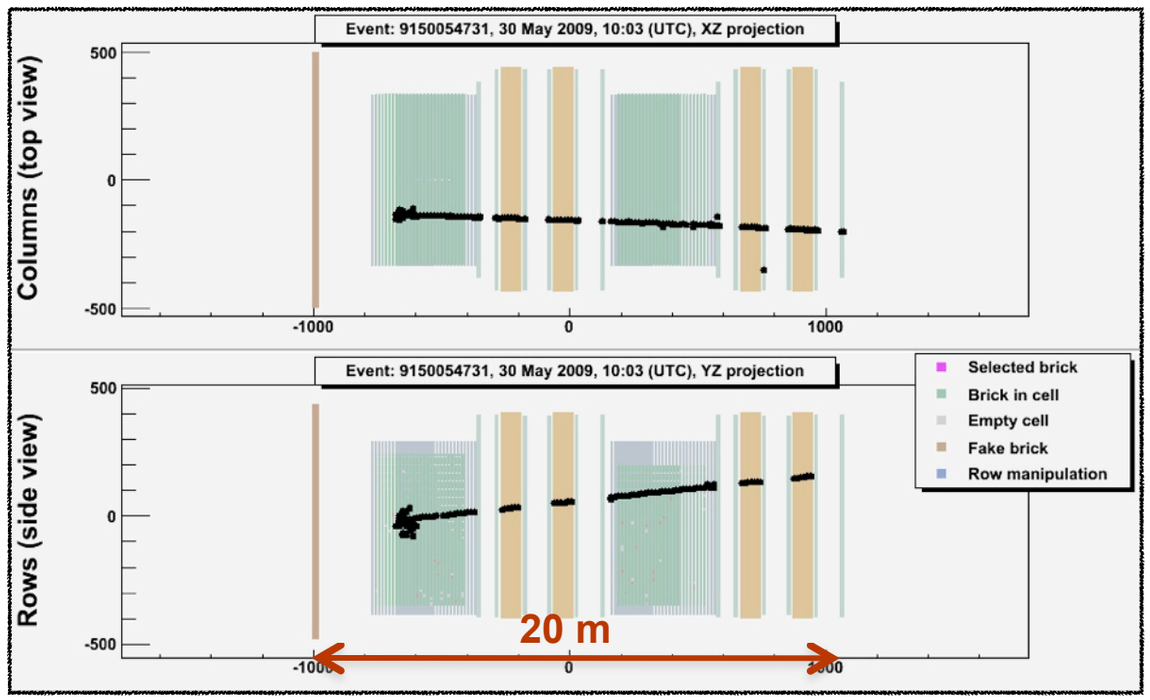
Resolution



Neutrino interaction in the target

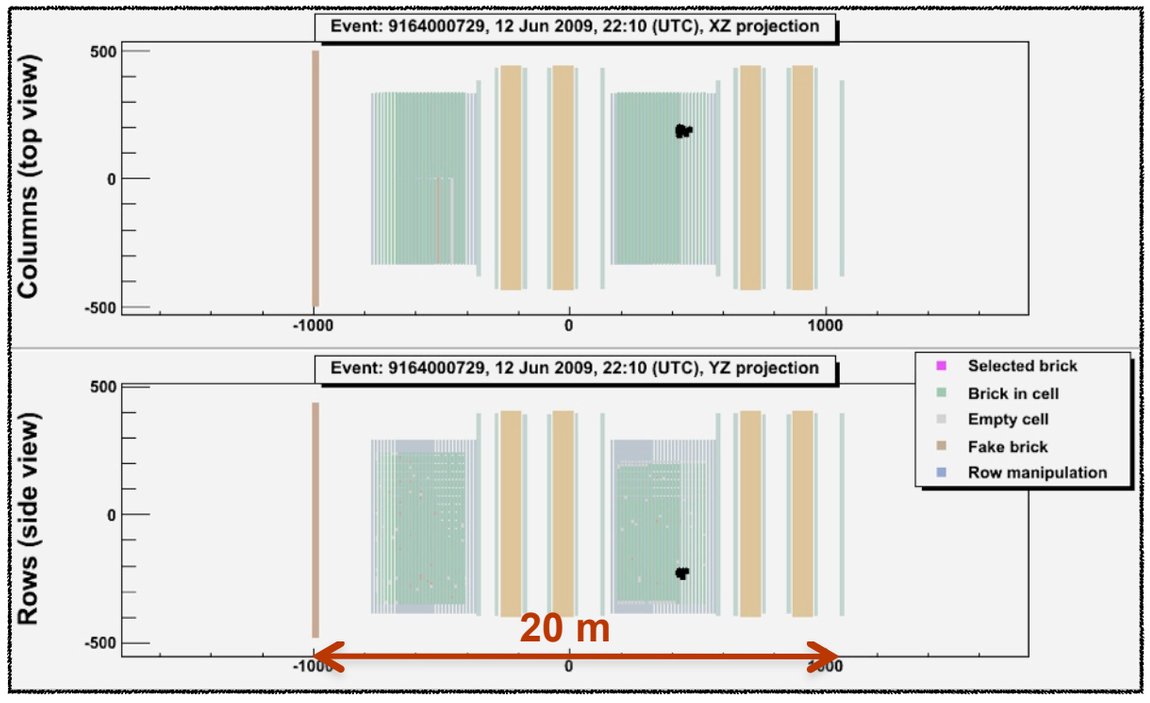
Charged Current Event

$$\nu_\mu N \rightarrow \quad \mu^- X$$



Neutral Current Event

$$\nu_\mu N \rightarrow \quad \nu_\mu X$$



Emulsion scanning

Parallel ECC analysis in ~10 labs
Numer of labs is increasing

NAPOLI SCANNING LAB

ECC Brick Scan & Analysis Load

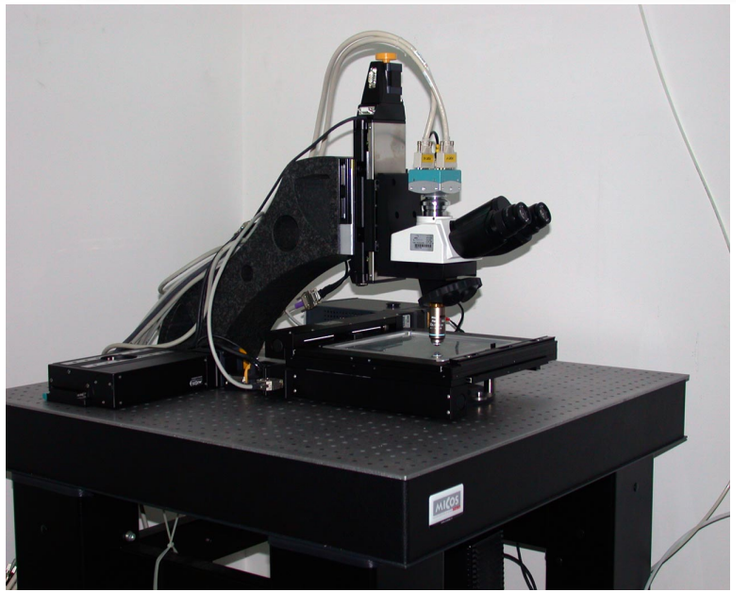
JAPAN : EU = 50 : 50

OPERA film data taking

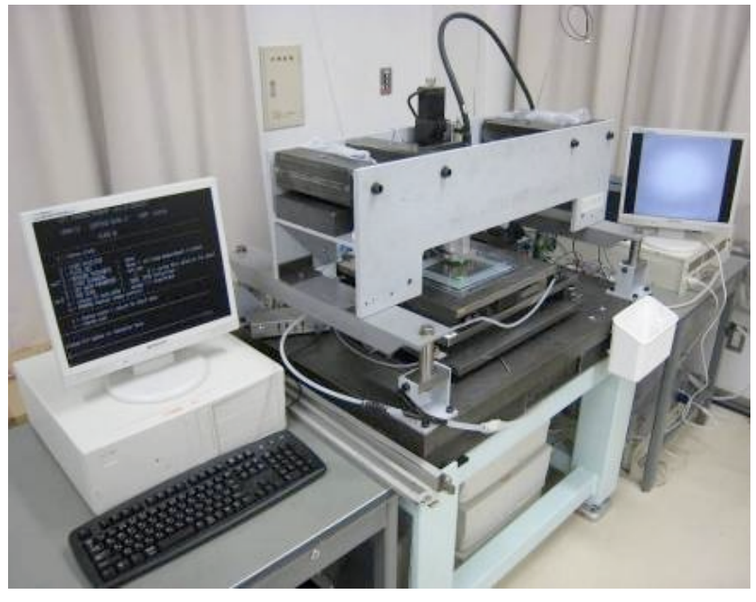
~20 bricks daily extracted from the target
analized using high-speed automated systems (~20 cm^2/h)

European Scanning System **S-UTS (Japan)**

Comon Data Base for data sharing/publication



- Customized commercial optics and mechanics
- Asynchronous DAQ software modular, decentralized, approach

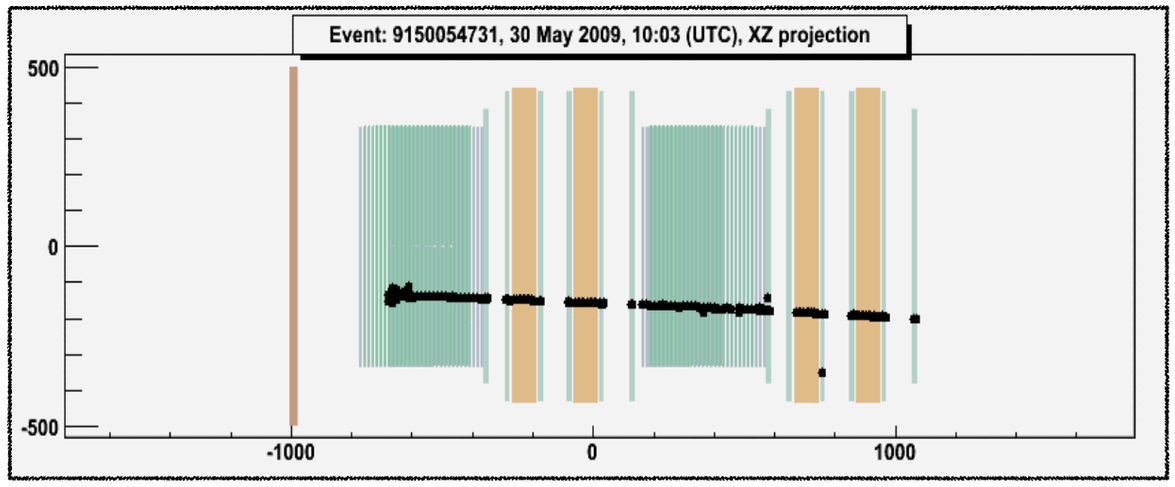


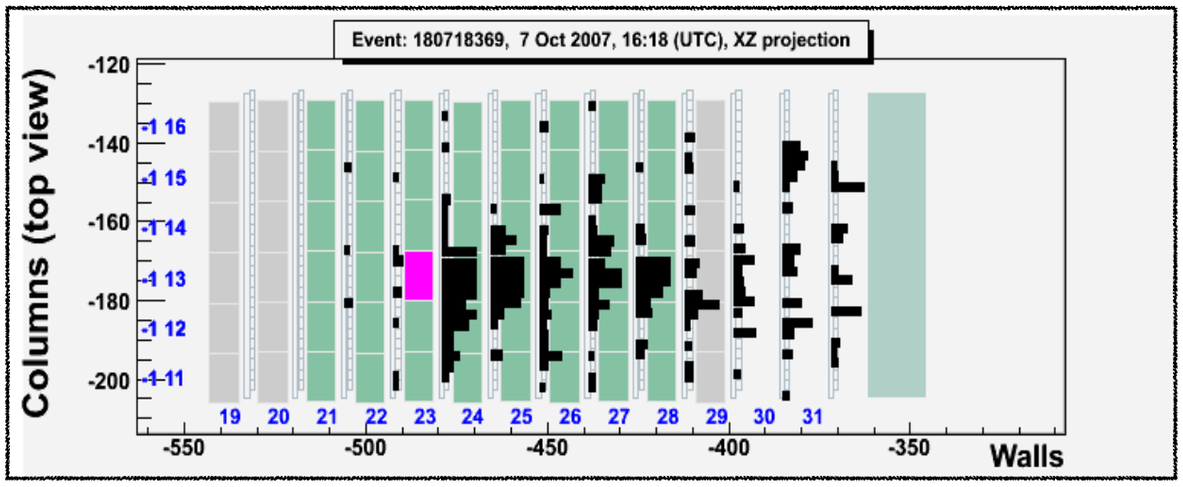
- Synchronization of objective lens and (constant speed) stage
- Hard-coded algorithms, custom electronics

