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JÜLICH FORSCHUNGSZENTRUM

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SPIN 2014

The 21st International Spin Physics Symposium

SPIN Physics at COSY:
recent results and future plans

October 23, 2014 | Andro Kacharava (JCHP/IKP, FZ-Jülich)

Outline

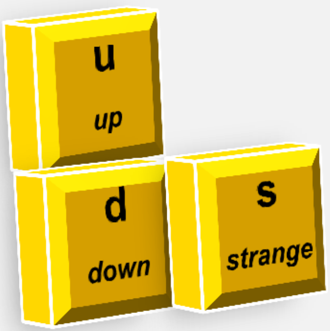
Introduction
- Overview of the program
- Experimental facilities

SPIN physics program: recent results
- Nucleon-nucleon scattering (ANKE, WASA)
- Meson production (ANKE, WASA)
- Spin-filtering (PAX)

Future plans
- EDM project (JEDI)

Introduction: Physics case

Non-perturbative QCD in the (u,d,s) sector



Structure of hadrons

nucleon, mesons, hyperons

Dynamics & interactions

nucleon-nucleon, meson-nucleon, hyperon-nucleon

meson-nucleus, medium effects

Symmetries and symmetry breaking

chiral symmetry

isospin & charge symmetry in reactions

discrete symmetries in meson decays

Introduction: SPIN program

Goal:

Extract the basic spin-dependent two-body scattering information via the study of 3-body final states

Tools:

- Hadronic probes (p,d)
- Double polarization (beam and target)

Topics:

1. NN scattering ↔ pp- and np-amplitudes, nuclear forces
2. Meson production ↔ NNπ amplitudes (ChPT), FSI
3. Strangeness production ↔ YN interaction, SU(3) symmetry

COSY proposal:
arXiv: nucl-ex/0511028

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

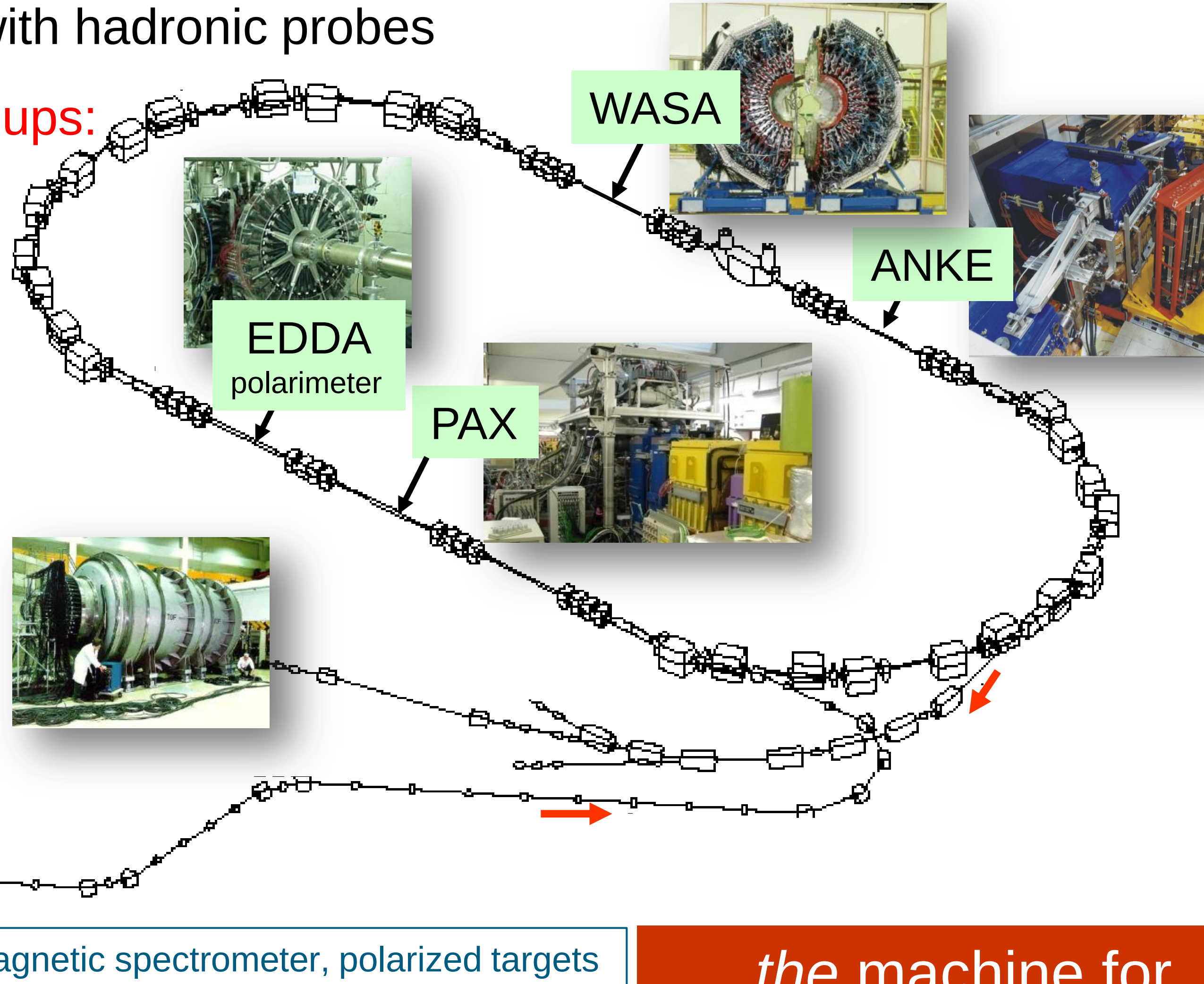
Introduction: COSY facility

Hadron physics with hadronic probes

Experimental set-ups:

- ANKE
- WASA
- EDDA
  (srEDM/JEDI)
- PAX

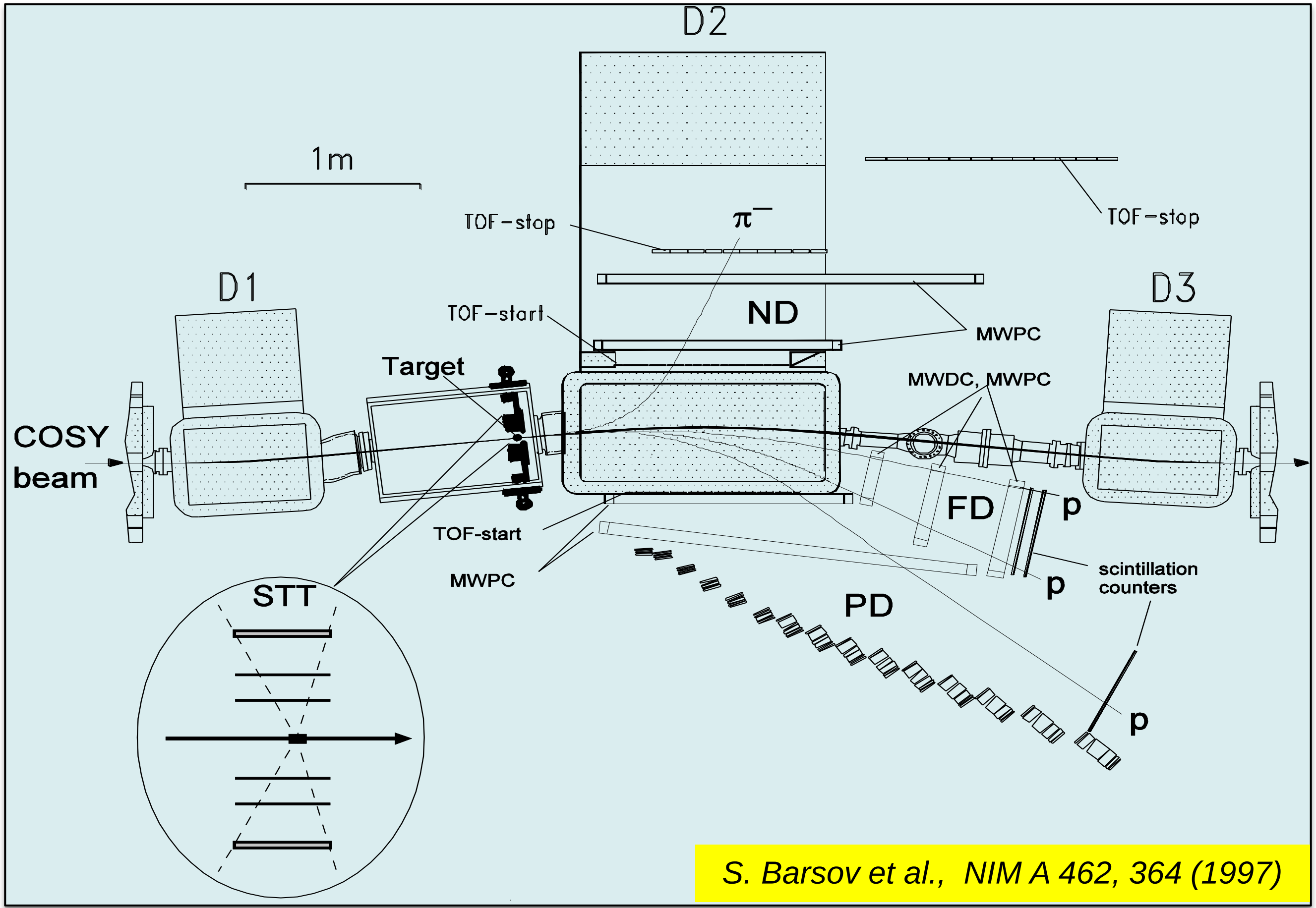
- TOF (ext.)



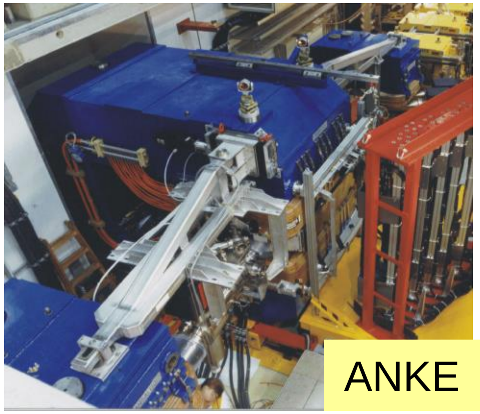
ANKE: magnetic spectrometer, polarized targets
WASA: electromagnetic calorimeter, pellet target
PAX: polarized targets, silicon telescopes

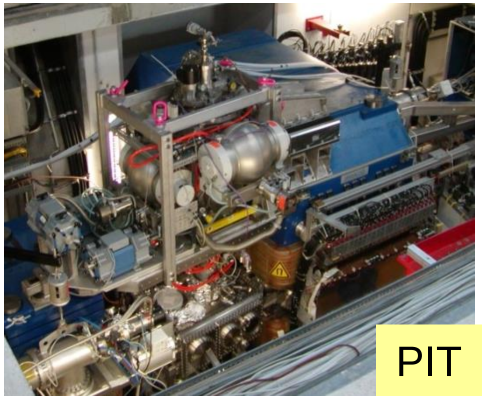
… *the* machine for hadron spin physics

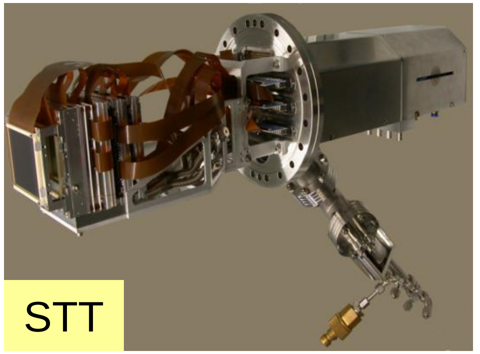
Apparatus: ANKE spectrometer



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







Main features:

- Excellent kaon identification (positive and negative)
- Low energy proton (spectator) detection (STT)
- Di-proton ($\{pp\}_s$) selection (by FD)
- Polarized (unpolarized) dense targets

NN scattering: Motivation (pp)

