NATIONAL RESEARCH CENTRE
«KURCHATOV INSTITUTE»

INSTITUTE FOR HIGH ENERGY PHYSICS

Russia 142281, Moscow region, Protvino, Nauki sq., 1

NRC KI IHEP: recent results at the U-70 machine

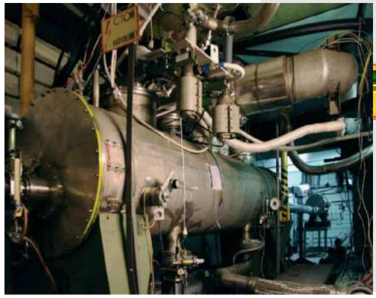
ICCPA'17

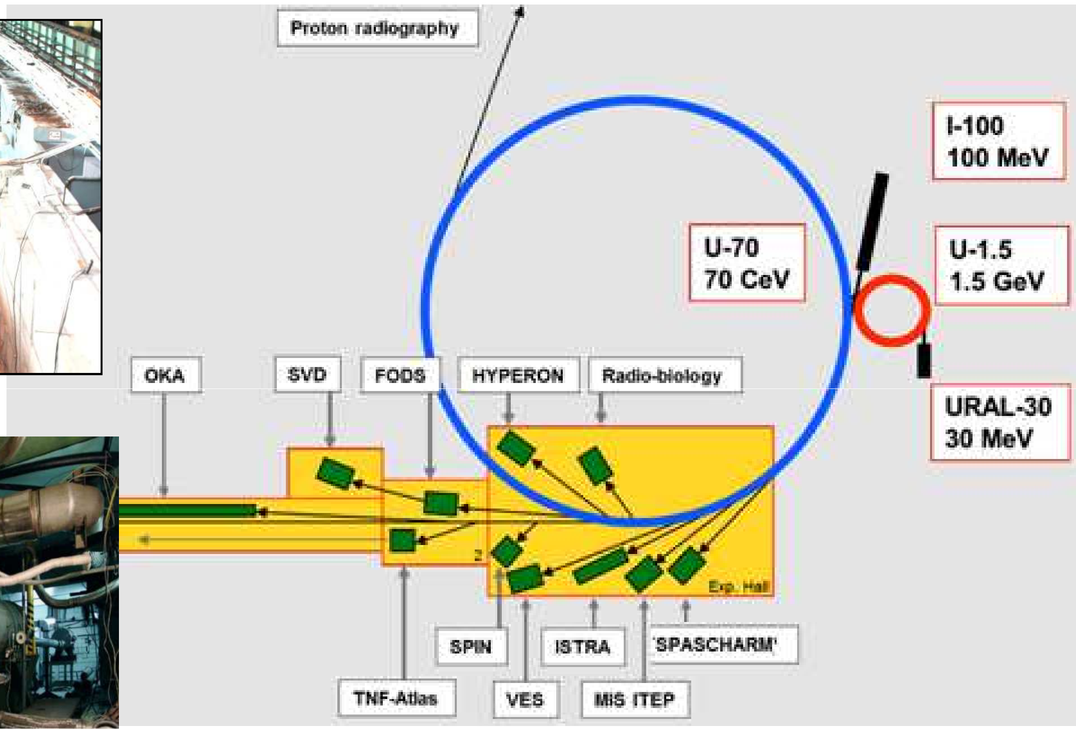
MEPhI, October 5

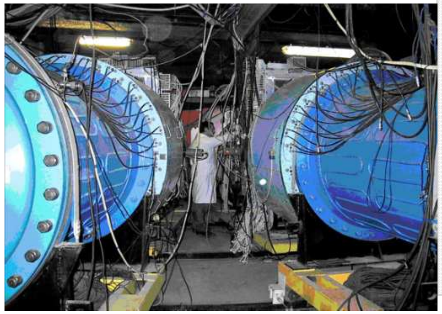
A.Zaitsev


NRC «Kurchatov Institute»
Institute for High Energy Physics
Protvino

Layout of accelerators and research facilities







E=70 GeV, (50 GeV)
I=1.7·10^{13}ppp(1.0·10^{13}ppp)
Beams : π+-, K+-,p,p̄, e+-,^{12}C

- Fast extraction
- Slow extraction
- Extraction by crystals
- Internal targets

Research directions:

- hadron spectroscopy
- rare kaon decays
- spin asymmetries
- baryon matter
- nuclear physics
- ………
- proton radiography
- radiobiology
- radiation hardness
- beam optics with crystals
- R&D on detectors
- ……….

R@D

Scintillators

Photomultipliers

Muon tomography

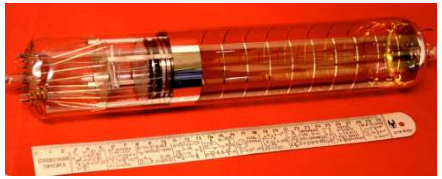
GaAs detectors

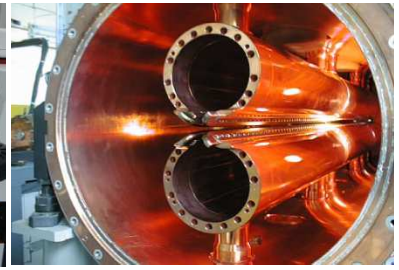
RFQ development

Beam optics

Superconducting systems

…….



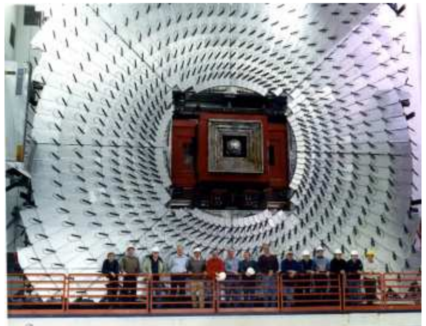


International collaborations

- USA
  - FNAL D0, MU2e
  - BNL PHENIX, STAR
- EUROPE
  - DESI XFEL , HERMES
  - FAIR PANDA
- CERN
  - LHC machine
  - ATLAS
  - CMS
  - LHCb
  - ALICE
  - COMPASS
  - DIRAC
  - NA 62
  - NA 64
- JAPAN
  - BELLE, BELLE II









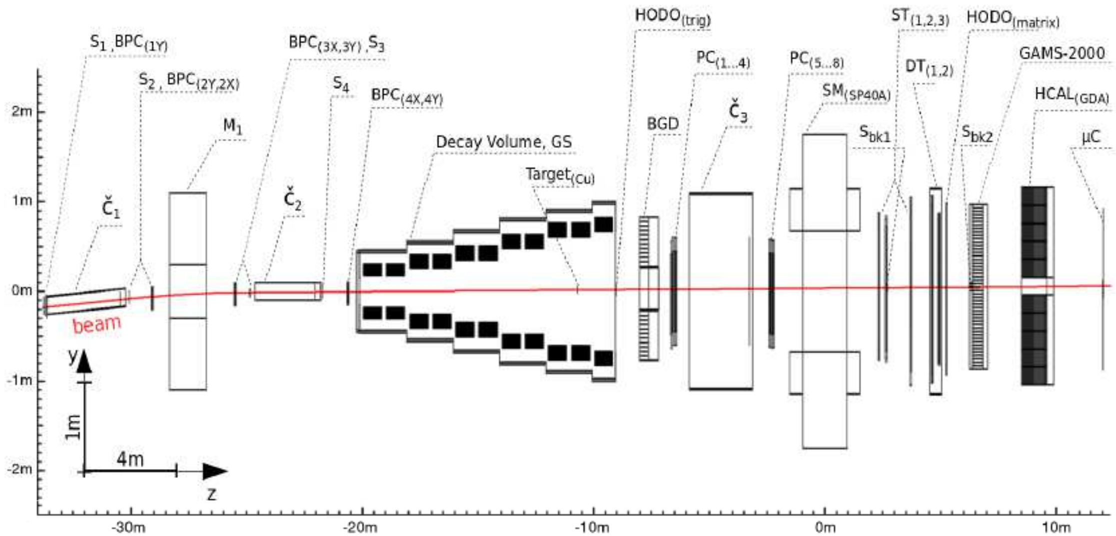





OKA Kaon decays

Separator (Panofsky scheme):

– Frequency 2865 MHz
– The resonator length is 2.74 m
– The average deflection field ~ 1 (.6) MV / m
– Operating temperature 1.8 K



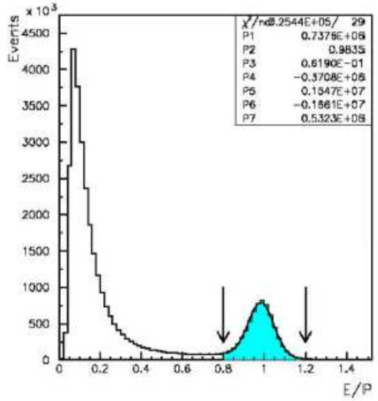
– The proton beam momentum 50 GeV
– Intensity ~ $7x10^{13}$ / spill
– Spill 2 sec, τ cycle = 9,7 s
– Secondary beam momentum 12.5 or 18 GeV
– Length of the channel ~ 200 m
– K^+ intensity ~$0.5x10^6$/spill
% K^+ in the beam up to 20%

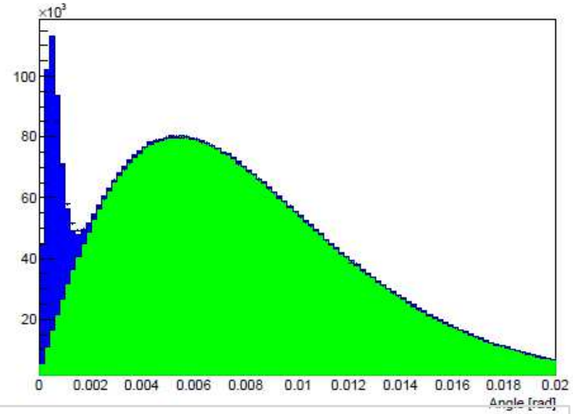
Analysis in progress:
1. Form factors of the decays: Ke3, Kμ3
2. Search for a heavy sterile neutrino in K^+→μ+ν
3. Study of the decay Kμ3γ
4. Study of the coherent process K^+ Z→ $K^+\pi^0$ Z
5. Exact measurement of BR Ke3
6. Study of the Ke3γ decay
7. Study of the decay Kμ2γ

Ke3 decay studies

OKA

arXiv:1708.09587v1



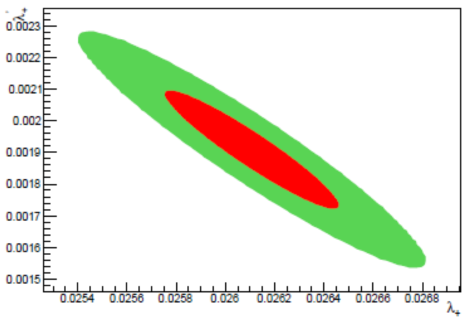


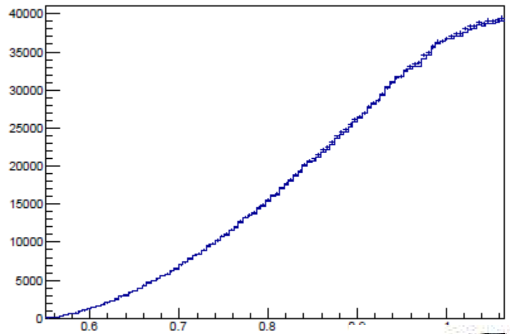
E/P plot - the ratio of the energy of the associated ECAL cluster to the momentum of the charged track (left); α - the angle between $\vec{p}_K$ *and* $\vec{p}_e + \vec{p}_\pi$ *in the lab-system(right).*

$$M = \frac{-G_F V_{us}}{2} \bar{u}(p_\nu)(1+\gamma^5)[((P_K + P_\pi)_\alpha f_+ + (P_K - P_\pi)_\alpha f_-)\gamma^\alpha - 2m_K f_S - i\frac{2f_T}{m_K}\sigma_{\alpha\beta}P_K^\alpha P_\pi^\beta]v(p_l)$$

$$f_+(t) = f_+(0)(1 + \lambda'_+ t/m_{\pi^+}^2 + \frac{1}{2}\lambda''_+ t^2/m_{\pi^+}^4)$$

About 5.25M events are selected for the analysis. The linear and quadratic slopes for the decay formfactor f+(t) are measured:
λ′+ = (26.1±0.35±0.28)×10⁻³ ,
λ″+ = (1.91±0.19±0.14)×10⁻³ .
The scalar and tensor contributions are compatible with zero.





