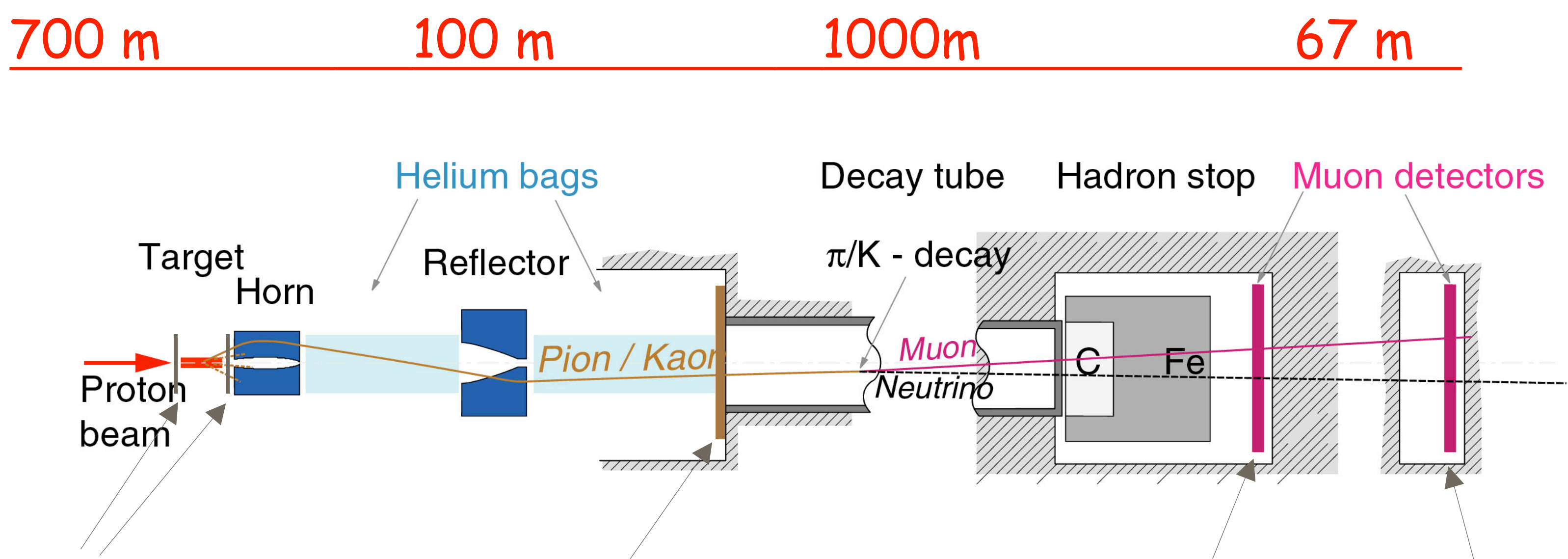
Sensitivity of CNGS muon detectors to beam-line misalignments

- OUTLINE:
  - ✓ Requirements for CNGS muon detectors
  - ✓ Beam Loss Monitors as muon detectors
  - ✓ Effects of beam-line alignment errors
  - ✓ Sensitivity reach to mis-alignments

CNGS beam-line monitoring

- CNGS main features:
  - High energy beam (10-30 GeV) optimized for □□ appearance
  - No near detector envisaged
  - □□ beam normalization performed at LNGS:
    - ✓ by experiments (OPERA/ICARUS)
    - ✓ with large area muon detectors (□□ interactions in up-stream rock)
- Requirements for monitors along beam-line
  - Detect mis-alignments of beam-line elements producing significant effects at LNGS:
    - ✓ Proton beam wrt Target
    - ✓ Horn / Reflector wrt beam axis
  - Monitor beam intensity/stability (relative calibration only)

CNGS: location of beam monitors



SEM foils
Proton wrt target
alignments

~~Hadron profile monitors~~
~~In principle~~
~~optics wrt p-beam~~
~~alignment~~

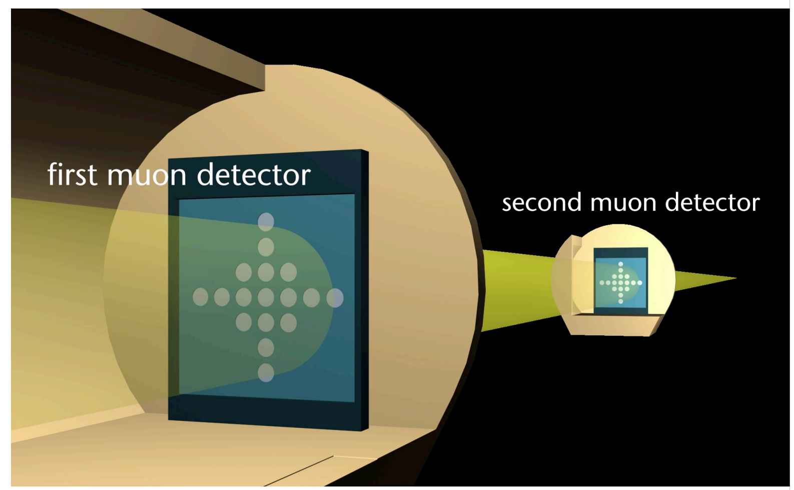
"Low energy μ"

