experiments
with
(conventional long baseline)
neutrinobeams

Overview

- vacuum neutrino oscillations – (very) short introduction
- conventional neutrinobeams
- two experiments
  - MINOS
  - OPERA
- outlook and conclusion

vacuum neutrino oscillations

(very) short introduction

neutrinos

we know: there are (at least) three different neutrino flavors "associated" with the corresponding charged lepton flavor

$$\nu_e \leftrightarrow e^-$$

$$\nu_\mu \leftrightarrow \mu^-$$

$$\nu_\tau \leftrightarrow \tau^-$$

„associated" means: look at the leptonic W^+ decay

$$W^+ \rightarrow \ell_\alpha^+ + \nu_\alpha \qquad (\alpha = e, \mu, \tau)$$

define: ν_α is that neutrino, that is emitted together with the positive charged lepton ℓ_α^+

neutrinos

most general case: the (neutrino) flavor eigenstates ν_α are not mass eigenstates ν_i

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle$$

ν of flavor α

ν of definite mass ν_i

leptonic mixing matrix
(simple case: identity matrix)

extending the standardmodel to include neutrino mass and leptonic mixing (lepton flavor violation!):

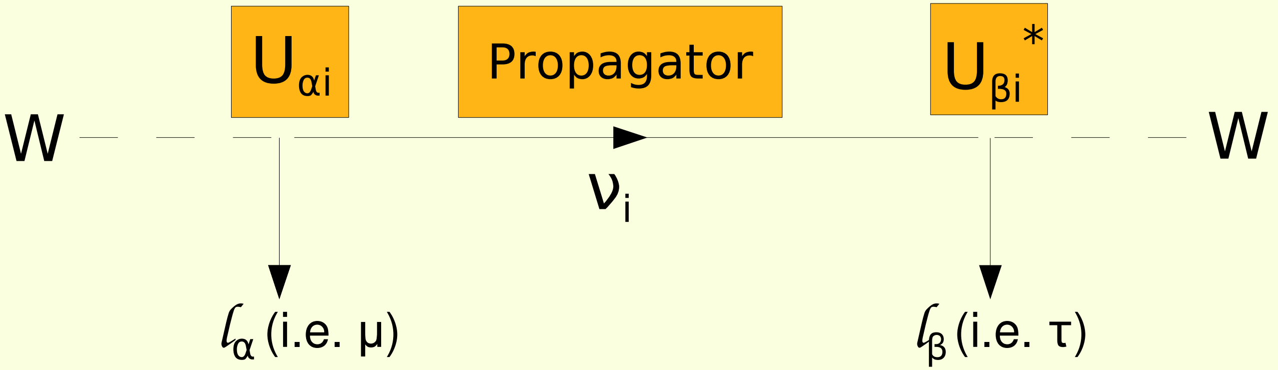
- number of different ν_i is the same as the number of different ℓ_α (=3)
- leptonic mixing matrix U is 3x3 and unitary: $UU^\dagger = U^\dagger U = 1$

  (what if you asume a 3x3 matrix and measure that it is not unitary...?)

neutrino oscillations

- look at W^+ decay again: a given charged lepton ℓ_α^+ can be accompanied by any ν_i (but not by any ν_α!)

$$Amp(W^+ \rightarrow l_\alpha^+ + \nu_i) = U_{\alpha i}$$



- to get the propagator, look at ν_i-rest frame with the proper time T_i, Schrödinger equation:

$$i\frac{\partial}{\partial t}|\nu_i(T_i)\rangle = m_i|\nu_i(T_i)\rangle \longrightarrow |\nu_i(T_i)\rangle = e^{-i m_i T_i}|\nu_i(0)\rangle$$

neutrino oscillations

by Lorentz invariance, propagator in lab-frame:

$$e^{-i m_i T_i} \approx e^{-i m_i^2 \frac{L}{2 E_i}}$$

L: distance from generation of ν_α to the detection of ν_β

E: energy of the neutrino ν_i

giving the transition amplitude:

$$Amp(\nu_\alpha \rightarrow \nu_\beta) = \sum_i U_{\alpha i} e^{-i m_i^2 \frac{L}{2 E_i}} U^*_{\beta i}$$

and the transition propability:

$$P(\nu_\alpha \rightarrow \nu_\beta) = |Amp|^2 = \delta_{\alpha\beta} - 4 \sum_{i>j} \Re(U_{\alpha i} U^*_{\alpha j} U^*_{\beta i} U_{\beta j} \sin^2(\Delta m_{ij}^2 \frac{L}{4E}))$$

$$+2 \sum_{i>j} \Im(U_{\alpha i} U^*_{\alpha j} U^*_{\beta i} U_{\beta j} \sin(\Delta m_{ij}^2 \frac{L}{2E}))$$

with $\Delta m_{ij}^2 = m_i^2 - m_j^2$

neutrino oscillations

... but thats look not very nice (for an experimentalist)!

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

The most common parametrisation of the leptonic mixing matrix is the one of Pontecorvo, Maki, Nakagawa and Sakata:

- Use 3 Euler-angulars Θ_{12}, Θ_{13}, Θ_{23} and a CP-violation phase δ (very similar to the quark mixing matrix).
- Furthermore, neutrinos are the only leftover particles of the SM that can be Majorana particles, that would add two more complex phases α_1 and α_2...

neutrino oscillations

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Majorana phases α

in ν-oscillation the mixing matrix only appears as UU^* combination, that phase is hidden...

$$U = \overbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}^{\text{„atmospheric“}} \cdot \overbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix}}^{\text{„cross-mixing“}} \cdot \overbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}^{\text{„solar“}} \cdot \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

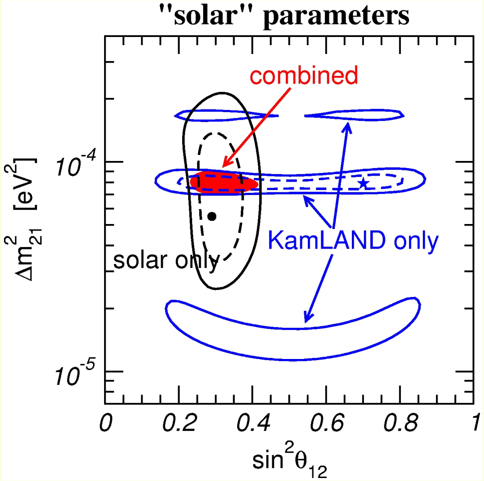
with $s_{ij} = \sin\Theta_{ij}$
and $c_{ij} = \cos\Theta_{ij}$

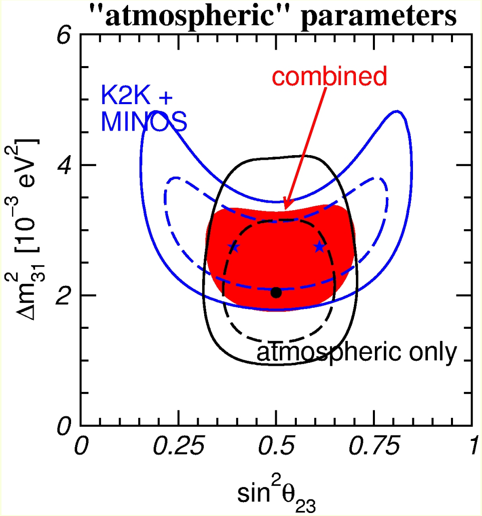
CP-violating phase δ

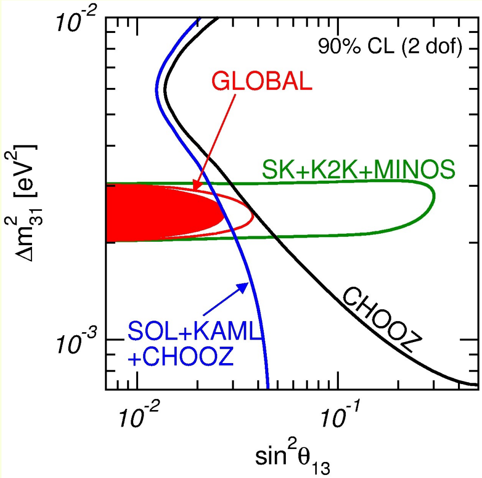
only observable if ALL mixing angles nonzero – the choice to put it next to Θ_{13} is arbitrary, but...

neutrino oscillations

	world best fit	**1σ-error**
Δm_{12}^2	$7.9 \pm 0.3\ (10^{-5}\,eV^2)$	4%
Δm_{23}^2	$2.5_{-0.25}^{+0.2}\ (10^{-3}\,eV^2)$	10%
$\sin^2\Theta_{12}$	$0.3_{-0.03}^{+0.02}$	9%
$\sin^2\Theta_{23}$	$0.5_{-0.03}^{+0.08}$	16%
$\sin^2\Theta_{13}$	$\leq 0.025\ (2\sigma)$	-







- $\Delta m_{13} \approx \Delta m_{23} >> \Delta m_{12}$: approximation by two flavor oscillation
- CP comes into the game: $s_{12}c_{12}s_{23}c_{23}s_{13}c_{13}{}^2 \sin(\delta)$

  (note the crucial role of Θ_{13} – it could hide CP violation if Θ_{13} is very small!)
- is Θ_{23} maximal (45°), smaller or larger?

neutrino oscillations

we can simplify the equations in a first order aproximation (several % error)

with $\Delta m_{23} >> \Delta m_{12}$ and Θ_{13} very small.

with L in km, E in GeV

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2(2\theta_{23}) \sin^2\left(\frac{1.27(\Delta m_{23}^2)L}{E_\nu}\right)$$

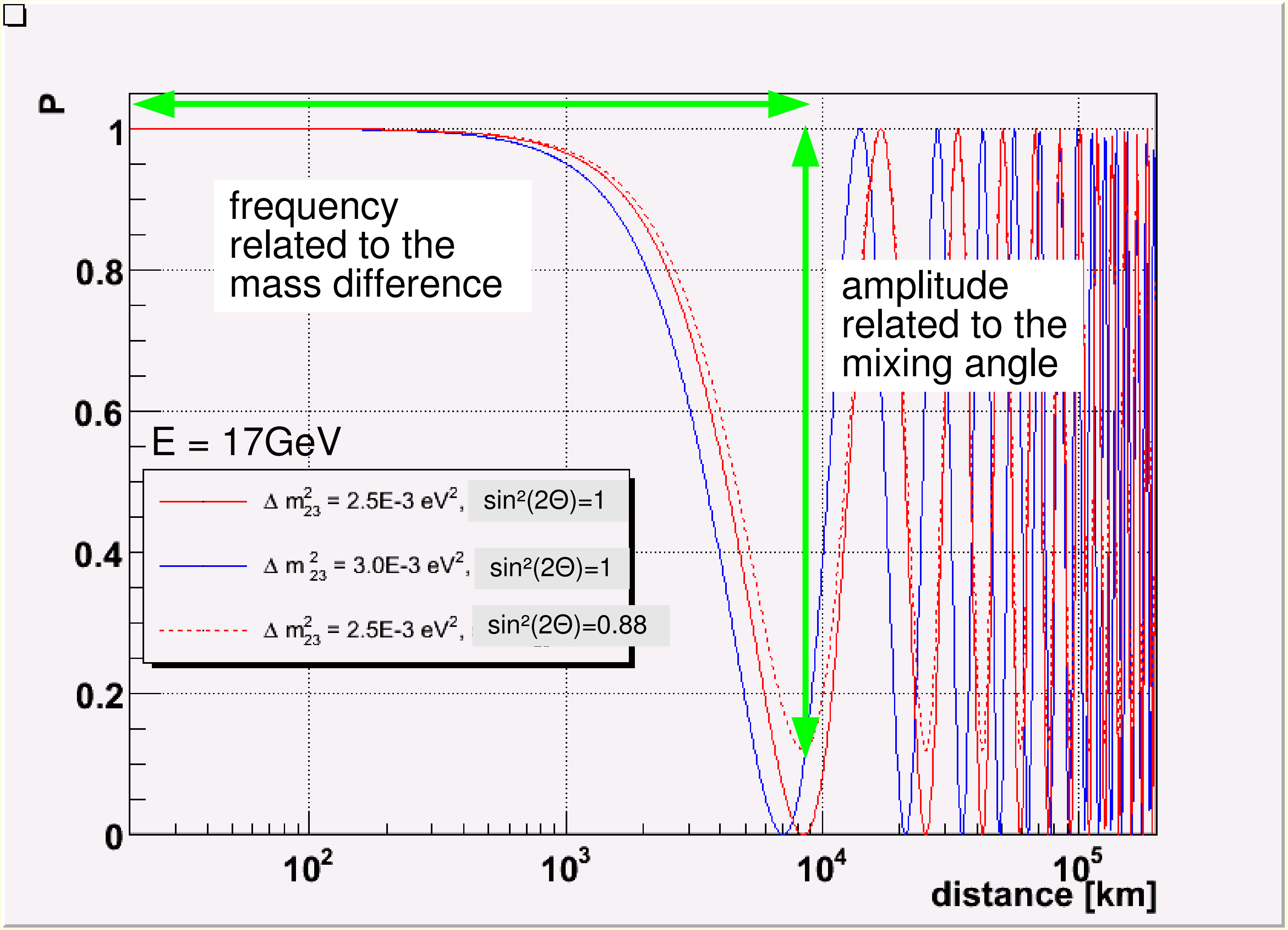
one can control experimentally L and E

one wants to measure: $\sin^2(2\Theta)$ and Δm^2

this is the same result you get from 2-flavor oscillation:

$$\begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \cos\theta_{23} & \sin\theta_{23} \\ -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \cdot \begin{pmatrix} \nu_2 \\ \nu_3 \end{pmatrix}$$

neutrino oscillations


frequency related to the mass difference

amplitude related to the mixing angle

E = 17GeV

Typical strategy in a few words...

How to measure a „survival propability“?

a good L/E value to look for ν_μ-disappearance:

$L/E \approx 250\text{km/GeV}$

typical neutrino-nucleus cross-section for GeV neutrinos:

$\sigma \approx 10^{-38}\ \text{cm}^2$

number of nucleons per kiloton target material:

$N \approx 10^{32}$ nucleons/kton

expected event rate in a detector:

$$\text{rate} = \Phi \times \sigma \times N_{\text{target}}$$

1event/(kton x 10^6 ν) - at a distance of several hundred km!

Typical strategy in a few words...

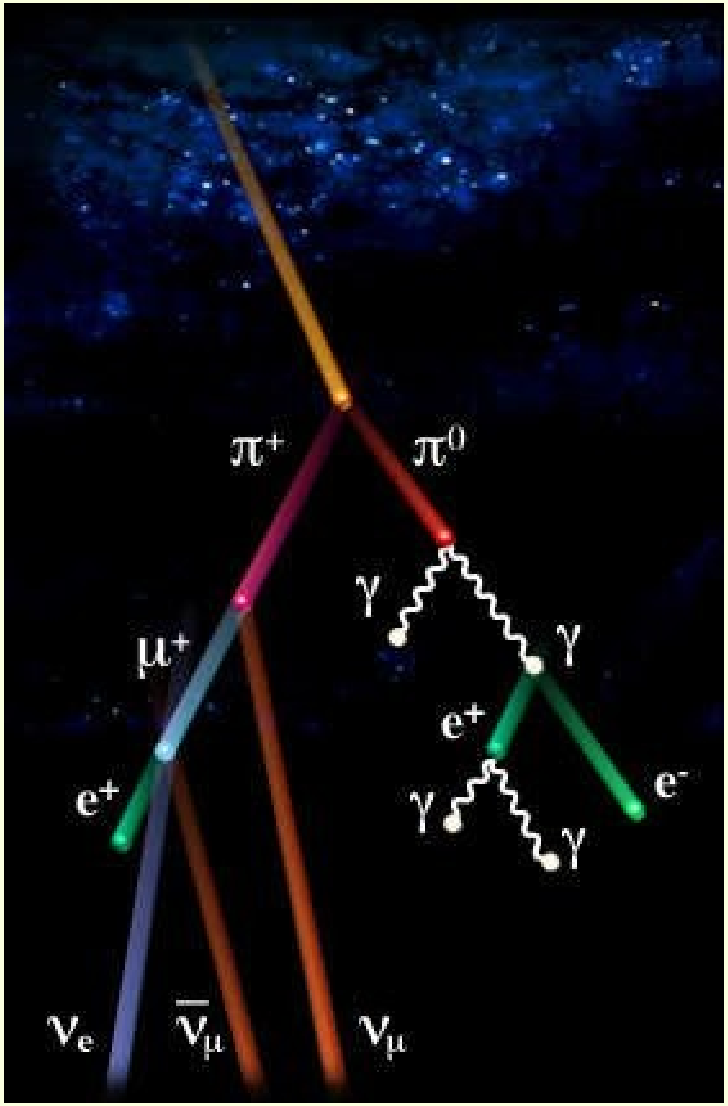
We need a neutrino source that provide:

- high flux at large distances
- known neutrino energy spectrum and high energy if you want to see tau-appearance
- distinct distance from source to the detector
- known neutrino flavor in the beam
- pure neutrino beam, low wrong-flavor contamination
- reduced background due to clear timing of neutrino arrival

We need artifical neutrino beams!

conventional neutrino beams

on the way to Θ_{23}



inspired by atmospheric neutrino generation ...

