Low-Energy Photonuclear Reactions—A Review

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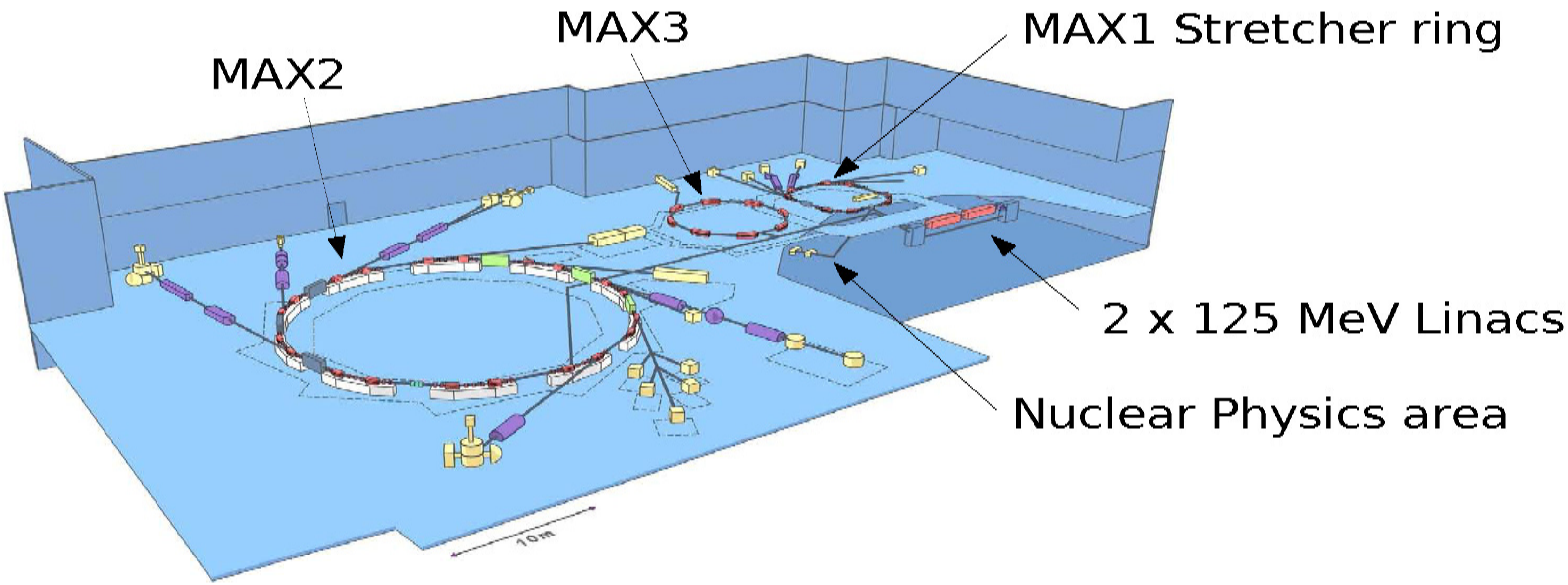
Monoenergetic Photon Beams

- Positron Annihilation in Flight
  - Livermore, Saclay
- Tagged Photons
  - Illinois, Saskatchewan, MAX-lab at Lund
    - [High-Energy: MAMI, Jefferson Lab]
- Compton Back-Scattering
  - LEGS at BNL, HIγS at TUNL
    - [High-Energy: GRAAL, SPRing-8]

Polarized Photon Beams

- Positron Annihilation in Flight
  - Unpolarized
- Tagged Photons
  - Polarized at High-Energy Facilities Only
- Compton Back-Scattering
  - Polarized

MAX-lab accelerator system



Parallel operation of the three rings

Nuclear Physics: ~45% of beam-time at MAX1

Thanks to Kevin Fissum

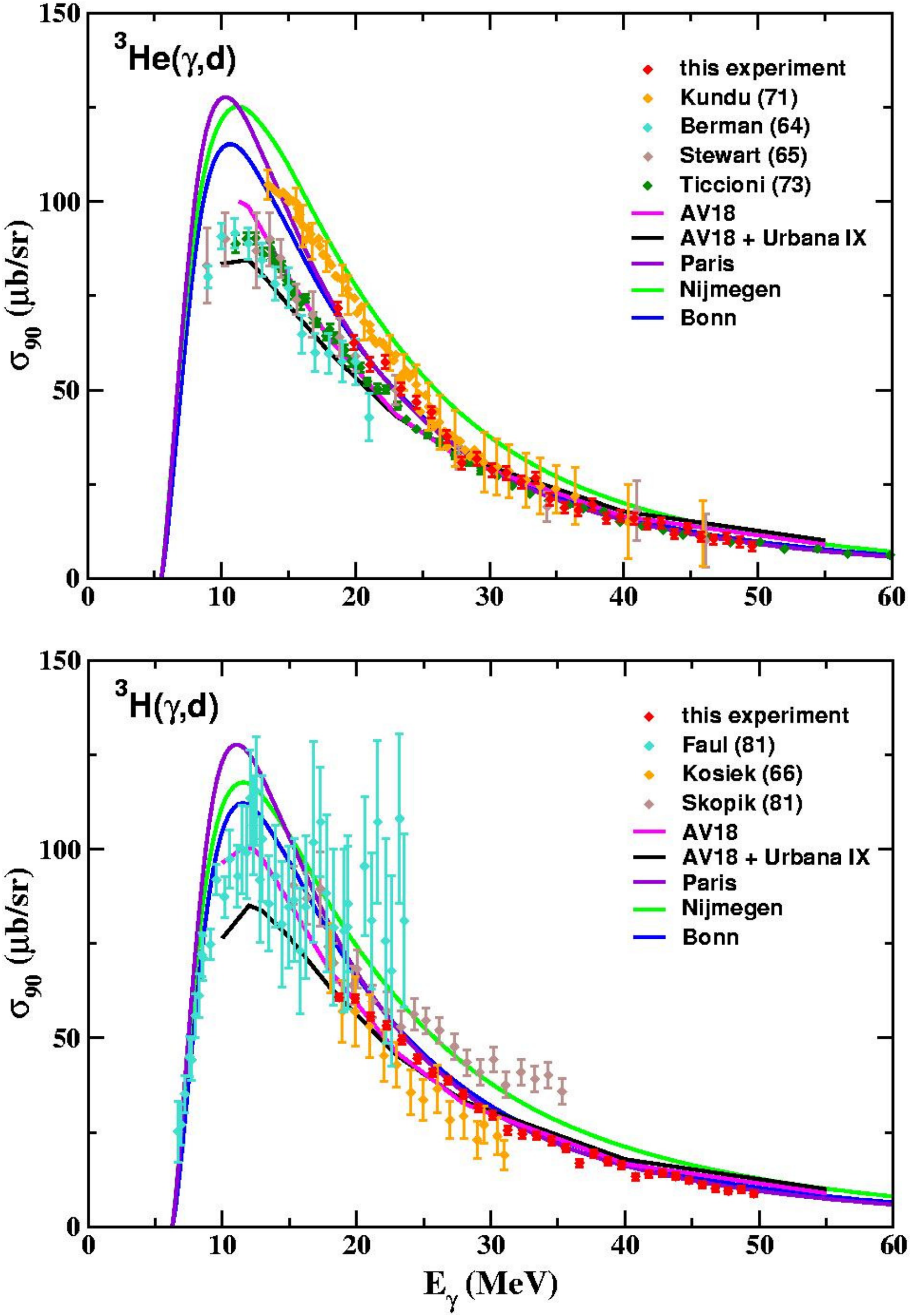
Research program

Present experimental programme

- Compton scattering
- Pion photoproduction
- Photoreactions on He isotopes
- Total photoabsorption cross-section of ^{6,7}Li
- Detector tests (PANDA electromagnetic calorimeter)
- Commissioning of linearly polarized photons

