CEBAF Large Acceptance Spectrometer

Measurement of the Neutron Magnetic Form Factor G_M^n at High Q^2 Using the Ratio Method on the Deuteron

Lamya Baashen

Brian Raue – FIU
Jerry Gilfoyle – University of Richmond
Cole Smith – University of Virginia

- ✓ **Definition and Meaning of the Elastic Nucleon Form Factor**
- ✓ **Scientific Motivation**
- ✓ **The Ratio Method**
- ✓ **CLAS12 Detector**
- ✓ **Analysis tools and Preliminary Neutron detection efficiency (NDE) results**
- ✓ **Summary**

Definition of the Electromagnetic Elastic Nucleon Form Factors (EEFFs)

The hadronic current:

$$\mathcal{J}^{\mu}_{hadronic} = e\bar{N}(p')\left[\gamma^{\mu}\overset{\text{Dirac}}{\boxed{F_1(Q^2)}} + \frac{\sigma^{\mu\nu}\, q_{\nu}}{2M}\overset{\text{Pauli}}{\boxed{F_2(Q^2)}} + \right] N(p)$$

The Sachs FFs:

$$G_E(Q^2) = F_1(Q^2) - \tau F_2(Q^2) \quad and \quad G_M(Q^2) = F_1(Q^2) + F_2(Q^2)$$

G_E: Describes the transverse distribution of charge

G_M: Describes the transverse distribution of magnetization

Where:

$$\tau = \frac{Q^2}{4\, M^2_{nucleon}}$$

Why we need to measure Form Factors

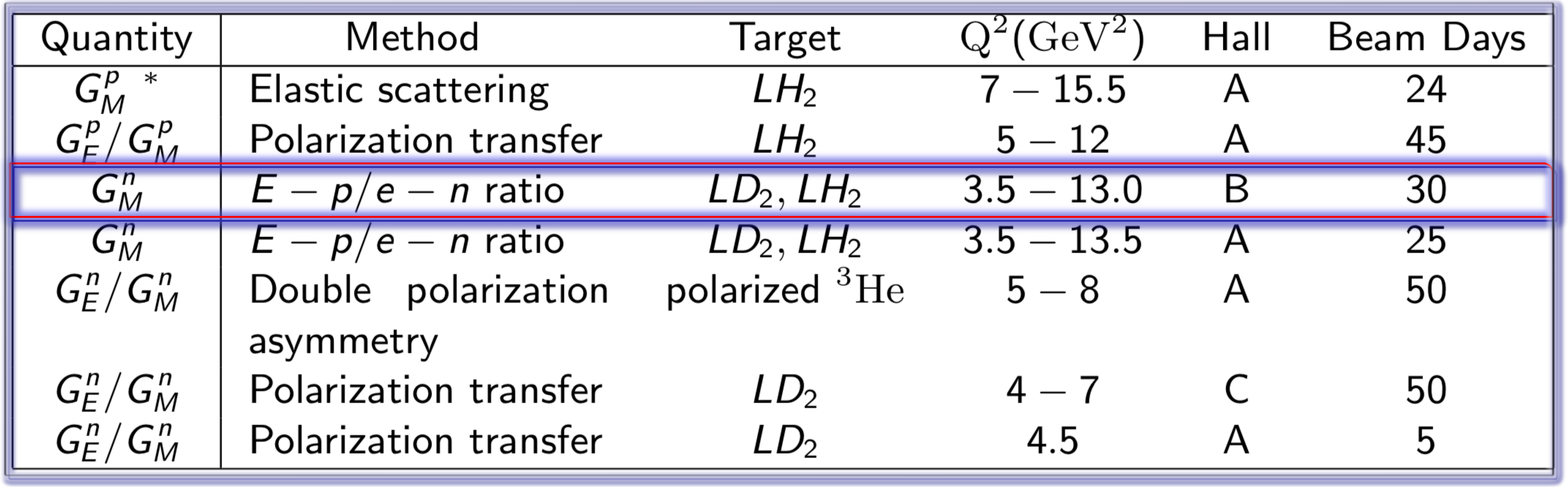
I. **Elastic form factors,** particularly at high Q^2**, have fundamentally changed our** QUALITATIVE **picture of the nucleon.**

II. **The form factors provide important constraints for GPDs:**

$$\int_{-1}^{1} dx H^q(x,\xi,Q^2) = F_1^q(Q^2) \quad and \quad \int_{-1}^{1} dx E^q(x,\xi,Q^2) = F_2^q(Q^2)$$

form factors thus play an important role in the entire GPD program

Listing of approved experiments for measuring EEFFs at Jefferson Lab



Quantity	Method	Target	$Q^2(\mathrm{GeV}^2)$	Hall	Beam Days
G_M^p *	Elastic scattering	LH_2	$7-15.5$	A	24
G_E^p/G_M^p	Polarization transfer	LH_2	$5-12$	A	45
G_M^n	$E-p/e-n$ ratio	LD_2, LH_2	$3.5-13.0$	B	30
G_M^n	$E-p/e-n$ ratio	LD_2, LH_2	$3.5-13.5$	A	25
G_E^n/G_M^n	Double polarization asymmetry	polarized $^3\mathrm{He}$	$5-8$	A	50
G_E^n/G_M^n	Polarization transfer	LD_2	$4-7$	C	50
G_E^n/G_M^n	Polarization transfer	LD_2	4.5	A	5

How Do We Measure G_M^n on a Neutron? Ratio Method

The ratio of the free nucleon e-n to e-p cross sections in terms of the free nucleon form factors:

$$R = \frac{\frac{d\sigma}{d\Omega}(D(e,e'n))}{\frac{d\sigma}{d\Omega}(D(e,e'p))} = a(Q^2)\,\frac{\overbrace{\sigma^n_{mott}\left({G_E^n}^2 + \frac{\tau_n}{\varepsilon_n}{G_M^n}^2\right)\left(\frac{1}{1+\tau_n}\right)}}{\underbrace{\sigma^p_{mott}\left({G_E^p}^2 + \frac{\tau_p}{\varepsilon_p}{G_M^p}^2\right)\left(\frac{1}{1+\tau_p}\right)}}$$

Requires a Precise Measurement of the Neutron Detection Efficiency (NDE)

$e\,p \rightarrow e'\,\pi^+(n)$

corrects for nuclear effects

the denominator is the precisely-known proton cross section.

