The very forward hadron calorimeter PSD for the future CBM@FAIR experiment

Vasily Mikhaylov

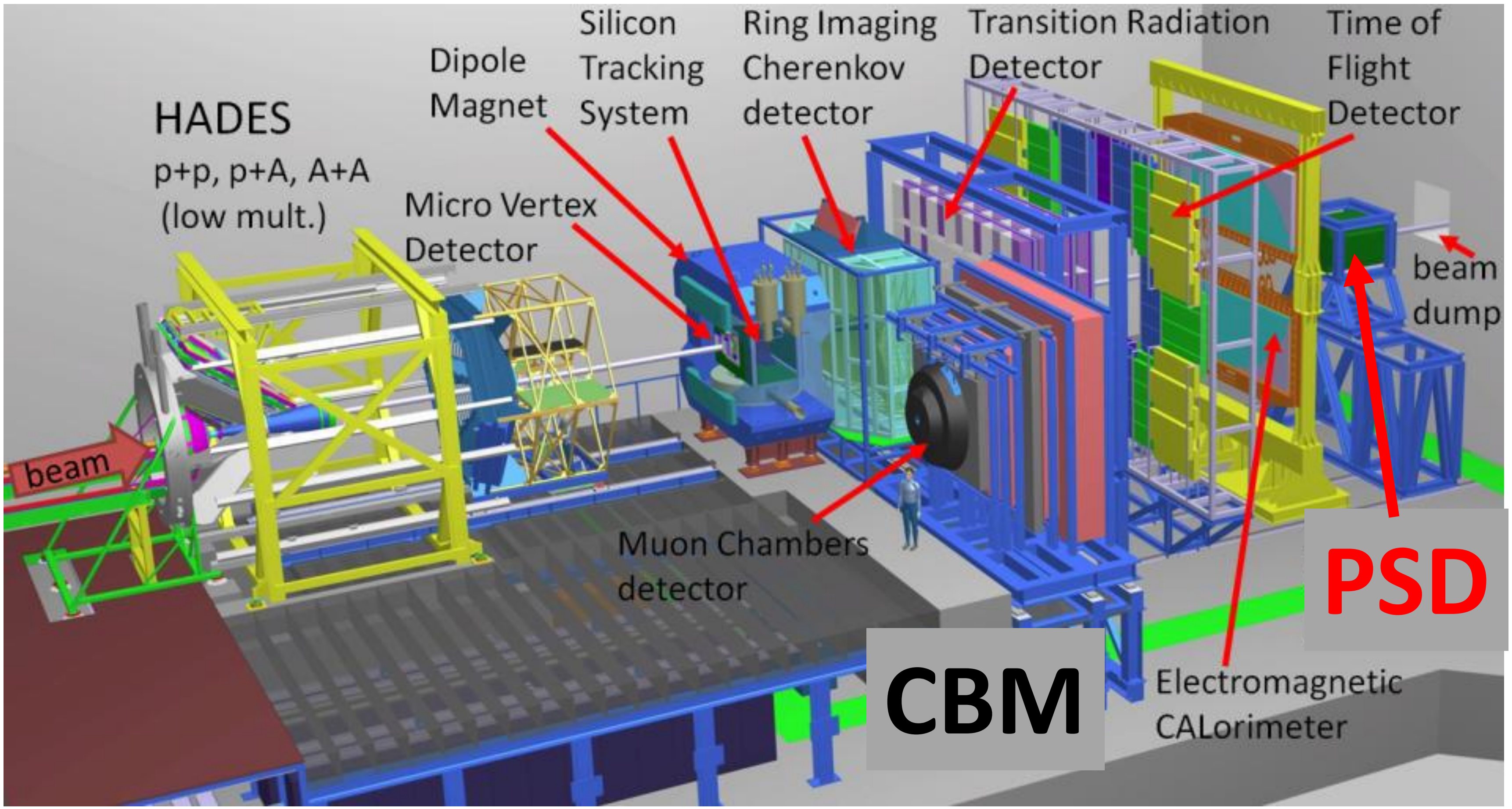
for the CBM Collaboration

Nuclear Physics Institute of the Czech Academy of Sciences

EUROPEAN UNION
European Structural and Investment Funds
Operational Programme Research,
Development and Education

MINISTRY OF EDUCATION,
YOUTH AND SPORTS

Compressed Baryonic Matter (CBM) experiment



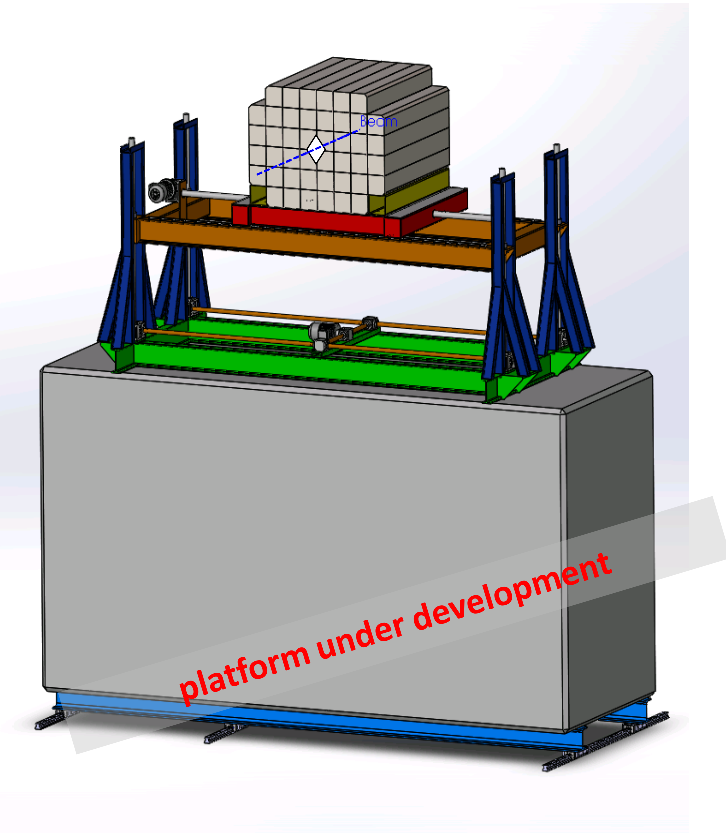
Projectile Spectator Detector (PSD)

Principle: detection of forward going projectile nucleons and nuclei fragments (spectators) produced close to the beam rapidity in nucleus-nucleus collisions

Purpose: measurement of the reaction centrality and reconstruction of the reaction plane

Features:

- compensating calorimeter with lead/scintillator sampling ratio 4:1
  good energy resolution ~55%/√E
- high transverse granularity by 44 modules
  transverse homogeneity of energy resolution, reaction plane measurements
- longitudinal segmentation of 10 sections per module
  longitudinal shower profile measurement, calibration
- light readout from a section through WLS fibers by photodiodes
  large dynamic range, no nuclear counting effect
- New design with a 20x20 cm^2 beam hole in the center
  drastic reduction of radiation damage from
- ability to operate at high collision rates up to 1MHz
- total 22 tons of weight on a platform movable in 3 dimensions



Similar calorimeter already operates at NA61@CERN, and another one called Zero Degree Calorimeter (ZDC) is being prepared for BM@N at NICA.

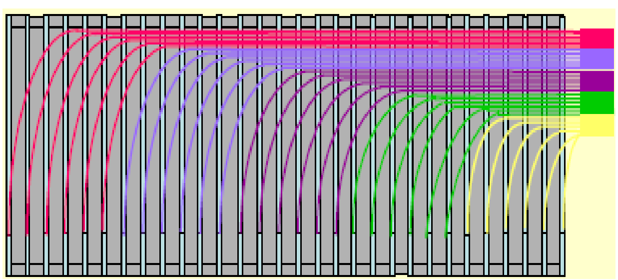
CBM PSD module design

Module properties:

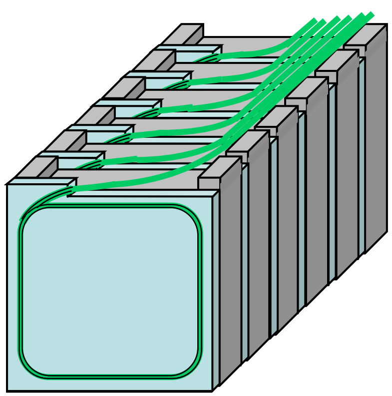
- 60 lead+scintillator plates in one module
- 1 section = 6 scintillator plates
- size = 20 x 20 x 120 cm^3
- depth ~ 5.6 hadron interaction lengths λ_{int}

  optimized for beam energy range of 2 – 35 GeV

TOP View



FRONT View

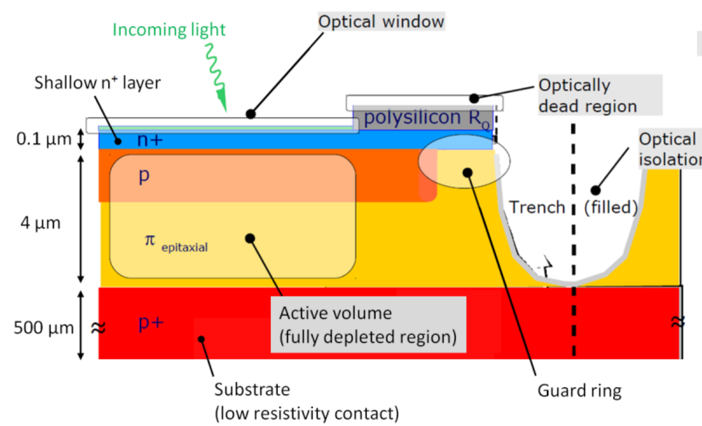


Light from each consecutive 6 layers is collected together via WLS-fibers and read-out by a single Hamamatsu Multi-Pixel Photon Counter (MPPC)

MPPC S12572-010P properties:

- size: 3x3 mm^2
- large dynamical range: 90000 pixels
- photon detection efficiency: ~10%
- high counting rate: ~1 MHz
- requirement: radiation hardness to neutrons

  ~2×10^{11} n_{eq}/cm^2 for CBM



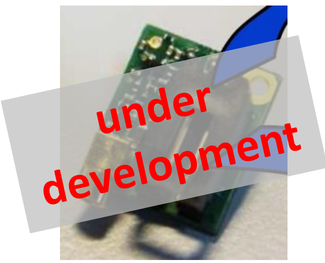
Typical MPPC structure

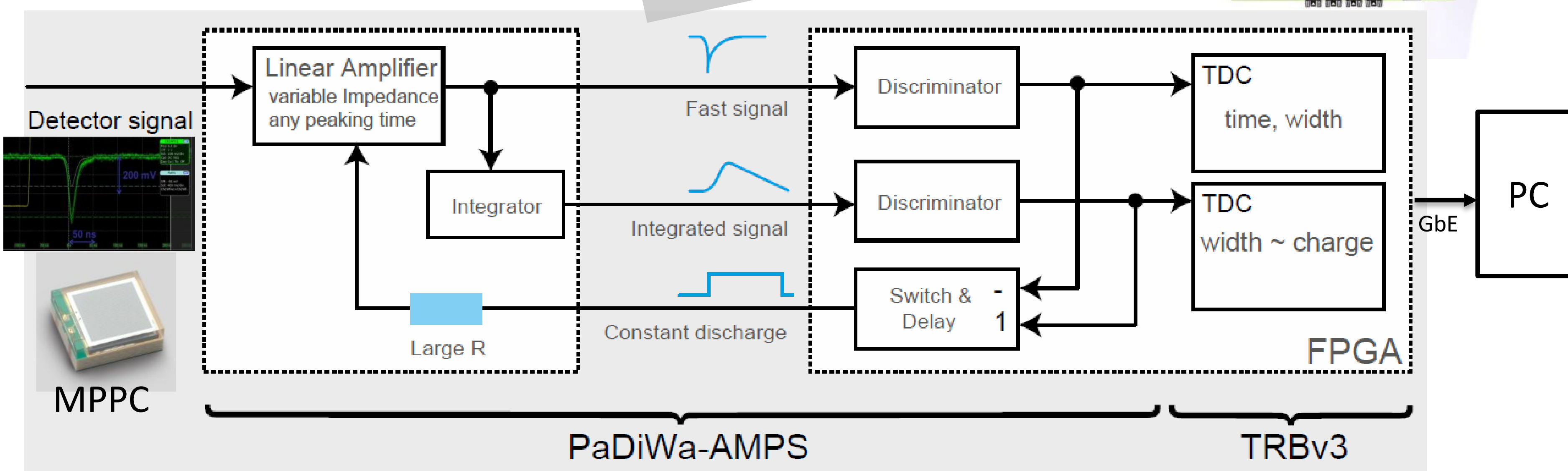
CBM PSD readout electronics

Preamplifier
- Attached to photodiode
- Optimized for
high capacitance inputs
- Gain ~ 60 V / V
- Good Signal / Noise

PaDiWa-AMPS (GSI)
- Method: Time-Over-Threshold (ToT)
- 8 MMCX input channels
- Time precision: < 50 ps
- Rel. charge resolution: < 0.5 %
- Dynamic range: 250 – 500
- Compact data : max. 50 MB/s

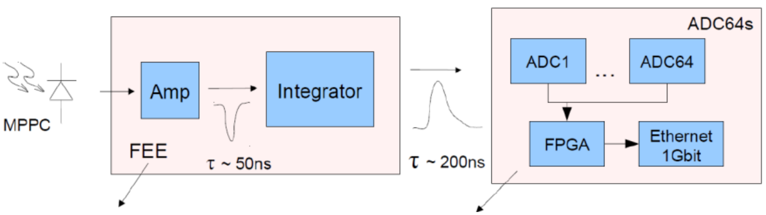
TRBv3 Trigger and Readout Board
- 4 FPGAs, 264 TDC channels
- Single edge & ToT measurement
- Time precision < 20 ps
- 50 MHz hit rate per channel
- Fast data transfer via gigabit Ethernet
- Internal trigger and slow control



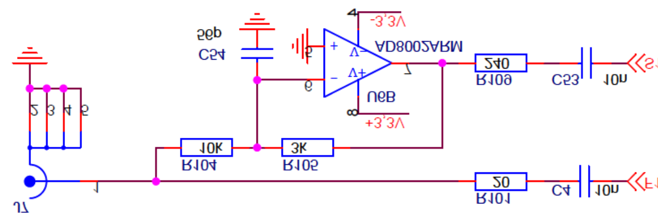


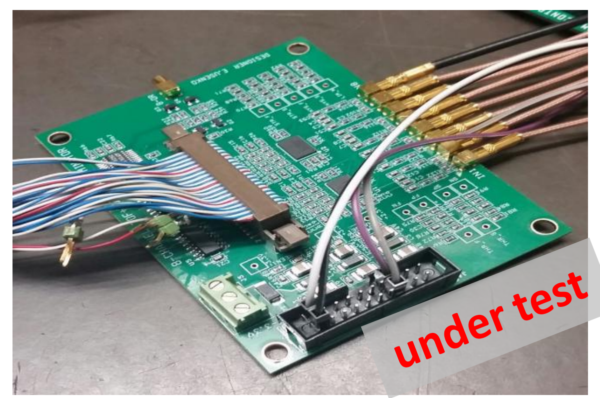
CBM PSD: Alternative readouts

ADC64s/ADC125s electronics (AFI, JINR, Dubna)
- Method: direct waveform digitization
- 64 channels, 12 bit ADCs
- Speed: 62.5/125 MS/s
- Dynamic range: ~150
- Up to 100 kHz real event rate
- Huge amount of data
- DSP is required on top



Time-Over-Threshold (ToT) board
- Method: Time-Over-Threshold (ToT)
- 8 MMCX input channels
- NINO chip based design
- Dynamic range: ~ 250
- Compact data: max. 50 MB/s
- Coupled to TRB3



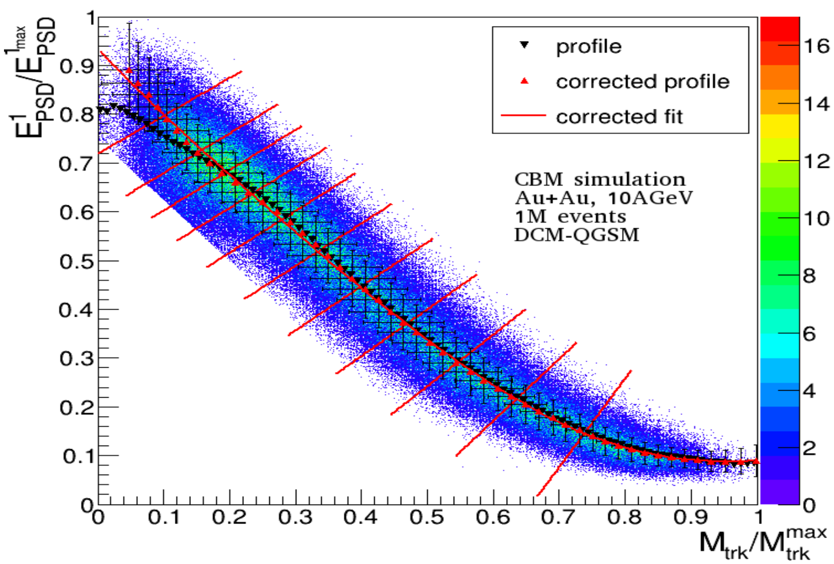


Centrality measurement in CBM

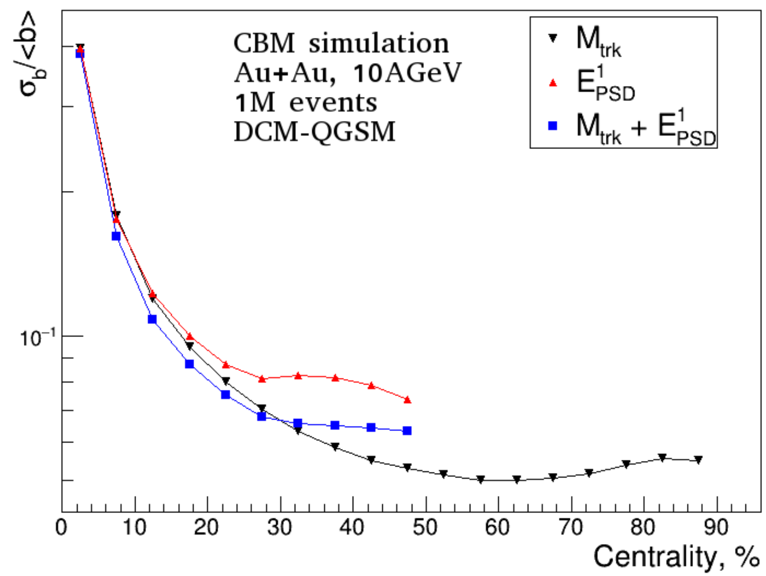
Particle multiplicities around midrapidity
measured by Silicon Tracking System

