Three-nucleon interaction dynamics studied via the deuteron-proton breakup

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Studies of the $^{1}H(\vec{d},pp)n$ Breakup at 130 MeV

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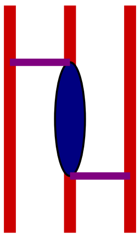
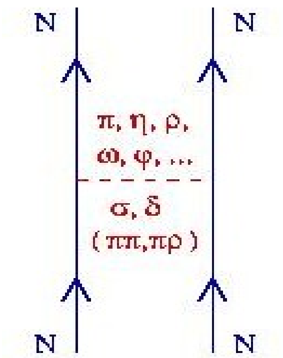


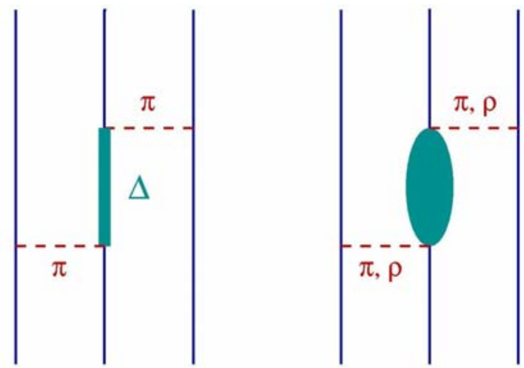
Kraków-Bochum Group
EFT/ChPT Group
Hannover/Lisboa Group

} Theory Support

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

Motivation





- Faddeev framework provides exact treatment for the 3N system
- Various approaches to construct the interaction (2N and 3N):
  - Realistic potentials + phenomenological 3NF models
  - Chiral Perturbation Theory
  - Coupled-Channels formalism with explicit Δ

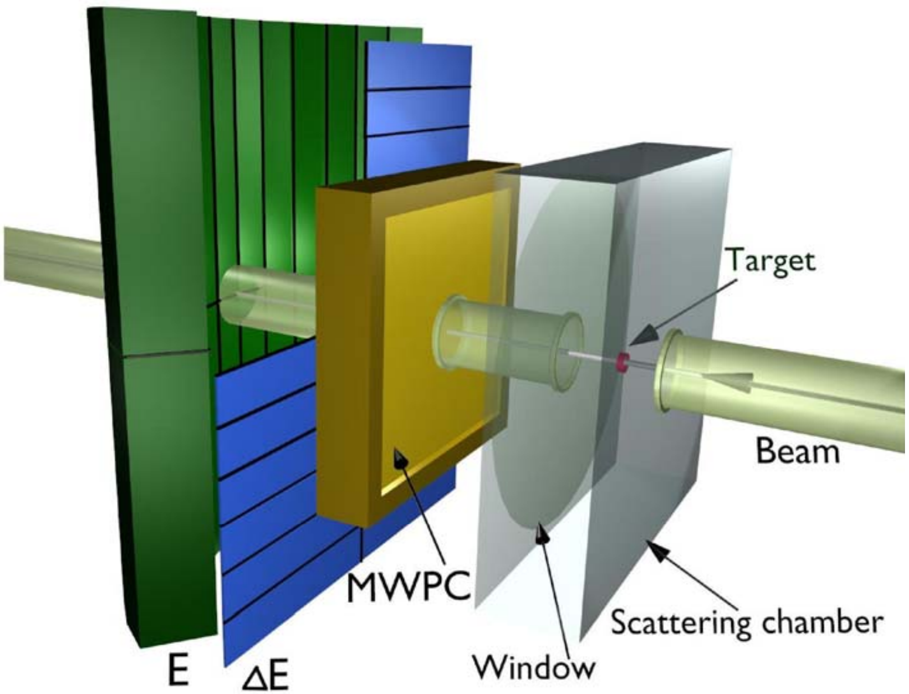
$^{1}H(\vec{d},pp)n$ Measurement at 130 MeV
Motivation

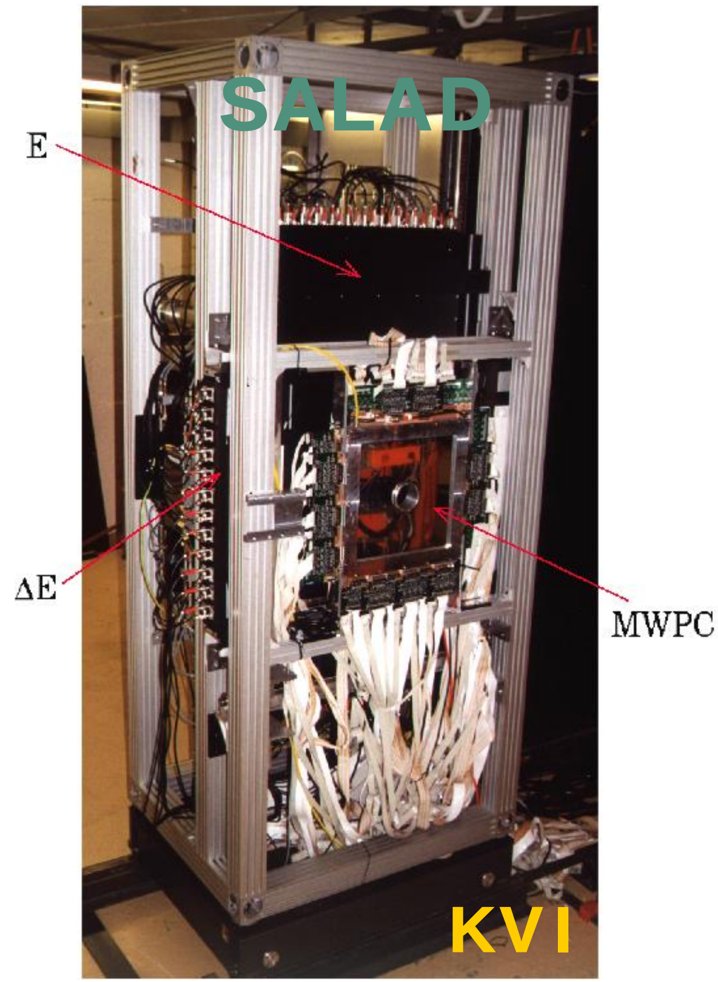
- Three-nucleon system is the simplest non-trivial environment to test predictions of the NN and 3N potential models
- Elastic scattering data demonstrate both success and problems of modern calculations
- Very few breakup data at medium energies (earlier PSI experiments provided only 14 kinematical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

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

Cross Section Results – Summary

- ✓ Nearly 1800 cross section data points
  - θ_1, θ_2 = 15° - 30°; grid 5° ; $\Delta\theta$ = ±1°
  - an additional set for θ_1, θ_2 = 13°
  - φ_{12} = 40° - 180°; grid 10°-20° ; $\Delta\varphi$ = ±5°
  - S [MeV] = 40 – 160; grid 4; ΔS = ±2
  - ➢ Statistical accuracy 0.01 – 0.05
  - ➢ Data very clean – accidentals below 2%
  - ➢ Systematic errors – 3% – 5%
- ✓ Global comparisons with theory (χ^2 test for all points, $\chi^2 = f(\varphi_{12})$, $\chi^2 = f(E_{rel})$, tests of normalization)