~90% tracking efficiency
spatial resolution <1μm & angular resolution < 2 mrad

Event analysis in OPERA

Electronic detector reconstruction





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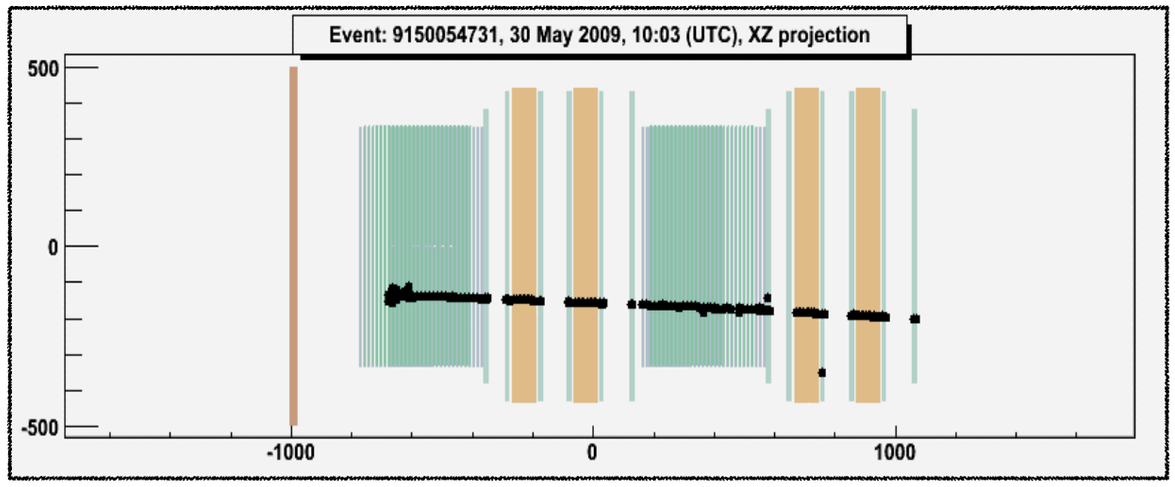
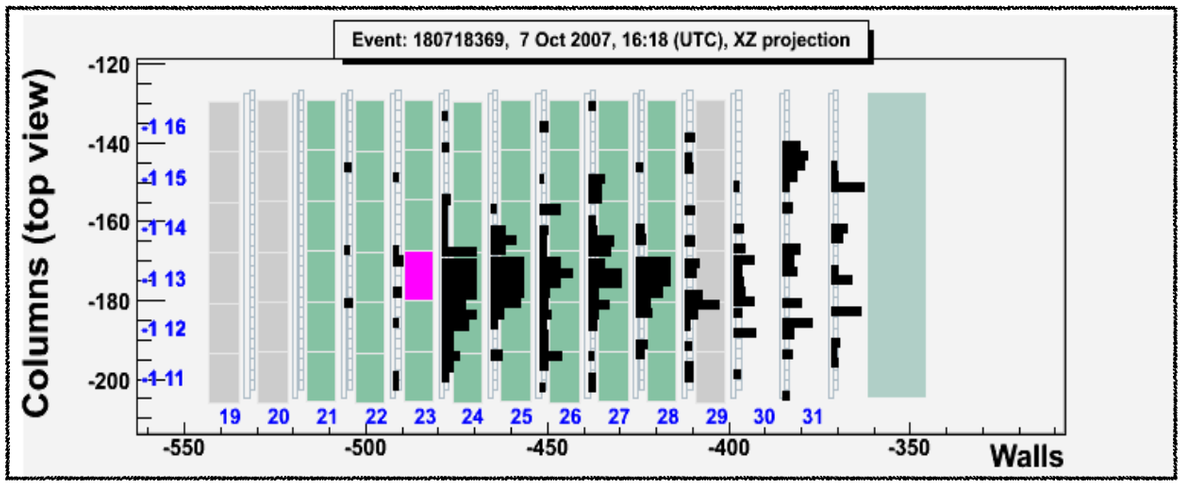
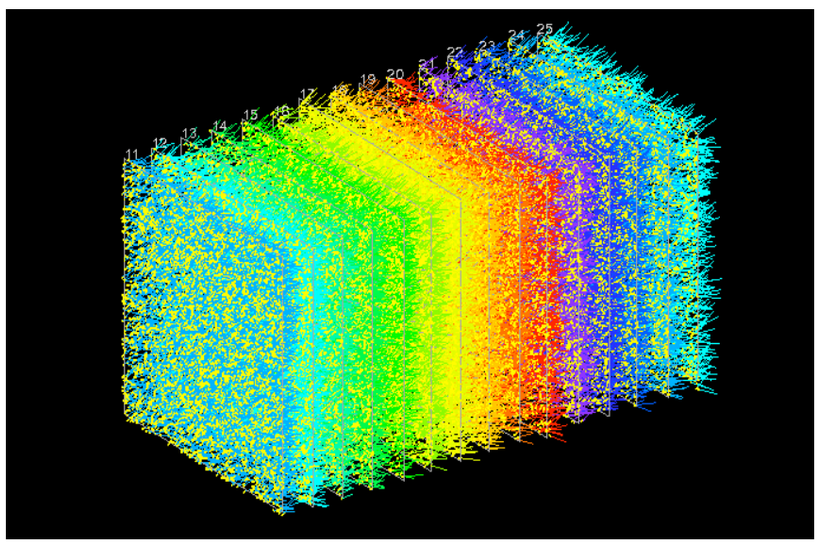
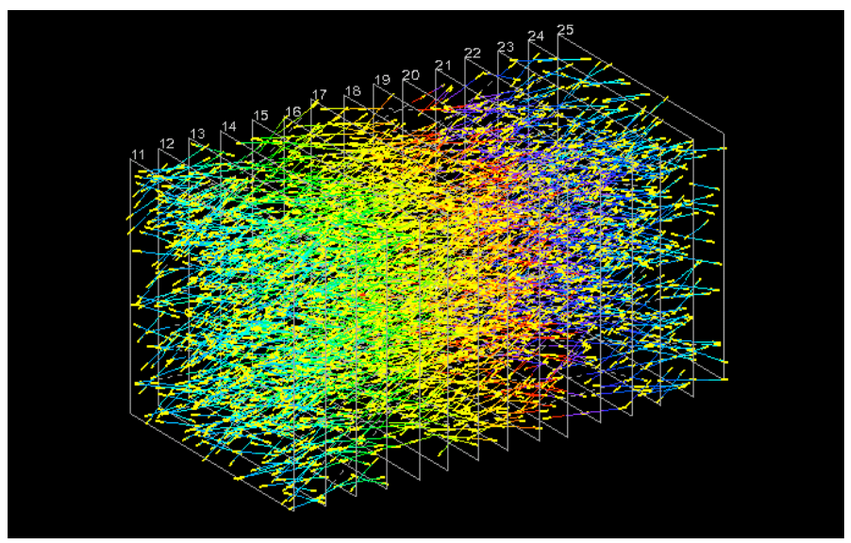
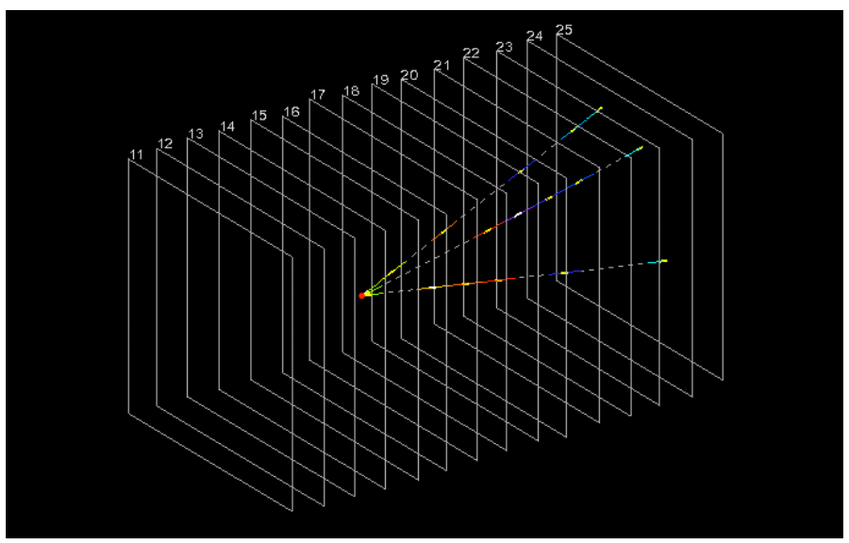




Vertex location in the brick







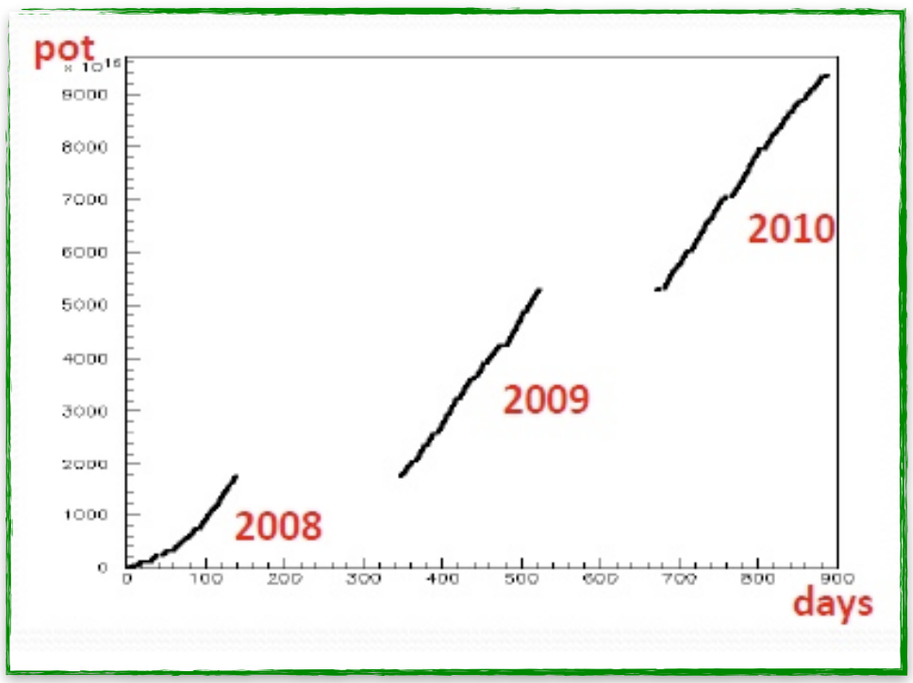
1. Scan 15 emulsion films around stopping plate

2. Reject passing through tracks

3. Search tracks making vertex

CNGS physics run

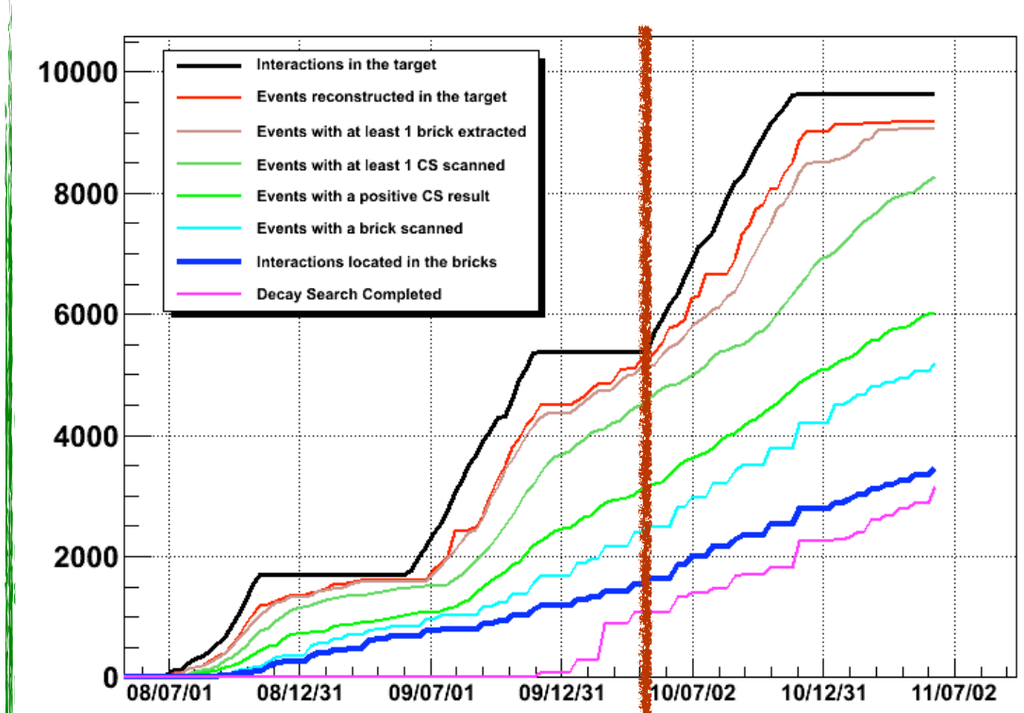
year	beam days	protons on target	SPS eff	trigger	run
2006		0.076×10^{19}		no brick	commissioning
2007		0.082×10^{19}		38	commissioning
2008	**123**	**1.78×10^{19}**	**61%**	**1698**	**Physiscs run**
2009	**155**	**3.52×10^{19}**	**70%**	**3693**	**Physiscs run**
2010	**187**	**4.04×10^{19}**	**81%**	**4248**	**Physiscs run**



- 9639 events collected
  (within 1 σ in agreement on the basis of pots)
- 2010 close to nominal year
- 2.1 nominal years in 3 years
- 2011 run in progress
- Aim at high-intensity runs in 2011 and 2012

Analysis status in ECC brick

2889 neutrino interactions located,
95% of the 2008-09 expected yield



Number of events for which the analysis is released:
(1.85×10^{19} pot corresponding to 20% of the total statistics)

1088 (187 NC)

With the above statistics, for $\Delta m^2 = 2.5 \times 10^{-3}$ eV^2 and full mixing,
OPERA expects ~ **0.5 ν_τ events**

New data will be released at the end of this month

Charm candidate events

Proof of the τ efficiency

- 20 charm events selected
  (3 events with 1-prong kink topology)
- Expected: 16.0 ± 2.9
  (0.80 ± 0.22 with kink)
- ~3 BG events expected

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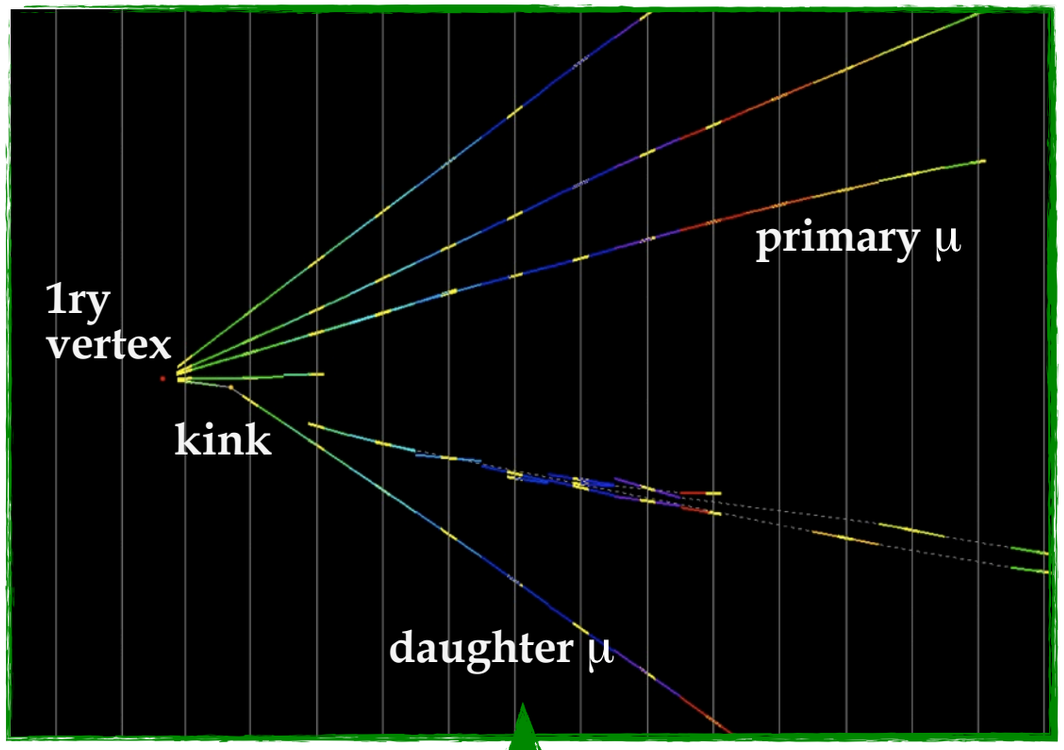

flight length:	1330 μm
kink angle:	209 mrad
IP of the daughter:	262 μm
daughter μ:	2.2 GeV/c
decay Pt:	0.46 GeV/c

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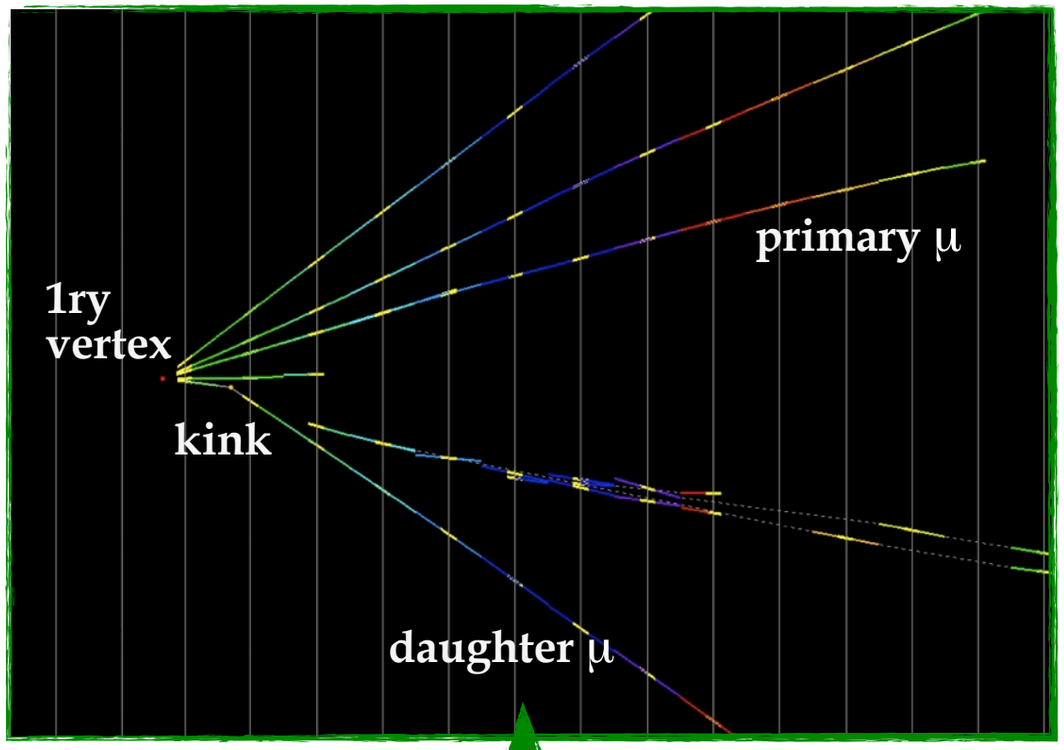

