The 22nd European Conference on Few-Body Problems in Physics

Investigation of the Three-Nucleon System Dynamics in the Deuteron-Proton Breakup Reaction

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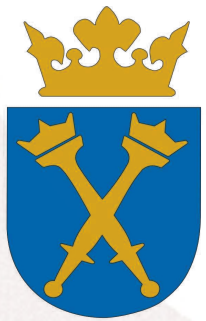


COLLABORATION

Jagiellonian University, Kraków, Poland

University of Silesia, Katowice, Poland

Forschungszentrum Juelich, Germany

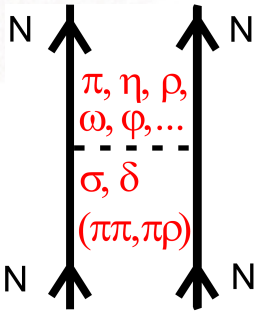
Institute of Nuclear Physics PAN, Kraków, Poland

KVI, Groningen, The Netherlands

In cooperation with theoretial groups:
Kraków-Bochum-Juelich
Hannover-Lisboa

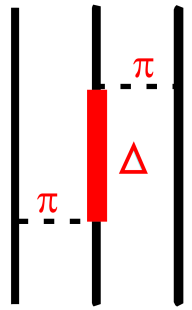
Goals & Motivations

- Few Nucleon interaction models (2N and 3N)
  - **Realistic potentials + phenomenological 3NF models**
  - **Chiral Perturbation Theory at NNLO**
  - **Coupled-Channels formalism with explicit Δ**



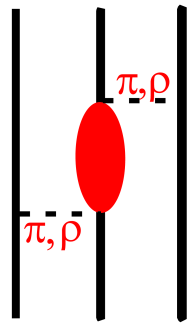
Coulomb interaction included !

A. Deltuva, Phys. Rev. C 80 064002, 2009



- Faddeev framework provides exact treatment for the 3N system

- Different effects to be traced
  - **Coulomb force action**
  - **Influences of 3NF**
  - **Relativistic effects - NEW ACHIEVEMENT !**



H. Witała, R. Skibiński, Eur. Phys. J. A 30, 369 (2006)

  - **Mutual interplay of the effects**

Experimental Tools: Three-Nucleon Scattering @ Medium Energies

- **Elastic: N + d → N + d**
  - Beams of p or d
  - Various observables

Rich Phase-Space:
- a large amount of kinematical configurations
- selectivity

- **Breakup: N + d → N + N + N**
  - Beams of p or d
  - Various observables

Leading Channel @ Intermediate Energies
nd total cross section
$\sigma_{br} > \sigma_{el}$

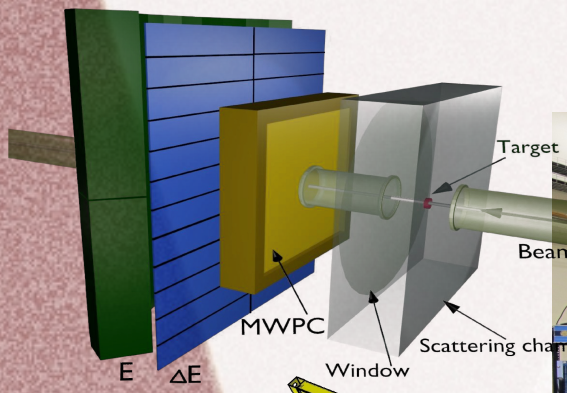
deuteron-nucleon breakup reaction
is best suited to study 3N system dynamics

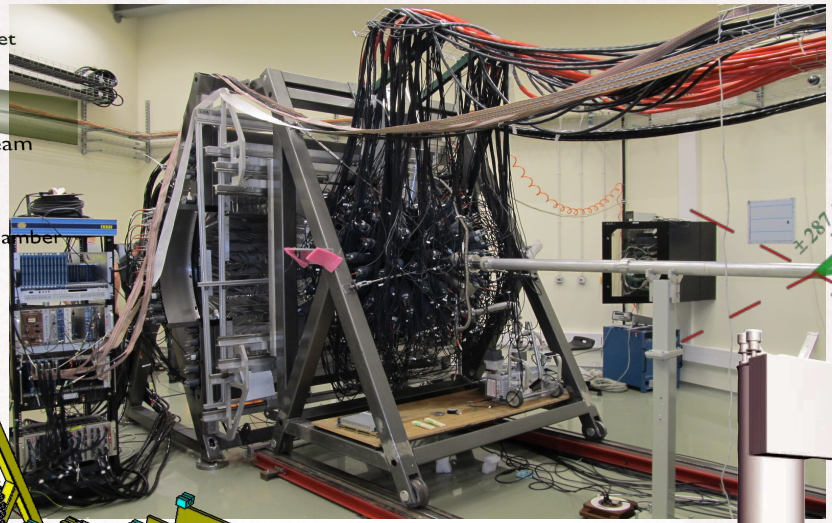
Experimental Tools: Apparatus

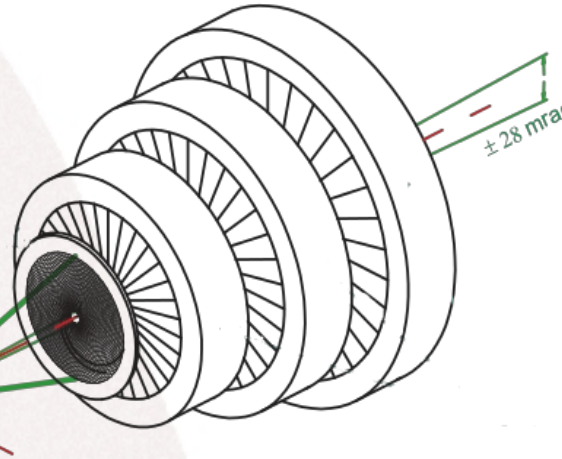
In order to reach meaningful conclusions about the interaction models experimental coverage of **large phase space regions** and as **precise data** as possible are needed.

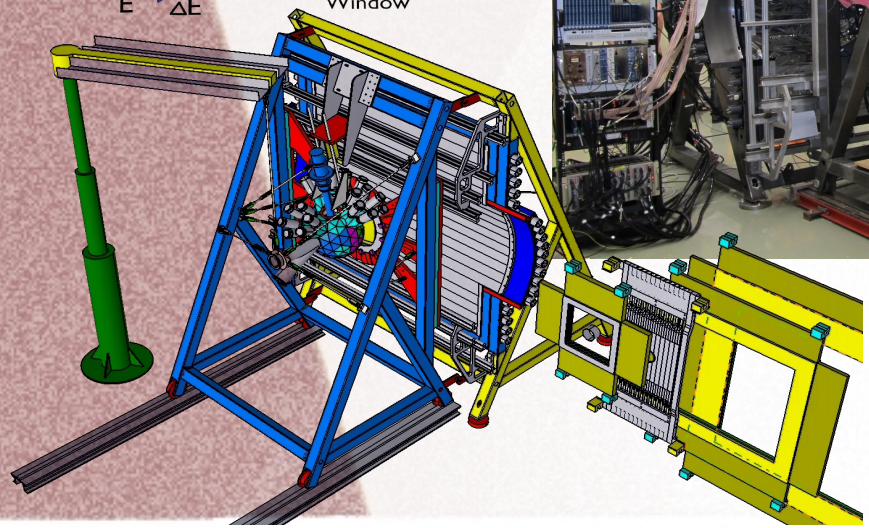
KVI

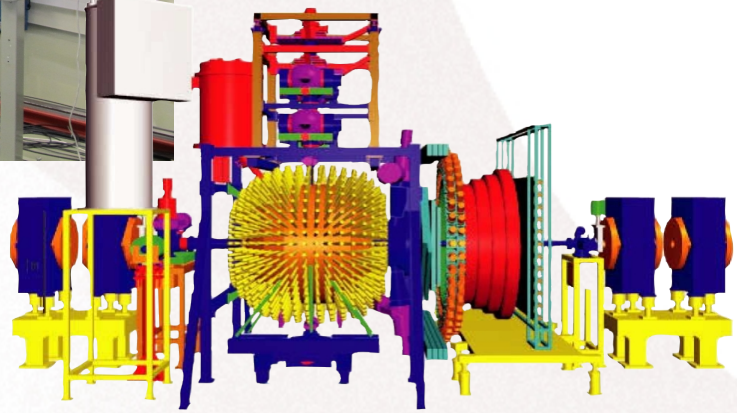
JÜLICH
FORSCHUNGSZENTRUM









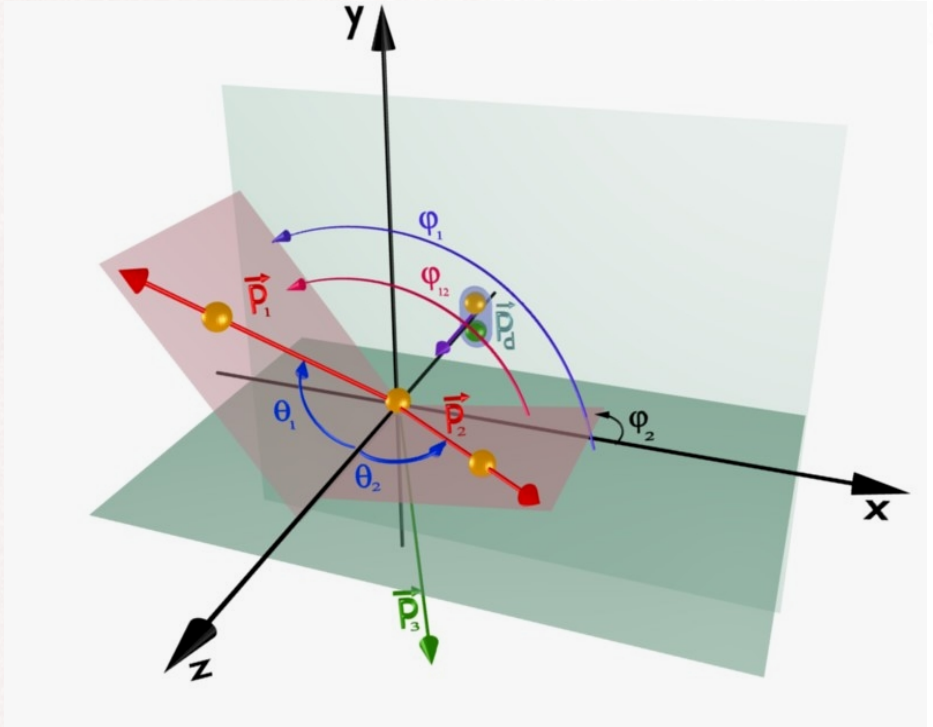


Breakup Reaction Kinematic

- **Three nucleons in the final state**
  - **9 variables**
- **Energy-momentum conservation – 4 equations**

Five independent kinematical variables:

$\theta_1, \theta_2, \varphi_{12}=\varphi_1-\varphi_2, E_1, E_2$

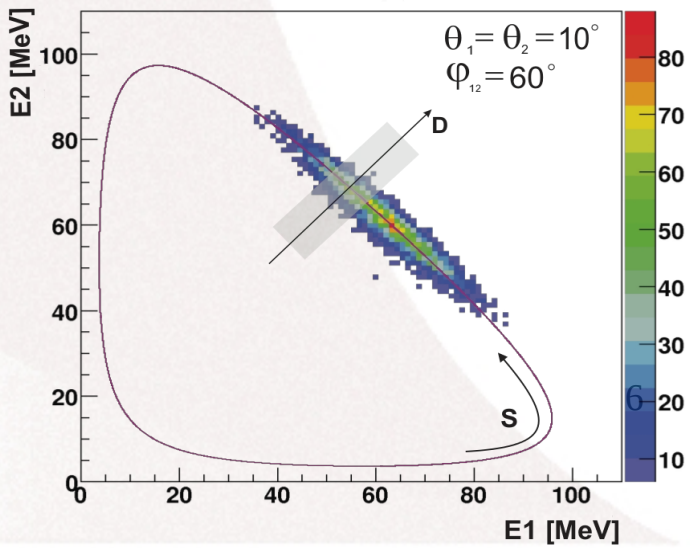


- ✓ Complete (exclusive) exp. – measured ≥ 5
- ✓ Inclusive exp. – measured ≤ 4 parameters

