What can MINOS and T2K do about the OPERA result?

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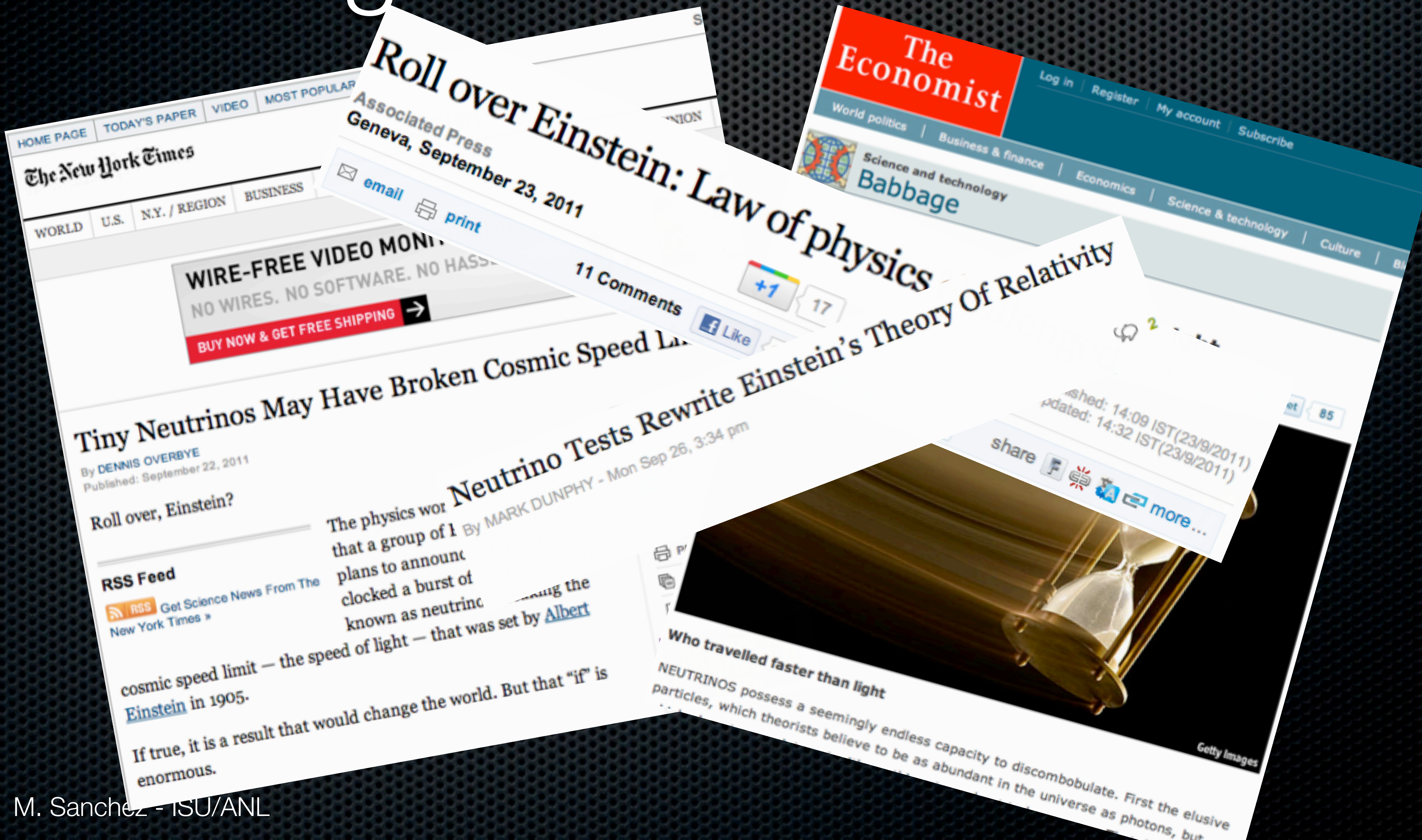
Caveats

- I am not an OPERA collaborator (IANAOC), so my knowledge of their measurement is limited to the talk, the paper and asking questions.
- I am not a T2K collaborator either, but I have been kindly provided with official information.
- I am interested observer as MINOS has made this measurement in the past and can do so again.
- I am not a theorist (IANAT), so I can only superficially comment on the possibilities being proposed.

...but I’ve been watching the show

Do neutrinos travel faster than light?



Surely, we have measured this before?

- 11 neutrinos from supernova 1987a were observed at Kamioka-II **in time*** with light (PRL 58 (1987) 1490)
- IMB (PRL 58 (1987) 1494) and Baksan (JETP Lett. 45 (1987) 589) also observed **in time*** neutrinos.
- Total neutrinos observed 24!
  - These are electron anti-neutrinos with energies **~10-40 MeV**.
- If OPERA result applies here, we would have observed neutrinos 4.1 years earlier.

* = little earlier

IMB		
t (s)	E (MeV)	σ_E (MeV)
$t \equiv 0.0$	38	7
0.412	37	7
0.650	28	6
1.141	39	7
1.562	36	9
2.684	36	6
5.010	19	5
5.582	22	5

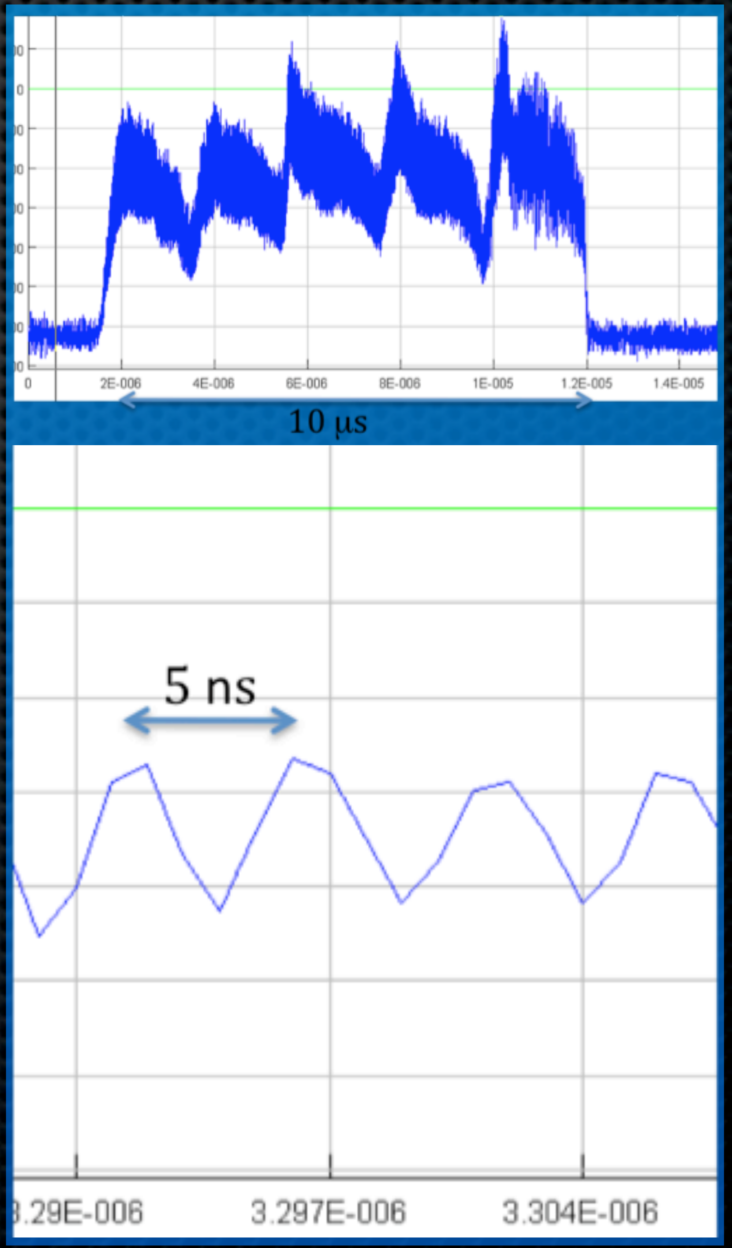
Baksan		
t (s)	E (MeV)	σ_E (MeV)
$t \equiv 0.0$	12.0	2.4
0.435	17.9	3.6
1.710	23.5	4.7
7.687	17.6	3.5
9.099	10.3	4.1

Kamiokande II		
t (s)	E (MeV)	σ_E (MeV)
$t \equiv 0.0$	20.0	2.9
0.107	13.5	3.2
0.303	7.5	2.0
0.324	9.2	2.7
0.507	12.8	2.9
1.541	35.4	8.0
1.728	21.0	4.2
1.915	19.8	3.2
9.219	8.6	2.7
10.433	13.0	2.6
12.439	8.9	1.9

Table from J. Ellis et. al. (2008)

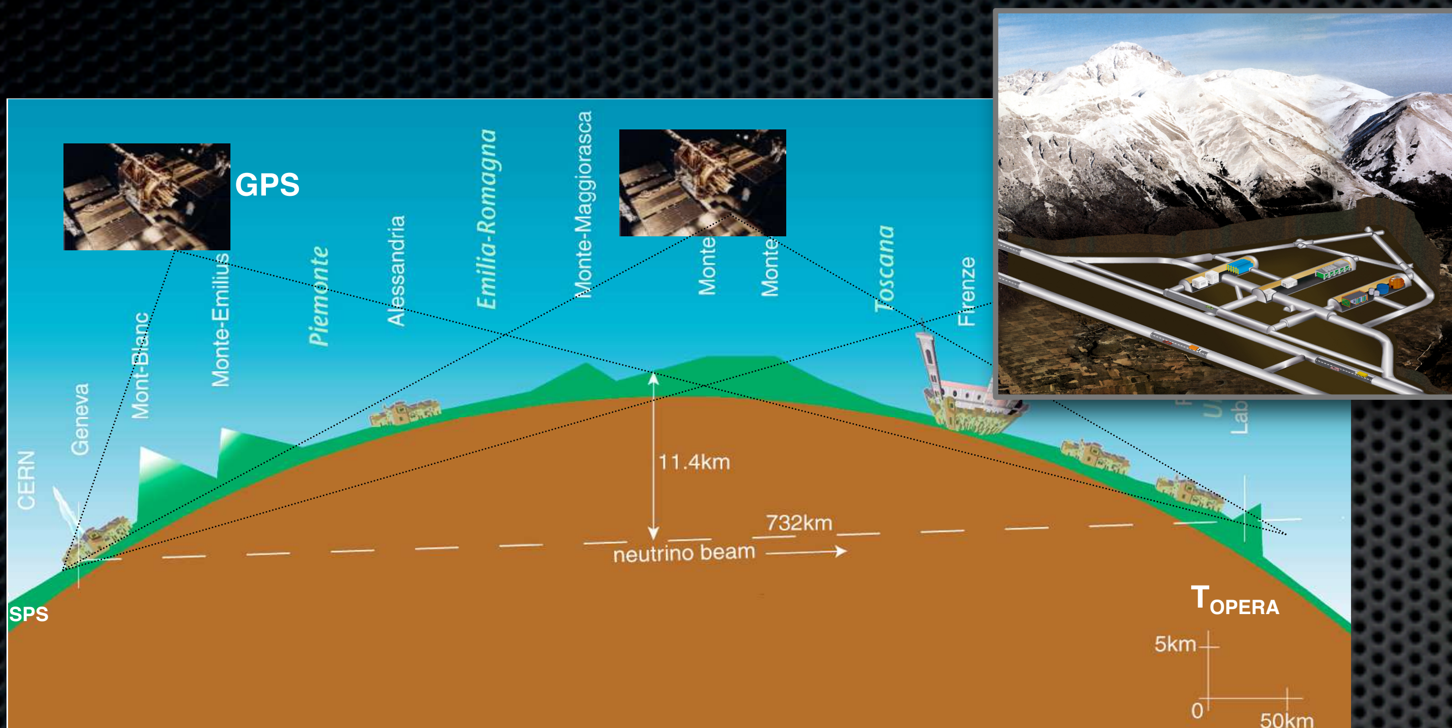
Time of flight in long-baseline experiments (muon neutrinos)