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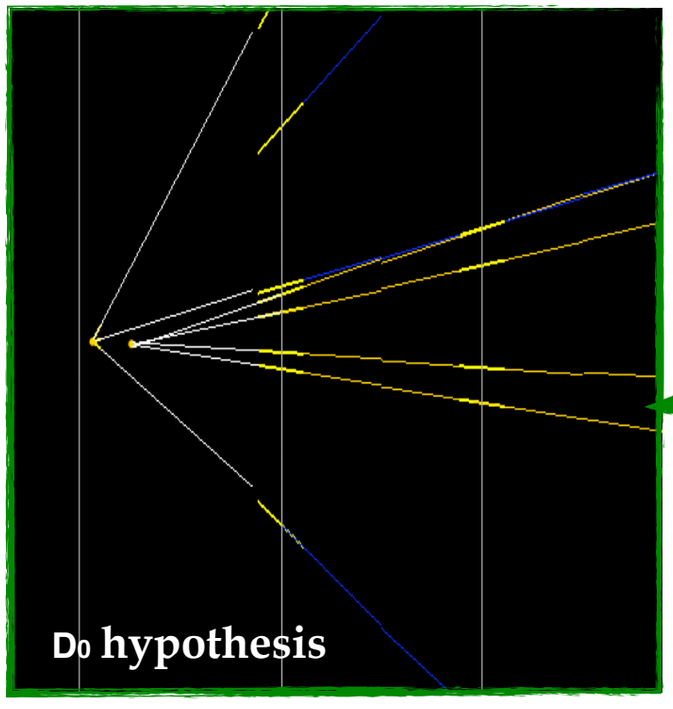

flight length: 313 μm
φ angle: 173.2 °
invariant mass: 1.7 GeV

The first $\nu\tau$ candidate was found

Physics Letters B 691 (2010) 138–145

Contents lists available at ScienceDirect

Physics Letters B

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Observation of a first ν_τ candidate event in the OPERA experiment in the CNGS beam

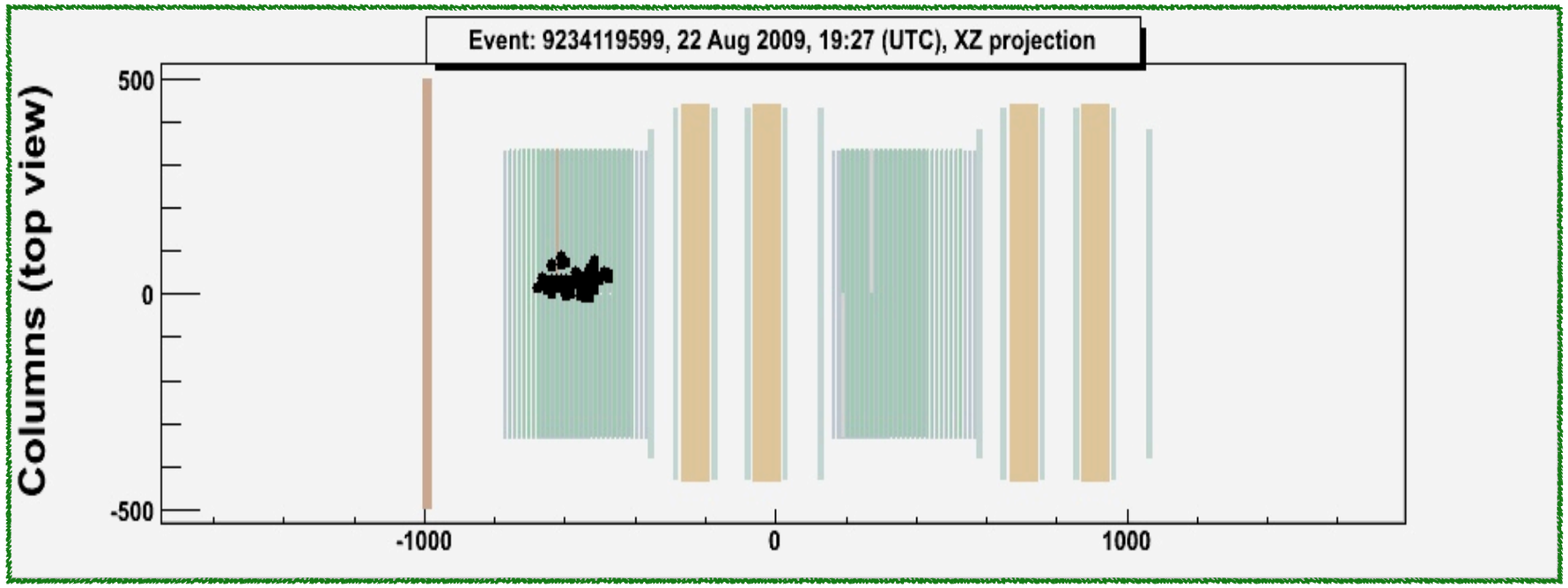
Event number 9234119599

taken on 22 Agust 2009, 19:27

This result was published in June 2010

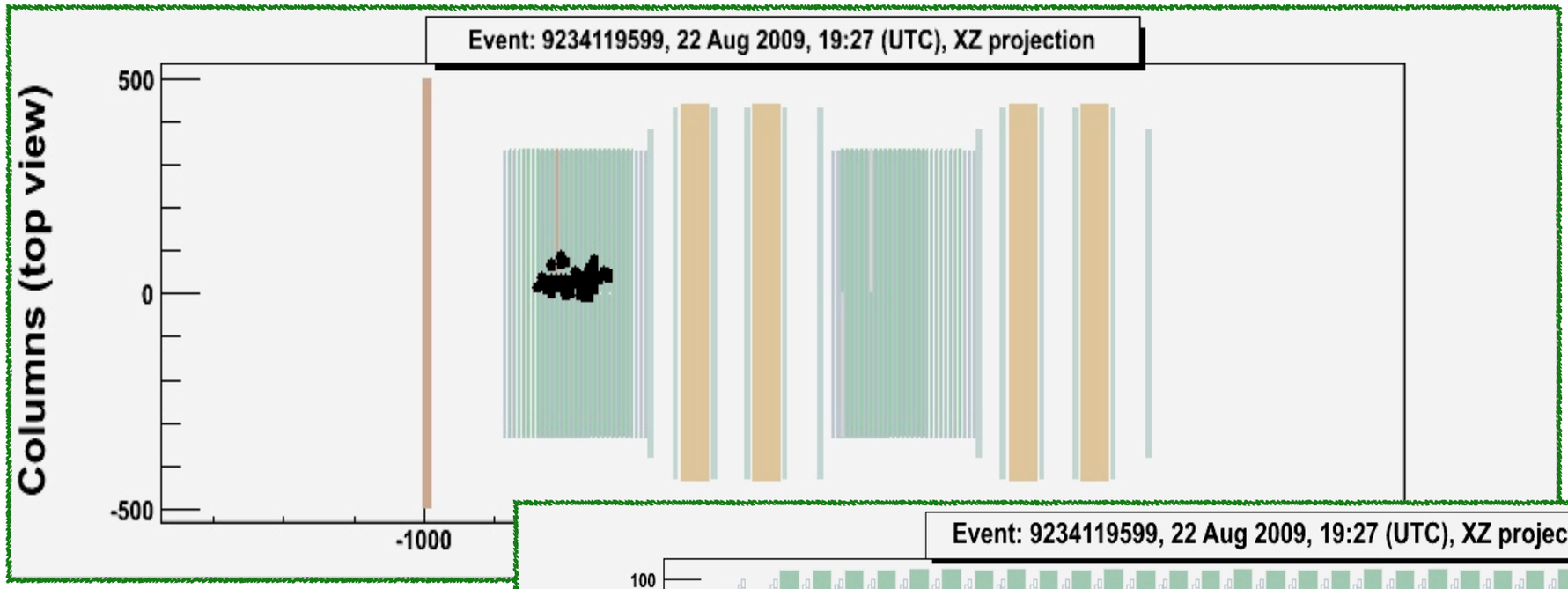
The first $\nu\tau$ candidate

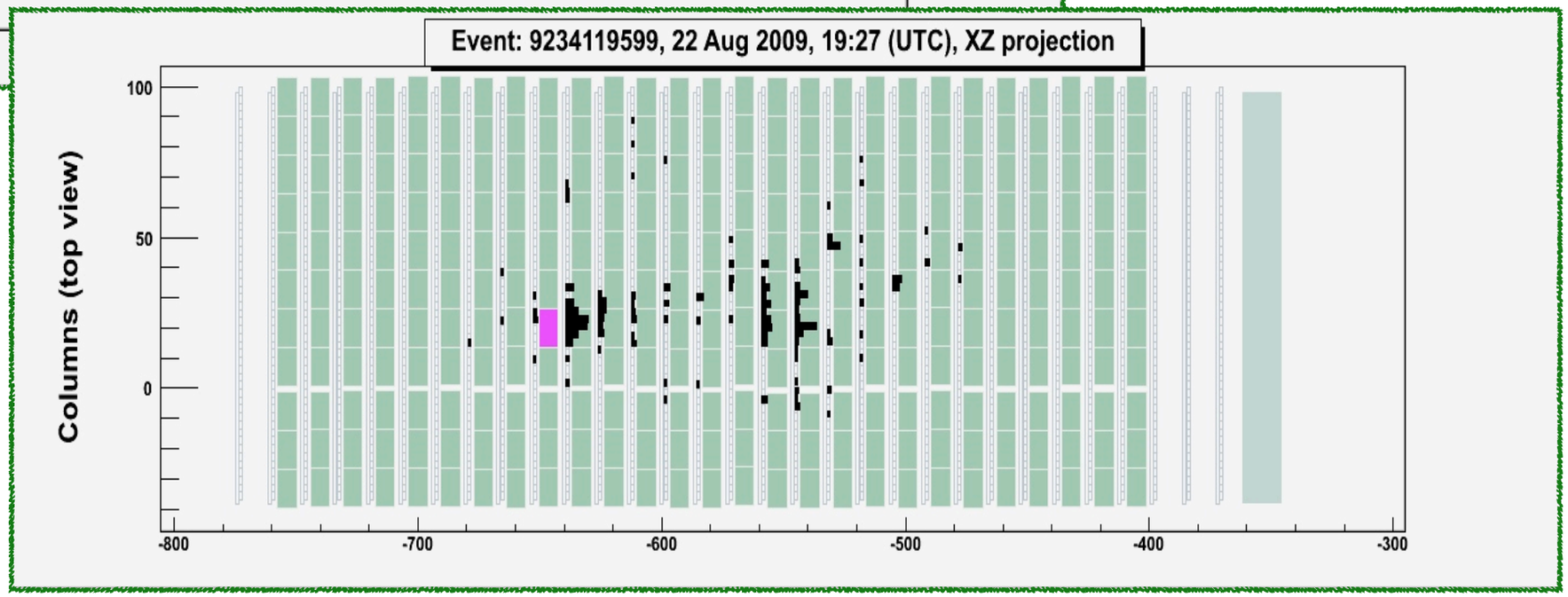
as seen by electronic detectors ...



The first $\nu\tau$ candidate

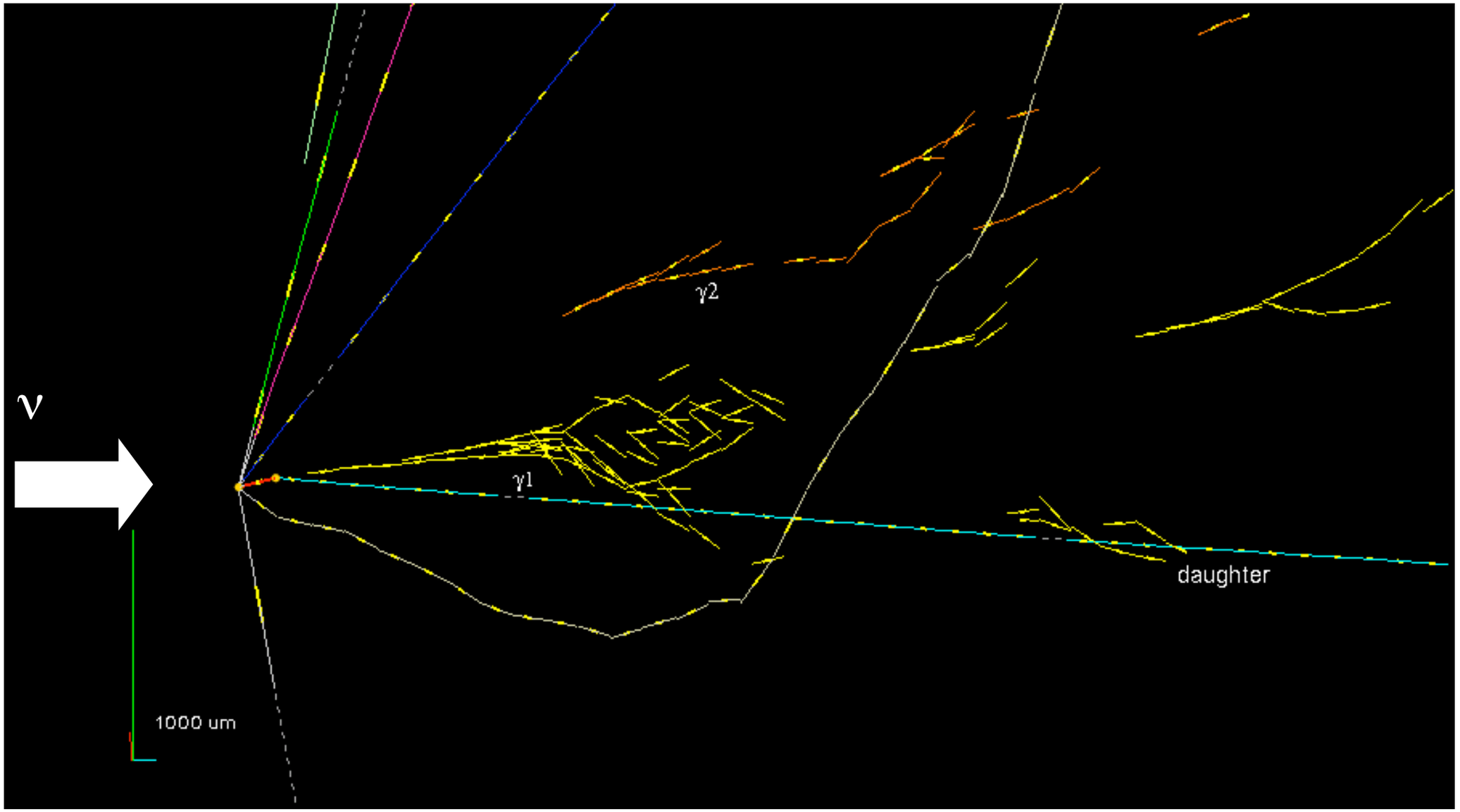
as seen by electronic detectors ...



