The complex nature of the abnormally weak absorption of cosmic ray hadrons in lead calorimeters at superhigh energies

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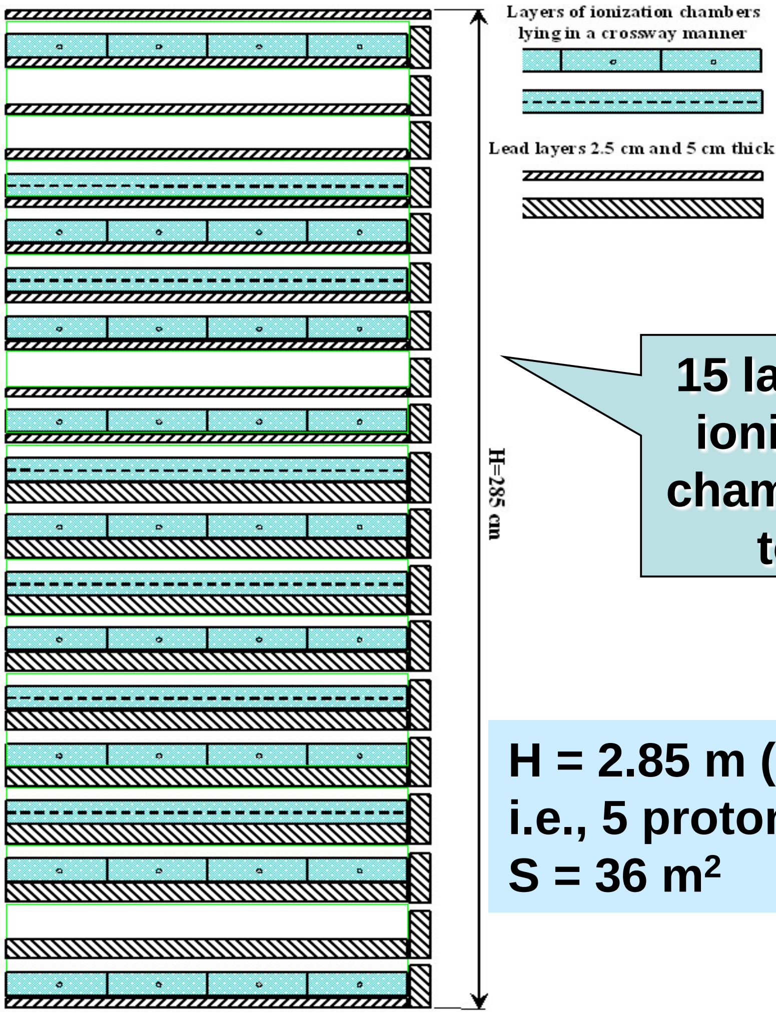
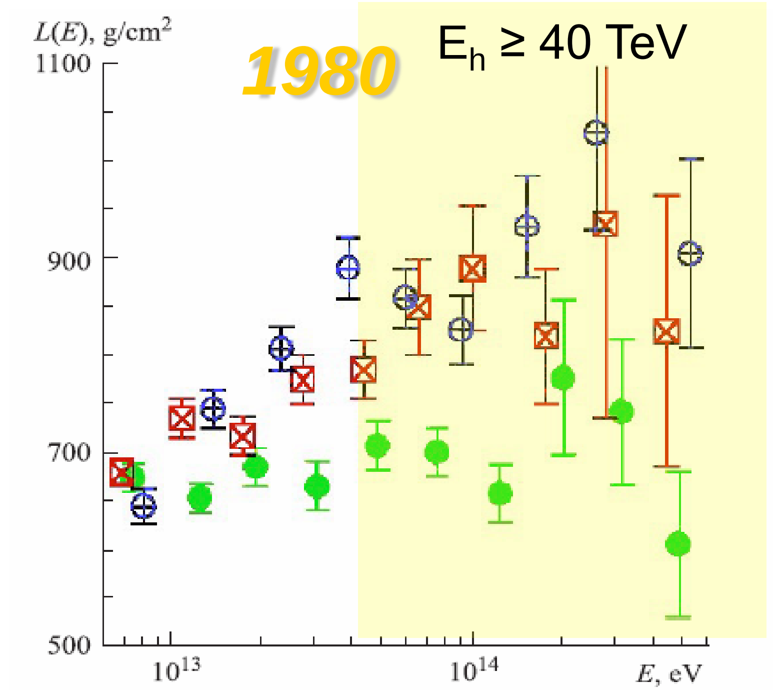
Large ionization calorimeter (LIC) within EAS array at the Tien Shans in 1973 - 1974

Profile of the LIC with lead absorber



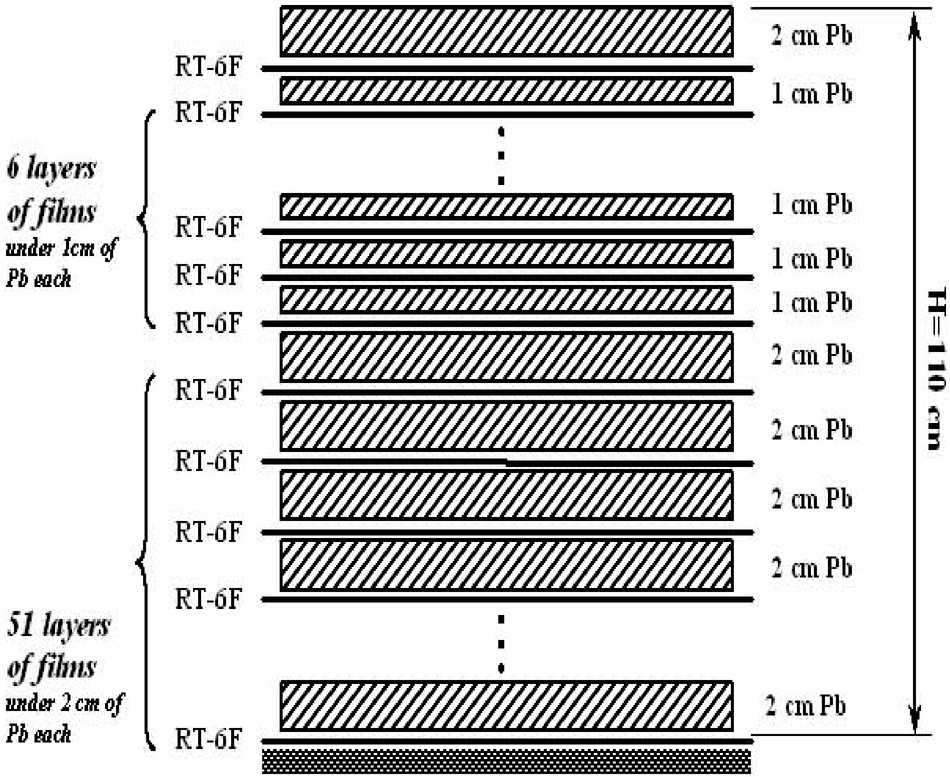
15 layers of ionization chambers in total