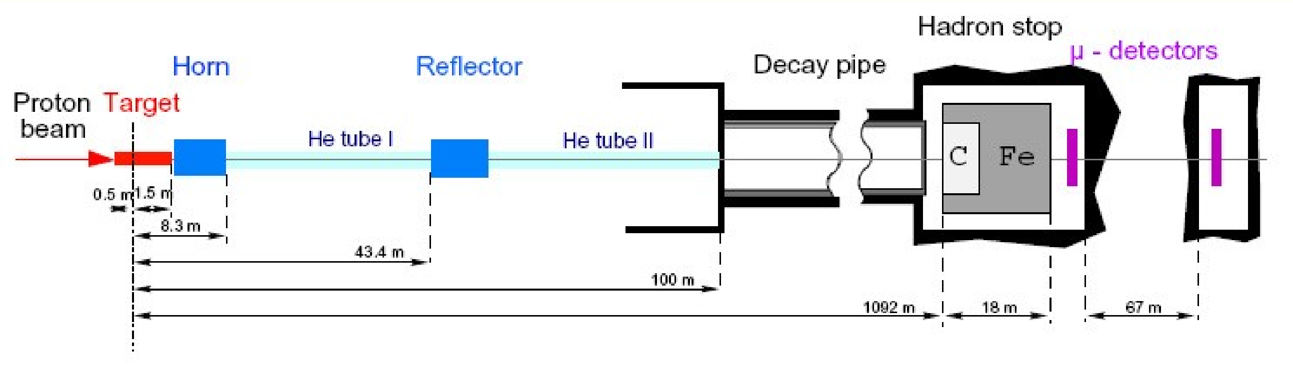
conventional neutrino beams

- “conventional“ means:

  „high energy protons hit a nuclear target and produce a secondary beam (of pions and kaons), whose decays yield a neutrino beam“

- “beam” means:

  “one wants to make use of focused forward-boosted secondaries that yields to forward boosted neutrinos“



conventional neutrino beams

- tau-neutrino beam from $D_S \rightarrow \nu_\tau + \tau$ (DONUT)
- electron neutrinos from $K_L \rightarrow \nu_e + e^- + \pi^+$ (proposed)
- most promising: a (anti-)muon neutrino beam via:

$\mathbf{p^+ + A \rightarrow \pi^+ + X}$ (about 90%)

↳ $\mathbf{\mu^+ + \nu_\mu}$ (99.99%)

$\mathbf{p^+ + A \rightarrow K^+ + X}$ (about 10%)

↳ $\mathbf{\mu^+ + \nu_\mu}$ (≈ 63.5%)

conventional neutrino beams

we need protons:

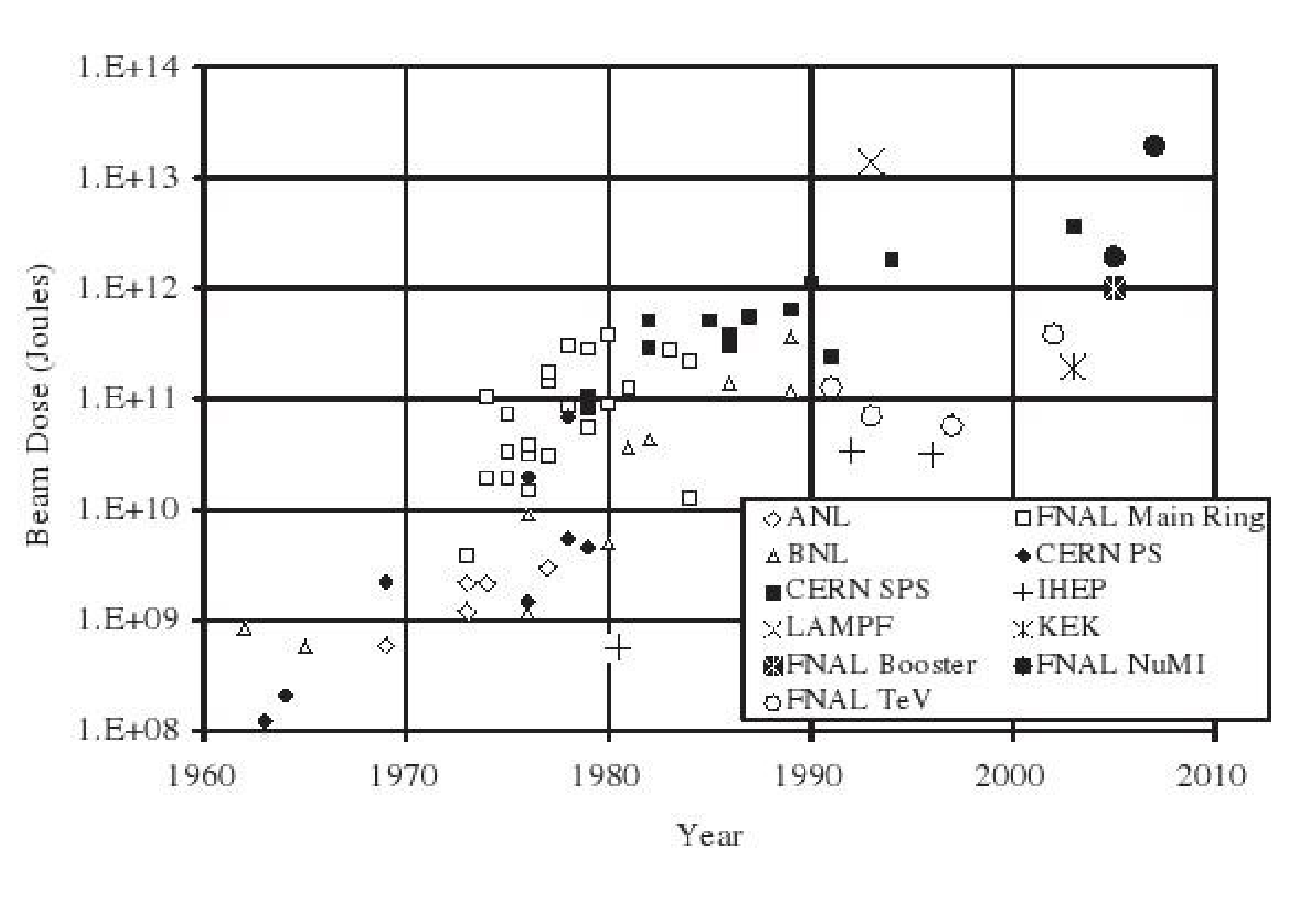
the proton source

conventional neutrino beams
- the proton source -

- keep in mind two rules of thumb:
  - Rule 1) $E_\nu = f(E_{\pi/K}) = f(E_p)$
    - in words: neutrino energy depends on proton energy (but not only!)
  - Rule 2) $\Phi_\nu = f(\Phi_{\pi/K}) = f(P_p)$
    - in words: neutrino flux depends on proton power (pot times E_p)

proton source	**experiments**	$\mathbf{E_{proton}}$	**pot/yr.**	**Power**	$\mathbf{E_\nu}$
SPS	OPERA	400 GeV	$0.45 \cdot 10^{20}$	0.12 MW	25 GeV
FNAL Main Injector	MINOS, NoνA	120 GeV	$2.5 \cdot 10^{20}$	0.25 MW	3-17 GeV
J-PARC	T2K	40-50 GeV	$11 \cdot 10^{20}$	0.75 MW	0.8 GeV

conventional neutrino beams
- integrated proton power -



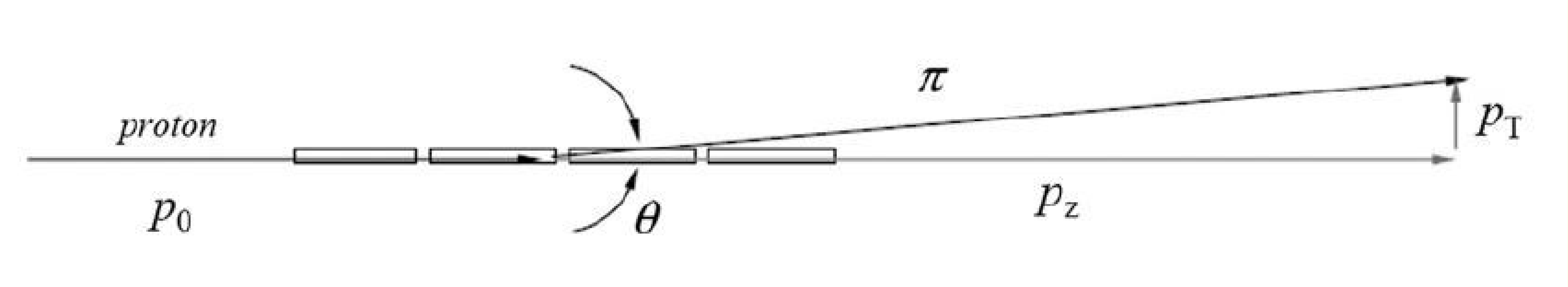
from: S. Kopp, Phys. Rep. 439, p. 101-159, 2007

conventional neutrino beams

we need nucleons:

the target

conventional neutrino beams
- the target -



- target lenght
  - the longer the more proton interactions
  - but trade-off: the longer the more secondary scatterings
- target material
  - high melting point (instantaneous power about 100 GW!!!)
  - high shock resistance
- target structure
  - „needle-like“ to reduce pathlenght for secondaries
  - for high energy neutrinos: evcuated regions between targets to „let the pions out“
  - for high power beams: segmented to avoid shockwaves

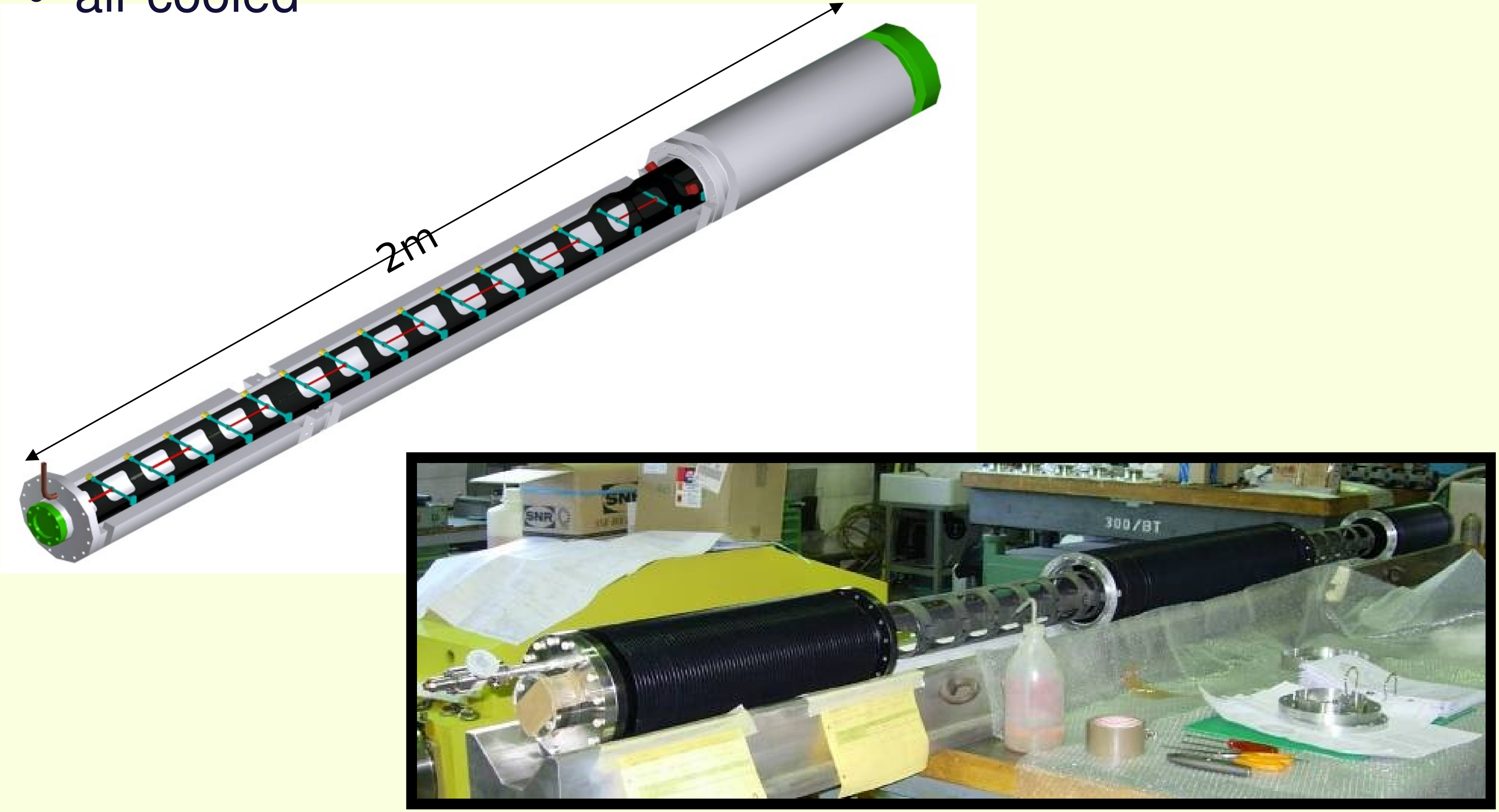
conventional neutrino beams
- the target -

- low Z materials reduce upheating (graphite)
- fill gaps of segmented targets with sealed gas/vacuum to reduce shockwave propagation
- no direct contact with cooling material like water or gas to avoid radioactive waste
- full remote access in case of broken target (barrel-like design)
- guideline: $\varnothing \approx 3 \cdot \sigma_P$, $\sigma_P^{SPS} \approx 1$mm, large σ_P prevents upheating

neutrino beamline	experiments	material	∅ [mm]	lenght [cm]
CNGS (SPS)	OPERA	graphite	4-5	200
NuMI (Fermilab)	MINOS, NoνA	graphite	6.4	90
J-PARC (KEK)	T2K	graphite	12-15	90
BoosterNeutrino	MiniBooNe	Be	10	60

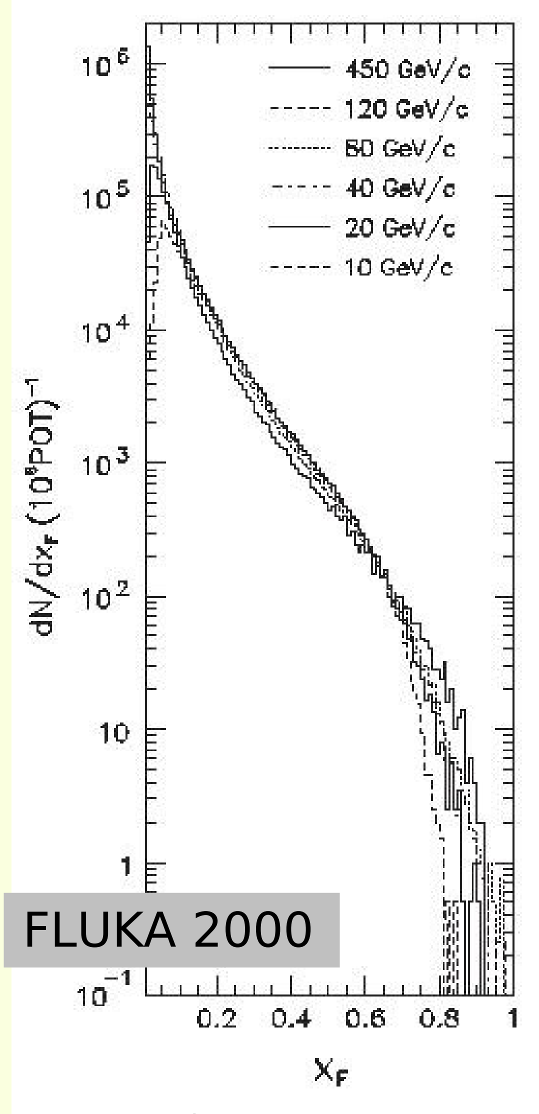
conventional neutrino beams
- the CNGS target -

- 13x10cm graphite rod, 9cm helium filled gaps
- air cooled



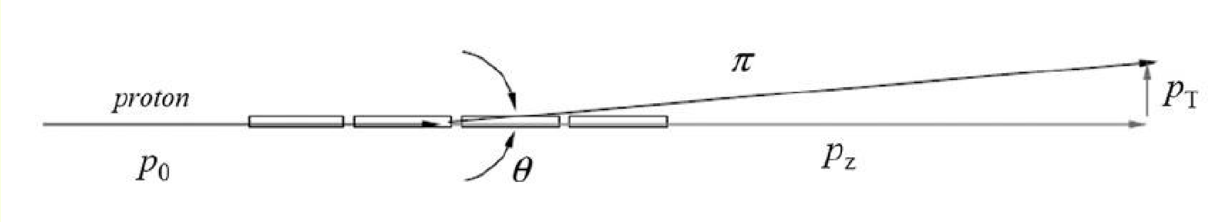
conventional neutrino beams
- the CNGS target -

conventional neutrino beams



- define: $x_F := p_Z/p_0$
- dN/dx_F (almost) independent of proton momentum

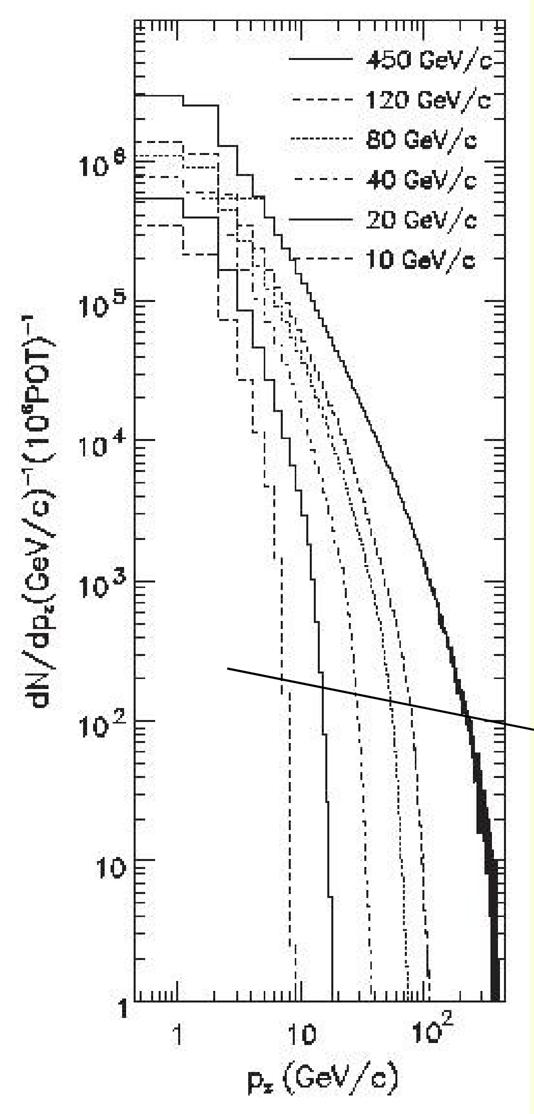
Pion momentum p_Z scales with incident proton momentum!



graphite-target, 94cm long,
6.4x15mm² transverse

from: S. Kopp, Phys. Rep. 439, p. 101-159, 2007

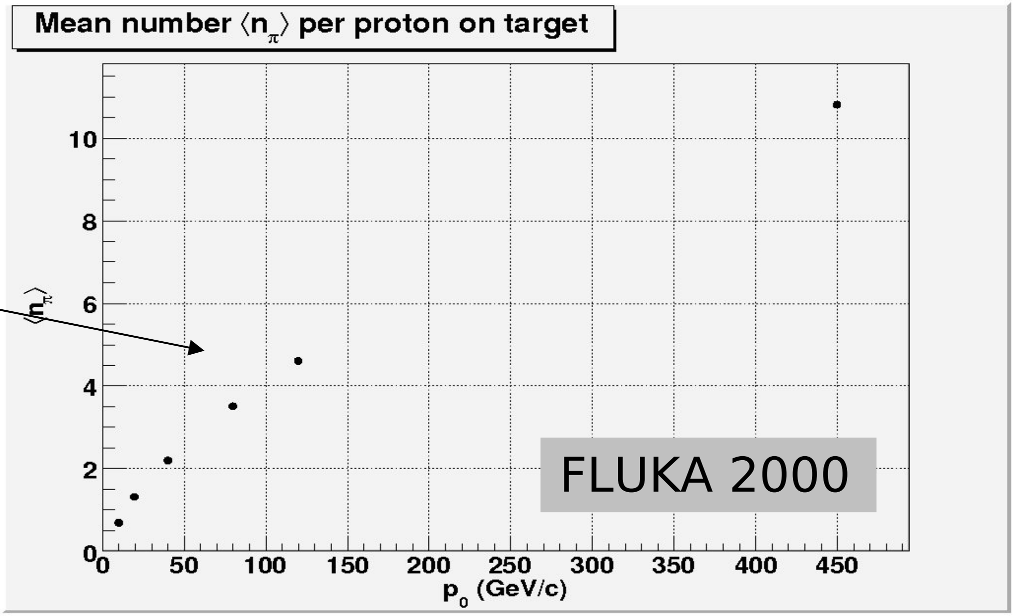
conventional neutrino beams



from: S. Kopp, Phys. Rep. 439, p. 101-159, 2007

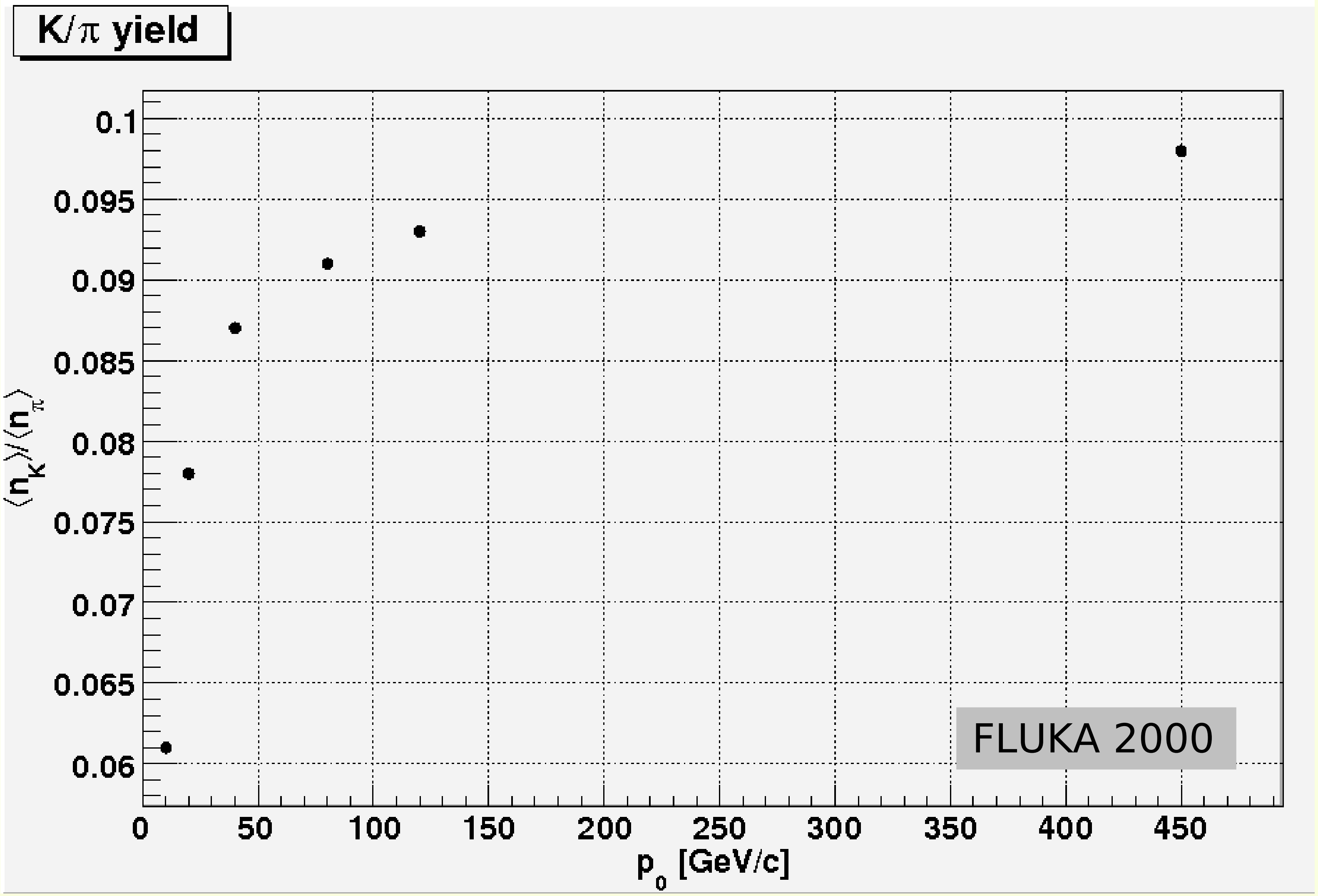
- integrals are the mean number of pions
- number of pions per „pot“ grow with proton energy