Energy measured at forward rapidity
measured by PSD calorimeter

Two independent ways to measure centrality.
STS generally performs better but can be improved by correlation with PSD by up to 10% for central events



The correlation between the energy deposited in the four central PSD modules (E^1_{PSD}) and the track multiplicity M_{trk} with cuts



Impact parameter resolution

Reaction plane reconstruction in CBM

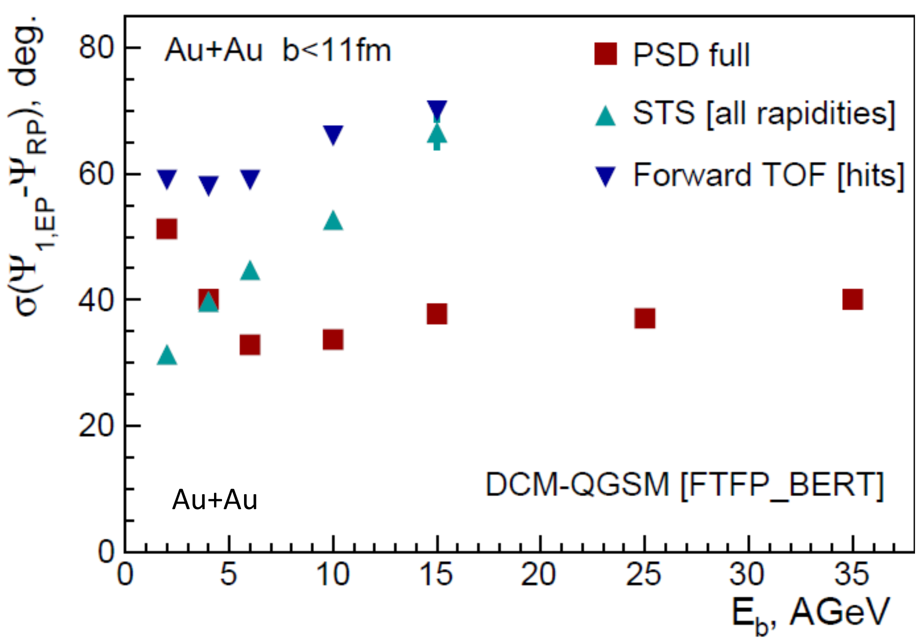
Particle hits around midrapidity
measured by Silicon Tracking System

Particle hits at forward rapidity
measured by Forward TOF

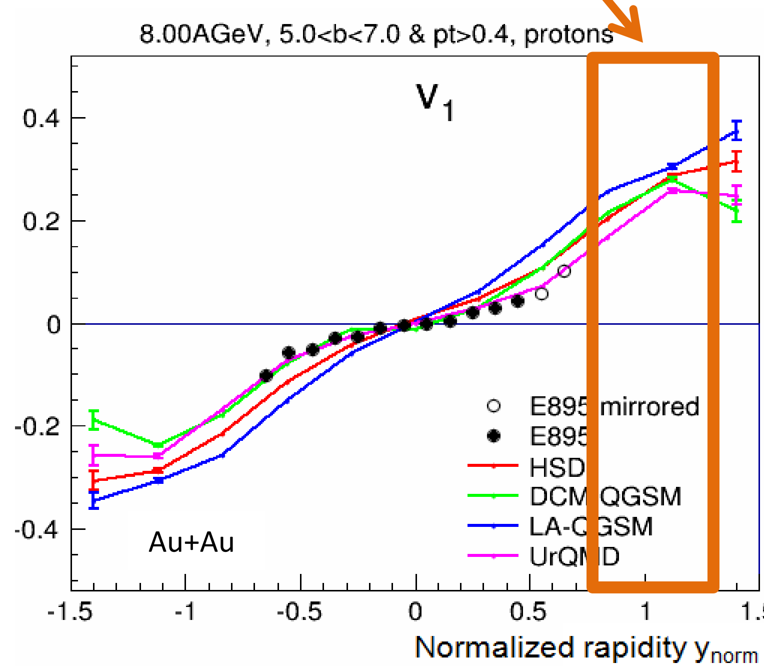
Energy measured at forward rapidity
measured by PSD calorimeter

The best for beam energies > 4 AGeV due to

- *sensitivity to neutral particles and fragments*
- *much stronger flow at forward rapidity*



Reaction plane resolution measured by PSD, STS, and forward TOF



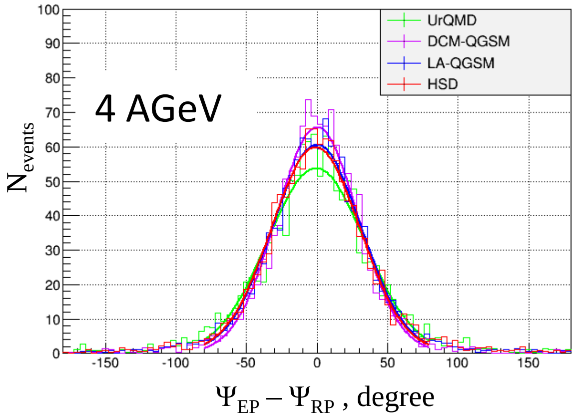
Directed flow v_1 for different collision models

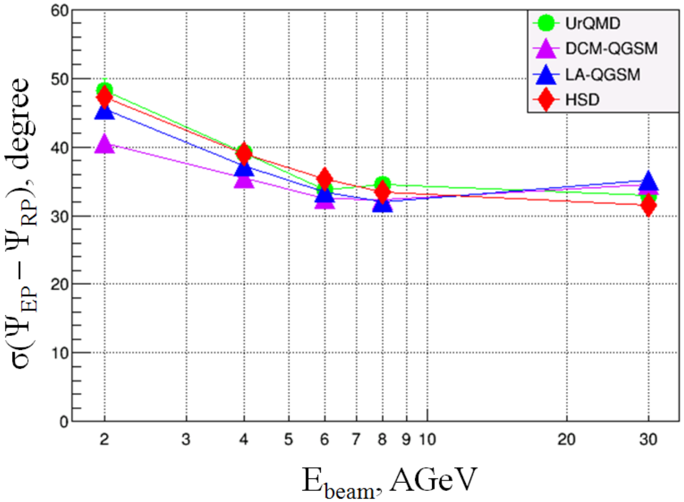
PSD reaction plane resolution for four heavy-ion collision models

Does not differ much for different models

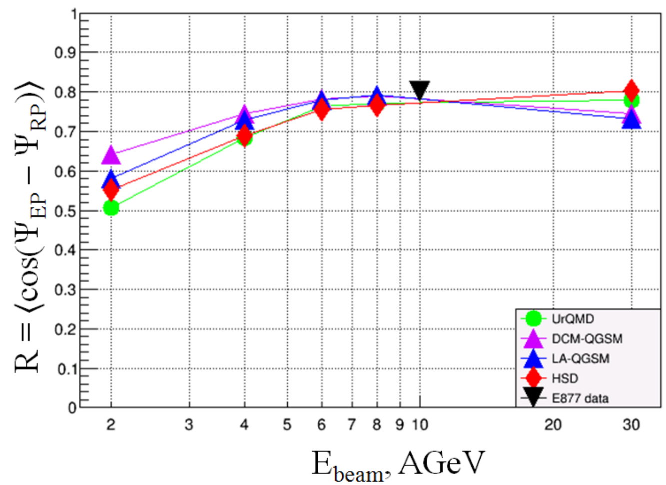
even though they have very different flow

Why?





Reaction plane resolution

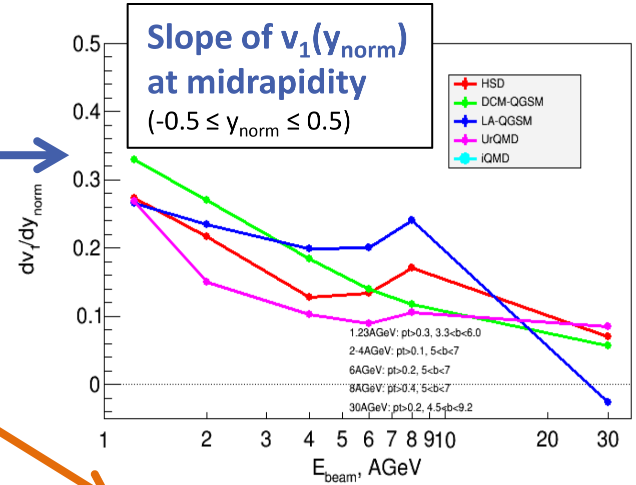


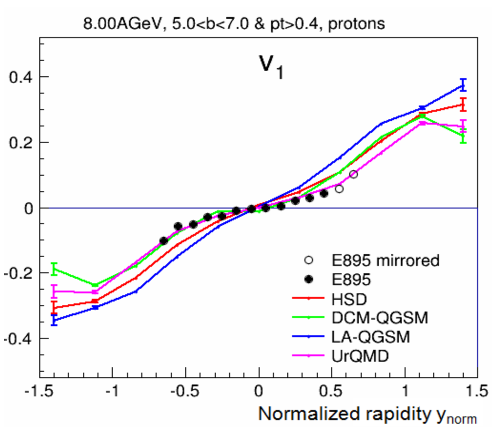
Reaction plane resolution correction factor

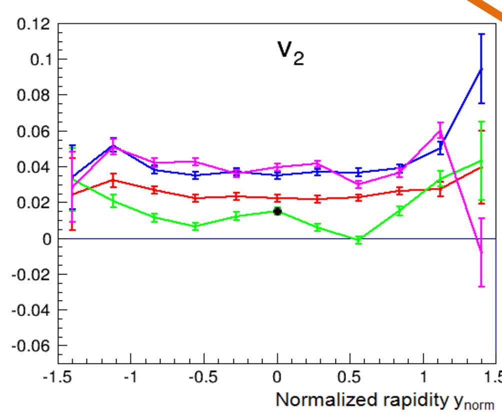
PSD reaction plane resolution for four heavy-ion collision models

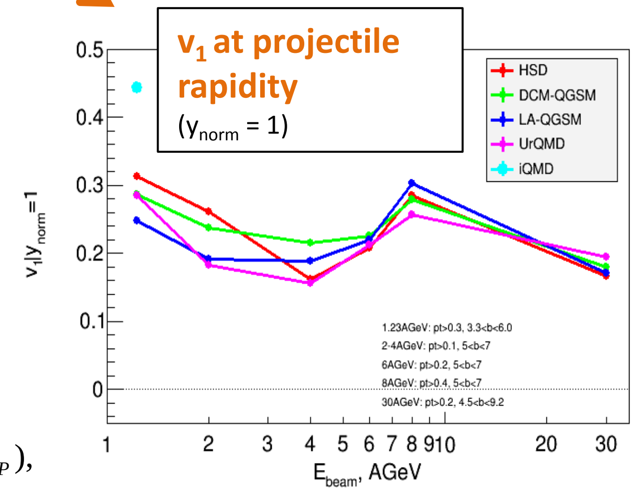
Because

directed flow is much more different at midrapidity then at forward (projectile) rapidity









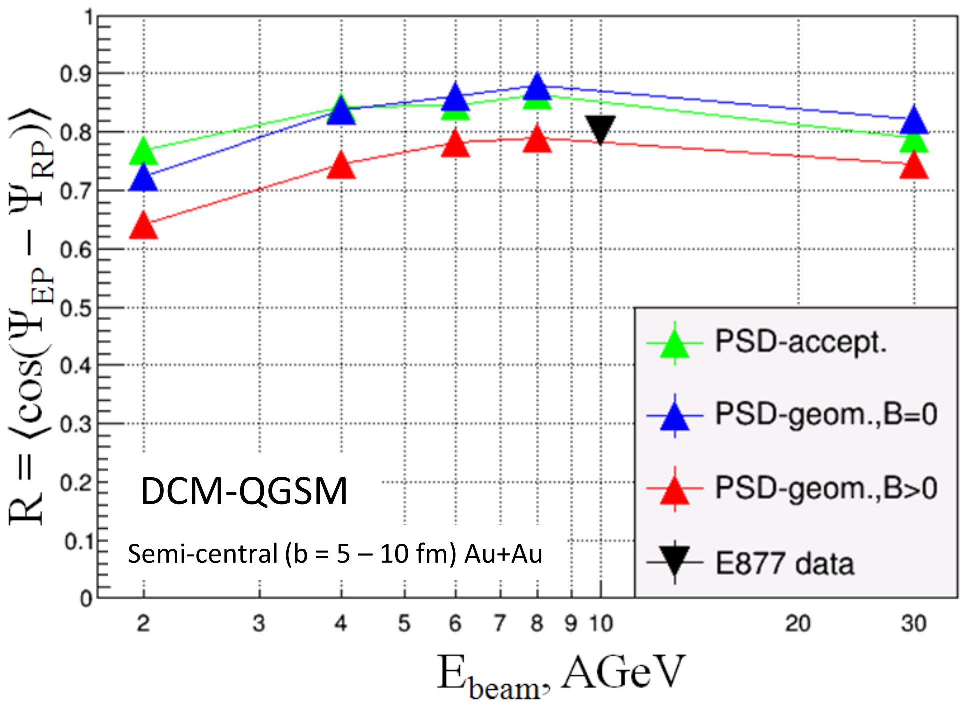
Directed flow $v_1 = \langle \cos(\varphi - \Psi_{RP}) \rangle$

Elliptic flow $v_2 = \langle \cos(2(\varphi - \Psi_{RP})) \rangle$

In non-central collisions flow of particles is usually described by Fourier decomposition with respect to reaction plane:

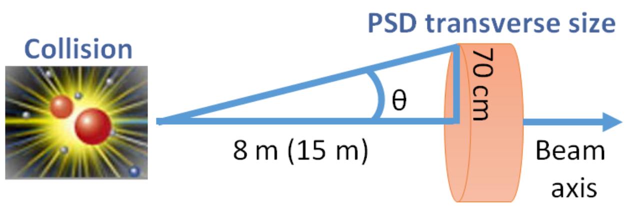
$$\frac{dN}{d\varphi} \sim 1 + 2\sum_n v_n \cos n(\varphi - \Psi_{RP}),$$

PSD reaction plane resolution design

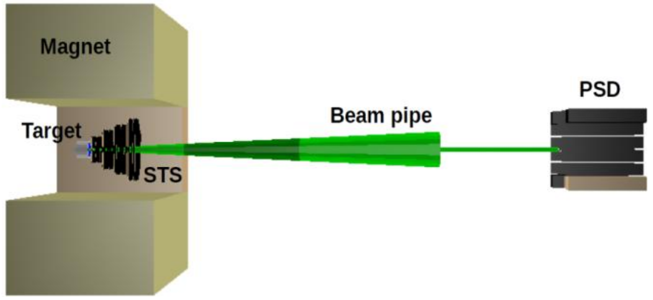


Reaction plane resolution correction factor

PSD-accept.: *Reconstruction by MC-tracks with PSD acceptance (ϑ-angle)*



PSD-geom., B=0: *Reconstruction with PSD geometry*
PSD-geom., B>0: *Reconstruction with PSD geometry and magnetic field*



- *Granularity is well chosen and produces almost no bias*
- *Magnetic field produces relatively small bias below 10%*

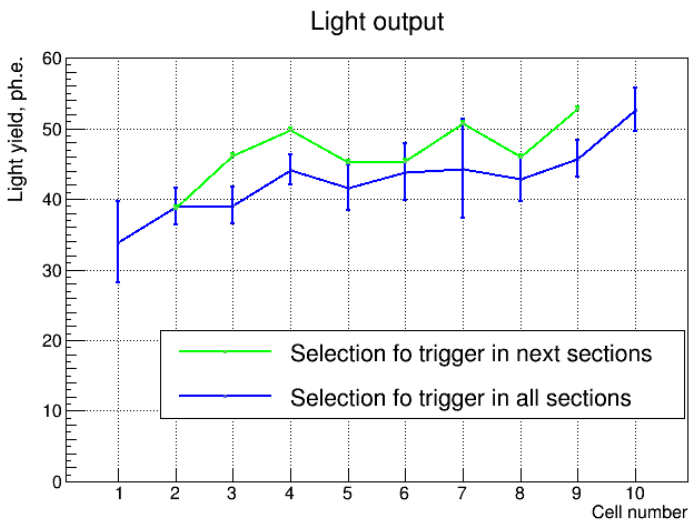
CBM PSD supermodule

Array of 3x3 calorimeter modules
was assembled for the beam tests at CERN in 2017-2018

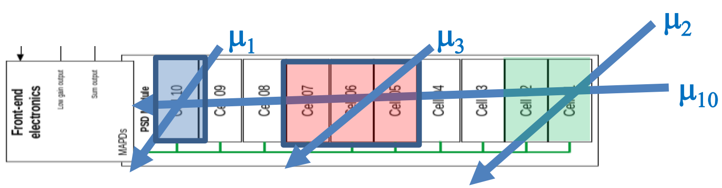
CBM PSD supermodule at T9 CERN beamline

All 44+1 modules for PSD
are already assembled at INR

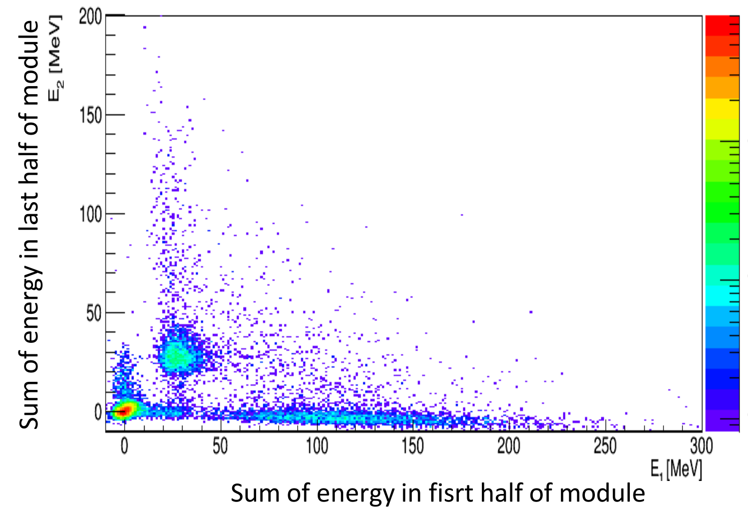
PSD supermodule quality assessment by cosmic muons



Light yield of each of 10 individual sections in module was measured by cosmic muons



