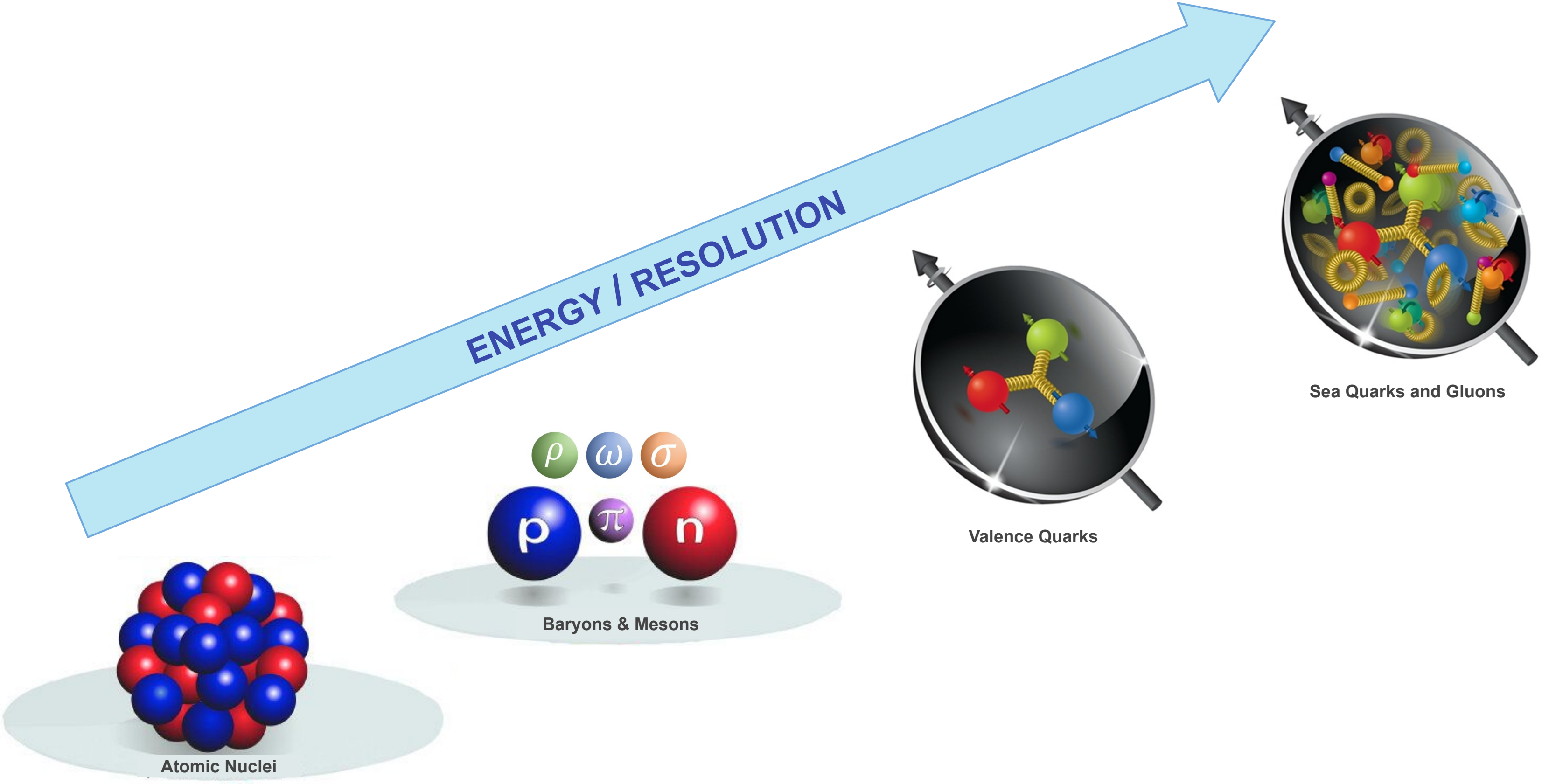
Investigating Nuclear Forces Through Low-Energy Polarization Observables

Thomas Krahulik
University of Virginia
August 22, 2024

Part I: The Nature of the Nuclear Force

Degrees of Freedom



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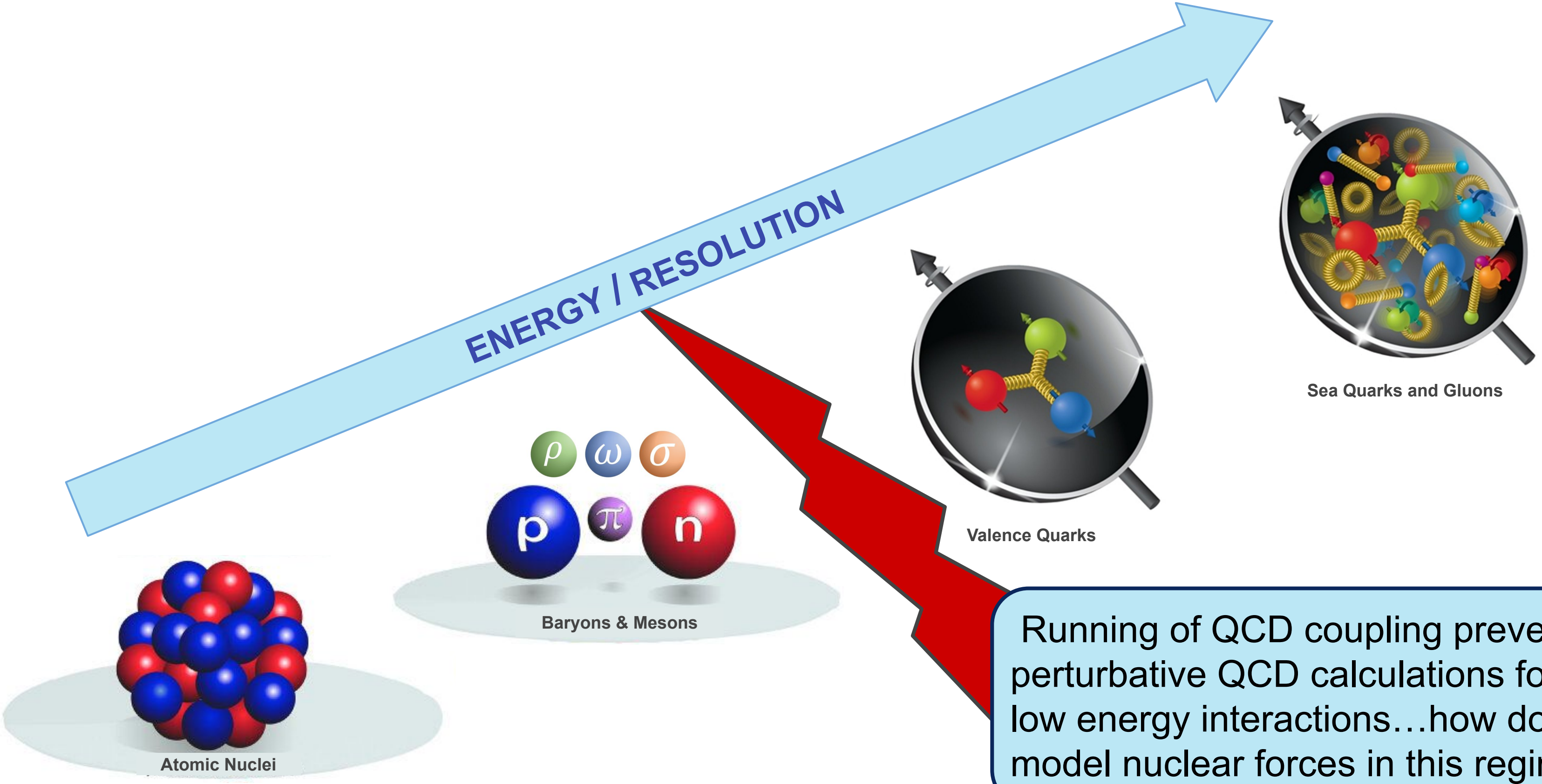
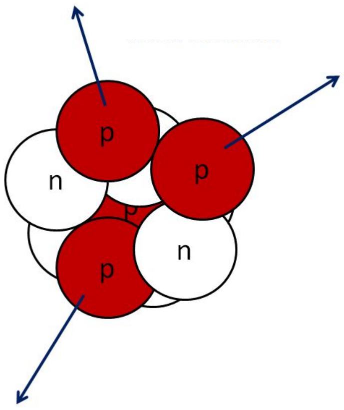
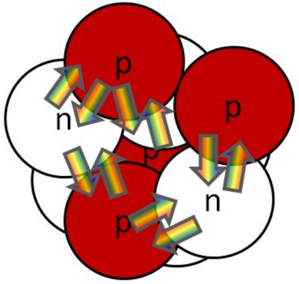


Running of QCD coupling prevents perturbative QCD calculations for low energy interactions…how do we model nuclear forces in this regime?

History: Yukawa’s Meson





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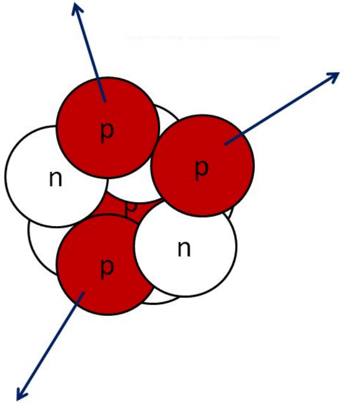

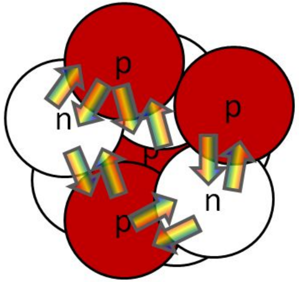

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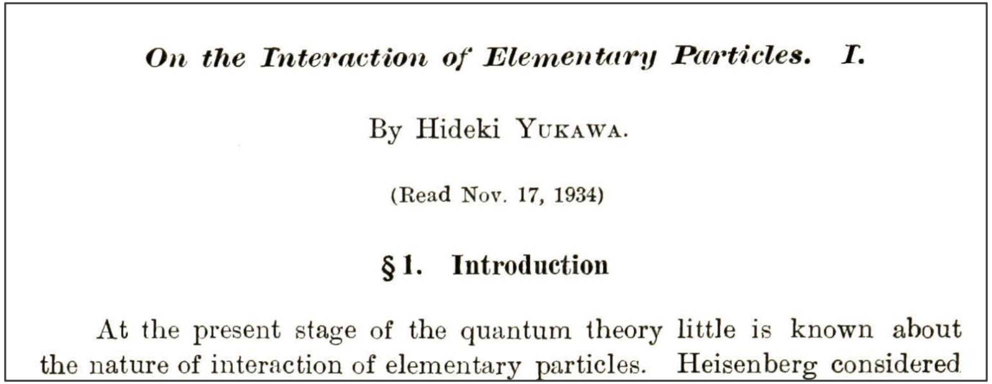
<u>1935:</u>
Massive mediator of nuclear force, based off photon in EM interactions.



On the Interaction of Elementary Particles. I.

By Hideki YUKAWA.

(Read Nov. 17, 1934)

§ 1. Introduction

At the present stage of the quantum theory little is known about the nature of interaction of elementary particles. Heisenberg considered

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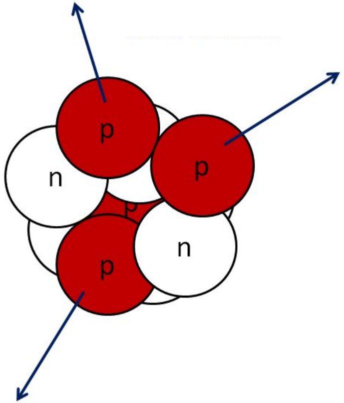

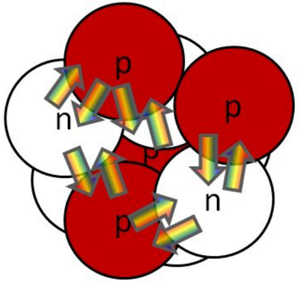

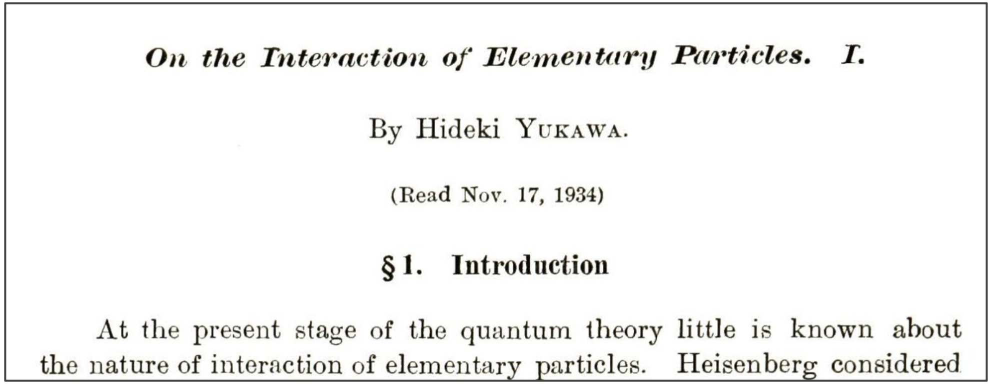

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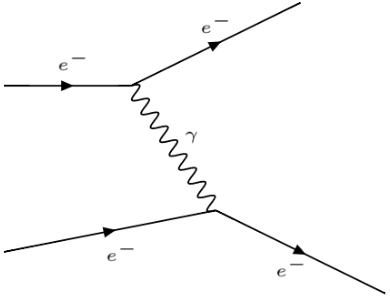

$$V(r) = \frac{q^2}{r}$$

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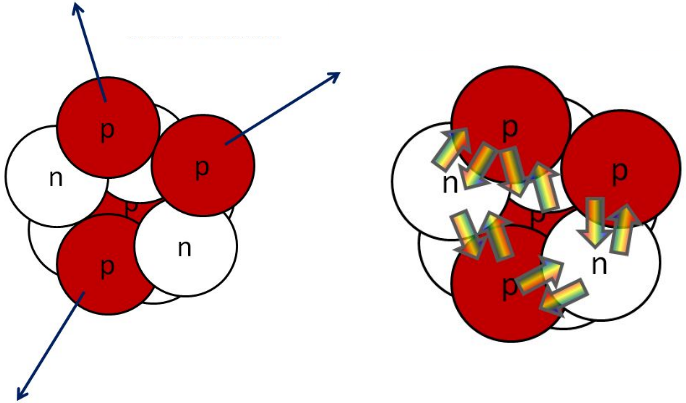

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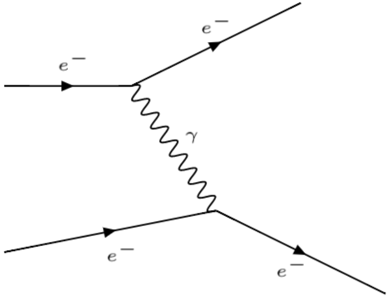

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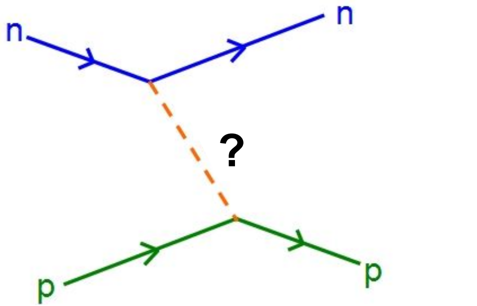

$$V(r) = -g^2 \frac{e^{-mr}}{r}$$

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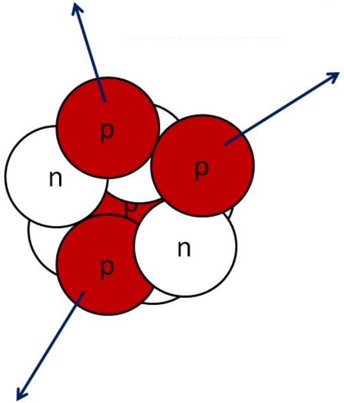

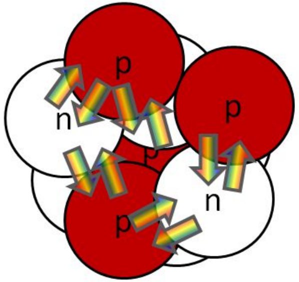

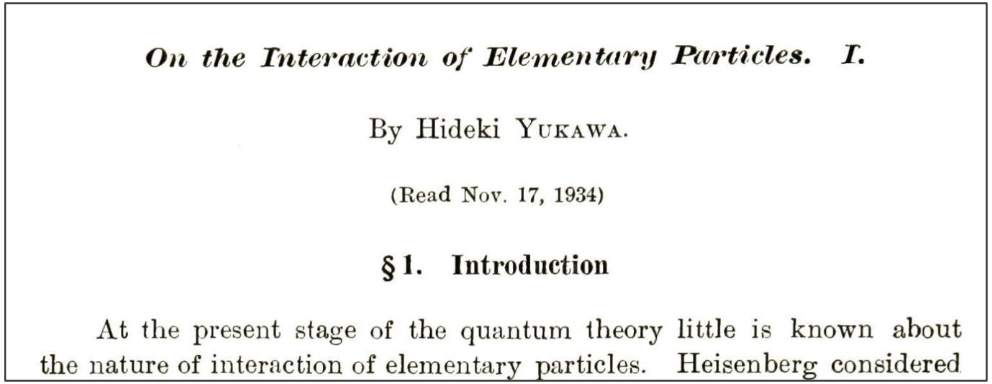

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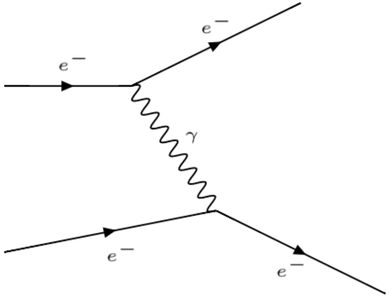

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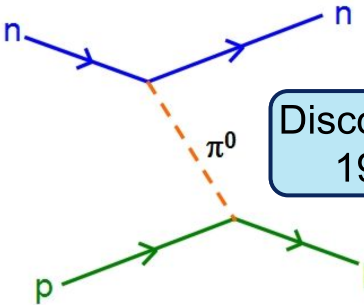

Discovered 1947

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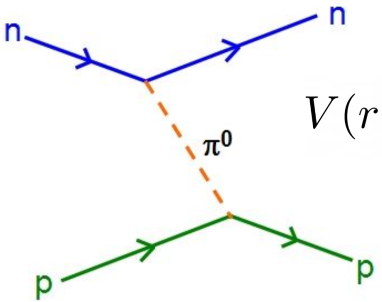
One Pion Exchange Potential



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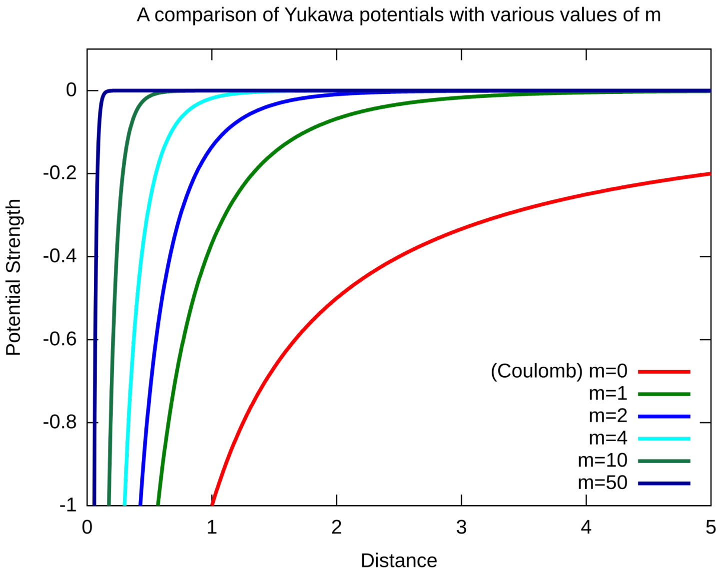

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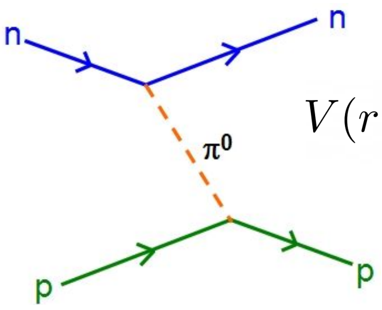

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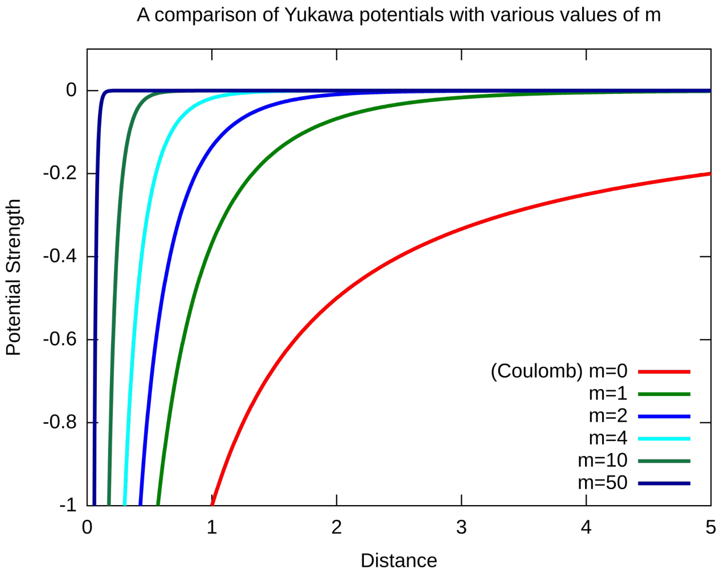
$$V_\pi(\vec{r}) = \frac{g^2}{3}(\vec{\tau_1}\cdot\vec{\tau_2})\left[\left(\vec{\sigma_1}\cdot\vec{\sigma_2}\right) + S_{12}(\vec{r})T(m_\pi r)\right]\frac{e^{-m_\pi r}}{r}$$

Yukawa Potential



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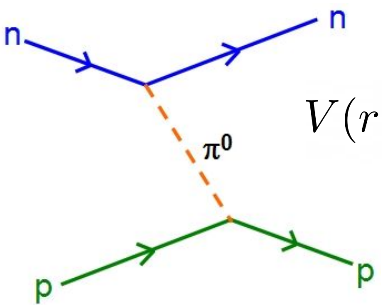

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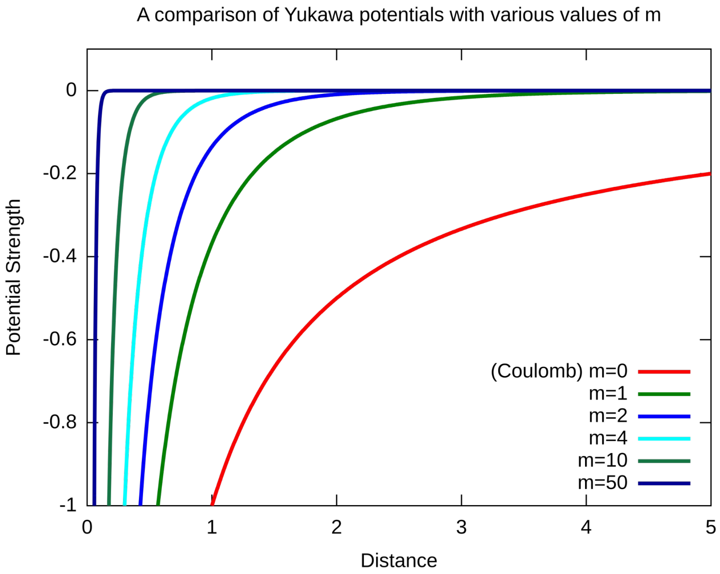

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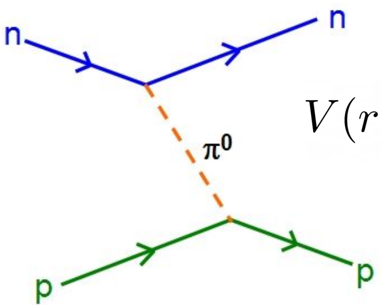
Isospin ("Flavor") Dependence

One Pion Exchange Potential



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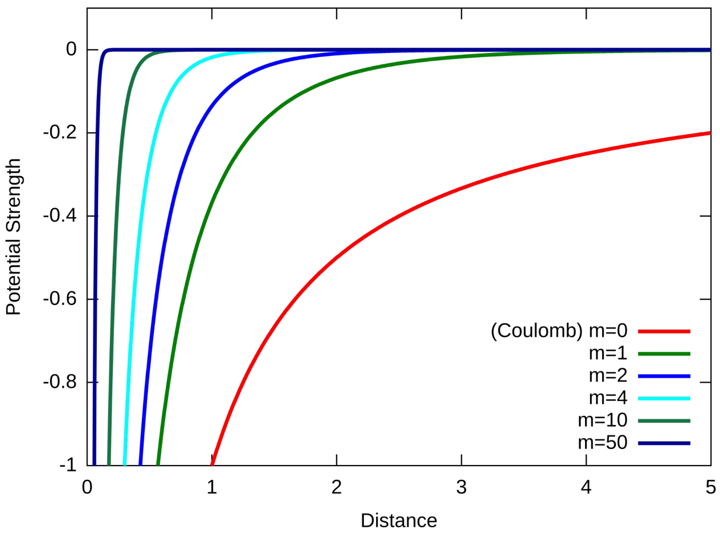
A comparison of Yukawa potentials with various values of m



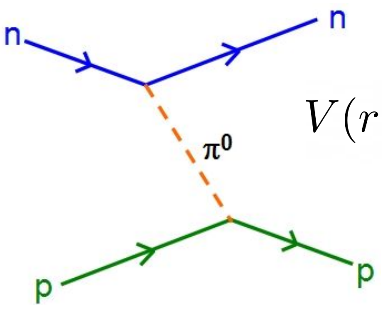
Spin-Spin Interaction

$$\vec{\sigma}_1\cdot\vec{\sigma}_2 = \begin{cases} -3\ (\text{singlet}) & \Longrightarrow \quad \vec{\tau}_1\cdot\vec{\tau}_2 = 1 \\ 1\ (\text{triplet}) & \Longrightarrow \quad \vec{\tau}_1\cdot\vec{\tau}_2 = -3 \end{cases}$$

Spin Tensor Force

- ➢ S_{12} = 0 for *pp, nn*
- ➢ S_{12} > 0 for *np*
- ➢ $S_{12}T$ very large for *np*
- ➢ Yields *np* Bound State!