$$z = 2E_\pi^*/M_K$$

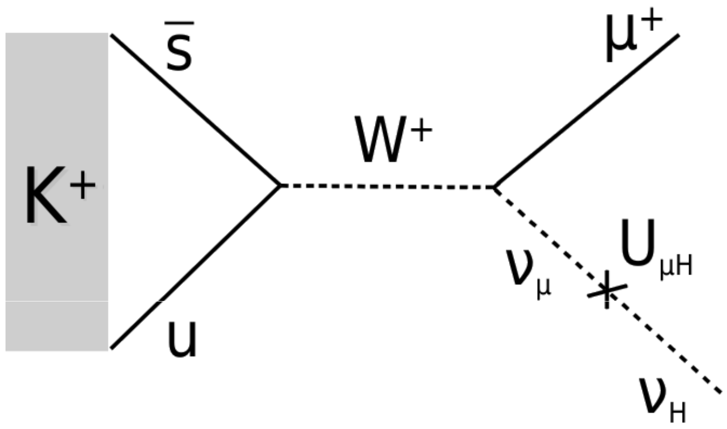
λ′ – λ″ correlation plot (left); Projection of the Dalitz-plot on z (right) axis

OKA

Search for heavy neutrino in $K^+ \rightarrow \mu^+ \nu_H$ decay

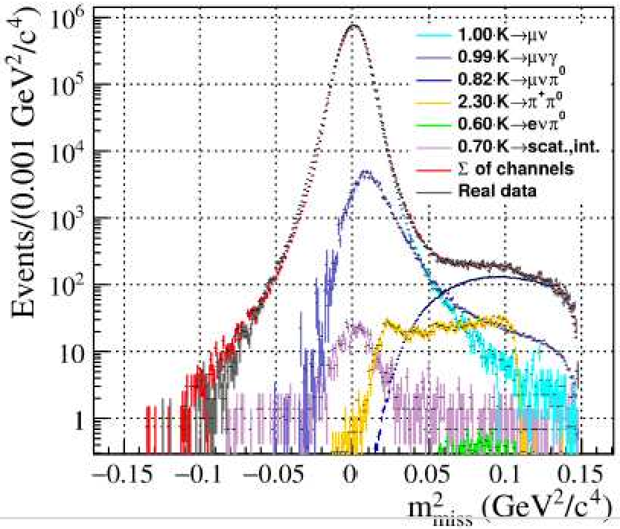
arXiv:1709.01473v1

A high statistics data sample of the $K+ \rightarrow \mu+\nu$ decay was accumulated by the OKA experiment in 2012. The missing mass analysis was performed to search for the $K^+ \rightarrow \mu^+ \nu_H$ channel with a hypothetic stable heavy neutrino in the final state. The obtained missing mass spectrum does not show peaks which could be attributed to existence of stable heavy neutrinos in the mass range $(220 < m_H < 375)$ MeV/c^2. As a result, we obtain upper limits on the branching ratio and on the value of the mixing element $|U_{\mu H}|^2$.

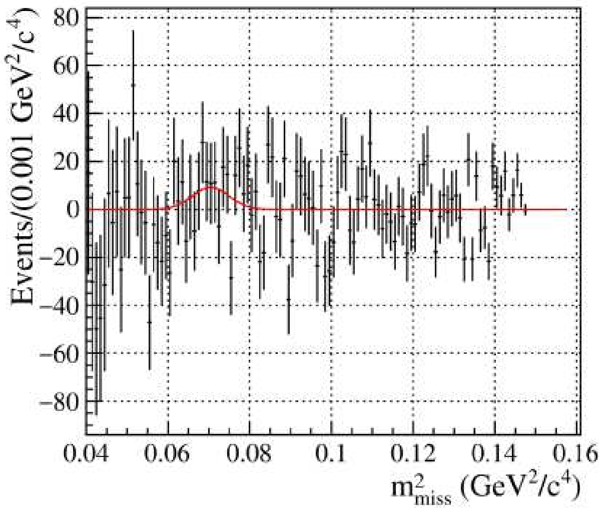


Production of a heavy sterile neutrino in the K+ decay

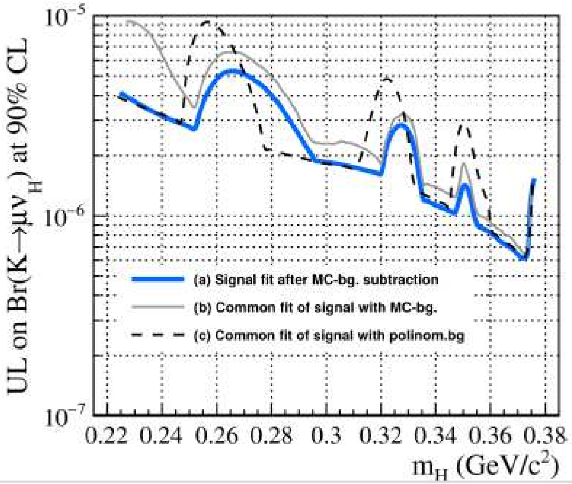
OKA



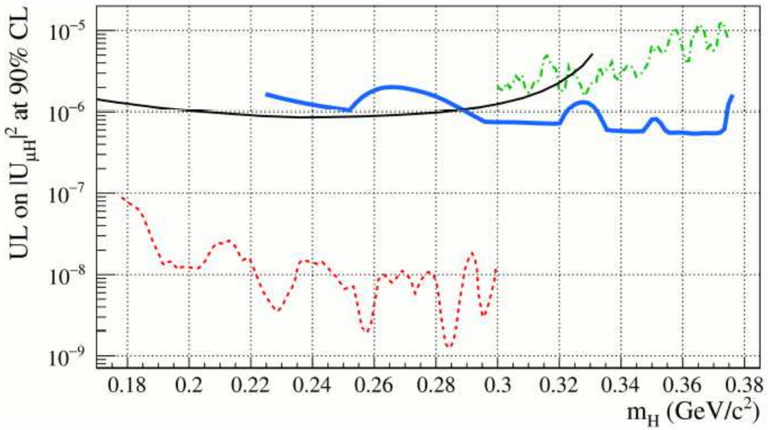
Missing mass distribution m^2_{miss} for the data and MC events



The residual signal distribution after subtraction of the fitted background

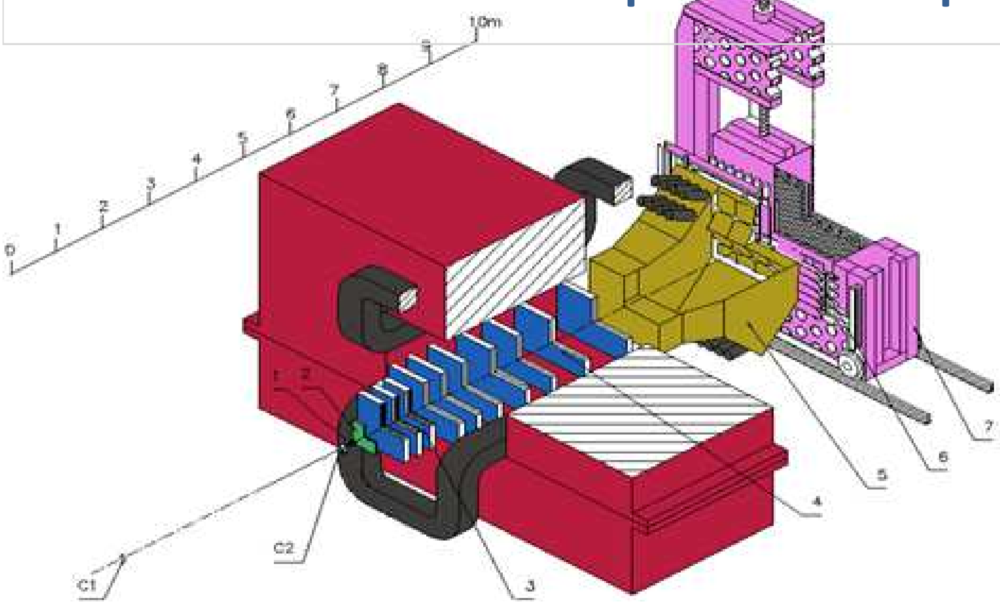


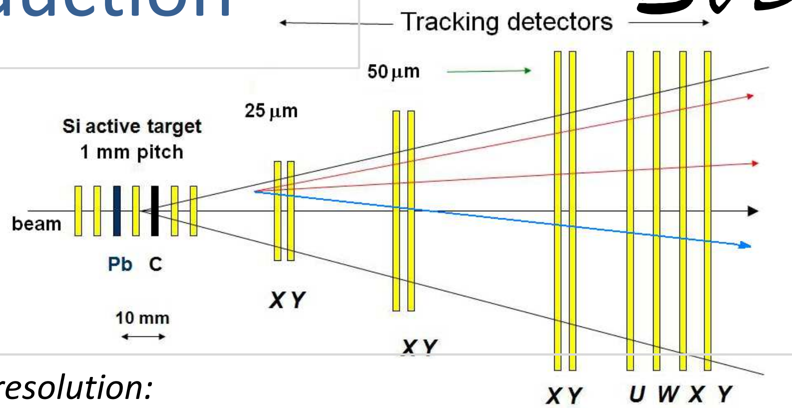
Upper limit for $Br(K^+ \rightarrow \mu^+ \nu_H)$ at 90% CL as a function of a heavy neutrino mass



The OKA upper limit on the mixing matrix element $|U_{\mu H}|^2$ at 90% CL is shown with solid blue curve, in comparison with preceding experiments

SVD Charmed particles production





Z-resolution:

for the primary vertex : 70-120 μm

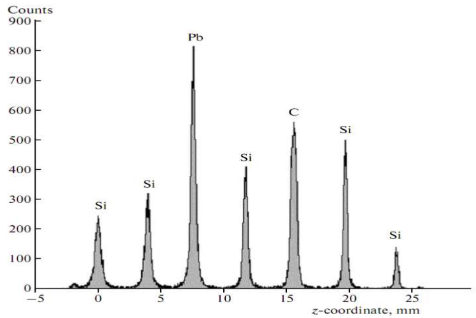
for the secondary vertex : 250-300 μm

X,Y-resolution for primary vertex : 8-12 μm

Impact parameter resolution : ~ 12 μm

Effective mass resolution :K^0 - 4.4 MeV, Λ^0 - 1.6 MeV

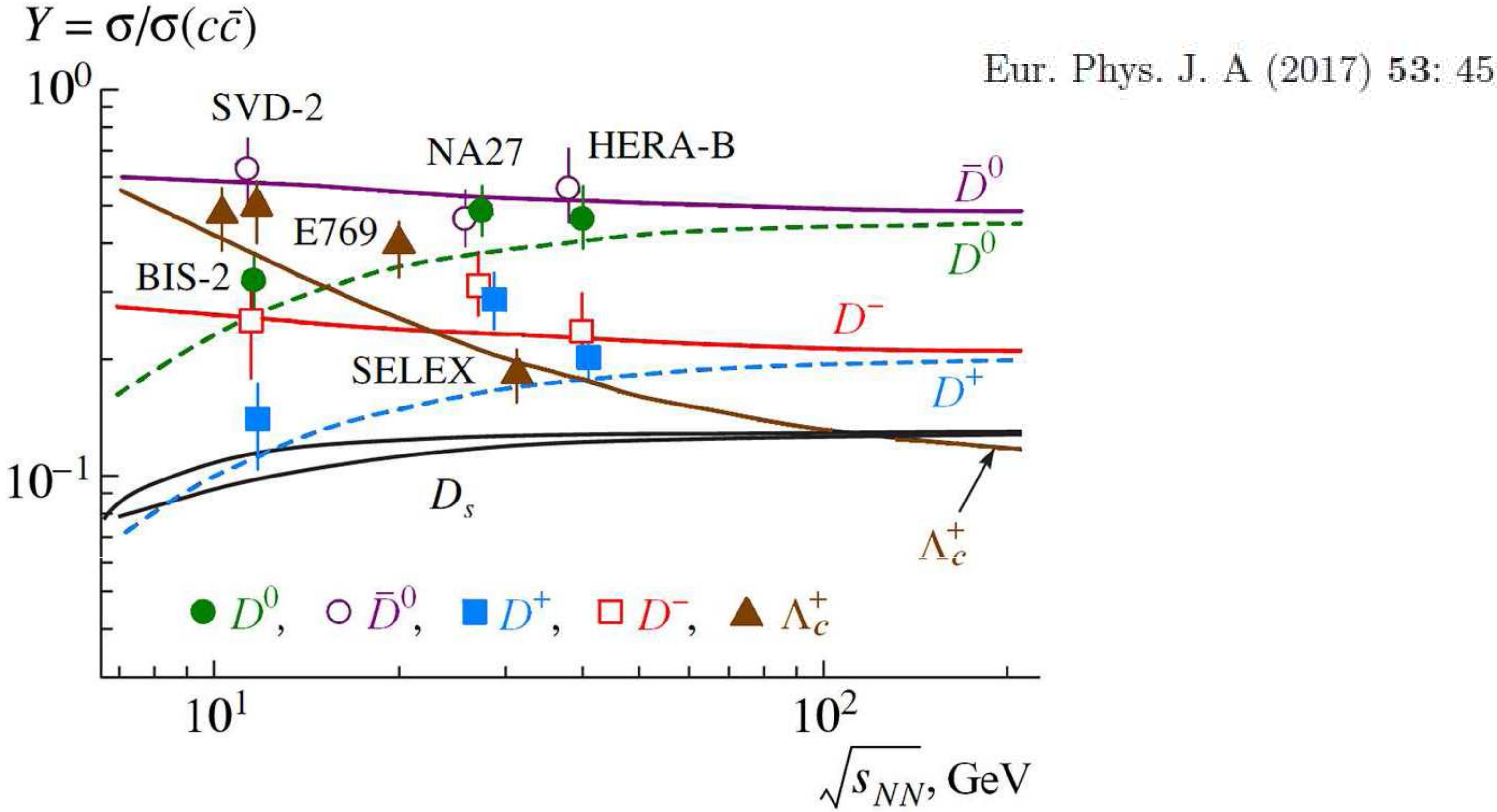
C1, C2 – beam scintillation counters;
1 – Si active target (AT);
2 – microstrip vertex Si-detector (MSVD);
3, 4 – MWPC of magnetic spectrometer (MS);
5 – threshold Čerenkov counter (ČC);
6 – scintillation hodoscope (SC);
7 – detector of γ-quanta (DEGA)



The reconstructed Z-coordinates of the primary vertices in AT

This setup has been constructed for study of charmed particles production in pp- and pA-interactions by the SVD collaboration including NRC KI IHEP (Protvino), JINR (Dubna), NPI MSU (Moscow).

RATIOS OF CHARMED PARTICLES YIELDS

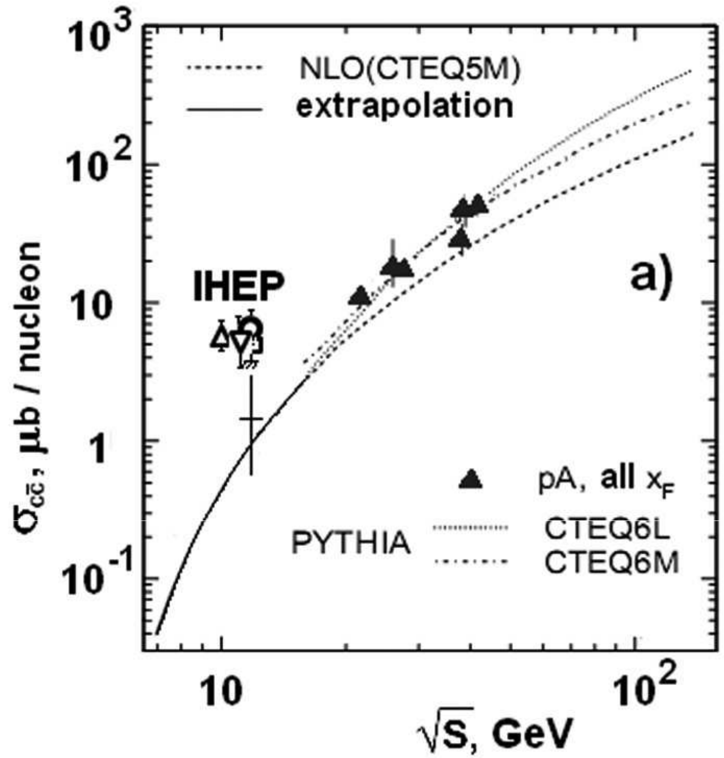


Relative yields of charmed particles. The theoretical curves (with designation of a particle) are taken from the predictions of the statistical hadronization model.

The results are compatible with the predictions of the statistical hadronization model

RESULTS:

$$\sigma_{tot}(c\bar{c}) = 7.1 \pm 2.3(stat) \pm 1.5(syst)\,\mu b/nucleon$$

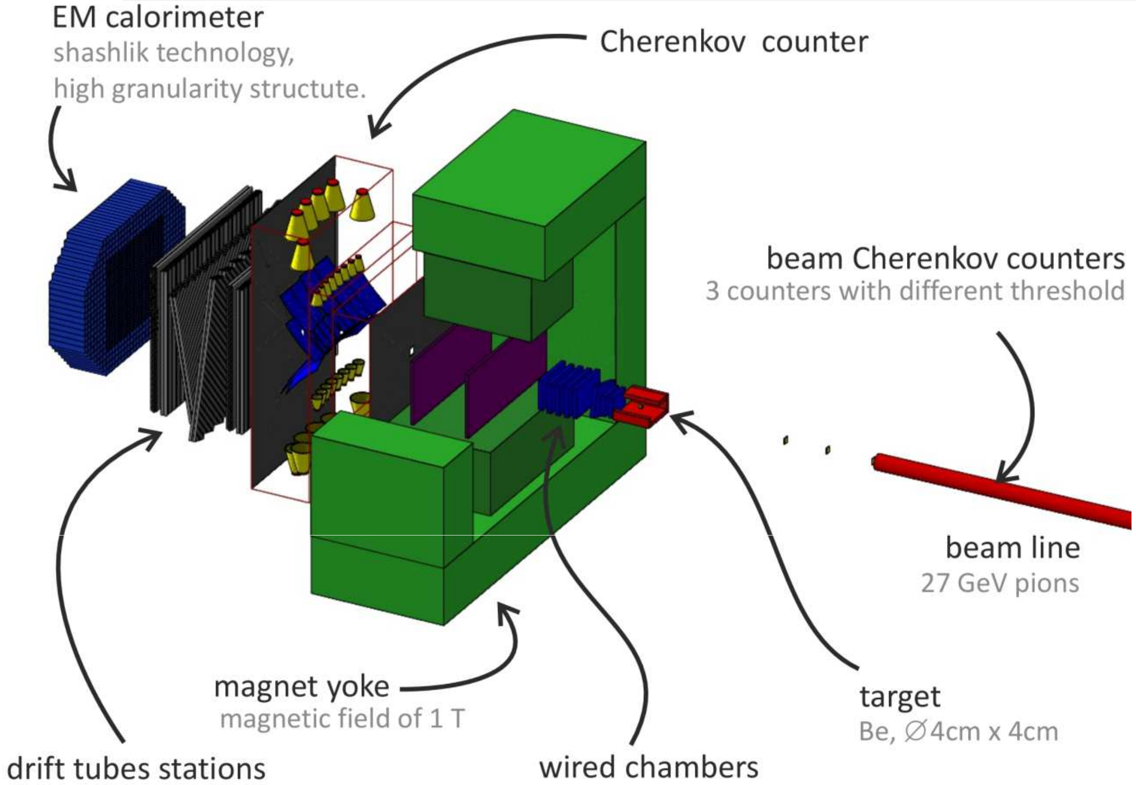


The total cross section for charm production in pA-interactions from SVD-2 and other experiments: ○ – SVD-2, ∇ – beam-dump with muon absorber , □ – SCAT bubble chamber experiment and Δ – the experiment with BIS-2 spectrometer.

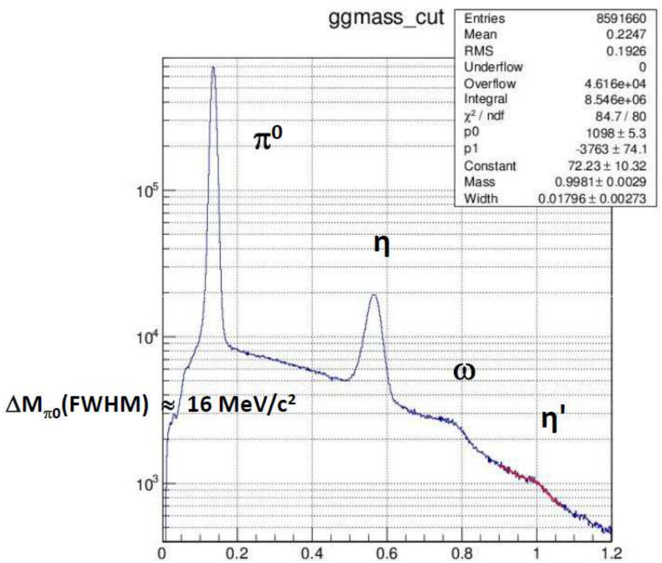
The total open charm production cross-section at √s = 11.8 GeV is well above QCD models predictions. Relative yields are close to the prediction of QGSM for D mesons and for Λ_c^+ baryon at this energy.

VES Meson spectroscopy

VES



Soft trigger
~ 10^{10} events

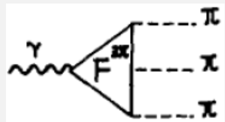


3 π
Exotics: JPC = 1-+ …..
Radial excitations: a1’, a2’ ….
Threshold effects: a1(1420)...
High spin a3(1880): a4(2040)...
ππ S-wave

ππ
Excitations: ρ’ …..
ηπ, η’π, ηηπ, ηππ, KKπ ….
Exotics, precision spectroscopy, isospin violation …..

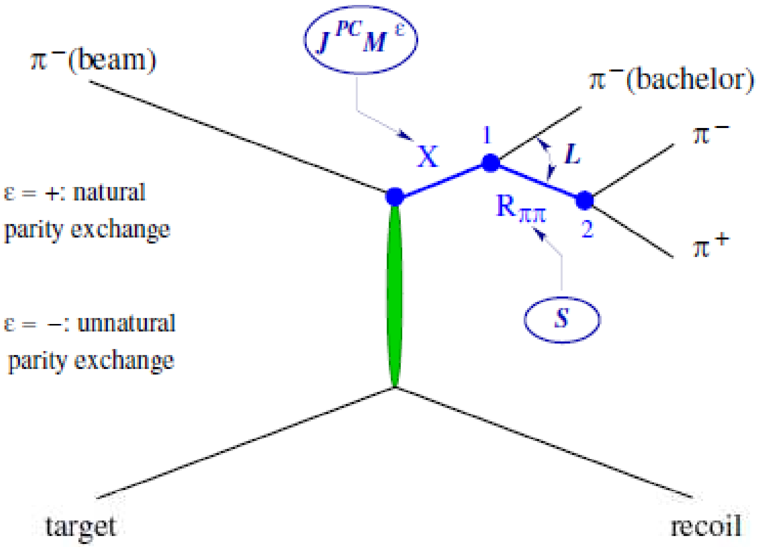
π^- Y*→X

X = 3 π
X = ππ
X = ηπ



VES Partial Wave Analysis

VES



- $\psi_i^{\varepsilon}(\tau)$ enumerated by its quantum numbers
- $i, \varepsilon = J^{PC} M^{\varepsilon}$ [isobar] π L
- has no free parameters

The mass-independent PWA events density:

$$\mathcal{I}(m,t',\tau) = \sum_{\varepsilon}\sum_{r}\left|\sum_{i} T_{ir}^{\varepsilon}(m,t')\bar{\psi}_i^{\varepsilon}(\tau,m)\right|^2$$

The density matrix:

$$\rho_{i,k}^{\varepsilon} = \sum_r T_{ir}^{\varepsilon} T_{kr}^{\varepsilon *}$$

The partial wave intensities:

$$I_k(m,t') = \rho_{k,k}^{\varepsilon}$$

Phase of wave i relative to wave k:

$$\phi(i-k)(m,t') = arg(\rho_{i,k}^{\varepsilon})$$

Data:	
Statistics	+-
Background	+-
Precision	+
Efficiency	+
Systematics	+-

Analysis (PWA)