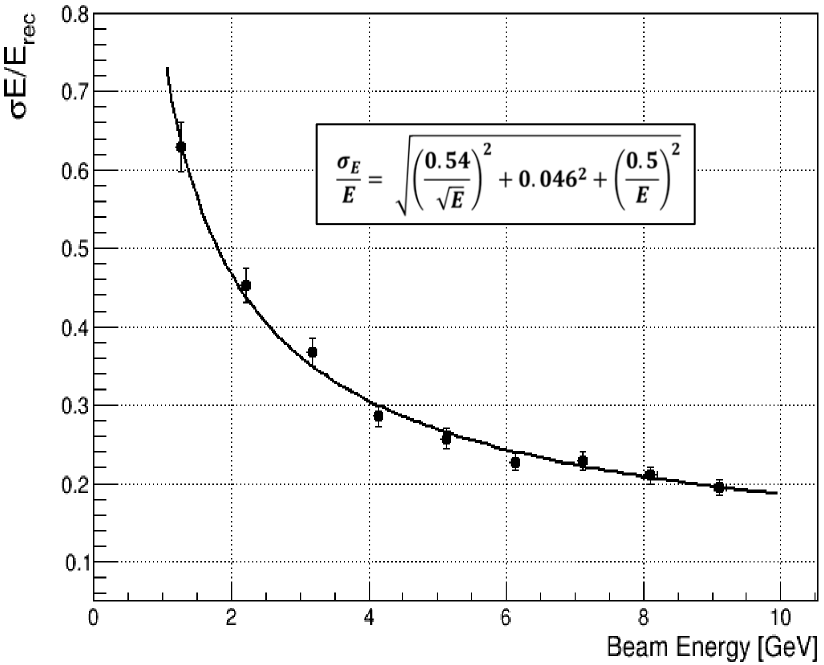
Measurement with horizontal and inclined tracks



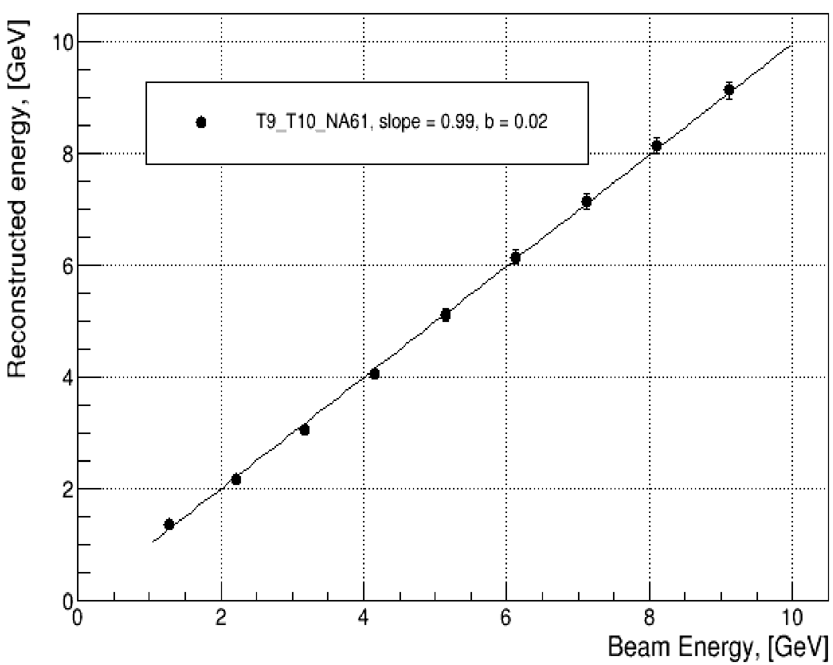
Identification of muons:

equal energy deposition in first and last halves of module

PSD supermodule at CERN



Supermodule energy resolution

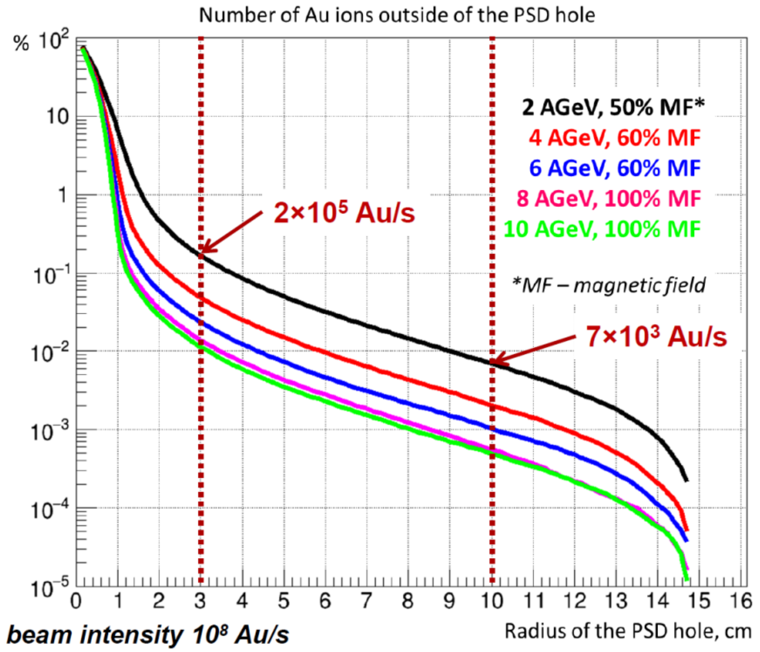


Supermodule energy linearity

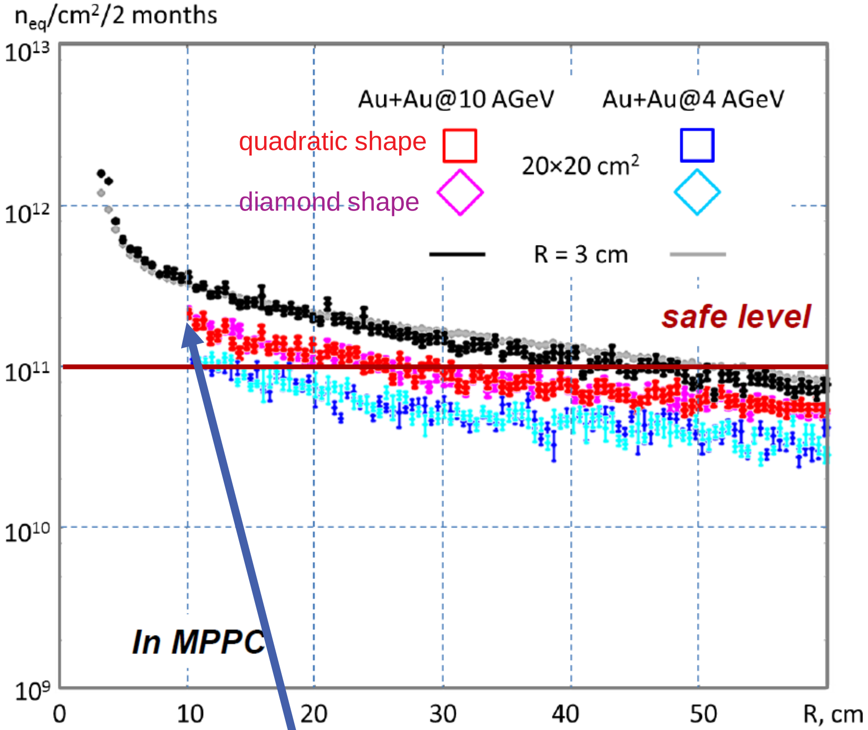
Supermodule performance was successfully tested at CERN T9 and T10 beamlines

CBM PSD radiation conditions

Enlarged beam hole 6x6 cm^2 -> 20x20 cm^2 significantly reduces the radiation damage



up to 30 times less ions hitting the calorimeter

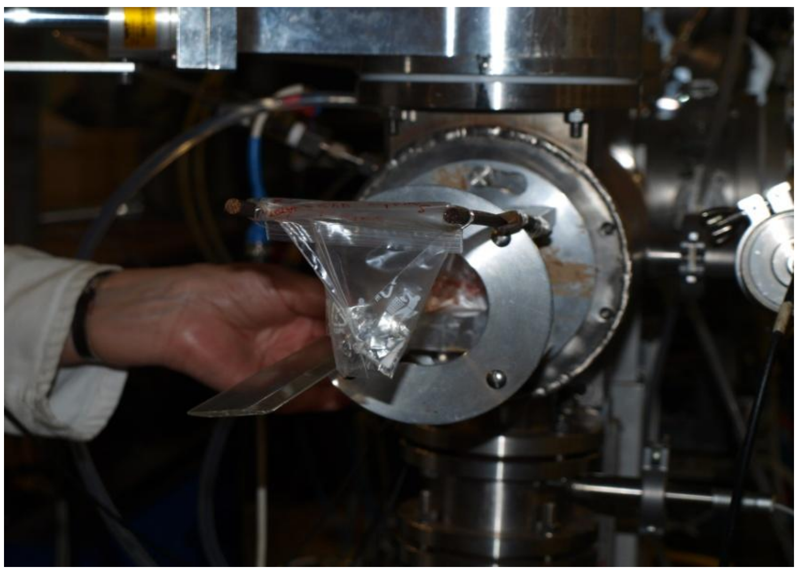


up to $2x10^{11}$ $neutrons_{eq}/cm^2$ for SiPMs located 10 cm close to the beam center

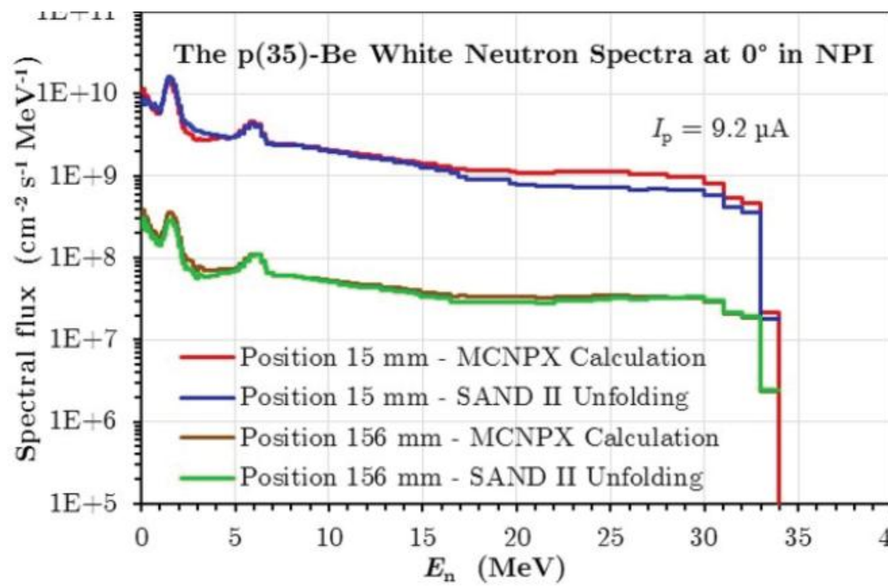
Neutron irradiation of MPPCs at NPI U-120M cyclotron

- ✓ Hamamatsu S12572-010P MPPCs were irradiated by total fluence in wide range from 6×10^{10} up to 9×10^{12} n_{eq}/cm^2

SiPMs placed at Cyclotron beam line

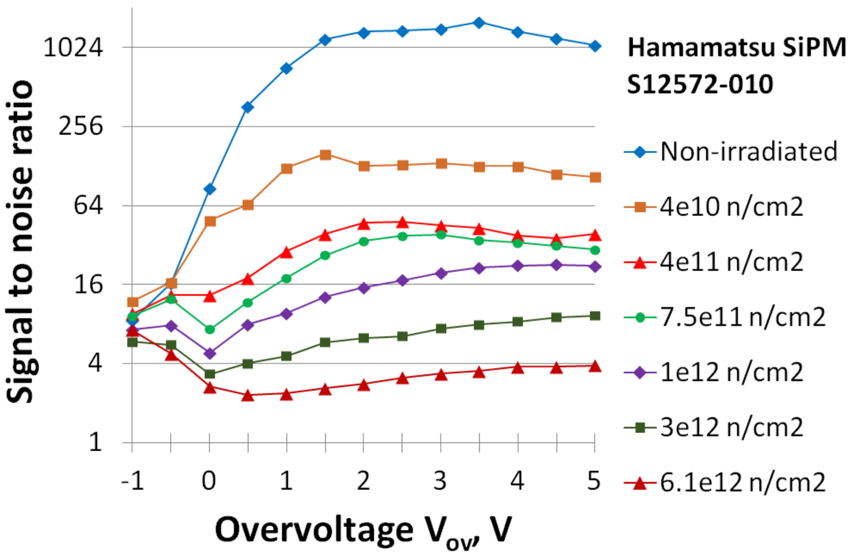


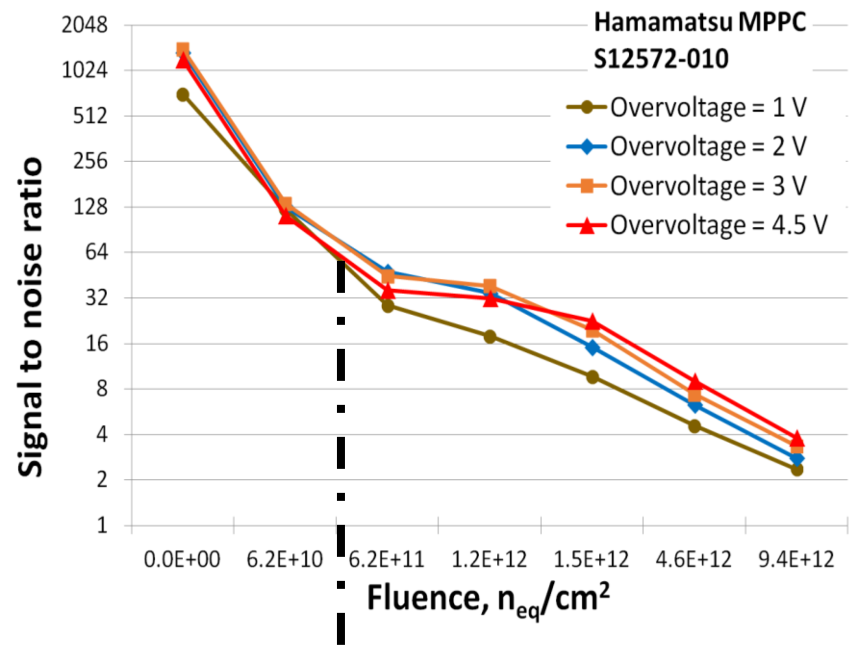
"White" neutron beam by Be(p) thick target



Courtesy of M. Majerle and M. Štefánik

Performance of MPPCs in lab



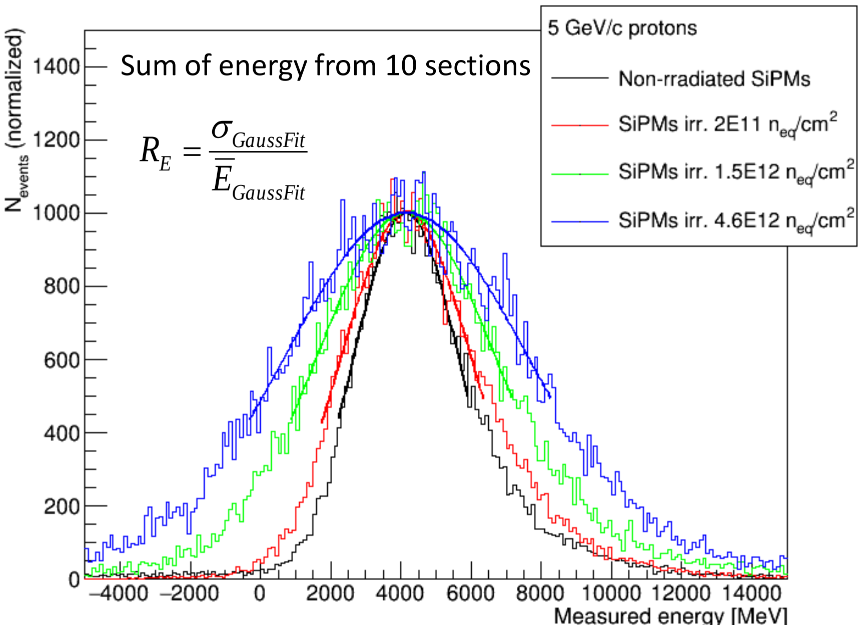


Signal to noise ratio $= Integral_{Signal}/\sigma_{Noise}$

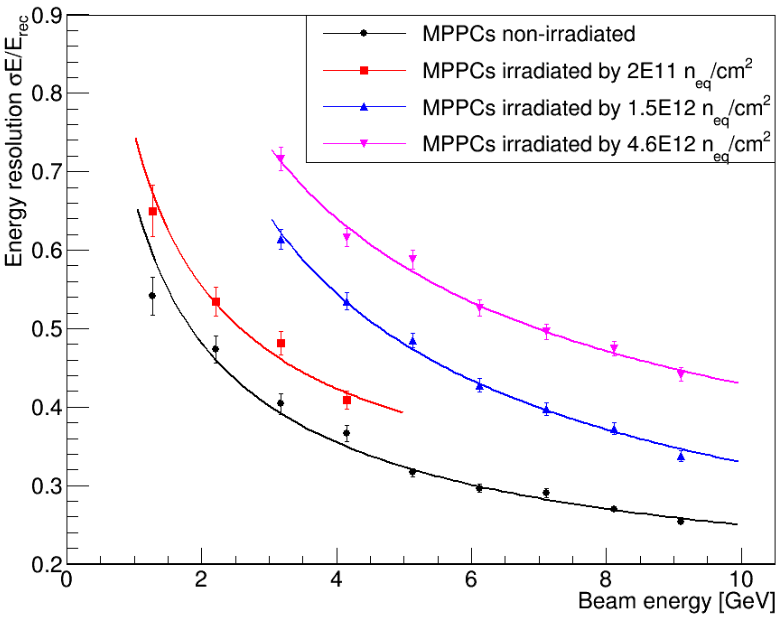
2x10^{11} neutrons$_{eq}$/cm^2 : SNR ~ 50

SiPM signal response was measured during illumination with 10 ns short pulses from 400 nm LED.
Pulse height was chosen such that signal was detectable by all the SiPMs.

