Beams collision monitoring and luminosity measurements in the interaction point at MPD/NICA

A.Litvinenko ,JINR
(alitvin@jinr.ru)
on behalf of the working group

working group

- JINR (Dubna)

S.G.Buzin, M.G.Buryakov, V. M.Golovatyuk, Z.A.Igamkulov, E.I.Litvinenko

- JINR (Dubna) + Dubna State University

S.P.Avdeyev, A.I.Malakhov, G.D.Milnov, A.G. Litvinenko

- INR RAS (Moscow)

A.B.Kurepin,

- Institute of Physics and Technology, MAS, Ulaanbaatar, 13330 Mongolia

M.Sovd, B.Otgongerel

- Anyone wellcome

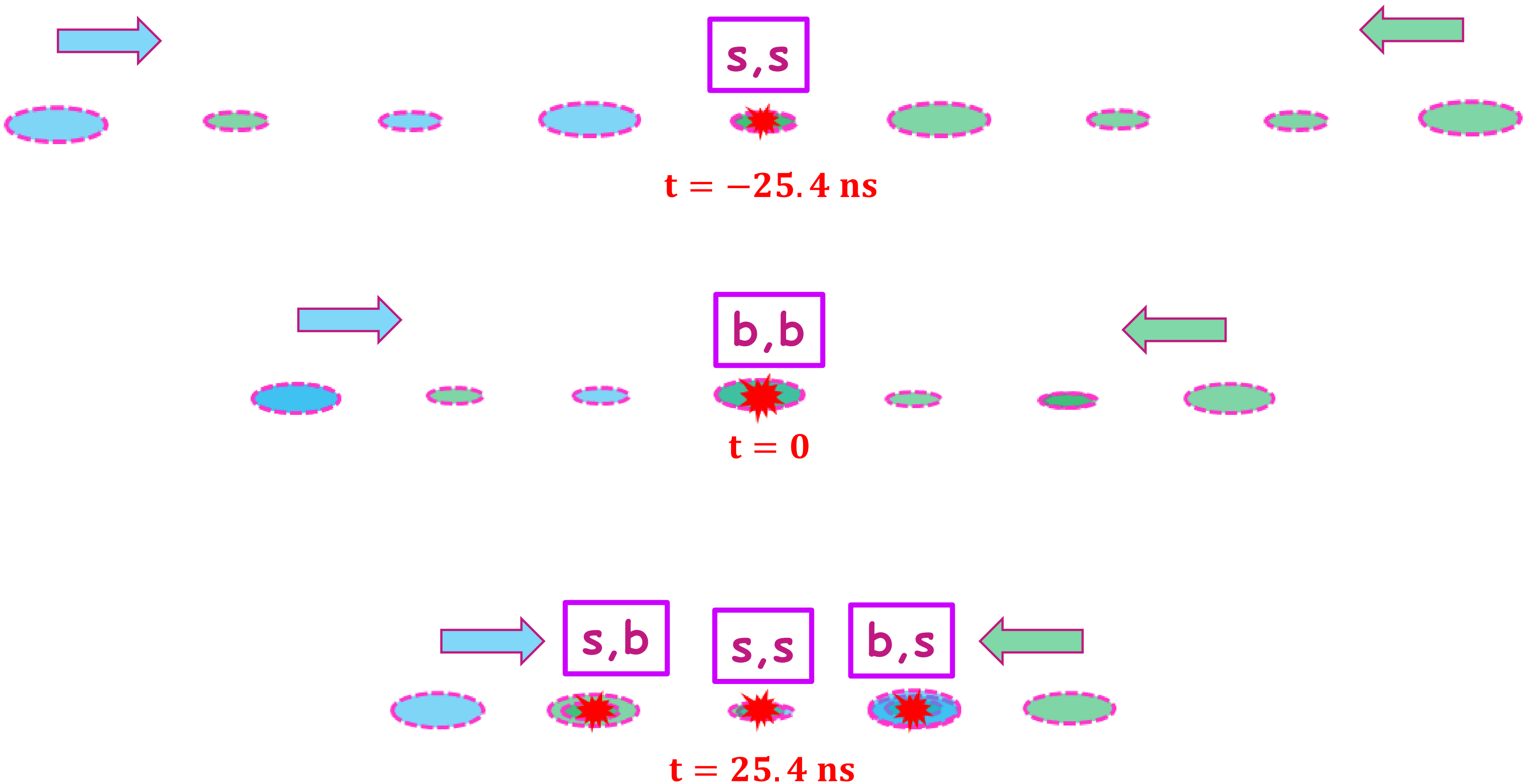
Time structure of AuAu collisions at NICA

Basic parameters (for $\sqrt{S_{NN}} = 11\ \mathrm{GeV}$)

1. Length (perimeter) of the ring $L = 503,04\ m$
2. Number of bunches $N_b = 22$
3. Number of satellites $N_s = 44$
4. R.M.S. of particles in a bunch $\sigma_z = 0.6\ m$
5. Time between bunches $t_{b-b} \approx 76.2\ ns$
6. Time between bunch and satellite $t_{b-s} \approx 25.4\ ns$
7. Time of single interaction bunches $\Delta\tau_{bb} \leq (6\sigma_z)/(2c\beta) \approx 6\ ns$
8. Revolution frequency $f_r \approx 0.56 \cdot 10^6\ Hz$

Collision types at NICA

1. satellite-satellite (s,s; $Z_{b,b} = 0\ m$)
2. bunch - bunch (b,b; $Z_{b,b} = 0\ m$)
3. bunch -satellite (b,s; $Z_{b,b} = 7.62\ m$)



Collision types and counting rate

Luminosity

number of events per second (counting rate)

$$R_{i,j} = \mathcal{L}_{i,j} \cdot \sigma \qquad \begin{cases} i = b, s \\ j = b, s \end{cases}$$

cross section

$$[\mathcal{L}] = cm^{-2}s^{-1}$$

Collision types and luminosity

$$\mathcal{L}_{b,b} = (N_b f_r)\frac{I_b I_b}{S_{eff,b,b}} \ ; N_b=22;\ z=0\ m$$

$$\mathcal{L}_{s,s} = (N_s f_r)\frac{I_s I_s}{S_{eff,s,s}} \ ; N_s=44;\ S_{eff,s,s} = S_{eff,b,b};\ z=0\ m$$

$$\mathcal{L}_{s,b} = (N_s f_r)\frac{I_s I_b}{S_{eff,s,b}} \ ; N_s=44\ ;\ Z_{bs} = \pm 7.62\ m$$

Collision types and luminosity

$$\mathcal{L}_{b,b}\left(\text{см}^{-2}\text{с}^{-1}\right) = (22 \cdot f_r)\frac{I_b^2}{S_{eff;b,b}}$$

$$\mathcal{L}_{s,s}\left(\text{см}^{-2}\text{с}^{-1}\right) = (44 \cdot f_r)\frac{I_s^2}{S_{eff;s,s}}$$

$$\mathcal{L}_{s,b}\left(\text{см}^{-2}\text{с}^{-1}\right) = (44 \cdot f_r)\frac{I_s I_b}{S_{eff;s,b}}$$

Collision types and counting rate

$$R_{s,s}/R_{b,b} = 2\cdot(I_s/I_b)^2 \le 2\cdot\left(10^{-1}\right)^2 = 0.02$$

$$R_{s,b}/R_{b,b} = 2\cdot\left(\frac{I_s}{I_b}\right)\cdot\left(\frac{S_{eff;bb}}{S_{eff;sb}}\right)$$

$$\frac{1}{S_{eff,bs}} = \int_{-\infty}^{\infty} dz_V \left(\frac{\exp\left(-(z_V - l_{bs})^2/(\sigma_z^2)\right)}{\sqrt{\pi}\sigma_z\cdot\left(S_{eff,\perp}(0)\right)\left(1+(z_V/\beta_{IP})^2\right)}\right)$$

$$\frac{1}{S_{eff,bb}} = \int_{-\infty}^{\infty} dz_V \left(\frac{\exp\left(-(z_V)^2/(\sigma_z^2)\right)}{\sqrt{\pi}\sigma_z\cdot\left(S_{eff,\perp}(0)\right)\left(1+(z_V/\beta_{IP})^2\right)}\right)$$

Collision types and counting rate

$$R_{s,s}/R_{b,b} = 2 \cdot \left(\frac{I_s}{I_b}\right) \cdot \left(\frac{S_{eff;bb}}{S_{eff;ss}}\right) \leq 0.02$$

$$\frac{1}{S_{eff,bb}} = \int_{-\infty}^{\infty} dz_V \left(\frac{\exp\left(-(z_V)^2/(\sigma_z^2)\right)}{\sqrt{\pi}\sigma_z \cdot \left(S_{eff,\perp}(0)\right)\left(1+(z_V/\beta_{IP})^2\right)}\right) = 6.85\ cm^{-2}$$

$$\frac{1}{S_{eff,bs}} = \int_{-\infty}^{\infty} dz_V \left(\frac{\exp\left(-\,(z_V - l_{bs})^2/(\sigma_z^2)\right)}{\sqrt{\pi}\sigma_z \cdot \left(S_{eff,\perp}(0)\right)\left(1+(z_V/\beta_{IP})^2\right)}\right) = 4.14 \cdot 10^{-2} cm^{-2}$$

