Elastic Electron Scattering From ^{3}He and ^{3}H Mirror Nuclei

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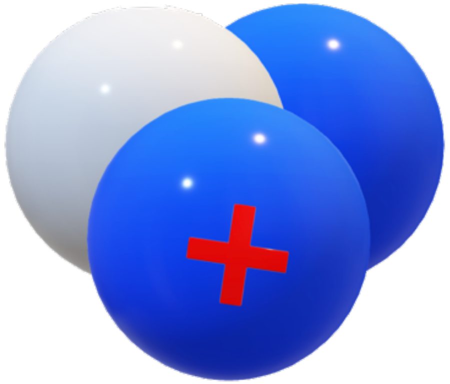
On behalf of the E12-11-112 collaboration

9th Workshop of the APS Topical Group on Hadronic Physics

April 14, 2021

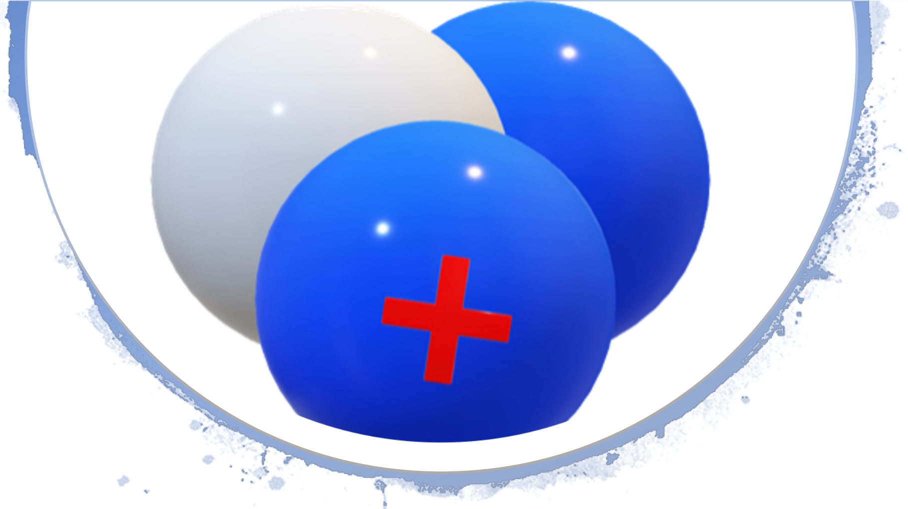


University of New Hampshire

Jefferson Lab
Exploring the Nature of Matter

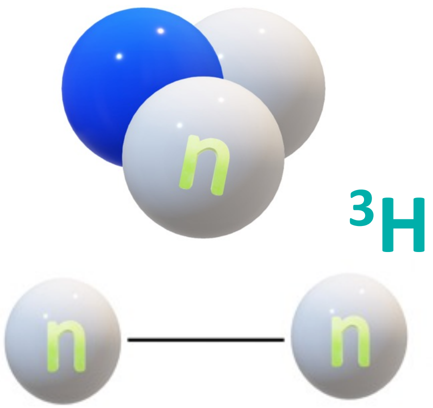
Talk Outline

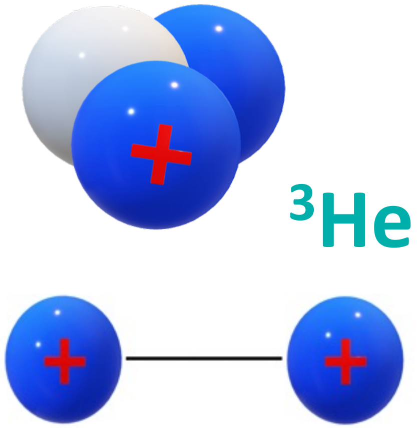
- Physics motivation
- Experimental setup
- Data analysis
- Future work



Motivation and Mirror Nuclei

Mirror nuclei are pairs of nuclei in which the proton number in one equals the neutron number in the other and vice versa.

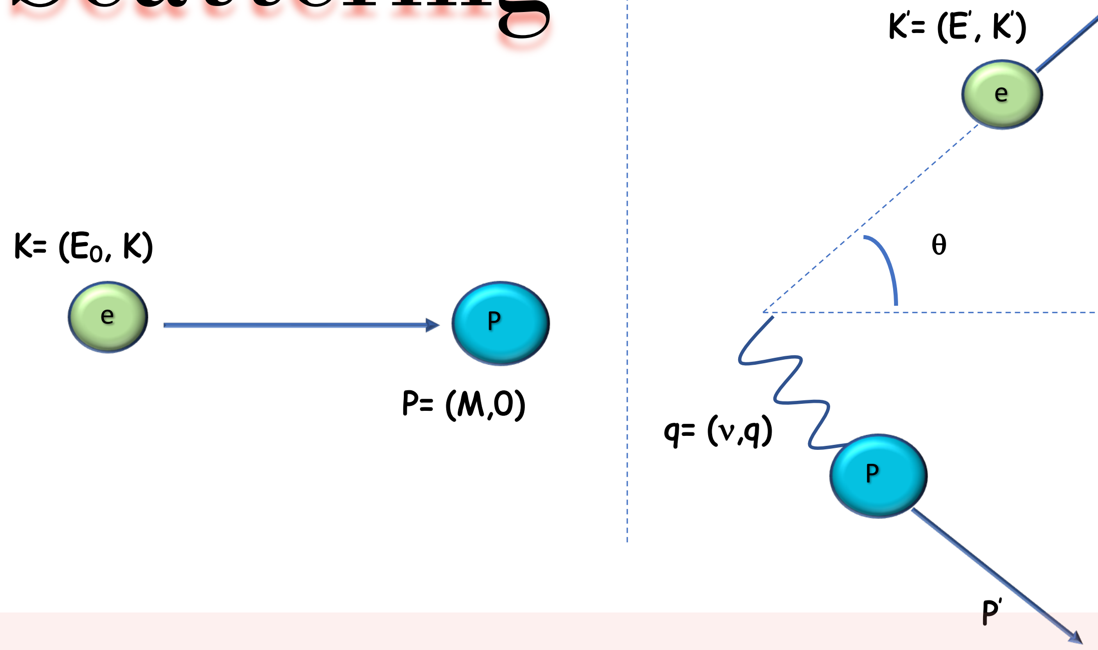


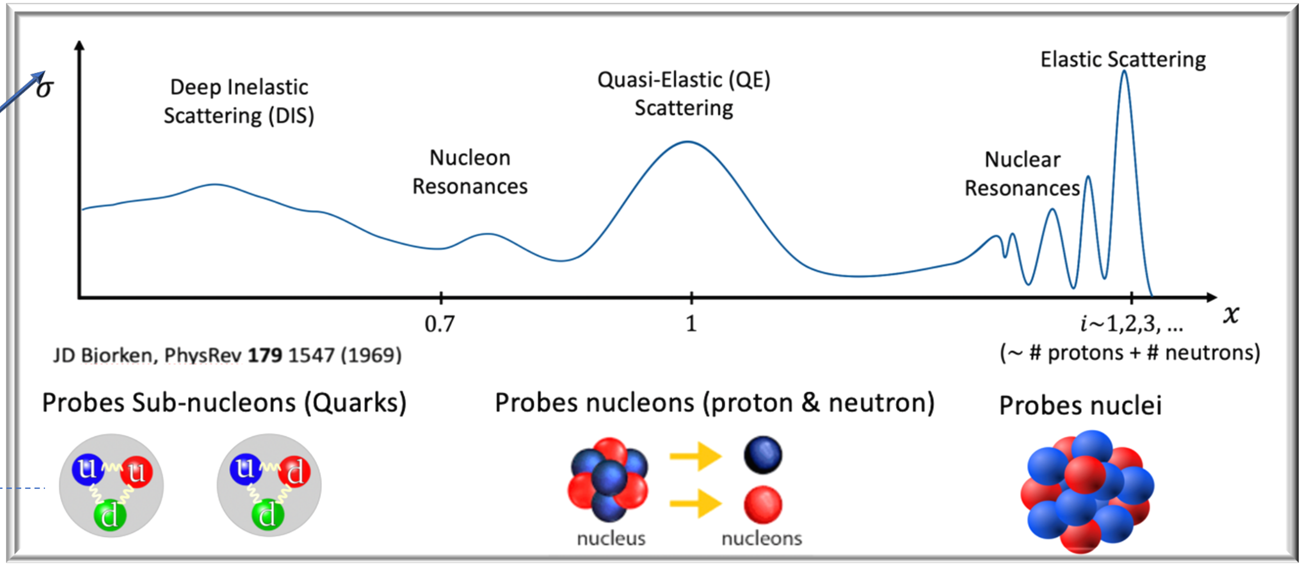


^{3}H and ^{3}He nuclei is the simplest pair of mirror nuclei.

Comparison of ^{3}H and ^{3}He mainly sensitive to difference in contributions from protons and neutrons.

Elastic Electron Scattering





- The kinetic energy of the scattering is conserved.
- The same particles are presented both before and after the scattering.
- we can be described the scattering by two variables the scattering angle θ,and the initial energy E_0.

- $Q^2 = -q^2 = 4E_0E'sin^2\left(\frac{\theta}{2}\right)$ Momentum Transferred to Target.
- $x = \frac{Q^2}{2M\nu}$ Bjorken x (Normalizes 4-momentum-transfer to known masses).
- $\nu = E_0 - E'$ The energy lost by the incident electron during scattering.
- $E' = \frac{E_0}{1+\frac{E_0}{M}(1-\cos\theta)}$ Scattered electron's final energy.

Form Factor

$$(d\sigma/d\Omega)_{exp} = (d\sigma/d\Omega)_{Mott}\, |F(q^2)|^2$$

Experimentally

Electron Cross section from Point like particle

$$\left(\frac{d\sigma}{d\Omega}\right)_{exp.} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott}\left[\frac{F_{ch}^2 + \tau F_M^2}{1+\tau} + 2\tau F_M^2 tan^2(\frac{\theta}{2})\right].$$

$$\tau = Q^2/_{4M^2}$$

Rosenbluth Cross Section

F_{ch} : Electric form factor

F_M : Magnetic form factor

- $F_M(Q^2)$ describes the magnetic structure of the target and equals the magnetic moment of the target at $Q^2 = 0$ in units of the nuclear magneton.
- $F_{ch}(Q^2)$ describes the electric structure of the target and equals the electric charge of the target at $Q^2 = 0$ in units of elementary charge.

Charge Form Factor and Charge Radius

$$F(q^2) = \int e^{\frac{iq\cdot x}{\hbar}} \rho(x) d^3x \xrightarrow{x \to r} 4\pi \int \rho(r) \frac{\sin(|q|r/\hbar)}{|q|r/\hbar} r^2 dr$$

- Recoil is negligible
- The validity of the Born approximation
- In non-relativistic limit

The charge distribution is spherically symmetric.

