Развитие физической программы HiptaN по исследованию редких процессов с большими p_T и предложения предварительных экспериментов

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10–13 Mar 2026 BINP Сессия-конференция СЯФ ОФН РАН

Stepan Shimanskiy

06.04.1957 – 26.12.2025

Summary

- **Hip$_T$aN experimental program introduction**
- **Feasibility studies. Proposals**
  - Σ^+, Σ^- measurements at BM@N
- **Experimental setup studies**
  - SC vs HTSC Magnet
  - High Granularity Neutron Detector
    - With BGO
  - Straw tubes
  - Aerogel

Motivation: Nuclotron is a good choice for rare processes with p_T > 0.5 GeV/c investigations

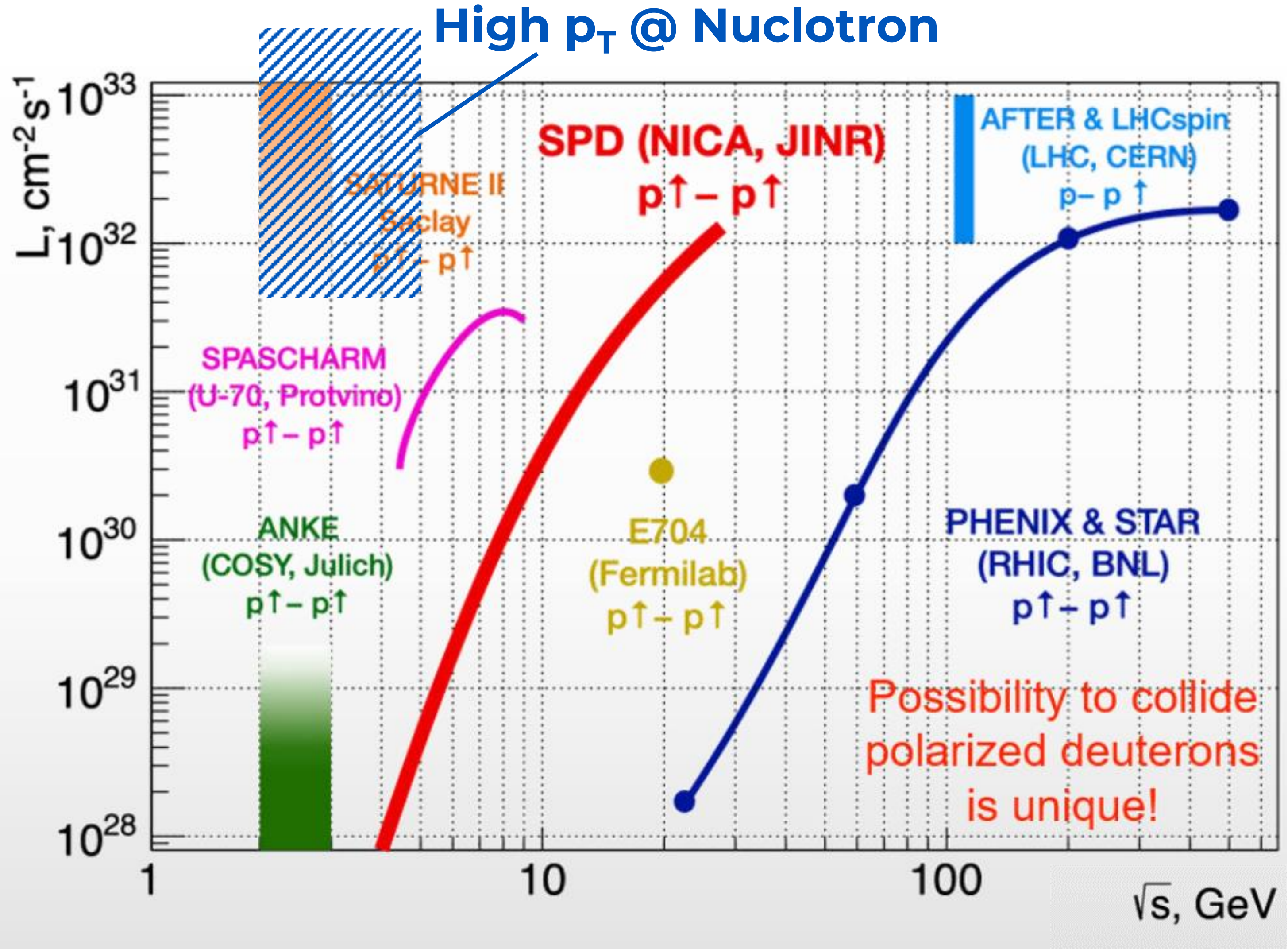
Maximal E_p	12 GeV
Maximal E_A(q/A=0.5)	6 GeV
Intensity (p) per spill 2 sec	up to 10^{10}
Time to fill the NICA rings	0.5 h
Collisions on NICA	3 h
Polarized beams	p↑, d↑, ^{3}He↑

Between NICA cycles Nuclotron will give beams to fixed target experiments

+ Polarized and cryogenic targets

MPD + BM@N

SPD + ? (High p_T @ Nuclotron)



Motivation: Unique possibility to measure neutrons with ~GeV energies

~1/3 of AA products @ Nuclotron energies – neutrons

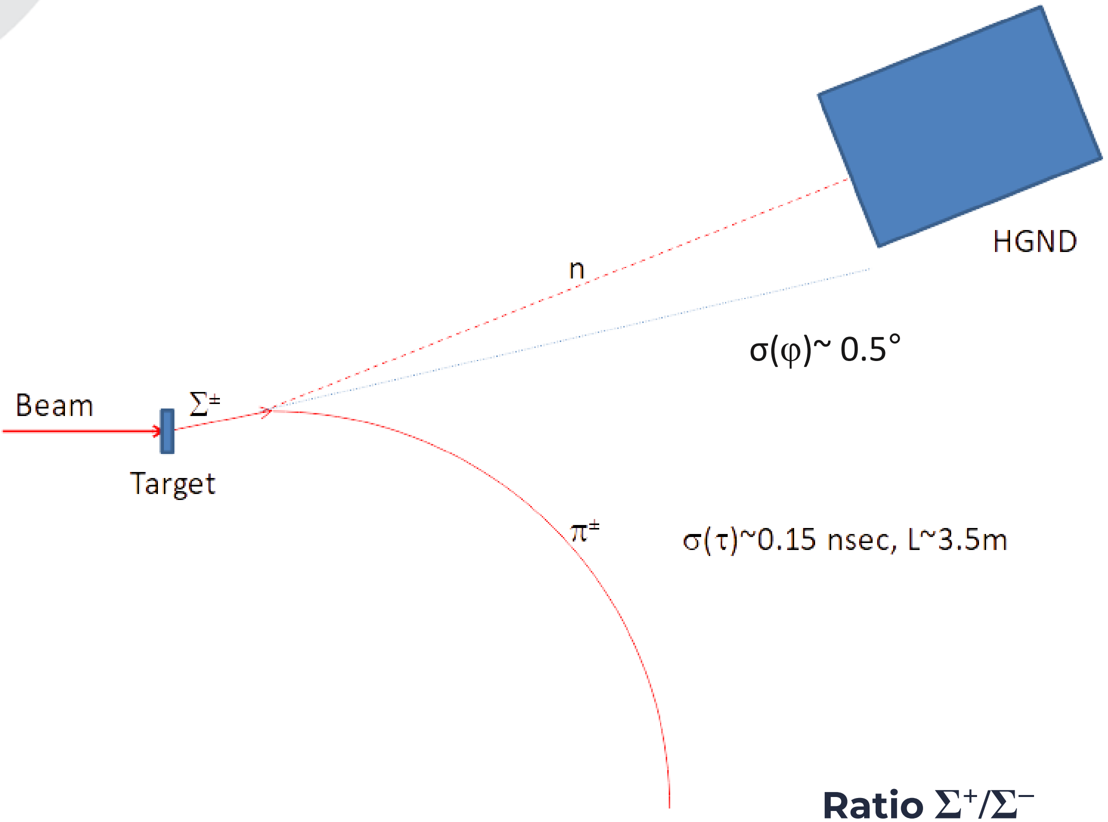
CC URQMD 10^5 ev.	2 GeV/c	3GeV/c	4GeV/c
all	2 520 772	2 579 414	2 640 908
P	271 961	266 605	266 161
N	271 720	266 368	266 624
π^0	43 878	64 268	85 051
π^+	37 929	55 837	74 365
π^-	37 969	55 702	74 208
K^0	230	1 121	2 398
K^+	235	1 110	2 304
Λ	225	951	1 922
Σ^0	86	468	927
Σ^+	66	372	788
Σ^-	83	362	785
antiK^0	2	45	130
K^-	3	33	130

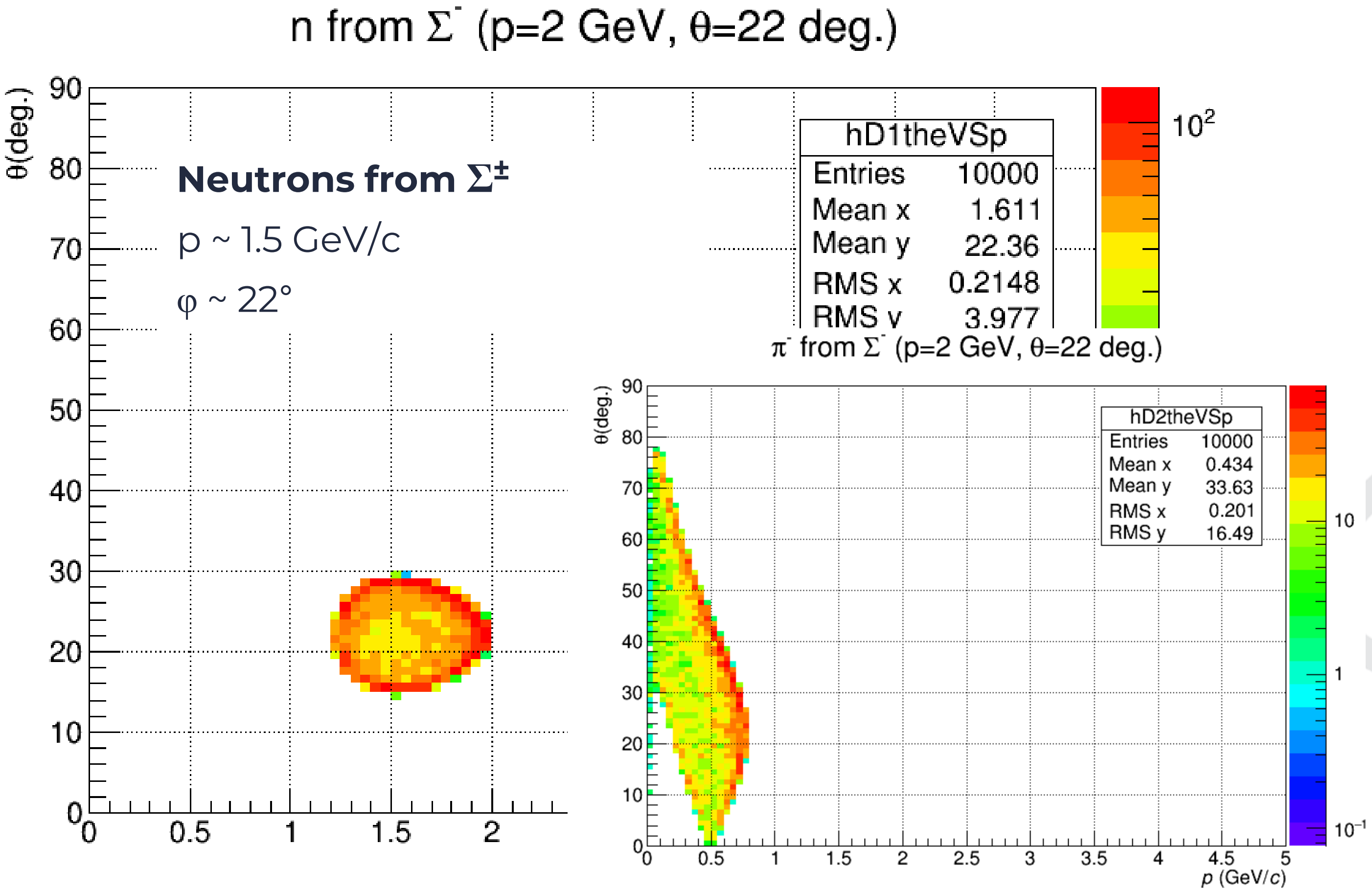
Highly granulated neutron detector HGND

- allows to measure neutrons in the range ~0.5 – 3 GeV (not reachable for homogeneous Ndet and HCALs)
- Opens possibility to measure Σ

Neutron detector is important not only for neutron registration, but also for hyperons

E_{kin} of neutrons @ midrapidities is ~ 0.5 – 3 GeV





Ratio Σ^+/Σ^-

Systematics in Σ^+/Σ^- can be minimized by reversing the magnet

Strangeness in dense nuclear matter and neutron stars

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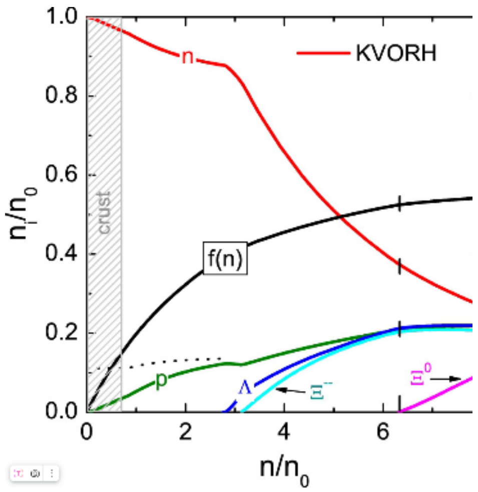
With the increase of density in nuclear stars, the role of Pauli blocking increases