Where:

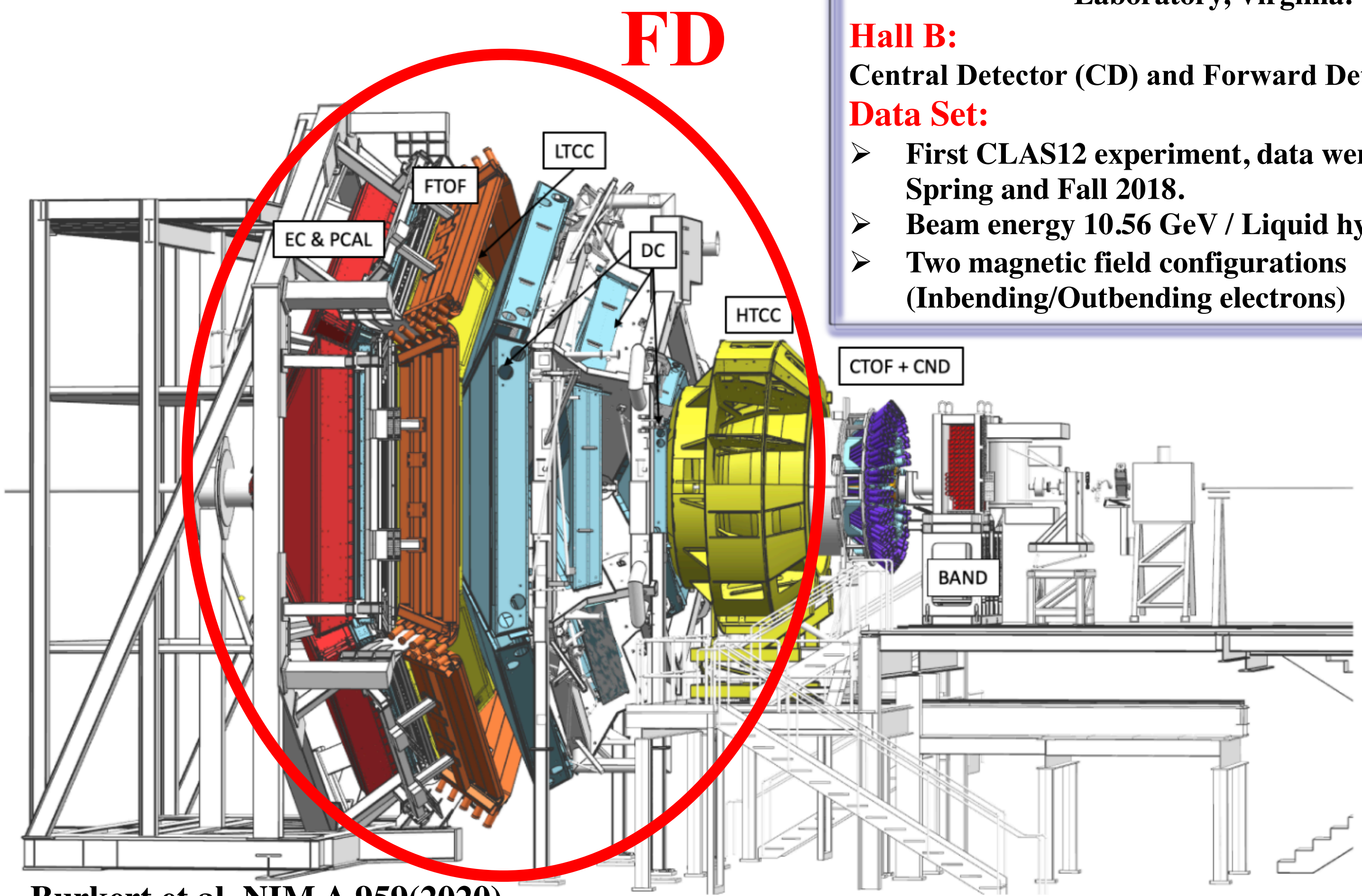
$$\sigma_{Mott} = \frac{\alpha^2 E' \cos^2(\frac{\theta_e}{2})}{4E^3 \sin^4(\frac{\theta_e}{2})}\ , \quad \tau = \frac{Q^2}{4\,M^2_{p,n}}\ , \quad Q^2 = 4EE'\sin^2\left(\frac{\theta_e}{2}\right)\ , \epsilon = \left[1 + 2(1+\tau)\tan^2(\frac{\theta_e}{2})\right]^{-1}$$

$$\boxed{G_M^n = \sqrt{\left[R_{corrected}\left(\frac{\sigma^p_{mott}}{\sigma^n_{mott}}\right)\left(\frac{1+\tau_n}{1+\tau_p}\right)\left({G_E^p}^2 + \frac{\tau_p}{\varepsilon_p}{G_M^p}^2\right) - {G_E^n}^2\right]\frac{\epsilon_n}{\tau_n}}}$$

Extracting G_M^n requires knowledge of other EEFFs

How We Measure Neutron Detection Efficiency(NDE) on CLAS12

$$e\,p \rightarrow e'\,\pi^+(n)$$



The CLAS12 Detector located in Hall B at Jefferson Laboratory, Virginia.

Hall B:

Central Detector (CD) and Forward Detector (FD)

Data Set:

- **First CLAS12 experiment, data were taken in the Spring and Fall 2018.**
- **Beam energy 10.56 GeV / Liquid hydrogen target.**
- **Two magnetic field configurations (Inbending/Outbending electrons)**

Burkert et al.,NIM A 959(2020)

