Neutron-Deuteron Breakup:
A Probe of the Neutron-Neutron Interaction

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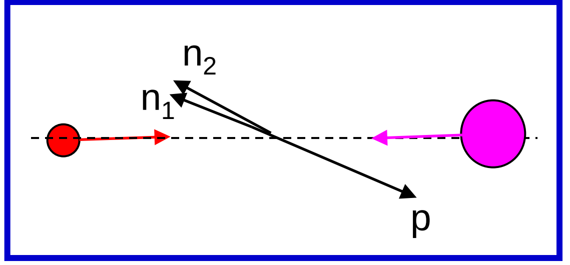
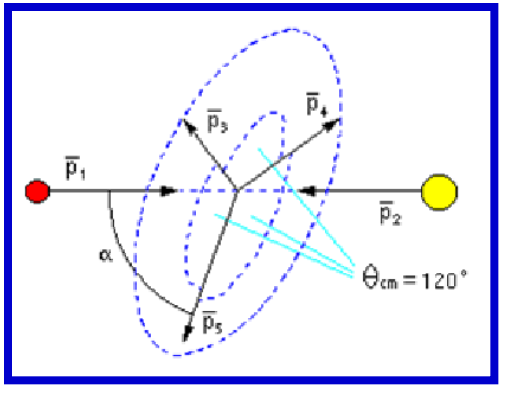
Low-Energy nd Breakup Observables:

Sensitive to S-wave NN Interaction

- **nn FSI cross-section measurement:**
  determination of the $^1S_0$ nn scattering length (a_{nn})



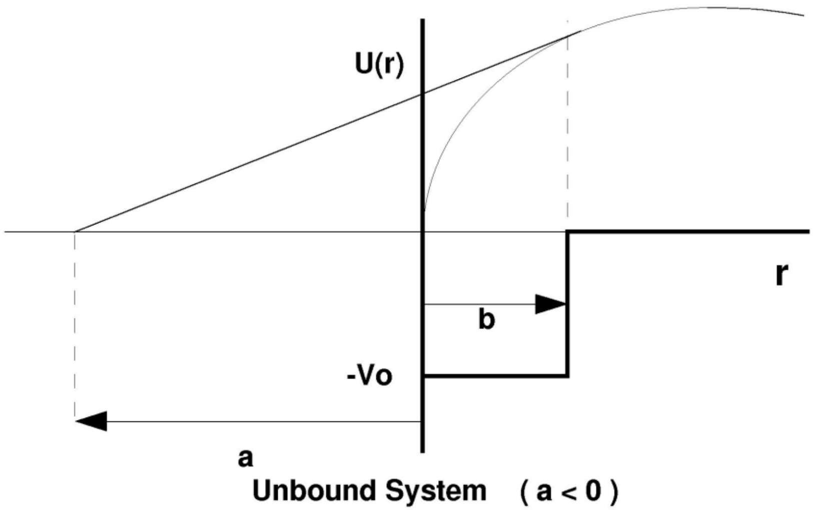
- **Star configuration cross-section measurement:**
  sensitive to the $^3S_1$ np interaction



- **What's next?**

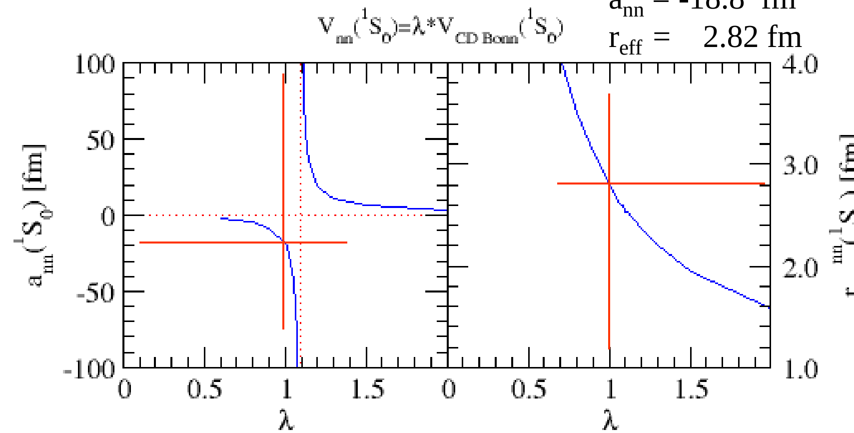
The neutron-neutron $^1S_0$ Scattering Length

1. Highly sensitive to the *nn* potential strength



$$\frac{\Delta V_{nn}}{V_{nn}} = 0.005 \Rightarrow \frac{\Delta a_{nn}}{a_{nn}} = 0.10$$

CD Bonn (λ=1.0)
a_{nn} = -18.8 fm
r_{eff} = 2.82 fm



H. Witala and W. Glockle, PRC 83, 034004 (2011).

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2. Limits CSB

$$\Delta a_{CSB} = \left| a_{nn}^N - a_{pp}^N \right|$$

ρ^0-ω mixing

$$\langle I = 1 | H_{em} | I = 0 \rangle \rightarrow m_u - m_d = 4 MeV$$

$$\Delta a_{CSB} = 1.2 \pm 0.4\ fm$$

G. A. Miller, B. M. K. Nefkens, and I. Slaus, Phys. Rep. **194**, 1 (1990)

Measurement of $^1S_0$ nn-Scattering Length

$$\sigma_{NN} = \tfrac{1}{4}\,\sigma_s + \tfrac{3}{4}\,\sigma_t$$

=0

$$\sigma_{nn} = \tfrac{1}{4}\,\sigma_s + \tfrac{3}{4}\,\sigma_t = \tfrac{1}{4}\,\sigma_s$$

$$\sigma_s = \frac{4\pi}{(1/a_{nn} - k^2 r_{nn}/2)^2 + k^2}$$

$$k \to 0$$

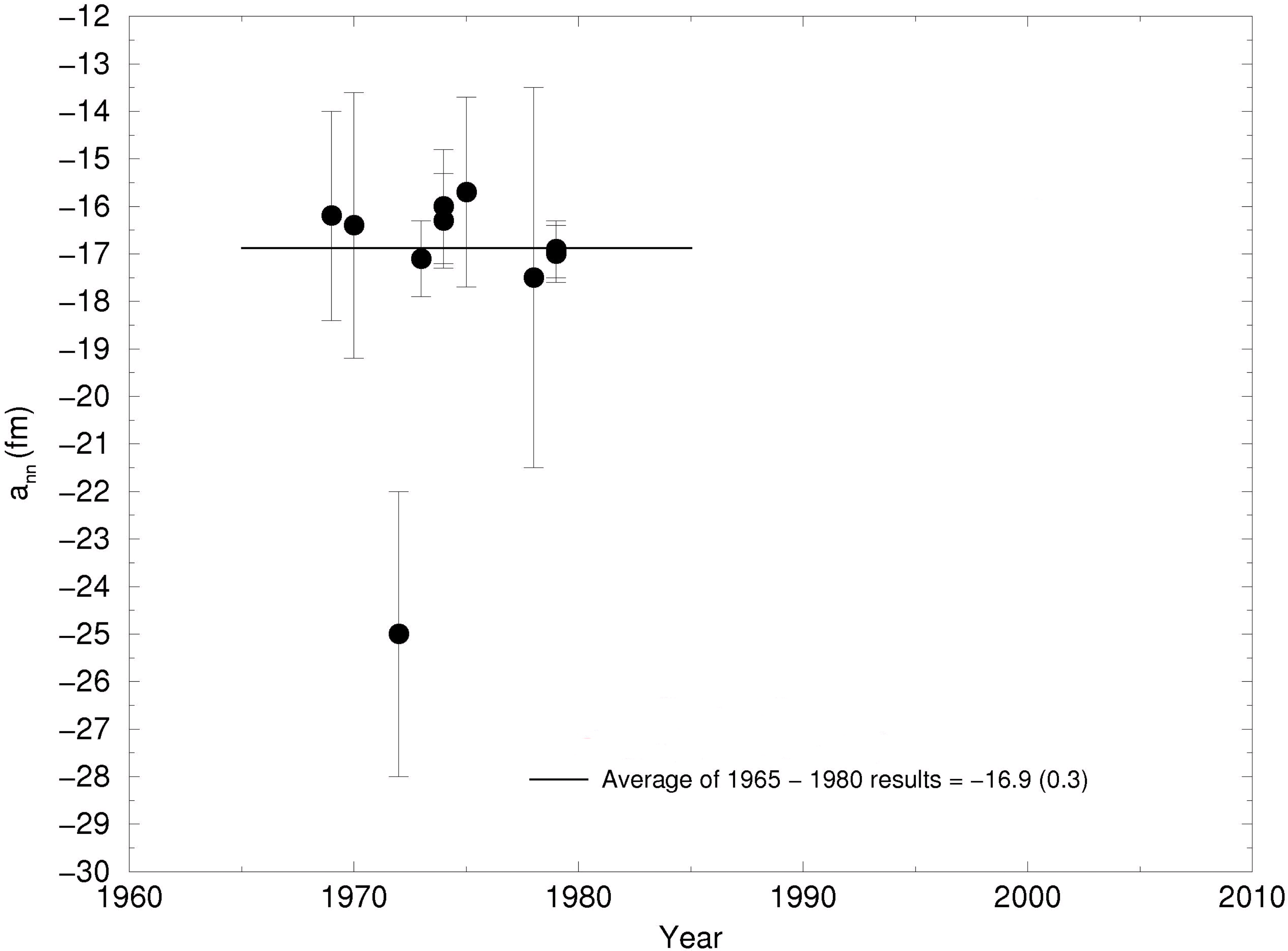
$$\sigma_s = 4\pi a_{nn}^2$$

$$\sigma_{nn} = \pi a_{nn}^2$$

$$\frac{\Delta a}{a} = \frac{1}{2}\frac{\Delta\sigma}{\sigma}$$

$$\frac{\Delta\sigma}{\sigma} = 2\frac{\Delta a}{a} = 2\left(\frac{0.5}{18}\right) = 0.055$$

Results from Kinematically Complete nd Breakup Measurements



Determinations of the $^1S_0$ a_{nn} Using $\pi^- + d \rightarrow n + n + \gamma$

$\pi^- + d \rightarrow n + n + \gamma$

$a_{nn} = -18.5 \pm 0.4 \pm 0.3$ fm C.R. Howell et al., Phys. Lett. B **444**, 252 (1998)

$a_{nn} = -18.6 \pm 0.4 \pm 0.3$ fm Q. Chen et al., Phys. Rev. C **77**, 054002 (2008)

$a_{nn} = -18.6 \pm 0.4 \pm 0.3$ fm B. Gabioud et al., Phys. Lett. B **103**, 9 (1981)

$a_{nn} = -18.7 \pm 0.6 \pm 0.3$ fm O. Schori et al., Phys. Rev. C **35**, 2252 (1987)