^{1}H(d,pp)n measured: directions and energies of two protons

arclength variable S

distance from kinematical curve D



Measurements @ KVI Groningen

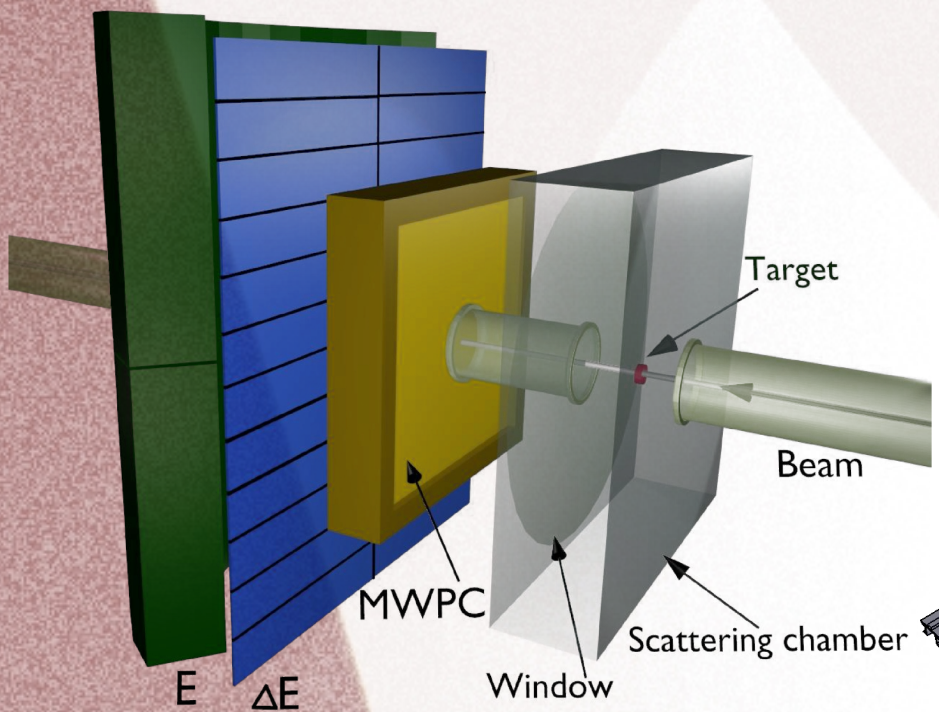
SALAD

- 140 ΔE-E telescopes
- 3 plane MWPC

angular acceptance:

θ = 12º – 38º

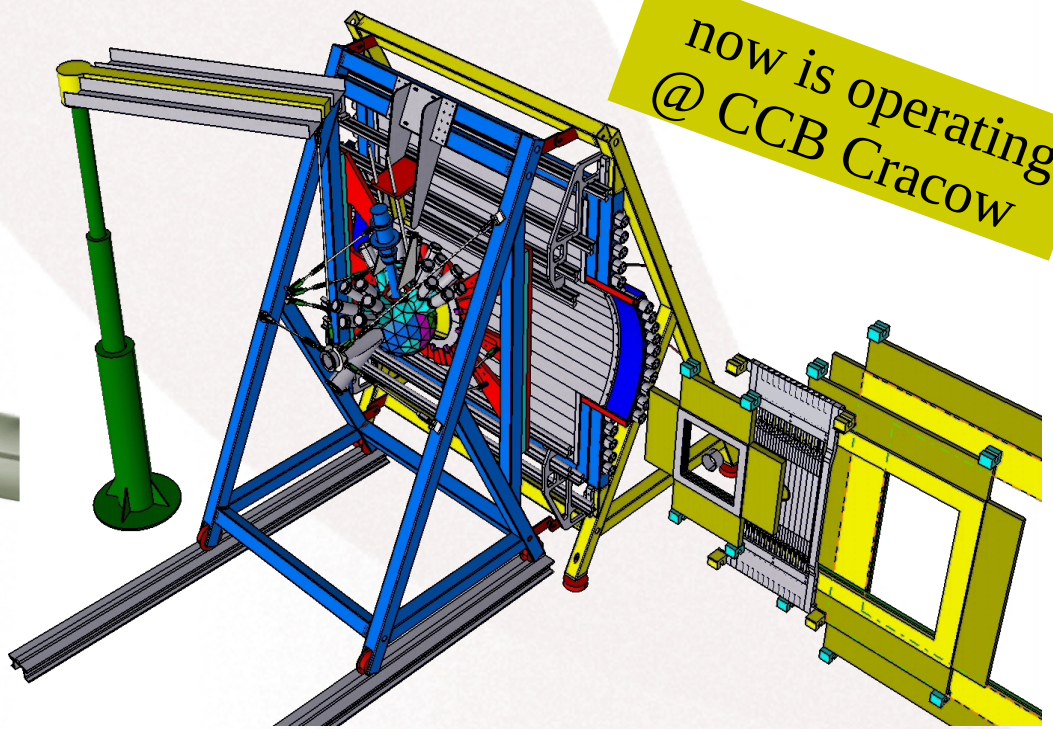
φ = 0º – 360º



BINA

- *Wall* - very similar to SALAD
- *Ball* - system of 149 phoswitch detectors

angular acceptance: nearly 4π



now is operating @ CCB Cracow

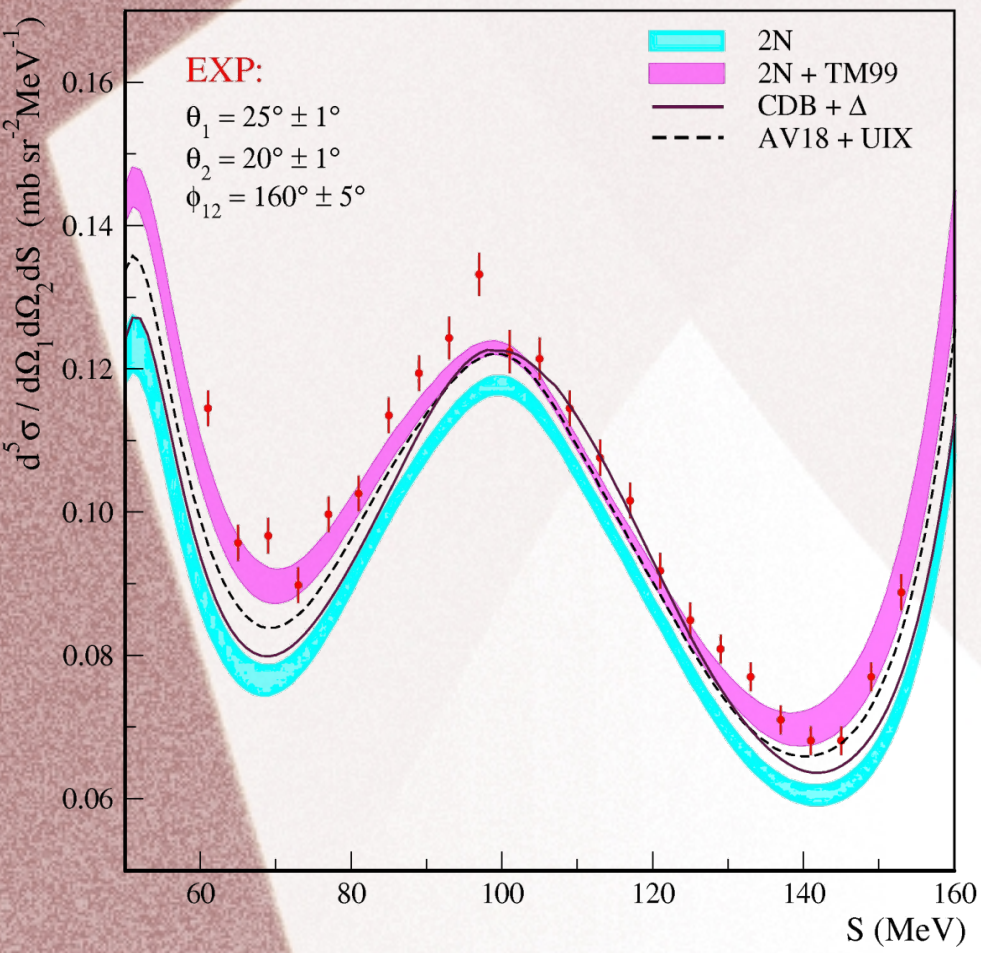
Cross Sections of ^{1}H(d,pp)n Breakup @ 130MeV

SYSTEMATIC STUDY !

- Nearly 1800 cross section data points
  - $\theta_1, \theta_2 = 15^o - 30^o$; grid 5^o; $\Delta\theta = \pm 1^o$
  - an additional set for $\theta_1, \theta_2 = 13^o$
  - $\varphi_{12} = 40^o - 180^o$; grid $10^o - 20^o$; $\Delta\varphi = \pm 5^o$
  - S [MeV] = 40 – 160; grid 4; $\Delta S = \pm 2$
  - Statistical accuracy 1% – 4%
  - Data very clean – accidentals below 2%
  - Systematic errors of 3% – 5%
- Global comparisons with theory (χ^2 for all points, $\chi^2 = f(\varphi_{12})$, $\chi^2 = f(E_{rel})$, tests of normalization)

Breakup Cross Sections @ 130 MeV

Example:



Faddeev calculations

Realistic NN potentials:

CD Bonn, NijmI, NijmII, Av18

3NF model: TM99, UIX

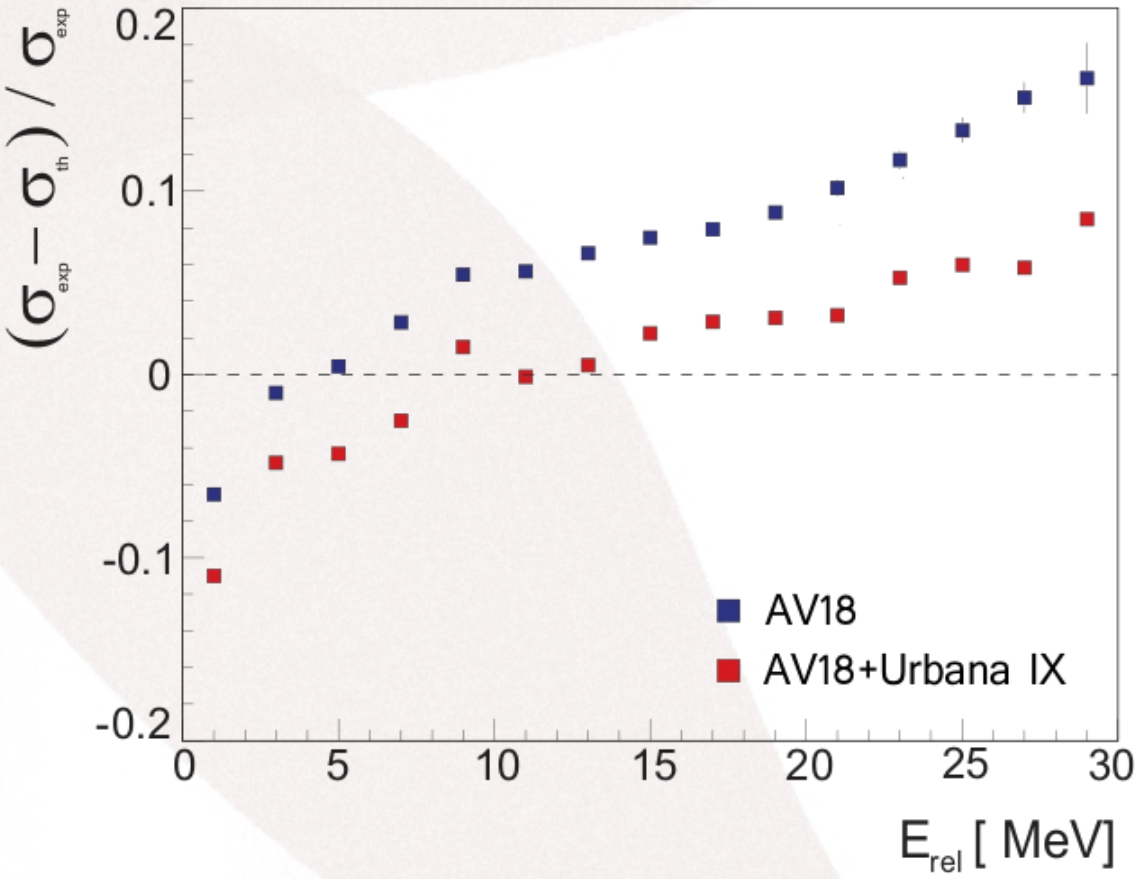
Coupled channels:

CD Bonn (modif.) + Δ

Conclusions

3NF influence

Including 3NF increases discrepancies at low E_{rel} and reduces them at higher E_{rel} values