One Pion Exchange Potential



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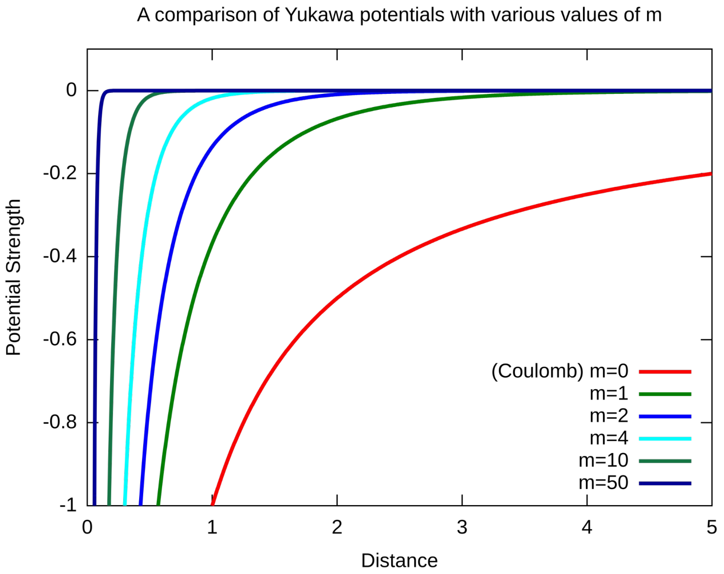
OPEP still struggles to accurately model short range interactions…



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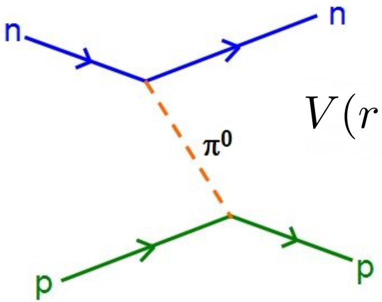

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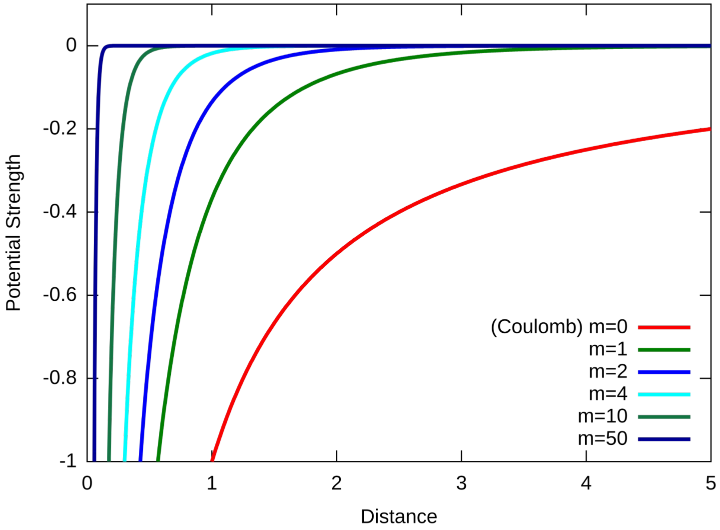
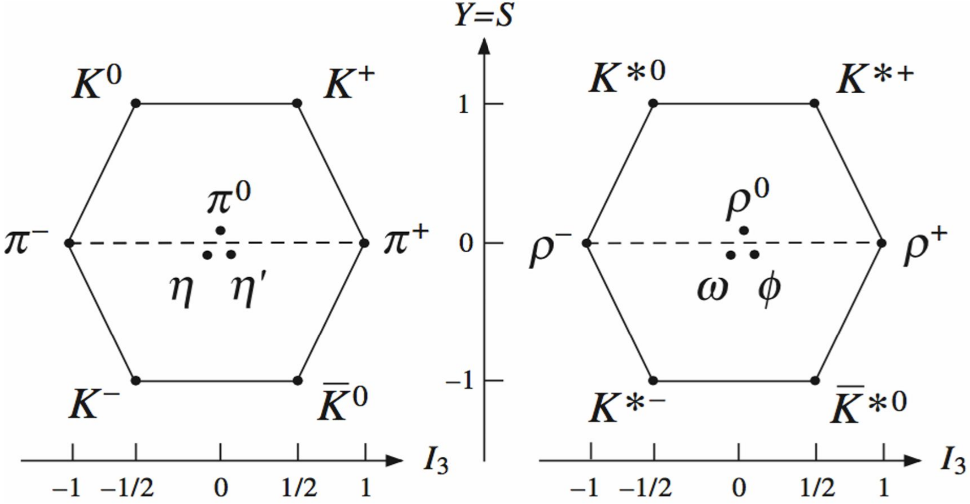
OPEP still struggles to accurately model short range interactions…

Improved with the addition of more mesons!

A comparison of Yukawa potentials with various values of m

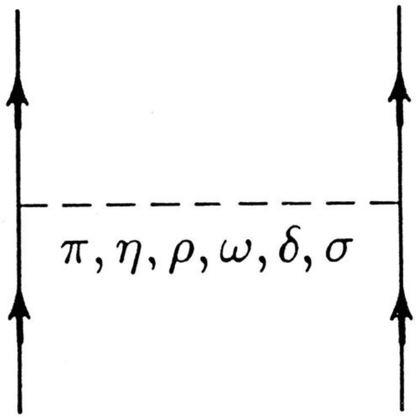


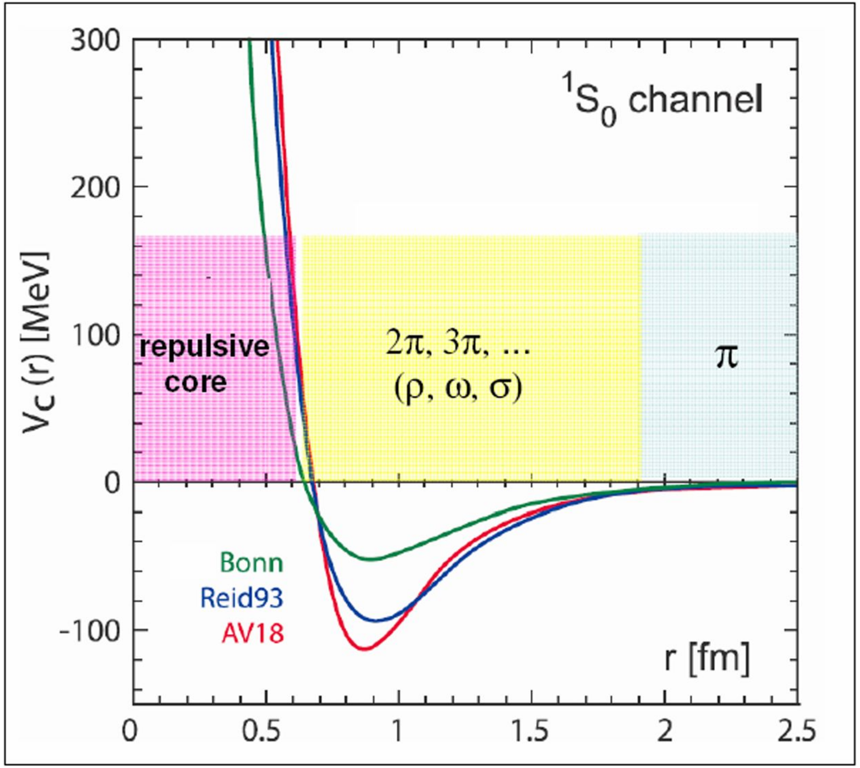


Meson Exchange Theory

One Boson Exchange Potential (OBEP)

$$V = \sum_{\alpha=\pi,\eta,\sigma,\rho,\omega,a_0} V_\alpha$$

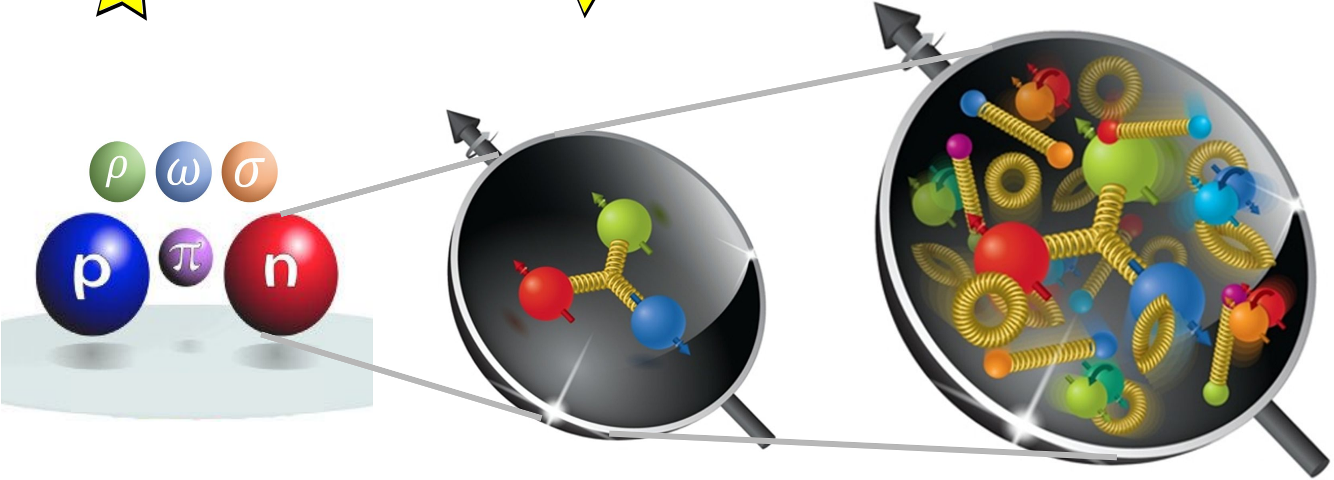




QCD developed in the 1970s and became widely accepted as *the* theory of the strong interaction.

$$\mathcal{L}_{QCD} \quad = \bar{\psi}_i\Big(i\gamma^\mu (D_\mu)_{ij} - m\delta_{ij}\Big)\psi_j - \tfrac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a$$

How do we handle low-energy (non-perturbative) QCD?
How do we reconcile QCD with Meson Exchange Theory?



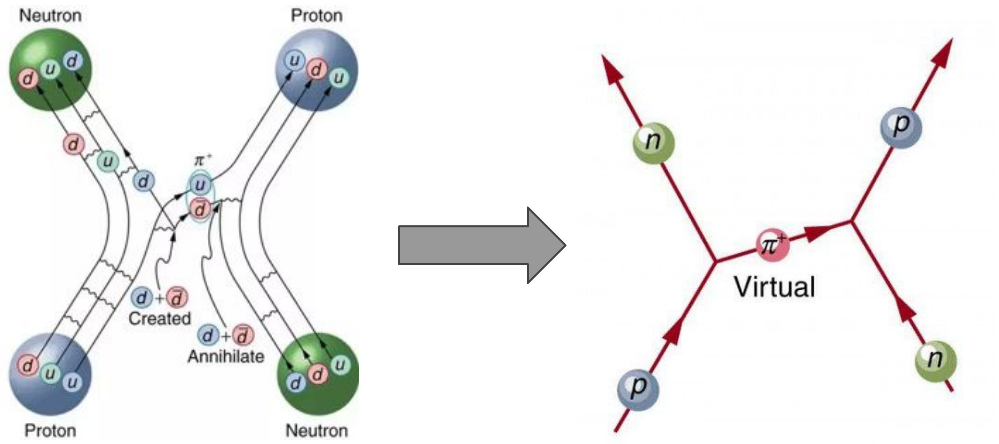
Chiral Effective Field Theory

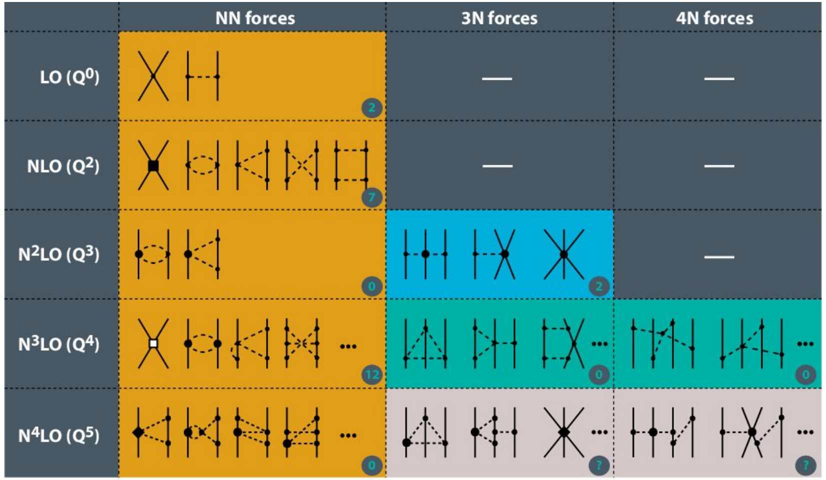
EFT treatment of strong interactions in massless quark limit, introducing **chiral symmetry**.

Chiral symmetry breaking results in pseudo-Goldstone boson - the pion - acting as a mediator for the strong force

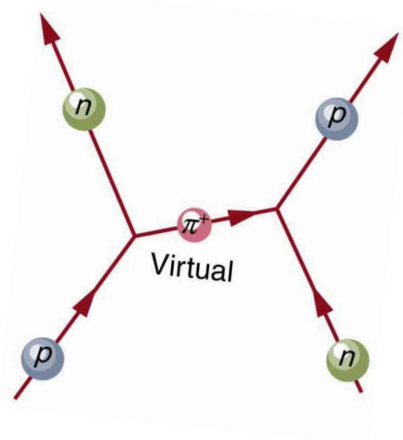
How To EFT:

1. Determine degrees of freedom
2. Identify relevant symmetries
3. Formulate general Lagrangian
4. Expand in low momentum
5. Calculate Feynman diagrams





Testing the Theory



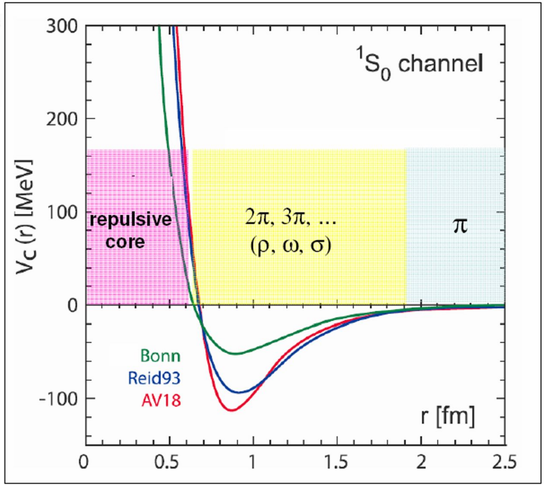


TABLE XIV. χ^2/datum for the CD-Bonn potential, the Nijmegen phase shift analysis [42], and the Argonne V_{18} potential [32] in regard to various databases discussed in the text.

	CD-Bonn potential	Nijmegen phase shift analysis	Argonne V_{18} potential
proton-proton data			
1992 *pp* database (1787 data)	1.00	1.00	1.10
After-1992 *pp* data (1145 data)	1.03	1.24	1.74
1999 *pp* database (2932 data)	1.01	1.09	1.35
neutron-proton data			
1992 *np* database (2514 data)	1.03	0.99	1.08
After-1992 *np* data (544 data)	0.99	0.99	1.02
1999 *np* database (3058 data)	1.02	0.99	1.07
***pp* and *np* data**			
1992 *NN* database (4301 data)	1.02	0.99	1.09
1999 *NN* database (5990 data)	1.02	1.04	1.21

TABLE XV. Deuteron properties.

	CD-Bonn	Empirical
Binding energy B_d (MeV)	2.224575	2.224575(9)
Deuteron effective range $\rho_d = \rho(-B_d, -B_d)$ (fm)	1.765	1.765(9)
Asymptotic S state A_S (fm$^{-1/2}$)	0.8846	0.8846(9)
Asymptotic D/S state η	0.0256	0.0256(4)
Matter radius r_d (fm)	1.966	1.971(6)
Quadrupole moment Q_d (fm^2)	0.270[a]	0.2859(3)
D-state probability P_D (%)	4.85	

[a] Without meson current contributions and relativistic corrections.

Tables Source: R. Machleidt (2000)

Theories are compared to world data of scattering cross sections and bound state properties.

Tunable parameters within each model have led to high degree of consistency with experimental data.

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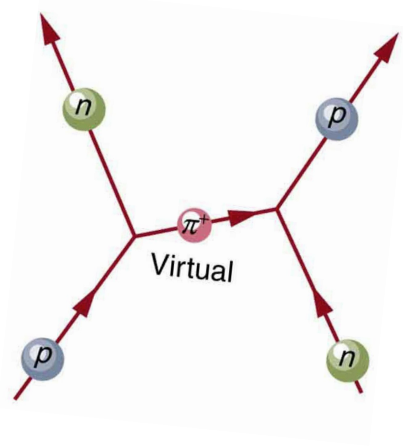

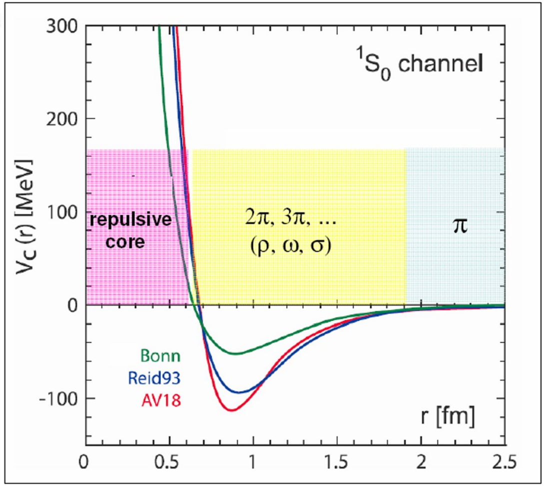

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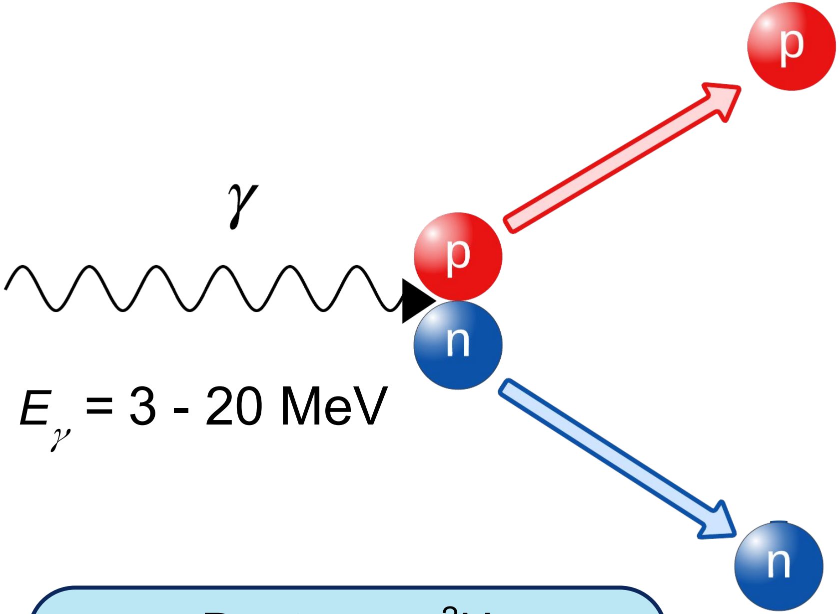
Investigate **polarization observables** to further probe nucleon interactions and perform rigorous tests of nuclear potential models and EFTs.