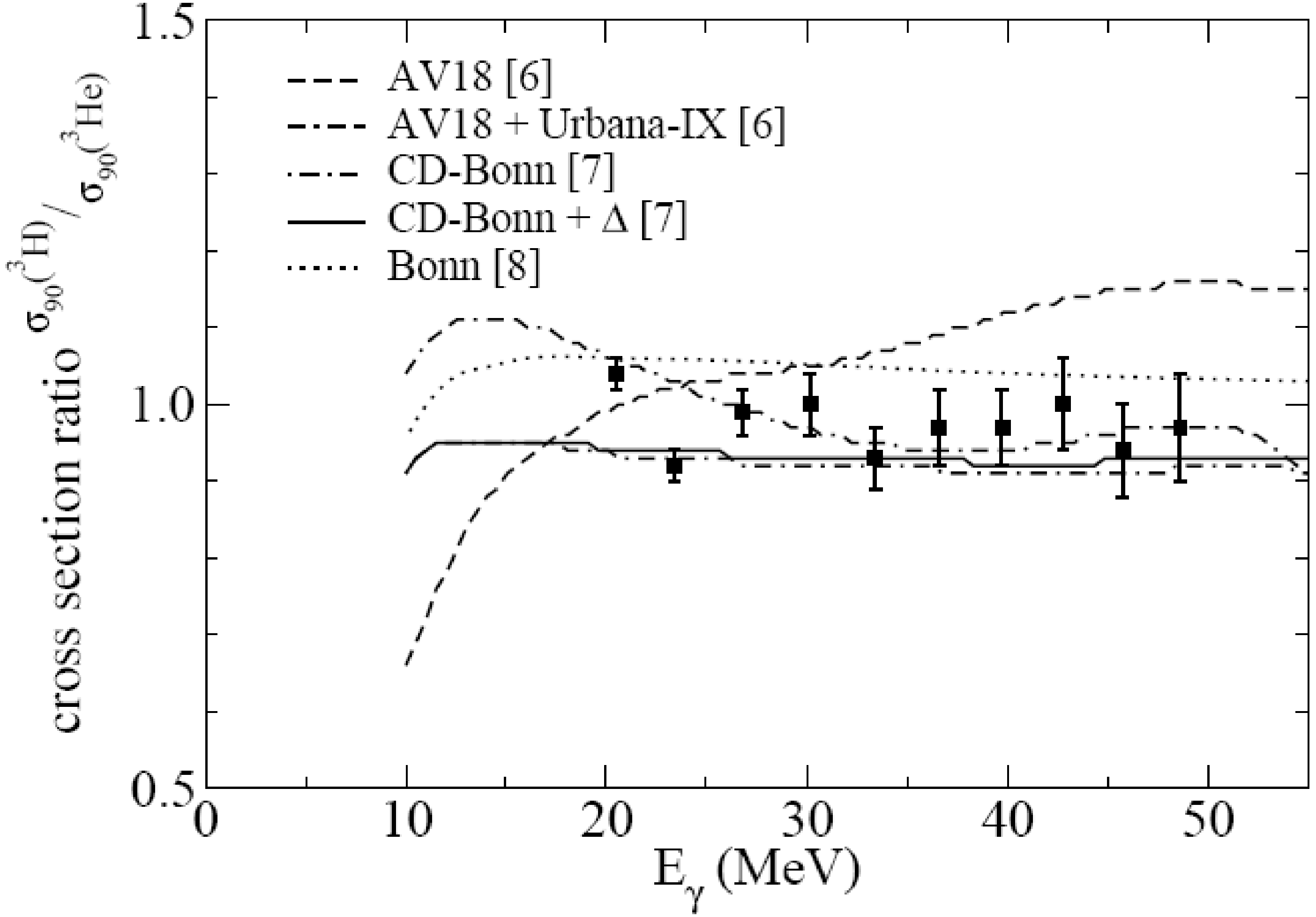
Participating institutes

1. Duke University, USA.
2. University of Edinburgh, UK.
3. University of Frankfurt, Germany.
4. George Washington University, USA.
5. University of Glasgow, UK.
6. University of Illinois at Urbana-Champaign, USA.
7. University of Kentucky, USA
8. Kharkov Institute of Physics and Technology, Ukraine.
9. University of Lund, Sweden.
10. University de Complutense Madrid, Spain
11. University of Mainz, Germany.
12. University of Manchester, UK.
13. Massachusetts Institute of Technology, USA
14. University of Massachusetts Dartmouth, USA.
15. University of Melbourne, Australia.
16. MAX-lab, Sweden.
17. Mount Allison University, Canada.
18. University of New Hampshire, USA.
19. Ohio University, USA.
20. Pakistan Insitute of Engineering and Science, Pakistan
21. Petersburg Nuclear Physics Institute, Russian Federation.
22. Rhodes University, South Africa.
23. Russian Academy of Science, Russian Federation.
24. University of Saskatchewan, Canada.
25. Stockholm University, Sweden.
26. Suleyman Demirel University, Turkey.
27. University of Regensburg, Germany.
28. University of Trento, Italy.
29. University of Tübingen, Germany.
30. Uppsala University, Sweden.
31. Yerevan Physics Institute, Armenia.
32. Weizmann Institute of Science, Israel



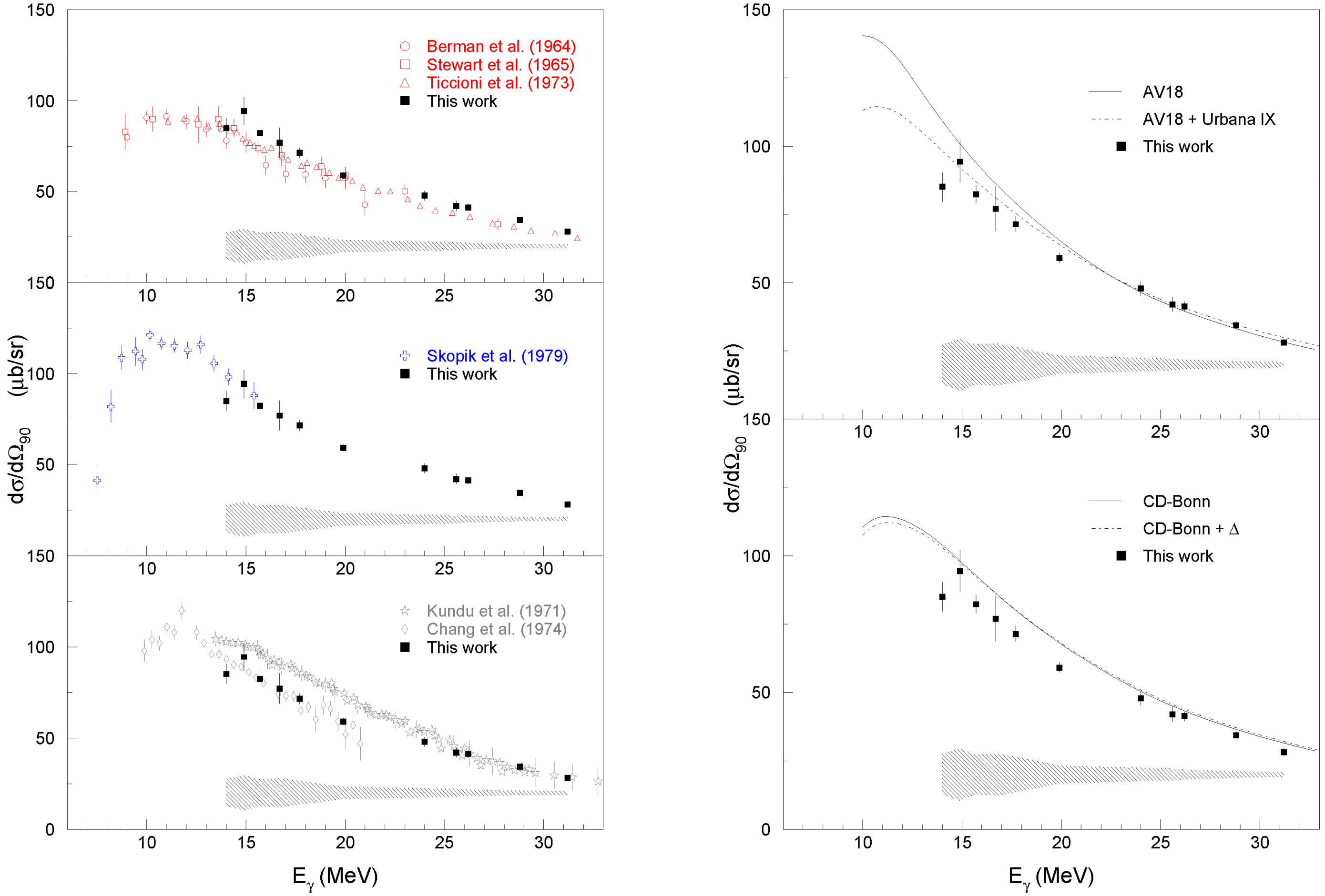
O'Rielly *et al.*
(SAL, 2004)

THE GEORGE WASHINGTON UNIVERSITY WASHINGTON DC



AV18 [6]
AV18 + Urbana-IX [6]
CD-Bonn [7]
CD-Bonn + Δ [7]
Bonn [8]
cross section ratio $\sigma_{90}(^3H)/\sigma_{90}(^3He)$
E_γ (MeV)
1.5
1.0
0.5
0
10
20
30
40
50

$^3He(\gamma,d)$ – see arXiv:0903.2943



Elastic Compton Scattering on D

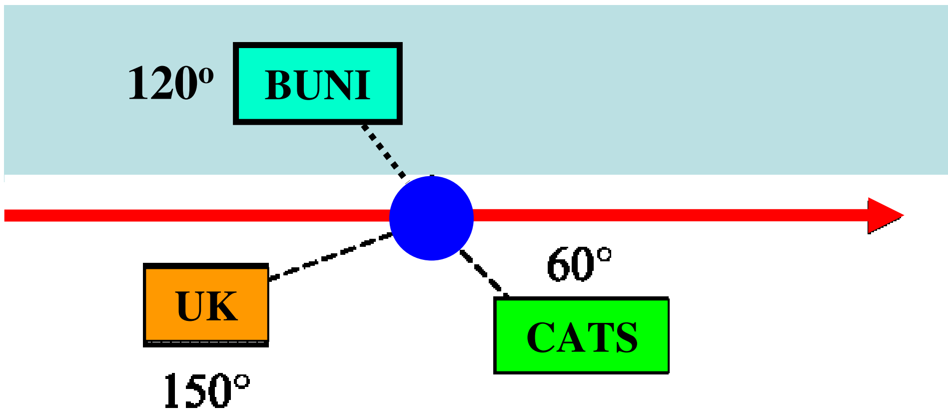
- Motivation
  - ***sum*** of proton and neutron polarizabilities
  - $\sigma_D(\omega) \approx r_0^2 - 2\, r_0\, (\alpha_p + \alpha_n)\, \omega^2$
- Requirements
  - must separate ***elastic*** from *breakup*!
    - ✓ monoenergetic (tagged) photons
    - ✓ high-resolution photon detector ($\Delta E/E < 2\%$ at 100 MeV)
- Data
  - Lucas – Illinois (1994) E_γ = 49, 69 MeV
  - Hornidge – SAL (2000) E_γ = 85-105 MeV
  - Lundin – Lund (2003) E_γ = 55, 66 MeV
- Theory
  - diagrammatic approach (Levchuk/L'vov)
  - EFT (Hildebrandt, Griesshammer, Hemmert, Phillips,…)

