Measuring Precise Absolute np Scattering Cross Sections at Intermediate Energies

S.E. Vigdor, Indiana University

1) Why a new np scattering experiment?
2) Approach to minimize systematic errors
3) Tagged neutron facility at IUCF Cooler
4) Experiment details
5) Results (M. Sarsour, et al., PRL 94, 082303 (2005); PRC paper in preparation)
6) Conclusions

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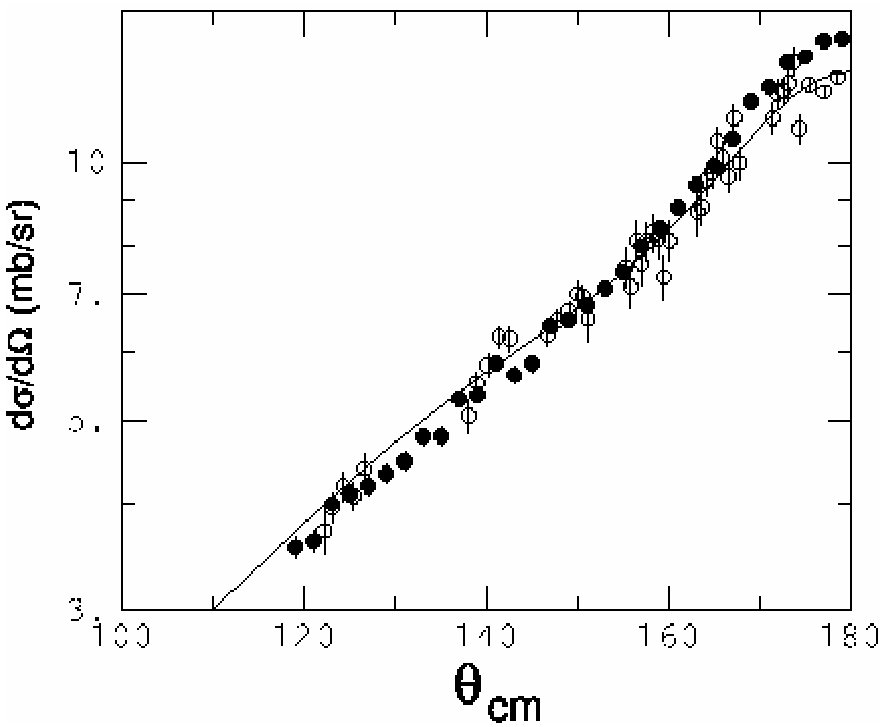
Development of a tagged neutron facility at intermediate energies

Indiana U.-Ohio U.- Uppsala Collaboration

T. Peterson[a,1], S.E. Vigdor[a,*], C. Allgower[a], B. Bergenwall[b], L.C. Bland[a], J. Blomgren[b], J. Doskow[a], T. Hossbach[a], W.W. Jacobs[a], C. Johansson[b], T. Kinashi[a], J. Klug[b], A.V. Klyachko[a], P. Nadel-Turonski[b], L. Nilsson[b], N. Olsson[b], M. Planinic[a,2], S. Pomp[b], J. Rapaport[c], T. Rinckel[a], E.J. Stephenson[a], U. Tippawan[b], S.W. Wissink[a], Y. Zhou[a]

ECT* Workshop on Nuclear Forces and QCD, Trento, 6/21/05

Who Needs Another np Scattering Experiment?



o B.E. Bonner *et al.*, Phys. Rev. Lett. **41**,1200(1978).
• T.E.O. Ericson *et al.*, Phys. Rev. Lett. **75**, 1046(1995).
— V. Stoks *et al.*, Phys Rev. C**48**, 792(1993).

Strong disagreements in shape among different medium-energy exp'ts

Few reliable absolute cross section standards at medium energies ⇒ normalization uncertain & inbred

Partial-wave analyses ignore most of the data! Allow normalizations to float by typically 5-10%

Uncertain back-angle $d\sigma/d\Omega$ have been used to extract controversial constraints on πNN coupling constant

"Vigorous" debate in literature and at conferences

de Swart & Timmermans propose angle-dependent renormalization to "salvage" data inconsistent with PWA – YIKES!

Need experimental resolution of experimental discrepancies!

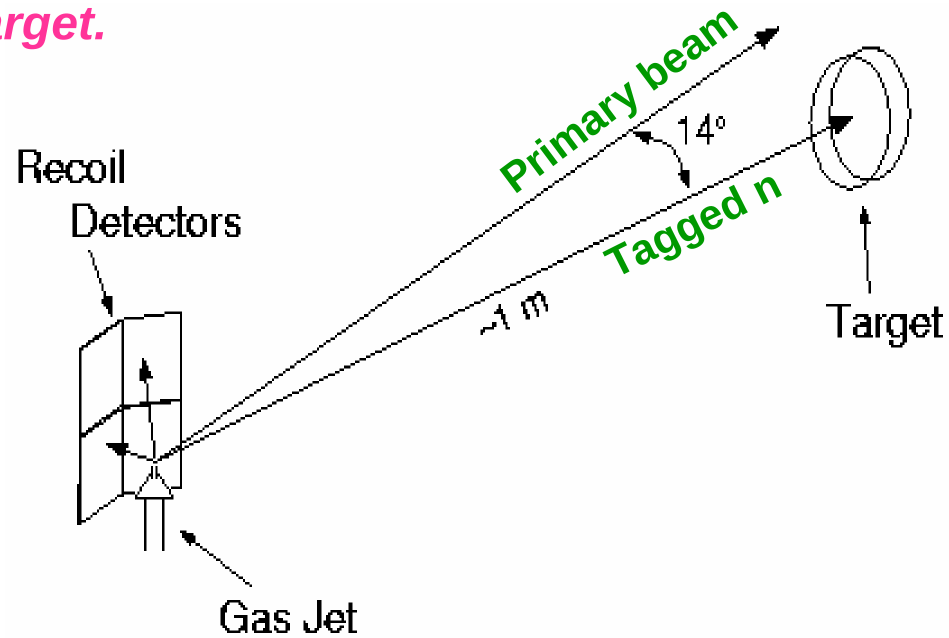
New Experiment, New Approach:

Tag production of neutron by detection of associated recoil particles from $^2H(p,n)2p \Rightarrow$ count n flux on scattering target!

Enable detection of low-energy recoils, while maintaining reasonable luminosity, by use of stored, cooled proton beam on ultra-thin (gas jet) production target.

Use large-acceptance secondary detector array to measure np scattering over broad angle range simultaneously.

Use carefully matched solid CH_2 and C secondary targets, with frequent swapping, to permit accurate subtraction of quasifree background, minimize reliance on kinematic cuts.

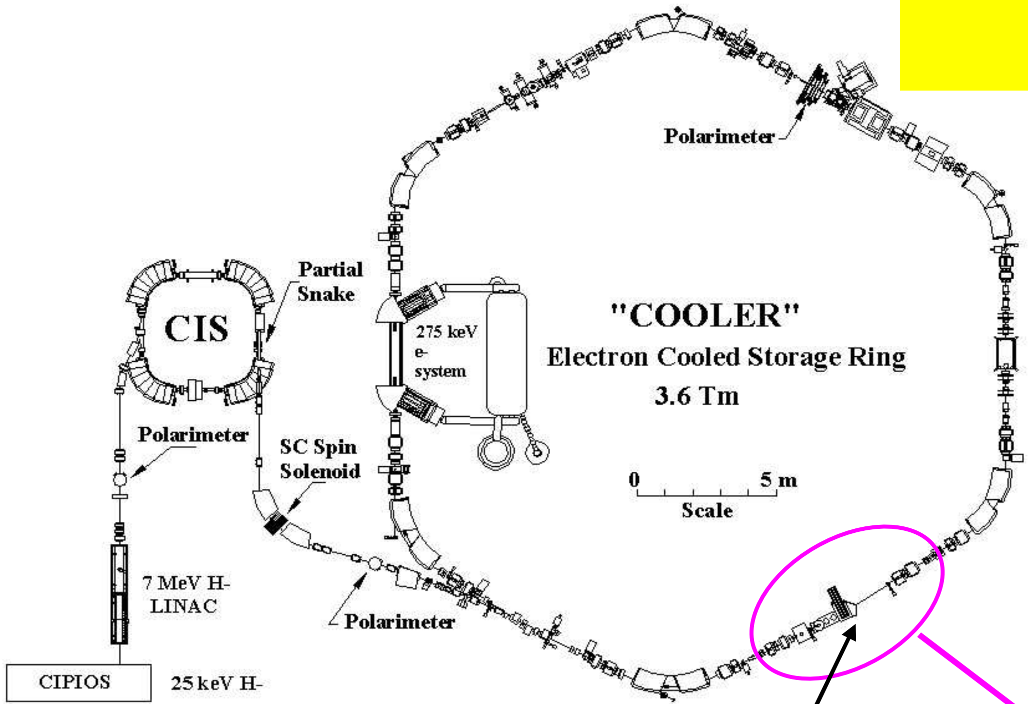


Measure acceptance of secondary detectors by proton tracking.

Build multiple internal cross-checks into data analysis procedures.

$\Rightarrow$ Kinematically complete double-scattering exp't with 1st target of negligible thickness!

