Muon multiplicities measured using an underground cosmic-ray array

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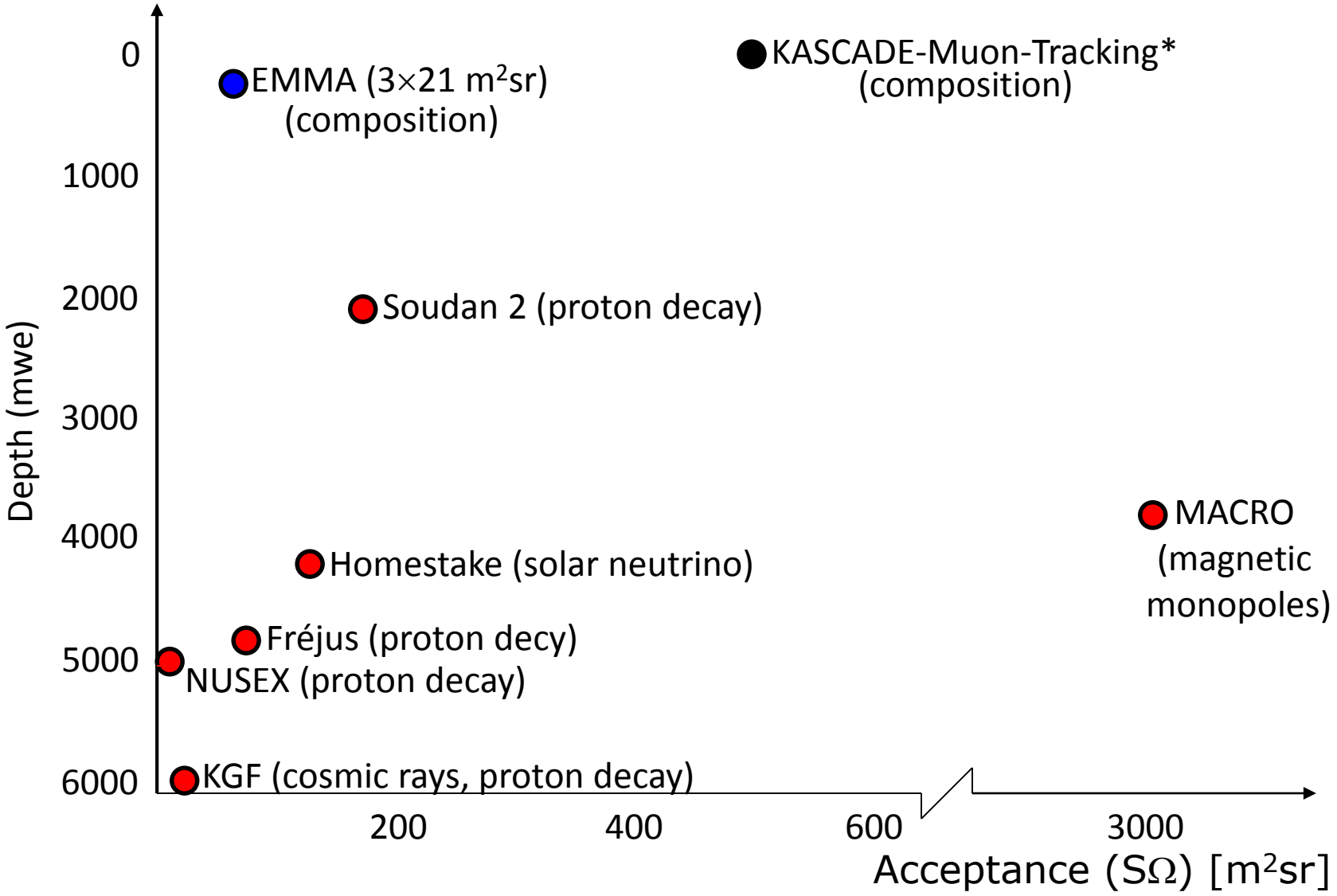
for the EMMA collaboration

- intro
- methods/examples
- comments/questions/discussion

CUPP
Leverage from the EU 2007–2013
POHJOIS-POHJANMAAN LIITTO
Council of Oulu Region
NIHAK
UNIVERSITY of OULU
OULUN YLIOPISTO
OULU SOUTHERN INSTITUTE
UNIVERSITY OF JYVÄSKYLÄ

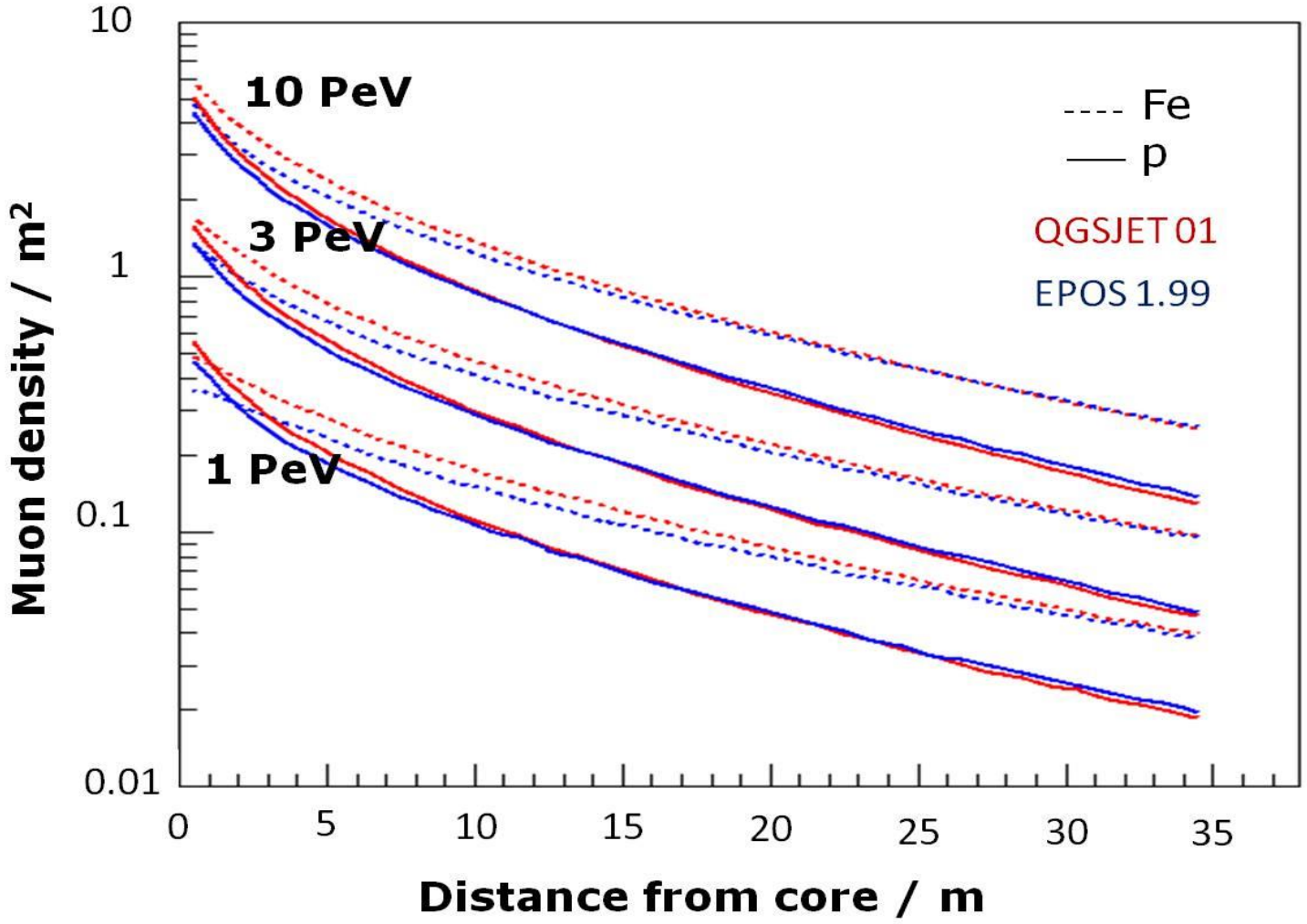
Some underground detectors



*The Muon-Tracking-Detector only, the full array is on ground and very large.