Experiment at Lund

- energies: **E_γ = 60-115 MeV using tagged photons**
  - two tagger settings: 115-95 and 97-60 MeV
  - bin data in 5 MeV energy bins (with 5% statistics)

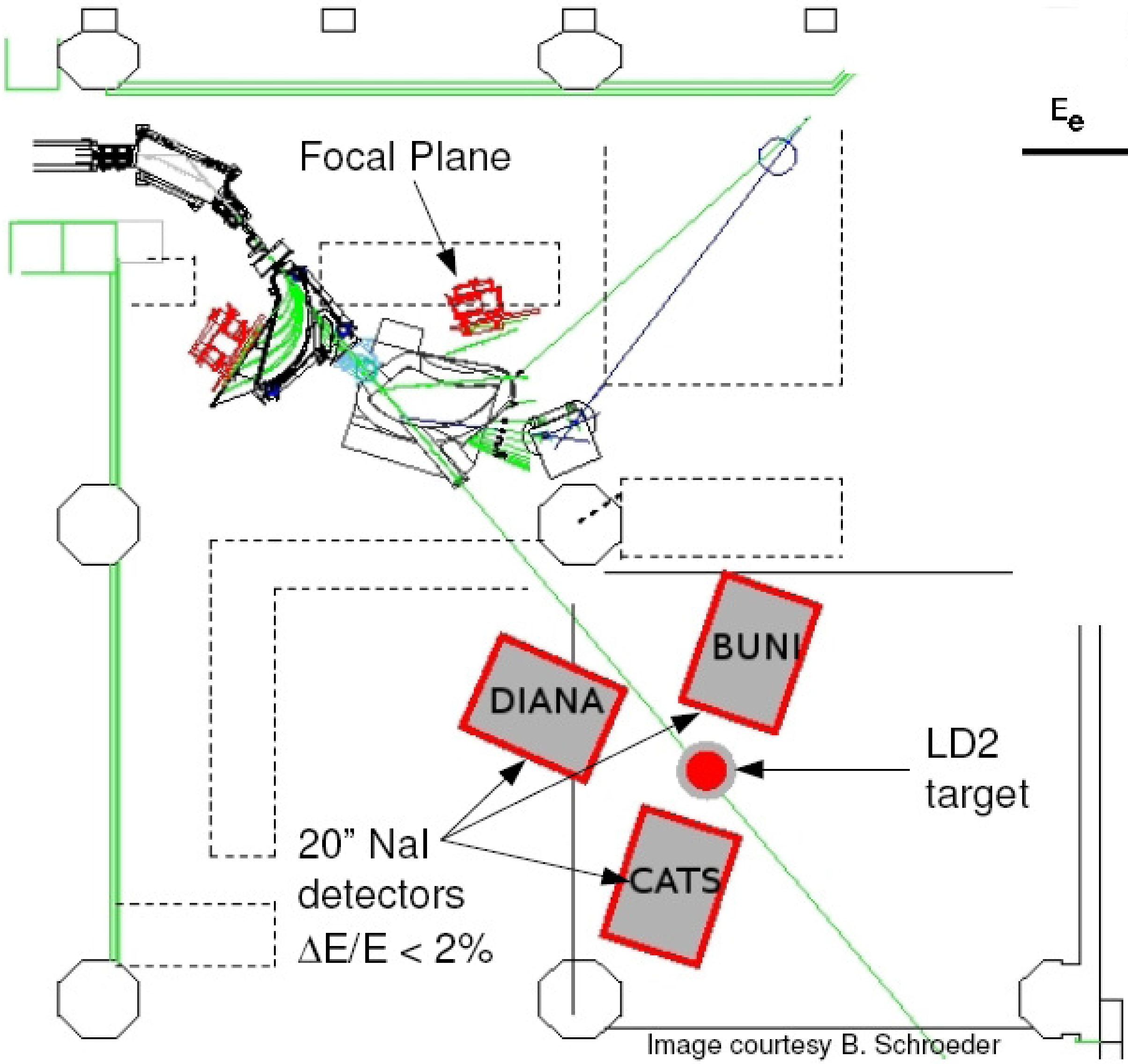
- angles: **θ_γ = 60°, 120°, 150°**
  - with 3 NaI detectors simultaneously

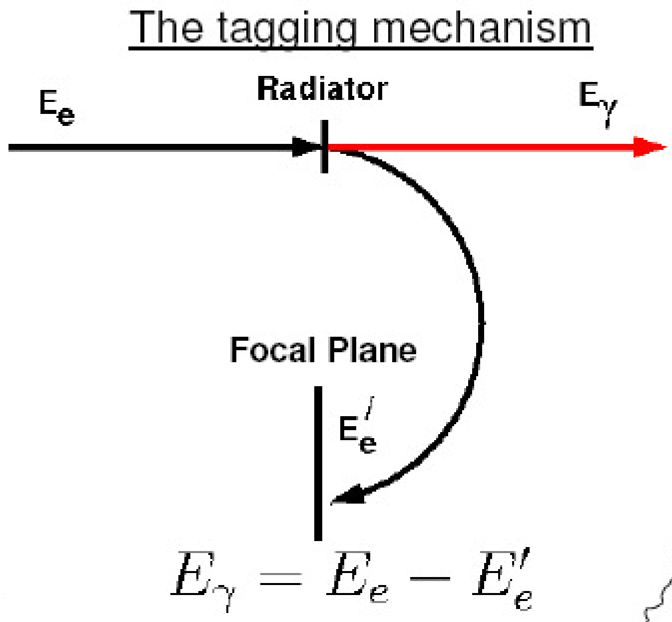
- detectors: 3 large-volume (50 cm × 50 cm) NaI's
  - excellent photon energy resolution ($\Delta E_\gamma/E_\gamma$ ~ 2%)

