Precision Studies of Three-Nucleon System Dynamics

Measured in a wide phase-space region cross sections and analyzing powers of the $^{1}H(\vec{d},pp)n$ reaction at 130 MeV used to trace subtle effects of 3NF and Coulomb force effects

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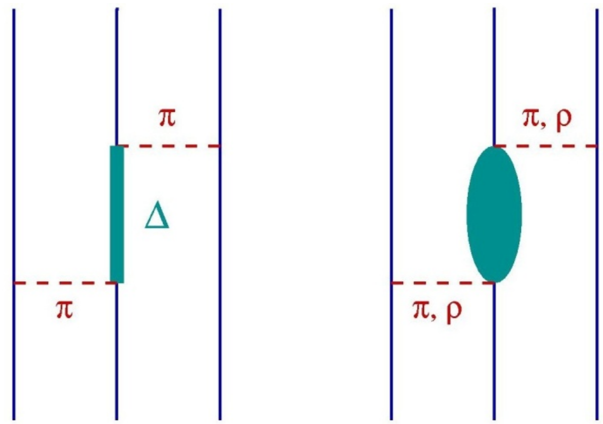

International Centre for Theoretical Sciences

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Nucleon-Nucleon Interaction and Nuclear Many-Body Problem

ICTS TIFR Mumbai

18-27 November 2010

Nucleon-Nucleon Interaction
Basis of Nuclear Physics

Modern NN potentials are in general able to

- reproduce properties of nuclear matter (eq. of state)
- reproduce binding energies of light nuclei
- reproduce global features of the bulk of the scattering observables in 2N and 3N systems

Role of precise knowledge of few-nucleon system dynamics

- **fundamental** for description of nuclei and nuclear processes
- key feature for **application** in calculation/simulation codes (fast reaction stage – INC, QMD, etc.);
  radiation shielding, spallation targets, dosimetry, medical irradiation procedures, biological and astrophysical models, …

Few-Nucleon System Dynamics
Key Issues of Models

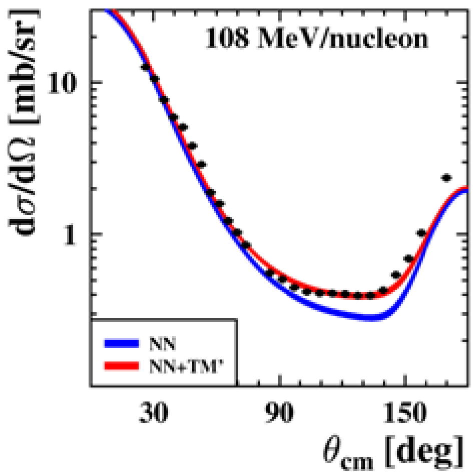
- Faddeev framework provides exact treatment for the 3N system
- Various approaches to construct the interaction
  - Realistic potentials + phenomenological 3NF models
  - Chiral Perturbation Theory
  - Coupled-Channels formalism with explicit Δ
- Different effects to be traced
  - Influences of 3NF
  - Coulomb force action
  - Relativistic effects

} Relatively new achievements for breakup !

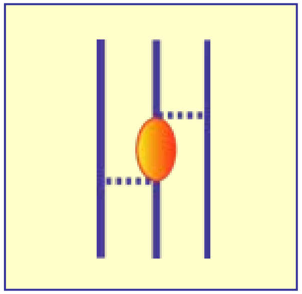
Pairwise Nucleon-Nucleon Interaction is not Enough !

Predictions of NN potentials alone

- fail to reproduce binding energies of 3N and 4N systems
- fail to reproduce minimum of the d(N,N)d elastic scattering cross section



- Introducing concept of **three-nucleon forces**: genuine (irreducible) interaction of three nucleons



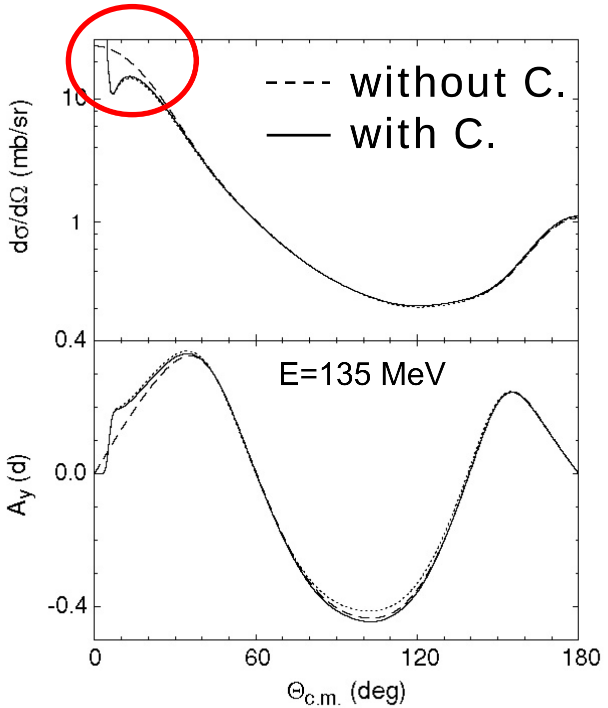
- Implementing 3NF into Faddeev framework (without affecting numerical accuracy)

$$V = \sum V_{NN} + \mathbf{V_4}$$

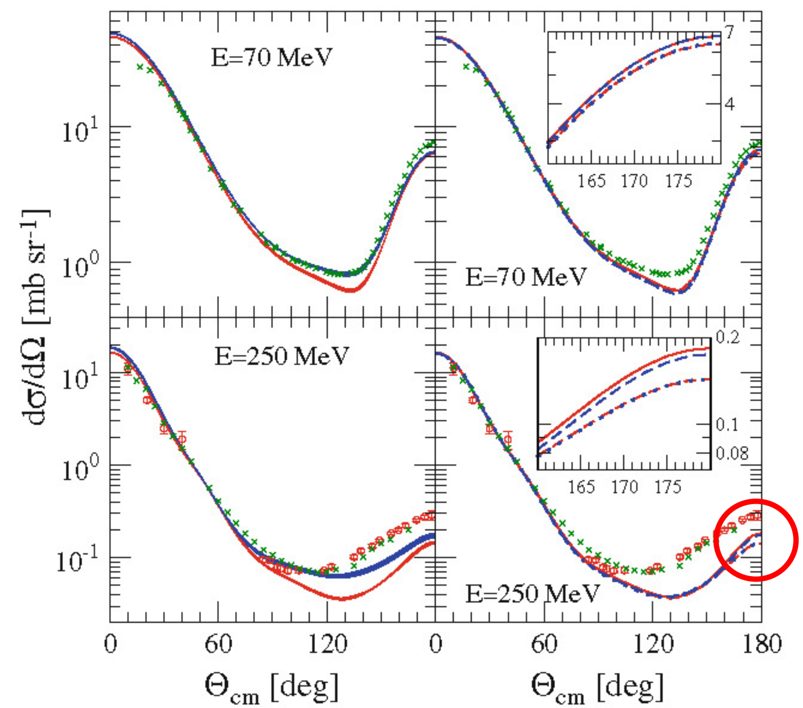
More Dynamical Effects ?
Coulomb force and relativity

Predictions for the N-d elastic scattering

Coulomb



3NF relativity



Effects small, located at extreme angles only !

$^{1}H(\vec{d},pp)n$ Measurements at 130 MeV

Motivation

- Three-nucleon system is the simplest non-trivial environment to test predictions of the NN and 3N potential models
- Very few breakup data at medium energies (earlier PSI experiments provided only 14 kinematical configurations)
- To reach meaningful conclusions about the interaction models needed experimental coverage of large phase space regions

$^1H(\vec{d},pp)n$ Measurements at 130 MeV

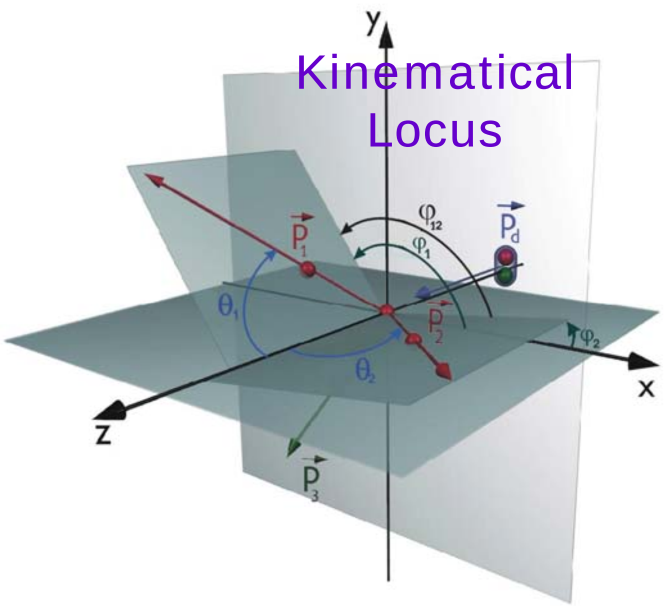
Breakup Reaction Kinematics

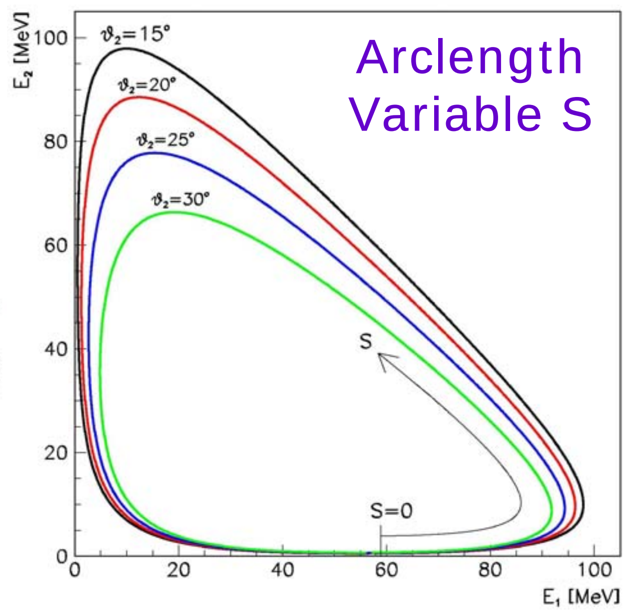
- Three nucleons in the final state - 9 variables
- Energy-momentum conservation – 4 equations
- Five independent kinematical variables
  - ✓ Complete (exclusive) experiment → measured ≥ 5
  - ✓ Inclusive experiment → measured ≤ 4 parameters

$^1H(d,pp)n$ measured: directions and energies of two protons, i.e.

θ_1, φ_1, E_1

θ_2, φ_2, E_2





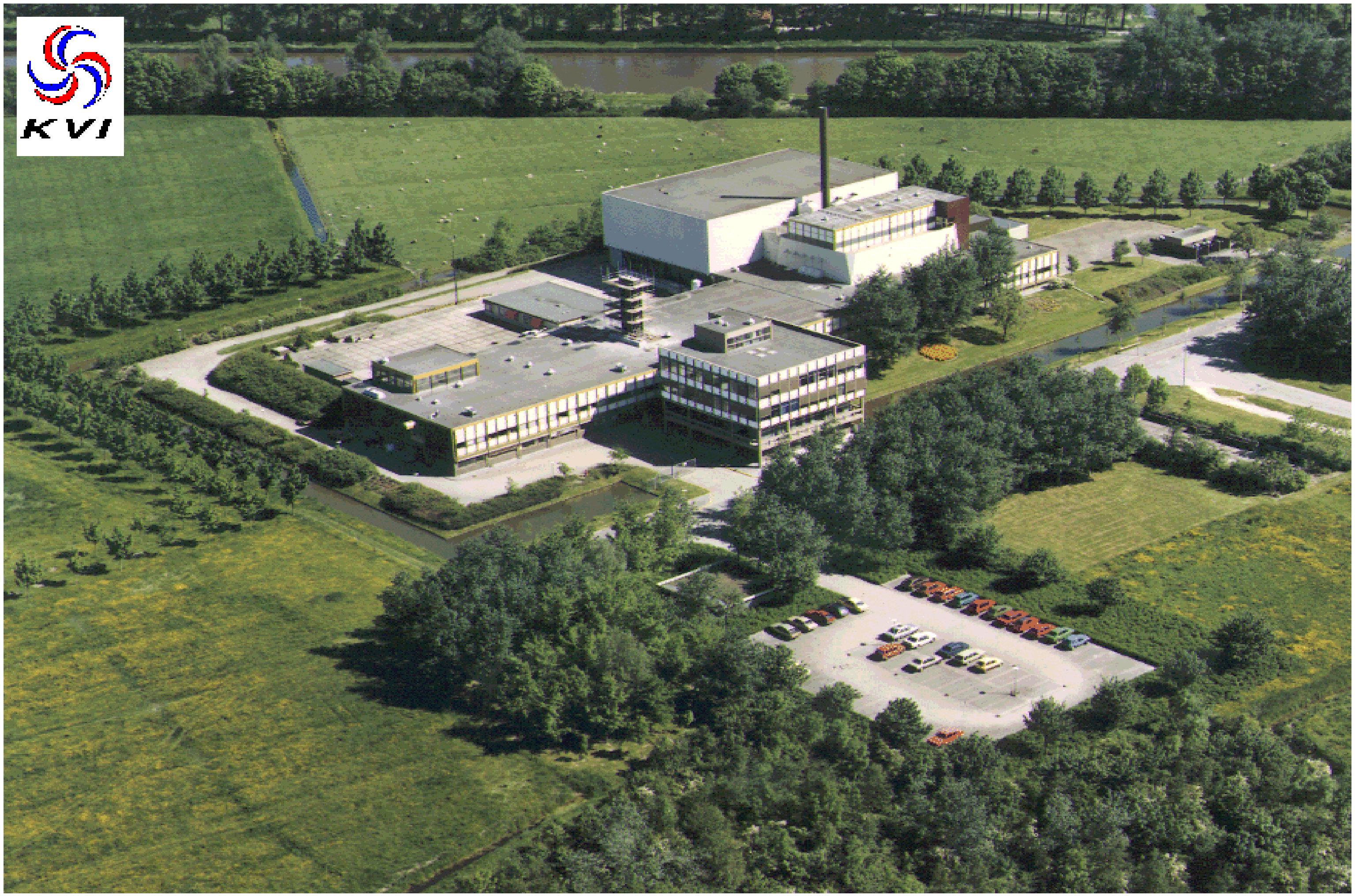
$^{1}H(\vec{d},pp)n$ Measurement at 130 MeV

Experimental Highligths – KVI and FZJ

- Polarized (vector & tensor) deuteron beam (50 pA, point-like focus on target)
- Liquid H_2 target (4 mm thickness)
- Determination of energies and emission angles of both protons
- Simultaneous measurement of the d-p elastic scattering channel
  - Absolute cross section normalization
  - Polarization monitoring
  - Geometry checks

$^{1}\mathrm{H}(\vec{d},pp)n$ Measurement at 130 MeV

Kernfysisch Versneller Instituut, Groningen



IoP
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Krakow

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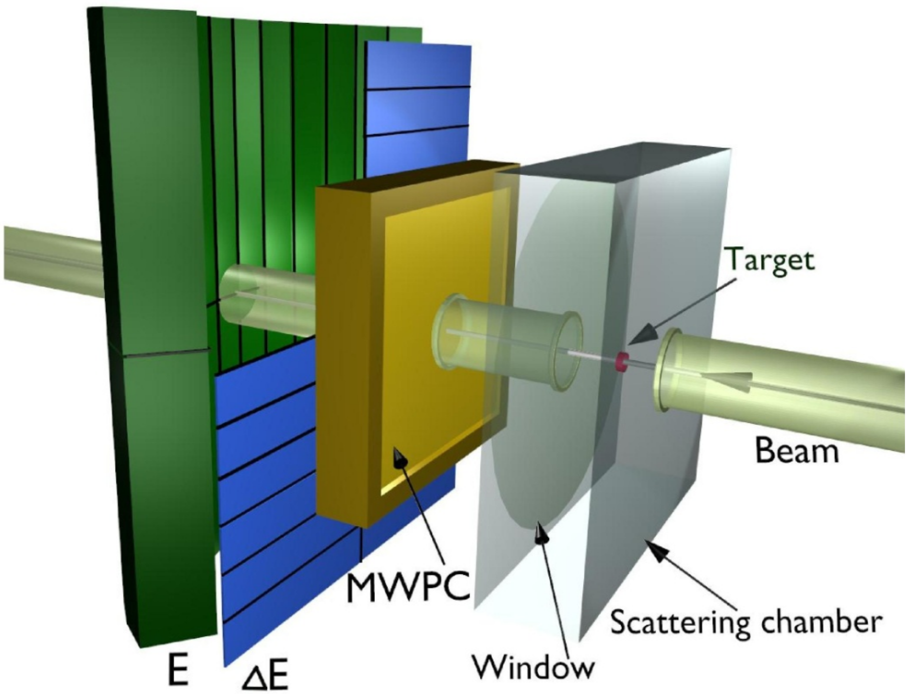
Katowice

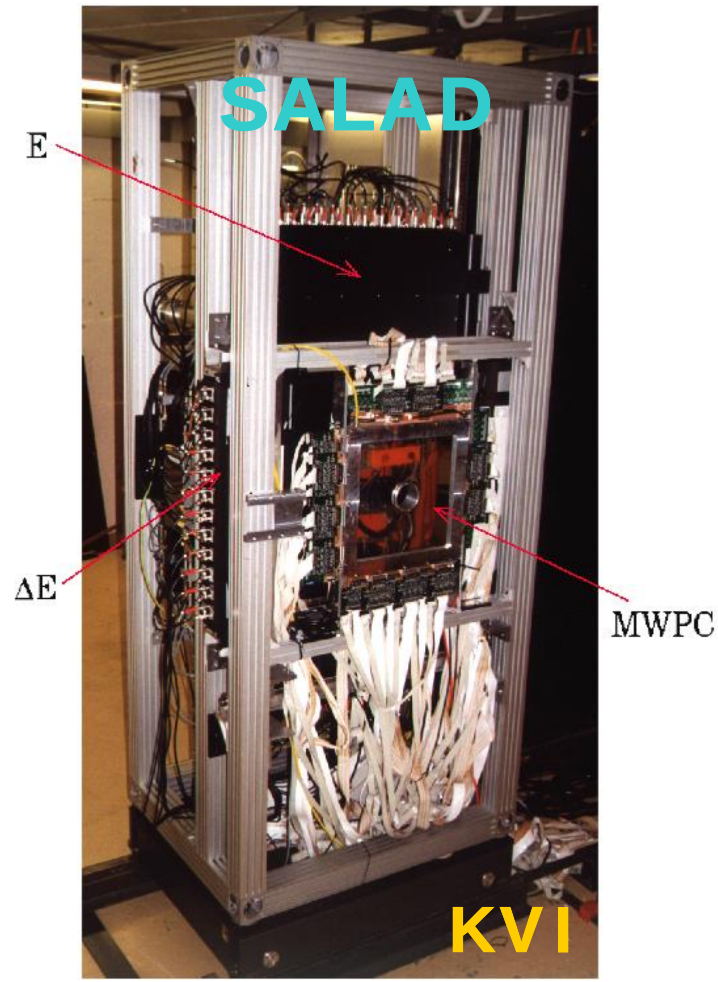
GEM

$^{1}H(\vec{d},pp)n$ Measurement at 130 MeV

Small Area Large Acceptance Detector

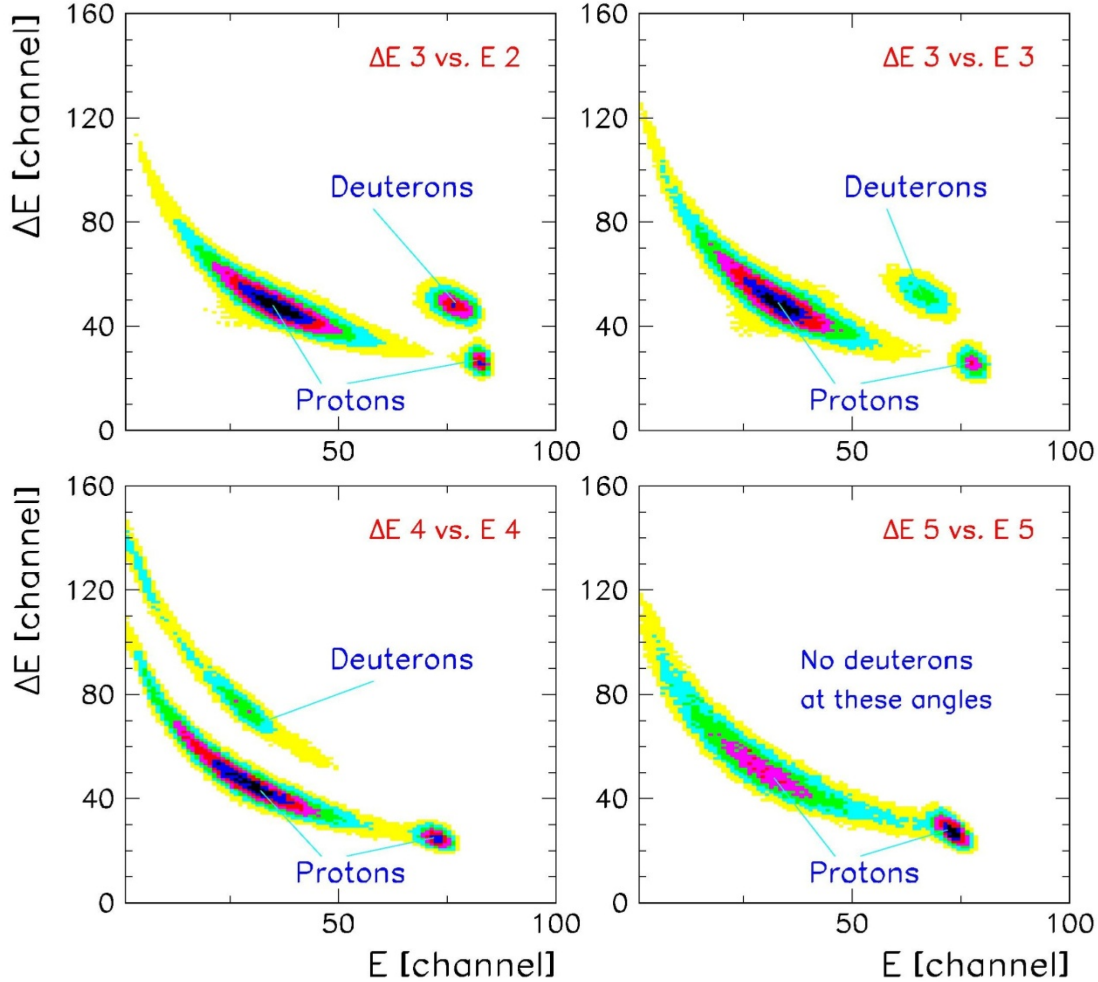
- ✓ 140 ΔE-E telescopes
- ✓ 3-plane MWPC
- ➔ Angular range :
  θ = (12º, 38º), φ = (0º, 360º)





