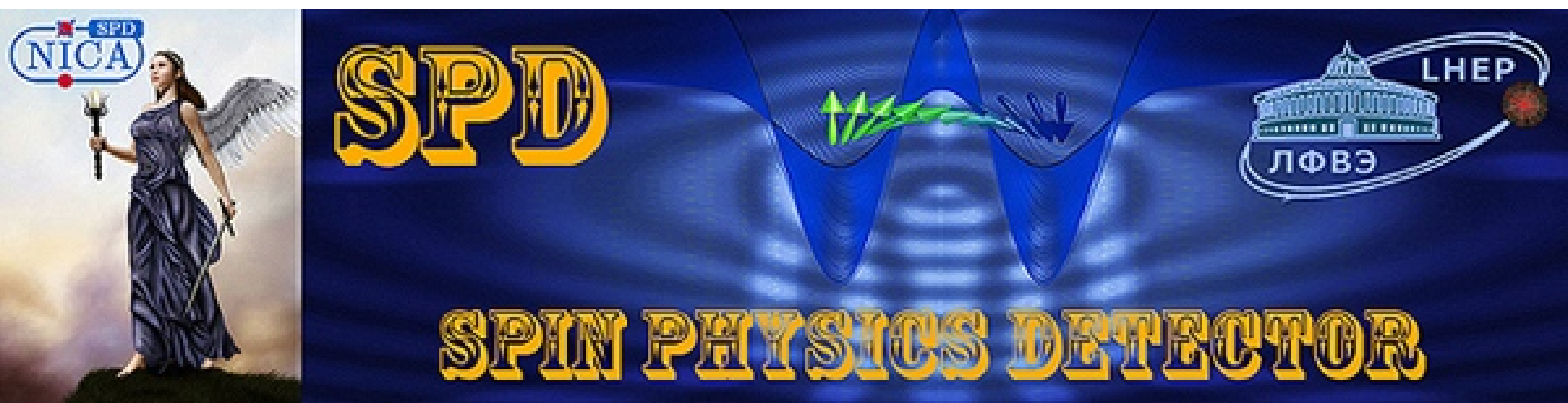
Zero degree calorimeter Conceptual design

I. Alekseev, A. Golubev, D. Kirin, V. Rusinov,
D. Svirida, A. Stavinsky, E. Tarkovsky
(ITEP, Moscow)



Main tasks

- Time tagging of the events for event selection;
- Luminosity measurement;
- Local polarimetry with forward neutrons;
- Spectator neutron tagging.

Requirements:

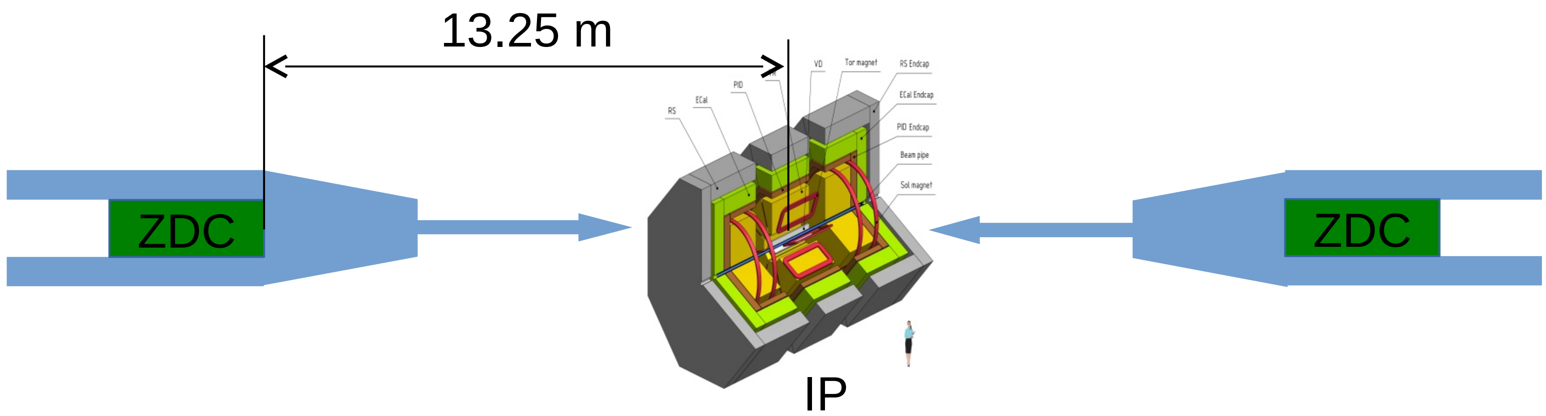
- Time resolution 150-200 ps;
- Energy resolution for neutrons 50-60%/$\sqrt{E} \oplus$ 8-10%;
- Neutron entry point geometry resolution 10 mm;
- Neutron to gamma discrimination.

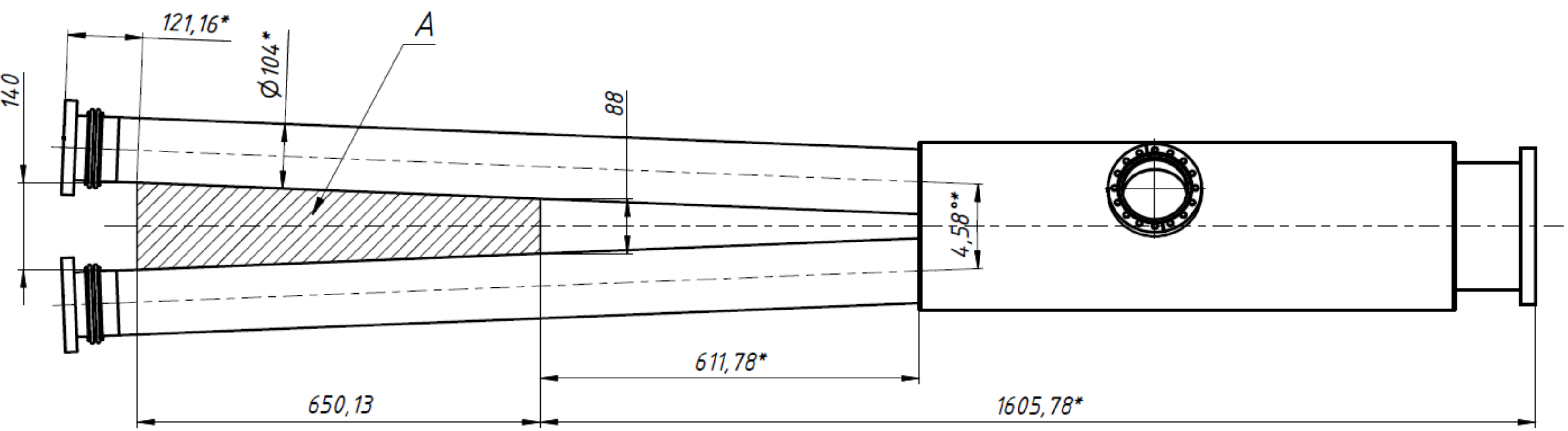
Questions:

Do we have enough space ?

Can we obtain the time resolution ?

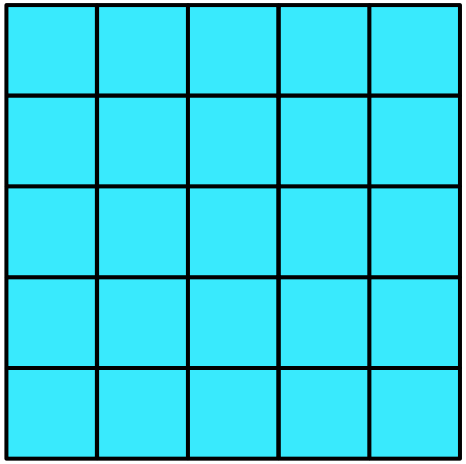
Position

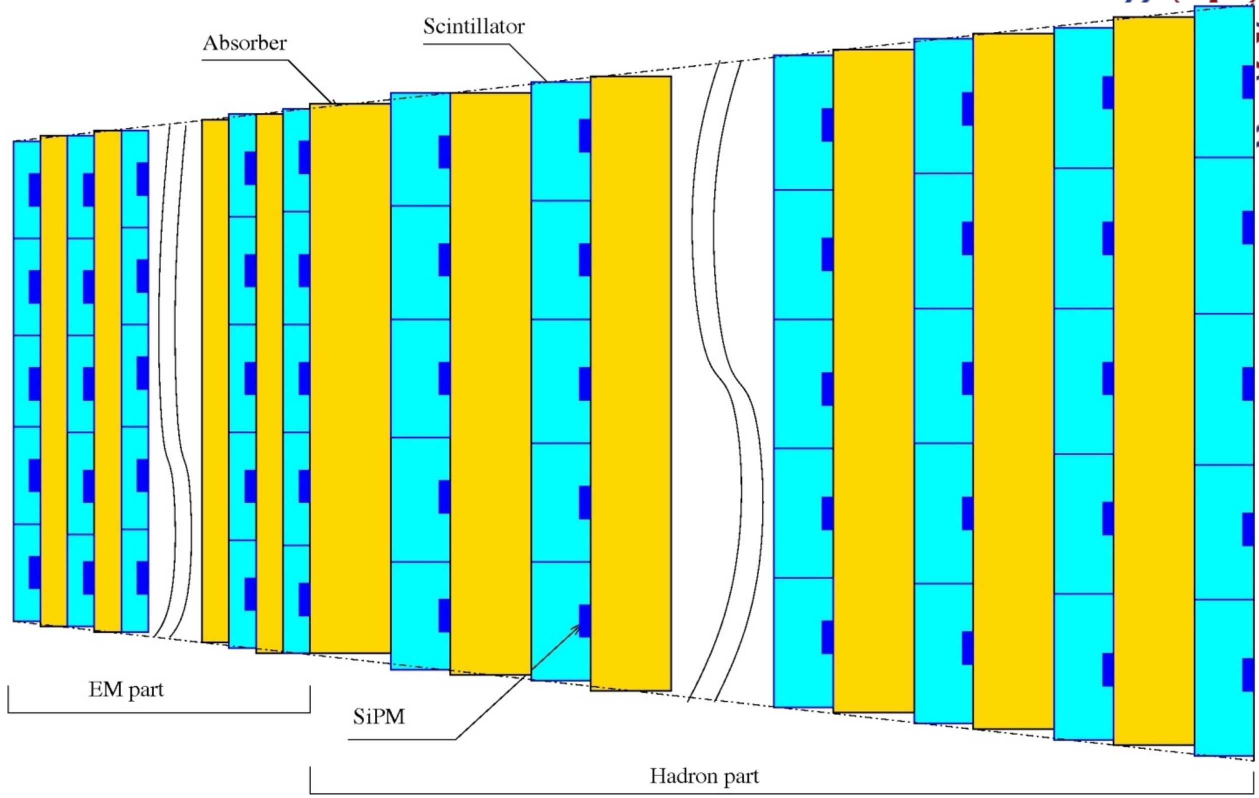




1. *Размеры для справок.
2. A – область возможного размещения Zero degree calorimeter.