$$\boldsymbol{n_\pi/\text{pot} \sim (p_0)^{0.7}}$$

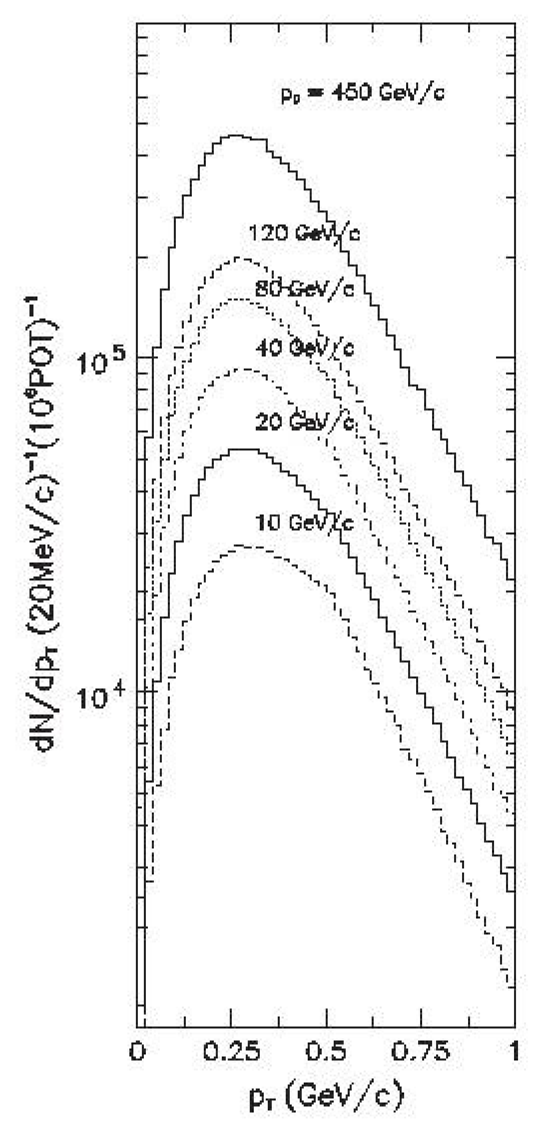


graphite-target, 94cm long, 6.4x15mm² transverse

conventional neutrino beams



conventional neutrino beams



from: S. Kopp, Phys. Rep. 439, p. 101-159, 2007

- important to understand beam divergence: transverse momentum p_T of secondaries
- process dominated by fermi motion of partons inside the nucleus of the target:

$$\sim 2\pi hc/1\text{fm} \approx 200\text{MeV}$$

- peak transverse momentum $\approx$ 280MeV
- $\Theta_\pi \approx p_T/p_\pi \approx 280\text{MeV}/E_\pi = 280\text{MeV}/(\gamma m_\pi)$
  $\approx 2/\gamma$

conventional neutrino beams - pion decay -

- pion (kaon) decay is a 2-body-decay: $\pi \rightarrow \mu + \nu_\mu$
- pion and kaon are spin zero particles, angular distribution is isotropic in CM frame, in the lab frame ($m_\nu = 0, \beta \approx 1$):

$$E_\nu \approx ((1-m_\mu^2/M^2)E)/(1+\gamma^2\tan^2\Theta_\nu)$$

$$\Theta_\nu^{max} \approx 1/\gamma \quad \text{(compare with } \Theta_\pi \approx 2/\gamma)$$

$$\Phi_\nu \sim (2\gamma/(1+\gamma^2\Theta_\nu^2)^2$$

- these squares in the flux formula makes neutrino beams complicated: You have to focus the pions and kaons or loose a factor $(1+(1+2)^2)^2/(1+1)^2 = 25$, that are 96% of your neutrinos, in comparison to a perfectly focused beam!

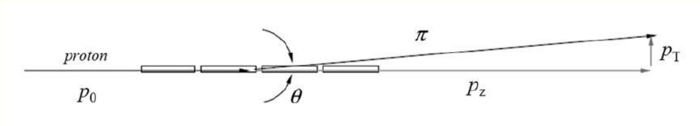
(of course this model is simplified)

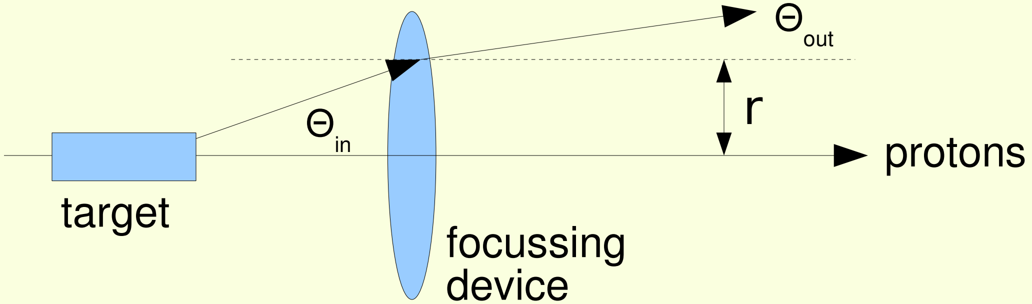
conventional neutrino beams

we need a beam:

focussing the secondaries

conventional neutrino beams - focussing -





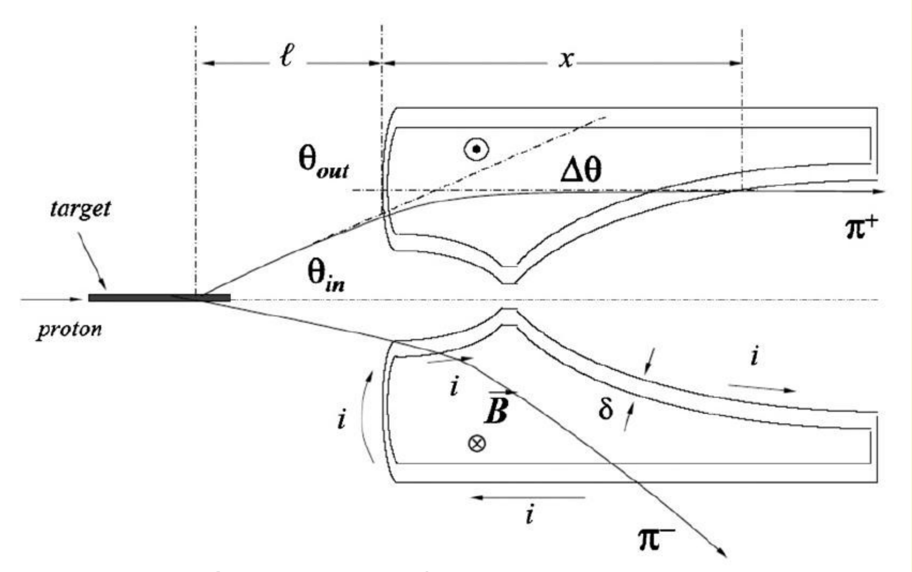
- perfect focussed mean: $\Theta_{out} = 0$
  - $\Theta_{in} \approx p_T/p_\pi$: particle with a large distance to the incident proton beam need large focussing F: F ~ r
  - magnetic line source in beam direction? Yes, but B ~ 1/r
  - here comes the trick: use a „magnetic line source“, but let particles with large distance r travel a longer distance x in the magnetic field!

$$\boxed{F \sim r \sim B(r) \cdot x(r)}$$

conventional neutrino beams
- focussing -

the solution:
parabolical horn
with inner conductor
shape $z = ar^2$
(this one shown here is in fact a double-horn)

$$\Delta\Theta = \frac{B\,x}{p} = \frac{\mu_0 I\,x}{2\pi r p} = \frac{\mu_0 I\,a r}{2\pi p}$$



from: S. Kopp, Phys. Rep. 439, p. 101-159, 2007

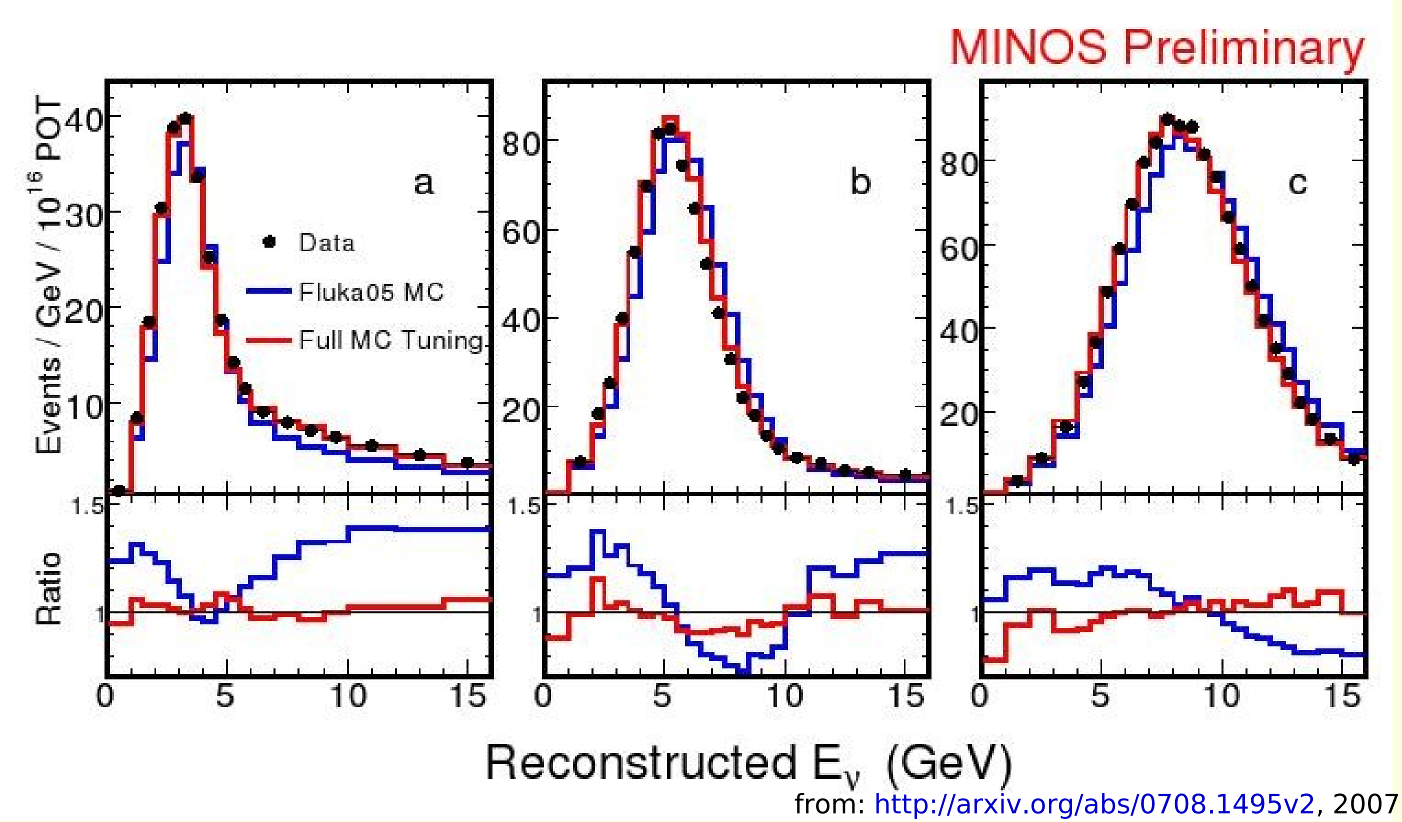
- with $\Delta\Theta = \Theta_{out} - \Theta_{in}$ perfect focussing means: $\Theta_{out} = 0$ or $\Delta\Theta = r/L$ a parabolic horn focuses a particular momentum for all angles:

$f = L = 2\pi p/(\mu_0 Ia) = \text{const}^*(p/I)$ f: focal lenght

- to give a pion a p_T-“kick“ of about 280MeV, a typcial horn needs the incredible current of $I \approx 150.000$A (pulsed)

conventional neutrino beams
- focussing -

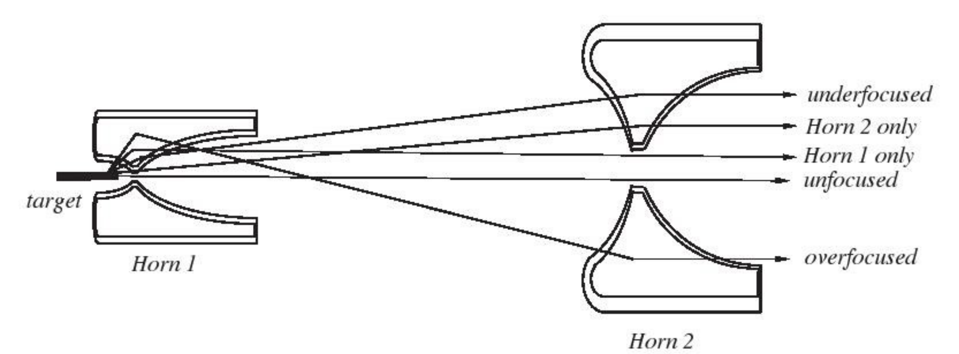
- one can use horn focal lenght f ~ p to vary the mean beam energy by adjusting the distance between target and horn, horn further downstream focusses higher momentum particles.



from: http://arxiv.org/abs/0708.1495v2, 2007

conventional neutrino beams
- focussing -

- but the target is not a point source and not all particles have the mean momentum, so many particles will end up under- or overfocused... additional horn(s) needed!



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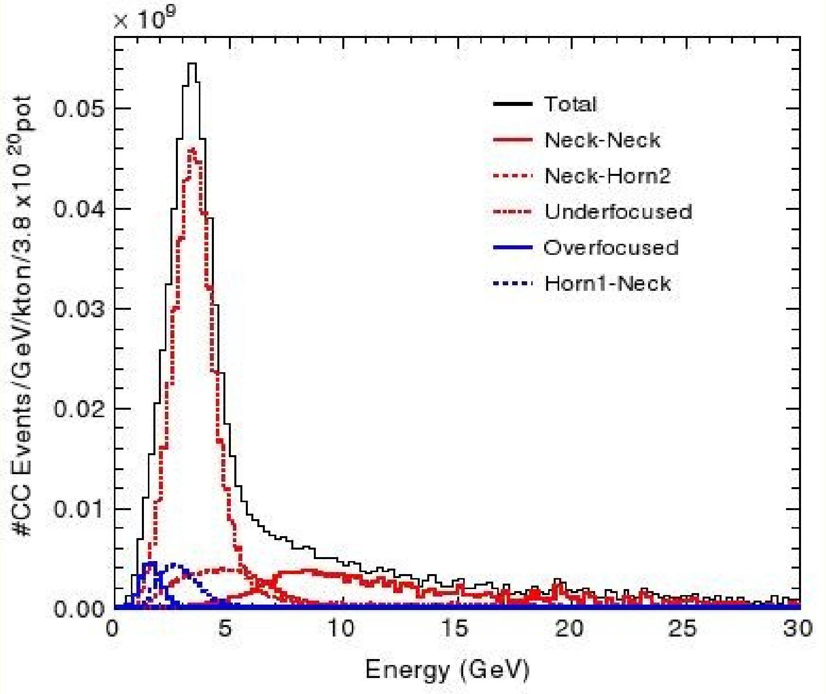
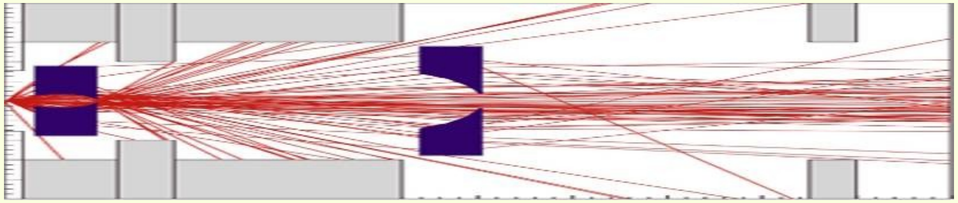
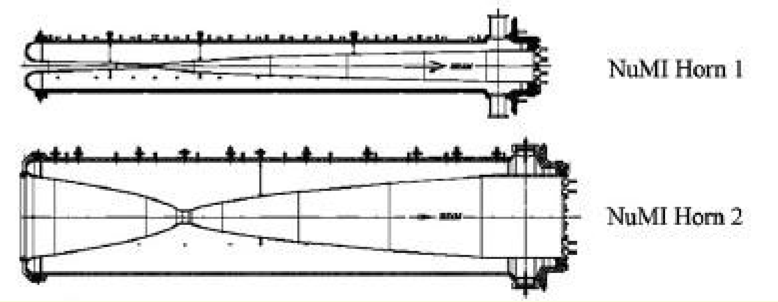
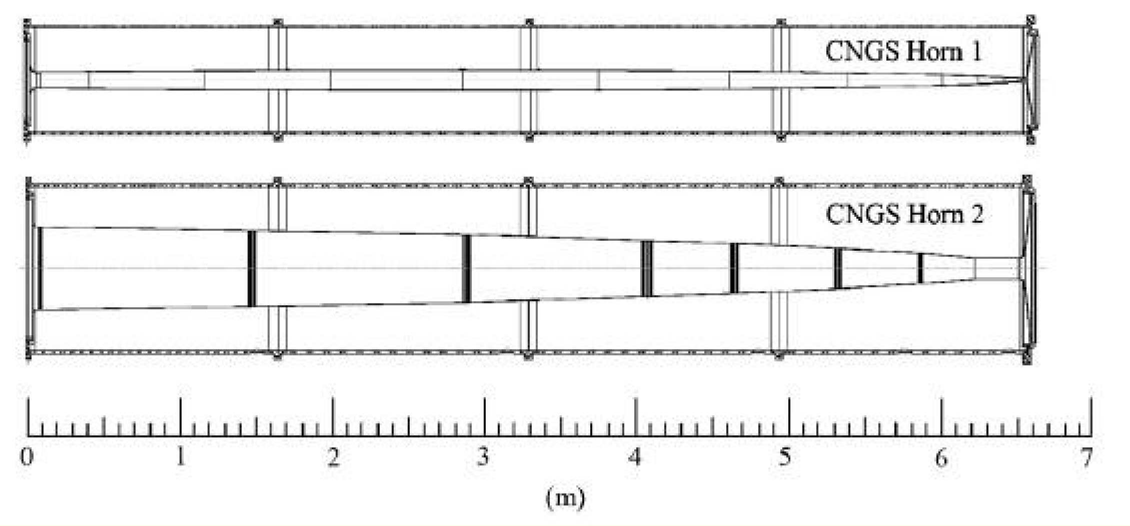