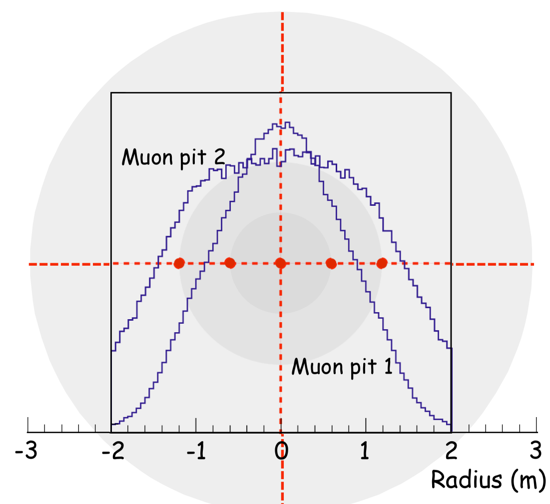
"High energy μ"

muons profile --> ν_μ profile

Choice of detectors and layout for the muon monitoring stations

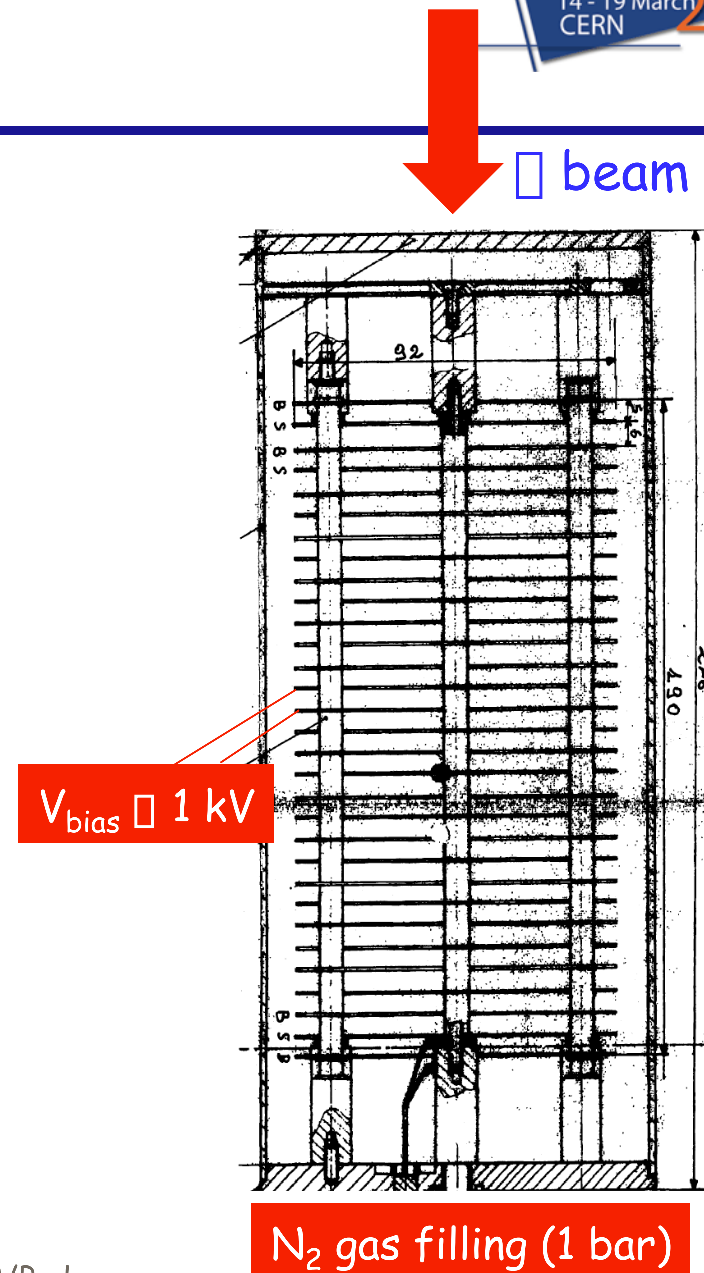
- **Detector:**
  - Choice based on results of studies on alignment errors
    - ✓ negligible effects on ν rate with alignment errors within predicted accuracy (for all beam line elements)
    - ✓ CERN-EP2001-037; CERN-SL-2001-016 EA
  - Emphasis on reliability
    - ✓ access to muon stations very restricted
- **Layout:**
  - Sample muon profile with sufficient accuracy to detect asymmetries
    - ✓ # of detectors, spacing, …