H = 2.85 m (850 g/cm^2, i.e., 5 proton's m.f.p.), S = 36 m^2

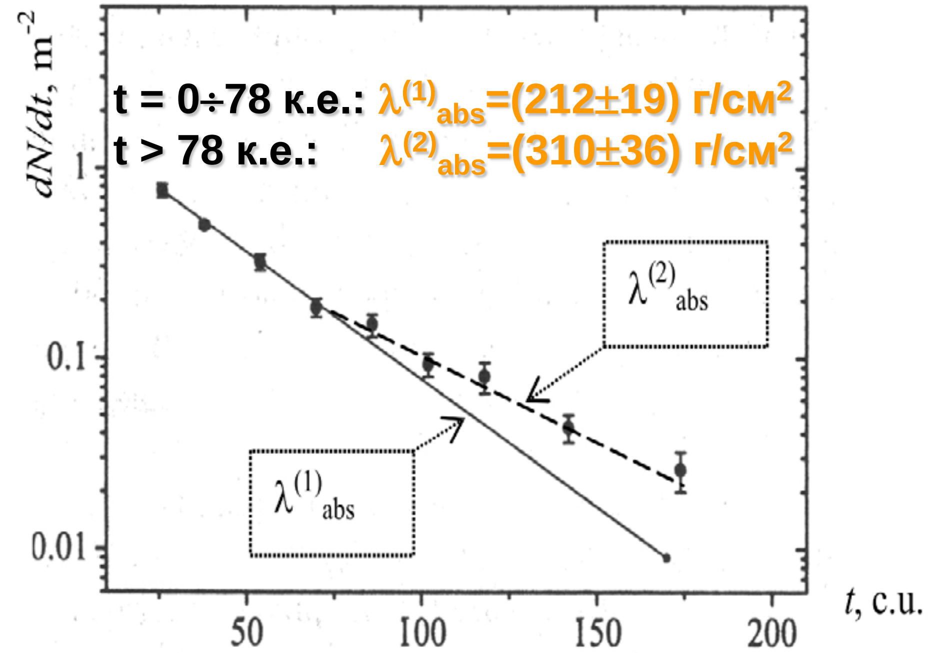


Attenuation length L(E) of hadronic component in EAS cores observed with ionization calorimeter: cross-circles – experiment, solid circles – Monte Carlo without charm (i.e., according to low energy hadronic models), crossed squares – Monte Carlo with charm ($\sigma^{prod}_{h\to c} \approx 30\% \sigma^{inel}_{hPb}$).

Exposition of the deep uniform lead XREC 110 cm thick in the 'Pamir' experiment (1980-ies)



Profile of the deep uniform lead XREC 110-cm thick exposed in the 'Pamir' experiment



Distribution of the cascade origin points for hadrons with $E_h(\gamma) \geq 6.3$ TeV obtained in the Pamir experiment by means of uniform Pb-chambers 110 cm thick.

Hypothesis: *the long-flying cosmic ray hadronic component (I.M.Dremin & V.I.Yakovlev, LPI RAS)*

Two possible explanations of the effect were proposed:

- essential contribution of charmed particles ($D^{0\pm}$, Λ_c);

  (note: the production cross sections σ_c^{prod} at $\sqrt{s}$ < 20 ГэВ, measured at that time with accelerators, were too small, i.e.,:
  σ_c^{prod} ~10 μb);

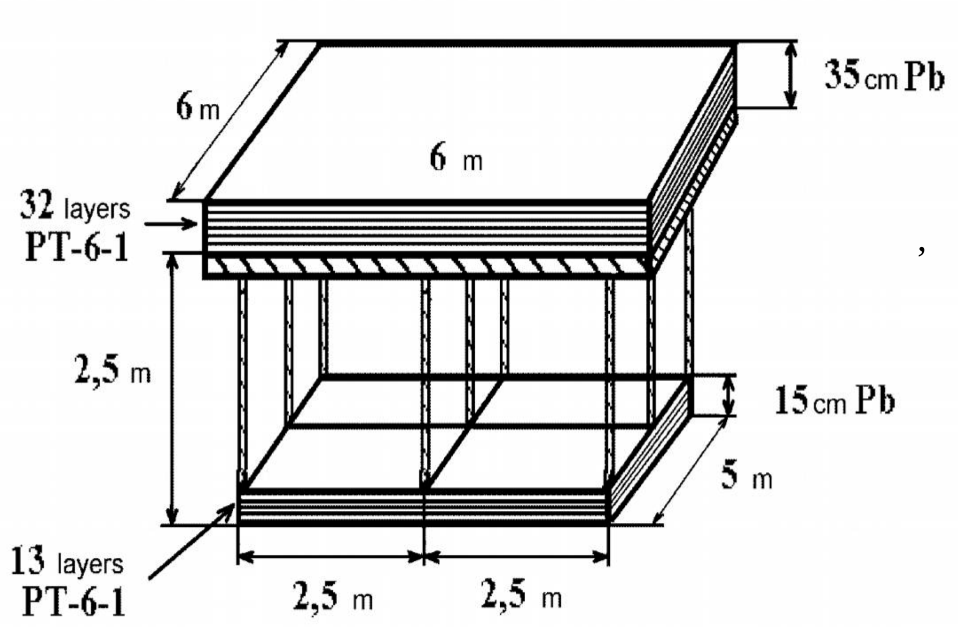
- manifestation of quark strange matter, т.е., existence of strangelets.

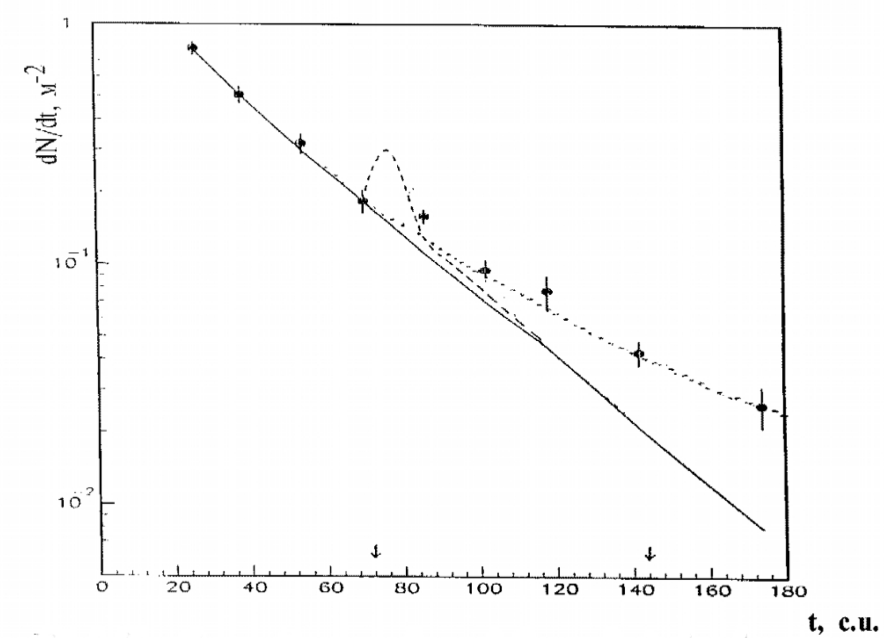
Both candidates can effectively carry energy deep in the lead calorimeter.

