

Polarimetry at Nuclotron/NICA/SPD

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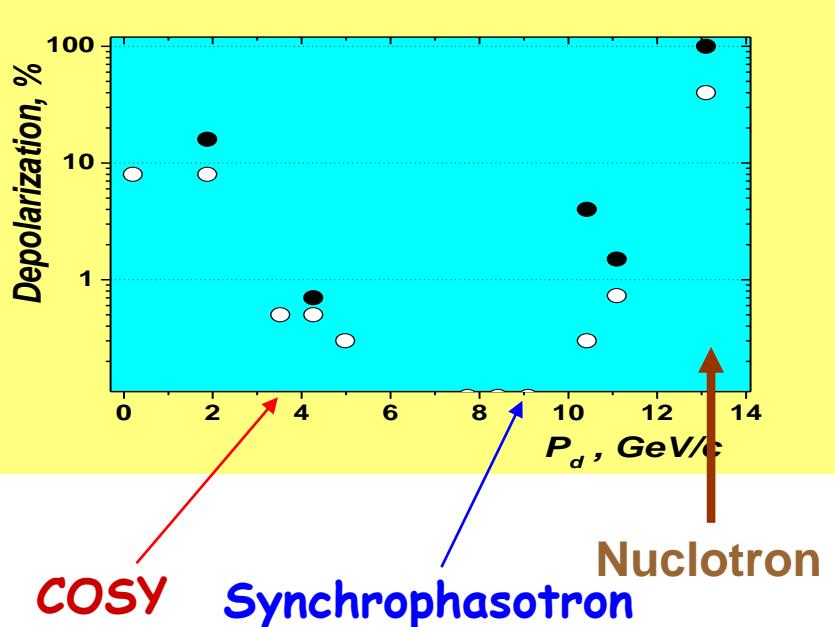
Dubna, SPD at NICA-2019

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

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



6.8

6.85

$$\gamma G_d = p + n Q_x + m Q_y$$

$$\gamma = E_d / m_d$$

$$G_p = 1.793$$

$$G_d = -0.143$$

Filatov's table for Nuclotron

	$\frac{1}{1}H$	$\frac{1}{2}H$	$\frac{1}{3}H$	$\frac{2}{3}He$
$E_k^{\max}, \text{ GeV/n}$	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
$\varepsilon', (\tau_{\text{yck}} = 0.5s)$	$7.0 \cdot 10^{-6}$	$2.8 \cdot 10^{-7}$	$1.0 \cdot 10^{-5}$	$1.1 \cdot 10^{-5}$
$w_d, (\tau_{\text{yck}} = 0.5s)$	$1.5 \cdot 10^{-3}$	$3.0 \cdot 10^{-4}$	$1.8 \cdot 10^{-3}$	$1.9 \cdot 10^{-3}$
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.

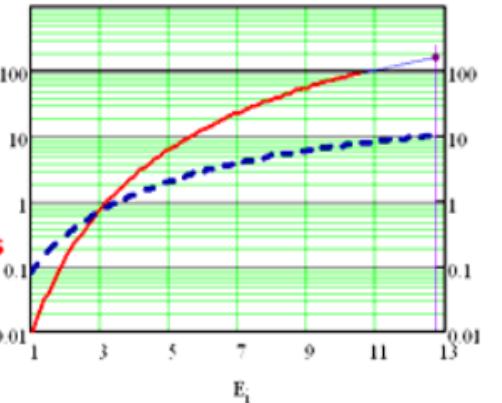


Fig. 4.7: NICA pp luminosity in units 10^{30} (left scale, solid line) and the number of particles per bunch in units $10^{11} \text{ cm}^{-2} \text{ s}^{-1}$ (right scale, dotted line) vs. the proton kinetic energy.

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 β_{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, ξ	- 0.067,
beam emittance ϵ_{nrm} , $\pi \text{ mm mrad}$	- 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 $T_{Lf} = 20000$ 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

2.2×10^{13} protons in each ring

1×10^{12} protons per bunch

0.5 m RMS bunch length ~ 3 ns

1.68 μ s

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

Nuclotron ring

upto 5 bunches or continuous

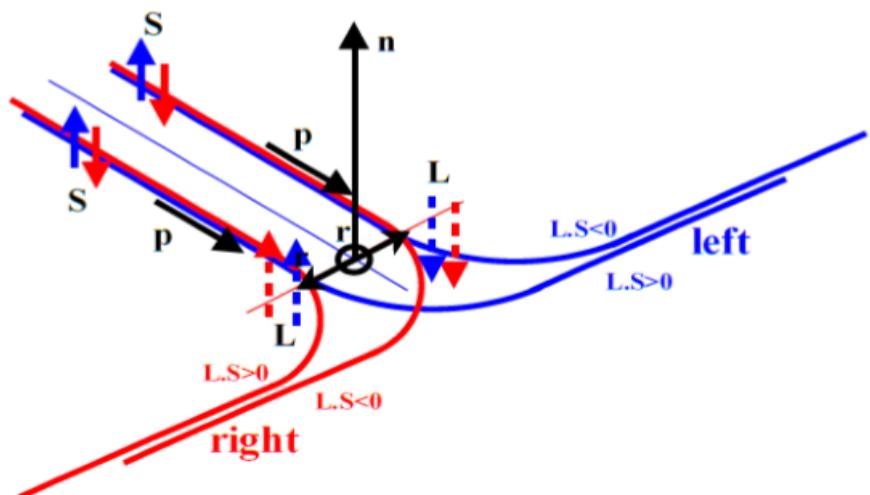
upto 5×10^{10} protons in ring

0.835 μ s

bunch length ~ 80 ns

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

Principle of Polarimetry



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

Azimuthal distribution:

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

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

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

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

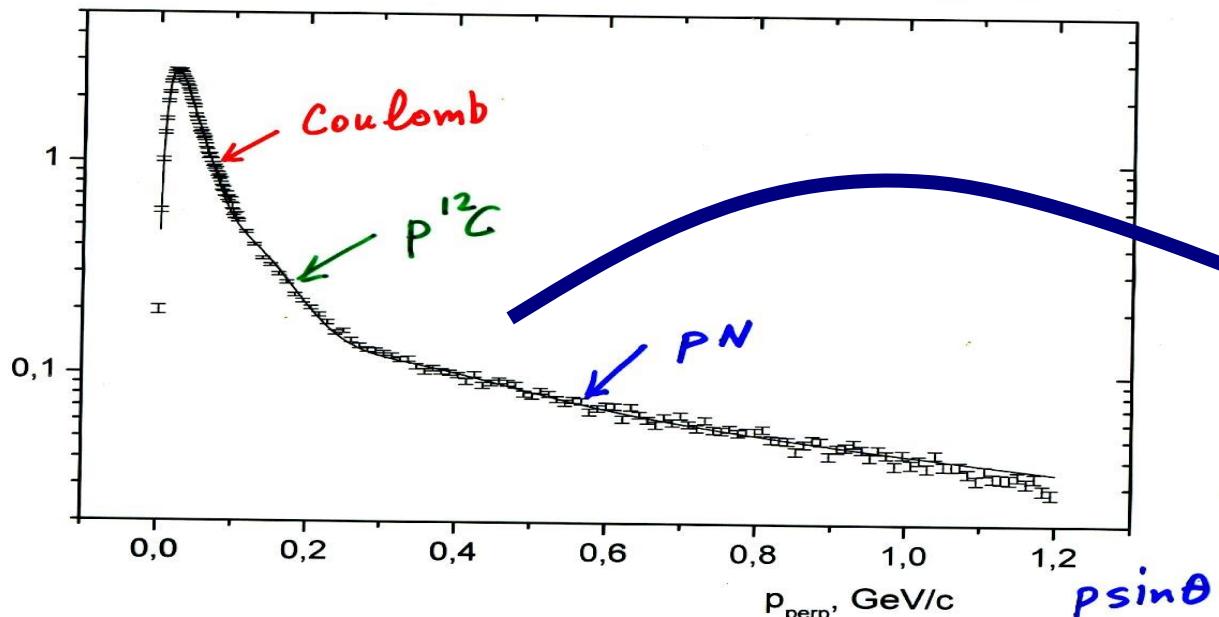
$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega} \right)_0 \left[1 + \frac{3}{2} p_y A_y + \frac{1}{2} p_{zz} A_{zz} + \frac{2}{3} p_{xz} A_{xz} + \frac{1}{6} (p_{xx} - p_{yy}) (A_{xx} - A_{yy}) \right]$$

FOM (Figure of Merit)