Tagged Neutron Facility

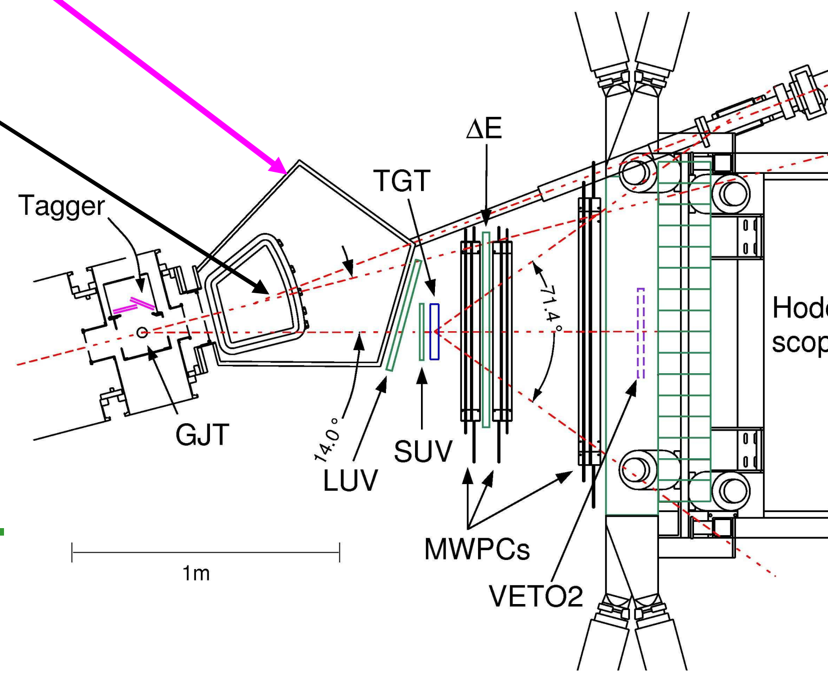


IUCF Cooler Parameters:

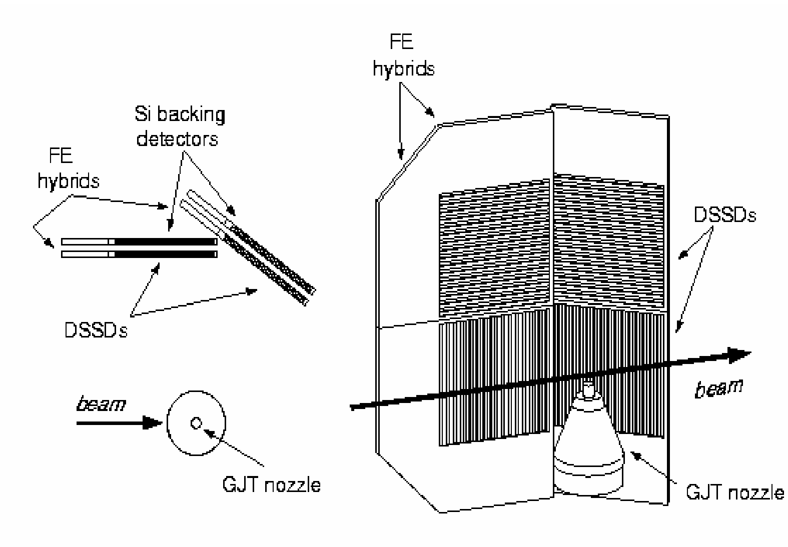
- Stored proton energy: 202.6 MeV
- Proton current: up to 2.0 mA
- "Coasting" (rf off) beam
- Time-averaged prod'n $\mathcal{L}$ ~1.0 × 10^{31} cm^{-2} s^{-1} on D_2 gas jet target
- Electron cooling ⇒ p beam with small energy spread, spot size, divergence

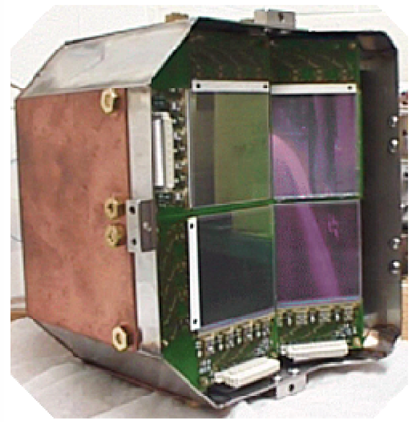
Tagged Neutron "Beam" Parameters:

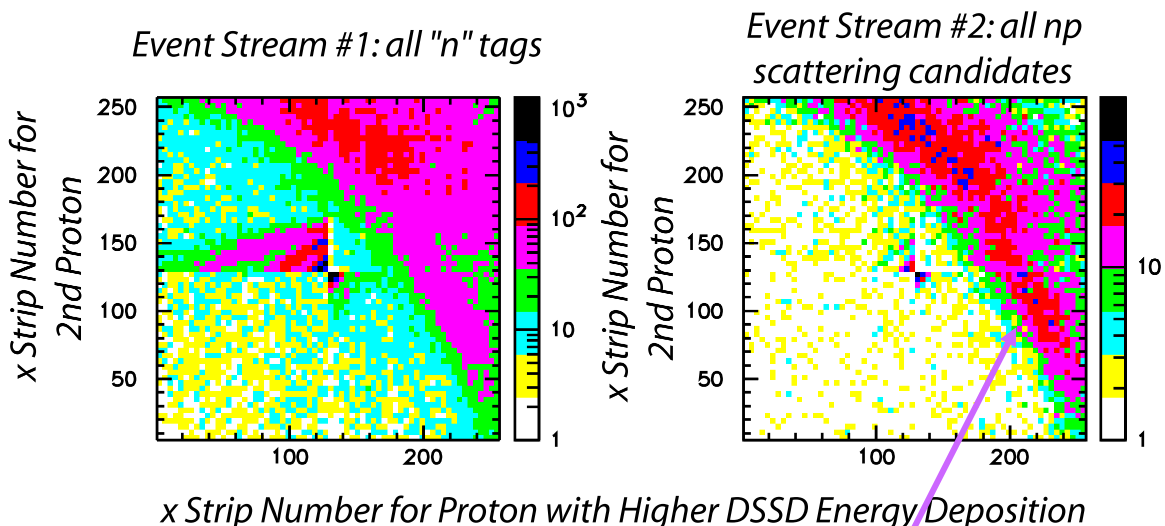
- Central Production angle = 14°.
- Angle acceptance = ±5°.
- Beam energy ≈ 185 – 198 MeV ⇒ approximate match to earlier high precision polarization data from IUCF.
- Tagged flux ≈ 100 Hz during Cooler flattop.
- Secondary target = 2.5 cm CH_2 ⇒ ~ 1 Hz free np scattering rate.



The Tagger ...







Position correlations between the two recoil protons reveal the band associated with the secondary scattering target.

4 silicon 6.4 $\times$ 6.4 cm^2 double-sided strip detectors (DSSD) + 4 silicon large-area pad (backing) detectors

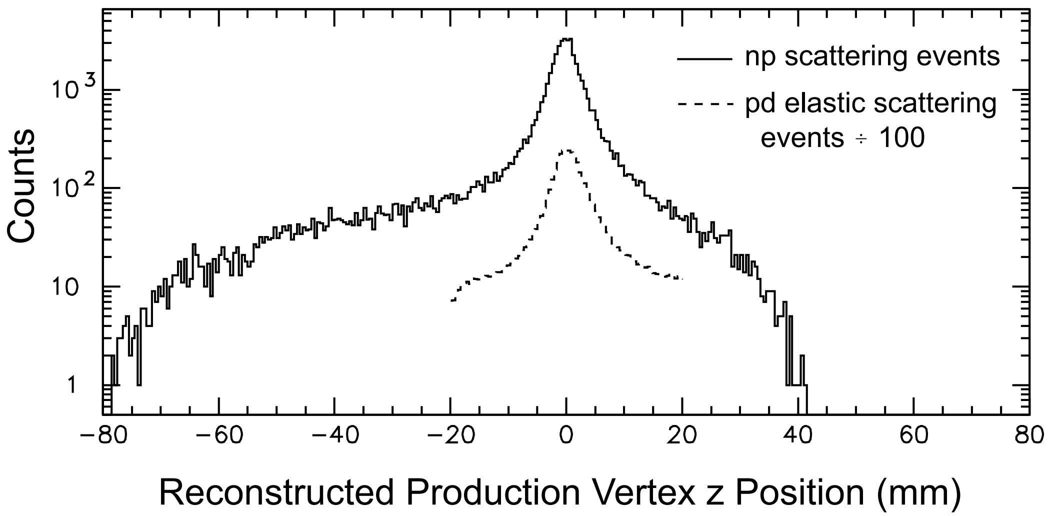
Place detectors ~10 cm from gas jet target to cover large solid angle

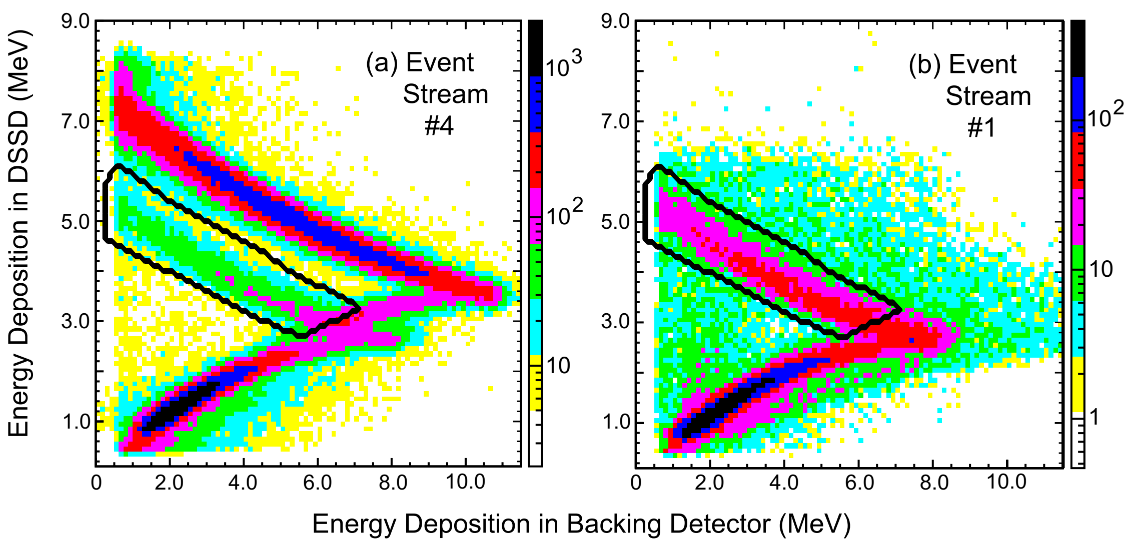
DSSD's $\Rightarrow$ energy, timing + 2-dim'l position (0.48 mm readout pitch) information for multiple particles

Backing detectors $\Rightarrow$ energy and particle ID for recoils that punch thru DSSD's (protons > 7 MeV)

Self-triggering readout electronics triggers on 2-particle coincidence among 64 logical pixels $\Rightarrow$ allow monitoring of tagged n flux