CNGS Beam, FLUKA 2000 simulation (from: CNGS workshop)

conventional neutrino beams
- focussing -





NuMI Horn 1

conventional neutrino beams
- focussing -

CNGS Horn 1

conventional neutrino beams

we need neutrinos from the secondaries:

decay pipe

conventional neutrino beams
- decay region -

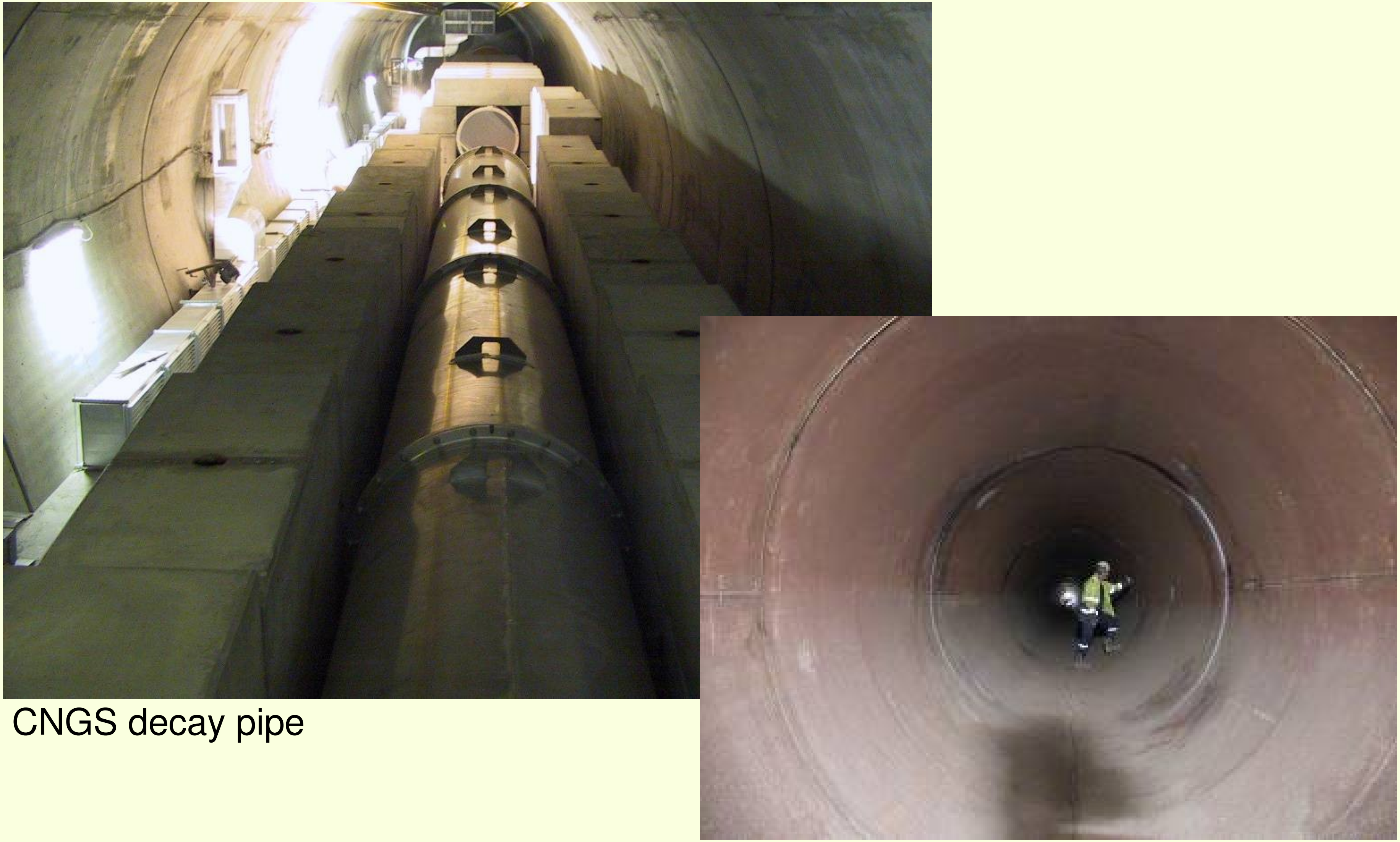
- after having the pions and kaons focussed, they decay into charged leptons and neutrinos
- reduce multi-scattering in decay pipe (vacuum, He)
- the longer the decay region, the more pions will decay (good!) but the more of the decay-daughter, mostly muons, will decay too – into electrons and electron neutrinos (bad!)
- y_π: pion lifetimes in decay pipe

$$y_\pi = \frac{L m_\pi c^2}{E_\pi c \tau_\pi}$$

neutrino beamline	experiments	pipe (m)	∅ [m]	y_π	filled
CNGS (SPS)	OPERA	1000	2.45	0.36	vacuum**
NuMI (Fermilab)	MINOS, NoνA	675	2	0.78*	He (NEW!)
J-PARC (KEK)	T2K	130	up to 5.4	0.43	He
BoosterNeutrino	MiniBooNe	50	1.8	0.36	air

* for NuMI medium energy configuration (10GeV)
**1mbar abs., 3mm Ti-window

conventional neutrino beams
- decay region -



CNGS decay pipe

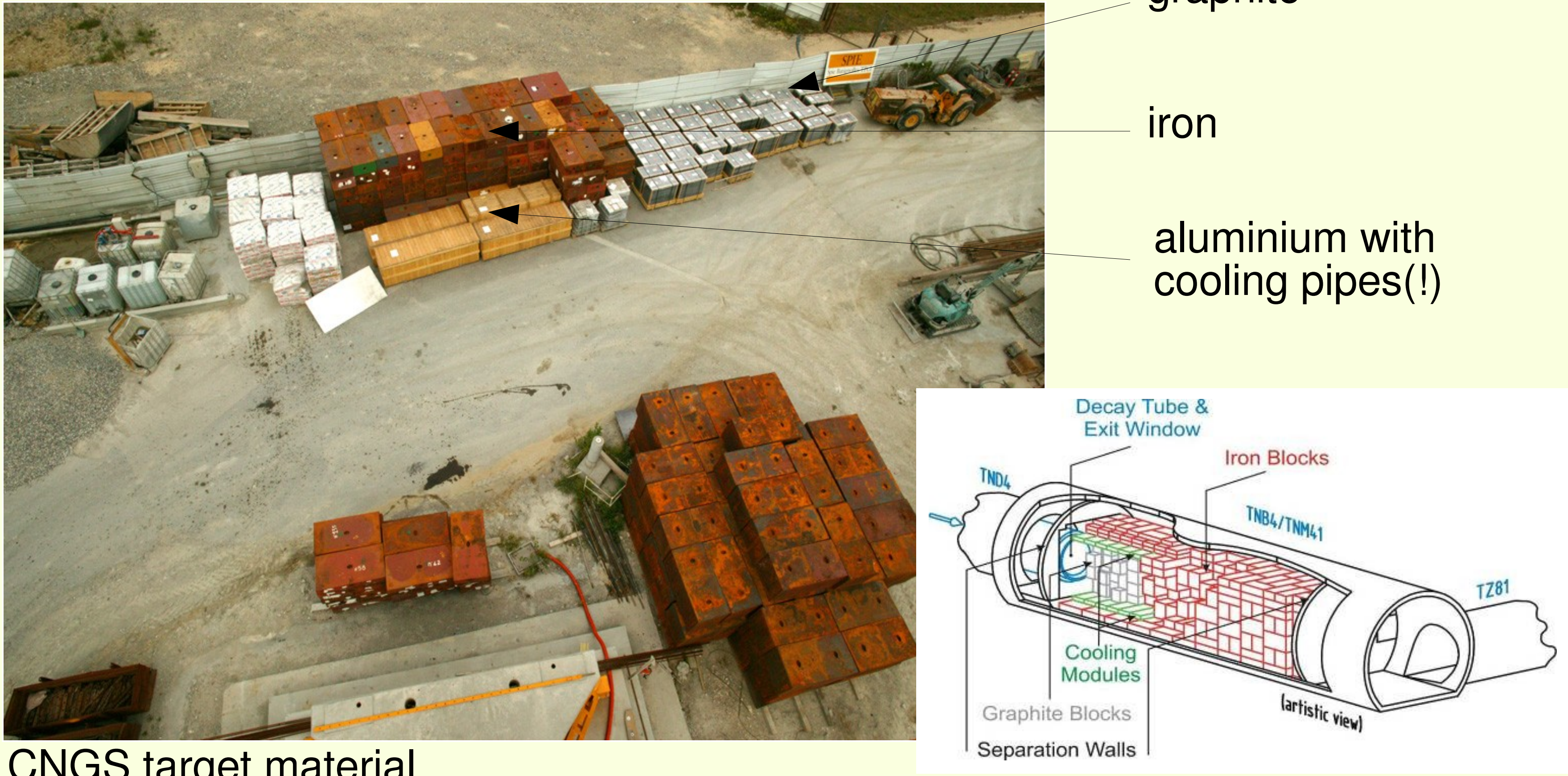
conventional neutrino beams

but not all pions will decay:

hadron stop

conventional neutrino beams
- hadron stop -

- many protons remain without interaction – you have to absorb them (and the undecayed secondary hadrons) before it comes to beam monitoring...


graphite

iron

aluminium with
cooling pipes(!)

CNGS target material

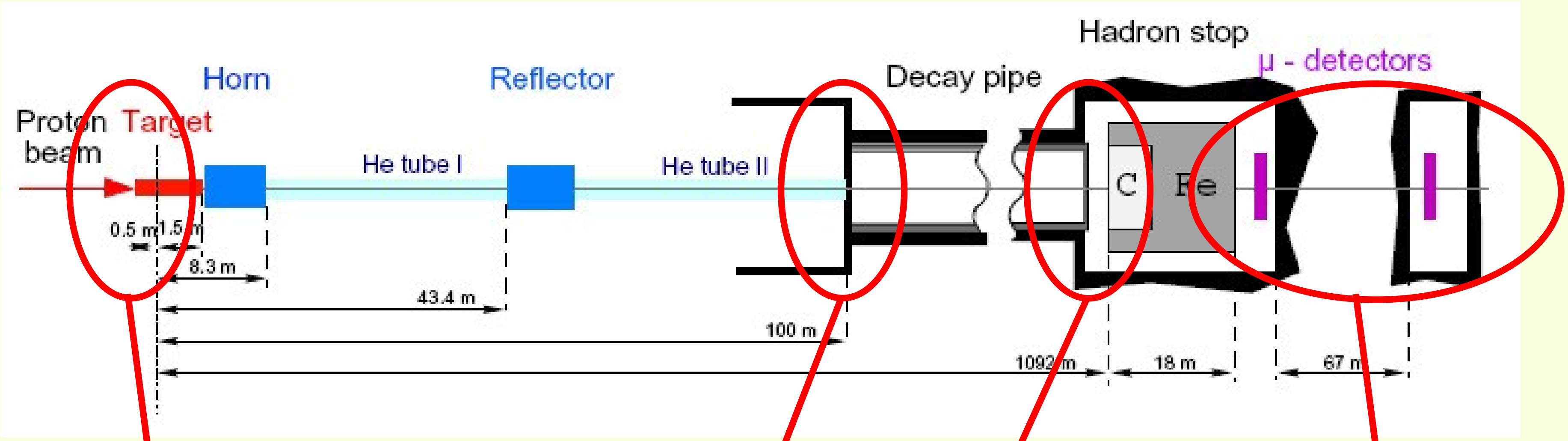
conventional neutrino beams

see what we got:

beam monitoring

conventional neutrino beams
- beam monitoring -

- remember you dump O(100GeV) protons bunches on solid targets to produce pion beams... monitoring needed!



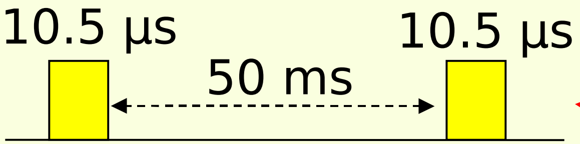
secondaries monitoring
- beam misalignement
- proton conversion ratio
- K/π ratio

proton monitoring
- intensity per pulse
- spot position
- spot size
- angle

muon monitoring
- flux measurement (muon flux related to neutrino flux)

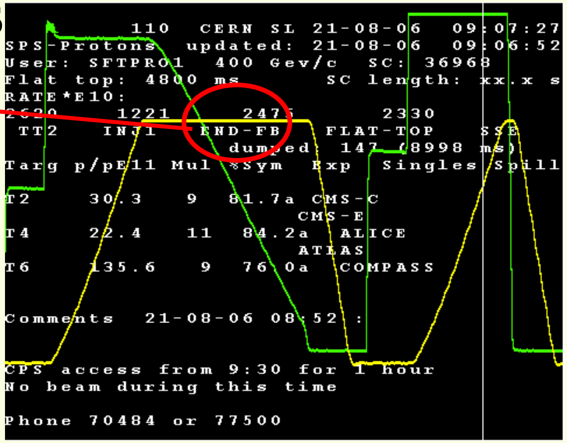
hadron monitoring
- proton alignment
- target monitoring

conventional neutrino beams
- proton monitoring -

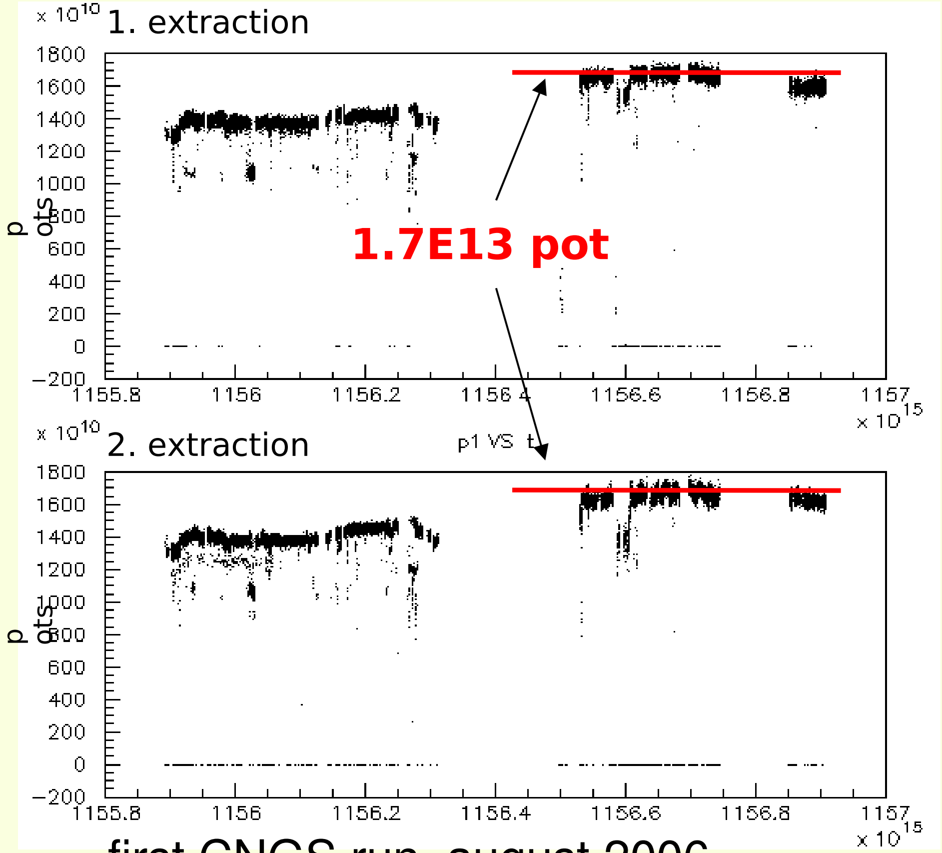


2 extractions per SPS cycle (~17s)

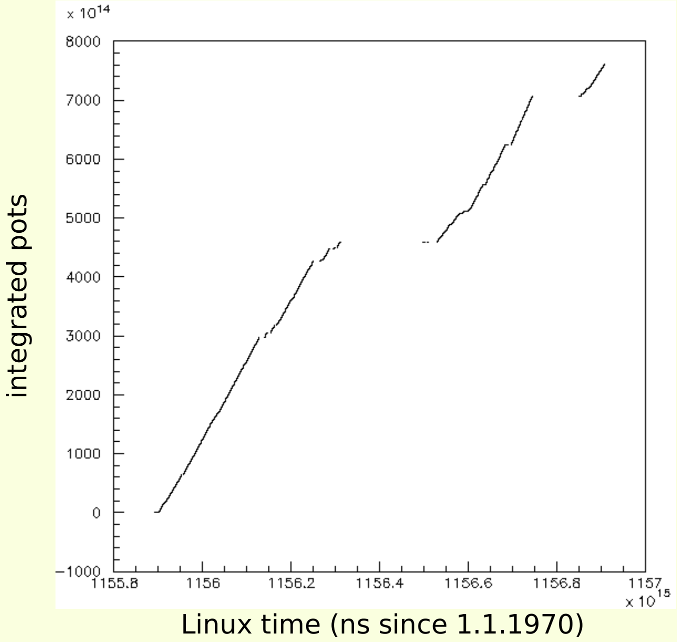
SPS



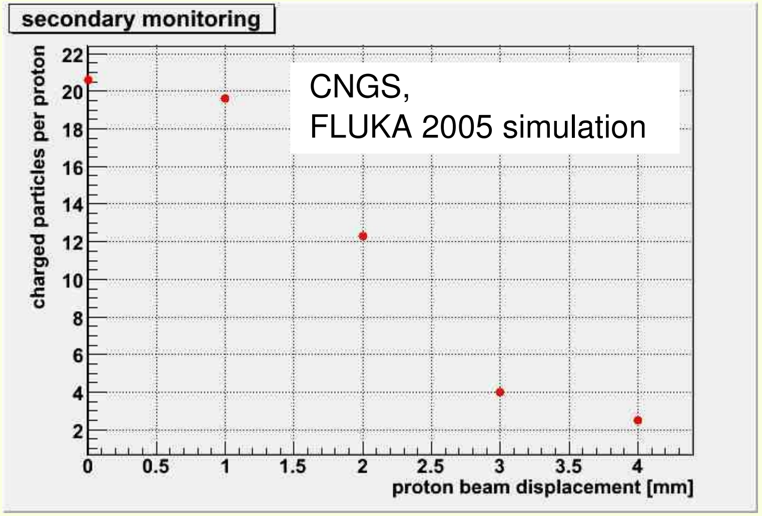
```
       110   CERN SL 21-08-06   09:07:27
SPS-Protons  updated: 21-08-06   09:06:52
User: SFTPRO1  400 Gev/c   SC: 36968
Flat top: 4800 ms        SC length: xx.x s
RATE*E10:
2620     1221      2475        2330
 TT2     INJ1    END-FB    FLAT-TOP    SSE
              dumped: 147 (8998 ms)
Targ p/pE11 Mul  %Sym  Exp  Singles Spill

T2     30.3   9   81.7a CMS-C
                        CMS-E
T4     22.4   11   84.2a  ALICE
                        ATLAS
T6    135.6    9   76.0a  COMPASS


Comments  21-08-06 08:52 :


CPS access from 9:30 for 1 hour
No beam during this time

Phone 70484 or 77500
```