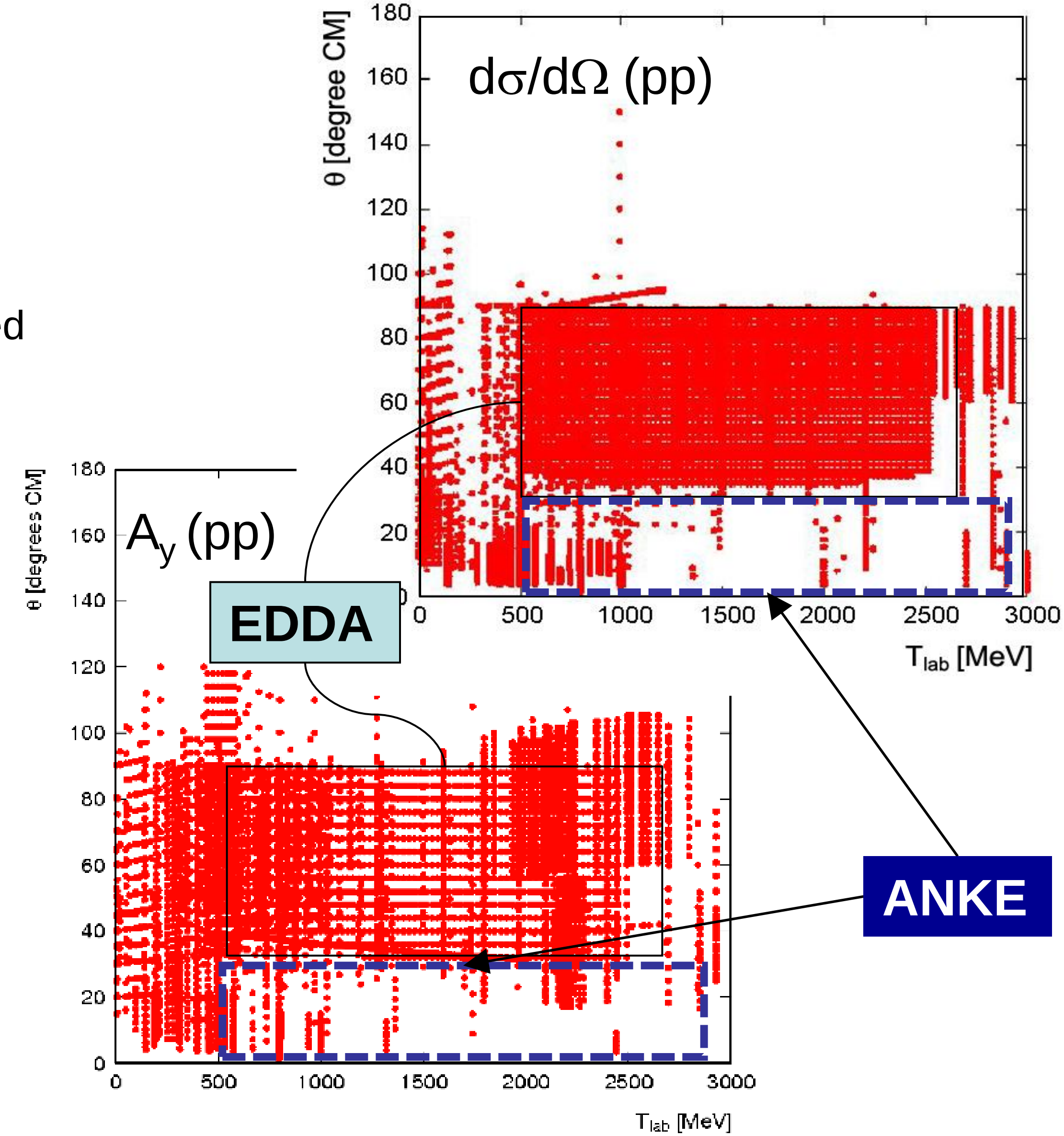
- Description of nucleon-nucleon interaction requires precise data for **P**hase **S**hift **A**nalysis (PSA)

- COSY-EDDA collaboration produced wealth of data ($35° < \theta_p < 90°$) for **pp elastic scattering**

- Large impact on PSA > 0.5 GeV: significantly reduced ambiguities in phase shifts (I=1)

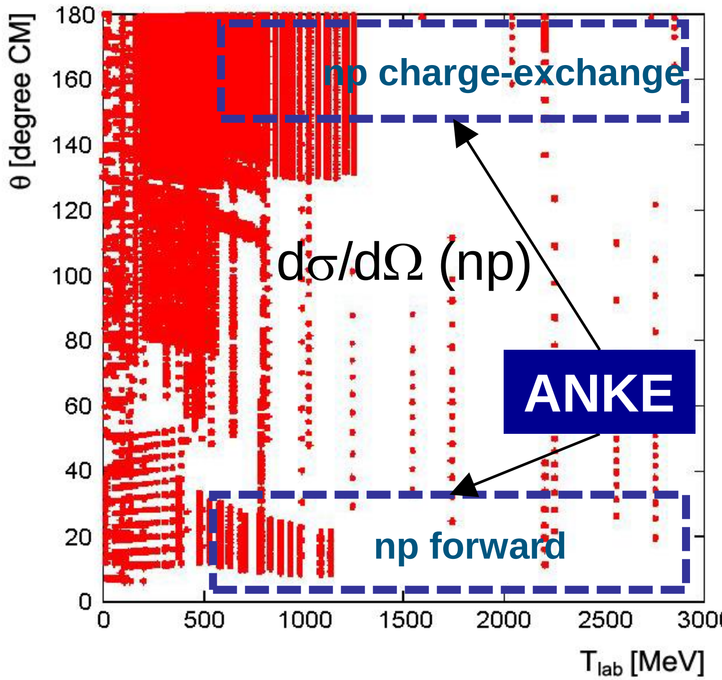
- No exp. data at smaller angles ($\theta_p < 35°$) above T_p=1.0 GeV

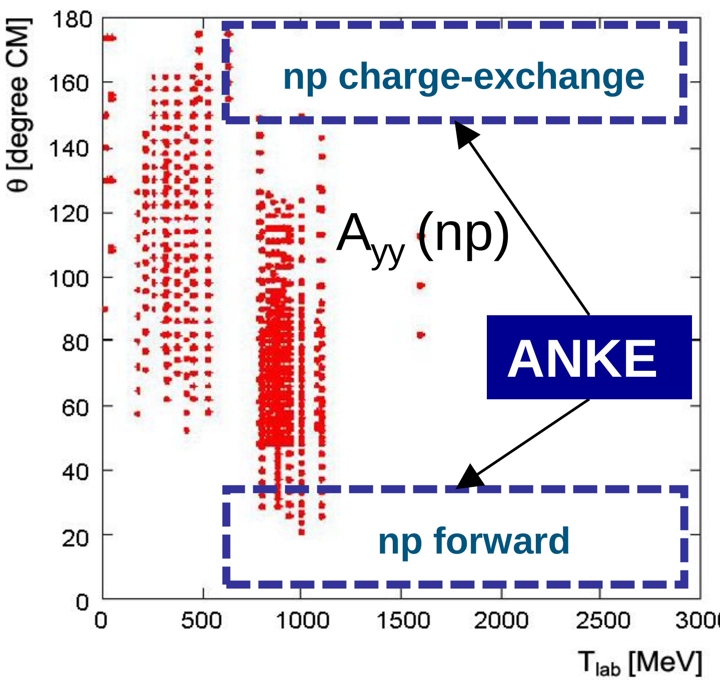
F. Bauer et al., PRL 90, 142301 (2003)
M. Altmeier et al., PRL 85, 1819 (2000)



NN scattering: Motivation (np)

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

NN scattering: Measurements at ANKE

- np system: different isospin channel
- via Charge-Exchange deuteron breakup:

deuteron beam: $\vec{d}p \to \{pp\}_s(0^0)+n$

deuteron target: $p\vec{d} \to \{pp\}_s(180^0)+n$

dp observables: $d\sigma/d\Omega$, T_{20}, T_{22}, $C_{N,N}$

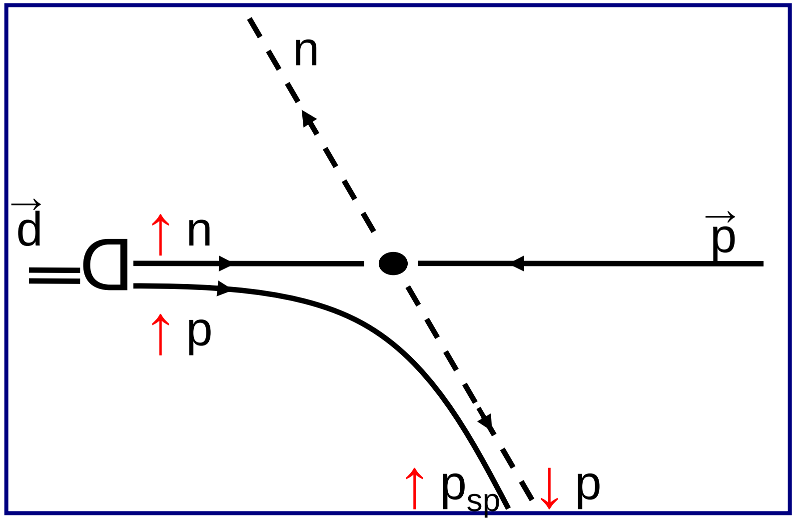
quasi-free

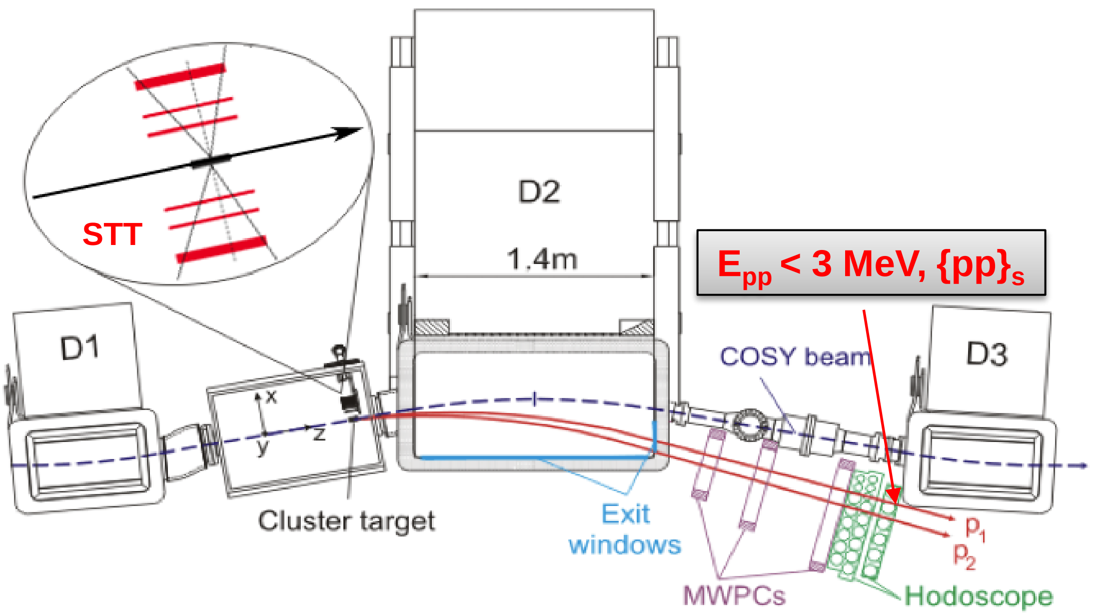
np observables: A_y, A_{yy}, C_{yy}, $C_{xy,y}$

- Transition from $d \to (pp)^1S_0$: $pn \to np$ spin flip
- np spin-dependent ampl.s:

$$\frac{d\sigma}{dq}, T_{20}, T_{22} \Rightarrow |\gamma|^2 + |\beta|^2, |\delta|^2, |\varepsilon|^2$$

