Detector for beams tuning and absolute luminosity measurements in the interaction point at MPD@NICA

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on behalf of the working group

beam convergence procedure
at the point of the interaction

working group

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A.B.Kurepin,

Anyone wellcome

Luminosity

number of events per second

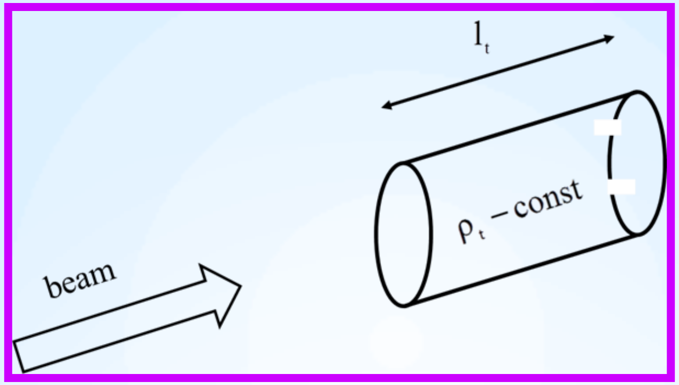
$$\frac{dR}{dt} = \mathcal{L} \cdot \sigma$$

cross section

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

key parameter of collider

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

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

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

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

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

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

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

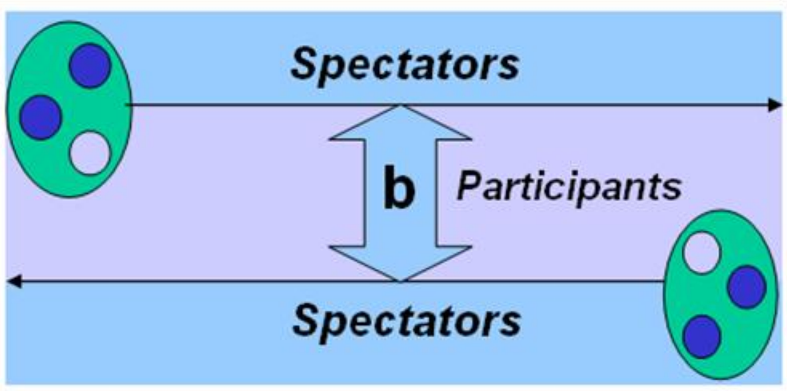
Admixture of pile up events for $t \leq 100\ ns$

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

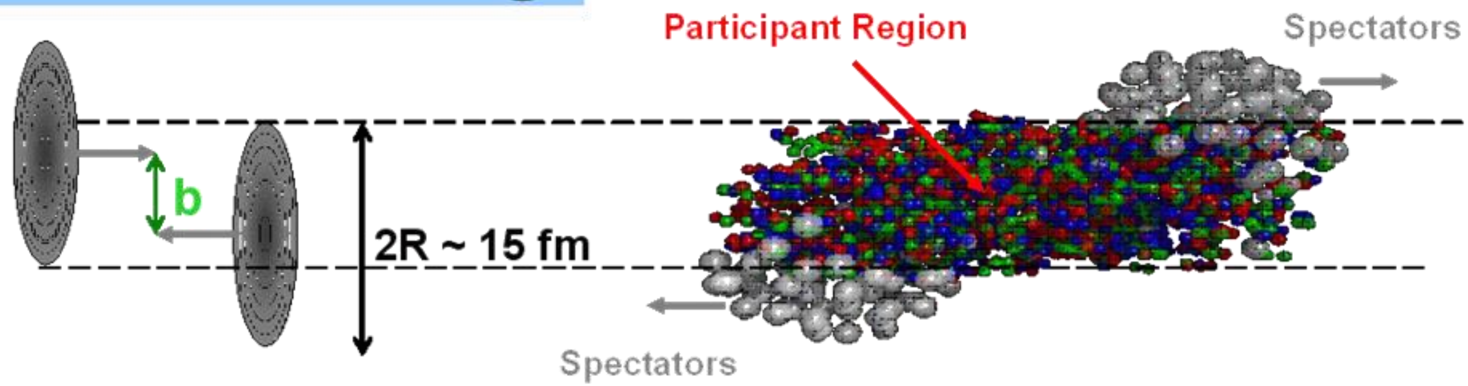
Favorable conditions for creating a "luminosity detector"

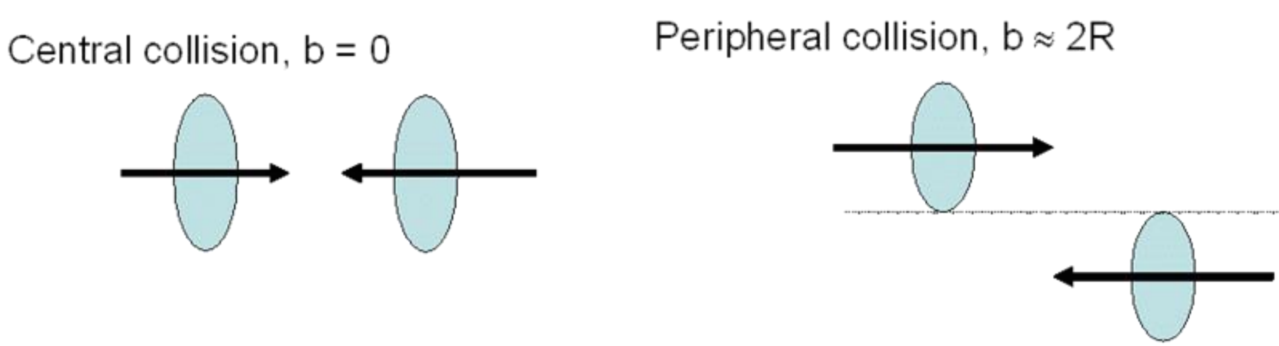
- Topology of Au + Au collisions when in a cone $\theta \leq 4^0$ along both beams many spectators are flying ($E_s \approx E_b = 5.5$ GeV) ($_{79}$Au)). Convenient for trigger.
- Long time between neighboring collisions. No overlapping events.
- The role of scattering on the residual gas is small.
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

The centrality determination – the observables:

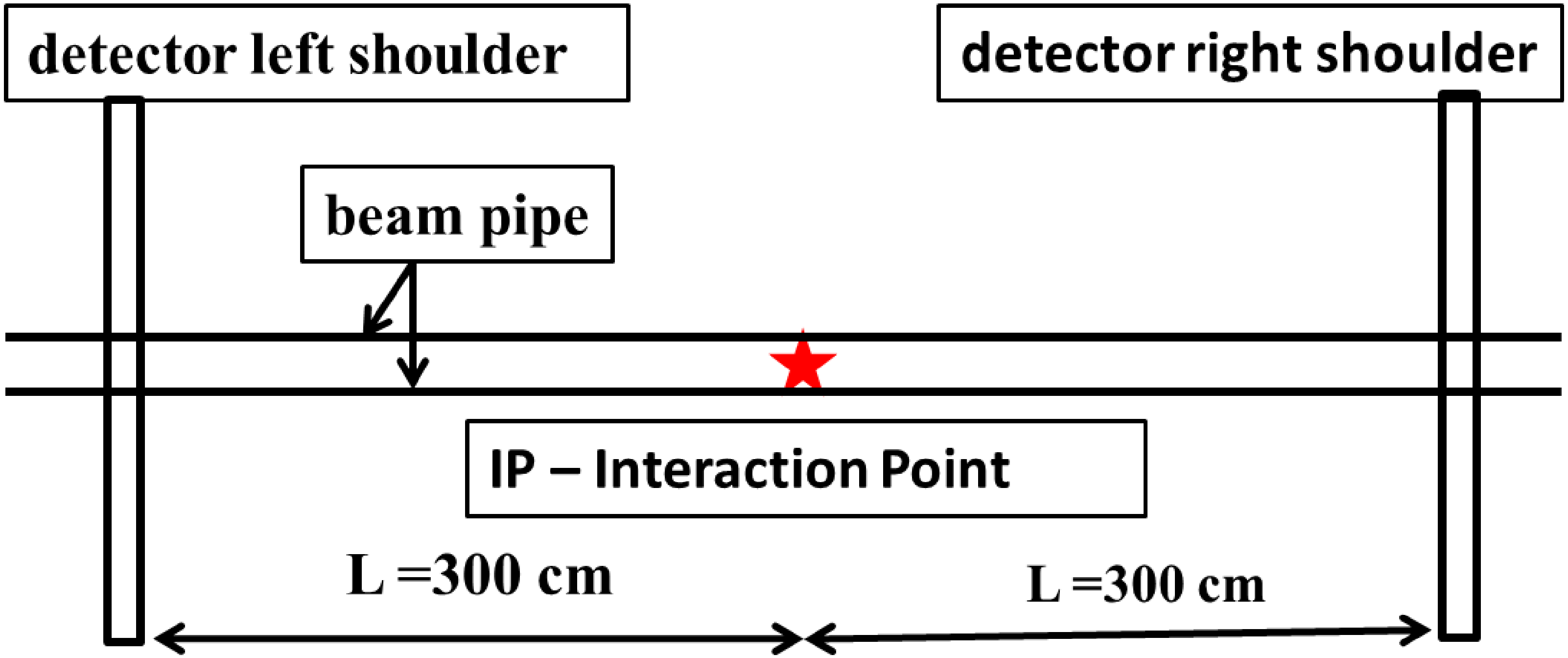


- The number of particles produced in the region of rapidity close to zero
- The total energy of spectators