first CNGS run, august 2006

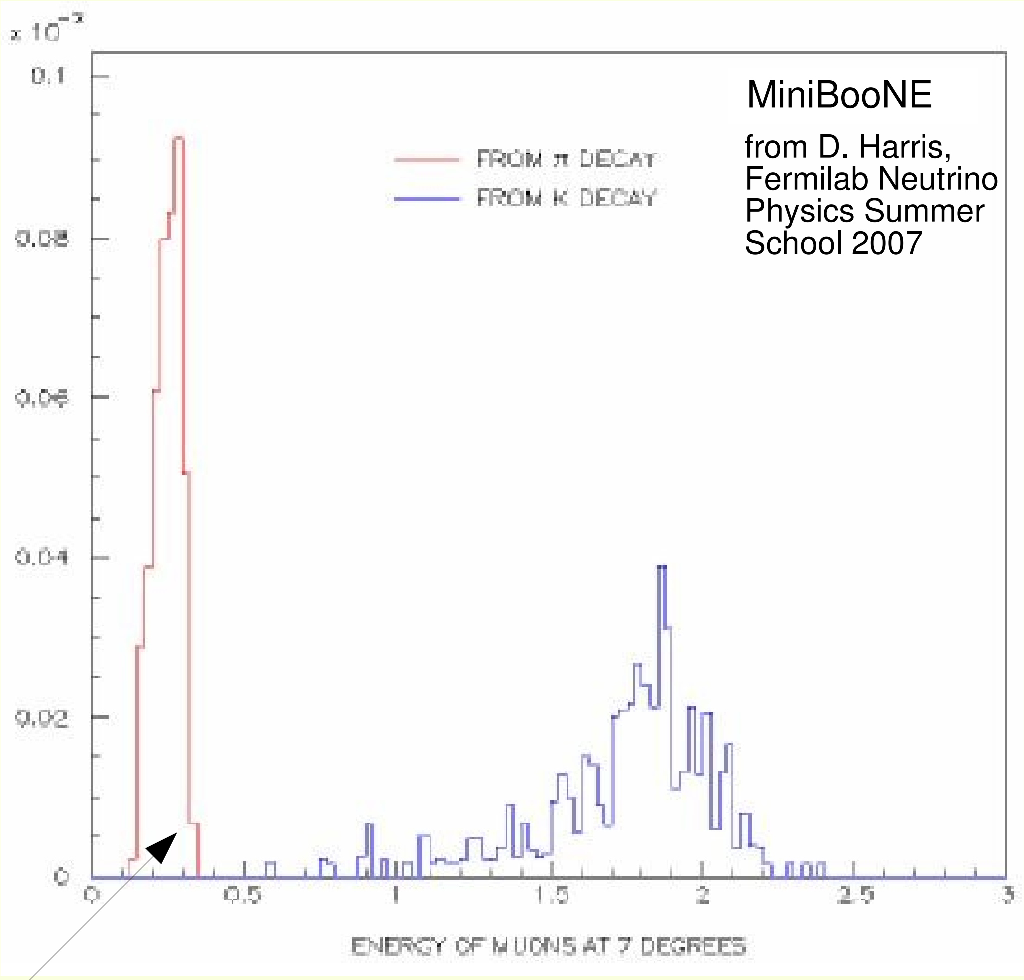


conventional neutrino beams
- secondary monitoring -



CNGS,
FLUKA 2005 simulation

data from A. Geschwendtner, CERN, 2006



MiniBooNE

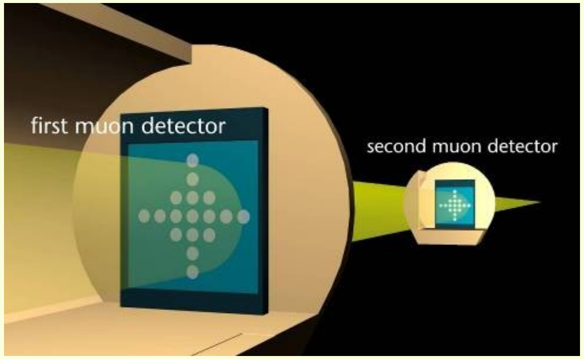
from D. Harris,
Fermilab Neutrino
Physics Summer
School 2007

MiniBooNe-spectrometer 7° off-axis in beamline:

- most pions have too high energy to produce a 7° muon

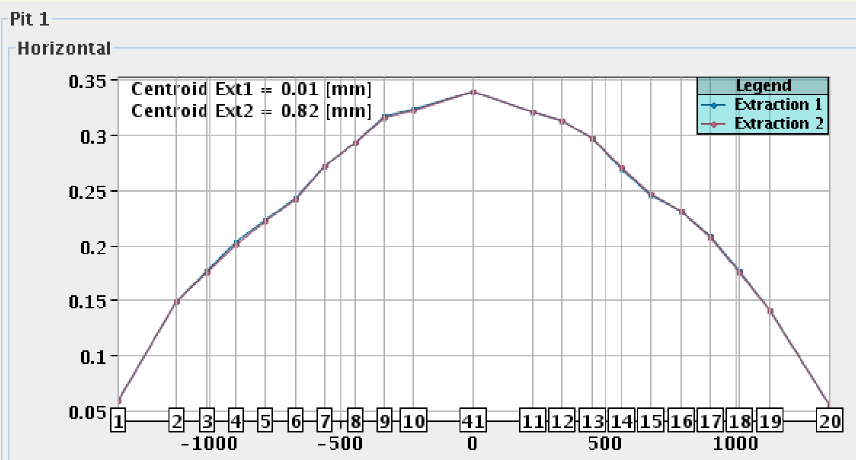
- very low energy pions decay upstream early

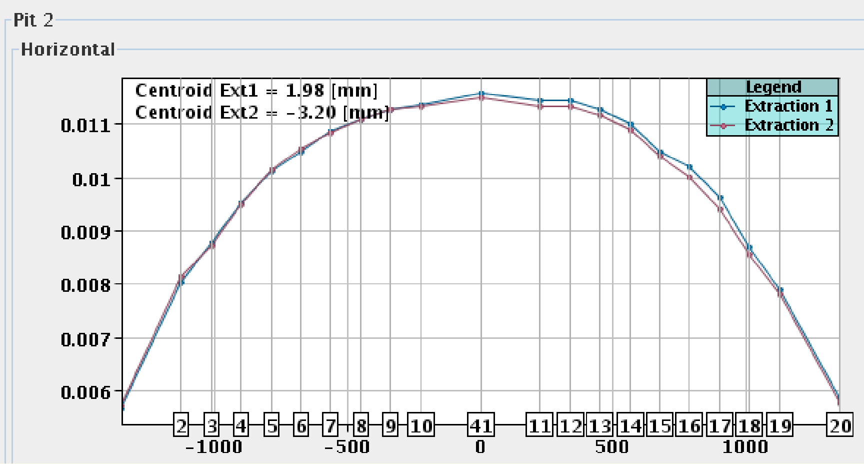
conventional neutrino beams - muon monitoring -



CNGS crosshair muon monitor

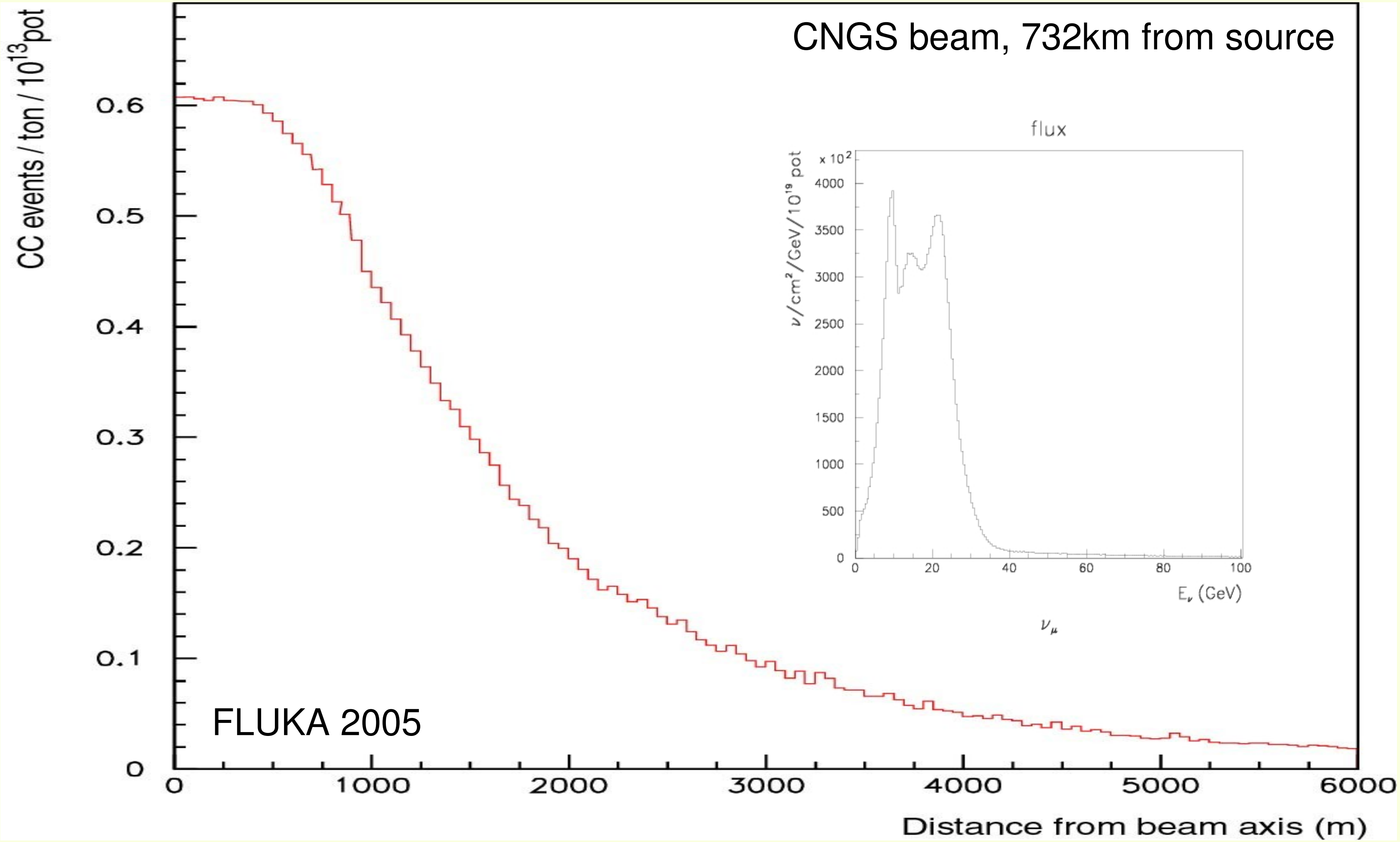
- measure muon intensity $\left(10^7 \frac{1}{cm^2\, 10.5\,\mu s}\right)$





data from 2007 CNGS physics run (ended oct. 26th. 2007)

conventional neutrino beams
- beamspread -



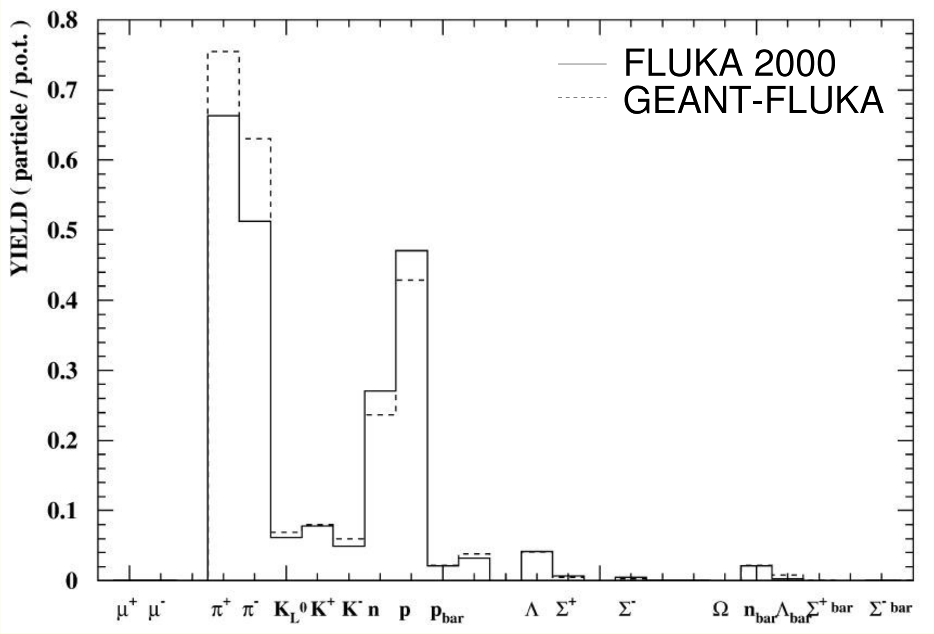
conventional neutrino beams

we only want pure muon-neutrinos:

beam contamination

conventional neutrino beams
- contamination -

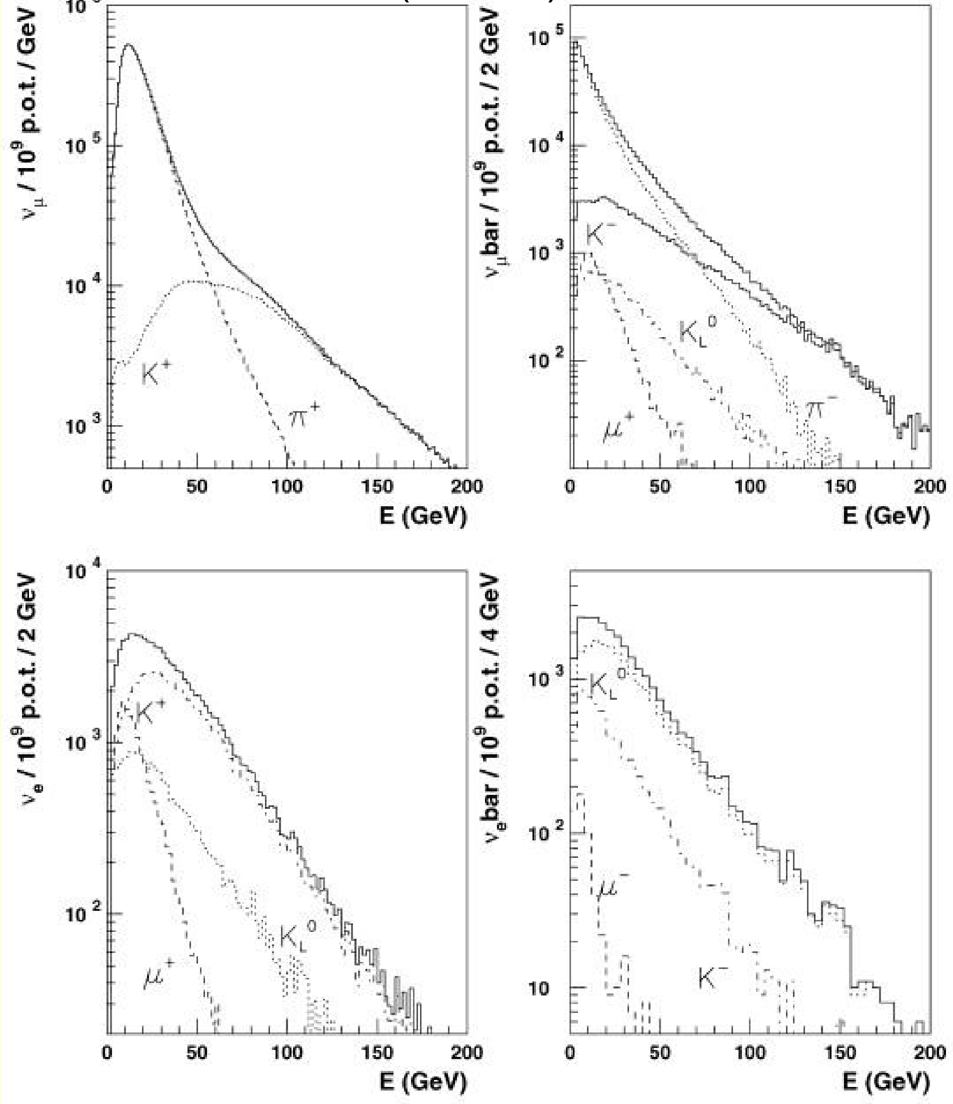
- unfortunately, there are not only ν_μ in the beams...
- large number of dedicated hadron production experiments:
  - NA56/SPY: SPS protons on Be-targets
  - HARP: low energy (up to 15GeV)
  - WANF neutrinos with experiments NOMAD and CHORUS



from: G. Collazuol et al., NIM A, 1999

conventional neutrino beams
- contamination -

WANF beam (CERN)



from: G. Collazuol et al., NIM A, 1999

CNGS beam

	beam content
ν_μ	100
anti-ν_μ	2.1
ν_e	0.8
anti-ν_e	0.07
ν_τ	~10^{-5}

a typical neutrino experiment:

MINOS

in 5 minutes...