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

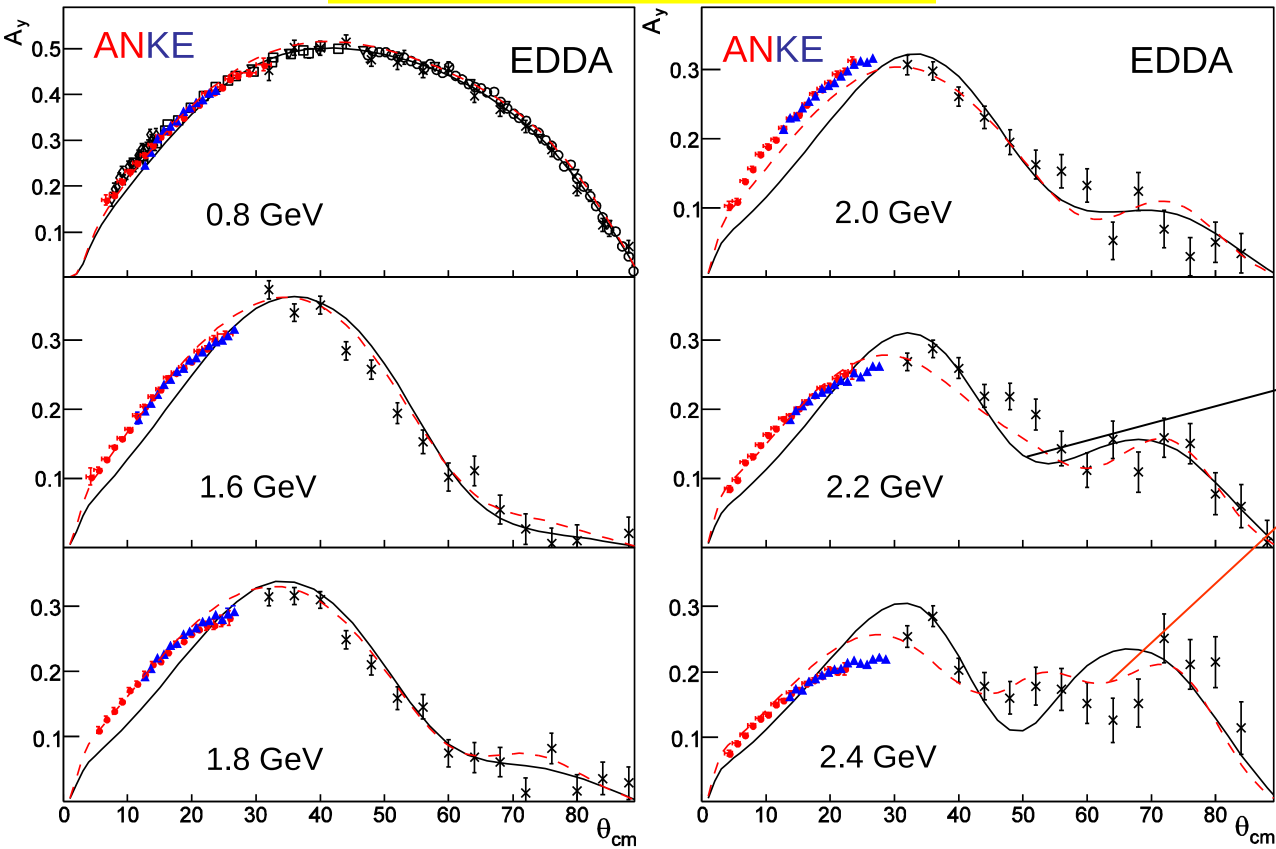


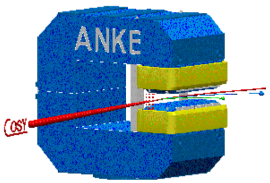


NN scattering: pp elastic

Single polarized **pp** elastic: analyzing power A_y

Z. Bagdasarian et al., arXiv:0145.9014





SAID (partial wave analysis) description of NN world data without and with ANKE results

See talk G. Macharashvili

great potential impact on NN phase shifts (SAID group)
fundamental quantities for nuclear physics

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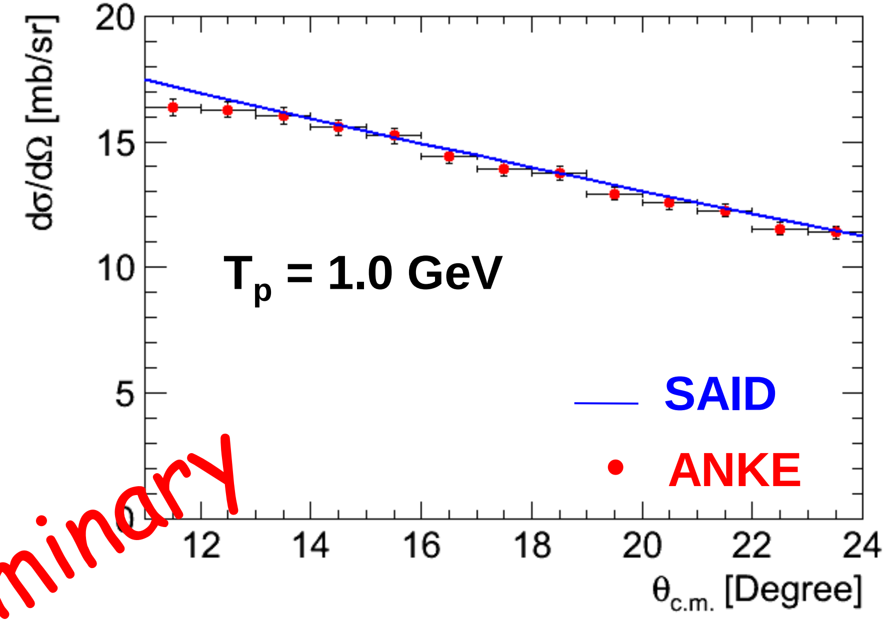
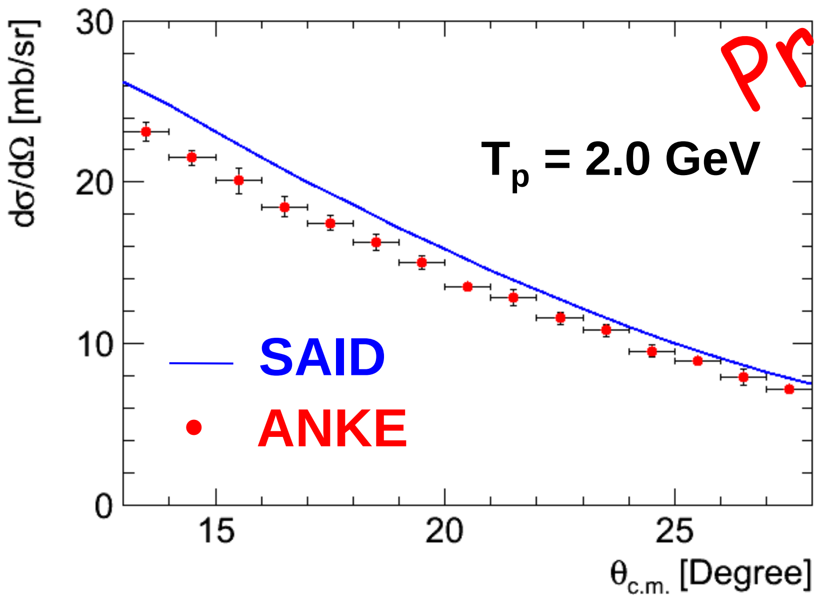
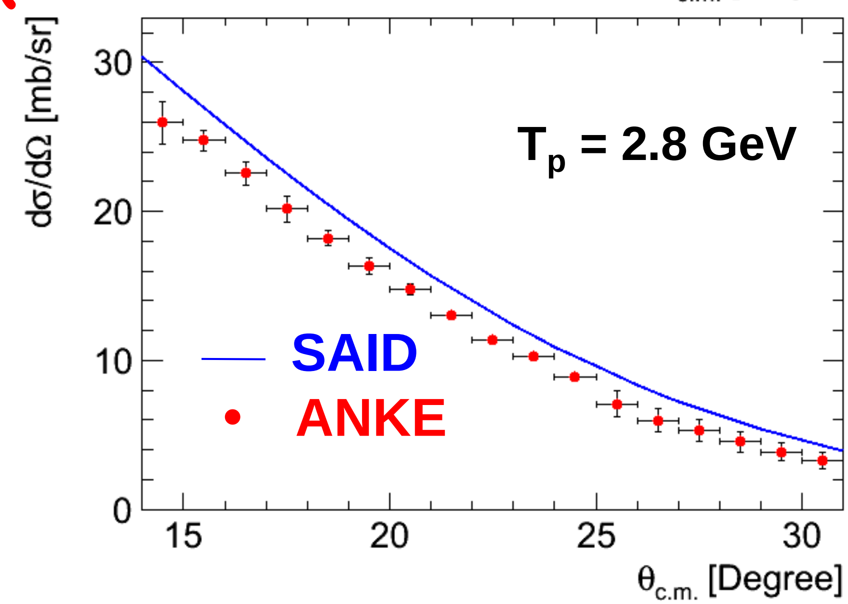
NN scattering: pp elastic

- **dσ/dΩ** at 8 beam energies: Tp = **1.0**, 1.6, 1.8, **2.0**, 2.2, 2.4, 2.6, **2.8**
- Precision measurements:
  - Luminosity by Schottky technique ~ 2%
  - Absolute cross section ~ 5%
- Details: *J. Stein et al., PR ST-AB 11, (2008)*



Preliminary





NN scattering: np system

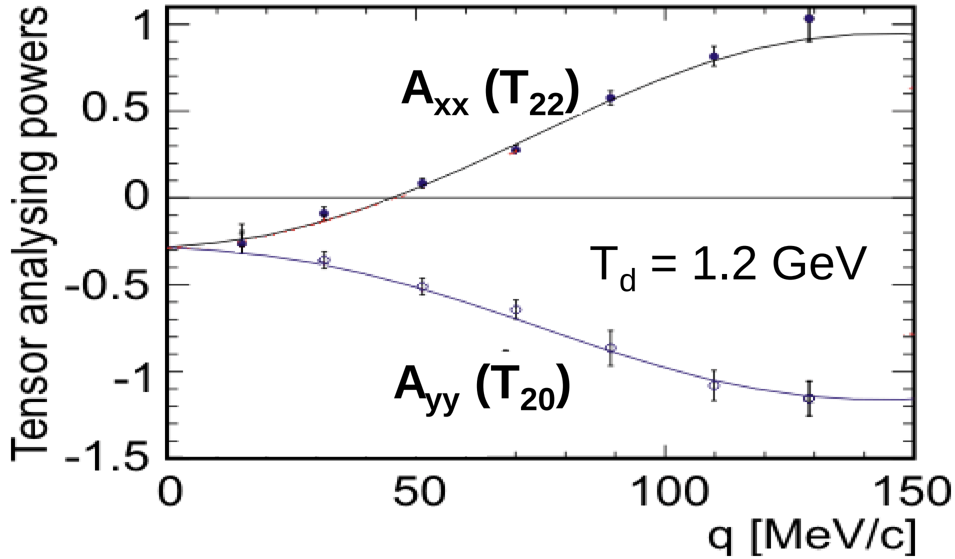
Di-proton program: {pp} in $^1S_0$ state

Deuteron breakup: $\vec{d}p \rightarrow \{pp\}_s n$ (polarized beam)

- np-data at T_d = 1.2 GeV:
  Proof of method !

- theory: Impulse approximation with current SAID input *[DB&CW, NPA 467, 575, (1987)]*

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

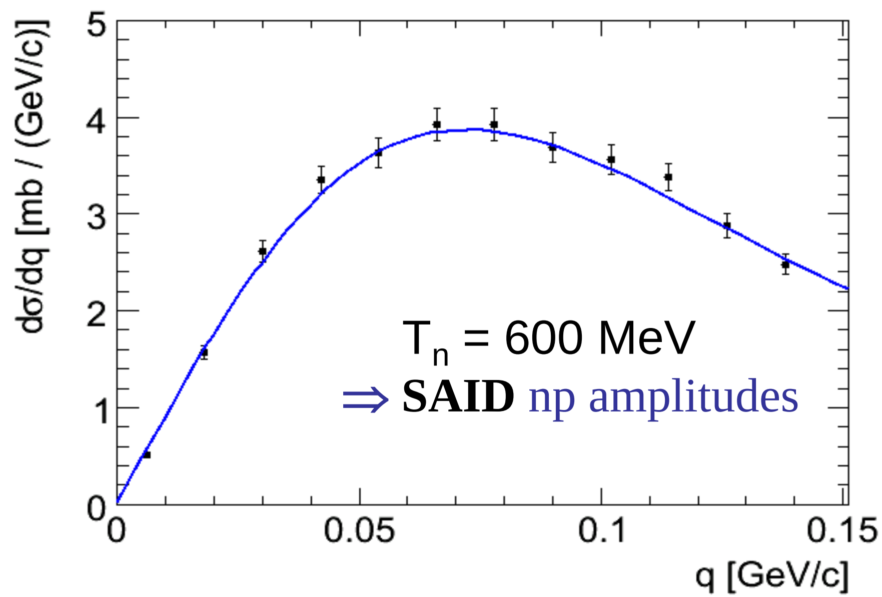


Achievements:

- Method works at T_d = 1.2 GeV
- Application to higher energies

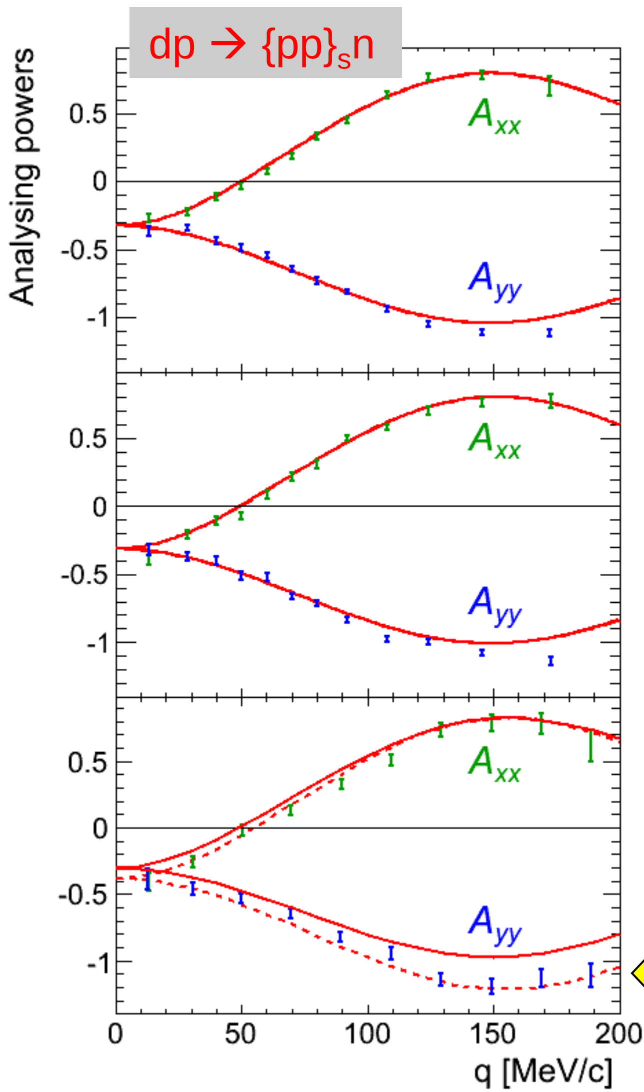
  T_d=1.6, 1.8, 2.27 GeV (for an angular range up to $\theta_{c.m.} < 35^0$)

Goal: deduce the energy dependence of the spin-dependent np-elastic amplitudes



NN scattering: np system (dσ/dq, A_{ii})

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

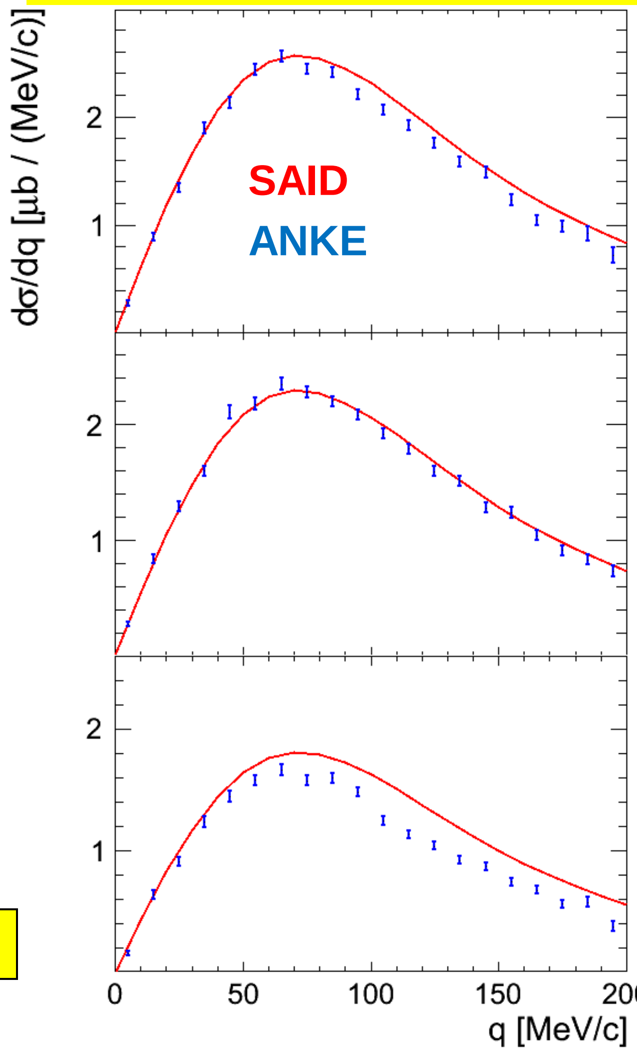


T_d = 1.6 GeV (800 MeV/A)

T_d = 1.8 GeV (900 MeV/A)

T_d = 2.27 GeV (1135 MeV/A)

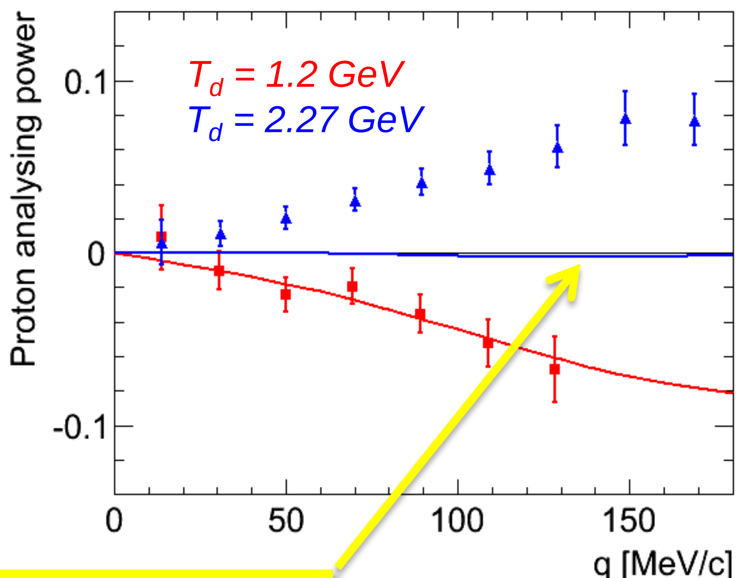
$\varepsilon(q)$ reduced by 25%



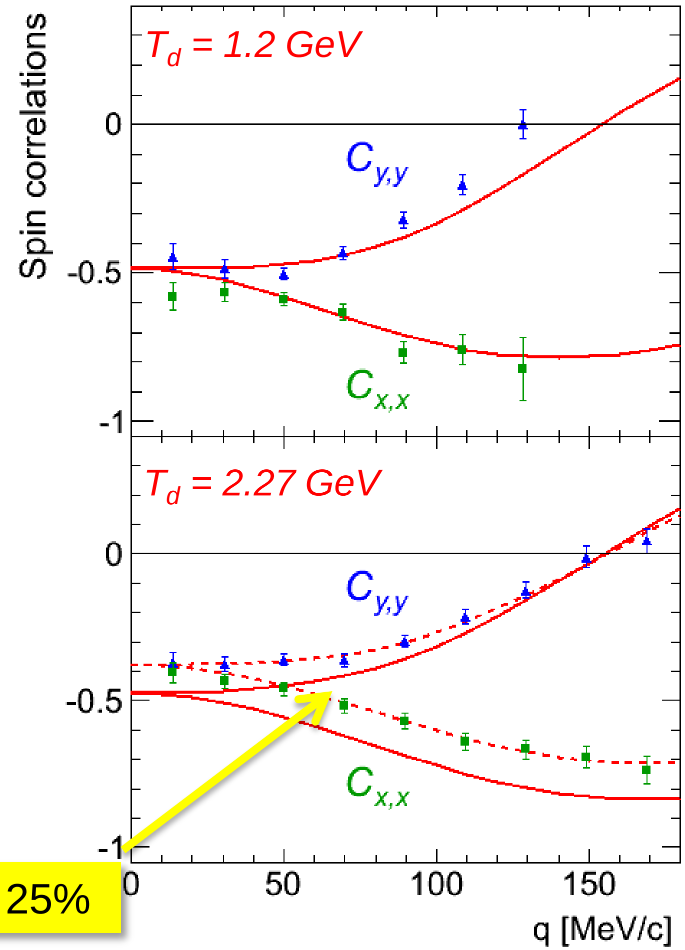
NN scattering: np system (A_y, $C_{i,i}$)

- $\vec{d}\vec{p} \rightarrow \{pp\}_s n$
- Di-proton system, E_{pp} < 3 MeV
- New: measurements for $C_{x,x}$ and $C_{y,y}$

D.Mchedlish. et al., EPJ A 49, 49 (2013)



problem with $\gamma(q)$



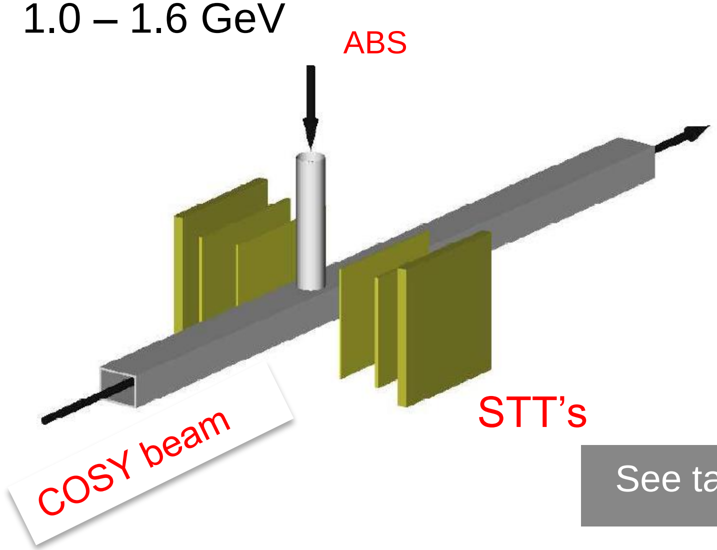
$\varepsilon(q)$ reduced by 25%

Challenge: put info (about np spin-dependent amplitudes) into the SAID program !

NN scattering: Extension of np-program

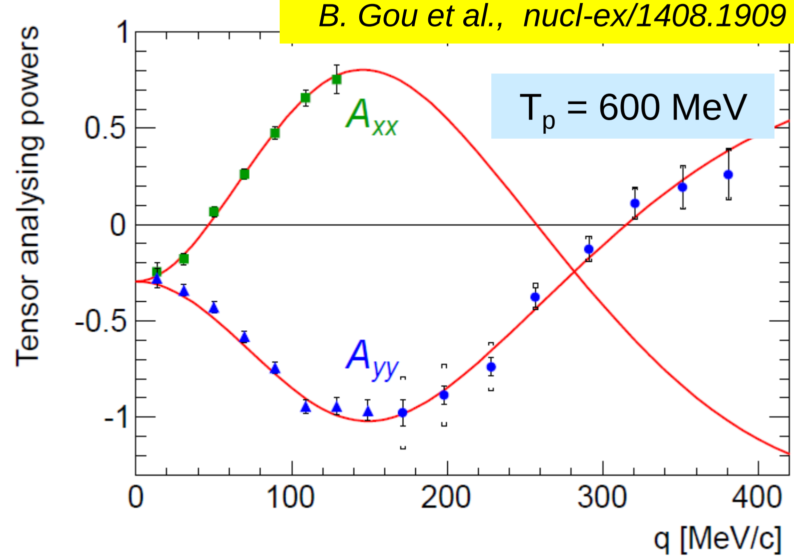
$\vec{p}d \rightarrow \{pp\}_s n$, $pn \rightarrow pn$ (quasi-free)

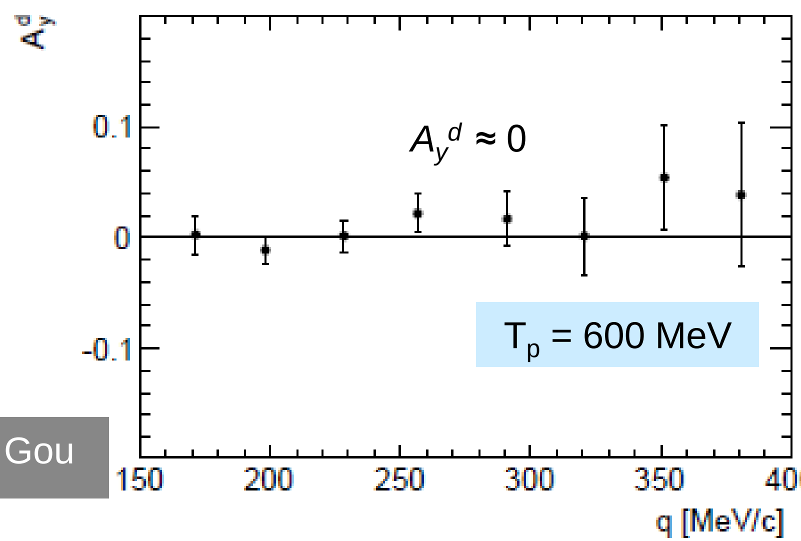
- Proton beam: extend to higher energies - require polarized deuteron target !
- Select {pp} system in $^1S_0$ state - both protons in the same STT ($E_{pp} < 3$ MeV)
- Compatible with results from lower *q* from ANKE, **proof of principle !**
- Agrees with theoretical predictions
- **Next:** on-going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