Concept

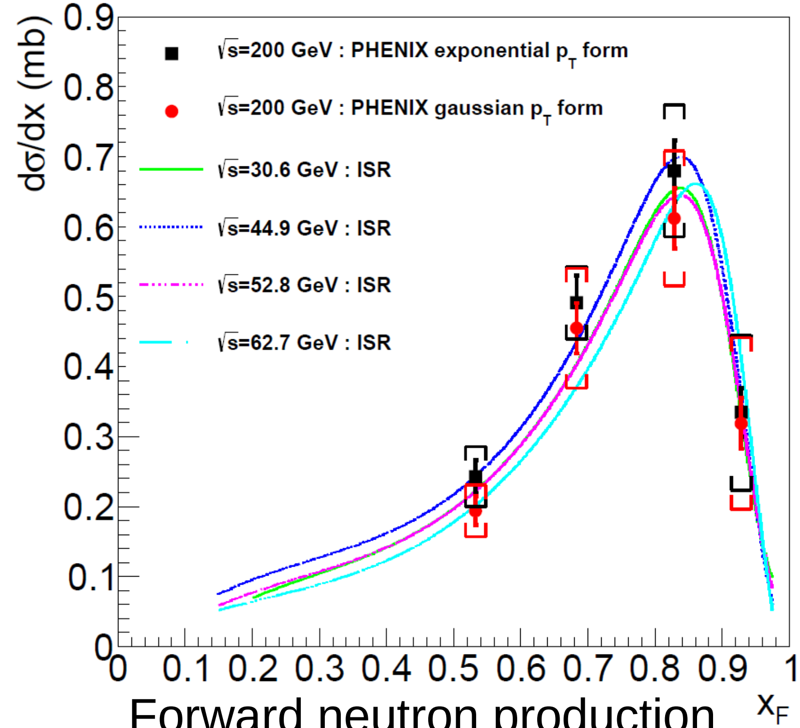




- Sampling calorimeter with fine segmentation, 5x5 matrix.
- SiPM light readout
- About 1000 channels
- Optimization based on MC and measurements with prototype is required
- Readout system based on electronics designed for the DANSS neutrino experiment at Kalininskaya NPP, modified to 500 MSPS digitization.

Radiation hardness

- Design goals:
  - PHENIX 100 krad
  - CMS 20 Grad
- HAMAMATSU SiPM:
  - 10^{11} n/cm^2 – working
  - 10^{12} n/cm^2 – practical limit
- Number of neutrons going from IP is not large – main problem beam halo etc.
- Similar results were obtained in detail simulations presented by S.Shimanskiy on May 13.



Forward neutron production

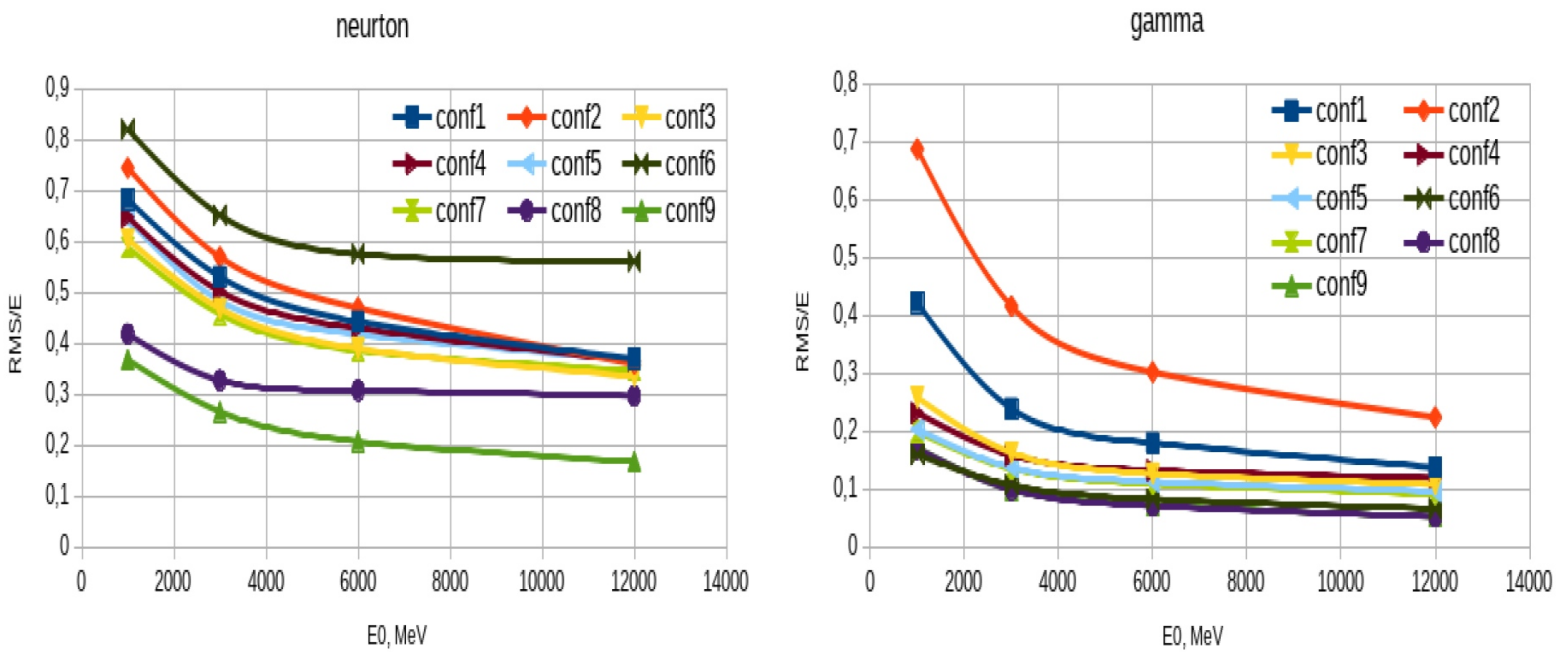
From IP for SPD@ NICA:
pp diffractive cone: e^{-Bt}
B ~ 16 GeV^{-2}
Size at 13 m ~ 25 cm
or S ~ 2000 cm^2
σ ~ 0.3 mb
L ~ 10^{32} cm^{-2} c^{-1}
N ~ 60 kHz ~ 30 cm^{-2} c^{-1}
or ~ **10^9 year^{-1}cm^{-2}**

Simulations

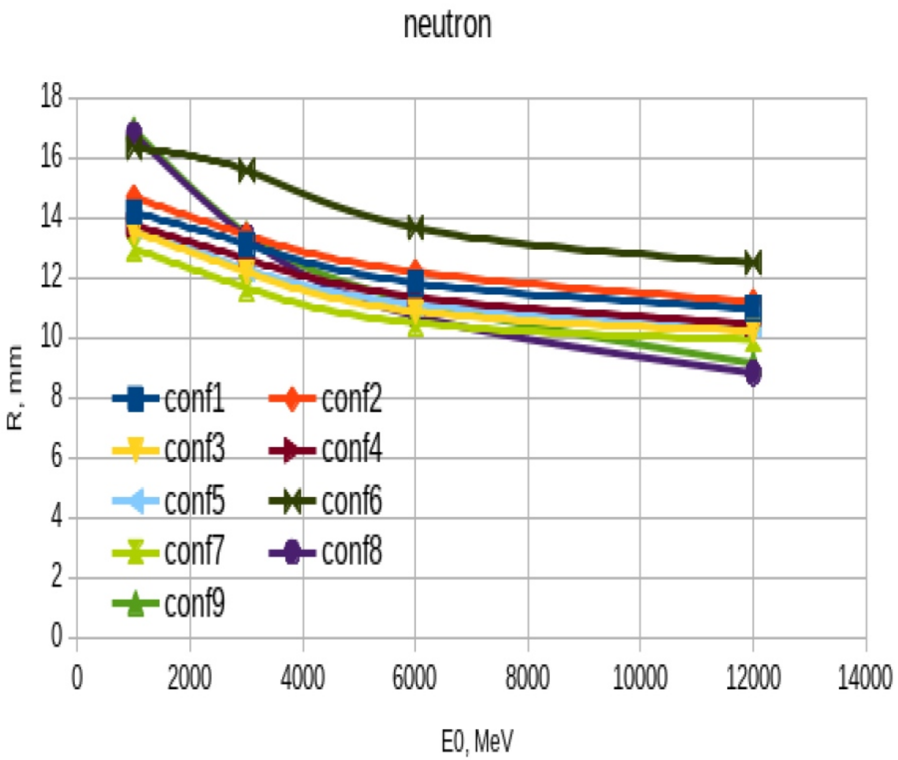
- Main idea of the simulations was to compare different detector configurations
- "Beam" particles: neutrons and gamma
- Energies: 1, 3, 6, 12 GeV
- Incident particles spread uniformly on the front side of the detector and go along the detector axis