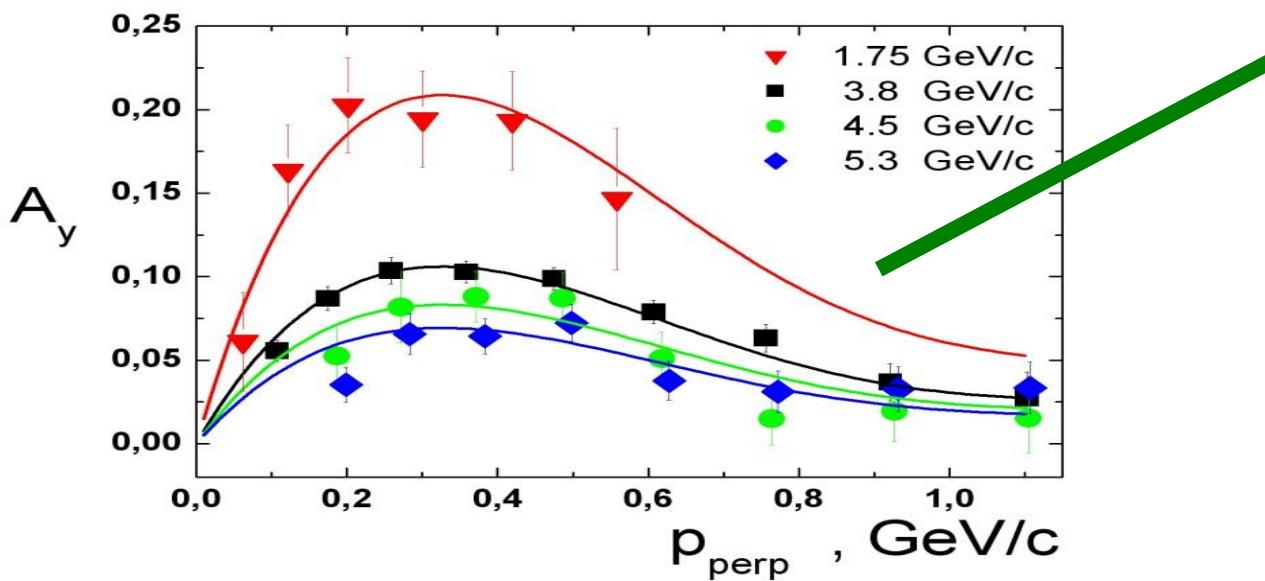
$p = 5.3 \text{ GeV/c}$

56 cm

one charge particle



$$F^2 = \int \epsilon(\theta) A_y^2(\theta) d\theta$$



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

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

$$\Delta A_y \sim 0.01$$

$$N \sim 10^7$$

Reactions that can be used in polarimetry

1-13 GeV/c

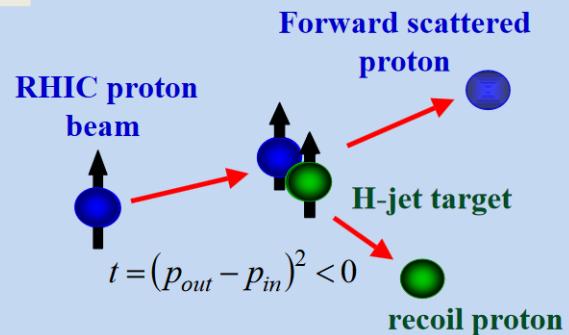
	Type of reaction	Cross-section/ Total cross-section	Analyzing power
1	pp scattering Elastic pp Quasi-elastic (CH_2) CNI	4 – 2 mb /~40 mb ~ 6-3 mb /~400 mb ~ 2 mb /~40 mb	(20 -7) % <20 % 4.5 %
2	Charge -exchange	< 1 mb /~45 mb	Up to 30%
3	Inclusive charged pion production	~ 30 μb /~40 mb	Up to 30%

HJet

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

Beam and target are both protons

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



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

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

P_{target} is provided by Breit Rabi Polarimeter

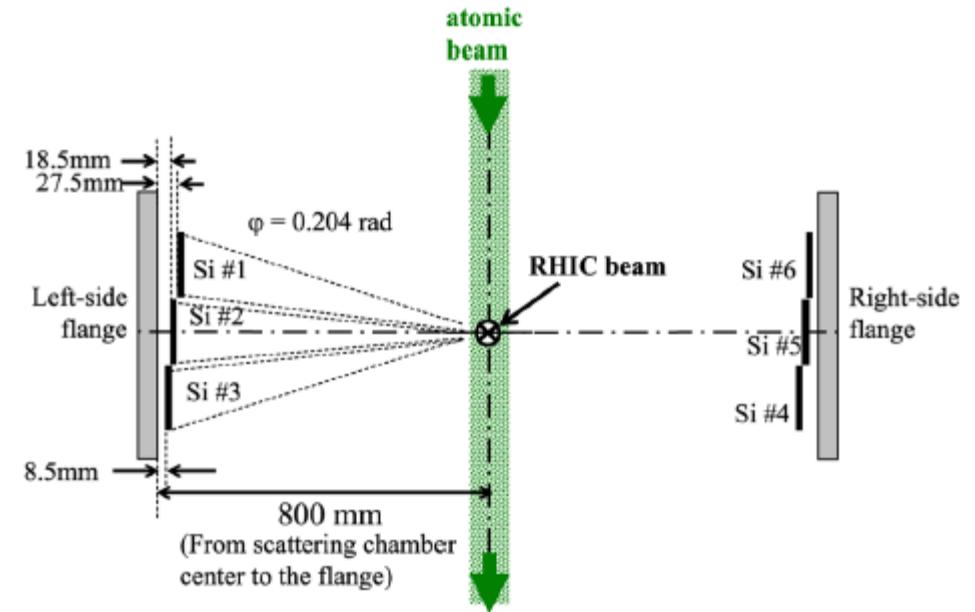
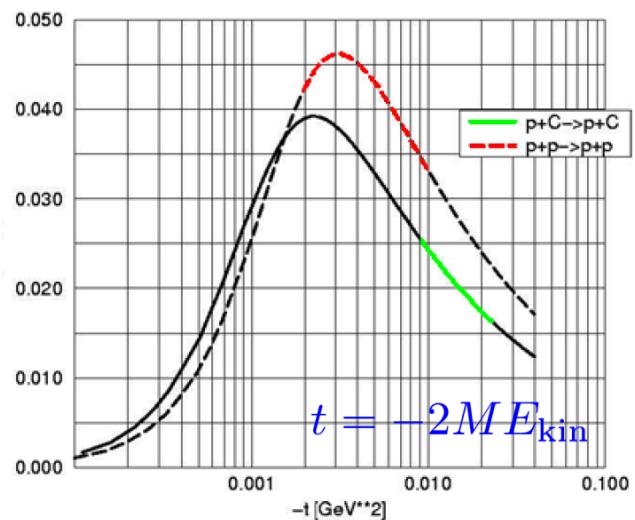
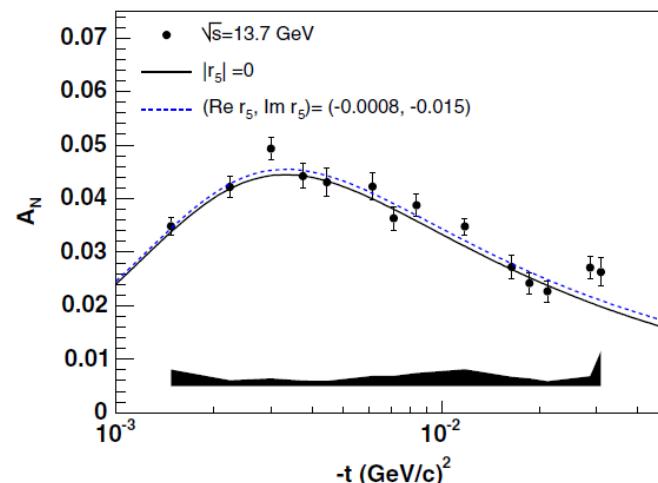
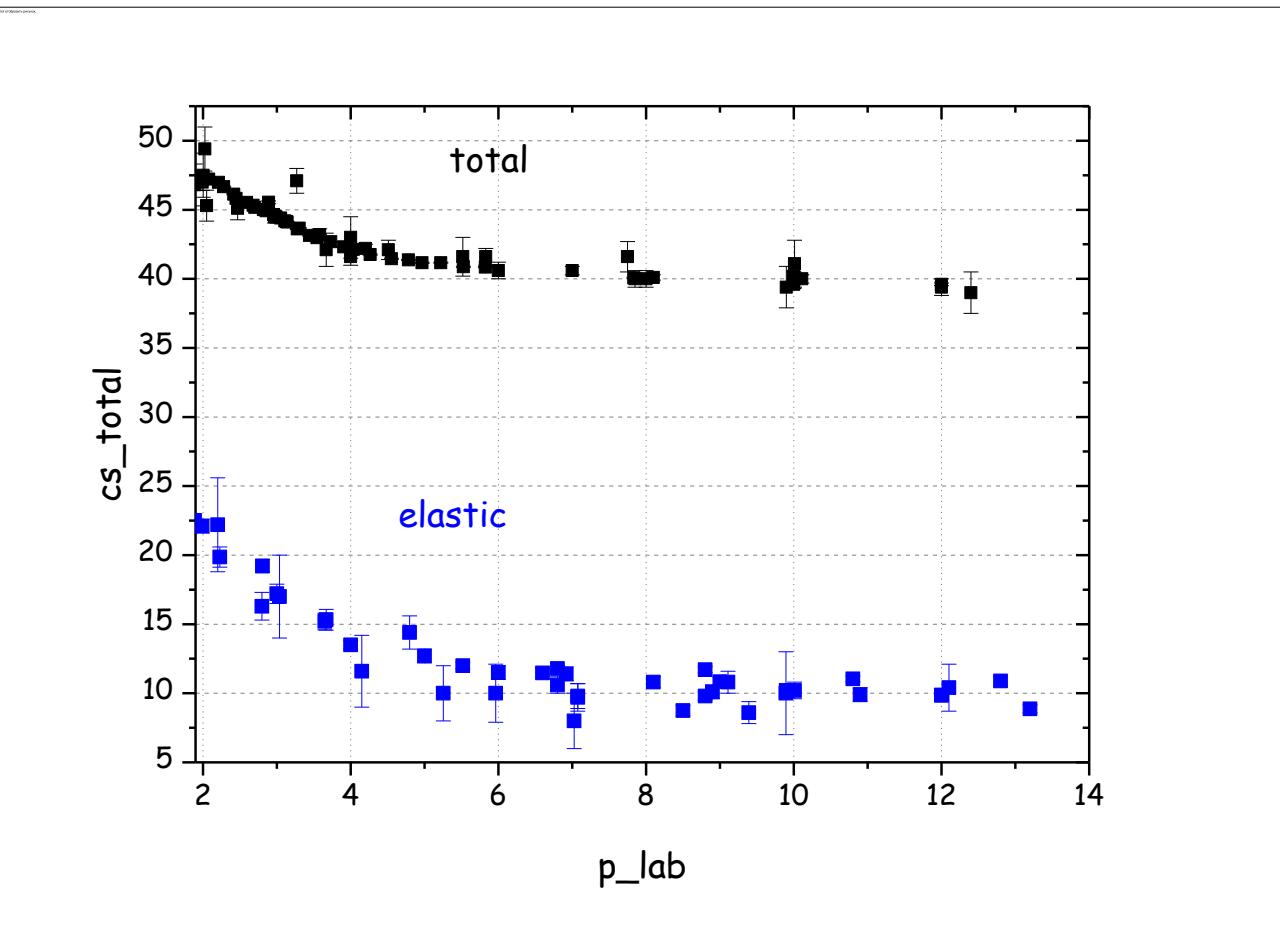