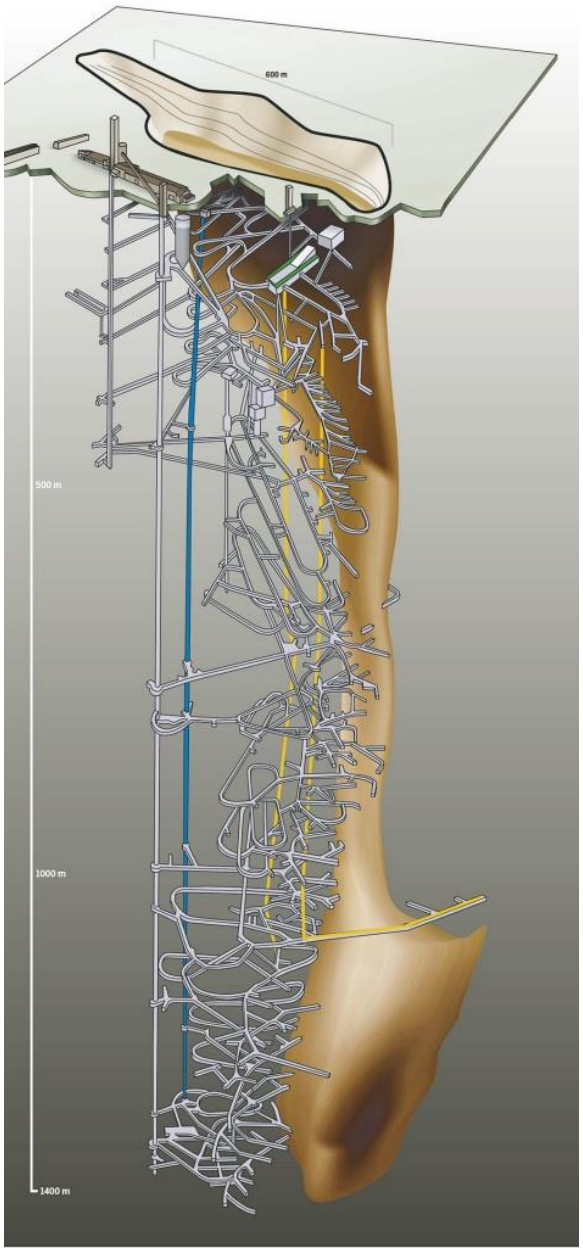
Simulated muon distributions

CORSIKA+QGSJET 01 and EPOS 1.99 – 50 GeV muon cutoff



+ muon density at the shower core ∝ primary energy
+ gradient ∝ mass

Pyhäsalmi mine (1.4 km)



+ opened 1962,

+ ore: copper, zinc and pyrite (gold, silver),

Experiment with Multi-Muon Array

+ designed for cosmic-ray composition studies around the knee energy (1 – 10 PeV),

+ measures air-shower initiated muon later lateral distributions event-by-event $\Leftarrow$ measuring the multiplicity and the lateral spread of high-energy muons in each shower,

+ operates 75 m below ground (210 mwe) in the Pyhäsalmi mine, Finland,

+ rock overburden $\Rightarrow$ muon cutoff energy of $\approx$ 50 GeV (for vertical muons) $\Rightarrow$ detected muons are mostly generated in the upper part of the air shower, or close to the primary interaction,

+ consists of 11 detector stations,

+ employs three different kinds of detectors,

+ muon tracking is used to extract the shower properties.

EMMA – detector Stations

+ 11 stations

  - 9 stations at 75 m-level and two at 45 m-level,
  - area ≈ 15 m^2 each,
  - tracking stations and sampling stations.

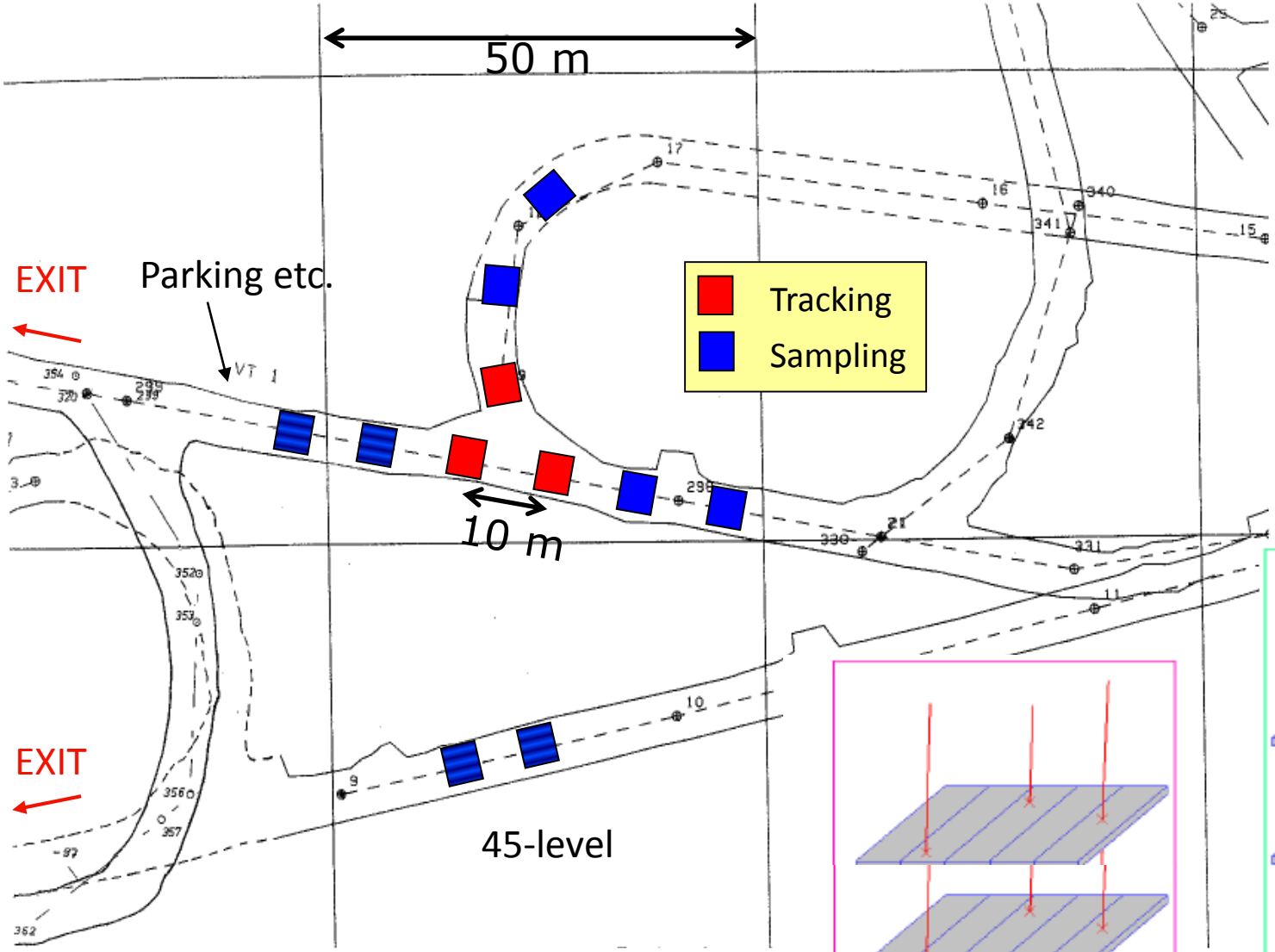
+ tracking stations

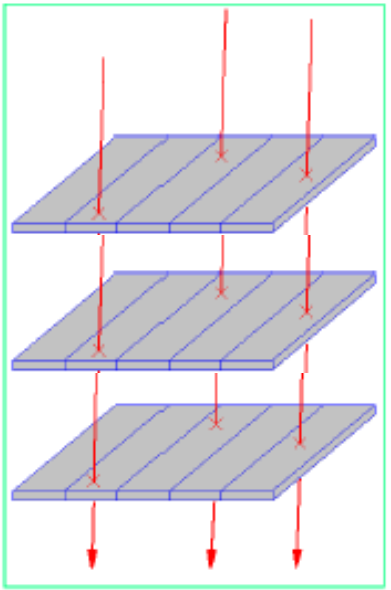
  - use all three detectors types,
  - muon multiplicities at the shower core (i.e. energy),
  - arrival angles (position is very accurate, $\sigma \sim 1$ cm^2),
  - on-line efficiency calibrations (12h bins),
  - tracking.

+ sampling stations

  - find muon multiplicities (or densities) in the tails (i.e. mass).