How We Measure Neutron Detection Efficiency(NDE) on CLAS12

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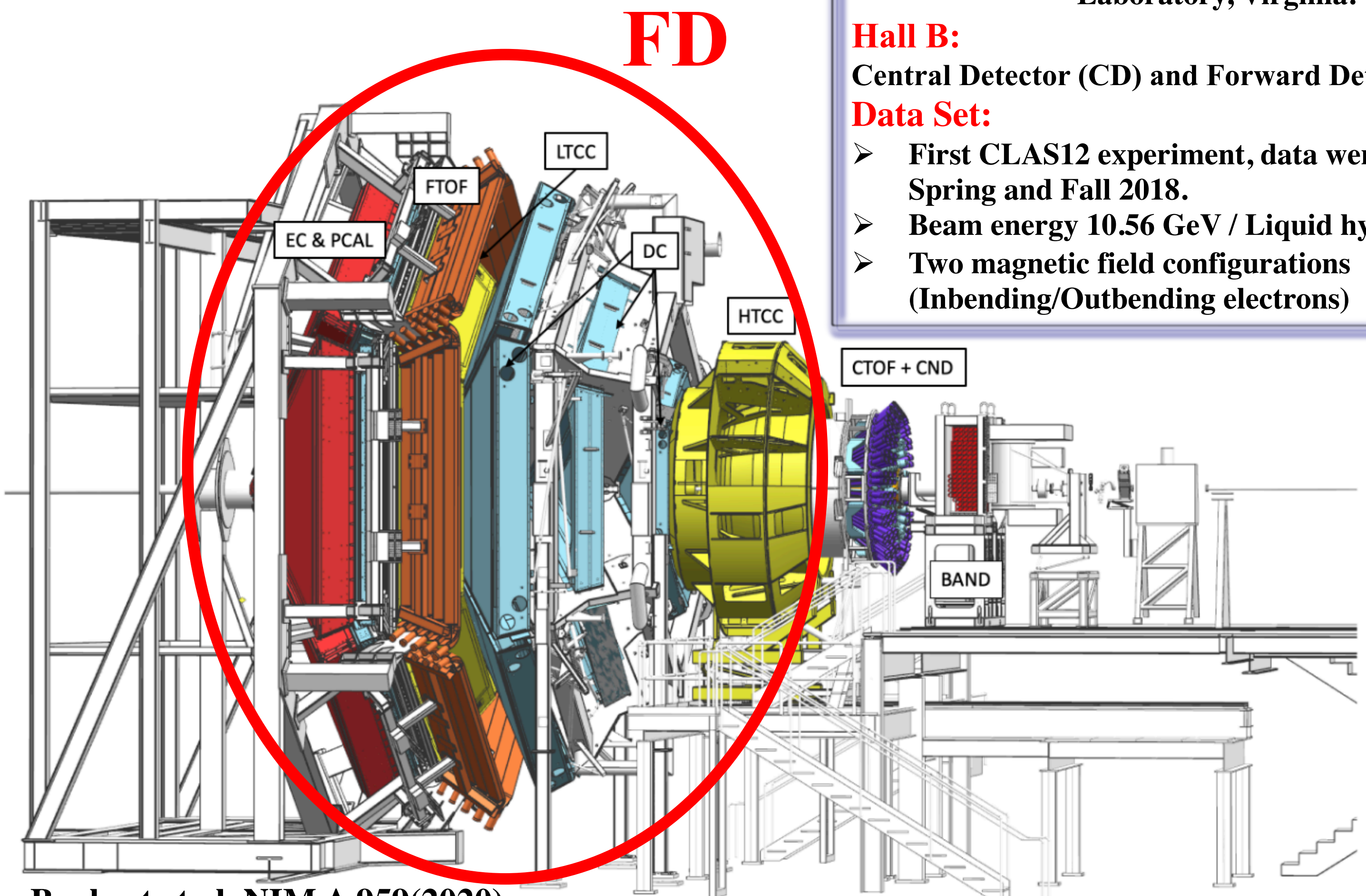

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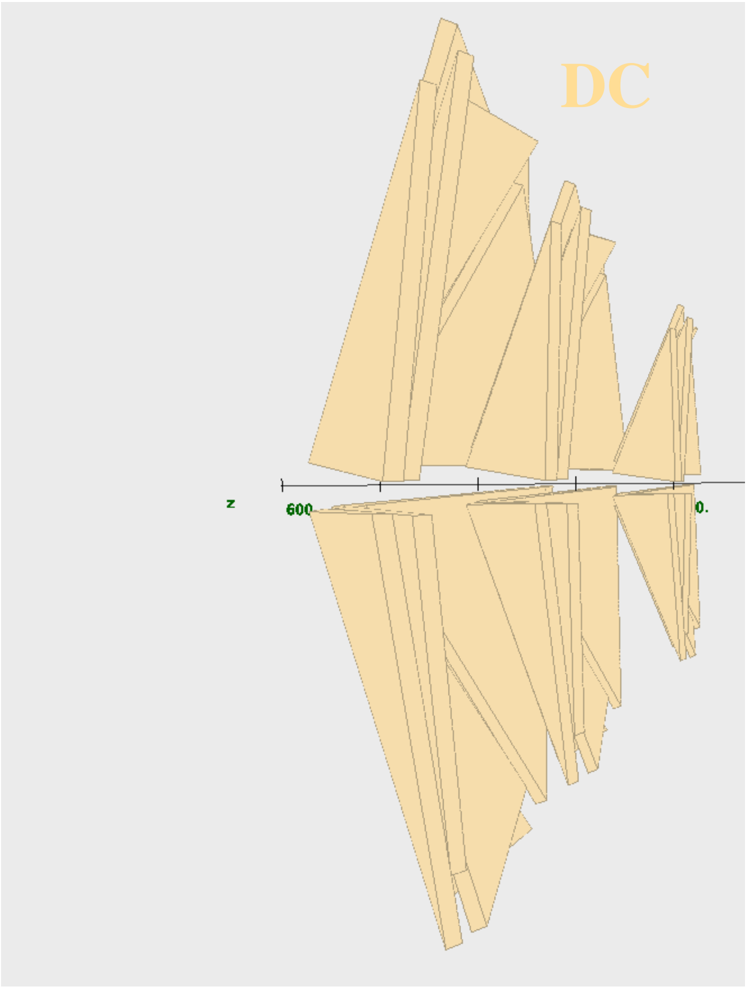