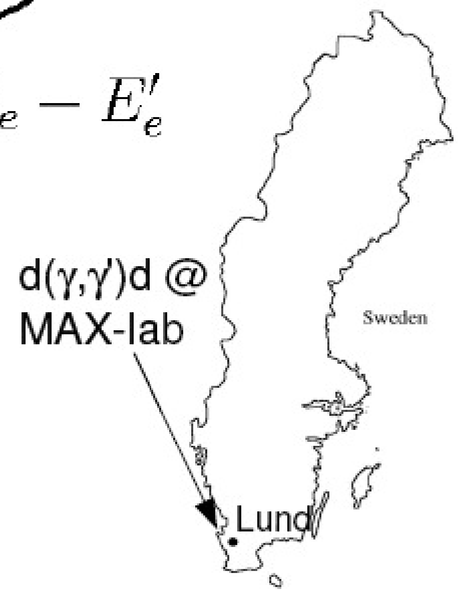


BUNI: Boston Univ.
CATS: Mainz Univ.
UK: Univ. of Kentucky

Experimental Setup





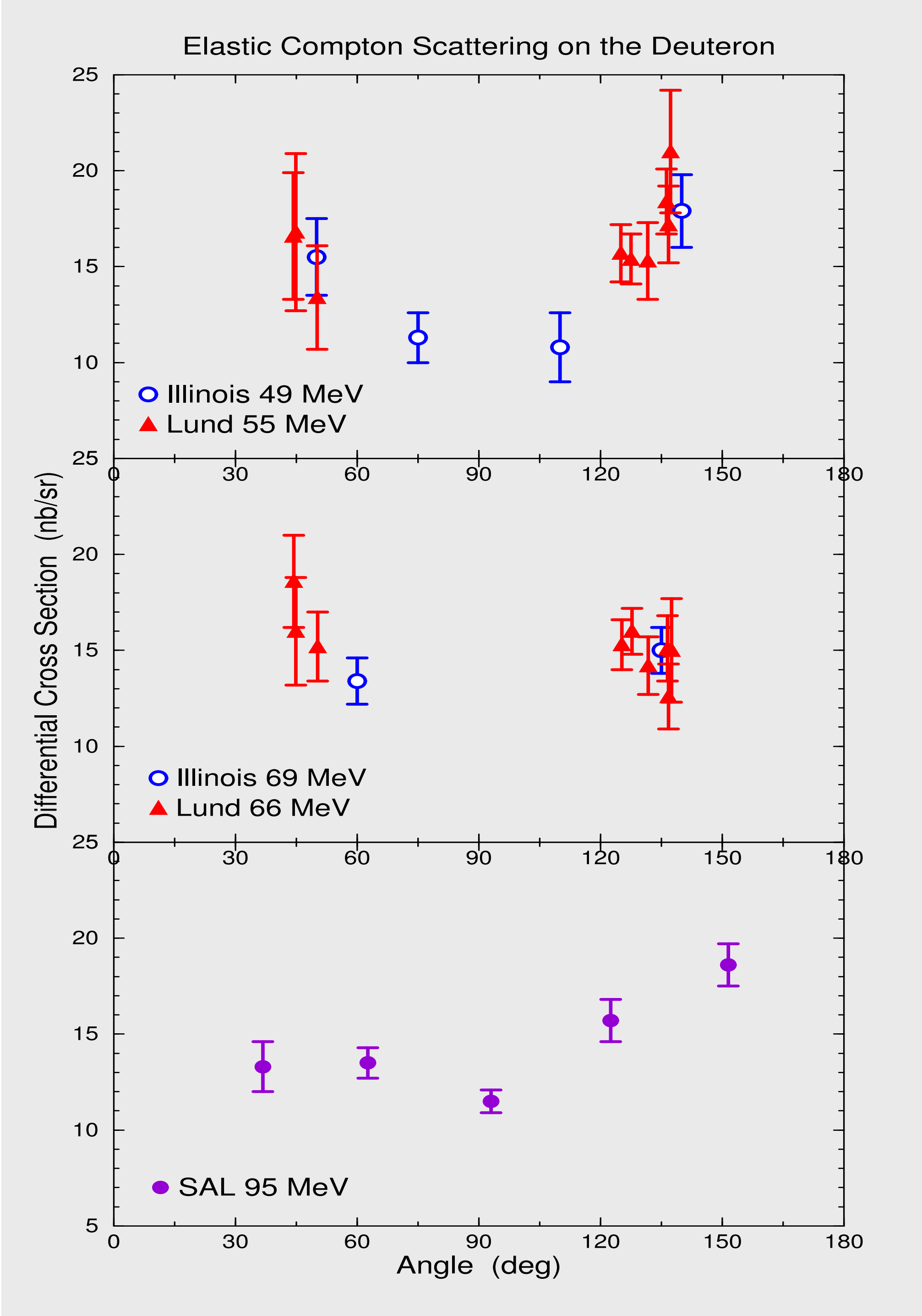


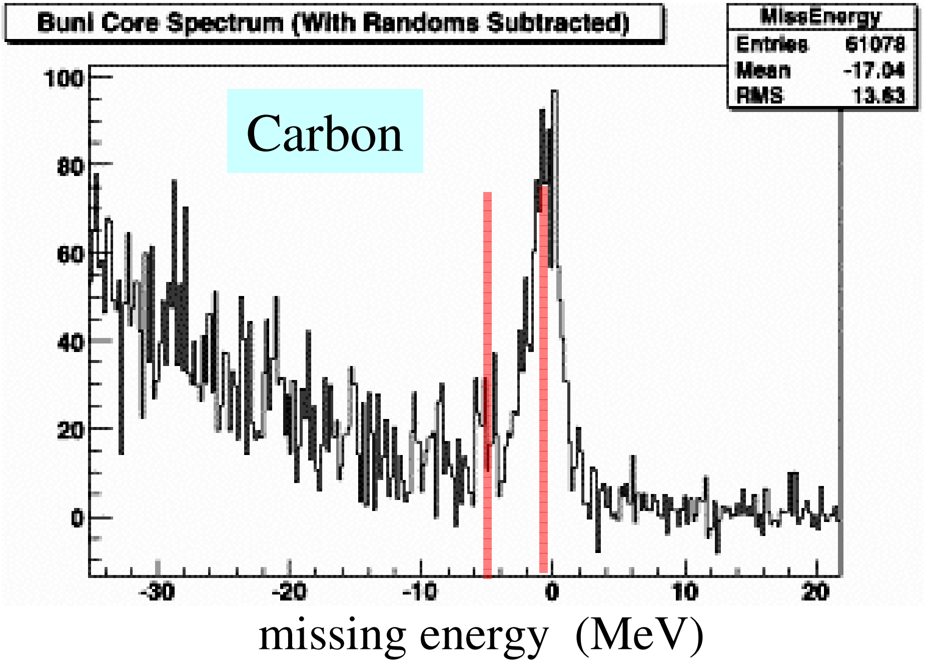
World Data Set

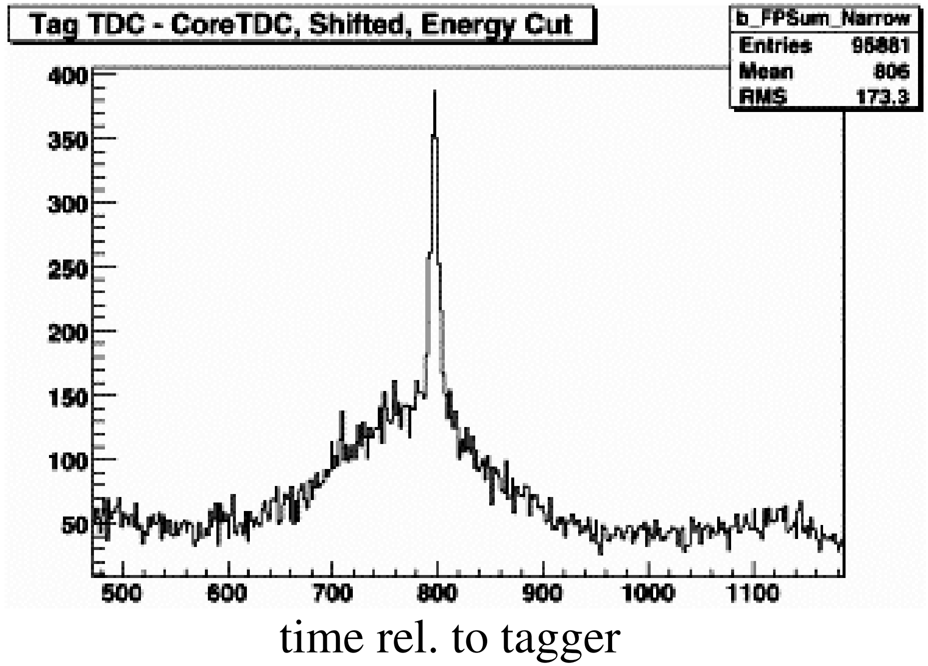
- **Lucas – Illinois (1994)**
  E_γ = 49, 69 MeV
- **Hornidge – SAL (2000)**
  E_γ = 85-105 MeV
- **Lundin – Lund (2003)**
  E_γ = 55, 66 MeV