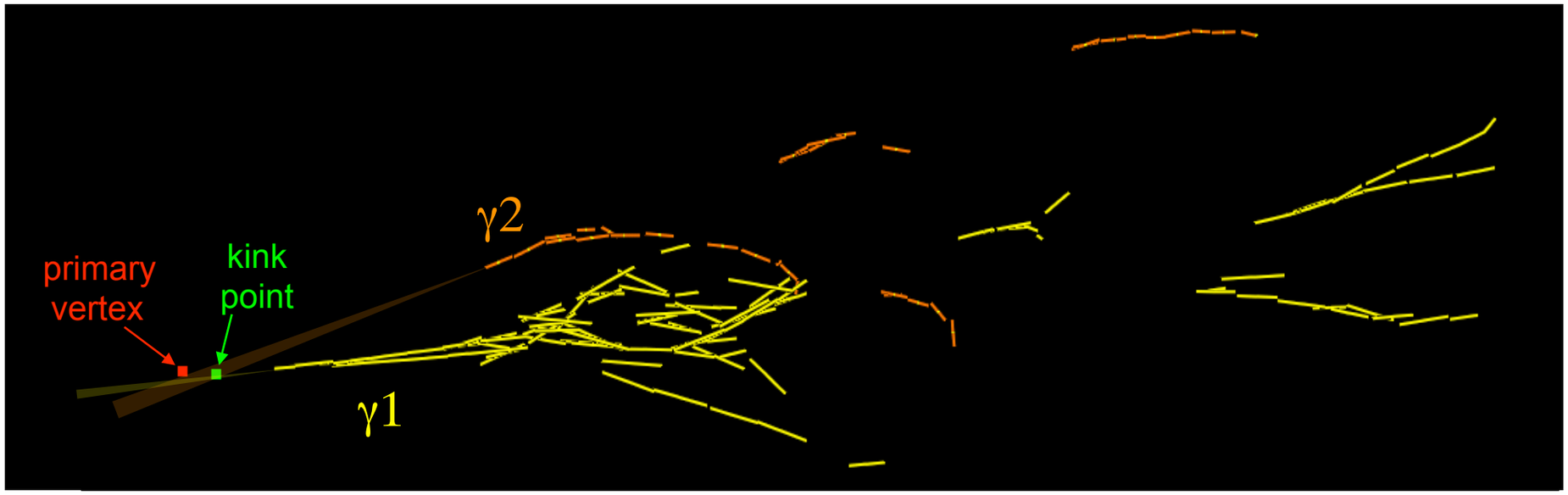


The first $\nu\tau$ candidate

... and as seen in emulsion



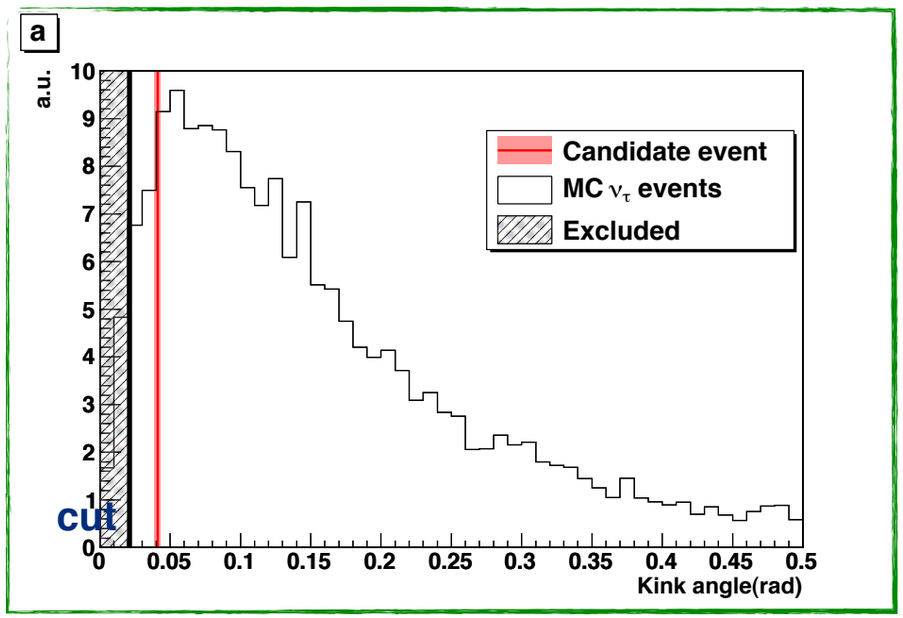
γ detection



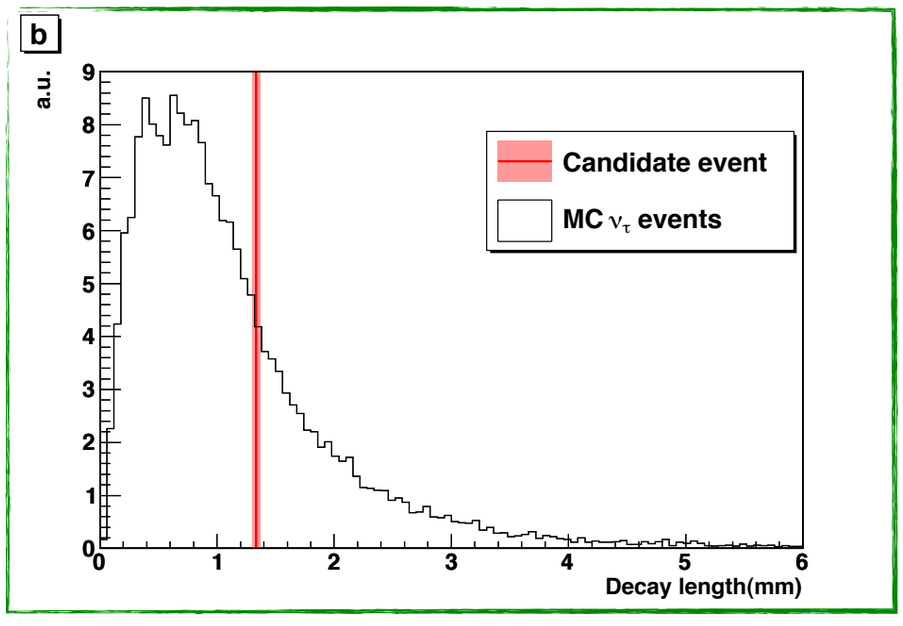
- Length avaliable for γ detection downstream of the vertices: 6.5 X_0
- Two γ detected, both assumed to come from secondary vertex after impact parameter analysis

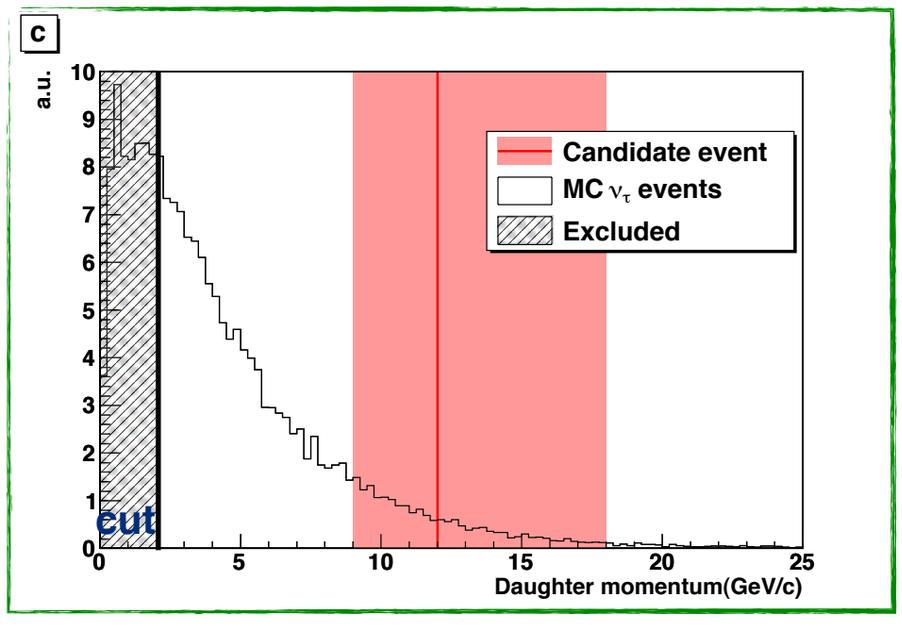
	Distance from 2ry vertex (mm)	IP to 1ry vertex (μm)	IP to 2ry vertex (μm)	Prob. of attach. to 1ry vtx	Prob. of attach. to 2ry vtx
1st γ	2.2	45.0	7.5	$<10^{-3}$	0.32
2nd γ	12.6	85.6	22	0.10	0.82

Features of the decay topology



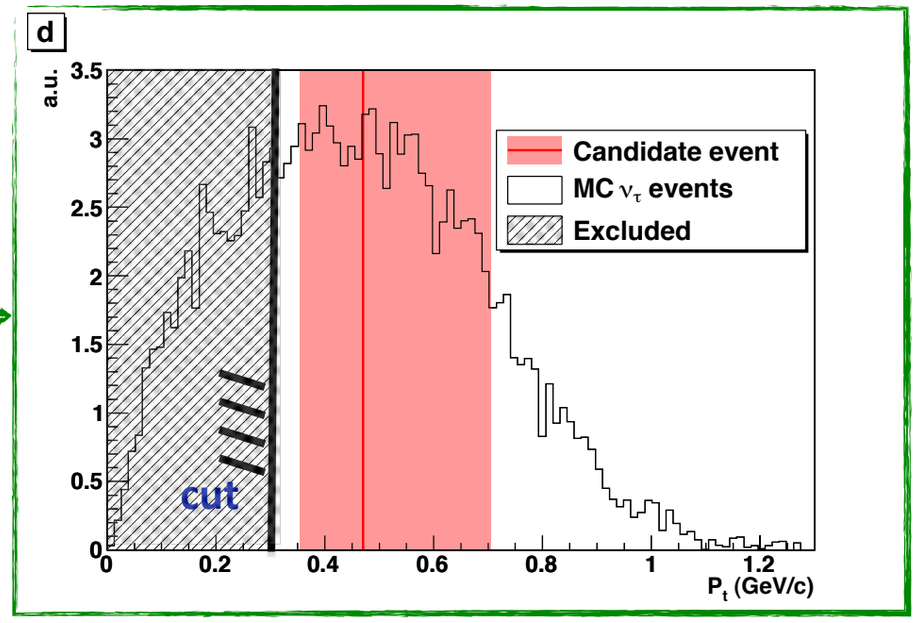
red bands: values for the "interesting" event with bands



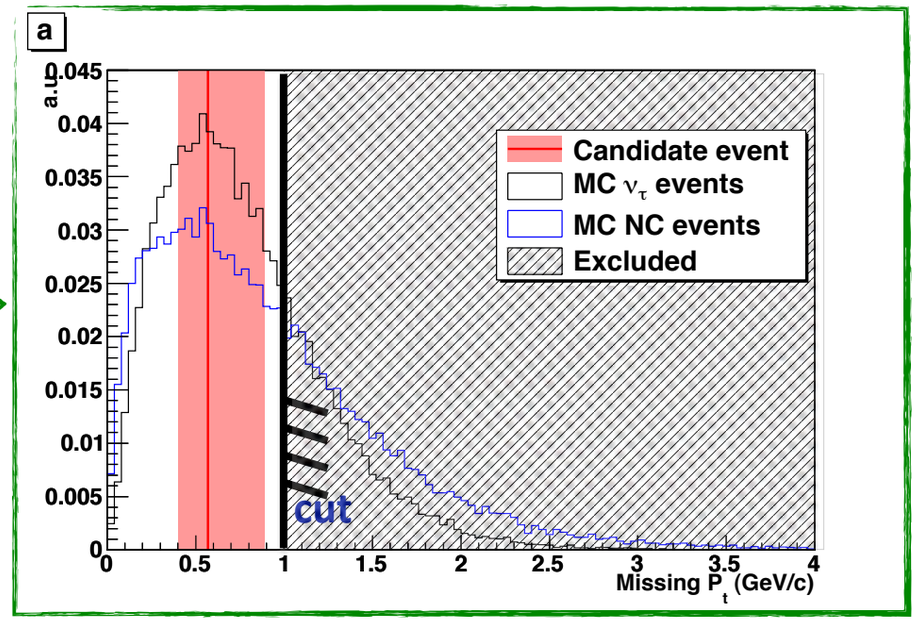


Kinematical cuts

Reject hadron interactions with small P_t at secondary vertex



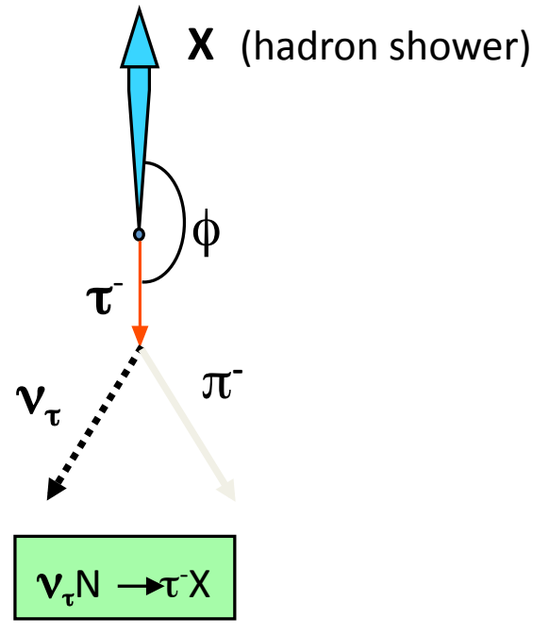
Reject NC events with large missing P_t at primary vertex