Average: $a_{nn} = -18.6 \pm 0.3 \pm 0.3$ fm

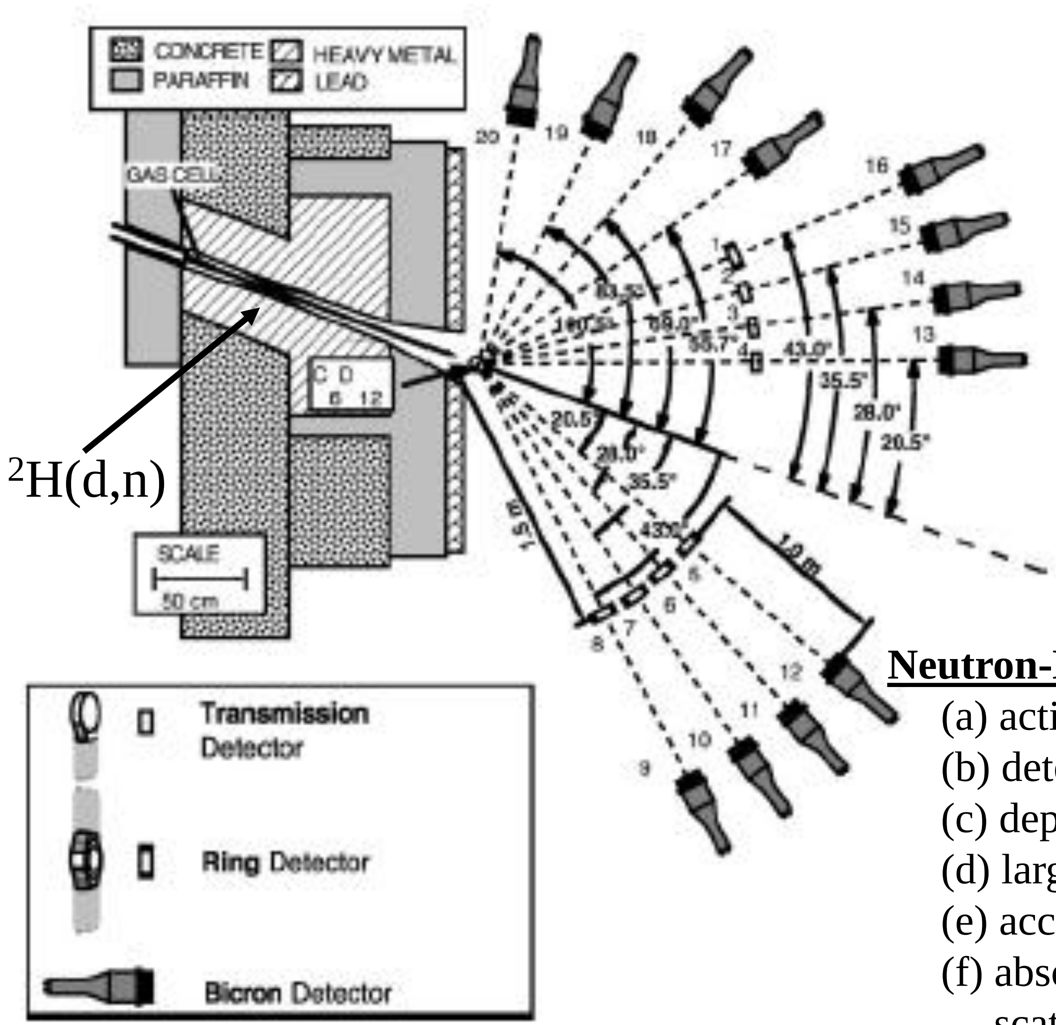
$$a_{nn}^N = -18.9 \pm 0.3 \pm 0.3\, fm$$ (corrected for MMI)

Investigation of reducing theoretical error
A. Gardestig and D.R. Phillips, Phys. Rev. C 73, 014002 (2006)

Constrains value of a_{nn} with EFT:
J. Kirscher and D.R. Phillips, arXiv;nucl-th, 1106.3171v1

$$\Delta a_{CSB} = \left| a_{nn}^N - a_{pp}^N \right| = \left| -18.9\, fm + 17.3\, fm \right| = 1.6 \pm 0.5\, fm$$

Recent Determination of the $^1S_0$ a_{nn} at TUNL



nn coincidence technique

$E_n = 13.0$ MeV

Neutron-Neutron Coincidence Technique

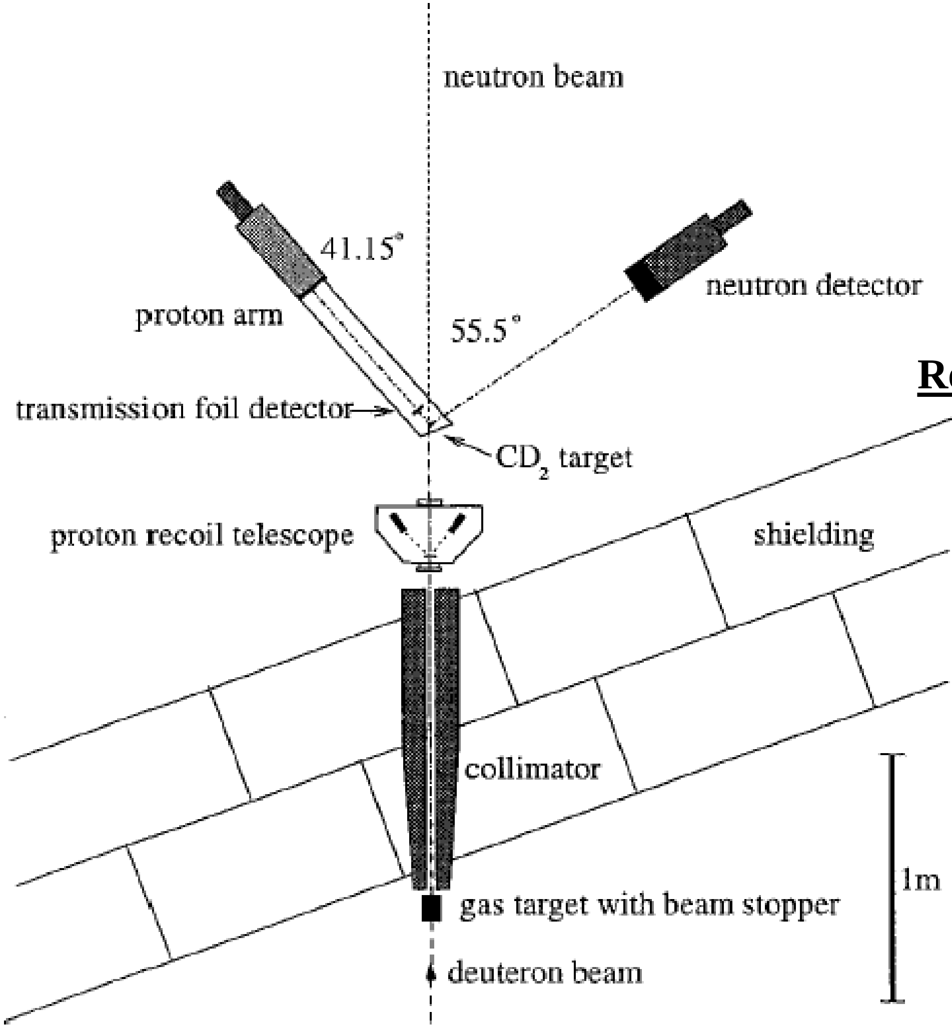
(a) active target (C6D12)
(b) detection of both FSI neutrons
(c) depends on efficiency of two neutron detectors
(d) large neutron attenuation corrections
(e) account for finite geometry effects
(f) absolute cross section normalized to nd elastic scattering

$a_{nn} = -18.7 \pm 0.7$ fm D.E. Gonzalez Trotter et al., Phys. Rev. Lett. **83**, 3788 (1999)
D.E. Gonzalez Trotter et al., Phys. Rev. C **73**, 034001 (2006)

A Warning

Nice value of a_{nn} you got there. It’ll be a real shame if something bad would happen to it.

Recoil Setup at University of Bonn



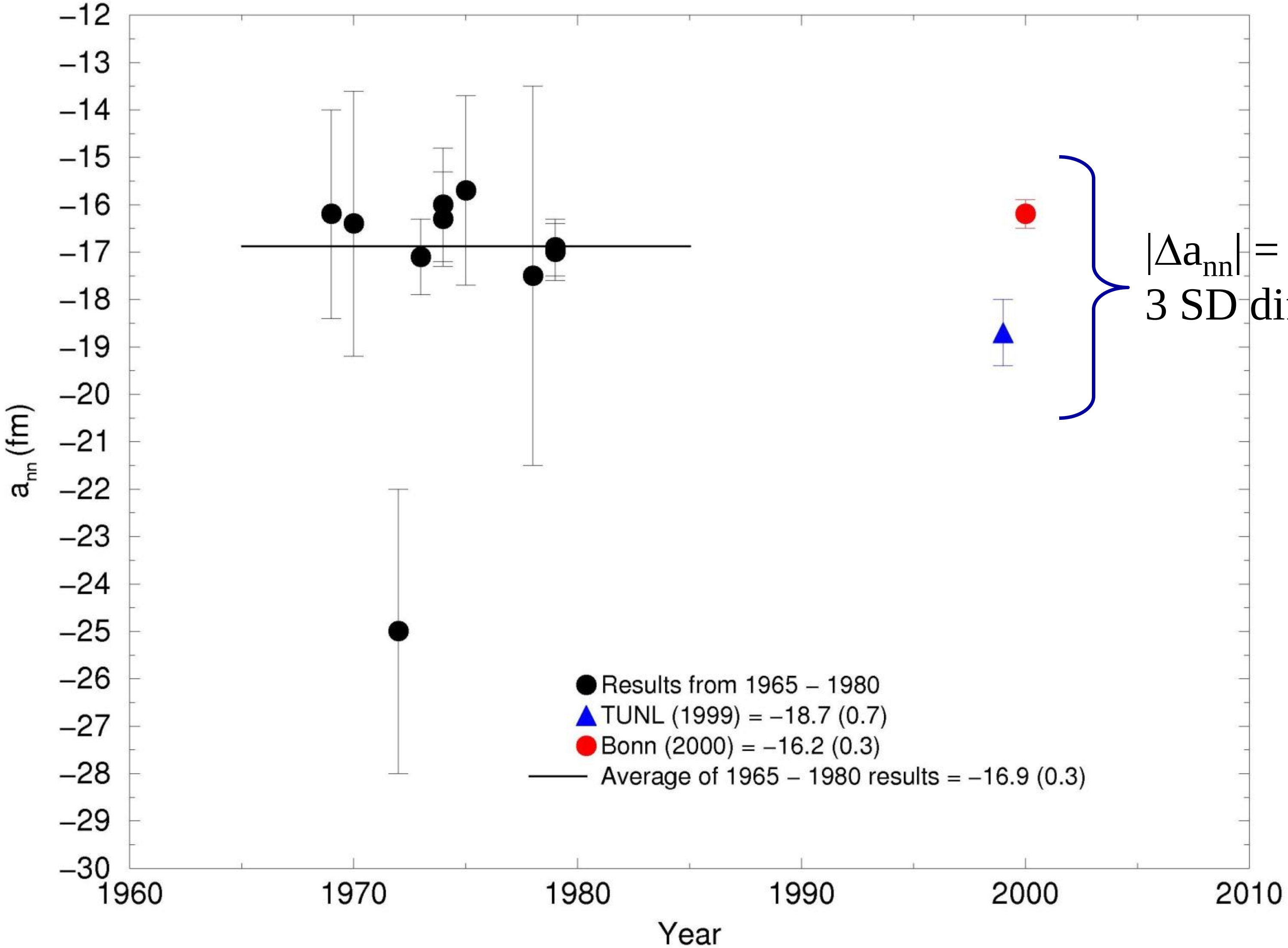
$E_n = 25.3$ MeV

Recoil Geometry Technique

(a) thin target (CD2)
(b) detect one FSI neutron with recoil proton
(c) depends on efficiency of only one neutron detector
(d) modest neutron attenuation corrections
(e) account for finite geometry effects

