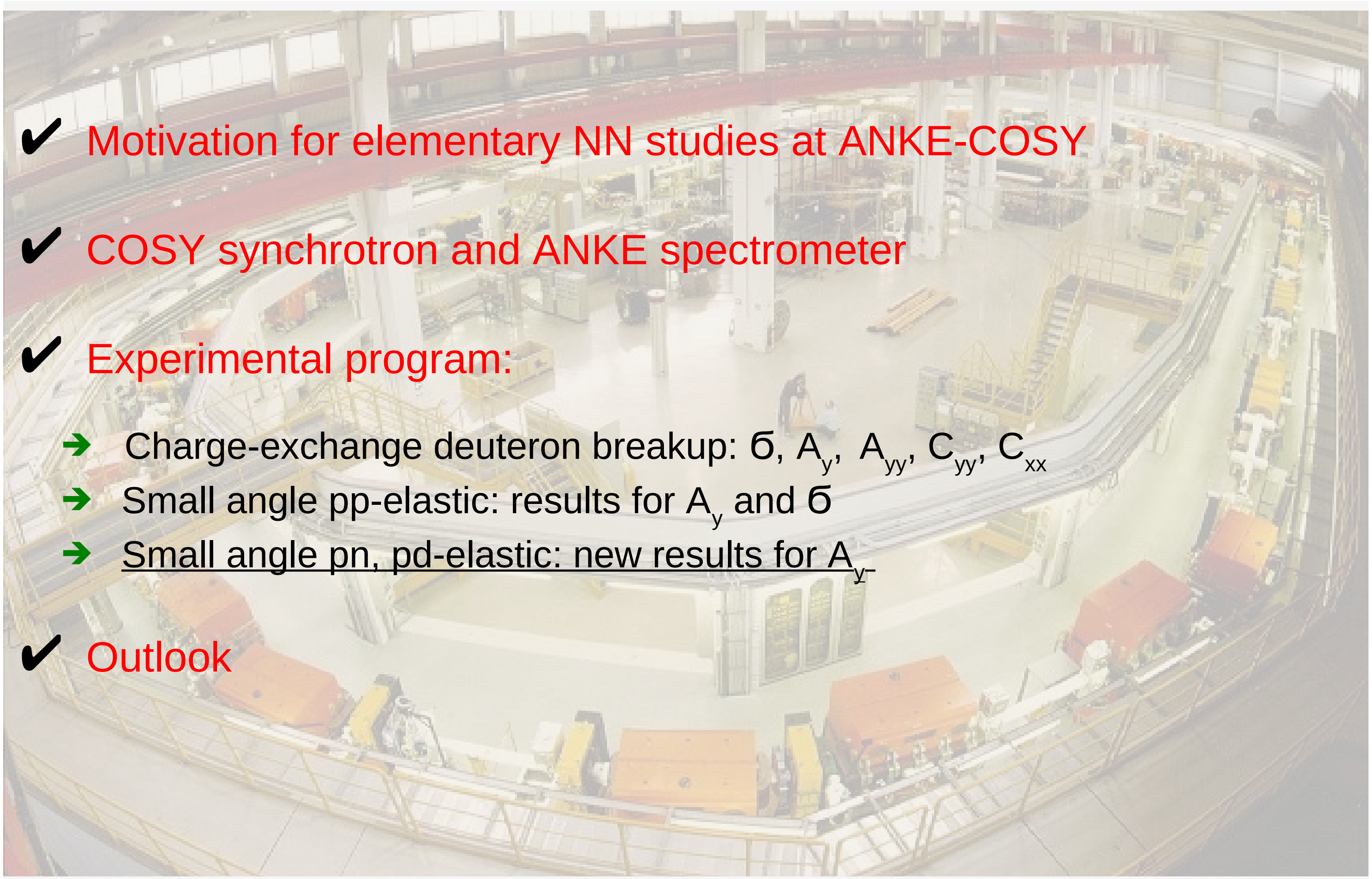
Изучение упругих *NN*-взаимодействий с использованием поляризованных пучков и мишени на ANKE-COSY

С. Дымов
(коллаборация ANKE)

Outline



- ✔ Motivation for elementary NN studies at ANKE-COSY
- ✔ COSY synchrotron and ANKE spectrometer
- ✔ Experimental program:
  - ➔ Charge-exchange deuteron breakup: б, A_y, A_{yy}, C_{yy}, C_{xx}
  - ➔ Small angle pp-elastic: results for A_y and б
  - ➔ <u>Small angle pn, pd-elastic: new results for A_y</u>
- ✔ Outlook

MOTIVATION: Nucleon-Nucleon (NN) interaction

Understand nuclear force in GeV region

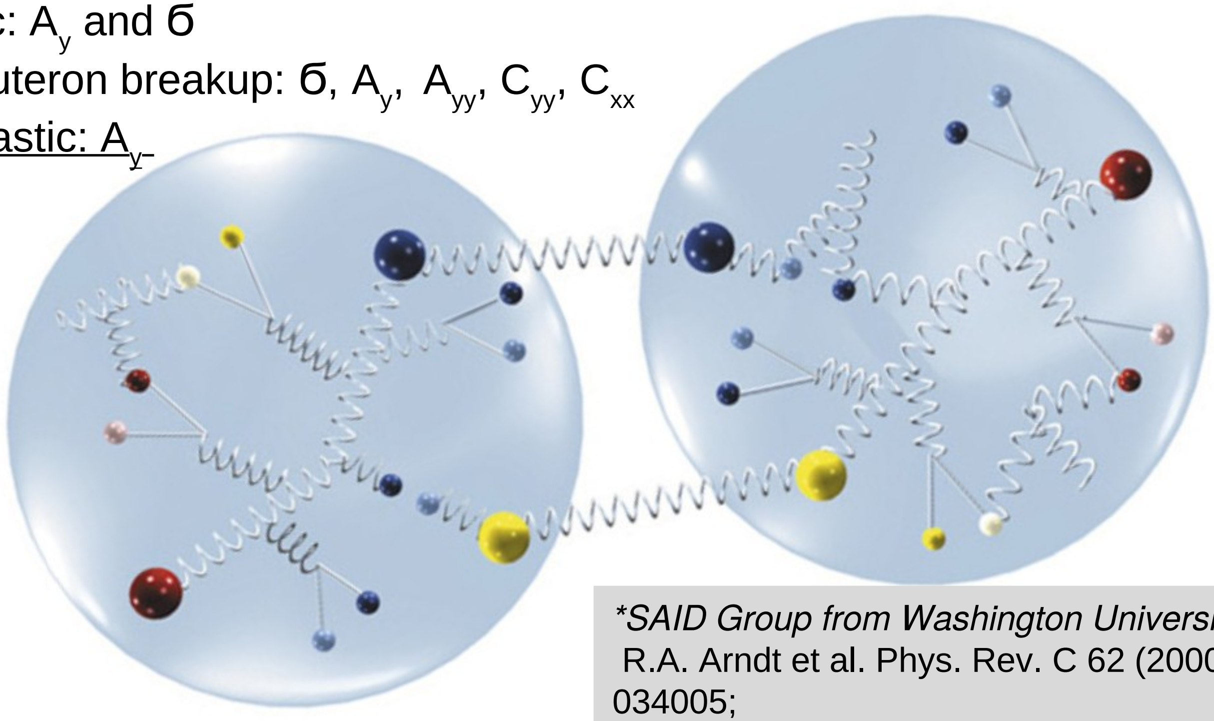
→ pp and np-amplitudes

→ Phase Shift Analysis*

→ Spin observables

ANKE

- Small angle pp-elastic: A_y and б
- Charge-exchange deuteron breakup: б, A_y, A_{yy}, C_{yy}, C_{xx}
- Small angle pn, pd-elastic: A_y



**SAID Group from Washington University:*
R.A. Arndt et al. Phys. Rev. C 62 (2000) 034005;
R.A. Arndt et al. Phys. Rev. C 76 (2007) 025209

MOTIVATION: Where are we in pp elastic?

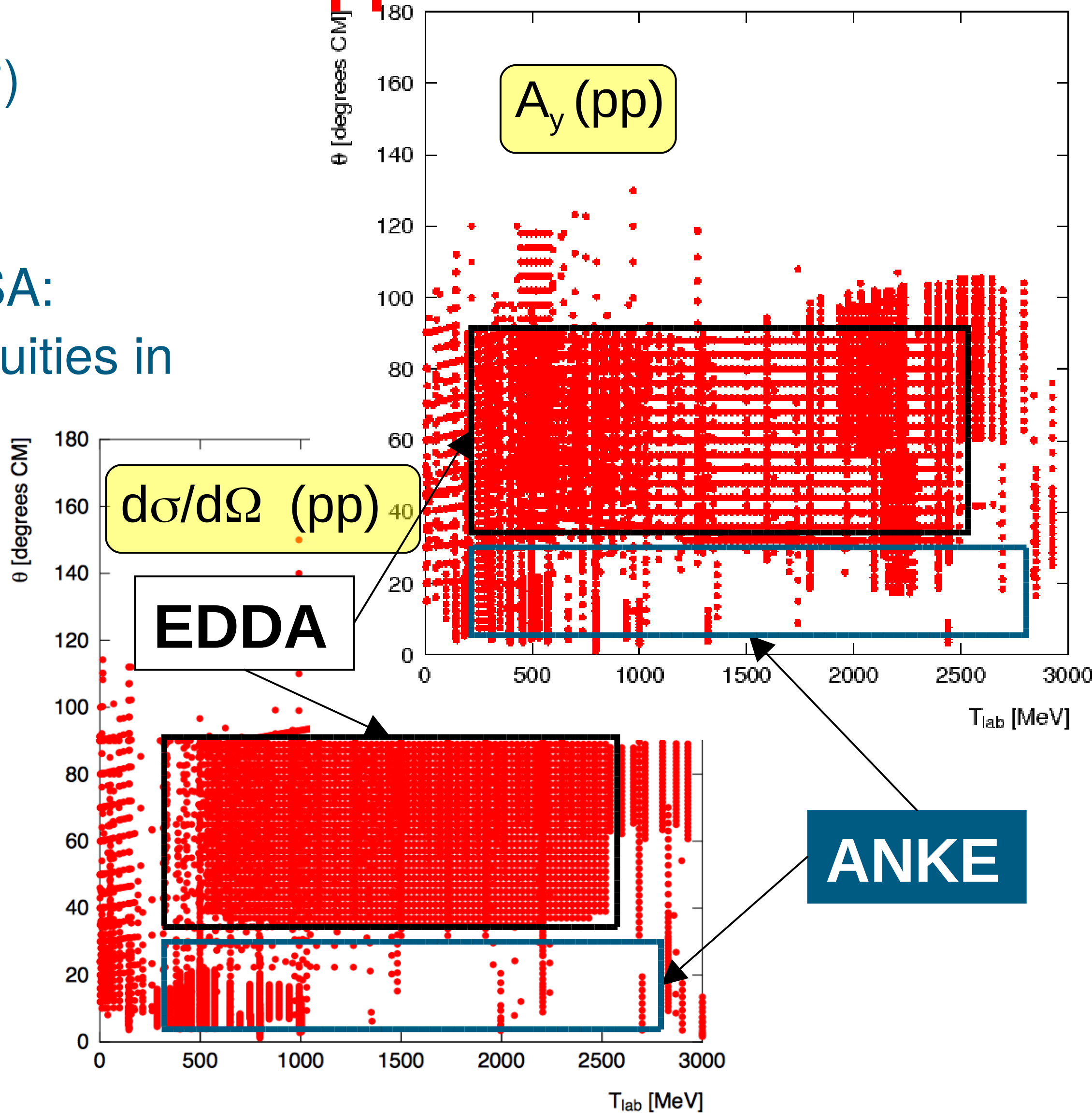
- Wealth of data ($35° < \theta_p < 90°$)
  $0.5 < T_p \lesssim 2.5$ GeV

- EDDA's large impact on PSA: significantly reduced ambiguities in phase shifts (I=1)

PRL 90, 142301 (2003)
PRL 85, 1819 (2000)

