Few-Body Systems

Testing different pieces of the few-nucleon system interaction models with the help of $^{1}H(\vec{d},pp)n$ breakup reaction

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Nucleon-Nucleon Interaction
Basis of Nuclear Physics

Modern NN potentials are <u>in general</u> able to

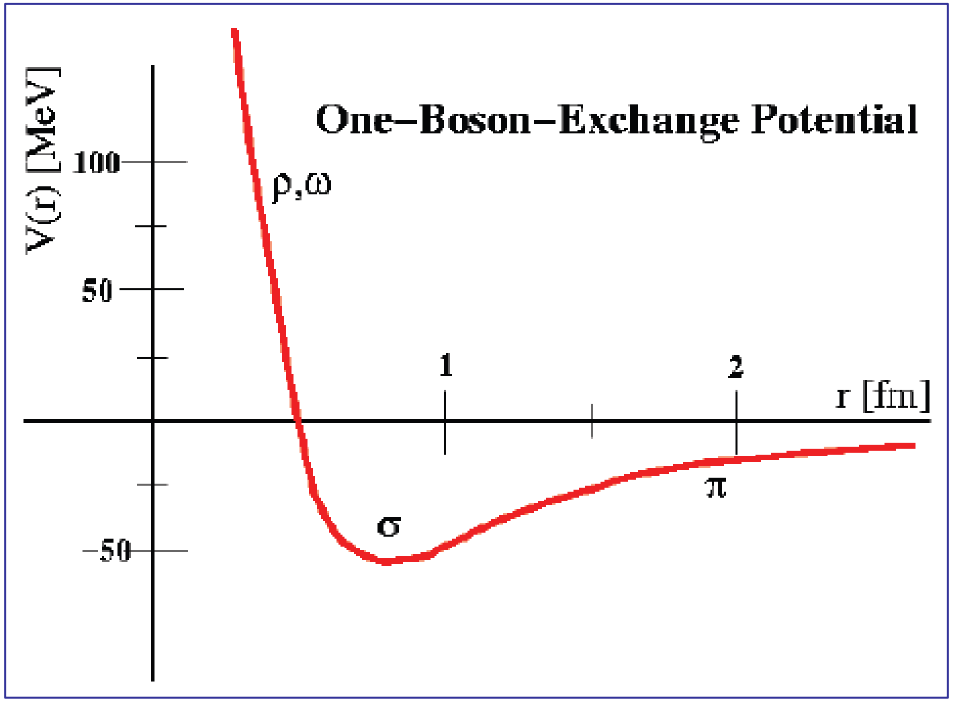
- reproduce properties of nuclear matter (eq. of state)
- reproduce binding energies of light nuclei
- reproduce global features of the bulk of the scattering observables in 2N and 3N systems

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, …

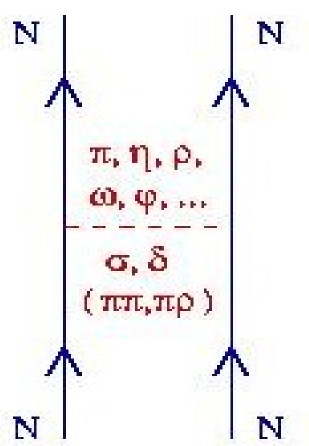
Two-Nucleon System
Nucleon-Nucleon Potential

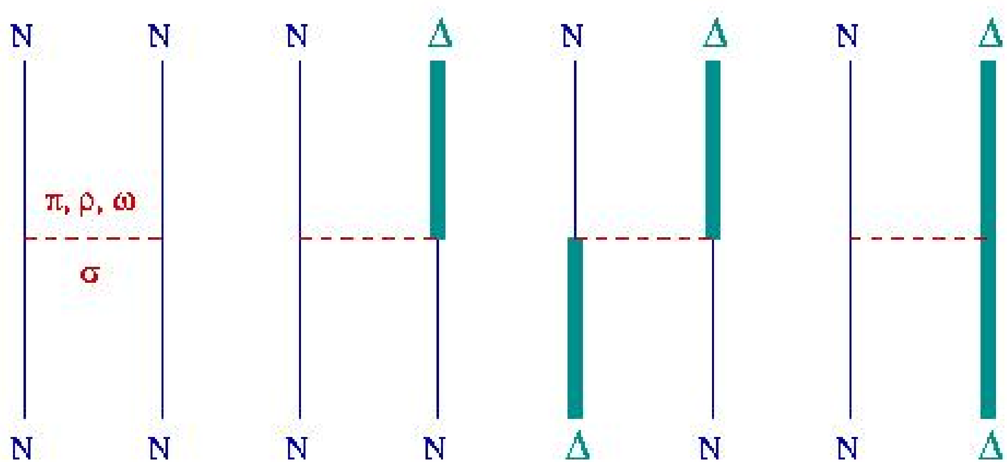
Meson exchange theory of NN force



Two-Nucleon System
Standard Interaction Models

- Meson exchange theory of NN forces - nucleonic degrees of freedom (CD Bonn, Nijm I, Nijm II, AV18)
- CD Bonn + explicit treatment of a single Δ-isobar degrees of freedom – coupled barion channels





Realistic **P**otentials **C**oupled-**C**hannels Potential

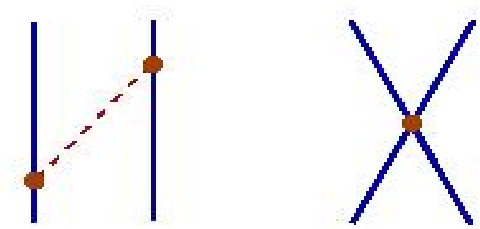
Two-Nucleon System
Effective Field Theory

Chiral Perturbation Theory

- NN effective potential obtained by systematic expansion in powers ν of small external momenta Q, $(Q/\Lambda_\chi)^\nu$, with $\Lambda_\chi \approx 1$ GeV (Ch. Sym. breaking scale); "easy" for π-π and π-N scattering amplitude, more demanding for N-N interaction
- Two kinds of contributions:
  - pion(s) exchanges (vertices of different order)
  - contact interactions (low energy constatnts)

Two-Nucleon System
EFT / ChPT Potential Model

LO:

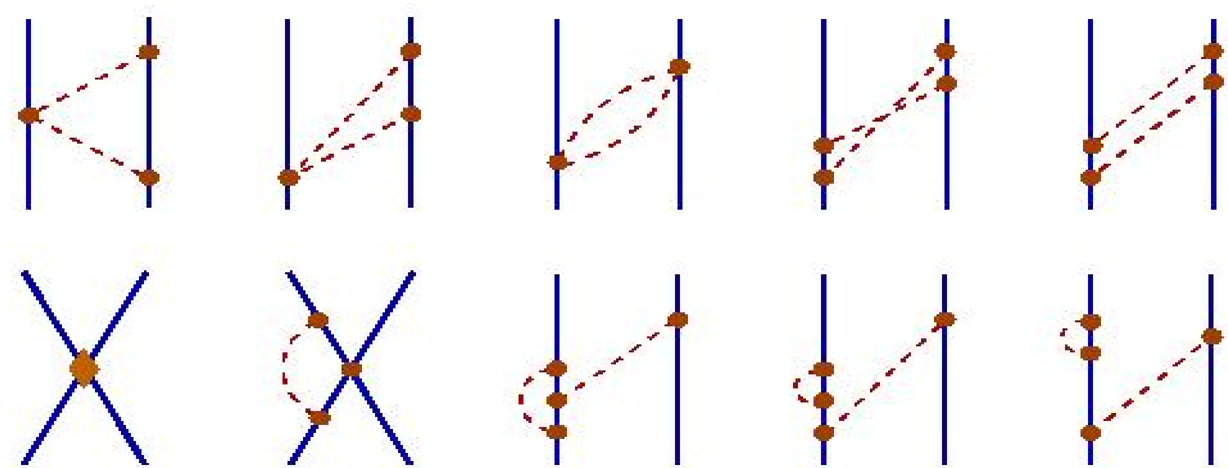


1π exchange (ν=0) & 2 LEC's

NLO:

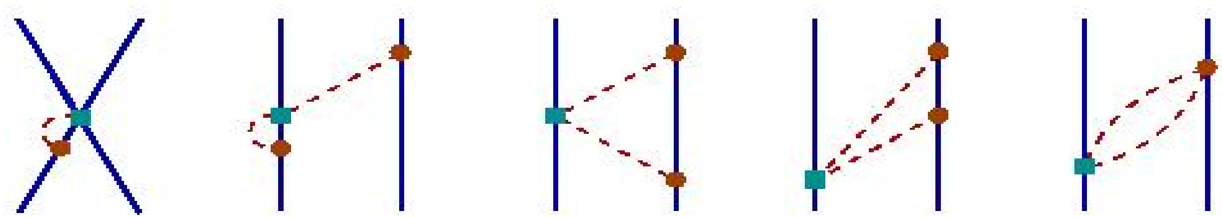
2π exchanges

& 7 LEC's (ν=2)
& corrections to
1π exchange



NNLO:

2π exch. (ν=3),
& corrections



Two-Nucleon System
Description of Data

Modern realistic NN potentials provide an excellent fit of all data from the 2N system

$\chi 2$ / data point

	CD Bonn	NijmI	NijmII	Av18	Coupl.Ch.
No. of parameters	45	41	47	40	~40
pp data	1.01	1.03	1.03	1.35	1.02
np data	1.02	1.03	1.03	1.07	1.03

Also the EFT/ChPT approach, with increasing order describes the 2N system very accurately - significant improvement from NLO to NNLO to NNNLO (26 LECs)

Is Two-Nucleon Dynamics Enough ?

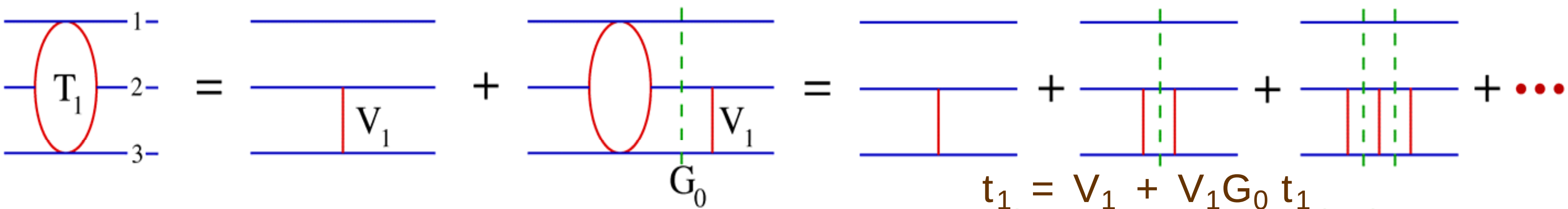
- Three-nucleon system is the simplest non-trivial environment to test predictions of the NN potential models
- Needed theoretical formalism which allows to conclude on **physical input** underlying the calcuated observables; i.e. avoiding any approximations of the assumed dynamics (due to numerical complexity)

⬇

Numerical solutions of the Faddeev equations
(W.Glöckle, H.Witała et al.)

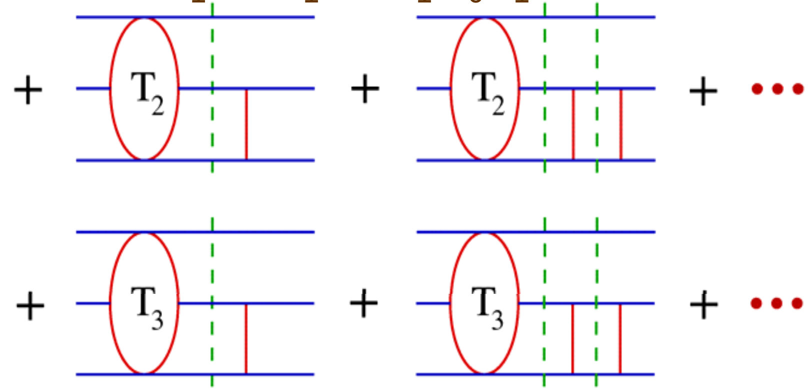
Three-Nucleon System
Faddeev Equations

Operators T_1, T_2, T_3, according to the last pairwise NN int.:



$t_1 = V_1 + V_1 G_0 t_1$

$$T_1 = t_1 + t_1 G_0 (T_2 + T_3)$$



$$\mathbf{T = tP + tPG_0T}$$

E.g. amplitude for breakup:

$U_0 = (1+P)T$ $\rightarrow$ Observables

Solution in partial-wave basis (off-shell t) – up to $\mathbf{j_{max}}$ & $\mathbf{J_{max}}$

RP: $j_{max}(NN) = 5$, $J_{max}(3N) = 25/2$, $Jmax(3NF) = 13/2$

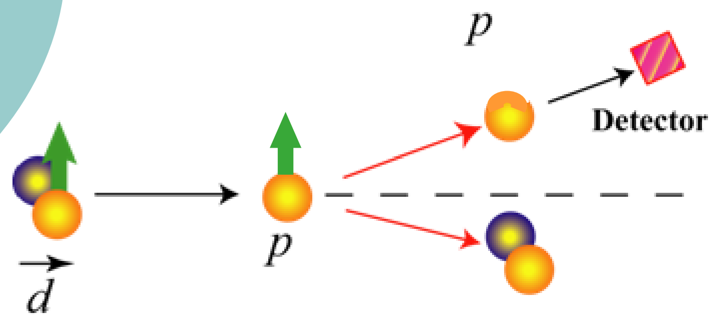
CC: $j_{max}(NN) = 5$, $j_{max}(N\Delta) = 4$, $Jmax(3B) = 31/2$

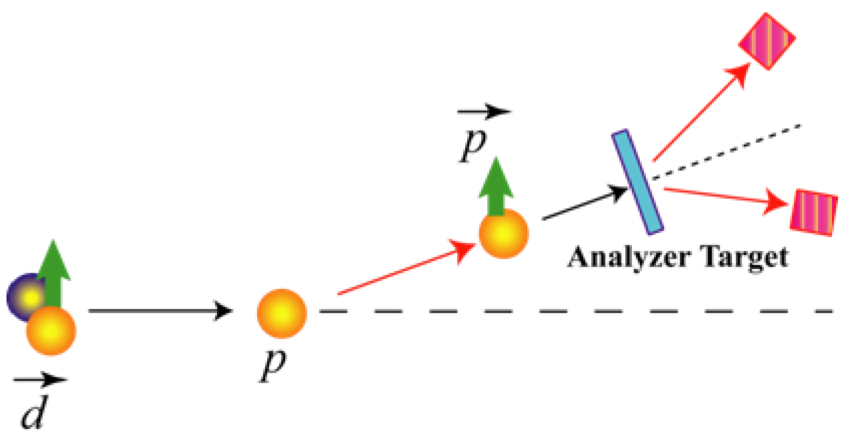
Is Two-Nucleon Dynamics Enough ?
Bound States of Few Nucleons

	^3H	^3He	^4He
Experimental	-8.48	-7.72	-28.3
CD Bonn	-8.01	-7.29	-26.3
NijmII	-7.66	-7.01	-24.6
Av18	-7.62	-6.92	-24.3
Coupl. Chan.	-8.00	-7.26	-26.1
ChPT-NNLO	-8.04	-7.22	-26.6
INOY-nonlocal	-8.46	-7.70	-29.1

Predictions of NN potentials alone obviously fail to reproduce 3N, 4N binding energies (E_B [MeV])

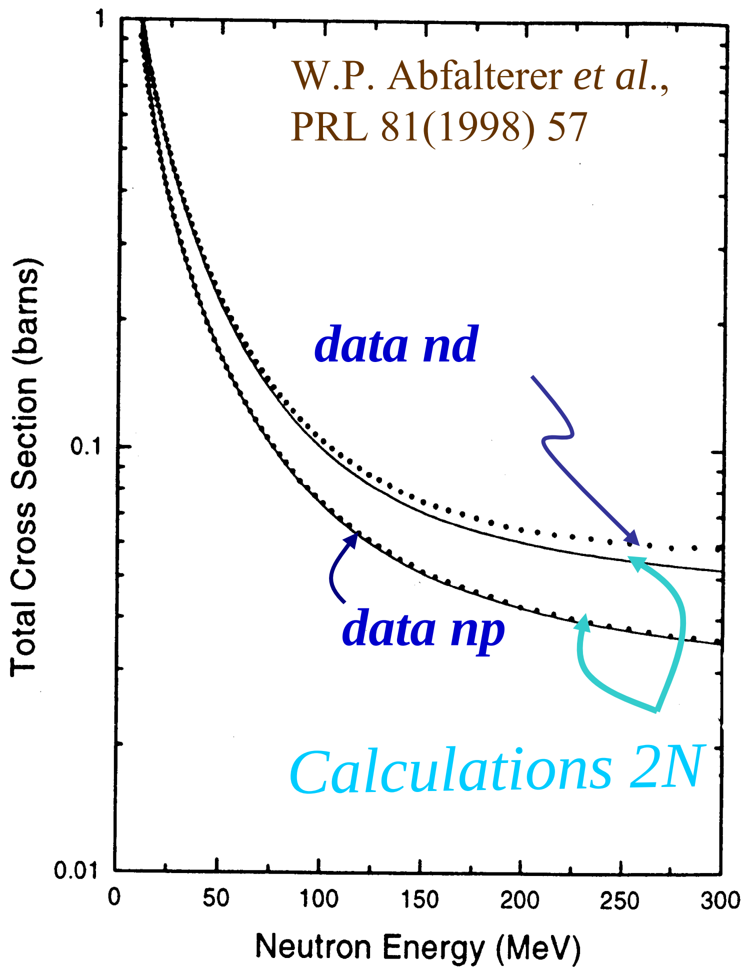
Elastic Nucleon-Deuteron Scattering Observables





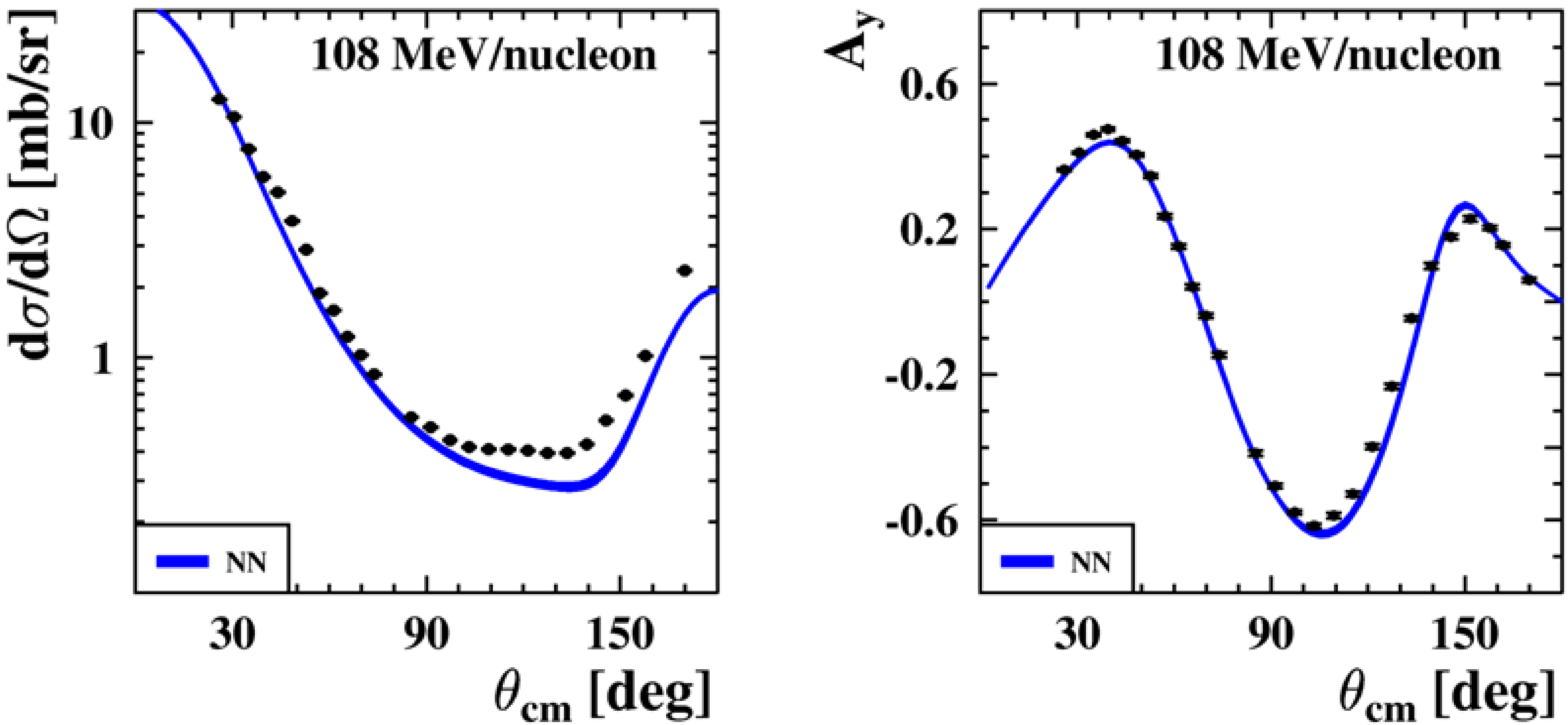
- **Differential Cross Section**
  - Overall strength
- **Spin Observables:**
  - Vector Analyzing Power iT_{11}
    - $L{\cdot}S$ interaction
  - Tensor Analyzing Powers T_{20}, T_{21}, T_{22}
    - Tensor interaction (D-state)
    - $(L{\cdot}S)^2$ interaction
  - Correlation Coefficients $C_{ij}^{k'}$
  - Transfer Coefficients $K_{ij}^{k'}$
    - Spin-Spin interaction

Is Two-Nucleon Dynamics Enough ?
Total Cross Section



Predictions of NN potentials cannot reproduce energy dependence of the total cross section of the n+d scatterng

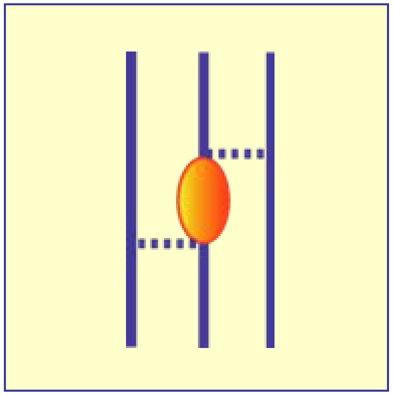
Is Two-Nucleon Dynamics Enough ?
Elastic Nucleon-Deuteron Scattering



Predictions of NN potentials alone fail to reproduce minimum of the d(N,N)d elastic scattering cross section

Pairwise Nucleon-Nucleon Interaction is not Enough !