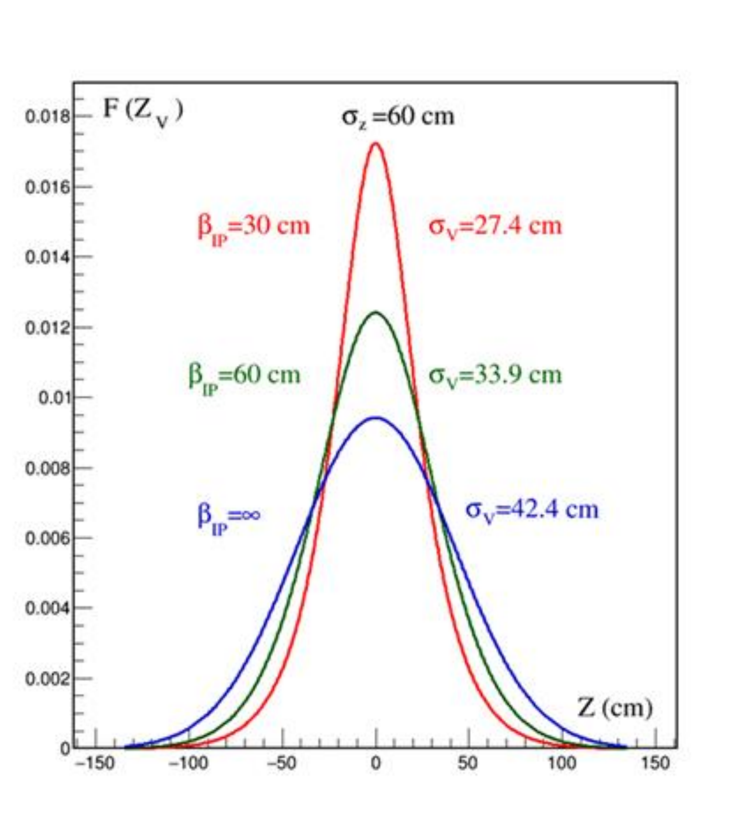
$$R_{s,b}/R_{b,b} = 2 \cdot \left(\frac{I_s}{I_b}\right) \cdot \left(\frac{S_{eff;bb}}{S_{eff;sb}}\right) \leq 0.6 \cdot 10^{-3}$$

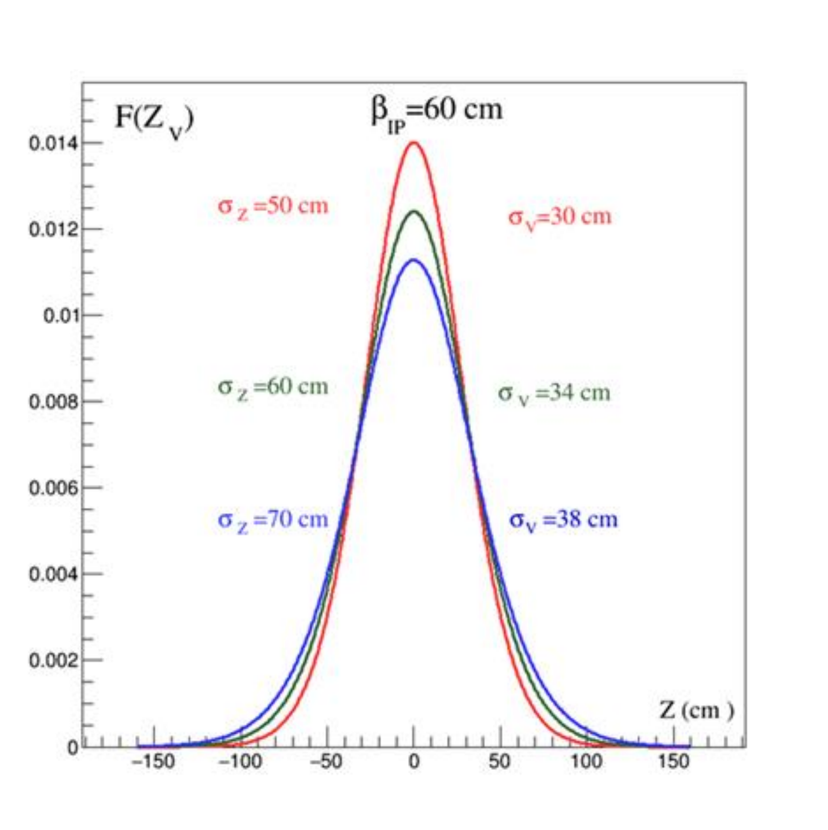
Conclusion I

1. Satellite-satellite collisions contribute no more than 2% to main bunch collisions.

2. Bunch-satellite collisions have a count rate less than three orders of magnitude compared to the count rate for collisions of the main bunches

vertex distribution





$$\tilde{\sigma}_V \approx (\sigma_z \beta_{IP}) / \sqrt{2 \cdot (\beta_{IP}^2 + \sigma_z^2)}$$

$$\sigma_V = 34\ \mathrm{cm}$$

Time structure of AuAu collisions at NICA

Collision parameters (for $\sqrt{S_{NN}} = 11\ \mathrm{GeV}$)

1. Cross section for minimum bias event $\sigma_{AuAu} \approx 6.2\ \mathrm{b}$
2. Max Luminosity $\mathcal{L} = 10^{27}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
3. Counting rate $\mathrm{R} = 6200\ s^{-1} = \mathcal{L} \cdot \sigma_{AuAu}$

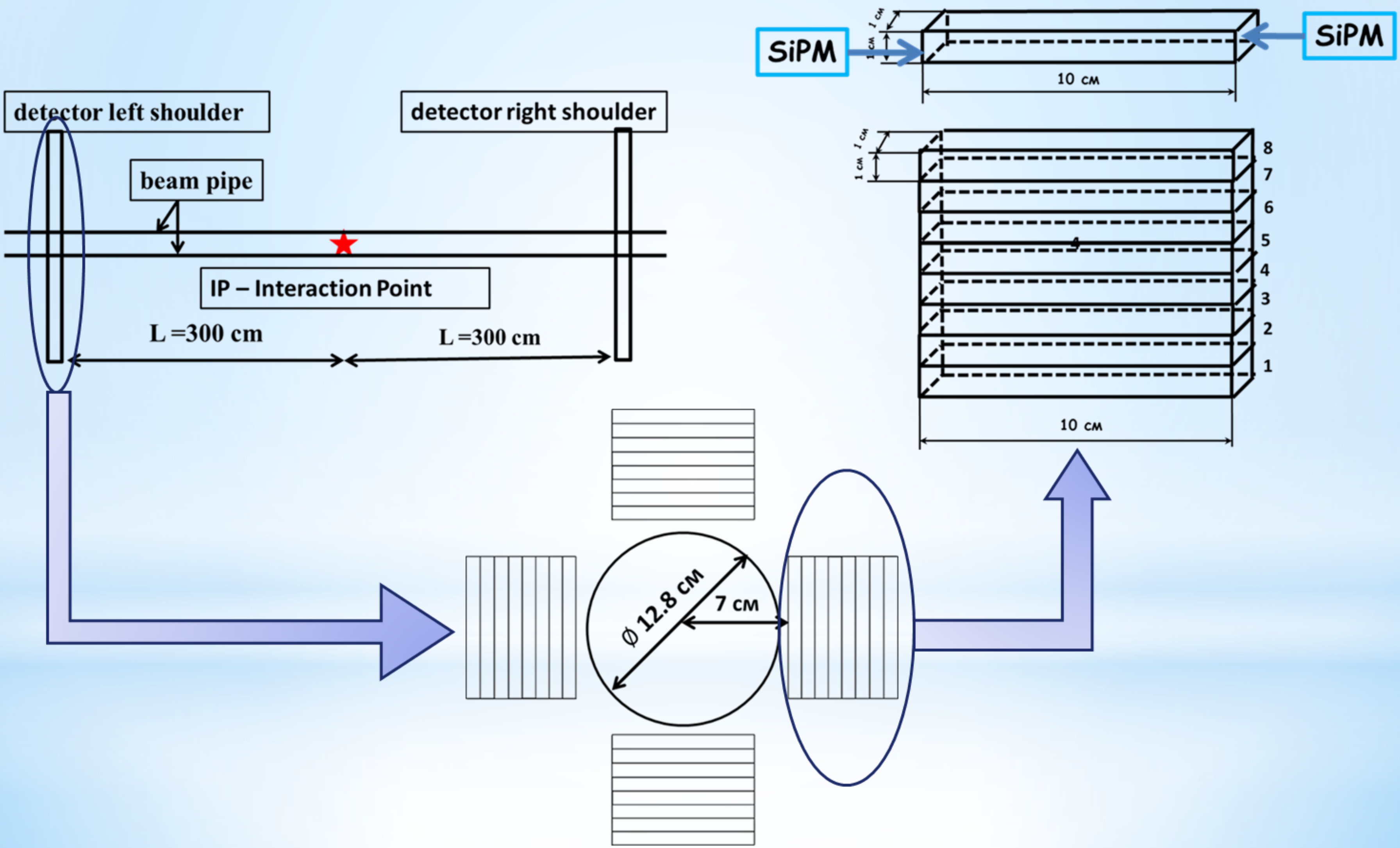
Scattering probability for a single crossing of bunches