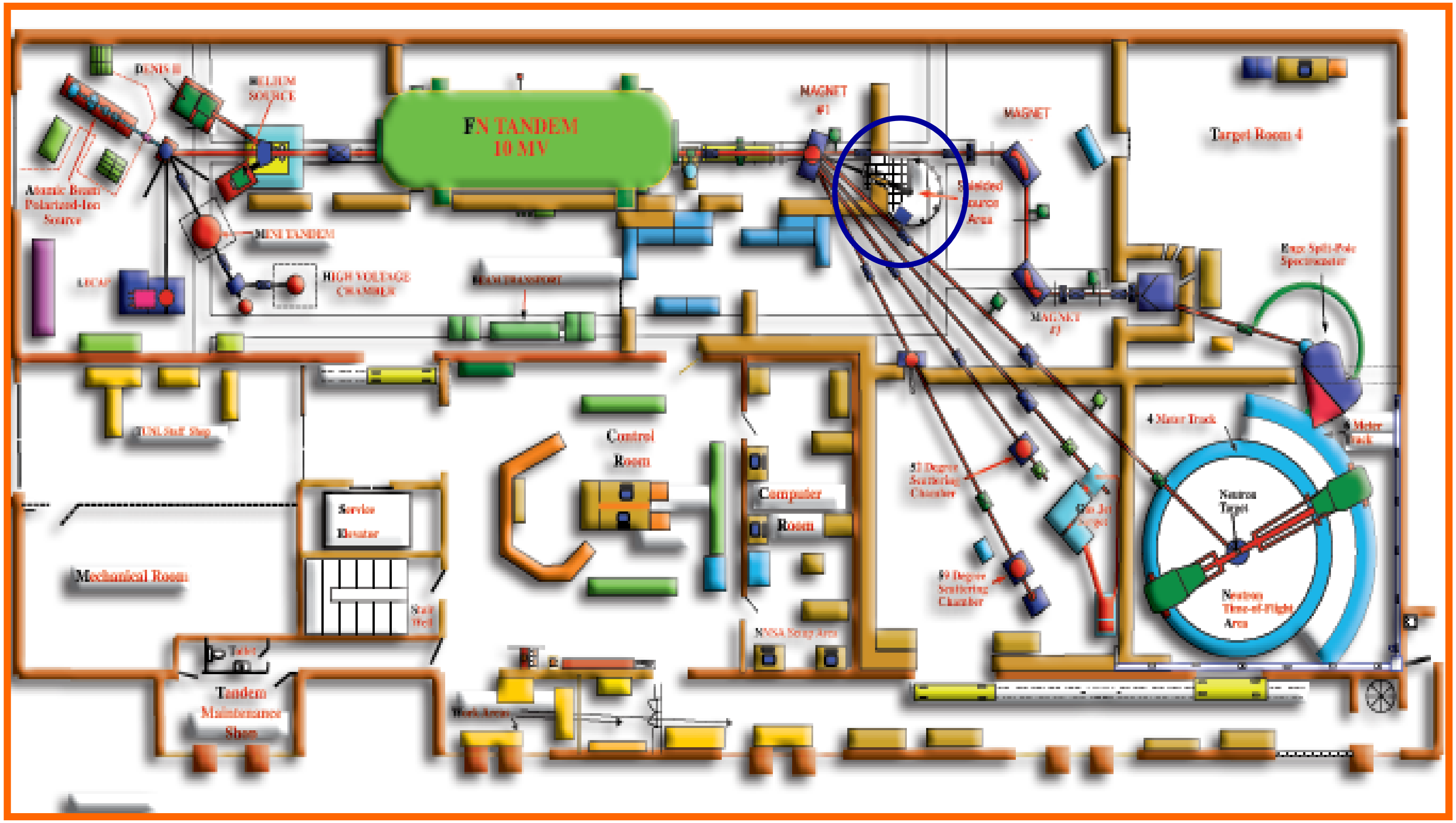
$a_{nn} = -16.2 \pm 0.4$ fm, V. Huhn et al., Phys. Rev. C 63, 014003-1 (2000)

Results from Kinematically Complete nd Breakup Measurements



$|\Delta a_{nn}| = 2.5 \pm 0.8$ fm
3 SD difference

Experiments Carried in the Tandem Laboratory



Experimental Setup for Recent nd Breakup Experiments at TUNL

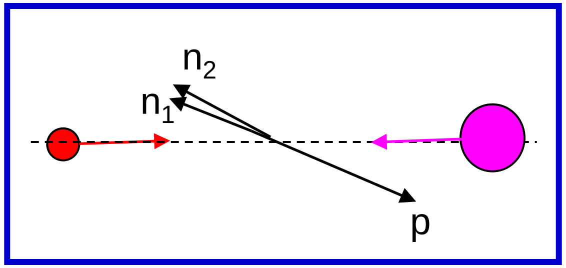
Cross-section Measurements:

- nn FSI to determine $^1S_0$ nn scattering length
- two star configurations (space and co-planar)

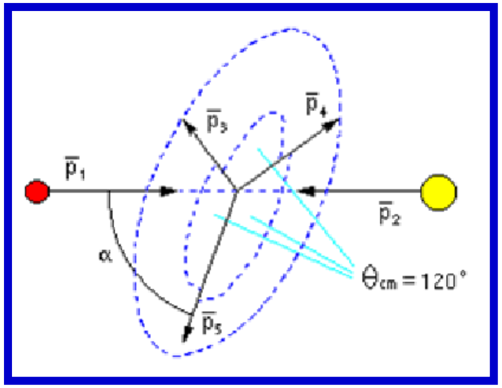
Both experiments use the same technique:

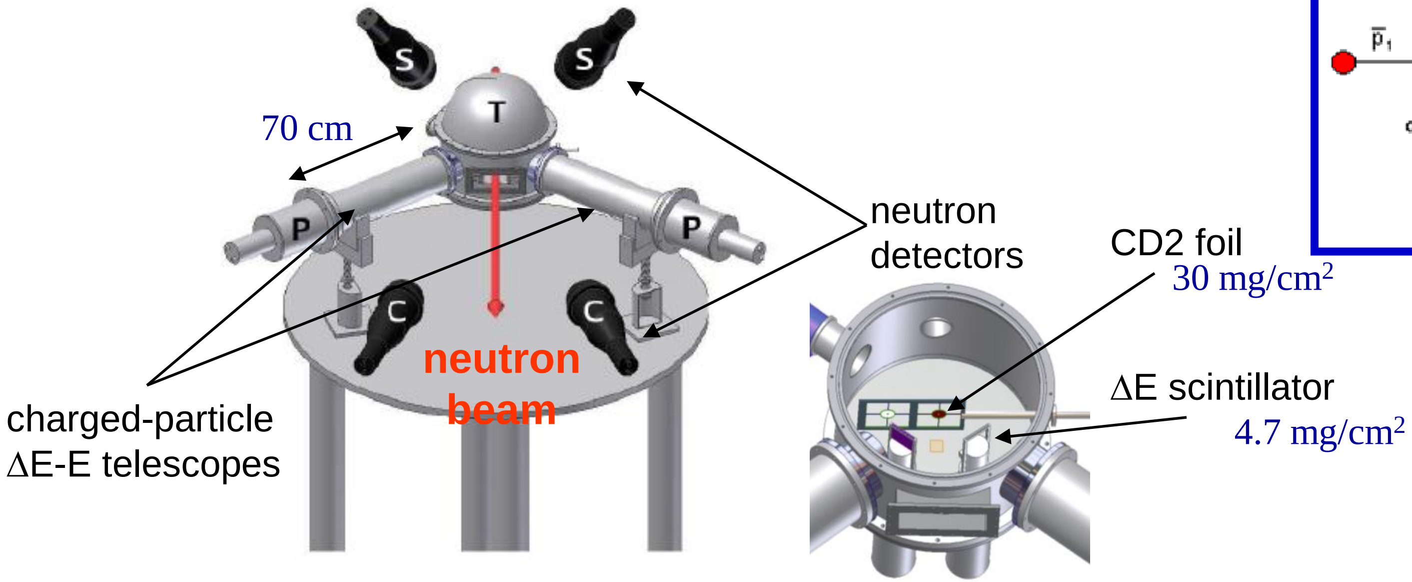
- neutron source: $^2H(d,n)$ reaction
- thin CD_2 foil target
- detection of proton in coincidence with one neutron
- normalization using concurrent nd elastic scattering

