High Granularity Neutron detector(HGN) for BM@N

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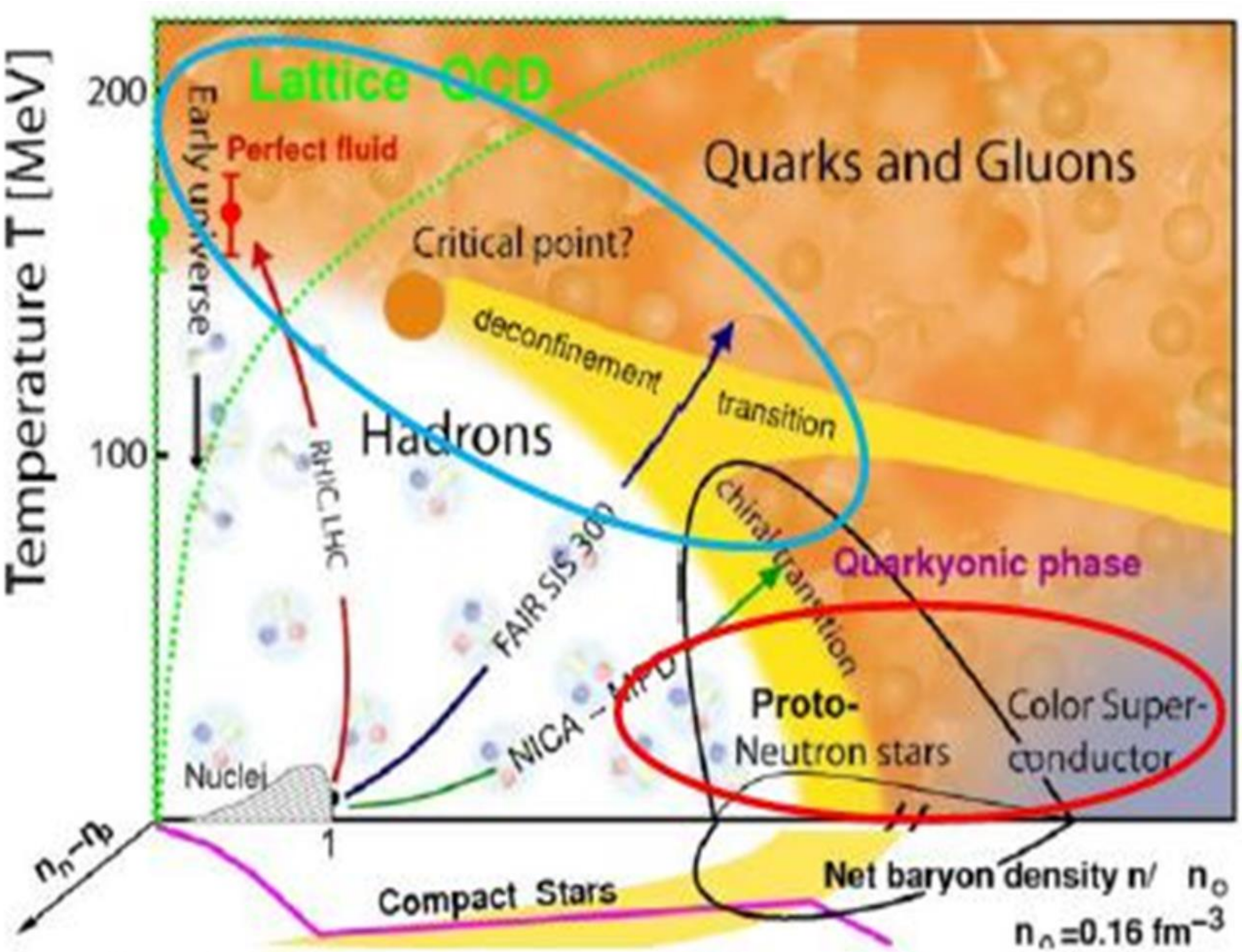
1. **Motivation**
2. **Geometry**
3. **Efficiency**
4. **Resolution**
5. **Test**
6. **Conclusion(ToDo)**

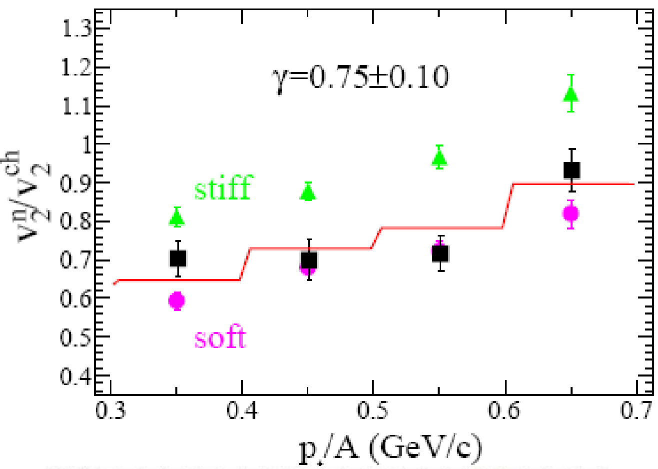
Motivation

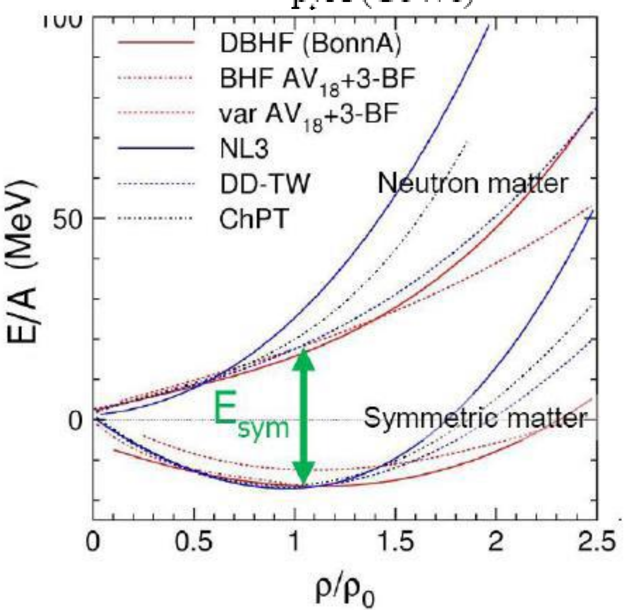


Temperature T [MeV]
200
100
Lattice QCD
Early universe
Perfect fluid
Quarks and Gluons
Critical point?
deconfinement
transition
Hadrons
RHIC LHC
FAIR SIS 300
NICA – MPD
chiral transition
Quarkyonic phase
Proto-
Neutron stars
Color Super-
conductor
Nuclei
1
$n_n - n_p$
Compact Stars
Net baryon density n/ n_0
n_0=0.16 fm^{-3}

Symmetry energy of nuclear matter: difference between binding energy of symmetric and asymmetric nuclear matter

ASY-EOS GSI





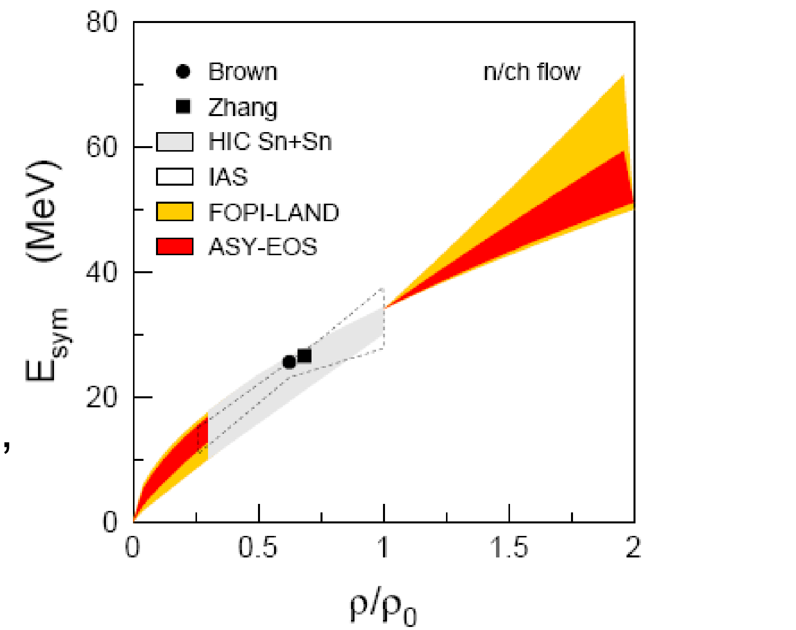
Symmetry energy constrained by measurements of v2 flows of neutrons and protons

$$E_A(\rho,\delta) = E_A(\rho,0)+E_{sym}(\rho)\cdot\delta^2$$

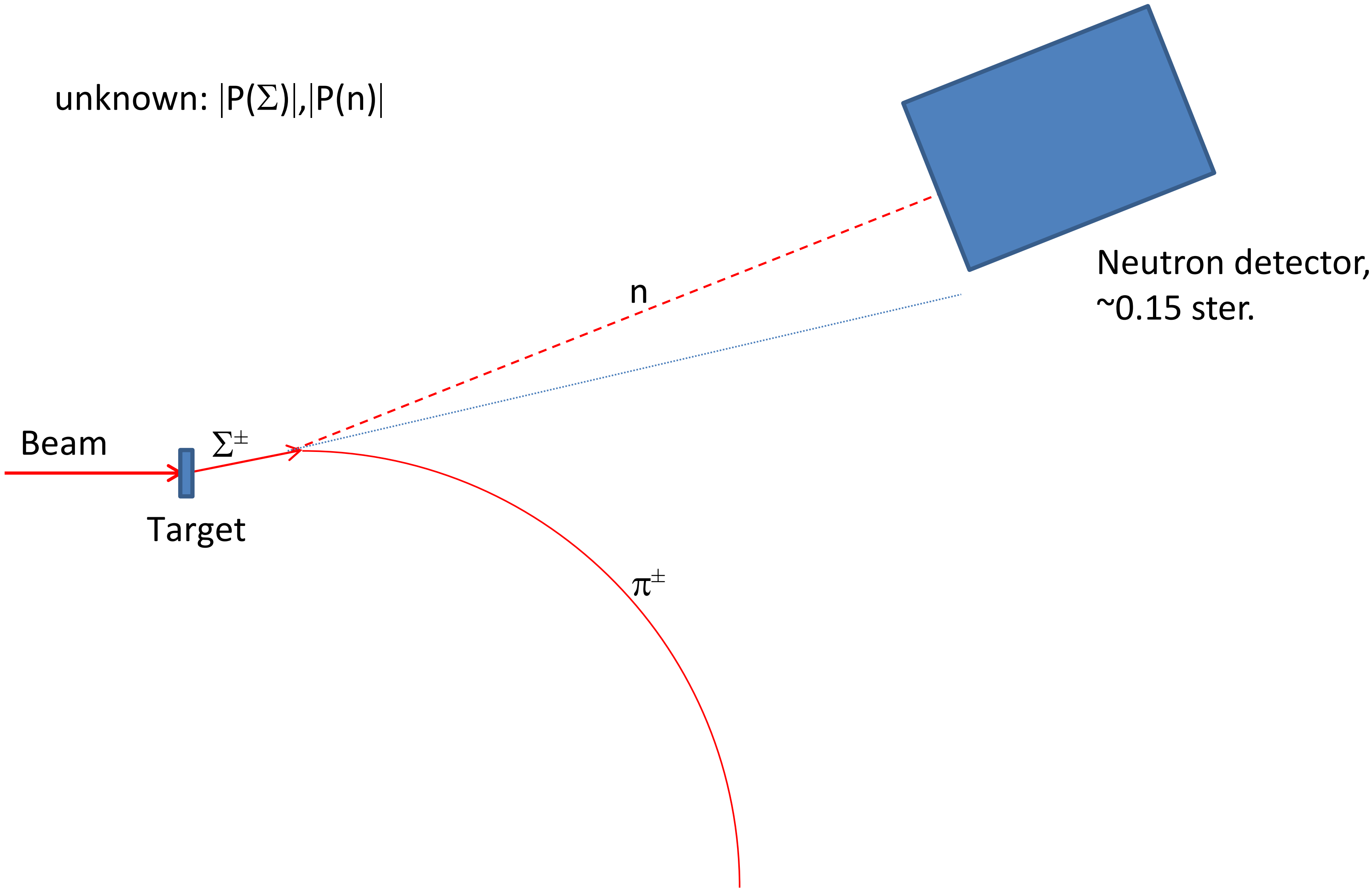
with $\delta= (\rho_n-\rho_p)/\rho$ $\quad E/A(\rho_o) = -16$ MeV

M.Kapishin report,

June 2021



unknown: $|P(\Sigma)|, |P(n)|$



Detector characteristics(goal).

To accomplish physical tasks following performance parameters should be met:

1.Neutron identification in the momentum range 1-3 GeV/c with an efficiency ≥ 50%

2.Time resolution 150-200 ps (corresponds dp/p~15% for p=2 GeV/c)

3.Neutron entry point geometry resolution ~3cm (dp/p~1% for L~3.5m-important for Sigma+-identification)

4.The acceptance of the detector of the order of 10-1ster.

5.Two neutron resolution within one arm (important for heavy ions collisions).

6.Neutron-photon and neutron-charge particle separation.

- **Simulated configurations**

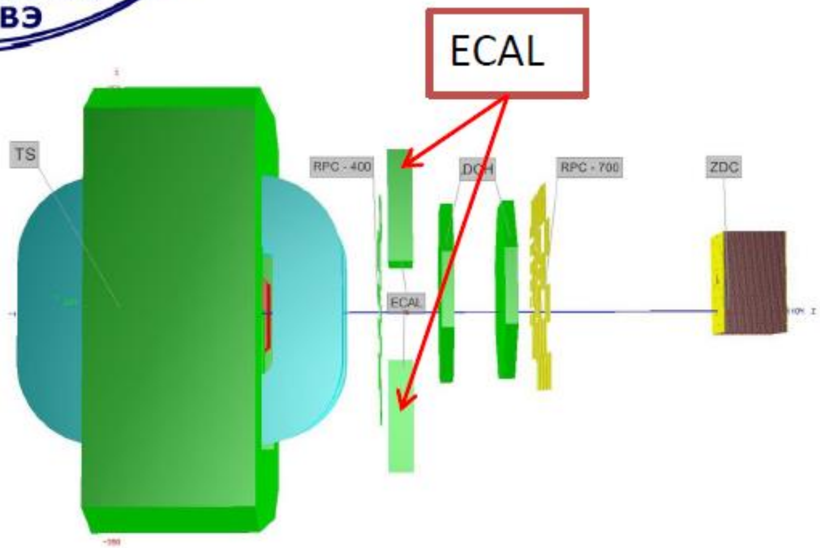
1.ECAL+Sci(30mm)x 9 slices+
W(20mm)x8 slices (with ECAL)

2.Sci(30mm)x 15 slices+
W(5mm)x6+ W(20mm)x8 slices(without ECAL)

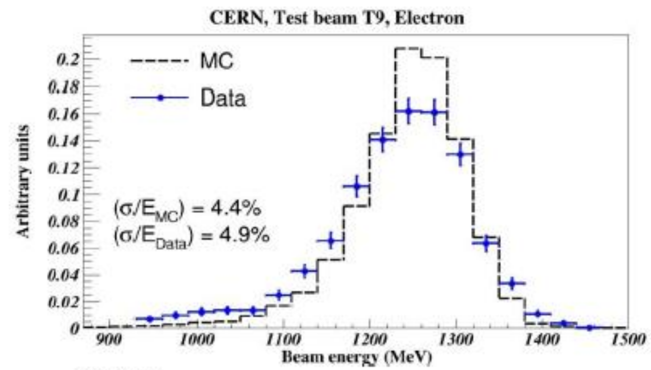
Simulation done with GEANT-4-10.5.1

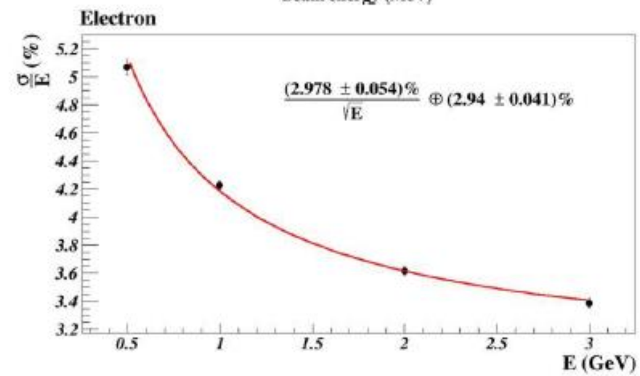
Generators: Box-generator,
DCM-QGSM-SMM ,
FTF

Electromagnetic calorimeter (optional)

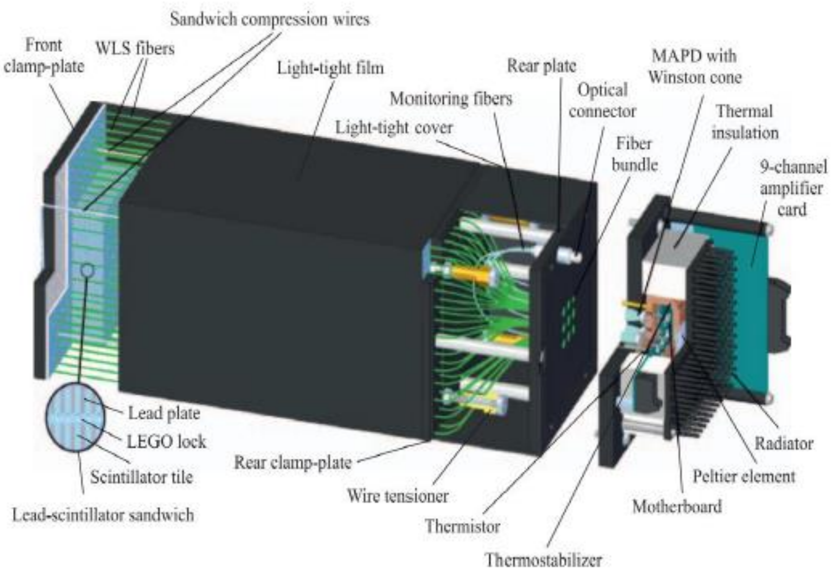


Energy resolution





Parameters	
Transverse size, mm²	40x40
Module size, mm²	120x120
Number of layers	220
Lead absorber thickness, mm	0.3
Polystyrene scintillator thickness, mm	1.5
Moli'ère radius, mm	26
Radiation length, X_0	11.8



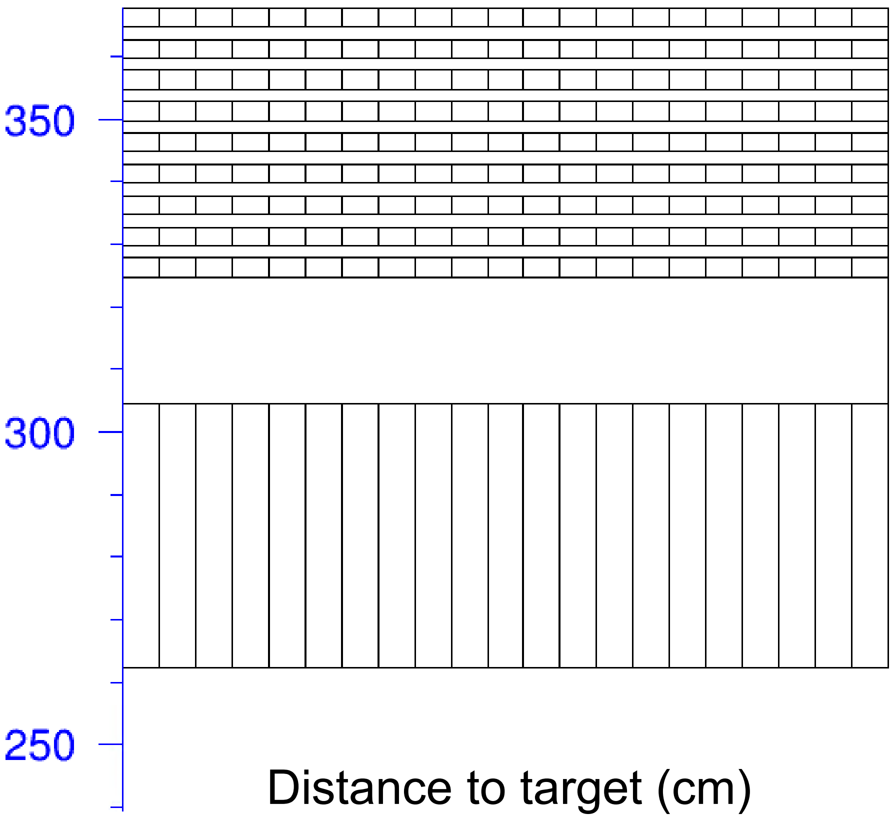
Design of the Shashlyk type calorimeter module

I.Tyapkin

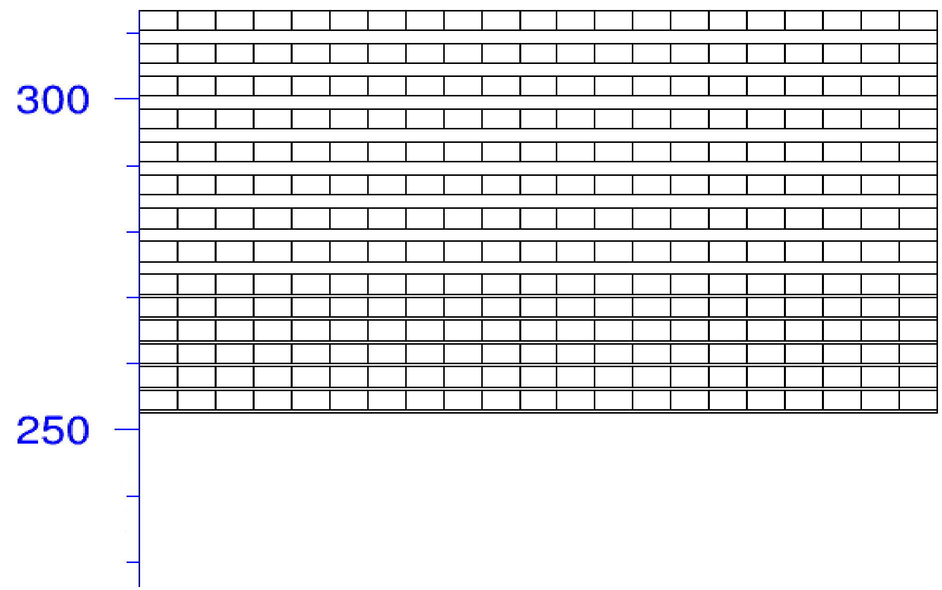
Simulations (P.Alekseev, N.Zhigareva, ITEP)

Version 1(with ECAL)