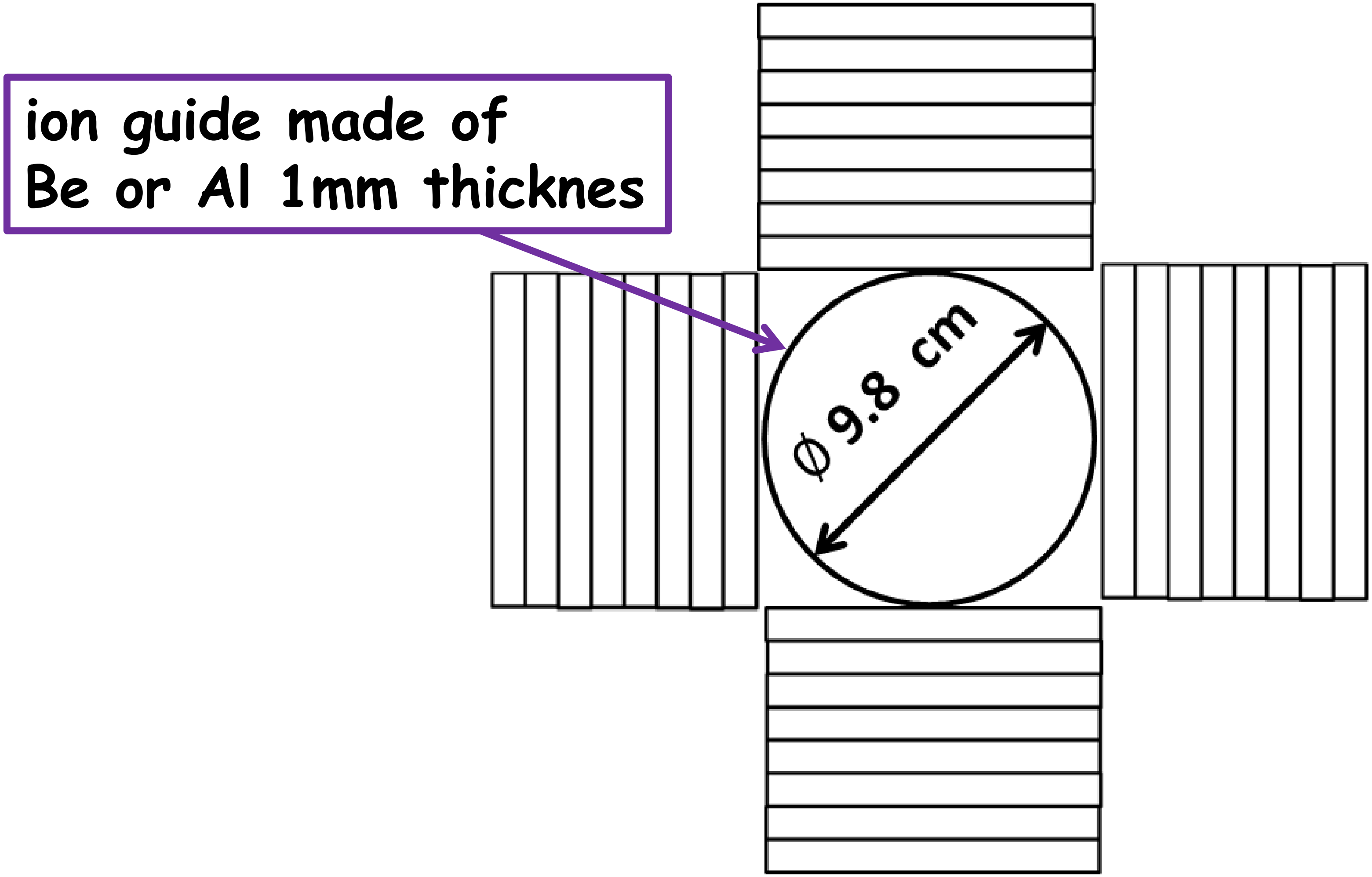




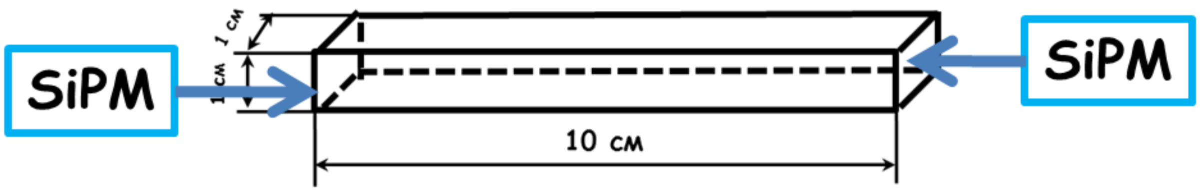
set-up view

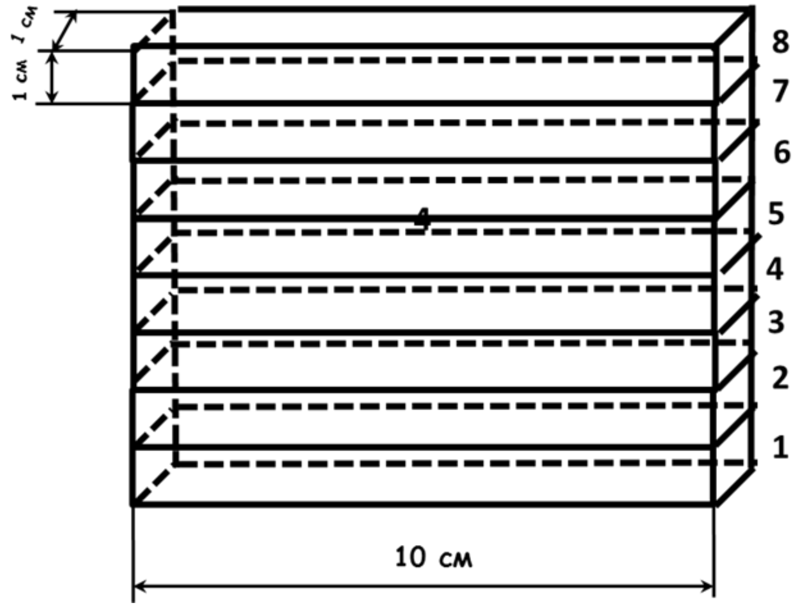

detector left shoulder
detector right shoulder
beam pipe
IP – Interaction Point
L =300 cm
L =300 cm

front view of the detector (one shoulder)



one plane of detector





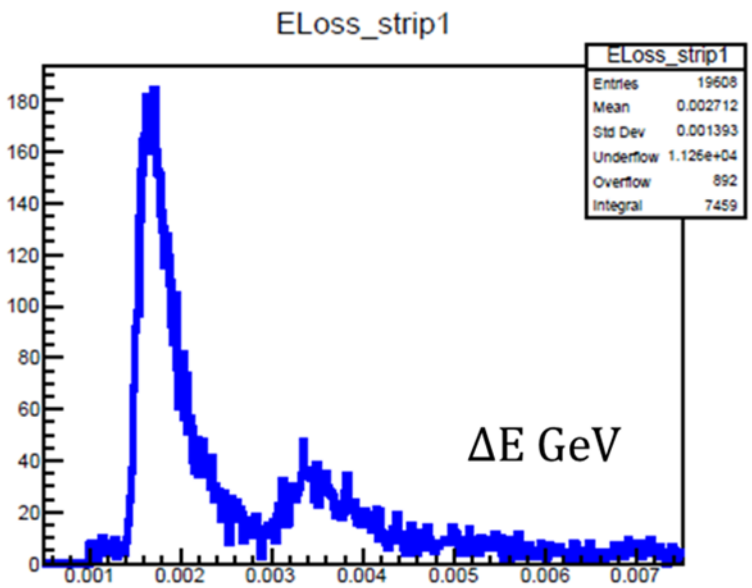
The plane consists of 100x10x10 mm^3 plastic scintillator strips viewed from both sides with silicon photomultipliers (SiPM)

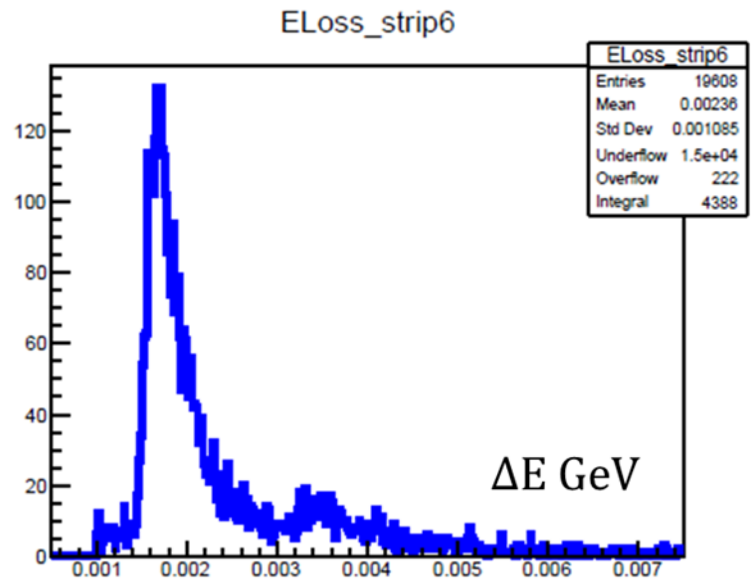
Simulation

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

Spectator energy $E_S \approx 5.5$ Gev/c

Energy loss spectrum in the scintillator

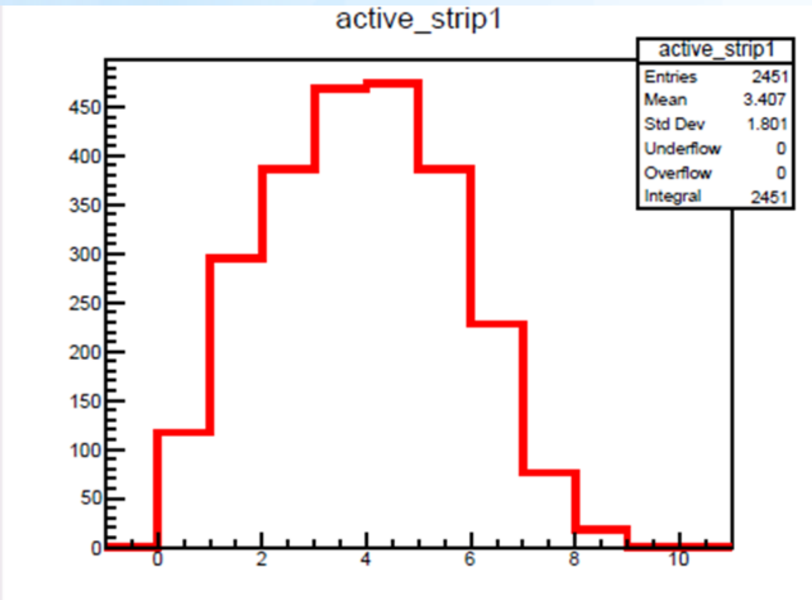


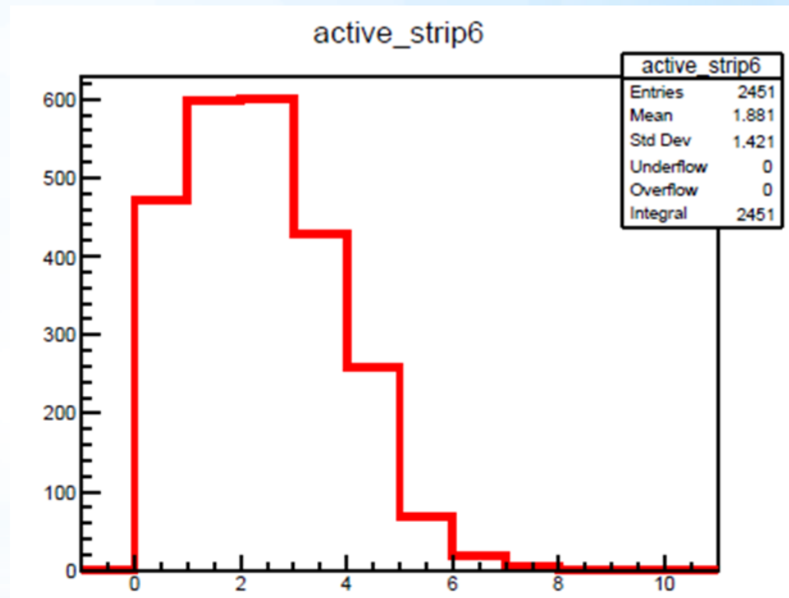


Simulation

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

strip occupancy (per 4 strips)





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

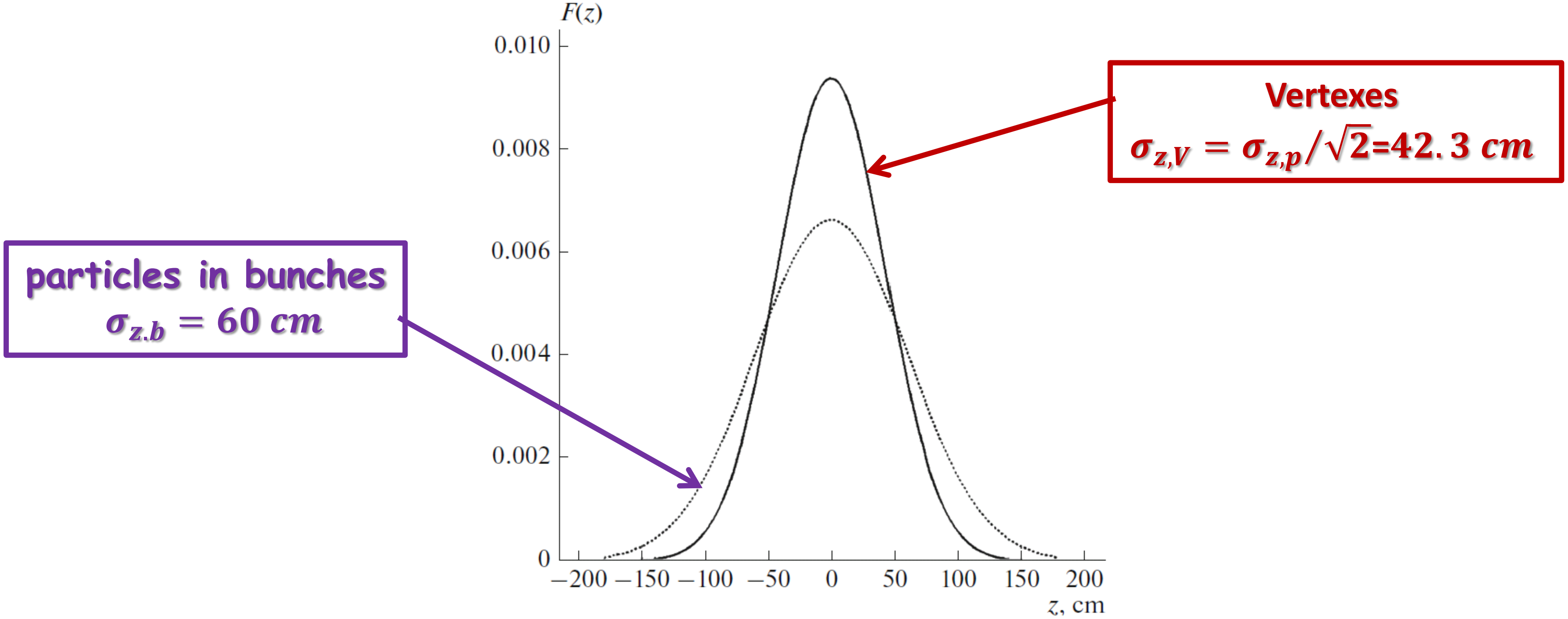
$$\langle n \rangle_6 = \frac{1.88}{4} = 0.47$$

Vertexes distribution.
Maximum for interaction vertexes distribution.

distribution of interaction vertices along the collision axis

simulation *Z. Igamkulov at al., Phys. of Part. and Nucl. Lett., 2019, **16**, p. 744*

without focusing



Using the detector for setting the convergence of the collider beams.

