CNGS - Neutrino Beam Studies

> Goals of the CNGS project ¬

ν - oscillation over Long Base-Line ¬ Appearance of ν_τ

>> Optimization of the ν beam line ¬

Simulation tools - Target - Magnetic lenses

>>> Effects of alignment errors ¬

Proton on target - beam line elements

>>>> Monitoring systems along the beam line ¬

At near and far locations

Neutrino Oscillations

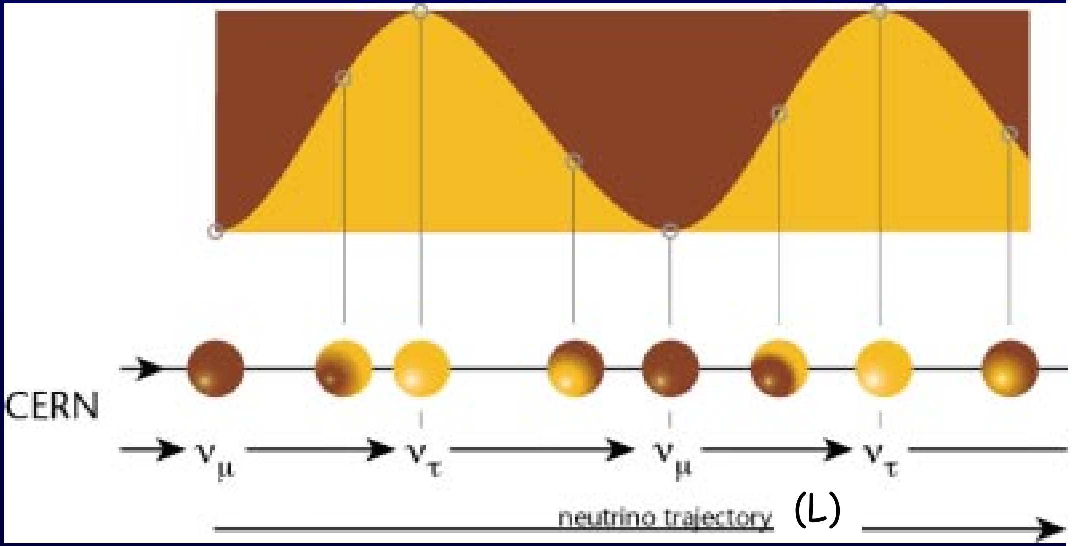
Neutrinos come in three flavors --> ν_e ν_μ ν_τ

neutral particles -- very small mass (zero?) -- weak interaction with matter

ν's can change flavor ?! -->

Yes, "if they have mass"!

$$Osc(\nu_1 \leftrightarrow \nu_2) = A \sin^2(1.27\,(m_2^2 - m_1^2)\,L/E_\nu)$$



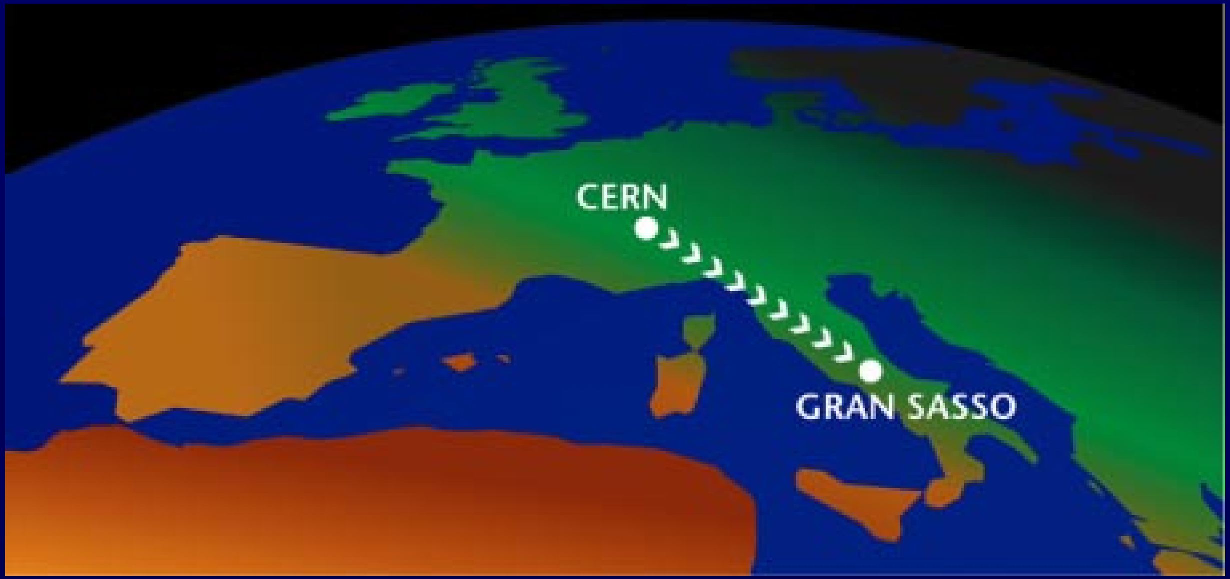
Hints from atmospheric ν experiments: $\nu_\mu \rightarrow \nu_\tau$

$L/E \approx 10^3$ km/GeV

$\Delta m^2 \approx 2.5\ 10^{-3}\ eV^2$

$A = \sin^2(2\theta) \approx 1$

Goal of the CNGS project



“Long Base-Line” $\nu_\mu \rightarrow \nu_\tau$ oscillation experiments

- build an intense ν_μ beam at CERN-SPS
- search for ν_τ appearance at Gran Sasso laboratory (730 km from CERN)

Other projects in the world >>> built to check ν_μ disappearance! <<<

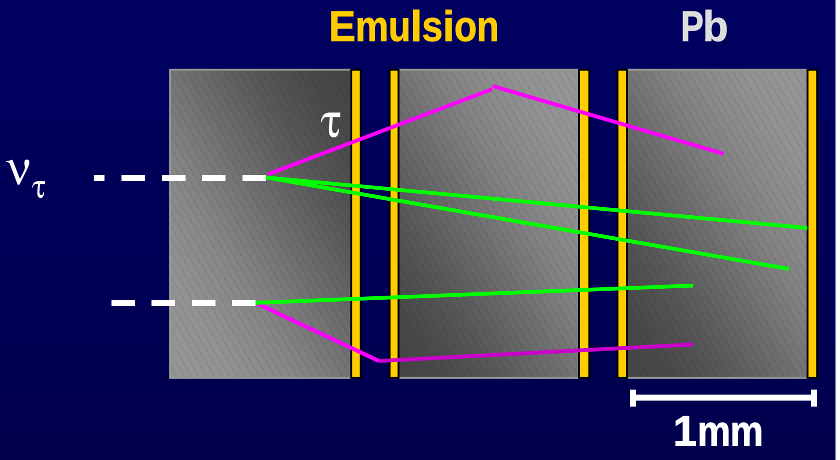
K2K (Japan) running; NuMI/MINOS (US) under construction

At Gran Sasso National Laboratory (LNGS):

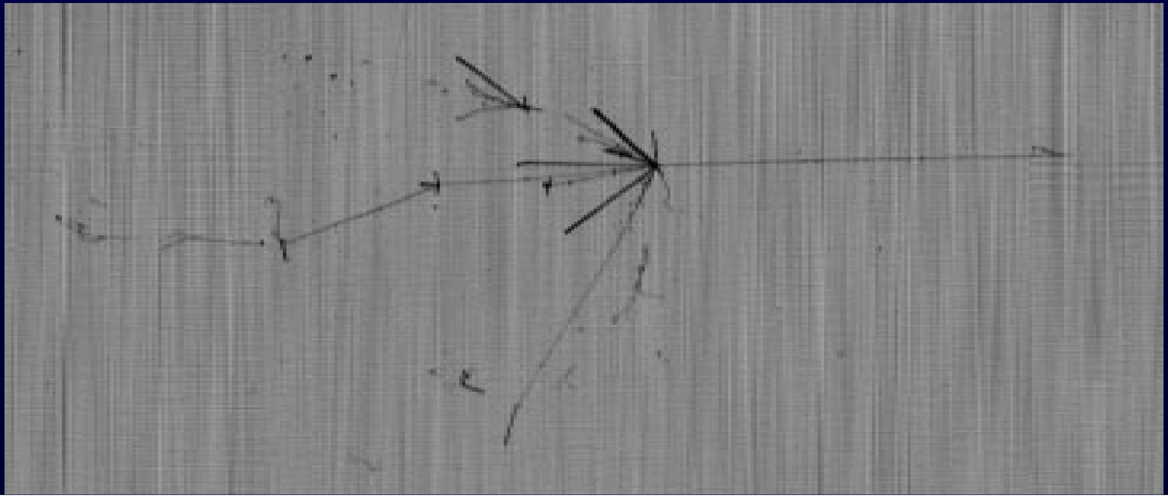
>>>> The Difficult Task: Detect the Tau-Neutrino <<<<

- two experiments in preparation:

1) OPERA --> CNGS1
(> 1 kt emulsion "target")



2) ICARUS --> ...
liquid argon TPC (example from 600 t module)

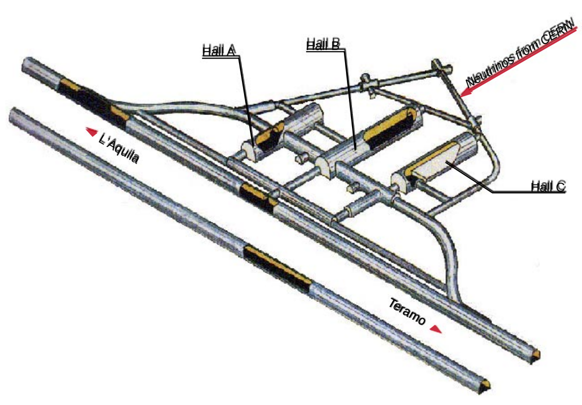


Why LNGS?

existing laboratory with
its infrastructure (since 1987)

Rock shielding from cosmic rays

Large halls directed to CERN

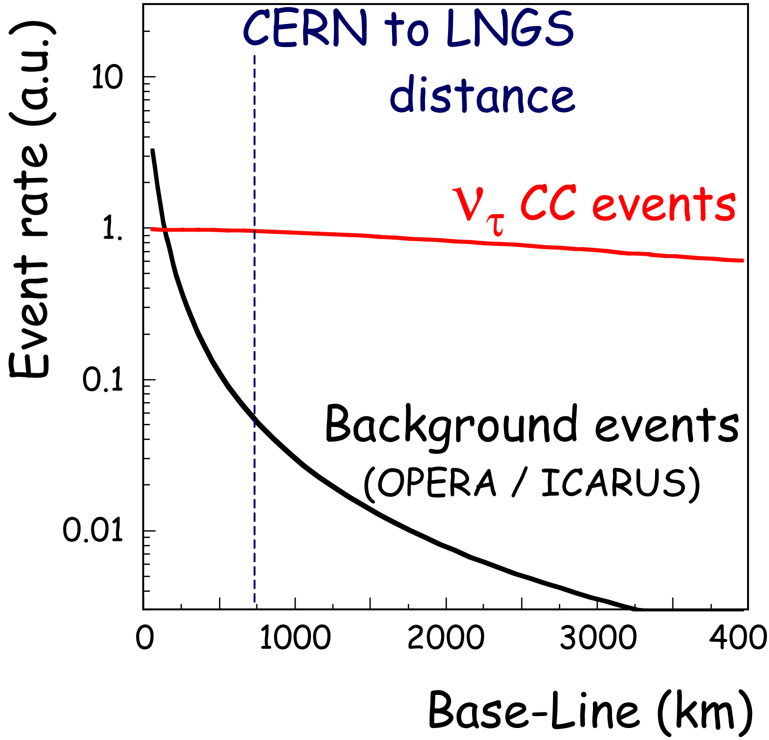


Why Long Base-Line?

Background low enough

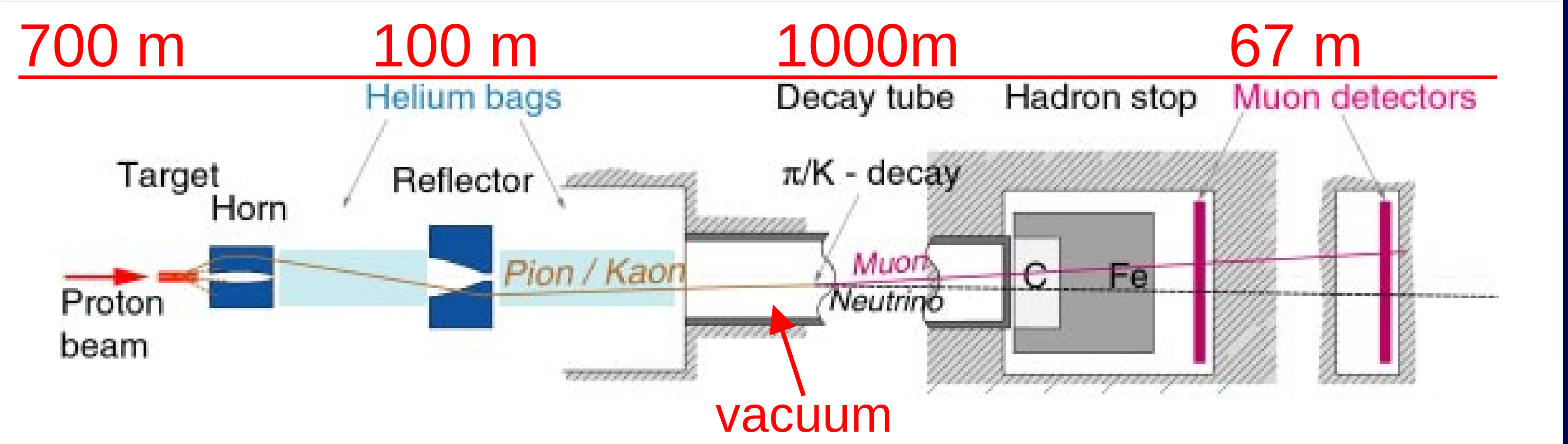
Event rate acceptable
--> 730 km almost perfect

$\Delta m^2 = 2.5\ 10^{-3}\ eV^2$
$\sin^2(2\theta) = 1$



CNGS: the main components

(based on CERN experience: PS / SPS neutrino beams -> WANF)



$p + C \rightarrow$ (interactions) $\rightarrow \pi^+, K^+, (\mu^+) \rightarrow$ (decay in flight) $\rightarrow \mu^+ + \nu_\mu$

+ few % of ($\bar{\nu}_\mu$, ν_e)

protons from SPS: 400 GeV/c, beam-size $\sigma = 0.5$mm

fast extraction (2 x 10 μs) - 2.4 10^{13} pot/spill - rep. rate = 6s

More information:

--> SL Seminar, K. Elsener, 12. 7. 2001

--> http://proj-cngs.web.cern.ch/proj-cngs

Recent ν beam studies

In the framework of the CNGS Secondary Beam Working Group

May 1999:	CNGS beam optimized for ν_τ appearance at LNGS
Sep. 2000:	"Workshop on Neutrino Beam Instrumentation" (K2K, NuMI, MiniBoone and CNGS presentations)
Dec. 2000:	"CNGS: Update on secondary beam layout" SL-Note 2000-063 EA
Feb. 2001:	"On Particle Production for High Energy Neutrino Beams" CERN-SL-2001-005 EA / Eur. Phys. J. C20 (2001) 13-27
May 2001:	"CNGS: effects of possible alignment errors" CERN-EP-2001-037 / CERN-SL-2001-016 EA
Oct. 2001:	…