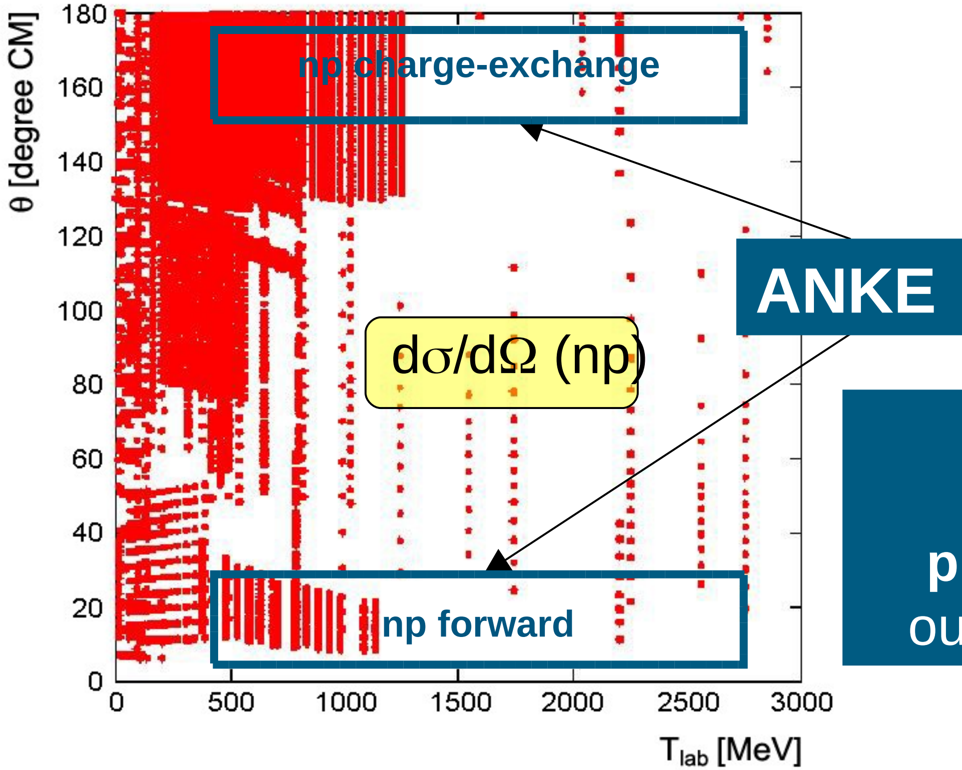
- No experimental data at smaller angles ($\theta_p < 35°$) above T_p=1.0 GeV

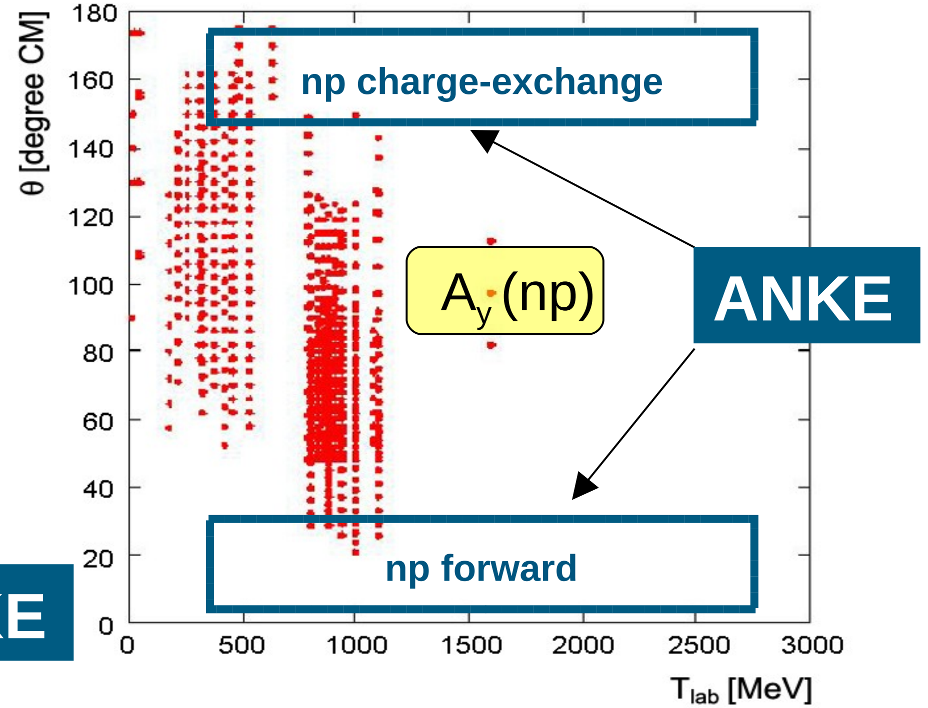
Source: http://nn-online.org/NN



MOTIVATION: Where are we in pn?

R. Arndt: ***Gross misconception within the community that np amplitudes are known up to a couple of GeV. np data above 800 MeV is a DESERT for experimentalists.”***





ANKE is able to provide the experimental data for both:
pp and np systems and improve our understanding of NN interaction

Source: http://nn-online.org/NN

Introduction: COSY storage ring

COSY (COoler SYnchrotron) at Jülich (Germany)

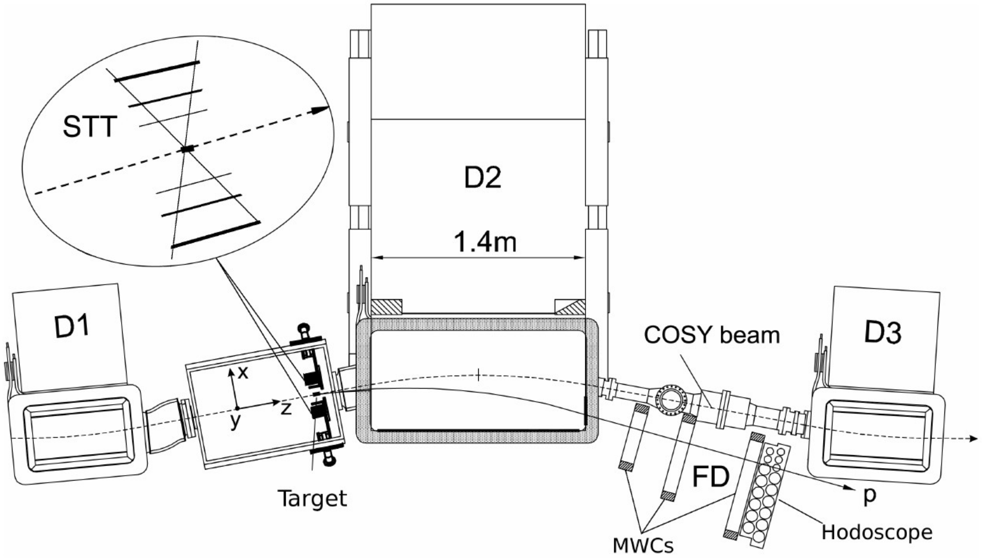
- Hadronic probes: protons, deuterons
- Polarization: beam and targets

- Energy range:

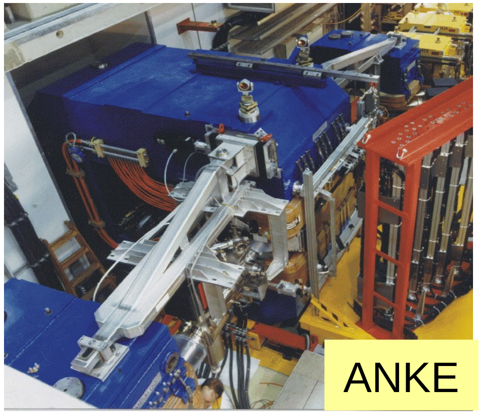
  0.045 – 2.8 GeV (p)

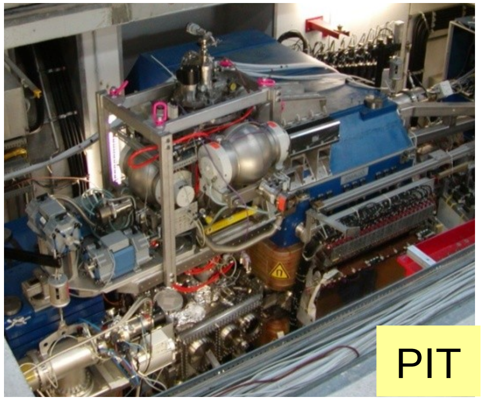
  0.023 – 2.3 GeV (d)
- Max. momentum ~ 3.7 GeV/c
- Energy variation (ramping mode)
- Electron and stochastic cooling
- Internal and external beams
- High polarization (p,d)
- Spin manipulation

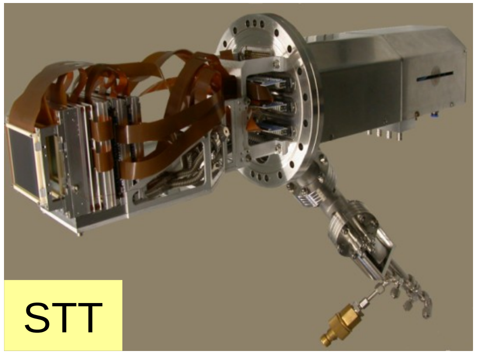
Apparatus: ANKE spectrometer



S. Barsov et al., NIM A 462, 364 (1997)







- Ideal for small angle elastic scattering studies
- Cluster jet target (H_2, D2) or polarised gas target (H, D)
- Silicon Tracking Telescope **(STT)**: ($5^\circ < \Theta^p_{cm} < 30^\circ$):

  Low energy proton (spectator) detection
- Forward detector built by Dubna group

Silicon tracking telescope at ANKE

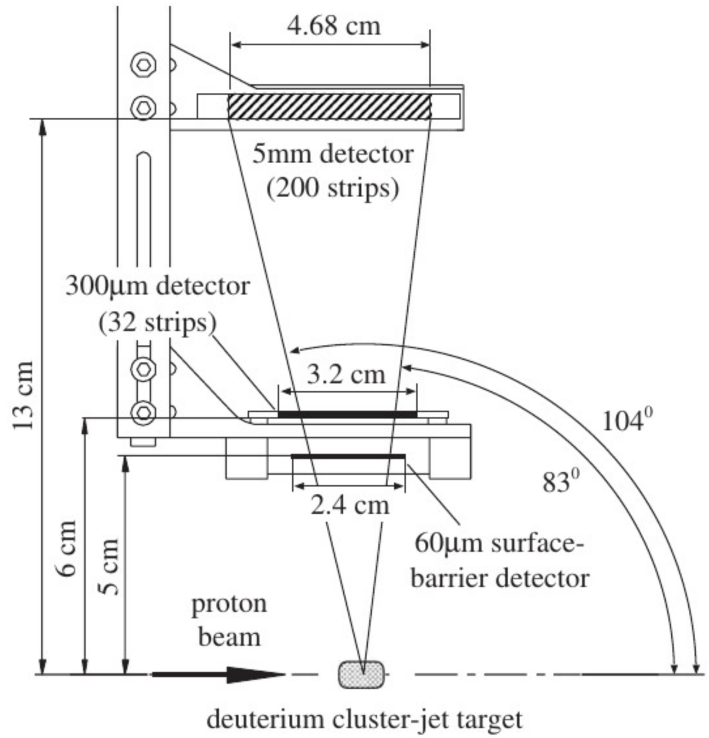
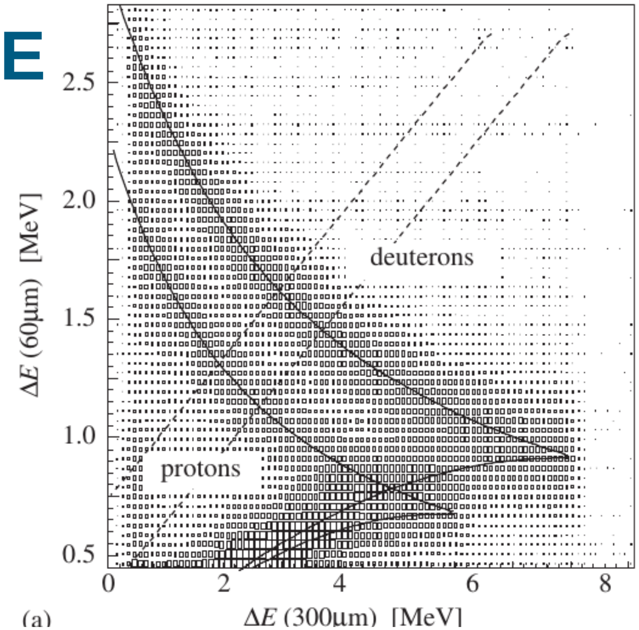
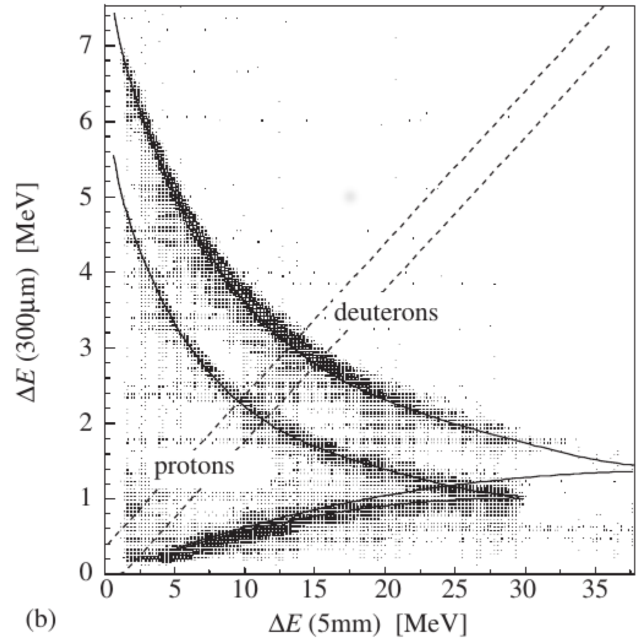


Fig. 1. Sketch of top view of the silicon telescope inside the ANKE target chamber showing the COSY beam, the cluster target and the telescope structure of three silicon detectors.





