

Моделирование оптических фотонов в кристаллах и пластических сцинтилляторах, используемых в эксперименте Mu2e

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Лаборатория ядерных проблем

23 июня, 2017 г.

План

1. Об эксперименте Mu2e и наши возможности
2. Фотоны в сцинтилляционном стрипе и особенности спектросмещающего оптического волокна
3. О пользе оптических наполнителей
4. Затухание света в стрипах разной длины
5. Кристаллы в электромагнитном калориметре
6. Распределение фотонов на торце кристаллов
7. Тест-бим измерения в Ереване и Фраскати
8. Заключение и опубликованные работы за отчетный период

Mu2e – эксперимент по поиску нарушения закона сохранения лептонного числа

План-схемы экспериментов MELC (Лобашов и др.),
MECO (BNL) и Mu2e (FNAL)

Первое упоминание об эксп. поиске конверсии относится к 1955 г.

[16] J. Steinberger and H. Wolfe, Phys. Rev **110** (1955) 1490.

$<5 \cdot 10^{**(-4)}$

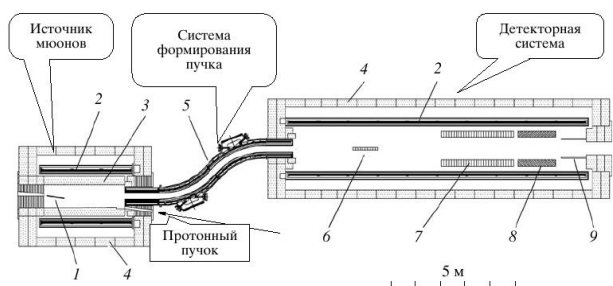


Рис. 1. Центральный горизонтальный разрез установки MELC: 1 – протонная мишень, 2 – сверхпроводящий соленоид, 3 – защита соленоида, 4 – стальное ядро, 5 – транспортный соленоид и коллиматор, 6 – мишень детектора, 7 – координатный детектор, 8 – калориметр, 9 – защита детектора и ловушка пучка.

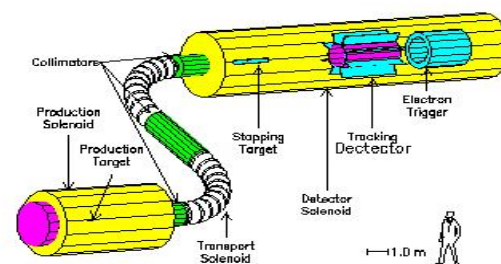
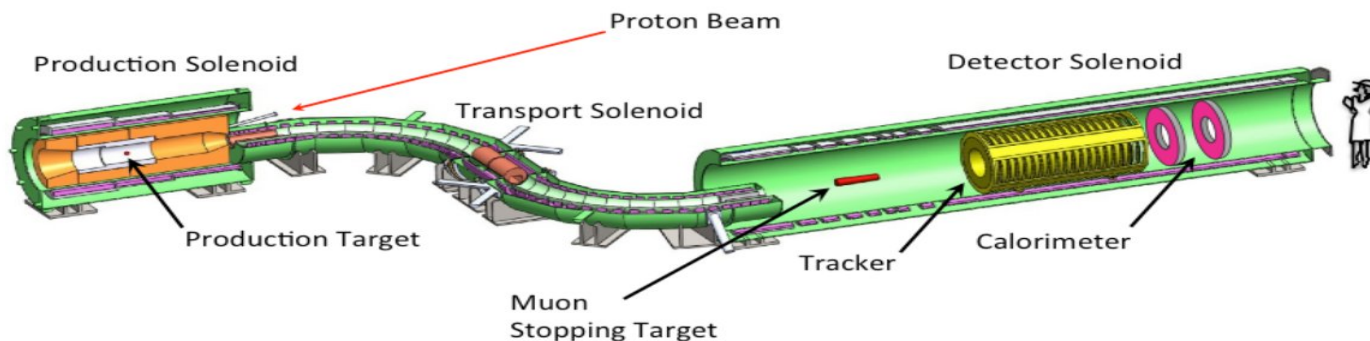


Fig. 1. The MECO experiment



R.M. Djilkibaev and V.M. Lobashev, Sov.J.Nucl.Phys. 49(2), 384 (1989);
V.S. Abadjev et al., "MELC Experiment to Search for the $\mu^- A \rightarrow e^- A$ Process", INR. Preprint 786/92 (1992).

M. Bachman et al., "A Search for $\mu^- N \rightarrow e^- N$ with Sensitivity Below 10^{-16} ",
Proposal to BNL, P940, (1997).

R.M. Carey et al., "Proposal to Search for $\mu^- N \rightarrow e^- N$ with a Single Event
Sensitivity Below 10^{-16} ", FERMILAB-PROPOSAL-0973.

Oct. 10, 2008

Му2е – эксперимент по поиску нарушения закона сохранения лептонного числа

$$R_{\mu e} = \frac{\Gamma(\mu^- + N(A,Z)) \rightarrow e^- + N(A,Z)}{\Gamma(\mu^- + N(A,Z)) \rightarrow \text{all muon captures}}$$

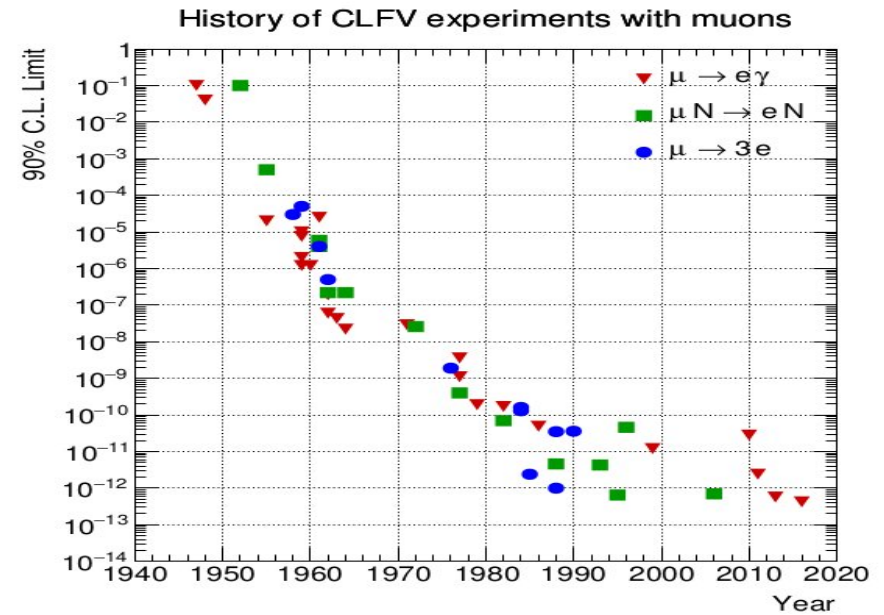
In 3 years: $\sim 10^{20}$ protons, $\sim 10^{18}$ stopped muons

→ A factor 10^4 improvement

$$R_{\mu e} \leq 6 \times 10^{-17} \text{ @ 90\% C.L.}$$

Table 4 Bounds at 90% CL on selected lepton flavor violating decays of pseudoscalar mesons

Channel	Upper limit	Experiment	Reference
$\pi^0 \rightarrow \mu^\pm e^\mp$	3.59×10^{-10}	KTeV	75
$\eta \rightarrow \mu^\pm e^\mp$	6×10^{-6}	Saturne SPES2	76
$K_L^0 \rightarrow \pi^0 \mu^\pm e^\mp$	7.56×10^{-11}	KTeV	75
$K_L^0 \rightarrow 2\pi^0 \mu^\pm e^\mp$	1.64×10^{-10}	KTeV	75
$K_L^0 \rightarrow \mu^+ e^-$	4.7×10^{-12}	BNL E871	74
$K^+ \rightarrow \pi^+ \mu^+ e^-$	1.3×10^{-11}	BNL E865, E777	73
$D^+ \rightarrow \pi^+ \mu^\pm e^\mp$	3.4×10^{-5}	Fermilab E791	77
$D^+ \rightarrow K^+ \mu^\pm e^\mp$	6.8×10^{-5}	Fermilab E791	77
$D^0 \rightarrow \mu^\pm e^\mp$	8.1×10^{-7}	BaBar	78
$D_s^+ \rightarrow \pi^+ \mu^\pm e^\mp$	6.1×10^{-4}	Fermilab E791	77
$D_s^+ \rightarrow K^+ \mu^\pm e^\mp$	6.3×10^{-4}	Fermilab E791	77
$B^0 \rightarrow \mu^\pm e^\mp$	9.2×10^{-8}	BaBar (347 fb ⁻¹)	79
$B^0 \rightarrow \tau^\pm e^\mp$	1.1×10^{-4}	CLEO (9.2 fb ⁻¹)	80
$B^0 \rightarrow \tau^\pm \mu^\mp$	3.8×10^{-5}	CLEO (9.2 fb ⁻¹)	80
$B^+ \rightarrow K^+ e^\pm \mu^\mp$	9.1×10^{-8}	BaBar (208 fb ⁻¹)	81
$B^+ \rightarrow K^+ e^\pm \tau^\mp$	7.7×10^{-5}	BaBar (348 fb ⁻¹)	82
$B_s^0 \rightarrow e^\pm \mu^\mp$	6.1×10^{-6}	CDF (102 pb ⁻¹)	83



При этом процесс

$$\mu \rightarrow e\gamma \quad (1)$$

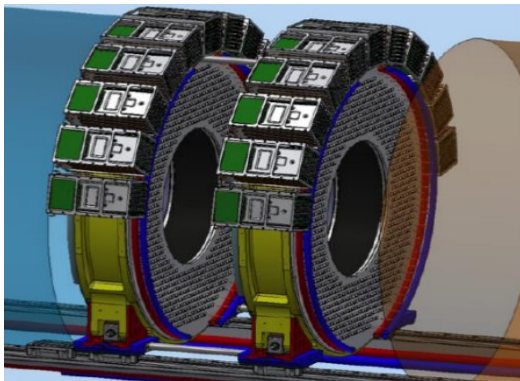
более чувствителен к новой физике чем

$$\mu \rightarrow e \quad \text{конверсия} \quad (2)$$

Предел $10^{**}(-14)$ для (1) приблизительно соответствует $10^{**}(-16)$ для (2)

Активность группы приходится на электромагнитный калориметер и защиту детекторной части установки от космических мюонов

Калориметер обеспечит триггер и еще 100 раз подавит космический фон



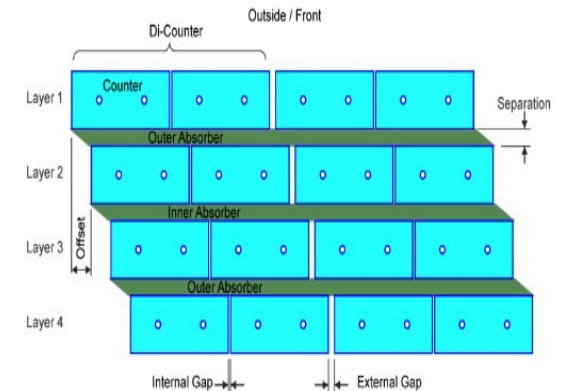
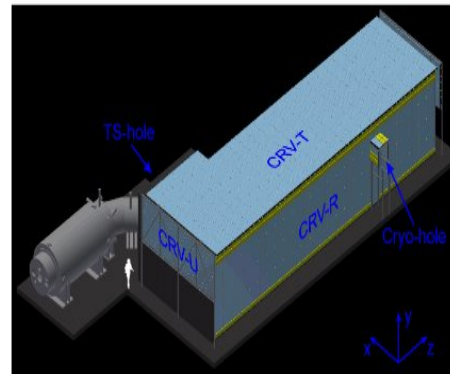
Внут. рад. – 37.4 см

Внеш. рад. - 66 см

CsI - 3.4см X 3.4см X 20см

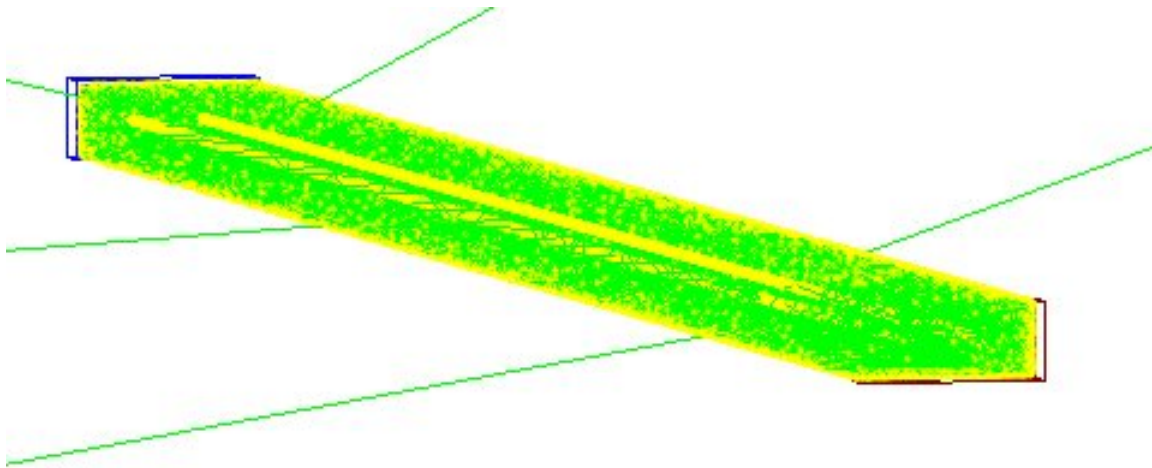
674 кристалла на диск

Каждый день 1 космический мюон будет имитировать 105 МэВ-ный электрон от конверсии



Неэффективность системы защиты
 $< 10^{**(-4)}$

The scintillator strip with dimensions $5 \times 2 \times 90 \text{ cm}^3$
Is considered



CRV Cryo strips

The strip was covered by TiO_2 with diffuse reflection

The scintillation light is collected by wavelength shifting (WLS)
fibers and detected by SiPMs by one ends

In this simulation the photodetector end of strip is black

The opposite end of strip and fiber both are **black** or **mirrored**

Сцинтиллятор и спектросмещающие волокна

	Scintillator Polyvinyltoluene H:C 11:10	Core Polystyrene C_8H_8	Cladding 1 Acrylic $C_5H_8O_2$	Cladding 2 Fluor-acrylic C_2H_4
Density (g/cm ³)	1.023	1.05	1.2	1.4
Refractive index	1.58	1.6	1.49	1.42

The density and refractive index of the scintillator and WLS fiber used in the simulation

A double-clad WLS fibers of diameter 1.2(1.4)mm was hosted in a holes (grooves)

$$W_{cladding} = (0.03 + 0.03) * D_{fiber}$$

Hole diameter – 2.6 mm (also varied in range 1.4-4.5 mm)

Groove size - $D_{fiber} + 50 \mu m$ ($50 \mu m$ seems to very small) !

The diameters of the holes and fibers 3 time more in figure than in simulation for clarity



The simulation was done with Geant4 version 10.3.1

The relevant physical and optical processes and involved particles are defined in the PhysicsList Class

The processes are standard electromagnetic processes:

ionization, bremsstrahlung, multiple scattering,
pair production, Compton scattering, photoelectric effect

The optical processes include:

scintillation light generation, Cherenkov emission,
bulk absorption, Rayleigh scattering, boundary
processes – reflection, refraction, absorption

The main photon generating process in plastic scintillator is the scintillation process.