- Introducing concept of **three-nucleon forces** : genuine (irreducible) interaction of three nucleons
  - how well matched to NN potential ?



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

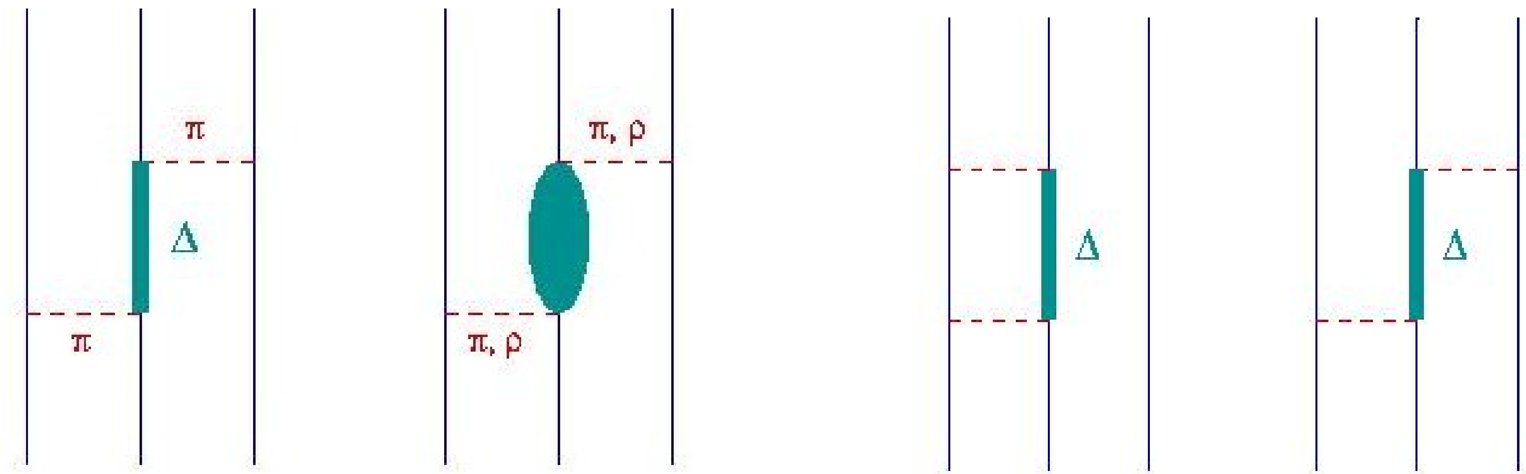
$$V = \sum V_{NN} + \mathbf{V_4}$$

$$T = tP + (1+tG_0)V_4(1+P) + \\ + tPG_0T + (1+tG_0)V_4(1+P)G_0T$$

Three-Nucleon System

Realistic/Coupled Channels Pot. & 3NF Models

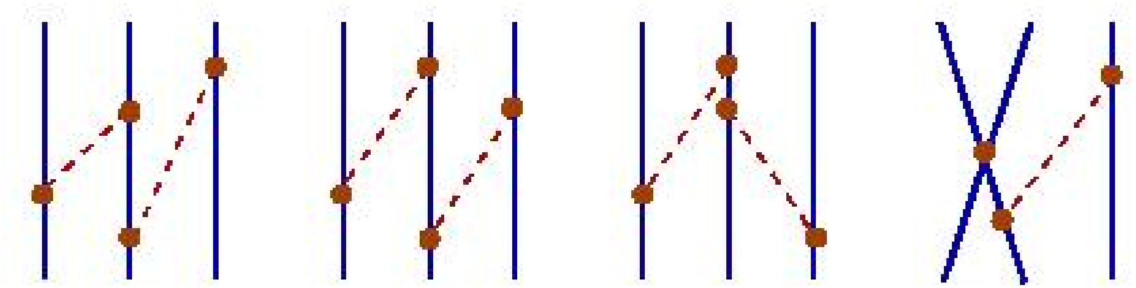
- Three-nucleon forces – only weak connection to the NN potentials (TM99, Urbana IX, Brazil)
- *Competing* Δ-excitation *effects* (two nucleon dispersion and effective 3NF) – resulting net Δ influence is rather small



Three-Nucleon System
3NF within ChPT

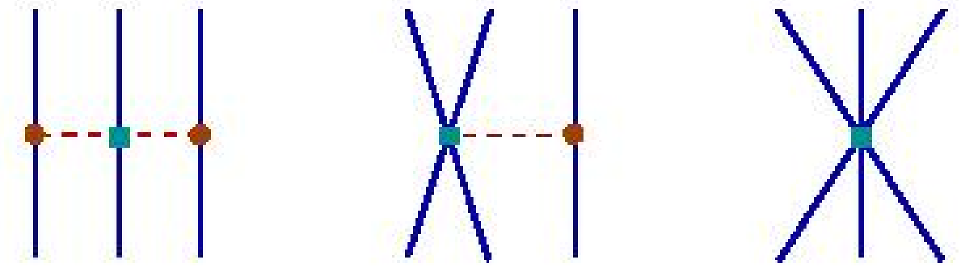
- Three-nucleon forces appear naturally, fully consistent with the 2N graphs

NLO:



All contributions cancel out !

NNLO:



Three possible topologies

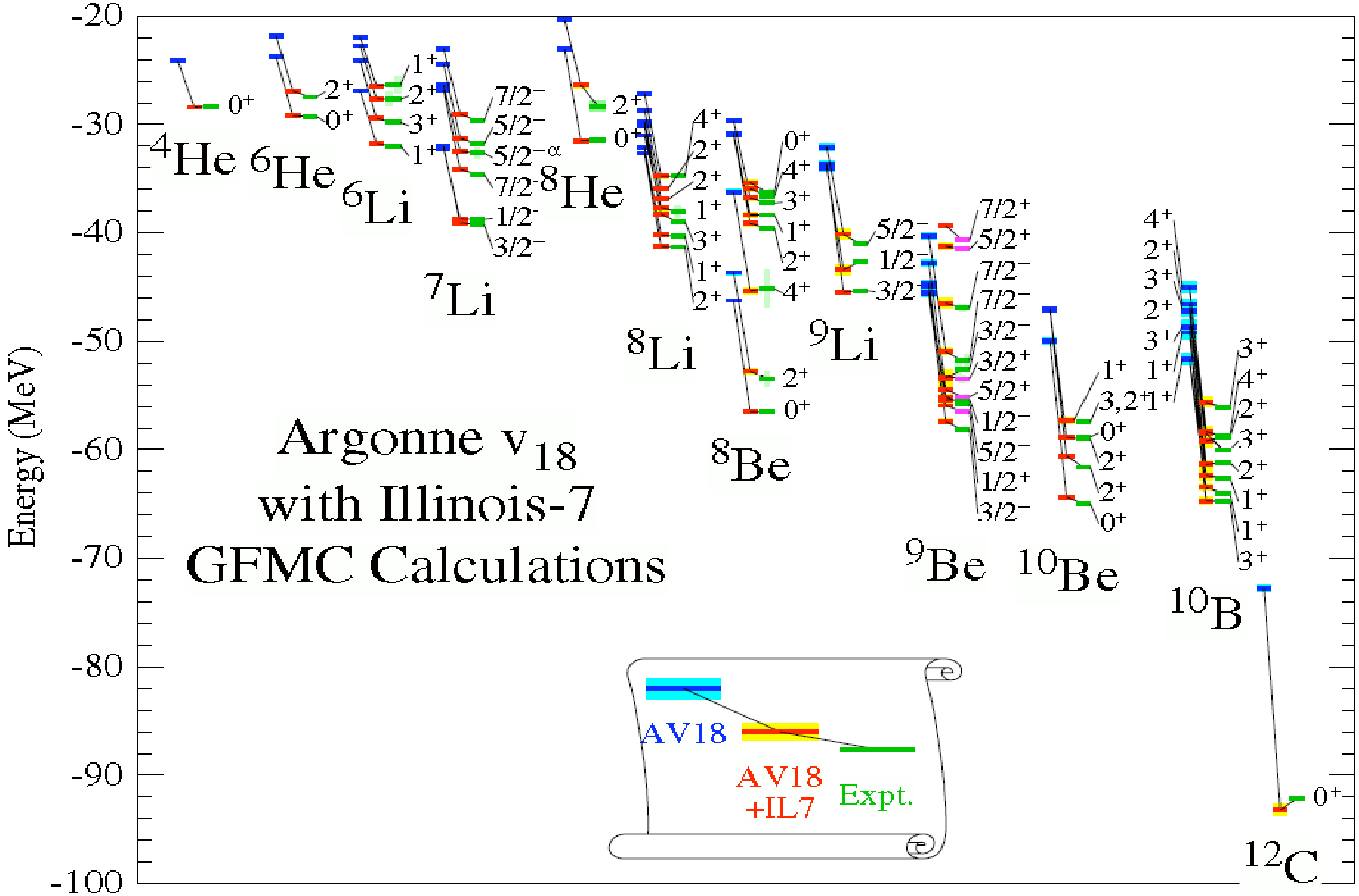
3NF Effects
Bound States of Few Nucleons

Predictions of NN potentials with 3NF models for 3N, 4N bounding energies (E_B [MeV]) do much better

	^3H	^3He	^4He
Experimental	-8.48	-7.72	-28.3
CD Bonn	-8.01	-7.29	-26.3
NijmII	-7.66	-7.01	-24.6
Av18	-7.62	-6.92	-24.3
CD Bonn + TM99	-8.48	-7.73	-29.2
NijmII + TM99	-8.39	-7.72	-28.5
Av18 + TM99	-8.48	-7.76	-28.8
Av18 + UIX	-8.48	-7.76	-28.5
CC CD Bonn + Δ	-8.36	-7.64	-28.4

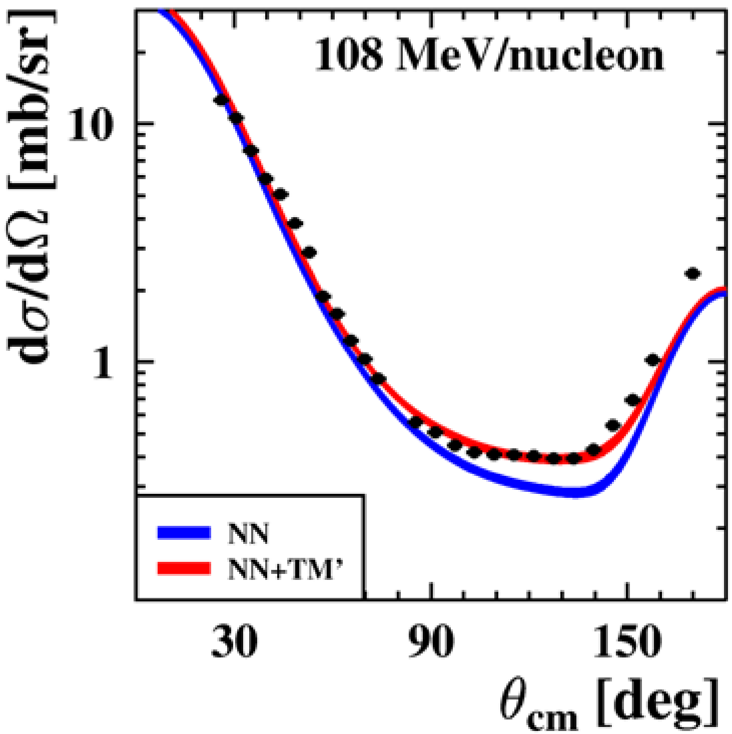
$E_B(^3H)$ used in 3NF fit (CD Bonn + TM99, NijmII + TM99, Av18 + TM99, Av18 + UIX)

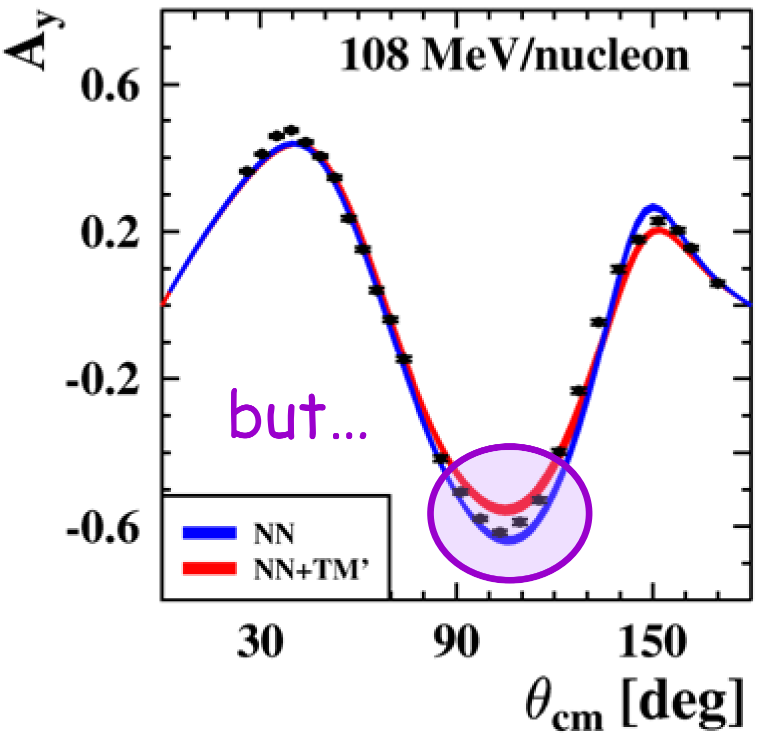
3NF Effects
Bound States of Few Nucleons



3NF Effects
Elastic Nucleon-Deuteron Scattering

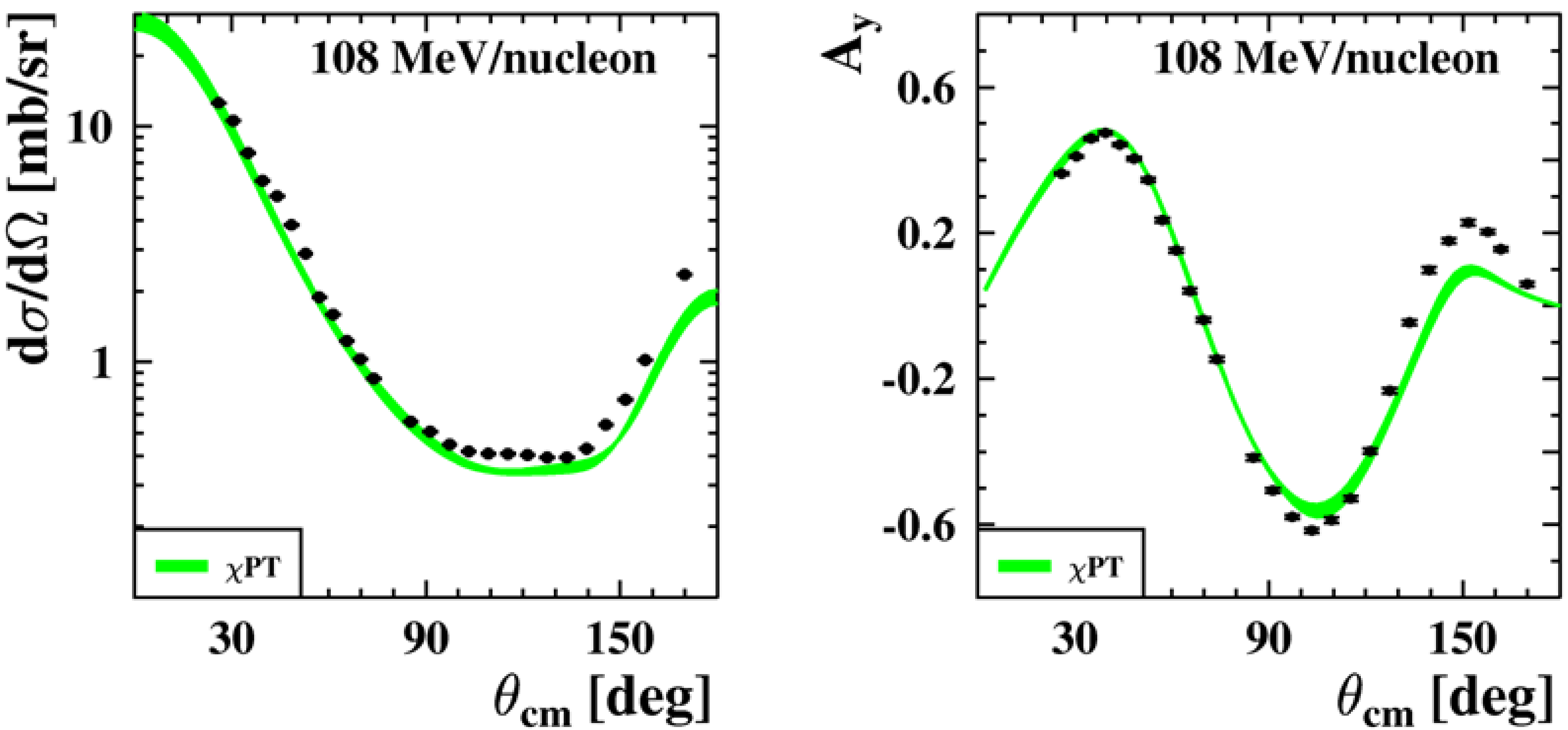
Predictions of NN potentials with 3NF models better reproduce minimum of the d(N,N)d scattering c.s.