Performance of MPPCs at CBM supermodule



Energy deposition for 4.2 GeV proton beam in a single module

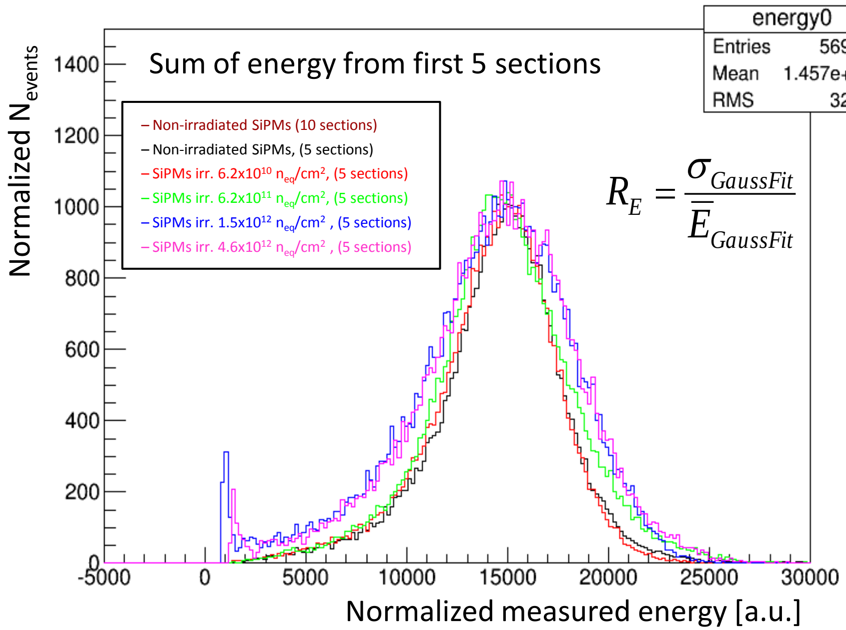


Single module energy resolution

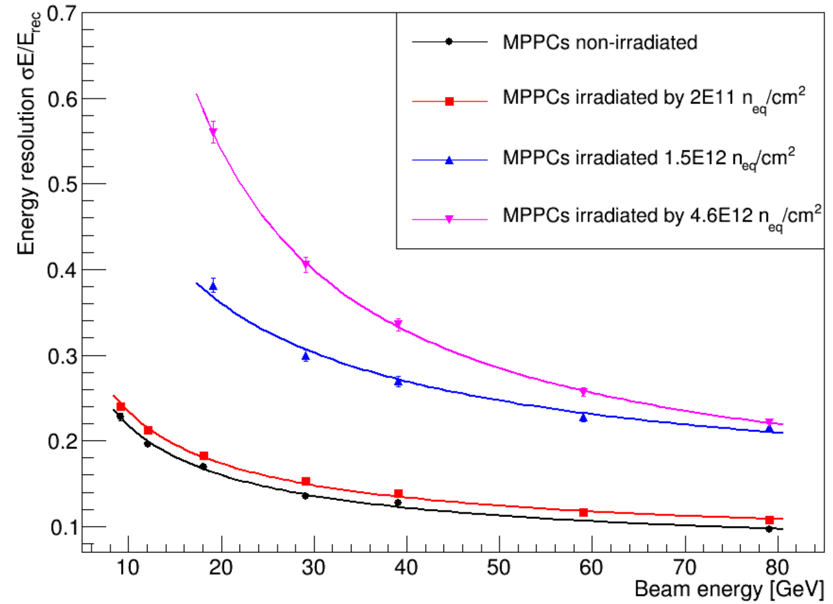
- Energy resolution dropped only slightly for MPPCs irradiated by $2x10^{11}$ n_{eq}/cm^2
- Energy resolution dropped in about 1.5 – 2 for MPPCs irradiated by ~10^{12} n_{eq}/cm^2 but SiPMs were proven to operate even after such a high neutron irradiation

Reconstruction was performed with the noise cut, which was applied individually for each section

Performance of MPPCs at NA61



Energy deposition for 4.2 GeV proton beam in a single module

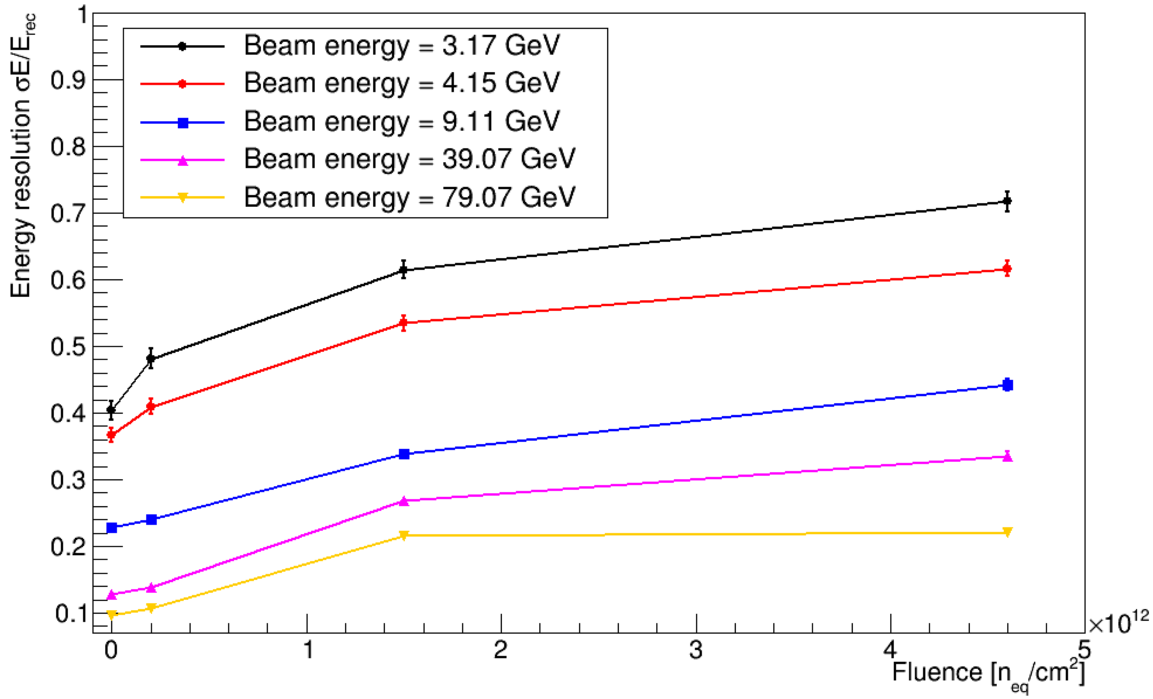


Single module energy resolution

- Energy resolution dropped up to 2 times for MPPCs irradiated by ~10^{12} n_{eq}/cm^2 but SiPMs were proven to operate even after such a high neutron irradiation

Reconstruction was performed with the noise cut, which was applied individually for each section

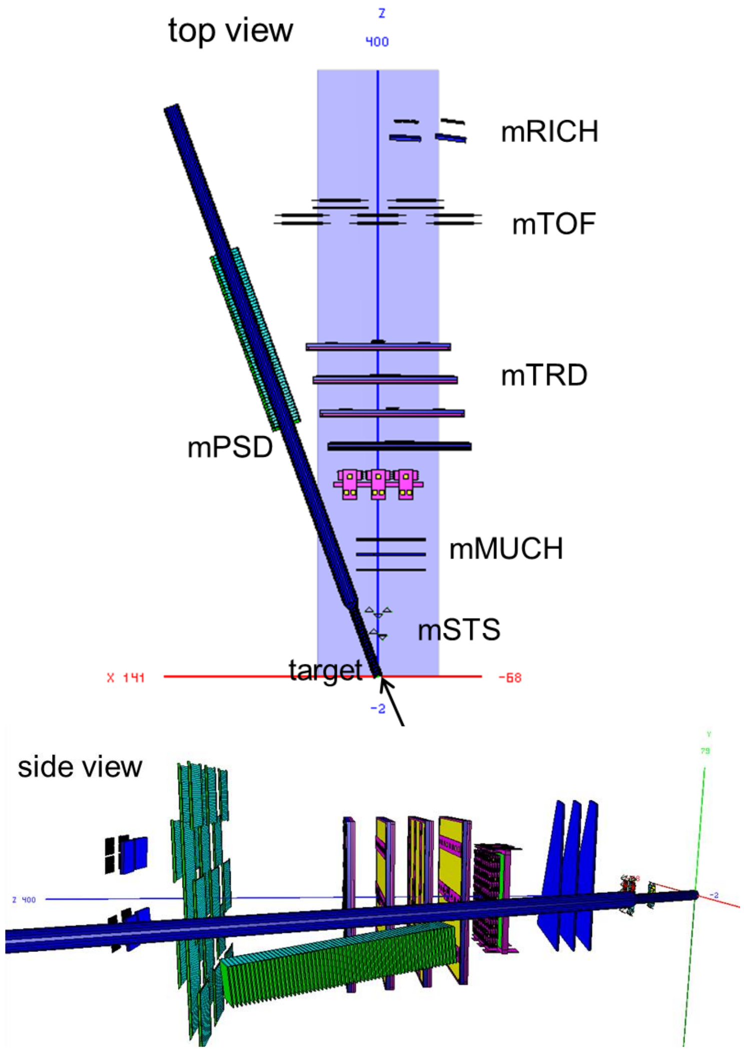
Performance of MPPCs at CERN

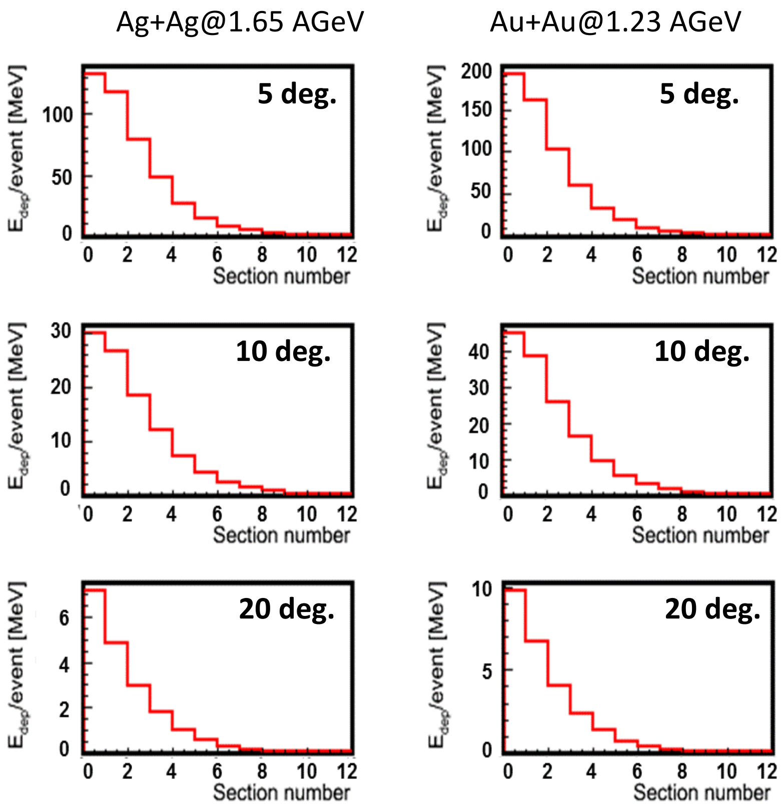


Single module energy resolution versus neutron fluence

- Calorimeter will operate well under irradiation of $2x10^{11}$ n_{eq}/cm^2 which corresponds to 1 year of operation at maximum beamrate of 1MHz
- It will operate further, but at some point damaged MPPCs must be replaced, especially at the center of calorimeter

Preparation of mPSD for mini-CBM





mPSD installation and integration in mCBM is planned for 2019

Summary

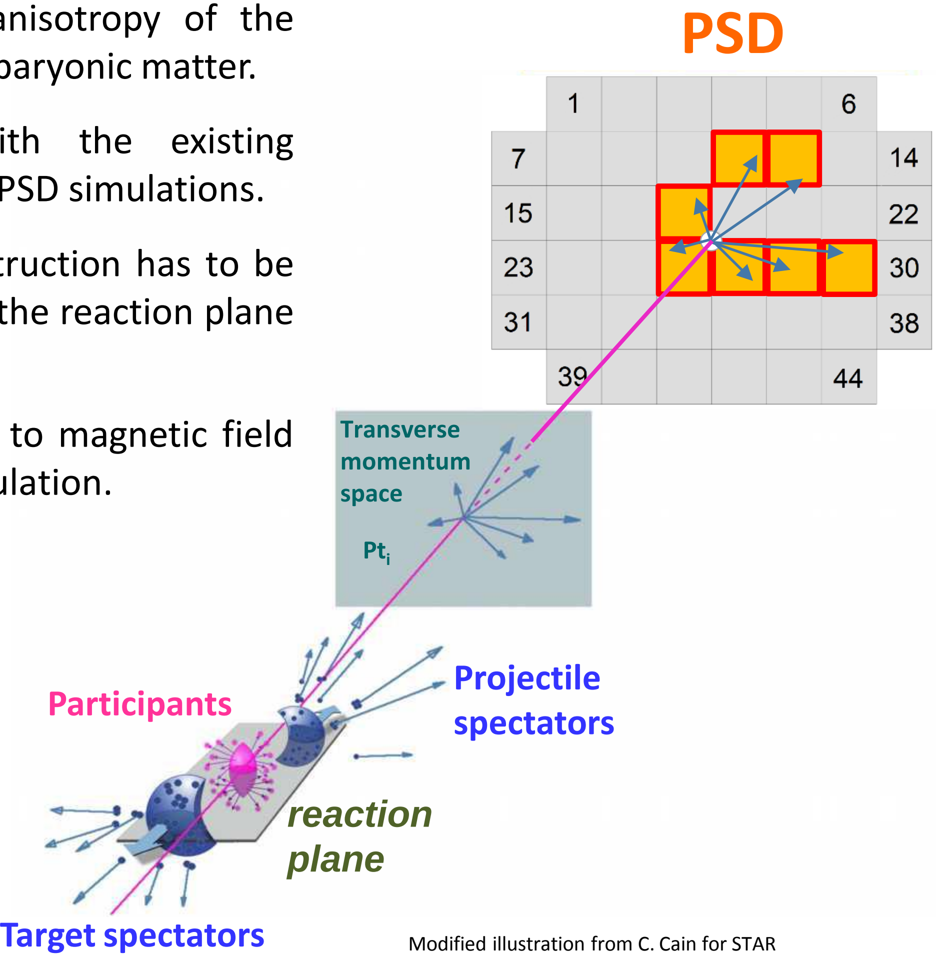
- Design and performance study of the Projectile Spectator Detector (PSD) for CBM is presented
- Physics performance of the PSD design is demonstrated with help of four different collision models and Monte-Carlo GEANT package:
  - up to 10% resolution improvement for collision centrality with PSD correlated to STS
  - reaction plane resolution is well reconstructed with $\sigma < 40\%$
- All the modules are already assembled, QA with cosmic muons completed
- Energy resolution and linearity were measured with PSD supermodule at CERN and satisfy TDR
  - stochastic term of energy resolution $\sigma_E \sim 54\%/\sqrt{E}$
- Radiation sustainability is sufficient for 1 year of operation at maximum beamrate of 1MHz and for whole experiment lifetime with exchange of photodiodes

- *Ongoing:*
  - *PSD platform design and construction*
  - *Readout electronics options evaluation*
  - *Preparation for mini-CBM*

backup

Motivation for collective flow and PSD performance simulations

- The collective flow reflecting the azimuthal anisotropy of the collision is used to study the equation of state of baryonic matter.
- Heavy-ion collision generator consistent with the existing experimental flow data has to be determined for PSD simulations.
- PSD performance for the reaction plane reconstruction has to be simulated. Magnitude of directed flow v_1 affects the reaction plane resolution.
- Effects of the detector granularity and bias due to magnetic field shall be studied during the PSD performance simulation.



Modified illustration from C. Cain for STAR

In non-central collisions flow of particles is usually described by Fourier decomposition with respect to reaction plane:

$$\frac{dN}{d\varphi} \sim 1 + 2\sum_n v_n \cos n(\varphi - \Psi_{RP}),$$

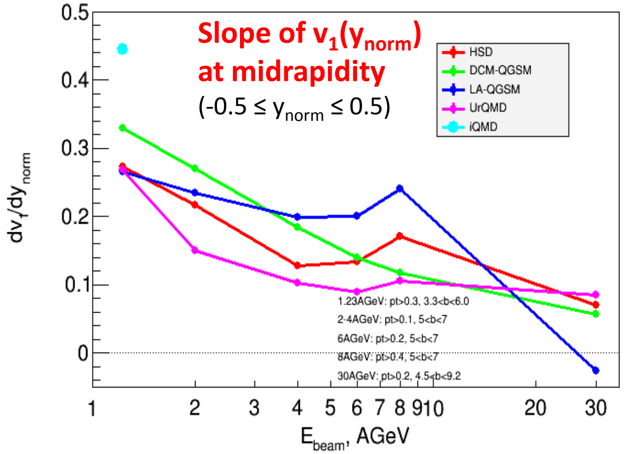
Directed flow

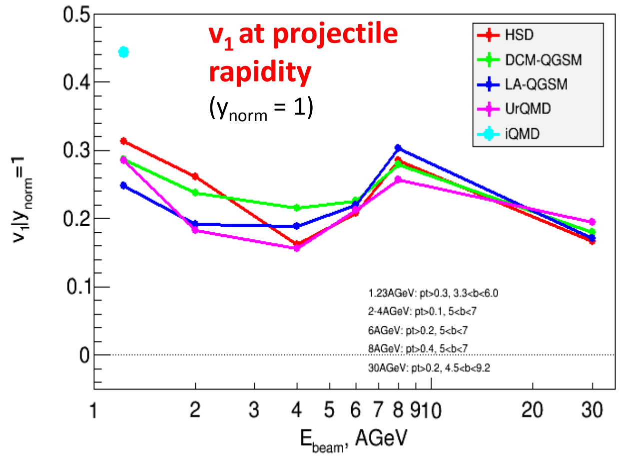
$$v_1 = \langle \cos(\varphi - \Psi_{RP}) \rangle$$

Elliptic flow

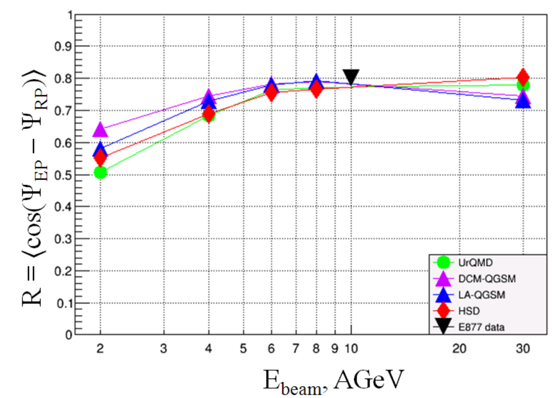
$$v_2 = \langle \cos(2(\varphi - \Psi_{RP})) \rangle$$