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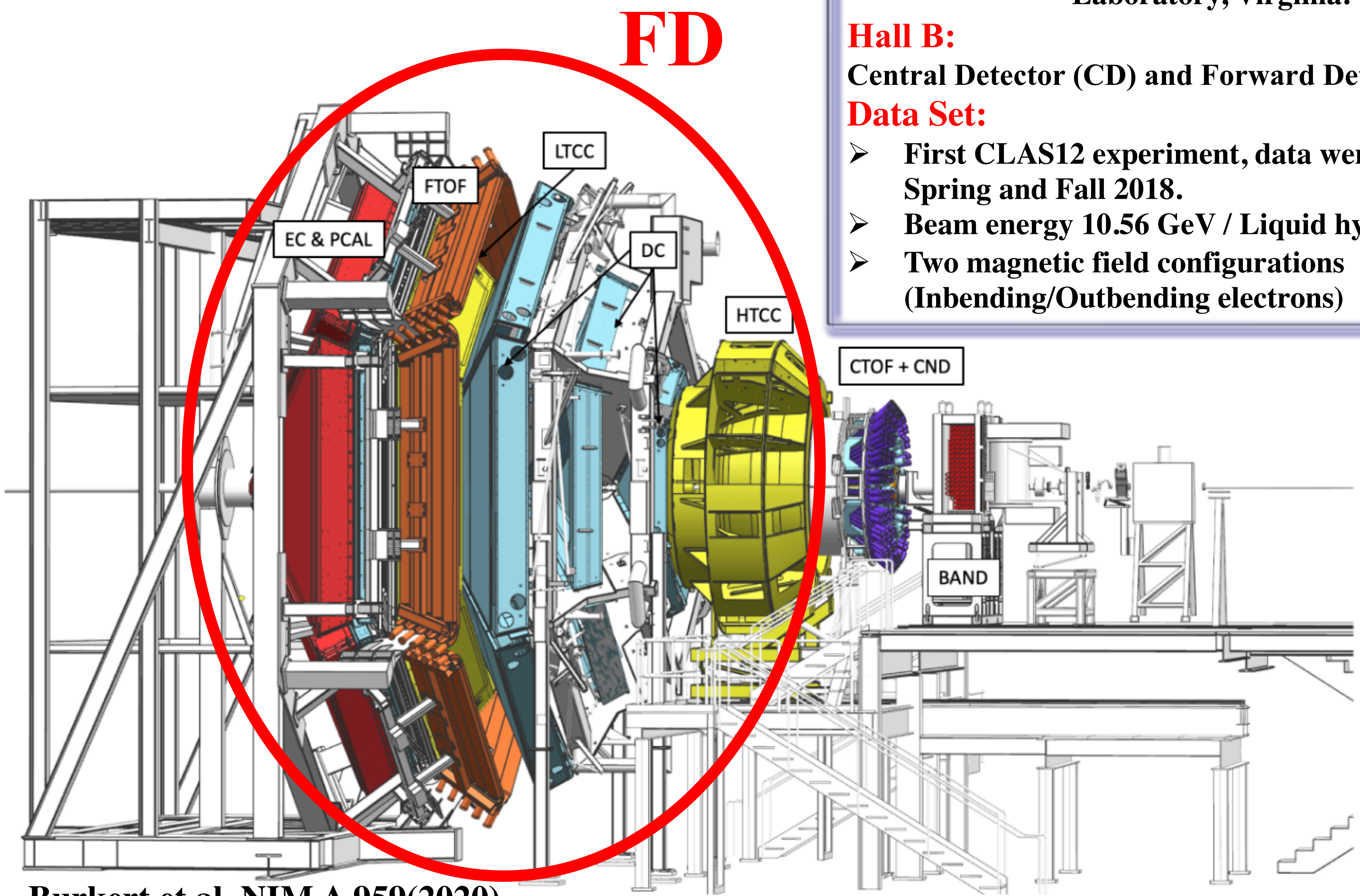

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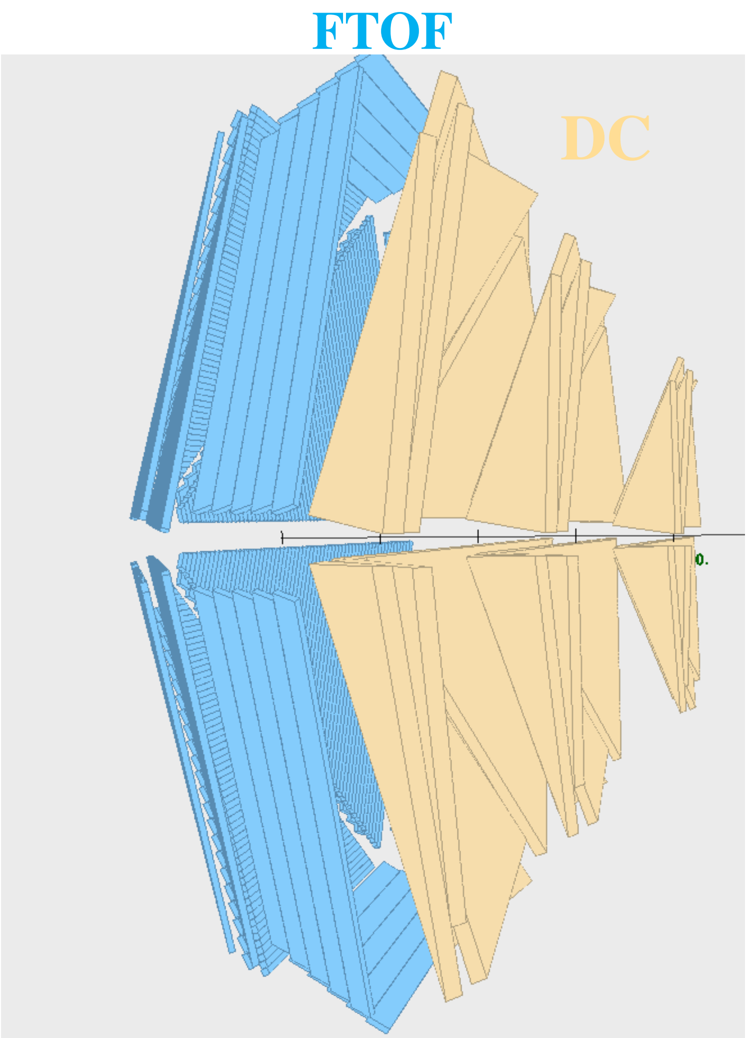

