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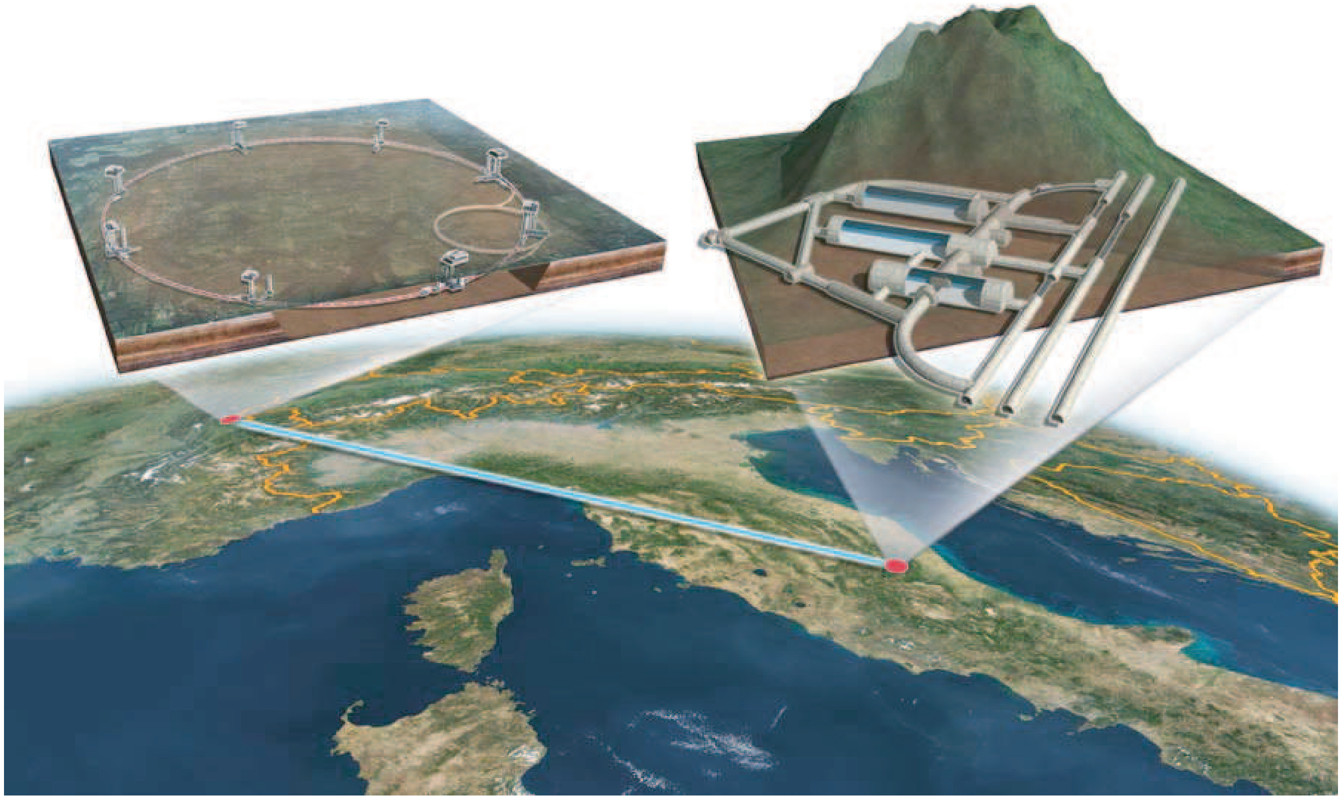
"CNGS neutrino beam: from CERN to Gran Sasso"



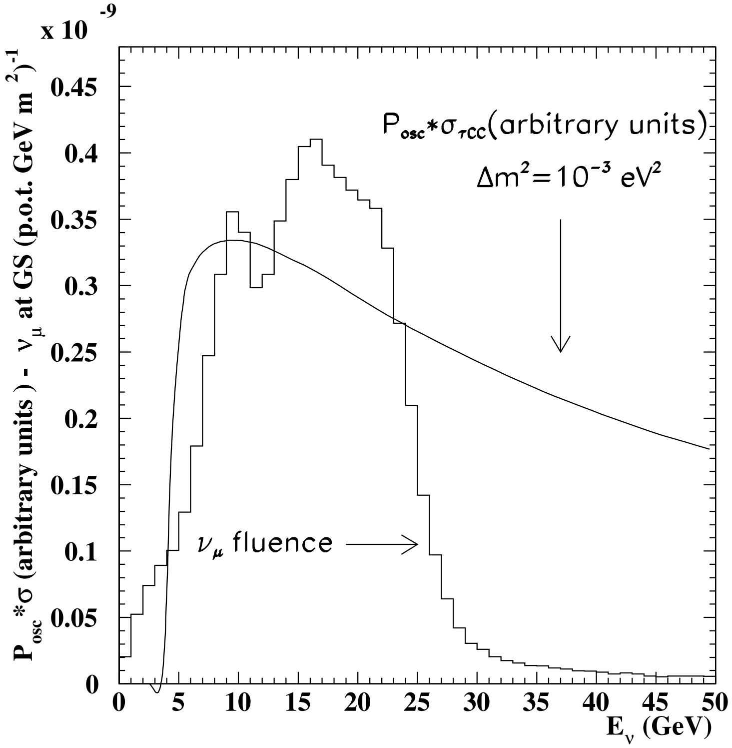
- **from design to installation of CNGS beam-line**
- **CNGS neutrino beam calculation**
- **CNGS beam commissioning**

... a long term study with P.R. Sala and A. Ferrari

Foreword

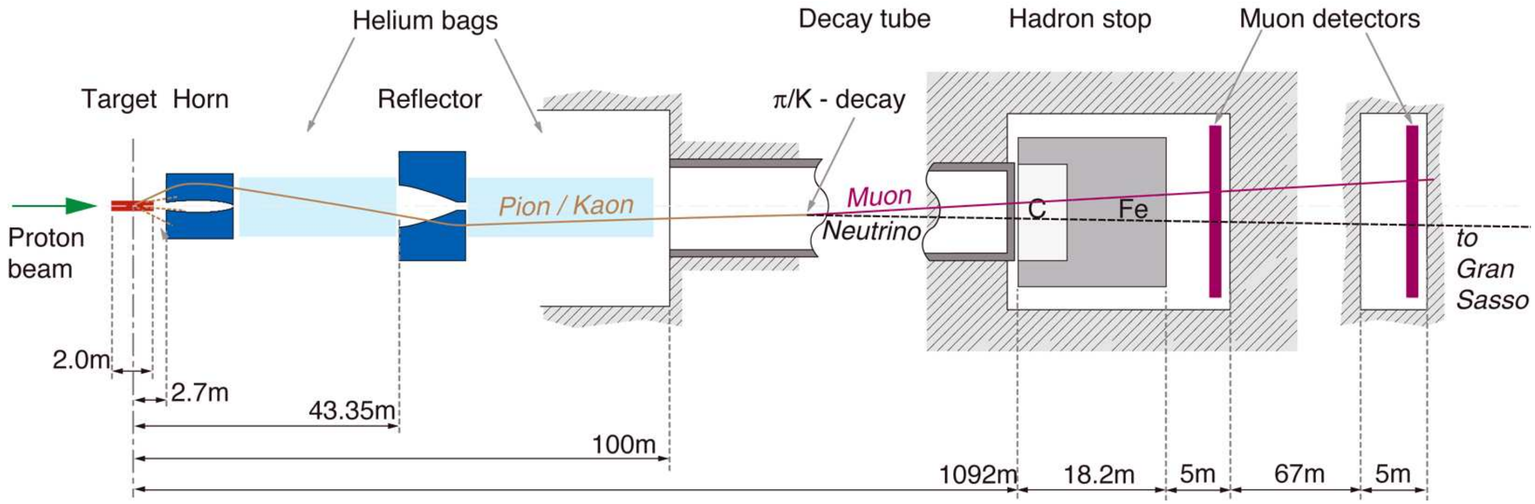
CNGS CERN to Gran Sasso neutrino beam: designed for $\nu_\mu \to \nu_\tau$ oscillation search looking for the ν_τ appearance in a pure ν_μ beam as observed in atmospheric neutrinos and K2K, MINOS experiments with Δm^2_{23} parameter in $1.5 \div 3.5\ 10^{-3}$ eV^2 range.

- *for $\Delta m^2_{23} \sim 10^{-3}$ eV^2, $\nu_\mu \to \nu_\tau$ oscillation probability over $L = 732$ km is $P_{osc} \propto (\Delta m^2_{23})^2 L^2 / E^2_\nu$*
- *the rate of detected ν_τ oscillation events $\propto P_{osc} \cdot \sigma_{\tau CC}$: $R \propto (\Delta m^2_{23})^2\ L^2 \int \phi_\nu(E_\nu) \frac{\sigma_{\tau CC}(E_\nu)}{E^2_\nu}\ dE_\nu$*
- *$\to$ the energy E_ν spectrum of ϕ_ν: well matched to $\sigma_{\tau CC}/E^2_\nu$ at ~ 15 GeV to maximize the signal rate*