The number of photon generated according Gaussian distribution with mean

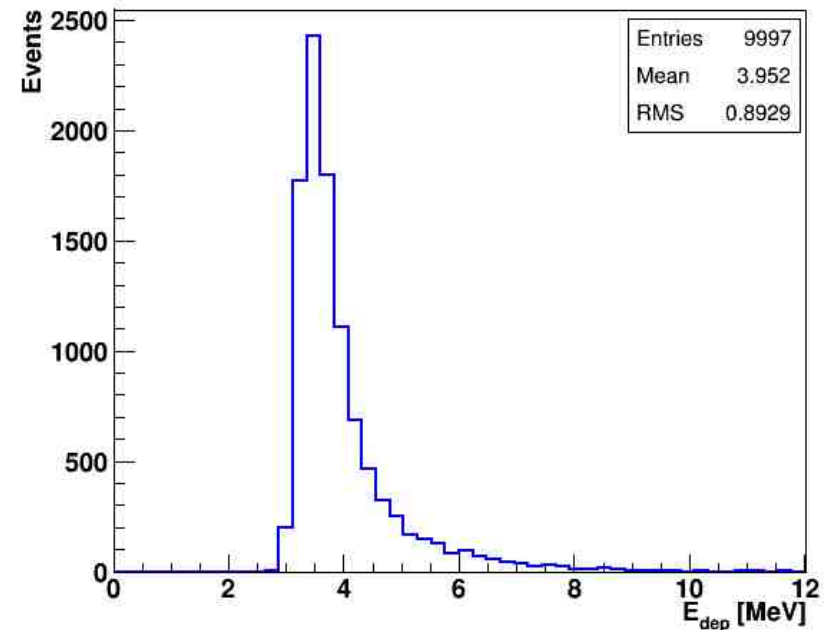
$$E_{dep} * LY (LY = 10000 \text{ ph/MeV}, \tau = 2.1 \text{ ns})$$

and dispersion

$$\sqrt{E_{dep} * LY}$$

Photons emitted isotropically along the primary track.

Cosmic muon energy deposition in 2 cm scintillator



For realistically treating the TiO_2 coating of the strip

we used Geant4 UNIFIED optical model with:

surface finish - polished back painted

type - dielectric-dielectric

$\sigma_\alpha = 1.3^0$ (characterised the roughness of the surface,
polished)

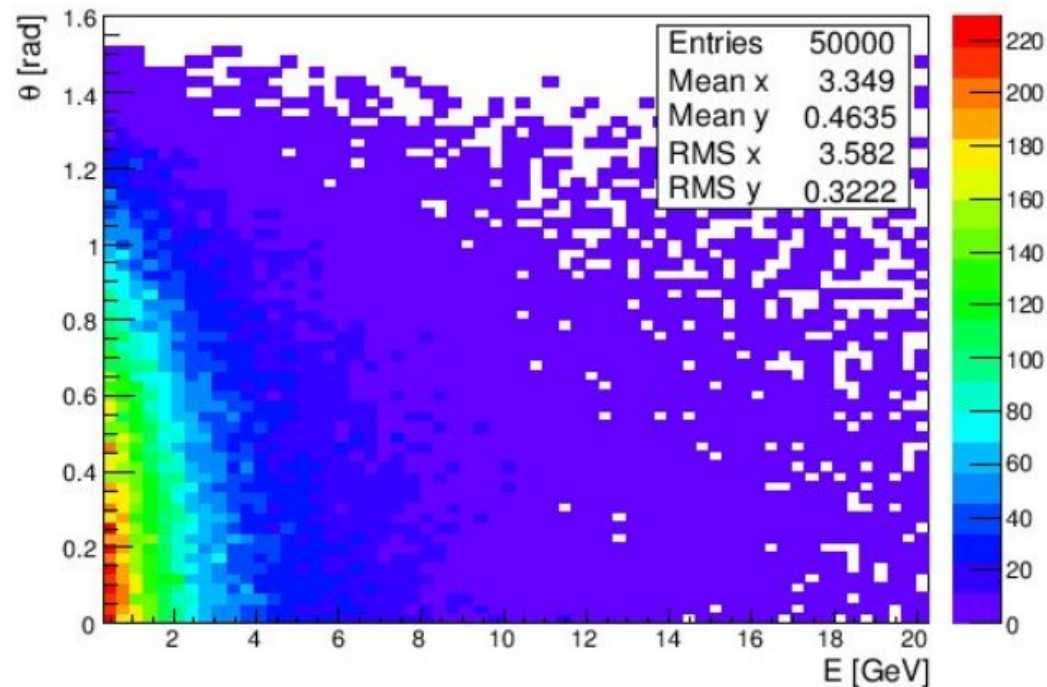
RC = 0.955 (reflection coefficient)

Результаты моделирования приведены в средних значения фотонов.

Переход на фотоэлектроны продемонстрирован на одном из рисунков.

The cosmic muons were used as beam particles. Muons were simulated according

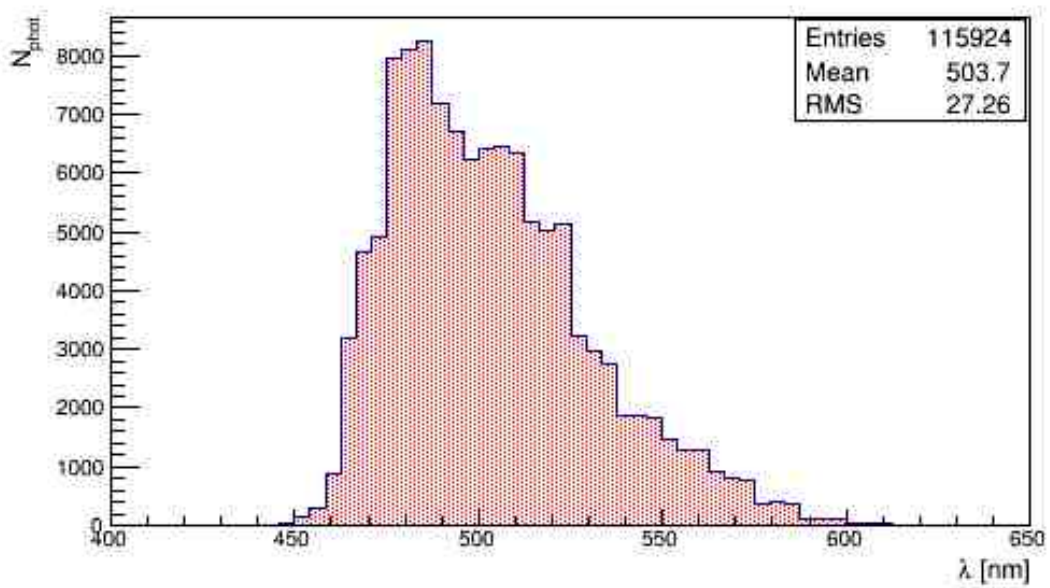
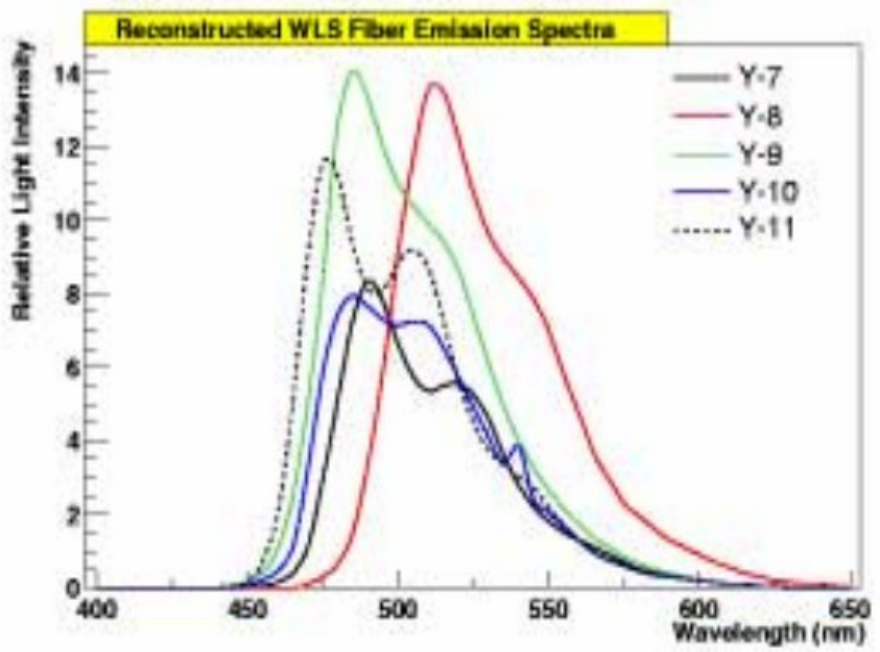
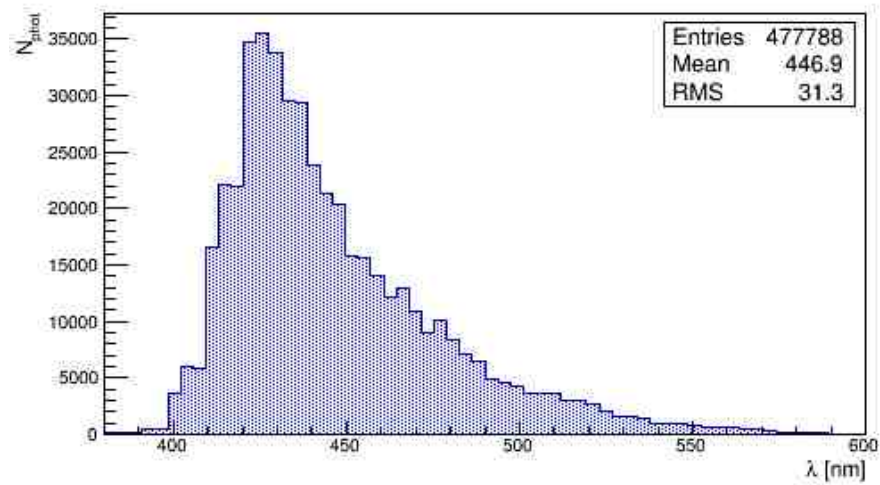
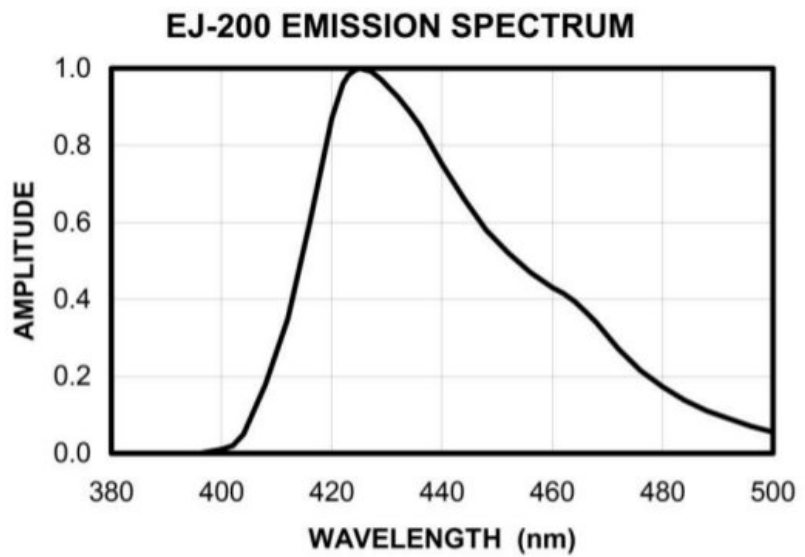
L.N. Volkova et al., Sov.J.Nucl.Phys 29, (1979) 645.



$\langle E \rangle = 3.3$ GeV if E in range 0.3-20 GeV

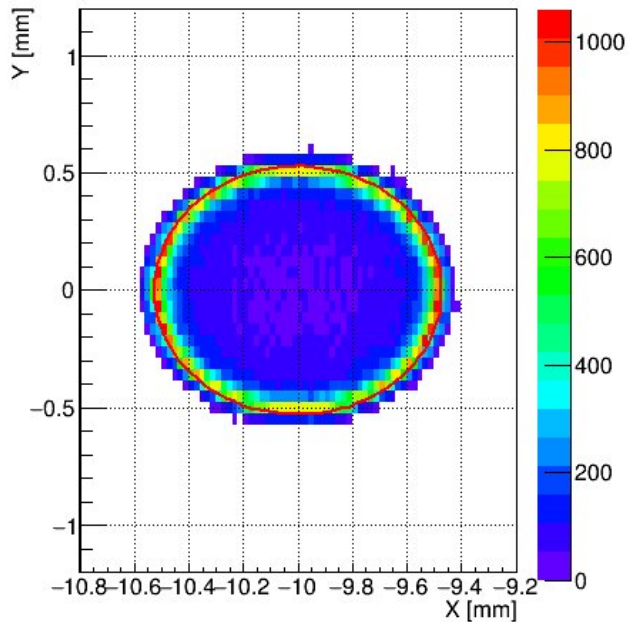
Cosmic muons penetrate into $5 \times 90 \text{ cm}^2$ side of strip at different distance from photodetector end perpendicularly (i.e. muons angular distribution is not used)

Now more realistic emission spectrum for scintillator and fiber are used (Ralf E. suggestion)



The opposite end of the strip is as well covered by TiO_2 And only fiber end is black or mirrored