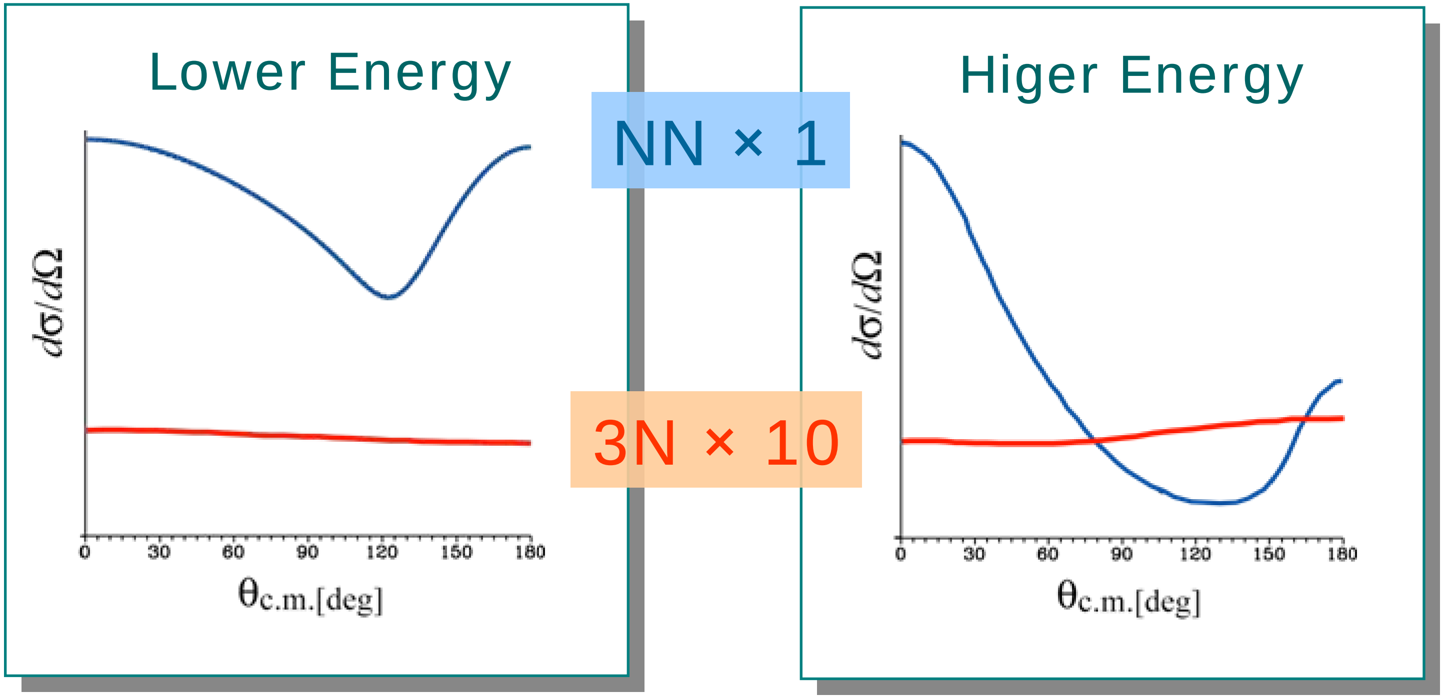
3NF Effects in ChPT @ NNLO
Elastic Nucleon-Deuteron Scattering

3NF contributions in ChPT similar (but weaker) to TM 3NF combined with realistic NN potentials

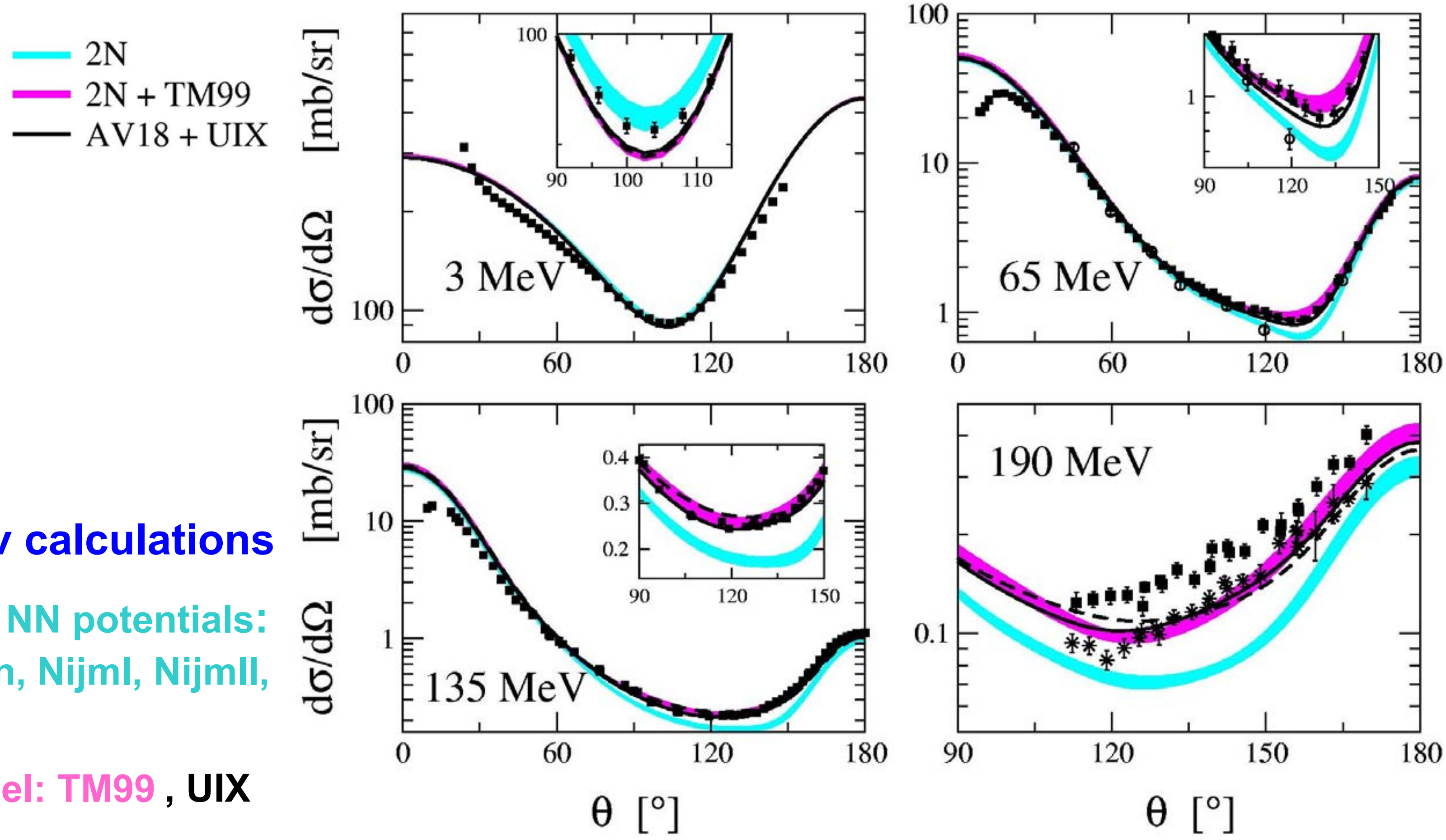


3NF Effects
Elastic Nucleon-Deuteron Scattering

Effects of 3NF in d(N,N)d c.s. minimum are energy dependent – *relative* enhancement of the effect with the incident energy



3NF Effects
Elastic Nucleon-Deuteron Scattering

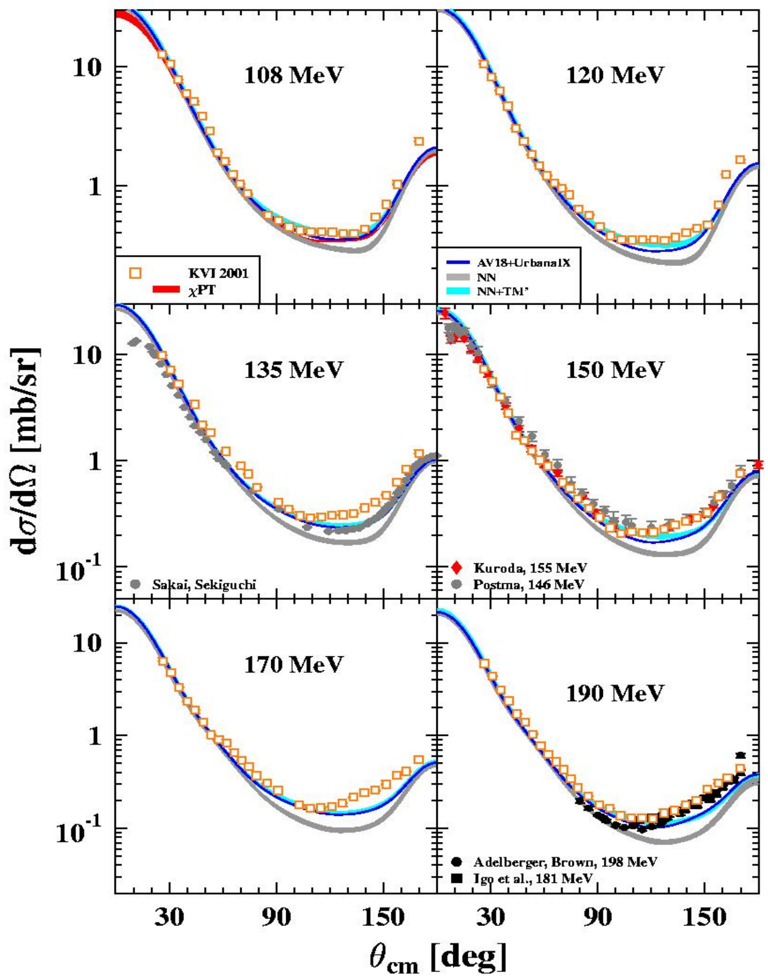


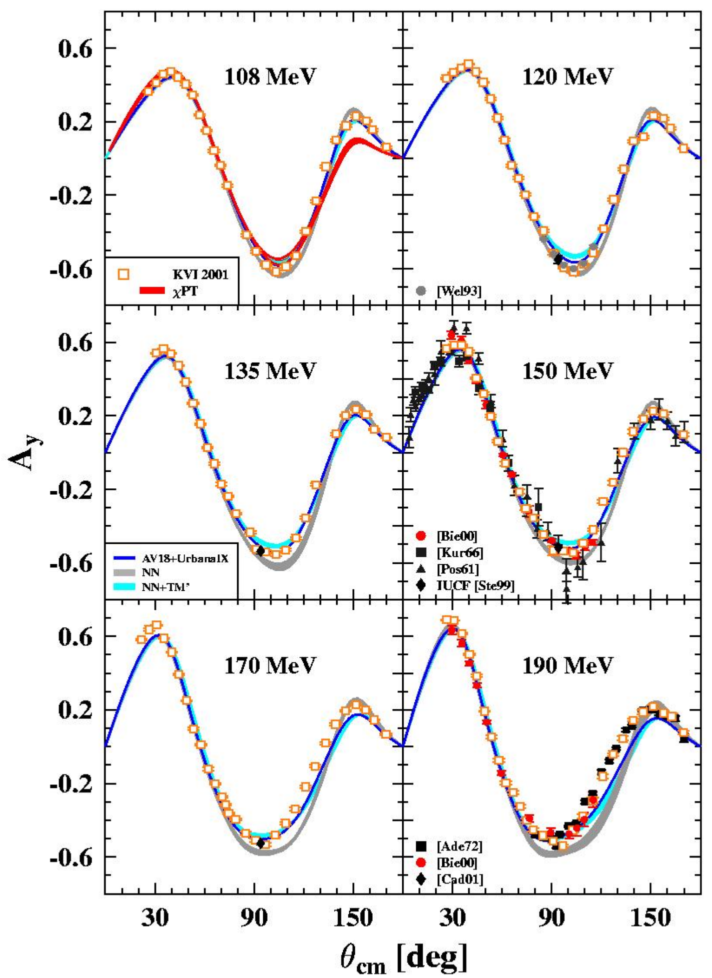
Faddeev calculations

Realistic NN potentials: (CD Bonn, NijmI, NijmII, Av18)

3NF model: TM99 , UIX

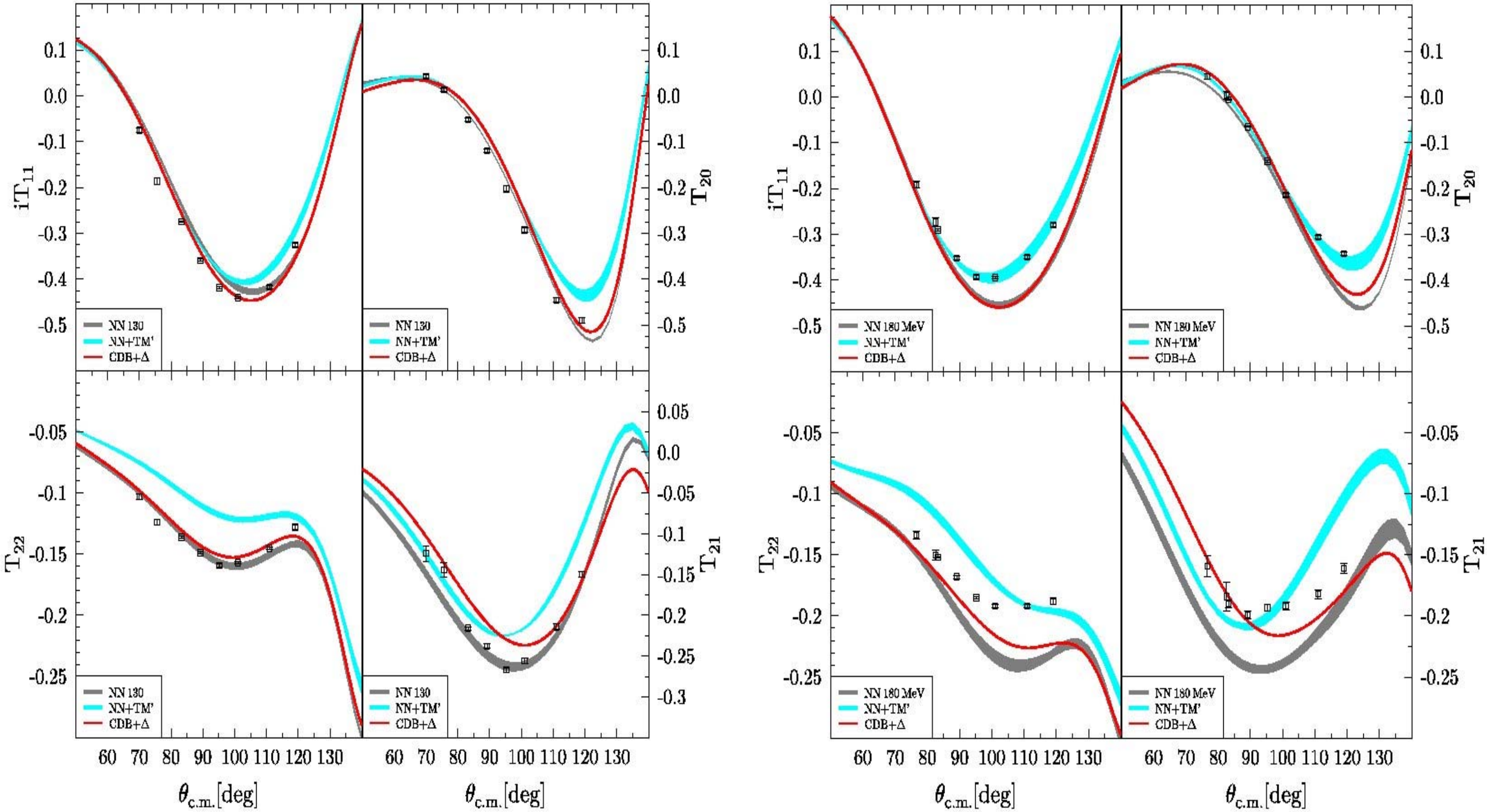
3NF Effects
Elastic Nucleon-Deuteron Scattering





3NF Effects
Elastic Deuteron-Nucleon Scattering

65 MeV/A **90 MeV/A**

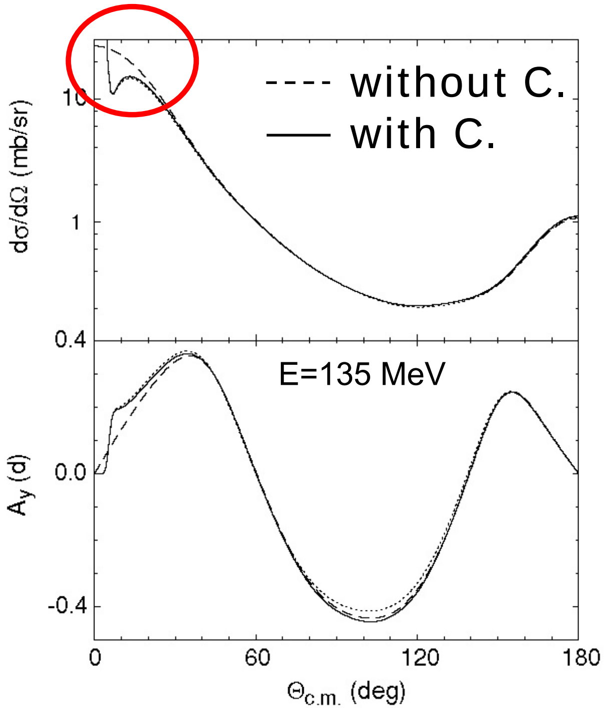


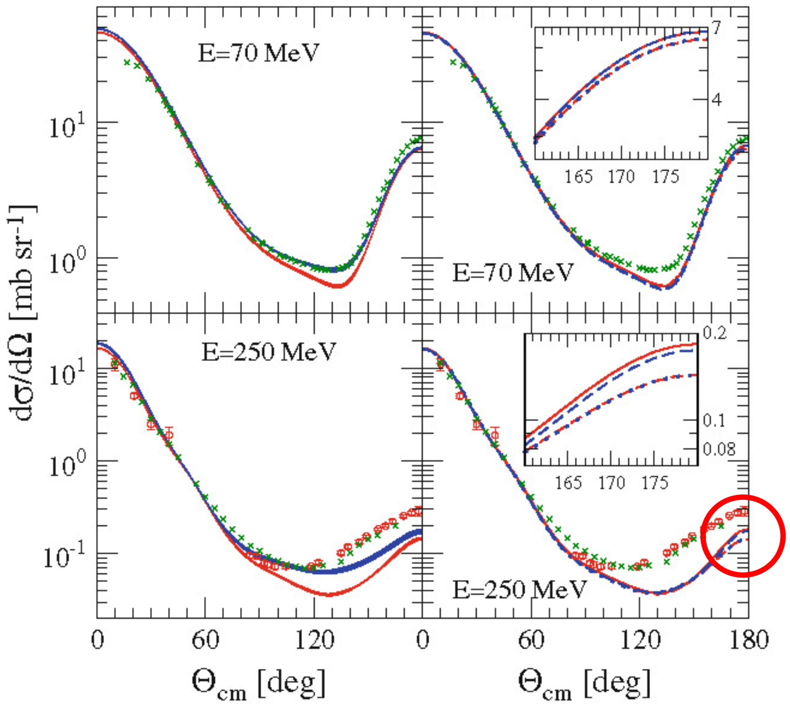
More Dynamical Effects ?