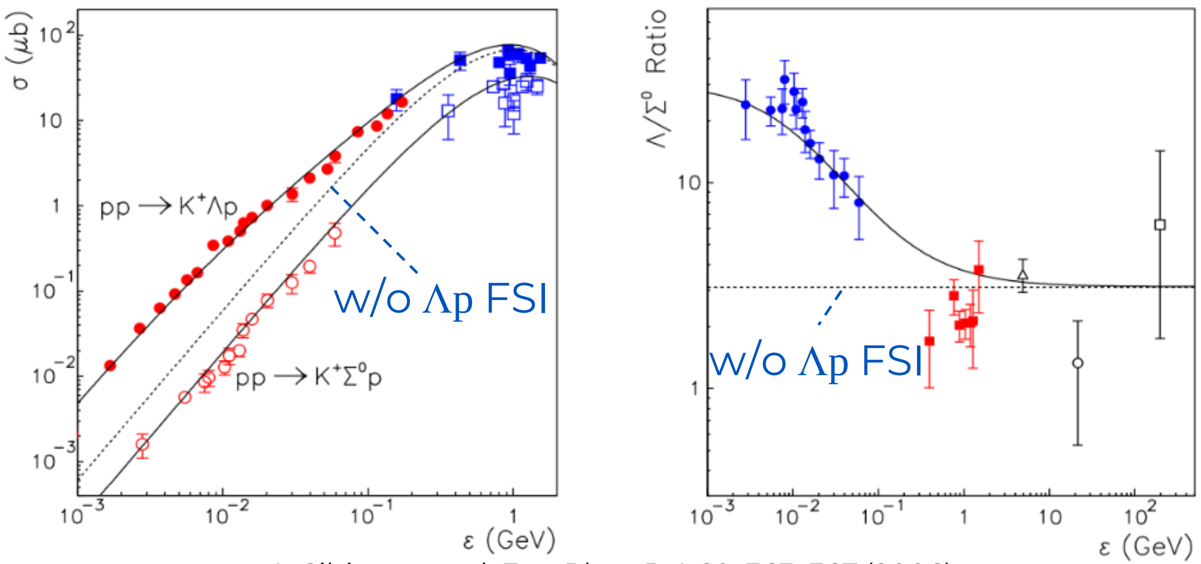
Way out 1* : production of Σ^- (also for compensation of p^+ electrical charge)

Way out 2 : (with further density increase) production of Λ: $n \to \Lambda^0$ (Σ^0)

* Schaffner-Bielich NPA 835 (2010) 279



K.A. Maslov , E.E. Kolomeitsev, D.N. Voskresensky PL B748 2015 369



A. Sibirtsev et.al. Eur. Phys. J. A 29, 363–367 (2006)

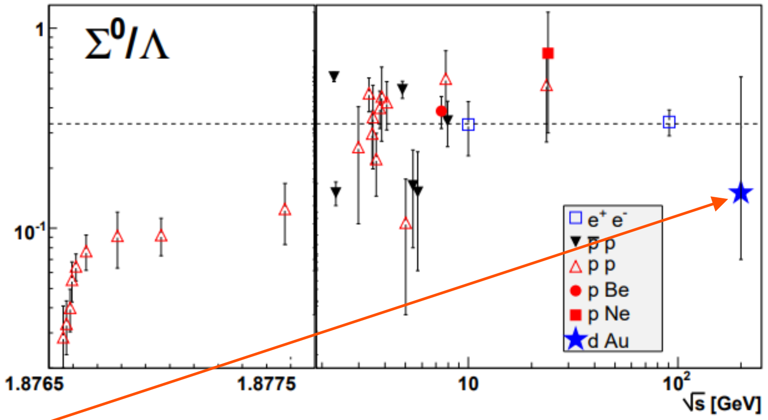


Figure 4: Σ^0/Λ results versus collision $\sqrt{s}$ ($\sqrt{s_{NN}}$ for p/d+A) [1]. Meson-nucleon reaction results are excluded for clarity, but exist only at intermediate energies and lie in the same range. The dashed line is the ratio of isospin degeneracy factors (1/3).

G. Van Buren (for the STAR Collaboration) arXiv:nucl-ex/0512018

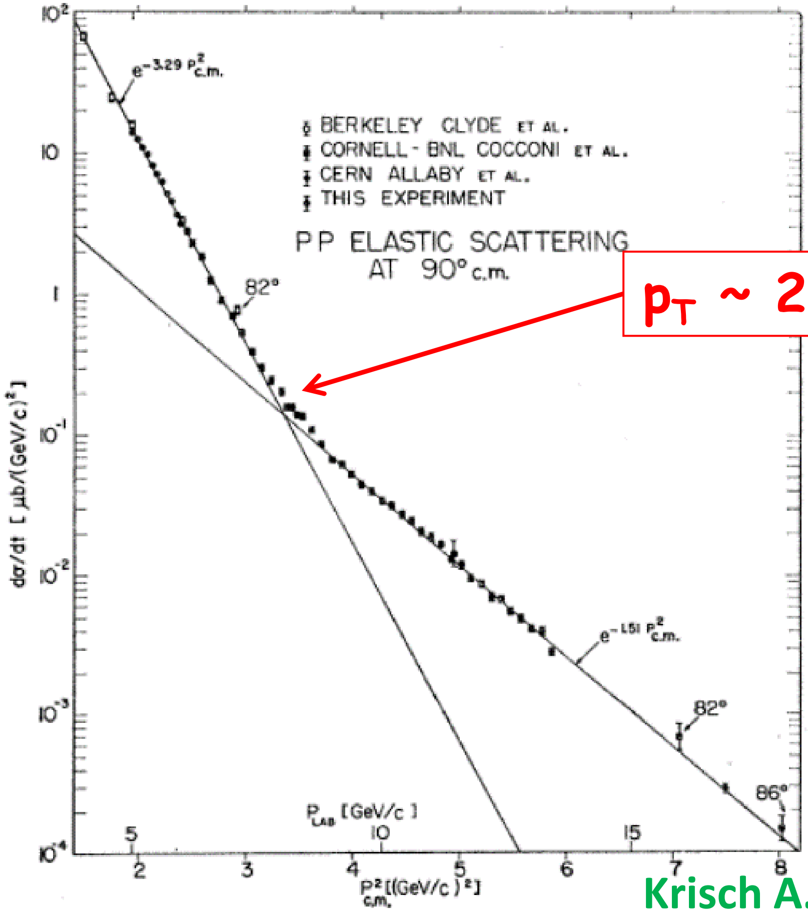
FSI depend on interaction point sizes (~$1/r^2$)

Λ/Σ ($E \to 0$) = 30, but Λ/Σ ($E >> 0$) = 3 for pp.

Lack of data for AA

Undescribed effects in unpolarized and polarized elastic scatterings pp → pp (90°)
Some examples

Scatterings of unpolarized particles

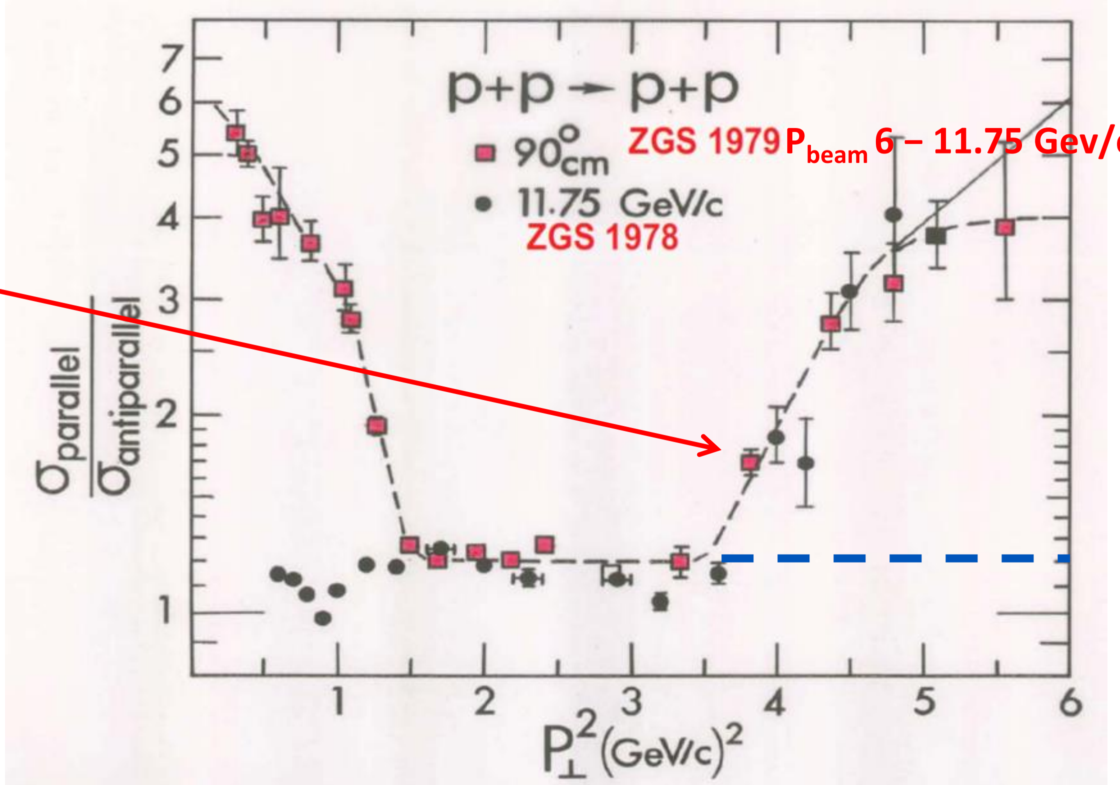


p_T ~ 2 GeV/c

C.W. Akerlof et al., Phys.Rev., vol.159, N5, 1138-1149, 1967

Krisch A. and Leksin G. – non pointlike structure of nucleon

Scatterings of polarized particles



A.M.T. Lin et al., PL 74B, 273;
E.A. Crosbie et al., PR D23, 600

Diquarks

Anomaly at p_T=2 GeV/C seen in p/π also

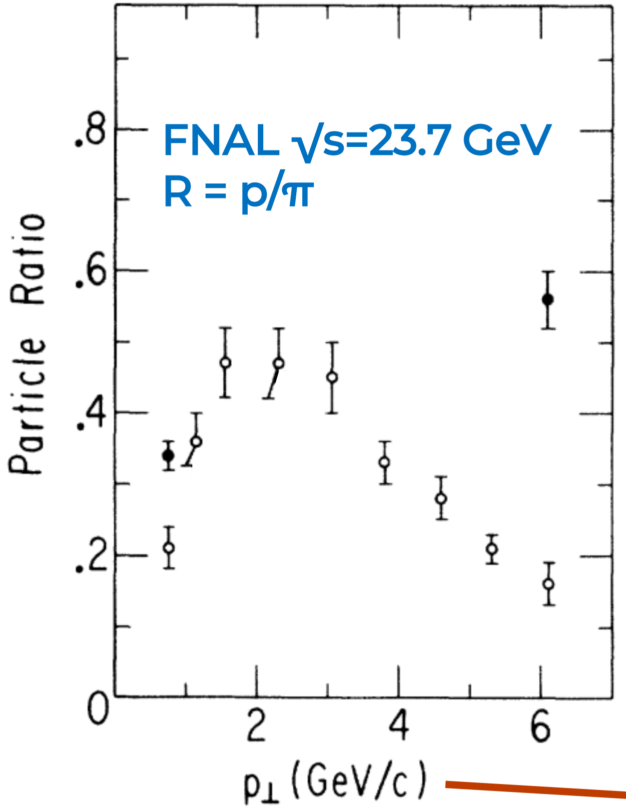
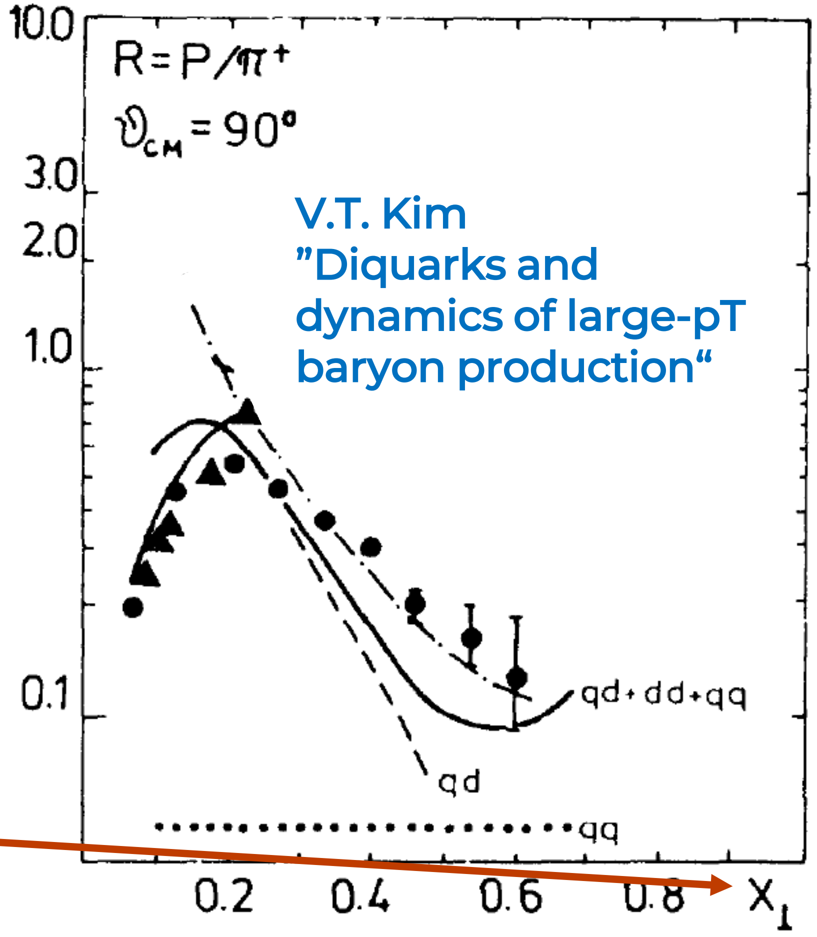


FIG. 20. Comparison of the cross-section ratio p/π^+ measured on tungsten at $\sqrt{s}=23.7$ GeV (closed circles), with that obtained by extrapolation to $A=1$ (open circles). Ratios obtained from the British-Scandinavian collaboration (Ref. 23) at $\sqrt{s}=23.4$ GeV are also plotted (closed squares).

FNAL Cronin et. Al. Phys Rev d11 (1975) 3105

$x_\perp = 2p_\perp/\sqrt{s}$.