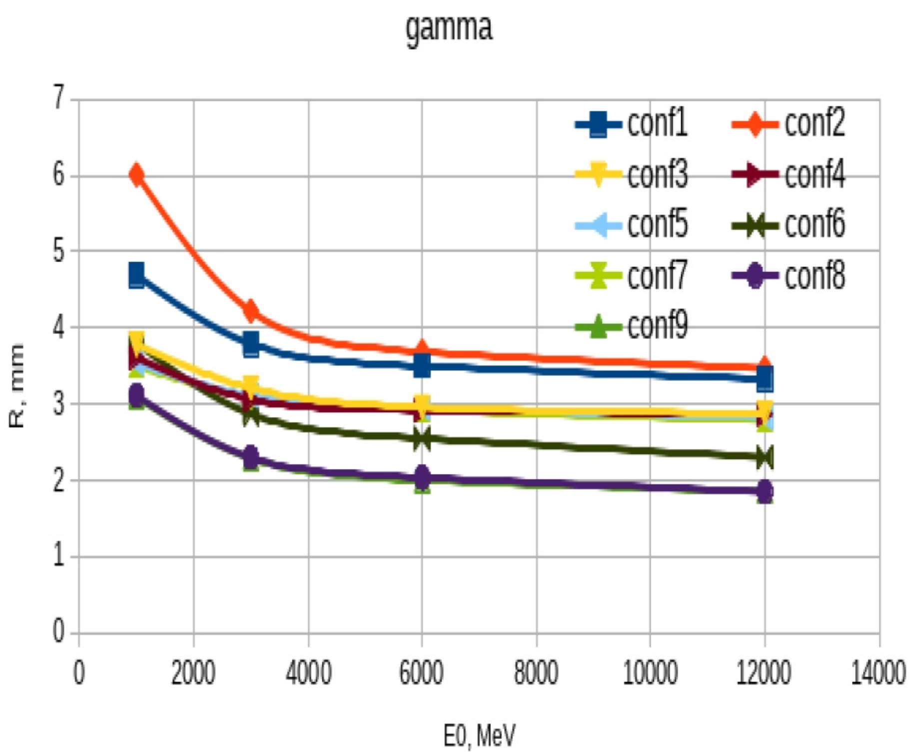
No	Configuration	Total length, nucl. int. len.
1	(Sci(20mm)+W(20mm))x16 active slices	3.4
2	(Sci(15mm)+W(30mm))x15 active slices	4.8
3	(Sci(10mm)+W(10mm))x33 active slices	3.6
4	(Sci(5mm)+W(5mm))x6slices+(Sci(20mm)+W(20mm))x14 active slices	3.3
5	(Sci(5mm)+W(5mm))x10slices+(Sci(20mm)+W(20mm))x13 active slices	3.3
6	(Sci(5mm)+Cu(5mm))x10slices+(Sci(20mm)+Cu(20mm))x13 active slices	2.0
7	(Sci(5mm)+W(5mm))x10slices+(Sci(10mm)+W(10mm))x26 active slices	3.4
8	(Sci(5mm)+W(5mm))x10slices+(Sci(10mm)+W(10mm))x26 active slices (14x14)	3.4
9	(Sci(5mm)+W(5mm))x10slices+(Sci(10mm)+W(10mm))x46 active slices (14x14)	5.4