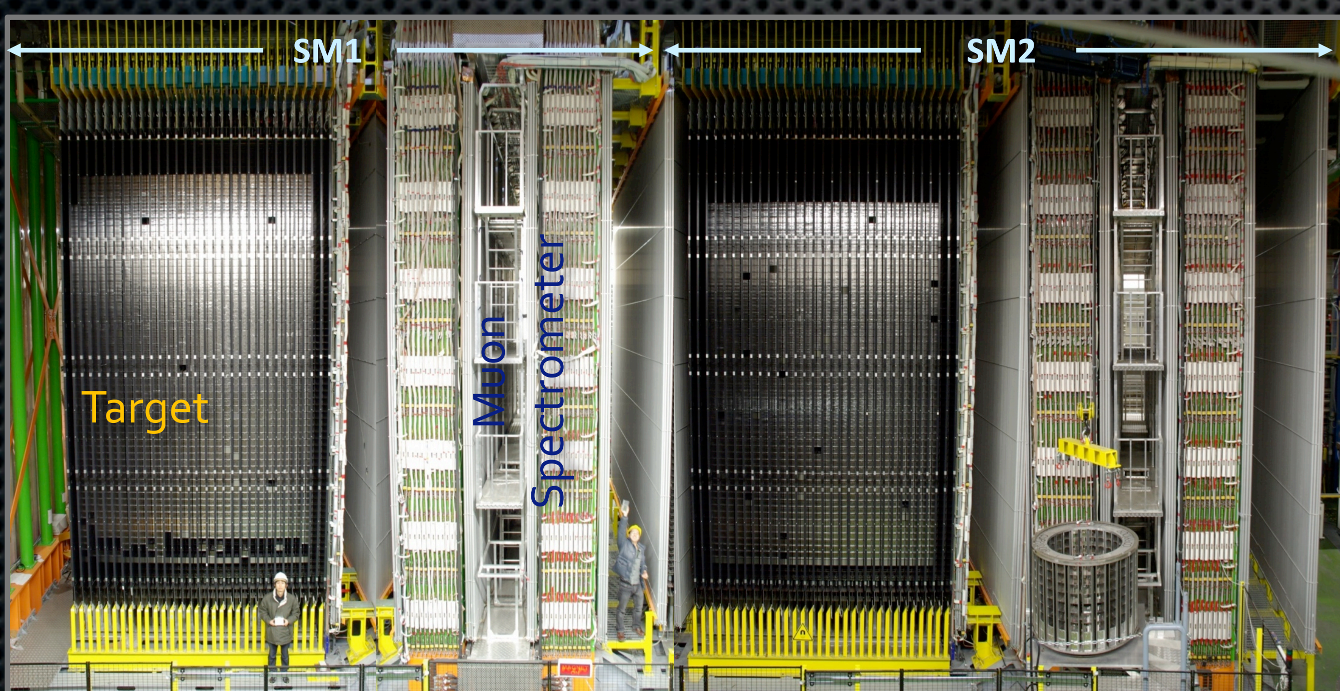
- A short baseline experiment at Fermilab in 1979, compared the speed of muon neutrinos to muons with energies larger than **30 GeV**. Imposing limits in the speed of those neutrinos.
- In 2007, the MINOS experiment measured time of flight for muon neutrinos in a long baseline experiment at energies of **~3GeV**.
- In 2008, J. Ellis et.al. (PRD 78, 033013, 2008) cites MINOS as a pioneering measurement and suggests using neutrinos as probes of Lorentz Violation.
  - It suggests that OPERA should upgrade its timing system to be able to do this and hopefully use their RF beam structure.
- In 2008, OPERA embarks in a timing upgrade that results in their recent measurement.



OPERA's proton beam structure

OPERA in a nutshell

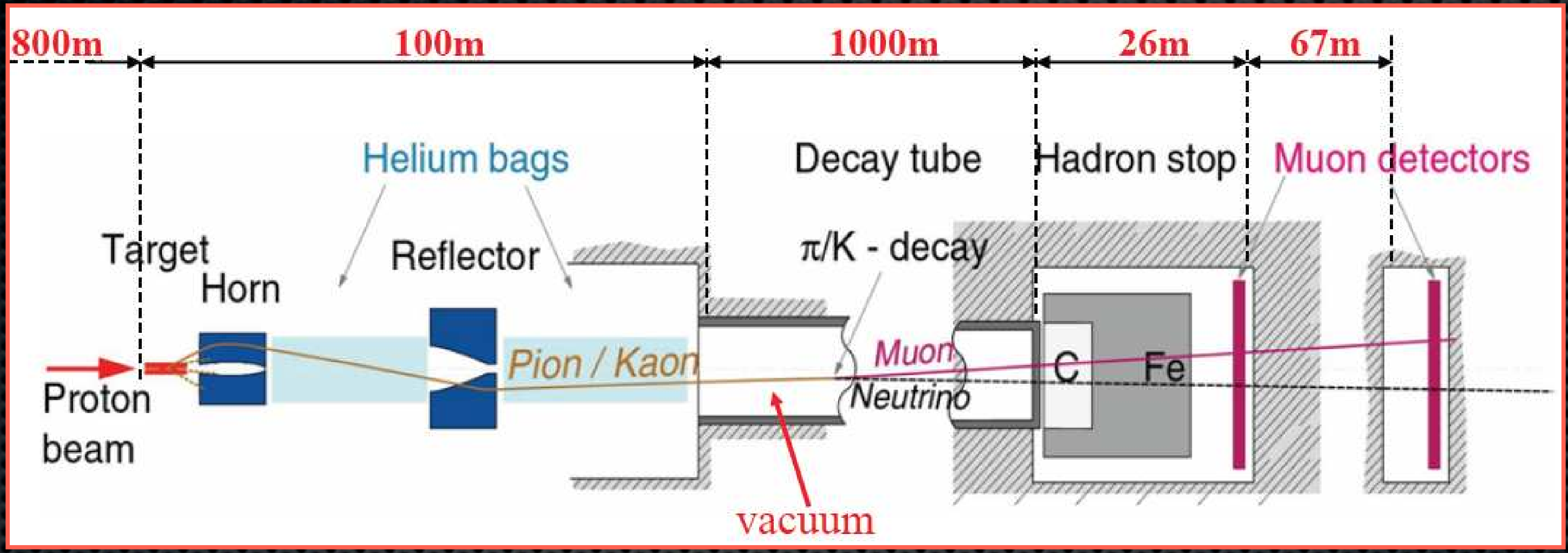


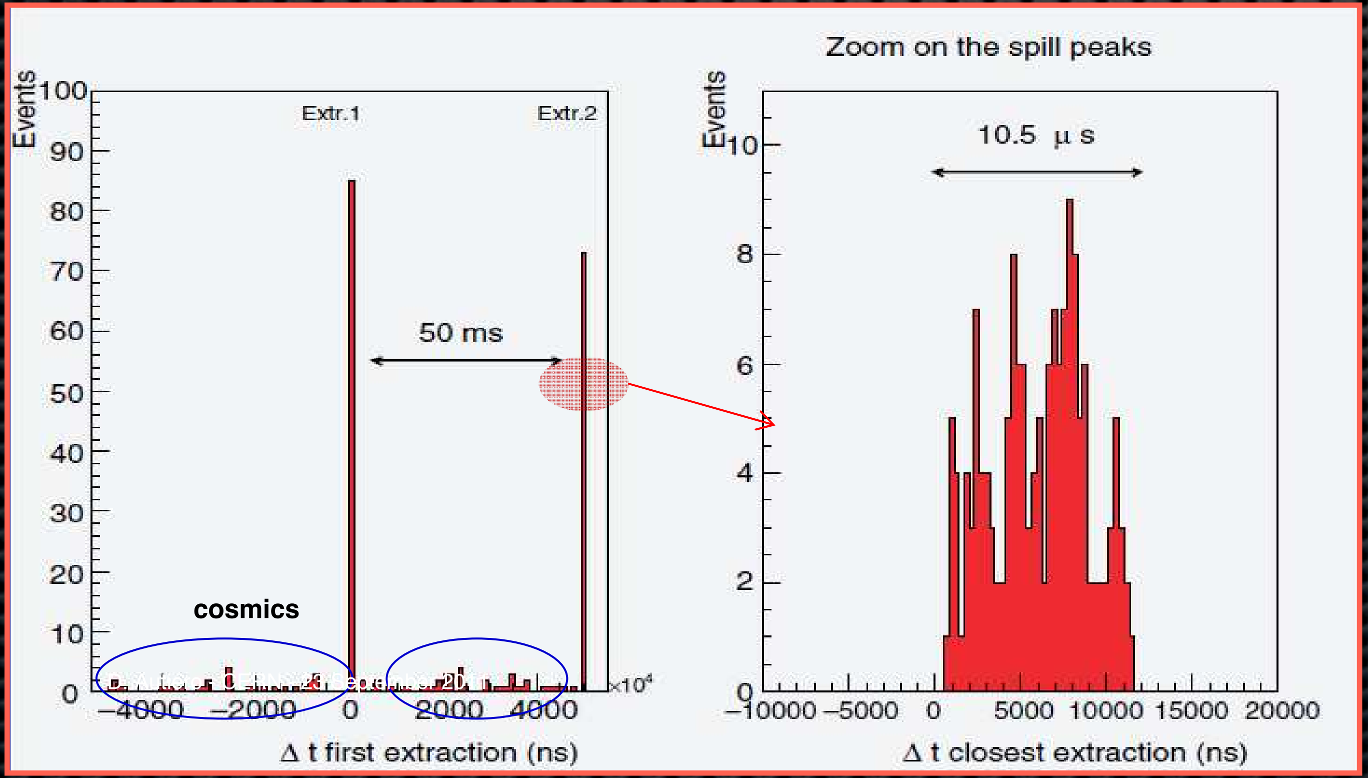


Taking data since 2008!

- Produce a high intensity beam of muon neutrinos at CERN. Distance similar to Fermilab - Soudan.
- If neutrinos oscillate, directly observe resulting tau neutrinos from the dominant oscillation mode.
- Far detector divided in two supermodules.
  - Target composed of lead/ emulsion bricks.
  - Muon spectrometers magnetized with 1.5T.
- **Major timing systems upgrade in 2008 to do this measurement.**

The CNGS beam

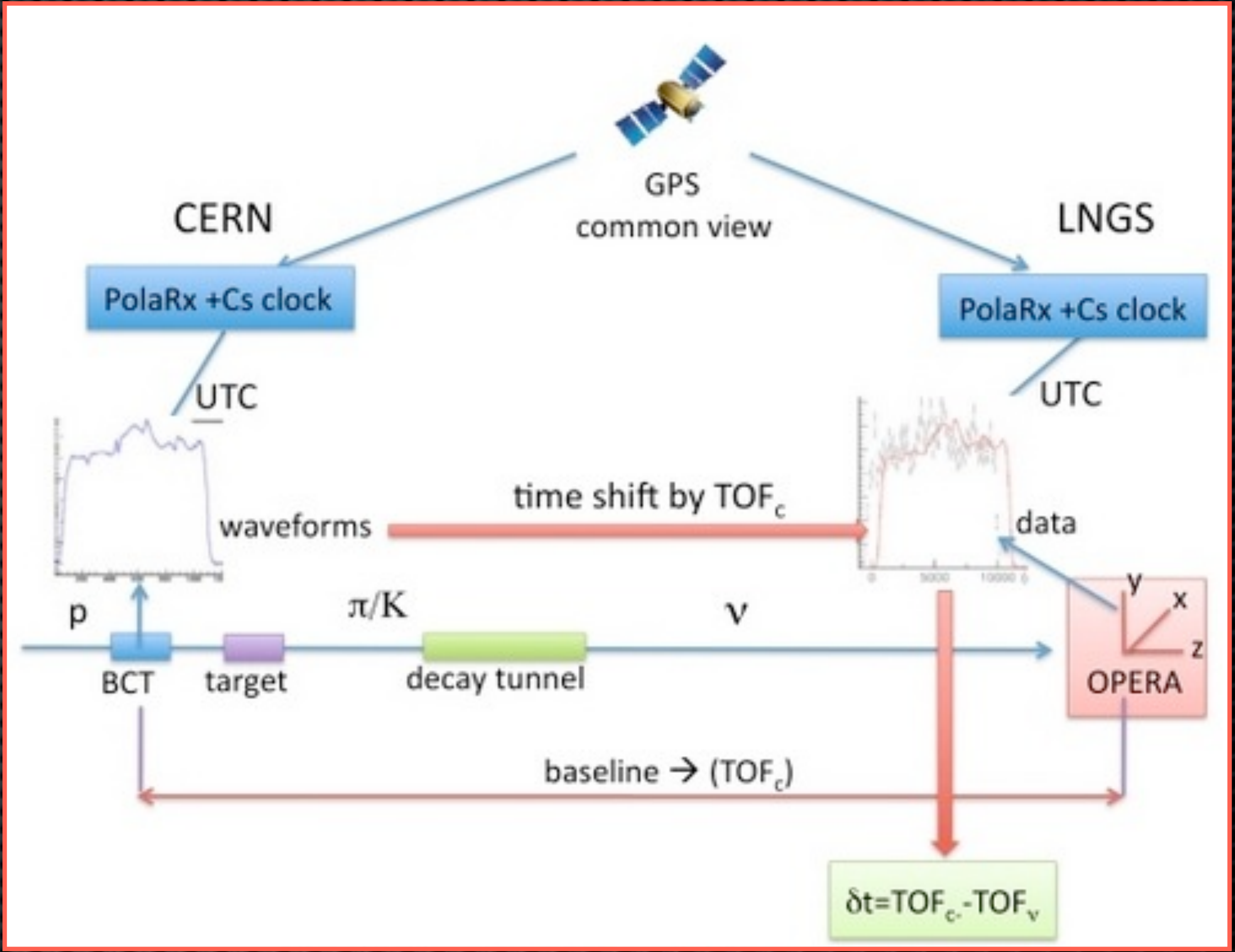




- SPS protons at 400 GeV/c
- Cycle length 6 s
- Two extractions of 10.5 usec, separated by 50 ms.
- Pure muon neutrino beam with peak at 17 GeV.