Bulk attenuation length for fiber core = 5 m

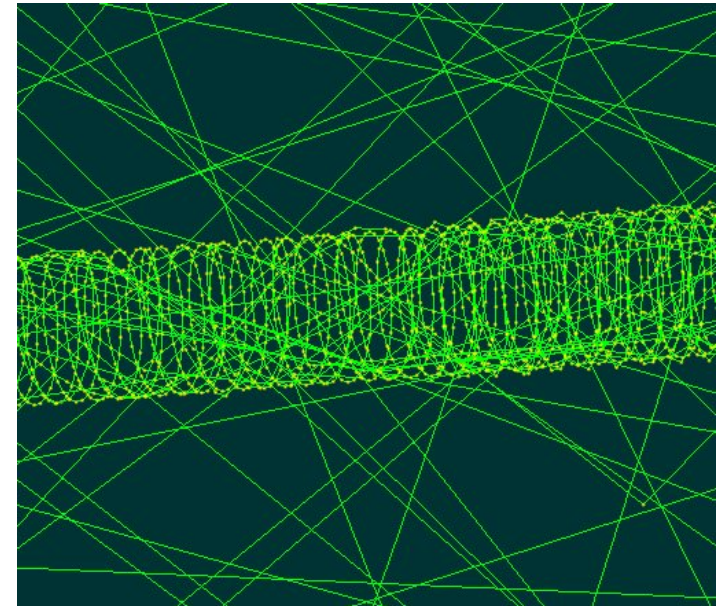


The light intensity increases towards the edge of the fiber core

The reason for this is=>

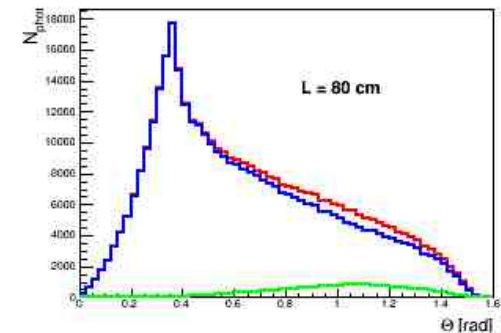
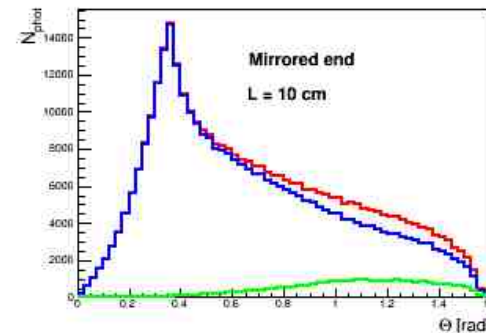
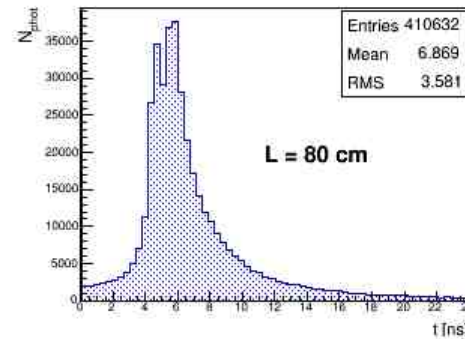
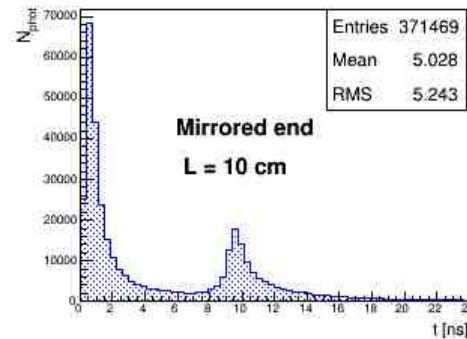
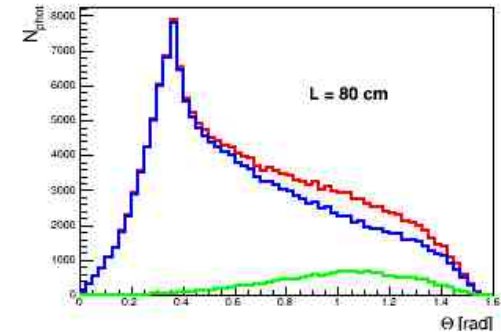
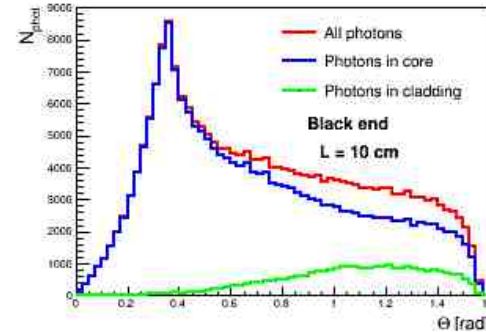
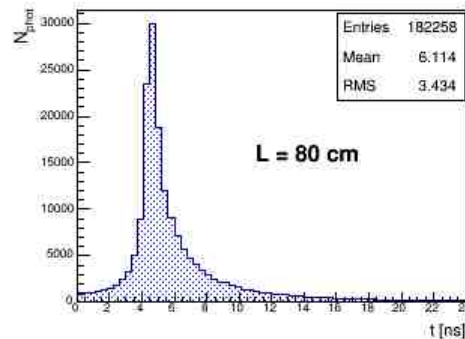
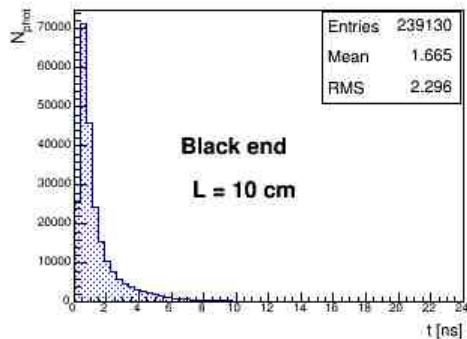
The red circle shows the border of the fiber core

Optical photon trajectory inside a WLS fiber



Clearly visible the circular structure track of photon
(2 events, 0.001ph/eV in scintillator)

Photons arrival time and angular distribution at fiber end



Photon arriving time at the end of fiber

Angular distributions of photons at the fiber end

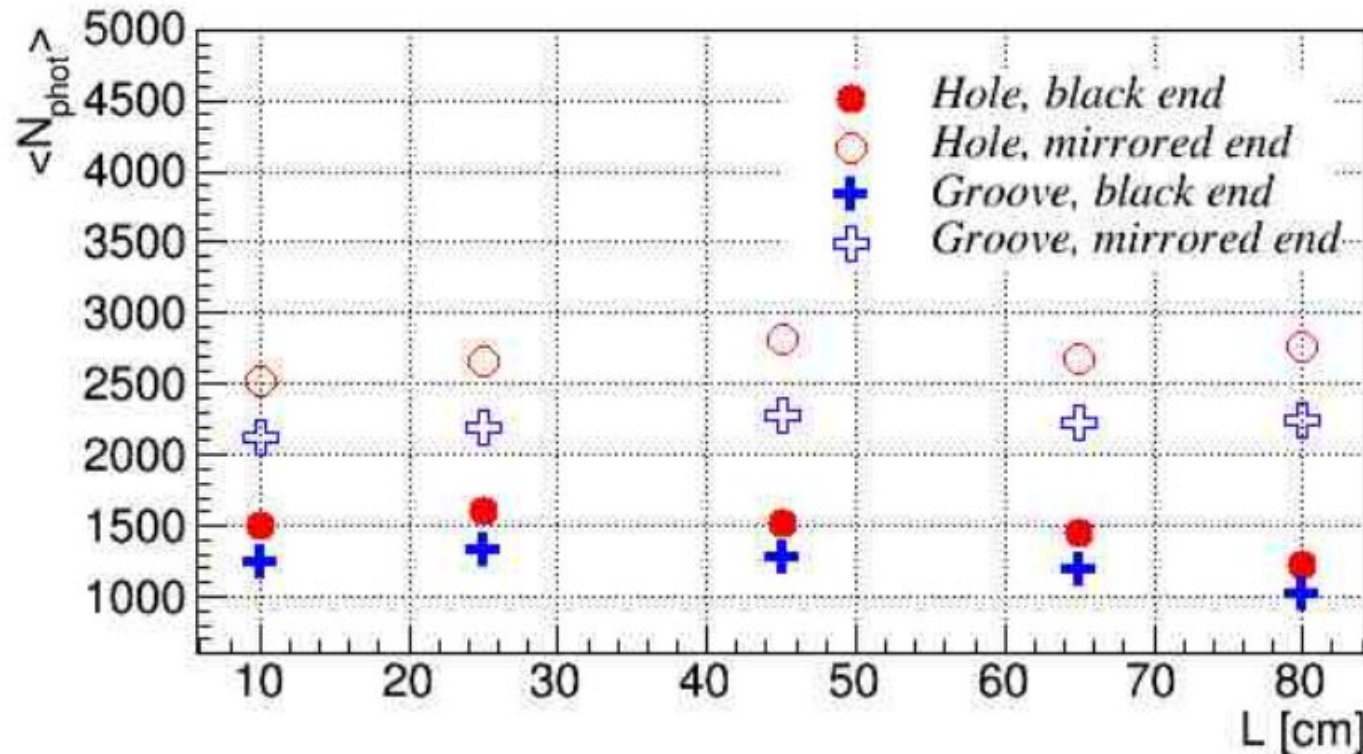
Muons penetrating at the distance 10 and 80 cm from the photodetector end of strip

This is the angle between the axis of the fiber and the photon

For mirrored strip end the signals from direct and reflected photons distinguishable

The most probable angle for photons
In core is $\sim 20^\circ$, in cladding $\sim 69^\circ$

Mean photon yield for fiber embedded in holes and grooves



$$\sum N(\text{hole}) / \sum N(\text{groove}) = 1.21$$

N=150 cosmic muons were simulated for each point in Figure

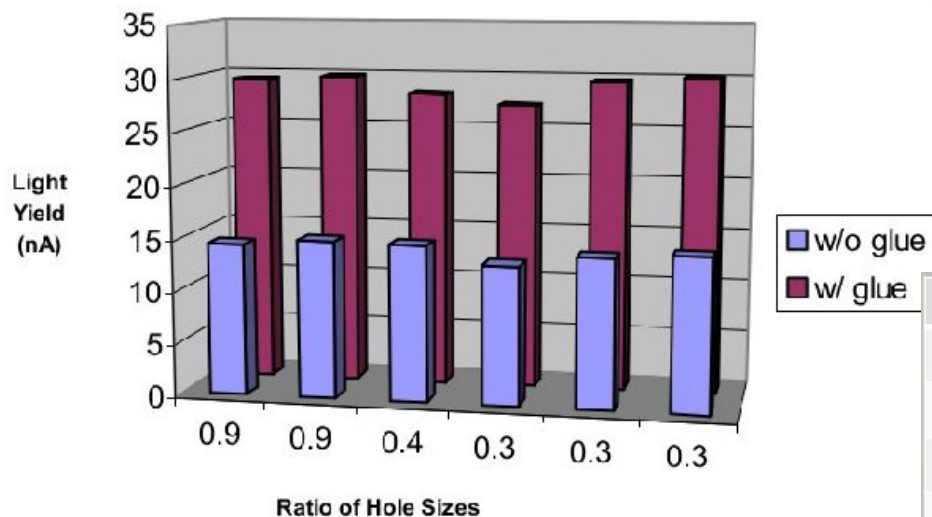
The muons penetrating a single point at a distance of 10, 25, 45, 65, 80 cm from the photodetector end of strip.

For all Figures scintillator bulk attenuation length $\lambda = 250 \text{ cm}$ unless otherwise stated

An indication of usefulness of filling the holes

FERMILAB-NICADD NOTES,
Rykalin et al. Minerva business

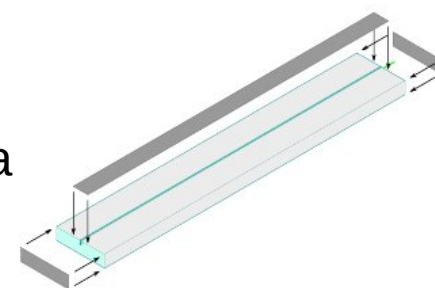
V.Glagolev, CRV Coll. Meeting, April 2015



Distance to PMT (cm)	water	Glycerin	rubber	UV glue
13	27 +/- 11 %		50 +/- 13 %	
23	50 +/- 13%	51 +/- 12 %	46 +/- 14 %	32 +/- 11 %
33	33 +/- 10 %	44 +/- 12 %	53 +/- 12 %	36 +/- 13 %
43	49 +/- 12 %	58 +/- 11 %	34 +/- 10 %	47 +/- 14 %
	<u>40 +/- 6 %</u>	<u>51 +/- 7 %</u>	<u>46 +/- 6 %</u>	<u>38 +/- 7 %</u>

Optical Coupler	Optical Gain		
	⁹⁰ Sr	¹³⁷ Cs	Muons
BC630	1.20 ± 0.01	1.24 ± 0.01	1.38 ± 0.03
EJ550	1.26 ± 0.02	1.23 ± 0.01	1.34 ± 0.01
EJ552	1.15 ± 0.02	1.04 ± 0.02	1.32 ± 0.01
NOA63	1.37 ± 0.02	1.37 ± 0.02	1.45 ± 0.03
NOA68	1.44 ± 0.04	1.44 ± 0.03	1.73 ± 0.03
NOA72	1.16 ± 0.01	1.10 ± 0.01	1.22 ± 0.02
Water	1.43 ± 0.02	1.52 ± 0.02	1.73 ± 0.06

N. Tosi et al
Oktober 9th, 2013, Bologna
1x4.5x200 cm³



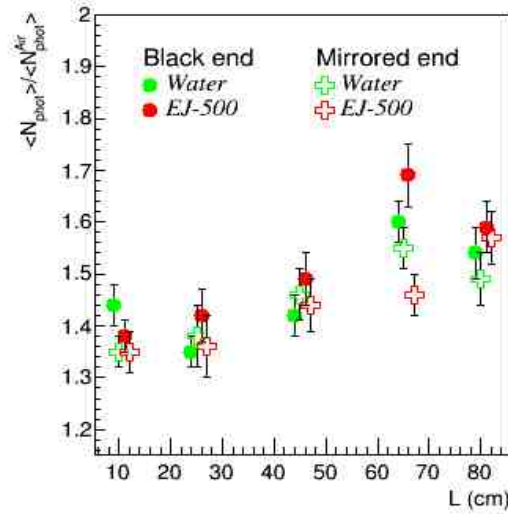
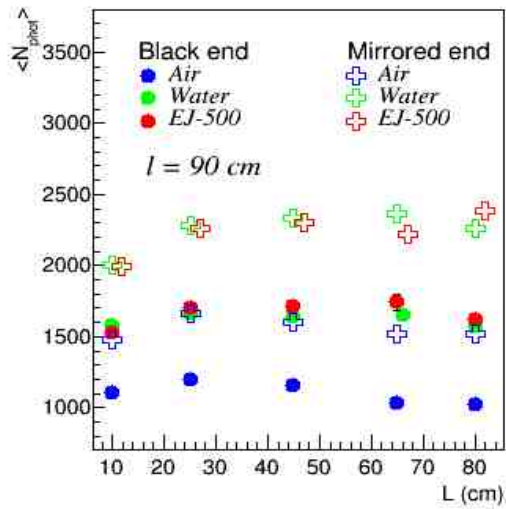
Simulation

Base Configuration	29 pixels/MIP	
Optical Glue only	34 pixels/MIP	+20%
Optical Glue and aluminum tape	48 pixels/MIP	+70%