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

Cross Section Results – Example

EFT/ChPT calculations

Faddeev calculations

Coupled channels calculations

NNLO – 2N only

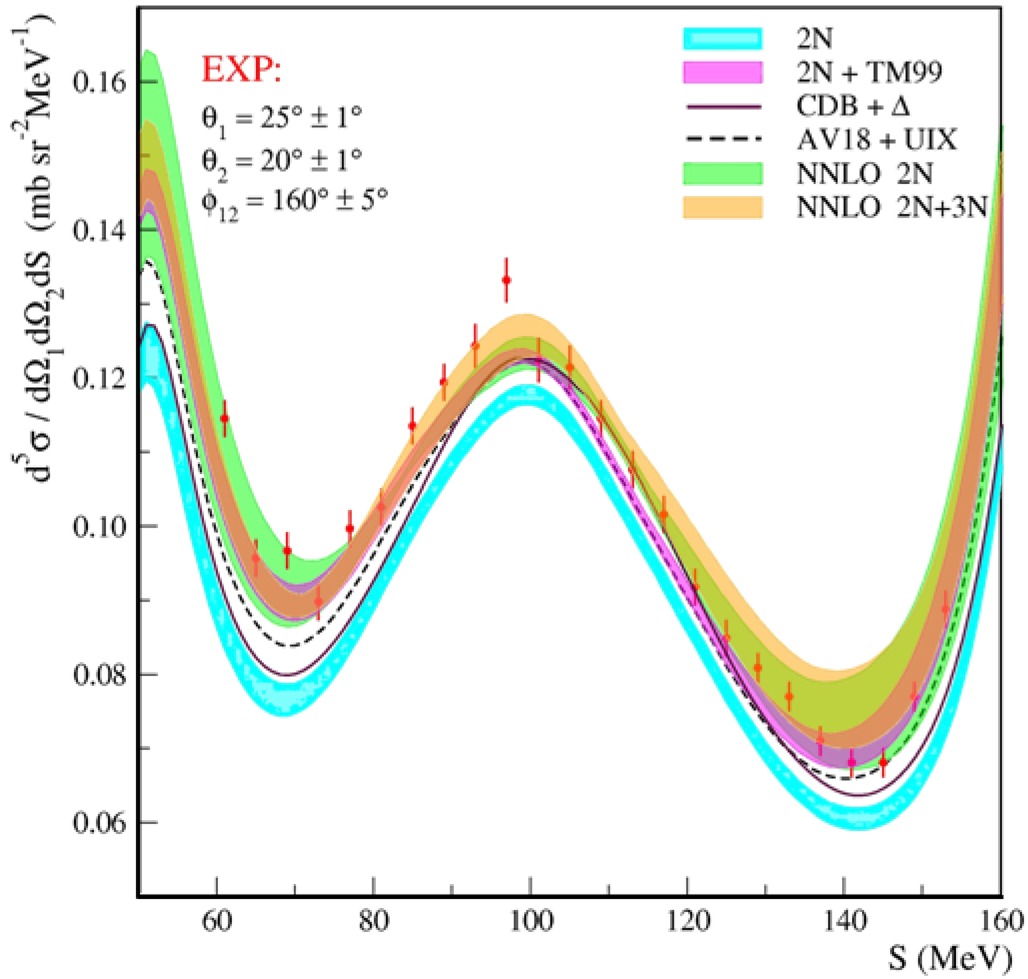
Realistic NN potentials:

(CD Bonn, Nijm I, Nijm II, Av18)

CD Bonn (modif.) + Δ

NNLO – 2N + 3 N

3NF model: TM99, UIX



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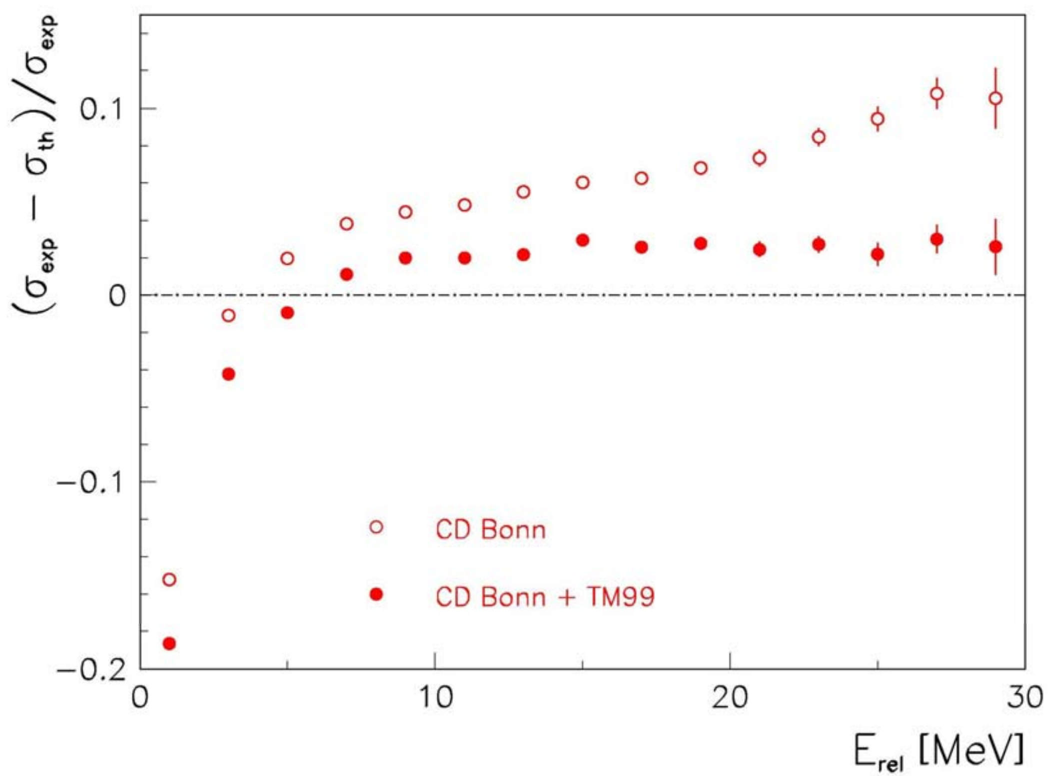
Cross Section Results – Exploring Phase Space

Relative χ^2 as a function of the relative azimuthal angle φ_{12} between the two proton trajectories



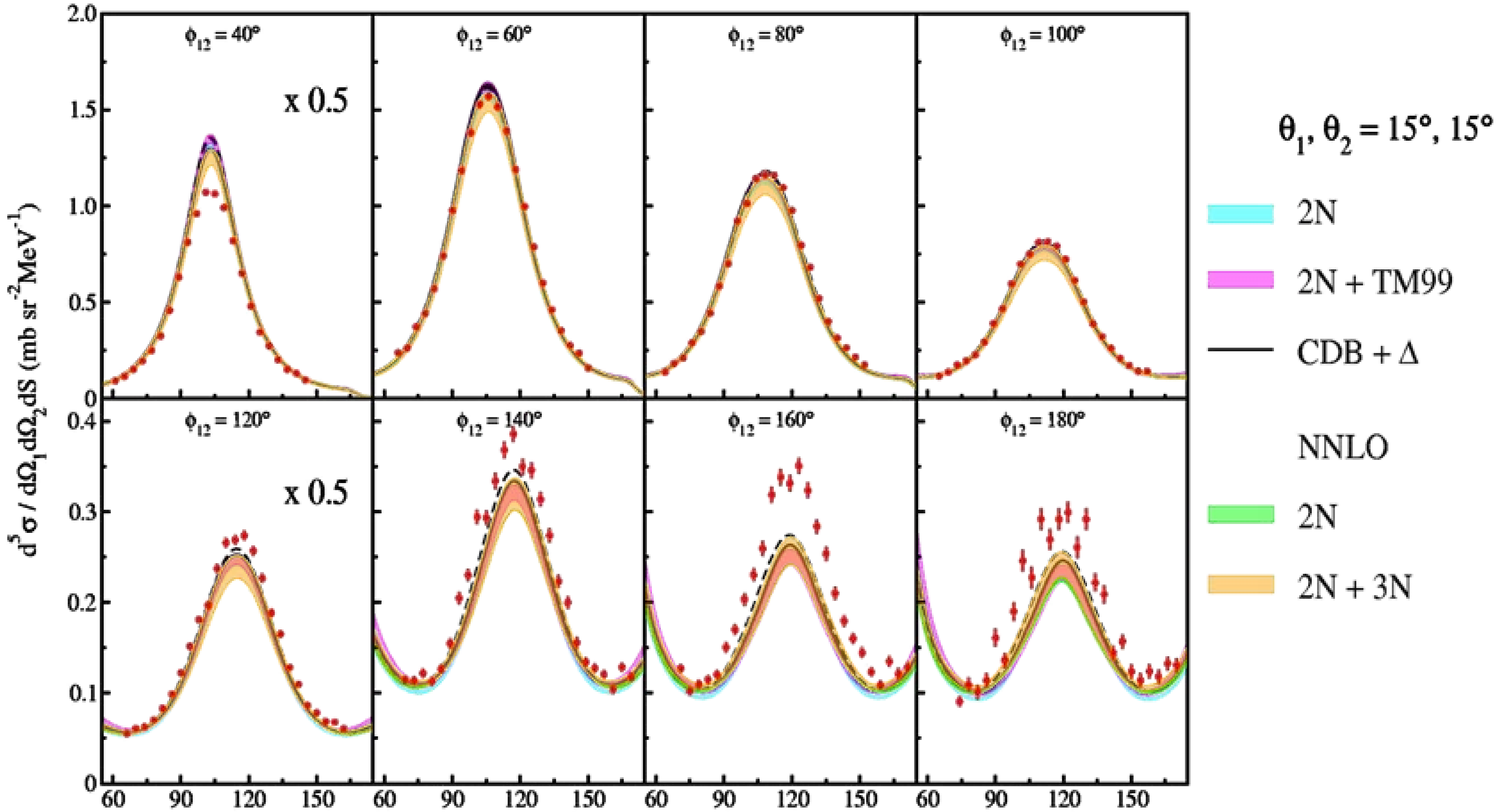
For large E_{rel} 3NF's improve description of the data when combined with the NN potentials