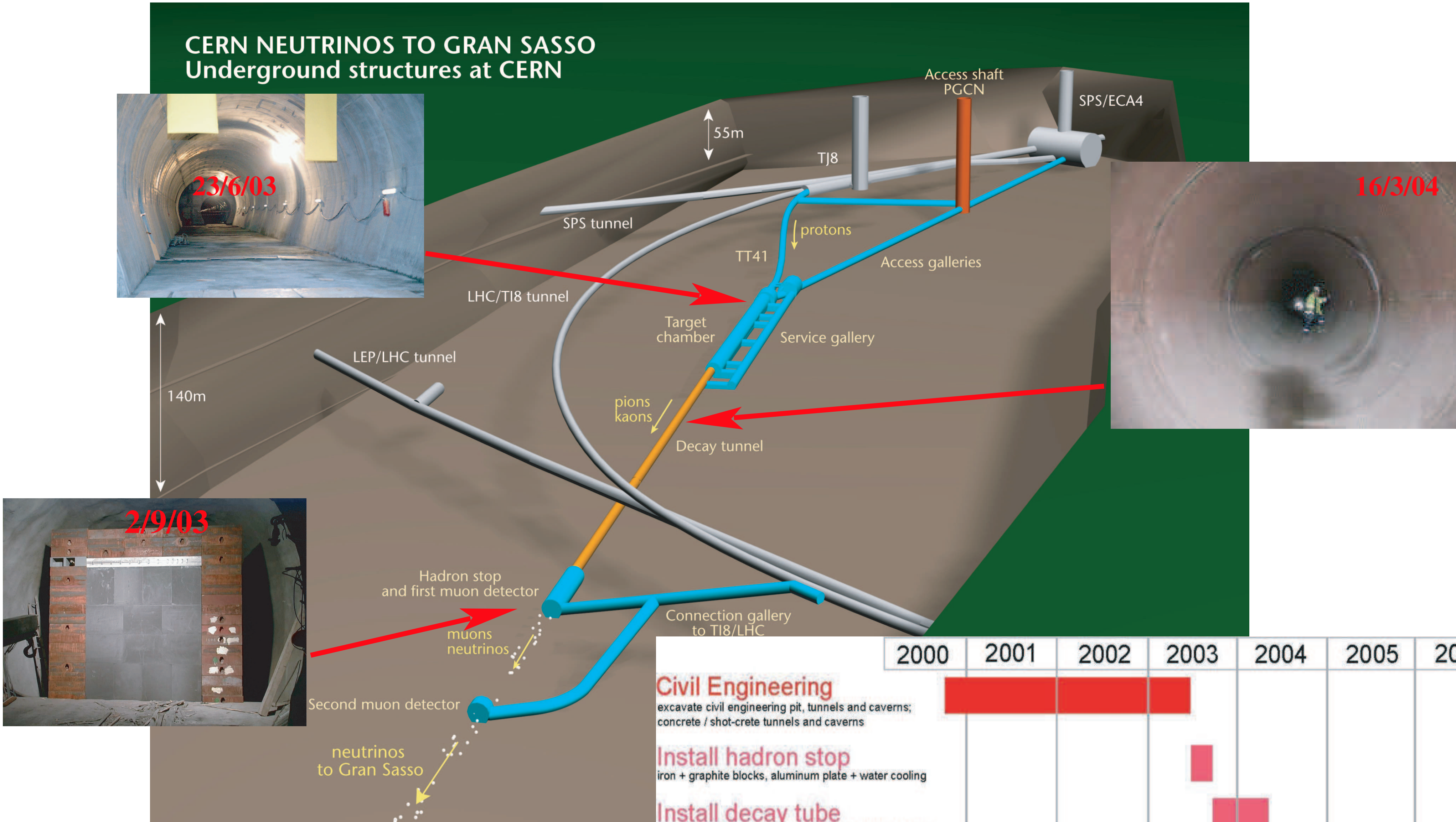


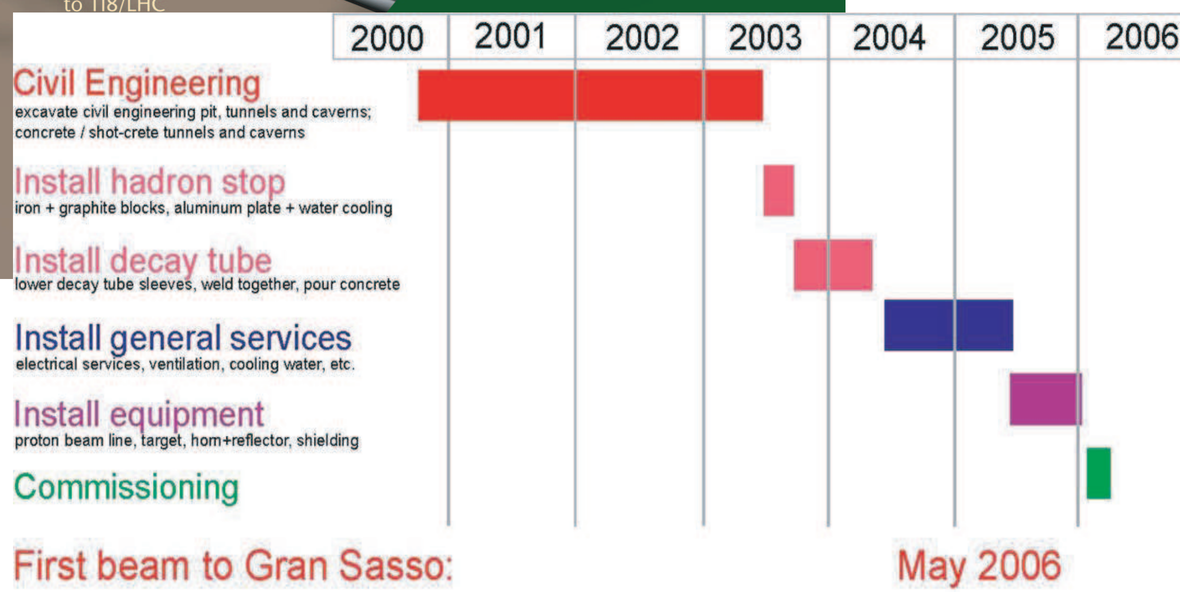
- *CNGS ν_μ beam at CERN SPS: ν's from decay of π, K produced by 400 GeV/c protons on C target*
- *CNGS design: accomplished on the experience of the previous WANF ν_μ beam for CHORUS and NOMAD which resulted in a strong benchmark for conventional neutrino beams*
- *both WANF and CNGS beams benefit of hadron production measurements of SPY (Secondary Particle Yields) experiment dedicated to neutrino beam production study*

CNGS neutrino beam-line



- *400 GeV/c protons extracted CERN SPS, directed on a carbon target where mesons are copiously produced*
- *positive (negative) secondary mesons: focused (defocused) by magnetic Horn + Reflector in 1 km decay tunnel toward Gran Sasso Lab where ν are generated in the decay in flight of π's and K's*
- *two He bags to minimize meson absorption before the decay*
- *residual mesons are absorbed in a massive C+Fe dump at the end of the beam line*
- *proton beam intensity: $4.5(7.6) \cdot 10^{19}$ p.o.t/year, shared (dedicated) operations*

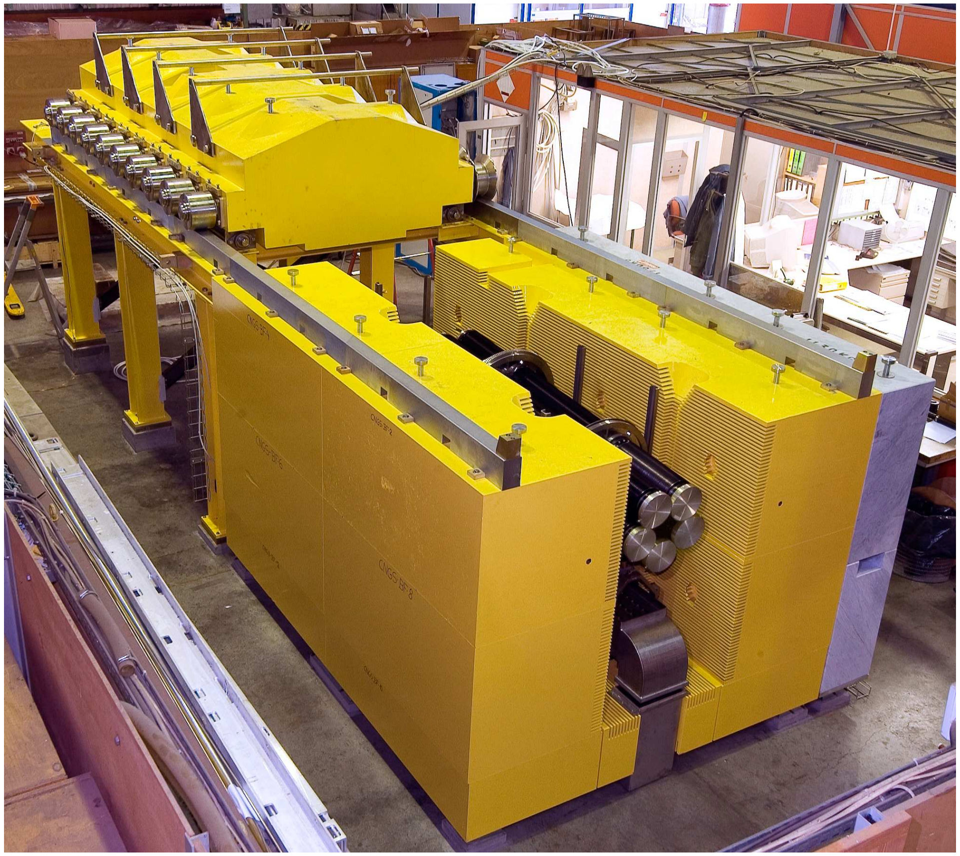

CERN NEUTRINOS TO GRAN SASSO
Underground structures at CERN
23/6/03
16/3/04
2/9/03
Access shaft
PGCN
SPS/ECA4
55m
TJ8
SPS tunnel
protons
TT41
Access galleries
LHC/TI8 tunnel
Target
chamber
Service gallery
LEP/LHC tunnel
140m
pions
kaons
Decay tunnel
Hadron stop
and first muon detector
muons
neutrinos
Connection gallery
to TI8/LHC
Second muon detector
neutrinos
to Gran Sasso


2000
2001
2002
2003
2004
2005
2006
Civil Engineering
excavate civil engineering pit, tunnels and caverns;
concrete / shot-crete tunnels and caverns
Install hadron stop
iron + graphite blocks, aluminum plate + water cooling
Install decay tube
lower decay tube sleeves, weld together, pour concrete
Install general services
electrical services, ventilation, cooling water, etc.
Install equipment
proton beam line, target, horn+reflector, shielding
Commissioning
First beam to Gran Sasso:
May 2006

CNGS proton beam

- two fast extractions of 400 GeV/c protons every 6 s, $2.4 \cdot 10^{13}$ ppp in $\Delta t = 10.5\ \mu$s interleaved by 50 ms, for a total of $4.5 \cdot 10^{19}$ pot/y, ultimate intensity: $3.5 \cdot 10^{13}$ ppp (tested)
- spatial, angular profile of proton spills: $\sigma_X = \sigma_Y = 0.53$ mm, $\sigma_\theta = 0.053$ mrad

graphite target... $4.5\,10^{19}$ pot/y, 0.52 MW !



- *"revolver target magazine": 5 He tubes with inserted nominal + spare targets*
- *nominal target: 13 graphite rods, $\ell = 10$ cm each for a total 3.3 λ_I, $\phi = 4$ mm ,*

  $\phi = 5$ mm the first 2, the more fired, to better dissipate heat

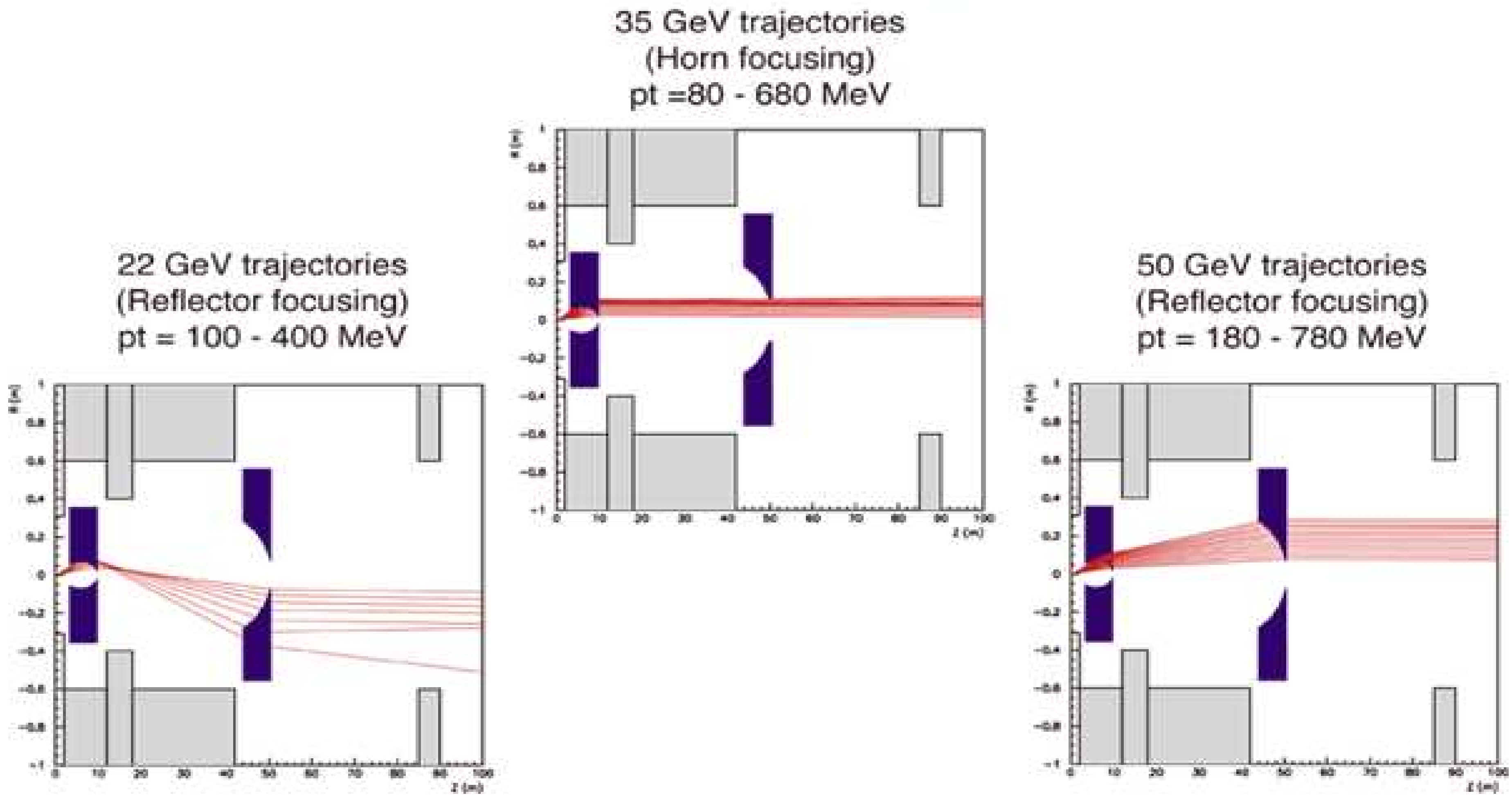
  first 8 rods: separated by 9 cm each to better develop meson production

  last 5 rods: packed to reduce longitudinal smearing in π production for a better focalisation

  can works at $3.5 \cdot 10^{13}$ ppp, 0.75 MW, for $7.6\,10^{19}$ pot/y (dedicated beam operation) !