Measurements are close to these values

K. Moats, Zernam Enterprises Inc,
April 2016

Hole filling influence - simulation



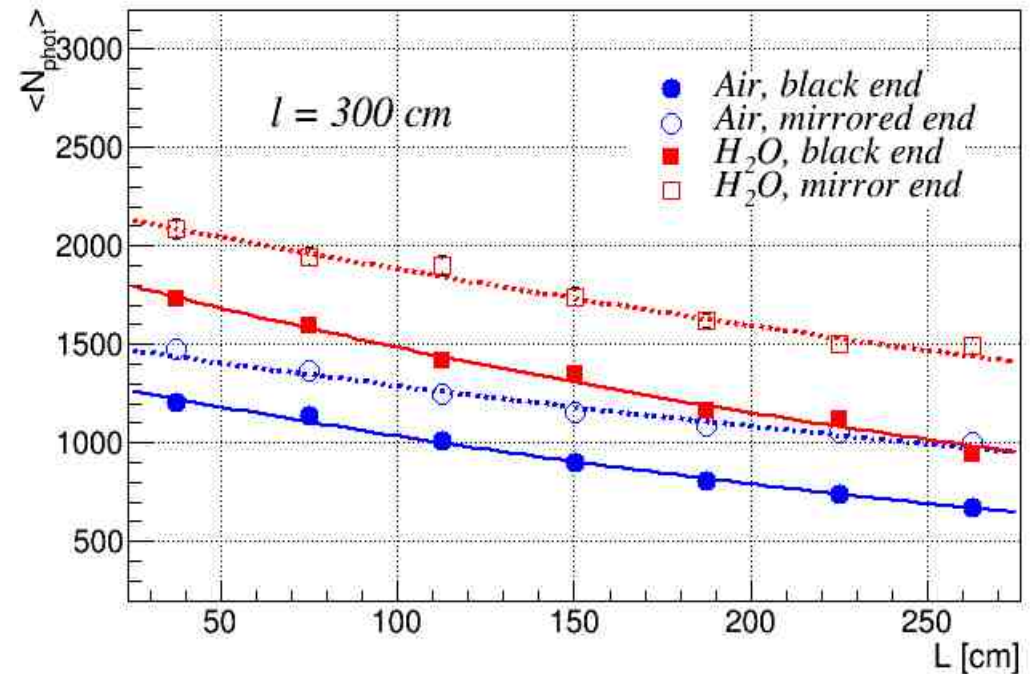
For these Figures the scintillator bulk attenuation length is:

$$\lambda = 250 \text{ cm}$$

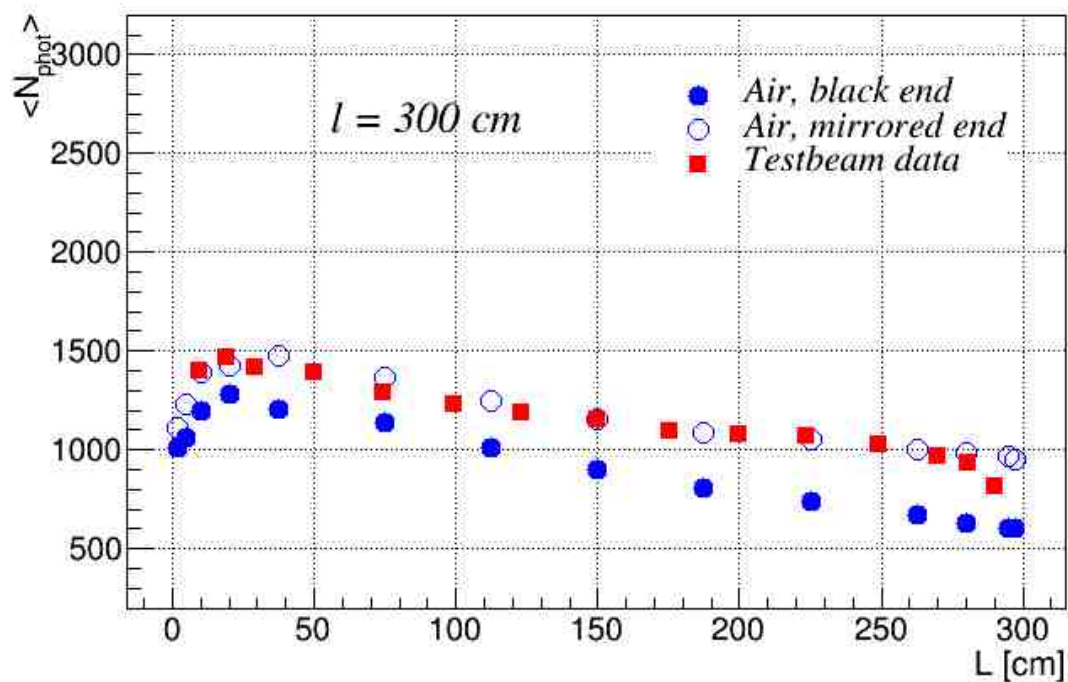
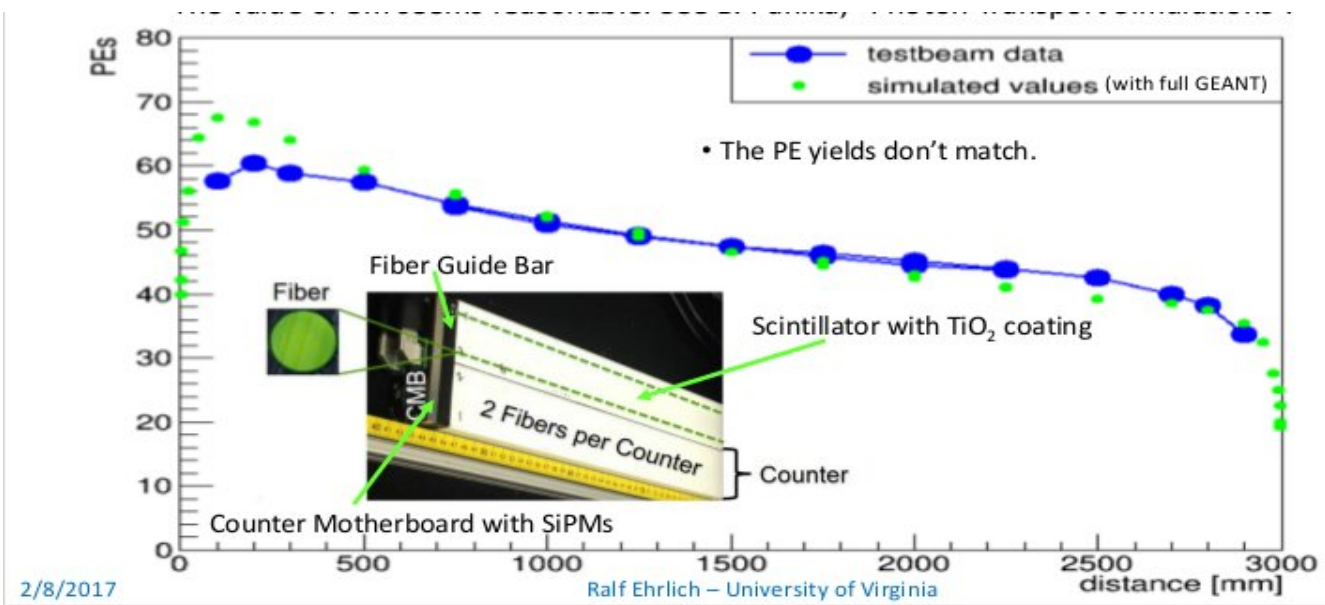
The optical cement and water increase light collection efficiency

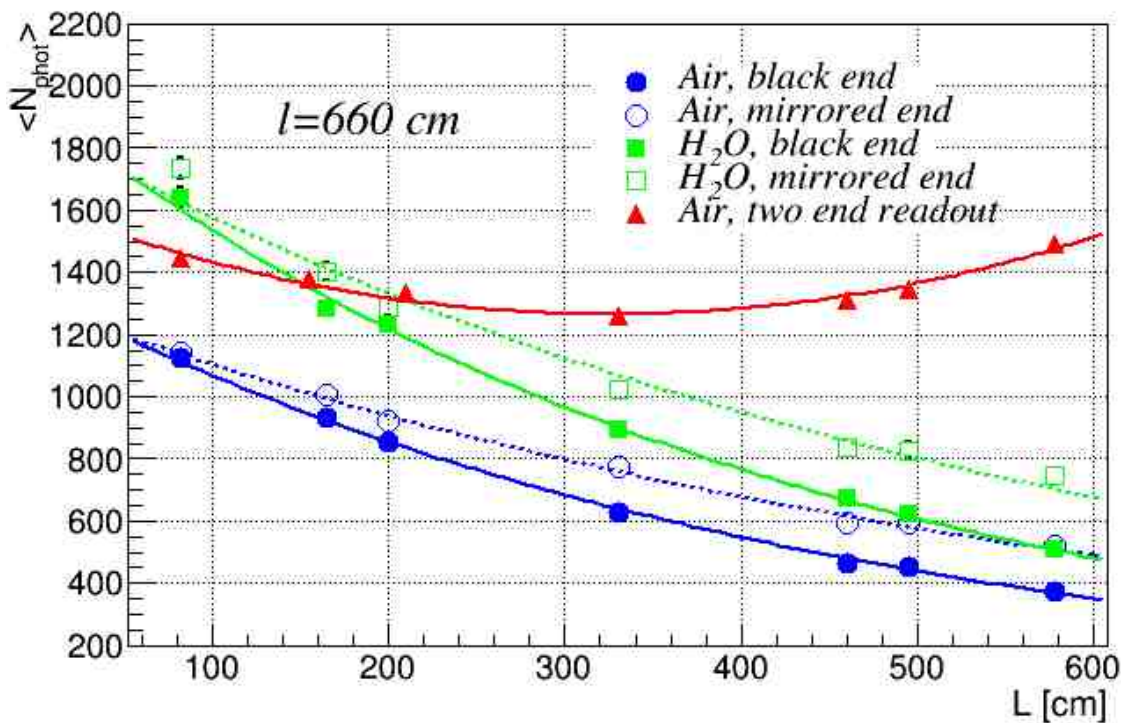
and smooth over different hole quality

For these Figures **N=300**



Сравнение тест-бим измерений в ун-те Вирджинии с моделированием





$$\lambda = 450 \pm 10 \text{ cm}$$

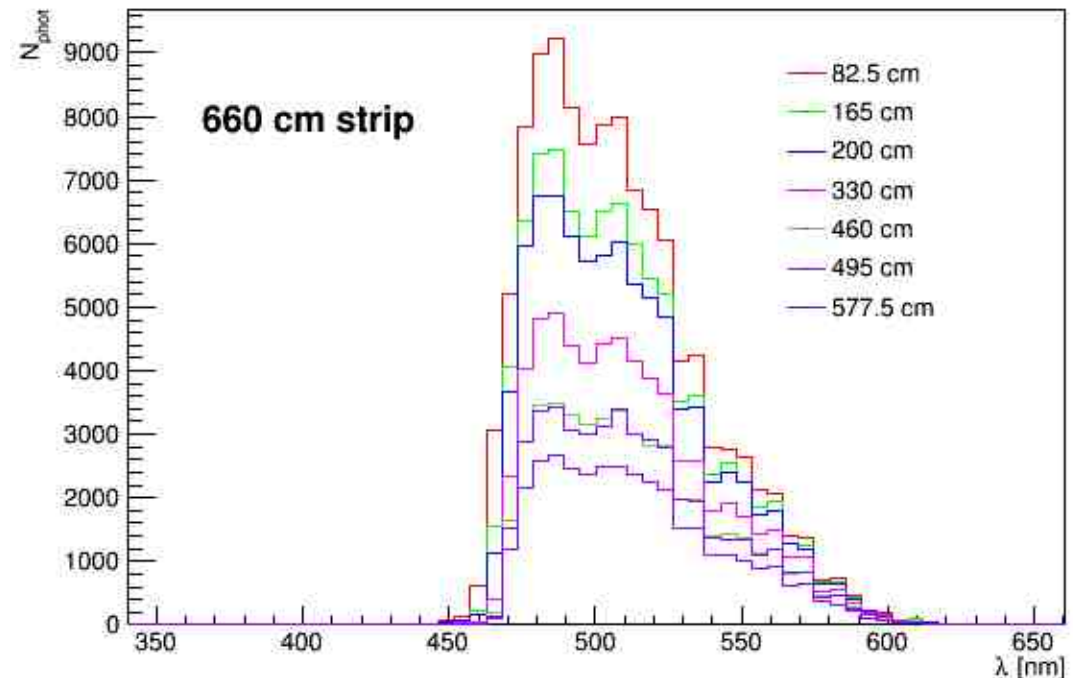
$$\lambda = 615 \pm 20 \text{ cm}$$

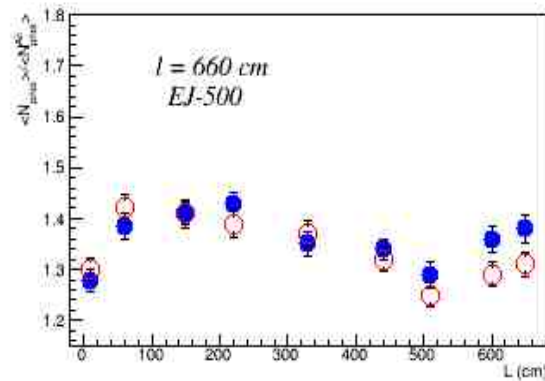
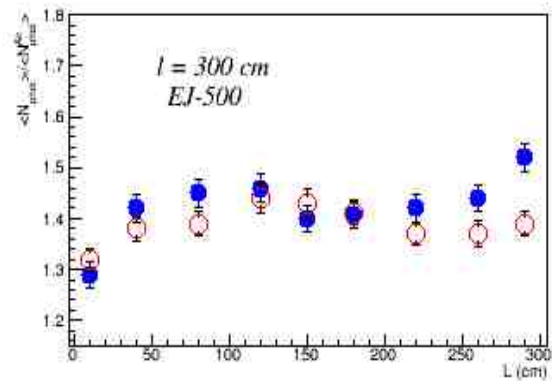
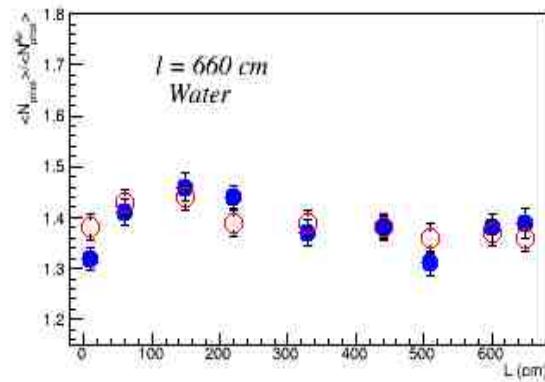
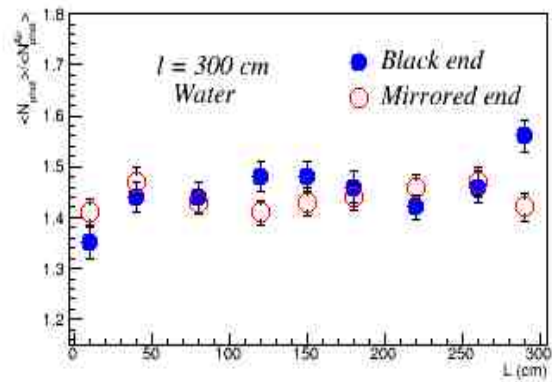
$$\lambda = 431 \pm 9 \text{ cm}$$

$$\lambda = 592 \pm 18 \text{ cm}$$

points correspond to readout from both strip ends

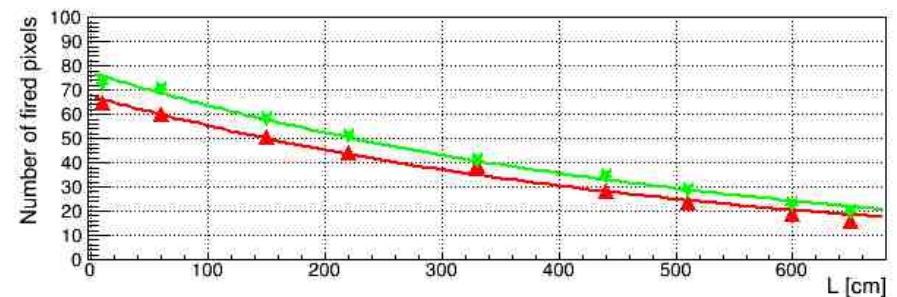
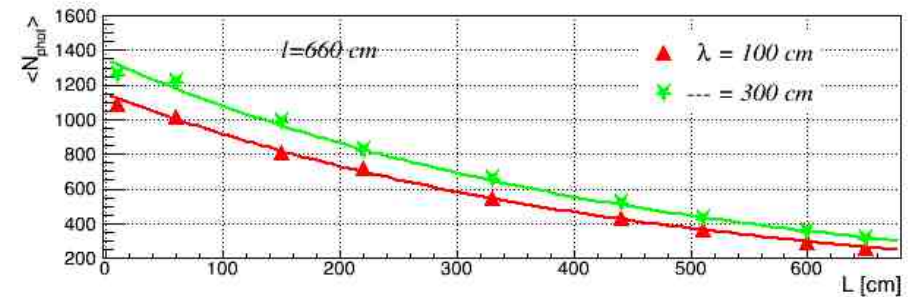
Spectrum of light exiting WLS fiber embedded in 660 cm strip when cosmic muons impinge at distance 82.5 to 575.5 cm from the photodetector end