$^{1}H(\vec{d},pp)n$ Measurement at 130 MeV

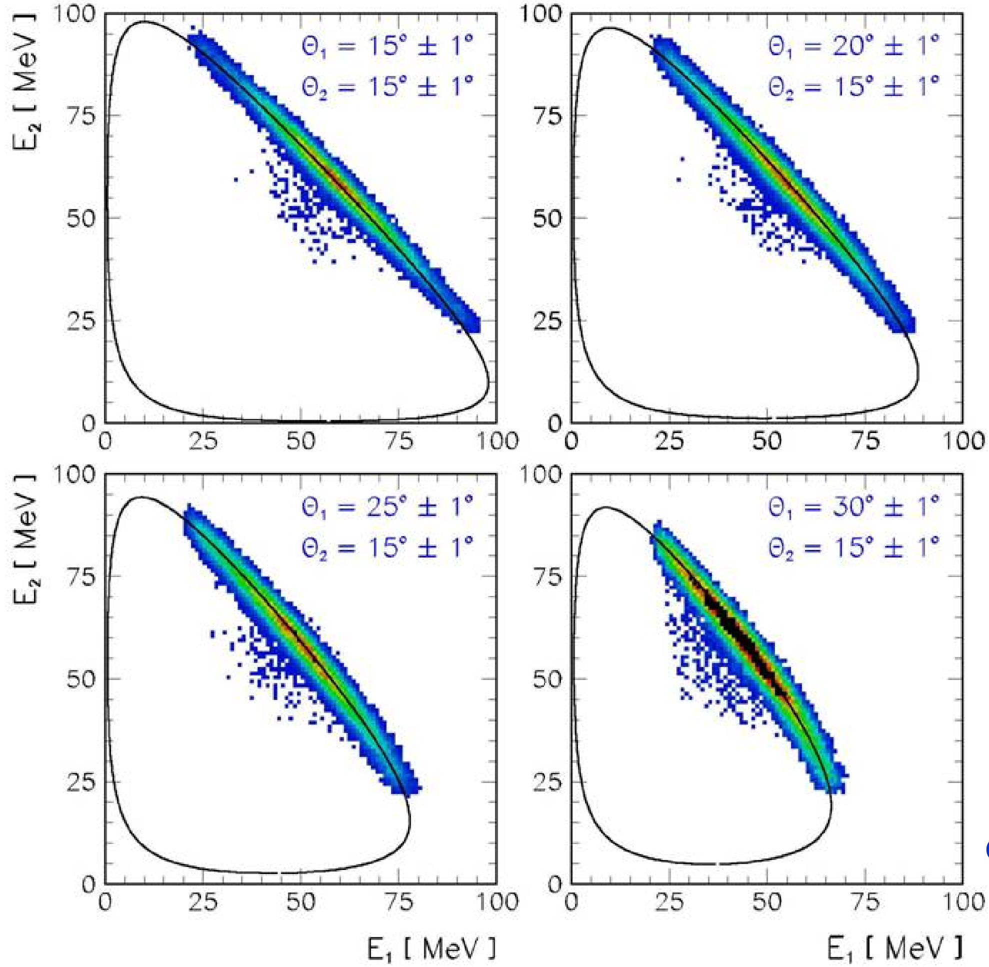
Data Analysis – ΔE-E Particle Identification



Perfect p vs. d separation in all 140 individual ΔE-E telescopes

$^{1}H(\vec{d},pp)n$ Measurement at 130 MeV

Data Analysis – E_1-E_2 Kinematical Spectra



Narrow and background-free kinematical spectra over the whole angular range

$\varphi_{12} = 90^{o} \pm 5^{o}$

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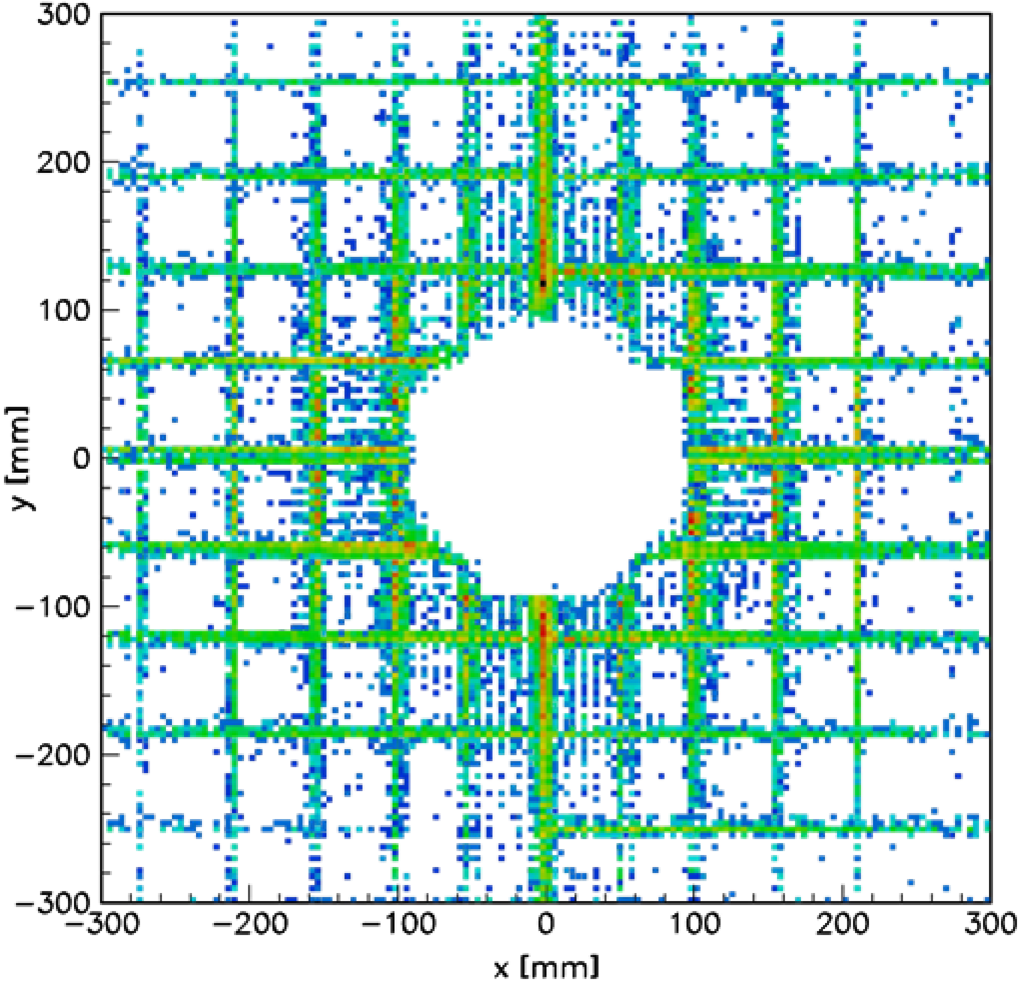
Data Analysis – ΔE-E Array Image on MWPC



MWPC projections for certain single events:

1. Condition:
   no hit in ΔE detector

2. Condition:
   hits in 2 adjacent E detectors

1 & 2 overlayed:
   image of ΔE-E telescopes on the MWPC plane

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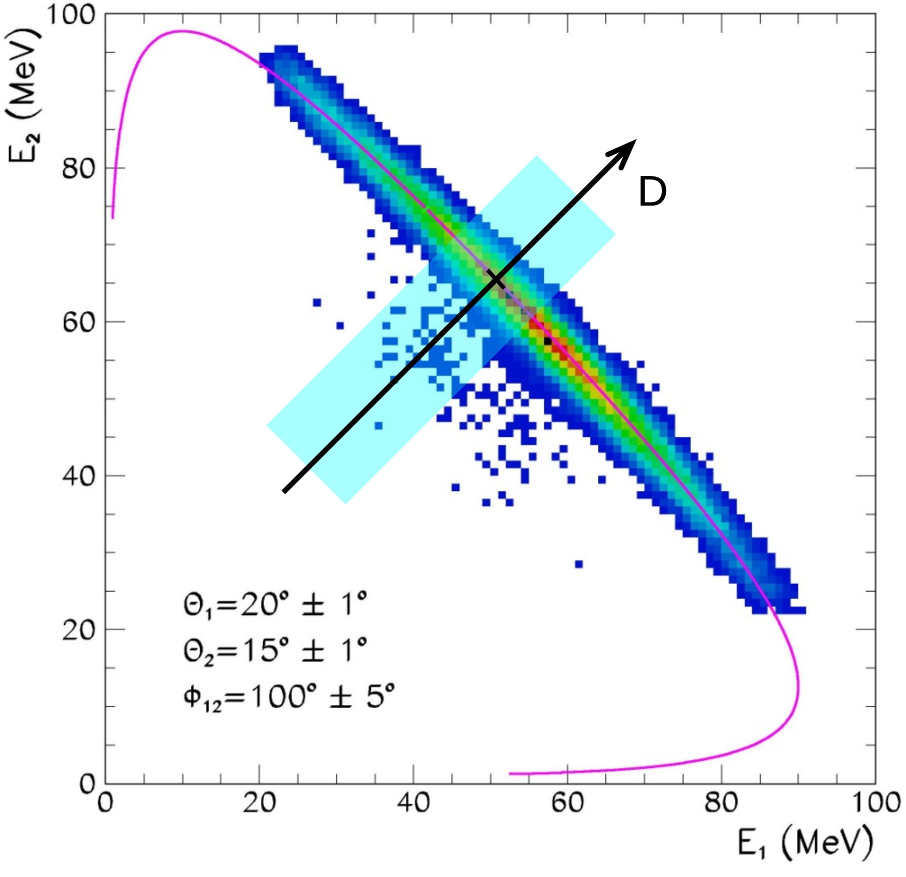
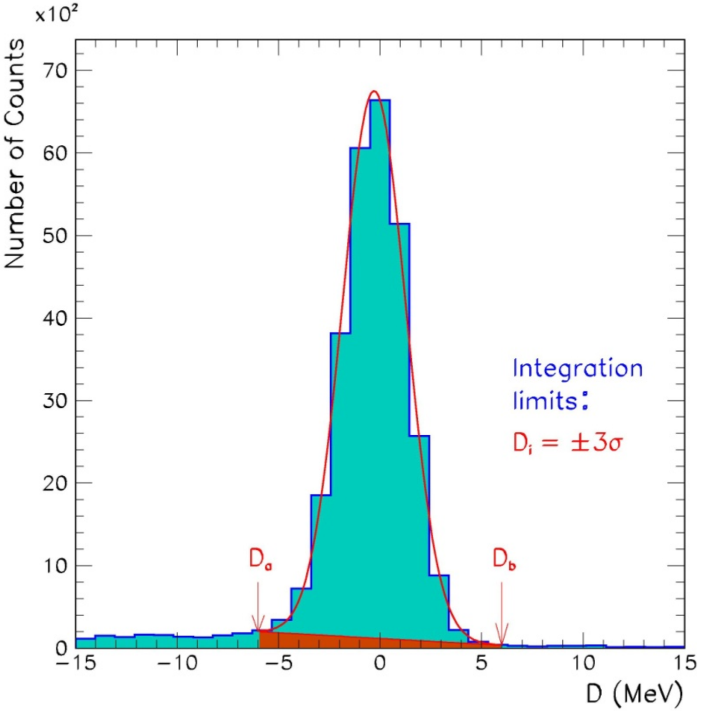
Data Analysis – E_1-E_2 Kinematical Spectra

Projection of events on the kinematical curve



Background subtraction



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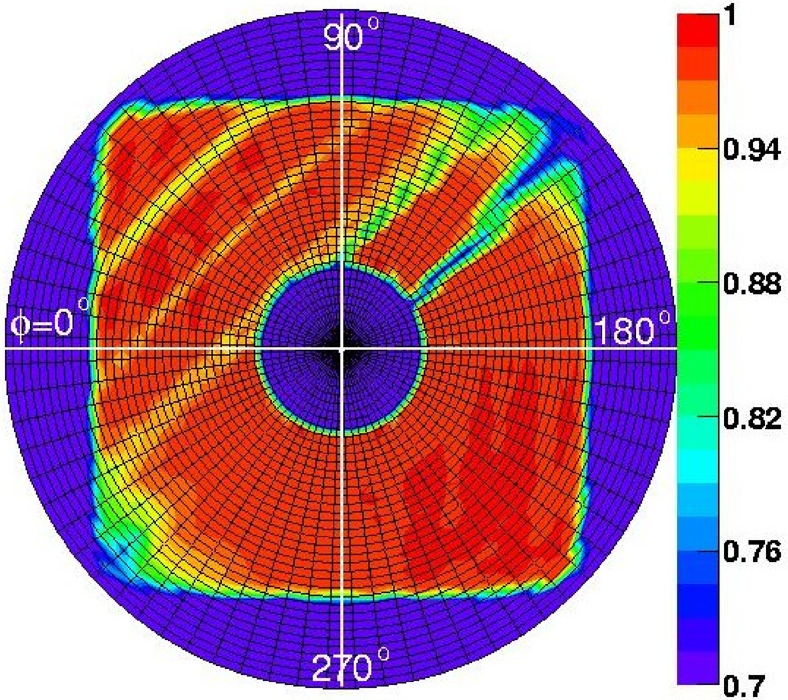
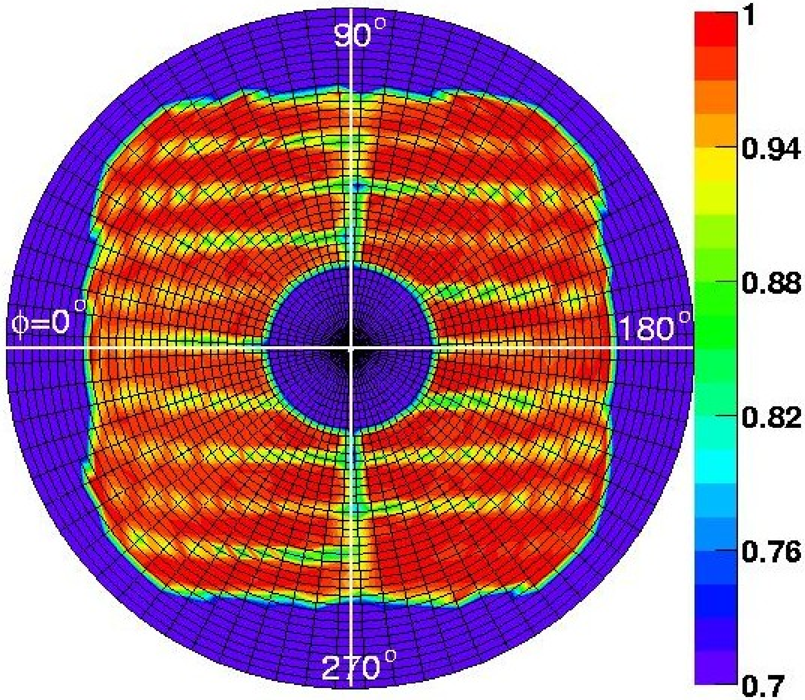
Data Analysis – Correction Factors

MWPC Efficiency

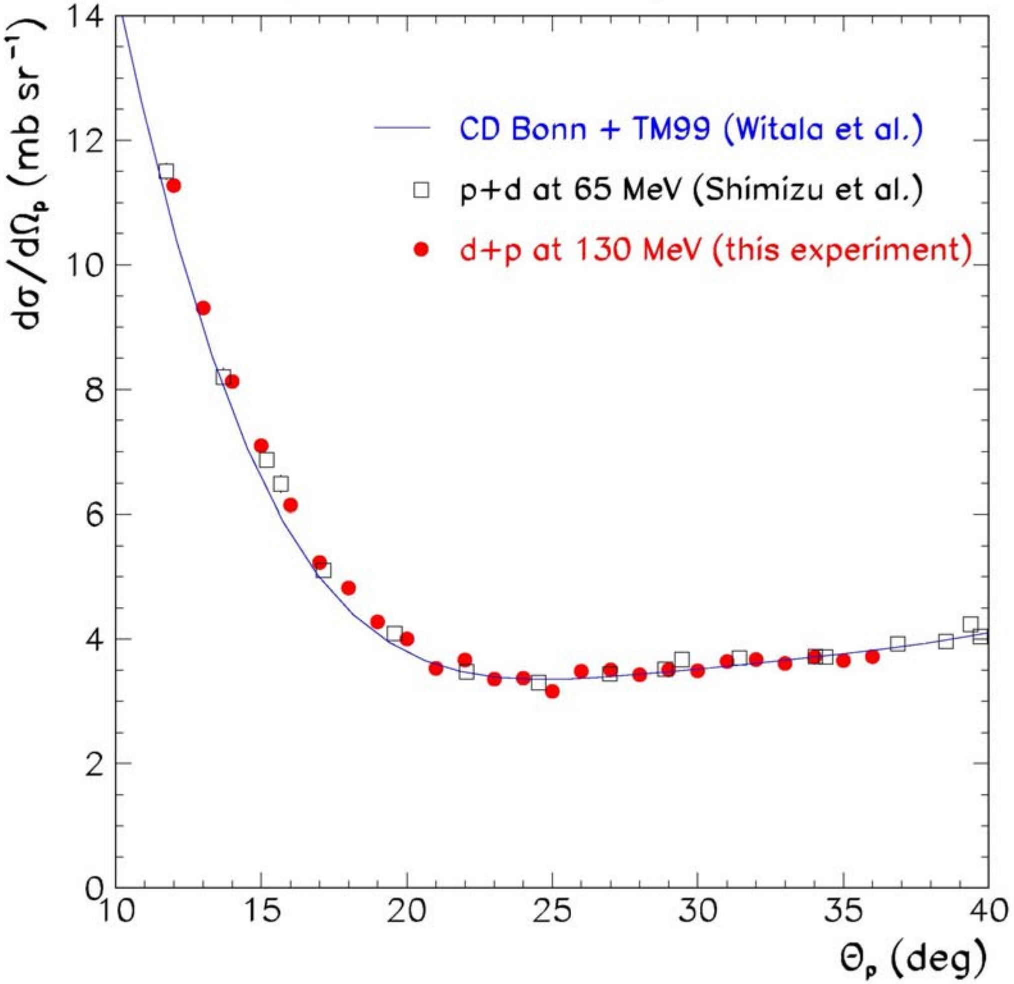


Detection Efficiency of Scint. Hodoscope



$^{1}H(\vec{d},pp)n$ Measurement at 130 MeV

Data Analysis – Cross Section Normalization



Reliable normalization of the breakup cross sections to the simultaneously measured $^{1}H(d,pd)$ elastic scattering