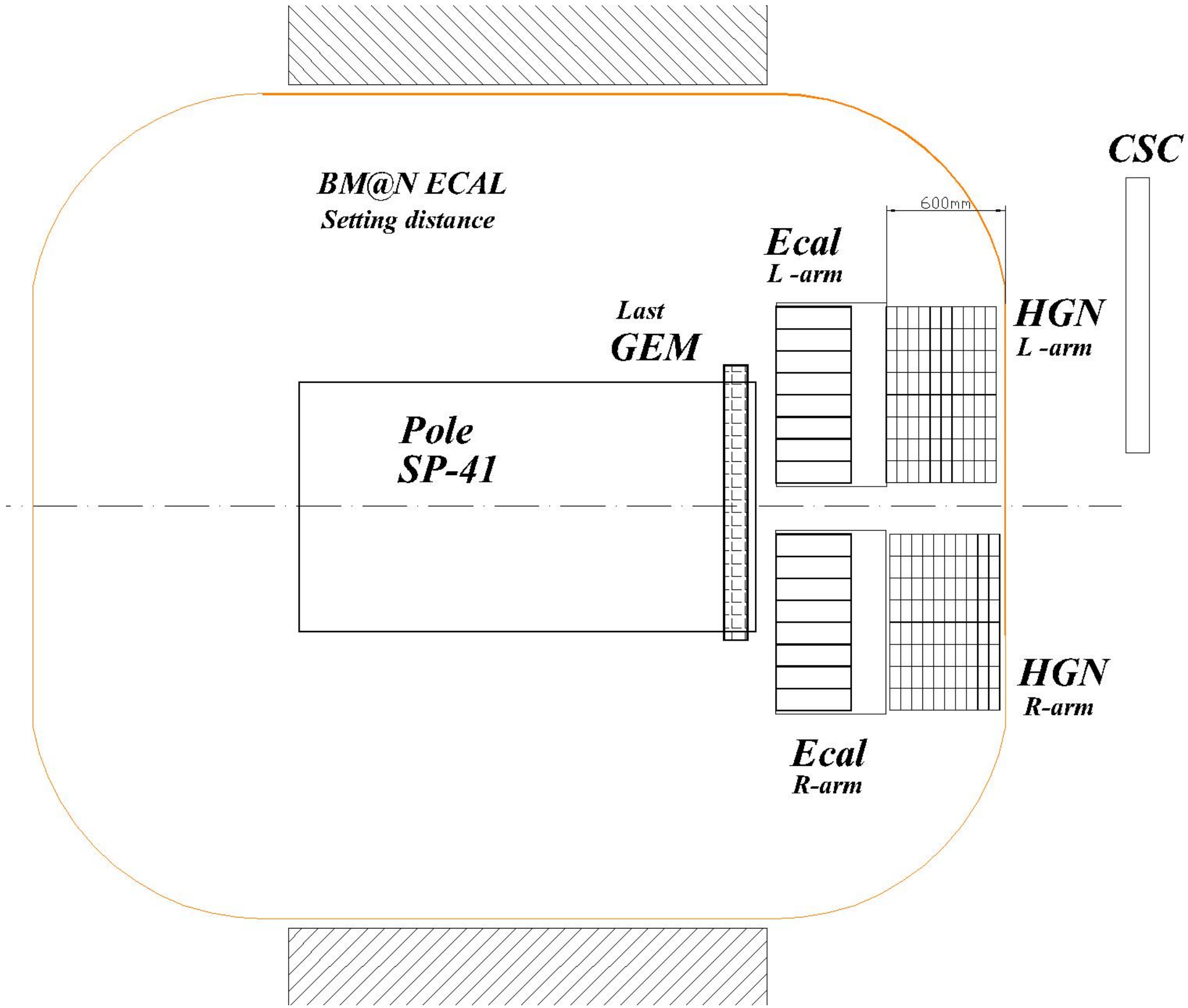
Acceptance: Version2/Version1~1.4



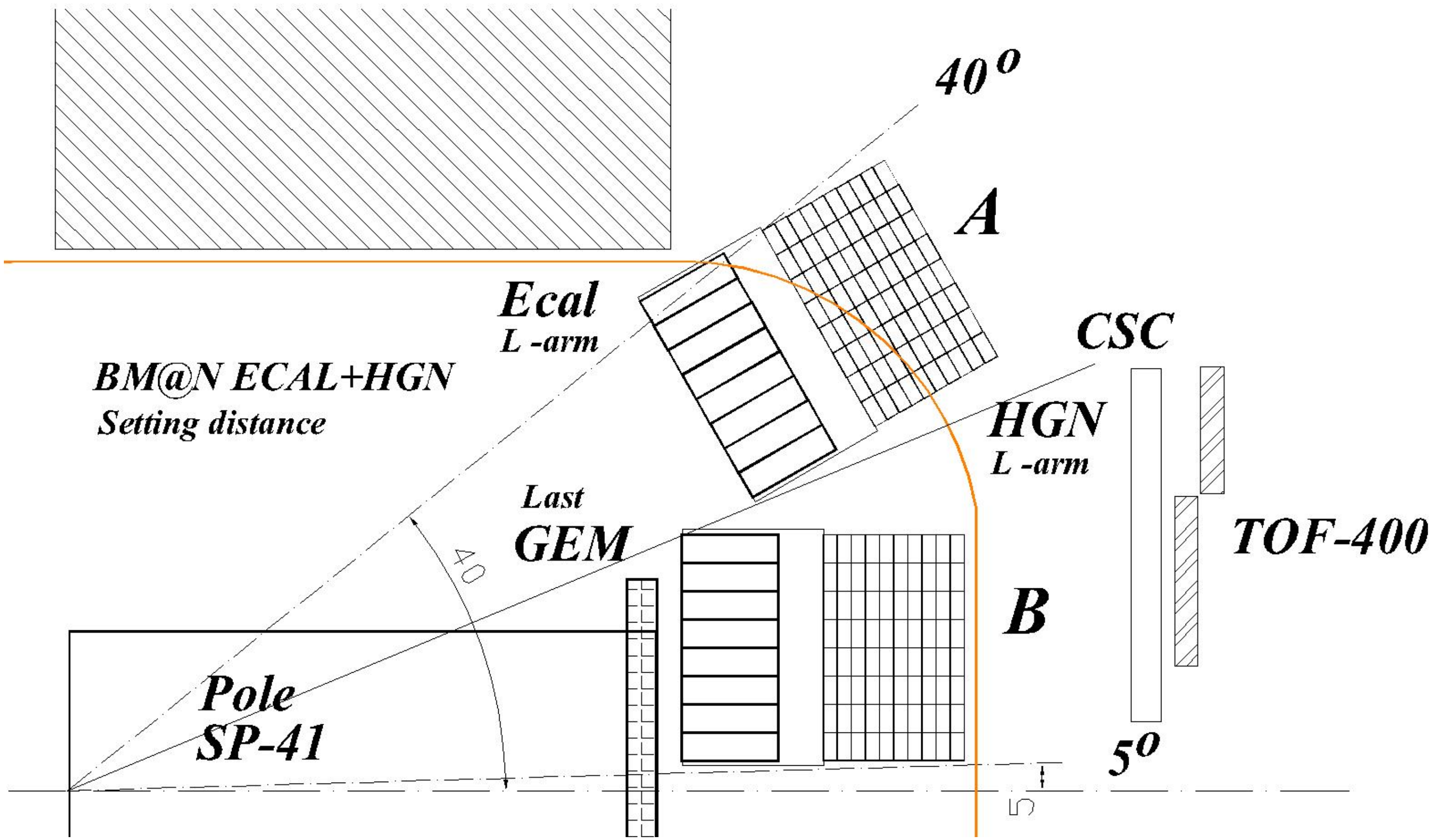
Version 2(without ECAL)



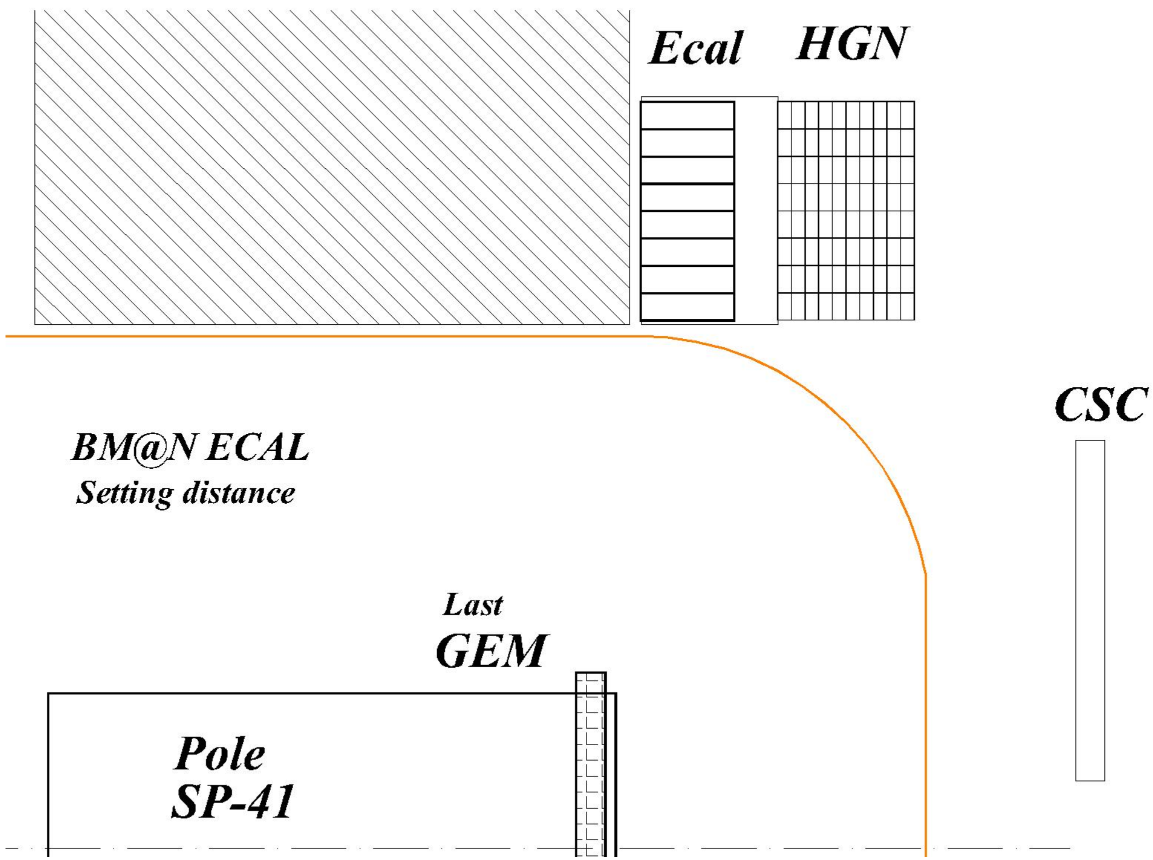
Proposed geometry(1)



Proposed geometry(2)

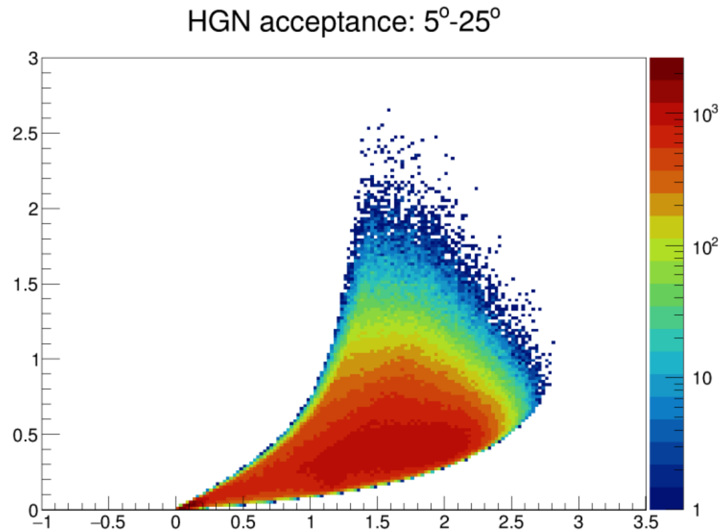


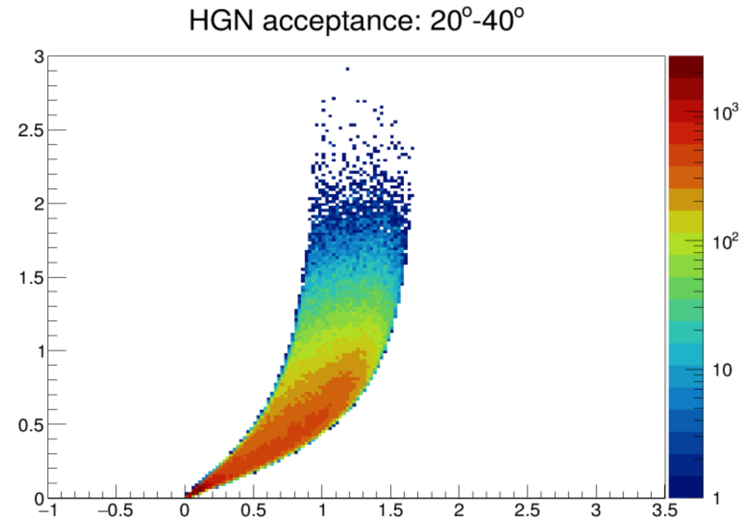
Proposed geometry(3)

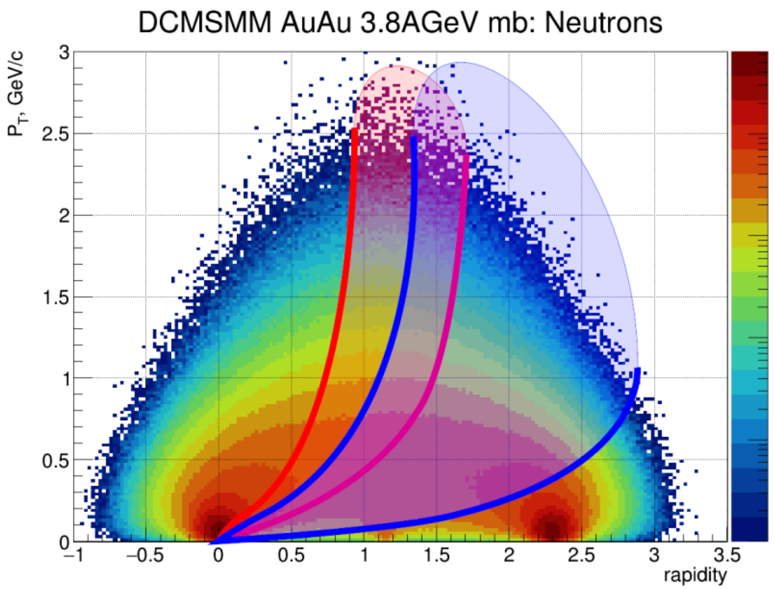


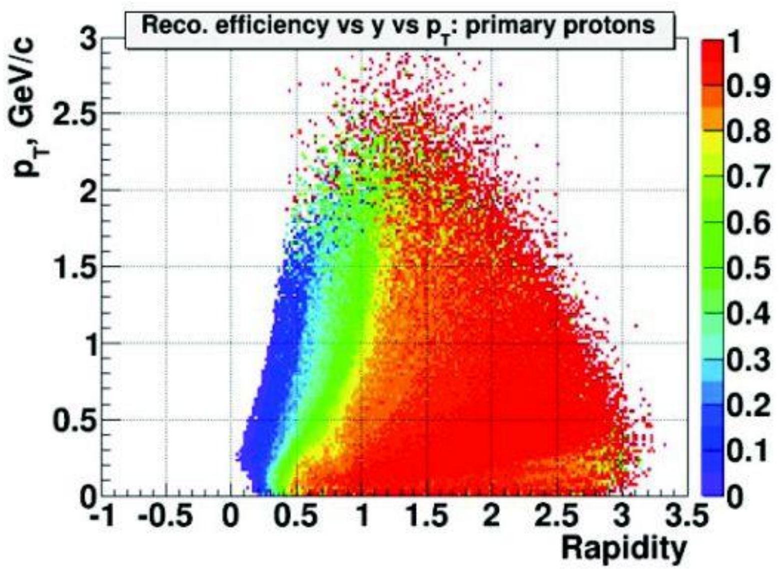
Simulations (P.Alekseev, N.Zhigareva, ITEP)