1. selection of collider parameters providing the most accurate hitting of beams into each other;
2. selection of collider parameters that optimize the transverse profile of colliding beams;
3. selection of collider parameters that optimize the longitudinal position of the interaction vertex and the longitudinal size of the bunches.

two observables

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

Time of Flight for Left and Right Shoulders

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

Trigger

$$\mathbf{|T_L - T_R| \le 10}\ \text{нс}$$

Efficiency

$$\boldsymbol{\varepsilon = 0.82}$$

Efficiency = Detected/Prodused

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

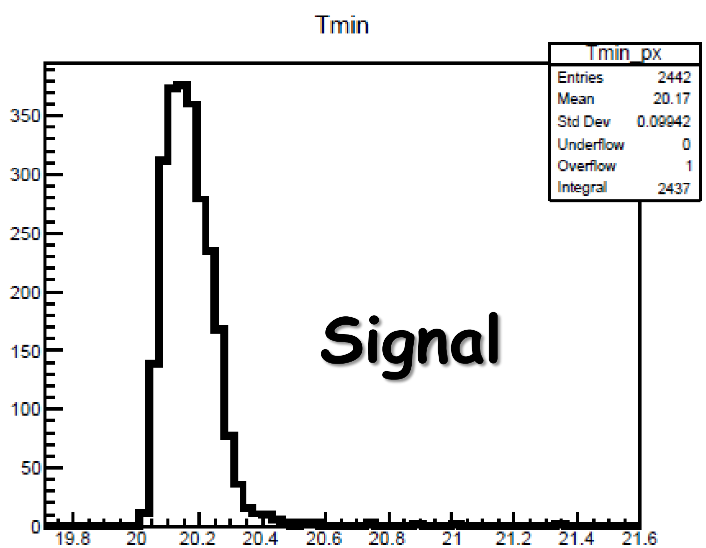
Background. Residual gas

Concentration of atoms in the residual gas

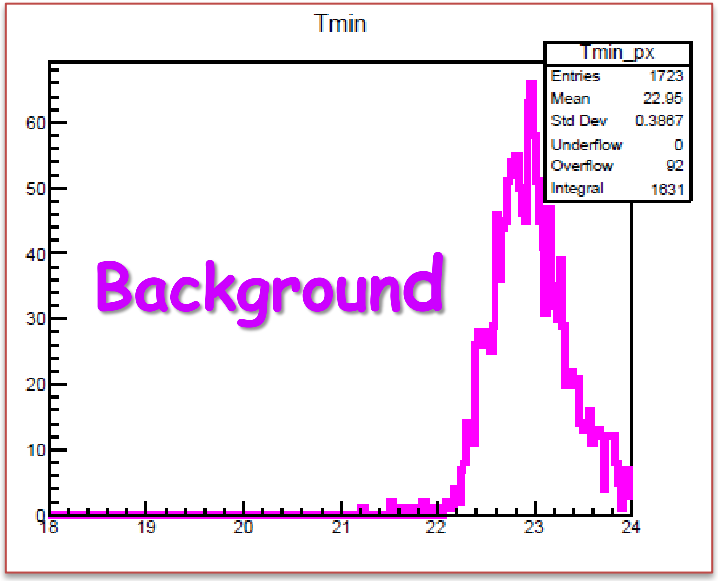
90% — H_2; 5% — CO; 5% — CO_2;

$p = 10^{-8}\mathrm{Pa}$; $T = 293$; $\sqrt{S_{N(Au),N(G)}} \cong 3.5\ \mathrm{Gev}$,

$B/S = 0.6 \cdot 10^{-3}$ - scattering rate.



$T_{\Sigma}(ns) = T_L + T_R$



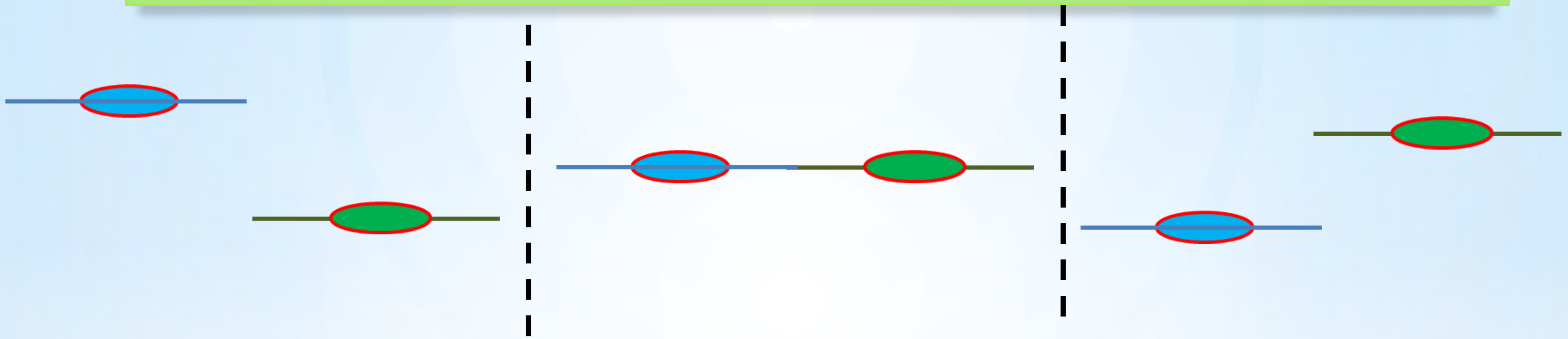
$T_{\Sigma}(ns) = T_L + T_R$

$B/S < 1.0 \cdot 10^{-5}$ -counting rate.

The possible strategy

the Vernier scan or Van der Meer scan

to measure the beam size by displacing the two beams against each other



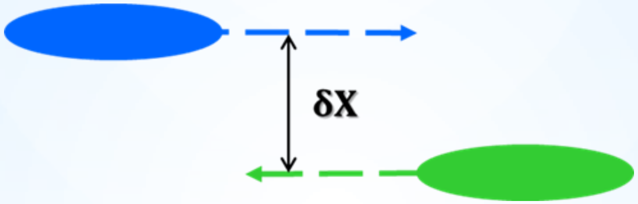
at RHIC and LHC the Van der Meer scan is commonly accepted procedure for calibration

the counting rate

$$R = \mathcal{L}\sigma$$

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

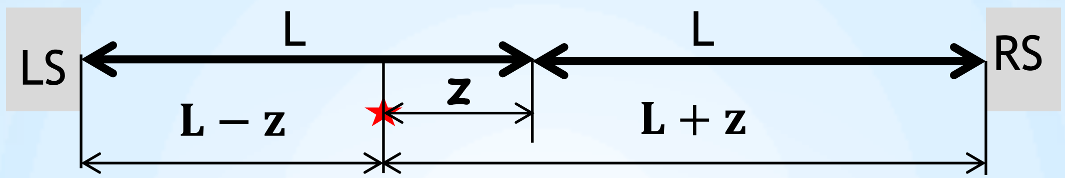
N_L, N_R-number of the beam ions in the left and right bunches



without focusing case

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

Vertex position



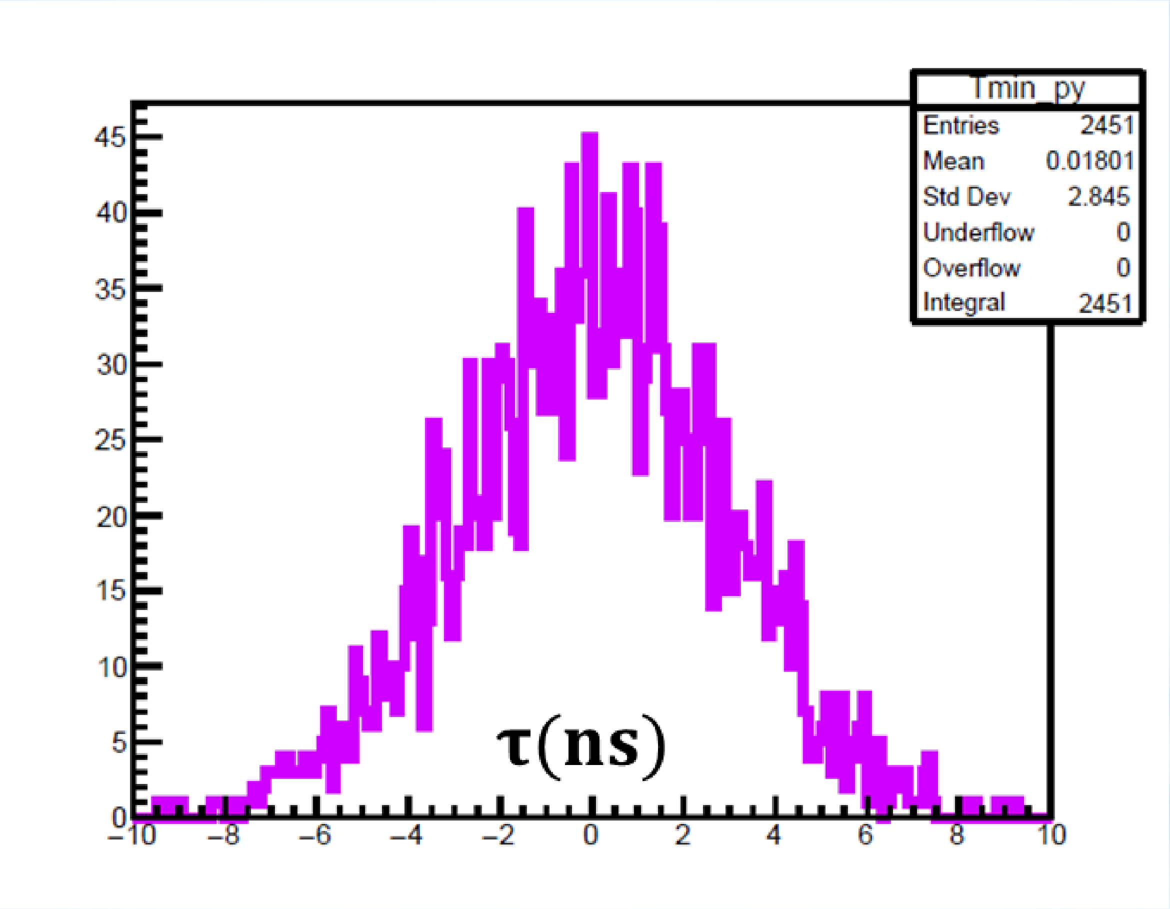
$$T_L = \frac{L-z}{c\beta}\ ;\ T_R = \frac{L+z}{c\beta};\ \tau = T_R - T_L = \frac{2z}{c\beta}$$

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

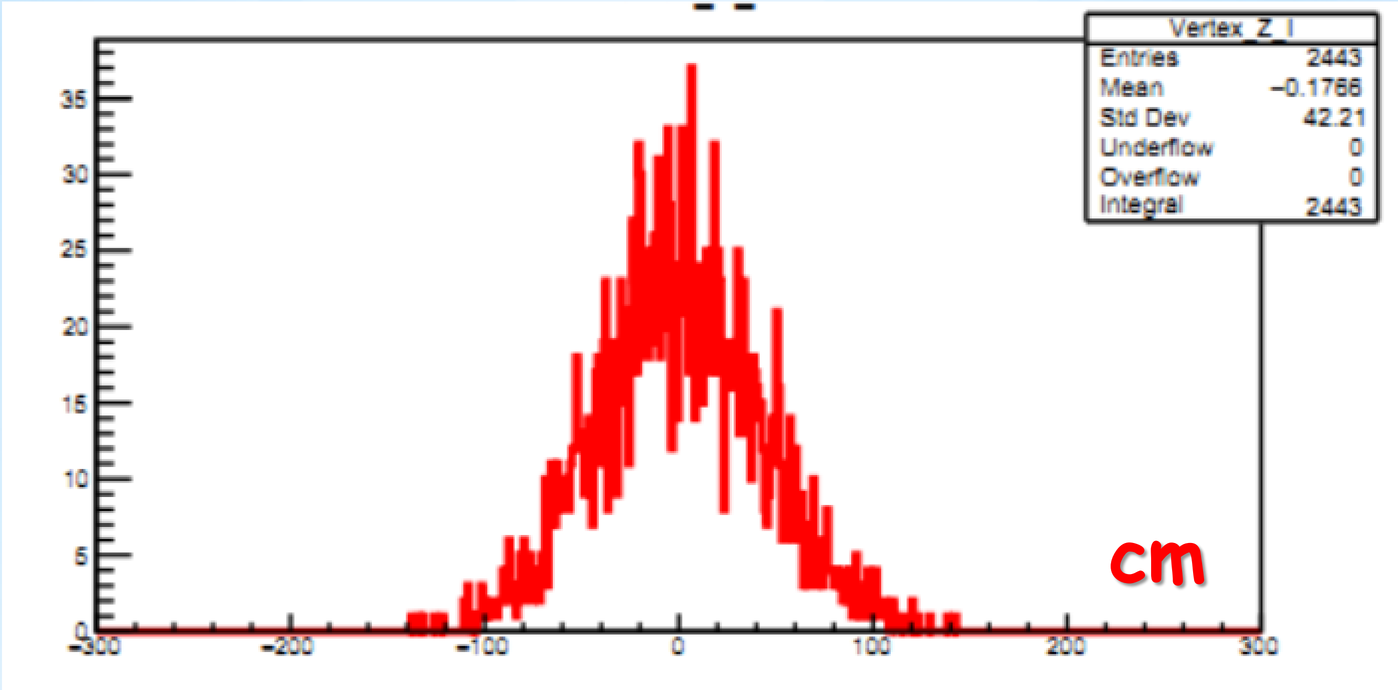
$$z = \frac{1}{2} c\cdot\tau \rightarrow z(cm) = 15\cdot\tau(ns)$$