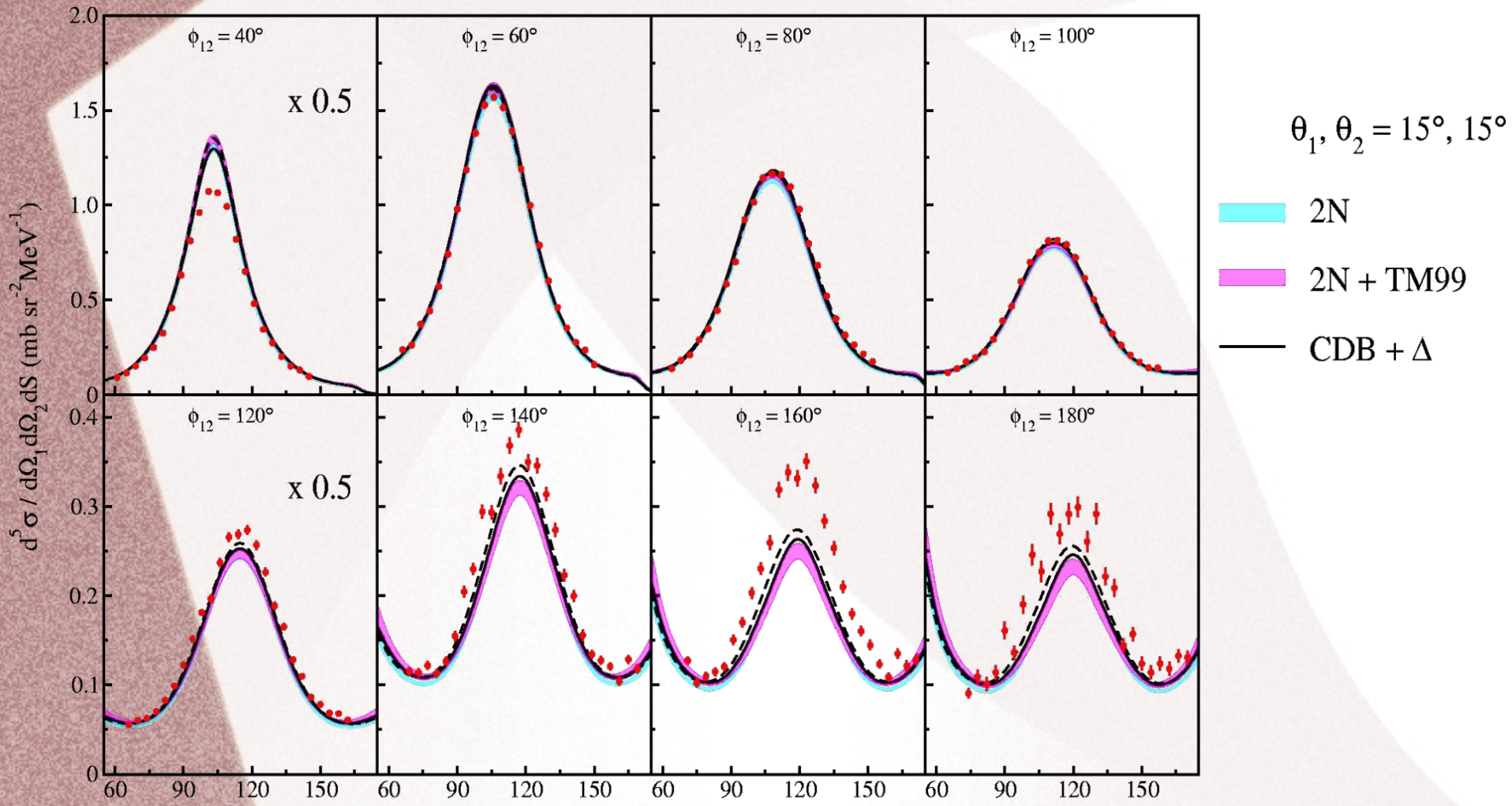


In general:
Including 3NF's reduces global χ^2 by about 30%

[Phys. Rev. C 72 (2005) 044006]

Breakup Cross Sections @ 130 MeV

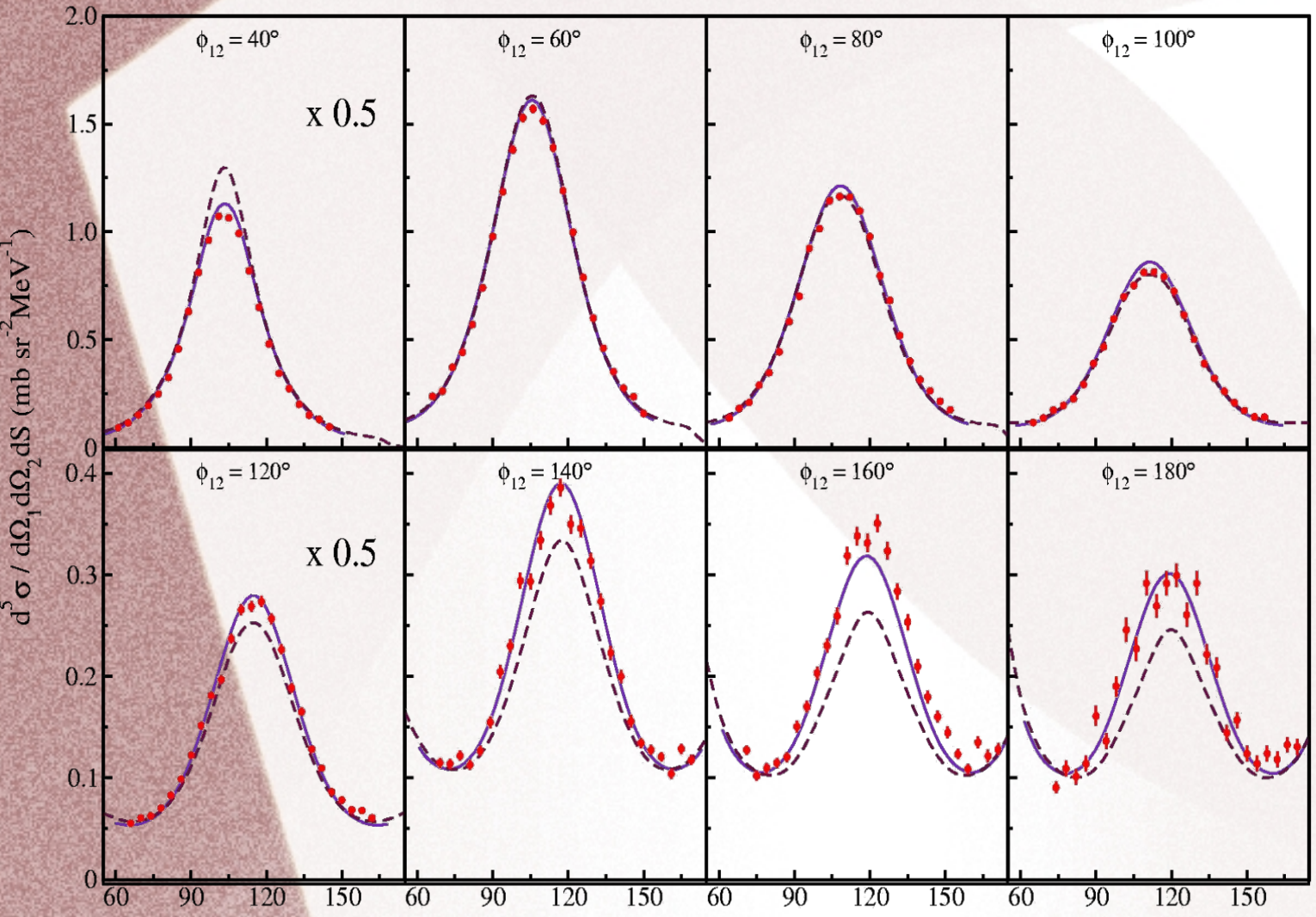
Discrepancies:



Breakup Cross Sections @ 130 MeV

Discrepancies removed by including Coulomb force !

