MCORD

MPD Cosmic Ray Detector for NICA

by Polish consortium NICA-PL

NARODOWE CENTRUM BADAŃ JĄDROWYCH ŚWIERK

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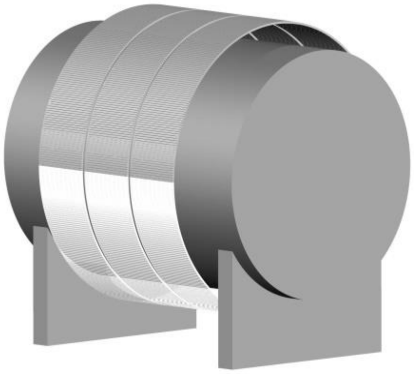
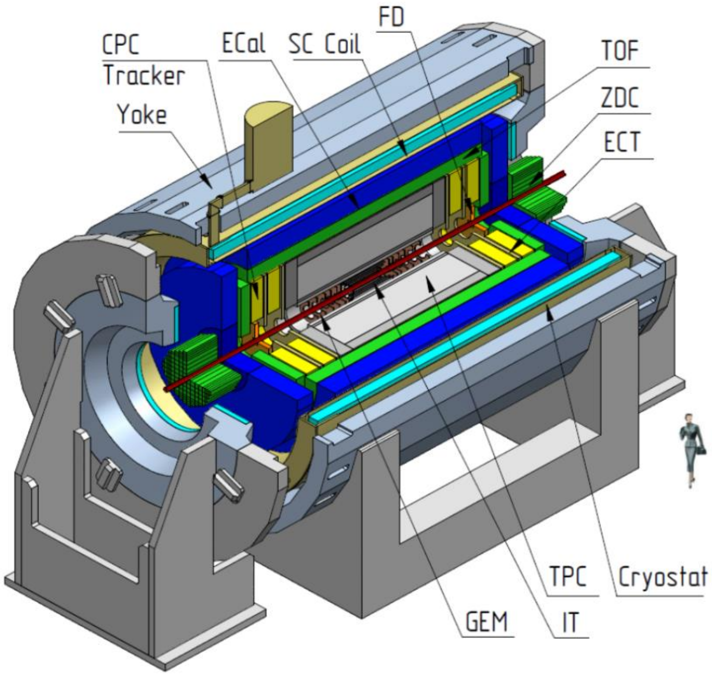
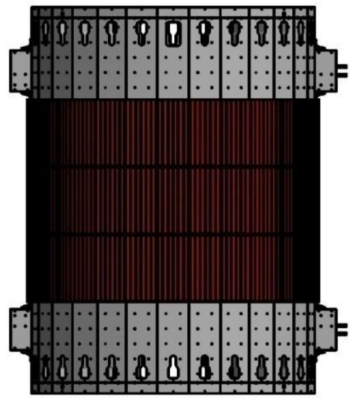
Outline

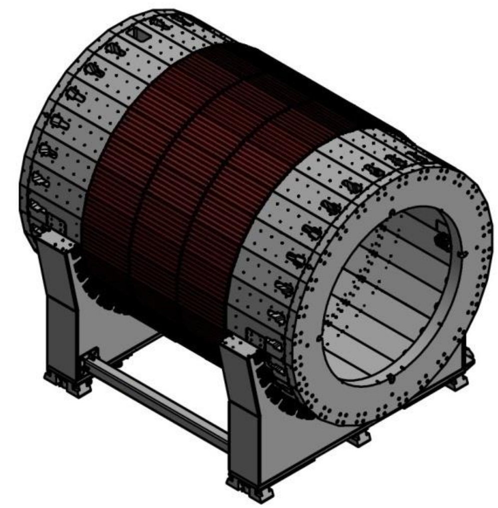
1. Design, modeling proposition
2. Last DAC Minutes
3. Trigger during commissioning
4. Muons detection – goals
5. Astrophysics
6. Present status of work
7. Conclusions

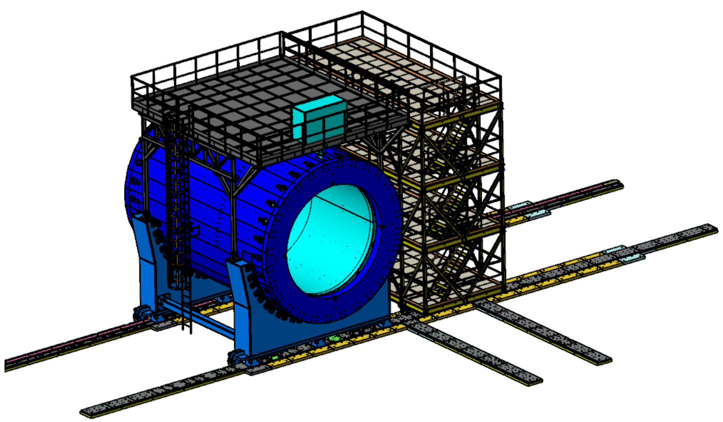


1. MCORD and MPD









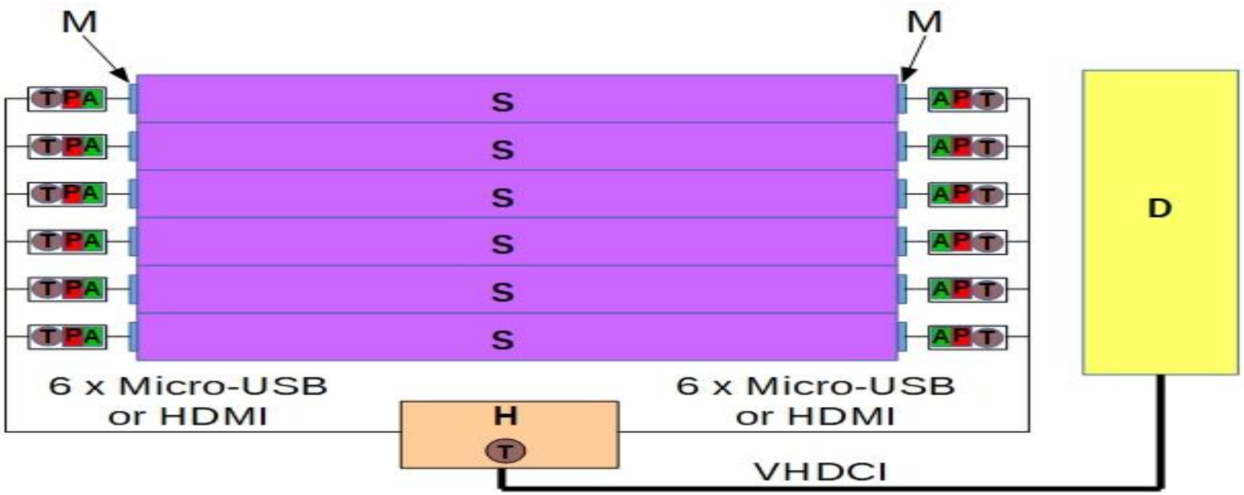
MCORD - One surface on full circumference

- FD Forward detector
- Superconductor solenoid (SC Coil)
- Inner Tracker (IT)
- Straw-tube Tracker (ECT)
- **Time-projection chamber (TPC)**
- **Time-of-Flight system (TOF)**
- **Electromagnetic calorimeter (EMC - ECal)**
- Zero degree calorimeter (ZDC).
- Cosmic Ray Detector (MCORD)

nica.jinr.ru/video/general_compressed.mp4

1. Design of detection system

THE MUON DETECTOR SCHEME OF ANALOG SIGNAL PATH



Position resolution
In X axis – up to 5 cm
In Y axis – 5-10 cm

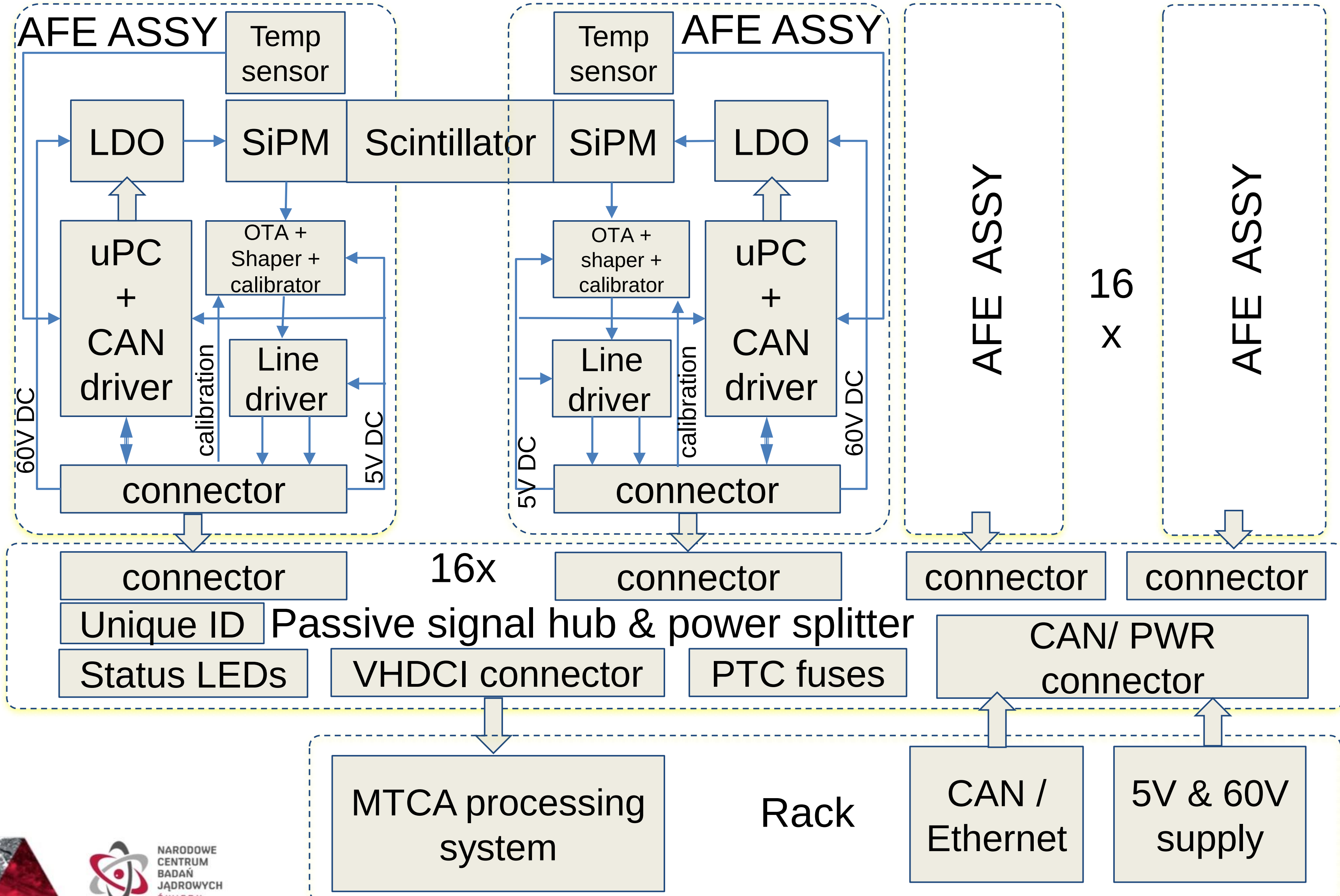
Time Resolution –
about 300-500 ps

Legend: S (violet) – plastic scintillator, M (blue) – SiPM, P (red) – power supply with temperature compensation circuit, T (brown) – temperature sensor, A (green) – amplifier, D (yellow) – MicroTCA system with ADC boards, H (orange) – Passive Signal Hub & Power Splitter.

Connector type examples:
1. Rugged Micro-USB
2. Rugged C3 HDMI
3. HDMI Industrial
4. HVCDI

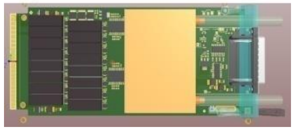
1. Design of digital electronic system

Dedicated Analog Front-End module: CAN network connectivity with unique ID chip as CAN address, Unique ID in every hub for cabling checking and identification of Hardware ID



MicroTCA (MTCA) configuration

Dedicated
Analog Front-End module



FPGA mezzanine card (FMC)

AMC FMC carrier board

MTCA Carrier Hub

- Standard MTCA crate (8U)
- Crate number depends on channel count and sampling speed At 125MS/s: 384 channels / crate
- 2xSAS-external cable + 1xEthernet cable for one section (8 scintillators)
- SAS cable fi 8mm (16 chanels), Etchernet cable 5mm (other signals and 60V power)

For several MTCAs one main MCH concentrates data from slave MCHs to generate the final muon trigger

We need cabling system that provides near 1GHz bandwidth and very low crosstalk <30dB@1GHz to maintain sub-ns precision of pulses time-of-arrival measurement.

2. MPD DAC took place 23.I.2019 – Minutes

1. MPD needs an effective trigger during commissioning, thus MCORD phase space coverage should be large.

2. The role of the MCORD detector in the MPD calibration procedure needs to be better understood.

3. The DAC encourages the MCORD team to look into the possibility for MCORD serving as muon identifier within the MPD system.

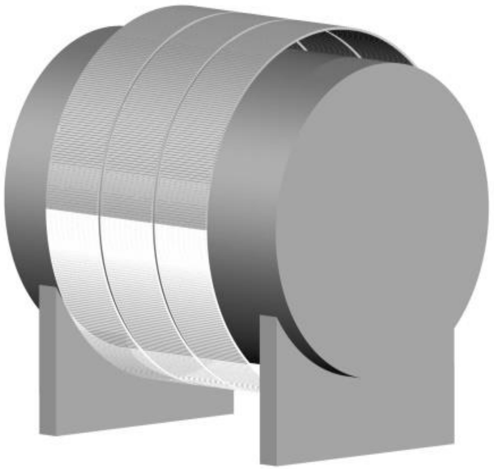
4. MCORD physics case for cosmic ray studies needs to be strongly improved.

