Latest results of OPERA

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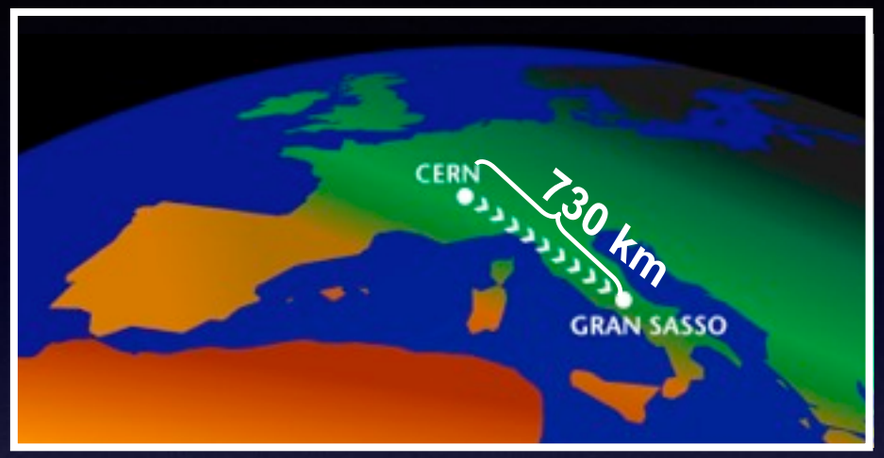
On behalf of the OPERA collaboration

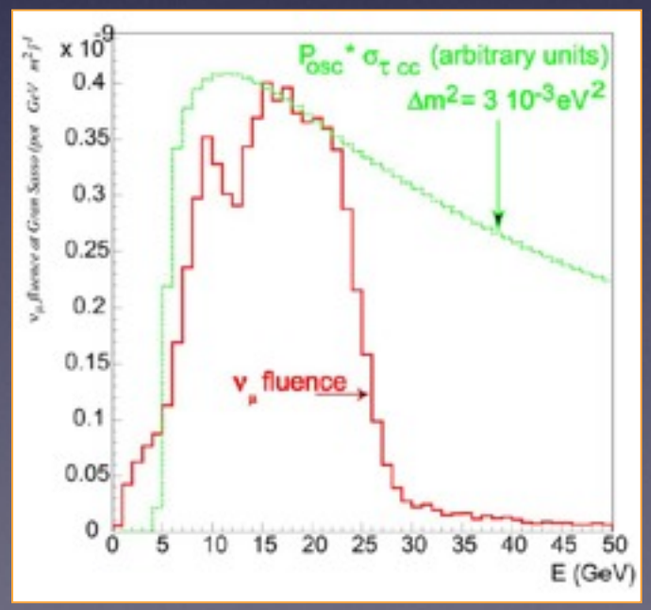
17th March 2014 - Rencontres de Moriond

OPERA experiment

- Goal: first direct observation of ν_τ appearance from ν_μ oscillation at atmospheric scale by τ detection (production threshold: 3.5 GeV).
- Full coverage of the parameter space ($\Delta m_{23}^2 \approx 2.4\times10^{-3}$ eV^2 and $\sin^2 2\theta_{23} \approx 1.0$) indicated by SuperK, T2K and MINOS.
- Long Baseline (730 km) experiment in the CNGS (CERN Neutrino To Gran Sasso) ν_μ beam.
- Located in the LNGS which is under 1400 m rock overburden.



Conventional high energy beam optimized for ν_τ CC interactions observation.

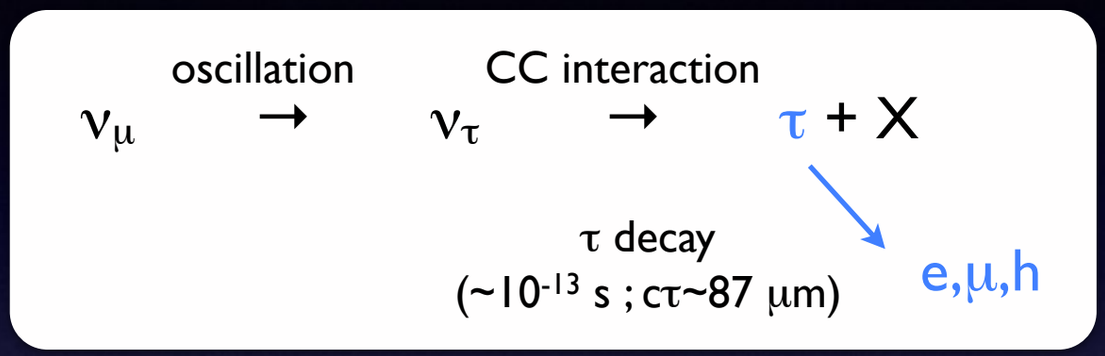


$\langle E_{\nu\mu} \rangle$	17 GeV
$(\nu_e + \bar{\nu}_e)/\nu_\mu$	0.87%
$\bar{\nu}_\mu/\nu_\mu$	2.1%
ν_τ prompt	negligible

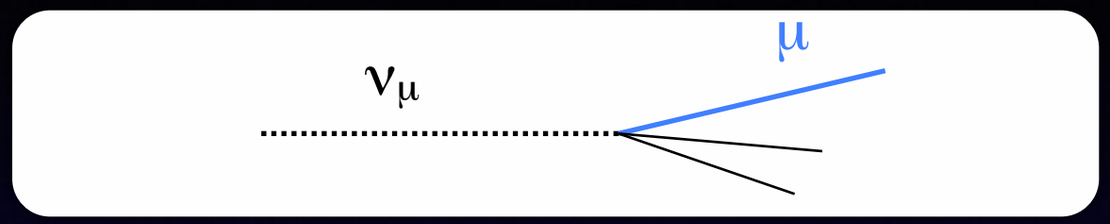
Low ν_e contamination which allows to put also constraints on $\nu_\mu \rightarrow \nu_e$ oscillation.

Detection principle

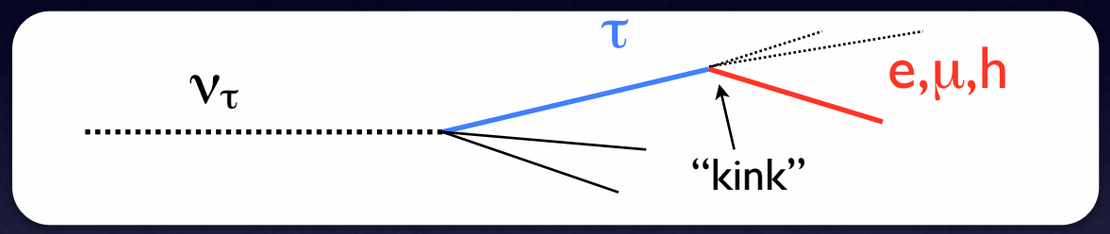
Physics process



Topology: ν_μ CC interaction



Topology: ν_τ CC interaction



- The detection of the τ lepton requires an identification of the decay "kink".

- The detector must fulfill the following requests:

1. Large mass due to small CC cross section (lead target).
2. Micrometric resolution to observe the kink (photographic emulsions).
3. Locate neutrino interactions (electronic detectors).
4. Identify muons to reduce charm background (electronic detectors).