A. Deltuva et al., Phys. Rev. C 73 057001, 2006



$\theta_1, \theta_2 = 15°, 15°$

Coupled Channel

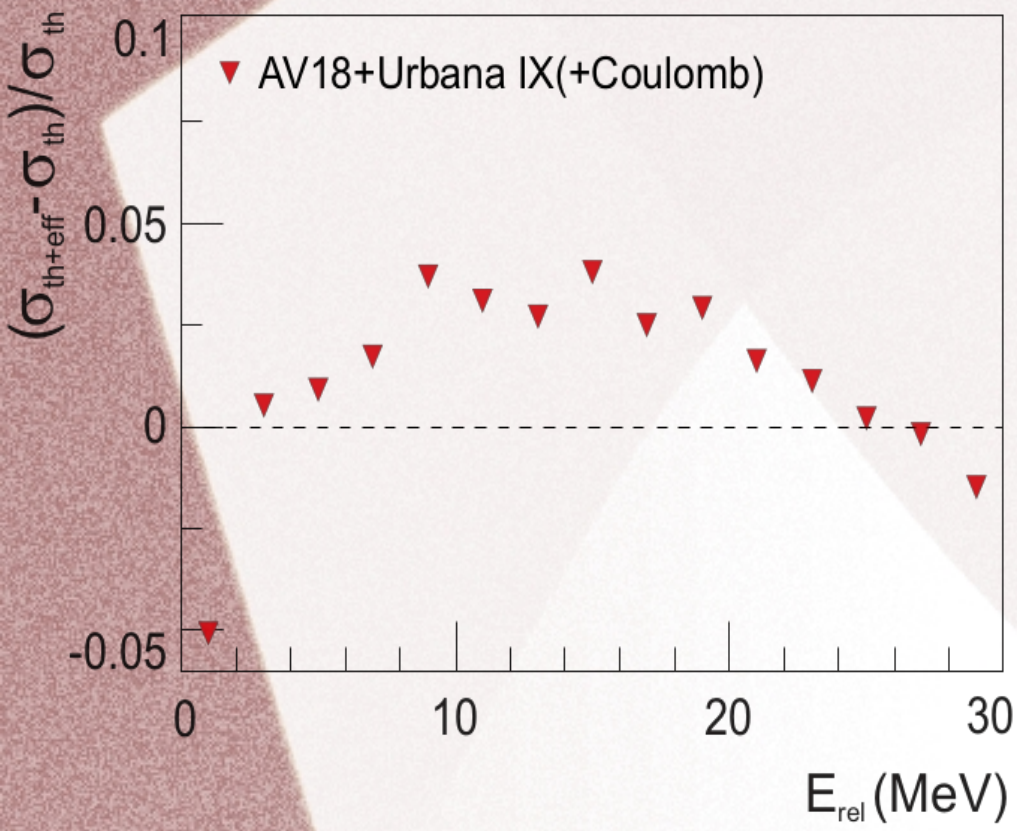
CDB + Δ

CDB + Δ + C

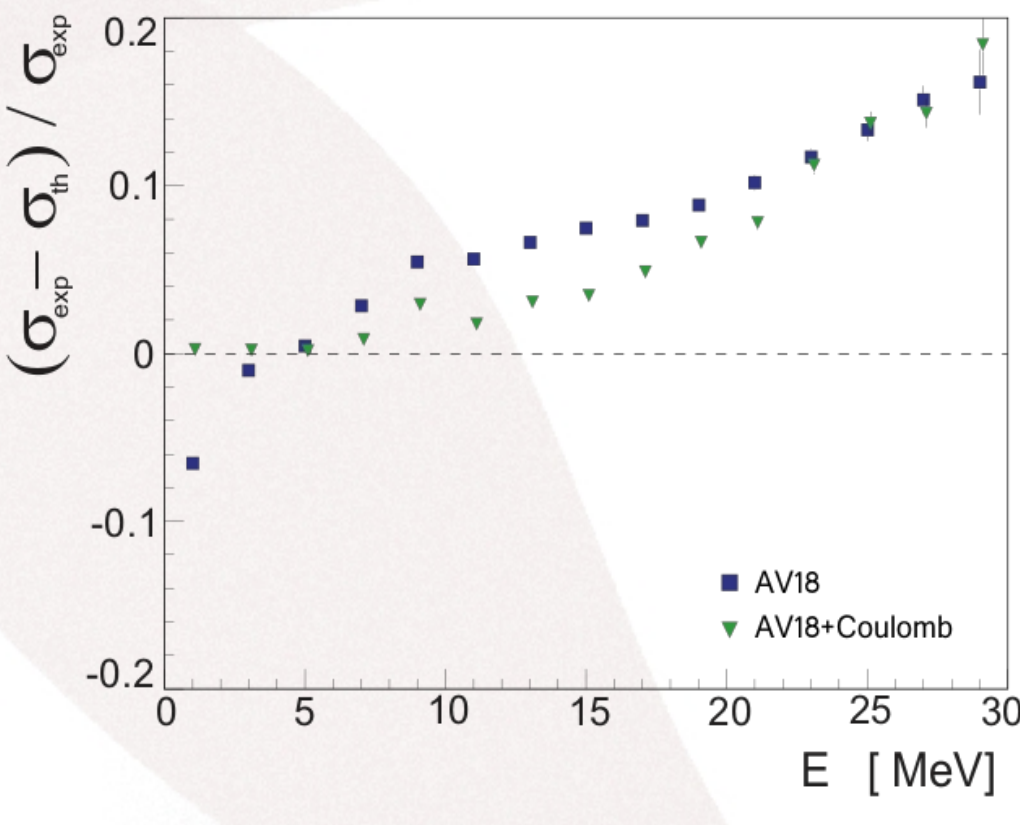
Coupled Channel with Coulomb

Conclusions: Coulomb Force

calculated effect



with respect to the experimental data

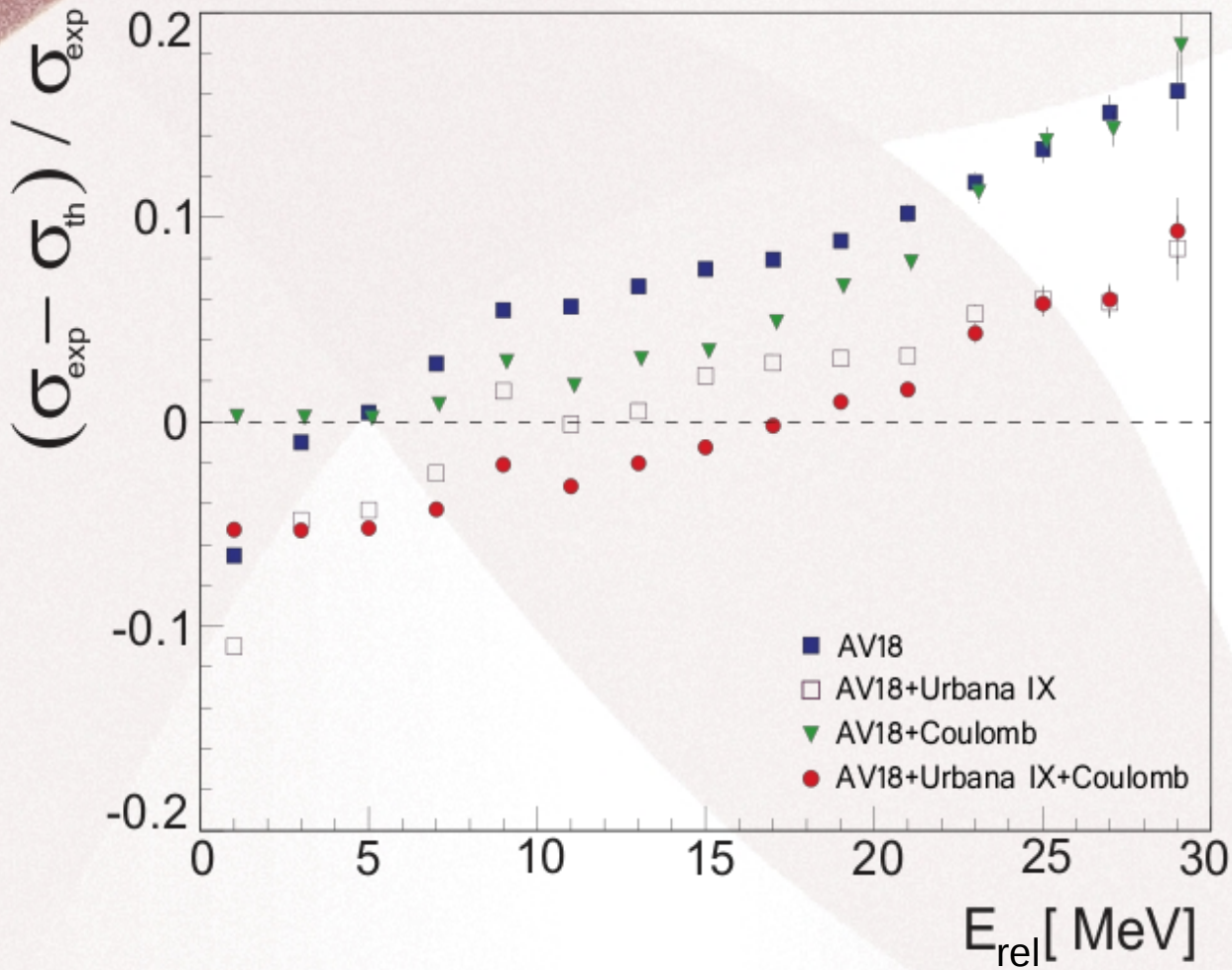


Clear signature of Coulomb effects at small relative energy values !

[Phys. Lett. B 641 (2006) 23]

Conclusions

Coulomb Force & 3NF



Coulomb force + 3NF gives much better agreement with the data !

Studies of Coulomb Force Effects
Dedicated Experiment @ 130 MeV

Apparatus: Germanium Wall @ FZ-Juelich

- QUIRL – ΔE detector with 2x200 spirals
- 2 PIZZAS – E detectors

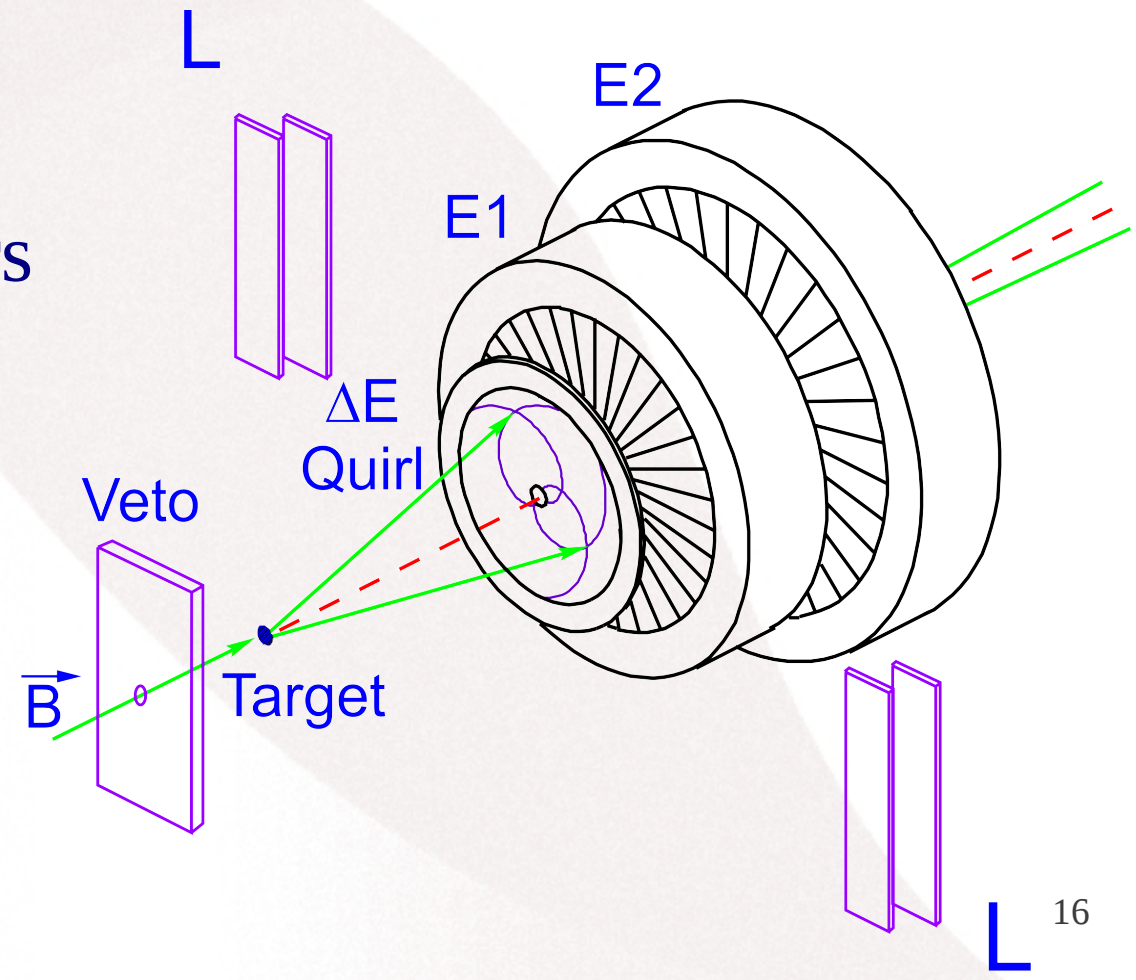
<u>angular acceptance</u>:

$\theta = 5^0 - 14^0$

$\varphi = 0^0 - 360^0$

$\vec{d}+p \rightarrow p+p+n$

$\vec{d}+p \rightarrow d+p$



Studies of Coulomb Force Effects
Dedicated Experiment @ 130 MeV

Nearly 1800 cross section data points:

$\theta_1, \theta_2 = 5^o–14^o$; grid 2^o; $\Delta\theta = \pm1^o$

✓ $\varphi_{12} = 20^o–180^o$; grid 20^o; $\Delta\varphi = \pm5^o$

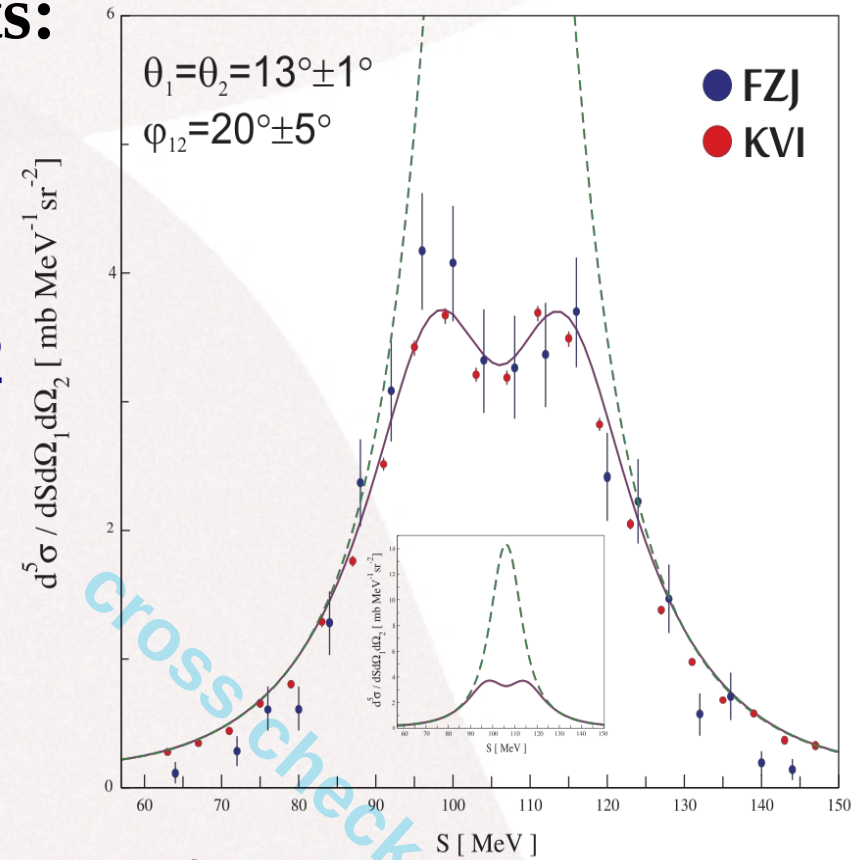
✓ S [MeV] = 40–180; grid 4; $\Delta S = \pm2$