$$w_1 = \frac{R}{f_r N_b} \approx 5 \cdot 10^{-4}$$

Admixture of pile up events for $t \leq 100\ ns$

$< 10^{-4}$ negligible

Detector

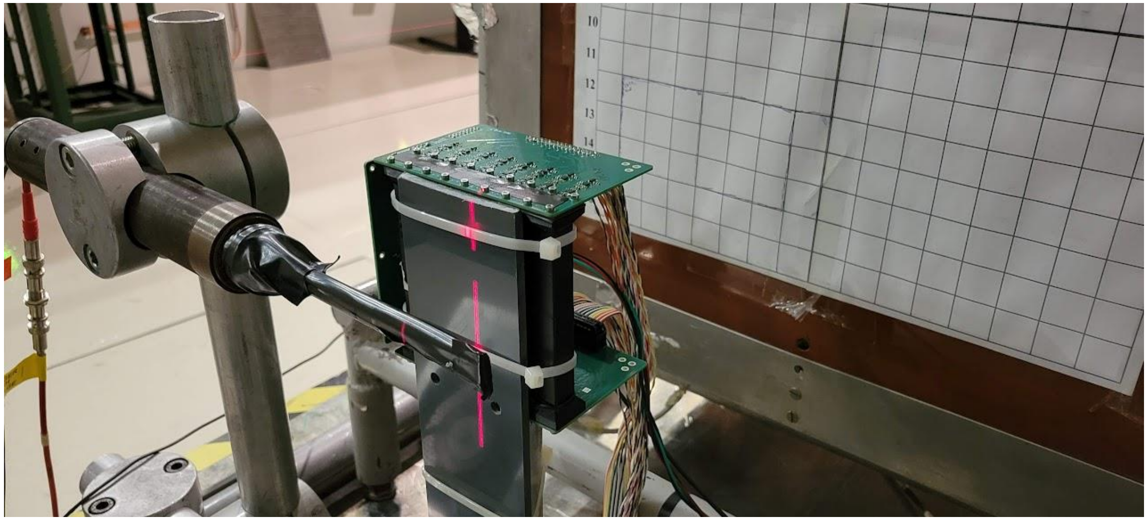


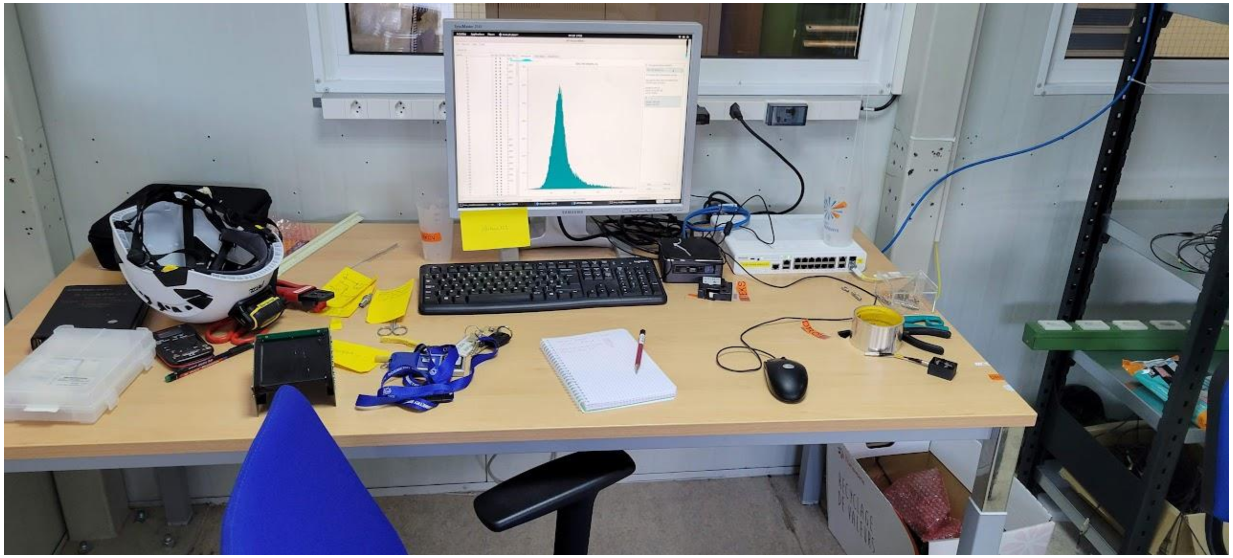
SiPM
SiPM
1 cm
1 cm
10 cm
detector left shoulder
detector right shoulder
beam pipe
IP – Interaction Point
L =300 cm
L =300 cm
8
7
6
5
4
3
2
1
10 cm
ϕ 12.8 cm
7 cm

Beam test at CERN

S.G.Buzin, M.G.Buryakov

Two planes





Detector, carent status

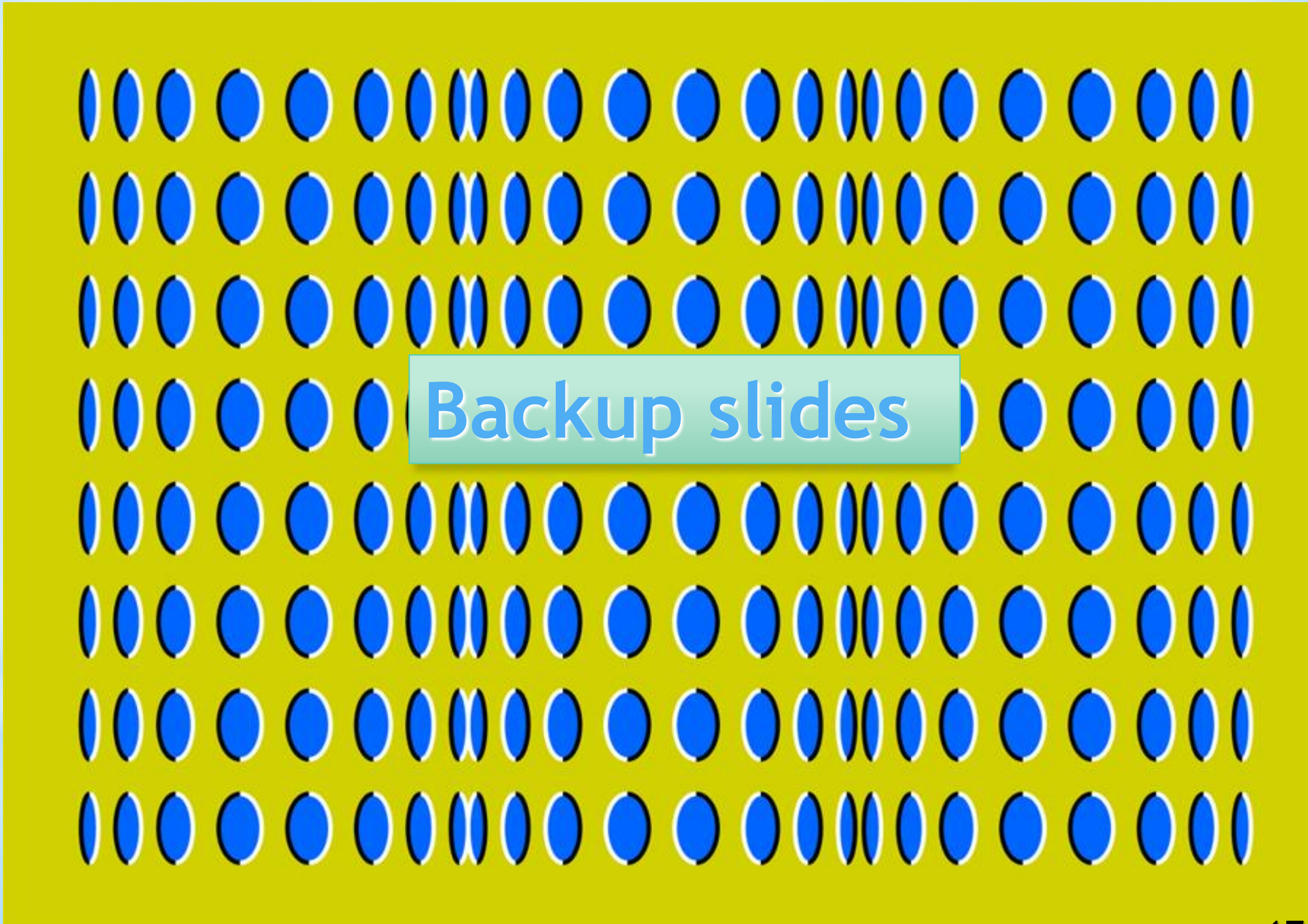
1. Two planes assembled.
2. Test measurement results are analyzed.
3. A solution to the SiPM heating problem is being studied.
4. The design of the luminosity detector installation is being developed on the MPD and separately from the MPD.
5. TDR in preparation.

Some achievements

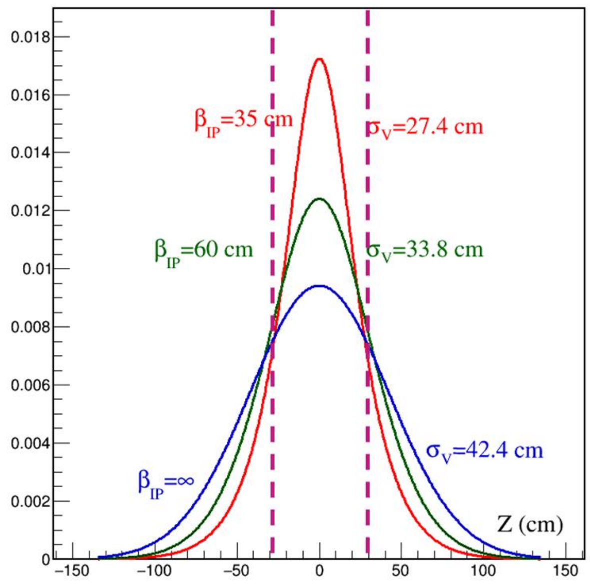
1. An article describing the operation of the detector (24 pages) will be published in No.5 (2023) of Nuclear Physics (Rus.).
2. An article on the study of the distribution of interaction vertices will be submitted for publication (Pepan Letters) no later than the end of May.
3. Received a grant from the Russian Science Foundation

   (2 years, 3,000,000 ₽)

Backup slides



Efficiency, Luminosity and beta function



$$N_L = N_R = 2.8 \cdot 10^9$$

$$\sigma_x = 1.1\ \text{mm};\ \sigma_y = 0.82\ \text{mm}$$

$$-30\ \text{cm} \leq Z_V \leq 30\ \text{cm}$$

	$\beta_{IP} = 35$ cm	$\beta_{IP} = 60$ cm	$\beta_{IP} = 10^4$ cm
$\mathcal{L}\ (cm^{-2}s^{-1})$	$5 \cdot 10^{26}$	$6.9 \cdot 10^{26}$	$9.1 \cdot 10^{26}$
Eff (ε)	0.756	0.635	0.517
$\mathcal{L}(cm^{-2}s^{-1})\varepsilon$	$3.8 \cdot 10^{26}$	$4.4 \cdot 10^{26}$	$4.7 \cdot 10^{26}$