2. Cosmic Ray Detector – Goals

a) Trigger (for testing or calibration)
- testing before completion of MPD (testing of TOF, ECAL modules and TPC)
- calibration before experimental session

b) Muon identifier (created inside of MPD)
- Pions and Kaons decays
- Rare mesons decays (etha, rho)
- Possible decays of new „dark" particles

c) Astrophysics (muon showers and bundles)
- unique for horizontal events
- working in cooperation with TPC and TOF

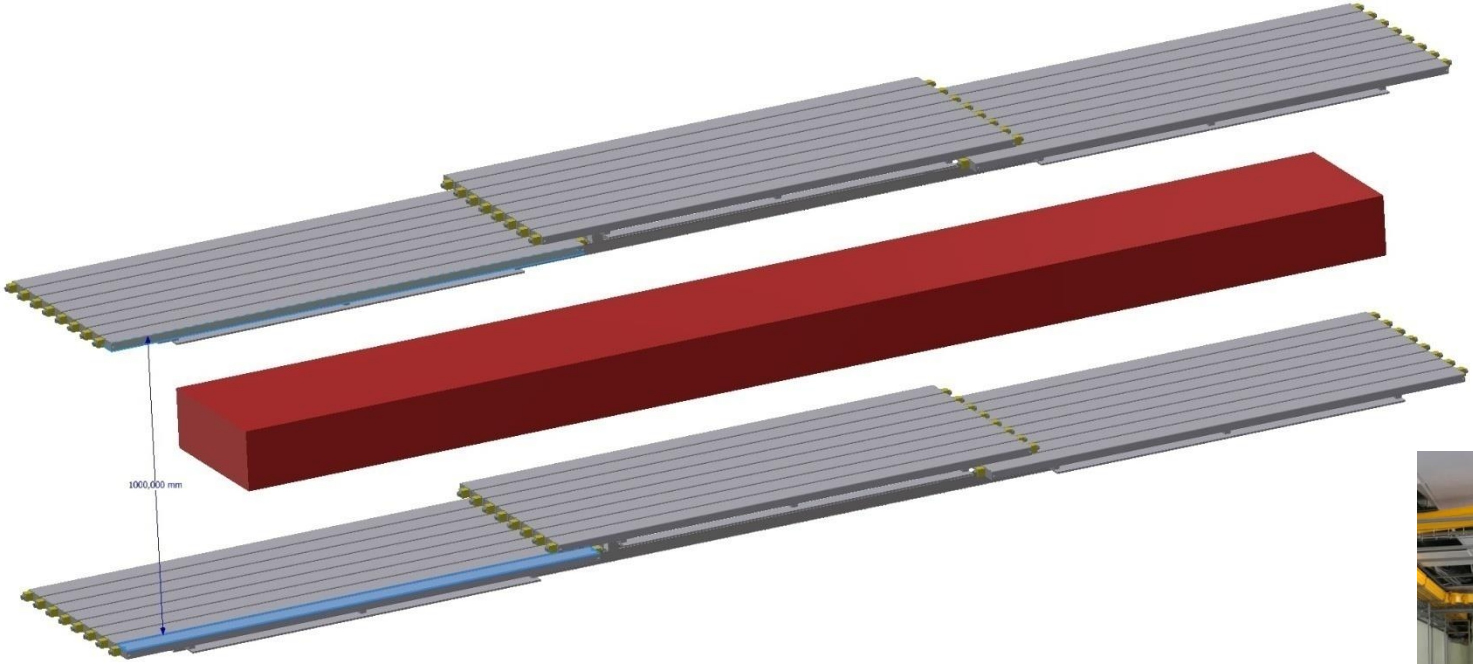


Additionally

d) Veto and Calibration (normal mode - track and time window recognition)
Mainly for TPC and eCAL

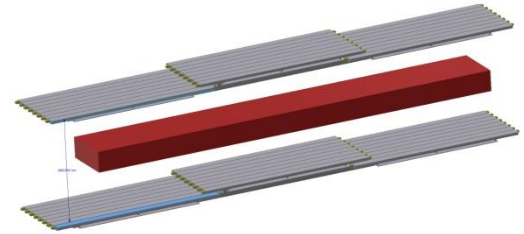
3. Trigger during commissioning

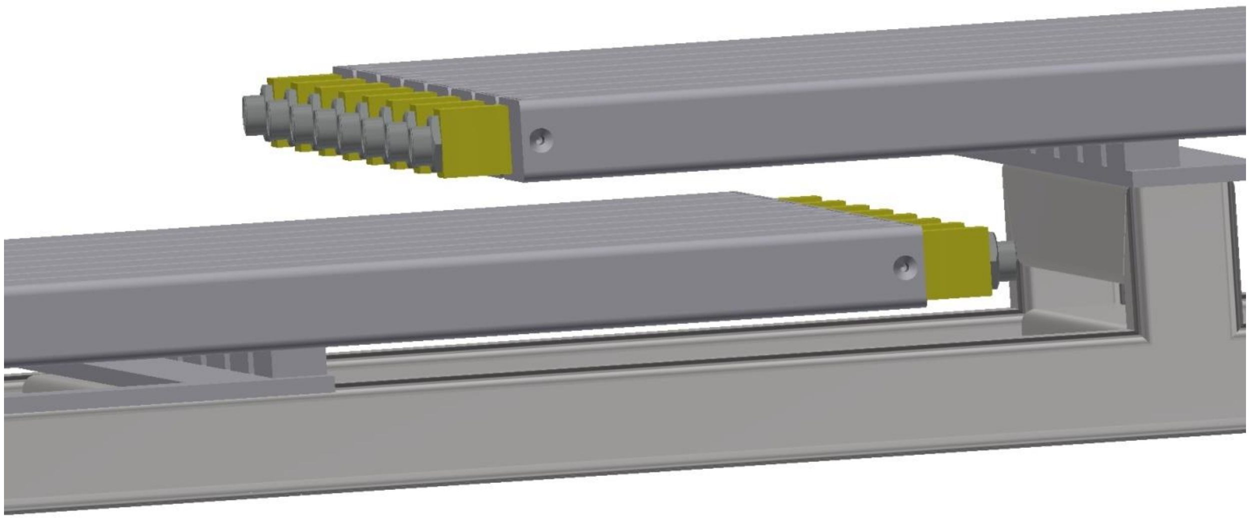
Example: testing of the TOF module

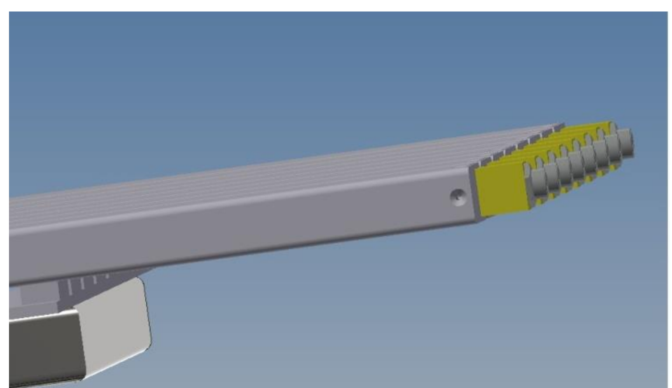


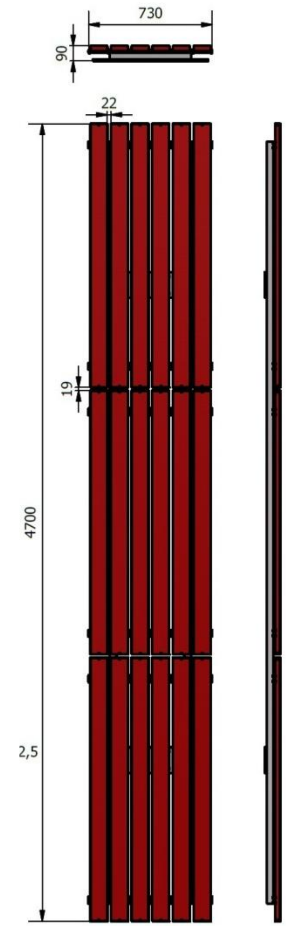
3. Trigger during commissioning

No Null Zone at MCORD



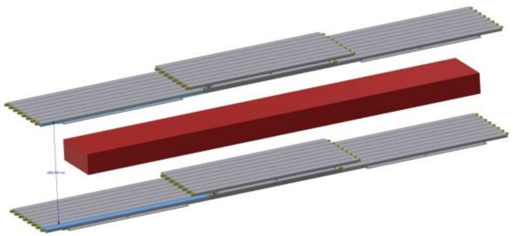






3. Trigger during commissioning

MCORD Module and smaller Section



(1 : 10)

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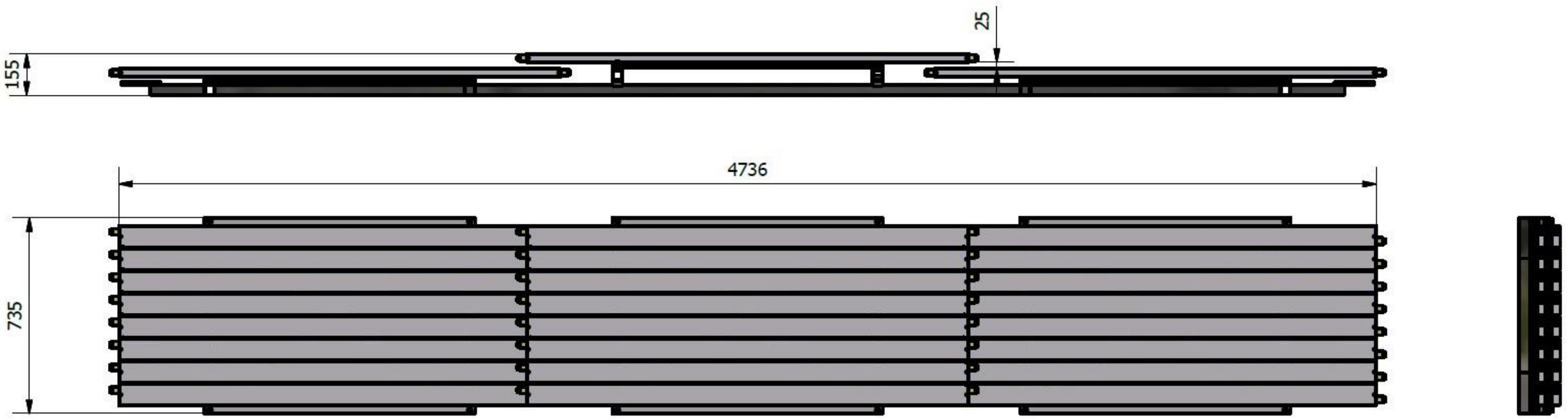

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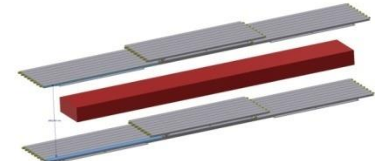
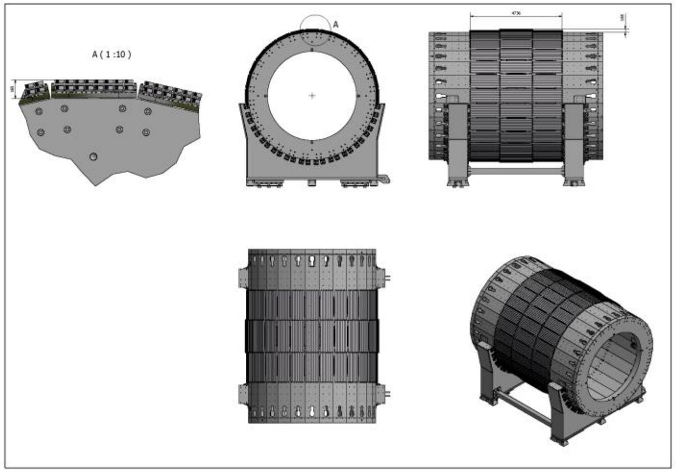
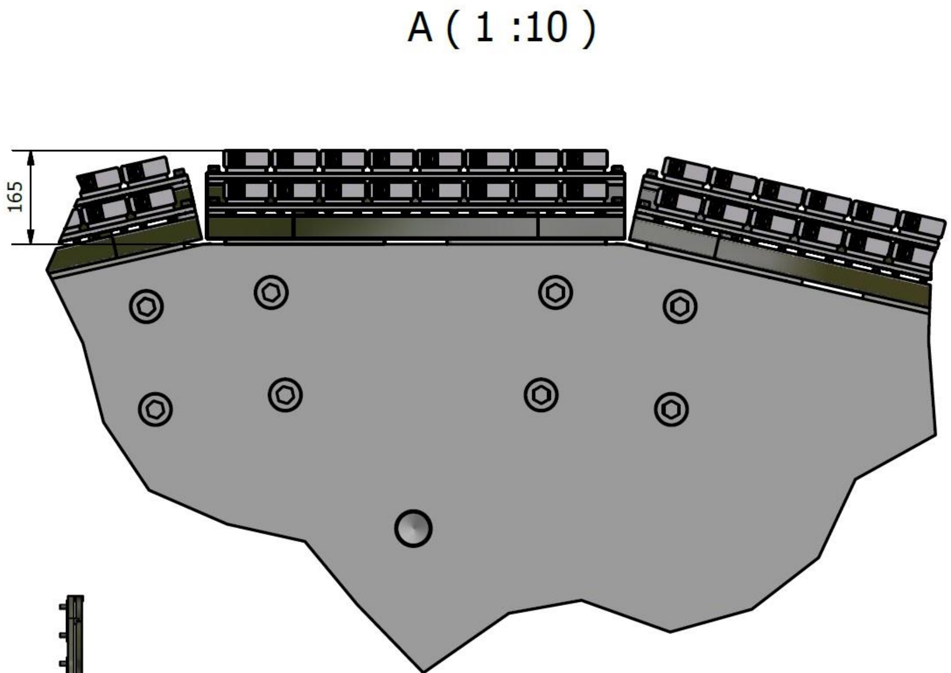
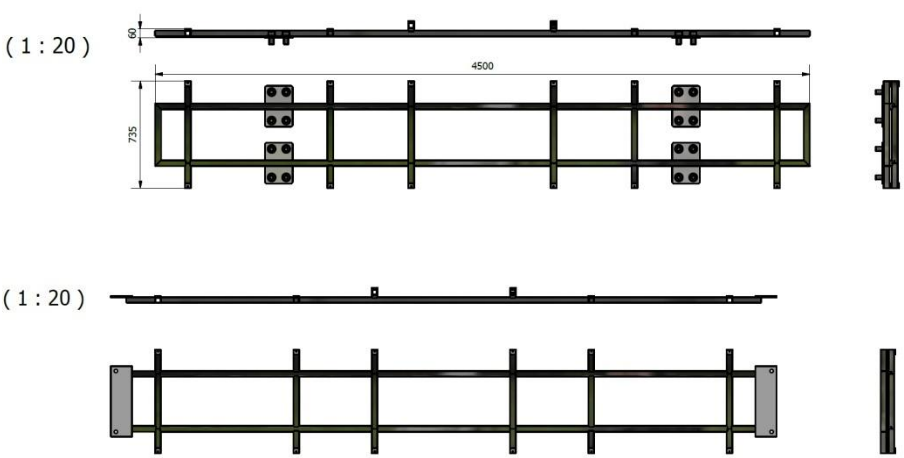
3. Trigger during commissioning