✓ Statistical accuracy 2%–5%

✓ Data very clean

– accidentals below 2%

✓ Systematic errors of 5%–19%



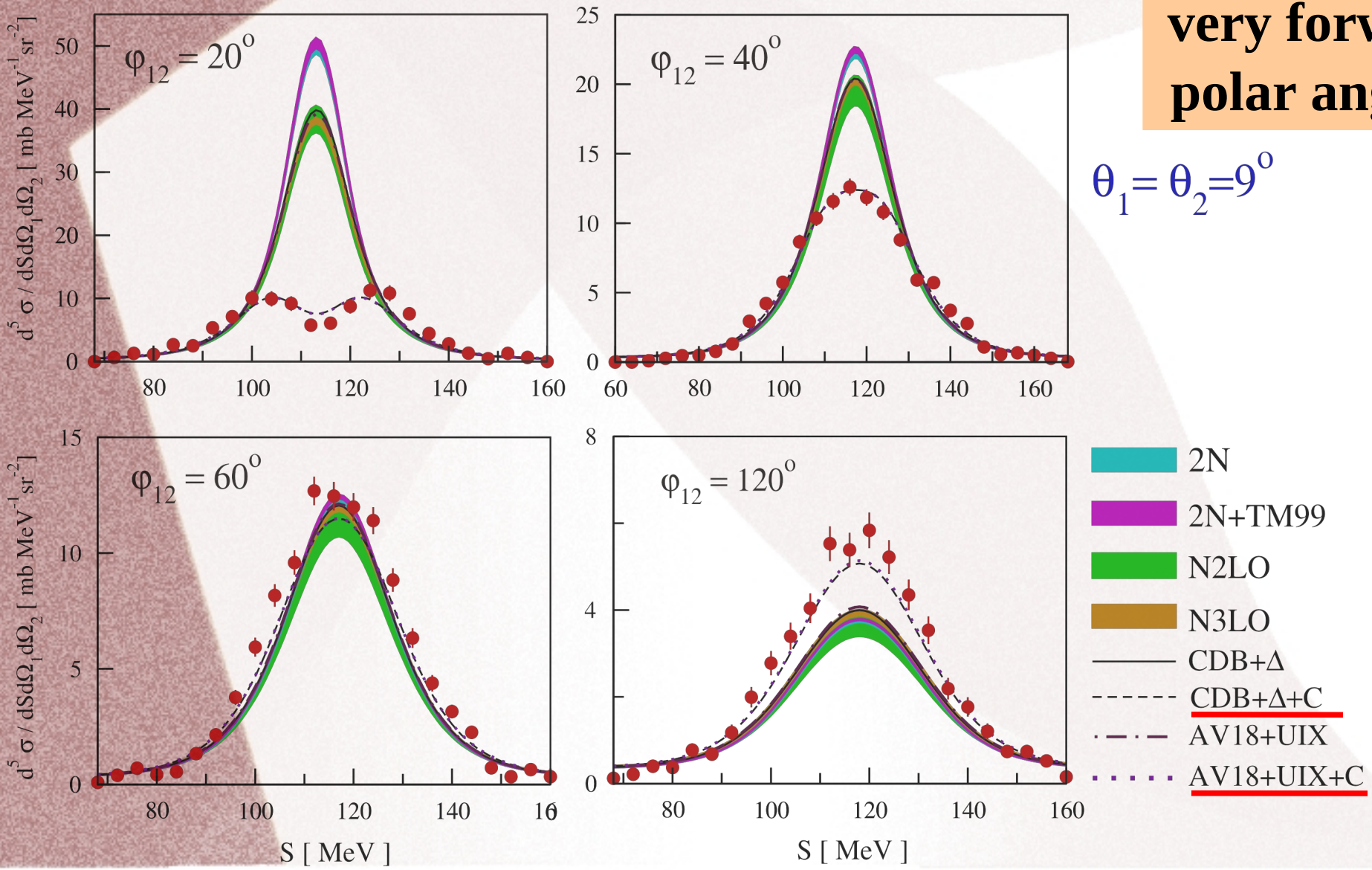
Global comparisons with theory (χ^2 /d.o.f.,

$\chi^2 = f(\varphi_{12})$, $\chi^2 = f(\theta_1, \theta_2)$, $\chi^2 = f(E_{rel})$)

Cross Sections of ^{1}H(d,pp)n Breakup @ 130MeV - FZ-Juelich Experiment

range of very forward polar angles

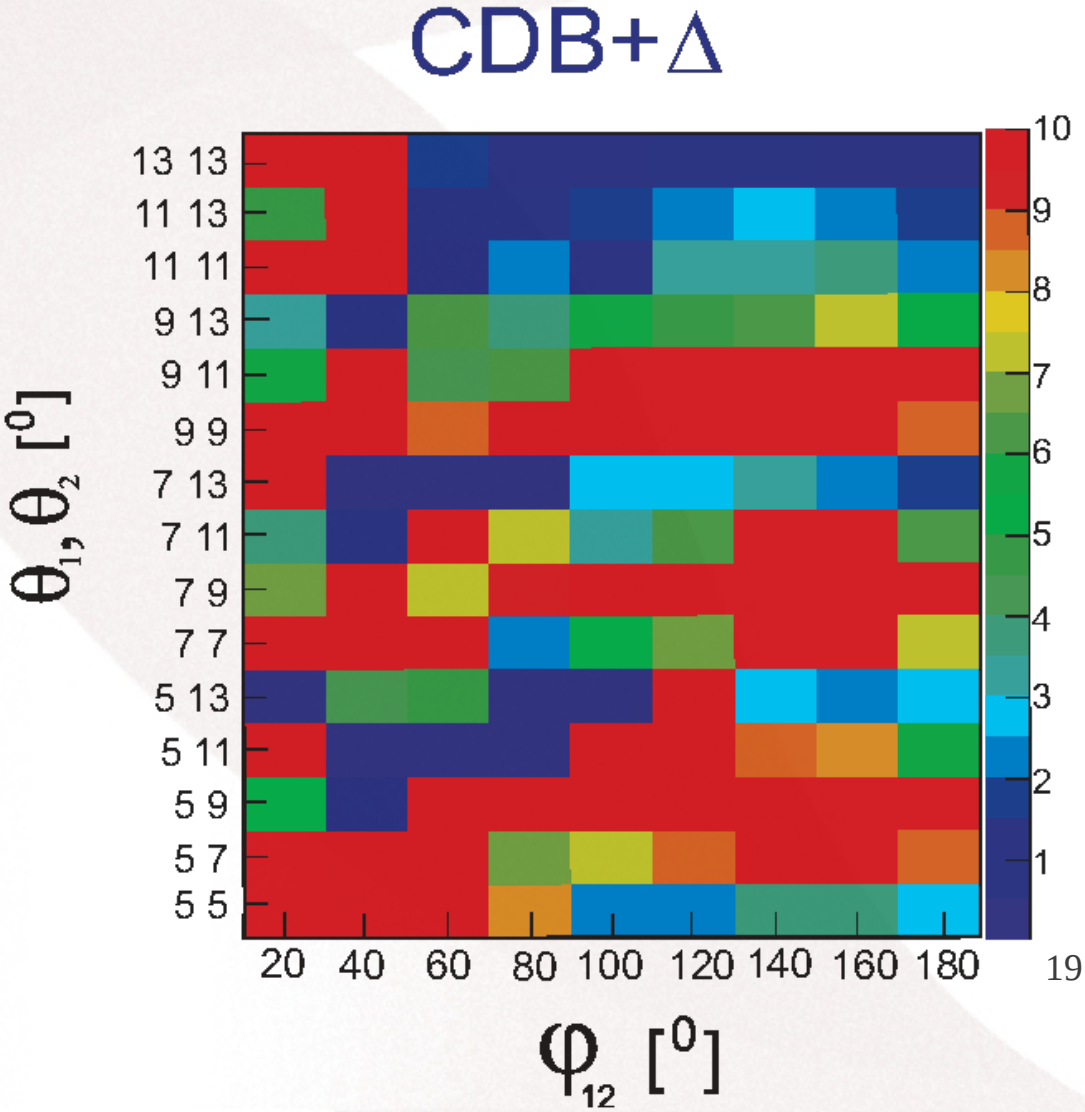
$\theta_1 = \theta_2 = 9^o$



Local Dependencies:

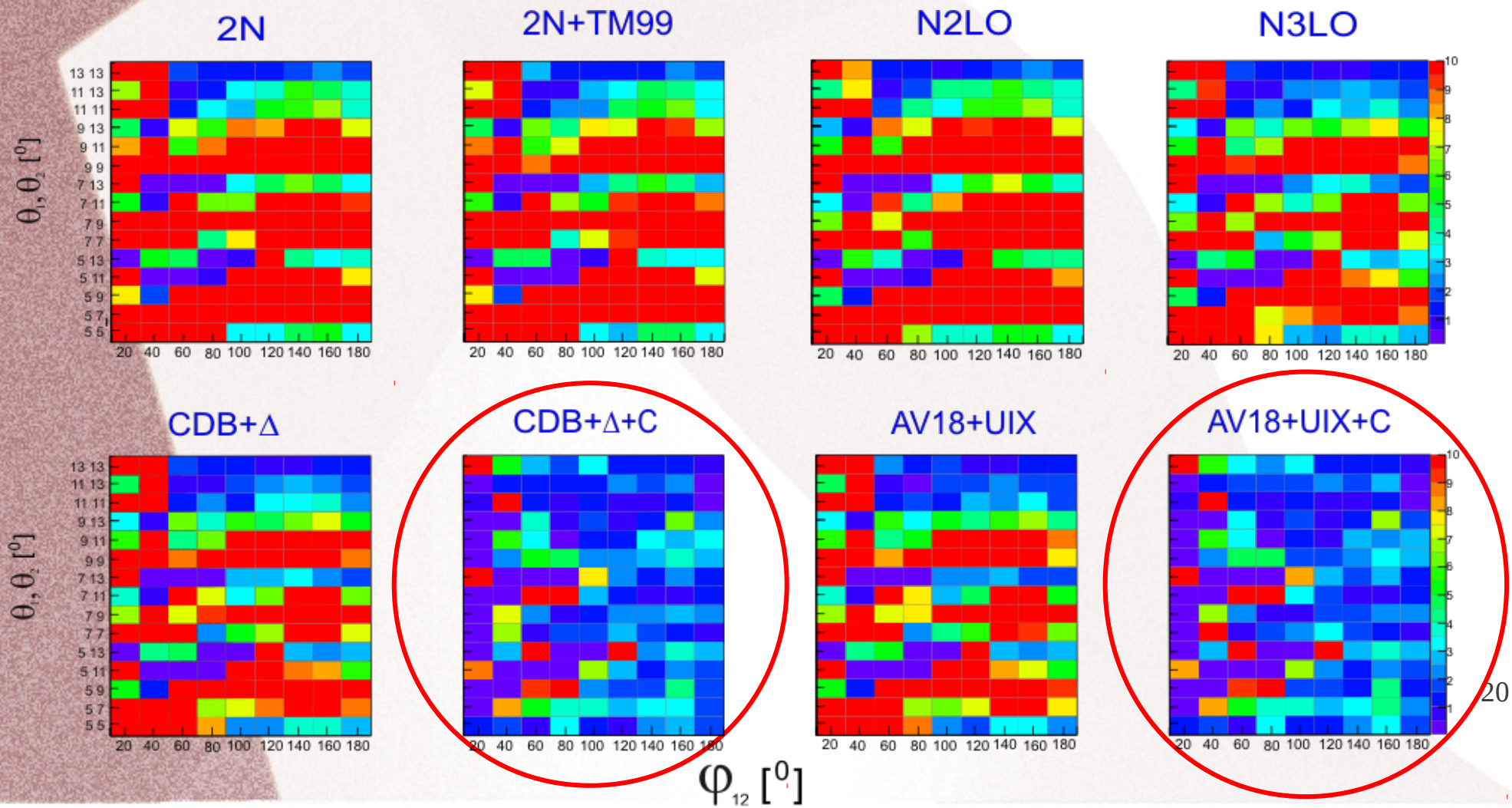
$$\chi^2/d.o.f. = \sum_{i=1}^{N} \frac{\left(\sigma^{\exp}(S_i) - \sigma^{th}(S_i)\right)^2}{\left(\Delta\sigma^{exp}(S_i)\right)^2}$$

calculated for
a given configuration
with respect to
the specific theory

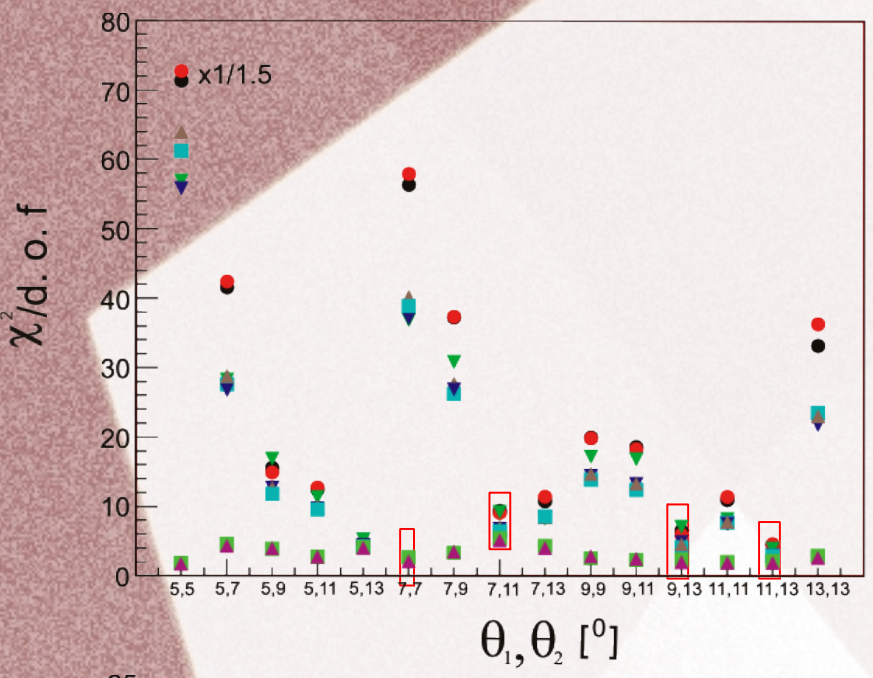


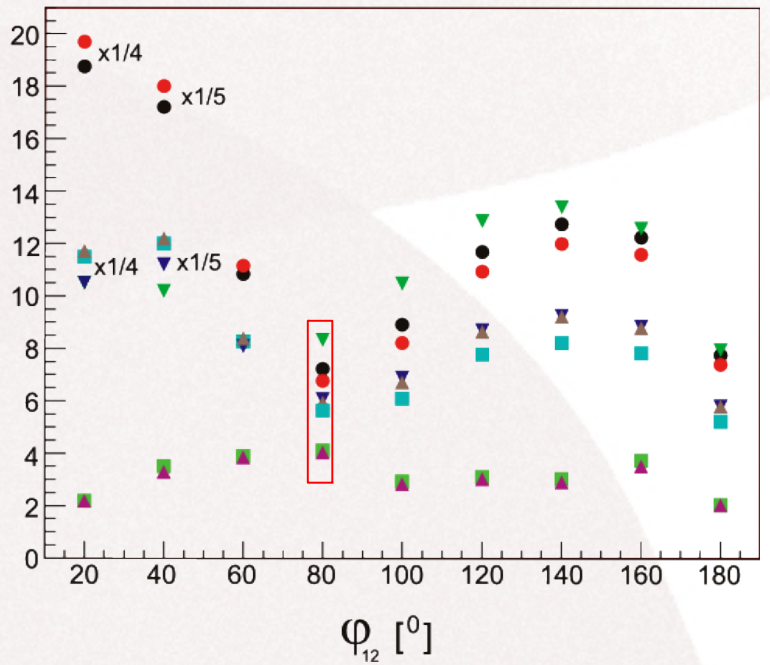
Local Dependencies:

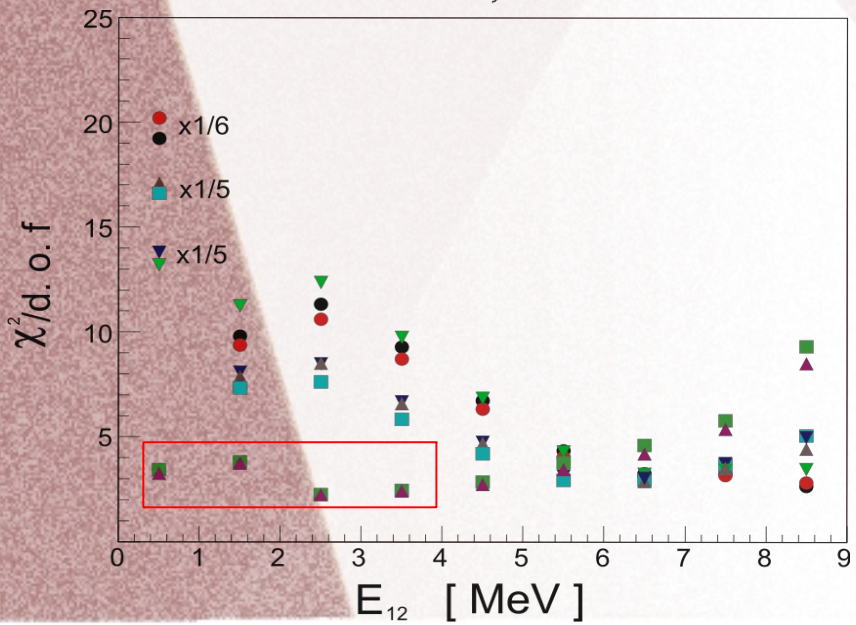
$$\chi^2/d.o.f. = \sum_{i=1}^{N} \frac{\left(\sigma^{\exp}(S_i) - \sigma^{th}(S_i)\right)^2}{\left(\Delta\sigma^{exp}(S_i)\right)^2}$$



Global Dependencies:





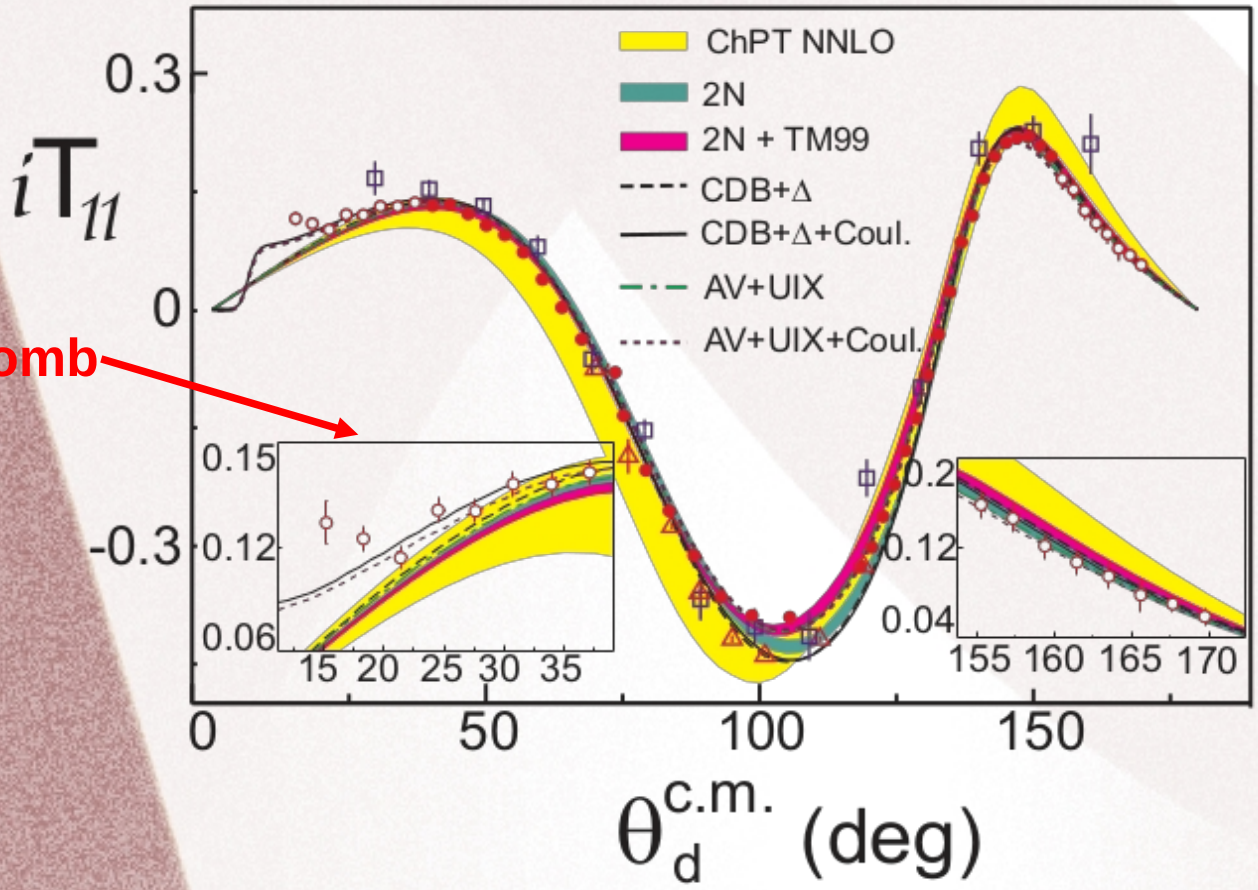


2N
2N+TM99
N2LO
N3LO
CDB+Δ
CDB+Δ+C
AV18+UIX
AV18+UIX+C

- ✓ Coulomb influence small at certain configurations: φ_{12} or θ_1 , θ_2
- ✓ Coulomb influence not important at $E_{rel} > 5$ MeV

Analyzing Powers @ 130 MeV at Very Forward Polar Angles

Values of iT_{11} are very small and agree quite well with theoretical predictions