Tasks for the luminosity detector

1. finding the parameters of the collider, for the most efficient hit of bunches into each other;
2. finding the parameters of the collider that optimize the transverse profile of colliding beams;
3. selection of collider parameters that optimize the longitudinal position of the interaction vertex

two observables

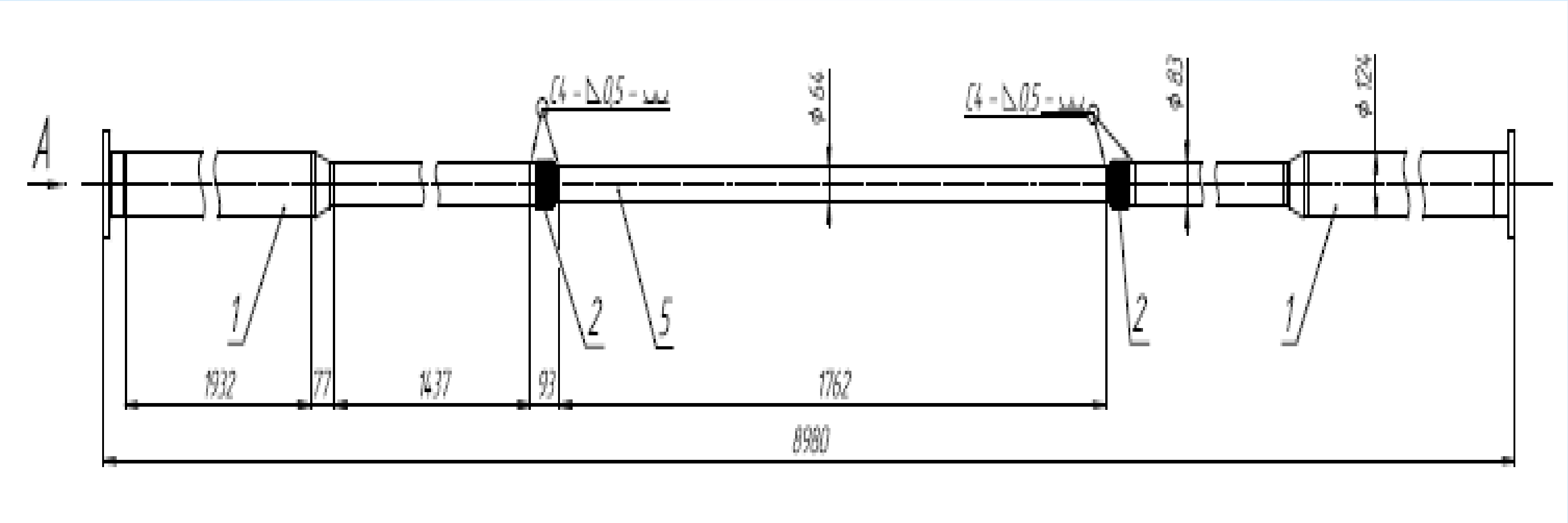
- ✓ the first one is the counting rate
- ✓ the second one is the distribution of interaction vertices obtained from ToF

Ion guide on MPD

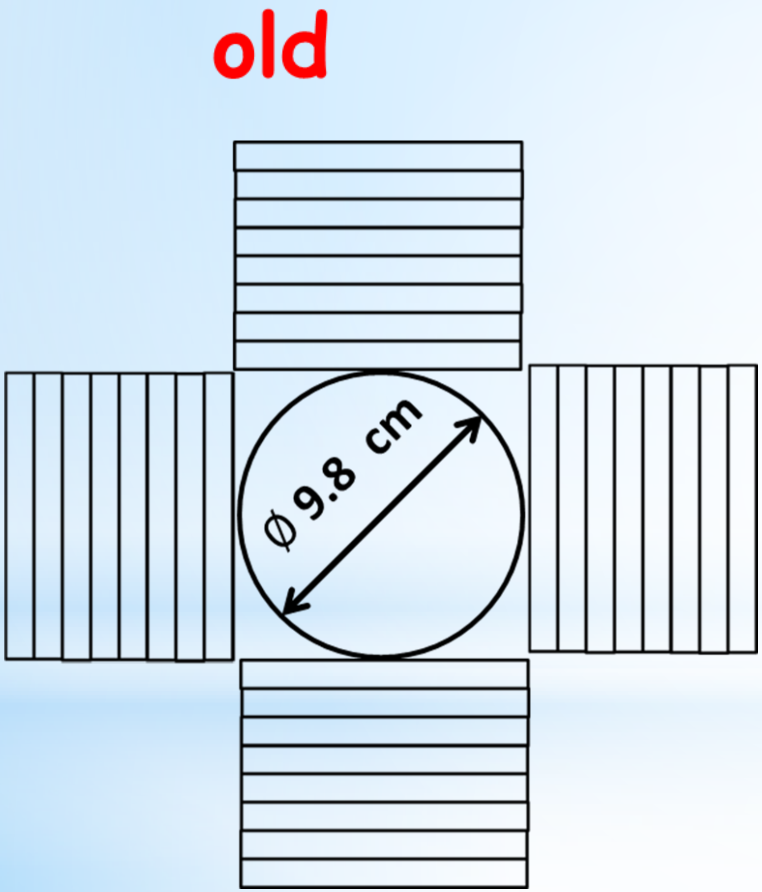
old

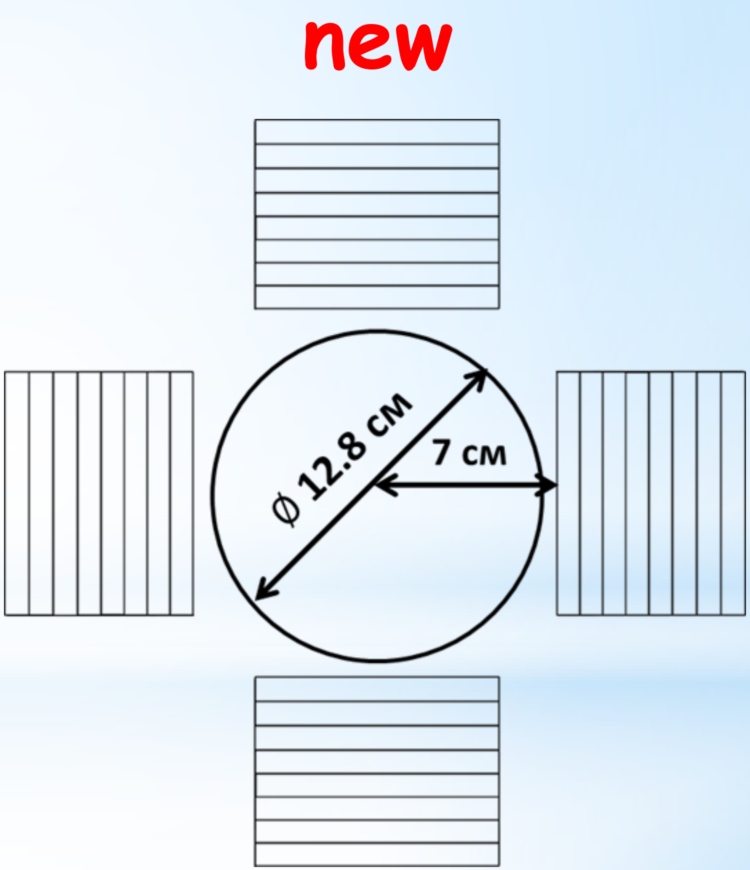
Ø 10 мм

new



What has changed since April this year





What has changed since April this year

$\sqrt{S_{NN}} = 11\ \mathrm{GeV}$

old	new
$\varepsilon = 82\%$	$\varepsilon = 77\%$
$R \approx 4900\ 1/s\,;(\approx 1.4\ \%)$	$R \approx 4600\ 1/s\,;(\approx 1,5\ \%)$

Efficiency = Detected/Produced

DCM-SMM (M. Baznat, A. Botvina, G. Musulmanbekov, V. Toneev, V. Zhezher, //arXiv:1912.09277 [nucl-th], 2019)

Time of Flight for Left and Right Shoulders

$$T_{L/R} = \min\{T_{L/R,\,i}\}$$

Trigger

$$|T_L - T_R| \leq 10 \text{ нс}$$

Efficiency

$\varepsilon =$ ~~82%~~ $\rightarrow \varepsilon = 77\%$

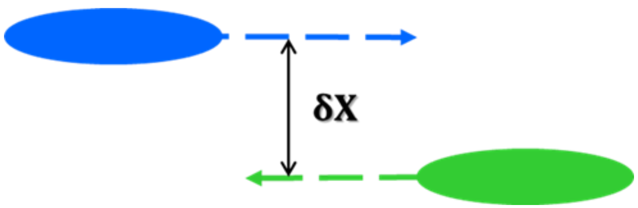
Efficiency = Detected/Produced

DCM-SMM (M. Baznat, A. Botvina, G. Musulmanbekov, V. Toneev, V. Zhezher, //arXiv:1912.09277 [nucl-th], 2019)

Transverse plane. Luminosity structure. Van der Meer scan.

$$\mathcal{L}(\delta X, \delta Y) = f_r \cdot N_b \cdot \frac{N_L N_R}{S_{eff}(\delta X, \delta Y)}$$

N_L, N_R-number of the beam ions in the left and right bunches



Van der Meer scan.

For normal distribution

$$\mathcal{L}(\delta X, \delta Y) = f_r \cdot N_b \cdot \frac{N_L N_R}{4\pi\sigma_x\sigma_y} \exp\left(-\frac{\delta X^2}{2\sigma_x^2}\right) \cdot \exp\left(-\frac{\delta Y^2}{2\sigma_y^2}\right)$$

Adjustment of beam convergence in the transverse plane

Conclusion I

Conclusion I

estimated time to adjust the convergence of beams in the transverse plane is about three hours
1.5 h – data taking;
1.5 h – setting collider modes;