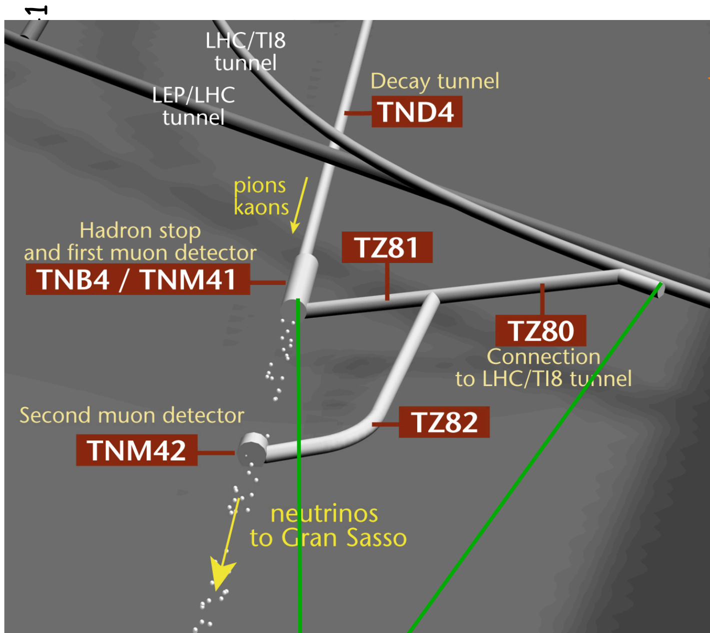
BLM's as detectors for the muon monitoring stations

- **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 (18x2 cables)
- **CONTRA:**
  - ✓ poor linearity at highest muon flux (under investigation)

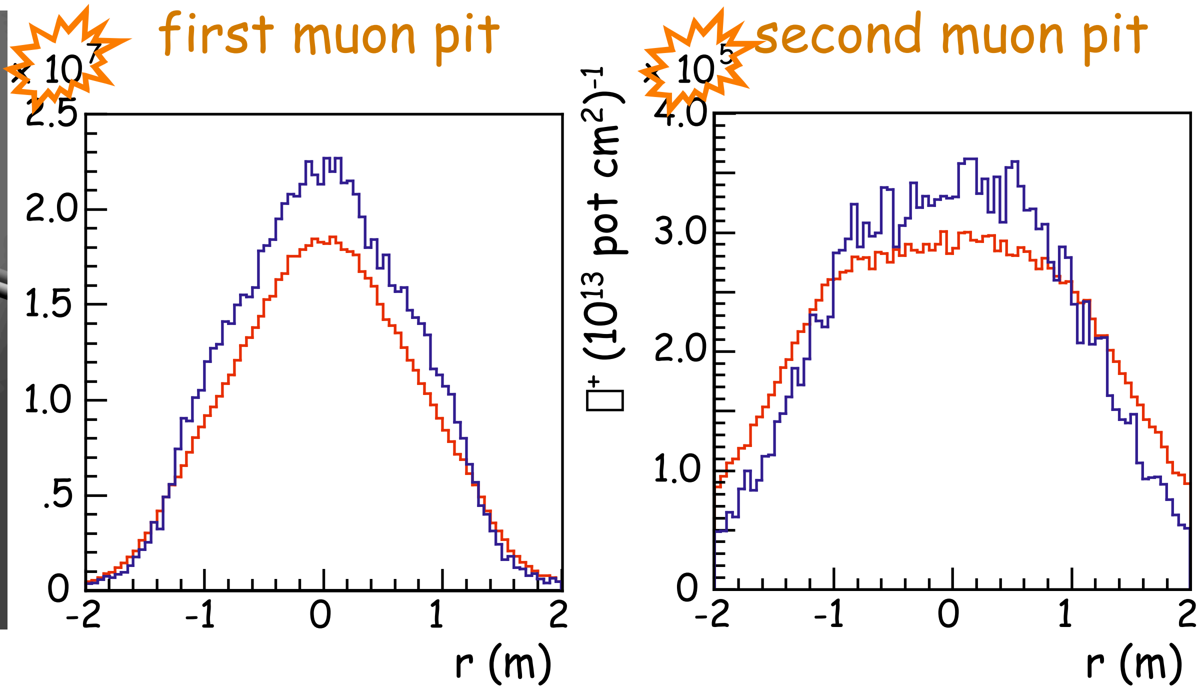


BLM's characteristics:

≈ matching muon beam intensity and pit layout



 200 m !



