

# Polarimetry at Nuclotron/NICA/SPD

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spin  $\frac{d\vec{S}}{dt} = \frac{e}{\gamma m} \vec{S} \times [(1 + G\gamma)\vec{B}_\perp + (1 + G)\vec{B}_l]$

momentum  $\frac{d\vec{p}}{dt} = \frac{e}{\gamma m} \vec{p} \times \vec{B}$

$$\gamma G_d = p + nQ_x + mQ_y$$

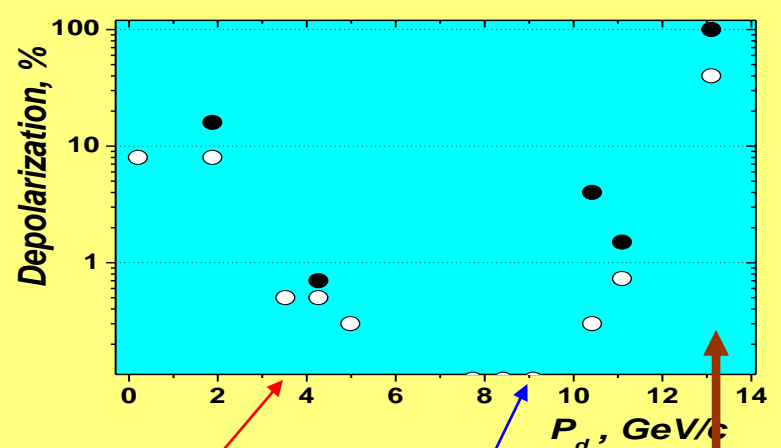
6.8                      6.85

$$\gamma = E_d / m_d$$

$$G_p = 1.793$$

$$G_d = -0.143$$

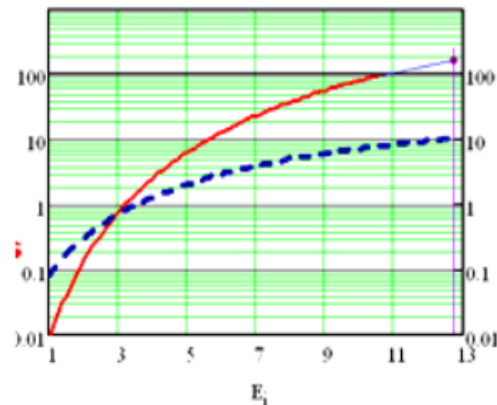
Filatov's table for Nuclotron



	$^1_1H$	$^1_2H$	$^1_3H$	$^2_3He$
$E_k^{max}$ , GeV/n	12.84	6.00	3.74	8.28
$\nu_{min} - \nu_{max}$	1.8 - 26.3	-1.05 - -0.144	7.92 - 39.5	-41.1 - -4.19
$\epsilon'$ , ( $\tau_{уск} = 0.5s$ )	$7.0 \cdot 10^{-6}$	$2.8 \cdot 10^{-7}$	$1.0 \cdot 10^{-5}$	$1.1 \cdot 10^{-5}$
$w_d$ , ( $\tau_{уск} = 0.5s$ )	$1.5 \cdot 10^{-3}$	$3.0 \cdot 10^{-4}$	$1.8 \cdot 10^{-3}$	$1.9 \cdot 10^{-3}$
Количество резонансов				
$\nu = kp \pm \nu_z$	6	—	8	9
$\nu = k$	25	1	32	37
$\nu = k \pm \nu_z (k \neq mp)$	44	2	55	64
$\nu = k \pm \nu_x$	49	2	63	73

#### 4.4.1. NICA luminosity.

The NICA luminosity in the polarized proton mode is estimated for the proton kinetic energy region from 1 to 12.7 GeV [11], Fig. 4.7.



**Fig. 4.7:** NICA  $pp$  luminosity in units  $10^{30}$  (left scale, solid line) and the number of particles per bunch in units  $10^{11} \text{ cm}^{-2} \text{ s}^{-1}$  (right scale, dotted line) vs. the proton kinetic energy.

The luminosity and total number of the stored particles has been calculated taking into account the beam space charge limits and other parameters listed below.

Parameters of NICA: circumference	- 503 m,
number of intersection points (IP)	- 2,
beta function $\beta_{min}$ in the IP	- 0.35 m,
number of protons per bunch	- $\sim 1 \cdot 10^{12}$ ,
number of bunches	- 22,
RMS bunch length	- 0.5 m,
incoherent tune shift, $\Delta_{Lasslett}$	- 0.027,
beam-beam parameter, $\xi$	- 0.067,
beam emittance $\varepsilon_{nm}$ , $\pi$ mm mrad	- 0.15 (normalized at 12.5 GeV).

The number of particles reaches a value about  $2.2 \cdot 10^{13}$  in each ring and the peak luminosity  $L_{peak} = 2 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$  at 12.7 GeV. Assuming the cooling time  $T_{cool} = 1500$  s, the luminosity life time  $T_{Lif} = 20000$  s with the beam polarization not less than 70% and the machine reliability coefficient  $k_r = 0.95$ , the average luminosity will be  $L_{aver} = L_{peak} \cdot 0.86$  or  $1.7 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$  [12] during the working time of the complex.

So, feasible schemes of manipulations with polarized protons and deuterons are suggested [10, 14]. The final scheme of the polarized proton acceleration up to required energy and beam manipulations at NICA will be approved at the later stages of the NICA project.

## NICA collider

22 bunches

$2.2 \times 10^{13}$  protons in each ring

$1 \times 10^{12}$  protons per bunch

0.5 m RMS bunch length  $\sim 3$  ns

1.68  $\mu\text{s}$

$$\text{Lumi} = \frac{N_1 * N_2 * f * n_b}{4 * \pi * \sigma_x * \sigma_y}$$

## Nuclotron ring

upto 5 bunches or continuous

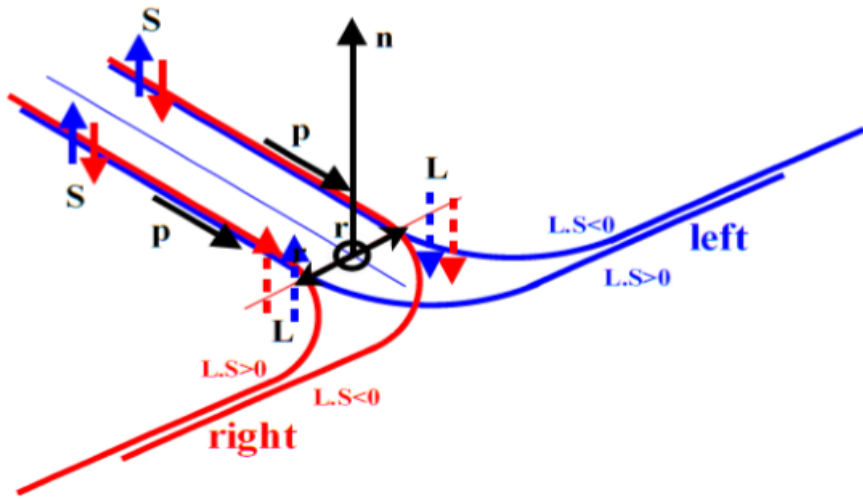
upto  $5 \times 10^{10}$  protons in ring

0,835  $\mu\text{s}$

bunch length  $\sim 80$  ns

$$\text{Lumi} = N/s * \rho_t * I$$

# Principle of Polarimetry



Due to  $L \cdot S$  coupling in NN interaction, incident particle with spin up or spin down relative to scattering plane scatters preferentially left, respectively right.

Azimuthal distribution:

$$I(\vartheta) = I_0 [1 + A_y(\vartheta) \vec{P}^{\text{fpp}} \cdot \vec{n}]$$

Following Basel convention (1960), spin- $\frac{1}{2}$  particles with spin up scatter preferentially to the left if analyzing power,  $A_y$ , is positive

$$A_y \bullet P_y = \frac{N_L - N_R}{N_L + N_R}$$

Spin 1/2

$$\frac{d\sigma}{d\Omega}(\Theta, \phi) = \left( \frac{d\sigma}{d\Omega} \right)_0(\Theta) \left[ 1 + \frac{1}{2} p_y A_y(\Theta) \right]$$

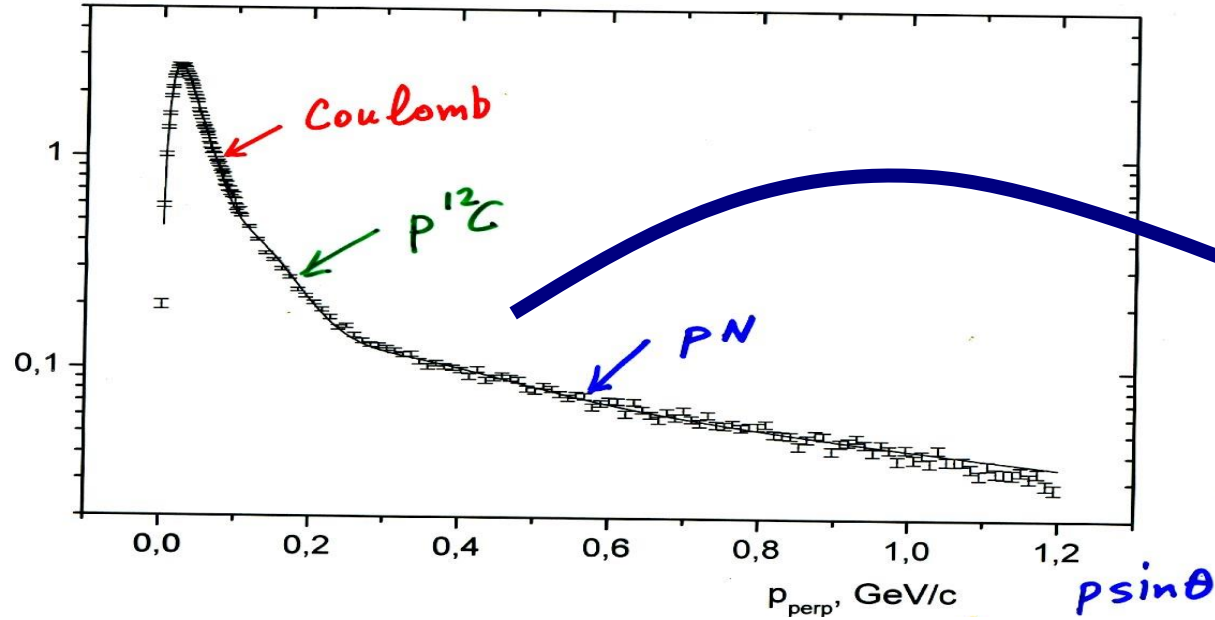
Spin 1

$$\frac{d\sigma}{d\Omega} = \left( \frac{d\sigma}{d\Omega} \right)_0 \left[ 1 + \frac{3}{2} p_y A_y + \frac{1}{2} p_{zz} A_{zz} + \frac{2}{3} p_{xz} A_{xz} + \frac{1}{6} (p_{xx} - p_{yy}) (A_{xx} - A_{yy}) \right]$$

# FOM (Figure of Merit)

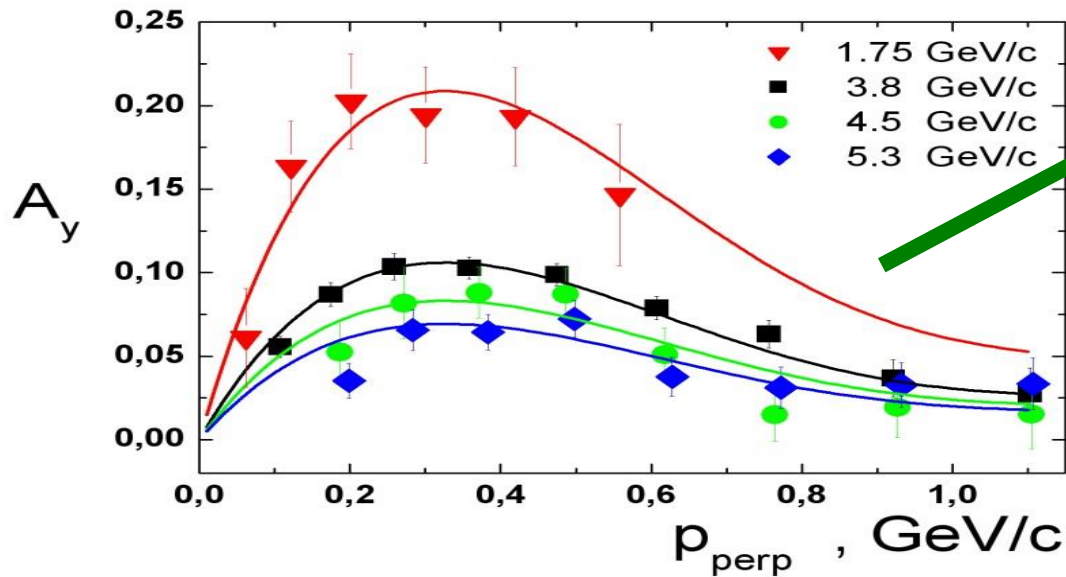
$p = 5.3 \text{ GeV/c}$   
56 cm

one charge particle



$$F^2 = \int_{\theta} \varepsilon(\theta) A_y^2(\theta) d\theta$$

$$\Delta P_y = \sqrt{\frac{2}{N_{inc} F^2}}$$



$$\Delta A_y = \frac{1}{P_y} \sqrt{A_y^2 \Delta P_y^2 + \frac{4N^+ N^-}{(N^+ + N^-)^3}}$$

$\Delta A_y \sim 0.01$        $N \sim 10^7$

# Reactions that can be used in polarimetry

## 1-13 GeV/c

	Type of reaction	Cross-section/ Total cross-section	Analyzing power
1	<p>pp scattering</p> <p>Elastic pp</p> <p>Quasi-elastic (CH2)</p> <p>CNI</p>	<p>4 – 2 mb / ~40 mb</p> <p>~ 6-3 mb / ~400 mb</p> <p>~ 2 mb / ~40 mb</p>	<p>(20 -7) %</p> <p>&lt;20 %</p> <p>4.5 %</p>
2	<p>Charge-exchange reactions</p> <p>p → n</p> <p>pp → n+X</p>	<p>&lt; 1 mb / ~45 mb</p> <p>0,07 mb / ~45 mb</p>	<p>up to 30%</p> <p>~ 7%</p>
3	Inclusive pion production	~ 30 μb / ~40 mb	up to 30%
4	Elastic proton-electron scattering	~ / ~2000 b at 10 GeV	