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

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

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

Cross Section Results – Discrepancies



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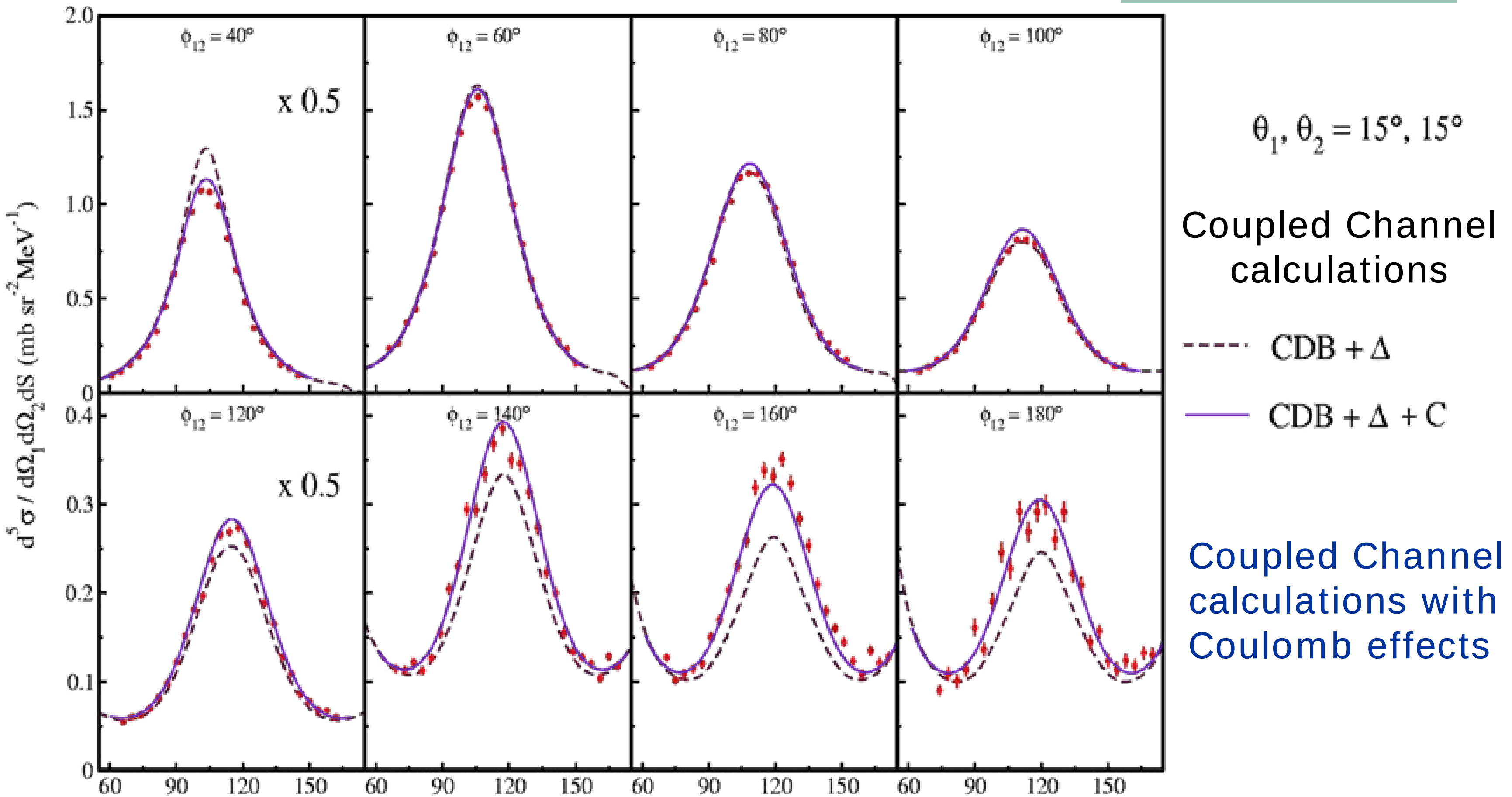
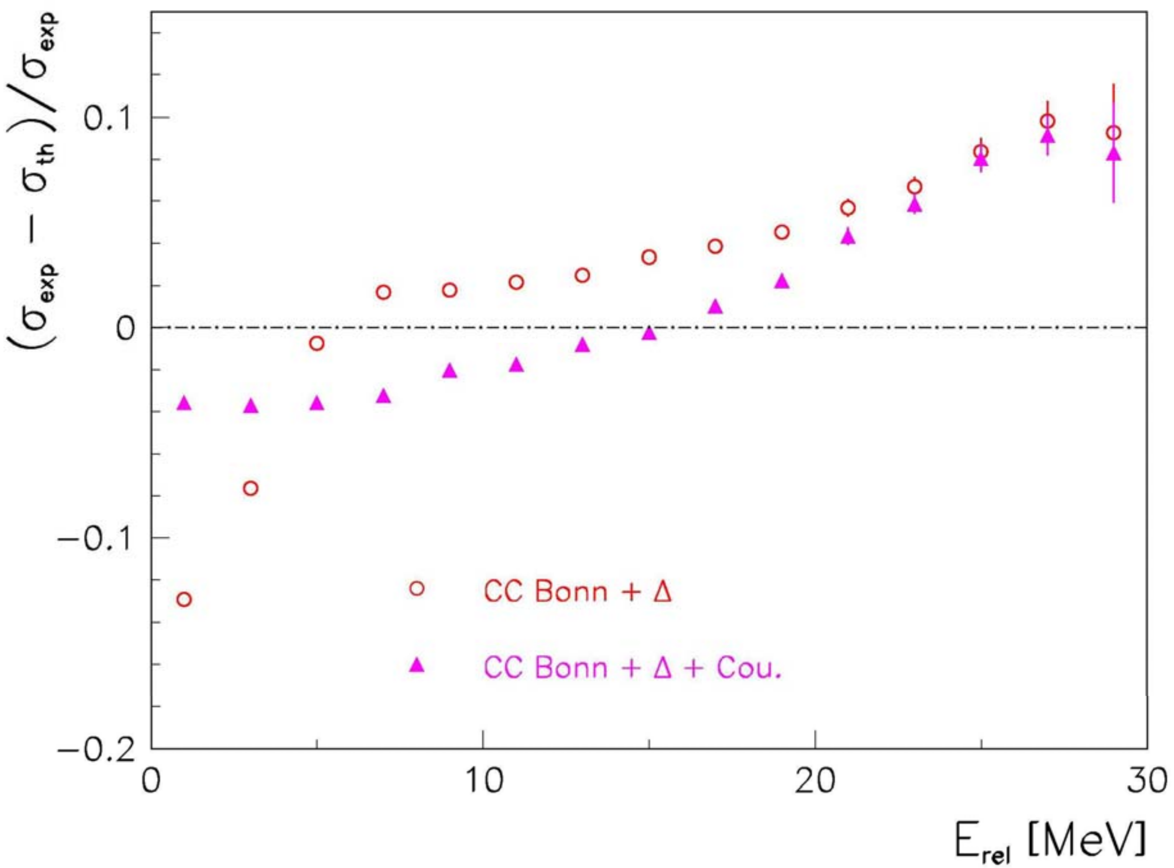
Cross Section Results – Discrepancies Cured



Predictions with Coulomb reproduce data much better !