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

τ distribution



Vertexes distribution from Time of Flight



$$\tilde{\sigma}_z = \sqrt{\left(\sigma_{z,V}^2 + \sigma_{z,\tau}^2\right)} = 42.3 \cdot (1 + 0.01)\ \text{cm}$$

$$\Delta z^{max}(\mathrm{cm}) = \frac{\sigma_z}{\sqrt{N_{tot}}}\left(1 + 0.01(\sigma_\tau(\mathrm{ns}) = 0.4) + 0.09(\varepsilon = 0.82)\right)$$

III. absolute luminosity

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

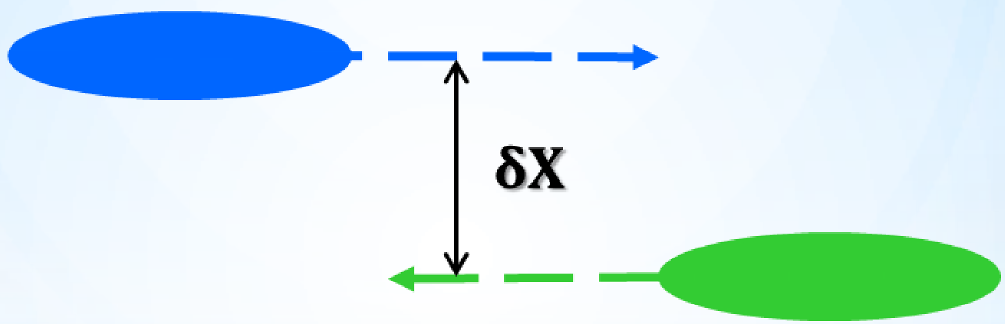
van der Meer scan

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

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

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

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

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

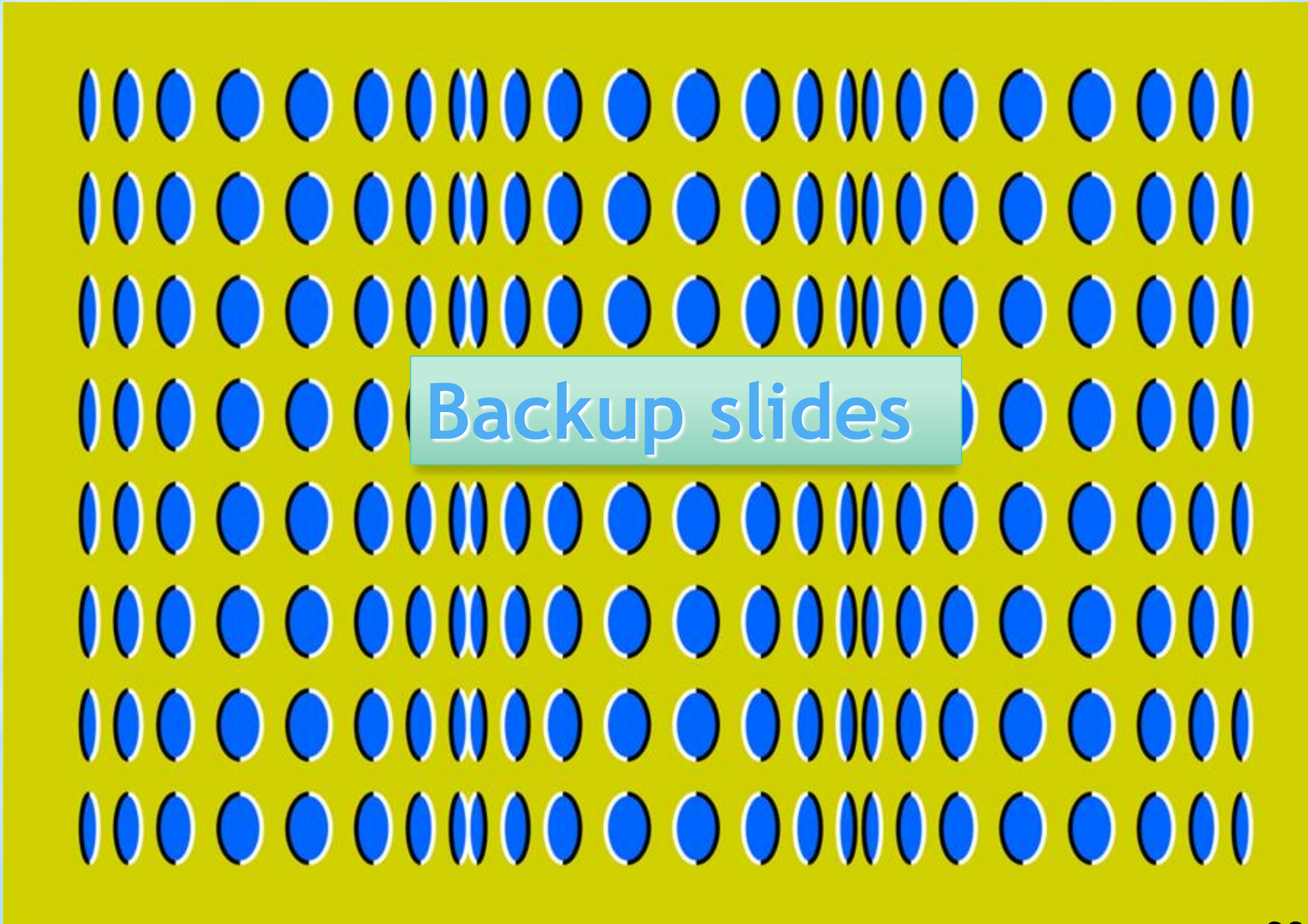
IN THE BEGINNING

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

$$B \sim N_b$$

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	$< 10^{-2}$

Backup slides



III. absolute luminosity — van der Meer scan

Suppose that a reaction is chosen, a detector is created, and measurements for a van der Meer scan are performed.

convenient to use normalized counting rate

$$\frac{dr_{1,2}(\delta X,\delta Y)}{dt} = \left(\frac{dR_{1,2}(\delta X,\delta Y)}{dt}\right)/(N_1 N_2 f)$$

$$\frac{dR_{1,2}(\delta X,\delta Y)}{dt} = (\sigma\varepsilon)2 \cdot N_1 N_2 f \iint dxdy \iint dud\xi p_1(x,y,u-\xi)p_2(x+\delta X,y+\delta Y,u+\xi)$$

$$\frac{dr_{1,2}(\delta X,\delta Y)}{dt} = (\sigma\varepsilon)2 \iint dxdy \iint dud\xi p_1(x,y,u-\xi)p_2(x+\delta X,y+\delta Y,u+\xi)$$

$$\iint \frac{dr_{1,2}(\delta X,\delta Y)}{dt} d\delta X d\delta Y = (\sigma\varepsilon)2 \iint d\delta X d\delta Y \left(\iint dxdy \iint dud\xi p_1(x,y,u-\xi)p_2(x+\delta X,y+\delta Y,u+\xi)\right)$$

III. absolute luminosity — van der Meer scan

$$\iint d\delta X d\delta Y \left(\iint dxdy p_{\perp}(x,y) p_{\perp}(x+\delta X, y+\delta Y)\right)=1$$

$$\iint \frac{dr_{1,2}(\delta X, \delta Y)}{dt} d\delta X d\delta Y = (\sigma \cdot \varepsilon)$$

$$\frac{dR}{dt} = \mathcal{L} \cdot (\sigma\varepsilon)$$

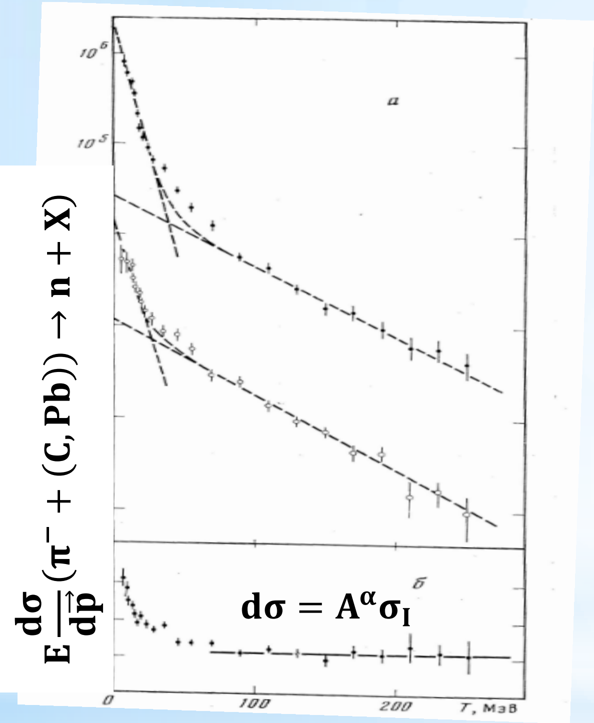
$$\mathcal{L} = \frac{\frac{dR_{1,2}(0,0)}{dt}}{\iint \frac{dr_{1,2}(\delta X, \delta Y)}{dt} d\delta X d\delta Y}$$

Experiment

ВЫХОДЫ НЕЙТРОНОВ И ПРОТОНОВ НА УГОЛ 90° ПОД ДЕЙСТВИЕМ $\pi^{\pm}$-МЕЗОНОВ ИЗ ЯДЕР C, Cu, Pb, U

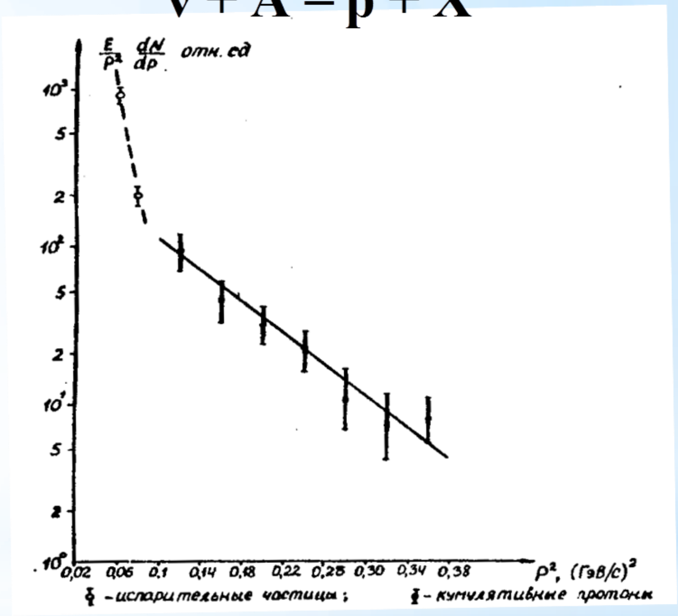
БАЮКОВ Ю. Д., ГАВРИЛОВ В. Б., ГОРЯИНОВ Н. А., ГРИЩУК Ю. Г., ГУЩИН О. В., ДЕГТЯРЕНКО П. В., КОРНИЕНКО Н. Л., ЛЕКСИН Г. А., ФЕДОРОВ В. Б., ШВАРЦМАН Б. Б., ШЕВЧЕНКО С. В., ШУВАЛОВ С. М.
ИНСТИТУТ ТЕОРЕТИЧЕСКОЙ И ЭКСПЕРИМЕНТАЛЬНОЙ ФИЗИКИ ГКИАЭ

Р.Аммар и др.,Препринт ФИАН, (48),(1989)

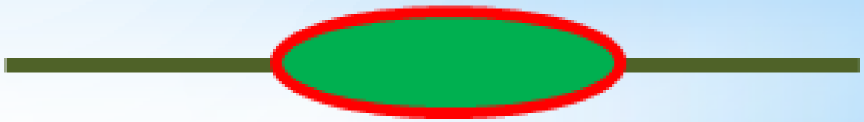


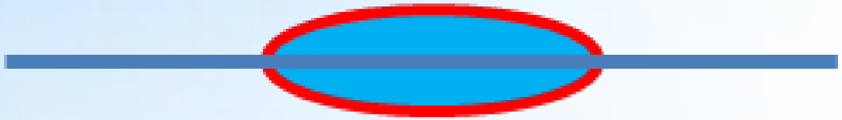
ЯДЕРНАЯ ФИЗИКА
JOURNAL OF NUCLEAR PHYSICS
т. 35, вып. 4, 1982