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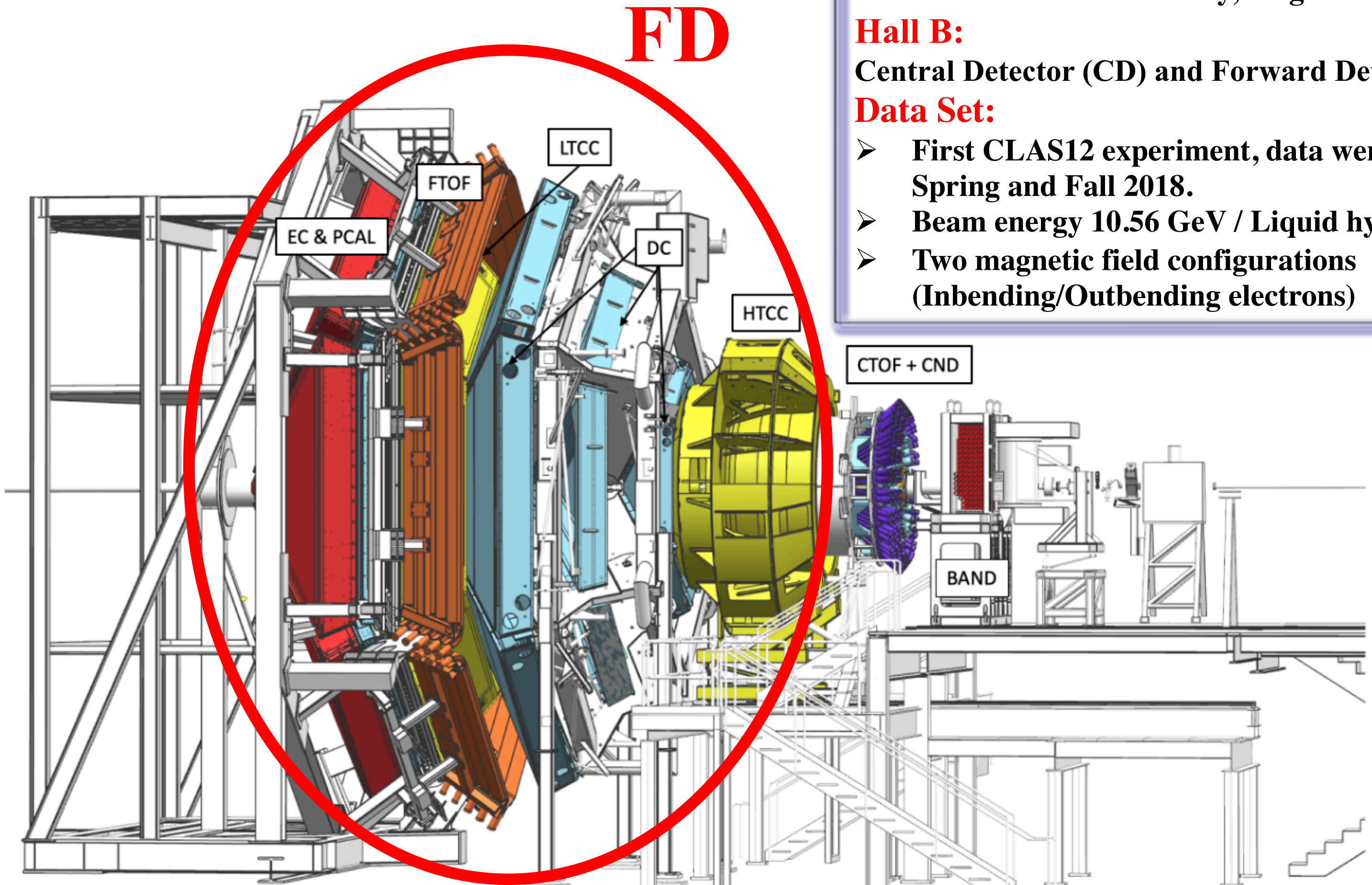

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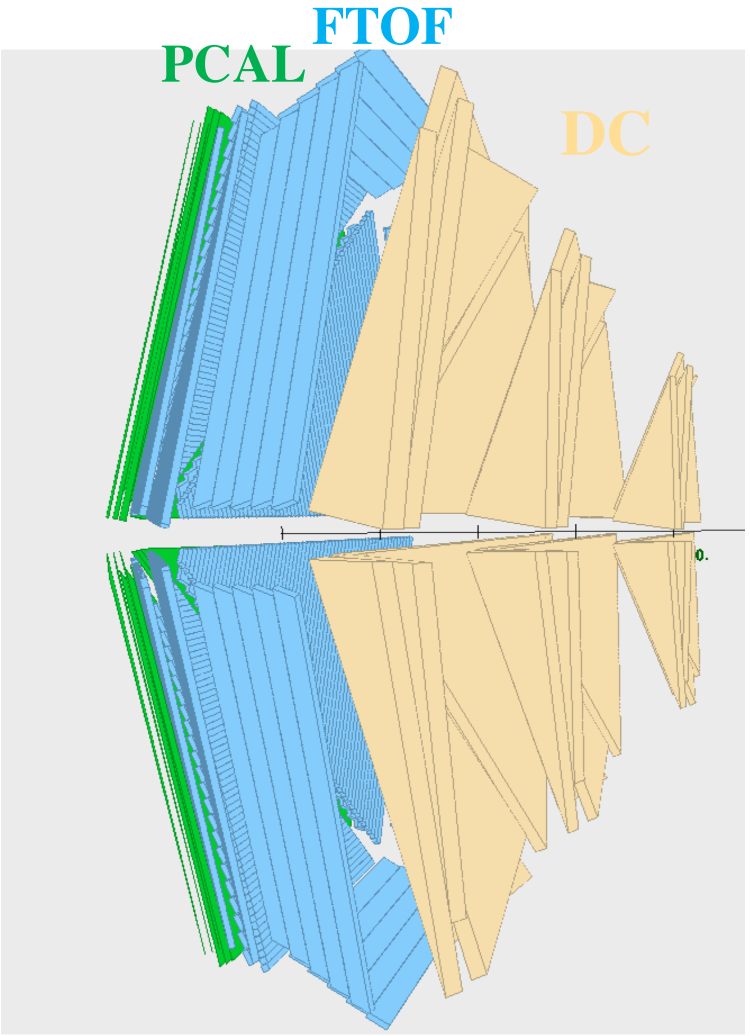