This procedure can be inverted to find the charge distribution of a target from its form factor.

$$\rho(r) = \frac{1}{(2\pi)^3} \int F(q^2) e^{\frac{-iq\cdot x}{\hbar}} d^3q$$

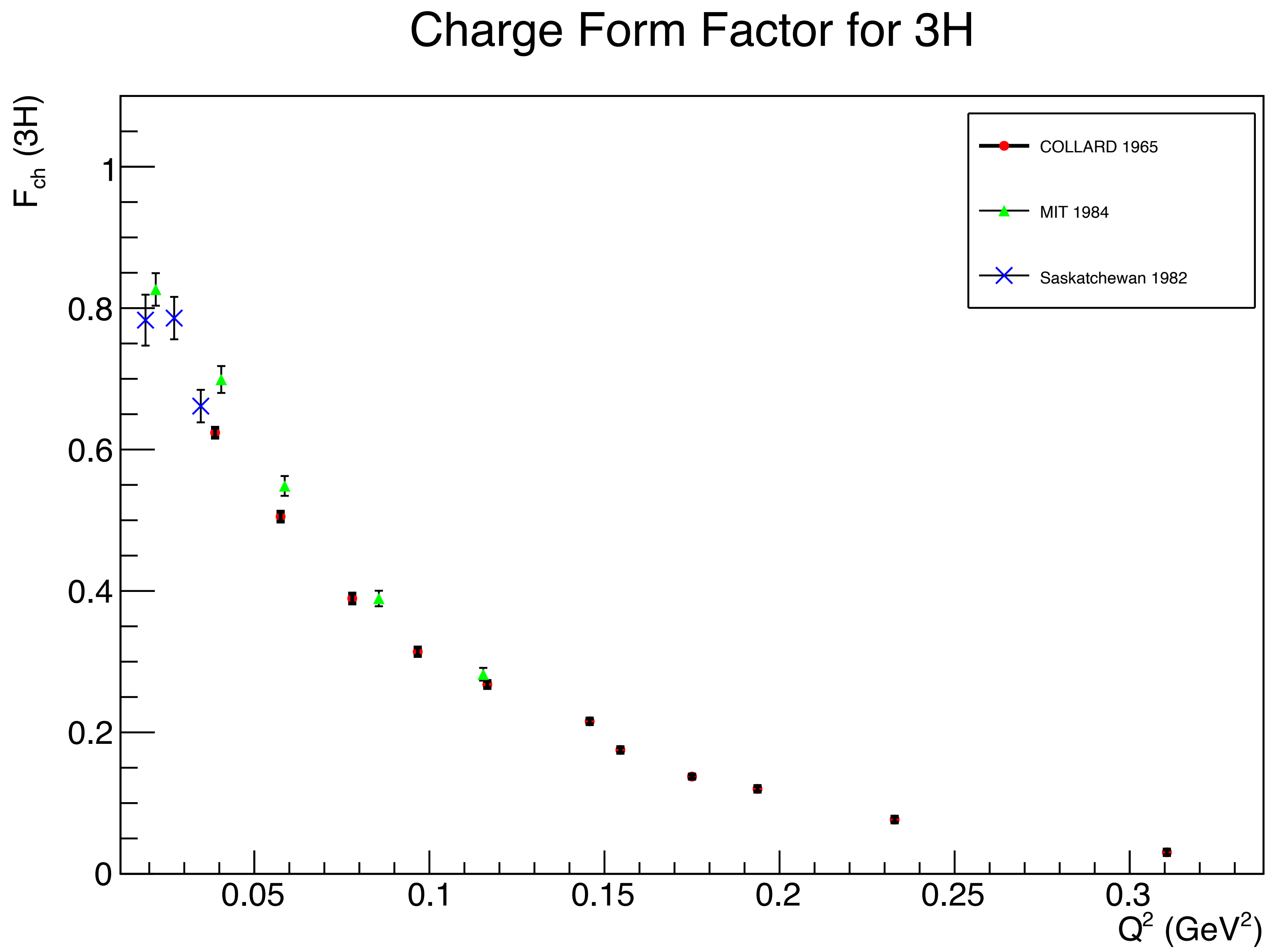
$$F(q^2) = 1 - \frac{1}{6}\, q^2 \langle {r^2}_{E(M)} \rangle + \frac{1}{5!} q^4 \langle r^4 \rangle - \cdots$$

$$\langle r^2 \rangle \equiv -6\, \hbar^2 \left. \frac{dF(q^2)}{dq^2} \right|_{q^2=0}$$

Mean Square of charge radii

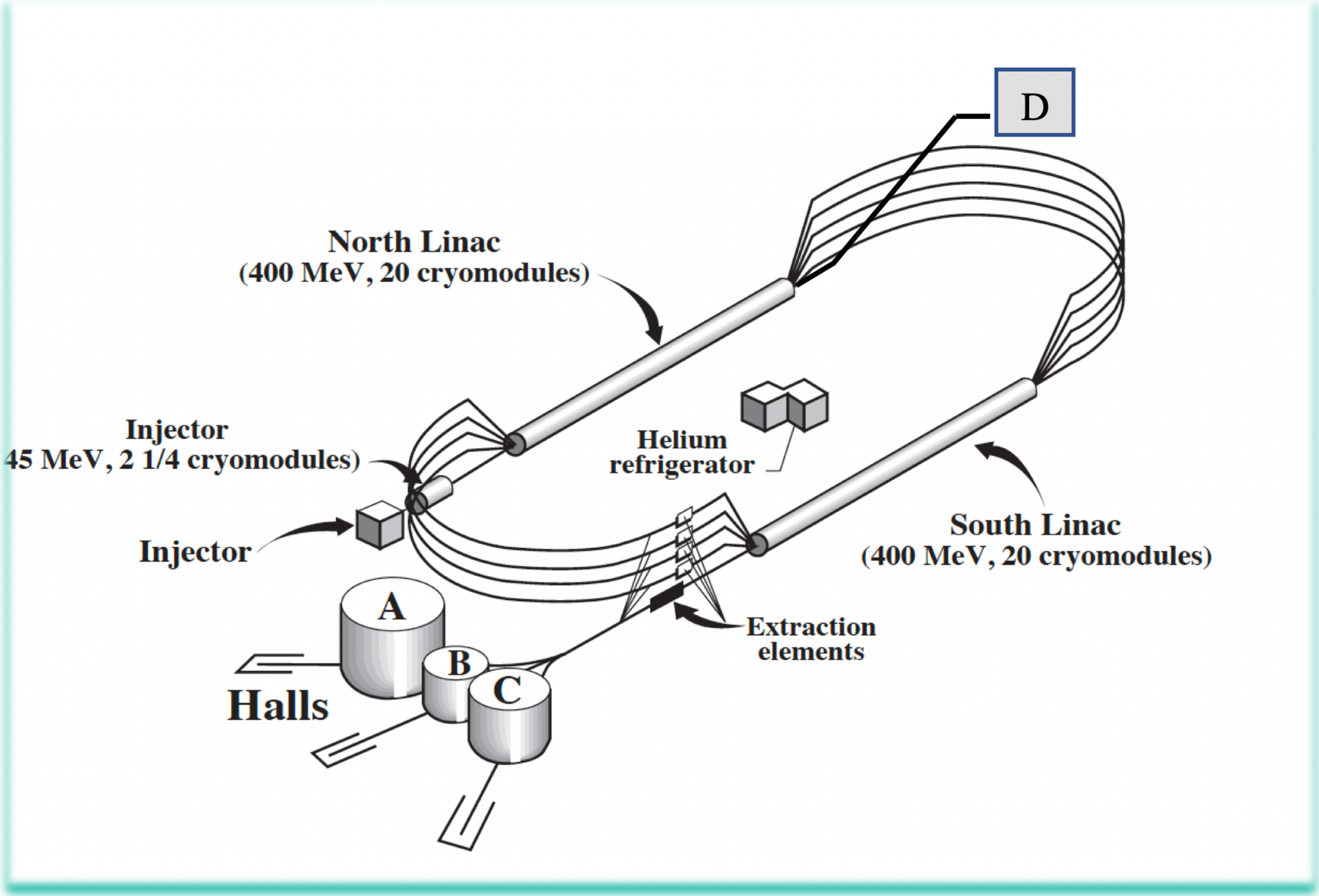
*Related to charge radius in infinite-momentum-frame
GA Miller, PRL **99** 112001 (2007)

^{3}H and ^{3}He Comparison



- ✓ The comparison of the ^{3}H and ^{3}He charge radii Minimize systematic uncertainties.
- ✓ Because there are better measurements for 3He, we can use a precise 3H/3He ratio measurement to help constrain the 3H data set.

limited Data for ^{3}H *At low* Q^2

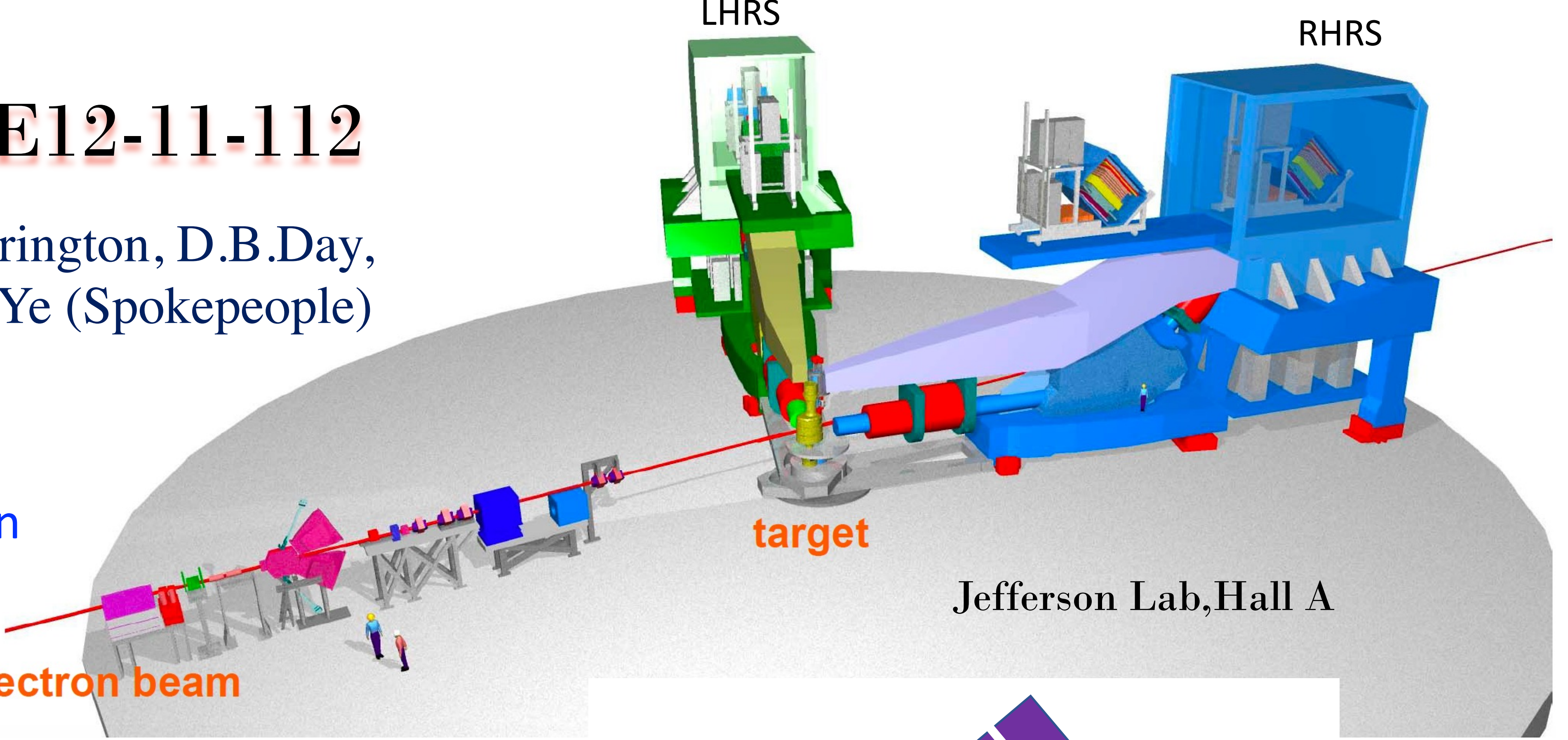


Jefferson Lab.