The time of flight (TOF) measurement

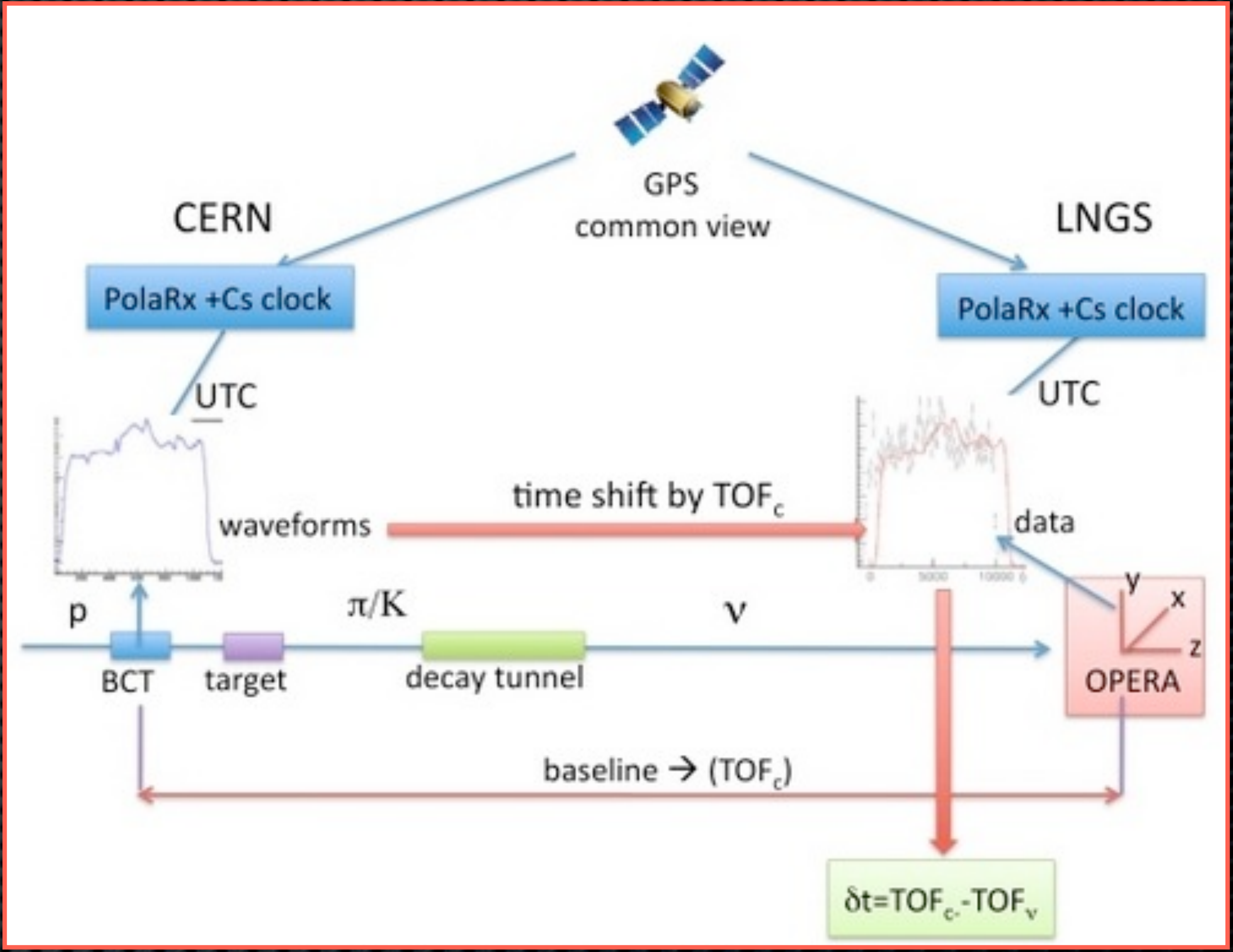
- Tag the neutrino production time, using the proton timing.
  - Accurately measured by a fast Beam Current Transformer (BCT) detector.
- Tag the neutrino interaction time.
- Accurate determination of the baseline.
- Long baseline helps with small effects.
- Use 15K neutrinos selected in same way as tau appearance analysis.
- Do a blind analysis.



Measure $\delta t = TOF_c - TOF_\nu$

The time of flight (TOF) measurement

- The time synchronization between the beam and the detector is done via GPS common view.
  - Error ~ 1ns
- The distance measurement is monitored over time.
  - Error 20 cm over 730km.
- Most measurements cross-checked with alternative techniques.
  - Overall precision ~10 ns.

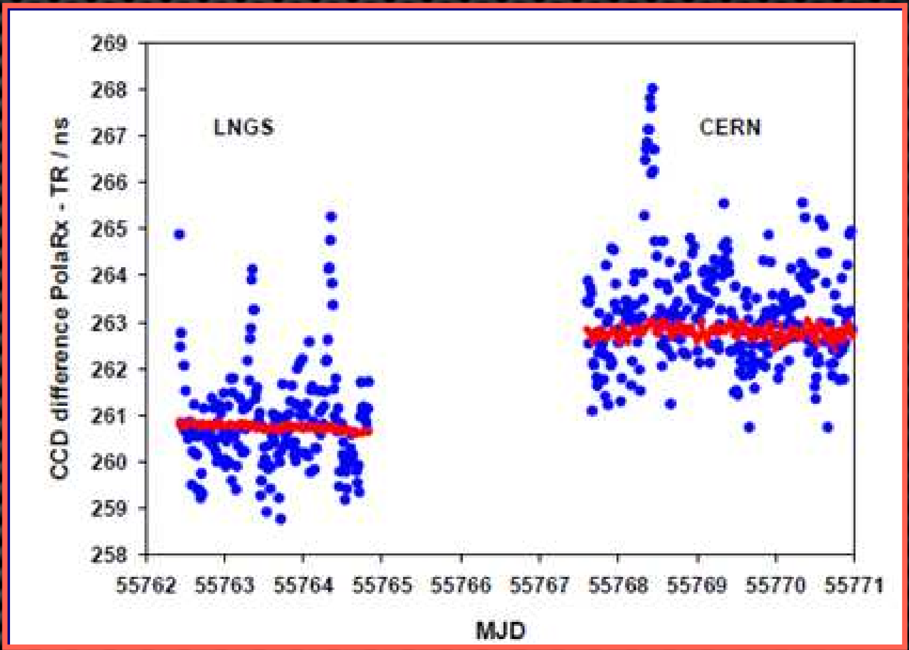


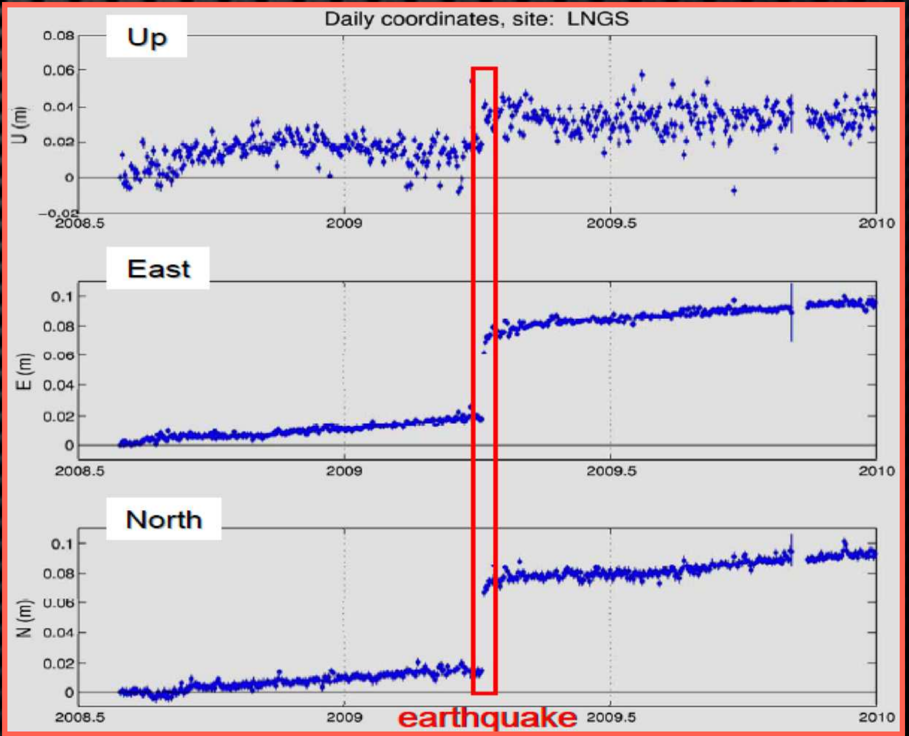
Measure $\delta t = TOF_c - TOF_\nu$

Did they do X?

X = insert favorite systematic/effect here

- Took into account variable neutrino production point.
- Used a portable time-transfer device between CERN and Gran Sasso.
- Monitored distance continuously, including effects for continental drift and earthquake.
- Used a portable time-transfer device for comparison time tags between start and end of detector timing chain as well as elements of the timing chain.
- Took into account relativity effects of different heights, ionosphere, etc.
- Did a blind analysis using obsolete timing resulting in a much larger than individual calibration contributions.





Many other checks done.

Delay calibrations summary

Item	Result	Method
CERN UTC distribution (GMT)	10085 ± 2 ns	• Portable Cs • Two-ways
WFD trigger	30 ± 1 ns	Scope
BTC delay	580 ± 5 ns	• Portable Cs • Dedicated beam experiment
LNGS UTC distribution (fibers)	40996 ± 1 ns	• Two-ways • Portable Cs
OPERA master clock distribution	4262.9 ± 1 ns	• Two-ways • Portable Cs
FPGA latency, quantization curve	24.5 ± 1 ns	Scope vs DAQ delay scan (0.5 ns steps)
Target Tracker delay (Photocathode to FPGA)	50.2 ± 2.3 ns	UV picosecond laser
Target Tracker response (Scintillator-Photocathode, trigger time-walk, quantisation)	9.4 ± 3 ns	UV laser, time walk and photon arrival time parametrizations, full detector simulation
CERN-LNGS intercalibration	2.3 ± 1.7 ns	• METAS PolaRx calibration • PTB direct measurement

Most measurements have crosschecks.

Summary of the time delay and uncertainties

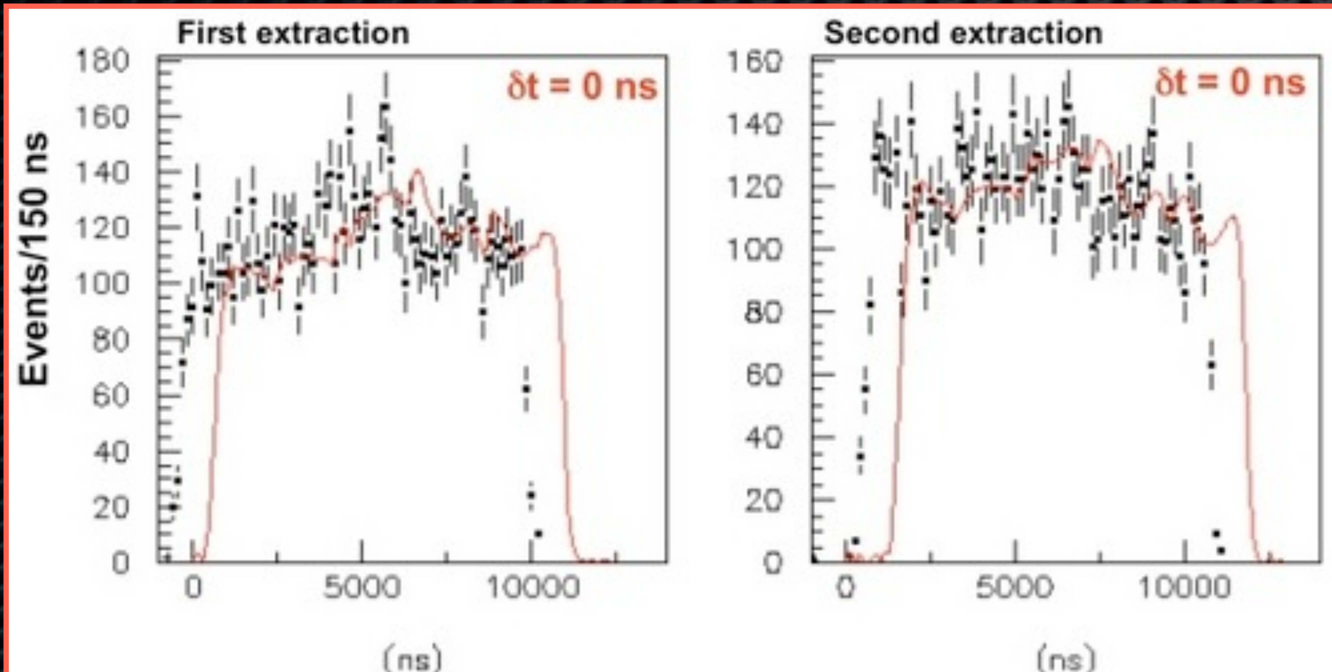
	Blind 2006	Final analysis	Correction (ns)
Baseline (ns)	2440079.6	2439280.9	
Correction baseline			-798.7
CNGS DELAYS :			
UTC calibration (ns)	10092.2	10085	
Correction UTC			-7.2
WFD (ns)	0	30	
Correction WFD			30
BCT (ns)	0	-580	
Correction BCT			-580
OPERA DELAYS :			
TT response (ns)	0	59.6	
FPGA (ns)	0	-24.5	
DAQ clock (ns)	-4245.2	-4262.9	
Correction TT+FPGA+DAQ			17.4
GPS syncronization (ns)	-353	0	
Time-link (ns)	0	-2.3	
Correction GPS			350.7
Total			**-987.8**

