8th International Conference on Nuclear Physics at Storage Rings

Laboratori Nazionali di Frascati, 9-14 October 2011

# EXTENSIVE HIGH PRECISION STUDIES OF PROTON DEUTERON BREAKUP REACTIONS @COSY

Pia Thöngren Engblom

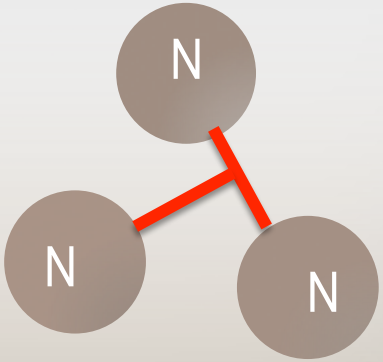
for the PAX Collaboration

University of Ferrara

The Royal Technical High School, Stockholm

COSY proposal 202

- 3 Nucleon (3N) interaction ~ 0.5-1 MeV
- 3N effects vary with observable & kinematics
- Ideal energy range for chiral EFT to be valid
- Few previous measurements exist 30-50 MeV

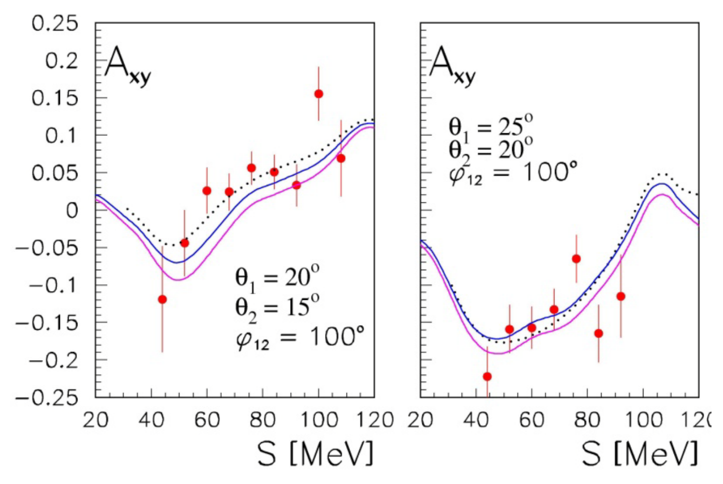


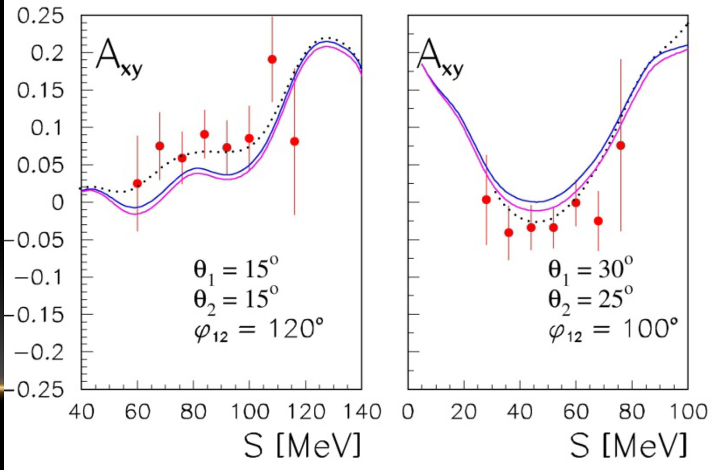
Measure doubly polarized pd breakup reactions

- Low energy range 30-50 MeV
- Large coverage
- High precision

# TENSOR ANALYZING POWERS 50 MEV/A

E Stephan, St Kistryn, N Kalantar-Nayestanaki, SPIN2010





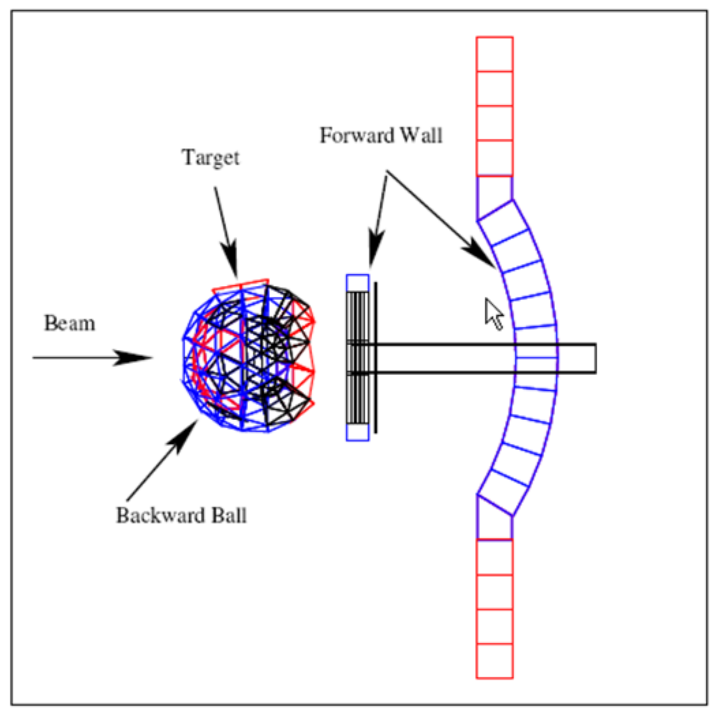
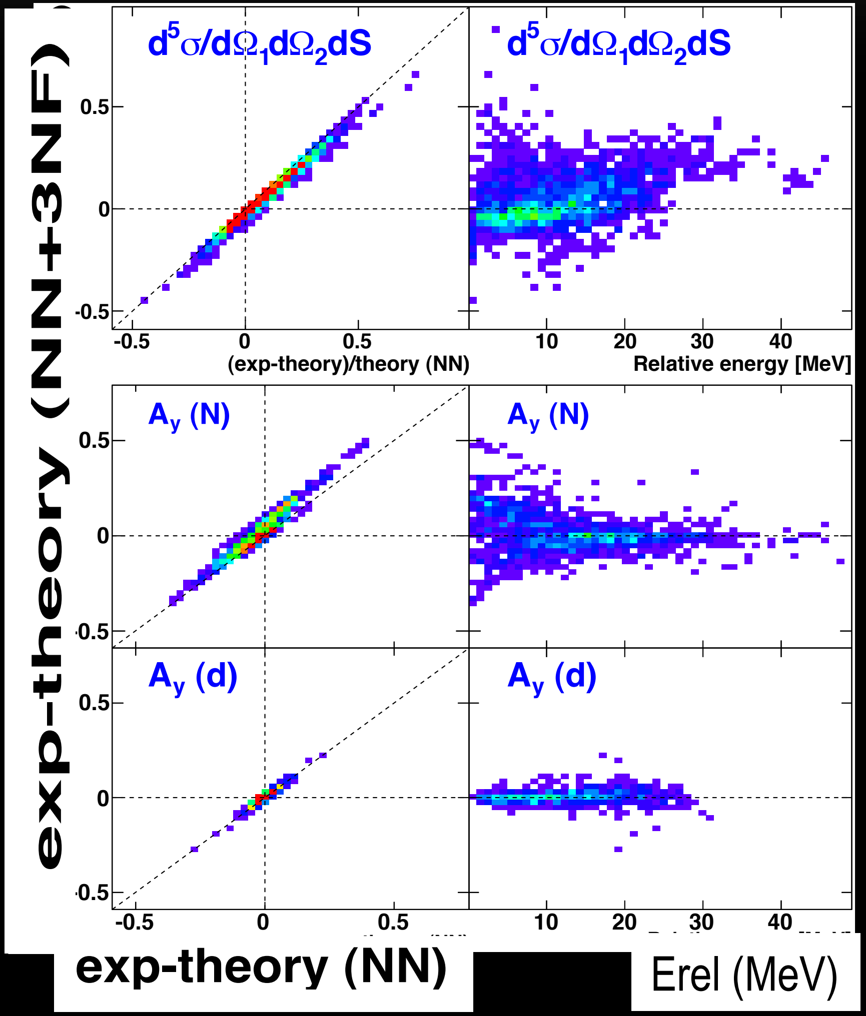


**Figure from arXiv:1108.1227,** N. Kalantar-Nayestanaki, E. Epelbaum, J.G. Messchendorp, A. Nogga

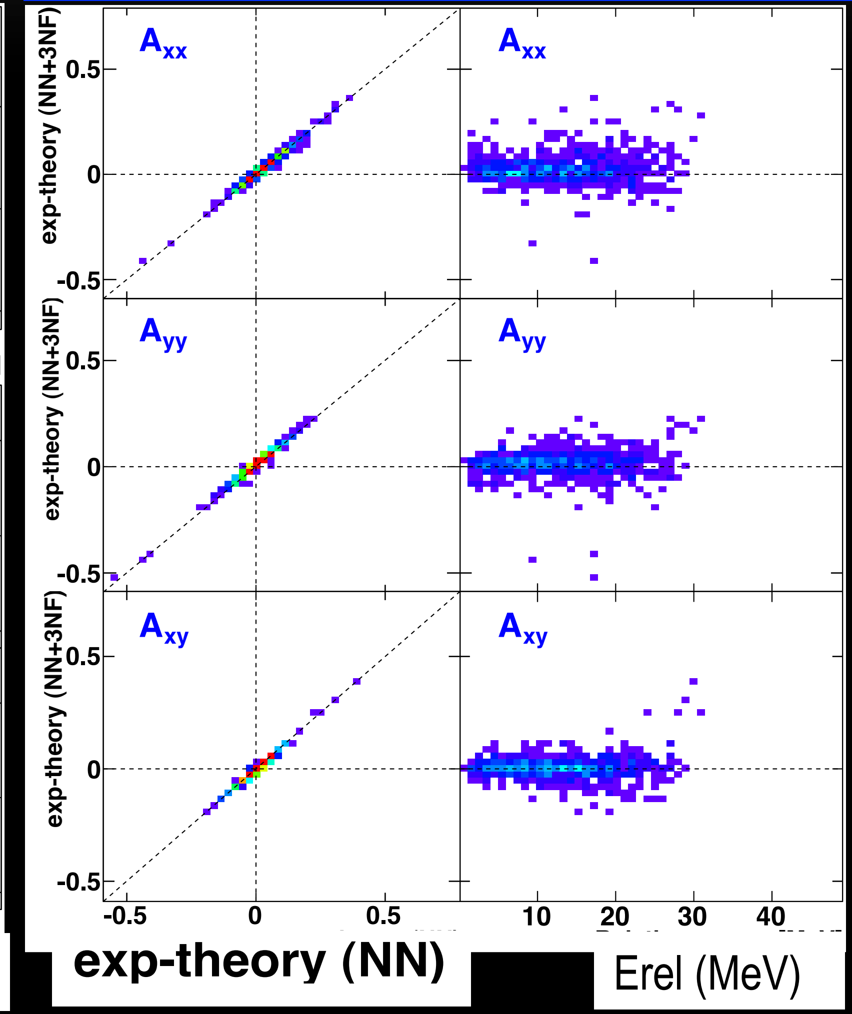
***Signatures of three-nucleon interactions in few-nucleon systems***