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

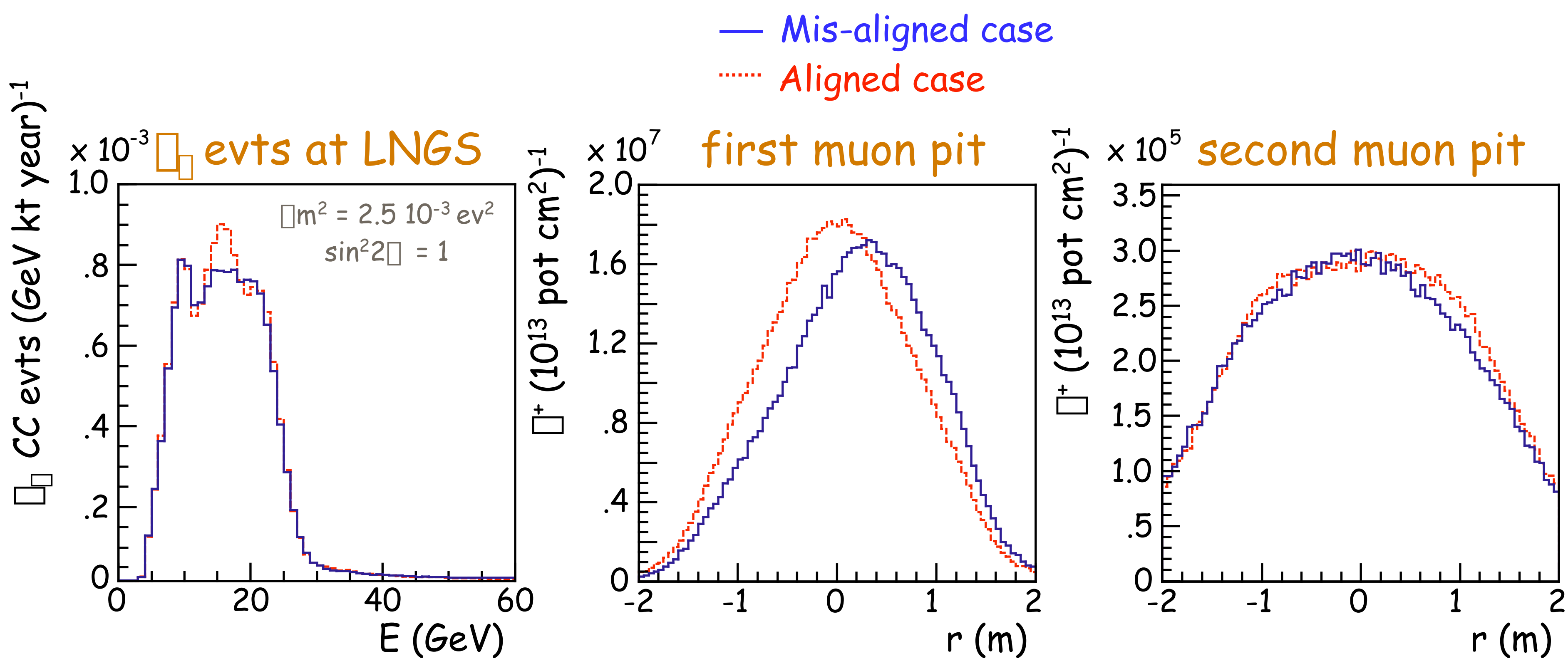
After 67 m of molasse (≈50 GeV range-out filter)

— Fluka standalone
— Fast parametric simulation

Effects of alignment errors

Example 1: 6 mm horn lateral displacement

(expected accuracy ≈ 0.1 mm!!)