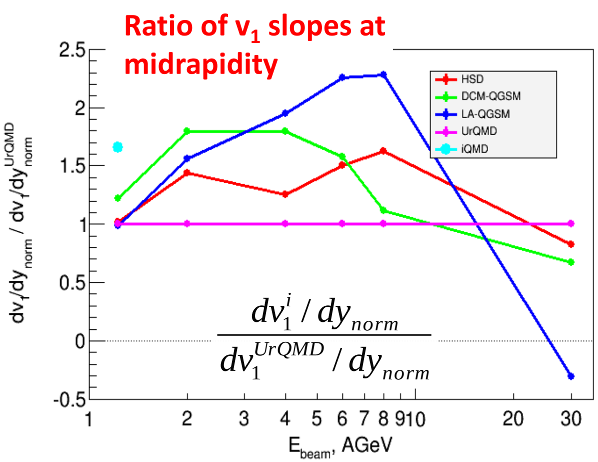
Ratios of v_1



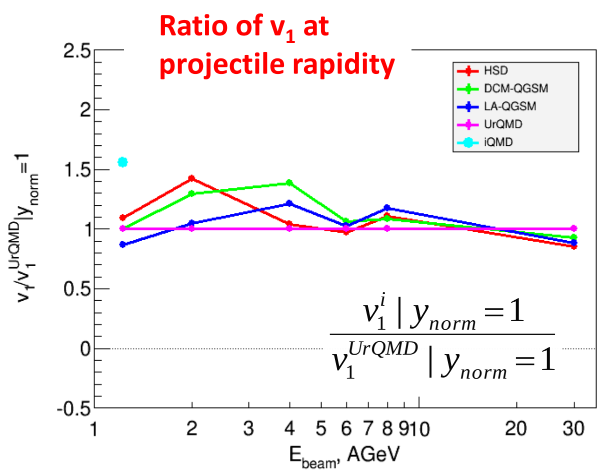


Reaction plane resolution correction factor





$$\frac{dv_1^i / dy_{norm}}{dv_1^{UrQMD} / dy_{norm}}$$



$$\frac{v_1^i \mid y_{norm}=1}{v_1^{UrQMD} \mid y_{norm}=1}$$

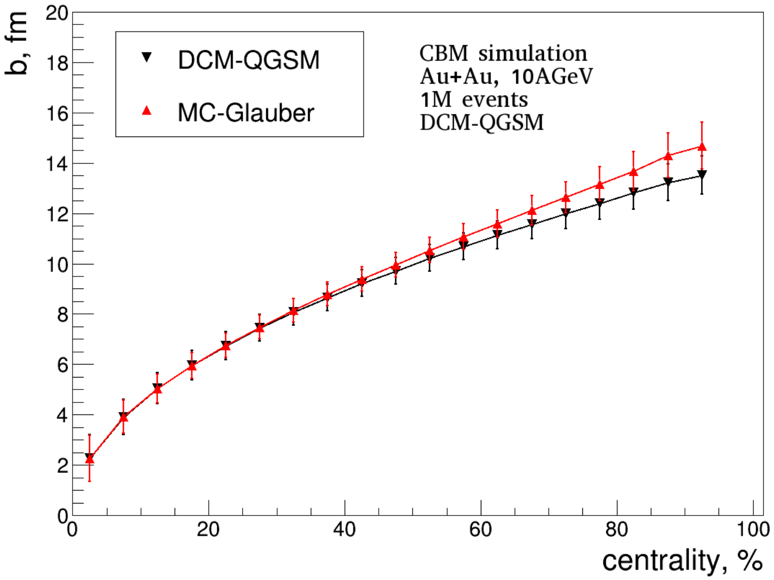
Answer:
v_1 differs a lot at midrapidity, but PSD measures at forward rapidity, where v_1 differs much less!

Centrality measurement in CBM

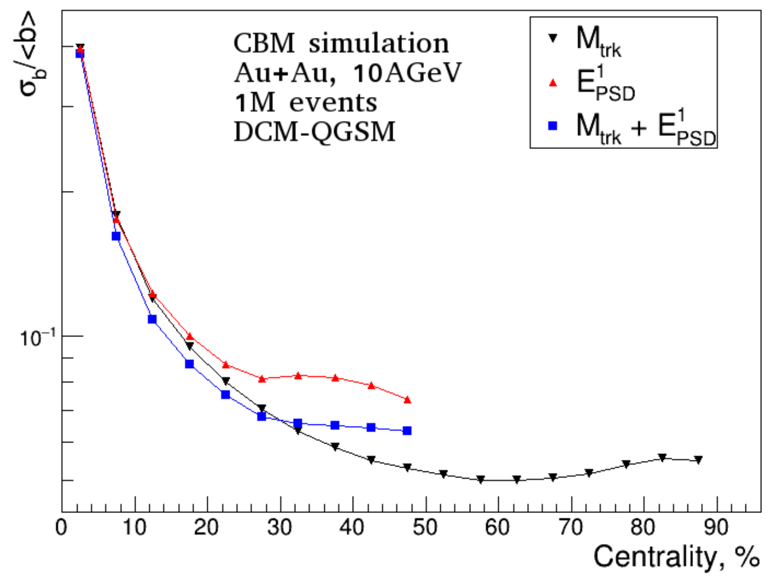
Particle multiplicities around midrapidity
measured by Silicon Tracking System

Energy measured at forward rapidity
measured by PSD calorimeter

Two independent ways to measure centrality.
STS generally performs better but can be improved
by correlation with PSD by up to 10% for central events



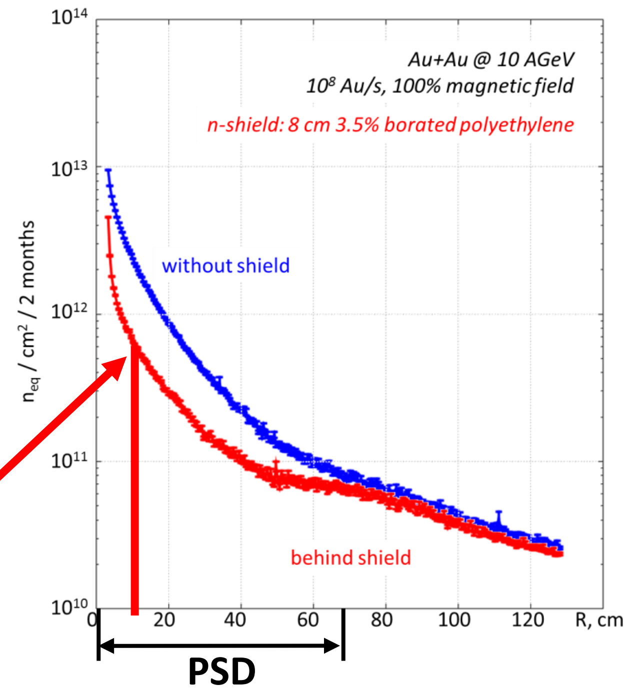
Average impact parameter versus centrality



Impact parameter resolution

Motivation for radiation hardness investigation of Silicon Photomultipliers (SiPM)

- High intensity beams at FAIR SIS100/300 up to $10^6/10^7$ interactions/s will lead to the high radiation emission to the detectors.
- PSD calorimeter works as a spallation target with moderator for neutron production.
- Passive parts of PSD including the scintillators are not very sensitive to the neutrons, but the active readout parts including the SiPMs are.

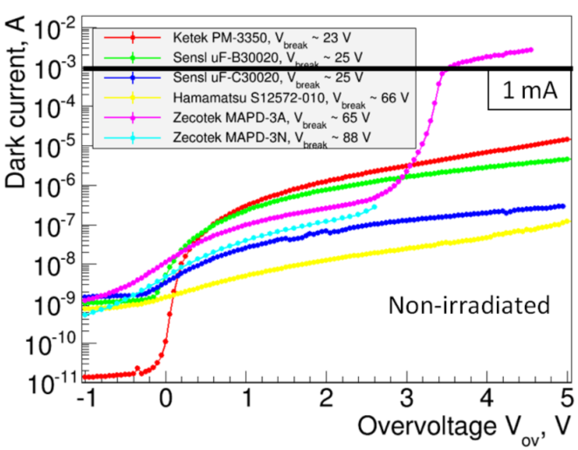


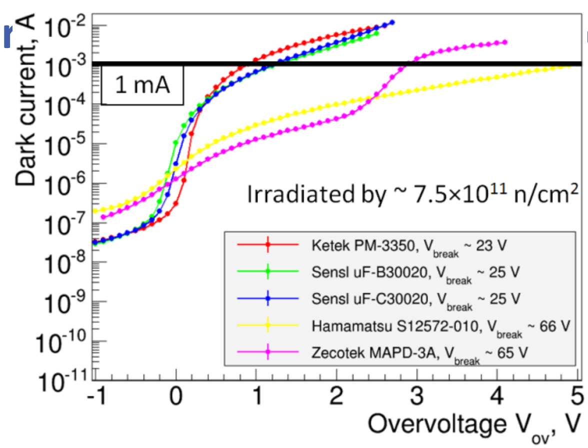
up to $5x10^{11}$ neutrons$_{eq}$/cm^2 for SiPMs located at 10 cm close to the beam hole

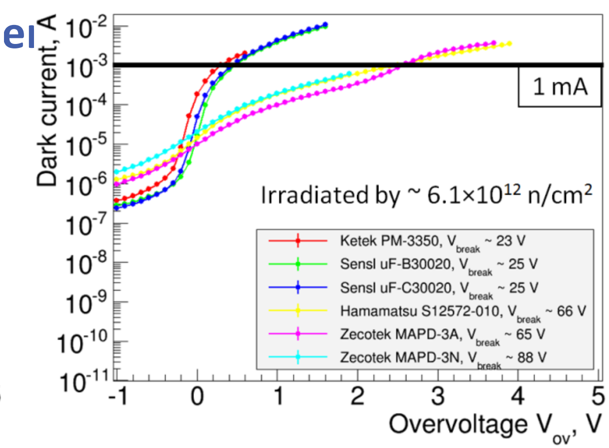
Choice of the SiPM

SiPMs with 3x3 mm^2 area sensitive to 400 – 550 nm light were chosen for the test

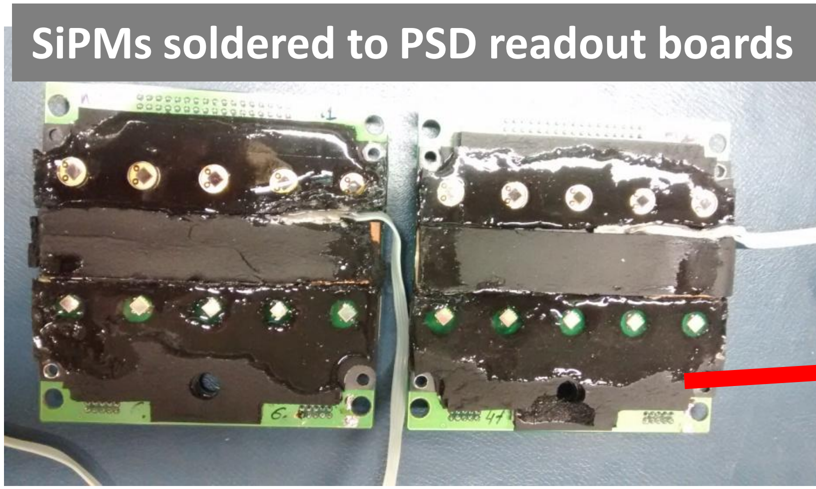
	Zecotek MAPD-3A	Zecotek MAPD-3N	Hamamatsu S12572-010P	Sensl uF-C30020	Sensl uF-B30020	Ketek PM-3350
Operating voltage (V)	~ 65	~ 90	~ 70	~ 25	~ 25	~ 25
Number of pixels	135000	135000	90000	11000	11000	3600
Effective pixel size (µm)	8	8	10	29	29	50
Gain	~ 6×10^4	~ 1×10^5	~ 1×10^5	~ 1×10^6	~ 1×10^6	~ 6×10^6
PDE (%)	~ 20	~ 30	~ 10	~ 25	~ 25	~ 40
Pixel recovery time (ns)	~ 2×10^3	~ 10^4	~ 10	~ 100	~ 100	~ 200

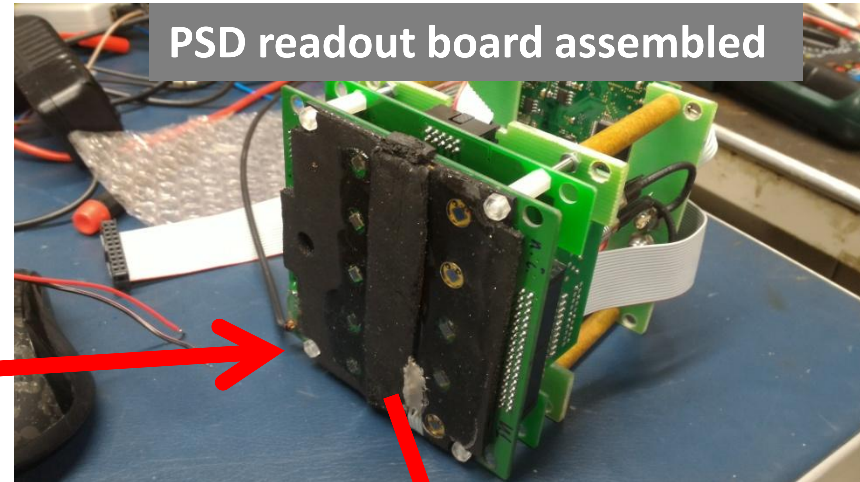


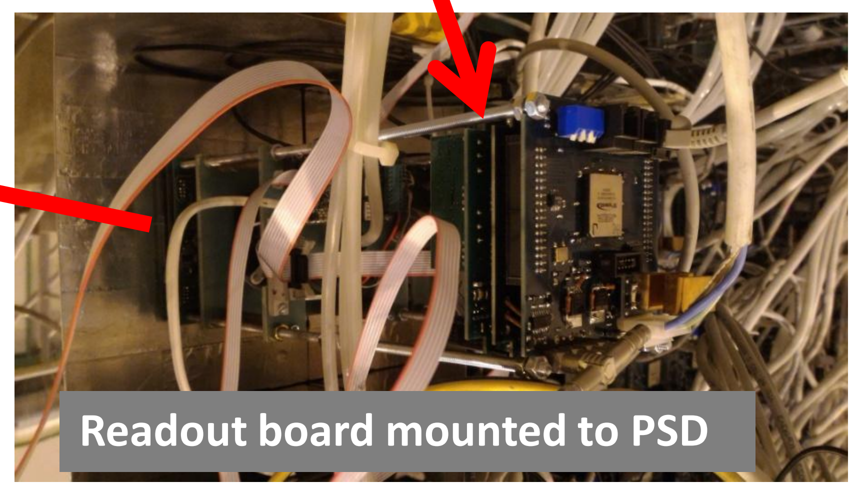




Experiments at NA61 PSD in CERN





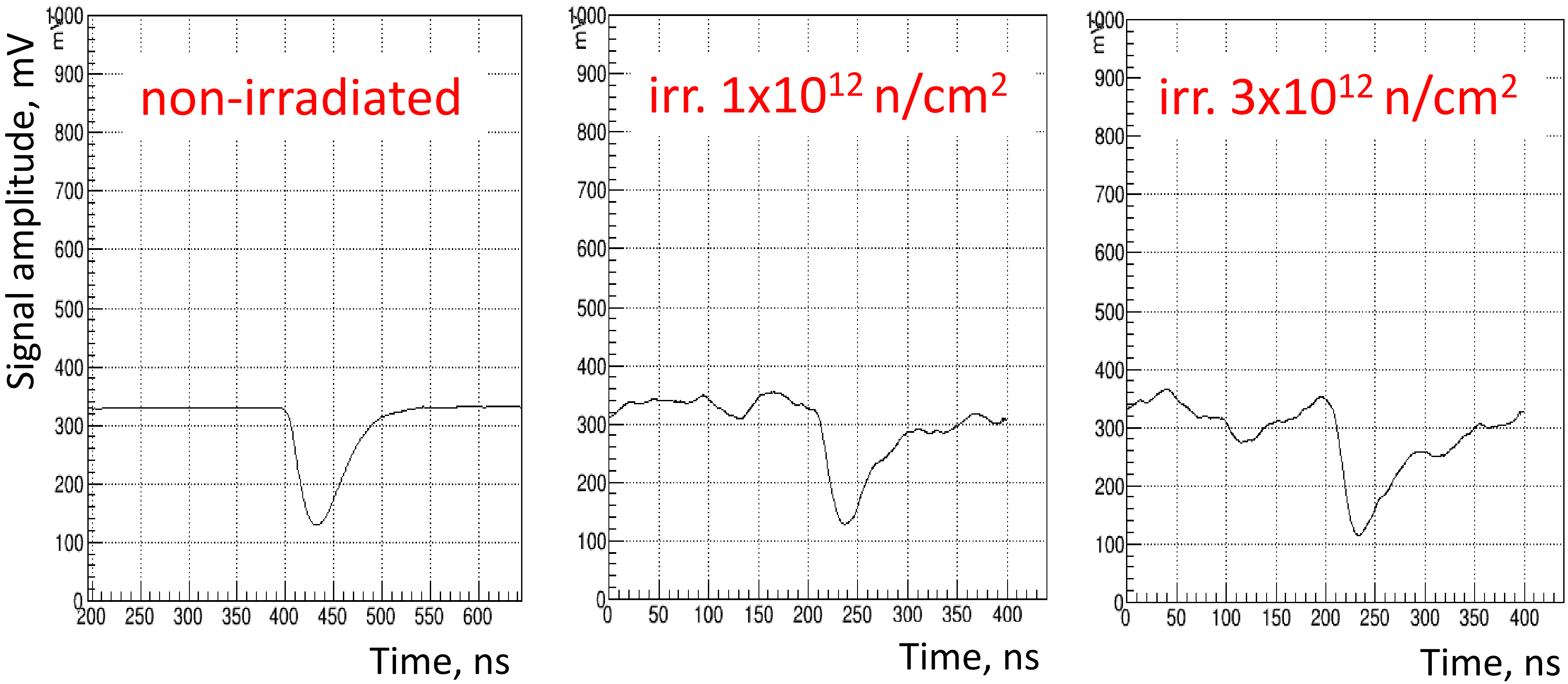


Difference between conducted tests

	Summer 2016 and 2017	September 2017	November 2017
Beamline	NA61	T10	T9
Beam momentum range	20 – 80 GeV/c	2 – 6 GeV/c	2 – 10 GeV/c
Proton selection	Not available	by TOF scintillators	By Cherenkov detector
Proton selection approx. mom. range	Not available	2 – 6 GeV/c	3.5 – 10 GeV/c
SiPMs utilized	Irradiated by 4E10, 4E11, 1E12 and 3E12 n/cm^2	Irradiated by 1E12 and 3E12 n/cm^2	
SiPMs calibration of overvoltages	Calibrated by LED relative to the muon calibration of non-irradiated SiPMs	Previous calibration from NA61 was utilized	Relative to the breakdown voltage measured in lab (seems to be more accurate)
Temperature stabilization	All SiPMs kept at 20 ^oC	Not available	
Temperature in the test hall	Not available	~ 26 ^oC	~ 18 ^oC