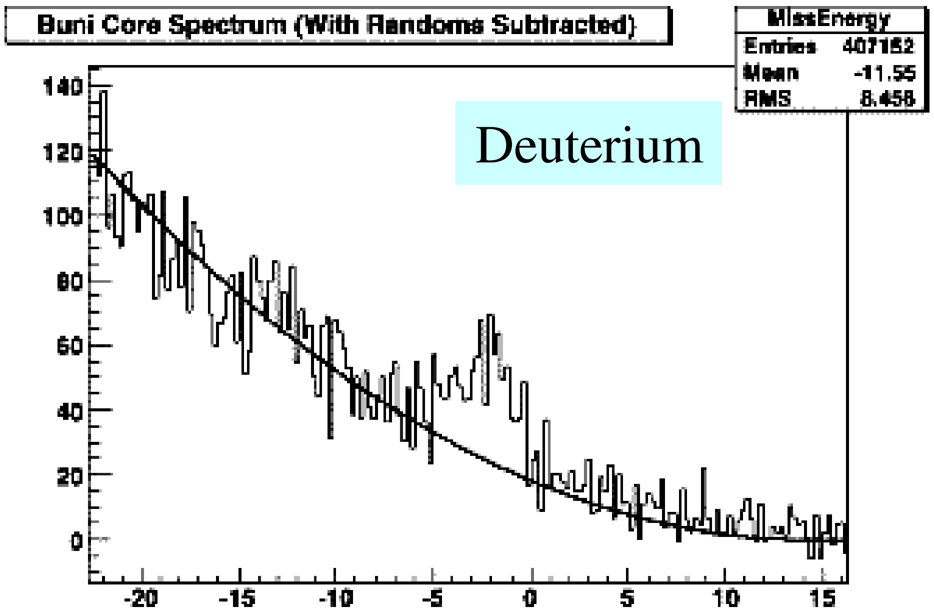
Thanks to Jerry Feldman

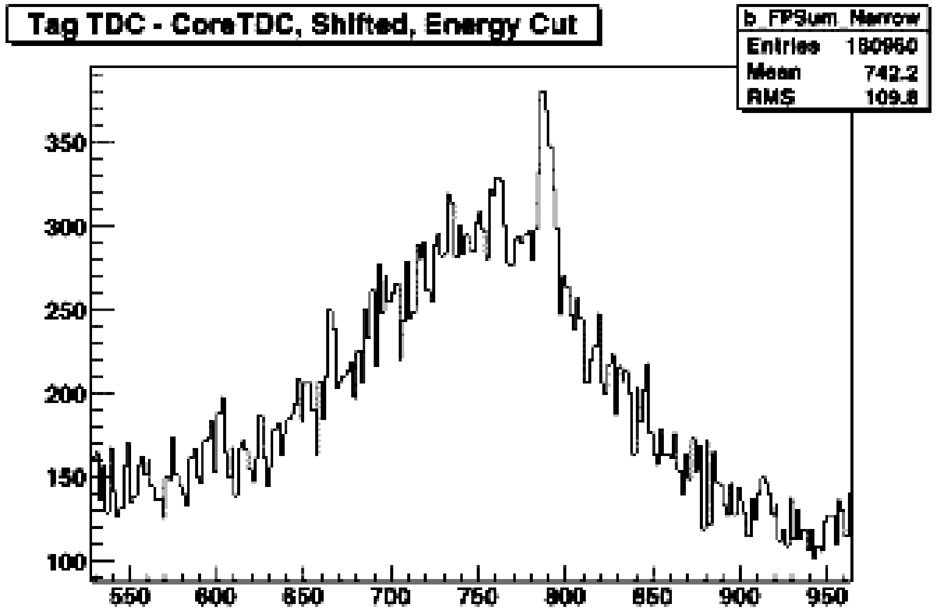
Berman



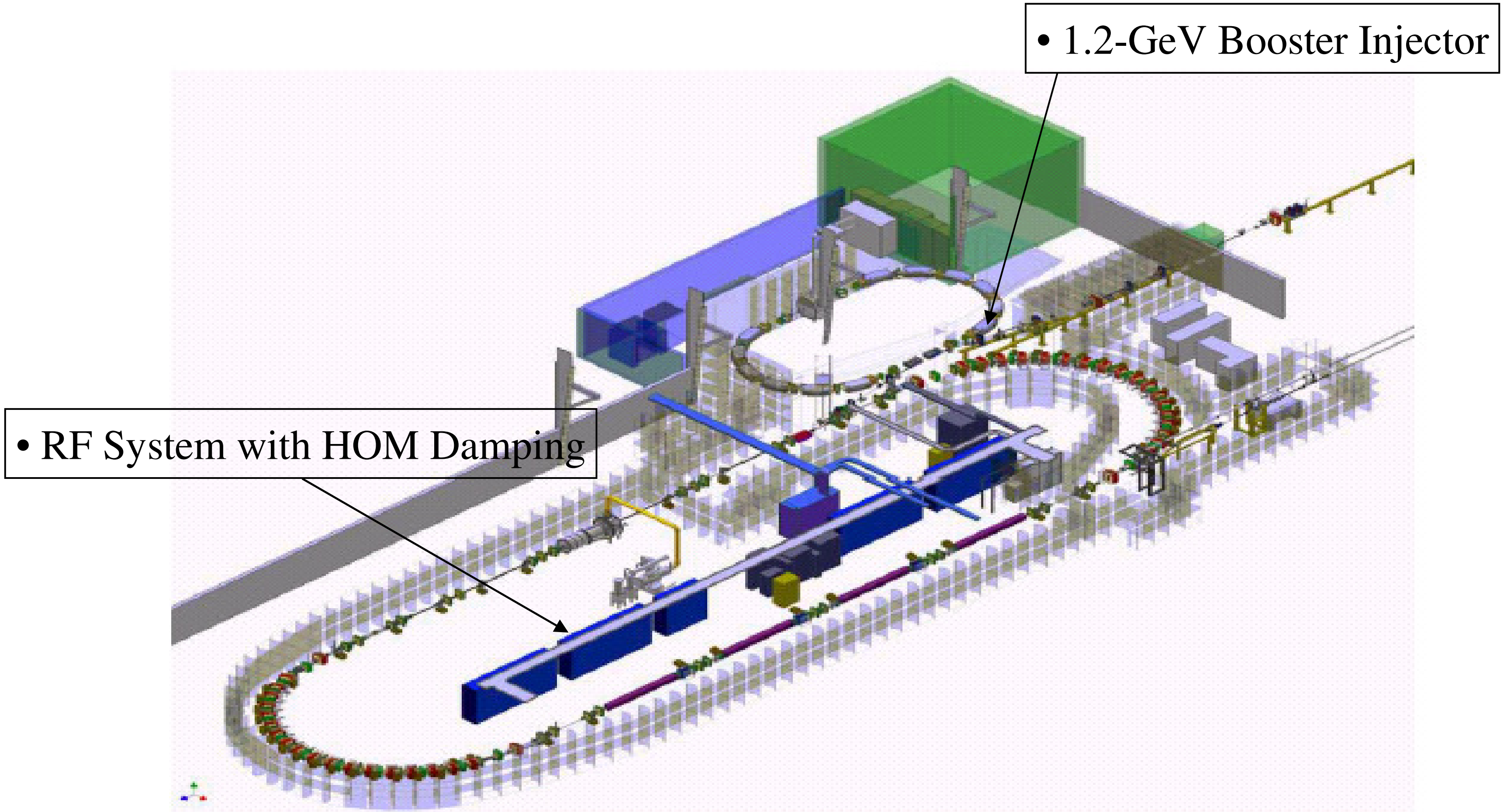

Buni Core Spectrum (With Randoms Subtracted)
MissEnergy
Entries 61078
Mean -17.04
RMS 13.63
Carbon
missing energy (MeV)


Tag TDC - CoreTDC, Shifted, Energy Cut
b_FPSum_Narrow
Entries 95881
Mean 806
RMS 173.3
time rel. to tagger


Buni Core Spectrum (With Randoms Subtracted)
MissEnergy
Entries 407152
Mean -11.55
RMS 8.458
Deuterium


Tag TDC - CoreTDC, Shifted, Energy Cut
b_FPSum_Narrow
Entries 180960
Mean 742.2
RMS 109.8

•Upgraded HIγS Facility

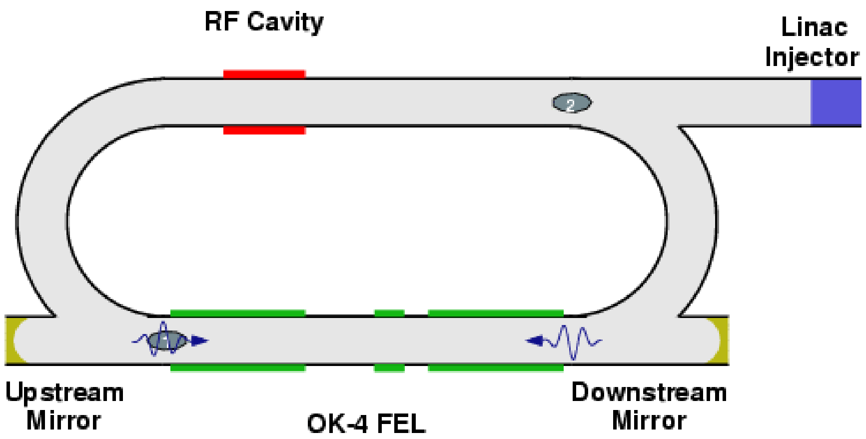


Thanks to Henry Weller

HIγS

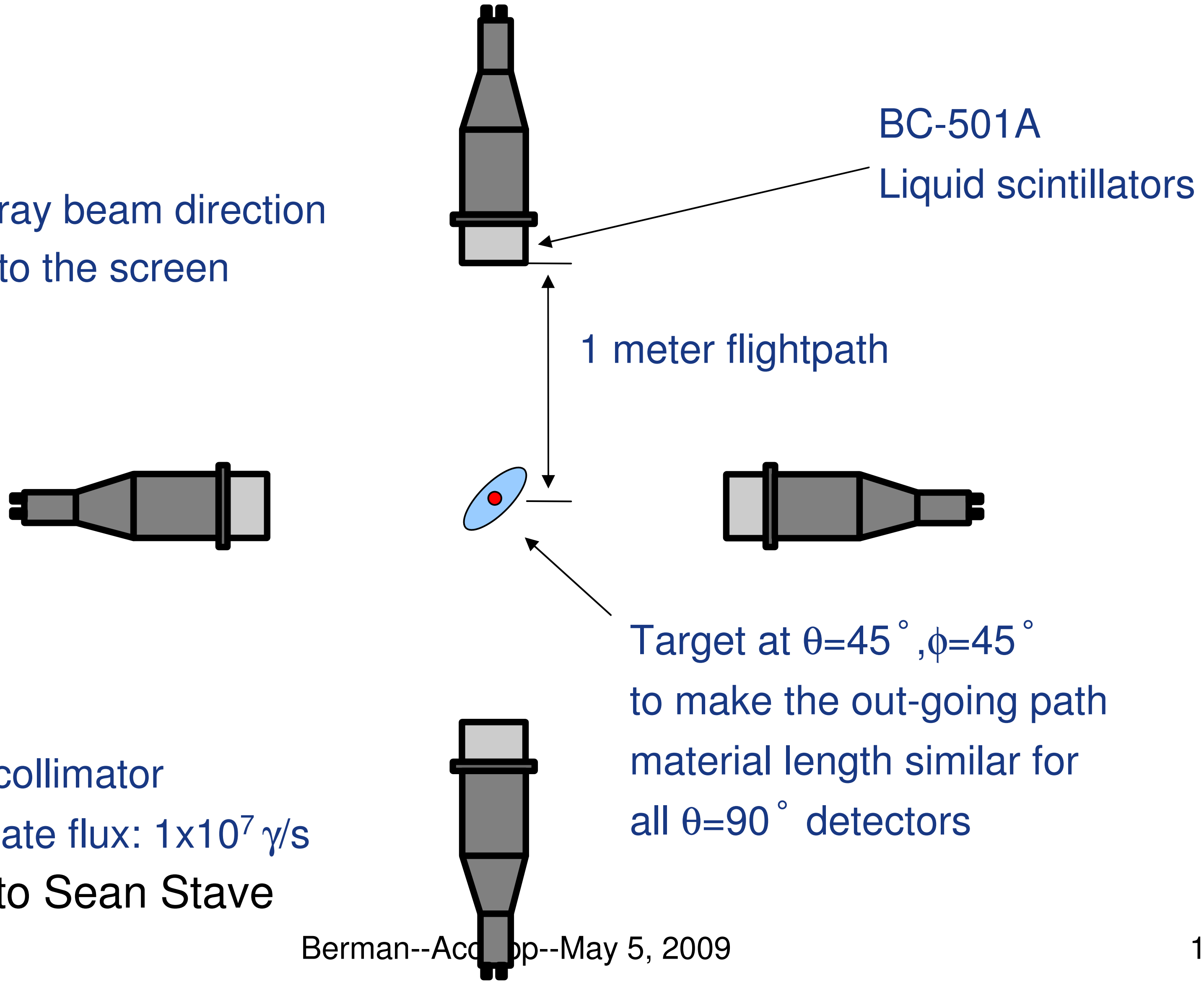
- ***Nearly Mono-energetic γ-rays from 2 to 160 MeV***
  - Tunable Energies
  - Energy resolution selected by collimator size
- ***Linearly and Circularly Polarized γ-rays***
- ***High Beam Intensities***
- ***Pulsed Beam***
  - TOF Techniques to reduce non-beam related backgrounds