Features of the decay topology

Signal :
$\phi = 180^o$

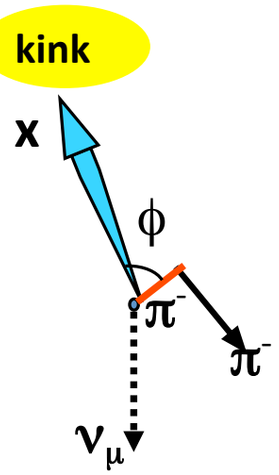
τ-decay



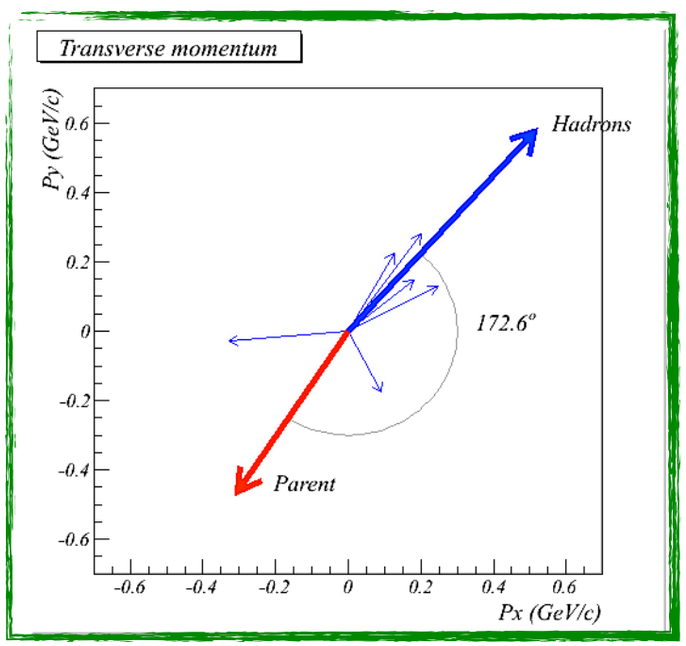
$\nu_\tau N \rightarrow \tau^- X$

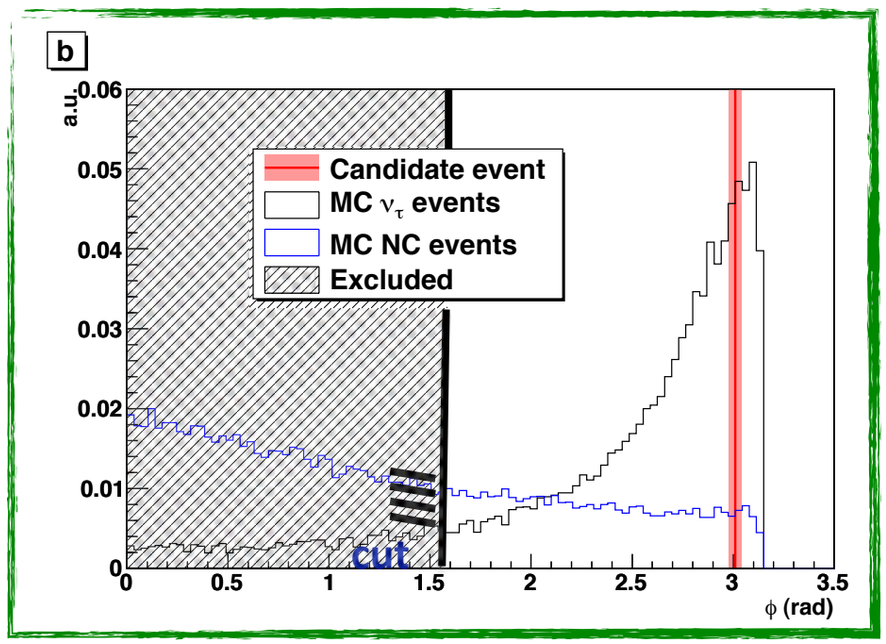
BG:
small ϕ

kink

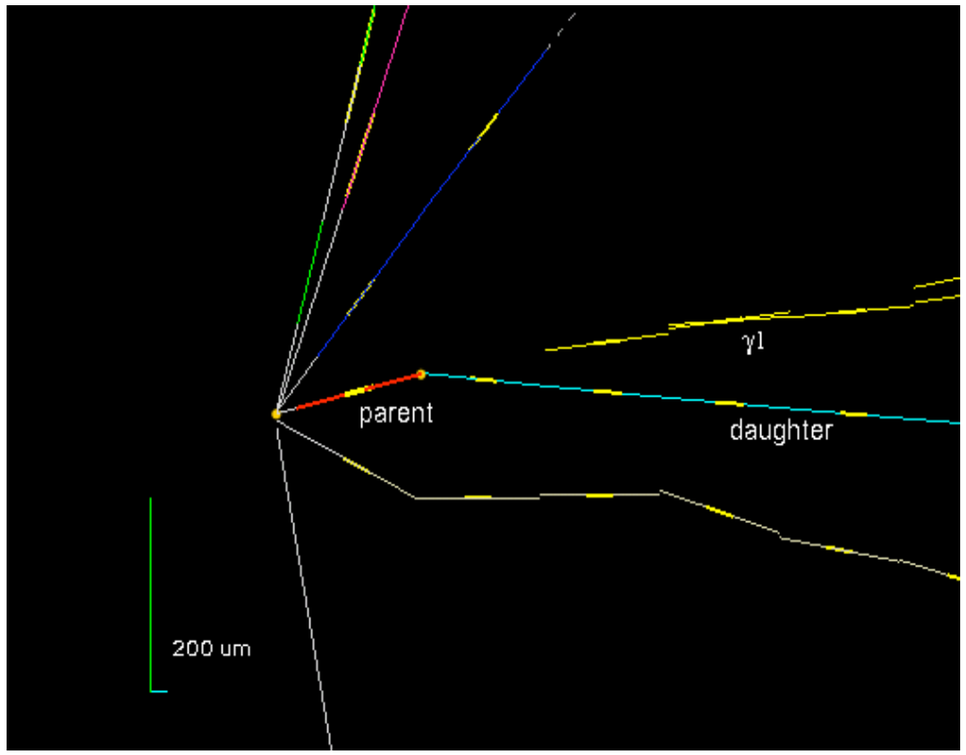


$\nu_\mu N \rightarrow \nu_\mu \pi^- X$



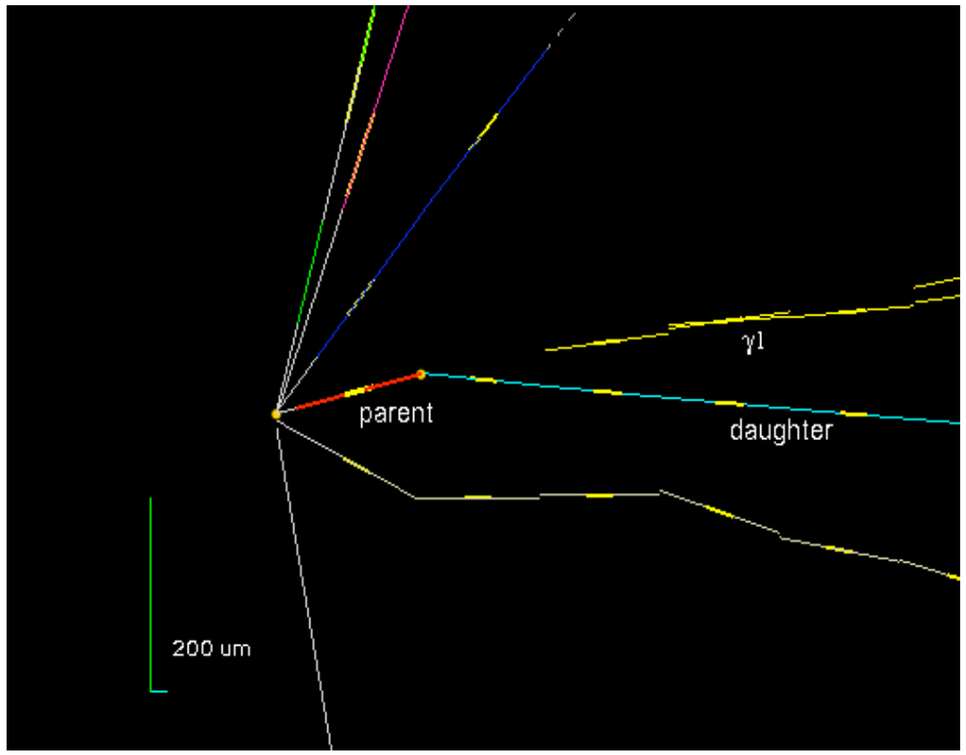


Kinematical variables



SELECTION CRITERIA	MEASURED
kink > 20 mrad	**41 ± 2 mrad**
decay length < 2600 μm	**1335 ± 35 μm**
P daughter > 2 GeV/c	**12 $^{+6}_{-3}$ GeV/c**
Pt > 300 MeV/c	**470 $^{+230}_{-120}$ MeV/c**
missing Pt < 1 GeV/c	**0.57 $^{+0.32}_{-0.17}$ GeV/c**
φ > 90°	**173 ± 2 °**

Kinematical variables



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φ > 90°	**173 ± 2 °**

The event passes all the kinematical cuts required

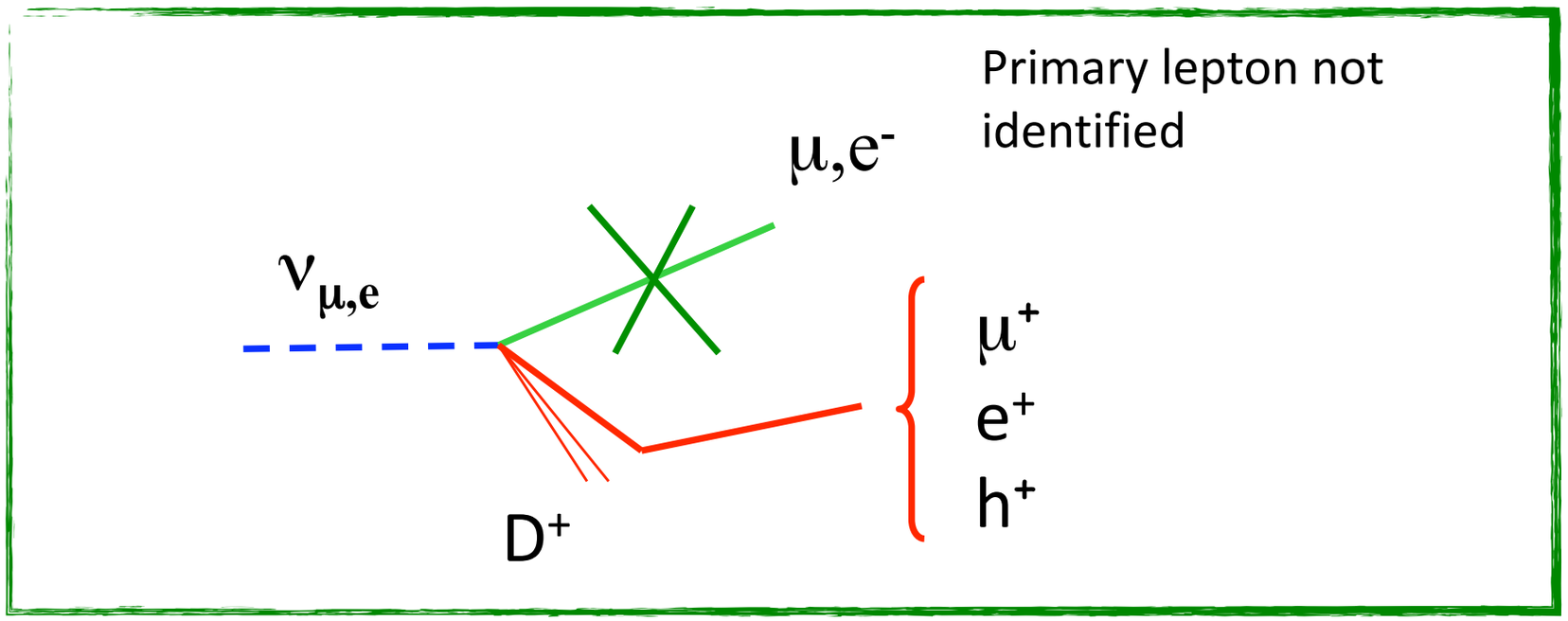
Background sources

- Prompt ν_τ ~10^{-7}/CC
- Decay of charmed particles produced in ν_e interactions ~10^{-6} /CC
- Double charm production ~10^{-6} /CC

Main backgrounds:

- Decay of charmed particles produced in ν_μ interactions ~10^{-5} /CC
- Hadronic reinteractions ~10^{-5} /CC

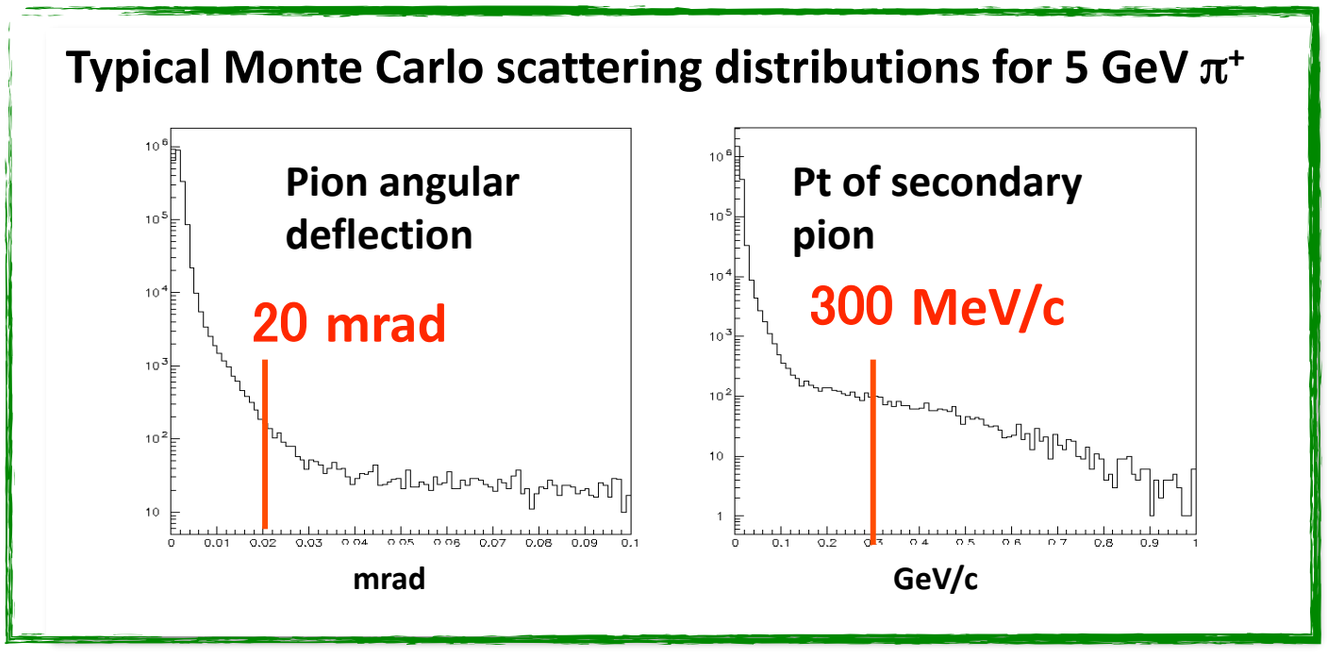
Charm background



- This background can be suppressed by identifying the primary lepton
  → 95% muon ID
- For the 1-prong hadronic channel **(7 ± 4) x 10^{-3}** background events are expected for the analysed statistics

Simulation of the hadronic BG

- 160 million events (0.5 - 15 GeV/c) of $\pi^+\pi^-k^+k^-p$ impinging 1 mm of lead, equivalent to 160 km of hadronic track length produced with FLUKA

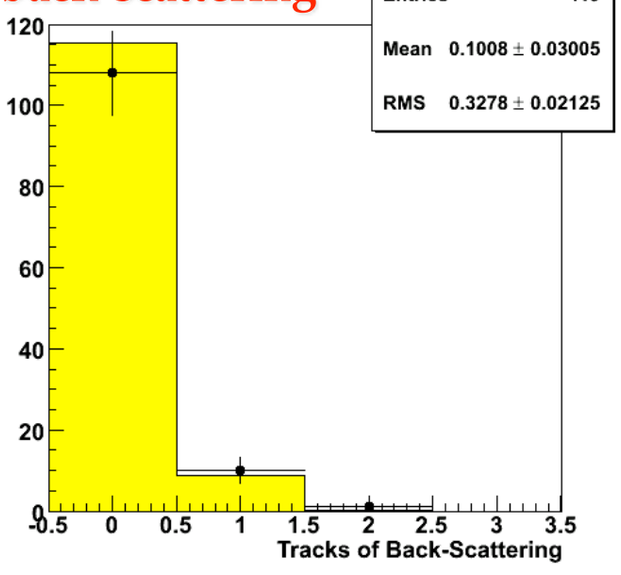


- Kink probability integrated over the ν_μ NC hadronic spectrum after 2 mm of Pb and taking in to account the cuts on the event global kinematics:

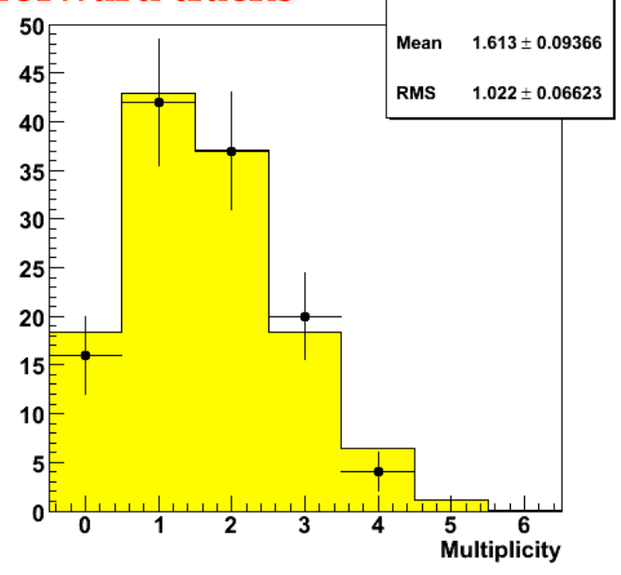
$(3.8 \pm 0.2) \times 10^{-5}$ kinks/NC

MC validation by beam test π events

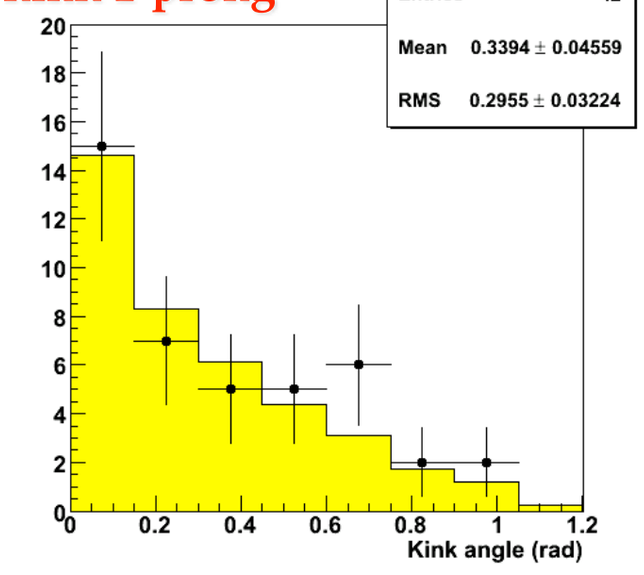
back-scattering



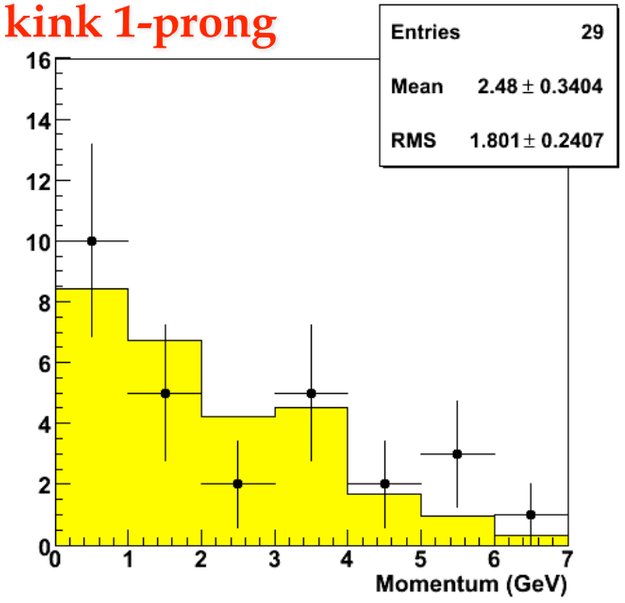
forward tracks



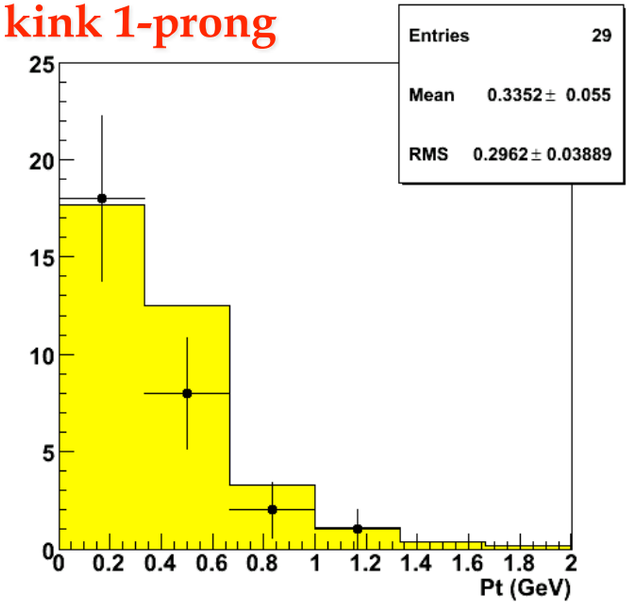
kink 1-prong



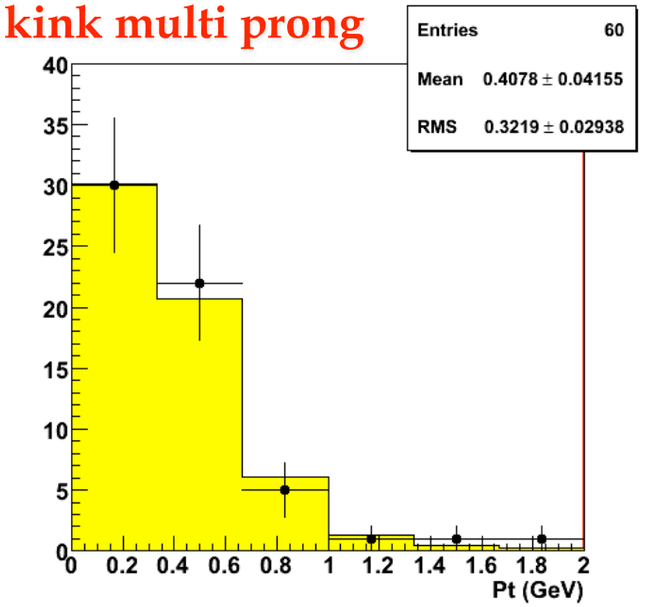
kink 1-prong



kink 1-prong

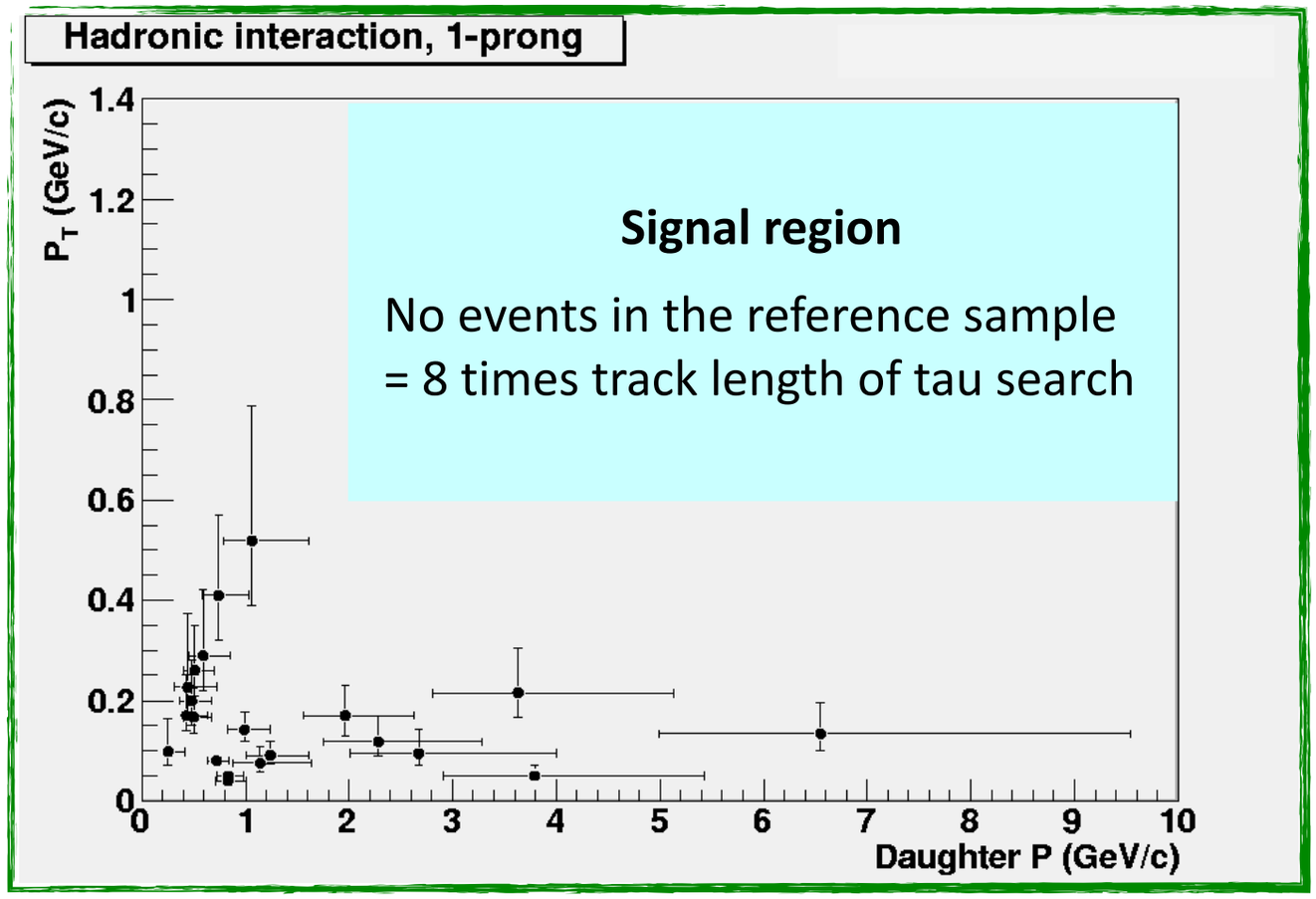


kink multi prong



- ECC brick exposed to 4 GeV/c pion: 18 times track length (20m) of τ search
- DATA/MC comparison: good agreement in normalization and shape

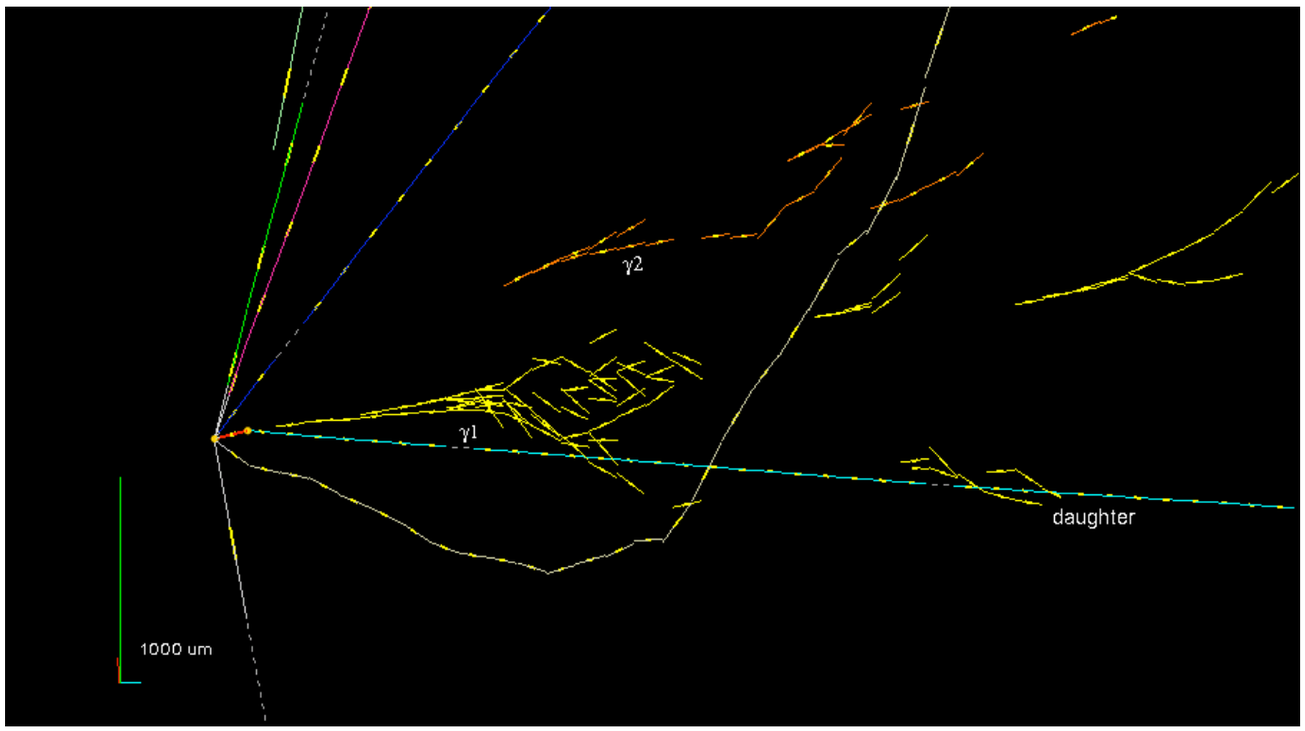
Hadronic BG study with data



- Search for "decay-like" interactions track far away from the primary vertex
- No background-like interaction has been found in the signal region
- The probability to have a background kink over 2 mm of lead is less than **1.54×10^{-3}** at 90% CL

Event interpretation

- This event passes all cuts, with the presence of at least 1 γ pointing to the secondary vertex
- This event is a ν_τ candidate with the $\tau \rightarrow$1-prong decay mode
- The invariant mass of the two detected γ is consistent with the mass π^0 value
- The invariant mass of the $\pi^- \gamma\gamma$ system is compatible with taht of ρ (770). The ρ appears in about 25% of the τ decays:



$$\tau \rightarrow \rho\ (\pi^-\ \pi^0)\ \nu_\tau$$

π^0 mass	ρ mass
120 ± 20 ± 35 MeV	$640\ ^{+125}_{-80}\ ^{+100}_{-90}$ MeV

Statistical significance

1 $\nu\tau$ candidate in the 1-prong decay channel observed

Statistical significance

1 $\nu\tau$ candidate in the 1-prong decay channel observed

Background expectation for $\tau \rightarrow$1-prong hadron decay :

0.018 ± 0.007 (syst) events

- Probability that the observed event is due to background: **1.8 %**
- Significance of ν_τ observation in OPERA: **2.36 σ**

Statistical significance

1 $\nu\tau$ candidate in the 1-prong decay channel observed

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0.018 ± 0.007 (syst) events

- Probability that the observed event is due to background: **1.8 %**
- Significance of ν_τ observation in OPERA: **2.36 σ**

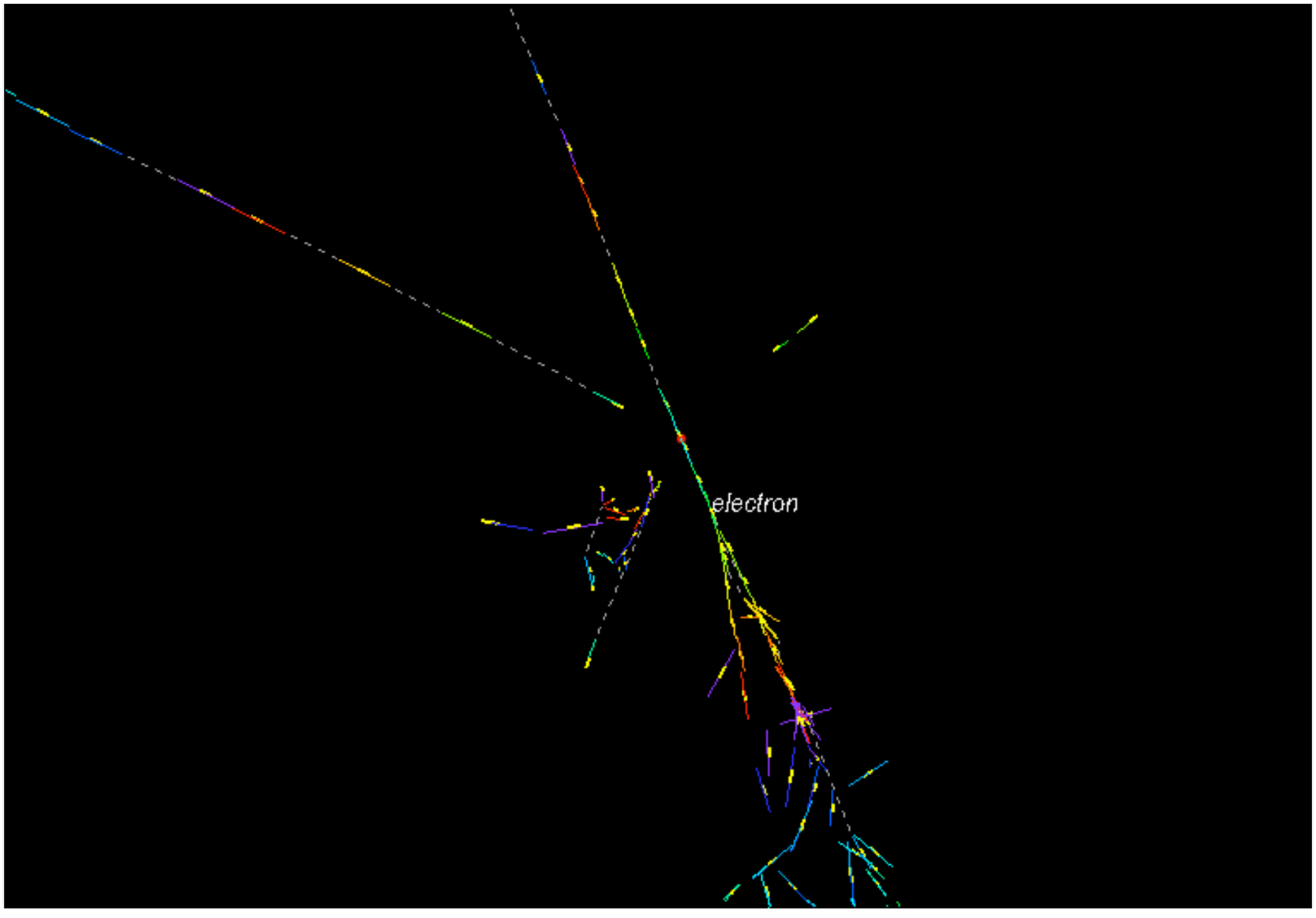
Total background from all decay modes:

0.045 ± 0.020 (syst) events

- Probability that the observed event is due to background: **4.5 %**
- Significance of ν_τ observation in OPERA: **2.01 σ**

ν_e events

13 ν_e candidate events have been located in the OPERA target



Conclusions

- The OPERA Collaboration is successfully operating a hybrid detector to search for ν_τ appearance in the CNGS beam

- The hybrid design concept in OPERA allows detailed study of each event, exploiting the best features of its nuclear emulsions, scintillators, RPC's and drift tubes