Energy resolution

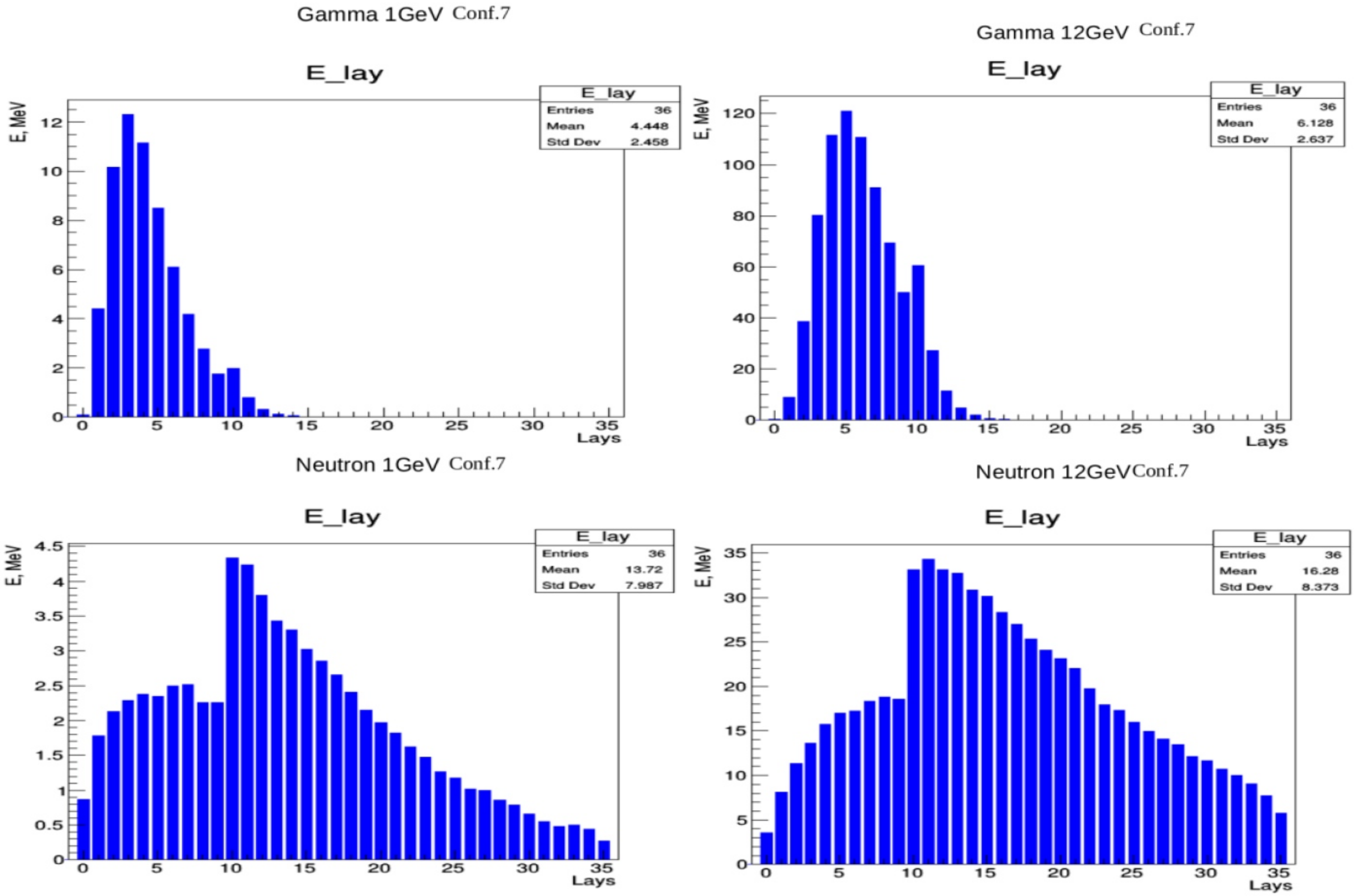


Space resolution





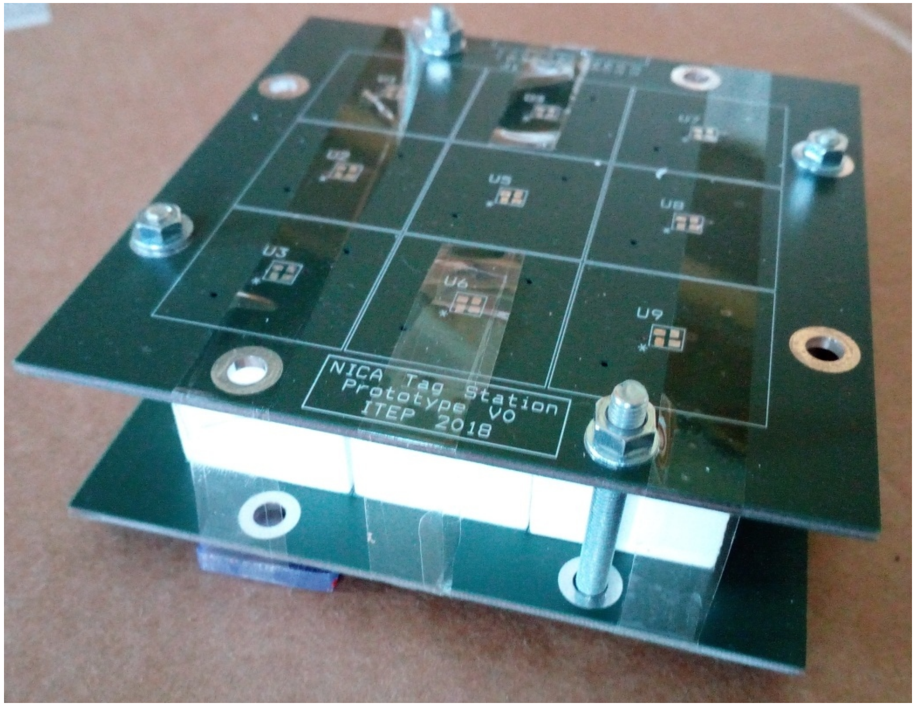
Photon to neutron discrimination



Time resolution test

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

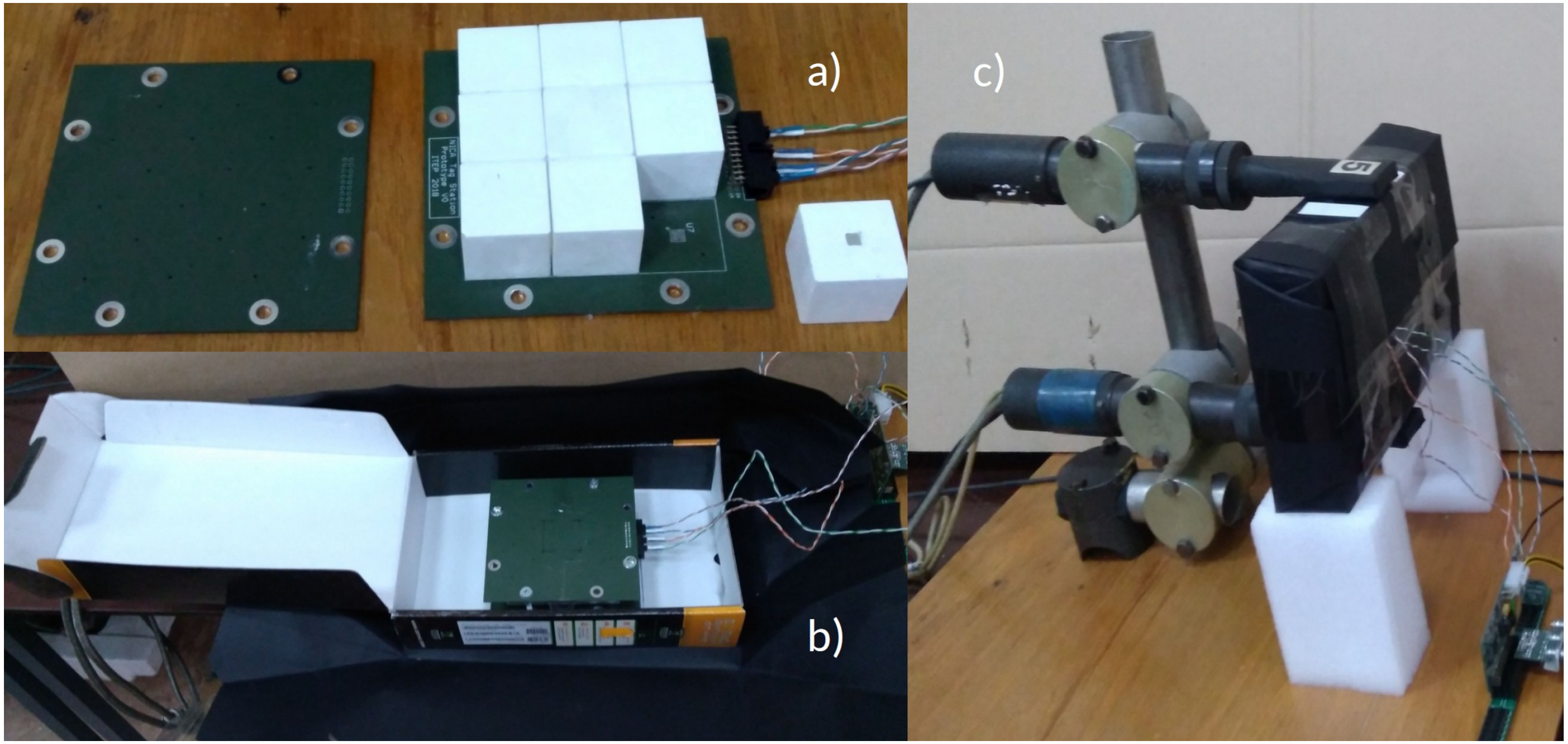


Test layout

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

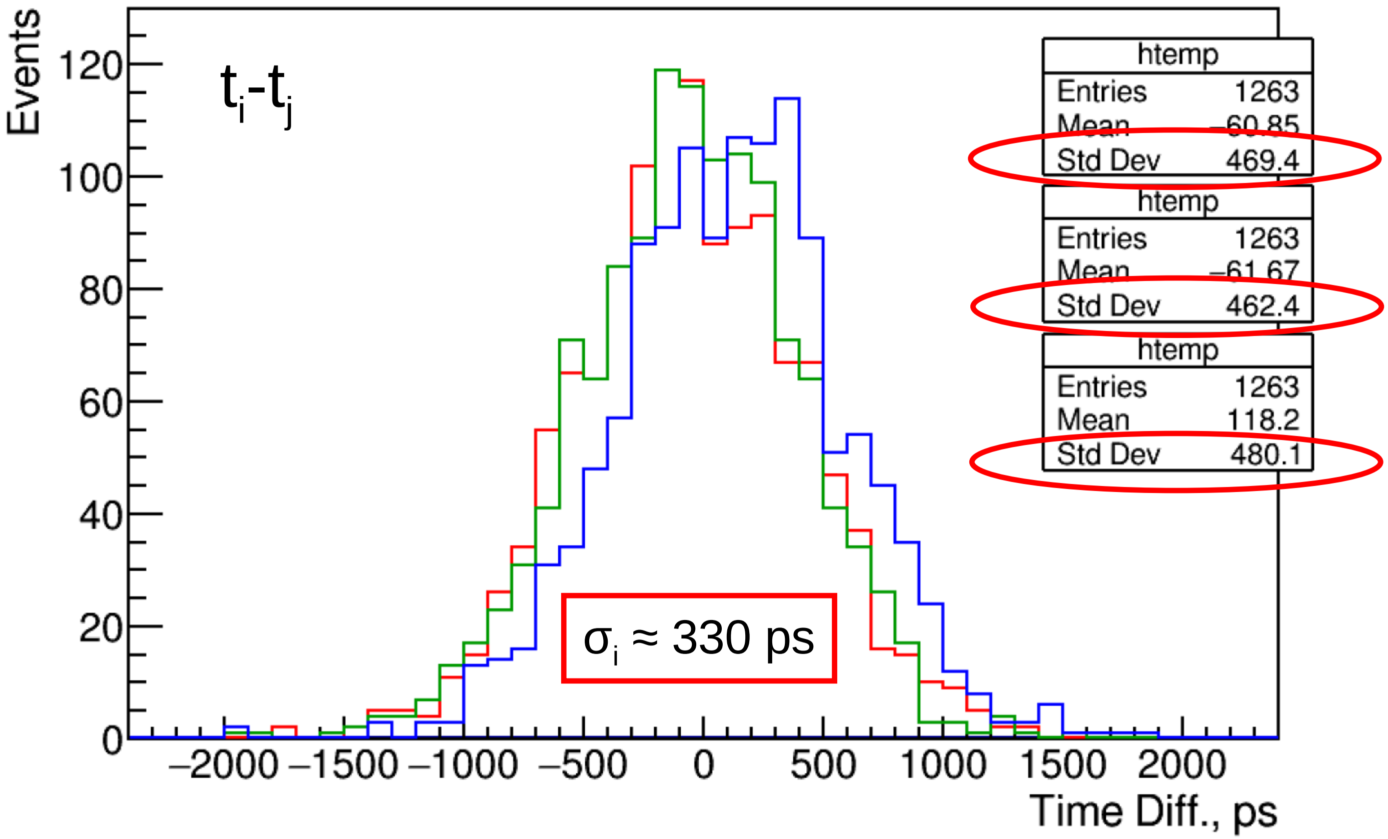


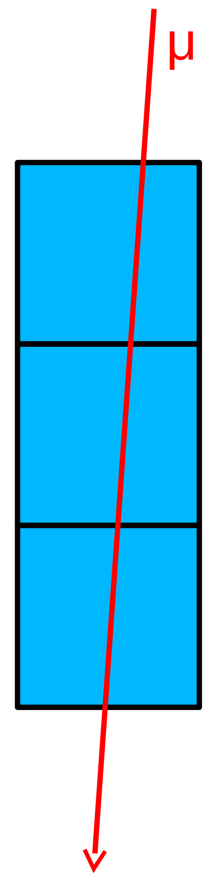
Test results

Hardware trigger on the central cube.

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

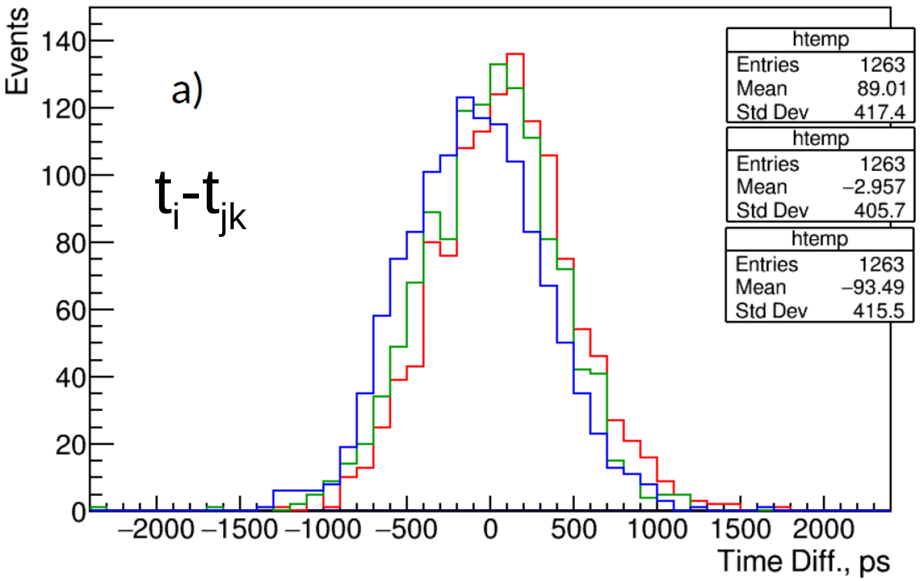
Software trigger – amplitude in all 3 cubes in the MIP region



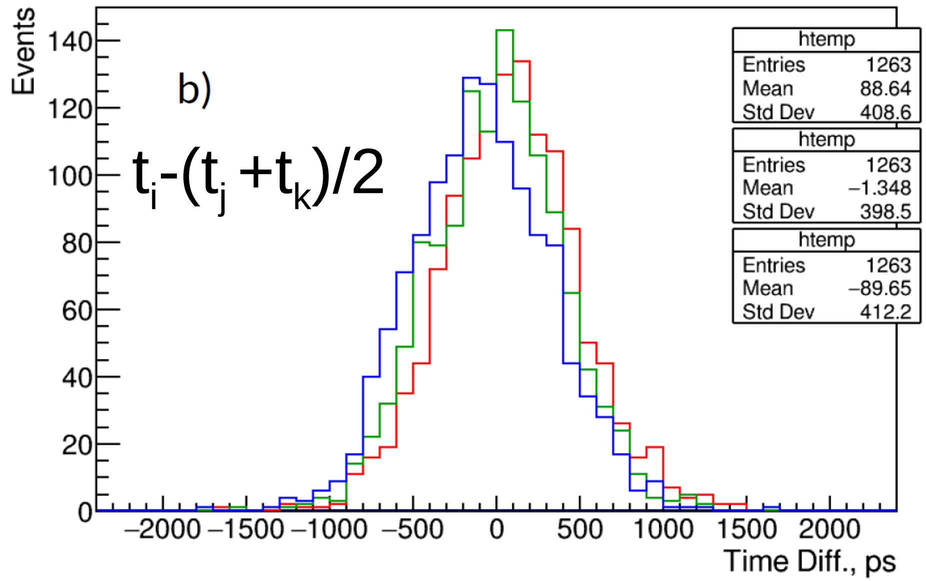


Propagation to calorimeter

- 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

Results

- ZDC calorimeter is a standard device **required** for collider experiment success (tagging, luminosity, local polarimetry)
- ZDCs are installed in **ALL** operating IPs at RHIC and LHC
- The concept of a sampling calorimeter with plastic scintillator and fine segmentation and SiPM readout is very promising
- The test with cosmic muons demonstrated that the time resolution can be reached

Future plans: ZDC

2020: Design and manufacture a new ZDC prototype.