This ansatz can be too simplistic and lead to erroneous results for weak waves and an uncontrolled systematic errors for large waves. A number of additional analyzes improve the reliability of the results:

- Variation of a set of waves
- Variation of the parameters of isobars
- Variation of the rank of the density matri
- Mapping channels $\pi^-\pi^-\pi^+$ and $\pi^-\pi^0\pi^0$

common (first two)

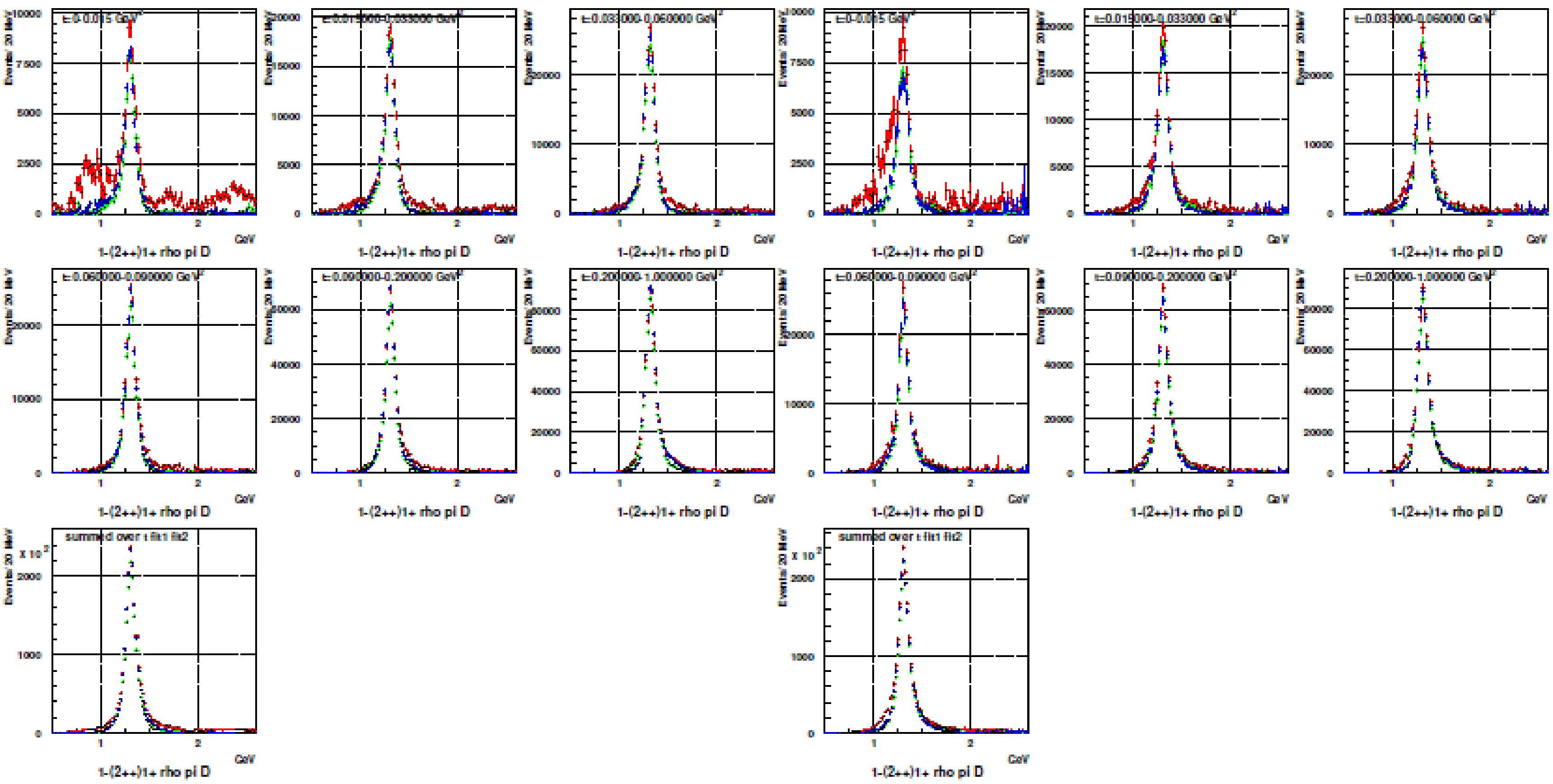
new: MESON2016, HADRON2017 (last two)

VES PWA example One wave out of a fifty

VES

Rank=1;Unlim. Rank;Unlim. Rank, highest eigenvalue

$\pi^- N \to \pi^-\pi^-\pi^+ N$ | $\pi^- N \to \pi^-\pi^0\pi^0 N$

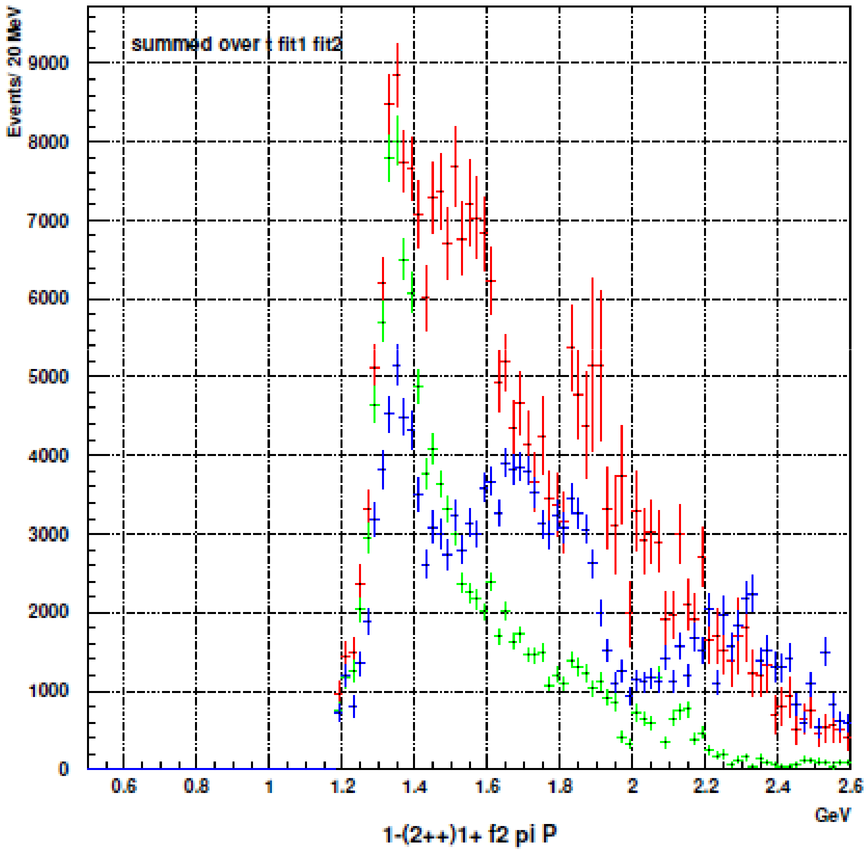


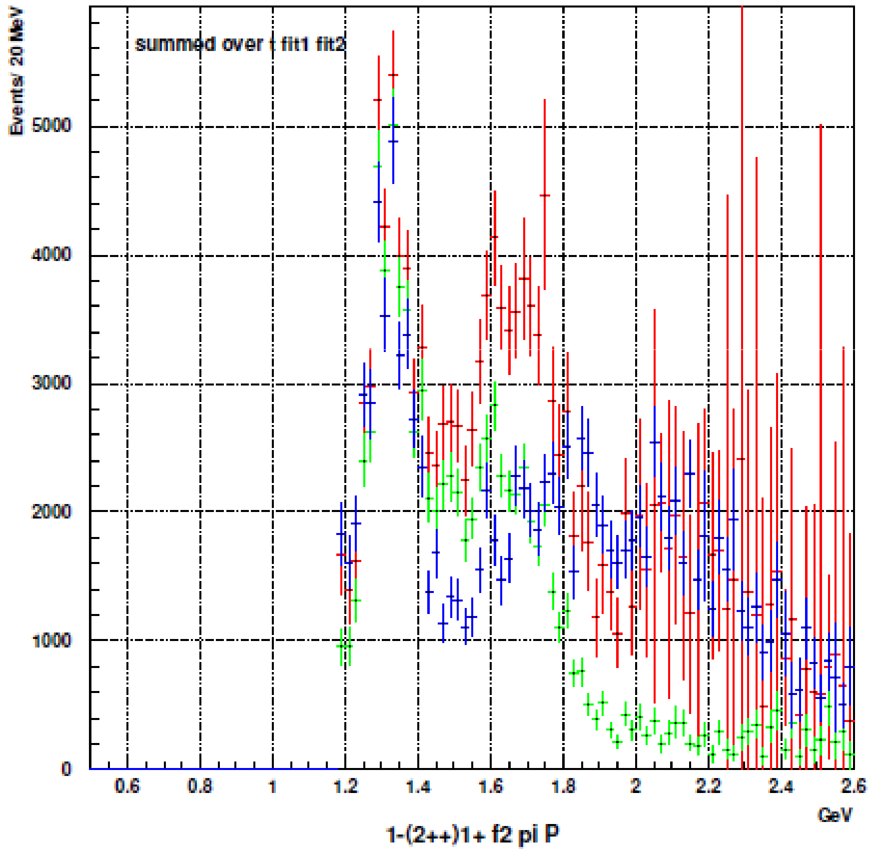
intensity of $2^{++}1^+\rho(770)\pi$ -the most stable btw. models and 2 systems

VES

Rank=1;Unlim. Rank;Unlim. Rank, highest eigenvalue

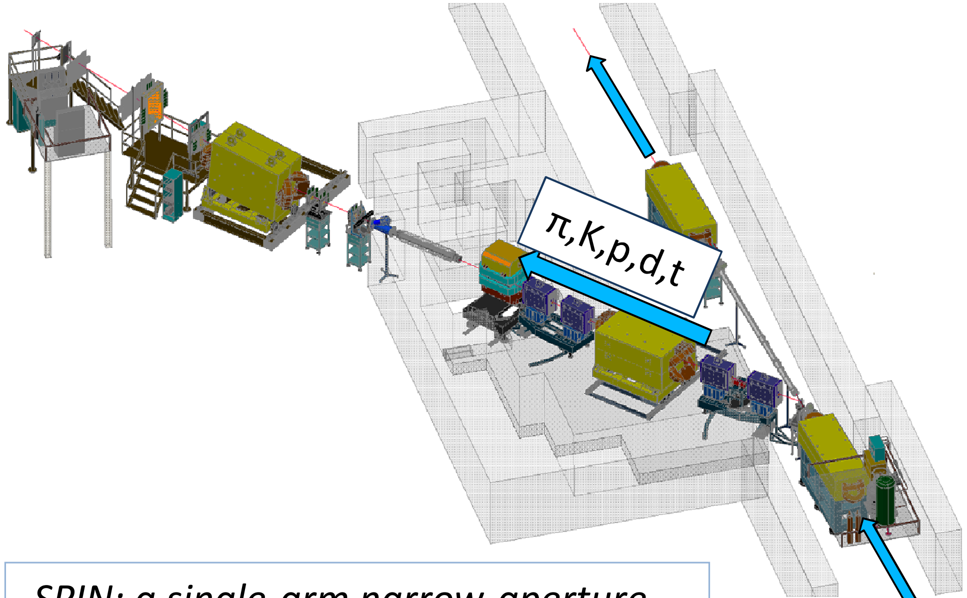
$\pi^- N \to \pi^-\pi^-\pi^+ N$ | $\pi^- N \to \pi^-\pi^0\pi^0 N$





intensity of $2^{++}1^{+} f_2(1270)\pi$ -the most model dependent

SPIN Cumulative reactions



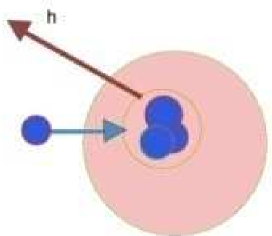
SPIN: a single-arm narrow-aperture spectrometer

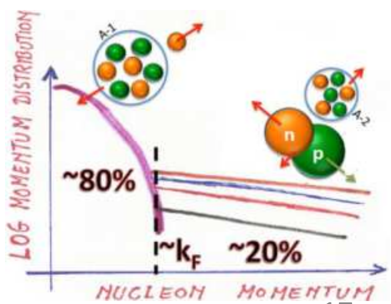
proton beam
10^{12}- 10^{13} /sec
or carbon ion
beam ~10^{9} /sec