EMMA at 75m below ground





EMMA

Detectors – drift chambers

Former LEP-DELPHI MUBs (or planks)

- Ar(92%):CO_2(8%)-mixture delivered from ground via ≈ 100 metres long pipeline through the rock (gas consumption ≈ 10 ℓ/min, NTP),

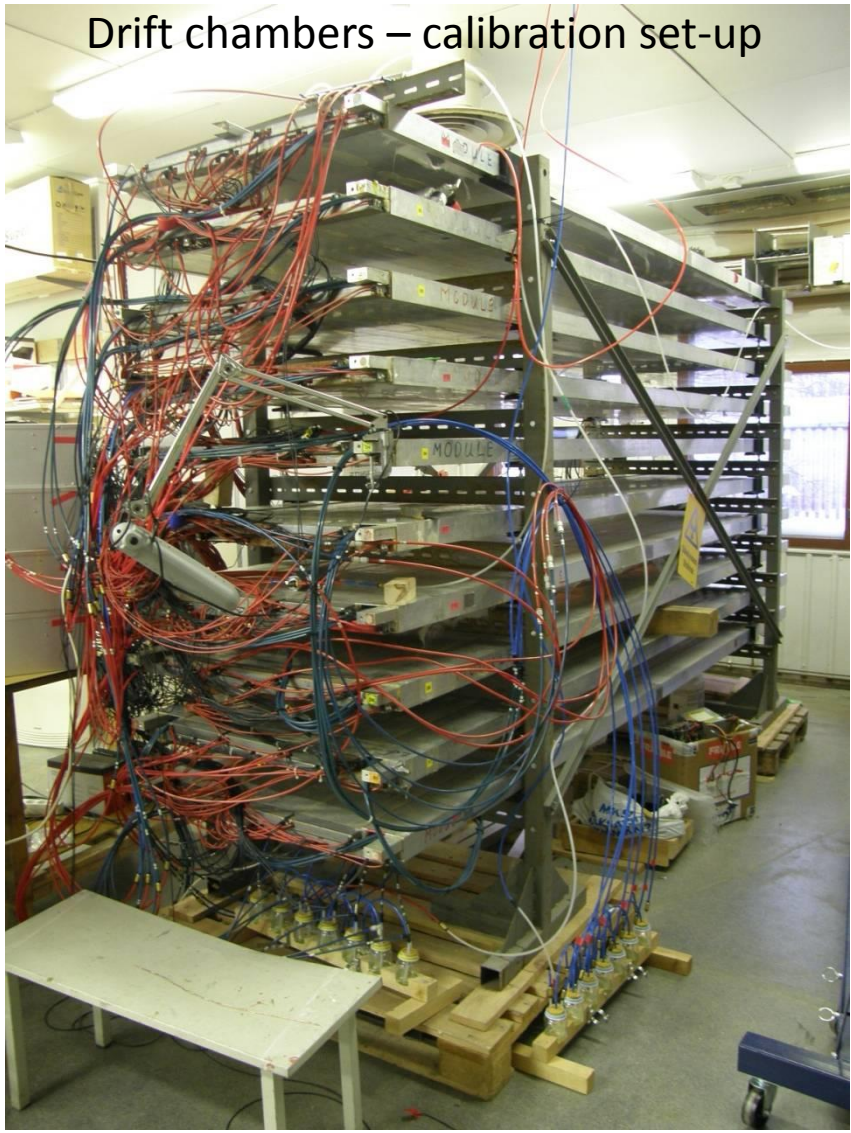
- seven position sensitive drift chambers (365×20 cm², 20 mm thick),

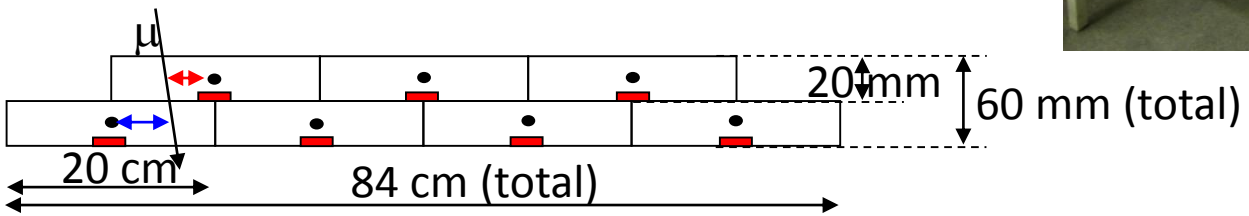
- arranged in lengthwise half-overlapping groups of 3 + 4 (area of 2.9 m²),

- position resolution (σ) ≈ ±1 cm²,

- total area ≈ 240 m² (84 planks).

Drift chambers – calibration set-up

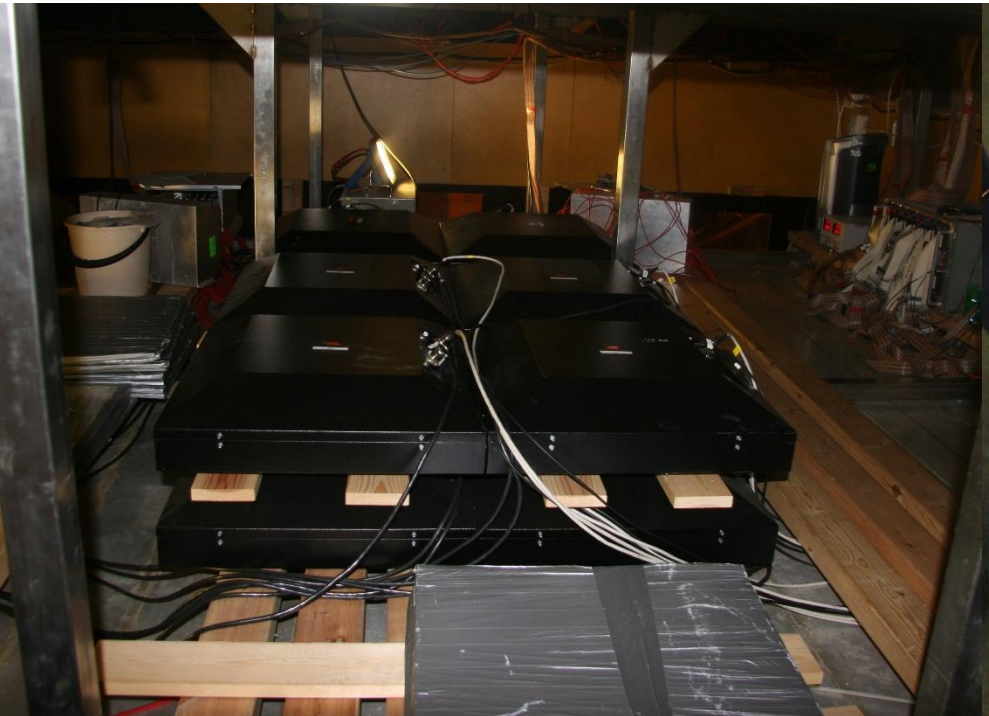


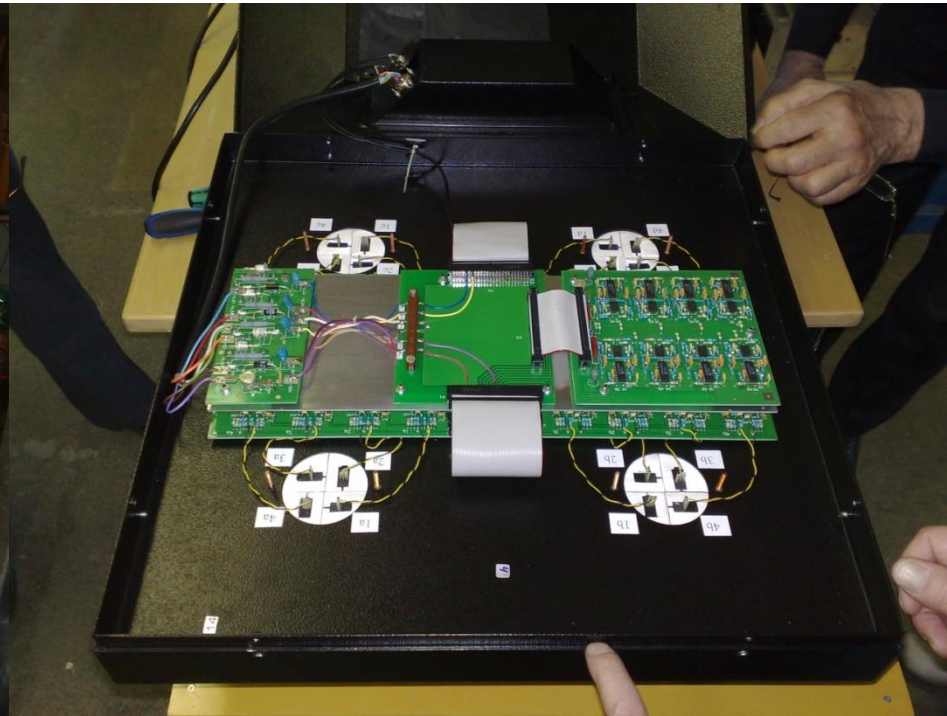


Detectors – SC16

Plastic scintillation detectors (SC16s from INR/RAS, Moscow)

- designed for EMMA (muon multiplicity, timing),
- 4×4 individual 12×12 cm^2, 3 cm thick pixels (area of 0.5×0.5 m^2),
- equipped with APDs (Avalanche Photo Diodes),
- total number of SC16s is 96 (or 1536 individual pixels, or 24 m^2),
- placed in the three central tracking stations,
- time resolution (σ) better than 2 ns.



