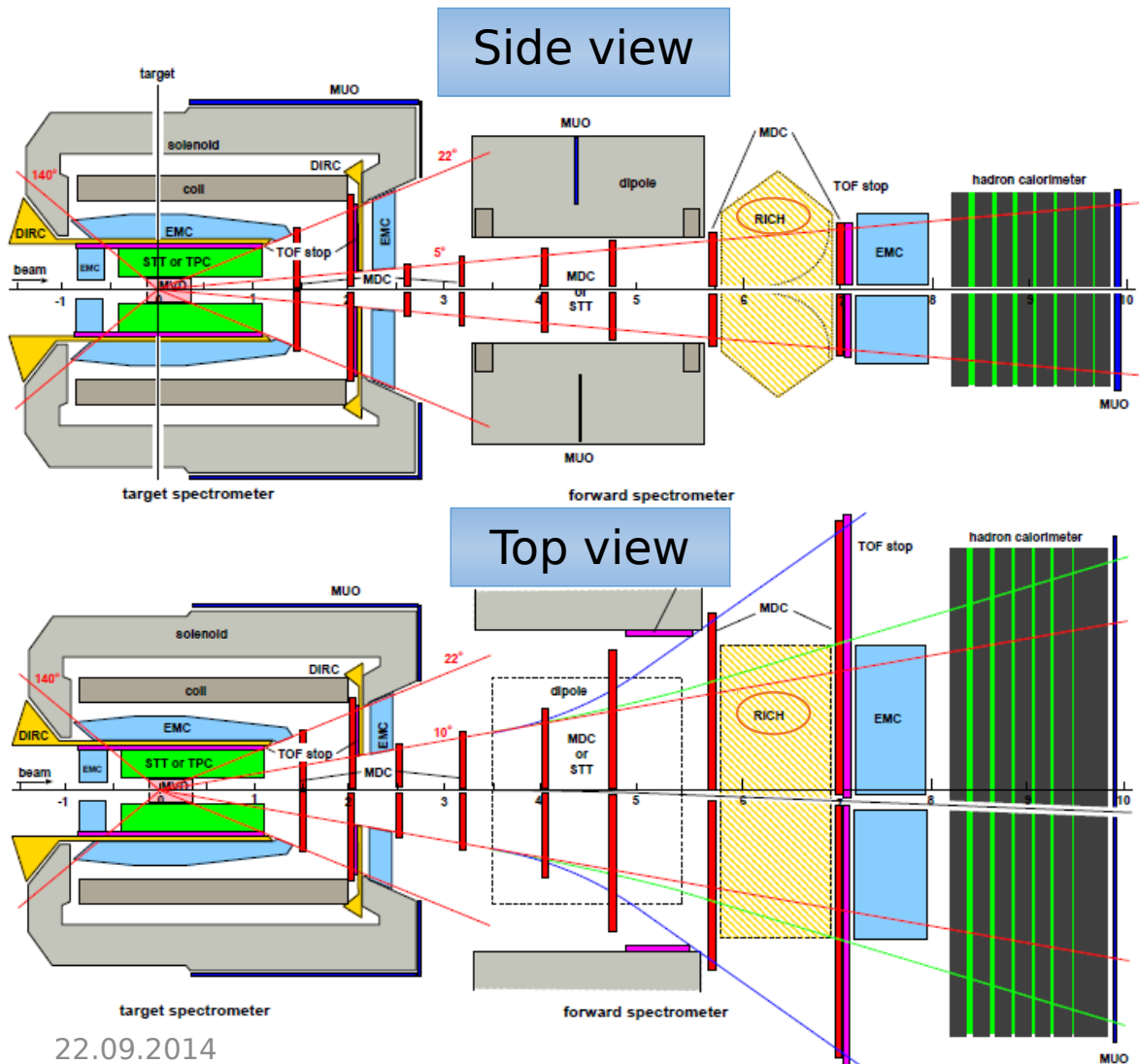


Деятельность группы ИЯФ СО РАН в ПАНДА

А.Е. Блинов, Дубна, 22.09.2014 г.

1. Введение в Forward RICH,
2. Измерения эффективности регистрации фотонов и радиационной стойкости прототипа ФАРИЧ на основе кремниевых цифровых фотоумножителей фирмы Филипс,
3. Возможность изучения экзотических заряженных состояний чармония в эксперименте ПАНДА с дейтериевой мишенью.

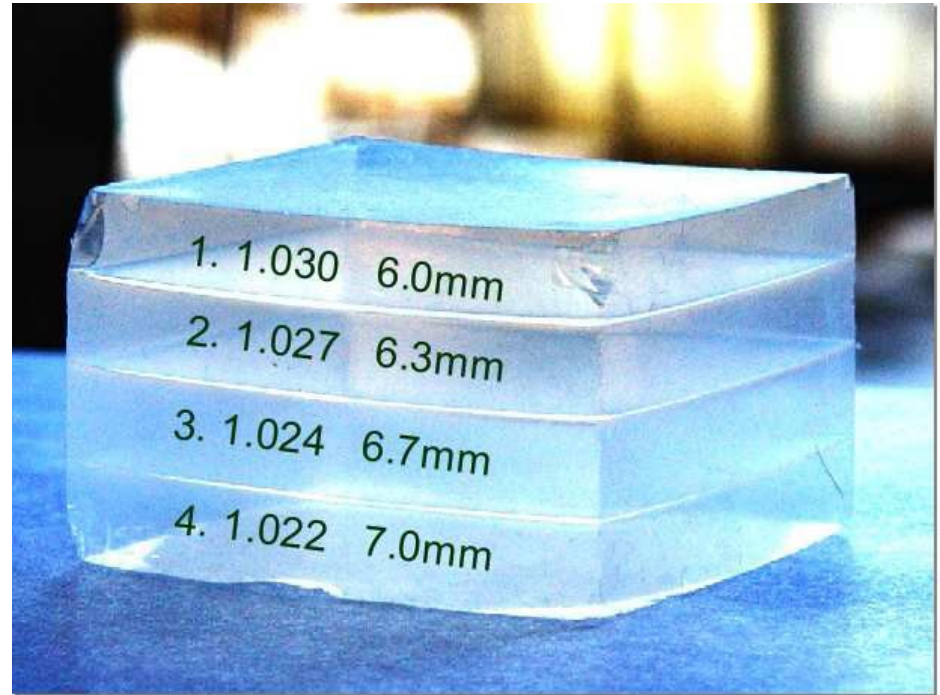
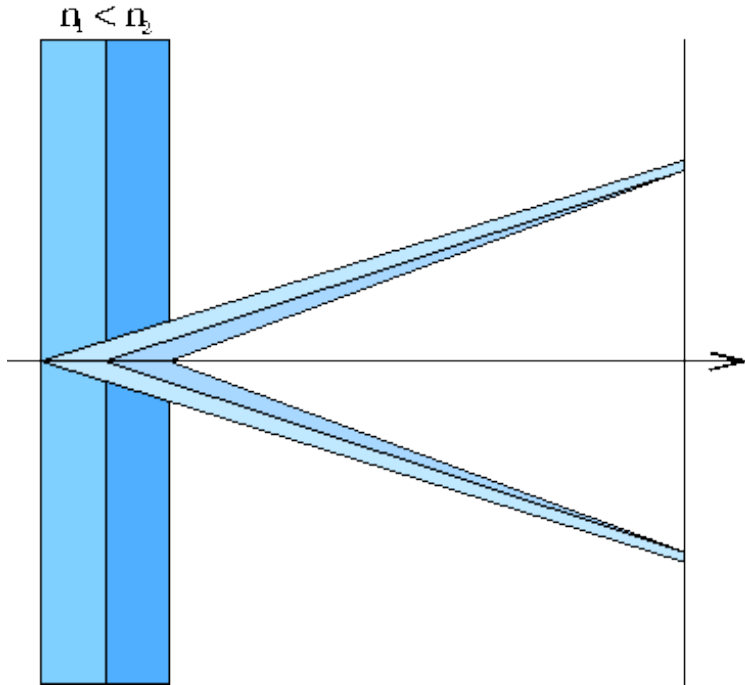
Forward RICH for PANDA



Old pictures dated 2005 just to represent position of FRICH

Forward RICH
 $|\theta_x| < 10^\circ$, $|\theta_y| < 5^\circ$
 PID π/K for $P > 3 \text{ GeV}/c$