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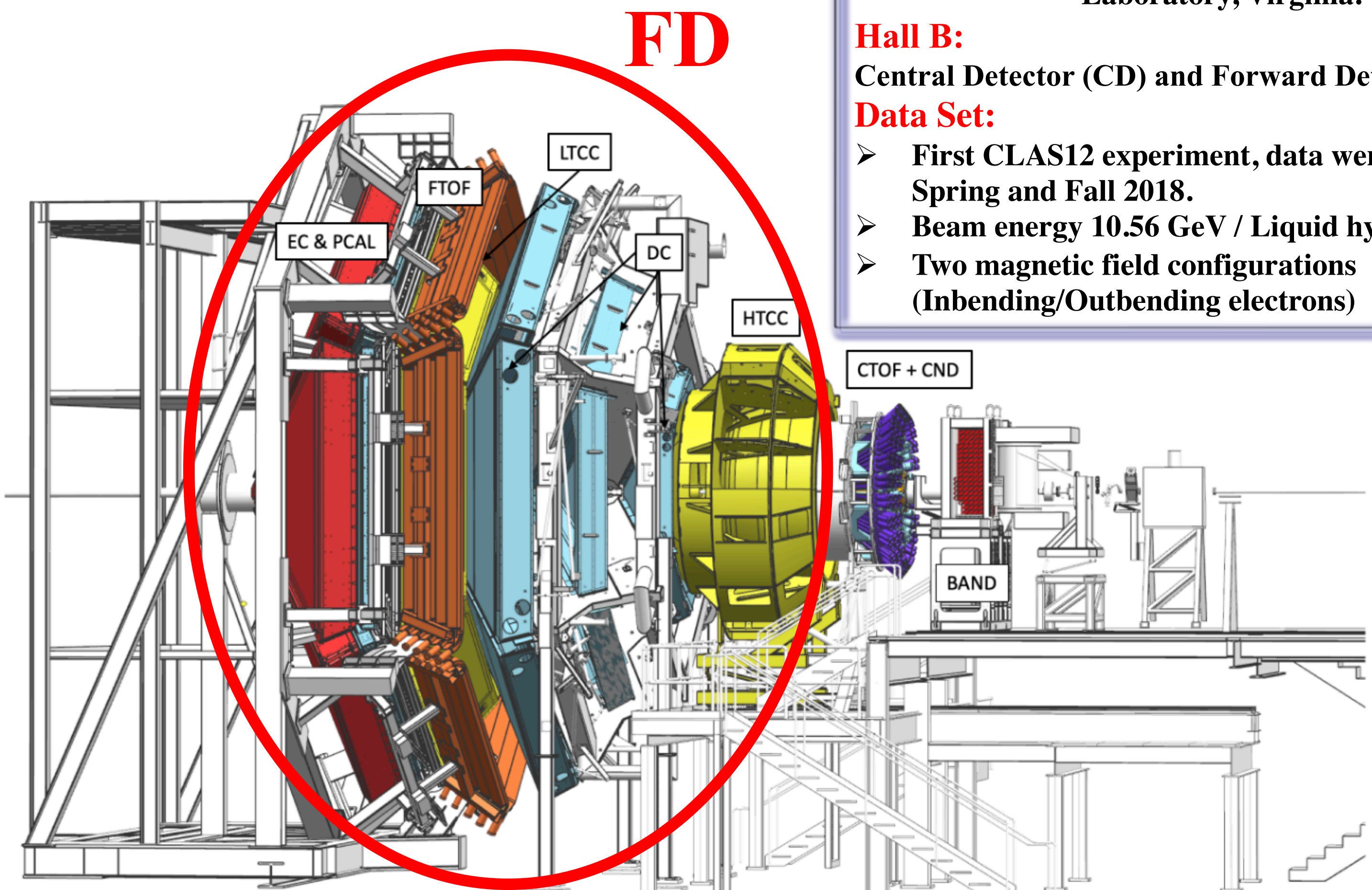

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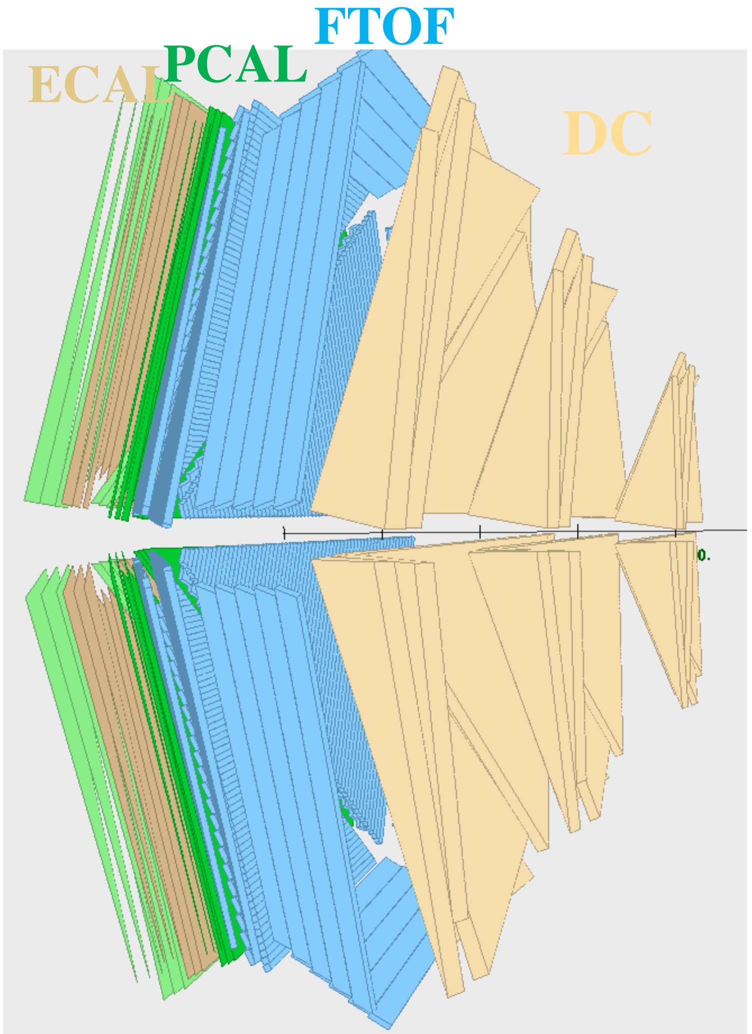