# Status 3n in pd breakup

## 65-190 MeV – various configurations

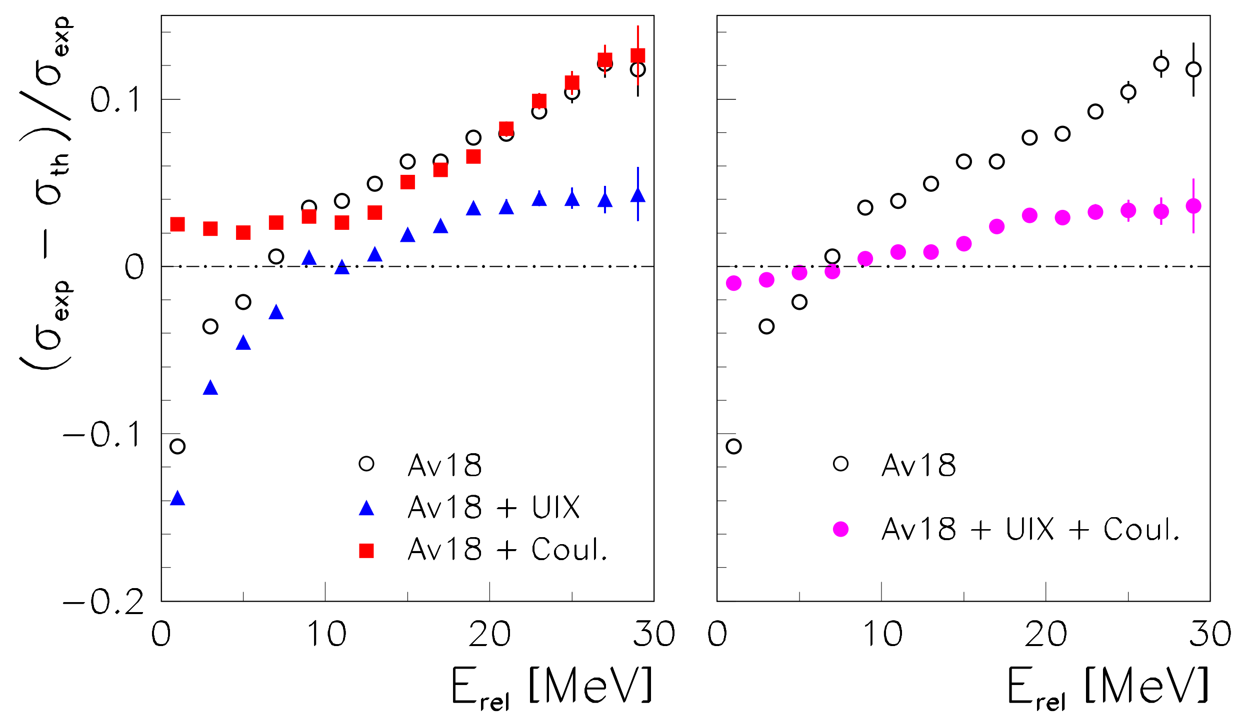


## 65 MeV



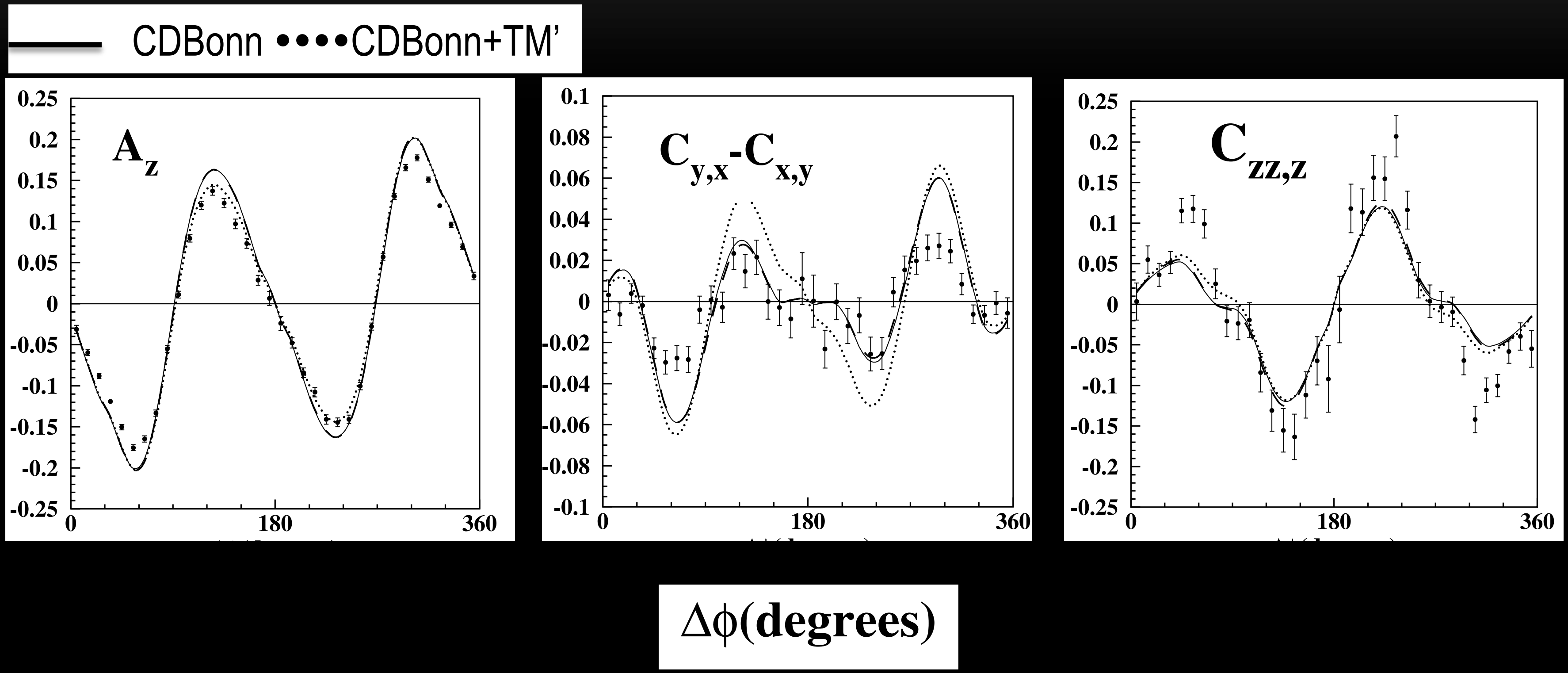
# 1H(D,PP)N REACTION @KVI AT 65 MEV/A BUP CROSS SECTIONS

St Kistryn, E Stephan and N Kalantar-Nayestanaki
SPIN 2010



H.O. Meyer et al., Phys. Rev. Lett. 93, 112502 (2004), T.J. Whitaker IUCF PhD thesis

# STATUS 3N IN PD BREAKUP: 135 MEV/A



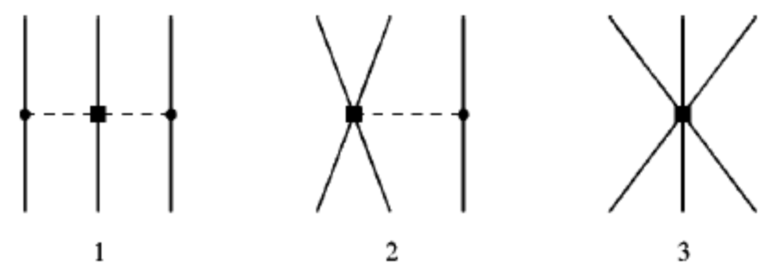
Axial observables

# MODERN THEORY OF NUCLEAR FORCES

Epelbaum, Prog. Part. Nucl. Phys. 57 (2006) 57

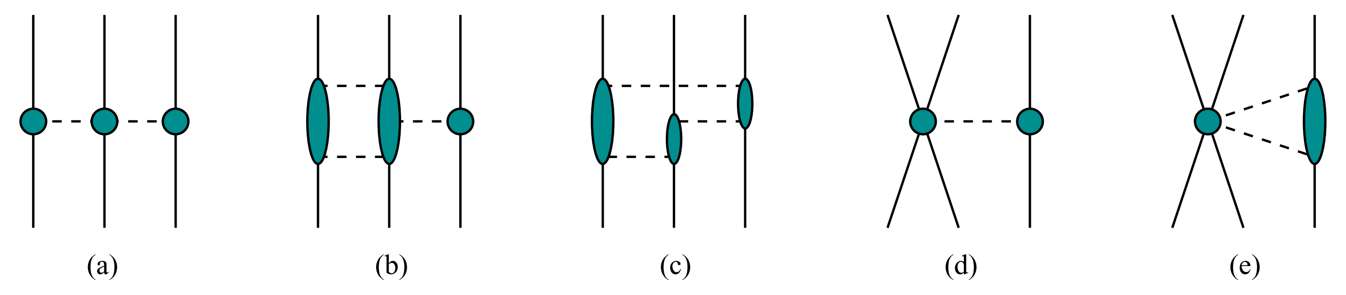
Epelbaum et al., PRC 66, 064001 (2002)

- **Chiral effective field theory:**
  - Systematic & model independent framework for low-energy hadron physics
  - Few body forces enter naturally with increasing order
- **At N2LO - first nonvanishing terms from the chiral Three-Nucleon Force (3NF)**
  - Two-pion exchange
  - One-pion exchange
  - Contact interaction



# MODERN THEORY OF NUCLEAR FORCES

- At N3LO – V. Bernard, E. Epelbaum H. Krebs,Ulf-G. Meißner , Phys. Rev. C 77, 064004 (2008)
  - derived long-range contributions to 3NF
  - short-range contributions and the leading relativistic corrections to the three-nucleon force (3NF)

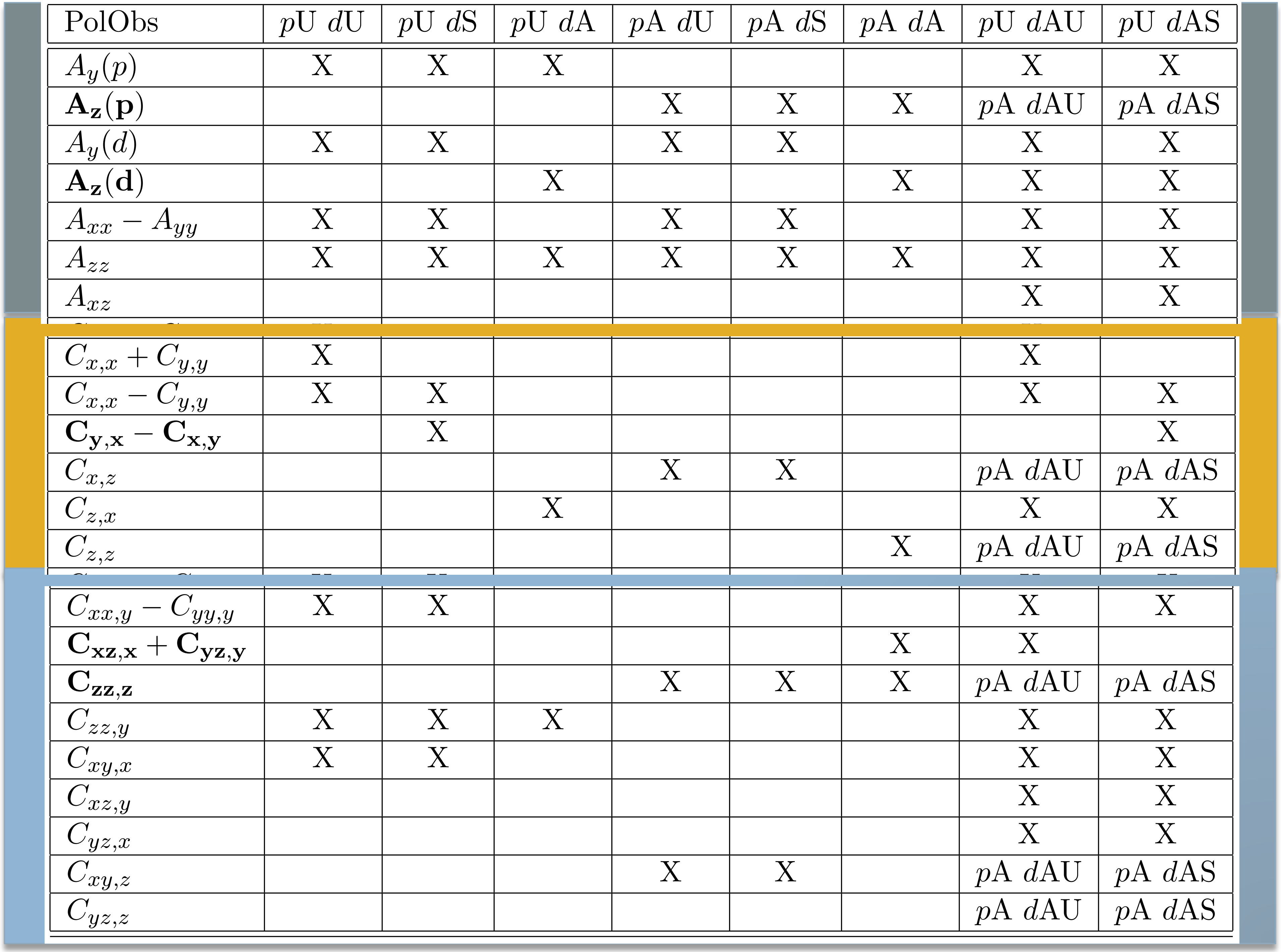


" Subleading contributions to the chiral three-nucleon force II: short-range terms and relativistic corrections"
V. Bernard, E. Epelbaum H. Krebs,Ulf-G. Meißner ,
arXiv:1108.3816v1

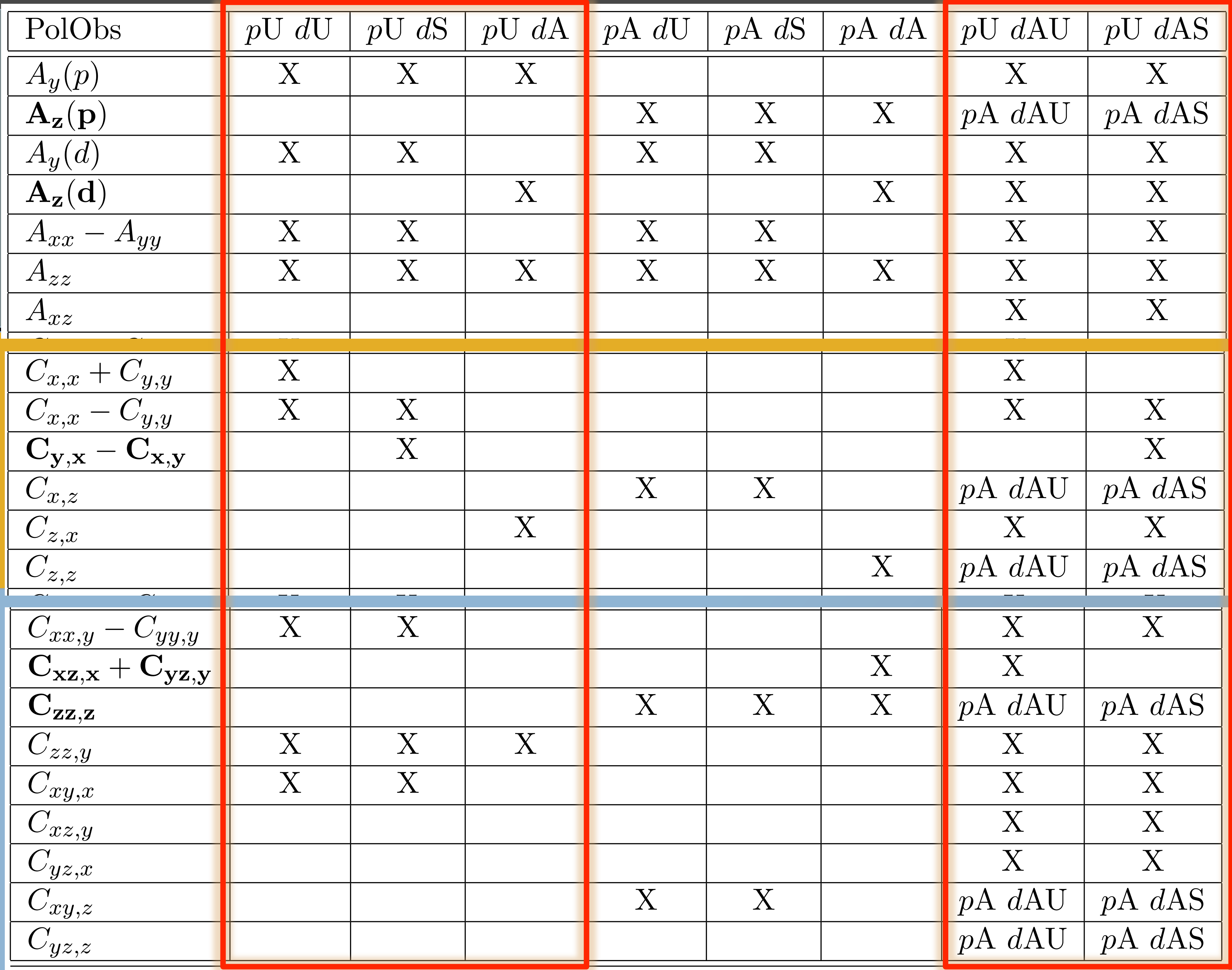
Calculations soon ready for scattering – priv. comm. Epelbaum