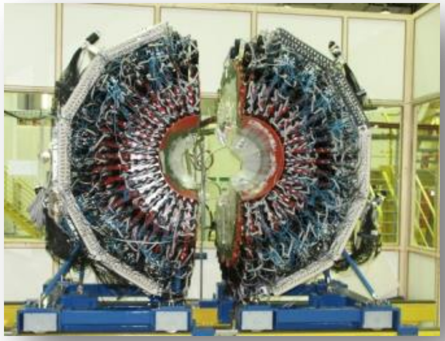
See talk Boxing Gou

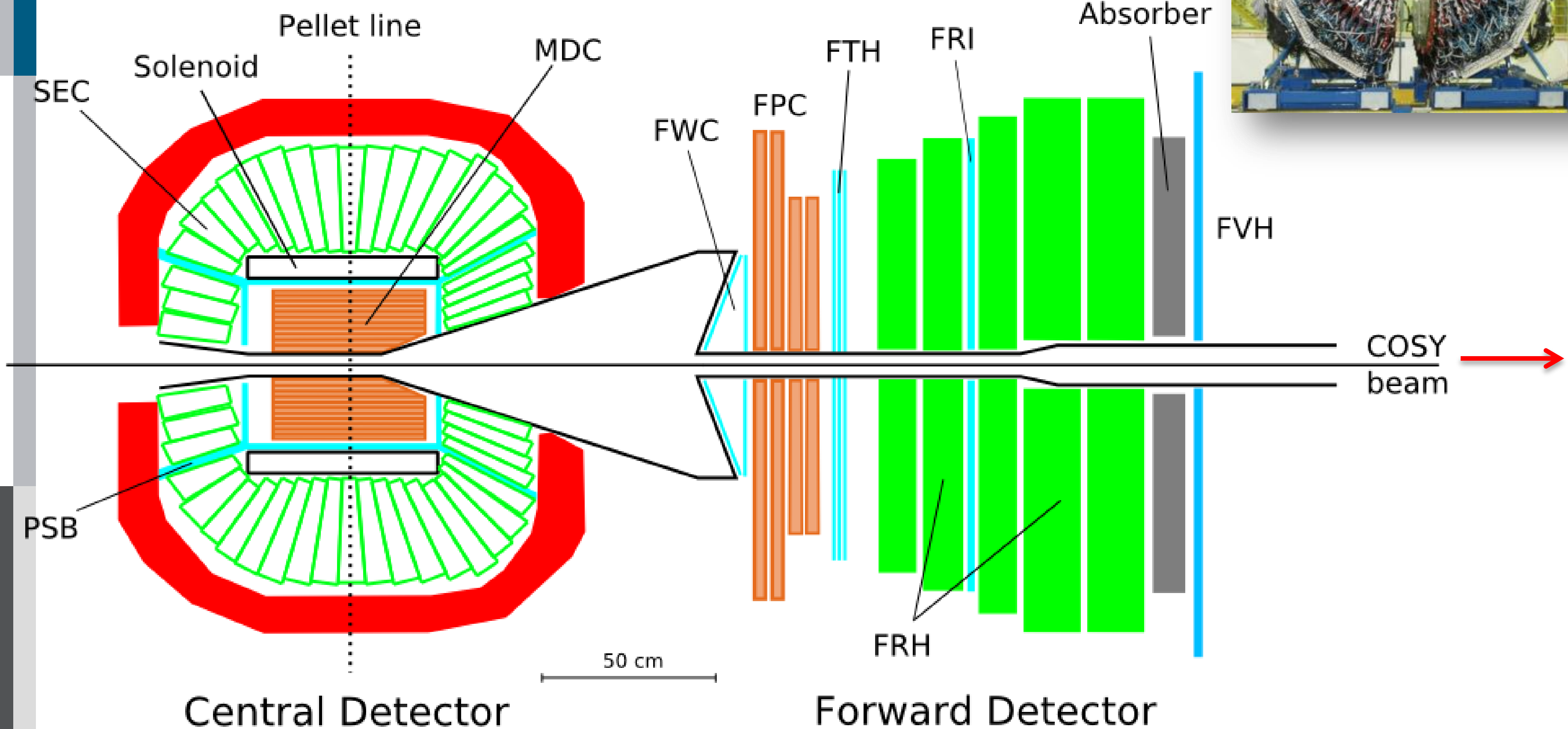
B. Gou et al., nucl-ex/1408.1909





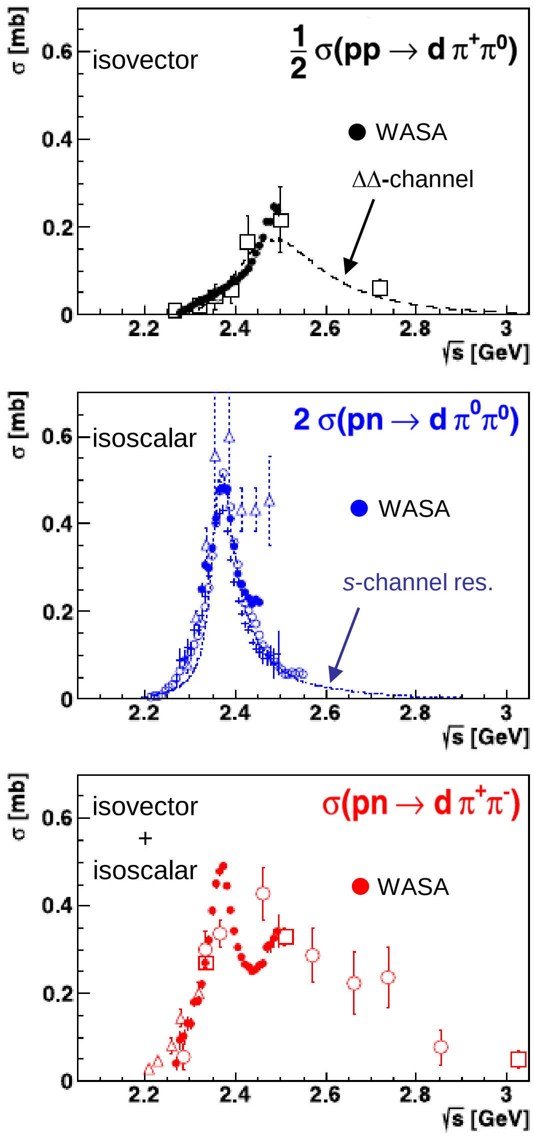
Apparatus: WASA-at-COSY





See talk M. Zieleinski

NN scattering: Exotic np resonance ?



Isospin decomposition of ABC resonancelike structure

Phys. Lett. B 721, 229 (2013)

→ pure isoscalar effect, M≈2.38 GeV; Γ≈70 MeV

→ consistent with $I(J^P)=0(3^+)$ assignment

Origin of structure: 6 quark bound state ?

→ effect should be present in elastic np scattering

Most sensitive observable in np scattering:

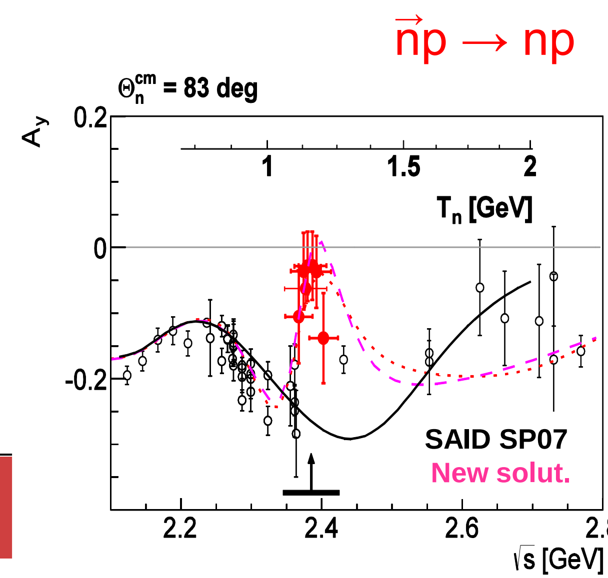
→ analyzing power A_y and its energy dependence near $\theta_{CM} \approx 90°$

First results:

PRL 112, 202301 (2014)

- corresponding signal at resonance position
- impact on elastic np-scattering

PRC 90, 035204 (2014)



Ongoing: PWA, cross-check using new ANKE observables

Meson production: Physics case (pion)

Extension of ChPT to the NN→NNπ process

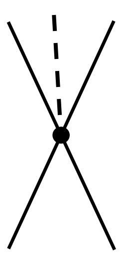
- A full data set of all observables in $pp \to \{pp\}_s\pi^0$ and $np \to \{pp\}_s\pi^-$

- Extract the relevant PW amplitudes and test the ChPT predictions
  (π is in a p-wave, initial & final NN-pairs in S-wave, di-proton $\{pp\}_s$ in $^1S_0$ state)

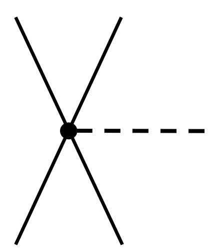
$pp \to \{pp\}_s\pi^0$ includes $^3P_0 \to {}^1S_0\, s$, $^3P_2 \to {}^1S_0\, d$ and $^3F_2 \to {}^1S_0\, d$
$np \to \{pp\}_s\pi^-$ adds $^3S_1 \to {}^1S_0\, p$ and $^3D_1 \to {}^1S_0\, p$

- p-wave amp.s (M_p^S, M_p^D) give access to the 4Nπ contact operator, controlled by the Low Energy Constant (**LEC**) **d**

NN→ NNπ



3N scattering



See talk V. Baru

LEC d connects different low-energy reactions: $pp \to de^+\nu$, $pd \to pd$, $\gamma d \to nn\pi^+$

Final goal is to establish that the same LEC controls NN→NNπ !

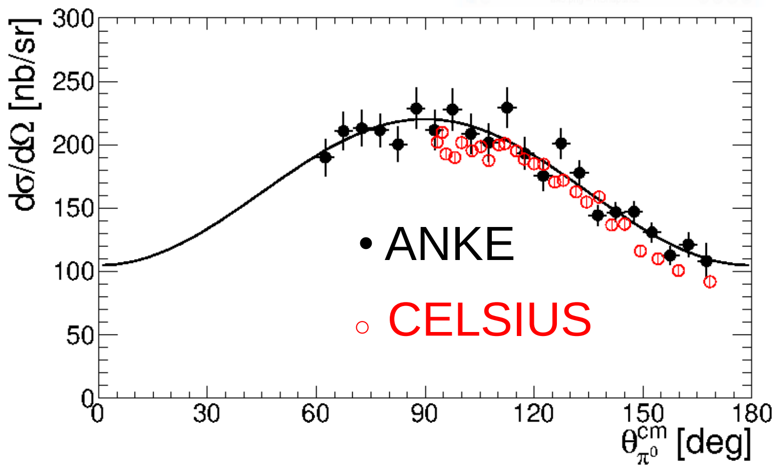
Meson production: π^0 channel

dσ/dΩ and A_y in $pp \to \{pp\}_s \pi^0$

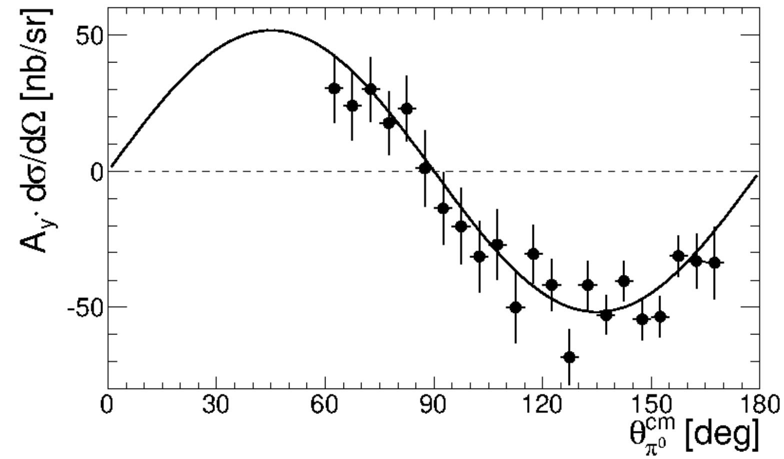
Near threshold at Tp=353 MeV

$$\left(\frac{d\sigma}{d\Omega}\right)_0 = \frac{k}{4p}\left(a_0 + a_2\cos^2\theta_\pi + a_4\cos^4\theta_\pi + \cdots\right)$$

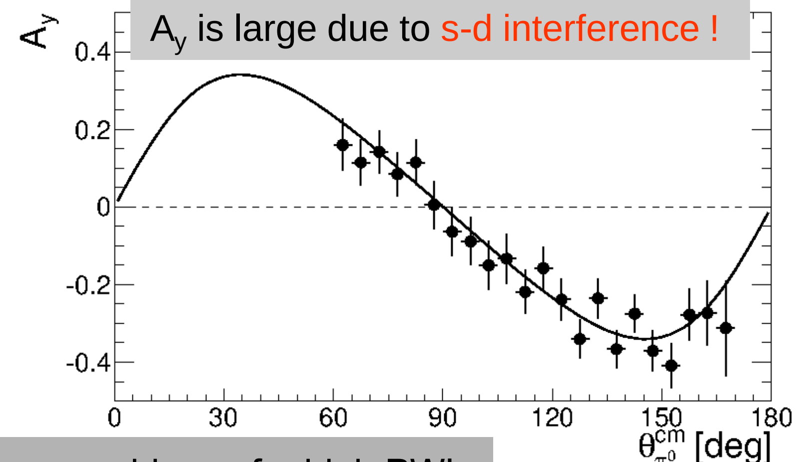
$$A_y\left(\frac{d\sigma}{d\Omega}\right)_0 = \frac{k}{4p}\sin\theta_\pi\cos\theta_\pi\left(b_2 + b_4\cos^2\theta_\pi + \cdots\right)$$



D. Tsirkov et al., PLB 712, 370 (2012)



A_y is large due to s-d interference !



