COSMIC RAYS INTRODUCTION AND DETECTORS

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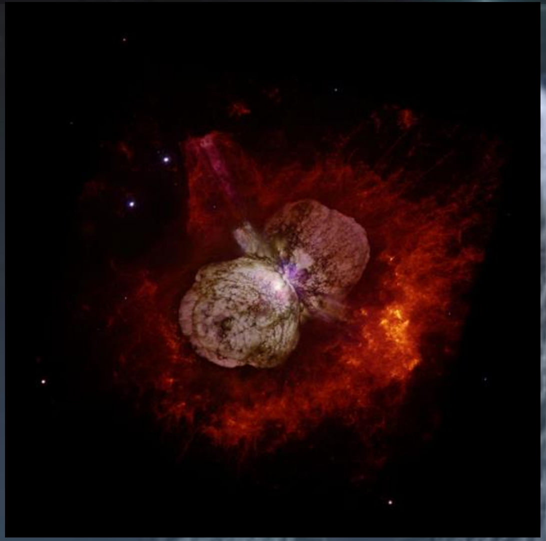
WHAT IS COSMIC RAYS PHYSICS - INTRO

- Cosmic rays (CR) first shown to come from space in 7/8/1912 by Victor Hess
- CR are high energy particles and nuclei coming from space
- Local source (The Sun) and galactic/extra galactic (?) sources
- CR physics – part of HEP (high energy physics) studies CR using their interactions with Earth atmosphere to infer properties and origins of CR

https://www.aps.org/publications/apsnews/201004/physicshistory.cfm

Cosmic Rays and Particles Group

http://en.wikipedia.org/wiki/Hypernova



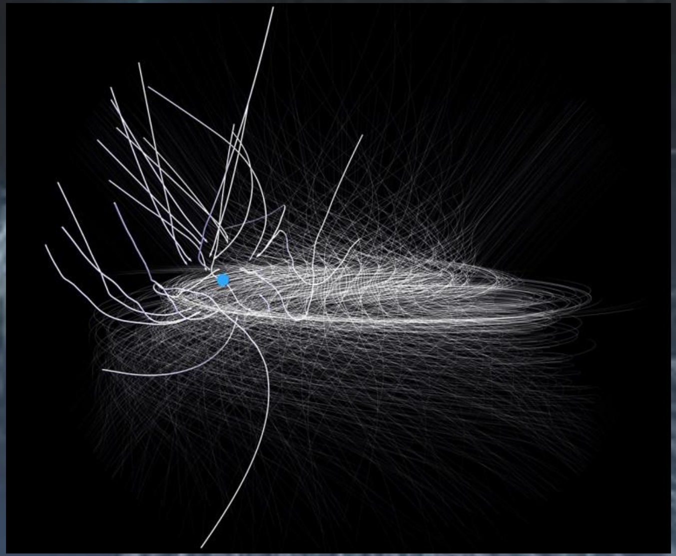
COSMIC RAYS AND ASTROPHYSICS: SOURCES OF ULTRA-HIGH ENERGY (UHE) CR

- Energy of UHECR from ~10^{15} up to 10^{21} eV and above
- The large mystery today is the origin and the nature of UHECR
- Possible sources:
  - **Neutron Stars**
  - **Active Galactic Cores**
  - (converting dark matter into high energy protons?)
  - **Hypernova Explosions (Fermi acceleration mechanism?)**
  - **Decay of unknown massive particles or dark matter**

Approximate composition of the primary cosmic ray at the energy of 10^{15}eV

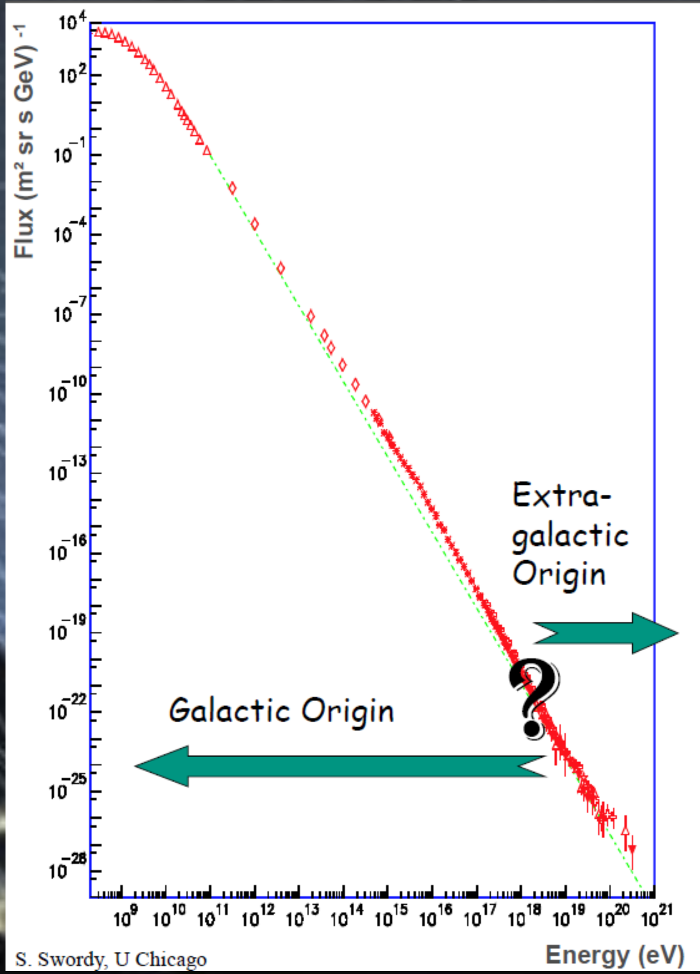
protons	40 %
α-particles (He nucleus)	20 %
Group of nucleus of CNO	20 %
Group of nucleus of Al	10 %
Group of nucleus of Fe	10 %

MYSTERY OF UHECR



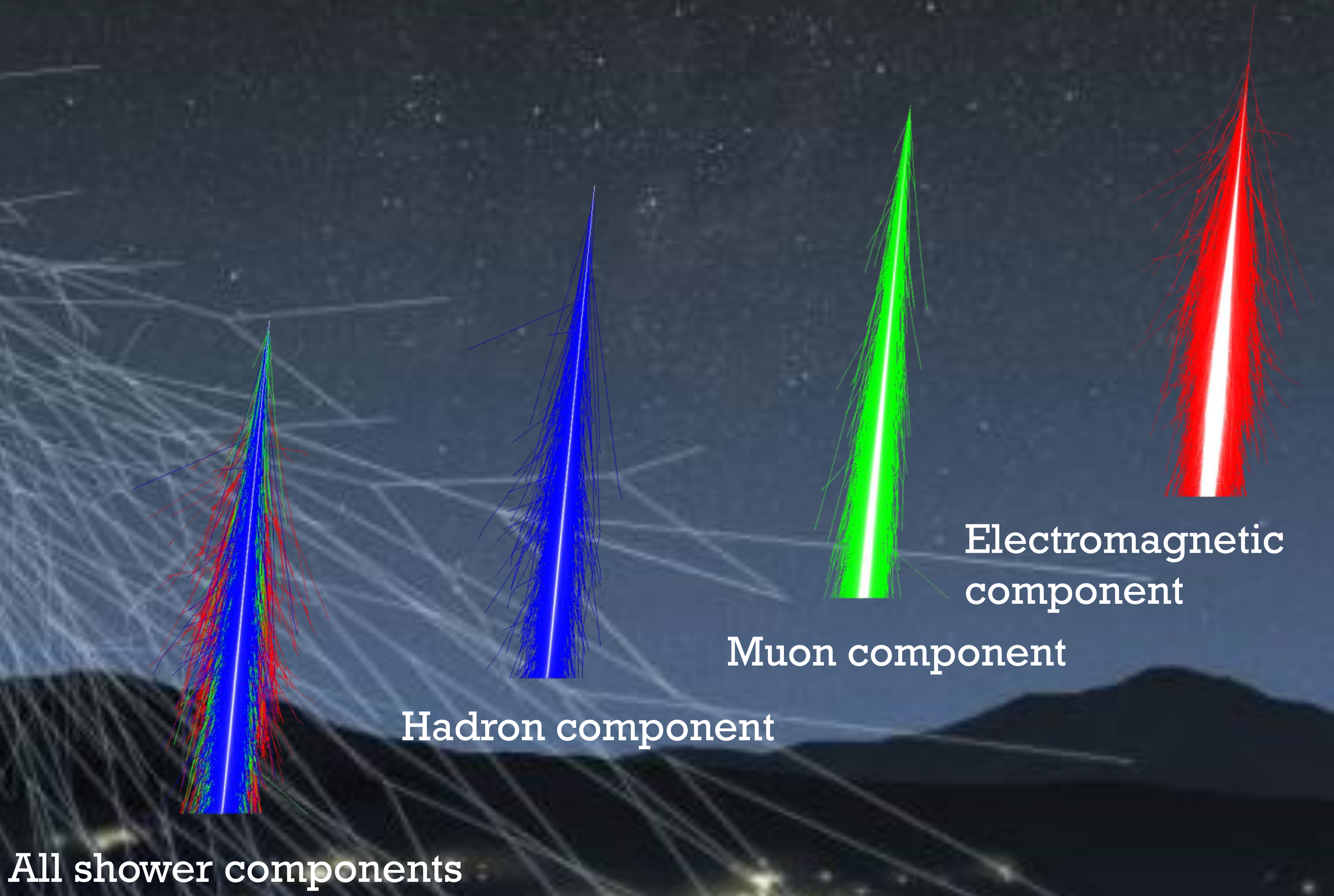
https://www.nas.nasa.gov/SC14/demos/demo4.html

- Due to galactic magnetic field, charged particles loose direction to origin
- Trapped in galaxy for $E<10^{15}$ eV for protons
- For $E>10^{17}$ eV, all extra-galactic?
- If so then anisotropy should be present but not found



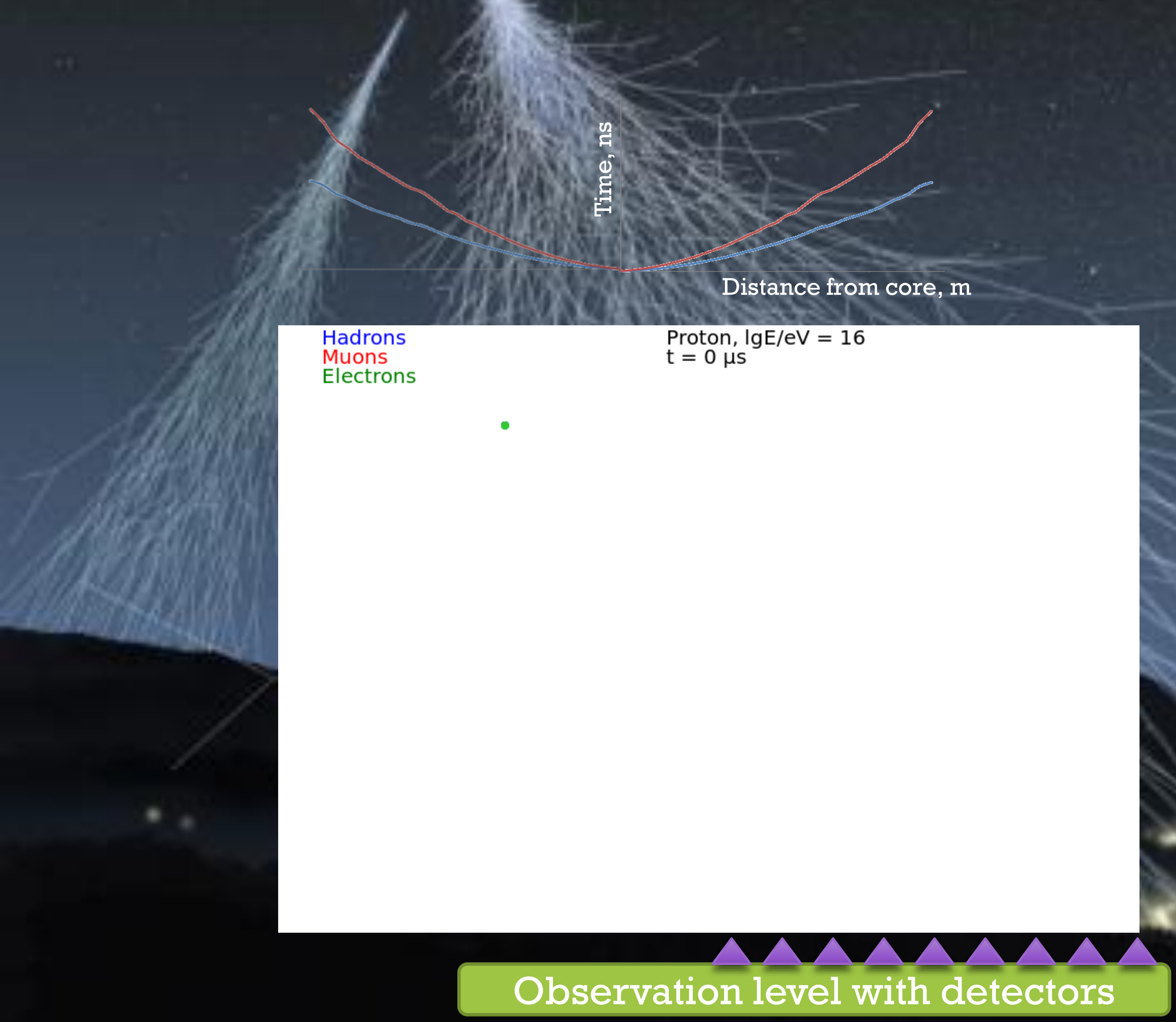
EXTENSIVE AIR SHOWER

- Discovery by Bruno Rossi in early 1930s, attributed to Pierre Auger (1938)
- A phenomenon that allows to study cosmic rays
- Extensive shower of particles born in hadronic and electromagnetic interactions in the atmosphere resulting from interactions between a primary particle from cosmic ray and air nuclei



All components together form a shower disk that can be up to few km in diameter

TYPICAL METHODS OF CR PHYSICS

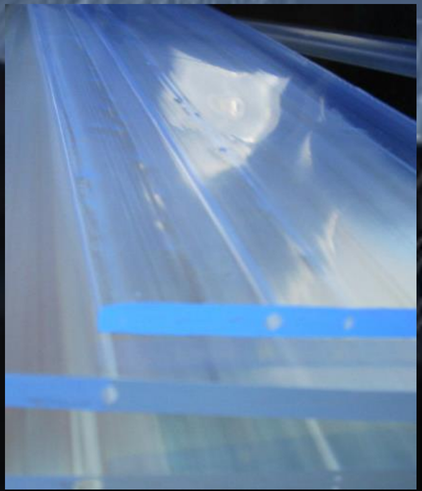


- Can reconstruct using particle density distribution
- Need to calibrate detection points to obtain equivalent MIP number
- If know time and width, additional methods can be used (CORSIKA)

TYPICAL DETECTOR SYSTEM COMPONENTS

A sample of liquid organic scintillator under the UV light.