Main purpose of the SPIN experiment is to obtain information on the nuclear matter structure by studying the spectra and composition of cumulative particles emitted with **large transverse momenta** (***p_T***) in hard proton-nucleus and nucleus-nucleus interactions. **Cumulative particles** are those generated in the kinematic regions that are **forbidden for scattering with the participation of free nucleons.**

Models for cumulative processes:

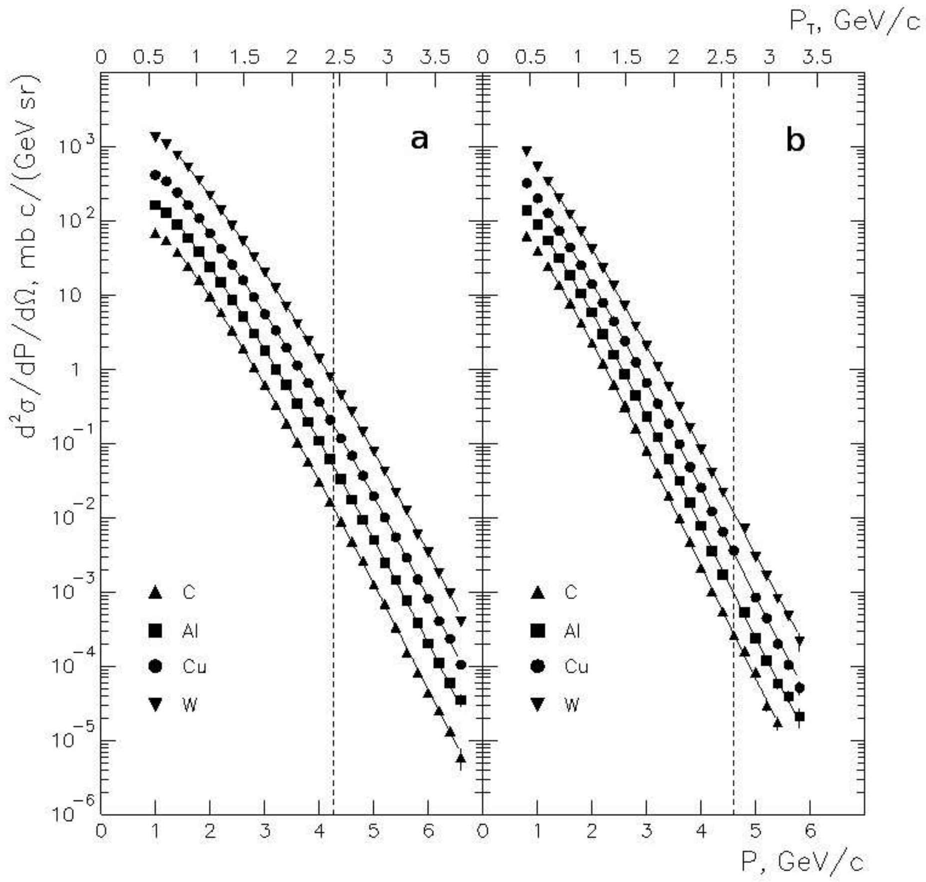
−Multiple scattering
−Multi-nucleon (multiquark) configurations (dense baryon matter)
− Short-range correlated (SRC) NN pairs with large relative momentum





V.V. Ammosov et al.,*Physics of Atomic Nuclei, 2013, Vol. 76, No. 10, pp. 1213–1218*

V.V.Ammosov et al. Yadernaya Fizika I Inzhiniring 4 (2013)773–778] , arXiv-1410.5582



Differential production cross sections for (a) positively and (b) negatively charged particles as functions of momentum. The upper horizontal axis shows the transverse momentum. Vertical dashed lines show the kinematic thresholds in interaction of free nucleons.

$pA \rightarrow h^{\pm} + X$

Proton beam, 50 GeV/c

Intensity 5×10^{12} /sec

Targets: **C, Al, Cu, W**

Angle of arm 35^0 (lab.syst.)

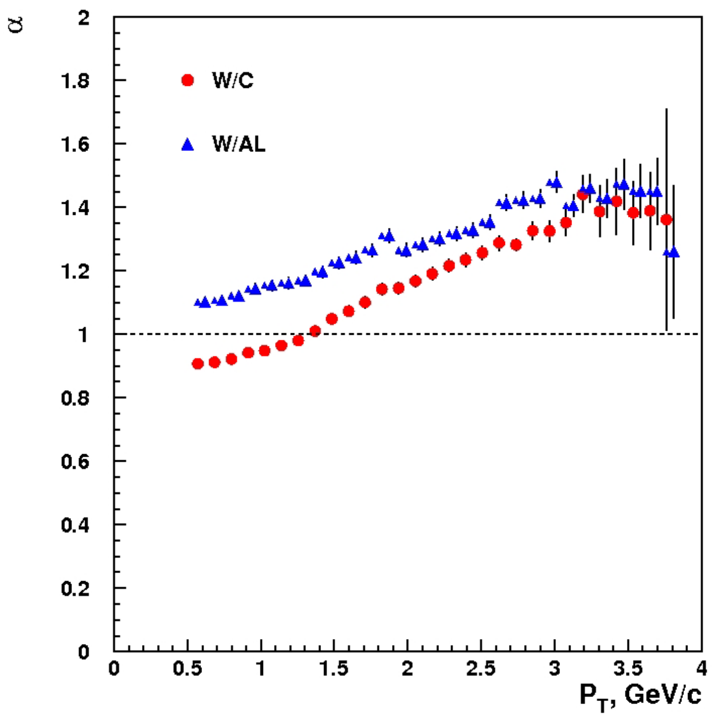
Production of cumulative particles with large transverse momentum (p> 2.5 GeV/c) has been observed **for the first time** for both positive and negative particles

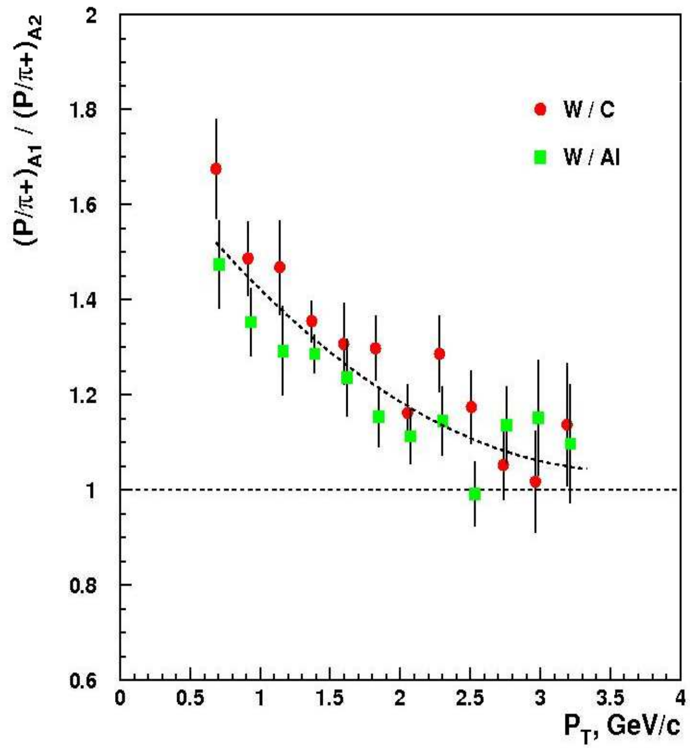
pA→h⁺ + X
Proton beam, 50 GeV/c
Intensity $5x10^{12}$ /sec
Angle of arm 35^0 (lab.syst.)

Strong dependence ($\alpha > 1$) of inclusive cross-section at high p_T on atomic mass is typical for the cumulative processes.

Absence of a strong dependence of the ratios ***p/π⁻*** and ***p/π⁺*** on the nucleus mass at large p_T values serves as an indication of **the local mechanism** of the particle production with a weak contribution from the intranuclear rescattering.

$\alpha = \ln(\sigma_1/\sigma_2) / \ln(A_1/A_2)$

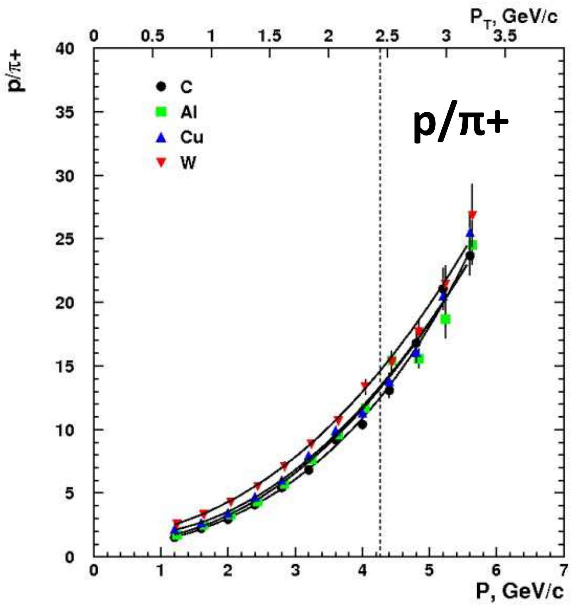


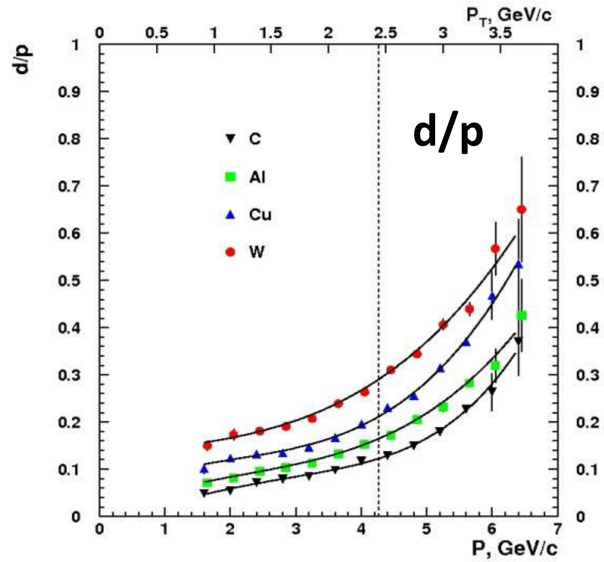


N. N. Antonov et al., JETP Letters, 2015, Vol. 101, No. 10, pp. 670–673

N. N. Antonov et al., JETP Letters, 2016, Vol. 104, No. 10, pp. 662–665

N. N. Antonov et al., JETP Letters, 2015, Vol. 101, No. 10, pp. 670–673

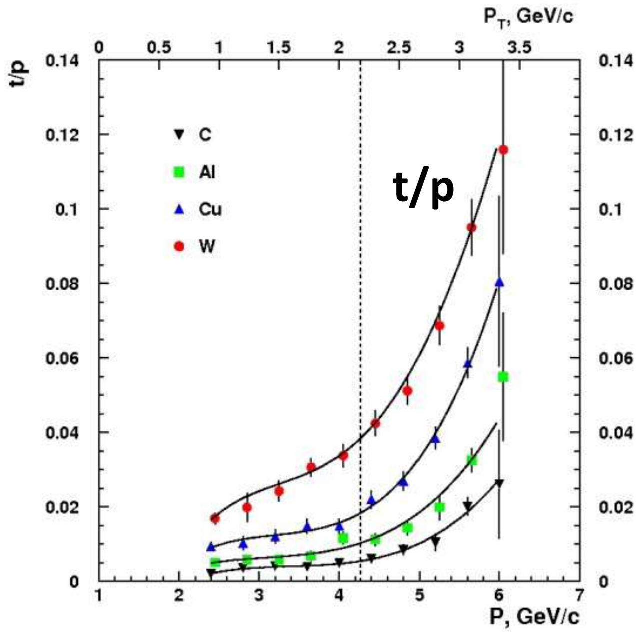




Fraction of π+ among all h+ at p_T >2.5 GeV/c is less than 5% for all targets.

Contributions of **d** and **t** increase rapidly with increasing transverse momentum.