A design of 2-tired XREC for testing of the charmed origin of penetrating particles

Hypothesis: **Excessive cascades are initiated by charm particles**

/Feinberg, Dremin, Yakovlev/ ($\sigma^{prod}_{\Lambda_c, D}$ **≈ 3 mb/nucleon** at $E_L \geq 20$ **TeV,** $x_{lab} \geq 0{,}1$)





- A layout and an image (1993) of a 2-storied XREC with 2,5 m air-gap

$$H = c\tau\gamma = c\tau \, E/m \approx 2.5 \text{ m}$$

- Distribution of cascade origin points in deep uniform lead chamber and in 2-storied XREC with 2,5 m air-gap

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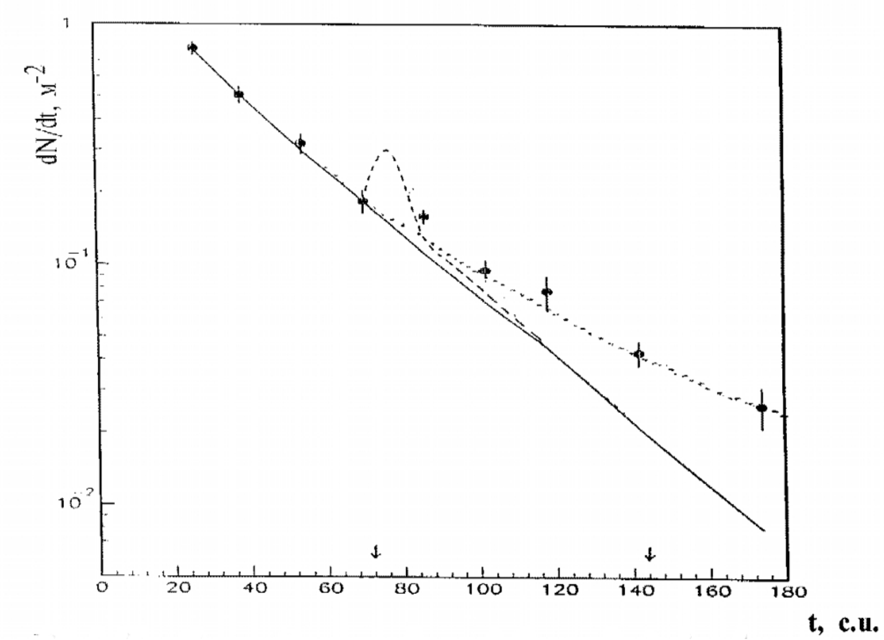

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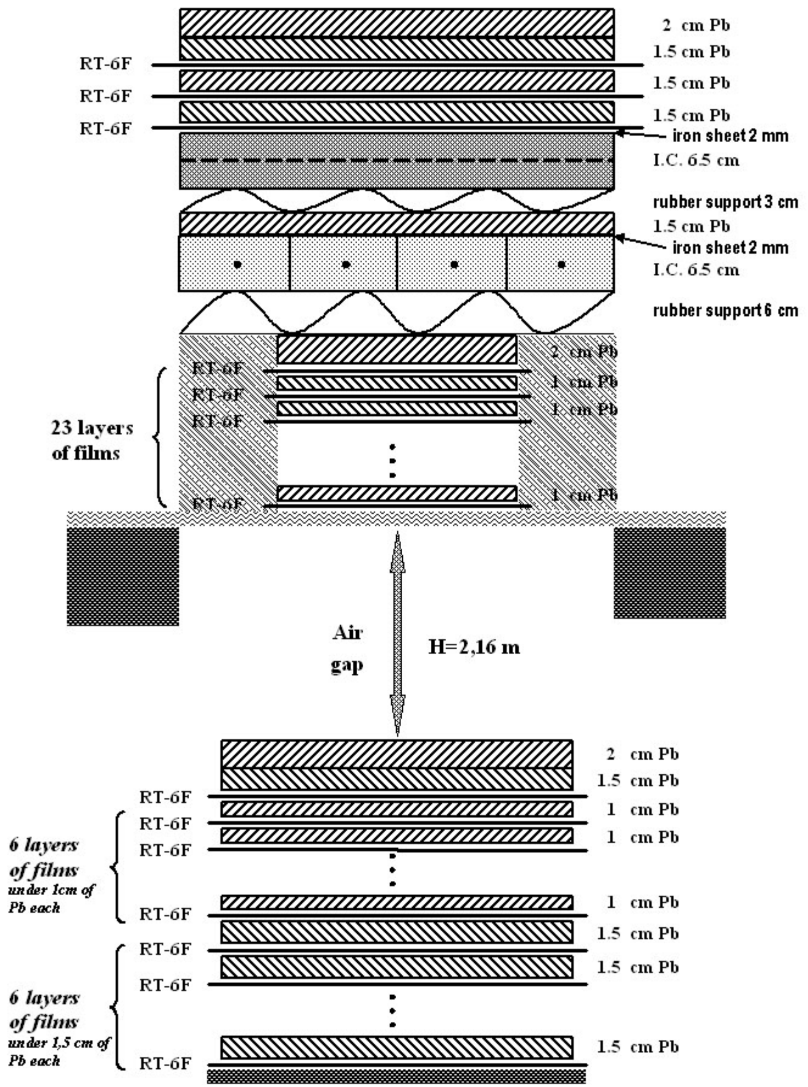
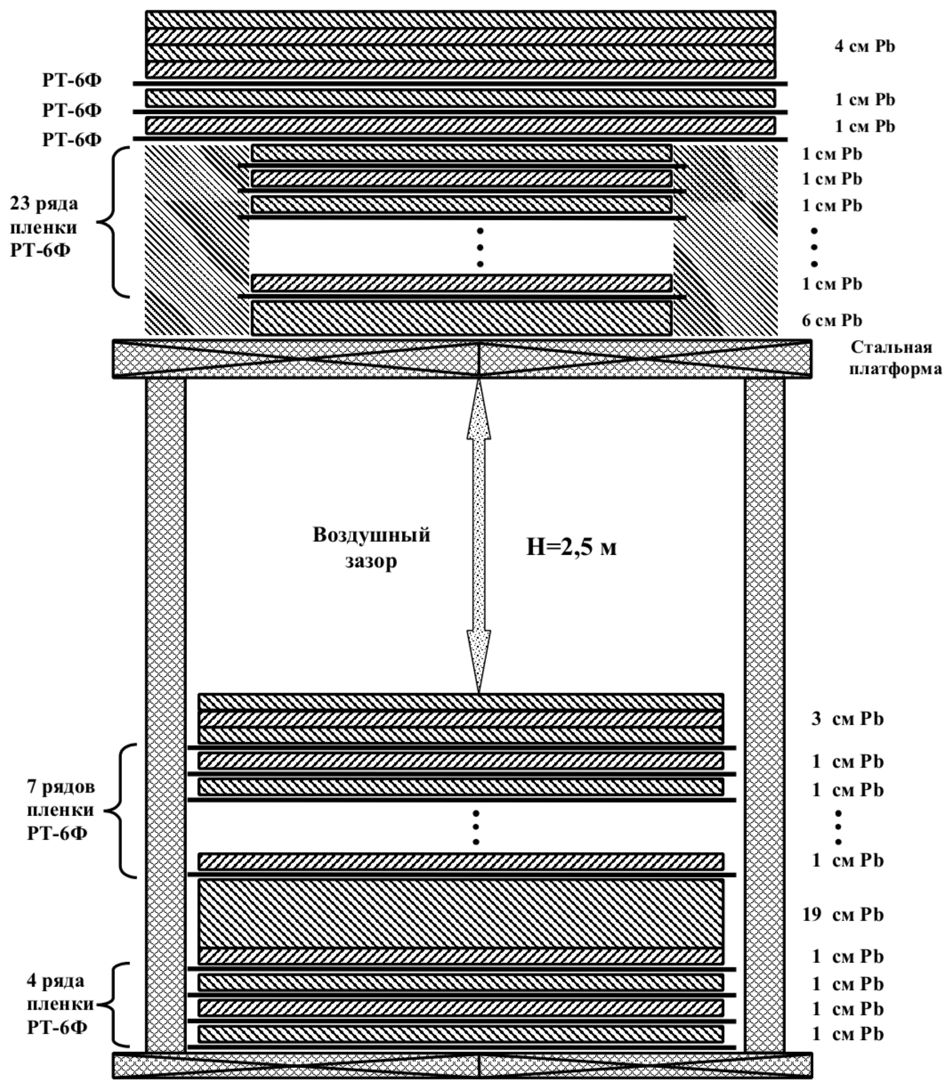
Two-storey XREC with air gap H at the Tien Shan Mountain Station (3340 m a.s.l., H=2.16 м) and at the Pamirs (4370 m a.s.l., H=2.5 m)