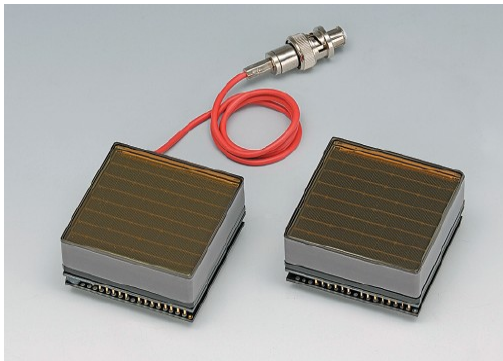
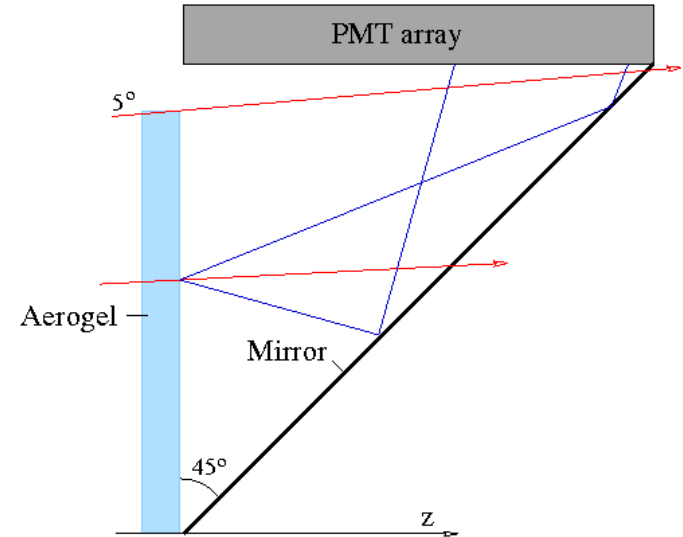
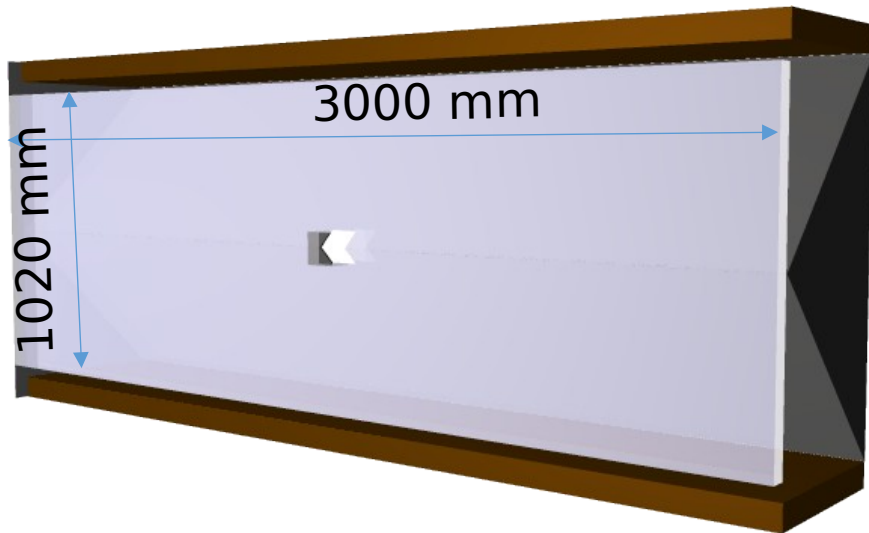
Идея ФАРИЧ (Focusing Aerogel RICH)



Повышение точности измерения черенковского угла по сравнению с одним слоем достигается за счет уменьшения

T.Iijima et al., NIM A548 (2005) 383
A.Yu.Barnyakov et al., NIM A553 (2005) 70

Baseline design based on focusing aerogel, flat mirrors and MaPMTs



Hamamatsu H8500 MaPMT

- flat panel,
- 8x8 anode pixels of 6mm size
- 89% active area ratio
- Bialkali photocathode
- Gain: $1.5 \cdot 10^6$
- Relatively cheap ($\approx \text{€}1600$ / unit)
- Robust
- Long lifetime

- 2-layer aerogel $n_1=1.050$, $n_2=1.047$ (no gas)
- Flat mirrors only
- MaPMT readout
- MC simulated PID performance:
 - π/K up to $P = 10$ GeV/c
 - μ/π up to $P = 2$ GeV/c

Detection & readout options for PANDA Forward RICH

MaPMT
H12700

ASIC
MAROC3

TDC
TRB

Baseline option

H12700B price: 1700 € per tube

Total MaPMT cost with spares: 2.3 M€

Digital Photon
Counter

Tile
FPGA

Module
FPGA

Data
concentrator
FPGA

Dare-to-try option

Total modules cost with spares: 2 M€

Needs liquid cooling below 0°C.



Digital Photon Counter (DPC) is a digital SiPM produced by Philips Digital Photon Counting

Tile

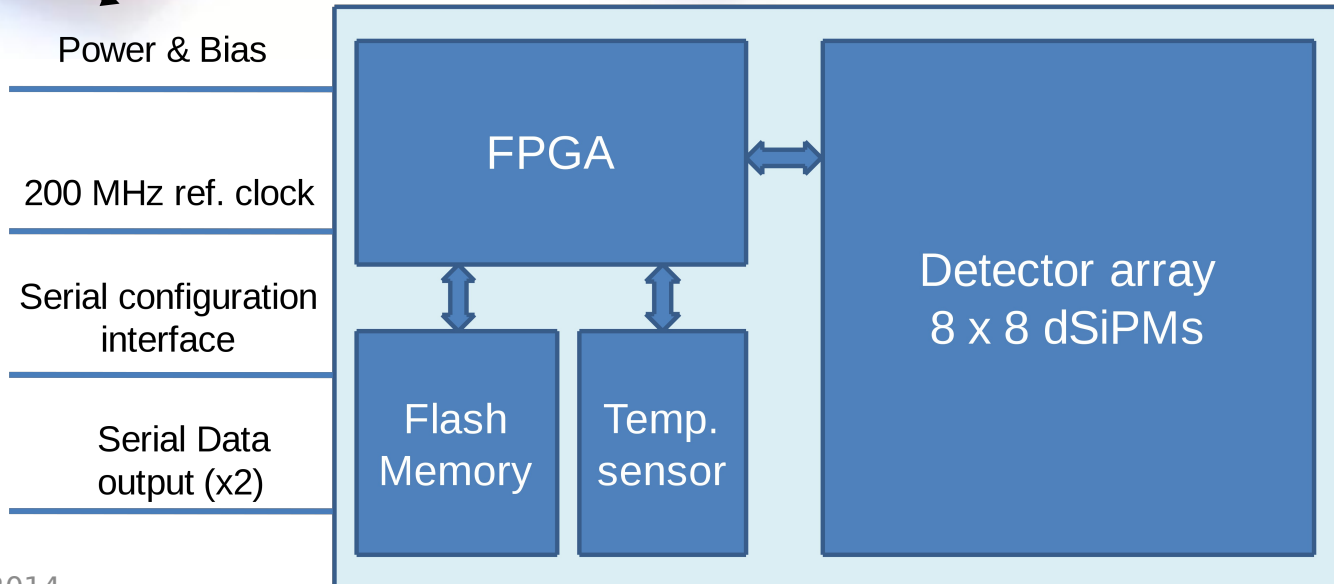
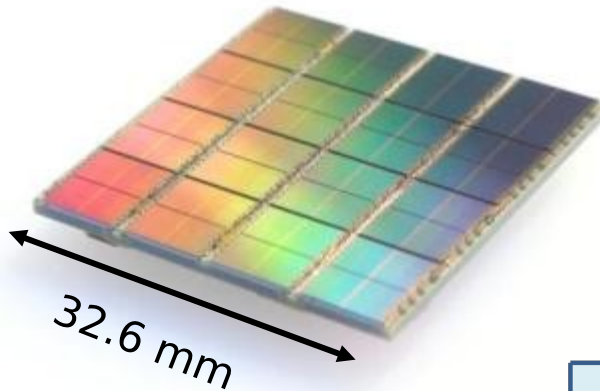
DPC3200-22-44 - 3200 cells/pixel
DPC6400-22-44 - 6396 cells/pixel

FPGA:

- Clock distribution
- Data collection/concentration
- TDC linearization
- Saturation correction
- Skew correction

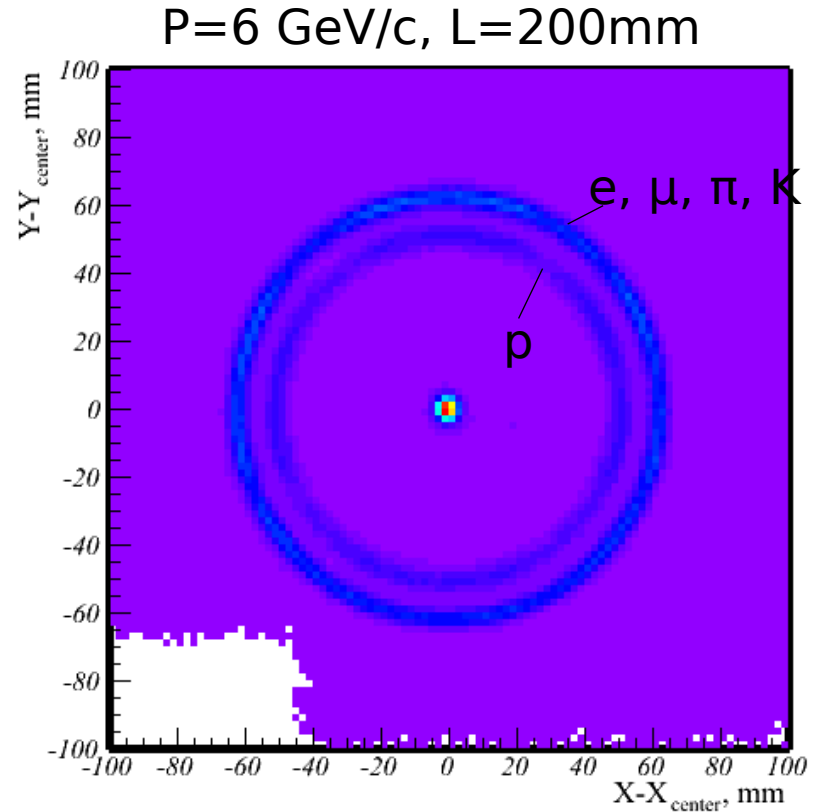
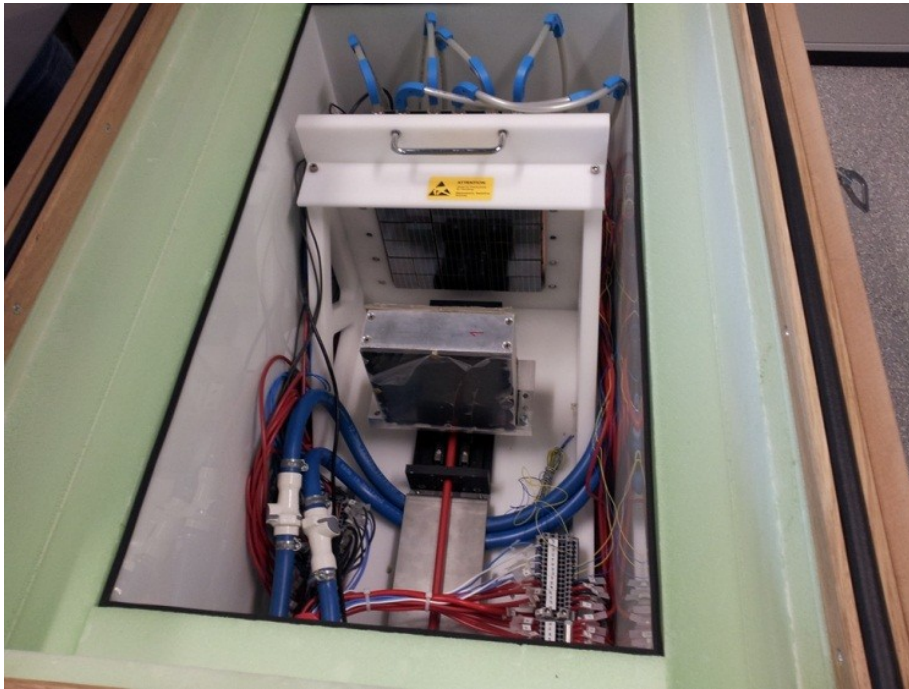
Flash:

- FPGA firmware
- Configuration
- Inhibit memory maps



Beam test of FARICH-PDPC prototype

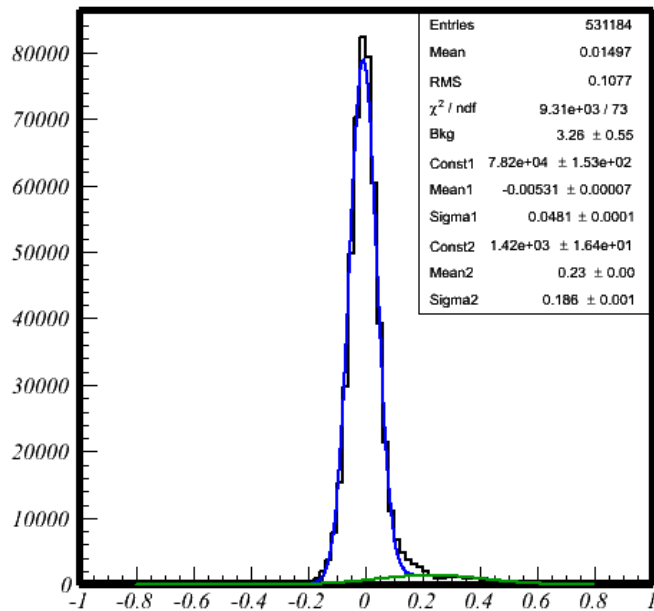
CERN PS/T10, June 2012



- Philips DPC array: 6x6 tiles=48x48 pixels=20x20cm²
- Cooled down to -40°C to reduce dark count rate (DCR)
- 4-layer aerogel with a focusing length of 200mm

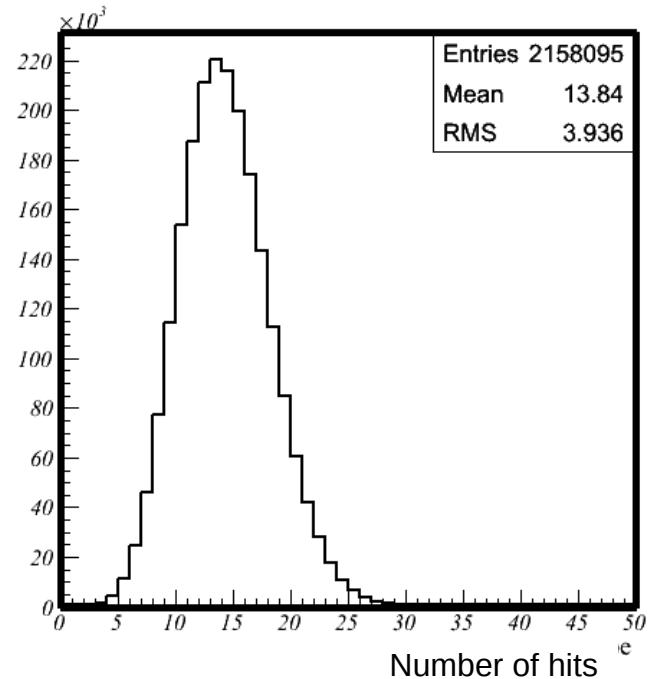
π/K : **7.6 σ** @ 4 GeV/c
 μ/π : **4.5 σ** @ 1 GeV/c

Philips DPC-FARICH: timing resolution and number of photoelectrons



Hit time w.r.t. fitted event time, ns

**$\sigma_{\text{narow}} = 48\text{ps}$
for single photons**



Number of hits

$\langle N_{\text{ph.el.}} \rangle = 12$

(accounted for optical crosstalks)

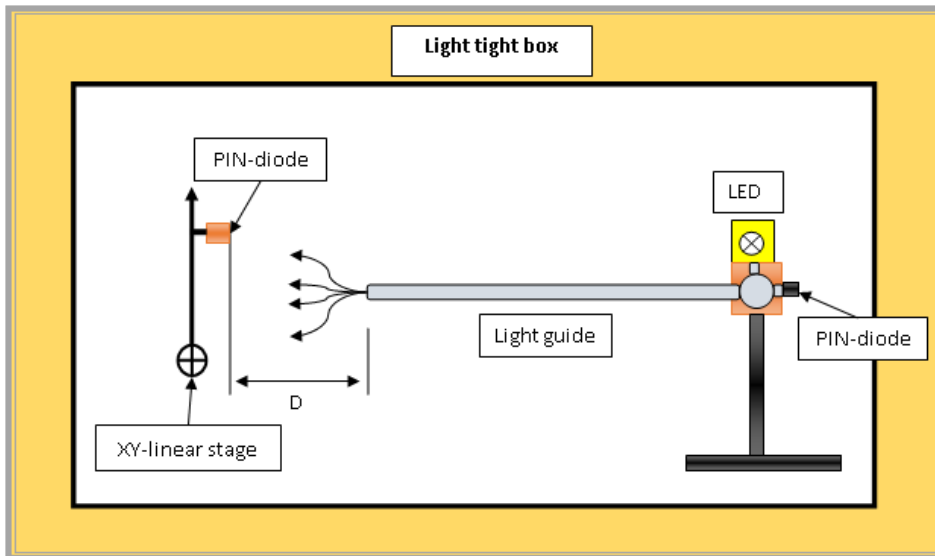
1.7 times lower than expected

R&D of Digital Photon Counter (DPC)

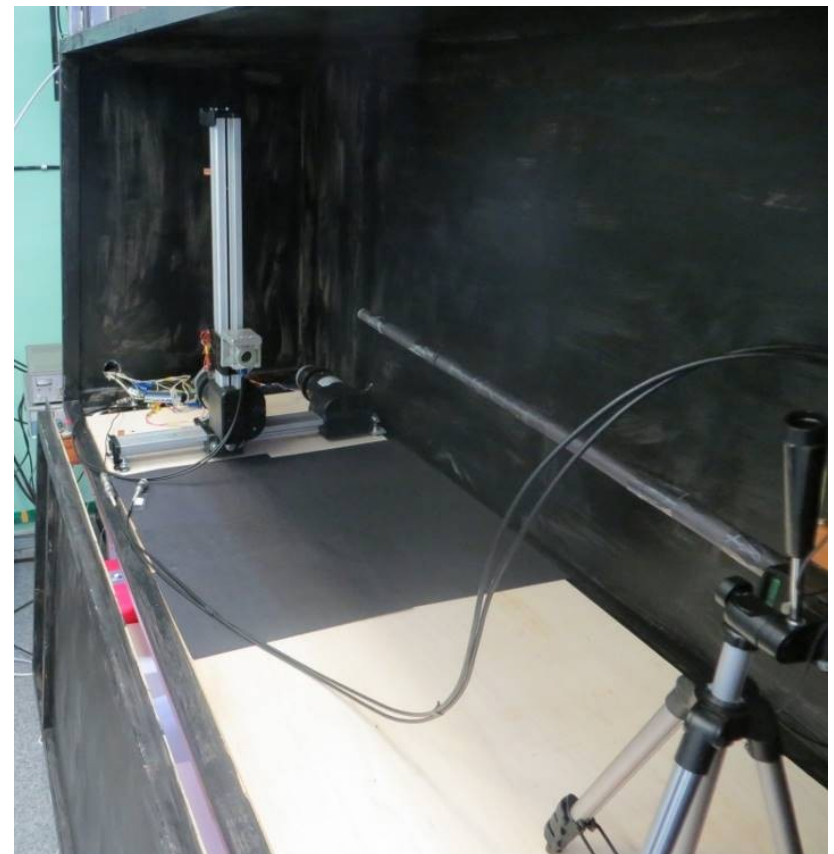
- Promising option for photon detection despite of high DCR and a need for cooling (down to -40°C for present DPC design).
- Previous beam tests and preliminary measurements have shown PDE deficiency: about 1.7-1.9 times lesser than Philips claimed value. We have to address this issue by measuring PDE of the FARICH prototype (6x6 DPC tiles) and understanding differences between our DPC calibration procedure and Philips one.
- Possible radiation aging/damage:
 - Beam tests.
 - MC simulation to evaluate expected dose for the PANDA Forward RICH.