Kinematical region

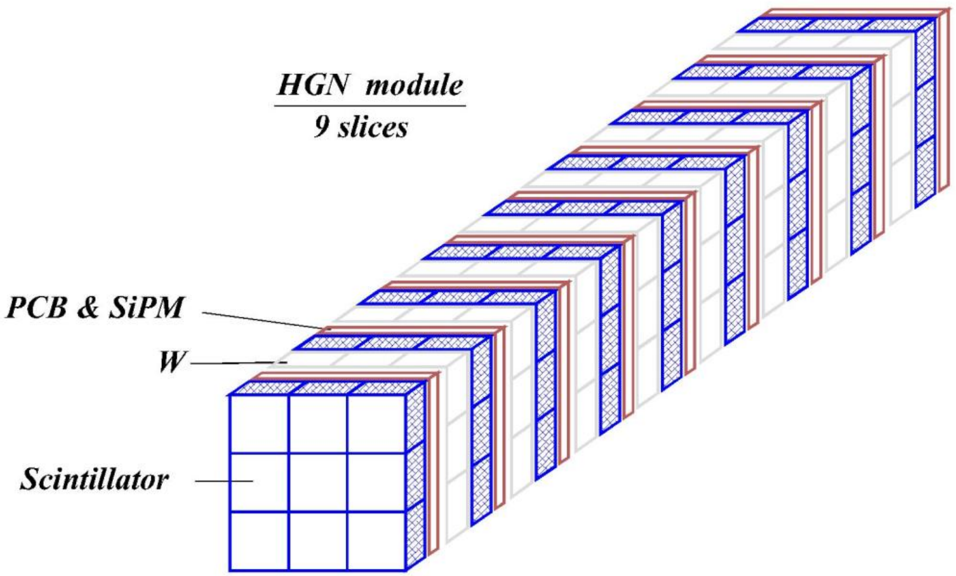


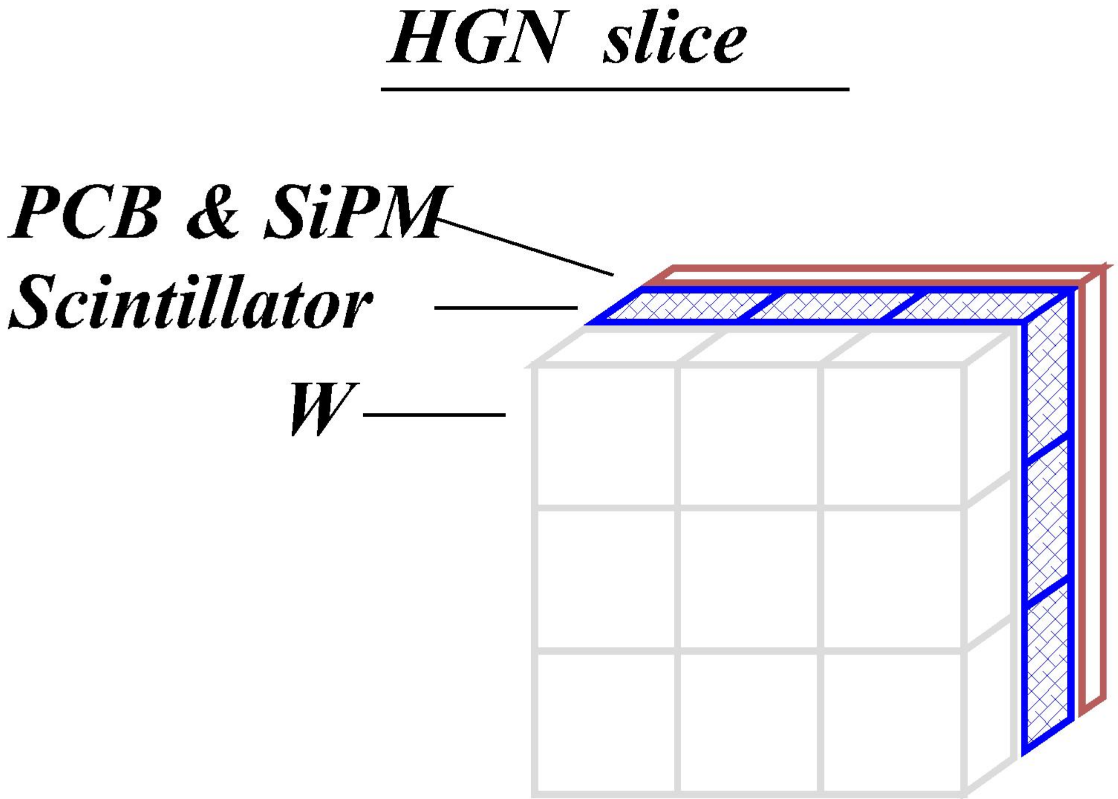




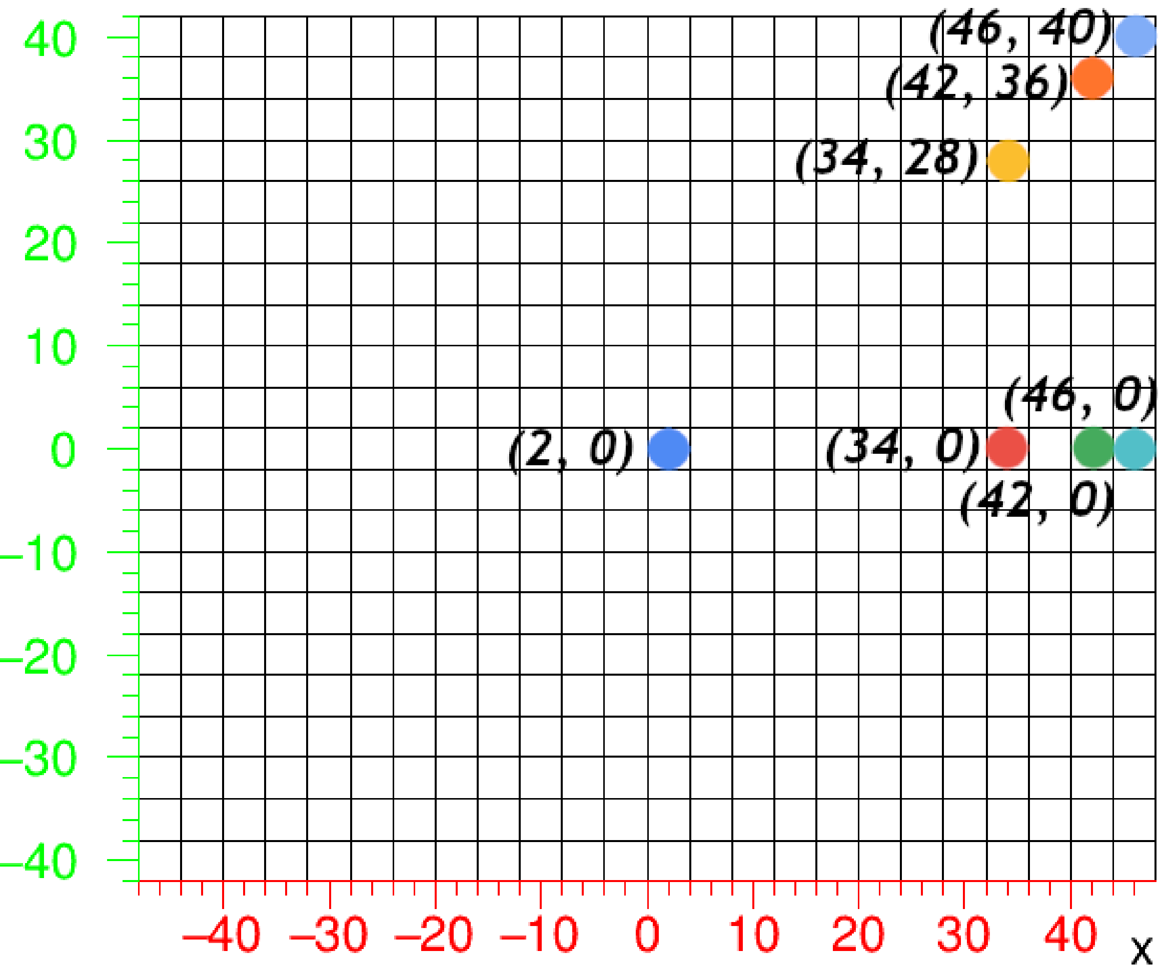


Detector module



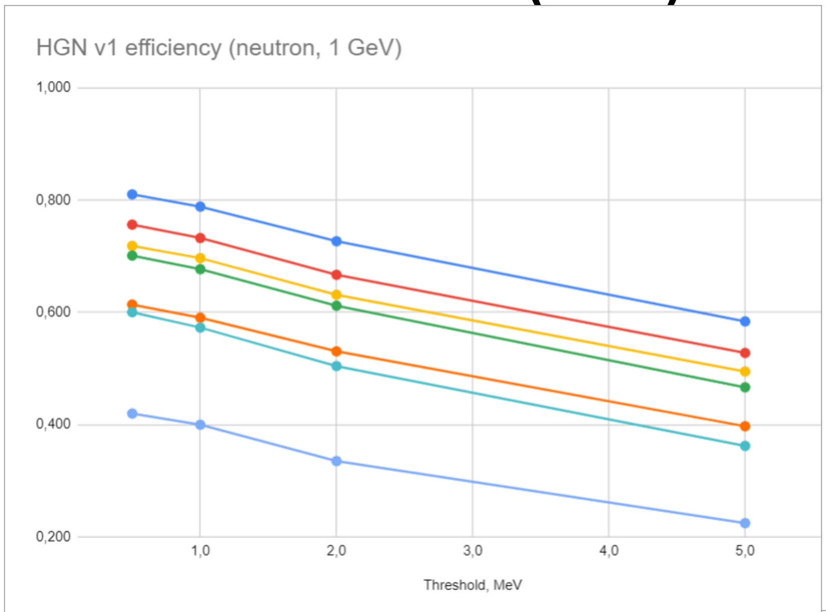


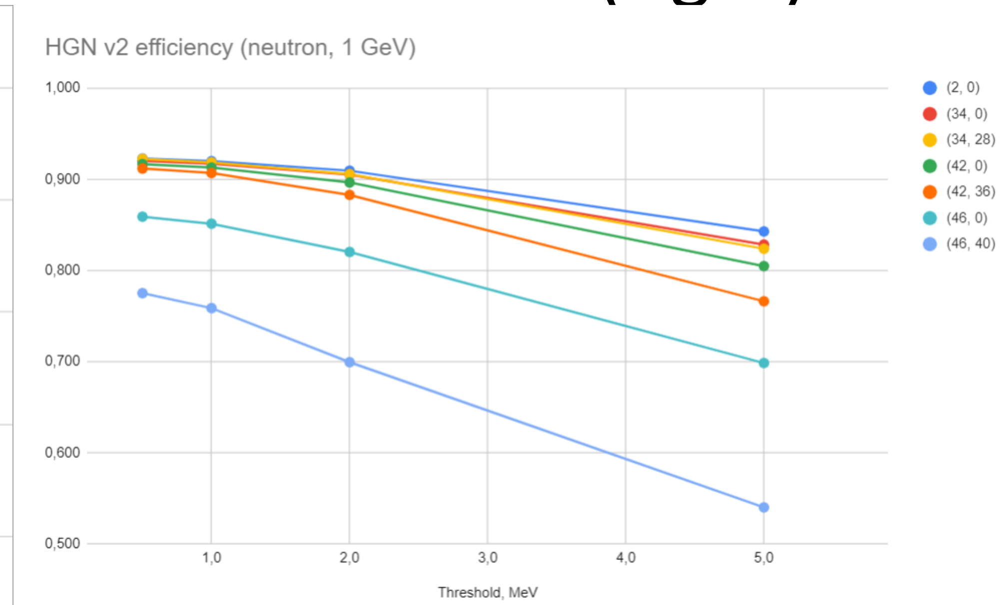
Detector efficiency

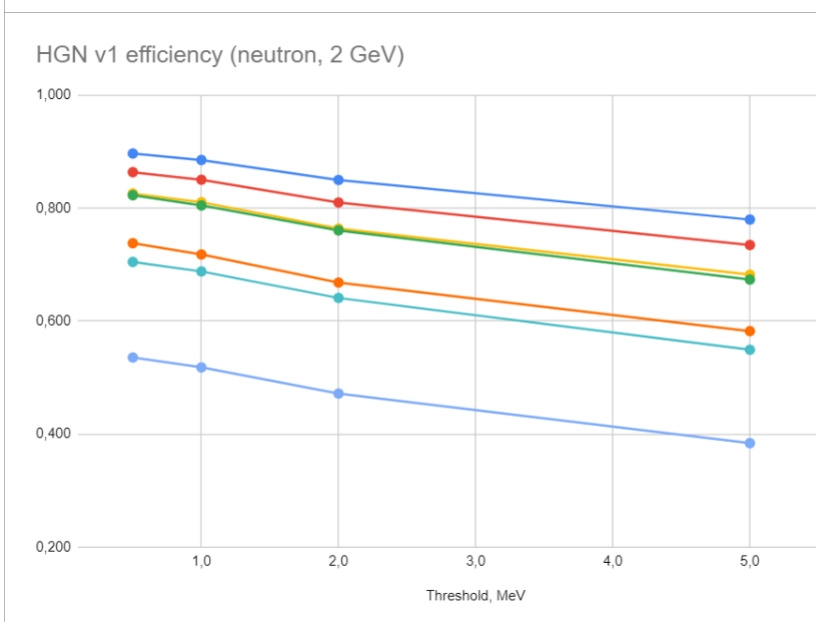


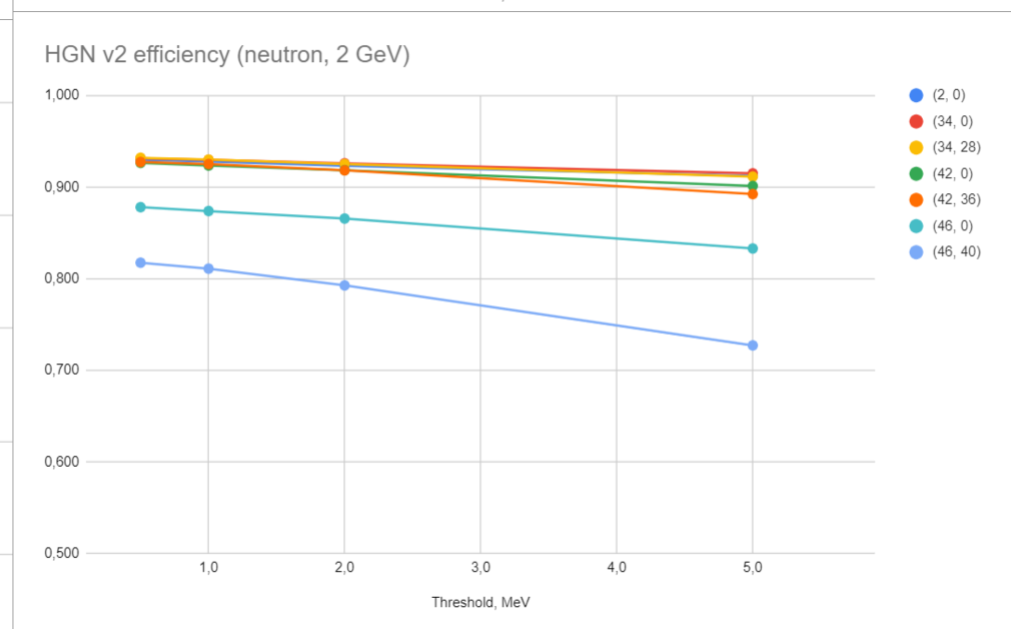
- Two(to reduce a noise) hits in HGN beyond threshold
- Principal points for efficiency calculation

Detector efficiency for neutrons
with ECAL(left) & without ECAL(right)