… Reconstructs 4-Momentum and Origin of the Tagged Neutron (or Proton):





Extended gas jet target has differential pumping tails

z of n prod'n determined event-by-event with $\sigma_z \approx 2$ mm by comparing p_n from energy vs. momentum conservation

Tagging measures E_n, θ_n with $\sigma_E \approx 60$ keV, $\sigma_\theta \approx 2$ mrad, n pos'n on 2ndary target with $\sigma_{x,y} \approx$ few mm

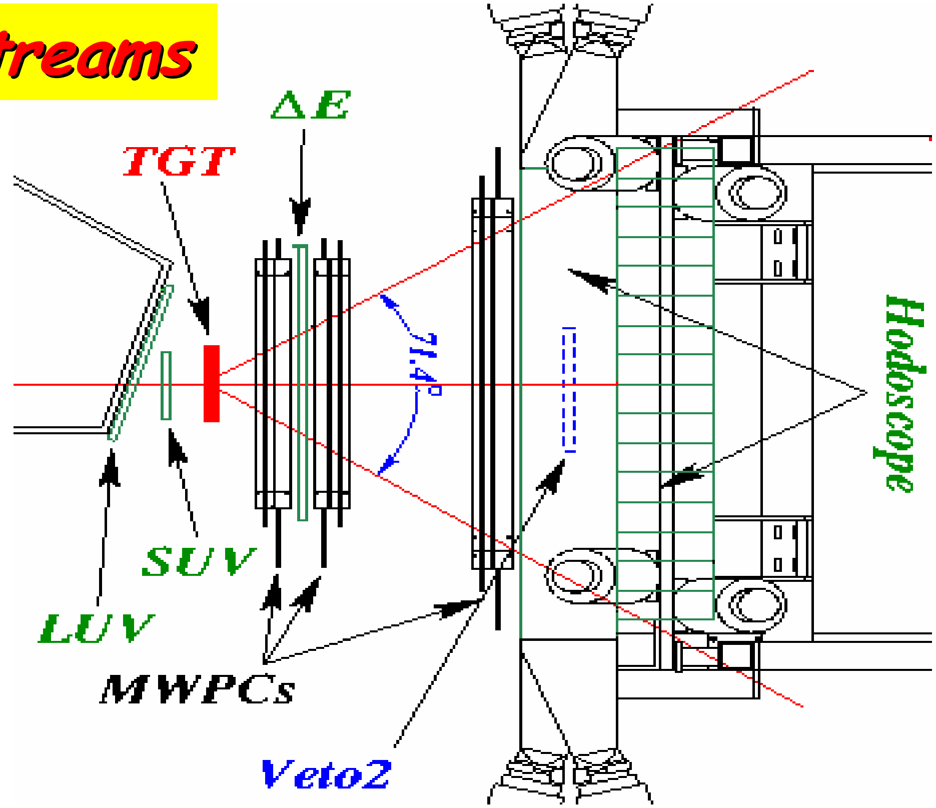
E_{DSSD} vs. E_{back} $\Rightarrow$ particle ID, distinction of protons that stop in DSSD or backing detector

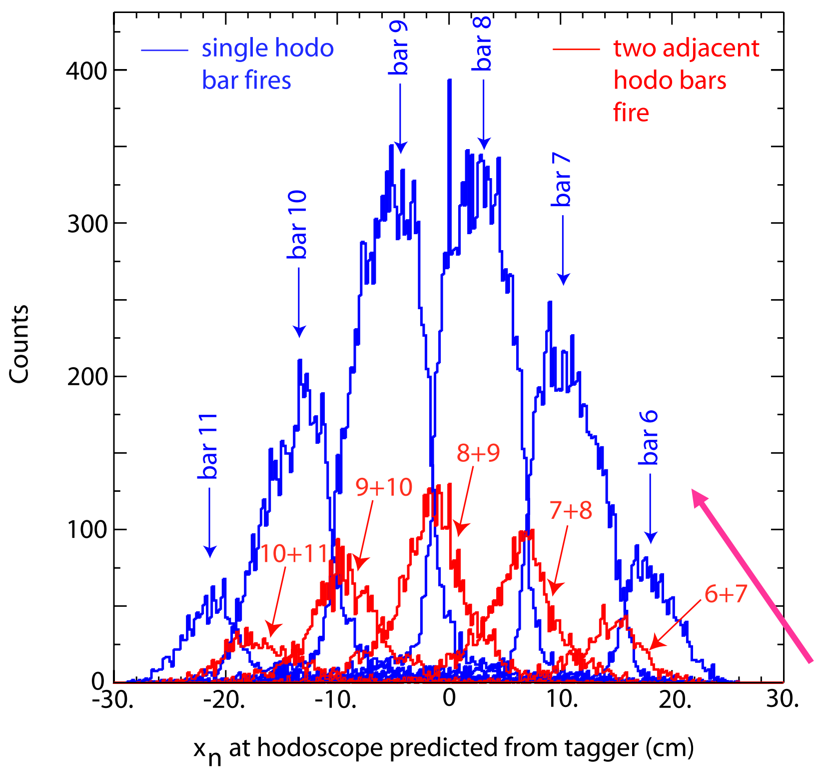
Secondary tagged p beam available via d recoils – permits simultaneous meas'ment of np and pp scattering with same target, detectors

Forward Detectors & Event Streams

2ndary tgt: 20 x 20 x 2.5 cm^3 CH_2 ($\Rightarrow$1.99$\times 10^{23}$ H atoms/cm^2) or C (graphite) of same transverse dim'ns and C atoms/cm^2

Forward detectors: plastic scintillators ($\Rightarrow E_p$ info, timing, triggering, veto beam protons) + multi-wire chambers for p ray-tracing





Forward array has 100% (>50%) acceptance for np scatt. from CH_2 at $\theta_{c.m.} \geq 130°$ ($\geq 95°$)

Forward hit pattern $\Rightarrow$ 3 mutually exclusive event streams to which we apply identical cuts:

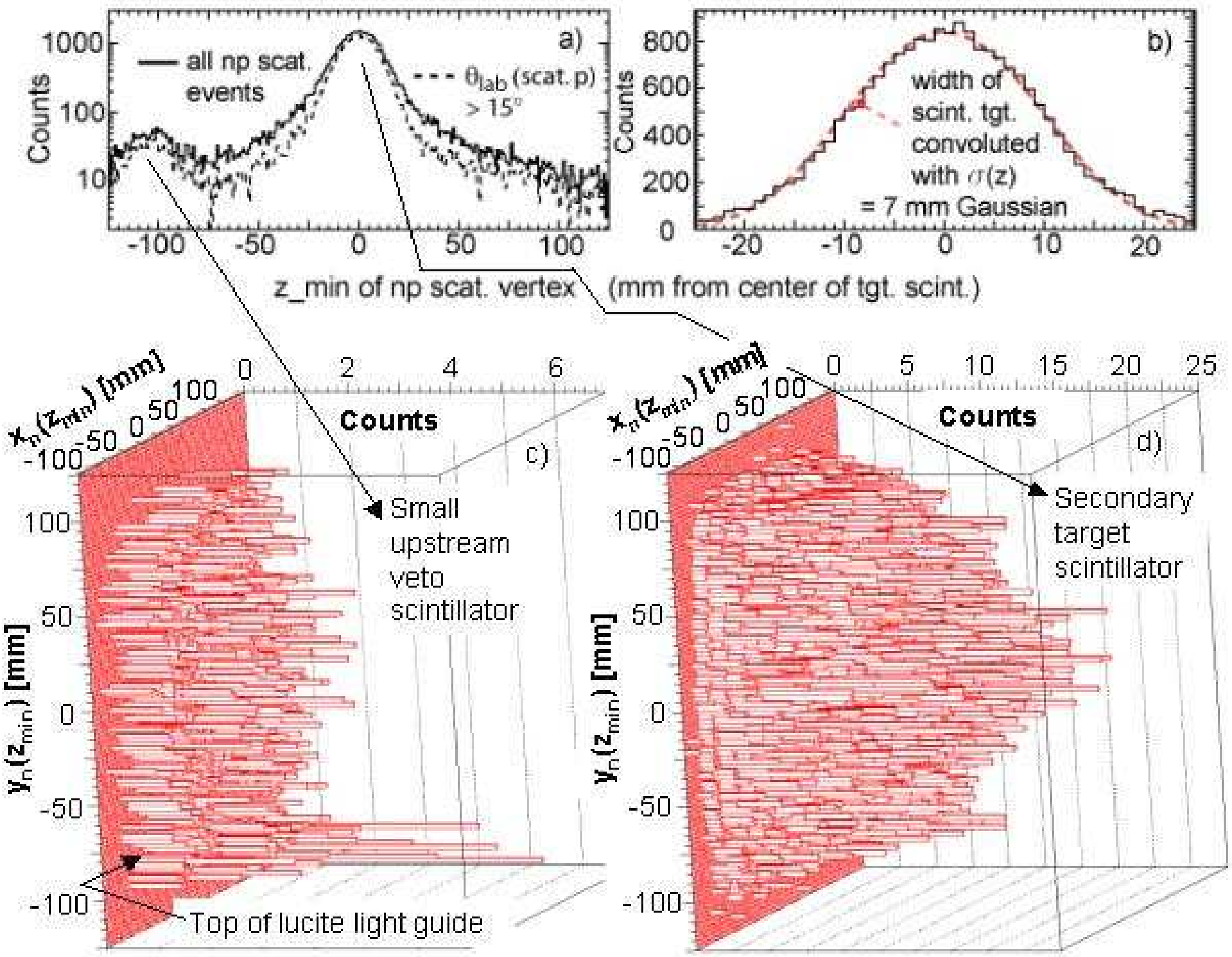
§1 ≡ tagged n's that don't interact

§2 ≡ np scattering candidates

§3 ≡ n's that convert in rear hodoscope (~20% efficiency)

Where the Neutrons Scatter:

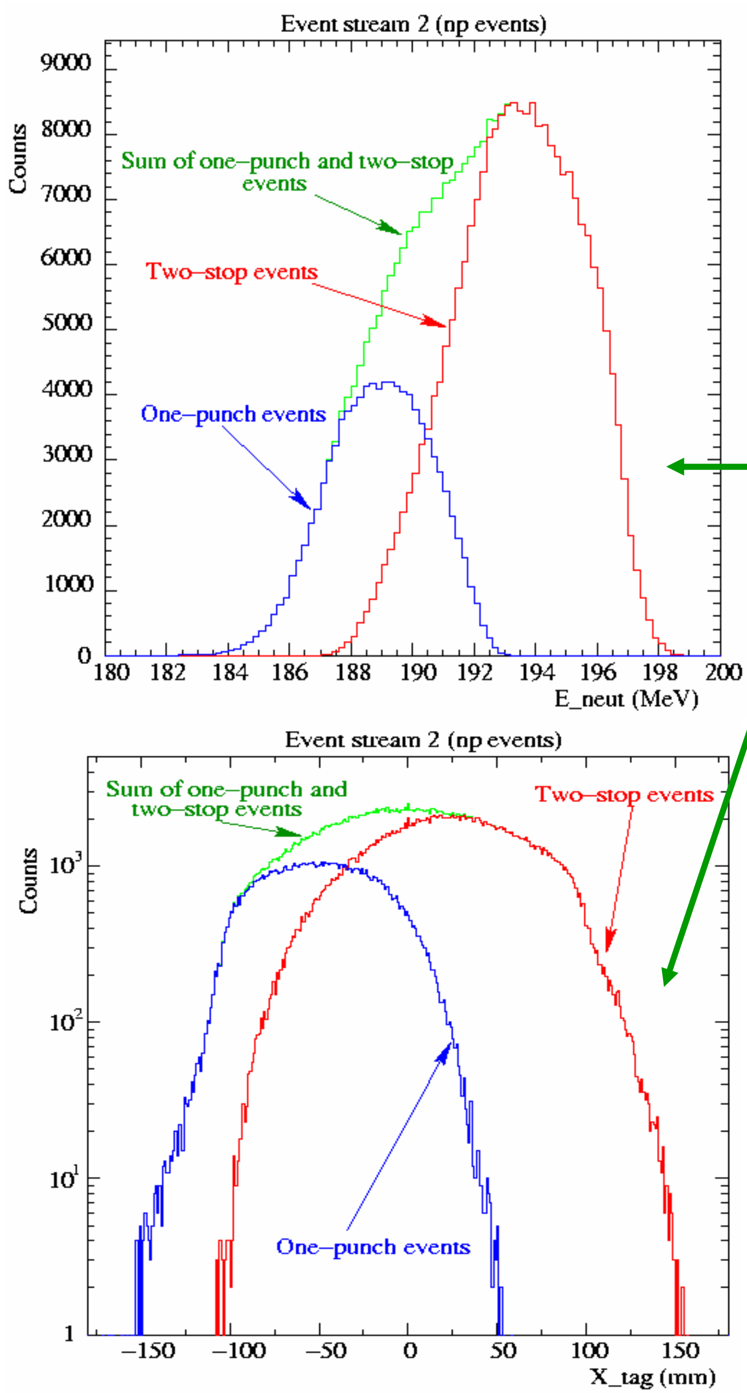
For np scattering candidates, the distance of closest approach of the tagged n and ray-traced p paths define the secondary scattering vertex in 3 dimensions ⇒ "medium-energy neutron radiography"



Transverse profiles of np scattering vertices

Illustrates the power of n tagging technique, but not actually used in free np event reconstruction, since vertex z resolution (~ 7 mm) depends on np scattering angle!

Two Subsamples to Compare:



Perform separate analyses of 2 event samples: "2-stop", both recoil p's stop in DSSD's; "1-punch", 1 of 2 p's stops in backing detector

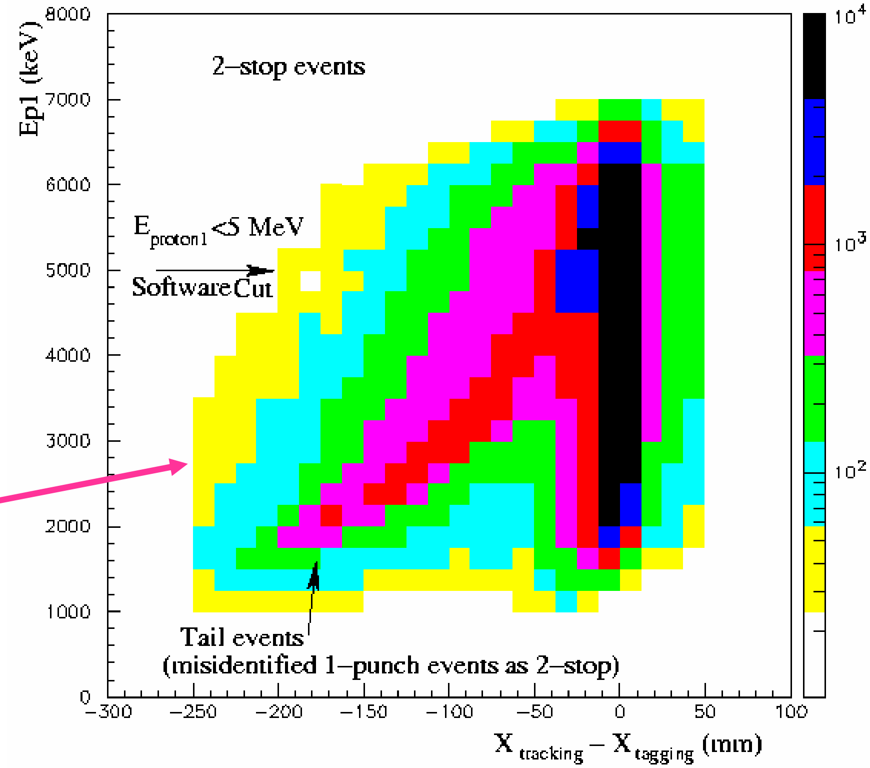
The two samples have quite different distributions in neutron energy and pos'n on CH_2 target $\Rightarrow$ compare $d\sigma/d\Omega$ results for the two as powerful internal consistency check on tagging technique

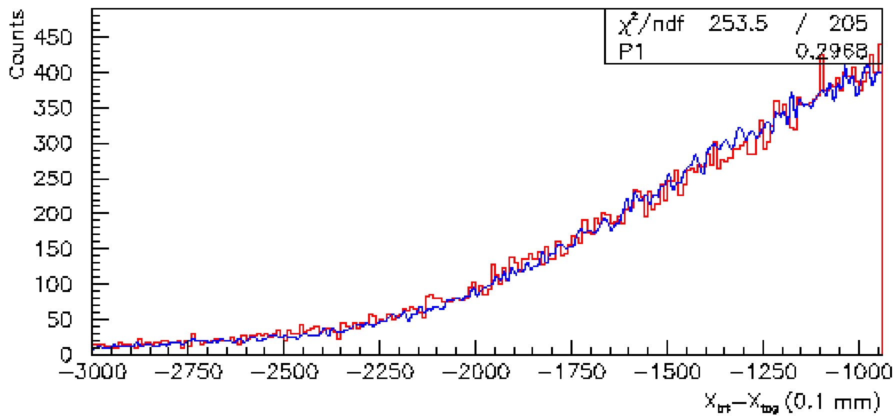
Ignore "2-punch" events, since tagged n energy typically much lower

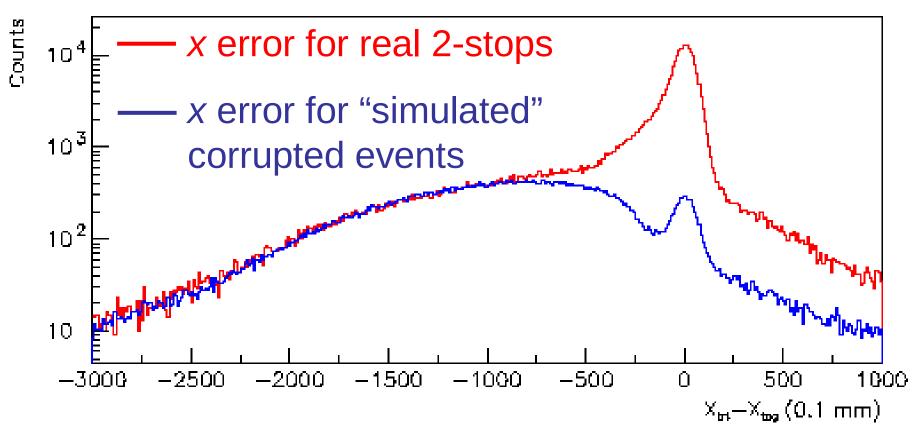
Also separately analyze 3rd sample of 2-stop events where one proton deposits near the maximum possible energy (> 5 MeV) in its DSSD. This sample most susceptible to systematic tagging errors from energy lost in dead layers at back of DSSD and front of backing detector.

From the "Best-Laid Plans" Dept: Conspiracy/Redundancy

Discovered during data analysis that apparent electronics malfunction removed all backing detector E info for ~23% (random) of events ⇒ mis-ID 1-punch and 2-punch events as 2-stop with systematic error in tagged n path!