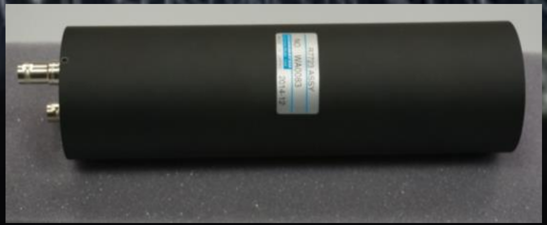
Composition:
Toluene (methylbenzene)
PPO (2,5-diphenyloxazole)
POPOP (1,4-di-(5-phenyl-2-oxazolyl)-benzene)



A sample of organic plastic scintillator under the sunlight.

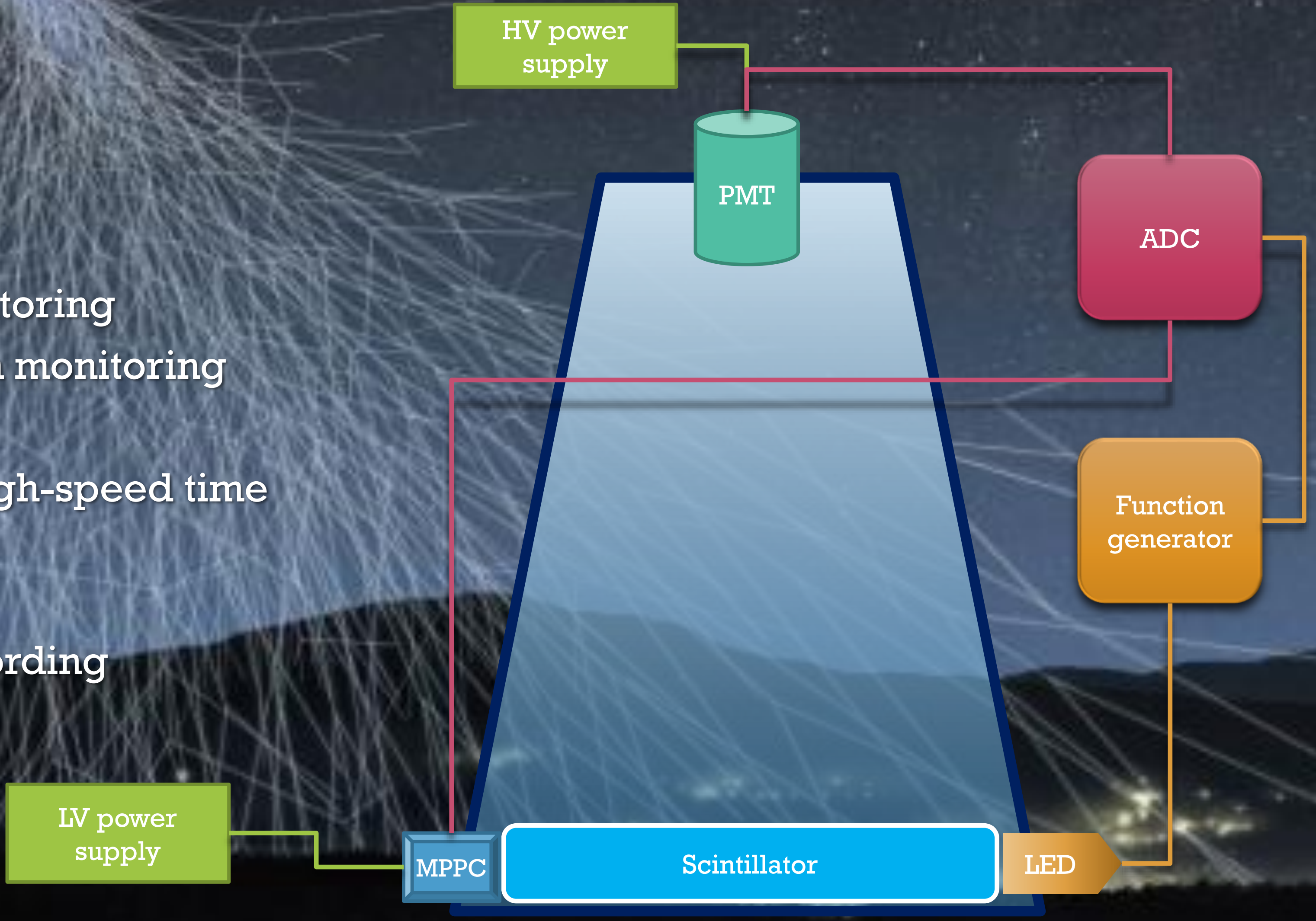
Composition:
Polyurethane
PPO (2,5-diphenyloxazole)
POPOP (1,4-di-(5-phenyl-2-oxazolyl)-benzene)

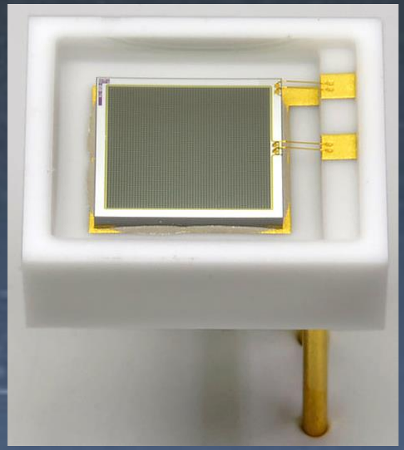
- 1 m^2 polysterene-based scintillators & scintillating glass with PMT 1 m above
- R7723 (H11284-30) Hamamatsu PMT (52 mm diameter)
  - 2kV max voltage
  - 1.7 ns pulse rise time
  - 1.1 ns time spread
- 500 MHz digitization CAEN DT5730B ADC
- Cherenkov-Vavilov light detector
- All channels MIP/cable/linear range calibrated
  - Photos from Horizon-T and D.U.C.K. detector systems



DETECTOR DESIGN CONSIDERATIONS

- Features:
  - PMT gain monitoring
  - MIP calibration monitoring (MPPC)
- Low-latency and high-speed time resolution
  - ns level
  - Waveform recording





MPPC from Hamamatsu

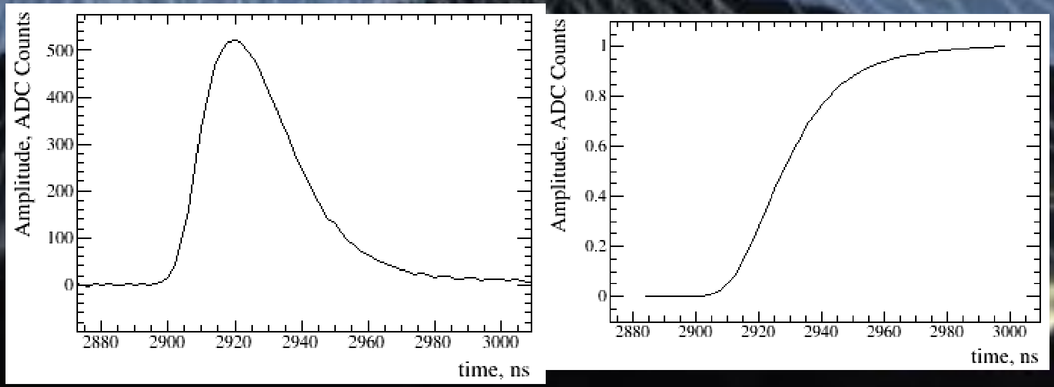
DATA ANALYSIS

- A typical pulse from the **MIP** is used for detector characterization
- The **pulse front** - between 10% and 50% of pulse CDF
- The **total duration** is 10%-90% of the pulse CDF
- **SD** with R7723 PMT **characteristics:**
  - pulse front: **7.16 ± 0.40 ns**
  - total duration: **21.6 ± 1.48 ns**
- **GD characteristics**
  - pulse front: **2.17 ± 0.13 ns**
  - total duration: **5.10 ± 0.67**

[corresponds to the technical characteristics of the PMT]

SD contribution:

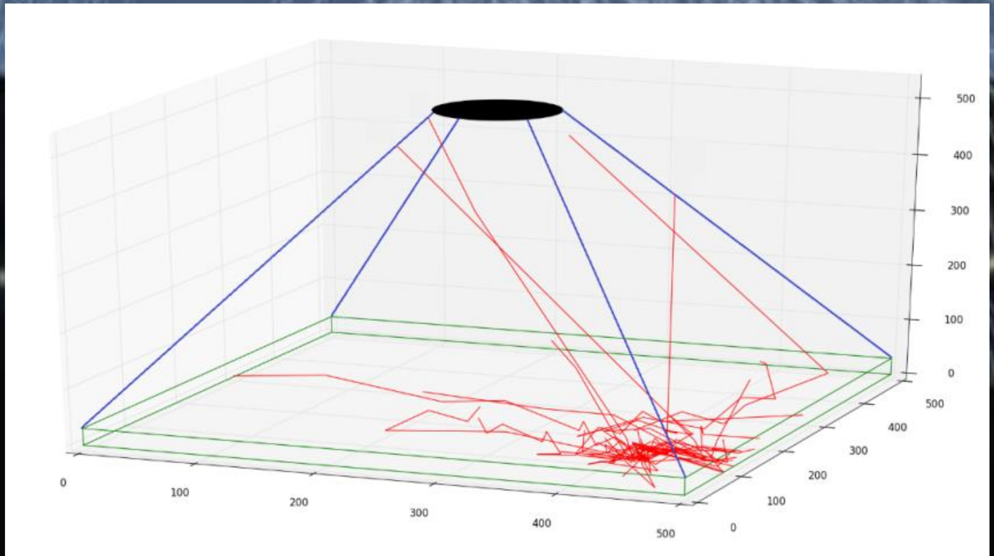
- pulse front: ~ **5 ns**
- total duration: ~ **15 ns**



Example of a typical inverted PMT pulse (left) and its normalized cumulative distribution(CDF) (right)

DETECTOR DESIGN AND SIMULATION

- Various designs were checked
  - Different PMT positions
  - Different medium shapes
  - Scintillator and glass
- PMT from the top results in better uniformity
  - Even with Cherenkov light in glass



- Calibration tests are for single MIP detection
- Bottom of the medium is painted in order to increase reflectivity

GLASS DETECTOR SIMULATION

- Relativistic charged particles emit only Cherenkov light while passing through optical glass. Cherenkov photons are emitted in a cone at fixed opening angle w.r.t. progenitor particle's trajectory (zenith angles of emitted photons):

$$\theta = \cos^{-1}\frac{1}{n_m\beta}$$

- Anisotropy of the emitted lights is confirmed in simulation
- Due to the anisotropy, it is necessary to use a transformation from particle's coordinate system to medium's coordinate system:

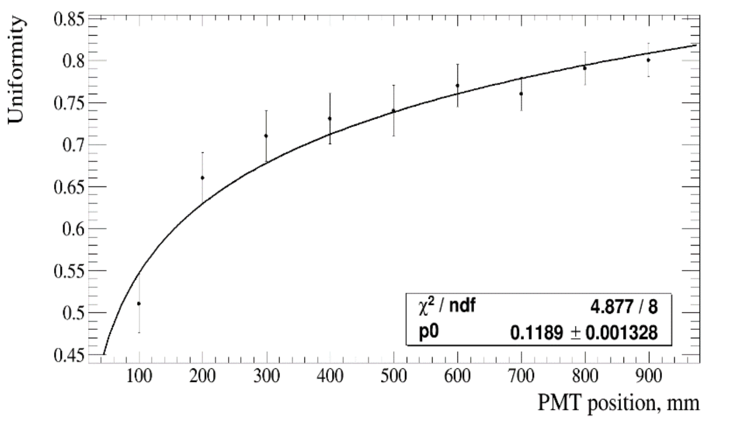
$$\begin{pmatrix} x'' \\ y'' \\ z'' \end{pmatrix} = \begin{pmatrix} \cos\theta\cos\varphi & \cos\theta\sin\varphi & \sin\theta \\ -\sin\varphi & \cos\varphi & 0 \\ -\sin\theta\cos\varphi & -\sin\theta\sin\varphi & \cos\theta \end{pmatrix} \begin{pmatrix} x \\ y \\ z \end{pmatrix}$$

where $\begin{pmatrix} x'' \\ y'' \\ z'' \end{pmatrix}$ - unit vectors in a particle's coordinate system, $\begin{pmatrix} x \\ y \\ z \end{pmatrix}$ - unit vectors in medium's coordinate system, θ, φ – progenitor particle's angles.