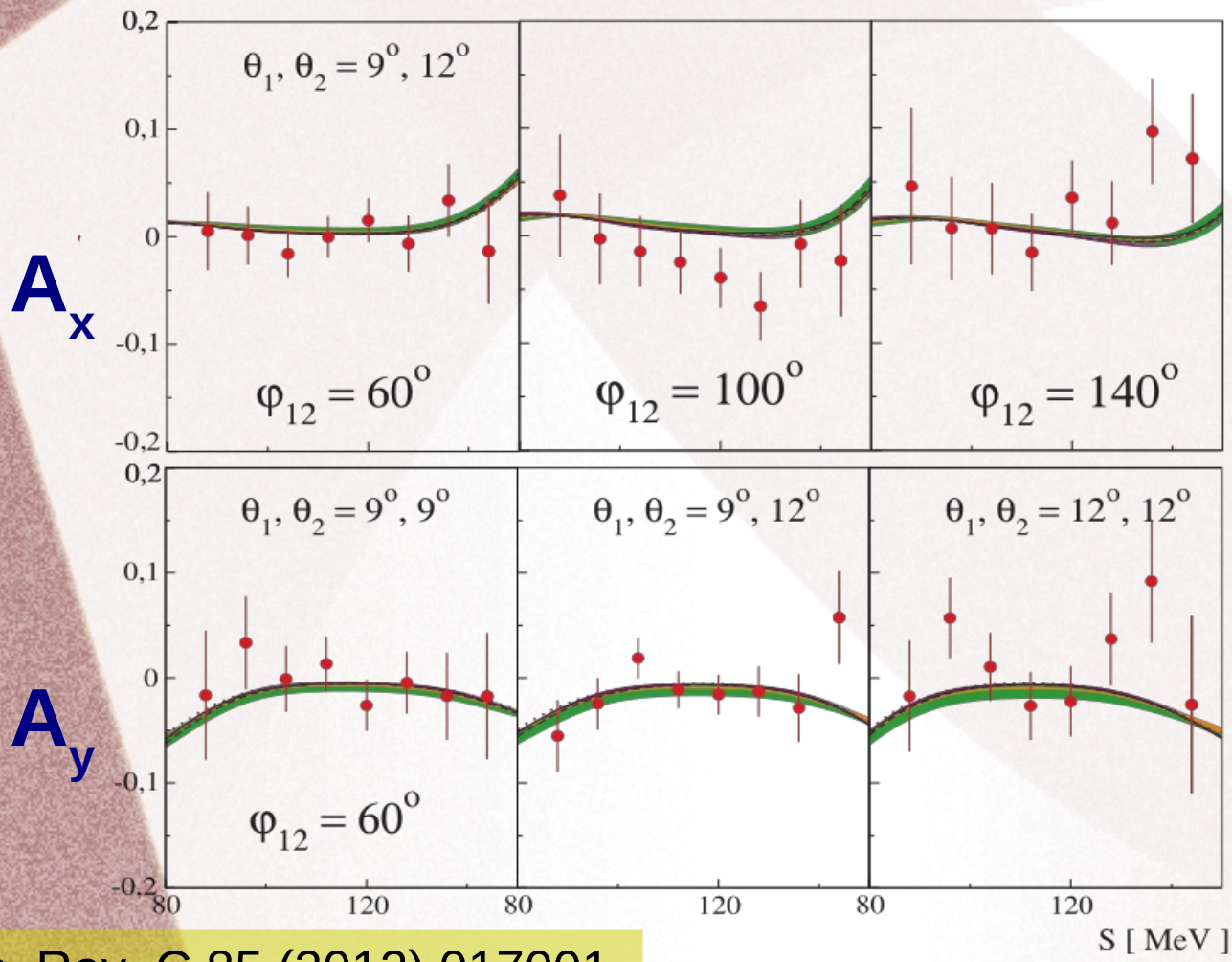
Coulomb

d+p elastic scattering

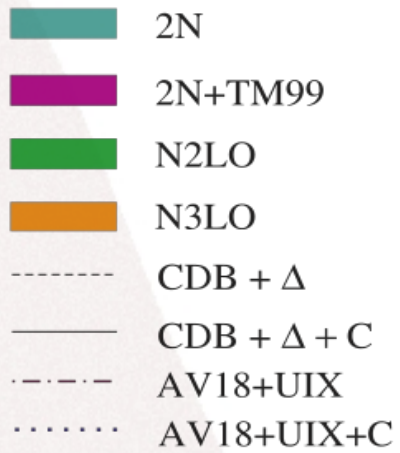
Phys. Rev. C 85 (2012) 017001

Analyzing Powers @ 130 MeV at Very Forward Polar Angles

A_x and A_y are very small and they are not sensitive to any dynamical effects



$^1H(\vec{d},pp)n$



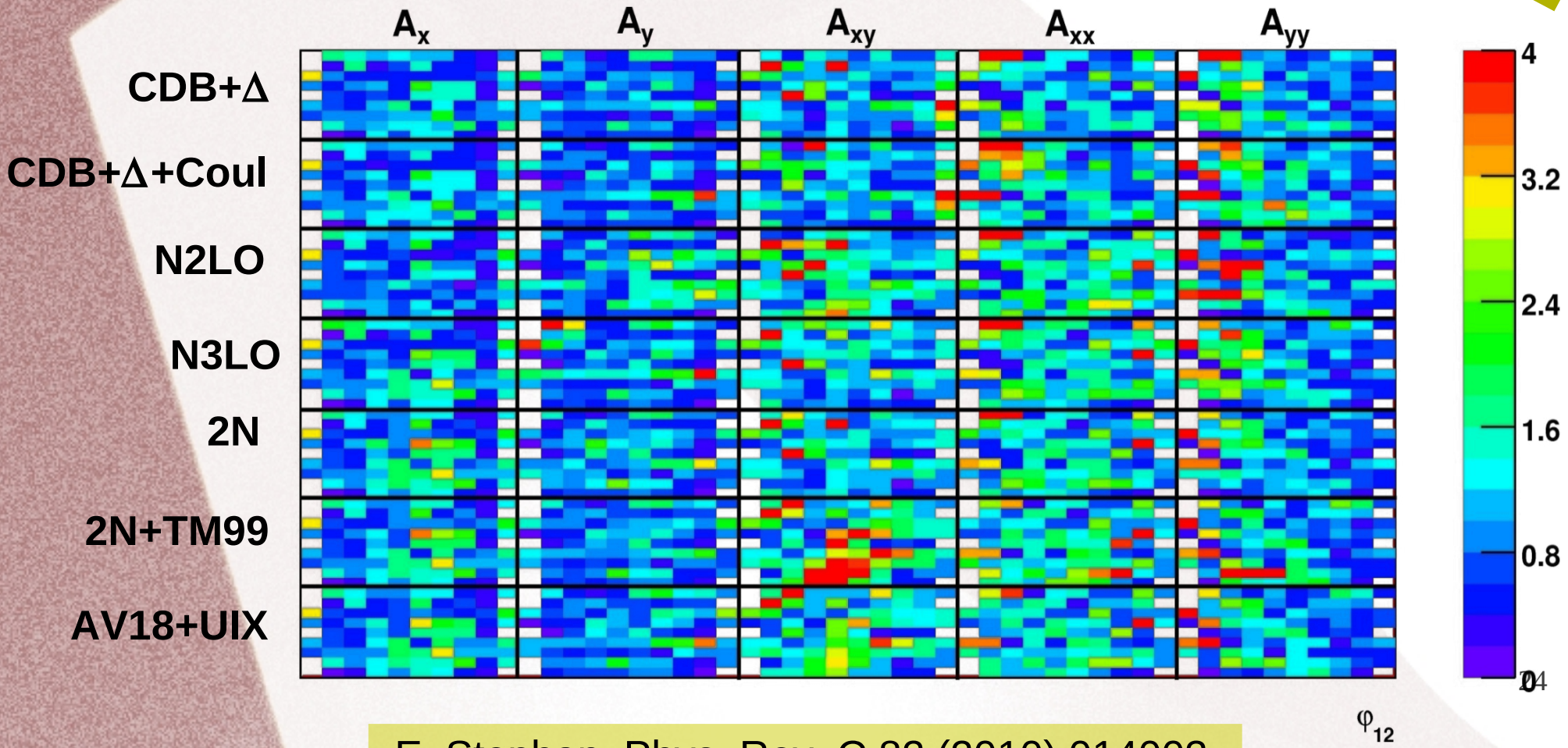
Phys. Rev. C 85 (2012) 017001

Breakup Analyzing Powers @ 130 MeV

χ^2/d.o.f. for all studied geometries:

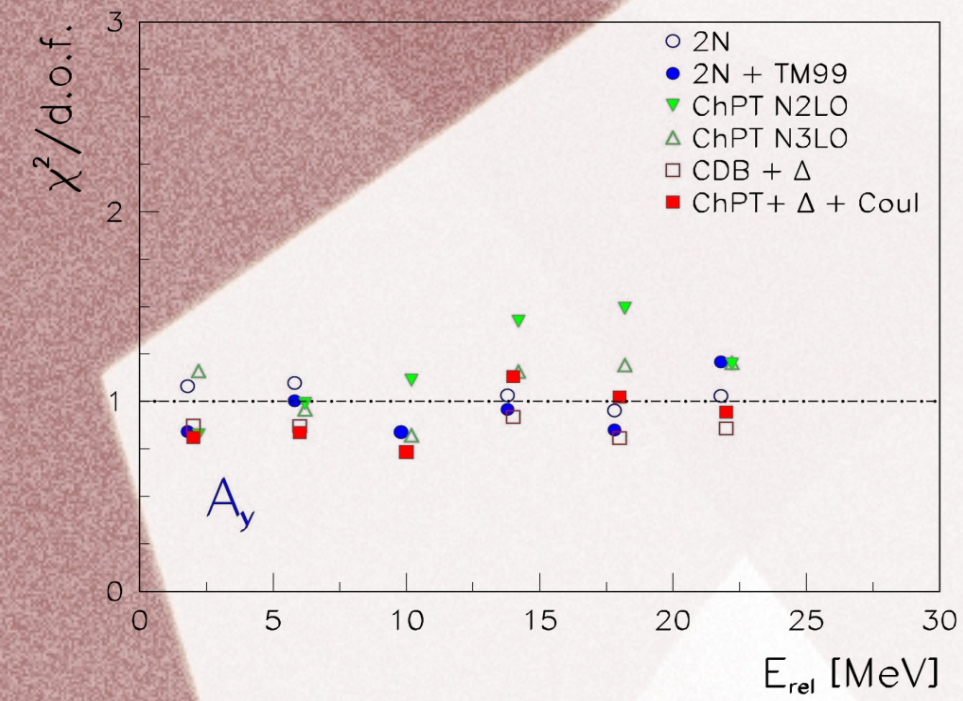
- very good description of vector analyzing powers
- model independent problem with description of tensor analyzing powers (2N+TM99, Av18+Urbana)

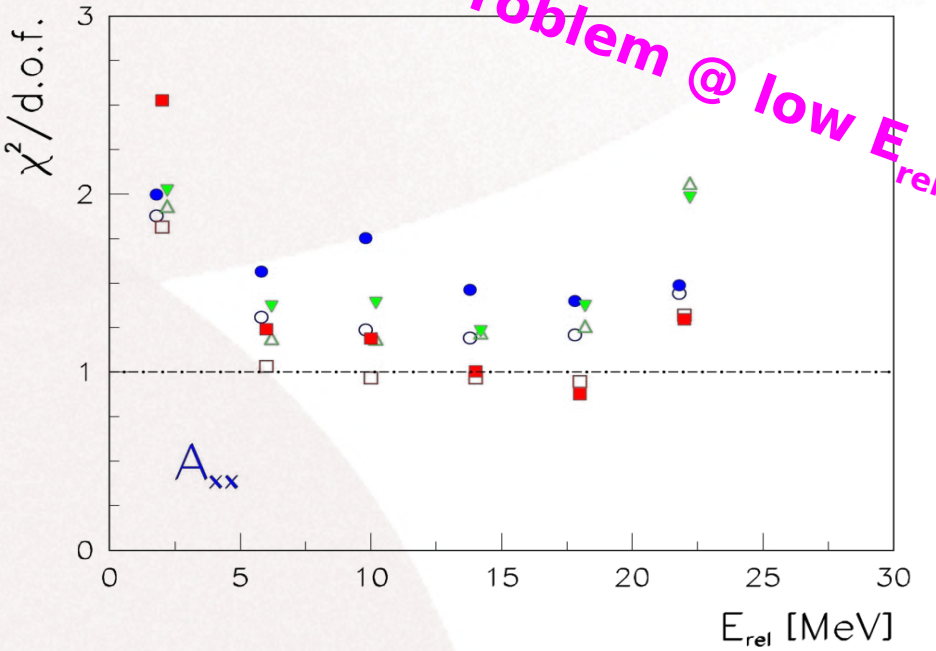
SYSTEMATIC STUDY !

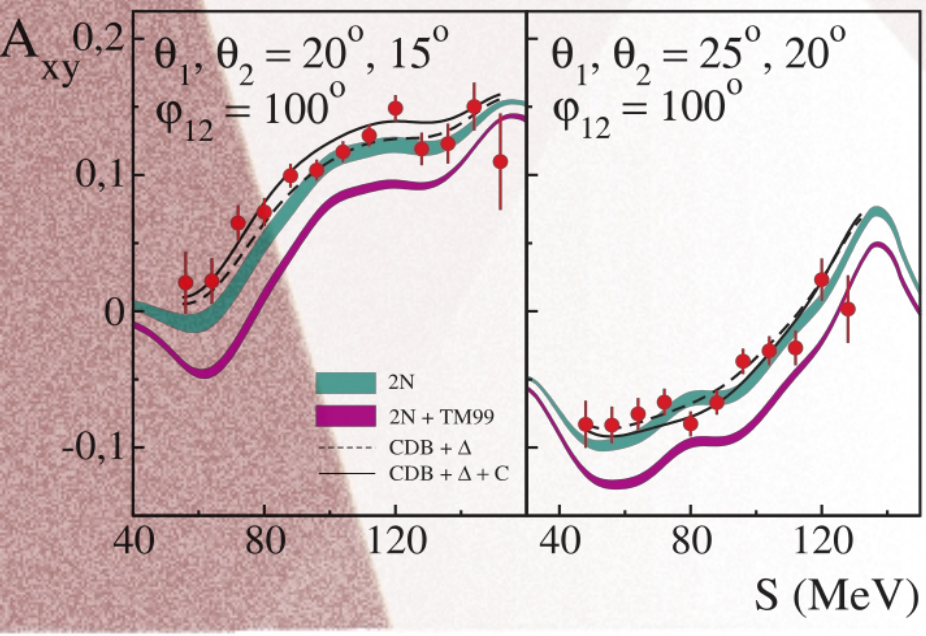


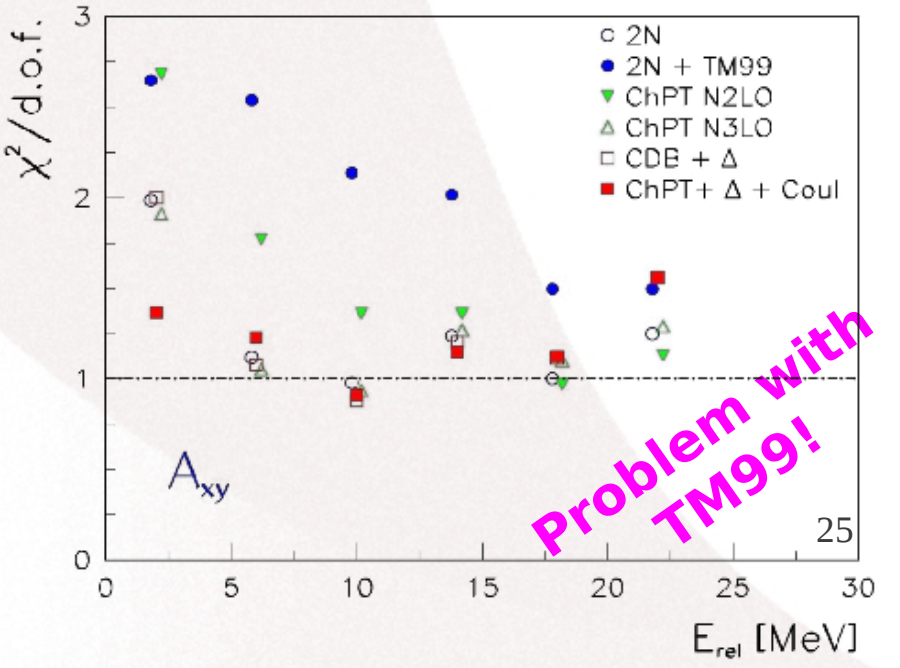
E. Stephan, Phys. Rev. C 82 (2010) 014003