DPC PDE measurement (1)

Wide-angle light source calibration by scanning setup



Custom-made scanning setup

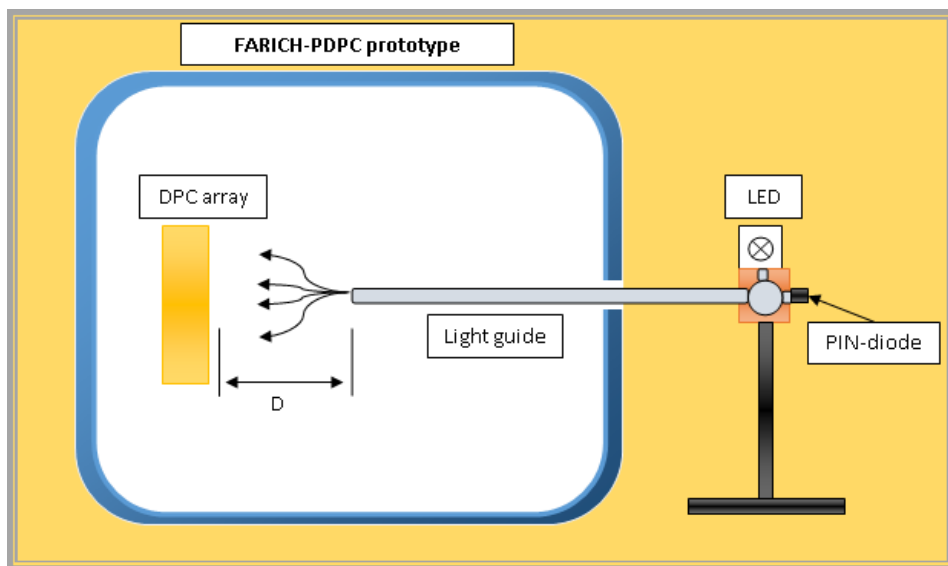


DPC PDE measurement (2)

Use wide-angle light source to illuminate DPC array

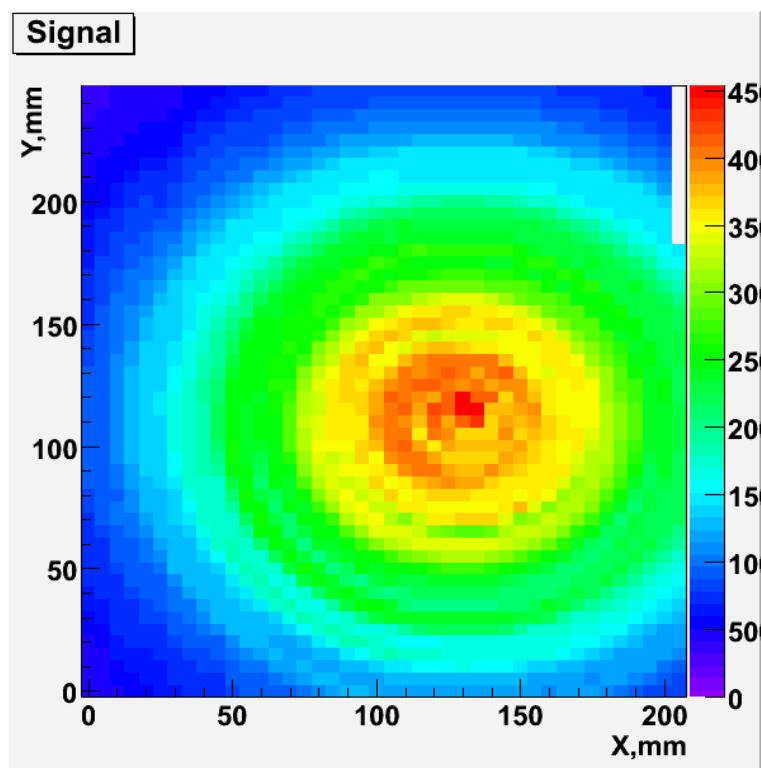
FARICH setup

DPC array
(6x6 tiles)

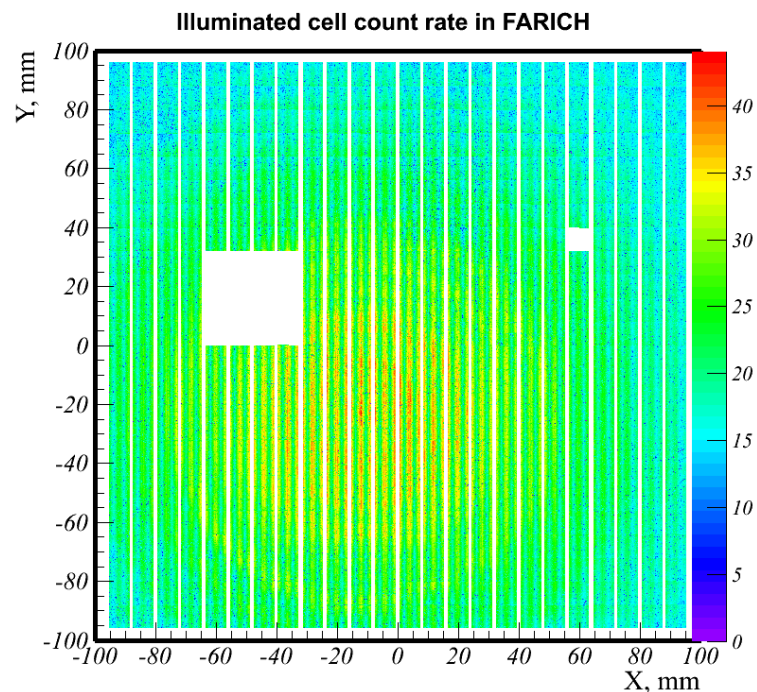


DPC PDE measurement (3)

Relative intensity map by scanning setup (5 mm step)



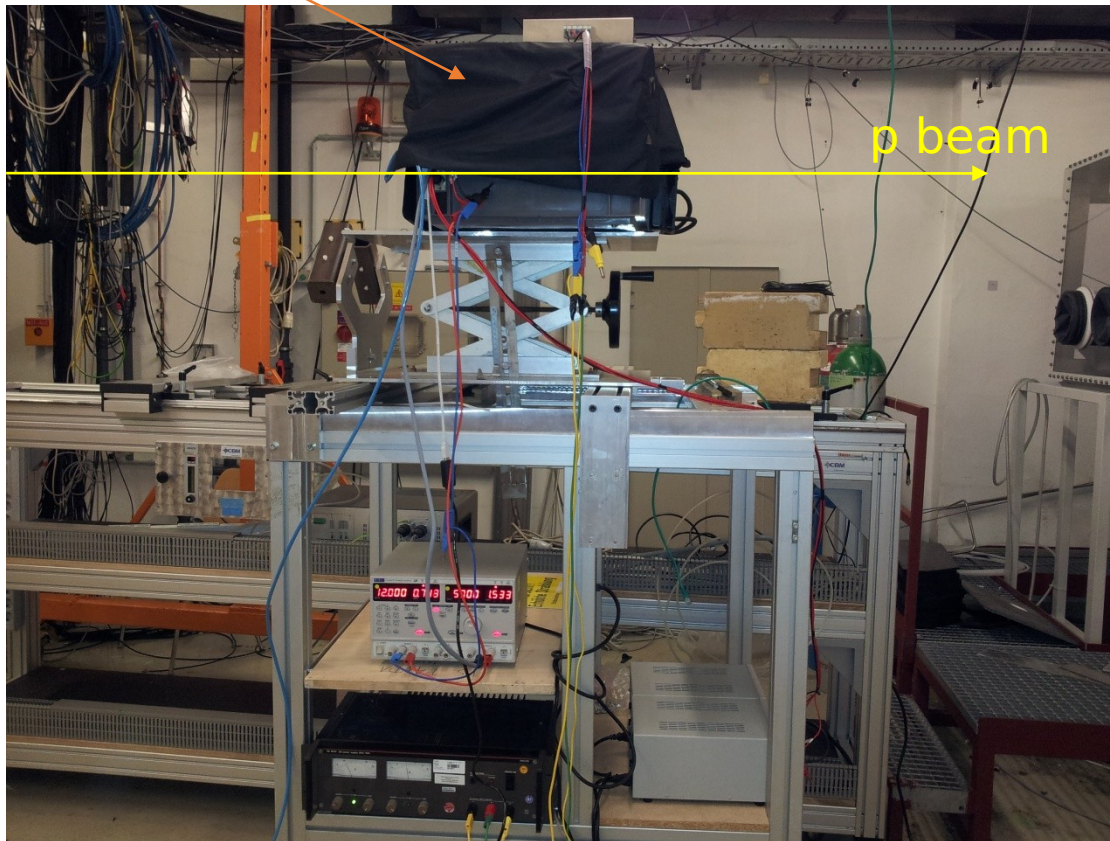
Count rate map for DPC array
2400x3072 cells, $T \sim 15^\circ\text{C}$



T variation during measurements results in the vertical lines with different count rate.