How the signals from 6 GeV/c protons look like

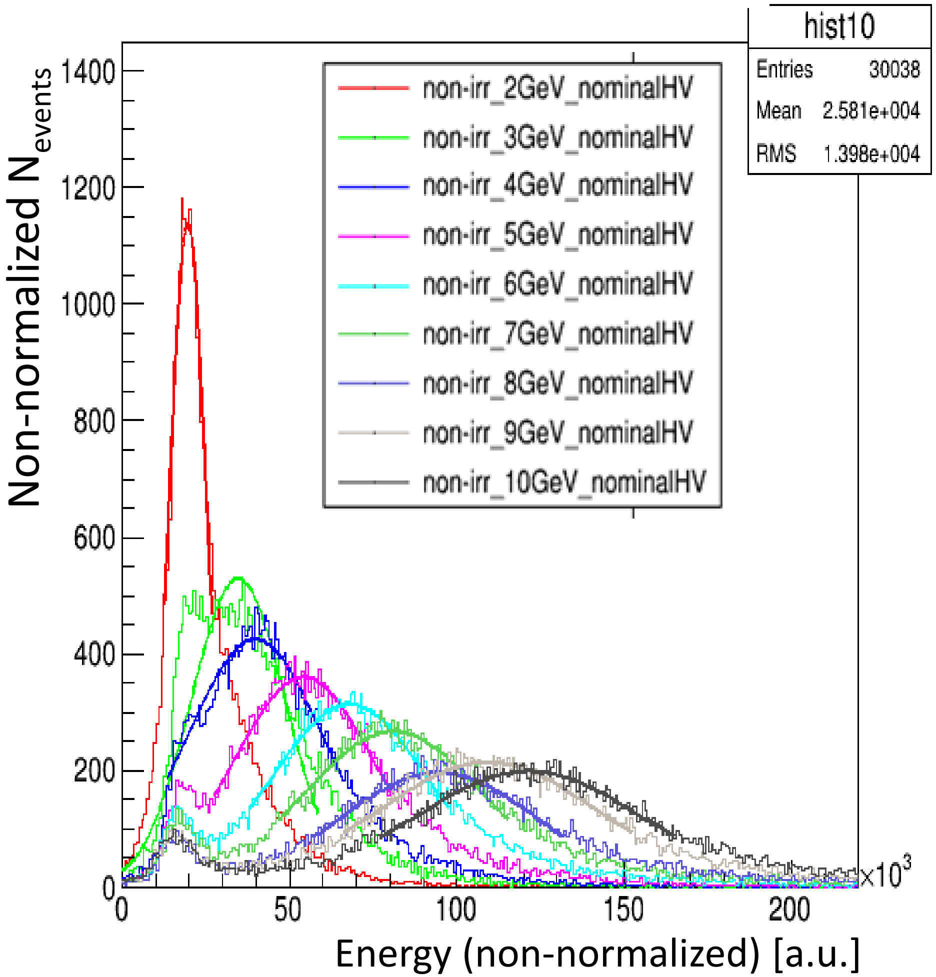
November 2017



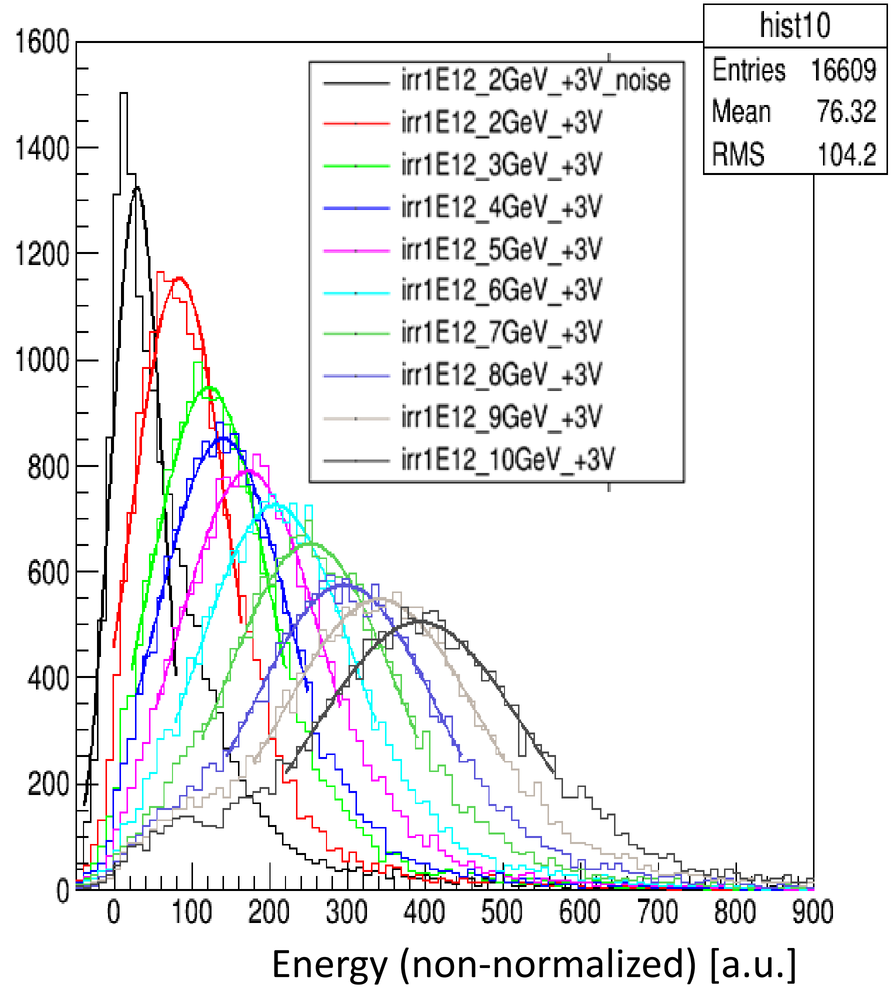
- Very high noise is clearly visible.

Energy scan

Non-irradiated

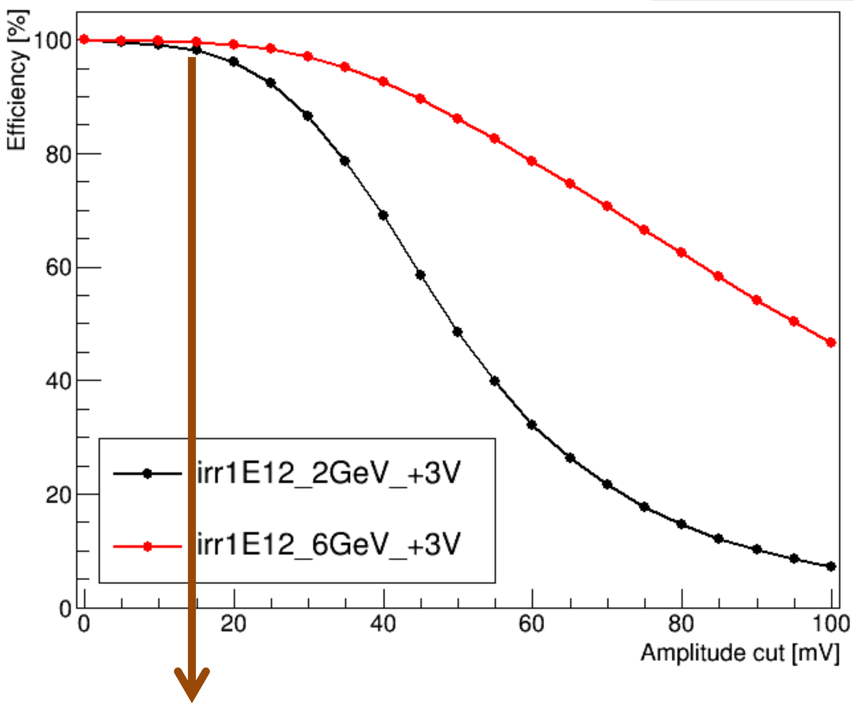


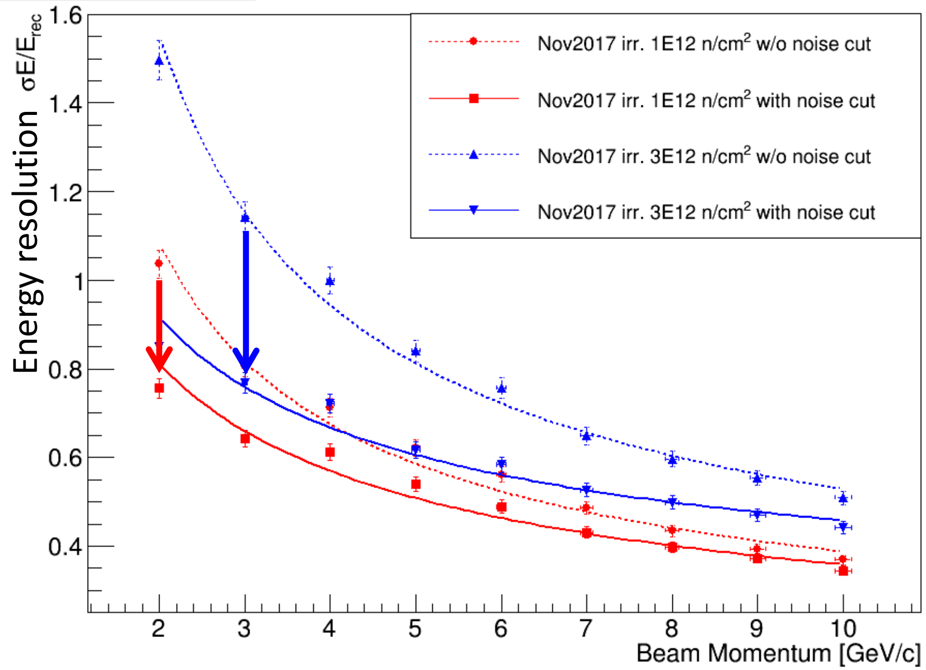
Irradiated 1E12 n/cm2



Noise reduction by the amplitude cut

November 2017





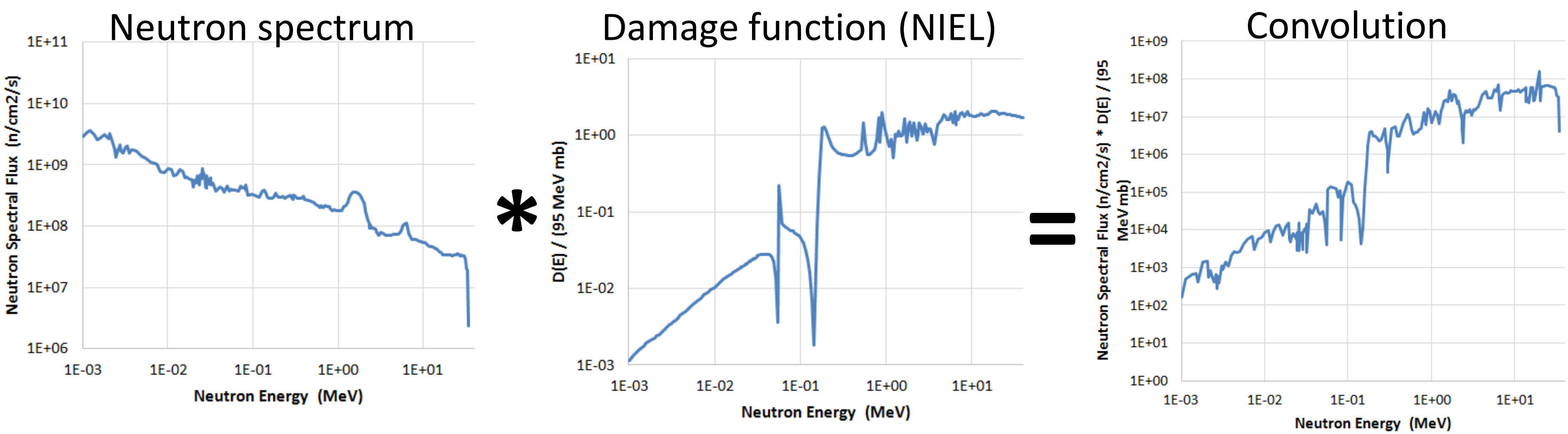
- The amplitude cut = 15 mV per section was chosen to have the minimal efficiency drop along with the good noise suppression.
- The energy resolution improved by 30 – 50 %.

** First 5 sections of NA61 PSD module were equipped with Hamamatsu SiPMs*

Next steps

- *We preliminarily estimated the 1MeV neutron fluence equivalent* *hardness factor to be: k ≈ 1.5.*

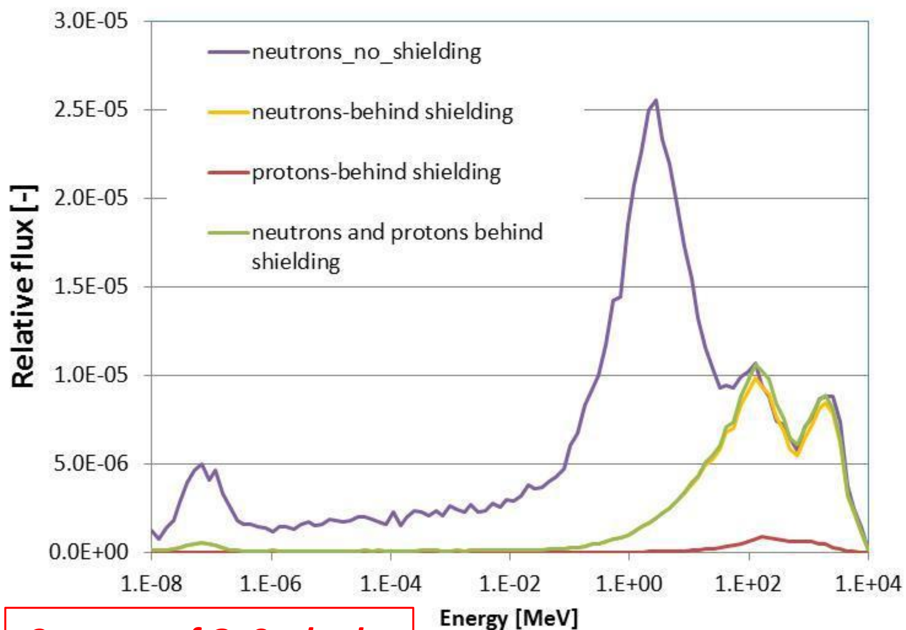
Then $1x10^{12}$ and $3x10^{12}$ n/cm^2 translate into $1.5x10^{12}$ and $4.5x10^{12}$ n_{eq}/cm^2.



To be continued

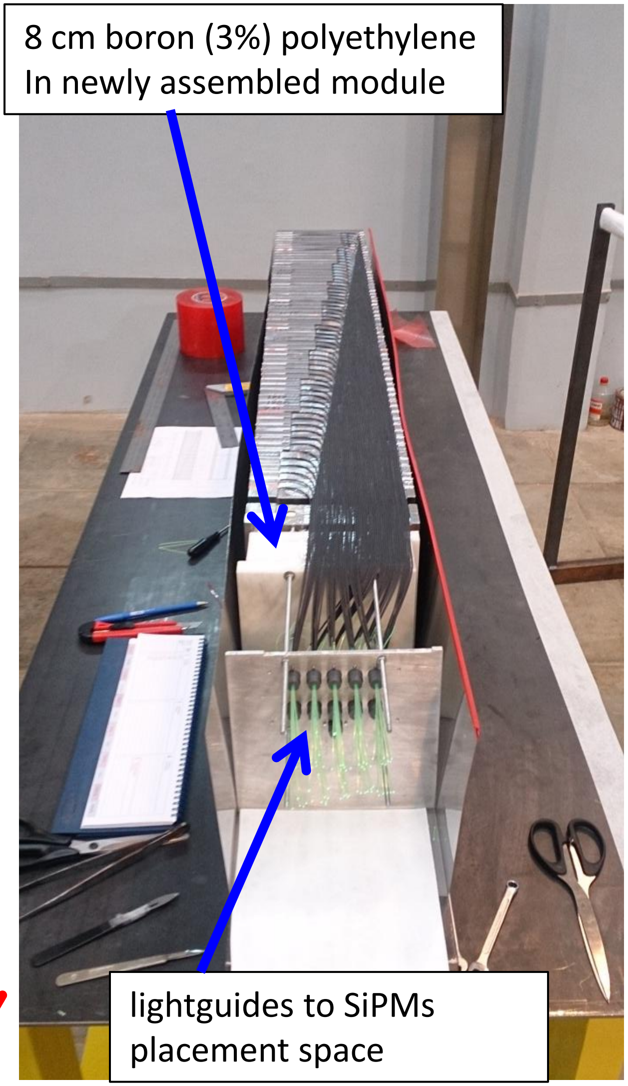
Neutron shielding simulation

- We reduced the neutron flux by 50-70% adding borated polyethylene between the PSD module lead/scintillator blocks and SiPMs.
- Low energetic neutrons are shielded the best, so we reduce the neutrons captured in SiPM by silicon and dopants, especially ^{10}B dopant having huge n cross-section.