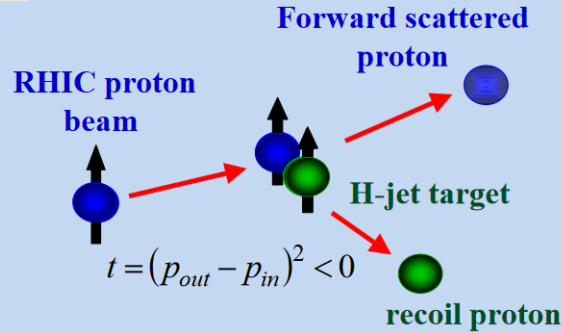
# HJet

Left-right asymmetry in elastic scattering:  
Interference between electromagnetic and hadronic amplitudes in the Coulomb-Nuclear Interference (CNI) region

$$A_N \approx \text{Im} \left( \phi_{SF}^{em} \phi_{NF}^{had} + \phi_{SF}^{had} * \phi_{NF}^{em} \right) / \left| \phi_{NF}^{had} \right|^2$$

Beam and target are both protons

$$A_N(t) = -\frac{\mathcal{E}_{target}}{P_{target}} = \frac{\mathcal{E}_{beam}}{P_{beam}}$$



$$P_{beam} = -P_{target} \frac{\mathcal{E}_{beam}}{\mathcal{E}_{target}}$$

$$\frac{\Delta P_{beam}}{P_{beam}} \approx \frac{\Delta P_{target}}{P_{target}} \oplus \frac{\Delta \mathcal{E}_{target}}{\mathcal{E}_{target}} \oplus \frac{\Delta \mathcal{E}_{beam}}{\mathcal{E}_{beam}} < 5\%$$

$P_{target}$  is provided by Breit Rabi Polarimeter

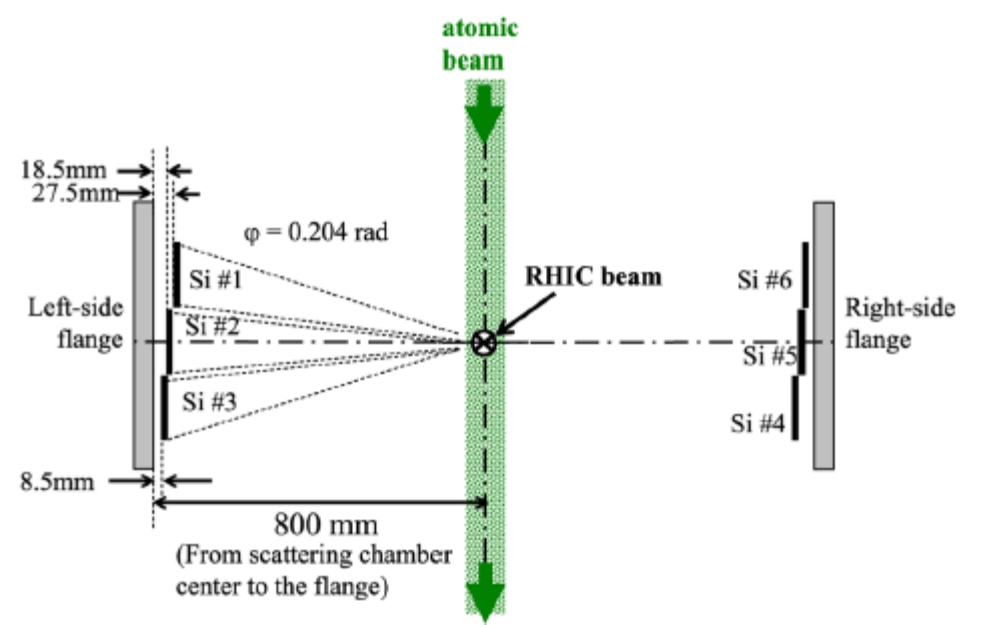
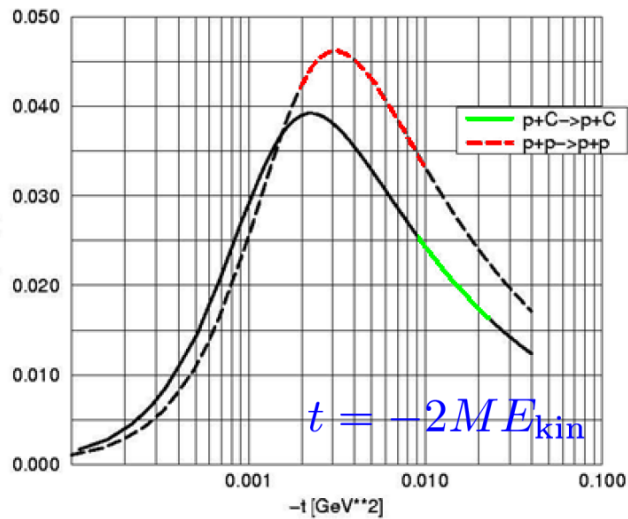
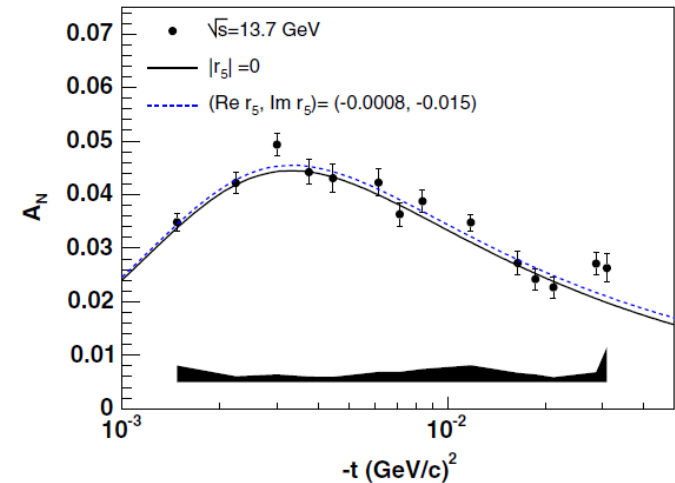
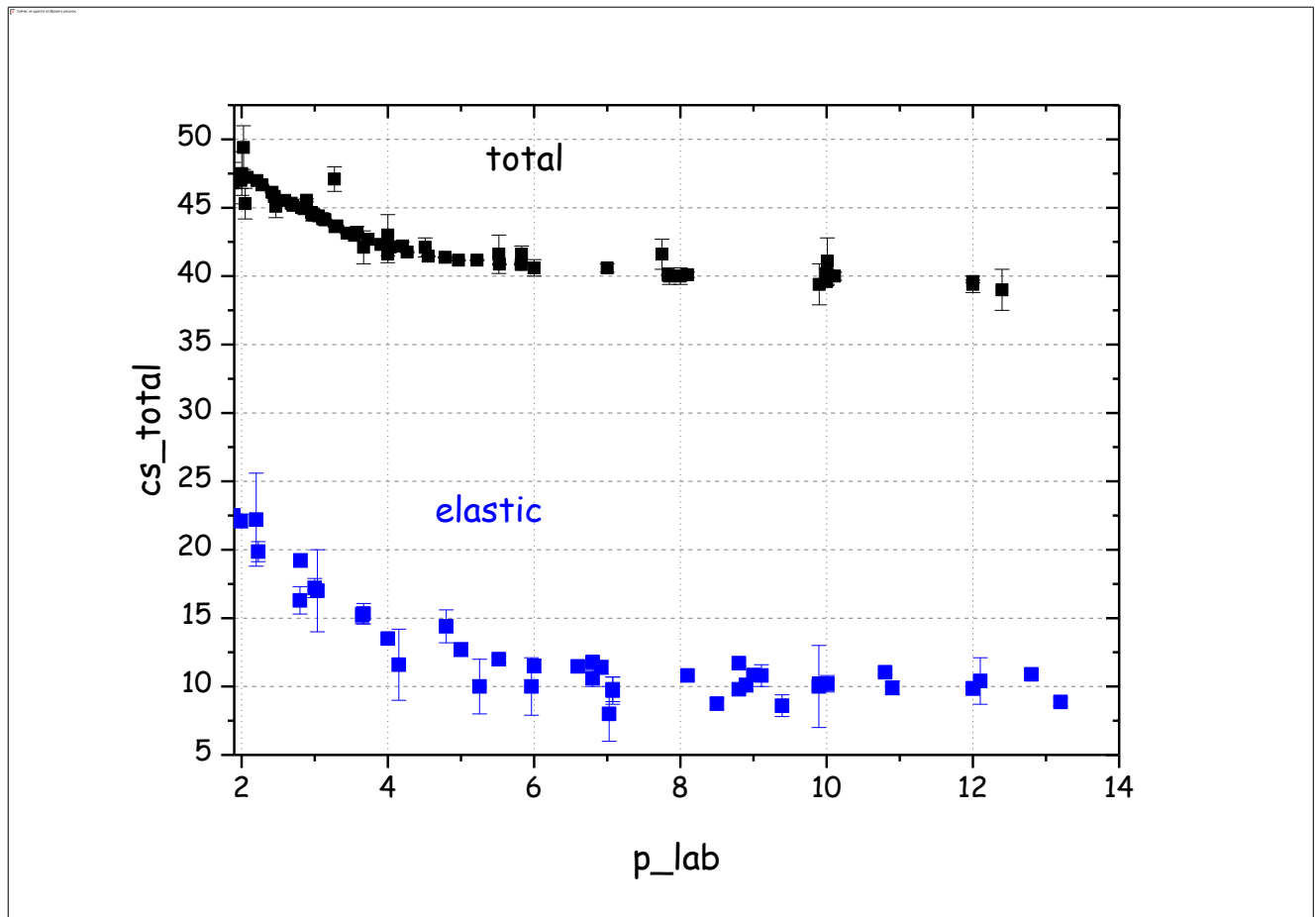


FIG. 2 (color online). Layout of the  $pp$  elastic scattering setup from the RHIC-beam view. The detectors were mounted on vacuum flanges on the scattering chamber and located to the left and right of the beam. Three pairs of silicon detectors covered an azimuthal angle of  $11.7^\circ$  centered on the horizontal midplane.



	NICA	RHIC
	503 m	3834 m
	1.66 $\mu$ s	12.65 $\mu$ s
	$2.2 \cdot 10^{13}$	$2.4 \cdot 10^{13}$
<b>time</b>	<b>turn numbers</b>	
1 s	$6.0 \cdot 10^5$	$7.9 \cdot 10^4$
10 s	$6.0 \cdot 10^6$	$7.9 \cdot 10^5$
1 m	$3.6 \cdot 10^7$	$4.7 \cdot 10^6$
10 m	$3.6 \cdot 10^8$	$4.7 \cdot 10^7$
1 h	$2.2 \cdot 10^9$	$2.9 \cdot 10^8$
10 h	$2.2 \cdot 10^{10}$	$2.9 \cdot 10^9$



H-jet  $1.2 \cdot 10^{12}$  protons/cm<sup>2</sup>  
H2(D2,CH4)-cluster  $10^{15}$  protons/cm<sup>2</sup>

$\sigma_{tot}$  (pp)  $\sim 40$  mb,  $\sigma_{el}$  (pp)  $\sim 10$  mb

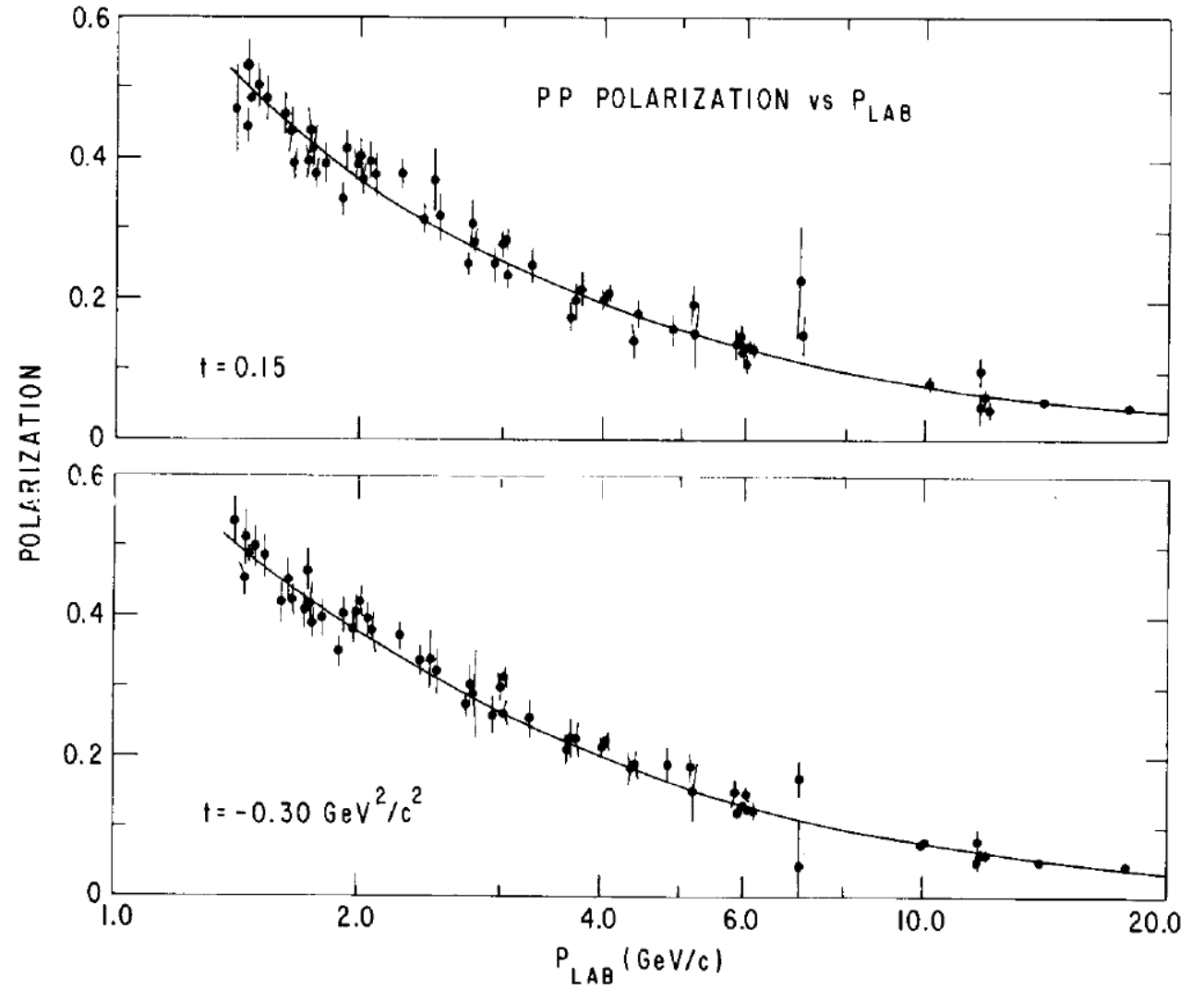
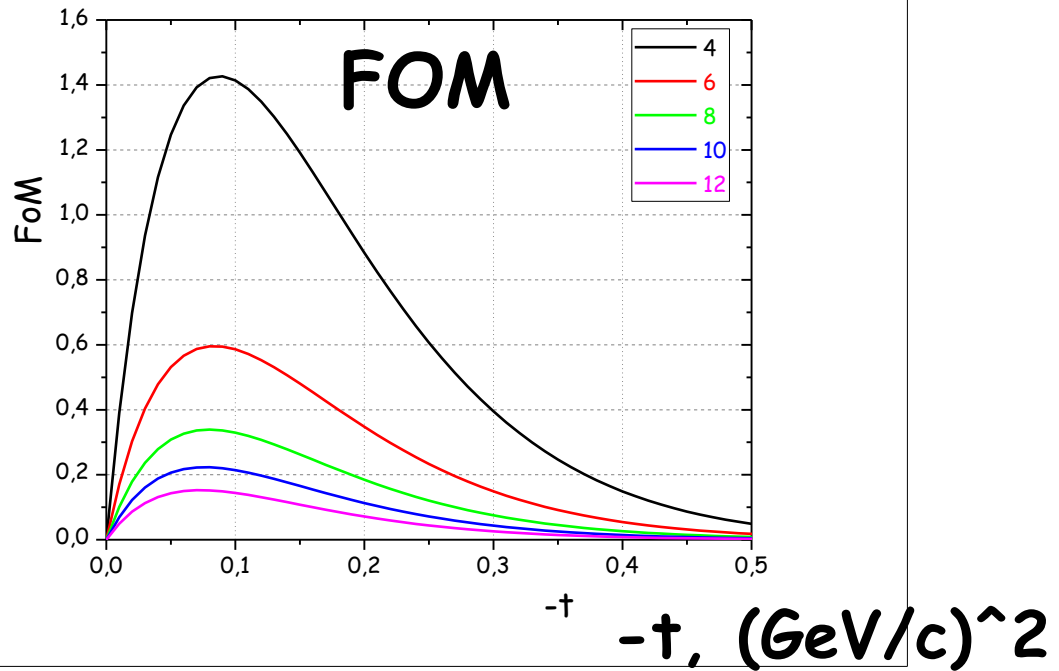
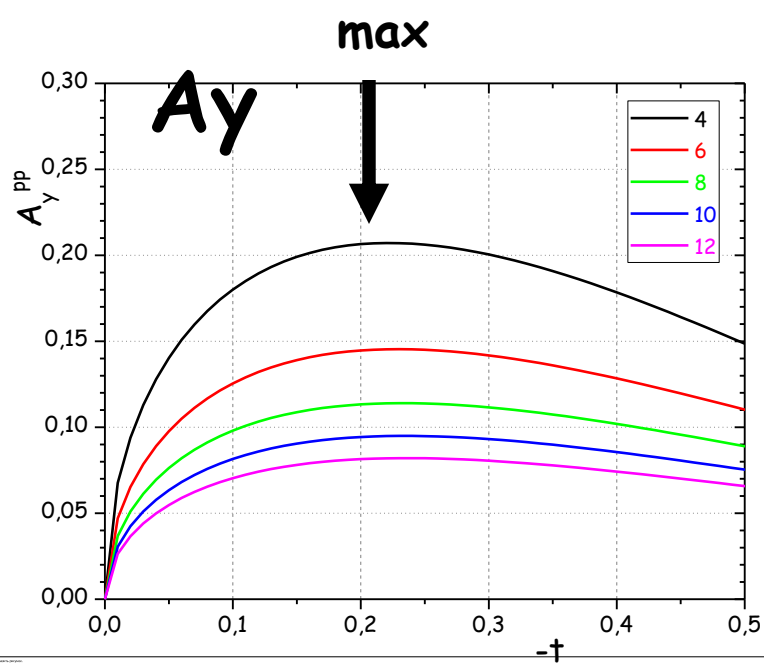
$N_{jet} = 2.2 \cdot 10^{13} * 1.2 \cdot 10^{12} * 40 \cdot 10^{-27} \sim 1$  interaction/turn