Able to accurately "simulate" all properties of corrupted events by artificially setting E_{back}=0 in software for remaining good 1- and 2-punch events

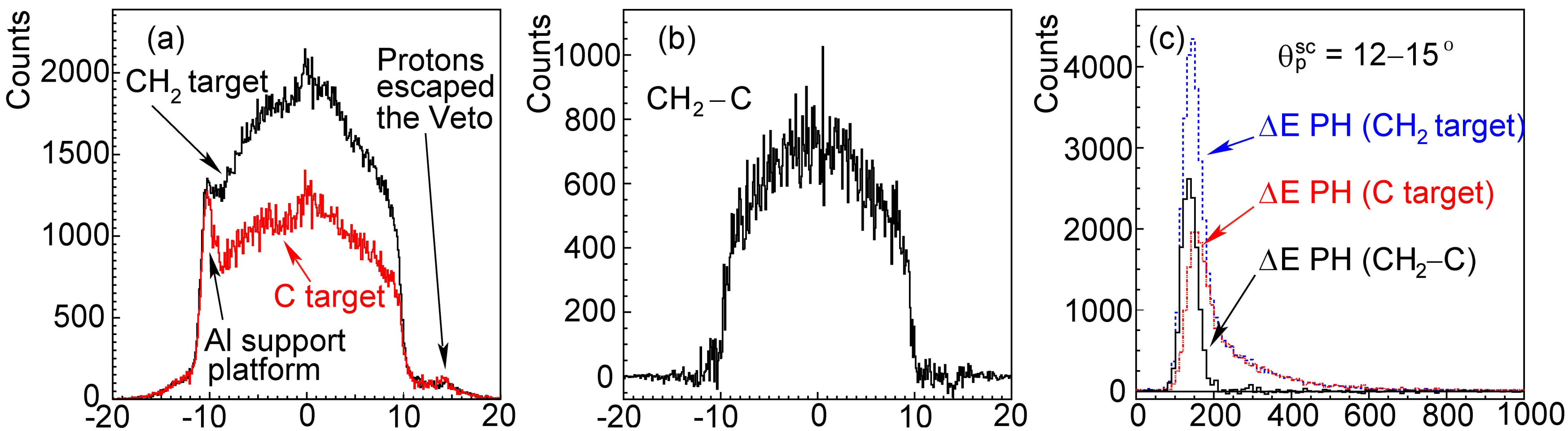
Accurate normalization of corruption rate by comparison of "simulated" to real 2-stop events with $E_{back} = 0$, $t_{back} \neq 0$

Subtraction removes bad events with little systematic error, but small loss of 1-punch statistics

Identifying Free np Elastic Scattering

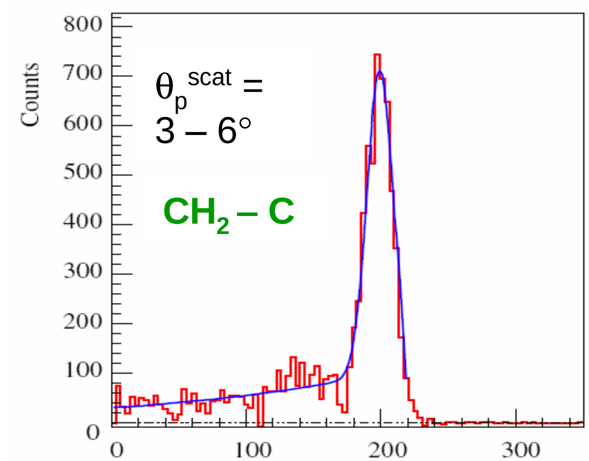
Rely on C subtraction to remove background from other sources and quasifree np scattering from protons bound in C nuclei

Normalize C to CH_2 data via pd elastic yield $\Rightarrow$ subtraction accurate to ~ 0.4%, judged from removal of known bkgd. features



Tagged n vertical position on secondary target (cm)

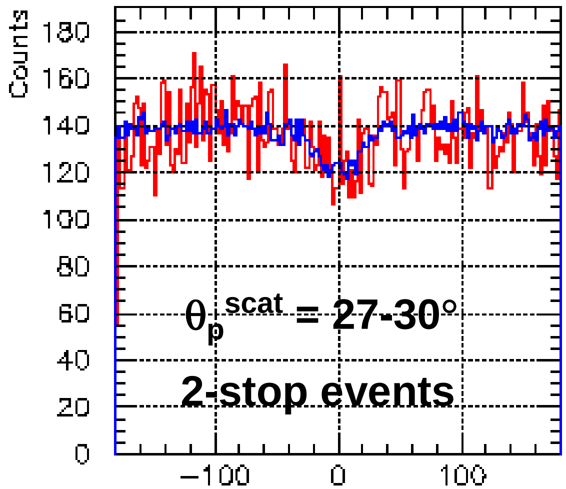
Pulse height in ΔE scintillator



Proton energy deposition in rear hodoscope

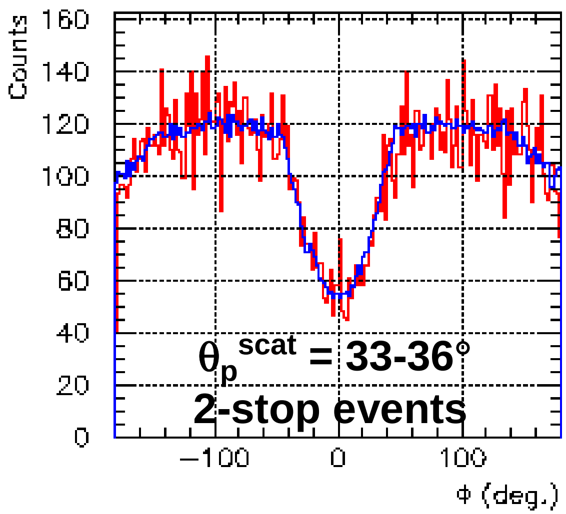
Minimize reliance on kinematic cuts – e.g., removes problem of "reaction tail" events in thick hodoscope, seen at left (only need to correct for reaction tail events below hodoscope hardware threshold)

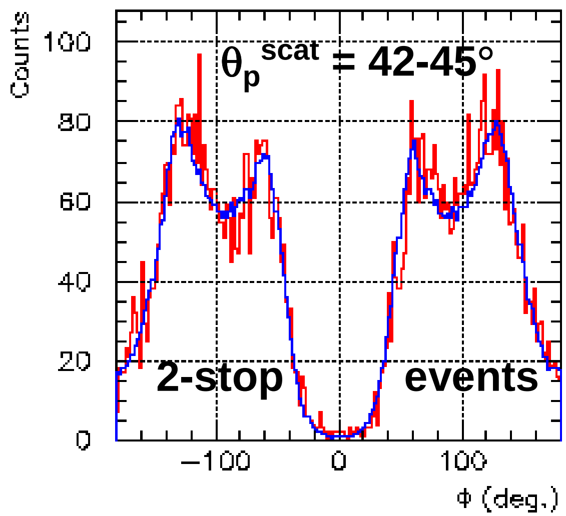
Calibrating Acceptance

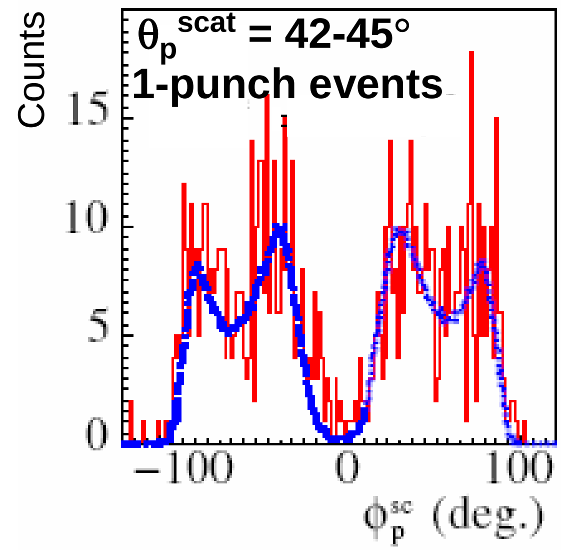


Proton ray-tracing ⇒ measure ϕ_p^{scat} distrib'n within each θ_p^{scat} bin

Use measured distrib'n of tagged n on CH_2 to simulate acceptance of forward detectors, separately for 2-stop and 1-punch events



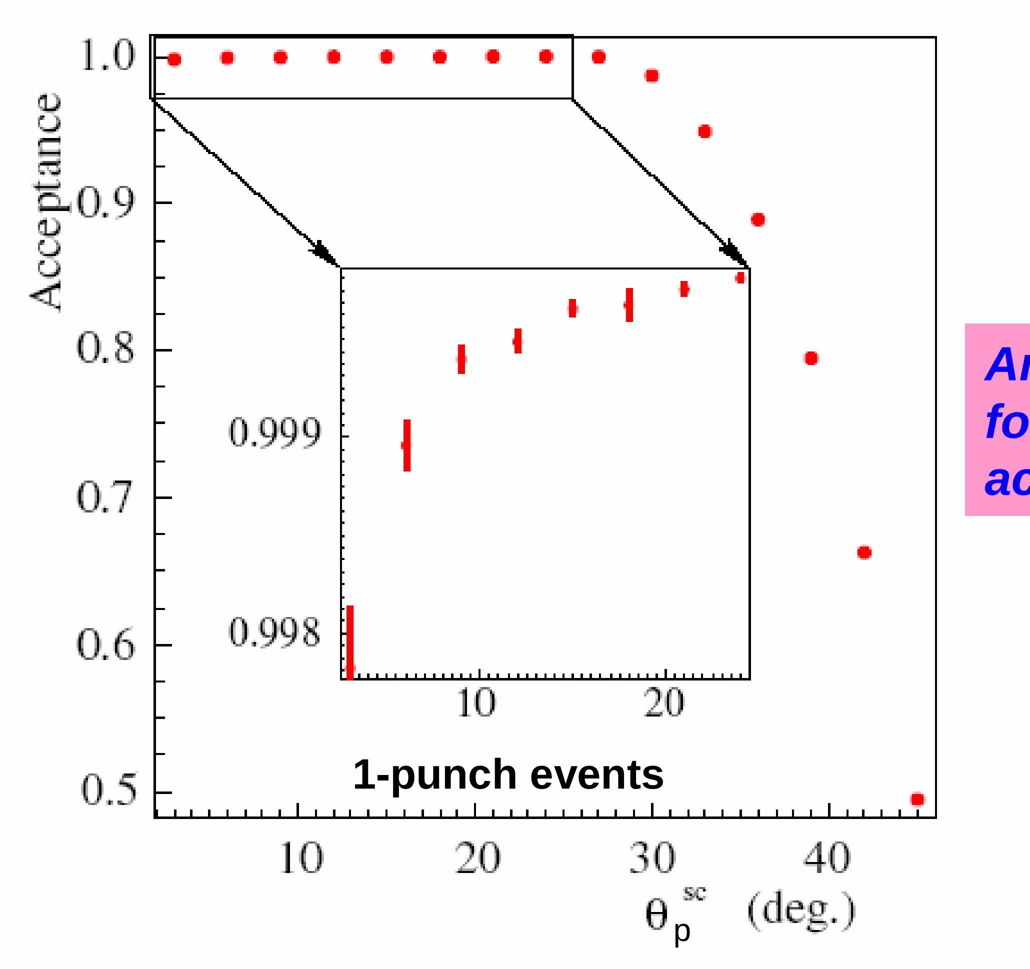




Allow slight adjustments from measured detector locations to optimize simultaneous fit to measured ϕ distributions for all θ_p^{scat} bins

All observed ϕ "structure" is geometric, from projecting rectangular detectors onto θ vs. ϕ!