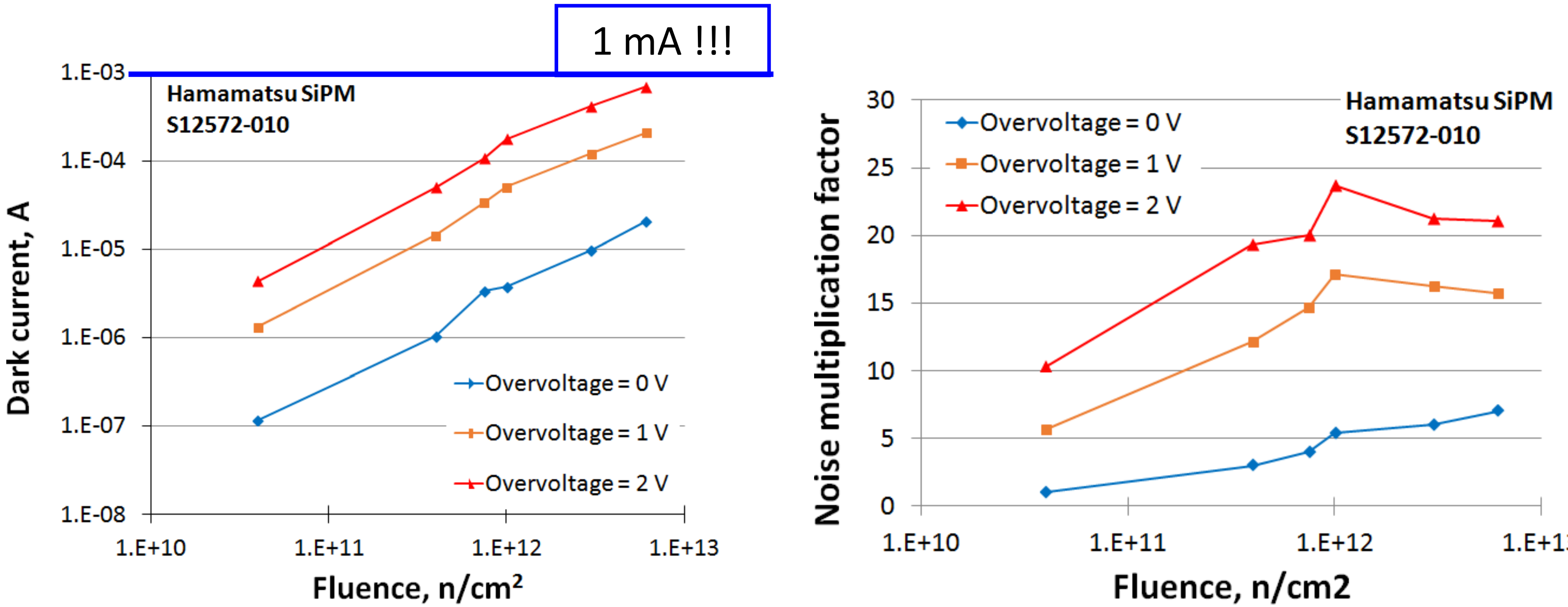


Courtesy of O. Svoboda

direction of neutrons will hitting PSD module

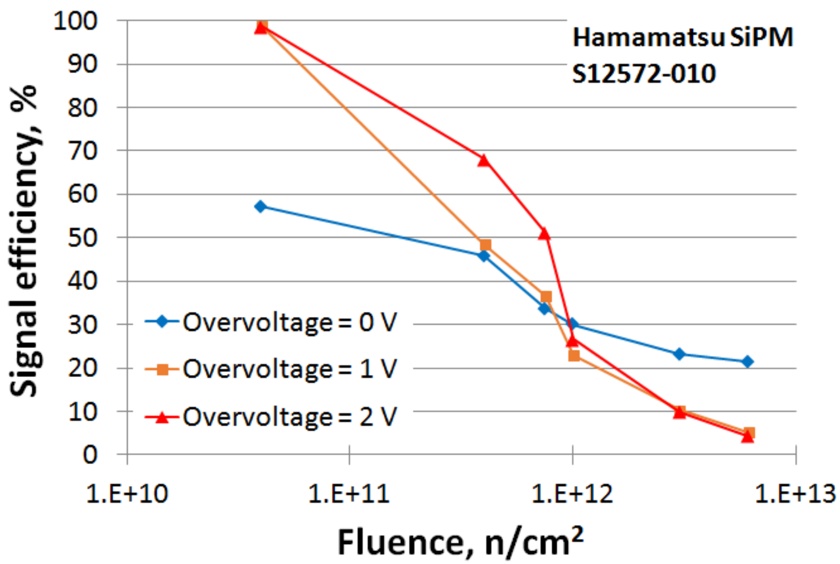


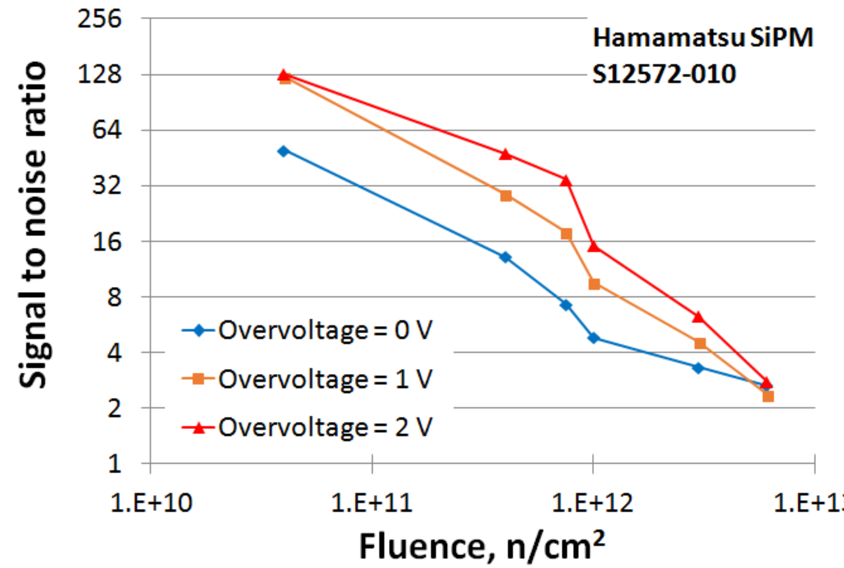
Hamamatsu SiPM performance in lab: Noise



- Dark current increases linearly with neutron fluence and can reach mA range.
- Noise increases in 10 – 20 times after irradiation.

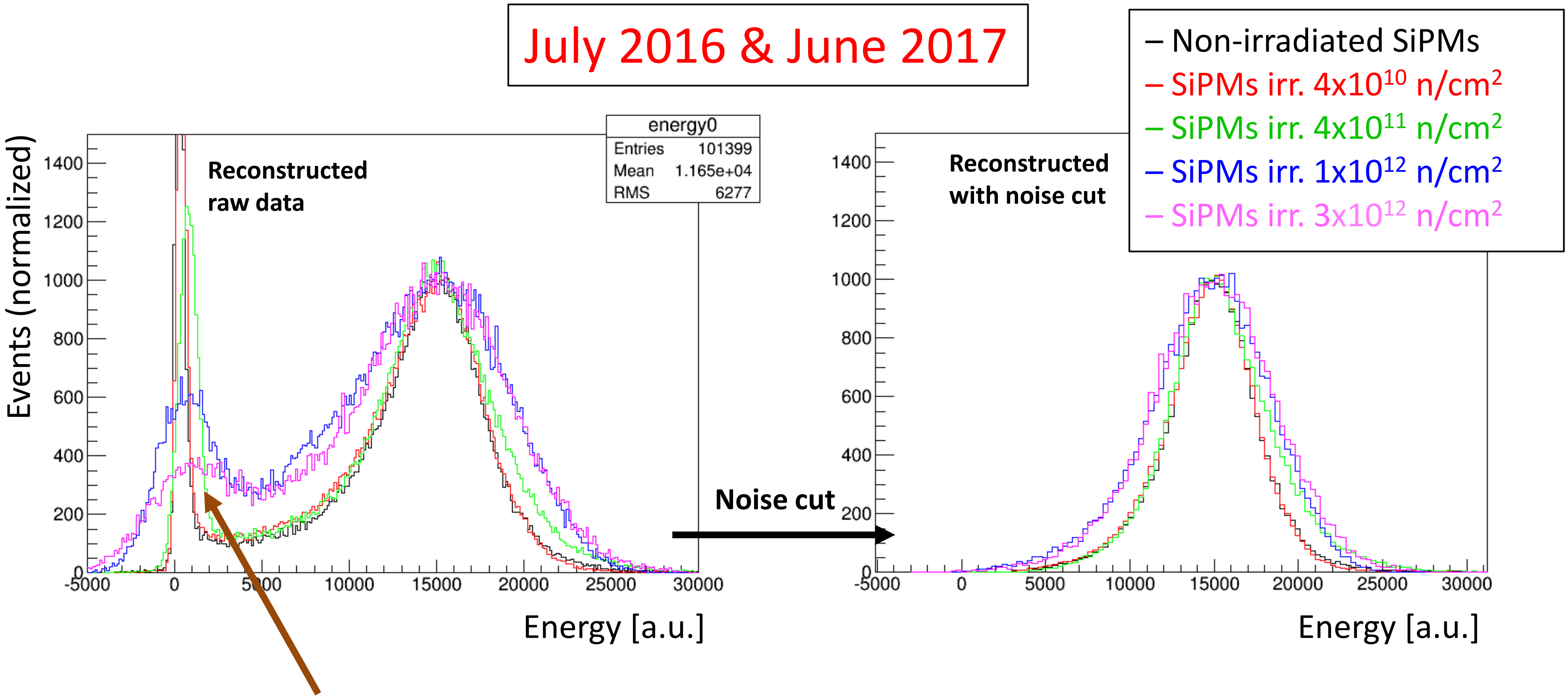
Hamamatsu SiPM performance in lab: Signal response to LED





- Signal drops to 50% of its original value at neutron fluence around 1×10^{12} n/cm^2.
- Signal to noise ratio drops to 10 at neutron fluence around 1×10^{12} n/cm^2.

NA61: Energy resolution for 80 GeV/c protons

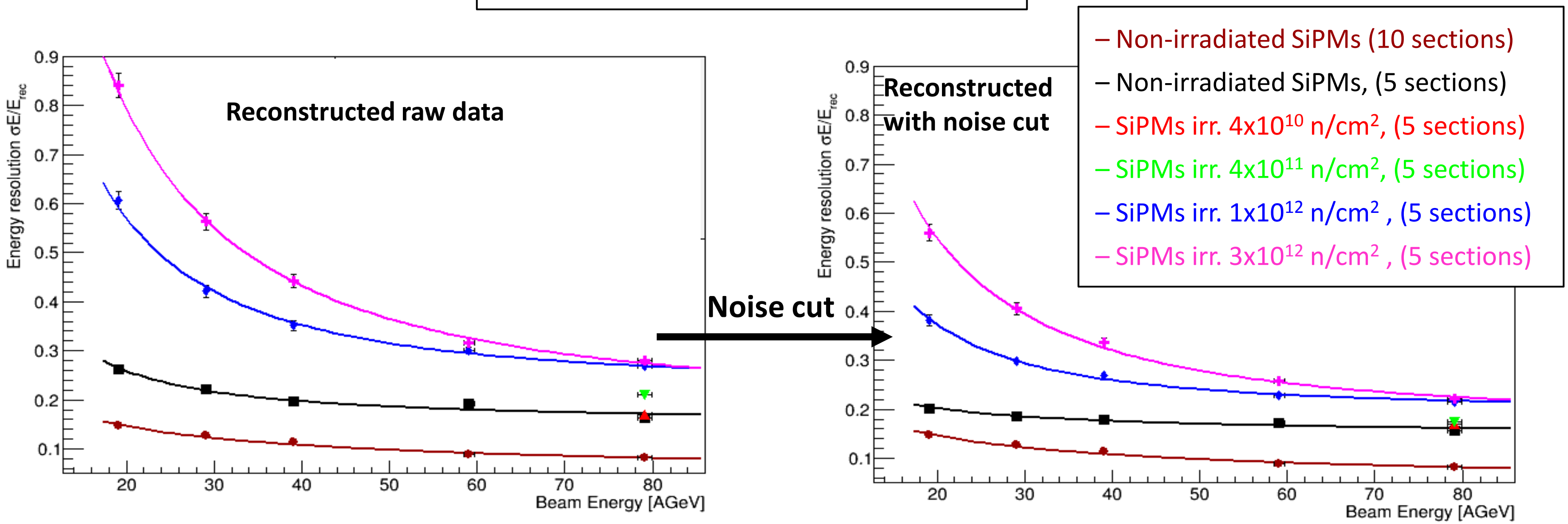


- Very high noise was cut out, significantly improving the energy resolution.

** First 5 sections of NA61 PSD module equipped with Hamamatsu SiPMs*

NA61: Energy resolution for 20 – 80 GeV/c protons

July 2016 & June 2017



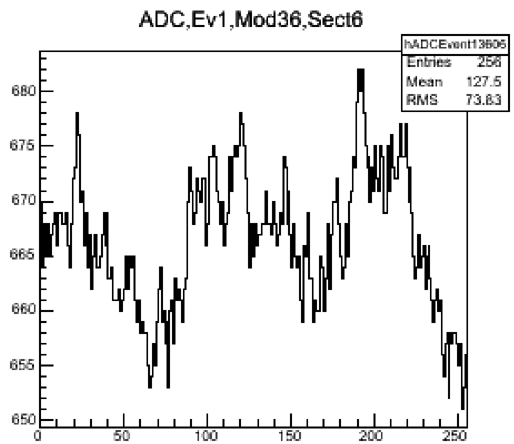
- Energy resolution dropped in 1.5 – 2.5 times after irradiation.
- **SiPMs were proven to operate even after such a high neutron irradiation.**

** First 5 sections of NA61 PSD module were equipped with Hamamatsu SiPMs*

Test of Hamamatsu SiPMs response at NA61 PSD: Waveforms

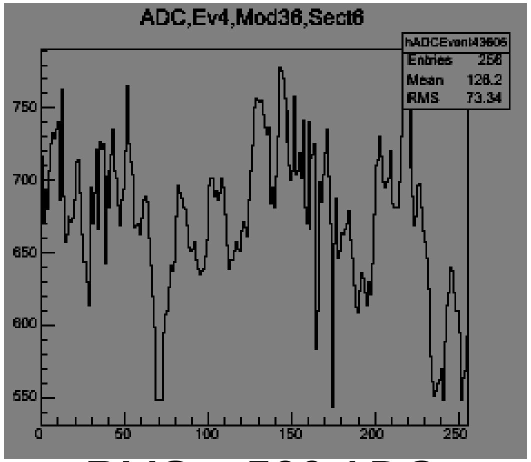
Noise

Non-irradiated



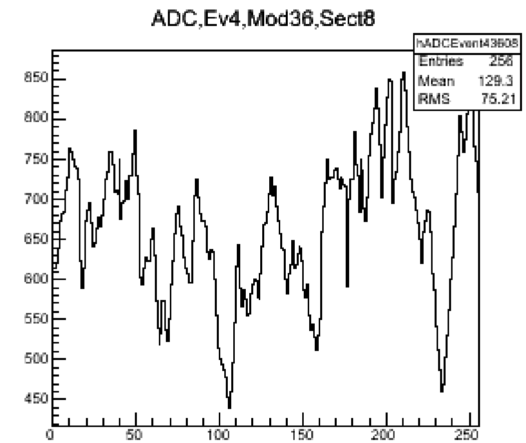
RMS ~ 50 ADC

Irradiated 3e11 n/cm2



RMS ~ 500 ADC

Irradiated 3e12 n/cm2

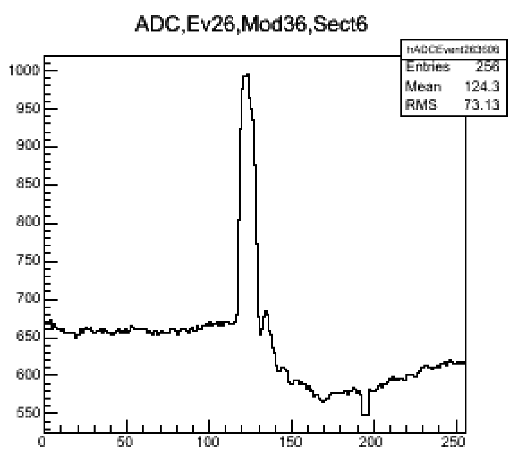


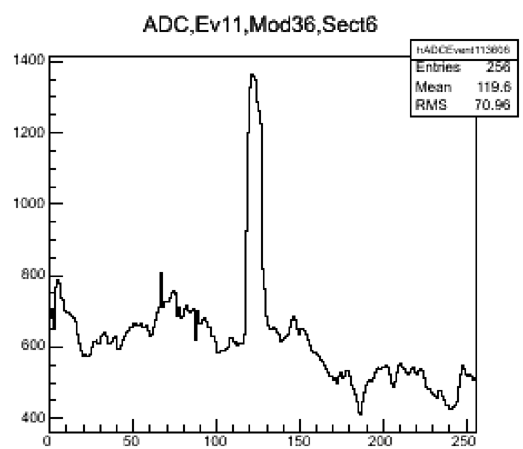
RMS ~ 1500 ADC

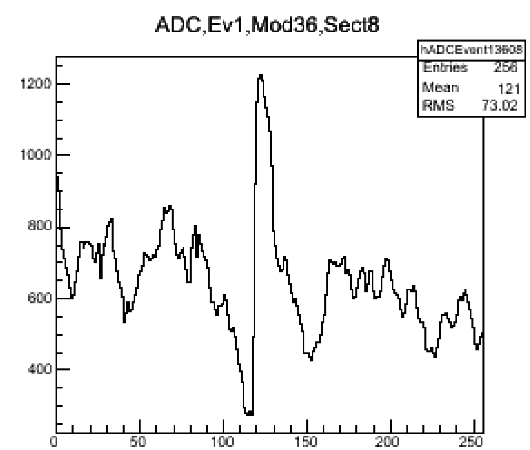
10 times more noise

30 times more noise

Proton

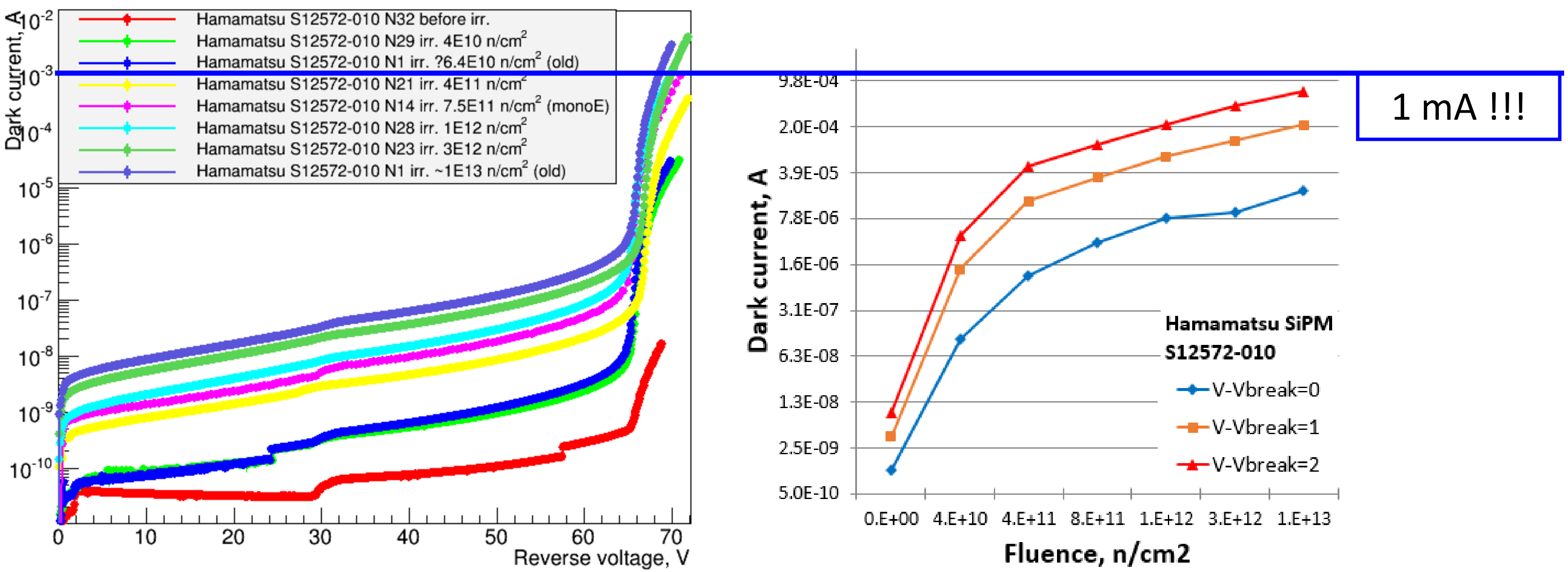






With the noise increased at 10-30 times SiPM cannot detect MIPs (~10-15 photons)!