Влияние вещества заполнения
отверстий в длинных сцинтилляторе
на эффективность сбора фотонов

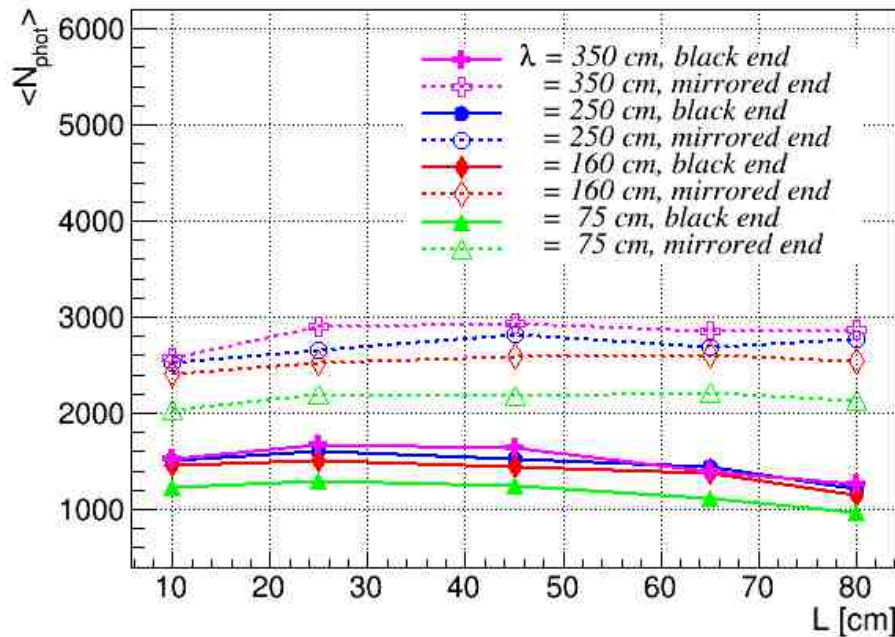
Фотоны были пересчитаны на
фотоэлектроны с использованием
программы GosSiP



P. Eckert et al.,
JINST 7, 2012,
P08011

Использовались характеристики
S10362-11-050C

Mean photon yield



for different scintillator attenuation length

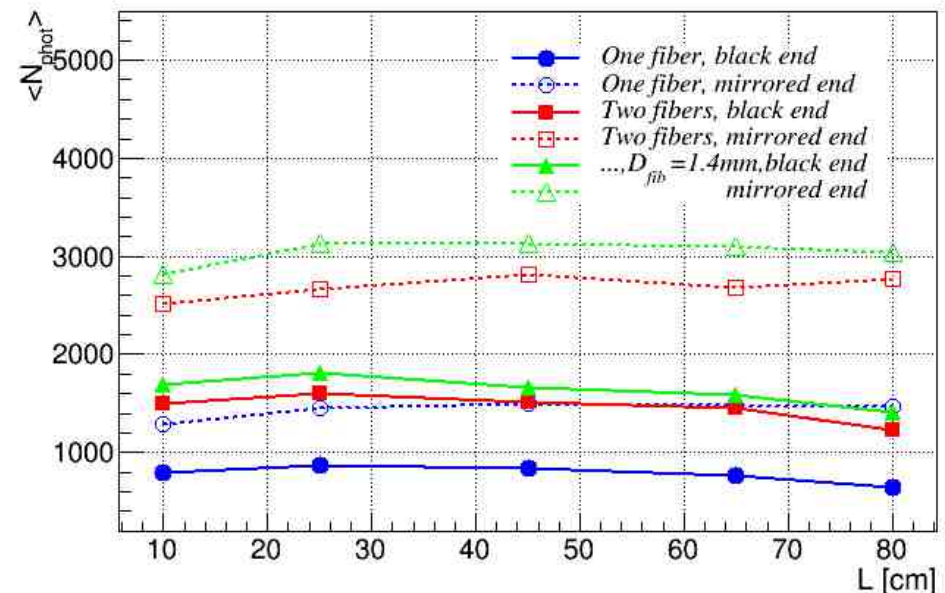
λ is bulk attenuation length !

N = 150

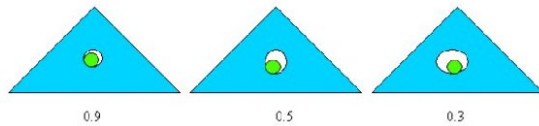
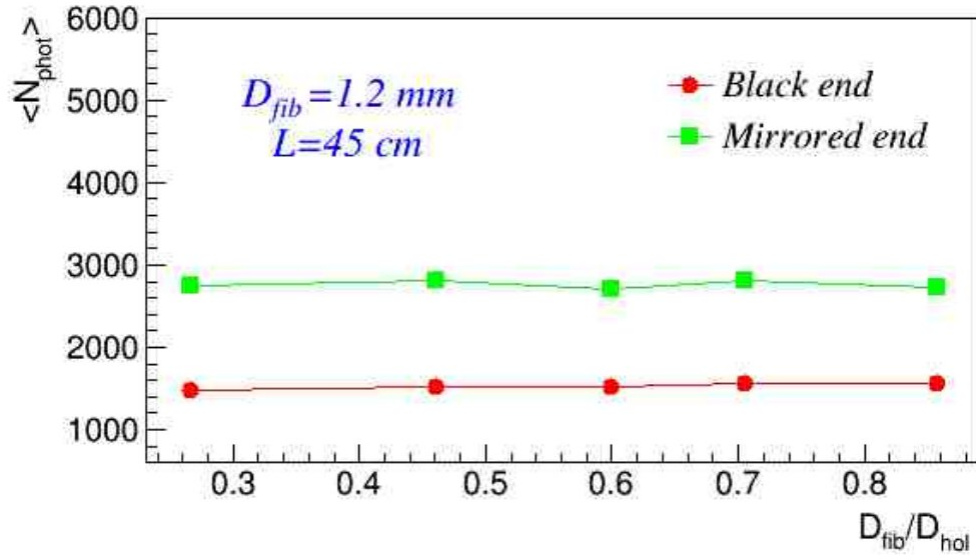
and different fiber size and fiber numbers

$$\sum N(2_{\text{fib}}) / \sum N(1_{\text{fib}}) = 1.87$$

$$\sum N(D_f = 1.4 \text{ mm}) / \sum N(D_f = 1.2 \text{ mm}) = 1.12$$



Hole size impact on photon yield



A la NICADD study

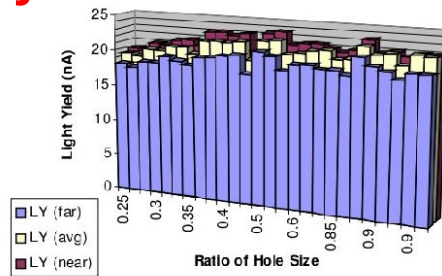
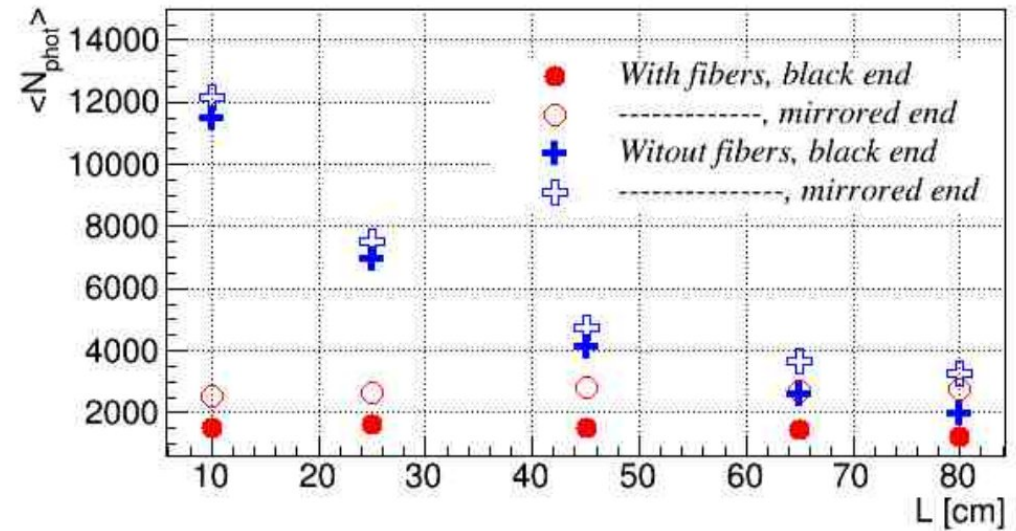


FIGURE 5. Effect on Light Yield due to the Hole Sizes

Photons from whole strip end



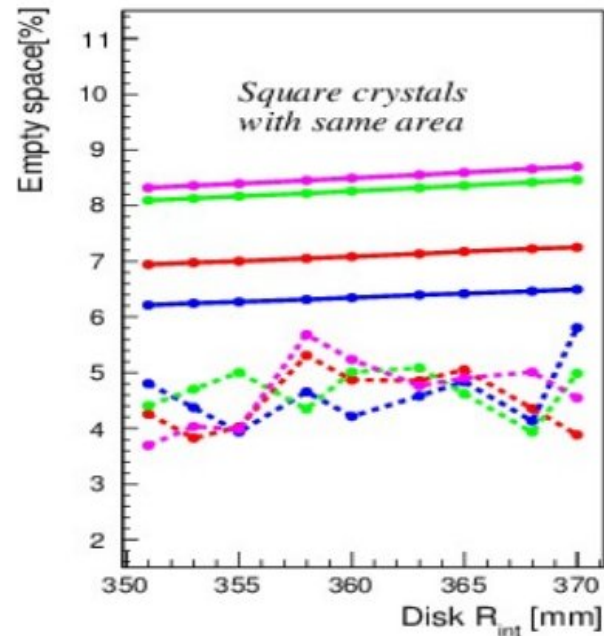
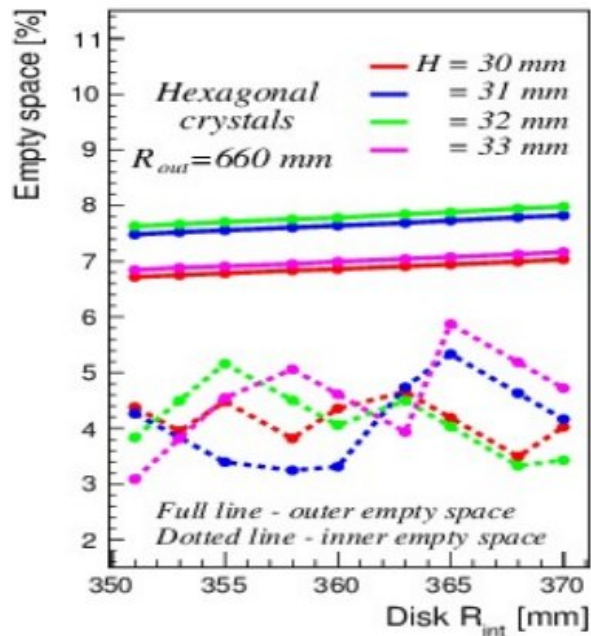
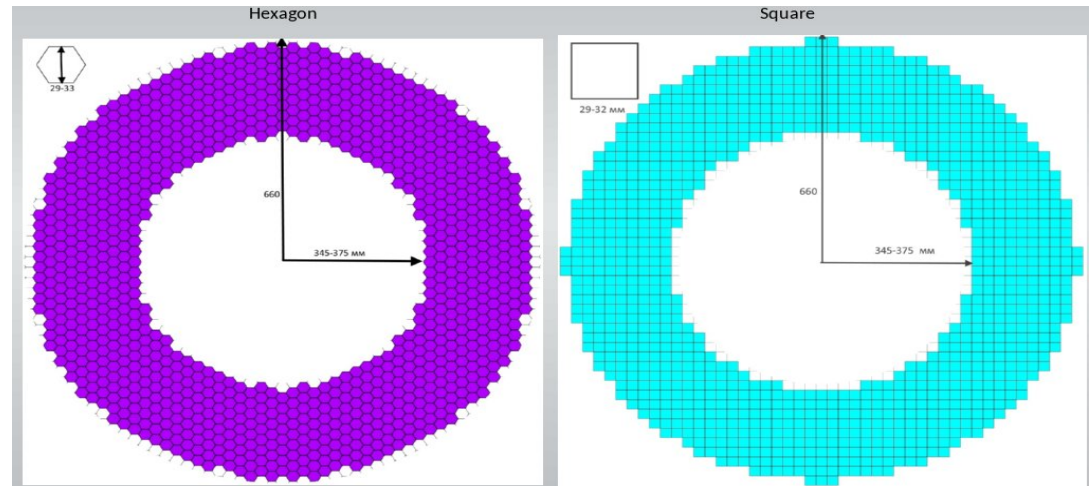
N = 150

$$\sum N(\text{Full end}) / \sum N(2\text{Fibers})$$

= 3,7 (black end)

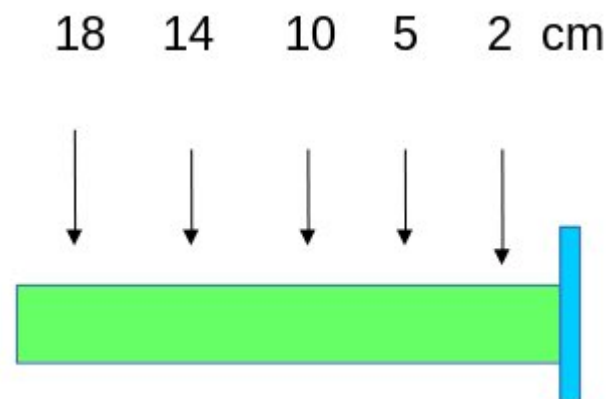
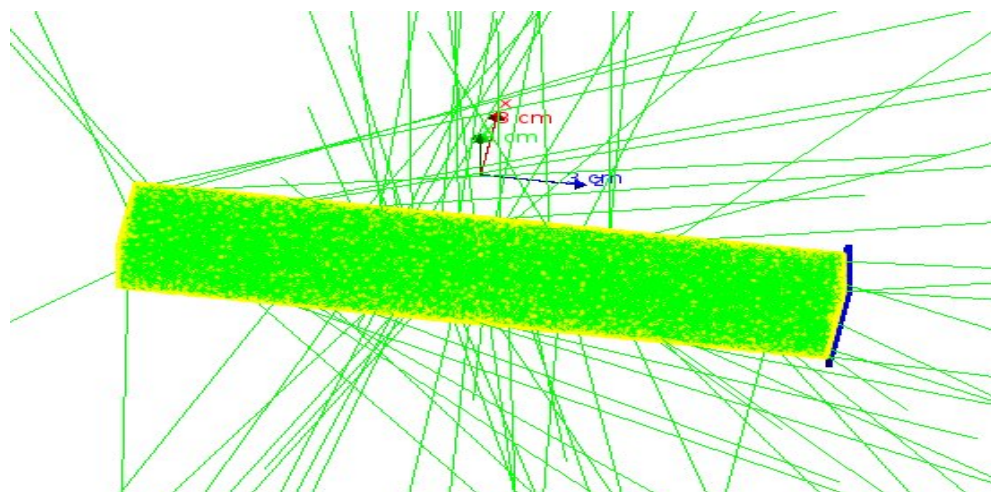
= 2.3 (mirrored end)