Identification of stopped protons of 2.5 - 30 MeV, deuterons of 3.5 – 40 MeV

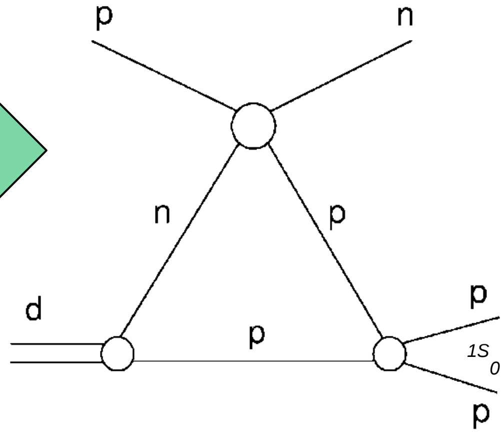
I. Lehmann et al., NIM A 530 (2004) 275

pn scattering via charge exchange d-breakup (1)

Impulse approximation: connection to the elementary np amplitudes

$dp \rightarrow \{pp\}_S n$ $\quad$ *$\{pp\}_S$ is $^1S_0$ proton pair*

$f_{np\rightarrow pn}$ (SAID)



Transition F.F. ~

$$\langle \psi_d | \sigma \cdot e^{iqr} | \psi_{pp} \rangle$$

F.F. is evaluated with PARIS wave function

np charge-exchange amplitudes in cm:

$$f_{np} = \alpha + i\gamma(\boldsymbol{\sigma}_\mathbf{n} + \boldsymbol{\sigma}_\mathbf{p}) \cdot \mathbf{n} + \beta(\boldsymbol{\sigma}_\mathbf{n} \cdot \mathbf{n})(\boldsymbol{\sigma}_\mathbf{p} \cdot \mathbf{n}) + \delta(\boldsymbol{\sigma}_\mathbf{n} \cdot \mathbf{m})(\boldsymbol{\sigma}_\mathbf{p} \cdot \mathbf{m}) + \varepsilon(\boldsymbol{\sigma}_\mathbf{n} \cdot \mathbf{l})(\boldsymbol{\sigma}_\mathbf{p} \cdot \mathbf{l})$$

with basis vectors in terms of initial and final cm momenta ***p*** and ***p***':

$$\mathbf{n} = \frac{\mathbf{p} \times \mathbf{p}'}{|\mathbf{p} \times \mathbf{p}'|}, \quad \mathbf{m} = \frac{\mathbf{p}' - \mathbf{p}}{|\mathbf{p}' - \mathbf{p}|}, \quad \mathbf{l} = \frac{\mathbf{p}' + \mathbf{p}}{|\mathbf{p}' + \mathbf{p}|}$$

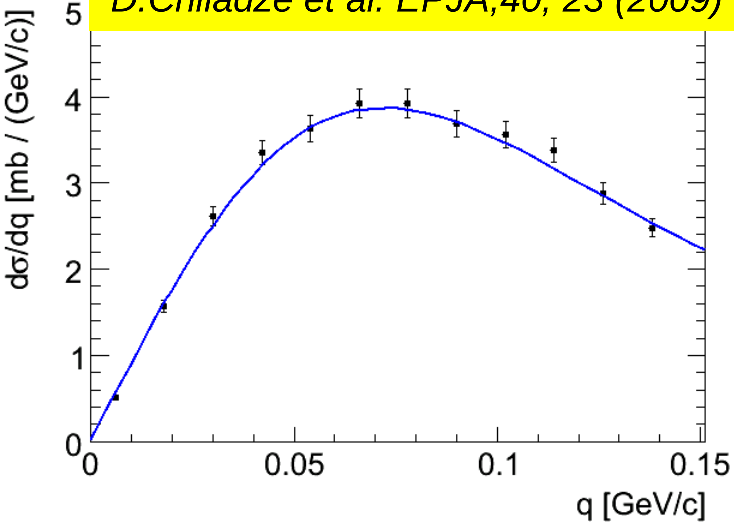
*D.V.Bugg & C.W., Nucl.Phys.A**467** (1987) 575*

Proof of principle at 585 MeV/A

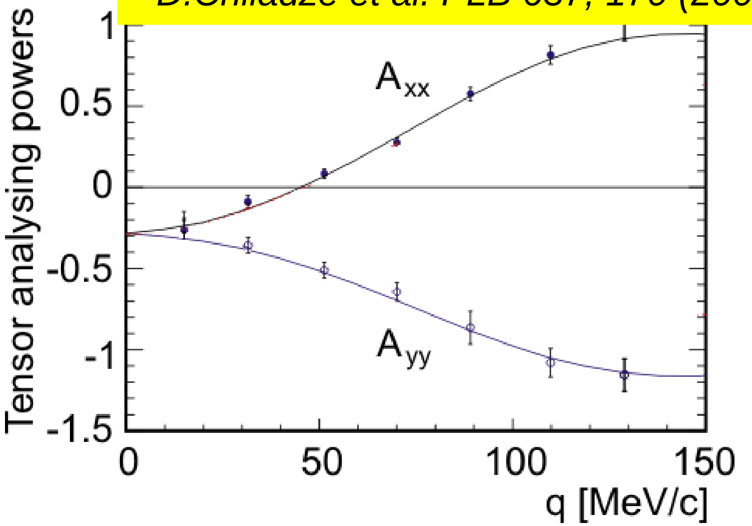
$\vec{d}p \rightarrow \{pp\}_s n \quad (E_{pp} < 3\ MeV)$

- Methodology is valid at $T_N = 585\ MeV$
- Application to higher energies $T_N = 0.8,\ 0.9,\ 1.135\ GeV$

D.Chiladze et al. EPJA,40, 23 (2009)



D.Chiladze et al. PLB 637, 170 (2006)

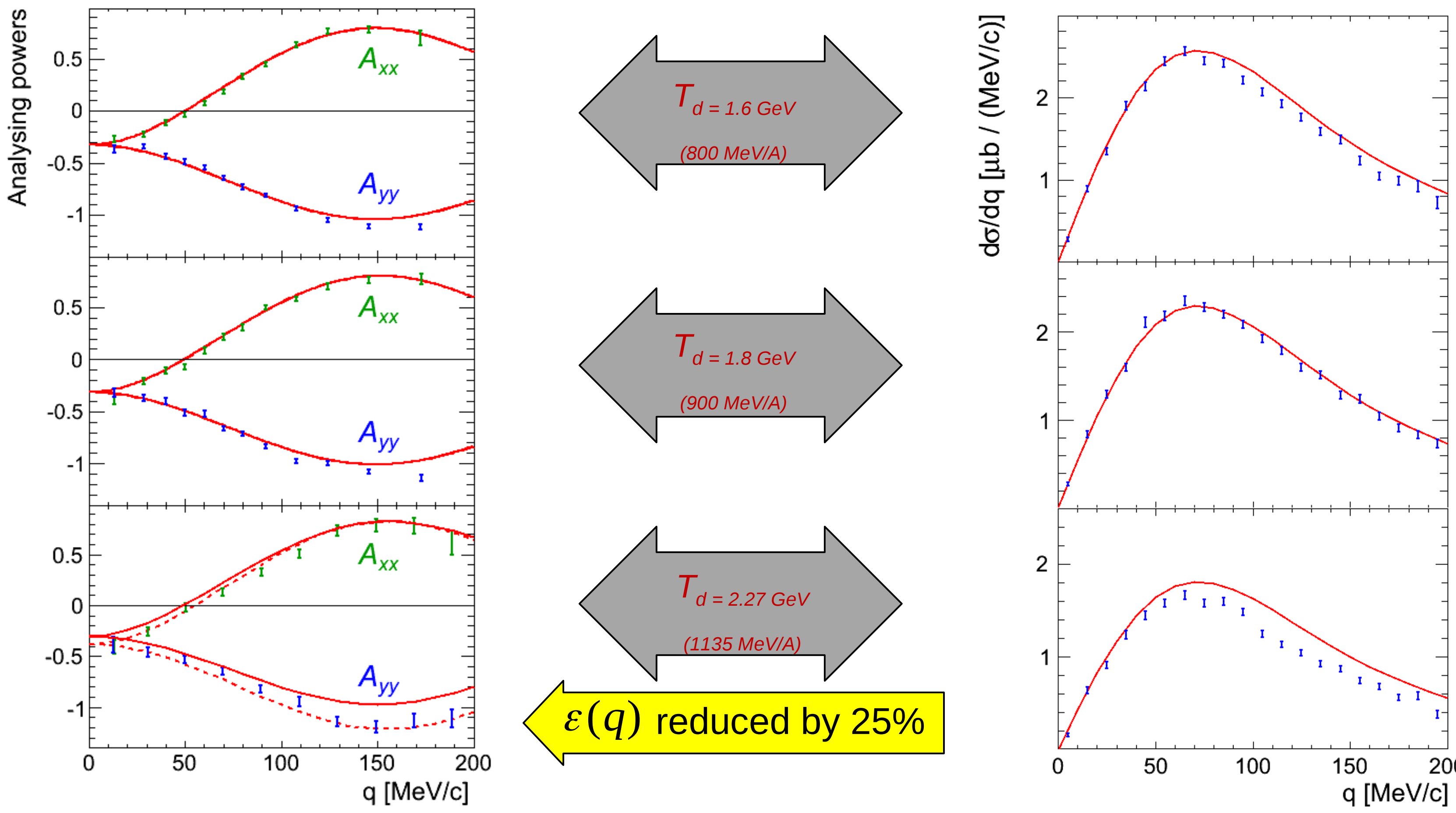


Input for impulse approximation predictions:
np charge-exchange amplitudes from current **SAID** solution at $T_N = 585\ MeV$

$\vec{d}p \to \{pp\}_s n$: $d\sigma/dq$, A_{xx}, A_{yy}

$E_{pp} < 3$ MeV

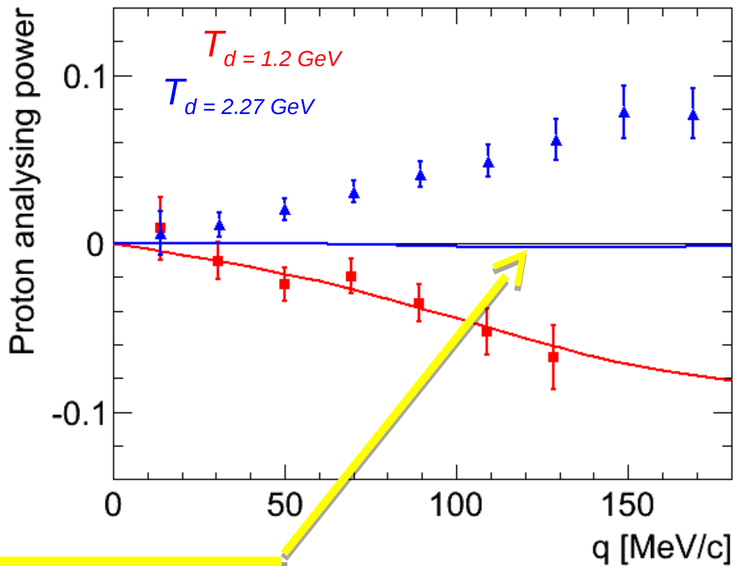
D.Mchedlishvili et al. EPJA, 49, 49 (2013)



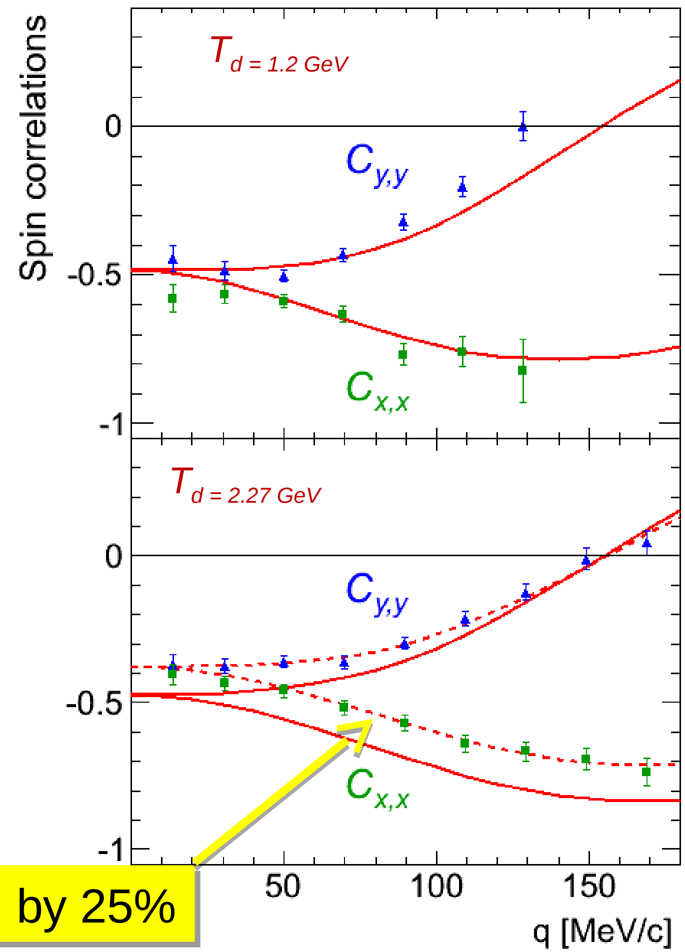
$\vec{d}\vec{p} \to \{pp\}_s n$: A_y^p, $C_{y,y}$, $C_{x,x}$