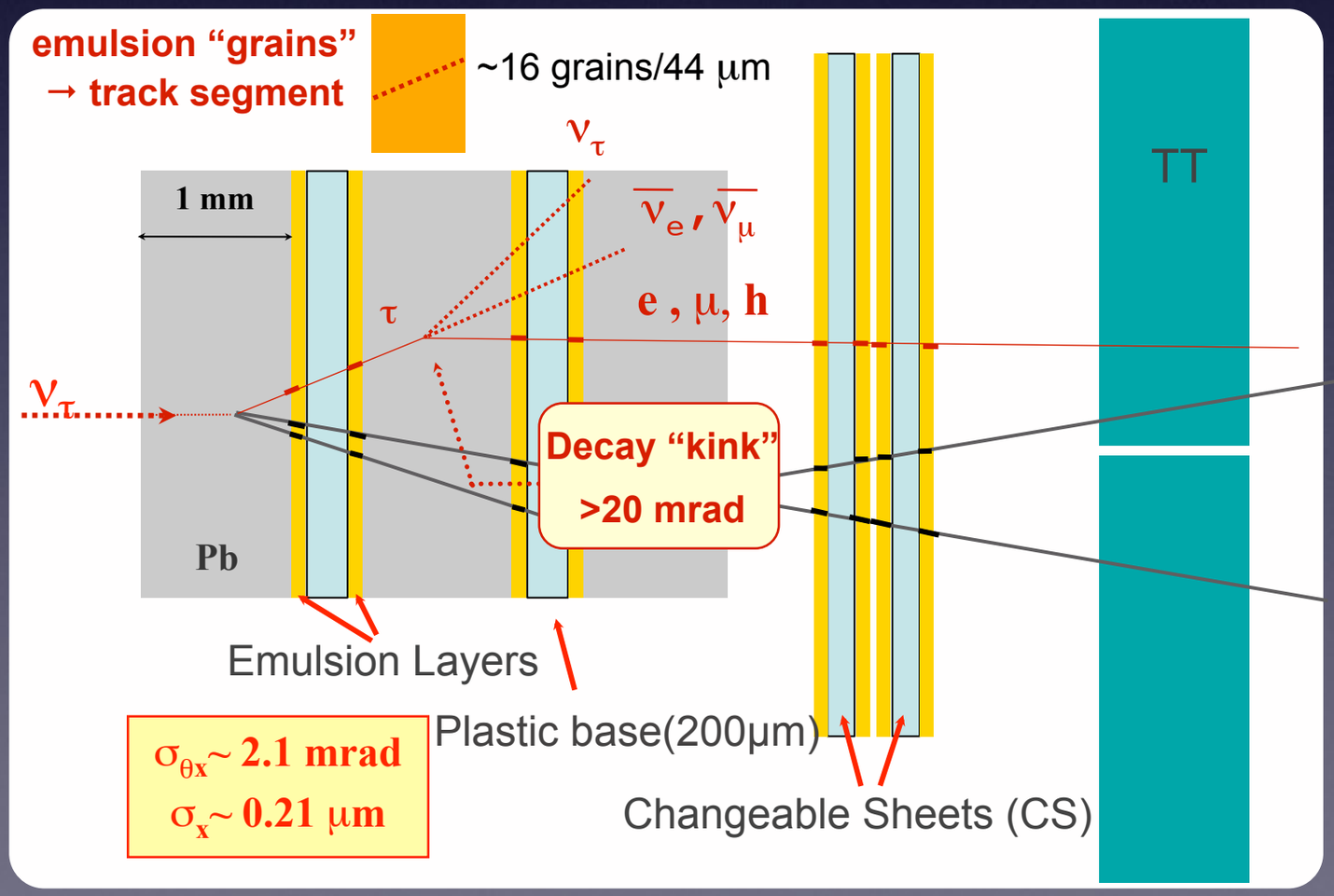
↓

OPERA: hybrid detector (emulsions + electronic detectors)

τ identification

- The identification is done in the lead-emulsion target, which is segmented in units called "bricks".
- The high granularity (300 hits/mm) of emulsions allows for an unambiguous measurement of the kink.

Lead-emulsion layers in brick



Brick structure

Brick weight: 8.3 kg

Sandwich of 56 (1mm) Pb sheets
+ 57 FUJI films (base + 2 emulsion layers)
+ 2 changeable sheets