Компановка калориметра из кристаллов с гексогональной и квадратной сечениями



Распределение оптических фотонов на торце кристаллов

Размер кристалла 3x3x20 см**3

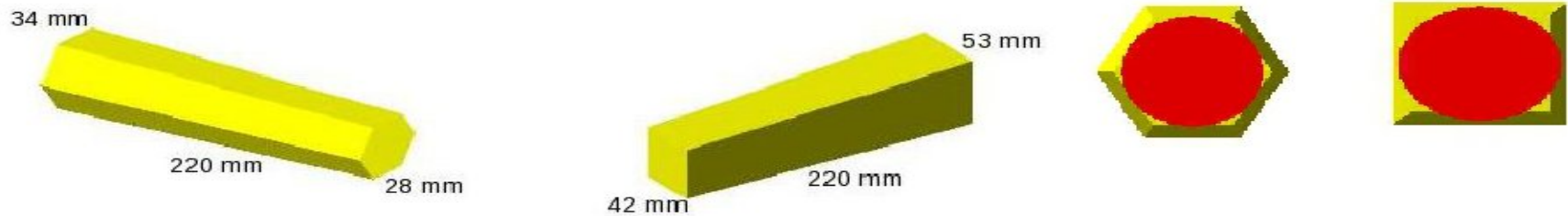


Фотоны собирались со всей
3x3 см**2 поверхности

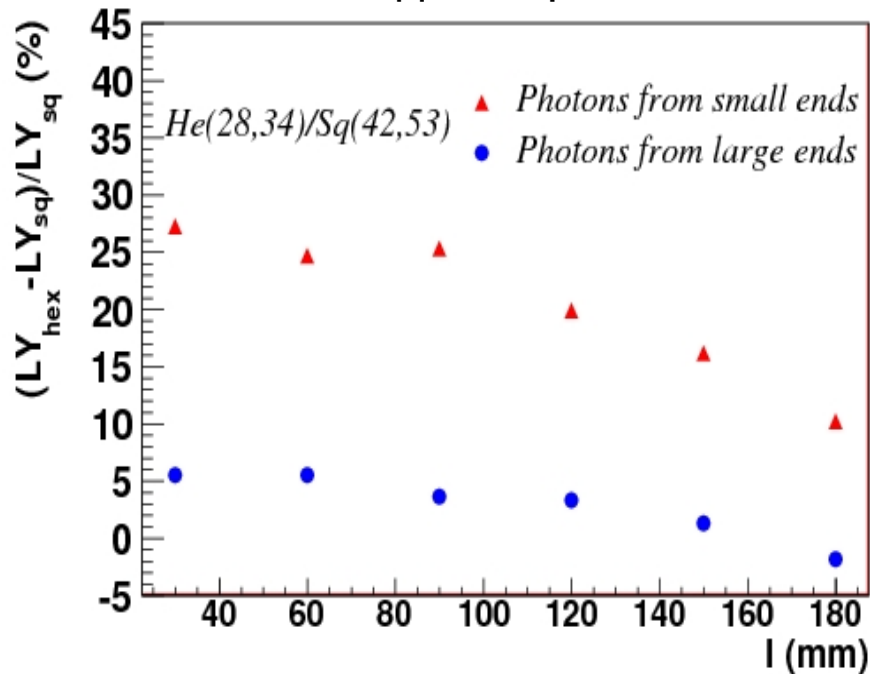
Относительный световыход кристаллов с гексогональной и квадратной сечениями

Цель данного исследования – преимущество гексогональной формв кристаллов незначительна

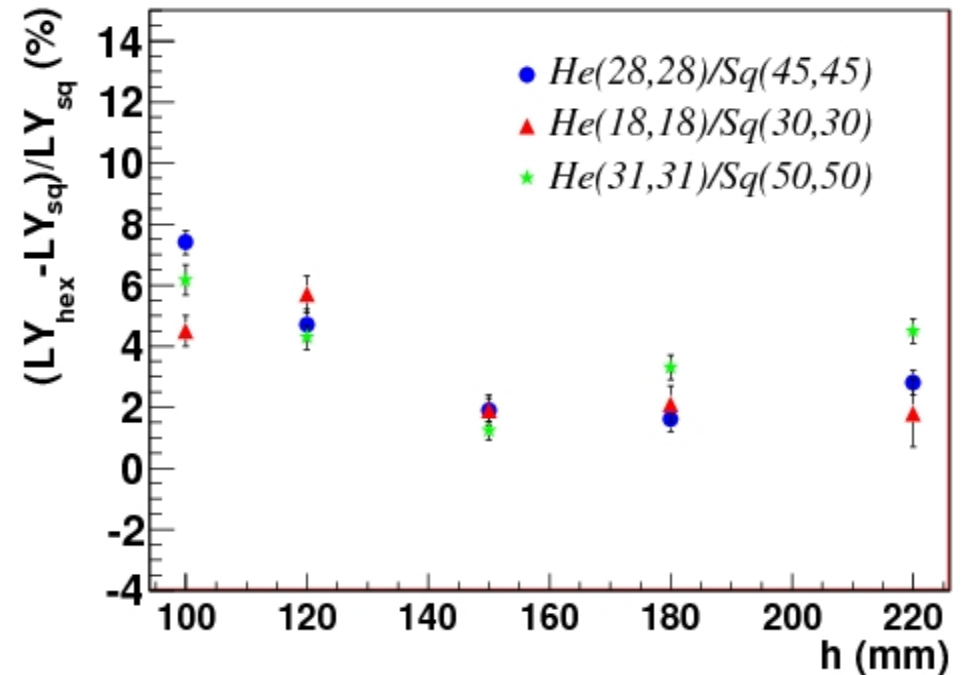
Two CsI crystals was used



Клиновидные кристаллы



Кристаллы неклиновидной формы



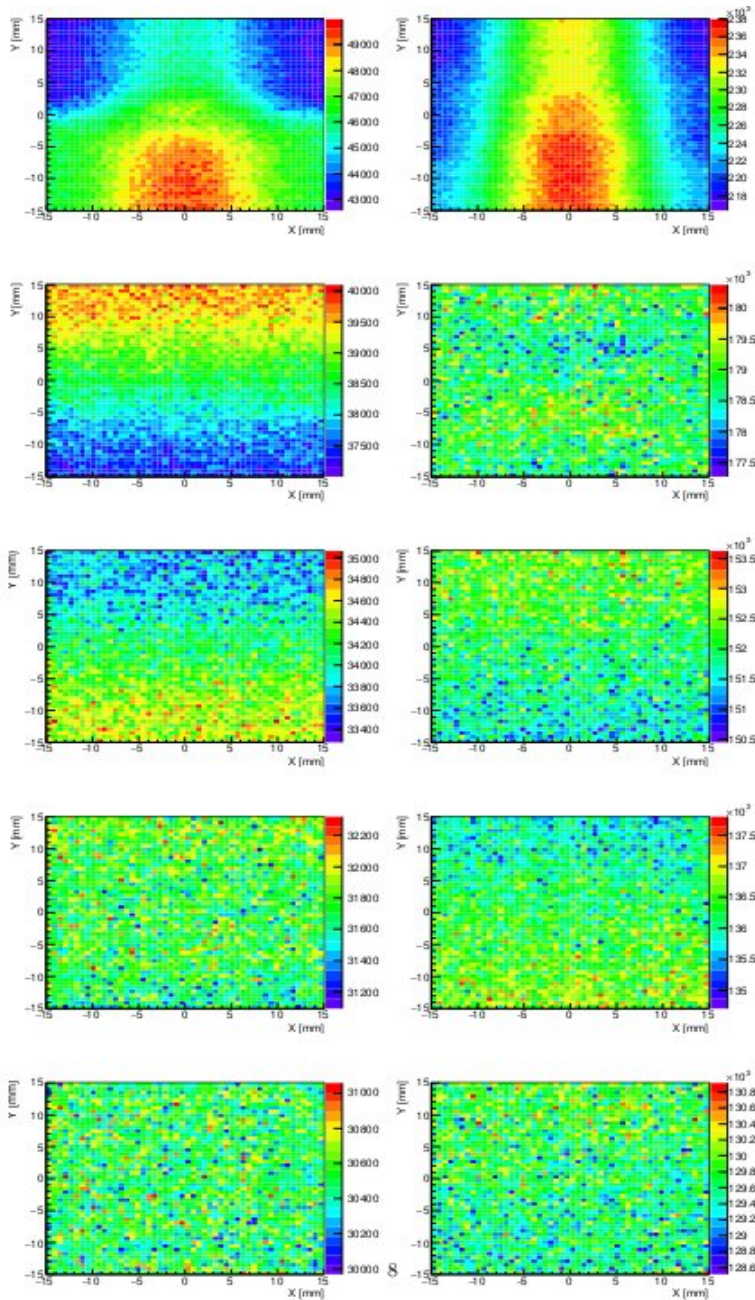


Figure 2: XY plot for optical photons that reached the photodetector side of the polished CsI (left column) and BaF₂ (right column) crystals with diffuse wrapping. Cosmic muons impinge perpendicularly to lateral side at a distance from the photodetector side of 1 = 2, 6, 10, 14, and 18 cm (rows from top to bottom) in -Y direction.

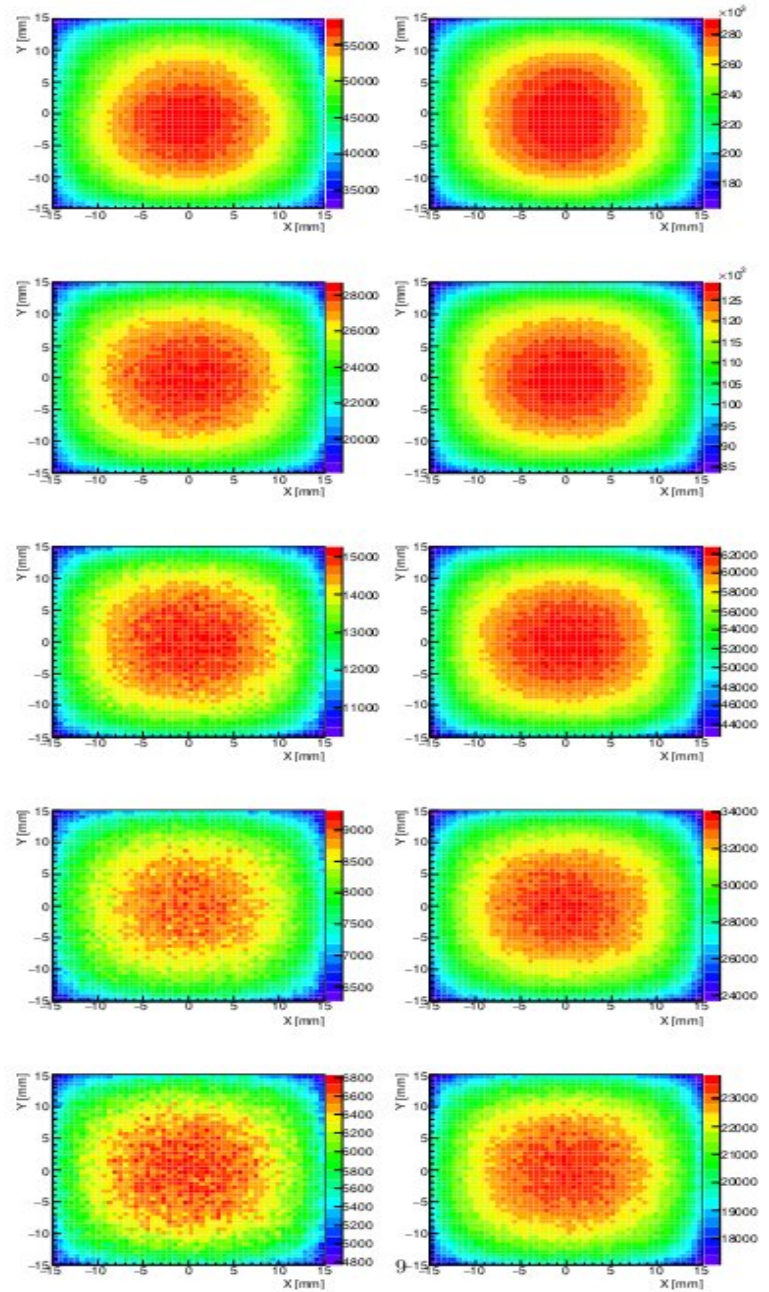


Figure 3: Same as in Figure 1, but for the ground crystal surfaces.

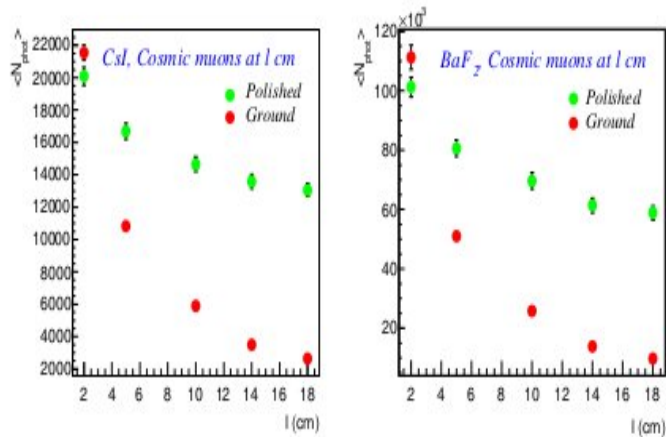


Figure 4: The mean value of the Gaussian fit of the number of optical photons arriving at the photodetector side of the CsI (left panel) and BaF₂ (right panel) crystals as a function of the distance from the cosmic muon impinging point.