CNGS Optimization

CNGS beam-line layout. Goal:

maximize neutrino flux in the LNGS direction

Improvements w.r.t. WANF-WBB:

--> increase intensity (proton on target)

--> improve focusing (target / horn / reflector layout)

--> increase size (decay length and width)

--> reduce material in horn/reflector and along beam-line

--> better knowledge of beam spectra (MC simulations)

Neutrino beam simulation tools

Requirements:

Detailed secondary particle production (π/K) in target

(including re-interactions due to hadronic cascade development)

3-D transport/decay of parent mesons/muons along beam-line

Available codes:

FLUKA Stand-alone

NEOBEAM (GEANT3 + FLUKA)

Very time-consuming due to LBL

1 pot → 10^{-6} neutrinos at LNGS

Hours for few % statistical accuracy:

Needed for final validation of beam layout and characteristics

Fast alternative:

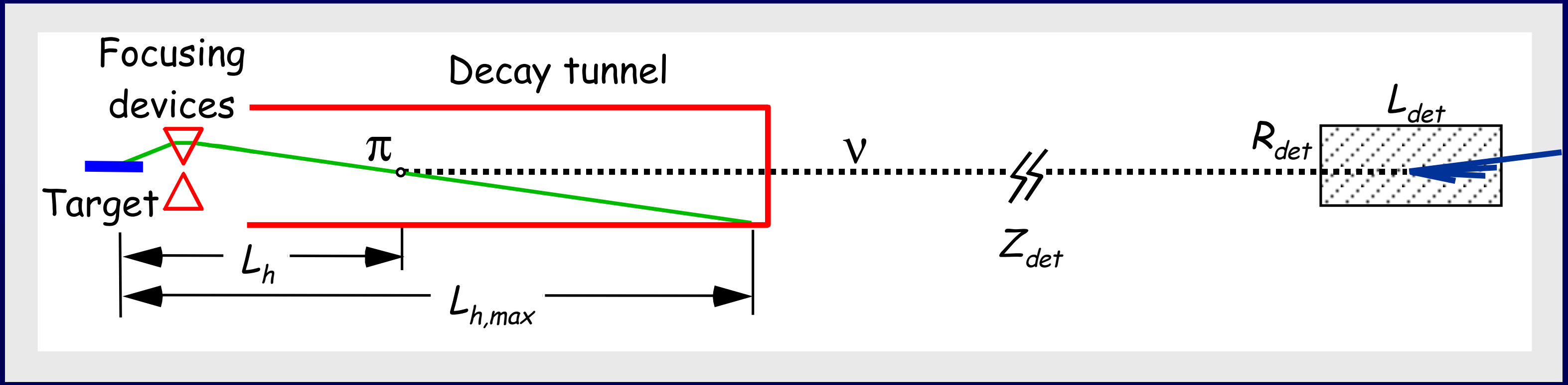
Parameterization of secondary particle production

+ fully biased tracking and decay kinematics

few % statistical accuracy in minutes

Useful during any optimization phases

A fast neutrino beam simulation:
phase-space weighting



$$W = \left[\left(1 - e^{-\frac{L_{h,MAX}}{\lambda_h}}\right) e^{-\frac{L_h}{\lambda_h}} \right] \left[e^{-\frac{L_{mat}}{\lambda_{int}}} \right] \left[BR \rightarrow \begin{matrix} \nu_\mu \mu \\ \nu_e X \end{matrix} \right] \left[\left(\frac{m_h}{E_h - p_h \cos\theta_{\nu h}} \right)^2 \right] \left[\sigma_0 \frac{m_h^2 - m_{\mu,X}^2}{2m_h} \frac{m_h}{E_h - p_h \cos\theta_{\nu h}} \right] \left[\frac{\pi R_{det}^2}{4\pi Z_{det}^2} N_A \rho_{det} L_{det} \right]$$

Hadron decay probability inside the tunnel

Interact. in material

2/3 body decay branching ratio

Probability that the ν is emitted in the detector direction

ν energy (E_ν) in lab frame

Total ν interaction cross-section (σ_0 E_ν)

Solid angle

Nucleon target density in the detector

1 meson = 1 neutrino !

BMPT parameterization of secondary particle yields from proton interactions on light nuclei

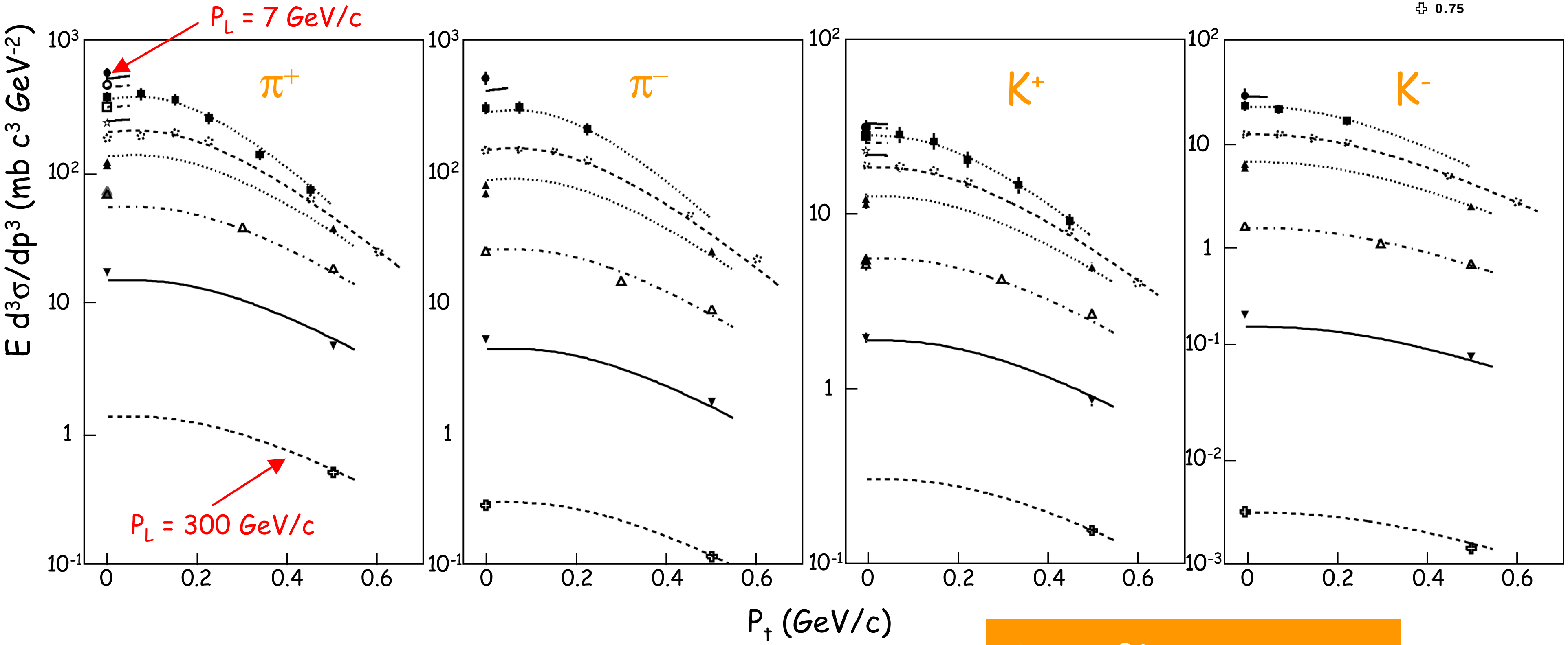
Empirical formula based on general physical arguments

M. Bonesini et al. (BMPT collab.), Eur. Phys. J. C 20 (2001) 13-27

Fit free parameters on exp. data from 400/450 GeV p-Be interactions

H.W. Atherton et al., CERN 80-07, 1980

G. Ambrosini et al. (SPY collaboration), Eur. Phys. J. C10 (1999) 605



Few % accuracy

BMPT parameterization:

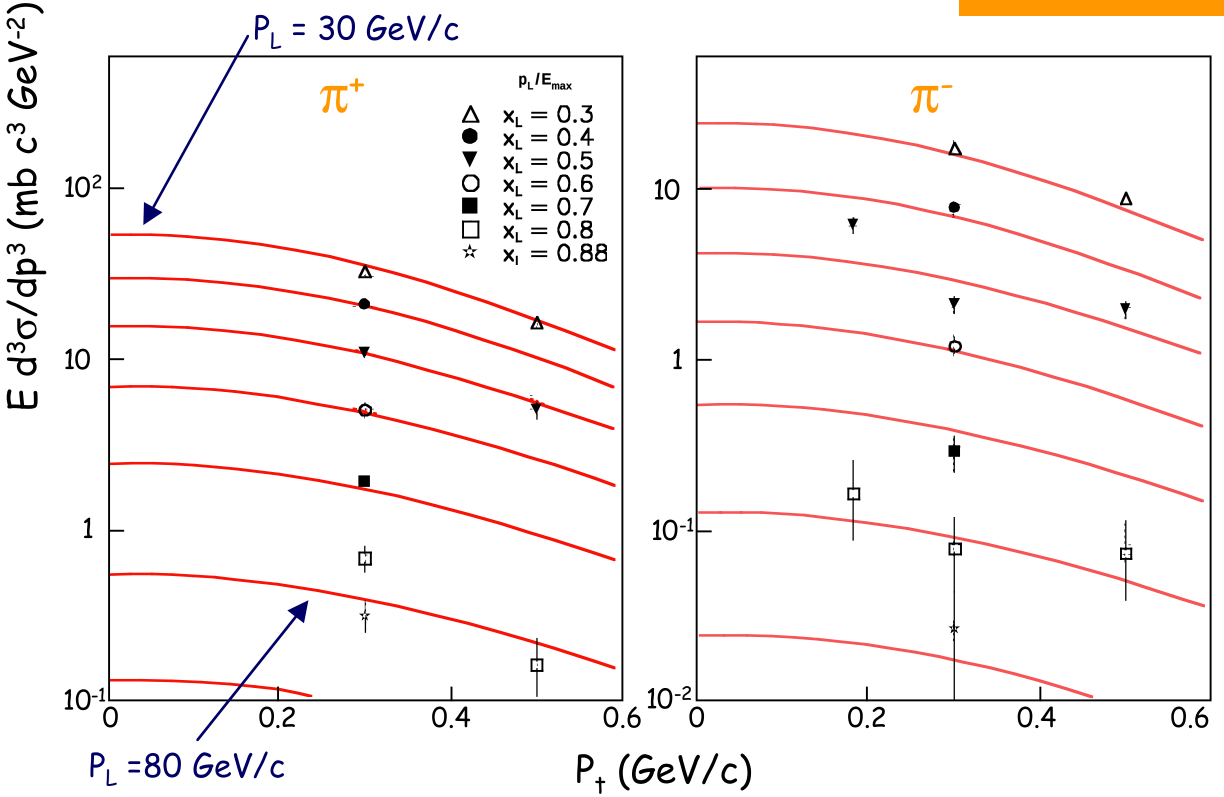
Scaling to different proton energy & target material

Well known dependence on Atomic Number and *x*.

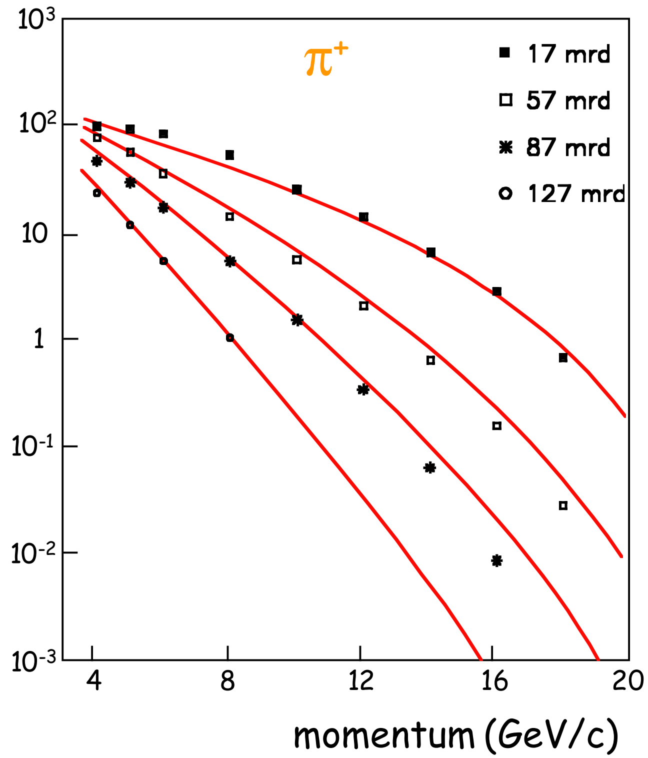
Comparison with exp. data

Validate the model

Barton et al.,
100 GeV/c p → C



Eichten et al.,
24 GeV/c p → Be



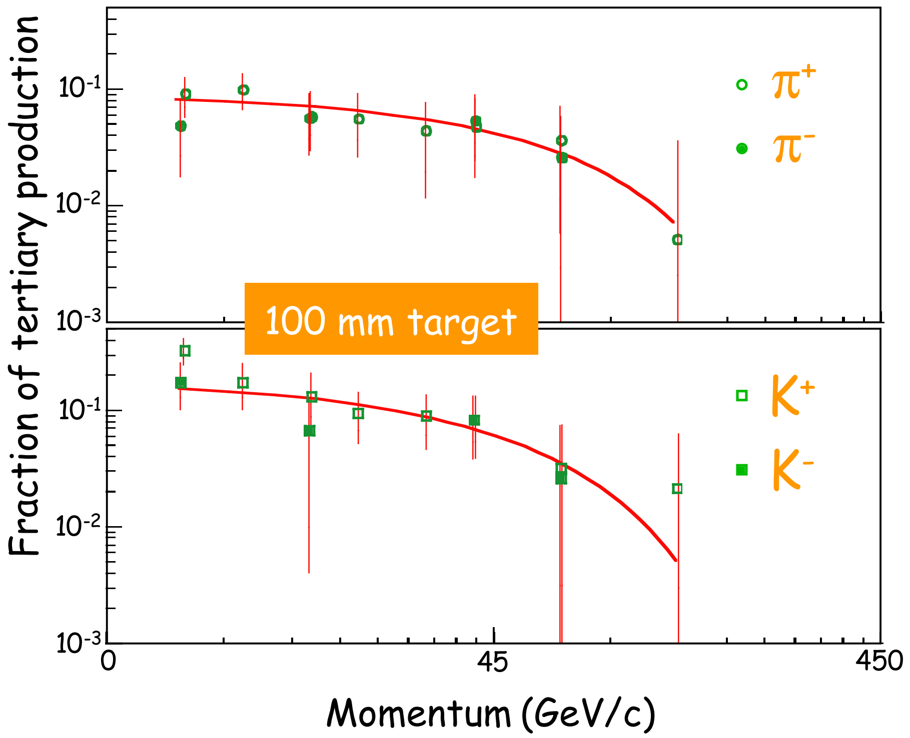
BMPT parameterization:

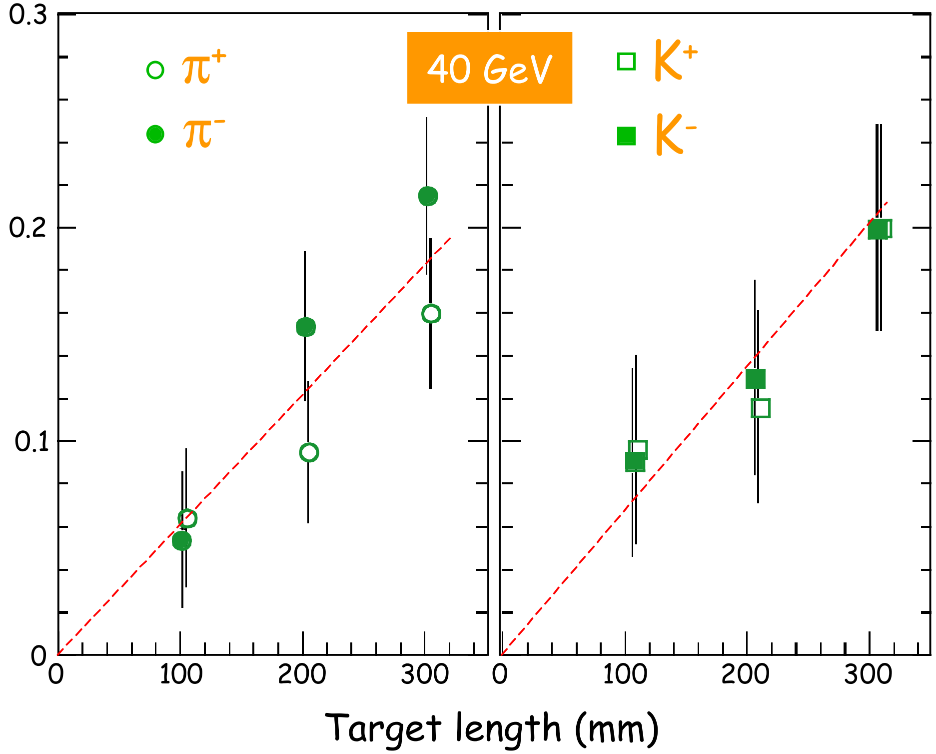
Secondary particle yield for finite length target

Accounting for forward-going leading particles
re-interactions (target geometry dependent)

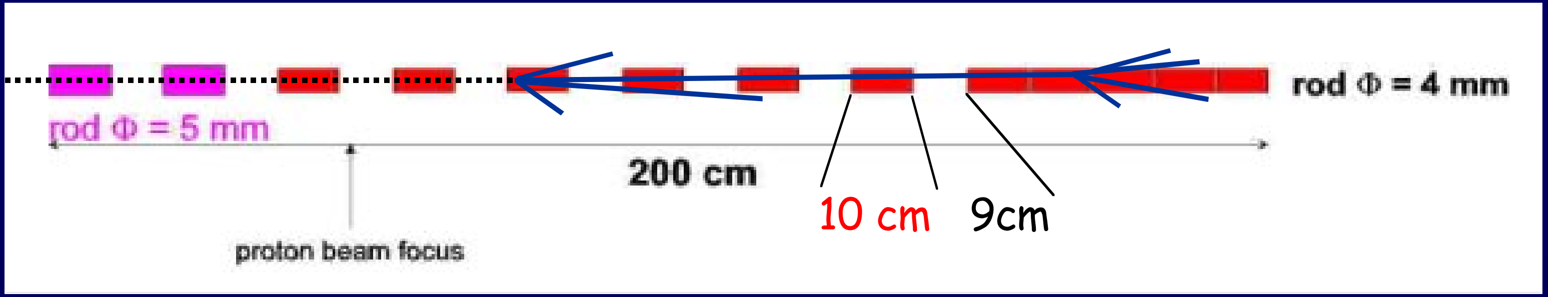
Comparison with SPY data from targets of different lengths

Important for long neutrino targets





CNGS target layout



Improved "WANF geometry":

Low Z material (Carbon)

to maximize secondary part. yield

Length ≈ 130cm (3 interaction lengths)

to absorb most protons

Ø = 4mm to 5mm

for full containment of p-beam

NOTE: Ø = 4 mm preferable to

maximize pion yield

Ø = 5 mm preferable for

target lifetime (heat dispersion)

proton beam alignment accuracy

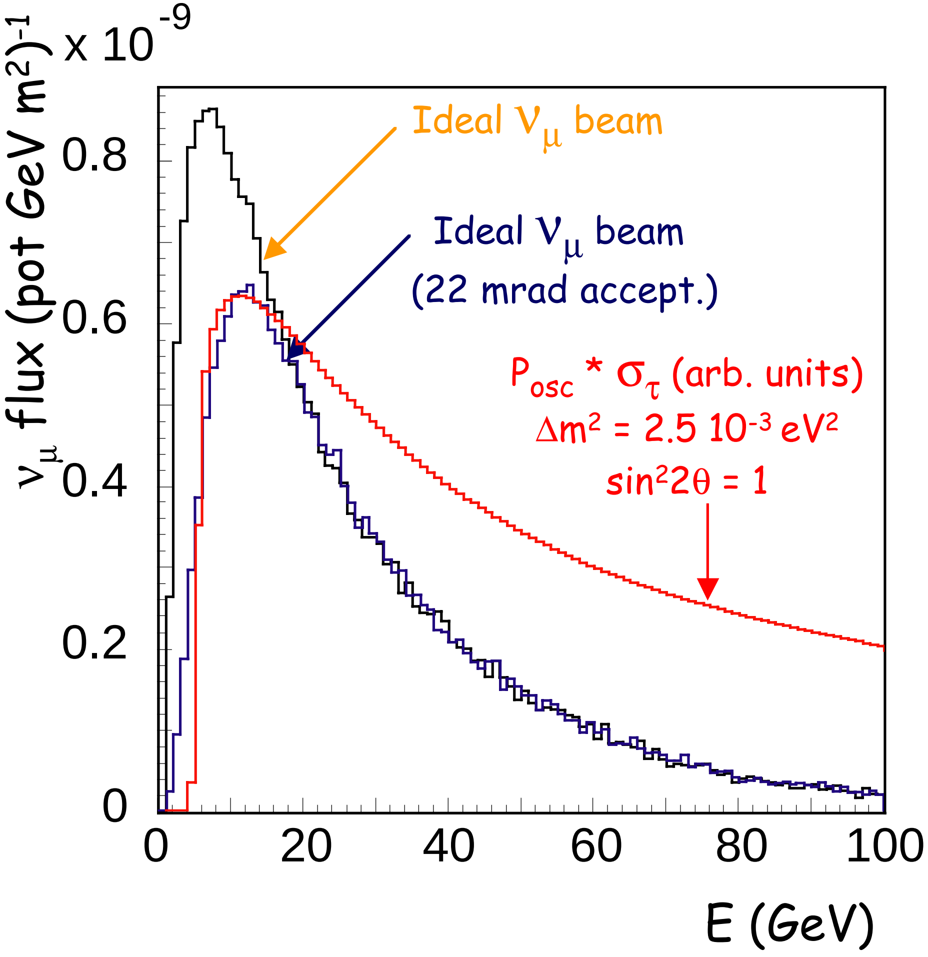
Interspaced layout

to "let the pions out" from sides

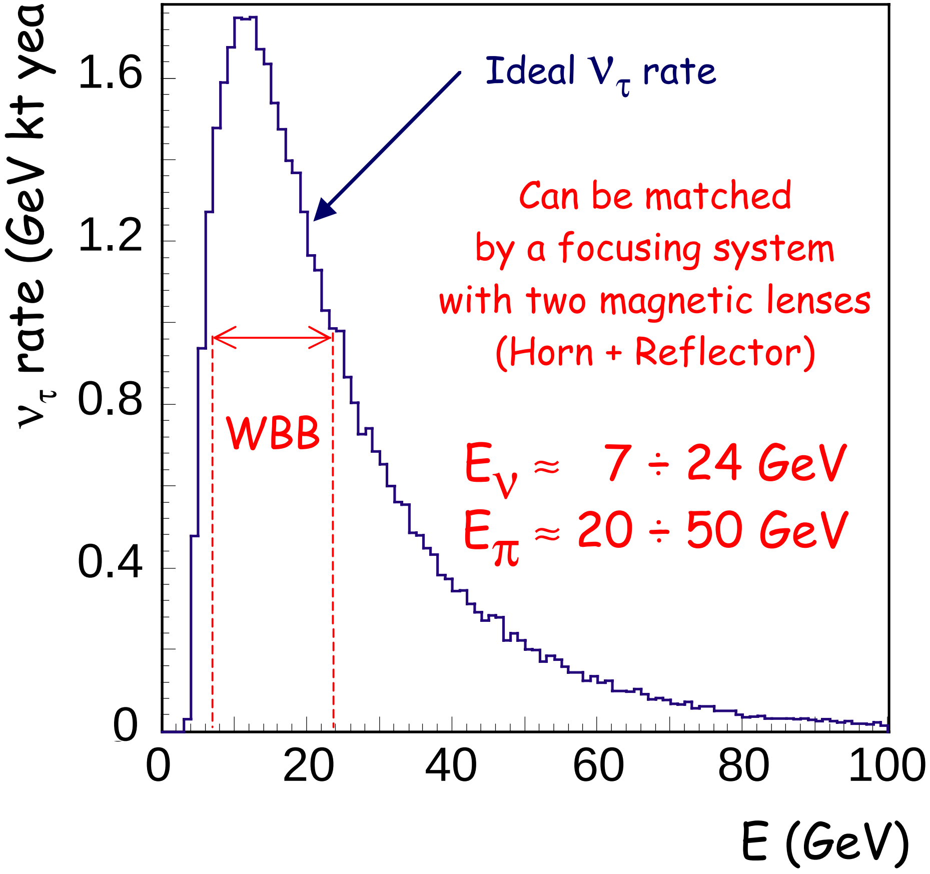
End "plug" (no rod spacing) to induce re-interaction of high energy pions

CNGS optimization: ν_τ appearance at Gran Sasso

Ideal neutrino beam: p_t=0 for all positive π/K -- No material -- $E_\nu = 0.42\ E_\pi$



Goal : best ν_τ beam



Can be matched
by a focusing system
with two magnetic lenses
(Horn + Reflector)

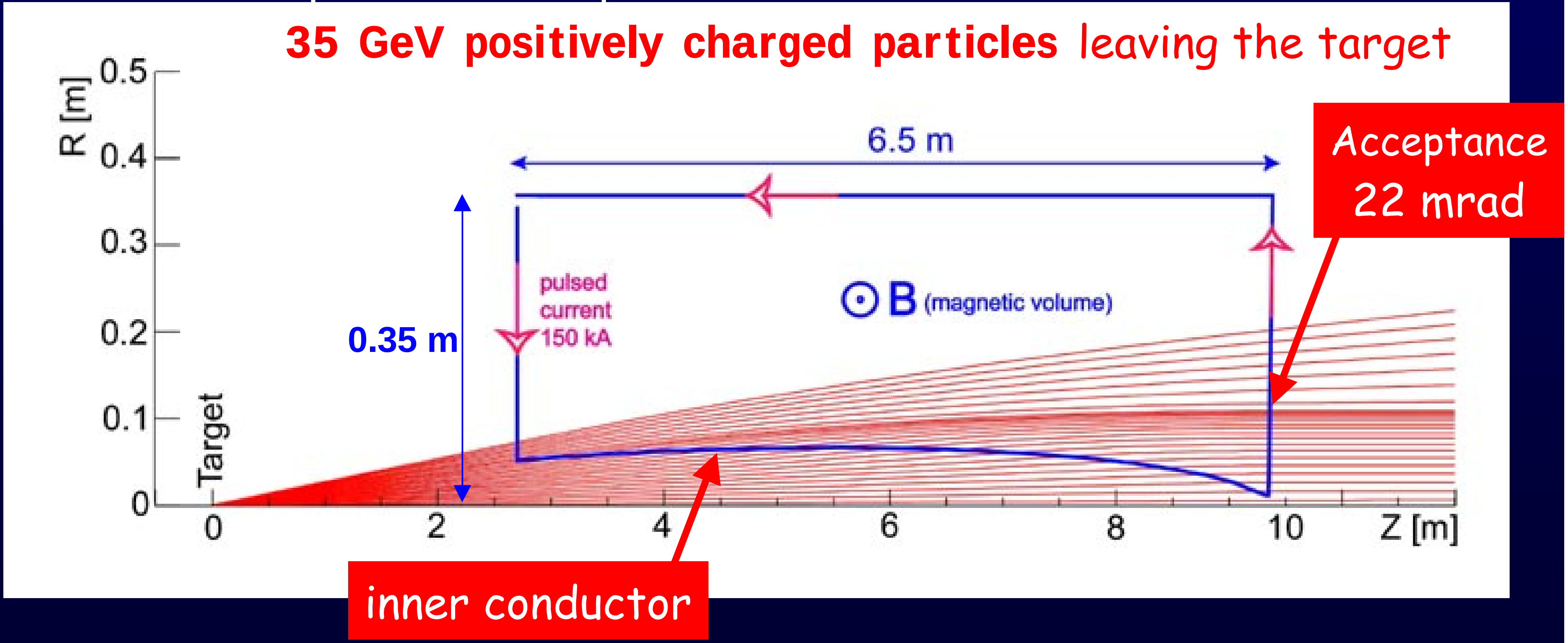
$E_\nu \approx 7 \div 24$ GeV
$E_\pi \approx 20 \div 50$ GeV

Principle of focusing with a Magnetic Horn

Magnetic volume given by "one turn" at high current ($B \approx I / r$):

- cylindrical outer conductor
- deflection proportional to ($B\,dL / p$)
- "parabolic" shape of inner conductor to focus

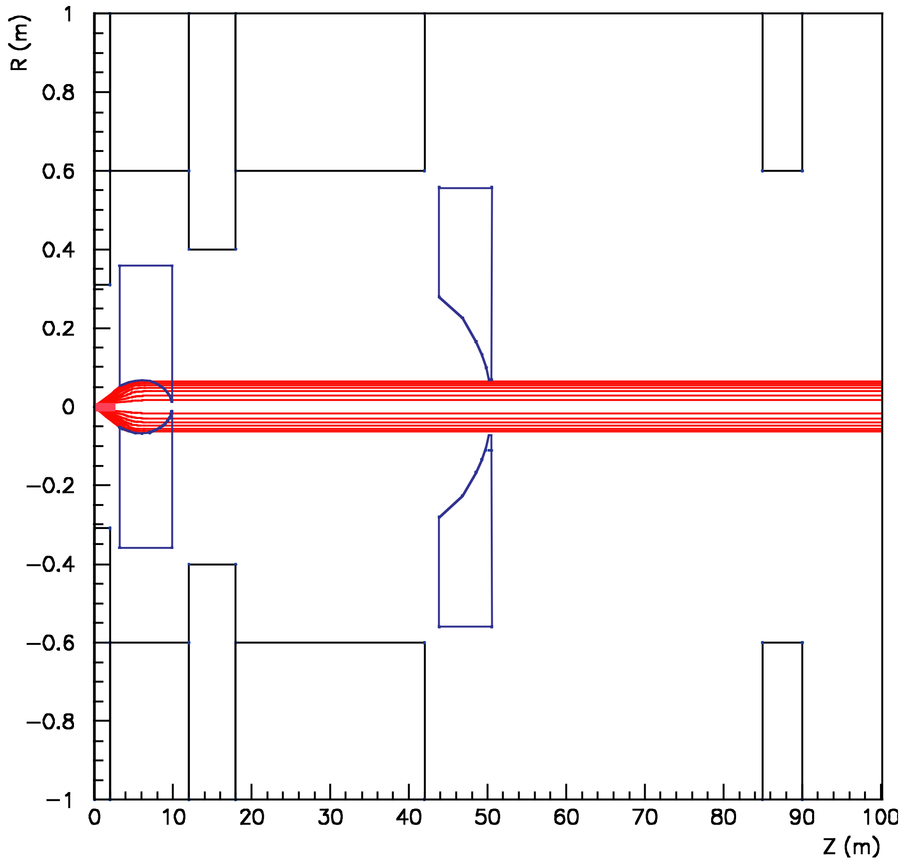
35 GeV positively charged particles leaving the target