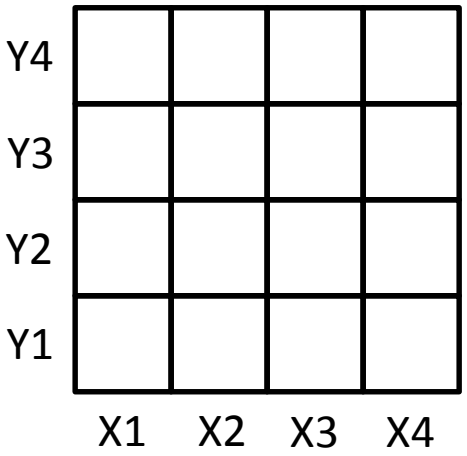


SC16s – in operation

Station G – Mid level

Station F – Bot level

SC16-pixels



LSTs – testing new electronics

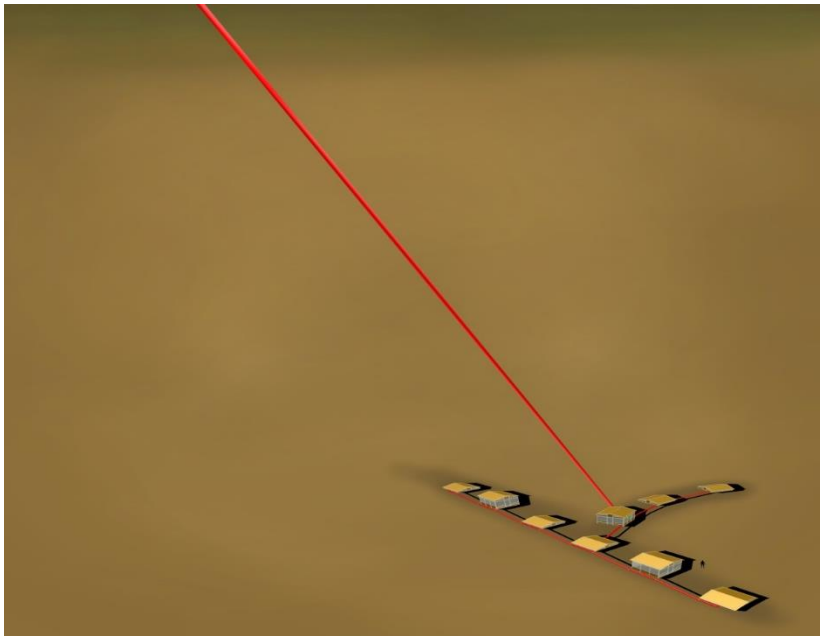
Limited Streamer Tubes (dismantled from KASCADE-Grande)

- gas-filled (with CO_2) position sensitive, area of 2.9 m^2 (1.0×2.9 m^2),
- the number of modules is 60 $\Rightarrow$ total area $\approx$ 174 m^2,
- a pad (or pixel) size is 2×8 cm^2.

New read-out electronics designed and expected to be in operation early next year.

Gas system

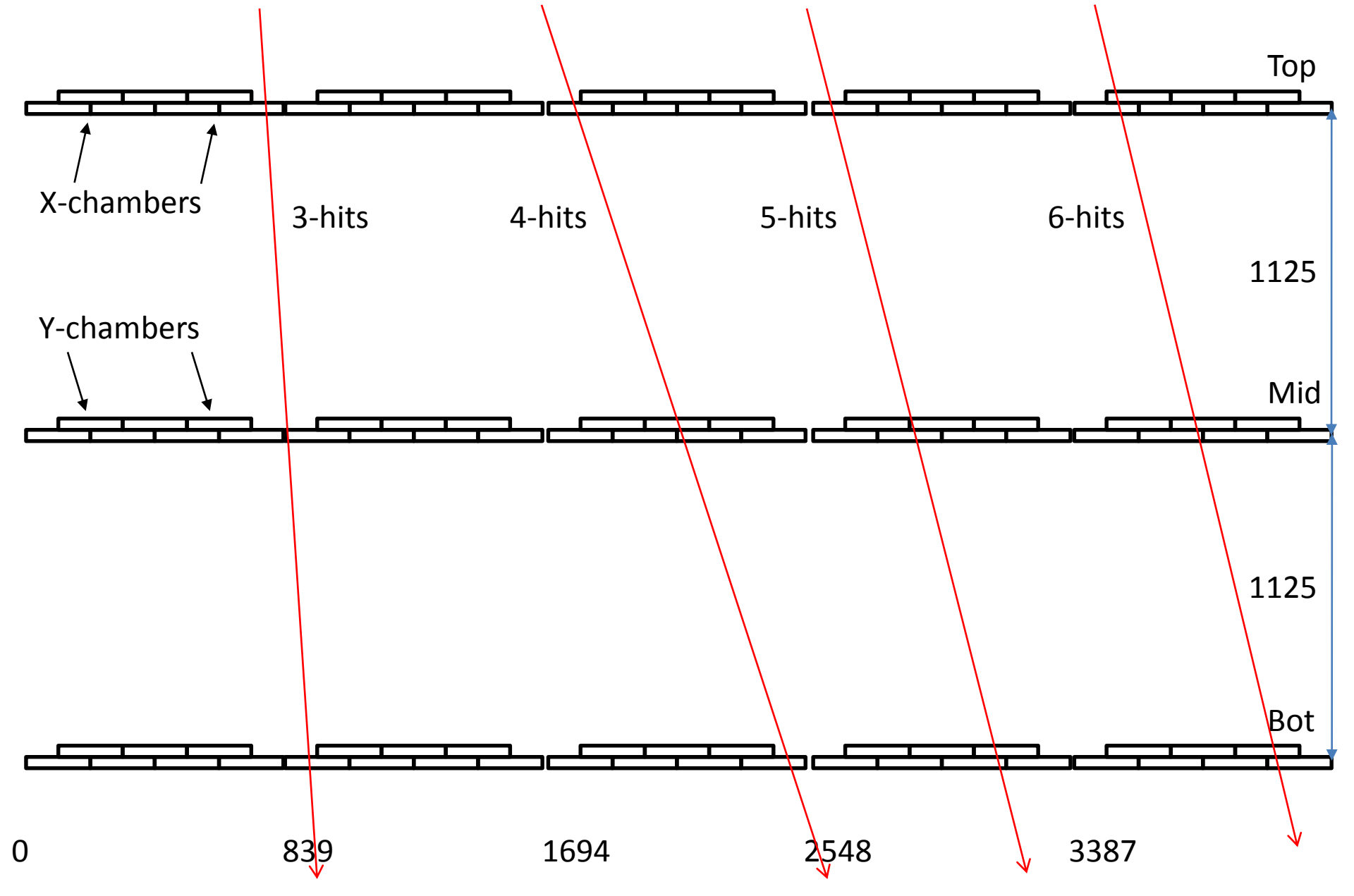
95 metre pipeline



+ Ar+CO_2-mixture for drift chambers,
+ CO_2 for LSTs,
+ Ar from LAr,
+ LAr and CO_2 in 3 m^3 tanks,
+ gas consumption ≈ 10 ℓ/min, NTP.

EMMA

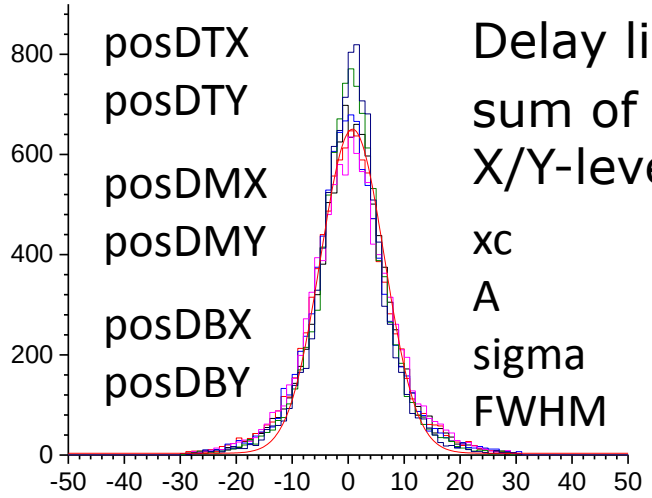
Tracking – possible tracks



Tracking – position resolutions

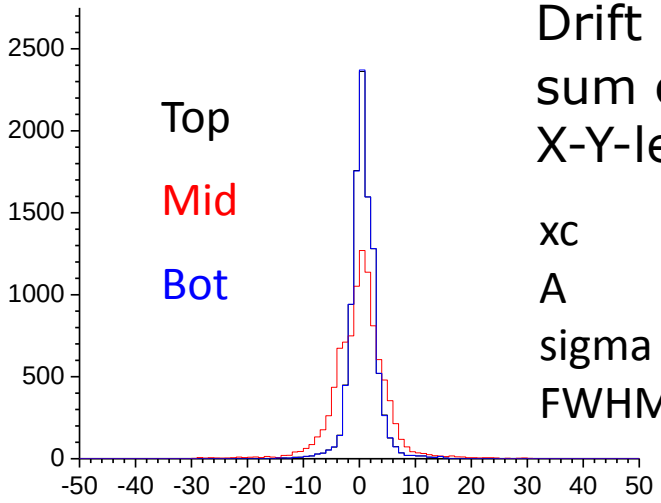
Residual $\Delta pos = pos_{track} - pos_{meas}$