Coulomb force and relativity

Predictions for the N-d elastic scattering

Coulomb 3NF relativity

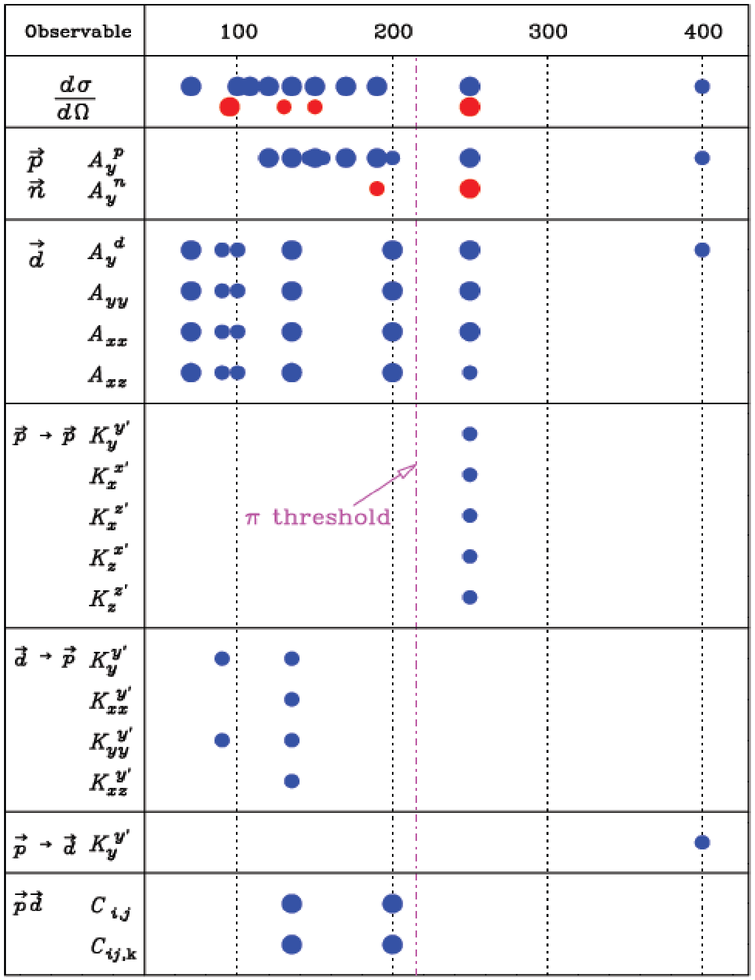




Effects small, located at extreme angles only !

3NF Effects
Elastic Nucleon-Deuteron Scattering

pd and *nd* Elastic Scattering at 70–400 MeV/nucleon



- Number of observables for the **elastic scatterng channel**, allowing a multi-dimensional study of 3NF
- **Only fraction** has been measured accurately and systematically (RIKEN/RCNP/IUCF/KVI)
- Not completely clear picture - still much to explore !
- Complementary studies needed at much richer field: **Nucleon-Deuteron Breakup**

Three-Nucleon System in Continuum

Cross Sections and Analyzing Powers of the $^{1}H(\vec{d},pp)n$ Breakup at 130 MeV

- Very few breakup data at medium energies (earlier PSI experiments – only 14 kinematical configurations)
- To reach meaningful conclusions about the interaction models needed experimental coverage of large phase space regions
- Different effects to be traced
  - Influences of 3NF
  - Coulomb force action
  - Relativistic effects

} Relatively new achievements for breakup !

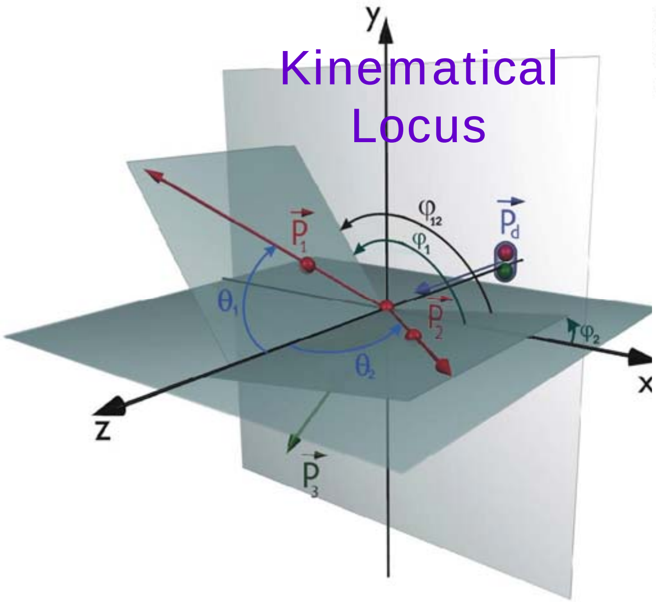
Breakup Reaction Kinematics

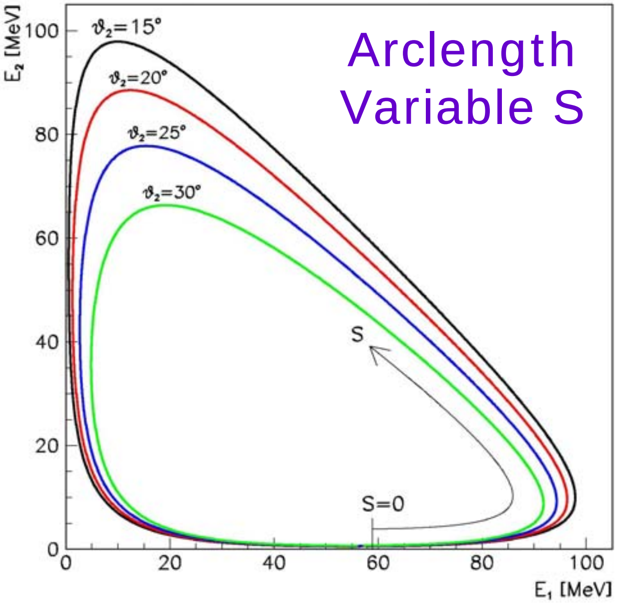
- Three nucleons in the final state - 9 variables
- Energy-momentum conservation – 4 equations
- Five independent kinematical variables
  - ✓ Complete (exclusive) exp. – measured ≥ 5
  - ✓ Inclusive exp. – measured ≤ 4 parameters

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

θ_1,φ_1,E_1

θ_2,φ_2,E_2





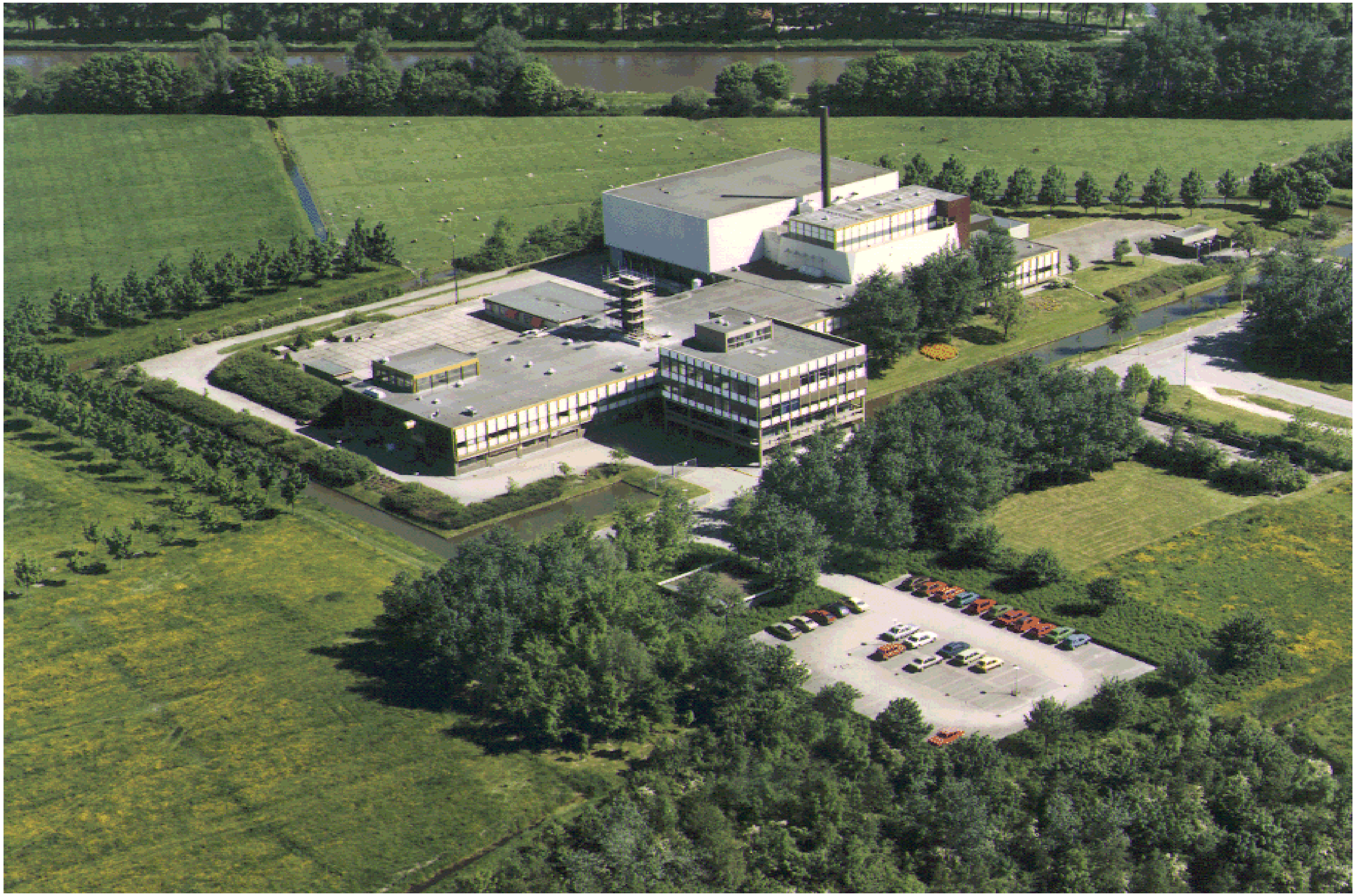
$^{1}H(\vec{d},pp)n$ Measurement at 130 MeV

Experimental Highligths

- 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

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

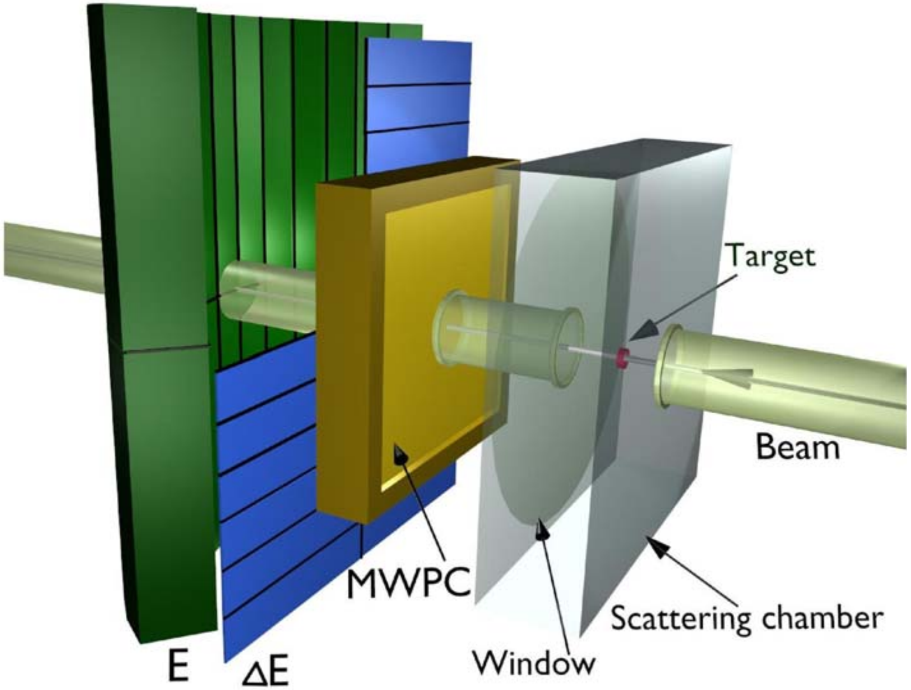
Kernfysisch Versneller Instituut, Groningen

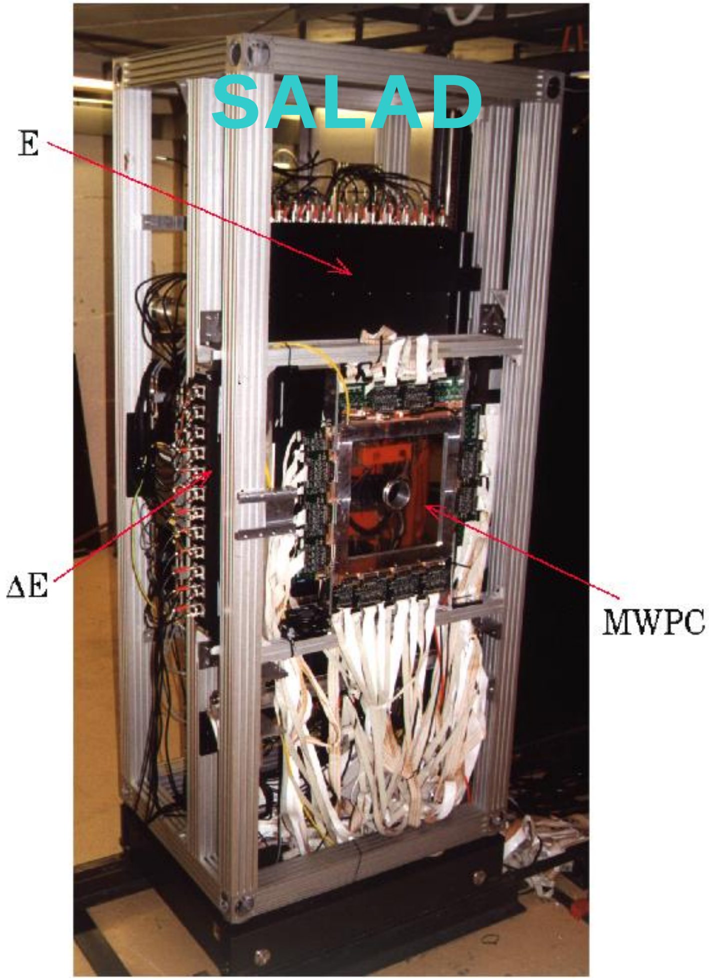


$^{1}H(\vec{d},pp)n$ Measurement at 130 MeV

Small **A**rea **L**arge **A**cceptance **D**etector

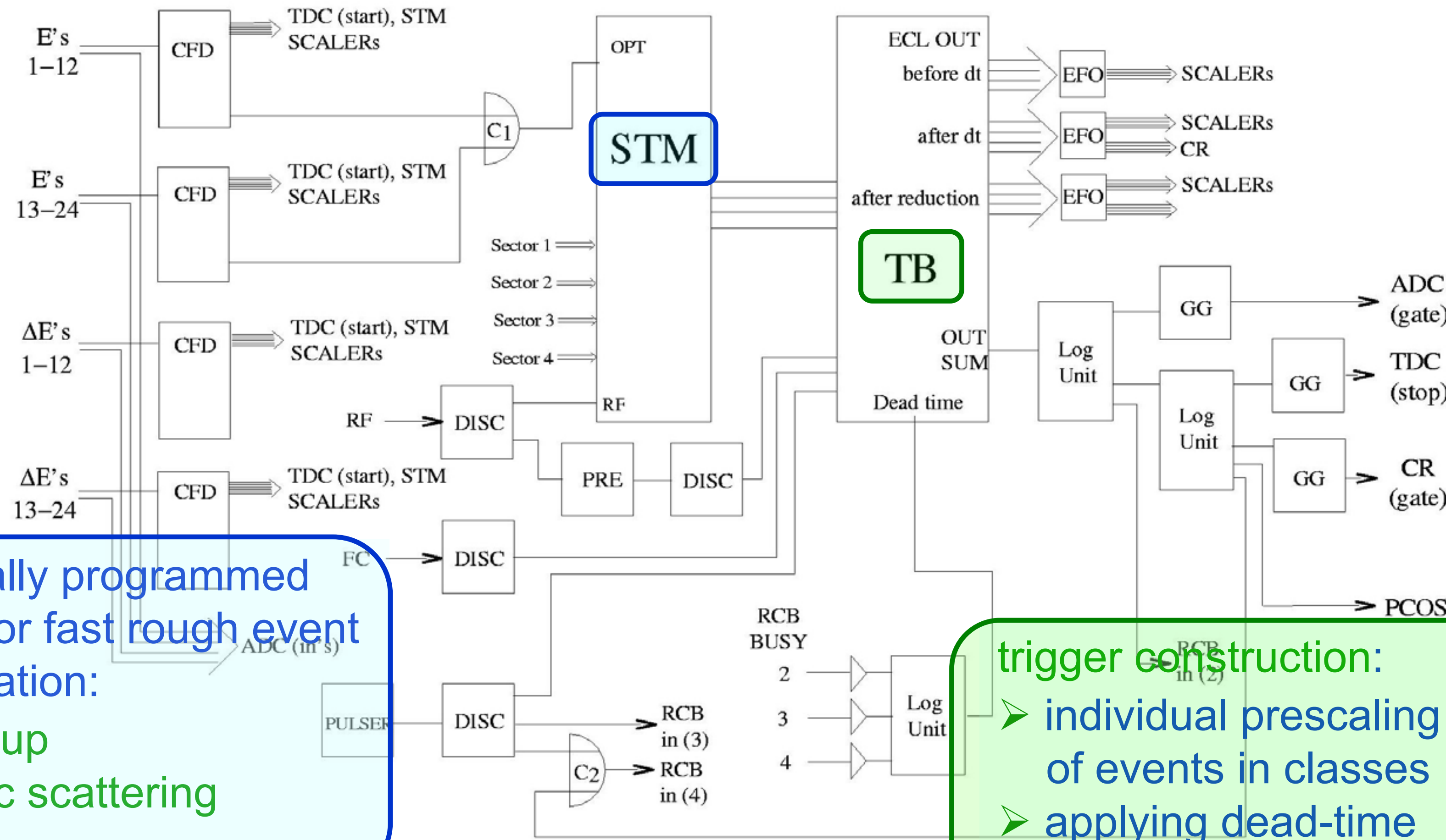
- ✓ 140 ΔE-E telescopes
- ✓ 3-plane MWPC
- ➔ Angular range :
  θ = (12º, 35º), φ = (0º, 360º)





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

On-Line Event Classification (Trigger Logic)



5 specially programmed MLU's for fast rough event identification:

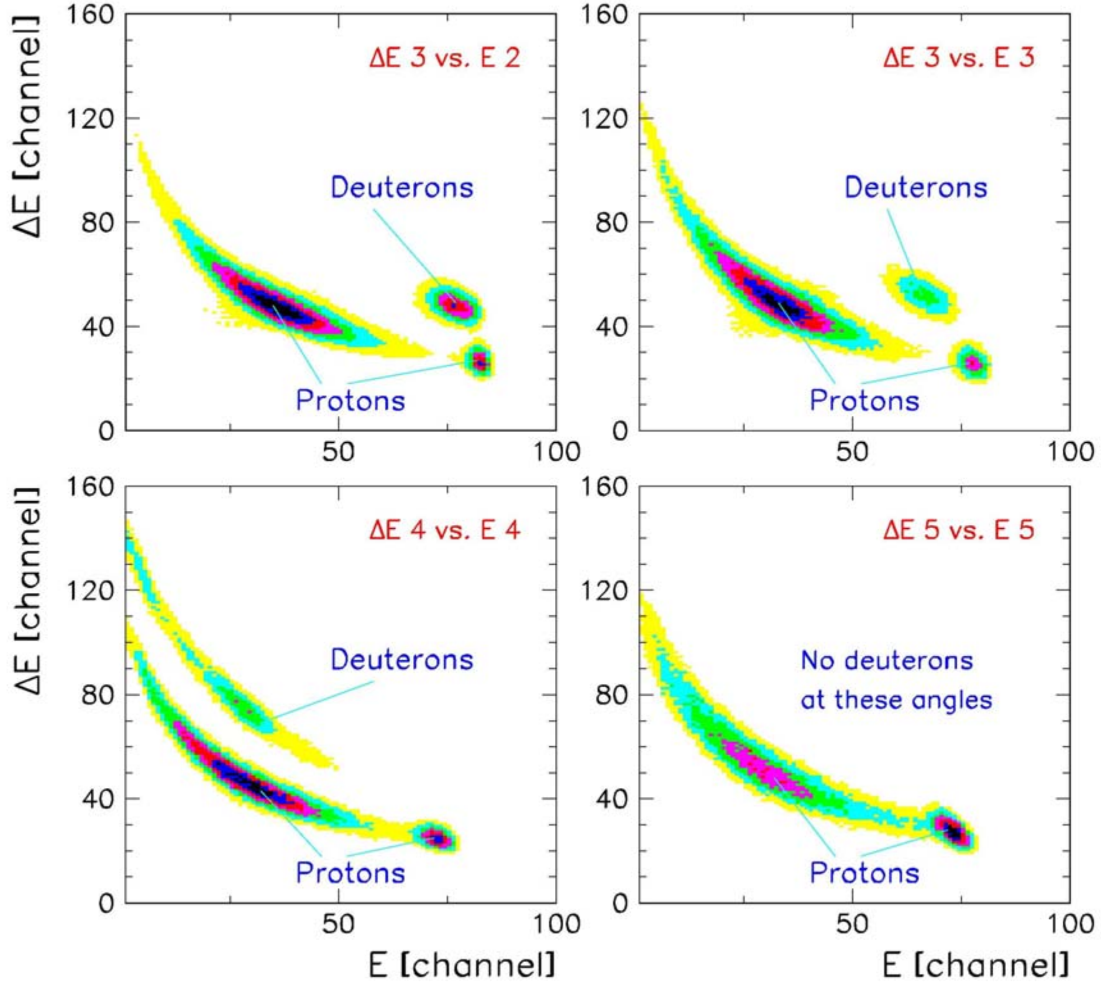
- breakup
- elastic scattering
- single

trigger construction:

- individual prescaling of events in classes
- applying dead-time
- generating main gate

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

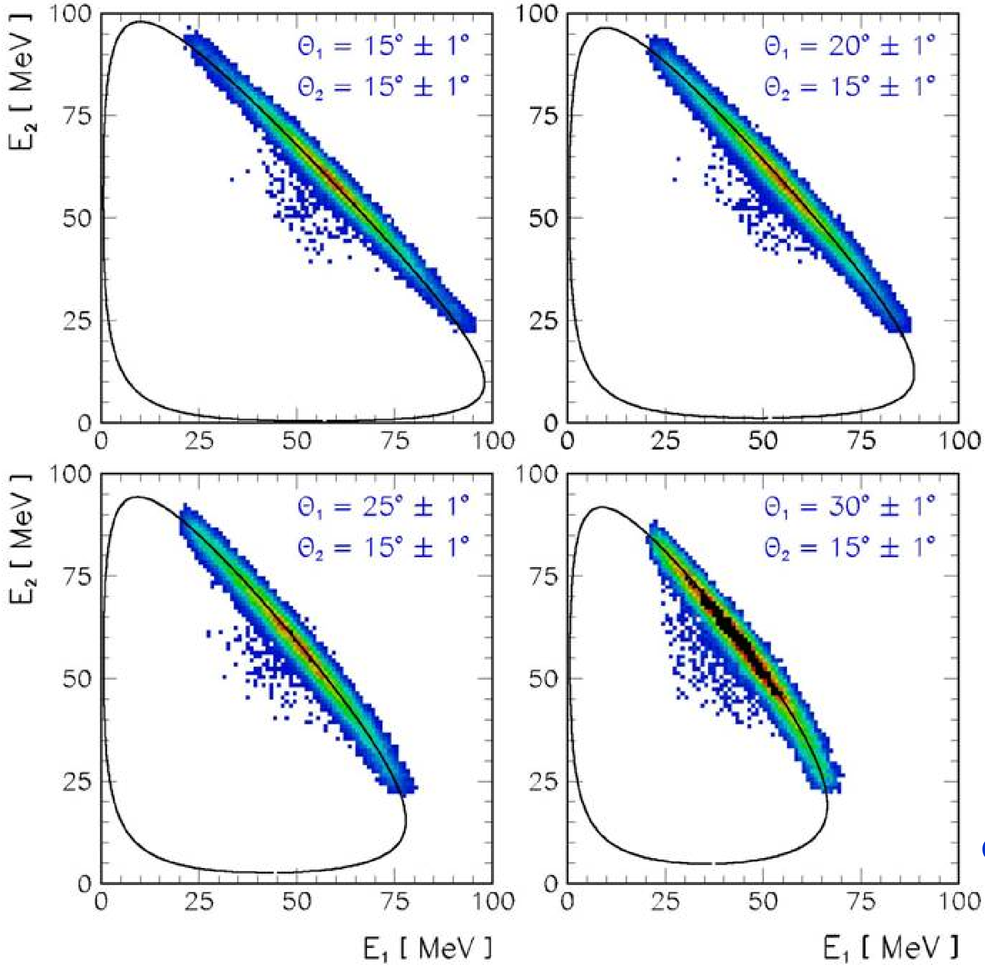
Data Analysis – ΔE-E Particle Identification



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

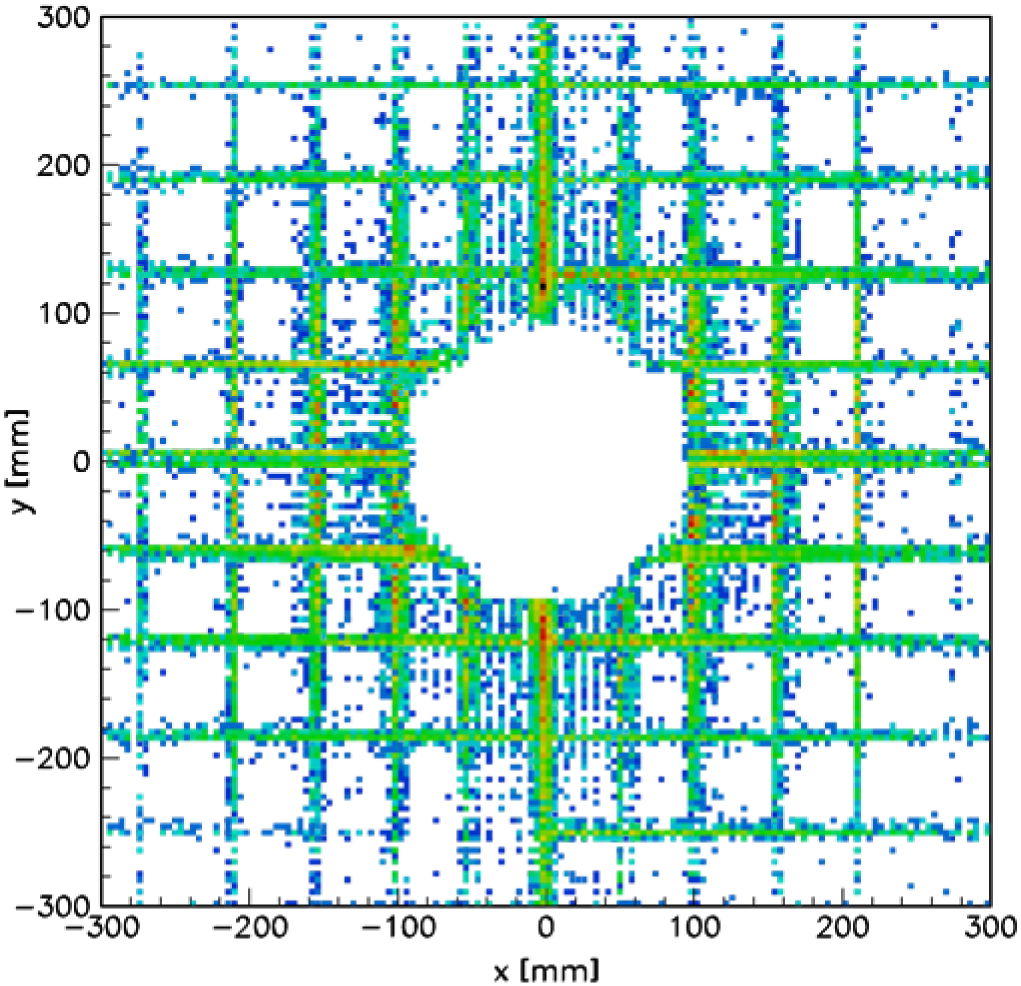


Narrow and background-free kinematical spectra over the whole angular range

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

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

Data Analysis – ΔE-E Array Image on MWPC



MWPC projections for certain single events:

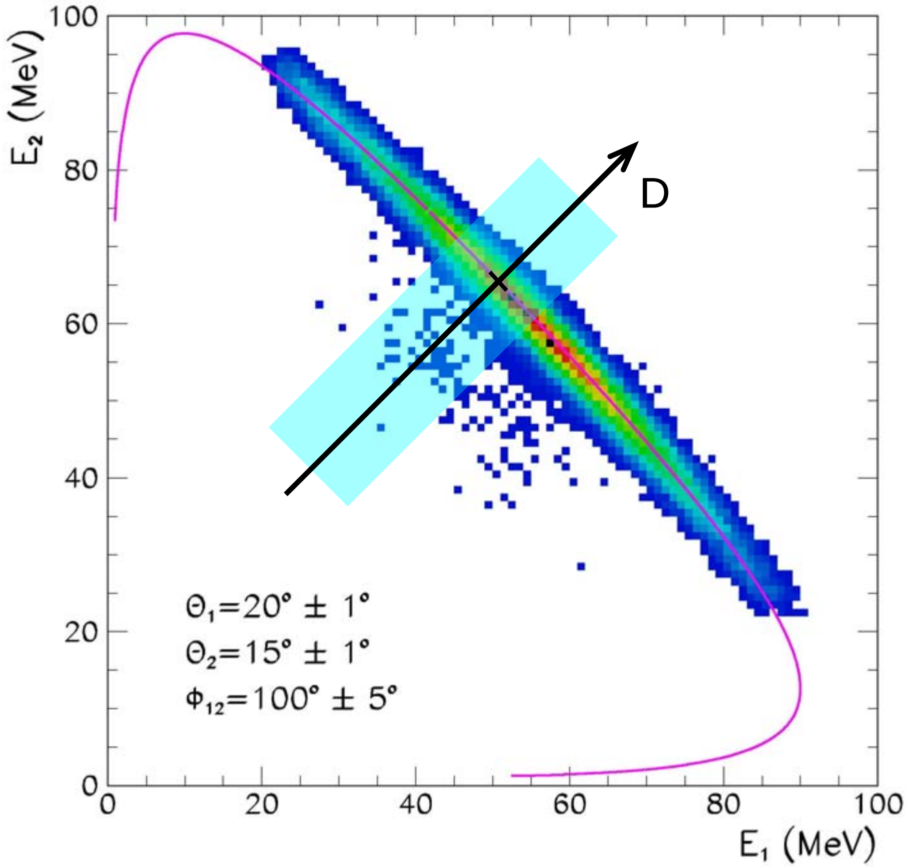
1. Condition:
   no hit in ΔE detector
2. Condition:
   hits in 2 adjacent E detectors

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

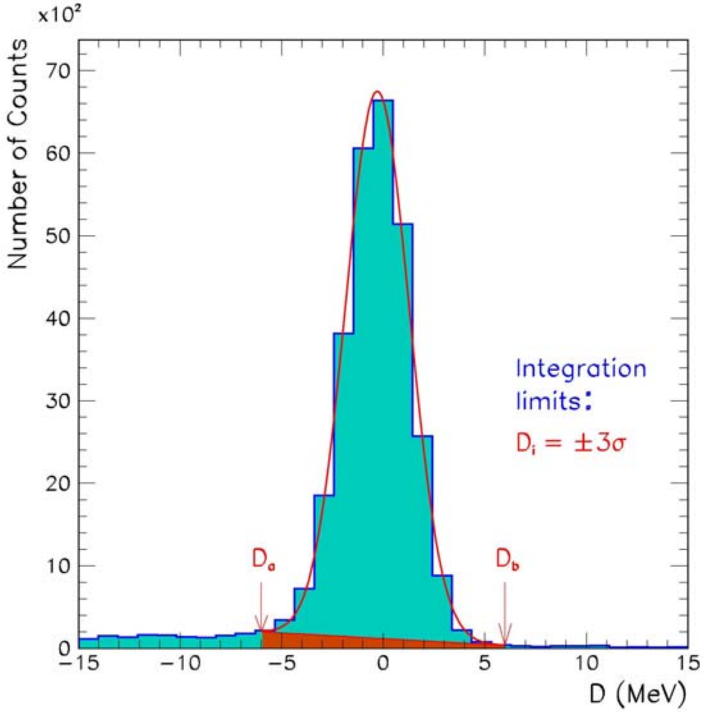
$^{1}H(\vec{d},pp)n$ Measurement at 130 MeV

Data Analysis – E_1-E_2 Kinematical Spectra

Projection of events on the kinematical curve

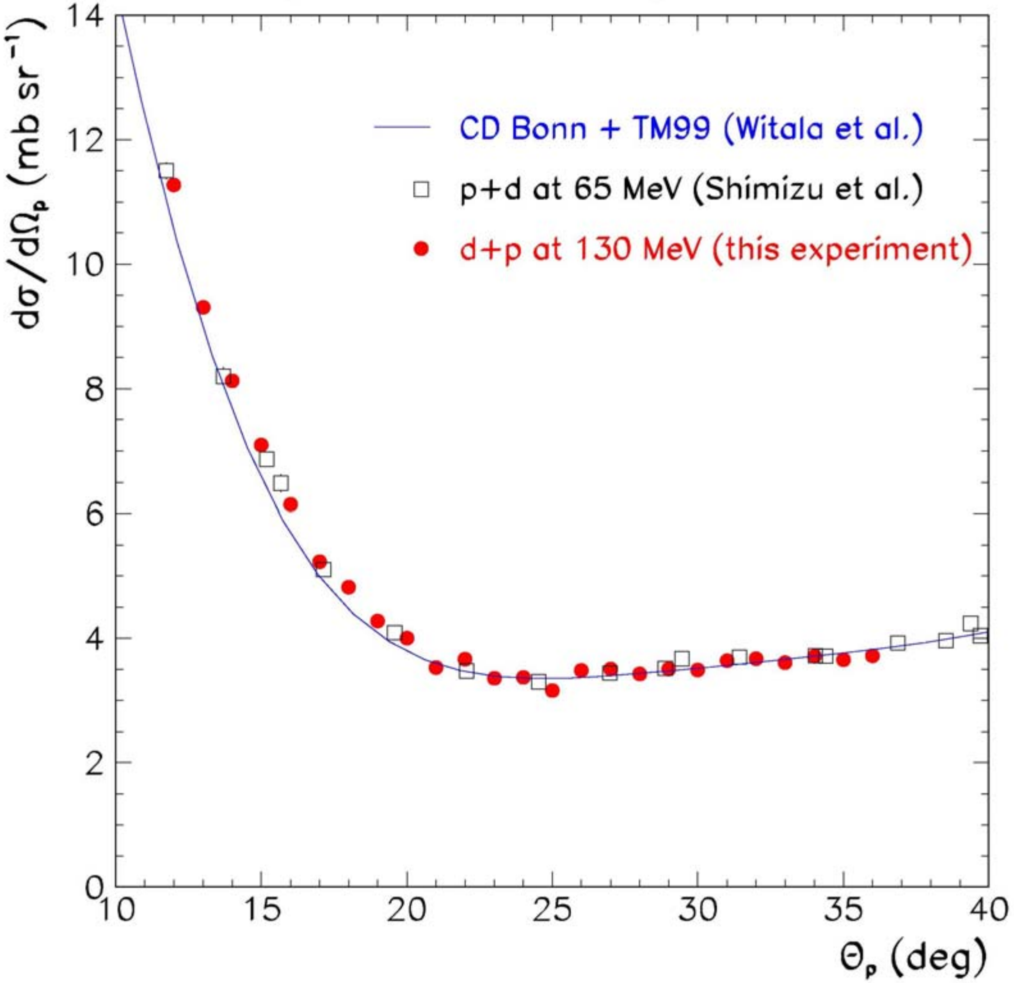


Background subtraction



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

^{1}H($\vec{d}$,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
Cross Section Results – Example

Faddeev calculations

Realistic NN potentials
CD Bonn, NijmI, NijmII, Av18

3NF models: TM99, UIX

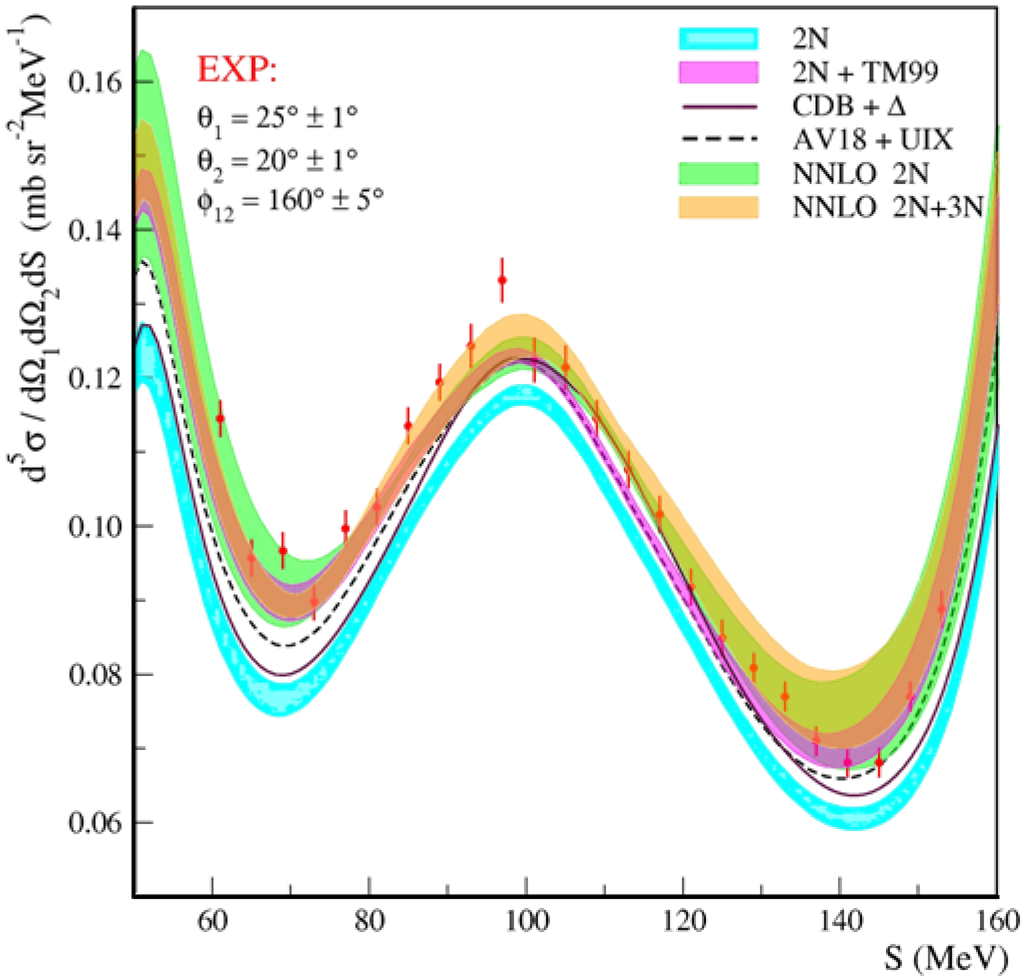
Coupled channel pot.