Acceptance 22 mrad

inner conductor

Horn / Reflector: secondary beam focusing



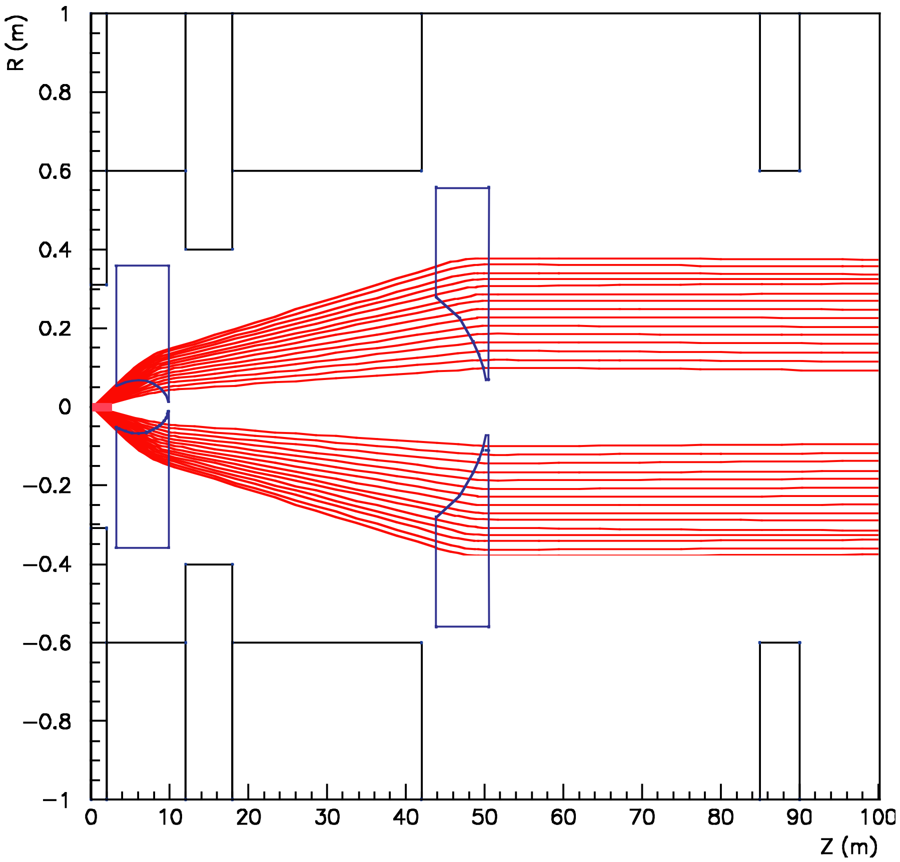
Horn Focusing:

positive particles trajectories

$p = 35$ GeV

$p_t = 80 - 680$ MeV

Horn / Reflector: secondary beam focusing



Reflector Focusing:

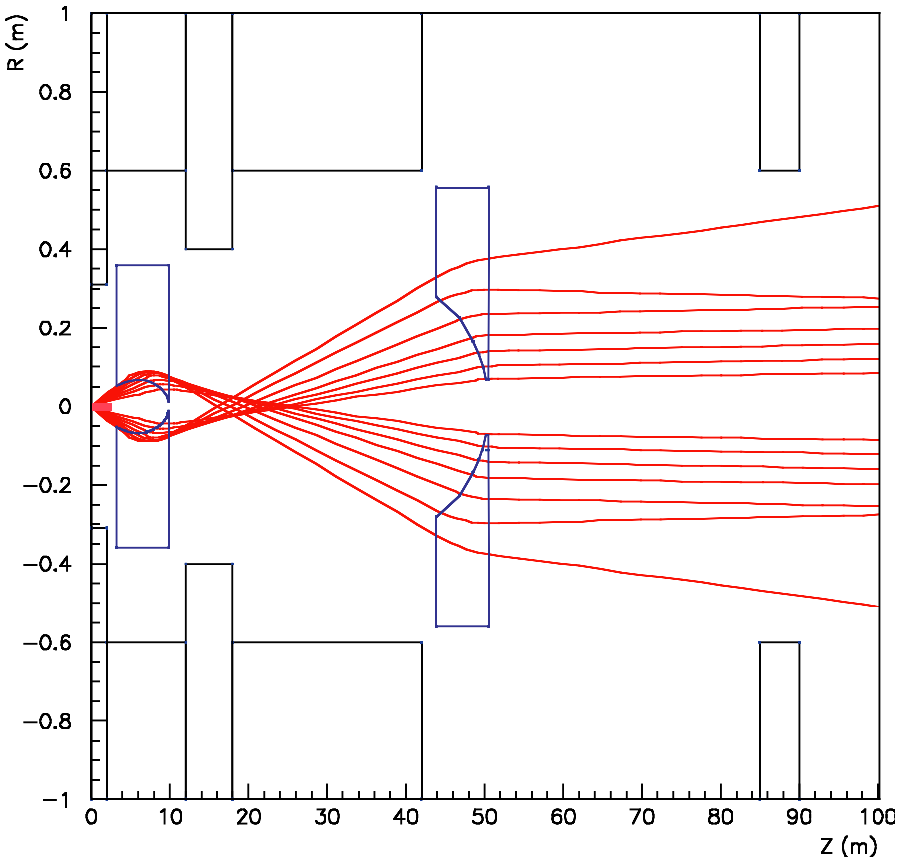
positive particles trajectories

$p = 50$ GeV

$p_t = 180 - 780$ MeV

(horn under-focused)

Horn / Reflector: secondary beam focusing



Reflector Focusing:

positive particles trajectories

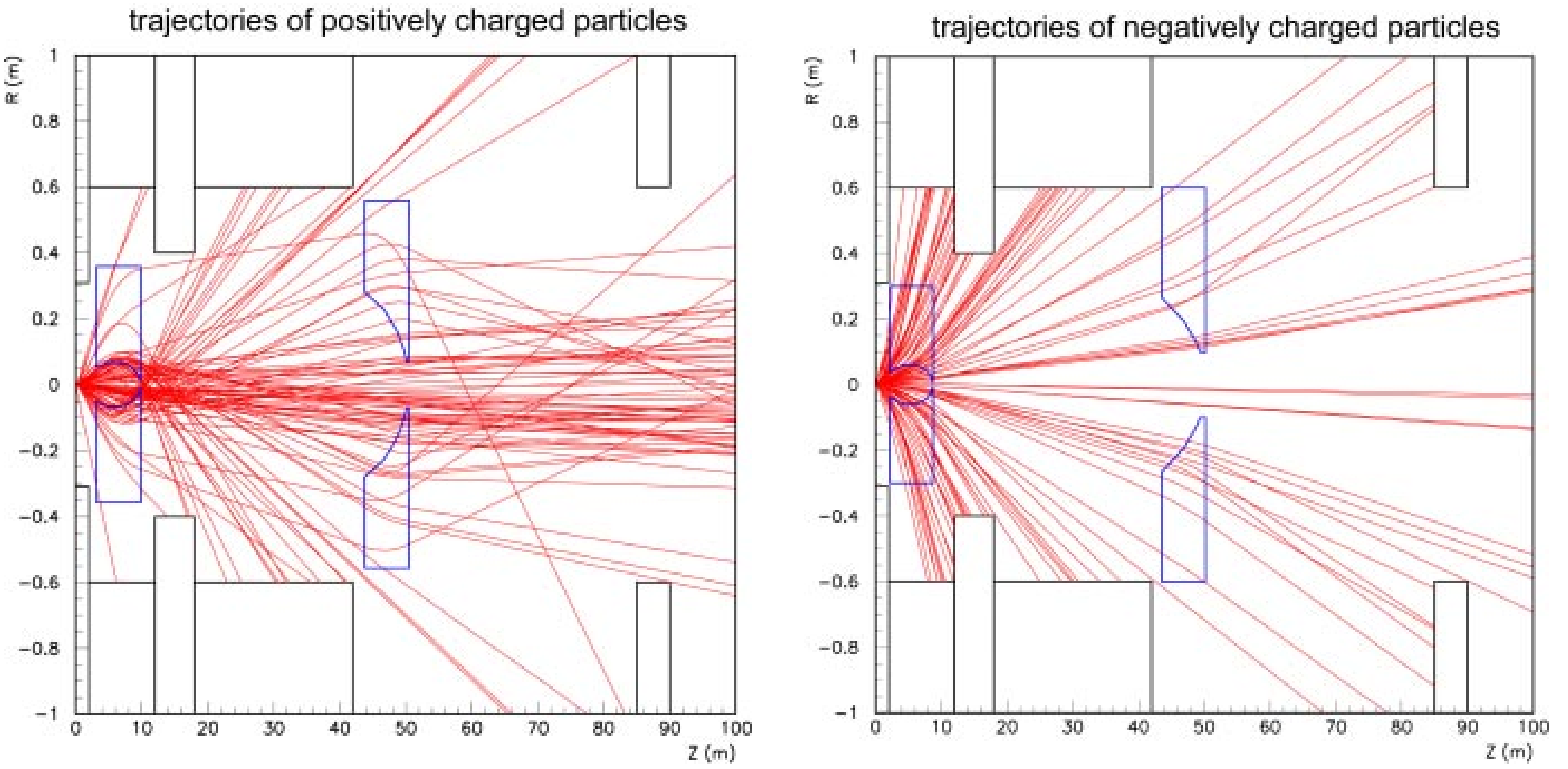
$p = 22$ GeV

$p_t = 100 - 400$ MeV

(horn over-focused)

Horn / Reflector: secondary beam focusing

Focused range = 20 ÷ 50 GeV



CNGS -- "Magnetic Horn" characteristics

Length: 6.5 m -- Diameter: 70 cm -- Weight: 1500 kg

Pulsed devices: 150kA (horn) / 180 kA (reflector), 1 ms

Water-cooled: distributed nozzles

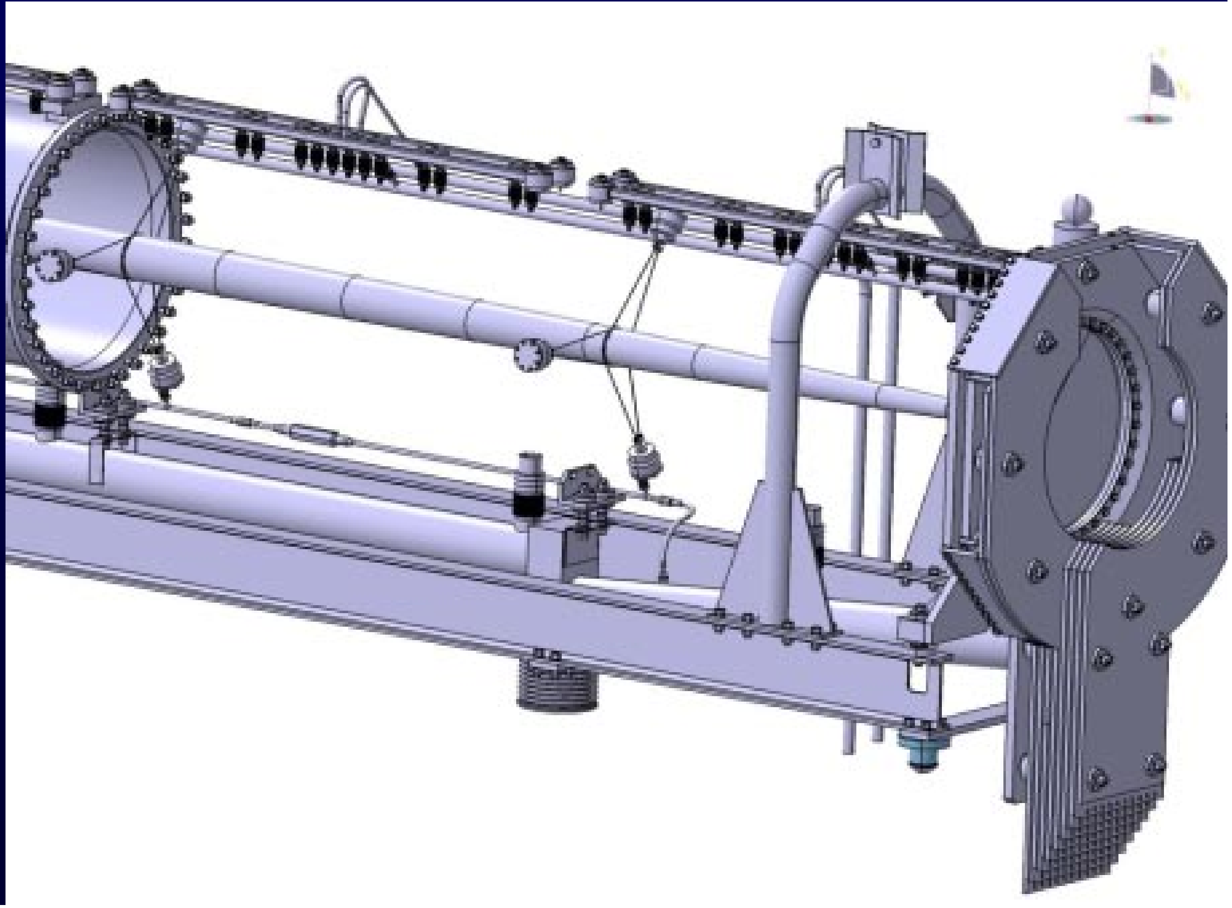
The inner conductor:

nearly parallel to
particle trajectories

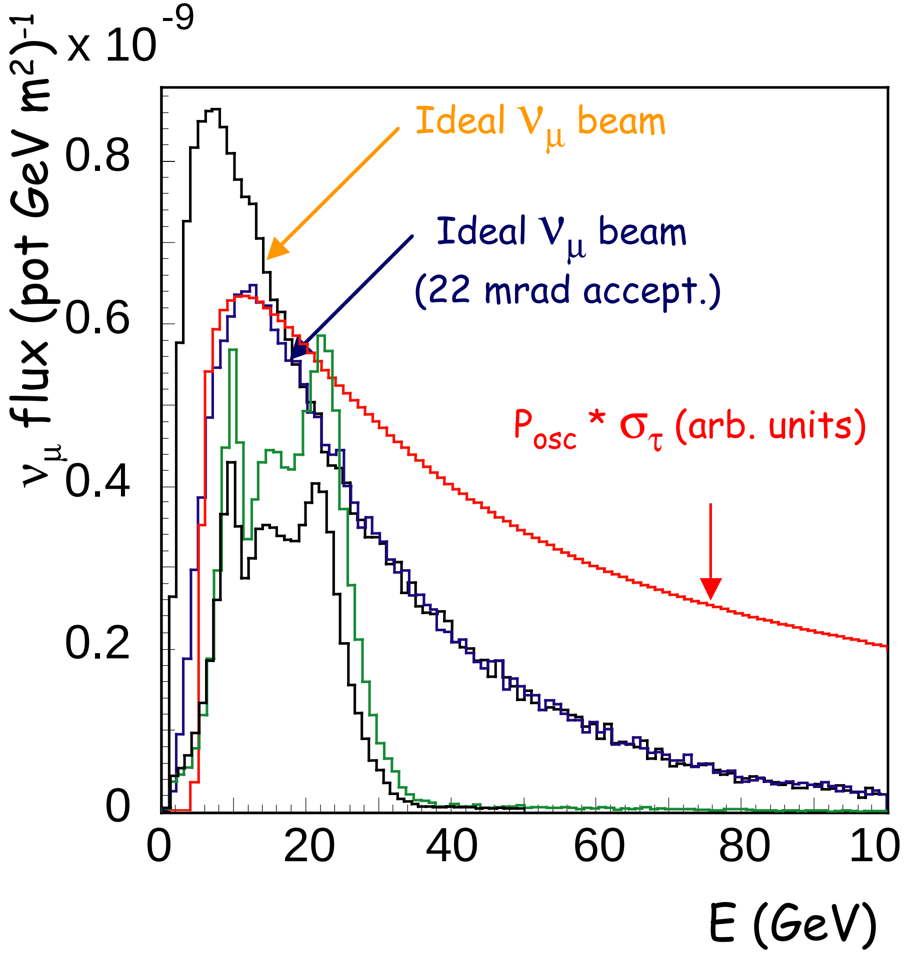
- as thin as possible
  (particle absorption)
- as thick as necessary
  (mechanical stability)