MCORD Instalation on MPD surface





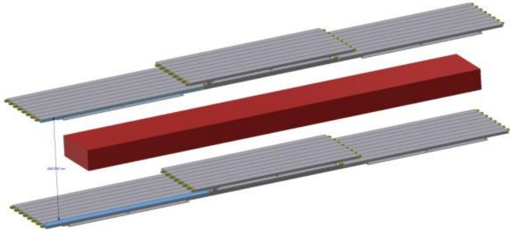




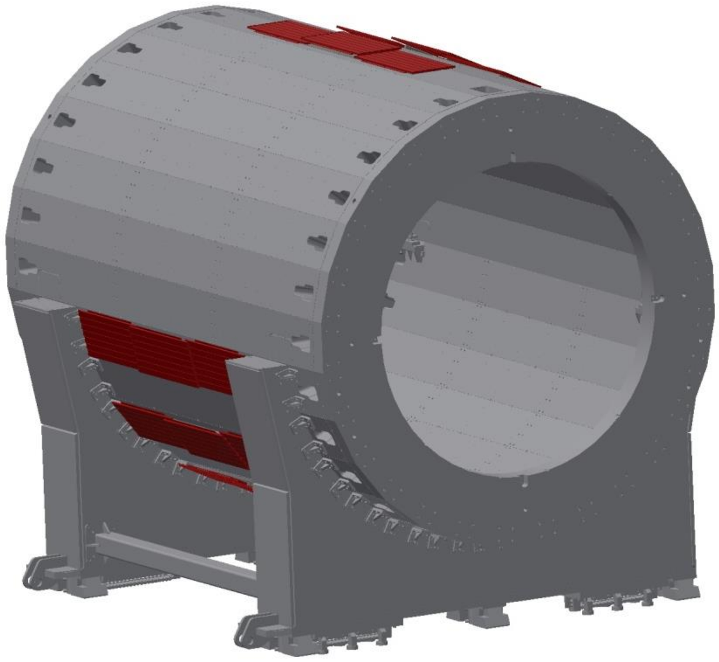
Modules Mounting on MPD surface

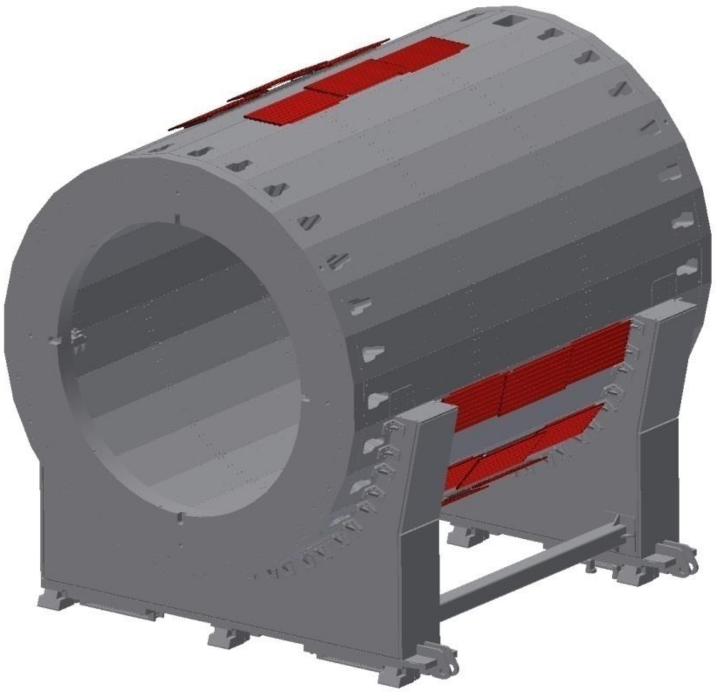
Detector mounted to steel frame	
Steel frame built with square profiles:	40x40 [mm]
Number of Modules:	28
Frame mounted to MPD by screws	
Weight of all modules:	4200 kg

3. Trigger during commissioning



If only 6-8 MCORD modules will be built.





Data processing and resolution

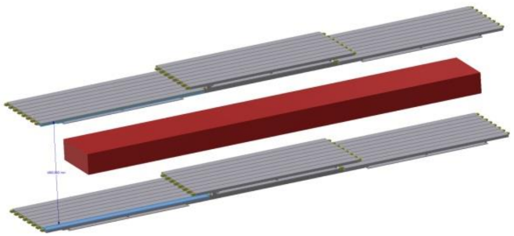
Latency estimation for L1 trigger (event without parameters)

- ✓ AFE cabling 8ns/m, with 10m cabling latency is 80ns
- ✓ ADC + SERDES latency: 400ns

Latency estimation for L2 trigger (event with parameters)

- ✓ MGT latency: 500ns
- ✓ Algorithm latency : 2-5μs
- ✓ Formatter and transmitter latency: 1μs

Estimated total latency: 3.5 – 7.5μs



RESOLUTION

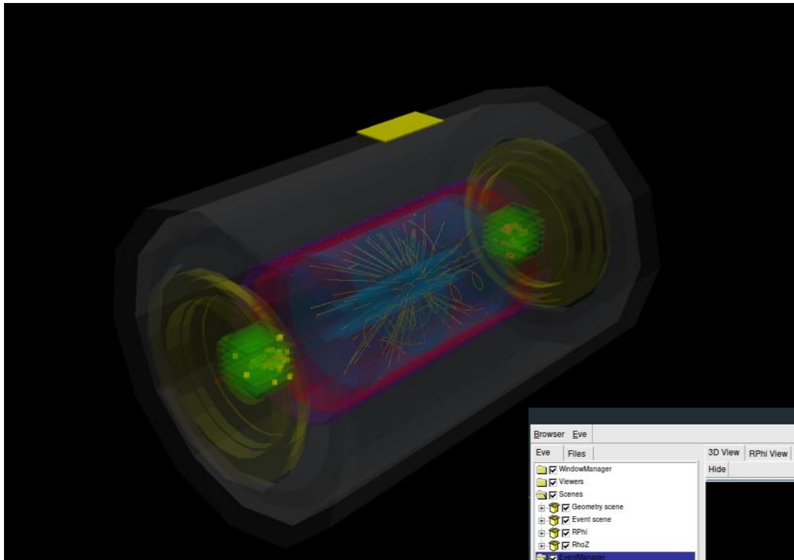
Position resolution: In X axis – up to 5 cm, In Y axis – 5-10 cm

Time Resolution – about 300-500 ps

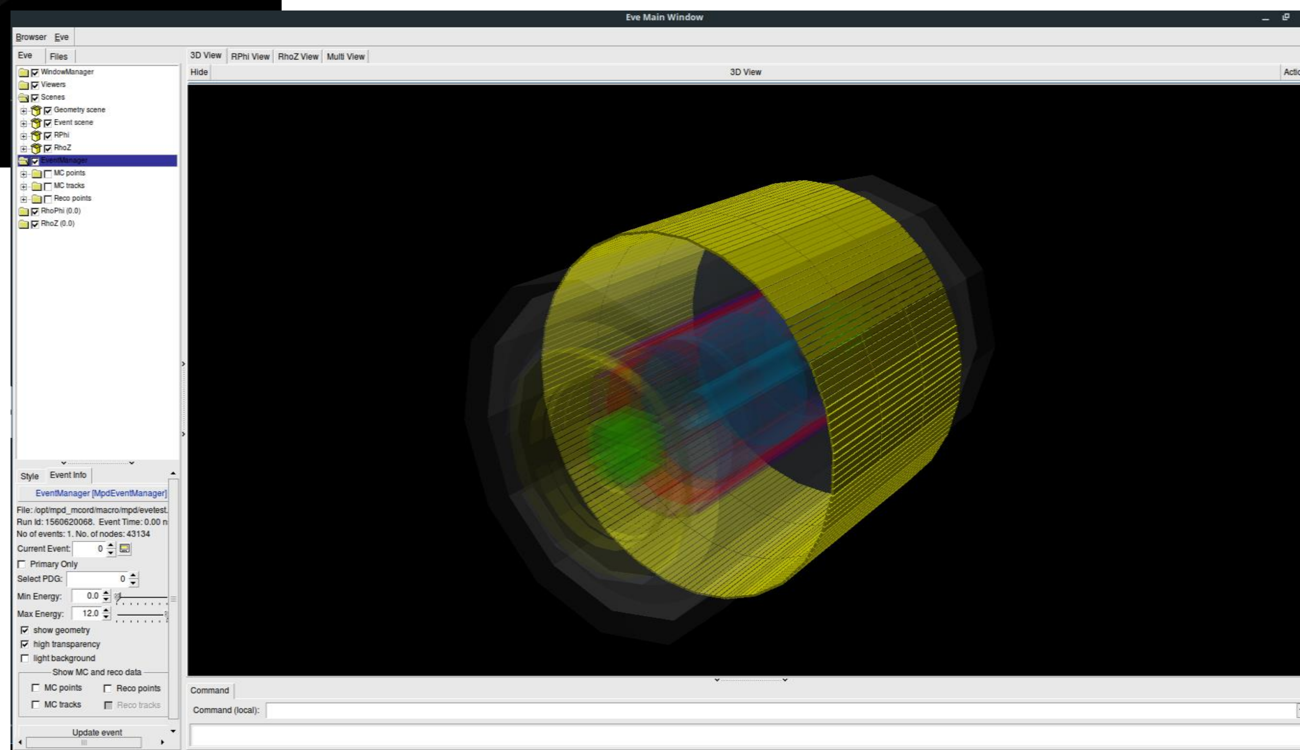
Number of events (particles): about 100-150 per sec per m2

Calculated Coincidence factor: about 98%

4. Muons detection – Goals



MCORD as a detector for recognition of muons created in MPD.
Dedicated for it – unlike other detectors.
The most interesting for us are processes based on muonic dilepton production.



Screenshots from EventDisplay with MCORD detector (yellow)

4. Muons detection – Goals

DATA

- **UrQMD 3.4**
- **Au+Au collisions at 11 GeV**
- **Central collisions (impact parameter < 3.5 fm)**

MUON production in UrQMD

- **No primary muons**
- **Secondary muons „-": 87.5% from pi-, 11% from K-**
- **Secondary muons „+": 74% from pi+, 8% from K+, 8% from Protons**

SIMULATION

- MpdROOT (MCORD branch created from MpdROOT in the middle of May)
- Default MC simulation (without vertex smearing)
- Only monolitic plastic scintillator present (with simplified geometry)
- 10k and 100k of events analyzed

Particles in MCORD

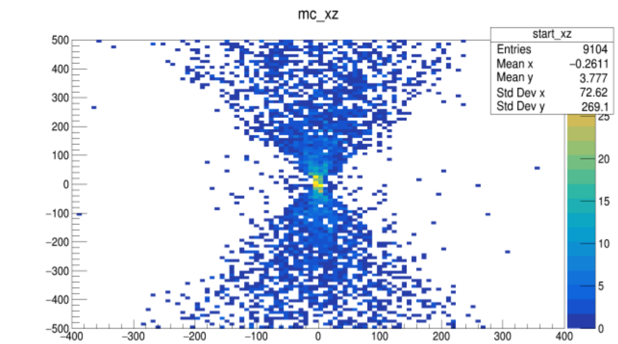
- 11% Anti-muons
- 7.3% Muons
- 4% pi+
- 3.1 % pi-
- 3% Anti-K0
- 2% protons
- 0.3% K-

- Huge portion of particles that loss energy in MCORD don't have assigned MCTrack (parent_no = -2, particle not stored in MC-stack?) – 1/3 of them are gamma quants.