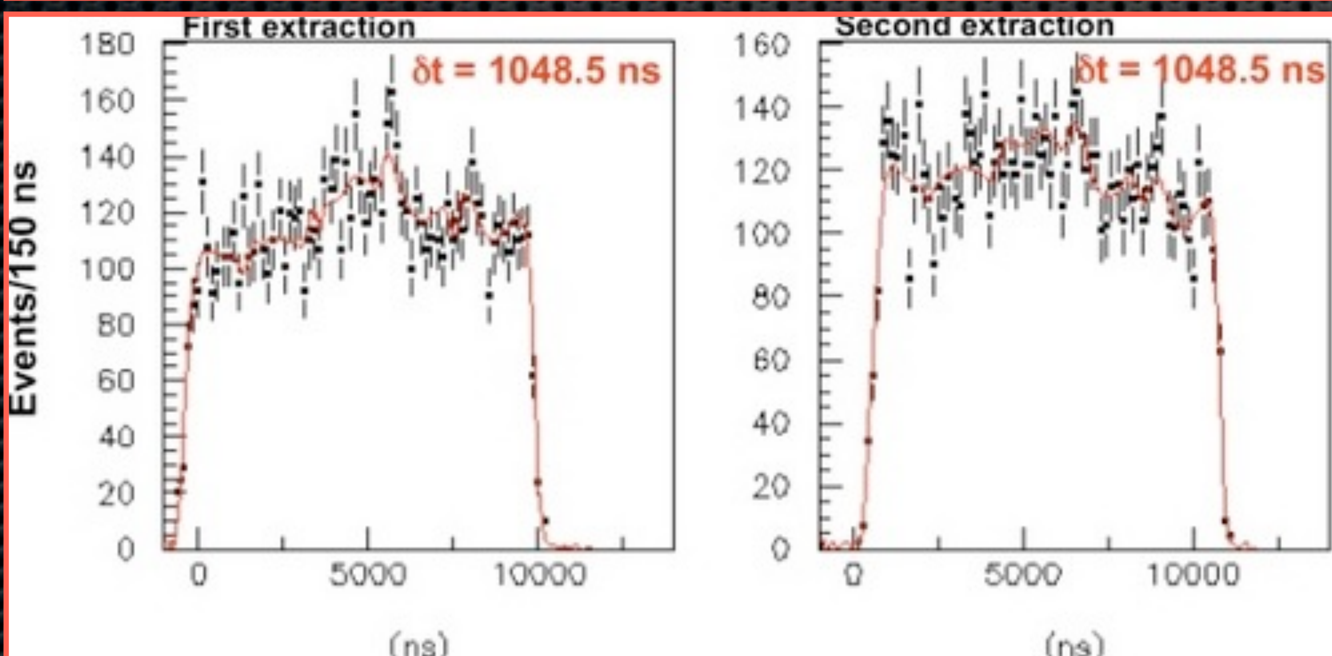
Systematic uncertainties	ns
Baseline (20 cm)	0.67
Decay point	0.2
Interaction point	2.0
UTC delay	2.0
LNGS fibres	1.0
DAQ clock transmission	1.0
FPGA calibration	1.0
FWD trigger delay	1
CNGS-OPERA GPS synchronisation	1.7
MC simulation for TT timing	3.0
TT time response	2.3
BCT calibration	5.0
Total sys. uncertainty (in quadrature)	**7.4**

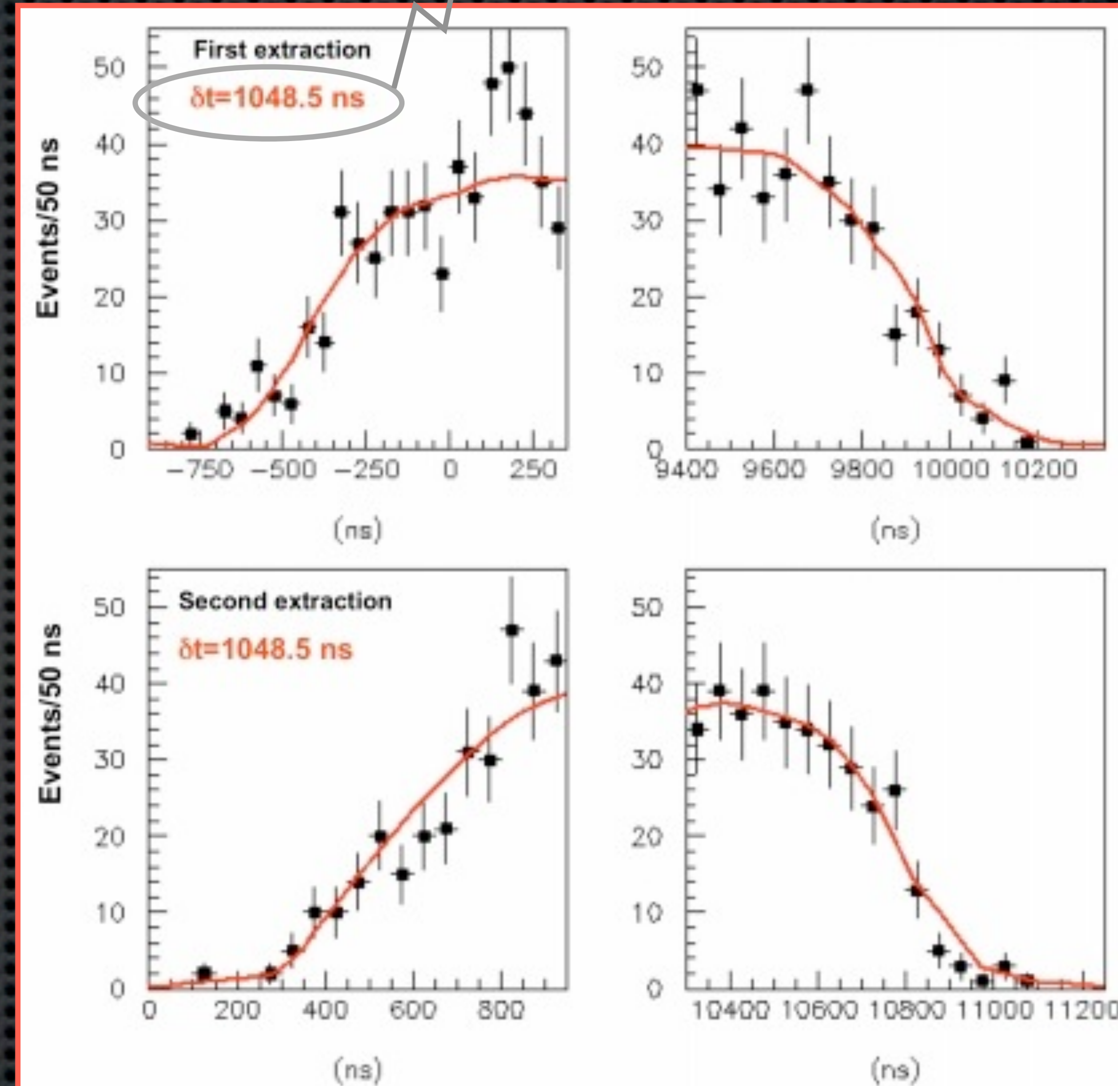
- Dominant systematic is BCT calibration.

The Opera results

corrected by -987.8 ns







After fit χ^2 /ndof ~1

$\delta t = TOF_c - TOF_\nu = (60.7 \pm 6.9\ (\text{stat.}) \pm 7.4\ (\text{sys.}))$ ns

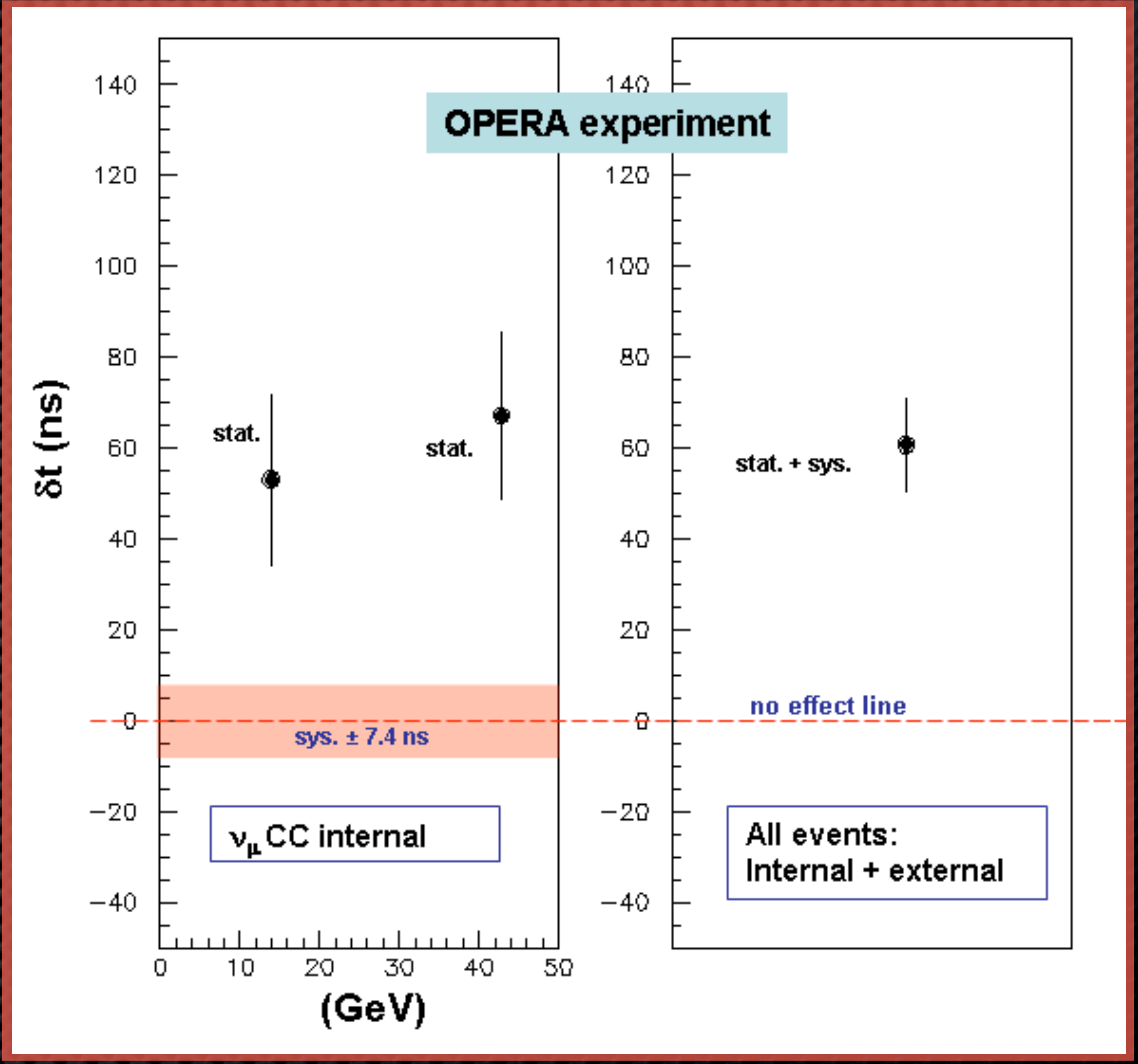
Neutrinos “arrive” 60 ns earlier.

http://indico.cern.ch/conferenceDisplay.py?confId=155620

http://arxiv.org/abs/1109.4897

Final result and energy dependence

- The Opera results do not show significant energy dependence.
- They show an early time of arrival of 60 ns with a significance of 6 sigma.



$\delta t = TOF_c - TOF_\nu = (60.7 \pm 6.9\ (\text{stat.}) \pm 7.4\ (\text{sys.}))\ \text{ns}$

What’s next?

as well as JPARC

- MINOS and T2K are set to do this measurement next.
- MINOS has a baseline very similar to OPERA (735km).
    - Beam spread similar to OPERA. Energy is lower than OPERA.
- T2K in Japan has a baseline of ~250 km and current timing sync is somewhat more precise than MINOS. Little data accumulated at this time.
    - Beam spread and energy is also different than MINOS/OPERA.


Fermilab Will Double-Check CERN's Revolutionary Faster-Than-Light Claim

By Rebecca Boyle Posted 09.26.2011 at 11:29 am 12 Comments

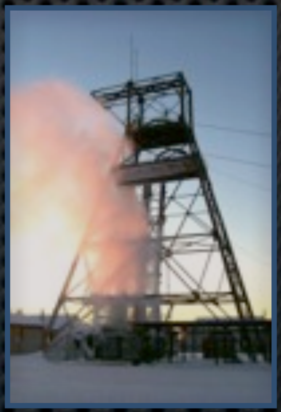
MINOS Experiment Far Detector *NuMI/Fermilab*

MINOS in a nutshell

Main **I**njector **N**eutrino **O**scillation **S**earch

- Produce a high intensity beam of muon neutrinos at Fermilab.
- Measure these neutrinos at the Near Detector and use it to predict the Far Detector spectrum.
- If neutrinos oscillate we will observe a distortion in the data at the Far Detector in Soudan.
- **Made TOF measurement in 2007!**

←long baseline→
735 km



Taking data since 2005!