Acceptance Results



Analyze data only for angle bins with acceptance ≳ 50%

Acceptance systematic errors typically < 0.5%, → 1.7% at $\theta_{c.m.} \approx 90°$

Extracting Absolute Cross Sections

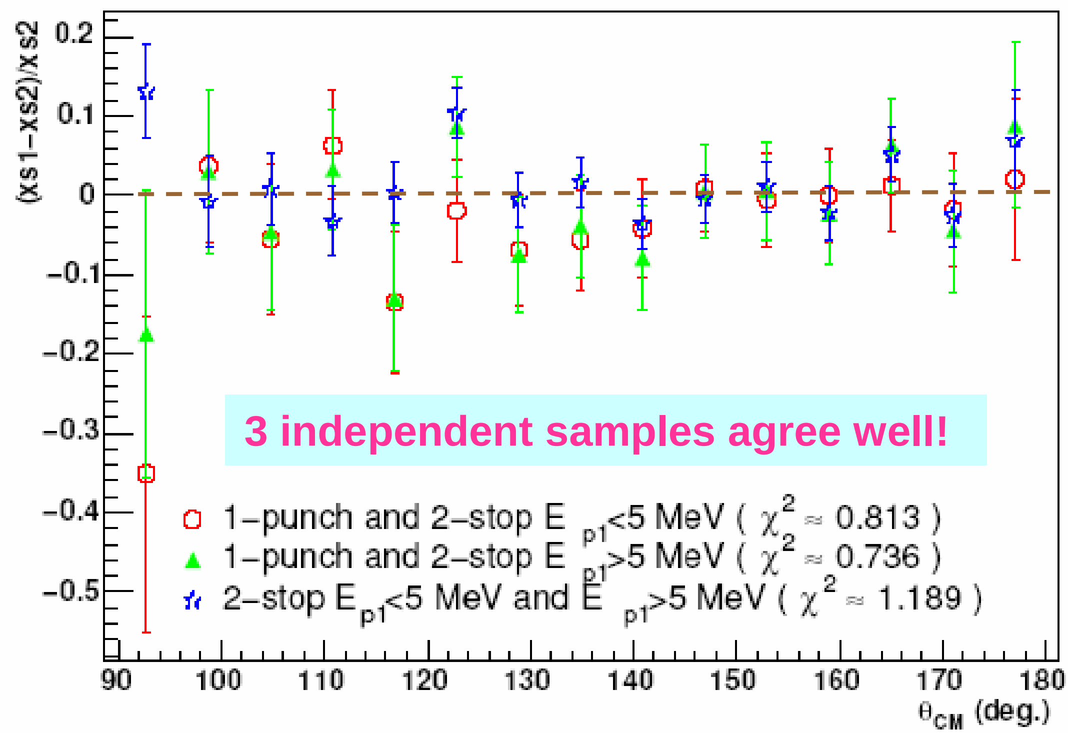
$$\left(\frac{d\sigma}{d\Omega}\right)_{lab} = \frac{N_2(\theta_p^{sc})\prod c_i}{(N_1+N_2+N_3)t_H|d\cos(\theta_p^{sc})|a_\phi(\theta_p^{sc})},$$

$N_2(\theta_p^{sc})/(N_1+N_2+N_3)$ = fraction of all tagged neutrons (after common cuts) yielding free np scat. in angle bin of interest

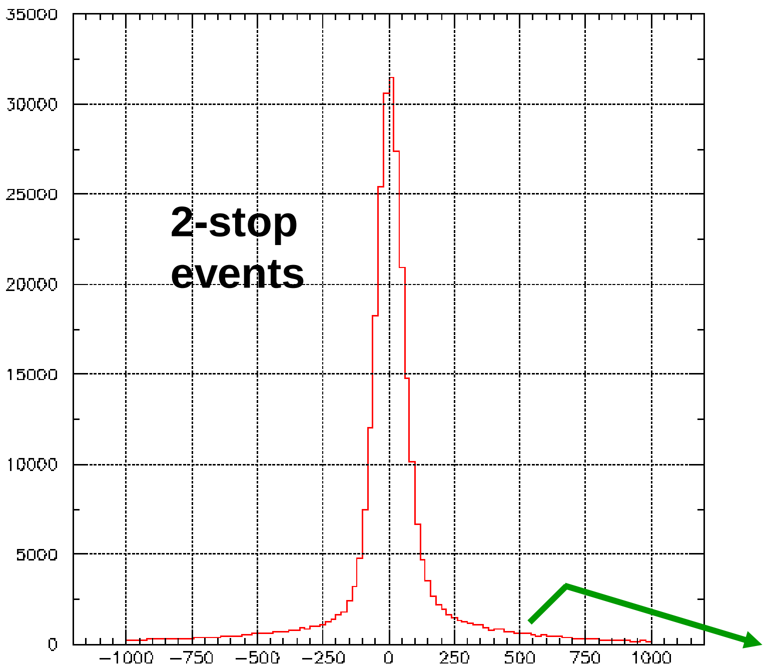
c_i = small correction factor(s) for inefficiencies, tagged n losses, backgrounds, differences in cuts or dead time among event streams (see next page)

t_H = secondary target thickness in H atoms/cm^2

$a_\phi(\theta_p^{sc})$ = azimuthal acceptance in angle bin of interest, from ϕ fits



Systematic Error Budget



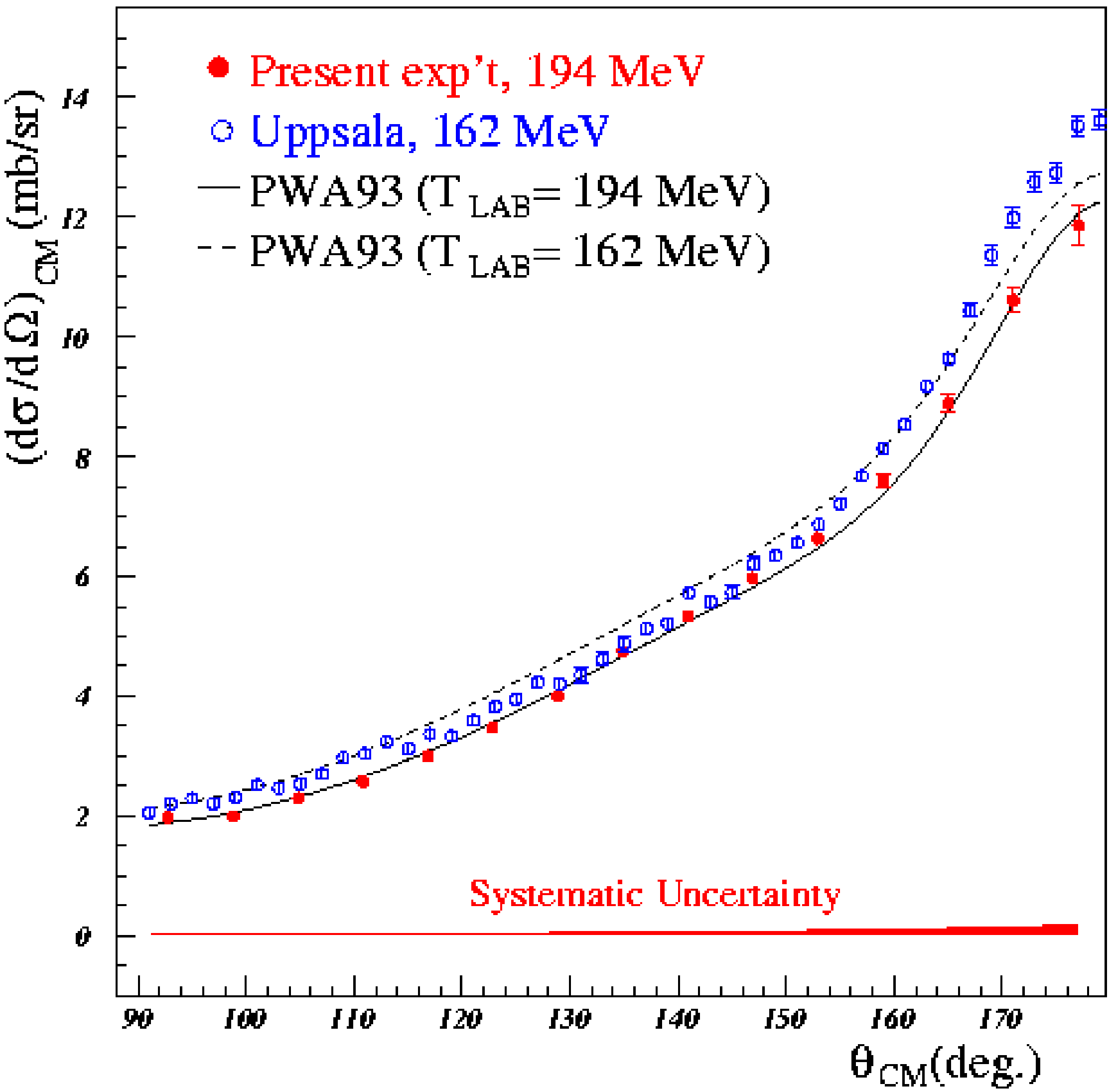
y(tracking) – y(tagging) on CH_2
(0.1 mm)

The net systematic error at this point in absolute dσ/dΩ is ±1.5%, with small angle-dependence. It is dominated by uncertainties regarding sequential reactions and tagging errors, which cannot be easily distinguished.

TABLE I: Correction factors and systematic uncertainties in correction factors for the np cross sections.