J.Alcorn *et al.*, Nucl. Instr. Meth. **A,** 522 (2004).

Experiment E12-11-112

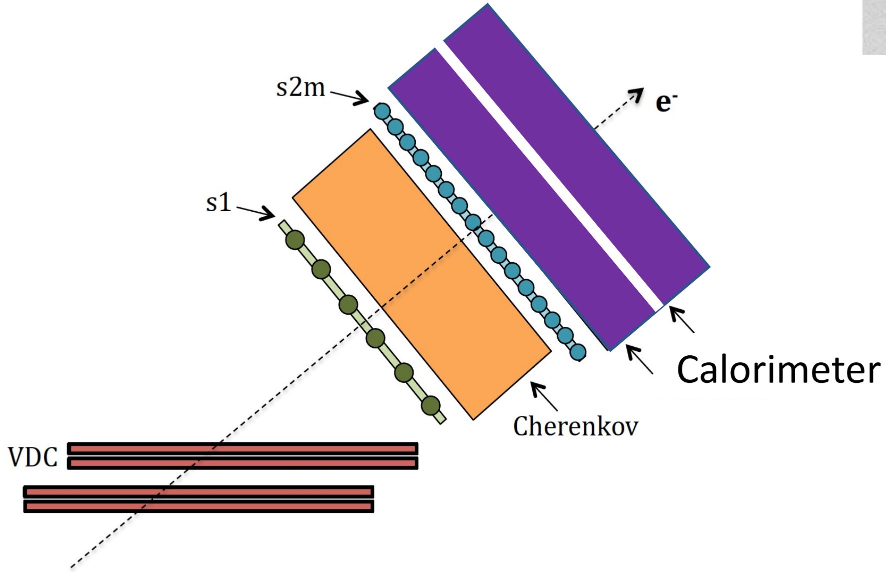
P. Solvignon, J.Arrington, D.B.Day, D. Higinbotham, Z. Ye (Spokepeople)



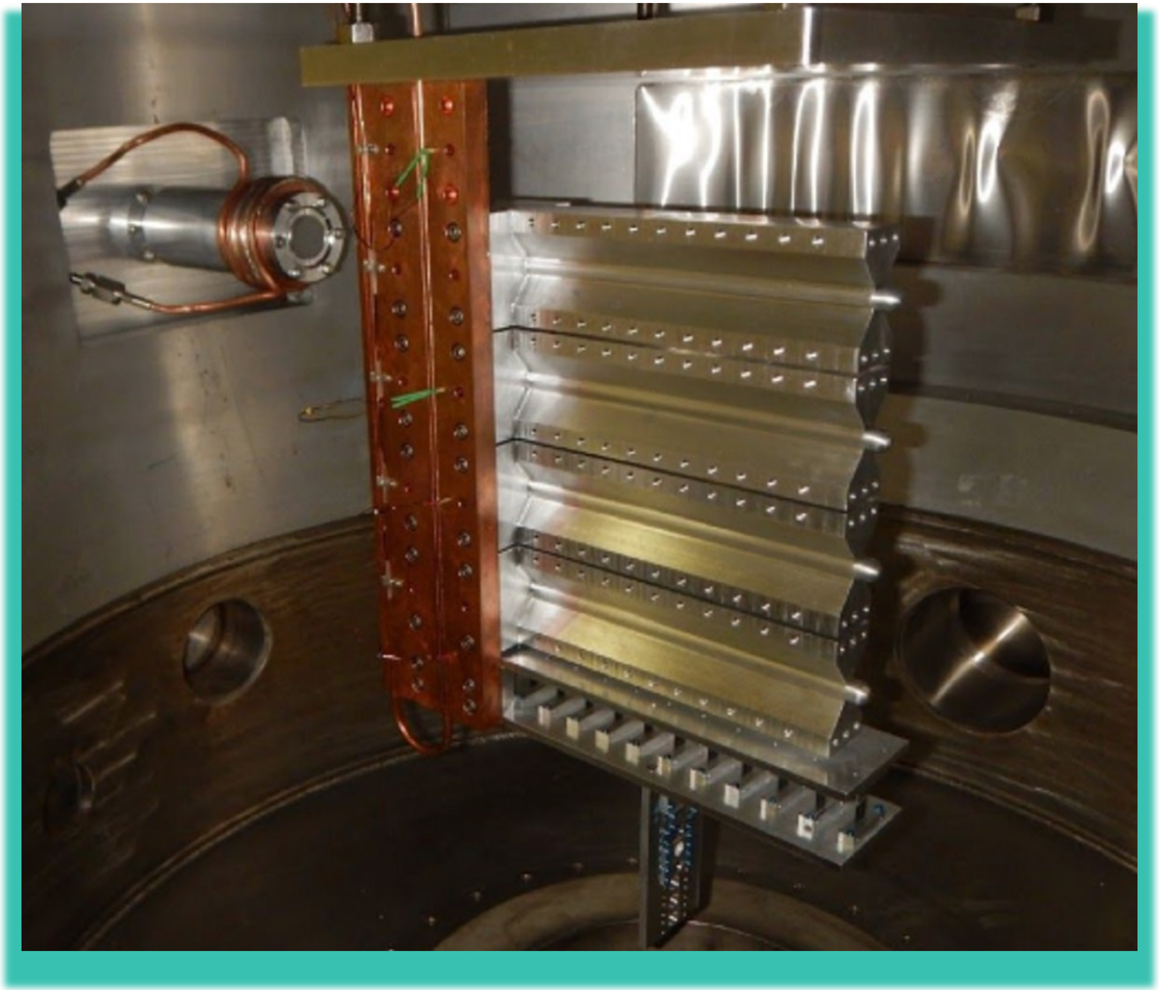
Experiment Configuration

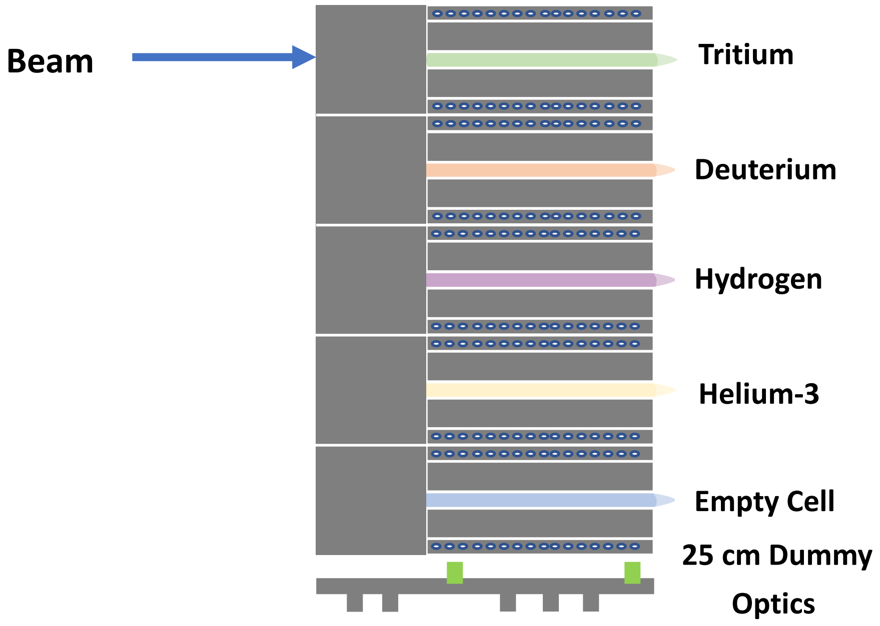
- Beam current: 5μA
- Beam energy: 1.171 GeV
- Momentum: 1.128 GeV
- Angle: 17 degree
- $Q^2 = 0.11\ GeV^2$

- Vertical Drift Chamber
  Position and angle of the electrons.
- Scintillator
  Used for trigger or measure time of the event.
- Cherenkov & calorimeters
  Pion rejection.



Nuclear Targets





- Consisted of five identical aluminum cells
- Each cell carved from block of Al
- Each one was filled with different gas and sealed
- Each target cell has a cylindrical fluid space with a length of 25 cm and a diameter of 1.27cm
- Atmospheres pressure for ^{3}H 13.75 (atm) ,^{3}He 17.49(atm) and ^{1}H 35.03 (atm)

S. N. Santiesteban *et al.*, Nucl. Instr. Meth. 940 (2019)351.

From Yield to The Cross Section

$$Yield = \frac{Number\ of\ Good\ Scattered\ Electrons}{Effective\ Luminosity}$$

$Effective\ Luminosity$ is the product of the number of incoming beam particles per unit time , the target particle density in the scattering material , and the target's thickness. Its unit [(area x time)−1].

$$Normalized\ Yield = \frac{N_e\,.\,ps}{Q\,.\rho_a\,.\,Boiling.\,\epsilon_{tot}.\,LT}$$