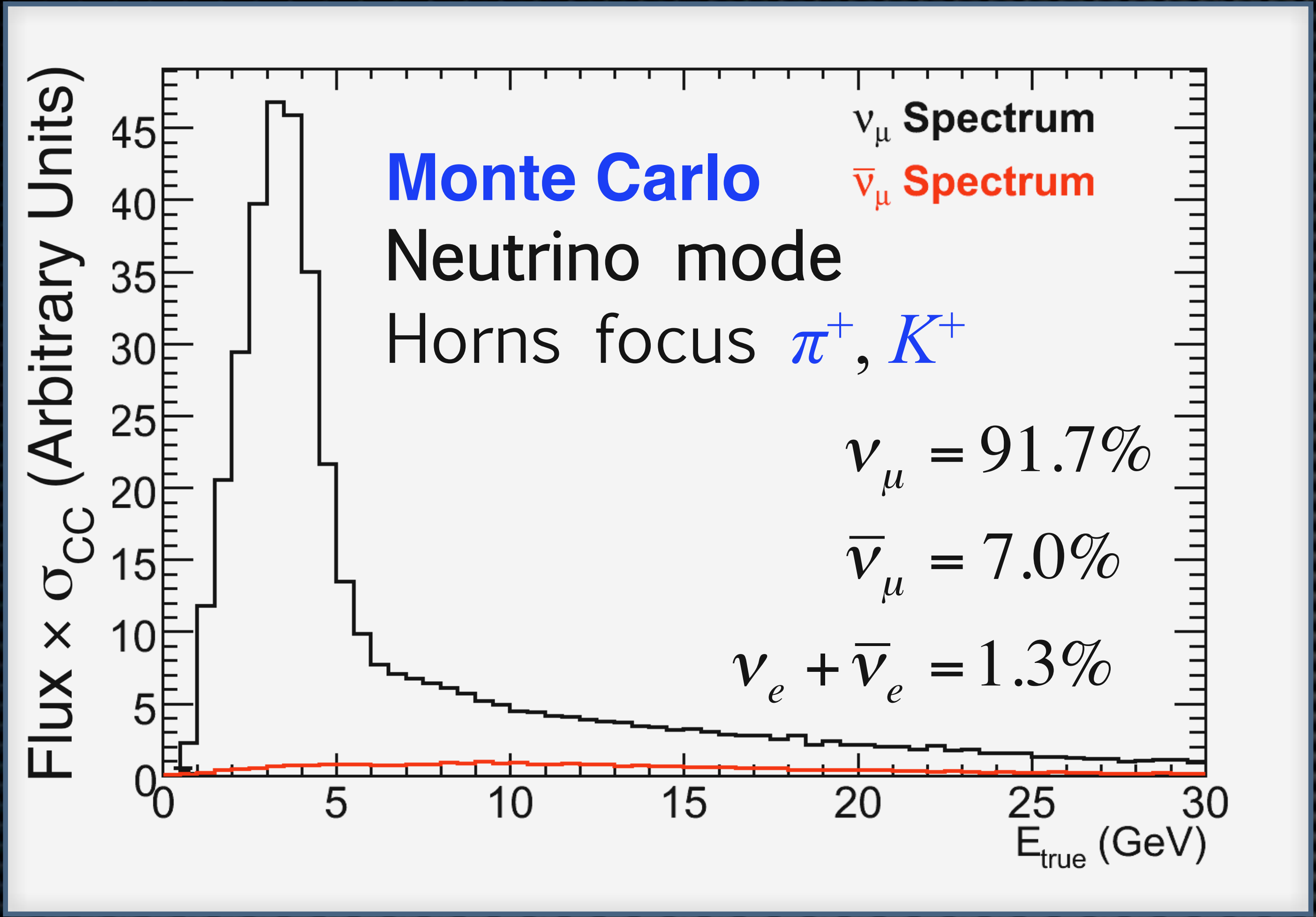
MINOS TOF measurement

- MINOS published a neutrino velocity measurement in 2007:
  - PRD 76, 072005, 2007.
- Consistent with speed of light to less than 1.8 sigma.
- Measurement limited by systematic errors.
  - Planning to reduce all of these systematics.

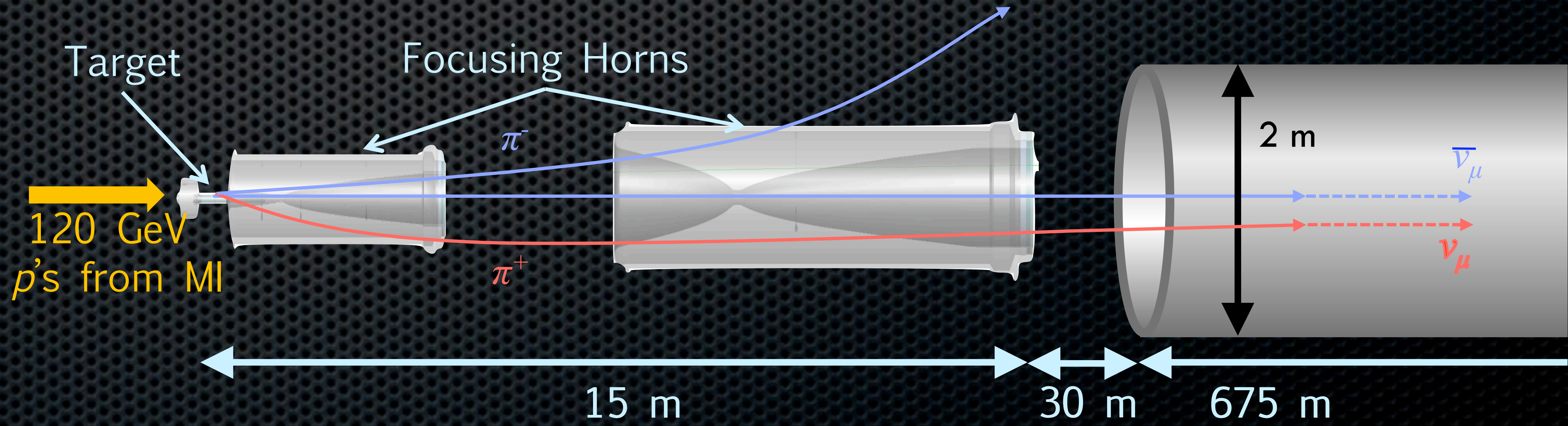
Baseline:	
Distance[a] ND to FD, L	$734\,298.6 \pm 0.7$ m [12]
Nominal time of flight, τ	$2\,449\,356 \pm 2$ ns
MINOS Timing System:	
GPS Receivers	TrueTime model XL-AK
Antenna fiber delay	1115 ns ND, 5140 ns FD
Single Event Time Resolution	<40 ns
Random Clock Jitter	100 ns (typical), each site
Main Injector Parameters:	
Main Injector Cycle Time	2.2 seconds/spill (typical)
Main Injector Batches/Spill	5 or 6
Spill Duration	9.7 μs (6 batches)
Batch Duration	1582 ns
Gap Between Batches	38 ns

	Description	Uncertainty (68% C.L.)
A	Distance between detectors	2 ns
B	ND Antenna fiber length	27 ns
C	ND electronics latencies	32 ns
D	FD Antenna fiber length	46 ns
E	FD electronics latencies	3 ns
F	GPS and transceivers	12 ns
G	Detector readout differences	9 ns
	Total (Sum in quadrature)	64 ns

NuMI beam

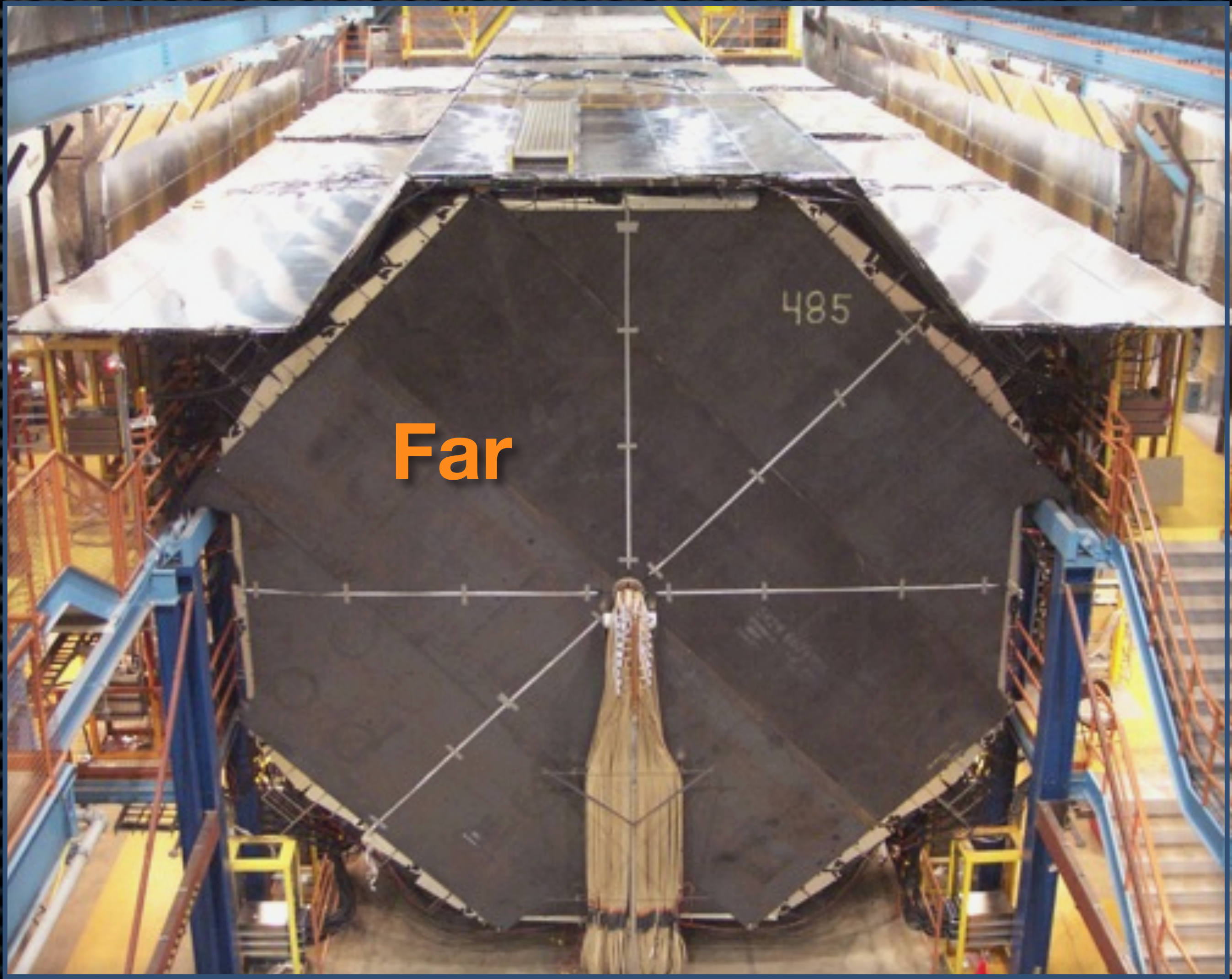


- Peaked at ~3 GeV.
- 10 µsec spill of 120 GeV protons every 2.2 sec.
  - 5 and 6 RF batch structure.
- Currently 275 kW typical beam power.
- Currently 3.0 x 10^{13} protons per pulse.