Two Bunch Mode



Created by Brent Perdue, 2005

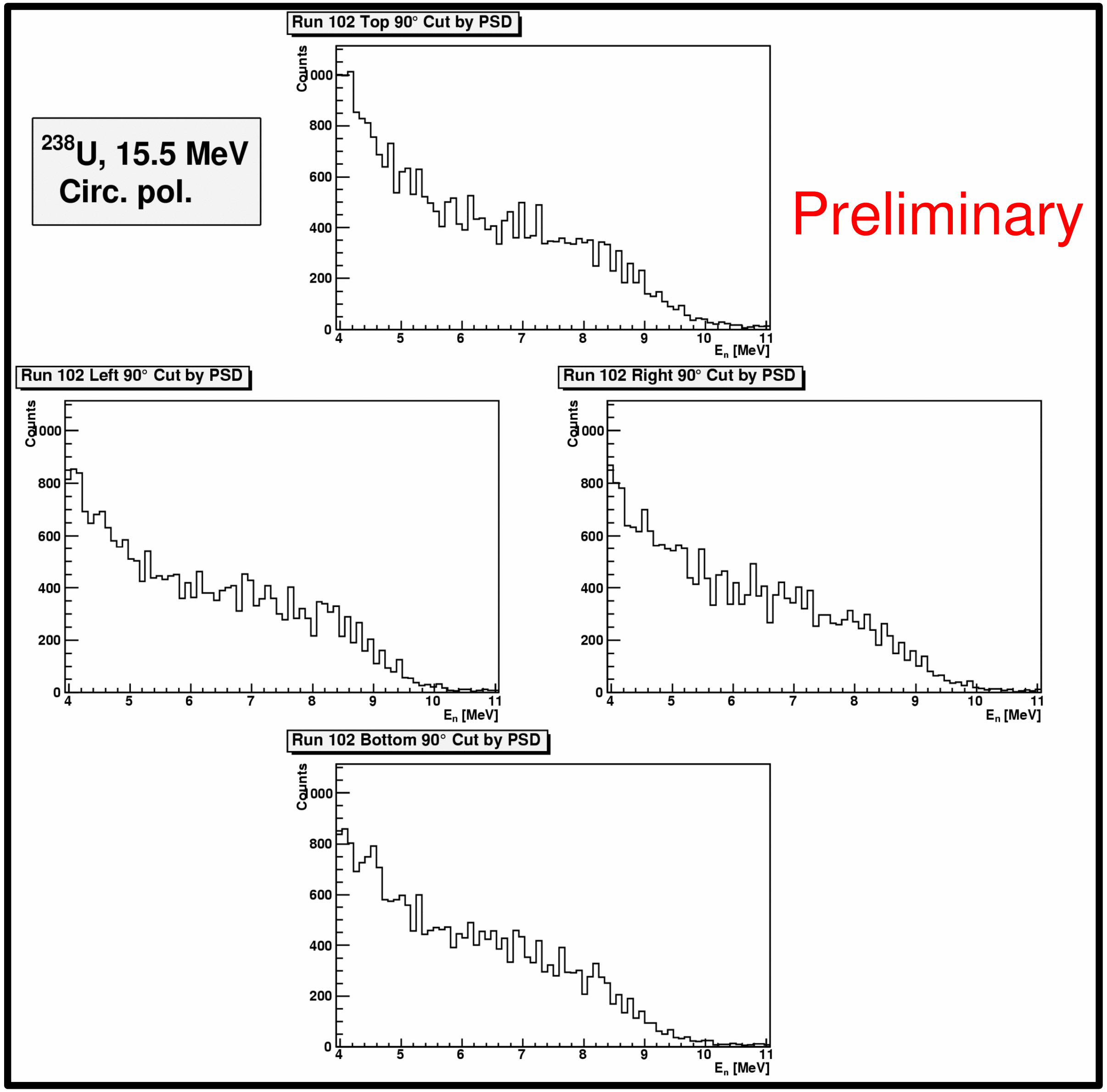
Experimental Setup



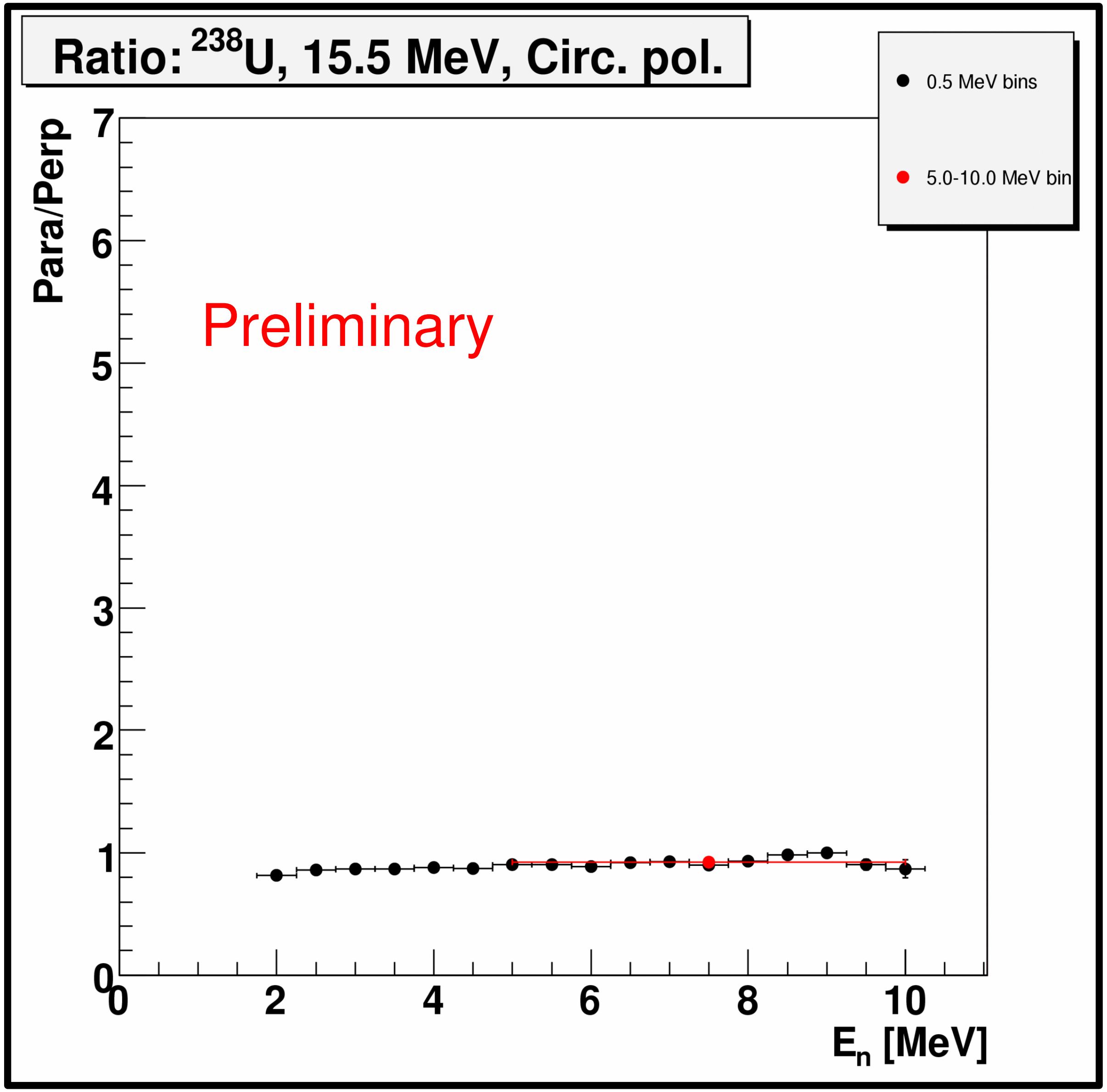
Using 1” collimator

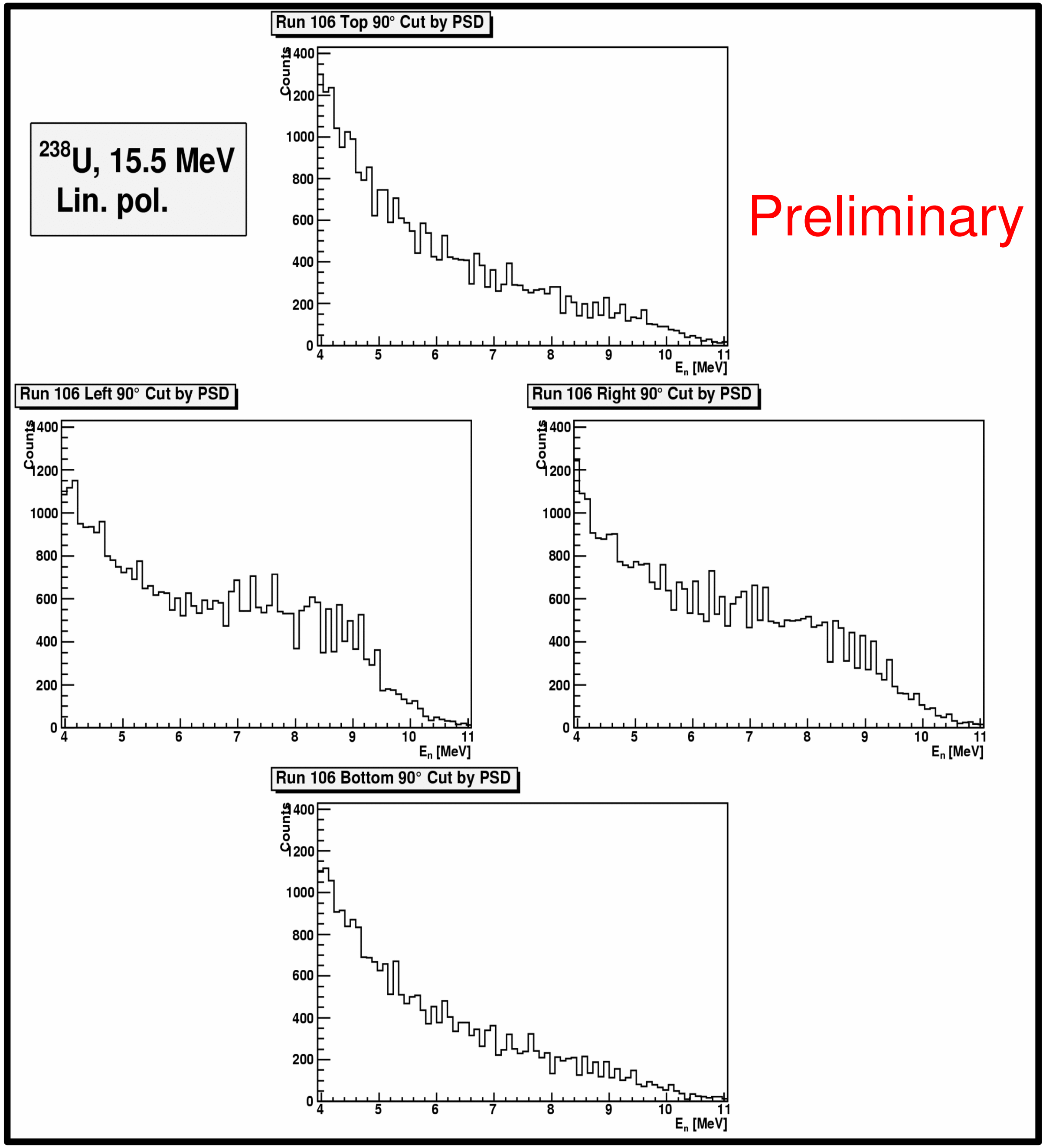
Approximate flux: 1×10^7 γ/s

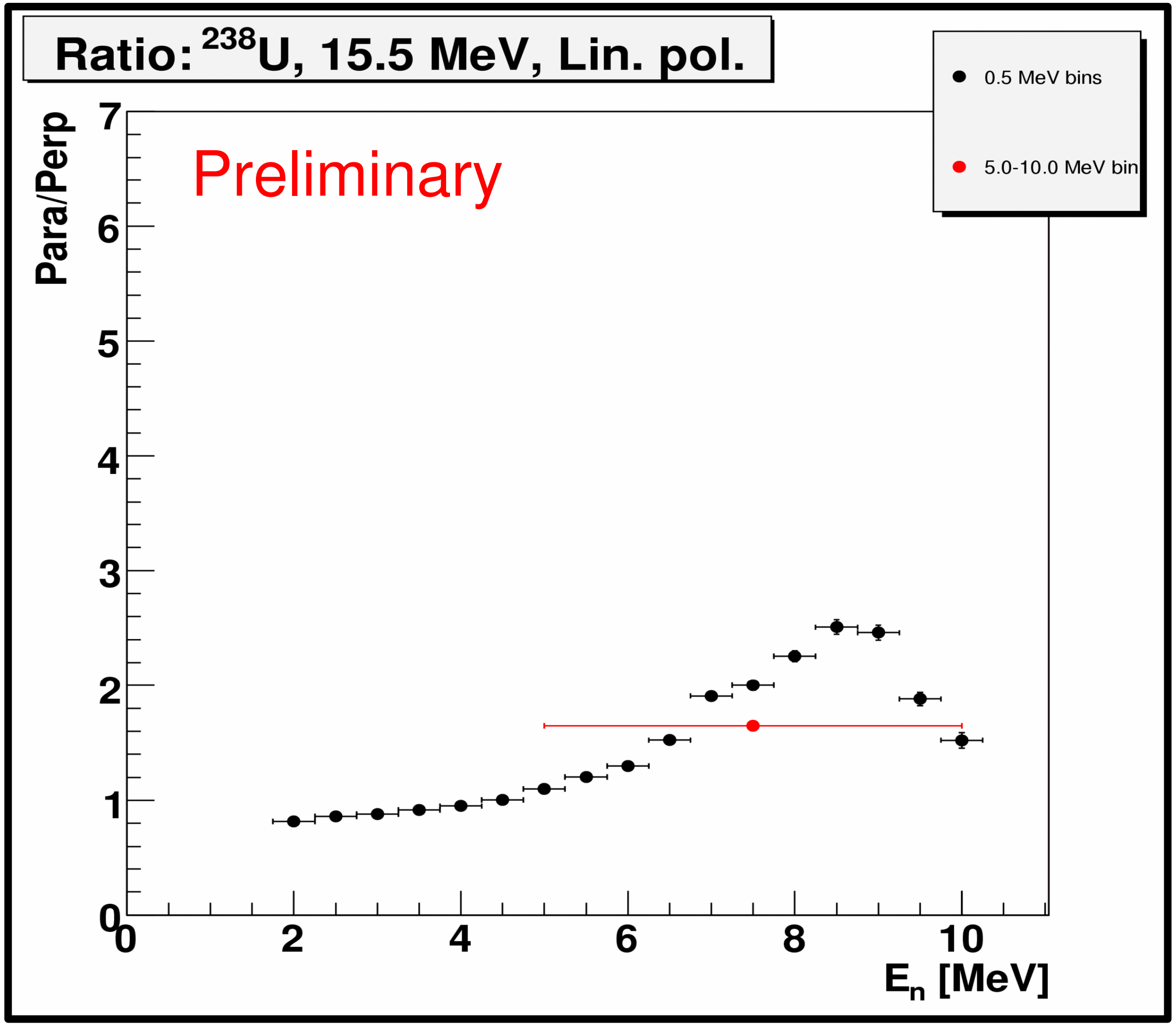
Thanks to Sean Stave



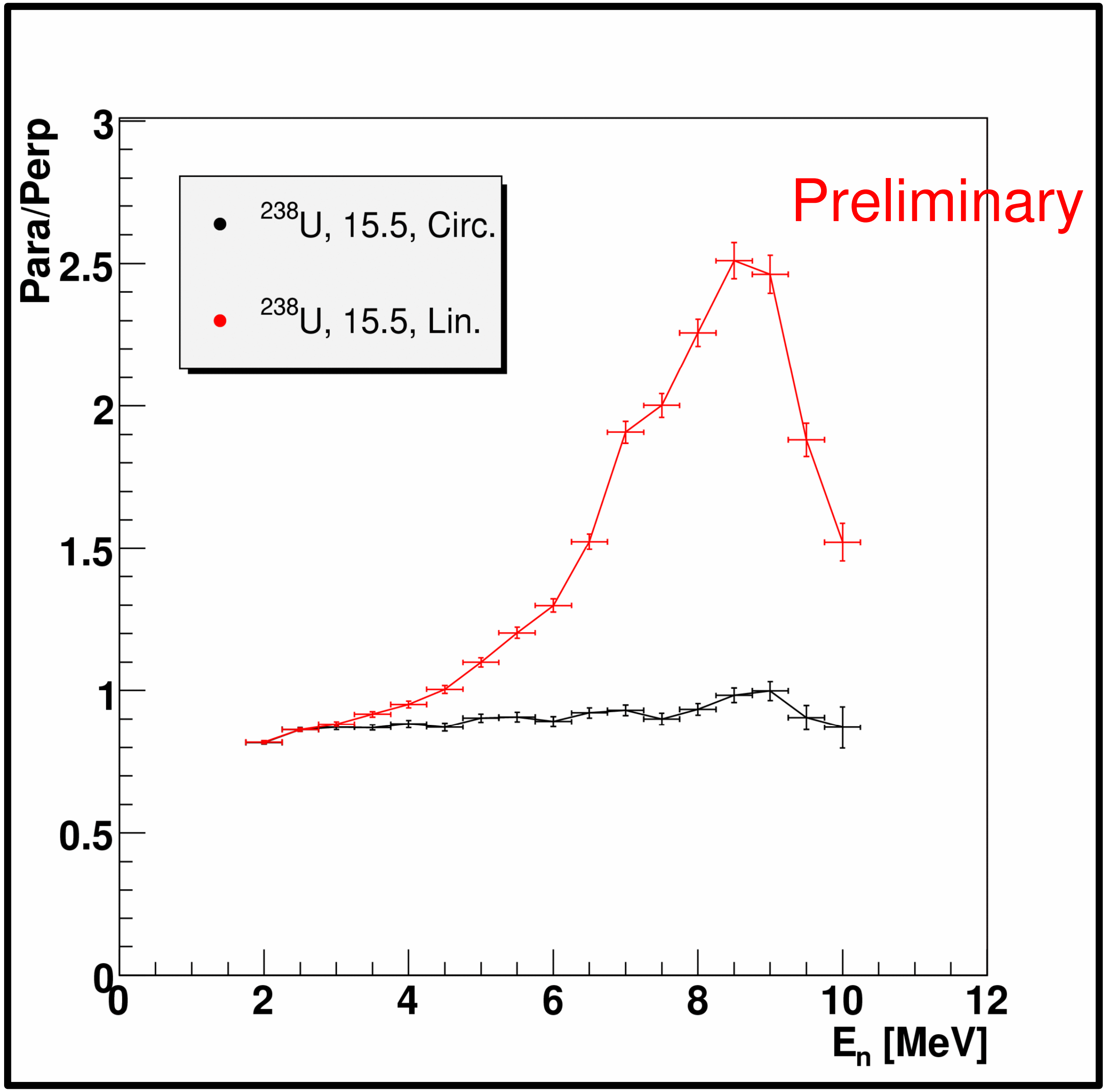
Preliminary

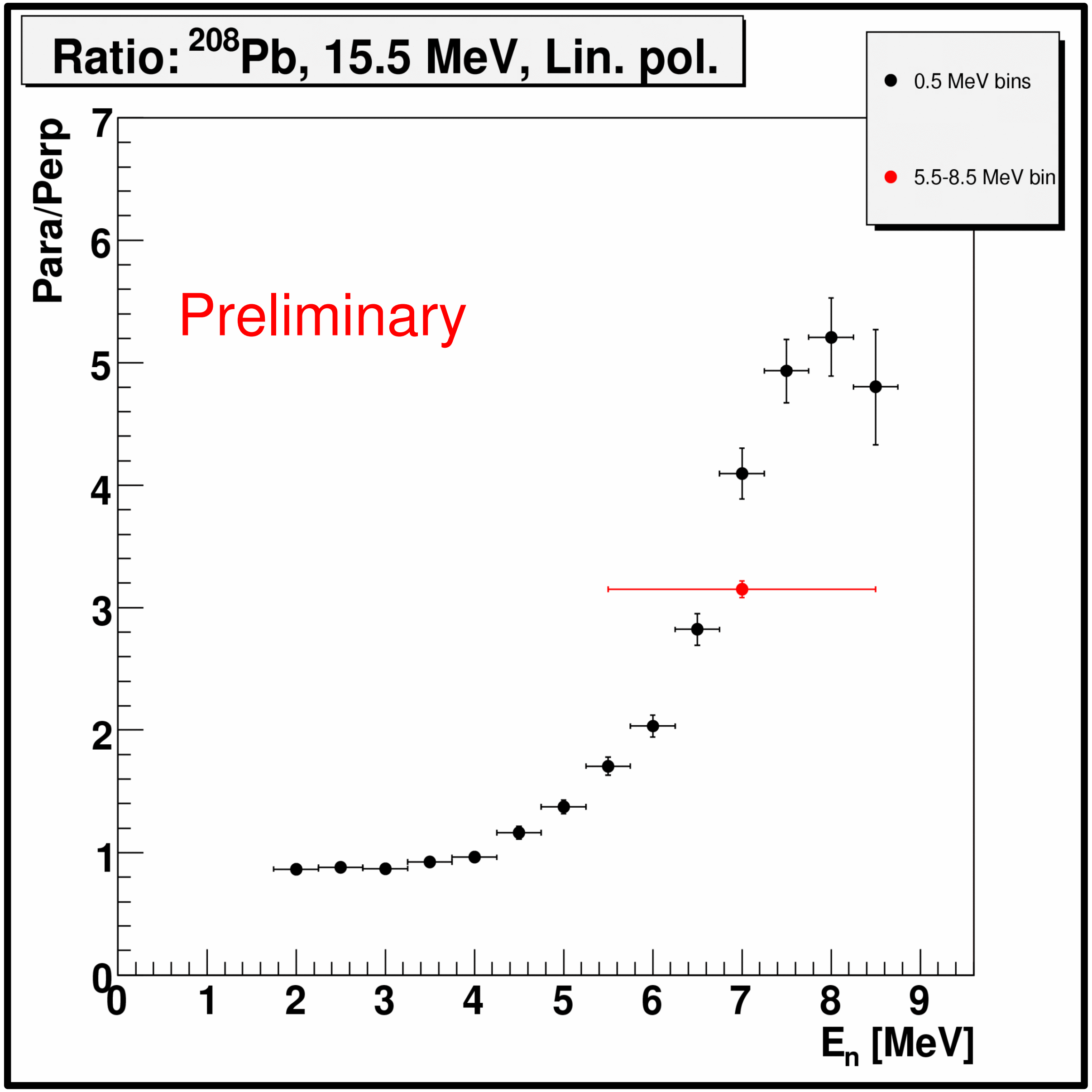

Ratio: 238U, 15.5 MeV, Circ. pol.
0.5 MeV bins
5.0-10.0 MeV bin
Para/Perp
Preliminary
0
1
2
3
4
5
6
7
0
2
4
6
8
10
En [MeV]


238U, 15.5 MeV
Lin. pol.
Preliminary
Run 106 Top 90° Cut by PSD
Run 106 Left 90° Cut by PSD
Run 106 Right 90° Cut by PSD
Run 106 Bottom 90° Cut by PSD
Counts
En [MeV]



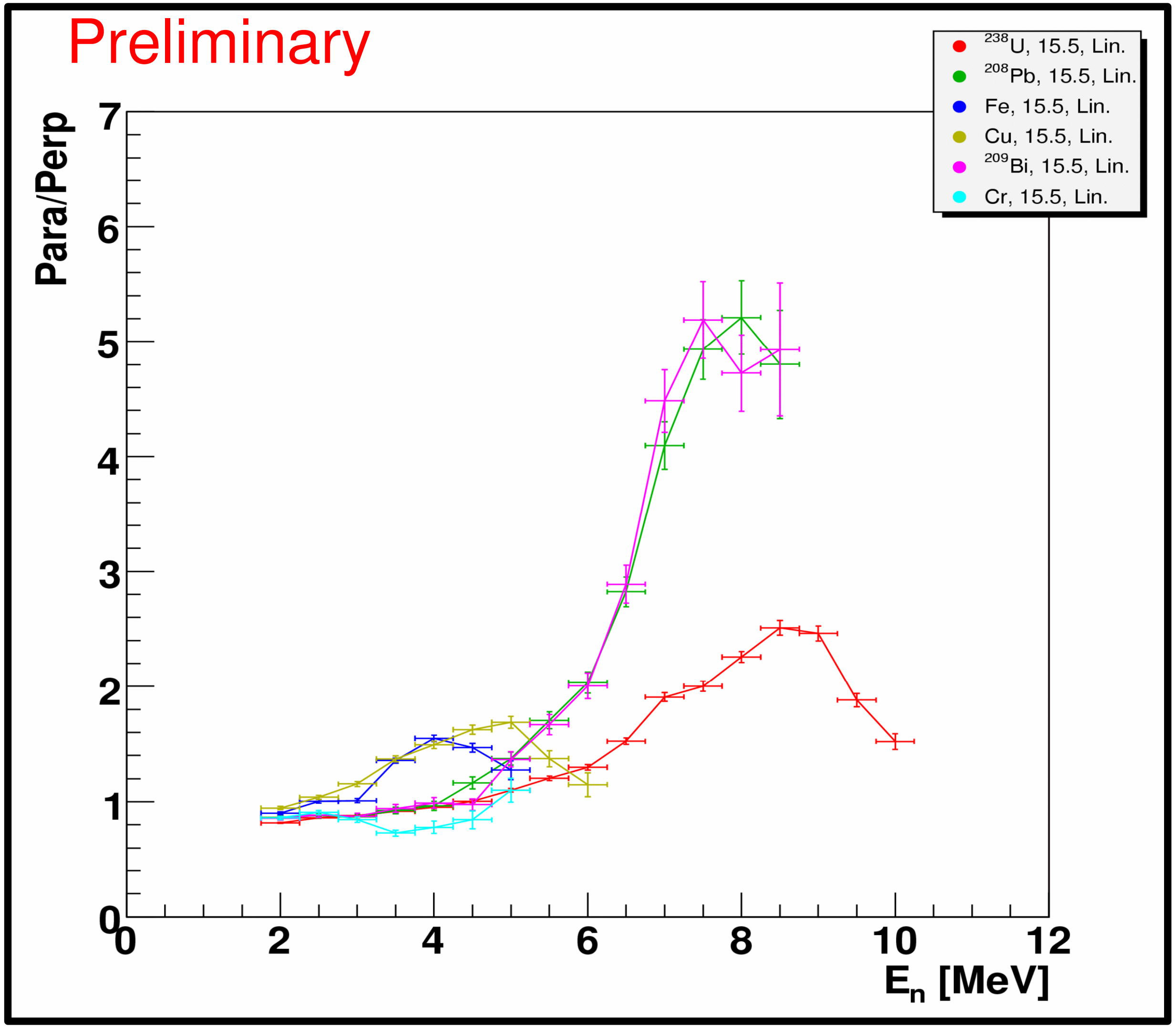
Ratio: 238U, 15.5 MeV, Lin. pol.