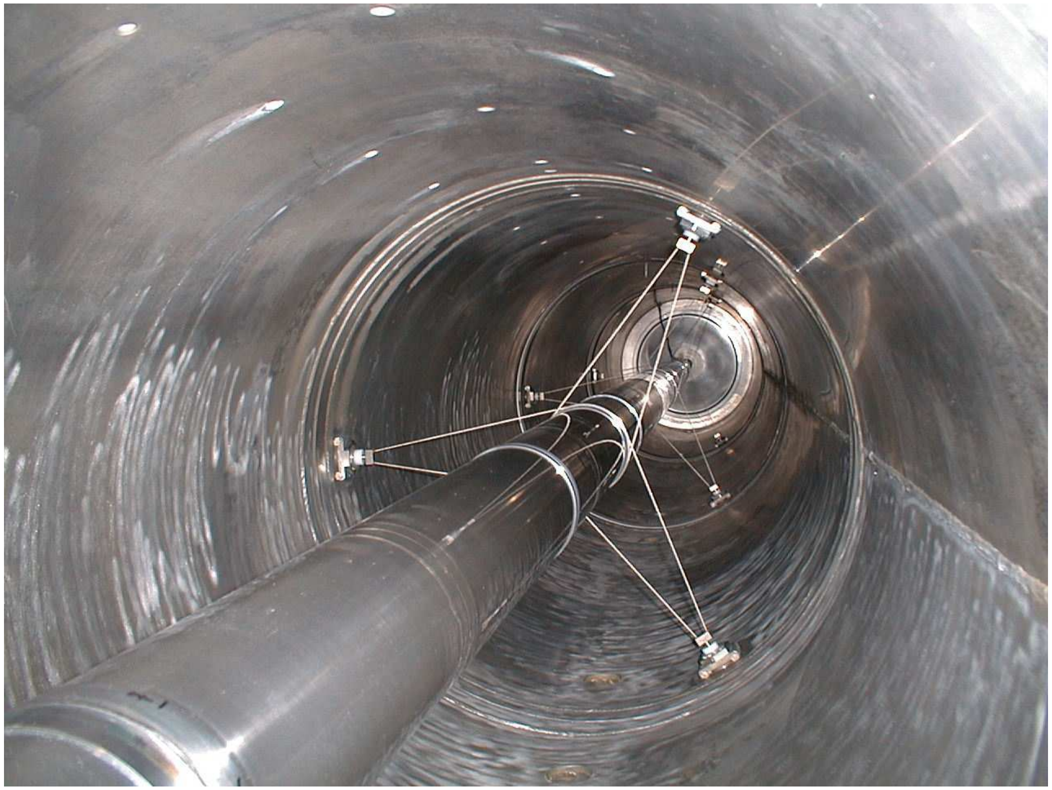
horn & reflector

CNGS focusing optics (positively charged particle trajectories)

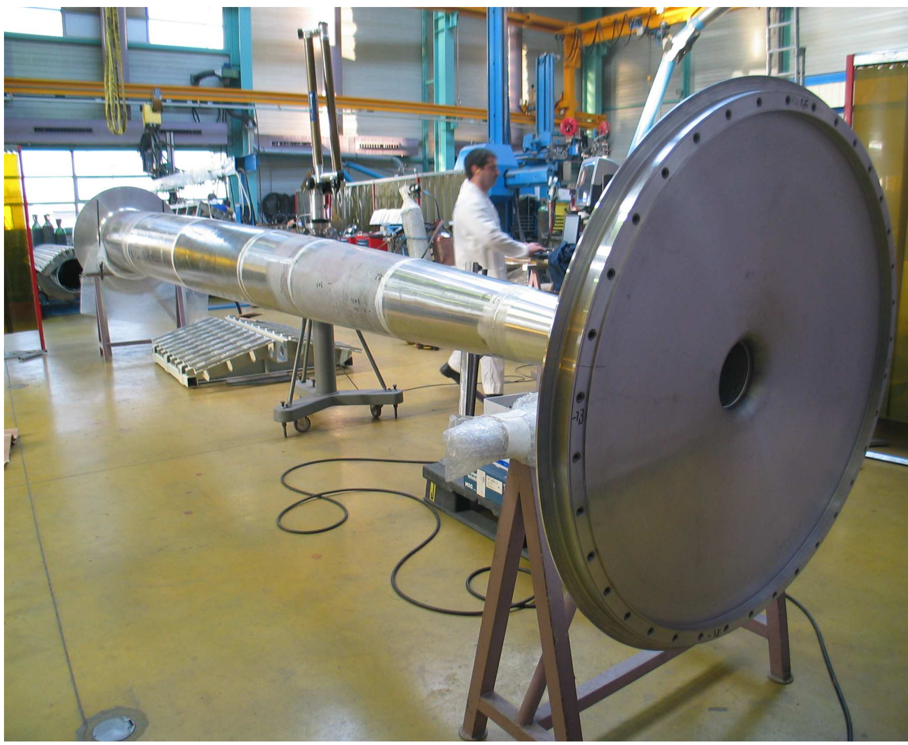


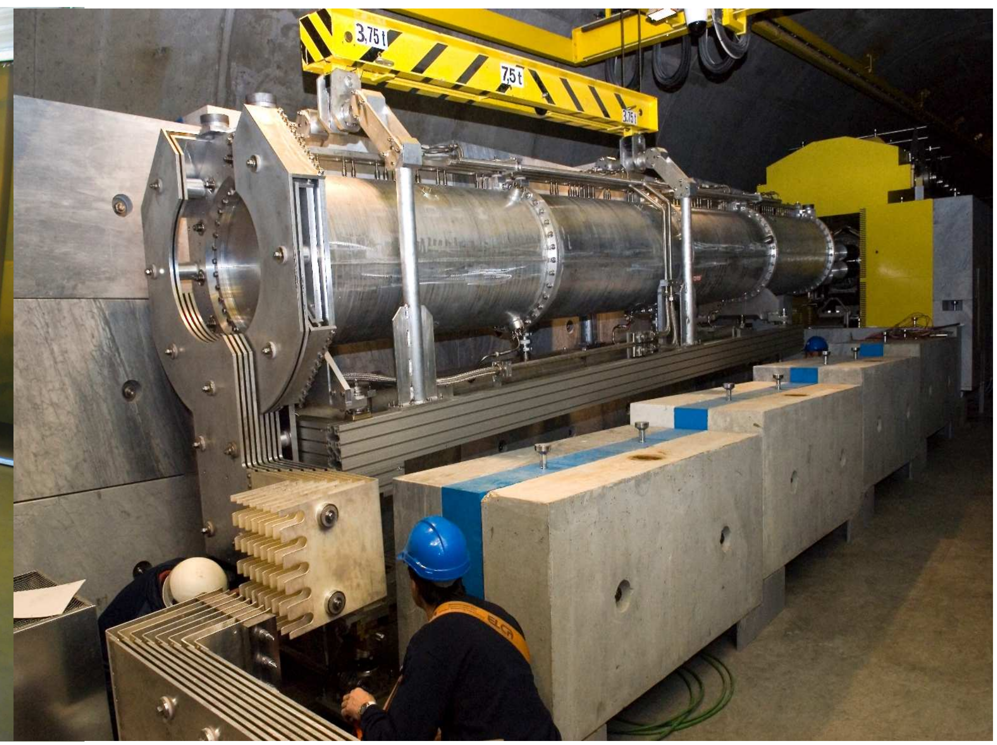
- *Horn & Reflector, $\ell = 6.5$ m each, magnetic lenses to focus π^+, K^+ in the 30-50 GeV range toward Gran Sasso by a pulsed currents $I_{horn} = 150$ KA and $I_{refl} = 180$ KA*
- *Horn: at 1.2 m from target to maximize angular acceptance/ focusing*

  Reflector at 42 m from target to complete the higher energy particle focusing



- *internal conductors: parabolic shape, only 1.8 mm thickness to minimize absorptions/reinteractions*
  but sufficient for mechanical stability
- *no material in between inner/outer conductor!*





Reflector and decay-tube installation

CNGS: conventional ν_μ beam from pion and kaon decay

to predict the ν beam flux and composition at Gran Sasso site $\rightarrow$ precise description of:

- $\pi^\pm,\ K^\pm$ *yields in p-target interactions*
- *focusing (defocusing) of positive (negative) secondaries and*

  their propagation/decay in the beam-line,

  development of hadronic interactions and cascades (reinteractions ...)

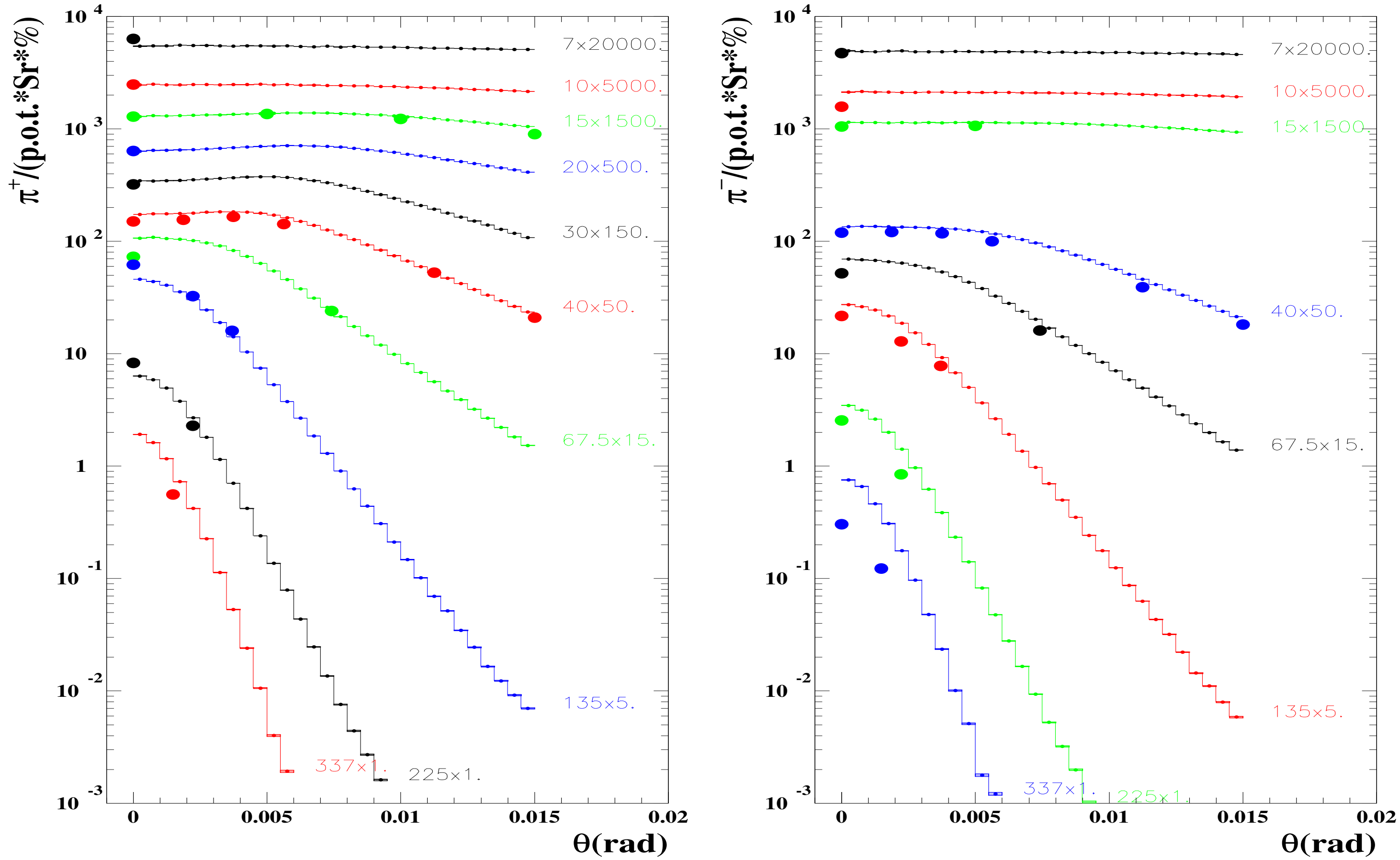
4 main sources of neutrinos:

- *proton interacting in proton target* $\rightarrow \pi^\pm,\ K^\pm,\ K^0, ...$: $\nu_\mu,\ \overline{\nu}_\mu,\ \nu_e,\ \overline{\nu}_e$
- *protons missing target: interactions in the materials along the beam-line:* $\rightarrow \overline{\nu}_\mu,\ \overline{\nu}_e$
- *"prompt neutrinos" from charm and K decays in the target and dump:* $\overline{\nu}_e$
- *particle reinteractions in the materials of the beam-line: affecting* ν_μ *and* ν_e*, mainly* $\overline{\nu}_\mu,\ \overline{\nu}_e$

... a conventional ν-beam is a complicated cascade of physical processes!

central point for high energy ν beam calculation: p-target $\rightarrow \pi^{\pm}$, $K^{\pm}$, K^0, ...