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

Discrepancies at low E_{rel} cured



Coupled Channel calculations

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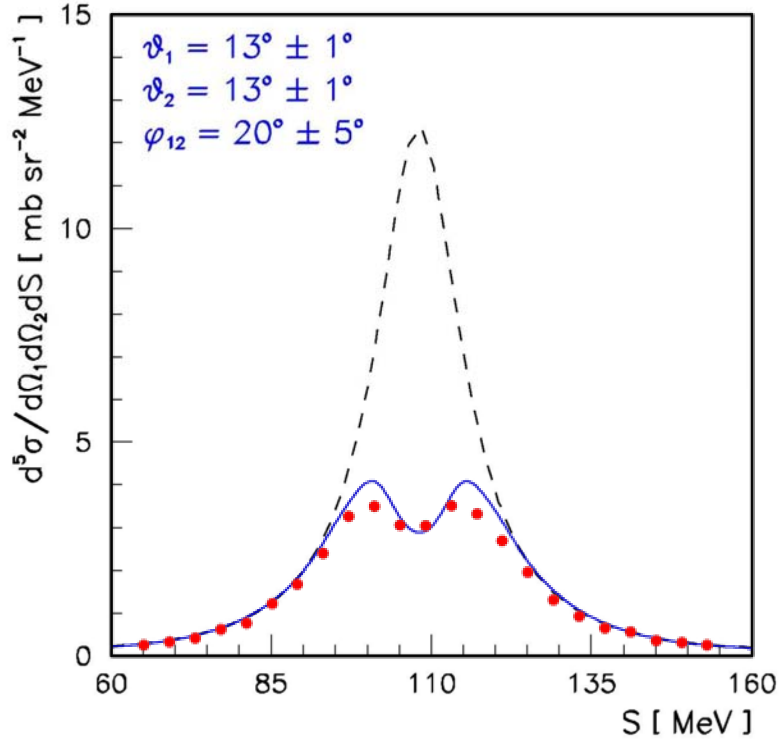
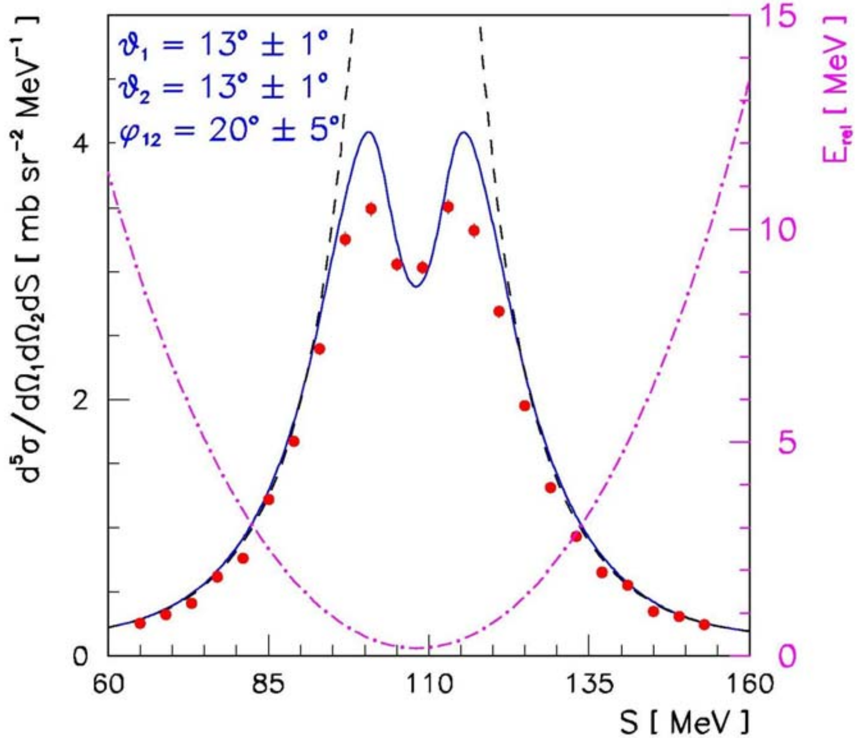
Cross Section Results – Coulomb Effects

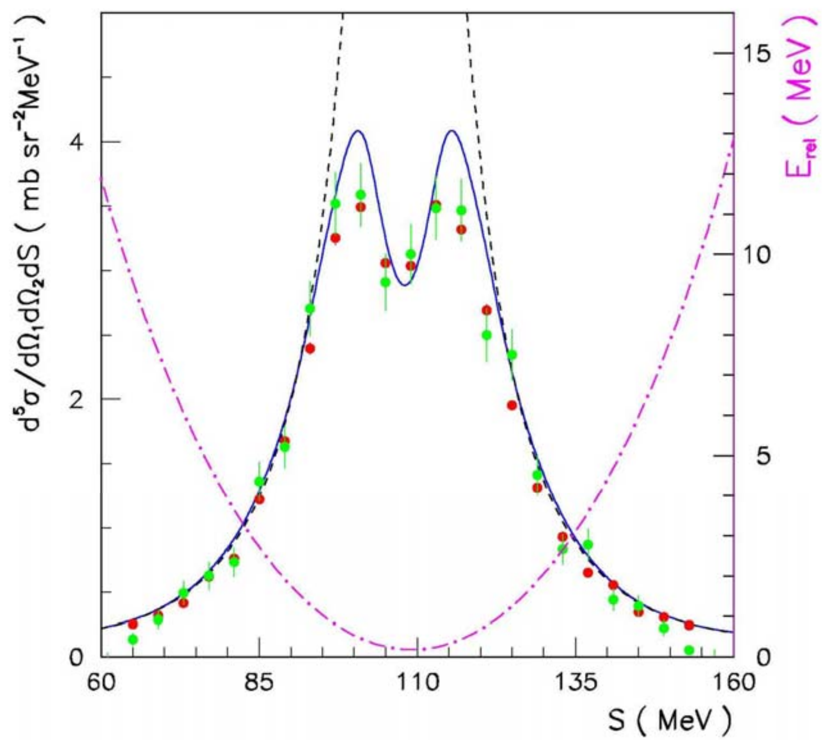


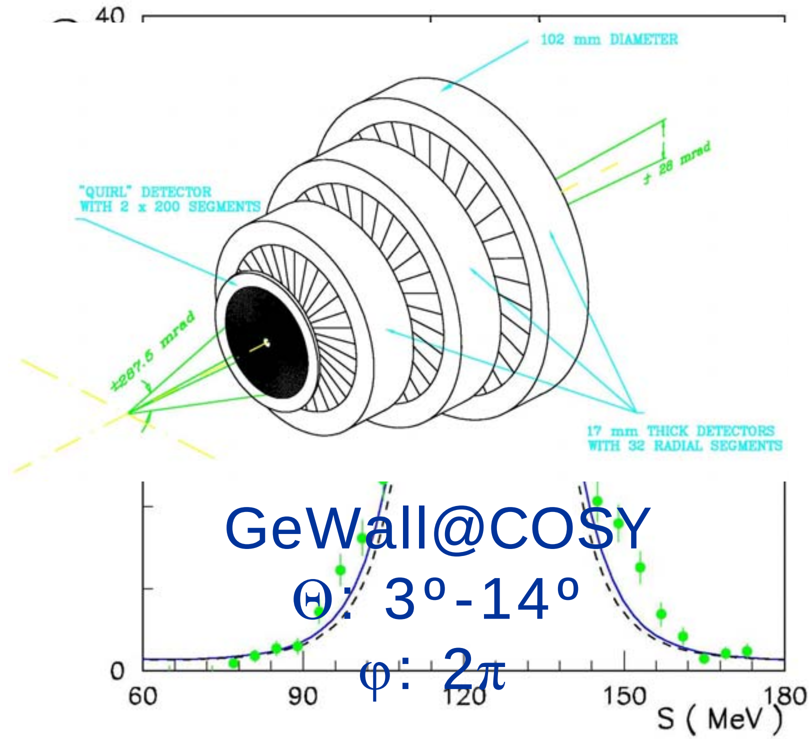


Acceptance limit
of KVI experiment

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

Coulomb effects – dedicated experiment





GeWall@COSY

Θ: 3º-14º

φ: 2π

Small sample result of FZJ experiment (arbitrary normalization)