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

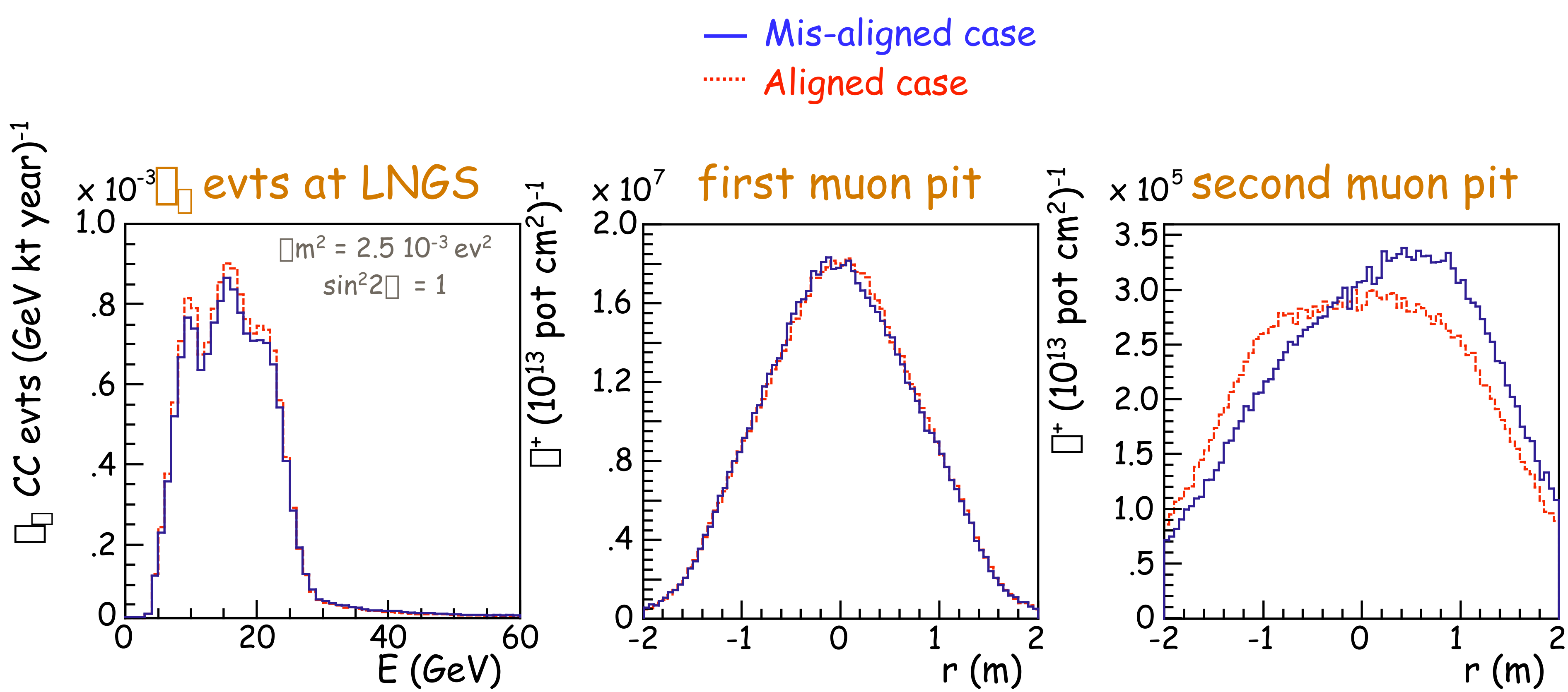
First muon pit very sensitive to Horn focused particles
Average displ. = 19.1 ± 0.5 cm

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

Effects of alignment errors

Example 2: 1 mm p-beam lateral displacement

(expected accuracy ≈ 0.1 mm!!)



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

Overall effects of CNGS beam-line misalignments

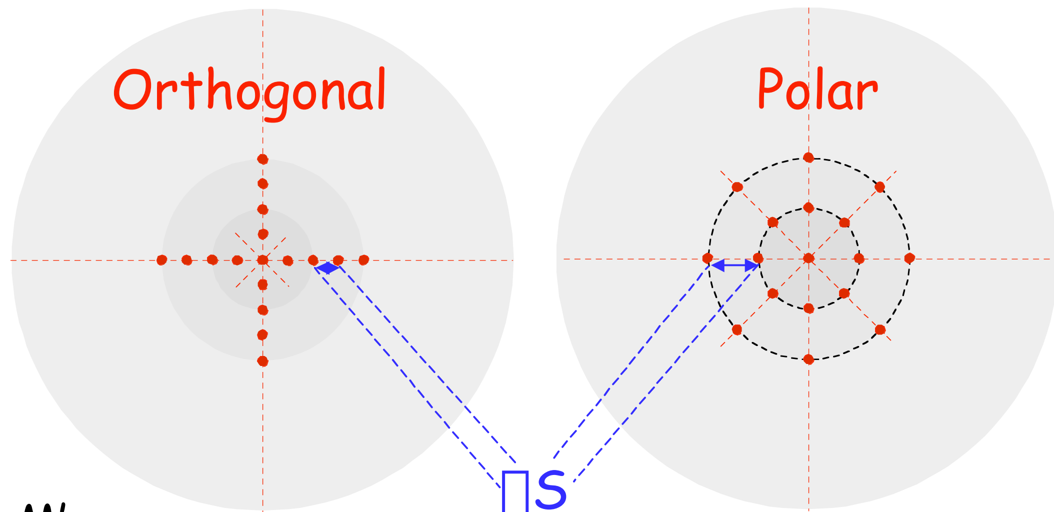
	ν_μ CC interact. loss (%)	1st muon chamber centroid displ. (cm)	2nd muon chamber centroid displ. (cm)
Proton beam lateral displacements (alignment accuracy ≈ 0.1mm)			
0.5 mm 1.0 mm	0. - 2.8	-0.6 -1.2	7.3 14.8
Proton beam angular displacements (alignment accuracy ≈ 0.1mr)			
0.5 mr 1.0 mr	0. -1.3	-1.2 -2.3	3.7 10.4
Horn lateral displacements (alignment accuracy ≈ 0.1mm)			
3 mm 6 mm	-1.0 -2.8	10.1 19.1	-0.6 -3.5
Reflector lateral displacements (alignment accuracy ≈ 0.1mm)			
10 mm 30 mm	-0.4 -3.0	5.7 21.5	-10.7 -18.8
>>>> Statistical accuracy of the MC simulation <<<<			
	0.2	0.5	1.2

- Small effects at LNGS
- Measurable along beam-line
- Muon monitors (complemented by SEM's at target) are sufficient to disentangle source of misalignment

Study of the layout of BLM's in the muon monitoring stations

Working hypotheses: ≤ 18 BLM's per pit
σ_{meas} ≤ 3% / "full scale" (mainly relative calibr.)
max signal adjusted at "full scale"
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} , ΔS, number of BLM's

No need for absolute calibration !