MINOS

Main Injector Neutrino Oscillation Search

- NuMI ν_μ-beam
- 2 detectors (near and far)
  - near: 1km away
    - beam composition
    - energy spectrum
  - far: 735km away
    - neutrino oscillation

MINOS

physics with **MINOS** – or with two detectors in a ν_μ-beam

- ν_μ-disappearance

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2(2\theta_{23}) \sin^2\left(\frac{1.27(\Delta m^2_{23})L}{E_\nu}\right)$$

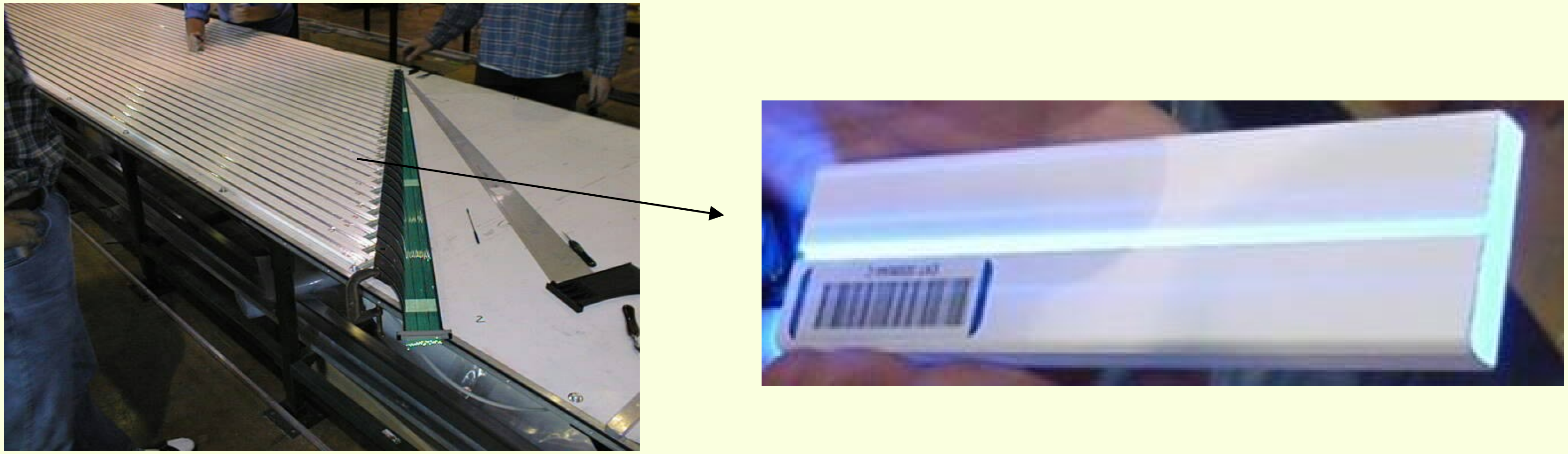
- ν_e-appearance

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2(2\theta_{23}) \sin^2(2\theta_{13}) \sin^2\left(\frac{1.27(\Delta m^2_{13})L}{E_\nu}\right)$$

- atmospheric neutrinos (beam independent)
- sterile neutrinos (NC rate in far detector)
- CPT violation (anti-ν_μ-beam)

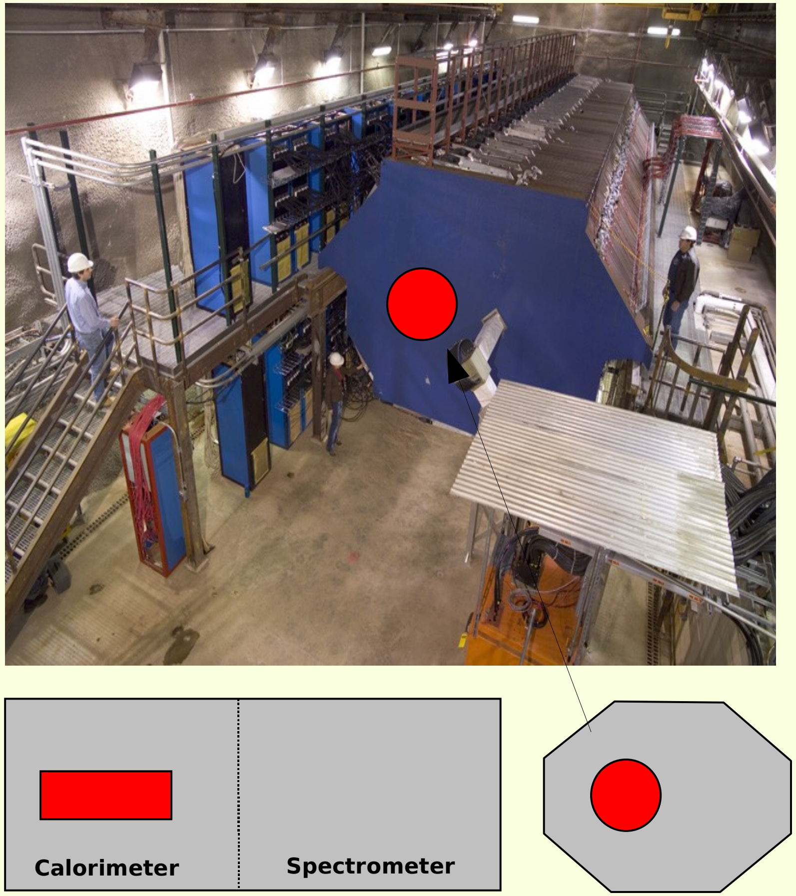
MINOS

- to reduce systematics: build to „identical“ detectors, a near one to monitor the beam (high rate), a far one to see the oscillation
- lack of money: „identical“ becomes „similar“
- both, **MINOS Near** and **MINOS Far** are steel/scintillator tracking calorimeters
  - magnetized (1.2T) 2.54cm thick iron plates
  - 800x4x1 cm plastic-scintillators



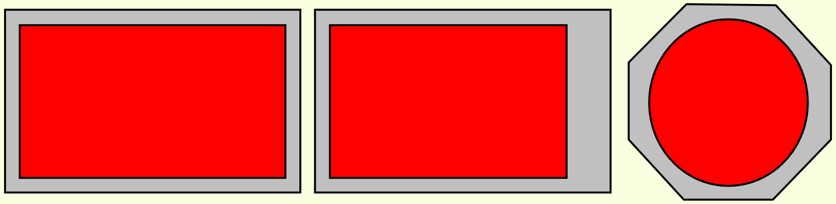
MINOS - detector

MINOS near detector



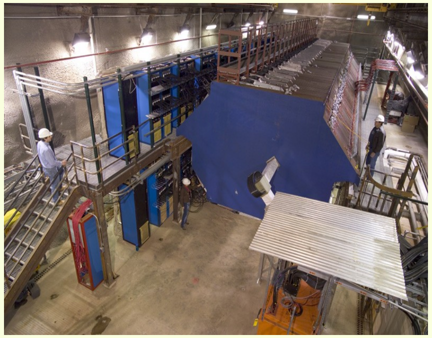
Fiducial Volume

MINOS far detector

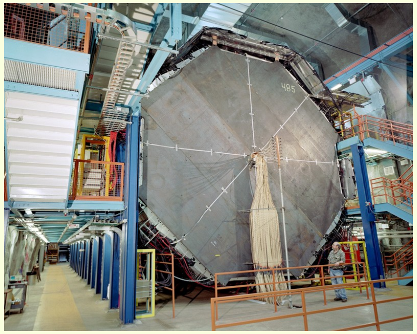


🟥 **Fiducial Volume**

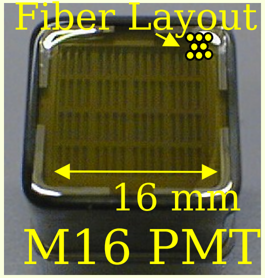
MINOS - detector



- 103m underground
- 0.9kt iron, 4x5x15m
- 282 steel, 153 scintillator planes
- 4x multiplexing behind plane 120
- Fast QIE[1] electronics (high rate, multi-neutrino events per spill)



- 705m underground (2100m W.E.)
- 5.4kt iron, 8x8x30m
- 484 steel/scintillator planes
- 8x multiplexing („bad“ multi-myon reco.)
- Slow electronics: preamplifier, shaper, sample-holder…

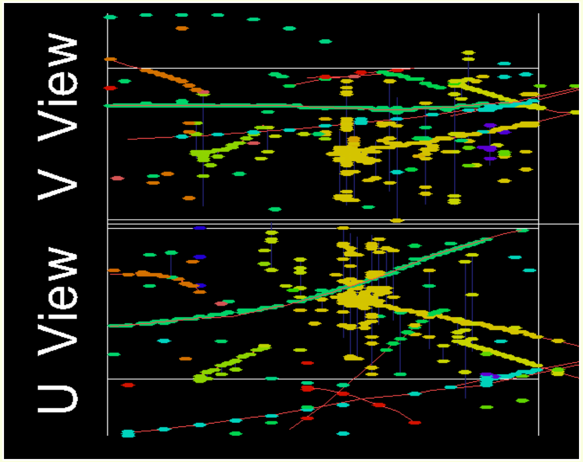


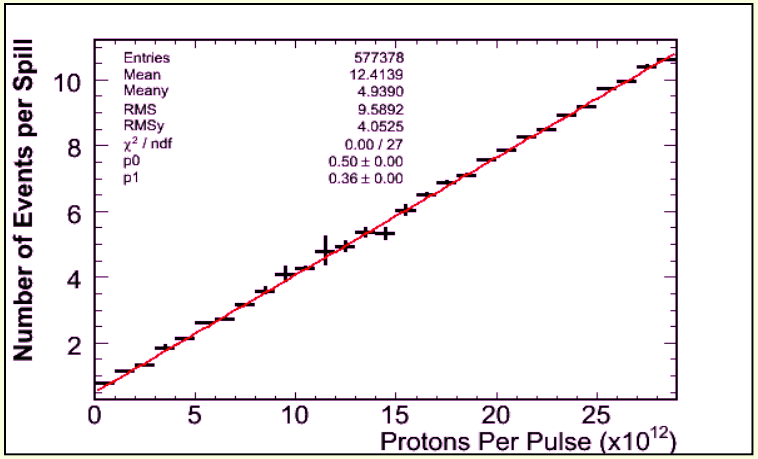
- alternate planes rotated by 90° (U: horizontal, V: vertical)
- both side readout, multipixel M16/M64 PMs, de-multiplexing
- GPS timestamp for FD/ND/Beam synchronisation and trigger
- continous untriggered readout during spill
- interspersed light injection system for calibration

1) QIE: charge (Q) to current (I) encoder

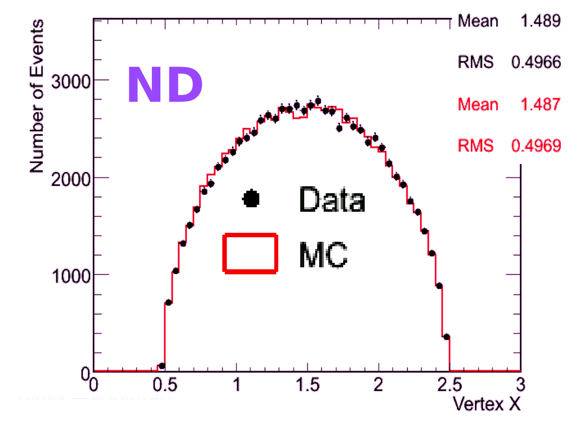
MINOS - detector

typical events(!) in MINOS near detector

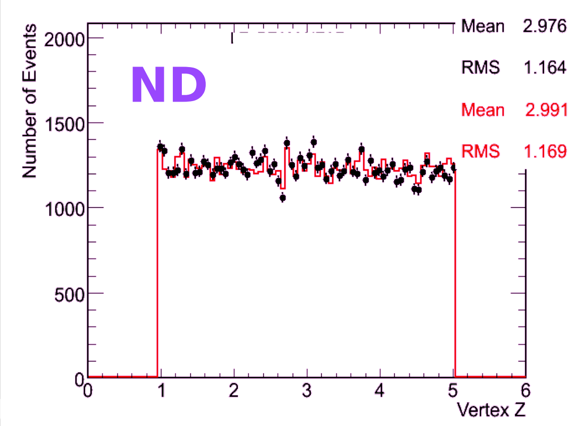




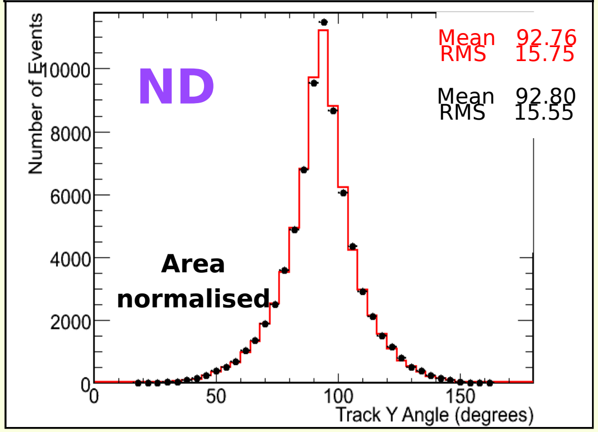
X Vertex



Z Vertex



Track Angle



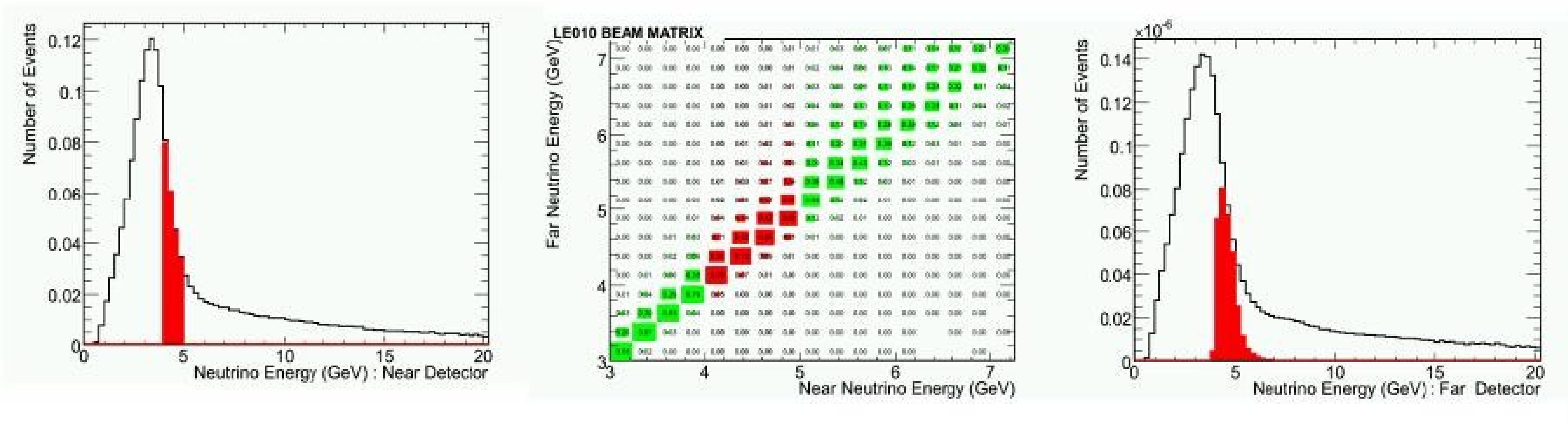
from: J. Nelson, Talk at Neutrino 2006, 2006

MINOS

- the aim (for alle 2-detector experiments):

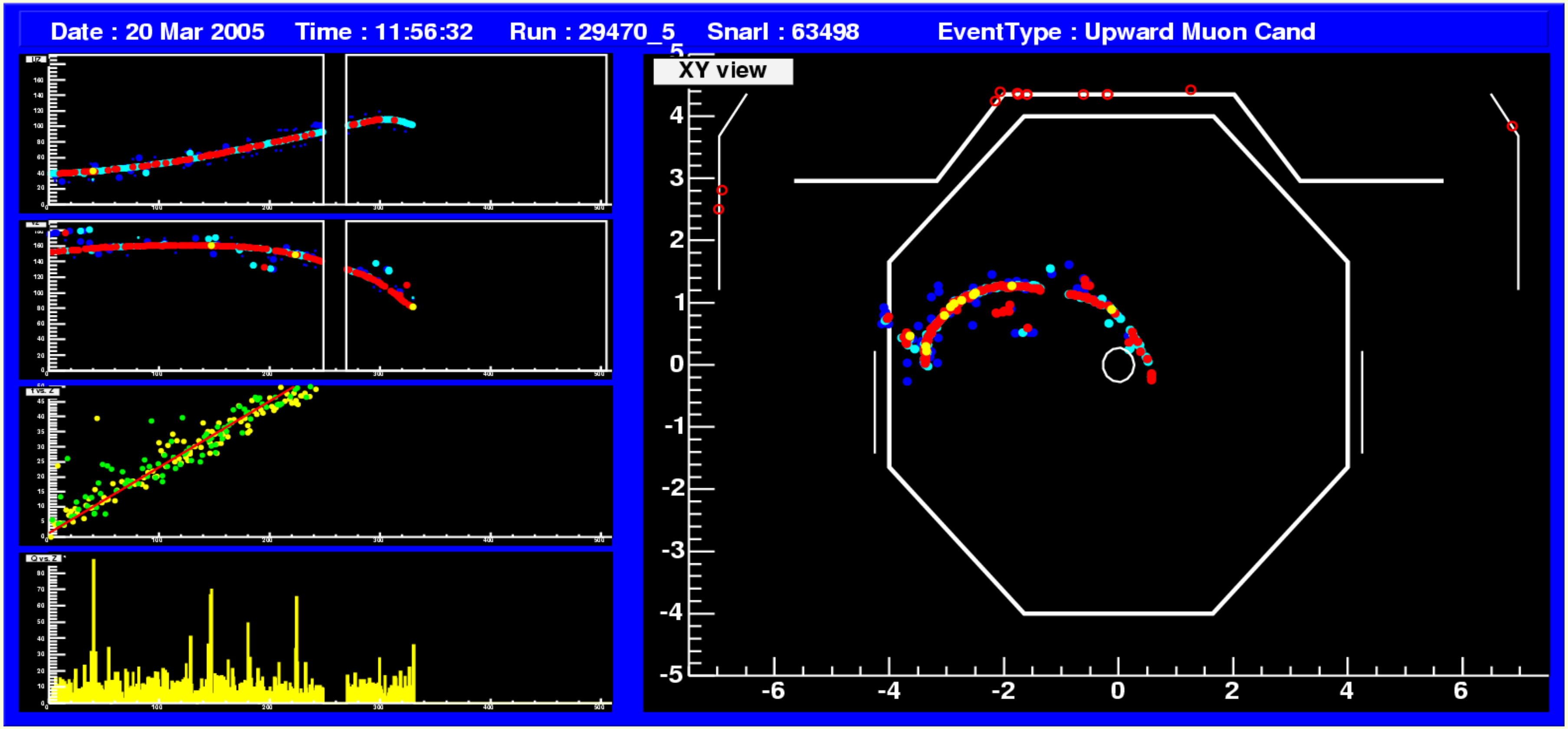
predict the unoscillated neutrino spectrum in the far detector from the near detector data...

MINOS uses a „beam matrix method“:
encode decay kinematics and beamline geometry to a matrix to transform ND energy spectrum to FD energy spectrum



MINOS - detector

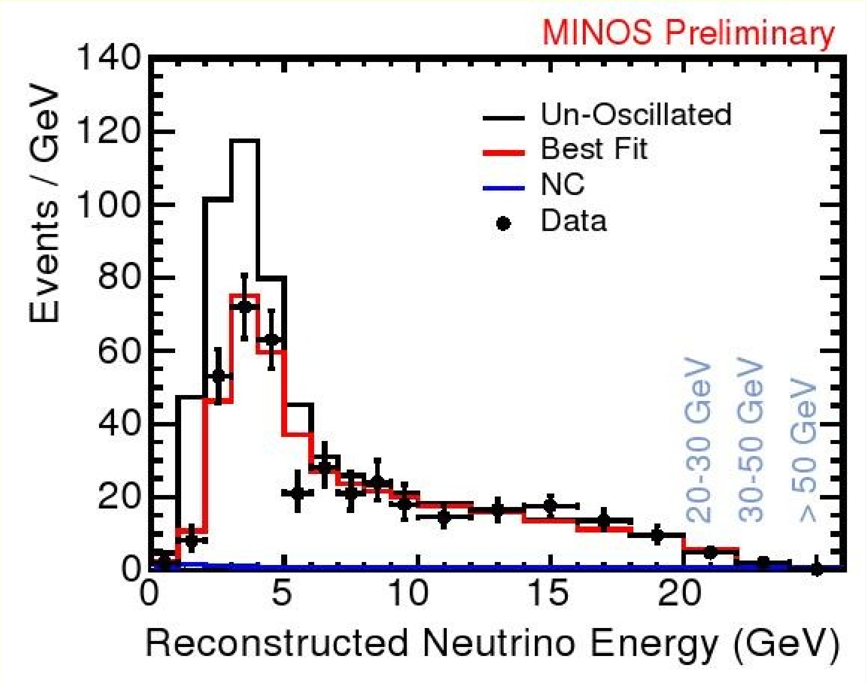
first event in MINOS far detector

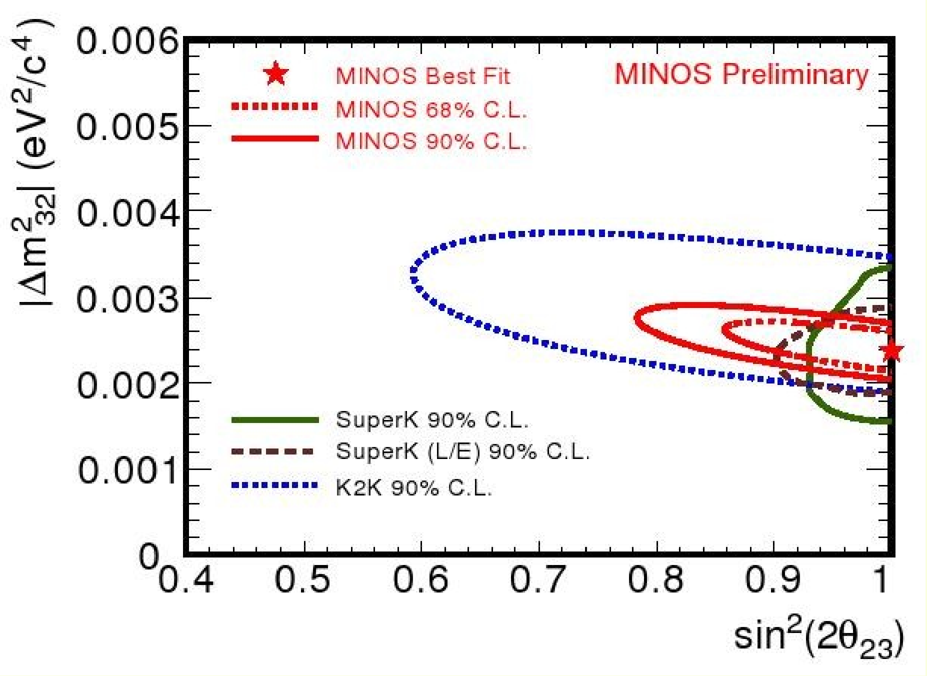


Date : 20 Mar 2005 Time : 11:56:32 Run : 29470_5 Snarl : 63498 EventType : Upward Muon Cand