$N_{cluster}$

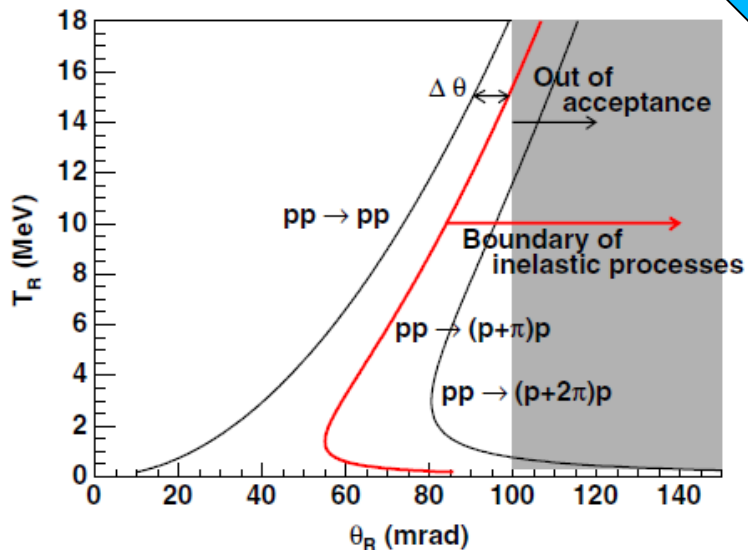
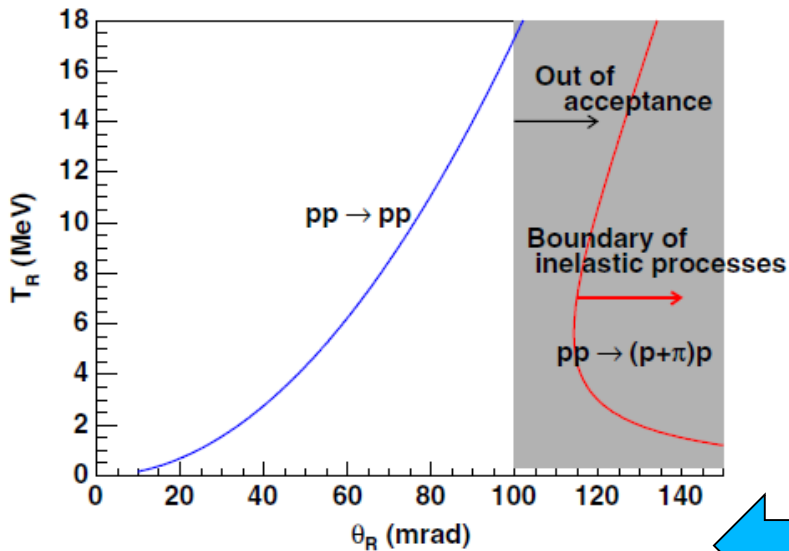
$\sim 10^3$

**NICA/RHIC = 7.62**





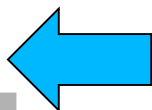
# Recoil protons



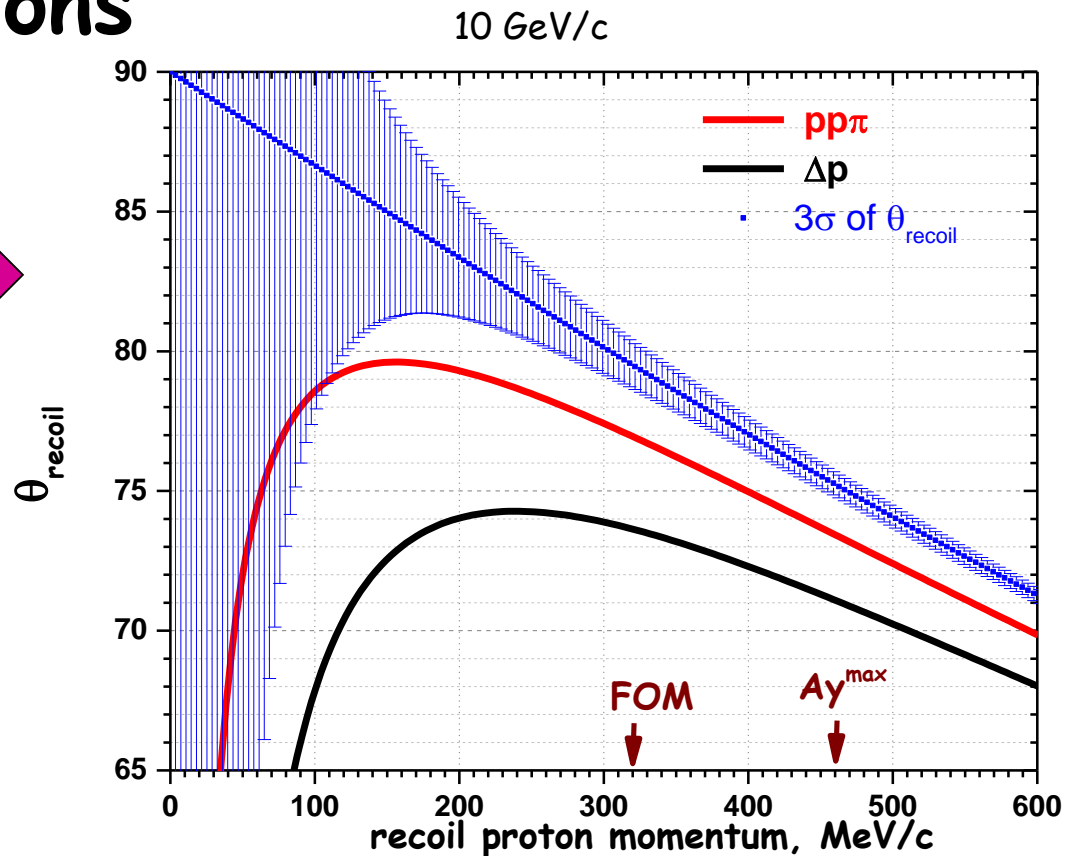
Elastic pp



CNI



1-13 GeV/c



0,3-0,5 GeV/c

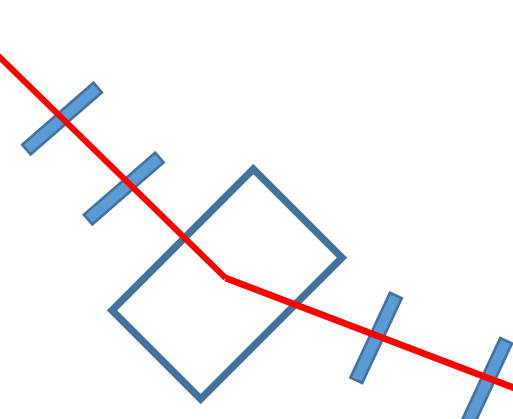
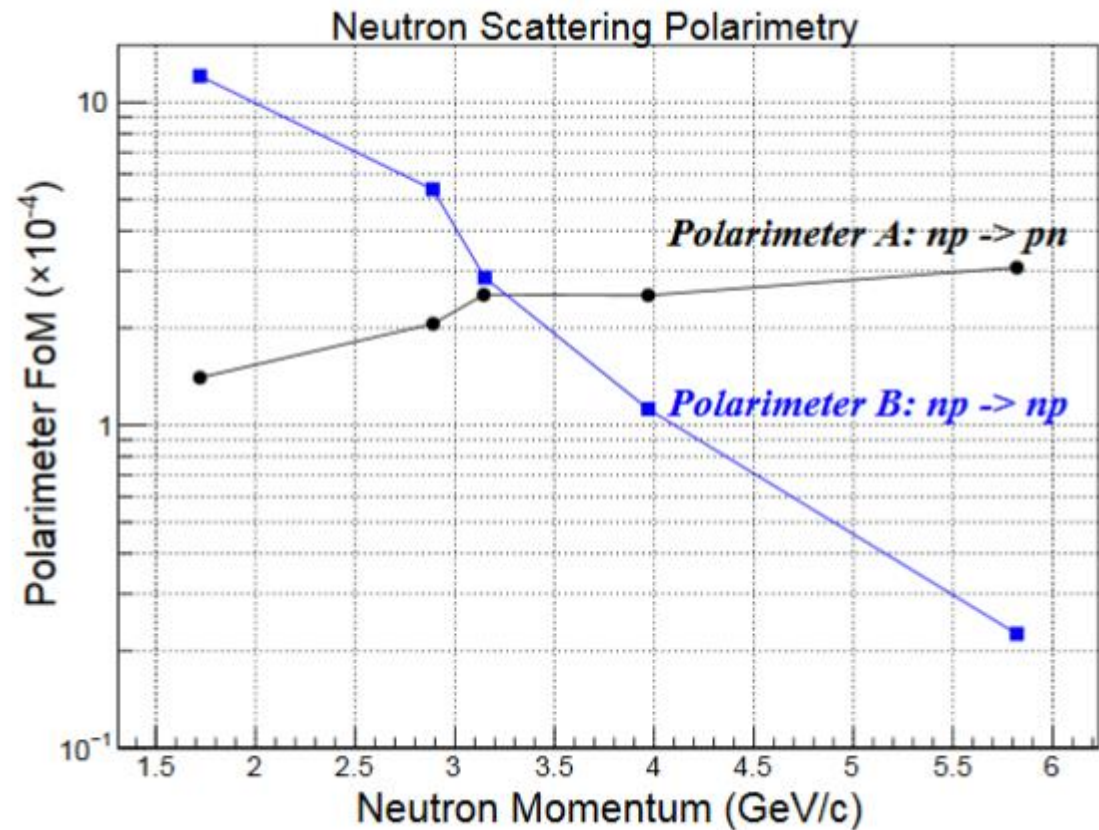
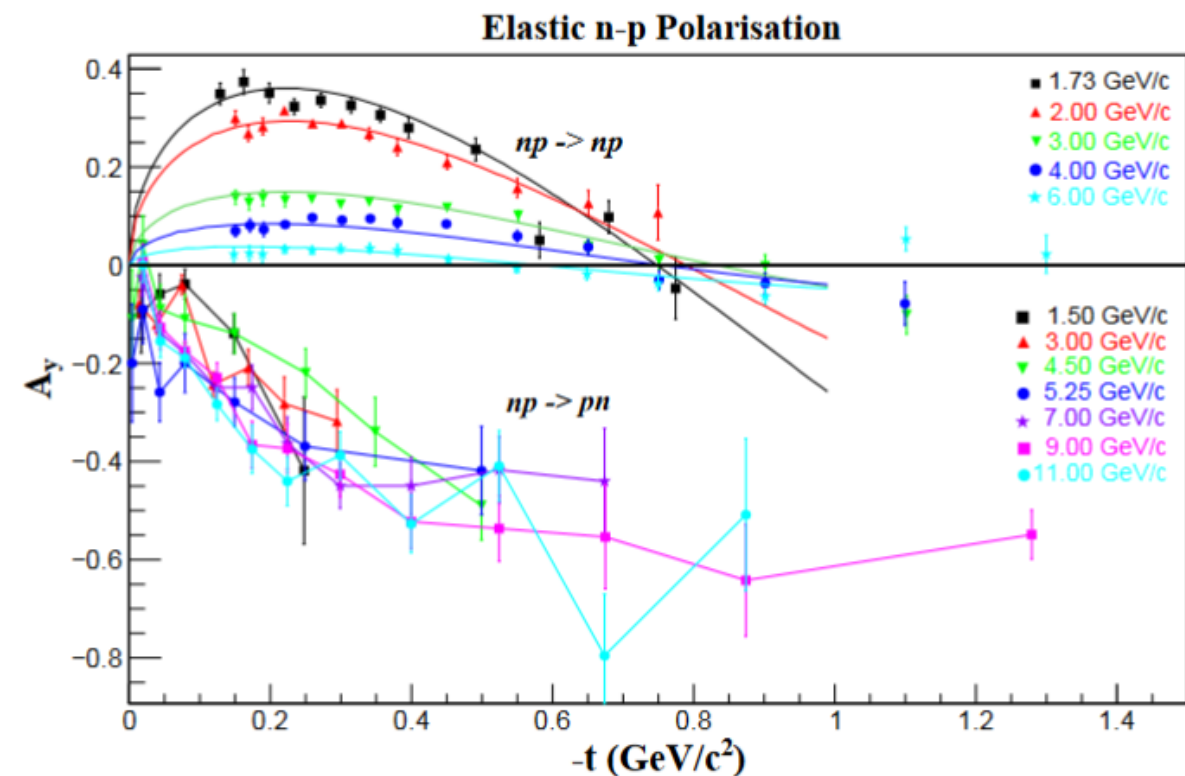


FIG. 12 (color online). Top: Calculation of  $T_R$ - $\theta_R$  correlation for  $pp \rightarrow pp$  and inelastic process at  $\sqrt{s} = 6.8$  GeV. Detectors cover  $10 < \theta_R < 100$  mrad. Bottom: The same for  $\sqrt{s} = 13.7$  GeV. The difference between the recoil angle of the elastic process and inelastic processes,  $\Delta\theta$ , decreases as  $T_R$  increases and  $\Delta\theta = 8.3$  mrad at  $T_R = 15$  MeV.