DPC radiation hardness test at COSY (FZ Julich), August 1-4, 2014

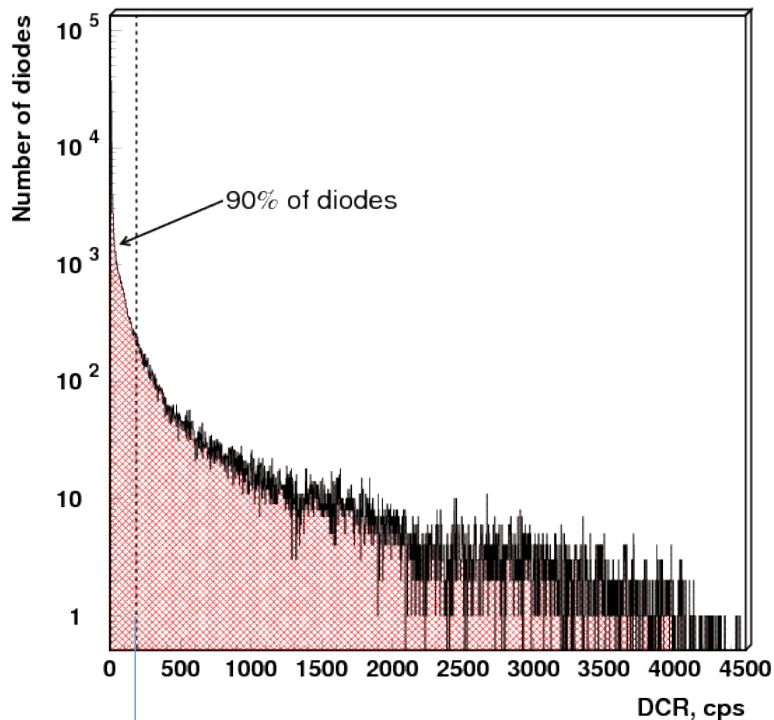
Box with 2
DPC tiles



- Protons with 800 MeV/c momentum
- Maximum fluence $\sim 4 \cdot 10^{11}$ p/cm² accumulated in 9 steps
- Tiles were at -18°C
- DCR scan of cells was done in beam stops
- Total dose is measured by ionization chamber provided by COSY team
- Beam profile is measured by MWPC ~ 1 m upstream of the detector

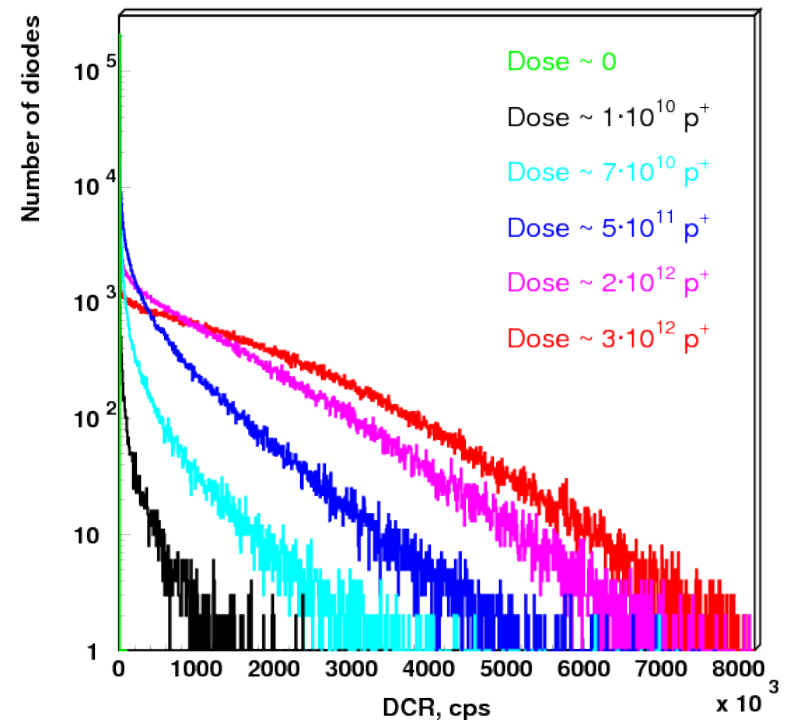
DPC irradiation (1)

Initial dark count rate (DCR) distribution of cells



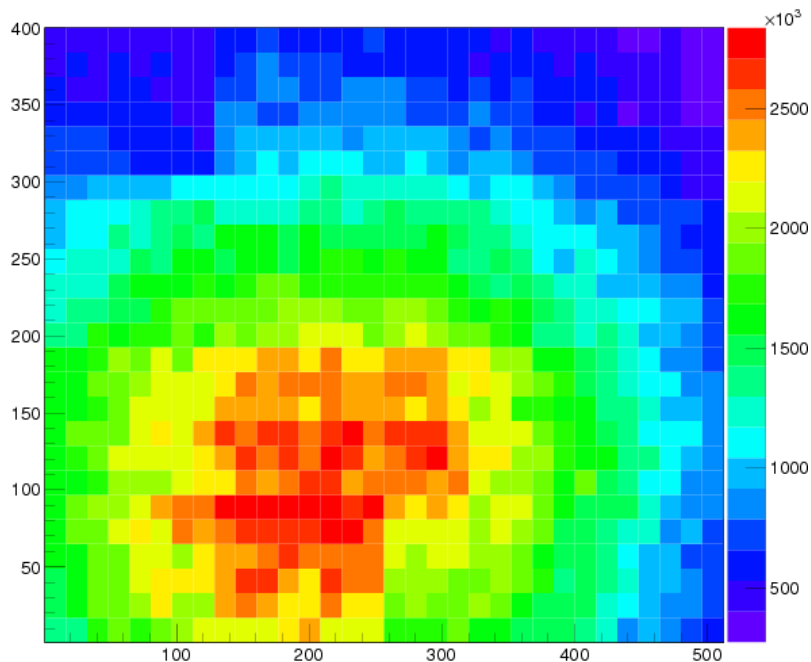
185

DCR distribution of cells for several total doses



DPC irradiation (2)

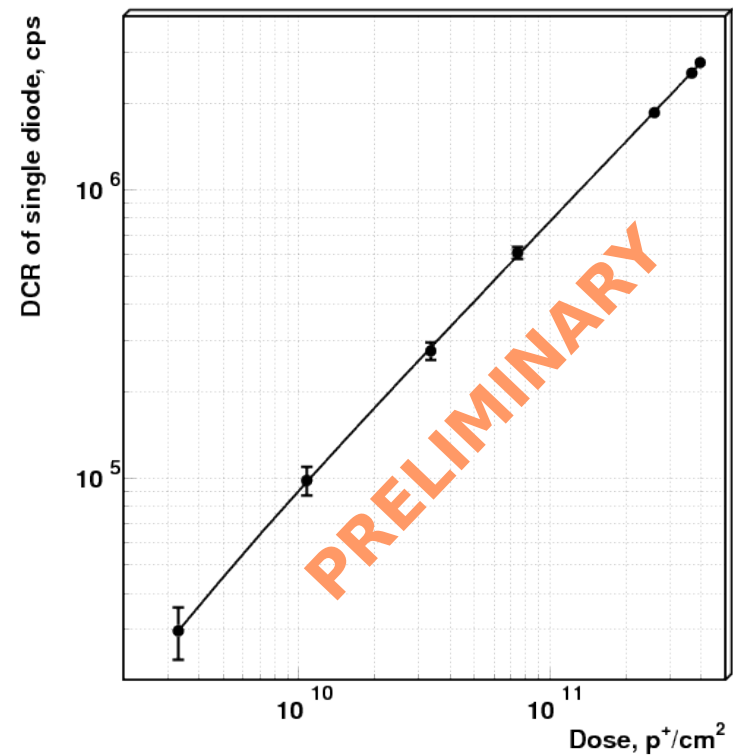
Dark count rate map after final dose



- Beam profile at the tile position is not precisely determined due to multiple scattering of protons in $\sim 1\text{m}$ of air
- We had to use DCR data to determine beam profile

Mean cell DCR in the central part of the tile vs fluence

Fit: $y = 7.65 \cdot 10^{-5} \cdot x^{0.910} - 5470$

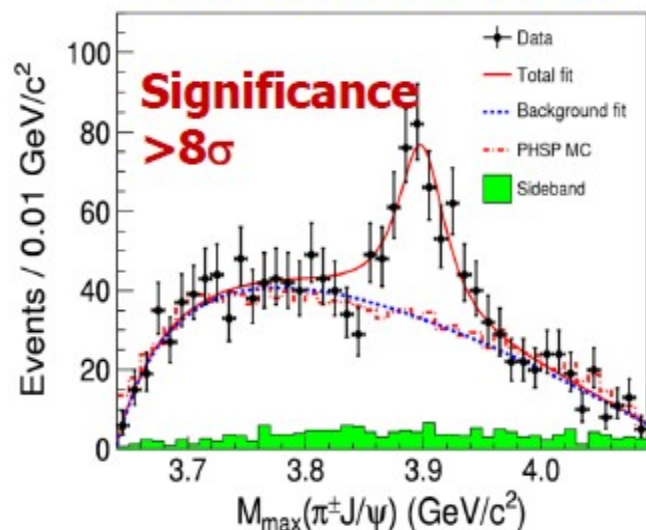


DPC radiation hardness

- DCR vs p fluence measured.
- Observed single event effects: tile and TEK FPGA failures: bit upsets in the inhibit on-chip memory. Can be recovered by FW reload. Special runs were acquired to evaluate frequency of such events, to be analyzed.
- Also we did several temperature scans to compare DCR vs temperature behavior before and after irradiation. To be analyzed.
- We should evaluate total fluence expected in PANDA Forward RICH for the experiment lifetime. MC simulation is in preparation.