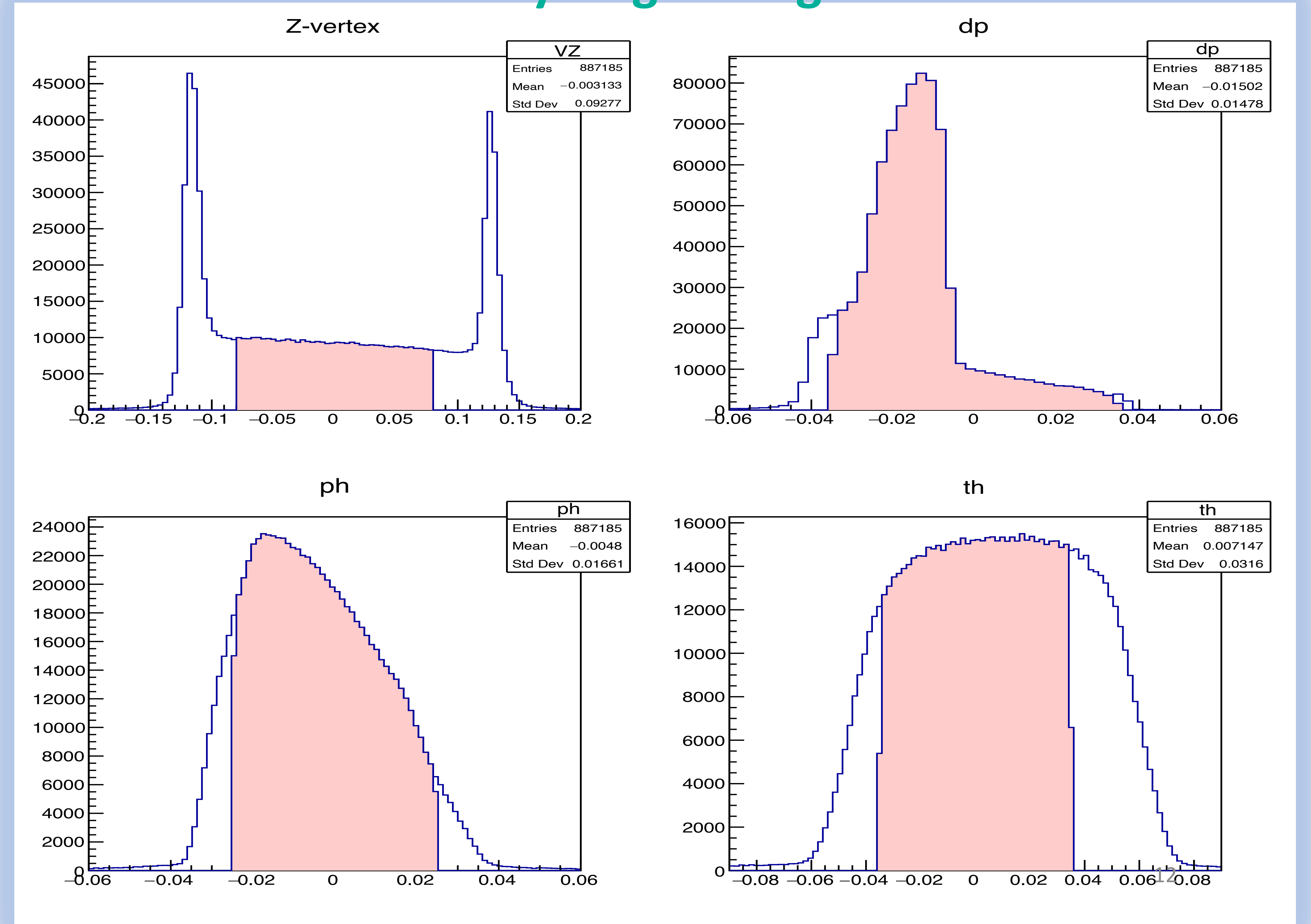
$$\left(\frac{d\sigma}{d\Omega}\right)_{exp} = \frac{N_e\,.\,ps}{N_{in}.\,\rho\,.\,\Delta Z.\,LT.\,\epsilon_{tot}}\frac{1}{\Delta\Omega}$$

$$\left(\frac{d\sigma}{d\Omega}\right)_{exp} = \frac{Yield}{\Delta\Omega}$$

- N_e is the number of good events.
- ps is the prescale factor for the production trigger.
- Q is the charge with stable beam current.
- ρ_a is the effective area density of the target (g/cm^2).
- $Boiling$ is the ratio of the effective gas target density at given beam current comparing to no beam.
- ϵ_{tot} is the product of all efficiencies.
- LT is the computer livetime.

Selection of Good Electrons

Hydrogen Target



Target length cut

TCut vz = "fabs(L.tr.vz)<0.08";

Acceptance Cut

TCut dp = "fabs(L.tr.tg_dp)<0.035";

TCut phi = "fabs(L.tr.tg_ph)<0.025";

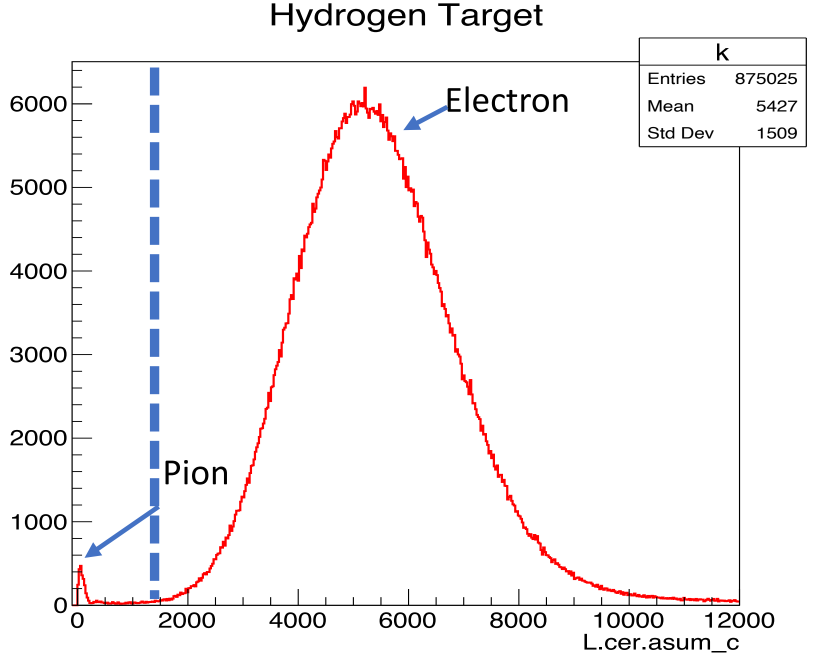
TCut theta = "fabs(L.tr.tg_th)<0.035";

PID Cut

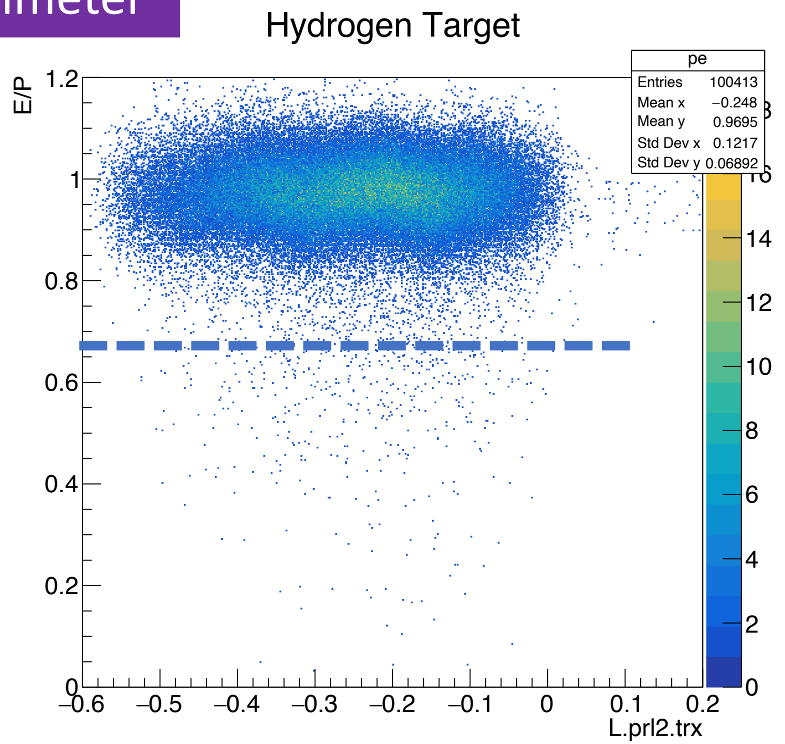
Cherenkov Cut >1500
Energy/ Momentum Cut >. 0.7

Trigger 1= S_1 & S_2
Trigger 2= S_1 & S_2 & Cherenkov
Trigger 3= S_1 || S_2 & Cherenkov

Cherenkov



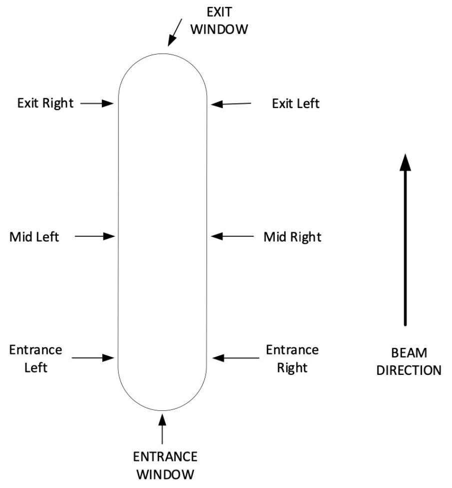
Calorimeter



Data Correction factors

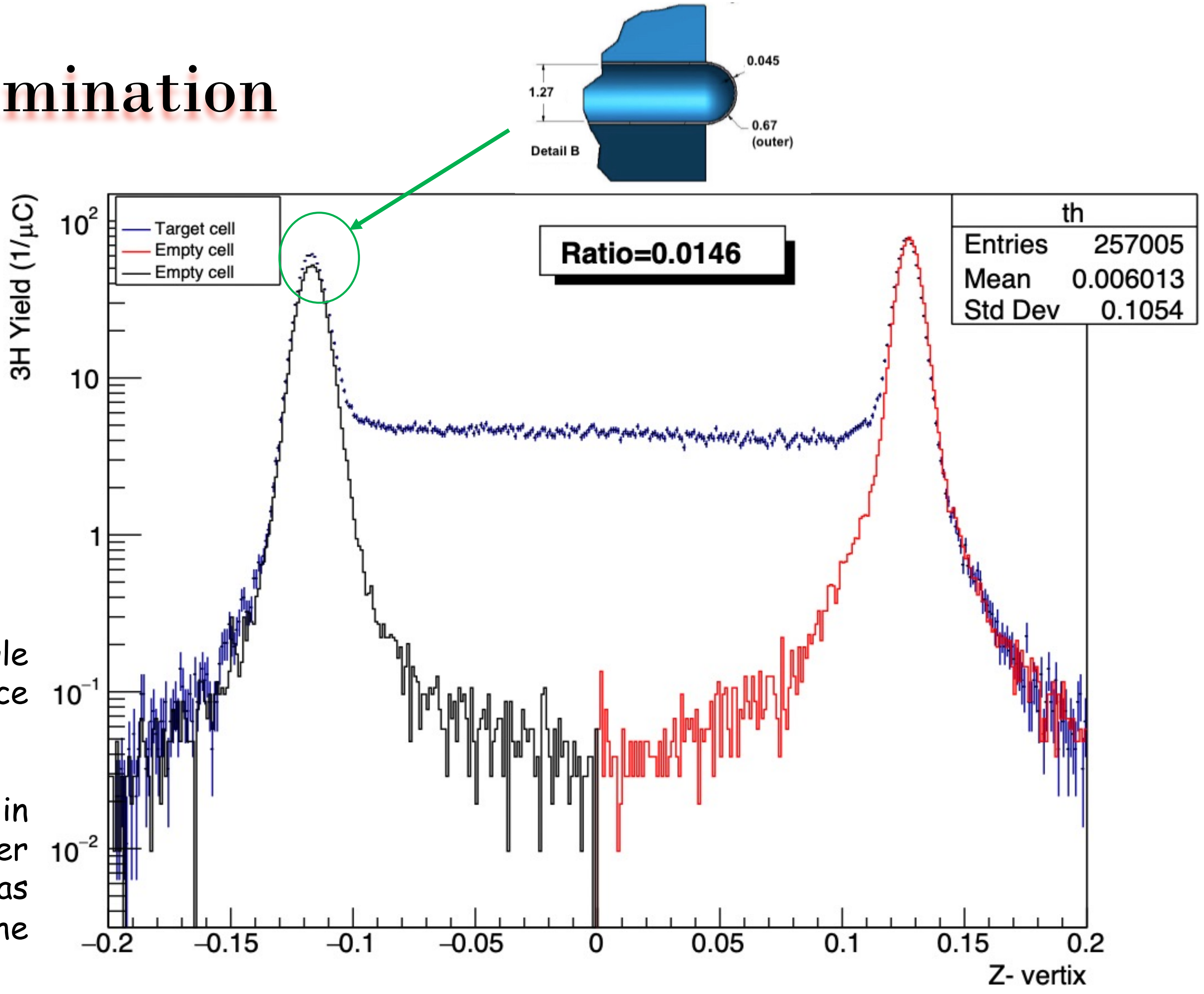
- Live time: Ave. 0.90
- Trigger1 Efficiency: Ave. 0.99
- VDC Efficiency: Ave. 0.97
- Cherenkov Efficiency Ave. 0.99
- Pion Rejecters Efficiency Ave. 0.99