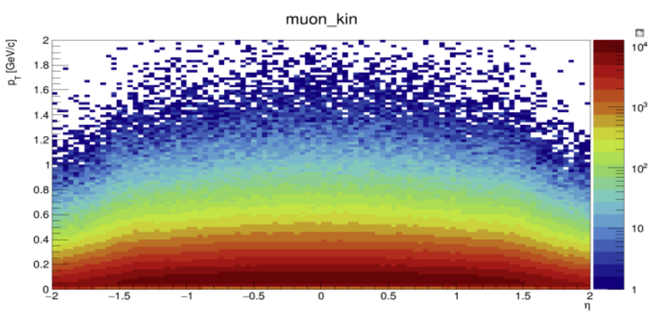
UrQMD model base on QCD for hadrons production – Very rare mesons decay probably does not exist in this model - **We should implement PLUTO model for UrQMD+PLUTO calculation** (ex. CBM in Darmstadt)

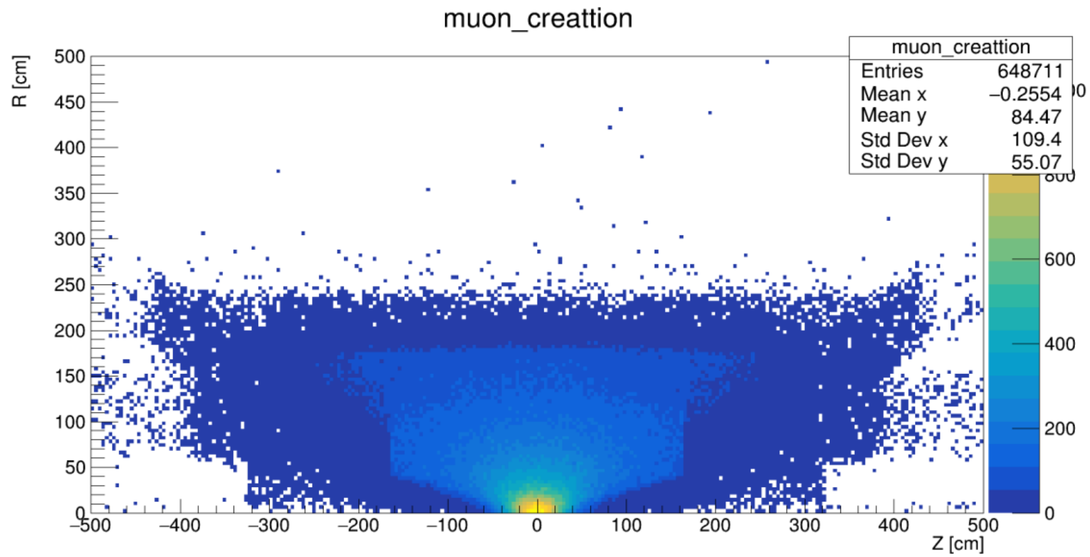
4. Muons detection – Goals

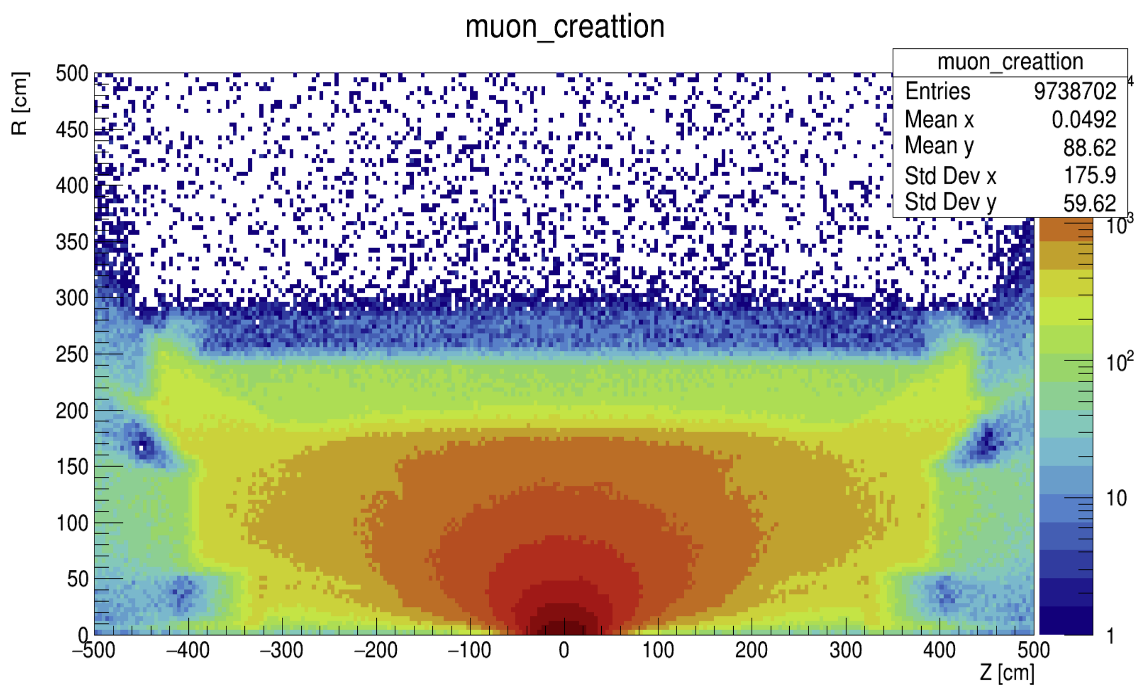
Points of creation of muons „-”



- **Pseudo rapidity and transverse momentum of muons „-”**

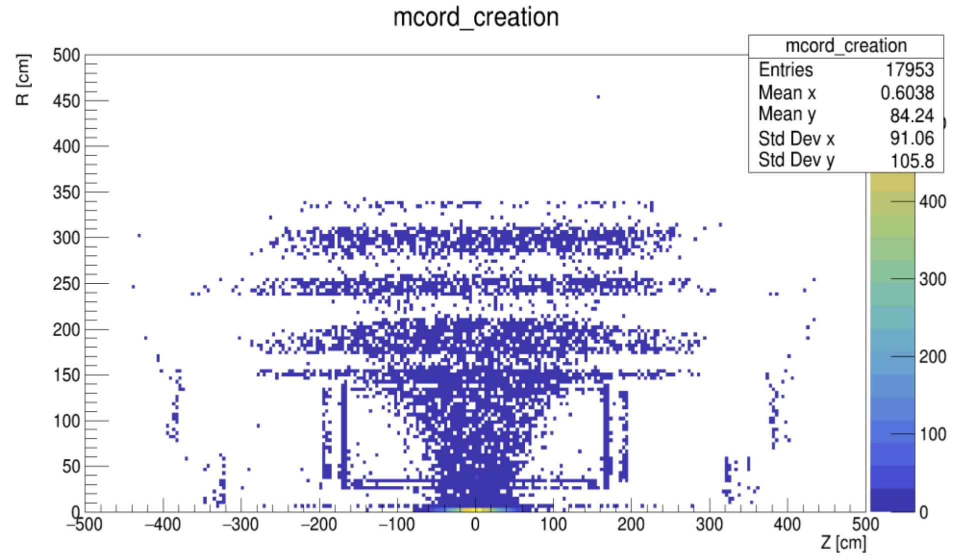




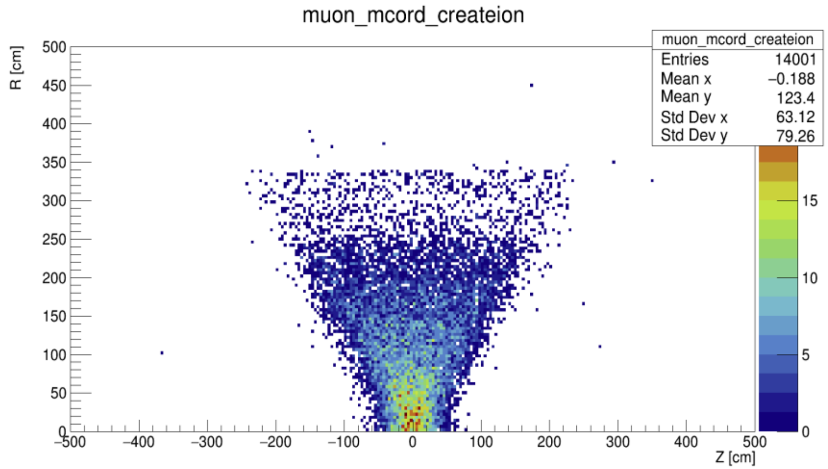


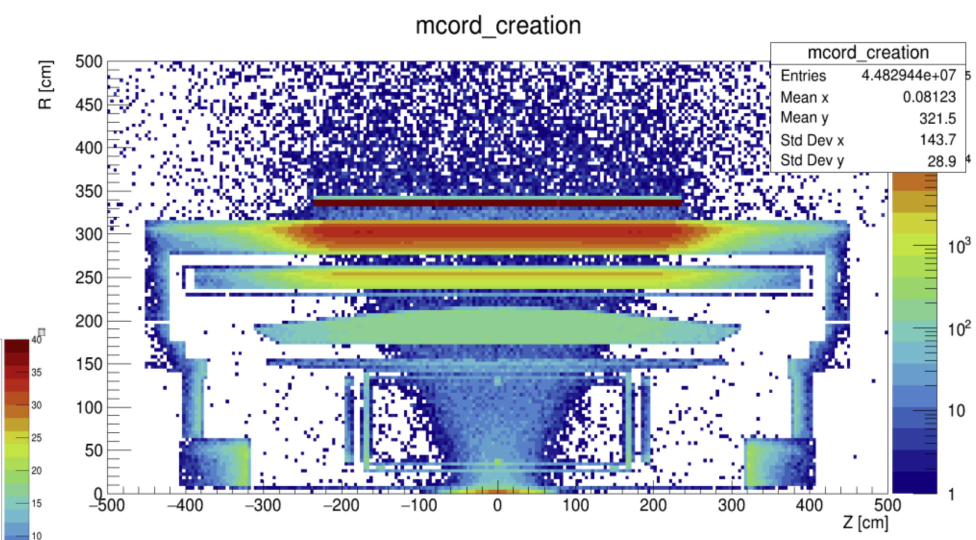
4. Muons detection – Goals

Position of the creation of the particles registered in MCORD

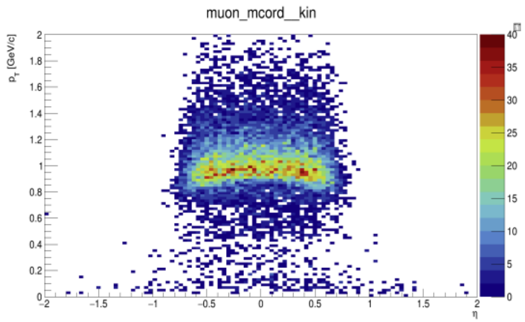


Creation position of muons „-” registered in MCORD





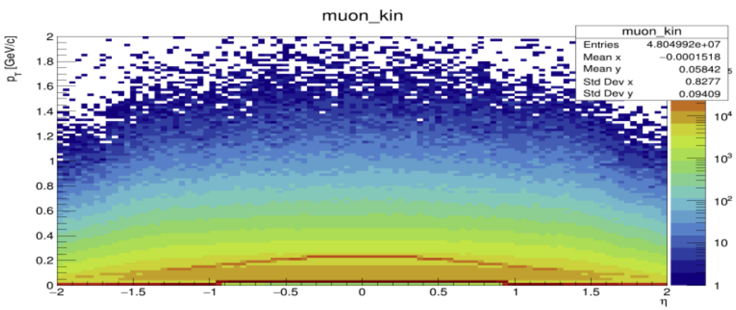
Kinematic properties of muons „-” in MCORD

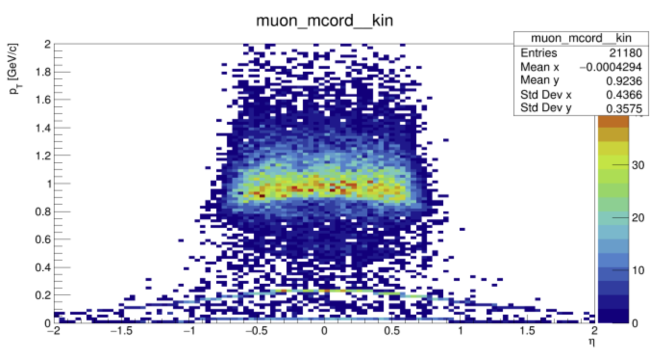


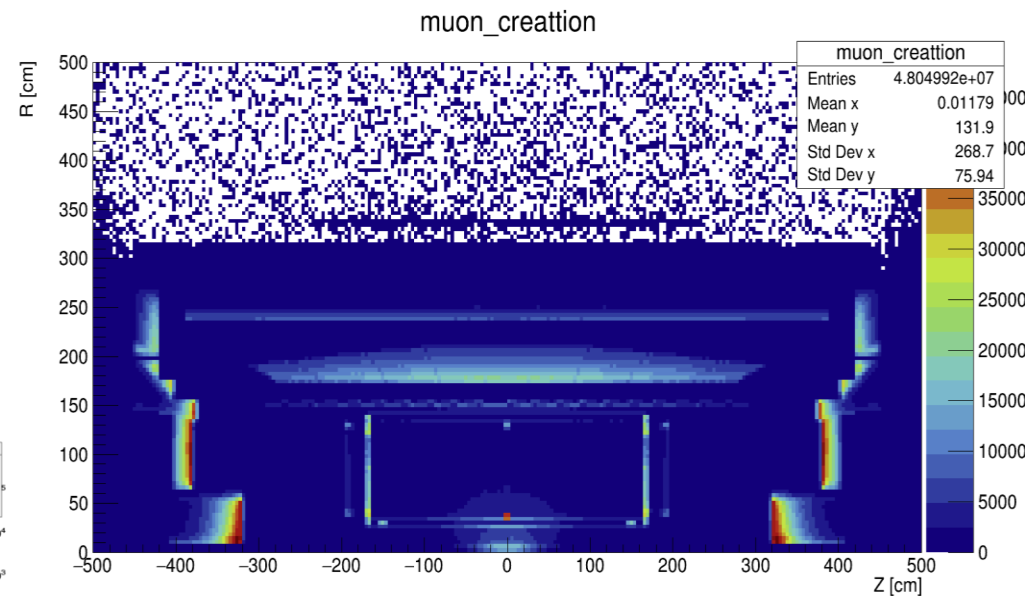
4. Muons detection – Goals

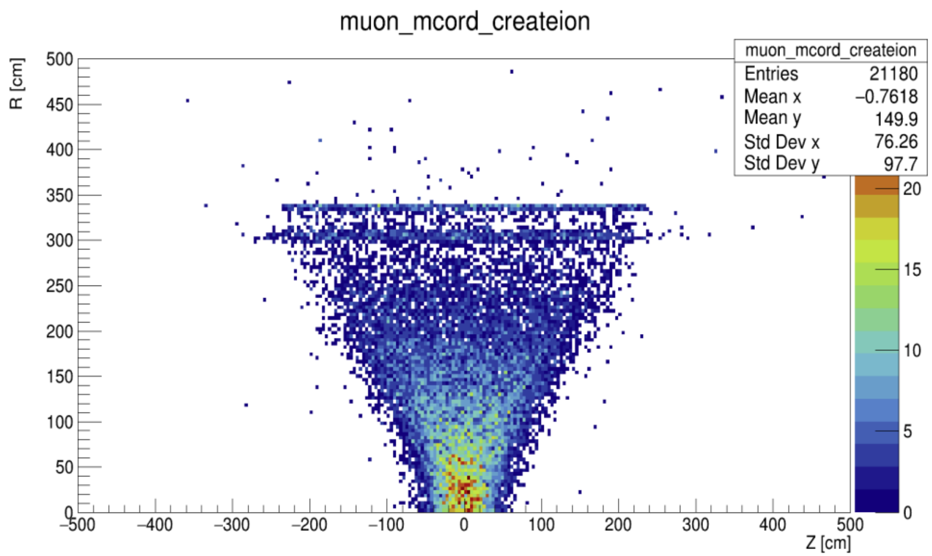
Points of creation of muons „+”

Pseudo rapidity and transverse momentum of muons „+”









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4. Muons detection – Goals

Motivation for the study of muon production in nucleus-nucleus interactions with MCORD at NICA.