Description of this anomaly using diquarks



V.T. Kim Mod. Phys Lett A 3 9 (1988) 909

Measurements of A_{nn} in pp, πp and ππ scatterings would give indication on diquark spin

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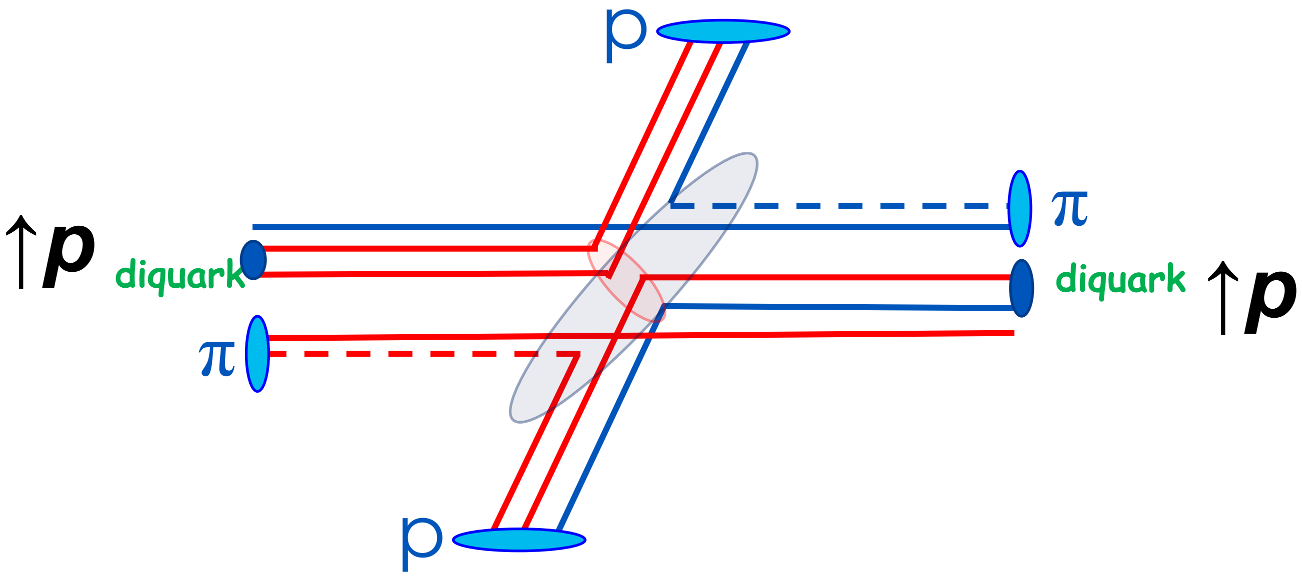
Exclusive reactions at high p_T



$$A_{n(pp)} \rightarrow 0$$ Diquark (S=0)

$$A_{nn(pp)} \neq 0 \rightarrow \text{dd} \ (S_d{=}1)$$

$$A_{nn(\pi p)} \neq 0 \rightarrow \text{qd} \ (S_d{=}1)$$

$$A_{nn(\pi\pi)} \neq 0 \rightarrow \text{qq}$$

Quark scaling rules are working in deuteron photo-dissociation reactions also

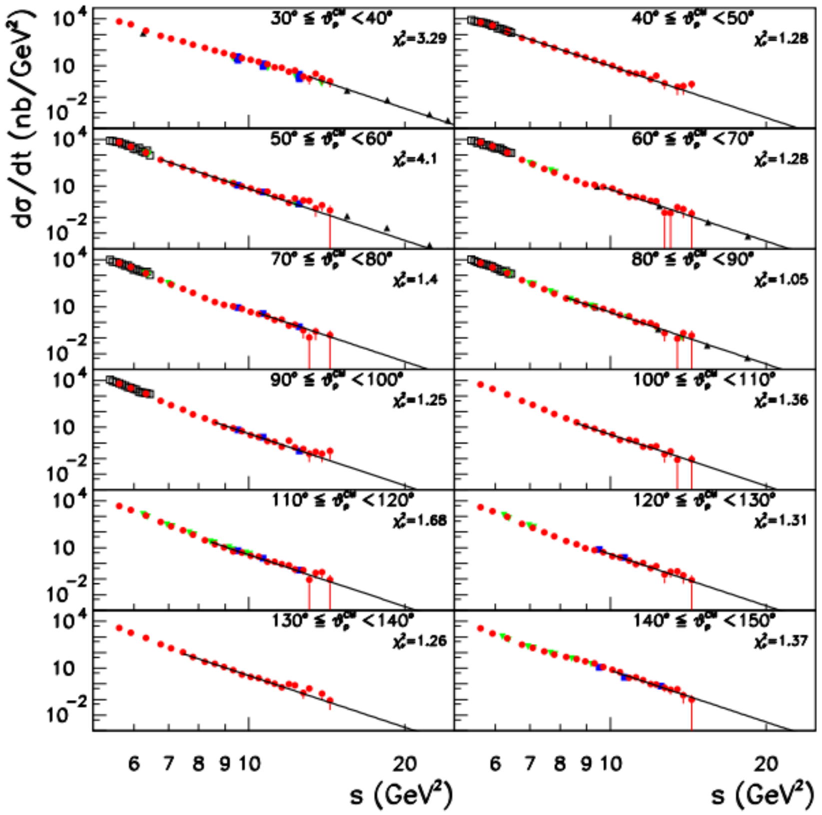


Figure 8: Fits of the cross sections $d\sigma/dt$ to s^{-11} for $P_T \geq P_T^{th}$ and proton angles between 30° and 150° (solid lines). Data are from CLAS (full/red circles), Mainz(open/black squares), SLAC (full-down/green triangles), JLab Hall A (full/blue squares) and Hall C (full-up/black triangles). Also shown in each panel is the χ^2_ν value of the fit. From Ref. [160].

Light-Front QCD* SLAC–PUB–10871 November 2004

Stanley J. Brodsky

$$s^{11}\frac{d\sigma}{dt}(\gamma d \to pn) \sim$$

constant at fixed CM angle

Proposal

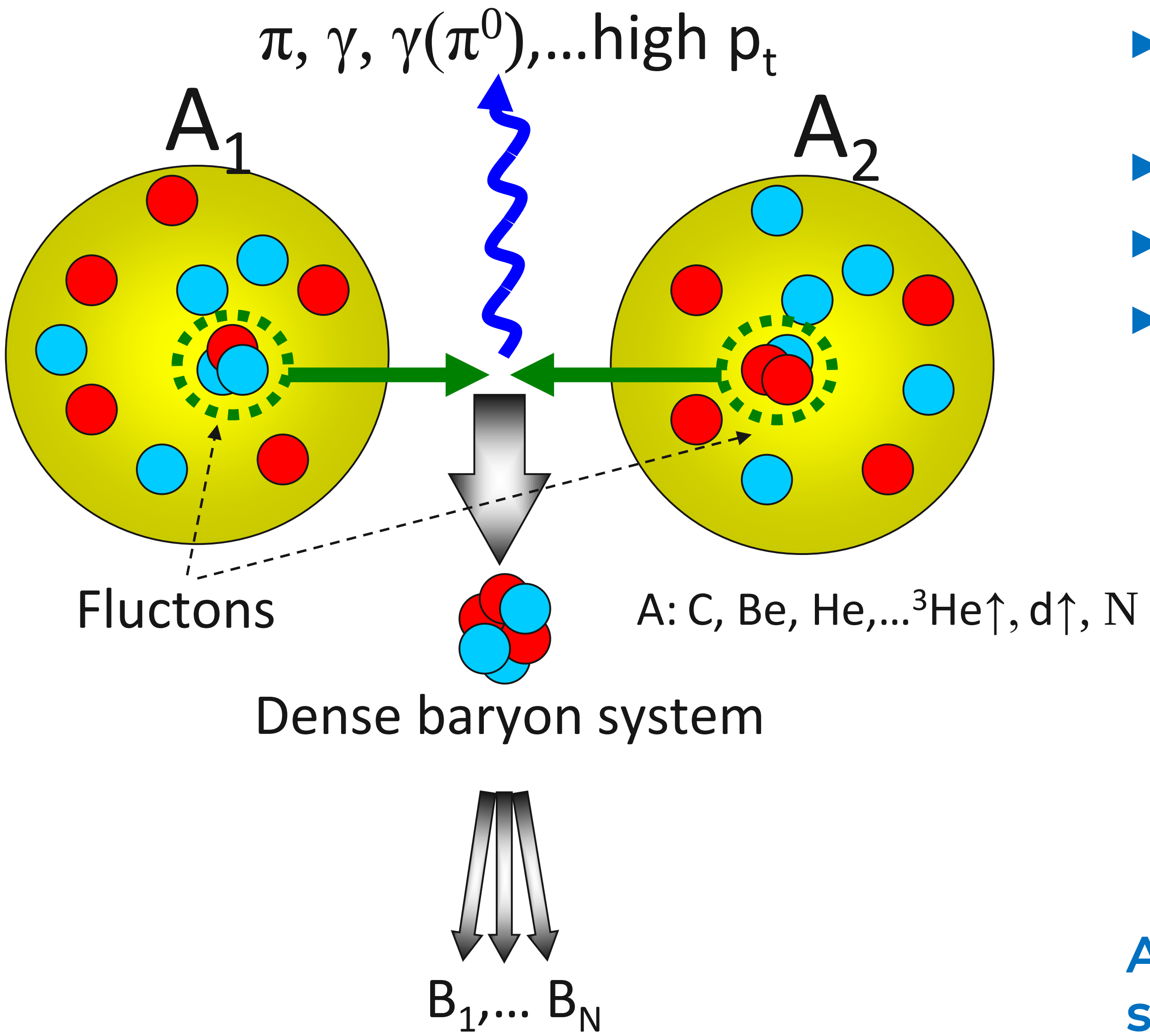
hard γ @ θ_{cms} = 90° :

p+n–>d+γ ~S^{-11} =>6-quark system

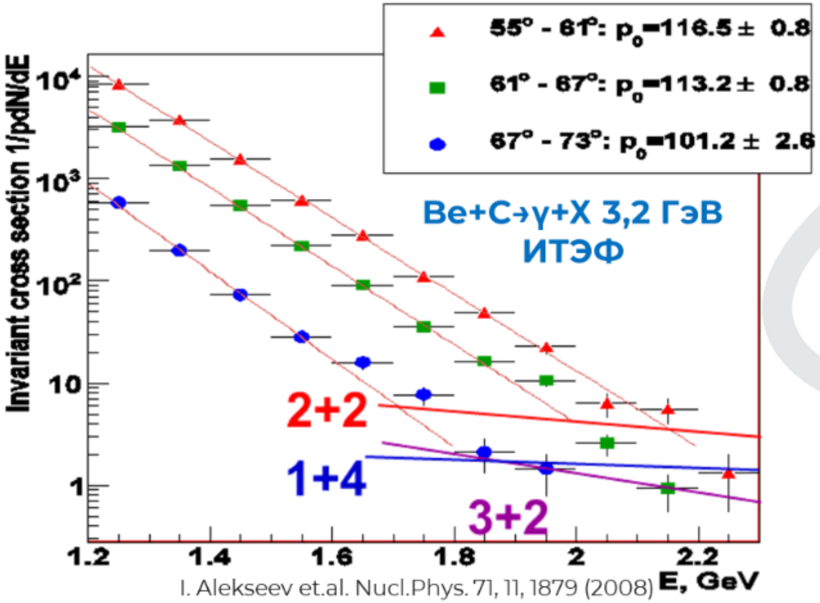
~S^{-9} => 3-diquark system

~S^{-7} => pn(point-like) system

Fluction-fluction interactions



- Use double-cumulative particle @90° in c.m.s. as trigger
- The recoil system is "cold" (δp→0) and dense (δx→0)
- Hence the **Pauli blocking** should play a role
- Way out: **bozonization, diquarks, strangeness production...**



I. Alekseev et.al. Nucl.Phys. 71, 11, 1879 (2008)

Analogues with cores of neutron stars and supernovae???

Mikhailov K.R. et.al. "Exotica in dense and cold nuclear matter" Phys. At. Nuc. 77 5 C 576 (2014)
A. V. Stavinskiy "Dense Baryonic Matter and Neutron Detectors" Phys. At. Nuc., 82, 9, 1325 (2019)

Feasibility studies. Proposal to consider hyperons measurements at BM@N using HGND

HIPTAN

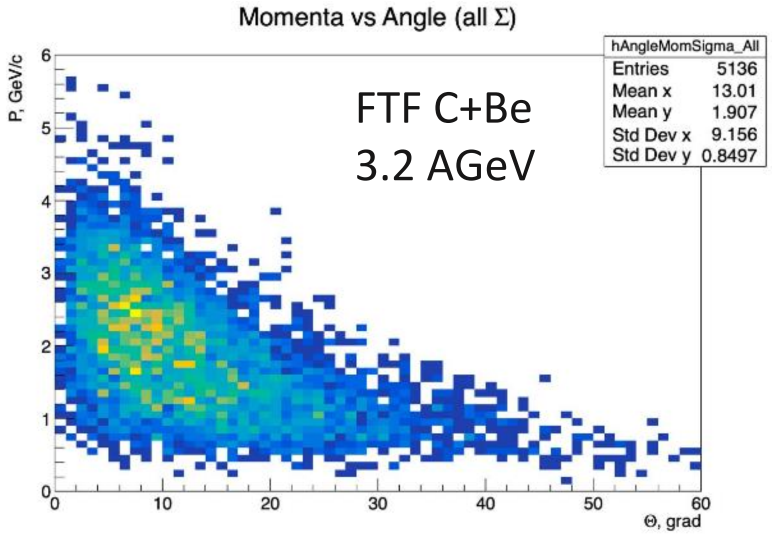
1. Look for Σ in next runs with 11x11 HGND

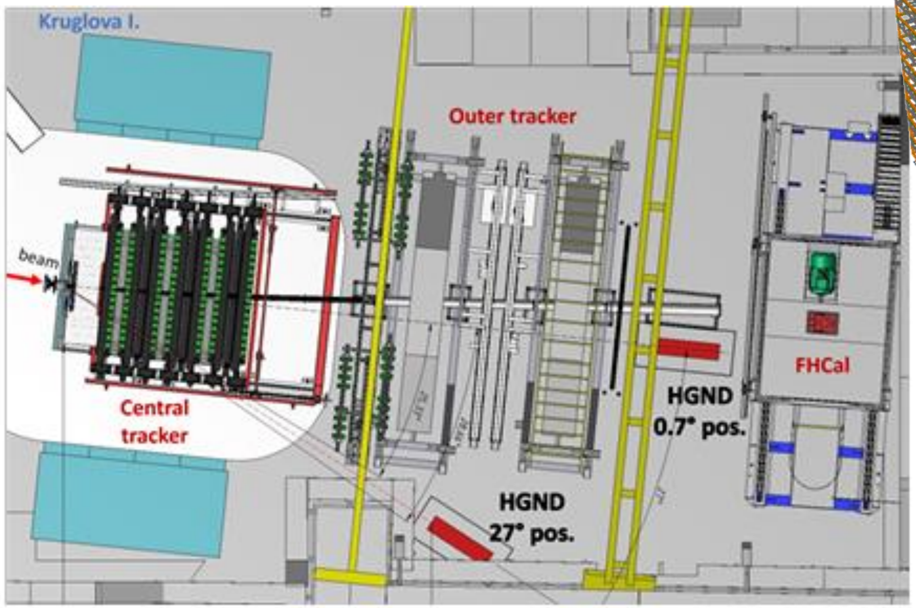
1. Develop methodic of Σ identification
   - ➢ Learn from Λ ID with incomplete tracking