- **A scheme of 2-tier XREC at TSS**

$S_{up} = 48\ m^2$, $S_{low} = 32\ m^2$, $E_\gamma^{th} \approx 6$ TeV

- **A scheme of 2-tier XREC at Pamirs**

$S_{up} = 36\ m^2$, $S_{low} = 24\ m^2$, $E_\gamma^{th} \approx 6$ TeV

Simulation of 2-storey XREC response with ECSim2.0 @FANSY 1.0 code accounting for charm production

- **MC code FANSY 1.0 (developed by R.A. Mukhamedshin of INR RAS) is a phenomenological hadronic interaction model implementing quark-gluon string theoretical approaches and assuming various charm production cross section parameters (in many features close to QGSGETII model except for the x-spectra of secondary particles including charmed ones: they appeared to be too soft as compared to the LHC data).**
- **MC code ECSim 2.0 is based on GEANT 3.21 and allows to calculate the detector response for XREC of a given design taking into account the exact experimental technique used in the 'Pamir' experiment.**

New technique of XREC data processing in the case of analysis of hadron absoption in lead calorimeters

Conventional technique of the *'Pamir'* experiment includes:

Reconstruction of hadronic cascades in the XREC applying the photometric procedures performed on microphotometers with diaphragms of radius $R = 84\ \mu m$;

New technique: selecting and counting of only individual darkness spots on each film of a given observational layer by the naked eye enhanced only by a magnifying 2^x glass.

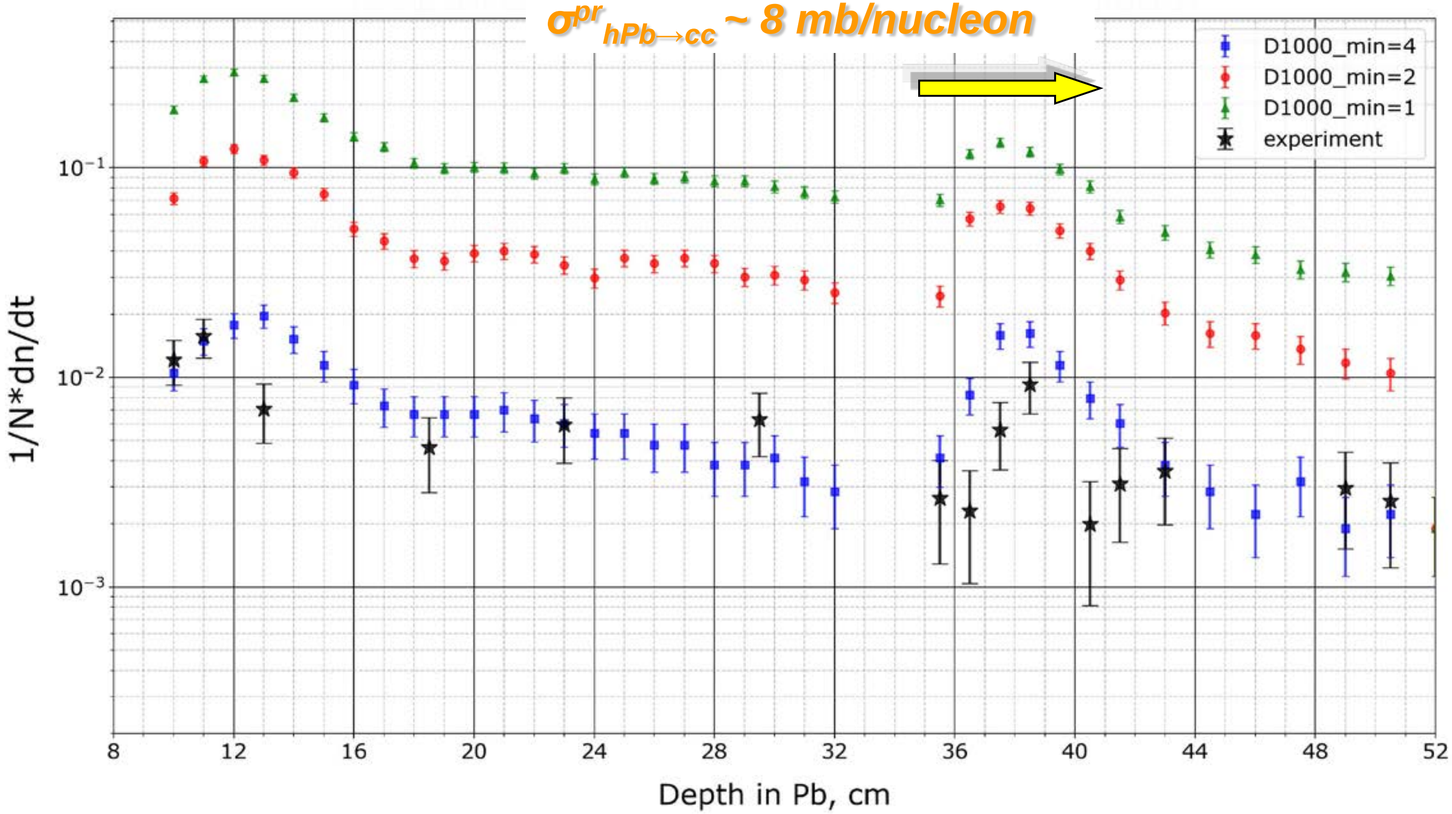
Advantages of the new technique proved by simulations:

- provide high sensitivity to determining of absorption curve parameters;
- increases the statistics of experimental data;
- does not implies conventional photometric procedures what is especially important given the uncertain sensitometric characteristics of new X-Ray films PT-6Φ used in this experiment;
- makes it possible to avoid ambiguities related to reconstruction of hadronic cascades (more stable to systematic errors).