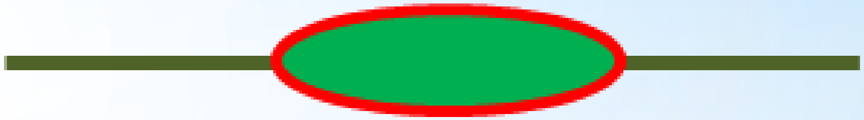
$\tilde{\nu} + A = p + X$

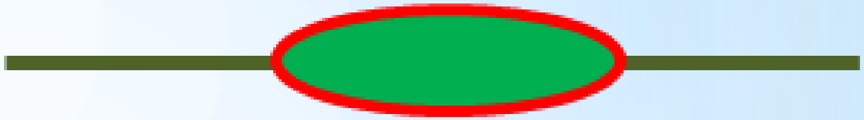


Fermi motion

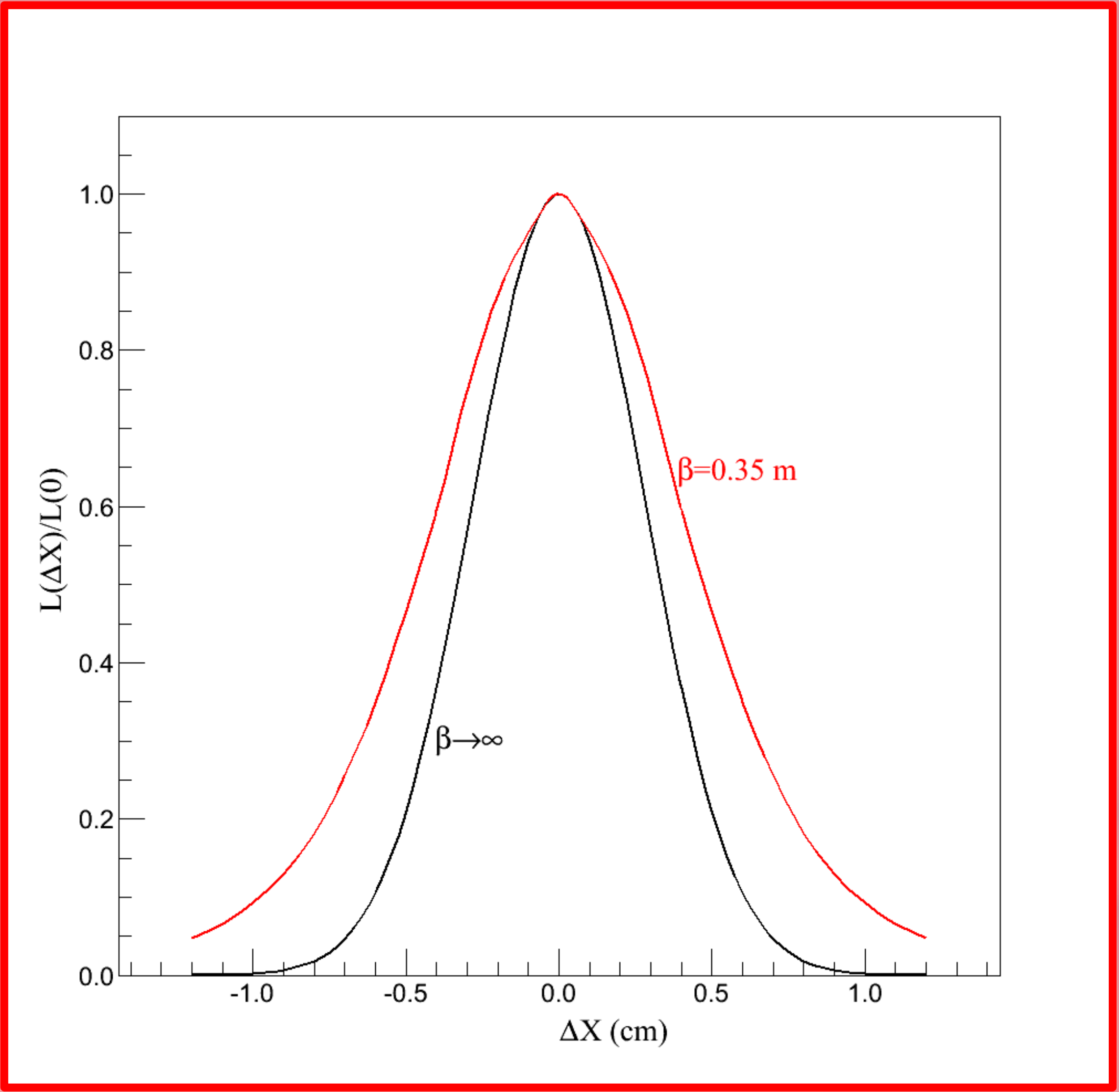








the Vernier scan or Van der Meer scan



Knowledge of luminosity is absolutely necessary for the following tasks:

1. When planning the measurements to calculate the counting rate.
2. When planning the experiment to calculate the overlay of signals from different events (pile-up events).
3. To prepare an effective intersection beams at the point of interaction.
4. To get information about trigger efficiency.
5. To get information about transversal bunch structure.
6. …

The possible strategy

the Vernier scan or Van der Meer scan

to measure the beam size by displacing the two beams against each other

at RHIC and LHC the Van der Meer scan is commonly accepted prosedure for calibration

26

The possible strategy

the Vernier scan or Van der Meer scan

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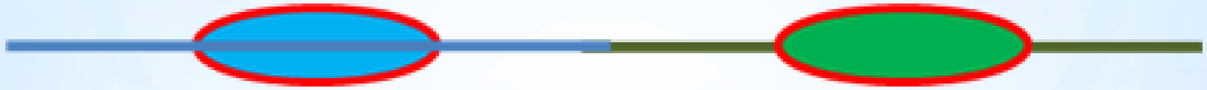

at RHIC and LHC the Van der Meer scan is commonly accepted prosedure for calibration

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The possible strategy

the Vernier scan or Van der Meer scan

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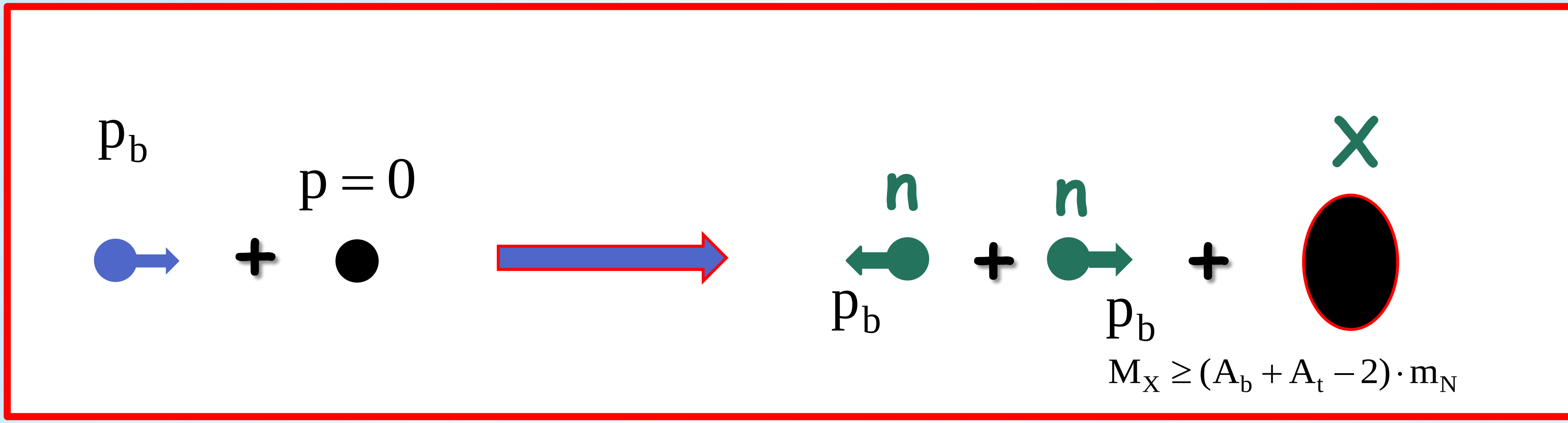
at RHIC and LHC the Van der Meer scan is commonly accepted prosedure for calibration

IMPORTANT

IT IS ENOUGH
TO DETECT SEPARATE EVENTS
(PILE-UP IS SMALL)

Background coming from interaction with residual gas and elements of the collider is absent because of the kinematic restrictions.



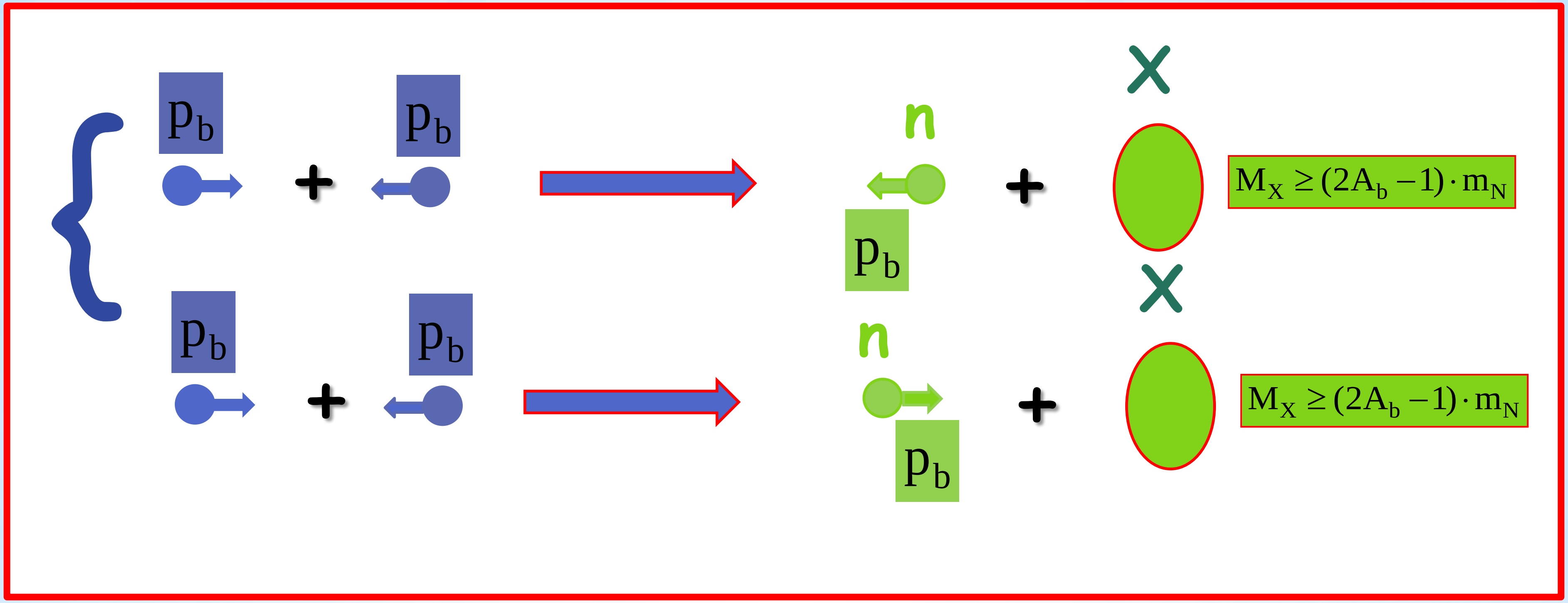
$$\sqrt{S_{NN}} = 2 \cdot E_b = 11 GeV$$

$$M(n,n) = 11 GeV$$

$$X_c \geq 20$$

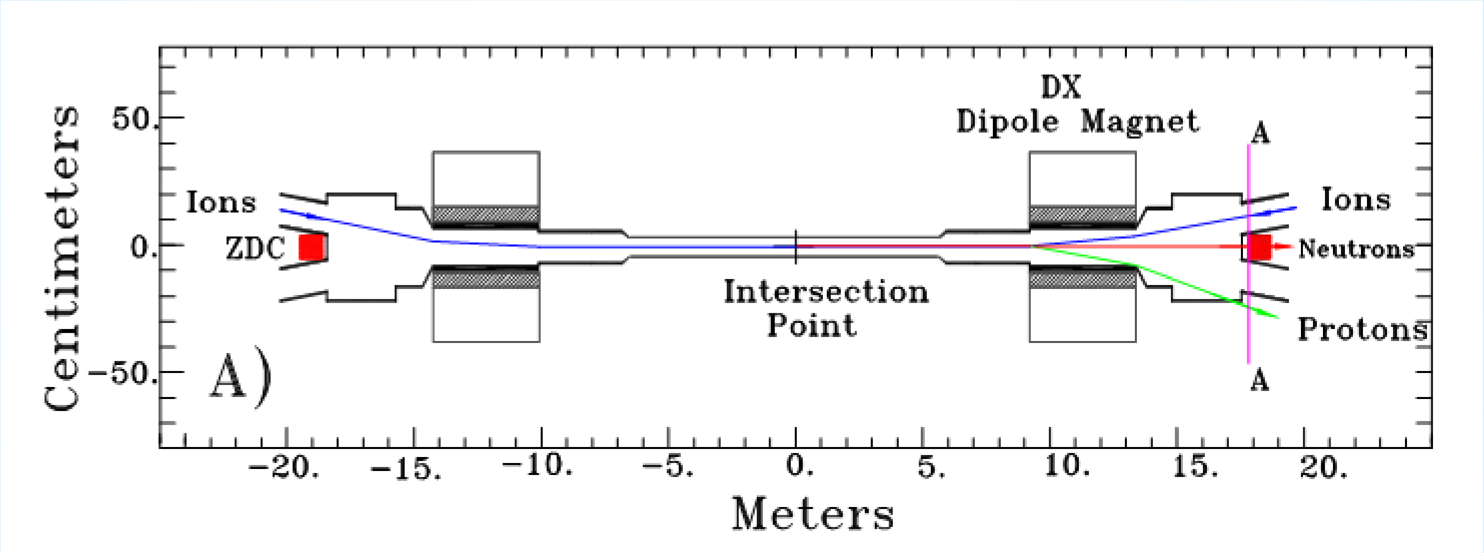
$$\frac{\text{background}}{\text{signal}} = \frac{N_b}{N_s} \leq \exp(-\frac{20}{0.14}) \cong 10^{-60}$$