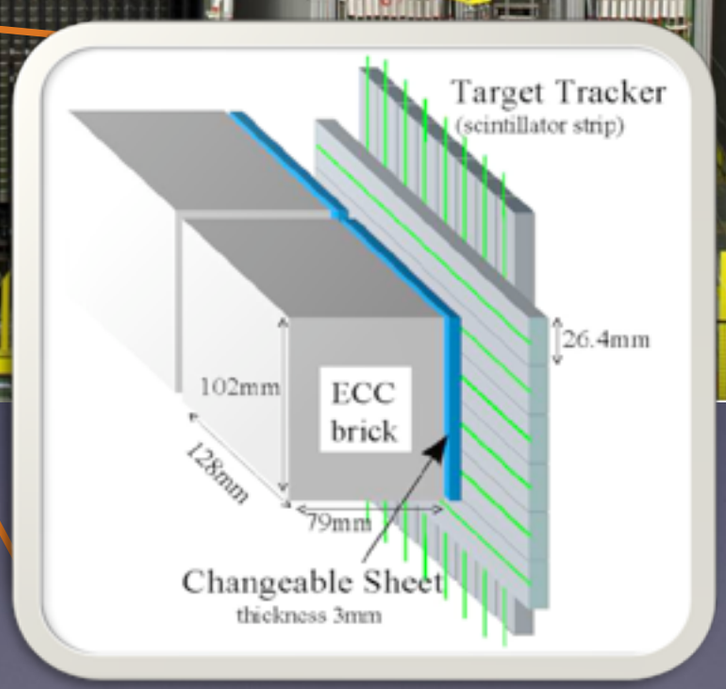
Event reconstruction in emulsions

The OPERA detector

SM1 SM2

Target area
~ 150000 ECC bricks → 1.25 kton

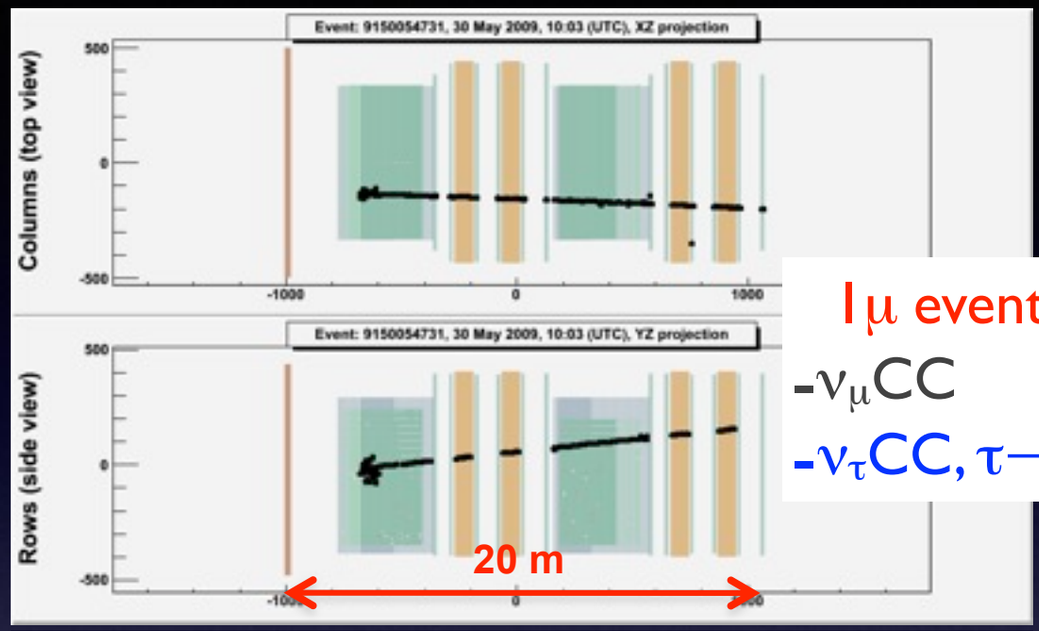
Muon Spectrometer
Dipole Magnet + RPC + Drift Tubes

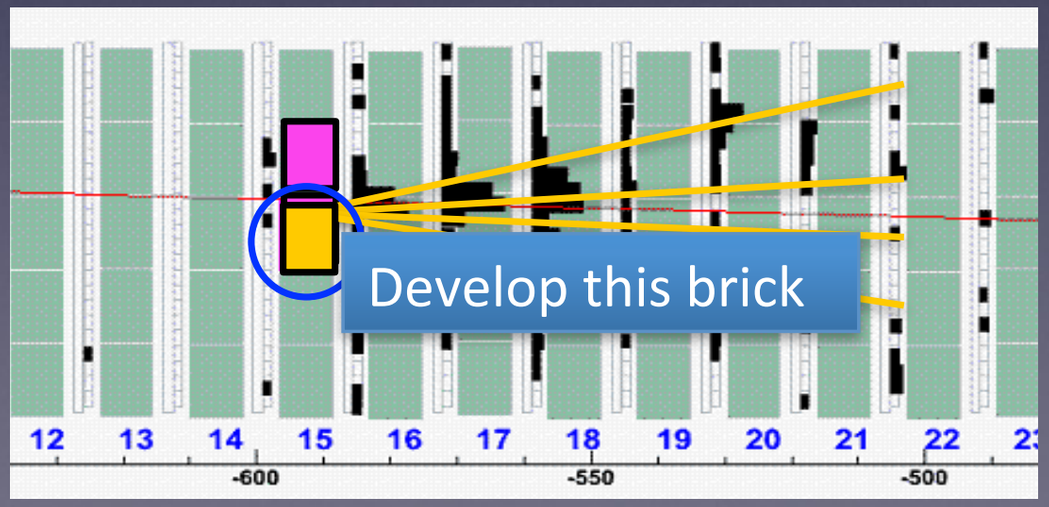


Δp/p (<50 GeV/c)	~ 20%
μ ID (with TT)	~ 95%

Event reconstruction: Electronic Detectors (ED)

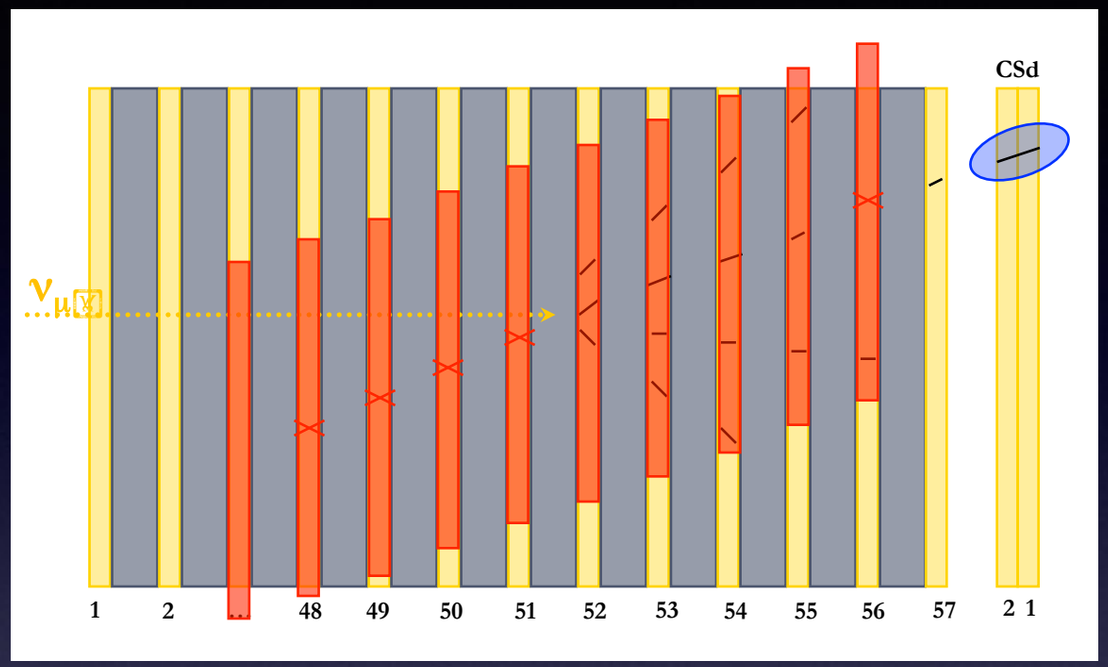
- Selection of contained and «on time» with CNGS beam spill.
- Track (muon) reconstruction and event classification as CC-like (1 μ) or NC-like (0 μ).
- The information provided by the ED allows to assign to each brick a probability to contain the ν interaction (brick finding algorithm).
- Brick removed by BMS (Brick Manipulating System).