In the existing NICA program the study of e^+e^- dileptons is mentioned as one of important goals. When the available energy in the process is larger than the two muon mass ($2 \cdot 105 = 210$ MeV/c^2), the lepton universality lead to the production of muonic dileptons.

The major sources of dileptons are:

1. The decays of light scalar (η, η' …) and vector (ρ, ω , φ ..) mesons.
2. Open charm meson decays.
3. Drell-Yan processes.
4. Thermal muon pairs from dense, hot matter.
5. Possible decays of new, beyond SM, “dark” particles (dark photon and Higgs-like particles).

These are very rare processes

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4. Muons detection – Goals

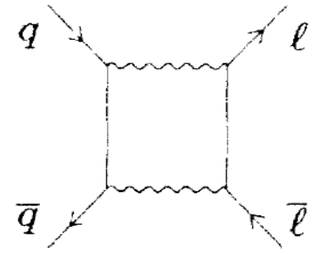
The decays of light mesons

There is a long list of yet unobserved semileptonic decays of η and η' mesons involving $\mu^+\mu^-$ pairs in the final state. An example of such processes is $\eta \to \mu^+\mu^- e^+e^-$ with present experimental upper limit $1.6 \cdot 10^{-4}$, while the theoretical prediction is $(1.6\text{-}2.0) \cdot 10^{-5}$. **NICA could improve such limits or observe such decays if only the ability of muon tagging and identification is provided.**

Up to now, the most precise value of the very rare $\eta \to \mu^+\mu^-$ decay (see reference 1) was extracted by the **SATURNE II** experiment . This fourth order electromagnetic, helicity violating, process (see figure) is strongly suppressed in the Standard Model. The measured branching ratio is, within uncertainties (of the order of 15%), compatible with SM expectation. However, it would be interesting to confirm this result as well as to perform the first measurement of $\eta' \to \mu^+\mu^-$ branching ratio.

In the $\rho \to \mu^+\mu^-$ decay, one can also search for the so-called ρ line shape broadening.

Decay mode	Measured value	Experiment	Theoretical value
$\eta \to \mu^+\mu^-$	$(5.7 \pm 0.7 \pm 0.5) \cdot 10^{-6}$	SATURNE II (1994)	$4.3 \cdot 10^{-6}$ (unitarity bound)
$\eta \to \mu^+\mu^- e^+e^-$	$< 1.6 \cdot 10^{-4}$ (at 90 C.L.)	WASA@CELSIUS (2008)	$(1.57\text{-}2.21) \cdot 10^{-6}$
$\eta \to \mu^+\mu^-\mu^+\mu^-$	$< 3.6 \cdot 10^{-4}$ (at 90 C.L.)	WASA@CELSIUS (2008)	$2.4 \cdot 10^{-9}$
$\eta \to \mu^+\mu^-\pi^+\pi^-$	$< 3.6 \cdot 10^{-4}$ (at 90 C.L.)	WASA@CELSIUS (2008)	$7.5 \cdot 10^{-9}$



Example of SM 4^{th} order electromagnetic process such as $\eta \to \mu^+\mu^-$.

1. Abegg et al., Phys.Rev. D50 (1994) 92-103

4. Muons detection – Goals

Decays of new, beyond SM, “dark” particles

The search for light (<1 GeV/c^2), very weakly interacting dark mater (see reference 3) still calls for more precise limits **based on analysis of the muon pair production.**

A hypothetical dark photon with mass larger than two muon mass would decay preferably into a $\mu^+\mu^-$ pair. Whereas the present experimental limits are often based on the search for maxima in e^+e^- invariant mass. The best present upper limit on the coupling constant ε that would characterize the strength of the interaction between dark and standard photons, **based on muonic dilepton production** from KLOE and BaBar (see reference 2) is of the order of 10^{-3}.

The search for maxima in $\mu^+\mu^-$ invariant mass spectra from meson Dalitz decays are therefore urgently needed.

Study of the meson transition form factor

Tagging of muons would allow to proceed with a precision study of the $\eta\rightarrow\mu^+\mu^-\gamma$ and $\omega\rightarrow\mu^+\mu^-\pi^0$ reactions and the subsequent transition form factor extraction of η and ω mesons (see reference 4).

Thermal muon pairs from dense, hot, strongly interacting matter

The spectra of dileptons invariant mass were measured in several heavy ion experiments and reveals enhancements with respect to the expectation in the 1– 3 GeV/c^2 energy region. This could be interpreted as a result of emission from hot, dense, strongly interacting matter. Evidence for the production of thermal muon pairs was reported e.g. by the NA60 experiment (Ref. 5) in In-In interactions at 158A GeV/c momentum. **Further energy and atomic number scan is clearly needed**.

2. **Anastasi et al., Phys.Lett. B784 (2018) 336-341**
3. **Raggi et al., Rivista del nuovo cimento, Vol. 38, N.10**
4. **Arnaldi et al., Phys.Lett. B757 (2016) 437-444**
5. **R.Arnaldi et al. Eur. Phys. J. C59: 607-623,2009)**

5. Astrophysics

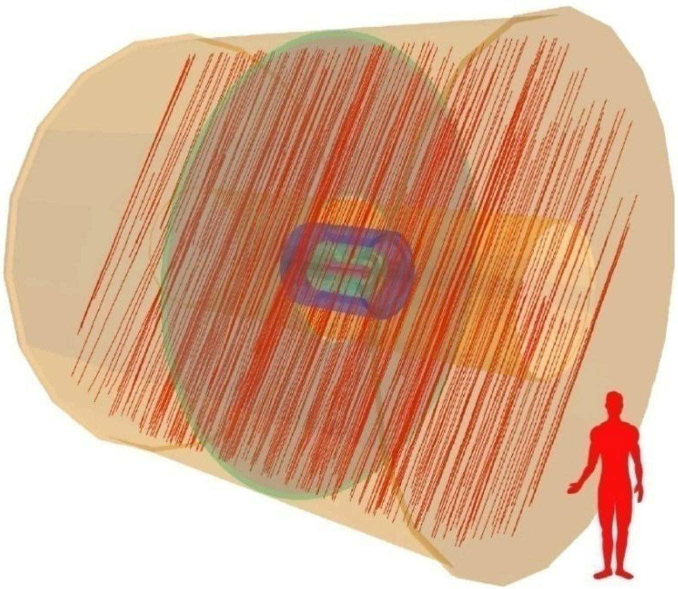
Detection (muon showers and bundles)

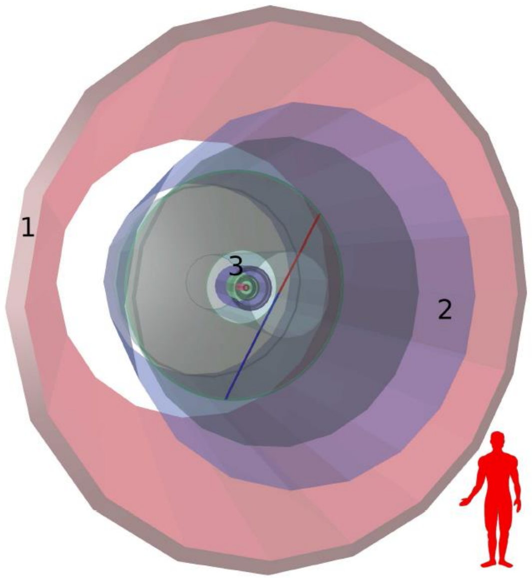
Disadvantages

- Rather small size of the detector
- Ground level location
- Only muons and hadrons detection (no e,γ)

Advantages

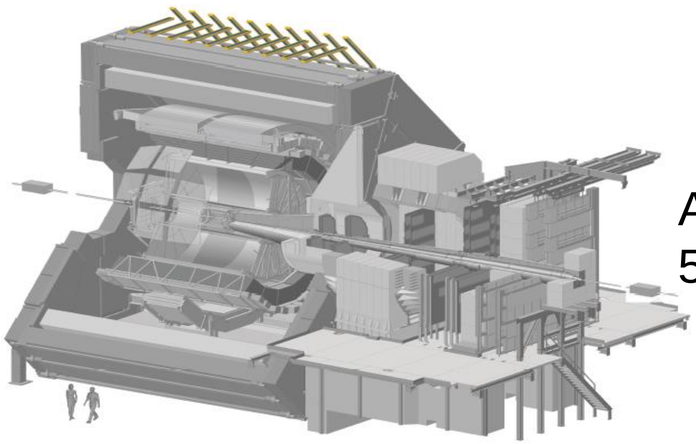
- Very high resolution (track and time)
- Determination of the possible source (High tracking capabilities)
- Unique for horizontal events
- Detector with magnetic field (Muon momentum spectrum and charge rate)
- Work in cooperation with TPC and TOF

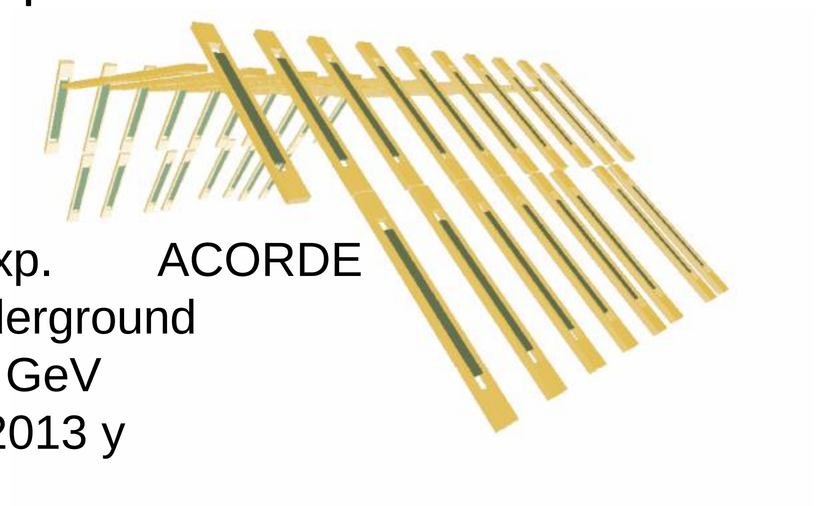




5. Astrophysics

Examples from other experiments





ALICE Exp. ACORDE
55 m underground
thr. 16 GeV
2010-2013 y

ALEPH Exp.
140 m under. (thr. 70 GeV) (1997-99y)

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Cosmic multi-muon events observed in the underground CERN-LEP tunnel with the ALEPH experiment

V. Avati [a,*], L. Dick [a,1], K. Eggert [a], J. Ström [a,2], H. Wachsmuth [a,3], S. Schmeling [b], T. Ziegler [b], A. Brühl [c], C. Grupen [c]

[a] *European Laboratory for Particle Physics (CERN), Geneva, Switzerland*
[b] *Institut für Physik, Johannes Gutenberg-Universität Mainz, Germany*
[c] *University of Siegen, Siegen, Germany*

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DELPHI Exp.
100 m under. (thr. 52 GeV) (99-2000y)

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Study of multi-muon bundles in cosmic ray showers detected with the DELPHI detector at LEP

DELPHI Collaboration
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5. Astrophysics

Recently, a new muon data type has been acquired from the extensive air showers (EAS) generated by primary cosmic rays (PRC), in particular multiplicity distribution of muons produced in EAS has been obtained.

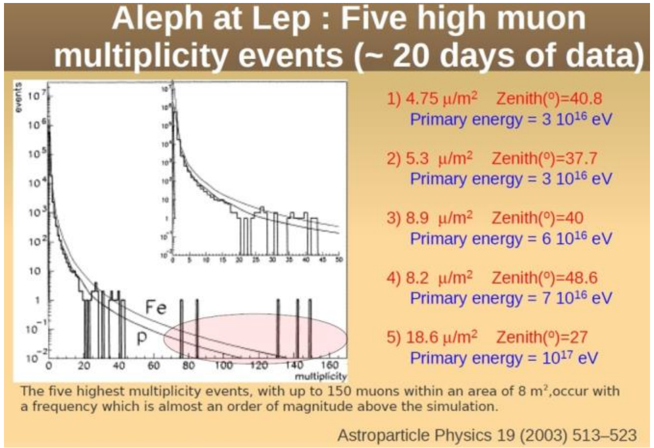
Muon distributions obtained using accelerator detectors (ALEPH and DELPHI at LEP, and ALICE at LHC) provide detailed information about mass composition of PRC. Moreover, using ALICE one is able to determine the possible source of PRC in the Universe issuing events with highest muon multiplicity.