Background Contamination



S. N. Santiesteban *et al.*, Nucl. Instr. Meth. 940 (2019).

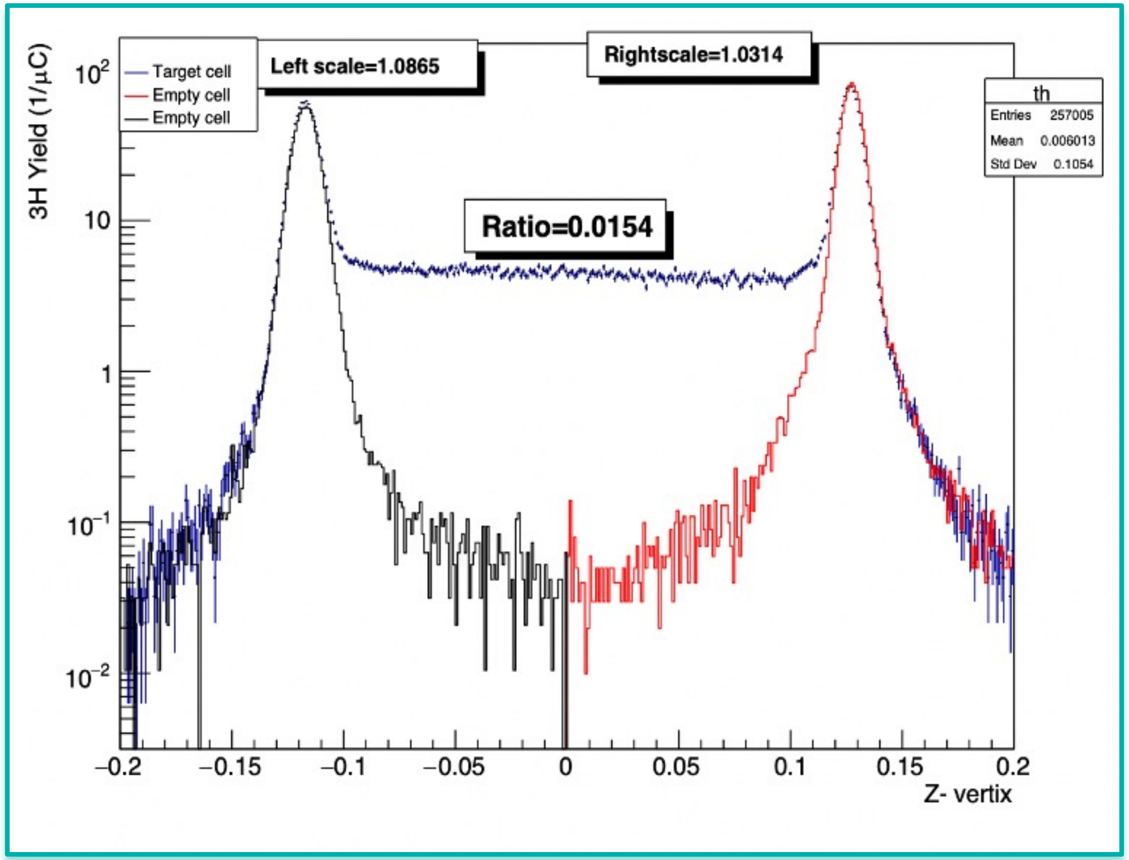
- The machining the cell from a single piece of aluminum and the end piece is very hard to reproduce.
- The scattering from the electrons in the upstream endcap is also shatter from the gas particles in the gas targets, which does not happen in the empty cells.

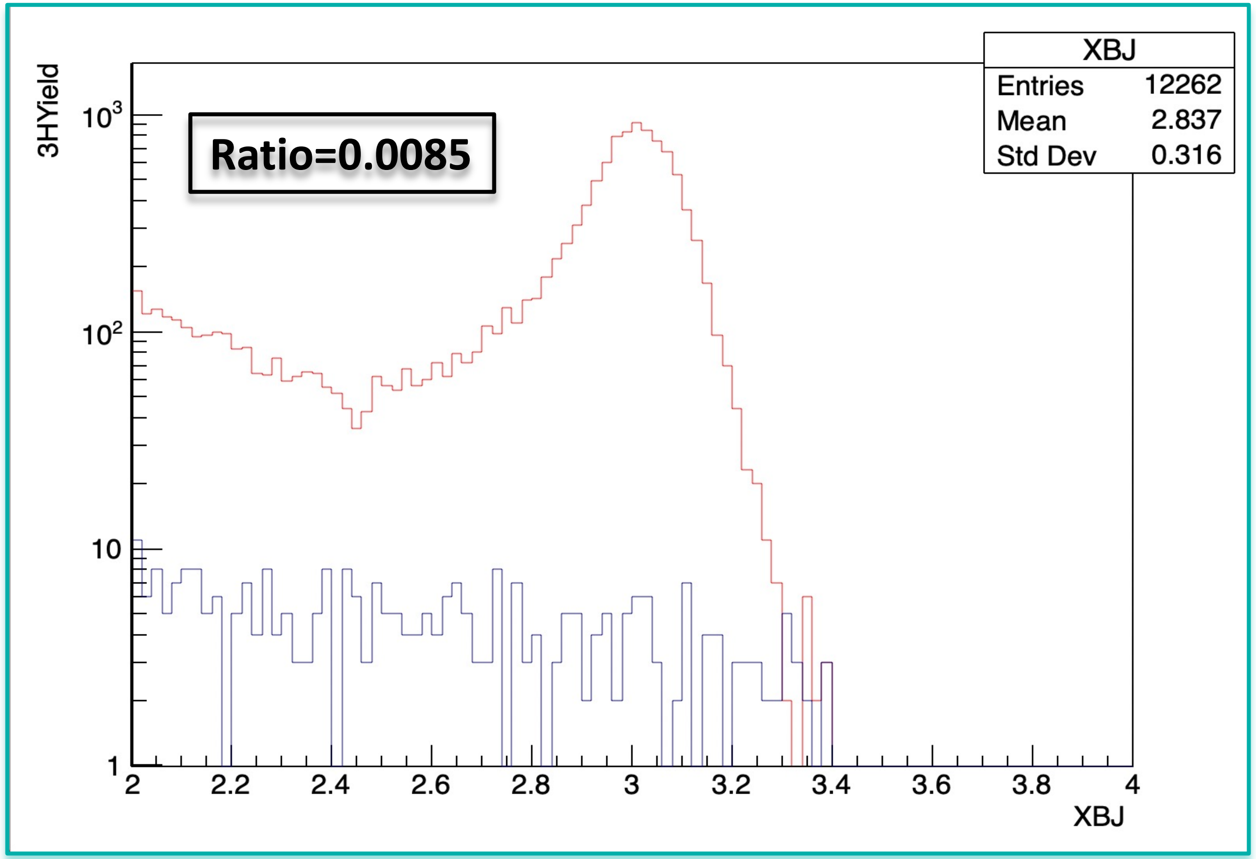


Tritium Target

Background Contamination

Tritium Target





Elastic Cross Section Monte Carlo

What is SIMC

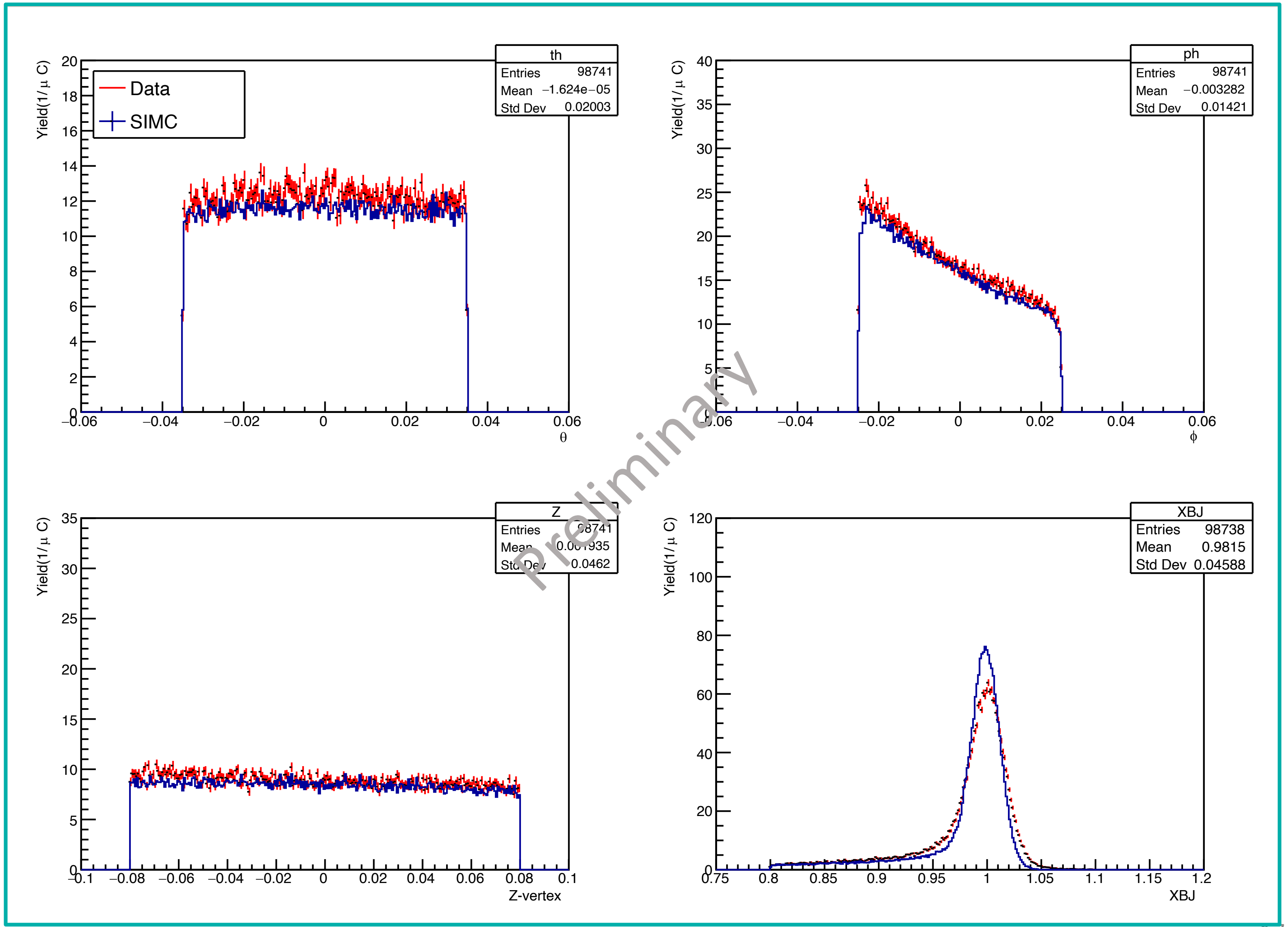
SIMC is a physics simulation Monte Carlo program primarily used by JLab's Halls A and C to simulate electron scattering experiments.