Studying the Deuteron



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Deuteron - ^2H

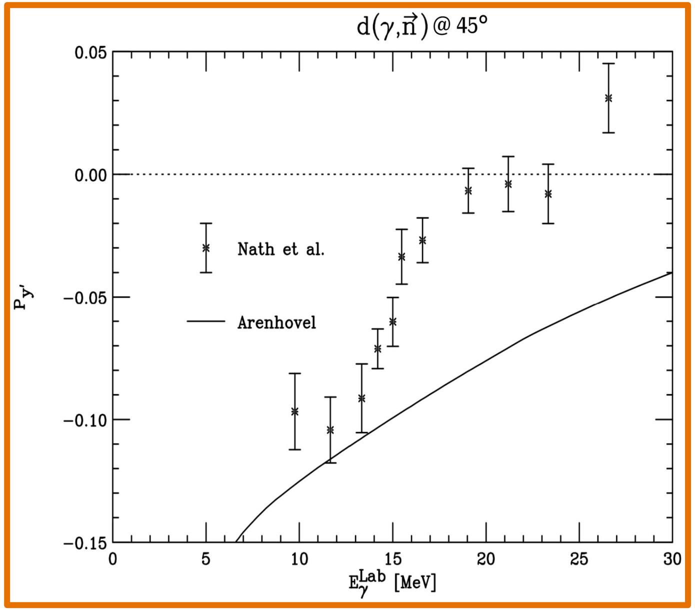
- ➢ Smallest multibody nucleus
- ➢ Mass = 1875.6 MeV
- ➢ Binding Energy = 2.2 MeV
- ➢ Spin = 1 : Spin Triplet

$d(\gamma,n)p$ offers insight into:

- ➢ Nucleon-Nucleon Interactions
- ➢ Big Bang Nucleosynthesis
- ➢ Astrophysical Bodies such as Neutron Stars

Emergent Problems in d(γ,n)p

"Neutron Polarization Puzzle"



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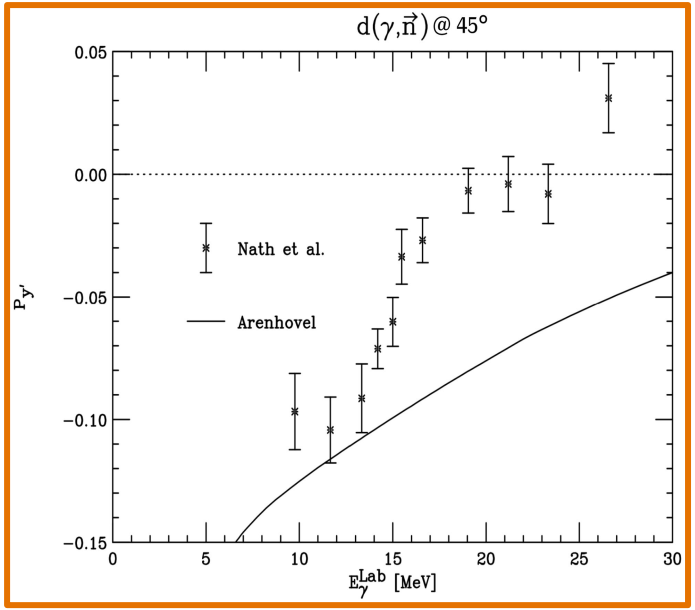

GDH Sum Rule

$$\int_0^\infty \frac{d\omega}{\omega}\Big(\sigma_P(\omega) - \sigma_A(\omega)\Big) = -4S\pi^2\alpha\frac{\kappa^2}{m^2}$$

Cross sections for inelastic photonuclear reactions with spin polarized targets

κ = Anomalous Magnetic Moment of Target

Emergent Problems in d(γ,n)p

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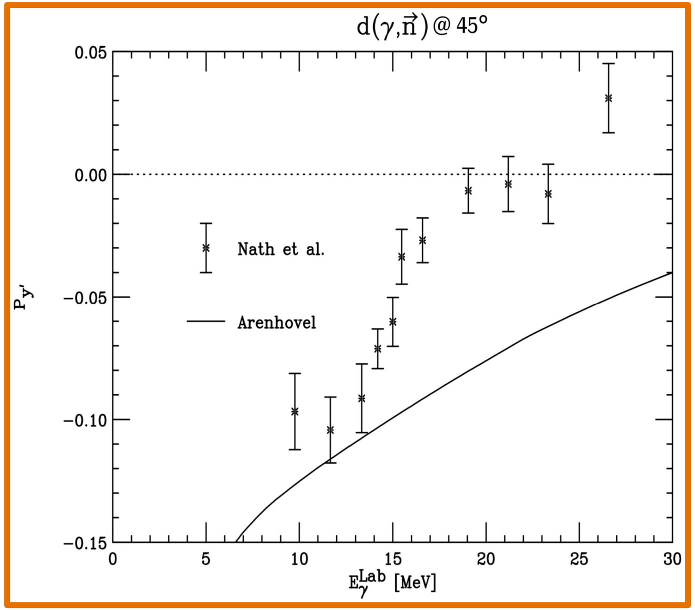

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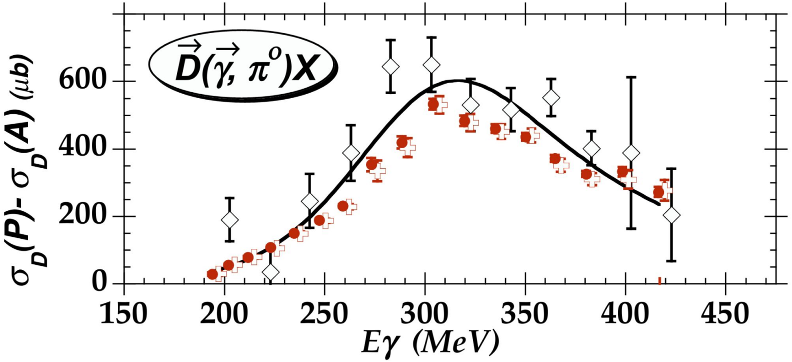
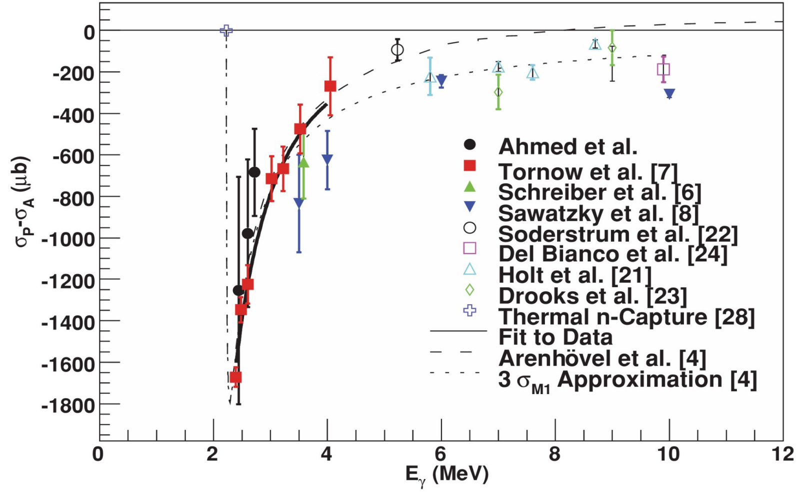
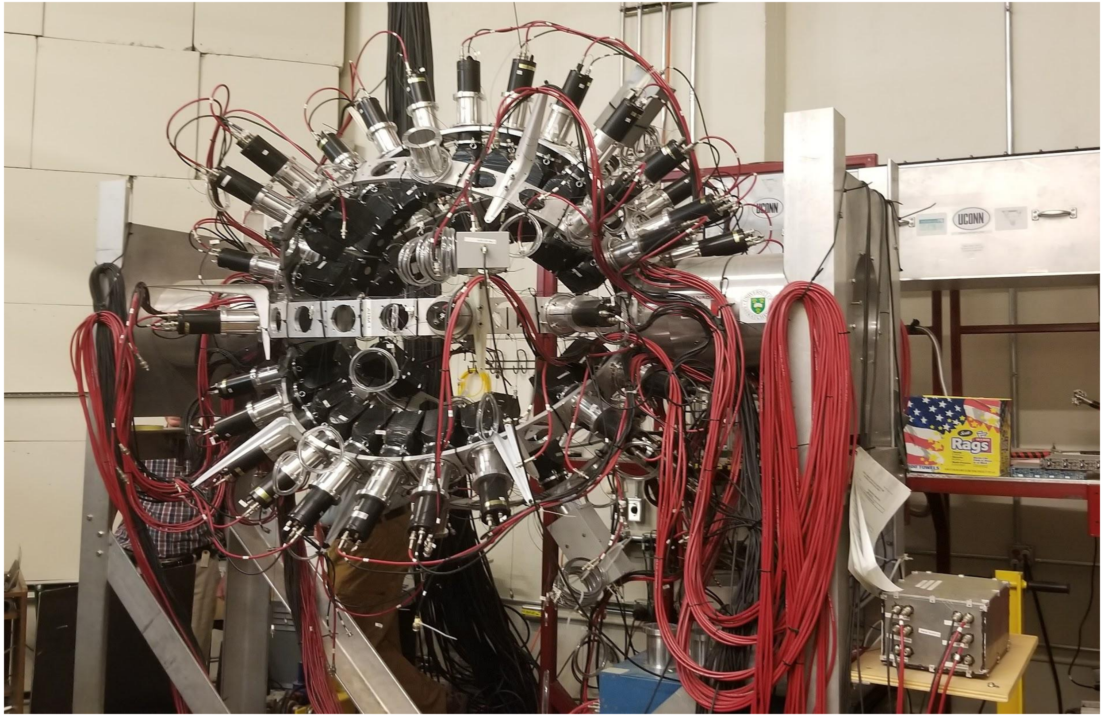




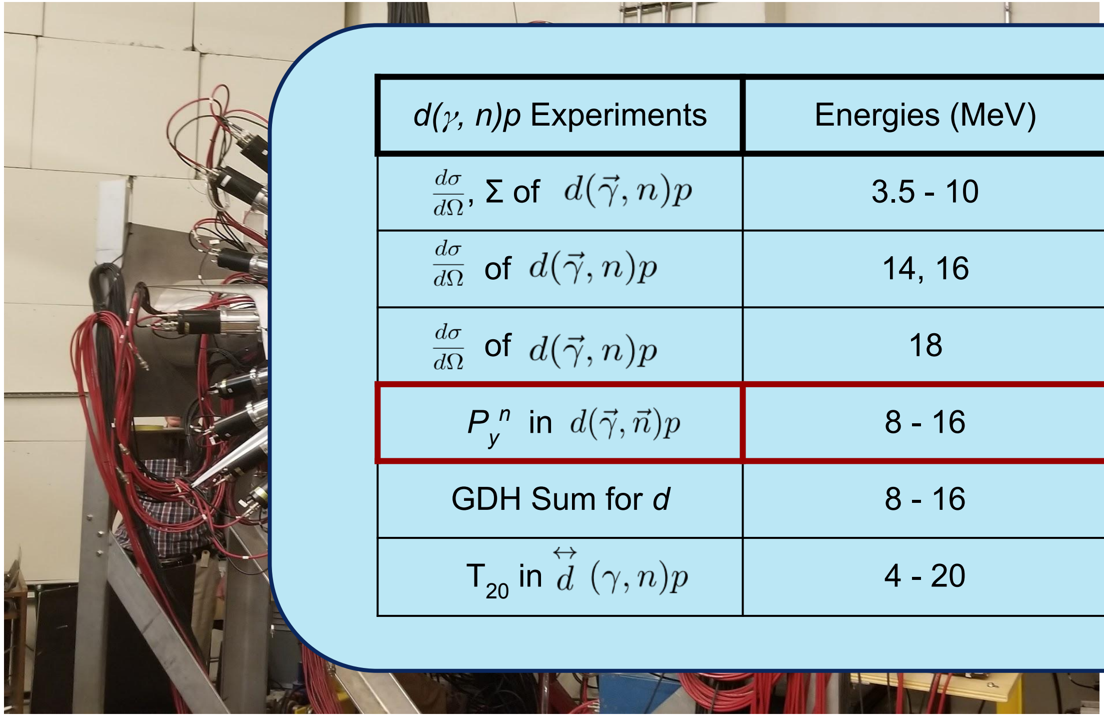
Background: d(γ,n)p Studies

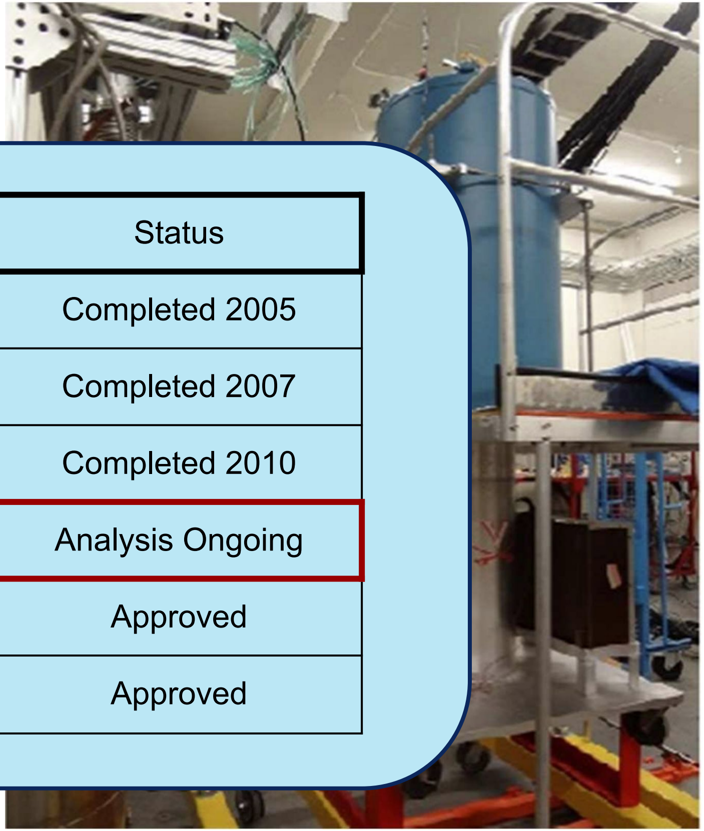


Blowfish Detector

HIγS Frozen Spin Target System

Background: $d(\gamma,n)p$ Studies





$d(\gamma, n)p$ Experiments	Energies (MeV)	Status
$\frac{d\sigma}{d\Omega}$, Σ of $d(\vec{\gamma},n)p$	3.5 - 10	Completed 2005
$\frac{d\sigma}{d\Omega}$ of $d(\vec{\gamma},n)p$	14, 16	Completed 2007
$\frac{d\sigma}{d\Omega}$ of $d(\vec{\gamma},n)p$	18	Completed 2010
P_y^n in $d(\vec{\gamma},\vec{n})p$	8 - 16	Analysis Ongoing
GDH Sum for *d*	8 - 16	Approved
T_{20} in $\overleftrightarrow{d}(\gamma,n)p$	4 - 20	Approved

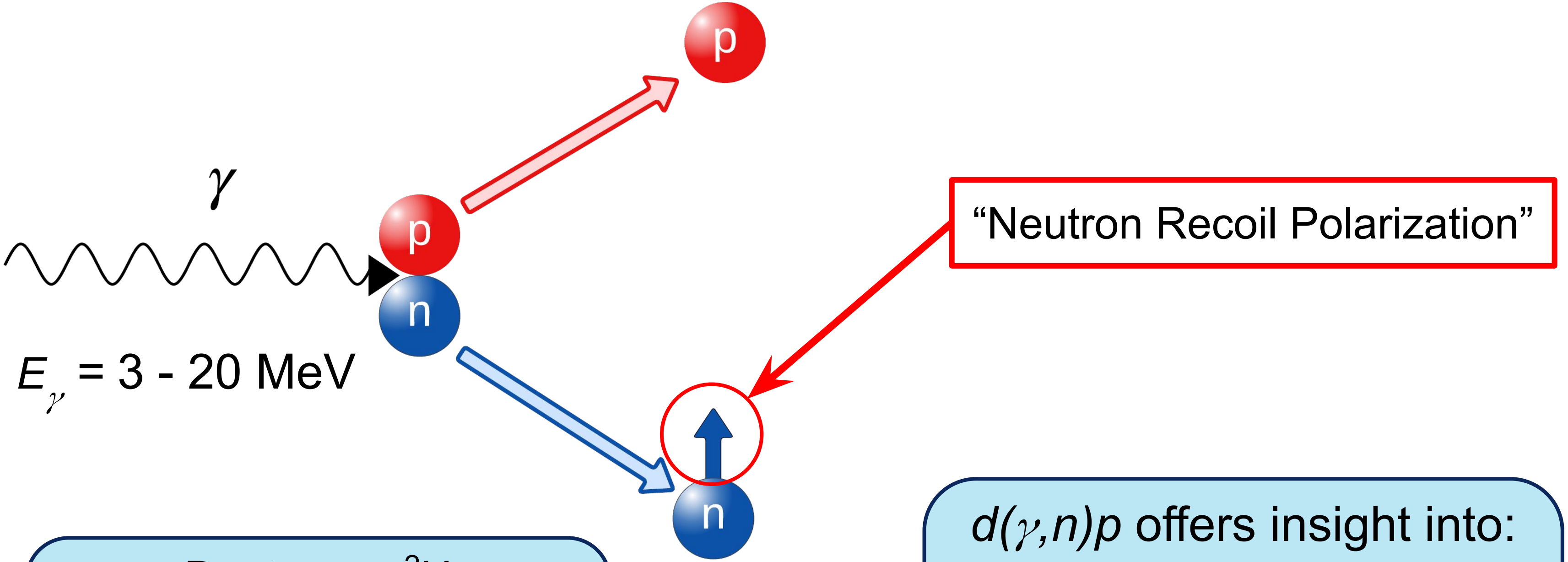
Blowfish Detector

HIγS Frozen Spin Target System

Part II: $d(\gamma,n)p$ Experiment

"A Measurement of Neutron Recoil Polarization in Deuteron Photodisintegration"

$d(\gamma,n)p$ Reaction



Deuteron - ^2H

- ➢ Smallest multibody nucleus
- ➢ Mass = 1875.6 MeV
- ➢ Binding Energy = 2.2 MeV
- ➢ Spin = 1 : Spin Triplet

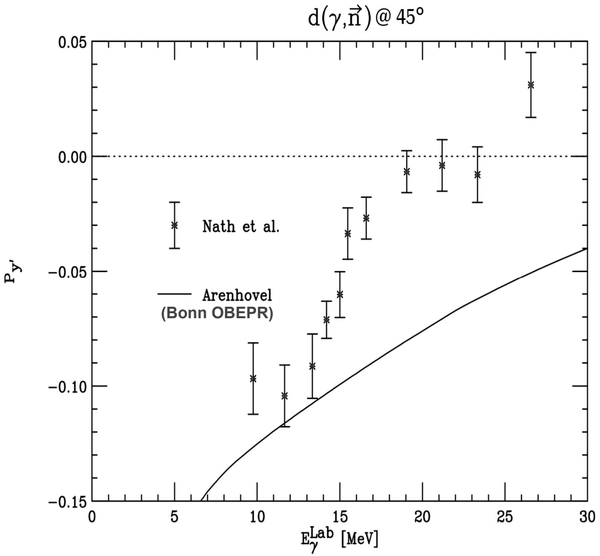
***d(γ,n)p* offers insight into:**

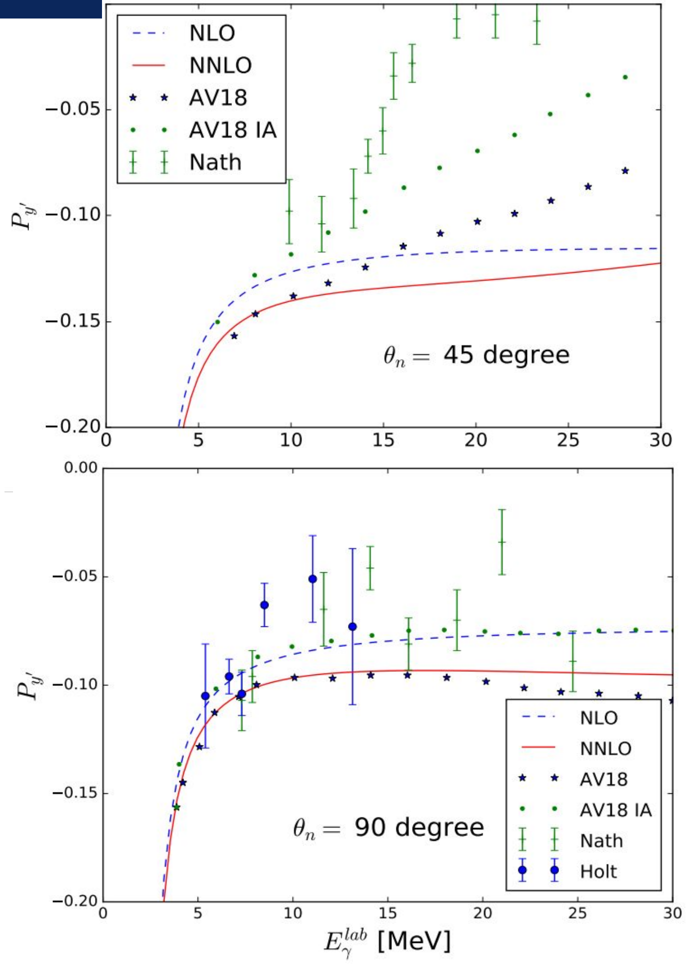
- ➢ Nucleon-Nucleon Interactions
- ➢ Big Bang Nucleosynthesis
- ➢ Astrophysical Bodies such as Neutron Stars

Outline

A. **Background and Motivation**
B. Experimental Setup
C. Data Analysis Methods
D. Monte Carlo Simulation

Motivation



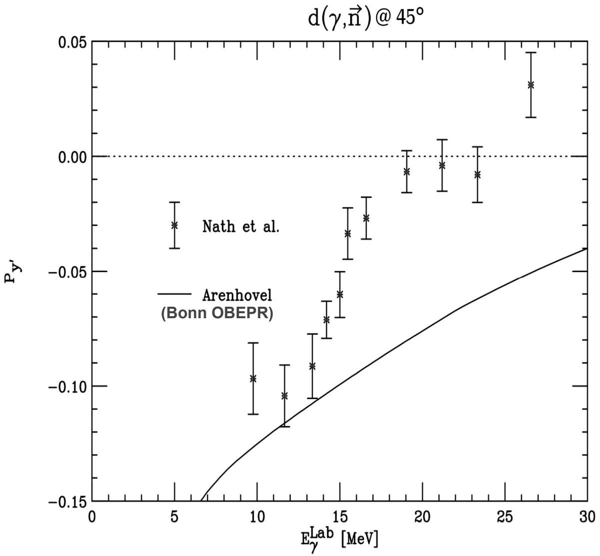


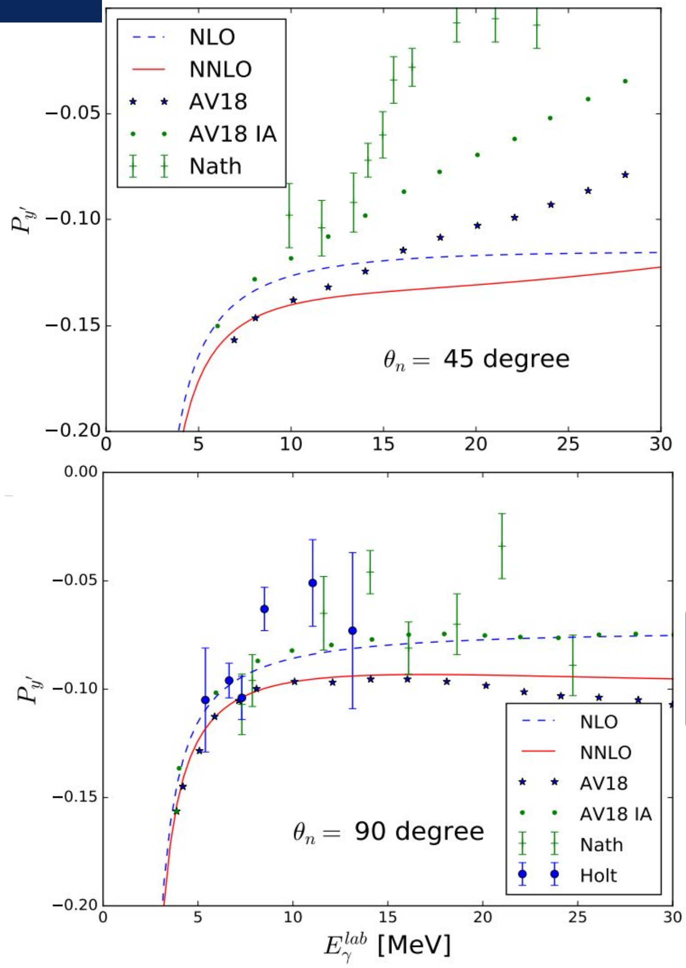
H. Arenhövel Few Body Sys. 4 (1988)

R. Nath et al Nucl. Phys. A 194 (1972)

Y.H. Song, S.I. Ando, C.H. Hyun (2017)

Motivation





Previous measurements of P_y^n used *untagged* bremsstrahlung beams (unknown E_γ) introducing systematic uncertainty

Our measurement uses a nearly monochromatic photon beam of known energy

H. Arenhövel Few Body Sys. 4 (1988)

R. Nath et al Nucl. Phys. A 194 (1972)

Y.H. Song, S.I. Ando, C.H. Hyun (2017)

Measurement

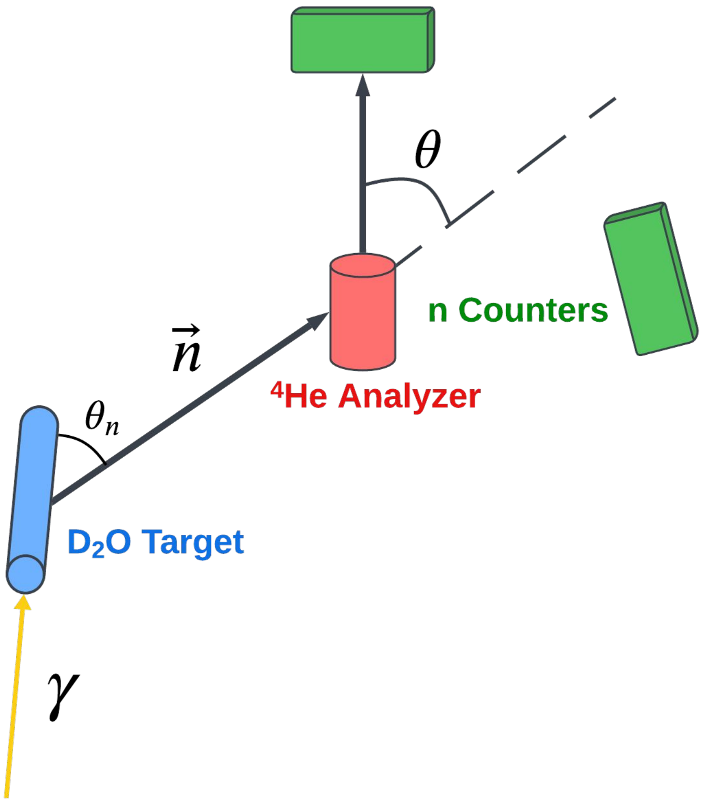
- Measuring left-right asymmetry of neutron scattering from He analyzers:

$$\frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = A(\theta) = P_y^m A_y(\theta)$$

- Modifying beam polarization enables extraction of multiple polarization observables:

$$P_y^m \frac{d\sigma\left(P_y^\gamma, \theta_n, \phi\right)}{d\Omega} = \left.\frac{d\sigma(\theta_n)}{d\Omega}\right|_{P_y^\gamma=0} \left[P_y^u(\theta_n) + P_y^\gamma P_y^l(\theta_n)\cos(2\phi)\right]$$

Circular: $P_y^\gamma = 0$
Linear: $P_y^\gamma = 1$
$\Big\}\ P_y^u, P_y^l$



Measurement

➢ Measuring left-right asymmetry of neutron scattering from He analyzers:

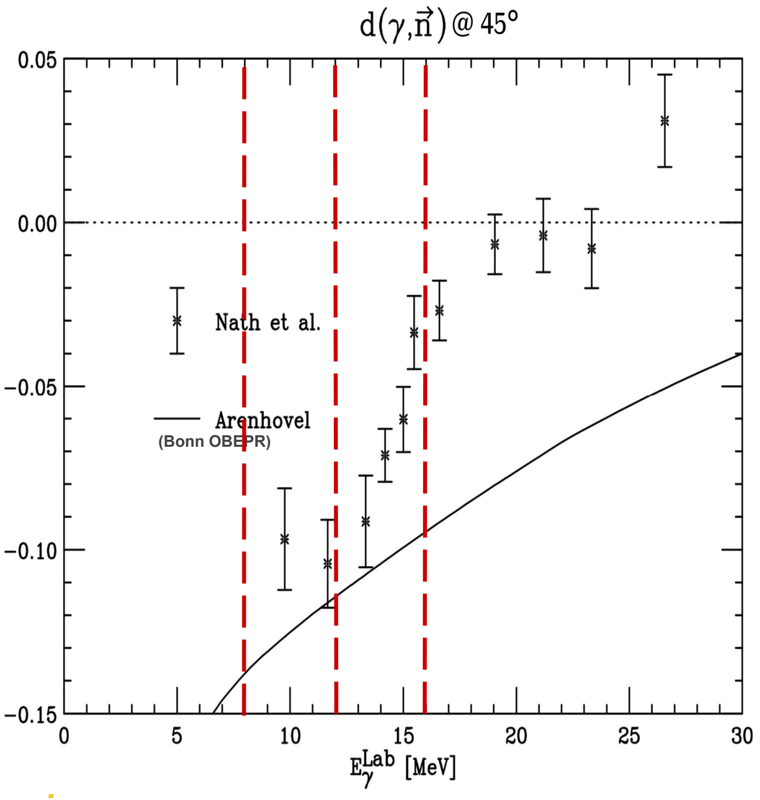
Measurement Parameters:

Beam Energy: E_γ = 8, 12, 16 MeV

Beam Polarization: P_y^γ = 0 and 1

Reaction Angles: θ_n = 45°, 90°, 135°

Linear: $P_y^\gamma = 1$



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HIγS at TUNL

HIγS = High Intensity Gamma Source

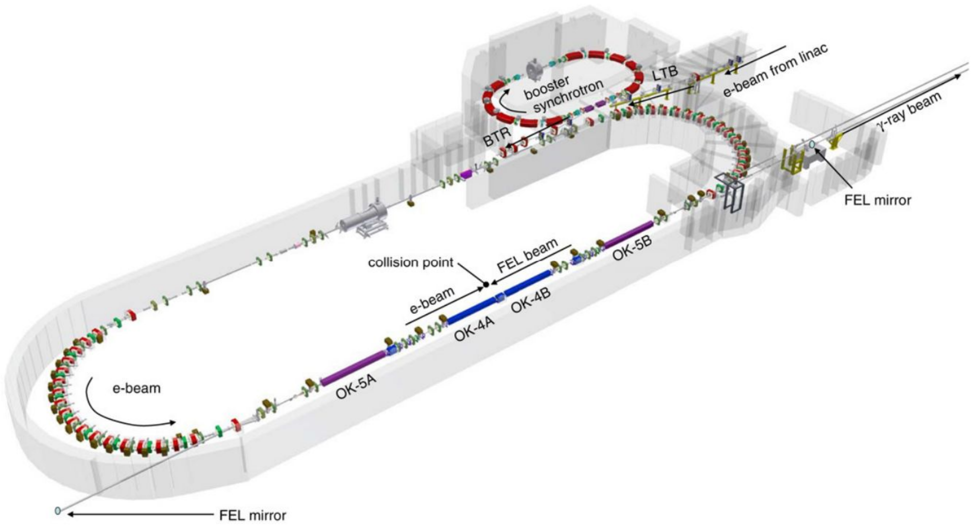
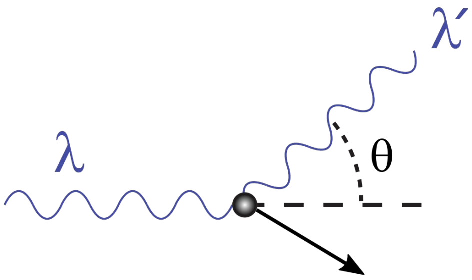


Image Credit: H. Weller et al (2009)

How It Works:

- ➢ Free Electron Laser (FEL) produces synchrotron radiation
- ➢ UV photons reflect in optical cavity
- ➢ Boosted to γ-rays (1-100 MeV) through **Compton backscattering**



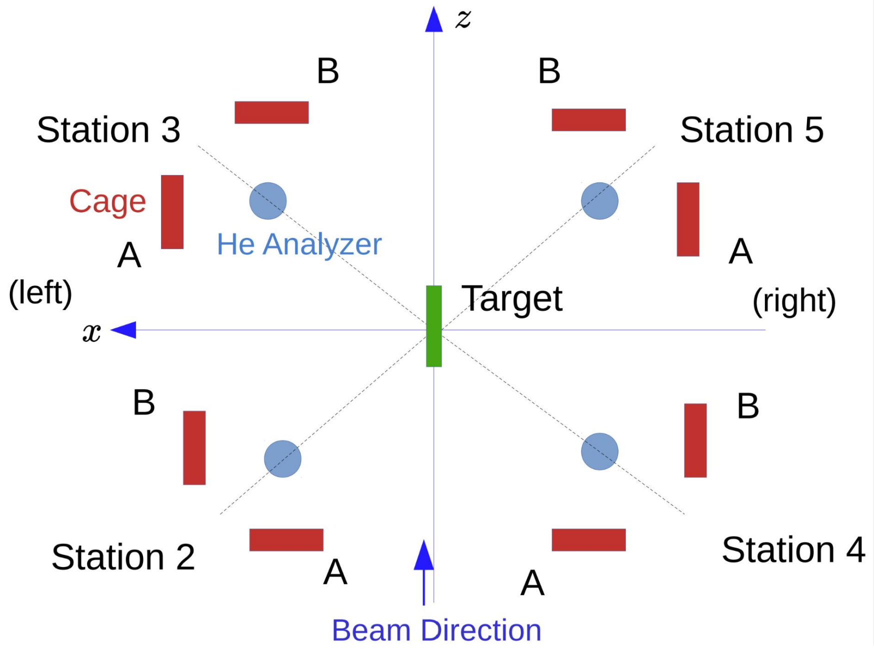
$$E'_\gamma \approx 4\gamma^2 E_\gamma$$

UV (3-100 eV) → γ-ray (1-100 MeV)

Beam Parameters

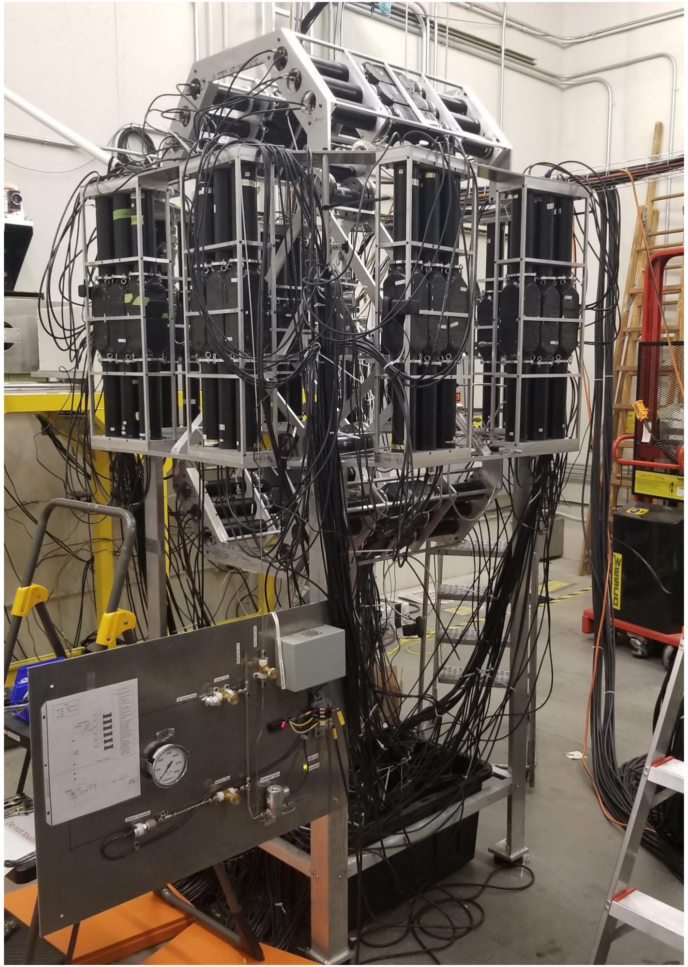
- ➢ E_γ = 1-100 MeV , $\Delta E/E \approx 3\%$
- ➢ Flux = 6×10^7 - 2.4×10^8 γ/s
- ➢ >95% Polarization - Linear or Circular

Experimental Setup

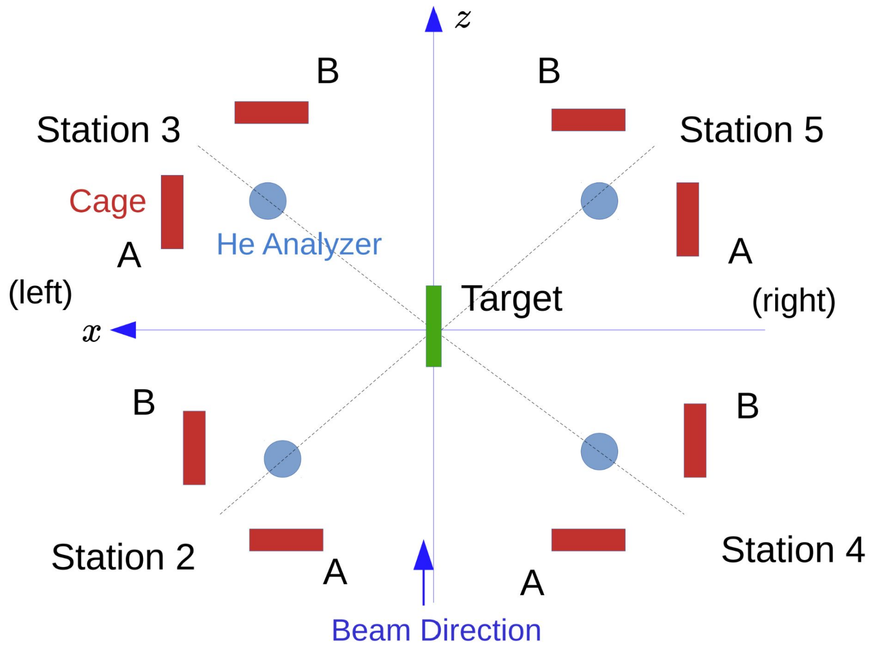


- ➢ Heavy water target (D_2O)
- ➢ 6 “Stations” of 1 Analyzer + 12 Neutron Counters
- ➢ In Plane (ϕ = 0) Analyzers: 2 at 45°, 2 at 135°
- ➢ Out of Plane (ϕ = 90°) Analyzers: 2 at 90°

Diagram Image Credit: T. Polischuk



Experimental Setup



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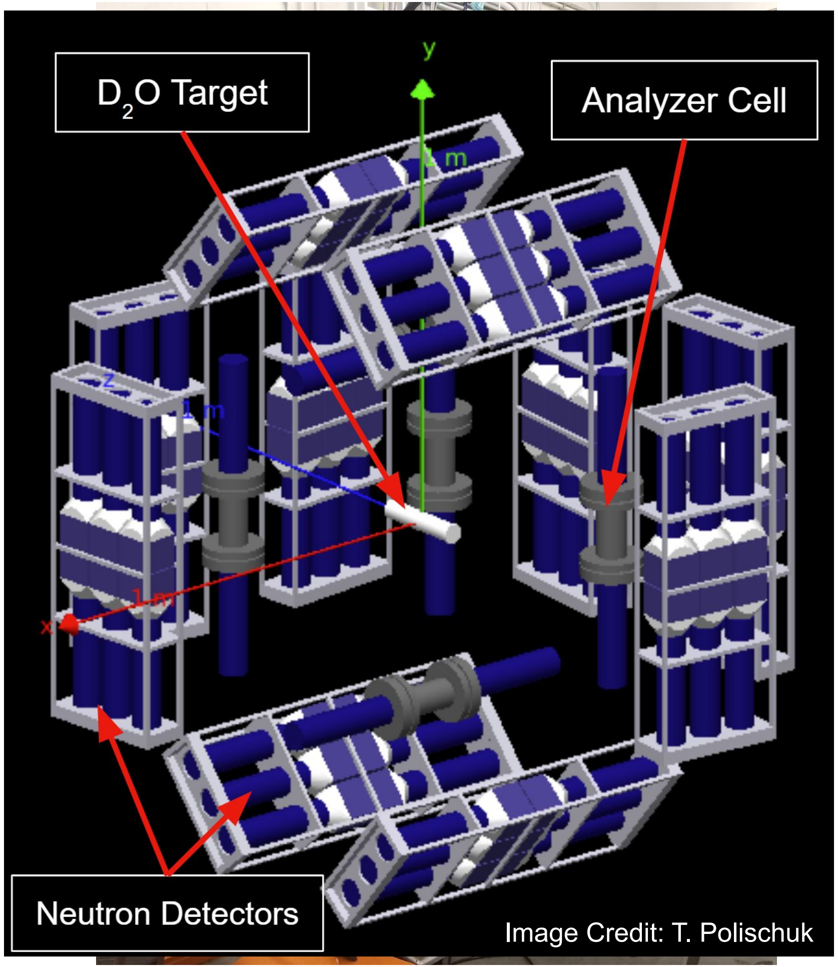
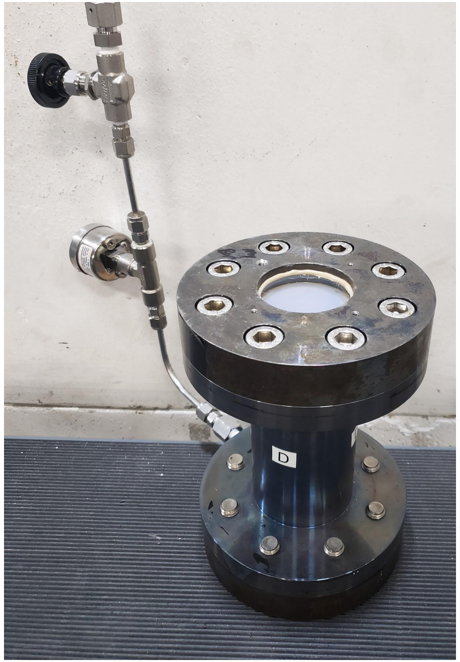
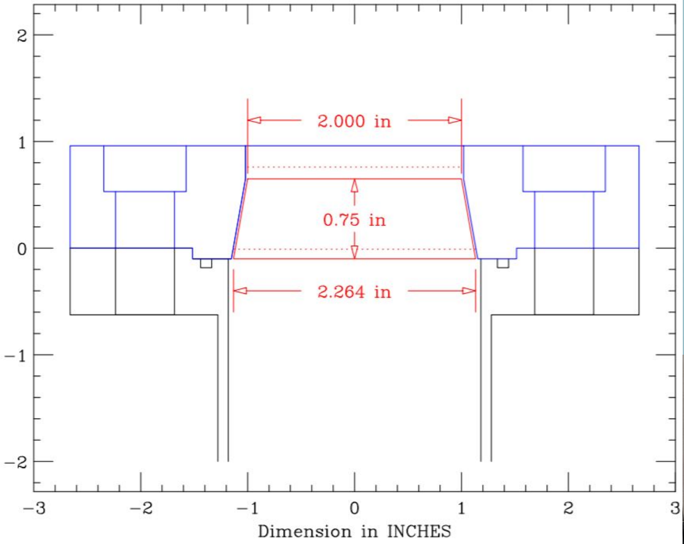


Polarization Analyzers

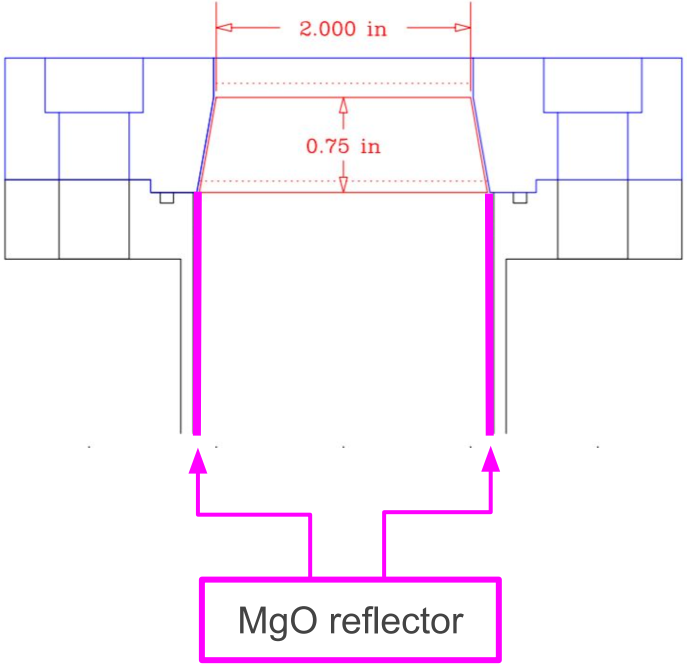




- ^{4}He Polarization Analyzers
- He-Xe gas mixture at 2500 PSI
- PMTs measure light output from Xe scintillation
- Glass windows designed to undergo compressive forces only to withstand high internal pressure

Analyzer Preparation

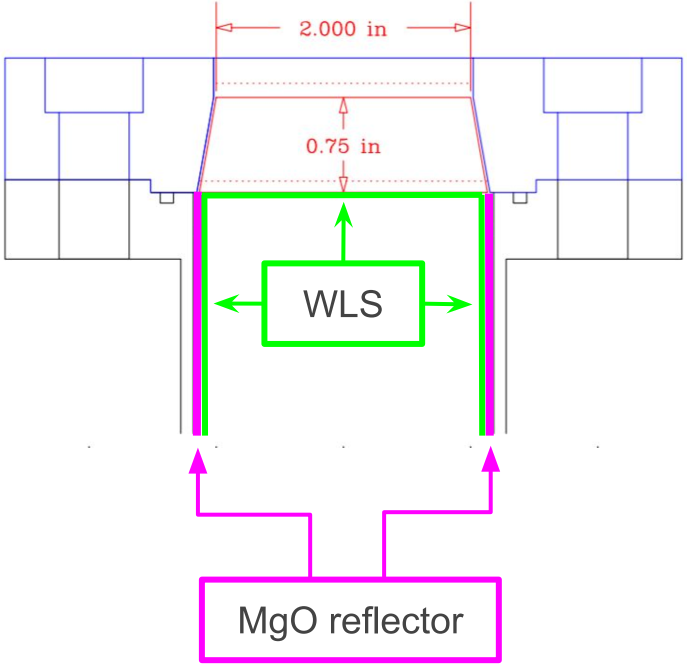
MgO layer for internal reflection



Analyzer Preparation

MgO layer for internal reflection

Wavelength shifter for
UV to visible light conversion



Neutron Detectors

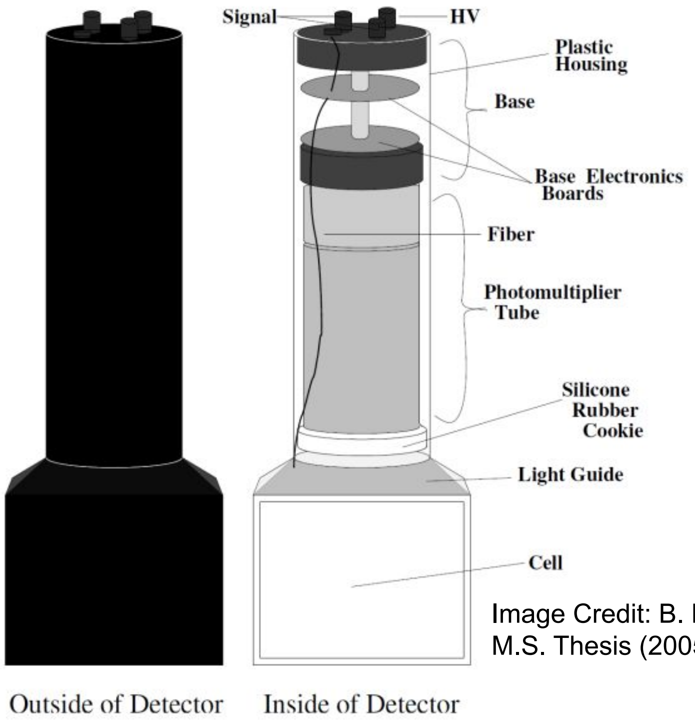


Image Credit: B. Bewer, M.S. Thesis (2005)

- BC-505 Liquid Organic Scintillators
- PMT for scintillation light output
- Excellent neutral particle ID capabilities with PSD

Neutron Detectors

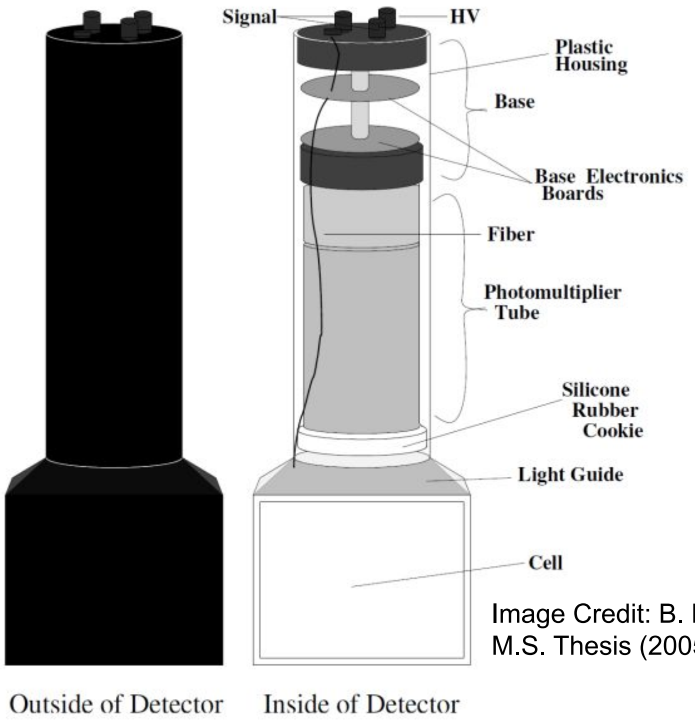


Image Credit: B. Bewer, M.S. Thesis (2005)

6 neutron counters assembled in a “cage”

- BC-505 Liquid Organic Scintillators
- PMT for scintillation light output
- Excellent neutral particle ID capabilities with PSD

Neutron Detectors

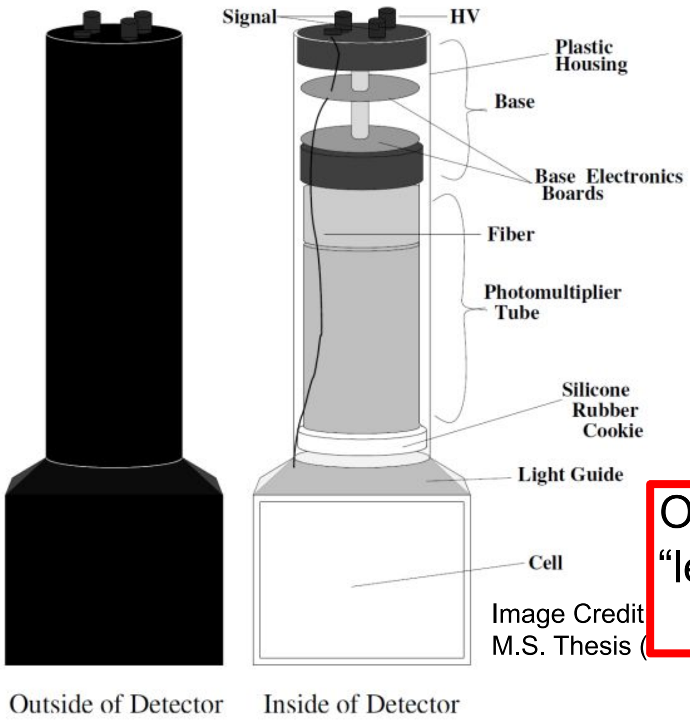
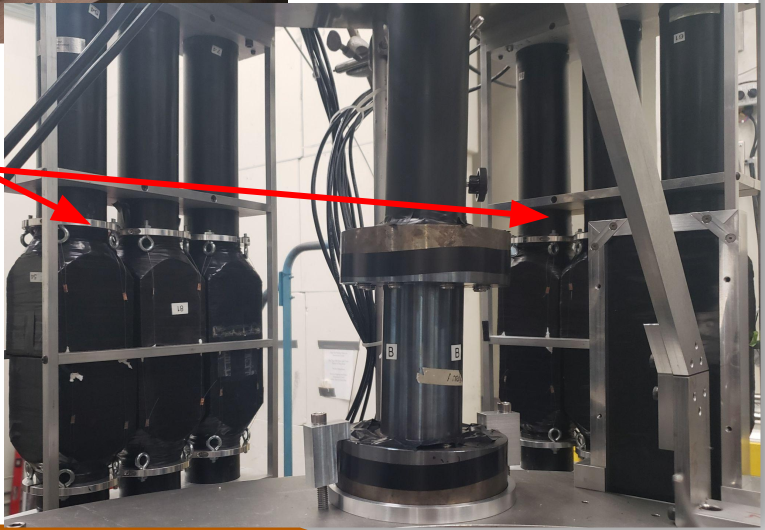


Image Credit
M.S. Thesis (

6 neutron counters assembled in a “cage”

One cage each at “left” and “right” of an analyzer



- ➢ BC-505 Liquid Organic Scintillators
- ➢ PMT for scintillation light output
- ➢ Excellent neutral particle ID capabilities with PSD

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Measuring left-right asymmetry in neutron scattering:

$$\frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = A(\theta) = P_y^m A_y(\theta)$$

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Which of the particles are neutrons?