$E_{pp} < 3$ MeV

D. Mchedlishvili et al. EPJA, 49, 49 (2013)



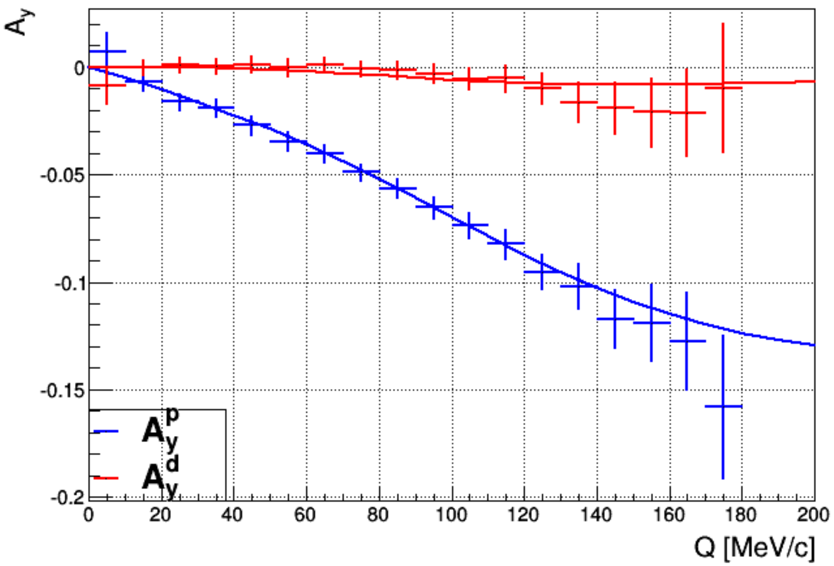
Problem with $\gamma(q)$

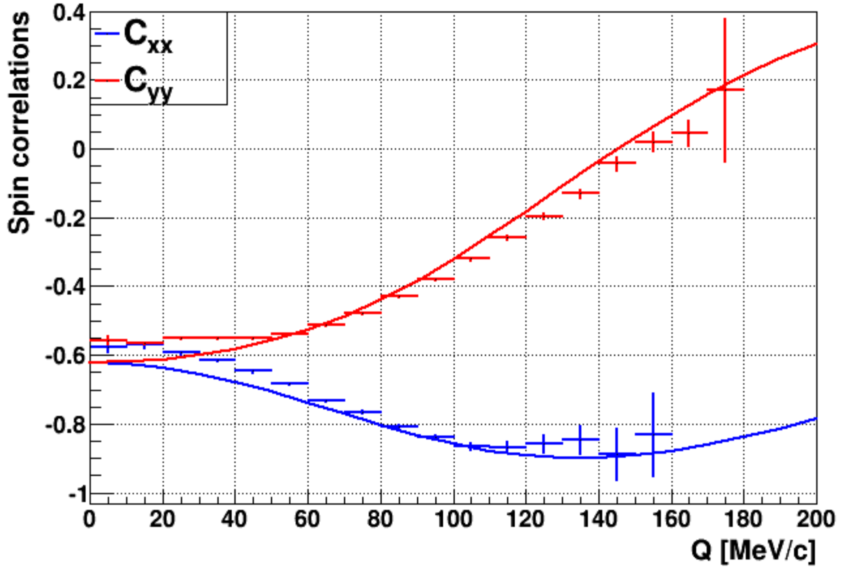


$\varepsilon(q)$ reduced by 25%

High statistics $\vec{d}\vec{p} \to \{pp\}_s n$ data at T_N=363 MeV

By-product result of a **np→{pp}$_s$π$^-$** study





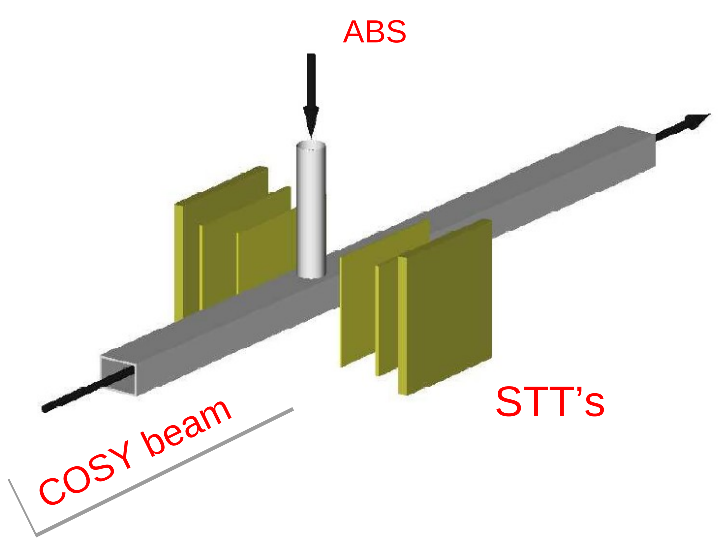
Impulse approximation model calculations by *C. Wilkin*
based on the SAID pn charge-exchange amplitudes (SP07)

S.Dymov et al., PLB 744, 391 (2015)

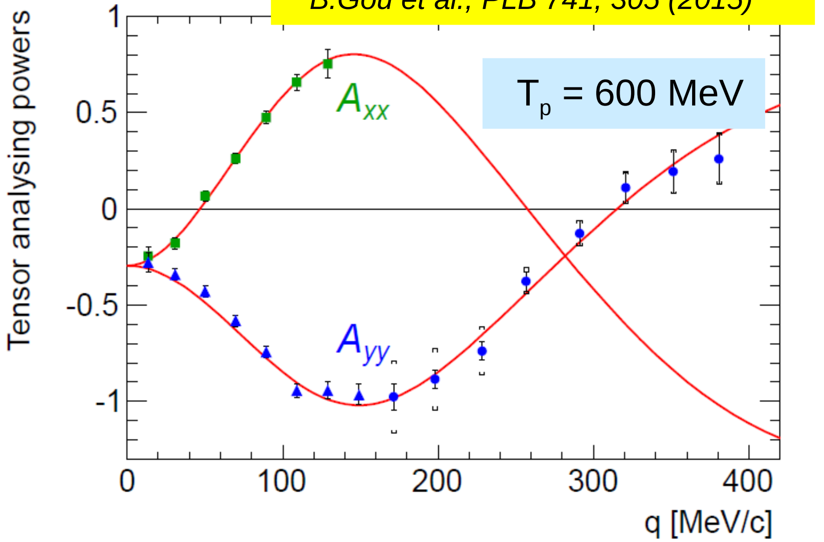
NN scattering: Extension of np-program

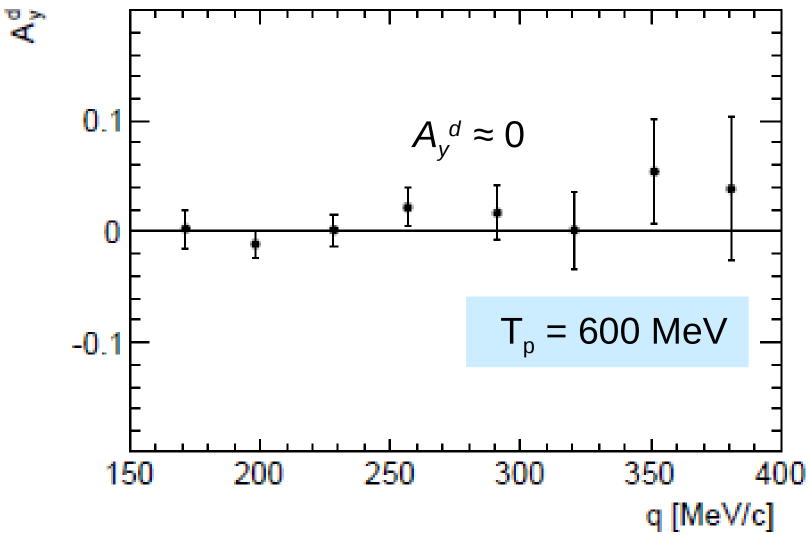
$\vec{p}\vec{d} \to \{pp\}_s n$, $pn \to pn$ (quasi-free)

- Proton beam: extend to higher energies - require polarized deuteron target !
- Select {pp} system in $^1S_0$ state - both protons in the same STT ($E_{pp} < 3$ MeV)
- Compatible with results from lower *q* from ANKE, **proof of principle !**
- Agrees with theoretical predictions
- **Cancelled:** double polarized exp.'s at 1.0 – 1.6 GeV



B.Gou et al., PLB 741, 305 (2015)



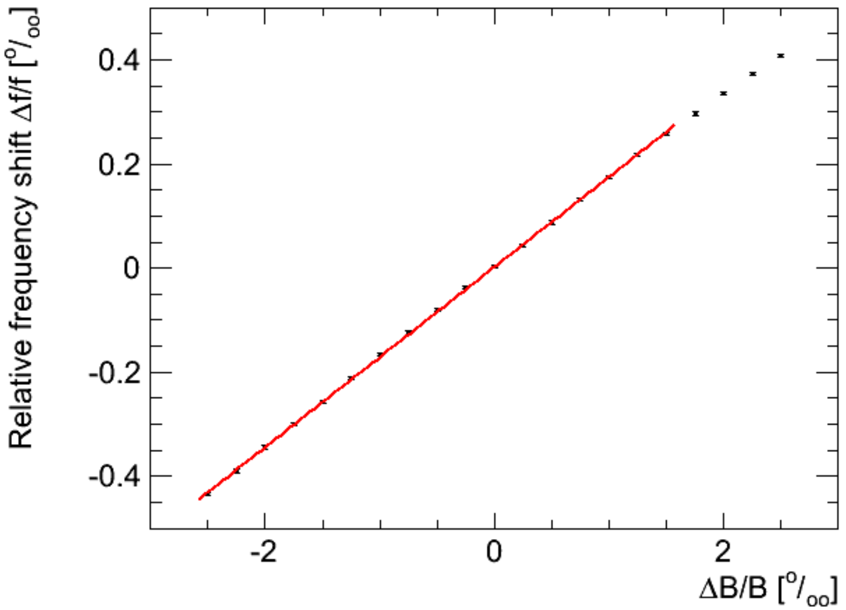


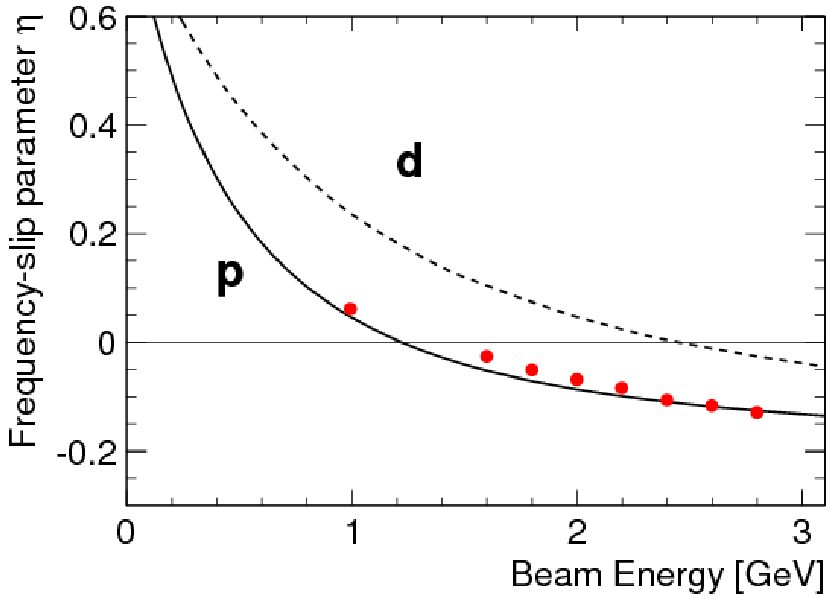
pp-elastic cross section: Target Density

$$n_T = \left(\frac{1+\gamma}{\gamma}\right) \frac{1}{\eta} \frac{1}{(dE/dx)m} \frac{T_0}{f_0^2} \frac{df}{dt}$$