Goal: best arrangement
best spacing (ΔS)
minimal number of BLM's

Detecting asymmetries in muon profiles

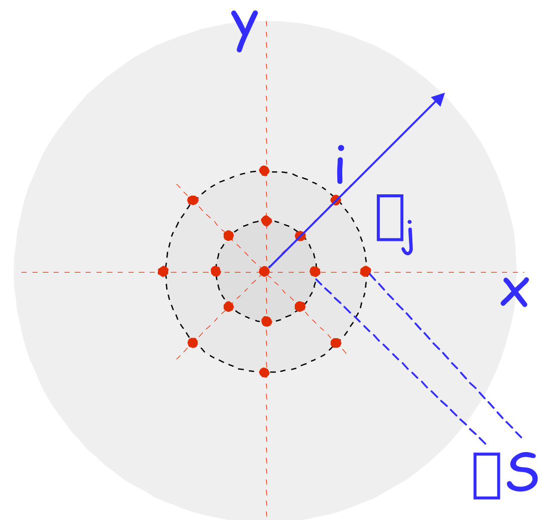
Estimators of projected displacements:

depend on left/right differences along given direction

$$Dx = \sum_{i,j} x_i W_{i,j} / \sum_{i,j} W_{i,j} = \Delta S \sum_{i>0,j} i\cos\phi_j [W_{i,j} - W_{-i,j}] / \sum_{i,j} W_{i,j}$$

$$Dy = \sum_{i,j} y_i W_{i,j} / \sum_{i,j} W_{i,j} = \Delta S \sum_{i>0,j} i\sin\phi_j [W_{i,j} - W_{-i,j}] / \sum_{i,j} W_{i,j}$$

(W_{ij} = muon flux measurement in each detector)



Errors:

$$\sigma_x \approx \sigma_{meas} \Delta S \sqrt{2 \sum_{i>0,j} (i\cos\phi_j)^2} / \sum_{i,j} W_{i,j}$$

$$\sigma_y \approx \sigma_{meas} \Delta S \sqrt{2 \sum_{i>0,j} (i\sin\phi_j)^2} / \sum_{i,j} W_{i,j}$$

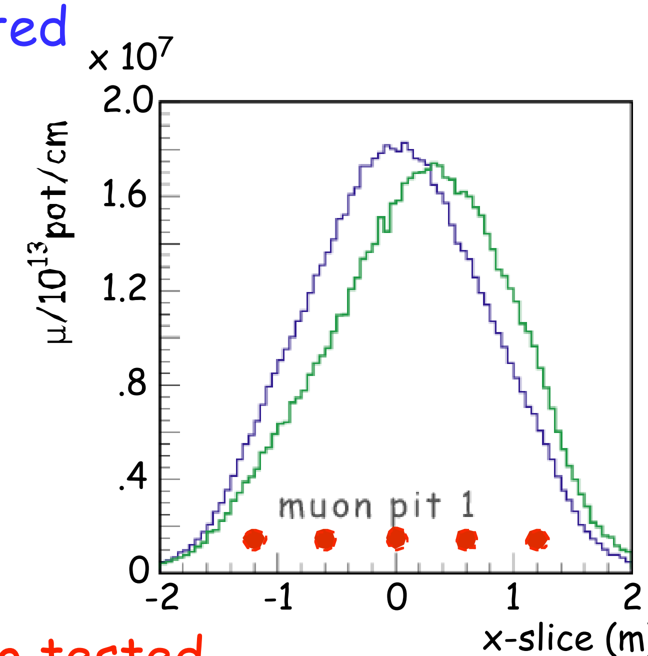
Estimator of sensitivity:

$$Dr = \sqrt{Dx^2 + Dy^2} \qquad D\theta = inv\sin(\frac{Dy}{Dr})$$

$$\sigma_\theta \approx \frac{\sigma_r}{Dr} = \sqrt{\sigma_x^2 + \sigma_y^2} \Big/ Dr$$