Breakup Analyzing Powers @ 130 MeV

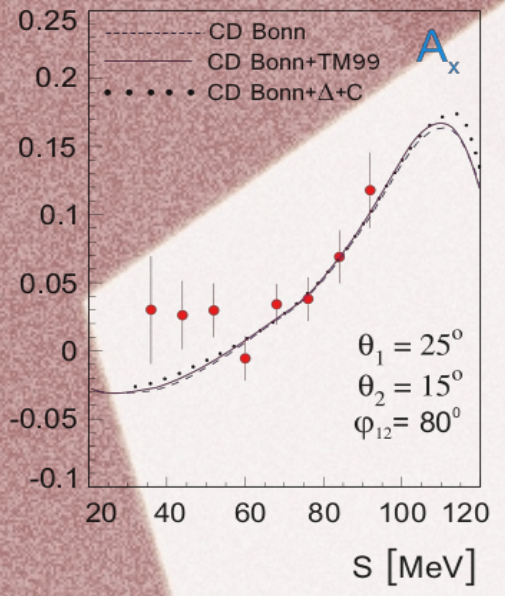


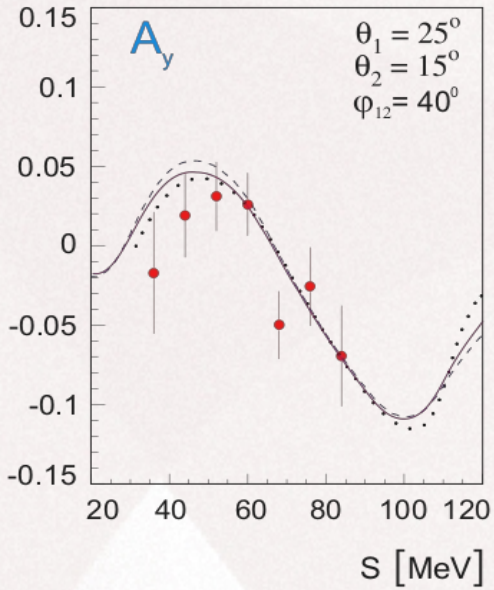






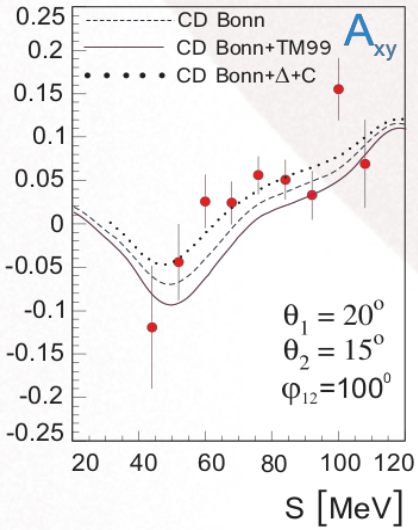
Breakup Analyzing Powers @ 100 MeV

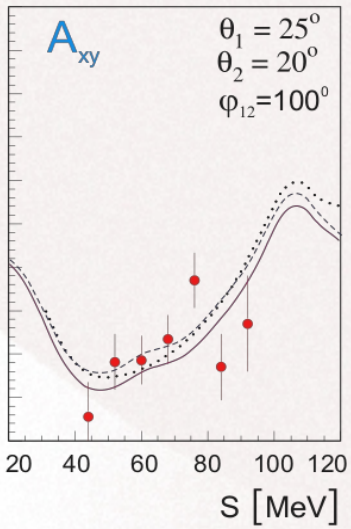


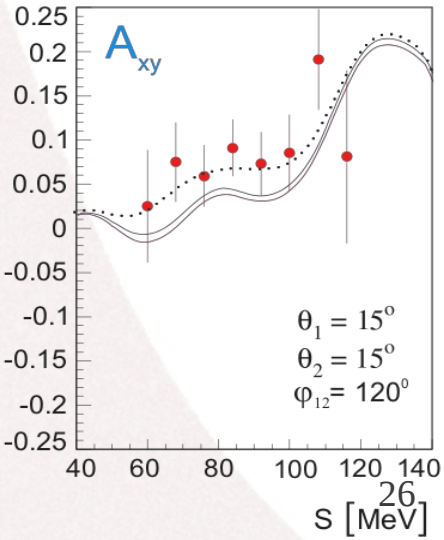


- ✓ Very small 3NF effects
- ✓ **Coulomb force effects seizable**

CD Bonn
CD Bonn+TM99
CD Bonn+Δ+C



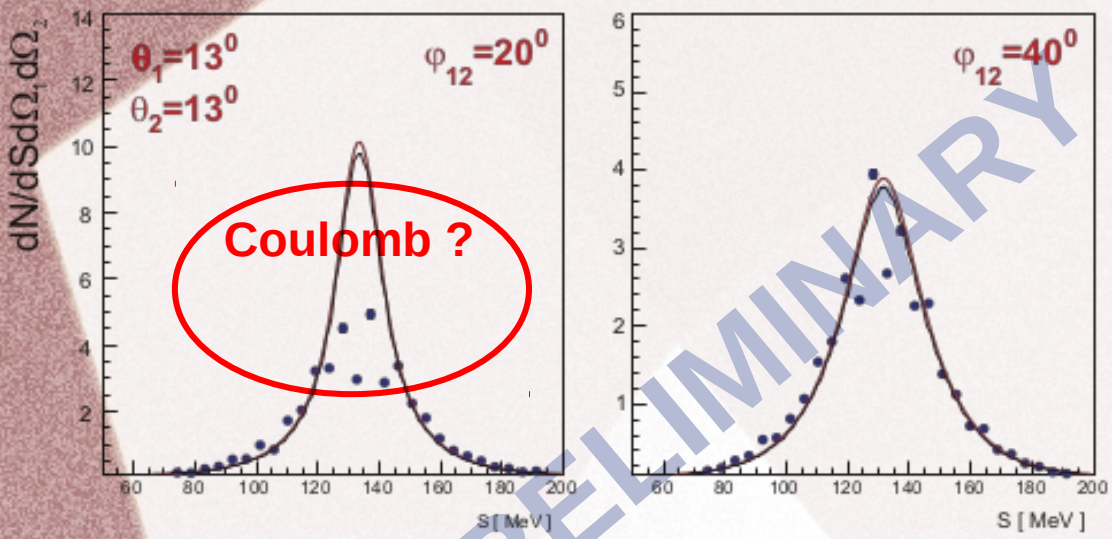


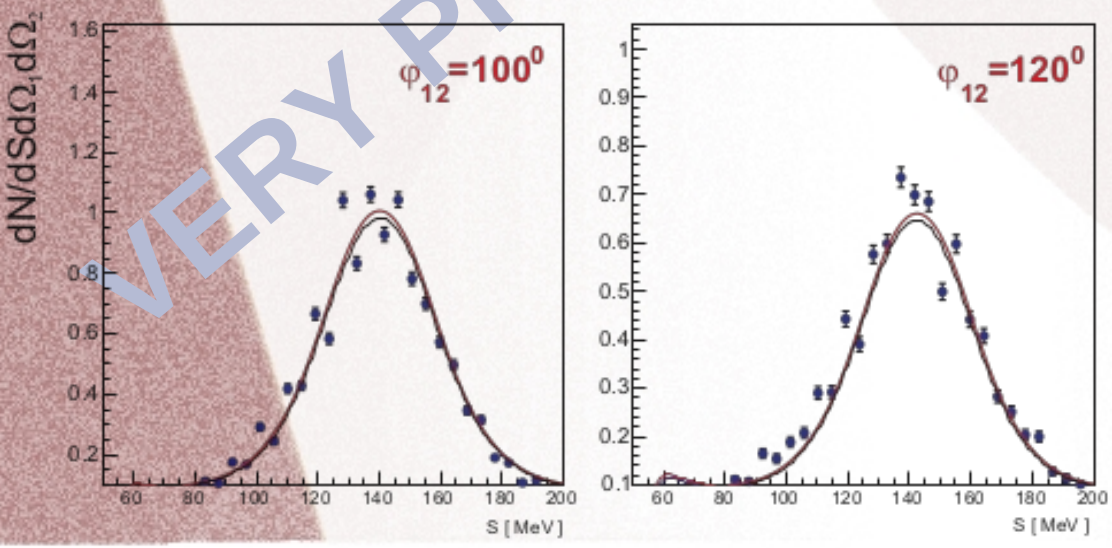


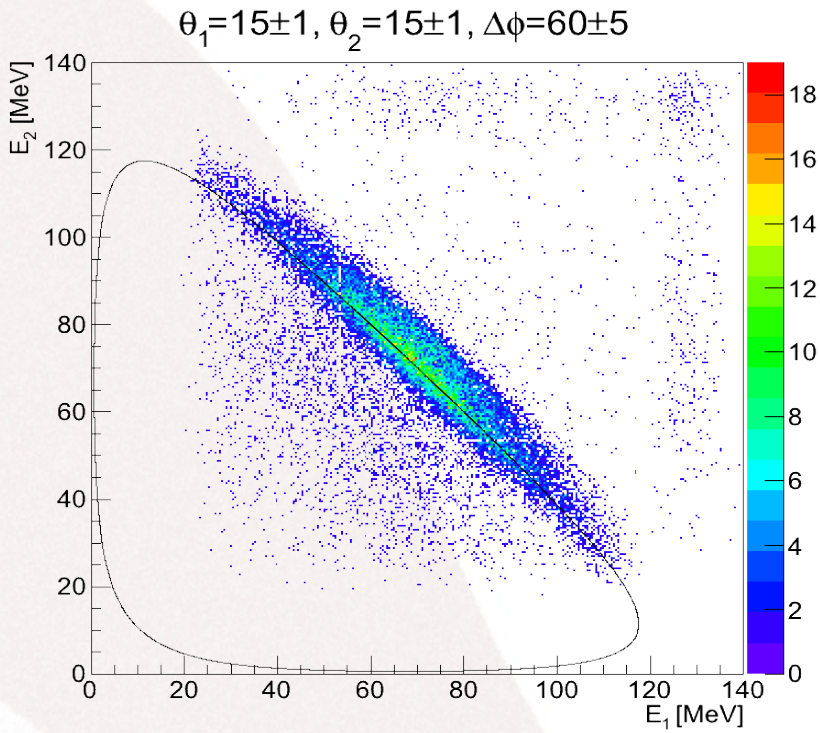
E. Stephan, Eur. Phys. J. A 49: 36, 2013

Ongoing Analysis: Unnormalized Cross Sections of ^{1}H(d,pp)n Breakup @ 160MeV

➔ comparing shapes of the experimental and theoretical distributions







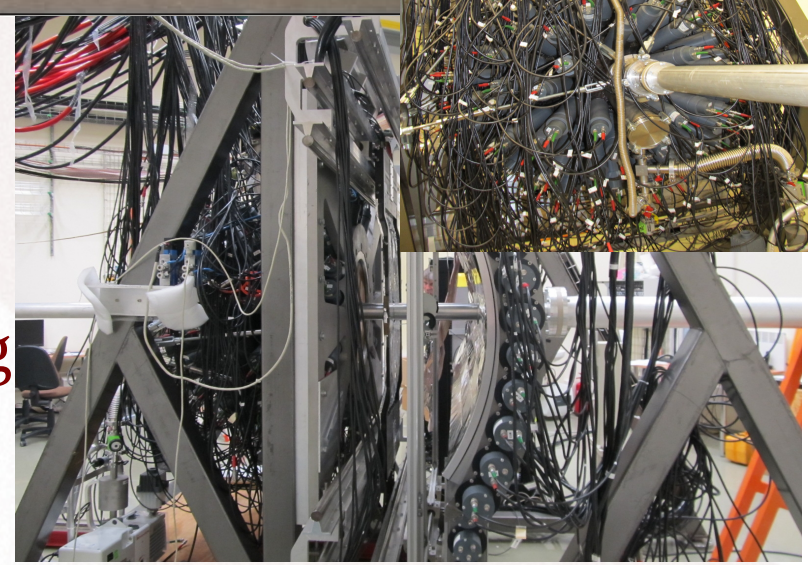
Poster: W. Parol

Outlook: BINA @ CCB Cracow

IFJ PAN

CYCLOTRON CENTER BRONOWICE

- **proton beam energy: 70 - 230 MeV**
- **energy resolution: ΔE/E < 0.7%**
- **intensity: 500 - 0.1 nA**
  (3.3 x 10^{12} - 6.6 x 10^{8} p/s)



GENERAL RESEARCH PROGRAM

- feasibility studies
- measurements of elastic scattering and breakup reactions – systematic and consistent data base for investigating of the 3N continuum at medium energies
- development of the detection system

Summary
^{1}H(d, pp)n Breakup Studies

- Systematic, precise sets of cross sections at 130 MeV (at 100, 160 MeV under analysis) and analyzing powers at 130 and 100 MeV
  - → **solid basis for comparing different approaches which predict the 3N system observables**
- **In the sector of cross sections the data reveal:**
  - → **significant** 3NF effect
  - → **large** Coulomb force influence
- **In the sector of analyzing powers:**
  - → vector analyzing powers: **very low sensitivity** to 3NF and Coulomb
  - → tensor analyzing powers: **Coulomb effects** visible only at 100 MeV, local problems with theoretical description

Systematic studies at various beam energies important !

THANK YOU
FOR
YOUR ATTENTION !

Analyzing powers for breakup reaction

$$f_P = \frac{N_P - N_0}{N_0} \qquad \varsigma' = (\theta_1, \theta_2, S)$$

$$f_p(\varsigma', \phi_{12}, \varphi) = [P_z \cdot \left(-\frac{3}{2}\sin\varphi \cdot A_x + \frac{3}{2}\cos\varphi \cdot A_y\right) +$$

$$P_{zz} \cdot \left(-\frac{1}{2}\sin 2\varphi \cdot A_{xy}\right) + P_{zz} \cdot \left(\frac{1}{2}\sin^2\varphi \cdot A_{xx} + \frac{1}{2}\cos^2\varphi \cdot A_{yy}\right)]$$