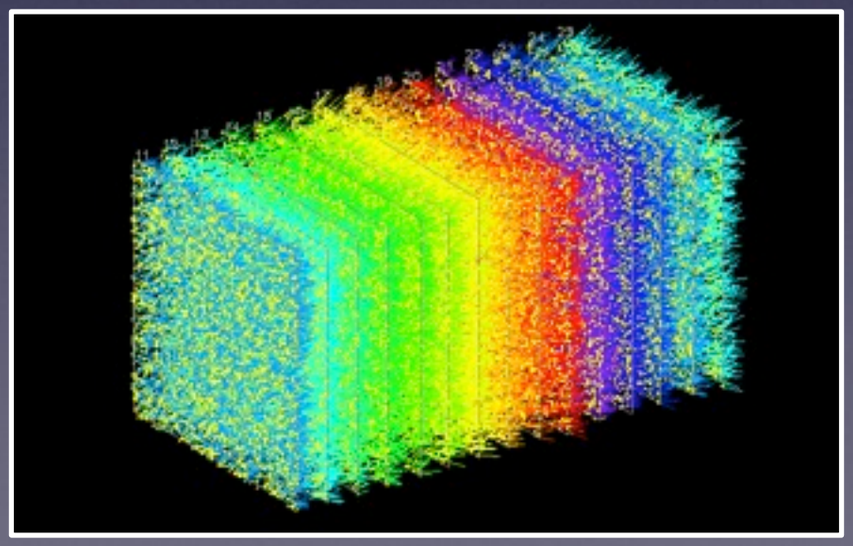


Event reconstruction: ECC brick

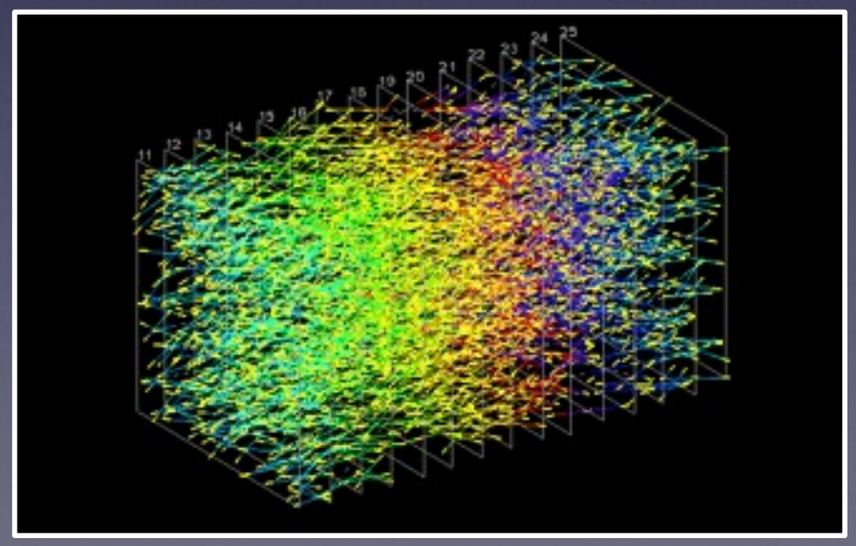
- CS analysis: they are scanned looking for a connection with the ED predictions (σ_{pos}~8 mm, σ_{θ}~15 mrad).
- If tracks are found, the brick is developed.
- CS to brick connection (σ_{pos}~70 μm, σ_{θ}~8 mrad) and scan-back: stopping point definition.
- Volume scan: topological vertex reconstruction and decay search.



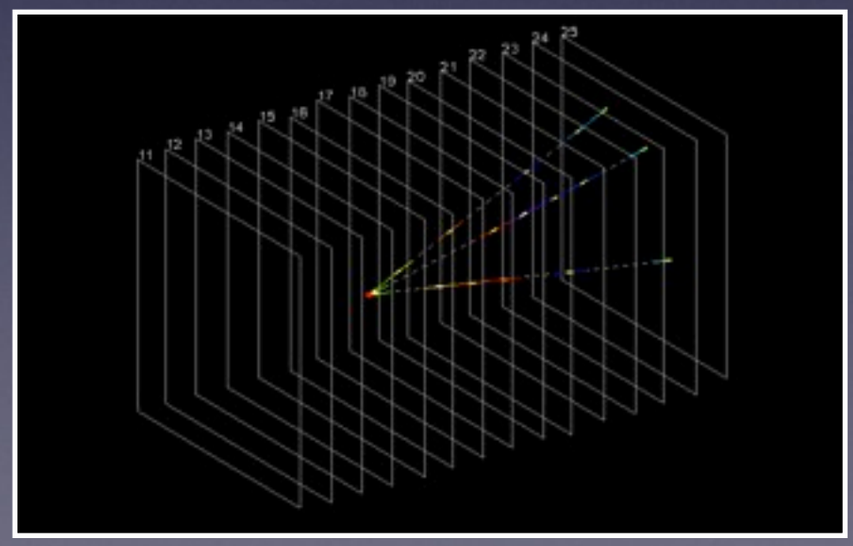
Volume scan (about 2 cm^3) around the tracks stopping point.



Film to film connection.

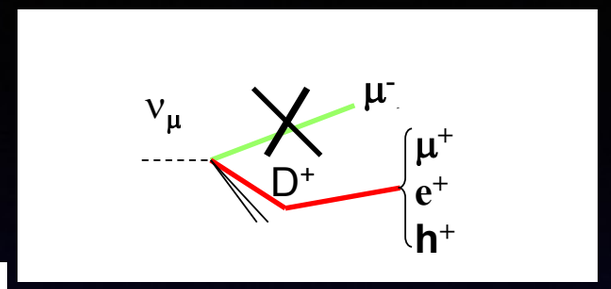


Converging tracks (in agreement with the CS).

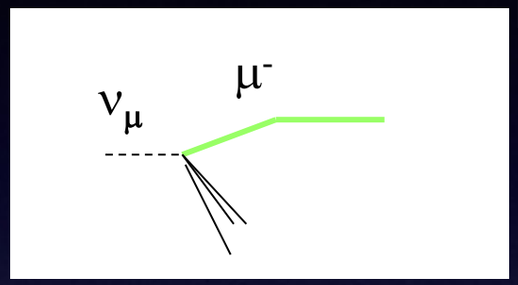


Backgrounds to $\nu_\mu \rightarrow \nu_\tau$

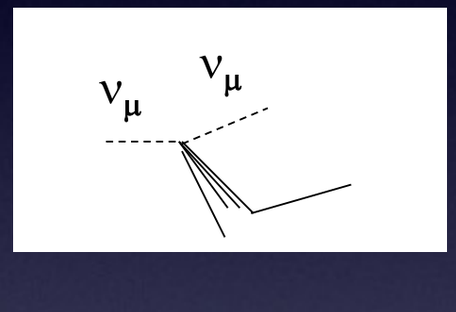
- ν_μCC charm production (4% of CC) with μ mis-identified.



- Large angle μ scattering.



- hadronic interactions (0.2% of NC).



Kinematical analysis - variables to reduce background:

- Flight length.
- Total p_T of τ daughters with respect to τ direction.
- Missing p_T at primary vertex with respect to the neutrino beam direction.
- Measure of ϕ: angle of τ with respect to hadronic shower in transverse plane to beam.

Status of Data Analysis

- Integrated beam intensity: 17.97×10^{19} p.o.t. which corresponds to 20% less than the experimental proposal value (22.5×10^{19} p.o.t.).
- 106422 on-time events recorded: 60% are (external) rock events and 20% are interaction in the spectrometers.
- 19505 interactions in the Target, 17057 events are contained in the Target.

years	Beam days	p.o.t (10^{19})	Status	Selected data sample	number of Decay Searched events
2008-2009	278	5.27	Completed	multi-bricks+all p_μ	2783
2010-2011-2012	687	12.7	In progress	1 brick+ p_μ <15 GeV	2186
Total	**965**	**17.97**		**~64%**	**4969**