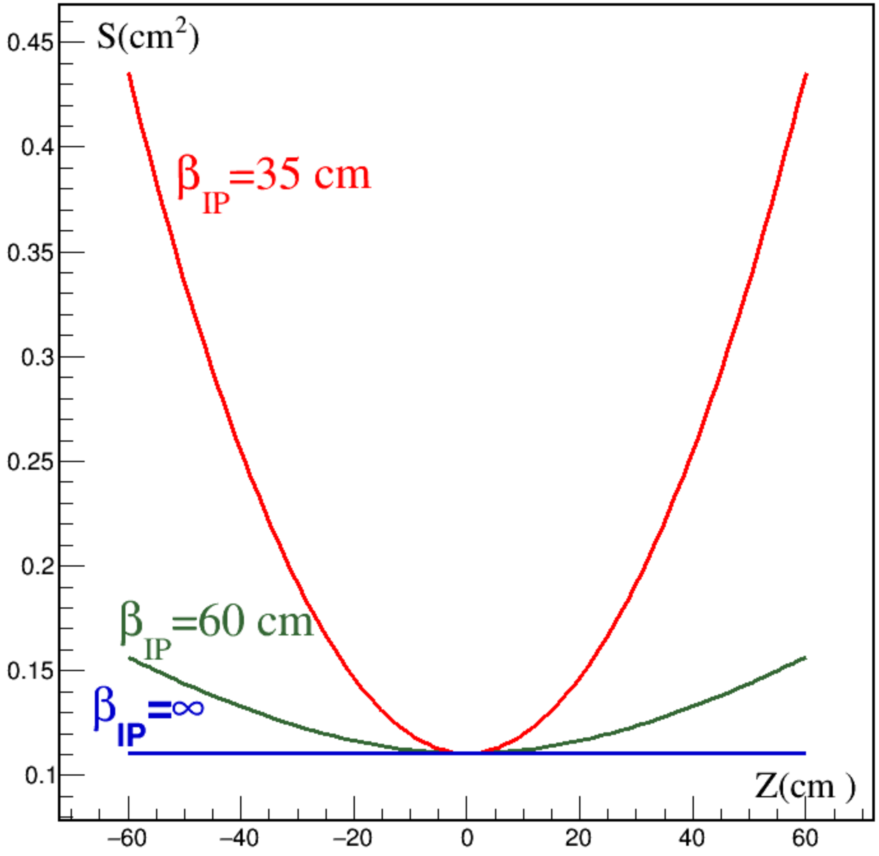
$\mathcal{L} = 10^{27}\ cm^{-2}s^{-1}$

δX	$N_{tr}/(10\ min)$	Errors
0	2 760 000	0.06 %
$\delta X = \sigma_X$	1 764 025	0.07 %
$\delta X = 2\sigma_X$	373525	0.16%
$\delta X = 3\sigma_X$	30661	0.60%

$\mathcal{L} = 10^{25}\ cm^{-2}s^{-1}$

δX	$N_{tr}/(10\ min)$	Errors
0	27600	0.6 %
$\delta X = \sigma_X$	17640	0.75 %
$\delta X = 2\sigma_X$	3735	1.6%
$\delta X = 3\sigma_X$	307	5%

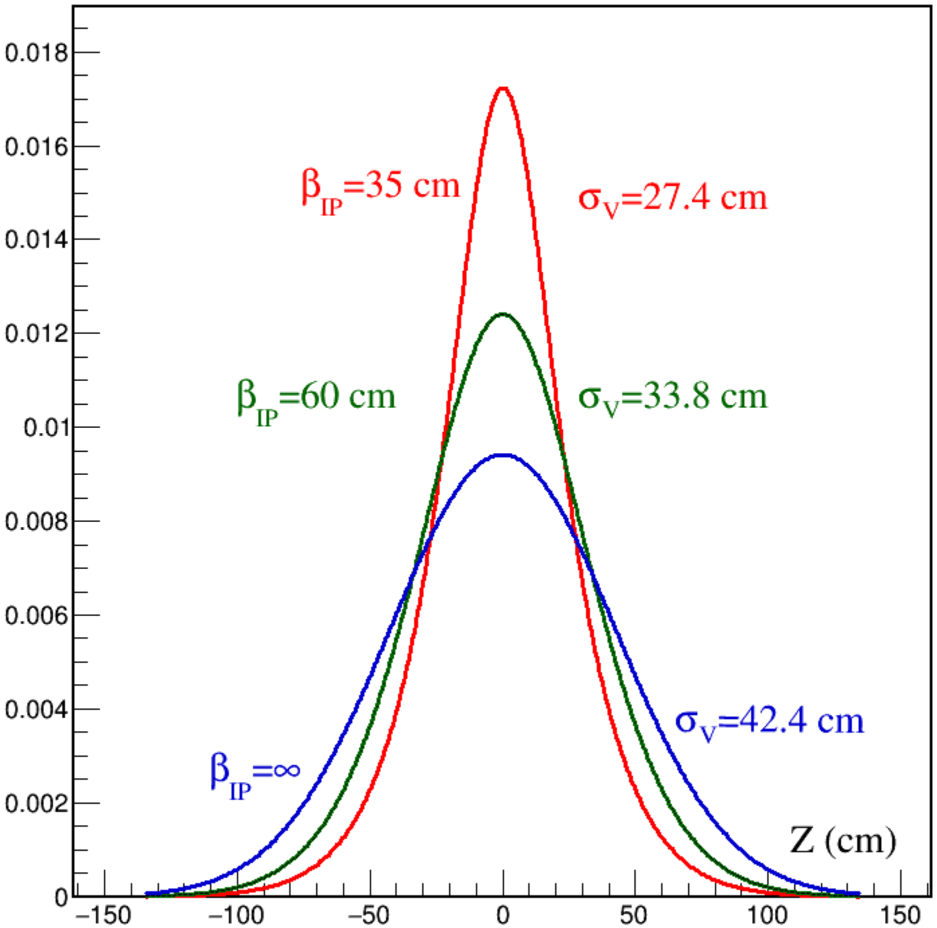
Beta function



Transverse area

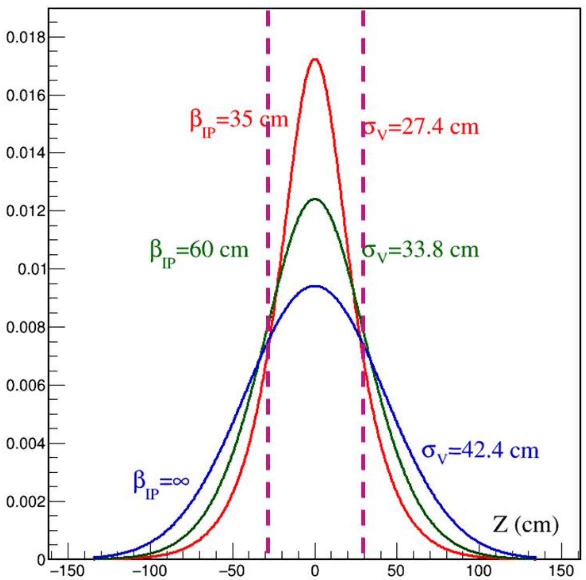
$$\mathbf{S}_{\mathbf{eff},\perp}(Z) = \mathbf{S}_{\mathbf{eff},\perp}(\mathbf{0})\left(\mathbf{1} + (\mathbf{Z}/\boldsymbol{\beta}_{\mathbf{IP}})^{\mathbf{2}}\right)$$

Distribution of interaction vertices



$$
\begin{cases}
P(Z_V) = N \dfrac{\exp\left(-Z_V^2/\sigma_Z^2\right)}{\left(1+\left(Z_V/\beta_{IP}\right)^2\right)} \\
N = \dfrac{1}{\int_{-\infty}^{\infty} \dfrac{\exp\left(-Z_V^2/\sigma_Z^2\right)}{\left(1+\left(Z_V/\beta_{IP}\right)^2\right)}\, dZ_V}
\end{cases}
$$

Efficiency, Luminosity and beta function



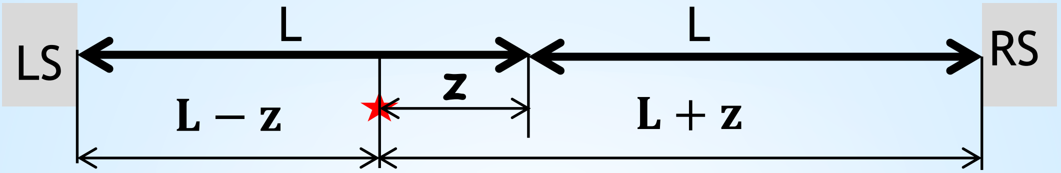
$$\mathbf{N_L = N_R = 2.8 \cdot 10^9}$$

$$\mathbf{\sigma_x = 1.1\ mm;\ \sigma_y = 0.82\ mm}$$

$$\mathbf{-30\ cm \leq Z_V \leq 30\ cm}$$

	$\beta_{IP} = 35$ cm	$\beta_{IP} = 60$ cm	$\beta_{IP} = 10^4$ cm
$\mathcal{L}\ (cm^{-2}s^{-1})$	$5 \cdot 10^{26}$	$6.9 \cdot 10^{26}$	$9.1 \cdot 10^{26}$
Eff (ε)	0.756	0.635	0.517
$\mathcal{L}(cm^{-2}s^{-1})\varepsilon$	$3.8 \cdot 10^{26}$	$4.4 \cdot 10^{26}$	$4.7 \cdot 10^{26}$

Vertex position



$$T_L = \frac{L-z}{c\beta}\ ;\ T_R = \frac{L+z}{c\beta};\ \tau = T_R - T_L = \frac{2z}{c\beta}$$

$$c = 3 \cdot 10^8;\ \beta = p/E;\ \sqrt{S_{NN}} = 11 \rightarrow \beta = 0.985 \approx 1$$

$$z = \frac{1}{2} c \cdot \tau \rightarrow z(\mathrm{cm}) = 15 \cdot \tau(\mathrm{ns})$$

$$\sigma_\tau = (300 \div 400)\ \mathrm{ps}\ ;\ \rightarrow \sigma_{z,\tau} \approx (4.5 \div 6)\ \mathrm{cm}$$