Data Analysis

Measuring left-right asymmetry in neutron scattering:

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Where are those neutrons going?

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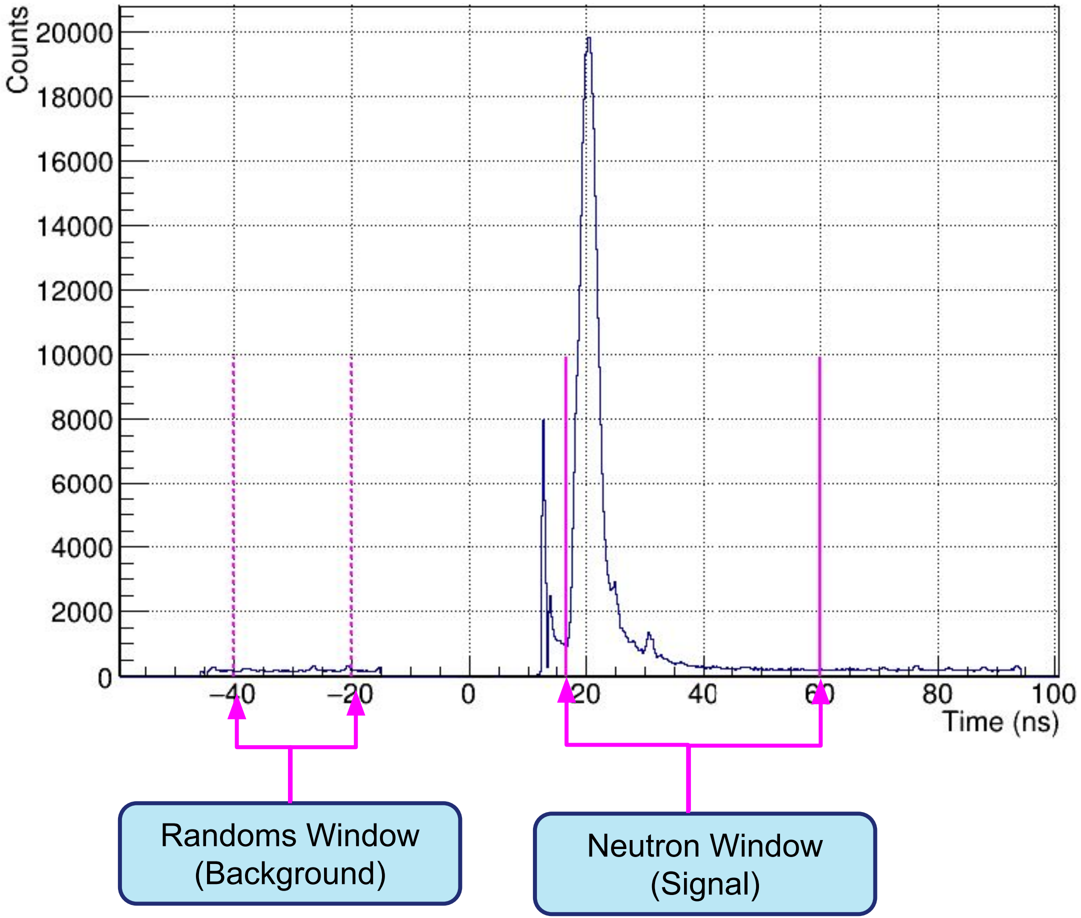
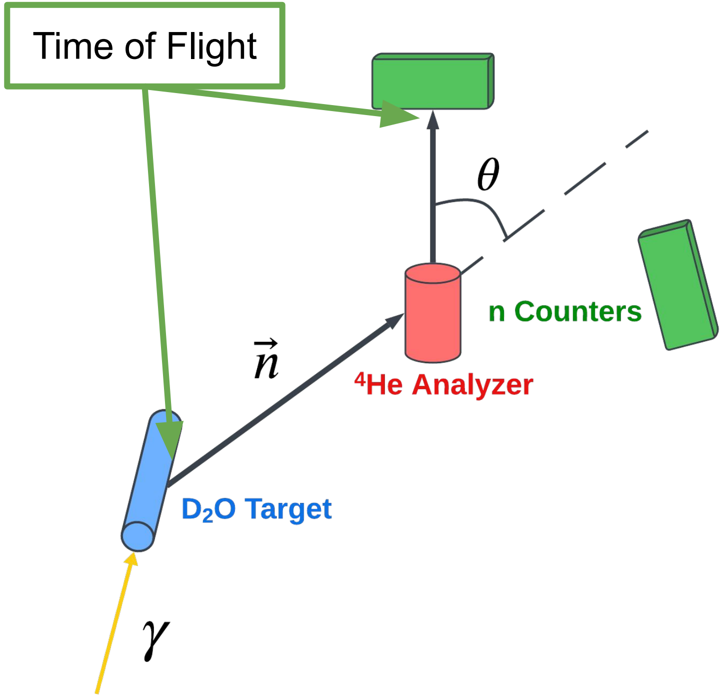
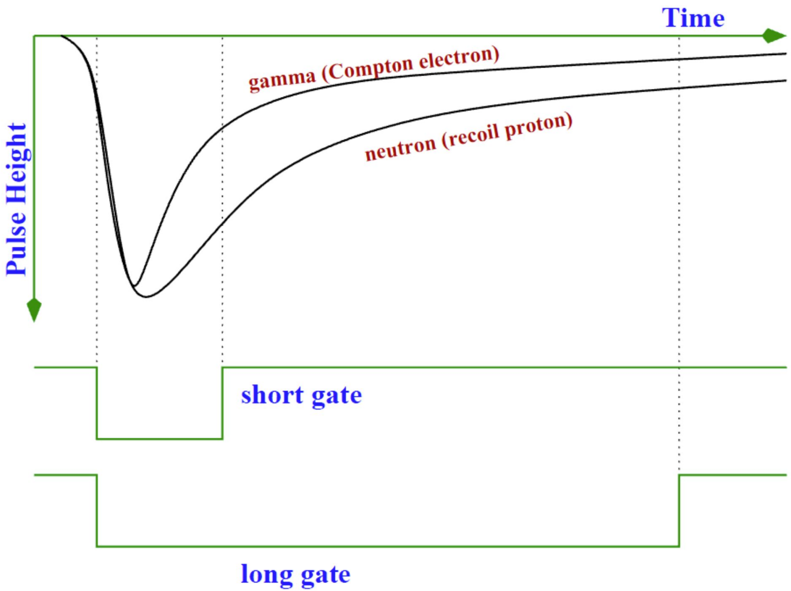
Particle ID


Counts
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
−40
−20
0
20
40
60
80
100
Time (ns)
Randoms Window (Background)
Neutron Window (Signal)

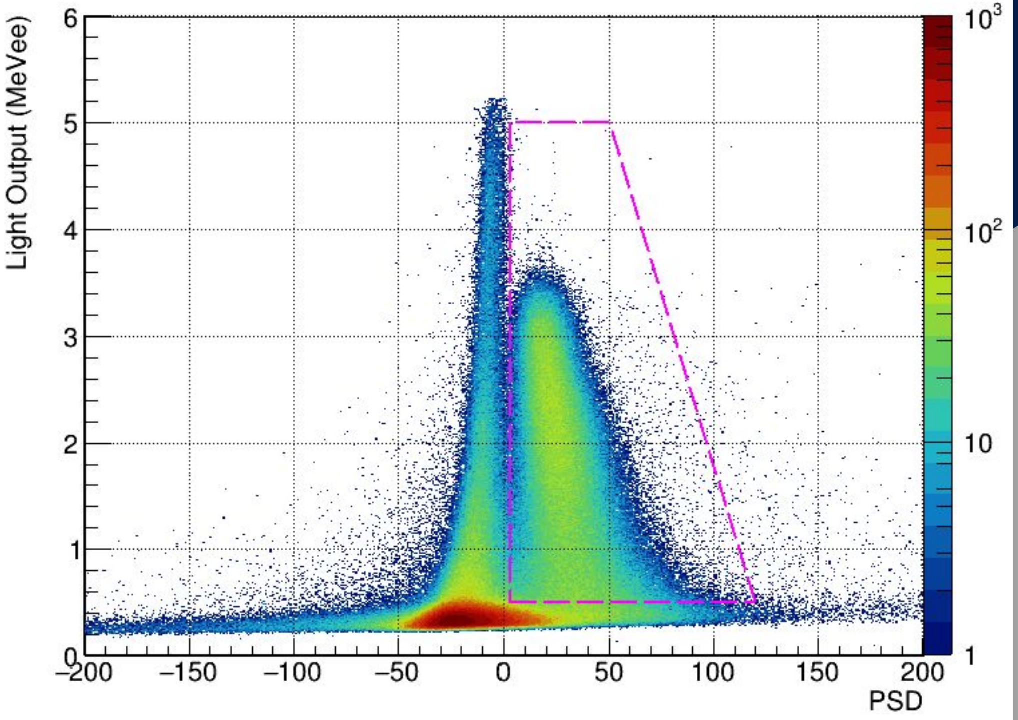

Time of Flight
θ
n Counters
$\vec{n}$
^{4}He Analyzer
D_2O Target
γ

Particle ID: PSD

PSD = Pulse Shape Discrimination



$$PSD = \frac{\text{Long Gate} - \text{Short Gate}}{\text{Long Gate}}$$



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Where are those neutrons going?

Particle ID

Data Analysis

Measuring left-right asymmetry in neutron scattering:

$$\frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = A(\theta) = P_y^m A_y(\theta)$$

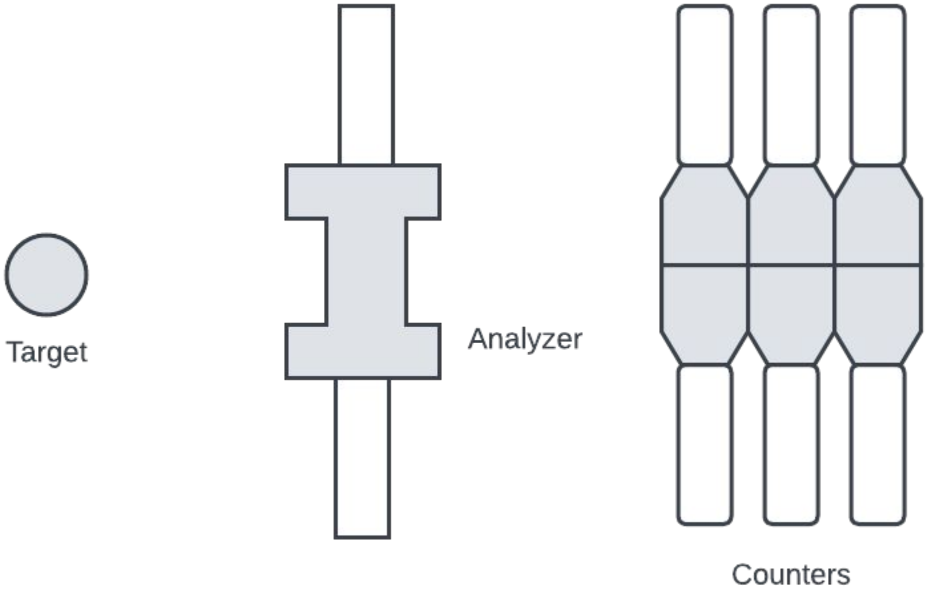
Which of the particles are neutrons?

Particle ID

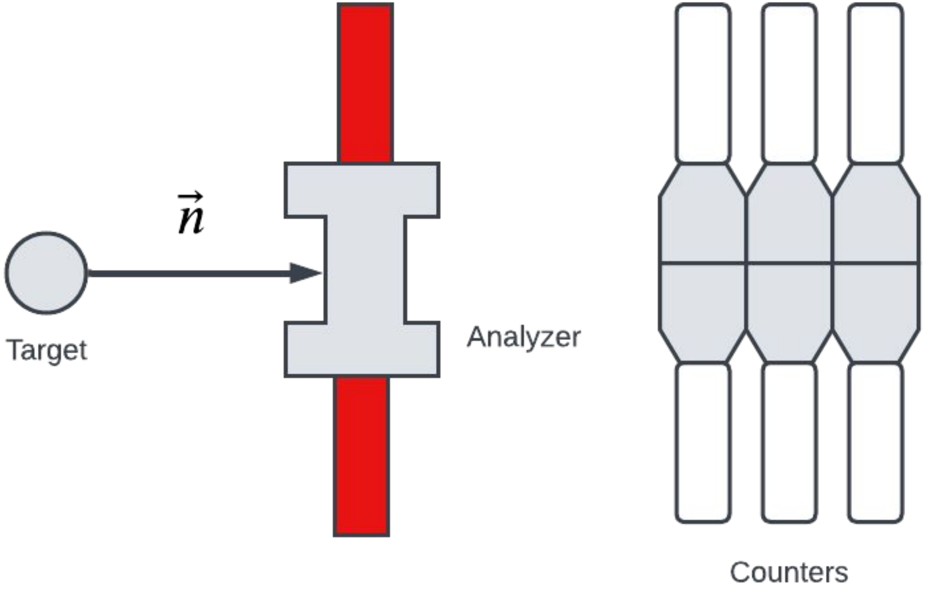
Where are those neutrons going?

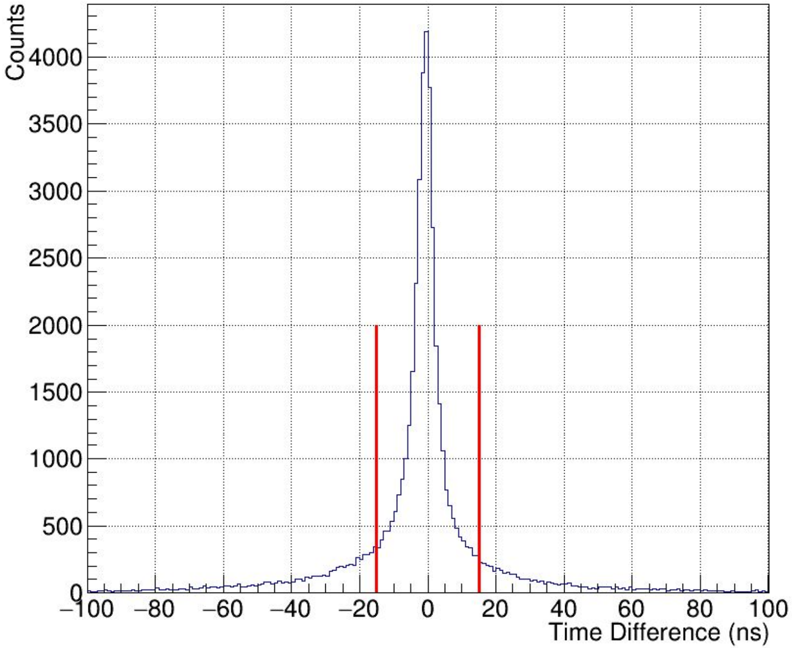
Particle Tracking

Tracking: Coincidences

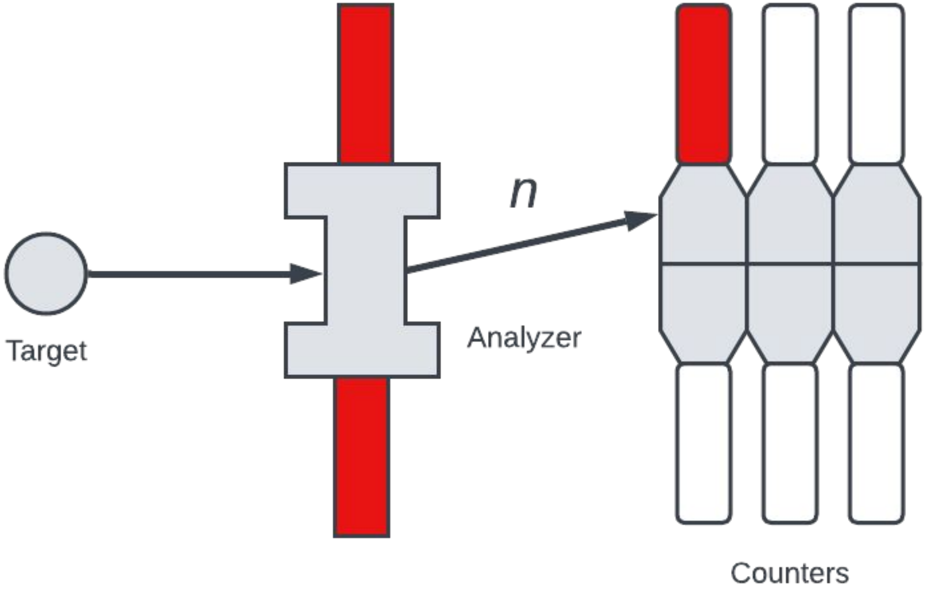


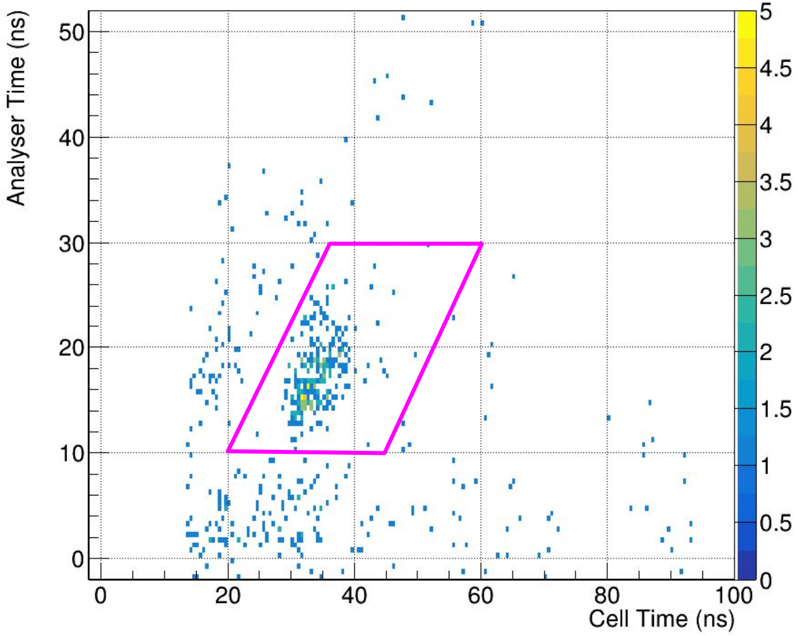
Tracking: Coincidences





Tracking: Coincidences

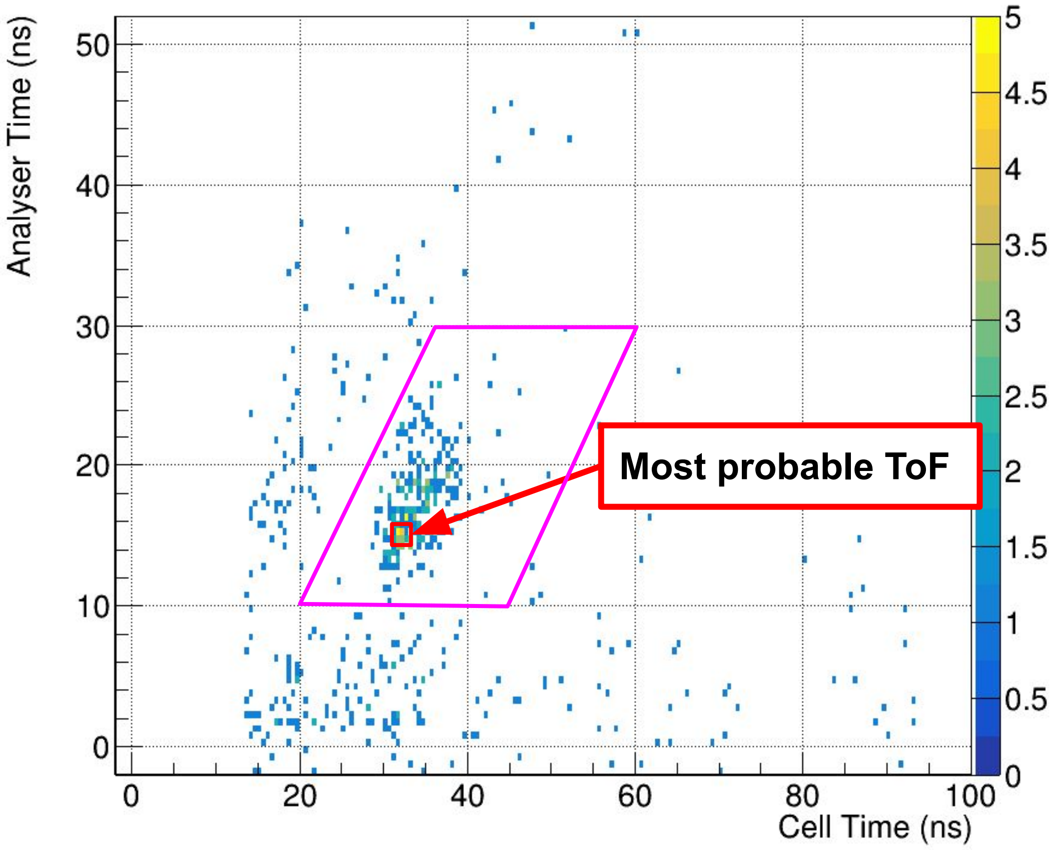


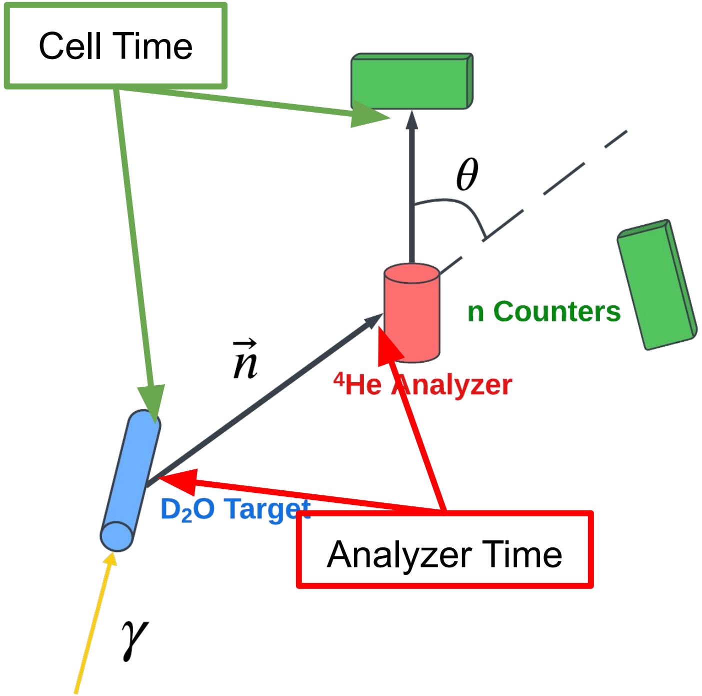


Only accept signals indicating particles that hit an analyzer and a counter.