# Polarized H-jet target

GeV/c	$\Delta\sigma$ , mb	$A_n$ , avr	$\Delta\phi$ , 60 cm	$\Delta\sigma \times \Delta\phi$ , mb	# turns per event	5%	# turns per 5%	Time
4	3,08	0,195	0,016	0,049	8.16 +02	1,1 +04	9,0 +06	~15 s
6	2,56	0,136	0,016	0,041	9,76 +02	2,2 +04	2.1 +07	~ 35 s
8	2,29	0,107	0,016	0,037	1,08 +03	3,5 +04	3,8 +07	~ 1 m
10	2,10	0,088	0,016	0,034	1,18 +03	5,2 +04	6,1 +07	~ 1,7 m
12	1,84	0,077	0,016	0,029	1,38 +03	6,9 +04	9,5 +07	~ 2,6 m
	0,0015-0,03							
6, CNI	2.81	0.030	0,032	0,09	4,4 +02	4,4 +05	2,0 +08	~ 6 m
100, CNI	1.65	0.030	0,032	0,053	7,6 +02	4,4 +05	3,3 +08	~ 1.15 h

# Comparison $np \rightarrow np$ and $np \rightarrow pn$ reaction

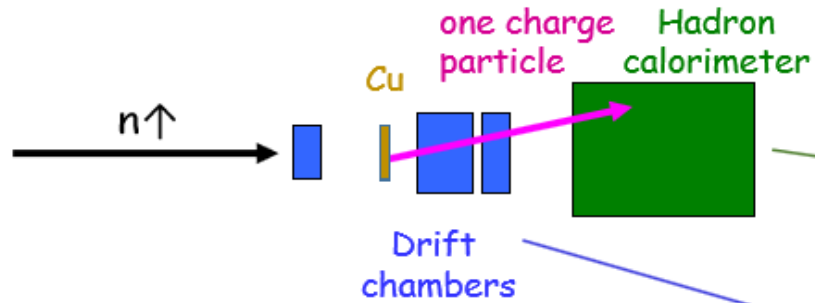


Top:  $t$ -dependence of the polarisation of  $np$  scattering for different values of  $plab$  [30, 31]. The smooth dotted lines show the fit of Ref. [34] to the  $np$  data.

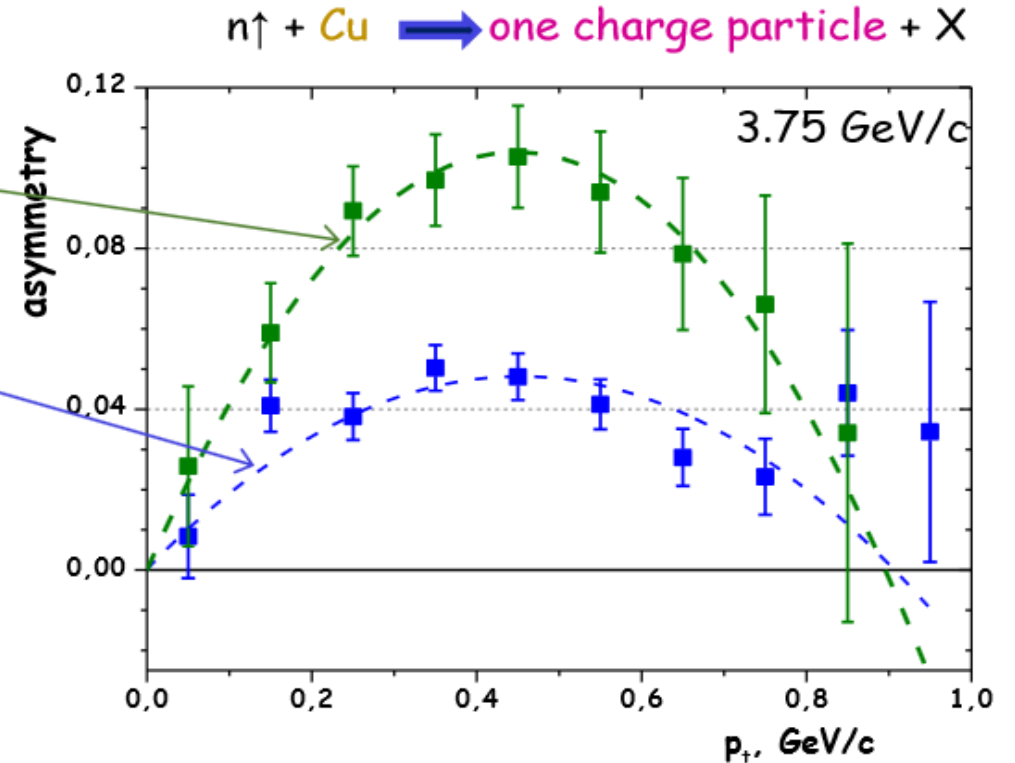
Bottom: the  $t$  dependence of charge-exchange  $np$  scattering for different values of  $plab$  [35, 36]. The color coding relates the data to momentum labels.

Neutron polarimeter figure of merit as a function of incident neutron momentum for the two polarimeter configurations. Blue squares: standard  $np$  scattering from CH scintillator (Polarimeter B), black circles: charge-exchange  $np$  scattering from Cu (Polarimeter A).

# Charge exchange reaction

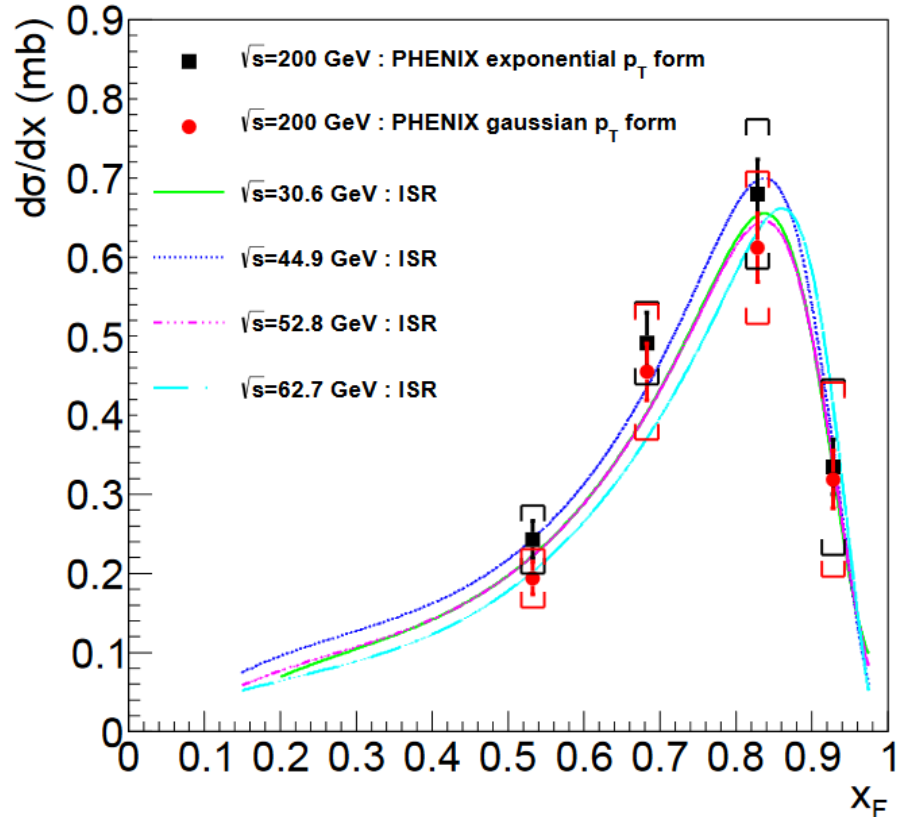


- 1) The observed asymmetry is unpredictably bigger than in np elastic scattering that usually used for neutron polarimetry
- 2) The length of the copper target is only 4 cm in comparison with the CH one (> 30 cm) used in the elastic np scattering, which makes it possible to improve the accuracy of determining the interaction vertex and the scattering angle.
- 3) Registration of charged particles moving forward is much easier than detection the recoil proton in np elastic scattering

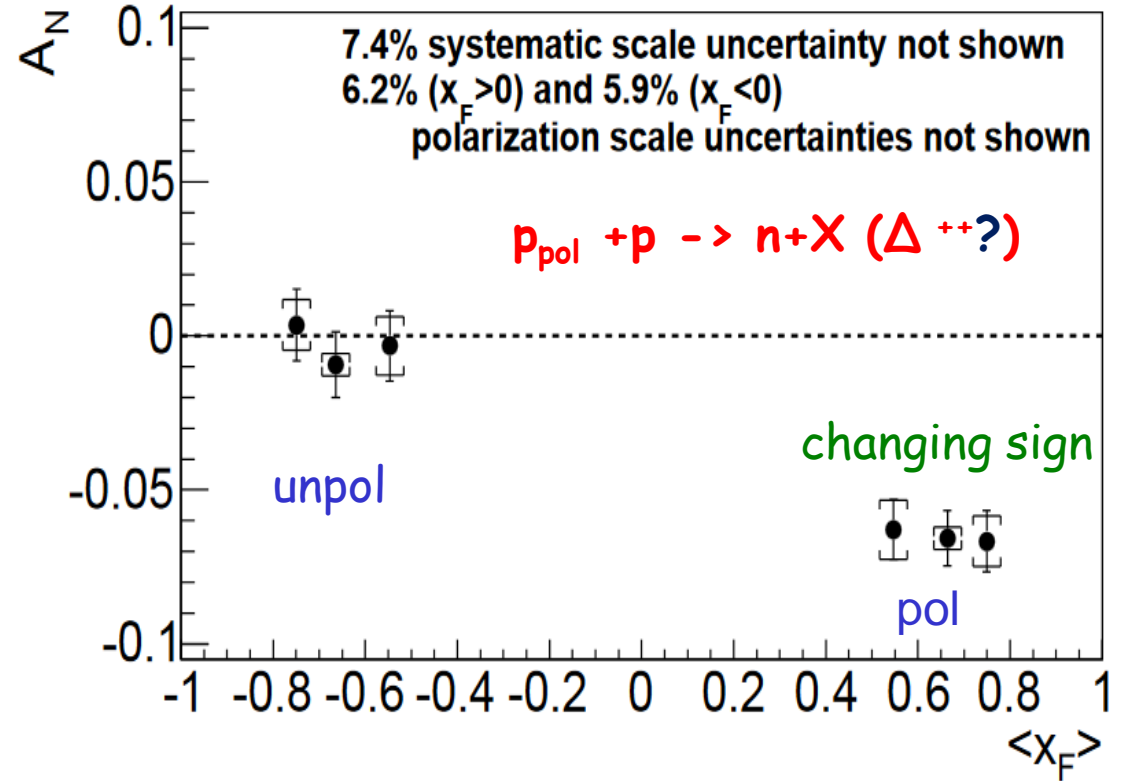


**The inverse reaction  $p + \text{Cu}$  (W) with detection neutron in forward direction by the hadron calorimeter can be used for measurement of the proton polarization at the NICA collider.**

(PHENIX Collaboration)

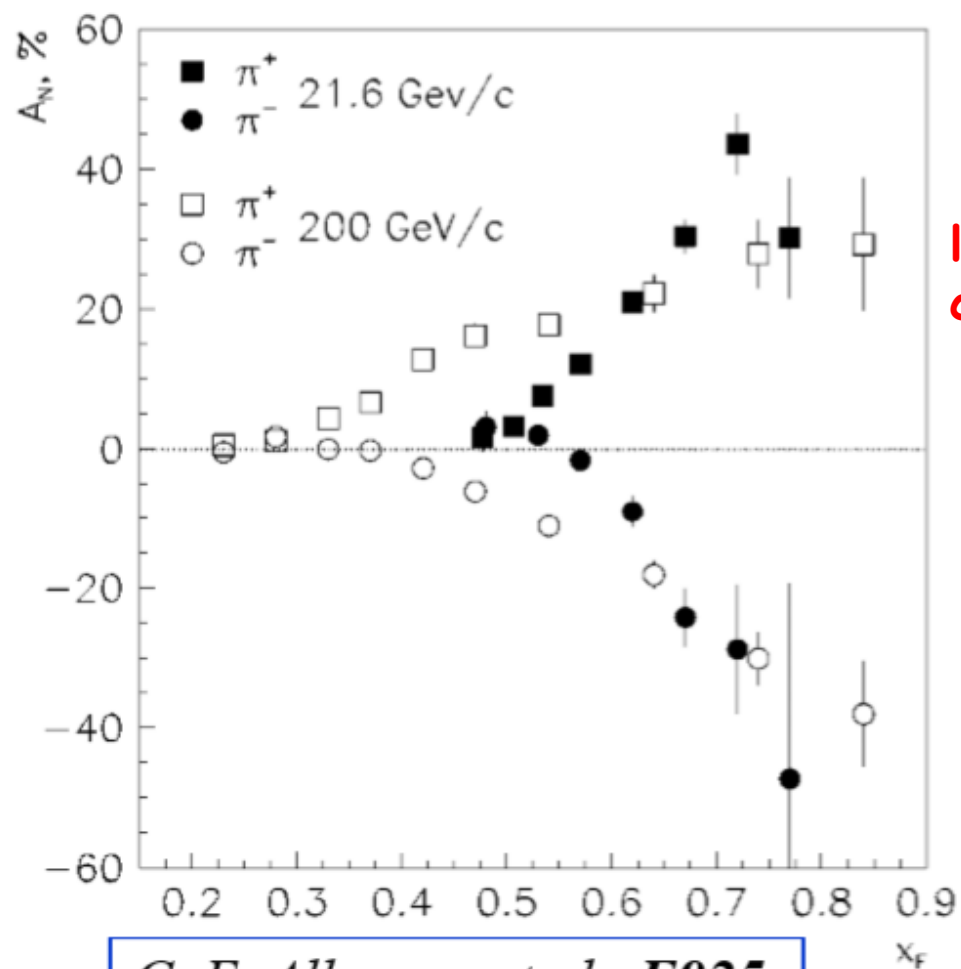


The cross section results for forward neutron production in p+p collisions at  $\sqrt{s}=200\text{ GeV}$  are shown. Two different forms, exponential (squares) and Gaussian (circles), were used for the  $p_T$  distribution. Statistical uncertainties are shown as error bars for each point, and systematic uncertainties are shown as brackets. The integrated  $p_T$  region for each bin is  $0 < p_T < 0.11 x_F \text{ GeV}/c$ . Shapes of ISR results are also shown. Absolute normalization errors for the PHENIX and ISR are 9.7% and 20%, respectively.