Try neural networks to improve neutron to photon discrimination, energy and space resolutions.

2021: Assemble ZDC prototype and test it with a hadron beam.

Design of the ZDC placement inside the cryostat.

Prepare for the production of ZDC and its electronics.

2022: ZDC and its electronics production.

2023: ZDC tests, development of the software.

2024: Installation in the cryostat and run.

Finance: 2020 + 2021: ~12 M roubles (18 months x 8 people)

ZDC in collider experiments

Outline

0. Introduction:
   - ZDC = neutron,γ detection at $|\eta| \geq 8.5$ (characteristics, status ...).

❶ Accelerator physics [pp, pA, AA]:
   - Luminosity monitoring/calibration, beam-tuning, IP5 crossing angle.

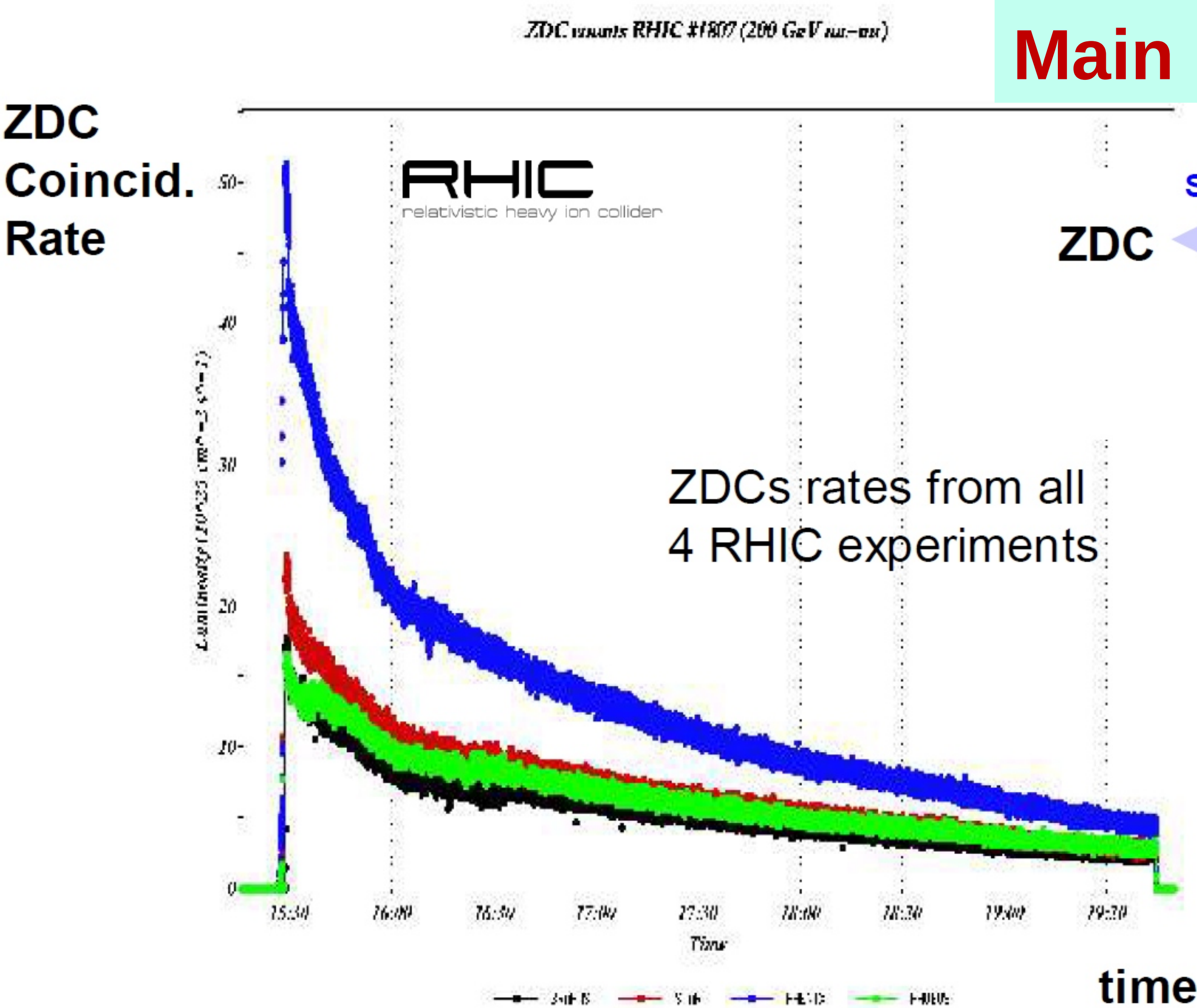
❷ High-energy nuclear physics [pA, AA]:
   - Online: minimum bias trigger, vertex.
   - Global event characterization: centrality, reaction-plane.
   - Absolute luminosity (via EM dissociation).

❸ Diffractive physics [pp, pA, AA]:
   - $I\!P + I\!P$: Tagging of rapidity gaps in central hard diffraction.
   - γ+A: Neutron-tagging of central hard QCD γ-production.
   - $\gamma+\gamma$: Neutron-tagging of QED processes.

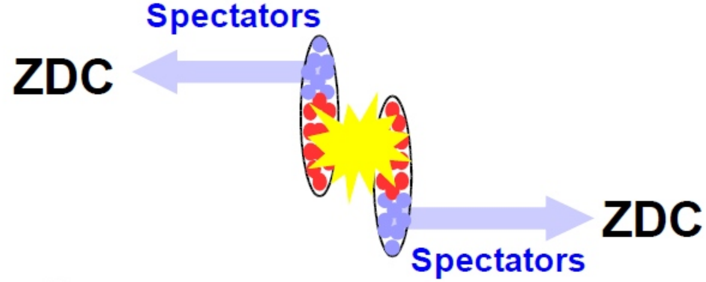
~~❹ UHE cosmic-ray physics [pp, pA, AA]:~~
   ~~- Calibration of >100-PeV forward hadronic cascade development.~~

+ Local polarimetry

Accelerator luminosity monitor



Main monitor at RHIC



- pp and pA and AA
- Collisions tuning
- Flattop history
- Vernier scans – beam size at IP measurements
- Beam crossing angle measurements

AA and pA min. bias. trigger and centrality

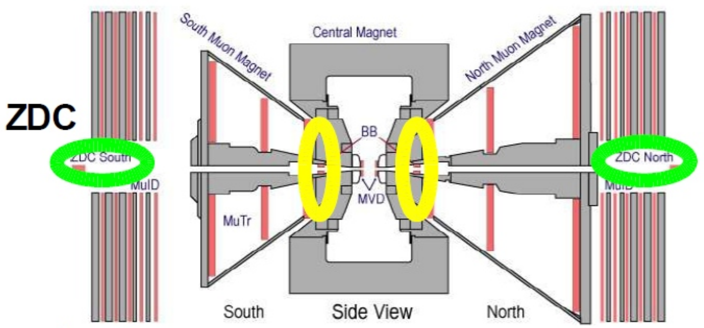
- Basic min. bias AA,pA trigger at RHIC:

  BBC ($3 < |\eta| < 4$) && ZDC ($|\theta| < 2$ mrad)

  [also vertex: $z = c \cdot (t_{left} - t_{right})$]

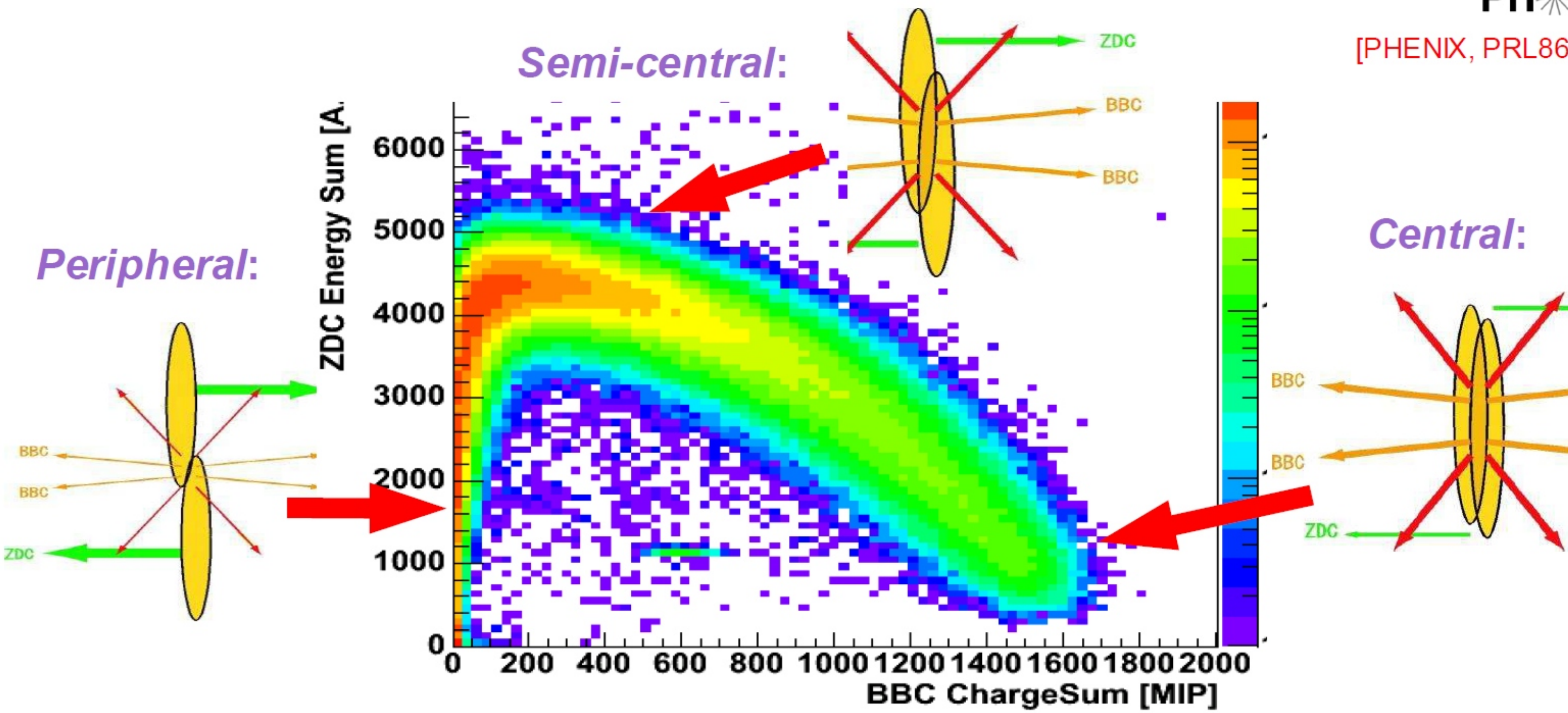
- Impact-parameter (b) determination:

  Directly related to max. energy density reached



PHENIX

[PHENIX, PRL86 (00) 3500]



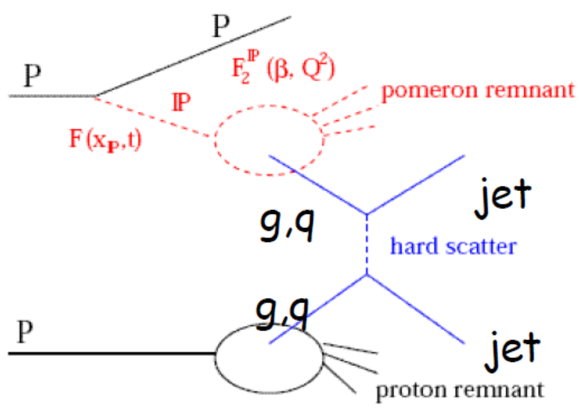
+ Event by event reaction plane determination

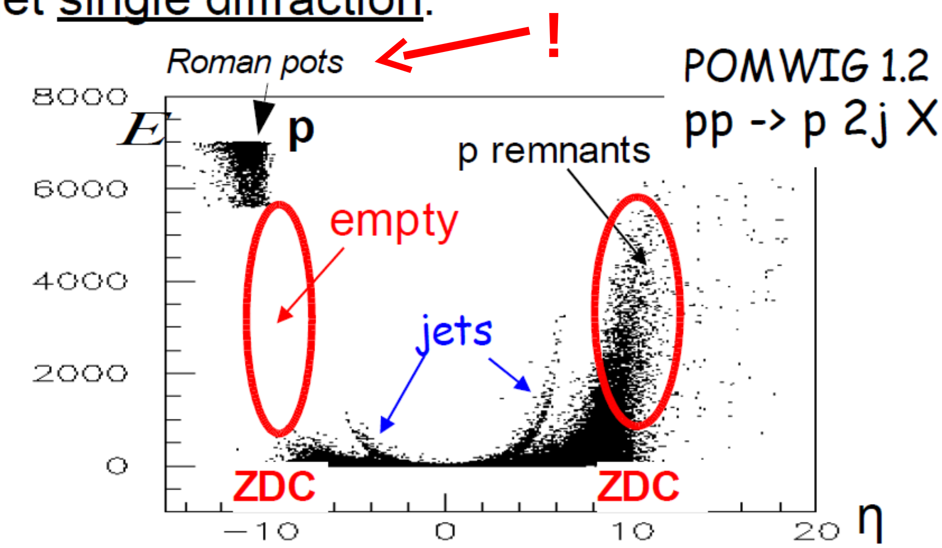
+ Absolute luminosity in Electromagnetic dissociation

AA and pA min. bias. trigger and centrality

- No ZDC activity = large rapidity gap. Complements (trigger & offline) leading proton detectors e.g. in dijet single diffraction:

[from A.Sobol CMS, Feb'06]

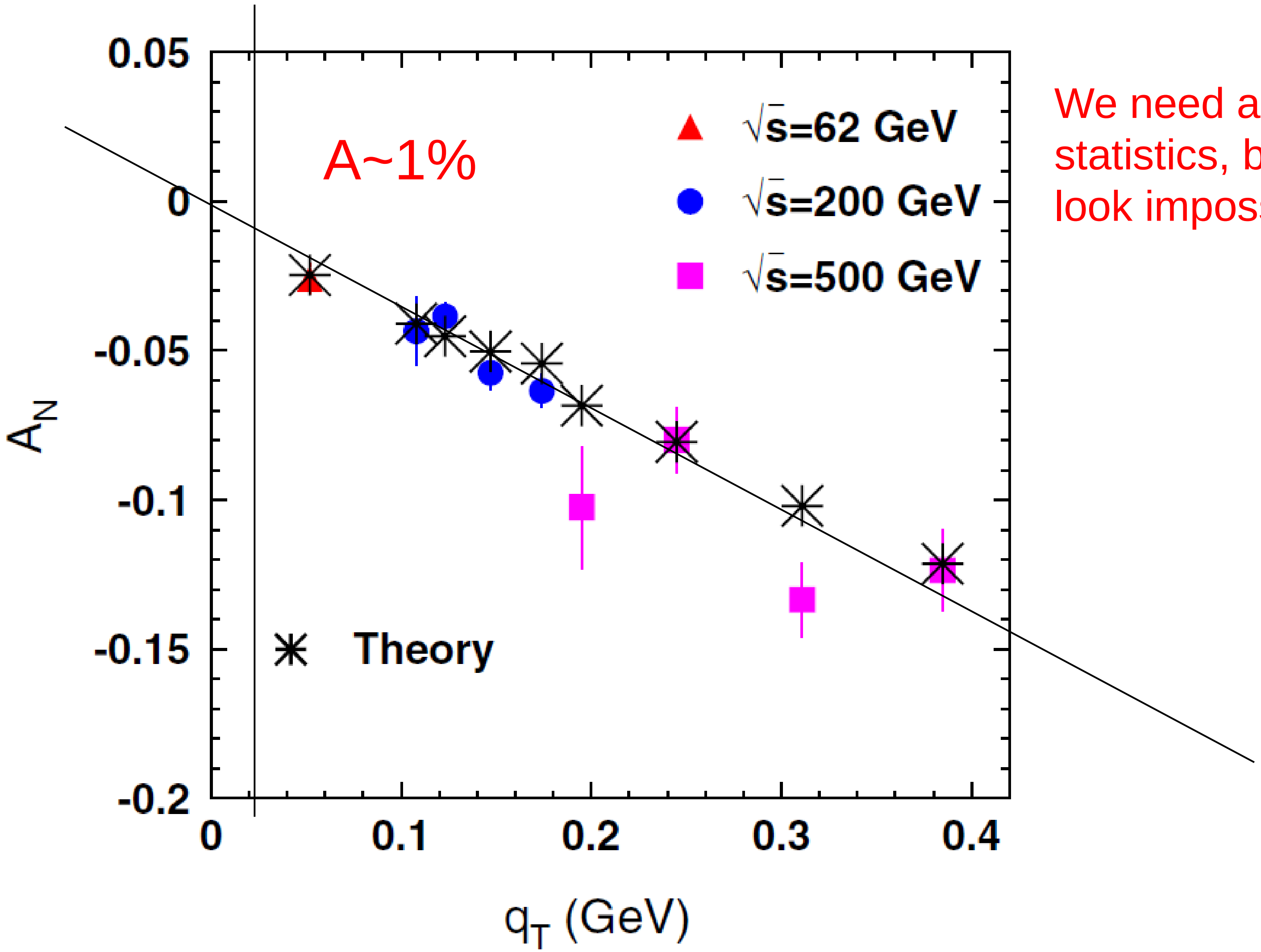




- Bottom line: ZDC reduces to “zero” holes & cracks in CMS (full 4π). Helps all diffractive ($I\!P$-, γ-mediated) analysis in pp,pA,AA.

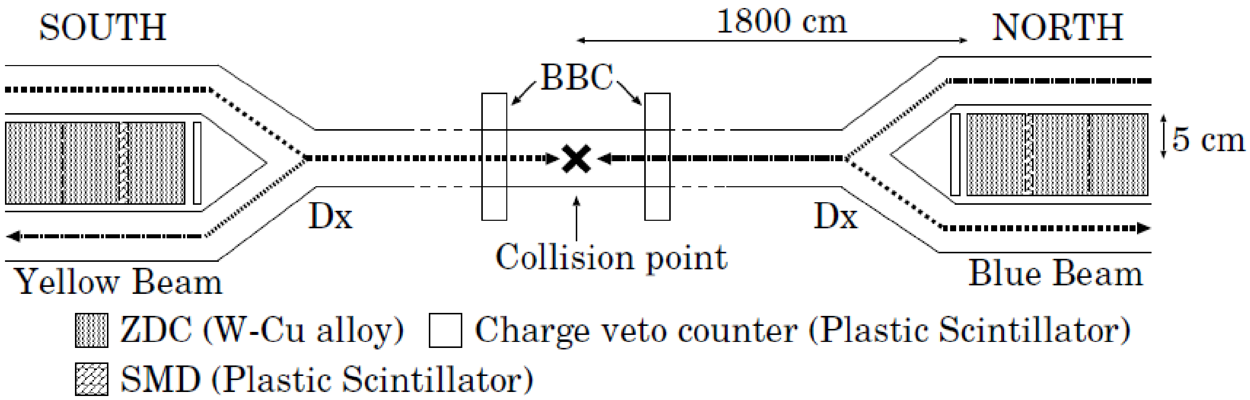
- All UPC measurements at RHIC: ZDC-triggered (neutron tagging) !