FIG. 2 (color online). Layout of the pp elastic scattering setup from the RHIC-beam view. The detectors were mounted on vacuum flanges on the scattering chamber and located to the left and right of the beam. Three pairs of silicon detectors covered an azimuthal angle of 11.7° centered on the horizontal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



	NICA	RHIC
	503 m	3834 m
	1.66 μ s	12.65 μ s
	2.2×10^{13}	2.4×10^{13}
time	turn numbers	
1 s	6.0×10^5	7.9×10^4
10 s	6.0×10^6	7.9×10^5
1 m	3.6×10^7	4.7×10^6
10 m	3.6×10^8	4.7×10^7
1 h	2.2×10^9	2.9×10^8
10 h	2.2×10^{10}	2.9×10^9



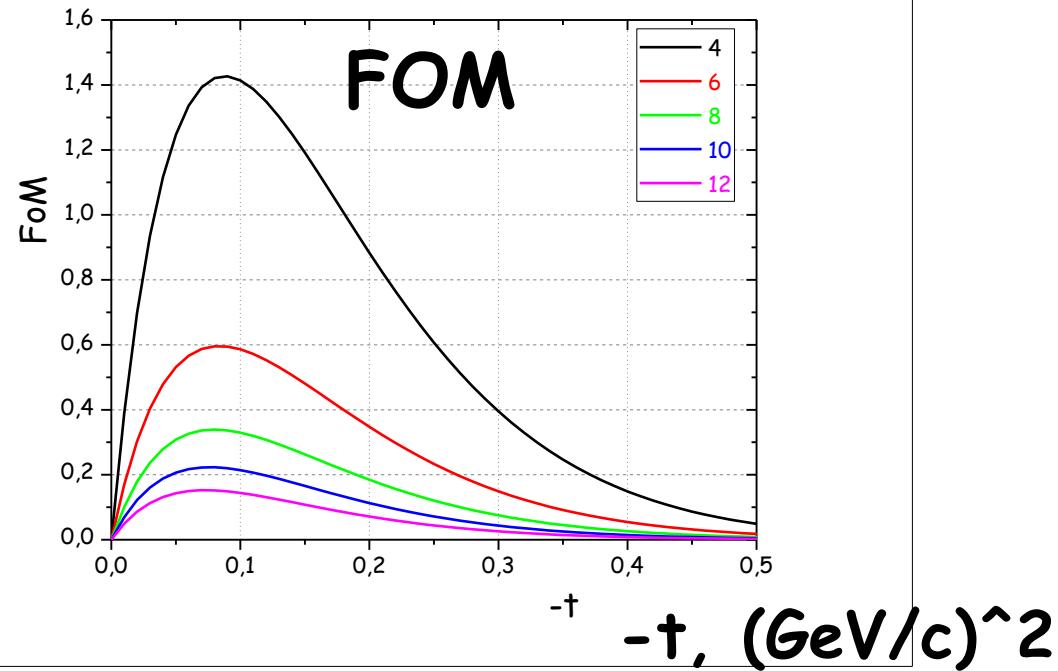
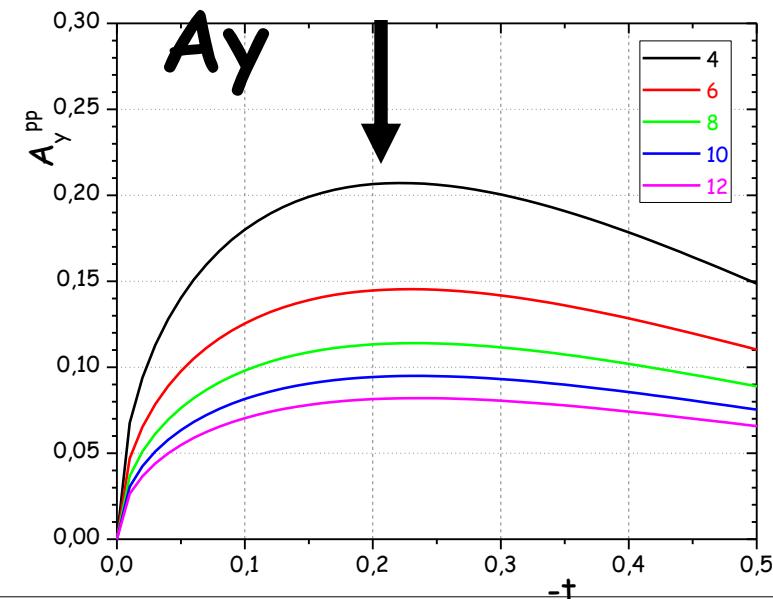
H-jet 1.2×10^{12} protons/cm²

σ_{tot} (pp) ~ 40 mb, σ_{el} (pp) ~ 10 mb

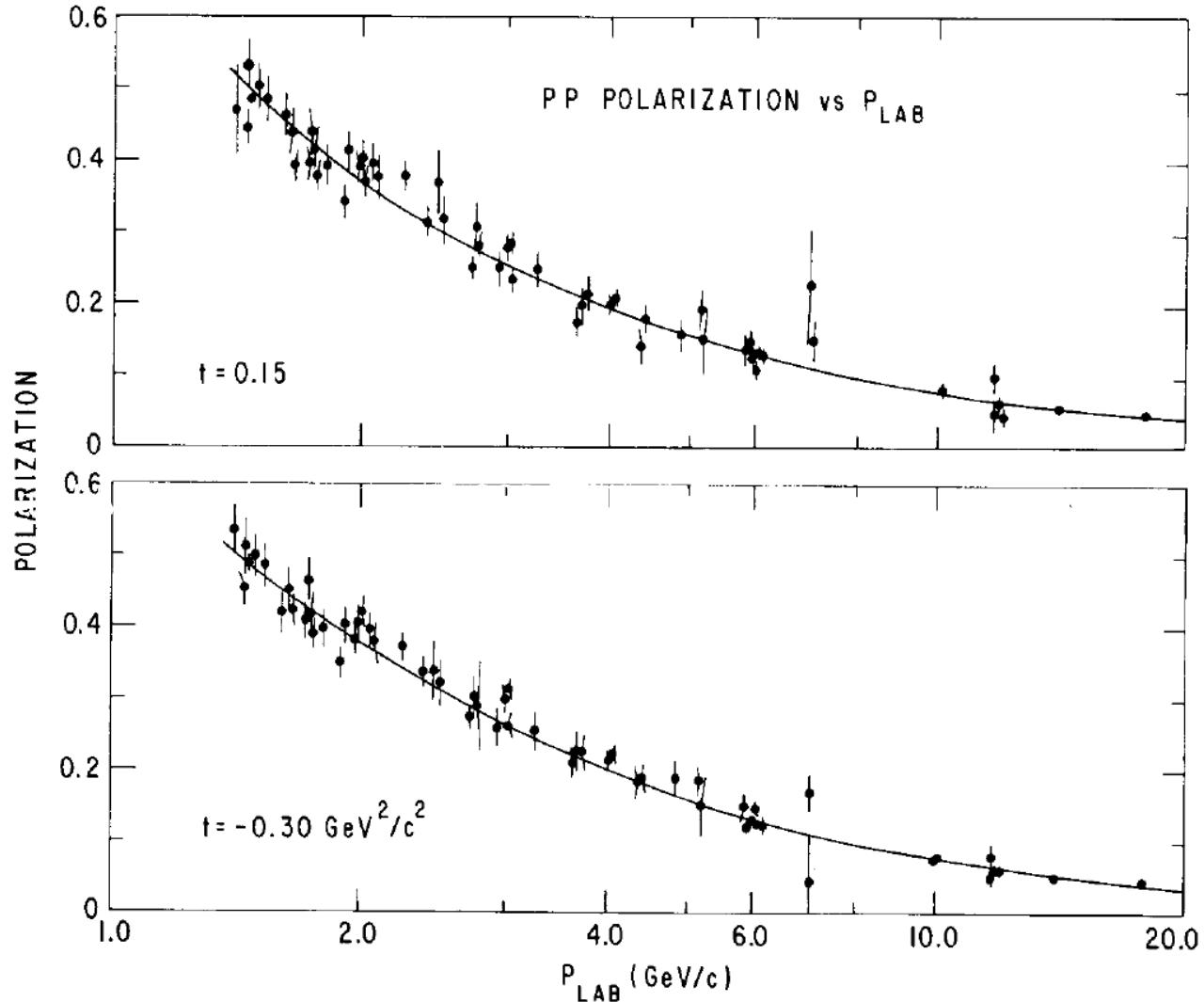
$$N = 2.2 \times 10^{13} * 1.2 \times 10^{12} * 40 * 10^{-27} \sim 1 \text{ interaction/turn}$$