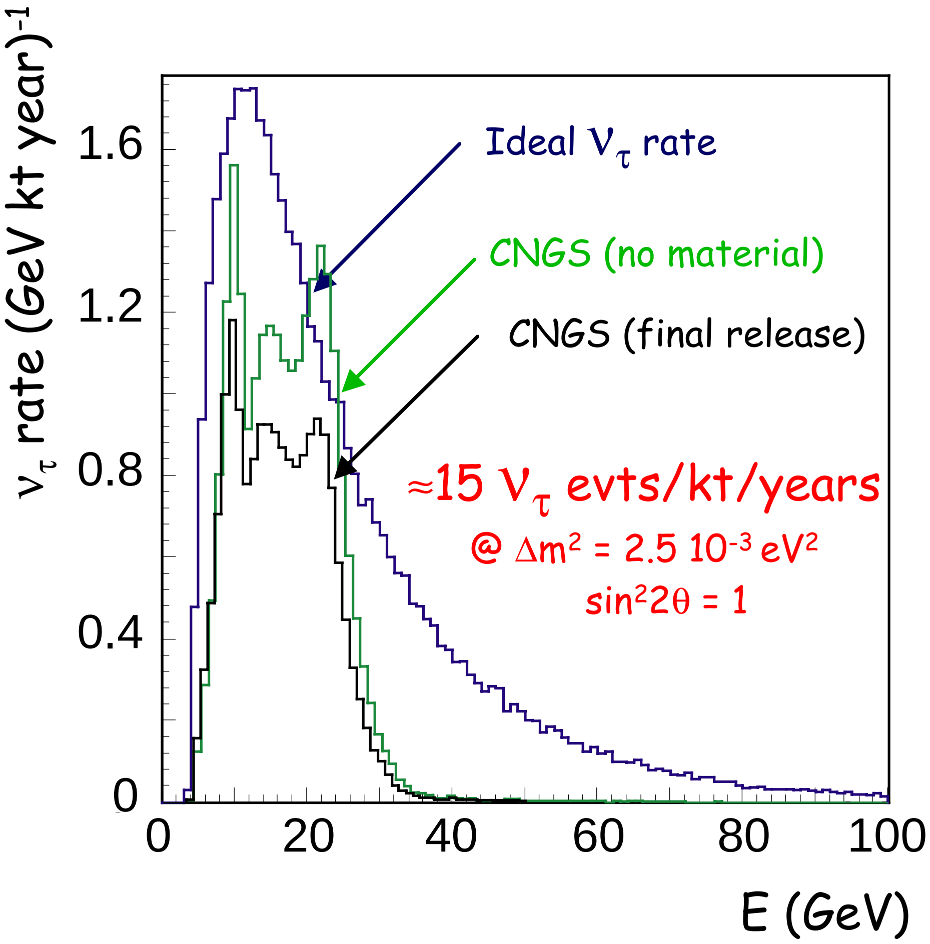
--> 2mm thick

--> 0.2 mm profile
accuracy



CNGS optimization: ν_τ appearance at Gran Sasso





$\approx 15\ \nu_\tau$ evts/kt/years

@ $\Delta m^2 = 2.5\ 10^{-3}\ eV^2$

$\sin^2 2\theta = 1$

Recent changes to CNGS layout

May 1999: CNGS beam optimised for ν_τ appearance at LNGS

Nov 2000: >>> hard work for Secondary Beam Working Group <<<

--> change of focusing (target / horn / reflector layout)

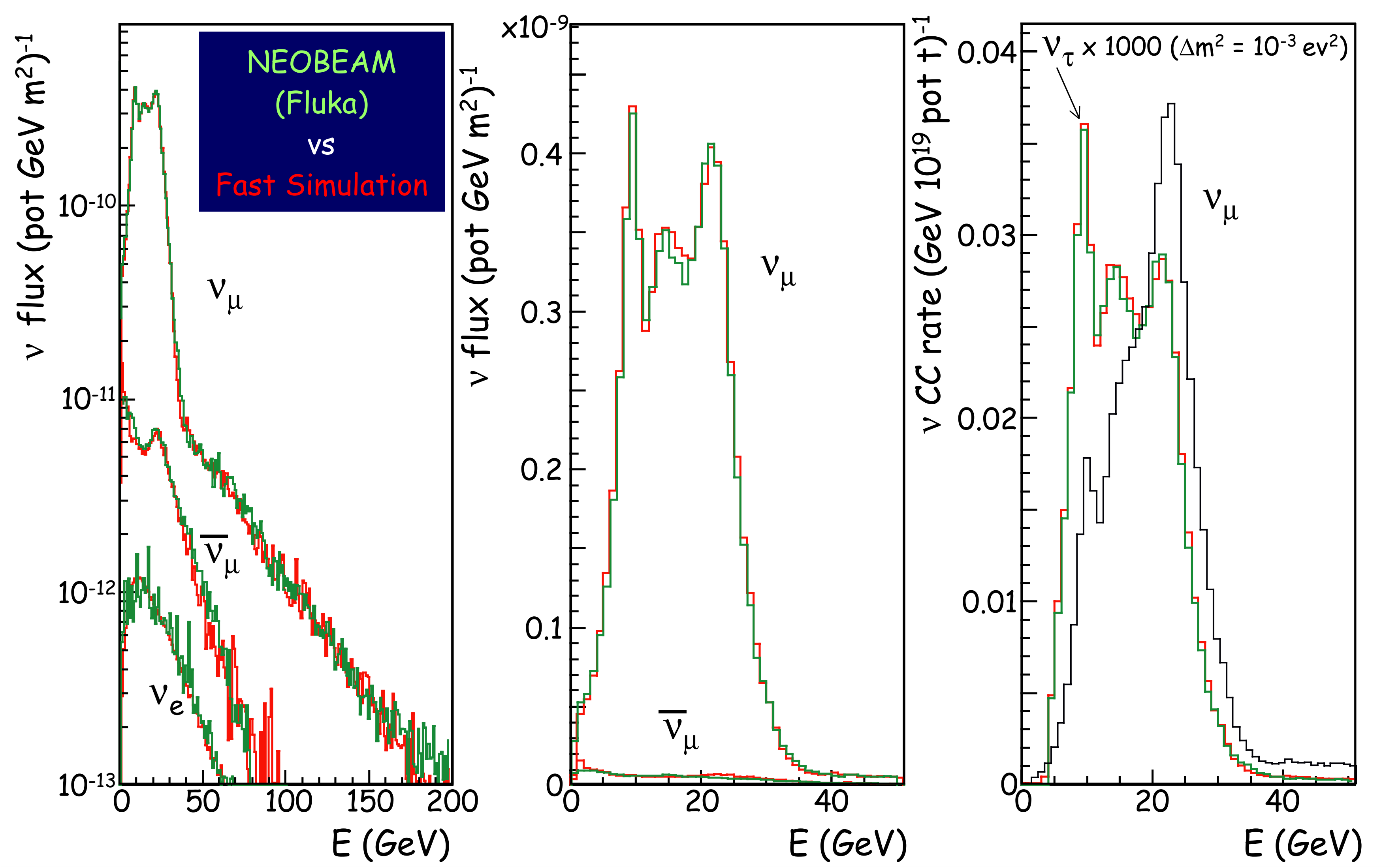
--> reduction of material in horn and reflector

--> increase current in horn and reflector
(WANF: 100 kA --> CNGS 1998: 120 kA
--> 1999: 150 kA
--> 2000: 150/180 kA)

Result: few % increase in ν_τ events rate at LNGS

CNGS beam validation:

Beam release from: “CNGS: Update on secondary beam layout”, SL-Note 2000-063 EA



Expected rates:

In 1 year of CNGS operation, we expect:

(4.8x10^{13} protons in SPS, 55% efficiency -- 1997)

protons on target	4.5 x 10^{19}
ν_μ in 100 m^2 at Gran Sasso	3.5 x 10^{13}
ν_μ "Charged Current" ($\nu + N \to N' + \mu$) events per kt	≈ 2600
Other "flavours" ν events: $\bar{\nu}_\mu$	55 (2.1%)
ν_e	21 (0.8%)
$\bar{\nu}_e$	2 (0.07%)

... In case of $\nu_\mu \to \nu_\tau$ oscillations ...

Δm^2 (oscillation parameter)	1	2.5	5	10^{-3} eV^2
ν_τ "detectable" events	2.5	15	60	

Effects of Alignment Errors

Optimization process:

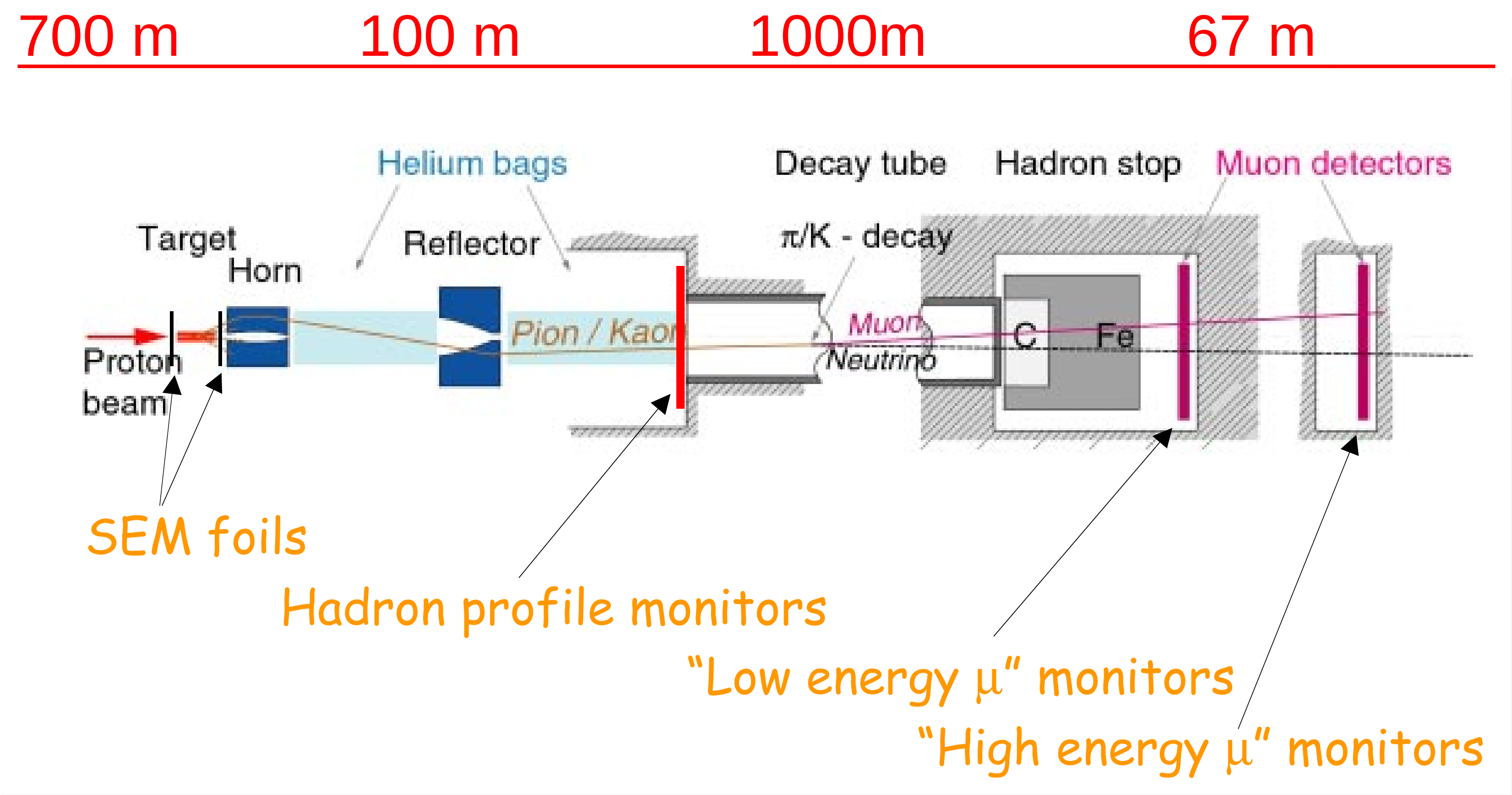
- Ideal alignments of beam-line
- Hard time to get few % increase in beam intensity at LNGS

Real world:

- Mis-alignments of beam-line elements:
  - Proton beam / Target
  - Horn / Reflector
  - (Geodesic pointing error…)
- Effects at Gran Sasso?
- Which detectors along beam-line (and where)?