- 1 ν_τ candidate was found in 2010 out a sample of 1088 fully analysed events

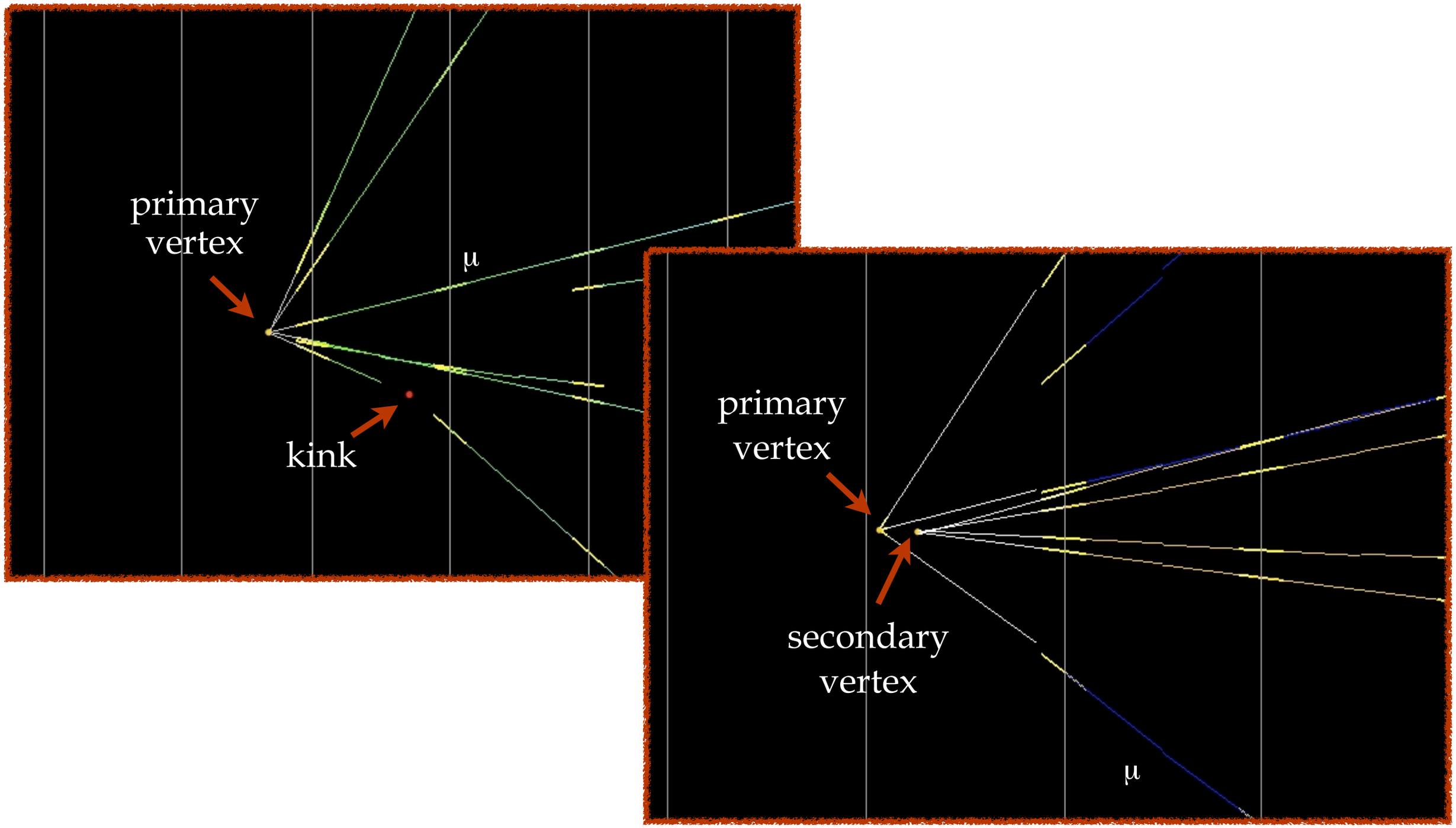
- Data taking in progress, more results to come in the near future!

Thank you for your attention!

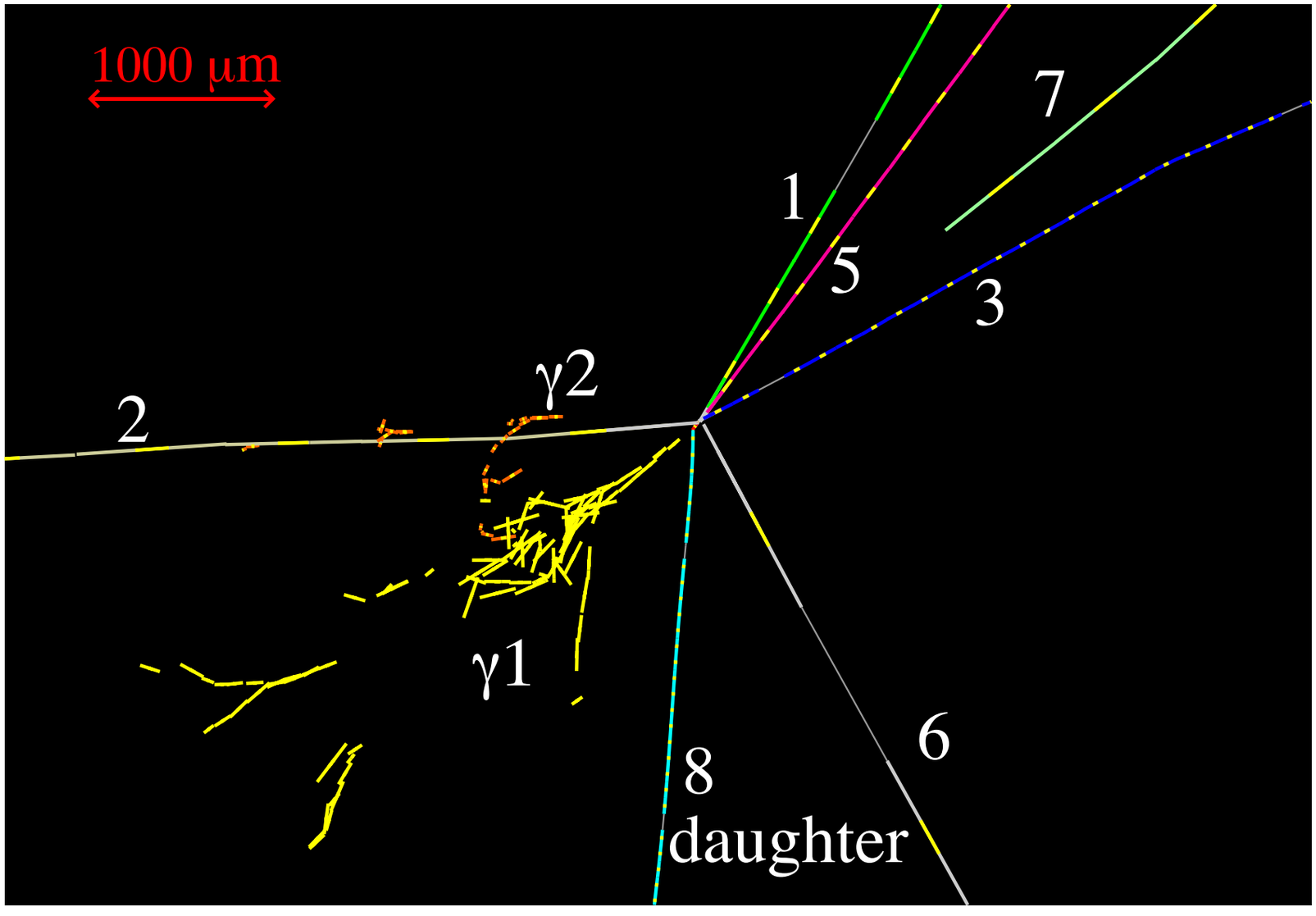
Backup slides

Charm candidate events

Proof of the τ efficiency



Event topological features

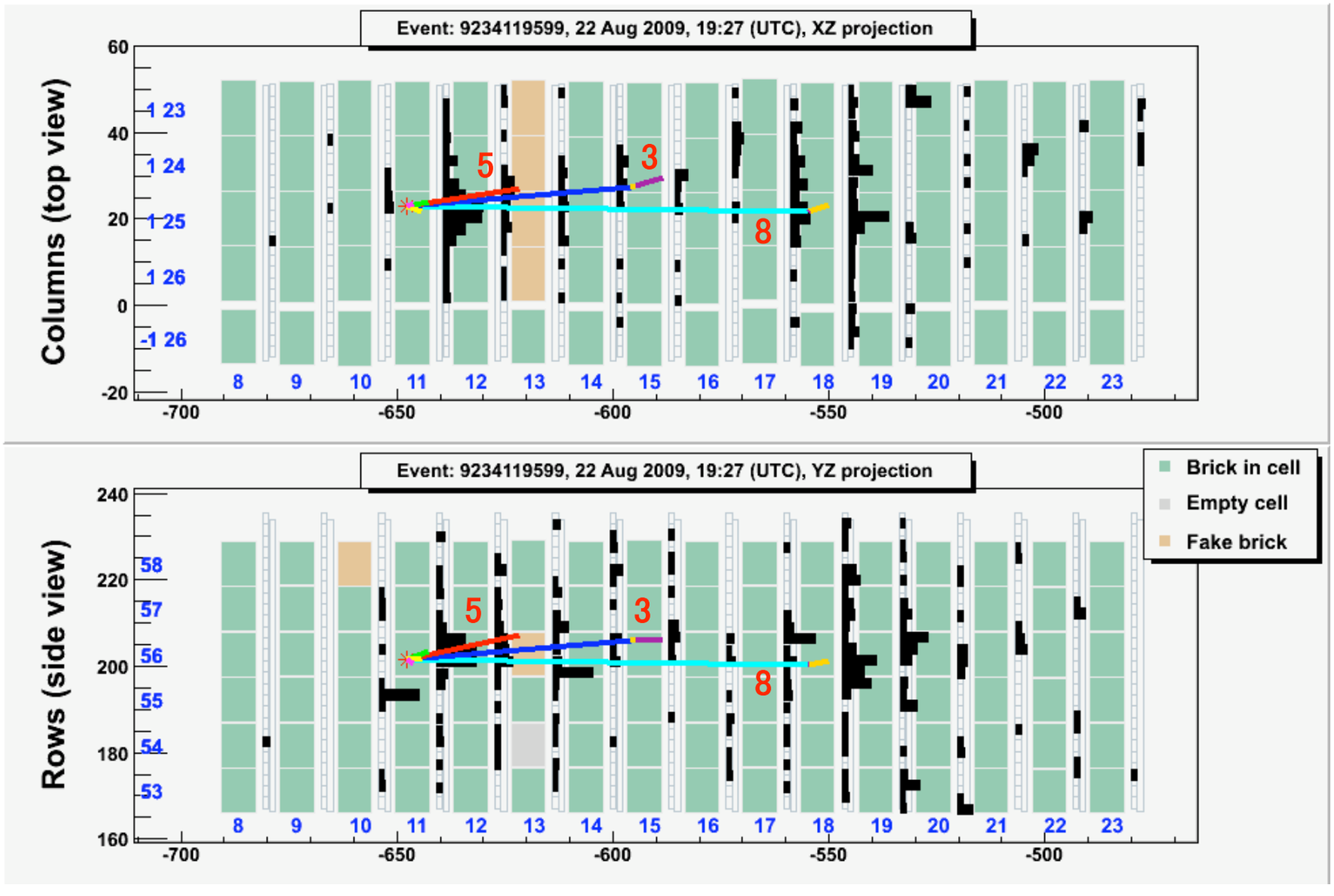


Kinematical variables

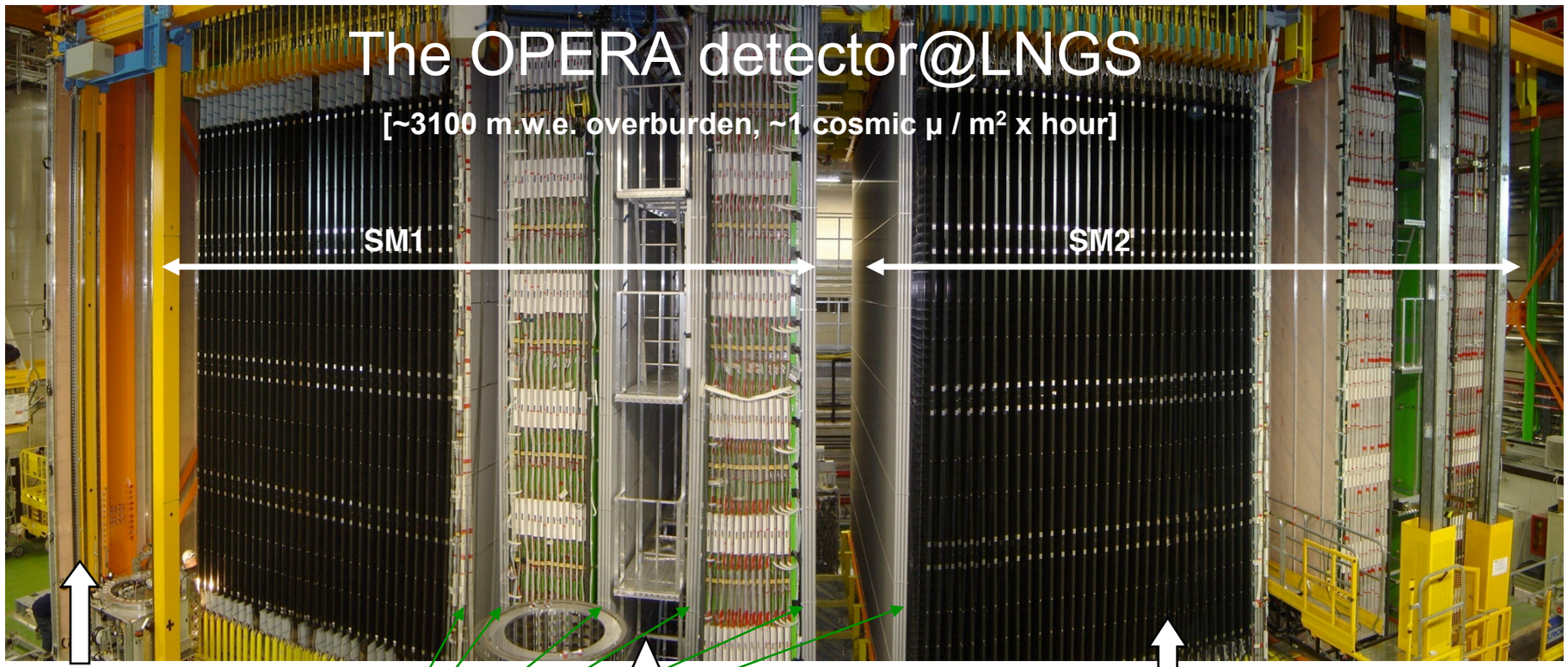
TRACK NUMBER	PID	Probability	MEASUREMENT 1			MEASUREMENT 2		
			tan Θ_X	tan Θ_Y	P (GeV/c)	tan Θ_X	tan Θ_Y	P (GeV/c)
1	HADRON range in Pb/ emul=4.1/1.2 cm	Prob(μ)≈10^{-3}	0.177	0.368	0.77 [0.66,0.93]	0.175	0.357	0,80 [0.65,1.05]
2	PROTON	range, scattering and dE/dx	-0.646	-0.001	0.60 [0.55,0.65]	-0.653	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	

The first $\nu\tau$ candidate

Vertex tracks followed down (through several bricks) to assess the
muon-less nature of the event.
Residual probability of ν_μCC event (due to a possibly undetected large angle muon) ~ 1%
"Nominal" value of 5% assumed



The detector



Veto (RPC)

High precision tracker
- 6 4-fold layers of drift tubes

Dipole magnet
- 1.53 *T*
- 22 XY planes of RPC

muon spectrometer (8×10 m^2)

Target + Target Tracker (6.7*m*)²

- target/SM: ~75000 *bricks* *(Pb – nuclear emulsions)* Mass/SM 0.625 kt
- Target tracker : 31 doublets XY (256 plastic scintillator strip + WLS fibres+ multi-anodes PMT) for trigger, brick selection and calorimetry

[Ref. JINST 4 (2009) P04018]

The first $\nu\tau$ candidate

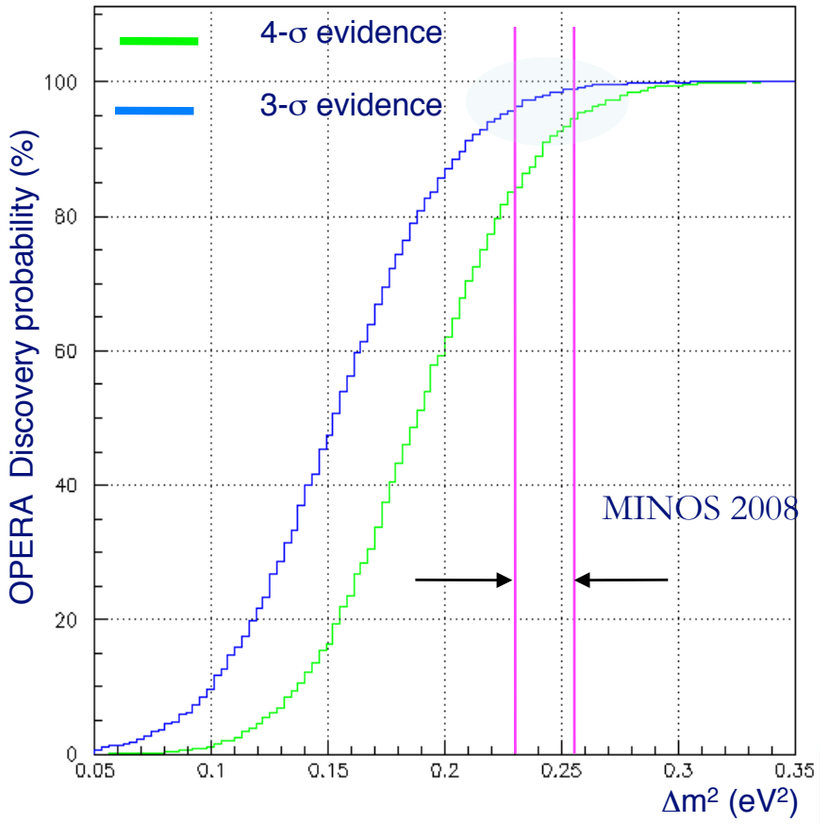
all the charged hadrons and electromagnetic particles attached to the primary vertex have been measured