Observation of $Z_c(3900)$ at BESIII

PRL110, 252001 (2013)

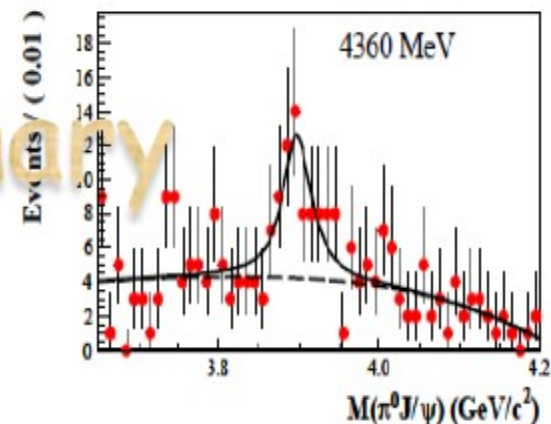
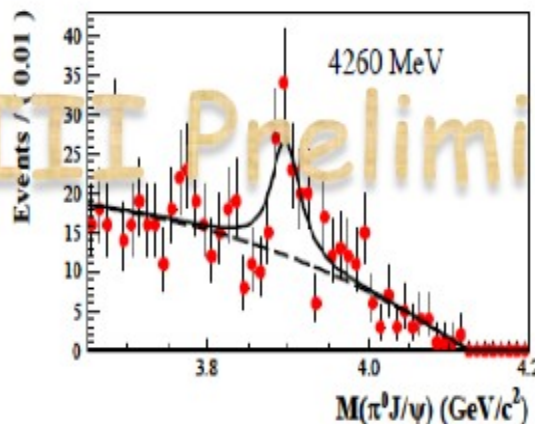
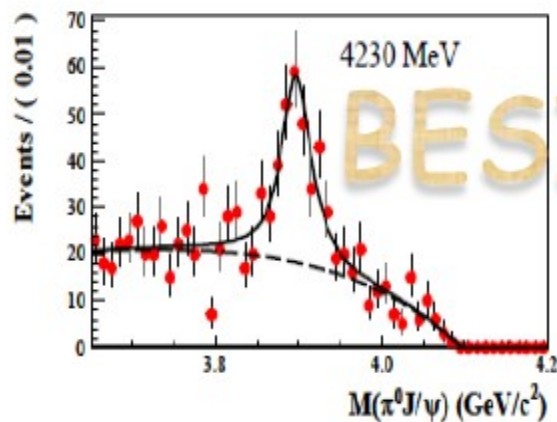


$$e^+e^- \rightarrow \pi Z_c(4020) \rightarrow \pi^+ \pi^- J/\psi$$

- $M = 3899.0 \pm 3.6 \pm 4.9 \text{ MeV}/c^2$
- $\Gamma = 46 \pm 10 \pm 20 \text{ MeV}$

$$e^+e^- \rightarrow \pi Z_c(4020) \rightarrow \pi^0 \pi^0 J/\psi$$

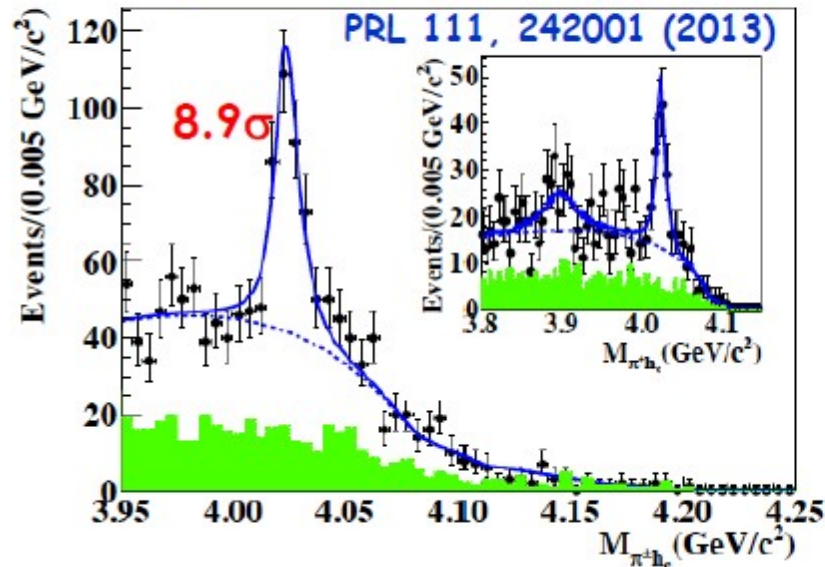
- $M = 3894.8 \pm 2.3 \text{ MeV}/c^2$
- $\Gamma = 29.6 \pm 8.2 \text{ MeV}$



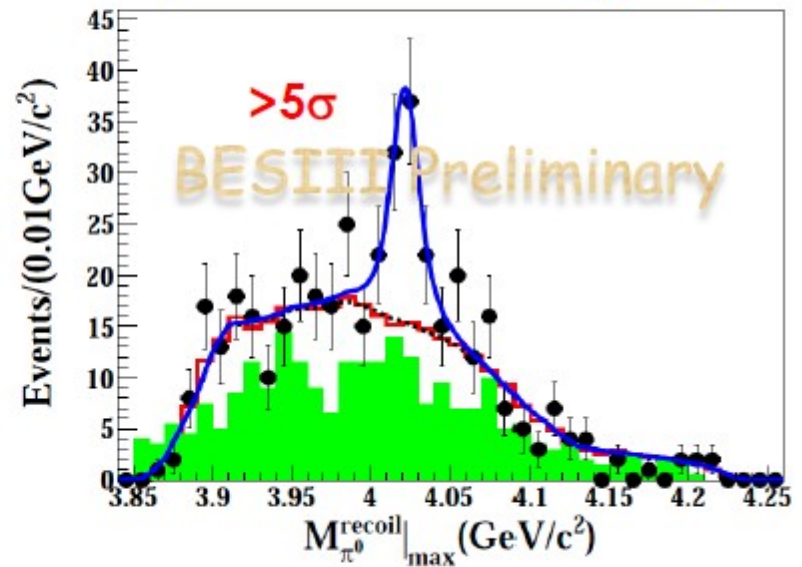
BESIII Preliminary

Observation of $Z_c(4020)$ in $e^+e^- \rightarrow \pi\pi h_c$

$$e^+e^- \rightarrow \pi^+\pi^-h_c$$



$$e^+e^- \rightarrow \pi^0\pi^0h_c$$



No significant: $Z_c(3900)$ (2.1σ)

$$M = 4022.9 \pm 0.8 \pm 2.7 \text{ MeV}/c^2$$

$$\Gamma = 7.9 \pm 2.7 \pm 2.6 \text{ MeV}$$

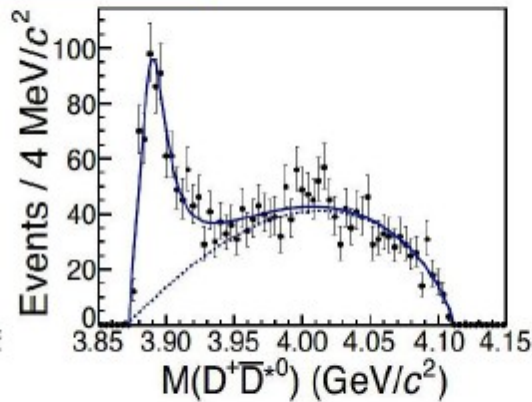
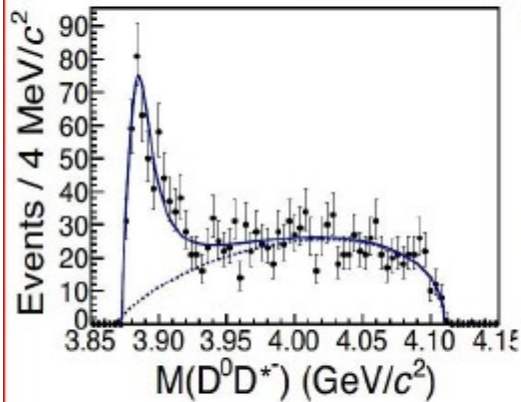
$$\frac{\sigma(e^+e^- \rightarrow \pi^0 Z_c(4020)^0 \rightarrow \pi^0 \pi^0 h_c)}{\sigma(e^+e^- \rightarrow \pi^\pm Z_c(4020)^\mp \rightarrow \pi^\pm \pi^\mp h_c)}$$

$$M = 4023.6 \pm 2.3 \pm 3.9 \text{ MeV}/c^2$$

\sqrt{s} (GeV)	$R_{\pi Z_c(4020)}$
4.230	$0.79 \pm 0.30 \pm 0.26$
4.260	$1.18 \pm 0.46 \pm 0.37$
4.360	$0.99 \pm 0.47 \pm 0.32$