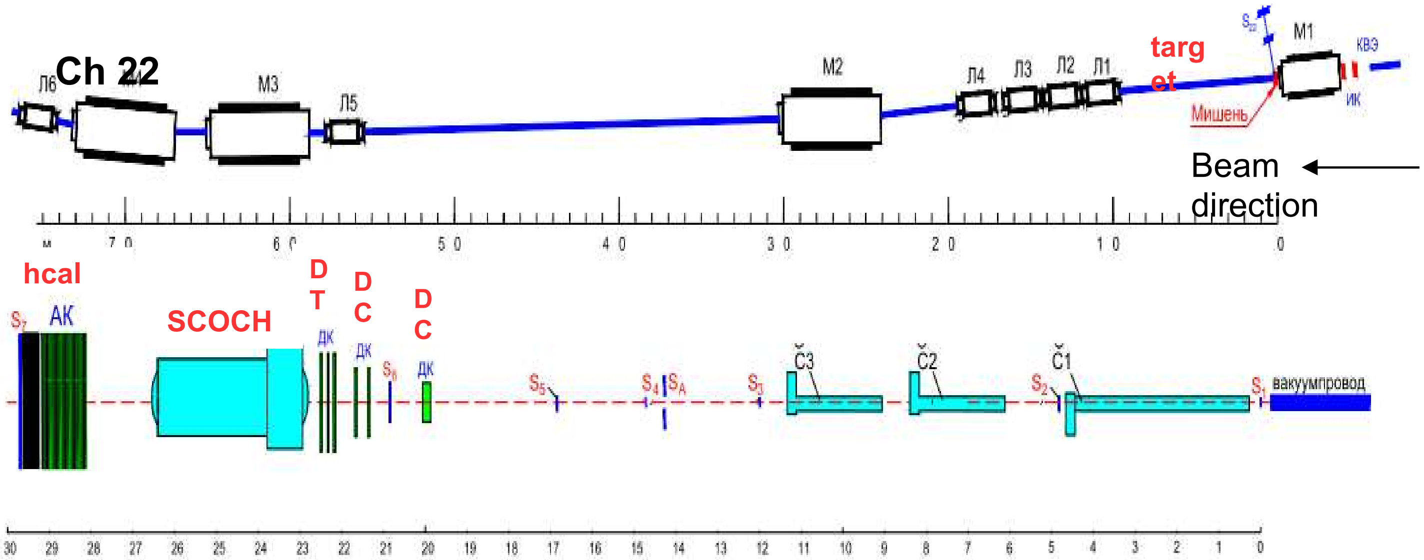
It indicates on the **knockout mechanism**.



FODS Nuclear-nuclear interactions

Acceleration of the carbon nuclei gave rise to a new direction of experimental research on the U-70. The first measurements of the production of hadrons and nuclear fragments at zero angle in nuclear-nuclear interactions were performed in 2016 on channel 22 of the IHEP accelerator. Accelerated carbon nuclei had a kinetic energy of 20 GeV per nucleon.

Nuclear targets were installed in the channel head. Optics of the channel made it possible to select positive or negative particles at given momentum. A large set up of detectors made it possible to determine the charge and mass of hadrons or nuclear fragments.

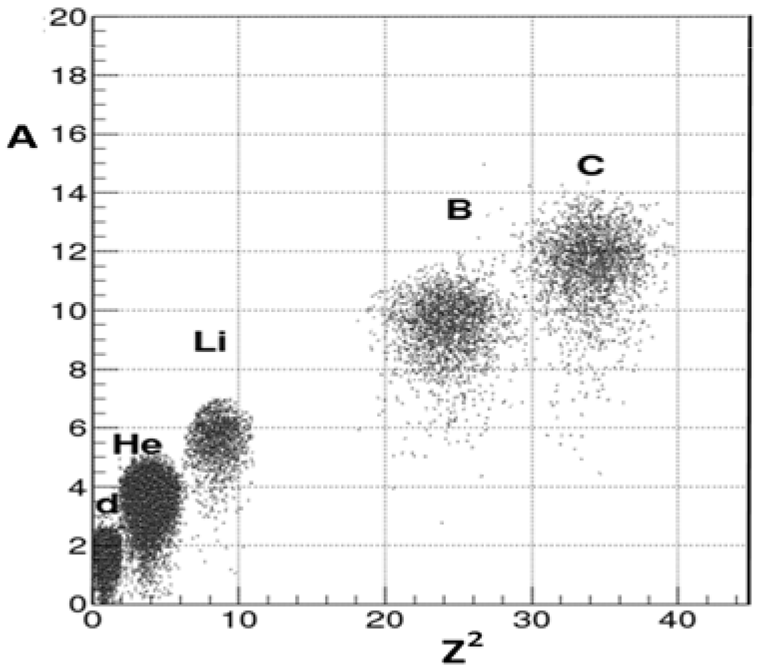


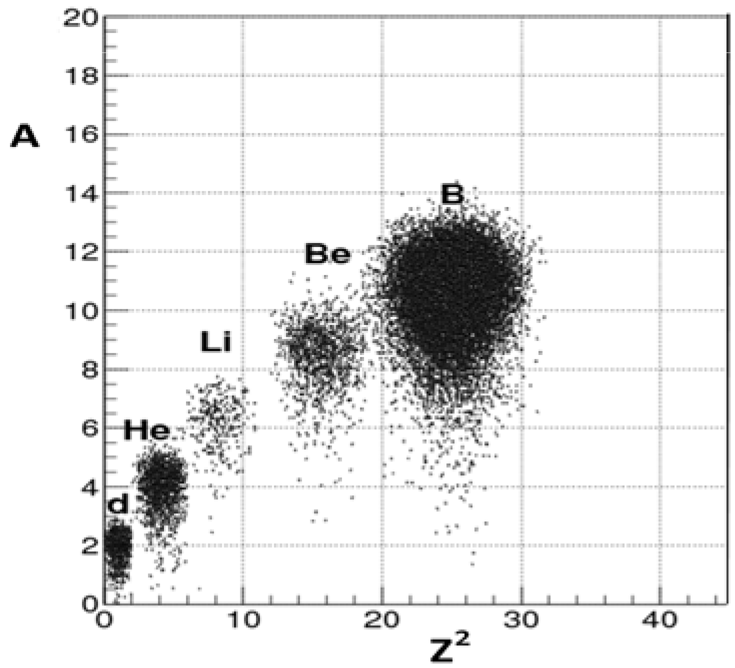
***Si**-scintillation counters, **Č**- Cherenkov counters, **SCOCH** – RICH detector, **hcal** - hadron calorimeter, **DT** – drift tubes, **DC** – drift chambers.*

FODS

Fragments separation

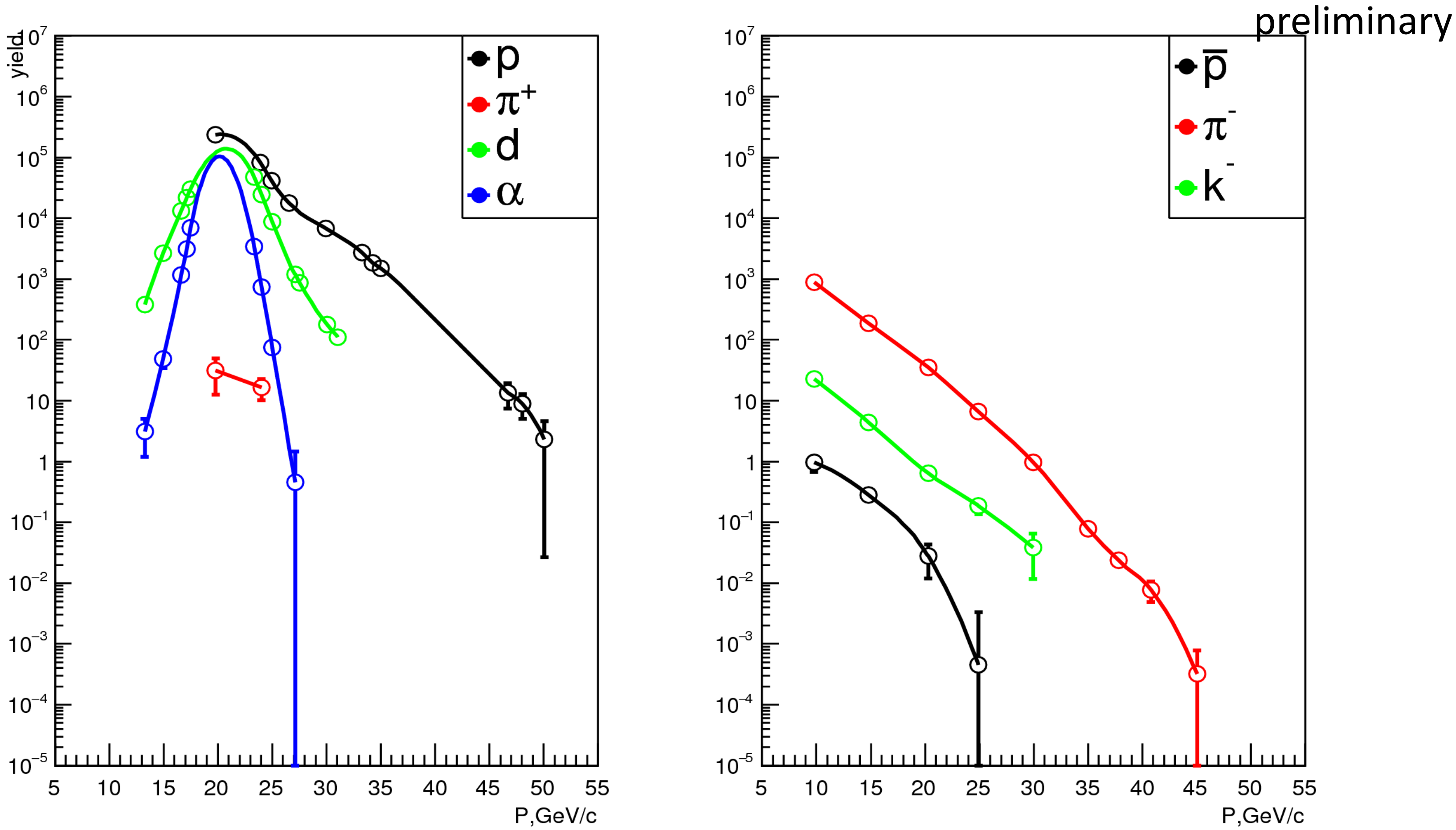
The first results on studying forward nuclei production in collisions of beam carbon at energy 25 GeV/n with nuclear targets on accelerator U-70 at using beam line 22 as spectrometer published: *M.Yu.Bogolyubsky et al., Physics of Atomic Nuclei, 2017, Vol. 80, N0 3, pp 455-460*.
The following puctures show fragment yields of carbon target at beamline rigidity 47 (left) and 53 GeV/c (right) and beam energy 25 GeV/n.