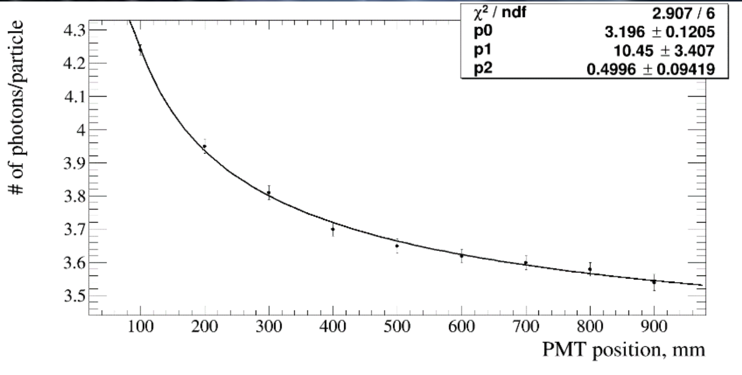
DETECTOR DESIGN AND SIMULATION

- PMT position above glass results in statistically significantly higher light yield:
  - 3.65 ± 0.04 detected photon per MIP for ‘above’
  - 3.19 ± 0.03 for ‘below’

    - Uniformity increases / saturates depending on position

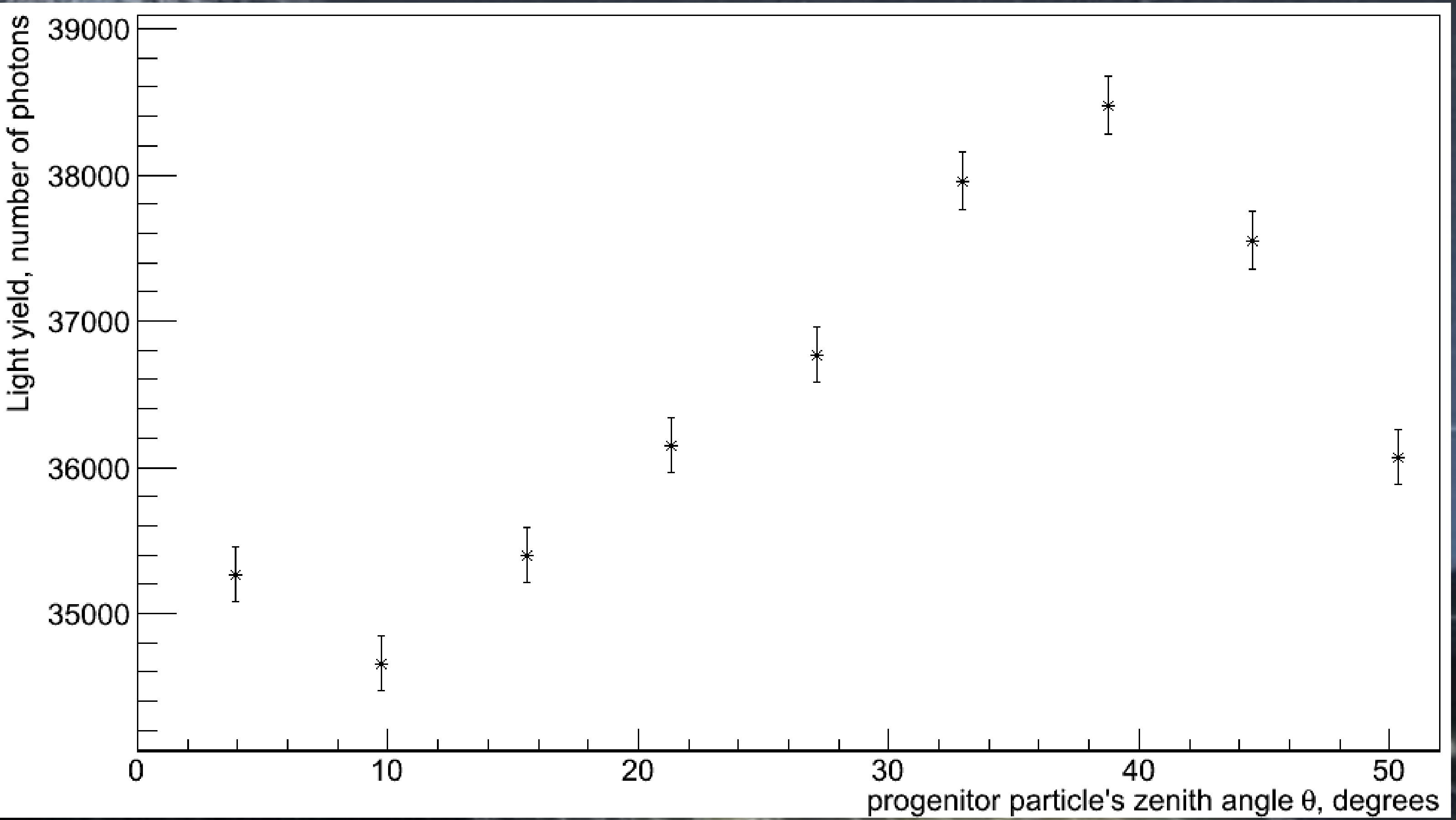


    - Detected photon number decreases



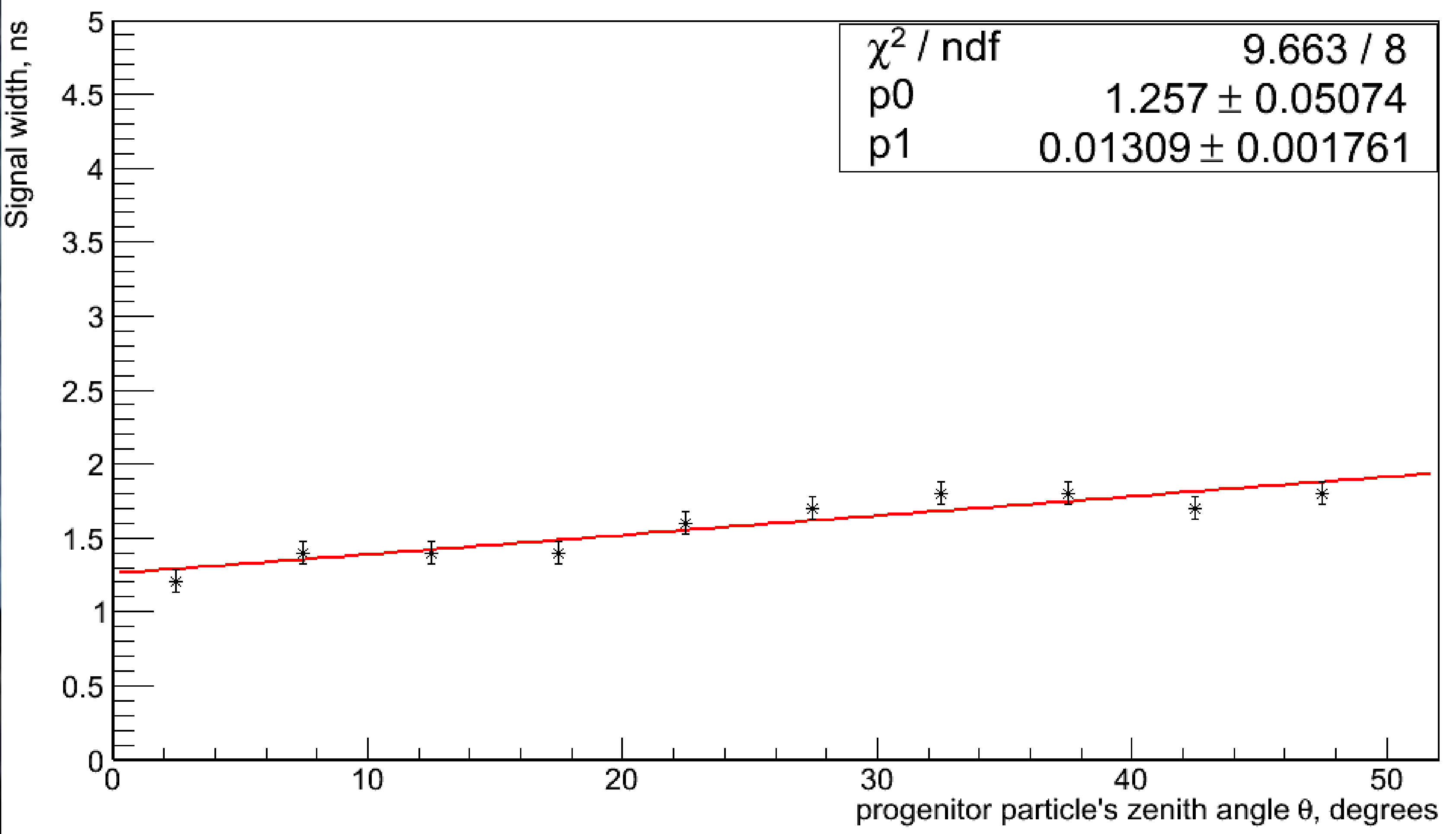
GLASS DETECTOR SIMULATION (CONT'D)

- Light yield vs. zenith angle θ



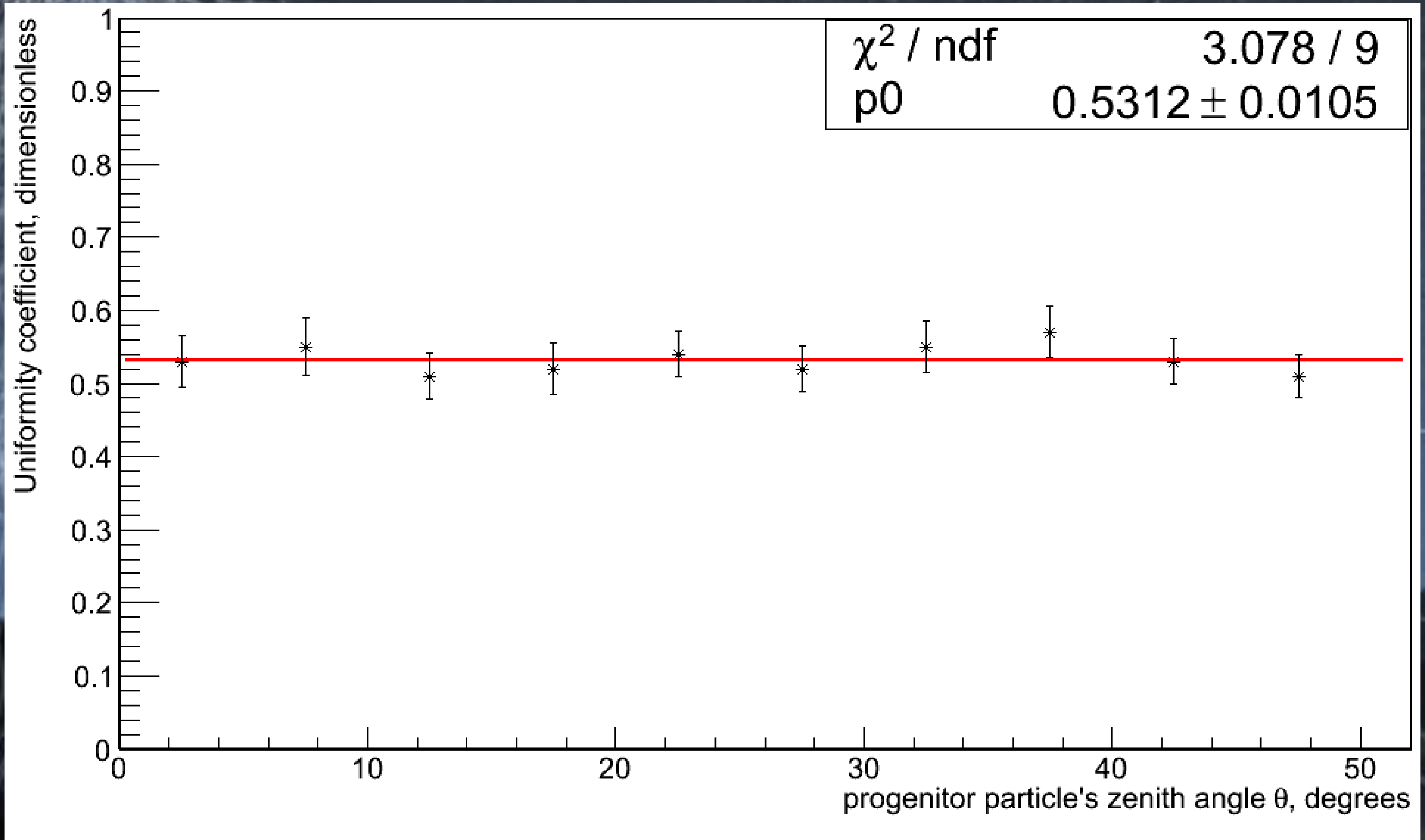
GLASS DETECTOR SIMULATION (CONT'D)

- Signal width vs. zenith angle θ



GLASS DETECTOR SIMULATION (CONT'D)