nn FSI

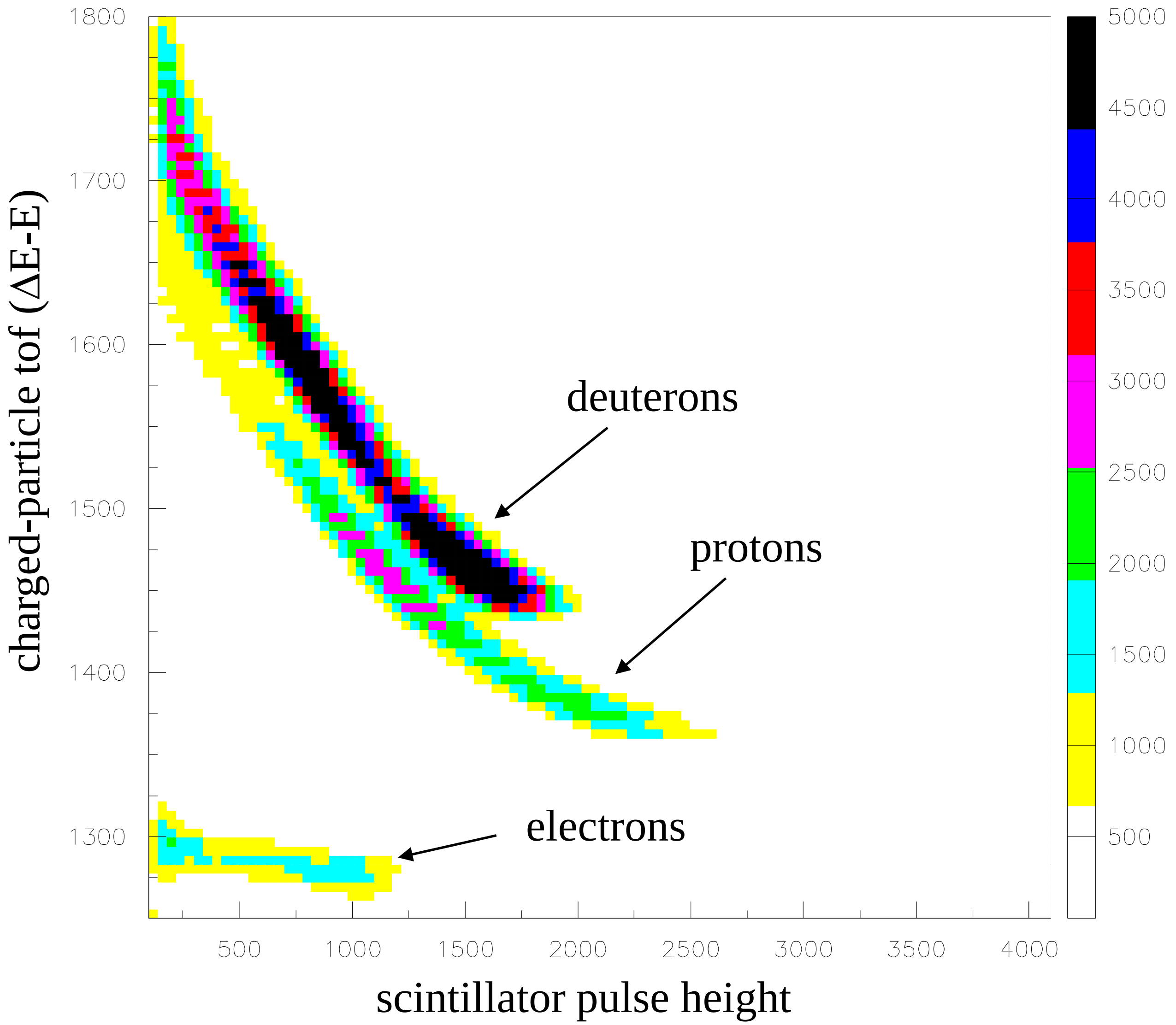


star

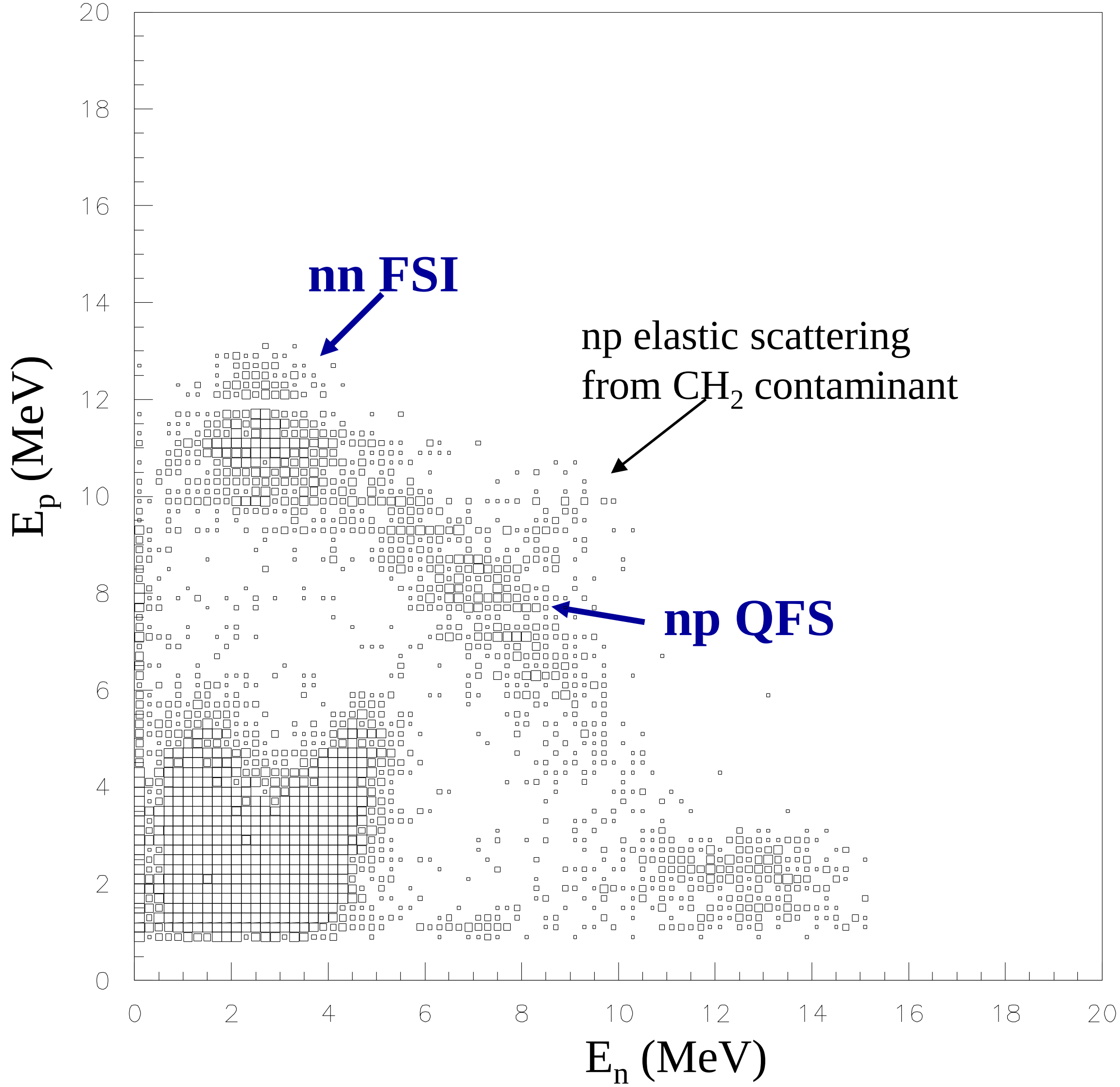




Charged-particle ID with PH-vs-TOF



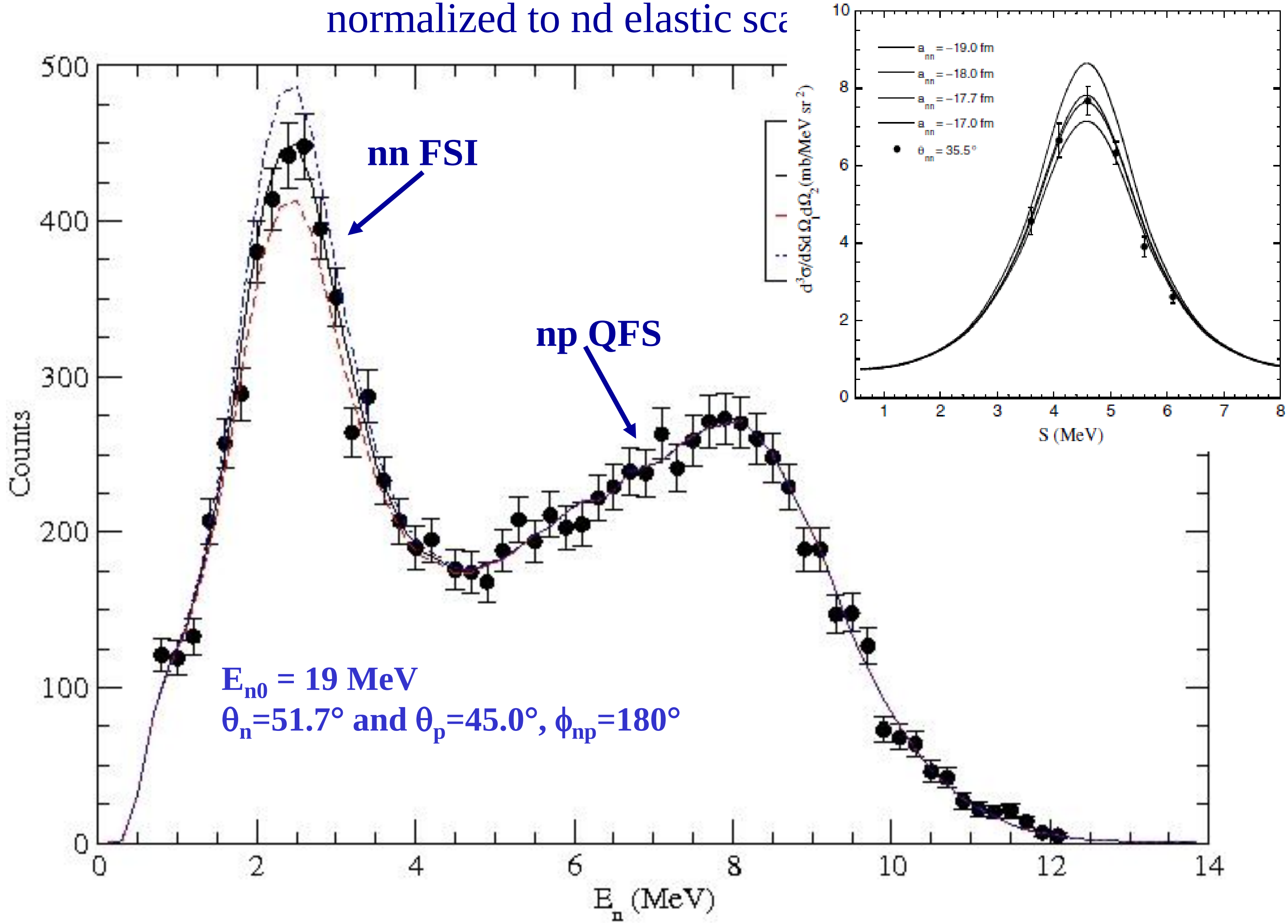
nn FSI: E_{n0} = 19 MeV
θ_n=51.7° and θ_p=45.0°, ϕ_{np}=180°