Intense Use of MC Simulations to get Reliable Answers

CNGS: possible monitor locations



700 m 100 m 1000m 67 m

SEM foils

Hadron profile monitors

“Low energy μ” monitors

“High energy μ” monitors

Reminder: measure the muons <--> measure the ν_μ neutrinos

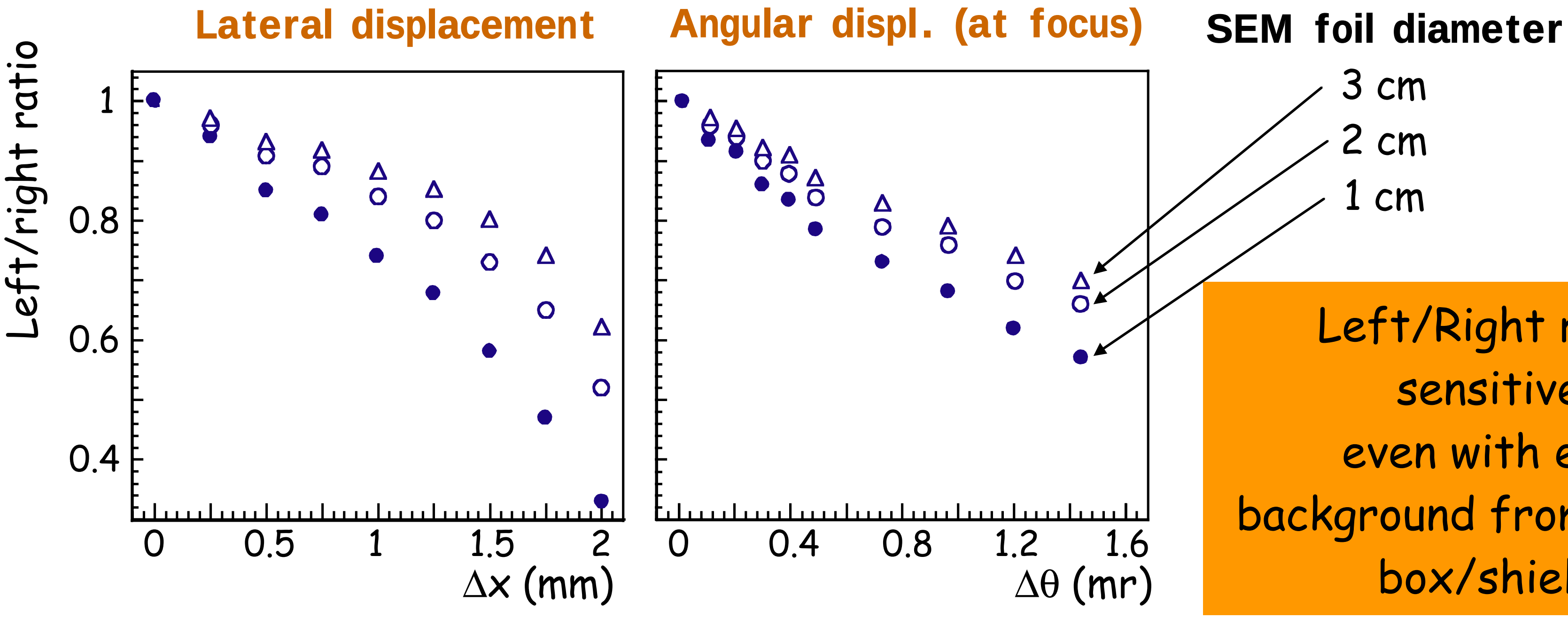
SEM split foils sensitivity

to proton beam mis-alignment w.r.t. target

Fluka detailed simulation of target and target box:

- >> All particles recorded (hadrons, $e^{\pm}$, γ)
- >> Very low threshold: 10 MeV (1 MeV for $e^{\pm}$, γ)

Downstream/Upstream ratio: multiplicity (beam steering)

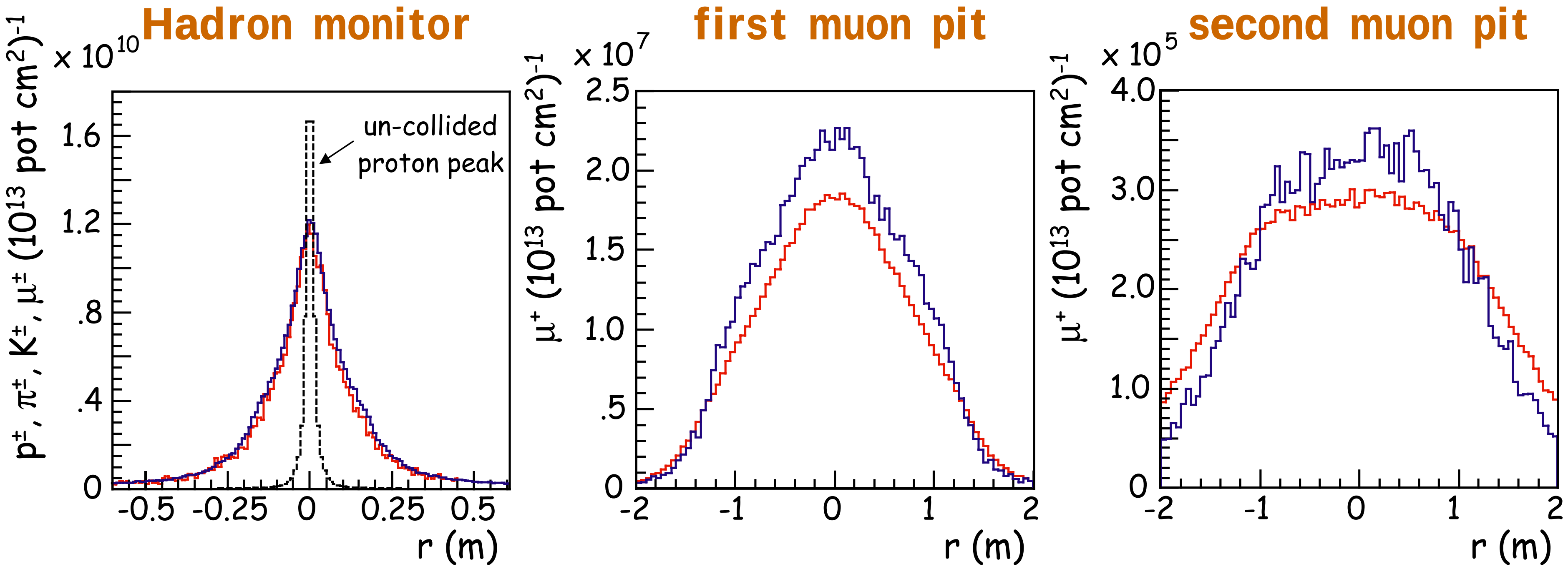


Left/Right ratio sensitive even with e.m. background from target box/shield

Expected CNGS particle profiles

at monitor locations

— Fluka standalone
— Fast simulation



In principle, very sensitive to mis-alignments of proton beam

But…

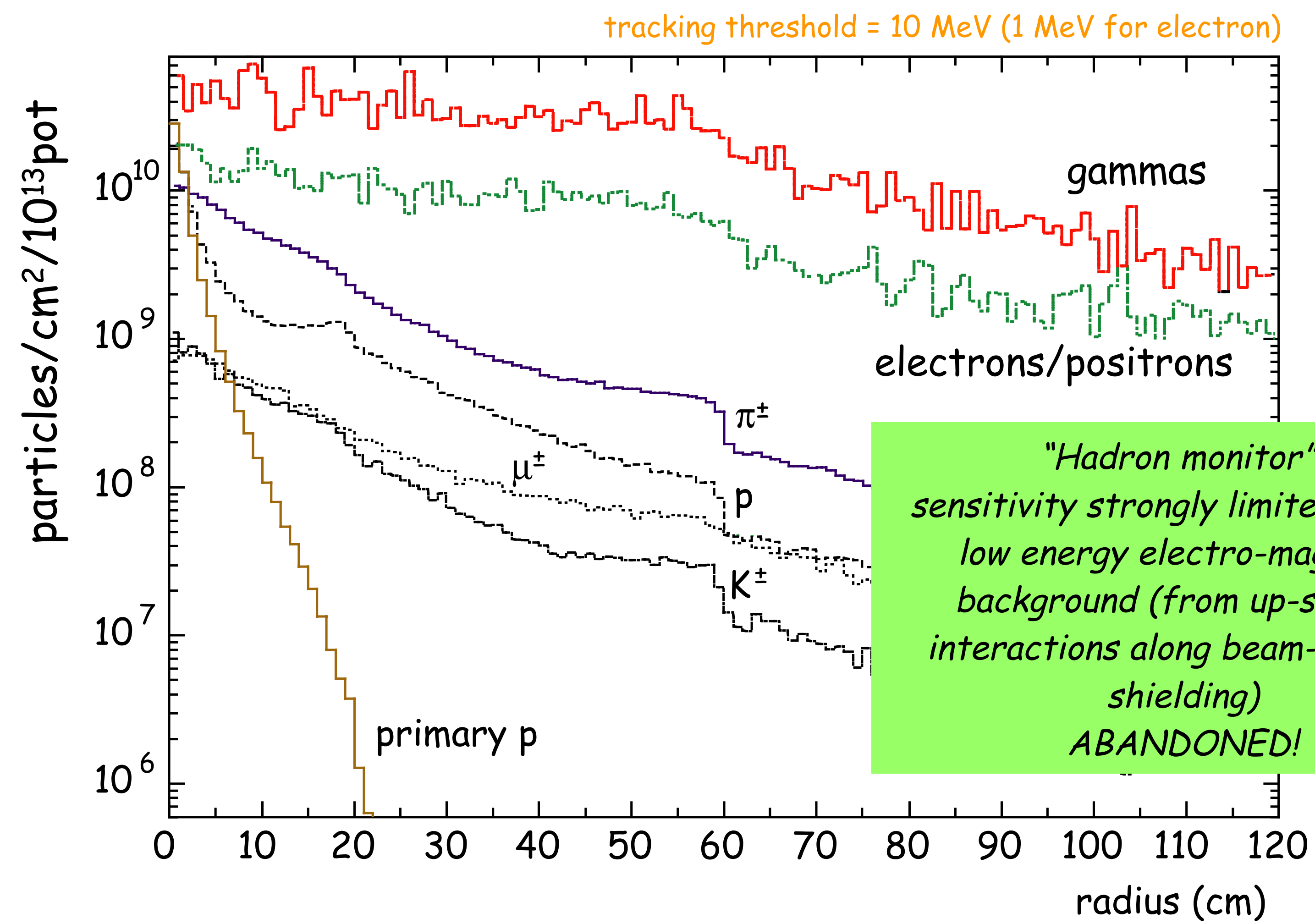
After 15 m Fe hadron dump (≈20 GeV range-out filter)

More sensitive to Horn mis-alignments

After 67 m of molasse (≈50 GeV range-out filter)

More sensitive to Reflector mis-alignments

Radial profiles at entrance to decay tunnel
(Fluka simulation: all particles)

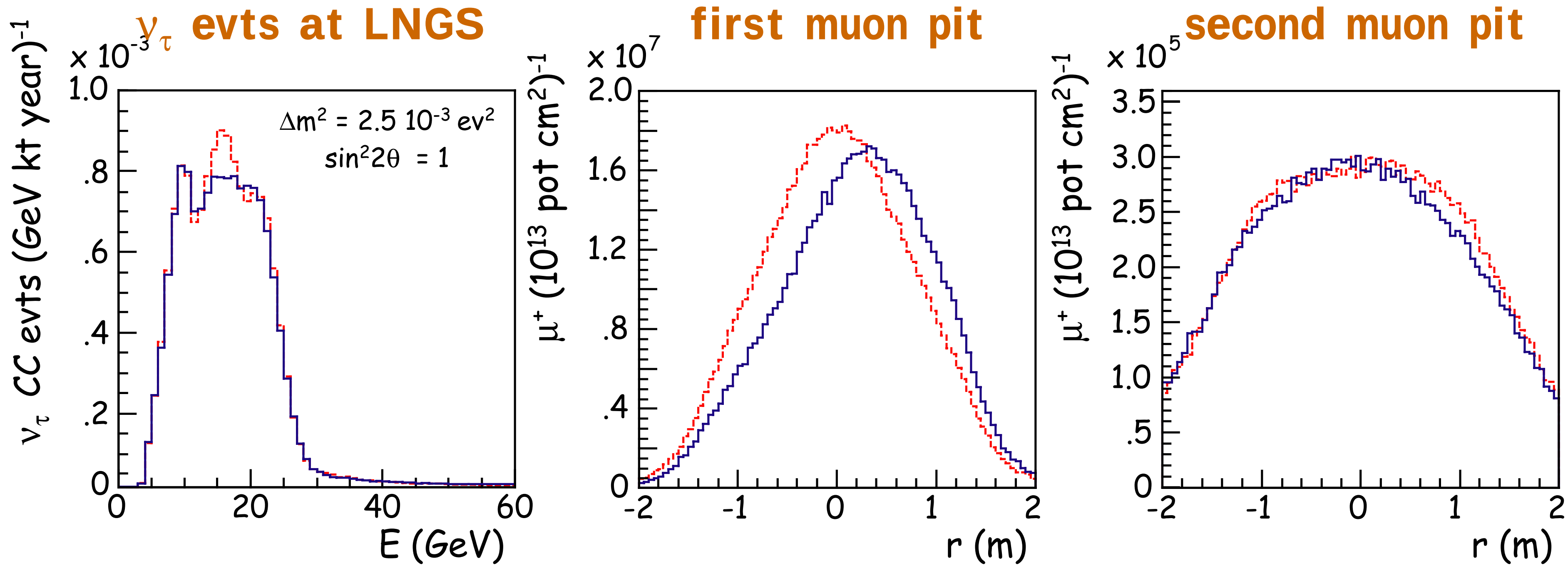


"Hadron monitor":
sensitivity strongly limited by flat low energy electro-magnetic background (from up-stream interactions along beam-line and shielding)
ABANDONED!

Sensitivity to mis-alignments

Example 1: **6 mm horn lateral displacement**

(expected accuracy ≈ 0.1 mm!!)



Clear loss around Horn focused momenta
Loss ≈ -2.8 ± 0.2 %

First muon pit very sensitive to Horn focused particles
Average displ. = 19.1 ± 0.5 cm

Second muon pit sensitive to much higher energies
Average displ. = -3.5 ± 1.2 cm

Reflector lat. displ.
(30 mm) -3.0 ± 0.2 % 21.5 ± 0.5 cm 18.8 ± 1.2 cm

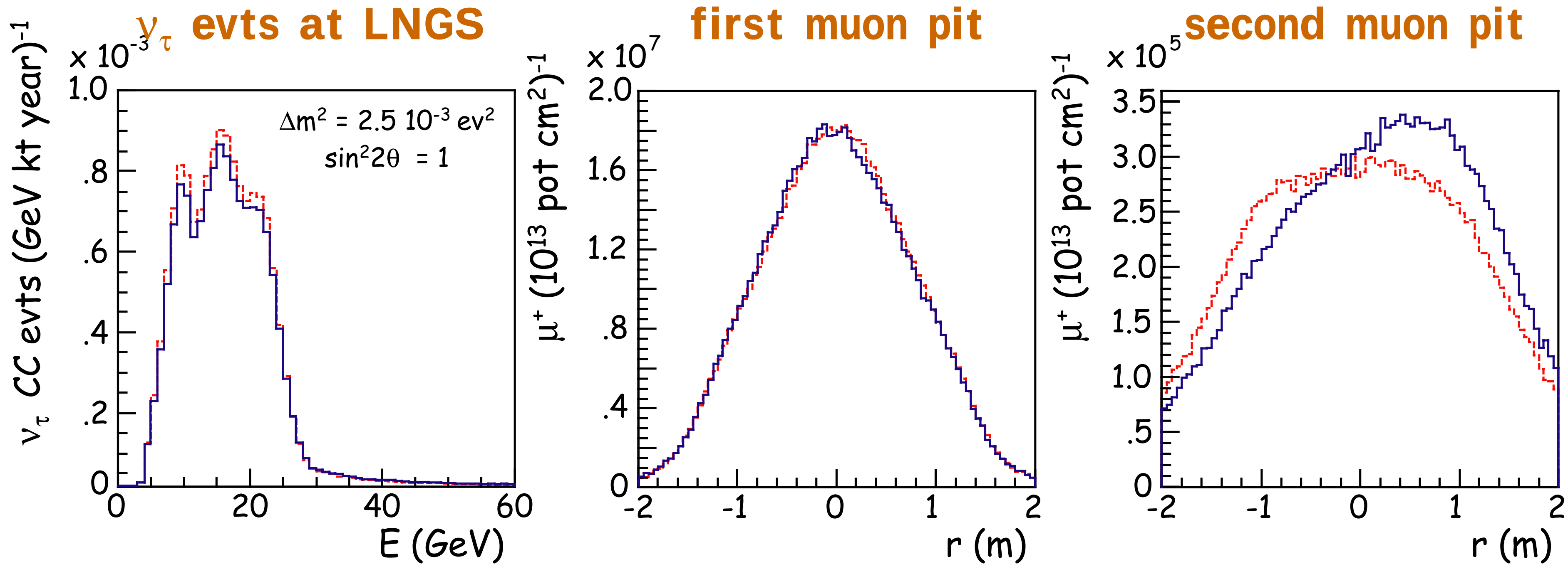
Sensitivity to mis-alignments

Example 2: **1 mm p-beam lateral displacement**

(expected accuracy ≈ 0.1 mm!!)