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

Vector and Tensor Analyzing Powers

- A few times more additional data points (supplementing cross sections)
- Potentially stronger sensitivity to small ingredients (sums of interfering amplitudes)
- Small Coulomb effects - it can be easier to trace 3NF

7 states:		ΔP_z 0.008	ΔP_{zz} 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		

60-80%

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

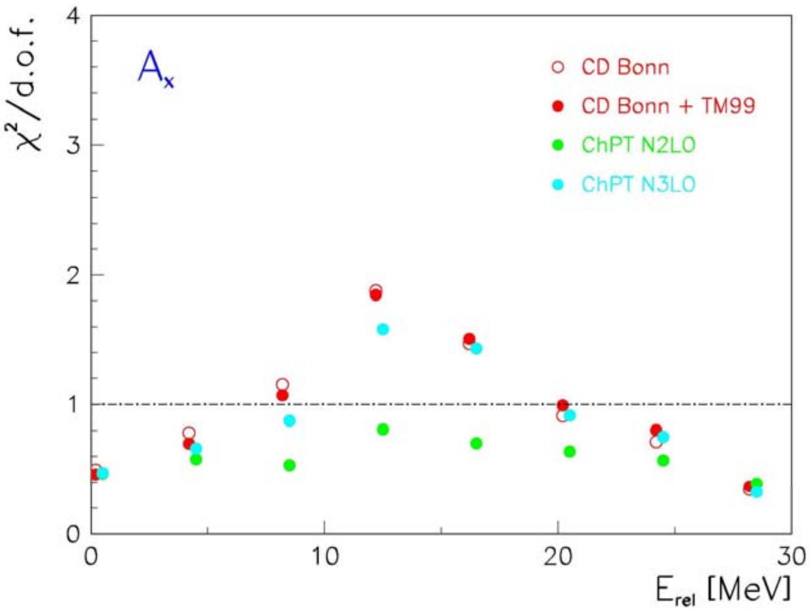
Analyzing Power Results – Summary

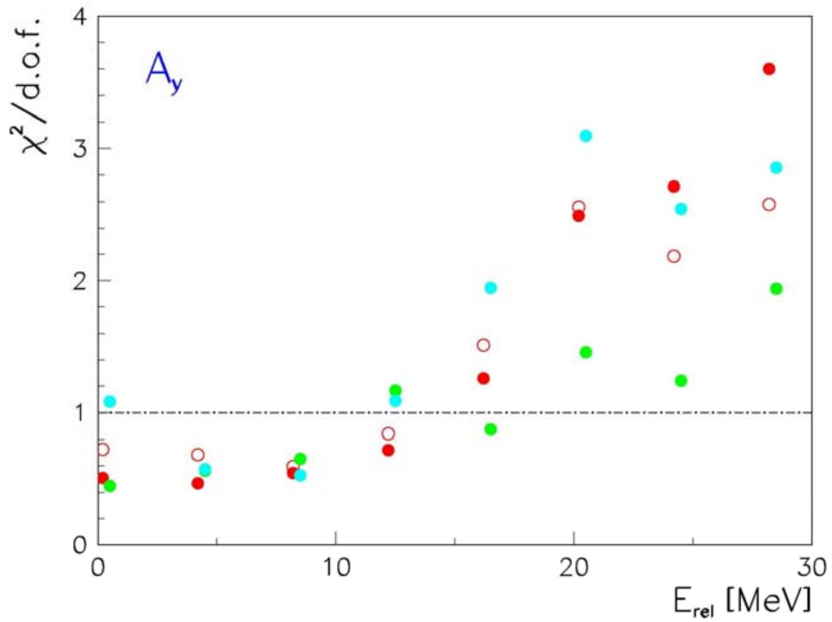
- ✓ Vector (A_x, A_y) and tensor analyzing powers (A_{xx}, A_{yy}, A_{xy}) determined in the large part of the phase space
- ✓ Nearly 800 data points per observable
  - $\theta_1, \theta_2 = 15^o – 30^o$; grid 5^o; $\Delta\theta =$ **$\pm 2^o$**
  - $\varphi_{12} = 40^o – 180^o$; grid 20^o; $\Delta\varphi =$ **$\pm 10^o$**

    non-negligible averaging
  - S [MeV] = 40 – 160; grid 4; $\Delta S = \pm 4$
  - ➢ Statistical accuracy 0.01 – 0.05
  - ➢ Systematic errors – analysis under way
- ✓ Global comparisons with theory (χ^2 test)