The  $x_F$  dependence of  $A_N$  for neutron production in the ZDC $\otimes$ BBC trigger sample. The error bars show statistical uncertainties and brackets show  $p_T$ -correlated systematic uncertainties.

# Polarimetry with inclusive pions



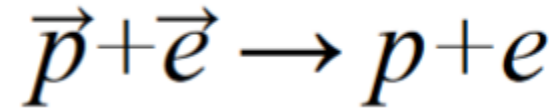
*C. E. Allgover, et al., E925*

FIG. 22. Comparison of inclusive analyzing powers  $A_N$  from carbon at 21.6 GeV/c and hydrogen at 200 GeV/c [2].

$pp \rightarrow \pi^+ X$	$0.55 < x_F < 0.6$ $\langle p_T \rangle = 0.7$ GeV/c	$0.6 < x_F < 0.65$ $\langle p_T \rangle = 0.7$ GeV/c	$0.65 < x_F < 0.7$ $\langle p_T \rangle = 0.8$ GeV/c
$A_N$ %	$15.7 \pm 1.5$	$23.7 \pm 2.0$	$29.1 \pm 2.9$
Required $N_{events}$	$\sim 5.5 \times 10^4$	$\sim 2.5 \times 10^4$	$\sim 1.6 \times 10^4$
$\sigma, \mu b$	$\sim 15$	$\sim 7$	$\sim 4$
$N_{events/spill}$	$\sim 13.6$	$\sim 6.4$	$\sim 3.6$
Exposition time	$\sim 11-14$ hours	$\sim 11-14$ hours	$\sim 12-15$ hours

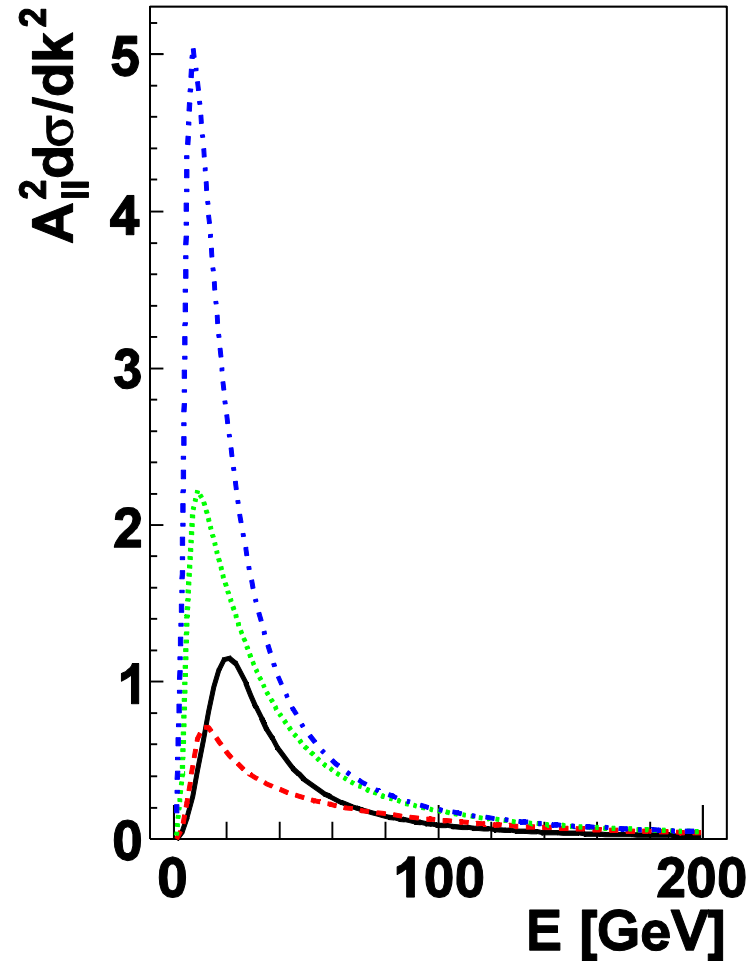
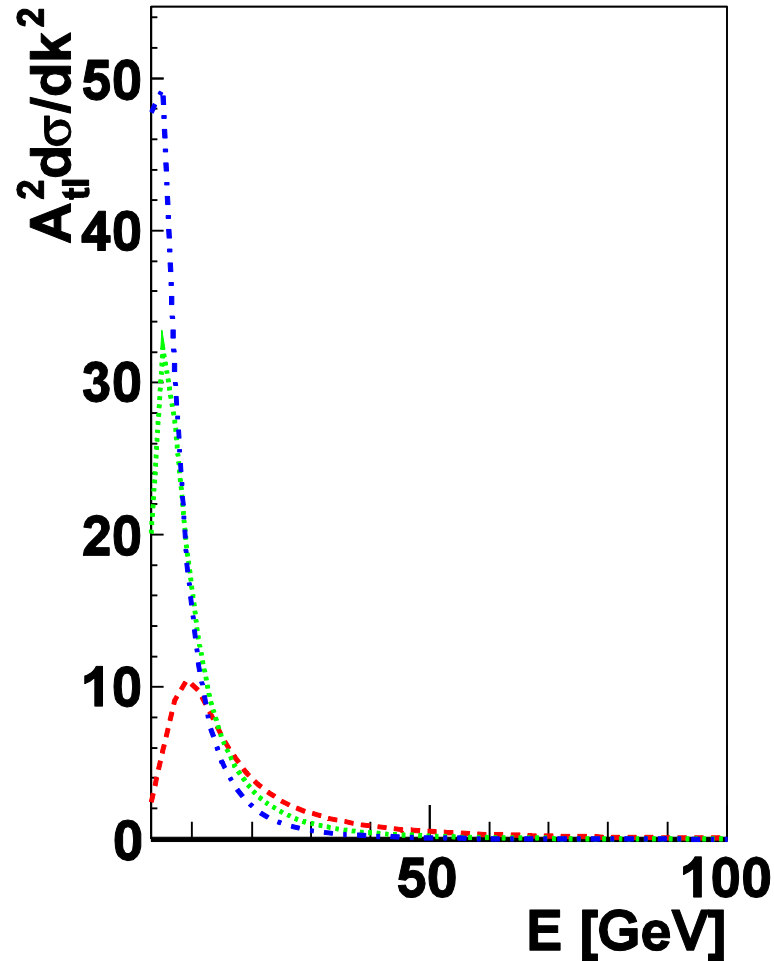
$pC \rightarrow \pi^+ X$	$0.55 < x_F < 0.6$ $\langle p_T \rangle = 0.7$ GeV/c	$0.6 < x_F < 0.65$ $\langle p_T \rangle = 0.7$ GeV/c	$0.65 < x_F < 0.7$ $\langle p_T \rangle = 0.8$ GeV/c
$A_N$ %	$12.5 \pm 1.1$	$22.8 \pm 1.5$	$30.2 \pm 2.4$
Required $N_{events}$	$\sim 10^5$	$\sim 2.5 \times 10^4$	$\sim 1.5 \times 10^4$
$\sigma, \mu b$	$\sim 110$	$\sim 50$	$\sim 30$
$N_{events/spill}$	$\sim 44$	$\sim 20$	$\sim 12$
Exposition time	$\sim 6-7$ hours	$\sim 3.5-4$ hours	$\sim 3.5-4$ hours

# Exotic polarimetry reaction



PHYSICAL REVIEW C 84, 015212 (2011)

double analyzing powers



Variation of differential quantities

$A_{tl}^2(k^2)(d\sigma/dk^2)$  (left)

$A_{ll}^2(k^2)(d\sigma/dk^2)$  (right)

$\theta_e = 0$  mrad (black solid line),  
10 mrad (red dashed line),  
30 mrad (green dotted line),  
50 mrad (blue dash-dotted line).



# Polarimetry

$$\epsilon(\theta_p) = N_f(\theta_p)/N_i$$

$$\mathcal{F}^2(\theta_p) = \epsilon(\theta_p)A_{ij}^2(\theta_p),$$

$$\left(\frac{\Delta P(\theta_p)}{P}\right)^2 = \frac{2}{N_i(\theta_p)\mathcal{F}^2(\theta_p)P^2} = \frac{2}{Lt_m(d\sigma/d\Omega)d\Omega A_{ij}^2(\theta_p)P^2},$$

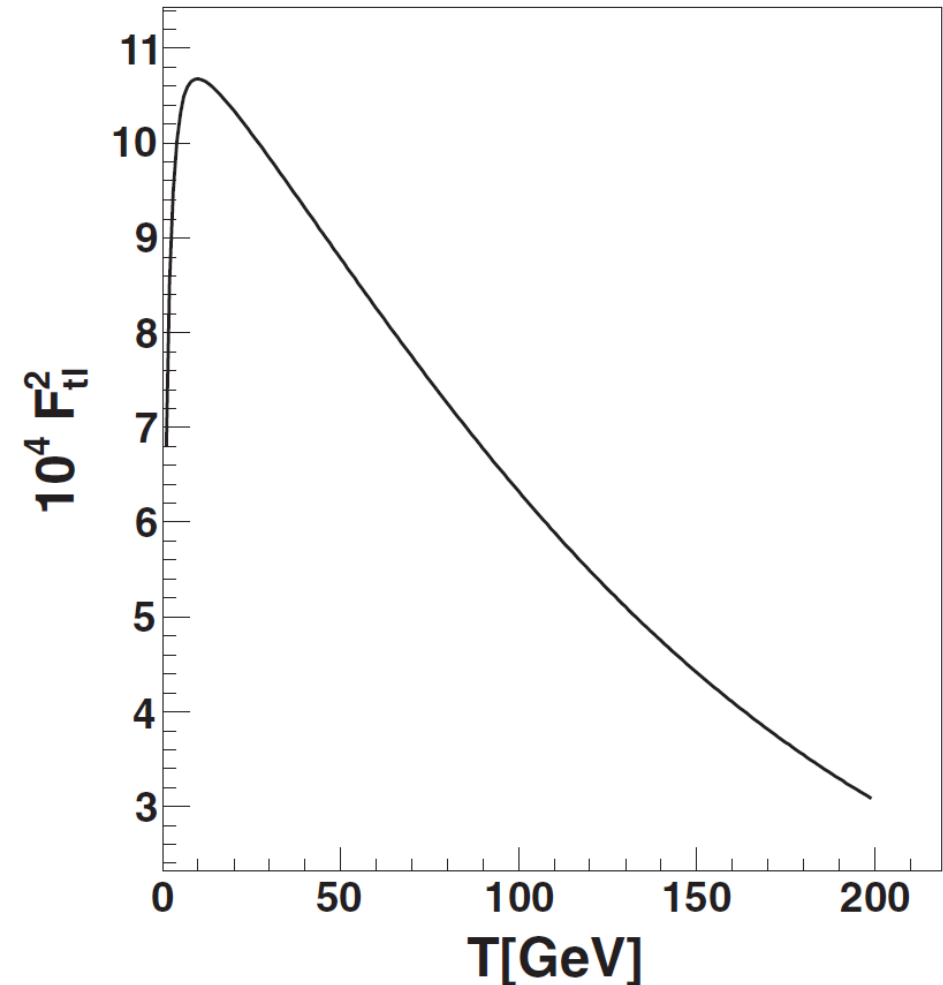
$$F^2 = \int \frac{d\sigma}{dk^2} A_{ij}^2(k^2) dk^2$$