$^1H(\vec{d},pp)n$ Measurement at 130 MeV

Data Analysis – Cross Section Normalization

Rate of breakup p-p coincidences:

$$N_{br}(S,\Omega_1,\Omega_2) = \frac{d^5\sigma}{d\Omega_1 d\Omega_2 dS}(S,\Omega_1,\Omega_2)\cdot\Delta\Omega_1\Delta\Omega_2\Delta S \times$$

$$\times \underbrace{\int_0^{\Delta t} I_d dt \cdot \rho_t D_t \cdot (1-\tau)}\cdot\varepsilon(\Omega_1,E_1)\,\varepsilon(\Omega_2,E_2)$$

Rate of elastic p-d coincidences:

$$N_{el}(\Omega_1^{el}) = \frac{d\sigma}{d\Omega_1^{el}}(\Omega_1^{el})\cdot\Delta\Omega_1^{el}\cdot\underbrace{\int_0^{\Delta t} I_d dt \cdot \rho_t D_t \cdot (1-\tau)}\cdot\varepsilon(\Omega_1^{el},E_1^{el})\,\varepsilon(\Omega_2^{el},E_2^{el})$$

Normalized breakup cross section:

$$\frac{d^5\sigma}{d\Omega_1 d\Omega_2 dS}(S,\Omega_1,\Omega_2) = \frac{d\sigma}{d\Omega_1^{el}}(\Omega_1^{el})\cdot\frac{N_{br}(S,\Omega_1,\Omega_2)}{N_{el}(\Omega_1^{el})}\times$$

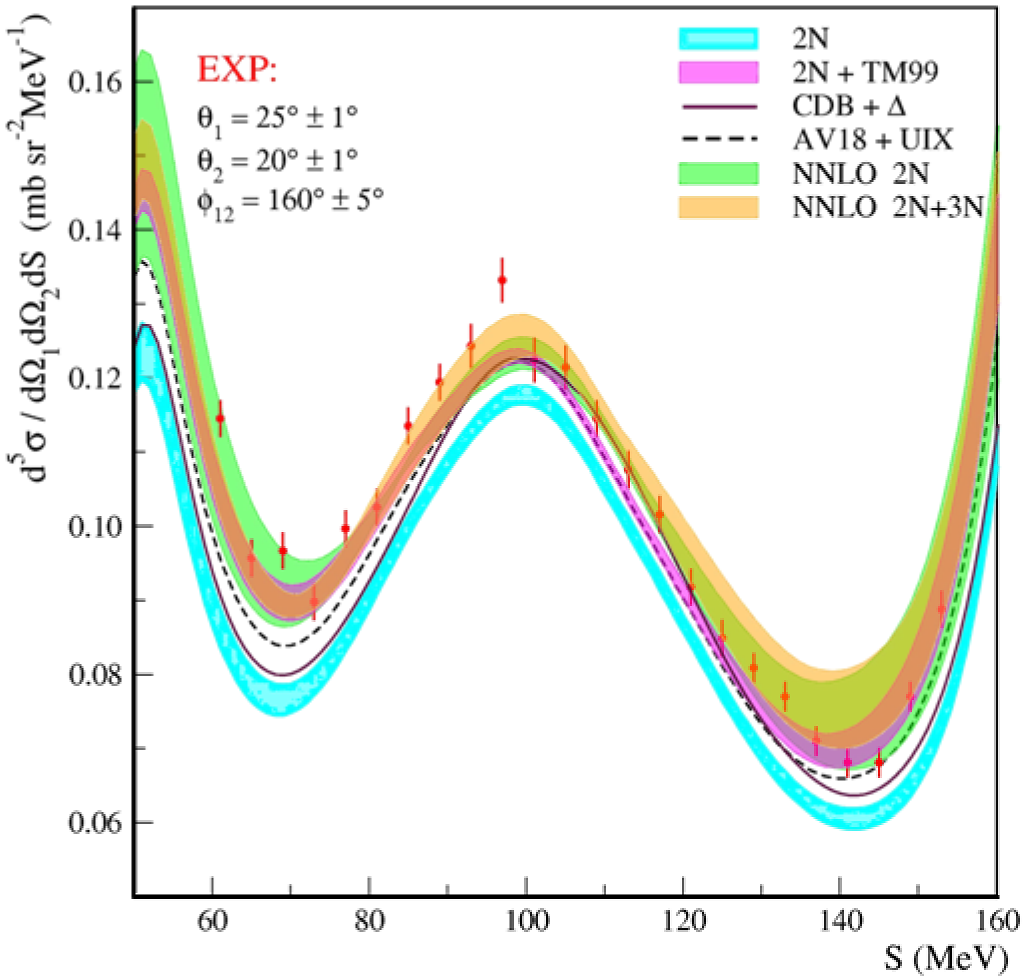
$$\times\frac{\Delta\Omega_1^{el}}{\Delta\Omega_1\Delta\Omega_2\Delta S}\cdot\frac{\varepsilon(\Omega_1^{el},E_1^{el})\,\varepsilon(\Omega_2^{el},E_2^{el})}{\varepsilon(\Omega_1,E_1)\,\varepsilon(\Omega_2,E_2)}$$

$^{1}H(\vec{d},pp)n$ Measurement at 130 MeV
KVI Cross Section Results – Summary

- ✓ Nearly 1800 cross section data points
  - $\theta_1, \theta_2 = 15^\circ - 30^\circ$; grid 5°; $\Delta\theta = \pm 1^\circ$
  - an additional set for $\theta_1, \theta_2 = 13^\circ$
  - $\varphi_{12} = 40^\circ - 180^\circ$; grid $10^\circ - 20^\circ$; $\Delta\varphi = \pm 5^\circ$
  - 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 /d.o.f.
  $\chi^2 = f(\varphi_{12})$, $\chi^2 = f(E_{rel})$

$^{1}H(\vec{d},pp)n$ Measurement at 130 MeV
Cross Section Results – Example

Faddeev calculations



Realistic NN potentials

CD Bonn, NijmI, NijmII, Av18

3NF models: TM99, UIX

Coupled channel pot.

CD Bonn (mod) + Δ

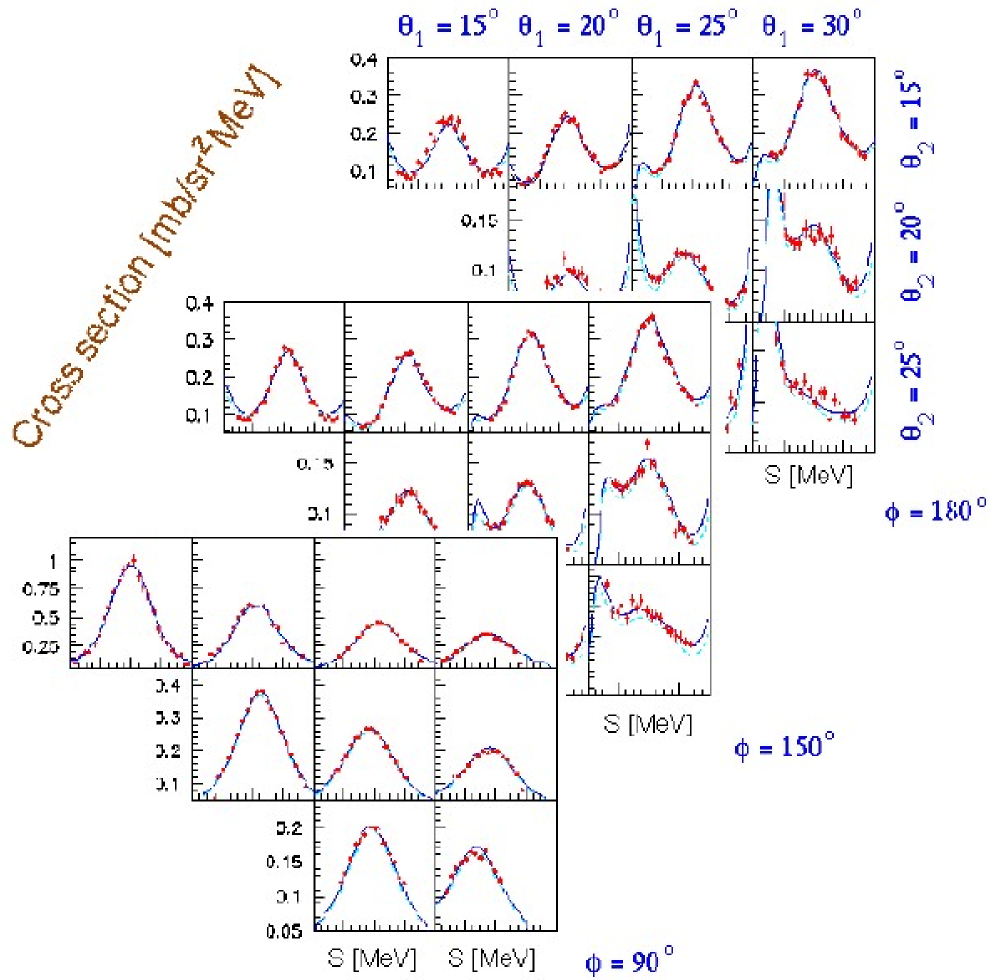
EFT/ChPT potentials

NNLO – 2N only

NNLO – 2N + 3 N

^{1}H($\vec{d}$,pp)n Measurement at 130 MeV

Cross Section Results – Exploring Phase Space



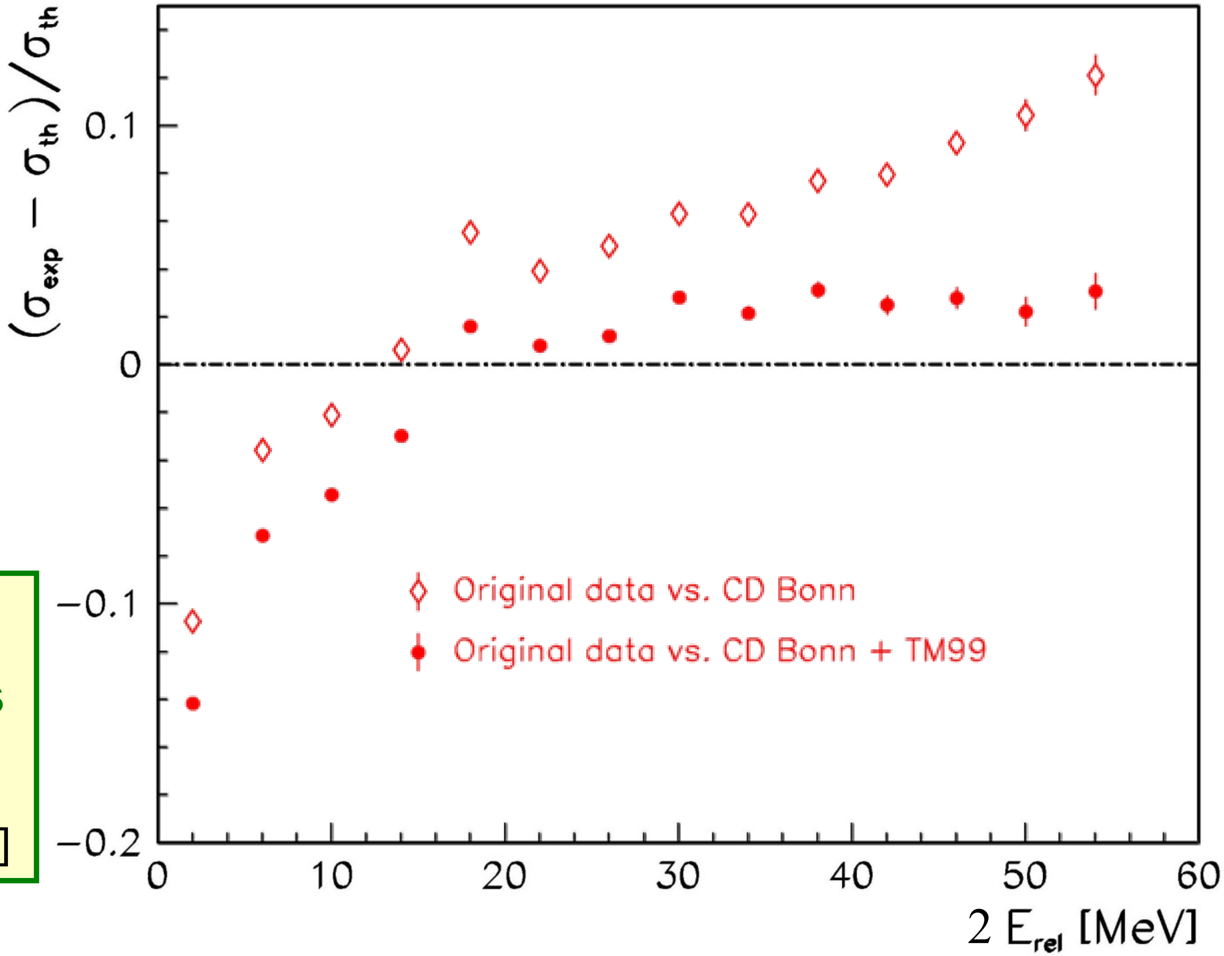
Breakup cross section is a function on 4-dim phase space.

With rich data one might (and should !) explore it by means of projections.

$^{1}H(\vec{d},pp)n$ Measurement at 130 MeV

Cross Section Results – E_{rel} Dependence & 3NF's

Including 3NF increases discrepancies at low E_{rel}, reducing them at higher E_{rel} values



In general:
Inculding 3NF's reduces global χ^2 by about 30%
[Phys. Rev. C 72 (2005) 044006]

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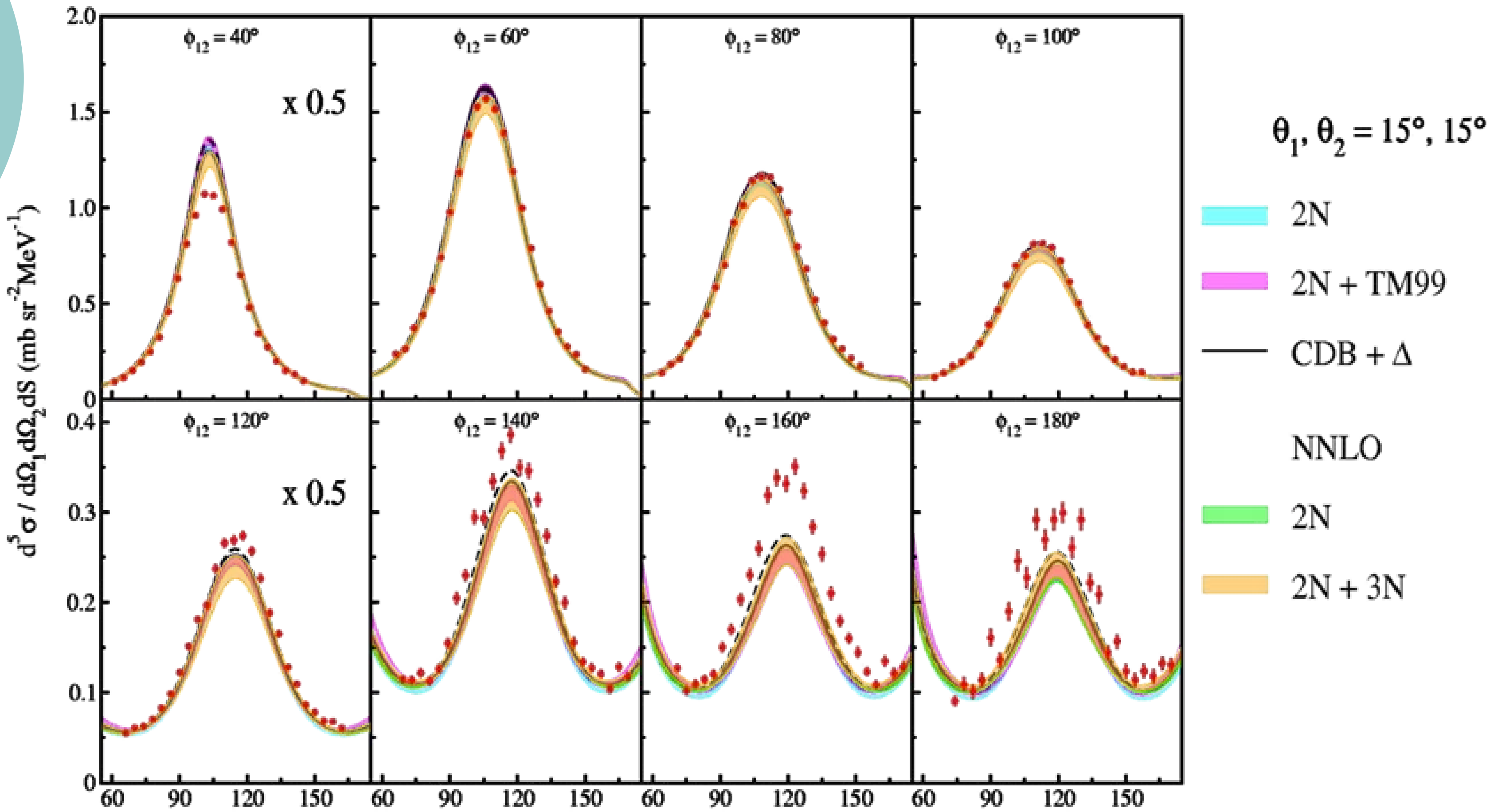
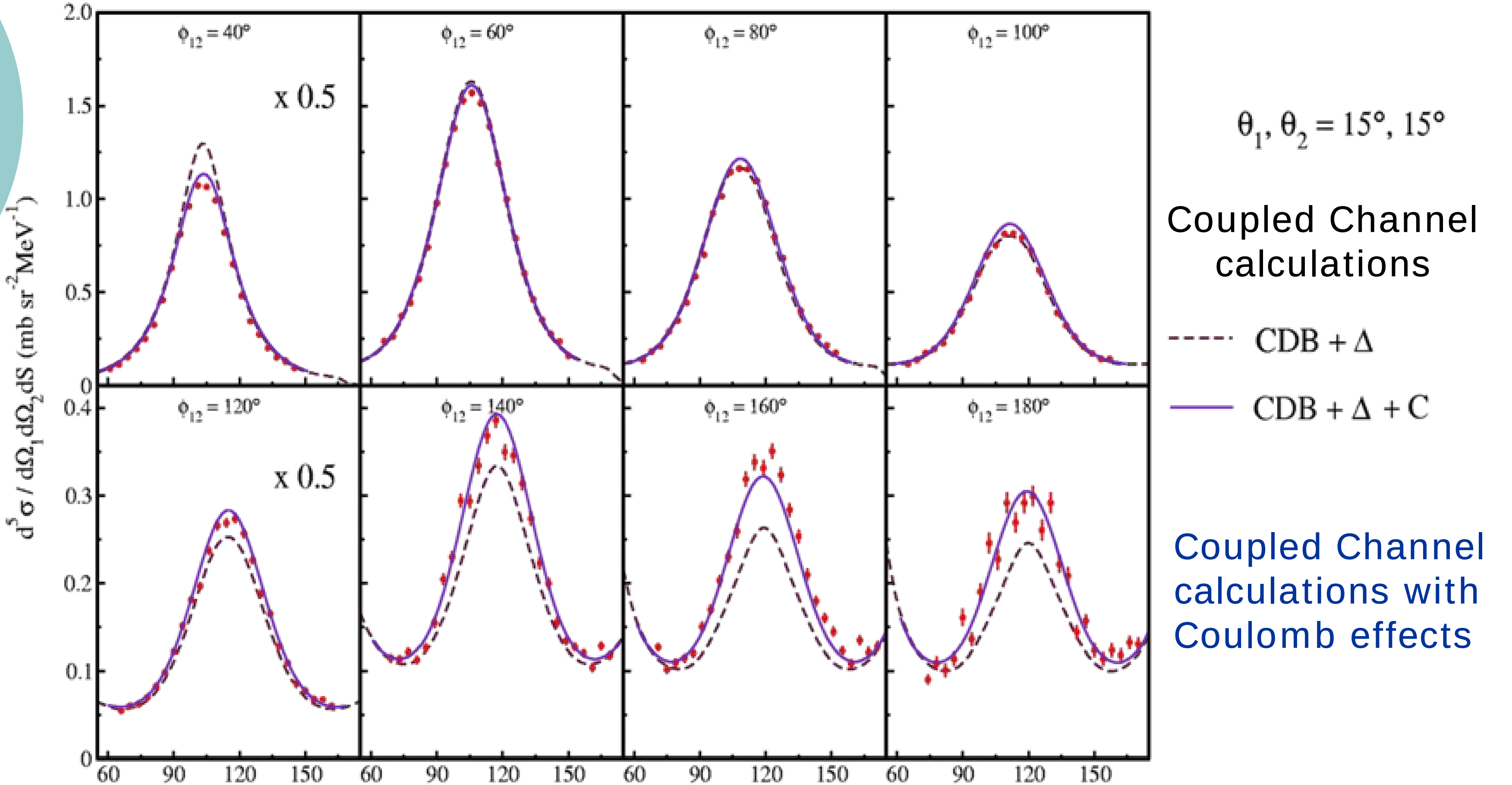
Cross Section Results – Discrepancies