Hadron yelds at p=20 GeV/n

FODS

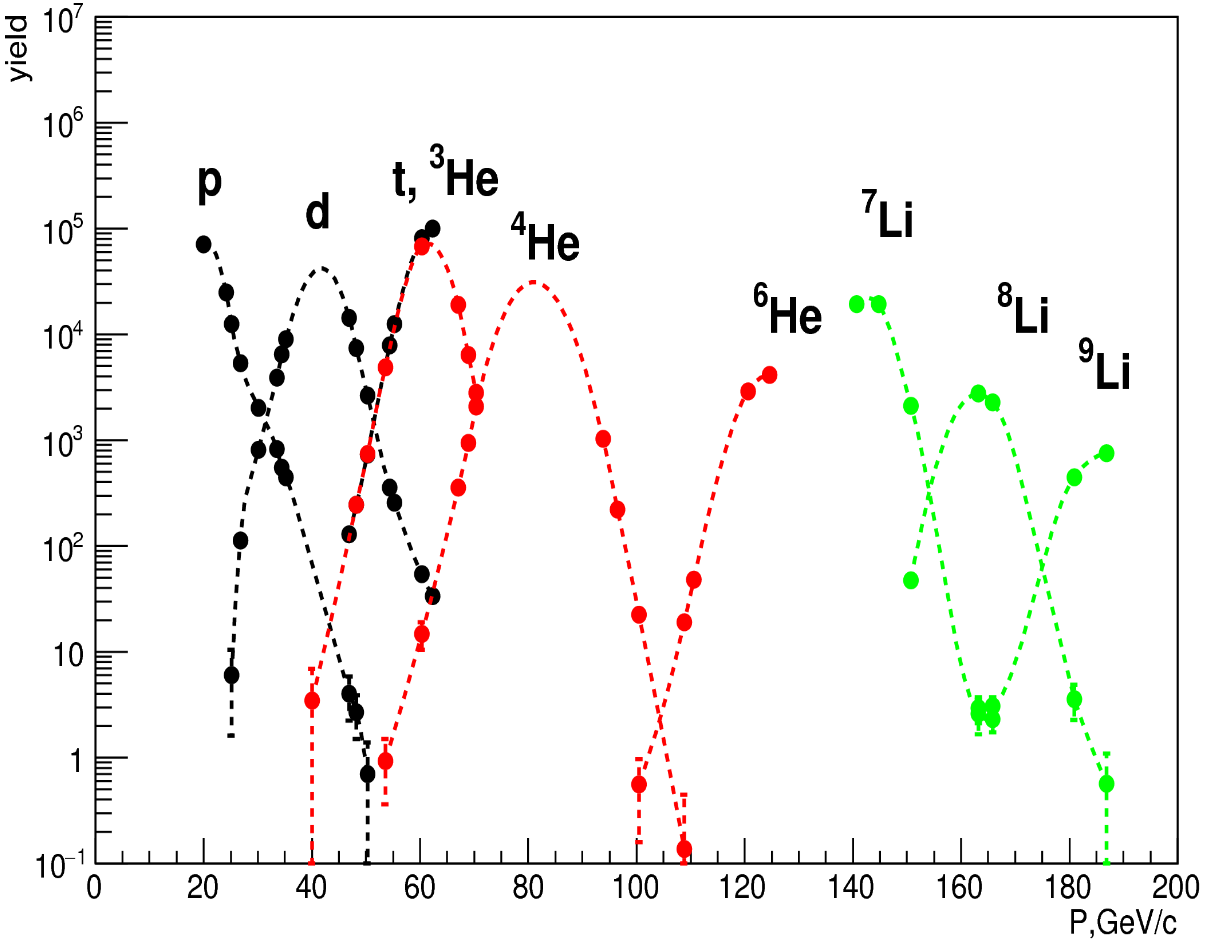


Yields versus the reduced lab momentum at zero angle for p, π^+ , d, α(left picture) and p̄, π^-, K^- (right picture) for C+C collisions at p=20 GeV/n.

FODS

Nuclear fragments

preliminary

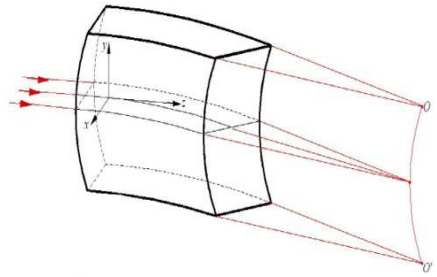


Yields versus the lab momentum at zero angle for different nuclear fragments for C+C collisions. The curves are drawn to guide an eye.

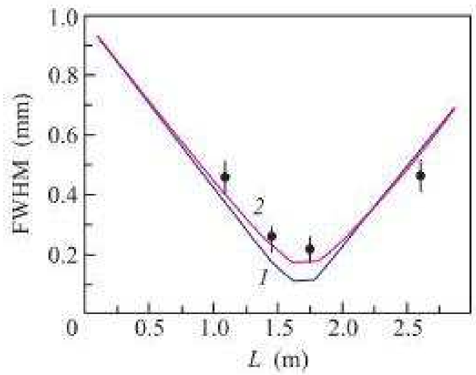
Beam focusing by crystal devices

CRYSTAL

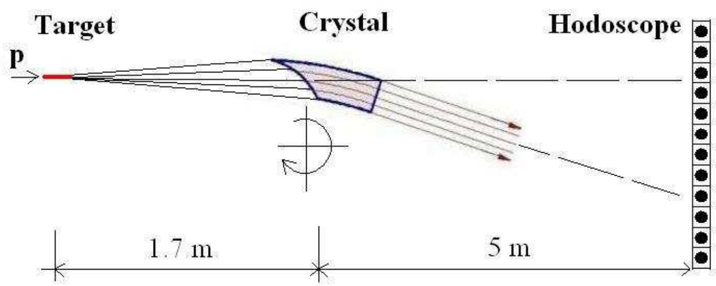
The focusing device on the basis of channeling in crystals of trapezoidal shape has been invented



Several crystals were tested in the mode of focusing of a parallel beam into a point in the U-70 experiments *[AG Afonin, EV Baranov, GI Britvich et al. JETP Letters 105 (12), 763-765, 2017]* The compression ratio of the beam, linearity, focus and deflection efficiency correspond to the expectations.



Reversed direction: the parallel beam formation from point-like source. *[A. G. Afonin et al, JETP Lett. 104 12 (2016)]* This first experiment with divergent beam of protons with an energy of 50 GeV was performed on the U-70 in Protvino. Proton beam with a divergence of about 1 mrad deflected by an angle of 1.8 mrad with an efficiency of about 15%.



New projects

– Spin physics with polarized target (SPASCHARM) – commissioning

– Elastic scattering with very high stastistics – LOI

– Search for fluctons (second arm in SPIN) – LOI

– Carbon-nuclear interaction at $\sqrt{s} \approx 7$ GeV (FODS)

– Low energy (in tens MeV) photons in carbon-nuclear interactions (SVD)

– Baryon spectroscopy in exclusive πp reactions (VES)

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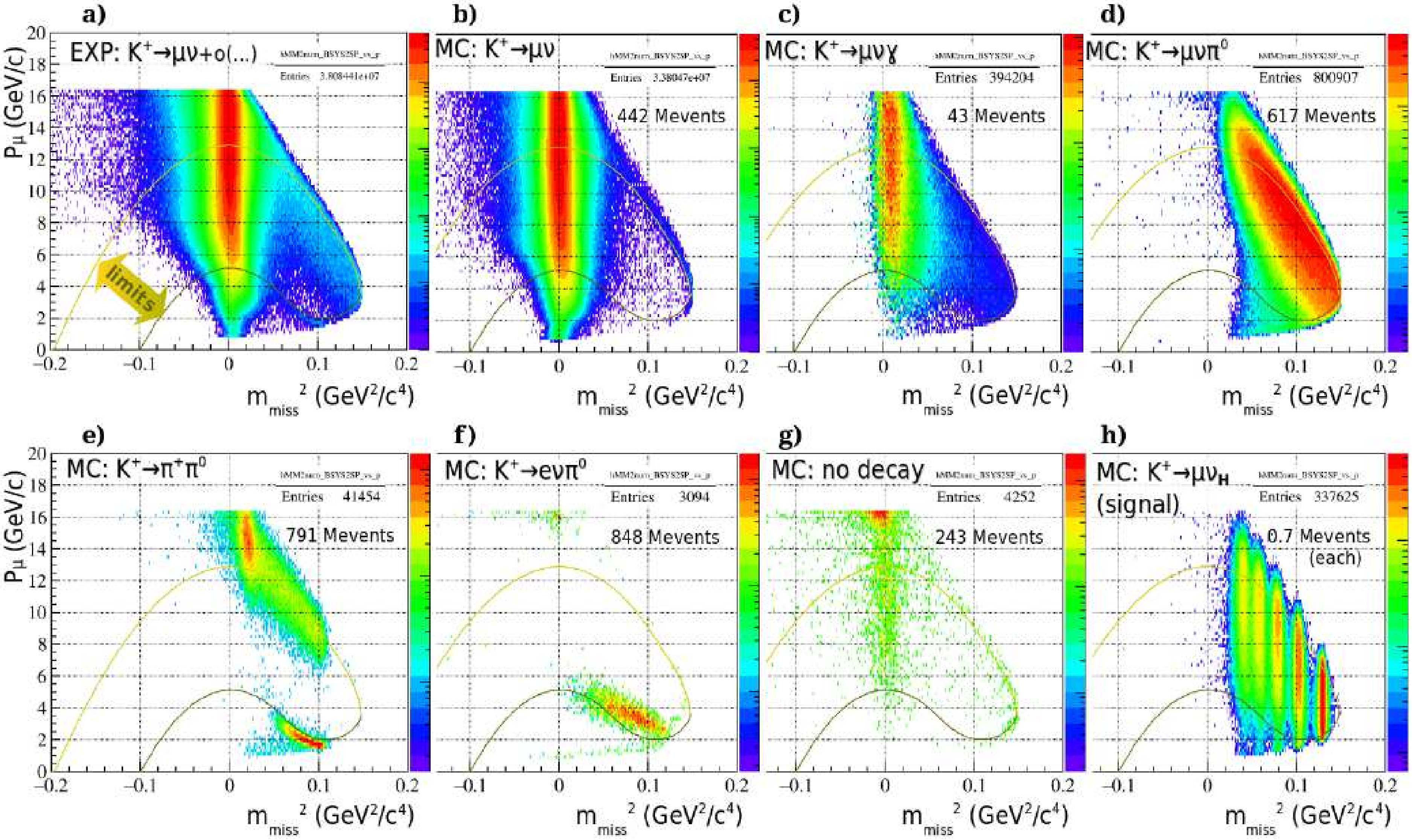
Thanks to V.Obraztsov, A.Vorobiev, Yu.Khokhlov, V.Gapienko, A.Volkov and Yu.Chesnokov for providing materials

THANK YOU

SPARE

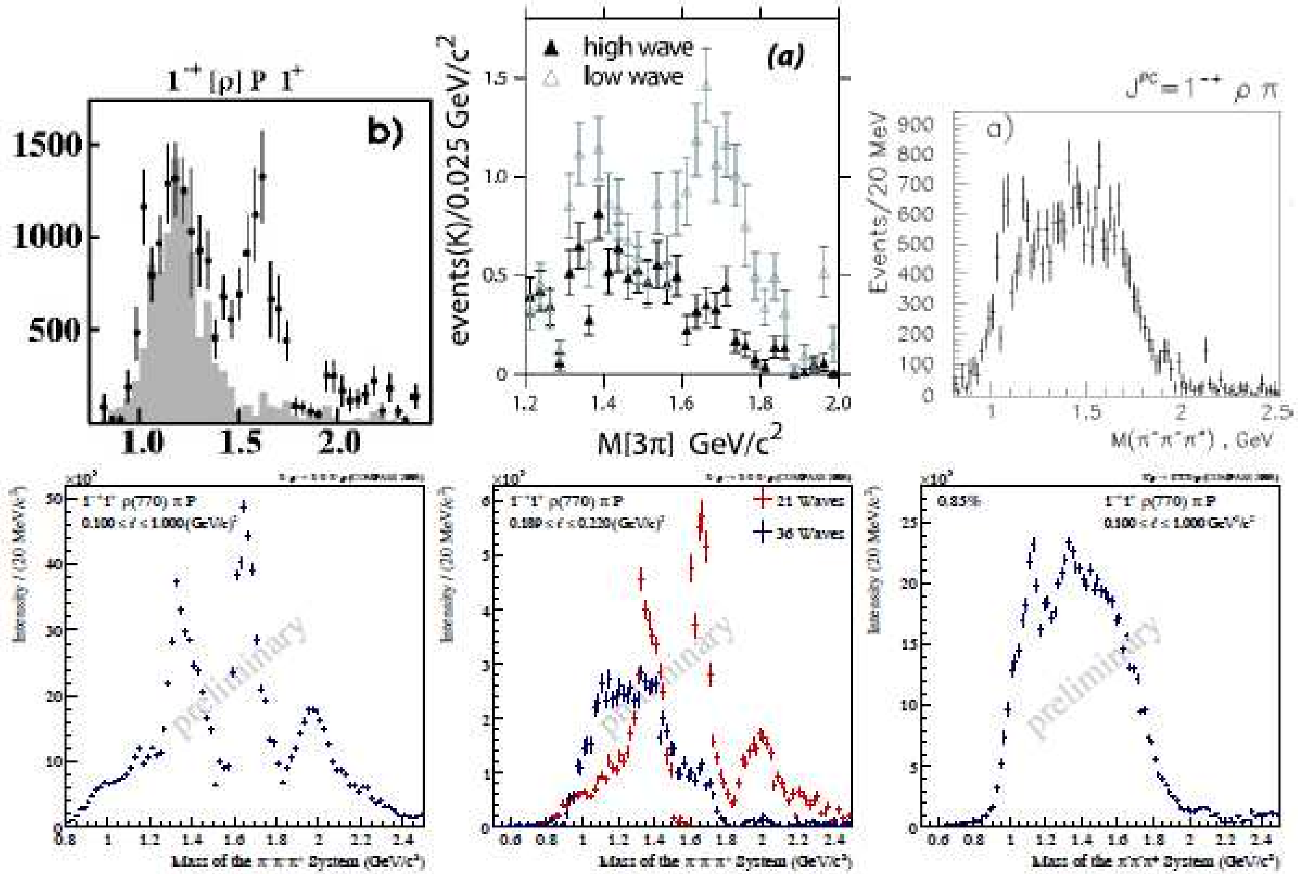

a)
EXP: K⁺→μν+o(...)
Entries 3.808441e+07
limits
b)
MC: K⁺→μν
Entries 3.38047e+07
442 Mevents
c)
MC: K⁺→μνγ
Entries 394204
43 Mevents
d)
MC: K⁺→μνπ⁰
Entries 800907
617 Mevents
e)
MC: K⁺→π⁺π⁰
Entries 41454
791 Mevents
f)
MC: K⁺→eνπ⁰
Entries 3094
848 Mevents
g)
MC: no decay
Entries 4252
243 Mevents
h)
MC: K⁺→μν_H
(signal)
Entries 337625
0.7 Mevents
(each)
P_μ (GeV/c)
m_miss² (GeV²/c⁴)