P_{miss} at primary vertex **$0.57\ ^{+0.32}_{-0.17}$** GeV/c
→ event kinematics almost closed (no neutral particle missing at the primary)

Sum of the modulus of the momenta at the primary vertex **$24.3\ ^{+6.1}_{-3.2}$** GeV/c

Total hadronic momentum at the primary vertex **~ 5.5** GeV/c
(not including that of the parent assumed to be a τ)

OPERA sensitivity



5 years, nominal 4.5 10^{19} pot

By assuming that $\Delta m^2_{23} = 2.5 \times 10^{-3}$ eV^2 and full mixing, we expected:

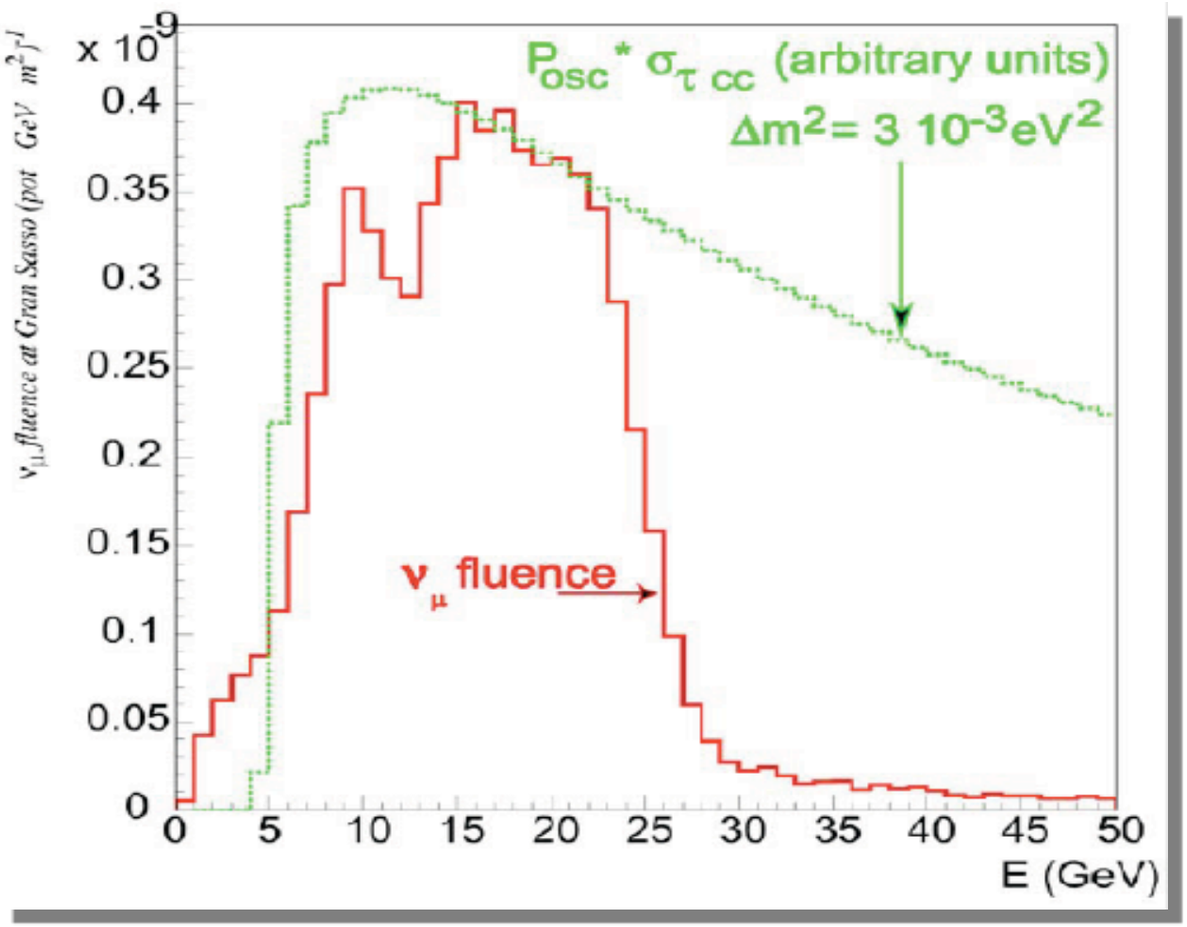
0.54 ± 0.13 (syst) ν_τ CC events in all τ decay channels and
0.16 ± 0.04 (syst) ν_τ CC events in the 1-prong hadron τ decay channel

and we observed 1 event.

This result allows us to exclude at the 90% CL

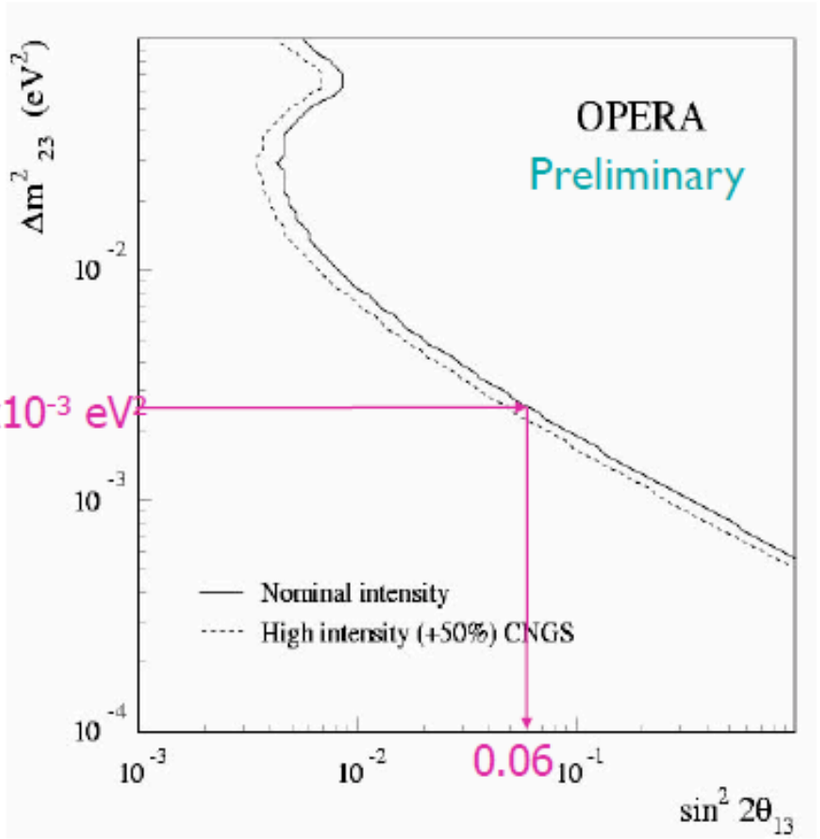
Δm^2_{23} values > 7.5×10^{-3} eV^2 (full mixing)

CNGS beam


x 10^-9
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
5
10
15
20
25
30
35
40
45
50
E (GeV)
P_osc * σ_τ cc (arbitrary units)
Δm²= 3 10⁻³eV²
ν_μ fluence

Sensitivity to θ_{13}

Simultaneous fit on:
E_e, missing p_T and visible energy



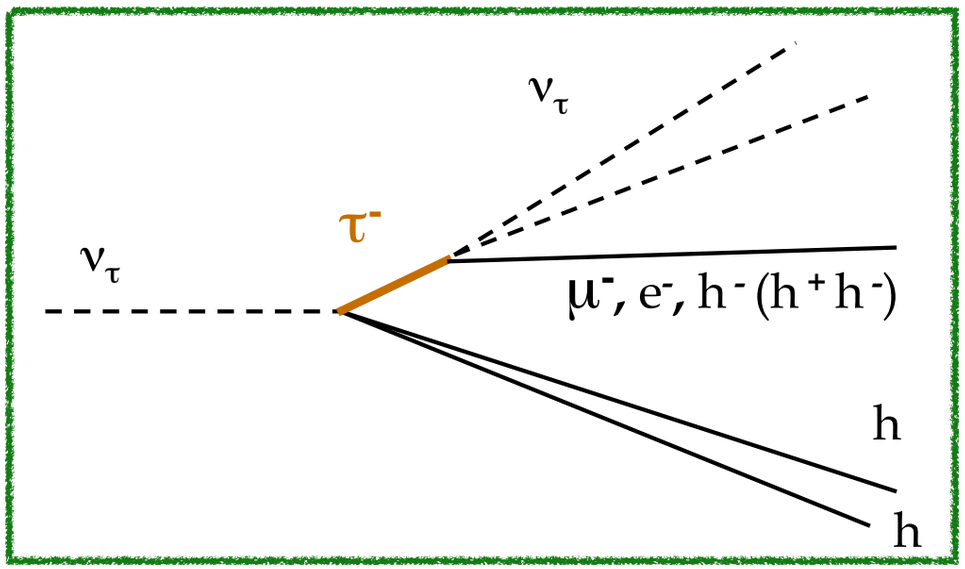
full mixing, 5 years run @ 4.5x10^{19} pot / year

Θ_{13} (deg)	Signal $\nu_\mu \to \nu_e$	Background			
		$\tau \to e$	ν_μCC	ν_μNC	ν_eCC beam
9	9.3	4.5	1.0	5.2	18
7	5.8	4.5	1.0	5.2	18
5	3.0	4.5	1.0	5.2	18

Limits at 90% CL for
$\Delta m^2 = 2.5\text{x}10^{-3}$ eV^2 full mixing

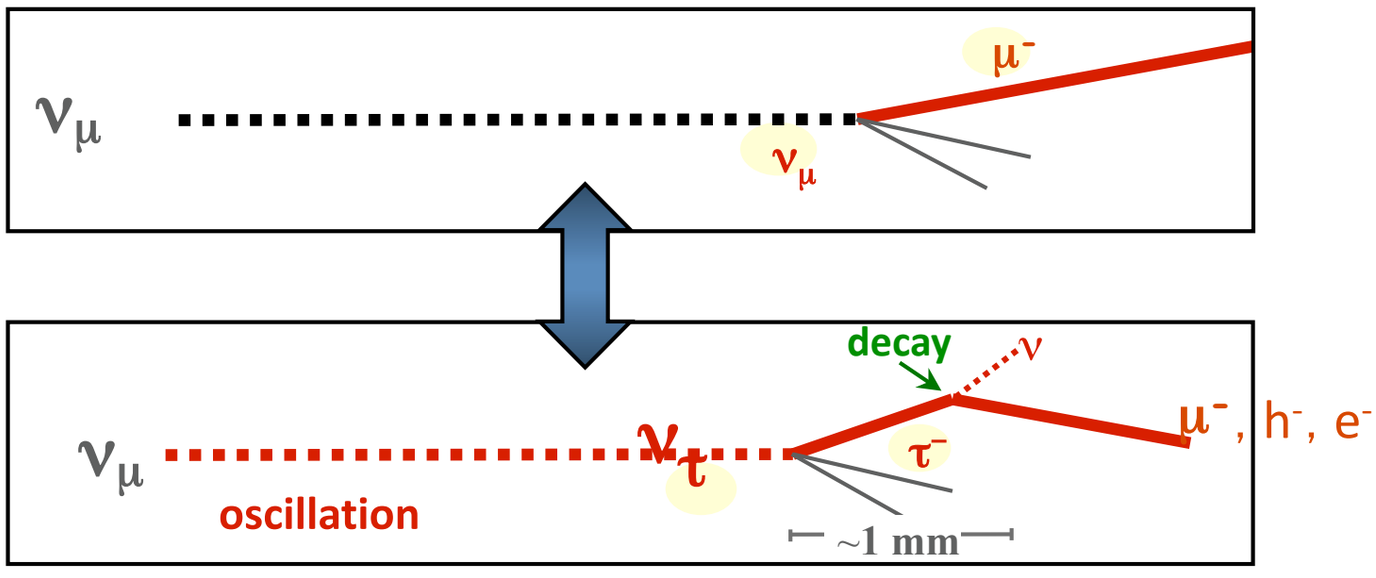
	$\sin^2 2\Theta_{13}$	Θ_{13}
CHOOZ	<0.14	11°
OPERA	<0.06	7.1°

Nuclear emulsions

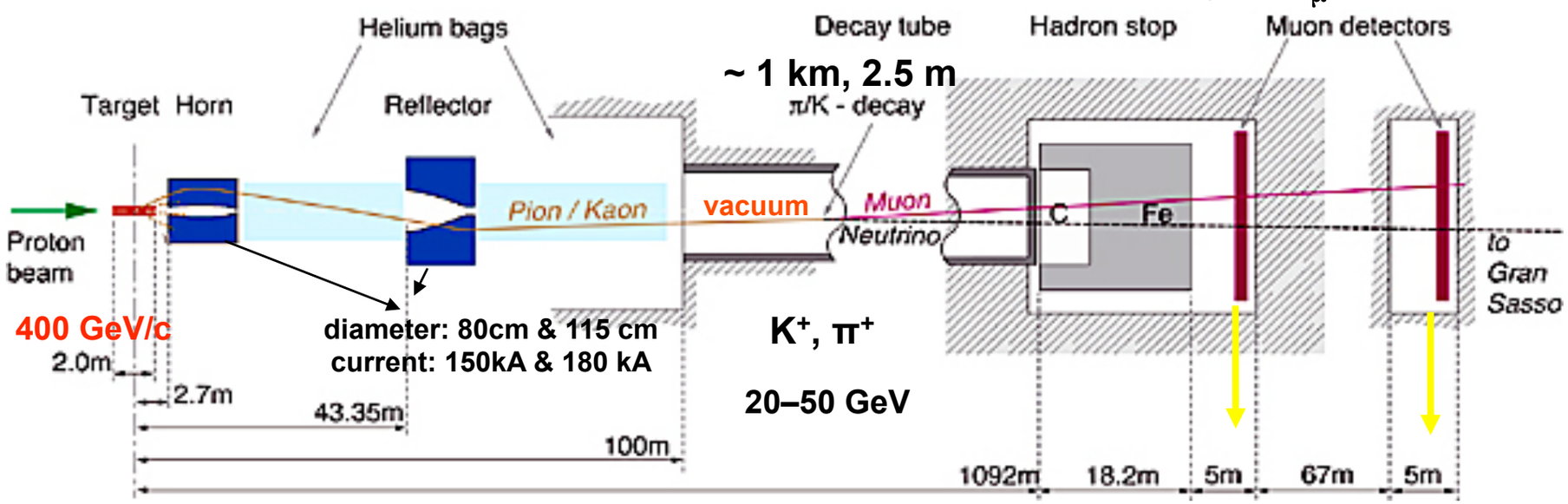


Decay modes

τ^-	→	e^-	(17.8 %)
τ^-	→	μ^-	(17.4 %)
τ^-	→	h^-	(49.5 %)
τ^-	→	$h^- h^+ h^-$	(15.2 %)



The CNGS neutrino beam



conventional neutrino beam with a high intensity and high energy proton beam, intense short beam pulses and small beam spots (<1mm)

- 400 GeV/c proton from the CERN SPS on graphite target, producing pions and kaons
- 6 s cycle length, 2 extractions every 50 ms, 10.5 μs pulse length
- beam intensity 2.4 **x** 10^{13} pot/extr
- average power at the target 510 kW
- neutrinos from pions and kaons decaying in flight
- muon detectors are used for online monitoring and tuning of the beam