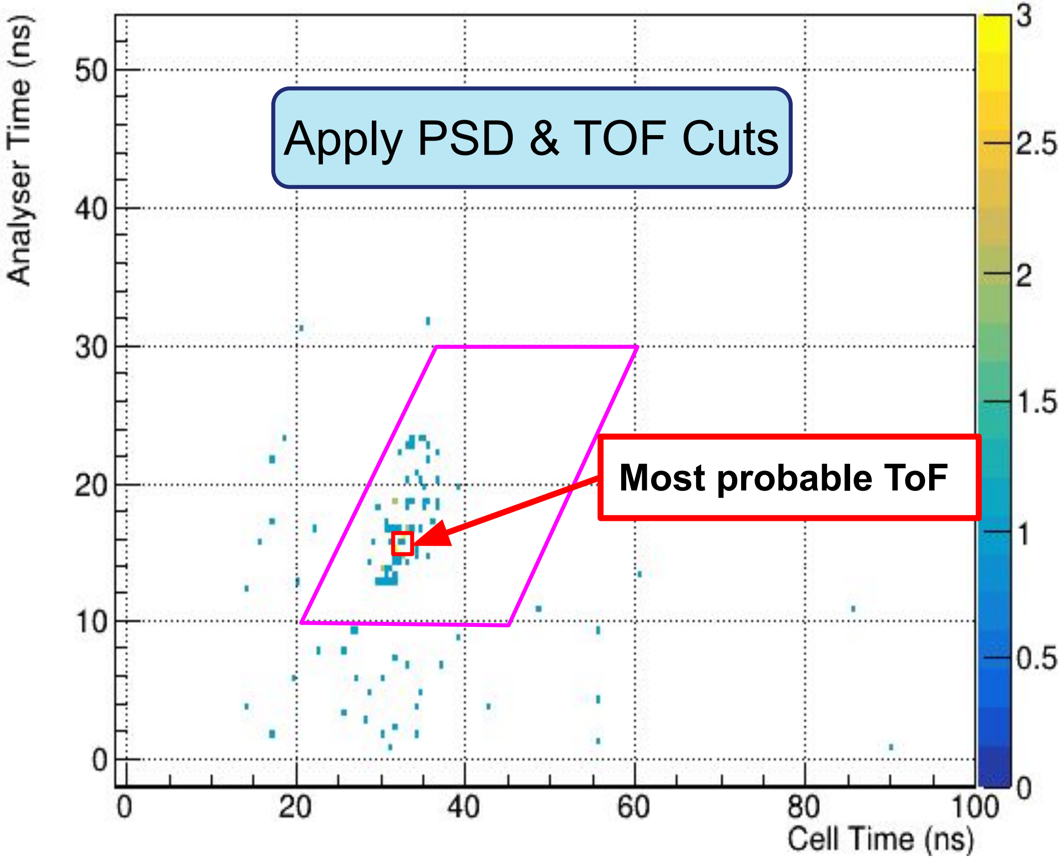
Some accidentals get through…

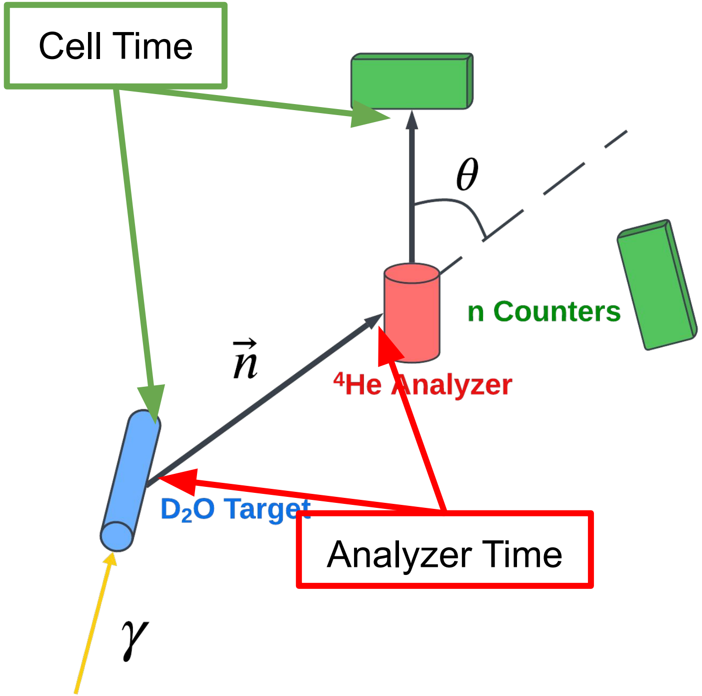
Tracking: Coincidences



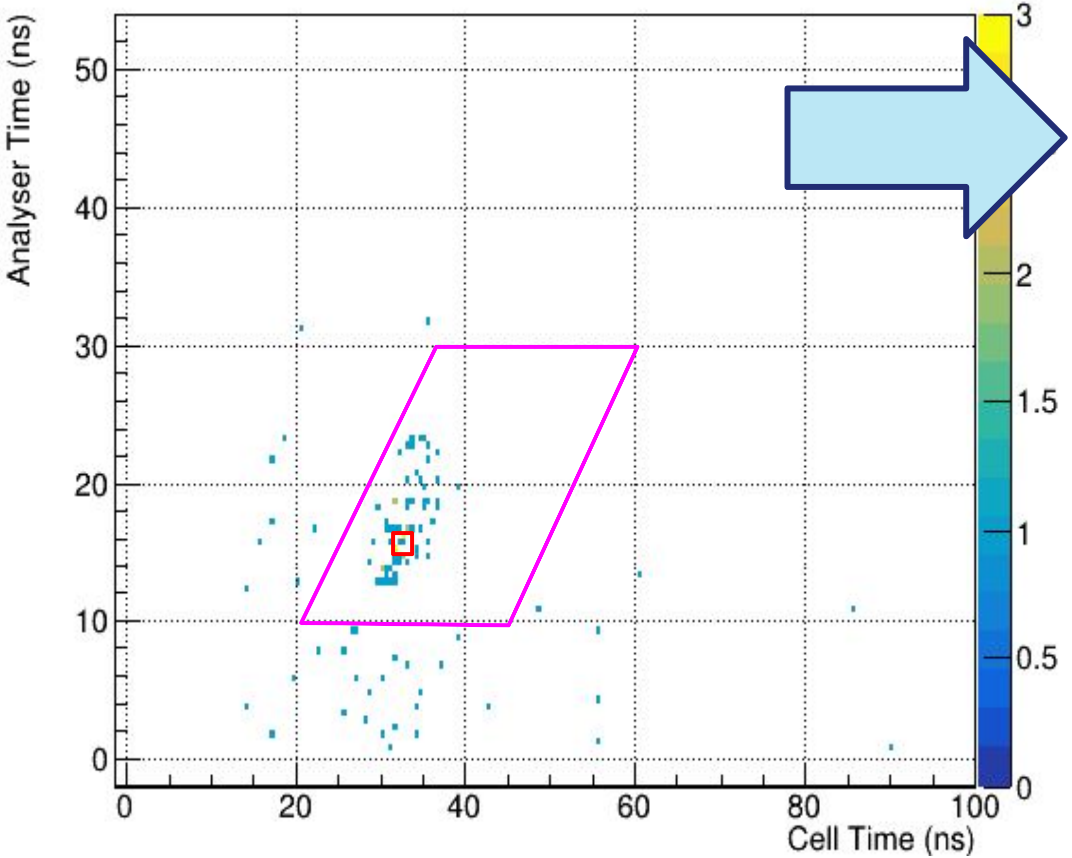


Tracking: Coincidences

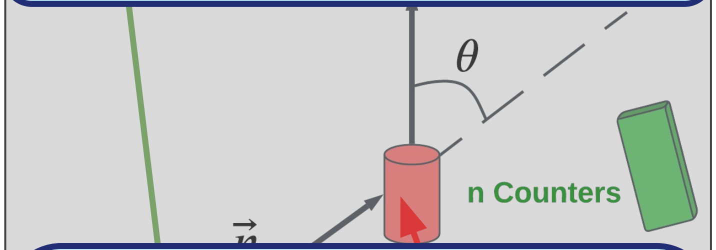




Tracking: Coincidences



Neutron Yield per Cell



$$\frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = A(\theta)$$

Outline

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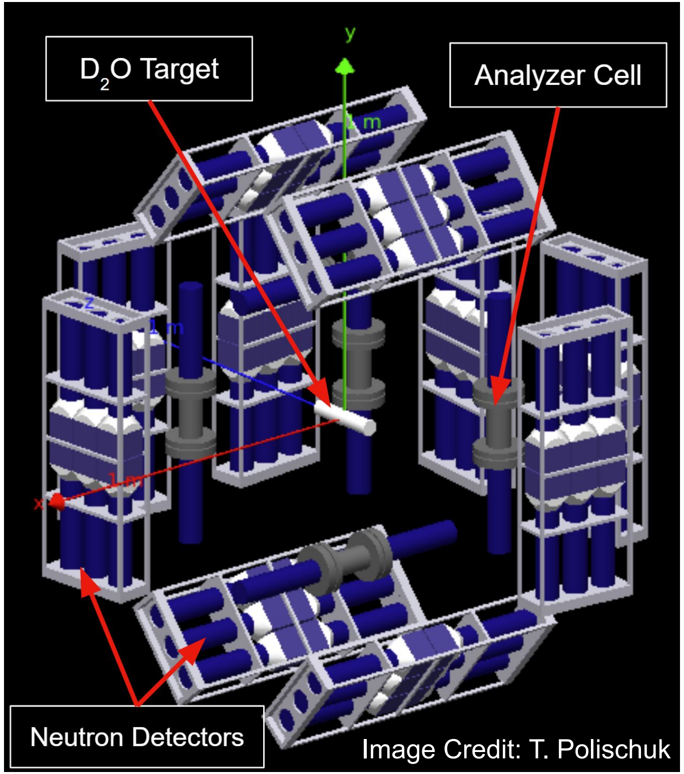
Simulation: Geant4

- Full model of experimental setup implemented in Geant4

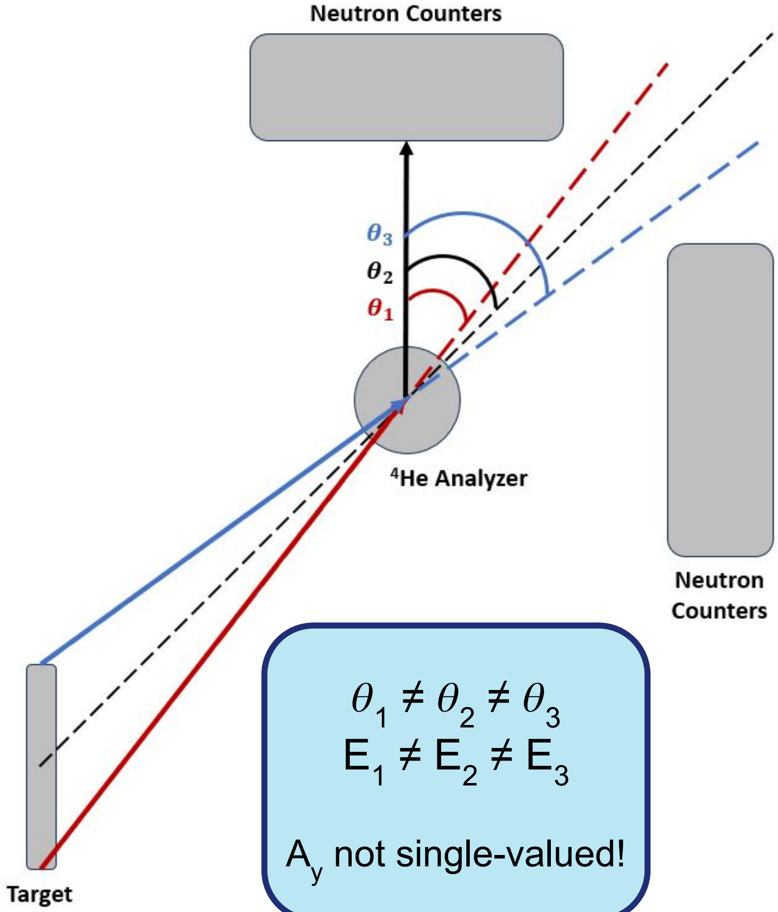
- Variety of methods for inputting initial parameters based on beam polarization, energy, etc.

- Includes physics model for computing realistic light output from detected particles

- Used to estimate background, calibrate detector gains, investigate instrumental asymmetries

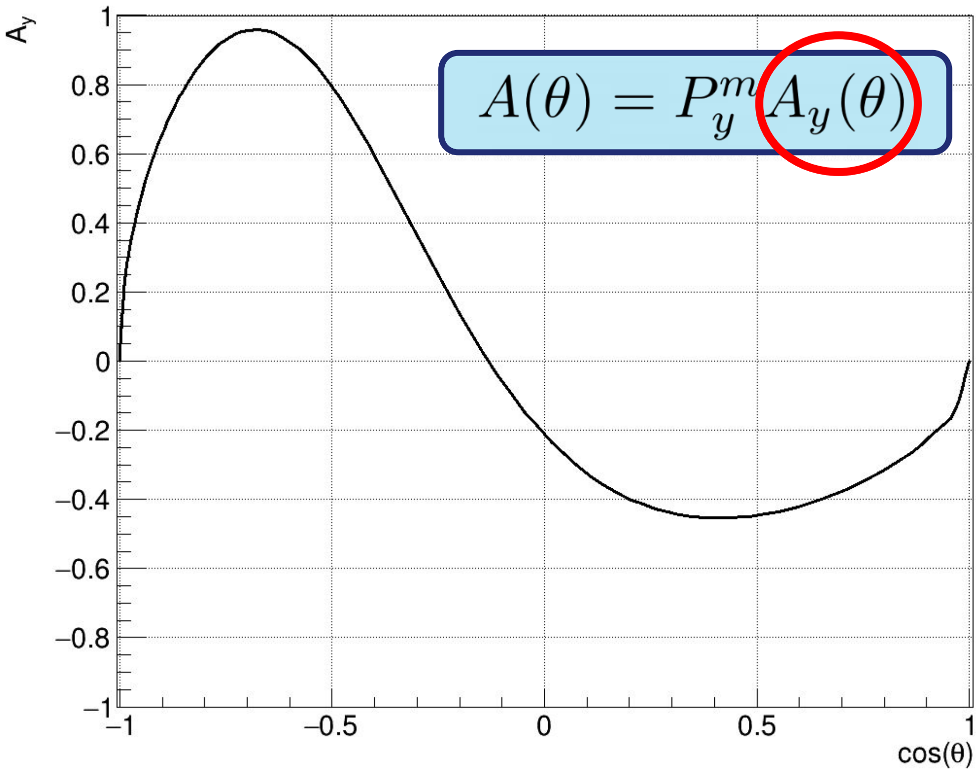


Simulation: A_y Angular Spread



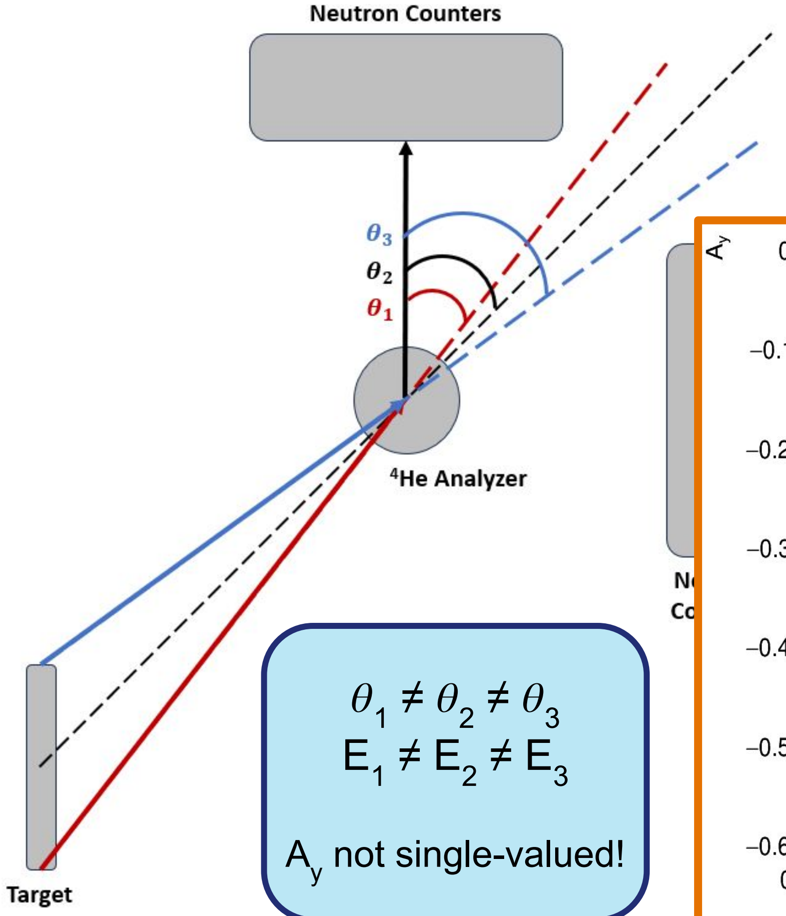
$\theta_1 \neq \theta_2 \neq \theta_3$
$E_1 \neq E_2 \neq E_3$

A_y not single-valued!



$$A(\theta) = P_y^m A_y(\theta)$$

Simulation: A_y Angular Spread



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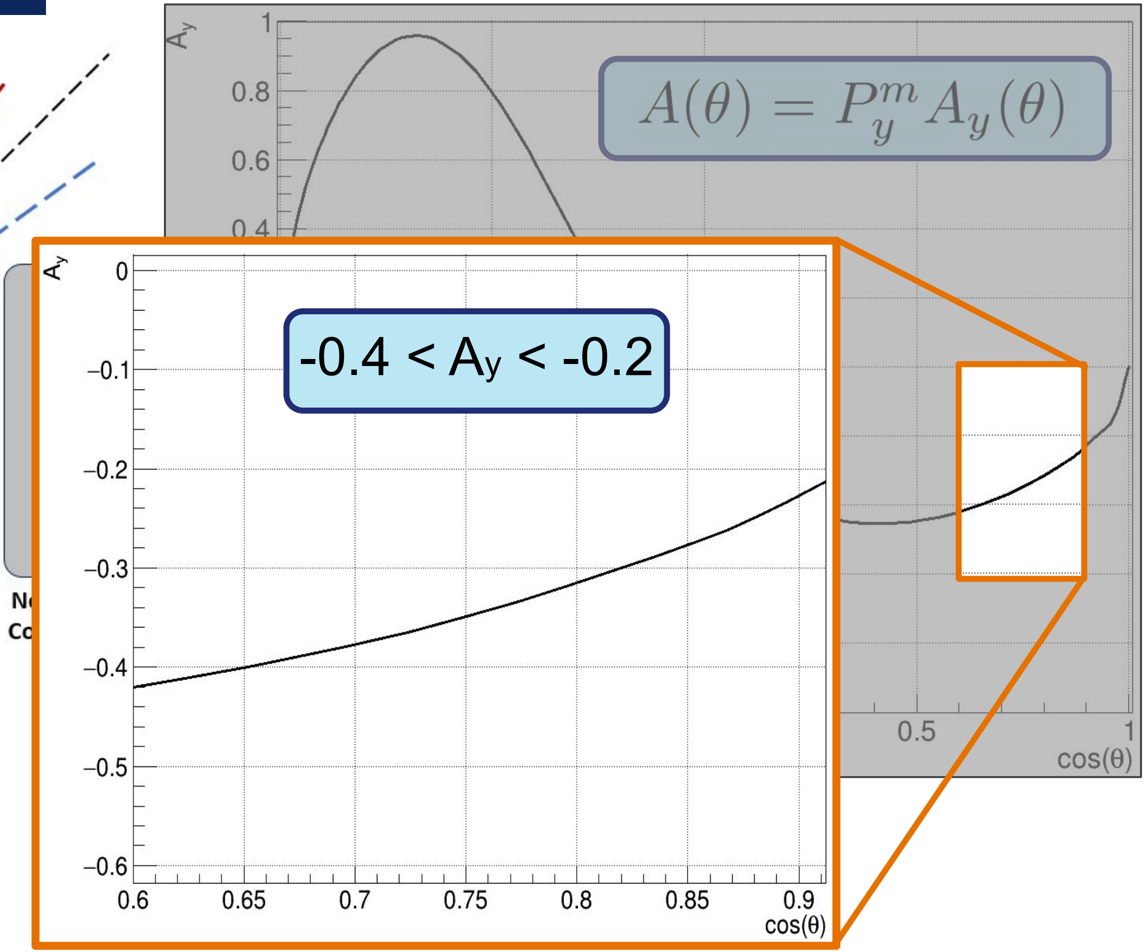
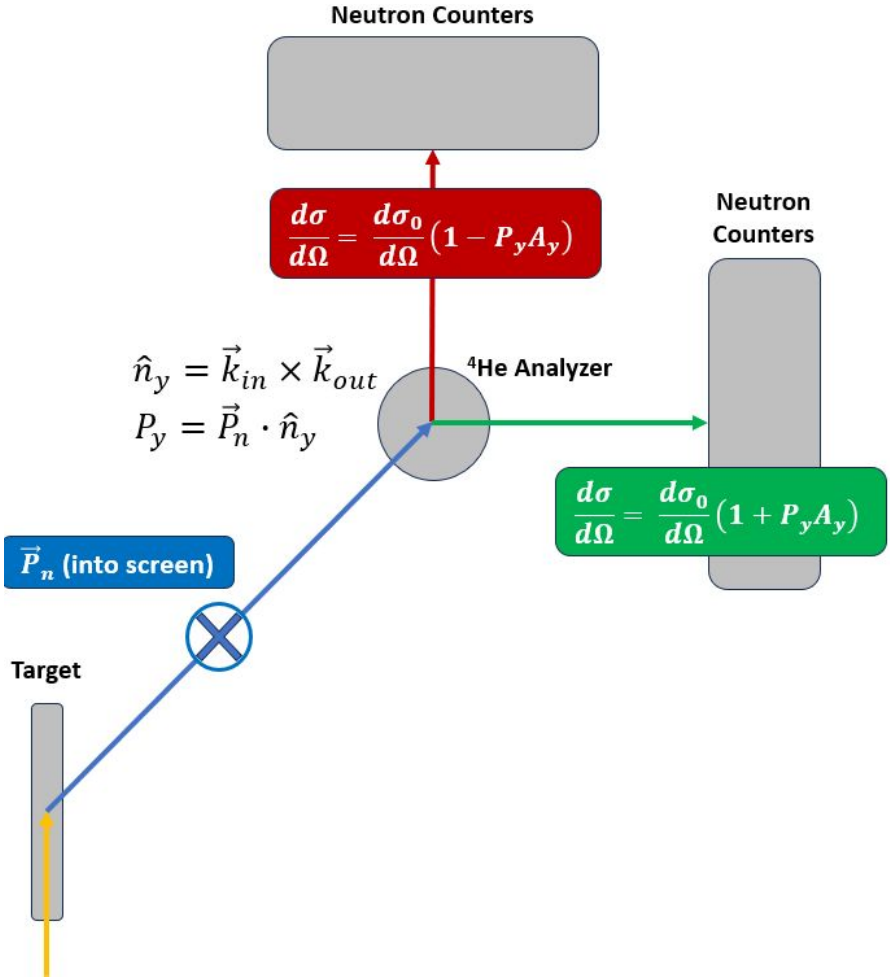


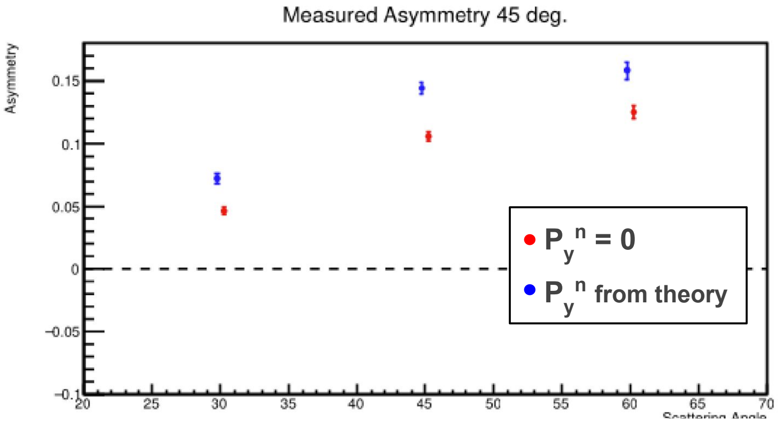
Modeling Polarized n Scattering

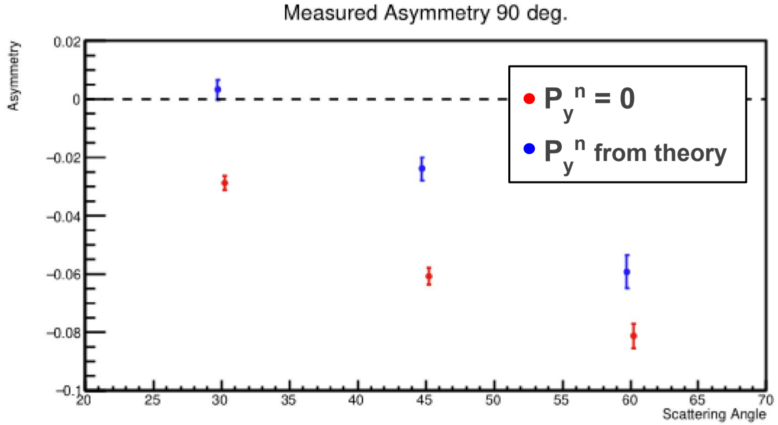
- Modification to low energy neutron scattering physics model in Geant4: G4ParticleHP
- Monte Carlo weighting of unpolarized cross section ($\frac{d\sigma_0}{d\Omega}$) provided by Geant4
- Handles polarization transport and depolarization effects from multiple scattering
- Produces simulated results of final measured asymmetries for direct comparison to experimental results