- Uniformity vs. zenith angle θ



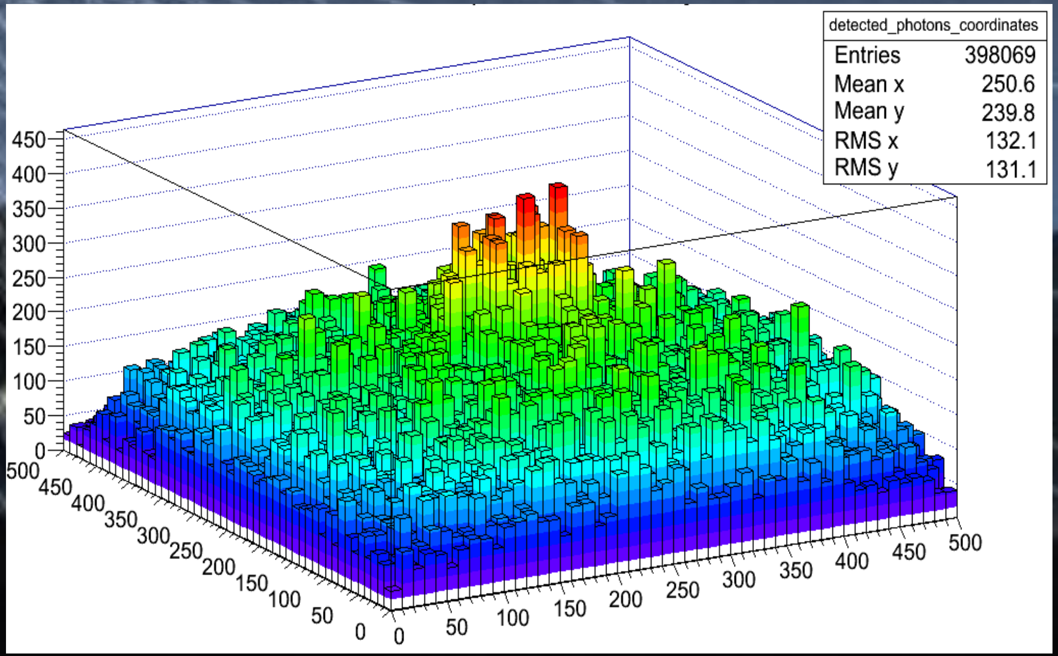
COMPARISON OF 4 DETECTOR MODELS

Medium Type	Light Yield, number of detected photons	Average signal width, ns	Uniformity
Glass, black edges	181062±426	1.8±0.1	0.74±0.07
Glass, white edges	230610±480	2.1±0.1	0.77±0.06
Scint, black edges	1609049±1269	7.5±0.1	0.68±0.12
Scint, white edges	1892122±1376	9.2±0.1	0.70±0.11

Parameters of 4 geometries obtained from the simulation

UNIFORMITY ACROSS THE SCINTILLATOR

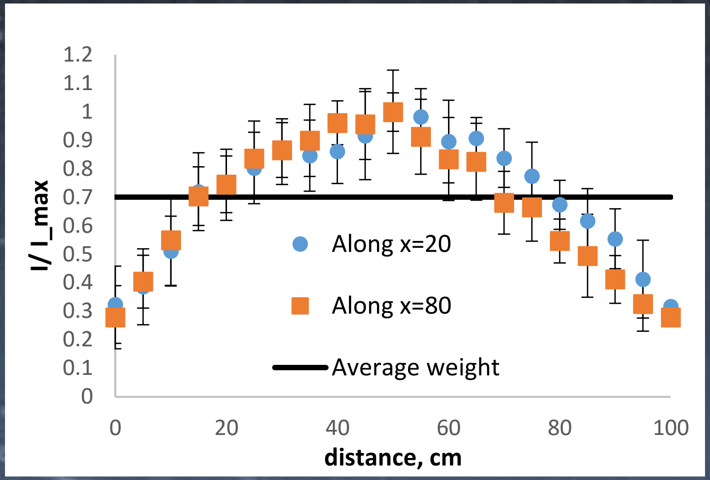
- ✓Progenitor particles' initial x,y-coordinates are distributed uniformly
- ✓Zenith θ and polar φ angles are distributed uniformly in corresponding ranges as well
- ✓Isotropic light yield (implemented physics for scintillator detector is correct)



Distribution of detected photons' progenitor particles' initial x,y-coordinates for scintillator detector with PMT above

SD DETECTOR RESPONSE UNIFORMITY

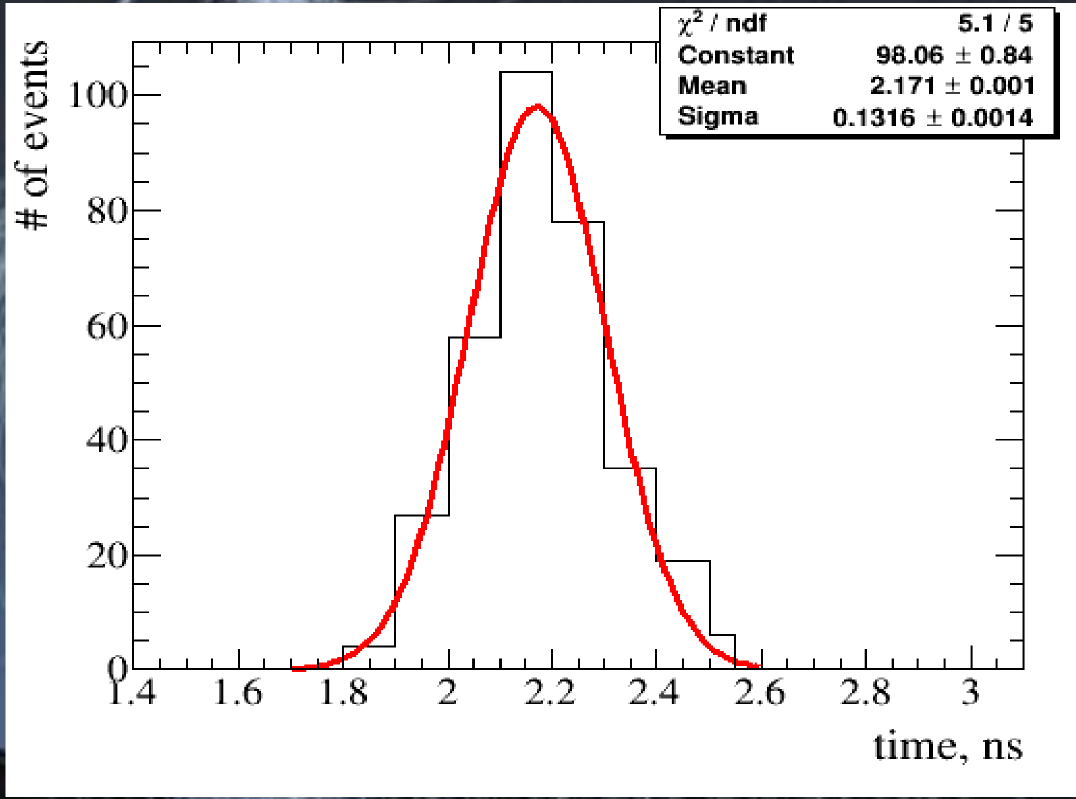
- The MIP signal calibration is done **at the center** of SD/GD, however, **particles arrive randomly**
- SD is scanned across using ^{60}**Co** radioactive source **along the lines** x = 20 cm, x = 80 cm and two diagonals
- PMT **dark current is subtracted**
- **Average weight value**(measure of non-uniformity) for several SDs is **0.7 ± 0.1**
- Light yield of scintillator itself is **uniform** across its volume; the rest is the **effect of the detector shape** (e.g. geometry).



SD Detector Response Uniformity

The size of **error bars** is due to the **low intensity** of the rad. source that was available.

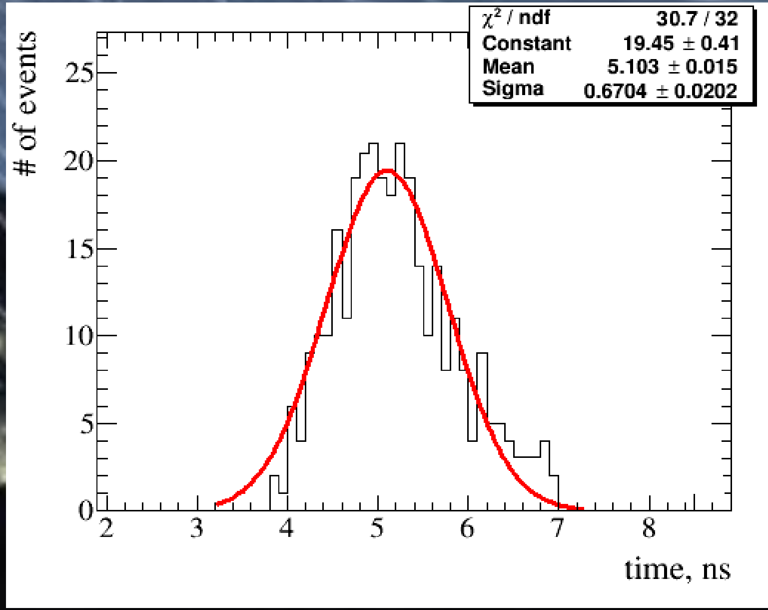
TIME RESPONSE MEASUREMENTS



~ 2.2 ns rise time response (10-50% of the pulse area) of the PMT+glass

~ 1.7 ns pulse width is limited by PMT, ADC characteristics and geometry

~ 5.1 ns total time response (10-90% of pulse area) of the PMT+glass

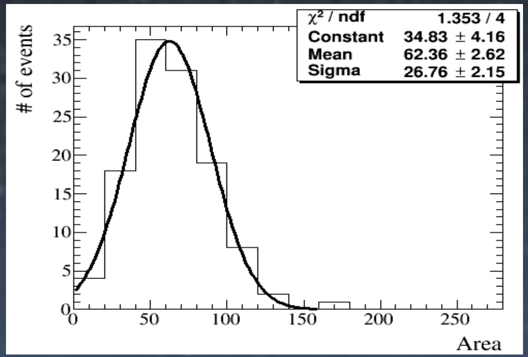


PMT CALIBRATION: PE CALIBRATION

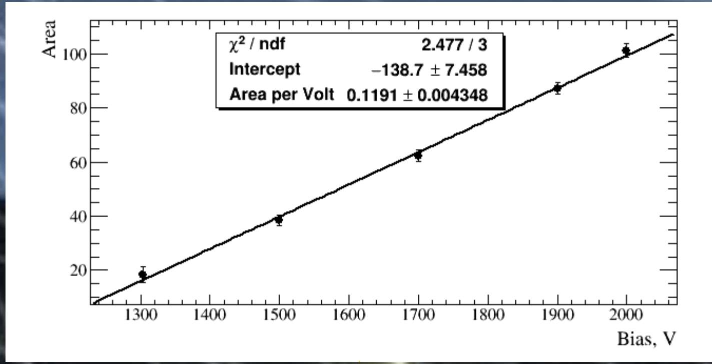
- PE calibration is needed to **calculate number of incident photons** in PMT pulse signal during detector operations

- Low light **LED pulse is fed to PMT** that is connected to DAQ via short cable (<1m)

- Care is taken to ensure that **pedestal has ~ 80% of all events** in order for single photon detection assurance



R7723 PMT single PE response pulse area at 1700V



Single PE pulse area vs. bias voltage for R7723 PMT

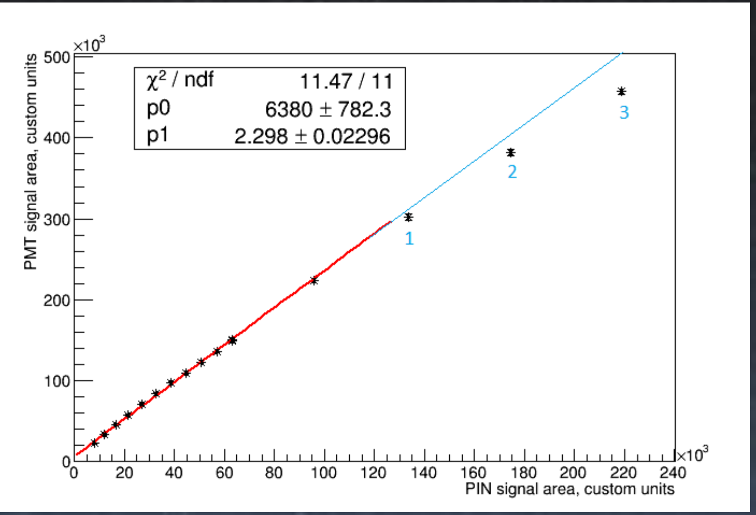
PMT NON-LINEARITY

- **PMT response saturates** for large input signals

I. **PMT** and Hamamatsu S3883Si **PIN diode** responses are measured for small signals with **several photons** detected

II. **Intensity** of incident light is **gradually increased**

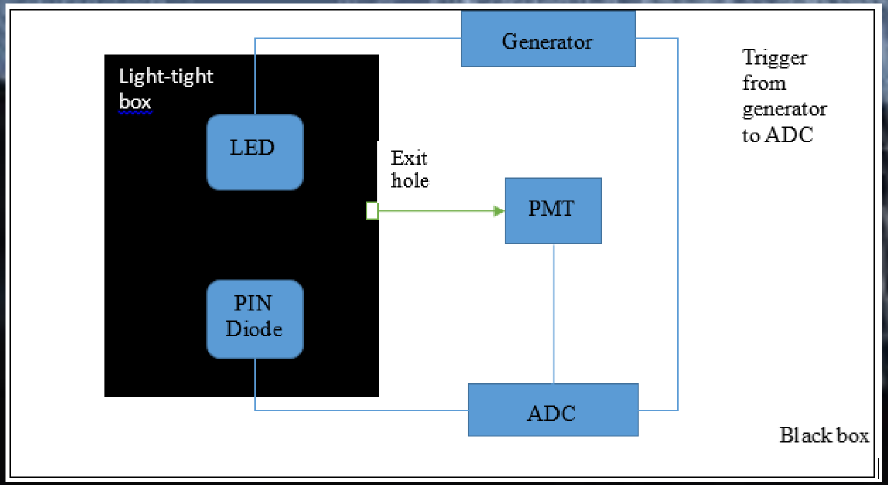
- **PIN diode** response is known to be **linear** up to **10^{10} photons**
- PMT signal is starts to be **nonlinear with deviation ~ 7%** near the ADC upped range limit