Features

- ✓ SIMC contains the geometry of the Hall A spectrometers including their various apertures and the materials that comprise them.
- ✓ SIMC uses an event generator to create electrons which scatter from a given target and records their final states as they were viewed by a detector.
- ✓ SIMC Includes radiative effects, multiple scattering, ionization energy loss and particle decay.
- ✓ Our version of SIMC works Nuclear elastic for 1H, 3H, 3He and any other target requires an elastic cross section model.

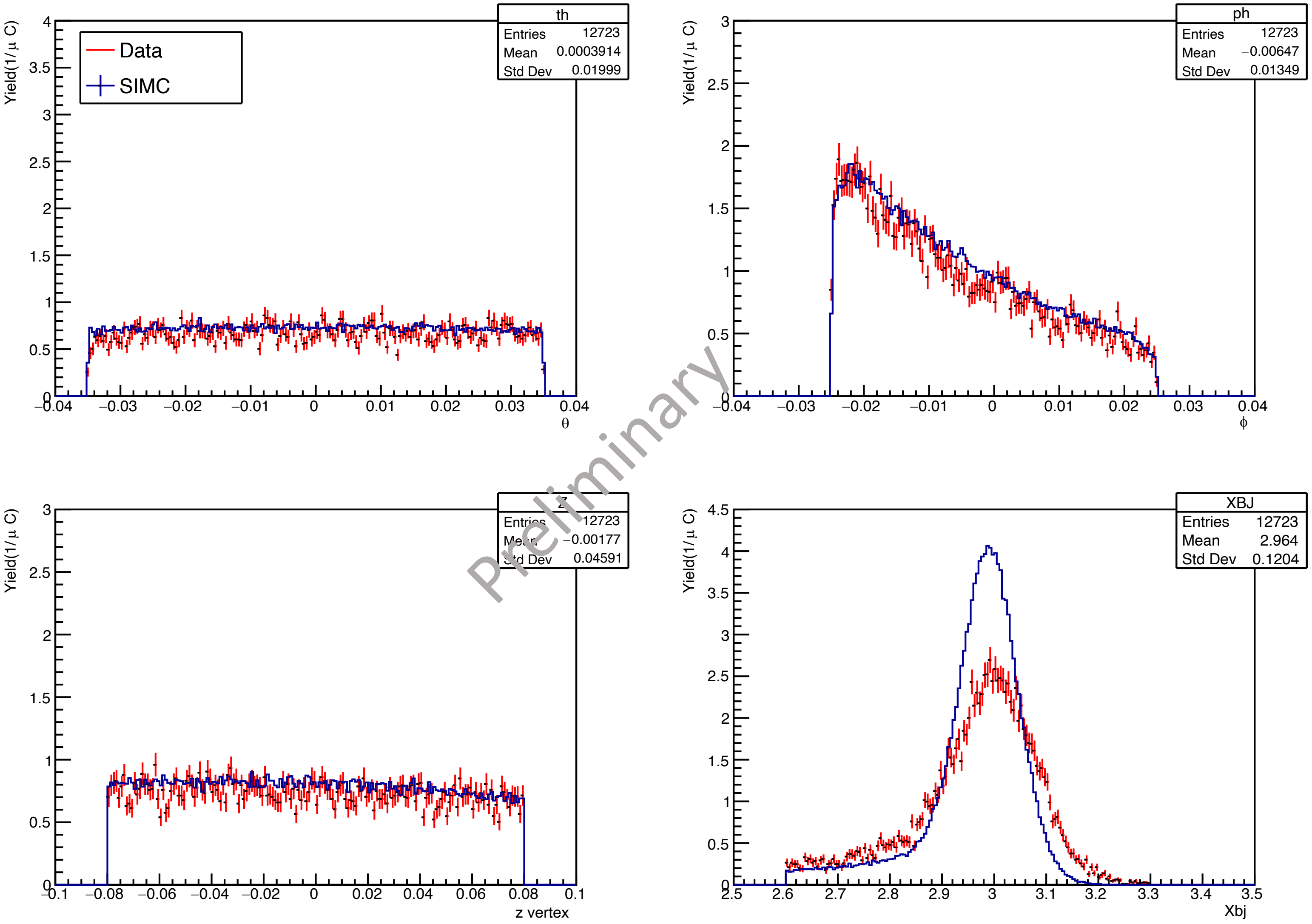
Agreement between the data and SIMC for Hydrogen target

- Shape agreement is good
- The resolution in XbJ slightly different
- The data Yield is 95 % of the SIMC Yield for 0.95< xbj< 1.1
- Present uncertainty ~5% and we expected uncertainty (~3%)



Agreement between the data and SIMC for ^{3}He target

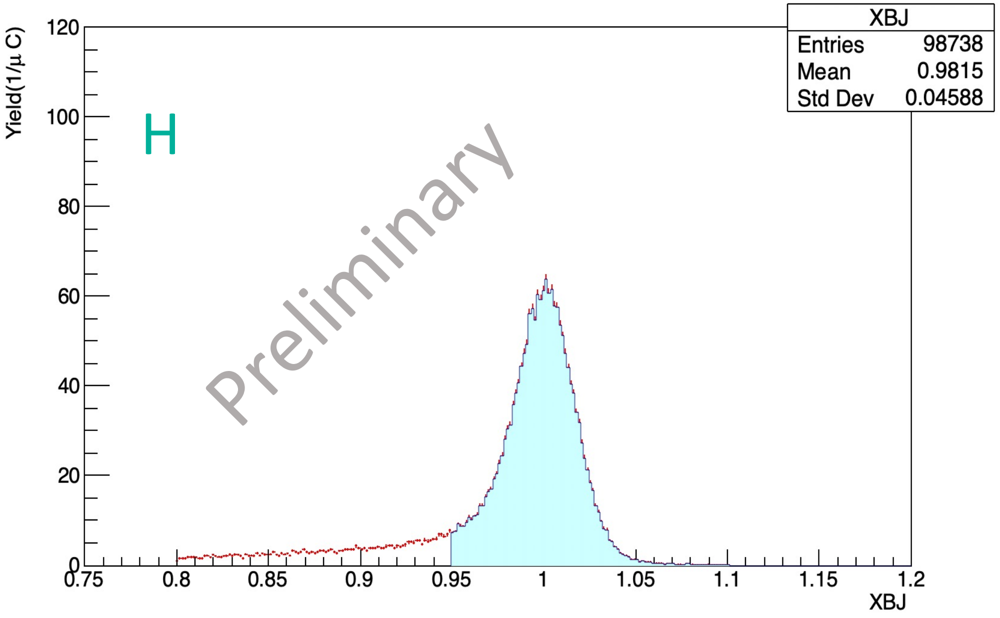
- Shape agreement is good
- The resolution in XbJ slightly different.
- The data Yield is 93 % of the SIMC for 2.6< xbj <3.3
- Present uncertainty ~5% and we expected uncertainty (~3%)

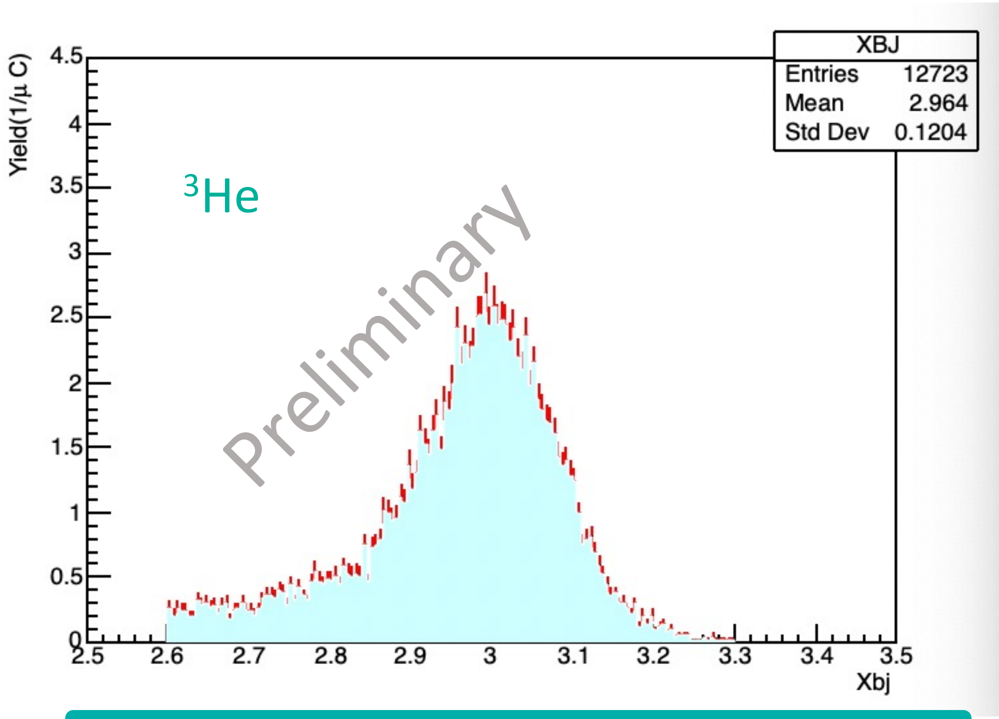


H & ^{3}He Preliminary Cross sections

Correction Factor

$$\left(\frac{d\sigma}{d\Omega}\right)_{exp} = \boxed{\frac{Yield_{exp}}{Yield_{SIMC}}}\left(\frac{d\sigma}{d\Omega}\right)_{SIMC}$$