Сравнение КОМПАСС с предыдущими 1^{-+} в 3π

E852, 21 волн, t'=0.1-1

E852, 21 и 36 волн, t'=0.189-0.220

VES главное соб. значение



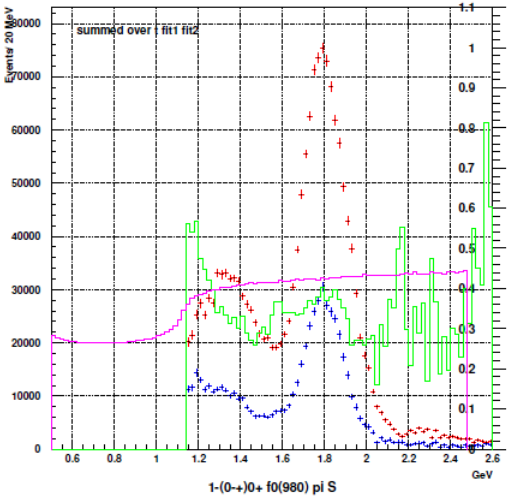
КОМПАСС, 21 волн, ранг=1, t'=0.1-1

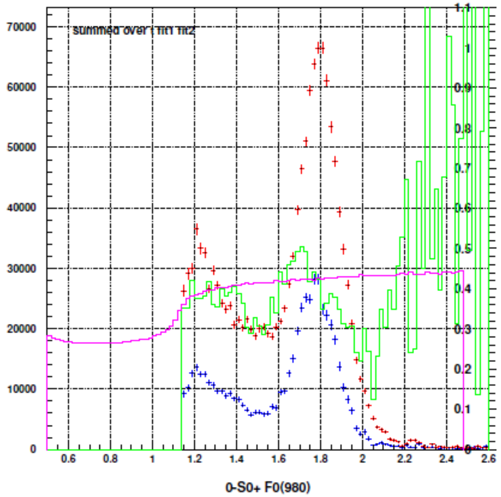
КОМПАСС, 21 и 36 волн, ранг=1, t'=0.189-0.220

КОМПАСС, 88 волн, ранг=1, t'=0.1-1, сумма 11 - t'-бинов

$\pi^- N \to \pi^- \pi^- \pi^+ N ; \pi^- N \to \pi^- \pi^0 \pi^0 N$

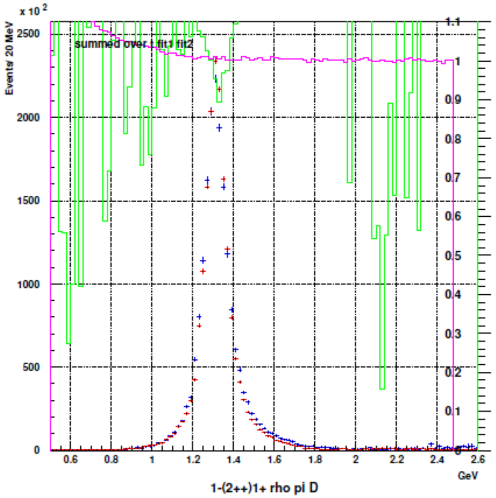
Rank=1 | Unlim.Rank,Highest Eigenvalue

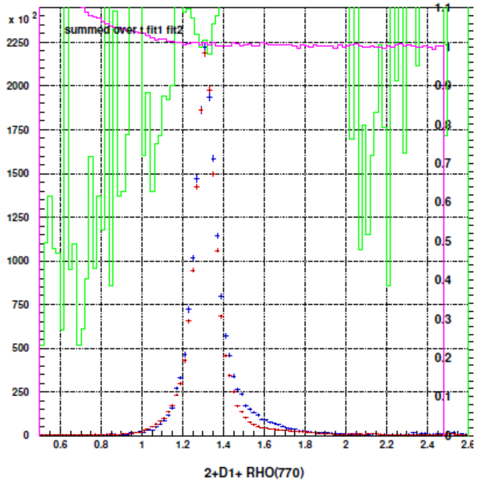


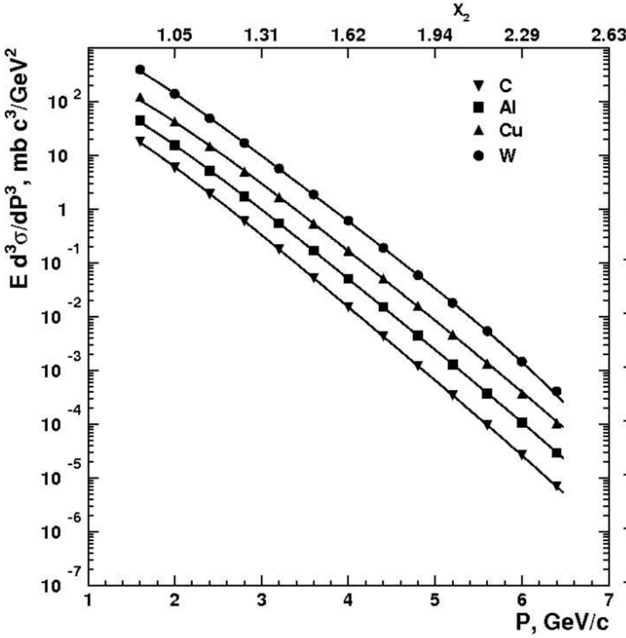


$\pi^- N \to \pi^- \pi^- \pi^+ N ; \pi^- N \to \pi^- \pi^0 \pi^0 N$

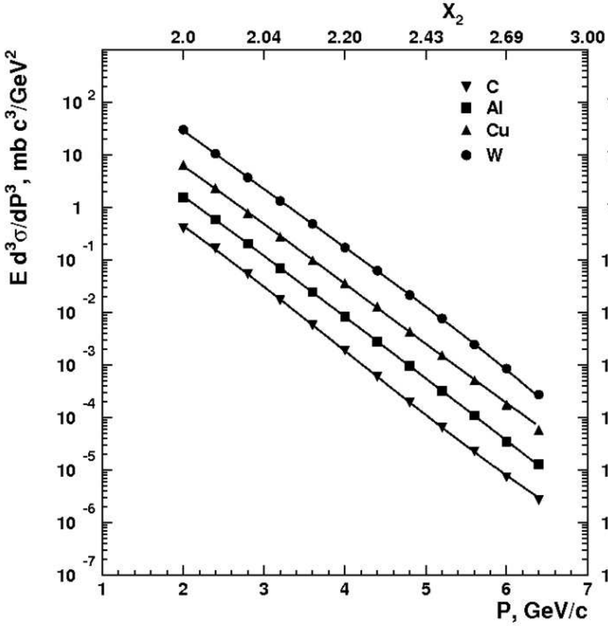
Rank=1 | Unlim.Rank,Highest Eigenvalue



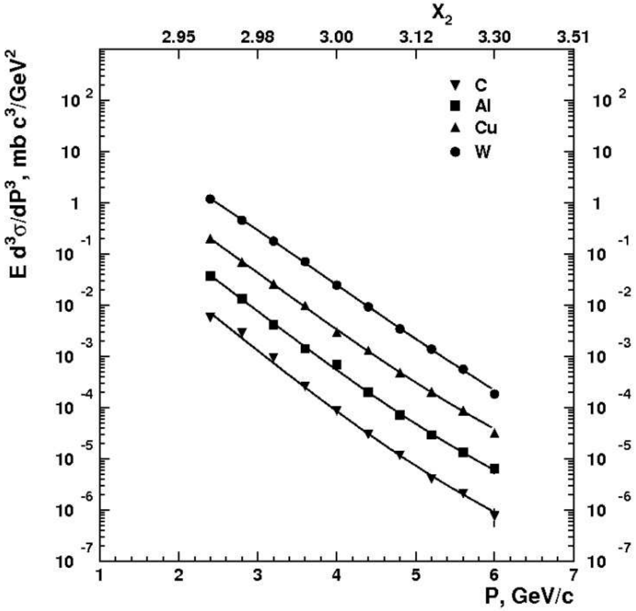




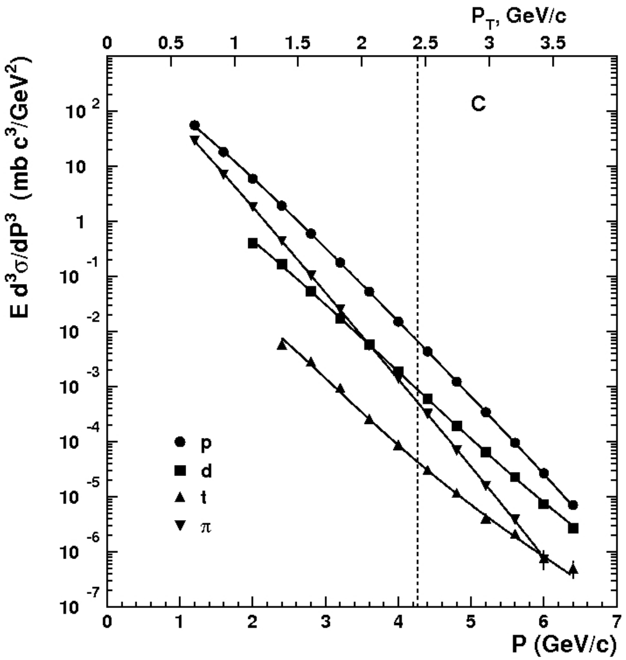
x_2
$E\,d^3\sigma/dP^3$, mb c^3/GeV^2
P, GeV/c
C
Al
Cu
W



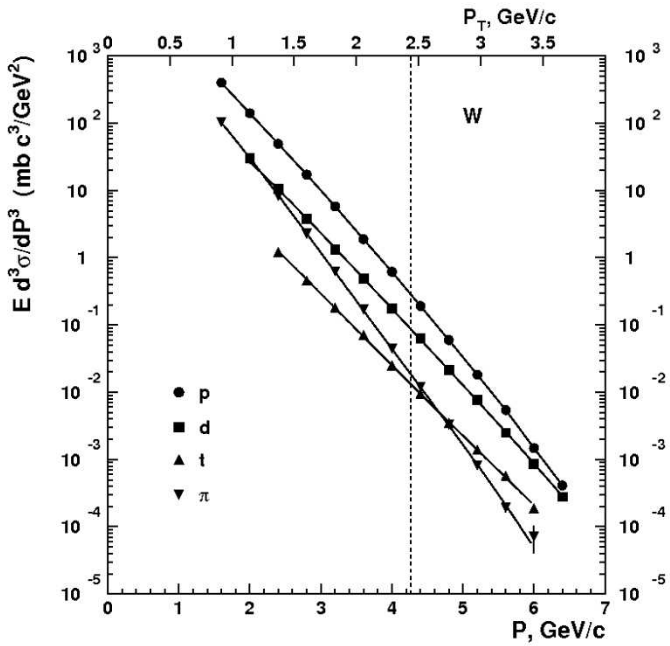
X_2
$E\,d^3\sigma/dP^3$, mb c^3/GeV^2
P, GeV/c
C
Al
Cu
W



X_2
$E\,d^3\sigma/dP^3$, mb c^3/GeV^2
P, GeV/c
C
Al
Cu
W



P_T, GeV/c
$E\,d^3\sigma/dP^3$ (mb c^3/GeV^2)
P (GeV/c)
C
p
d
t
π



P_T, GeV/c
$E\,d^3\sigma/dP^3$ (mb c^3/GeV^2)
P, GeV/c
W
p
d
t
π