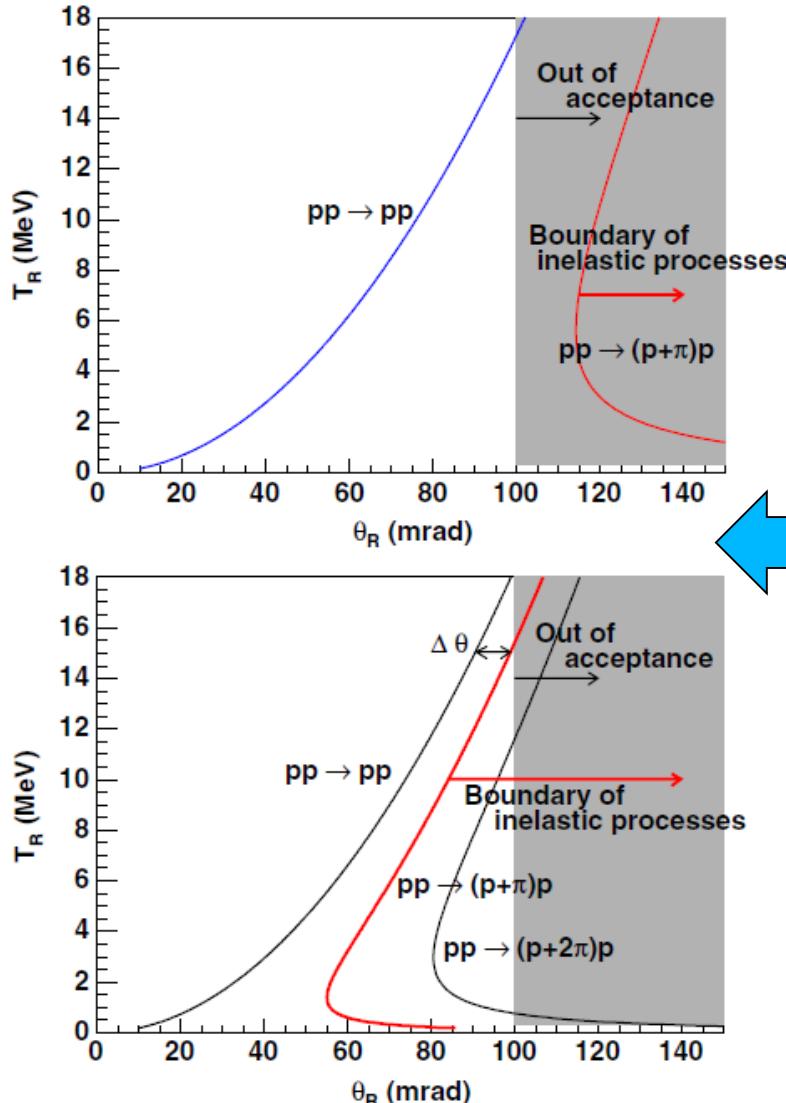
NICA/RHIC = 7.62

max



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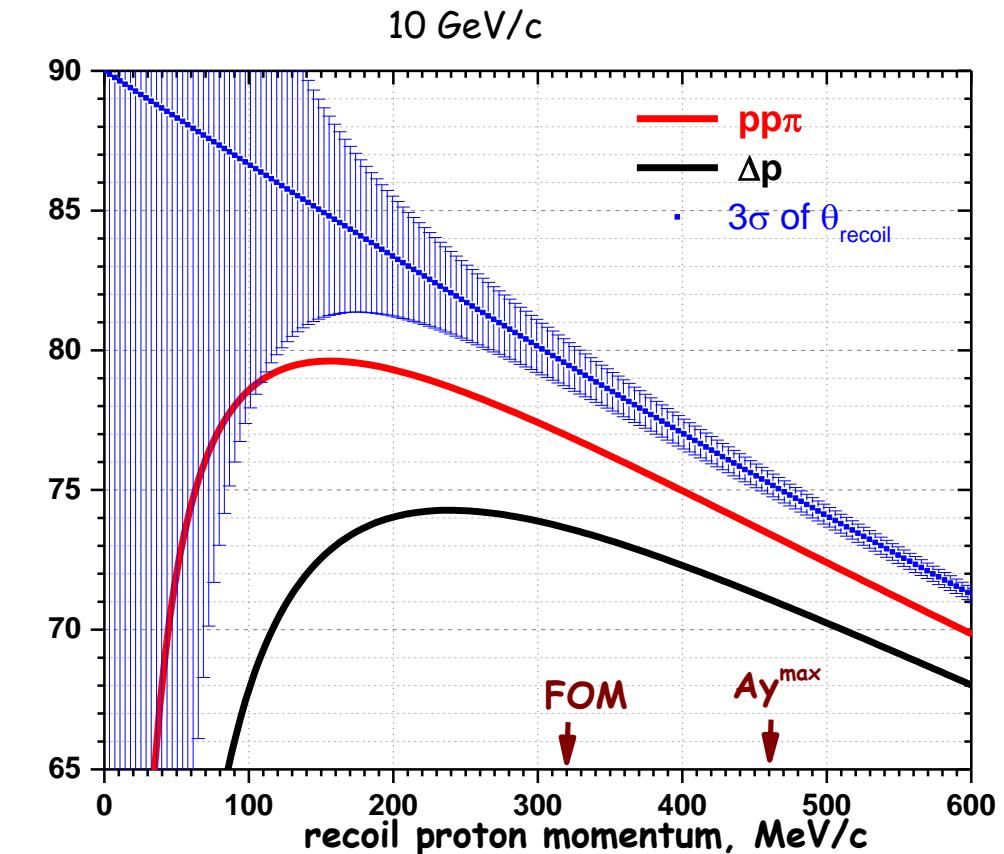




Elastic pp

CNI

1-13 GeV/c



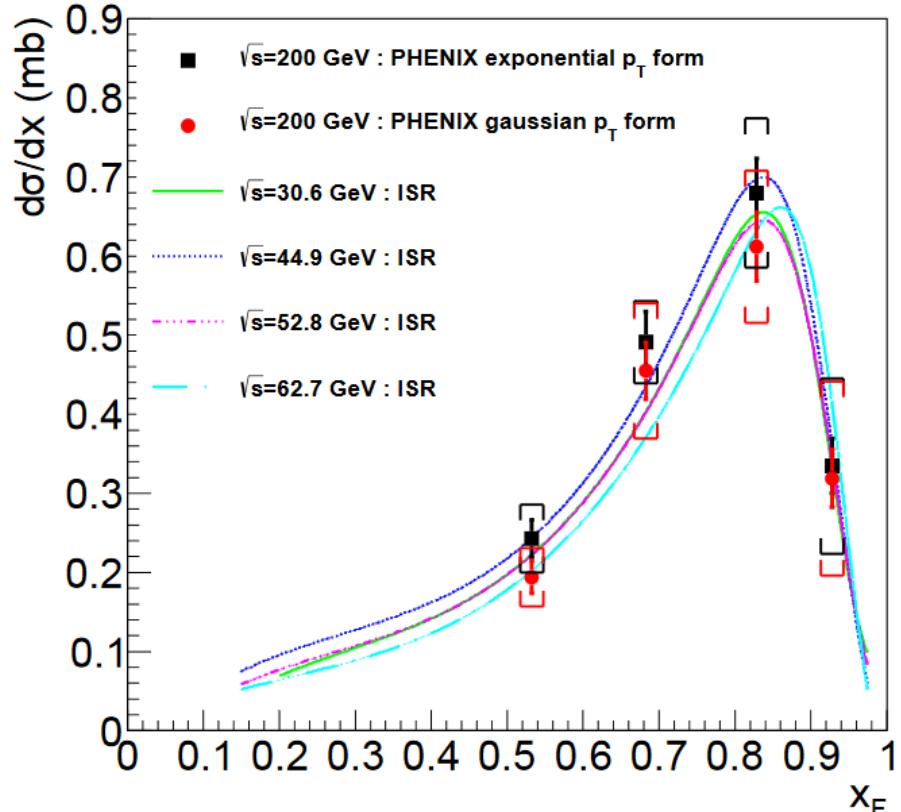
0,3-0,5 GeV/c

FIG. 12 (color online). Top: Calculation of T_R - θ_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.