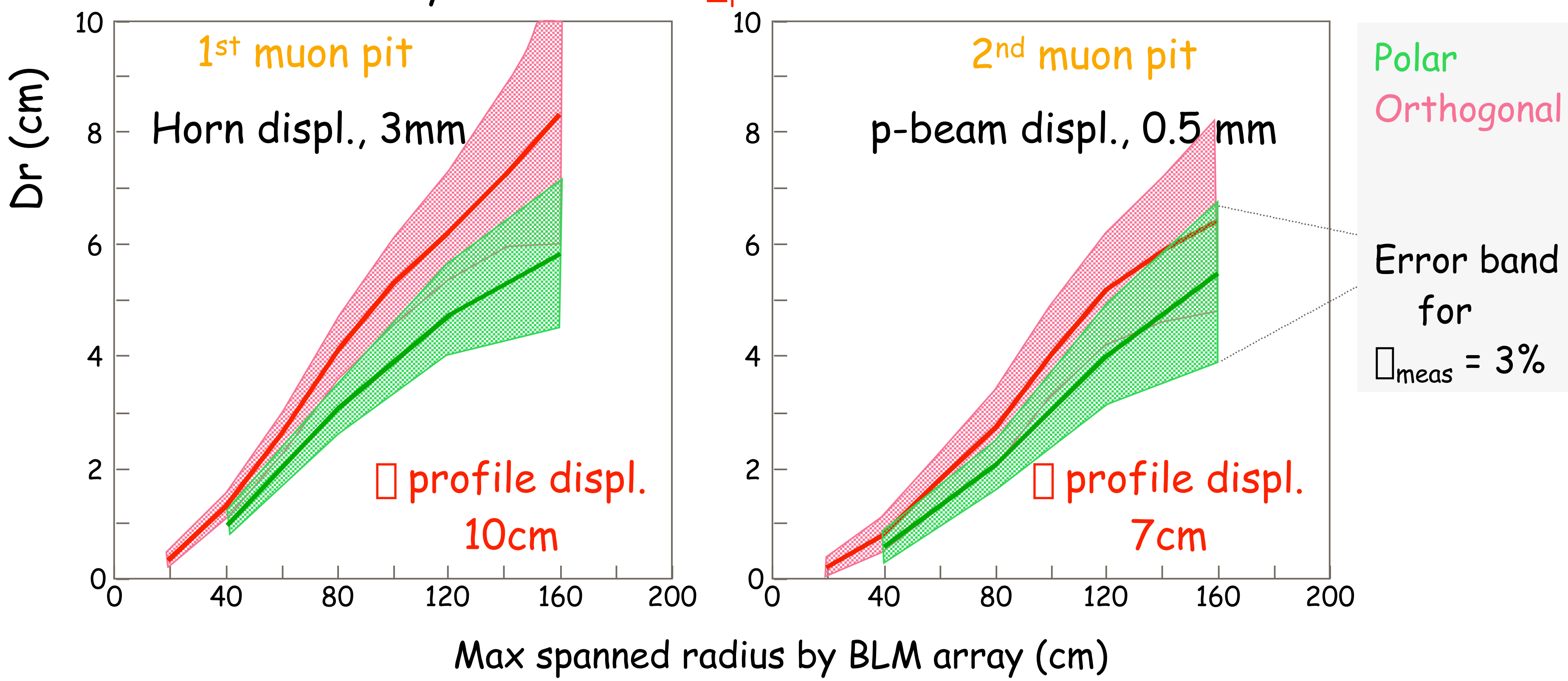
Simulations

- Extensive simulation of possible misalignments
  - Proton beam wrt target - horn/reflector wrt beam-axis
    - ✓ Focus on small displacements (sensitivity)
    - ✓ Several displacement directions (x,y)
- Wide variety of arrangements of 17 BLM's tested
  - Orthogonal configuration
    - ✓ 4 BML's per row
    - ✓ Spacing for 10cm to 50cm
  - Polar configuration
    - ✓ 8 BLM's per circle
    - ✓ Spacing from 20cm to 100cm
  - Non-uniform spacing also tested
    - ✓ Grouping BLM's where muon profiles vary rapidly
- Double BLM's density (33 per muon station) also tested