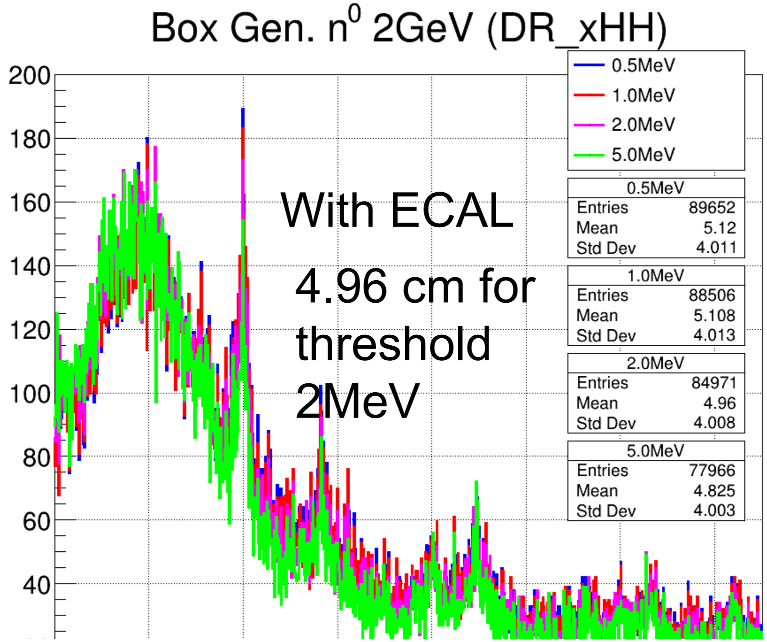


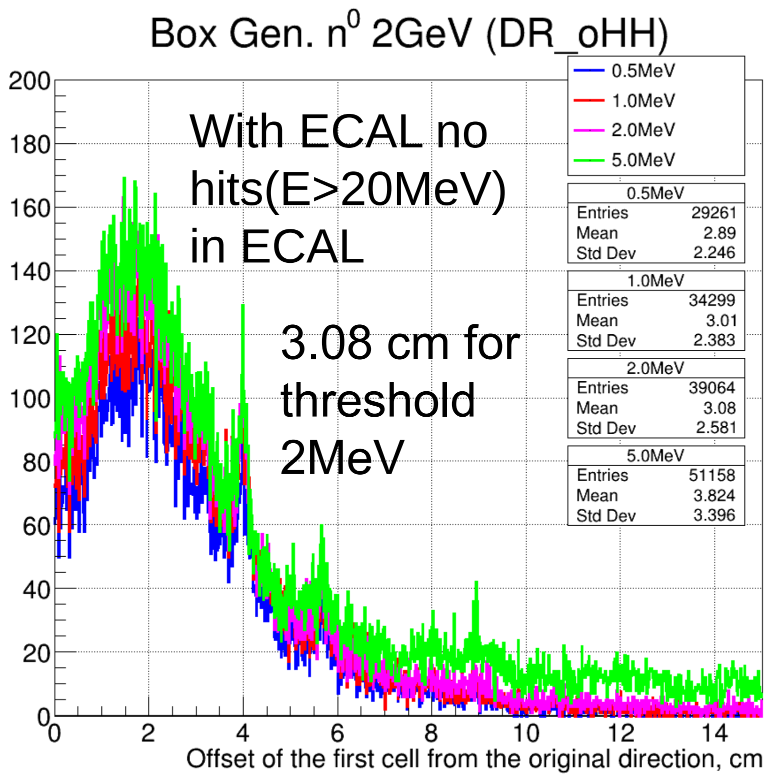


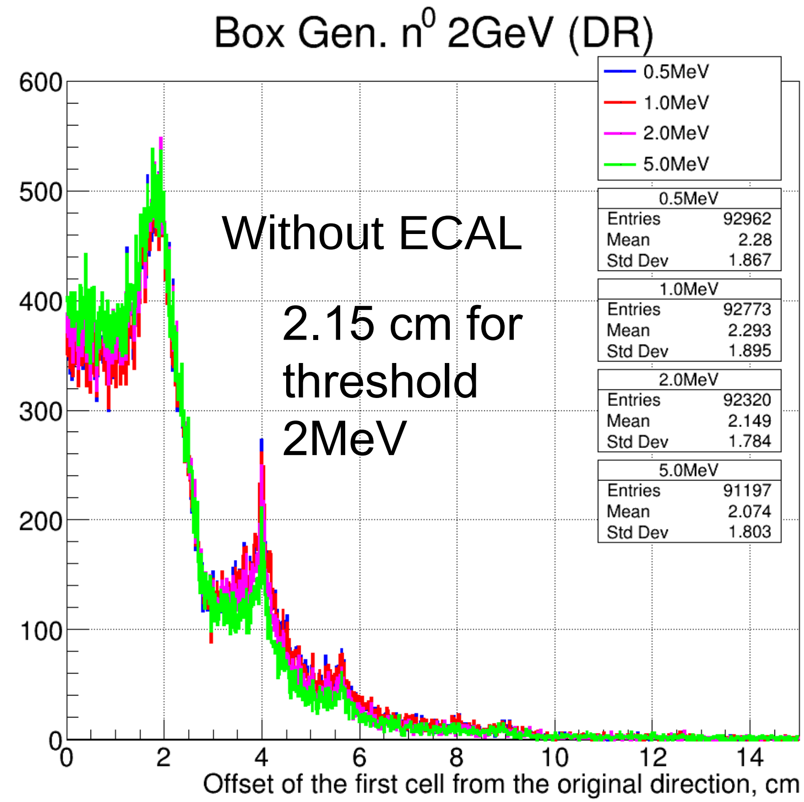




Space resolution







ToF resolution

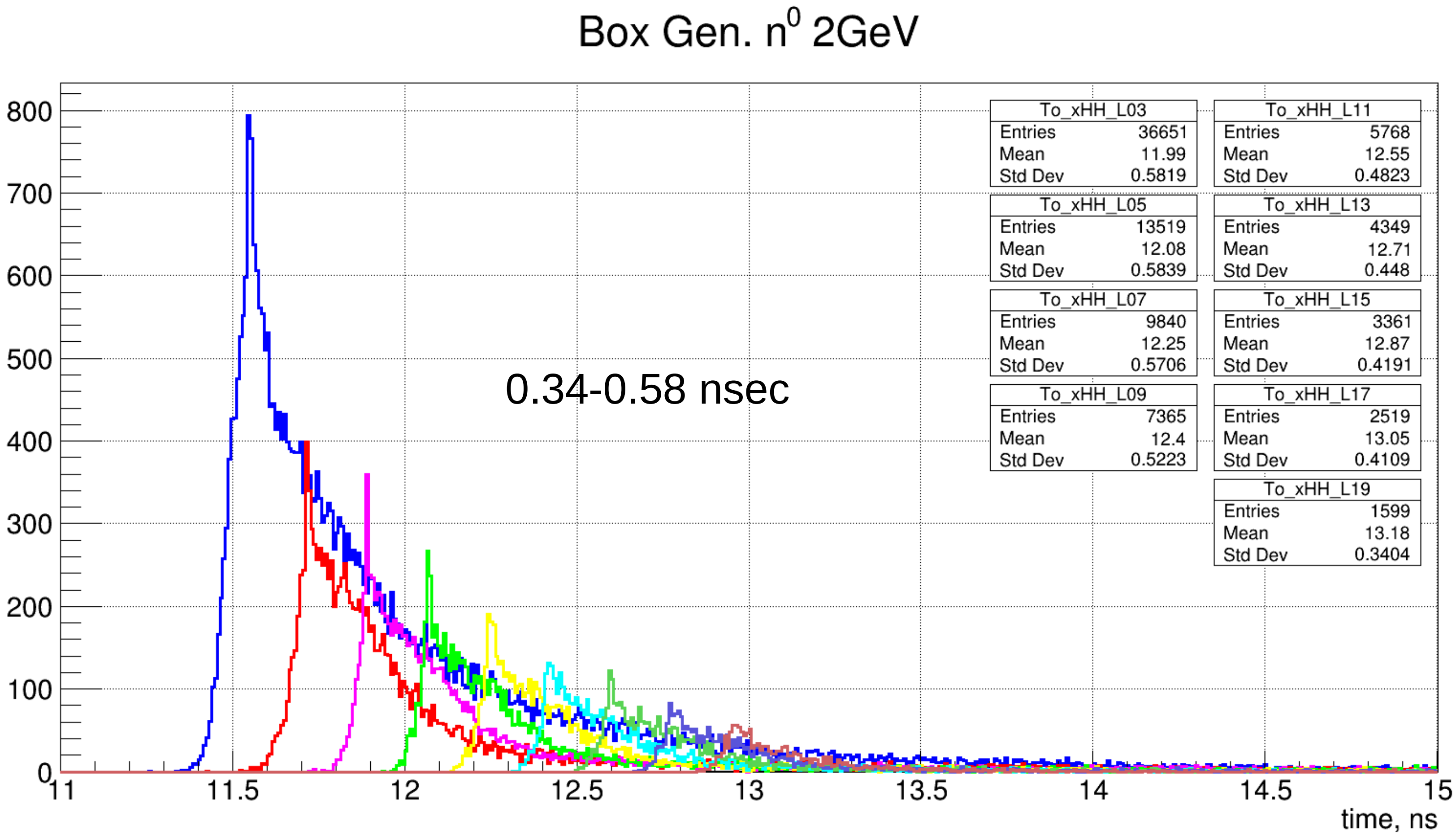
ToF distribution

for each active HGN layer

Version with ECAL

No cut for ECAL hits

Threshold 2MeV



ToF resolution

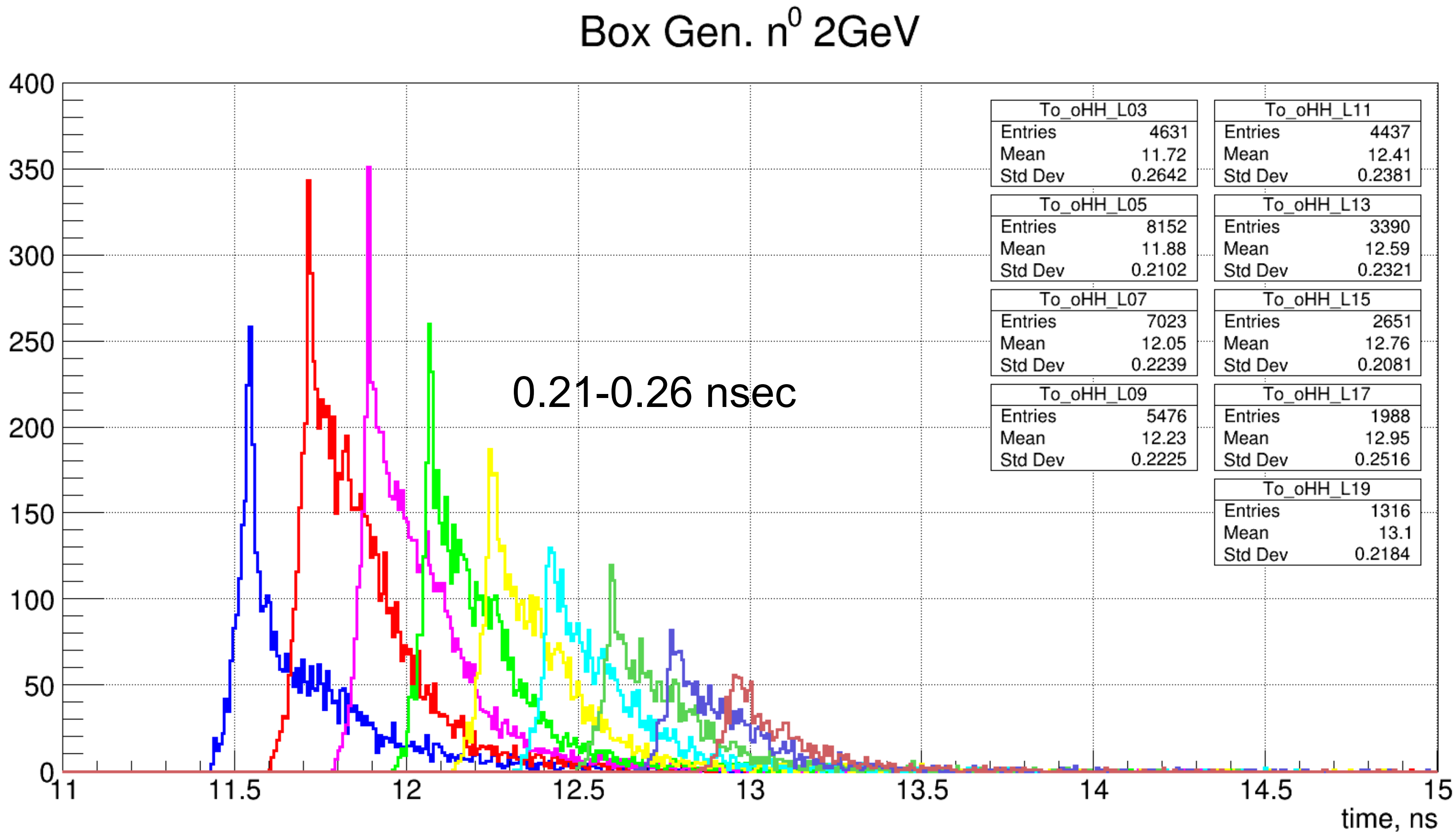
ToF distribution

for each active HGN layer

Version with ECAL

no ECAL (>20MeV) hits

Threshold 2MeV



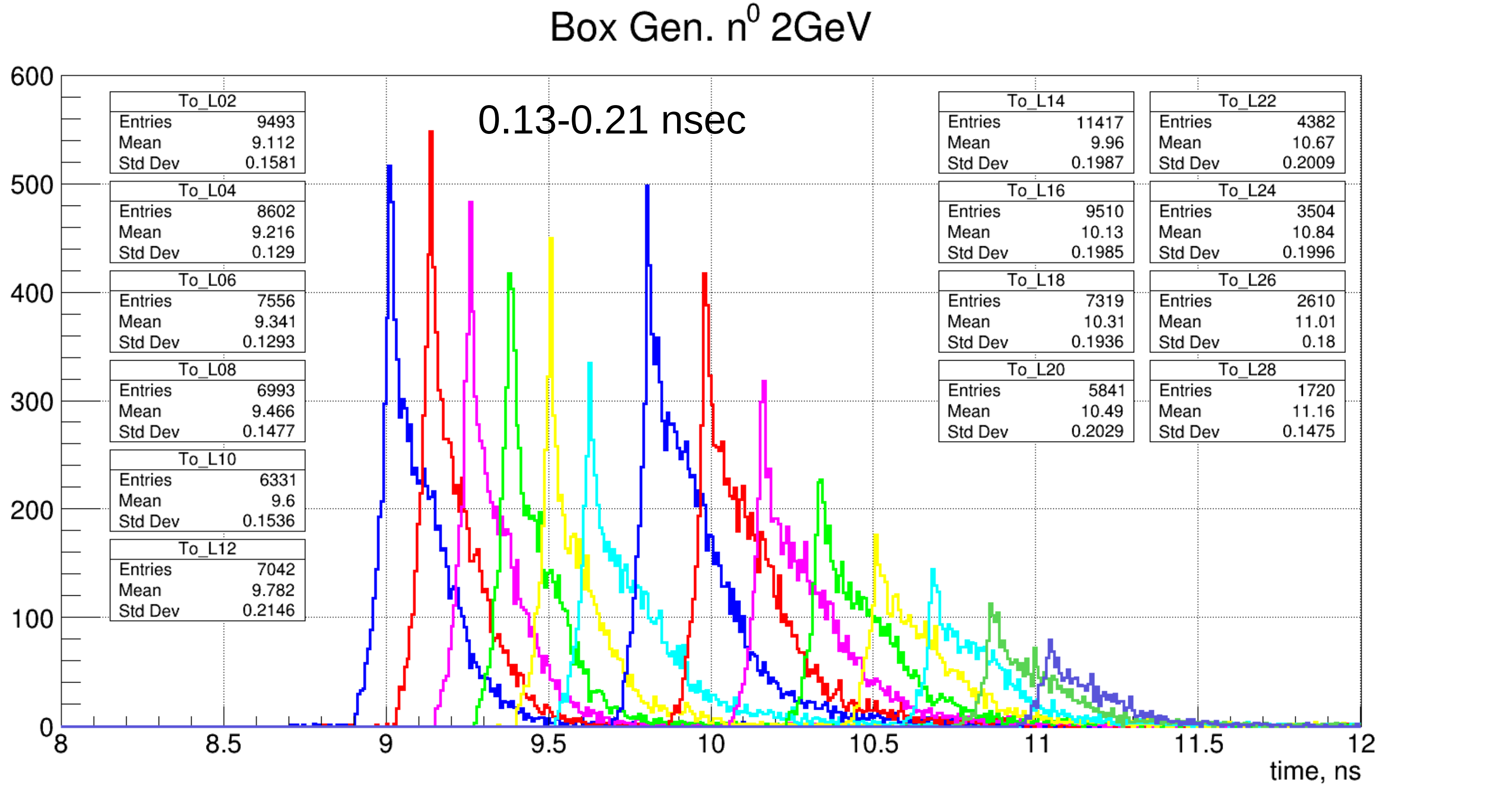
ToF resolution

ToF distribution

for each active layer

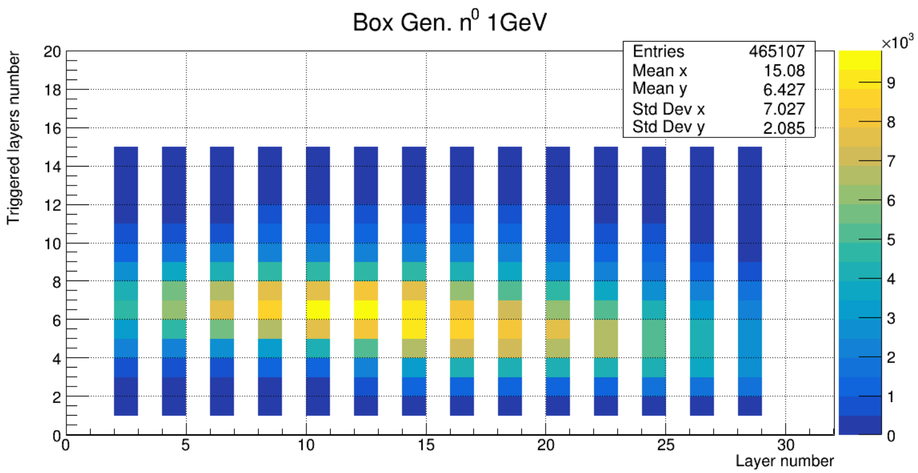
Version without ECAL

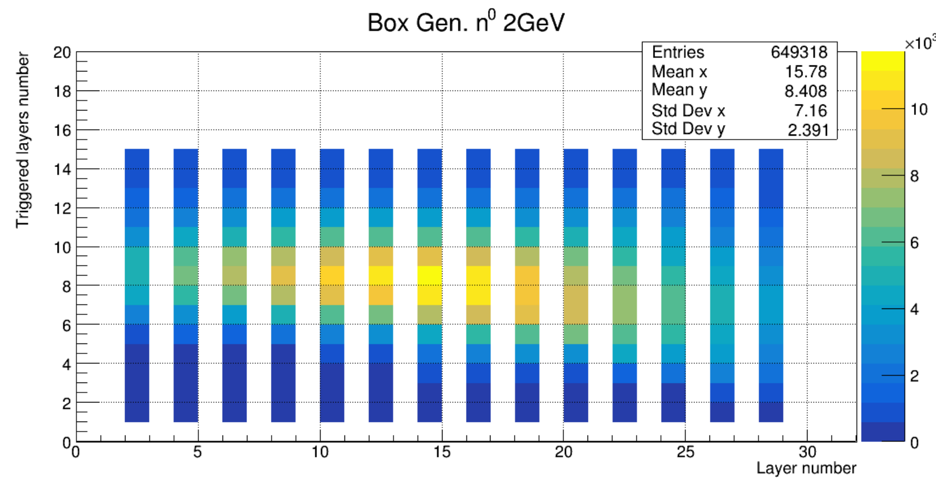
Threshold 2MeV



Photon-neutron

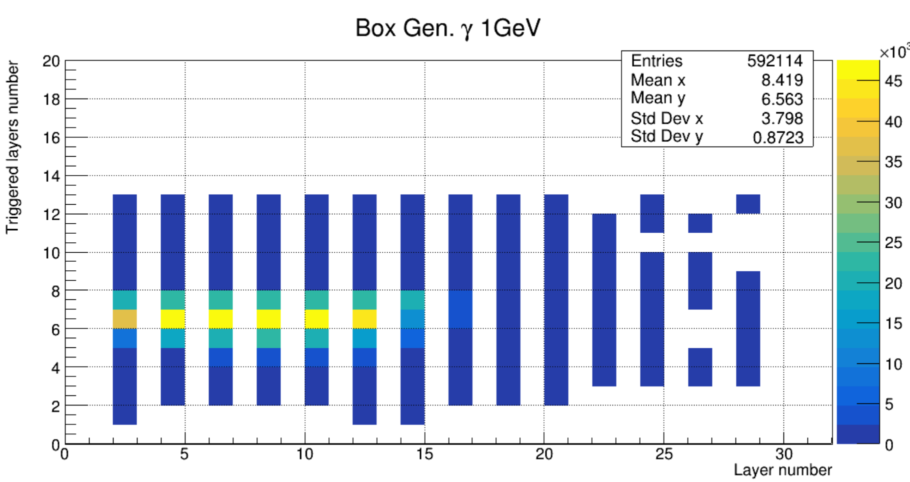
neutron(up),photon(down), box generator, center of detector

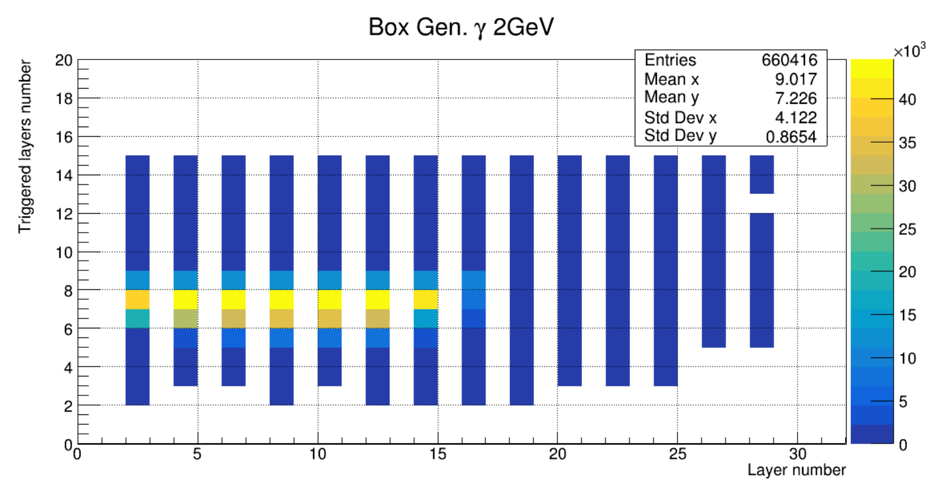




1GeV Version without ECAL(6 (Sci(3cm)+W(0.5cm) layers + 2GeV

-----------------------------+9(Sci(3cm)+W(0.5cm) layers-----------------------------------



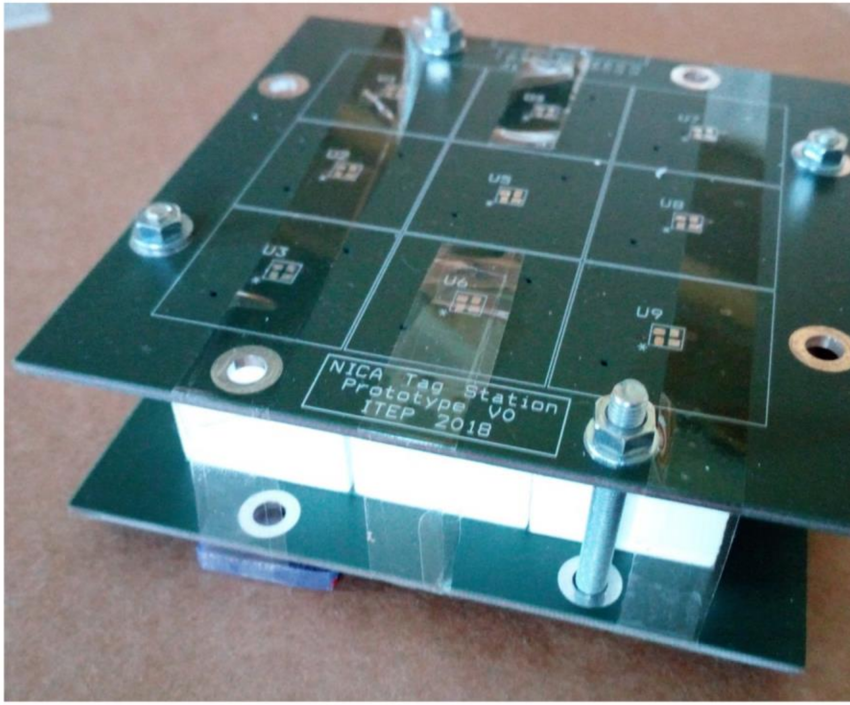


Time resolution test

I.Alekseev, V.Rusinov,
D.Svirida, E.Tarkowsky(ITEP)

Average energy deposit per tile ~ 6 MeV

- Plain: 3x3 scintillator cubes 3x3x3 cm^3 each
- 3X3 mm^2 SENSL 30050 SiPM (2668 pixels)
- Whitened cubes with direct readout

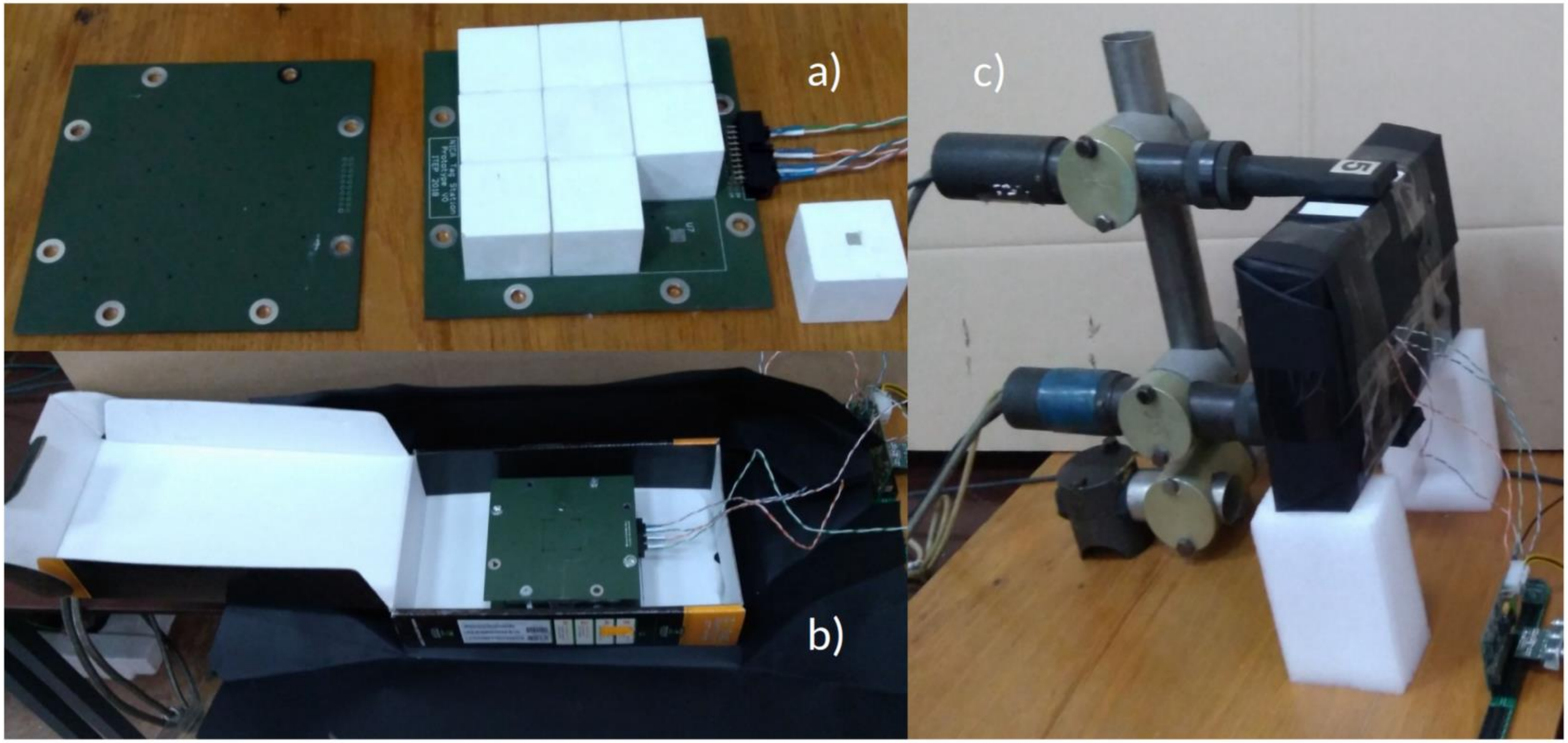


Test layout

DANSS SiPM power and preampifier board

Two types of digitization:

- ✓ Tektronix TDS3054B scope with 5 Gsampl/s
- ✓ DANSS with 125 Msampl/s WFD, but a large dynamic range

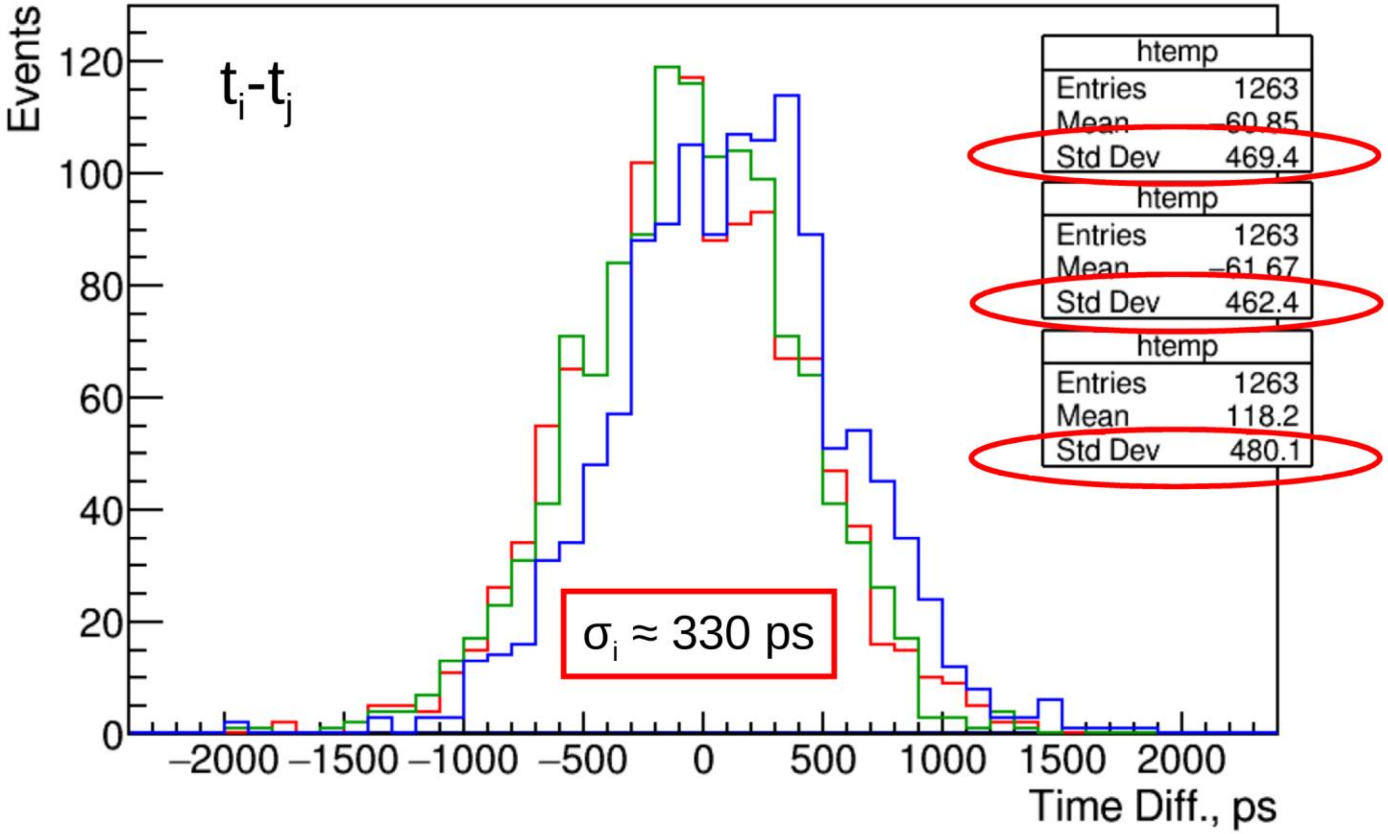


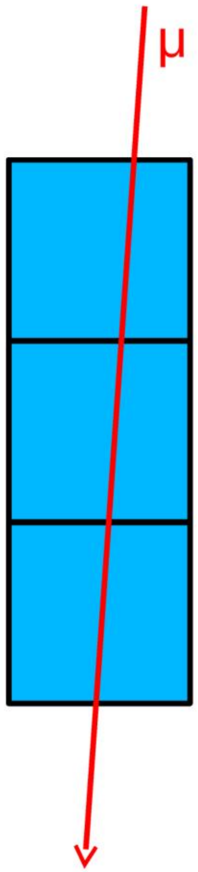
Test results

Hardware trigger on the central cube.

Light collection ~ 120 ph.e./MIP or ~20 ph.e./MeV

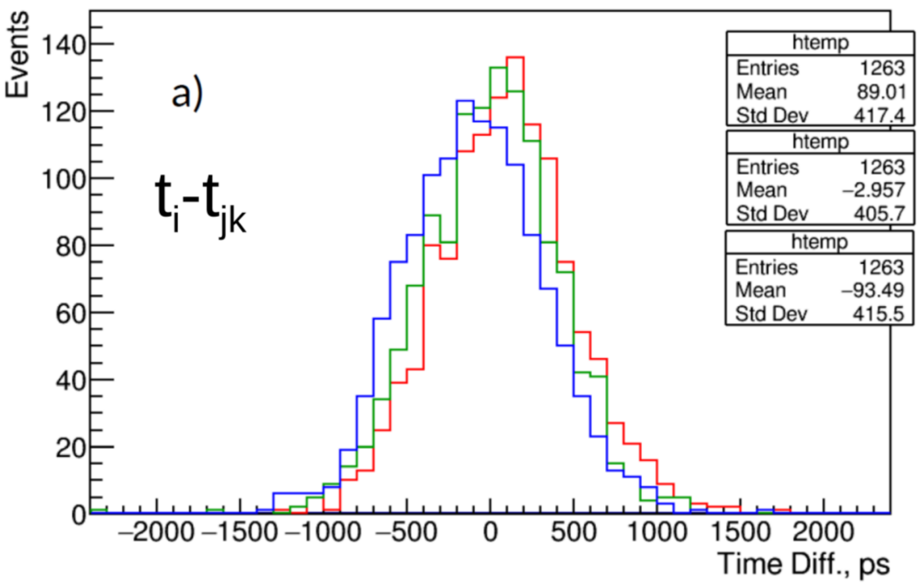
Software trigger – amplitude in all 3 cubes in the MIP region



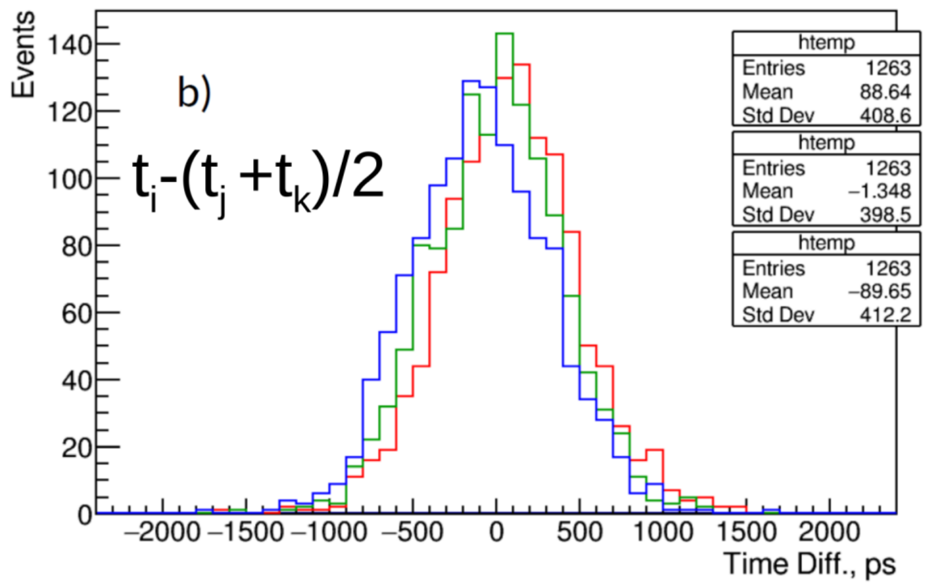


Propagation to calorimeter

- Both methods are working
- Time resolution scales ~ $1/\sqrt{E}$
- Aim of 200 ps could be reached at ~160 MeV particle energy



Use sum of digitized signals



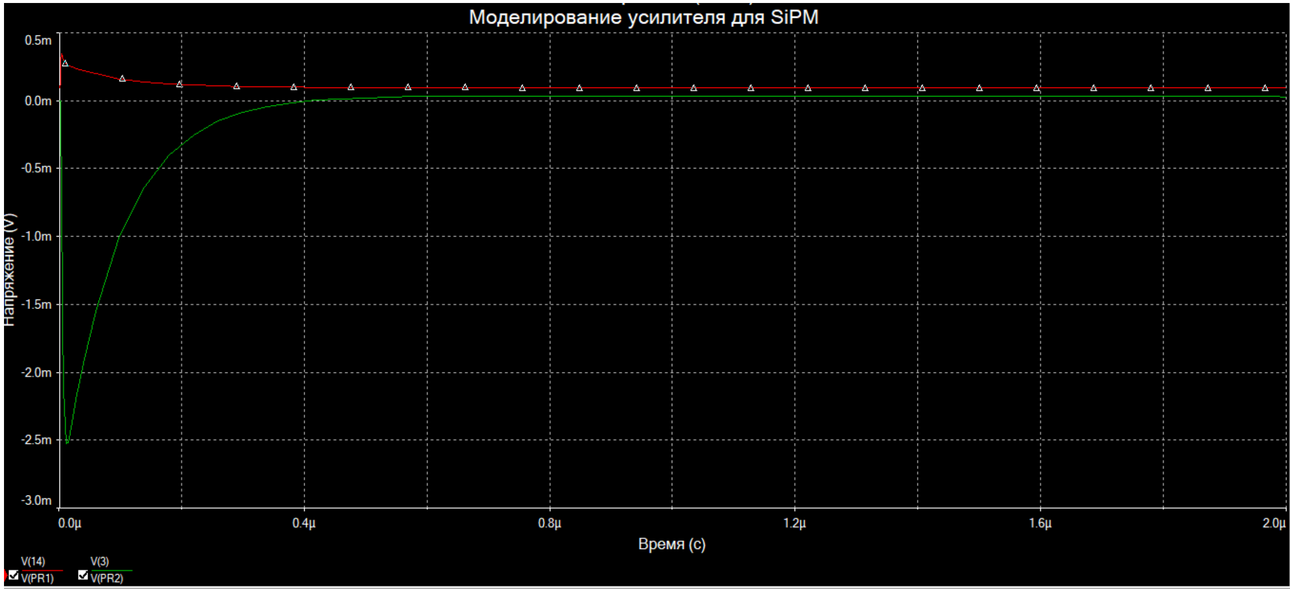
Use average time

A.Martemianov,
G.Taer(ITEP)

It is planned to place 9 SiPM (according to the number of scintillator sells in one active layer of the detector module), a voltage converter and preamplifiers on the common board. That will allow us to transmit the signal to the rack with QDC, TDC and discriminator modules.