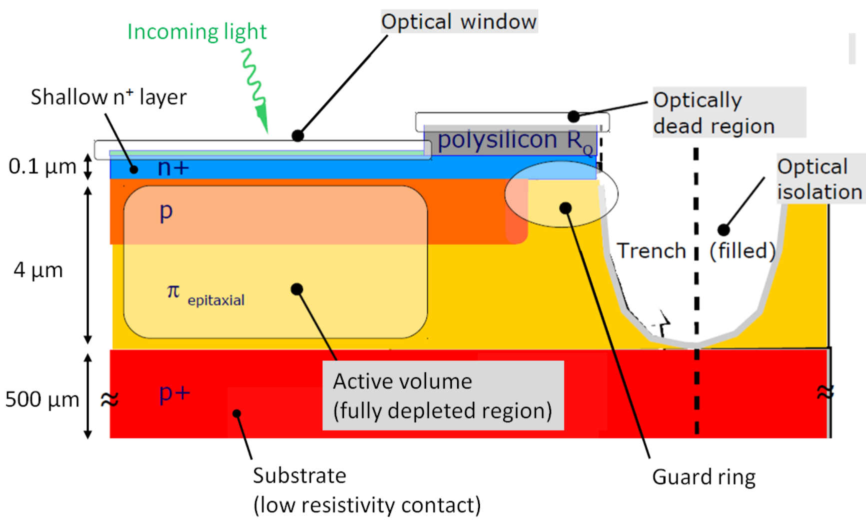
Dark currents



- Dark currents of SiPMs irradiated by ~ 4e11 n/cm^2 reach 50 µA at overvoltage = 2V
- Dark currents of SiPMs irradiated by ~ 1e12 n/cm^2 reach 200 µA at overvoltage = 2V
- Dark currents of SiPMs irradiated by ~ 1e13 n/cm^2 reach 1 mA at overvoltage = 2V
- We need external power supply (5 channels) for the next tests in CERN!

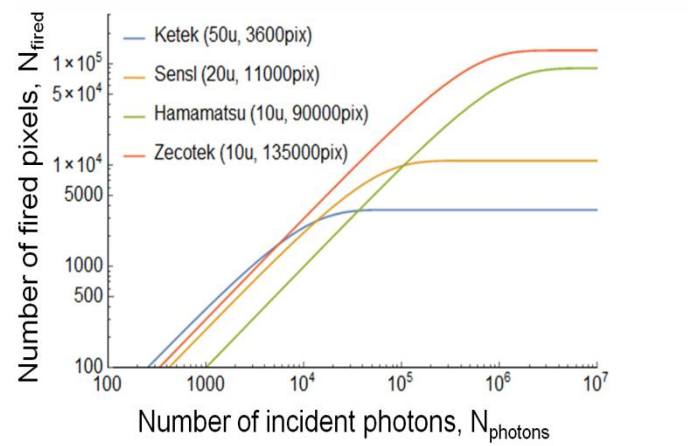
SiPM details

SiPM structure

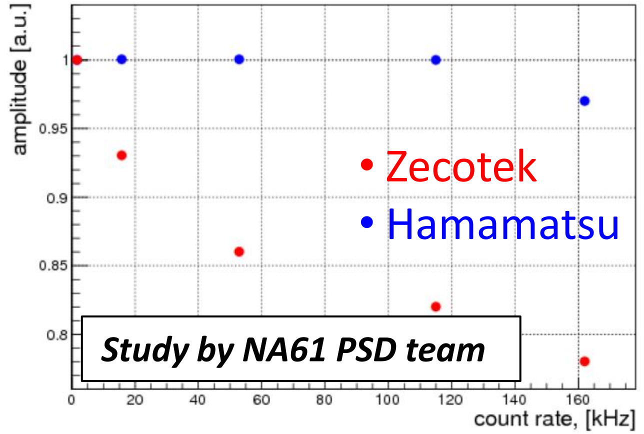


Dynamic range of different SiPMs

$$N_{fired} = N_{pixels}(1 - \exp\{-N_{photons} \times PDE/N_{pixels}\})$$



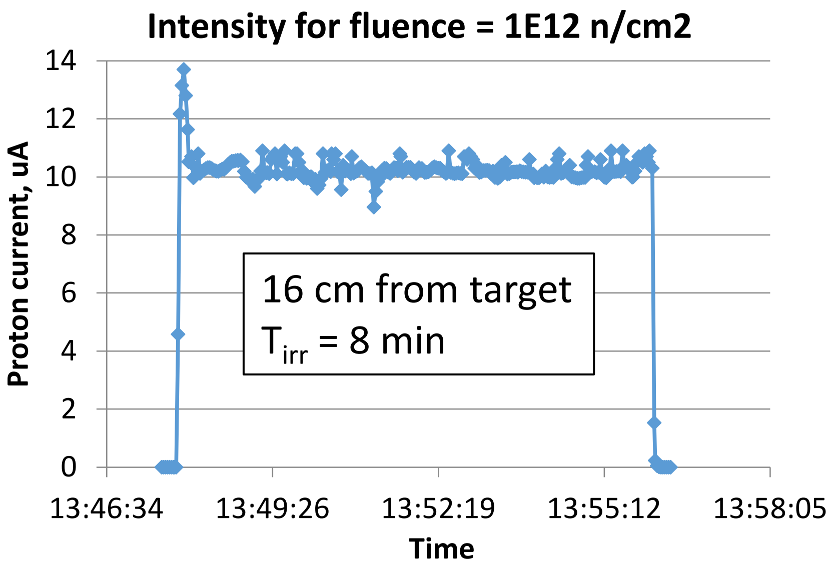
Normalized response vs proton beam rate

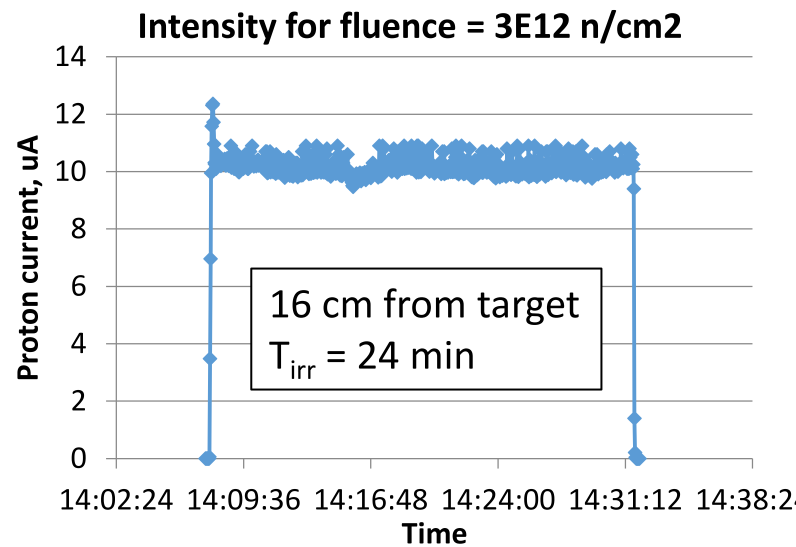


V. Mikhaylov, Tests of PSD module response with irradiated SiPMs at CERN beams in 2017

Details on neutron irradiation experiments

Proton energy = 35 MeV

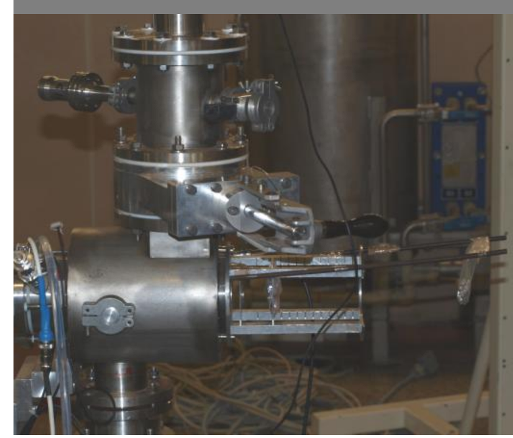




SiPMs prepared for irradiation

SiPMs located at the holder

SiPMs located at cyclotron



SiPM breakdown voltage after irradiation

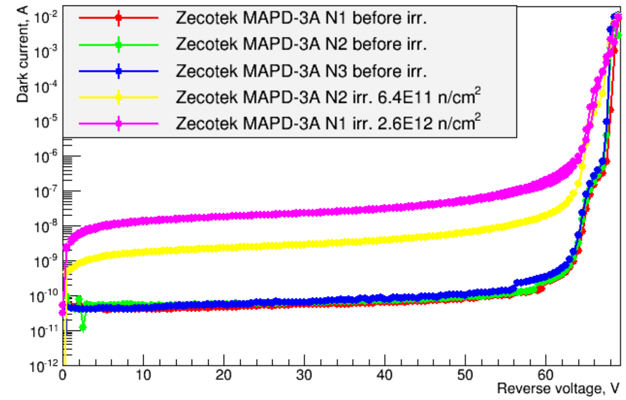
SiPM type->	Zecotek MAPD-3A	Hamamatsu S12572-010P
Sample N	$V_{breakdown}$, V ± 0.2V	$V_{breakdown}$, V ± 0.2V
20	64.4	66.7
21	64.8->65.2	67.6->67.1
22	65	67
23	64.9	67.1
24	64.9	67.4
25	64.7	66.7
26	64.7	66.7
27	64.4	66.1
28	64.4	66
29	64.2->64.3	65.9

Samples 20–24: 2E11 n/cm²

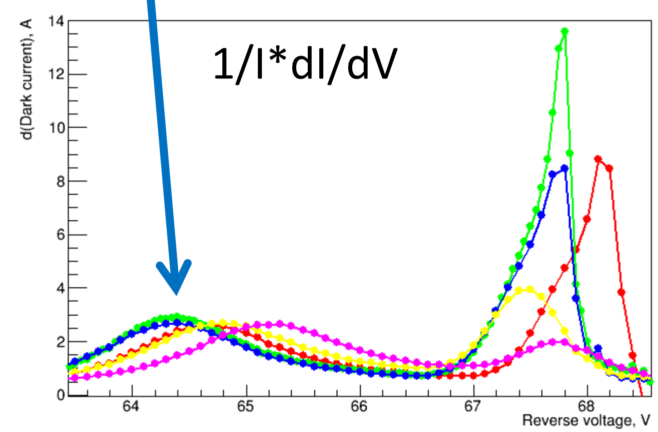
Samples 25–29: 2E10 n/cm²

Variation of $V_{breakdown}$ measured for few SiPMs is less than 0.5V.

** SiPMs irradiated by "white" neutron spectrum*

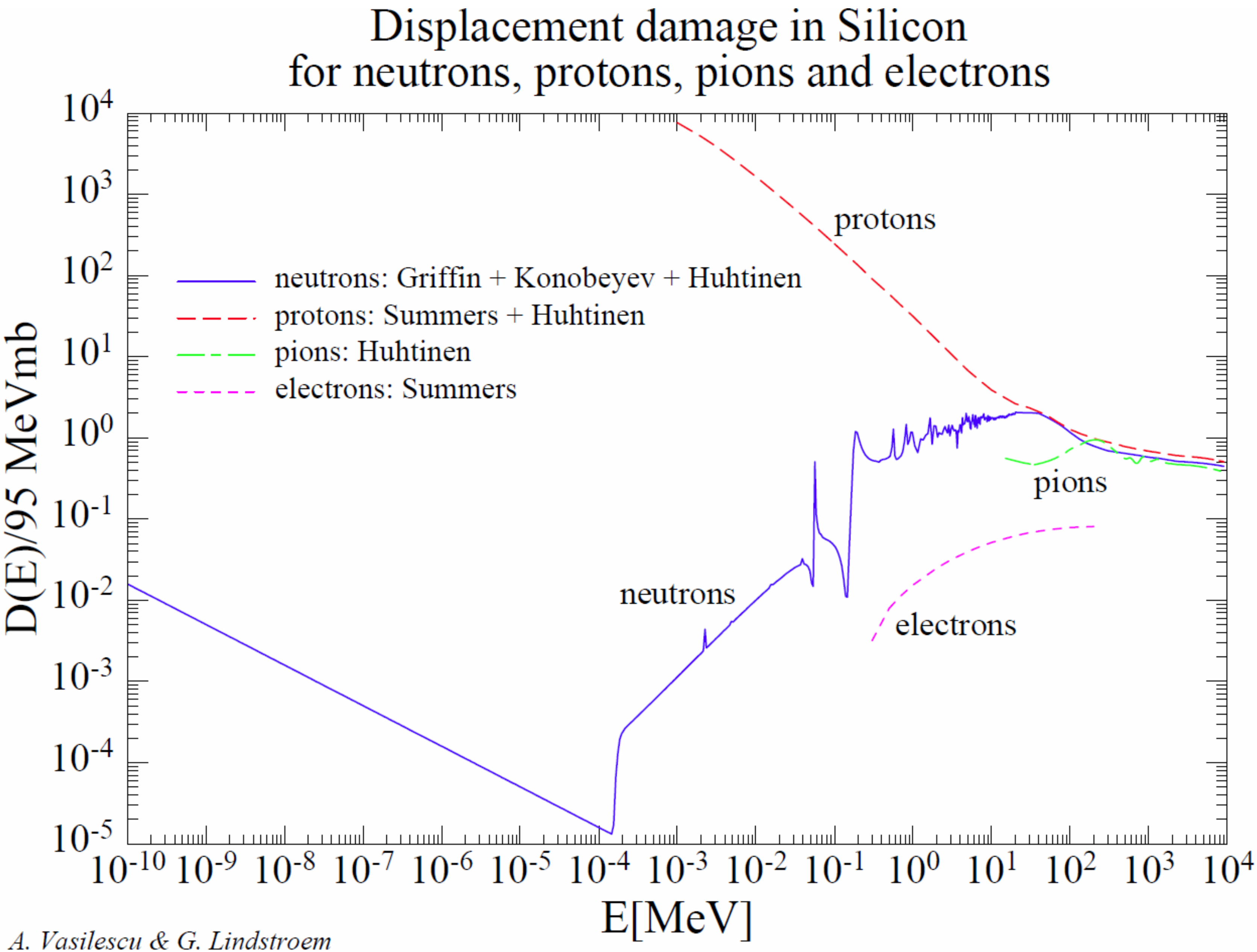


V_{break} = 65 ± 0.2V

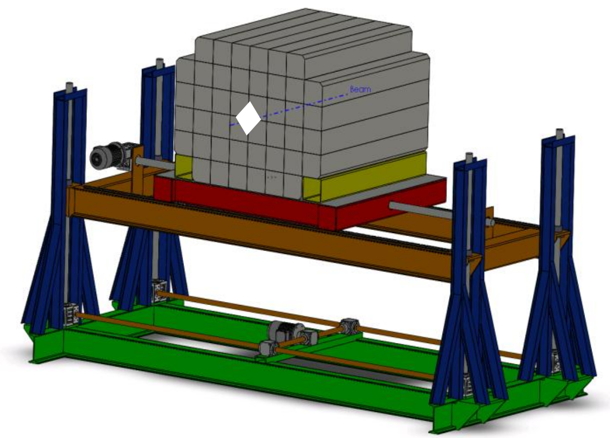


ΔV_{break} (6.4e11 n/cm²) ~ 0.4V

V. Mikhaylov, Tests of PSD module response with irradiated SiPMs at CERN beams in 2017


Displacement damage in Silicon
for neutrons, protons, pions and electrons
D(E)/95 MeVmb
E[MeV]
neutrons: Griffin + Konobeyev + Huhtinen
protons: Summers + Huhtinen
pions: Huhtinen
electrons: Summers
protons
neutrons
pions
electrons
A. Vasilescu & G. Lindstroem

Projectile Spectator Detector (PSD)

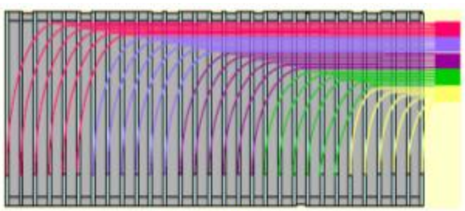


Principle: detection of forward going projectile nucleons and nuclei fragments (spectators) produced close to the beam rapidity in nucleus-nucleus collisions

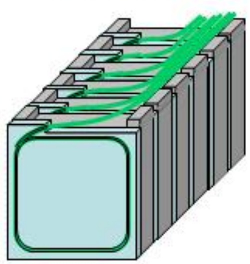
Purpose: measurement of the reaction centrality and reconstruction of the reaction plane

Features:

- compensating calorimeter with lead/scintillator sampling ratio 4:1
  good energy resolution ~55%/√E
- high transverse granularity by 44 modules
  transverse homogeneity of energy resolution, reaction plane measurements
- module of 5.6 hadron interaction lengths and transverse size of 20x20x120 cm^3
  optimized for beam energy range from 2 up to 35 GeV
- longitudinal segmentation: 10 sections/module, 1 section = 6 scintillator plates
  longitudinal shower profile measurement, calibration
- light readout from a section through WLS fibers by 3x3 mm^2 Hamamatsu MPPC
  large dynamic range, no nuclear counting effect
- ability to operate at high collision rate up to 1MHz
- total 22 tons of weight on a platform movable in 3 dimensions



TOP View



FRONT View

Similar calorimeter already operates at NA61@CERN, and another one called Zero Degree Calorimeter (ZDC) is being built for BM@N at NICA.