H cross section: 5.175 ± 0.0134 µb/sr

^{3}He cross section: 1.427 ± 0.0127 µb/sr

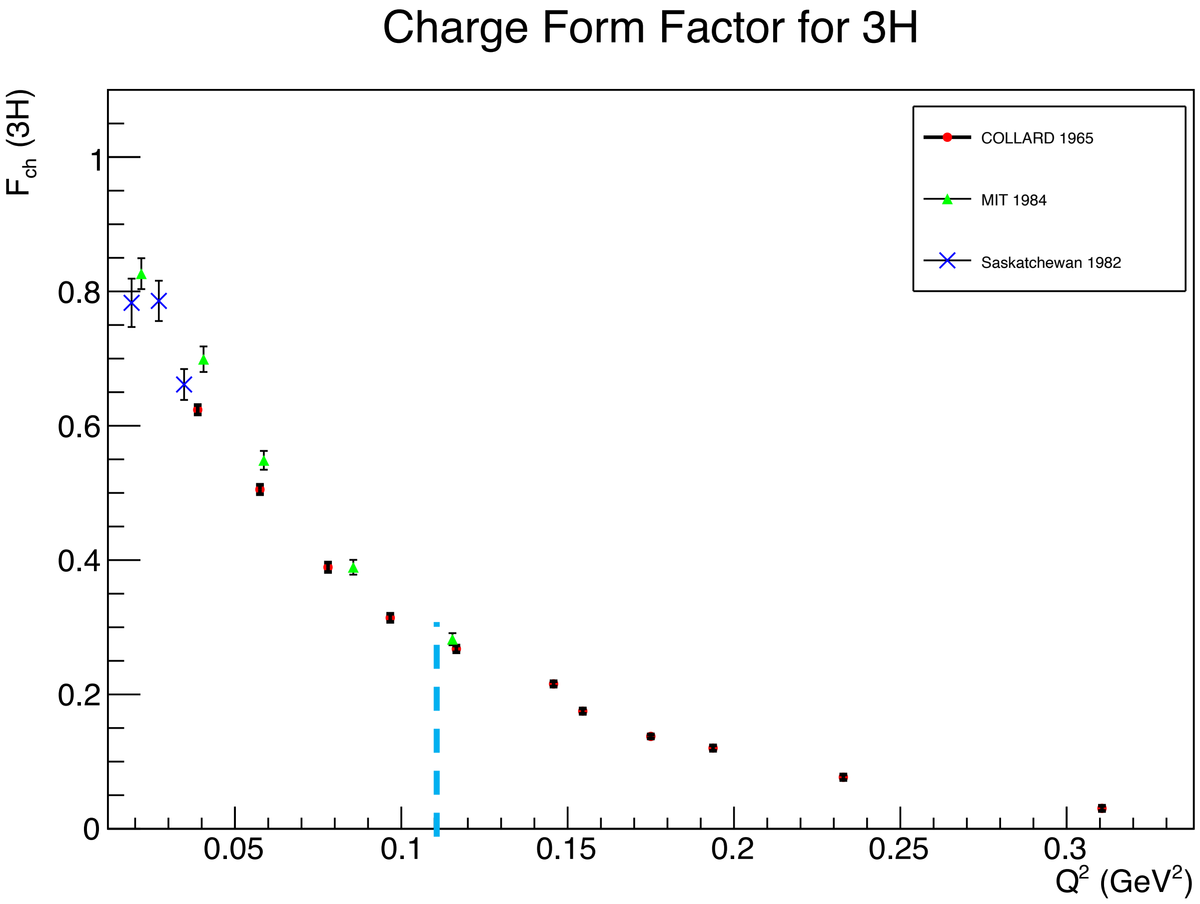
Preliminary Cross Section ± statistical uncertainty only

Expected Results

$At\ low\ Q^2 \approx 0.11\ GeV^2$

$$\frac{\sigma\ ^3H}{\sigma\ ^3He} \rightarrow \frac{F_{ch}\ ^3H}{F_{ch}\ ^3He} \rightarrow$$

Uncertainty ~1.5% in the RATIO

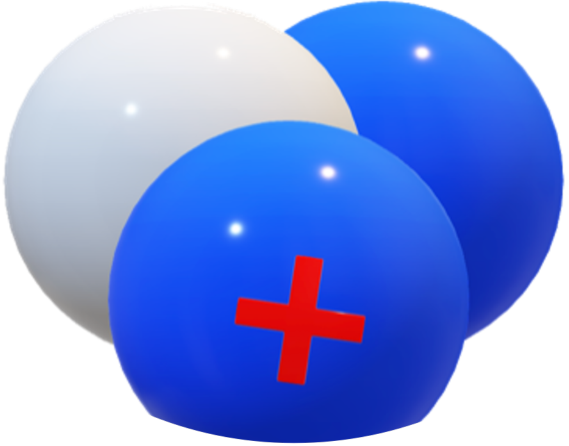


One data point at

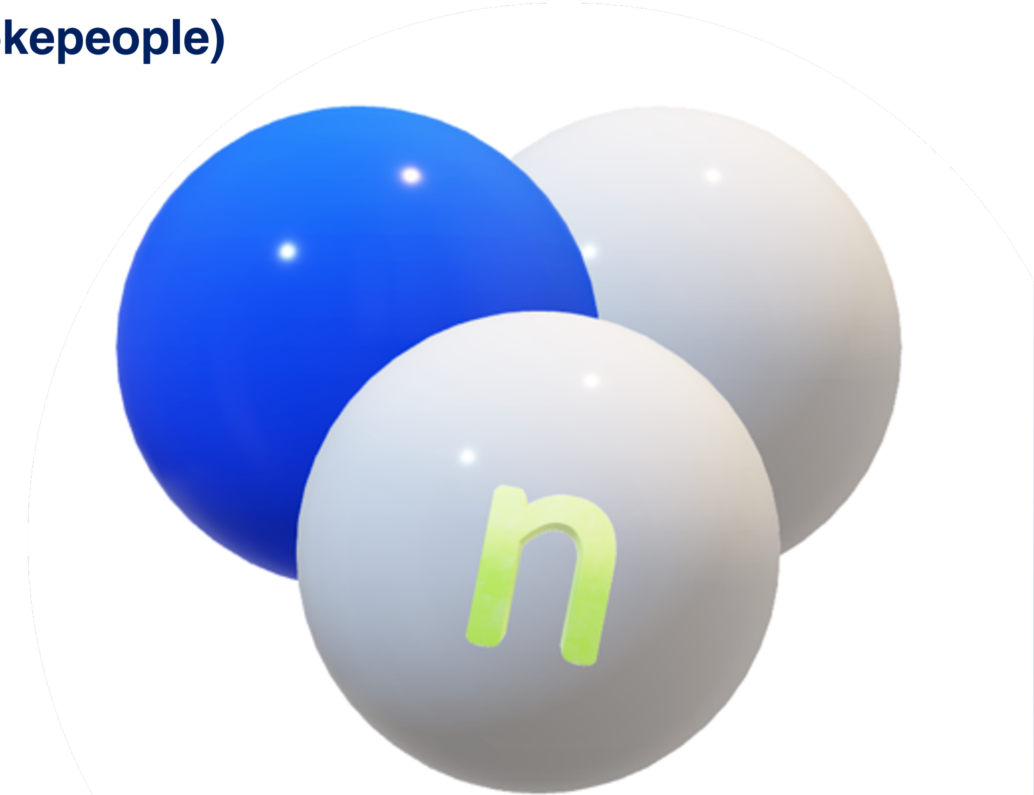
- Beam energy: 1.171 GeV
- Momentum: 1.128 GeV
- Angle: 17 degree

This new data point will improve global fits and can be compared to the 3H/3He ratio for the experiments that have tried extracting the charge radii of 3H and give inconsistent results.

Thank you



Dr. Elena Long (Advisor)
P. Solvignon, J.Arrington, D.B.Day, D. Higinbotham, Z. Ye (Spokepeople)
Tritium group's members.



Backup Slides

Rosenbluth Separation Technique

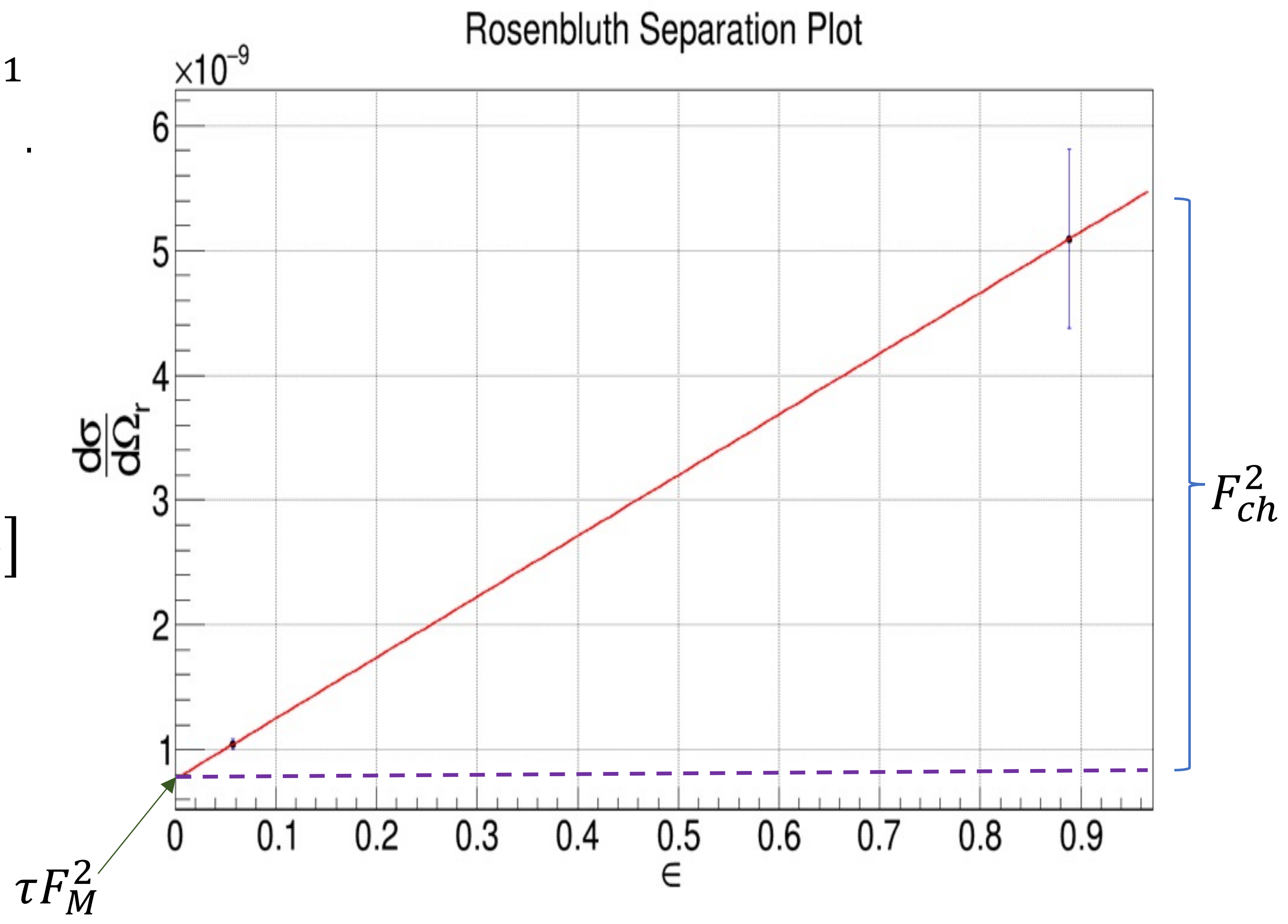
$$\left(\frac{d\sigma}{d\Omega}\right)_{exp} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott}\left[F_{ch}^2 + \frac{\tau}{\epsilon}F_M^2\right](1+\tau)^{-1}$$

It is valid at low Q^2 when the cross section is dominated by F_{ch} and is mostly insensitive to F_M.

$$\left(\frac{d\sigma}{d\Omega}\right)_{r} = \frac{\left(\frac{d\sigma}{d\Omega}\right)_{exp}}{\left(\frac{d\sigma}{d\Omega}\right)_{Mott}}\epsilon(1+\tau) = \left[\epsilon F_{ch}^2 + \tau F_M^2\right]$$

$$\epsilon^{-1} = \{1 + 2(1+\tau)tan^2(\theta/2)\}$$

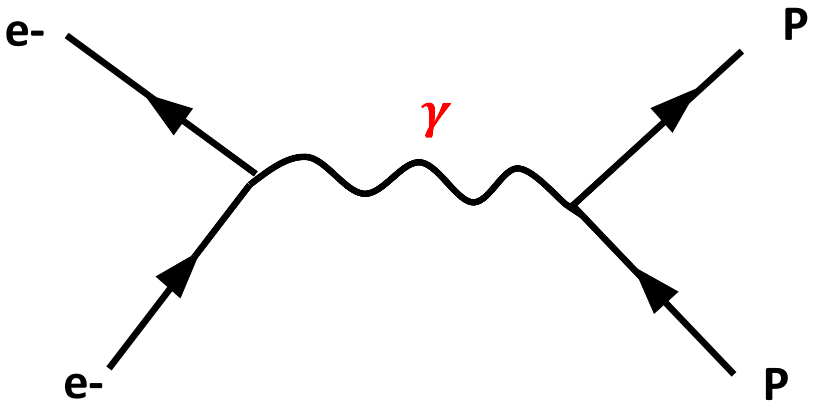
- we need at least 2 cross section measurements at the same Q^2 (but different angles) to try and separate F_{ch} and F_M.