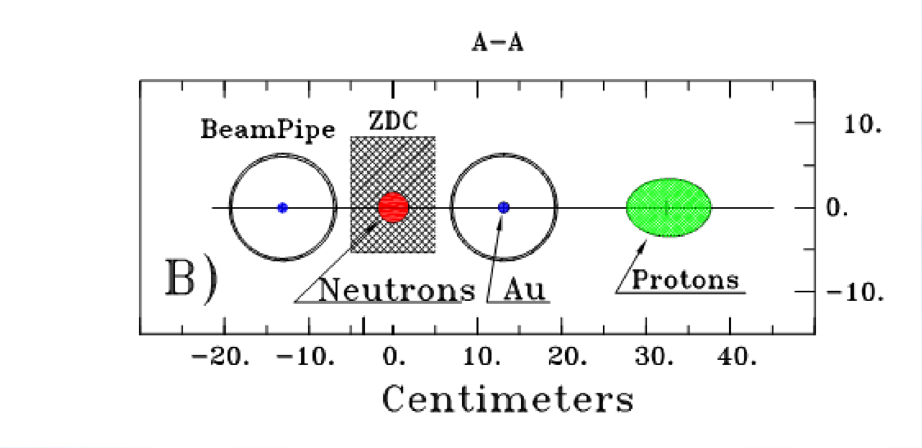
Background coming from pile-up.



$$\frac{\text{background}}{\text{signal}} = \frac{N_b}{N_s} \leq \frac{k \cong 1}{f \cdot N_b} \cong 10^{-6}$$

The RHIC Zero Degree Calorimeters





Оценки для NICA: Длина кольца 503,4 м
Отсюда время для скорости света $1.678 \cdot 10^{-6}$ s

Скорость для p=4.5 GeV/c β=0.9779
Частота обращения f=0.583 MHz

$$L = 10^{27} cm^{-2} s^{-1};\ N_{1/2} = 2.3 \cdot 10^{9}\ part./bunch;\ N_b = 22$$

Отсюда находим площадь пересечения

$$S = 4\pi\sigma^2 = \frac{(2.3 \cdot 10^9)^2 \cdot 22 \cdot 0.58 \cdot 10^6}{10^{27}} = \frac{6,8 \cdot 10^{25}}{10^{27}} = 6,8 \cdot 10^{-2} (cm^2)$$

$$\sigma = 0.74 \cdot 10^{-1} cm = 0.74 \cdot 10^{-3} m = 0.74 mm = 740\,\mu m$$

Если же учесть изменение светимости за счёт бета функции, то исходная светимость должна быть в 1/0.37 = 2.7 больше, что даёт:

$$S = 2,95 \cdot 10^{-2} (cm^2) \Rightarrow \sigma = 0.48 \cdot 10^{-1} cm$$

Оценки для NICA: Длина кольца 503,4 м
Отсюда время для скорости света $1.678 \cdot 10^{-6}$ s

Скорость для p=4.5 GeV/c β=0.9779
Частота обращения f=0.583 MHz

$$L = 10^{27} cm^{-2} s^{-1}; \; N_{1/2} = 2.3 \cdot 10^{9} \text{ part./bunch}; N_b = 22$$

Отсюда находим площадь пересечения

$$S = 4\pi\sigma^2 = \frac{(2.3 \cdot 10^9)^2 \cdot 22 \cdot 0.58 \cdot 10^6}{10^{27}} = \frac{6{,}8 \cdot 10^{25}}{10^{27}} = 6{,}8 \cdot 10^{-2} (cm^2)$$

$$\sigma = 0.74 \cdot 10^{-1} cm = 0.74 \cdot 10^{-3} m = 0.74 mm = 740\,\mu m$$

Если же учесть изменение светимости за счёт бета функции, то исходная светимость должна быть в 1/0.39 = 2.56 больше, что даёт:

$$S = 2{,}66 \cdot 10^{-2} (cm^2) \Rightarrow \sigma = 0.46 \cdot 10^{-1} cm$$

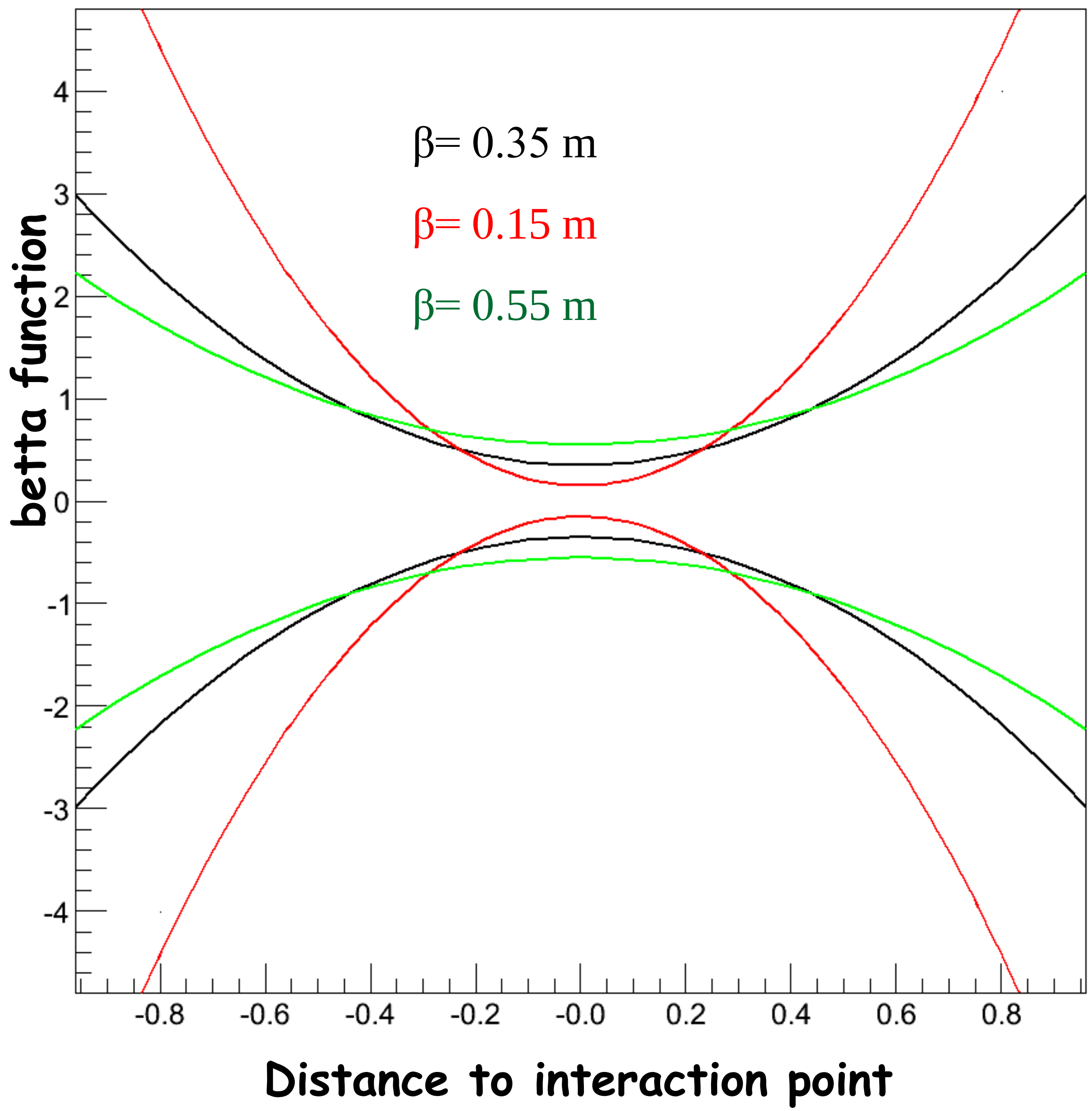
Оценку поперечных размеров можно получить опираясь на известный акксептанс и бета функцию.

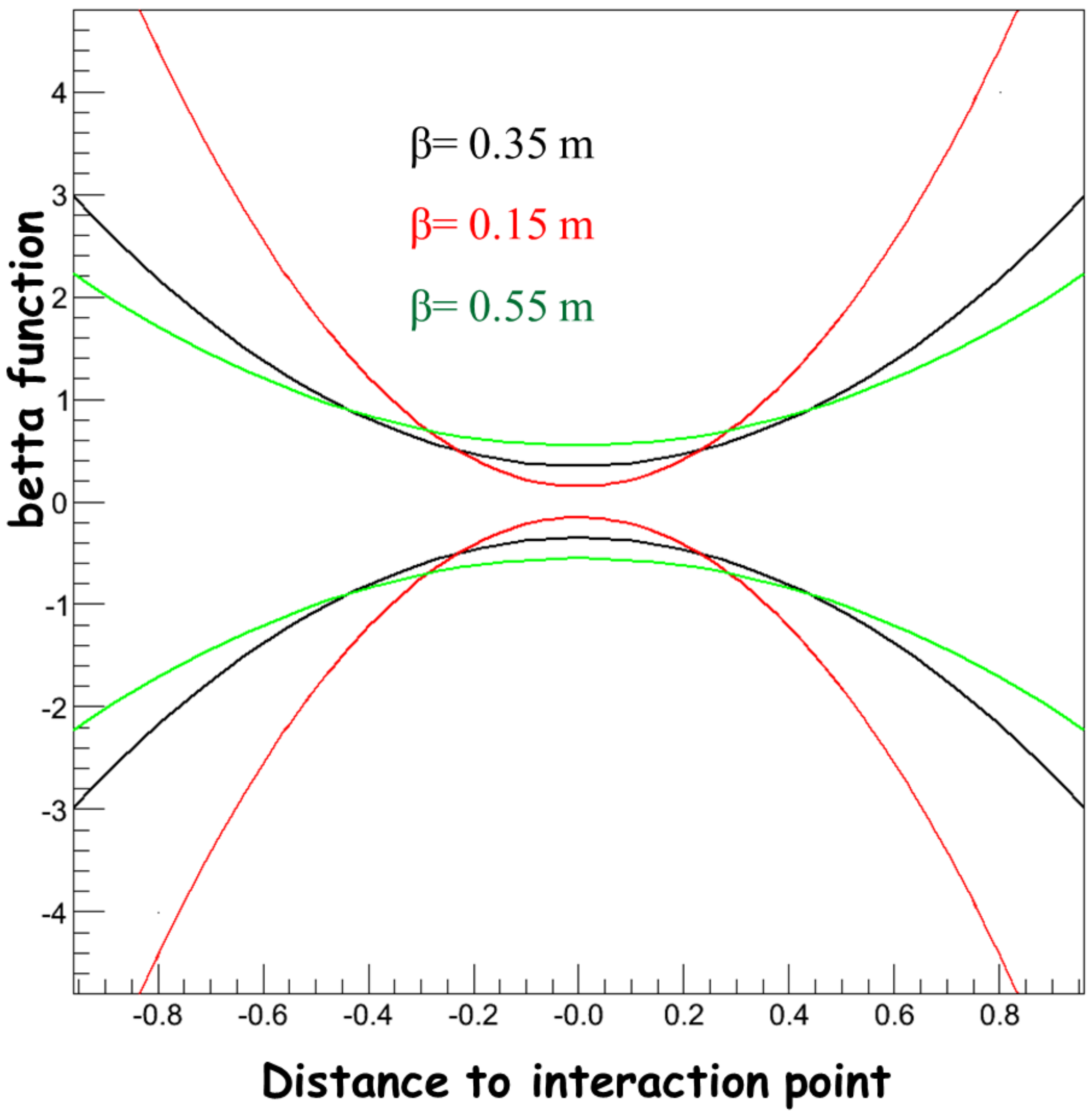
$$\sigma = \sqrt{\beta_{IP} \cdot \varepsilon / \pi}$$