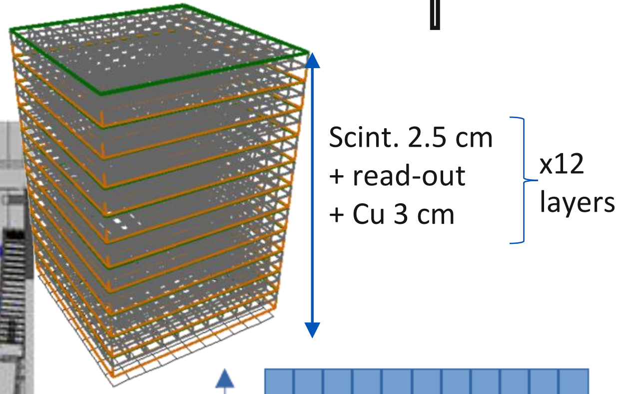
2. Correlation experiments pd, Λp, Λd, ΛΛ

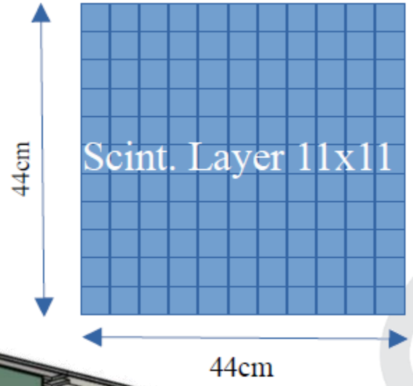
1. As background (with “semi-exotic” trigger)

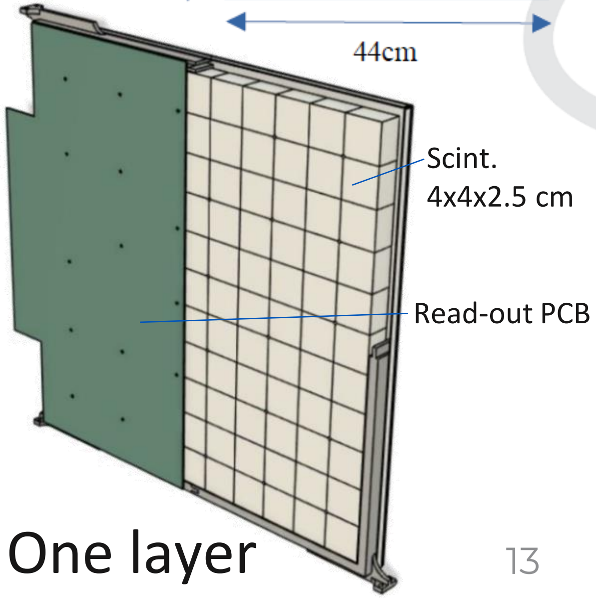
BM@N acceptance: $p_{T(p)}$<1.5GeV/c θ<20°



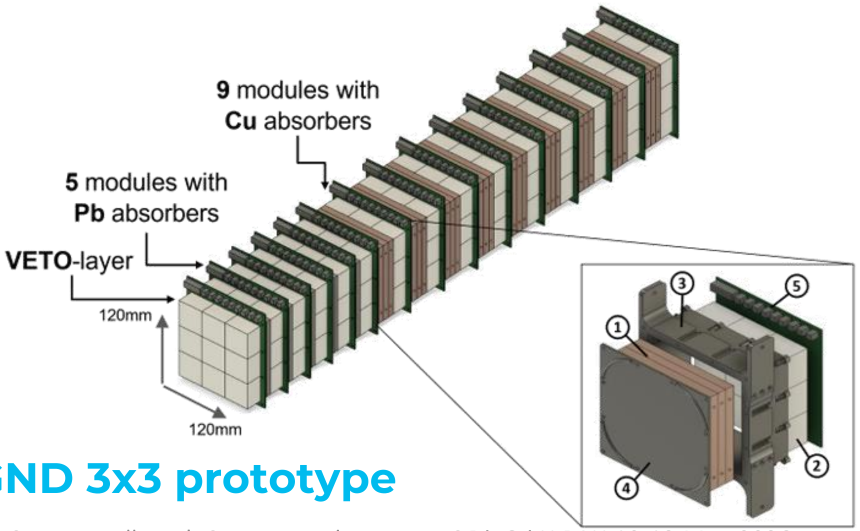






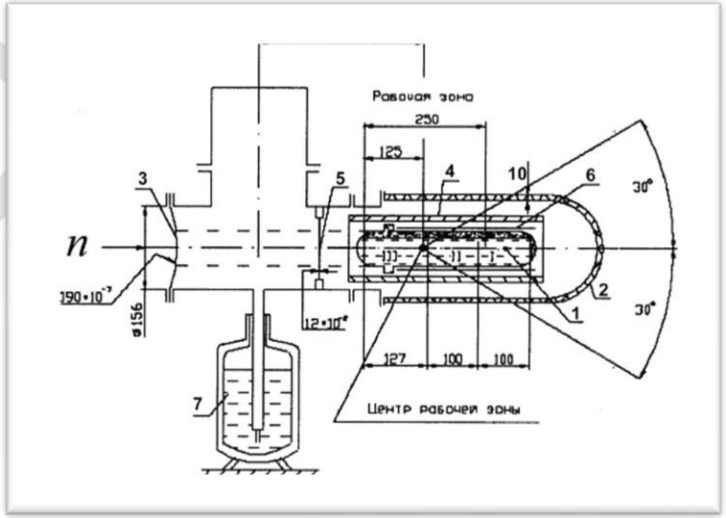


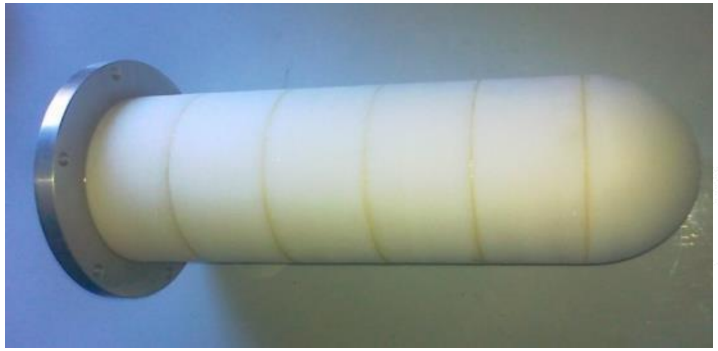
One layer



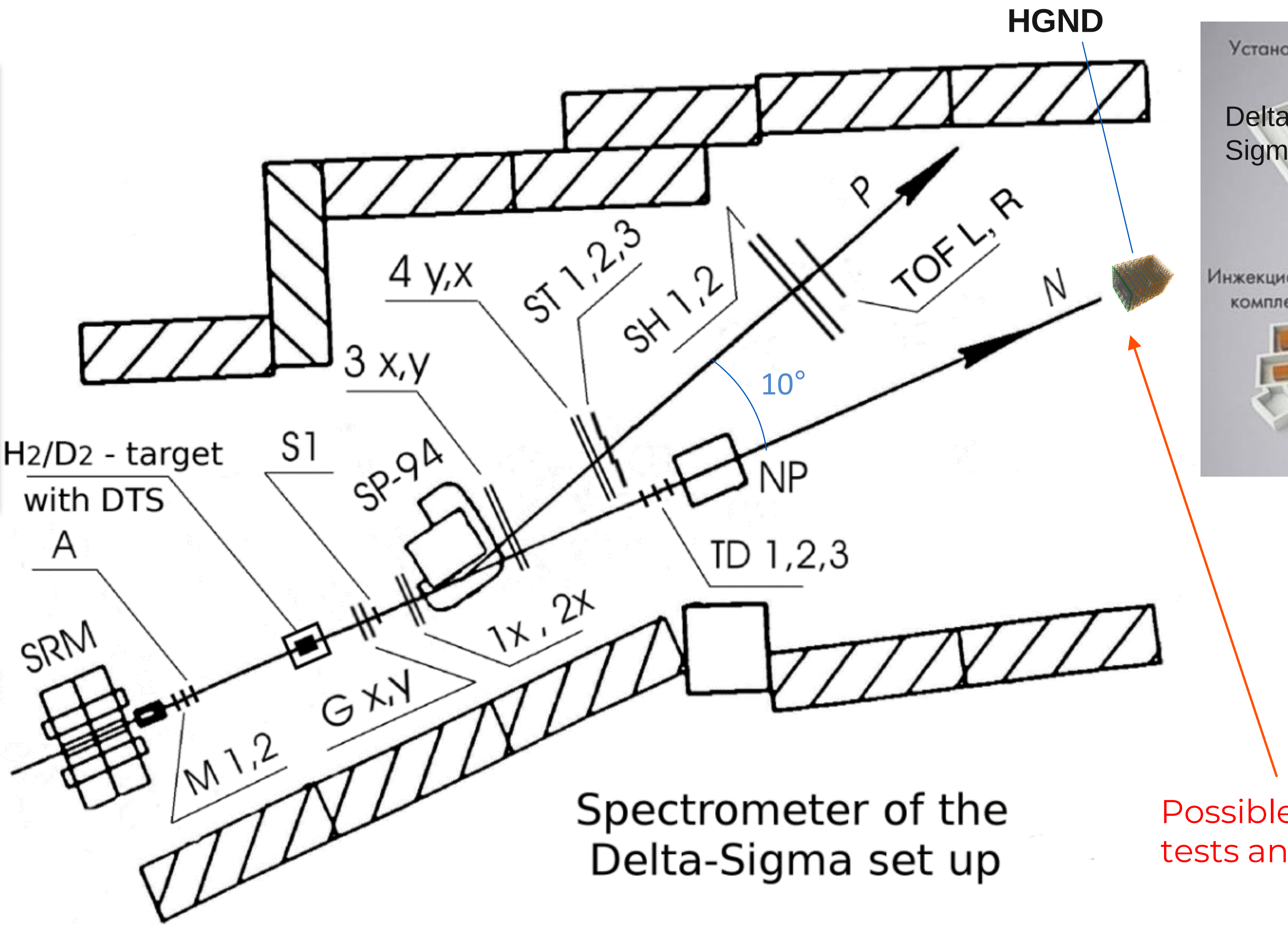
HGND 3x3 prototype

Delta-Sigma experimental place @ Nuclotron neutron beams



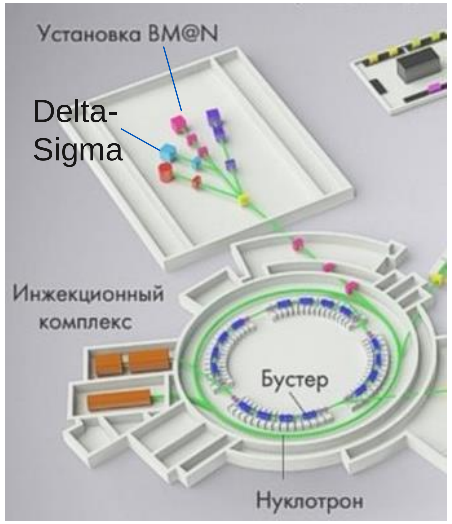


H_2/D_2 Cryogenic target



Spectrometer of the Delta-Sigma set up

Possible place for HGND tests and calibration



Experimental setup (vesion 0.0)