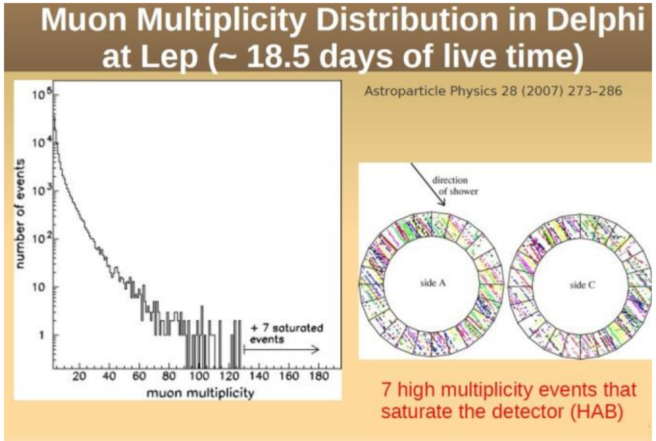
MCORD sub-detector, as well as analyses of possible cosmic ray data using MCORD.

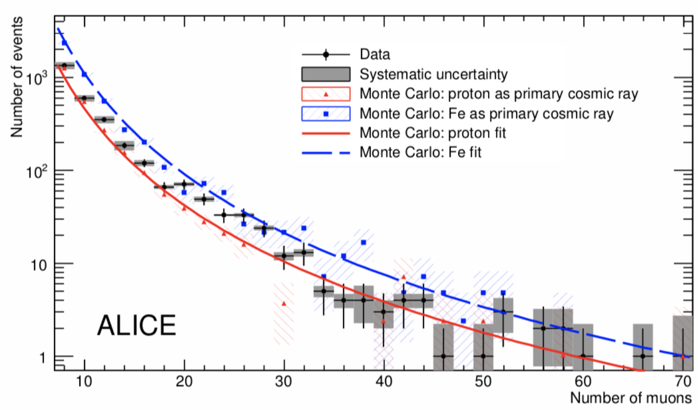
- The existing ALEPH, DELPHI, and ALICE cosmic ray data contain information on muon production in EAS only for vertical showers (those with zenith angles not far from zero degree).
- The proposed MCORD detector along with the MPD time projection show the unique opportunity of the very precise measurement of atmospheric muon multiplicity distributions as a function of the zenith angle of PRC, up to nearly horizontal showers. **Such measurements, up to now, were never possible.**
- Using accelerator apparatus understanding of the PRC energy and mass composition as well as the propagation of EAS particles in the Earth's atmosphere was achieveable.

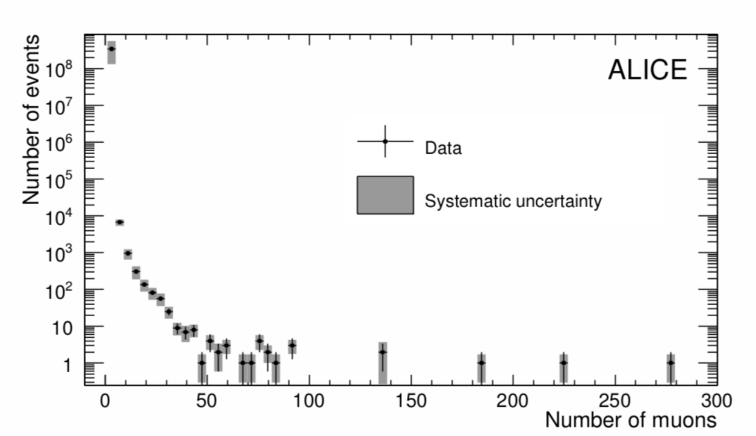
5. Astrophysics

High Muon Multiplicity Events in different experiments









Comparisons with simulation results (KORSIKA+QGSJET) are in agreement for low multiplicities (for low energy). For high multiplicities (only few events) results are almost an order of magnitude above the simulations results.

Problem with current hadronic interaction model for extremely high energy >10E15 eV ???

Bibliography:

Bruno Allesandro prezentation on ALICE collaboration workshop Feb 2013

ALICE Collaboration, JCAP 01 (2016) 032

K. Shtejer: CERN-THESIS-2016-371

5. Astrophysics

Horizontal Events Experiments needs more data.
Very low statistics – many years of observation.
In most cases those measurements are provided with other types of measurements in the same time.
A special attention is paid to muon groups of large multiplicity.

Example: DECOR exp. 2002-2003y
(near horizontal observation (60-90 deg. angular range)
1-10 PeV primary particle) (see ref. 2)

Bibliography:

1. Pavluchenko, V. P.; Beisembaev, R. U., Muons of Extra High Energy Horizontal EAS in Geomagnetic Field and Nucleonic Astronomy, 1995 ICRC....1..646P
2. Yashin I. et al., Investigation of Muon Bundles in Horizontal Cosmic, 2005 (28) ICRC p.1147-1150
3. Neronov A. et al., Cosmic ray composition measurements, 2017, arXiv:1610.01794v2 [astro-ph.IM]
4. Shih-Hao Wang, 2017_Cosmic ray Detection ARIANNA Station, PoS ICRC2017_358

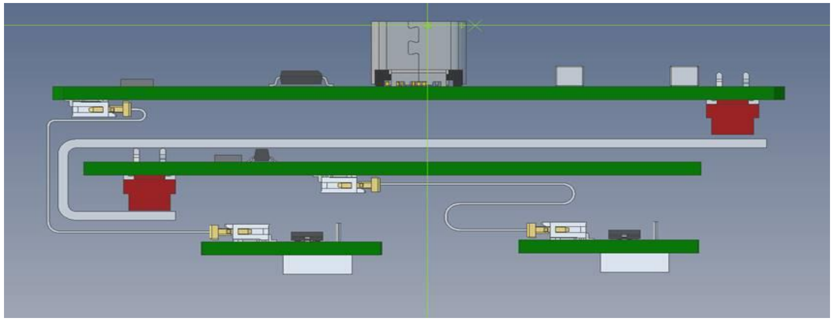
6. Present status of work

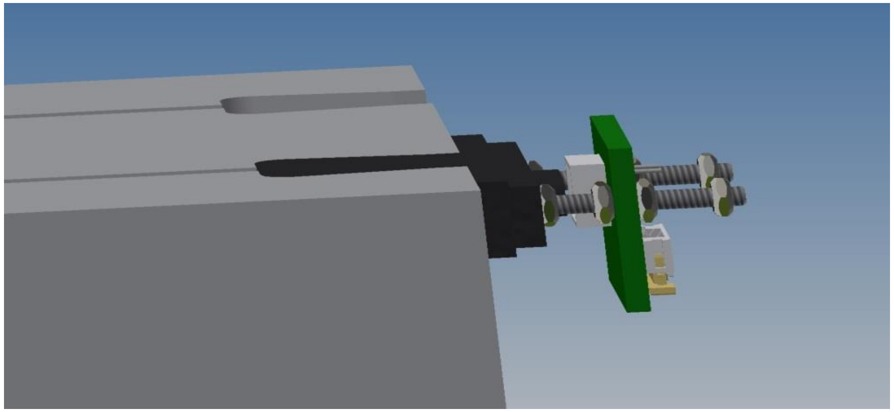
Our team is building a demonstrator with a full functionality (signal analysis).
Two sections (2x8 scintillators) or two half-sections (2x4 scintillators).
It will be ready by the end of 2019 year.

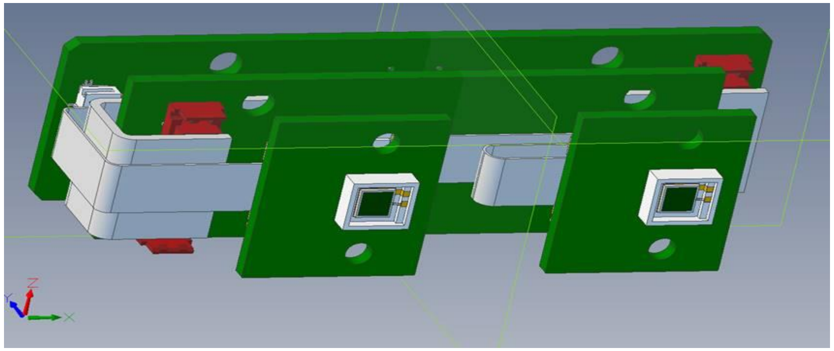
1. SiPMs (Hamamatsu) – We chosen models – ordered – paid – waiting for shipment
2. Scintillators (NUVIA) – We chosen size and type – ordered the first 4 pcs for testing – waiting for shipment – next step tests and invoice for final 8-16 pcs
3. Set of equipment for testing and calibration measurement – We designed the Set – ordered – paid – received – ready to use.
4. Electronic (CreoTech) – Prototype AFE, Hub modules and adapters - We designed – ordered – paid – waiting for production.
5. Electronic (CreoTech) – Prototype FMC-TDC boards - We designed – ordered – paid – waiting for production.
6. Electronic (CreoTech) – Production AFE and converter modules - We designed – ordered – waiting for invoice.
7. Mechanical connection scintillator-SiPM-fiber-AFE – We designed – 3D printed connectors – production of electronic boards – waiting for scintillators

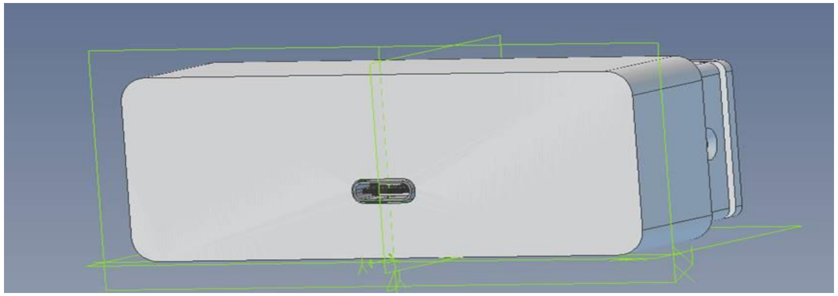
6. Present status of work

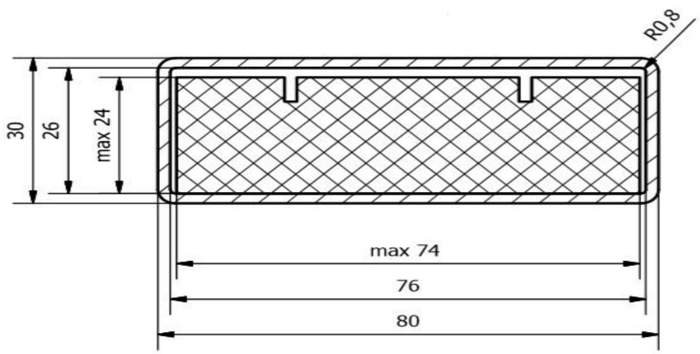
Mechanical connection scintillator-SiPM-fiber-AFE









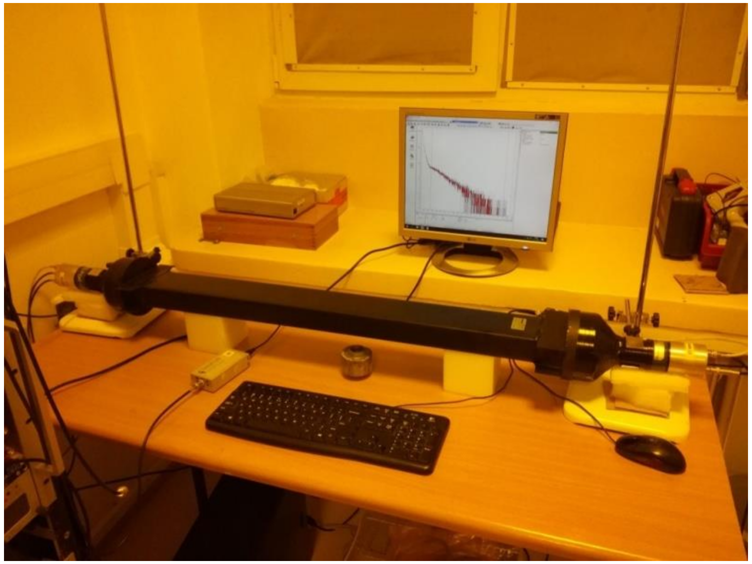


6. Present status of work

<u>Laboratory tests at NCBJ Swierk – test site ready to use</u>

Available equipment:

- long tiles (~100-150 cm) from NUVIA (Czech Rep.) and UNIPLAST (Russia)
  with and without Wavelength Shifting (WLS) fibers
- 5" Ø PMTs (XP45D2 and ETL9390)
- medium and small SiPMs (6x6 and 1x1 mm) from Hamamatsu (in future 25x25 mm)
- first measurements of light output and light attenuation along 100x10x5 cm plastic tile
- double-side 5 inches dia PMTs readout
- Co-60 gamma-rays energy calibration