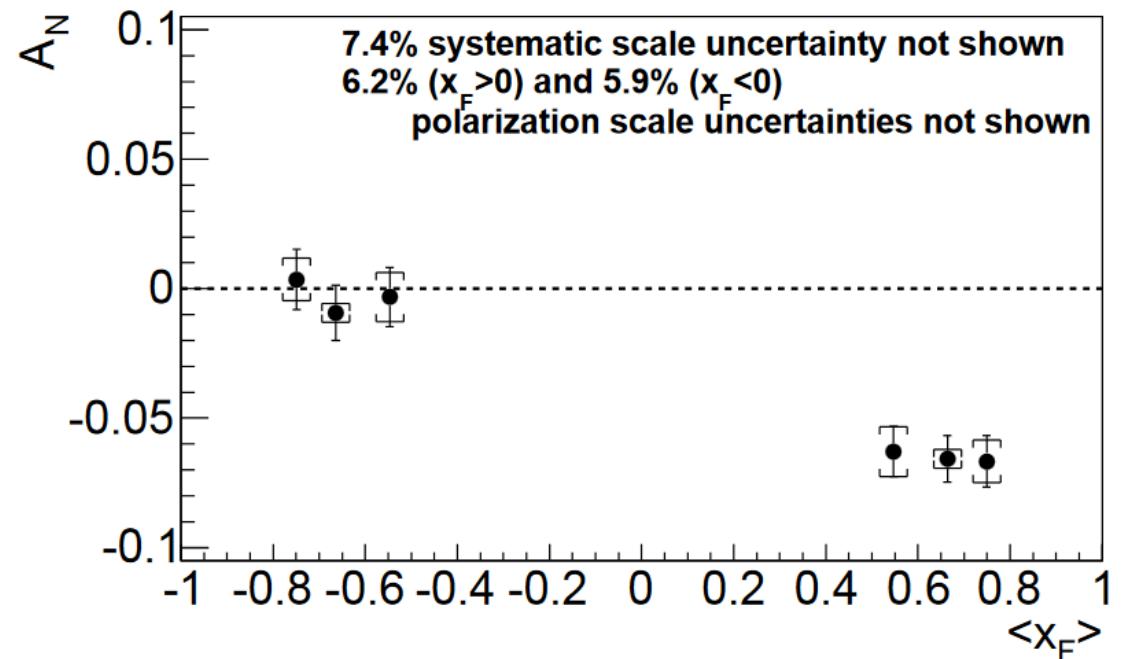
GeV/c	$\Delta\sigma$, mb 0.1-0.2	An, avr	$\Delta\phi$, 60 cm	$\Delta\sigma \times \Delta\phi$,	# turns per event	5%	# turns per 5%	Time
4	3,08	0,195	0,016	0,049	8.16 +02	1,1 +04	9,0 +06	~15 s
6	2,56	0,136	0,016	0,041	9,76 +02	2,2 +04	2.1 +07	~ 35 s
8	2,29	0,107	0,016	0,037	1,08 +03	3,5 +04	3,8 +07	~ 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

Inclusive cross section and single transverse spin asymmetry for very forward neutron production in polarized p+p collisions at $\sqrt{s} = 200$ GeV

(PHENIX Collaboration)

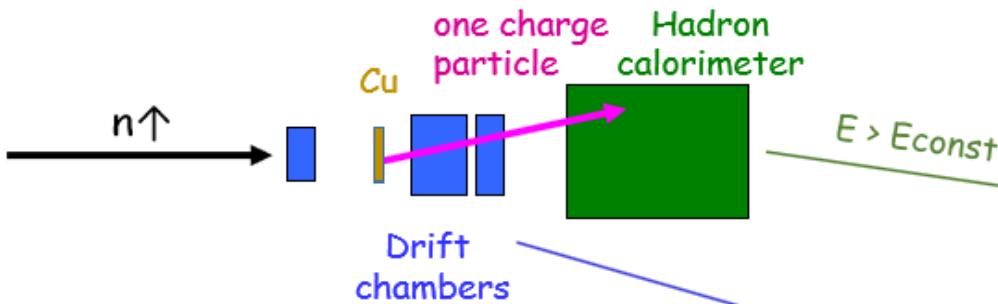


The cross section results for forward neutron production in p+p collisions at $\sqrt{s}=200$ GeV are shown. Two different forms, exponential (squares) and Gaussian (circles), were used for the pT distribution. Statistical uncertainties are shown as error bars for each point, and systematic uncertainties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

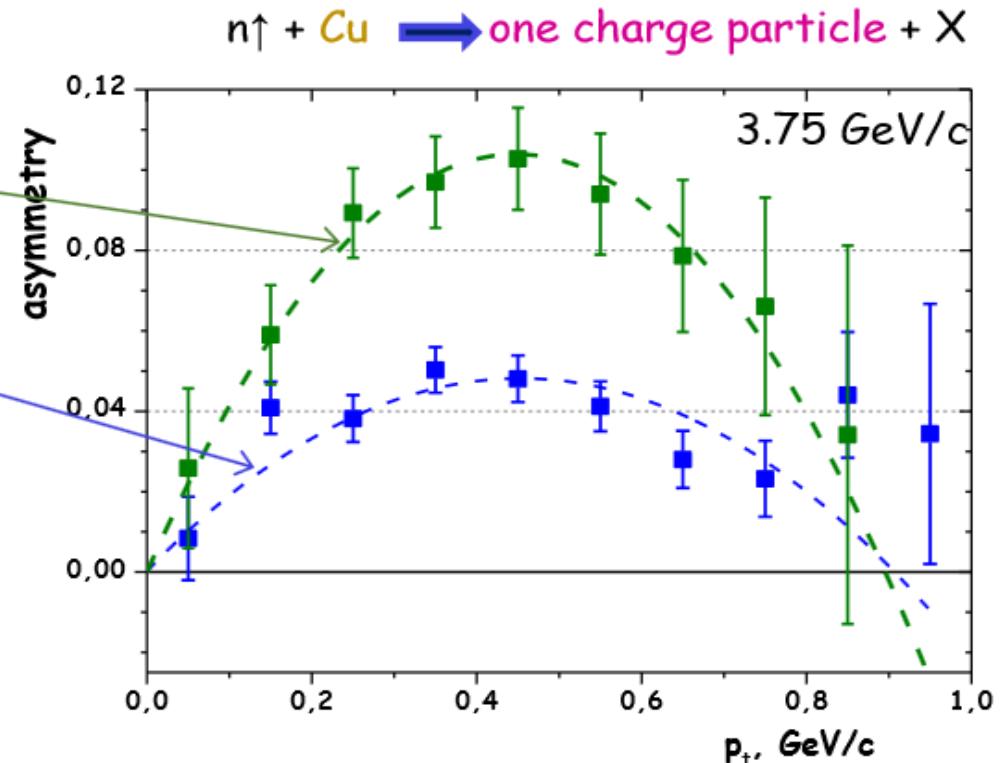


The x_F dependence of A_N for neutron production in the ZDC⊗BBC trigger sample. The error bars show statistical uncertainties and brackets show pT-correlated systematic uncertainties.