— Mis-aligned case

······ Aligned case



Uniform loss at any momenta
Loss ≈ -3.0 ± 0.2 %

First muon pit insensitive
(Horn/Reflector dominate)
Average displ. = -1.2 ± 0.5 cm

Second muon pit sensitive to high energy part. direction
Average displ. = 14.8 ± 1.2 cm

p-beam angular displ. (1 mr)	-1.3 ± 0.2 %	2.3 ± 0.5 cm	10.4 ± 1.2 cm

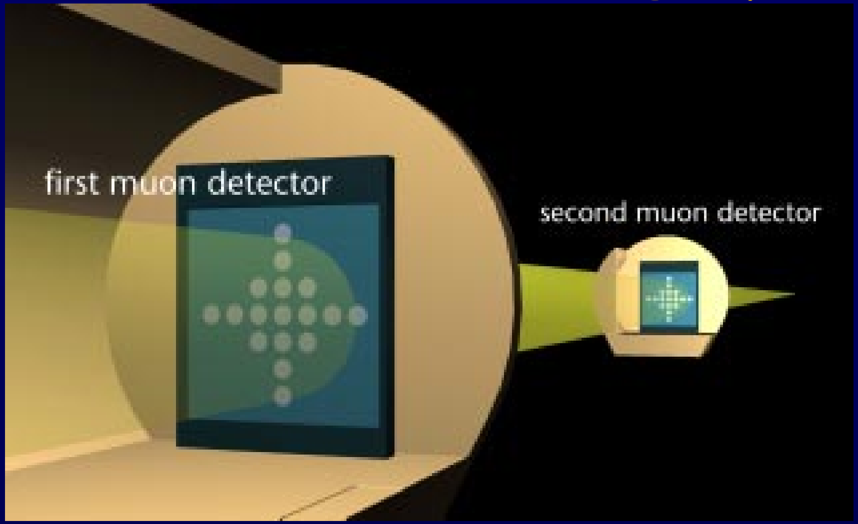
Overall sensitivity

to beam-line misalignments

	ν_τ CC interact. loss (%)	1st muon chamber average displ. (cm)	2nd muon chamber average displ. (cm)	1cm SEM after target L/R asymmetry (%)
Proton beam lateral displacements (alignment accuracy ≈ 0.1mm)				
0.5 mm	**0.**	**-0.6**	**7.3**	**14**
1.0 mm	**- 2.8**	**-1.2**	**14.8**	**27**
Proton beam angular displacements (alignment accuracy ≈ 0.1mr)				
0.5 mr	**0.**	**-1.2**	**3.7**	**21**
1.0 mr	**-1.3**	**-2.3**	**10.4**	**32**
Horn lateral displacements (alignment accuracy ≈ 0.1mm)				
3 mm	**-1.0**	**10.1**	**-0.6**	
6 mm	**-2.8**	**19.1**	**-3.5**	
Reflector lateral displacements (alignment accuracy ≈ 0.1mm)				
10 mm	**-0.4**	**5.7**	**-10.7**	
30 mm	**-3.0**	**21.5**	**-18.8**	
>>>> Statistical accuracy <<<<				
	0.2	**0.5**	**1.2**	**< 1**

> Small effects at Gran Sasso
>> Measurable along beam-line
>>> Monitors are sufficient to disentangle source of misalignment

Detectors for the muon monitoring system:

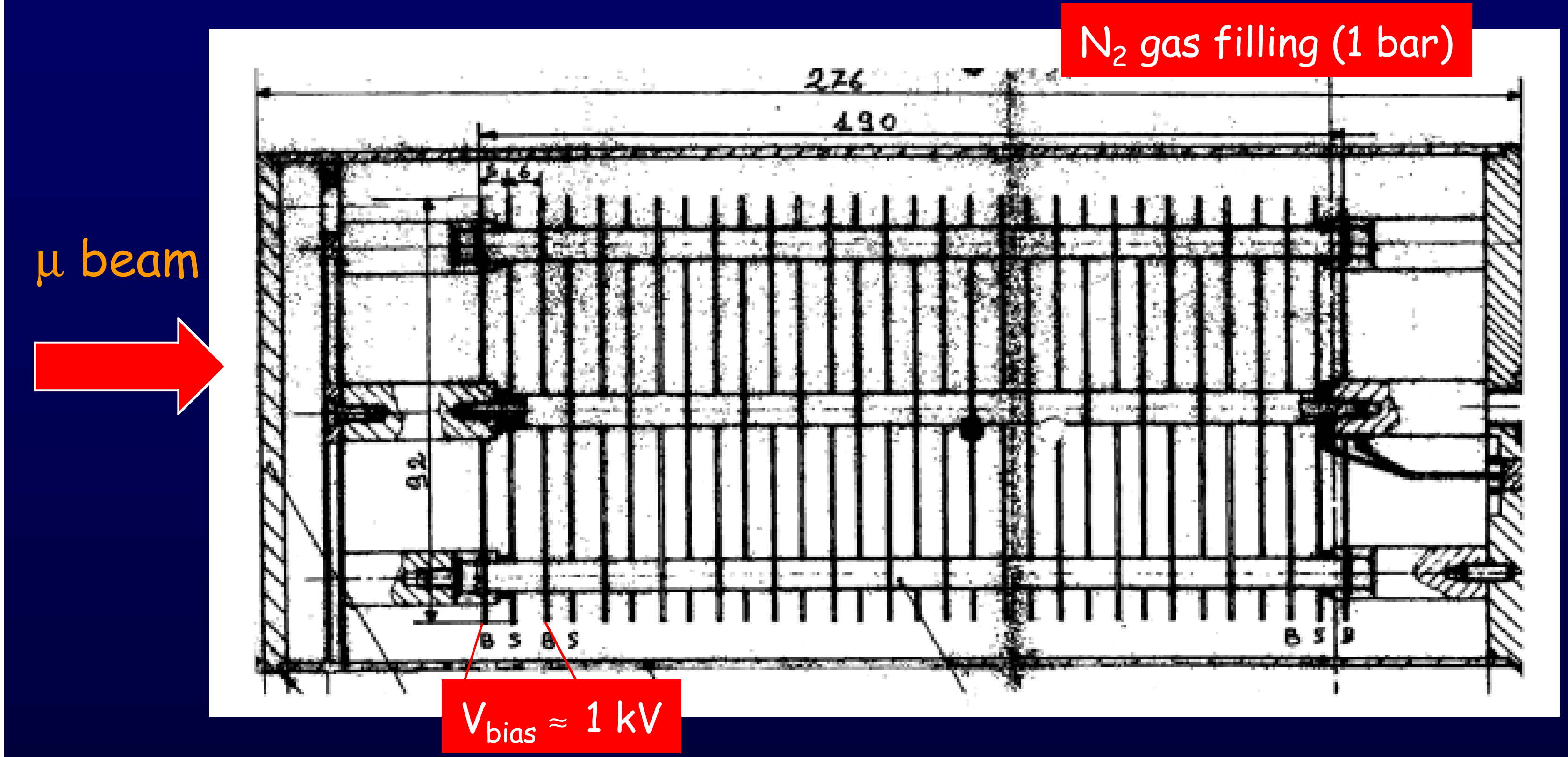


- Muon detector system at WANF neutrino beam:
  array of Si detectors in each muon pit

- CNGS muon detectors: not yet designed
  - Si detectors one option ("base-line") <-- WANF !
  - BLM ionisation chambers another option
  - … other options…

NOTE: Access to muon detector stations very restricted

Beam Loss Monitor Ionisation Chambers
as muon detectors



N_2 gas filling (1 bar)

μ beam

$V_{bias} \approx 1$ kV

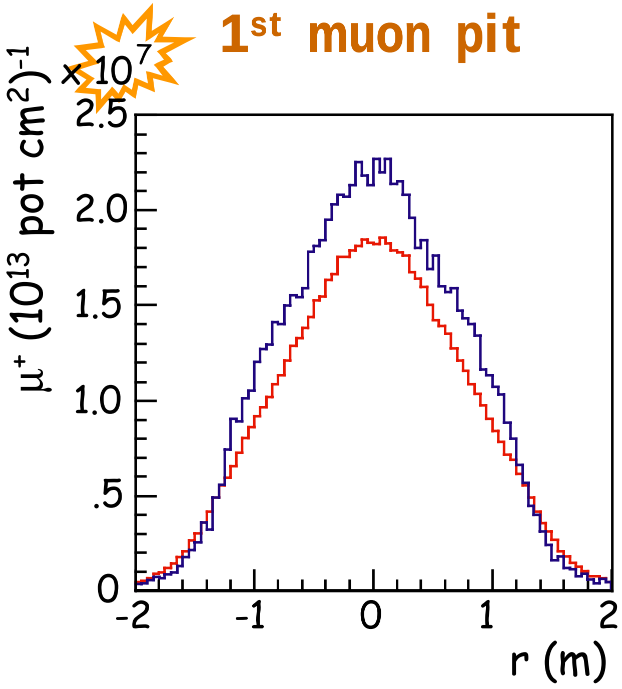
Pro: robust, stable in time, large signals (allow distant electronics ≈ 1 km), good S/N
ready to use (with front-end electronics & DAQ) in modules of 36

Contra: poor linearity at highest μ flux (under investigation)

BLM's characteristics:

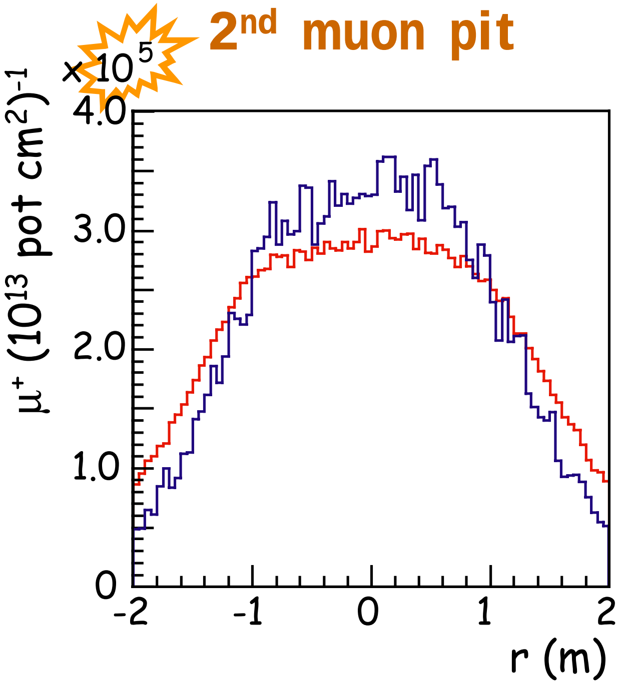
≈ matching muon beam intensity and pit layout

1^{st} muon pit

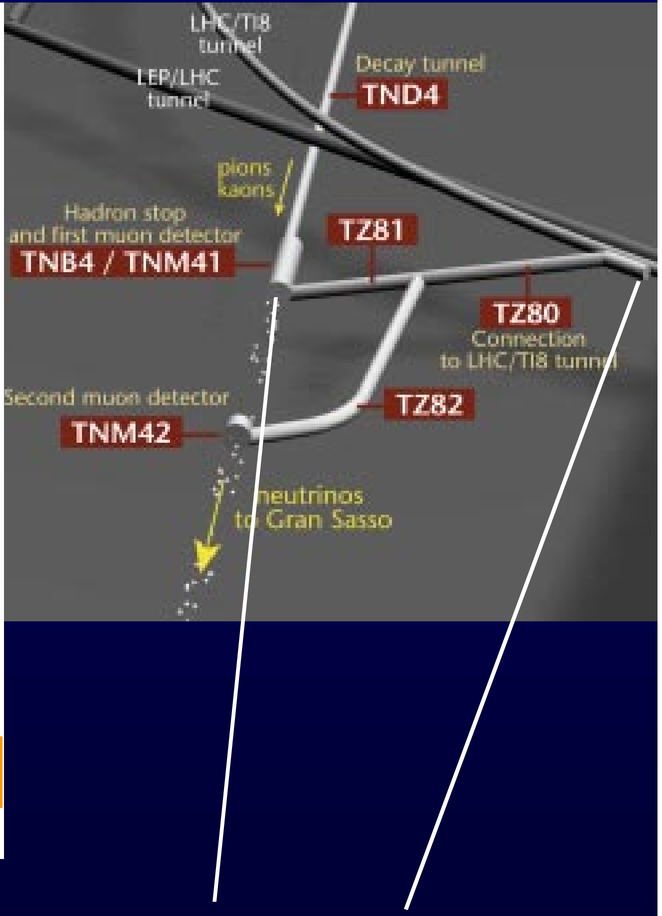


Sensitive to Horn displ.

2^{nd} muon pit



Sensitive to p-beam displ.



≈ 200 m !

Sensitivity to beam-line mis-alignments using BLM's in the muon pits:

Working hypotheses: < 18 BLM's per pit

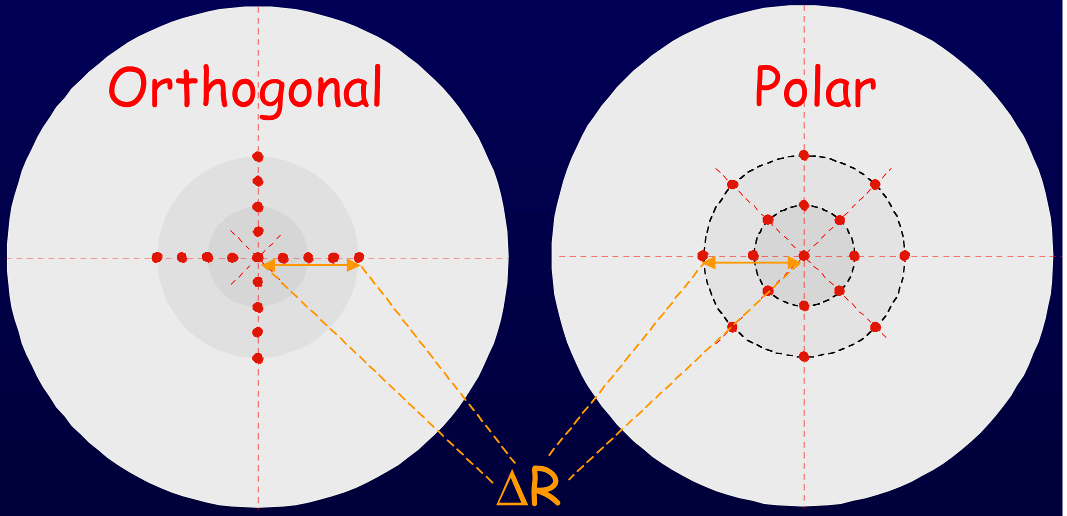
σ_{meas} = 3% / "full scale" (noise + relative calibr.)

good linearity over full signal range

Arrangements (17 BLM's):

Centered on beam axis

Left/Right symmetric



Estimator:

weighted sum of (L-R) differences

depends on σ_{meas} , ΔR, number of BLM's

No need for absolute calibration !