Amplifiers.

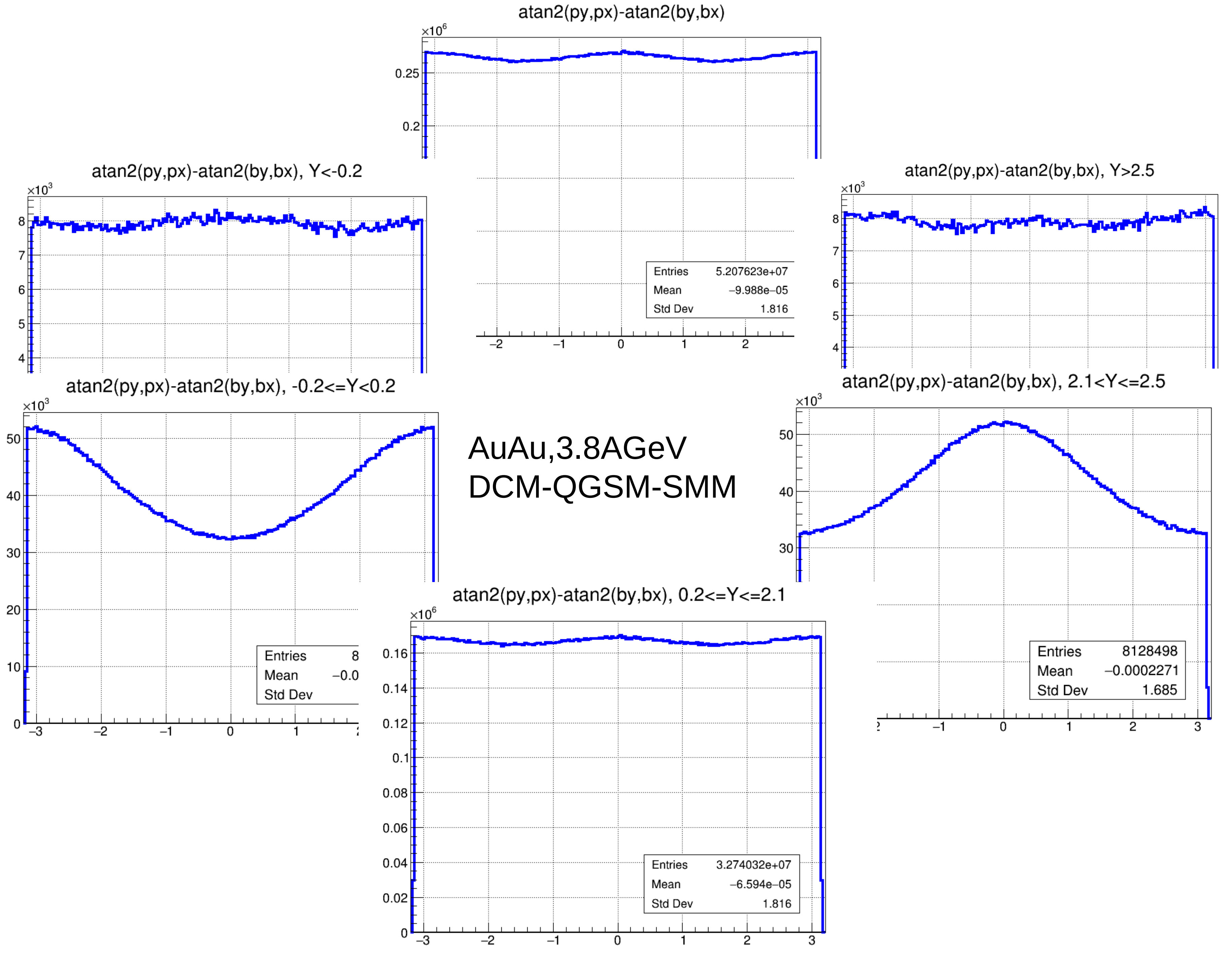
High-frequency current amplifiers with the shaping of the output pulse duration are offered. The amplifier does not differentiate the output signal with a long time of fall time, because it does not have capacitors at the input. The amplifier will have a low noise level (~500mKV RMS at amplification equal 5), which is very important for TOF measurement. The gain will select depending on the type of SiPM and subsequent electronics. Supply voltage for amplifiers - +-5V.



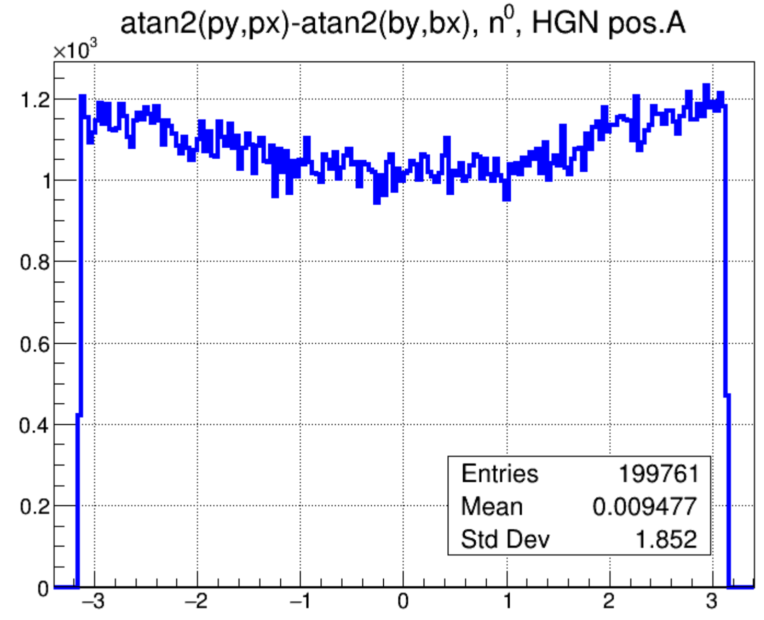
Detector response for V1,V2 (simulation)

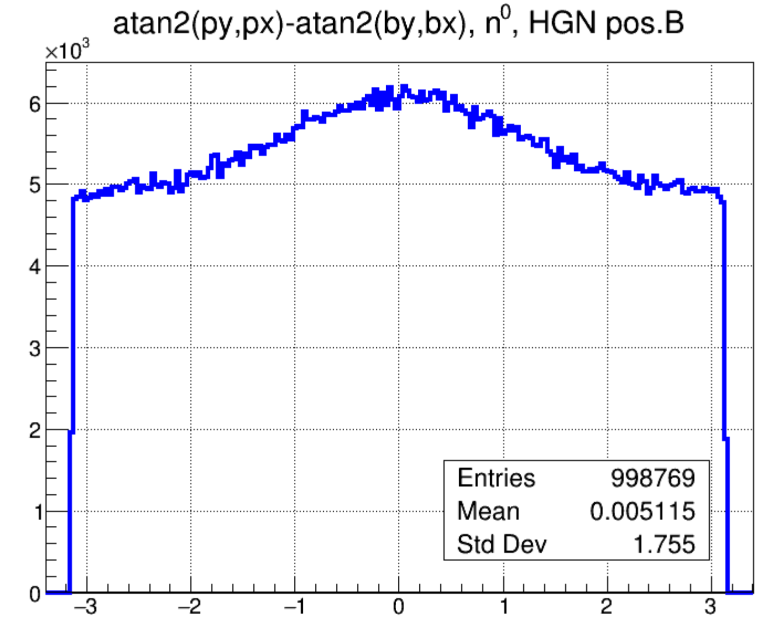
Simulations started with two event generators:

DCM-QGSM-SMM & FTF

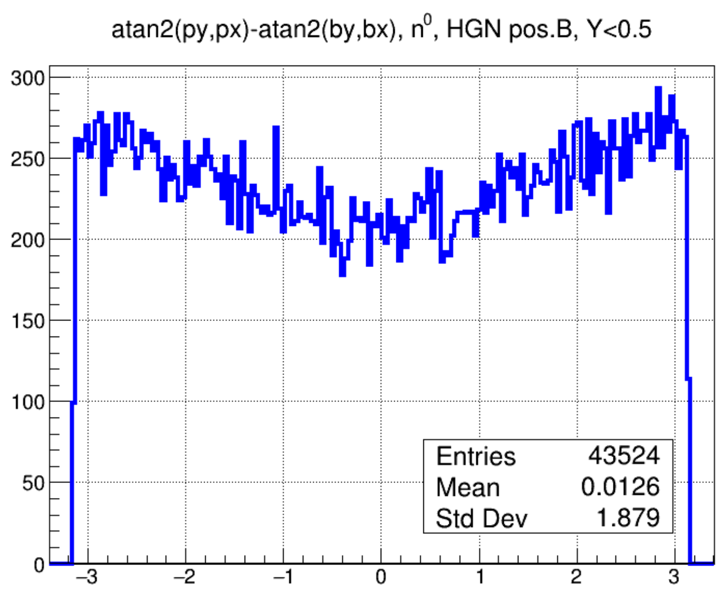


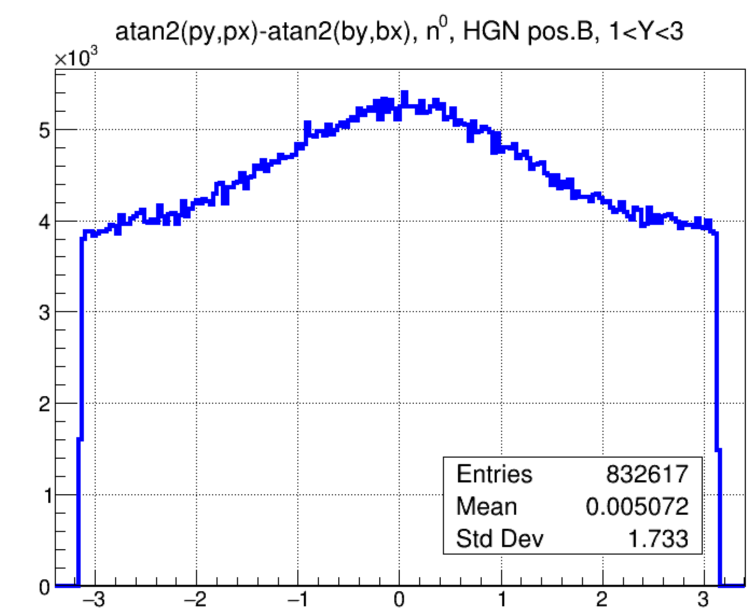
atan2(py,px)-atan2(by,bx)
Entries 5.207623e+07
Mean −9.988e−05
Std Dev 1.816
atan2(py,px)-atan2(by,bx), Y<-0.2
atan2(py,px)-atan2(by,bx), Y>2.5
atan2(py,px)-atan2(by,bx), -0.2<=Y<0.2
Entries 8
Mean −0.0
Std Dev
atan2(py,px)-atan2(by,bx), 2.1<Y<=2.5
Entries 8128498
Mean −0.0002271
Std Dev 1.685
AuAu,3.8AGeV
DCM-QGSM-SMM
atan2(py,px)-atan2(by,bx), 0.2<=Y<=2.1
Entries 3.274032e+07
Mean −6.594e−05
Std Dev 1.816





XeSn,3.9AGeV DCM-QGSM-SMM





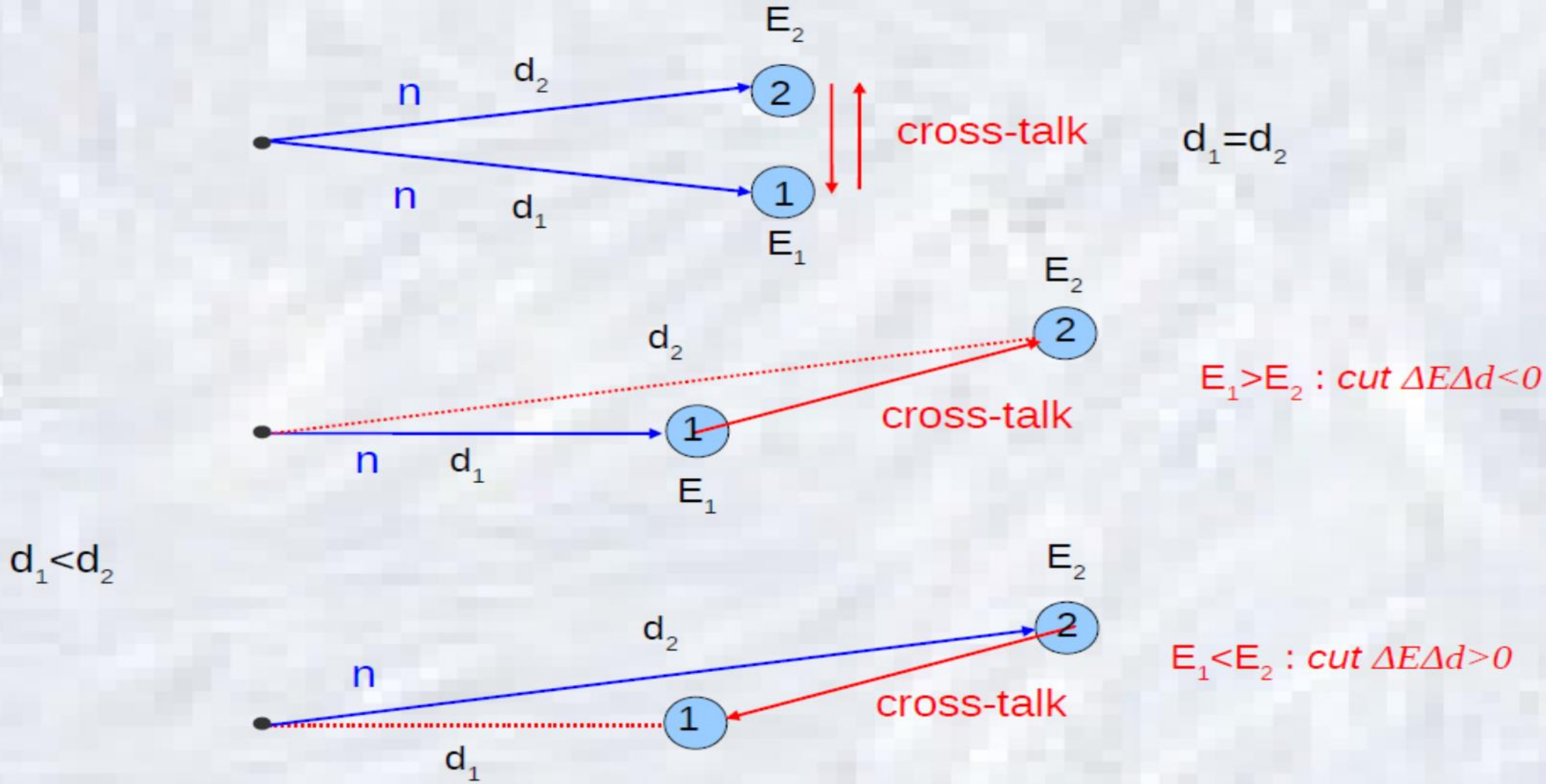
Conclusions

1. Neutron detector provides important increasing of BM@N physical program
2. Simulation shows that proposed version of HGN provides neutron iidentification at BM@N energy range

TO DO
-1. Simulation of detector response V1,V2
1.Version with or without ECAL?
2. Prototype production
3. Prototype beam test

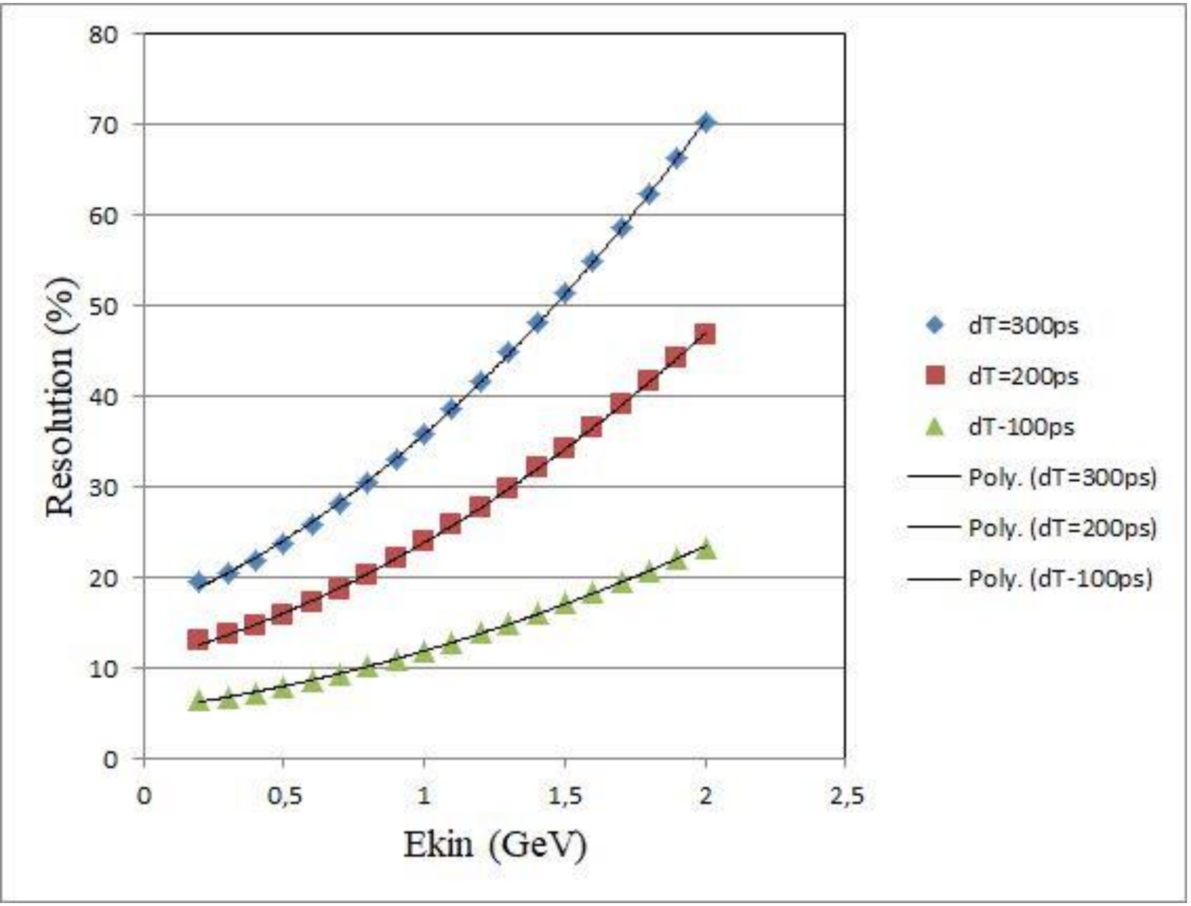
Cut Cross-Talks

J.Pluta et al. NIM A411(1998) 417



Bayukov Yu.D. et al. Phys. Lett., B189, 1987, p. 291

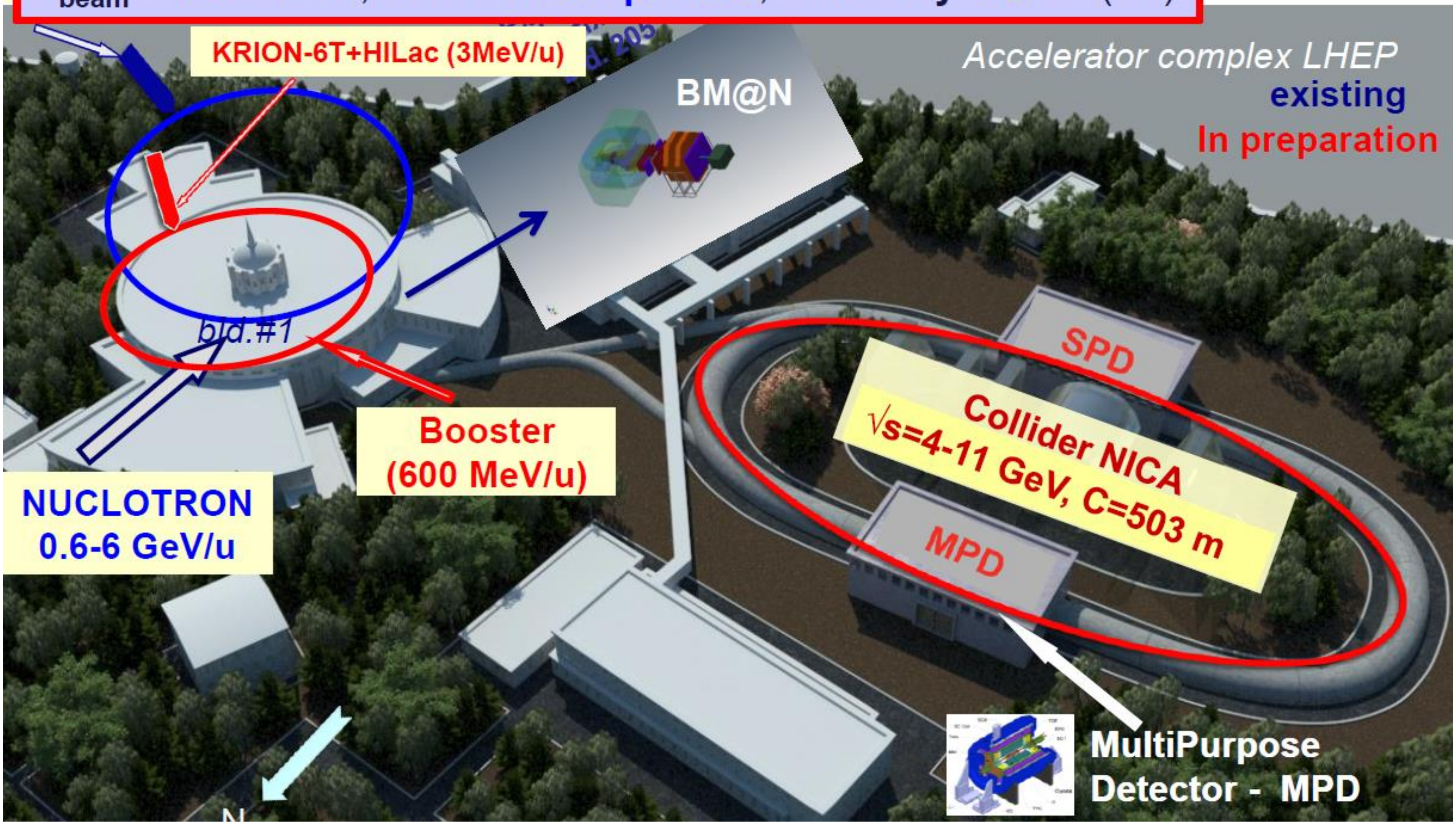
Energy resolution



Neutrons
L=3.4m

Complex NICA

Parameters of Nuclotron for BM@N experiment:
E_{beam} = **1-6** GeV/u; ***beams***: *from* **p** to **Au**; **Intensity~10⁷** c⁻¹ (Au)



CC,UrQMD,10^5 ev.	2AGeV	3AGeV	4AGeV	10AGeV	30AGeV
All particles	2968383	3269875	3555732	4785049	6861519
P	980372	973357	964317	934470	899765
N	982267	974936	965797	937139	900696
Λ	1393	5493	10405	30537	57559
Σ^+	489	2347	4389	11135	17909
Σ^0	623	2918	5653	12424	19557
Σ^-	549	2277	4321	11209	18108
π^+	178772	269480	354107	714208	1286150
π^0	205822	312142	407661	796030	1418912
π^-	178205	267809	354088	713459	1286178
K^+	1607	6884	13574	45080	108427
K^0	1506	6741	13218	44376	108090
antiK^0	30	279	942	11760	51677
K^-	27	279	918	11516	51639

3AGeV: $K^+ + K^0$ (13625) ~ $\Lambda+\Sigma$(13035).