$^{1}H(\vec{d},pp)n$ Measurement at 130 MeV

Cross Section Results – Discrepancies Cured

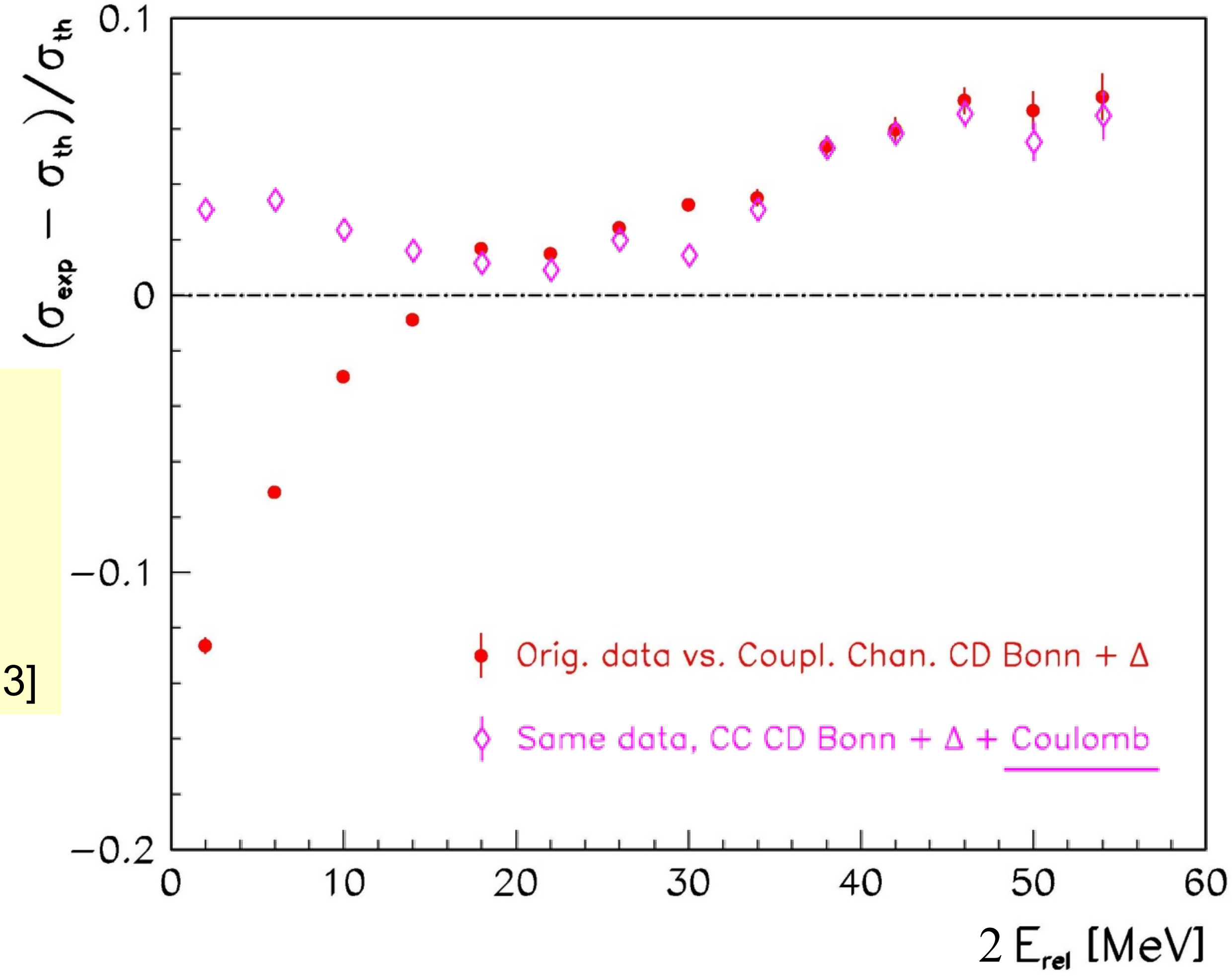


Coupled Channel calculations with Coulomb effects

Predictions with Coulomb reproduce data much better !

$^{1}H(\vec{d},pp)n$ Measurement at 130 MeV

Cross Section Results – E_{rel} Dep. & Coulomb



Clear signature of Coulomb effects at small relative energy values !

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

What about 3NF effects ?

$^1H(\vec{d},pp)n$ Measurement at 130 MeV
Cross Section Results – 3NF & Coulomb Effects

In the realistic potentials approach and within the ChPT **only** n+D system was considered

Now Coulomb effects <u>and</u> phenomenological 3NF can be calculated simultaneously !

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

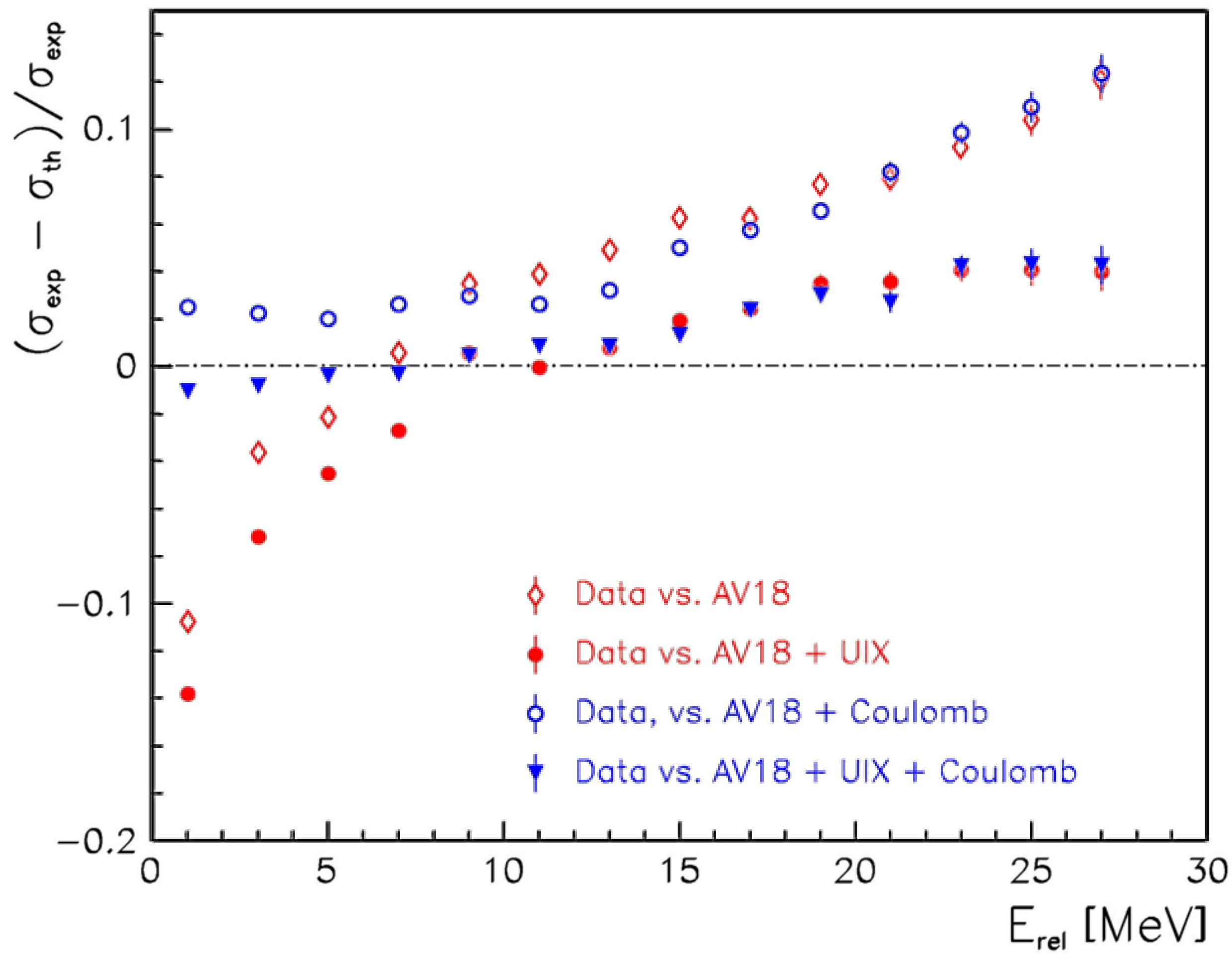
↓

Quantitative comparison of the role of both contributions

$^{1}H(\vec{d},pp)n$ Measurement at 130 MeV

Cross Section Results – 3NF & Coulomb Effects

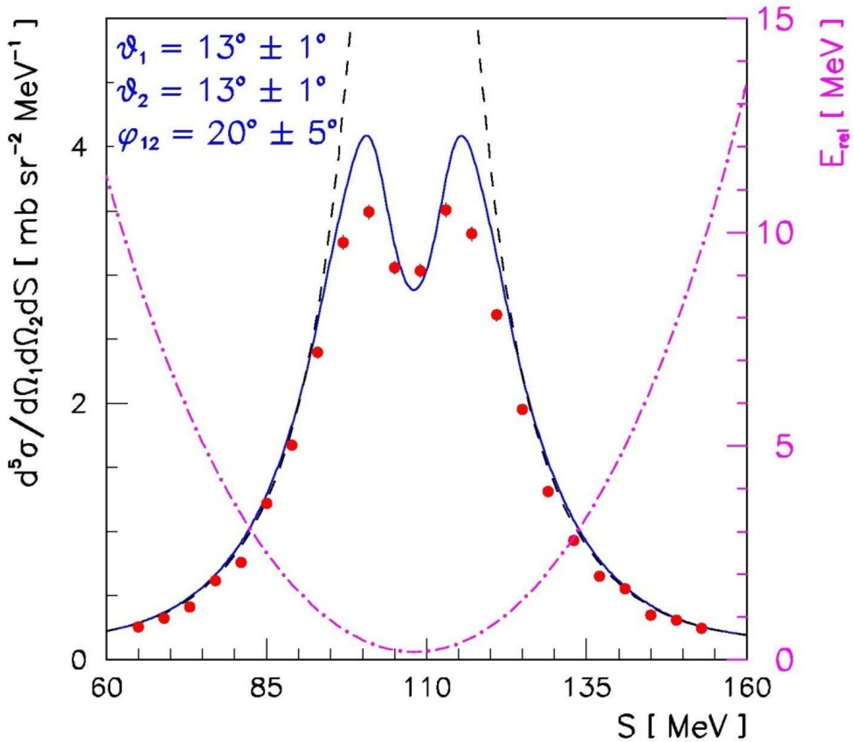
Including Coulomb force effects improves the agreement with the data at low E_{rel} values



The best agreement is reached when both, the Coulomb force and the 3NF are taken into account !

$^1H(\vec{d},pp)n$ Measurement at 130 MeV

Cross Section Results – Coulomb Effects



Acceptance limit of KVI experiment

Apparent discrepancy is understood:

Data

→ exp. averaging

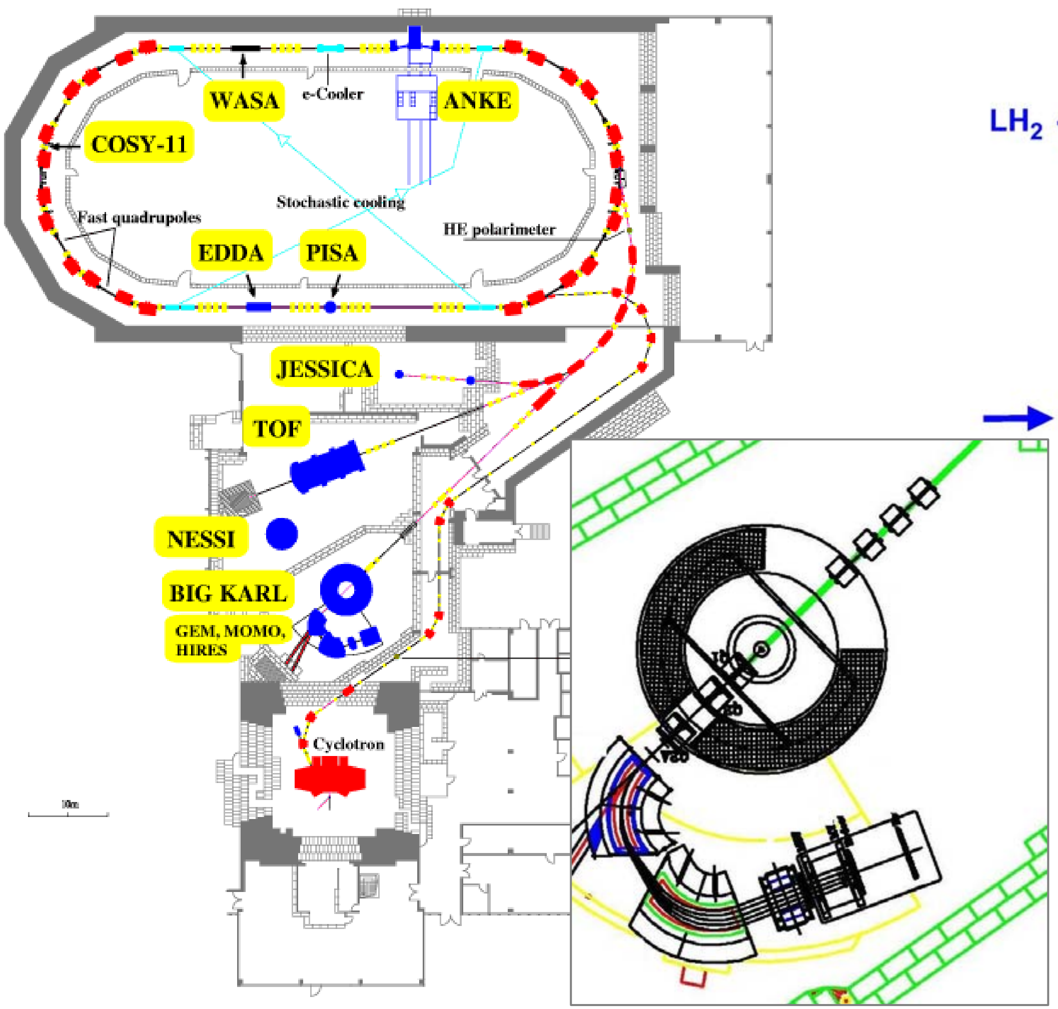
Calculations

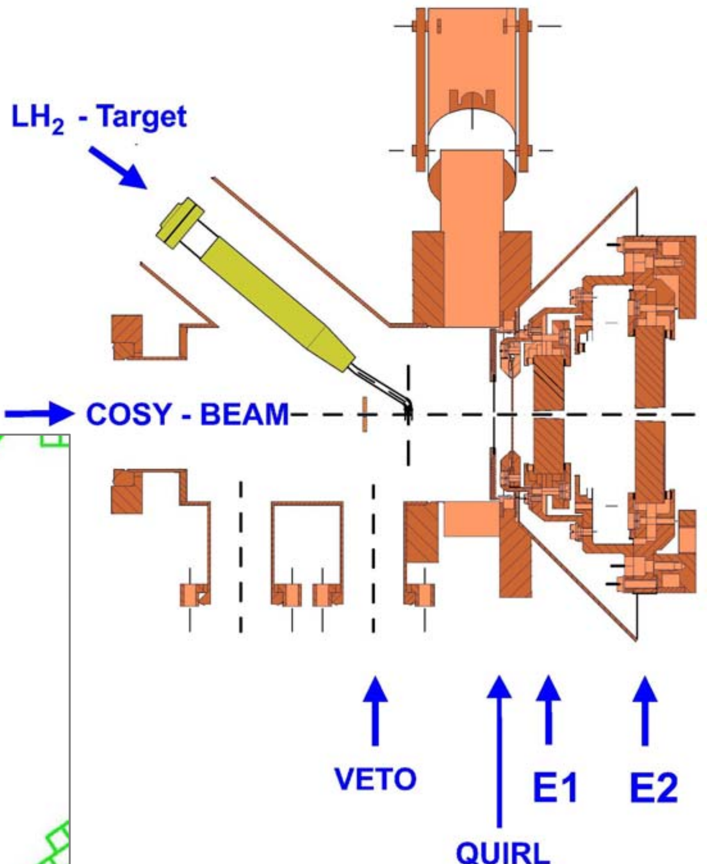
→ point geometry

Final plot comes soon

$^{1}H(\vec{d},pp)n$ Measurement at 130 MeV

Germanium Wall Exp. @ COSY / BigKarl

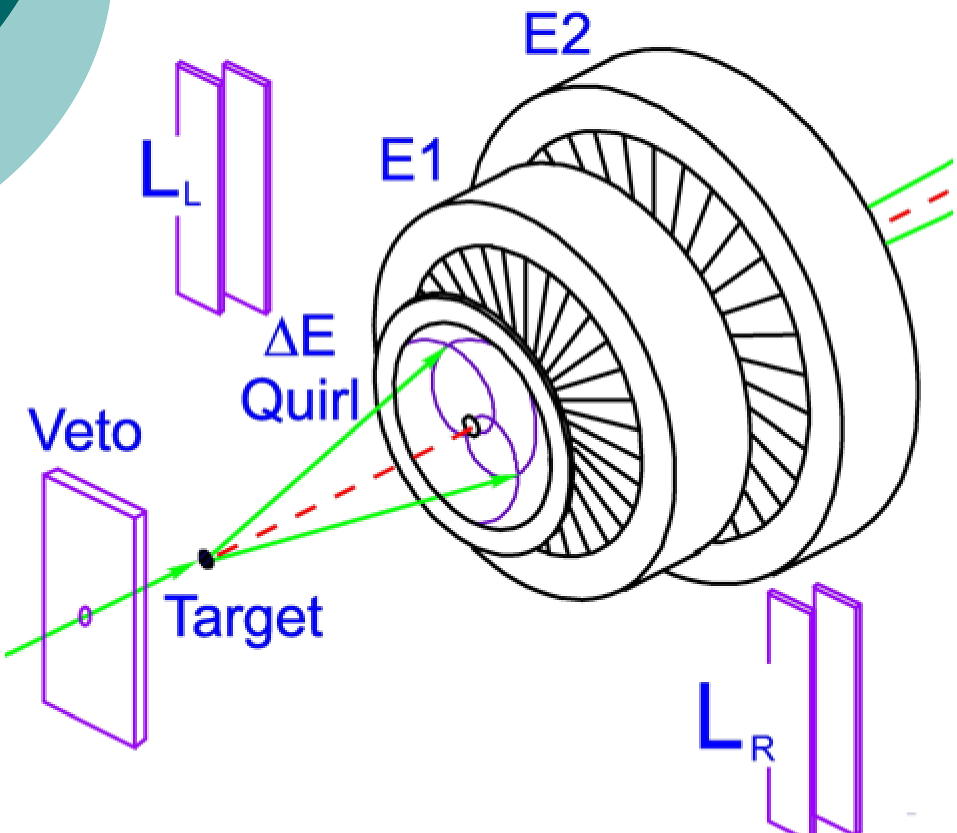


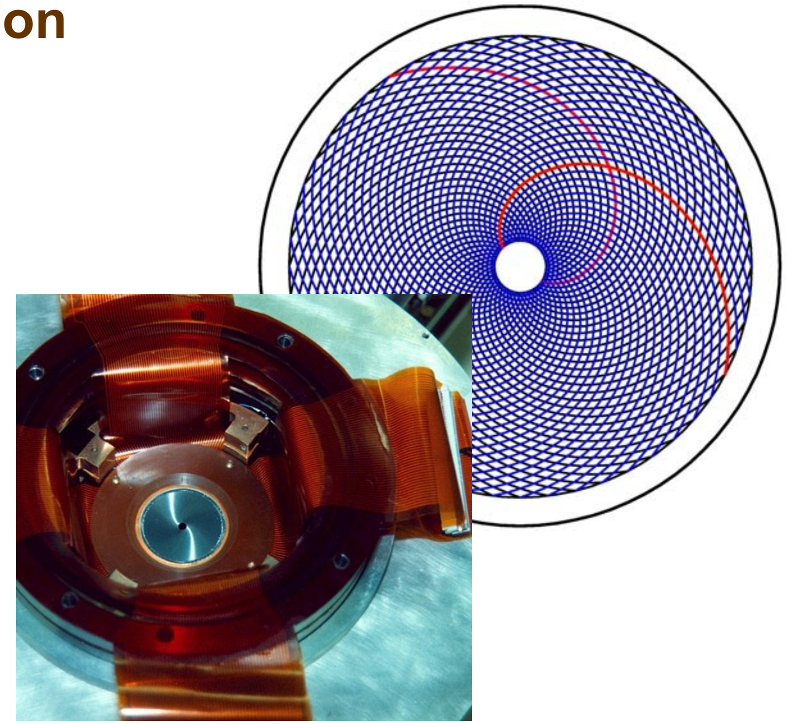


$^{1}H(\vec{d},pp)n$ Measurement at 130 MeV

Germanium Wall Exp. @ COSY / BigKarl

Very forward−angle region
θ = 5º - 15º



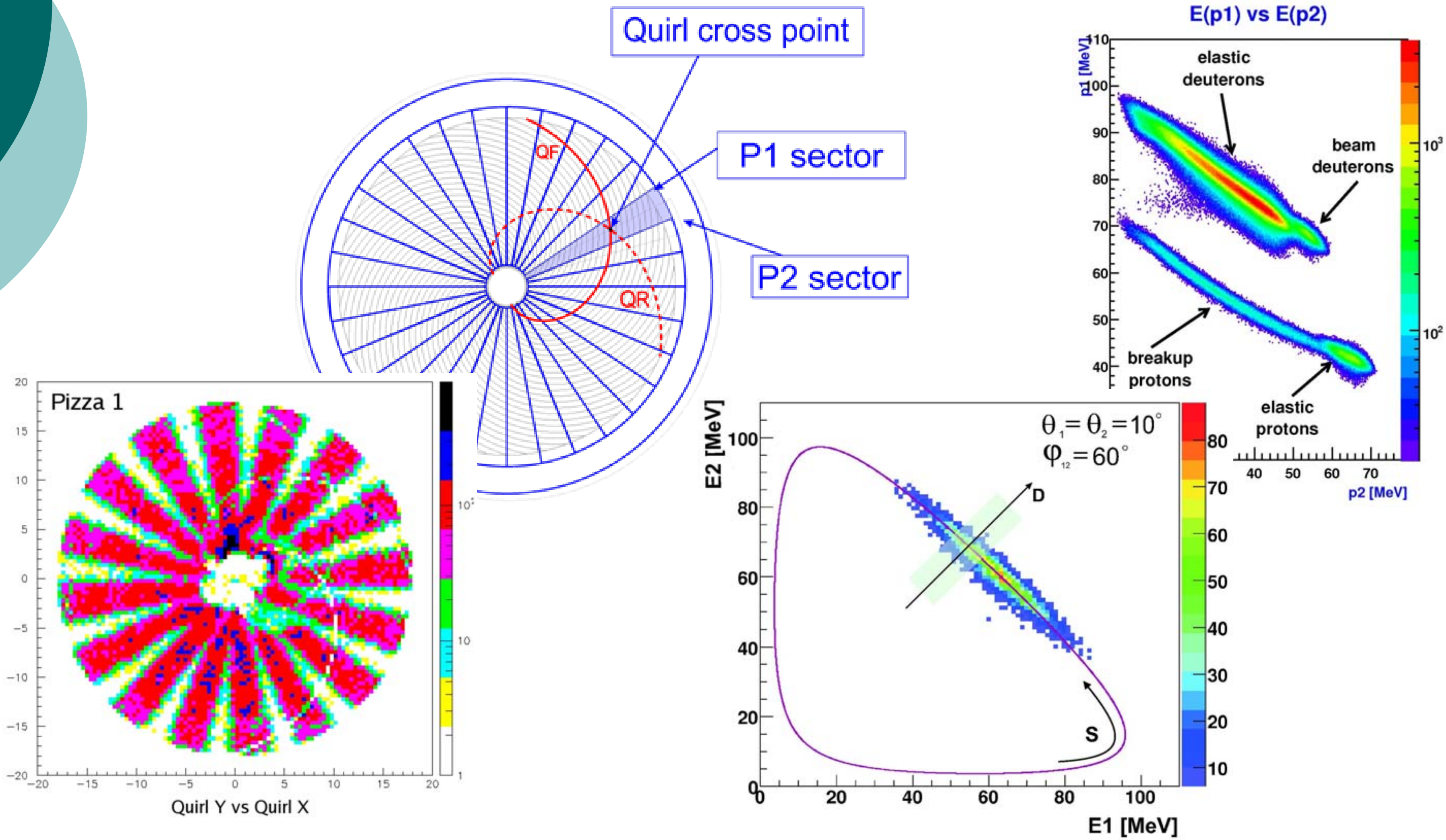


Quirl

2•200 spiral segments
pixel 0.011-0.101 mm^2

^{1}H($\vec{d}$,pp)n Measurement at 130 MeV

Germanium Wall Exp. @ COSY / BigKarl



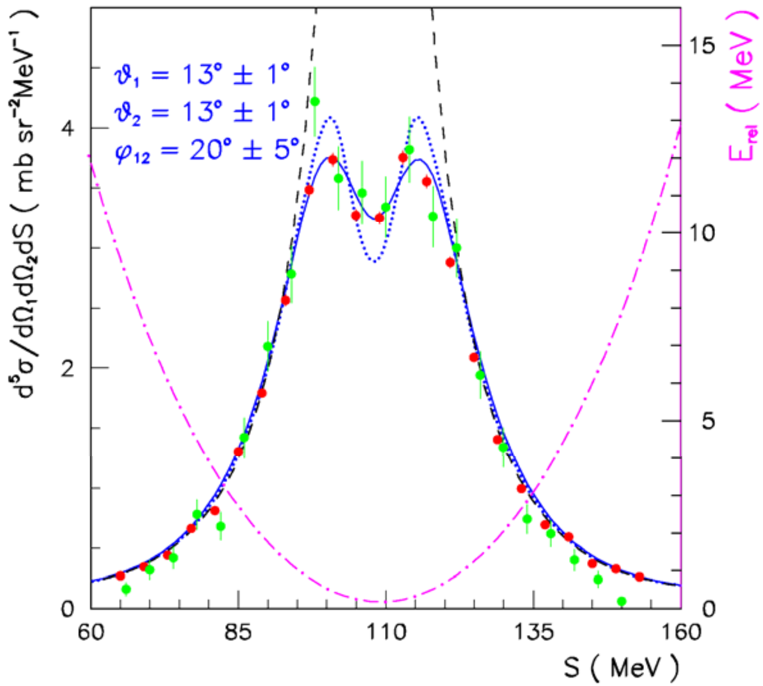
$^{1}H(\vec{d},pp)n$ Measurement at 130 MeV
FZJ Cross Section Results – Summary

- ✓ Nearly 2700 cross section data points
  - $\theta_1, \theta_2 = 5^o - 13^o$; grid 2^o; $\Delta\theta = \pm 1^o$
  - $\varphi_{12} = 20^o - 180^o$; grid 20^o; $\Delta\varphi = \pm 5^o$
  - S [MeV] = 40 – 180; grid 4; $\Delta S = \pm 4$
  - ➢ Statistical accuracy 2% - 5%
  - ➢ Data very clean – accidentals below 2%
  - ➢ Systematic errors of 5% - 10%
    - ✗ Certain configs. still with large systematic uncert.
- ✓ Global comparisons with theory: χ^2 /d.o.f.
  $\chi^2 = f(\varphi_{12})$, $\chi^2 = f(\theta_1,\theta_2)$, $\chi^2 = f(E_{rel})$

^{1}H($\vec{d}$,pp)n Measurement at 130 MeV

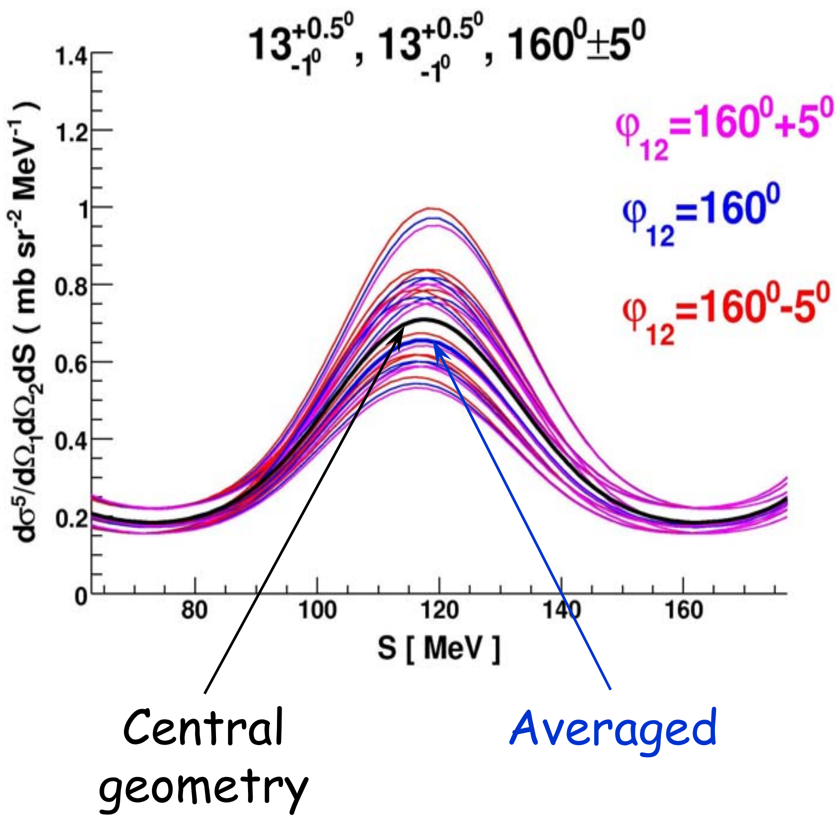
Cross Section Results – Averaging

Averaging important !



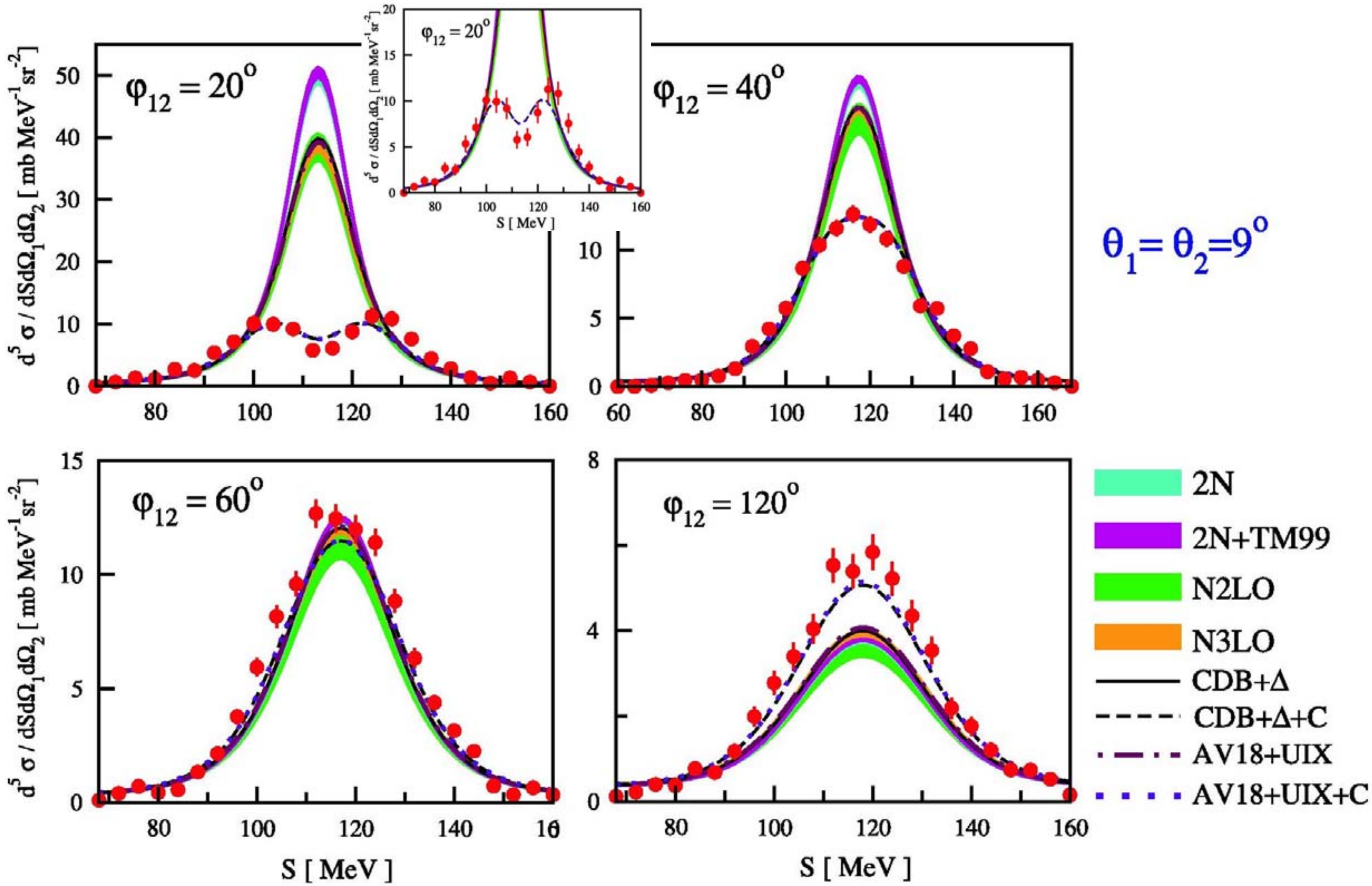
Comparison

● KVI ; ● FZJ



^{1}H($\vec{d}$,pp)n Measurement at 130 MeV

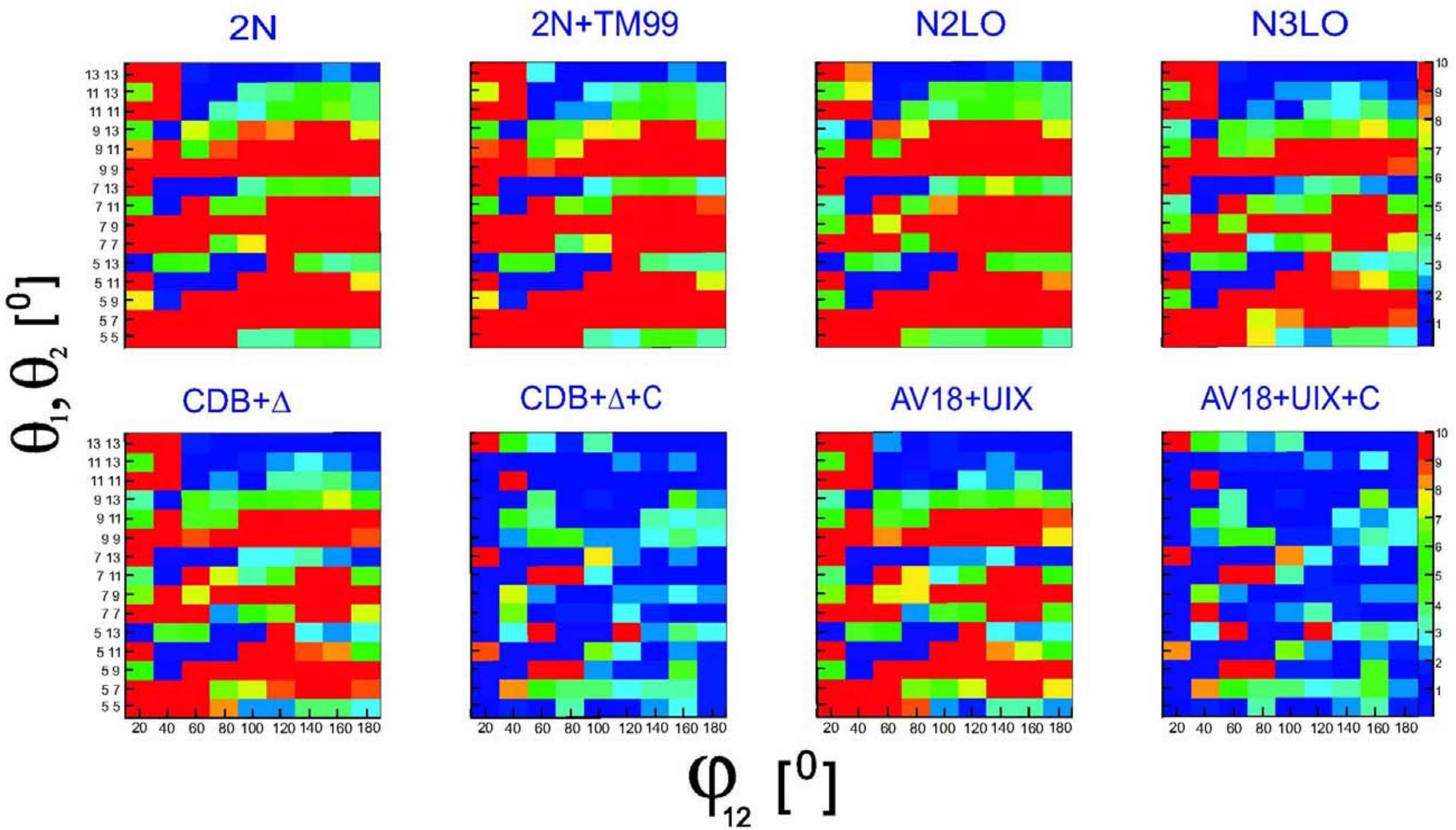
Cross Section Results – Examples



$^1H(\vec{d},pp)n$ Measurement at 130 MeV

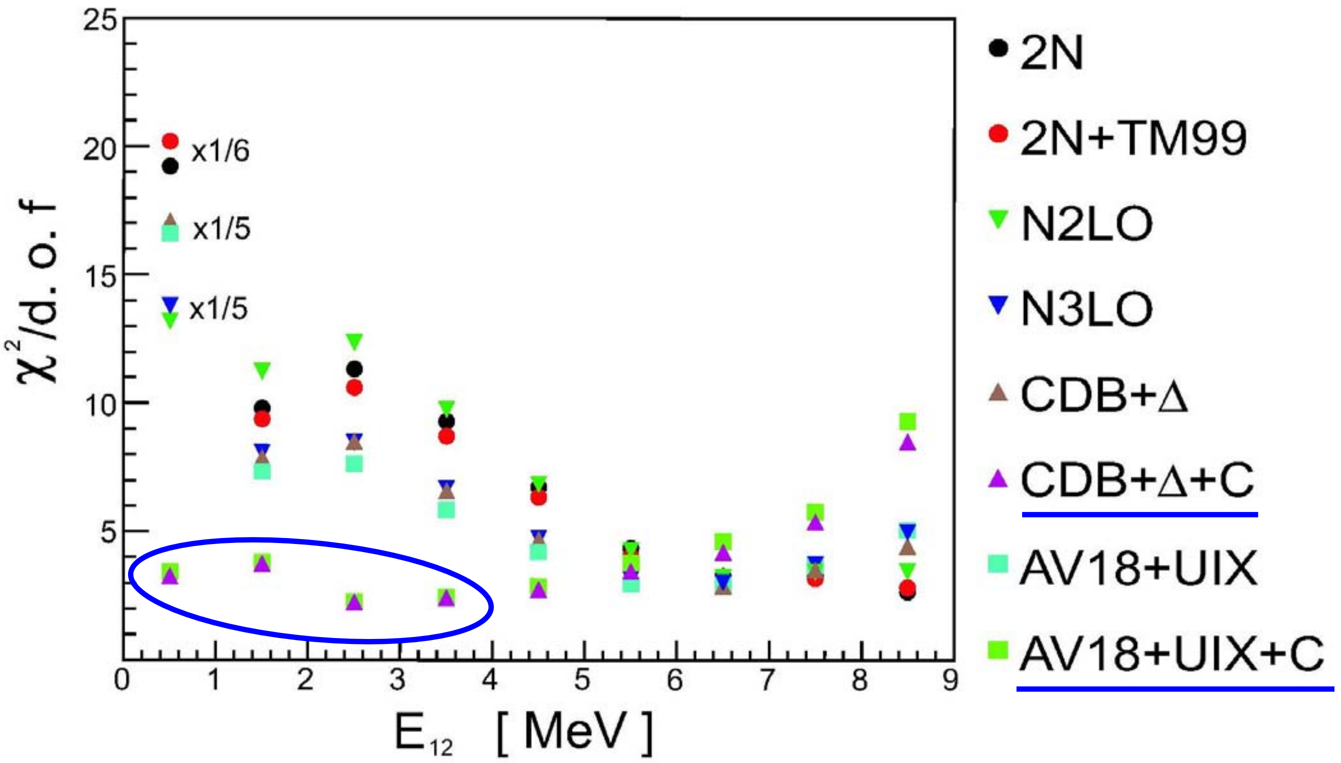
Cross Section Results – Global Comparison