CD Bonn (mod) + Δ

EFT/ChPT potentials

NNLO – 2N only

NNLO – 2N + 3 N



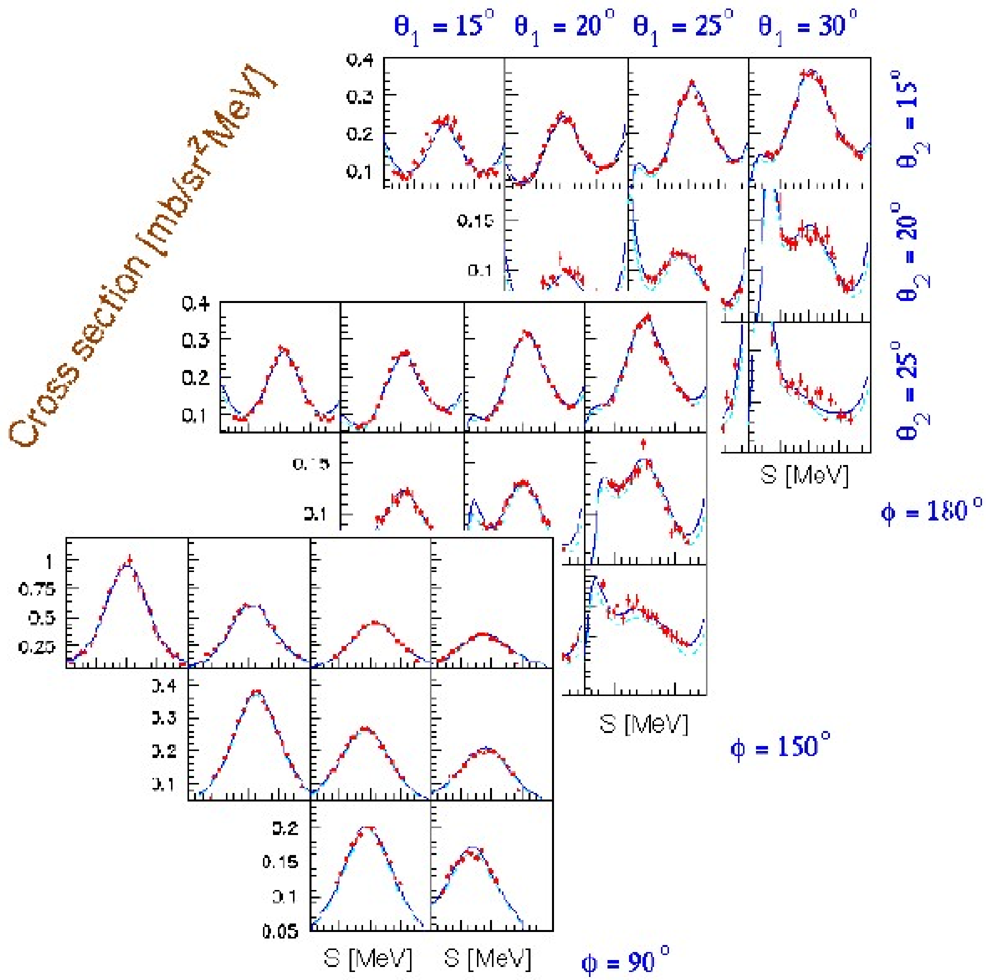
$^{1}H(\vec{d},pp)n$ Measurement at 130 MeV

Cross Section Results – Summary

- ✓ Nearly 1800 cross section data points
  - θ_1, θ_2 = 15° - 30°; grid 5° ; $\Delta\theta = \pm 1°$
  - an additional set for θ_1, θ_2 = 13°
  - φ_{12} = 40° – 180°; grid 10° – 20° ; $\Delta\varphi = \pm 5°$
  - 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)

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

Cross Section Results – Exploring Phase Space



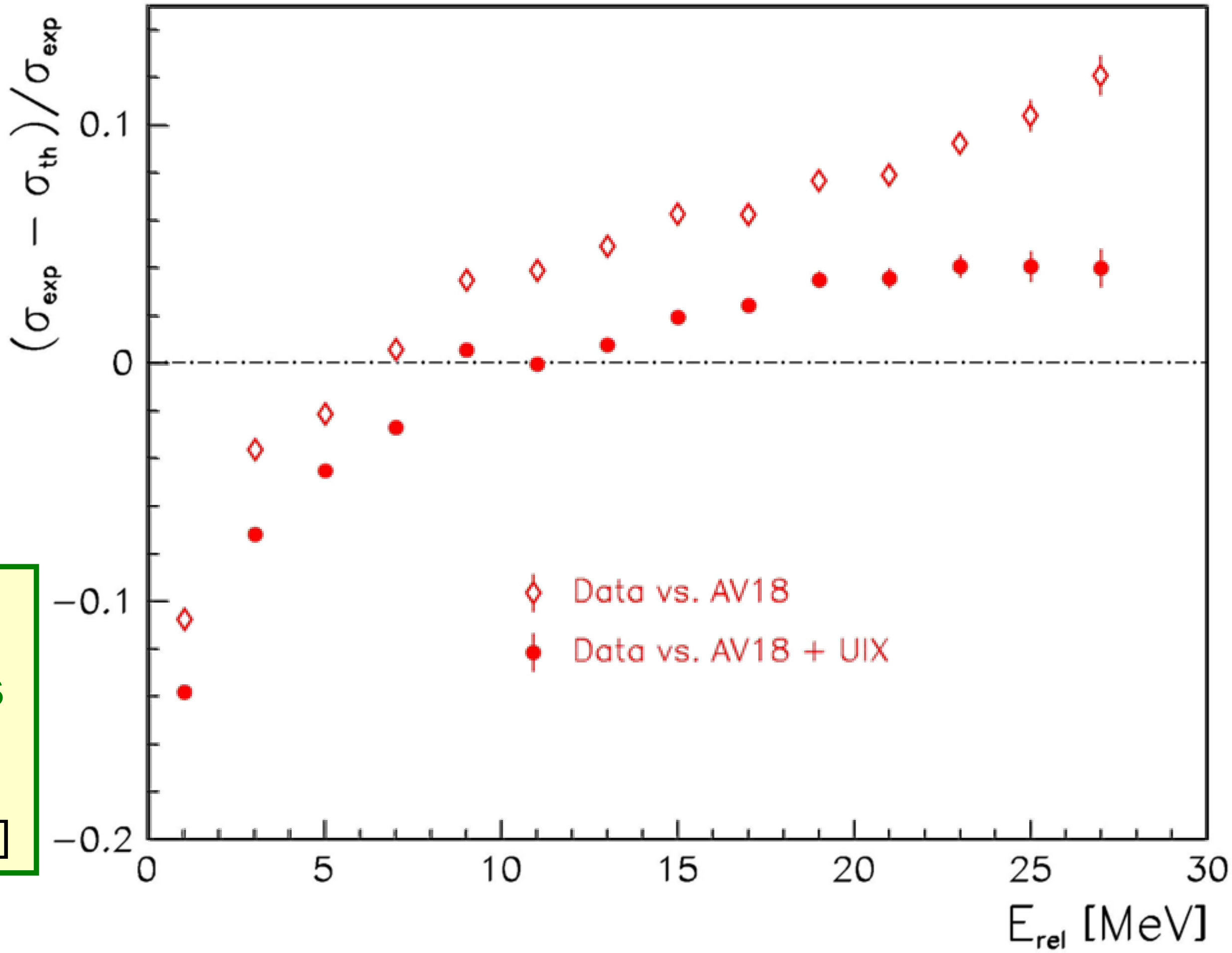
Breakup cross section is a function on 4-dim phase space.

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

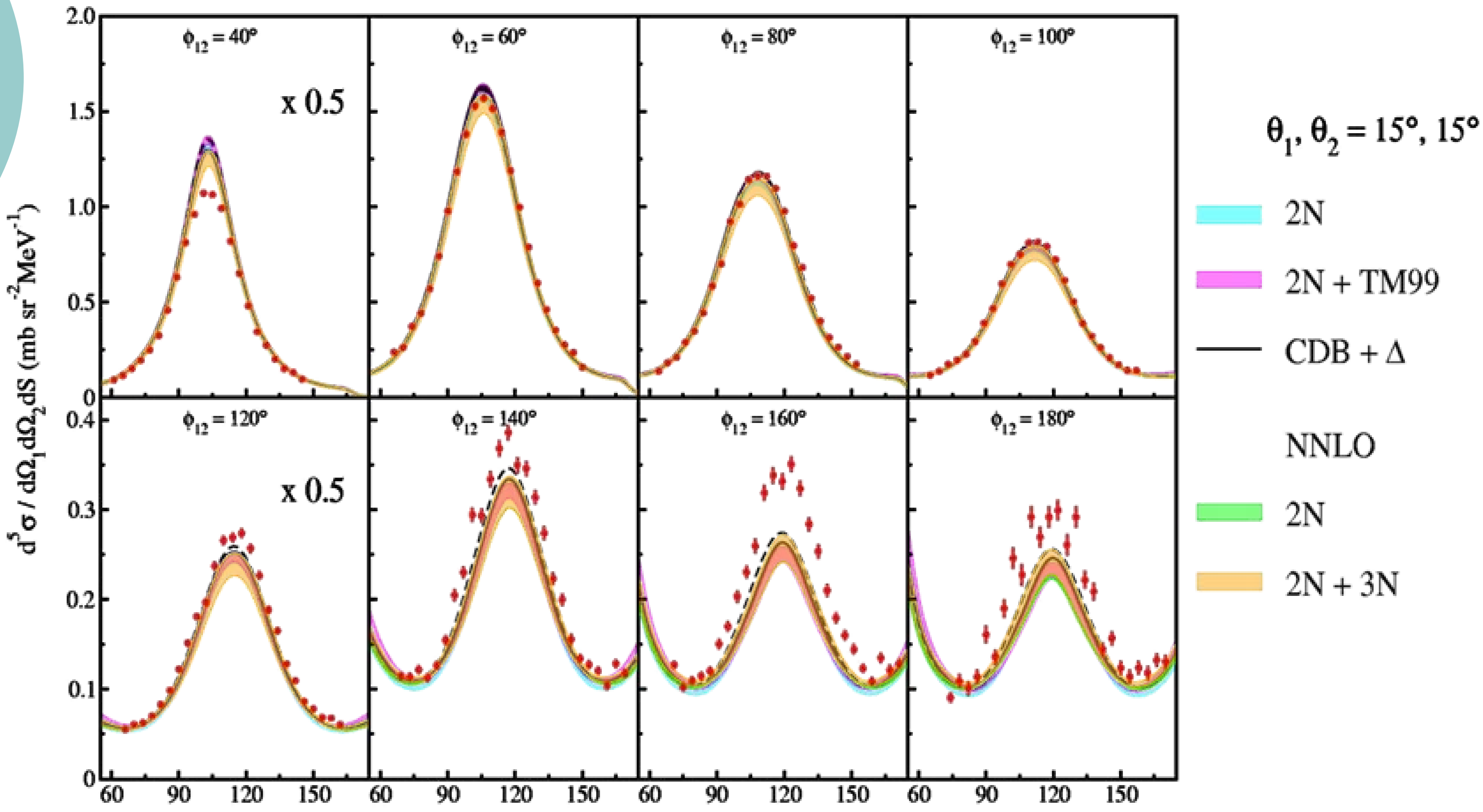
Including 3NF increases discre-pancies at low E_{rel}, reducing them at higher E_{rel} values



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

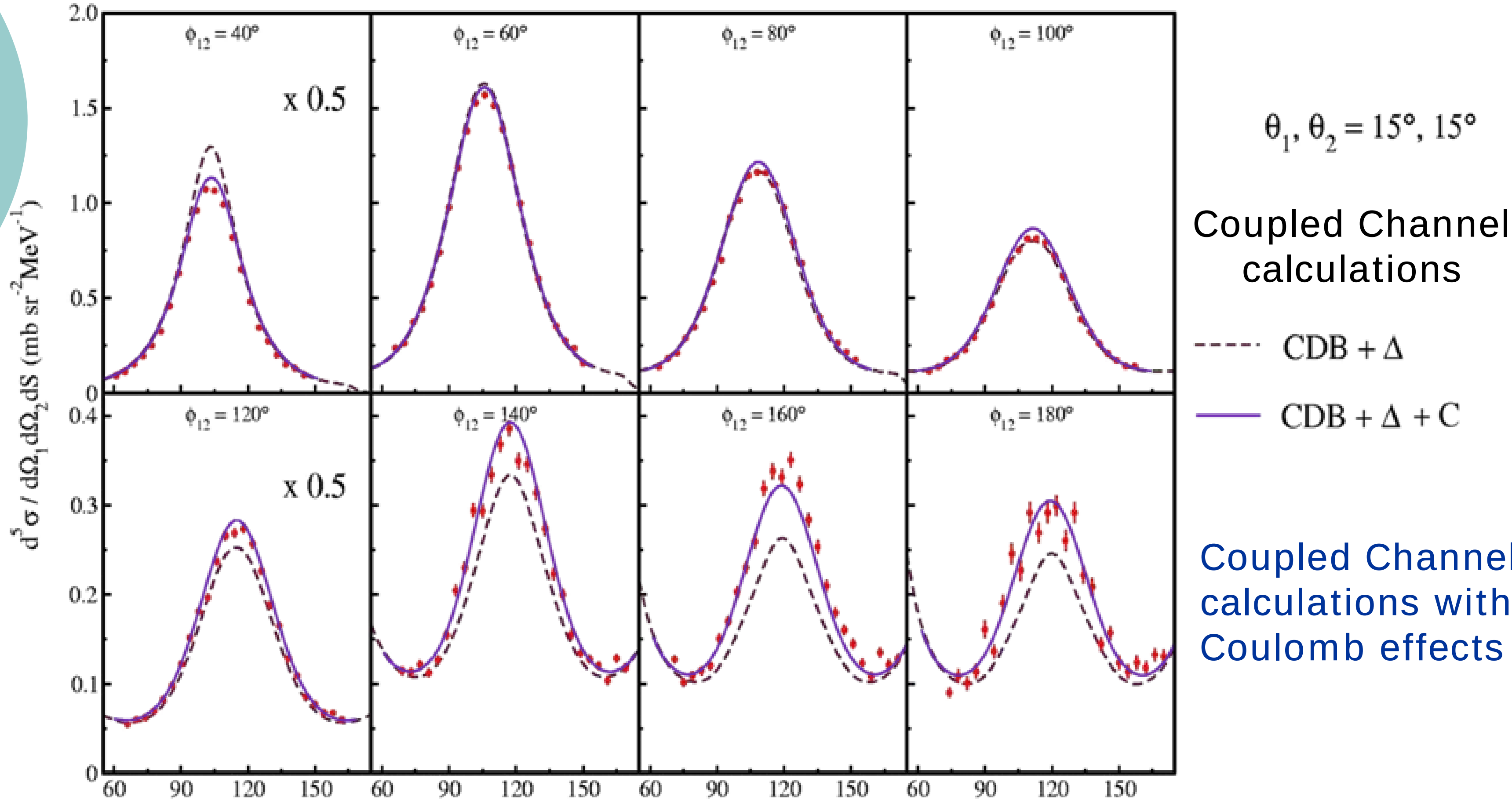
$^1H(\vec{d},pp)n$ Measurement at 130 MeV

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

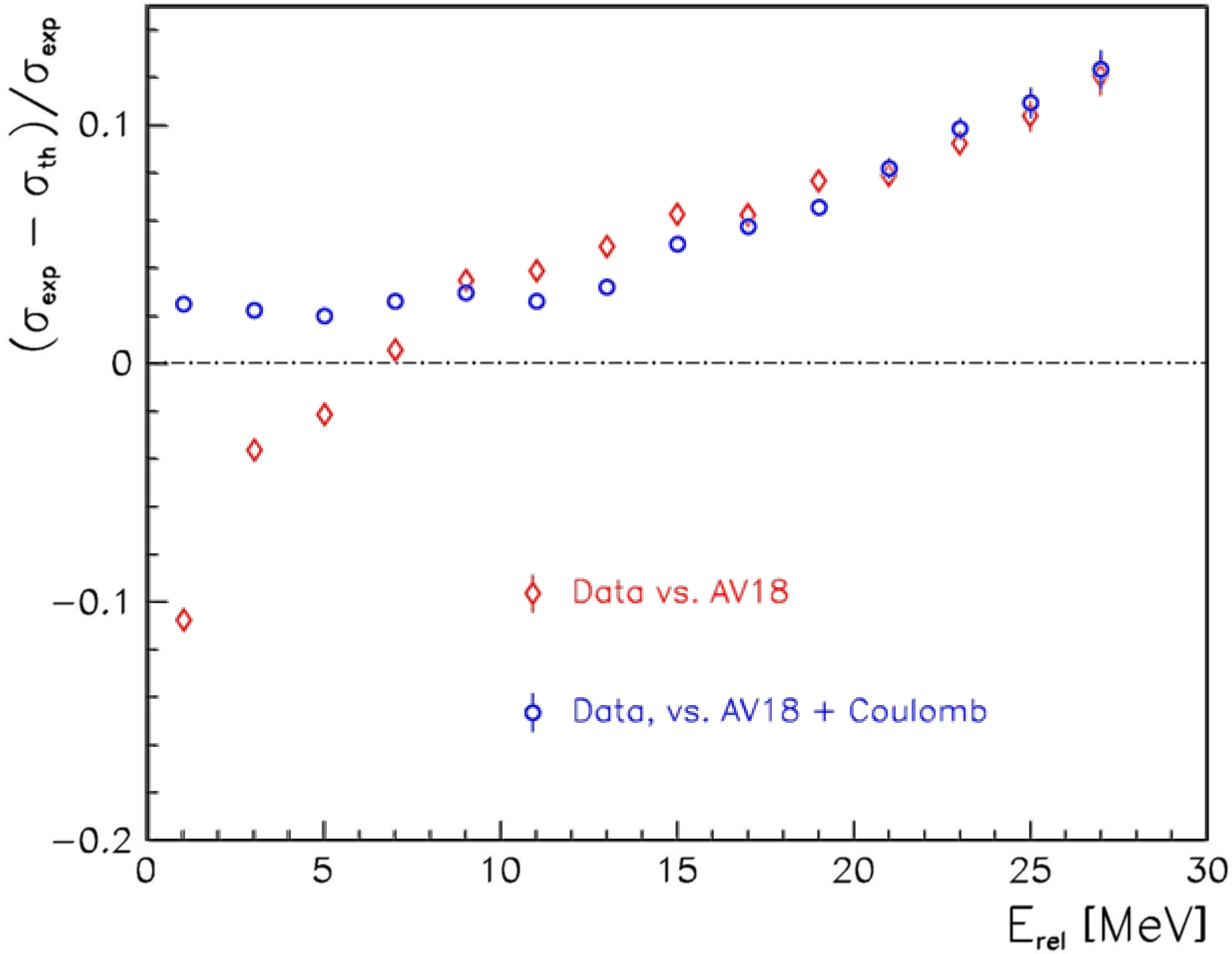
Predictions with Coulomb reproduce data much better !