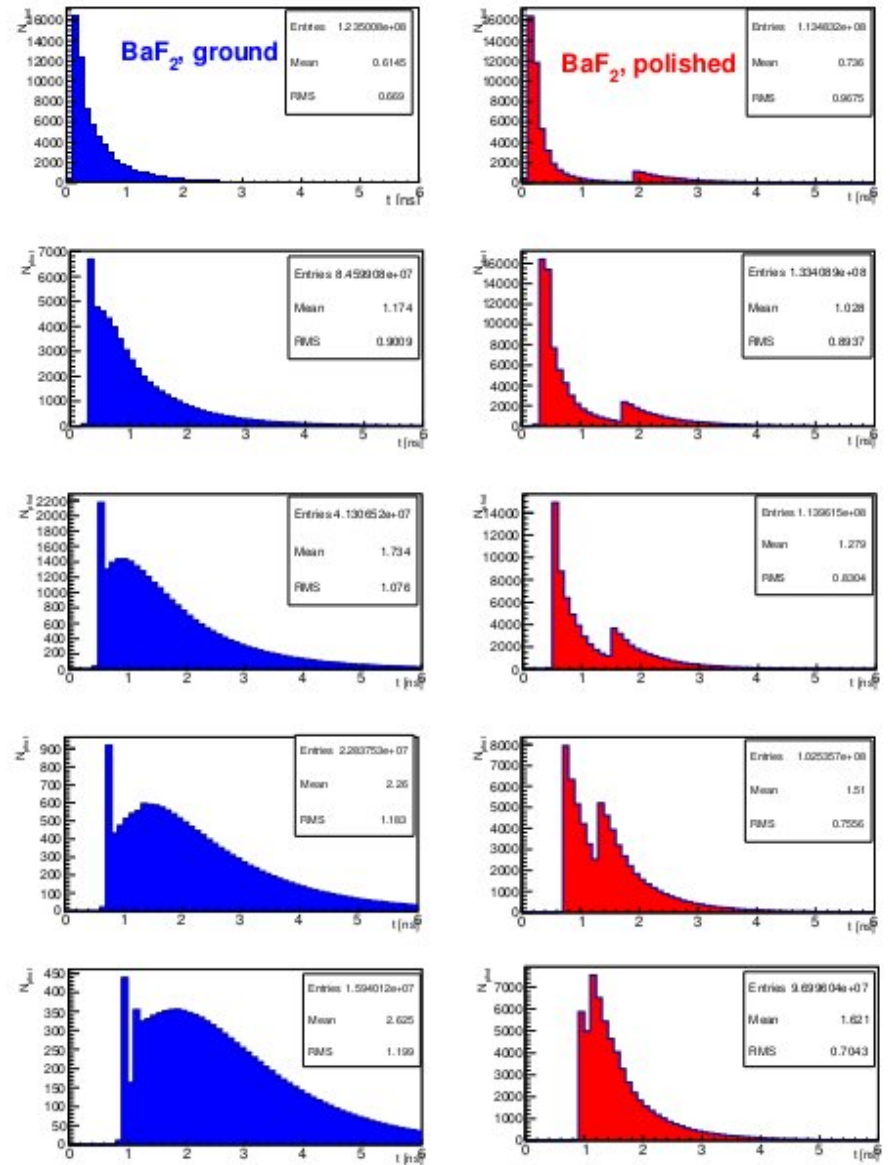
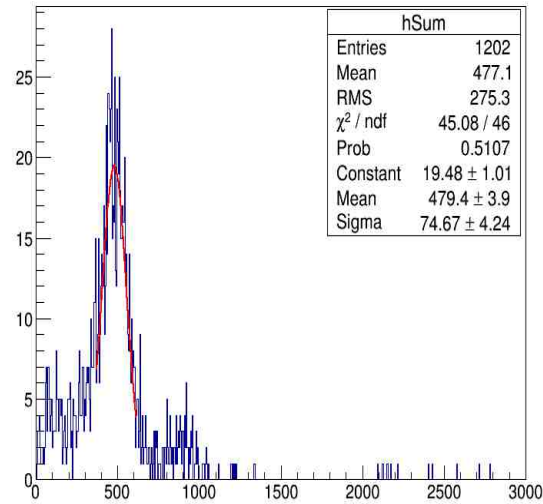


Figure 8: Optical photon arrival time at the photodetector side of the polished (right column) and ground (left column) BaF₂ crystals. Cosmic muons impinge perpendicularly to the lateral side at a distance of $l = 2, 6, 10, 14,$ and 18 cm (rows from top to bottom) from the photodetector side in -Y direction.

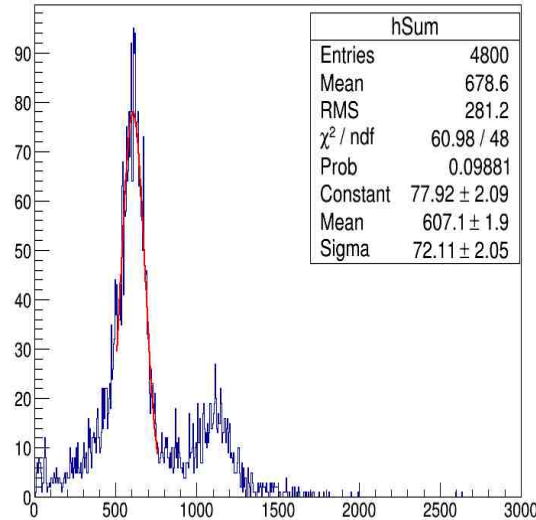
Тест-бим измерения в Ереване (предварительный анализ)

Суммарное энерговыделение в 9-ти кристаллах при разных энергиях электронного пучка (измерения)

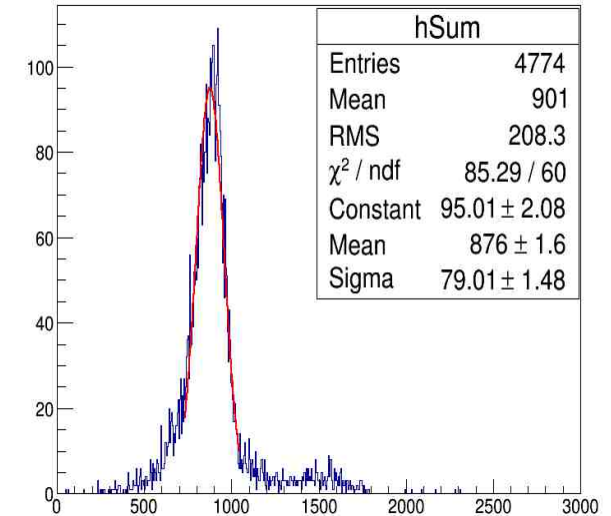
SUM 15MeV



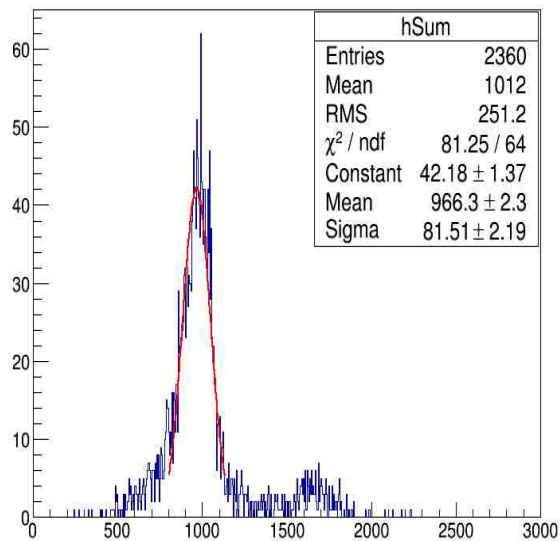
SUM 20MeV



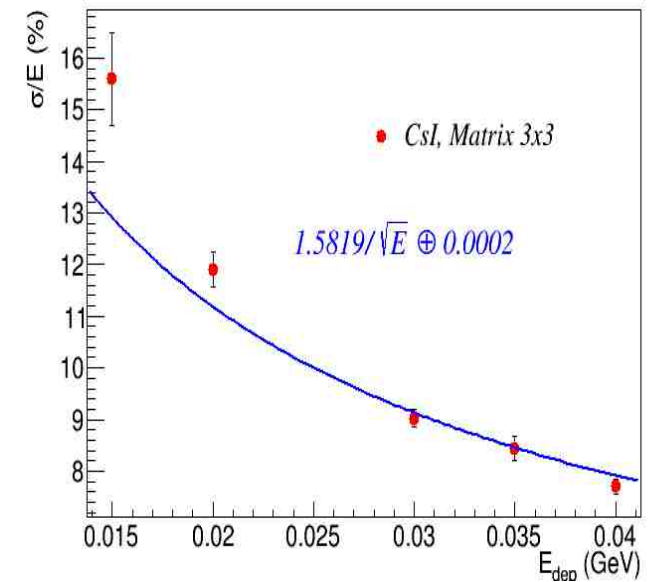
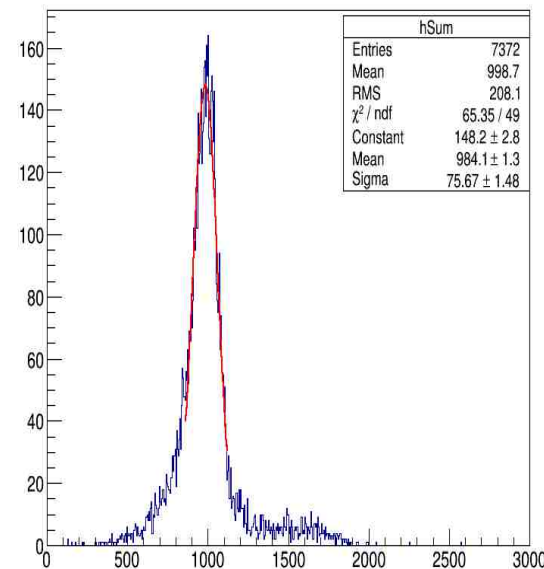
SUM 30MeV



SUM 35MeV



SUM 40MeV



Тест-бим измерения в Фраскати (матрица 3x3, CsI, электронный пучок и космика)

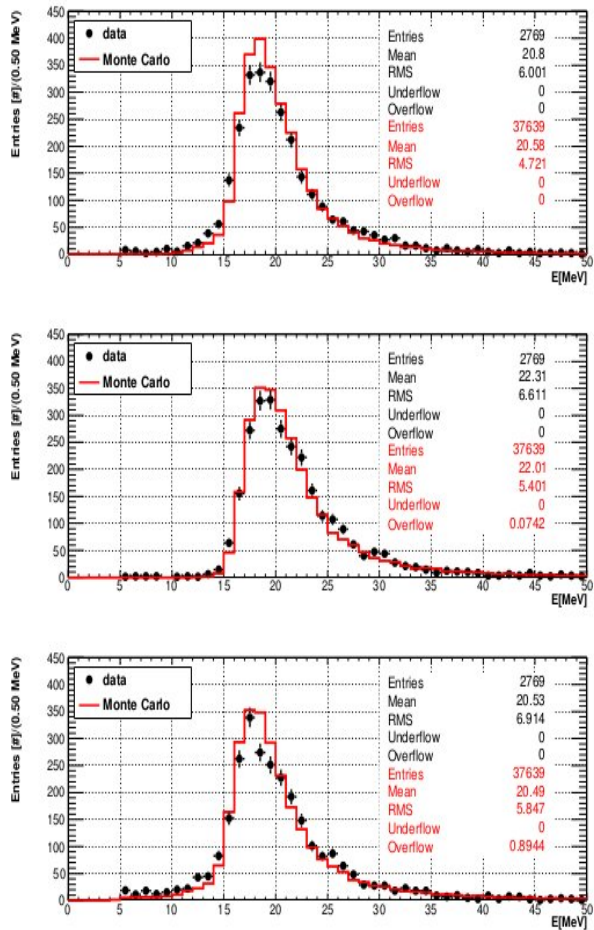


Figure 9: Distributions of the crystal energy for the prototype central column after MIP selection. MC distributions are superimposed.

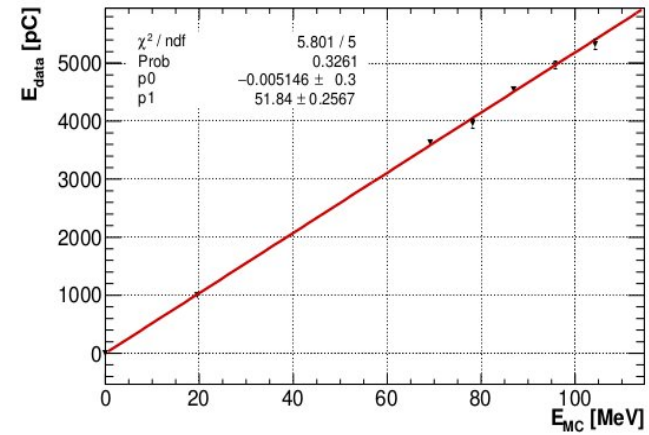


Figure 13: Reconstructed total charge of the prototype in the calibration runs as a function of E_{dep} with the constrain to pass trough the axis origin.

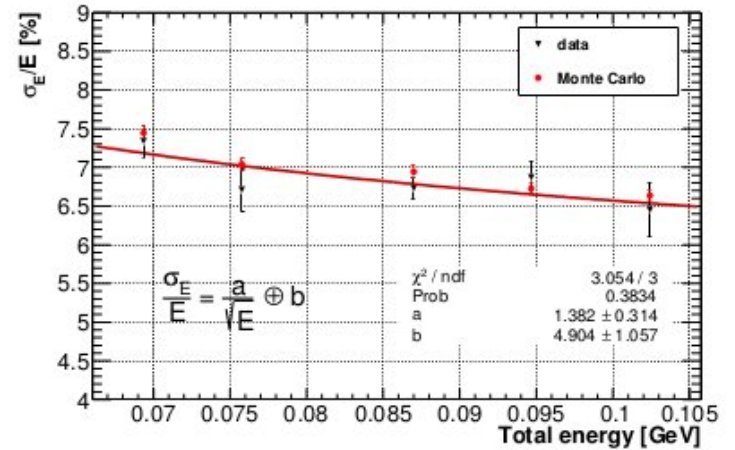


Figure 15: Energy resolution from data (black) compared with Monte Carlo (red).

Заключение и опубликованные работы

При помощи Geant4 10.3.1 смоделированы оптические фотоны с сцинтилляторных пластинах различной длины и кристаллах BaF2 и CsI. В пластины были вложены сспекторосмещающие оптические волокна.

На количество оптических фотонов было исследовано влияния:
расположения волокон, заполнения отверстий в сцинтилляторах,
длины затухания света в сцинтилляторах, диаметр оптических волокон
и отверстий в сцинтиляторе.

Исследовано распределение интенсивности света в поперечном сечении оптического волокна

Проведен анализ заполнения дисков электромагнитного калориметра кристаллами с квадратным и гексогональным сечениями и доли незаполненных участков дисков. Изучено затухание света в кристаллах BaF2 и CsI и распределение фотонов на торцах кристаллов.

Моделирование и анализ тест-бим измерений привели к согласованным результатам. Эти данные позволяют быть уверенным в выборе кристаллов CsI для калориметра эксперимента Mu2e.

Опубликованные работы за отчетный период 2012-2017 гг.

1. Measurement of the energy and time resolution of a undoped CsI + MPPS array for the Mu2e experiment, O. Atanov et al., [JINST 12 \(2017\) no.05, P05007](#).
 2. The calorimeter of the Mu2e experiment at Fermilab, O. Atanova et al., [JINST 12 \(2017\) no.01, C01061](#).
 3. Design, status and test of the Mu2e crystal calorimeter, M. Martini et al., [FERMILAB-CONF-16-274-PPD, arXiv: 1606.05448](#).
 4. Design and status of the Mu2e electromagnetic calorimeter, N. Atanov et al., [Nucl.Instr.Meth. A824 \(2016\) 695-698](#).
 5. Scintillation light simulation in big-sized BaF2 and pure CsI crystals, Z. Usubov, [arXiv:1604.00827](#).
 6. Responce of LYSO:Ce scintillation crystals to low energy gamma-rays, K.G. Afanaciev et al., [Phys.Part.Nucl.Lett. 12 \(2015\) no.2, 319-324](#).
 7. Mu2e Technical Design Report, L. Bartoszek et al., [FERMILAB-TM-2594, FERMILAB-DESIGN-2014-01, arXiv:1501.05241](#).
 8. Light output simulation of LYSO single crystal, Z.U. Usubov, [arXiv:1305.3010](#).
 9. Electromagnetic calorimeter simulation for future mu->e conversion experiment, Z.U. Usubov, [arXiv:1212.4322](#).
- [Доклады и ноты эксперимента Mu2e](#): Mu2e-doc-4739, Mu2e-doc-5238, Mu2e-doc-5796, Mu2e-doc-7148.