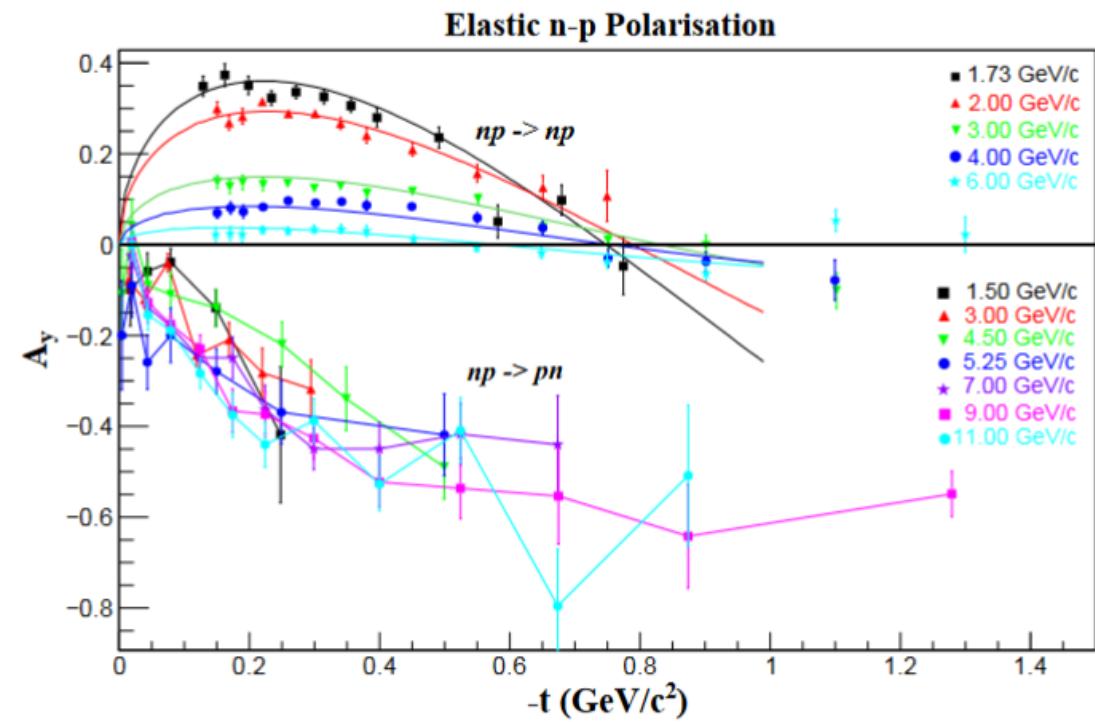
Charge exchange reaction



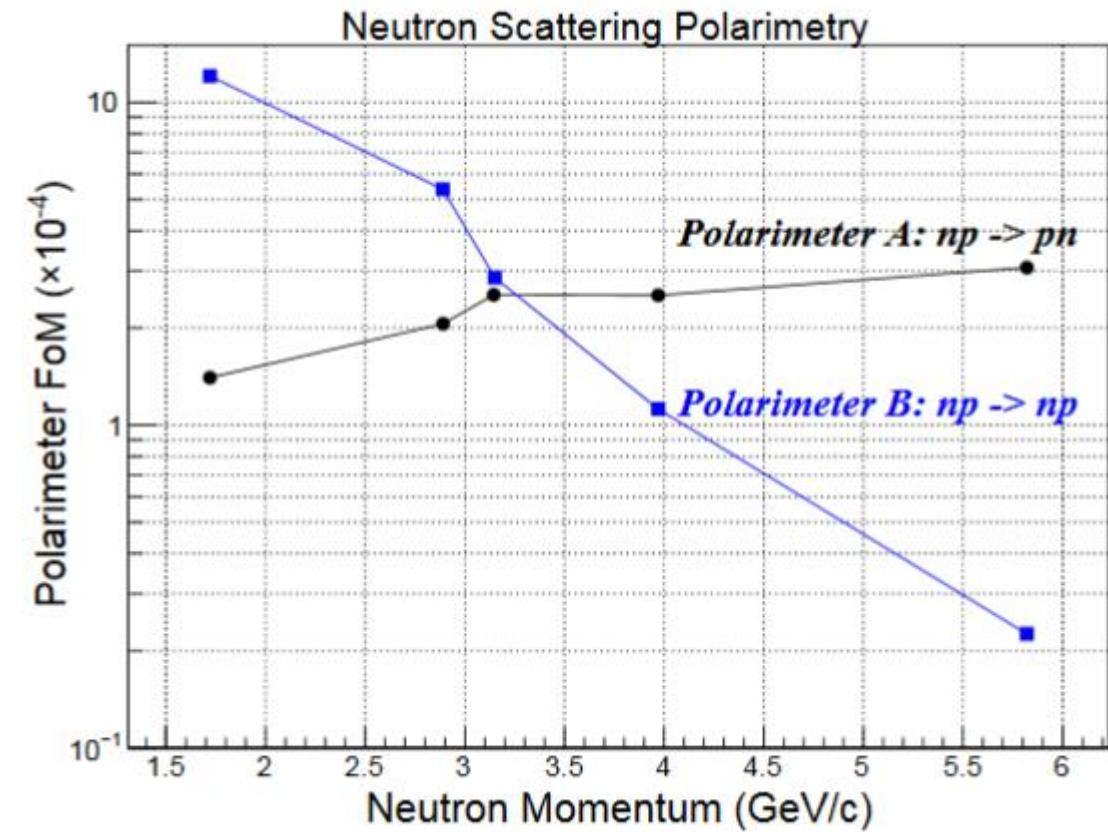
- 1) The observed asymmetry is unpredictably bigger than in np elastic scattering that usually used for neutron polarimetry
- 2) The length of the copper target is only 4 cm in comparison with the CH one (> 30 cm) used in the elastic np scattering, which makes it possible to improve the accuracy of determining 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 $p + Cu$ (W) with detection neutron in forward direction by the hadron calorimeter can be used for measurement of the proton polarization at the NICA collider.



Top: t-dependence of the polarisation of np scattering for different values of p_{lab} [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 p_{lab} [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 of Fig. 5. Blue squares: standard np scattering from CH scintillator (Polarimeter B), black circles: charge-exchange np scattering from Cu (Polarimeter A).