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

Vector Analyzing Power Results

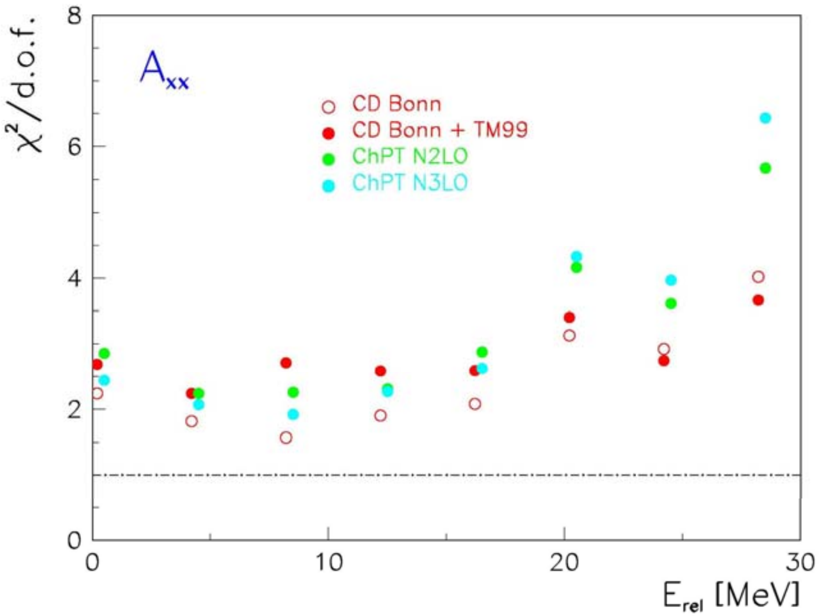




ChPT N2LO

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

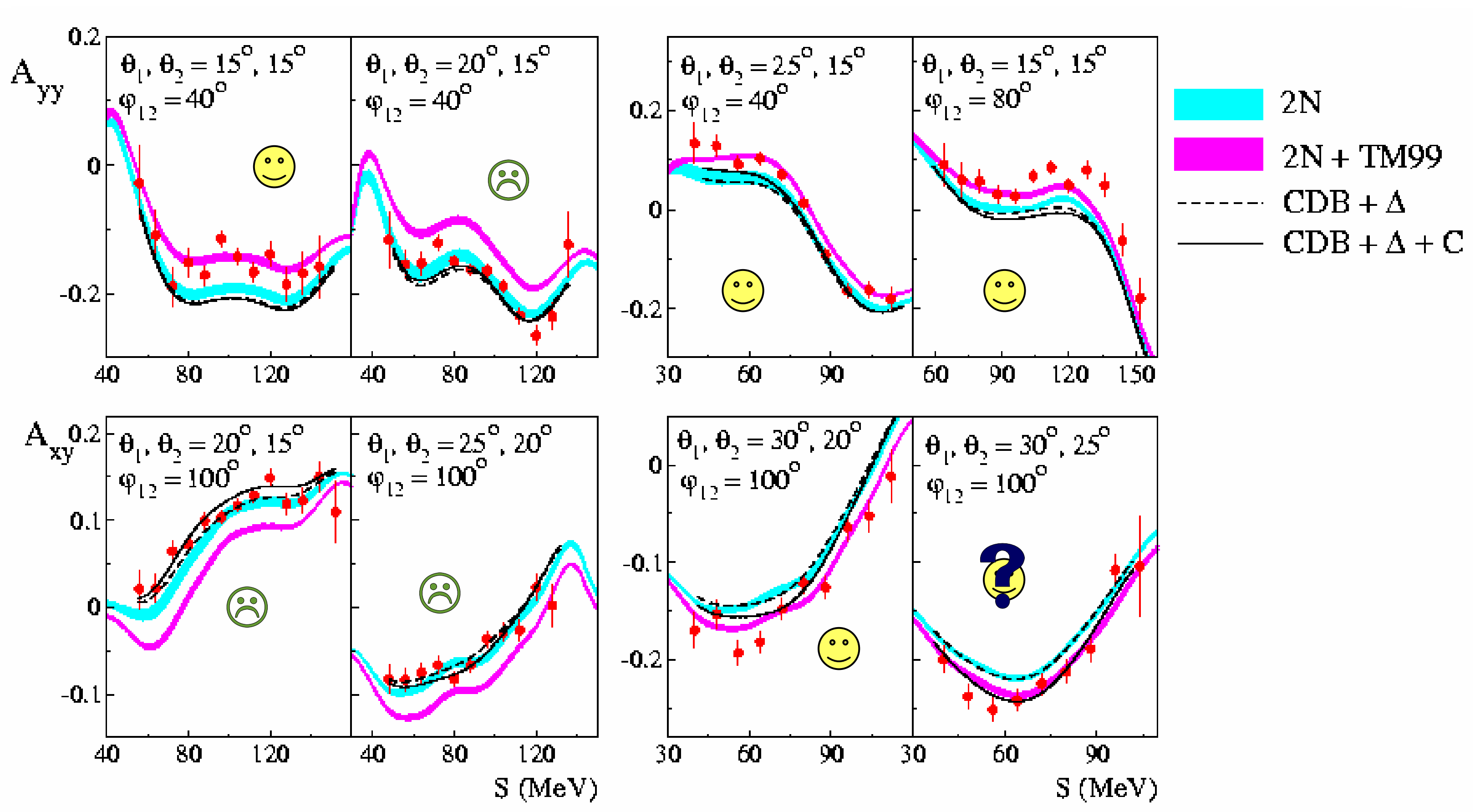
Tensor Analyzing Power Results



Description not satisfactory!