Спасибо за внимание !

Back up

Optical photons

Slides from [G.Santin](#) presentation:
adopted from tutorials by [Peter Gumplinger](#)

- Physically optical photons should be covered by the electromagnetic category, but
 - optical photon wavelength is \gg atomic spacing
 - treated as waves \rightarrow no smooth transition between optical and gamma particle classes
- G4OpticalPhoton: wave like nature of EM radiation
- **G4OpticalPhoton \Leftrightarrow G4Gamma**
 - New particle type
 - No smooth transition

- Optical photons are produced by the following Geant4 processes:
 - **G4Cerenkov**
 - **G4Scintillation**
 - **G4TransitionRadiation**

- Classes located in **processes/electromagnetic/xrays**

- Warning: these processes generate optical photons **without energy conservation**

- Optical photons undergo:
 - bulk absorption
 - Rayleigh scattering
 - wavelength shifting
 - refraction and reflection at medium boundaries

Optical properties associated to G4Material

- Optical properties can be specified as properties table in G4Material
 - reflectivity, transmission efficiency, dielectric constants, surface properties
- Photon spectrum properties also defined in G4Material
 - scintillation yield, time structure (fast, slow components)
- Properties are expressed as a function of the photon's momentum
- New: Some of the properties previously part of the optical processes are now part of the G4MaterialPropertiesTable

В рамках Geant4 реализованы 3 оптические модели

Glisur, Unified, LUT (look-at-table)

(OpSurface->SetModel(1 или 2, или 3);)

LUT модель задается таблицами и выполнена пока только для
BGO кристалла

Граница сред, обработка поверхности и обертка кристалла
задаются соответствующими командами

OpSurface->SetType(dielectric-dielectric);
OpSurface->SetFinish(ground or polished or)

Example 5.10. Dielectric metal surface properties defined via the G4OpticalSurface.

```
G4LogicalVolume* volume_log;

G4OpticalSurface* OpSurface = new G4OpticalSurface("name");

G4LogicalSkinSurface* Surface = new
  G4LogicalSkinSurface("name", volume_log, OpSurface);

OpSurface -> SetType(dielectric_metal);
OpSurface -> SetFinish(ground);
OpSurface -> SetModel(glisur);

G4double polish = 0.8;

G4MaterialPropertiesTable *OpSurfaceProperty = new G4MaterialPropertiesTable();

OpSurfaceProperty -> AddProperty("REFLECTIVITY", pp, reflectivity, NUM);
OpSurfaceProperty -> AddProperty("EFFICIENCY", pp, efficiency, NUM);

OpSurface -> SetMaterialPropertiesTable(OpSurfaceProperty);
```

```
const G4int NUM = 2;

G4double pp[NUM] = {2.038*eV, 4.144*eV};
G4double specularlobe[NUM] = {0.3, 0.3};
G4double specularspike[NUM] = {0.2, 0.2};
G4double backscatter[NUM] = {0.1, 0.1};
G4double rindex[NUM] = {1.35, 1.40};
G4double reflectivity[NUM] = {0.3, 0.5};
G4double efficiency[NUM] = {0.8, 0.1};

G4MaterialPropertiesTable* SMPT = new G4MaterialPropertiesTable();

SMPT -> AddProperty("RINDEX", pp, rindex, NUM);
SMPT -> AddProperty("SPECULARLOBECONSTANT", pp, specularlobe, NUM);
SMPT -> AddProperty("SPECULARSPIKECONSTANT", pp, specularspike, NUM);
SMPT -> AddProperty("BACKSCATTERCONSTANT", pp, backscatter, NUM);
SMPT -> AddProperty("REFLECTIVITY", pp, reflectivity, NUM);
SMPT -> AddProperty("EFFICIENCY", pp, efficiency, NUM);

OpSurface -> SetMaterialPropertiesTable(SMPT);
```


Энергия, выделенная в 3x3 матрице из CsI кристаллов размером 3см x 3см x 20 см

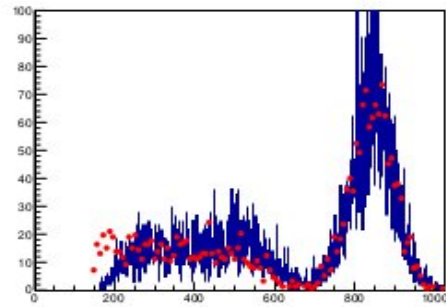
Электроны, 105 МэВ, в центр торца
матрицы

2.09	4.02	1.88
3.93	71.8	4.07
2.04	3.93	2.03

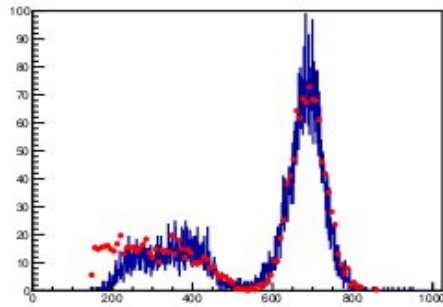
[] = МэВ

Космические лучи, в центр
верхней стороны

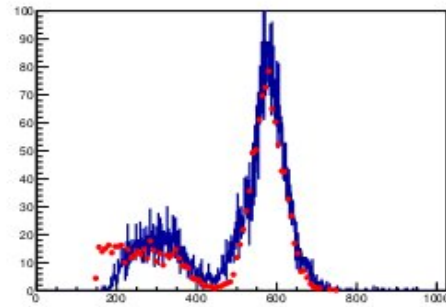
0.55	18.91	0.76
0.64	19.58	0.79
1.15	19.66	1.07



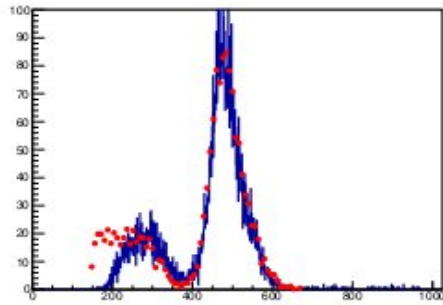
(a)



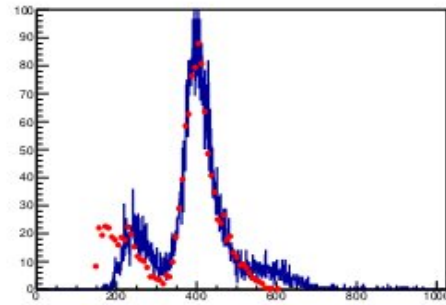
(b)



(c)



(d)



(e)

Figure 6. Experiment (blue line) and simulation (red dot) Energy Spectrum of different LYSO pixel lengths: (a) $L=05$ mm,(b) $L=10$ mm,(c) $L=15$ mm,(d) $L=20$ mm,(e) $L=25$ mm.

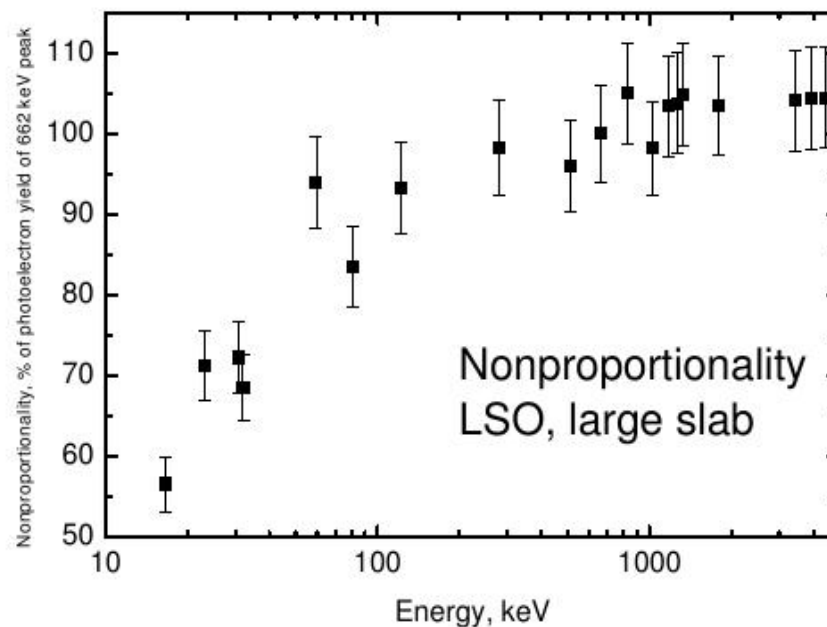
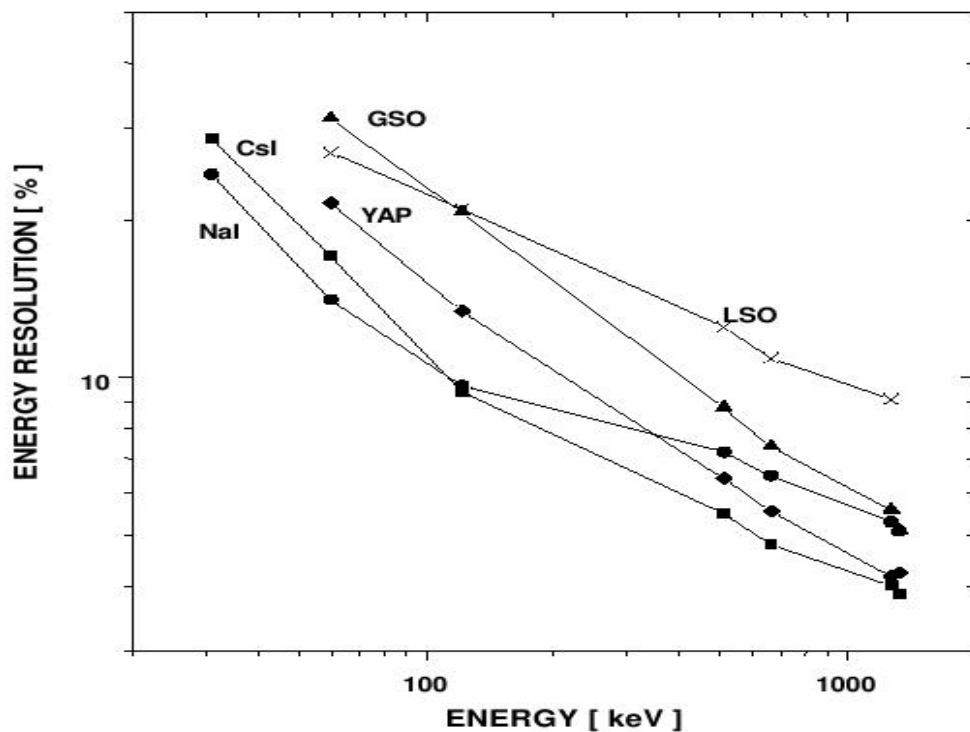


TABLE IV
LIGHT OUTPUT AND ENERGY RESOLUTION OF $4 \times 4 \times 10 \text{ mm}^3$
SCINTILLATORS AT 662 keV (^{137}Cs)

Scintillators	Light output (%)		Energy resolution (%)	
	PMT	APD	PMT	APD
LSOref	100	100	12.4	9.5
LSOA	136	111	11.8	10.4
LSOB	134	118	11.2	9.8
LSOg	117 ± 7	134 ± 2	12 ± 1	10.2 ± 0.1
LYSOg	111 ± 5	128 ± 5	13 ± 1	10.2 ± 0.3
GSO	44	53	13.7	7.5
BGO	12	42	20.9	10.5

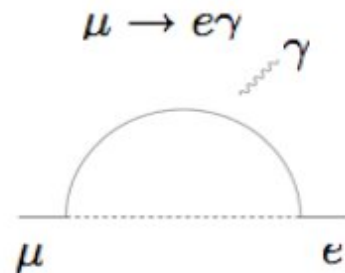
Table 2
Scintillating properties of oxyorthosilicates for 511 keV and 662 keV

Sample	$\Delta E/E$, [%] for 511keV	Δ_{sc} , [%] for 511keV	$\Delta E/E$, [%] for 662keV	Δ_{sc} , [%] for 662keV	photoelectron yield, [phe/MeV] for 662keV
YSO(1)	11.9±0.6	11.0±0.7	9.4±0.5	8.5 ±0.6	6230±190 ^c
YSO(2)	12.1±0.7	11.3±0.8	11.1±0.5	10.4 ±0.7	6950±210 ^b
LSO(1)	10.0±0.6	8.9±0.6	8.4±0.5	7.4±0.5	5730±170 ^a
LSO(2)	13.5±0.7	12.8±0.8	11.9±0.6	11.3±0.7	6860±210 ^b
GSO	10.5±0.6	6.2±0.3	9.2±0.5	5.3±1.0	1630±50 ^a
LGSO	14.5±0.8	13.7±0.8	12.4±0.6	11.6±0.7	4600±180 ^a 5040±150 ^c

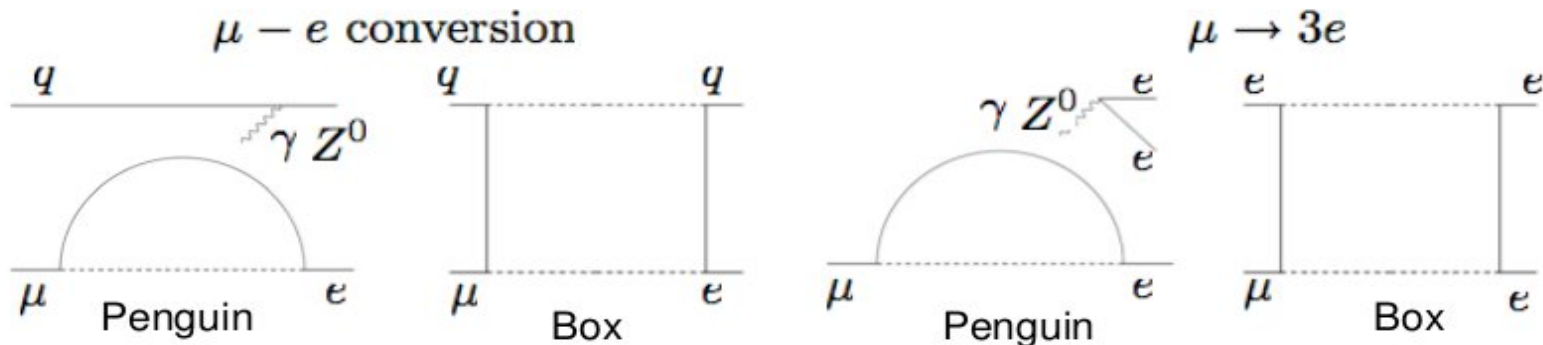
a – XP2020Q, b – XP3312, c – XP3212

Which process of muon-LFV processes?

In SUSY SM, charged-LFV processes come from one-loops.



Internal lines in loops are SUSY particles.



A typical case: Photon penguin dominance

$$R(\mu \text{ Ti} \rightarrow e \text{ Ti}) \simeq 6 \times 10^{-3} Br(\mu \rightarrow e \gamma)$$

$$Br(\mu \rightarrow 3e) \simeq 7 \times 10^{-3} Br(\mu \rightarrow e \gamma)$$