Polarimetry with inclusive pions

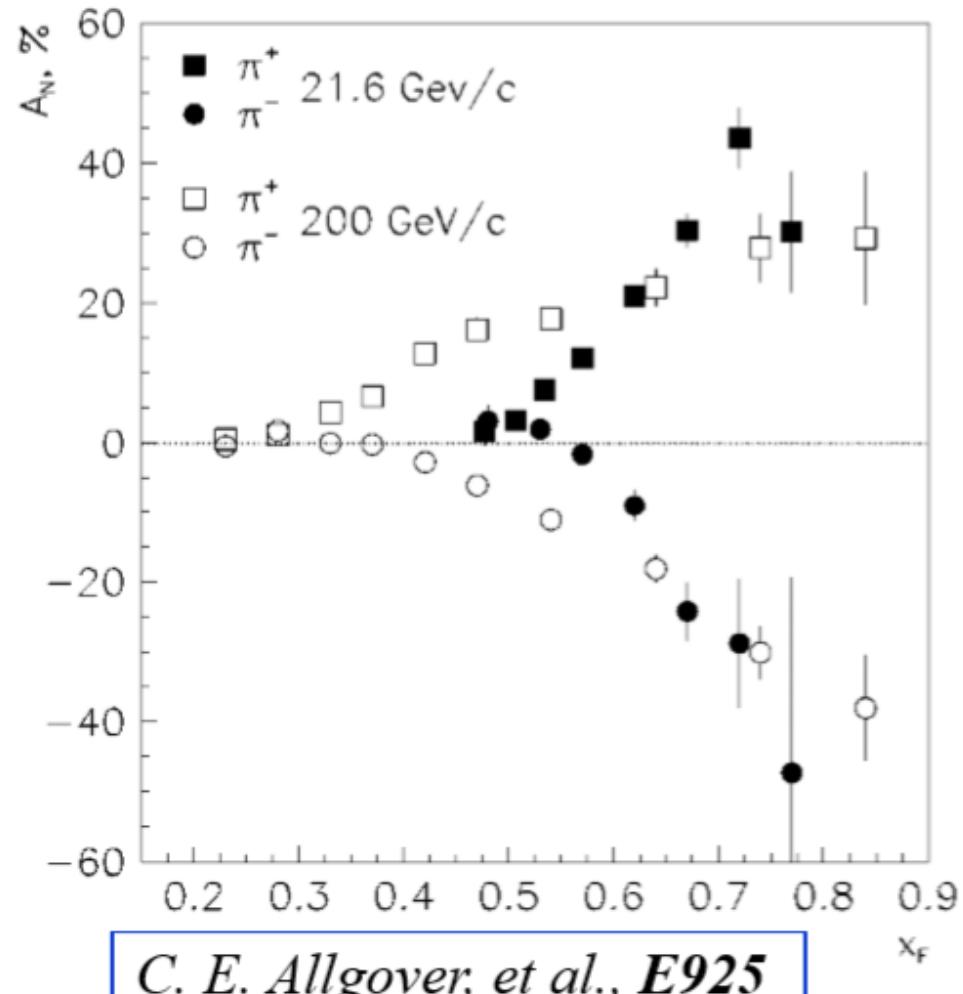


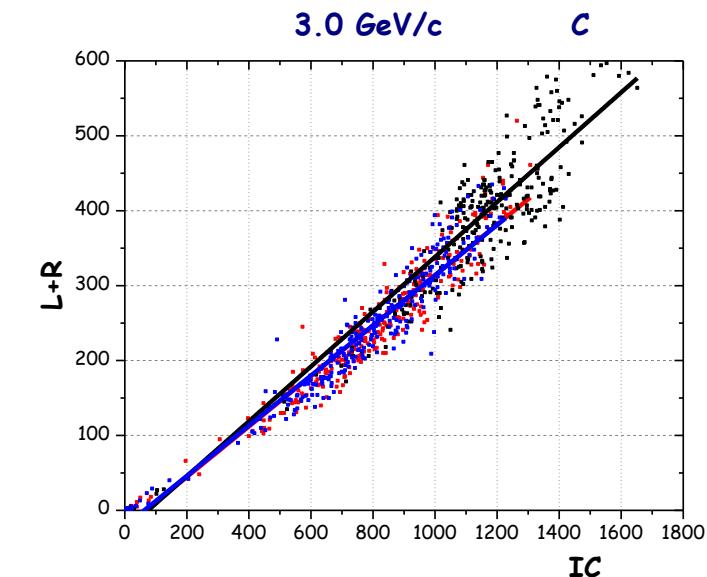
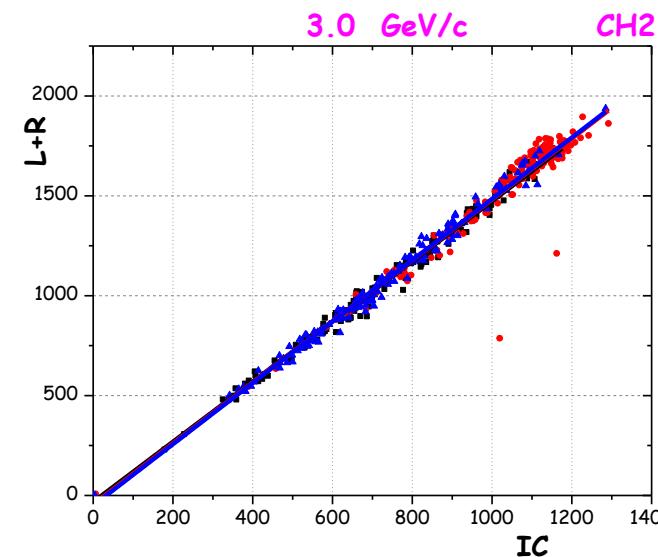
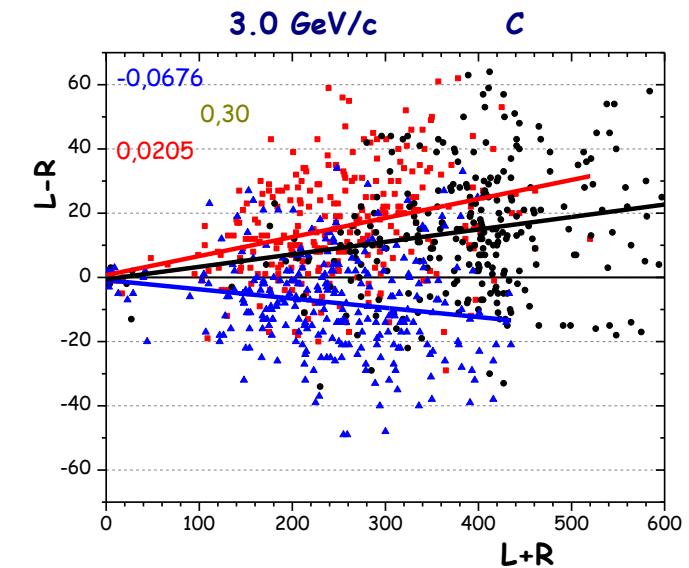
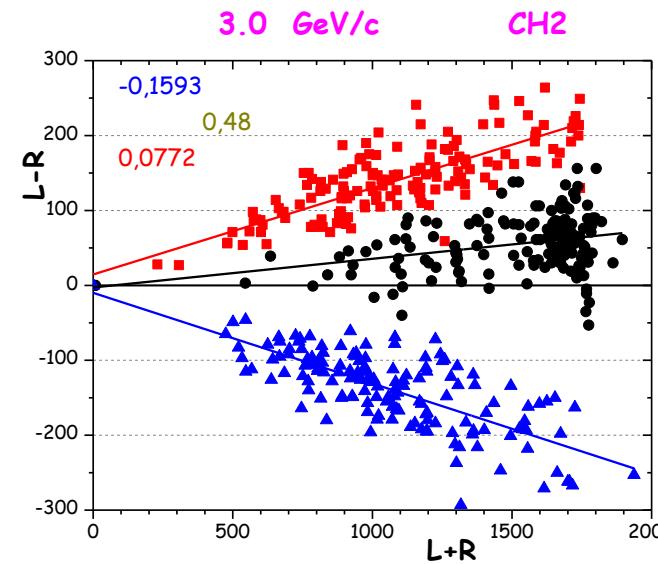
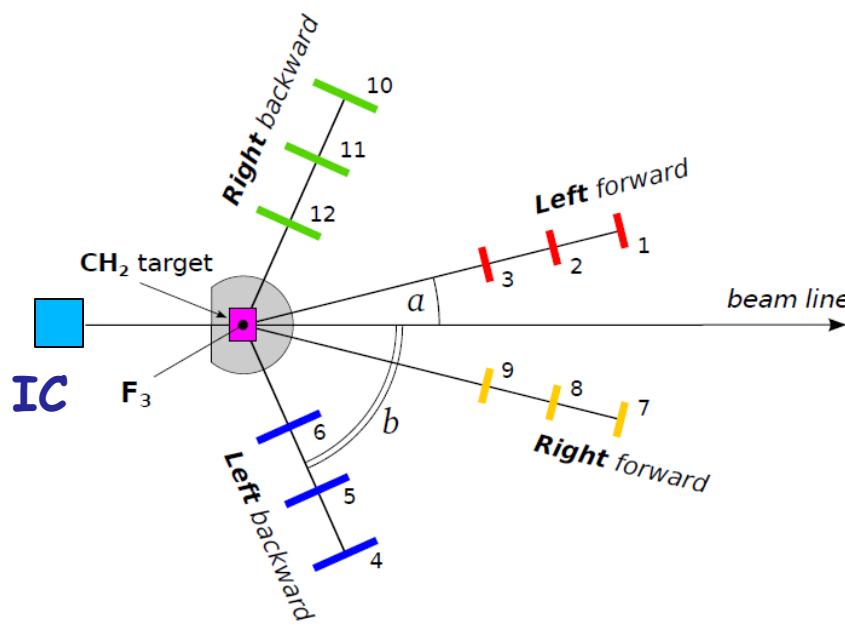
FIG. 22. Comparison of inclusive analyzing powers A_N from carbon at 21.6 GeV/c and hydrogen at 200 GeV/c [2].

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

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

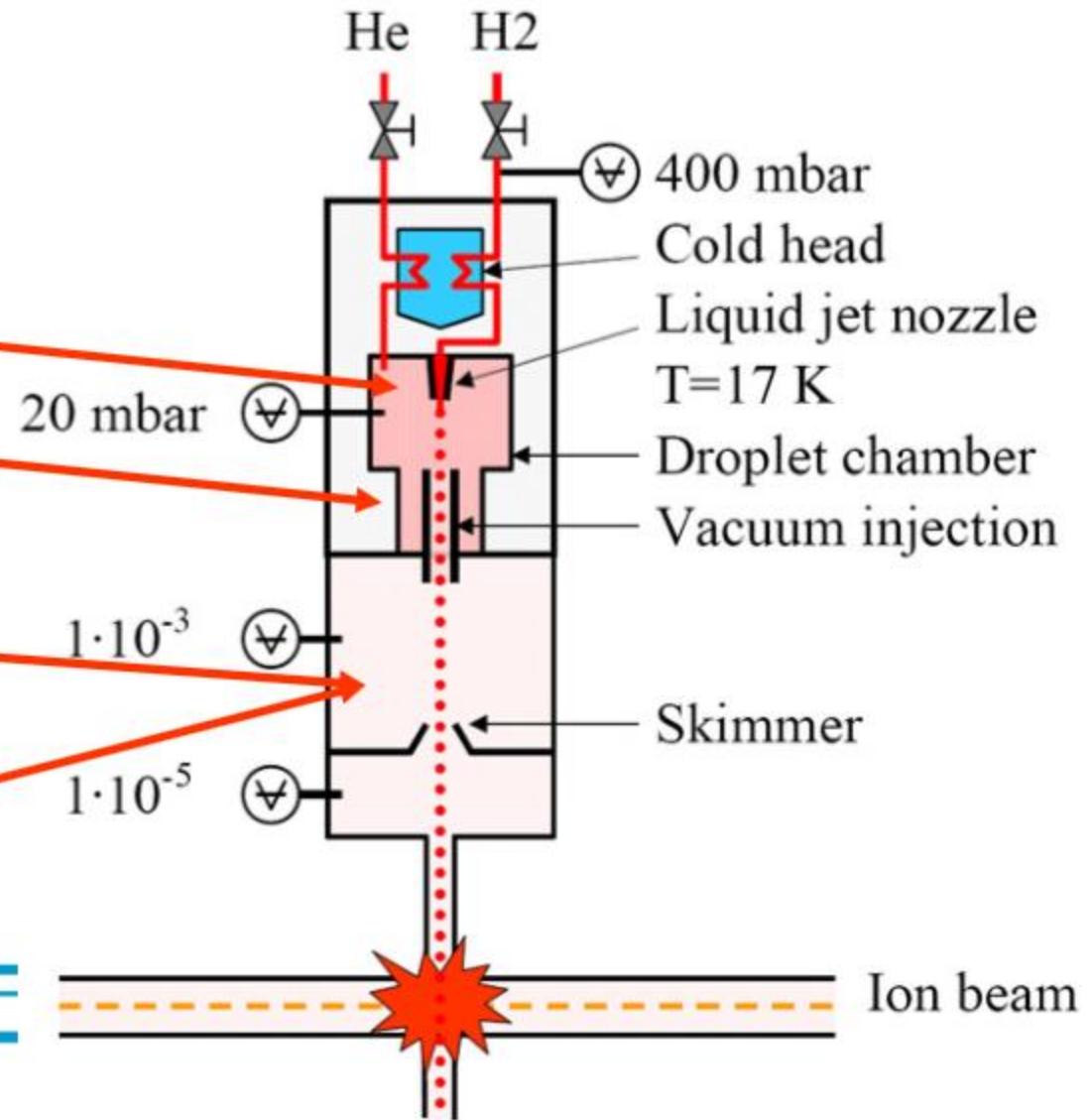
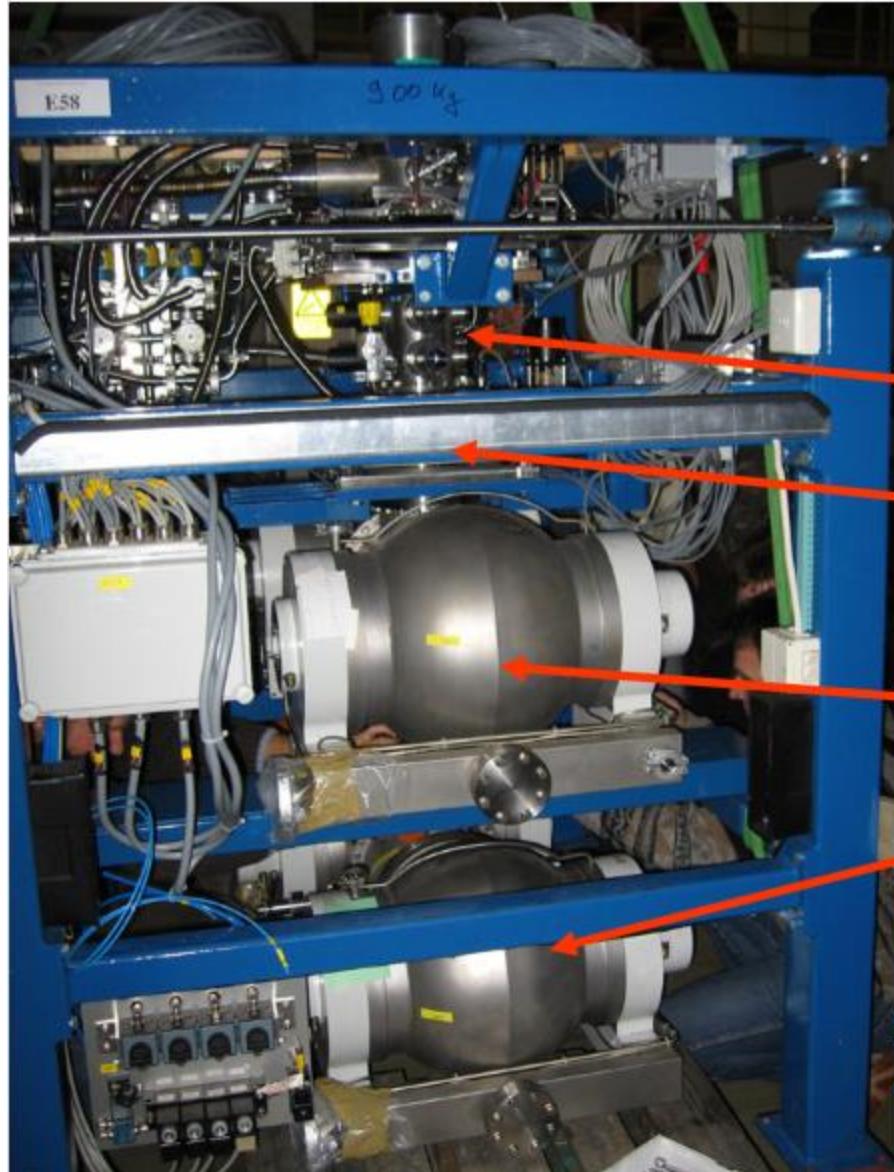
F3 - polarimeter