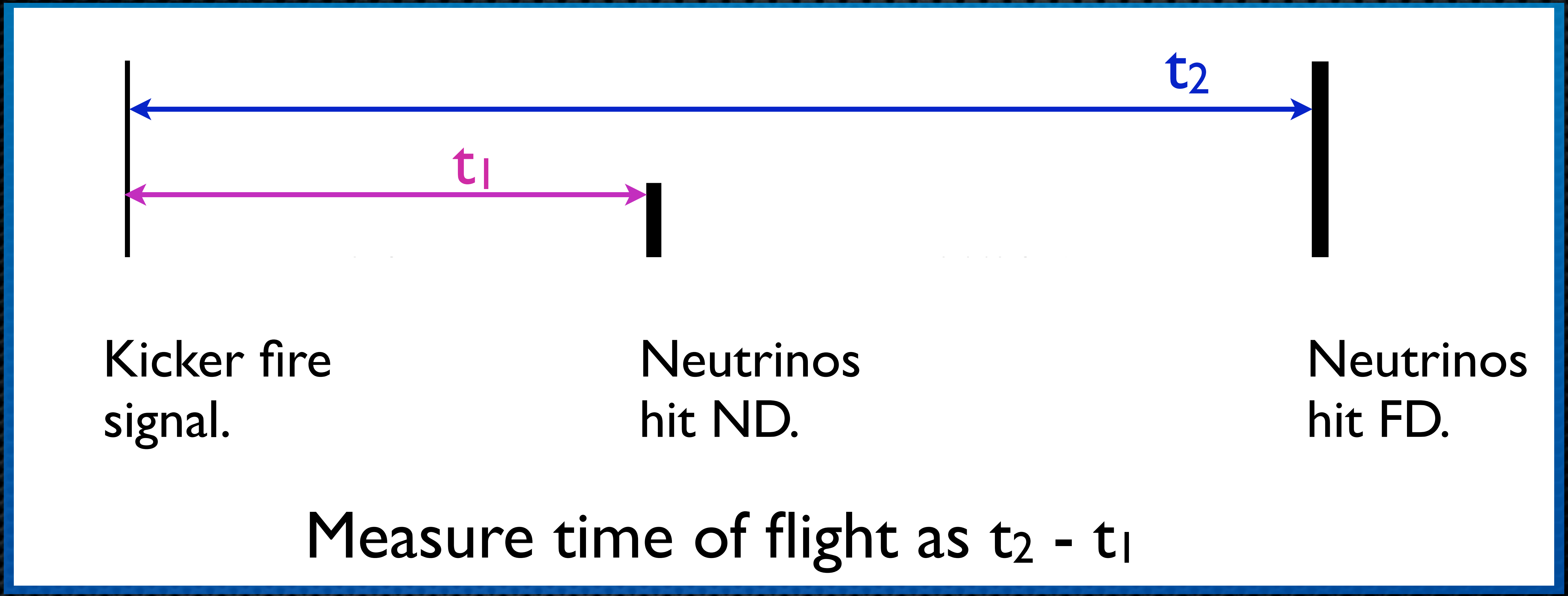


MINOS key strength

- Functionally identical: **Near and Far detectors**
- Octogonal steel planes (2.54cm thick ~1.44X_0). **Magnetized detector.**
- Alternating with planes of scintillator strips (4.12cm wide, Moliere rad ~3.7cm).
  - **Near (ND)**: ~ 1kton, 282 steel squashed octagons. Partially instrumented.
  - **Far (FD)**: 5.4 kton, 486 (8m/octagon) fully instrumented planes.

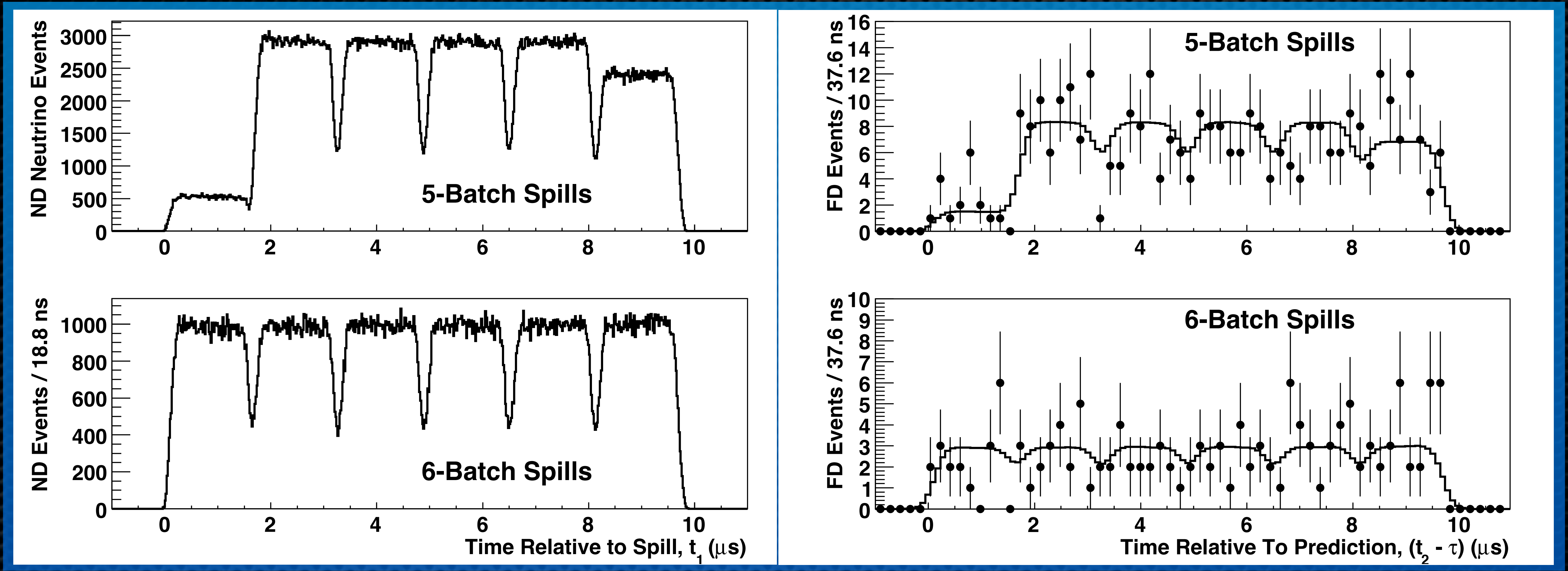


Why do it with MINOS?



- Measuring the time of flight with neutrinos from ND and FD, cancels out systematics relative to the proton beam time profile.
- **MINOS is a neutrino to neutrino measurement.**

The MINOS measurement

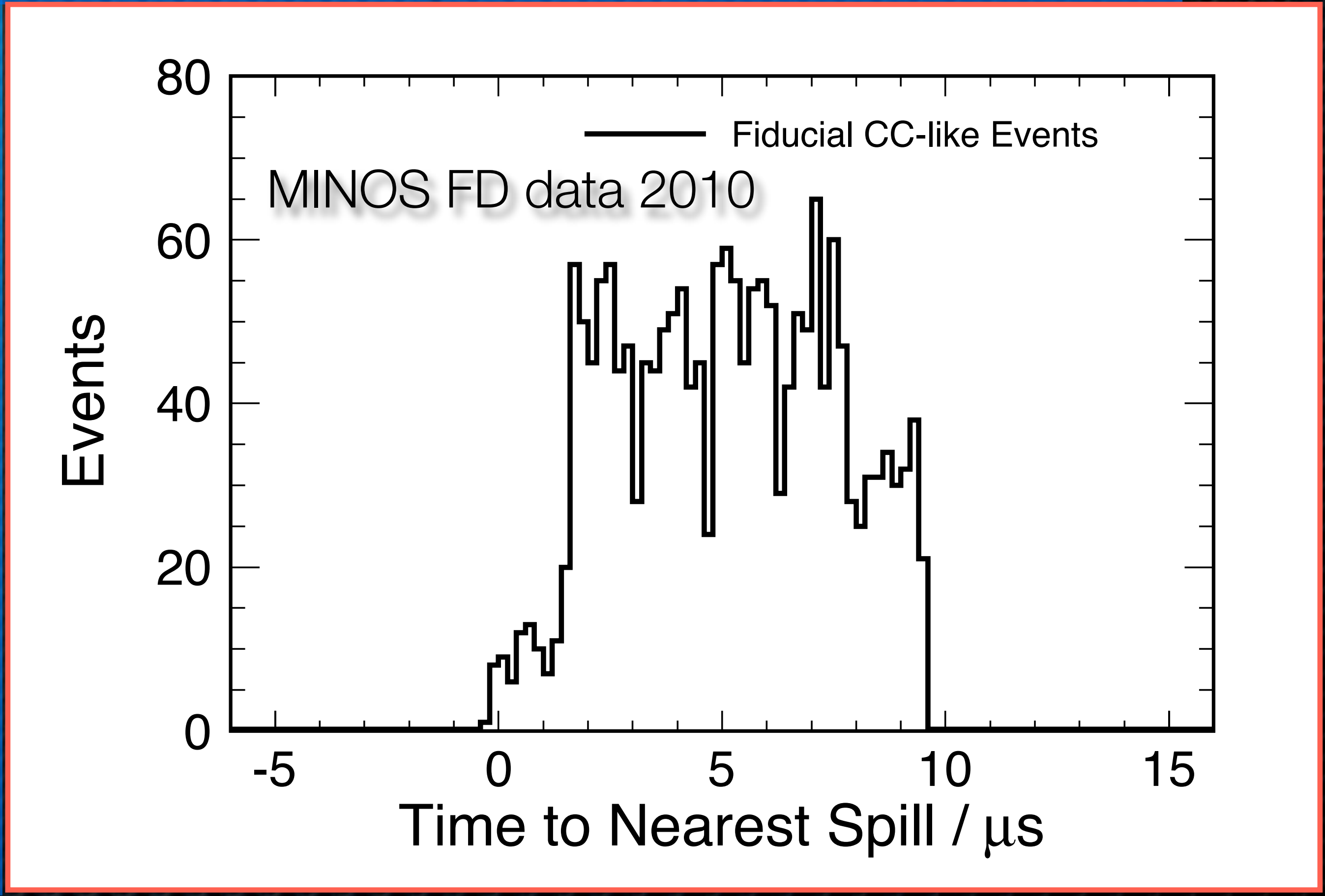


$$\delta = -126 \pm 32\ (\text{stat.}) \pm 64\ (\text{sys.})\ \text{ns} \quad 68\%\ \text{C.L.}$$

- The distributions in the Far Detector are predicted on the basis of measured neutrinos in the Near Detector.
- **MINOS is a neutrino to neutrino measurement.**

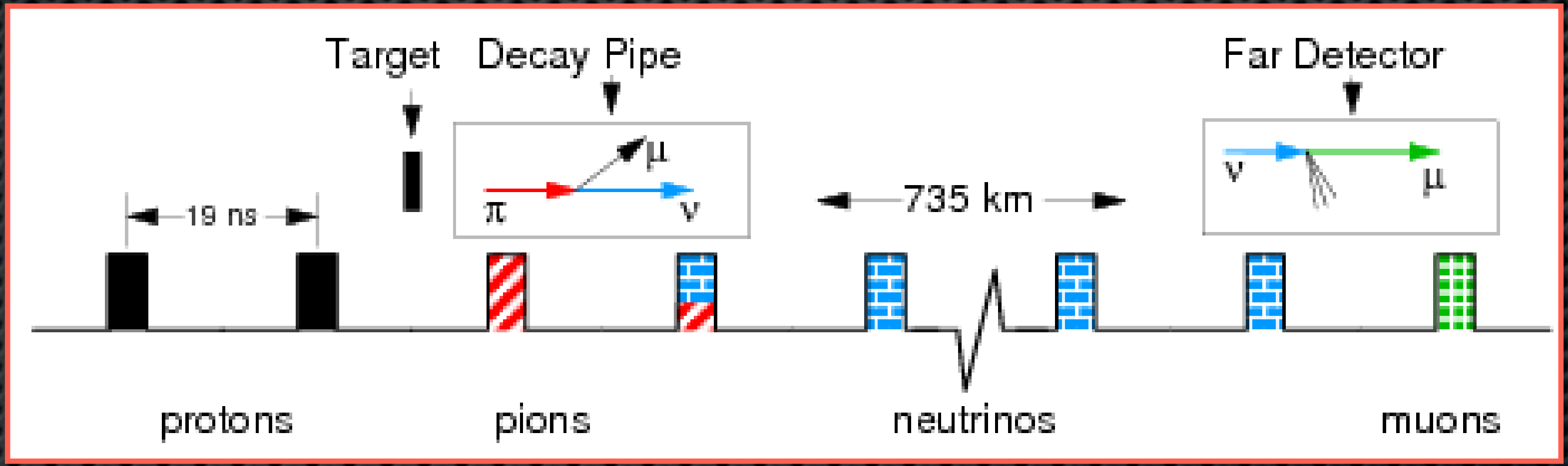
Future of TOF in MINOS

- MINOS getting ready to repeat TOF measurement to independently verify or rule out OPERA's result.
- Short term (6-9 months):
  - Analyze data sample increased by a factor of 9 with respect to 2007 result. Use RF batch structure: 1.6 µsec batches with 100 nsec gaps.
  - Reduce major systematics. Collaborate with experts from NIST.
- Medium term (~1 year):
  - Upgrade the timing system to take all new data from "now" on with better timing.
  - Analyze data taken by the shutdown. Lower statistics but more precise.
  - Crosscheck OPERA directly using proton beam timing profile.



Future of TOF in MINOS+

- MINOS+ running in the NOvA era with upgraded timing system proposes to independently verify or rule out OPERA's result.
- Long term (2013+):
  - Higher energy peaked at ~**7GeV**.
  - Aim to achieve **O(1 nsec)** total systematic error.