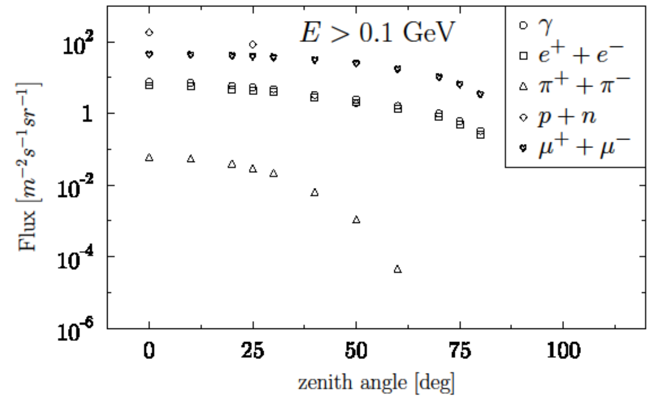
NARODOWE CENTRUM BADAŃ JĄDROWYCH ŚWIERK

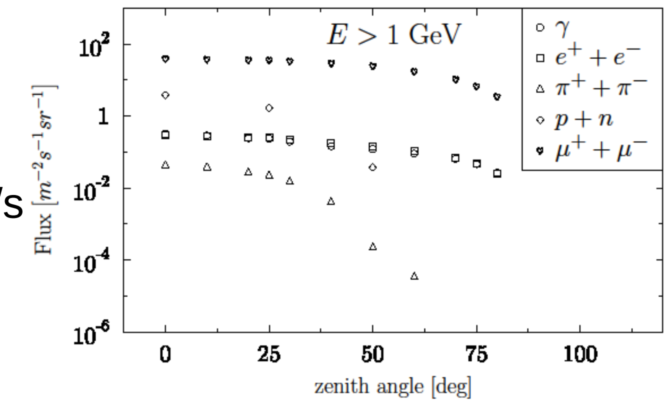
6. Present status of work – simulations

CORSIKA simulation of Cosmic Showers

Angular distribution of atmospheric cosmic shower particles

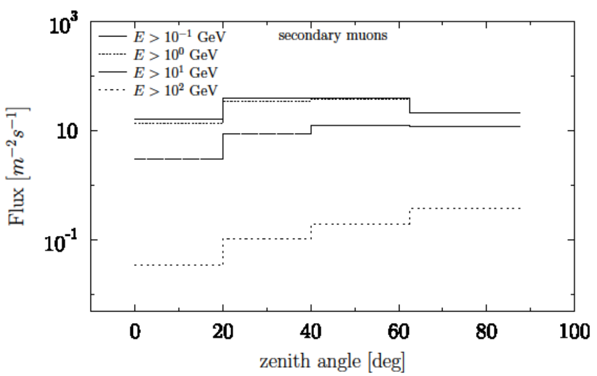
E [GeV]	0	25	50	75
0.1- 1	5.912	3.829	0.612	0
1-10	29.931	26.935	16.637	2.224
10-100	7.976	7.884	7.291	4.186
100~1000	0.087	0.092	0.108	0.142

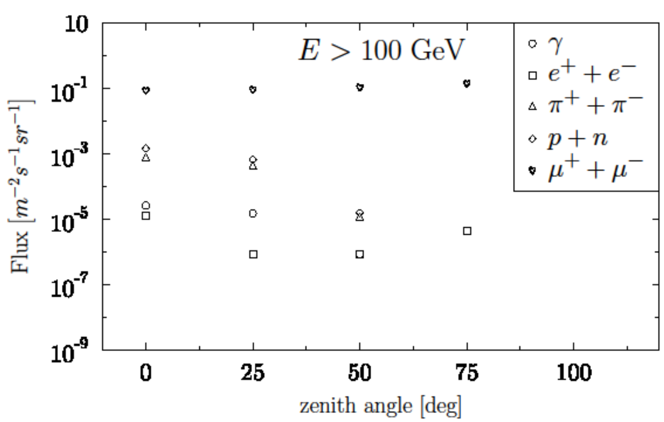


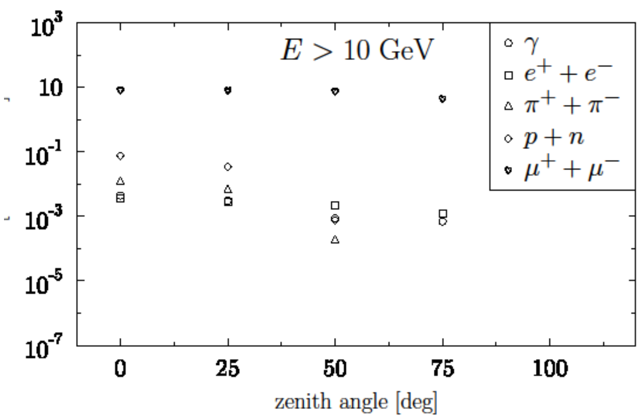


Muon Flux from all angle for E>1GeV is about 100-130 count/m2/s

It gives (6.72m x 4.7m = 31.58m2) about 3000-4300 count/s



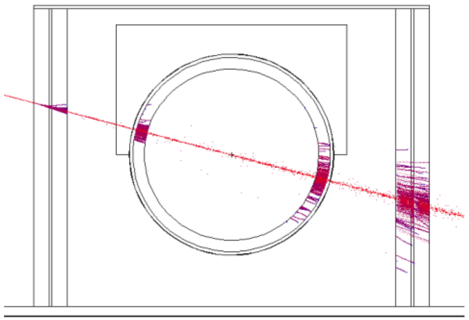




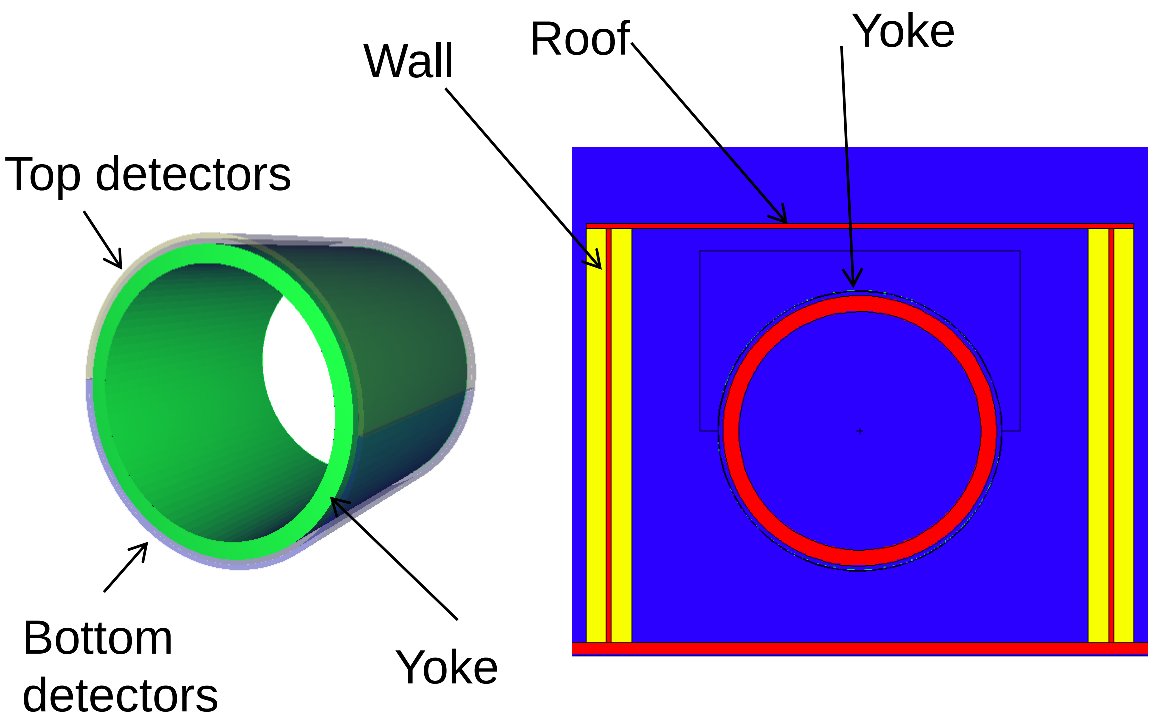
6. Present status of work – simulations

MCNP calculations for MCORD muon detector (MCNP 6.11, MCNPX 2.7.0. number of iteration 1E9)

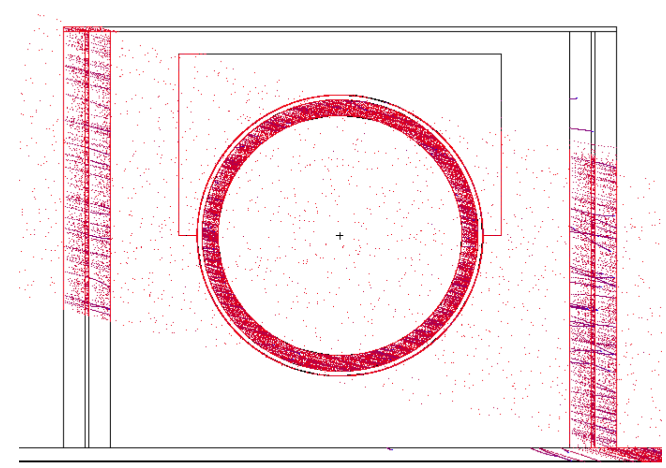
- Two half-cylinders of plastic (currently evaluated 1 cm thick)
- Implemented surface emission, 1 meter wall with 10 cm of steel as a construction elements, 10 cm steel as a roof
- Implemented energy distibution as a function of muon incident angle:
    - Angles: 0, 25, 50 and 75°   Energy: 0.1 – 100 GeV
- Yoke thickness: 30 cm, hall width 12 m (to be changed , need more information)
- Calulated muon transmission through MCORD and inside the MPD



- **Expected about 114 muons per second through 1m2 MPD surf.**



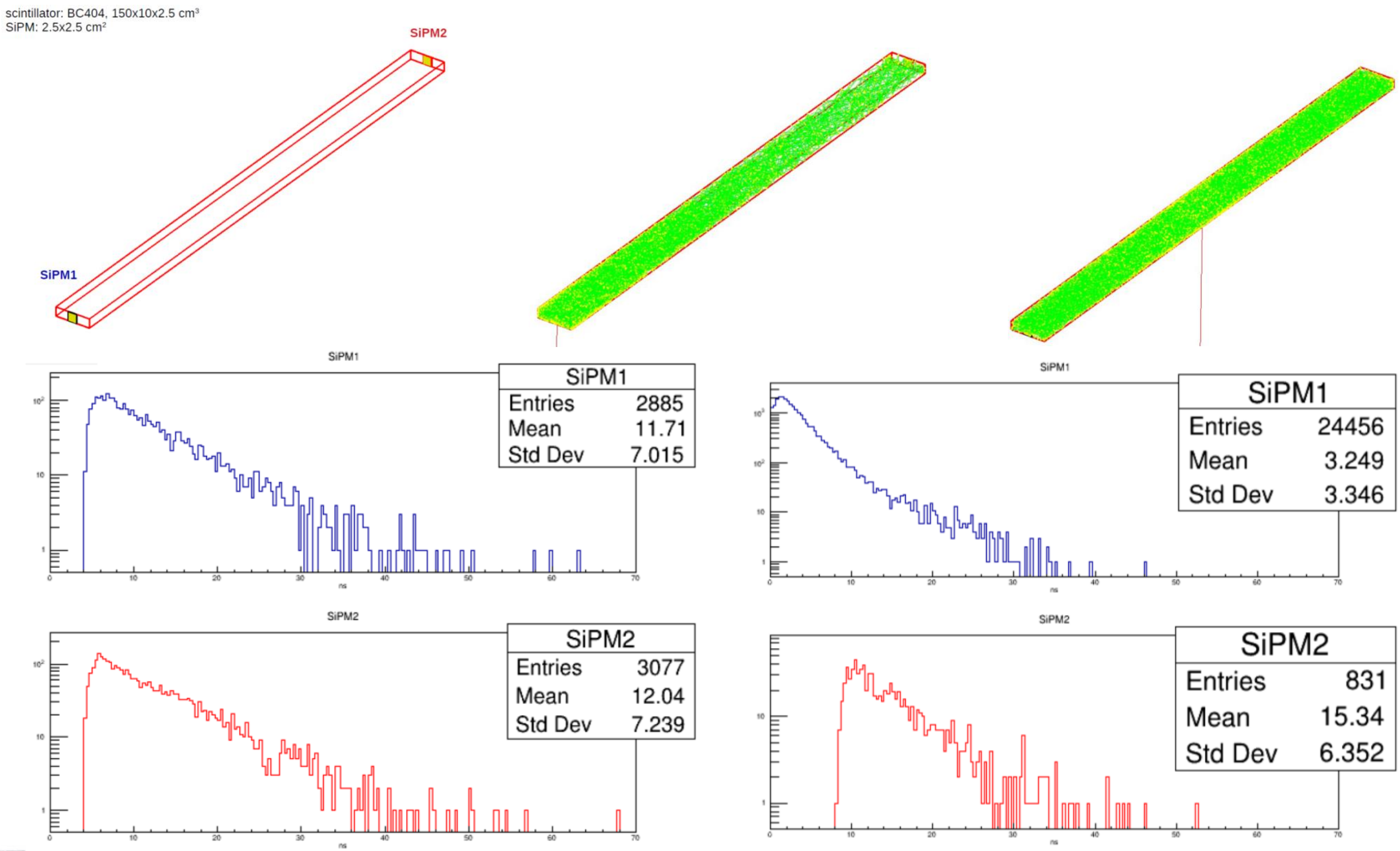
Muons through MPD cross section, 75°



- **Bottom-to-top muon coincidence ratio 98%**

6. Present status of work – simulations

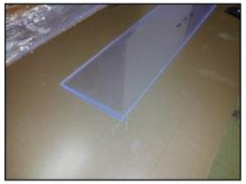
GEANT4 simulation of photon production and distributions in scintillators

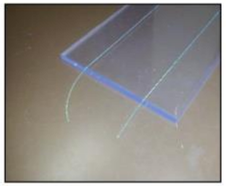


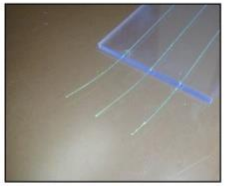
6. Present status of work - FTR

Size estimation	**Detector MCORD**
Diameter:	7 m
Length:	4.5 m
Circumference:	22 m
No. of scintillators:	**660 pcs**
No. of SiPM:	**1320 pcs**
No. of mTCA:	**4 crates**


no fibers


2 side fibers


2 up fibers


3 up fibers

False trigger rate (FTR) estimation

SiPM-SiPM coinc._gate: 20 ns (two ends of one scintillator)

scintillator trigger_gate: 100 ns (two scintillators on MCORD cylinder)

cosmic muon rate: **<150 cps/m2**

DCR (dark count rate)