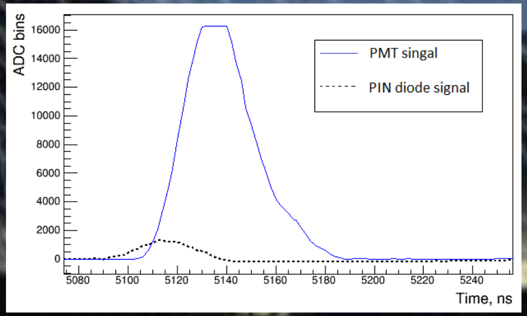
PIN signal area vs PMT signal area

	Deviation, %
Point 1	3.7 ± 0.3
Point 2	6.6 ± 0.2
Point 3	11.3 ± 0.2

Deviation of points from linearity



Schematic of PMT linearity measurement experiment

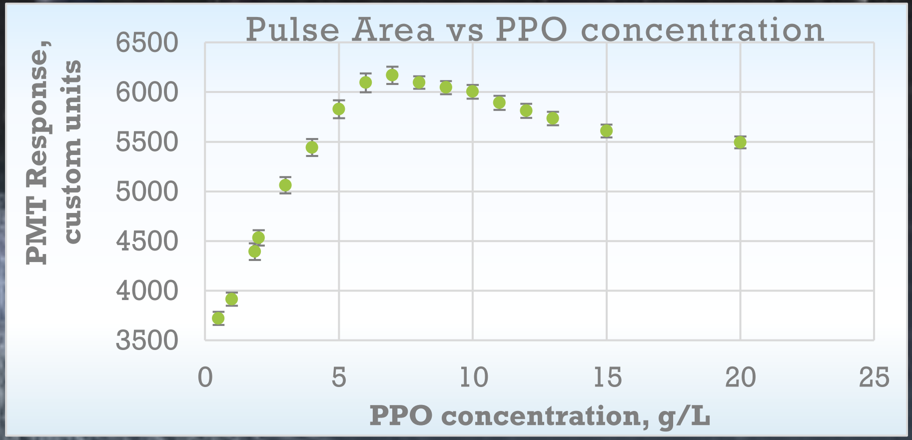


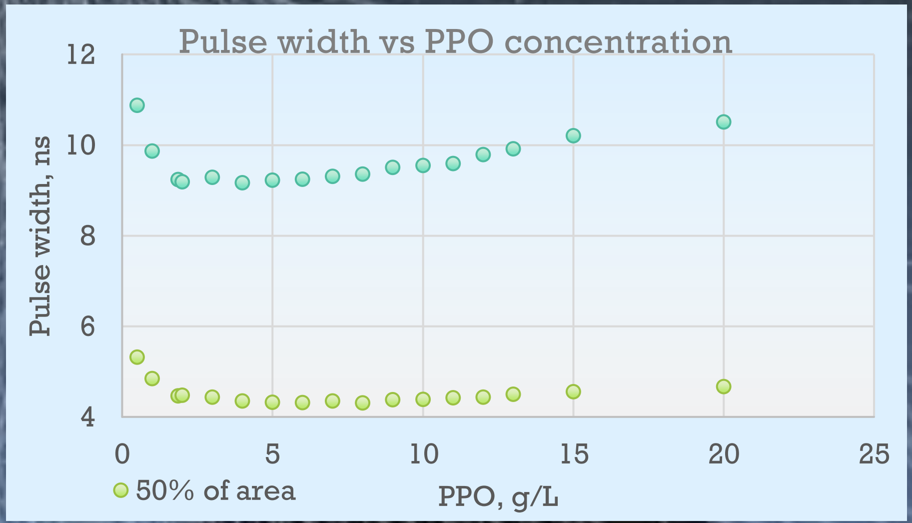
PMT and PIN diode pulse at point 3

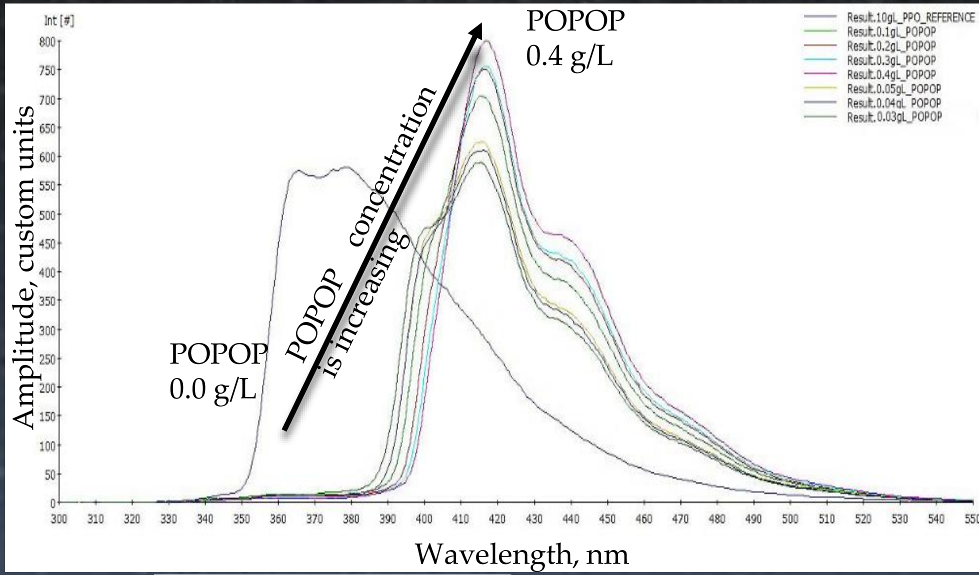
Linearity holds from 1 MIP and up to 3000 MIP for glass medium

SCINTILLATOR TESTING

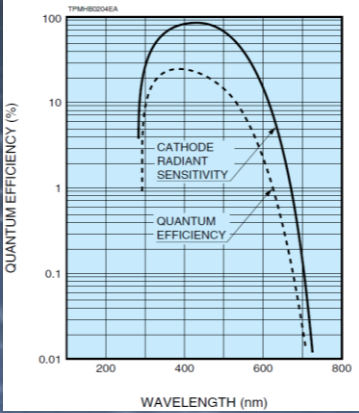
- The light yield and light emission time were tested vs. PPO and POPOP concentration.
- The scintillator light output spectrum vs POPOP concentration was accessed
- Signal gain depends on the PMT used.

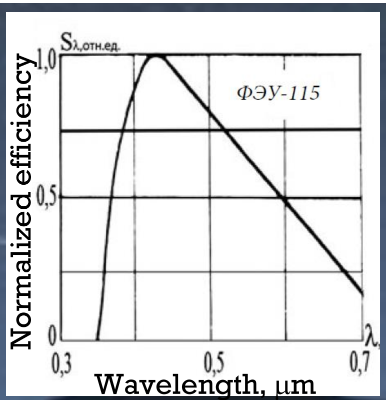




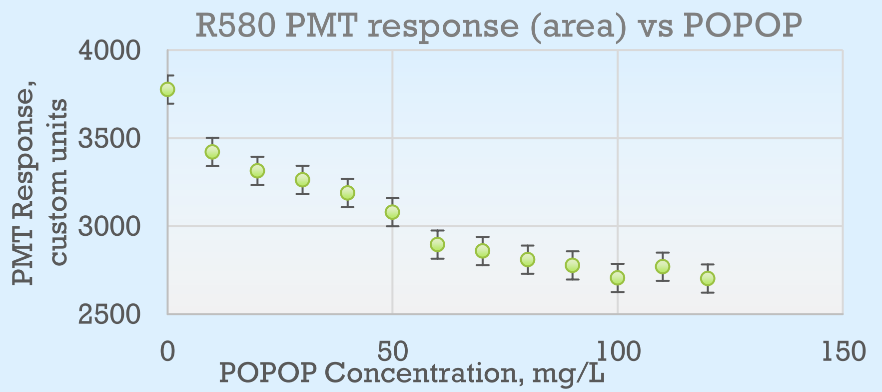


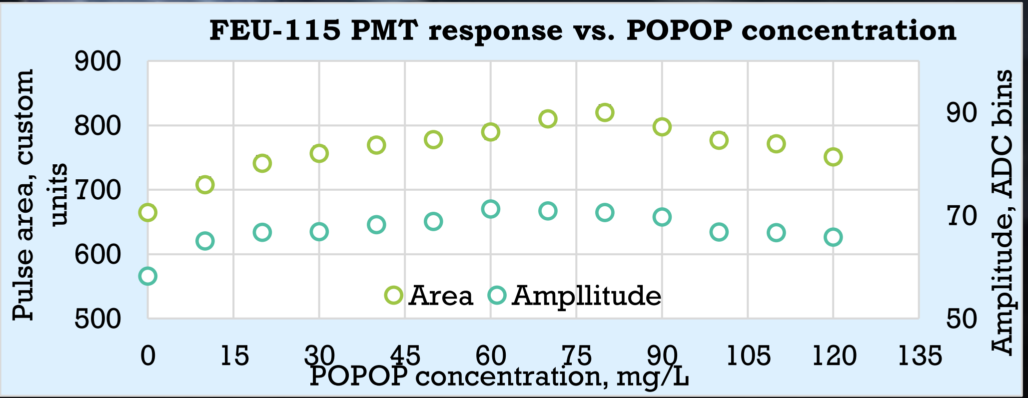
FEU-115 is not UV sensitive The R580 PMT is partially UV sensitive,



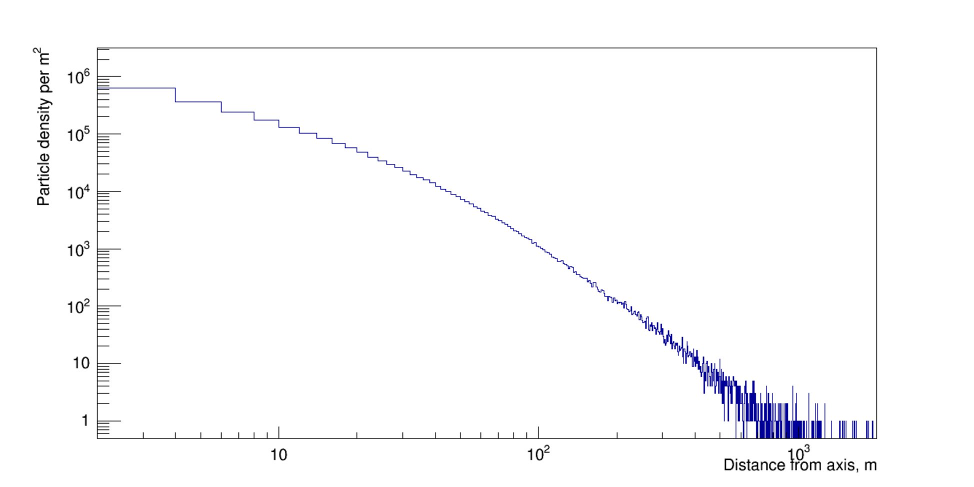


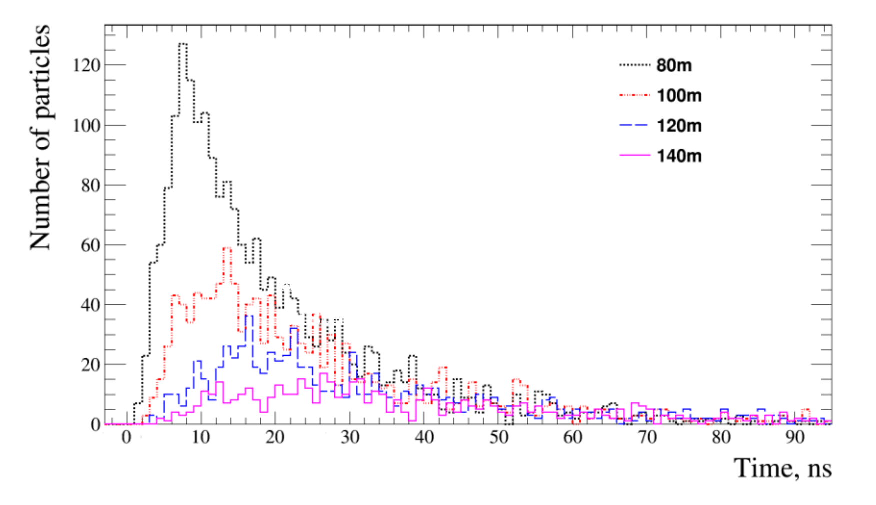
Spectral sensitivity for R580 (left) and FEU-115 (right)