R246-F-12h



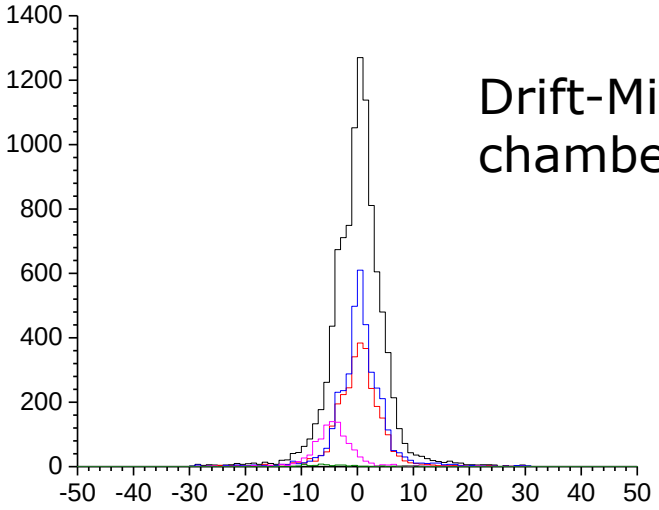
Delay line
sum of each
X/Y-level (6)

xc	0,78
A	9206
sigma	5,68
FWHM	13,37

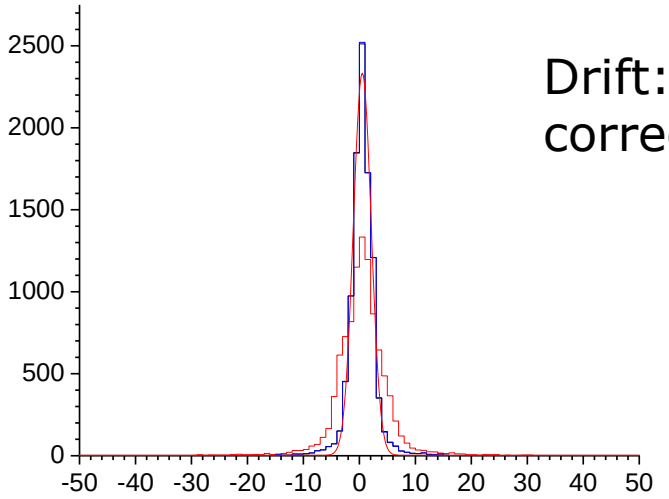


Drift
sum of each
X-Y-level (3)

xc	0,52
A	9301
sigma	1,59
FWHM	3,75



Drift-Mid: 5×6
chamber pairs



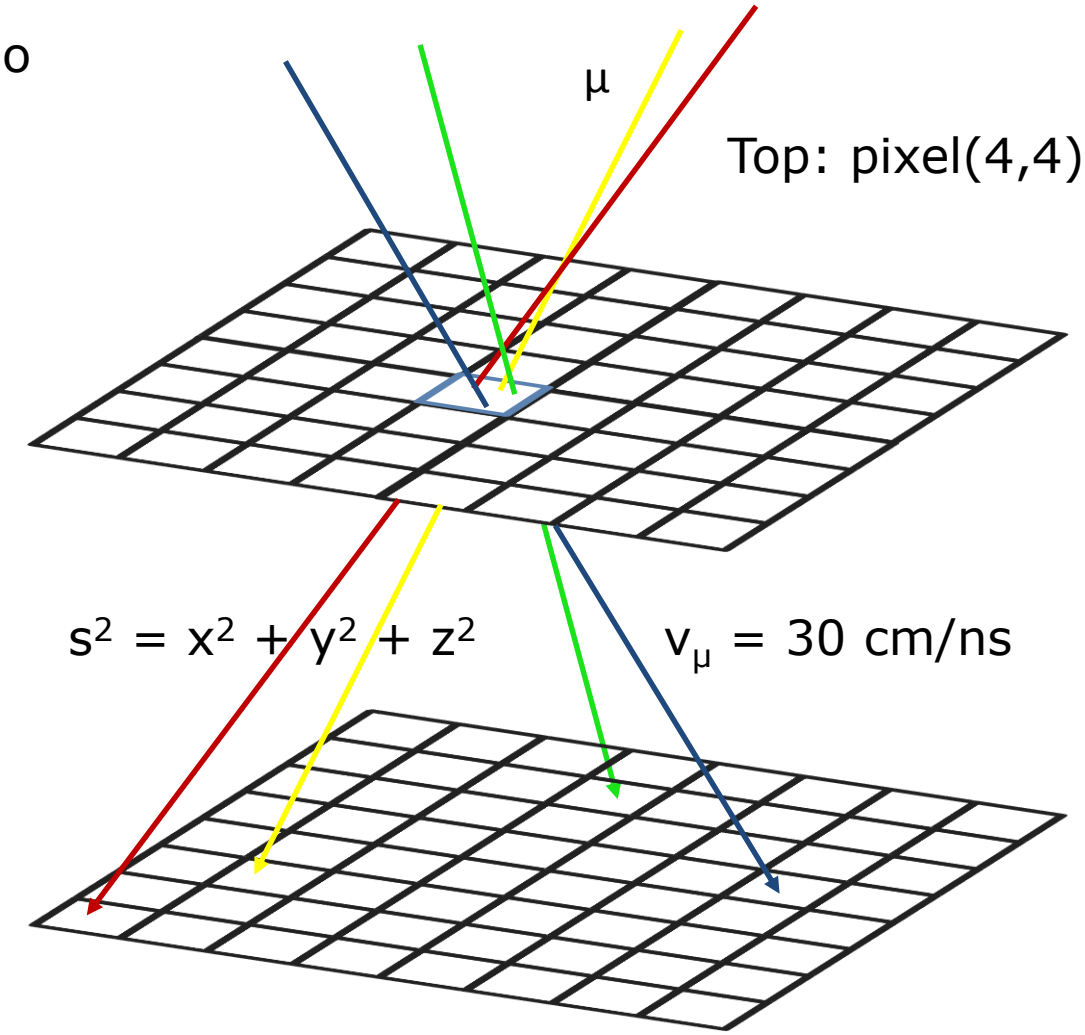
Drift: Mid
corrected

SC16 – delay matching/timing

(use tracking and)

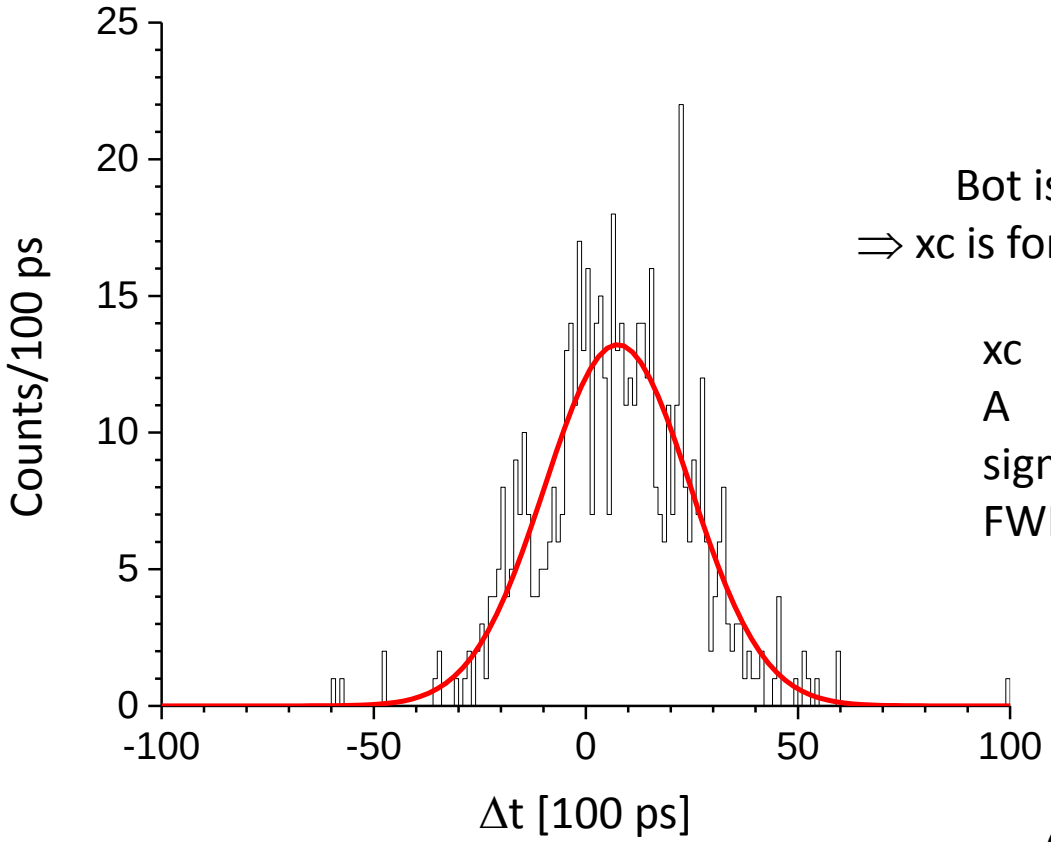
find coincs between (pixels in) two levels and correct for TOF.