Z coordinate. Maximum of interaction point distribution from ToF

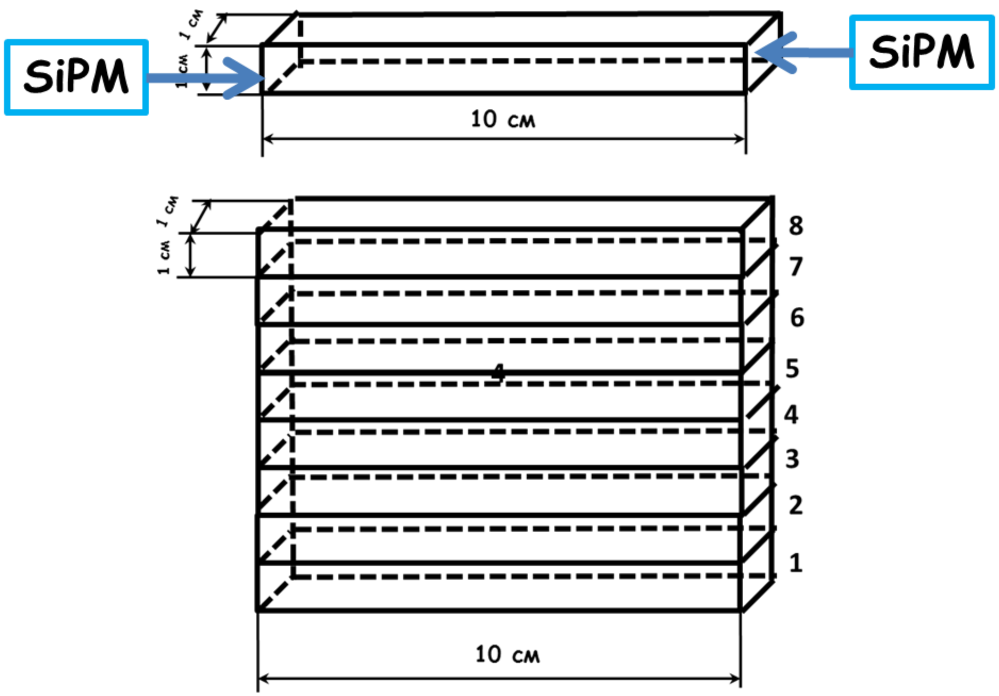
$$\tilde{\sigma}_z = \sqrt{\left(\sigma_{z,V}^2 + \sigma_{z,\tau}^2\right)} = 34 \cdot (1 + 0.016)\ \text{cm}$$

$$\Delta Z(\text{cm}) = \frac{\tilde{\sigma}_z}{\sqrt{\text{N}_{\text{tot}}}} = \frac{34 \cdot (1 + 0.016)\ \text{cm}}{\sqrt{\text{N}_{\text{tot}}}}$$

$$\mathcal{L} = 10^{25}\ cm^{-2} s^{-1}$$

δX	$N_{tr}/(10\ min)$	Errors
0	27600	0.6 %
$\delta X = \sigma_X$	17640	0.75 %
$\delta X = 2\sigma_X$	3735	1.6%
$\delta X = 3\sigma_X$	307	5%

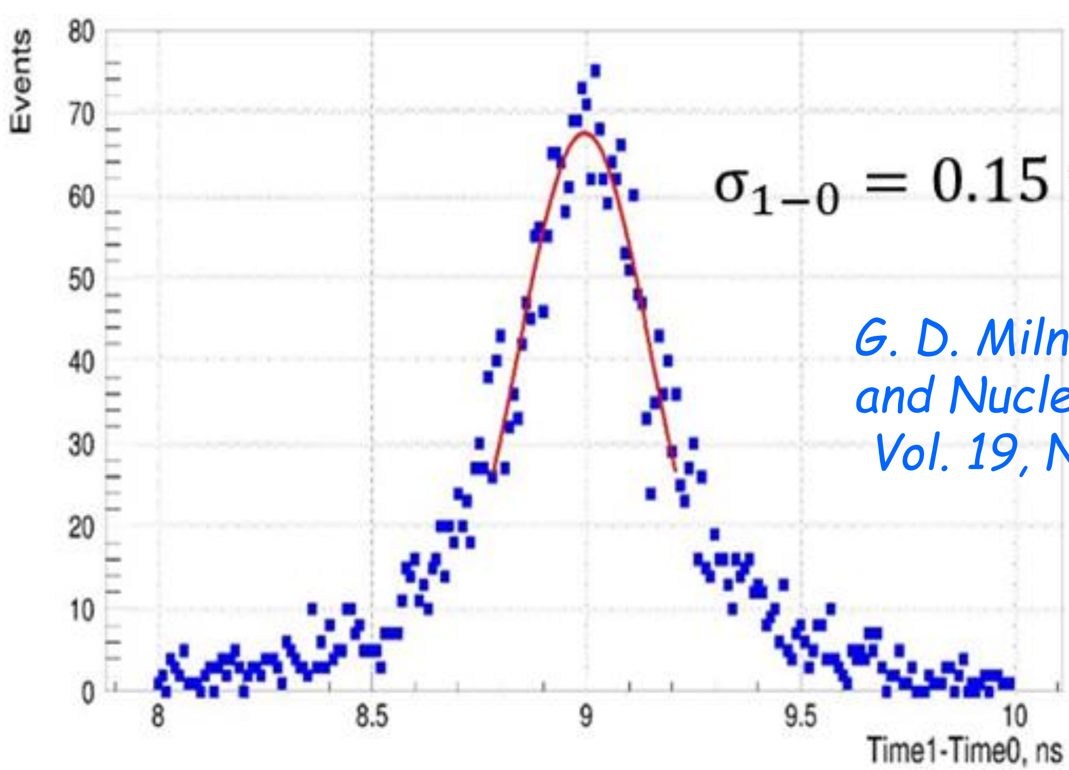
One plane of detector



The plane consists of $100x10x10$ mm^3 plastic scintillator (organic polystyrene (PS) scintillator with the addition of 1.5% p-terphenyl and 0.05% POPOP) strips viewed from both sides with silicon photomultipliers (SiPM HAMAMATSU S13360-6025CS)

Space muons. ToF of counters

$$\sigma_{1-0} = \sqrt{2\sigma^2} \rightarrow \sigma = \sigma_{1-0}/\sqrt{2}$$



$\sigma \approx 100$ ps

$\sigma_{1-0} = 0.15$ ns

G. D. Milnov et al., Physics of Particles and Nuclei Letters, 2022, Vol. 19, No. 4, pp. 362–367.

Adjustment of beam convergence along interaction line

Conclusion II

setting beam convergence along the collision axis does not require record time-of-flight resolutions. Even 400 picoseconds enough.

$$\Delta Z(\mathrm{cm}) = \frac{\tilde{\sigma}_z}{\sqrt{\mathrm{N_{tot}}}} = \frac{34 \cdot (1 + 0.016)\ \mathrm{cm}}{\sqrt{\mathrm{N_{tot}}}}$$

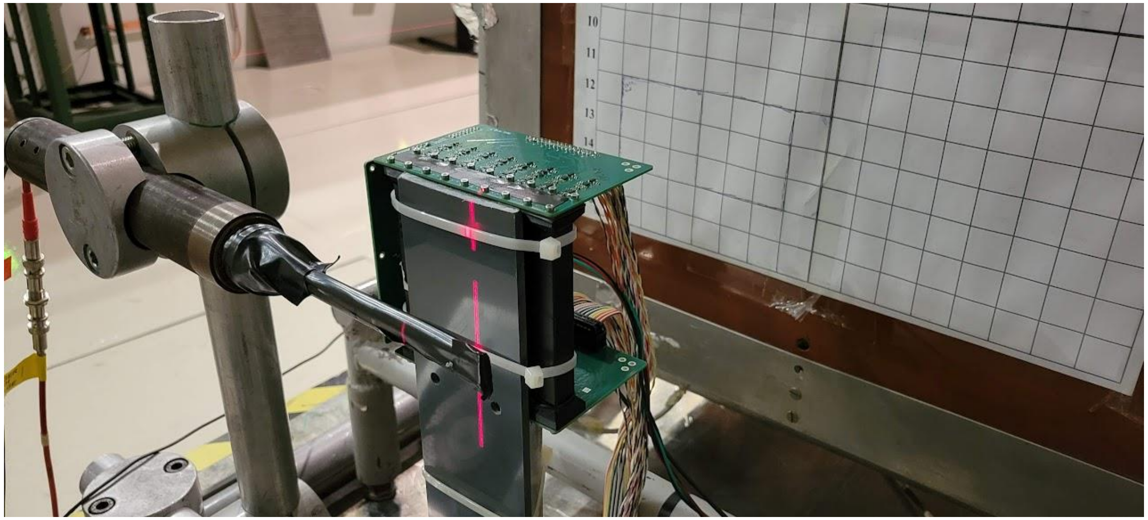
$$\mathcal{L} = 10^{25}\ cm^{-2} s^{-1}$$

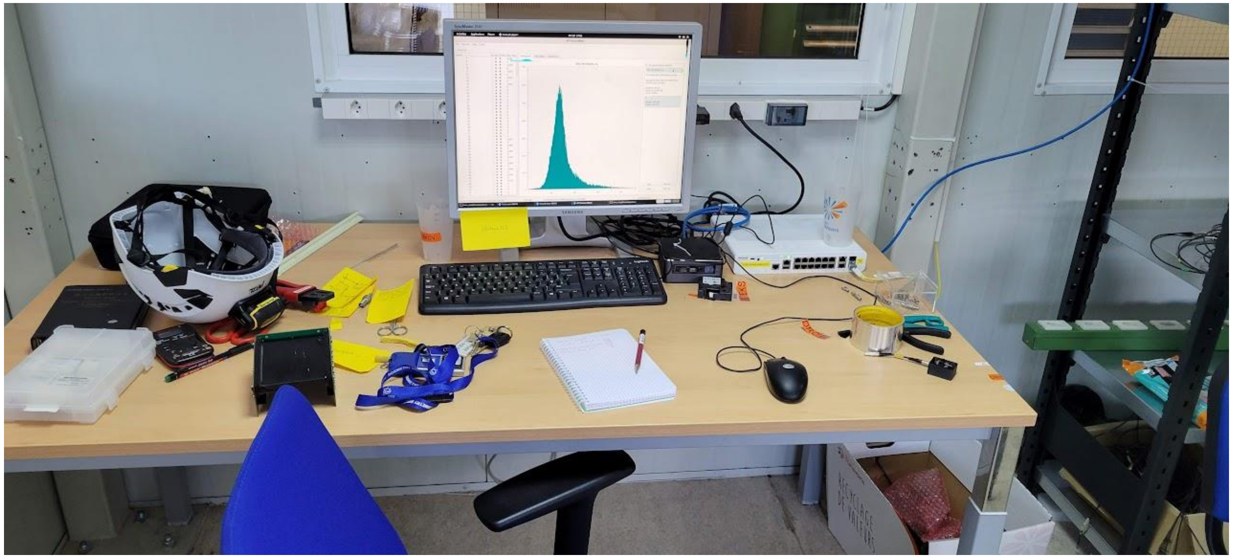
δX	$N_{tr}/(10\ min)$	Errors
0	27600	0.6 %
$\delta X = \sigma_X$	17640	0.75 %
$\delta X = 2\sigma_X$	3735	1.6%
$\delta X = 3\sigma_X$	307	5%