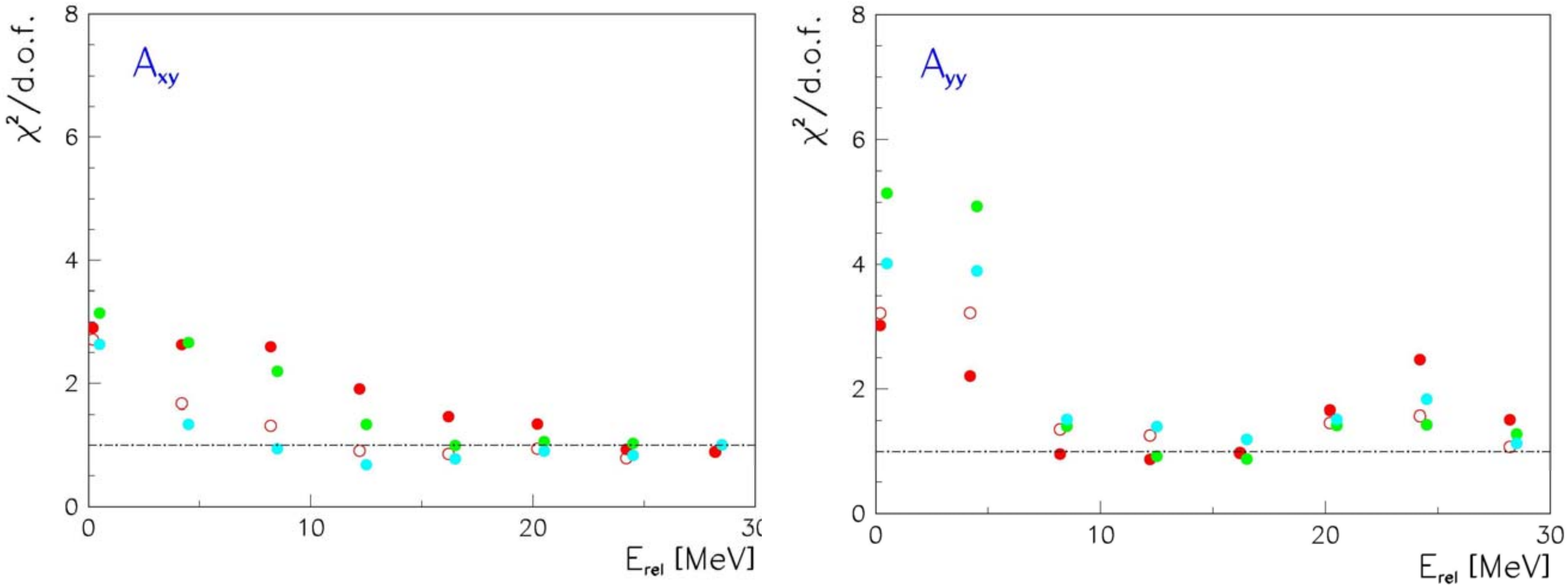
Tensor Analyzing Power Results

configurations with predicted strong 3NF effects



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

Tensor Analyzing Power Results

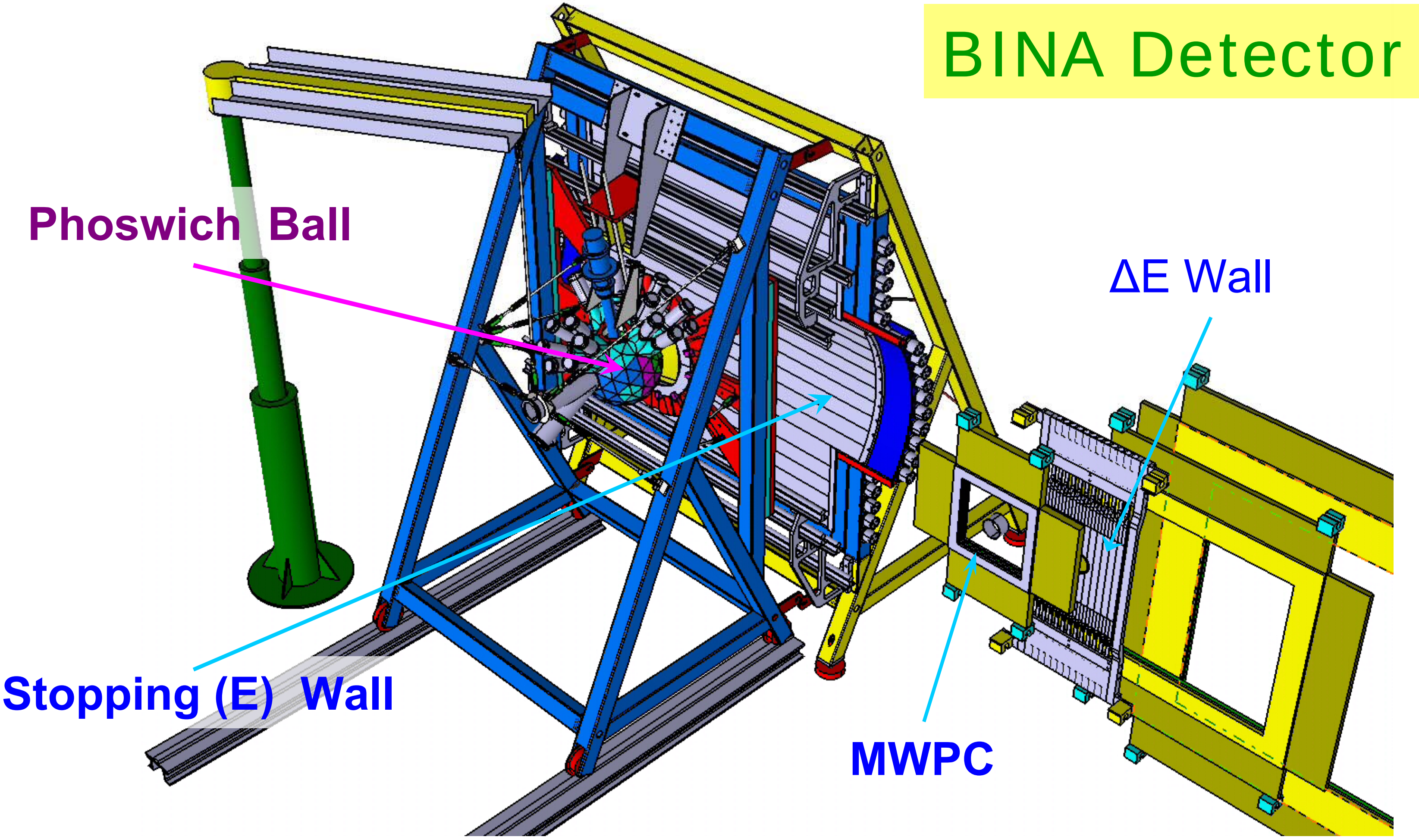


NN, ChPT N3LO

Conclusions:

- Systematic, precise set of cross sections and analyzing power data obtained at E_d = 130 MeV
  - basis for comparing different approaches which predict the 3N system observables
- Significant 3NF effects observed in cross section
- Found large influence of Coulomb force
- Vector analyzing powers reveal very low sensitivity to 3NF
  - best description given by ChPT (2NLO) – will this fact be confirmed by full calculation at 3NLO or at lower energy?
- Tensor analyzing power sensitive to 3NF, but...
  - current models of 3NF do not provide precise description of A_{xx} and A_{xy} – problems with spin part of 3NF?

BINA detection system at KVI

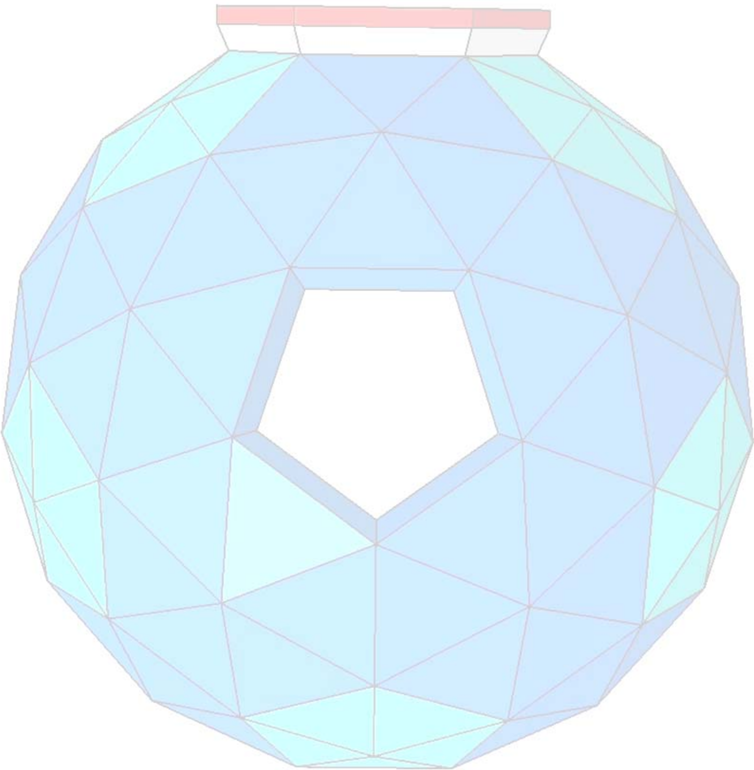


Investigations of 3N/4N continuum

Summary

- Rich set of high precision cross sections and analyzing powers data:
  - Data at E_d = 130 MeV supplemented with results for forward proton angles (GeWall@COSY)
  - Complete set for E_d = 100 MeV (BINA)
  - Measurements for pd systems at 180 and 135 MeV (BINA)
- Developments in theoretical calculations for 3N system (3N force, Coulomb interaction, relativistic effects, higher order in ChPT ...)
- Studies of breakup processes in dd system (BINA) at 130 MeV

Thank you for your attention!



$$\varsigma = (\theta_1, \theta_2, \varphi_{12}, S)$$

$$\sigma_p(\varsigma,\varphi_1) = \sigma_0(\varsigma)\cdot\left[1 + P_z\cdot\left(-\frac{3}{2}\sin\varphi_1 A_x + \frac{3}{2}\cos\varphi_1 A_y\right) + P_{zz}\cdot\left(-\sin\varphi_1\cos\varphi_1 A_{xy}\right) + P_{zz}\cdot\left(\frac{1}{2}\sin^2\varphi_1 A_{xx} + \frac{1}{2}\cos^2\varphi_1 A_{yy}\right)\right]$$

$$\frac{N_P - N_0}{N_0} = a\cdot\sin\varphi_1 + b\cdot\cos\varphi_1 + c\cdot\sin\varphi_1\cdot\cos\varphi_1 + d\cdot\sin^2\varphi_1 + e\cdot\cos^2\varphi_1$$