χ^2 calculated for a given configuration with respect to the specified theory



$^1H(\vec{d},pp)n$ Measurement at 130 MeV

Cross Section Results – Global Comparisons

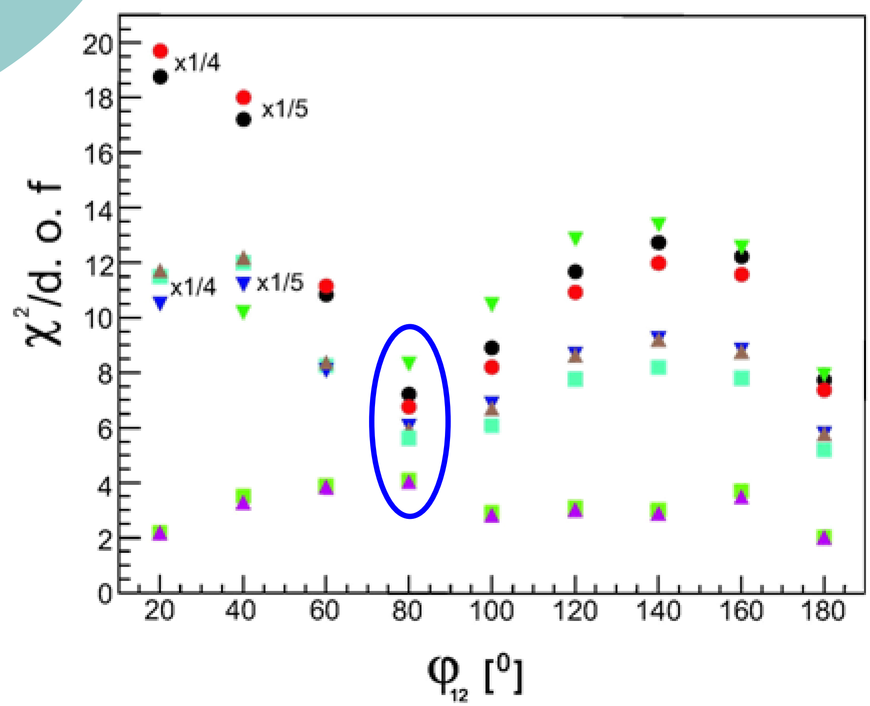


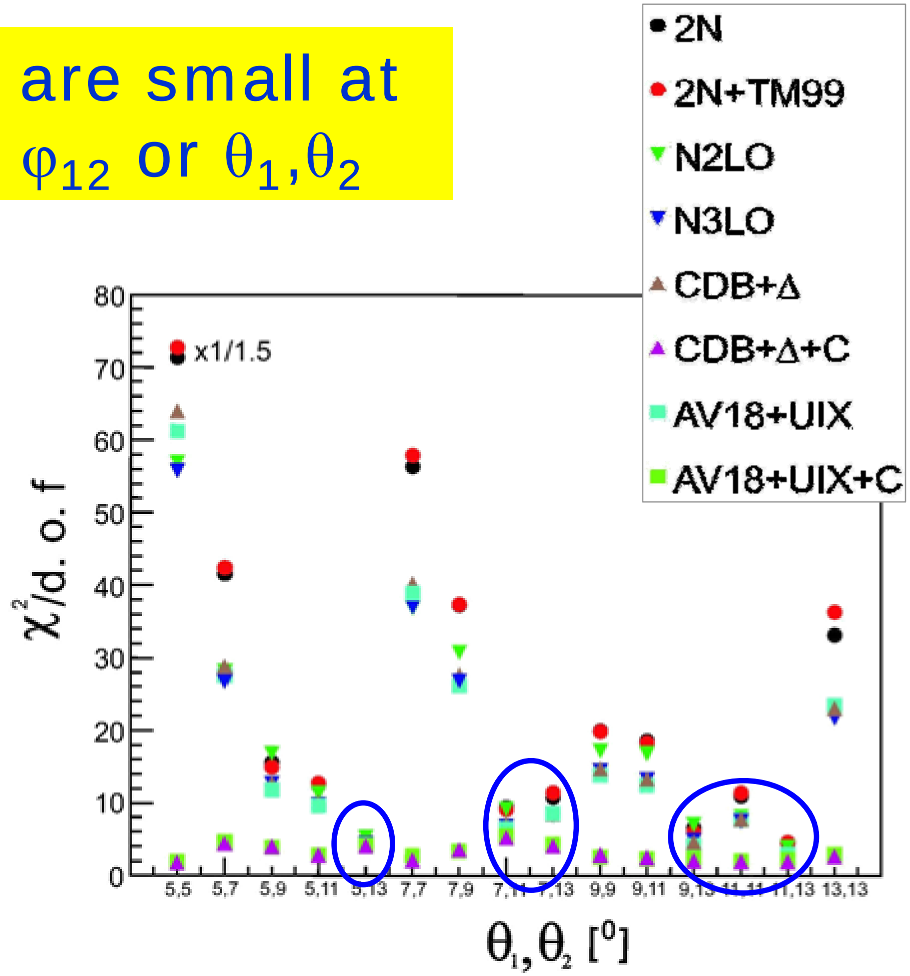
Coulomb influences not important at E_{12} > 5 MeV

$^{1}H(\vec{d},pp)n$ Measurement at 130 MeV

Cross Section Results – Global Comparison

Coulomb influences are small at certain geometries: φ_{12} or θ_1,θ_2



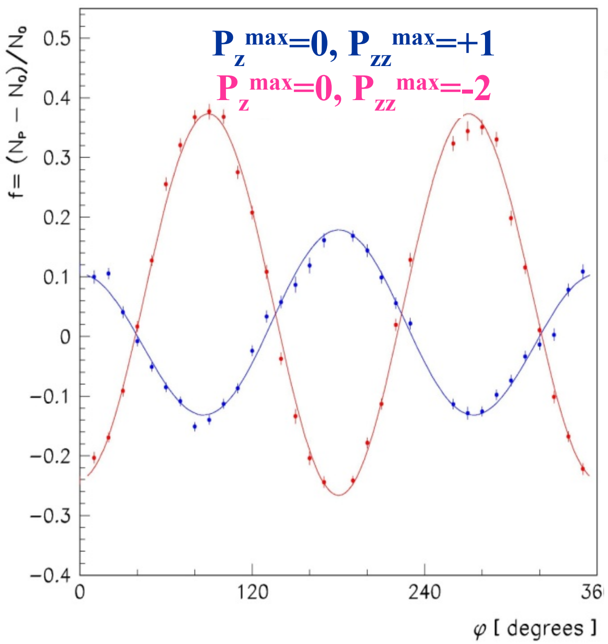


$^1H(\vec{d},pp)n$ Measurement at 130 MeV

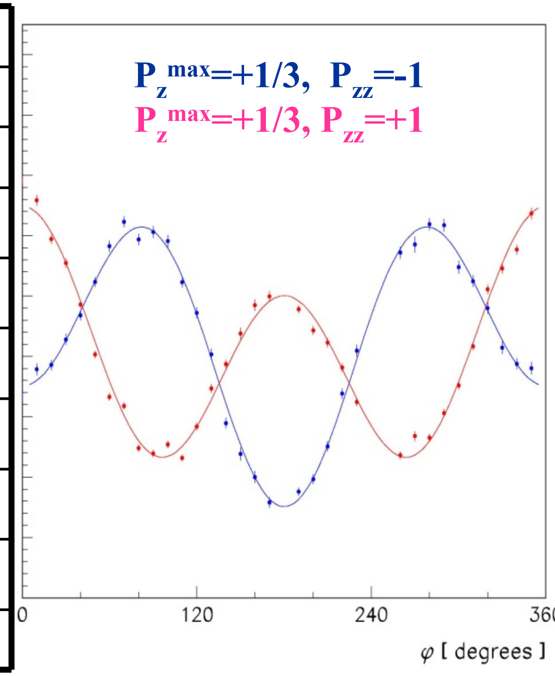
Analyzing Power Results – Beam Polarization

Elastic $^1H(\vec{d},pd)$ scattering – azimuthal (φ) distribution at selected polar (θ) angle, where T_{ii}'s are known

$$\sigma_P(\theta_p,\varphi_p)=\sigma_0(\theta_p)\cdot\left[1+\sqrt{3}\cdot iT_{11}(\theta_p)\cdot P_z\cdot\cos\varphi_p-\frac{\sqrt{3}}{2}\cdot T_{22}(\theta_p)\cdot P_{zz}\cdot\cos 2\varphi_p-\frac{\sqrt{2}}{4}\cdot T_{20}(\theta_p)\cdot P_{zz}\right]$$

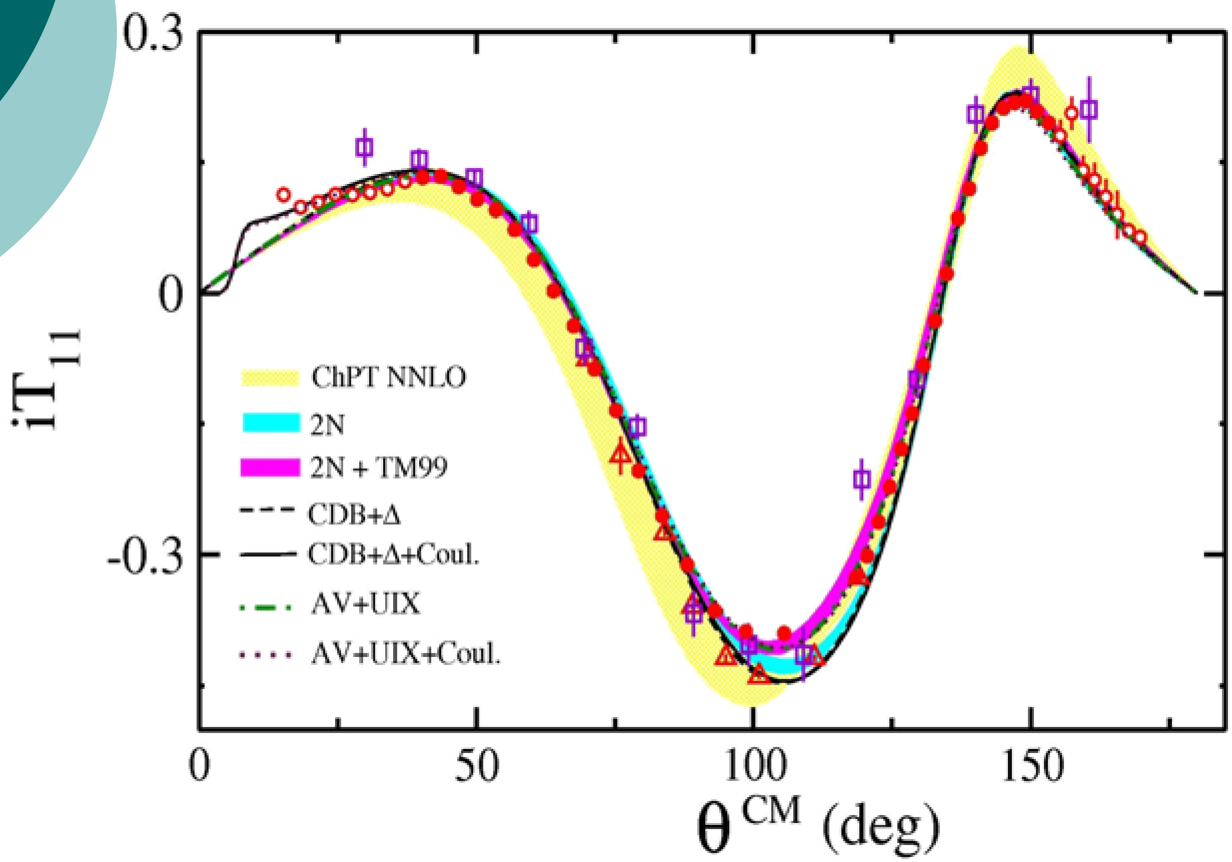


7 states:		ΔP_z	ΔP_{zz}
		0.008	0.05
P_z^{max}	P_{zz}^{max}	P_z	P_{zz}
+1/3	-1	0.265	-0.73
+2/3	0	0.480	-0.08
-2/3	0	-0.469	0.06
0	+1	-0.058	0.52
0	-2	0.009	-1.37
+1/3	+1	0.219	0.61
0	0		



$^{1}H(\vec{d},pp)n$ Measurement at 130 MeV

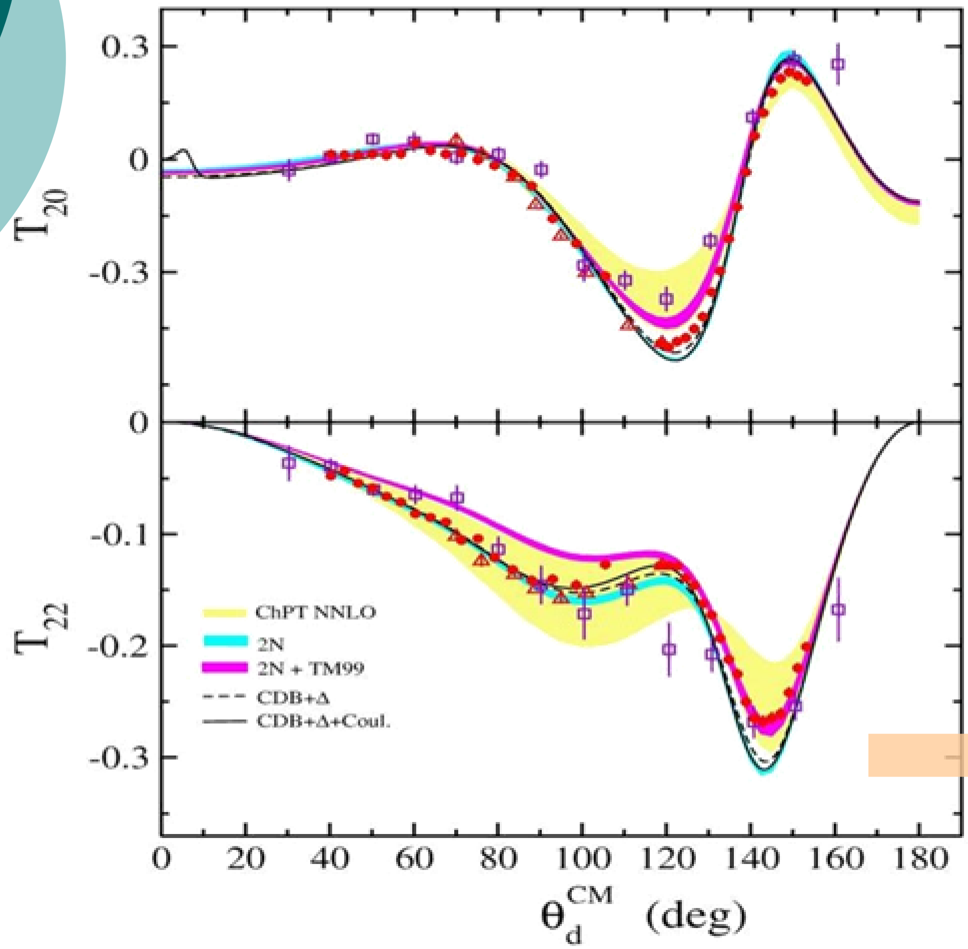
Analyzing Power Results – Elastic Scattering



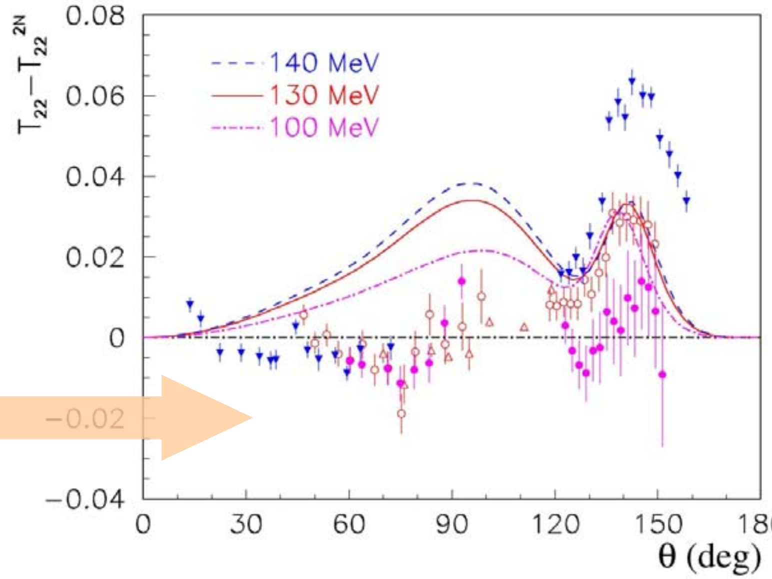
- E. Stephan et al., Phys. Rev. C 76, 057001 (2007)
- GeWall @ COSY
- H. Mardanpour et al., Eur. Phys. J. 31, 383 (2007)
- H. Witała et al., Few-Body Systems 15, 67-85 (1993)