Targets
p, d, He^3,... (incl. polarized)
JINR

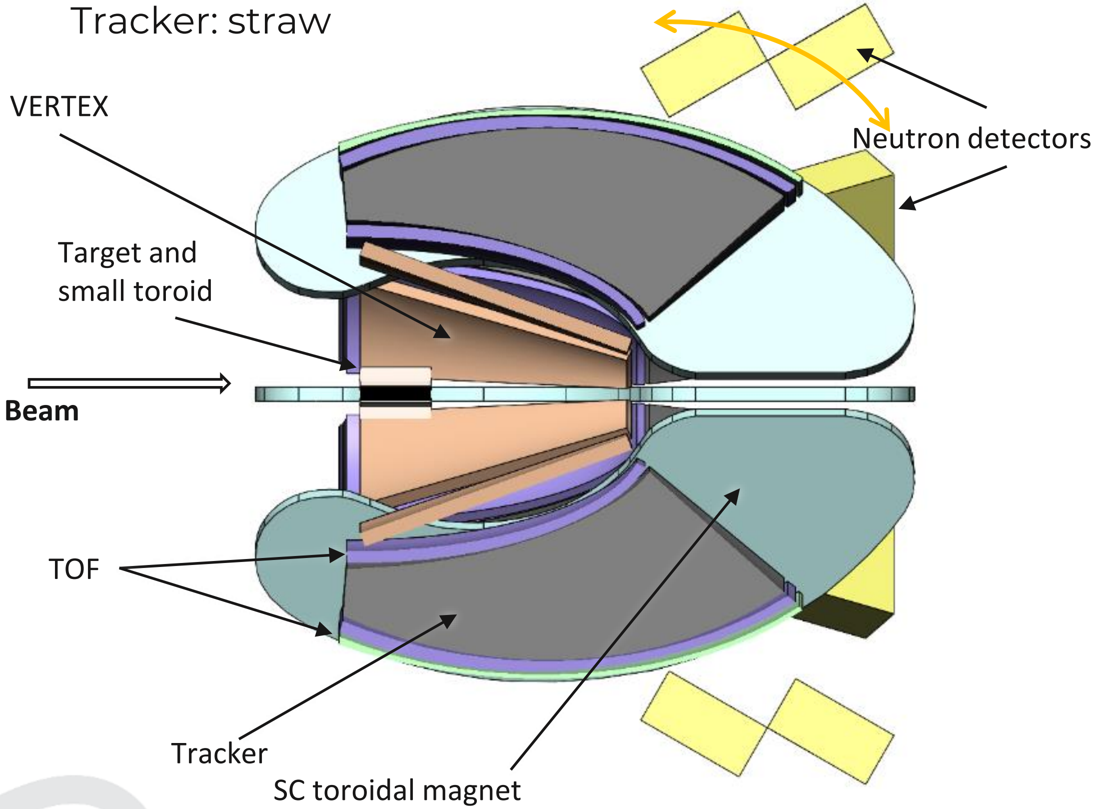
Vertex detector
JINR

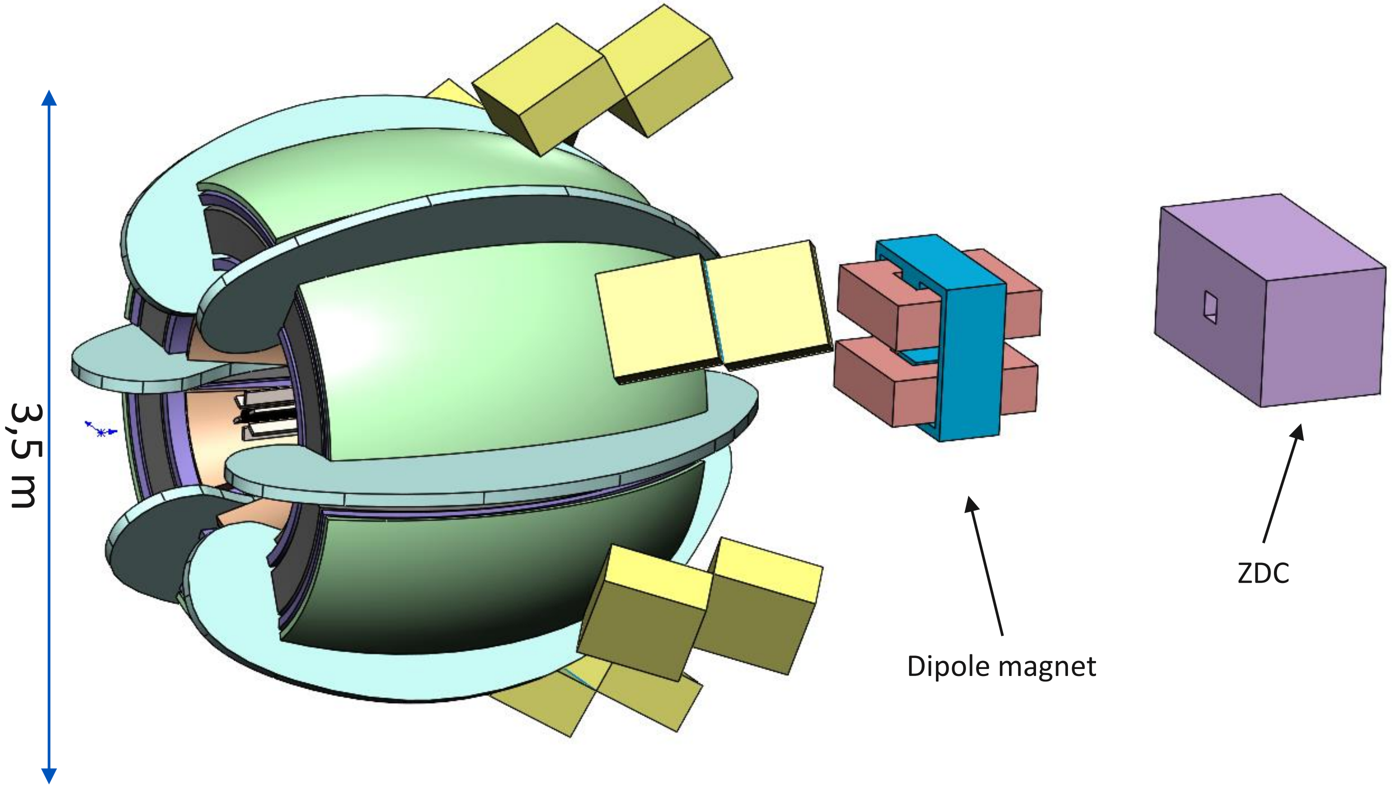
TOF and Tracker
TOF: Δt < 100ps
Tracker: straw

SC toroidal magnet
Budker INP RAS

Neutron Detector
- Accepatance ~0.25 sr (~40% full accepatance @ central rapidities)
- Time resolution < 150ps
- Δp/p < 2% ⇒ PID, tracking (together with vertex detector)

Dipole magnet and small angles detectors
- Spectators registration
- ZDC





SC toroid. Cold vs. High temperature: pros&cons

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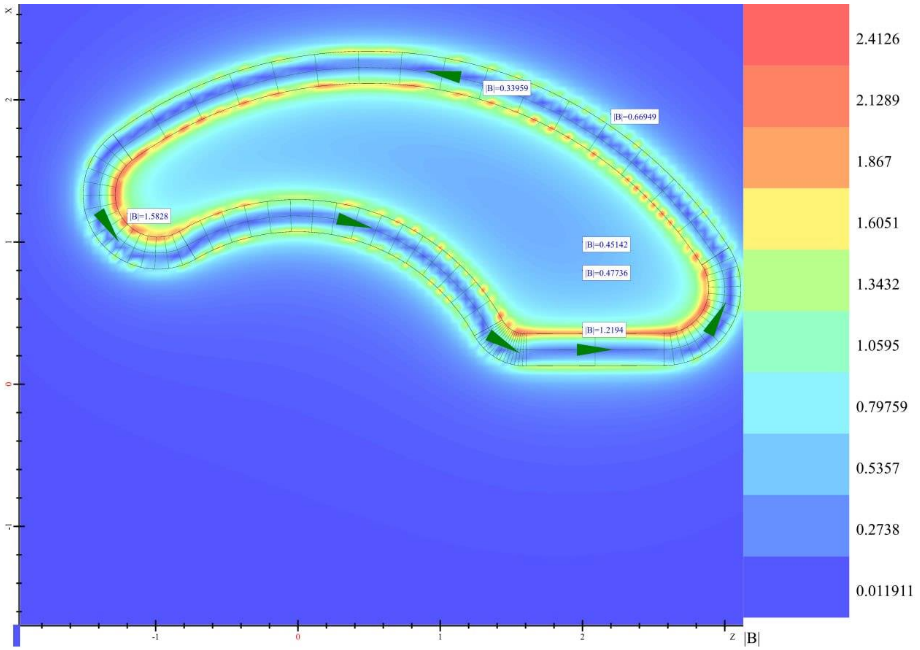
Cold (He) SC toroid:

- Typical NbTi wires use
- State of art design
- Winding tooling is well established
- Maximum field 2 T is reached
- Larger coil section



magnetic field map

HTSC toroid:

- Need selection for HTSC tapes for uniform and maximum parameters.
- Need work for cable assembling from original tapes
- Winding tooling is not well established
- A lot of design work is required
- Maximum field 2 T is reached only for 40 K temperature use (but cooling equipment for 40 K is commercially available in China for example)
- Maximum field 1.3-1.5 T may be reached for 77 K
- Coil section is smaller for about 30-40 %
- Smaller operation cost

HTSC cable

=> Needs development work for both toroid versions to compare and choose the appropriate one.

Highly granulated neutron detector HGND

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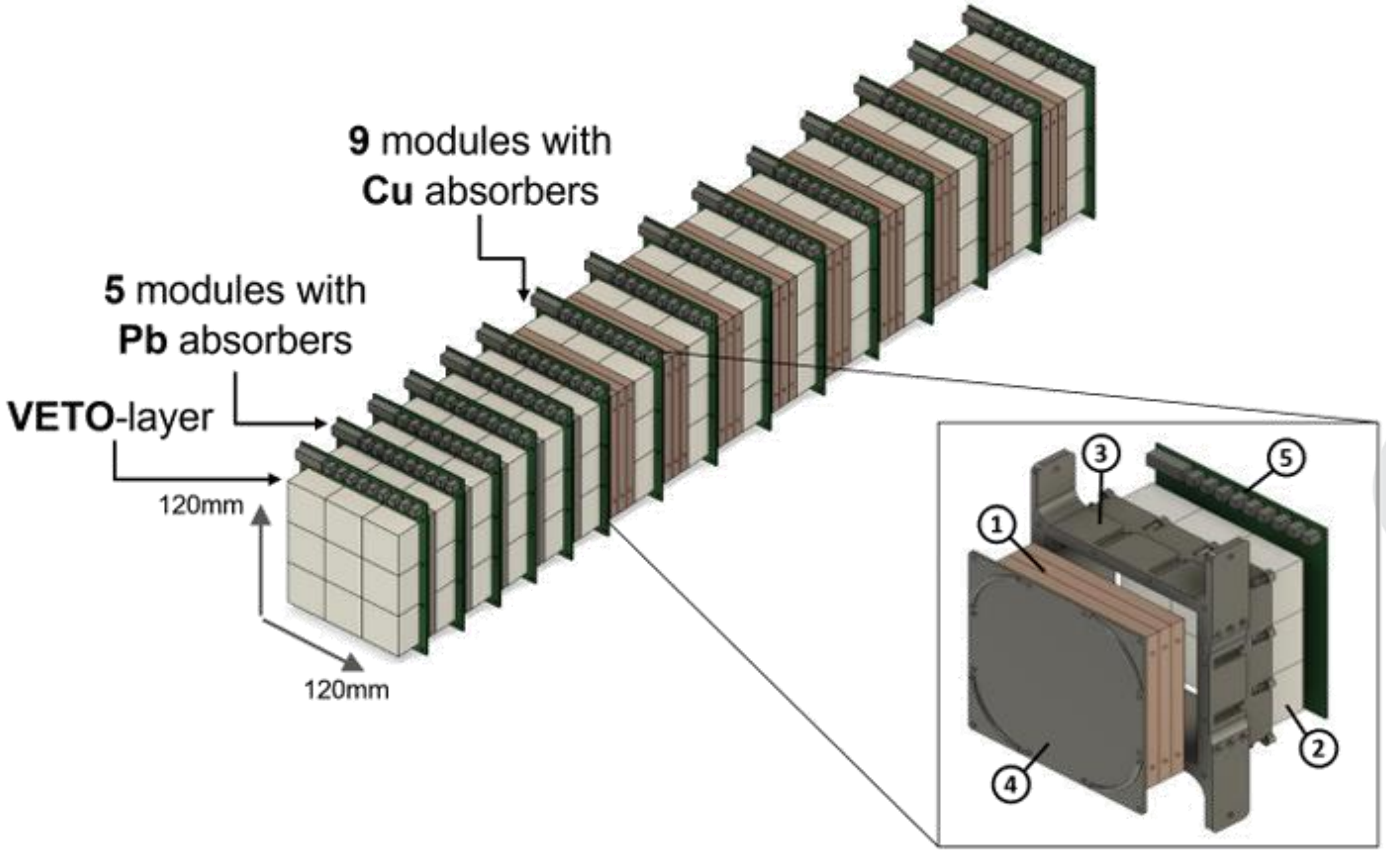
3D detector
Analogues: ZDC for SPD и HGND for BM@N

Signal registration in each cell

- Modular structure
- Neutron measurement by TOF
- σ(t) < 150 ps
- ~5 cells/neutron
- Detecting >1 neutron in module
- Detecting p, d, γ(need to change absorber to BGO)...

HGND prototype for BM@N



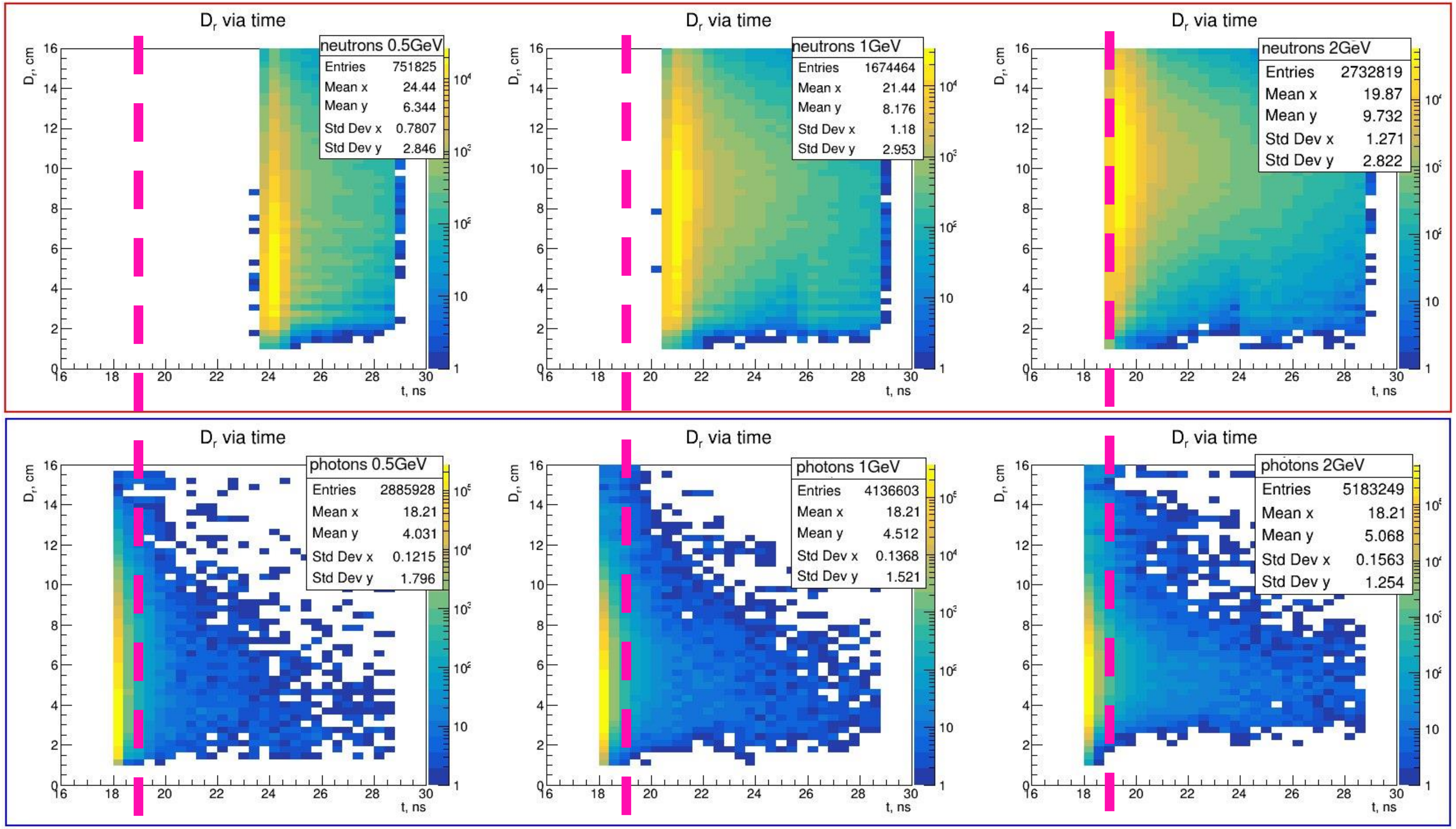
11x11 HGND: neutron/photon separation

Dispersion of hits position vs. time

Separation efficiency: 98%

Neutrons:

Photons:

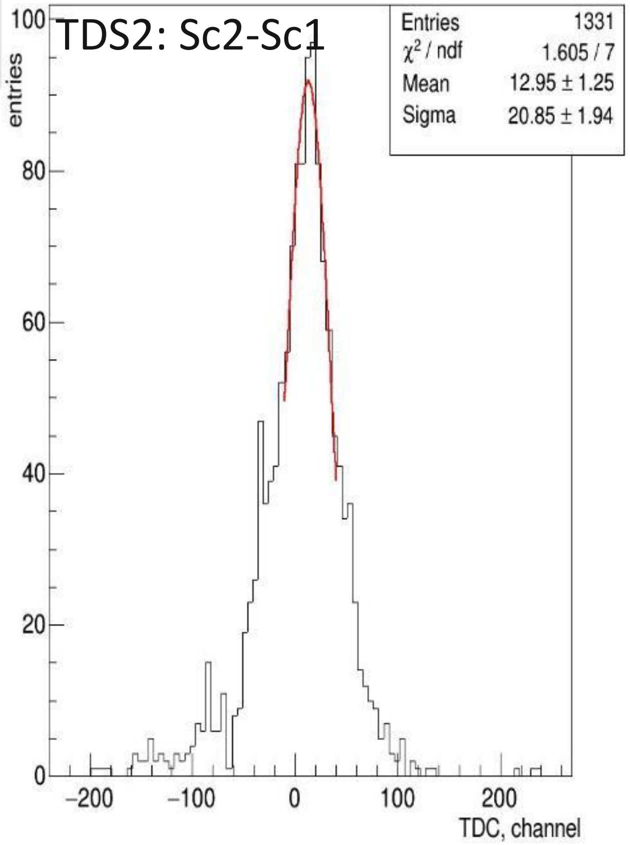


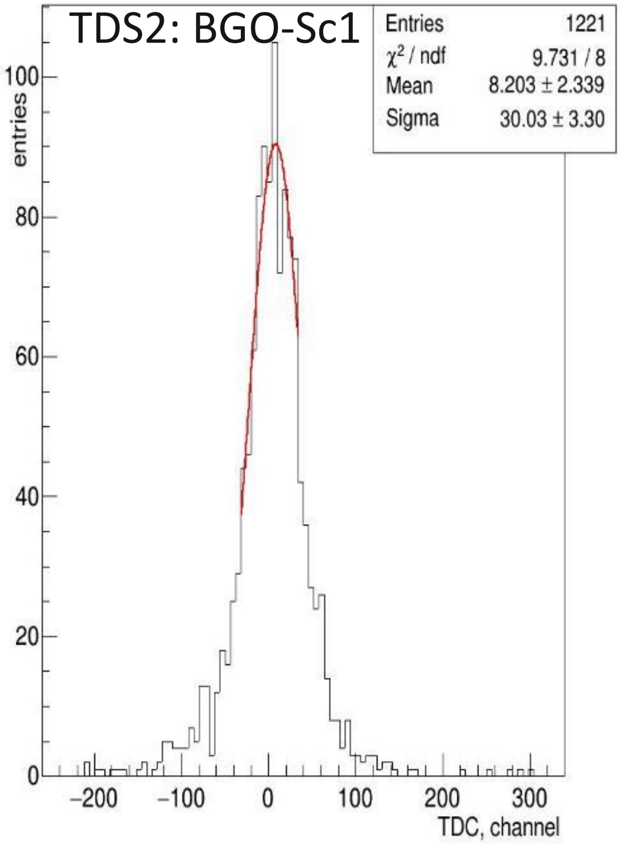
E = 0,5 GeV E = 0,5 GeV E = 0,5 GeV

A. Stavinskiy et. al. for publication in PEPAN 57, 5 (2026)

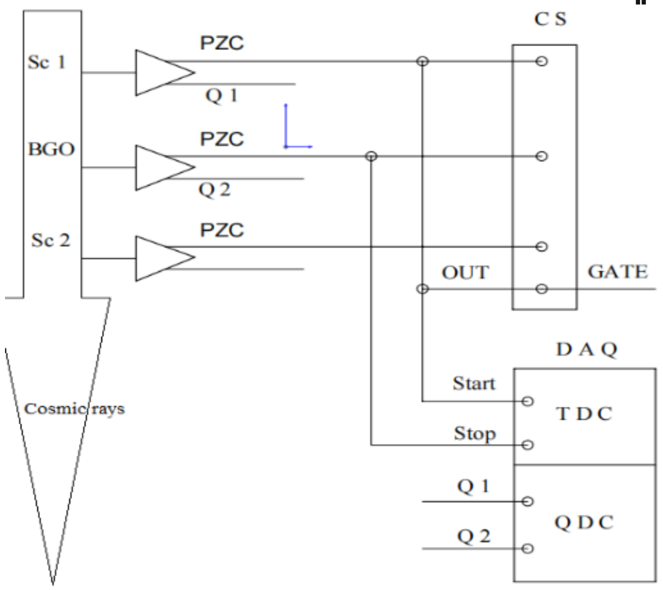
HGND with active absorber (BGO)
Cosmic rays test

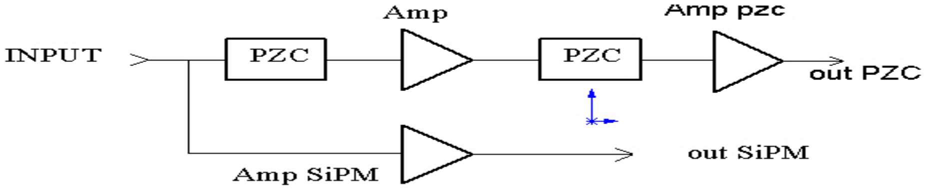
Time resolution for BGO crystal: 147 psec

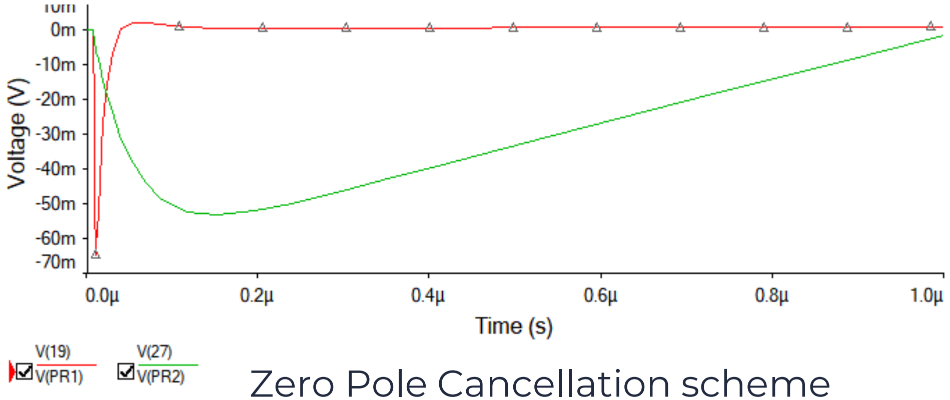




$$T_{BGO} = \sqrt{|sigma\mathrm{TDS1}^2 - sigma\mathrm{TDS2}^2/2|} * 35\mathrm{psec}$$







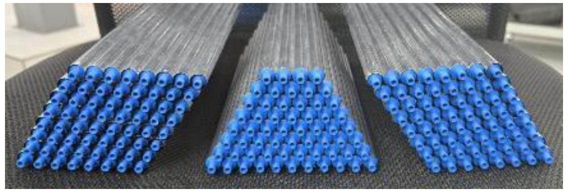
Zero Pole Cancellation scheme

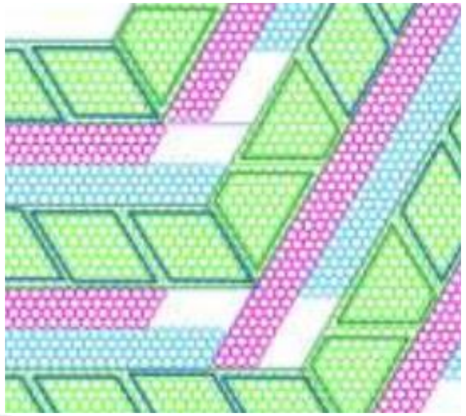
Straw tubes based tracking detector

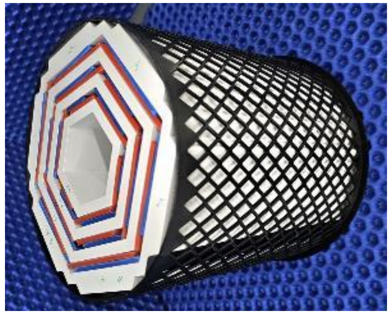
SPD straw tracker

“Straw Tracker of the future Spin Physics Detector at NICA collider”
V. Bautin, T. Enik et. al. PoS TIPP2023 (2025) 125)

- Main tracker system of SPD ~2m long, D~1.6 m
- Straw diameter 10 mm, thickness 36 um PET
- Spatial resolution of 150 um
- Barrel is made of 6 modules with up to 30 double-layers, with the ZUV orientation (0,+/-2^{o})
- Endcaps are made of 12 double-layers with the XYUV orientation
- Rate O(100 kHz)
- ~20000 straws







The straw tracker are using of in the different experiments

Straw winding

- ATLAS
- LHCb
- PANDA
- CBM
- COMPASS
- Mu2e
- NA64
- SVD-2
- GLUEX
- COZY-TOF
- ..

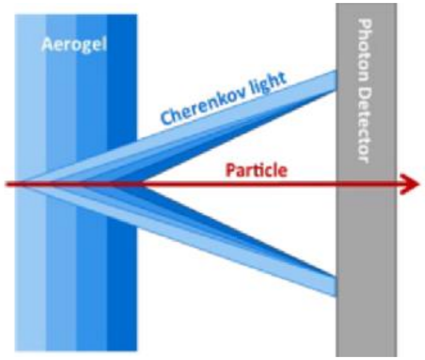
Straw welding

V. Bautin, S. Bulanova, T. Enik et. al.
NIM A 1081 (2026) 170767

- NA62
- SPD
- KEDR
- COMET
- SHiP
- DUNE
- OKA
- VES
- SPASCHARM
- ..

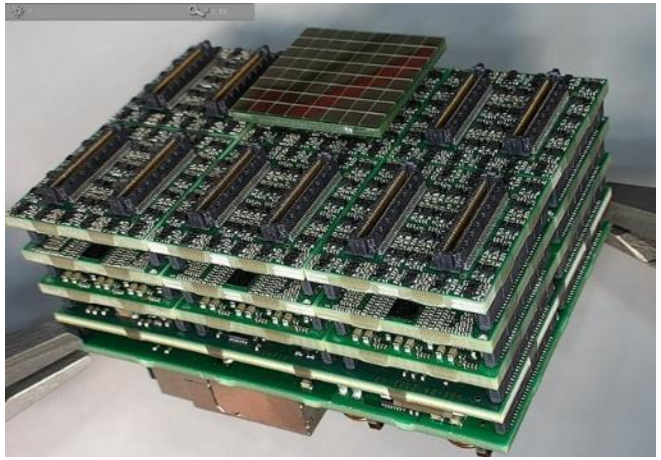
Aerogel based Cherenkov detectors for future HEP experiments   A.Barnyakov et. al.

FARICH for reliable π/K and μ/π separation

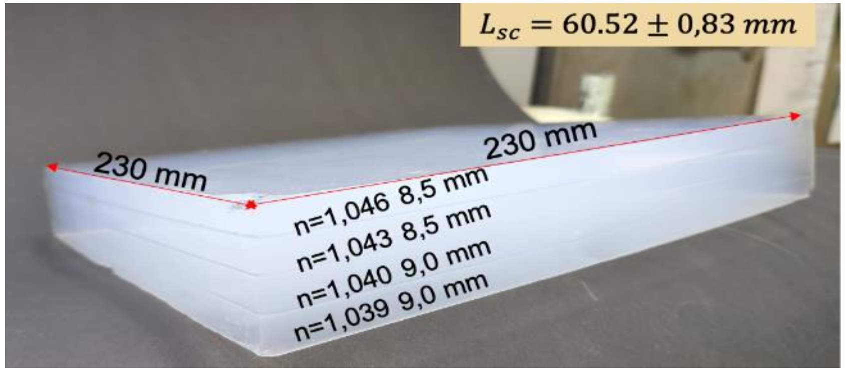


The technique has been developed since 2004

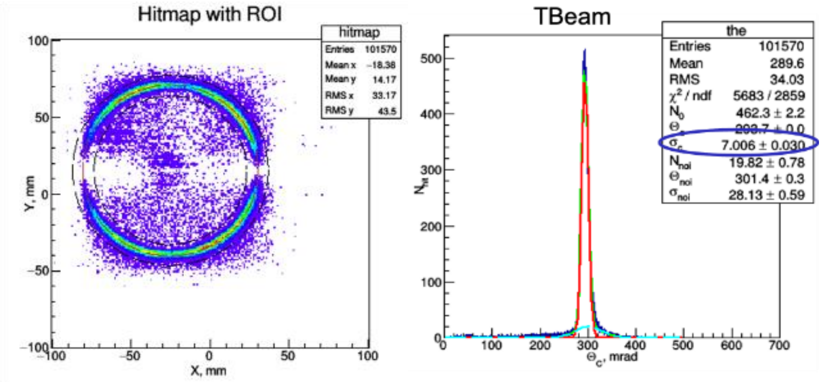
The most crucial issue now is position-sensitive photon detectors and FEE+DAQ issues.