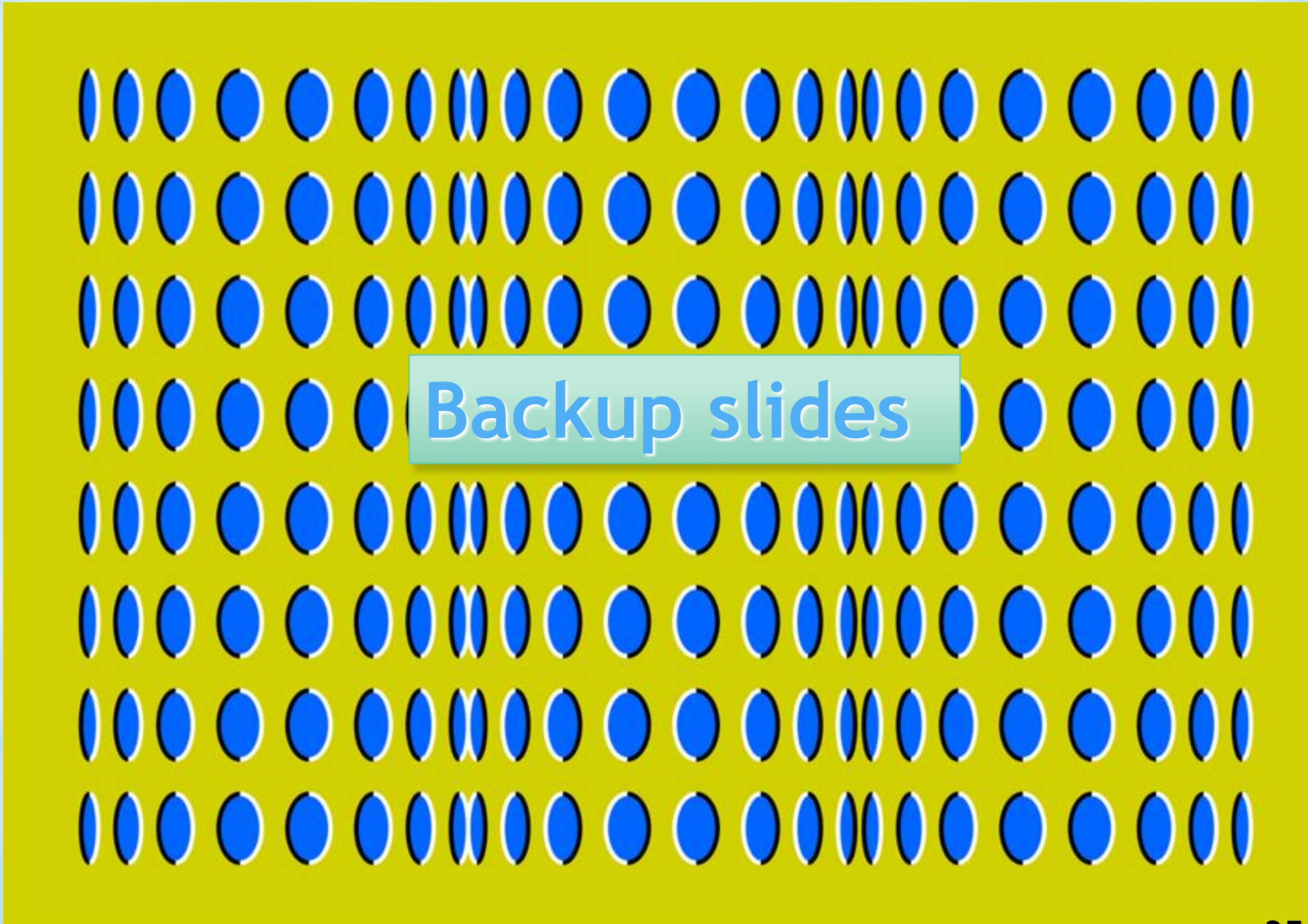
Beam test at CERN

S.G.Buzin, M.G.Buryakov

Two planes

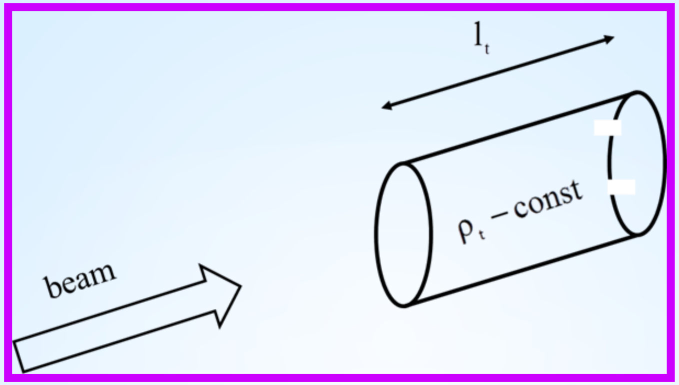






Backup slides

Fixed target luminosity



$$\mathcal{L} = \frac{N_{bm} N_t f}{S}$$

- Nt - the number of target atoms in volume through which the beam passes
- N_{bm} - numbers of particles per burst
- f - repetition rate
- S - transverse beam area

Fixed target luminosity

$$\mathcal{L} = N_{bm} N_A \frac{\rho(g/cm^3) l_t(см)}{A_t} f$$

Example

Nuclotron $f = 0.1\ 1/s$

$A_t = 208$ (Pb)

l_t = 0.1 cm

$N_{bm} = 10^{10}$

$$\mathcal{L} = 3.3 \cdot 10^{30}\ cm^{-2} s^{-1}$$

Time structure of AuAu collisions at NICA

Collision parameters (for $\sqrt{S_{NN}} = 11\ \mathrm{GeV}$)

1. Cross section for minimum bias event $\sigma_{AuAu} \approx 6.2\ \mathrm{b}$
2. Max Luminosity $\mathcal{L} = 10^{27} \mathrm{cm}^{-2} \mathrm{s}^{-1}$
3. Counting rate $\mathrm{R} = 6200\ s^{-1} = \mathcal{L} \cdot \sigma_{AuAu}$

Scattering probability for a single crossing of bunches

$$w_1 = \frac{R}{f_r N_b} \approx 5 \cdot 10^{-4}$$

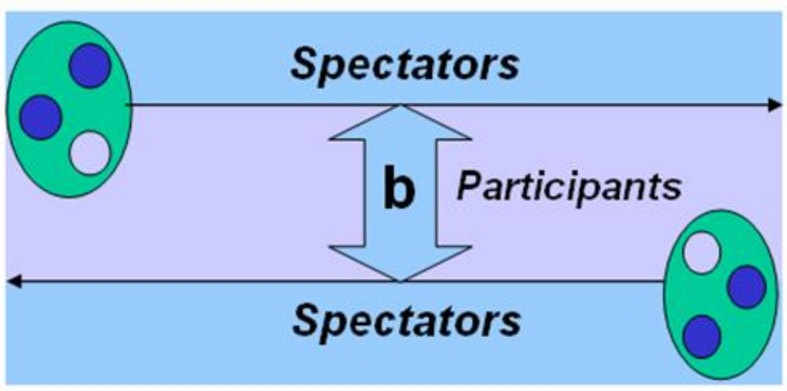
Admixture of pile up events for $t \leq 100\ ns$

$< 10^{-4}$ **negligible**

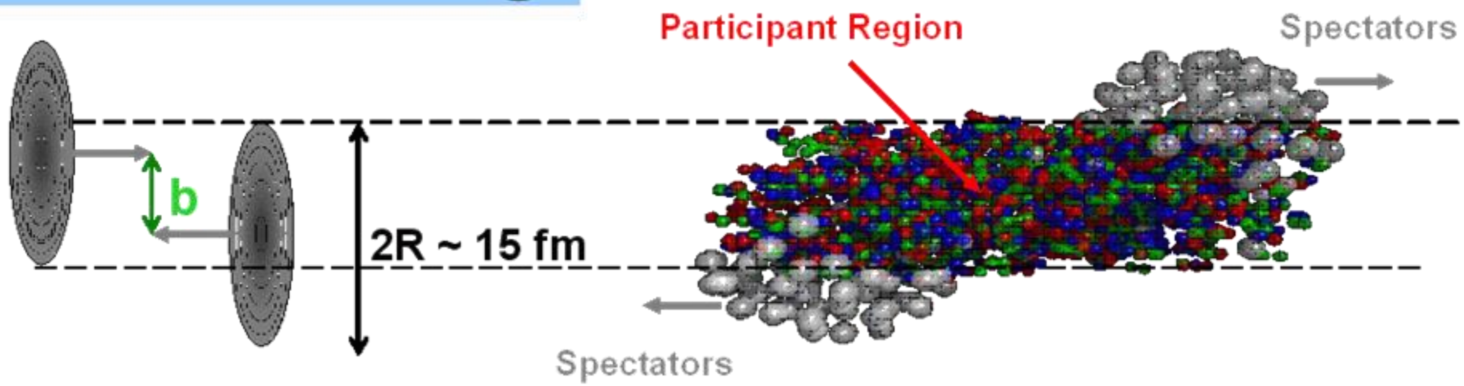
Favorable conditions for creating a "luminosity detector"

- Topology of Au + Au collisions when in a cone $\theta \leq 4^0$ along both beams many spectators are flying ($E_s \approx E_b = 5.5$ GeV) ($_{79}$Au)). Convenient for trigger.
- Long time between neighboring collisions. No overlapping events.
- The role of scattering on the residual gas is small.
  - ✓ Low counting rate.
  - ✓ Small energy.
  - ✓ Large asymmetry of events.