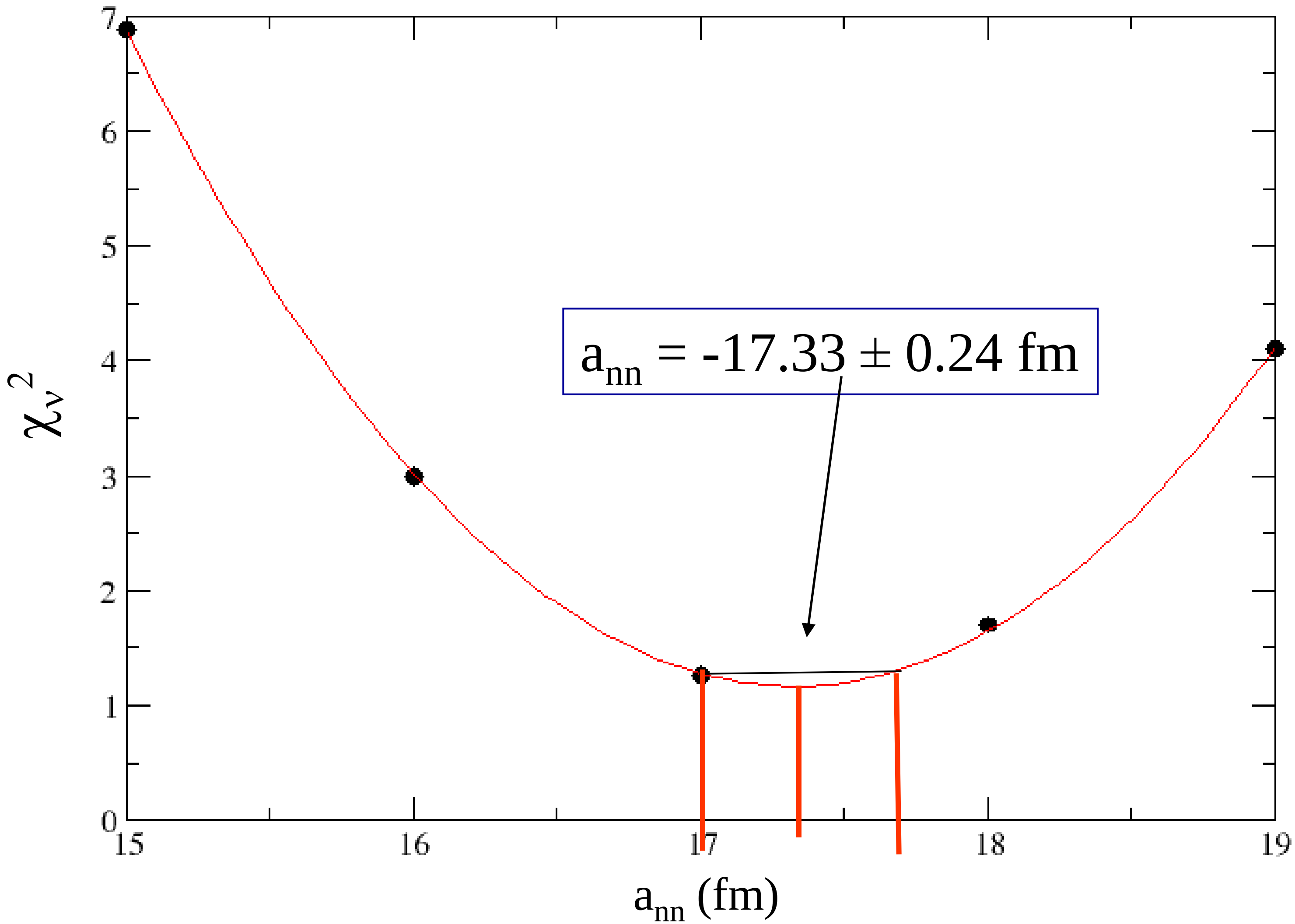
E_n Spectrum

normalized to nd elastic sca

nn coincidence technique (En = 13 MeV)
Gonzalez Trotter et al (TUNL 1999)



Analysis



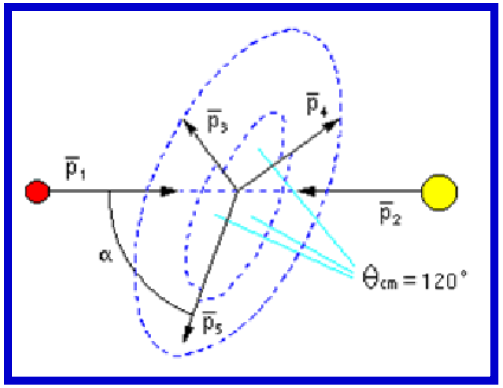
Summary of Systematic Errors

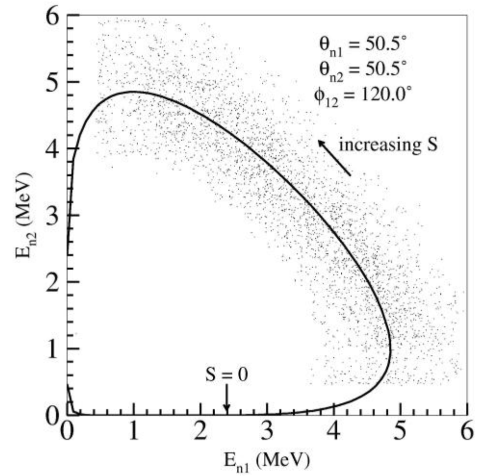
Description	**Uncertainty**	**Δa_{nn} (fm)**
Neutron detector efficiency	±2.0%	±0.36
nd elastic scattering cross section	±1.5%	±0.27
nd elastic yields	±0.5%	±0.09
Neutron detector solid angle	±1.0%	±0.18
Proton detector solid angle	±0.8%	±0.15
ΔE_n (bin width)	±2 keV	±0.18
Δl_n (n-detector position error)	±3 mm	±0.09
$\Delta\theta_p$ (proton angle alignment error)	0.06°	±0.10
Total uncertainty		**±0.56**

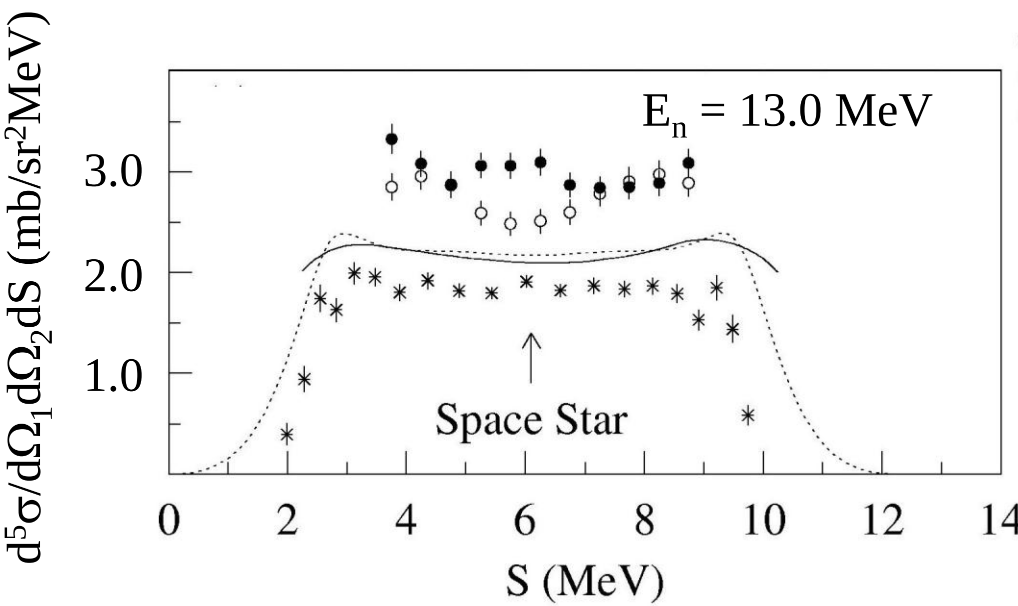
Results

a_{nn} = -17.3 ± 0.2 (stat) ± 0.6 (syst) *fm* ***present work***
a_{nn} = -16.2 ± 0.3 (stat) ± 0.3 (syst) *fm* ***Huhn et al. (2000)***
a_{nn} = -18.7 ± 0.1 (stat) ± 0.7 (syst) *fm* ***Gonzalez Trotter et al. (2006)***