$^1H(\vec{d},pp)n$ Measurement at 130 MeV

Analyzing Power Results – Elastic Scattering



Different energy dependence of T_{22} data and theory in angular regions

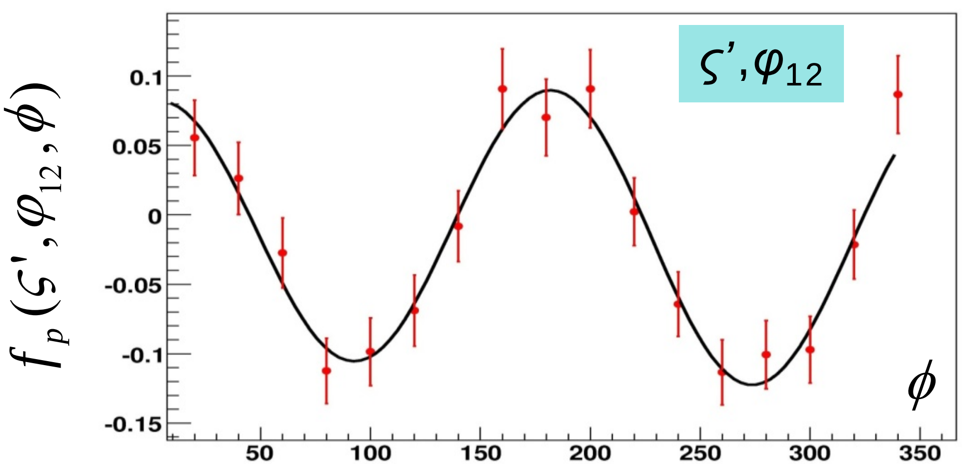


$^1H(\vec{d},pp)n$ Measurement at 130 MeV

Breakup Analyzing Powers – Extraction

Azimuthal (Φ) distribution at every kinematical point ($\theta_1,\theta_2,\varphi_{12},S$) $\equiv$ (ς',φ_{12}), with known P_z and P_{zz} of rate asymmetry $f_P(\varsigma',\varphi_{12},\Phi)$ for pol. and unpol. states

$$f_p(\varsigma',\varphi_{12},\phi) = \left[P_z \cdot \left(-\frac{3}{2}\sin\phi \cdot A_x + \frac{3}{2}\cos\phi \cdot A_y \right) + P_{zz} \cdot \left(-\frac{1}{2}\sin 2\phi \cdot A_{xy} \right) + \right.$$
$$\left. + P_{zz} \cdot \left(\frac{1}{2}\sin^2\phi \cdot A_{xx} + \frac{1}{2}\cos^2\phi \cdot A_{yy} \right) \right]$$



$A \equiv A(\varsigma',\varphi_{12})$

$^{1}H(\vec{d},pp)n$ Measurement at 130 MeV
Analyzing Power Results – Summary

- ✓ 5 x ~800 data points A_x, A_y, A_{xx}, A_{xy}, A_{yy}
  - $\theta_1, \theta_2 = 15^o - 30^o$; grid 5^o ; $\Delta\theta = \pm 2^o$
  - $\varphi_{12} = 40^o - 180^o$; grid 20^o ; $\Delta\varphi = \pm 10^o$
  - S [MeV] = 40 – 160; grid 4; $\Delta S = \pm 4$
  - ➢ Statistical accuracy 0.01 – 0.05
- ✓ 2 x ~300 data points A_x, A_y
  - $\theta_1, \theta_2 = 6^o - 12^o$; grid 3^o ; $\Delta\theta = \pm 1.5^o$
  - $\varphi_{12} = 60^o - 180^o$; grid 40^o ; $\Delta\varphi = \pm 20^o$
  - S [MeV] = 40 – 160; grid 4; $\Delta S = \pm 8$
  - ➢ Statistical accuracy 0.02 – 0.04

$^{1}H(\vec{d},pp)n$ Measurement at 130 MeV

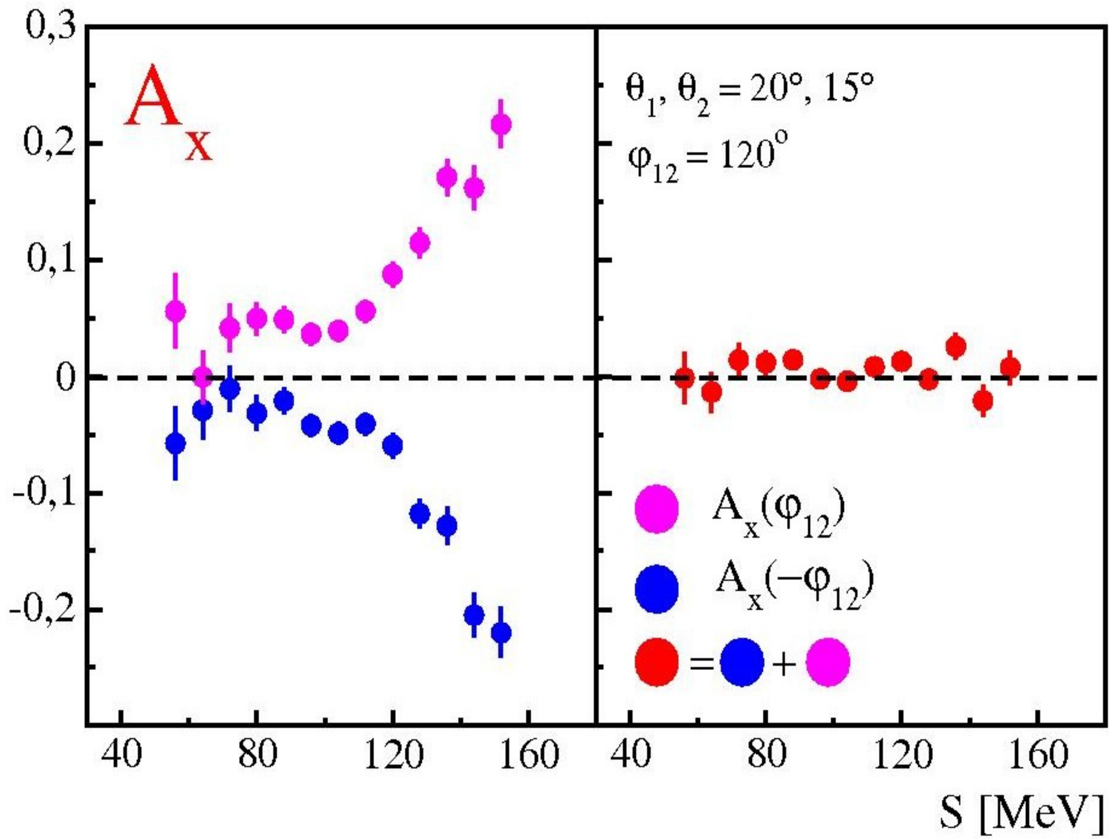
Analyzing Power Results – Parity Test of Data

Parity symmetry

$$A_\beta(\varsigma',-\varphi_{12}) = $$
$$= (-1)^\mu \bullet A_\beta(\varsigma',\varphi_{12})$$

$\mu = 1$ for $\beta = x, xy$

$\mu = 0$ for $\beta = y, xx, yy$



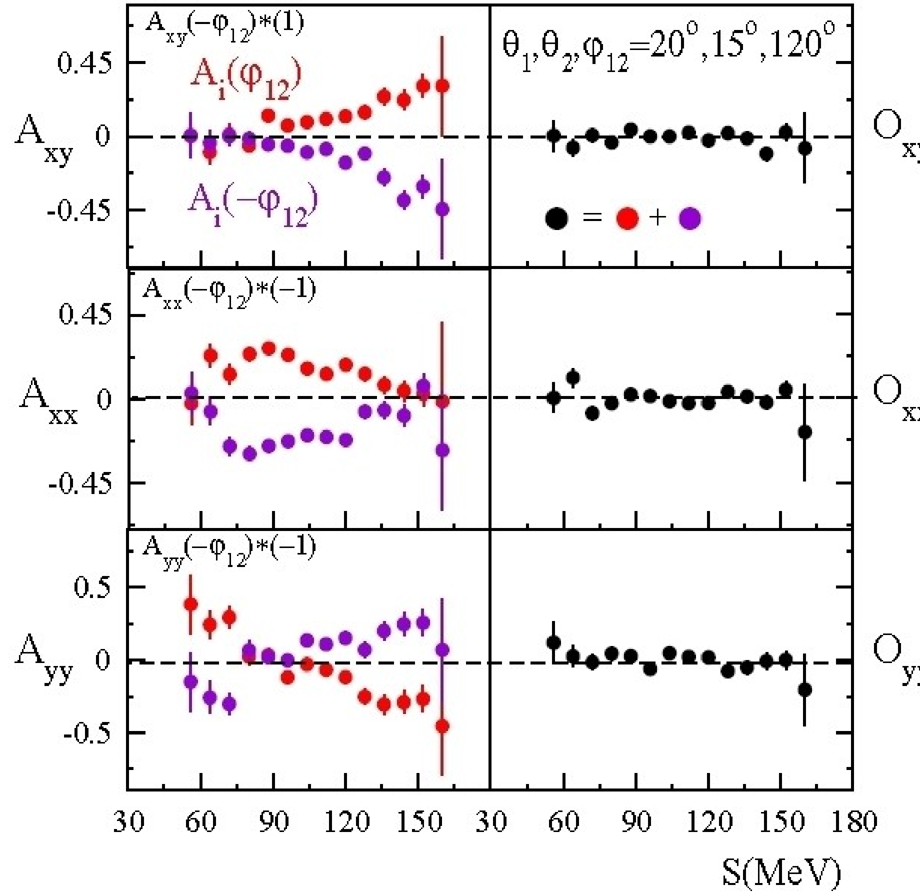
Parity-forbidden combinations

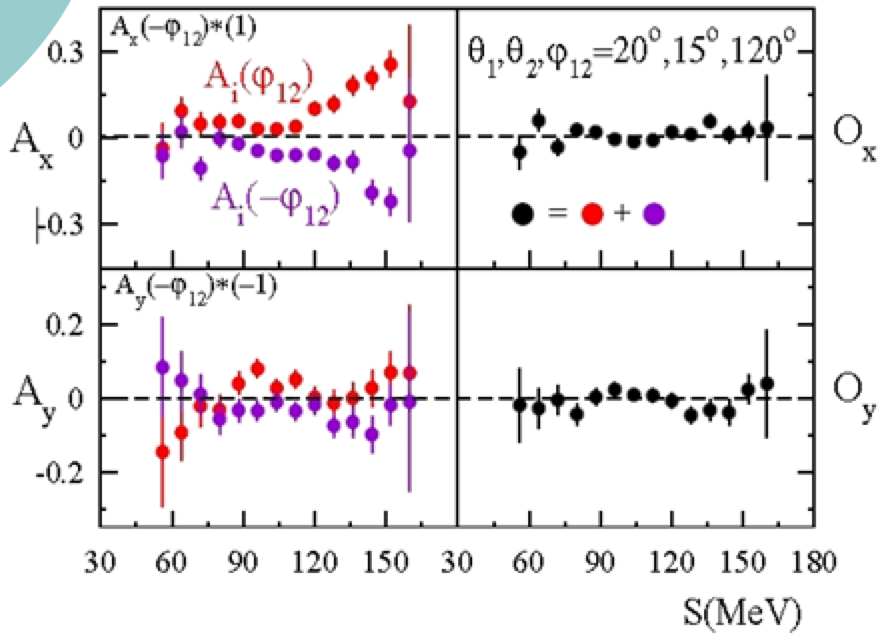
$$O_\beta(\varsigma',\varphi_{12}) = A_\beta(\varsigma',\varphi_{12}) + (-1)^{1-\mu} \bullet A_\beta(\varsigma',-\varphi_{12})$$

^{1}H($\vec{d}$,pp)n Measurement at 130 MeV

Analyzing Power Results – Parity Test of Data

Parity-forbidden combinations

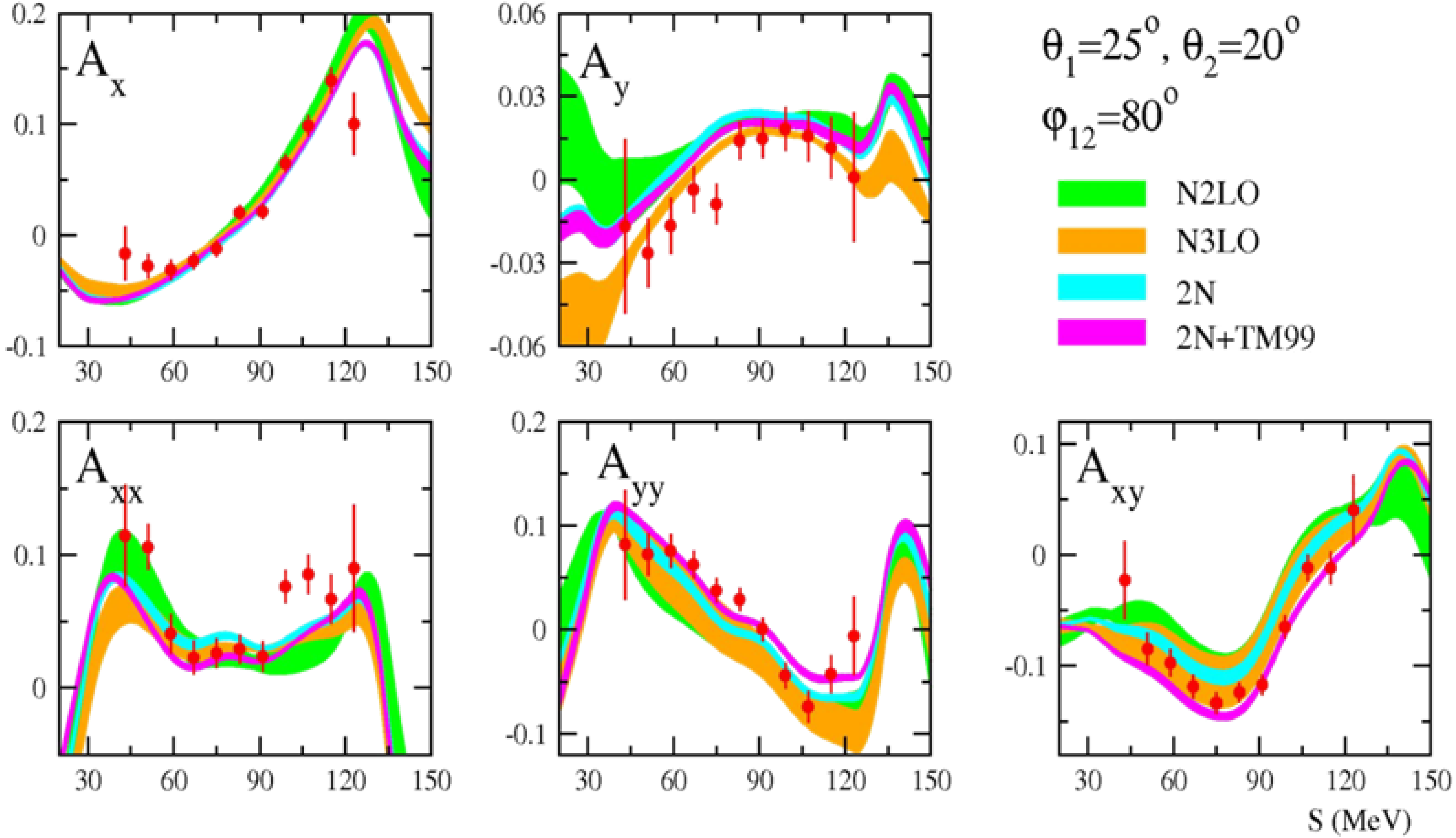




$$O_\beta(\varsigma',\varphi_{12}) = A_\beta(\varsigma',\varphi_{12}) + (-1)^{1-\mu} \bullet A_\beta(\varsigma',-\varphi_{12})$$

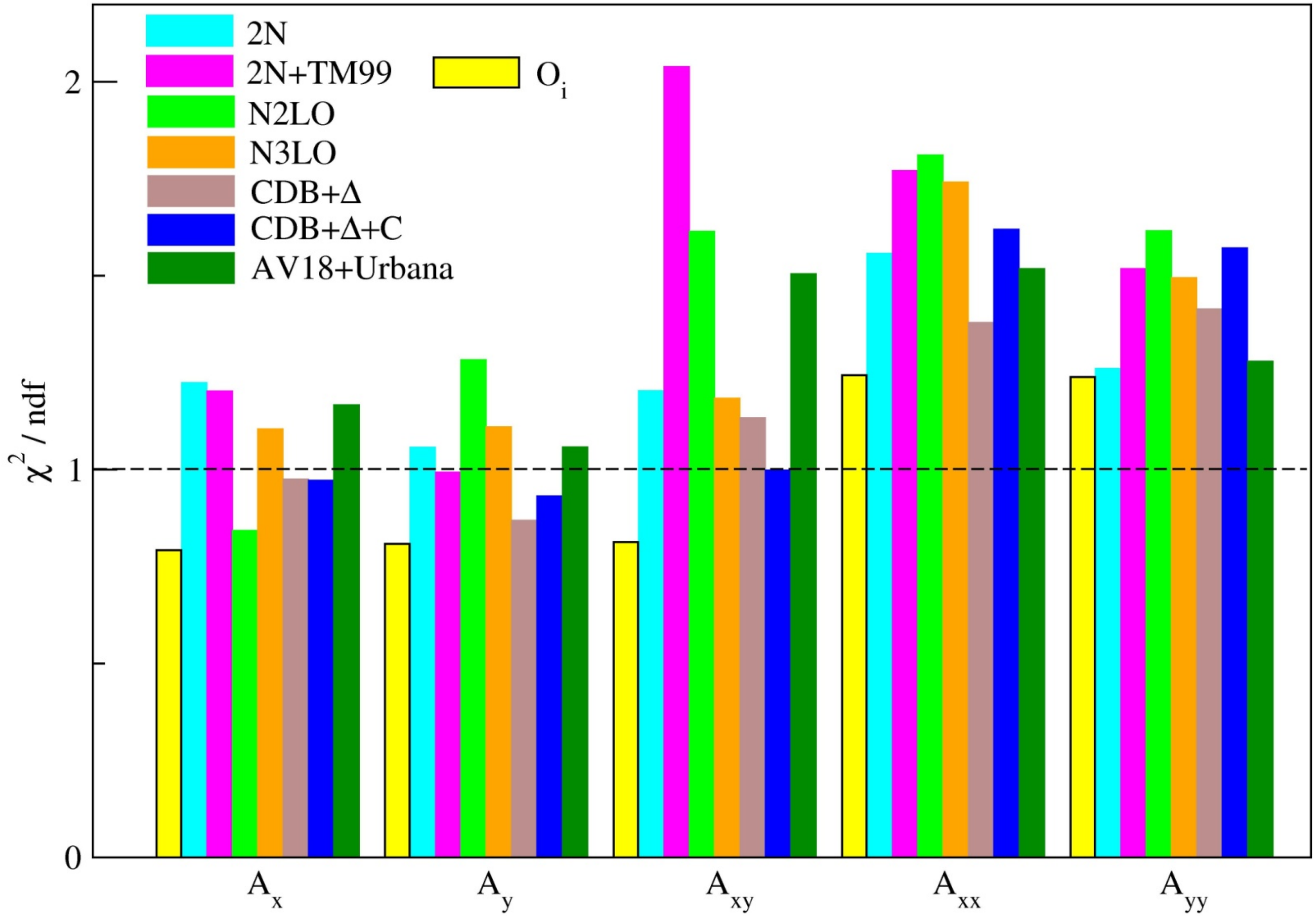
$^{1}H(\vec{d},pp)n$ Measurement at 130 MeV