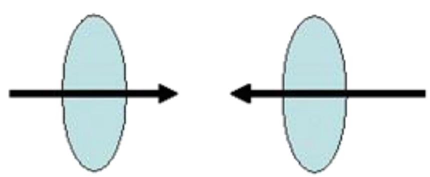
The centrality determination - the observables:



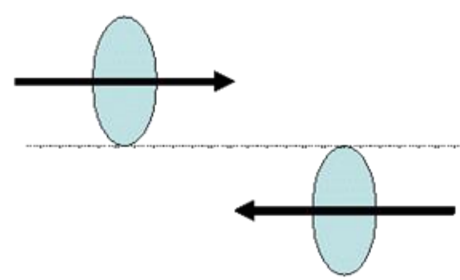
- The number of particles produced in the region of rapidity close to zero
- The total energy of spectators



Central collision, b = 0



Peripheral collision, b ≈ 2R

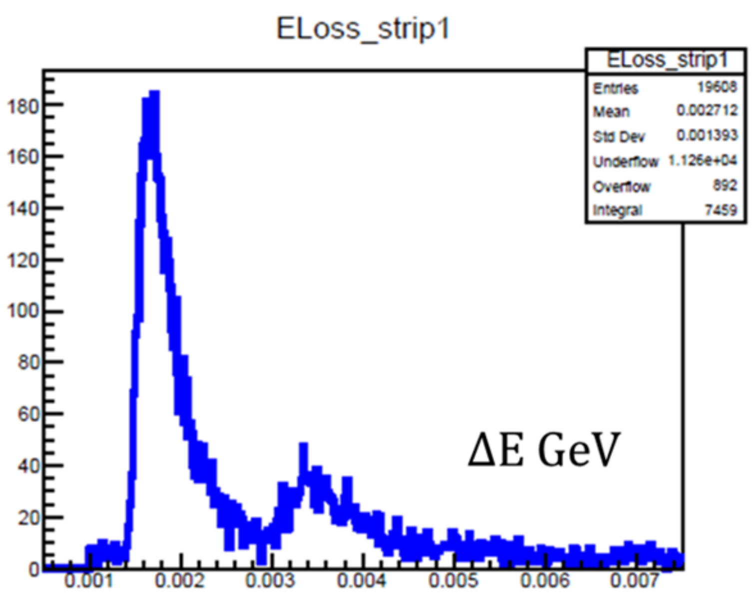


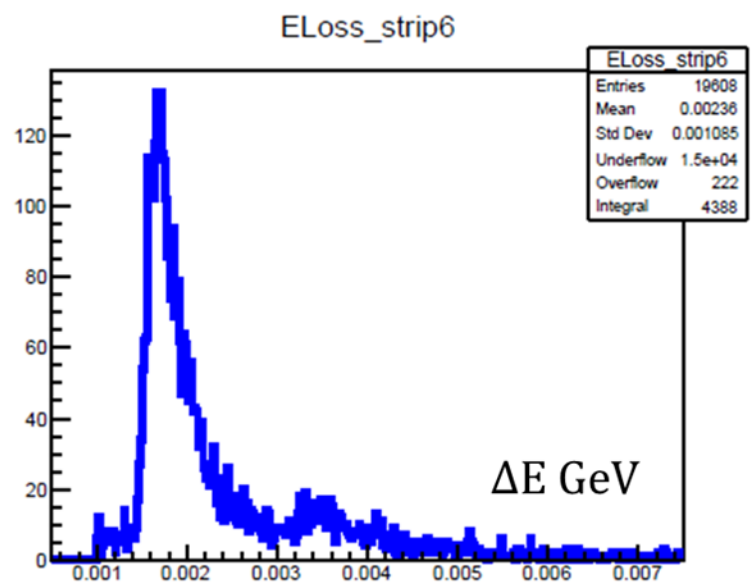
Simulation

Detector operating conditions ($\sqrt{S_{NN}} = 11\ \mathrm{GeV}$)

Spectator energy $E_S \approx 5.5\ \mathrm{Gev/c}$

Energy loss spectrum in the scintillator

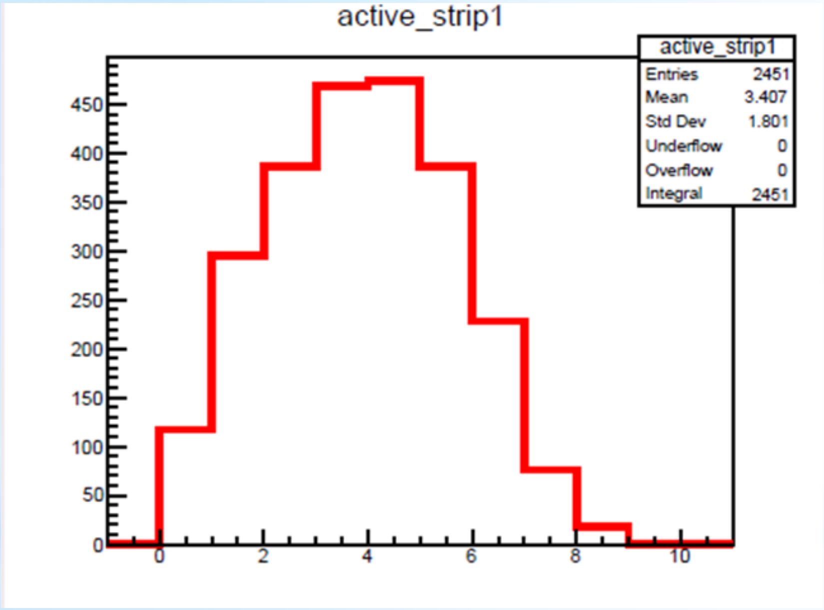


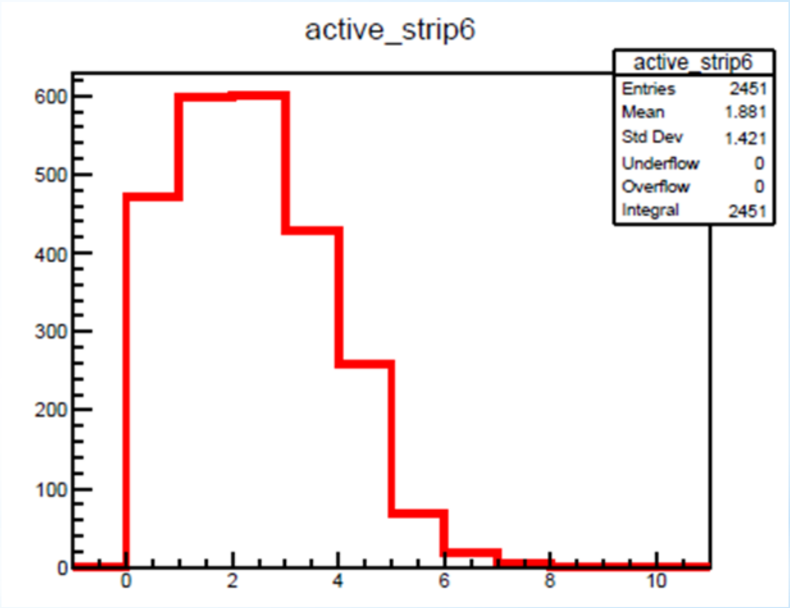


Simulation

Detector operating conditions $(\sqrt{S_{NN}} = 11\ \text{GeV})$

strip occupancy (per 4 strips)





$$\langle n \rangle_1 = \frac{3.4}{4} = 0.85$$

$$\langle n \rangle_6 = \frac{1.88}{4} = 0.47$$

III. absolute luminosity

S. van der Meer, CERN-ISR-PO-68-31, 1968

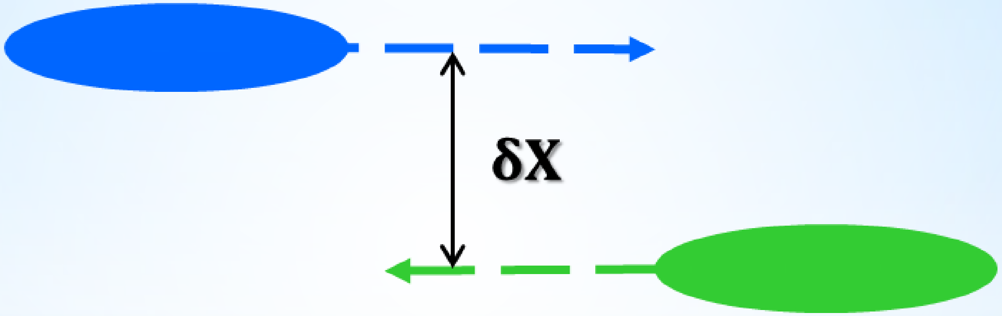
van der Meer scan

CALIBRATION OF THE EFFECTIVE BEAM HEIGHT IN THE ISR

ISR-PO/68-31
June 18th, 1968

by

S. van der Meer



at RHIC and LHC the van der Meer scan is commonly accepted procedure for calibration

Definitions and normalizations

$$\mathcal{L} = \ (N_L N_R \mathrm{f_r N_b})/(\mathrm{S_{eff}})$$

$$\frac{1}{\mathrm{S_{eff}(\delta X, \delta Y)}} = \left(\int_{-\infty}^{\infty} \mathrm{dx\, p_\perp(x - \delta X/2) p_\perp(x + \delta X/2)}\right) \cdot \left(\int_{-\infty}^{\infty} \mathrm{dy\, p_\perp(y - \delta Y/2) p_\perp(y + \delta Y/2)}\right)$$

$$\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} d(\delta X) d(\delta Y) \frac{1}{S_{eff}(\delta \mathrm{X}, \delta Y)} = 1$$

III. absolute luminosity

$$\mathcal{L} = \frac{\dfrac{dR_{1,2}(0,0)}{dt}}{\iint \dfrac{dr_{1,2}(\delta X, \delta Y)}{dt} d\delta X d\delta Y}$$

stage 0

IN THE BEGINNING

$$S \sim (N_b)^2$$

$$B \sim N_b$$

N_b(1/bunch)	$\mathcal{L}$ ($cm^{-2}s^{-1}$)	N_{AuAu}(1/s)	$N_{\mathcal{L}D}$ (1/s)	N_{AuAu}(1/m)	$N_{\mathcal{L}D}$ (1/m)	B/S
$2 \cdot 10^9$	10^{27}	6000	4900	360000	294000	$< 10^{-5}$
$2 \cdot 10^8$	10^{25}	60	49	3600	2940	$< 10^{-4}$
$2 \cdot 10^7$	10^{23}	0.6	0.49	36	29.4	$< 10^{-3}$
$2 \cdot 10^6$	10^{21}	0.006	0.0049	0.36	0.29	$< 10^{-2}$