$F^2$  has Max at  $E \sim 10$  GeV

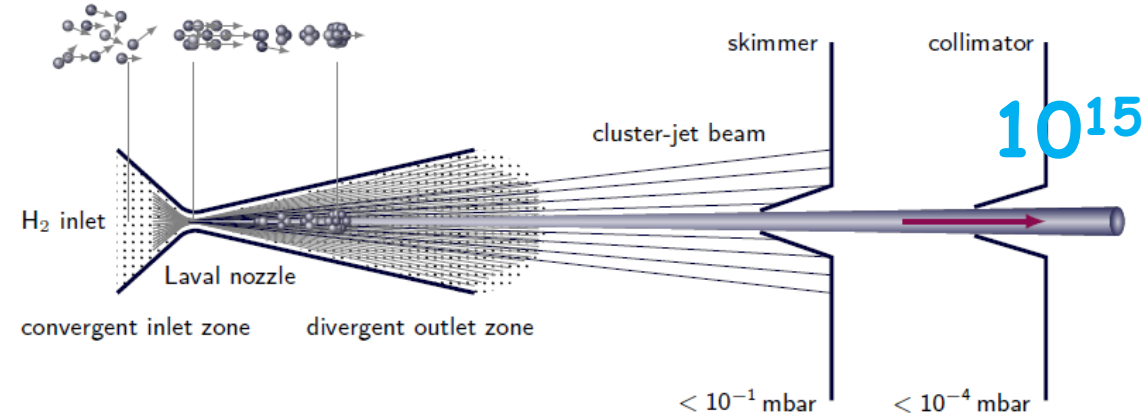
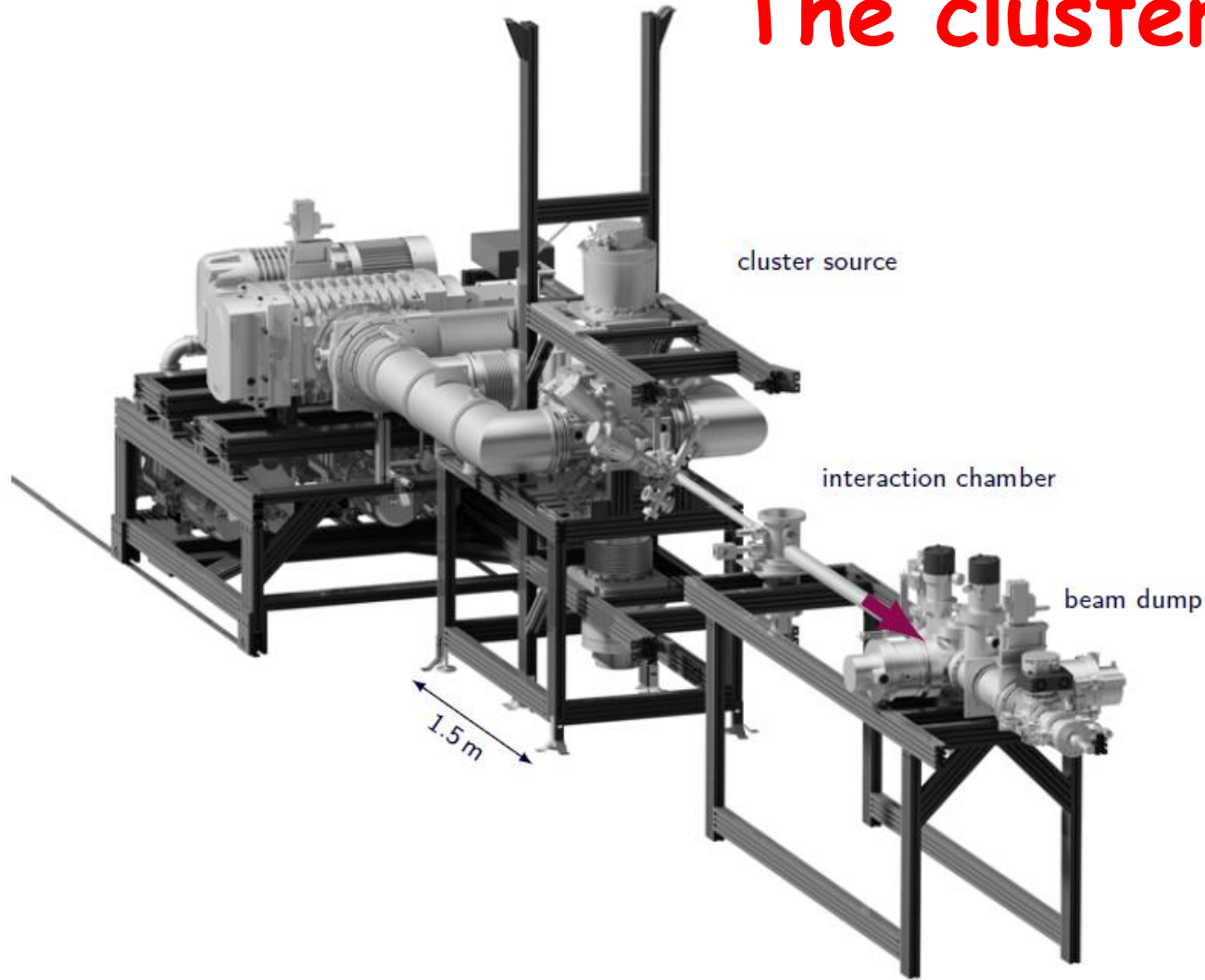
N beam =  $1.3 \times 10^{19}$  p s<sup>-1</sup> NICA

N target  $\sim 10^{12}$  atomes/cm<sup>2</sup> Jet target

$\Delta P = 1\%$  in  $t = 21$  min



# The cluster target

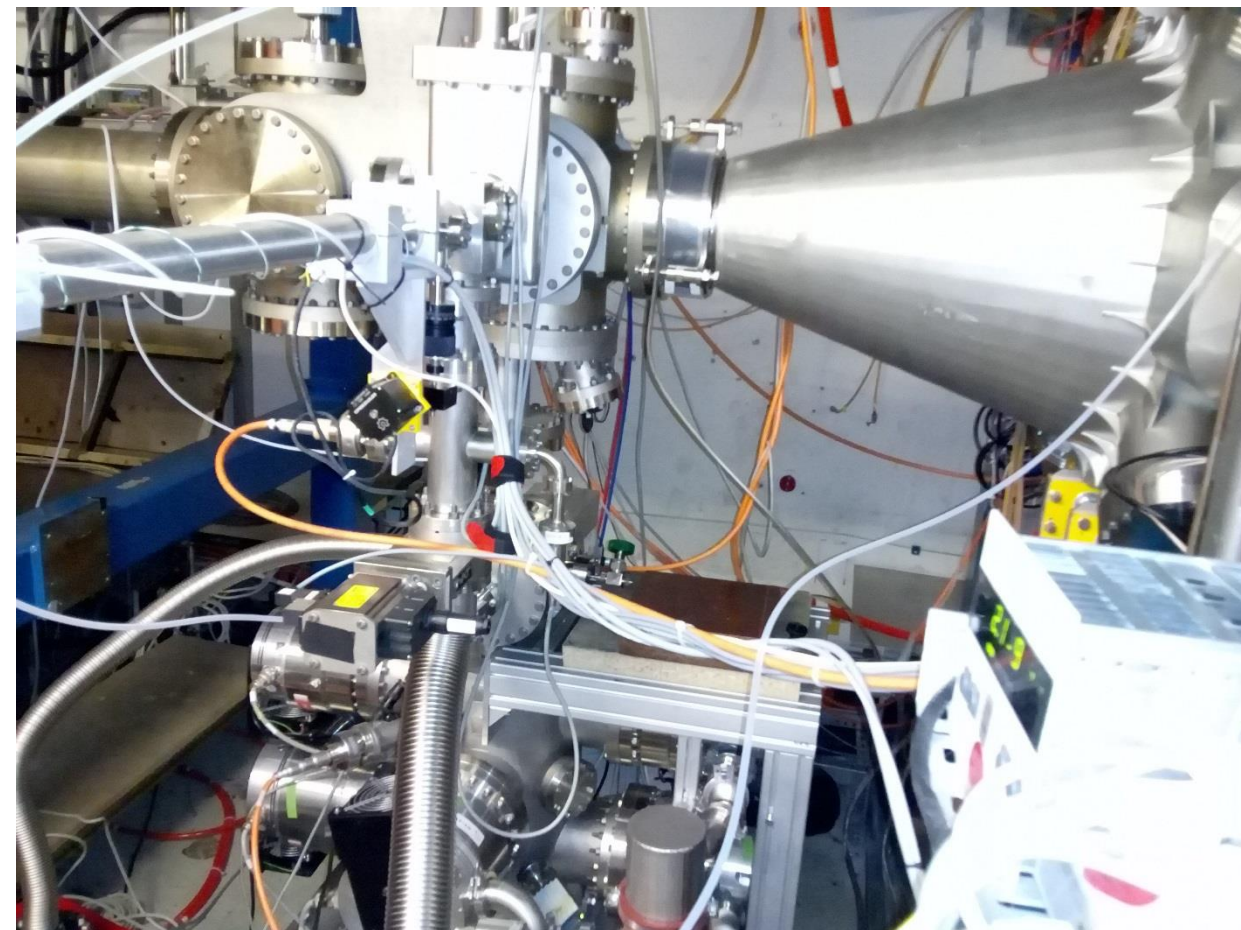
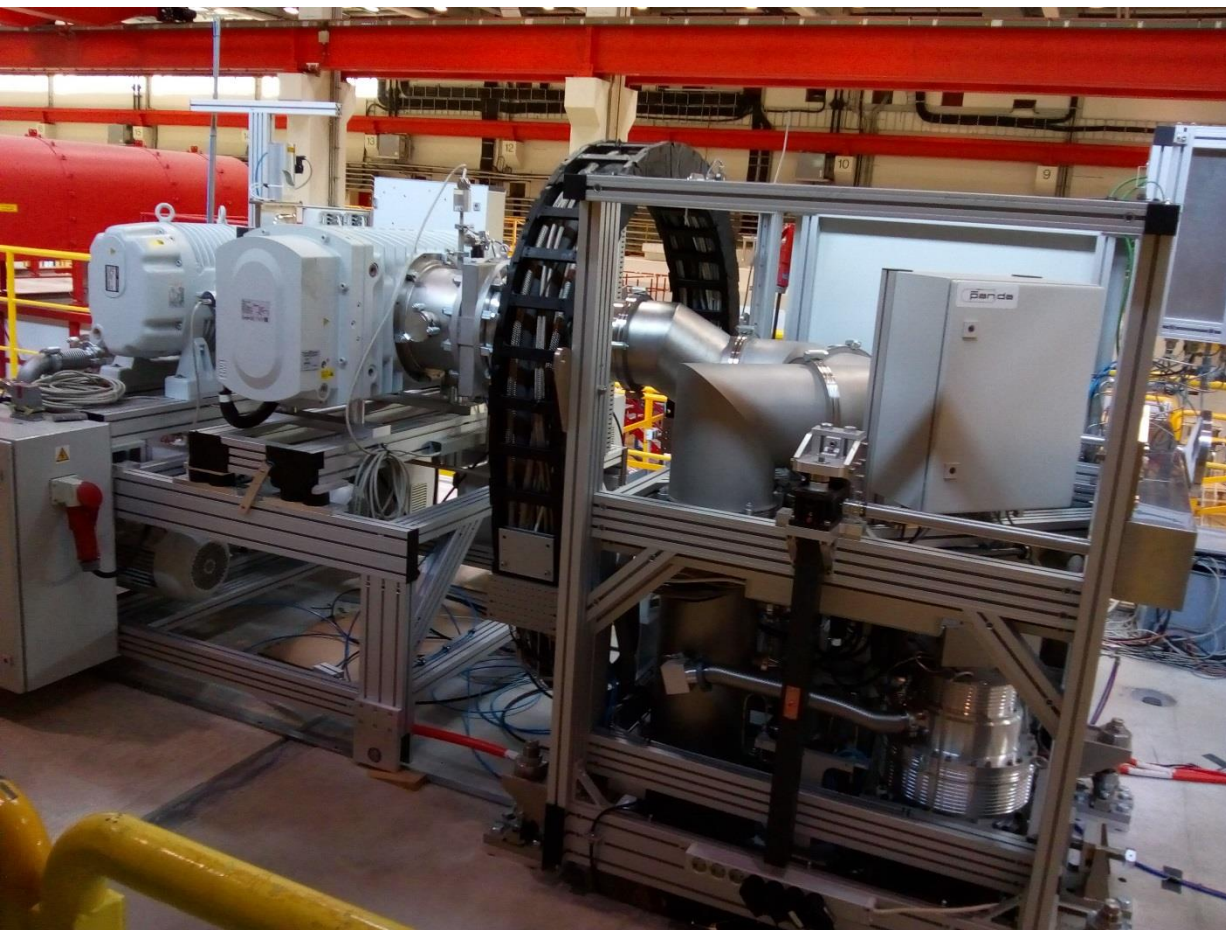


Schematic representation of the cluster production process.

Overview of the cluster-jet target prototype for the PANDA experiment

ESPERANZA DIANE KÖHLER  
Mass spectroscopy of hydrogen  
cluster-jets and beam density  
optimisation studies

# The cluster target at the COSY beam



# CONCLUSION

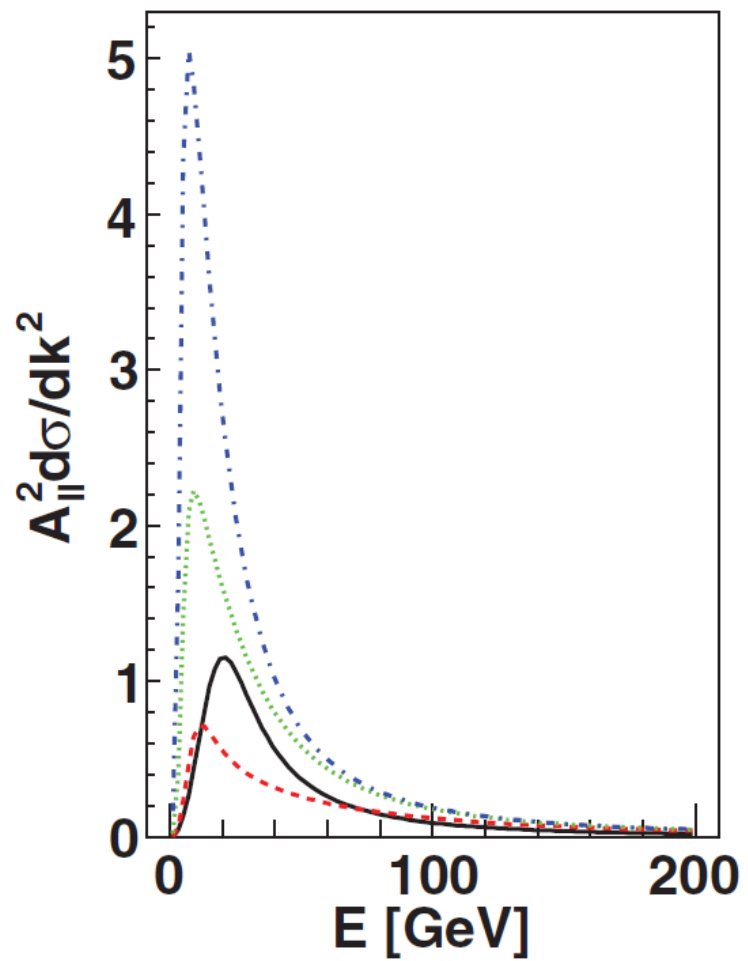
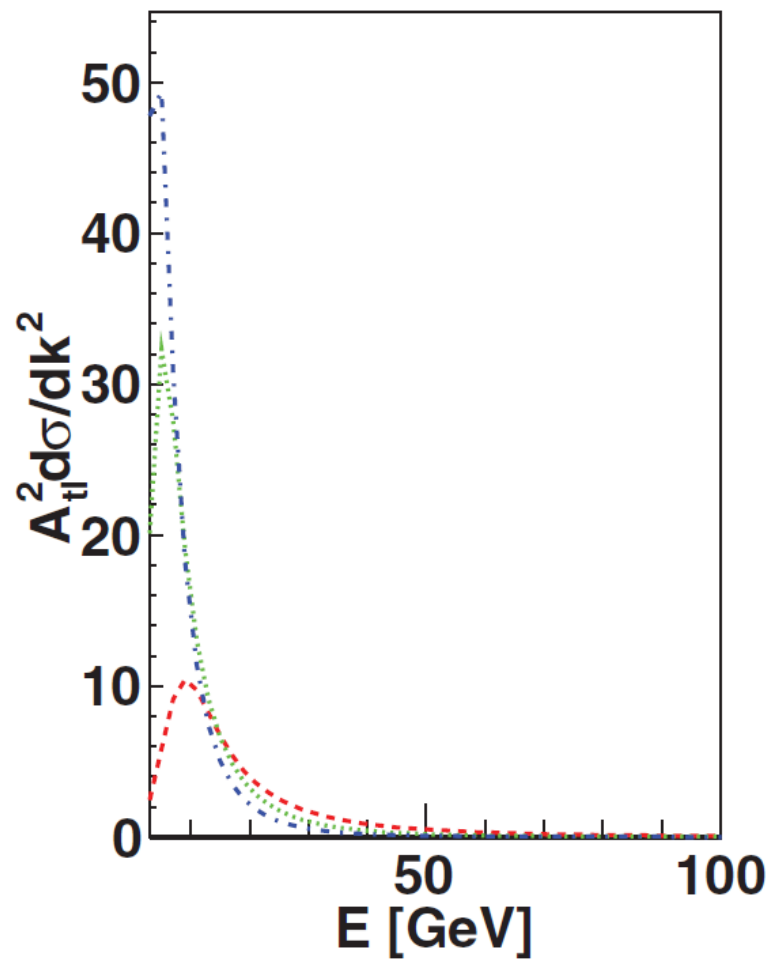
Elastic pp scattering with detecting a recoil proton is the best reaction for proton polarimetry in momentum interval from 1 to 13 GeV/c