- muon multiplicities,
- fast timing,
- background reduction,
- initial guess for arrival angles,
- etc.



SC16 – delay matching/timing

Time difference Δt("one pixel on Top" – "8×16 on Bot") after delay matching, Station G, SC16 positions taken from tracking.



Bot is reference
⇒ xc is for delay matching

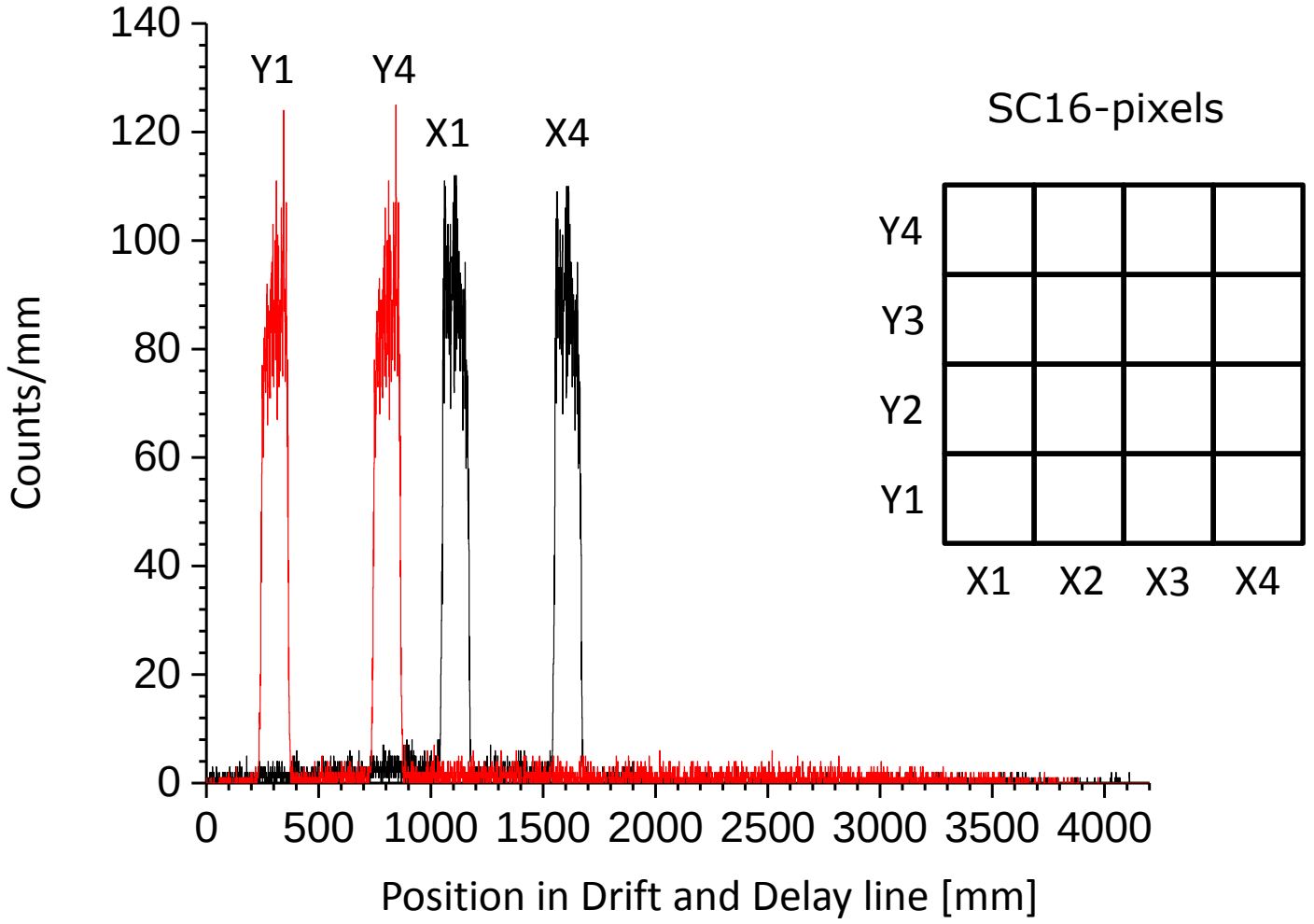
xc	7,48
A	570
sigma	17,2 (× 100 ps)
FWHM	40,5 (× 100 ps)

(TOF corrected)

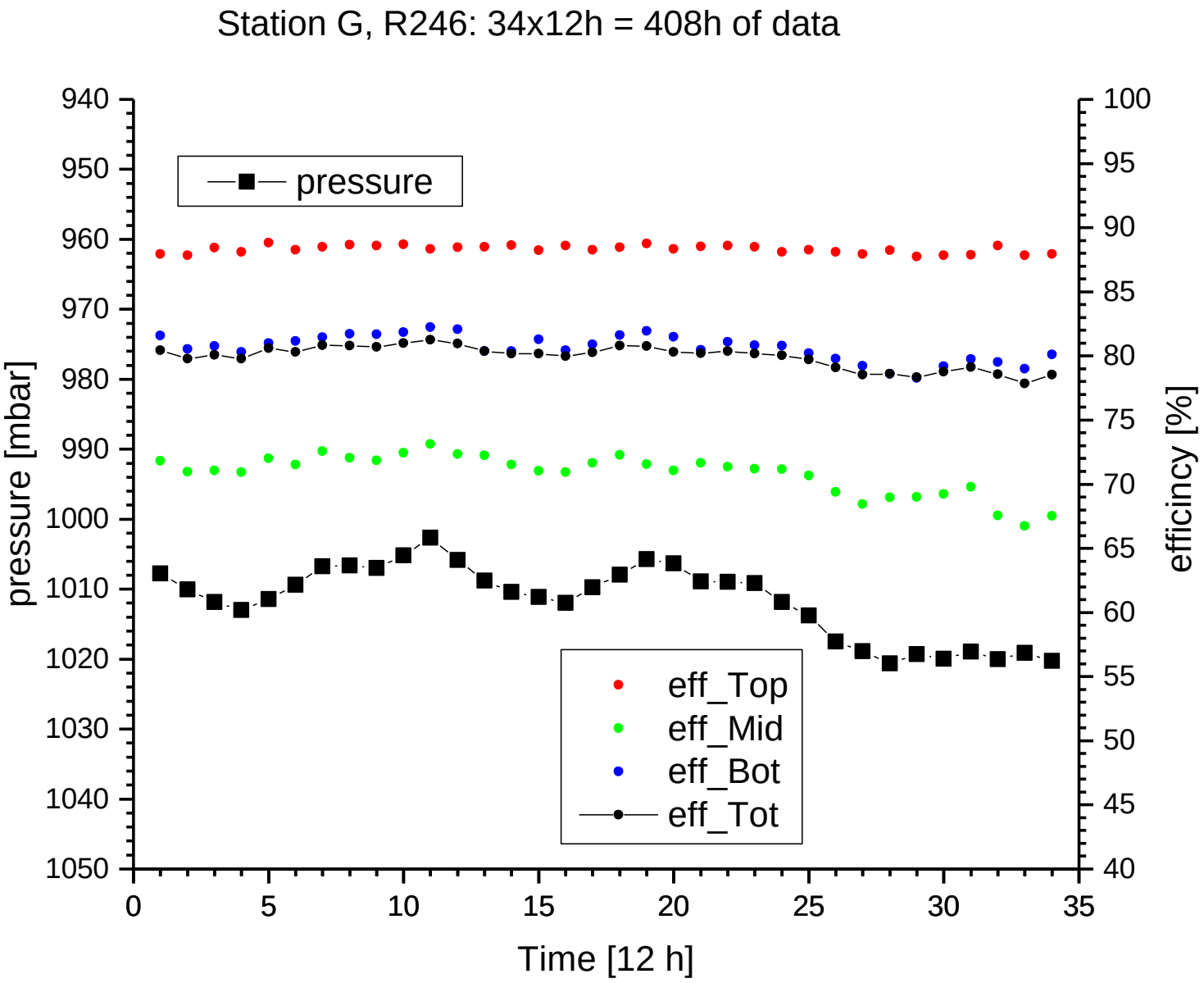
(The gap between the levels is 1125 mm)

SC16 – positions

extracted using tracking, Station G



Tracking – efficiency



Effciency - example

Check effciencies using single muon flux:

$$\text{Flux } [\text{Hz/m}^2] = (n_{obs} \times \text{eff}_{detection} \times \text{eff}_{geometry}) / (D \times \text{Area}_{active})$$

n_{obs} = the number of observed (single) muons,

$\text{eff}_{detection}$ = detection efficiency, e.g., for 6-hit track = $1/\Sigma e_i$ where e_i is the muon detection efficiency of chamber i,