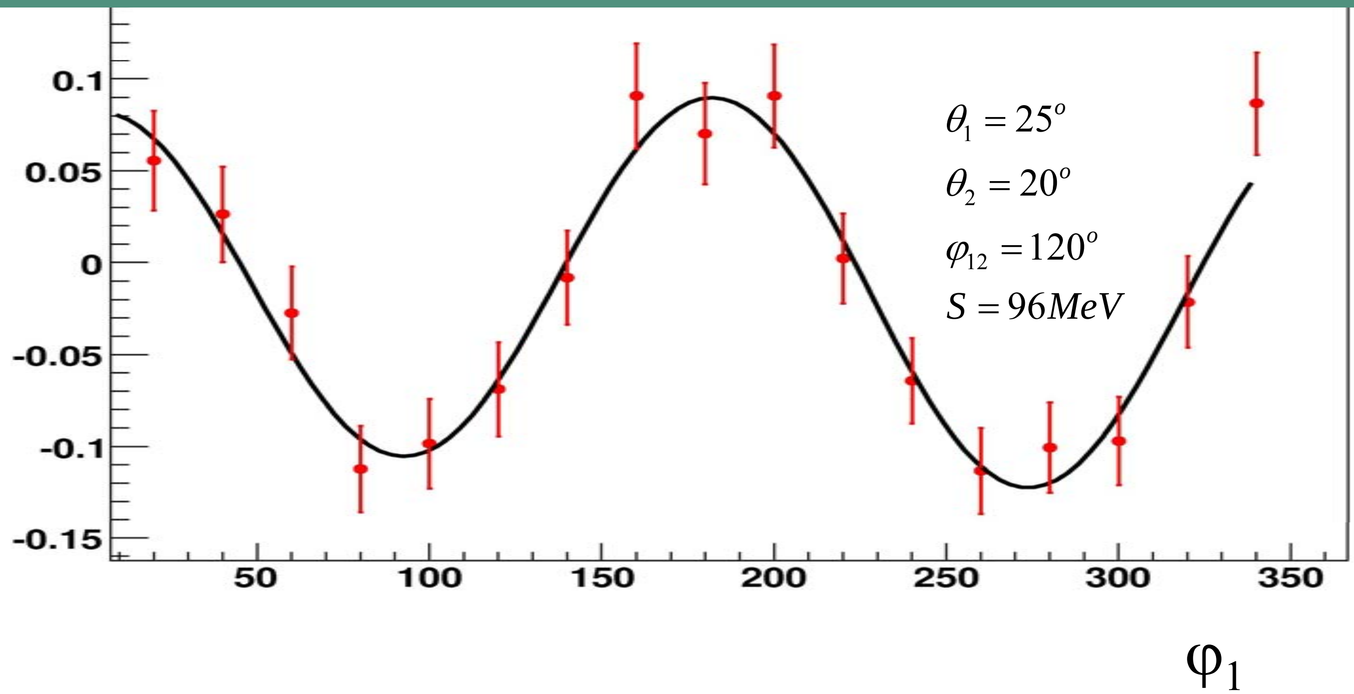
$$a = -\frac{3}{2}P_z A_x(\varsigma)$$

$$b = \frac{3}{2}P_z A_y(\varsigma)$$

$$c = -P_{zz}A_{xy}(\varsigma)$$

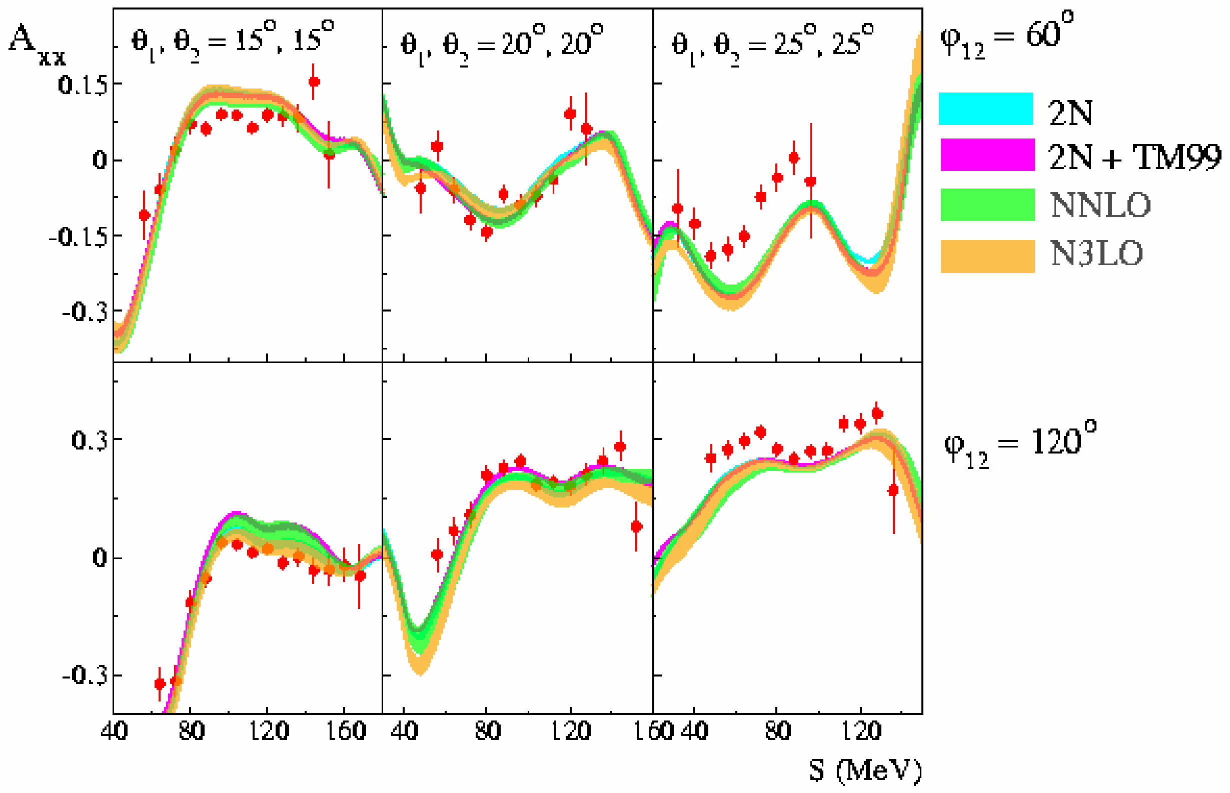
$$d = \frac{1}{2}P_{zz}A_{xx}(\varsigma)$$

$$e = \frac{1}{2}P_{zz}A_{yy}(\varsigma)$$

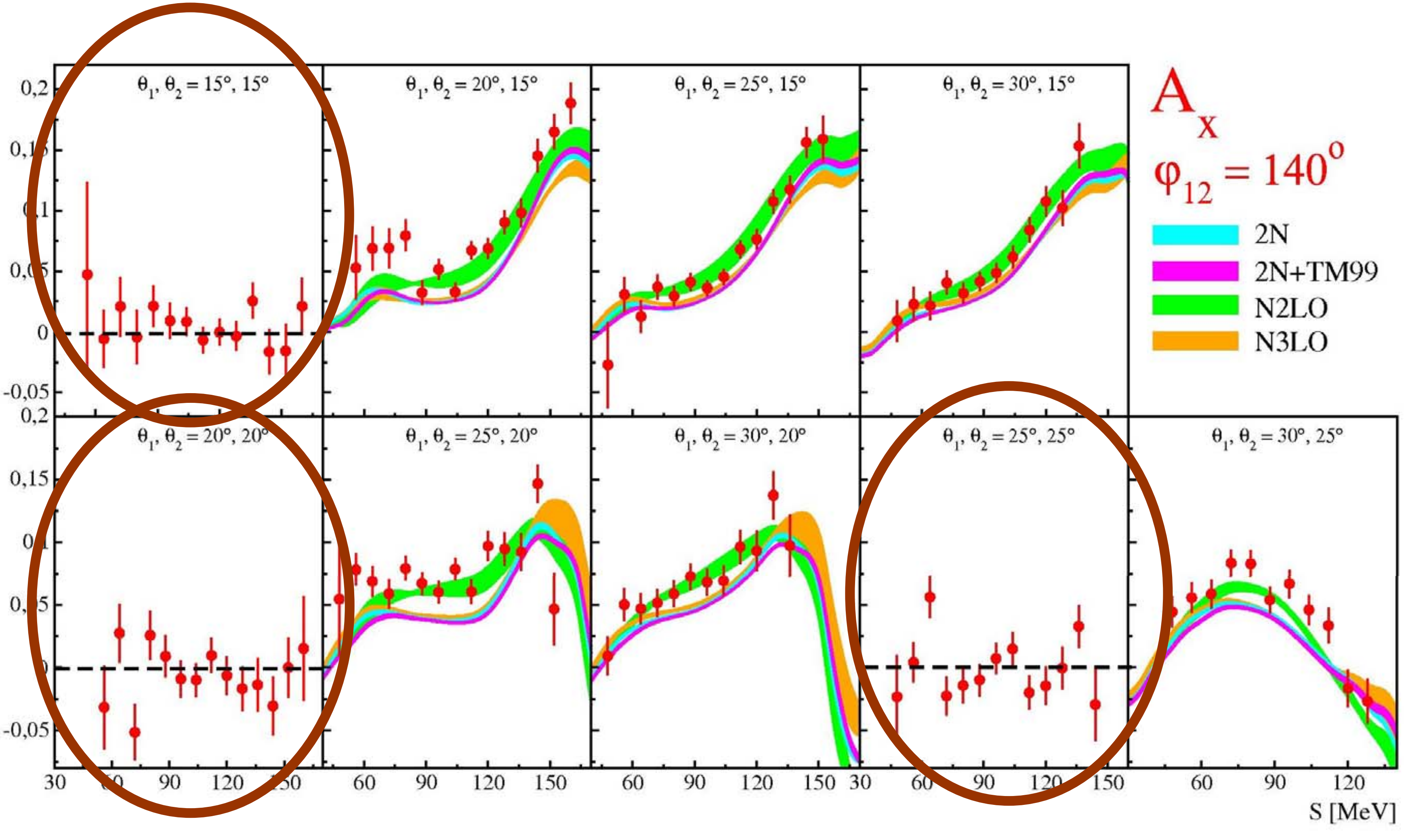


Tensor Analyzing Power Results

examples of A_{xx}, symmetric configurations with φ_{12}=60°, 120°



Analyzing Power Results



S [MeV]