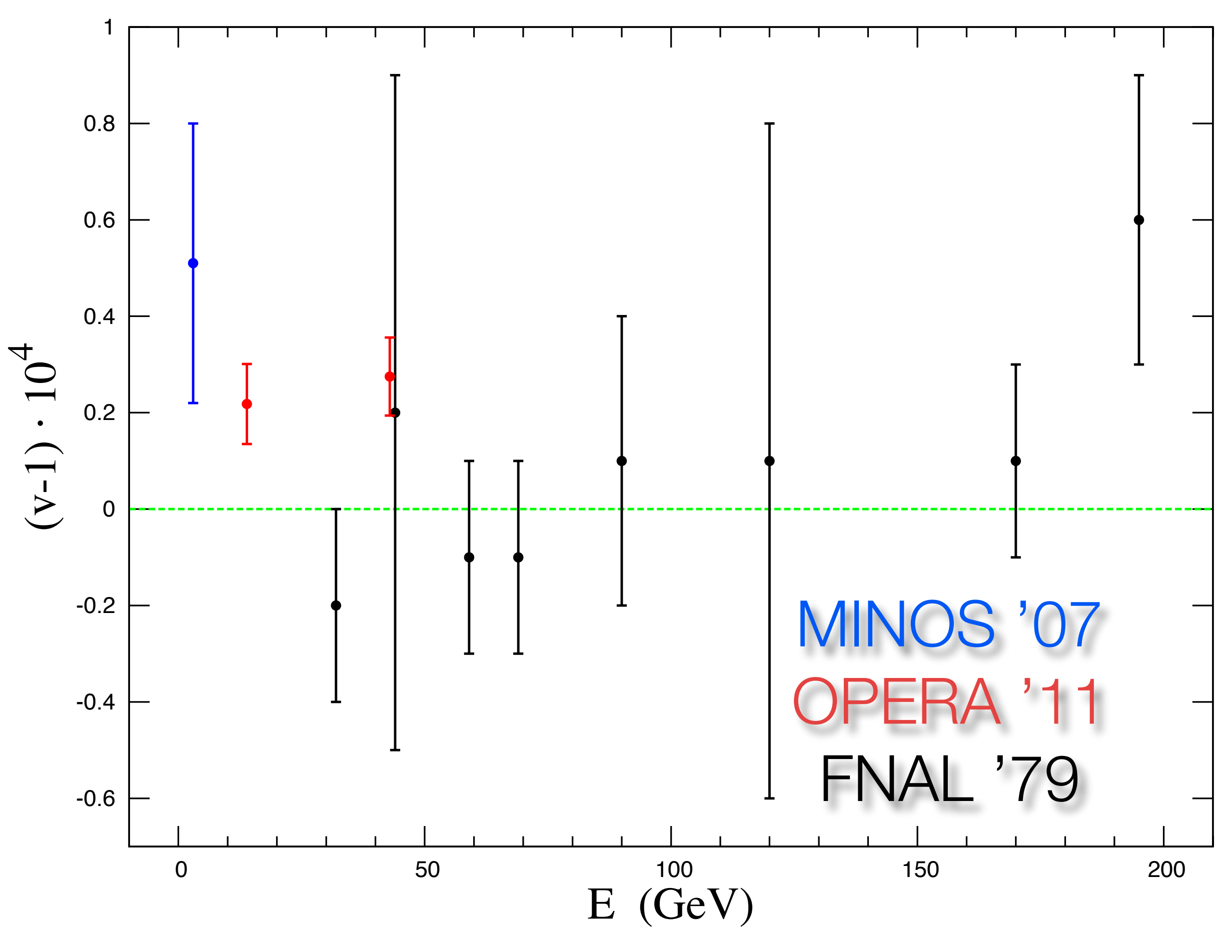


- Key improvements:
- Aim to use the bunch structure, 19 nsec spacing of 2 nsec-width pulses.
- Re-measure distance from Fermilab to Soudan.
- More precise temporal calibration of the FD using auxiliary detectors.

Energy dependence for all muon neutrino data

OPERA-reassessing data on the energy dependence of the speed of neutrinos

Giovanni AMELINO-CAMELIA,[1,2] Giulia GUBITOSI,[3] Niccoló LORET,[1,2]
Flavio MERCATI,[4] Giacomo ROSATI,[1,2] and Paolo LIPARI[2]



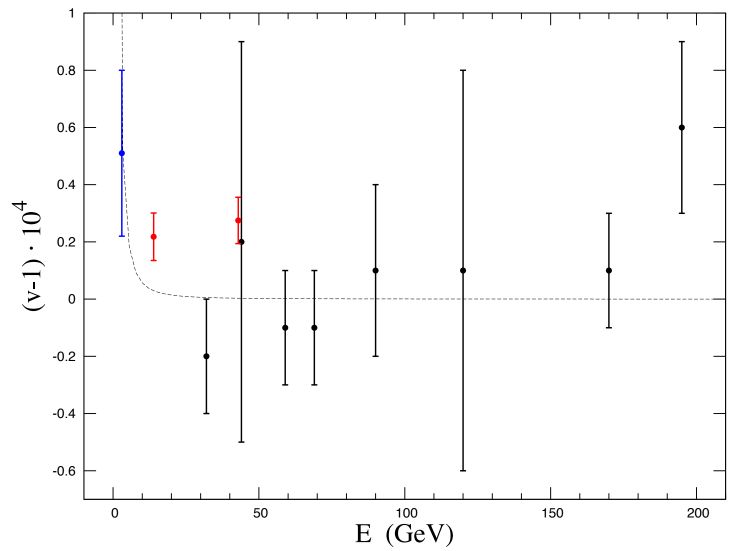


FIG. 3. Fit with the special-relativistic-tachyon hypothesis.

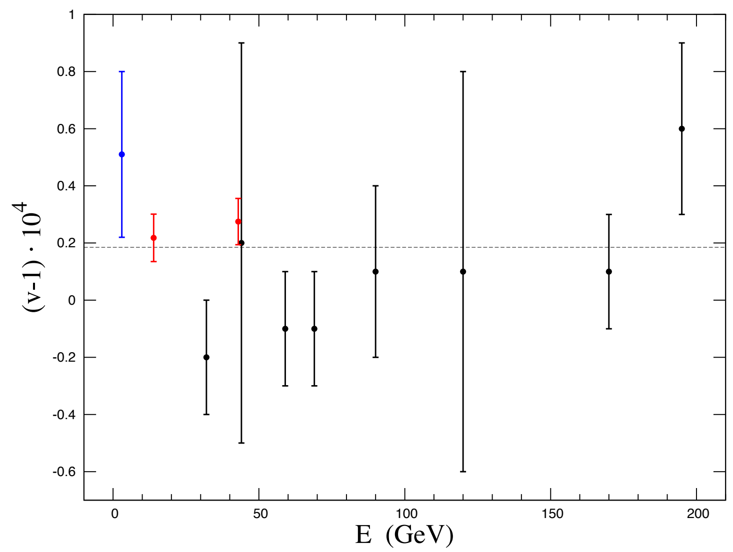
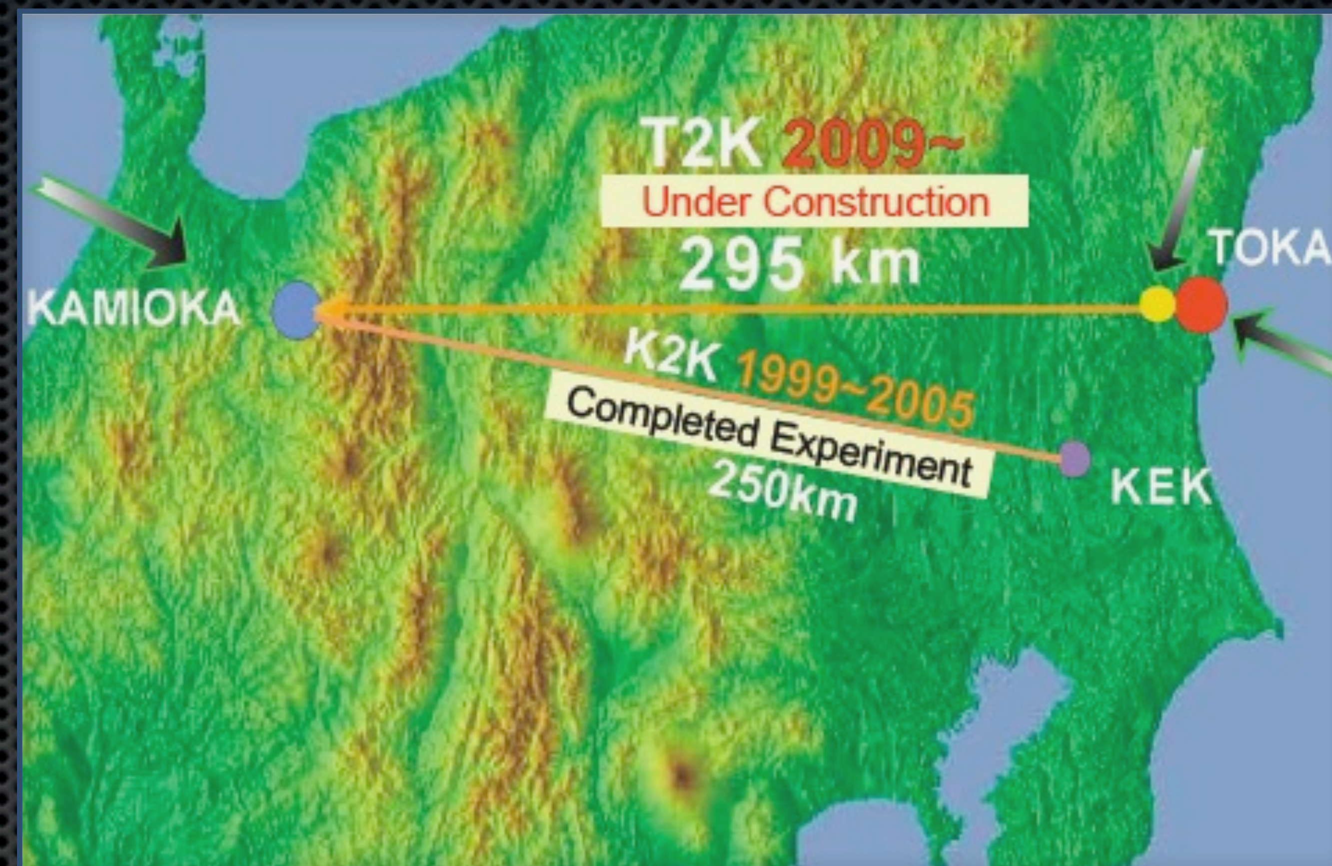


FIG. 4. Fit with the Coleman-Glashow hypothesis.

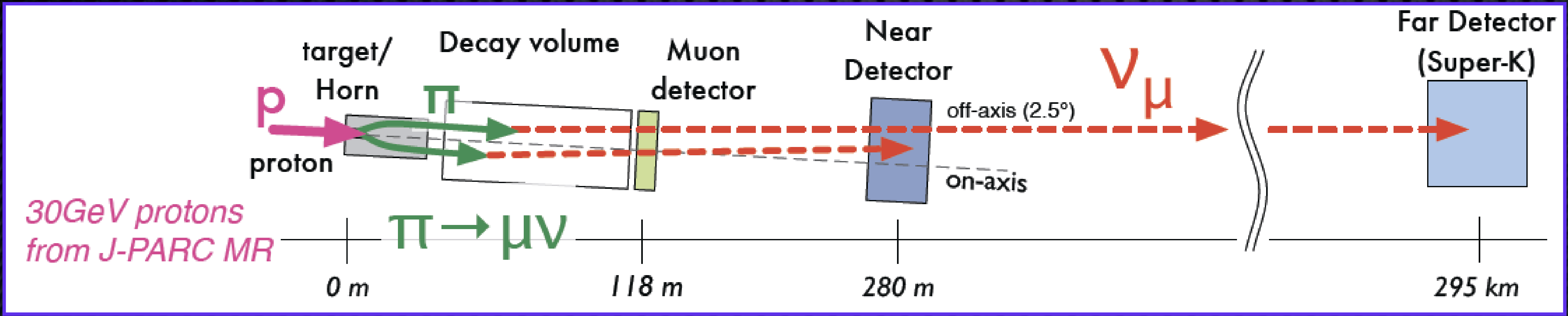
T2K in a nutshell

- Build a high intensity off-axis beam of muon neutrinos at JPARC (2.5º away from SuperK).
- Use existing large Water Cherenkov detector SuperK
- Build a near detector complex to understand beam, cross-sections, etc.
- If neutrinos oscillate, electron neutrinos are observed at the Far Detector at Kamioka.