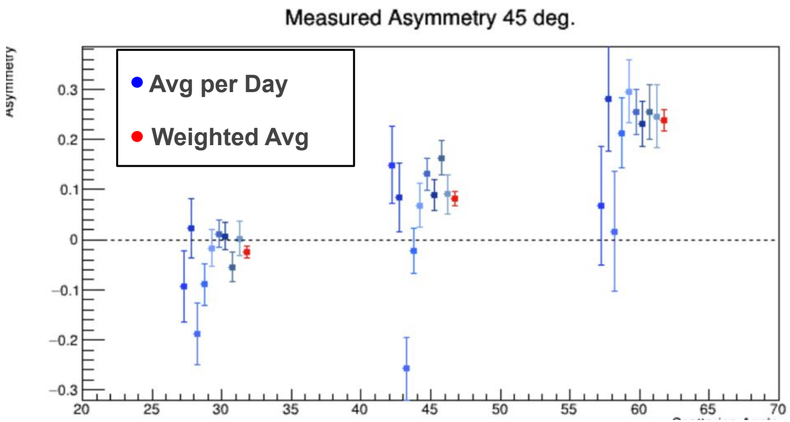
Simulation vs. Data

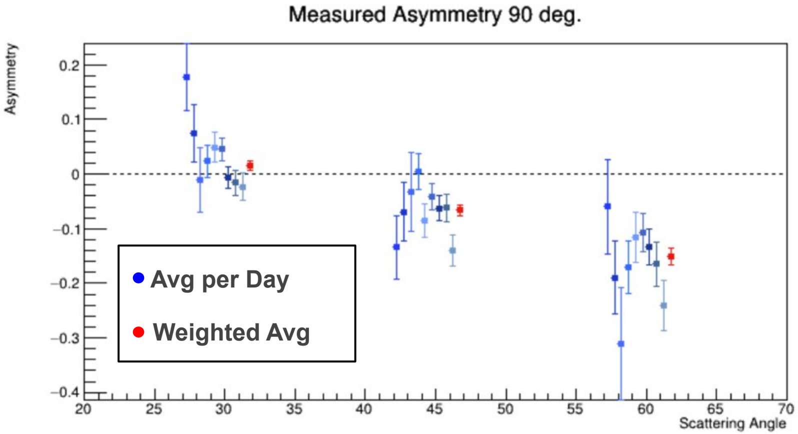
Simulated Asymmetries





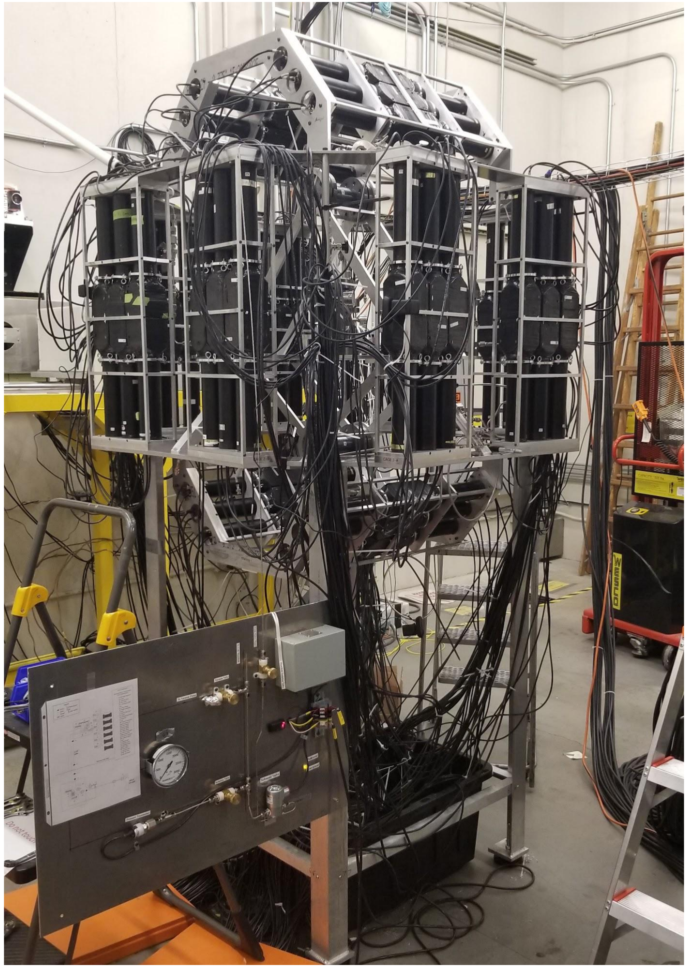
Experimental Asymmetries





Summary

- ➢ Polarization observables offer window into how the strong interaction manifests in nucleon-nucleon interactions
- ➢ Experiment to measure P_y^n in $d(\gamma,n)p$ performed at HIGS (TUNL) in Fall 2023
- ➢ Measurement will investigate long-standing discrepancies between experimental measurements and theoretical calculations
- ➢ Expecting final results soon!



Acknowledgements

Collaborators:

- ➢ Blaine Norum -UVA
- ➢ Rob Pywell - USask
- ➢ Tanner Polischuk - USask
- ➢ Haoyu Chen - UVA
- ➢ Matt Roberts - UVA

*UVA = University of Virginia
*USask = University of Saskatchewan

TUNL Faculty/Staff:

- ➢ Werner Tornow - Duke University
- ➢ Calvin Howell - Duke University
- ➢ with much support from the TUNL Staff!

This work supported in part by the Department of Energy under grant No. DE-SC0016443
and the Natural Sciences and Engineering Research Council of Canada.

Thank You!

Questions?

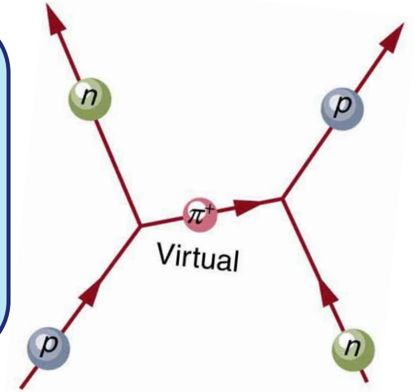
Backup Slides

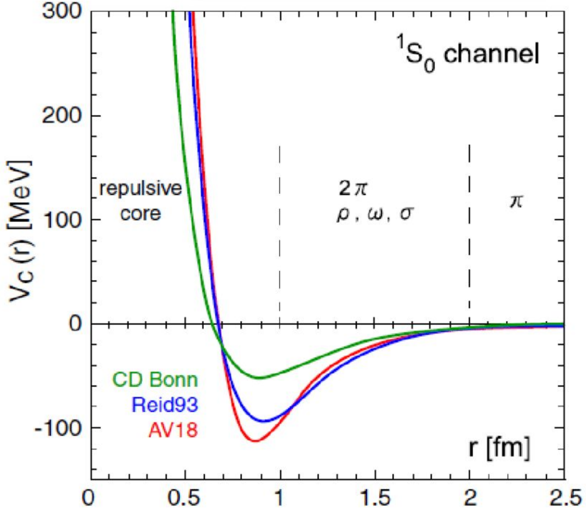
Outline

A. **Background and Motivation**
B. Experimental Setup
C. Data Analysis Methods
D. Monte Carlo Simulation

Why Investigate d(γ,n)p?

- ➢ Probe NN interactions
- ➢ Described by nucleon potential models and EFTs - often use meson exchange to model nuclear forces





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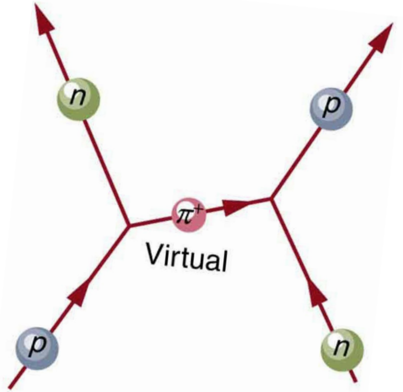

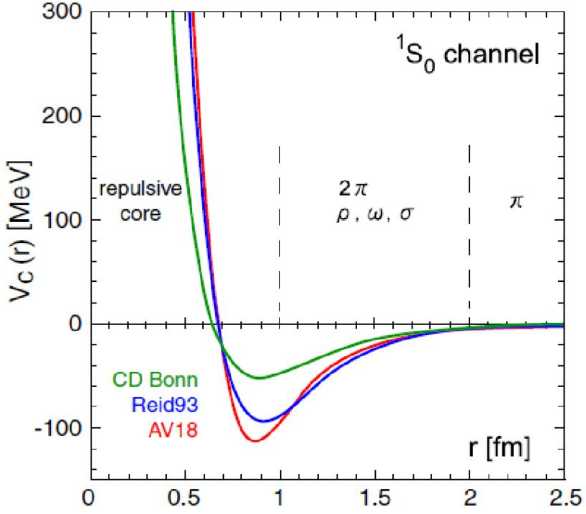

Theories fit to world data of scattering and bound states.

TABLE XIV. χ^2/datum for the CD-Bonn potential, the Nijmegen phase shift analysis [42], and the Argonne V_{18} potential [32] in regard to various databases discussed in the text.

	CD-Bonn potential	Nijmegen phase shift analysis	Argonne V_{18} potential
proton-proton data			
1992 *pp* database (1787 data)	1.00	1.00	1.10
After-1992 *pp* data (1145 data)	1.03	1.24	1.74
1999 *pp* database (2932 data)	1.01	1.09	1.35
neutron-proton data			
1992 *np* database (2514 data)	1.03	0.99	1.08
After-1992 *np* data (544 data)	0.99	0.99	1.02
1999 *np* database (3058 data)	1.02	0.99	1.07
***pp* and *np* data**			
1992 *NN* database (4301 data)	1.02	0.99	1.09
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Table Source: R. Machleidt (2000)

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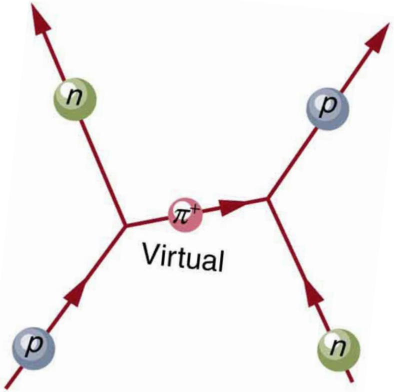

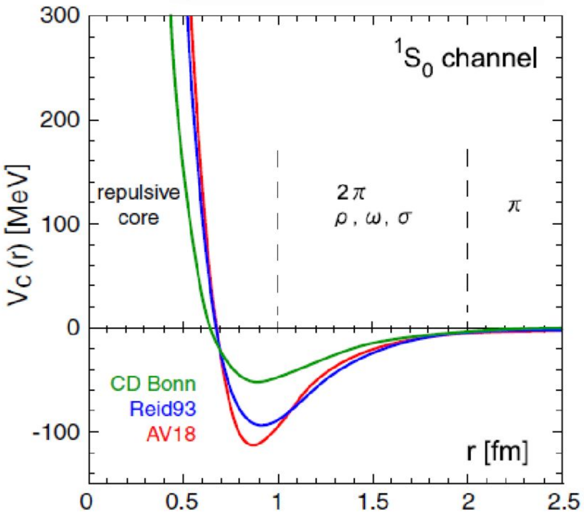

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Investigate **polarization observables** to further probe nucleon interactions and perform rigorous tests of nuclear potential models (and EFTs).

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HIγS at TUNL

HIγS = High Intensity Gamma Source

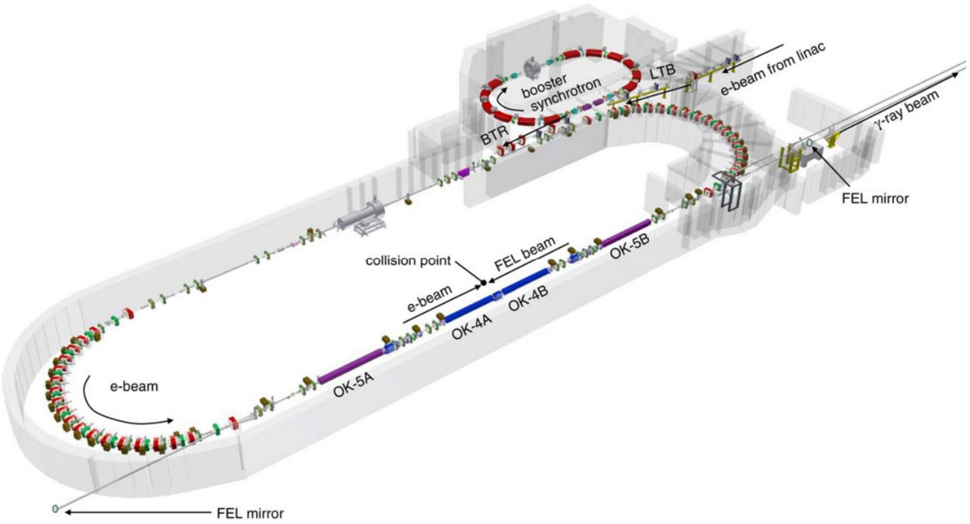

Image Credit: H. Weller et al (2009)

Beam Parameters

- E_γ = 1-100 MeV , $\Delta E/E \approx 3\%$
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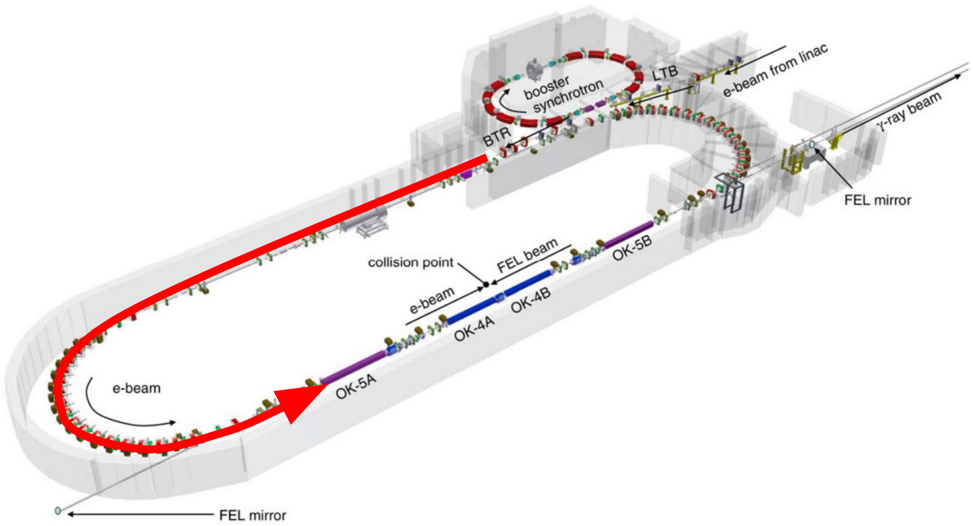

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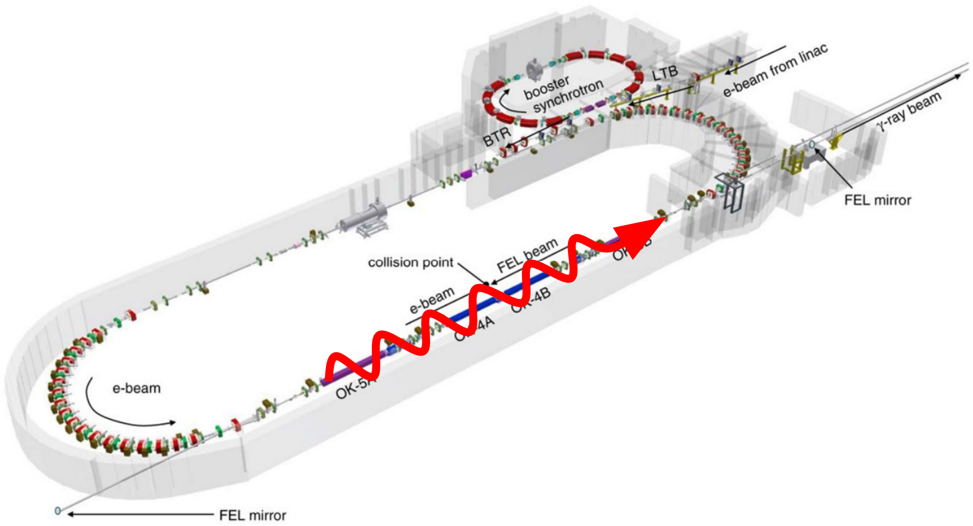

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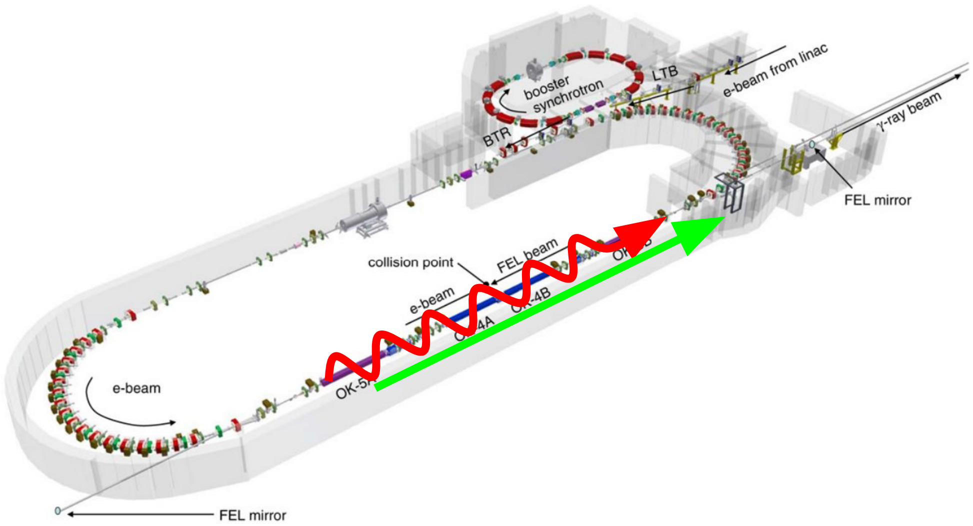

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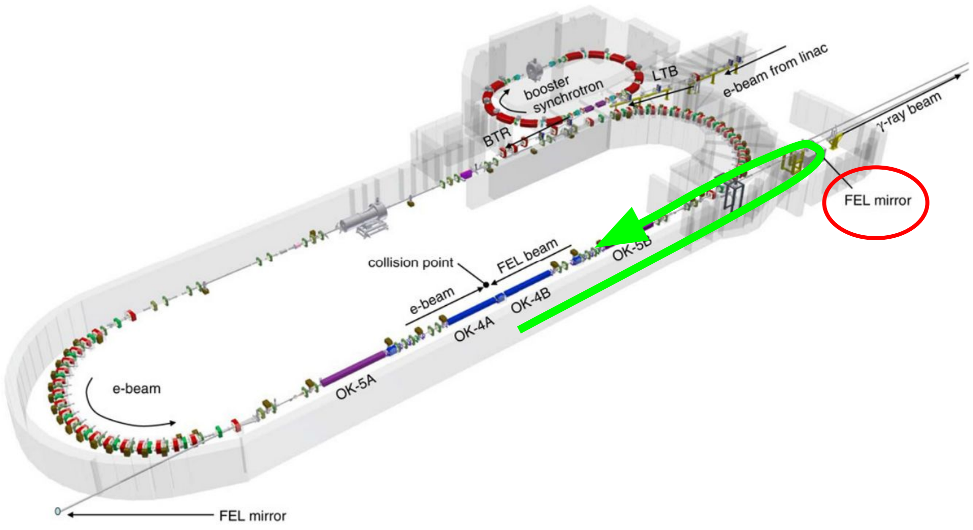

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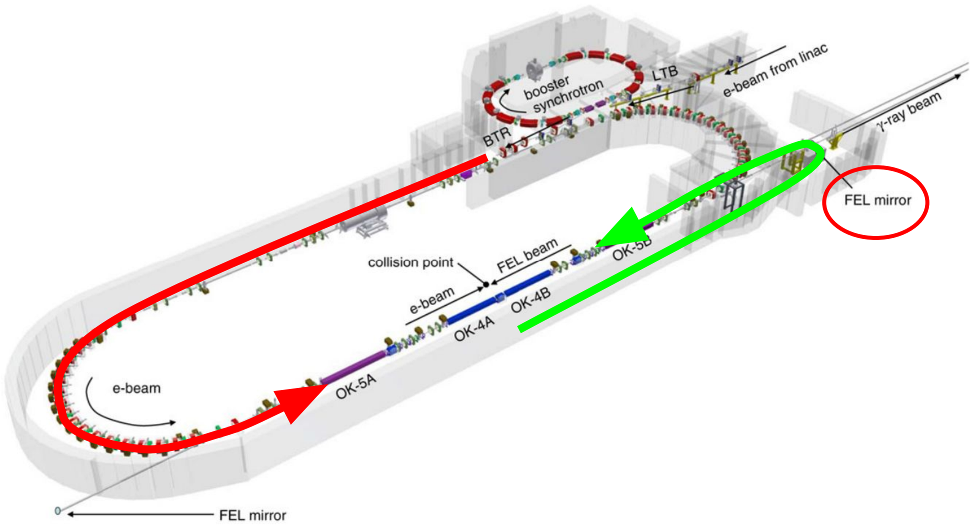

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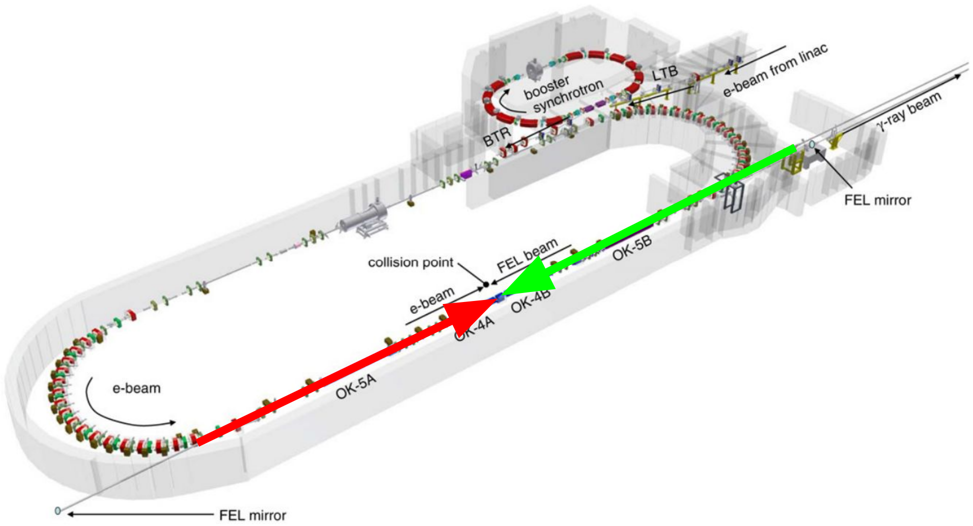

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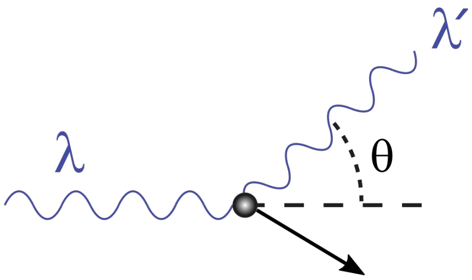