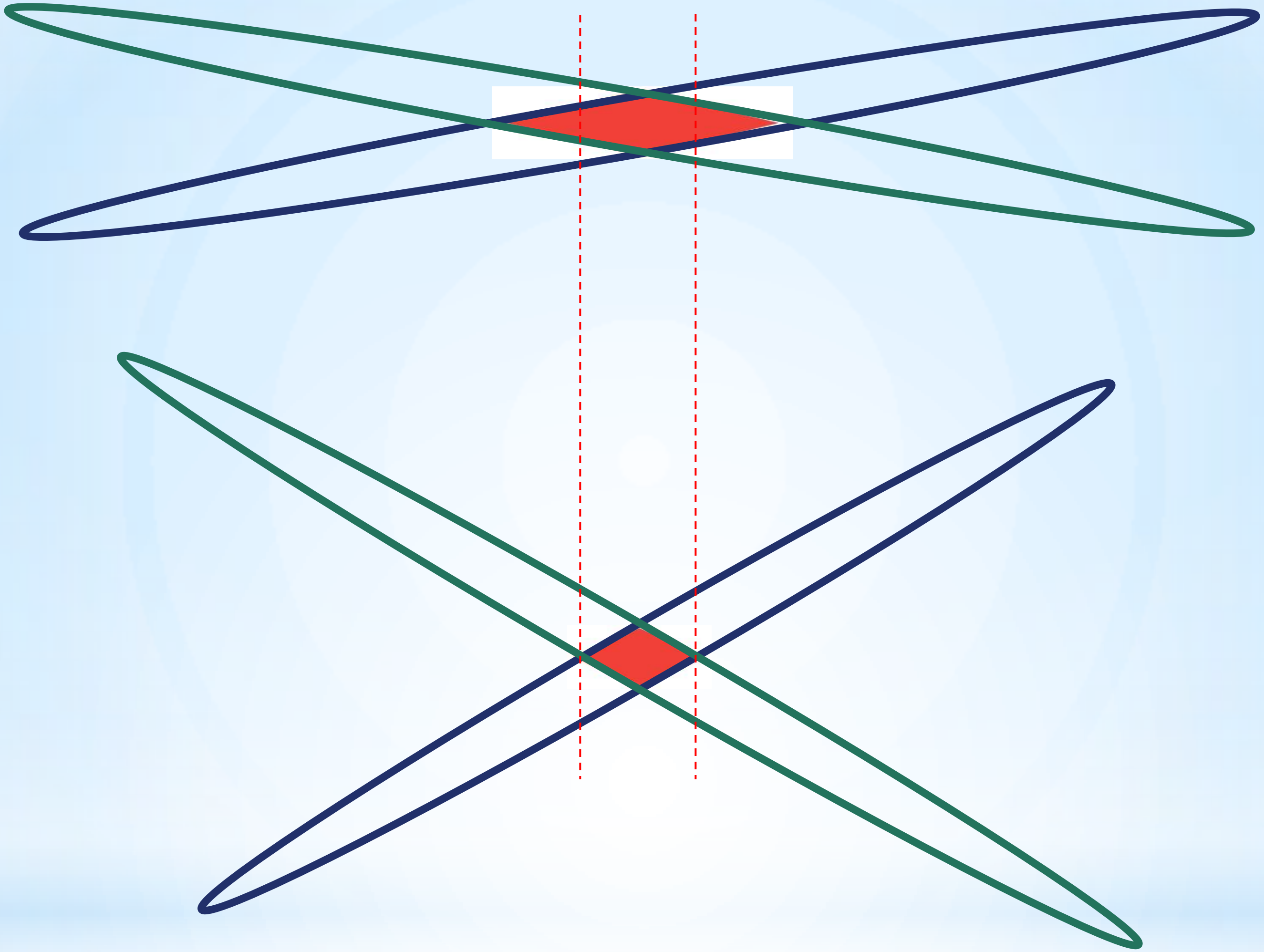
Для параметров NICA:
$$\begin{cases} \beta_{IP} = 0.35\text{m} = 35\text{cm} \\ \varepsilon(\pi\ \text{mm} \cdot \text{mrad}) = 40 \\ \varepsilon(\pi\ \text{cm} \cdot \text{rad}) = 4 \cdot 10^{-3} \end{cases}$$

Это даёт:
$$\begin{cases} \sigma = 0.211\text{cm};\ S_\sigma = 4\pi\sigma^2 = 0{,}56\text{cm}^2; \\ S_{\varepsilon,\beta} = 4\varepsilon\beta = 0{,}56\text{cm}^2; \end{cases}$$

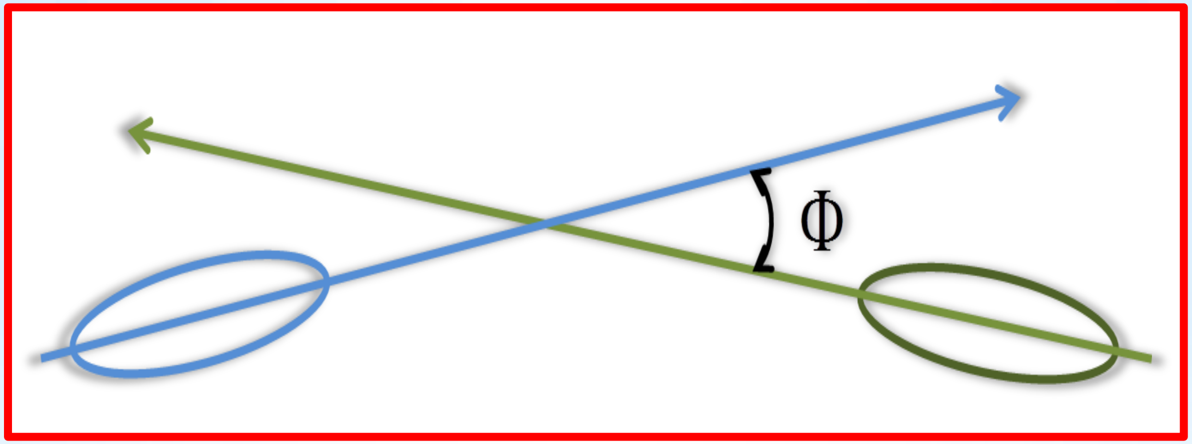
При интесивности $2.3 \cdot 10^9$; $N_b = 22; f = 0.58 \cdot 10^6$Гц
имеем: $L = 1.2 \cdot 10^{26} cm^{-2} c^{-1}$ (без учёта изменения профиля пучка)


β= 0.35 m
β= 0.15 m
β= 0.55 m
betta function
4
3
2
1
0
-1
-2
-3
-4
-0.8
-0.6
-0.4
-0.2
-0.0
0.2
0.4
0.6
0.8
Distance to interaction point


β= 0.35 m
β= 0.15 m
β= 0.55 m
betta function
Distance to interaction point
4
3
2
1
0
-1
-2
-3
-4
-0.8
-0.6
-0.4
-0.2
-0.0
0.2
0.4
0.6
0.8



Colliding beams luminosity non zero crossing angle



Hourglass effect

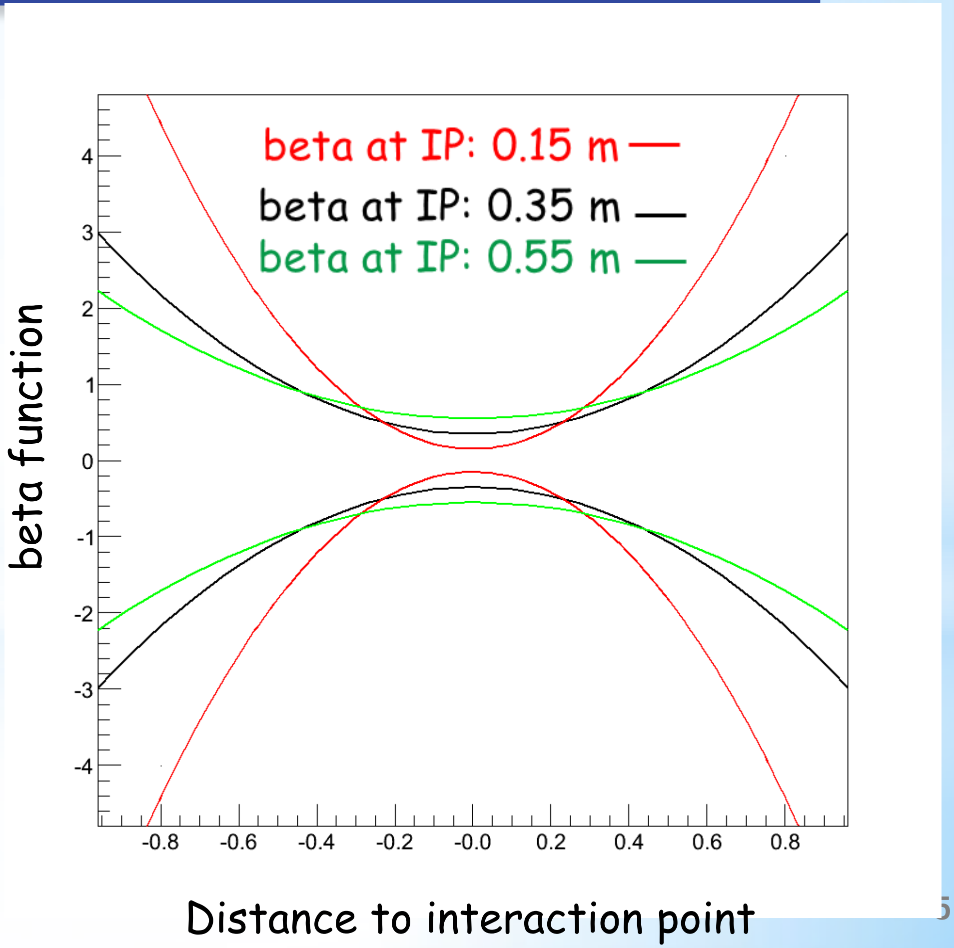
The dependence of the transverse beam size from the distance to the intersection point becouseof the beta function

$$S_{eff} = 4\pi\sigma^2 = 4\pi\varepsilon\beta$$

NICA

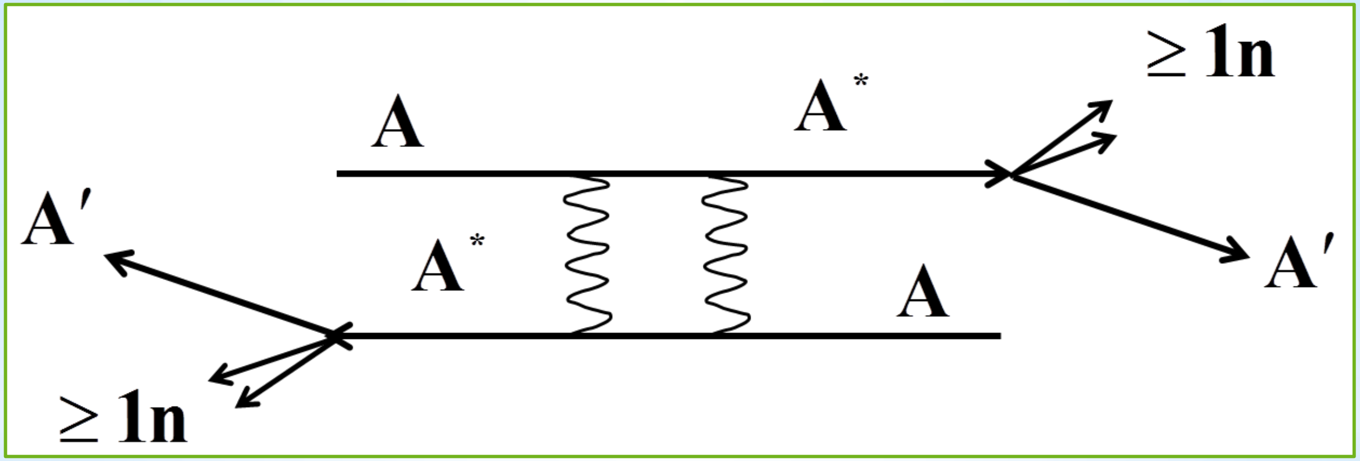
$$\beta_{IP} = 0.35m;$$
$$\varepsilon = 40\pi mm \cdot mrad;$$

beta at IP: 0.15 m —
beta at IP: 0.35 m —
beta at IP: 0.55 m —



This report discusses the initial steps for the problem of the luminosity control at the collider NICA

Reaction of Mutual Electromagnetic Dissociation (the ultra peripheral collisions b $> 2R_A$)



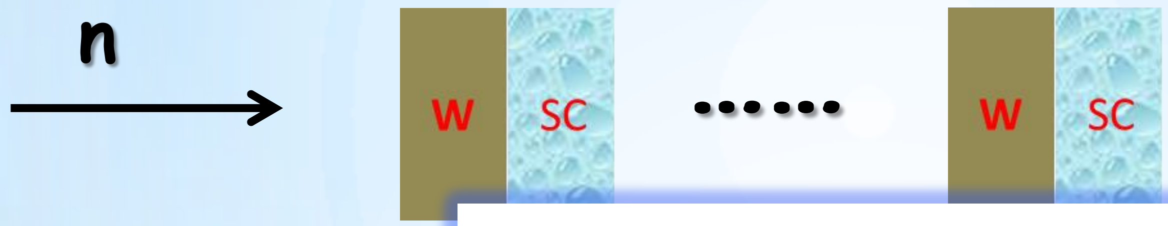
In beam rest-frame $A^* \to A' + n; p(n) < 0.15\ GeV/c$