$\nu_\mu \rightarrow \nu_\tau$ oscillation analysis

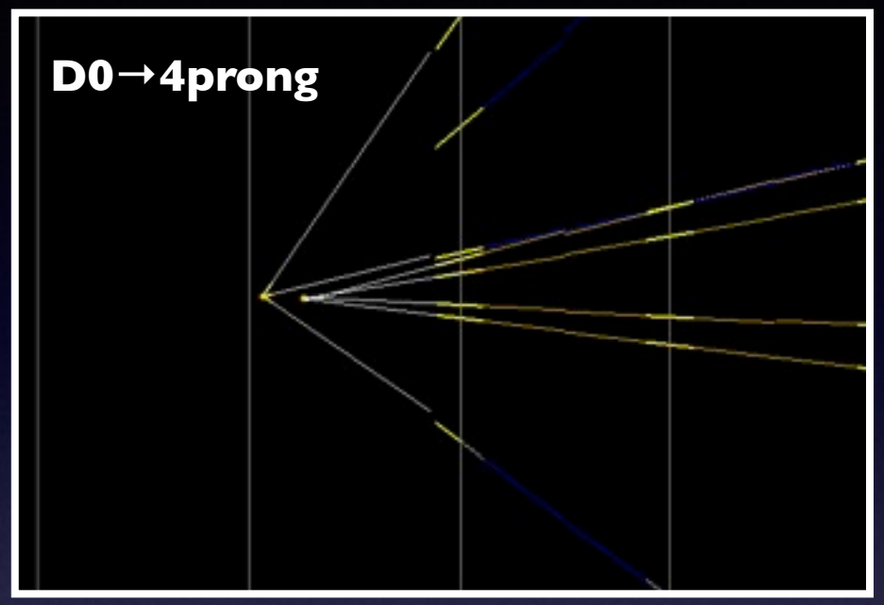
- The expected number of events for the scanned statistics is:

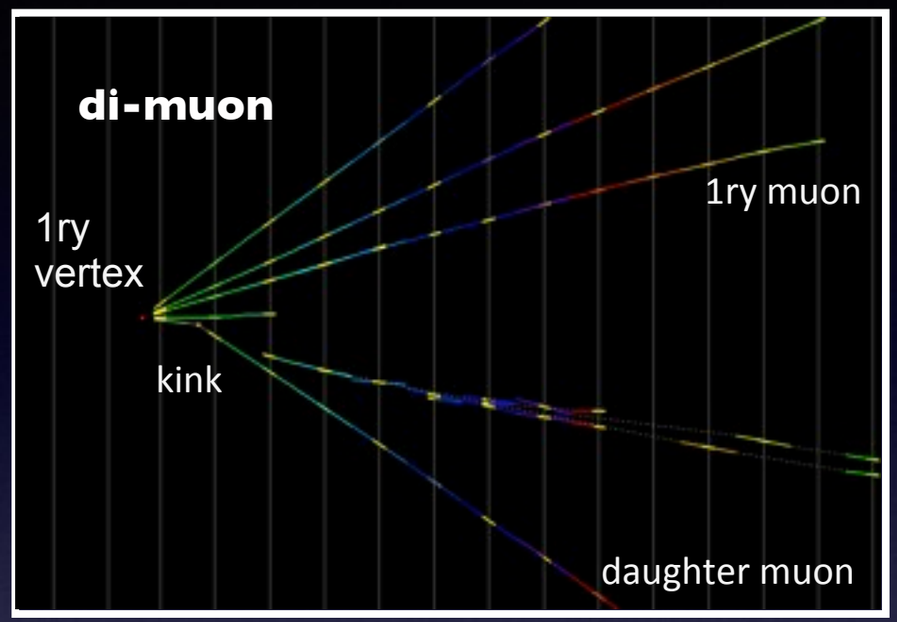
Decay channel	expected signal events at $\Delta m^2=2.32 \times 10^{-3}$ eV^2		PRELIMINARY	
	Full sample 18×10^{19} p.o.t.	Analysed sample	background analysed sample	Observed events
$\tau \rightarrow \mu$	0.90	0.56	0.026	1
$\tau \rightarrow e$	1.06	0.49	0.065	
$\tau \rightarrow h$	0.70	0.66	0.045	1
$\tau \rightarrow 3h$	0.99	0.51	0.090	1
Total	3.65	2.22	**0.216**	**3**

- 3 observed events in the $\tau \rightarrow h$, $\tau \rightarrow 3h$ and $\tau \rightarrow \mu$ channels.
- The probability to be a background fluctuation is 7.29×10^{-4}.
- This corresponds to a **3.4 σ significance** of non-null observation.

$\nu_\mu \rightarrow \nu_\tau$ control sample: charm events

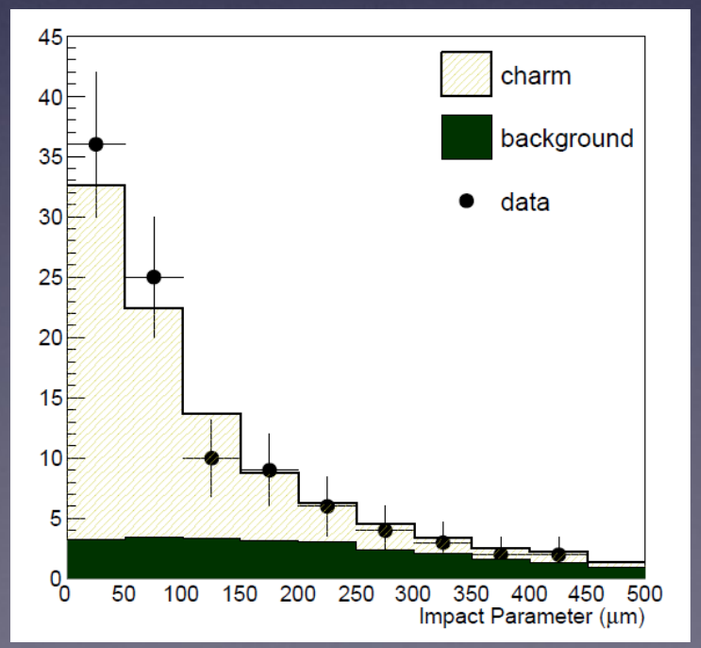
- Charm lifetime and decay topologies analogous to τ ⇒Benchmark for τ decay finding efficiency.



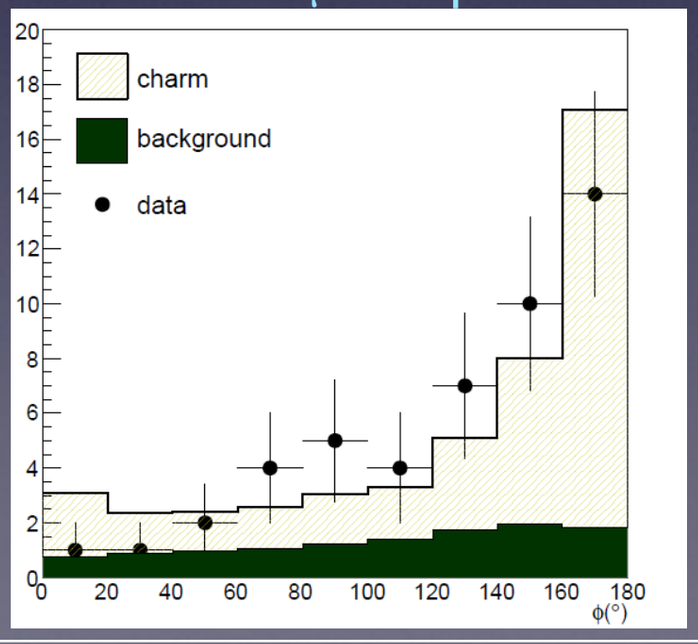


- On the 2008-2010 data sample: 50 charm events observed, 53±5 were expected.