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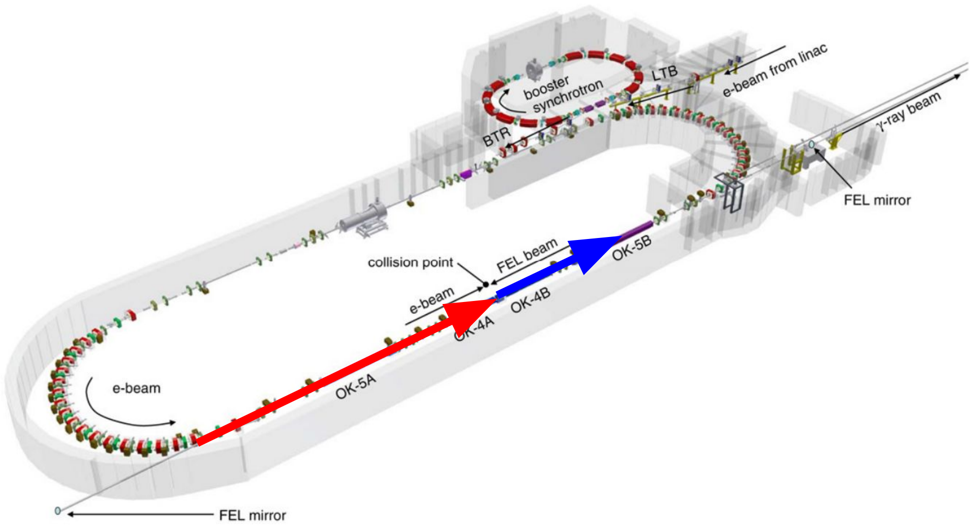

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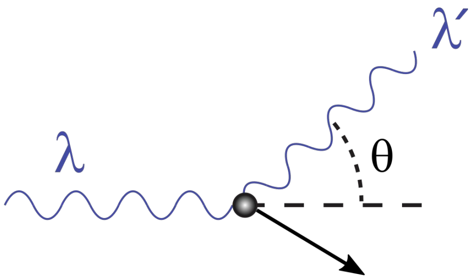

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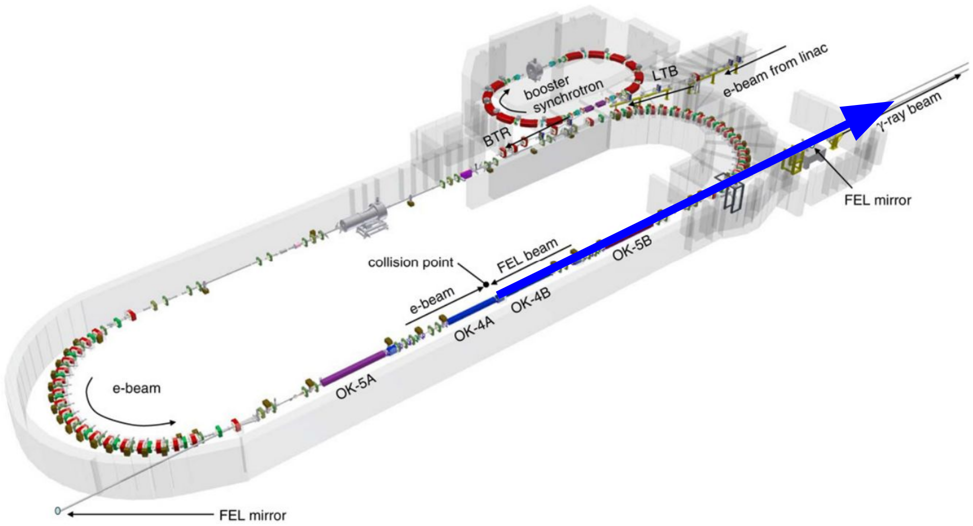

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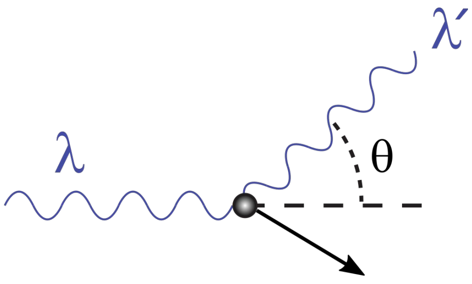

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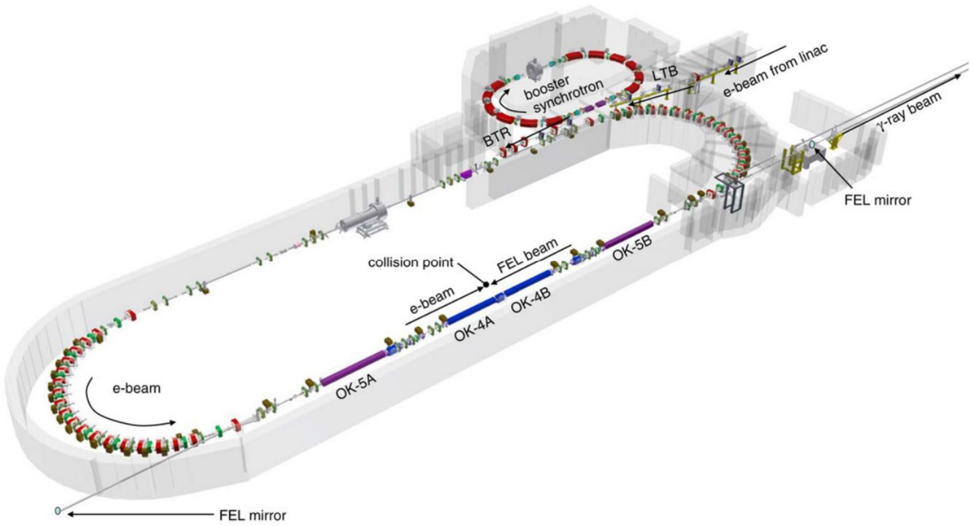

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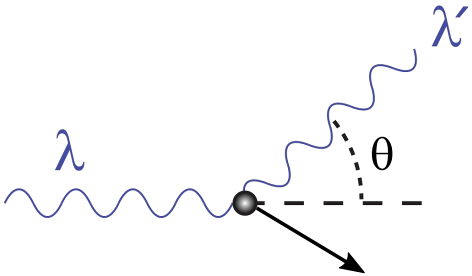

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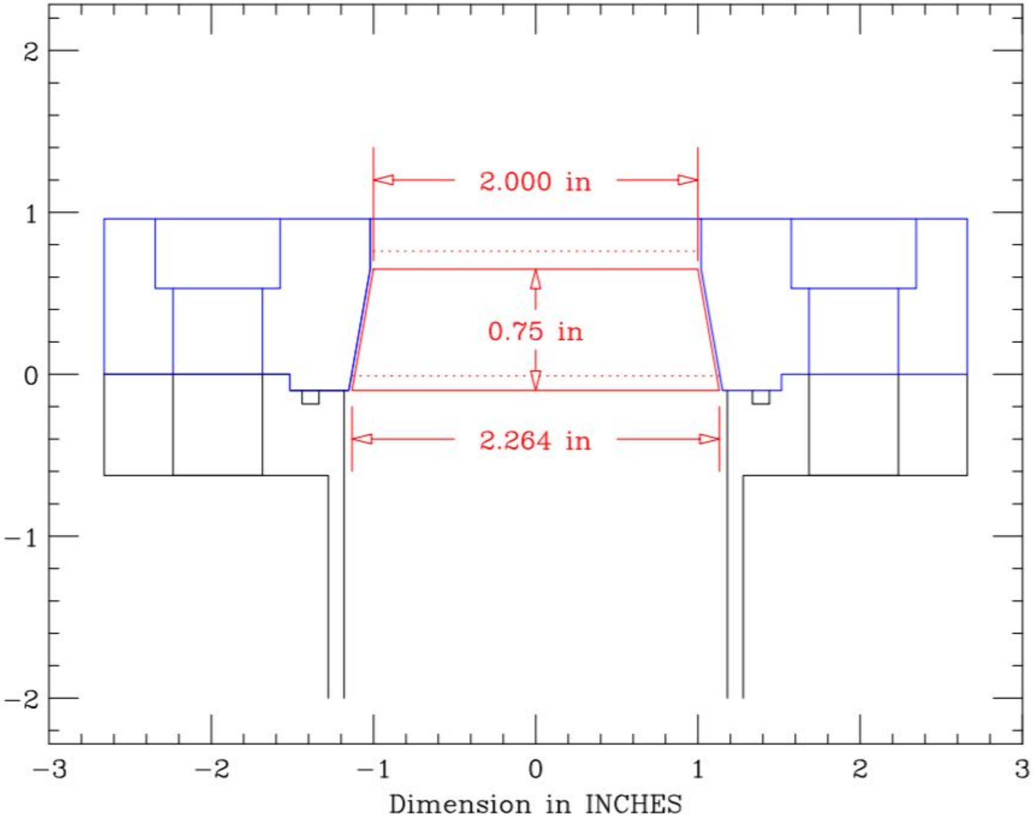
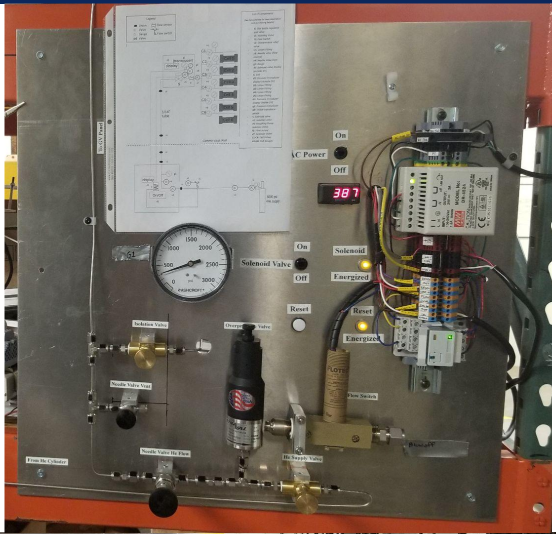
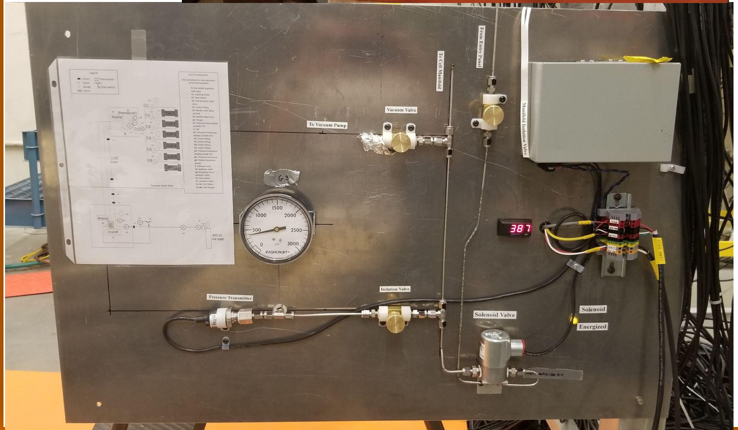
Analyzer Design

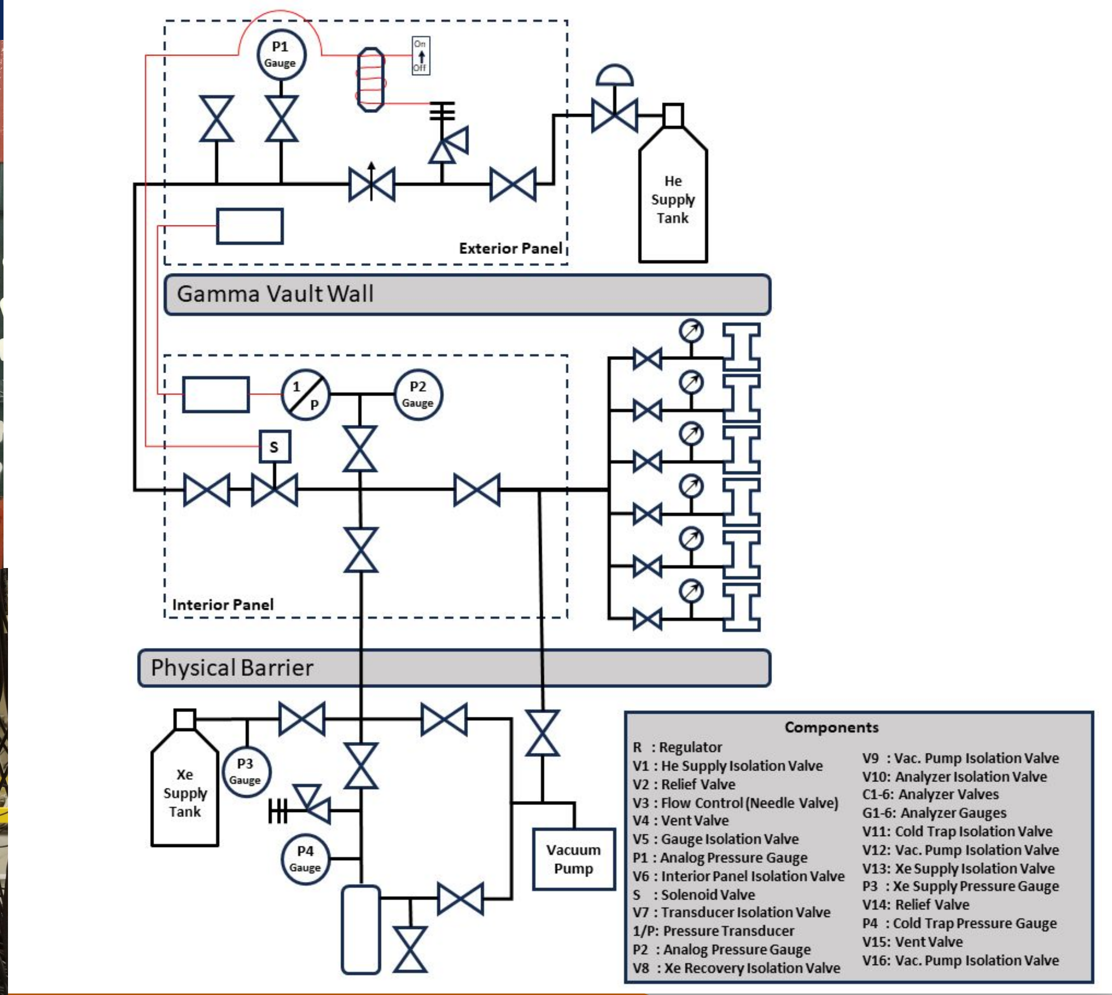


- Beveled flange and window: Forces on glass are compressive, much better than shear forces
- Epoxy holding glass in steel flange - no glass-steel contact, protects against irregularities in either material
- Pressure tests performed to 4000 PSI for 2 to 3 weeks on each analyzer assembled and used

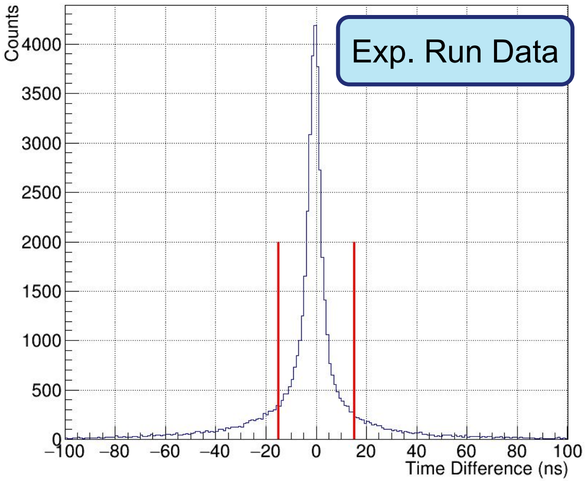
Gas Handling

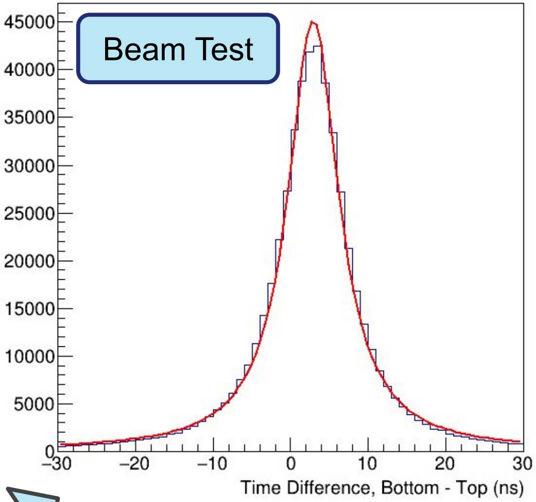


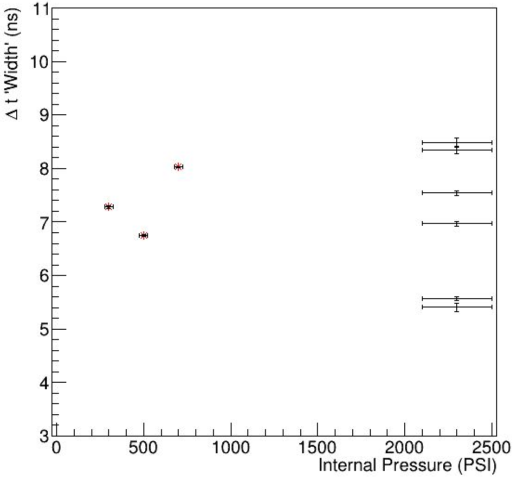




Analyzer Signal Timing

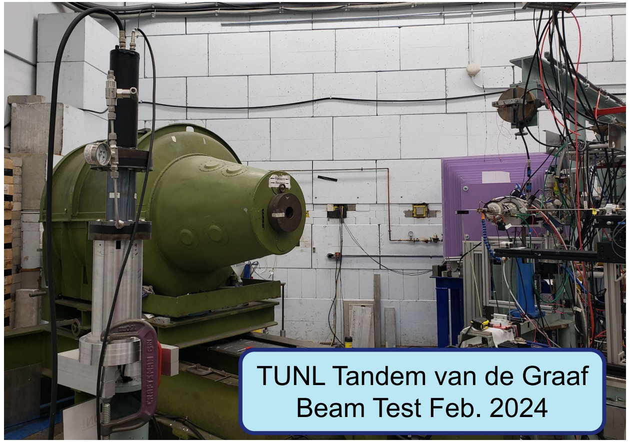






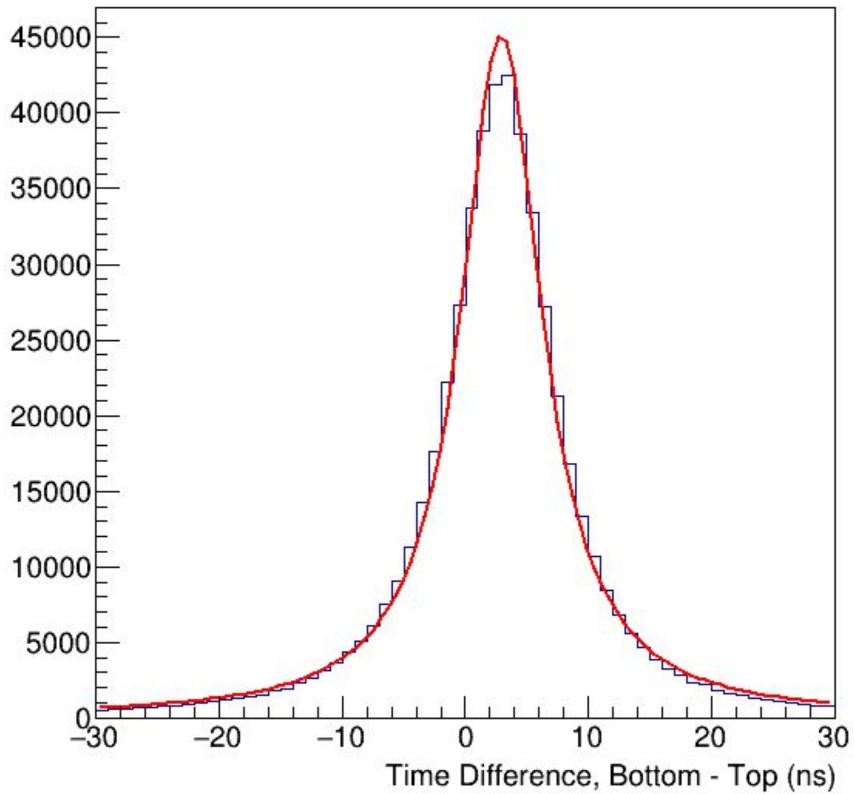
No dependence on internal pressure

Looking into dependence on inner coatings



TUNL Tandem van de Graaf
Beam Test Feb. 2024

Time Difference Characterization

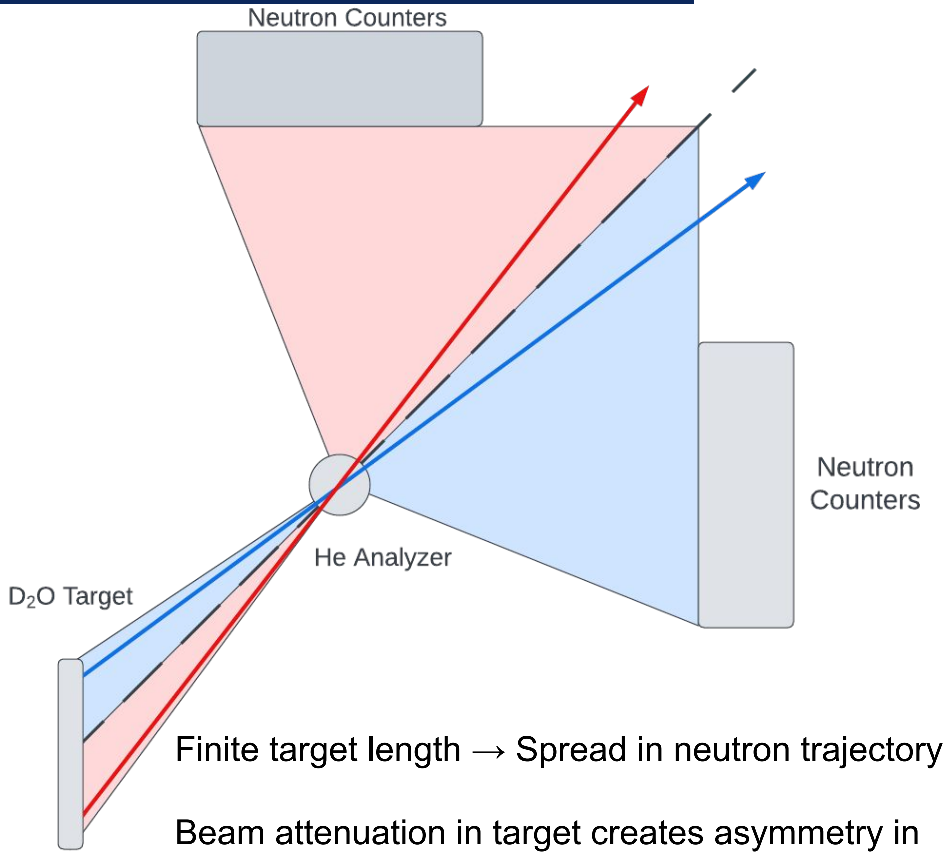


- Time difference between top and bottom PMTs on analyzer
- Fit Function: Breit-Wigner

$$P(t) = \frac{A}{(t - t_0)^2 + \frac{\Gamma^2}{2}}$$

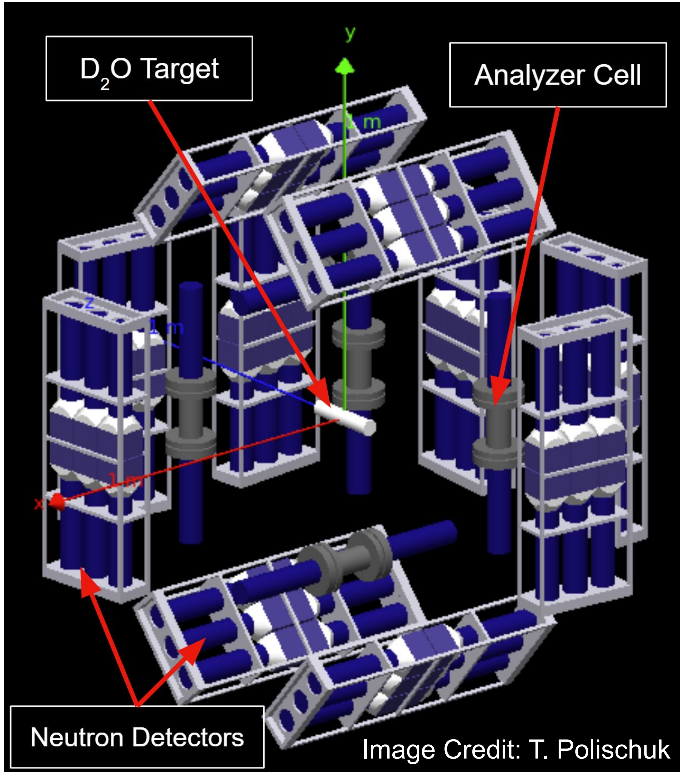
- Parameters:
  - A = Constant
  - t_0 = Mean / Time Offset
  - Γ = Width of Peak
- Also performed Gaussian fit to top part of peak….FWHM very similar
- Nonzero t_0 due to off-center from beam

Simulation: Geometric Asymmetry



Finite target length → Spread in neutron trajectory

Beam attenuation in target creates asymmetry in trajectories → "Geometric Asymmetry"



Corrections calculated from Geant4