# 22 OBSERVABLES

$$
\begin{aligned}
\sigma = \sigma_0(1 + p_y A_y(p) + p_z A_z(p) + \frac{3}{2} q_y A_y(d) + \frac{3}{2} q_z A_z(d) \\
+\frac{3}{4}(q_x p_x + q_y p_y)(C_{x,x} + C_{y,y}) + \frac{3}{4}(q_x p_x - q_y p_y)(C_{x,x} - C_{y,y}) + \frac{3}{4}(q_y p_x - q_x p_y)(C_{y,x} - C_{x,y}) \\
+\frac{3}{2} q_x p_z C_{x,z} + \frac{3}{2} q_z p_x \ C_{z,x} + \frac{3}{2} q_z p_z C_{z,z} + \frac{1}{6}(q_{xx} - q_{yy})(A_{xx} - A_{yy}) + \frac{1}{2} q_{zz} A_{zz} + \frac{2}{3} q_{xz} A_{xz} \\
+\frac{1}{6}(q_{xx} - q_{yy}) p_y (C_{xx,y} - C_{yy,y}) + \frac{1}{2} q_{zz} p_z C_{zz,z} + \frac{1}{2} q_{zz} p_y Czz, y + \frac{2}{3} q_{xy} p_x C_{xy,x} + \frac{2}{3} q_{xz} p_y C_{xz,y} + \frac{2}{3} q_{yz} p_x C_{yz,x} \\
+\frac{2}{3} q_{xy} p_z C_{xy,z} + \frac{2}{3} q_{yz} p_z C_{yz,z} + \frac{1}{3}(q_{xz} p_x + q_{yz} p_y)(C_{xz,x} + C_{yz,y}))
\end{aligned}
$$



| PolObs | $p$U $d$U | $p$U $d$S | $p$U $d$A | $p$A $d$U | $p$A $d$S | $p$A $d$A | $p$U $d$AU | $p$U $d$AS |
|---|---|---|---|---|---|---|---|---|
| $A_y(p)$ | X | X | X | | | | X | X |
| $\mathbf{A_z(p)}$ | | | | X | X | X | $p$A $d$AU | $p$A $d$AS |
| $A_y(d)$ | X | X | | X | X | | X | X |
| $\mathbf{A_z(d)}$ | | | X | | | X | X | X |
| $A_{xx} - A_{yy}$ | X | X | | X | X | | X | X |
| $A_{zz}$ | X | X | X | X | X | X | X | X |
| $A_{xz}$ | | | | | | | X | X |
| $C_{x,x} + C_{y,y}$ | X | | | | | | X | |
| $C_{x,x} - C_{y,y}$ | X | X | | | | | X | X |
| $\mathbf{C_{y,x} - C_{x,y}}$ | | X | | | | | | X |
| $C_{x,z}$ | | | | X | X | | $p$A $d$AU | $p$A $d$AS |
| $C_{z,x}$ | | | X | | | | X | X |
| $C_{z,z}$ | | | | | | X | $p$A $d$AU | $p$A $d$AS |
| $C_{xx,y} - C_{yy,y}$ | X | X | | | | | X | X |
| $\mathbf{C_{xz,x} + C_{yz,y}}$ | | | | | | X | X | |
| $\mathbf{C_{zz,z}}$ | | | | X | X | X | $p$A $d$AU | $p$A $d$AS |
| $C_{zz,y}$ | X | X | X | | | | X | X |
| $C_{xy,x}$ | X | X | | | | | X | X |
| $C_{xz,y}$ | | | | | | | X | X |
| $C_{yz,x}$ | | | | | | | X | X |
| $C_{xy,z}$ | | | | X | X | | $p$A $d$AU | $p$A $d$AS |
| $C_{yz,z}$ | | | | | | | $p$A $d$AU | $p$A $d$AS |



| PolObs | pU dU | pU dS | pU dA | pA dU | pA dS | pA dA | pU dAU | pU dAS |
|---|---|---|---|---|---|---|---|---|
| $A_y(p)$ | X | X | X |  |  |  | X | X |
| $\mathbf{A_z(p)}$ |  |  |  | X | X | X | pA dAU | pA dAS |
| $A_y(d)$ | X | X |  | X | X |  | X | X |
| $\mathbf{A_z(d)}$ |  |  | X |  |  | X | X | X |
| $A_{xx} - A_{yy}$ | X | X |  | X | X |  | X | X |
| $A_{zz}$ | X | X | X | X | X | X | X | X |
| $A_{xz}$ |  |  |  |  |  |  | X | X |
| $C_{x,x} + C_{y,y}$ | X |  |  |  |  |  | X |  |
| $C_{x,x} - C_{y,y}$ | X | X |  |  |  |  | X | X |
| $\mathbf{C_{y,x} - C_{x,y}}$ |  | X |  |  |  |  |  | X |
| $C_{x,z}$ |  |  |  | X | X |  | pA dAU | pA dAS |
| $C_{z,x}$ |  |  | X |  |  |  | X | X |
| $C_{z,z}$ |  |  |  |  |  | X | pA dAU | pA dAS |
| $C_{xx,y} - C_{yy,y}$ | X | X |  |  |  |  | X | X |
| $\mathbf{C_{xz,x} + C_{yz,y}}$ |  |  |  |  |  | X | X |  |
| $\mathbf{C_{zz,z}}$ |  |  |  | X | X | X | pA dAU | pA dAS |
| $C_{zz,y}$ | X | X | X |  |  |  | X | X |
| $C_{xy,x}$ | X | X |  |  |  |  | X | X |
| $C_{xz,y}$ |  |  |  |  |  |  | X | X |
| $C_{yz,x}$ |  |  |  |  |  |  | X | X |
| $C_{xy,z}$ |  |  |  | X | X |  | pA dAU | pA dAS |
| $C_{yz,z}$ |  |  |  |  |  |  | pA dAU | pA dAS |

# A SAMPLING METHOD TO COMPARE WITH THEORY

x is the set of parameters needed to determine the kinematics, at any point of phase space

$$O^{th}(x) = \frac{\int \sigma_0(x)\varepsilon(x)O^{th}(x)dx}{\int \sigma_0(x)\varepsilon(x)dx}$$

For a kinematically complete experiment, over some region $\gamma$ of phase space

- The correctly averaged theoretical value is the mean

$$\boxed{O^{th}(\gamma) = \left\langle O^{th} \right\rangle = \frac{\sum O^{th}(x_k)}{N(\gamma)}}$$

J. Kuros▯-Żołnierczuk, P. Thörngren-Engblom, H.O. Meyer, T.J. Whitaker, H. Witała, J. Golak, H. Kamada, A. Nogga and R. Skibiński, Few-Body Systems **34**, 259 (2004)

# A METHOD TO COMPARE BUP WITH THEORY

x is the set of parameters needed to determine the kinematics, at any point of phase space

$$O^{th}(x) = \frac{\int \sigma_0(x)\varepsilon(x)O^{th}(x)dx}{\int \sigma_0(x \qquad )dx}$$

Obs-th from a grid of precalculated theoretical values

For a kinematically complete

γ of phase space

- The correctly averaged theoretical

$$\boxed{O^{th}(\gamma) = \langle O^{th} \rangle = \frac{\sum O^{th}(x_k)}{N(\gamma)}}$$

J. Kuros-Żołnierczuk, P. Thörngren-Engblom, H.O. Meyer, T.J. Whitaker, H. Witała, J. Golak, H. Kamada, A. Nogga and R. Skibiński, Few-Body Systems **34**, 259 (2004)

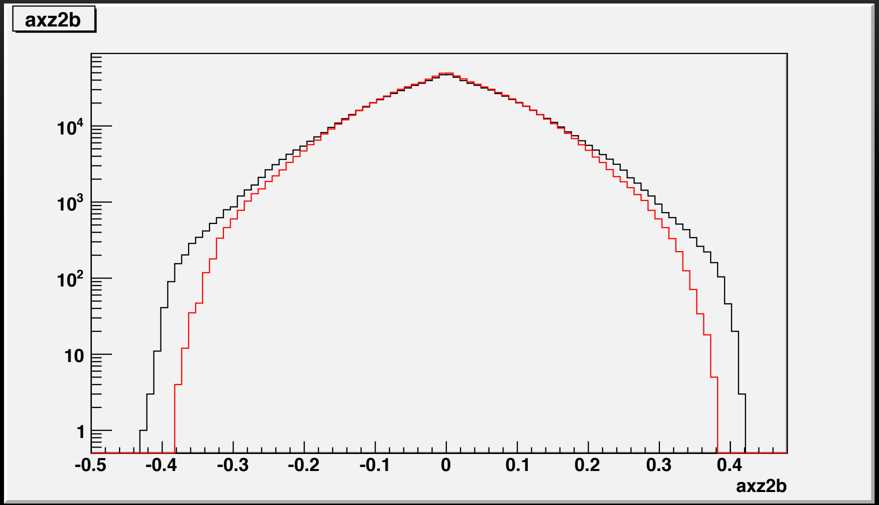
# GRID EXAMPLES

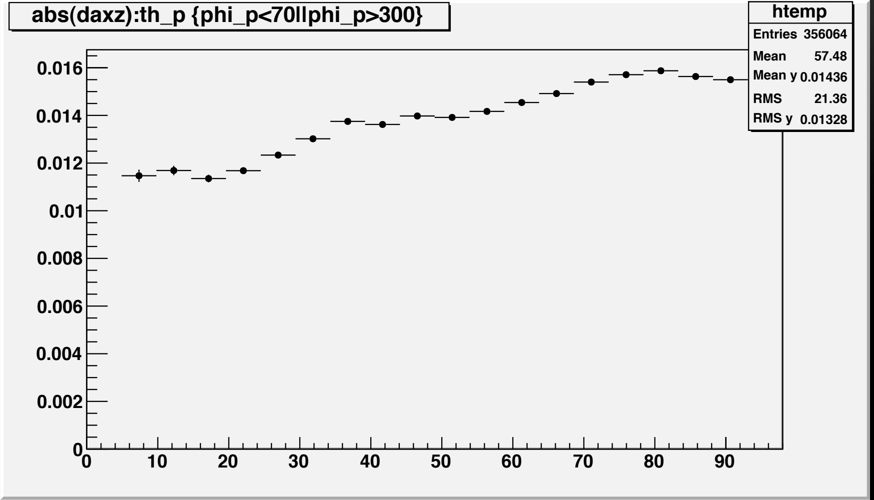
- Theoretical framework & calculations: Epelbaum & Nogga

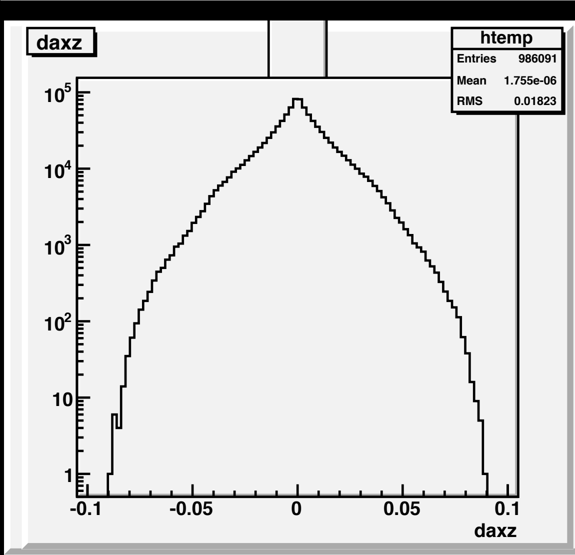
| GRID SPACING | |
|---|---|
| p # of steps | 20 |
| Θp # of steps | 9 |
| Θp [deg] | 5..90 |
| Θp # steps | 18 |
| Θp [deg] | 10..180 |
| φp,q # steps | 37 |
| φp,q [deg] | 0..360 |
| # of grid points | 4,435,560 |

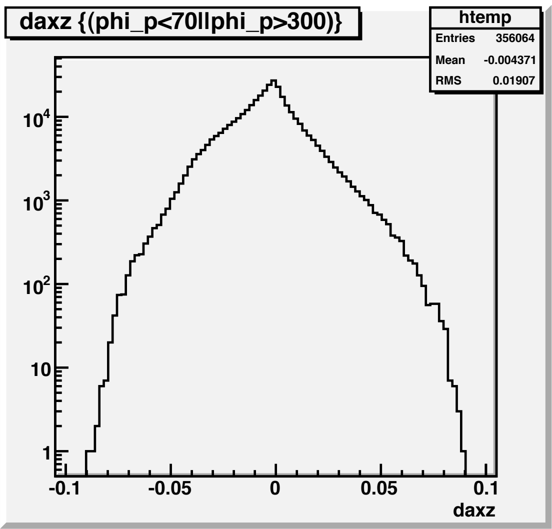
Using the sampling method & phase space simulation

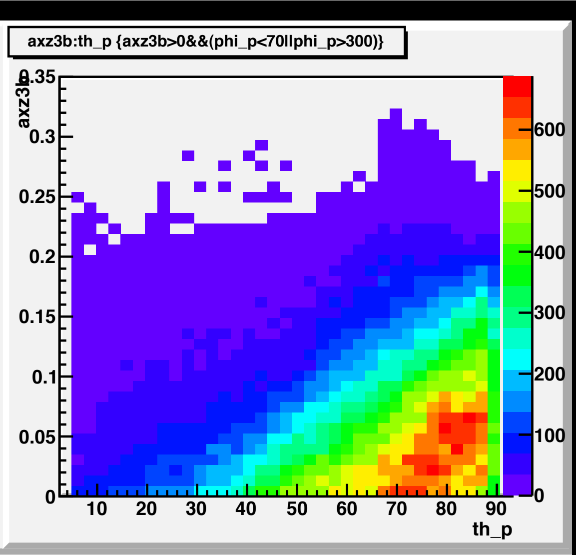
# @ 49 MEV - AXZ


axz2b
$10^4$
$10^3$
$10^2$
10
1
-0.5
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
axz2b