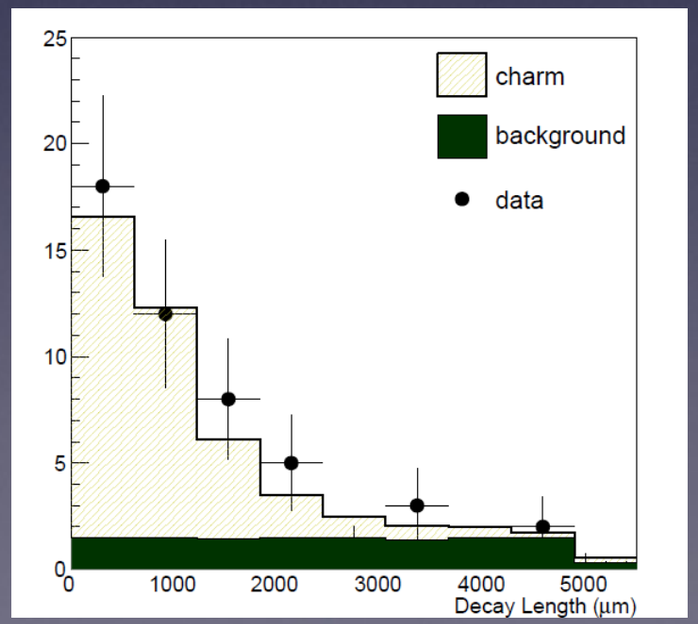
Impact Parameter



Angle in the transverse plane between μ and parent



Decay Length

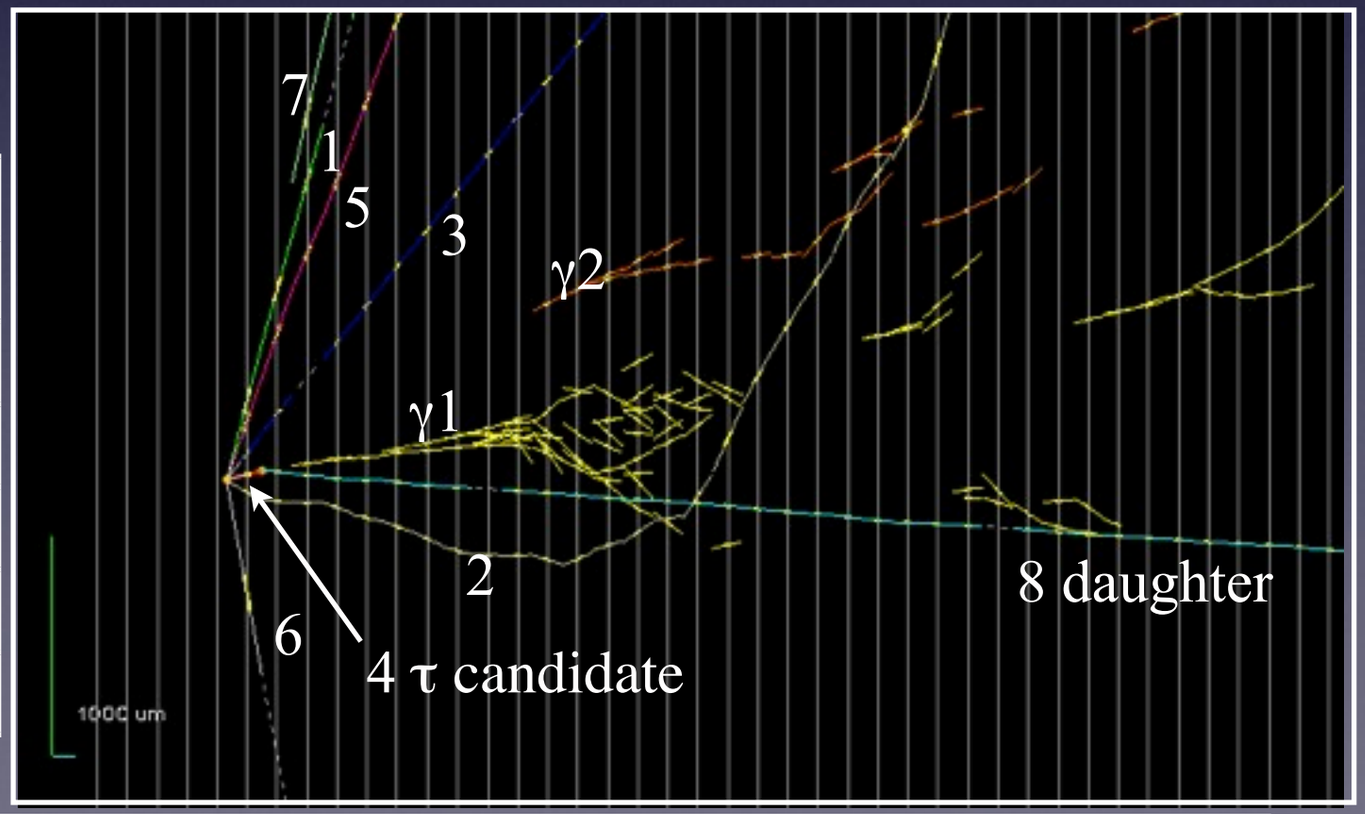


First candidate

- In the decay search of 2008 and 2009 data we found a ν_τ candidate (*Phys. Lett. B 691 (2010) 138*).
- The event (0 μ event) passes all selection criteria for the signal and it is classified as a possible decay of a τ into 1 prong hadron.
- All primary tracks incompatible with muon hypothesis.
- The decay mode is compatible with $\tau \rightarrow \rho\ (\pi^-\pi^0)\ \nu_\tau$ which has a branching ratio of 25%.

Kinematical variables

Variable	Observed	Cut
Kink angle (mrad)	41 ± 2	>20
Decay length (μm)	1335 ± 35	< 2 lead plates
P daughter (GeV/c)	$12\ ^{+6}_{-3}$	>2
Daughter Pt (MeV/c)	$470\ ^{+230}_{-120}$	>300
Missing Pt (MeV/c)	$570\ ^{+320}_{-170}$	<1000
Φ angle (deg)	173 ± 2	>90