Note: our analysis showed that the selection criteria for dark spots in the experiment give the same result as for simulations if we select spots with optical density $D1000_{min} \geq 0.04$ 'measured' within a photometer diaphragm of radius $R = 1$ mm.

Comparison of Tien Shan experimental data (1-year exposition of 2-storied XREC) with simulation sets

$\sigma^{pr}_{hPb\rightarrow cc}$ ~ 8 mb/nucleon



The fractions of nucleons and pions among incident particles are assumed to be 60% and 40%, respectively. Angular distributions of incident hadrons are also taken into account.

t

Darkness spot number distribution, normalized to an X-Ray film, by the depth *t* of observation layers in the TSS XREC, expressed in cm, for 3 optical density threshold values *D1000min = 0.01/0.02/0.04*

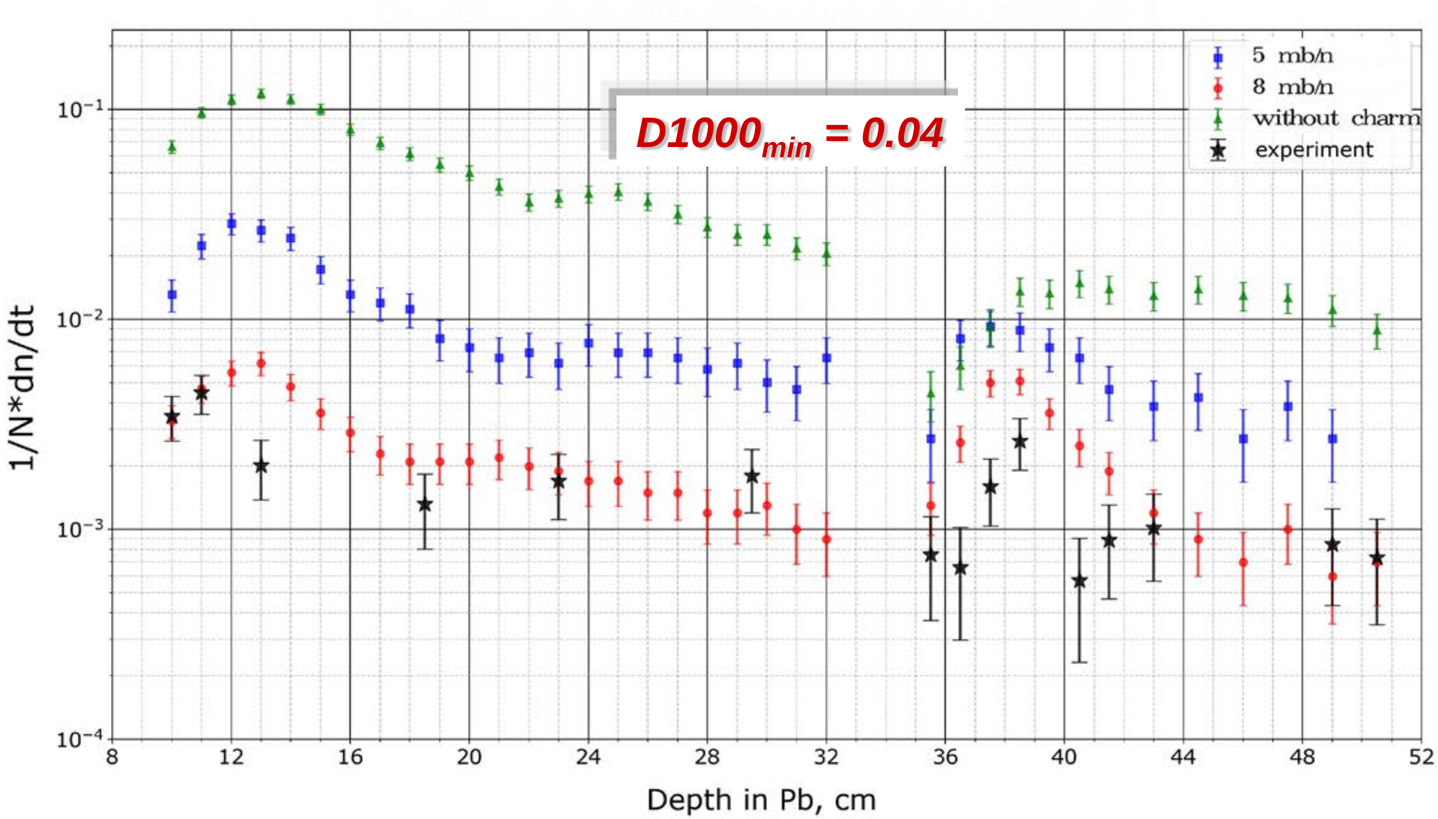
Selection criteria

Experiment: darkness spots are selected by naked eye enhanced by a magnifying glass.

Simulation: optical density threshold $D1000_{min}$ = 0.01/0.02/0.04.

Note: → E-m peak maximum shifts to the right with increasing $D1000_{min}$.

Sensitivity of the Tien Shan 2-storied XREC to the charm particle production cross section



t

The fractions of nucleons and pions among incident particles are assumed to be 60% and 40%, respectively, and angular distributions of incident hadrons are also taken into account.

Darkness spot number distribution, normalized to an X-Ray film, by the depth *t* of observation layers in the XREC, expressed in cm, for 3 values of $\sigma^{pr}_{pp\rightarrow cc} \approx 0./5./8.$ mb/n