Σ^+ DECAY MODES Fraction ($\Gamma i/\Gamma$)

$p\pi^0$ (52 %)

$n\pi^+$ (48 %)

Σ^0 DECAY MODES Fraction ($\Gamma i/\Gamma$)

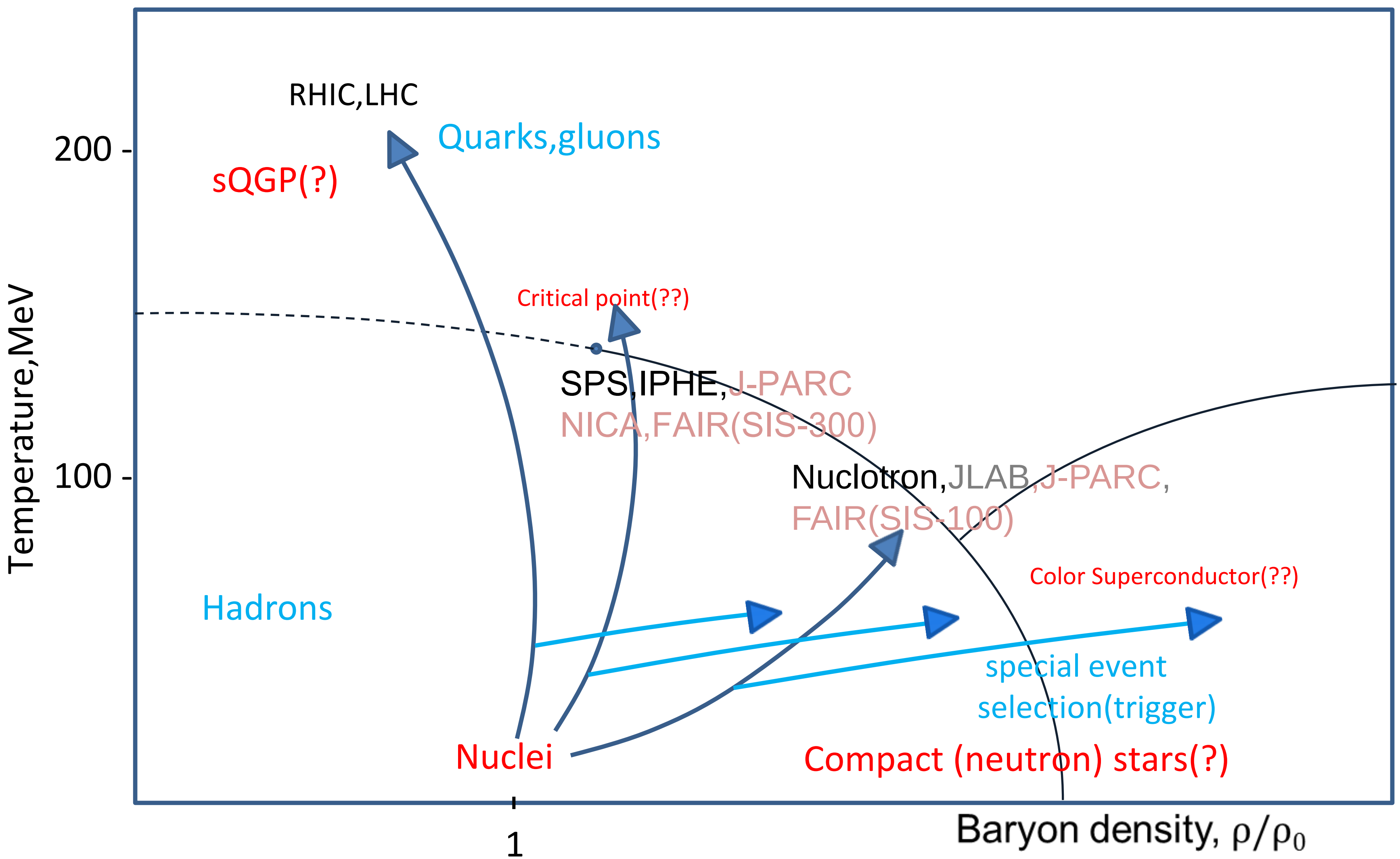
$\Lambda\gamma$ (100 %)

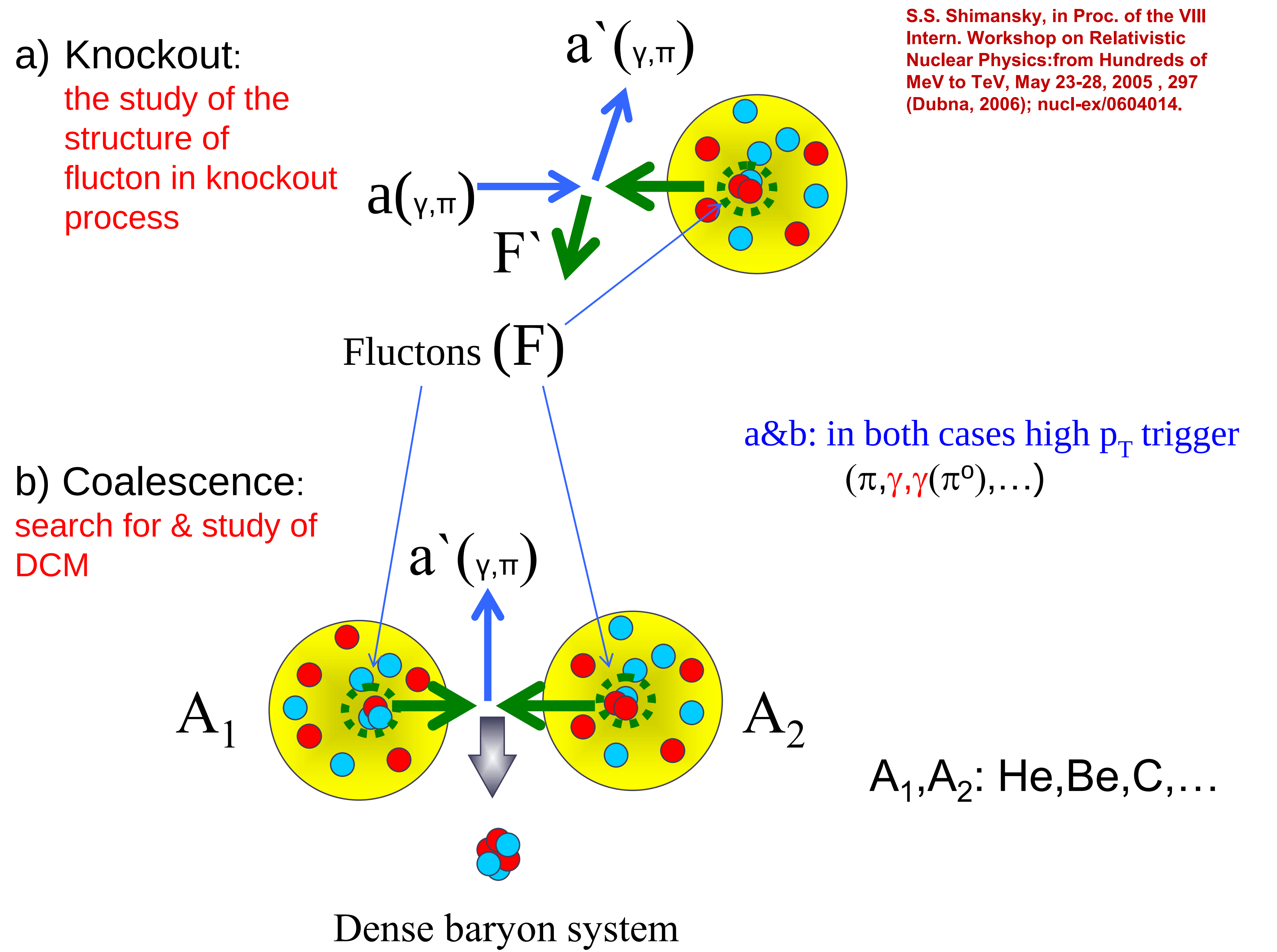
Σ^- DECAY MODES Fraction ($\Gamma i/\Gamma$)

$n\pi^-$ (100 %)

To identify Σ one needs detectors for γ and n.

Phase diagram of nuclear matter

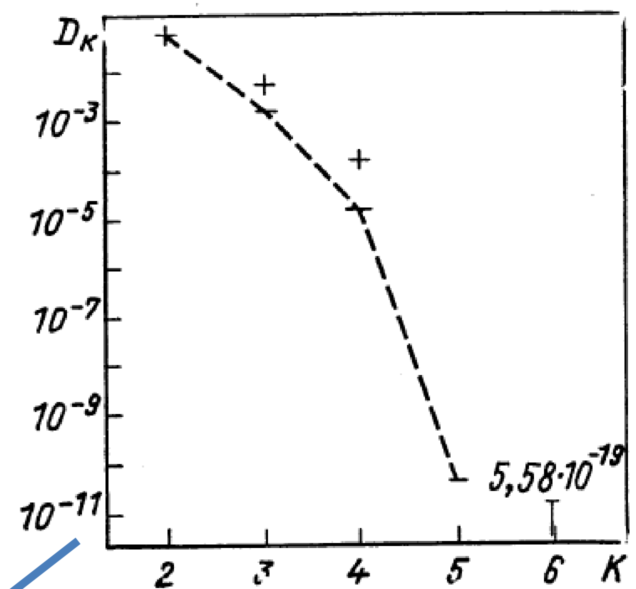




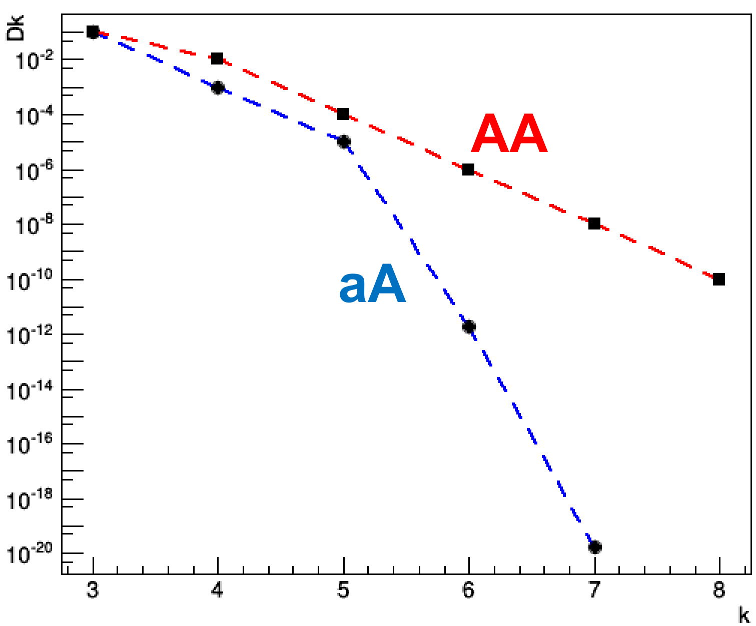
S.S. Shimansky, in Proc. of the VIII Intern. Workshop on Relativistic Nuclear Physics:from Hundreds of MeV to TeV, May 23-28, 2005 , 297 (Dubna, 2006); nucl-ex/0604014.
a) Knockout:
the study of the structure of flucton in knockout process
a`(γ,π)
a(γ,π)
F`
Fluctons (F)
a&b: in both cases high p_T trigger
(π,γ,γ(π°),…)
b) Coalescence:
search for & study of DCM
a`(γ,π)
A_1
A_2
A_1,A_2: He,Be,C,…
Dense baryon system

Why AA ?

	a_{2N}, %	a_{3N}, %	$(a_{2N})^2$, %
^{3}He	8.0±1.6	0.18±0.06	0.64
^{4}He	15.4±3.3	0.42±0.14	2.4
^{12}C	19.3±4.1	0.55±0.17	3.7



Flucton probability as a function of number of nucleons.
V.K.Luk'yanov,A.I.Titov, PEPAN,1979,vol.10(4),p.815

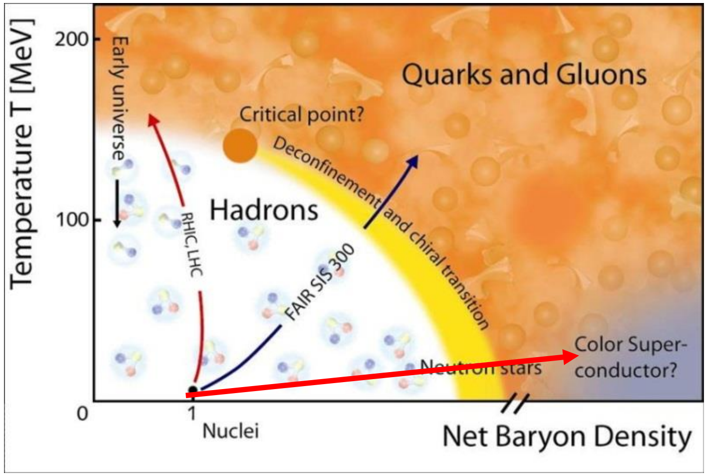


dramatic decreasing
of the cross sections with N:
----> max N~4

Flucton+flucton probability as a function of total number of nucleons.

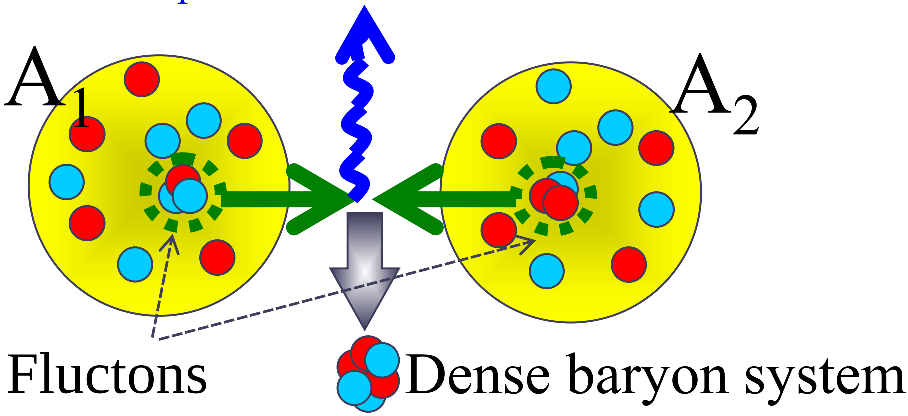
FLINT experiment @ ITEP

Phase diagram*



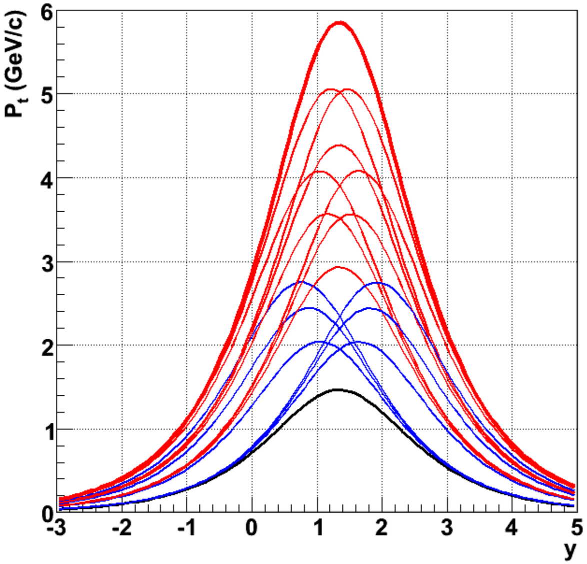
*http://www.gsi.de/forschung/fair_experiments/CBM
/

Scheme of process



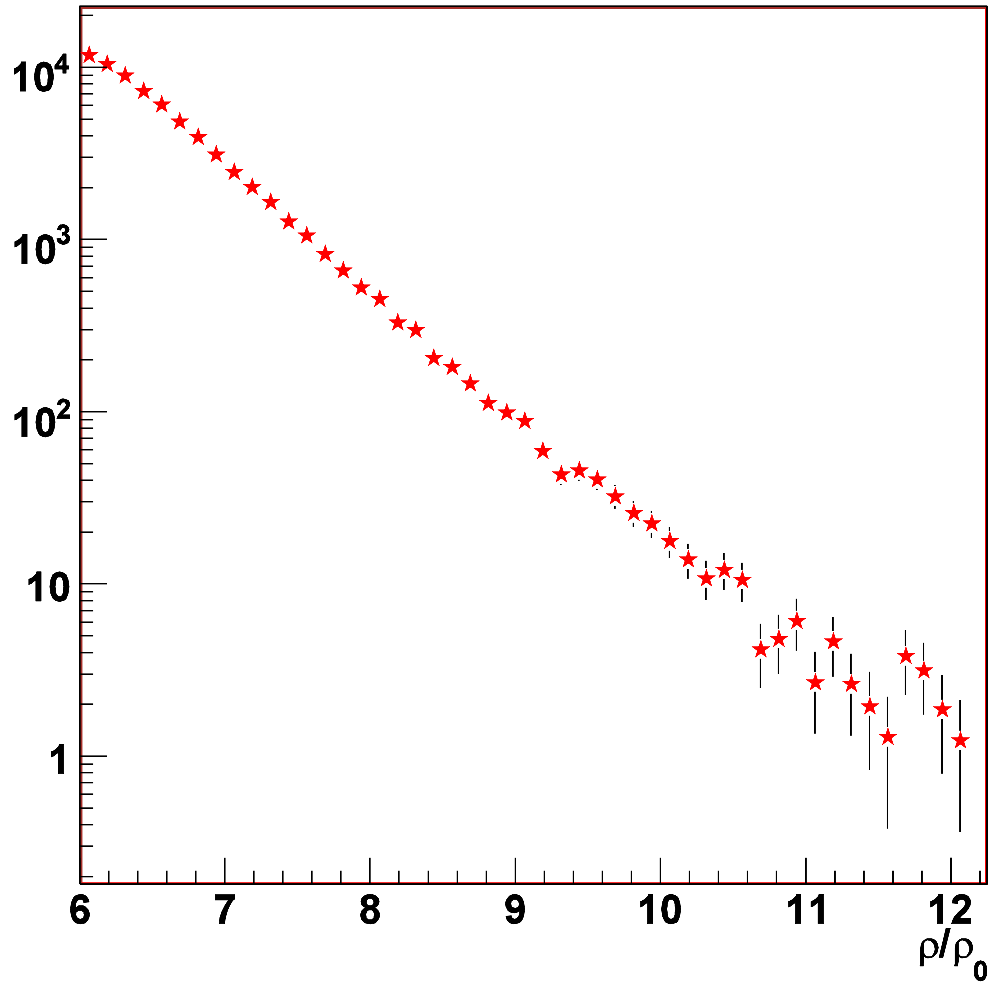
Kinematical limits for different subprocesses:
1N+1N(black line)
1N+Flucton(2N,3N,4N)&Flucton+1N(blue lines)
Flucton+Flucton(red lines)

He+He @ 6 AGeV

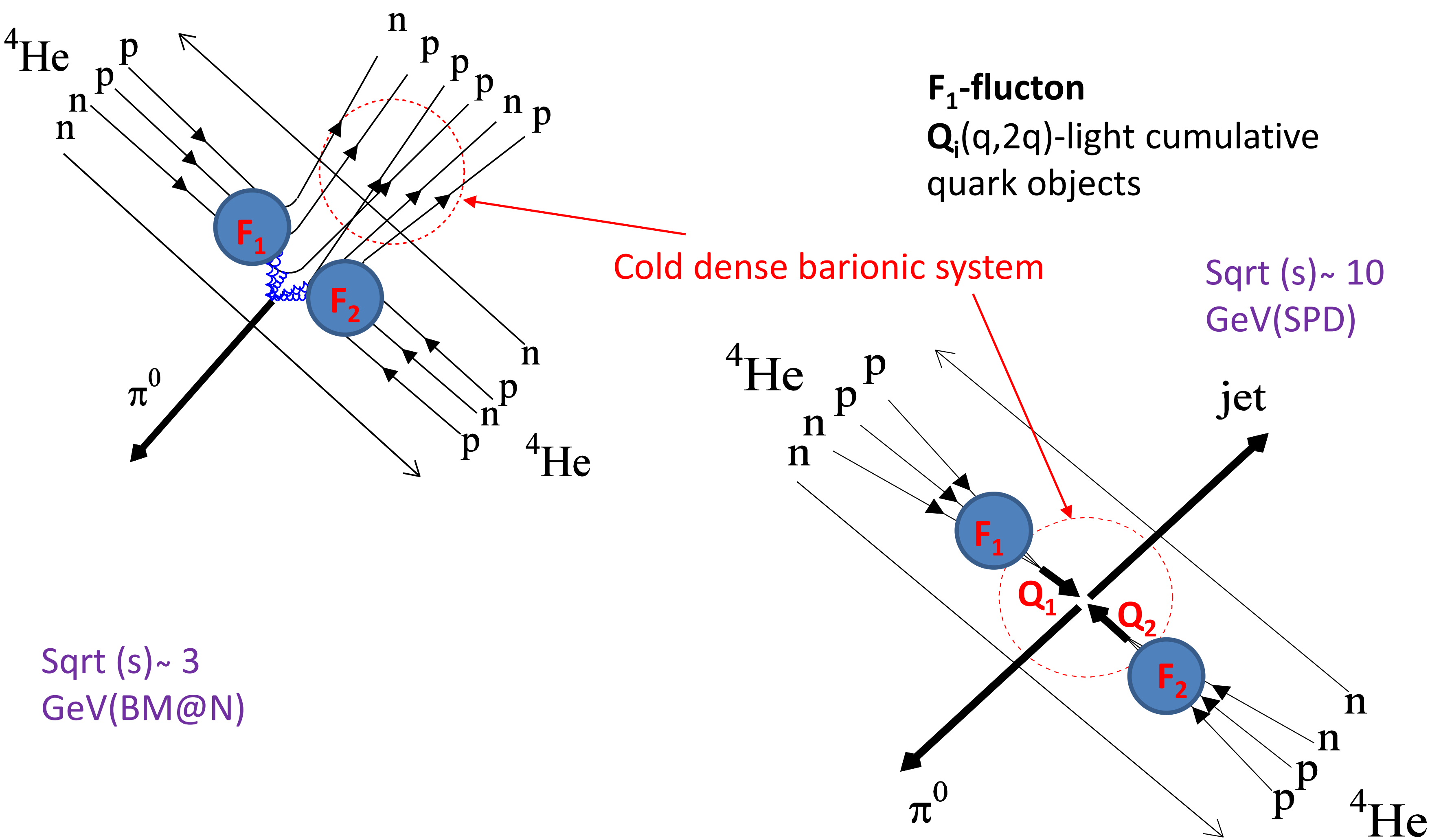


An estimate of baryon density

r_f~1.5fm



BM@N<->SPD



F_1-flucton
Q_i(q,2q)-light cumulative quark objects

Sqrt (s)~ 10 GeV(SPD)