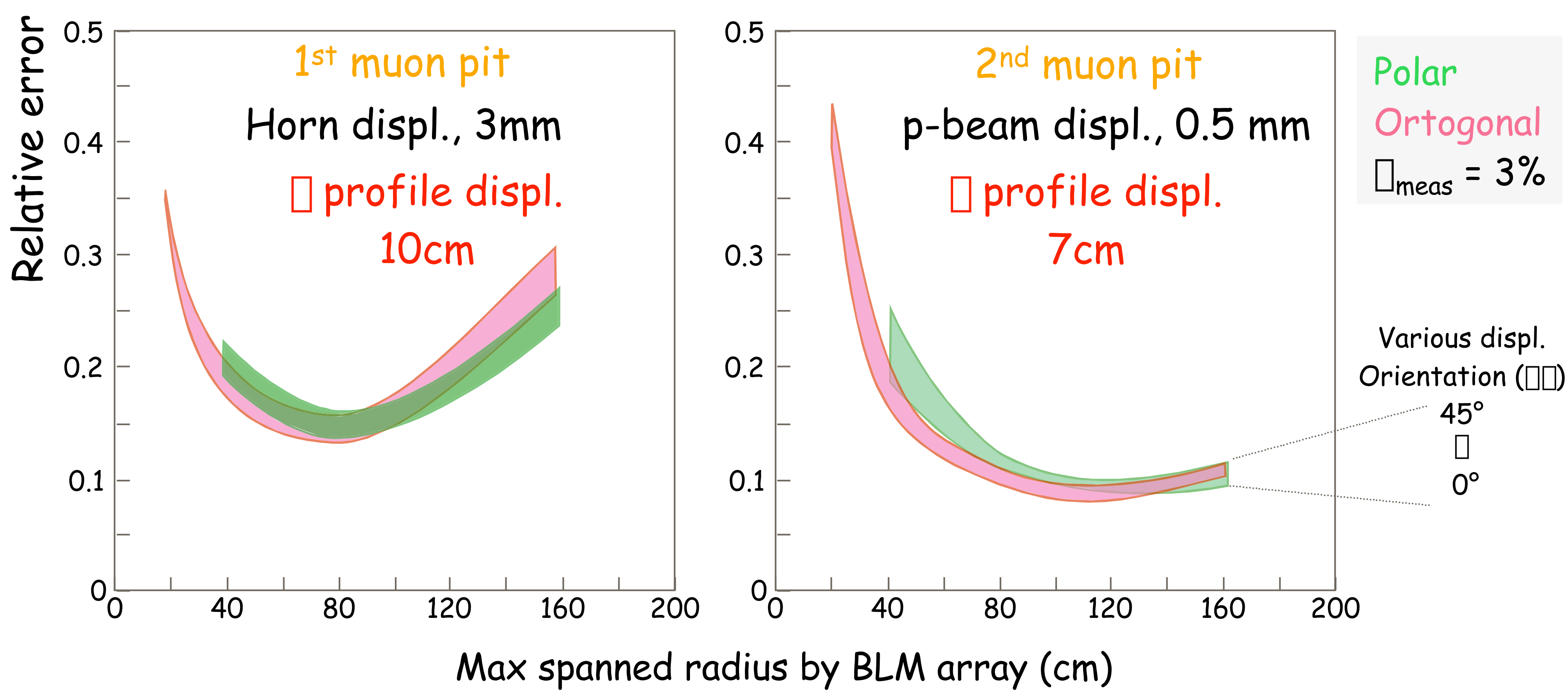
Sensitivity to beam-line mis-alignments (I)

- Estimator "Dr" approaches muon profile average displacement when the full distribution is sampled
- Best sensitivity for minimum σ_r/Dr



Sensitivity to beam-line mis-alignments (II)

- Best monitor spacing, □S, depends on muon profile width
- Polar/orthogonal configurations ≈ equivalent sensitivity



Sensitivity to beam-line mis-alignments (III)

$□_{meas}$ = 3% / "full scale"

	$□_□$CC interact. Loss (%)	Centroid 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 detecting displ. with negligible effect at LNGS (assuming $□_{meas}$ = 3% / full scale)
- ✓ 32+1 BLM --> factor 2.5 better (more detailed description of muon profiles)
- ✓ 1 motorized BML for x-y scanning and cross-calibration

Summary

- ✓ Misalignments of the beam-line elements -within project values- will not affect [illegible] event rate at Gran Sasso
- ✓ Muon monitoring arrays (based on BLM's) - located after the CNGS dump - should provide reliable information to control beam intensity and misalignments
- ✓ Optimization of BLM's design and layout is underway to match CNGS highest muon flux

BLM characteristics

Ionization camber

- Diameter: 9.2cm
- Length: 19cm
- Volume: 1liter
- Filling: N_2 (99.9%)
- Pressure: 1bar
- Ionization energy: 27eV
- Sensitivity: 5 10^{-5}C/Gy
- Efficiency: 4 10^3pairs/part.
- Bias Voltage: 800V (50-1200V)
- Rise-time: 300ns
- Dynamics: > 10^6
- Radiation resist.: > 10^6Gy

Calibration

- Single source (137Cs - 3mCi) --> few % cross-calibration & time stability

Electronics and DAQ

- Acquisition mode: integration
- ADC: full scale 10V
- Resolution: 12bit
- Integrator capac.: min 50pF, max 50□F
- DAQ unit: 36(+4) channels, 1 CPU+Timinig
- Signal cables: 18 channels
- Cable length: max 1500m
- Acqusition time: 3ms (36ch.)

Performance (Cable <500m; C_{min} = 1nF)

- Drift: 1bit/s
- Noise: 3bit
- Sens.: 4 10^3 part./bit
- Full scale: 1.6 107 part.