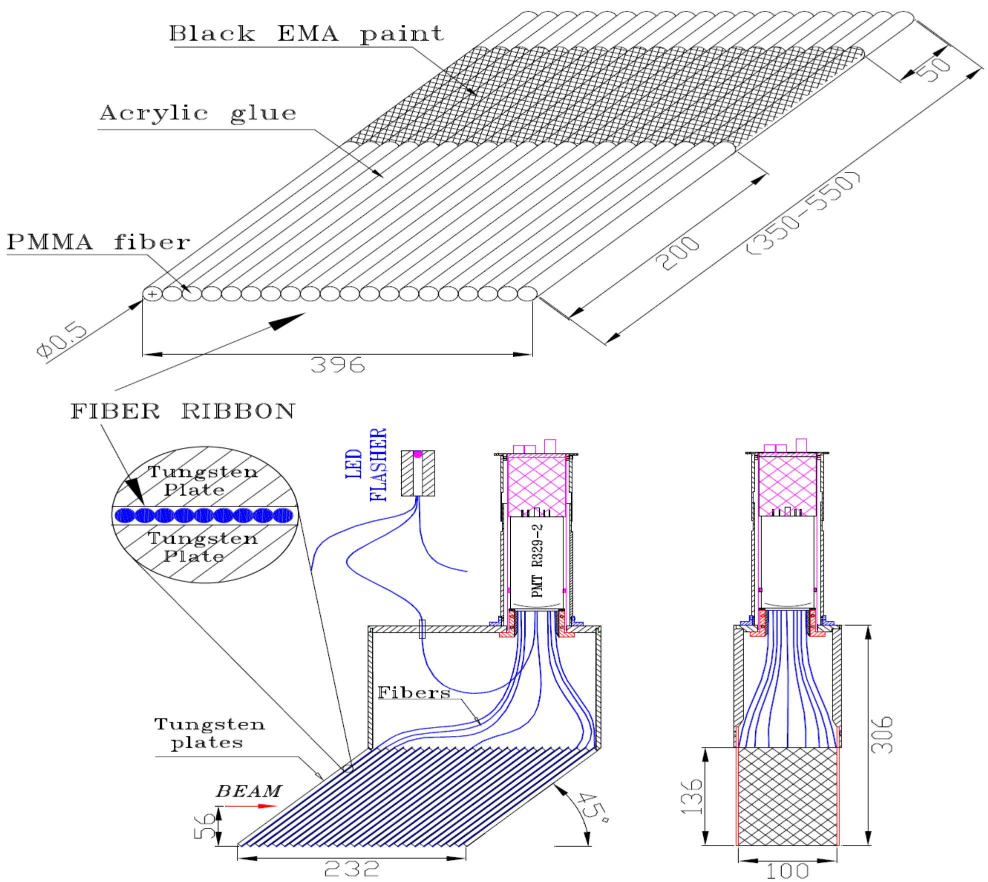
Local polarimetry



We need a huge statistics, but it does not look impossible

The technology





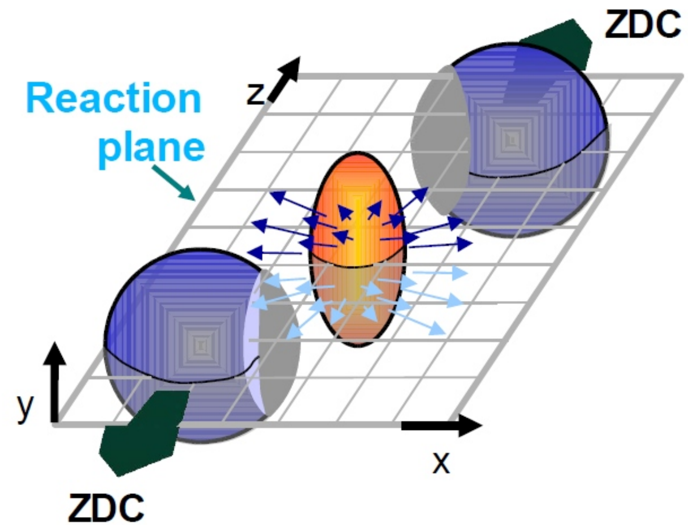
ZDC: sampling Cerenkov calorimeter

~1 ph.e./GeV

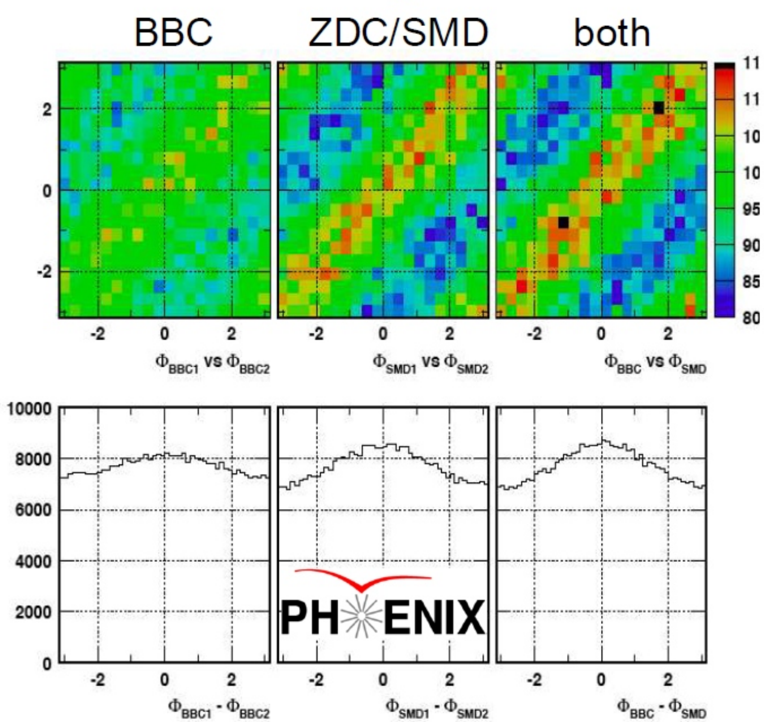
$$\frac{\Delta E}{E} = \frac{65\%}{\sqrt{E\ (\mathrm{GeV})}} + 15\%$$

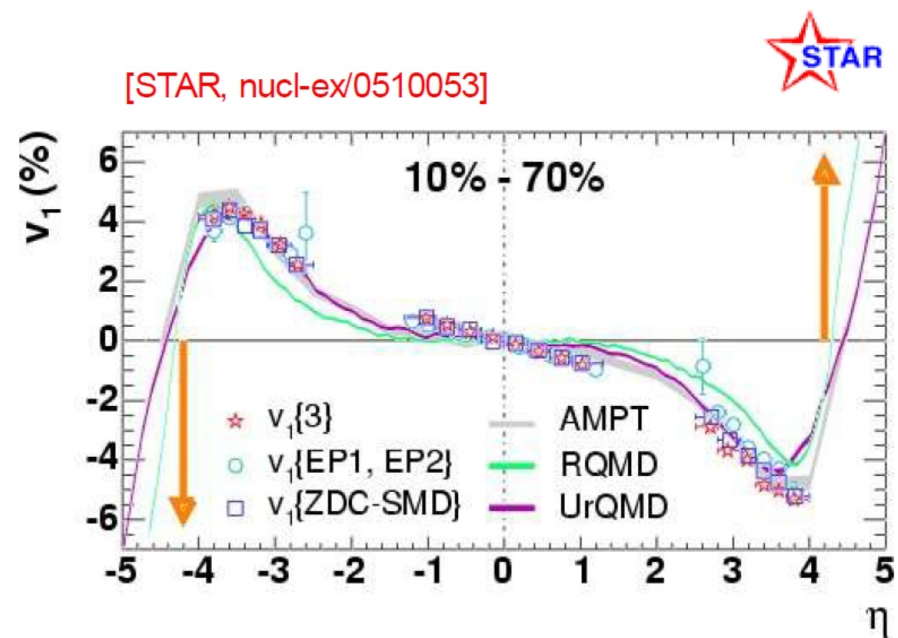
(2.2) AA reaction-plane determination

- Event-by-event reaction plane obtained from sidewards deflection of spectator neutrons ("bounce-off"):
- Elliptic flow directly related to initial parton pressure.



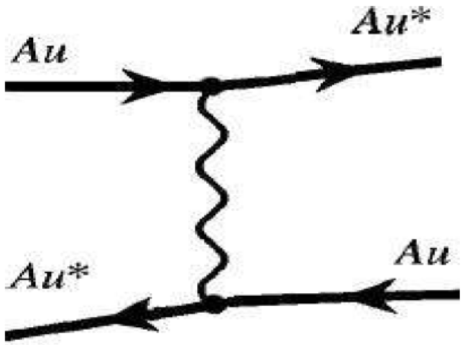
Directed flow v1 is largest at ZDC location:





(2.3) pA, AA absolute luminosity

- Reference process: Electromagnetic dissociation (plus forw./back. neutron emission) computable within ~5%:



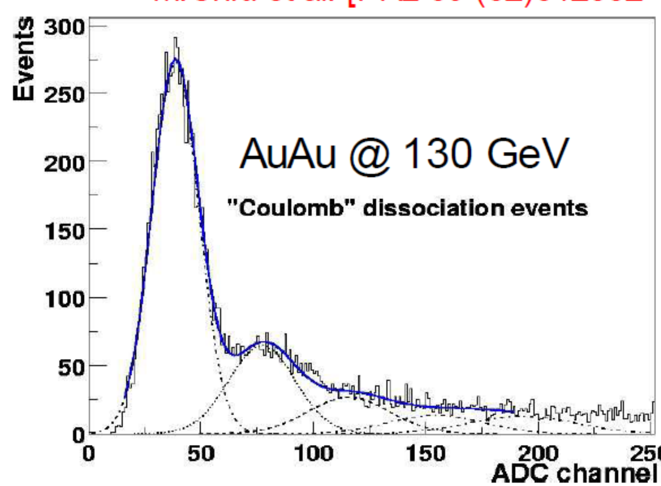
		RHIC	LHC
Hadronic:	AuAu → X	6.8 barns	8 barns
EM:	AuAu → AuAu + e^+e^-	33 kbarns	
	AuAu → AuAu + 2(e^+e^-)	680 barns	
	AuAu → Au+Au* ↳ X+neutrons	92 barns	220 barns
	AuAu → Au*+Au* ↳ X+neutrons, Y+neutrons	3.67±0.26 b	~6.7 barns