Source	Correction Factor (c_i)	Uncertainty in c_i
Accid. tagger coinc.	1.0003	$< \pm$ 0.001
Non-D_2 tagger background	1.0067 (2-stop); 1.0044 (1-punch)	$\pm$ 0.002
n pos'n unc. on CH_2	1.0000	$\pm$ 0.001
n atten'n before CH_2	1.005	$\pm$ 0.0025
C bkgd. subtraction	1.0000	$\pm$ 0.004
Reaction tail losses	1.004	$\pm$ 0.002
Neutron polarization effects	Angle-dependent: $>$ 0.9988 (1-punch) $<$ 1.0014 (2-stop)	$\pm$ 0.001
Software cut losses	1.010	$\pm$ 0.005
Sequential react'ns & x_{tag}(n) errors	1.063	$\pm$ 0.010
CH_2 tgt. thickness	1.0000	$\pm$ 0.004
np scattering acceptance	1.0000	$\leq \pm 0.001$ ($>120°$) $\rightarrow \pm 0.017$ ($90°$)
MWPC efficiency	1.017	± 0.002
Trigger inefficiency	$1.002 + 0.008 \times \cos^2(\theta_p^{LAB})$	$\pm [0.001 + 0.004 \times \cos^2(\theta_p^{LAB})]$
Dead time diffs.	0.991	$\pm$ 0.005
Scattering angle errors	1.000	angle-dependent, $\leq \pm 0.004$
Corrupted event subtraction	1.000	$< \pm 0.001$
Net	$\approx$ 1.10	$\approx \pm 0.015$

At Long Last: Results!



Overall normalization uncertainty in present data ≅ ± 1.5%

Error bars in plot statistical only, but statistics dominate!

Data analyzed in E_n slices, each slice corrected slightly via PWA to E_n=194.0±0.15 MeV

Results are averaged over 3 independent samples (1-punch; 2-stop $E_p^{max} \leq 5$ MeV; 2-stop $E_p^{max} > 5$ MeV) that agree in shape and magnitude within stat. errors (χ^2/point ≈ 1)

Shape, magnitude both in excellent agreement with Nijmegen PWA93; small deviations probably ⇒ small parameter adjustments in PWA

Systematic deviations from Uppsala (our collaborators!) data larger than can be explained by E-dependence!

Conclusions

Tagged neutron facility has allowed medium-energy np backscattering measurement with tight control of systematic errors in absolute $d\sigma/d\Omega$.

Results (hopefully!) resolve extensive discrepancies in np database. Excellent agreement with PWA validates "low" value of πNN coupling strength and controversial data rejection criteria in PWA analyses.

Precise cross section measurements with secondary beams are challenging. It is dangerous to "salvage" questionable data by applying parameterized corrections uninformed by any detailed knowledge of what went wrong in the experiment.

Results provide new absolute standard for medium-energy neutron-induced cross sections to < 2%.

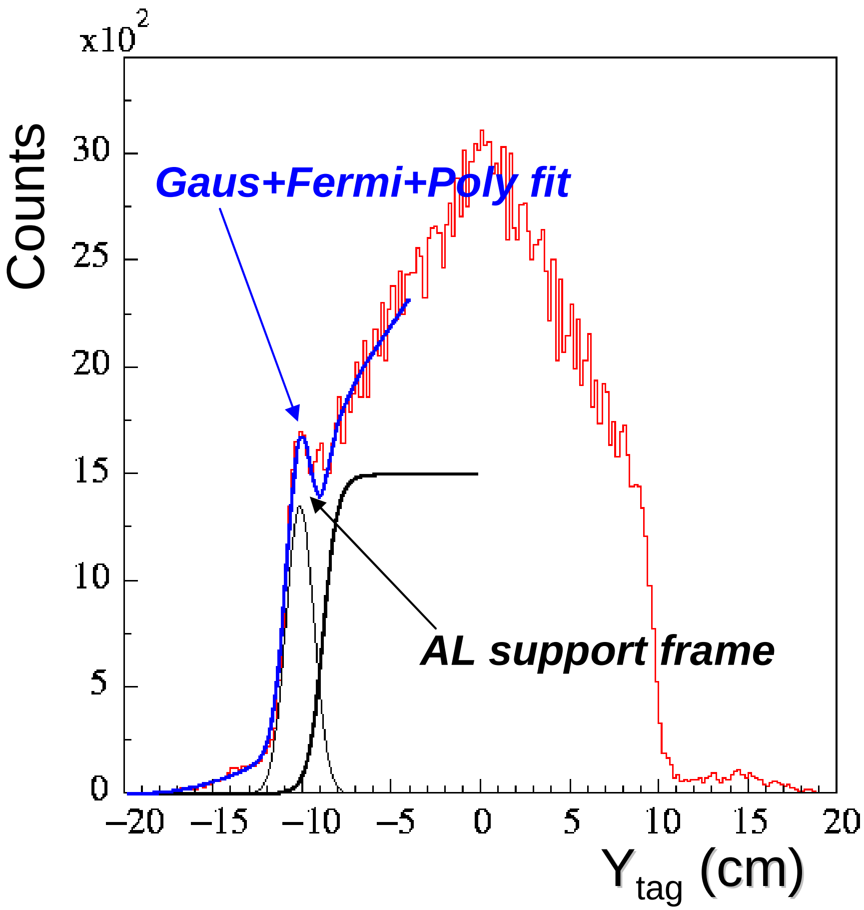
IUCF Cooler was elegant facility that made this experiment possible. Operations funding ceased in 2002. This was one of the final experiments performed at the facility.

Systematic Errors : Background subtraction

1. Secondary target

Judged from the extent to which the aluminum frame peak is successfully removed from the Y_{tag} spectrum.

Ratio of the events in the Gaussian distribution (after to before) subtraction ≈ $(1.94\pm0.54)\times10^{-3}$

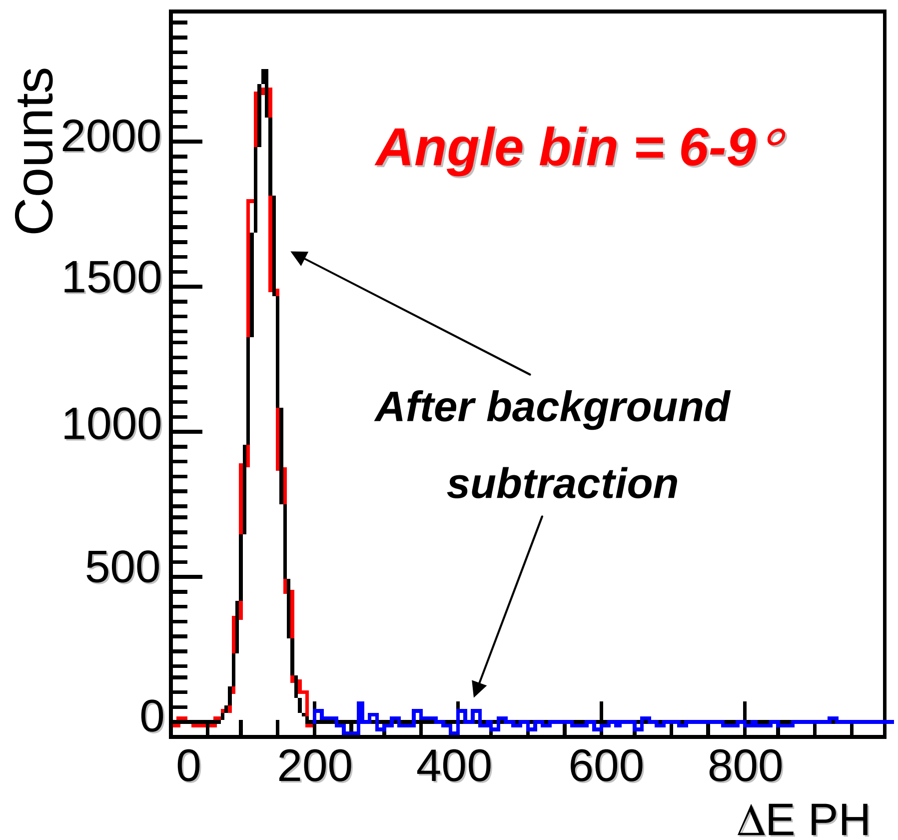


2. ΔE Detector

Real ΔE peak within ($\Delta E_{mean}\pm4\sigma$)

Σ outside the real peak range after background subtraction/Σ before background subtraction = Background that survives subtraction.

Weighted average ≈ $(2.97\pm0.24)\times10^{-3}$



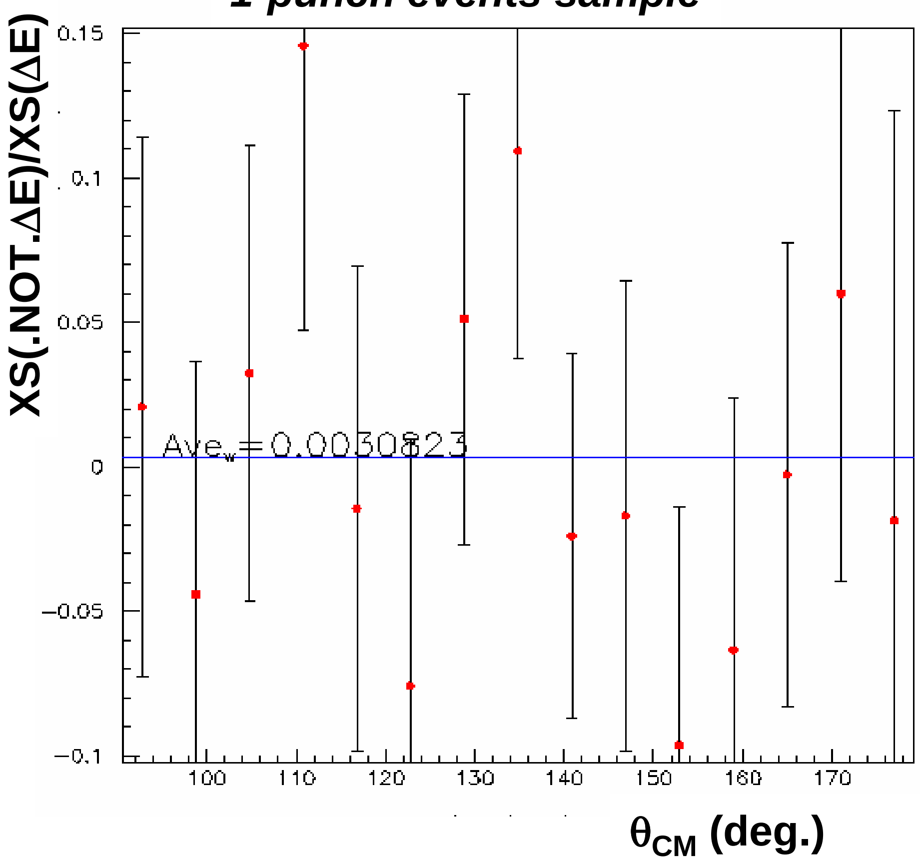
Systematic Errors : Software cuts (ΔE cut)