MINOS

preliminary result from $2.50*10^{20}$ pot





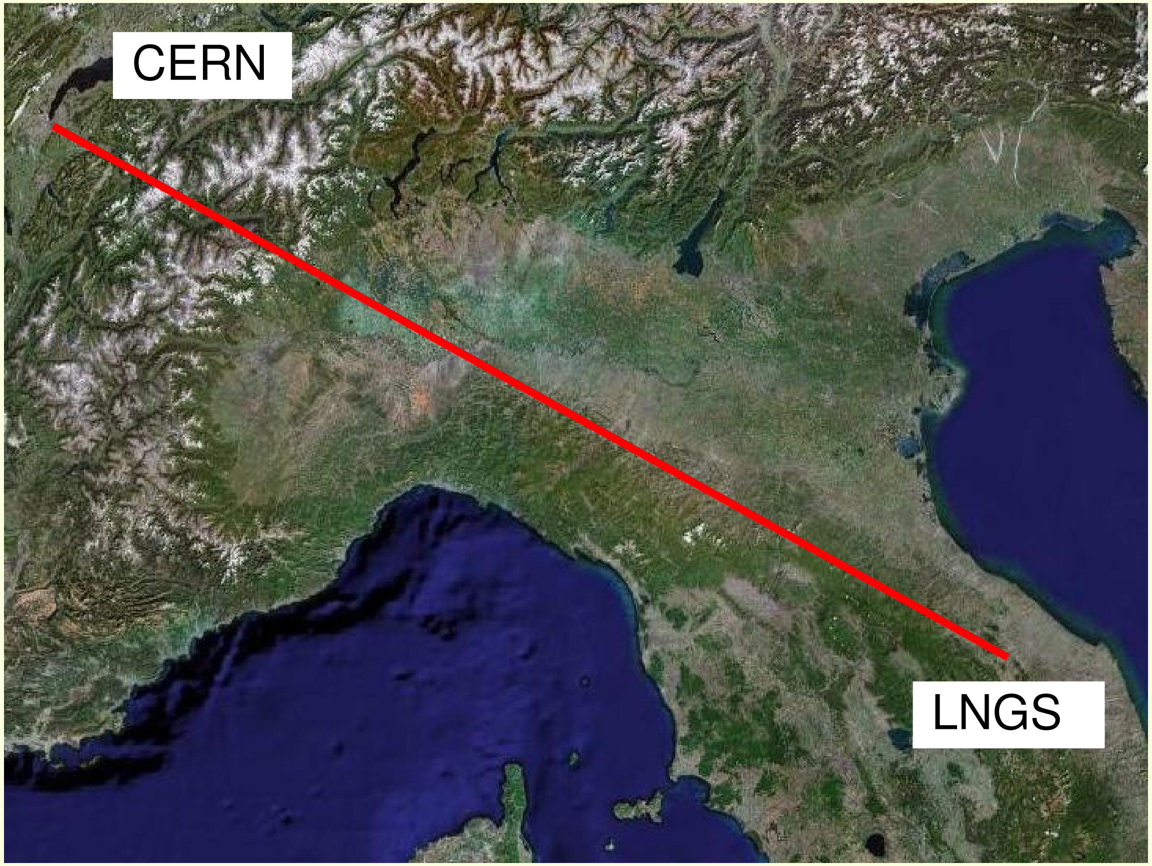
from: http://arxiv.org/abs/0708.1495v2, 2007 a not so typical neutrino experiment:

OPERA

in 5 minutes...

OPERA

Oscillation Project With Emulsion Tracking Apparatus



- CNGS ν_μ-beam (high energy)
- 1 detector
    - far: 732km away
        - neutrino oscillation
        - tau detection

OPERA

physics with **OPERA** – or with a specialised detector

- ν_τ-appearance, CNGS beam above τ-threshhold

$$P(\nu_\mu \rightarrow \nu_\tau) \approx \sin^2(2\theta_{23}) \sin^2\left(\frac{1.27(\Delta m_{23}^2)L}{E_\nu}\right)$$

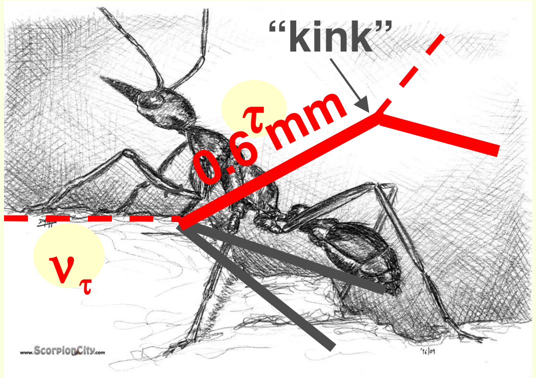
- ν_e-appearance

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2(2\theta_{23}) \sin^2(2\theta_{13}) \sin^2\left(\frac{1.27(\Delta m_{13}^2)L}{E_\nu}\right)$$

- atmospheric neutrinos (beam independent)
- sterile neutrinos (NC rate in far detector)
- rare events: muon emission from nuclei...

OPERA

- to observe τ-leptons from ν_τ-CC: spatial resolution ~10 µm



- low eventrate: need high target mass (about 2000 tons)
- only affordable detection principle that combines that:

  Emulsion Cloud Chamber (ECC): lead-emulsion-sandwich

  \- high spatial resolution due to photo-emulsion

  \- high mass due to interspaced lead layers

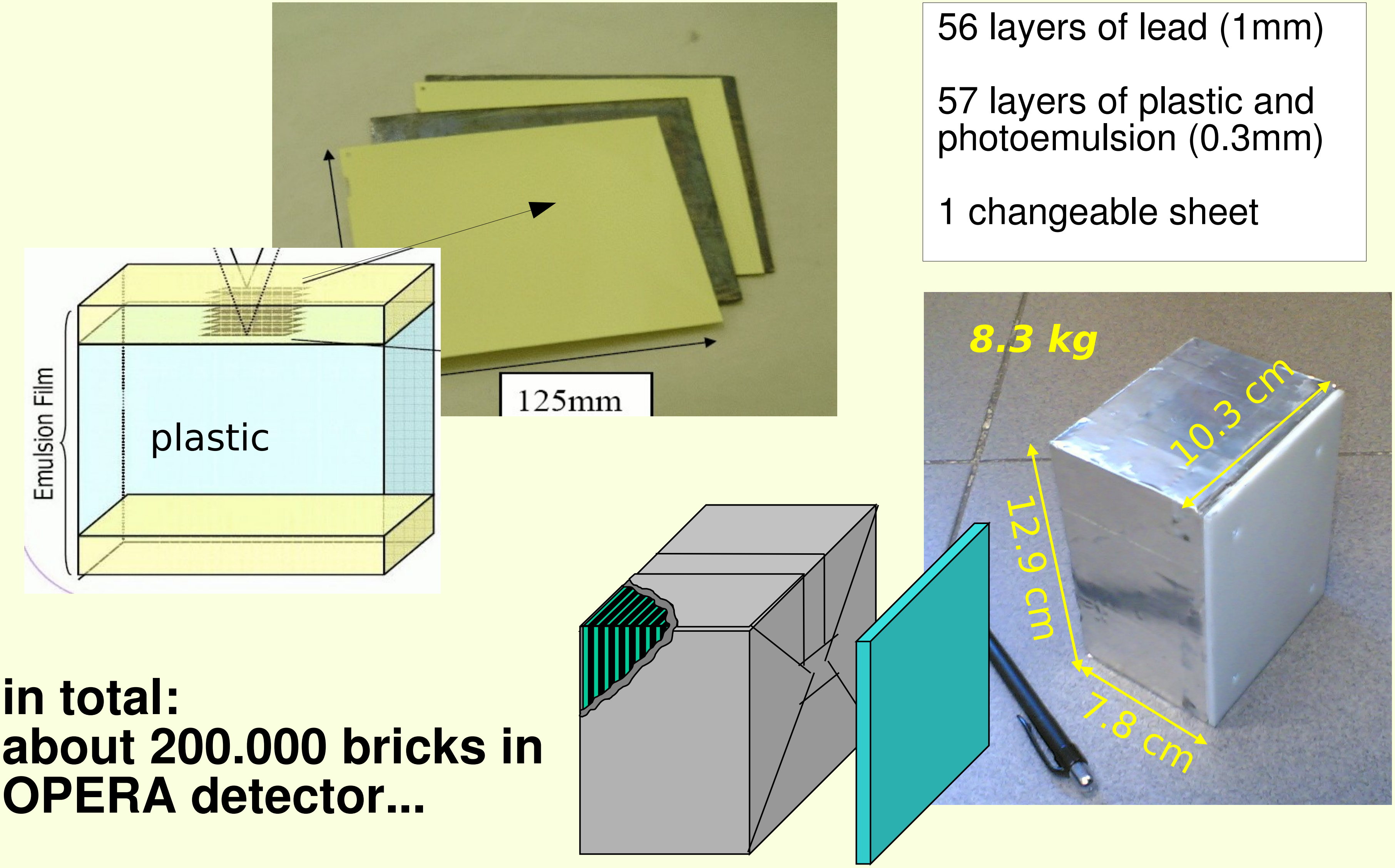
  But: ECC are passive – **need electronic detectors** for triggering, spectrometer, bgd. reduction...

OPERA – ECC principle

56 layers of lead (1mm)

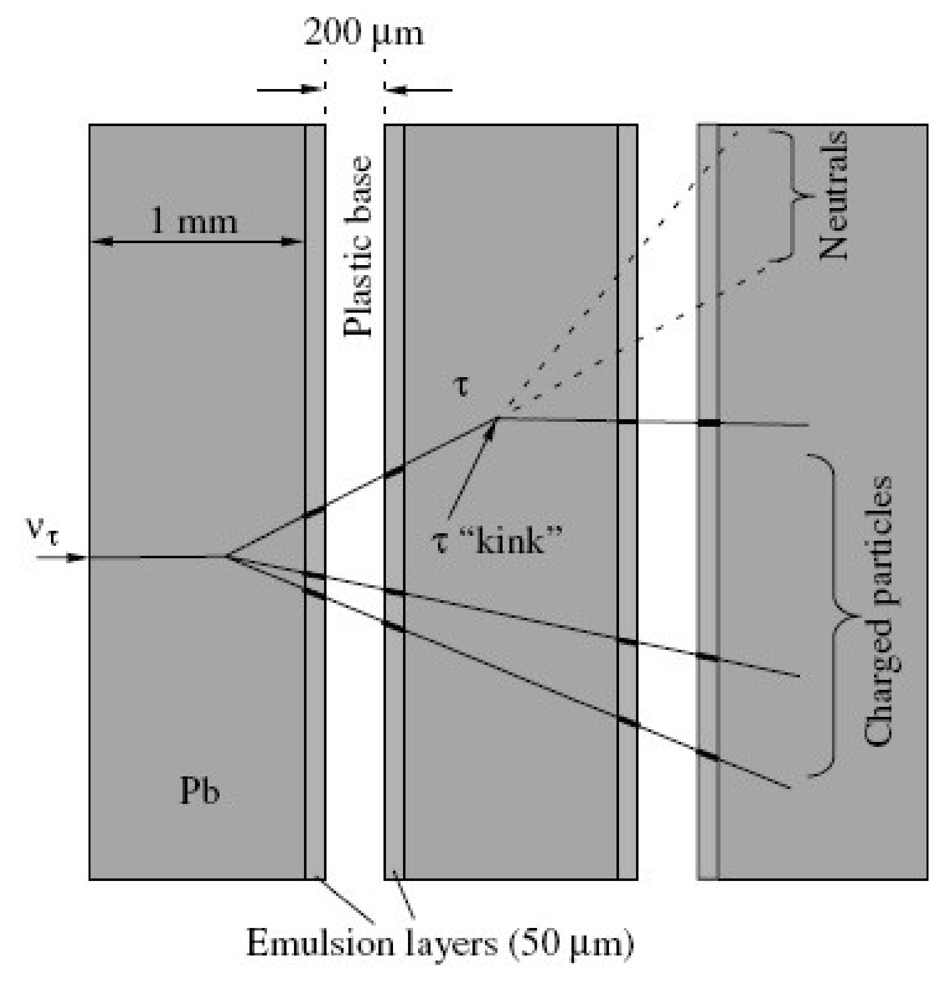
57 layers of plastic and photoemulsion (0.3mm)

1 changeable sheet

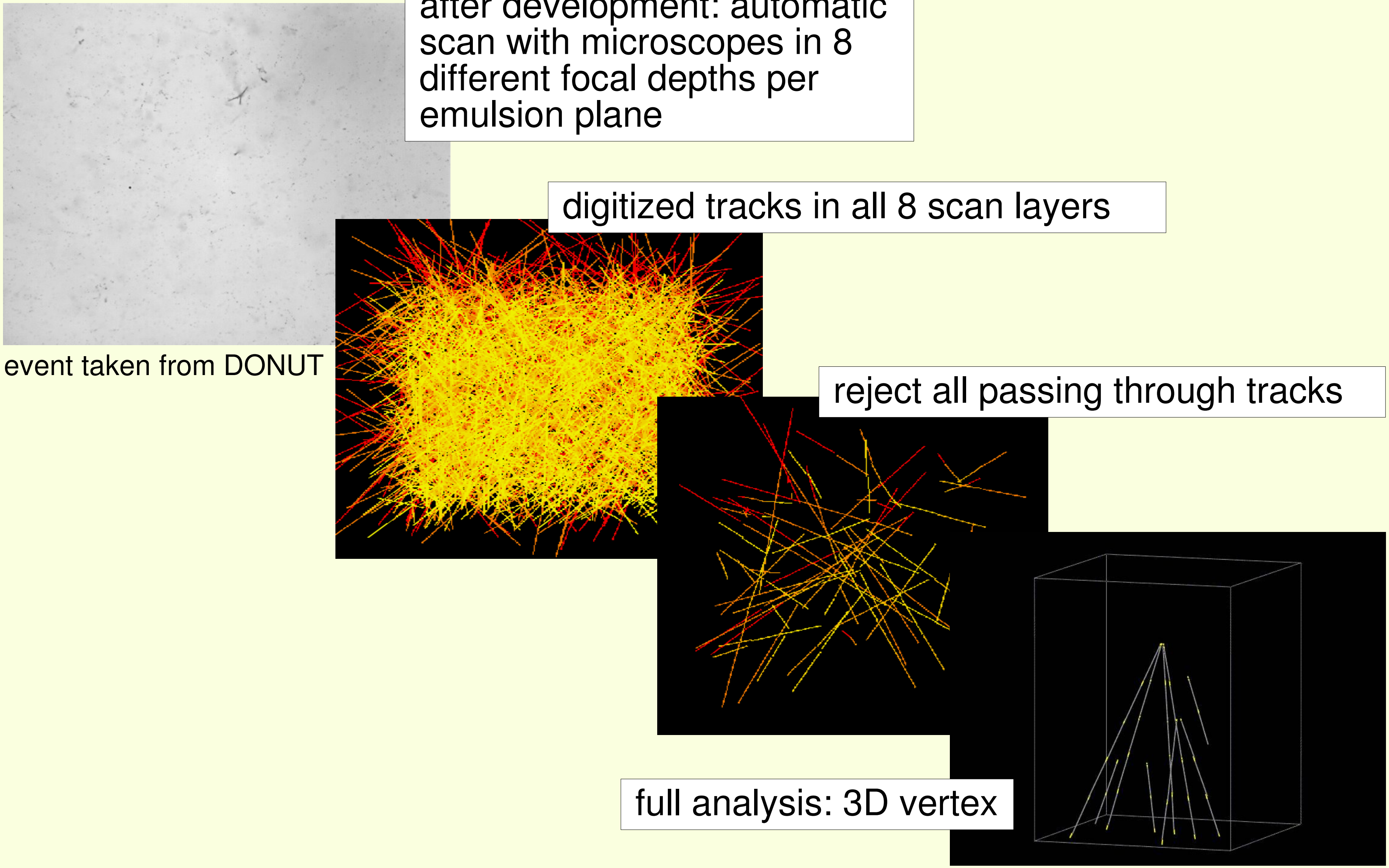


in total:
about 200.000 bricks in OPERA detector...

OPERA – ECC principle



OPERA



after development: automatic scan with microscopes in 8 different focal depths per emulsion plane

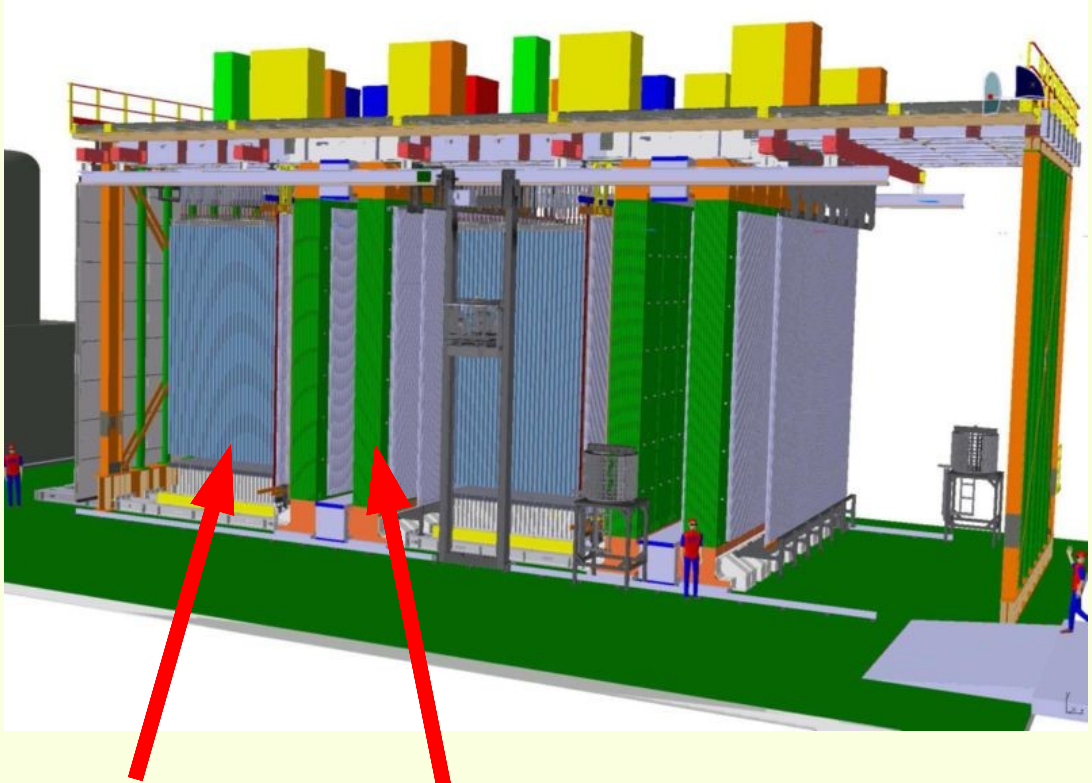
event taken from DONUT

digitized tracks in all 8 scan layers

reject all passing through tracks

full analysis: 3D vertex

OPERA



target section with electronic target tracker

spectrometer: Magnet, HPT, RPC, XPC

located in LNGS, italy:

shielding of 1400 m rock (3300m water equivalent)