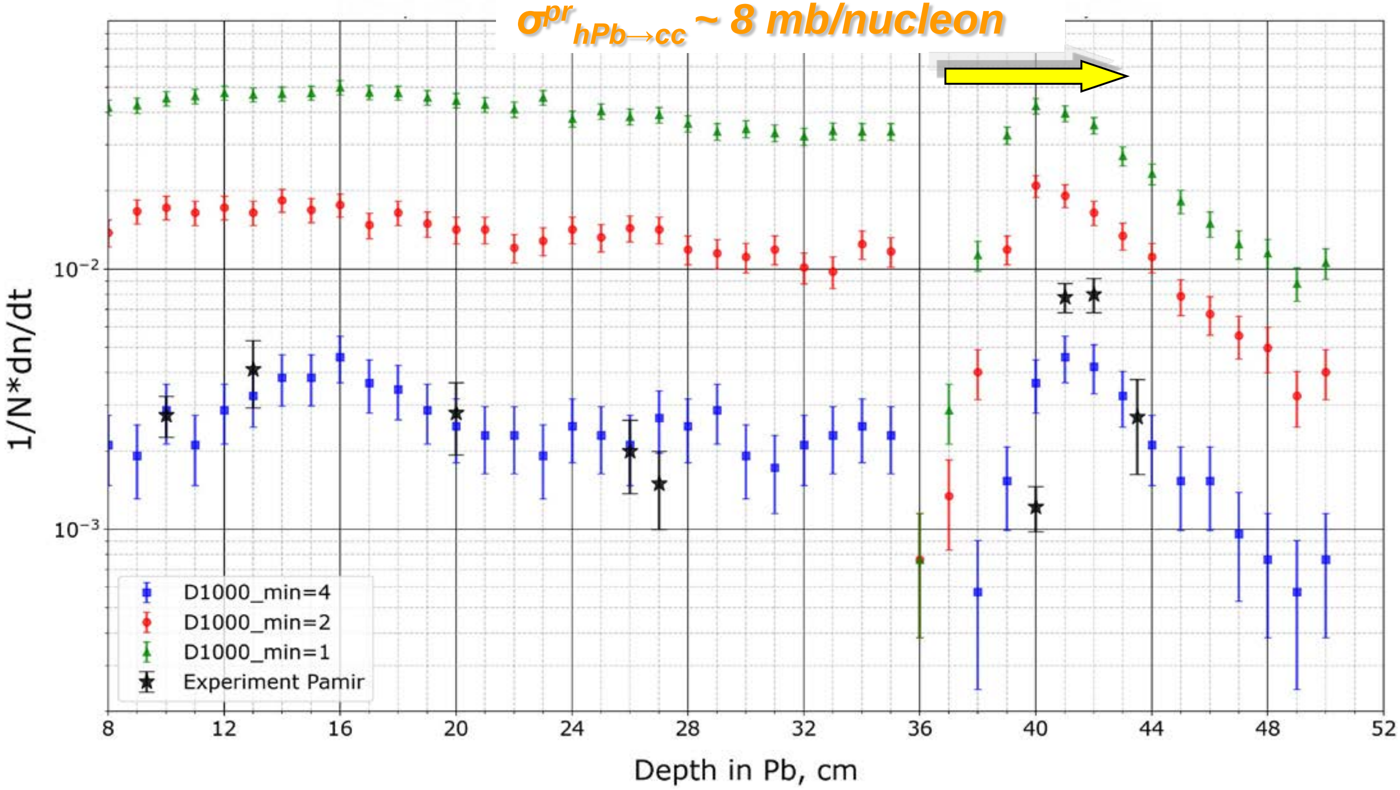
Selection criteria

Experiment: darkness spots are selected by naked eye enhanced by a magnifying glass.

Моделирование: optical density threshold $D1000_{min} = 0.04$

Pamir experimental data (1-year exposition of 2-storied XREC) as compared with simulation ones

$\sigma^{pr}_{hPb\to cc}$ ~ 8 mb/nucleon



The fractions of nucleons and pions among incident particles are assumed to be 70% and 30%, respectively, and angular distributions of incident hadrons are also taken into account.

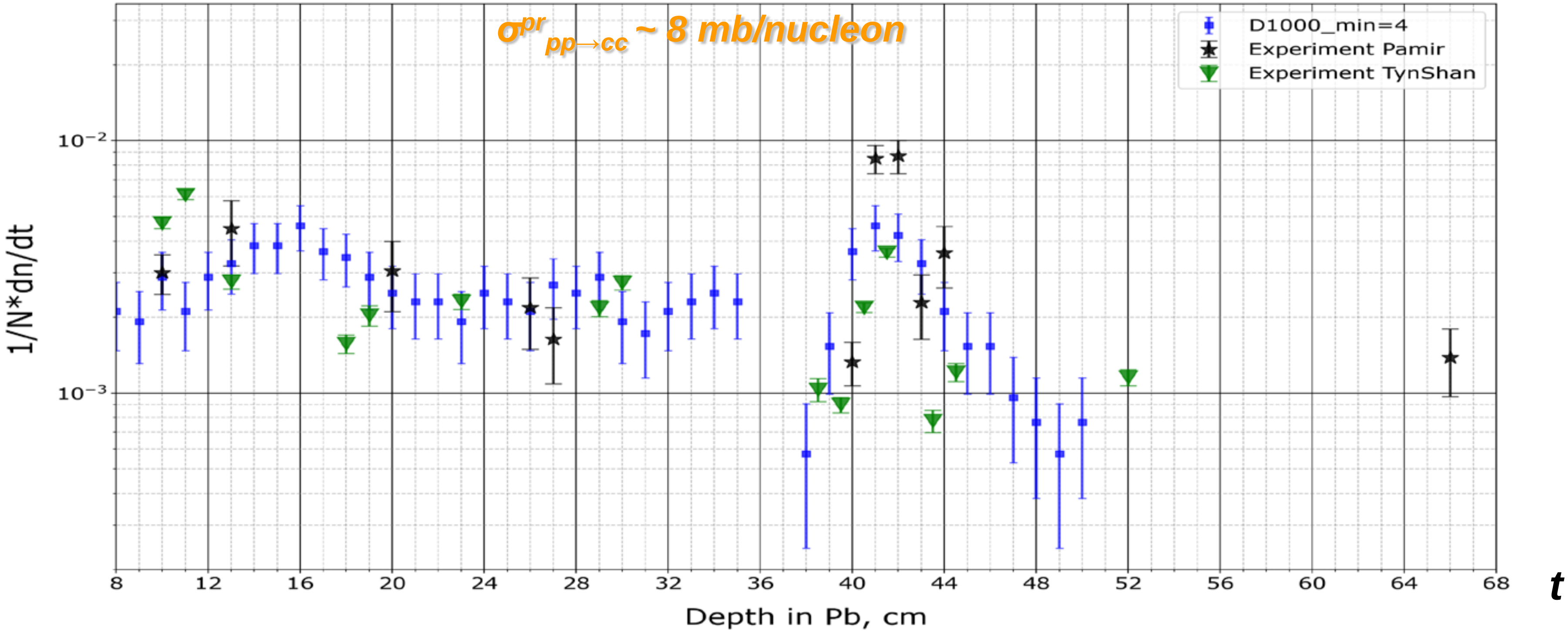
t

Darkness spot number distribution, normalized to an X-Ray film, by the depth *t* of observation layers in the Pamir XREC expressed in cm

Selection criteria

optical density threshold *D1000*$_{min}$ = 0.01/0.02/0.04 (only in the case of simulations while experimental spots were selected by naked eye and a magnifier). Note: EM peak maximum shifts to the right with increasing *D1000*$_{min}$

Combined results of exposition of 2-tier XRECs at Tien Shan and Pamirs in comparison with model calculations