The Space Star Anomaly
n +d → n + n + p

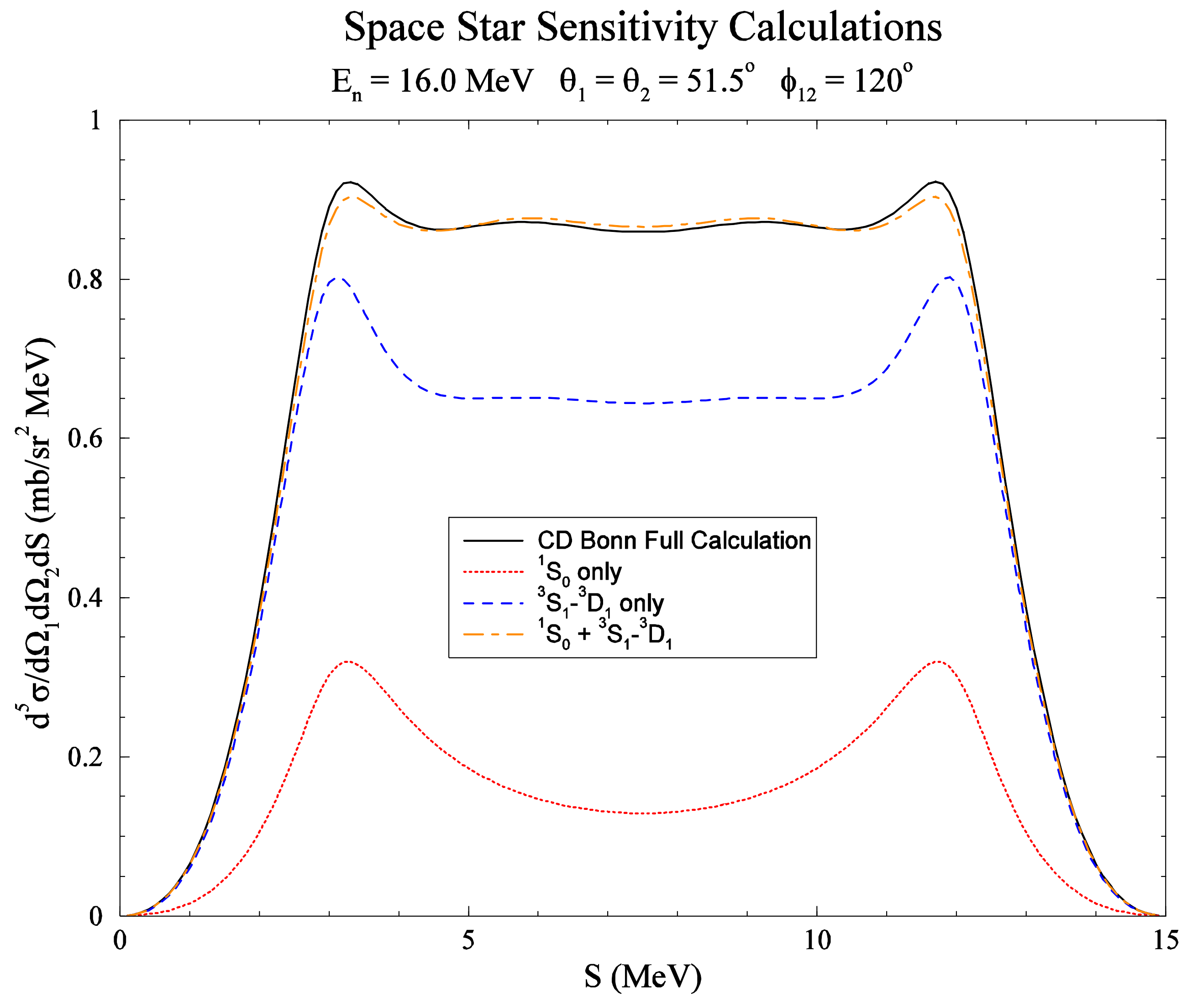




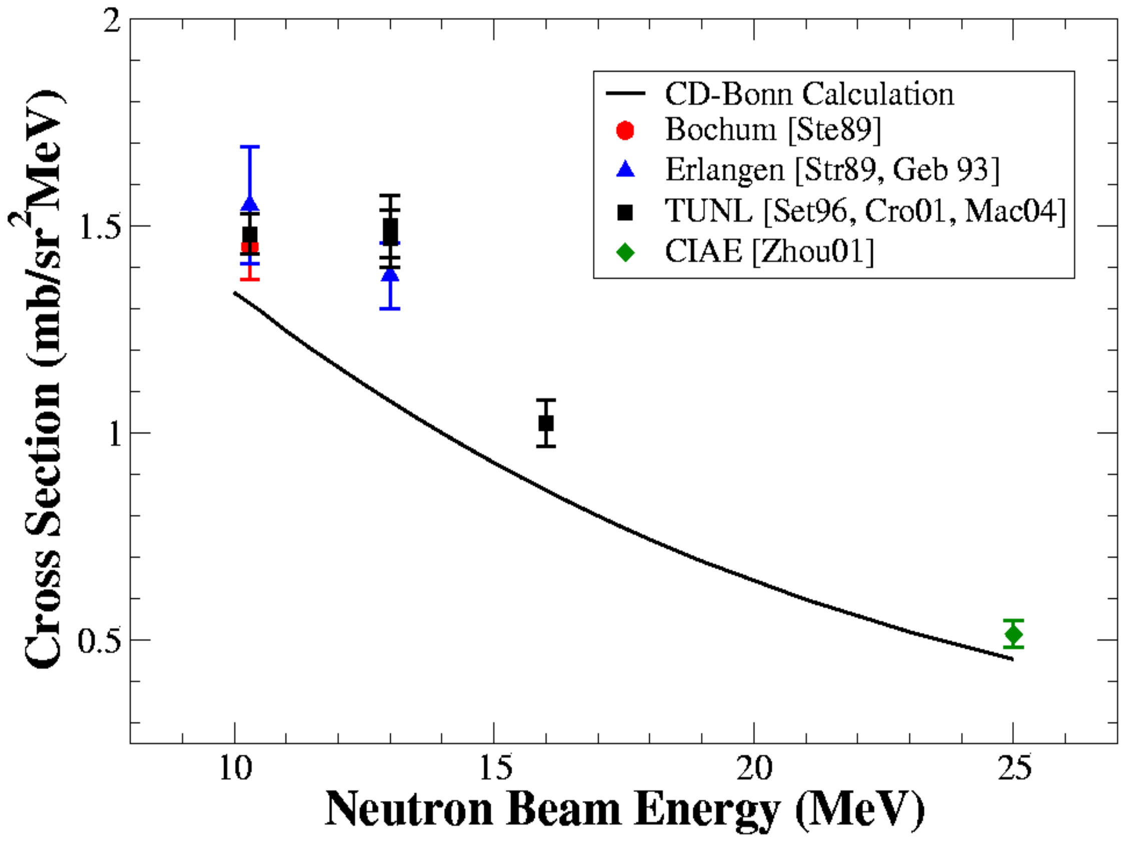


- ● nd data, TUNL 1996
- ○ nd data, Erlangen Univ. 1988
- ✳ pd data, Univ. Cologne 1991

The Space Star: NN interaction sensitivity



Previous Space-Star Measurements



New Space and Coplanar Star Measurements

E_{n0} = 16.0 and 19.0 MeV

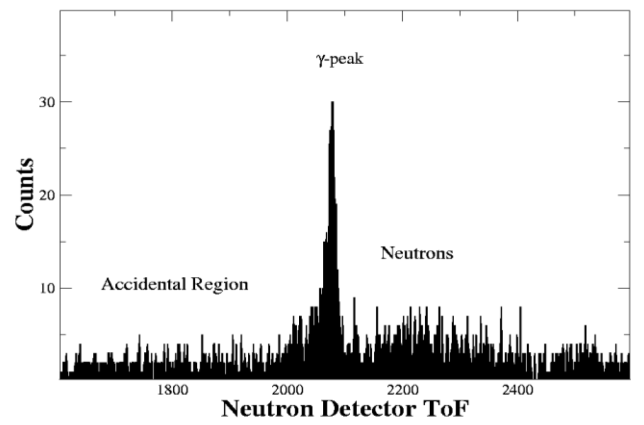
Space Star:

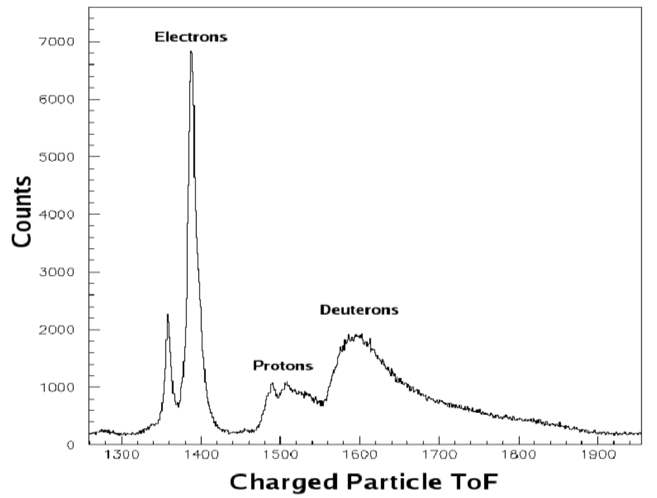
$\theta_n = 52.0°$, $\theta_p = 52.0°$ and $\phi_{np} = 120°$

Coplanar Star:

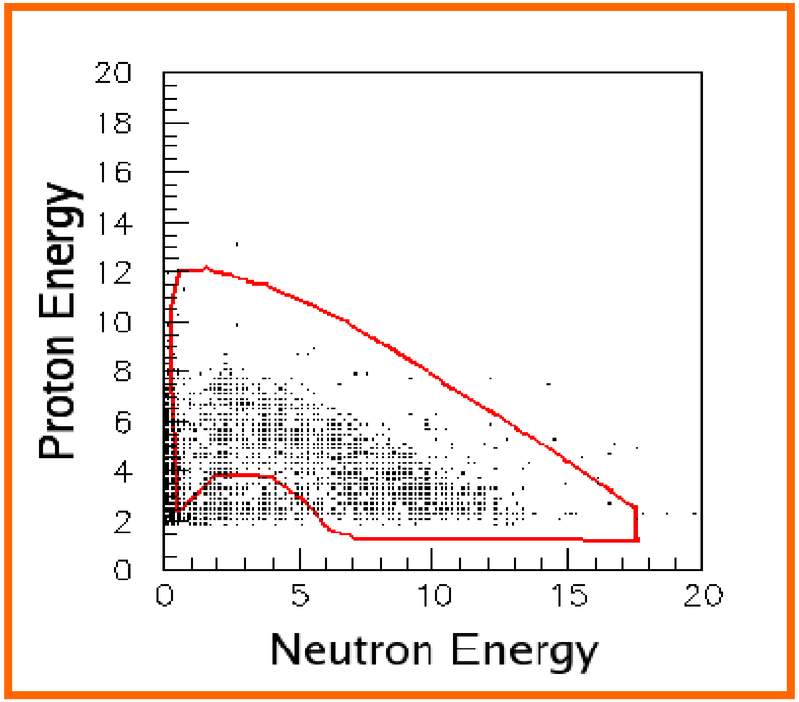
$\theta_n = 18.5°$, $\theta_p = 52.0°$ and $\phi_{np} = 180°$

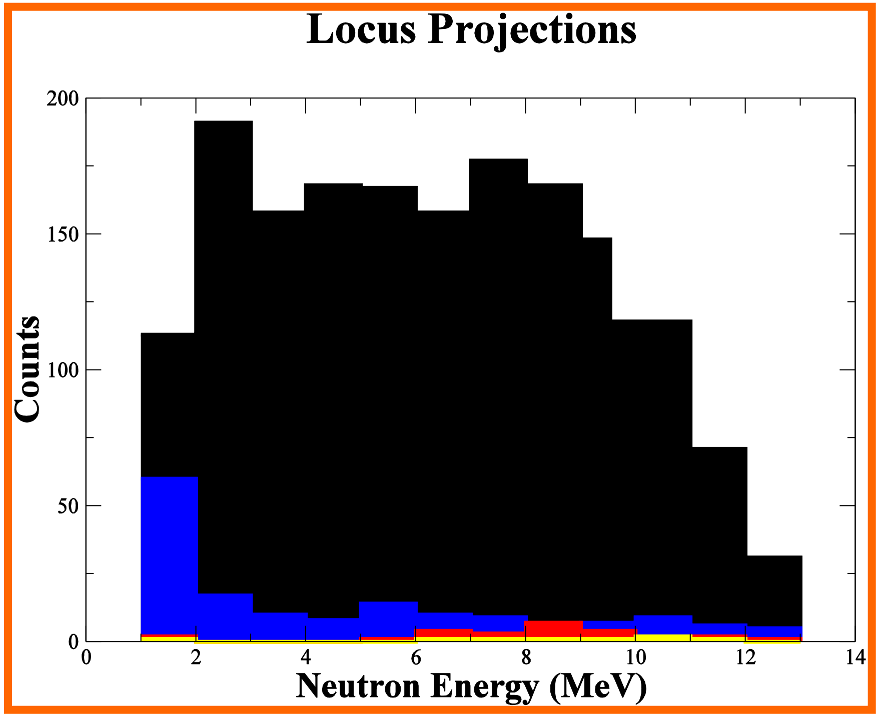
- Neutron and proton energies were determined by ToF.
- The ΔE detector was used as TDC start.
- Timing spectra were calibrated to *np* and *nd* elastic scattering.