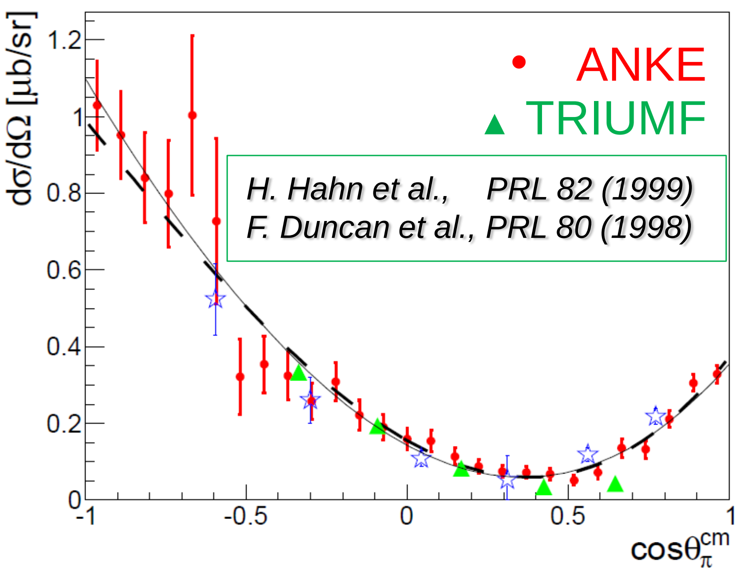
- well represented by retaining **only** pion **s and d waves**, no evidence for high PW's;
- assuming coupling between NN-channels and invoking Watson theorem allows to estimate corresponding amplitudes with their phases: M_s^P, M_d^P and M_d^F

Meson production: π^- channel

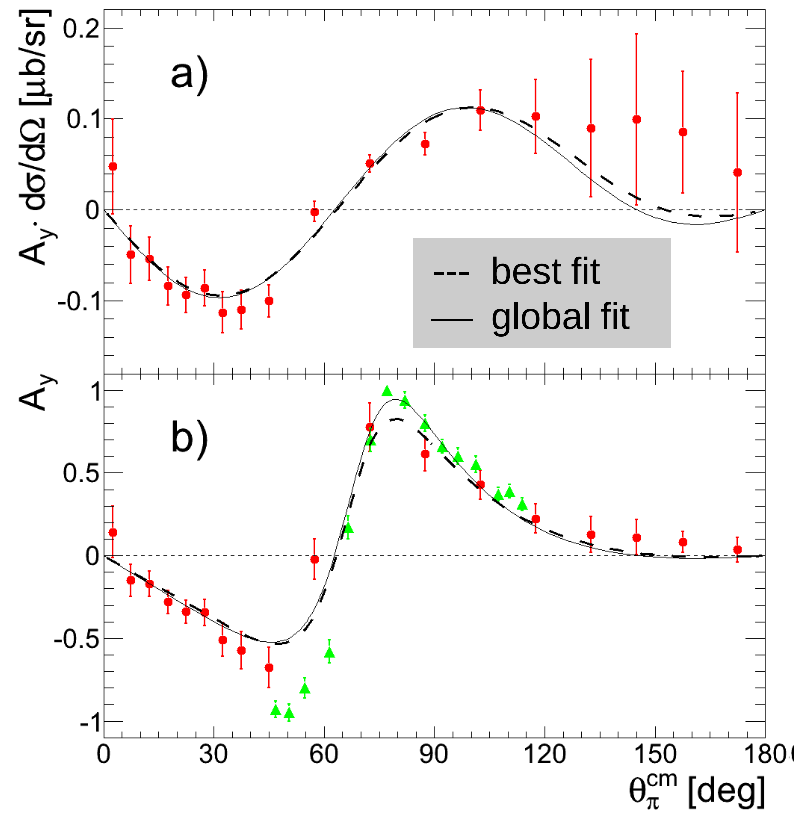
dσ/dΩ and A_y in $pn \to \{pp\}_s \pi^-$ T_p=353 MeV

$$\left(\frac{d\sigma}{d\Omega}\right)_0 = \frac{k}{4p} \sum_{n=0} a_n \cos^n \theta_\pi ,$$

$$A_y \left(\frac{d\sigma}{d\Omega}\right)_0 = \frac{k}{4p} \sin\theta_\pi \sum_{n=0} b_{n+1} \cos^n \theta_\pi$$



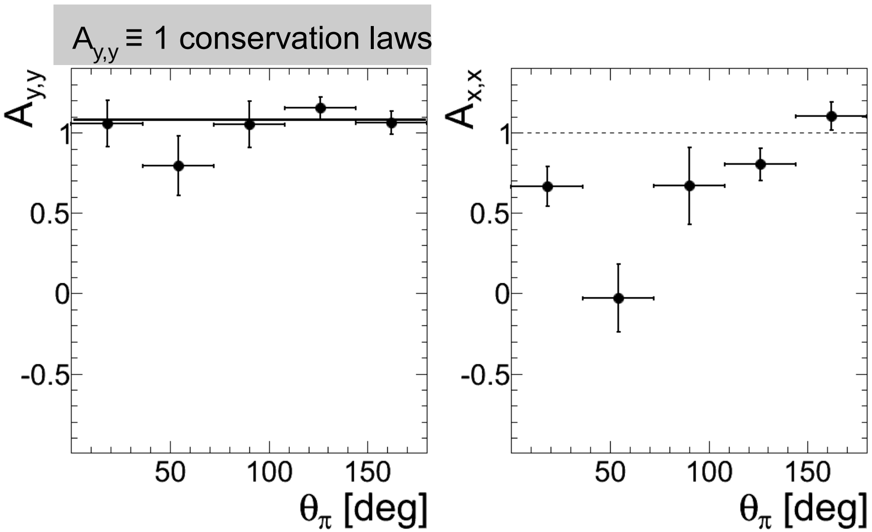
S. Dymov et al., PLB 712, 375 (2012)



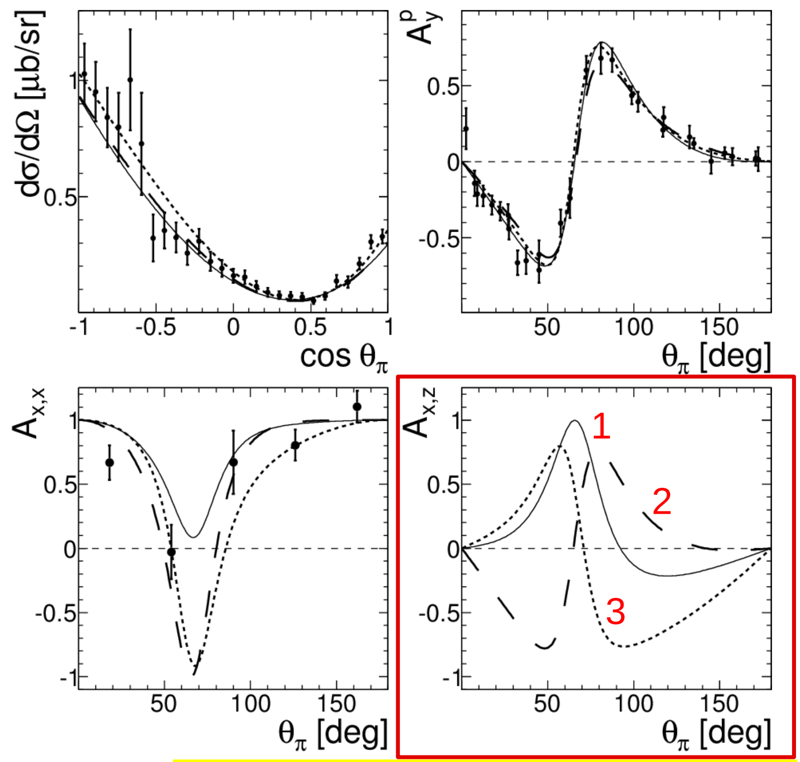
- both observables are described in terms of *s*-, *p*-, and *d*- wave pion amplitudes;
- an amplitude analysis of the <u>combined</u> data sets allowed to obtain: M_s^P, M_d^P, M_d^F, M_p^S, M_p^D

Meson production: π^- channel

$A_{x,x}$ and $A_{y,y}$ in $\vec{n}\vec{p}\to\{pp\}_s\pi^-$ (T_p=353 MeV)



All Observables in $np\to\{pp\}_s\pi^-$ (ANKE data)



S. Dymov et al., PRC 88, 014001 (2013)

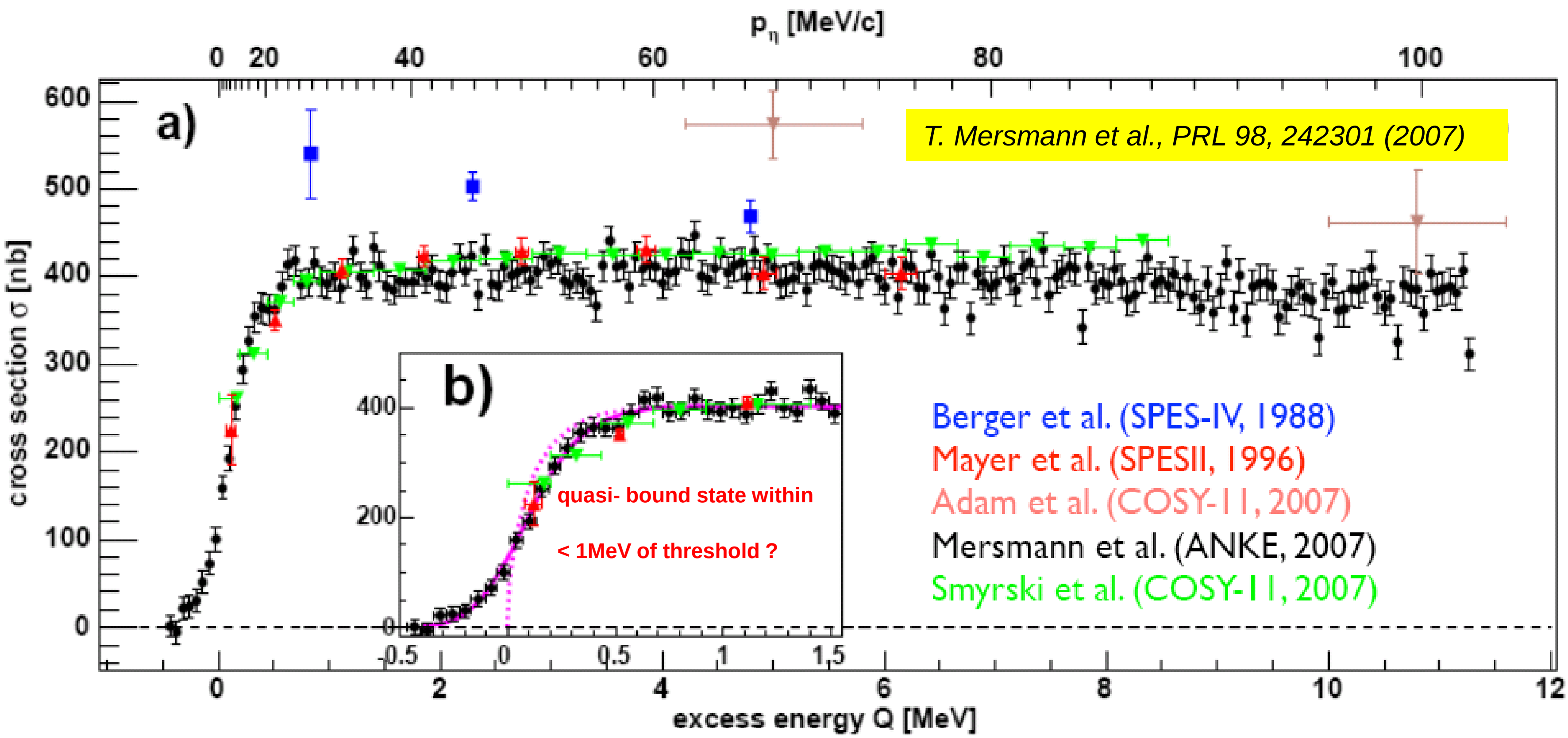
***$A_{x,z}$* measurement in:**

- *$pp\to\{pp\}_s\pi^0$ will test the PWA assumptions*
- *$pn\to\{pp\}_s\pi^-$ will choose between the solutions*

Data will allow a robust PW decomposition for both channels and determine relevant pion **p**-wave production strength making contact with ChPT theory !