η parameter is connected to the momentum compaction factor a:

$$\eta = \frac{1}{\gamma^2} - \alpha$$

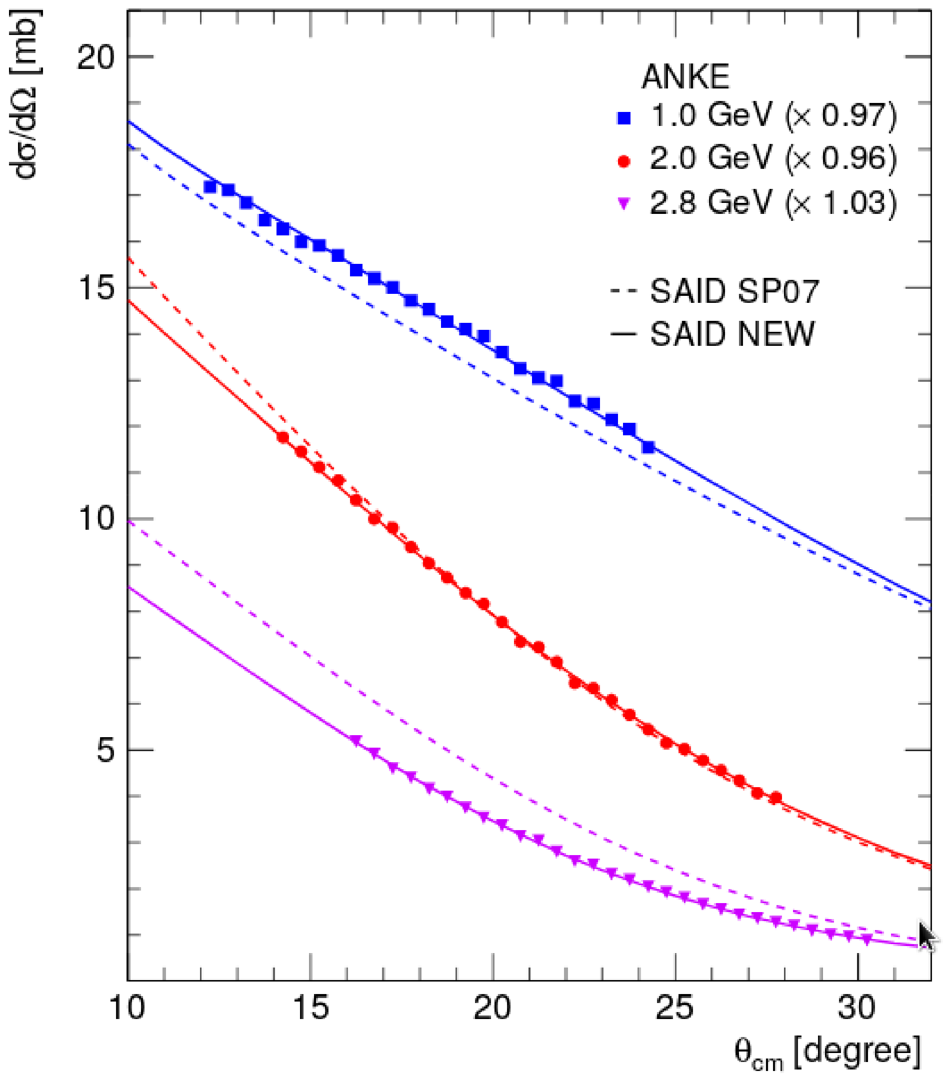


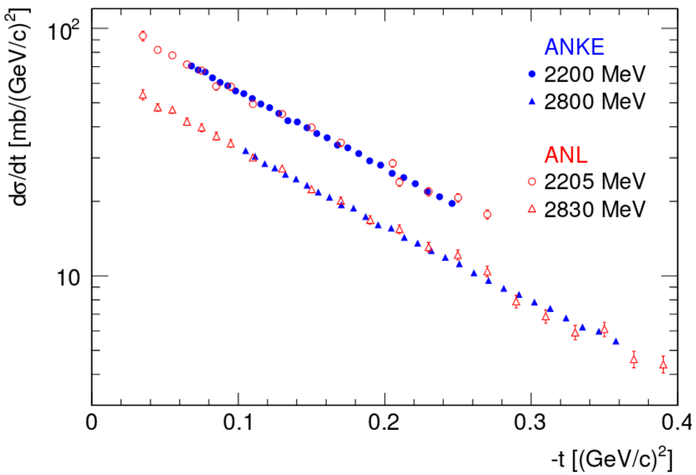


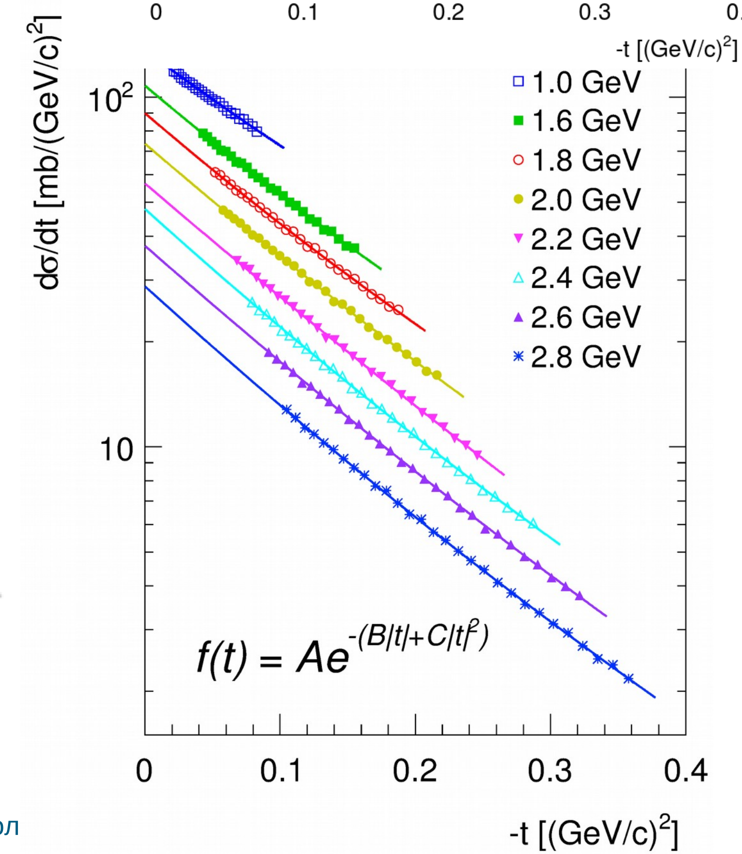
Mean revolution frequency shift is connected to ΔB/B change in the bending magnets via momentum compaction factor α:

$$\frac{\Delta f}{f_0} = \alpha \frac{\Delta B}{B}$$

pp-elastic cross section: Results







D. Mchedlishvili et al., PLB 755, 92, (2016)

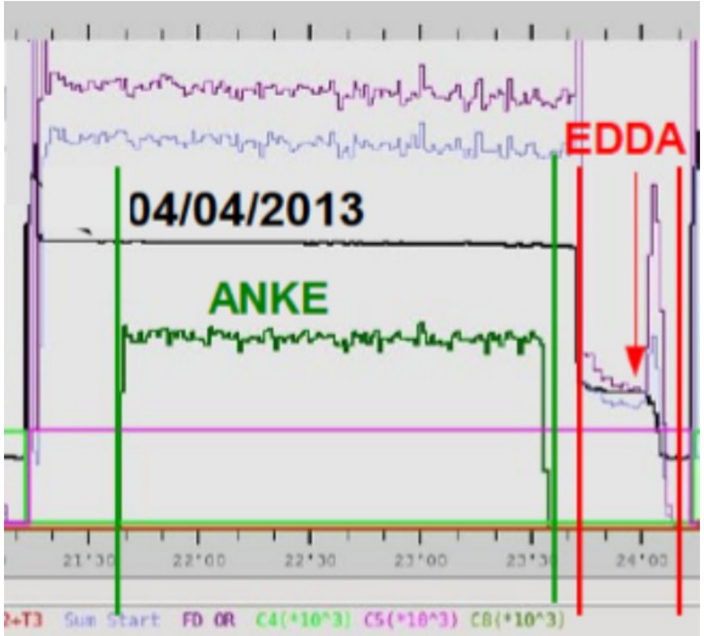
Analyzing power in pp- and pn-elastic scattering: back-to-back measurements

Polarized proton beam:

- T_p= 0.796 GeV (compare with existing experimental data)
- T_p =1.6, 1.8, 1.965, 2.157, 2.368 GeV (new)
- Same beam settings for pp- and pn-experiments

Beam polalization:

P_y~50%, spin flipped every cycle (5 min)



Targets:

Unpolarized H_2, D_2 cluster jet, d~$5 \cdot 10^{14}$ cm^{-2}

Beam polarimetry:

EDDA detector, last 20 sec of each cycle

Triggers:

- Self-triggering STT Layer 2
- FD*STT coincidence

Beam polarization measurement by EDDA

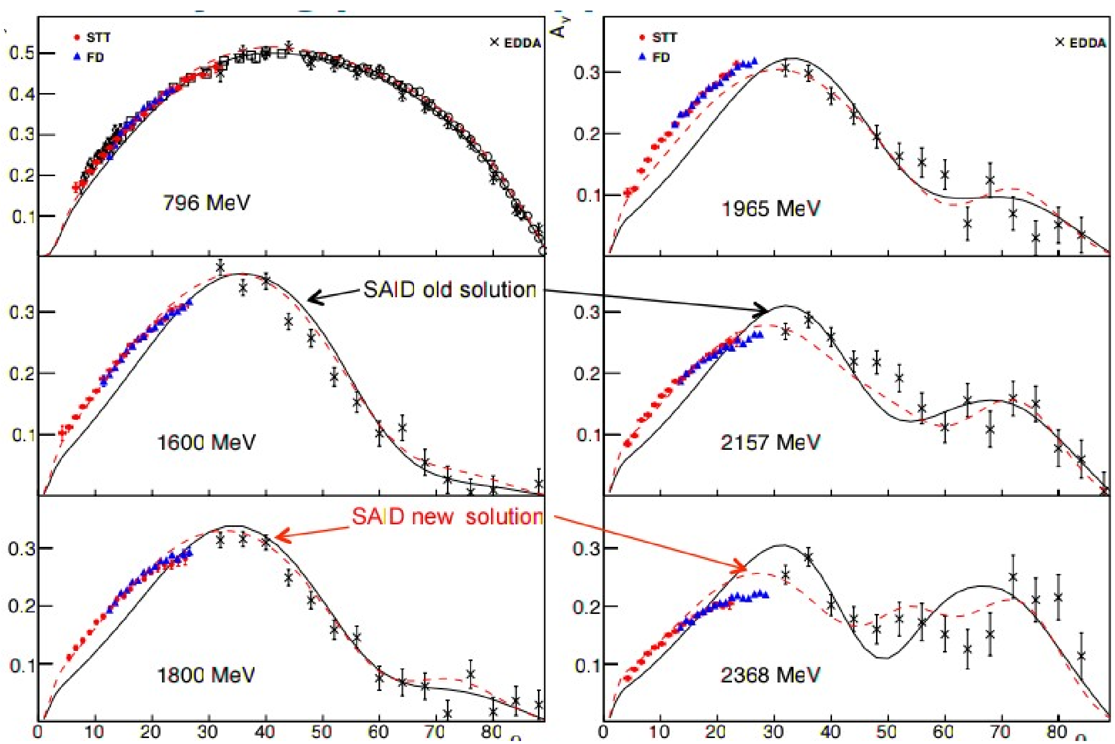
- Carbon fibre target (pC)
- Known effective pC analyzing power
- Scintillator semi-rings (φ asymmetry)

Beam Energy T_kin [MeV]	Av. Polarisation P [%]	Statistical Error P_er [%]
796	55.4	0.8
1600	50.4	0.3
1800	- 50.8	1.1
1965	- 42.9	0.8
2157	- 50.1	1.0
2368	43.5	1.5

- LEP: P~90% at injection
- EDDA: P~50% at experiment energy
- ~1% statistic and 3% systematic error