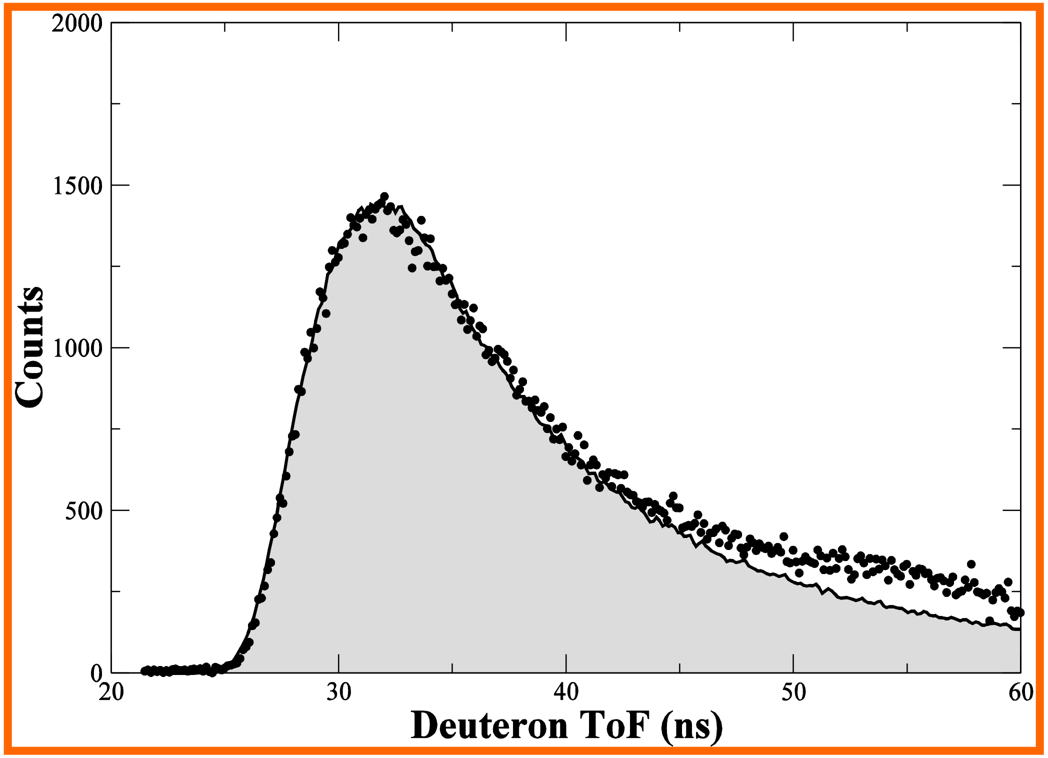
Measured Particle Energy Spectra for the Space Star Configuration





nd Elastic Scattering Normalization

Deuteron ToF Spectrum



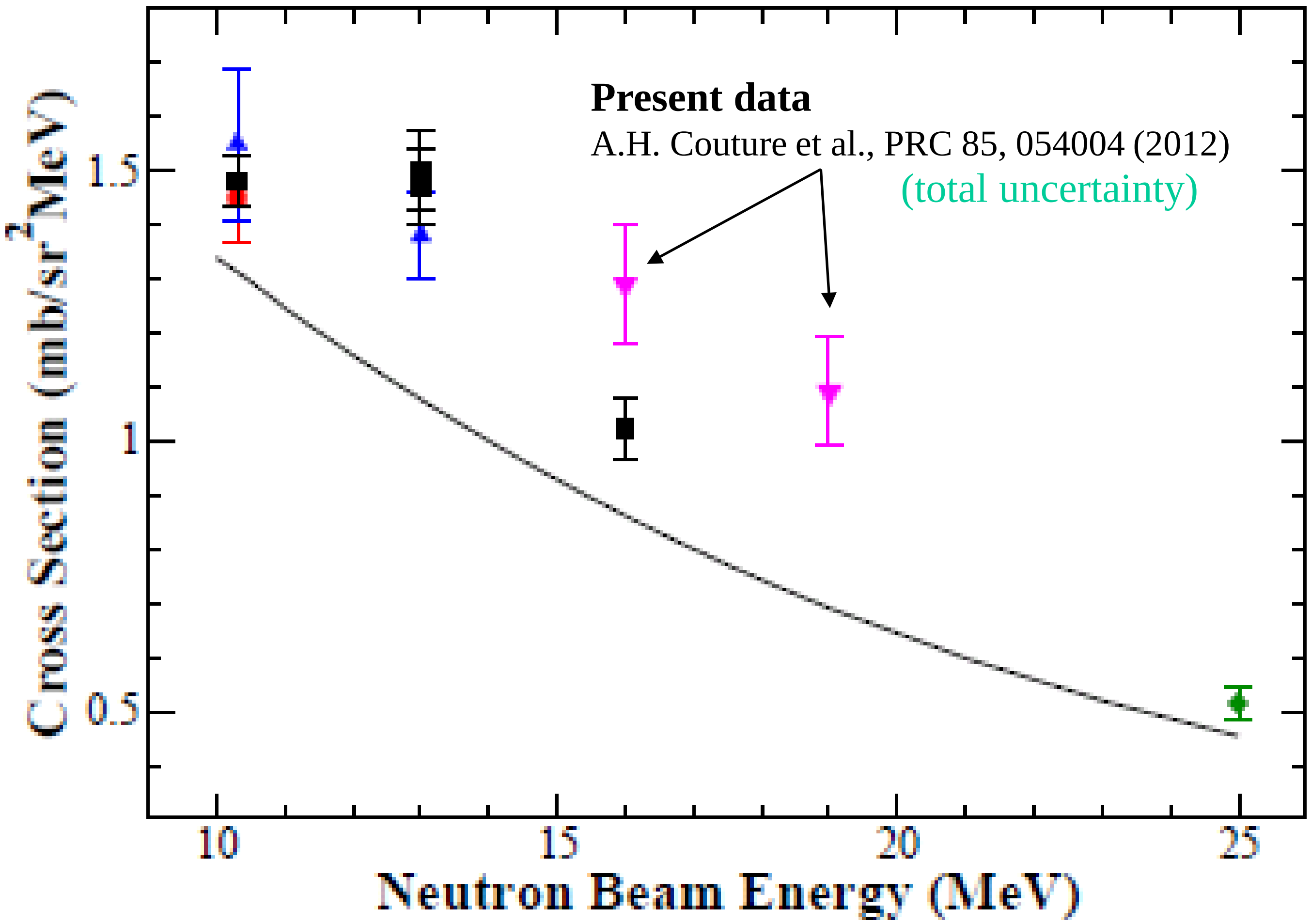
Excellent agreement between Monte Carlo and data for high energy deuterons. ($\chi^2 \approx 1$)

Systematic Uncertainties
E_{n0} = 16.0 MeV

Source of Uncertainty	Estimated Uncertainty
Elastic Normalization	±4.0%
Background Subtraction	±2.0%
Solid Angle	±0.3%
Detector Efficiency	±3.2%
Neutron Attenuation	±1.0%
Energy Binning	±1.0%
Total (SST)	±5.7%
Total (CST)	±5.7%

$$\left(\frac{\Delta Y_{ndbu}}{Y_{ndbu}}\right)_{sys} = \left[\left(\frac{\Delta Y_{nde}}{Y_{nde}}\right)^2 + \left(\frac{\Delta Y_{SBU}}{Y_{SBU}}\right)^2 + \left(\frac{\Delta \Omega_n}{\Omega_n}\right)^2 + \left(\frac{\Delta \varepsilon_n}{\varepsilon_n}\right)^2 + \left(\frac{\Delta \alpha_n}{\alpha_n}\right)^2 + \left(\frac{\Delta E_n}{E_n}\right)^2\right]^{\frac{1}{2}}$$

Results



Present data
A.H. Couture et al., PRC 85, 054004 (2012)
(total uncertainty)
Cross Section (mb/sr^{2}MeV)
1.5
1
0.5
10
15
20
25
Neutron Beam Energy (MeV)

Findings and Conclusions

- Measured $^1S_0$ using nd breakup n-p coincidence technique

  a_{nn} = -18.7 ± 0.1 (stat) ± 0.7 (syst) *fm* ***TUNL (1999, 2006)***

  a_{nn} = -17.3 ± 0.2 (stat) ± 0.6 (syst) *fm* ***present work***

  a_{nn} = -16.2 ± 0.3 (stat) ± 0.3 (syst) *fm* ***Bonn (2000)***

- This new a_{nn} value suggests an energy and geometry dependence in a_{nn} from nd breakup ➔ The effective $^1S_0$ interaction in the nd system differs from potenial models.
- Measured cross sections for the space and co-planar star configurations in nd breakup at 16 and 19 MeV using the n-p coincidence technique.
- The new space-star cross-section data are about 35% larger than theory and the co-planar star data are about 35% below theory.

What's next?

- Measured $^1S_0$ using nd breakup n-p coincidence technique
  - $a_{nn} = -18.7 \pm 0.1$ (stat) ± 0.7 (syst) *fm* ***TUNL (1999, 2006)***
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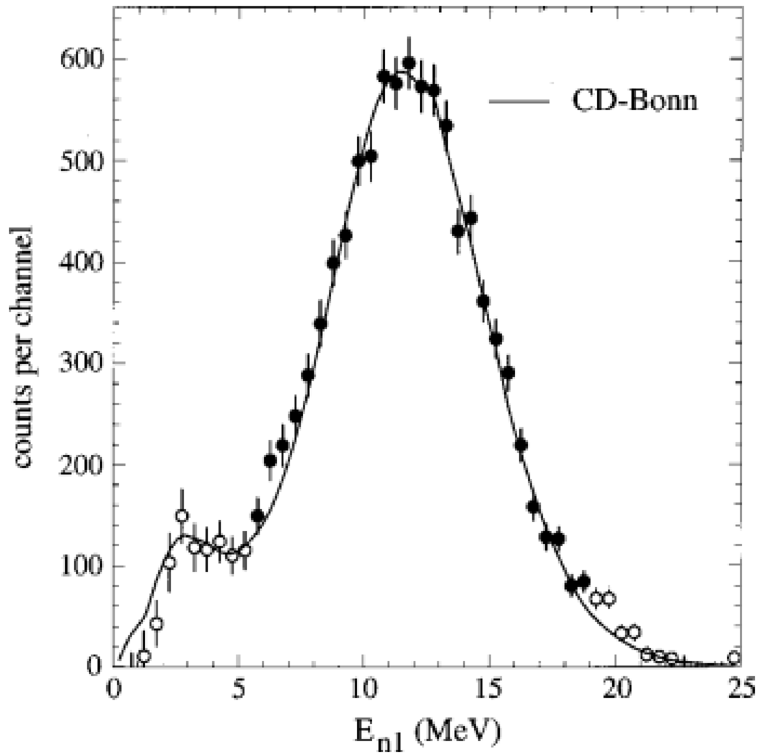
1. QFS