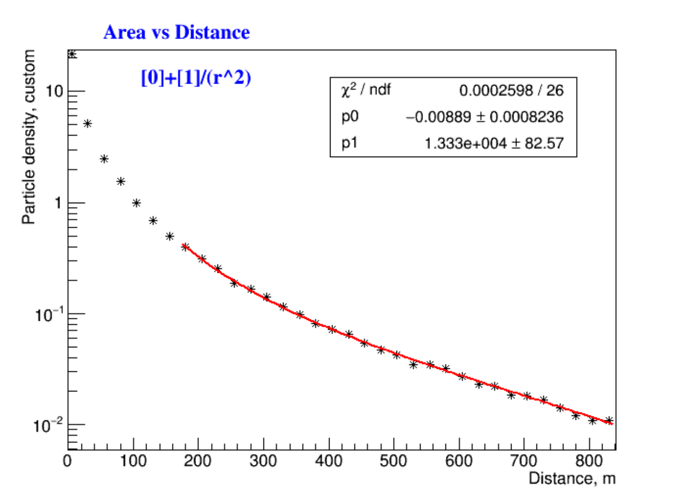


CORSIKA SIMULATION FOR STANDARD EAS DEFINITION





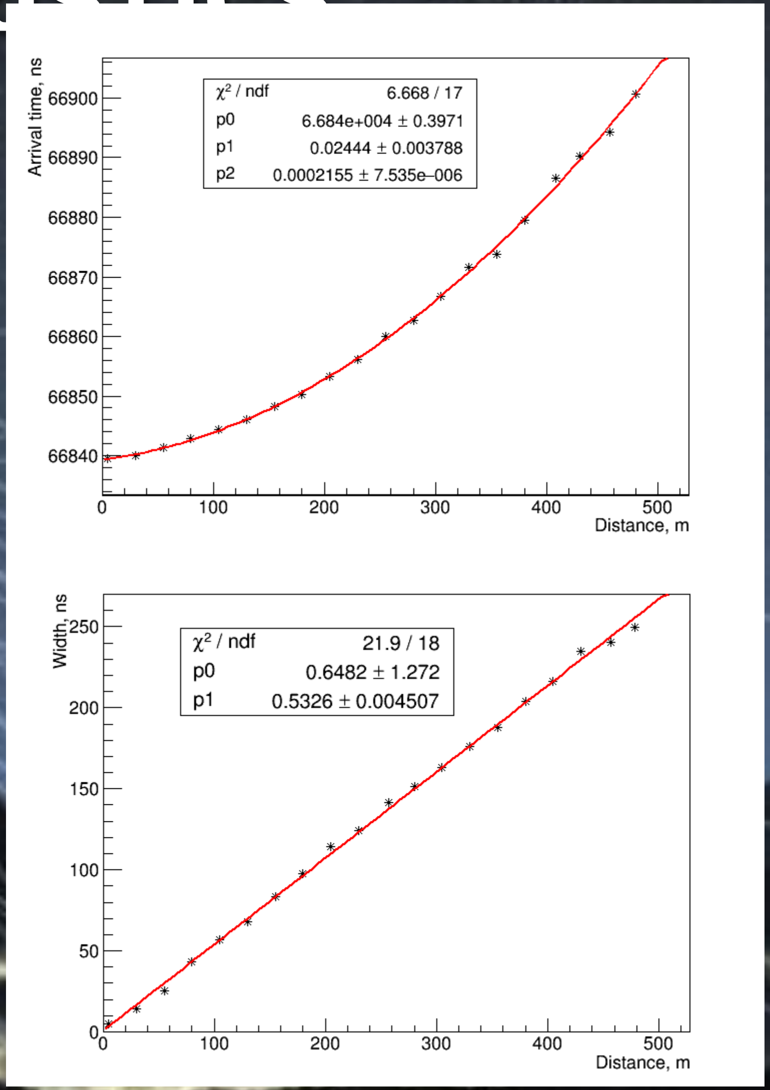
- CORSIKA* simulation software is based on our understanding of HEP, thus simulating a '**standard**' shower.
  - Plots are for E=10^{17} eV proton.
- At observation level, such EAS has a single disk with particle density decreasing as ~$1/r^2$ (far) from the axis



* D. Heck, J. Knapp, J.N. Capdevielle, G. Schatz, T. Thouw. CORSIKA: A Monte Carlo Code to Simulate Extensive Air Showers, Forschungszentrum Karlsruhe Report FZKA (6019)

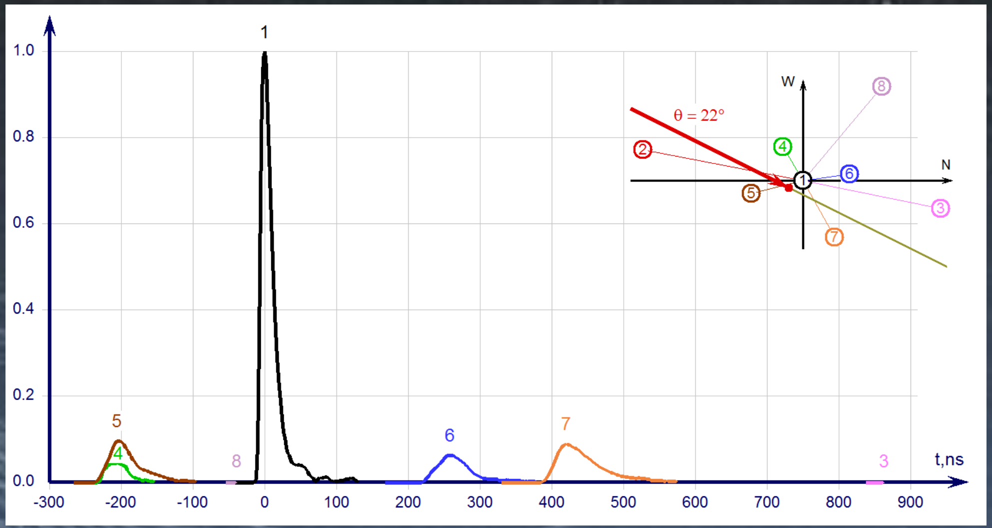
STANDARD EAS CHARACTERISTICS

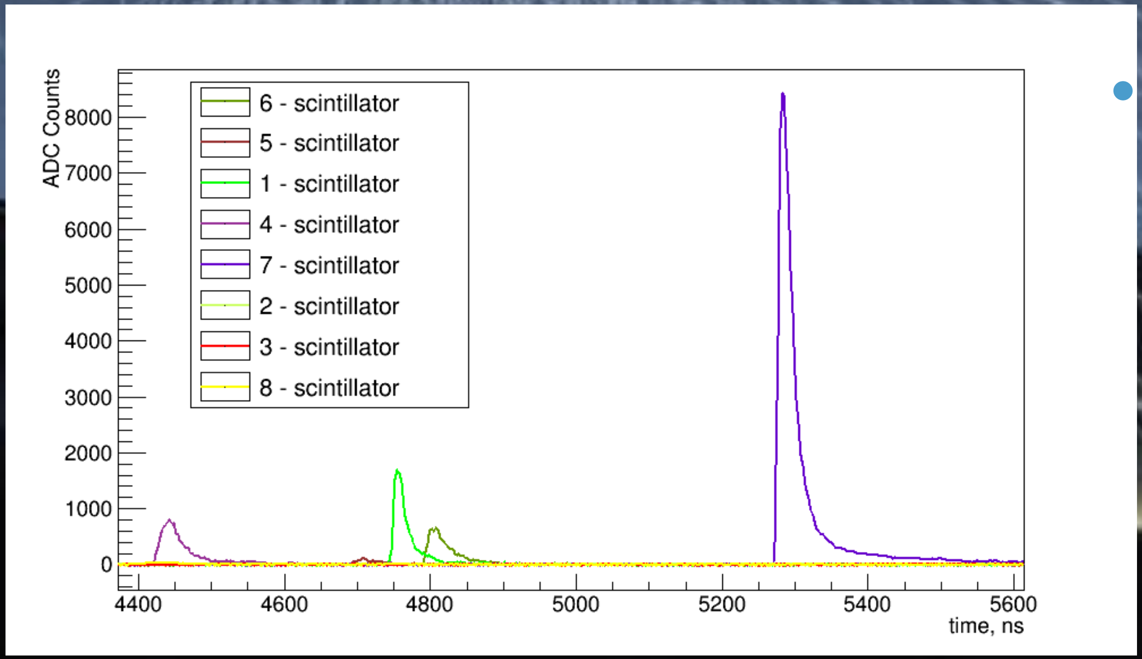
- Disk arrival time ~r^2 (used for arrival direction determination)
- Disk passage time (e.g. width) is growing with ~r
- *Can use particle density and <u>pulse width</u> additional information from each detection point*
  - *<u>Need time resolution <10ns</u>*



DATA EXAMPLES FOR STANDARD EAS

- Standard EAS signal from each HT detector
- Corresponds to simulation

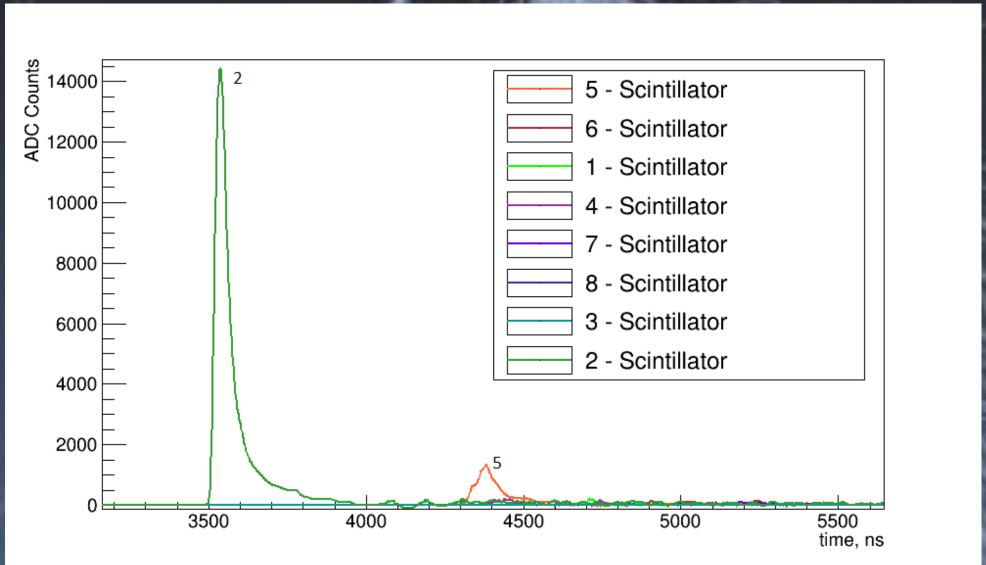


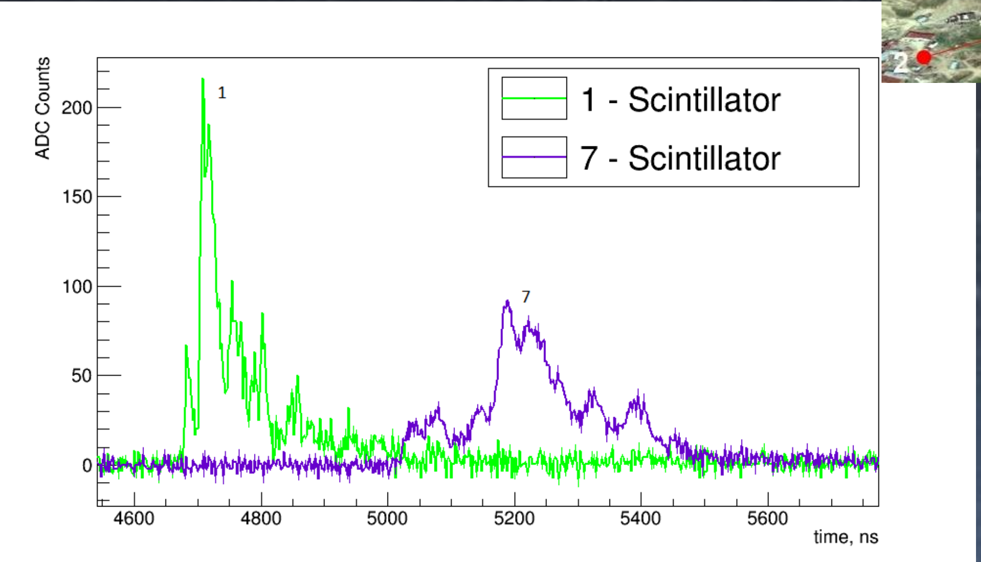


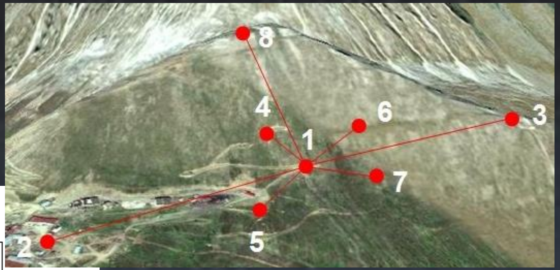
- Estimated Energy:
  - $\sim 10^{16}$ eV (top) at low angle
  - $\sim 2 \cdot 10^{16}$ eV (left) high zenith angle

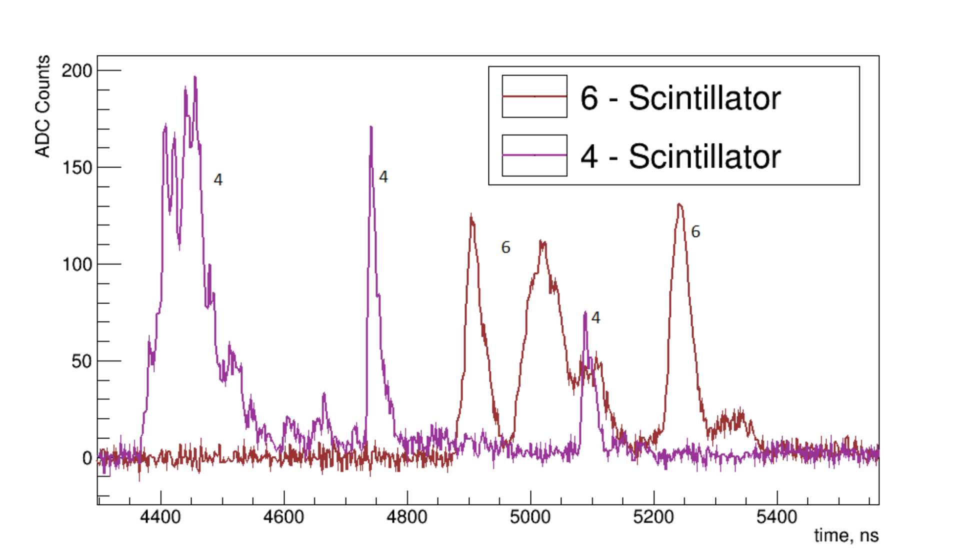
UNUSUAL EAS EXAMPLE

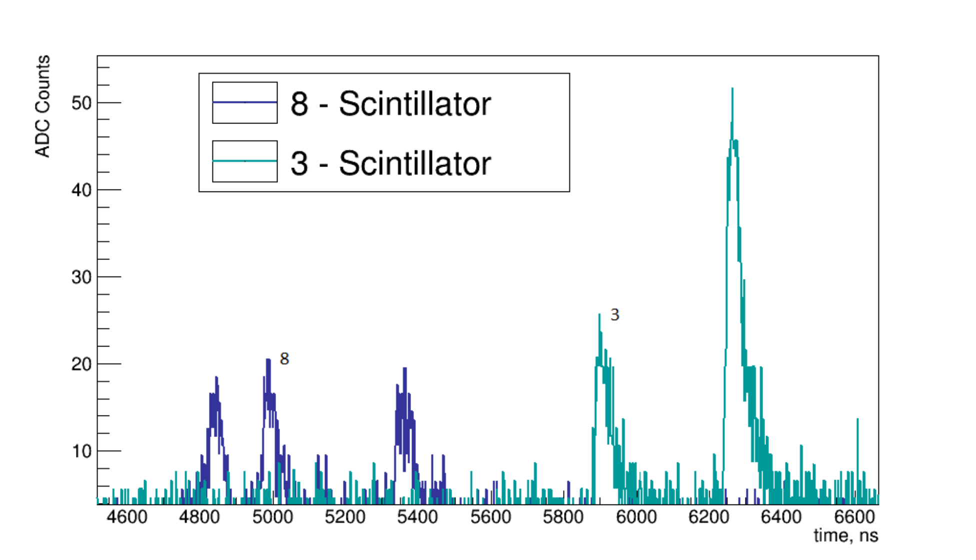
Event of Jan26 '16 at Horizon-T. Typical behavior: separation between peaks increases with distance from axis