- *experimental data (Be): NA20 ('80) 400 GeV/c, SPY ('99) 450 GeV/c, $5 \div 7$ % accuracy*
- *M.C. hadronic generators: the most suitable, FLUKA (2000), $\sim 15 \div 20$ % accuracy at 450 GeV/c*



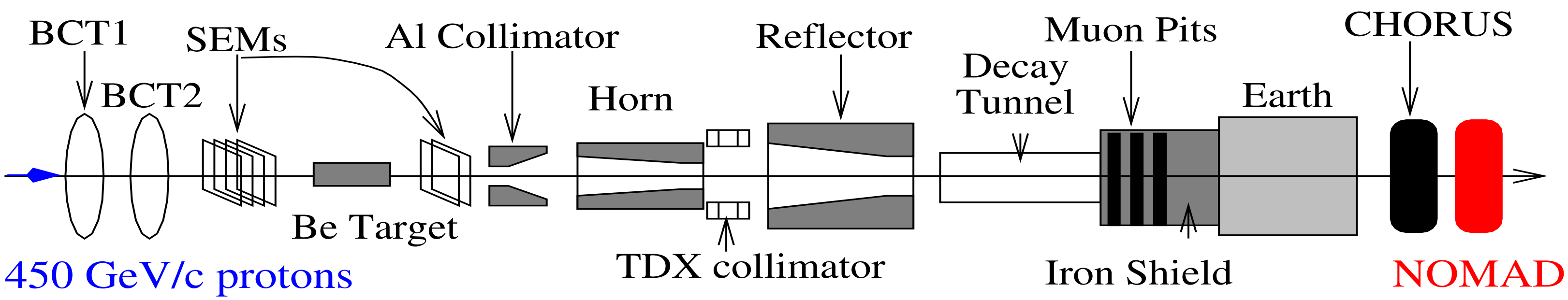
π production from 450 GeV/c proton on 10 cm Be target: FLUKA (—), NA20/SPY rescaled data (●)

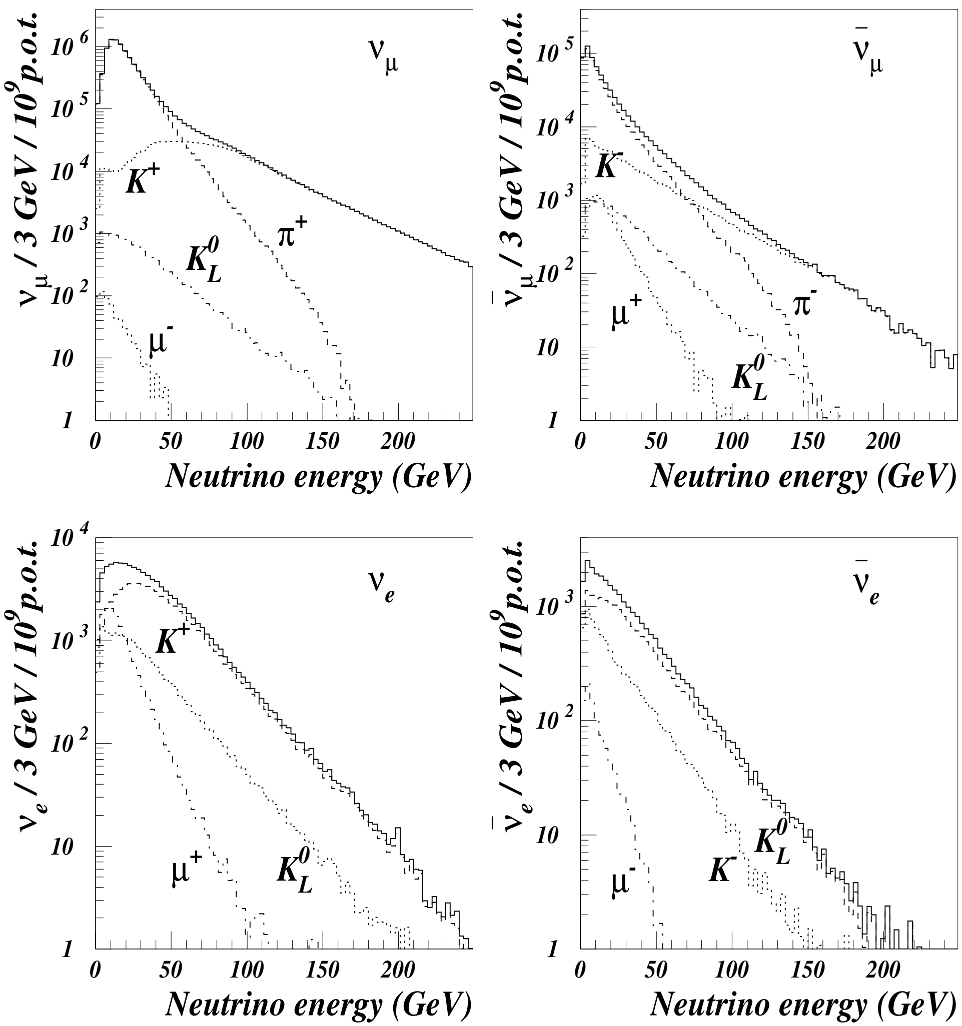
sensitivity on ν_μ oscillation searches limited by hadronic cross-section knowledge!

to improve the ν beam description and reduce the systematics:

tuning of the FLUKA Be meson yields to NA20, SPY data with reweighting functions...

Comparison with the WANF data (NOMAD L = 840 m)





- ν_μ: $< E_{\nu_\mu} >\sim 24.3$ GeV
- $\overline{\nu}_\mu$: 7 %, $< E_{\overline{\nu}_\mu} >\sim 17.2$ GeV
- ν_e: 1 %, $< E_{\nu_e} >\sim 36.4$ GeV
- $\overline{\nu}_e$: 0.3 %, $< E_{\overline{\nu}_e} >\sim 27.6$ GeV

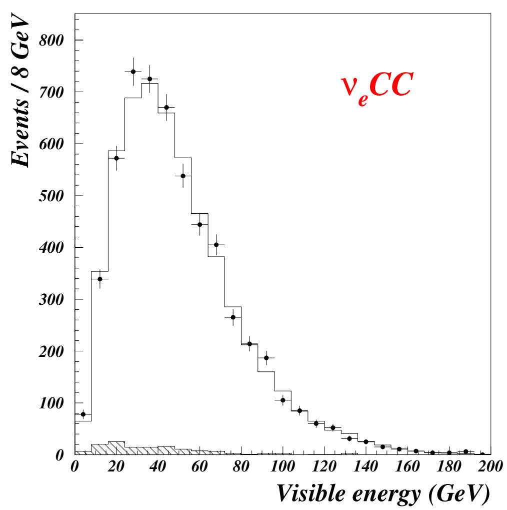
correct reconstruction of:

- ν_μ: from π^+, K^+ + ... decays
- $\overline{\nu}_\mu$: from π^-, K^-, K^0 + ... decays
- $\overline{\nu}_e$: from K^0, K^- + ... decays

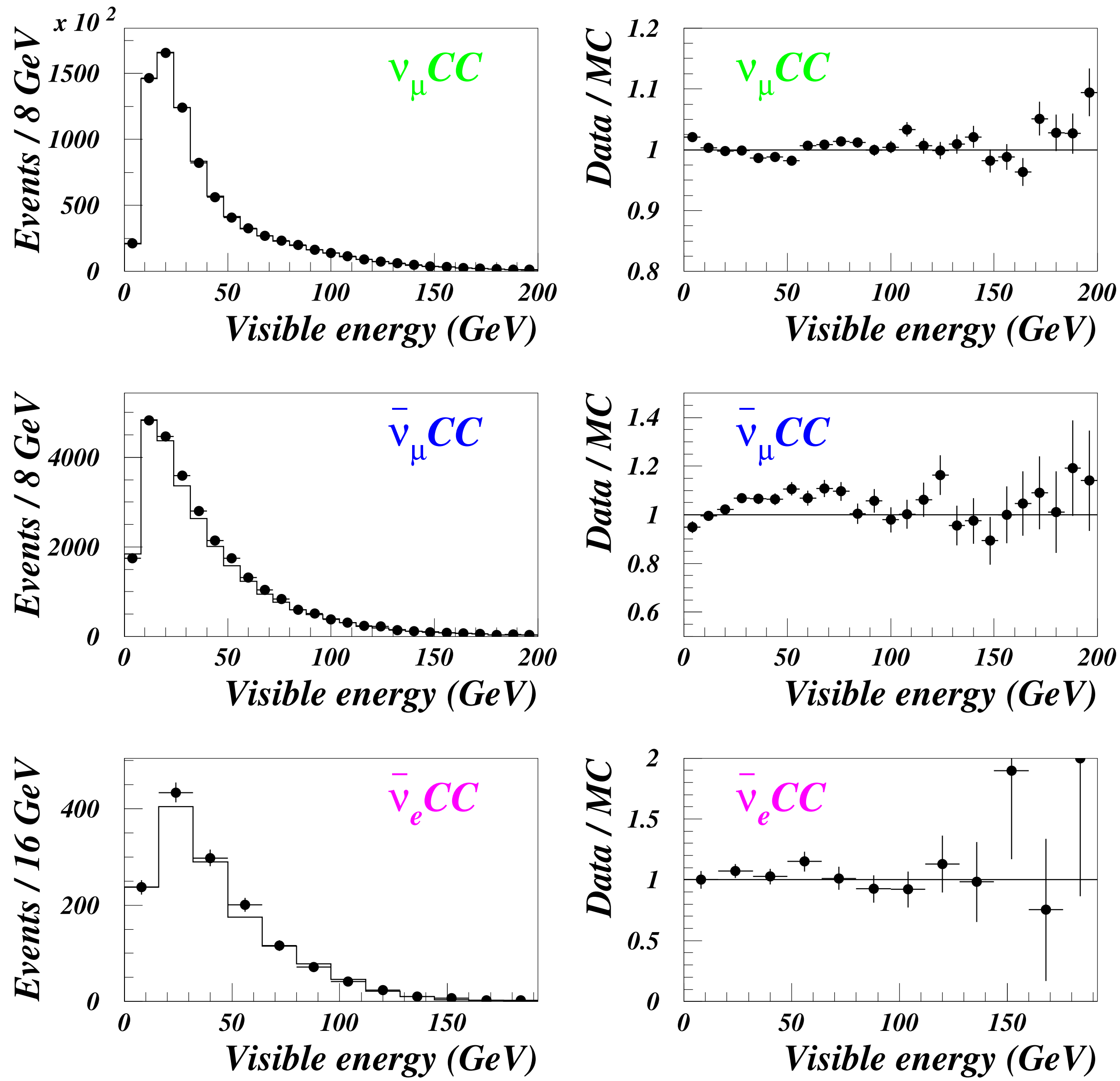
prediction of ν_e (:K^+, K^0 and μ^+) which was the main background for $\nu_\mu \to \nu_e$ search in NOMAD!

NOMAD data at CERN WANF: ν_μCC, $\overline{\nu}_\mu$CC, $\overline{\nu}_e$CC control-sample for ν_eCC

- *prompt isolated "μ" in the final state*
- *prompt isolated "e" in the final state*
- *charge/momentum measurements,* $B = 0.4$*T,* $\Delta p/p \sim$ *4 % at 1 GeV/c*
- *visible energy (hadrons + leptons)* $\Delta E/E_{e.m.} \sim 3.5$ *%* $/\sqrt{E(GeV)}$
- *syst. errors on ν flux: 7 % on ν_μ, ν_e* *ν_e/ν_μ: 4.2 % normaliz., 5 % E_ν-dep.*



very good agreement !