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

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

↓

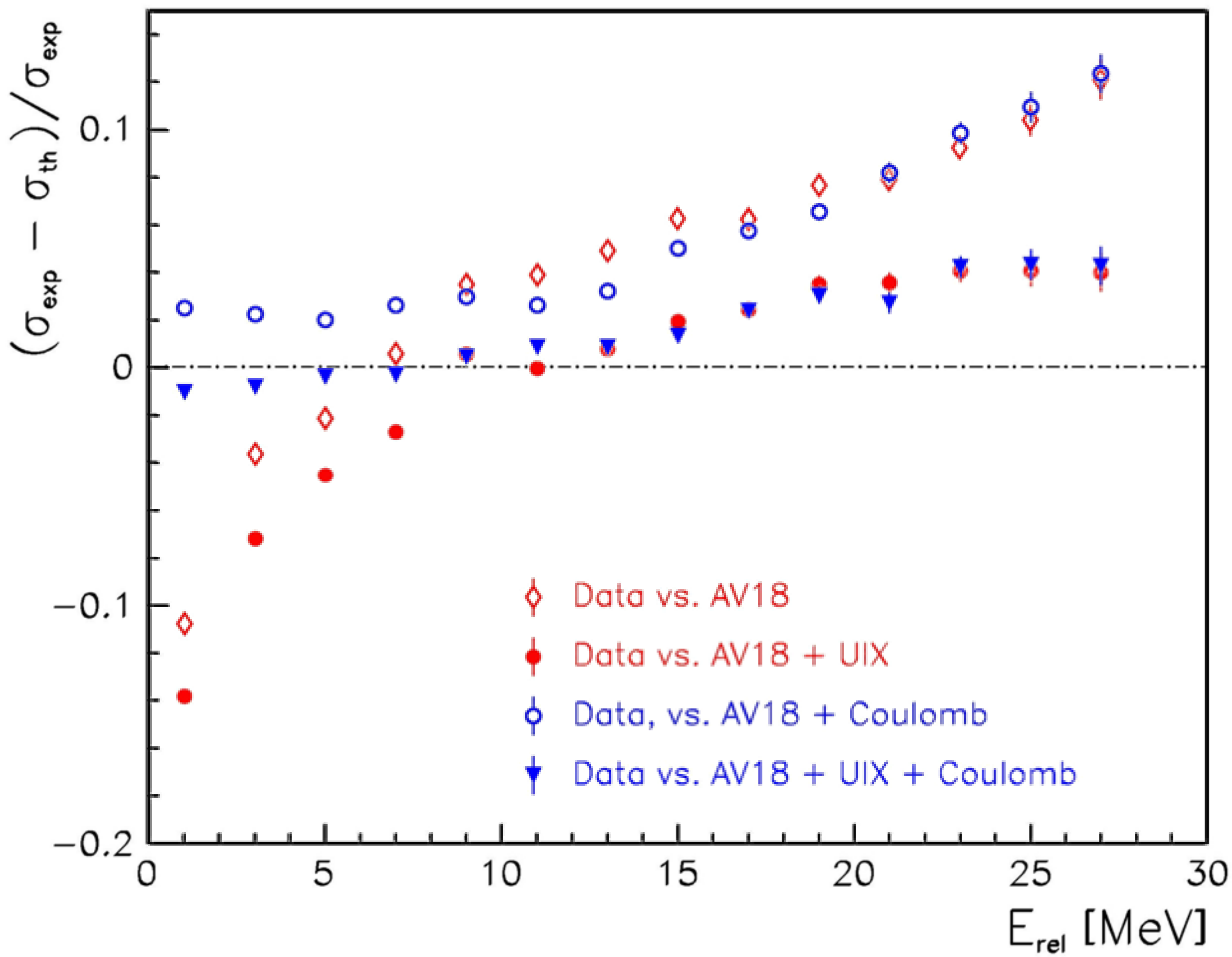
Quantitative comparison of the role of both contributions

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

Cross Section Results – 3NF & Coulomb Effects

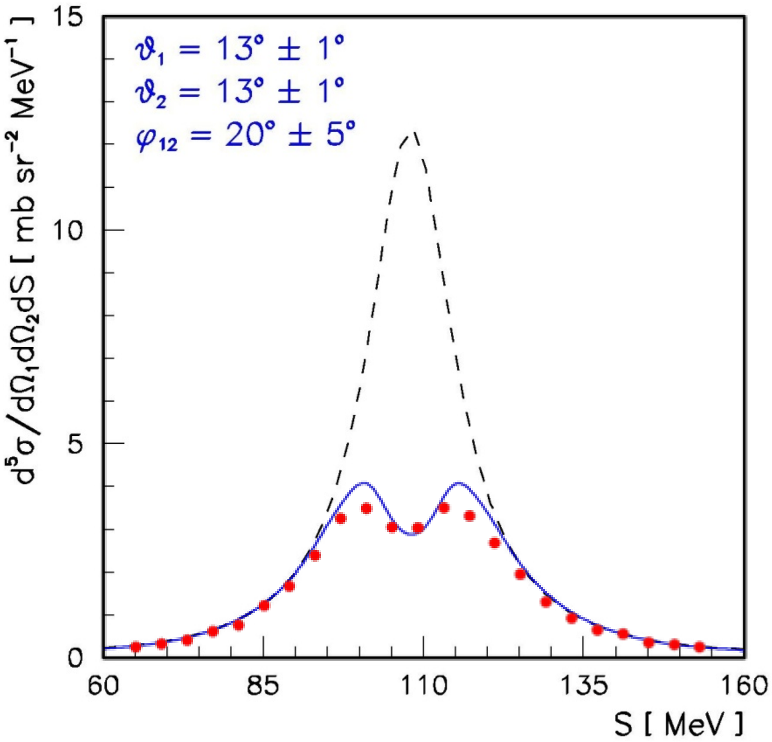
Including Coulomb force effects improves the agreement with the data at low E_{rel} values

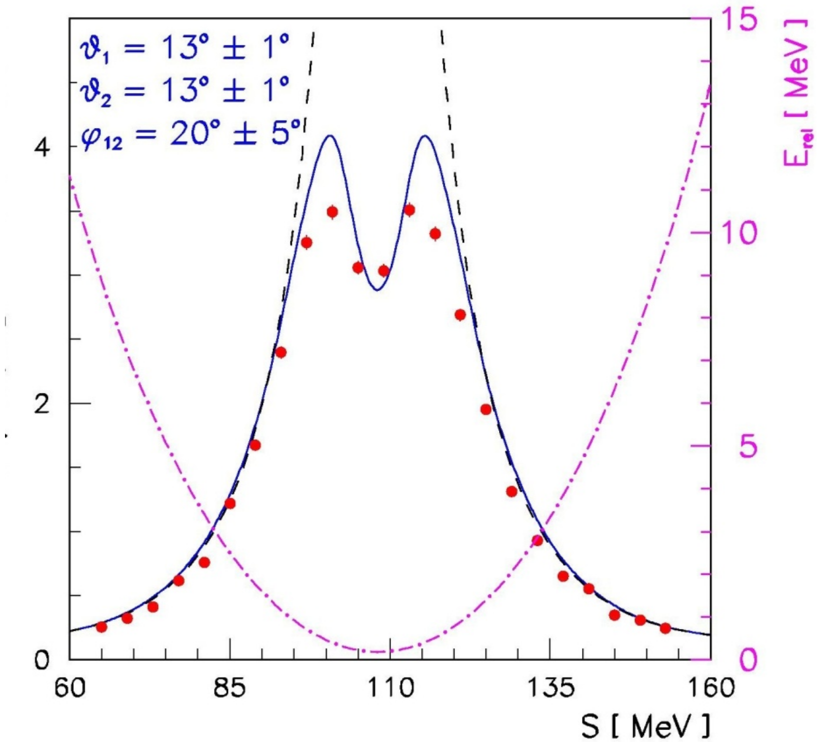
The best agreement is reached when <u>both</u>, the Coulomb force <u>and</u> the 3NF are taken into account !



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

Cross Section Results – Coulomb Effects





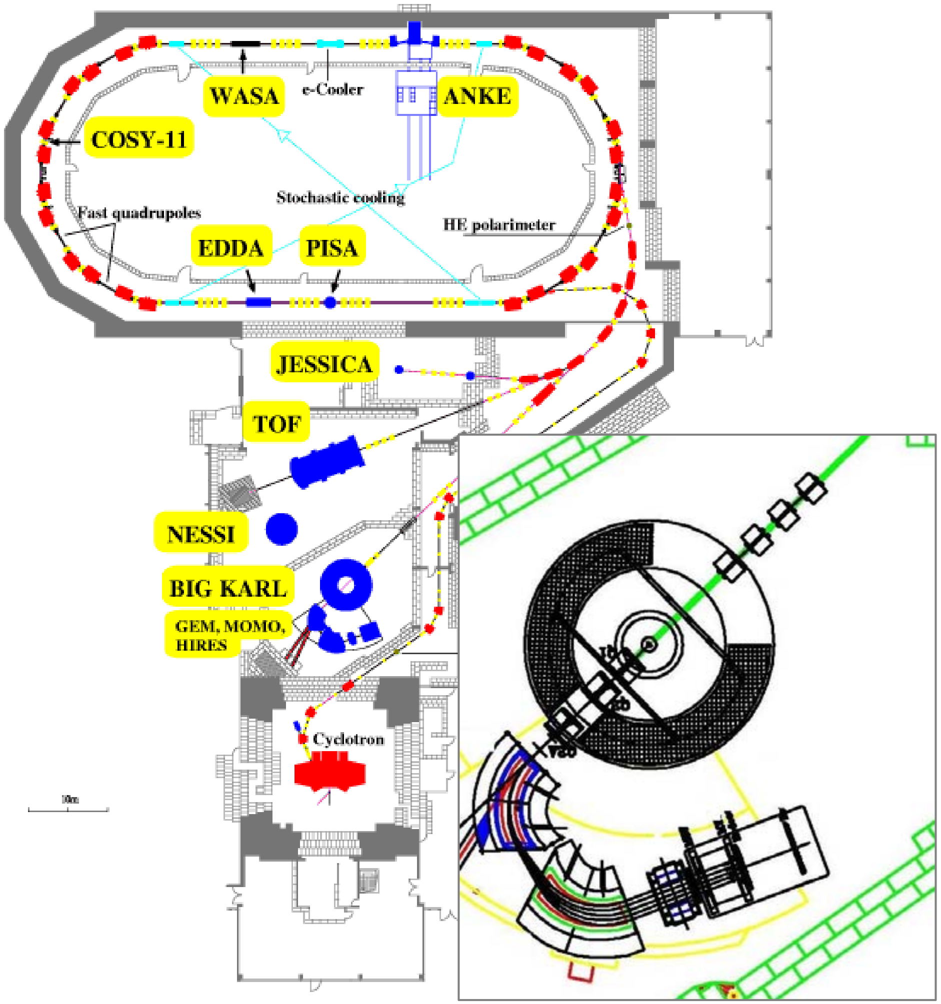
Acceptance limit of KVI experiment

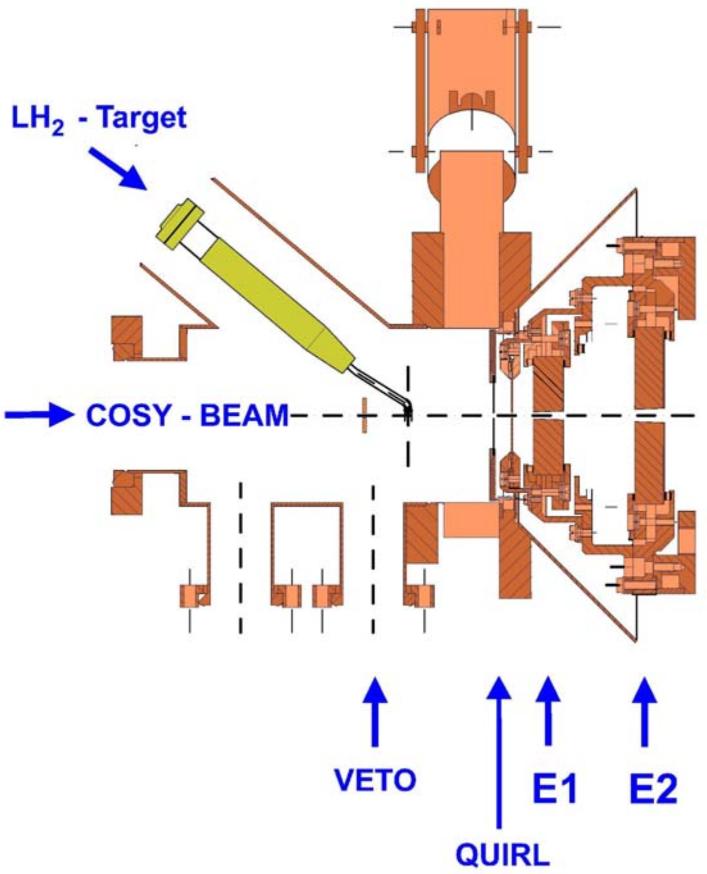
$^{1}H(\vec{d},pp)n$ Measurement at 130 MeV

Germanium Wall Exp. @ COSY / BigKarl

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

Germanium Wall Exp. @ COSY / BigKarl

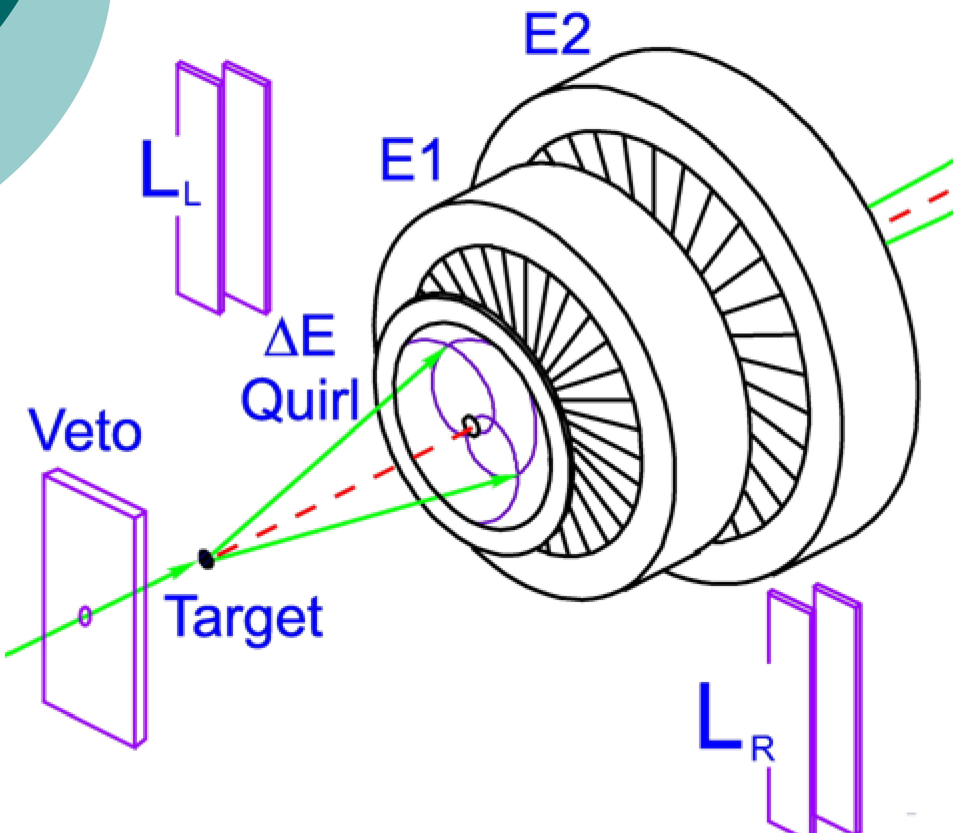


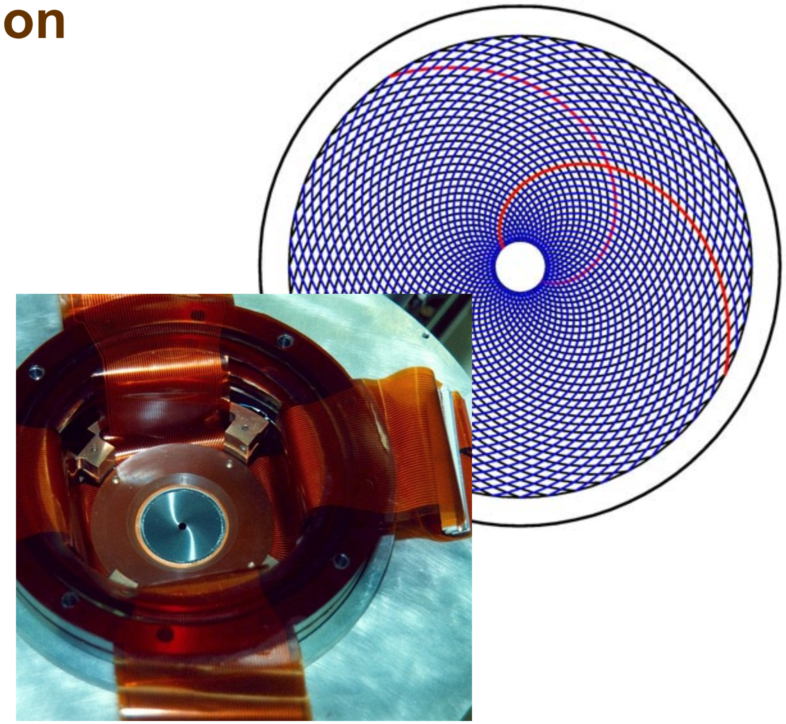


$^{1}H(\vec{d},pp)n$ Measurement at 130 MeV

Germanium Wall Exp. @ COSY / BigKarl

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



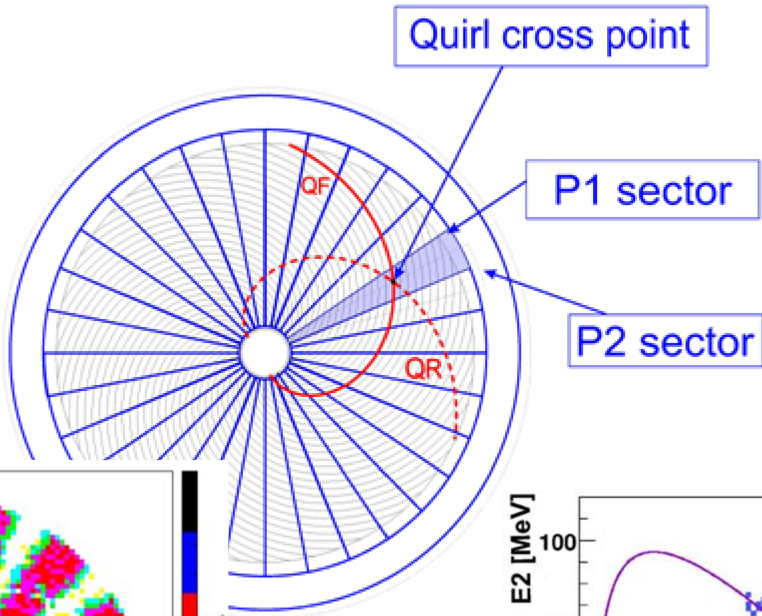


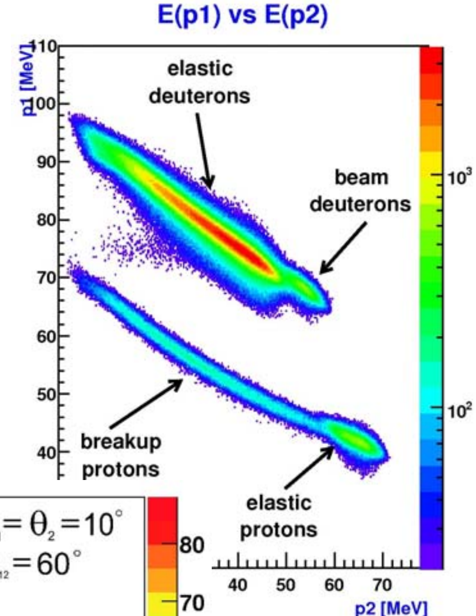
Quirl

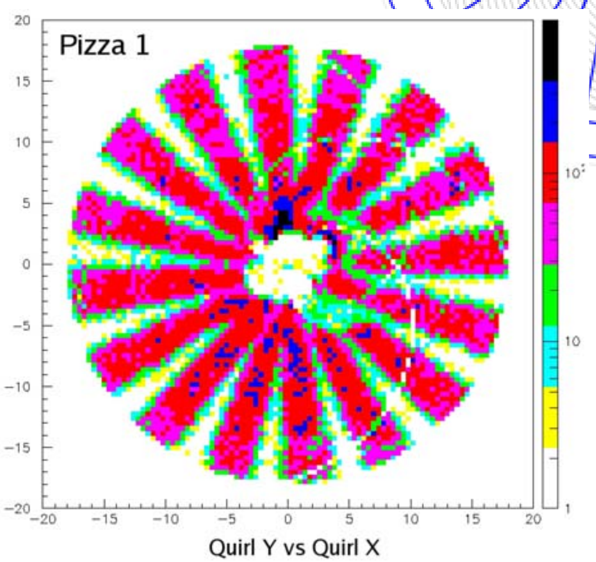
2•200 spiral segments
pixel 0.011-0.101 mm^2