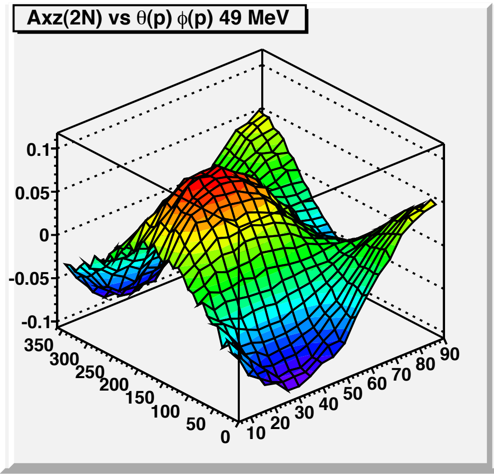

abs(daxz):th_p {phi_p<70||phi_p>300}
htemp
Entries 356064
Mean 57.48
Mean y 0.01436
RMS 21.36
RMS y 0.01328
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
0
10
20
30
40
50
60
70
80
90

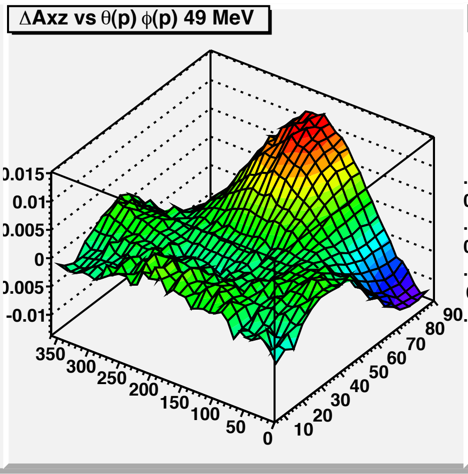

daxz
htemp
Entries 986091
Mean 1.755e-06
RMS 0.01823
$10^5$
$10^4$
$10^3$
$10^2$
10
1
-0.1
-0.05
0
0.05
0.1
daxz

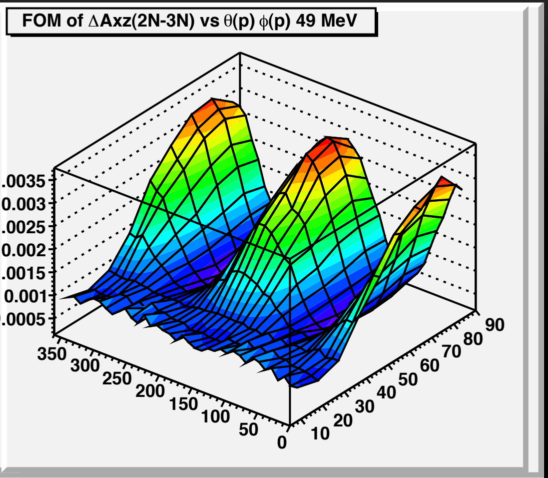

daxz {(phi_p<70||phi_p>300)}
htemp
Entries 356064
Mean -0.004371
RMS 0.01907
$10^4$
$10^3$
$10^2$
10
1
-0.1
-0.05
0
0.05
0.1
daxz

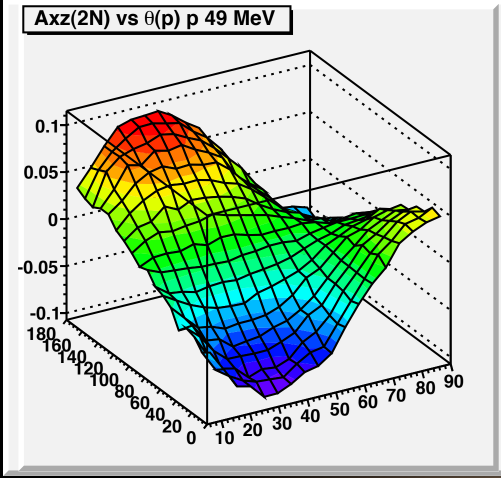

axz3b:th_p {axz3b>0&&(phi_p<70||phi_p>300)}
axz3b
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
10
20
30
40
50
60
70
80
90
th_p
600
500
400
300
200
100
0