$0.86 \cdot 10^6 \nu_\mu$CC, ν_μCC-MC (–) normalized to data (●)

CNGS beam description with FLUKA

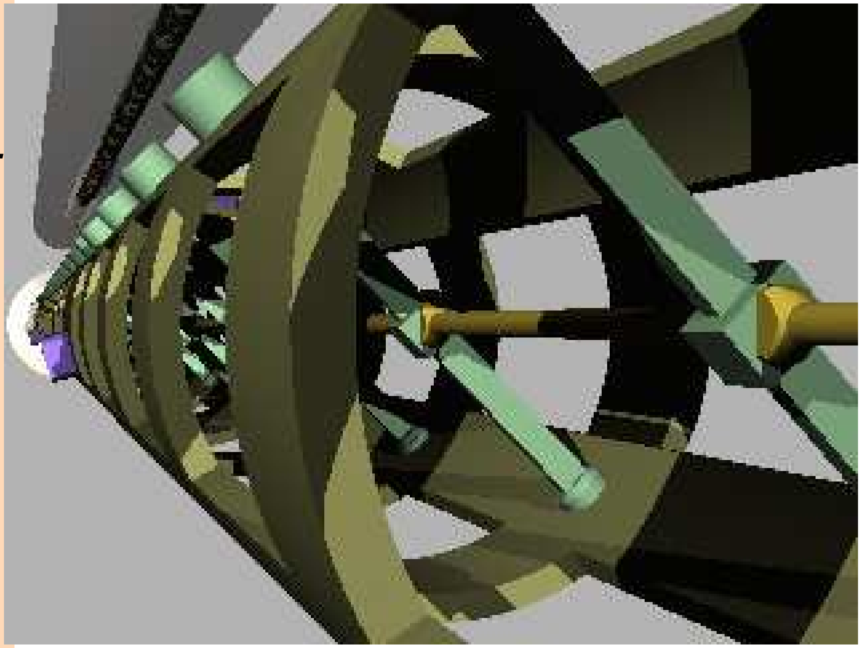
CNGS beam-line facility fully described within FLUKA for various MC simulation purposes:

- *energy dep., radioprotection studies: mechanical stress/heating of materials, dose equivalent rate*
- *to monitor beam response,i.e. μ distributions at muon-pits*
- *predict neutrino beam energy spectrum/composition at Gran Sasso*

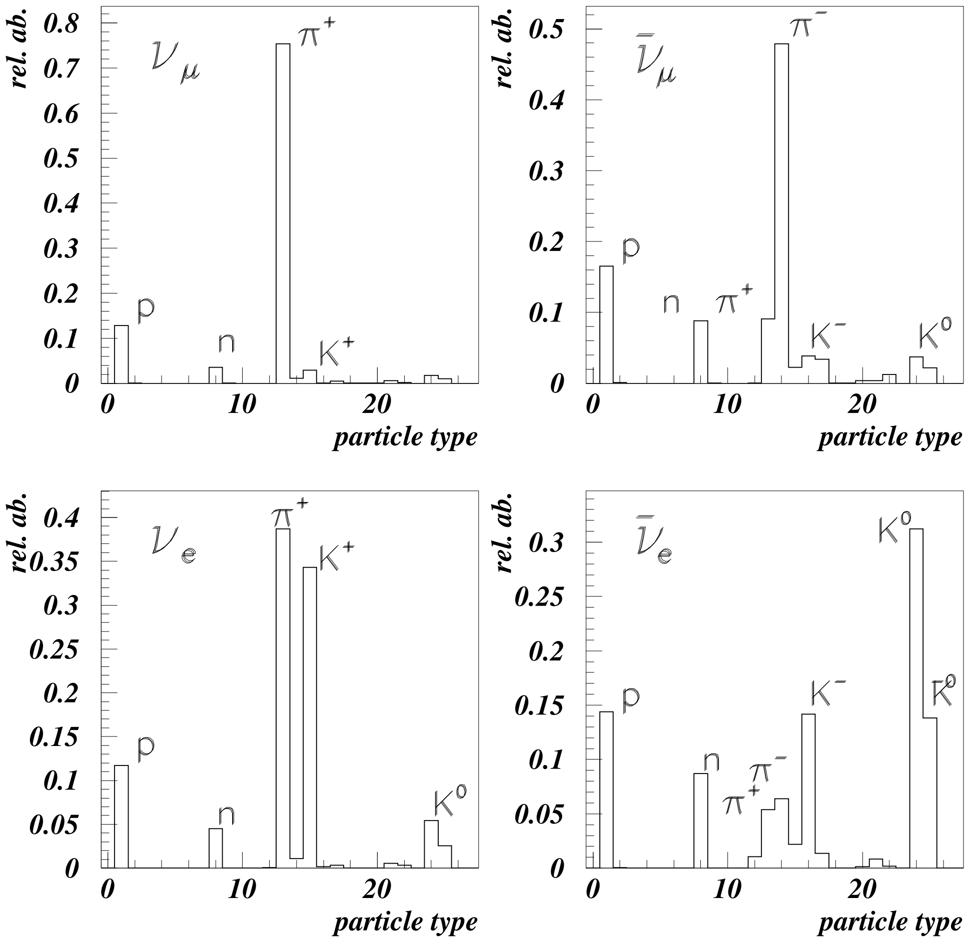
- Detailed geometry/composition description of beam-line from p injection to hadron-stop - including beam monitors perfectly modeling target chamber, graphite rods, supports,..

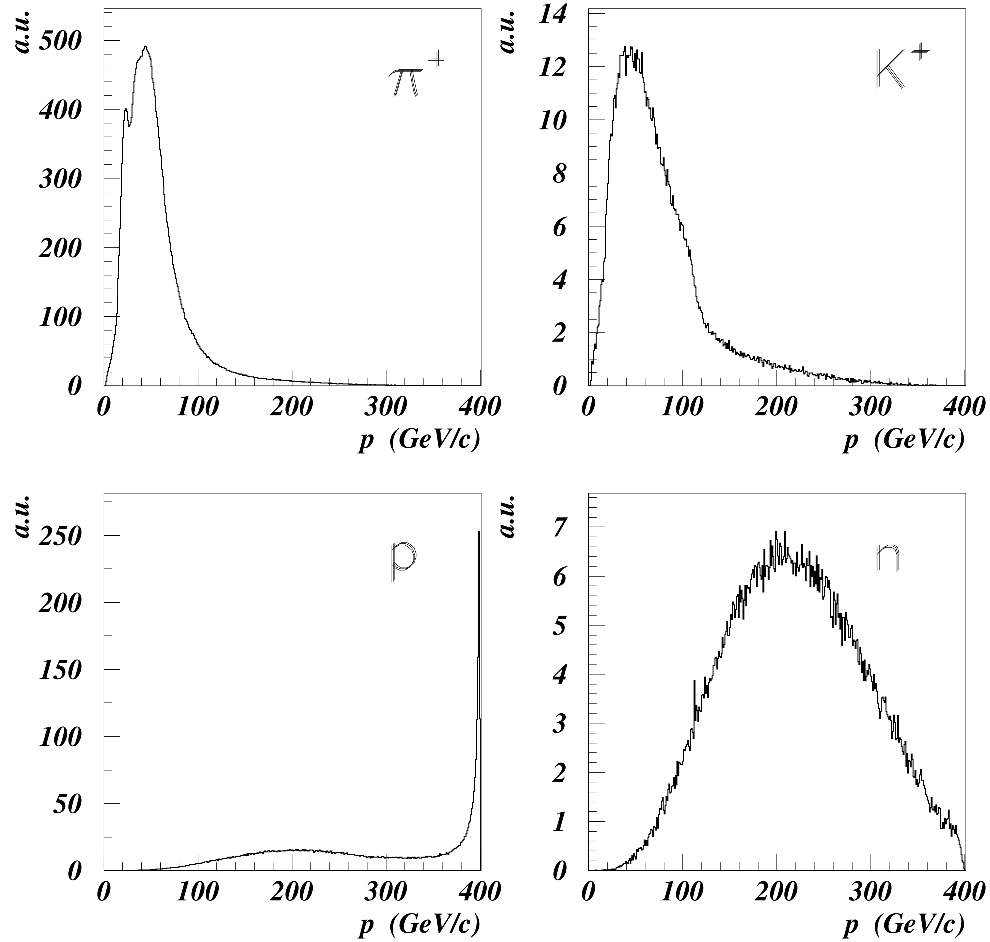
- Various types of biasing, i.e. for ν beam simulations:

- *decay length biasing applied to meson, muons: decay sampled every 10 m*
- *ν direction from π, K 2-body decay: biased as $e^{(1-\cos\theta)/\lambda}$, θ: angle sampled to beam-direction transformed in CMS, $\lambda = 0.25$, decay direction inverted for ν_e and $\overline{\nu}_e$ (at low E_ν: $\pi, K \to \mu \to \nu_e$)*



neutrino ancestors: ν-parents at the exit of rod where p interacts





- ν_μ: completely dominated by π^+
- ν_e: K^+ also !

$\rightarrow$ effects of hadr.-prod. convoluted to focusing effects, meson decay-chain and meson life-time!

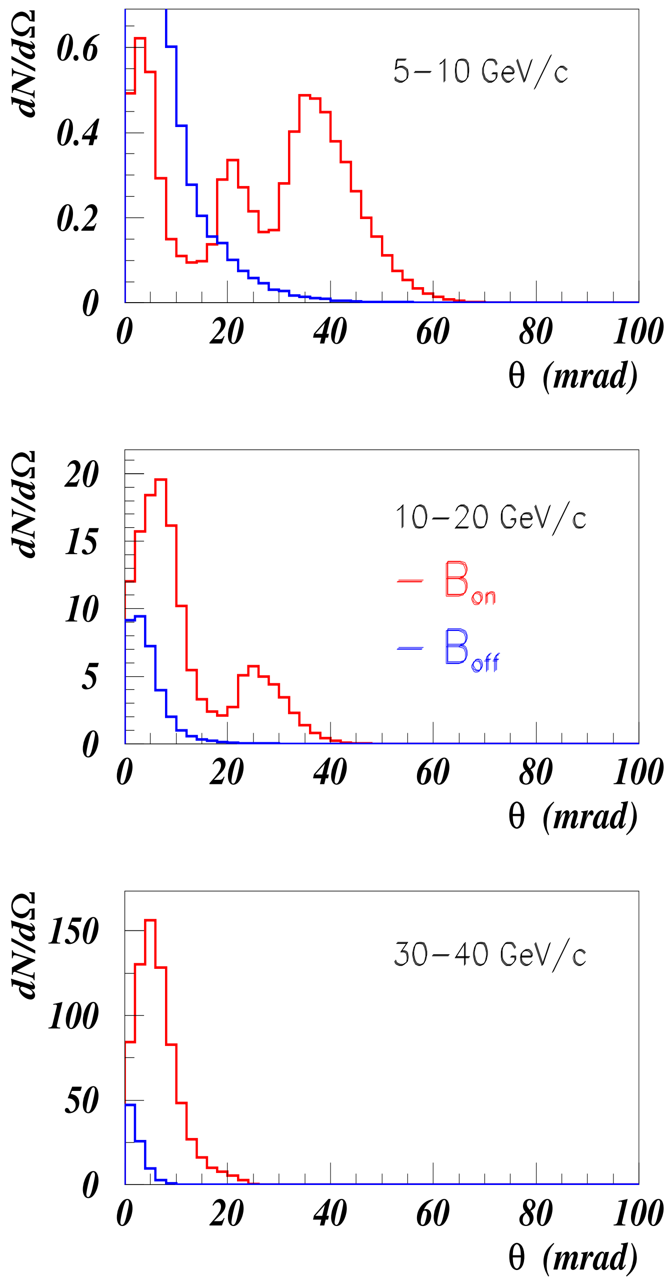
only 0.4 % of the neutrino flux from meson produced in proton interactions out-of-target

energy spectrum of ν_μ in-target ancestors:

- spike in π^+ as effect of focusing optics
- p-production is effective via reinteractions

Horn & Reflector focalisation (π^+ for ν_μ)

- at low momenta (< 10 GeV/c): Horn focus π^+ up to 35 mrad, over-focusing for $\theta \leq 15$ mrad; Reflector extends up to 60 mrad
- at higher momenta: combined angular acceptance of Horn + Reflector extends up to 20 mrad for momenta $p \sim 50$ GeV/c