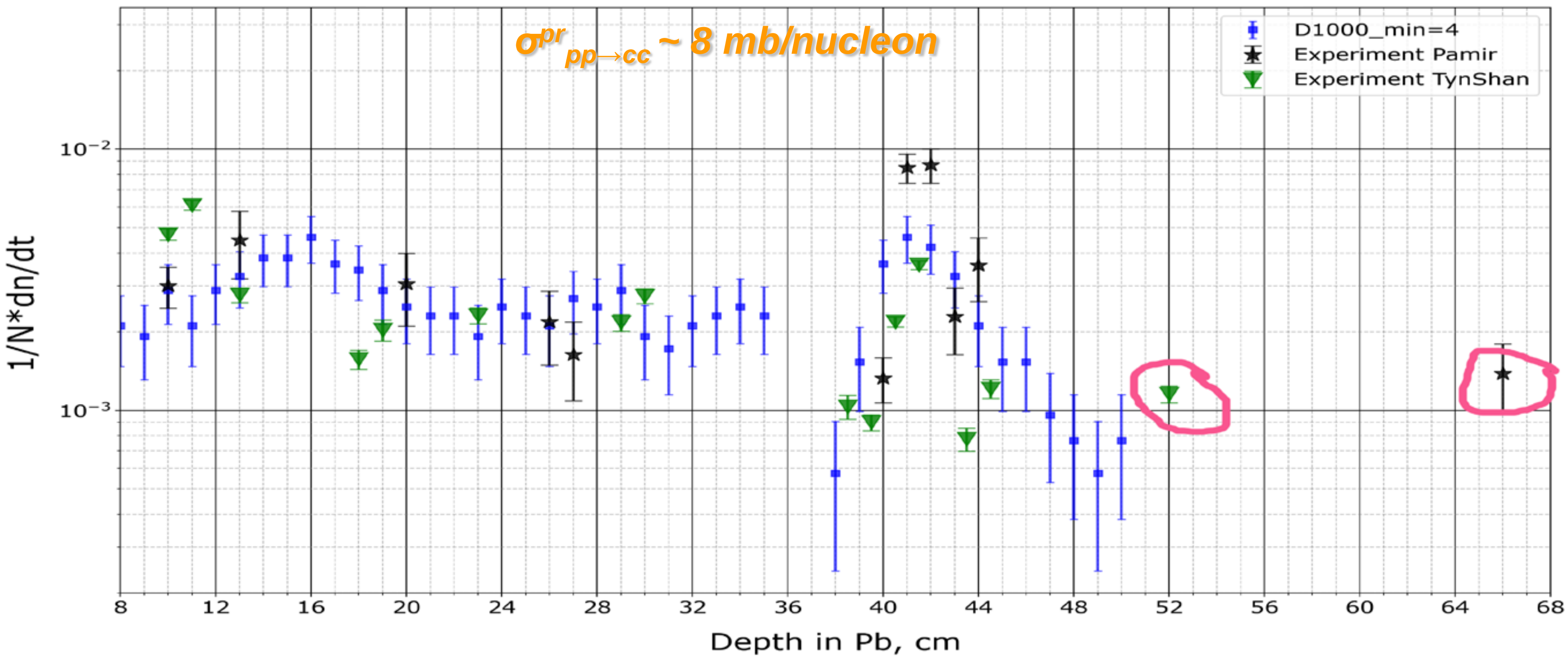
Darkness spot number distribution, normalized to an X-Ray film, by the depth *t* of observation layers, expressed in cm, in 2-tier XREC of both types

Selection criteria

Experiment: **darkness spots are selected by naked eye enhanced by a magnifying glass.**

Моделирование: **optical density threshold *D1000min = 0.04*, $\sigma^{pr}_{pp\to cc}$ ~ 8 *mb/n***

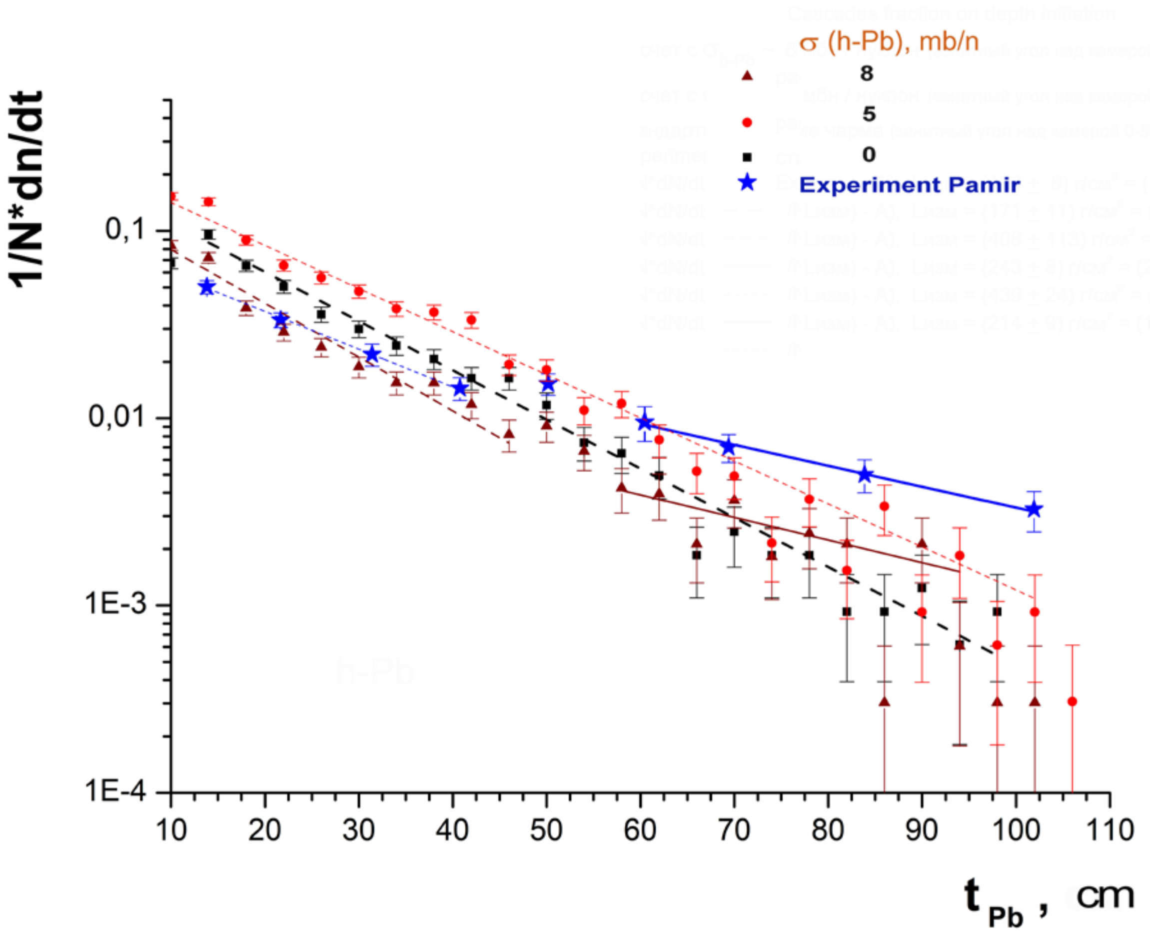
Combined results of exposition of 2-tier XRECs at Tien Shan and Pamirs in comparison with model calculations



Darkness spot number distribution, normalized to an X-Ray film, by the depth t of observation layers, expressed in cm, in 2-tier XREC of both types

!!! A significant excess of hadrons is observed at extremely large depths in both XRECs!!!