Extracting Neutron Detection Efficiency

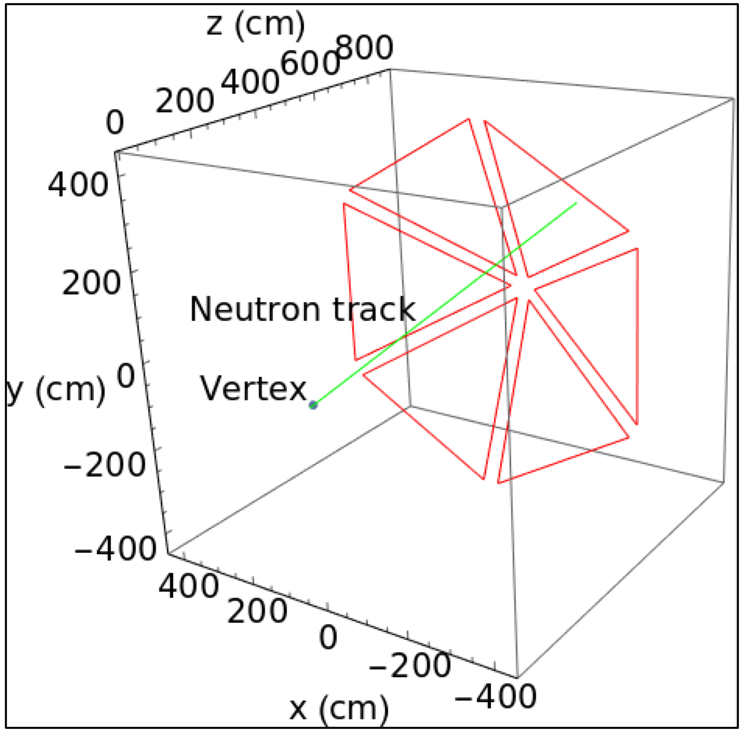
Determine the neutron detection efficiency (NDE) by using:

$$\boxed{e\,p \rightarrow e'\,\pi^+(n)}$$

1. Select $e'\,\pi^+$ final state with no other charged particles $p(e, e'\,\pi^+)X_n$.
2. Assume the missing particle is a neutron, calculate the missing momentum of the neutron and its trajectory through CLAS12 from the $e'\,\pi^+$ vertex
3. Check if the neutron's path intersects with the front face of PCAL/ECAL.

Yes → count as expected neutron

NO → skip the event



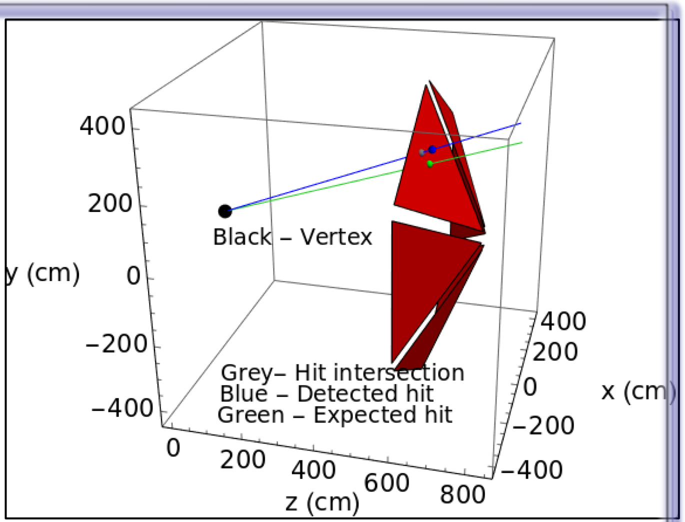
Lachniet et al., PRL 102, 192001(2009)

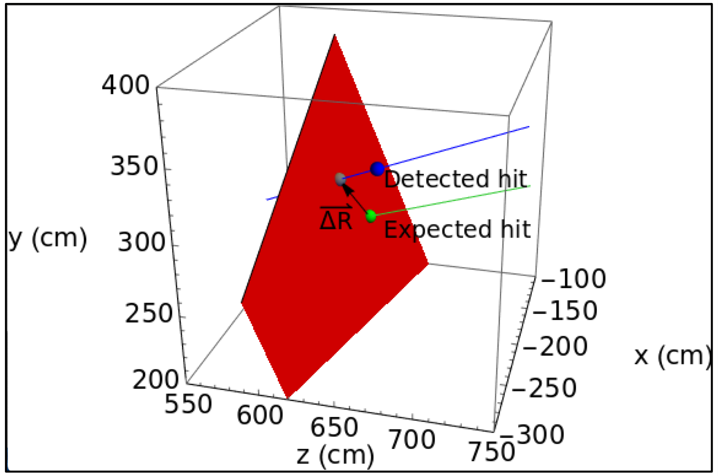
Extracting Neutron Detection Efficiency

4. Loop over neutral PCAL/ECAL hits:
   - ✓ Get intersection of ray with the PCAL/ECAL face by drawing a line from the e′ π^+ vertex to the actual neutral PCAL/ECAL hit.
   - ✓ Calculate ΔR for each actual neutral PCAL/ECAL hits, which is the distance between the intersection of the PCAL/ECAL hit and the intersection of the expected neutron trajectory.
   - ✓ Select hit with the smallest ΔR.