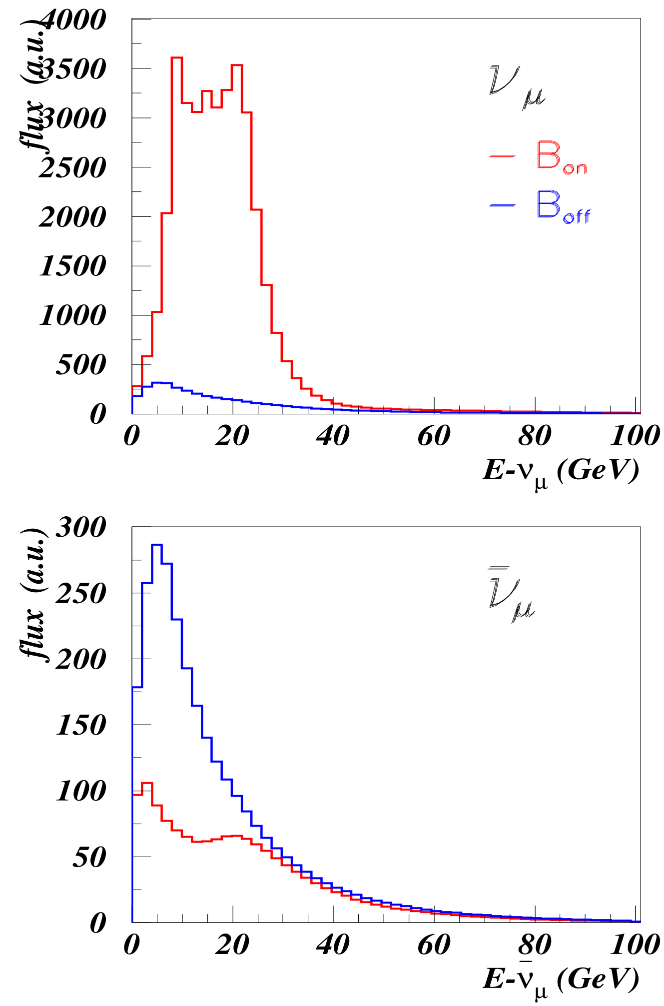


at the Gran Sasso site:

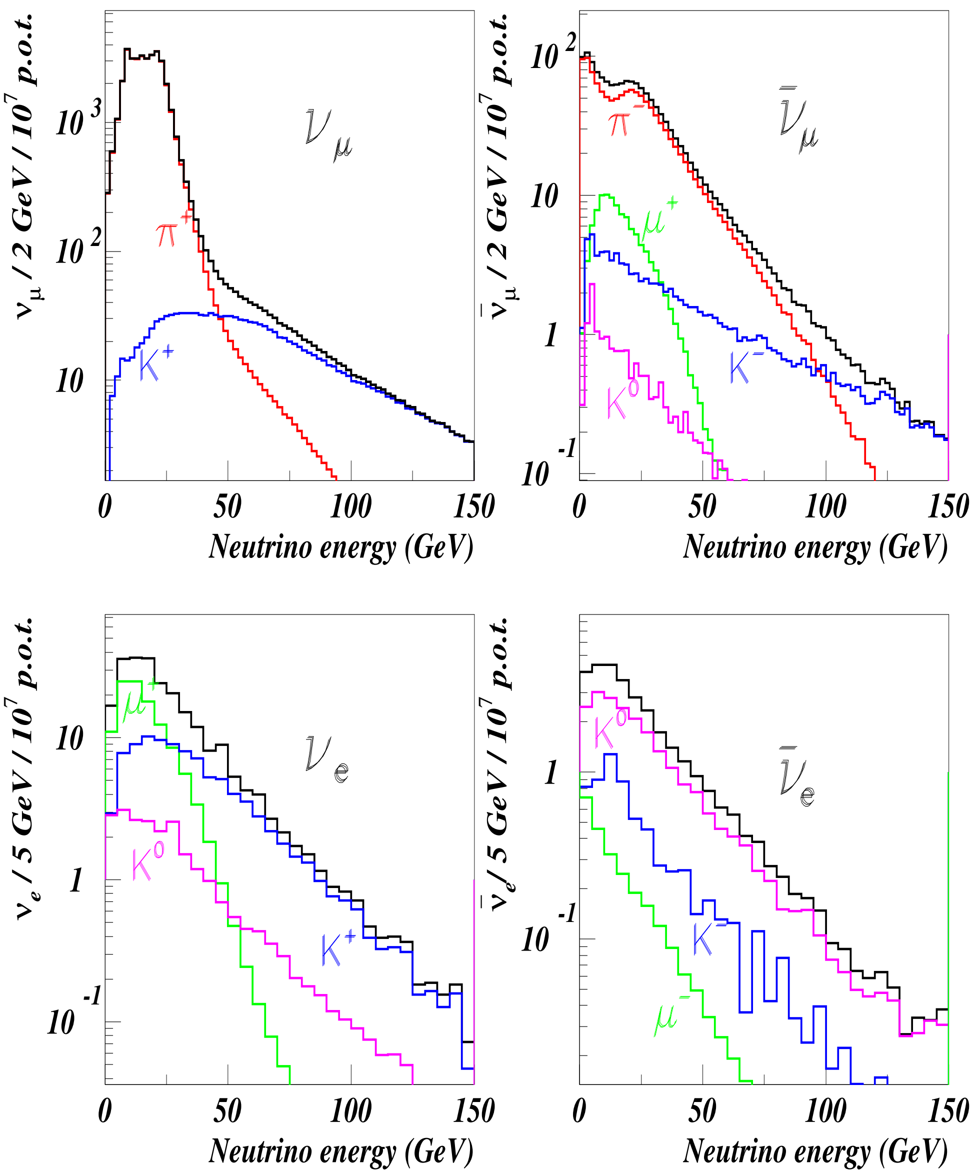
- $\phi(\nu_\mu^{Bon}) \,/\, \phi(\nu_\mu^{Boff}) = 10.1$
- $\phi(\overline{\nu}_\mu^{Bon}) \,/\, \Phi(\overline{\nu}_\mu^{Boff}) = 0.52$

$\rightarrow$ the ν_μ flux increased by 10 (twice than at WANF)

$\overline{\nu}_\mu / \nu_\mu$ contamn. reduced by 20



neutrinos at Gran Sasso



	Flux (ν/cm^2/10^{19}pot)	$< E_\nu >$ $[GeV]$	ν_i/ν_μ (%)	ν_i/ν_μ-CC (%)
ν_μ	$7.4 \cdot 10^6$	17.9		
$\overline{\nu}_\mu$	$2.9 \cdot 10^5$	21.8	3.9	2.40
ν_e	$4.7 \cdot 10^4$	24.5	0.65	0.89
$\overline{\nu}_e$	$6.0 \cdot 10^3$	24.4	0.08	0.06

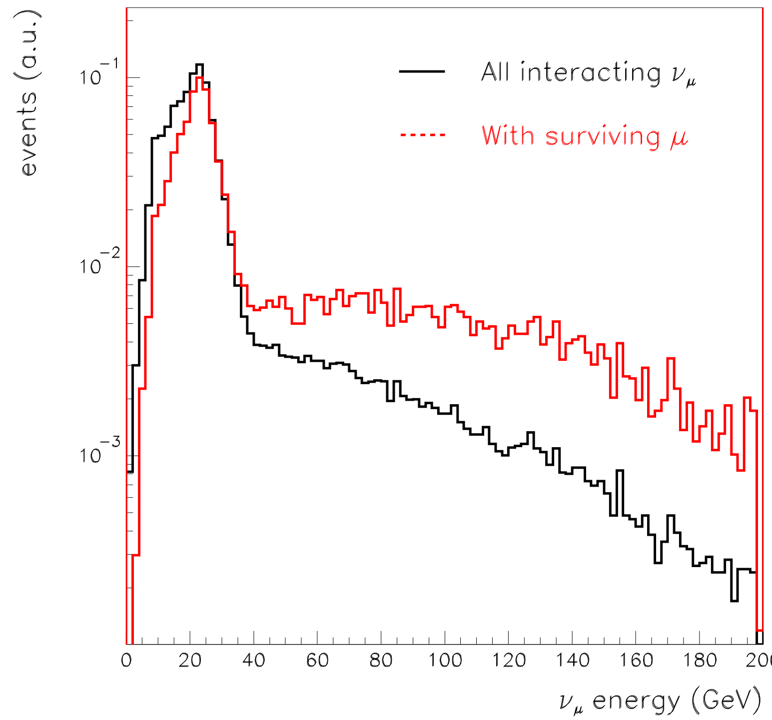
expected event rate: 2800 ν CC/kt/y-low ν_i/ν_μ

last ν-parent

- ν_μ: from π^+ (97 %), K^+ (3 %)
- $\overline{\nu}_\mu$: from π^- (85 %), μ^+ (8 %), K^- (6 %)+ ...
- ν_e: from μ^+ (47 %), K^+ (39 %), K^0 (10 %) + ...
- $\overline{\nu}_e$: from K^0 (70 %), K^- (22 %) μ^- (8 %)

μ from ν interactions in the Gran Sasso rock: a monitor for ν flux

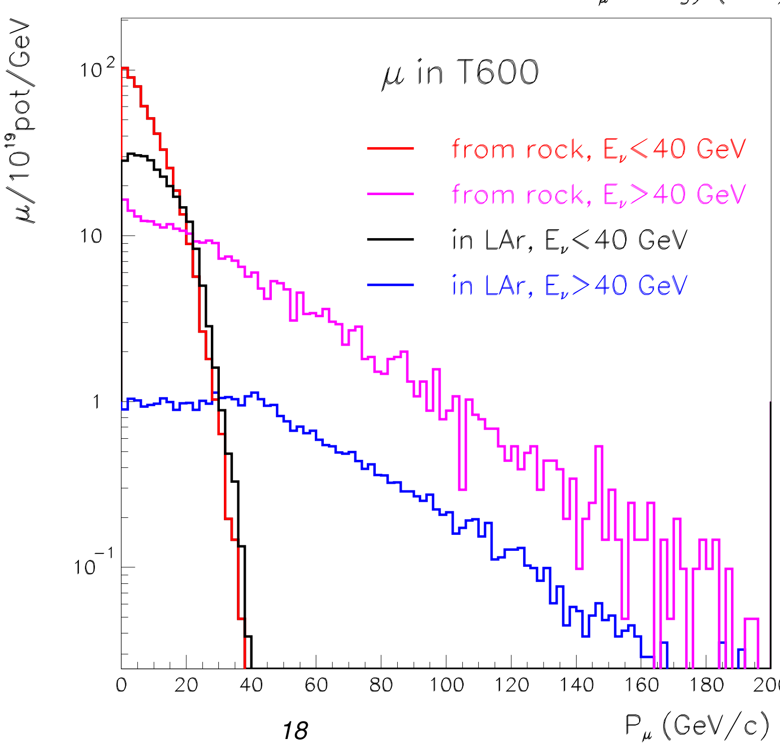
- *ν interaction points uniformly sampled within a 300 m rock dept*
- *expected ν-fluence: $41\mu/m^2/10^{19}$ pot $\rightarrow 0.9\mu/m^2/$day (nominal beam)*



ICARUS T600: $\sim 3500\mu/y$ (nominal beam intensity) of which 870 with $P_\mu > 20$ GeV coming mainly from high energy ν_μ

assuming a good knowledge of bulk of ν beam (internal ν interactions in T600)

$\rightarrow$ measurement of ν-fluence above 40 GeV with good statistical accuracy



evolution of the CNGS project

- *optimized Horn and Reflector optics, $I_{Horn} = 150$ kA, $I_{Refl} = 180$ kA, thin inner conductors*
- *strongly reduced amount of material inserted in the beam-line, $\sim 0.1\lambda_I$ downstream the target, only $\sim 3\%$ of ν_μ's from terziary decays with a reinteraction downstream the target (this fraction increases up to 23 % for $\overline{\nu}_\mu$'s)*

$\rightarrow$ enhancement of ν_μ flux at the Gran Sasso optimizing E_ν spectrum for $\nu_\mu \rightarrow \nu_\tau$ appearance,
keeping low $\overline{\nu}_\mu$ and ν_e contamination (factor $\sim$2 less than WANF):
2800 ν-CC$/kt/y$ are expected, a factor 2 more than the '98 conceptual design!

due to the proton beam size and target configuration

- positioning of proton beam on target surface

- beam-line optics, horn and reflector positioning and currents,...

are not critical for CNGS neutrino flux calculation at 732 km of distance

using the same simulation tools successfully tested at CERN WANF
the neutrino flux can be predicted at Gran Sasso site within a ~ 6 % systematics
ν_e/ν_μ ratio within 3% normalization error plus 3 % bin-to-bin energy error (A.G., NOW-04)

CNGS neutrino beam commissioning

three weeks from July 10 increasing proton intensity up to 10^{13} ppp,

to monitor and align beam components - only 10^{17} pot used:

- *proton beam horizontal/vertical/angular scans on the target:*

  multiplicity optimization to check efficiency with which protons are converted into secondaries

  - *multiplicity: compare TBID signal downstream the target with beam current monitor upstream*
  - *alignment of beam elements*

  BPM2 proton position monitor + TBIDs: Sec. Emission Monitor, 12 μm Ti foils, different shape +...