- π/K–separation up to 8.5 GeV/c
- μ/π–separation up to 1.7 GeV/c
- K/p–separation from 3 to 14 GeV/c



Very promising progress in focusing aerogels production was achieved in 2022-2023. Several the largest 4-layer tiles of the focusing aerogel were produced in Novosibirsk



The beam test results are in good agreement with simulation. The expected (required) angle resolution for single Chrenkov photon was obtained experimentaly.

A.Yu. Barnyakov, et al., Nucl. Instr. and Meth. A 553 (2005) 70–75

A.Yu. Barnyakov, et al., Int. J. of Mod. Phys. A 39, No. 26n27, 2442012 (2024)

A.Yu. Barnyakov, et al., Phys. Part. Nucl. 56, No. 3 (2025) 652–655

Conclusions

HIP$_T$AN

- A new experimental program **Hip$_T$aN** is presented. Investigation of rare processes in high p_T region on fixed targets at Nuclotron is the main goal of the project.
- Unique properties of Nuclotron complex (high intensity, polarized beams, polarized targets) together with the development of new neutron detector open unique possibilities to study npQCD problems and cold dense baryonic matter
- Experimental setup for investigations at high p_T is proposed
  - Modular and comprehensive
  - 3.5m SC toroid: cold and high temperature versions discussed
  - High Granularity Neutron Detector
    - Algorithms of signal/noise separation
    - Active BGO absorber
  - Straw tubes tracker
  - Aerogel

холл Лаборатории Теоретической Физики
ОИЯИ, г. Дубна

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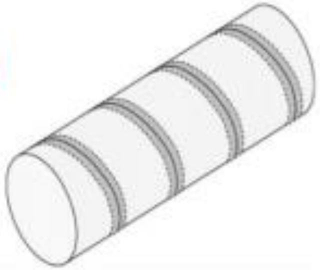
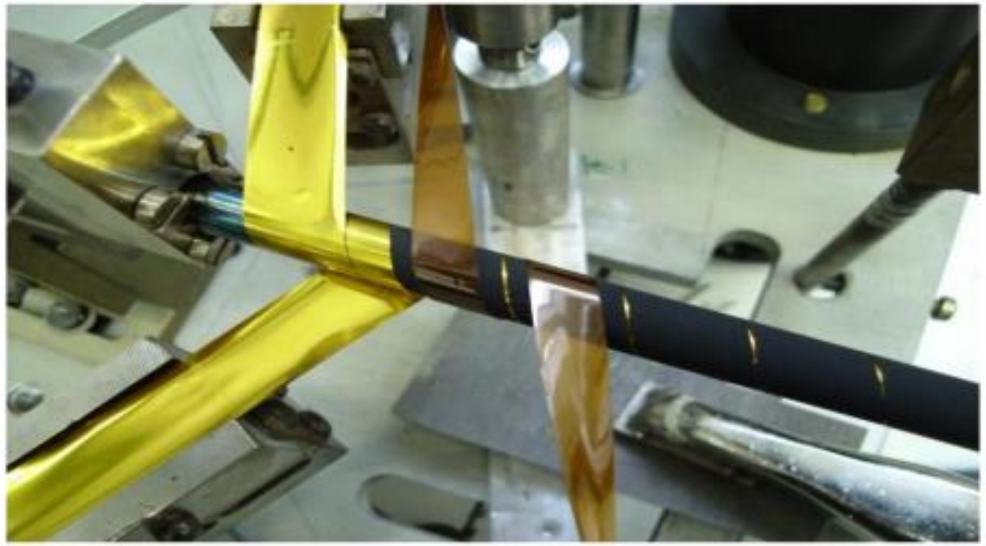
Backup slides

STRAW winding

- radiation resistance+
- shape retention+
- diffusion of gases-
- elastic deformation range-
- sensitivity to humidity-

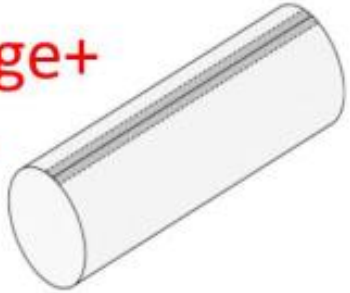


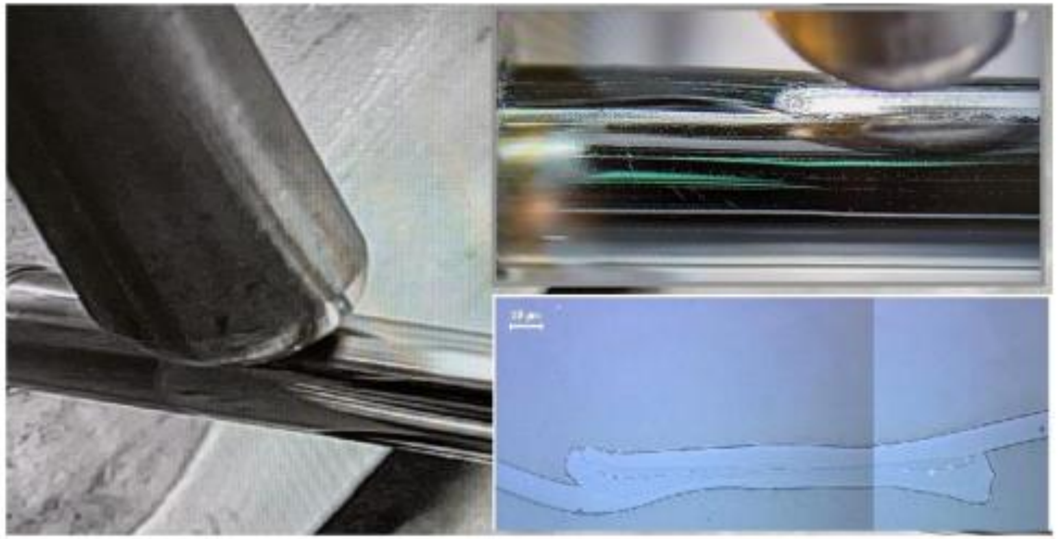


ATLAS, LHCb, COMPASS, COZY-TOF, NA64, Mu2e, PANDA, CBM...

STRAW welding

- elastic deformation range+
- sensitivity to humidity+
- diffusion of gases+
- retains shape under-pressure-
- radiation resistance-





NA62, COMET, SHiP, DUNE, SPD...

Several problems @ Nuclotron energies of $\sqrt{(s_{NN})}$ ~ 2 - 5 GeV

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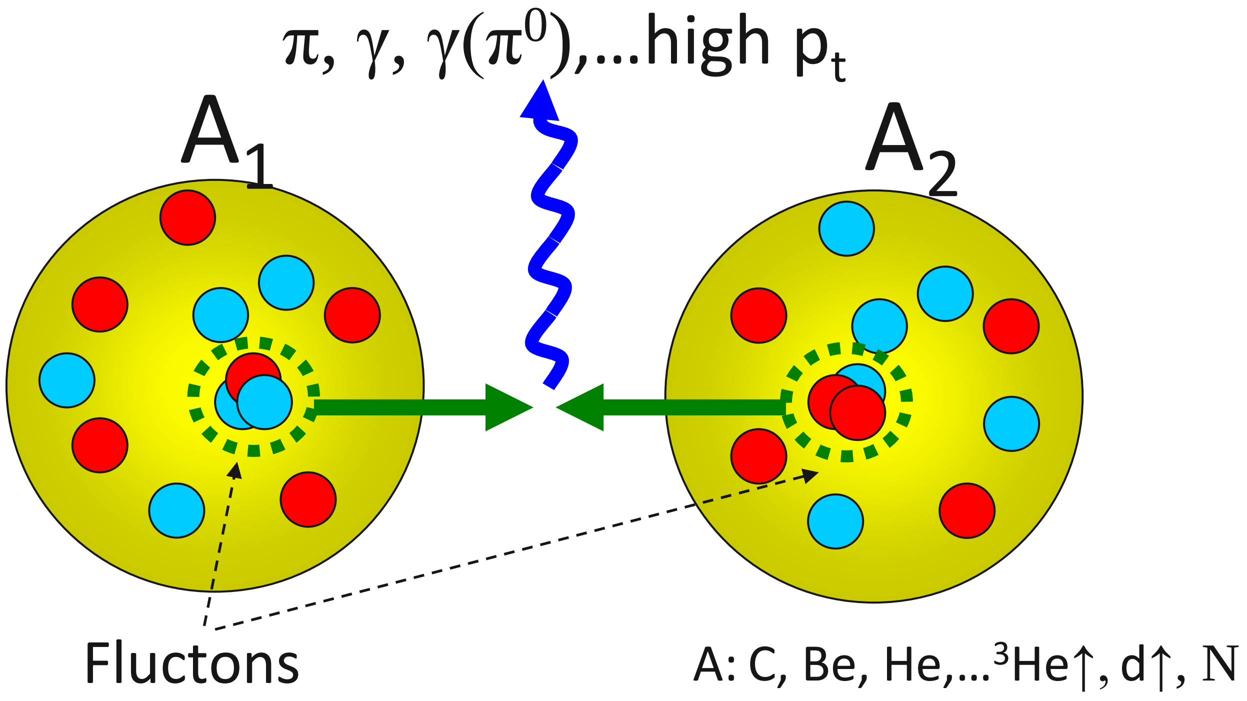
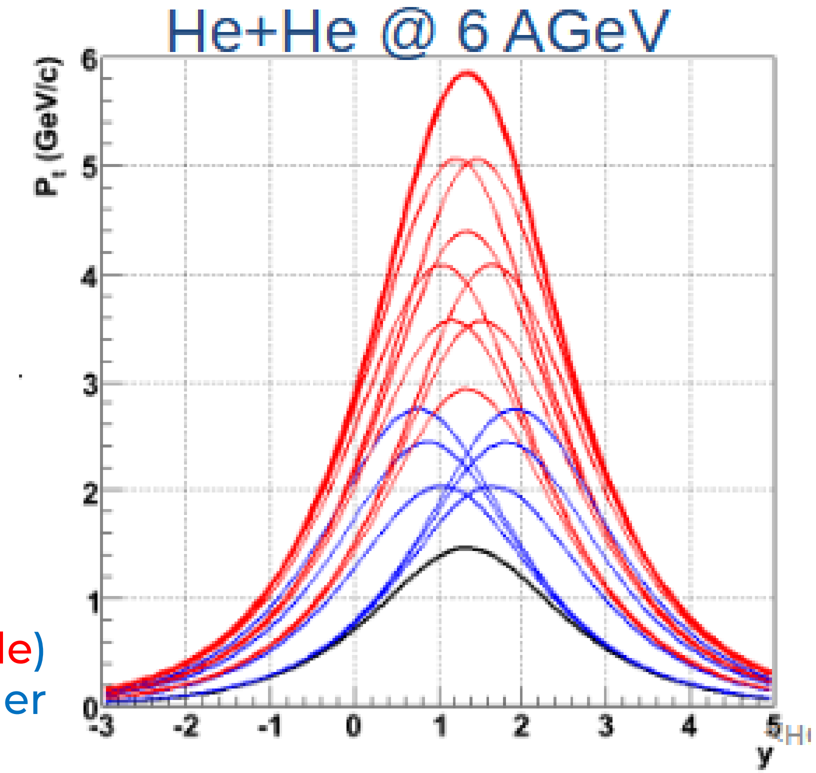
- Big unexplained spin effects @high p_T
- Diquarks (incl. strange) : are used in models, but no experimental proof of their existence @high p_T
- Excessive production of baryons and deuterons @ p_T > 0,5 GeV/c
- No data on $n\uparrow + n\uparrow$ and $p\uparrow + n\uparrow$ @high p_T reactions to search for isotopic symmetry breaking in strong interactions
- Properties of multi-nucleon (multiquark) systems are studied poorly, no certainty in their Nature (fluctons, SRC,…?)
- The role of strange quarks in multi-nucleon (multiquark) systems (and in evolution of neutron stars)

Fluction-flucton interactions



- Using double-cumulative particle @90° in c.m.s. as trigger
- At central rapidities the kinematical limits of double-cumulative processes are mostly decoupled from 1N + xN



Kinematical limits of (double) cumulative trigger

Аномалия в асимметрии сечений поляризованных нейтронов при фоторасщеплении дейтрона E_γ = 0.8 – 1.6 ГэВ

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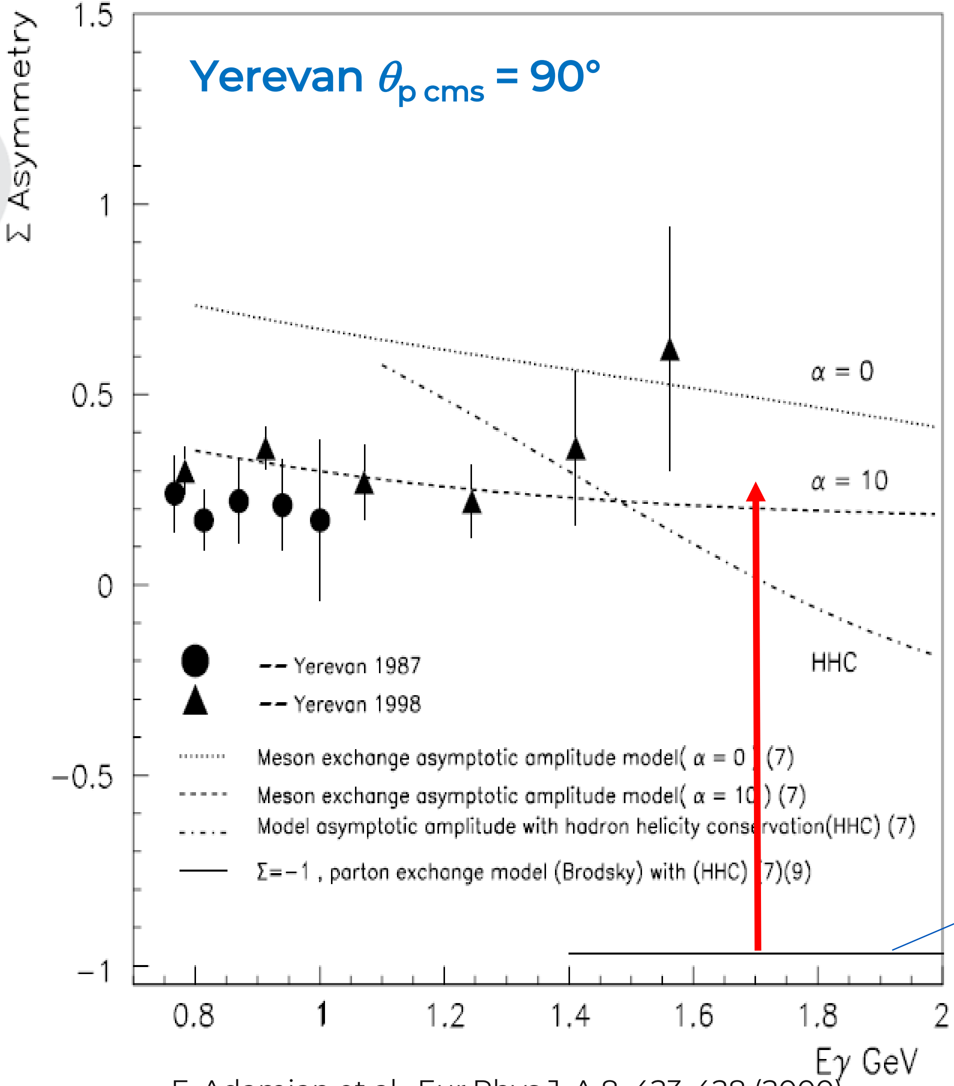