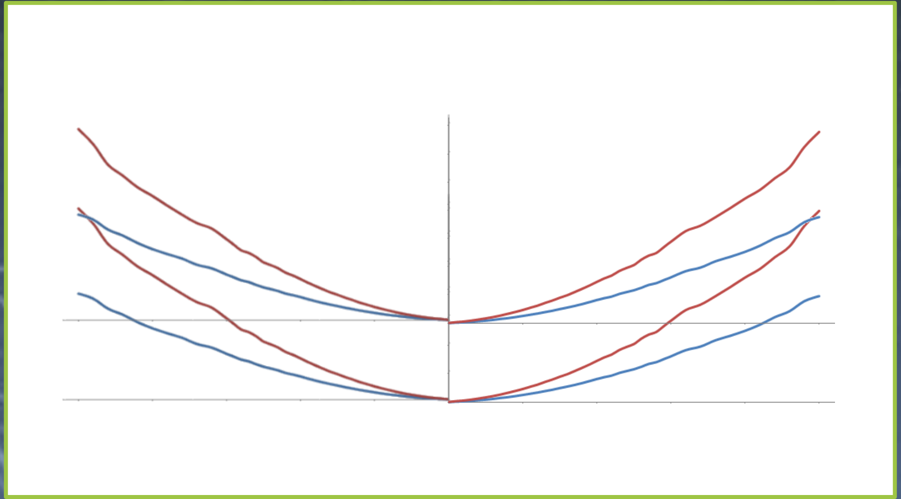


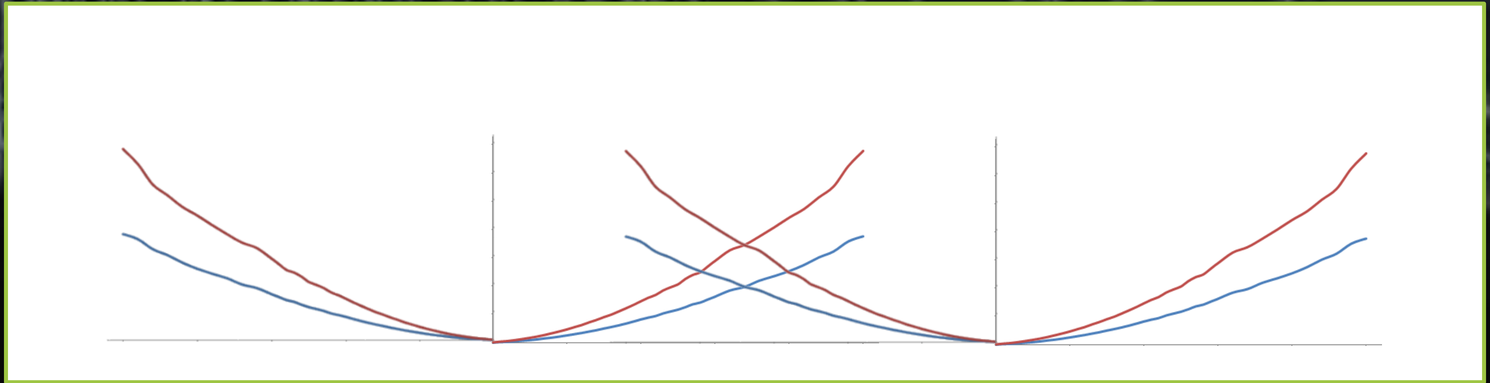




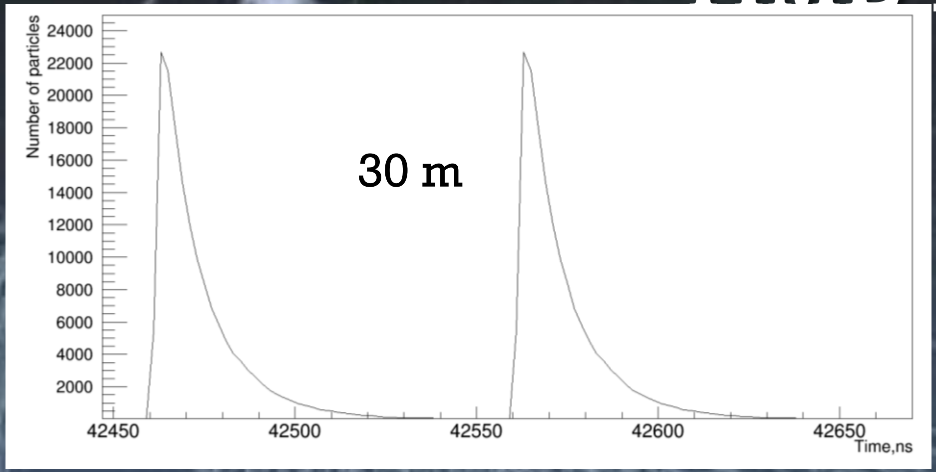
MODELING ATTEMPT AT UNUSUAL EVENTS BY COMBINING SIMULATED DISKS

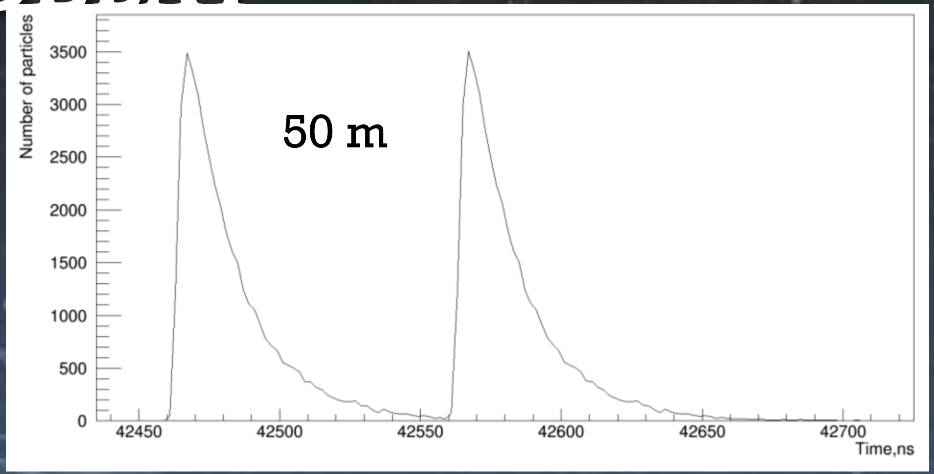
- To approximate response of a detector from arrival of two disks separated in time and space, two simulated disks are overlaid.
- Following cases were simulated:
  - Two disks of the same energy falling with delay at the same distance from their centers (time delay)
  - Two disks of the same energy falling at the same time at different distances from their centers (spatial separation)
  - Two disks of different energies falling at the same time at different distances from their centers

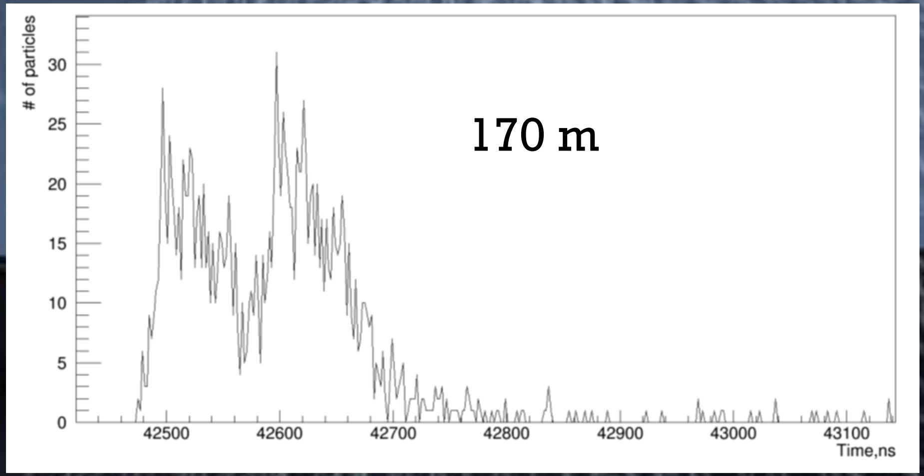




COMBINING SIMULATED DISKS: TIME DELAY







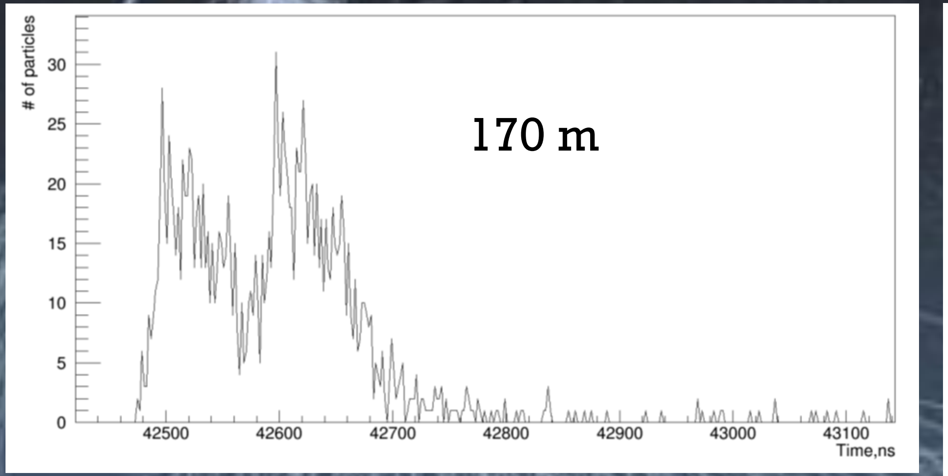
Time delay between disks centers - **100** ns.

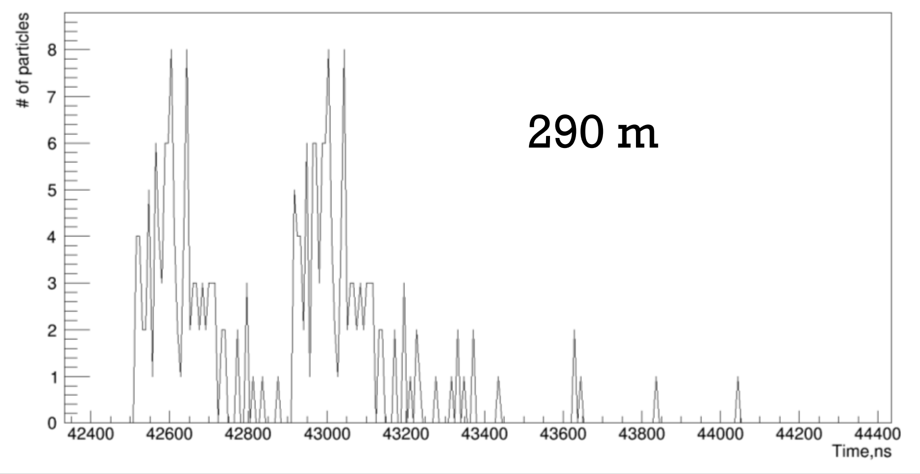
Energy of each primary – 10^{17} eV

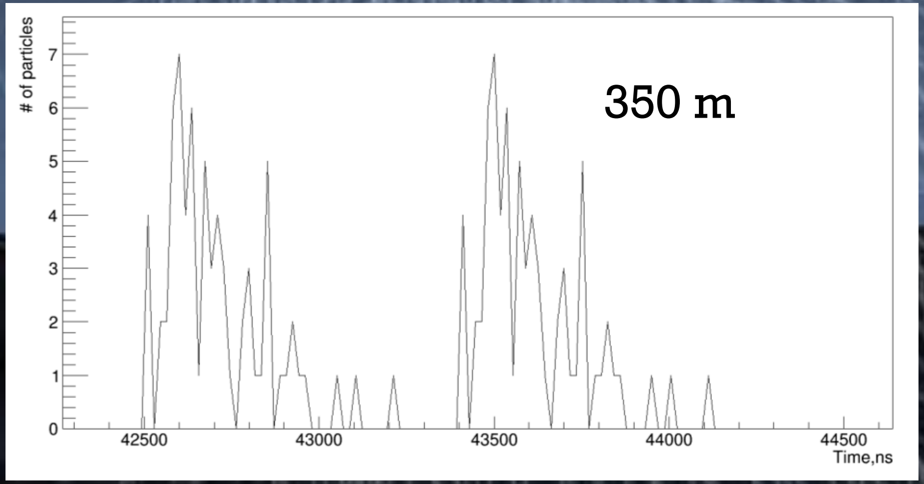
Farther from the EAS axis the disks become wider, so combining two pulses results in overlapping of the shower fronts.