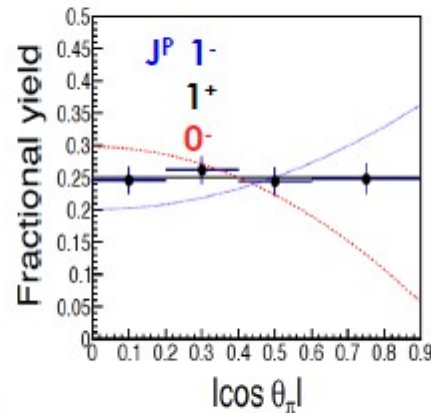
Observation of $Z_c(3885)$ and $Z_c(4025)$

$$e^+e^- \rightarrow \pi^- (D^* \bar{D})^+$$



$$M = 3883.9 \pm 1.5 \pm 4.2 \text{ MeV}/c^2$$

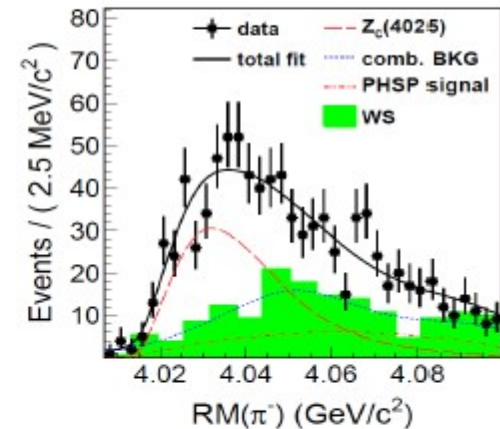
$$\Gamma = 24.8 \pm 3.3 \pm 11.0 \text{ MeV}$$



- fits favor 1⁺ distribution assumption

PRL 112, 022001 (2014)

$$e^+e^- \rightarrow \pi^- (D^* \bar{D}^*)^+$$



$$M = 4026.3 \pm 2.6 \pm 3.7 \text{ MeV}/c^2$$

$$\Gamma = 24.8 \pm 5.6 \pm 7.7 \text{ MeV}$$

PRL 112, 132001 (2014)

the Z_c states at BESIII

C_{channel}	$M_{\text{mass}} \text{ (MeV}/c^2)$	$W_{\text{width}} \text{ (MeV)}$
$\pi J/\psi$	$3899.0 \pm 3.6 \pm 4.9$ $3894.8 \pm 2.3 \text{ (Prel.)}$	$46 \pm 10 \pm 20$ $29.6 \pm 8.2 \text{ (Prel.)}$
$(D \bar{D}^*)^\pm$	$3883.9 \pm 1.5 \pm 4.2$	$24.8 \pm 3.3 \pm 11.0$
	2σ difference	1σ difference
πh_c	$4022.9 \pm 0.8 \pm 2.7$ $4022.9 \pm 0.8 \pm 2.7 \text{ (Prel.)}$	$7.9 \pm 2.7 \pm 2.6$
$(D^* \bar{D}^*)^\pm$	$4026.3 \pm 2.6 \pm 3.7$	$24.8 \pm 5.6 \pm 7.7$
	1σ difference	2σ difference

Close to $D \bar{D}^*$
threshold (3875 MeV)

Close to $D^* \bar{D}^*$ threshold
(4017 MeV)

- At least 4-quarks; Near threshold;
- Isospin: $I=1$, hint of a new spectroscopy ?
- Whether they are two states need further understanding (couple channel analysis? quantum number determination? interference?)

Наблюдение $Z_b(10610)$ и $Z_b(10650)$ на BELLE

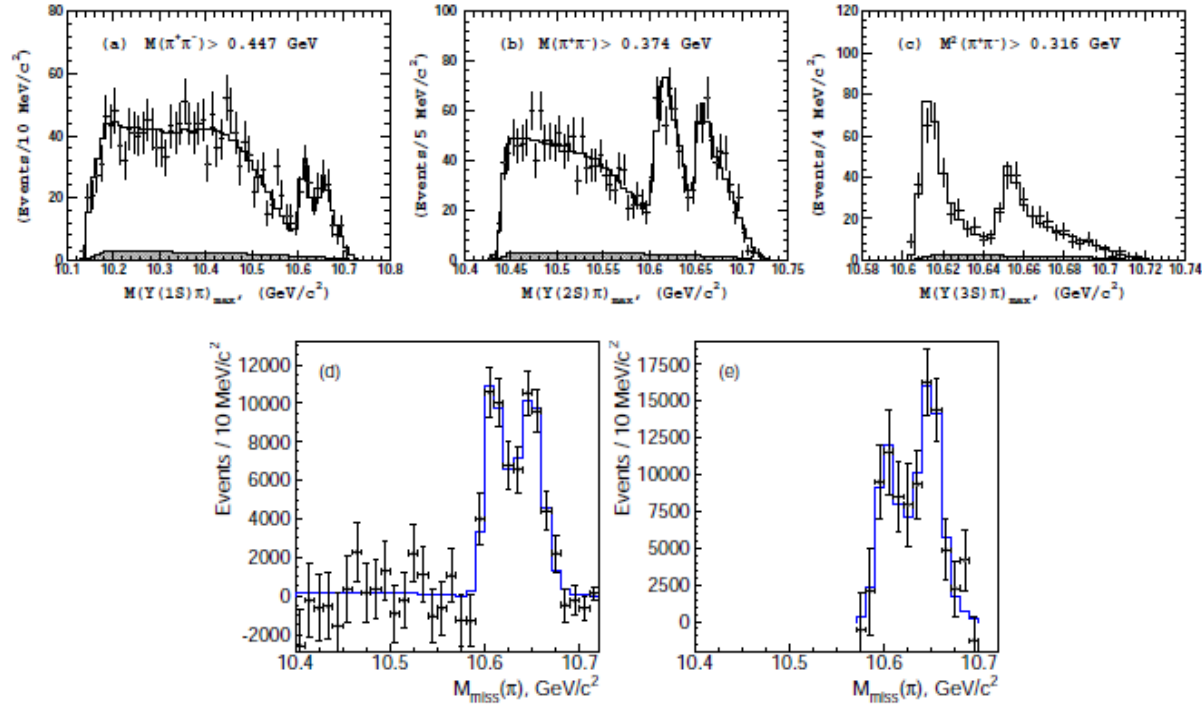


Figure 1: Invariant mass spectra of the (a) $\Upsilon(1S)\pi^\pm$, (b) $\Upsilon(2S)\pi^\pm$, (c) $\Upsilon(3S)\pi^\pm$, (d) $h_b(1P)\pi^\pm$ and (e) $h_b(2P)\pi^\pm$ combinations.

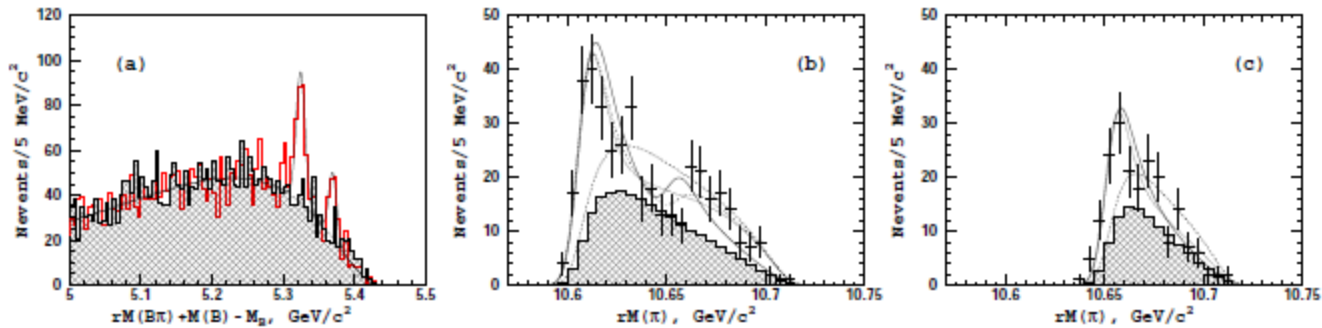


Figure 3: Missing mass of the pairs formed from the reconstructed B candidate and charged pion (a) and missing mass of the charged pions for the $B\pi$ combinations for (b) $\Upsilon(5S) \rightarrow B\bar{B}^*\pi$ and (c) $\Upsilon(5S) \rightarrow B^*\bar{B}^*\pi$ candidate events.

Параметры $Z_b(10610)$ и $Z_b(10650)$

$$M_1 = (10607.4 \pm 2.0) \text{ MeV}/c^2, \quad M_2 = (10652.2 \pm 1.5) \text{ MeV}/c^2,$$

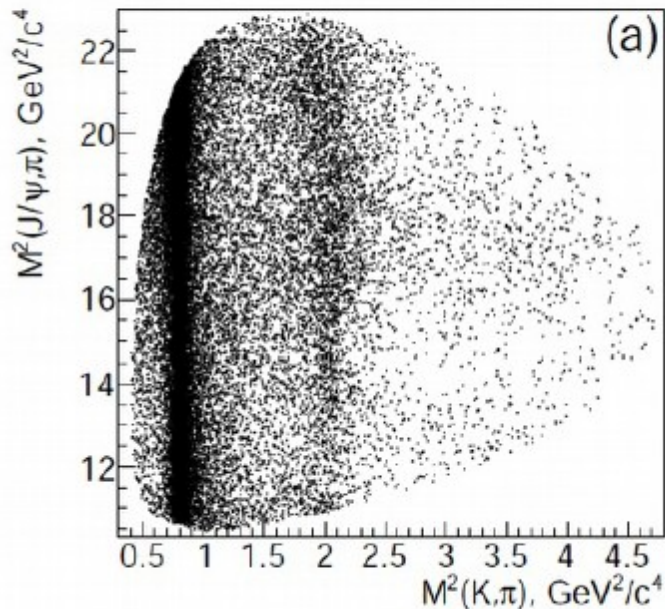
$$\Gamma_1 = (18.4 \pm 2.4) \text{ MeV}, \quad \Gamma_2 = (11.5 \pm 2.2) \text{ MeV}.$$

Table 1: Branching fractions (\mathcal{B}) of $Z_b(10610)$ and $Z_b(10650)$ assuming that the observed so far channels saturate their decays.