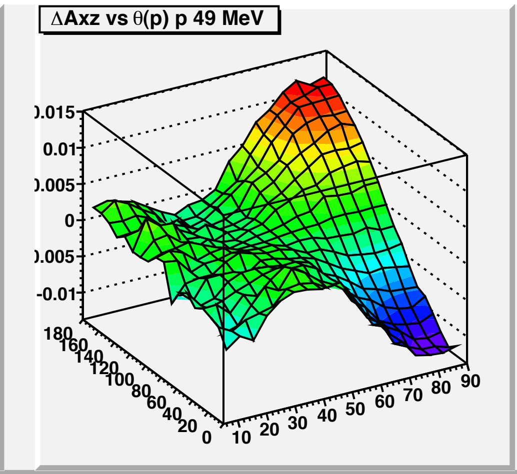
# @ 49 MeV - Axz

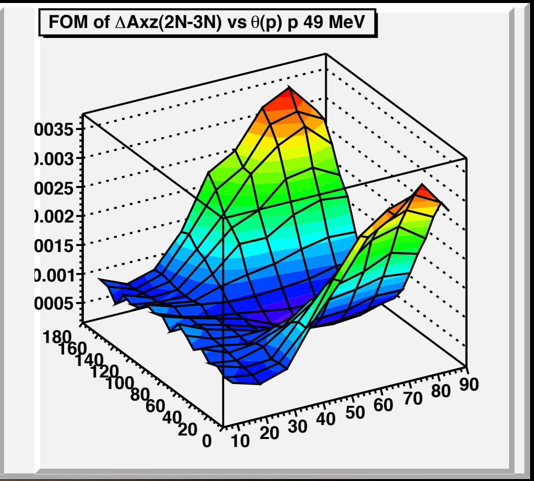

Axz(2N) vs $\theta(p)$ $\phi(p)$ 49 MeV


$\Delta$Axz vs $\theta(p)$ $\phi(p)$ 49 MeV

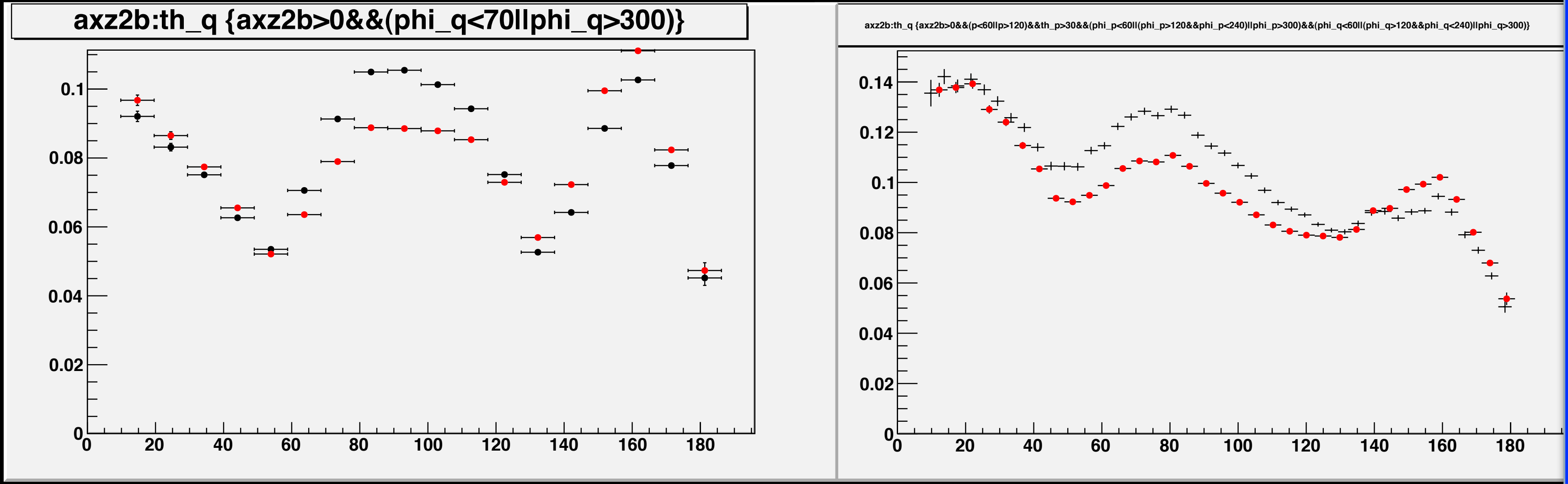

FOM of $\Delta$Axz(2N-3N) vs $\theta(p)$ $\phi(p)$ 49 MeV


Axz(2N) vs $\theta(p)$ p 49 MeV


$\Delta$Axz vs $\theta(p)$ p 49 MeV

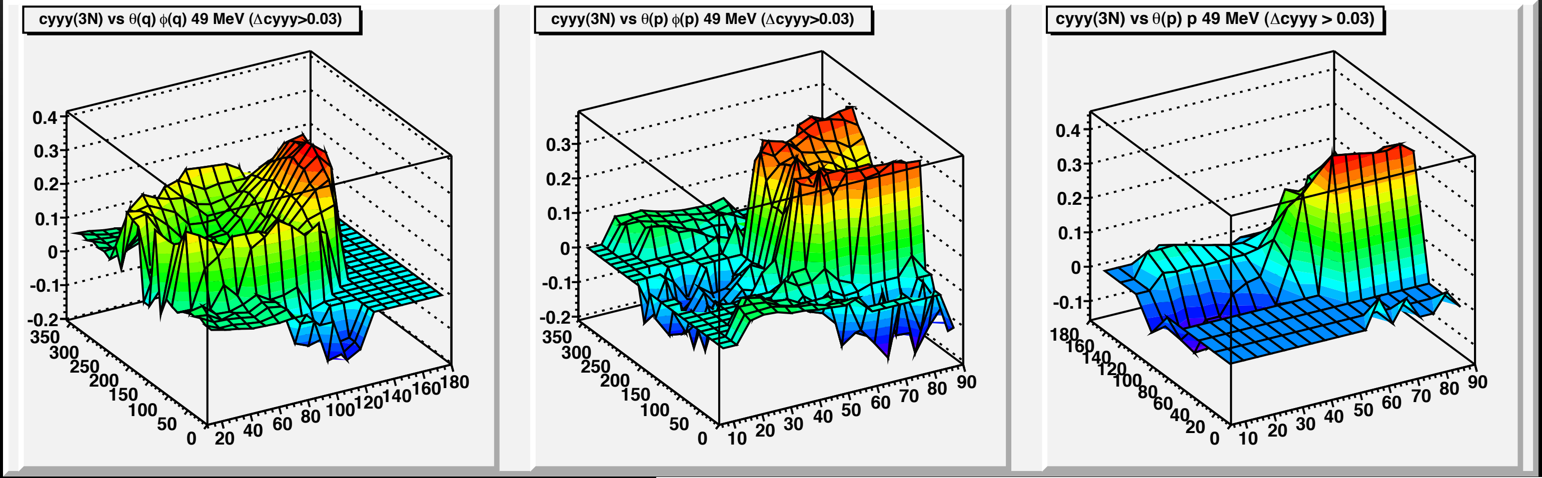

FOM of $\Delta$Axz(2N-3N) vs $\theta(p)$ p 49 MeV

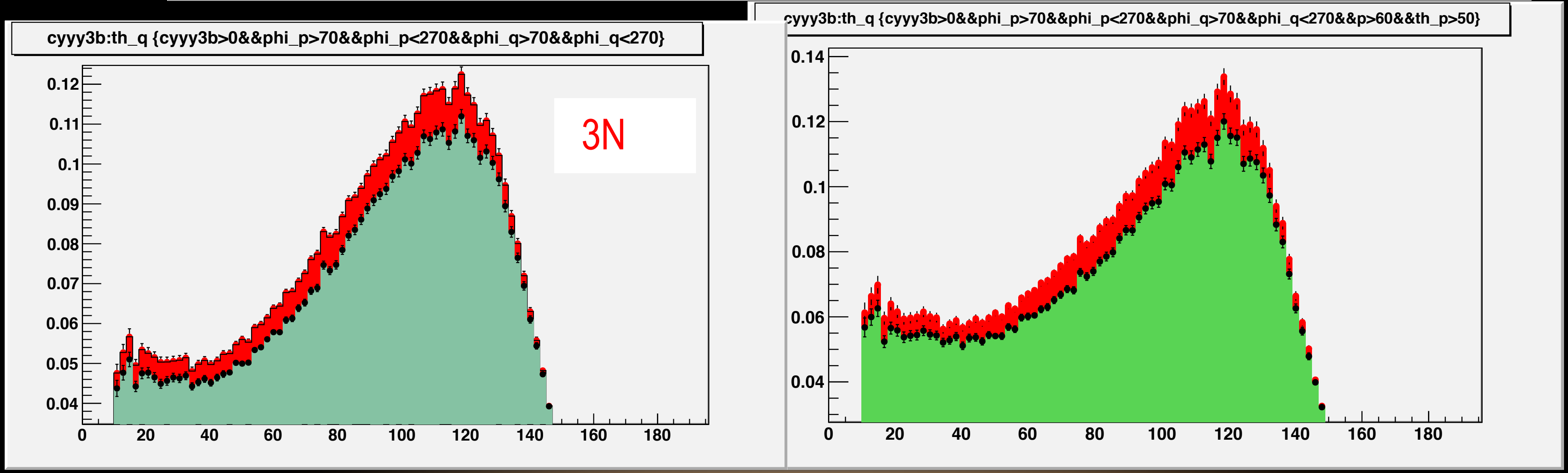
# @ 49 MEV - AXZ VS Θ Q



θq

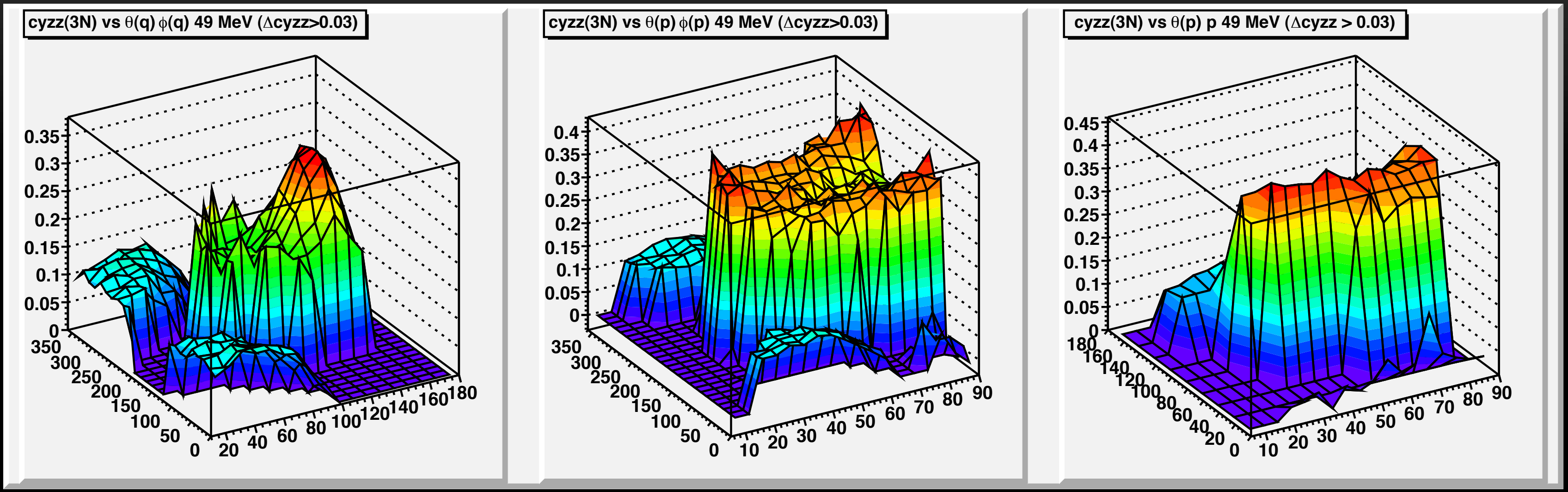
# @ 49 MEV - CYY,Y

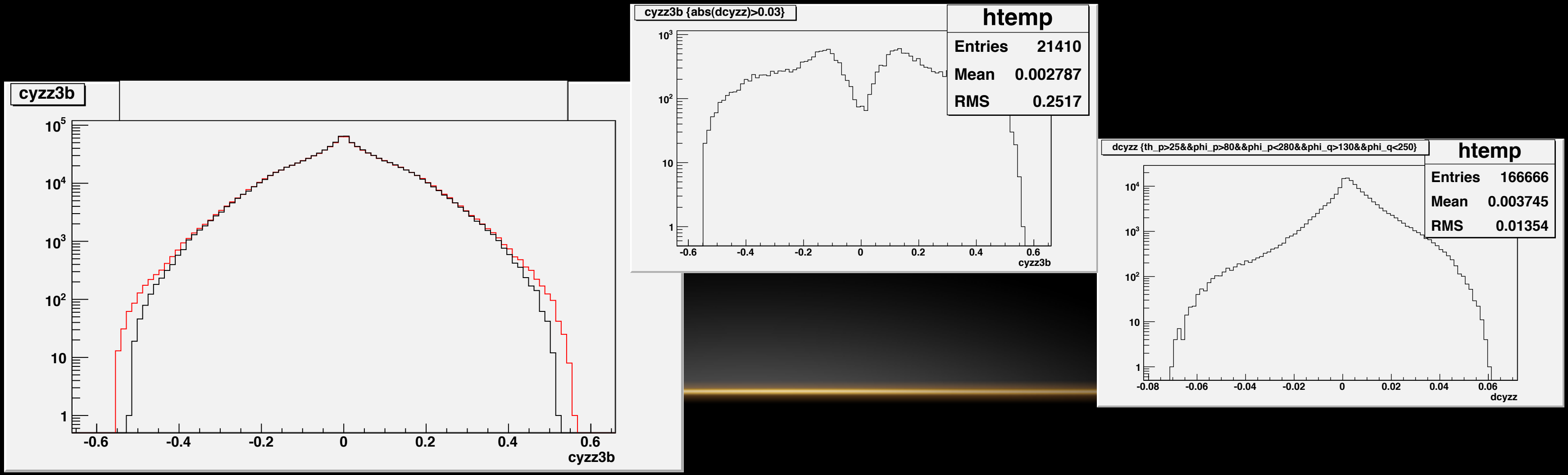




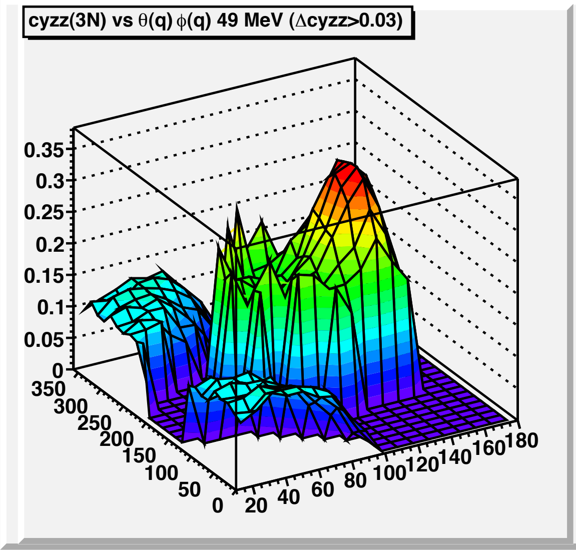
θq

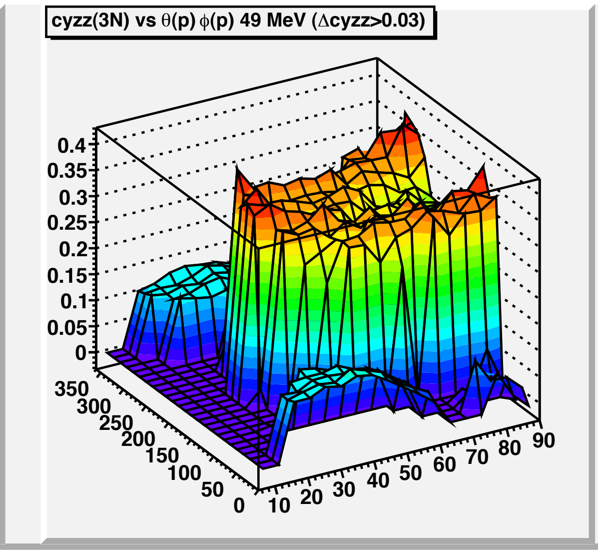
# @ 49 MEV - CYZ,Z

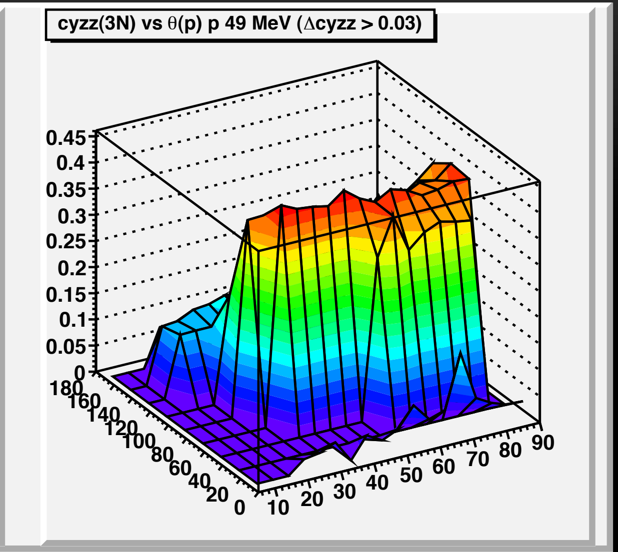

cyzz(3N) vs θ(q) ϕ(q) 49 MeV (Δcyzz>0.03)
cyzz(3N) vs θ(p) ϕ(p) 49 MeV (Δcyzz>0.03)
cyzz(3N) vs θ(p) p 49 MeV (Δcyzz > 0.03)

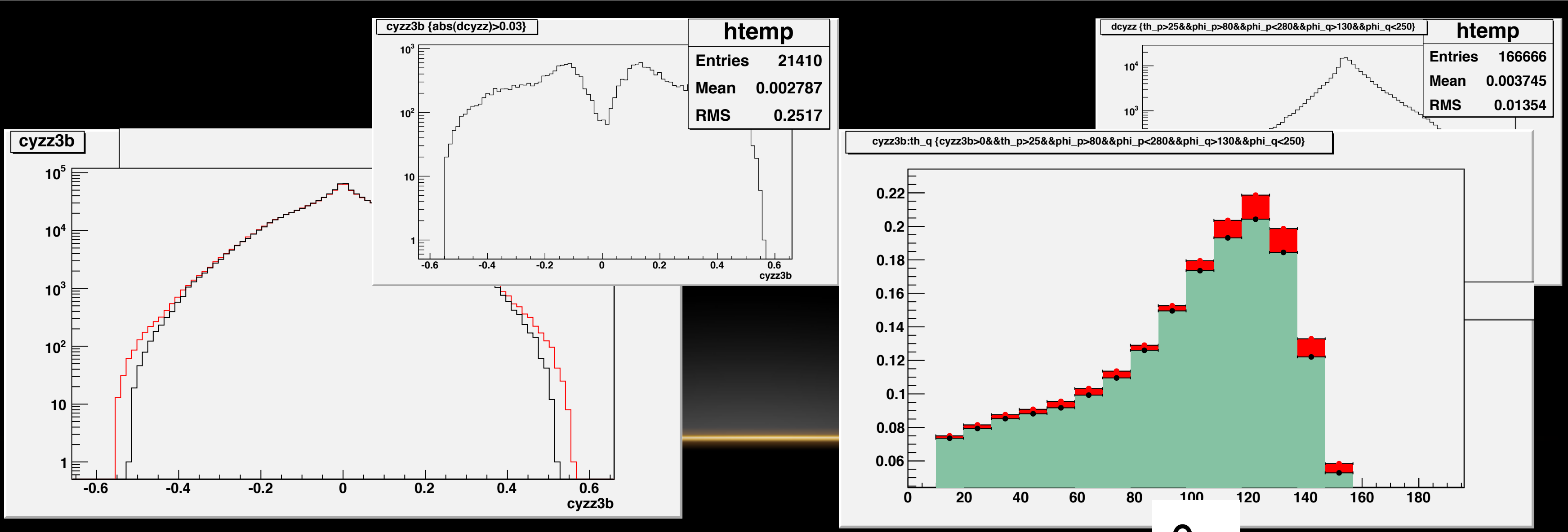

cyzz3b
cyzz3b {abs(dcyzz)>0.03}
htemp
Entries 21410
Mean 0.002787
RMS 0.2517
cyzz3b
dcyzz {th_p>25&&phi_p>80&&phi_p<280&&phi_q>130&&phi_q<250}
htemp
Entries 166666
Mean 0.003745
RMS 0.01354
dcyzz