Eta Meson production: η-^{3}He (FSI)

d+p→^{3}He+η: Total C.S.



- Precision data, "step function": 0→ 400 nb w/i 0.5 MeV
- Strong FSI ! implies large ^{3}Heη scattering length (~ 10 fm)

Eta Meson production: Bound state ?

- d+p→ ^{3}He+η: Angular distribution

A strong phase variation of the s-wave at low Q

←→

indication for a **quasi-bound state?**

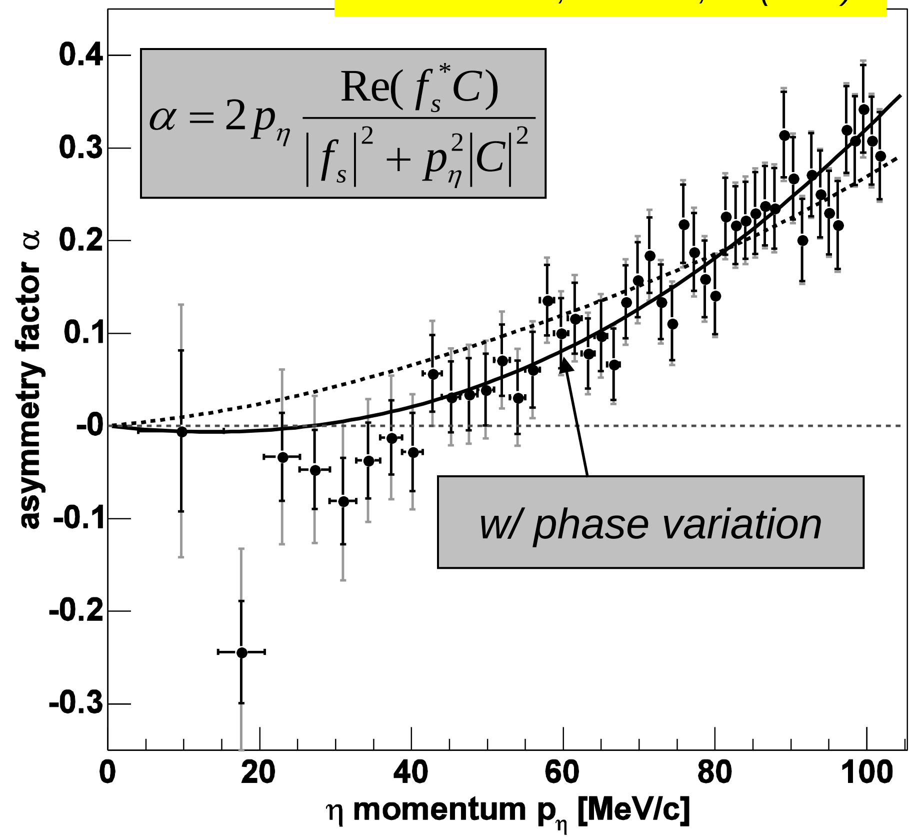
Data can be described well by assumption of
a pole close to threshold

- $\vec{d}$+p→ ^{3}He+η: Analyzing power T_{20}

$$\frac{d\sigma}{d\Omega} = \frac{1}{6} p_p p_\eta \left[|A|^2 + 2|B|^2 \right] \qquad T_{20} = \sqrt{2} \left[\frac{|B|^2 - |A|^2}{|A|^2 + 2|B|^2} \right]$$

$$|A|^2 = \frac{p_p}{p_\eta}(1 - \sqrt{2} T_{20}) \frac{d\sigma}{d\Omega} \qquad |B|^2 = \frac{p_p}{p_\eta}(1 + \frac{1}{\sqrt{2}} T_{20}) \frac{d\sigma}{d\Omega}$$

C. Wilkin et al., PLB 654, 92 (2007)



Determination of the energy dependence of the amplitudes *A* and *B* by measurement of T_{20}

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Eta Meson production: Role of spin

Studies with polarized deuterons:

$\vec{d}p \rightarrow {}^3He+\eta$:

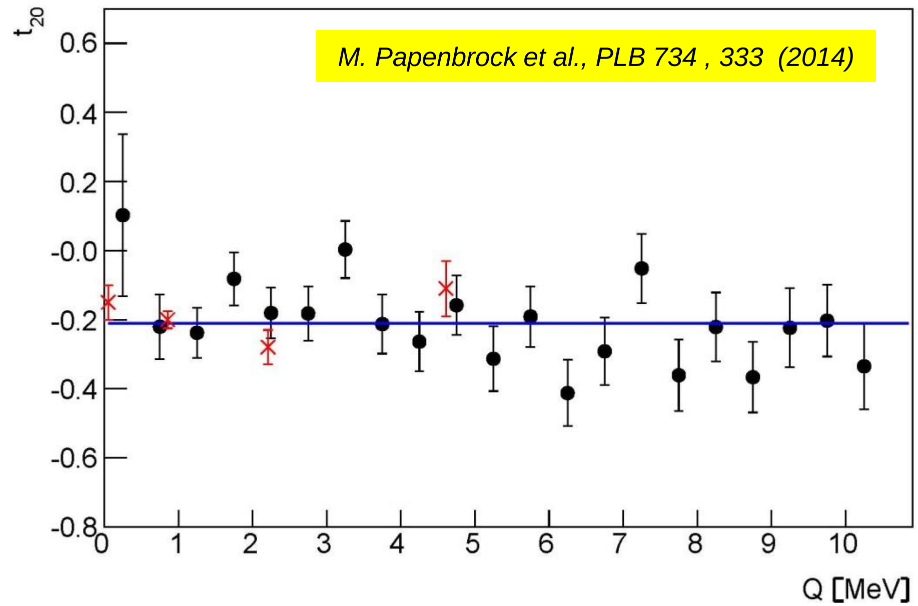
- Role of the spin of the entrance channel
  S_{dp} = 1/2 or S_{dp} = 3/2
- Data close to threshold consistent with T_{20}=constant

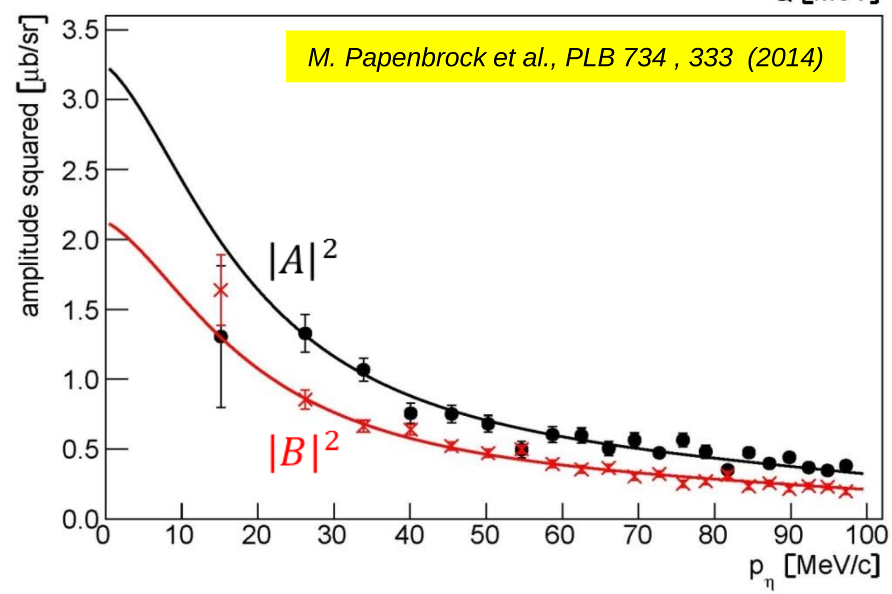
- S-wave amplitudes are of similar size:
  $|A|^2(p_f)$ and $|B|^2(p_f)$ can be calculated

- No significant different energy dependence of $|A|^2$ and $|B|^2$

- Rapid variation of the amplitudes with energy near threshold is due to an S-wave FSI: **common** to the 2 diiferent spin states

- Data are valuable input for model development



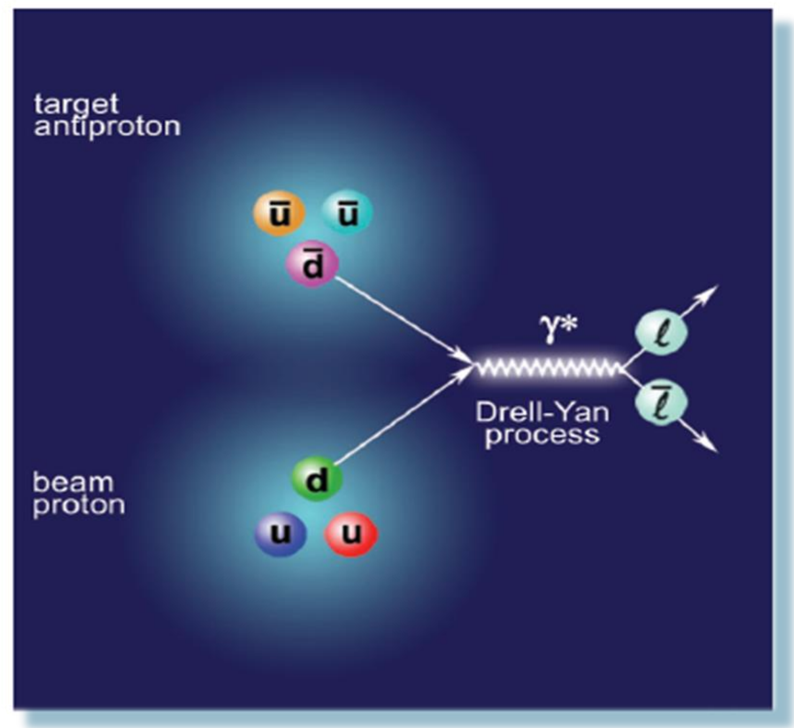


PAX: Physics case

Polarized Antiproton EXperiments

- Investigation of Drell-Yan processes in scattering of polarized proton-antiproton beams at HESR (FAIR)
- The transfersity distribution is directly accessible uniquely via the double transferse spin asymmetry (A_{TT}) in the Drell-Yan production of lepton pairs

$$A_{TT} \equiv \frac{d\sigma^{\uparrow\uparrow} - d\sigma^{\uparrow\downarrow}}{d\sigma^{\uparrow\uparrow} + d\sigma^{\uparrow\downarrow}} = \hat{a}_{TT} \frac{\sum_q e_q^2 h_1^q(x_1, M^2)\, h_1^{\bar{q}}(x_2, M^2)}{\sum_q e_q^2 q(x_1, M^2)\, \bar{q}(x_2, M^2)}$$



But

- Polarized proton beams ☺
- Polarized antiproton beams ☹

See PAX Proposal: arXiv: hep-ex/0505054

PAX: Polarization of antiprotons (method)