Future goal: remove C contribution



The WASA-at-COSY Pellet Generator

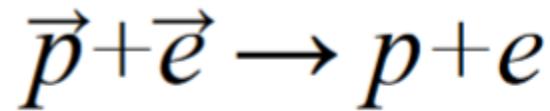
Alfons Khoukaz



Important Data of the WASA Pellet Target

pellet rate (H_2)	8000 pellets/s
pellet rate (D_2)	20000 pellets/s
pellet diameter	20 – 25 μm
target thickness (H_2)	$4 \cdot 10^{15}$ atoms cm^{-2}
target thickness (D_2)	$8 \cdot 10^{15}$ atoms cm^{-2}
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 l_n /day
deuterium usage	250 l_n /day
helium consumption (H_2)	250 l_n /day
helium consumption (D_2)	1000 l_n /day

Exotic reaction



E. Tomasi-Gustafsson

Polarimetry

Polarized beam
on polarized target

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

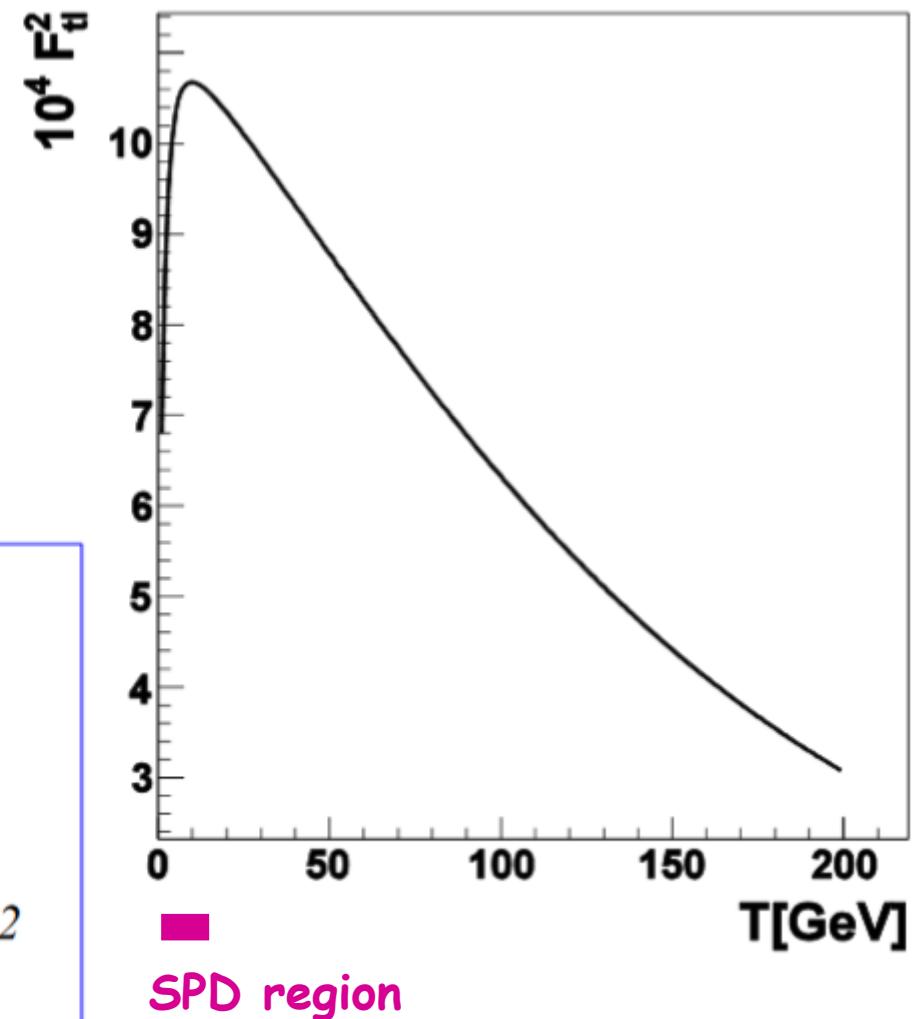
F^2 Max at $E \sim 10$ GeV

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

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

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

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



CONCLUSION

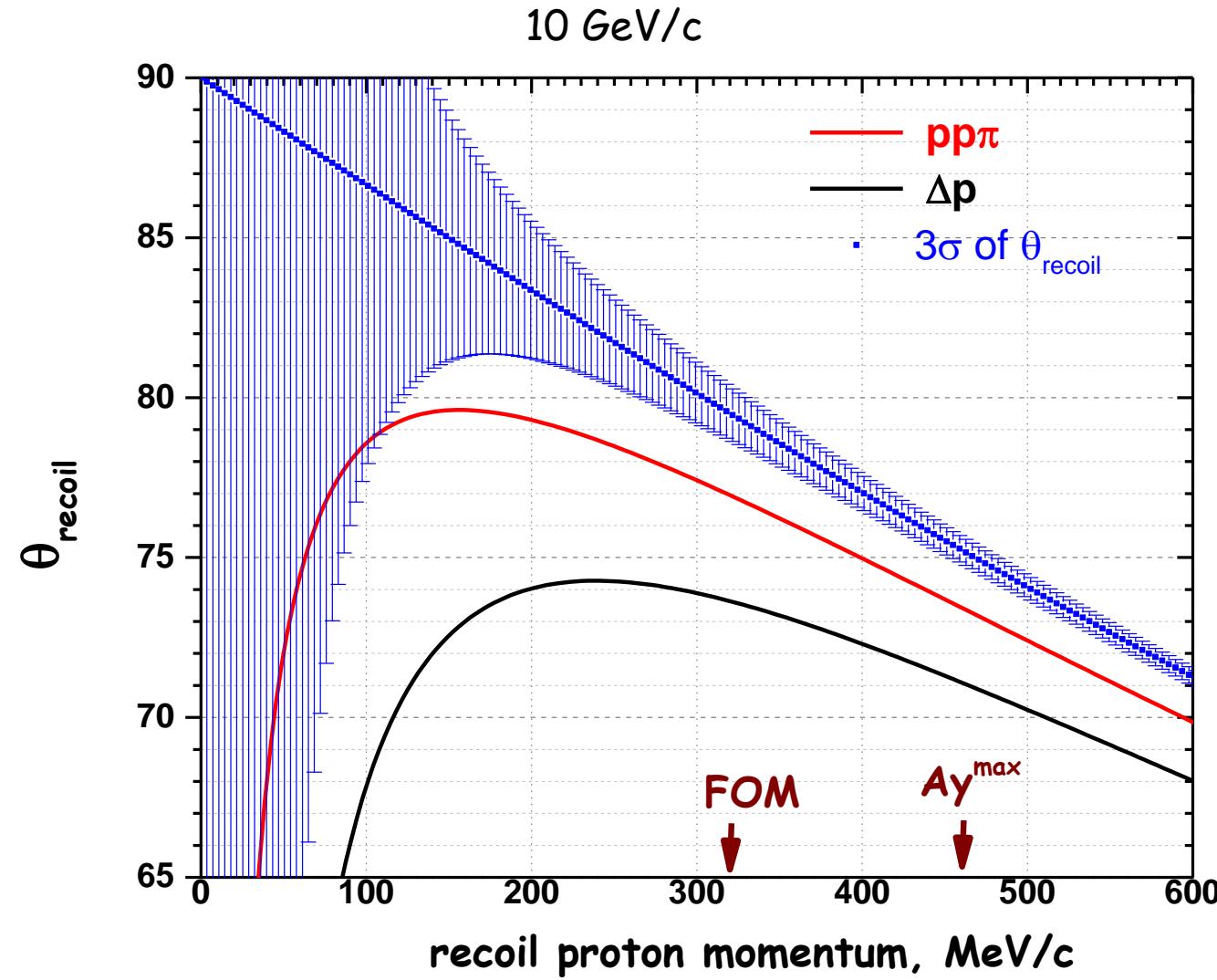
Elastic pp scattering with detecting a recoil proton is the best reaction for proton polarimetry in momentum interval from 1 to 13 GeV/c

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

p (pol) + d & d (pol) + p

Thank you!

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



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 γ 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

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

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

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