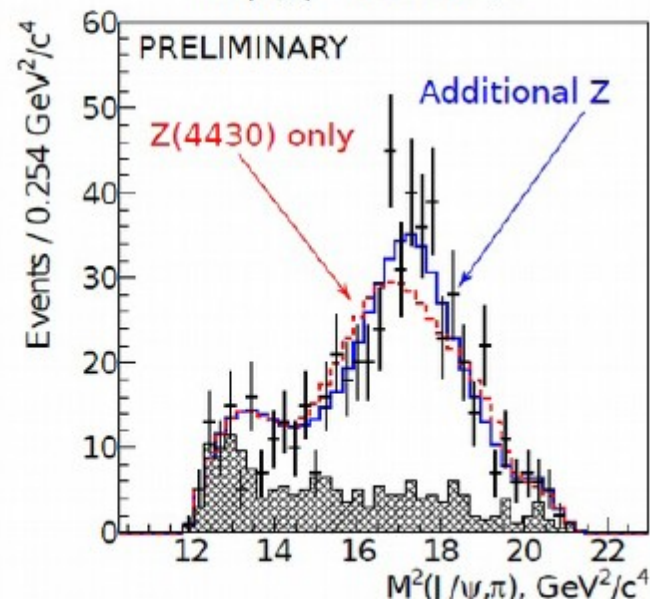
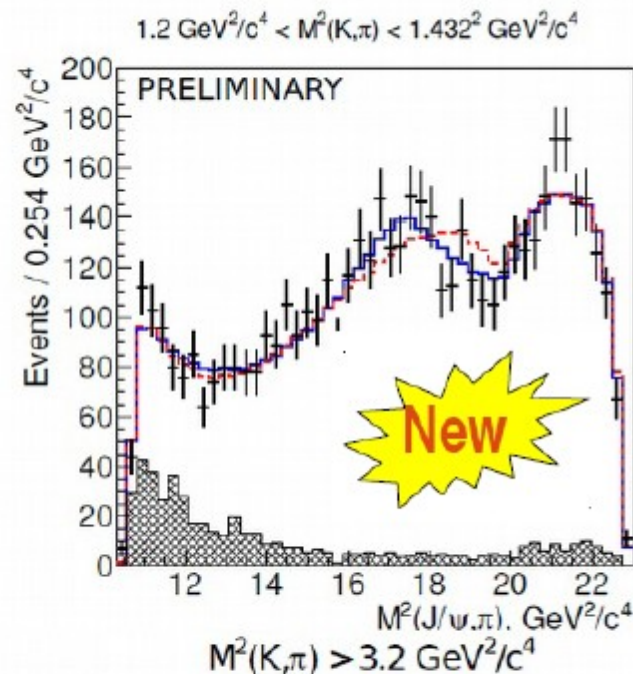
Channel	\mathcal{B} of $Z_b(10610)$, %	\mathcal{B} of $Z_b(10650)$, %
$\Upsilon(1S)\pi^+$	0.32 ± 0.09	0.24 ± 0.07
$\Upsilon(2S)\pi^+$	4.38 ± 1.21	2.40 ± 0.63
$\Upsilon(3S)\pi^+$	2.15 ± 0.56	1.64 ± 0.40
$h_b(1P)\pi^+$	2.81 ± 1.10	7.43 ± 2.70
$h_b(2P)\pi^+$	2.15 ± 0.56	14.8 ± 6.22
$B^+ \bar{B}^{*0} + \bar{B}^0 B^{*+}$	86.0 ± 3.6	–
$B^{*+} \bar{B}^{*0}$	–	73.4 ± 7.0



$$B^0 \rightarrow J/\psi K^- \pi^+$$



- 4D amplitude analysis
- 10 K^* resonances, $Z^+(4430)$, $Z^+(\text{new})$
- 6.6σ significance
- $M = 4196^{+31+17}_{-29-13} \text{ MeV}/c^2$
- $G = 370 \pm 70^{+70}_{-132} \text{ MeV}$
- $J^P=1^+$



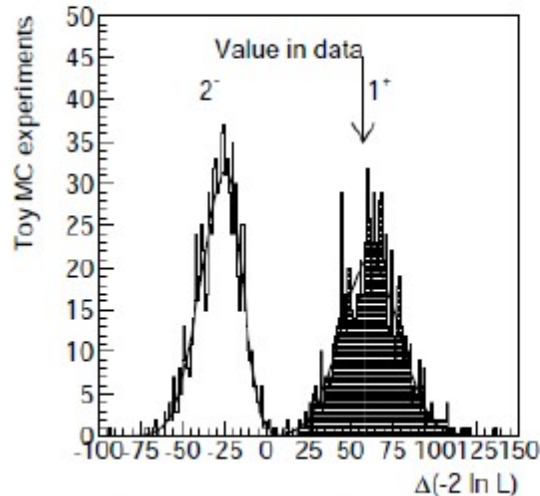


$Z^+(4200)$

Preliminary results



$J^P=1^+$, other J^P are excluded



Exclusion levels of other spin-parity hypothesis

Model	0^-	1^-	2^-	2^+
Without $K^*(1680)$	8.5σ	8.5σ	8.0σ	9.0σ
Without $K_0^*(1950)$	8.4σ	8.8σ	7.3σ	8.9σ
LASS	6.1σ	7.4σ	4.4σ	7.0σ
Free masses and widths	7.6σ	7.9σ	5.9σ	7.8σ
Free r	7.4σ	8.7σ	7.5σ	9.2σ
Nonresonant ampl. (S)	7.6σ	8.1σ	7.2σ	8.5σ
Nonresonant ampl. (S,P)	7.4σ	8.1σ	7.2σ	8.4σ
Nonresonant ampl. (S,P,D)	7.2σ	8.1σ	7.1σ	8.4σ

TABLE III. The fit fractions and significances of all resonances in the default model ($J^P = 1^+$).

Resonance	Fit fraction	Significance (local)
$K_0^*(800)$	$(7.1_{-0.5}^{+0.7})\%$	22.5σ
$K^*(892)$	$(69.0_{-0.5}^{+0.6})\%$	166.4σ
$K^*(1410)$	$(0.3_{-0.1}^{+0.2})\%$	4.1σ
$K_0^*(1430)$	$(5.9_{-0.4}^{+0.6})\%$	22.0σ
$K_2^*(1430)$	$(6.3_{-0.4}^{+0.3})\%$	23.5σ
$K^*(1680)$	$(0.3_{-0.1}^{+0.2})\%$	2.7σ
$K_3^*(1780)$	$(0.2_{-0.1}^{+0.1})\%$	3.8σ
$K_0^*(1950)$	$(0.1_{-0.1}^{+0.1})\%$	1.2σ
$K_2^*(1980)$	$(0.4_{-0.1}^{+0.1})\%$	5.3σ
$K_4^*(2045)$	$(0.2_{-0.1}^{+0.1})\%$	3.8σ
$Z_c(4430)^+$	$(0.5_{-0.1}^{+0.4})\%$	5.1σ
$Z_c(4200)^+$	$(1.9_{-0.5}^{+0.7})\%$	8.2σ

Поиск экзотических заряженных состояний чармония в эксперименте ПАНДА с дейтериевой мишенью

Достоинства: резонансное рождение заряженных чармониев в антипротон-нейтронных столкновениях и, возможно, большая, чем у обычного чармония, константа связи таких состояний с N-N каналом.

- Недостаток: низкая (~ 100 МэВ) монохроматичность столкновений вследствие фермиевского движения нуклонов в дейтерии.
- Точность реконструкции массы Z_c по продуктам распада в канале $J/\psi + p$ оценивается в 10-20 МэВ.
- Точность можно значительно повысить при реконструкции массы отдачи к протону дейтерия ($P \sim P_F \sim 70$ МэВ/с), который поглощается в вак. камере.
- Такое измерение можно (?) провести, если поместить внутрь ВК один слой кремниевого вершинного детектора, который для мягких протонов будет работать как калориметр полного поглощения.

Заключение

1. Ведется работа по выбору оптимальной конструкции ФАРИЧ,
 2. Ведется работа с прототипом из 6x6 DPC фирмы Филипс для оценки возможности его использования в ФАРИЧ:
 - а. измеряется эффективность регистрации фотонов,
 - б. измеряется радиационная стойкость,
 - в. начато моделирование для оценки получаемой в эксперименте дозы.
 3. Отмечена возможность резонансного рождения экзотических заряженных состояний чармония в эксперименте ПАНДА с дейтериевой мишенью, что, в частности, позволит измерить константу связи с каналом нуклон-антинуклон,
 4. Отмечена возможность значительного улучшения разрешения по массе таких резонансов при реконструкции протона отдачи слоем кремниевого вершинного детектора, помещенным внутрь вакуумной камеры.
- Для обоснования целесообразности такой модификации эксперимента ПАНДА нужно моделирование, опыта которого недостает.

ЗАИНТЕРЕСОВАВШИЕСЯ ЛИЦА ПРИГЛАШАЮТСЯ К СОТРУДНИЧЕСТВУ!