Analyzing power in $\vec{p}p$-elastic: Results

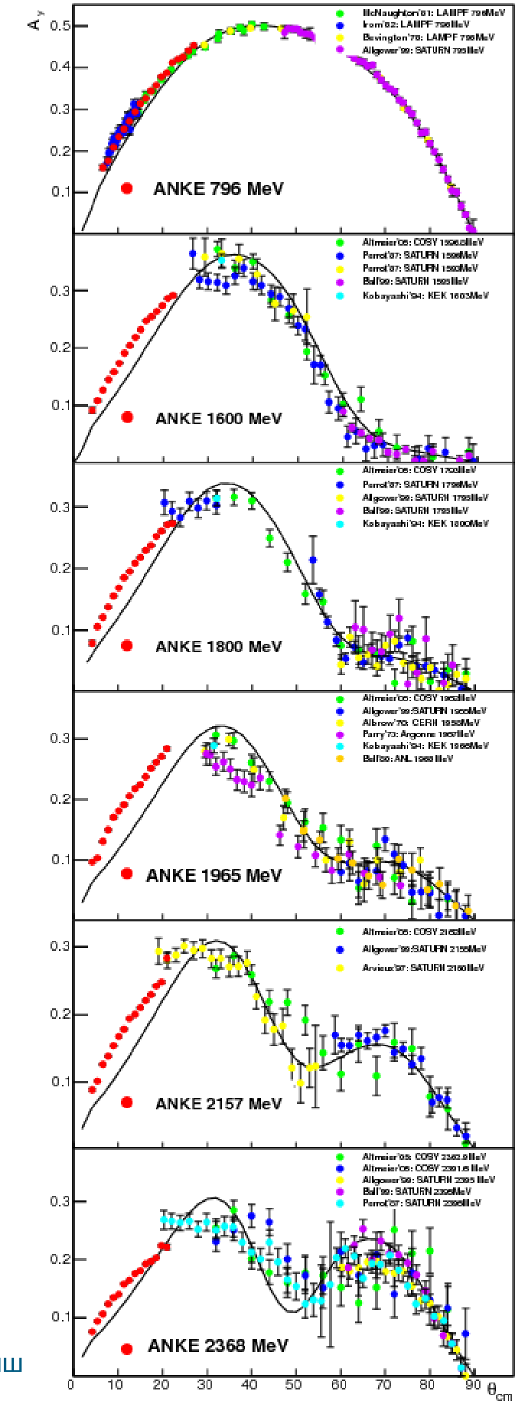
Z. Bagdasarian et al. Phys. Lett. B 739 (2014) 152



SAID (partial wave analysis) old solution (SP07)

SAID new solution (AD14)

- Agreement with the existing data at 0.8 GeV
- New data at five energies



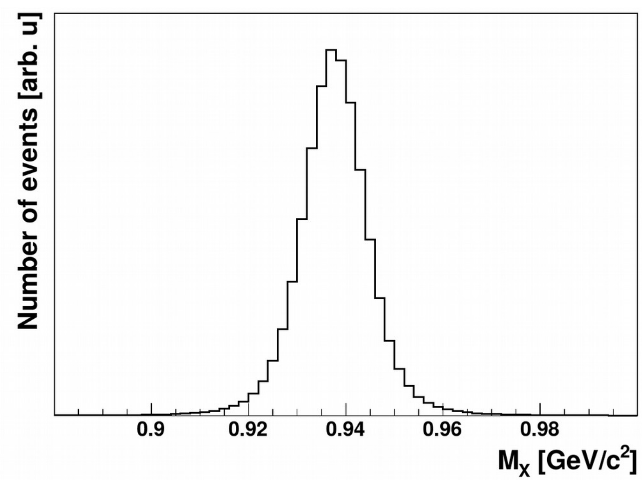
Analyzing power in $\vec{p}$d elastic: New results

Left-right symmetry of STT ➡ Cross ratio method ➡
Systematic errors suppressed in first order

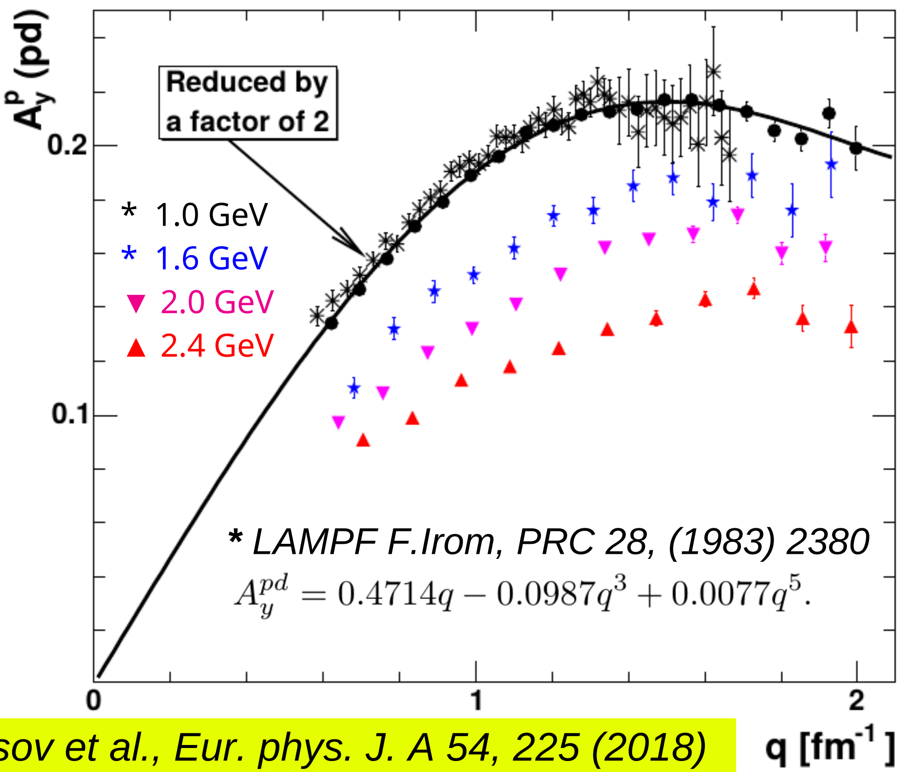
$$\varepsilon = \frac{L-R}{L+R} = PA \qquad L = \sqrt{L_1 L_2} = \sqrt{L\uparrow R\downarrow} \qquad R = \sqrt{R_1 R_2} = \sqrt{L\downarrow R\uparrow}$$

Deuteron in STT (STT trigger)

Angle defined from deuteron energy
$\sigma(\Theta) < 0.2^0$, $\sigma(E_d) < 2\%$



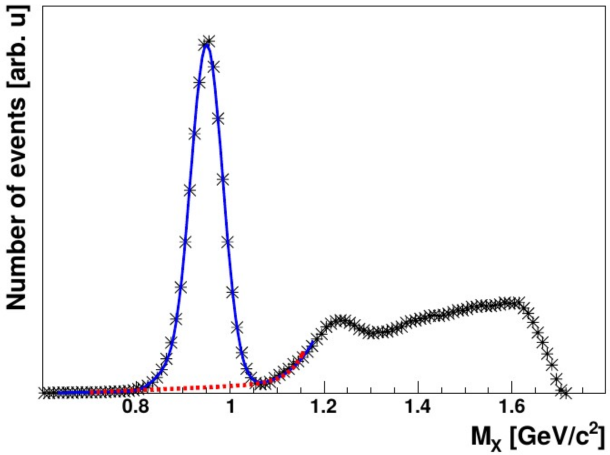
Missing mass in pd → dX



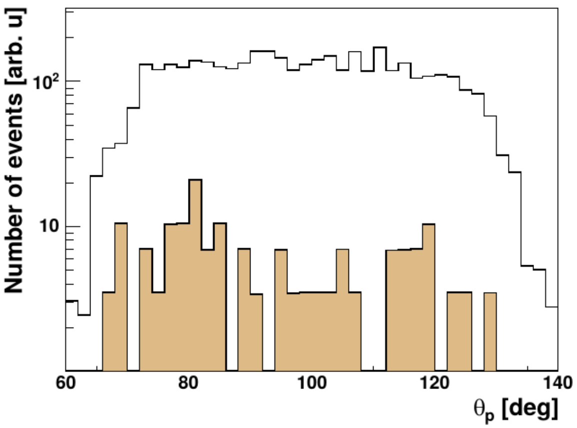
S. Barsov et al., Eur. phys. J. A 54, 225 (2018)

Analyzing power in pn quasi-free elastic: (1) New results

- Fast proton in FD in coincidence with spectator proton in STT
- No detector Left-Right symmetry – cross ratio not applicable
- Must define ratio of luminosity with beam spin up and down: use ratio of deuterons from pd-elastic taken with STT-trigger $(L_d^\uparrow \cdot R_d^\uparrow)/(L_d^\downarrow \cdot R_d^\downarrow)$
- Very low and unpolarized background in Mx spectra, except 800 MeV, where deuterons from $pd \to d\pi^0 + p_{spec}$ in FD suppressed by dE/dX
- Only the right STT was used to suppress quasi-free pp-elastic



Missing mass Mx in $pd \to pX + p_{spec}$



Simulation: pn-quasi (empty histogram) and pp-quasi elastic counts. Left STT in coincidence with FD

Analyzing power in pn quasi-free elastic (2):

Results at 800 MeV

<u>800 Mev is a test energy</u>:
compare with SAID SP07, data

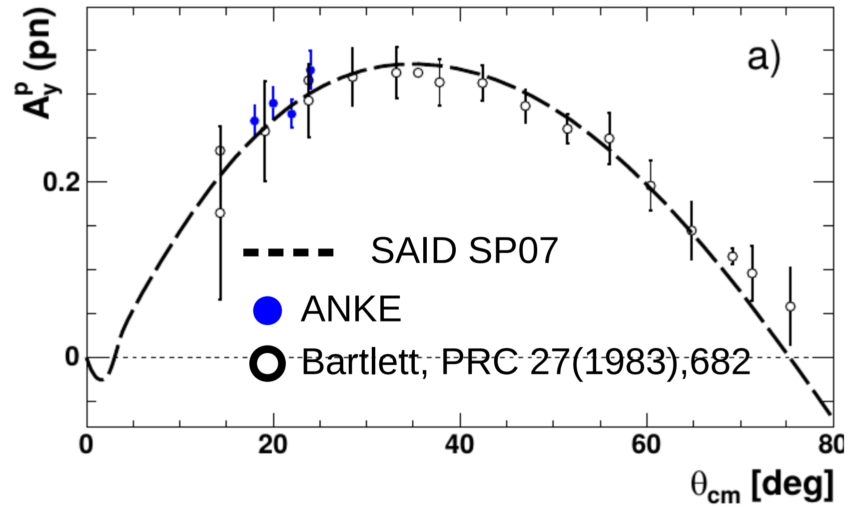
Quasi-free kinematics: $p_T > p_{spec}$

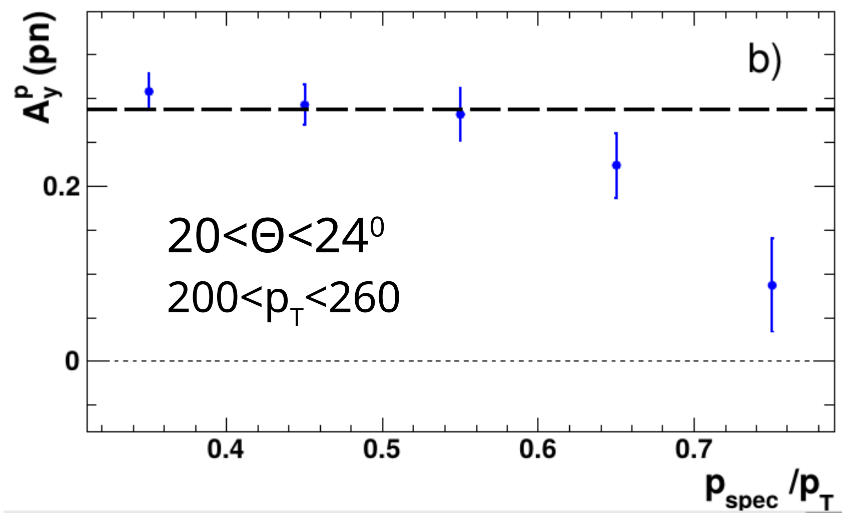
Smallest p_T are at 800 MeV $100<p_T<260$ MeV/c

Cuts for quasi-free scenario:

$p_{spec}/p_T < 0.5$, $p_T>190$ MeV/c

→ $\Theta_{cm} > 17^0$ at 800 MeV,
full acceptance at higher energies





Analyzing power in pn quasi-free elastic (3):