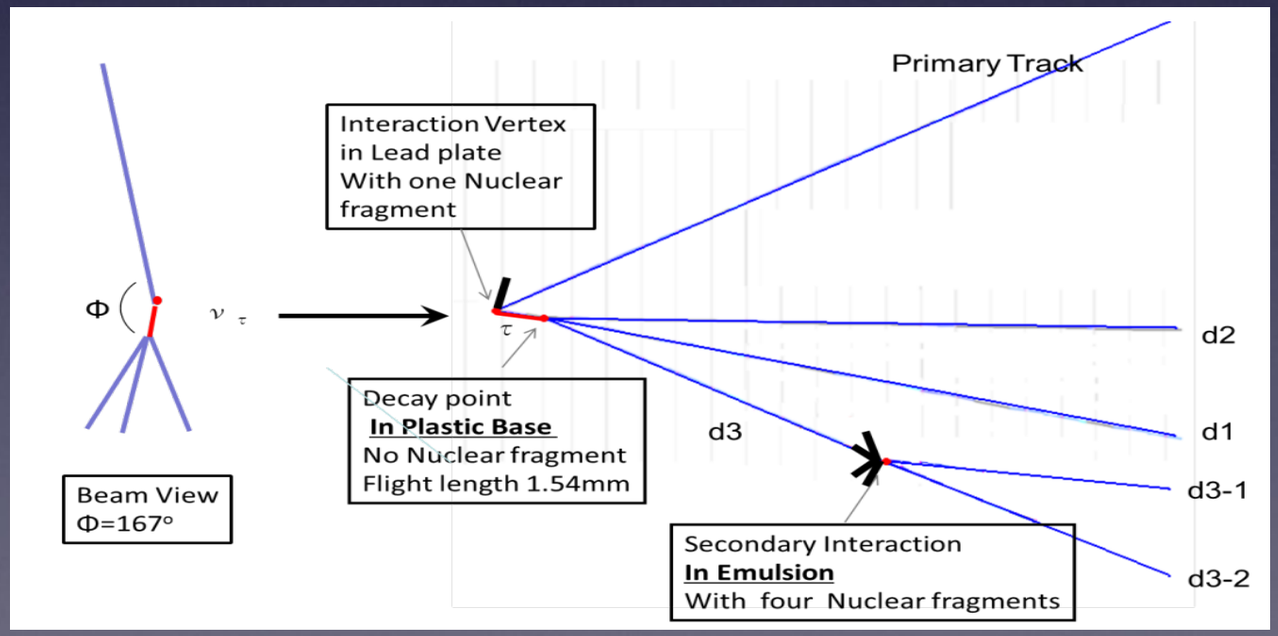


Second candidate

- The event (0 μ event) passes all selection criteria for the signal and it is classified as a possible decay of a τ into 3 prong hadrons (*JHEP 1311(2013) 036*).
- The primary track (p=2.8±0.7 GeV/c) is incompatible with μ hypothesis (momentum/range correlation).
- All tracks are identified as hadrons.

Kinematical variables

Variable	Observed	Cut
Kink angle (mrad)	87.4 ± 1.5	>20 & <500
Decay length (μm)	1446 ± 10	< 2600
P daughter (GeV/c)	8.4 ± 1.7	>3
Min. invariant mass (MeV/c^2)	960 ± 130	>500 & <2000
Invariant mass(MeV/c^2)	800 ± 120	>500 & <2000
Missing Pt (MeV/c)	310 ± 110	<1000
Φ angle (deg)	167.8 ± 1.1	>90

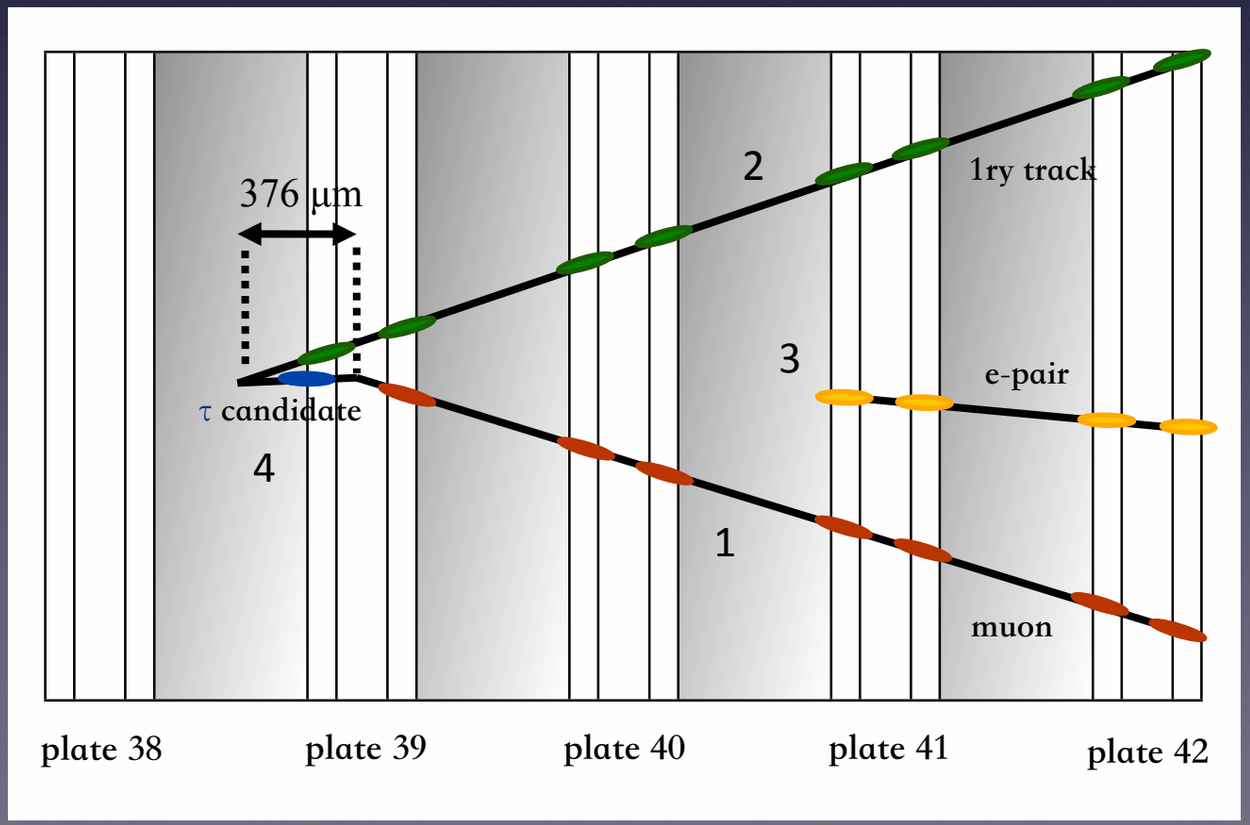


Third candidate

- The event (1 μ event) (*ArXiv:1401.2079*) passes all selection criteria for the signal and it is classified as a possible decay of a τ into μ (branching ratio of 17.7%).
- The track at 1ry vertex was followed into the downstream brick where it disappears after having crossed 18 lead plates. It is classified as a hadron by its momentum-range correlation.
- The muon (track 1) was also found in the CS and it agrees with the μ track reconstructed in the ED. Its charge is negative at 5.6 sigmas.
- The γ attachment to the decay vertex is excluded.