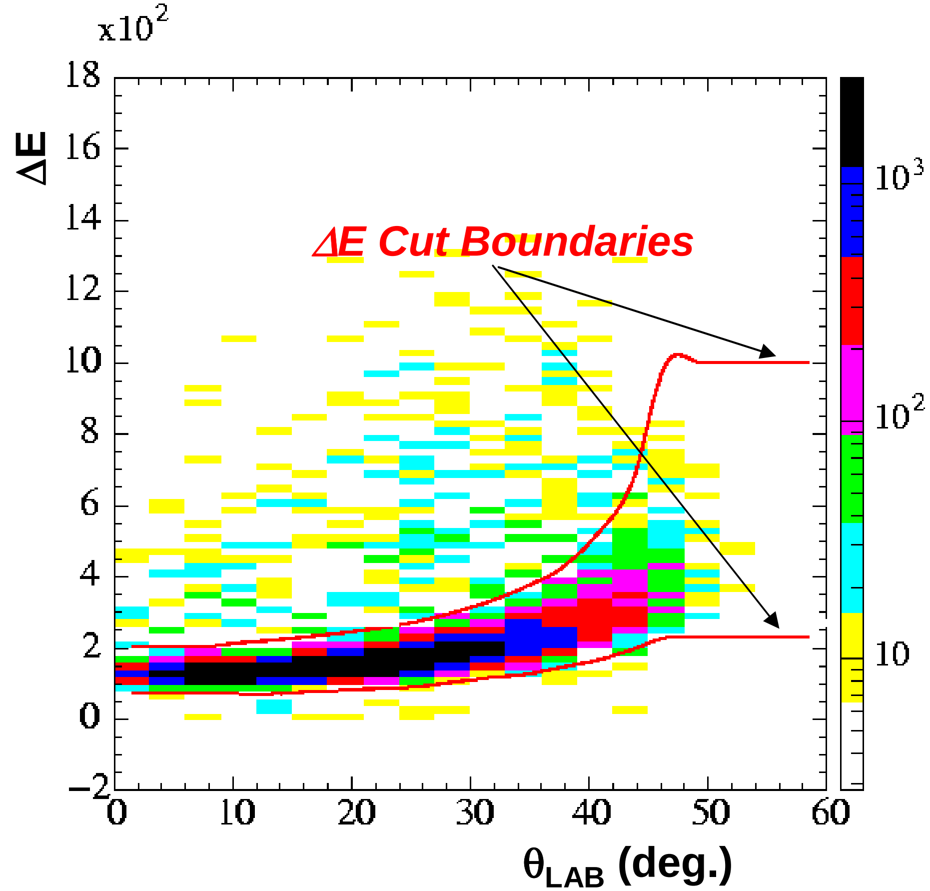
Efficiency of ΔE cut judged by looking at :

$$R = \frac{d\sigma/d\Omega\,(\text{outside } \Delta E \text{ cut})}{d\sigma/d\Omega\,(\text{inside } \Delta E \text{ cut})}$$

The overall weighted average (weighted by the statistical contribution of each data set) ≈ 0.01 ± 0.005

1-punch events sample





Systematic Errors : Sequential Reaction in the secondary target

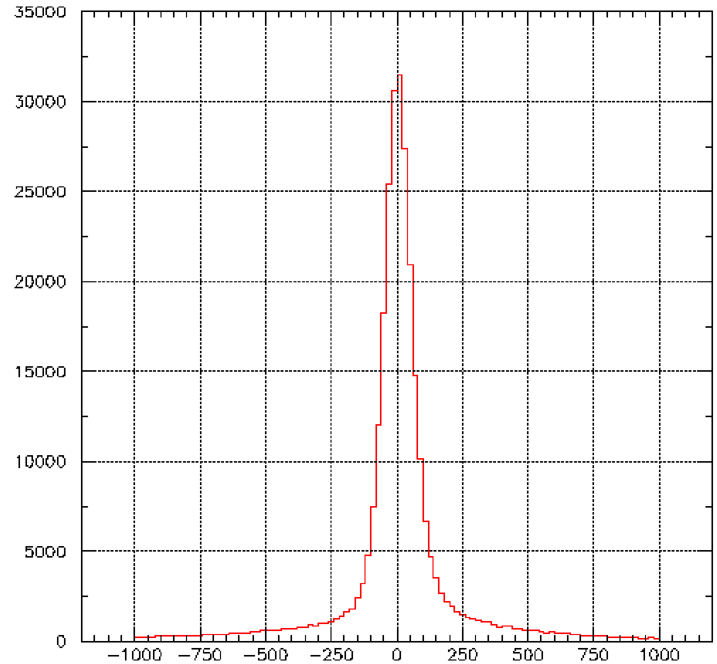
Events where the neutrons undergo scattering or reaction before the one that gives rise to the observed forward proton.

Distorted events! Incorrect neutron's incidence angle or energy

Sequential reaction events eliminated by only including events that fall within ±3σ narrow peak of zero in both X_{track}-X_{tag} and Y_{track}-Y_{tag} in the cross section.

For event streams 1&3, the tagged neutron yields simply reduced by the same factor for events stream 2.

The correction to the neutron flux due to these events ≈ 1.063±0.010



y(tracking) – y(tagging) on CH_2 (0.1 mm)

Systematic Errors : Neutron Polarization Effects

$$\varepsilon_{np}(\theta,\phi) \equiv P_n^{prod} A_{np}(\theta) cos(\phi),$$

$P_n^{prod} \approx -0.10$ for D(p,n)

$$\delta(\theta) = \int_0^{2\pi} \varepsilon_{np}(\theta,\phi) a_\phi(\theta) d\phi / \int_0^{2\pi} a_\phi(\theta) d\phi.$$

$c_i(\theta) = 1.0 - \delta(\theta)$

While product of reaction polarization and np analyzing power ~ 1%, the left-right asymmetry of the forward detector array is small: essentially zero for proton angles below 25°, and opposite in sign for 1-punch vs. 2-stop events at larger angles. Therefore, correction and error are negligible.

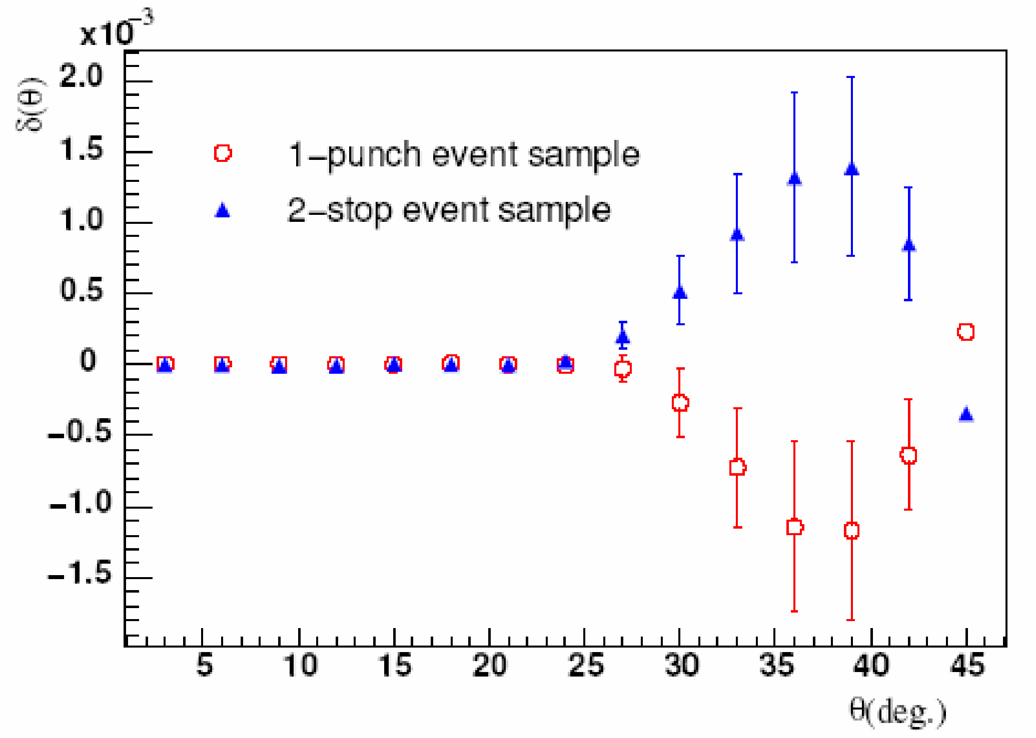


Table 1. Final np Scattering Cross Section Results at 194.0 ± 0.15 MeV

θ_{CM} (deg.)	$(d\sigma/d\Omega)_{CM}$ (mb/sr)	Statistical Error	Systematic Error
177.02	11.86	0.34	0.19
171.04	10.62	0.19	0.17
165.02	8.89	0.14	0.14
158.97	7.61	0.11	0.12
152.92	6.64	0.10	0.10
146.89	5.98	0.08	0.09
140.86	5.34	0.08	0.08
134.85	4.75	0.07	0.07
128.84	4.01	0.06	0.06
122.83	3.47	0.06	0.05
116.81	3.01	0.05	0.05
110.80	2.57	0.05	0.04
104.79	2.31	0.05	0.04
98.76	2.00	0.05	0.04
92.74	1.98	0.06	0.04

Note : The systematic errors are very highly correlated among different angle bins, and mostly reflect overall normalization uncertainties