Results at 1600 and 2200 MeV

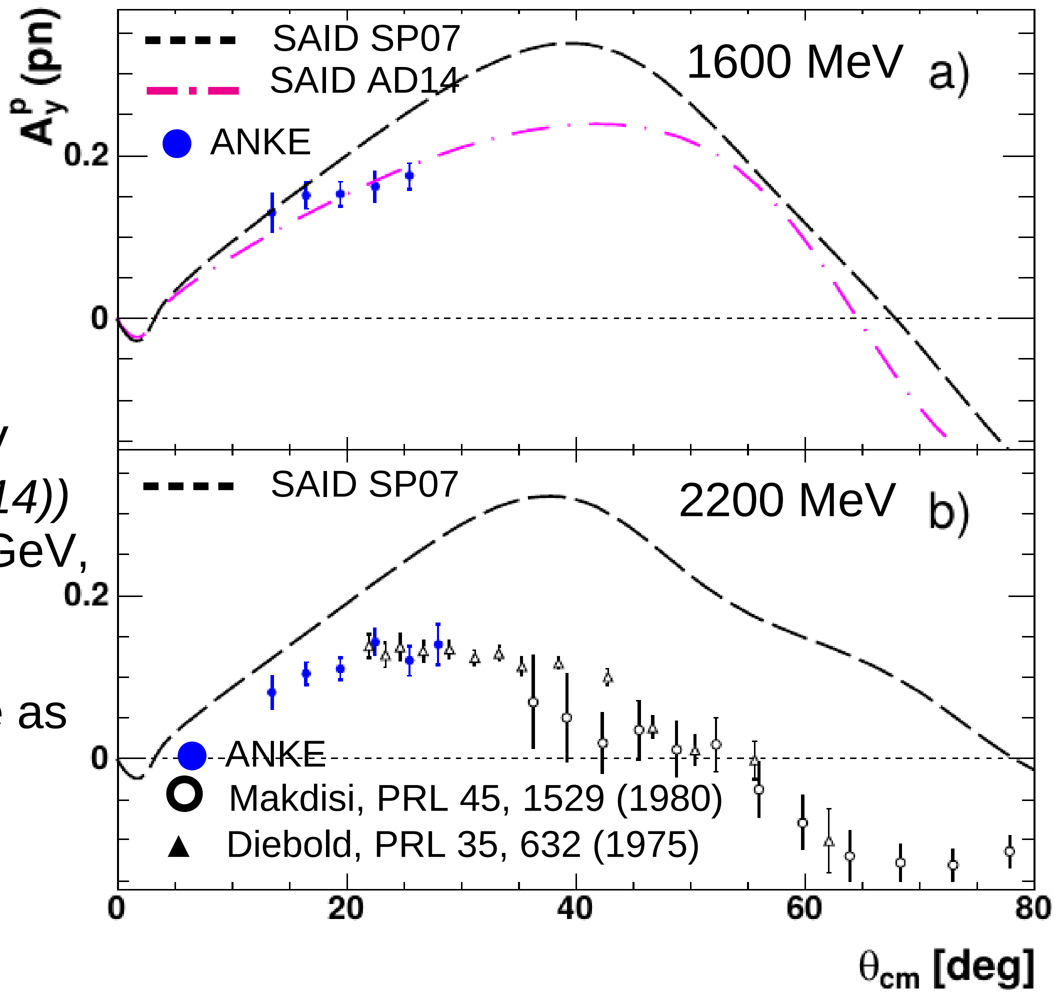
<u>SAID SP07:</u>

based on data < 1.5 GeV,
fails at T_p=1.6-2.4 GeV

<u>SAID AD14:</u>

Includes WASA data at ~1.1 GeV
(Adlarson, PRL 112, 202301 (2014))
Expected to work only up to 1.5 GeV,
But fits ANKE data at 1.6 GeV

A_y^p decreasing with energy same as in pd-elastic



S. Barsov et al., Eur. phys. J. A 54, 225 (2018)

Заключение

- вклад ANKE в базу данных по NN-рассеянию в каналах:
  - Зарядово-обменное pn- рассеяние на углы ~ 180^0
  - pp-, pn- и pd-рассеяние на малые углы
- Данные ANKE согласуются:
  - С данными других экспериментов
  - С результатами SAID PSA SP07 в области его применимости
  - С результатами SAID SAID PSA, модифицированного с учётом данных WASA в области резонанса *d**
- Данные ANKE позволяют:
  - Определить амплитуды зарядово-обменного pn-рассеяния
  - Расширить энергетический диапазон анализа парциальных сдвигов

Спасибо!

pn scattering via charge exchange d-breakup (2)

***dp*→{*pp*}$_s$*n*: Spin observables**

Unpolarised intensity depends only upon spin-flip amplitudes:

$$I = |\beta|^2 + |\gamma|^2 + |\varepsilon|^2 + |\delta|^2 R^2$$

Define a ratio of form factors by

$$R = S^+(k,\tfrac{1}{2}q)/S^-(k,\tfrac{1}{2}q)$$

Terms can be separated by measuring with polarized beams/targets:

Unpolarised cross section

$$\frac{d^4\sigma}{dt\,d^3k} = \tfrac{1}{3} I \left\{S^-(k,\tfrac{1}{2}q)\right\}^2$$

d and *p* vector analysing powers

$$I A_y^d = 0$$

$$I A_y^p = -2\Im(\beta^*\gamma)$$

d tensor analysing powers

$$I A_{xx} = |\beta|^2 + |\gamma|^2 + |\varepsilon|^2 - 2|\delta|^2 R^2$$

$$I A_{yy} = |\delta|^2 R^2 + |\varepsilon|^2 - 2|\beta|^2 - 2|\gamma|^2$$

d-p vector spin correlations

$$I C_{y,y} = -2\Re(\varepsilon^*\delta)R$$

$$I C_{x,x} = -2\Re(\varepsilon^*\beta)$$

d-p tensor spin correlation

$$I C_{yy,y} = -2A_y^p$$

*D.V.Bugg & C.W., Nucl.Phys.A**467** (1987) 575*

Charge exchange d-breakup at ANKE

Vector and tensor polarized deuteron beams:

Proof of principle at 585 MeV/A:

Cross section — *D. Chiladze et al. EPJA,40, 23 (2009)*
Tensor analyzing powers — *D. Chiladze et al. PLB 637, 170 (2006)*

Measurements up to highest d-beam energy:

Cross section
Tensor and vector analyzing powers — *D. Mchedlishvili et al. EPJA, 49, 49 (2013)*
Spin correlations

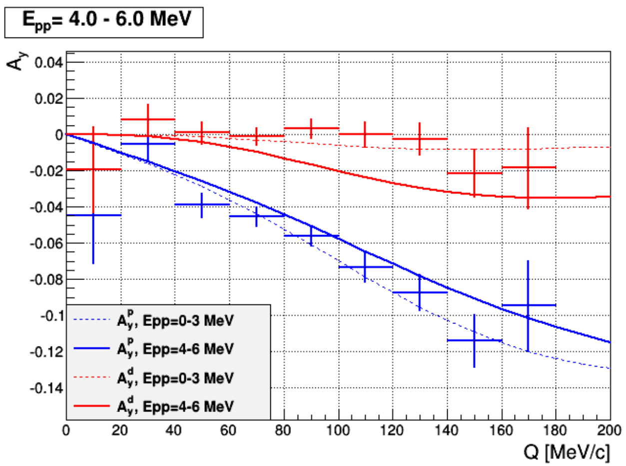
High statistics data at 363 MeV/A:
Vector analyzing powers, Spin correlations — *S.Dymov et al., PLB 744, 391 (2015)*

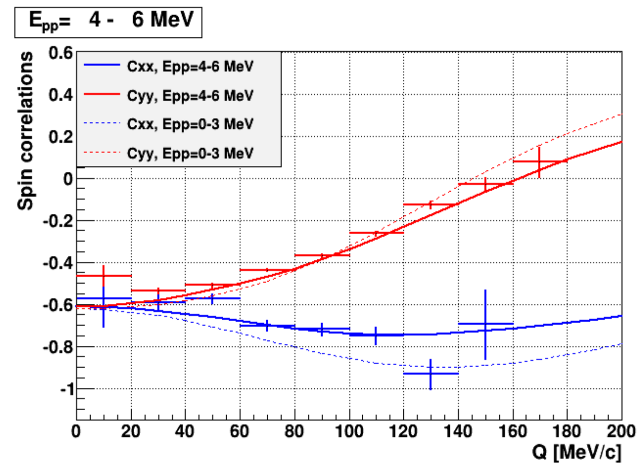
Polarized proton beams:

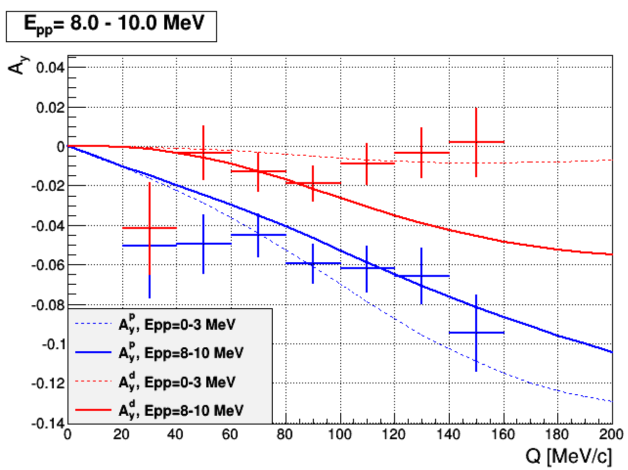
Extension of q range at 600 MeV/A:
Tensor and vector analyzing powers — *B.Gou et al., PLB 741, 305 (2015)*

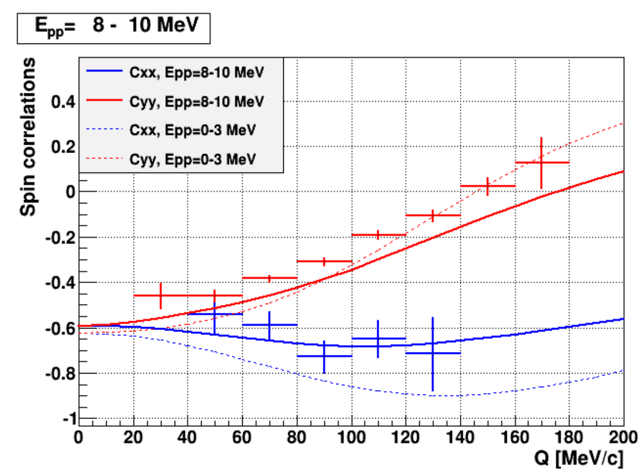
$\vec{d}\vec{p}\to\{pp\}_S n$ data at T_N=363 MeV: higher E_{pp} cuts

Higher waves in *pp* system are important,
proper integration with acceptance needed







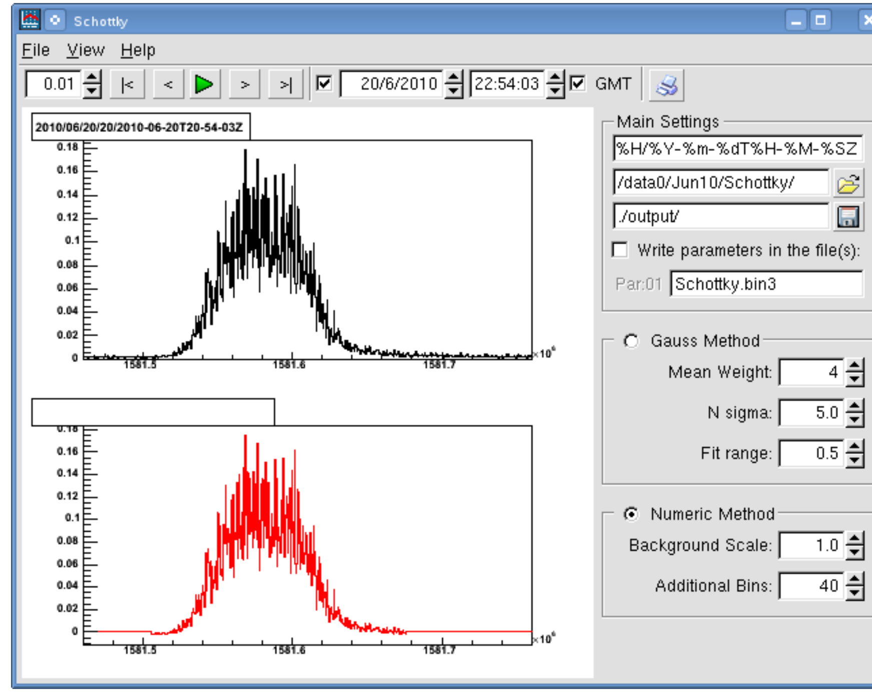


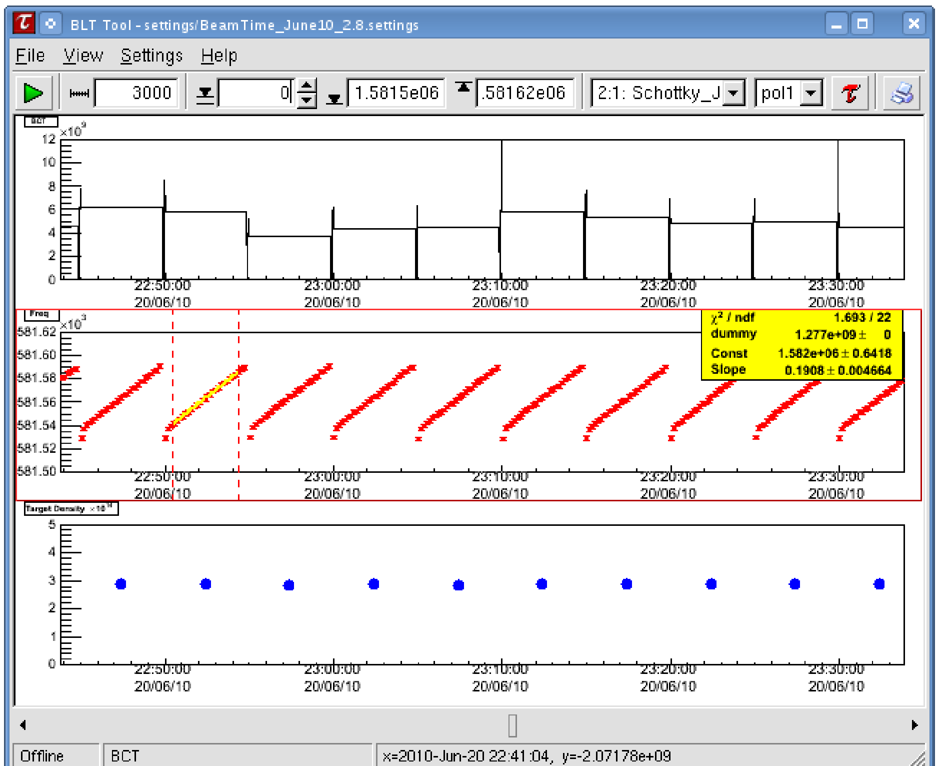
S.Dymov et al., PLB 744, 391 (2015)

pp-elastic cross section: Target Density (2)