0.5 MeV bins
5.0-10.0 MeV bin
Preliminary
Para/Perp
0
1
2
3
4
5
6
7
0
2
4
6
8
10
En [MeV]


Para/Perp
3
2.5
2
1.5
1
0.5
0
0
2
4
6
8
10
12
E_n [MeV]
^{238}U, 15.5, Circ.
^{238}U, 15.5, Lin.
Preliminary



Ratio: 208Pb, 15.5 MeV, Lin. pol.
0.5 MeV bins
5.5-8.5 MeV bin
Para/Perp
Preliminary
0
1
2
3
4
5
6
7
8
9
E_n [MeV]

Elemental Identification



Summary and Prospects for the Future

- Although the main efforts in photonuclear physics have shifted to higher energies (notably at Jefferson Lab) in the past 25 years, the new facilities at MAX-lab and HIγS are now beginning to produce significant low-energy photonuclear data.
- At both MAX-lab and HIγS, important experiments on few-body nuclei have been done or are under way.
- At MAX-lab, the Compton-scattering experiments that are underway promise to help us to understand and quantify the hitherto elusive nucleon polarizabilities.
- At HIγS, Compton-scattering experiments with polarized photons will enable us to quantify their spin polarizabilities as well.
- At HIγS, new data on photoneutron spectra from heavy nuclei enable one to distinguish fissionable nuclei from others.
- Most exciting, the fact that we now have polarized monoenergetic photon beams with intensities comparable to or greater than the unpolarized beams of the past means that virtually the entire field of low-energy photonuclear reactions can be re-done, with the expectation of uncovering a wholly new generation of both basic and applied physics results.

–To be continued…