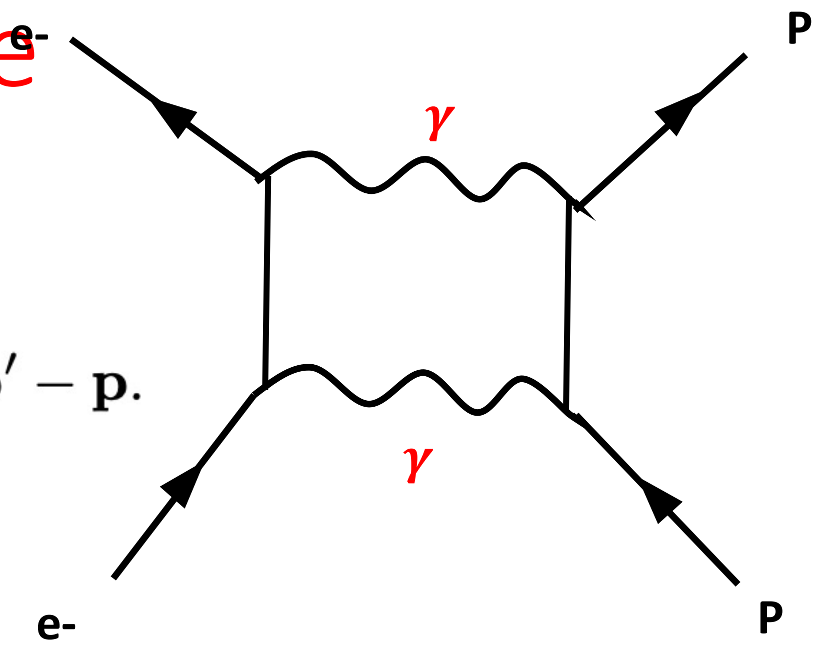
Example of a Rosenbluth separation technique using data for elastic e -^{3}He at Q^2 = 55.1 fm^{-2}

S. K. Barcus, Ph.D. thesis, College of William & Mary, 2019.

One and two photo exchange



$$E_\gamma = 0$$
$$\mathbf{p}_\gamma = \Delta \mathbf{p} = \mathbf{p}' - \mathbf{p}.$$



One of the insights of subatomic physics is that at the microscopic level forces are caused by the exchange of force-carrying particles. For example the Coulomb force between two electrons is mediated by excitations of the electromagnetic field – i.e. photons

Let the incoming electron have momentum p and the outgoing scattered electron have momentum p . For elastic scattering, the energy of the electron is unchanged E′ = E The electron has picked up a change of momentum Δp = p′ − p from absorbing the virtual photon, but absorbed no energy. So the photon must have energy and momentum

Charge Form Factor and Charge Radius

$$F(q^2) = \int e^{\frac{iq\cdot x}{\hbar}} \rho(x) d^3x \xrightarrow{x \to r} 4\pi \int \rho(r) \frac{\sin\left(|q|r/\hbar\right)}{|q|r/\hbar} r^2 dr$$

- **The charge distribution is spherically symmetric.**

This procedure can be inverted to find the charge distribution of a target from its form factor.

$$\rho(r) = \frac{1}{(2\pi)^3} \int F(q^2) e^{\frac{-iq\cdot x}{\hbar}} d^3q$$

For a hard sphere of charge the charge radius, R, is roughly given by

$$R \approx \frac{4.5\hbar}{q}$$

Charge Form Factor and Charge Radius

$$e^{i\frac{qr}{\hbar}} = \cos\left(\frac{qr}{\hbar}\right) + i\sin\left(\frac{qr}{\hbar}\right)$$

At very low q²

$$R \ll \frac{\hbar}{q} \implies \frac{Rq}{\hbar} \ll 1$$

$$i\sin\left(\frac{Rq}{\hbar}\right) \to 0$$

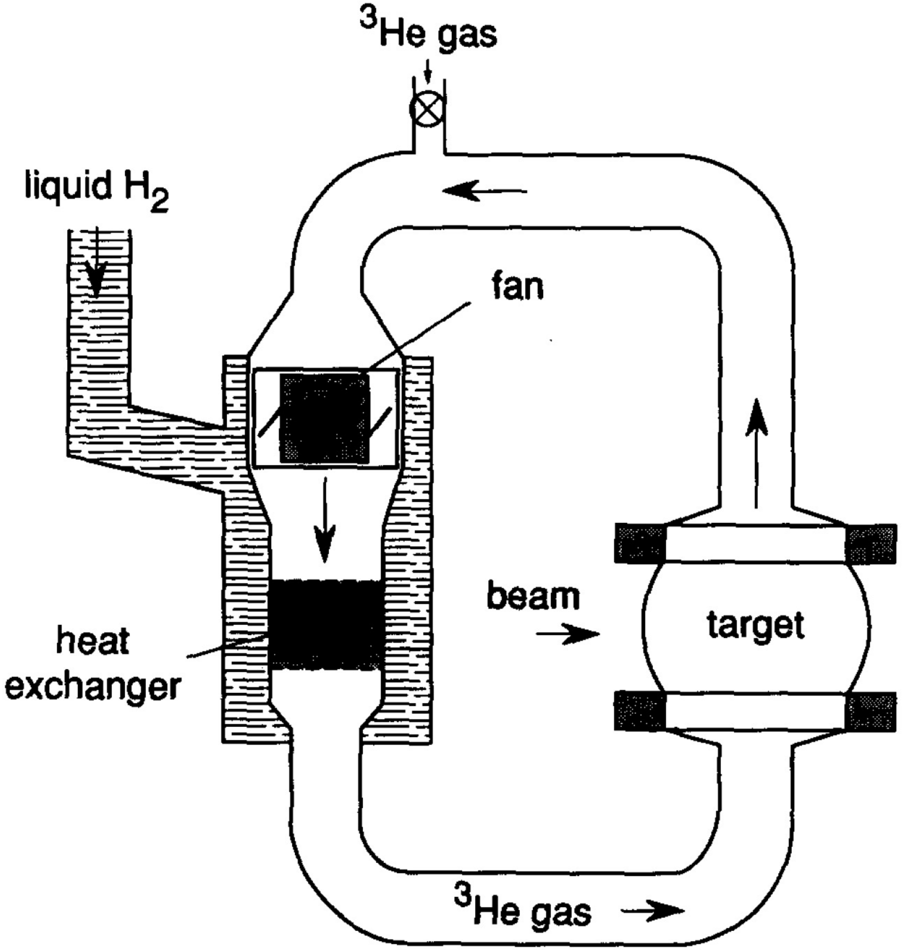
$$e^{i\frac{qr}{\hbar}} = \cos\left(\frac{qr}{\hbar}\right)$$

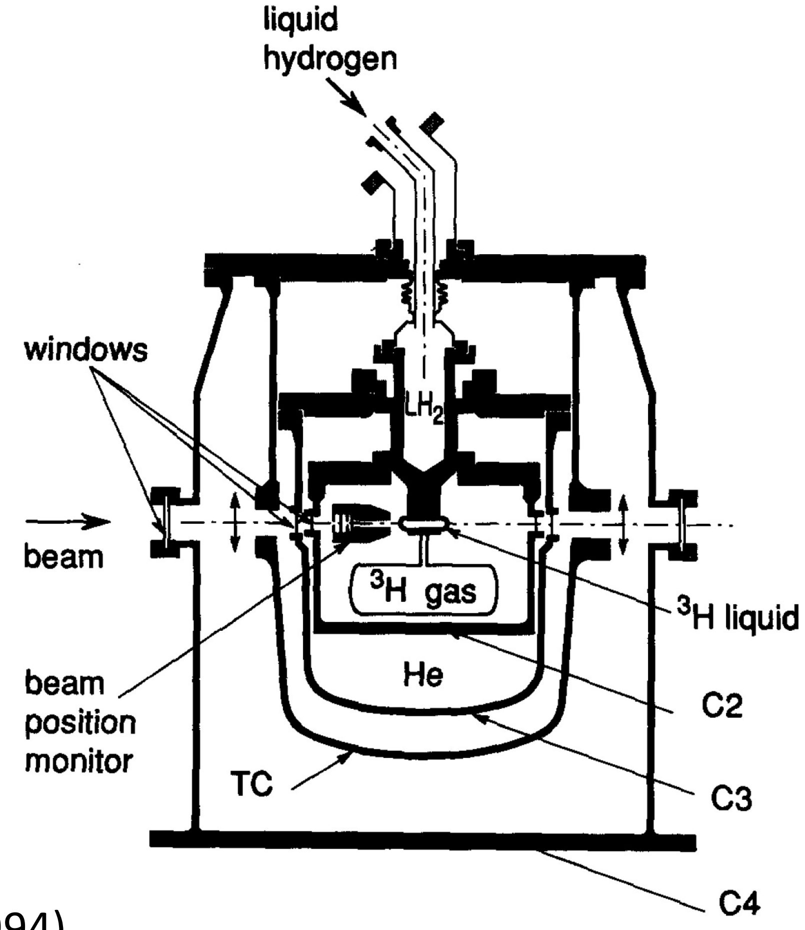
$$\cos(x) = 1 - \frac{x^2}{2!} + \frac{x^4}{4!} - \frac{x^6}{6!} + \ldots$$

$$q \cdot r = |q||r|\cos(\omega)$$

$$F(q^2) = \int_0^\infty \int_{-1}^{1} \int_0^{2\pi} \rho(r)\left(1 - \frac{1}{2}\frac{|q||r|\cos(\omega)}{\hbar}\right) r^2 d\phi\, d\cos(\omega)\, dr$$

3He and 3H Target cells





A. Amroun et al. Nuclear Physics A579 (1994).

3He and 3H Target cells

The target was 3H dissolved in a thin titanium and copper metal foil, made at the Isotope Division of Oak Ridge National Laboratory. The copper was evaporated to a thickness of 1.97 mg/cm on a 2.18 mg/cm titanium foil in order to improve the thermal conductivity.
The oil was then warmed to about 450'C and exposed to H2 gas.
The result is a material which is partly a solution of gaseous hydrogen in the solid metal and partly the compound TiH2.
Unfortunately, the foil was wrinkled and consequently its absolute 3H areal density was not known.