$\text{eff}_{geometry}$ = corrects for losses in detector area ("broken" chambers, gaps between the chambers),

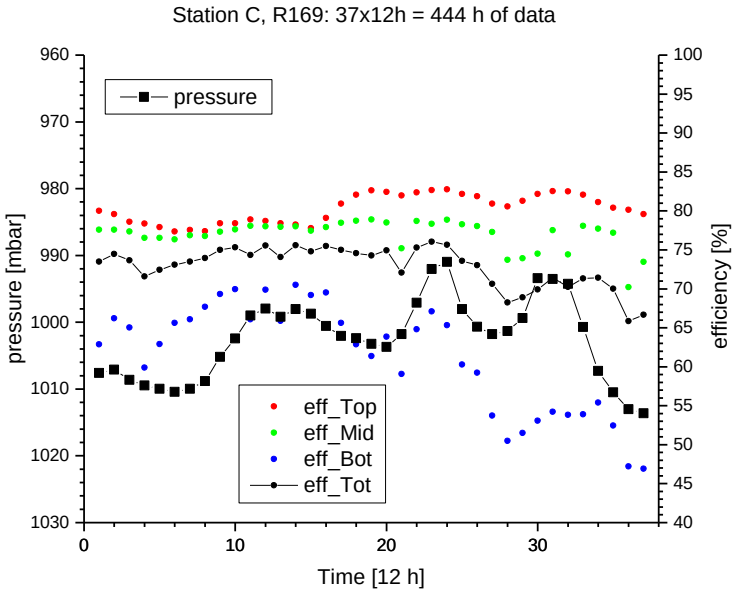
D = duration,

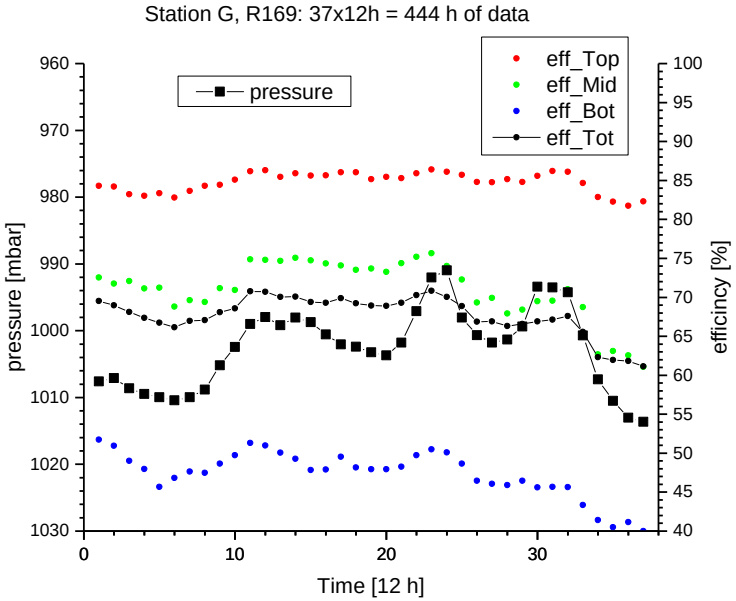
Area_{active} = detector area.

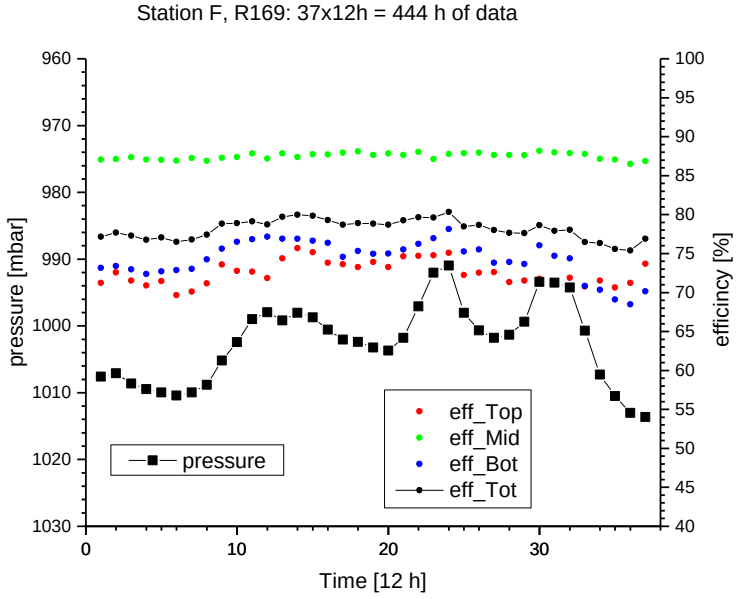
However, this is a simplified picture. In reality '$\text{eff}_{geometry}$' requires assumptions on the muon distribution (through he rock) which is assumed here to be simple, or $\sin\theta\cos\theta$ where θ is the zenith angle.

$\Rightarrow$ here we simply use muon flux per steradian, or [Hz/m^2·sr].