Kinematical variables

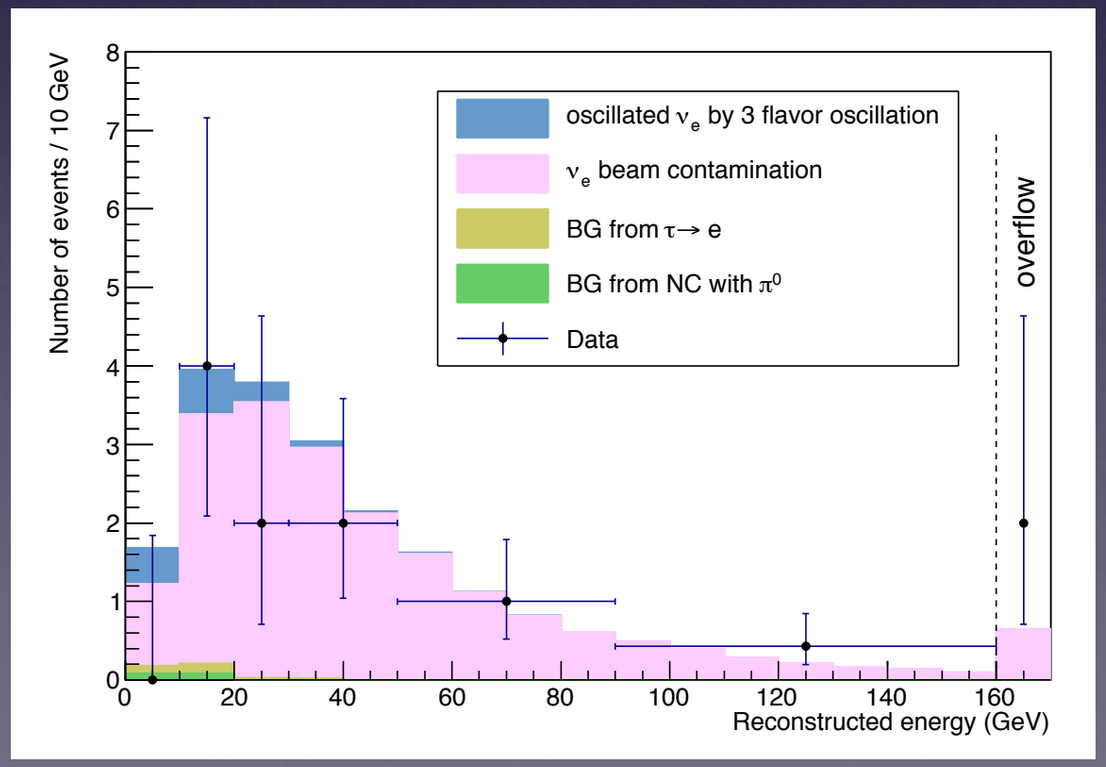
Variable	Observed	Cut
Kink angle (mrad)	245 ± 5	>20 & <500
Decay length (μm)	151 ± 10	< 2600
Pμ (GeV/c)	2.8 ± 0.2	>1 & <15
Daughter Pt (MeV/c)	690 ± 50	>250
Φ angle (deg)	155 ± 15	>90



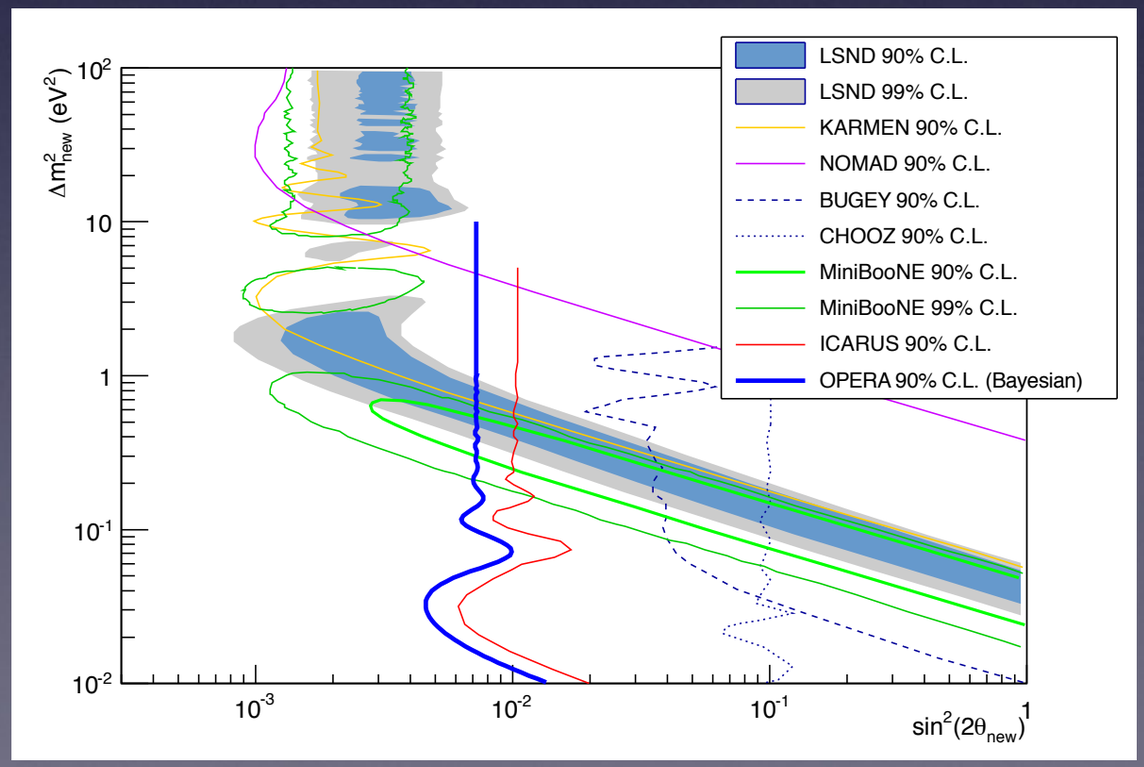
$\nu_\mu \rightarrow \nu_e$ Analysis

- In the 2008 and 2009 runs a dedicated ν_e search was performed.
- Out of 505 neutrino events without muon 19 candidates were found (19.4 expected).
- In the standard 3 flavour scenario, the observation is compatible with a background-only hypothesis.
- A specific analysis for non-standard oscillation at large Δm^2 resulted in a competitive limit (*JHEP 1307 (2013) 004*).

Standard scenario ($\sin^2(2\theta_{13}) < 0.44$)



Non-standard oscillations ($\sin^2(2\theta_{new}) < 7.2\times10^{-3}$)



Conclusions

- The OPERA detector has been taking physics data successfully for 5 years (2008 - 2012) corresponding to 17.97×10^{19} p.o.t (80% of nominal).
- The detector is still running for cosmic muons data taking.
- Background studies showed good agreement between data and MC.

$\nu_\mu \rightarrow \nu_\tau$ oscillation results:

- In the analyzed data **three τ candidates have been observed**.
- A significance of 3.4 σ of non-null observation has been obtained (simple counting method).
- Analysis is on-going: more statistics is expected and some events are under investigation. A significance of 4 σ is within reach.

$\nu_\mu \rightarrow \nu_e$ oscillation results:

- 19 ν_e events observed for 19.4 expected.
- Bound on a non standard ν oscillation: $\sin^2(2\theta_{new})<7.2\times10^{-3}$ at 90% C.L.
- With the increase of sample size, OPERA should be able to access the parameter region below $\sin^2(2\theta_{new})=5.0\times10^{-3}$.

OPERA collaboration

IIHE ULB Bruxelles

IRB Zagreb

Bari
Bologna
LNF Frascati
LNGS
Napoli
Padova
Roma
Salerno

LAPP Annecy
IPHC Strasbourg

OPERA is an international collaboration made of ~ 140 physicists from 25 institutions and 10 countries.

Aichi
Toho
Kobe
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Hamburg

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INR RAS Moscow
LPI RAS Moscow
SINP MSU Moscow
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