CLOSE TO THE CENTER, EACH DISK SIGNAL COULD BE DIFFERENTIATED EASILY. HOWEVER, HARDLY DISTINGUISHABLE MULTIPEAK EVENT CAN OCCUR FAR FROM THE CENTER

COMBINING SIMULATED DISKS: TIME DELAY 2

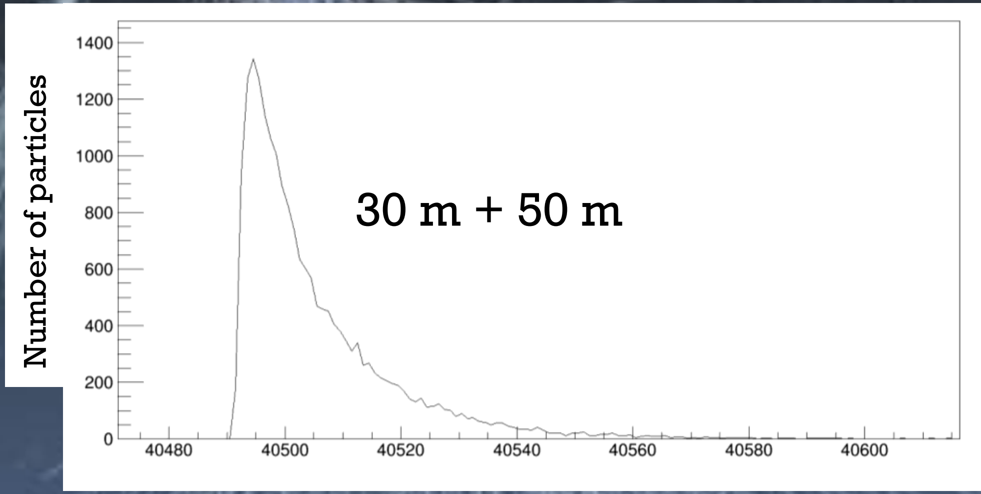


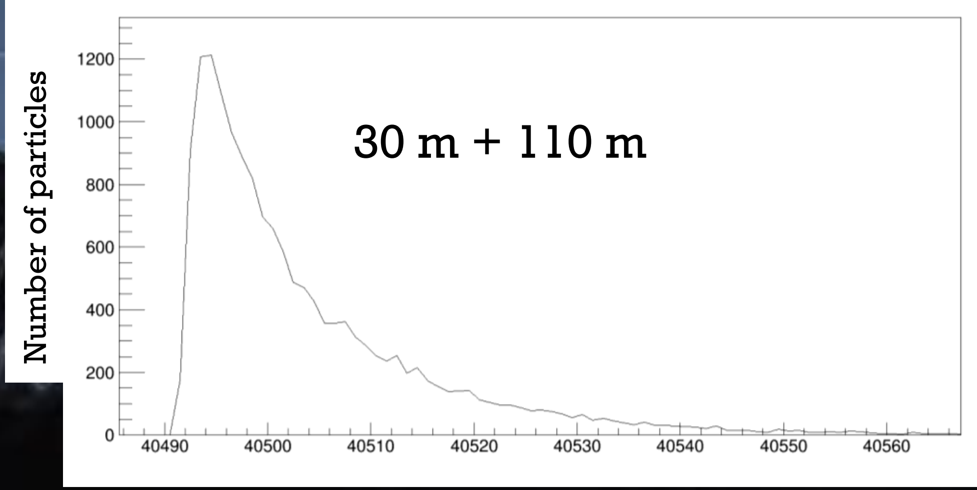




Although at even larger distances from the center of the shower (>300 meters) signals become separated clearer, it happens because of low density of particles in the shower disk. Still, wide particle distributions are observed as expected from disk width.

COMBINING SIMULATED DISKS: SPATIAL SEPARATION



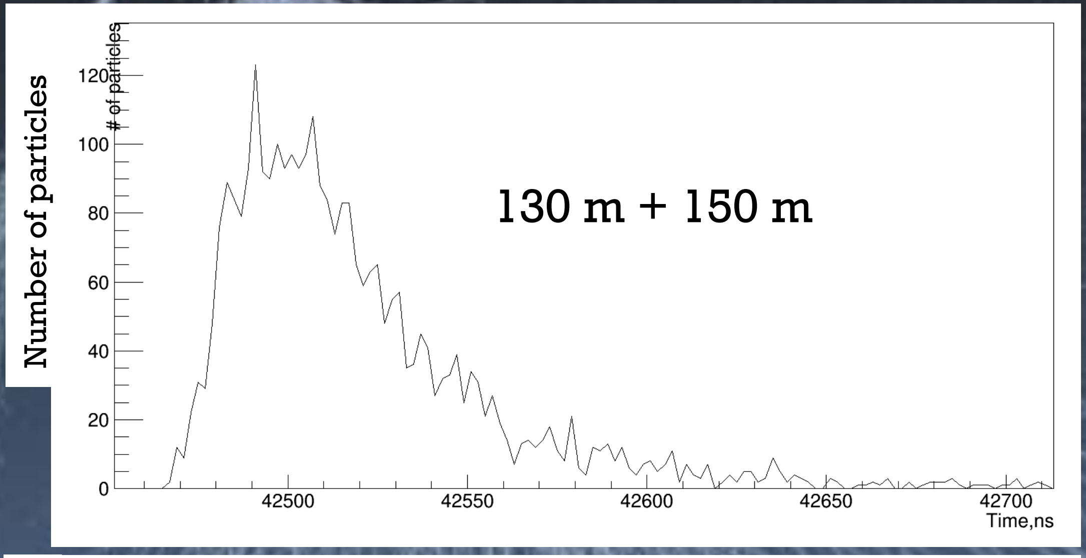


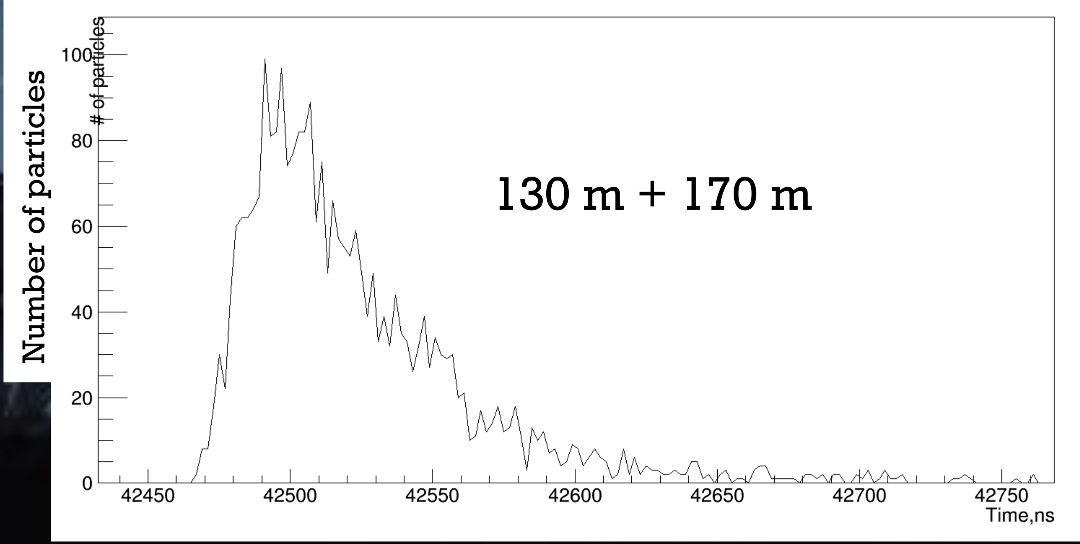
ENERGY – 10^16 EV

THE PARTICLE DENSITY SO MUCH HIGHER CLOSER TO THE AXIS THAT CONTRIBUTION OF THE SECOND DISK IS NOT CLEARLY VISIBLE

EACH FIGURE SHOWS DISTANCES FROM THE DISK AXIS ON THE LEFT THEN FROM THE AXIS ON THE RIGHT

COMBINING SIMULATED DISKS: SPATIAL SEPARATION



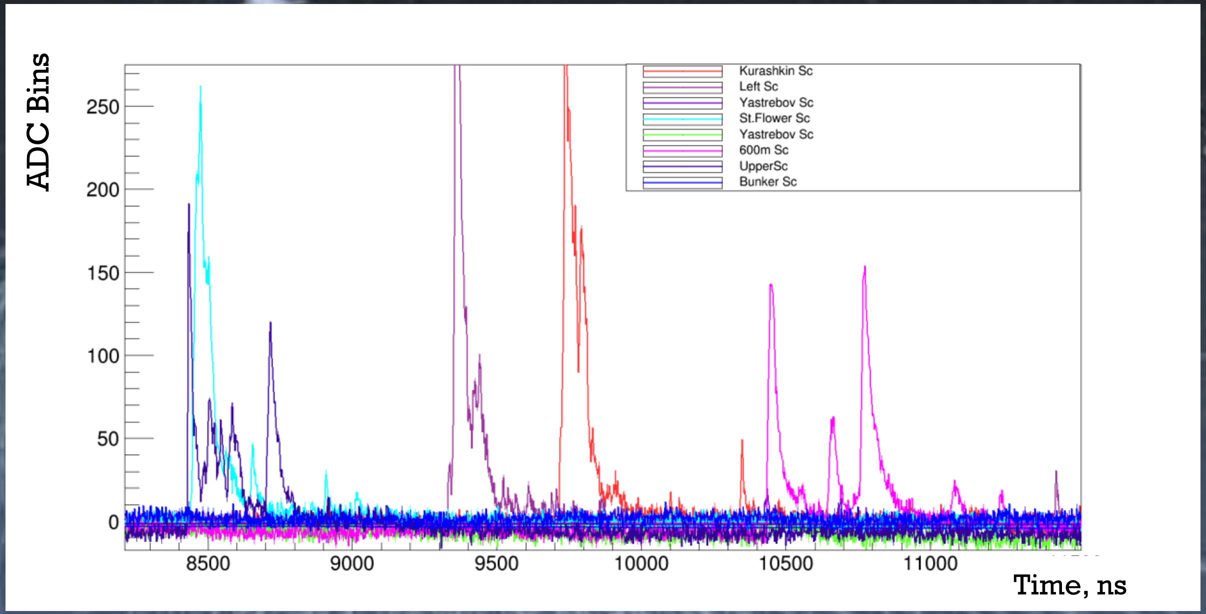


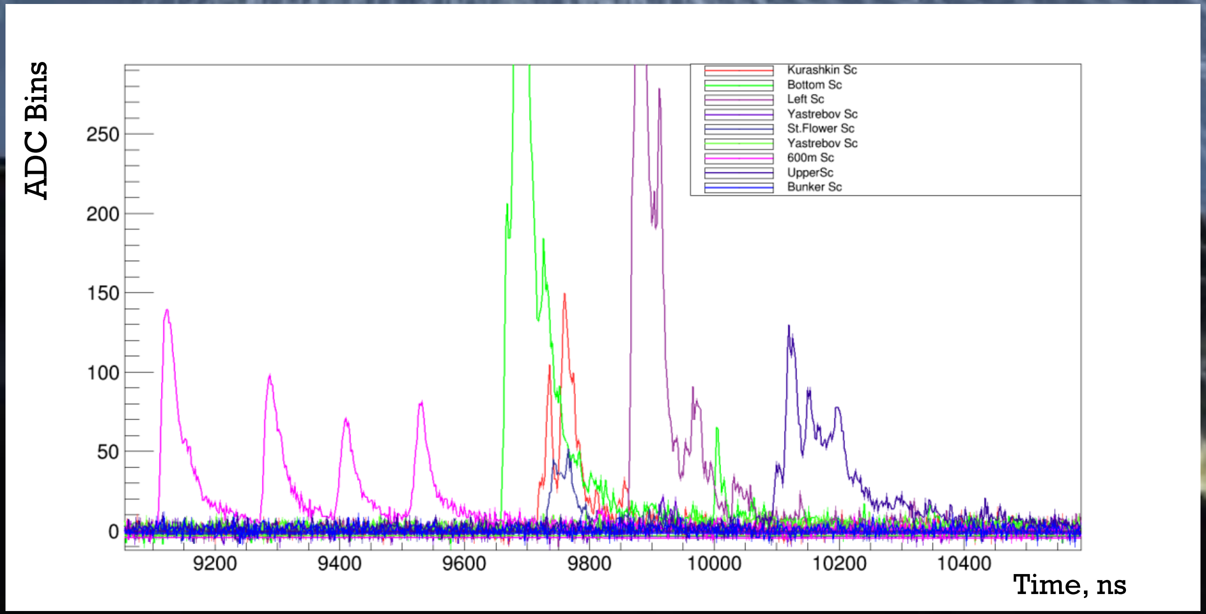
Energy – 10^17 eV

Even far from the center of the shower combination does not give any distinguishable peaks

Thus, no multi-peak behavior can be seen in this case

HORIZON-T UNUSUAL EVENTS INITIAL ANALYSIS





Multipeak signals at distances far from the axis of EAS noticeably separated in time. For such events, pulses' widths and separation between pulses can be measured. Shown are clear separation at 600m detection point of Horizon-T (in magenta). Analysis showed that typical width of pulses is ~30-50 ns with expected >500s at such distance from axis.

Moreover, separation time between disks **increases** with distance to the shower axis.

CONCLUSION

- Cosmic ray detectors need to be fast, simple and with high dynamic range
- Detector of Unusual Cosmic casKades (DUCK) is in construction stage
- Unusual events show common features:
  - narrow multiple pulses far from expected axis
  - Multy-peaked pulses near axis with peaks overlap
  - Time separation between pulses increases with distance from axis
- Simple combination of simulated disks doesn't give similar picture
- Possible explanation: multiple showers originating from primary fragmentation with high transverse momentum
  - This mechanism can not be explained within current particle physics