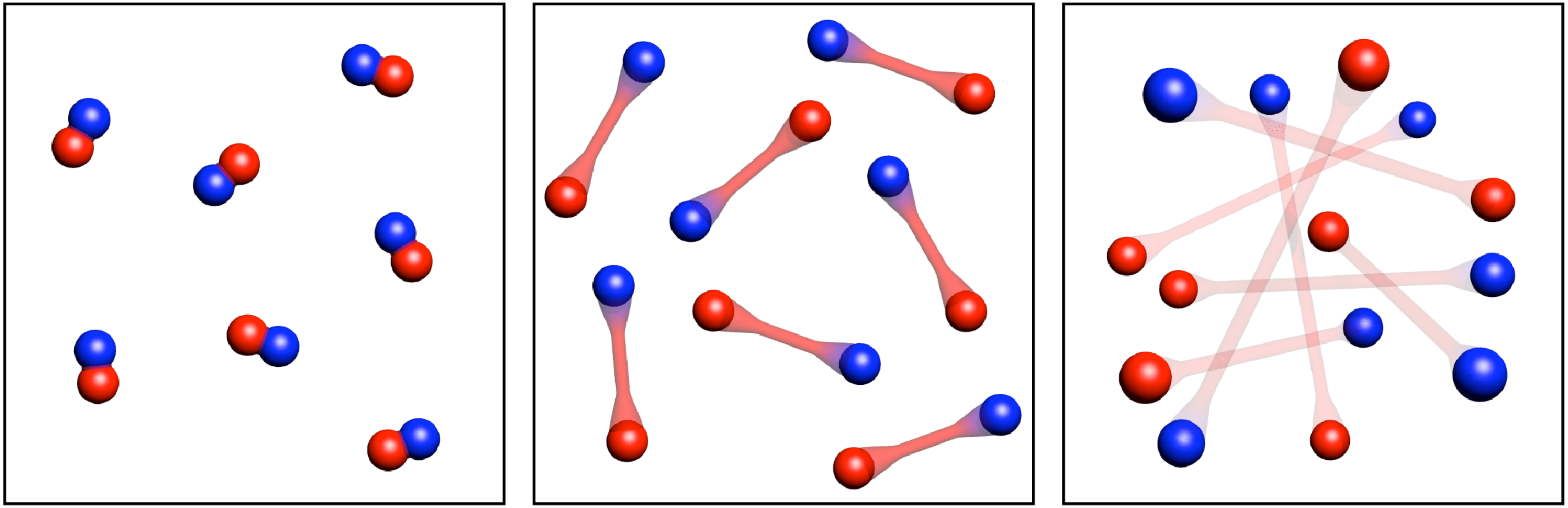
Sqrt (s)~ 3 GeV(BM@N)

E»1GeV(no FSI)

Model baryon=quark+diquark:
“ diquark: T=S=1 or 0.”
И.Ю.Кобзарев, Б.В.Мартемьянов, М.Г.Щепкин
УФН 162, вып.4,1992,стр.1-41
See, also, Anisovich A.V., et al., Int. J. Modern Phys. A, 25:15 (2010);
arXiv:1001.1259[hep-ph]
(**Quark-Diquark Systematics of Baryons)**

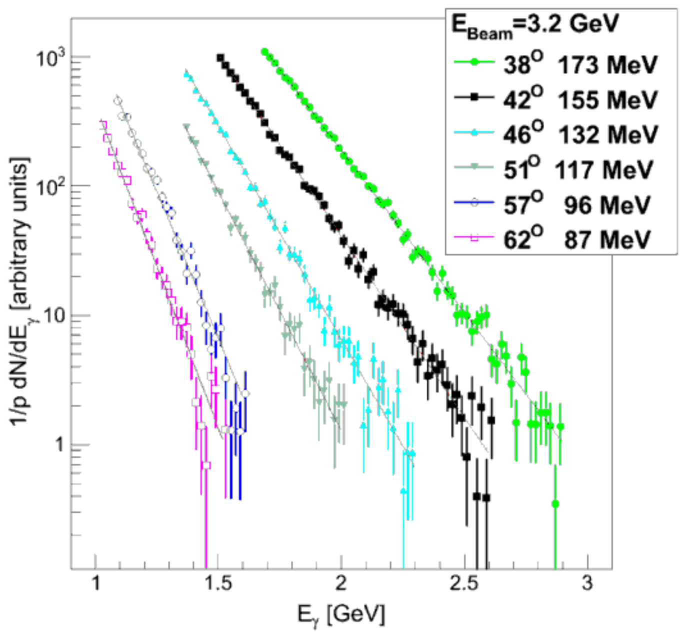
Does the theory of DCM really exist?

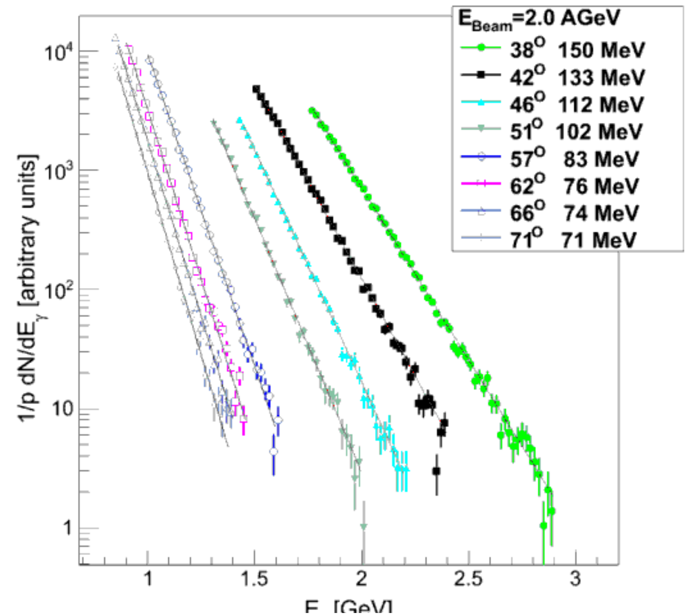
Lattices just started (see, for example):
Unitary Fermions on the Lattice
With: Michael Endres, Jong-Wan Lee, Amy Nicholson
Major outstanding problem in LGT: QCD at finite fermion number
BEC-Bose-Einstein condensation



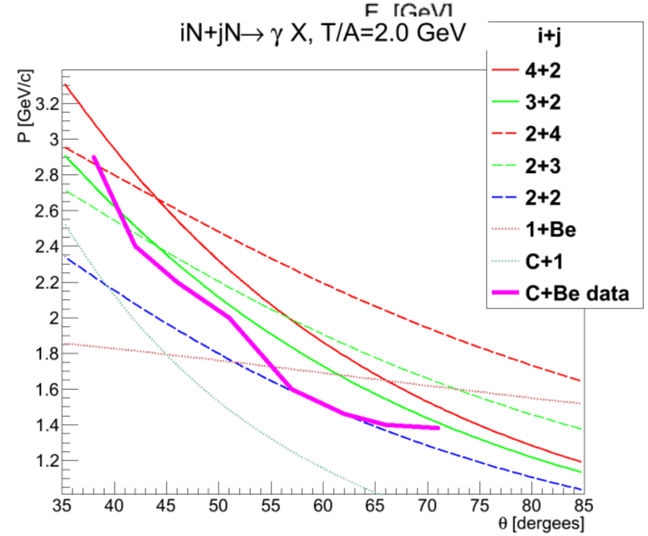
BEC of Molecules — Crossover Superfluid — BCS state

FLINT DATA: Photon spectra CBe→γX





FLINT have got data for flucton-flucton
interaction up to 6 nucleons kinematical region, which cannot be explained neither p+Be nor C+p interactions



Six nucleons system: n!n¡p!p¡+??

Does we already see phase transition?

Experimental program

1). Search for and the study of new state of matter at high density and low temperature corner of phase diagram

- search for the dense baryonic droplet in correlation measurements with high p_t cumulative trigger
- femtoscopy measurements for the dense baryonic droplet
- izotopic properties of the droplet
- strangeness production in the droplet
- fluctuations
- search for an exotic in the droplet

2) Dense cold matter contribution in ordinary nuclear matter and its nature SRC,flucton,…

- nuclear fragmentation
- hard scattering

Proposed measurements:

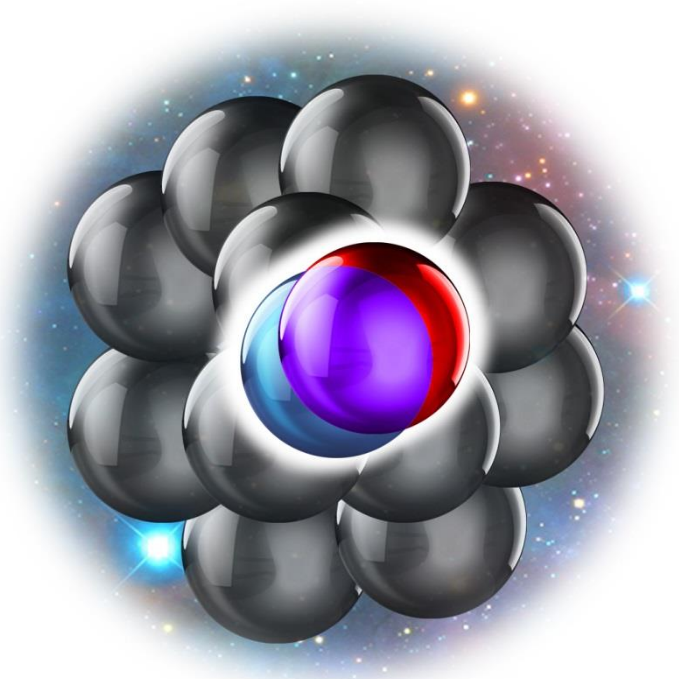
1.Trigger's particles: γ, π, K^-,K^+,p, d, …(p_t /E_0~1)

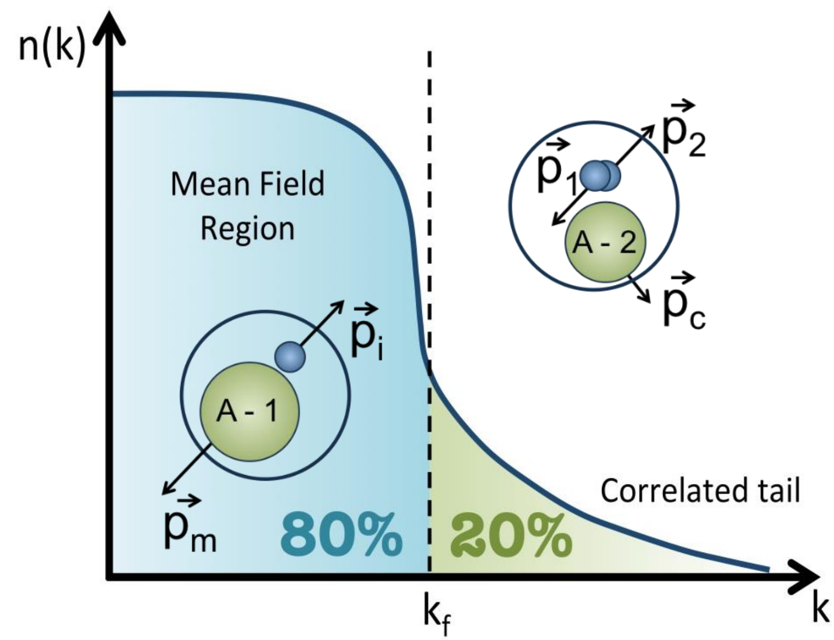
2. Recoil particles: nucleon, multinucleon systems,
   nuclear fragments, exotic states

3. Measurement values: $<N(p_t ,y)>$ vs X_{trig} and E_0(2-6GeV/nucleon);

-ratios(p/n, ^3He/t,…);correlations between recoil particles

2N-Short Range Correlations



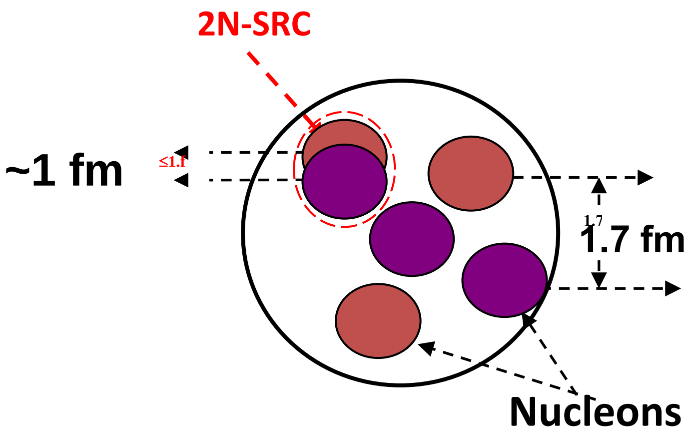


Occasionally nucleons are at close proximity in the nucleus

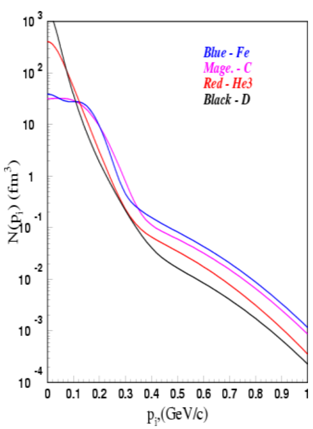
Each individual nucleon has high momentum

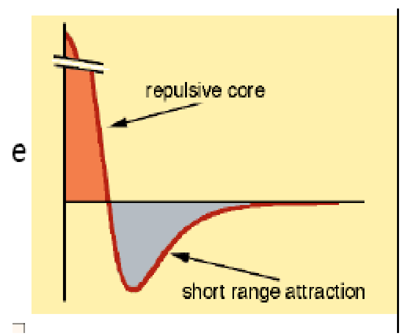
Low center of mass momentum of the pair relative to k_F

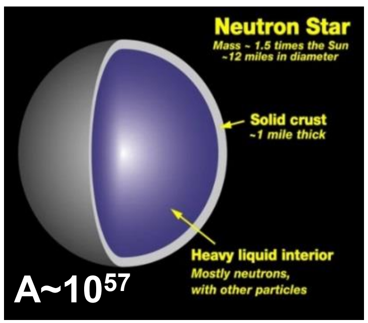
What SRC can teach us?

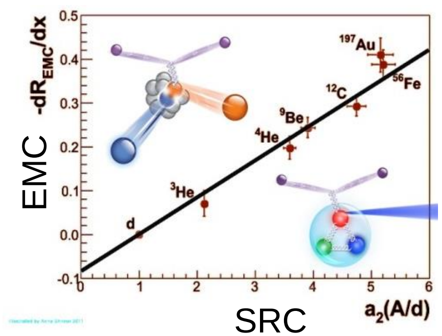


- High momentum component of the nuclear wave function
- **The strong short-range force between nucleons (tensor force, repulsive core, 3N forces)**
- Cold dense nuclear matter (from deuteron to neutron stars)
- **Nucleon structure modification in medium (EMC and SRC)**









Recent high-momentum-transfer triple-coincidence 12C(e, e'pN) and 12C(p, 2pn) measurements [1-4] have shown that nucleons in the nuclear ground state form nucleon pairs with large relative momentum and small center-of-mass (CM) momentum, where large and small are relative to the Fermi momentum of the nucleus (kF). We refer to these pairs as short-range correlated (SRC) pairs [5-7]. In the range of missing-momentum (the knocked-out proton's pre-scatter momentum in the absence of re-interactions) from 300– 600 MeV/c, these pairs were found to dominate the nuclear wave function, with neutron-proton (np) pairs nearly 20 times more prevalent than proton-proton (pp) pairs, and by inference neutron-neutron (nn) pairs (see figure 1). The strong preference for np pairs is due to the dominance of the tensor part of the NN interaction at the probed sub-fm distances [8-10]. These observations were also confirmed in recent measurements on heavier nuclei reaching all the way up to 208Pb [16].

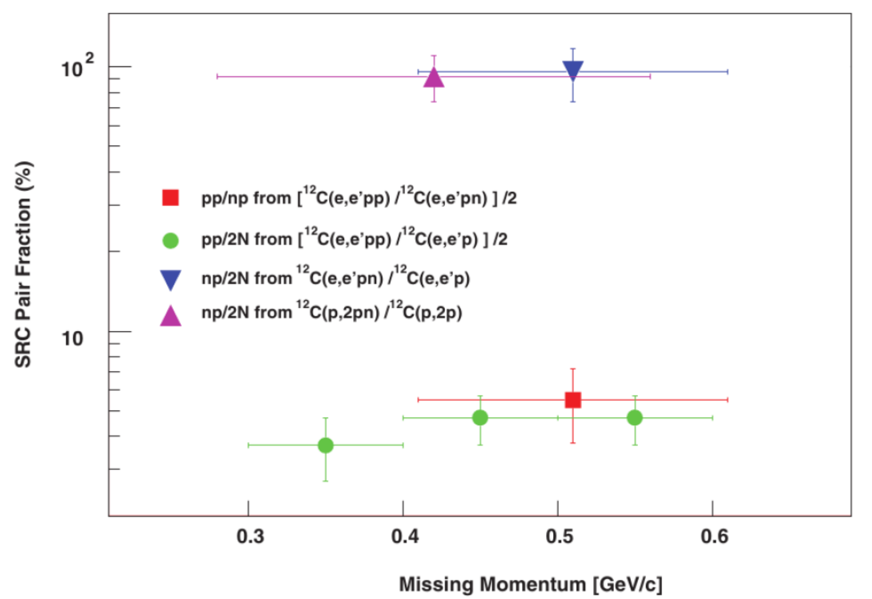


Figure 1: The fractions of correlated pair combinations in carbon as obtained from the ^{12}C(e, e'pp) and ^{12}C(e, e'pn) reactions measured at JLab [1,2] as well as from previous, ^{12}C(p,2pn) data from BNL [3,4].

JLAB

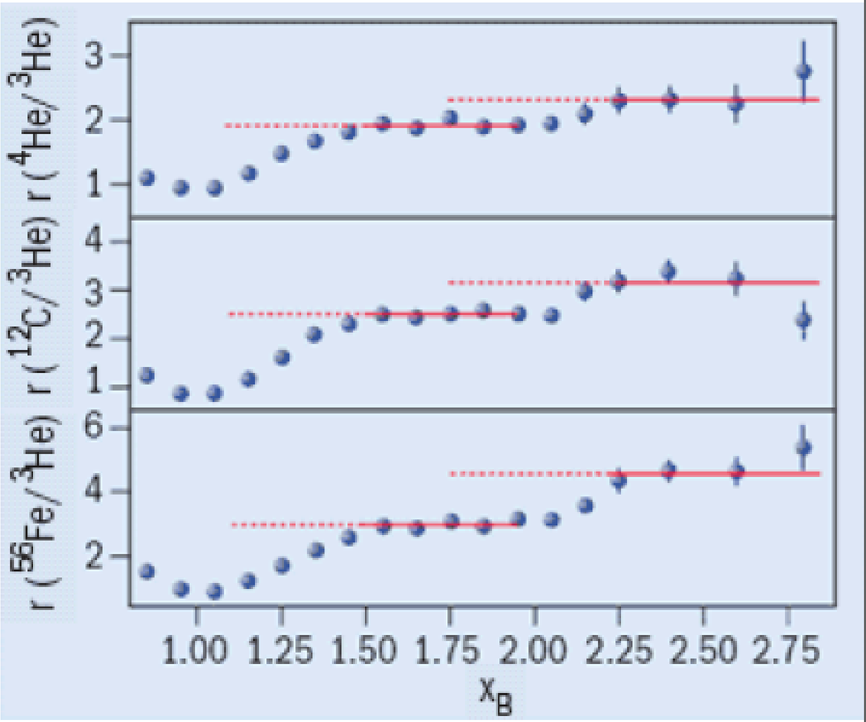
Phys.Rev.Lett. 96 (2006) 082501

Measurement of 2- and 3-Nucleon Short Range Correlation Probabilities in Nuclei

K.S. Egiyan,[1] N.B. Dashyan,[1] M.M. Sargsian,[10] M.I. Strikman,[28] L.B. Weinstein,[27] G. Adams,[30] P. Ambrozewicz,[10] M. Anghinolfi,[16] B. Asavapibhop,[22] G. Asryan,[1] H. Avakian,[34] H. Baghdasaryan,[27] N. Baillie,[38] J.P. Ball,[2]

$$r(A, {}^3\mathrm{He}) = \frac{A(2\sigma_{ep} + \sigma_{en})}{3(Z\sigma_{ep} + N\sigma_{en})} \frac{3\mathcal{Y}(A)}{A\mathcal{Y}({}^3\mathrm{He})} C^A_{\mathrm{rad}}, \qquad (2)$$

where Z and N are the number of protons and neutrons in nucleus A, σ_{eN} is the electron-nucleon cross section, $\mathcal{Y}$ is the normalized yield in a given (Q^2,x_B) bin [30] and C^A_{rad} is the ratio of the radiative correction factors for A and ^{3}He ($C^A_{\mathrm{rad}} = 0.95$ and 0.92 for ^{12}C and ^{56}Fe respectively). In our Q^2 range, the elementary cross section correction factor $\frac{A(2\sigma_{ep}+\sigma_{en})}{3(Z\sigma_{ep}+N\sigma_{en})}$ is 1.14 ± 0.02 for C and ^{4}He and 1.18 ± 0.02 for ^{56}Fe. Fig. 1 shows the resulting ratios integrated over $1.4 < Q^2 < 2.6$ GeV^2.