Analysis of the experimental data obtained with Pamir deep uniform lead XRECs 110-cm thick



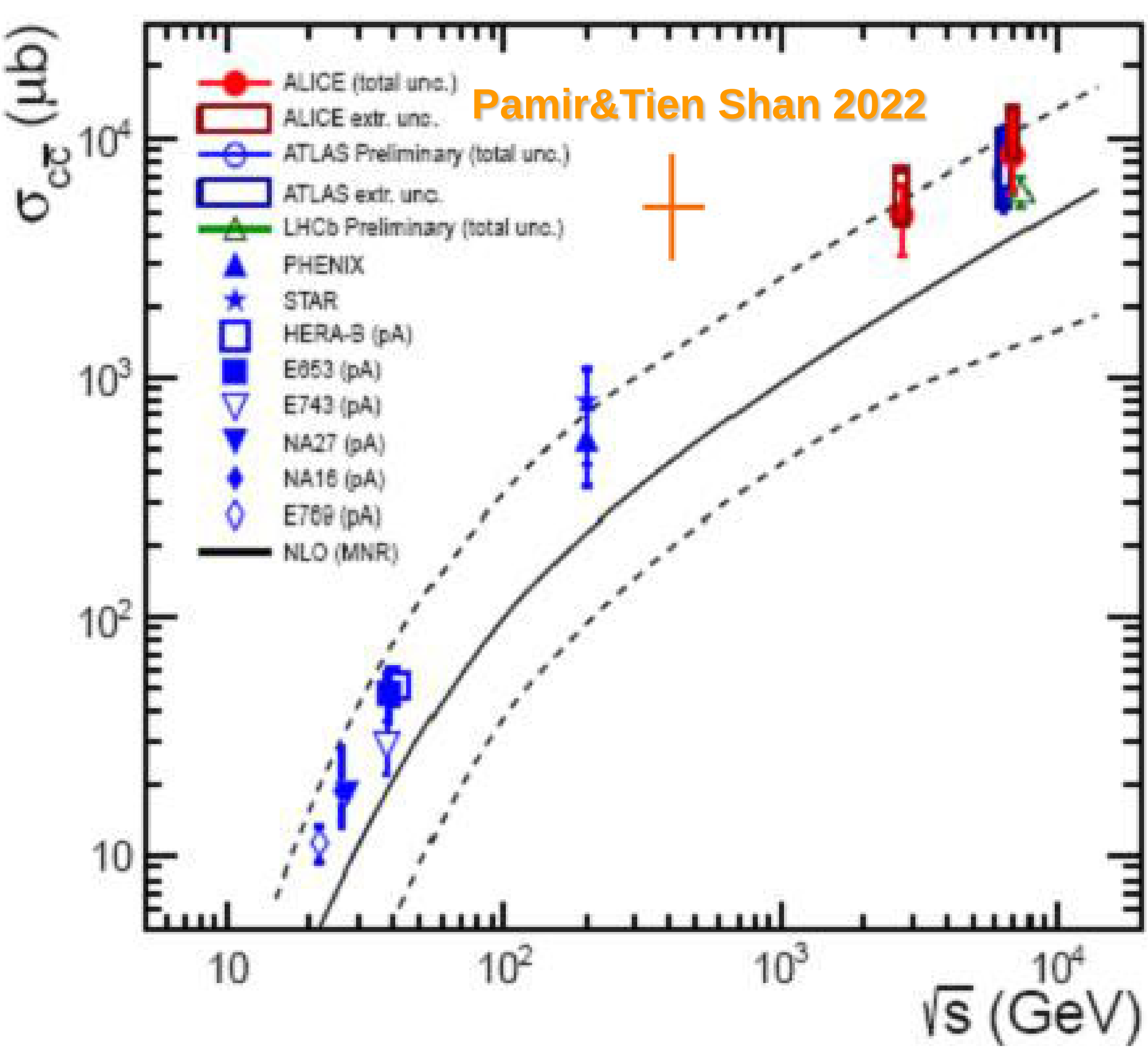
Distributions of hadron cascade origin points produced in uniform lead XREC. Experimental points are shown by blue stars. Simulated data are obtained for $\sigma^{pr}_{hPb\to cc}$ ~ *8* (triangles), 5 (circles) and *0* (squares) mb/nucleon at $x_{Lab} \gtrsim 0.1$ on the assumption that the fractions of nucleons and pions among incident particles are 70% and 30%, respectively.

Recent RHIC and LHC results

$$\sigma_{cc}^{tot}(2.76\ \text{TeV}) = 4.8 \pm 0.8\,(\text{stat.})\,^{+1.0}_{-1.3}\,(\text{syst.}) \pm 0.06\,(\text{BR}) \pm 0.1\,(\text{FF.}) \pm 0.1\,(\text{lum.})\,^{+2.6}_{-0.4}\,(\text{extr.})\ \text{mb}.$$

$$\sigma_{cc}^{tot}(7\ \text{TeV}) = 8.5 \pm 0.5\,(\text{stat.})\,^{+1.0}_{-2.4}\,(\text{syst.}) \pm 0.1\,(\text{BR}) \pm 0.2\,(\text{FF.}) \pm 0.3\,(\text{lum.})\,^{+5.0}_{-0.4}\,(\text{extr.})\ \text{mb}.$$

(12% σ^{inel})



The total charm production cross section at $\sqrt{s}$ =2.76 and at 7 TeV was evaluated by extrapolating from the central rapidity range to the full phase space.

<u>Simulations:</u> perturbative-QCD calculations accounting for Next-to-Leading Order (NLO) corrections

Important note.

Due to the high energy threshold (E_{th} ≥ 4 TeV), XREC experiments observe production of the fastest particles in the forward kinematic cone x_{Lab}>0.1, i.e., they make it possible to study the kinematic fragmentation region of a projectile particle, into which the overwhelming fraction of energy is released at LHC energies.

On the contrary, in collider experiments they observe only the central kinematic region of emerging particles and are forced to extrapolate their data to the unobserved forward fragmentation region (‘forward region’), where x_F ≥ 0.1.

!!! XREC experiments should be considered as complementary ones to collider experiments !!!

Conclusions

- **The nature and position of the features in the absorption curves, obtained in both experiments with a 2-tier XRECs and as a result of model calculations, are in good agreement with each other, which indicates the correct interpretation of the experimental data as the observation of the birth and decay of charmed particles;**
- **Calorimetric experiments in cosmic rays with 2-tier RECs are rather sensitive to the cross section for charm production in the forward cone, which is not accessible for observation in collider experiments.**
- **Charmed particle production cross section in the forward kinematic region ($x_{lab} \geq 0.1$) is as high as**

$$\sigma_{pp \rightarrow charm} \sim 8 \text{ mb/nucleon}$$

***Note:* accounting for more realistic and hard x-spectra may decrease this value**

- **The excess of hadron cascades in the depths of lead calorimers can only be partially explained by the contribution of charmed particles; additional sources of this excess may be strangelets emitted by strange quark stars, or beams of high-energy direct muons generated by charmed hadrons in the atmosphere.**

Prospects :

- **Upgrade of a 2-tier REC by replacing the sensitive element from X-Ray film with extended (12 x 400 см) plastic scintillation counters with fiber-optic signal readout or ionization chambers.**
- **Continuation of researches at the Tien Shan Mountain Station related to the study of the features of absorption of high-energy CR hadrons at great depths of a lead absorber using a 2-tier scintillation/ionization calorimeter.**


Thank you for attention!