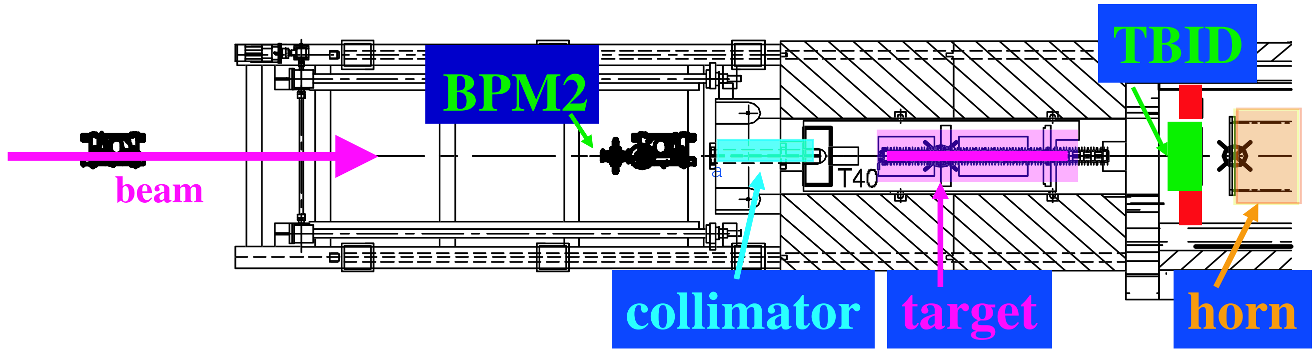
- *monitoring of μ in the muon pits downstream Hadron-stop:*

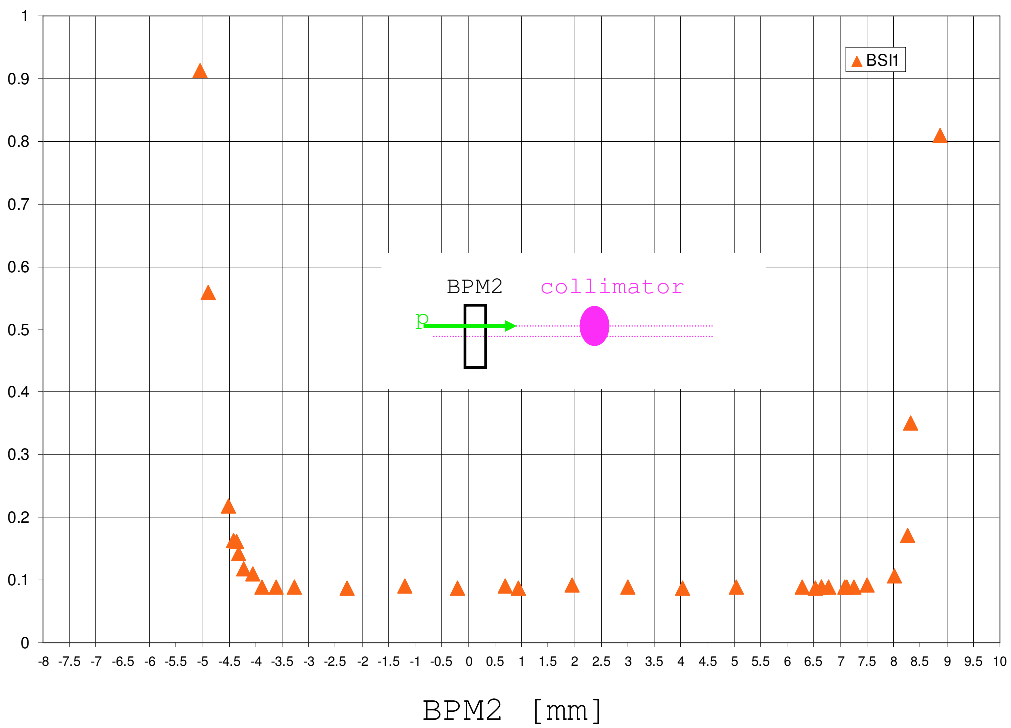
  - *absolute μ intensity*
  - *μ beam horizontal/vertical profile shape*
  - *μ beam horizontal/vertical profile center*

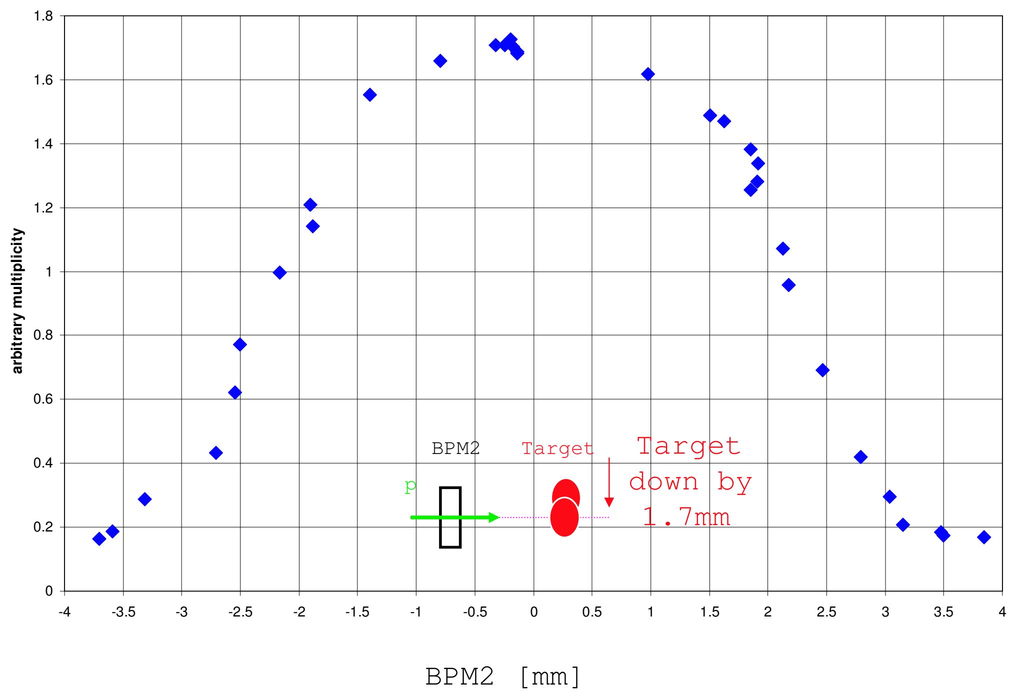
  many BLMs (Beam Loss Monitor, N_2 ionization chambers), up $7.7 \times 10^7 \mu$ per cm^2 and 10.5 μs

comparison data vs expectations in order to align the different elements...

centering of proton beam, collimator and target







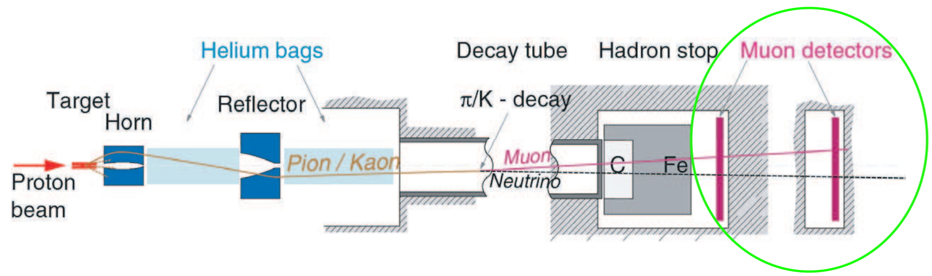
collimator ($\phi = 1.4$ cm): horiz. beam position scan target OUT, reading from TBID

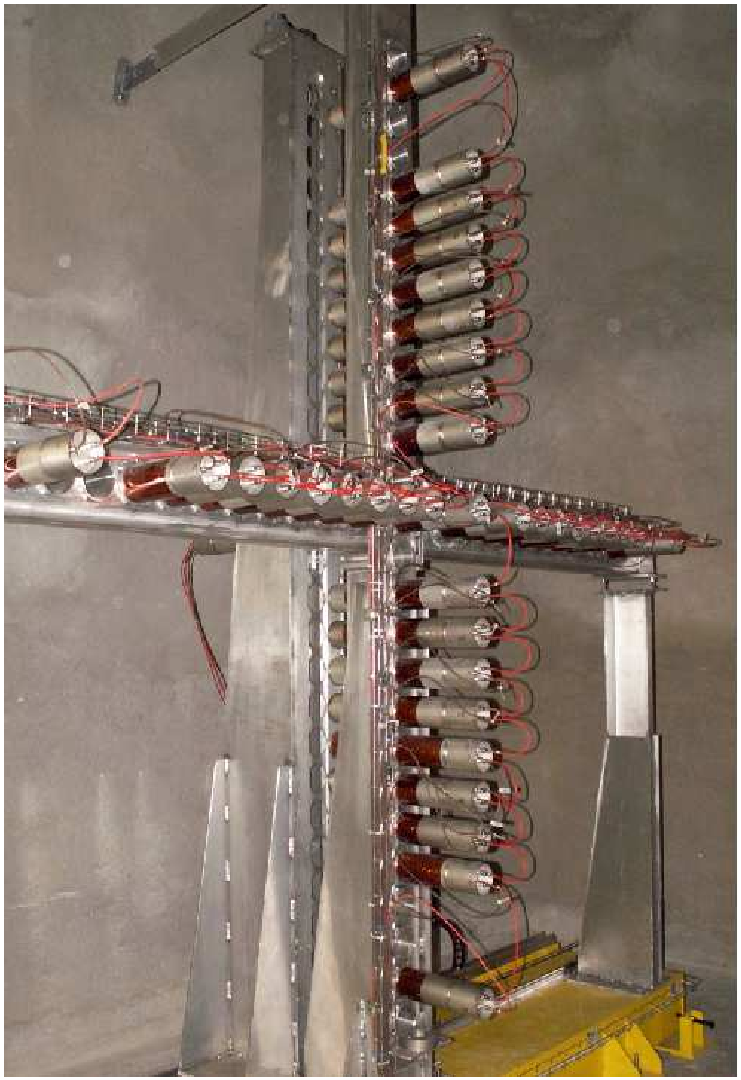
horiz. beam position scan

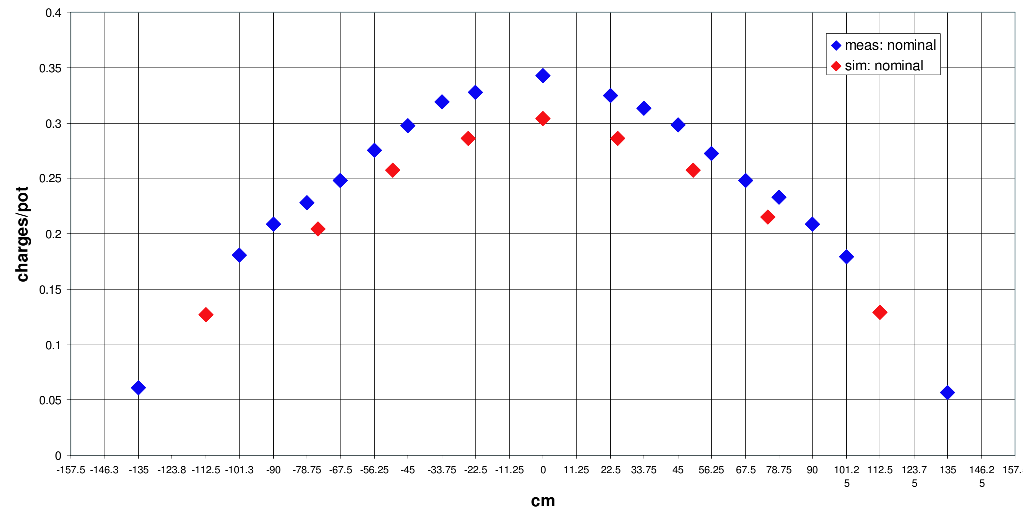
target IN, intensity on TBID vs. BPM2 position