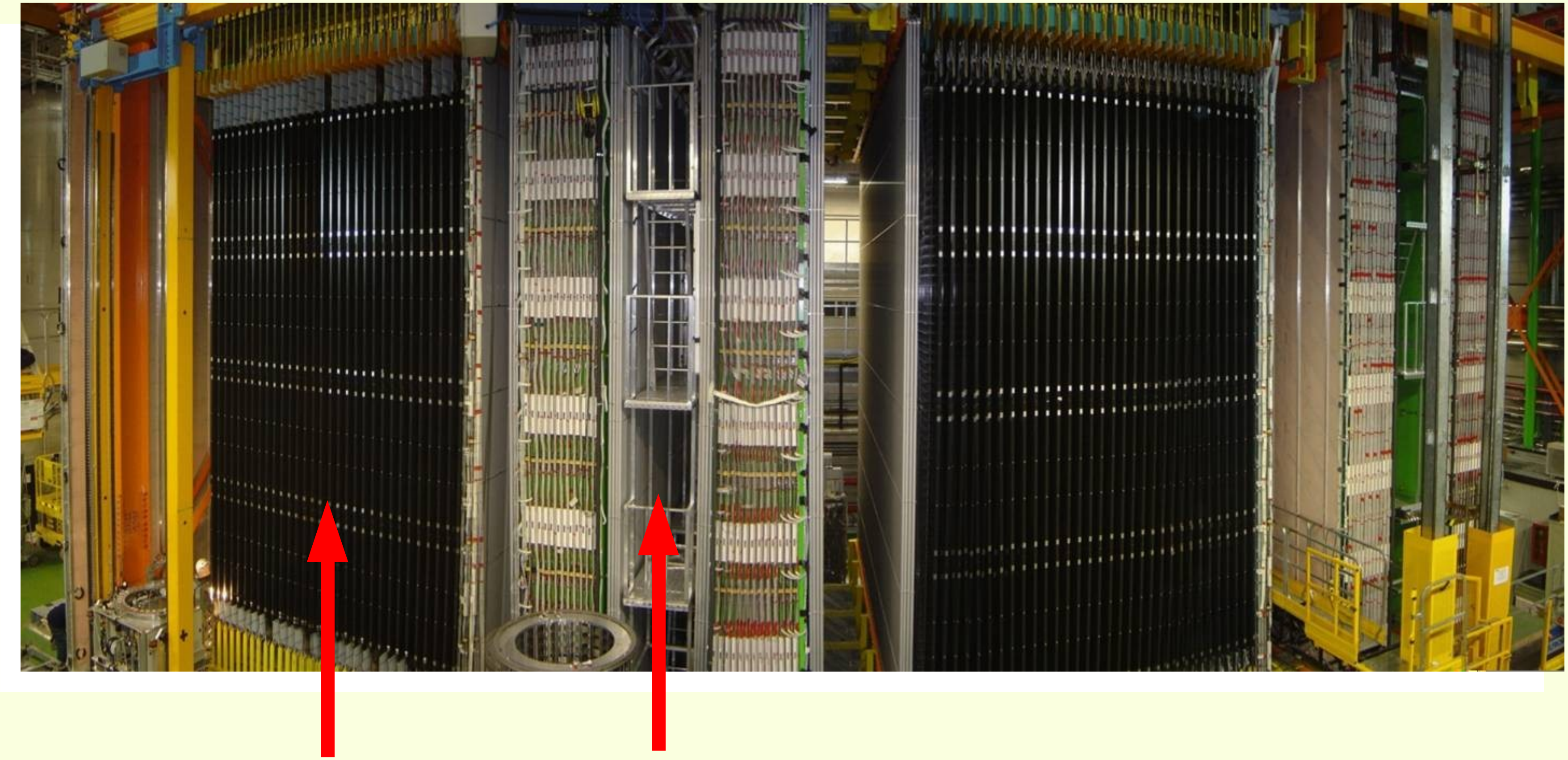
weight: about 2000 tons target, 5000 tons total

size: 20x9x9m

hybrid-detector:

- ECC for tau vertex
- 2 large spectrometers with 1.5T magnet field

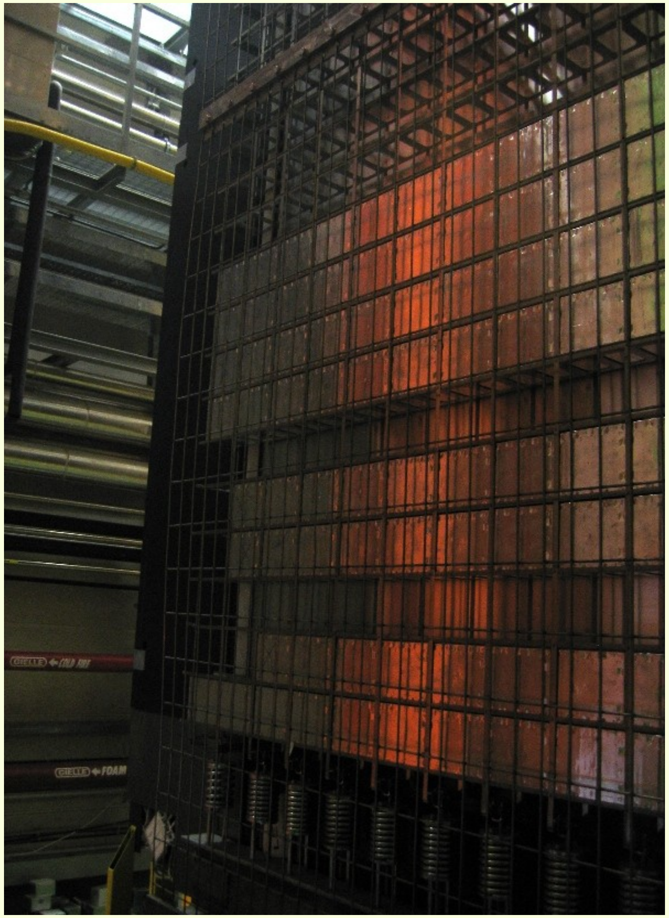
OPERA

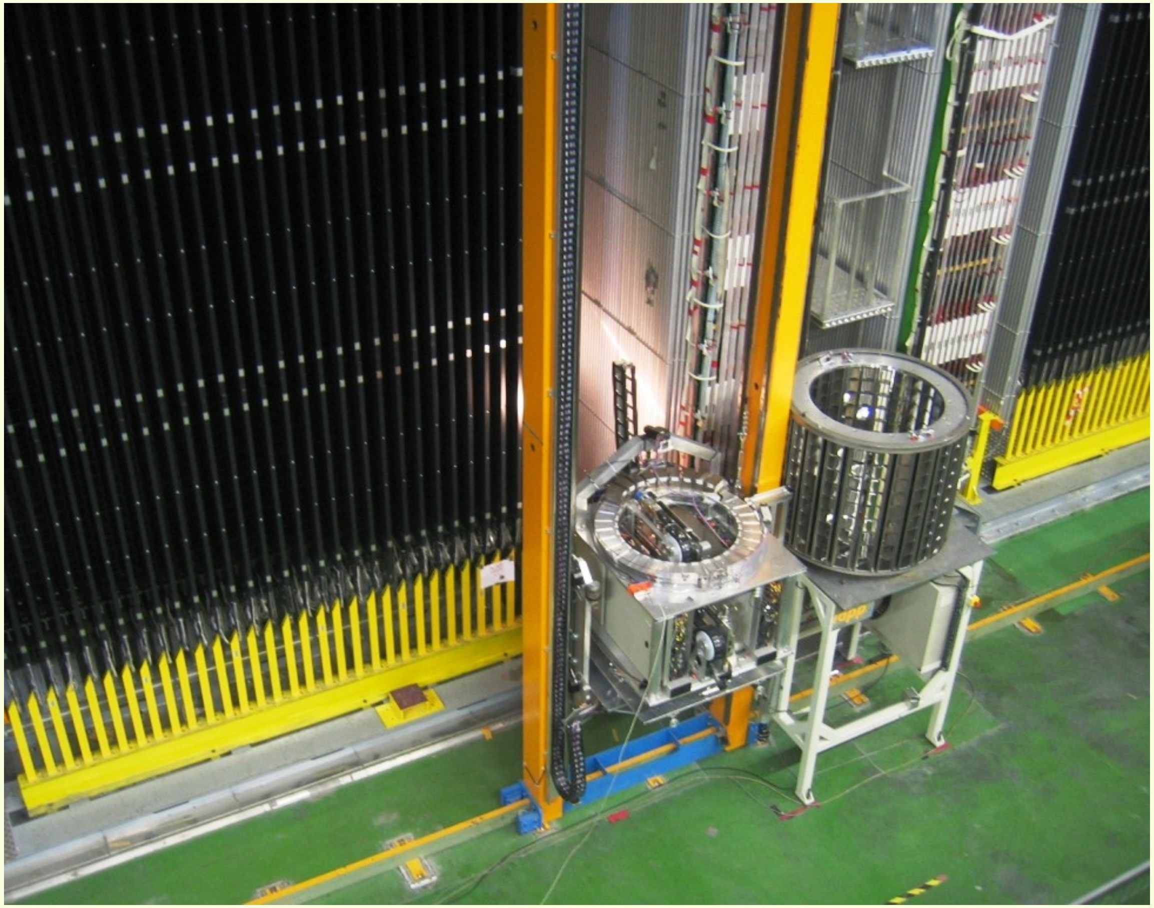


target section
with electronic
target tracker

spectrometer:
Magnet, HPT,
RPC, XPC

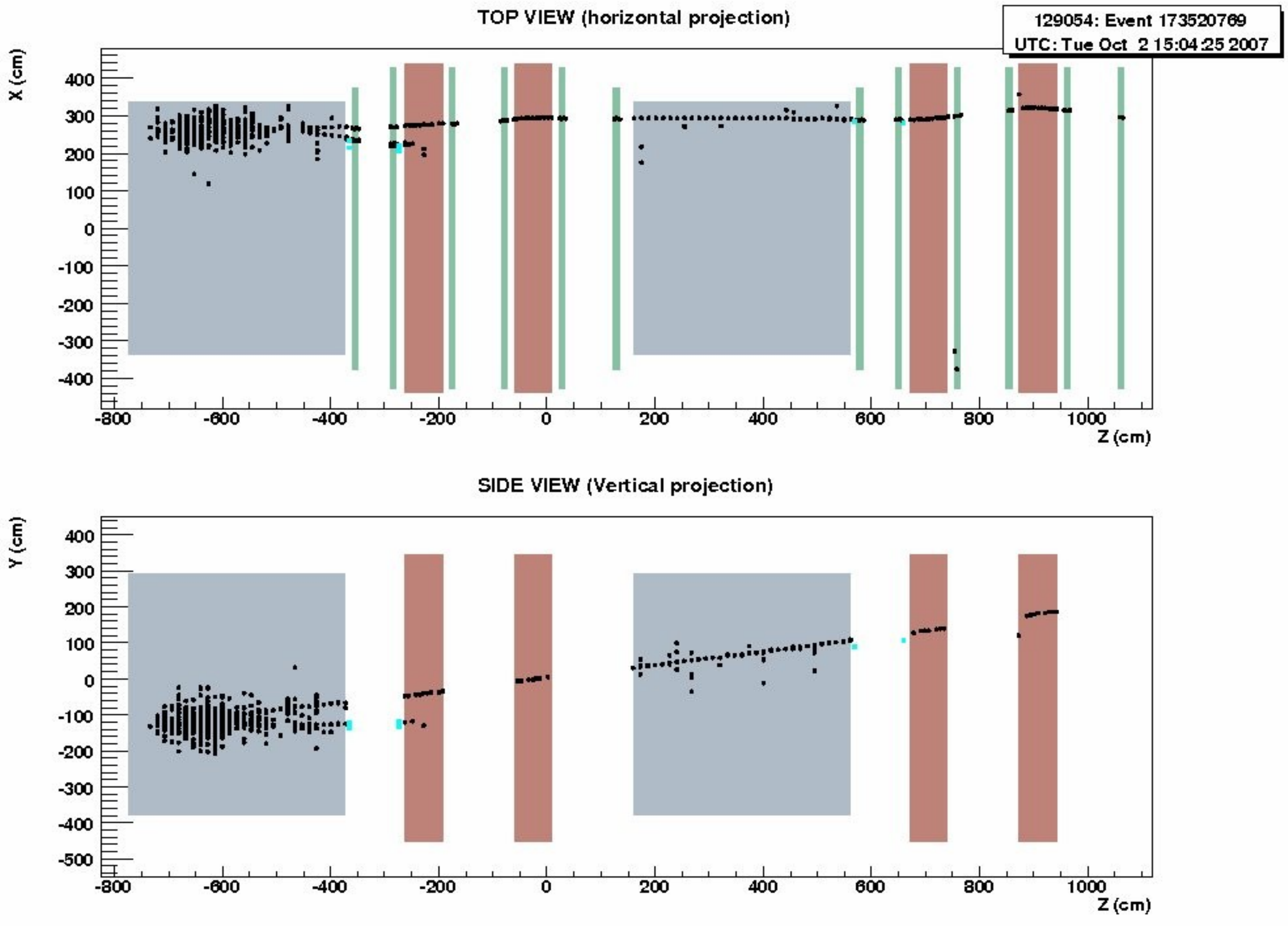
OPERA





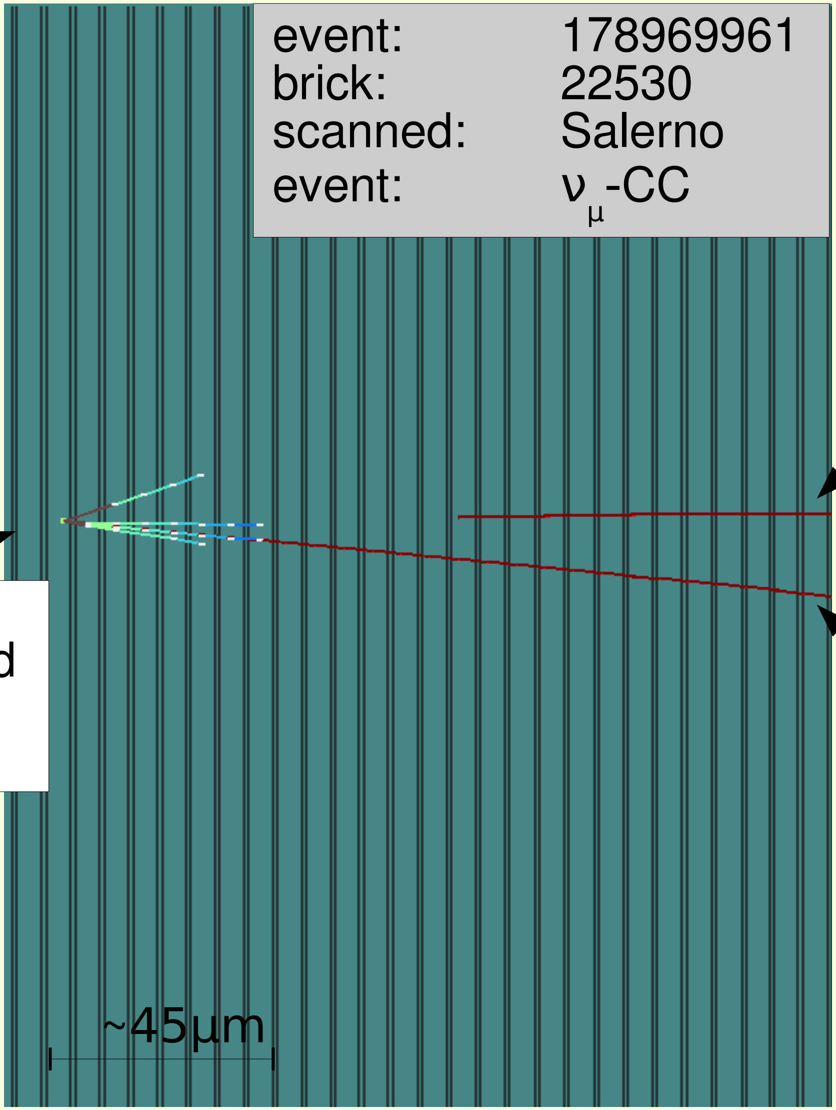
OPERA

electronic detectors



OPERA

emulsion



event:	178969961
brick:	22530
scanned:	Salerno
event:	ν_μ-CC

center of gravity extrapolation from shower (gamma conversion) starting plate 38

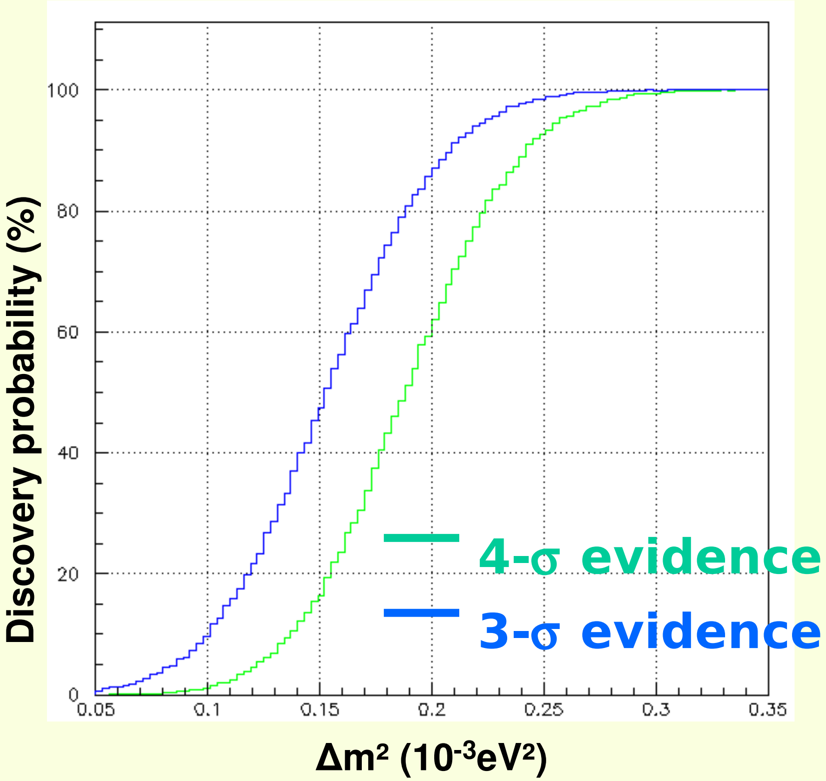
vertex found between lead plate 24 and 25

muon track

OPERA

after 5 years nominal running and 25% reduced target mass we expect about 30000 ν_μ CC events

τ^- Decay	Signal ÷ $(\Delta m^2)^2$ – Full mixing		Background: Charm H. intera. Muon scat.
	Δm^2 = 2.5 x 10^{-3} eV²	Δm^2 = 3.0 x 10^{-3} eV²	
$\tau^- \rightarrow \mu^-$	2.9	4.2	0.17
$\tau^- \rightarrow e^-$	3.5	5.0	0.17
$\tau^- \rightarrow h^-$	3.1	4.4	0.24
$\tau^- \rightarrow 3h$	0.9	1.3	0.17
ALL	10.4	15.0	0.76



conclusion

conclusion

- conventional neutrino beams are challenging but under control, only two running long baseline beams worldwide
- neutrino cross sections and p-hadron interactions still under investigation, several experiments worldwide
- **MINOS** first high precision results will set the borders for future searches
- **OPERA** will confirm or exclude 3-flavor oscillation model

outlook

- next generation of neutrino oscillation experiments need monochromatic beams: off axis experiments on their way
  - **T2K** (Japan)
  - **NoνA** (USA)

  precision experiments to extend search for Θ_{13} and CP violation

- next to next generation experiments need much higher flux and purity:
  - **Neutrino Factories** (μ storage rings)
  - **Beta Beams** (β-decaying ion storage ringe)

  use matter effects (very long baseline: 8000km) for highest precision

END

Thanks for your attention!