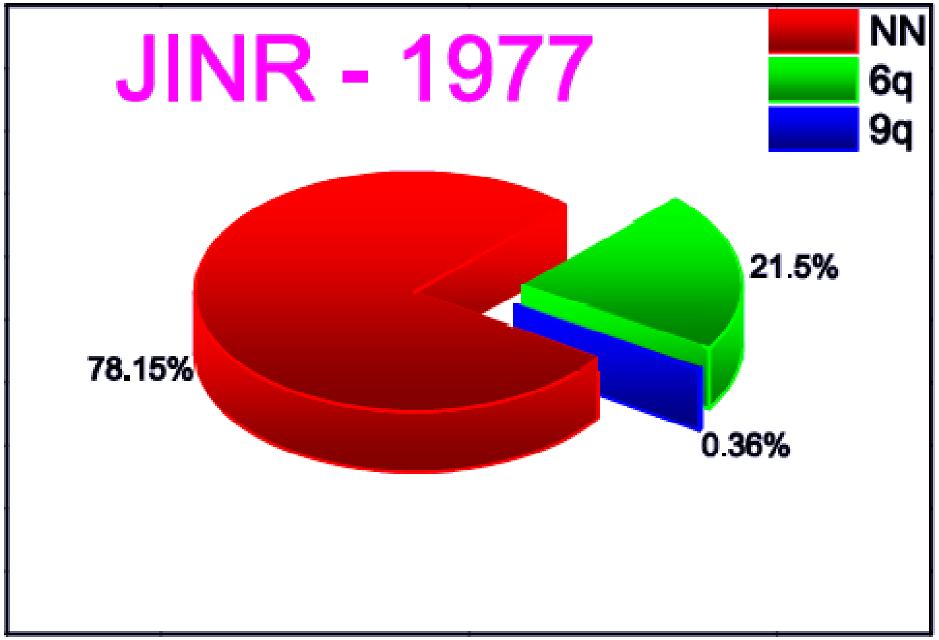
- No rescattering

$x_B = Q^2/2m_N\upsilon$

Leptonic and hadronic probes give same result

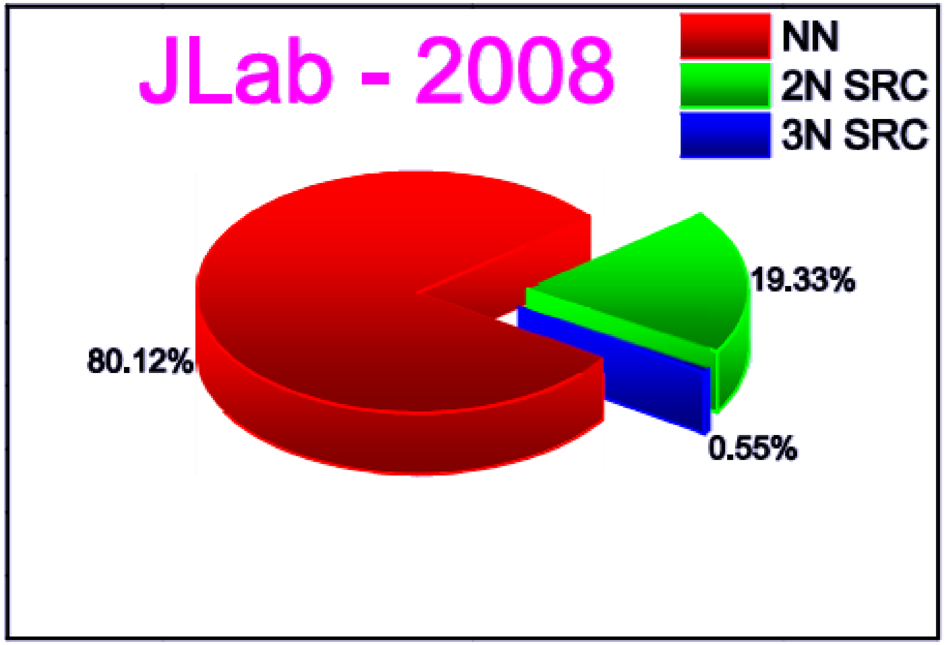
RNP - program at JINR

V.V.B., V.K.Lukyanov, A.I.Titov, PLB, 67, 46(1977)



eA - program at JLab

R.Subedi et al., Science 320 (2008) 1476-1478
e-Print: arXiv:0908.1514 [nucl-ex]

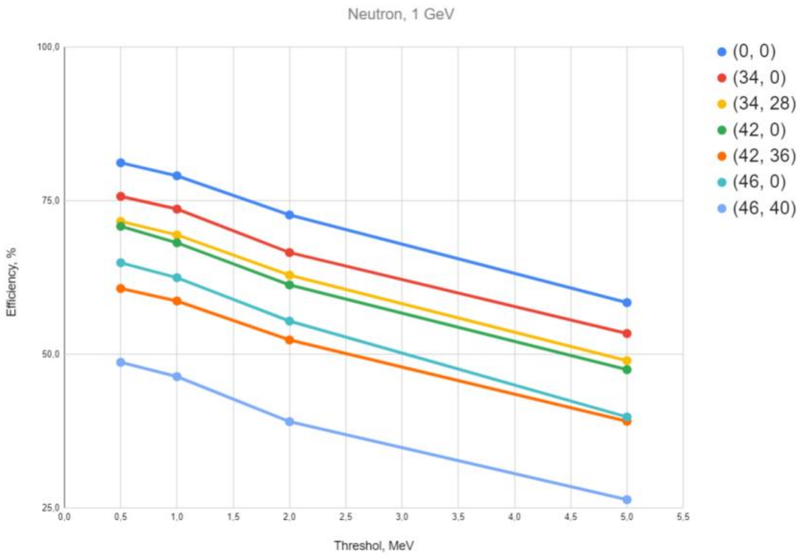


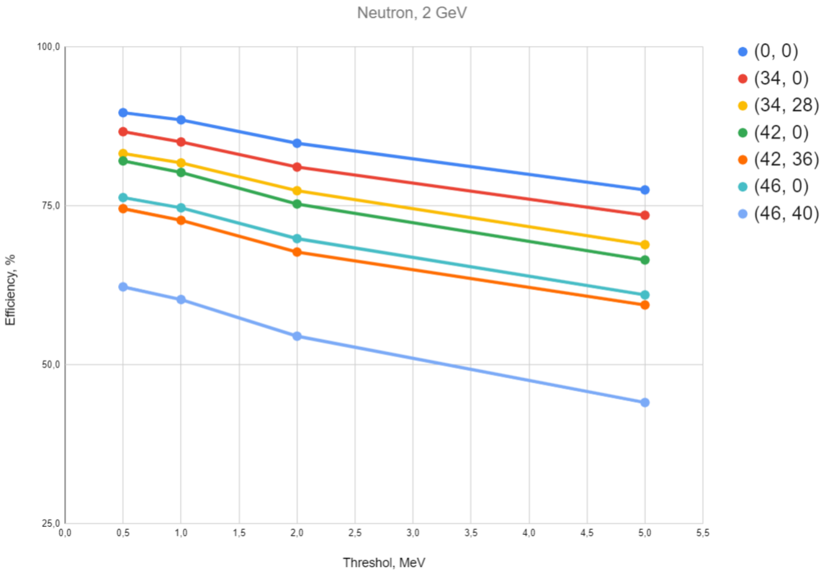
Probing Cold Dense Nuclear Matter

R. Subedi,[1] R. Shneor,[2] P. Monaghan,[3] B. D. Anderson,[1] K. Aniol,[4] J. Annand,[5] J. Arrington,[6] H. Benaoum,[7,8] F. Benmokhtar,[9] W. Bertozzi,[3] W. Boeglin,[10] J.-P. Chen,[11] Seonho Choi,[12] E. Cisbani,[13] B. Craver,[14] S. Frullani,[13] F. Garibaldi,[13] S. Gilad,[3] R. Gilman,[11,15] O. Glamazdin,[16] J.-O. Hansen,[11] D. W. Higinbotham,[11*] T. Holmstrom,[17] H. Ibrahim,[18] R. Igarashi,[19] C.W. de Jager,[11] E. Jans,[20] X. Jiang,[15] L.J. Kaufman,[9,22] A. Kelleher,[17] A. Kolarkar,[23] G. Kumbartzki,[15] J. J. LeRose,[11] R. Lindgren,[14] N. Liyanage,[14] D. J. Margaziotis,[4] P. Markowitz,[10] S. Marrone,[24] M. Mazouz,[25] D. Meekins,[11] R. Michaels,[11] B. Moffit,[17] C. F. Perdrisat,[17] E. Piasetzky,[2] M. Potokar,[26] V. Punjabi,[27] Y. Qiang,[3] J. Reinhold,[10] G. Ron,[2] G. Rosner,[28] A. Saha,[11] B. Sawatzky,[14,29] A. Shahinyan,[30] S. Širca,[26,31] K. Slifer,[14] P. Solvignon,[29] V. Sulkosky,[17] G. M. Urciuoli,[13] E. Voutier,[25] J. W. Watson,[1] L.B. Weinstein,[18] B. Wojtsekhowski,[11] S. Wood,[11] X.-C. Zheng,[3,6,14] and L. Zhu[32]

The protons and neutrons in a nucleus can form strongly correlated nucleon pairs. Scattering experiments, where a proton is knocked-out of the nucleus with high momentum transfer and high missing momentum, show that in ^{12}C the neutron-proton pairs are nearly twenty times as prevalent as proton-proton pairs and, by inference, neutron-neutron pairs. This difference between the types of pairs is due to the nature of the strong force and has implications for understanding cold dense nuclear systems such as neutron stars.

Detector efficiency (with ECAL)





Neutron, 1 GeV				
ECAL hit	any or null	null	at least one	Maximal efficiency, %
HGN hit	at least two	at least two	one	
Threshold, MeV	Efficiency, %			
0.5	81,2	33,4	4,3	85,5
1.0	79,1	37,4	5,0	84,1
2.0	72,7	41,5	6,9	79,6
5.0	58,4	48,7	5,9	64,3

Neutron, 2 GeV				
ECAL hit	any or null	null	at least one	Maximal efficiency, %
HGN hit	at least two	at least two	one	
Threshold, MeV	Efficiency, %			
0.5	89,7	29,0	2,0	91,7
1.0	88,5	34,1	2,5	91,0
2.0	84,8	38,8	4,0	88,8
5.0	77,5	51,1	5,9	83,4

ToF resolution

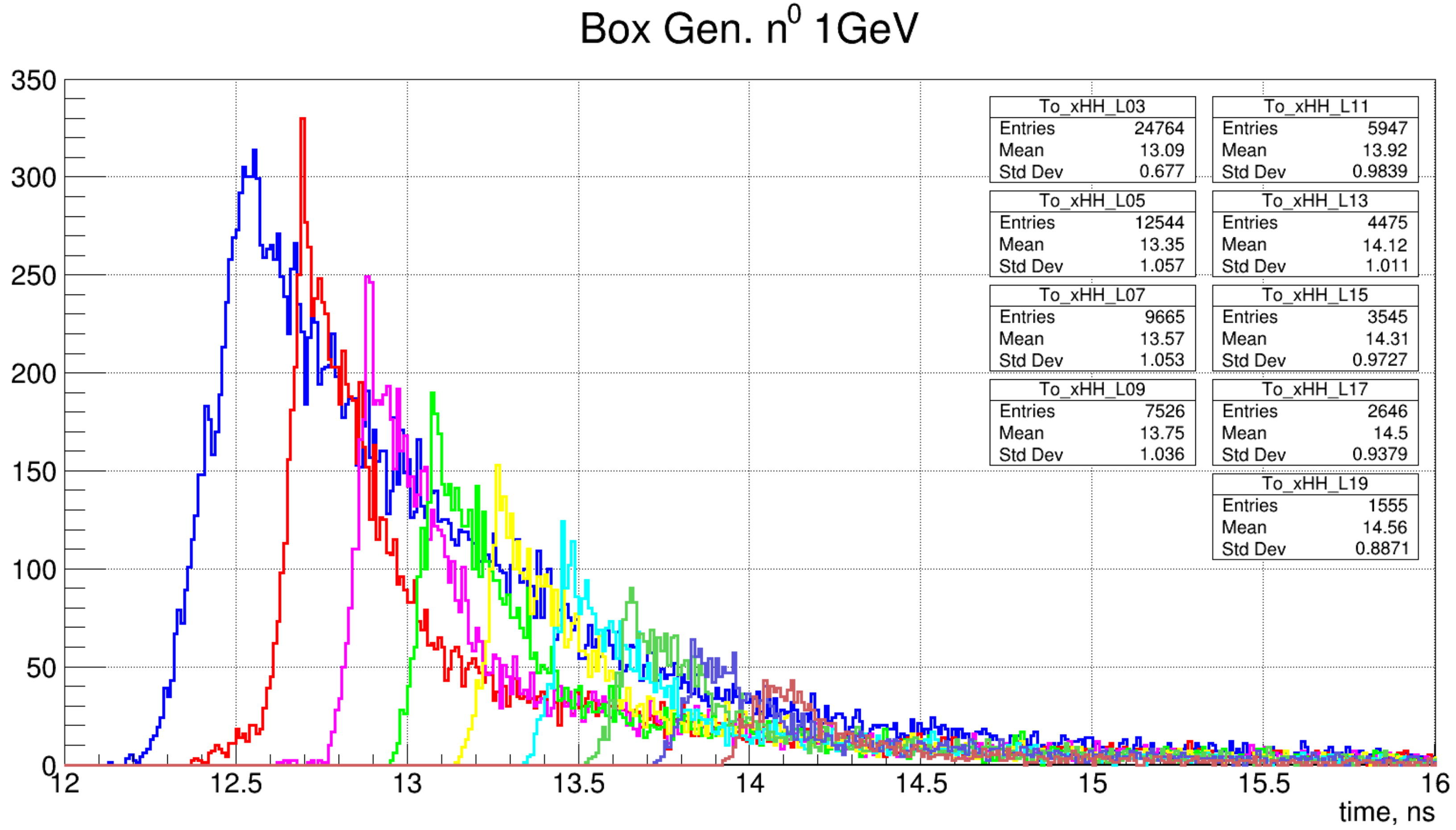
ToF distribution

for each active layer

Version with ECAL

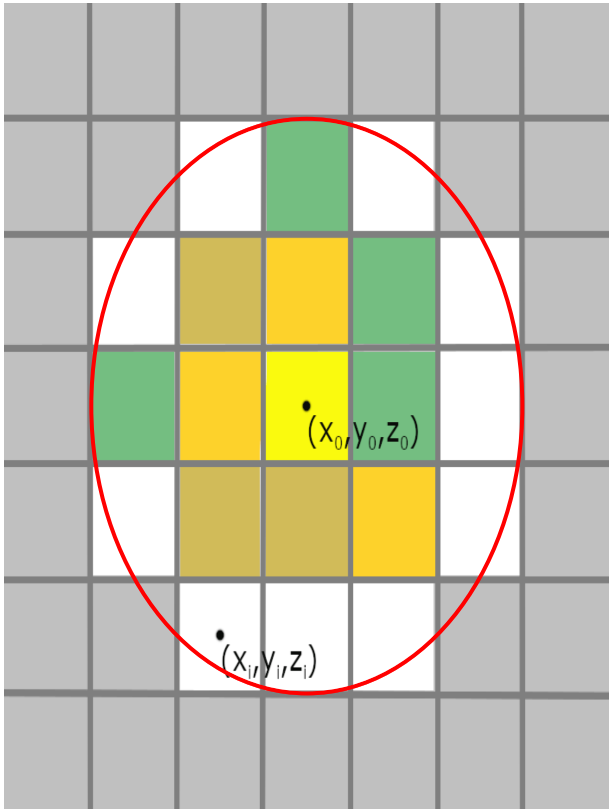
no cut for ECAL hits

Threshold 2MeV



Cluster parameters

- Minimal cell energy is 30 MeV, other cells are ignored
- Cluster radius is 10 cm (21 cells of 5x5 area)
- Cluster parameters are:
  - energy
  - center gravity
  - weighted average time (t_{wa})
  - time spread (t_{sp})
  - normalized moment (M_{norm})

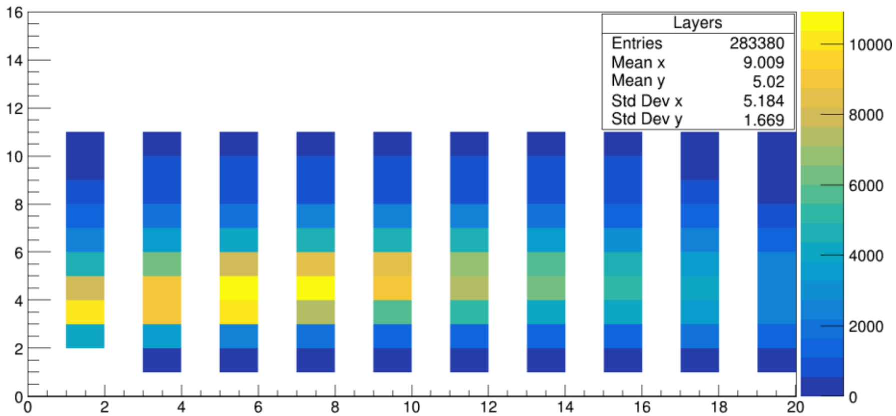


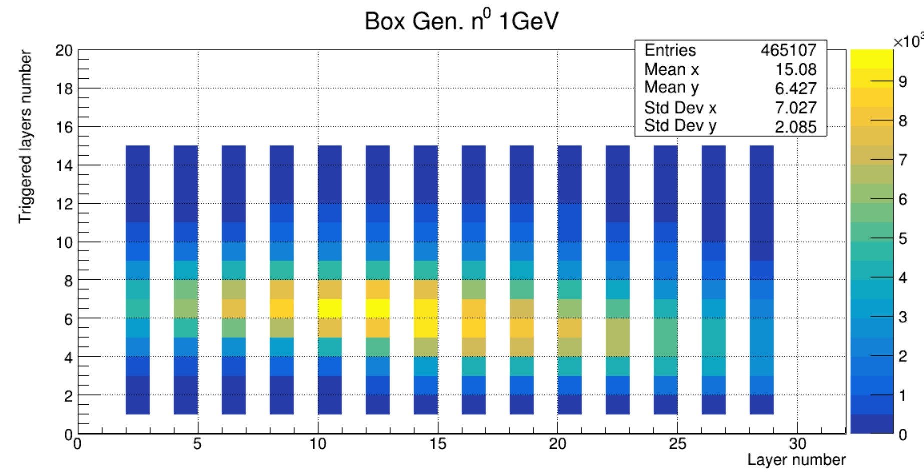
$$t_{wa} = \frac{\sum E_i \cdot t_i}{\sum E_i} \qquad t_{sp} = \frac{\sum E_i \cdot (t_i - t_0)^2}{\sum E_i}$$

$$M_{norm} = \frac{\sum E_i \times ((x_i - x_0)^2 + (y_i - y_0)^2 + (z_i - z_0)^2)}{\sum E_i}$$

Photon-neutron

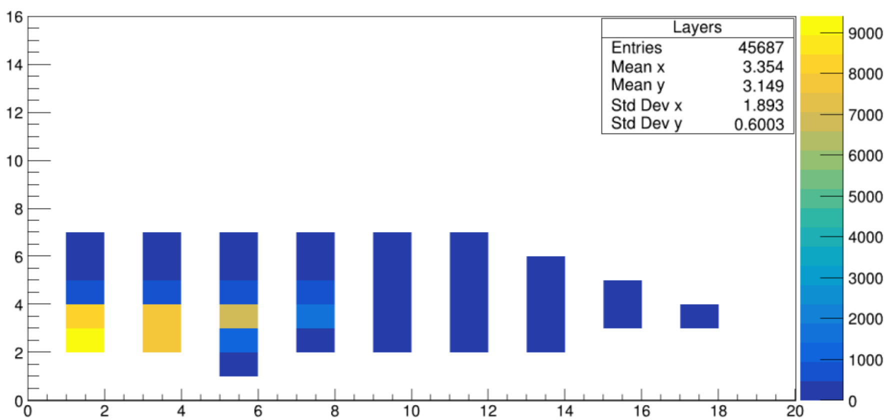
E=1GeV, neutron(up),photon(down), box generator, center of detector

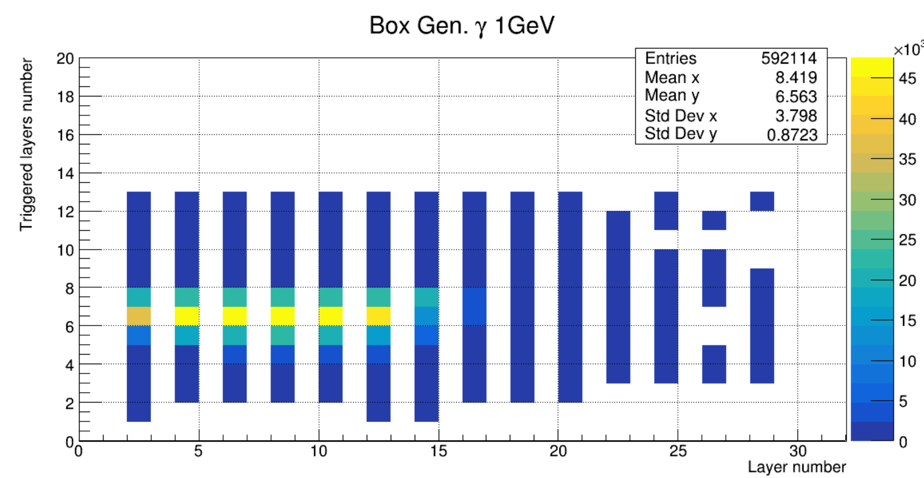




First layer-ECAL+9layers Sci(3cm)+W(2cm)

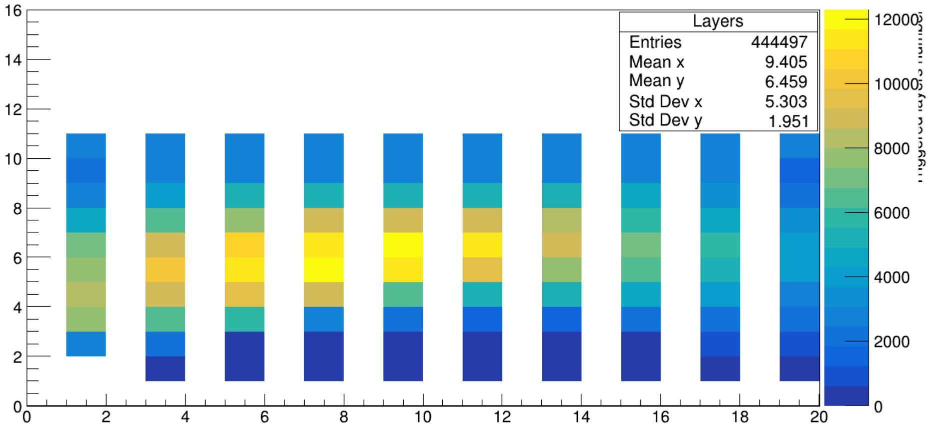
6 thin(Sci(3cm)+W(0.5cm) layers instead of ECAL

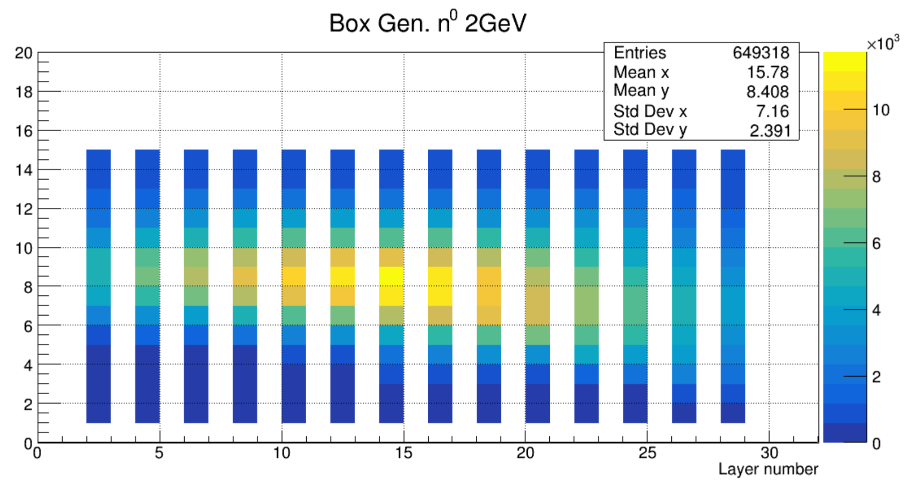




Photon-neutron

E=2GeV, neutron(up),photon(down), box generator, center of detector





First layer-ECAL+9layers Sci(3cm)+W(2cm)

6 thin(Sci(3cm)+W(0.5cm) layers instead of ECAL