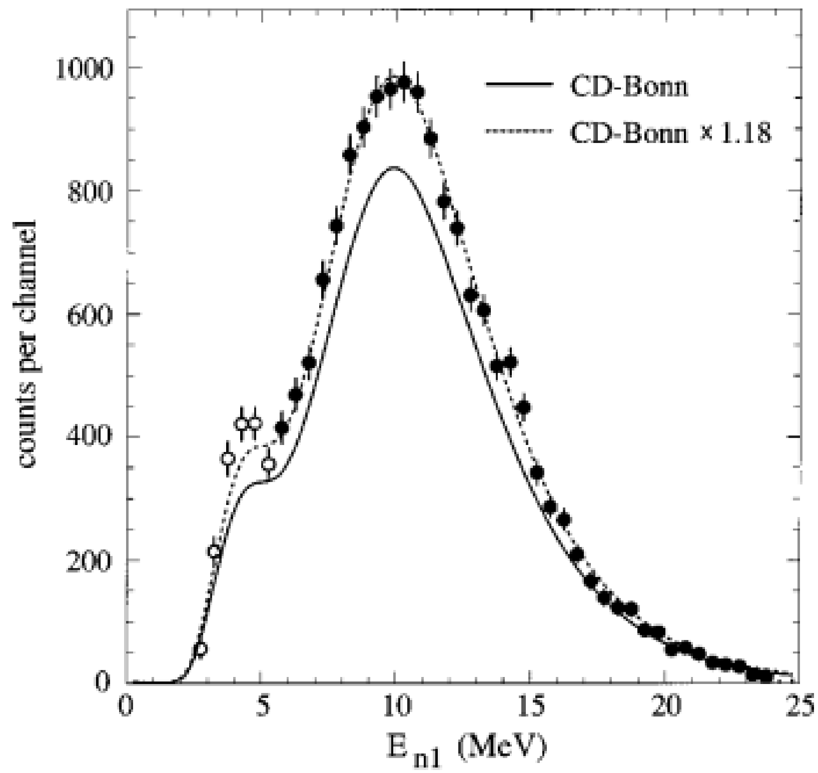
W. von Witsch *et al*. (Bonn)

^{2}H(n,np)n @ E_n=26 MeV

np QFS

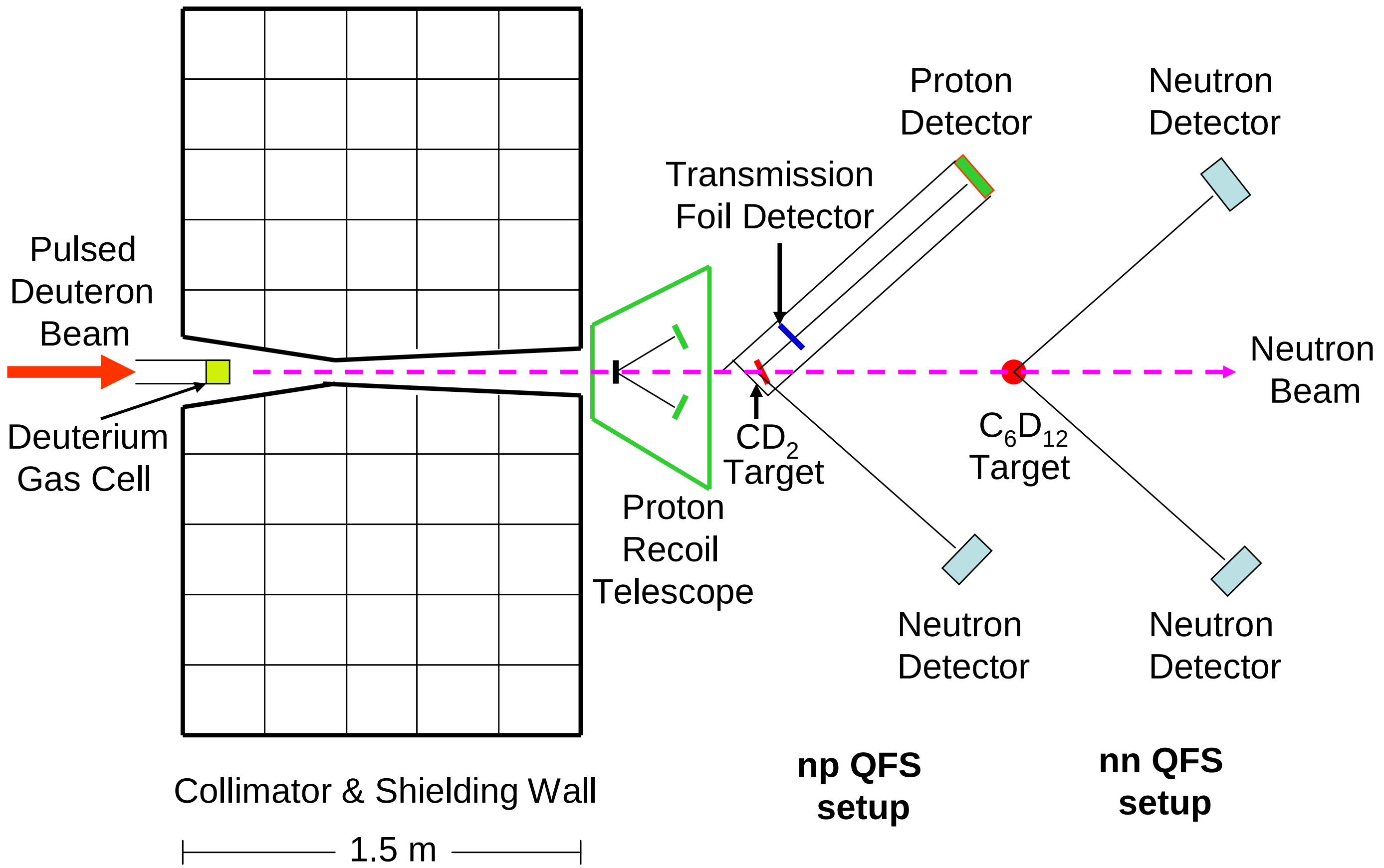


nn-QFS

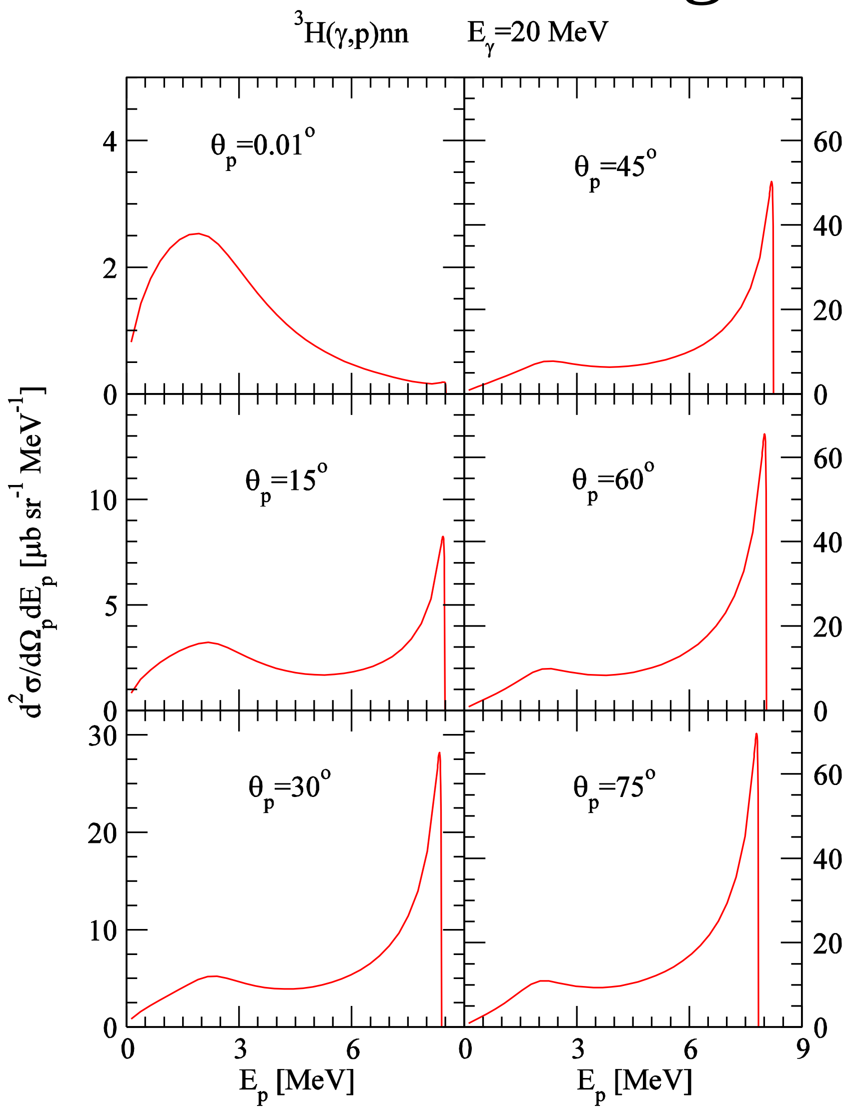


^{2}H(n,nn)p

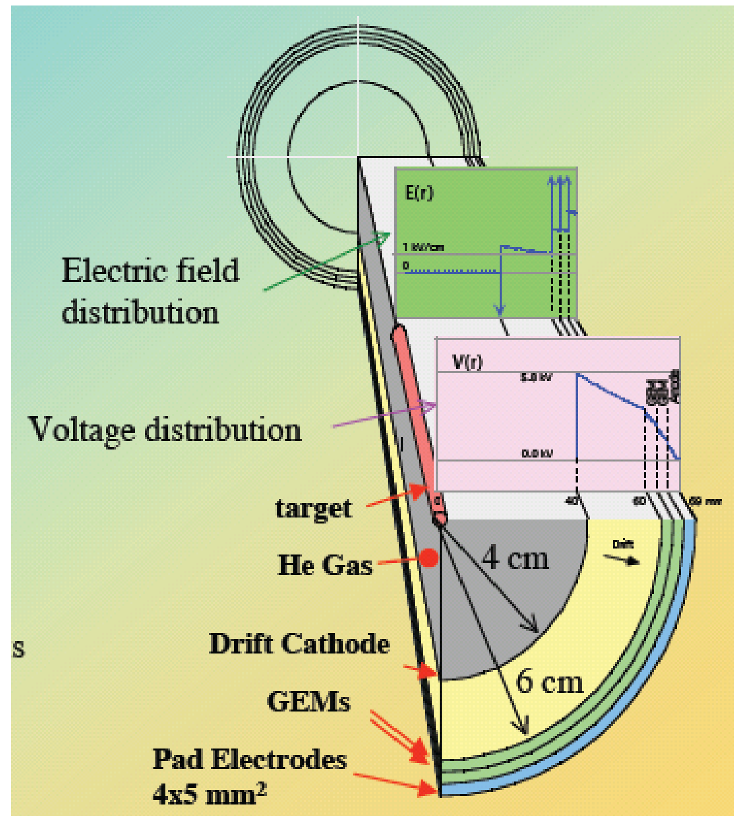
Proposed experimental setup



Photodisintegration of ^{3}He and ^{3}H



At HIγS with Radial Time Projection Chamber



Developing proposal for submission to the 2012 HIγS PAC

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