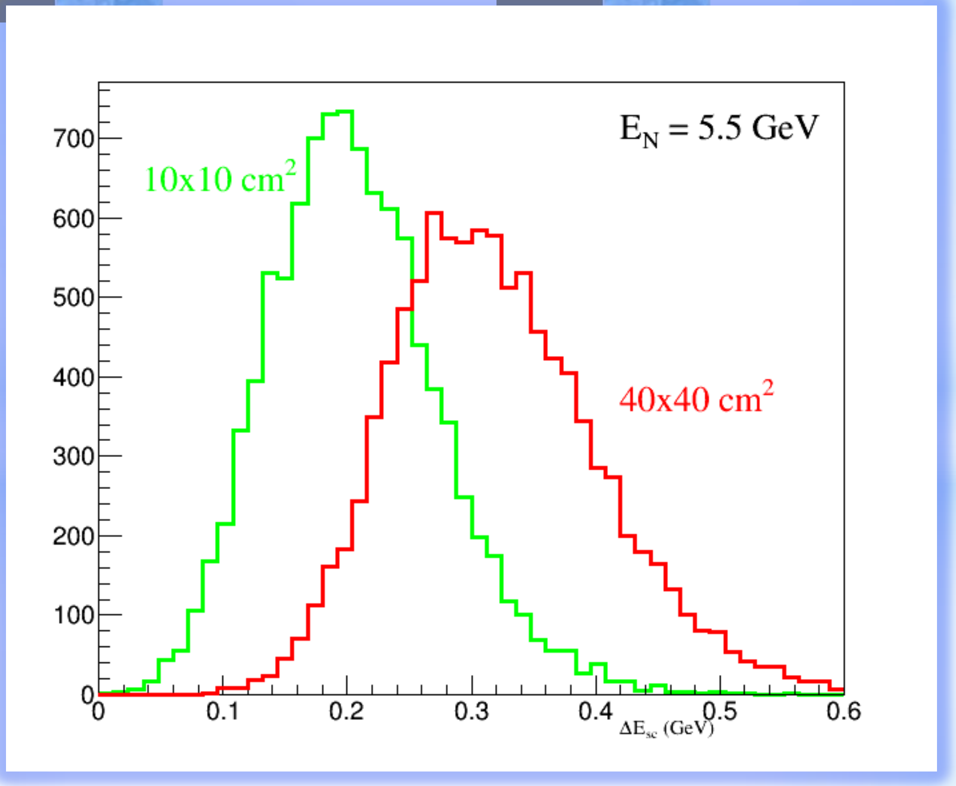
$\sqrt{S_{NN}} = 4GeV; \Theta < 0.085rad; \sqrt{S_{NN}} = 1GeV; \Theta < 0.028rad;$

Calorimeters NZDC

the simulation

W(4мм)xSC(4mm)x70pc





Working group

Control of luminosity at the interaction points in the collider NICA	A.B.Kurepin A.G.Litvinenko I.N.Meshkov	R&D Technical proposal
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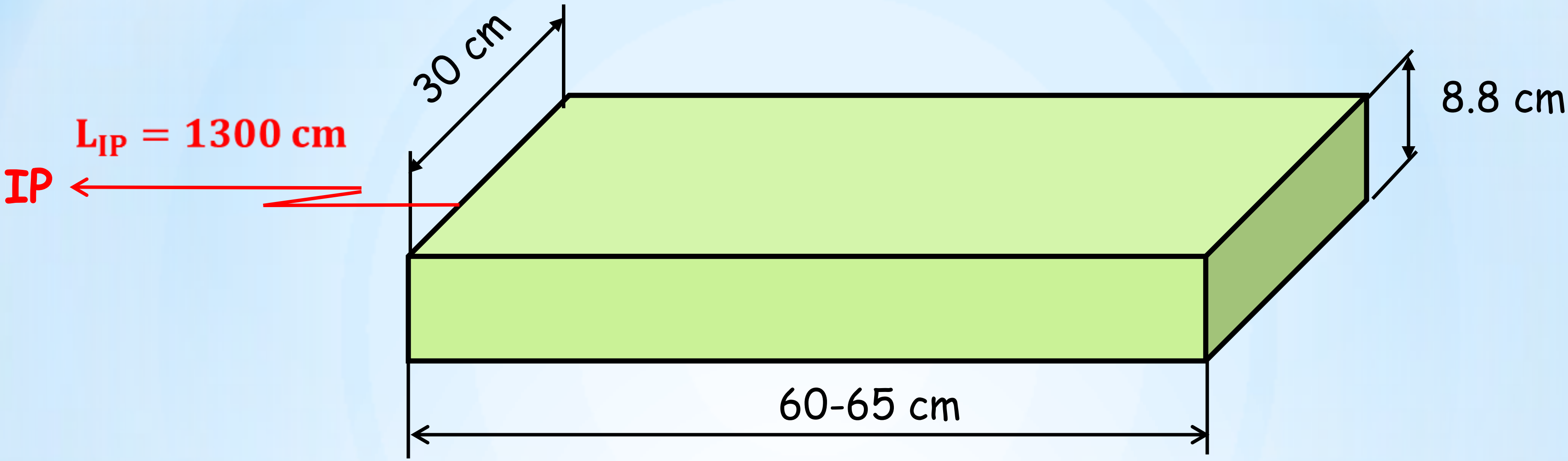
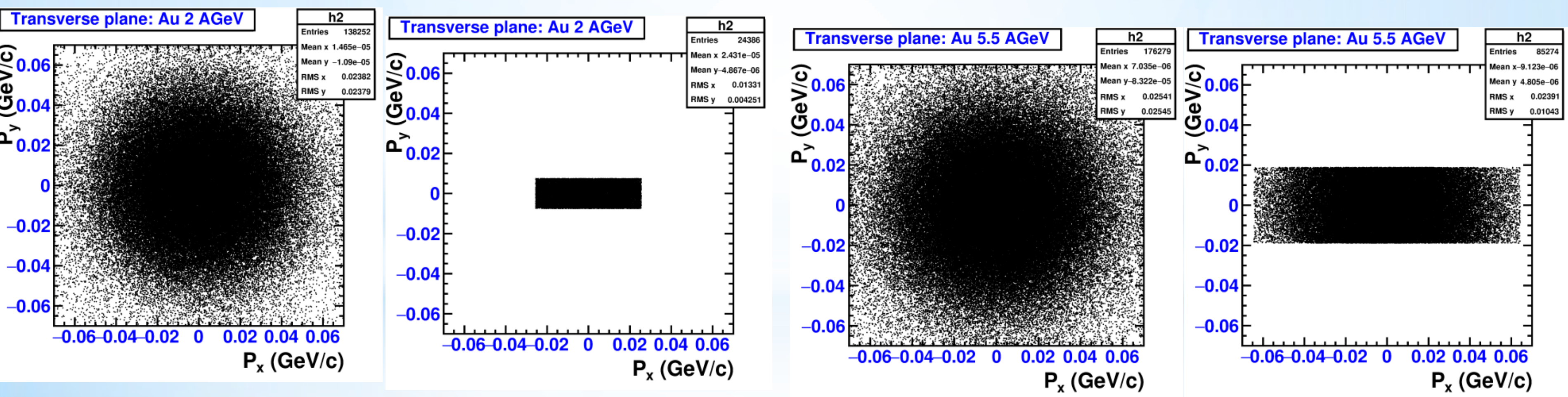
Calorimeters INZDC (Acceptance)

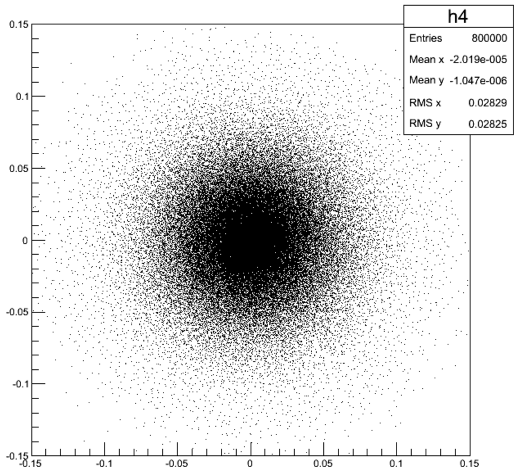


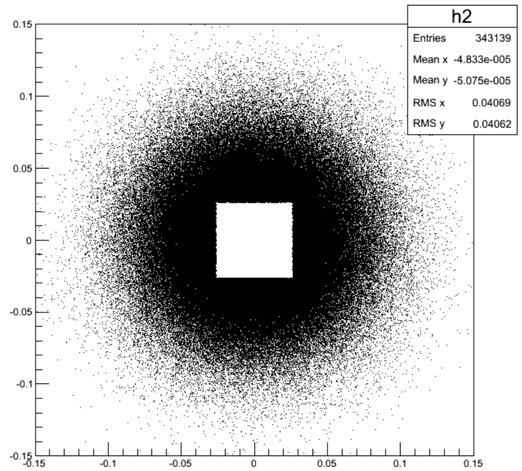


$\sqrt{S_{NN}} = 4$ GeV; Acc = 0.18

$\sqrt{S_{NN}} = 11$ GeV; Acc = 0.48

ZDC@MPD for luminosity





$$\sqrt{S_{NN}} = 4 \text{ GeV}; Acc = 0.43$$

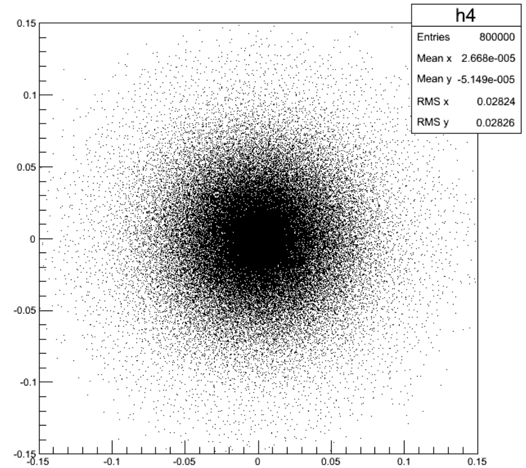
Counting rates

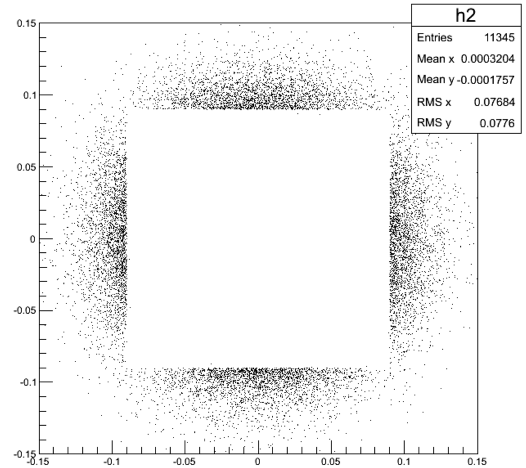
- EM $N_{ev} = 5900 \, ^1/_c$
- Nucl $N_{ev} = 6000 \, ^1/_c$

$$\sqrt{S_{NN}} = 11 \text{ GeV}; Acc = 0.014$$

Counting rates

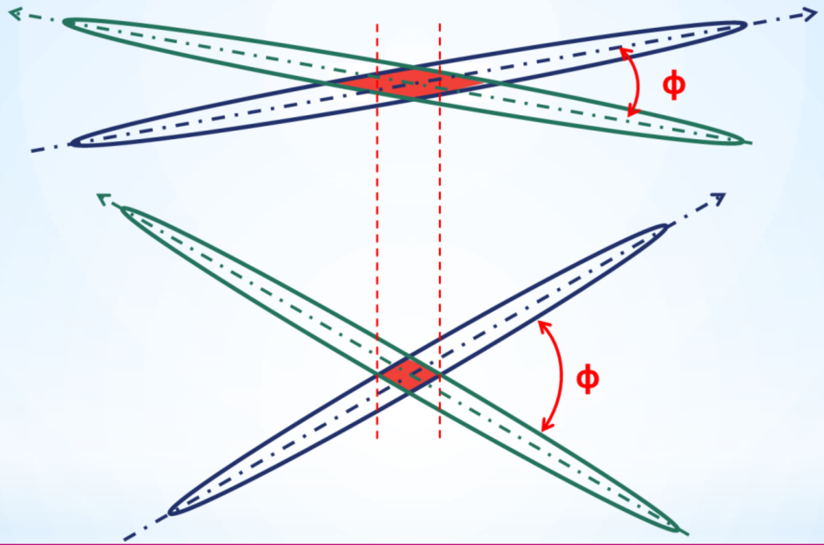
- EM $N_{ev} = 360 \, ^1/_c$
- Nucl $N_{ev} = 6000 \, ^1/_c$





Colliding beams luminosity non zero crossing angle

collision at non-zero angle is used to reduce the size of the interaction region



But non-zero angle of collision leads to a reduction of energy

$$S(\Phi) = S(0)\cdot K(\Phi);\ K(\Phi) = 1 - 0.5\cdot(1-\cos(\Phi)) < 1$$

CALIBRATION OF THE EFFECTIVE BEAM HEIGHT IN THE ISR

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

by

S. van der Meer

Goals and time table

Goals:

1. Monitoring the optimization of the beams overlapping at IP.
2. Measure the relative luminosity in the process of data acquisition.
3. Measurement of the collider absolute luminosity.

Preliminary time table:

End of 2016

1. The concept of the detector
2. The first version of the CDR
3. Preparation of the program of test measurements

End of 2017

1. The final version of the CDR, the TDR option.
2. Manufacturing the detector module for test measurements.
3. Performing the test measurements.