PVT or PS plastic	(No fiber)	PVT or PS plastic + WLS	
DCR (@ 5 p.e.)	~10 kcps	DCR (@ 3 p.e.):	~10 kcps
noise-noise FTR:	**<0.1 cps (8,67xE-2)**	**noise-noise FTR:**	**<0.1 cps**
noise-cosmic FTR:	**<0.1 cps (7,81xE-2)**	**noise-cosmic FTR:**	**<0.1 cps**

7. Conclusions - MCORD Detector

SCINTILLATORS

Number of scintillators:	672 pcs
Dimensions of scintillators:	72x22x1650 [mm]
Scintillators are placed in the rectangle profile:	80x30x1700 [mm]
Weight of detector:	6.5 kg
Material of scintillators casing:	Aluminum alloy

MODULES

Number of detector in one module:	24
Number of Modules:	28
Dimensions of module:	730x90x4700 [mm]
Weight of one module:	~180 kg

SiPM/MMPC

Number of SiPMs (Chanels)	1344
Number of SiPMs (with two fibers)	2688

RESOLUTION

Position resolution: In X axis – up to 5 cm, In Y axis – 5-7 cm
Time Resolution – about 300-500 ps

Number of events (particles):	about 100-150 per sec per m2
Calculated Coincidence factor:	about 98%

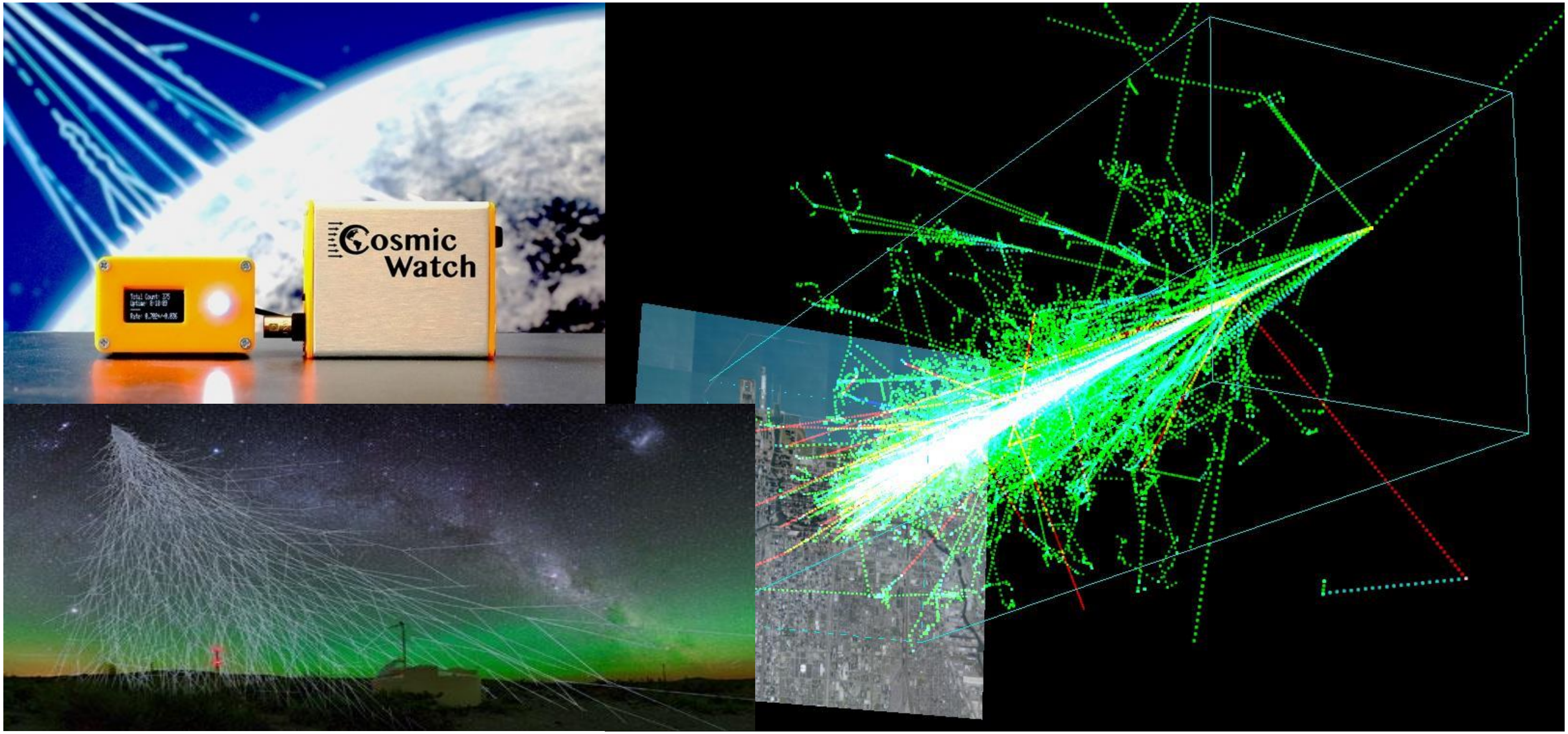
7. Conclusions

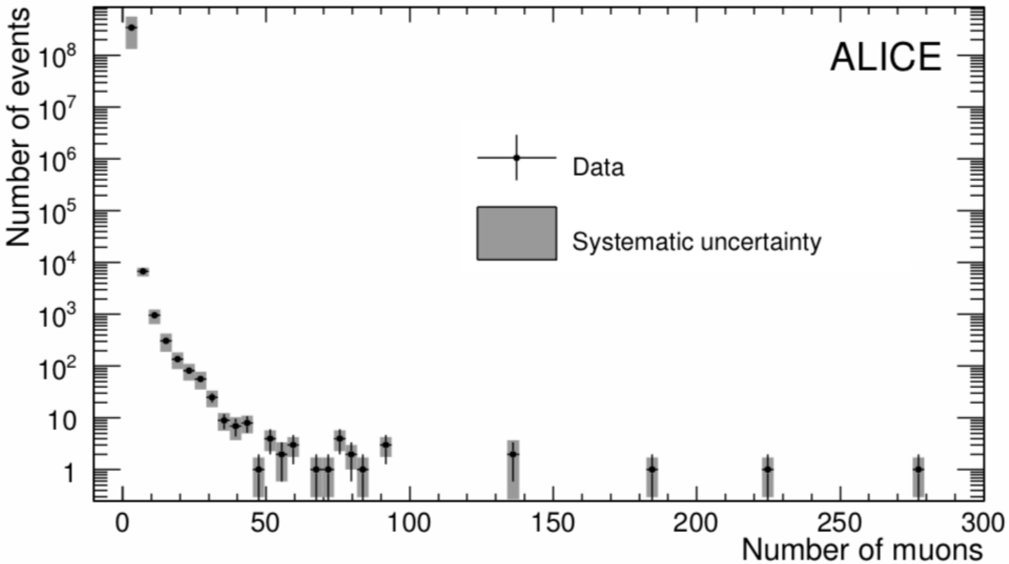
1. Cosmic Ray Detector is necessary for good calibration of TPC, TOF and ECAL, MPD detectors **before completion of the MPD .**
2. MCORD can be useful for detection of rare processes of **muonic dilepton production.** UrQMD model base on QCD for hadrons production – very rare mesons decays probably do not exist in this model - **We should implement PLUTO model for UrQMD+PLUTO calculation.**
3. Additionally MCORD can be used for astrophysics observations similar to past collider experiments. Research of main trivial mechanism of **multi-muon event generation (EAS muons).**
4. Cosmic ray detector might be helpful for better calibration of TPC TOF, before each experimental session.
5. Our team has a realistic plan and is capable of building this detector. The First demonstration will be ready by end of 2019

Our group is a member of the Polish consortium NICA-PL

Polish consortium NICA-PL

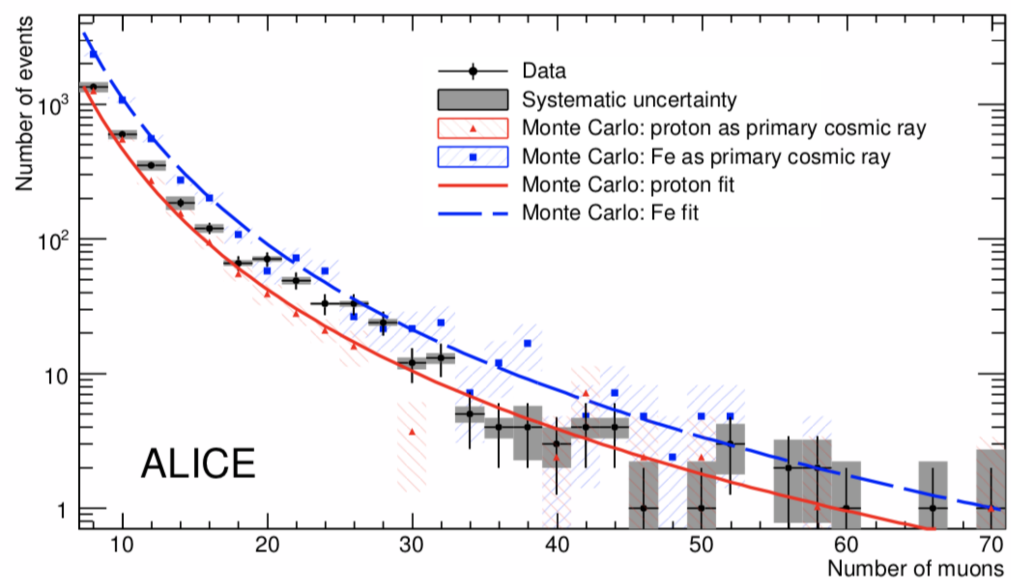
Thank You for Attention!

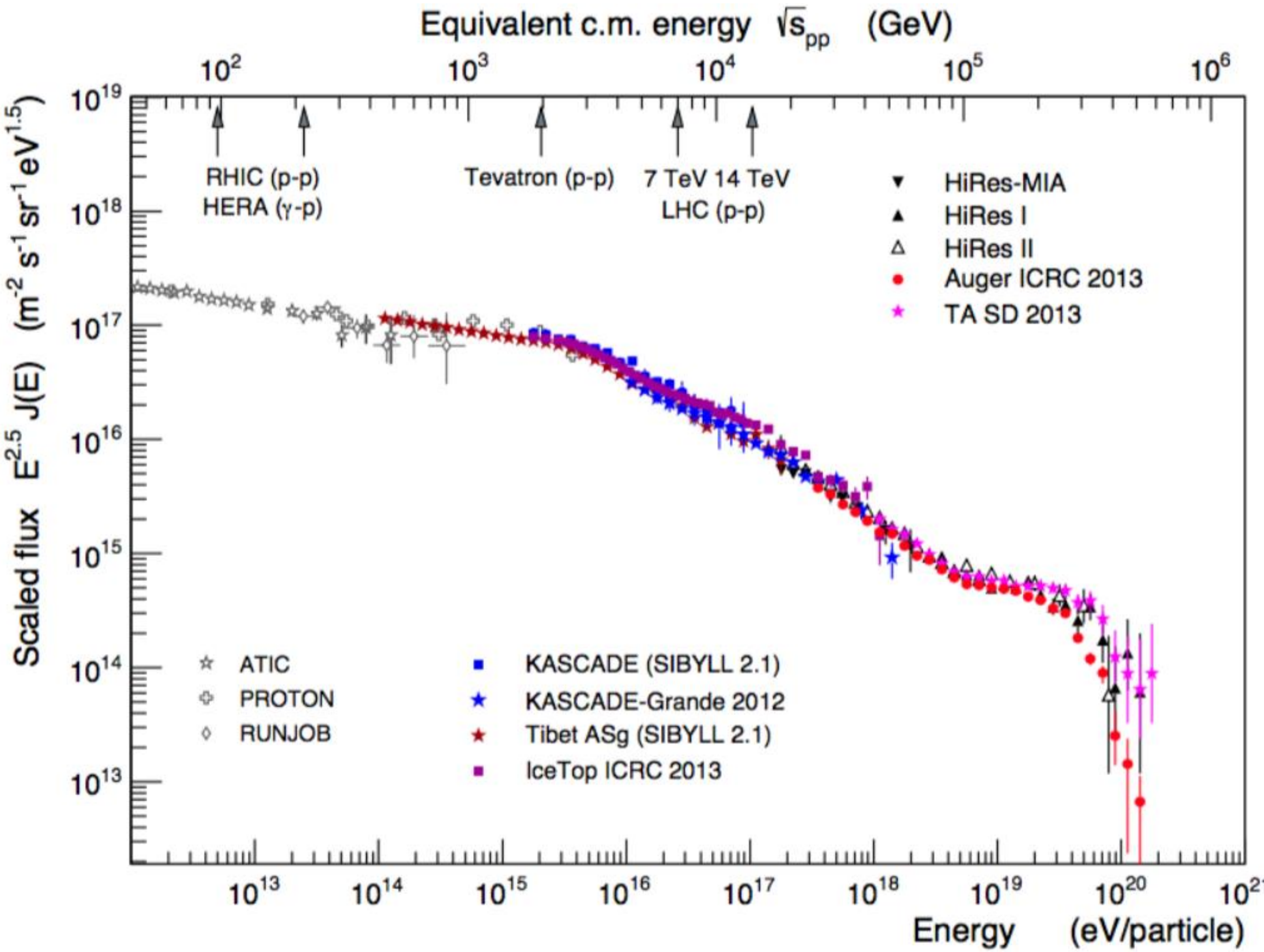




ALICE Collaboration, JCAP 01 (2016) 032

K. Shtejer: CERN-THESIS-2016-371





All-particle cosmic-ray energy spectrum derived from from direct and indirect (air shower experiments) measurements, as well as results from different hadronic models