Effciency - example

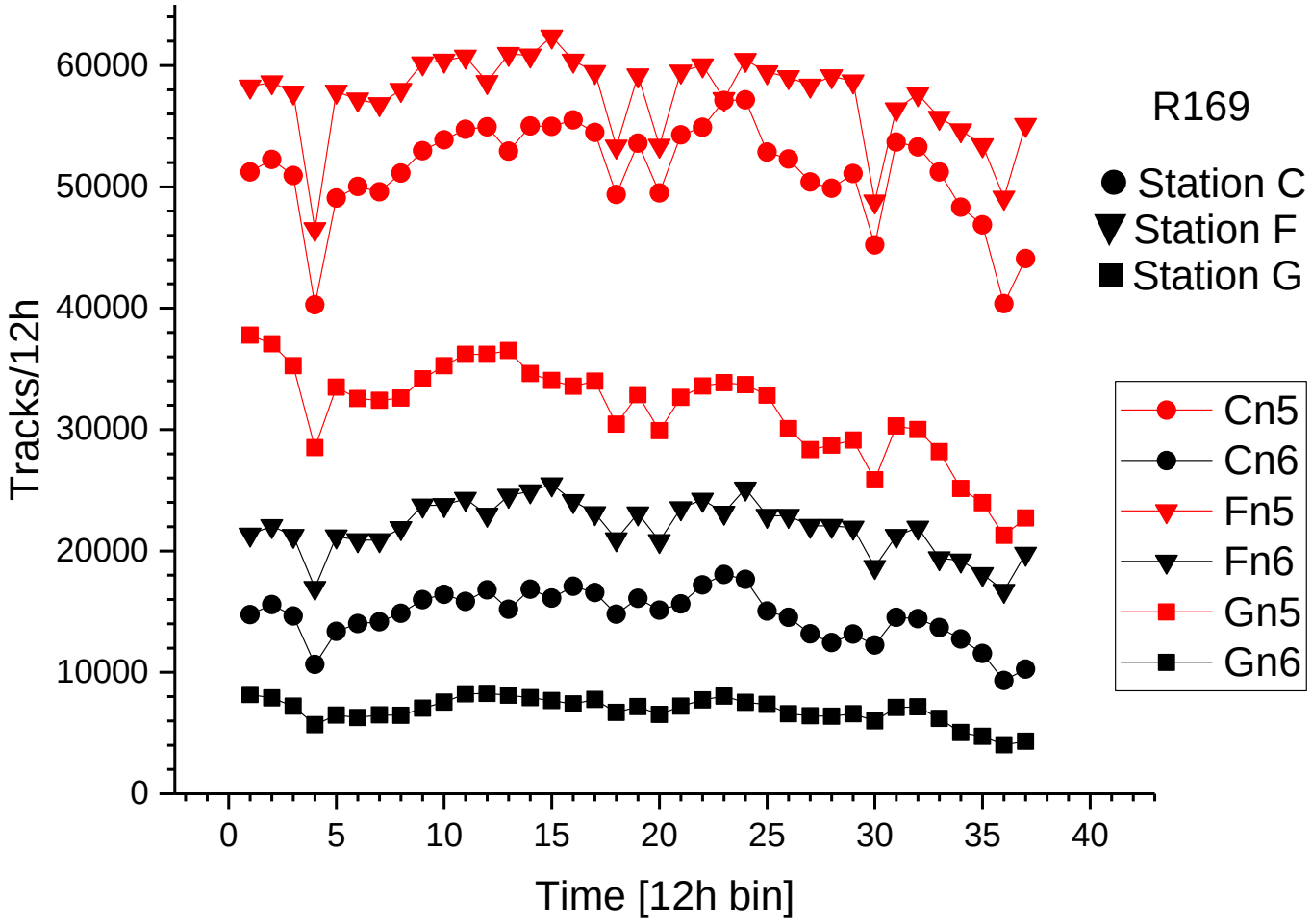






Effciency - example

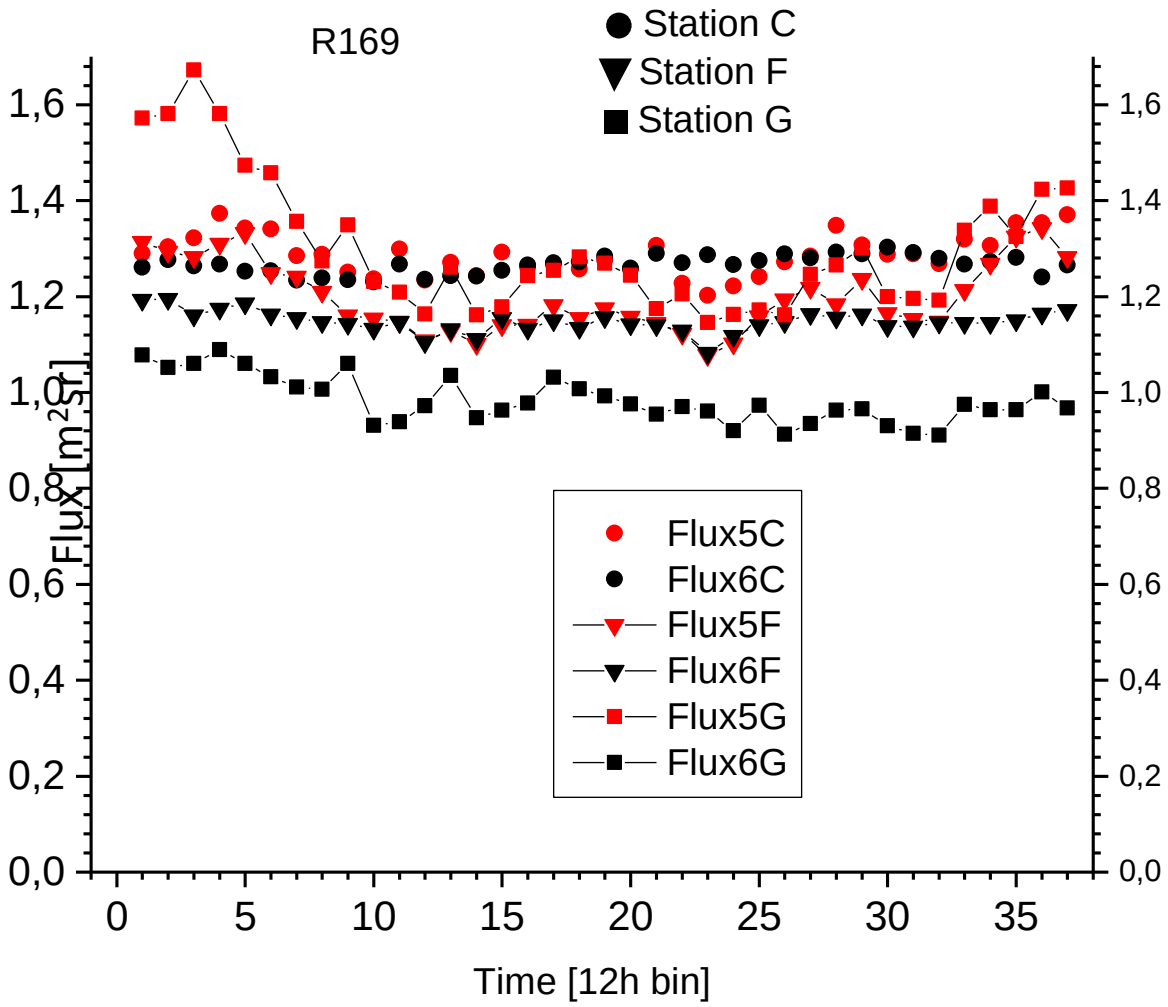
Tracking – single muon rates in three Stations using 5 and 6-hit tracks.



Effciency - example

Preliminary

Tracking – single muon flux



Multi-Muon tracks

Example

- the number of detected multi-muon tracks in run R246 (391h):

Multiplicities (Mult.) of 5, 6 and 5&6-hit track events in each Station:

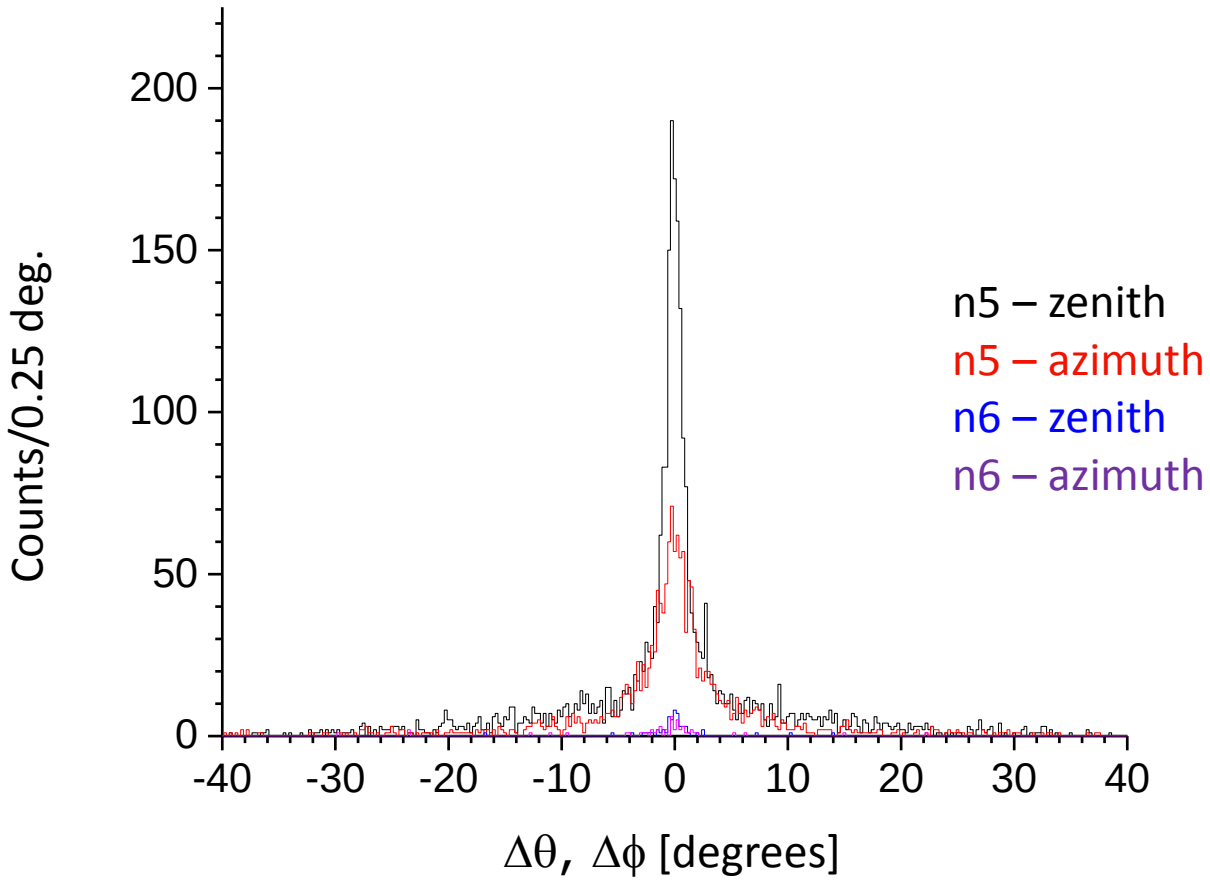
\	R246-C			R246-F			R246-G		
Mult.	5-hit	6-hit	5&6-hit	5-hit	6-hit	5&6-hit	5-hit	6-hit	5&6-hit
1	1736543	371113	1985682	1578439	346277	1824135	2049245	456026	2360382
2	797	30	61482	819	25	50849	1011	40	73093
3	44	1	225	34	0	197	48	0	281
4	3	0	30	3	0	18	5	0	23
5	0	0	2	1	0	3	2	0	5
6	1	0	2	0	0	2	1	0	3
7	0	0	0	0	0	0	0	0	1
8	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0

Note: the numbers of detected tracks, no efficiency etc. corrections used.
In the composition analysis measured efficiencies are used as an input in the simulation codes.

Tracking – angles

R246-G

Angular distributions $\Delta\theta$, $\Delta\phi$ (zenith and azimuth), Station G, all showers with more than one track.



Conclusions

Hardware:

- LST-electronics in progres,

- Last four detector stations will record data by the end of this year.

Software:

Data analysis can/will be carried out with the small number of program packages:

+ calibrations (two different codes for positions and effs.),

+ tracking,

+ shower simulation.

The next step is to implement SC16s (fully) into the tracking code.

Thank you

EMMA collaboration + SAB, May 2015

Drift chambers – efficiency