# @ 49 MEV - CYZ,Z



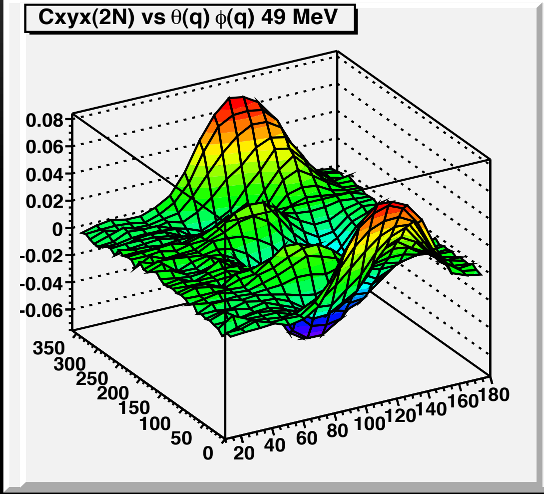


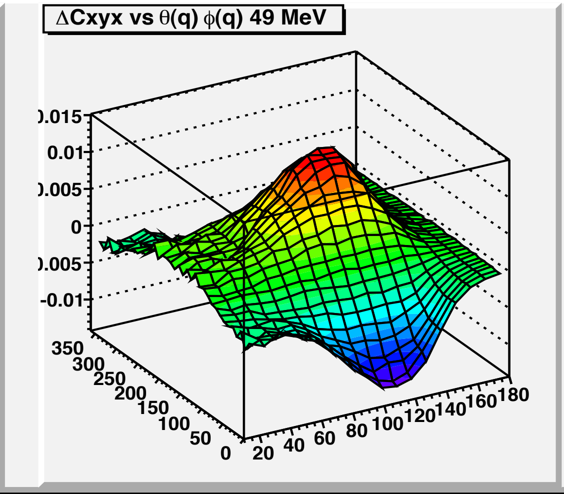


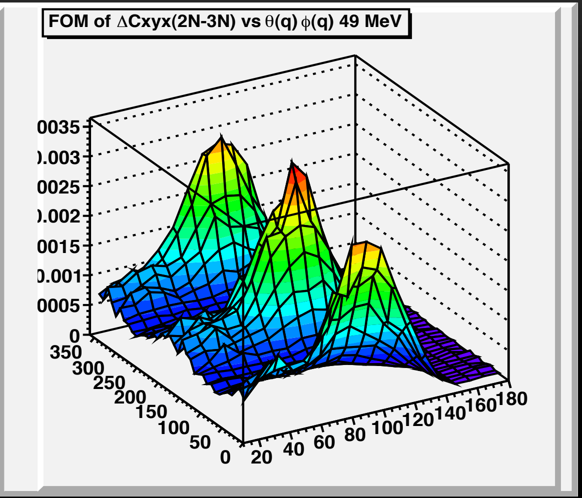


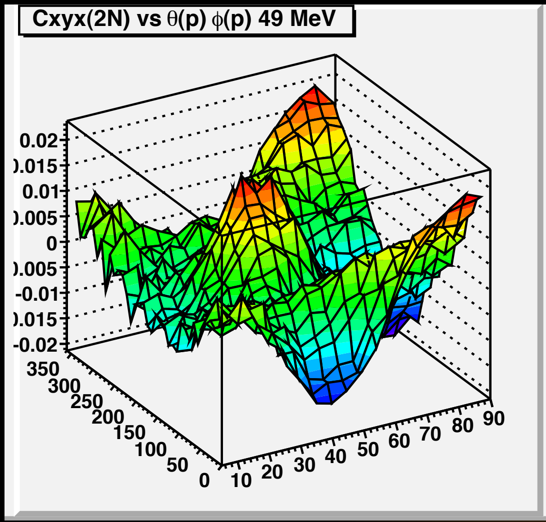
θq

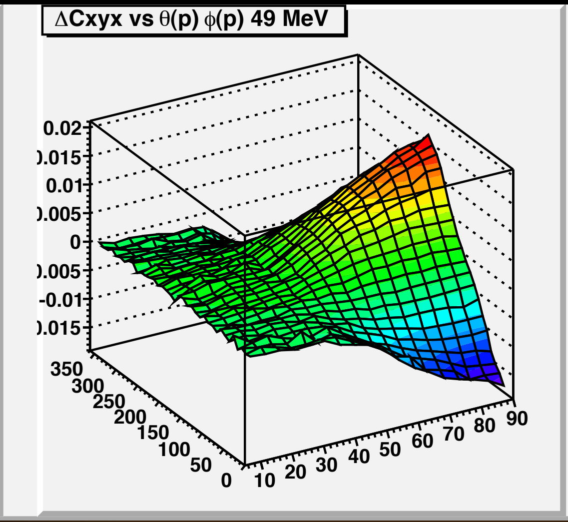
# @49 MEV - CXY,X

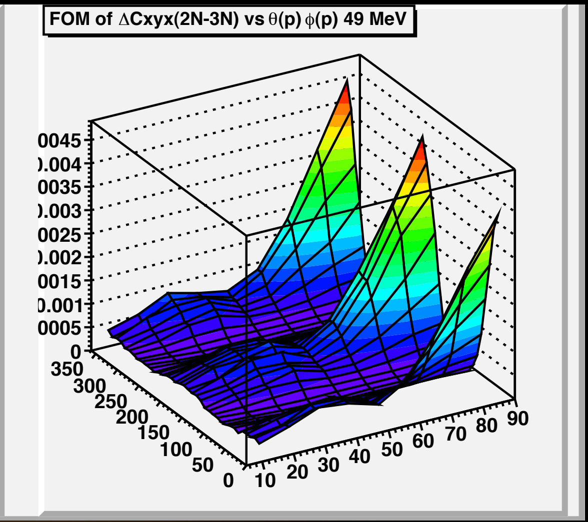

Cxyx(2N) vs θ(q) φ(q) 49 MeV


ΔCxyx vs θ(q) φ(q) 49 MeV

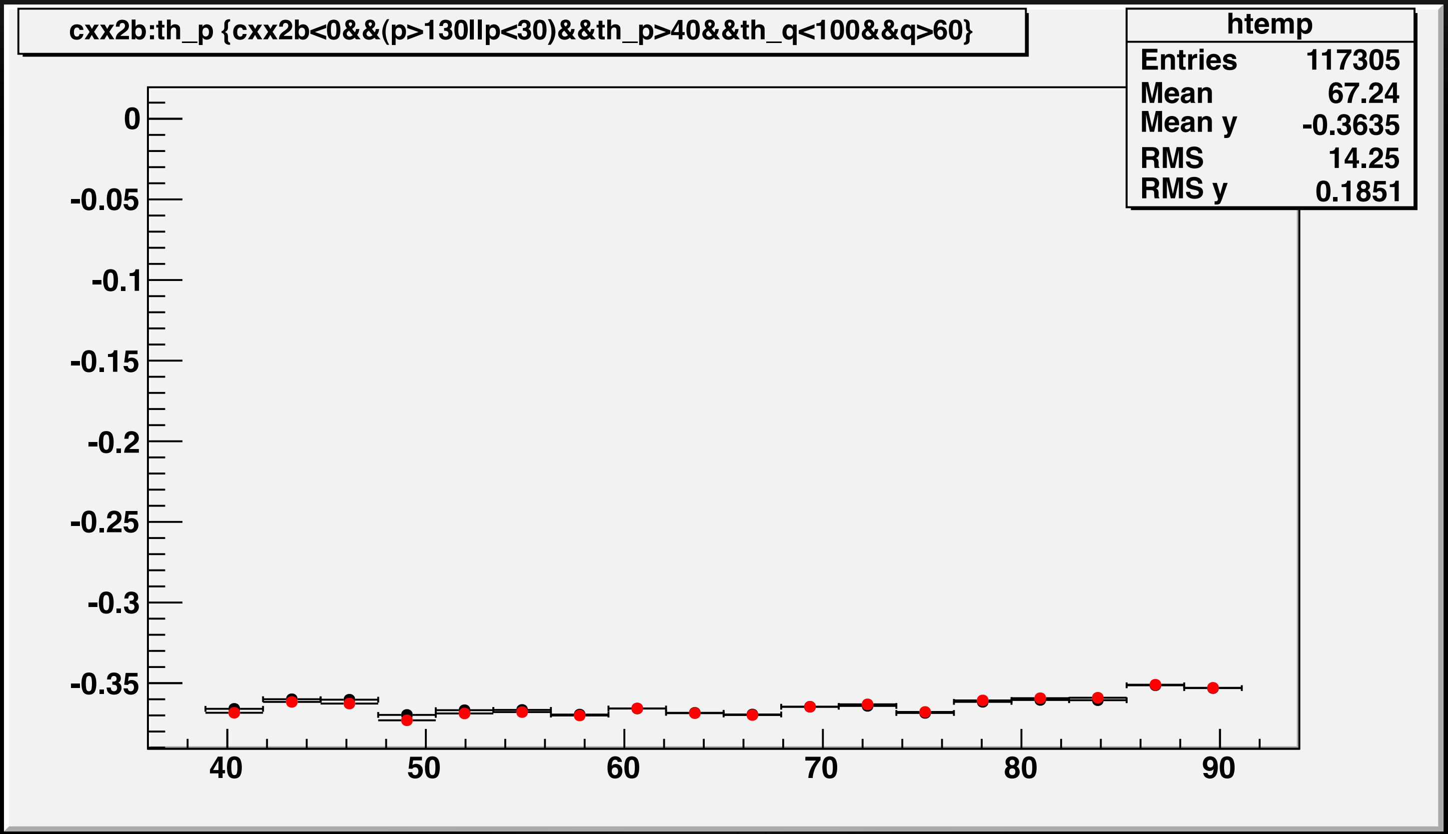

FOM of ΔCxyx(2N-3N) vs θ(q) φ(q) 49 MeV


Cxyx(2N) vs θ(p) φ(p) 49 MeV


ΔCxyx vs θ(p) φ(p) 49 MeV

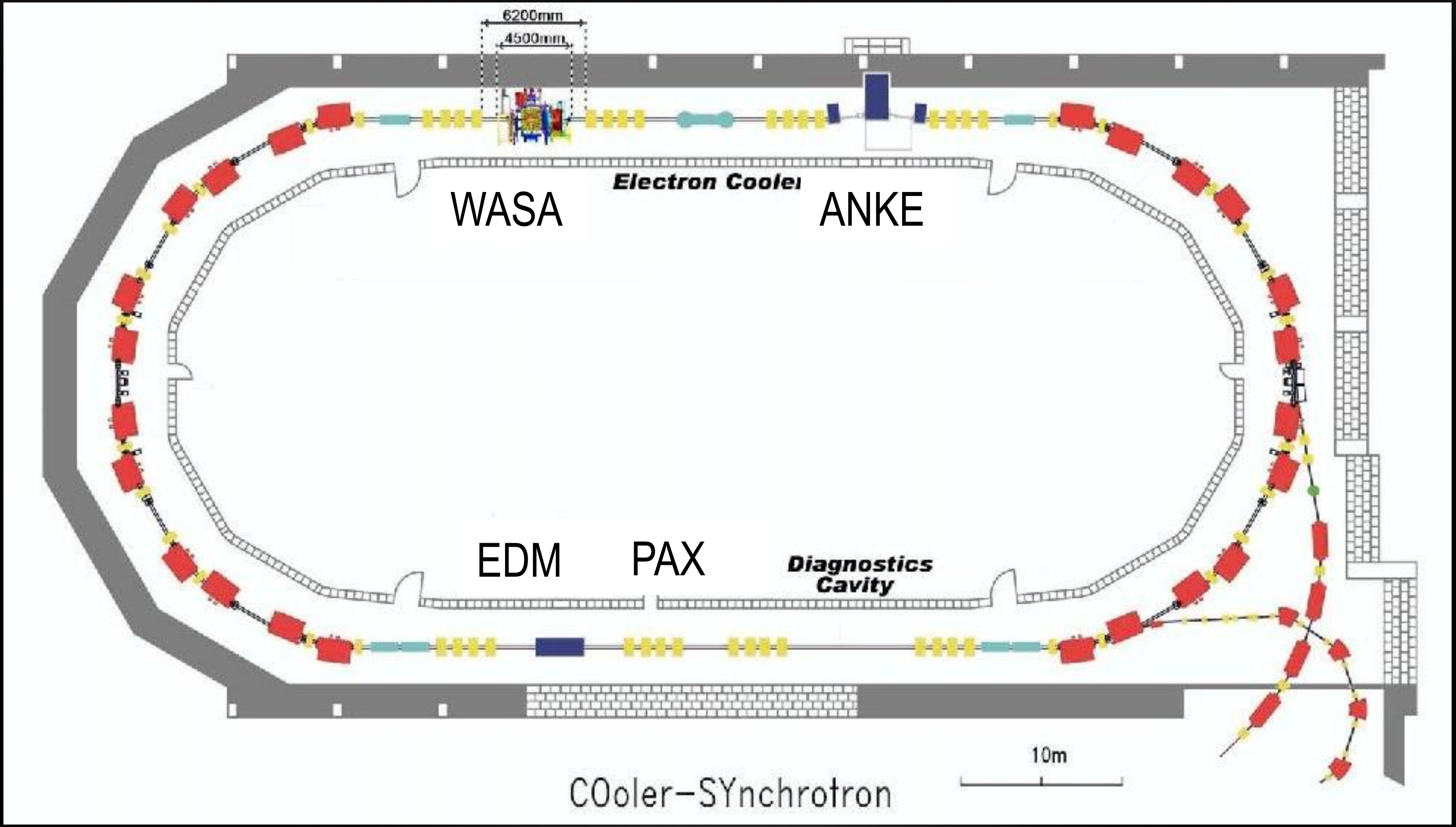

FOM of ΔCxyx(2N-3N) vs θ(p) φ(p) 49 MeV

# @ 49 MEV – CXX VS ΘP



θp

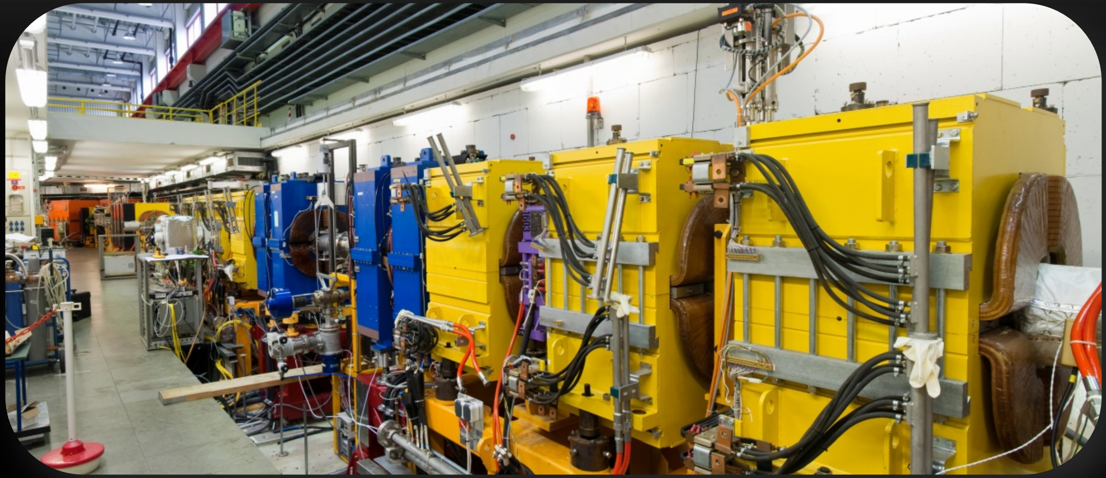
# COSY –
# COOLER SYNCHROTRON AND STORAGE RING