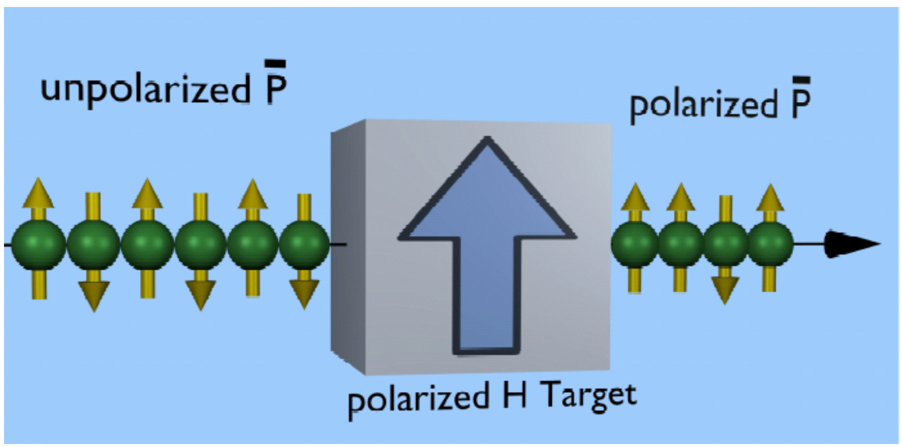
Polarized Antiproton EXperiments

- Too small spin-flip cross section for polarization build-up by ep scattering

  D. Oellers et al., Phys. Lett. B 674, 269 (2009)

- Anti(proton) polarization by spin-filtering process is very promising

  W. Augustyniak et.al., PLB 718, 64 (2012)



$$\sigma_{tot} = \sigma_0 + \sigma_1(\vec{P}\cdot\vec{Q}) + \sigma_2(\vec{P}\cdot\hat{k})(\vec{Q}\cdot\hat{k})$$

P: Beam particle spin orientation
Q: Target particle spin orientation
K: Beam momentum direction

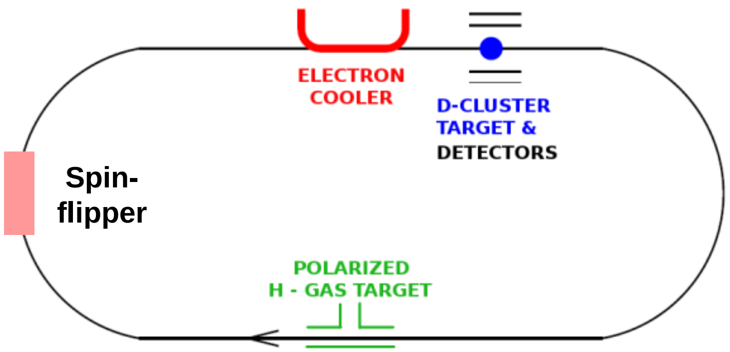
$$P(t) = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow} = \tanh\left(\frac{t}{\tau_1}\right) \approx t\cdot\tilde{\sigma}_1\cdot Q\cdot d_t\cdot f$$

Reduces beam intensity

See talk P. Lenisa

PAX: Transverse polarization buildup

Experiment with COSY / schematic



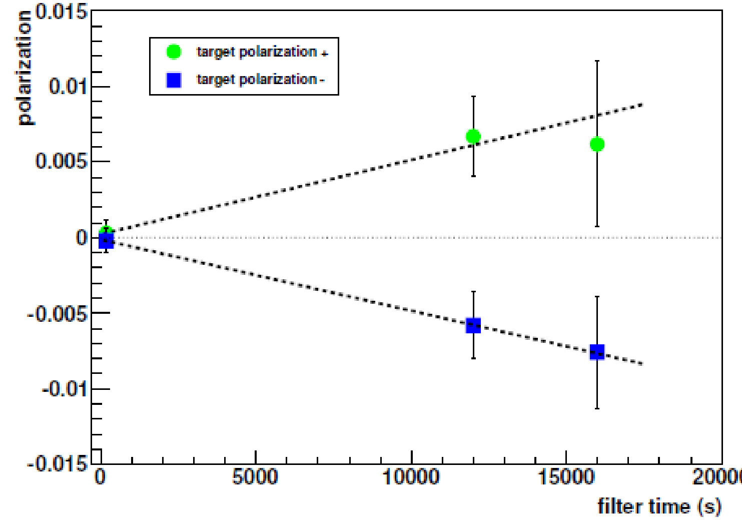
C. Weidemannet al., arXiv:0145.9014

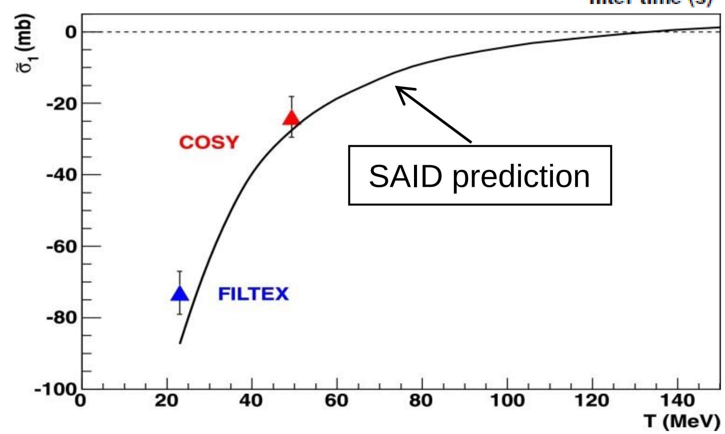
Milestones for the Field:

- Confirms understanding of spin-filtering as a viable method to polarize a stored beam
- Confirms complete control of the systematics of the experiment
- Does not cover for the lack of knowledge of the pbar-p interaction

See talk G. Ciullo

Results

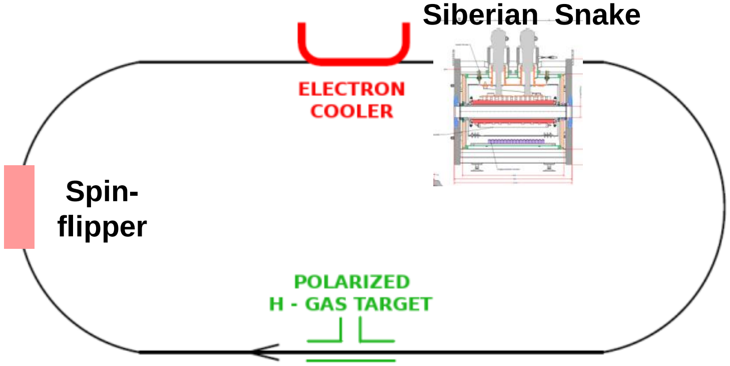




W. Augustyniak et.al., PLB 718, 64 (2012)

PAX: Next – Long. polarization buildup

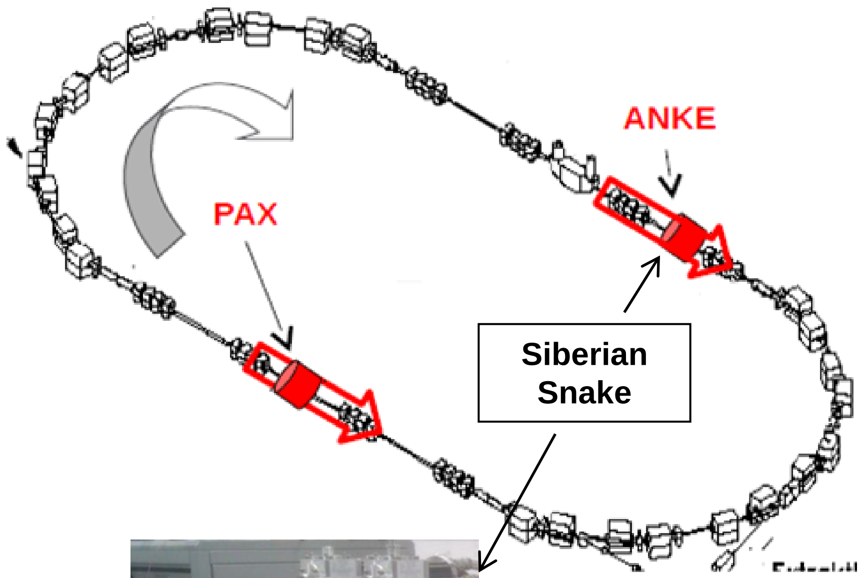
Experiment with COSY / schematic



- Spin filtering with
  - Longitudinal polarized gas target
  - Longitudinal polarized beam

$$\sigma_{tot} = \sigma_0 + \sigma_1(\vec{P}\cdot\vec{Q}) + \sigma_2(\vec{P}\cdot\hat{k})(\vec{Q}\cdot\hat{k})$$

- Superconducting solenoid ordered
- Longitudinal beam polarimeter (in progress)



First ever longitudinal spin-filtering test: highest polarization could be reached !

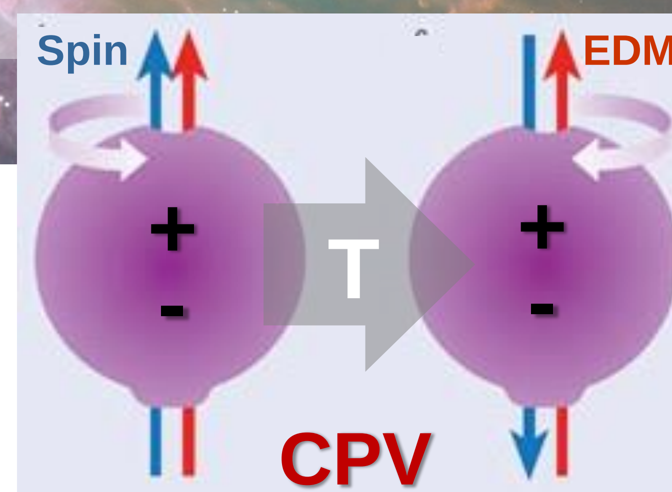
Future: EDM project – Physics Case

Baryon asymmetry

$$\frac{N_B - N_{\bar{B}}}{N_\gamma} \sim 10^{-11}$$

not accounted for in Standard Model $\sim 10^{-18}$

Nature seems to violate CP much stronger than the Standard Model predicts



See also talk D. Eversheim

New sources of CP-violation (CPV) required!

Electric Dipole Moments (EDM) of fundamental particles:

- Compelling physics case
- Sensitivity; discovery potential

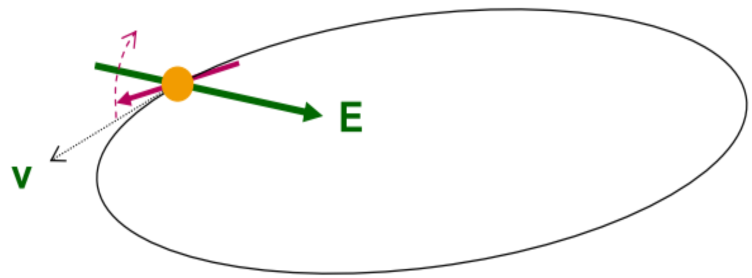
Future: EDM project – Charged particles

Why charged particles?

- Highest sensitivity (goal 10^{-29} e cm)
- Identification of the CPV-source

How? A new method:

- Polarized particles in precision storage ring
- Tracking of spin rotation due to torque in radial electric field



$$\frac{d\vec{S}}{dt^*} = \vec{d} \times \vec{E}^*$$

↑ EDM

Where? Forschungszentrum Jülich

- Storage ring (COSY) and polarized beams
- Accelerator and experimental experience in spin physics
- Strong environment (FZJ infrastructure, cooperations (JARA))
- **JEDI** (**J**ülich **E**lectric **D**ipole moment **I**nvestigations) collaboration has formed; > 100 members (11 countries world-wide)

JEDI: EDM project- New findings

- EDMs are sensitive to new sources of *CP* violation
- COSY: ideal starting point for R&D and pre-cursor experiment
- A time marking system with EDDA detector has been setup
- Best SCT until now: $t_{SCT} \approx 400$ s → Maximize SCT to ≈ 1000 s
- Precision of Spin Tune measurement: $\sigma_\nu \approx 10^{-10}$

Next steps:

- Pre-cursor experiment at COSY:
  proof of principle with limited sensitivity planned near future
- Use RF Wien filter to generate a net EDM effect
- Use Spin Tune as precision tool to study systematic errors
- Dedicated storage ring:
  different option are currently under investigation,
  conceptual design report end of 2018

See talks:

A. Lehrach
E. Stephenson
A. Saleev
S. Mey
S. Chekmenev

Summary

- COSY - unique opportunities for hadron physics with polarized hadronic probes (beam & target) – High precision + Spin
- ANKE, WASA, PAX - state-of-the art facility to investigate a broad and exciting field of hadron physics
- Physics: "NN interaction, ChPT, FSI " – selected examples and further plans at COSY

Transition phase *from precision to ultimate precision* spin physics:

⇩

- New opportunities to explore spin manipulations at COSY: ideal starting point for R&D and a pre-cursor experiment for EDM search