Goal: best arrangement

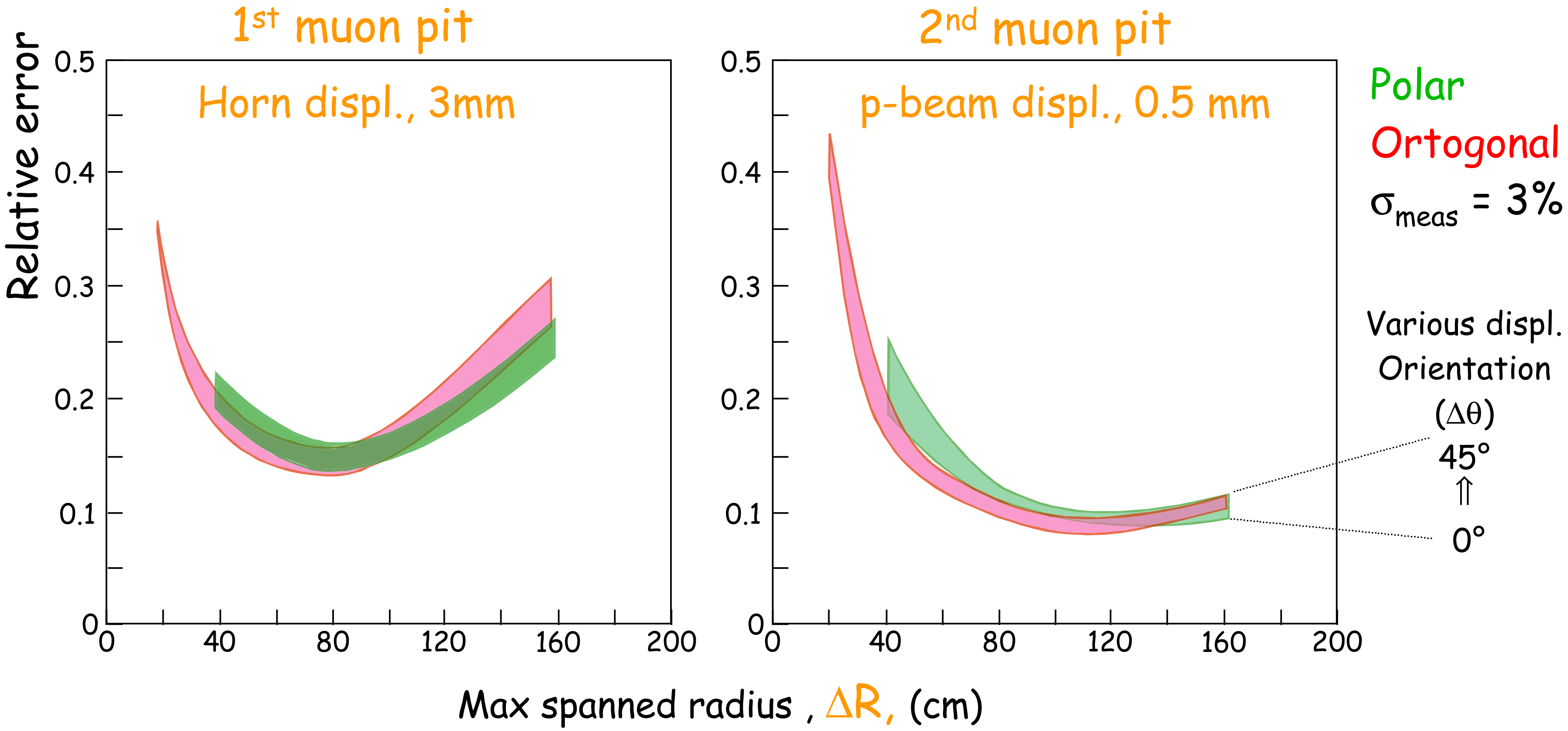
best spacing (ΔR)

minimal number of BLM's

Sensitivity to beam-line mis-alignments using BLM's in the muon pits: (2)

>> Best ΔR depends on muon profile width

>> Polar/orthogonal configs --> equivalent sensitivity



Sensitivity to beam-line mis-alignments using BLM's in the muon pits: (3)

σ_{meas} = 3%	ν_τ CC interact. Loss (%)	Average profile displ. (cm)	Relative error (%)	
			16 BLM's	32 BLM's
1st muon chamber (max spanned radius = 80 cm) ***Horn lateral displacements***				
3 mm	-1.0	10.1	14%	6%
6 mm	-2.8	19.1	8%	3%
2nd muon chamber (max spanned radius =120 cm) ***Proton beam lateral displacements***				
0.5 mm	0.	7.3	18%	7%
1.0 mm	-2.8	14.8	10%	4%

\>> wide variety of configurations (uniform/non-uniform spacing) give comparable sensitivity

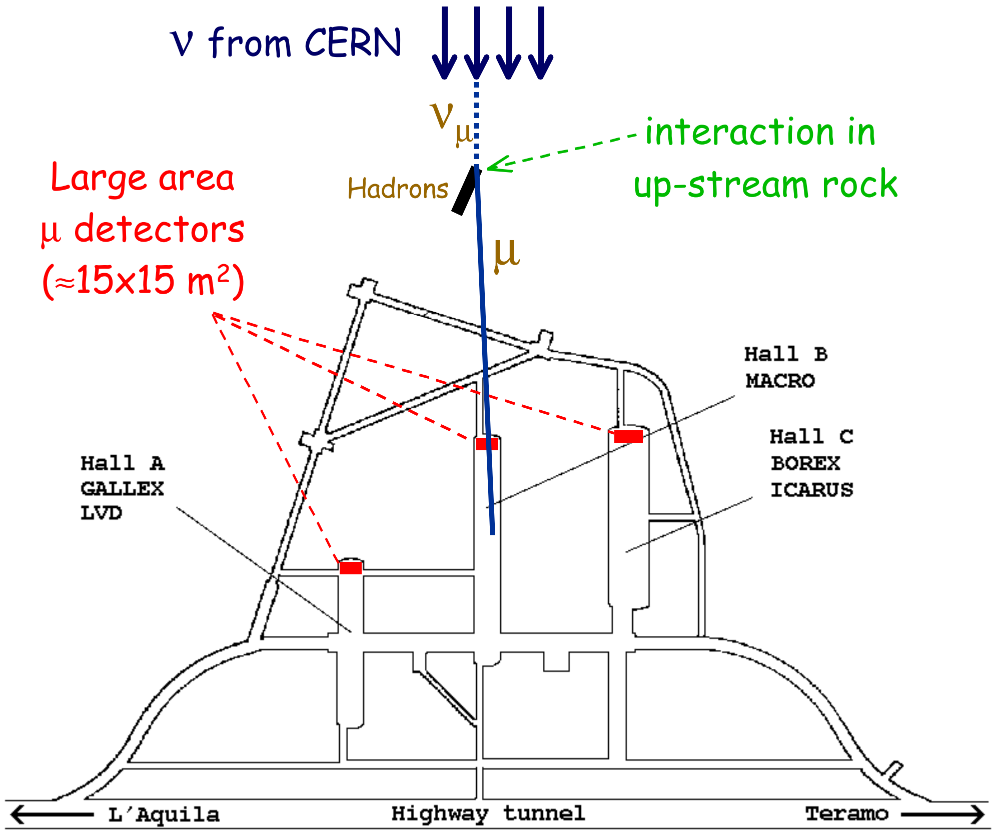
\>> 16+1 BLM's allow detect displ. with negligible effect at LNGS (if σ_{meas} = 3%)

\>> 32+1 BLM --> factor 2.5 better (more detailed description of muon profile)

\>> 1 motorized BML for x-y scanning --> useful complement!

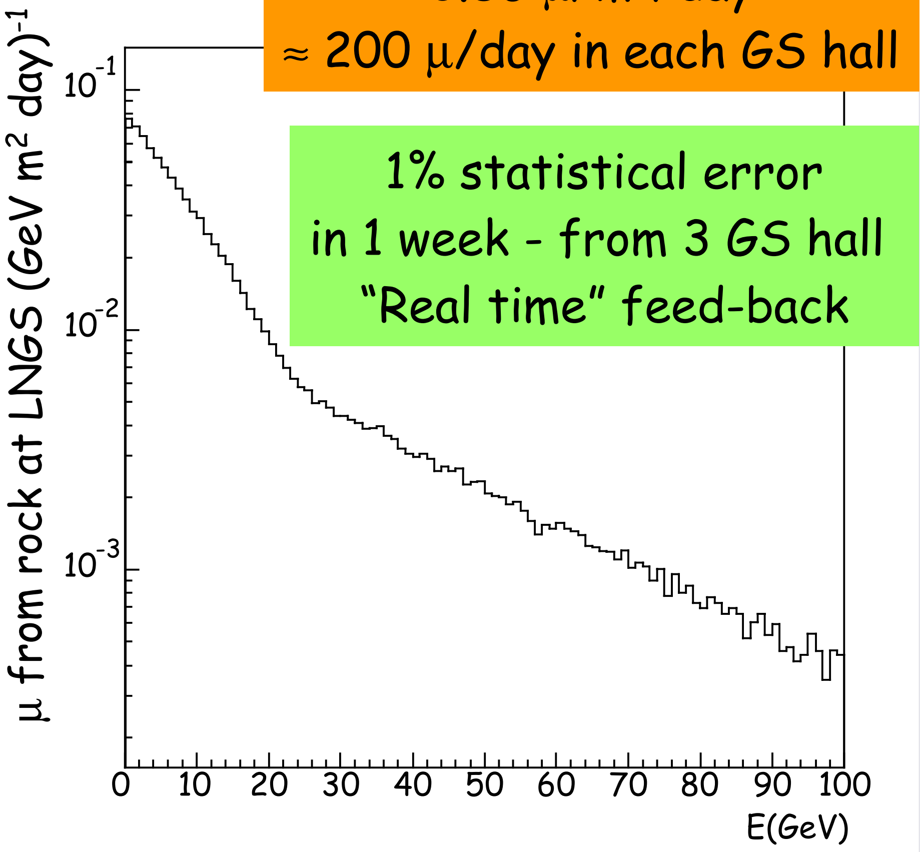
Neutrino flux monitors at Gran Sasso

Monitor time-stability of beam intensity



interaction in up-stream rock

Large area μ detectors (≈15x15 m²)



0.86 μ/m²/day

≈ 200 μ/day in each GS hall

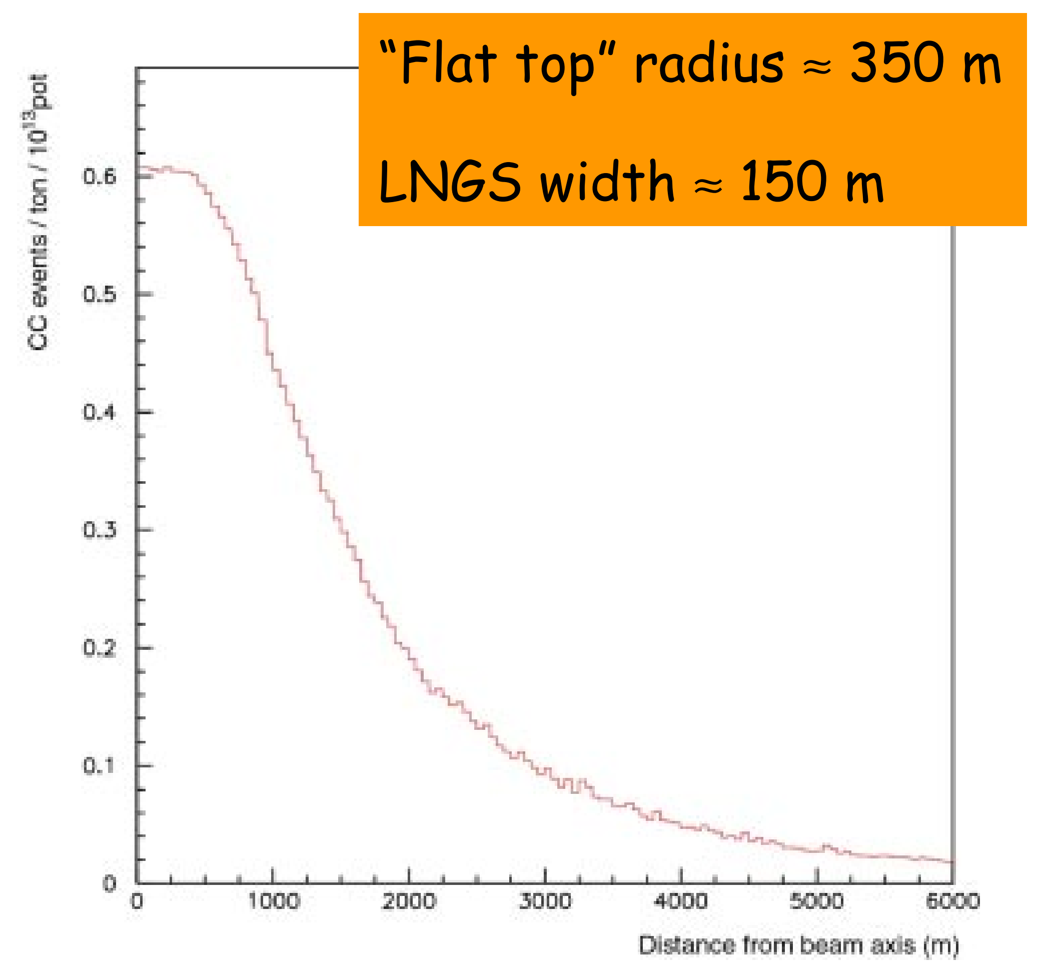
1% statistical error

in 1 week - from 3 GS hall

“Real time” feed-back

Geodesic pointing accuracy

Radial distributions of the neutrino beam at LNGS



"Flat top" radius ≈ 350 m

LNGS width ≈ 150 m

Wrong pointing by 0.5 mrad
(360 m at LNGS)

-3% ν_τ CC loss !!

Expected pointing accuracy
< 0.1 mrad

Summary (optimistic…)

› The CNGS neutrino beam is well tuned for $\nu_\mu \rightarrow \nu_\tau$ appearance over Long Base-Line

›› Misalignments of the beam line elements within project values will not affect ν_τ event rate at Gran Sasso

››› Muon monitoring arrays (based on BLD's) - located after the CNGS dump - should provide reliable information to control beam intensity and misalignments

›››› Large area detectors at Gran Sasso would provide "on-line" feedback on overall beam performance