Dedicated software package determines:

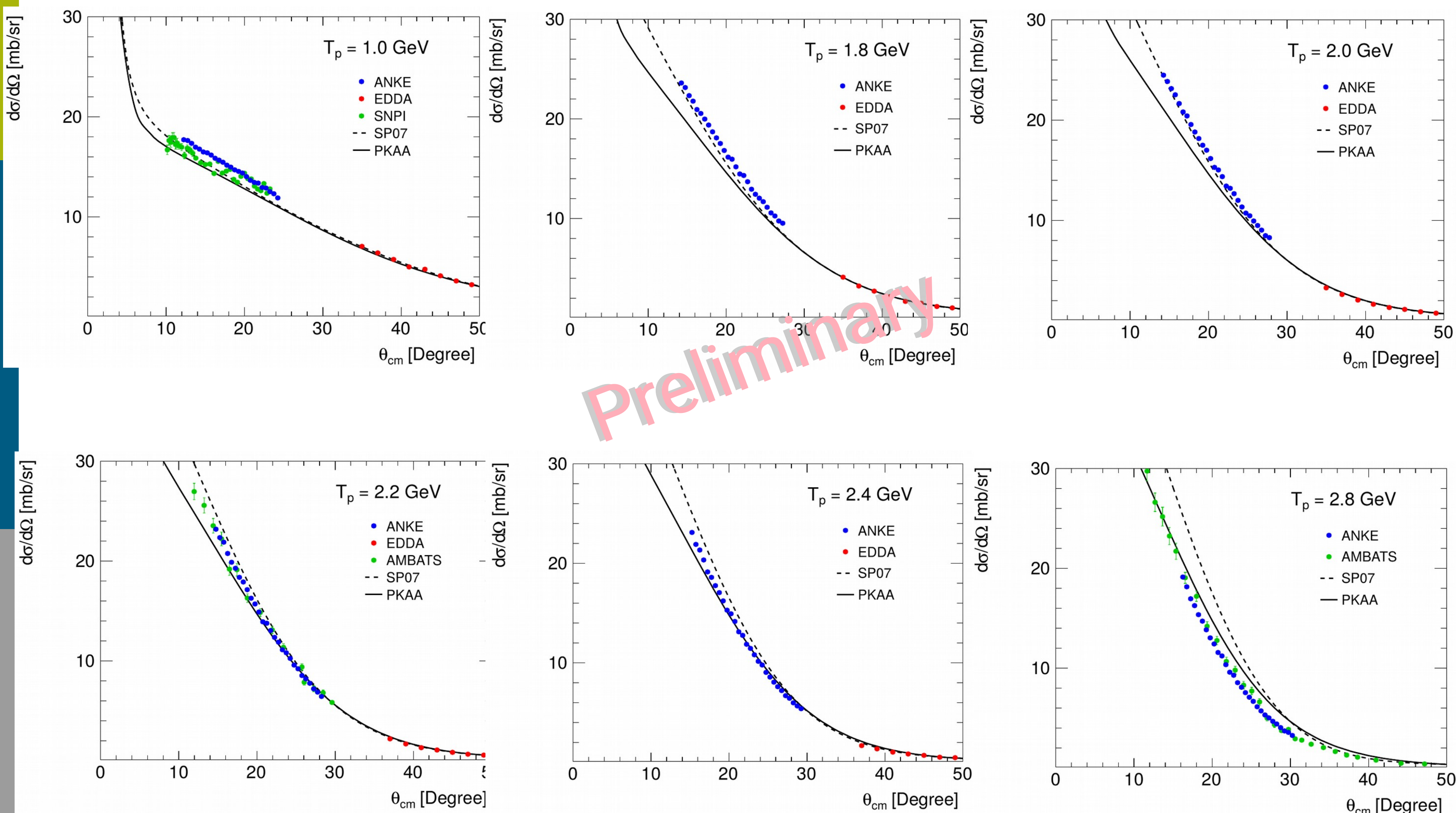
- •Revolution frequency
- •Frequency shift
- •Target density

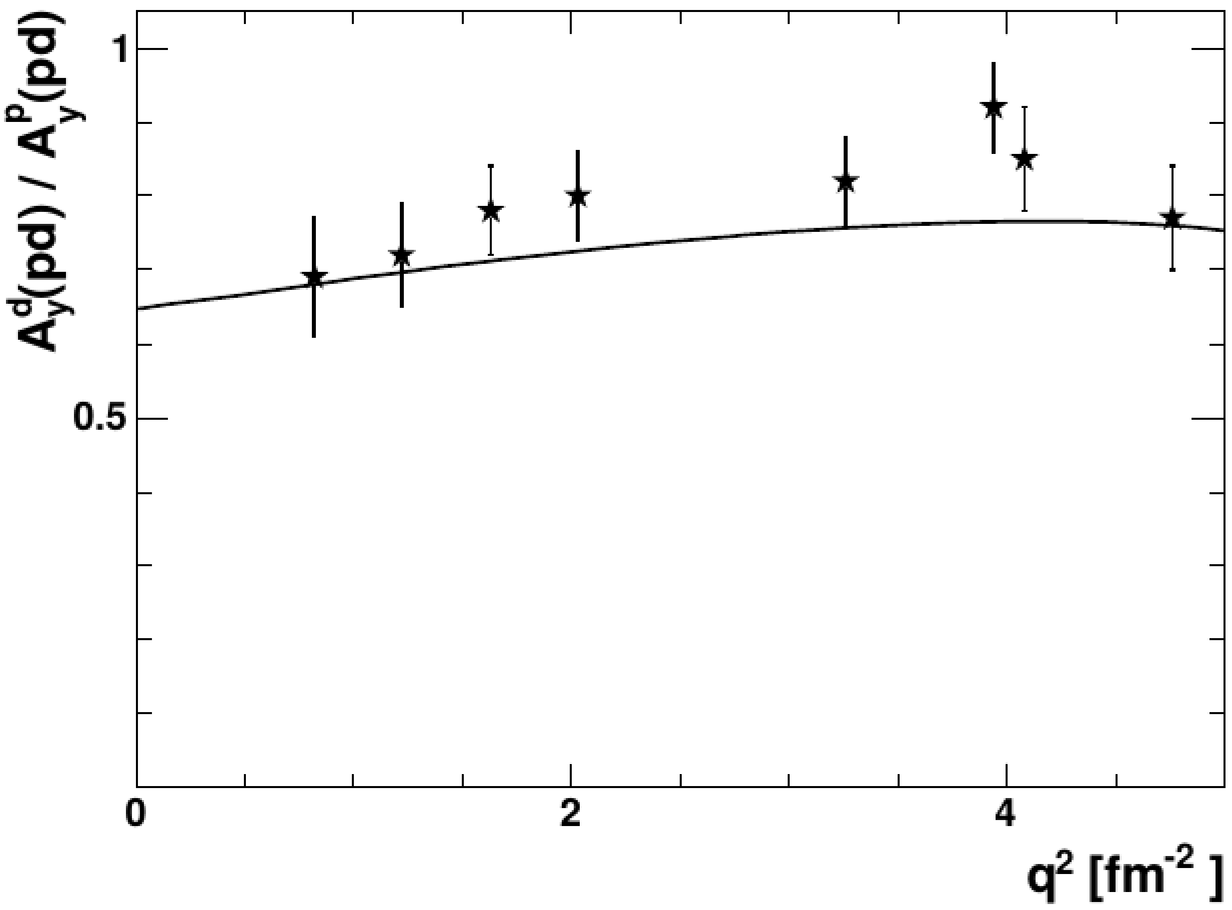




Luminosity error 3%

pp-elastic cross section: Results (1)





$A_y^d(pd) / A_y^p(pd)$
1
0.5
0
2
4
q^2 [fm^{-2}]

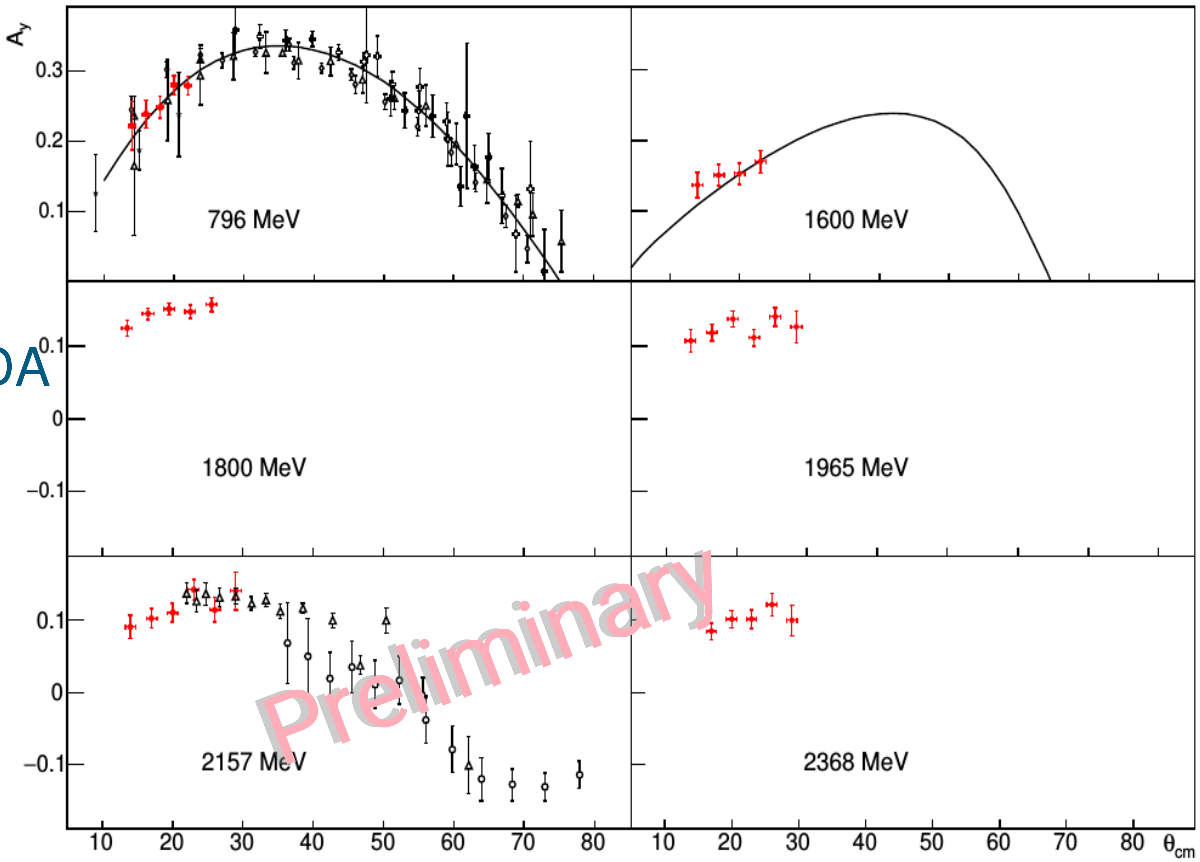
np program: quasi-elastic pn

$\vec{p}d \rightarrow ppn$

T_p = 0.8, 1.6, 1.8, 2.0, 2.2, 2.4 GeV

Polarization with EDDA

- Fast proton in FD
- Slow proton in STT



Compatible with existing data

SAID SP07 describes well at 796 MeV. Dedicated SAID solution at 1.6 GeV