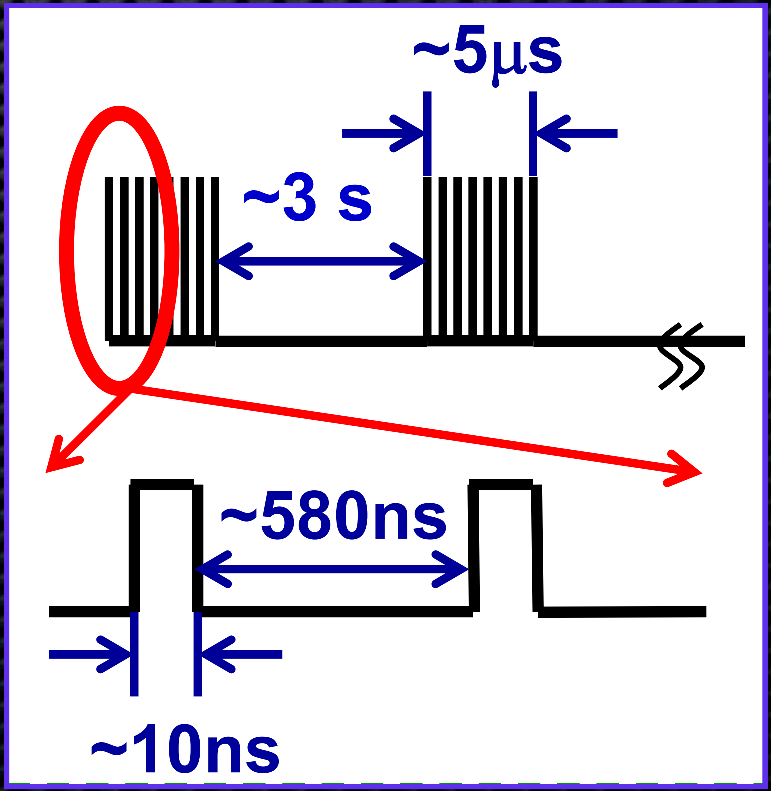


Assessing TOF measurement

The T2K beam

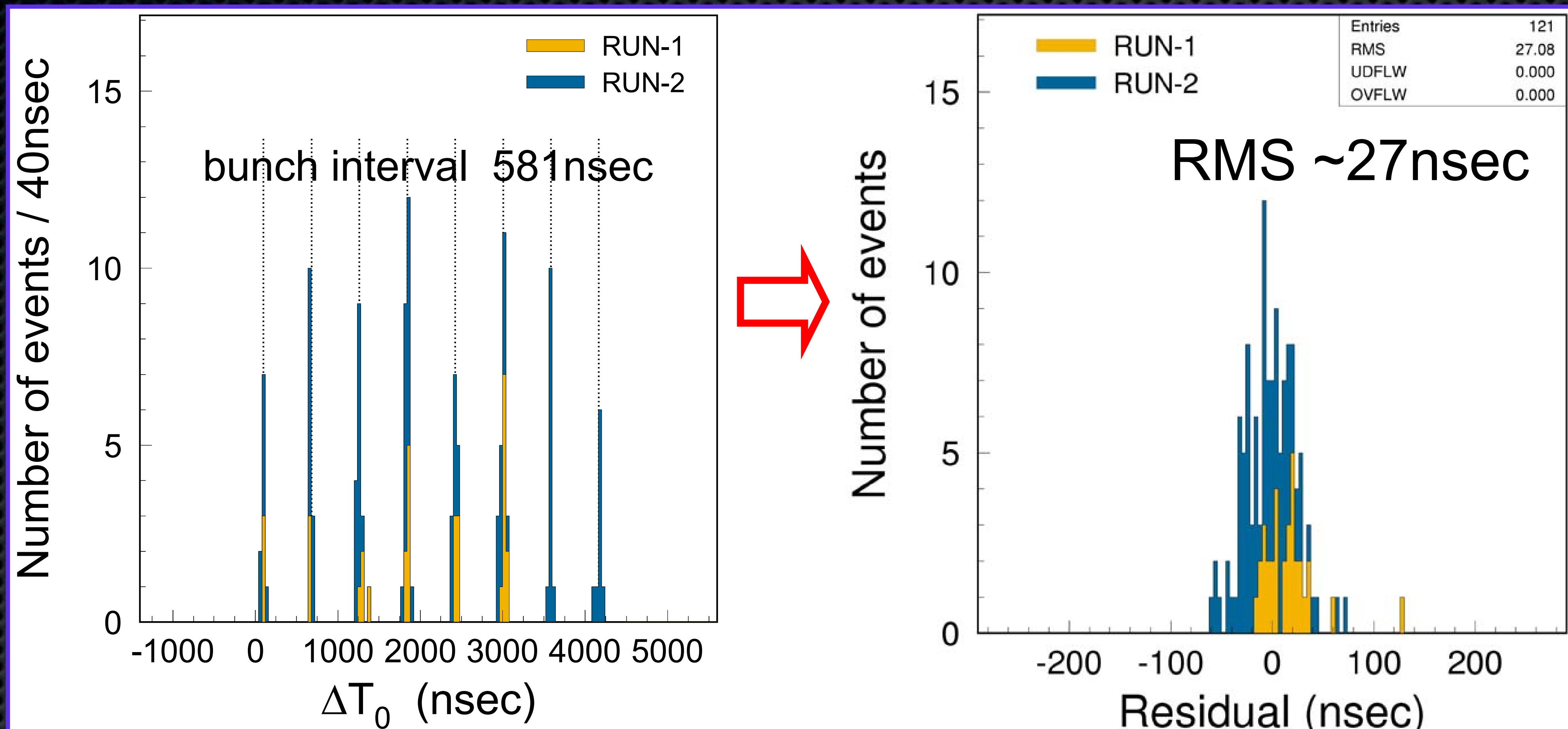


- Neutrino energy peaked at ~0.6 GeV.
- Proton beam extracted every 3 sec.
- Beam spill width ~5μsec.
  - 6 bunches/8 bunches before/after Summer '10.
- Neutrino production graphite target, He air cooled.



Thanks to Hayato-san.

T2K beam structure in SK



- Consider TOF from Tokai to Kamioka, various offsets in the beam-line and SK and photon TOF in the SK detector.
- The eight dotted vertical lines 581 nsec-interval bunch center position fitted to the observed FC event timing.
- Residual from mean beam timing ~ 27nsec. Demonstrates stable beam timing, NOT an absolute timing measurement.

Thanks to Hayato-san.

T2K timing and distances

- Distance between the target and center position at Super-Kamiokande: 295,335.2±0.7 m.
- T2K GPS time synchronization system provides O(50ns) scale between neutrino timestamps at SK and beam spill timestamps at J-PARC.
  - System uses Rb clock as a time base for two independent commercial GPS receivers.
- Shorter baseline and reconstruction resolution makes it more difficult.

Circumference	1567 m
Beam power	~750 kW
Beam kinetic energy	30 GeV
Beam intensity	$\sim 3 \times 10^{14}$ p/spill
Spill cycle	~0.5 Hz
Number of bunches	8/spill
RF frequency	1.67 – 1.72 MHz
Spill width	$\sim 5\ \mu$sec

- See NIM paper for exp details: http://arxiv.org/abs/1106.1238

Official T2K status on TOF

- T2K has assessed its TOF capability and cannot make a definitive statement on the OPERA neutrino TOF anomaly at this point in time.

- T2K will assess a possibility to improve our experimental sensitivity for a measurement to cross-check the OPERA anomaly in the future.

Thanks to Hayato-san.

But, would Einstein really be wrong?

- Theorists are having a field day even if the measurement is not yet confirmed.
- There are **75** papers on the arxiv with “superluminal neutrino” in the abstract, **33 of them were written the week following the announcement, 25 in this past week!**

Here is a biased pick of a few theory papers.
Remember caveat: IANAT

Would Einstein really be wrong?

On the Possibility of Superluminal Neutrino Propagation

Jean Alexandre[1], **John Ellis**[1,2] and **Nick E. Mavromatos**[1,2]

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[2] Theory Division, Department of Physics, CERN, CH 1211 Geneva 23, Switzerland.

Abstract

We analyze the possibility of superluminal neutrino propagation $\delta v \equiv (v-c)/c > 0$ as indicated by OPERA data, in view of previous phenomenological constraints from supernova SN1987a and gravitational Čerenkov radiation. We argue that the SN1987a data rule out $\delta v \sim (E_\nu/M_N)^N$ for $N \leq 2$ and exclude, in particular, a Lorentz-invariant interpretation in terms of a 'conventional' tachyonic neutrino. We present two toy Lorentz-violating theoretical models, one a Lifshitz-type fermion model with superluminality depending quadratically on energy, and the other a Lorentz-violating modification of a massless Abelian gauge theory with axial-vector couplings to fermions. In the presence of an appropriate background field, fermions may propagate superluminally or subluminally, depending inversely on energy, and on direction. Reconciling OPERA with SN1987a would require this background field to depend on location.

Note that J. Ellis, A. Rubbia, S. Sakharov et.al. have a paper from 2008 that suggested neutrinos as probes of Lorentz Violation.

Would Einstein really be wrong?

New Constraints on Neutrino Velocities

Andrew G. Cohen* and Sheldon L. Glashow†

Physics Department, Boston University

Abstract

The OPERA collaboration has claimed that muon neutrinos with mean energy of 17.5 GeV travel 730 km from CERN to the Gran Sasso at a speed exceeding that of light by about 7.5 km/s or 25 ppm. However, we show that such superluminal neutrinos would lose energy rapidly via the bremsstrahlung of electron-positron pairs ($\nu \to \nu + e^- + e^+$). For the claimed superluminal neutrino velocity and at the stated mean neutrino energy, we find that most of the neutrinos would have suffered several pair emissions en route, causing the beam to be depleted of higher energy neutrinos. Thus we refute the superluminal interpretation of the OPERA result. Furthermore, we appeal to Super-Kamiokande and IceCube data to establish strong new limits on the superluminal propagation of high-energy neutrinos.

Would Einstein really be wrong?

The steeply falling (with energy) form of dE/dx means that neutrinos with initial energy greater than E_T rapidly approach a terminal energy, E_T, which is essentially independent of the initial neutrino energy. Adopting the OPERA result $\delta = 5 \times 10^{-5}$ and using the OPERA baseline of 730 km we find a terminal energy of about 12.5 GeV. Few, if any, neutrinos will reach the detector with energies in excess of 12.5 GeV. Thus the CNGS beam would be profoundly depleted and spectrally distorted upon its arrival at the Gran Sasso. Using the expression for Γ above we may also establish that *any* superluminal neutrino with the velocity claimed by OPERA of *any* specific initial energy much greater than 12.5 GeV has a negligible probability of arriving at the Gran Sasso without having lost most of its energy. The observation of neutrinos with energies in excess of 12.5 GeV cannot be reconciled with the claimed superluminal neutrino velocity measurement.

Would Einstein really be wrong?

Dimension-hop may allow neutrinos to cheat light speed

12:05 23 September 2011 by Lisa Grossman

Read more: "Neutrinos: Complete guide to the ghostly particle"

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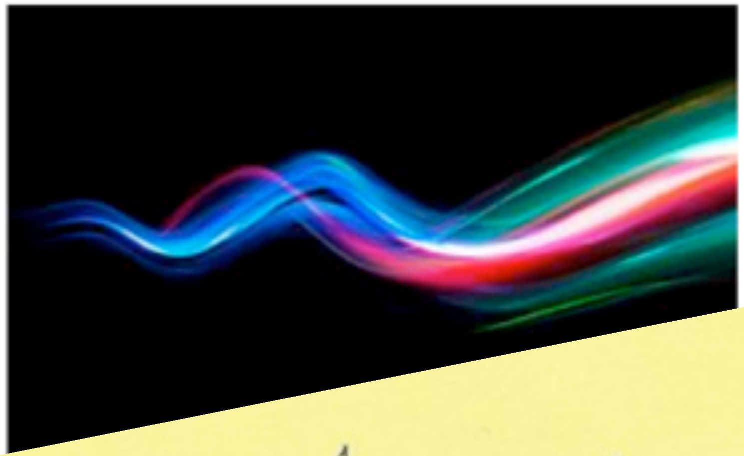

A CERN experiment claims to have caught neutrinos breaking the universe's most fundamental speed limit. The ghostly subatomic particles seem to have zipped faster than light from the particle physics laboratory near Geneva, Switzerland, to a detector in Italy.

Fish that physics textbook back out of the wastebasket, though: the new result contradicts previous measurements of neutrino speed that were based on a supernova explosion. What's more, there is still room for error in the departure time of the supposed speedsters. And even if the result is correct, thanks to theories that posit extra dimensions, it does not necessarily mean that the speed of light has been beaten.

"If it's true, it's fantastic. It will rock the foundation of physics," says Stephen Parke of Fermilab in Batavia, Illinois. "But we still have to confirm it."

- Extra-dimensions, really?

Would Einstein really be wrong?

Apparent faster than light propagation from light sterile neutrinos

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(Dated: September 28, 2011)

Recent data from the OPERA experiment seem to point to neutrinos propagating faster than light. One possible physics explanation for such a result is the existence of light sterile neutrinos which can propagate in a higher dimensional bulk and achieve apparent superluminal velocities when measured by an observer confined to the 4D brane of the standard model. Such a model has the advantage of easily being able to explain the non-observation of superluminal neutrinos from SN1987A. Here we discuss the phenomenological implications of such a model and show that it can provide an explanation for the observed faster than light propagation of neutrinos.

Other papers calculate the curvature of such brane.

Summary of current measurements

- Electron anti-neutrinos from supernova 1987a arrived in time with light. Neutrino energies from supernovae are **~10-40 MeV**.

  $|v-c|/c \leq 2\times10^{-9}$

- A short baseline experiment at Fermilab tested in 1979, muon neutrinos with energies larger than **30 GeV**:

  $|v-c|/c \leq 4\times10^{-5}$

- The MINOS experiment used muon neutrinos at energies of **~3GeV** (2007):

  $(v-c)/c = 5.1 \pm 2.9\times10^{-5}$ $(1.8\ \sigma)$

- Opera's result with muon neutrinos is at **~17 GeV**:

  $(v-c)/c = \delta t\,/(TOF_c - \delta t) = (2.48 \pm 0.28\ (\text{stat.}) \pm 0.30\ (\text{sys.}))\ \times10^{-5}$

Final Thoughts

- From the Economist (Oct 1st, 2011):

  For in their heart of hearts, even the sceptics who say they think the result from OPERA must be a mistake hope that it is not.

- However, extraordinary claims require extraordinary proof.
- **But even if you really do NOT hope it to be true...**

  We are unlikely to ever build another neutrino experiment without planning to measure TOF at the highest precision possible, even if OPERA is proven wrong.