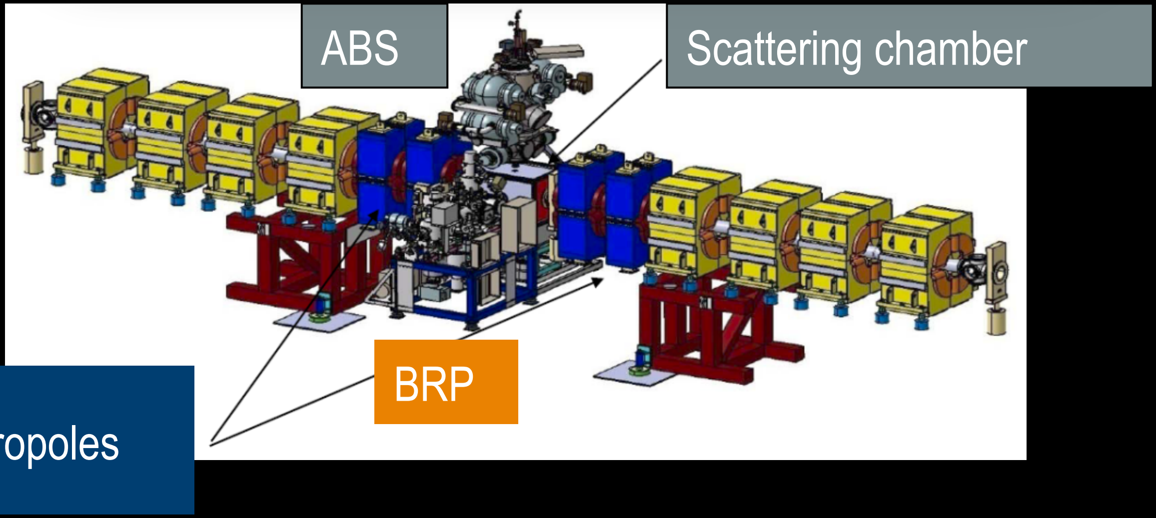


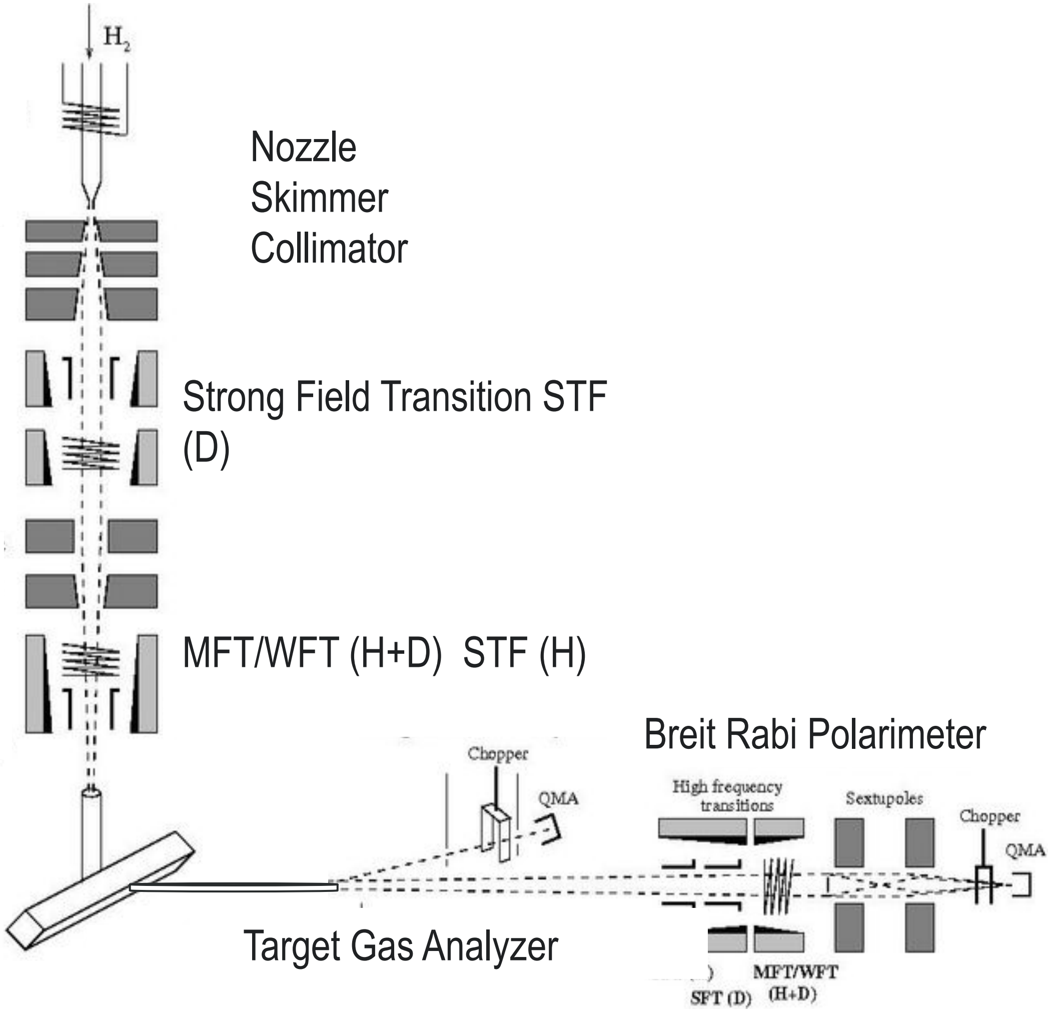
inauguration of COSY in 1993

# EXPERIMENTAL SETUP

PAX interaction point







Dissociator
$H_2 \rightarrow 2H$

Nozzle
Skimmer
Collimator

Sextupoles

HF transitions

Strong Field Transition STF (D)

Sextupoles

HF transitions

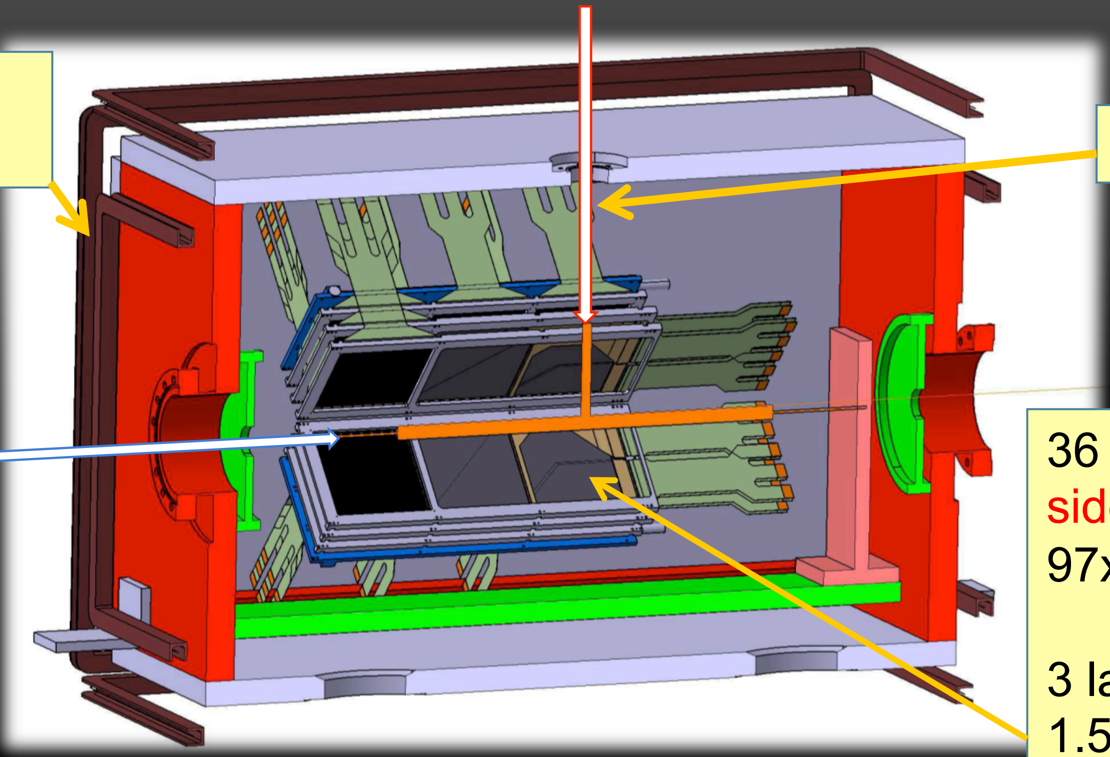
MFT/WFT (H+D) STF (H)

Breit Rabi Polarimeter

Target Cell

Target Gas Analyzer

# SCATTERING CHAMBER



Guide field coils
(x, y, z)

Atomic beam

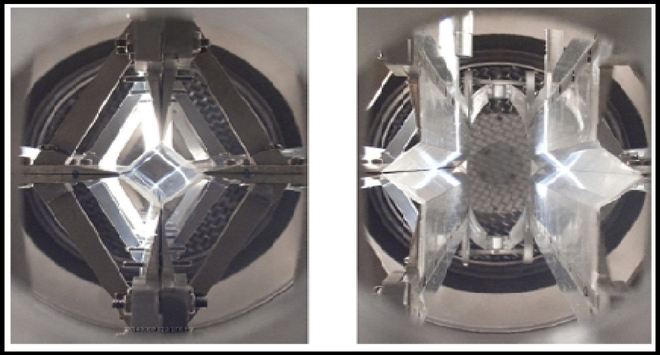
Stored beam

36 Silicon double sided strip detectors
97x97 mm

3 layers: 2 x 300μm; 1.5 mm

pitch 0.76 mm
< 1 mm vertex reconstruction

400 mm



Openable teflon storage cell

# BEAM TIME ESTIMATES

- Assumptions:
- statistical uncertainty of 0.002
- # stored polarized protons $\geq 10^9$
- target thickness of 5 · 1013
- duty factor of 0.9
- polarization of the beam $P \geq 0.5$
- target polarization $Q \approx 0.8$.
- # of events of the order of $5 \cdot 10^7$ with roughly $10^6$ events per ten degree bin in the azimuthal angle $\varphi$.

# SUMMARY - TOTAL BEAM TIME

| Polarized proton beam | 49 MeV | 30 MeV |
|---|---|---|
| $\sigma_{tot}$ breakup | 212.2 mb | 145 mb |
| Acceptance | 5 % | 8 % |
| Measuring time | ≥ 5 days/tgt scenario | ≥ 3 days/tgt scenario |
| Beam time/energy | 2 weeks | 2 weeks |

- With longitudinal and vertical beam polarization:

  Four run periods of two weeks each, separated by at least four months.

# SUMMARY

- pd breakup at 30-50 MeV where few previous measurement exist
- Measure most observables with large phasespace coverage – direct comparison of experiment & theory

➨ Would provide precise data for constraints of chiral EFT in a relevant energy range 30-50 MeV

  - Independent determination of Low Energy Constants *D* & *E*
  - New effects of 3NF that appear at N3LO can be accessed

More information:
COSY Proposal 202, PTE et al., ***Measurement of Spin Observables in the pd Breakup Reaction,***
http://www2.fz-juelich.de/ikp/publications/PAC39/PAX_proposal202.1_202.pdf

- Theory: E Epelbaum & A Nogga
- PAX Experiment: S Barsov, S Bertelli, M Contalbrigo, D Chiladze, A Kacharava, P Lenisa, N Lomidze, B Lorentz, G Macharashvili, S Merzlyakov, S Mikirtytchiants, A Nass, D Oellers, F Rathmann, Schleichert, H Ströher, PTE, M Tabidze, S Trusov, C Weidemann for PAX and ANKE Collaborations
- COSY accelerator group: D Prasuhn & B Lorentz et al.

*Thank you for your attention!*

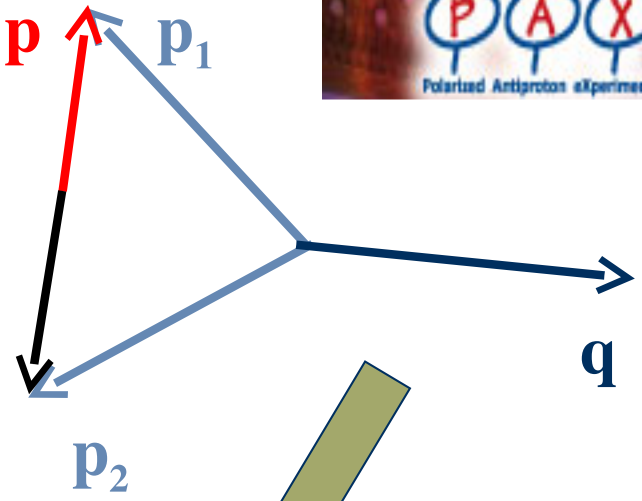
# Three-body final state

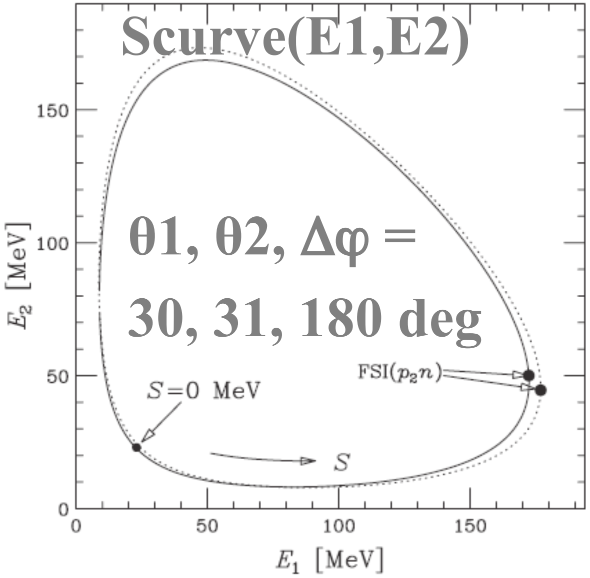
## Jacobi momenta

$$\mathbf{p} = \tfrac{1}{2}\,(\mathbf{p}_1 - \mathbf{p}_2)$$

$$\mathbf{q} = -\,(\mathbf{p}_1 + \mathbf{p}_2)$$

$$\Delta\varphi = \varphi\,(\mathbf{p}) - \varphi\,(\mathbf{q})$$

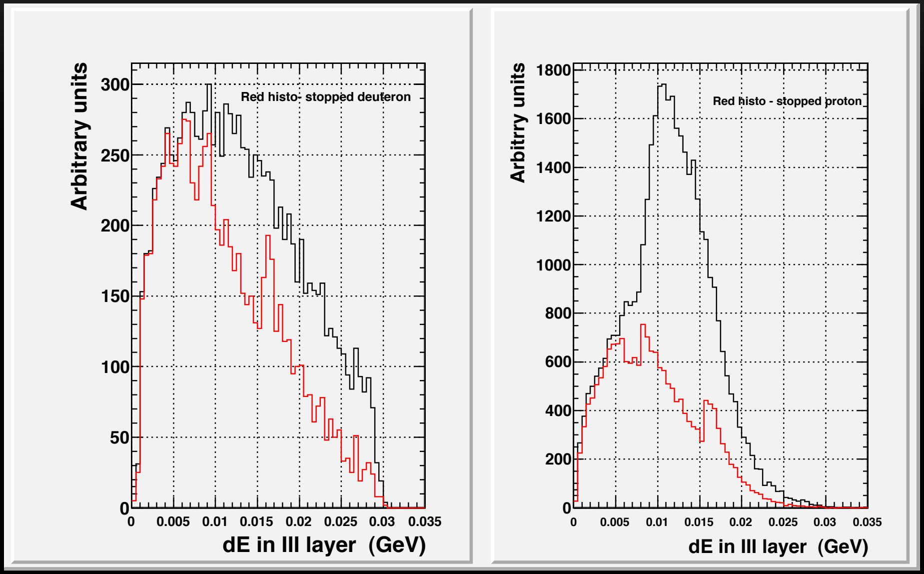




G.G.Ohlsen, NIM 179 (1981) 283

- five-dimensional phase space
- 4 angles and mom: $\theta_p, \theta_q, \varphi_p, \varphi_q,\ p$
- If azimuthal symmetry $\theta_p, \theta_q, \Delta\varphi, p$
- Find relevant independent parameter & observable