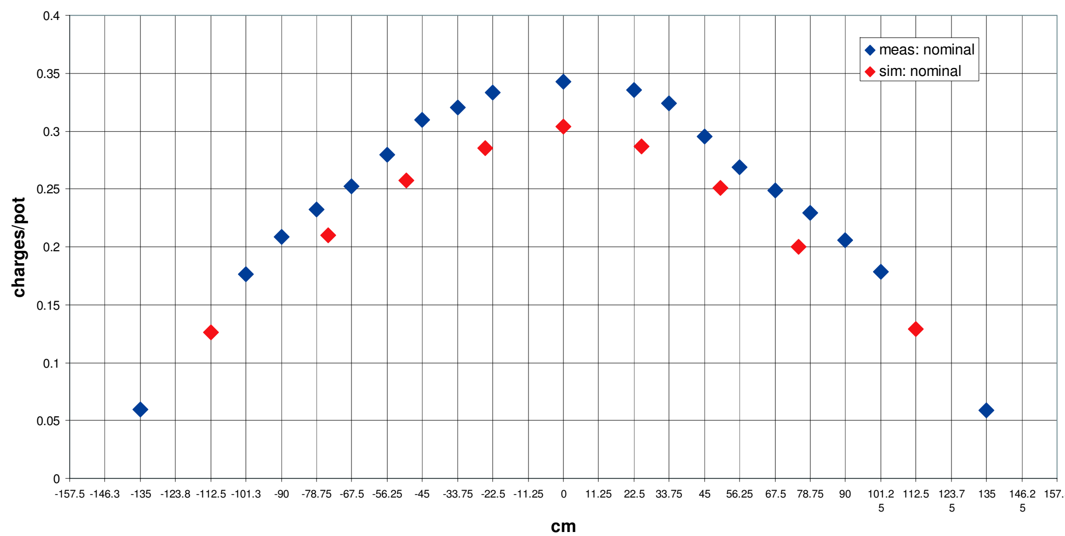
absolute μ signal in first μ-pit PRELIMINARY

37 fixed BLM monitors + 1 movable







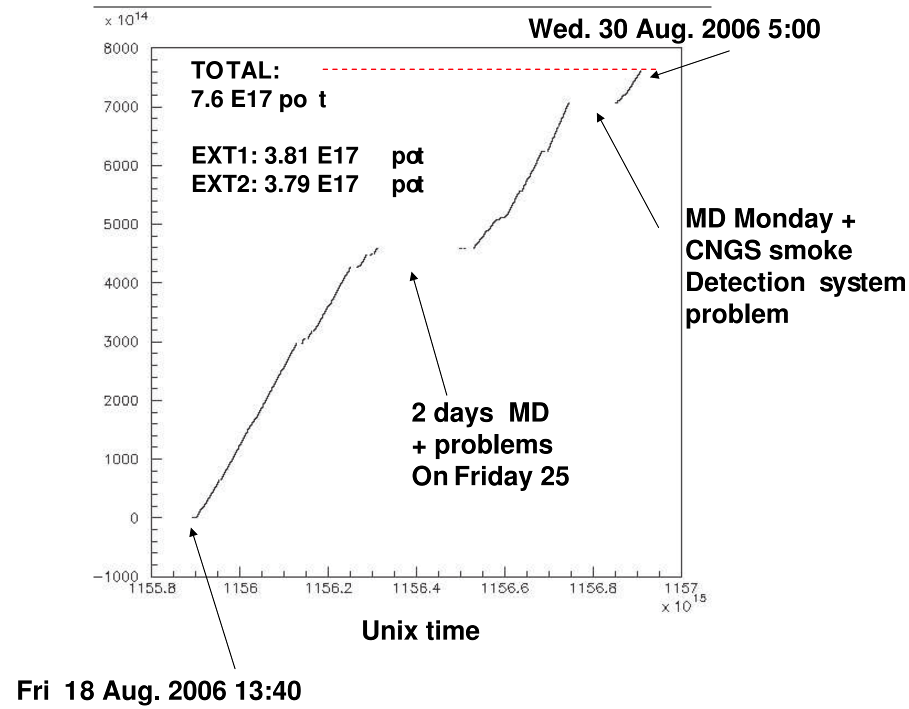


horizontal (top) - vertical (bottom) profiles

neutrino beam: well centered, good initial agreement of data vs. expectations !

Conclusions

- *CERN to Gran Sasso CNGS ν beam was designed for $\nu_\mu \rightarrow \nu_\tau$ oscillation search looking for ν_τ appearance, Δm^2_{23} in $1.5 \div 3.5 \times 10^{-3}$ eV^2*
- *the project was approved on December 1999*
- *civil engineering- equipment design- production and installation phases lasted 6 years and handed over to operation on 18 August 06*
- *commissioning showed that proton beam and secondary beam parameters are within specification*

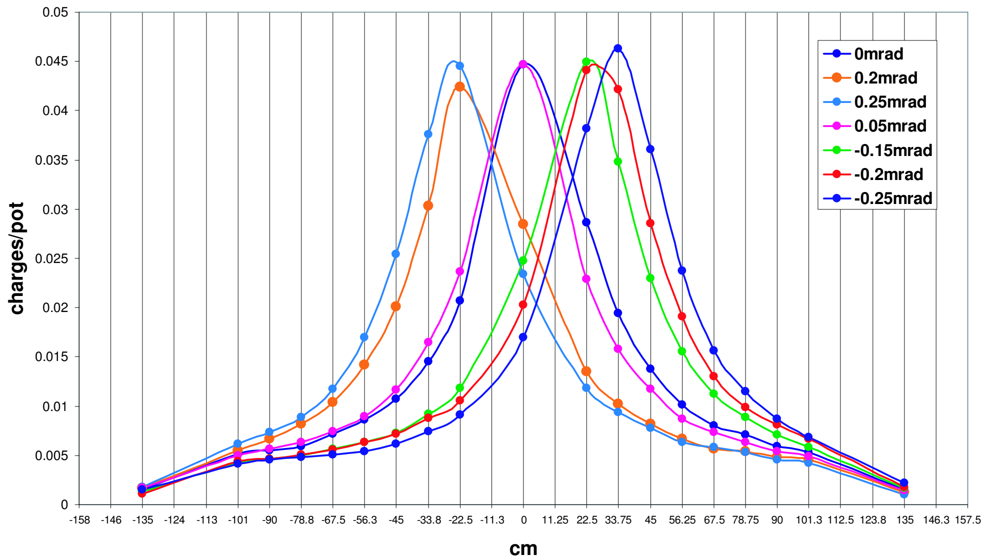


CNGS operations:
1.7×10^{13} *ppp,* 7.6×10^{17} *pot*

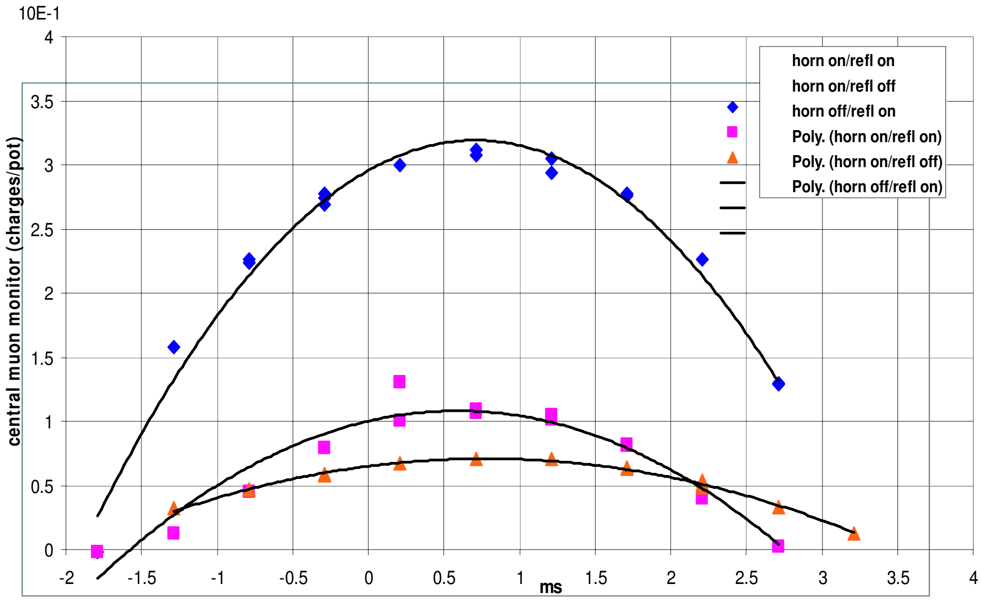
CNGS is operational - now the neutrino beam has to be carefully measured/studied the toughest and more interesting part is still ahead!

thank you to all the colleagues from INFN, CERN and Laboratories all over the world who contributed to the project's success!

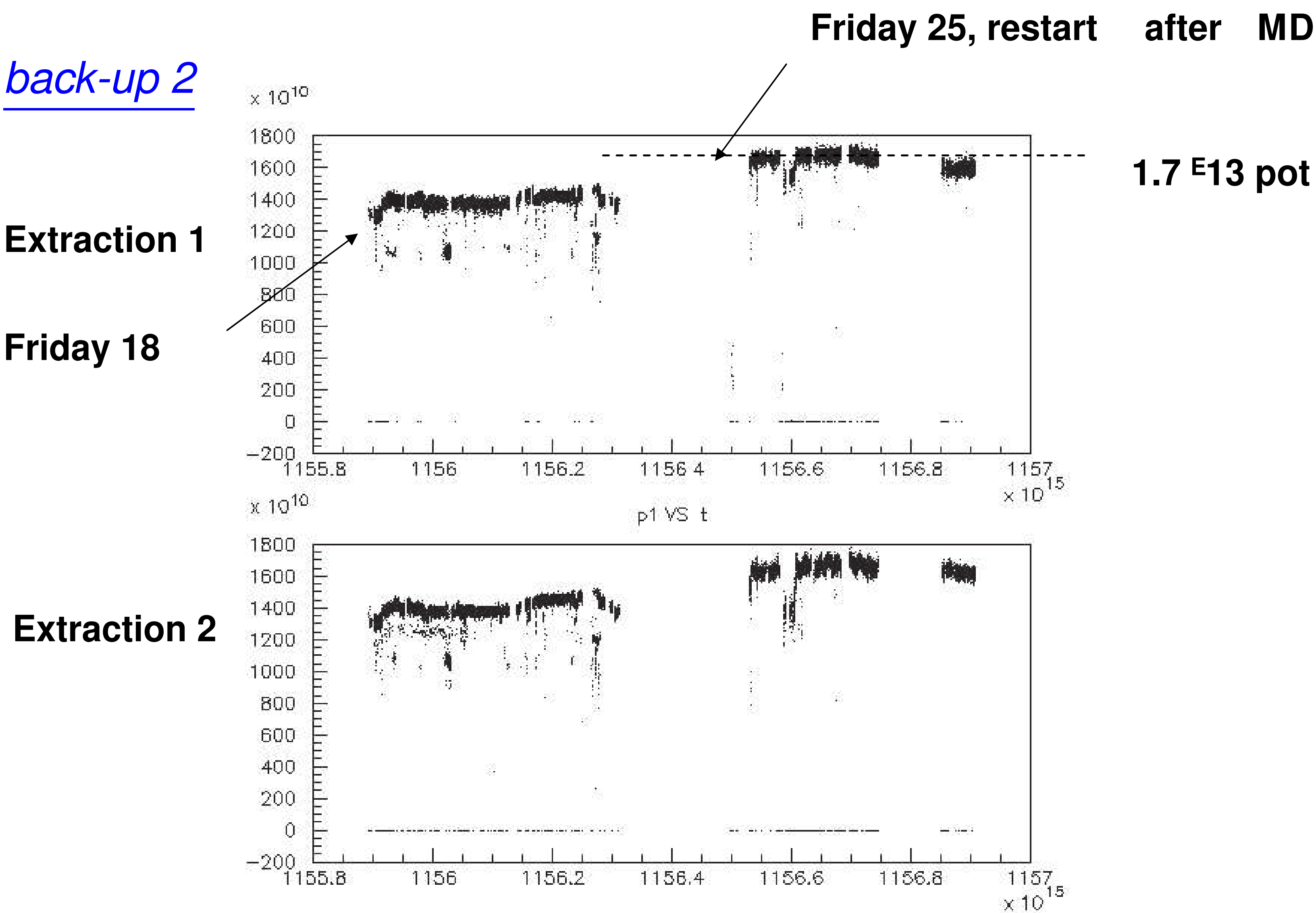
back-up 1



angular scans: response of BLM's in pit-1 target OUT



timing of horn/reflector: responce of central muon monitor *back-up 2*



extraction 1 - 2 in the first operation period