AuAu: Baltz&White [NIMA 417 (98) 1]
dAu: Klein&Vogt [PRC 68 (03) 017902]

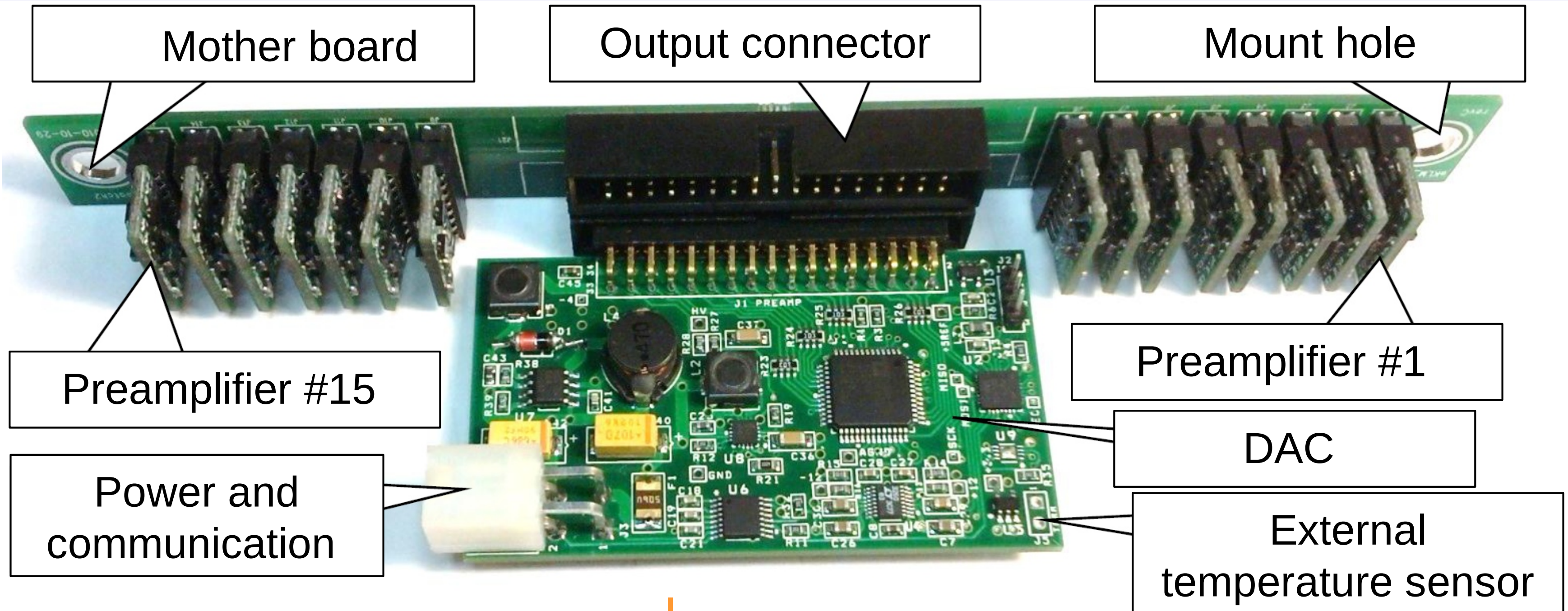
TABLE I. Ratios of cross sections for experiment and theory. The values of σ_{tot} and σ_{geom} are in barns.

σ_i	PHENIX	PHOBOS	BRAHMS	[3]	[4]
σ_{tot}	...	...	...	10.8 ± 0.5	11.2
σ_{geom}	...	...	...	7.1	7.3
$\frac{\sigma_{geom}}{\sigma_{tot}}$	0.661 ± 0.014	0.658 ± 0.028	0.68 ± 0.06	0.67	0.659
$\frac{\sigma(1,X)}{\sigma_{tot}}$	0.117 ± 0.004	0.123 ± 0.011	0.121 ± 0.009	0.125	0.139
$\frac{\sigma(1,1)}{\sigma(1,X)}$	0.345 ± 0.012	0.341 ± 0.015	0.36 ± 0.02	0.329	...
$\frac{\sigma(2,X)}{\sigma(1,X)}$	0.345 ± 0.014	0.337 ± 0.015	0.35 ± 0.03	...	0.327
$\frac{\sigma(1,1)}{\sigma_{tot}}$	0.040 ± 0.002	0.042 ± 0.003	0.044 ± 0.004	0.041 ± 0.002	...

M.Chiu et al. [PRL 89 (02)012302



SiPM bias and preamplifiers



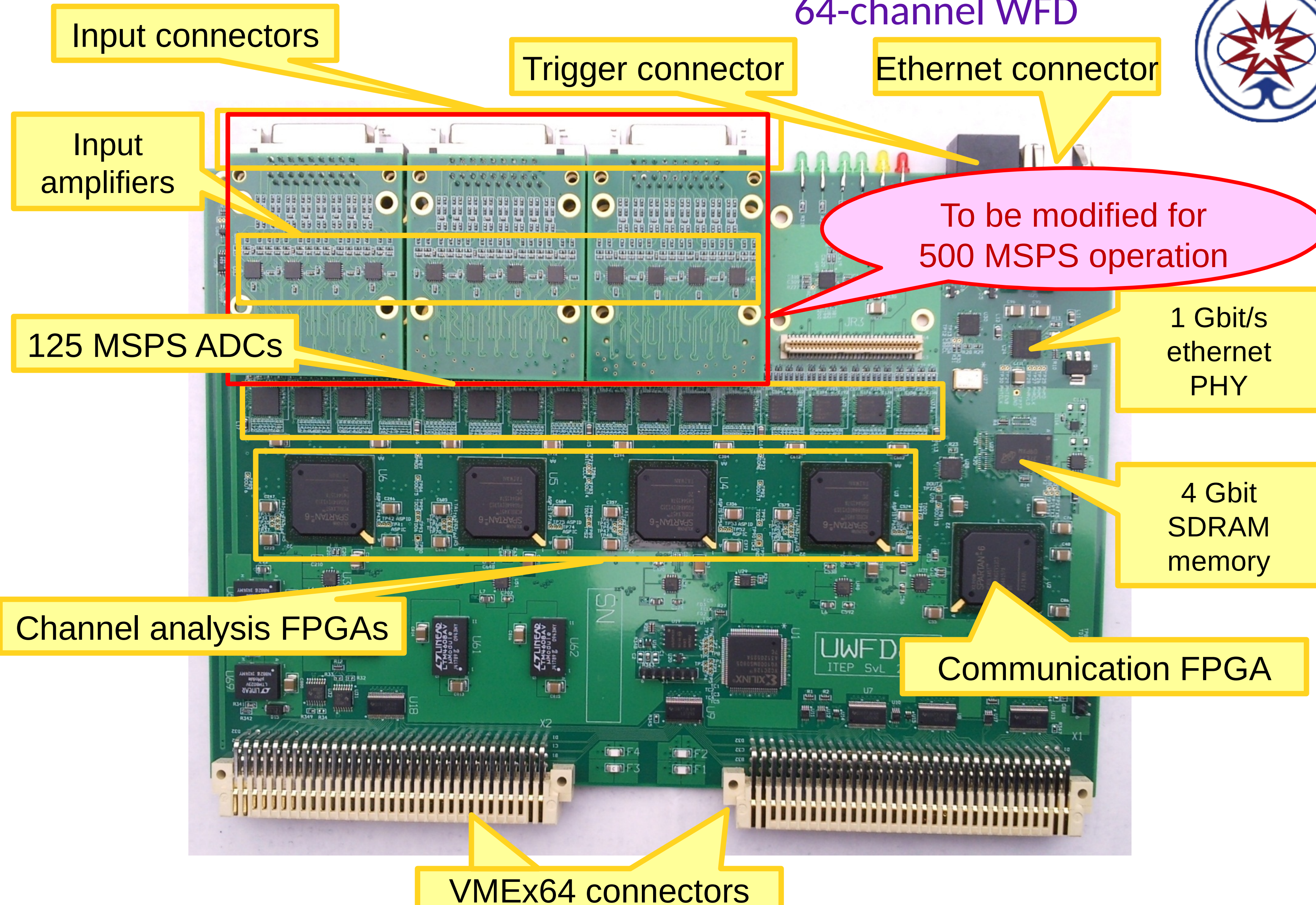
The mother board (18x180 мм²) hosts:

- 15 preamplifiers
- Power and bias board
- Output connector

The power and bias board provides:

- Power for preamplifiers and its control
- Common cathode voltage for SiPMs, its precise setting and measurement in the range 10-65 V
- Setting and monitoring of the individual anode voltages in the range ±10V
- Readout of common bias current
- Readout of the external temperature sensor as well as onboard CPU and DAC temperatures

64-channel WFD



Igor Alekseev (ITEP)

- 64 channels of 125 MSPS 12 bit flash ADCs
  - 16 channels of 500 MSPS
- VME 64x standard 6U single slot width board
- 64-bit block transfer support
- Xilinx Spartan-6 FPGAs for digital signal processing and communication
- 4 Gbit of SDRAM for data storage
- 1 Gbit Ethernet connection for faster readout
- Multitrigger and triggerless operation
- Base line subtraction and zero suppression for wave form storage
- Selftrigger with prescale for SiPM noise measurements
- Internal or external clock operation
- Deadtimeless operation

Instruments and Experimental Techniques, 2018, Vol. 61, No. 3, pp. 349–354.

Performance at DANSS