A **cluster target** (protons or deuterons) should be installed in Nuclotron ring instead of the existing target station

$p(\text{pol}) + d$  &  $d(\text{pol}) + p$

**Thank you!**





$\vec{p} + \vec{e} \rightarrow p + e$  Exotic polarimetry reaction  
*polarimetry*

*Polarized beam  
 on polarized target*

$$F^2 = \int \frac{d\sigma}{dk^2} A_{ij}^2(k^2) dk^2$$

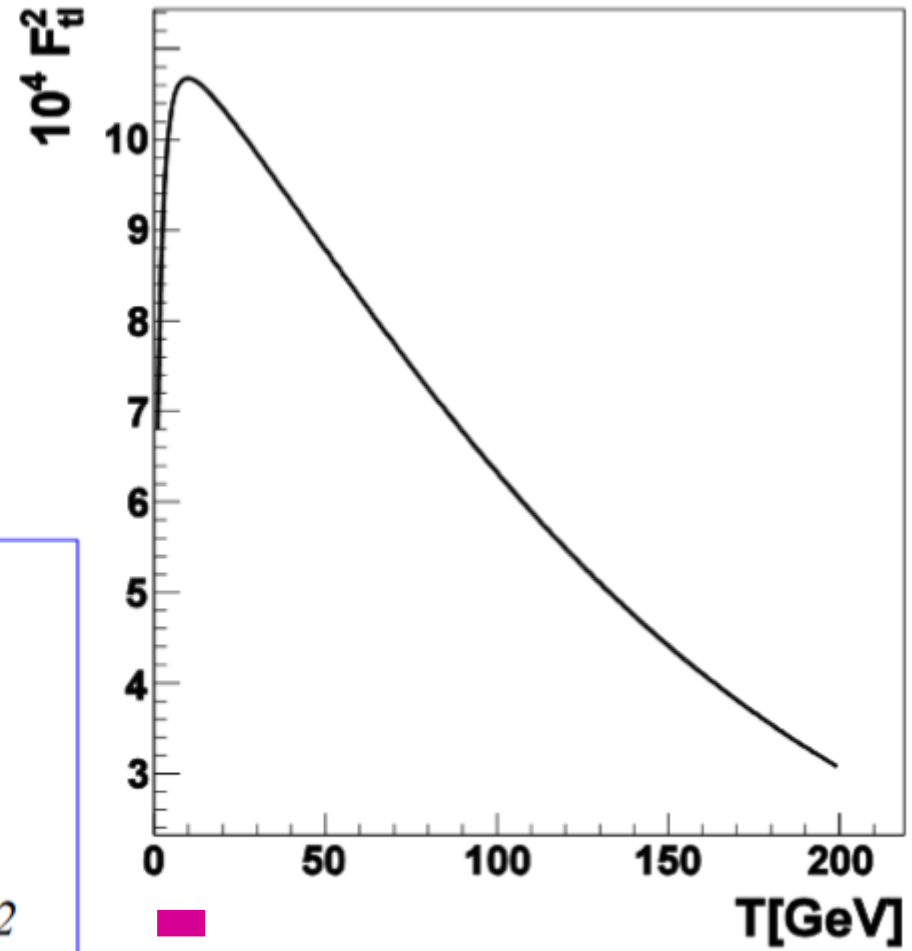
*$F^2$  Max at  $E \sim 10$  GeV*

*$L = 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$*

*$N_{\text{beam}} = 6 \times 10^{17} \text{ p s}^{-1}$*

*$N_{\text{target}} = 2 \times 10^{14} \text{ atoms/cm}^2$*

*$\Delta P = 1\%$  in  $t = 3\text{m}$*



SPD region

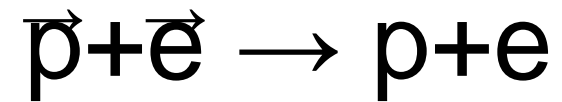
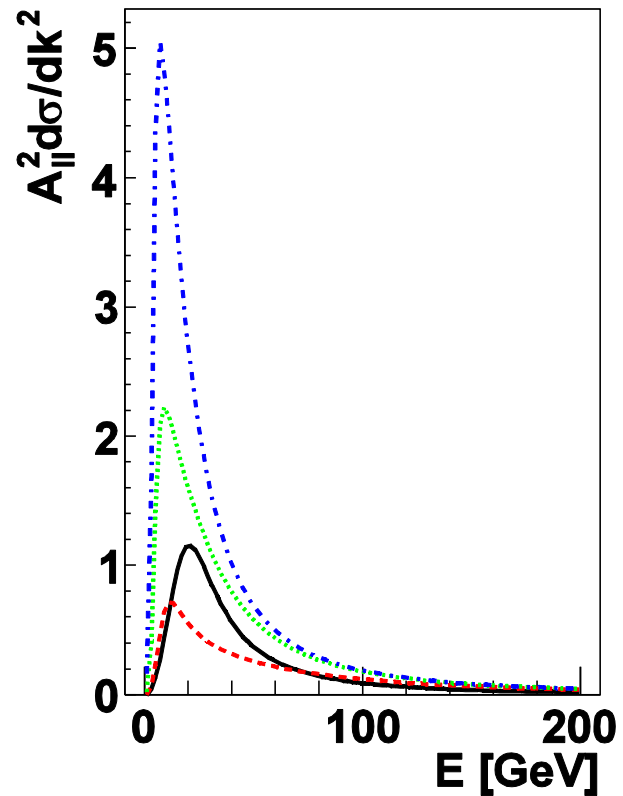
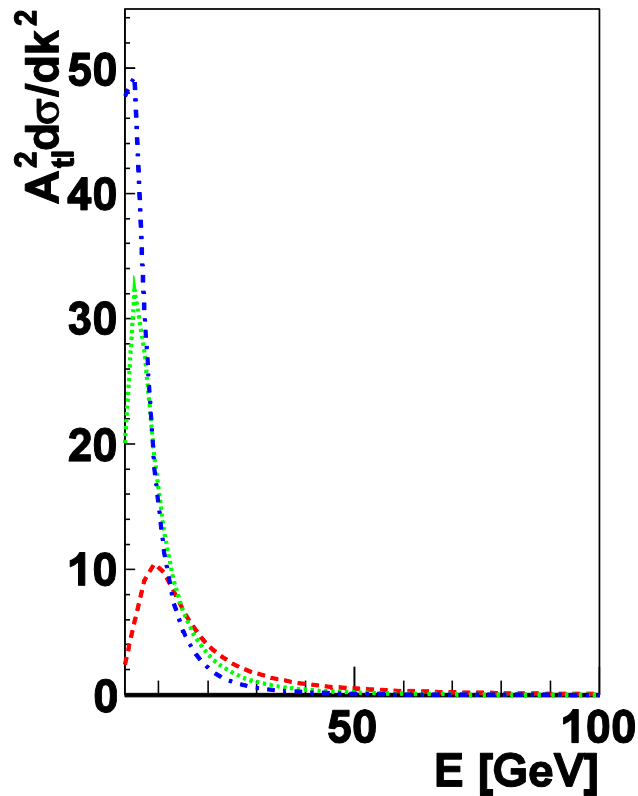
The spin correlation coefficients when both initial particles have arbitrary polarization,  $p + e \rightarrow p + e$ .



# Figure of Merit

$$\mathcal{F}^2(\theta_p) = \epsilon(\theta_p) A_{ij}^2(\theta_p), \quad \epsilon(\theta_p) = N_f(\theta_p)/N_i$$

$$\left(\frac{\Delta P(\theta_p)}{P}\right)^2 = \frac{2}{N_i(\theta_p)\mathcal{F}^2(\theta_p)P^2} = \frac{2}{Lt_m(d\sigma/d\Omega)d\Omega A_{ij}^2(\theta_p)P^2},$$



$\theta_e = 30$  mrad

$\theta_e = 10$  mrad

$\theta_e = 0$

$\theta_e = 50$  mrad

# *Polarimetry of high energy proton beams*

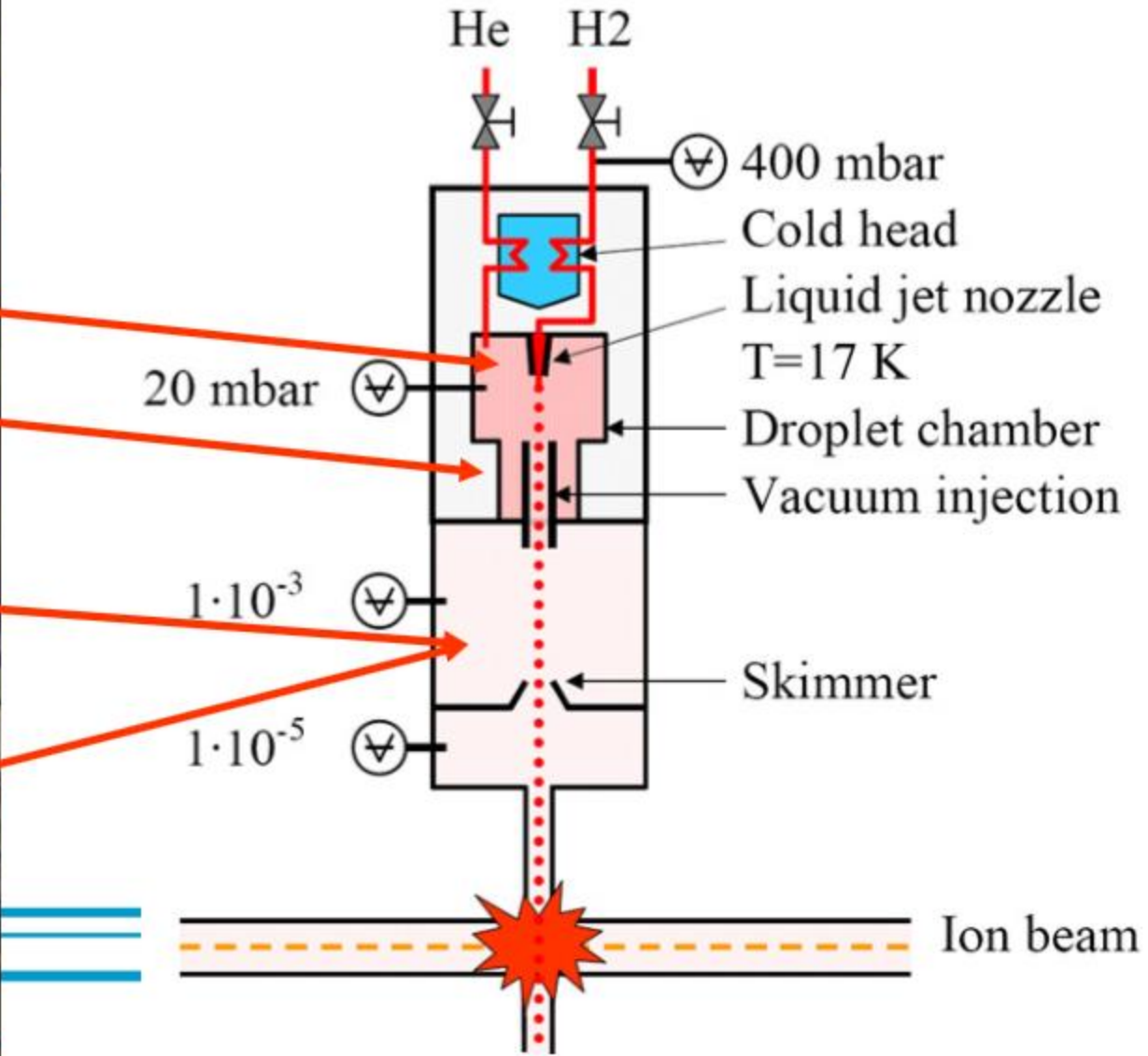
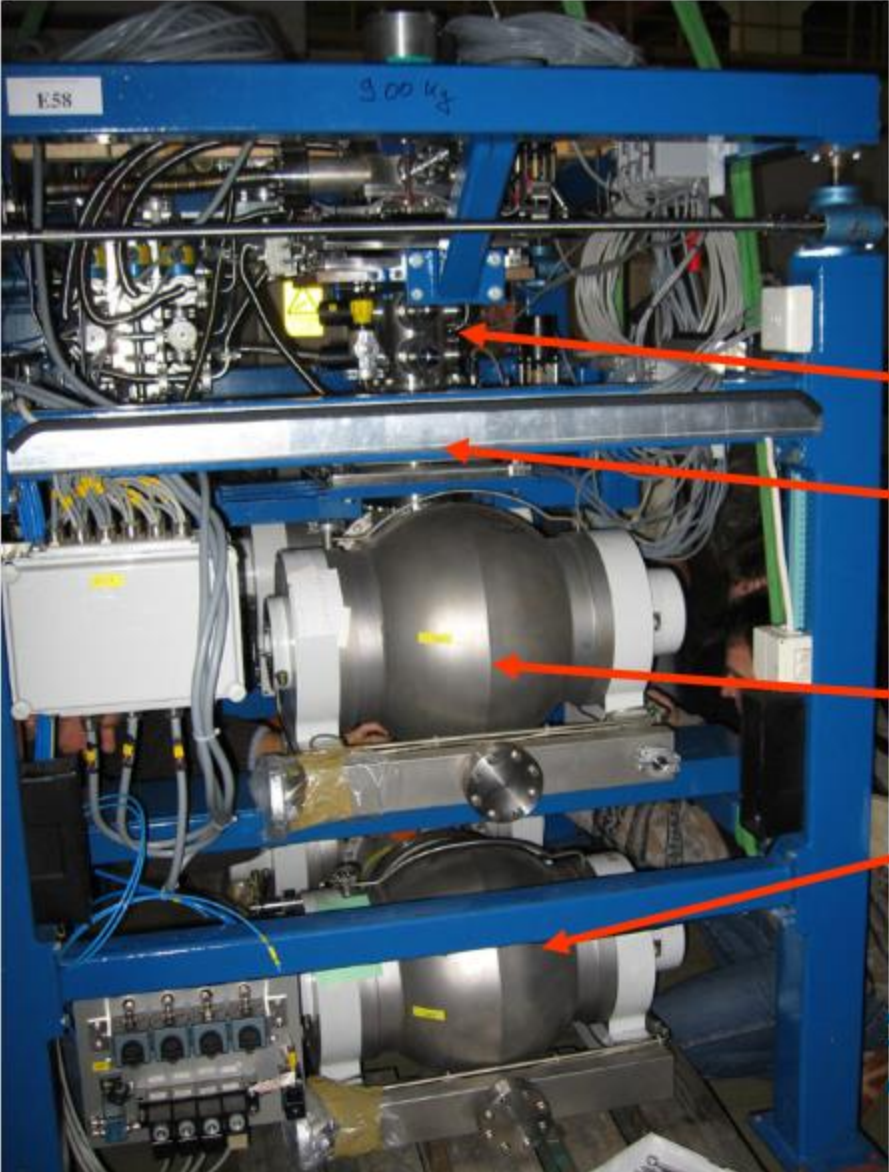
PHYSICAL REVIEW C **84**, 015212 (2011)