Analyzing Power Results – Examples



$^{1}H(\vec{d},pp)n$ Measurement at 130 MeV

Analyzing Power Results – Global Comparison



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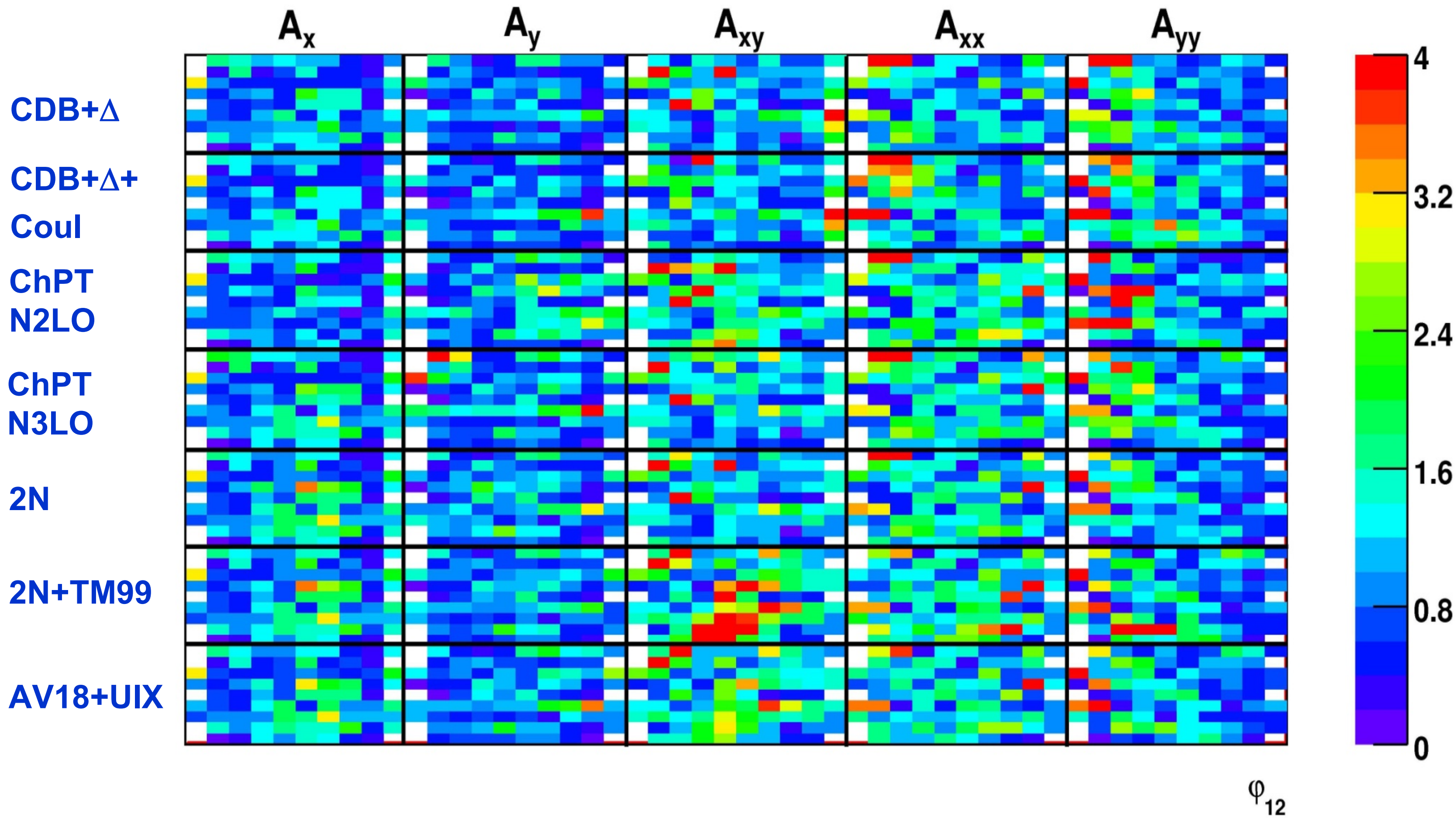
$^1H(\vec{d},pp)n$ Measurement at 130 MeV

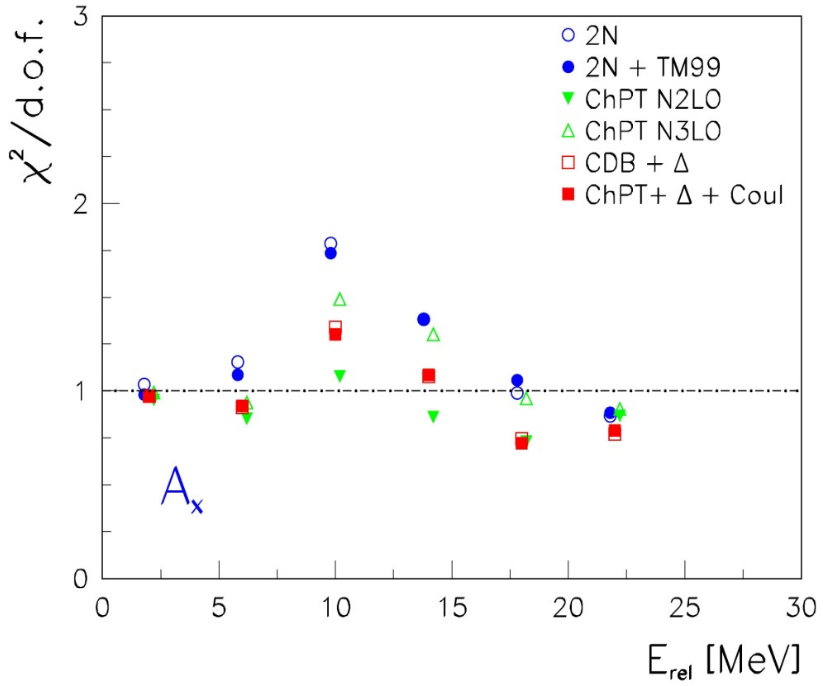
Analyzing Power Results – Global Comparison

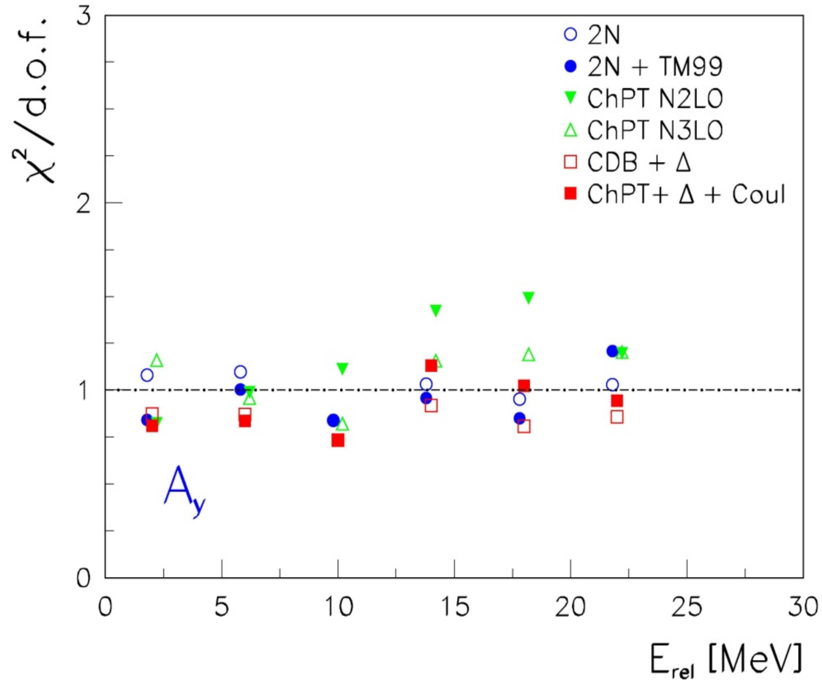
χ^2 calculated for a given configuration with respect to the specified theory



$^{1}H(\vec{d},pp)n$ Measurement at 130 MeV

Vector A_x, A_y Analyzing Power Results



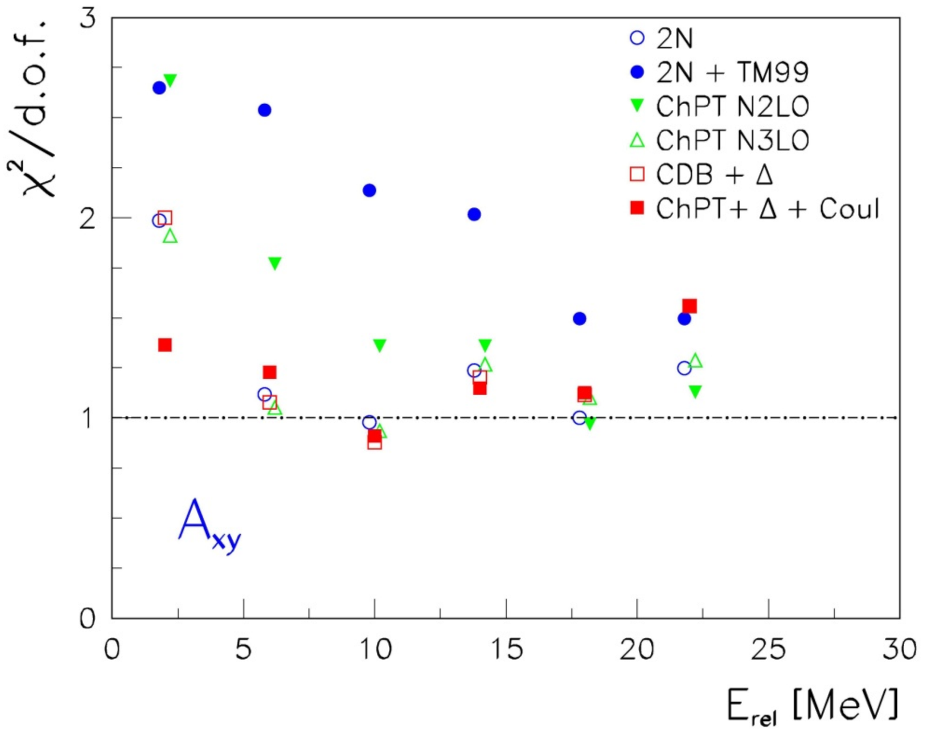


Rather good description by all approaches.

Sensitivity to neither 3NF nor Coulomb force !

$^{1}H(\vec{d},pp)n$ Measurement at 130 MeV

Tensor A_{xy} Analyzing Power Results

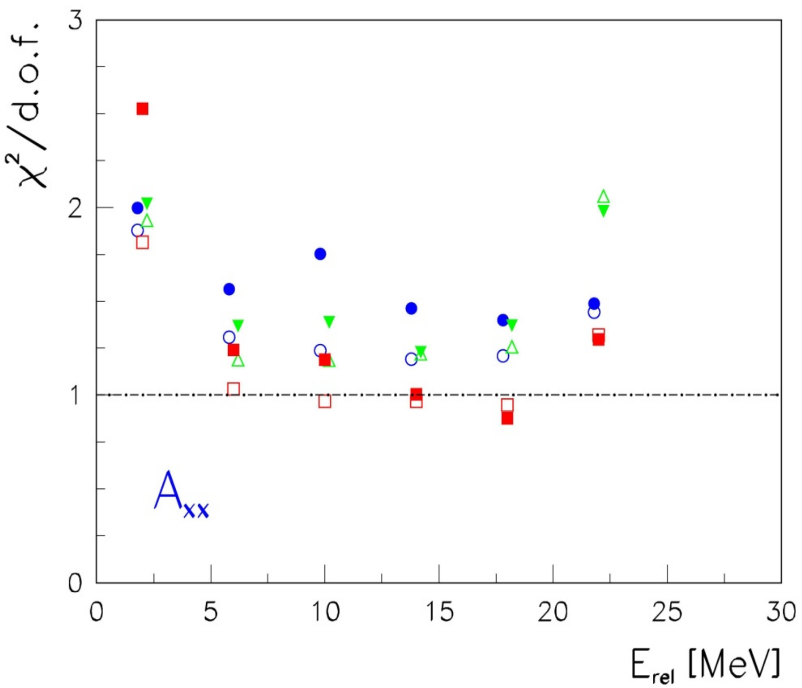


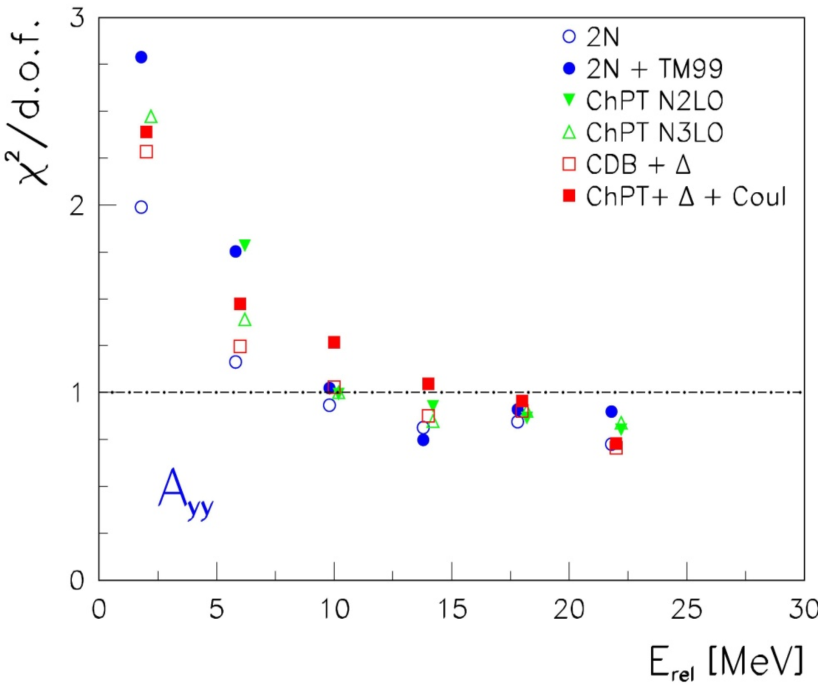
No sensitivity to Coulomb force.

Problem with TM99 3NF !

$^{1}H(\vec{d},pp)n$ Measurement at 130 MeV

Tensor A_{xx}, A_{yy} Analyzing Power Results





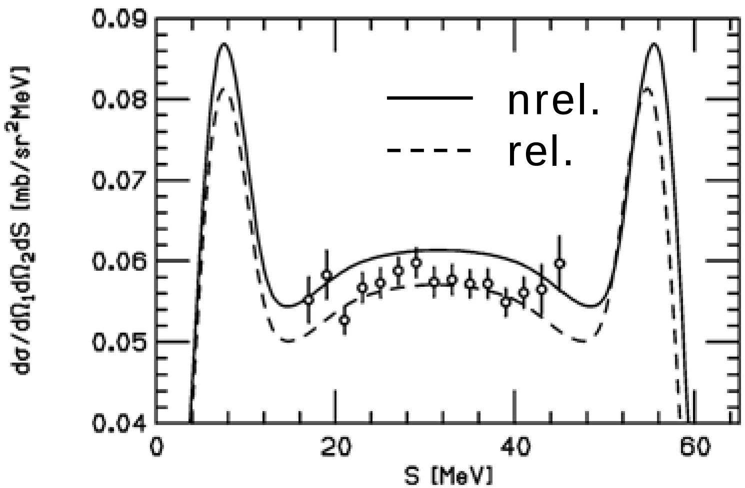
No sensitivity to 3N and Coulomb forces.

General problems at low E_{rel} values !

$^2H(\vec{p},pp)n$ Measurements

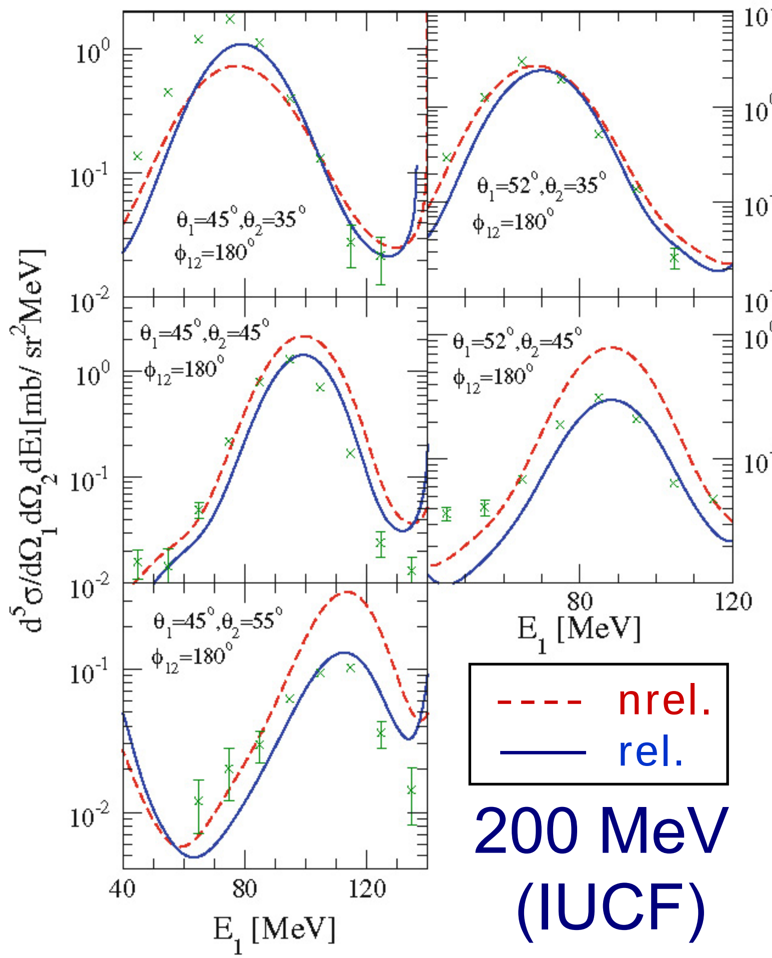
Cross Section Results – Relativistic Effects

CD Bonn potential



65 MeV (PSI)

$\theta_1 = \theta_2 = 54^o, \varphi_{12} = 120^o$



200 MeV (IUCF)

$^{1}H(\vec{d},pp)n$ Measurements at 130 MeV

Summary

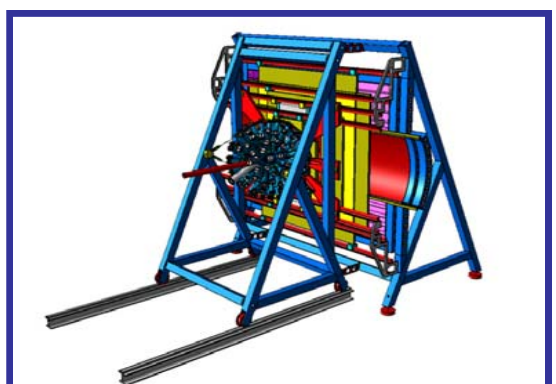
- Systematic, precise sets of **cross sections** and analyzing powers obtained at E_d = 130 MeV
  ➡ basis for comparing different approaches which predict the 3N system observables
- Showed significant 3NF effects for cross sections !
- Found large influence of the Coulomb force on c.s.
- Relativistic effects to be studied in detail
- Interplay of different ingredients of 3N system dynamics – inspection started !
- Discrepancies – hint of missing pieces in dynamic models
- Follow further precise and rich data sets, as well as theoretical advances !

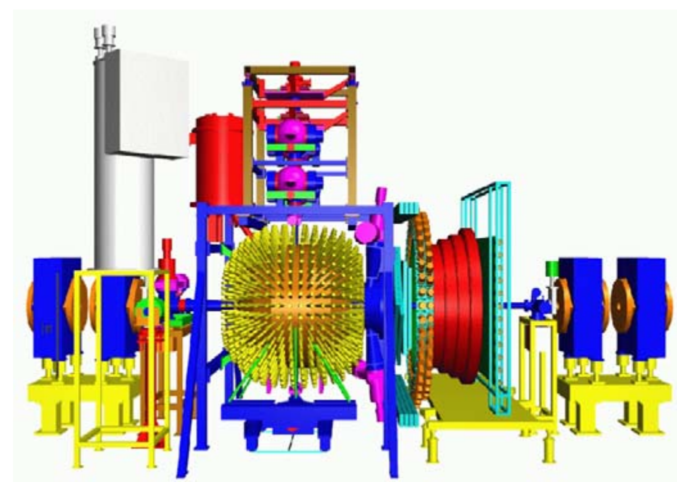
Breakup Measurements

Outlook and Wishes (3N and 4N systems)

- Prospects for further results:
  - Evaluating the data accumulated in several experiments at KVI
  - More measurements:
    - Japan: RIKEN, RCNP, RIBF, ...
    - Projects for PAX@COSY & WASA@COSY
    - KVI
    - INP Cracow

Personal, surely incomlete view





Breakup Measurements

Outlook and Wishes (3N and 4N systems)

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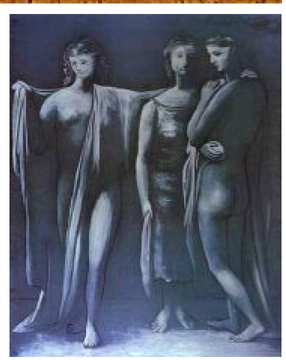
- Prospects for further results:
  - Evaluating the data accumulated in several experiments at KVI
  - More measurements:
    - Japan: RIKEN, RCNP, RIBF, ...
    - Projects for PAX@COSY & WASA@COSY
    - KVI
    - INP Cracow
- Awaited theoretical achievements:
  - 3NF at N^3LO (close ahead…)
  - ChPT with Δ (work in progress…)
  - ✓ Realistic potentials with Coulomb
  - Rigorous calculations for 4N system (dreamed for !)

Three Body Systems
Remain Attractive !








Thank You
for attention