F. Adamian et al., Eur.Phys.J. A 8, 423-428 (2000)

Fig. 8. The energy dependence of the cross-section asymmetry Σ for $\theta_p = 90°$ in the cms.

$$\Sigma = (N_n \rightarrow -N_n \uparrow)/(\bar{P}_\gamma \uparrow N_n \rightarrow +\bar{P}_\gamma \rightarrow N_n \uparrow)$$

Предложение
hard γ **@** θ_{cms} = 90° :

p↓↗+n↓–>d+γ => A_{pn}
p↓↗+p↓->d+π⁺ => A_{pp}

$$R = \frac{p\downarrow\nearrow + n\downarrow \rightarrow d+\gamma}{p\downarrow\nearrow + p\downarrow \rightarrow d+\pi^+} \neq 1$$

$$R = \frac{p\downarrow + n\downarrow \rightarrow d+\gamma}{p\nearrow + n\downarrow \rightarrow d+\gamma} \neq 1$$

Модель партонного обмена (Brodsky) предсказывает Σ = -1

Спиновые переменные T20, K0 также не описываются и в dd, dp, de реакциях

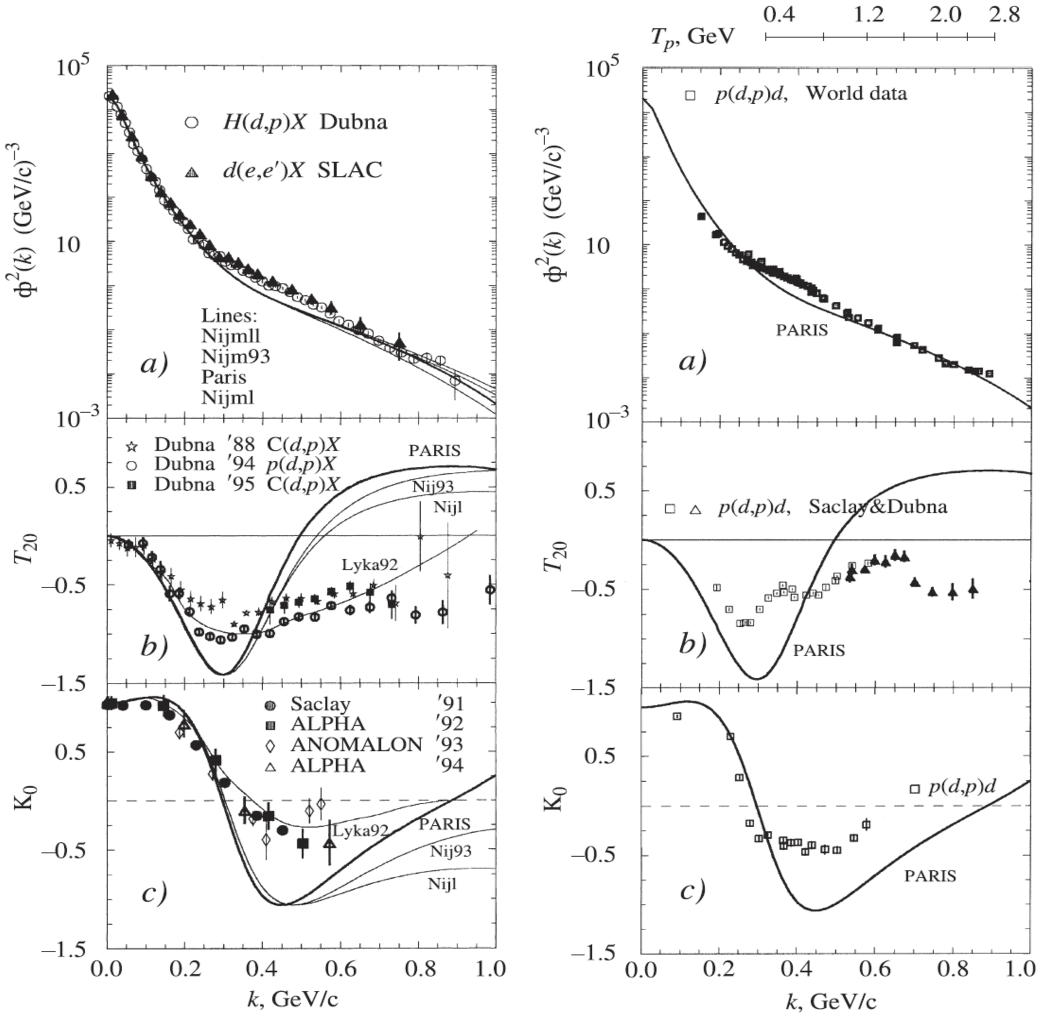


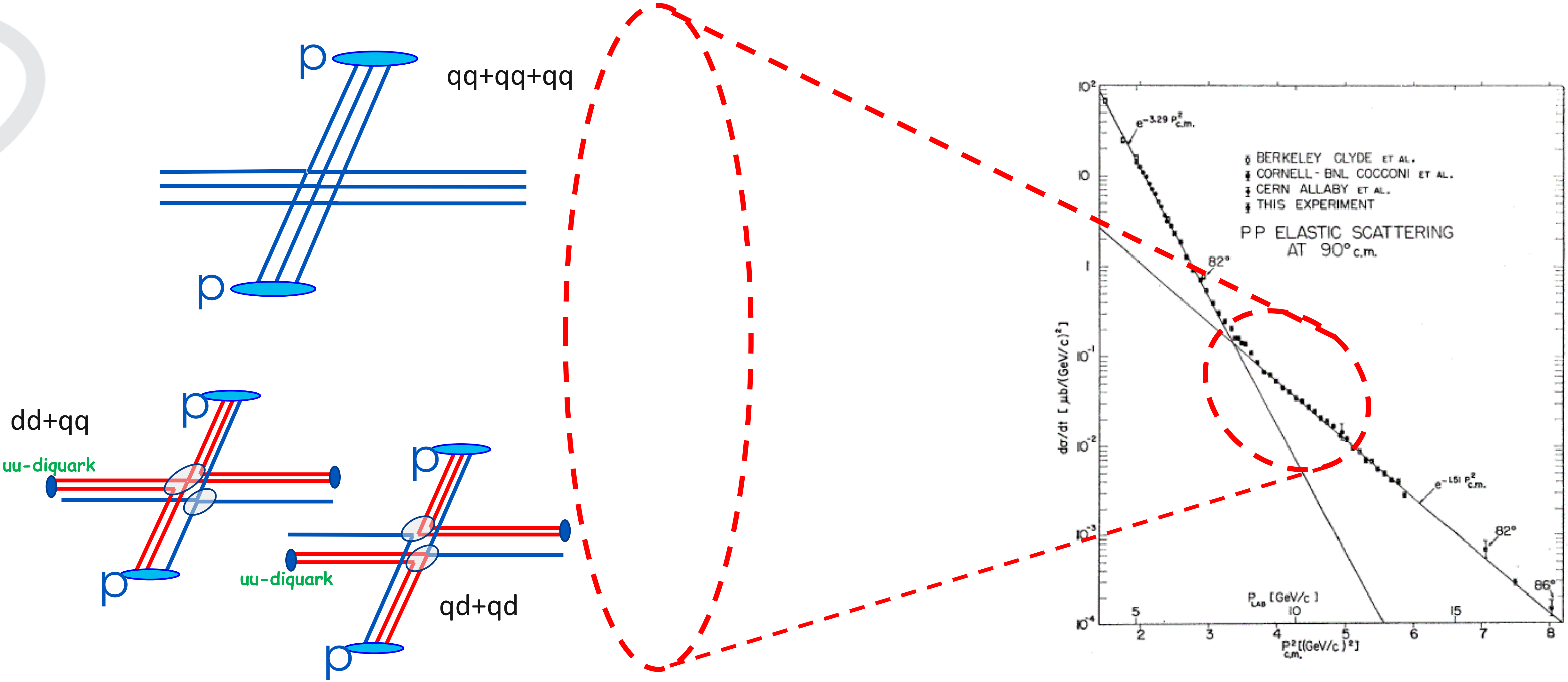
Рис. 5. Сводка данных экспериментов по фрагментации (слева) и упругому рассеянию «назад» (справа) поляризованных и неполяризованных дейтронов

F. Lehar, Current experiments using polarized beams of the JINR LHE accelerator complex, *Phys.Part.Nucl.* 36 (2005) 501-528

CC URQMD 10^5 ev.	2 GeV/c	3GeV/c	4GeV/c	10GeV/c	30GeV/c
all	2 520 772	2 579 414	2 640 908	2 882 405	3 283 145
P	271 961	266 605	266 161	248 805	228 866
N	271 720	266 368	266 624	248 612	228 820
π^0	43 878	64 268	85 051	162 099	282 712
π^+	37 929	55 837	74 365	145 040	255 919
π^-	37 969	55 702	74 208	144 887	254 974
K^0	230	1 121	2 398	8 278	20 299
K^+	235	1 110	2 304	8 365	20 332
Λ	225	951	1 922	5 878	11 331
Σ^0	86	468	927	2 451	3 857
Σ^+	66	372	788	1 972	3 278
Σ^-	83	362	785	2 099	3 247
antiK^0	2	45	130	2 027	9 500
K^-	3	33	130	2 102	9 623

3 А ГэВ: K^0**+**K^+(2 231)~$\Lambda+\Sigma$(2 153)

The presumptive mechanisms of interaction with scattering on the diquark



But to distinguish between qq, qd, dd scatterings it is not enough to measure elastic scatterings

Reactions with diquarks in inelastic exclusive measurements pp → pp (90°)
All particles with p_T>0.5GeV/c

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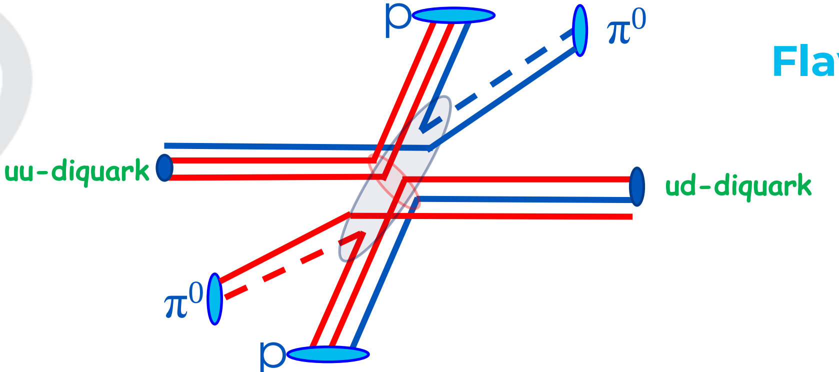

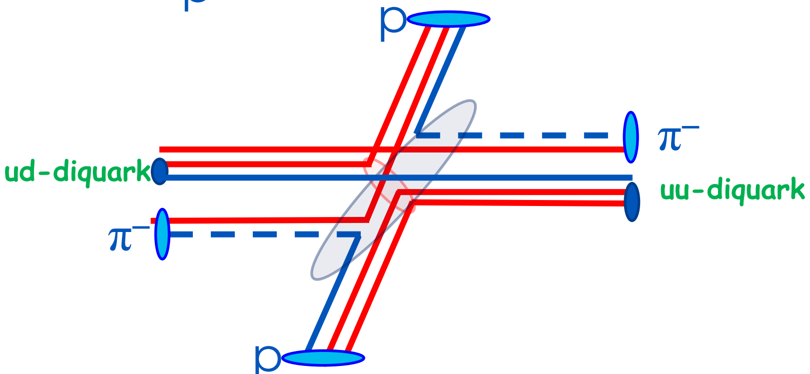

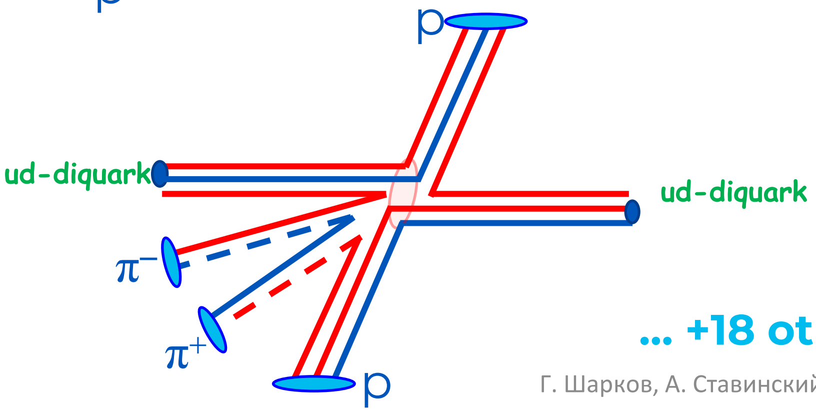

Flavor structure

$$\frac{d\sigma(pp \to pp\pi^0\pi^0)}{d\sigma(pp \to pp\pi^+\pi^-)} \approx \frac{12}{7} \approx 1.7$$

With uu and ud diquarks

$$R = \frac{N(\pi^+\pi^-)}{N(\pi^0\pi^0)} = \frac{2}{7}$$

Without diquark

$$R = \frac{N(\pi^+\pi^-)}{N(\pi^0\pi^0)} \to 0$$

Diquark ud only

Measuring the $\pi^{\pm}$ and π^0 ratios one can get the indications on presence and composition of diquarks

… +18 other diagrams