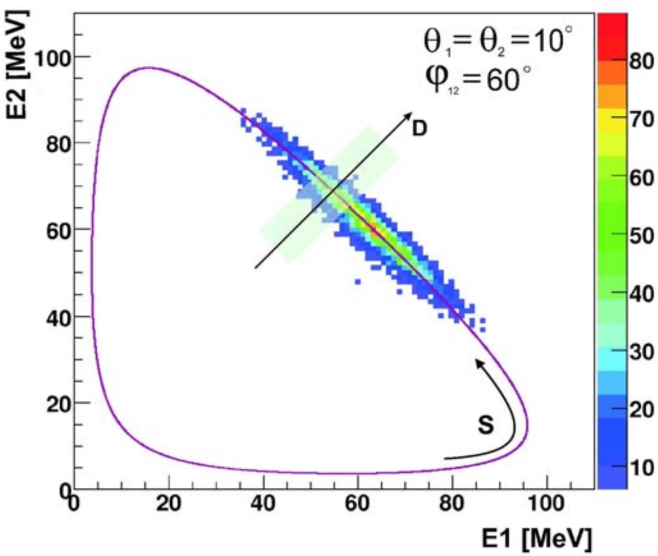
$^{1}H(\vec{d},pp)n$ Measurement at 130 MeV

Germanium Wall Exp. @ COSY / BigKarl







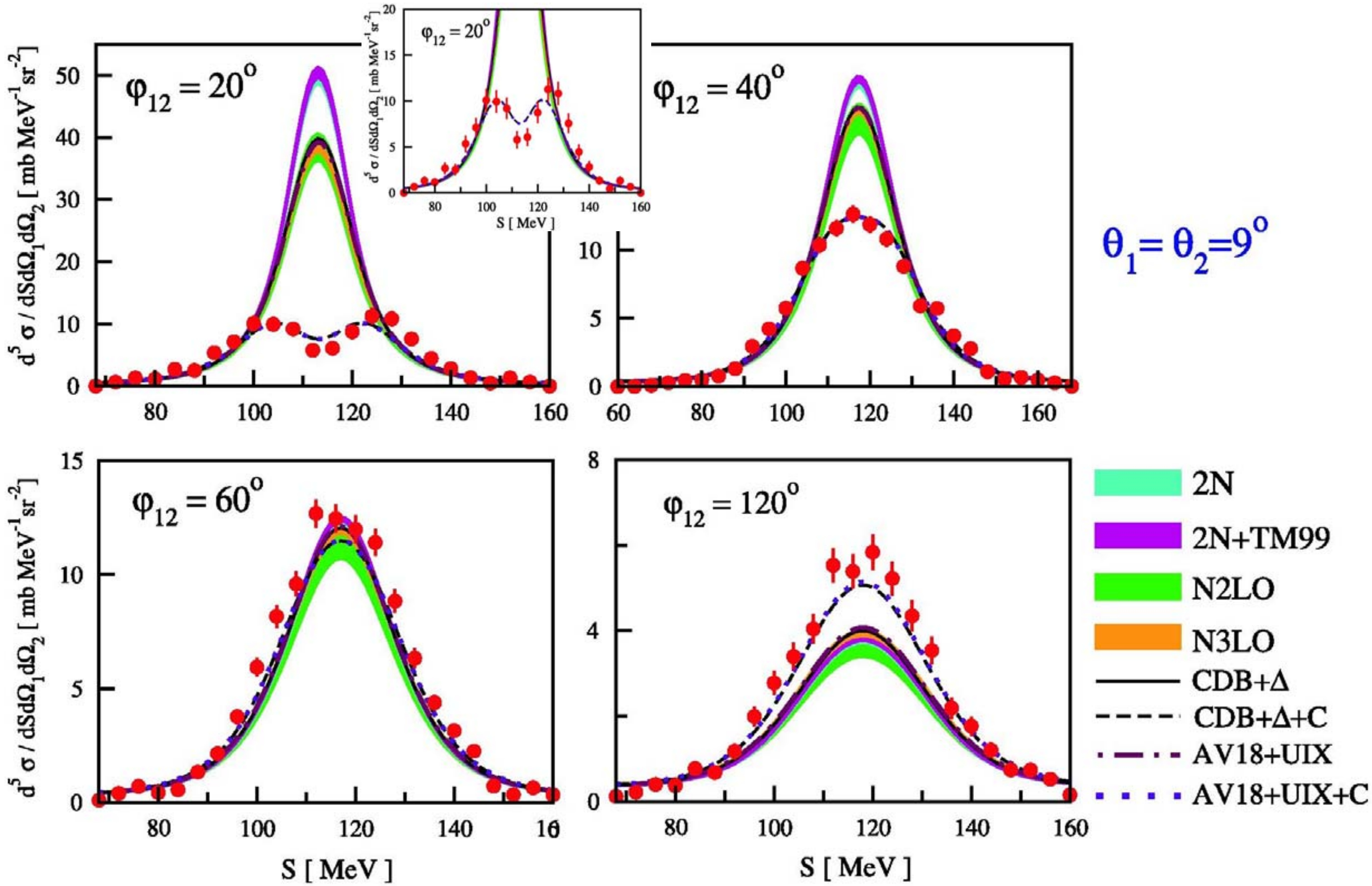


$^{1}H(\vec{d},pp)n$ Measurement at 130 MeV
FZJ Cross Section Results – Summary

- ✓ Nearly 2700 cross section data points
  - $\theta_1, \theta_2 = 5^\circ - 13^\circ$; grid 2°; $\Delta\theta = \pm 1^\circ$
  - $\varphi_{12} = 20^\circ - 180^\circ$; grid 20°; $\Delta\varphi = \pm 5^\circ$
  - 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.
  $\chi^2 = f(\varphi_{12})$, $\chi^2 = f(\theta_1,\theta_2)$, $\chi^2 = f(E_{rel})$

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

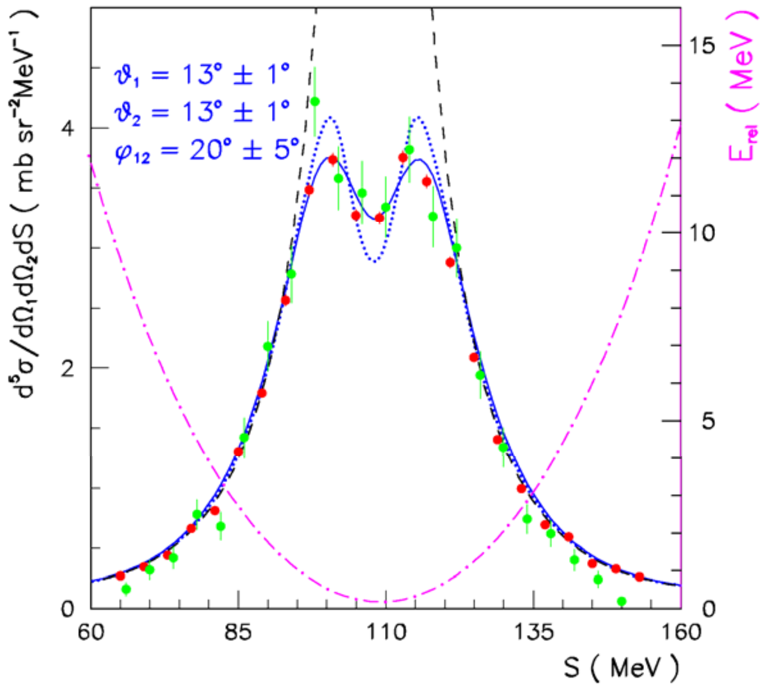
Cross Section Results – Examples

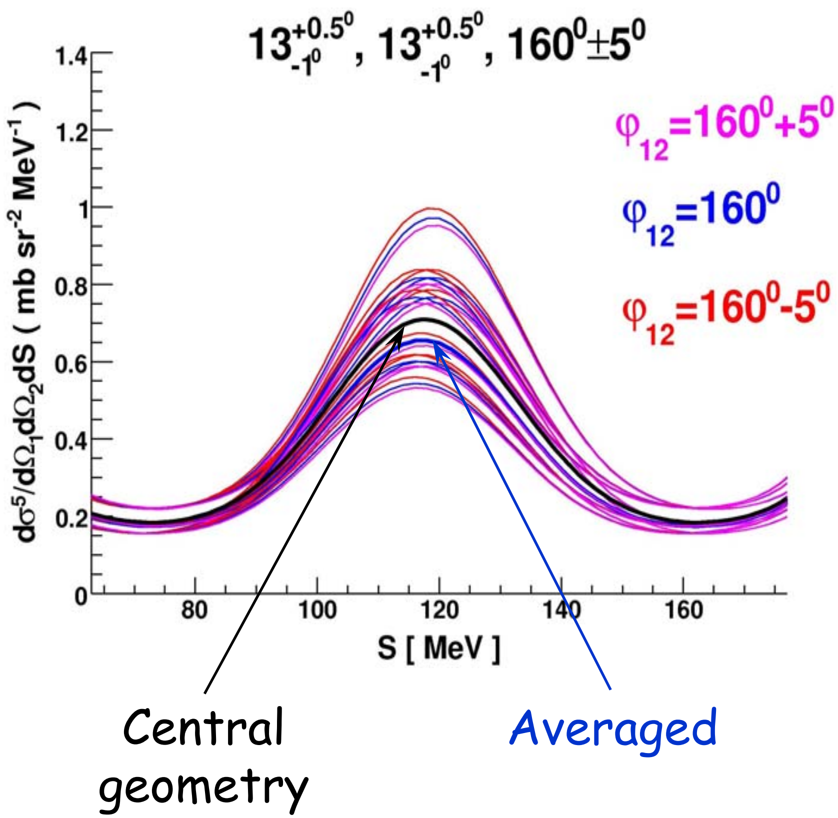


$^1H(\vec{d},pp)n$ Measurement at 130 MeV

Cross Section Results – Averaging

Averaging important !





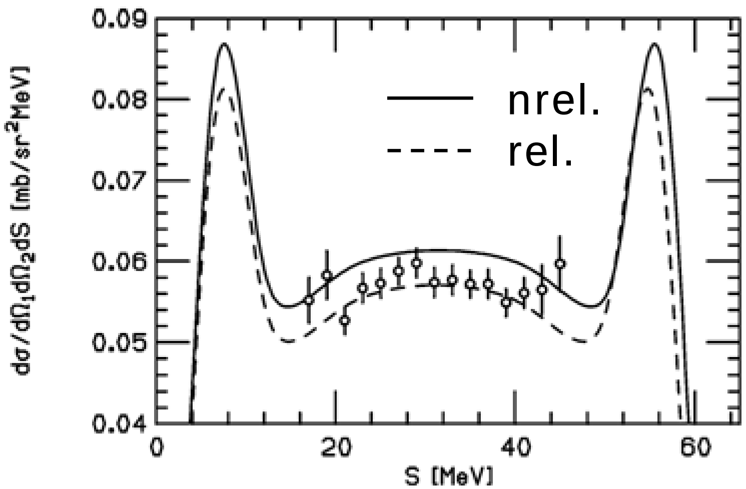
Comparison

● KVI ; ● FZJ

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

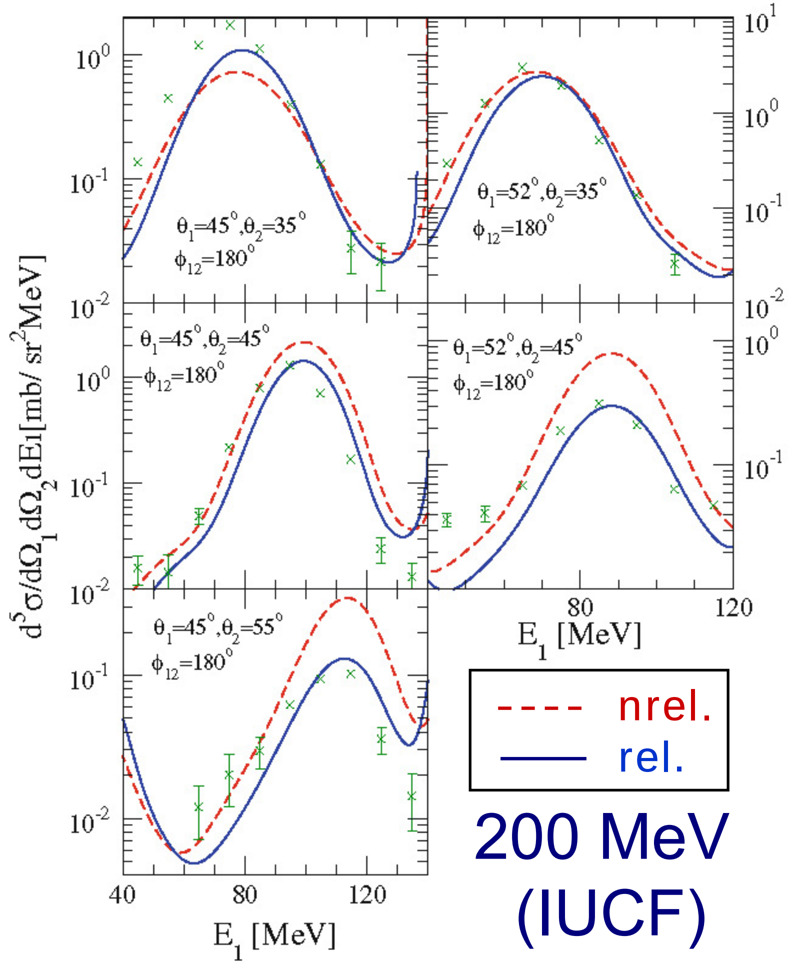
Cross Section Results – Relativistic Effects

CD Bonn potential



65 MeV (PSI)

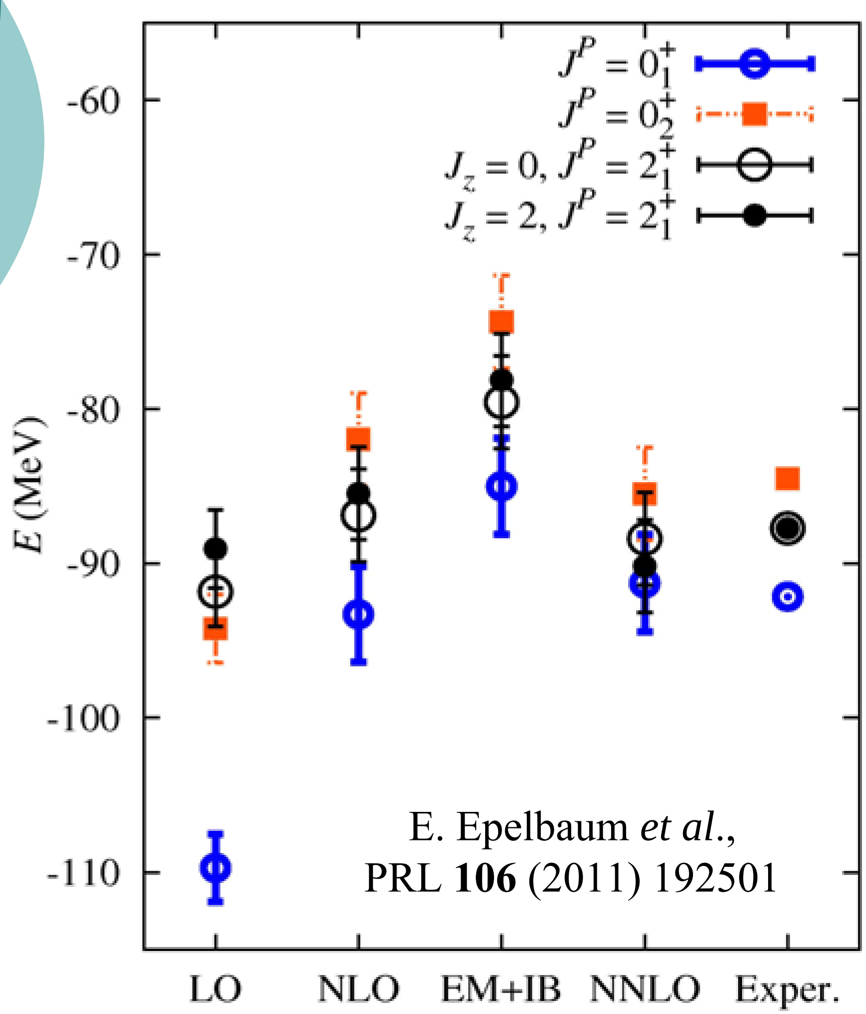
$\theta_1 = \theta_2 = 54^o, \varphi_{12} = 120^o$



nrel.
rel.

200 MeV (IUCF)

Efekty 3NF + Coulomb
Stan Hoyle'a dla ^{12}C



Stan w ^{12}C dzięki któremu zachodzi fuzja $3\alpha \rightarrow {}^{12}C$ we wnętrzu gwiazd (^{12}C katalizatorem w CNO)

Nuclear Lattice Simulations

Jedynie przy uwzględnieniu obu efektów, sił Coulomba oraz sił trójciałowych (komponent NNLO) można bez dopasowania (*ab initio*) otrzymać właściwą sekwencję poziomów

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

Summary

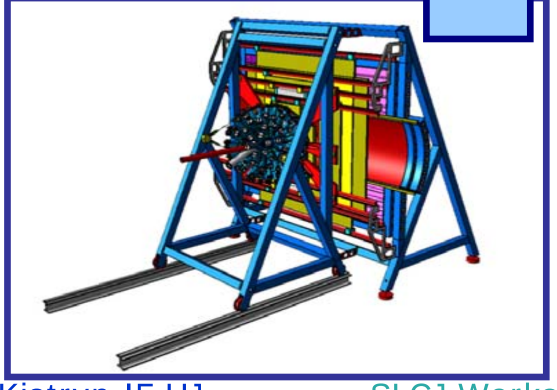
- Systematic, precise sets of **cross sections** (and analyzing powers → E.S.) obtained at E_d = 130 MeV
  ➡ basis for comparing different approaches which predict the 3N system observables
- Showed significant 3NF effects for cross sections !
- Found large influence of the Coulomb force on c.s.
- Relativistic 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 !

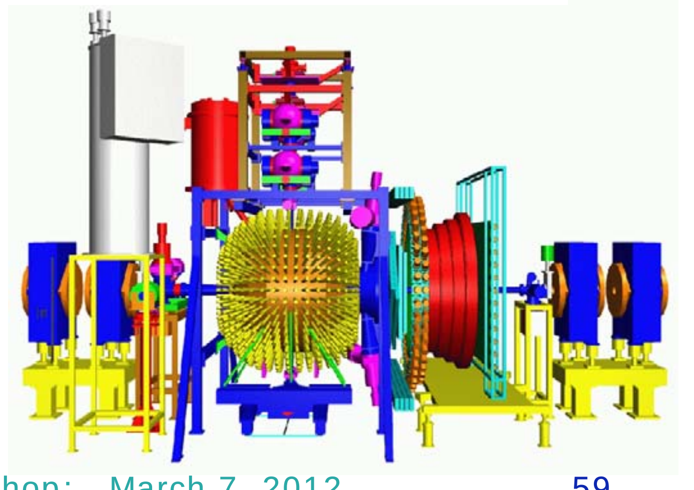
Breakup Measurements

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 incomplete view





Breakup Measurements

Outlook and Wishes (3N and 4N systems)

Personal, surely incomplete view

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  - Evaluating the data accumulated in several experiments at KVI
  - More measurements:
    - Japan: RIKEN, RCNP, RIBF, ...
    - Projects for PAX@COSY & WASA@COSY
    - BINA@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 !)


22-nd EUROPEAN CONFERENCE ON
FEW-BODY PROBLEMS IN PHYSICS
CRACOW, POLAND
9 - 13 September 2013
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