# Addition for bup
# Si 3rd layer 1.5 mm



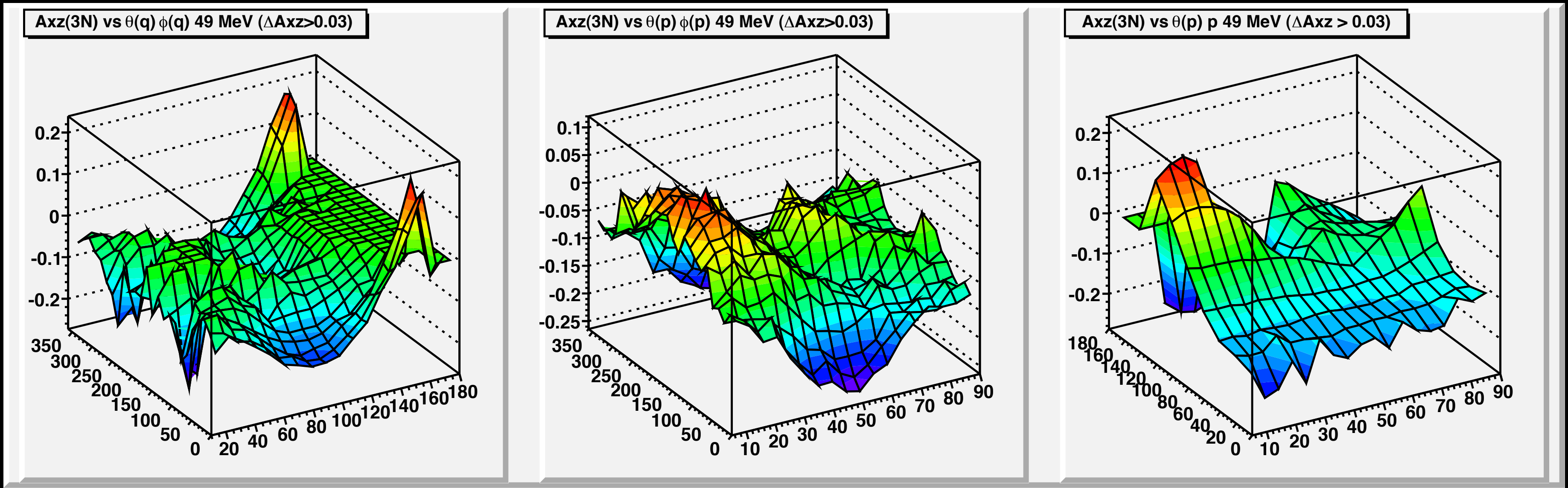
## HERMES detector system:

A capacitor array was adopted to distribute the charge into a high gain and a low gain channel, thus they could read out energy deposits over a large dynamic range.

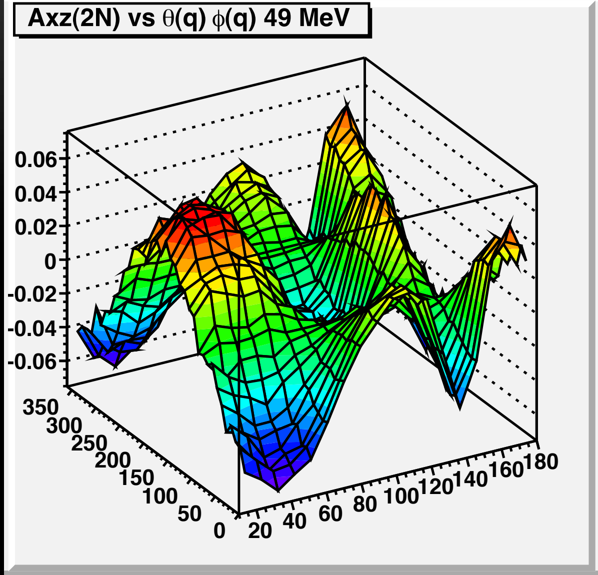
## For PAX detectors:

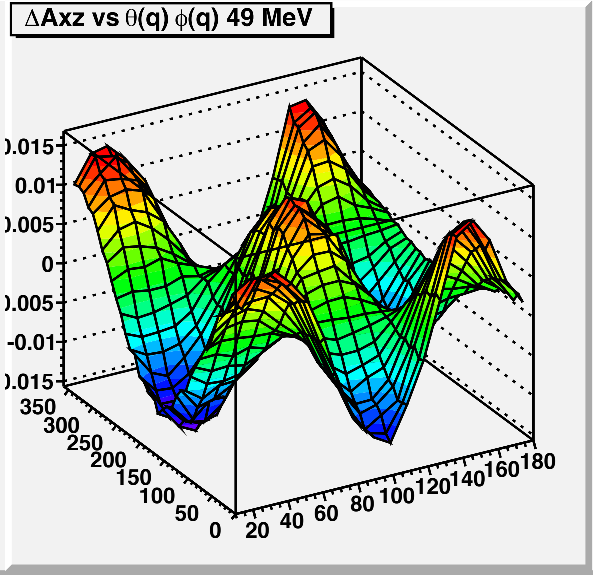
capacitor-shunt to reduce the collected charge delivered to the chips.

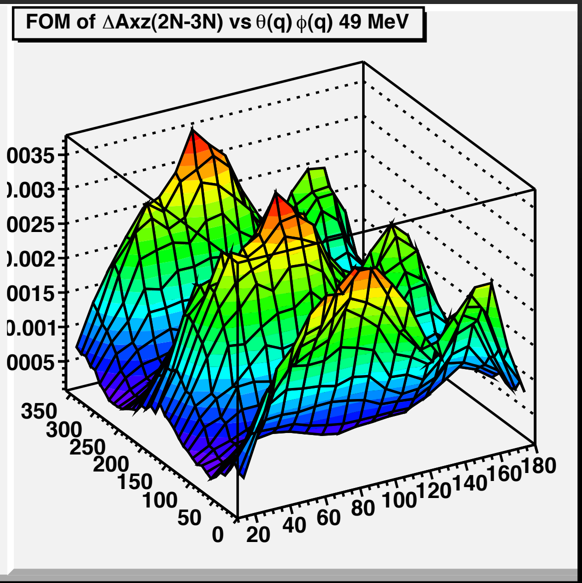
# Axz

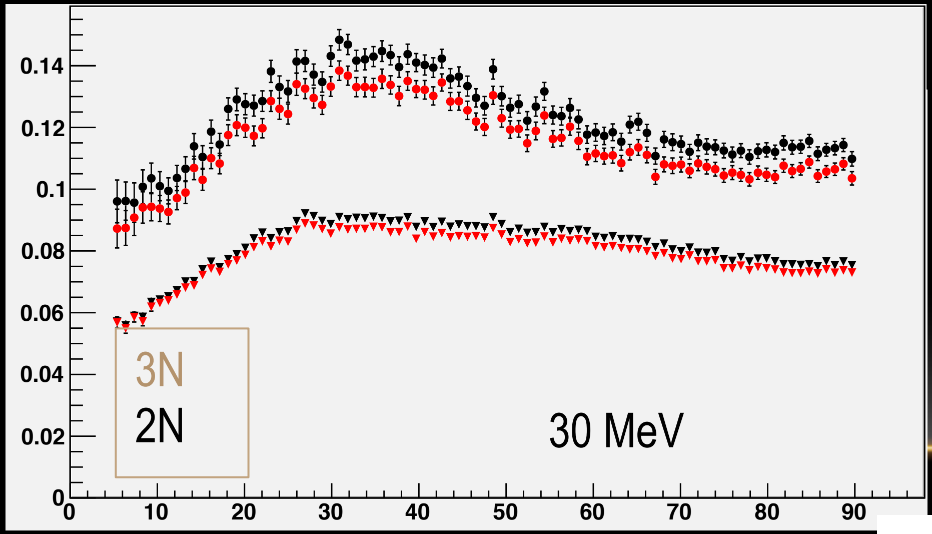

Axz(3N) vs θ(q) ϕ(q) 49 MeV (ΔAxz>0.03)
0.2
0.1
0
-0.1
-0.2
350
300
250
200
150
100
50
0
20
40
60
80
100
120
140
160
180
Axz(3N) vs θ(p) ϕ(p) 49 MeV (ΔAxz>0.03)
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25
350
300
250
200
150
100
50
0
10
20
30
40
50
60
70
80
90
Axz(3N) vs θ(p) p 49 MeV (ΔAxz > 0.03)
0.2
0.1
0
-0.1
-0.2
180
160
140
120
100
80
60
40
20
0
10
20
30
40
50
60
70
80
90

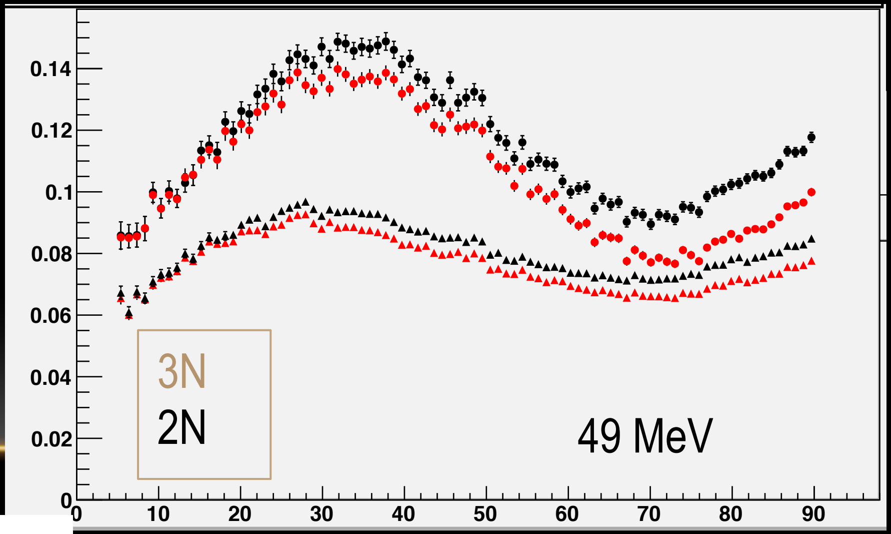
# AXZ


Axz(2N) vs θ(q) ϕ(q) 49 MeV


ΔAxz vs θ(q) ϕ(q) 49 MeV


FOM of ΔAxz(2N-3N) vs θ(q) ϕ(q) 49 MeV





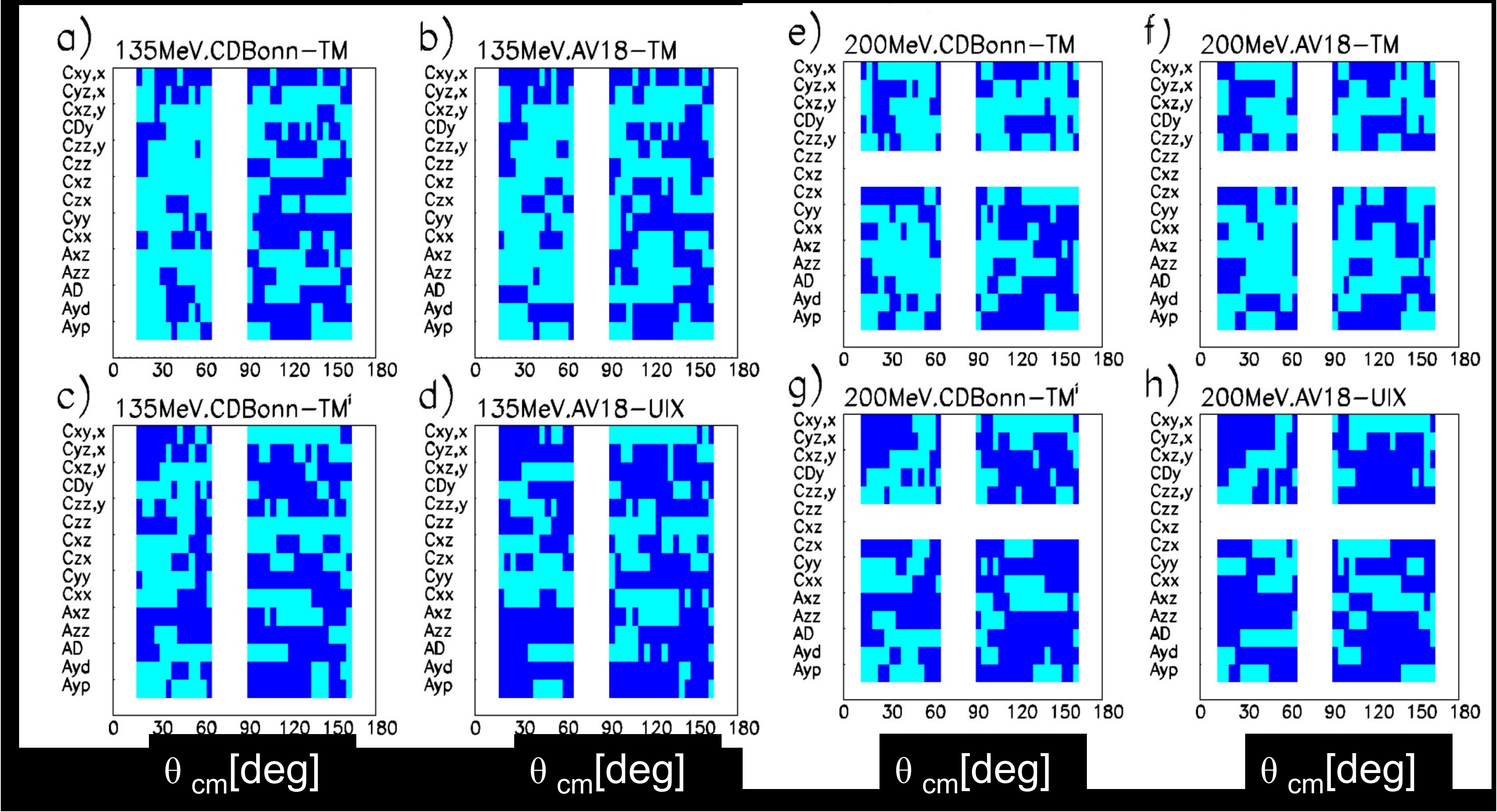
θp

**B.v. Przewoski et al., PRC 74, 064003 (2006), arXiv:nucl-ex/0411019**

# PD ELASTIC 135 & 200 MEV 3NFS

Each pixel corresponds to one of the 868 data points

A pixel is colored **blue if 3NF improves the agreement**



# 1H(D,PP)N REACTION @KVI AT 65 MEV/A BUP CROSS SECTIONS

St Kistryn, E Stephan and N Kalantar-Nayestanaki
SPIN 2010