## **Polarization effects in elastic proton-electron scattering**

G. I. Gakh,<sup>1</sup> A. Dbeyssi,<sup>2</sup> D. Marchand,<sup>2</sup> E. Tomasi-Gustafsson,<sup>2,\*</sup> and V. V. Bytev<sup>3</sup>

# The WASA-at-COSY Pellet Generator

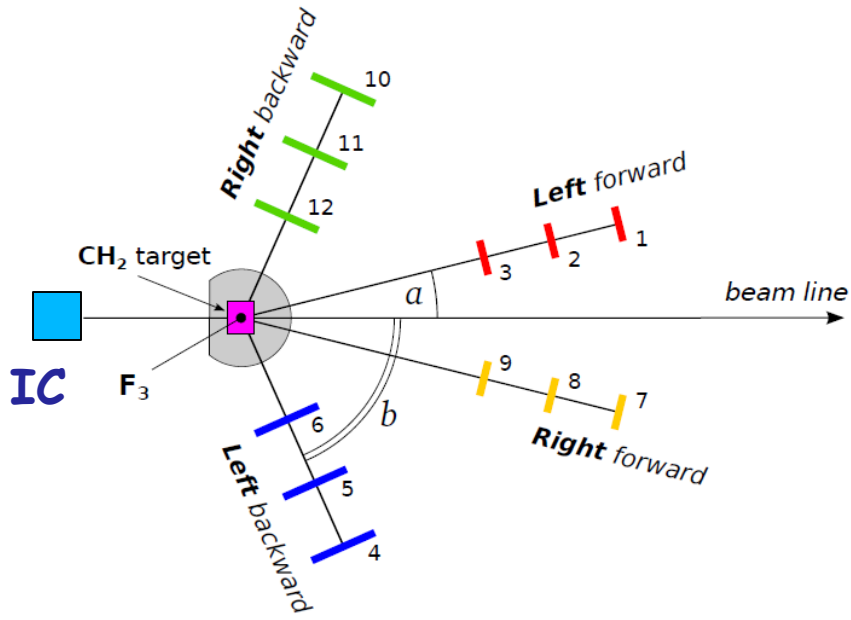
Alfons Khoukaz



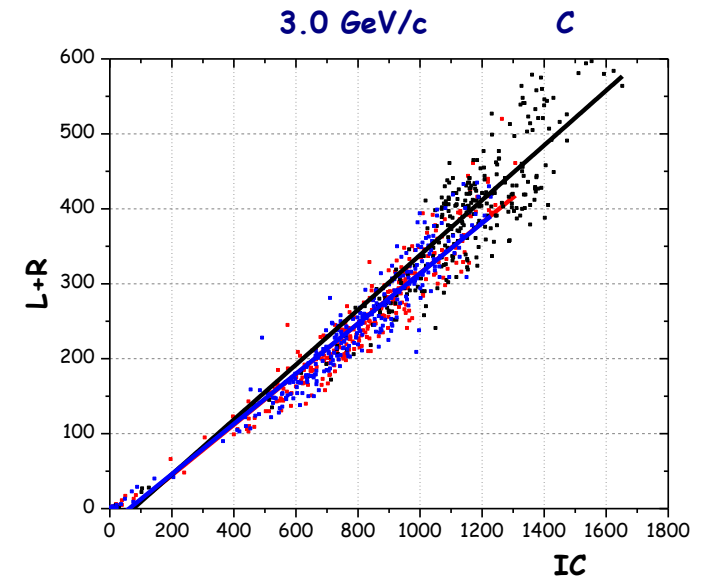
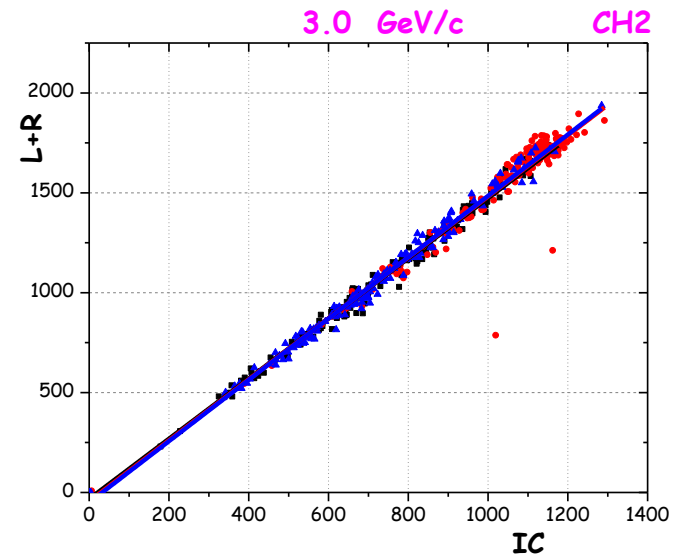
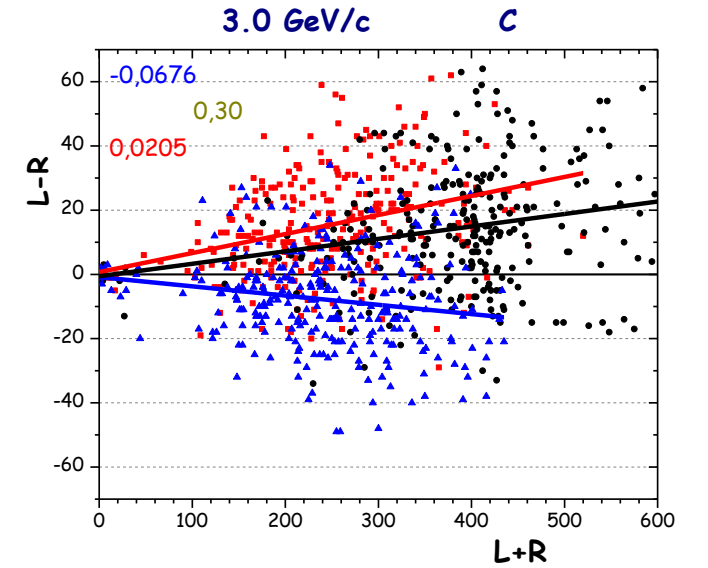
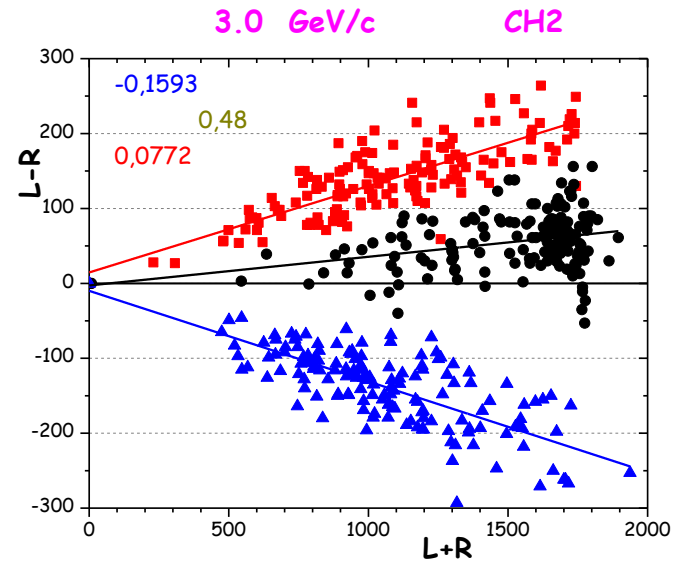
# Important Data of the WASA Pellet Target

pellet rate (H <sub>2</sub> )	8000 pellets/s
pellet rate (D <sub>2</sub> )	20000 pellets/s
pellet diameter	20 – 25 μm
target thickness (H <sub>2</sub> )	4·10 <sup>15</sup> atoms cm <sup>-2</sup>
target thickness (D <sub>2</sub> )	8·10 <sup>15</sup> atoms cm <sup>-2</sup>
pellet distance	5 mm
target diameter at interaction point	
with 0.7 mm skimmer	2.5 mm
with 1.0 mm skimmer	3.5 mm
hydrogen consumption	250 I <sub>n</sub> /day
deuterium usage	250 I <sub>n</sub> /day
helium consumption (H <sub>2</sub> )	250 I <sub>n</sub> /day
helium consumption (D <sub>2</sub> )	1000 I <sub>n</sub> /day

# F3 - polarimeter



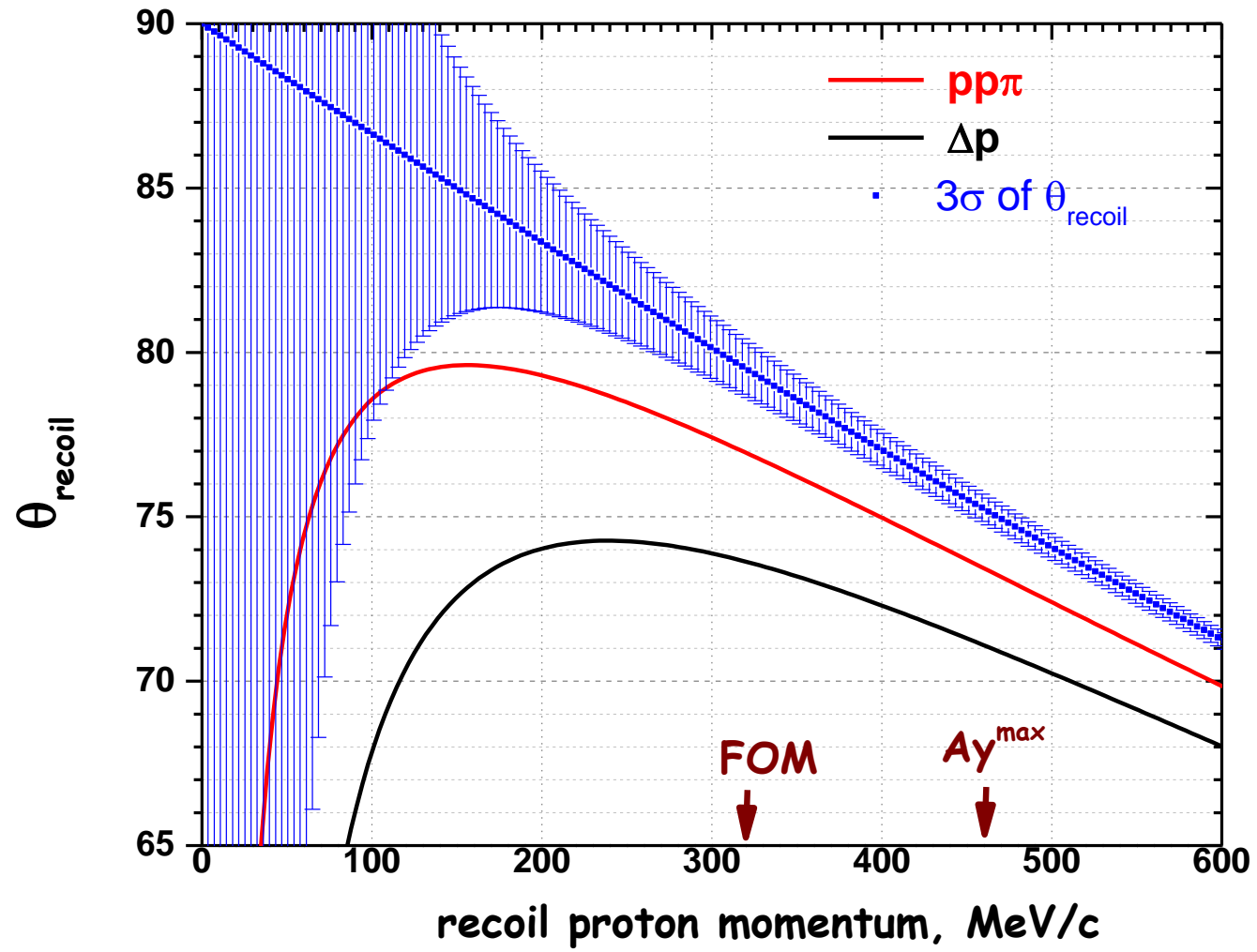
Future goal: remove C contribution





$$A_y \bullet P_y = \frac{N_L - N_R}{N_L + N_R}$$

10 GeV/c





Proton spin precession in the rest frame is described by the Thomas–Frenkel equation, which was previously called the BMT equation (Thomas 1927; Frenkel 1926; Bargman et al. 1953):

$$\frac{d\vec{S}}{dt} = \frac{e}{\gamma m} \vec{S} \times [(1 + G\gamma)\vec{B}_\perp + (1 + G)\vec{B}_l]. \quad (5.1)$$

Here,  $G = (g - 2)/2 = 1.792817$  is the anomalous magnetic moment of the proton in the units of the nuclear magneton;  $m$  and  $\gamma$  are the mass and Lorentz factor of the proton, respectively;  $B_\perp$  and  $B_l$  are the transverse and longitudinal components

of the magnetic field, respectively;  $t$  is time; and these parameters are defined in the laboratory frame. The equation of momentum rotation under the action of the Lorentz force has the form

$$\frac{d\vec{p}}{dt} = \frac{e}{\gamma m} \vec{p} \times \vec{B}. \quad (5.2)$$

$$\frac{d\vec{S}}{dt} = \frac{e}{\gamma m} \vec{S} \times [(1 + G\gamma)\vec{B}_\perp + (1 + G)\vec{B}_l]$$

$$\frac{d\vec{p}}{dt} = \frac{e}{\gamma m} \vec{p} \times \vec{B}.$$