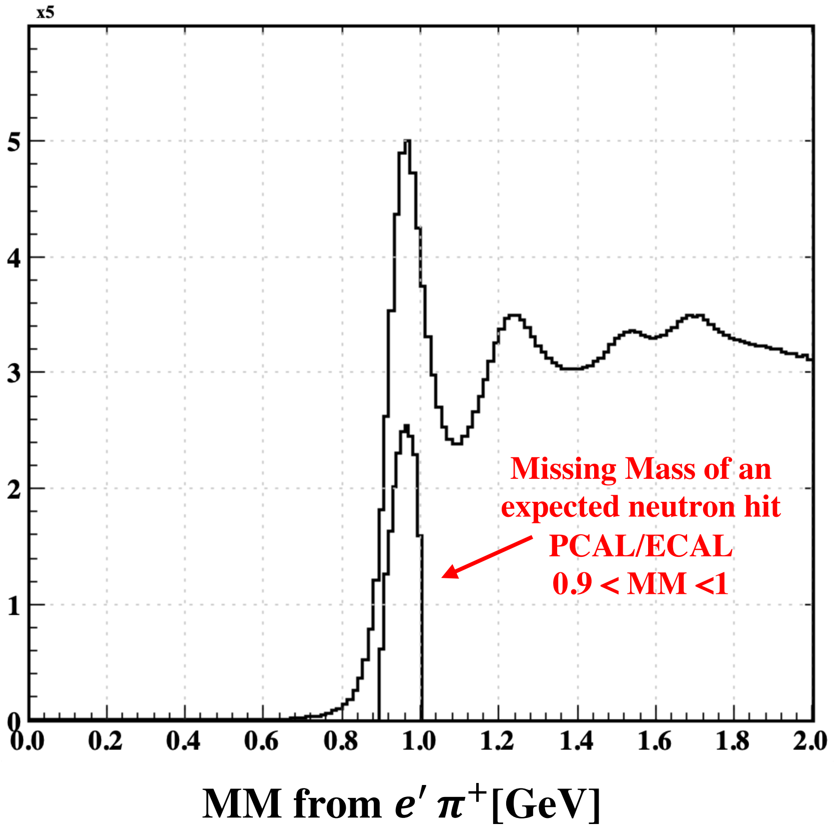
5. Applied some kinematics cuts to identify neutrons.

$$\boxed{\mathbf{NDE} = \frac{N_{detected}\,(n)}{N_{expected}\,(n)}}$$

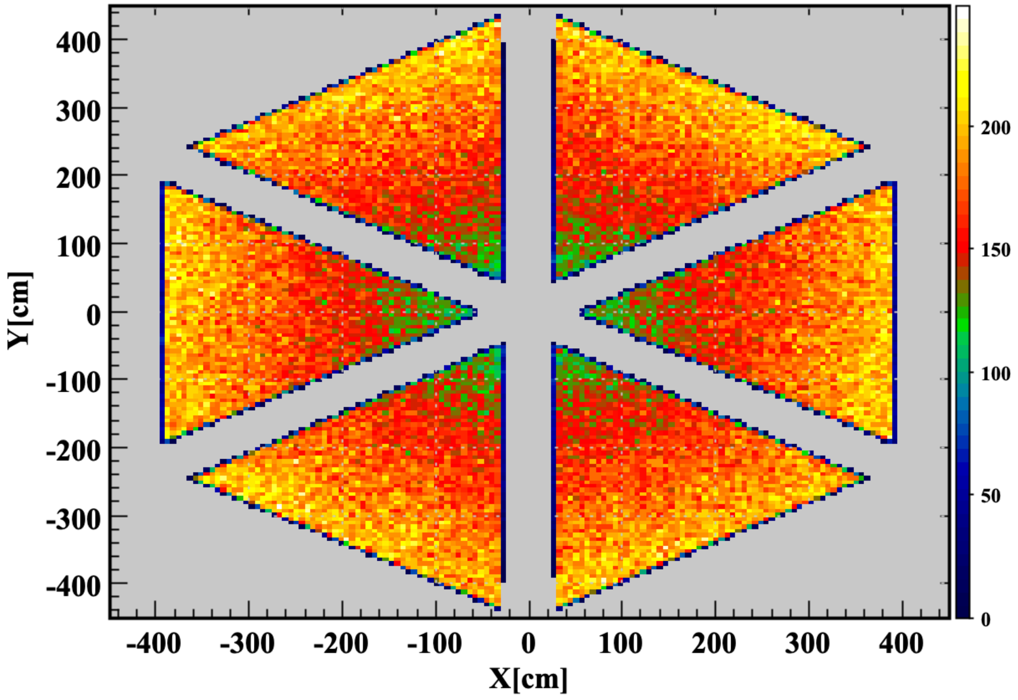




Missing Mass of Expected Neutron PCAL/ECAL

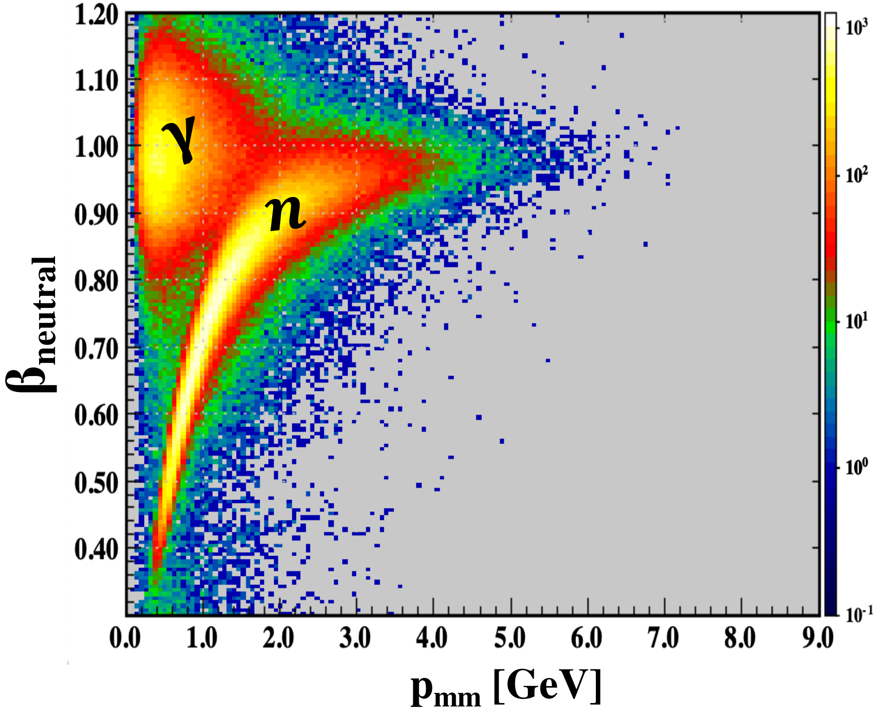


Intersection point of expected neutron with front face of PCAL/ECAL



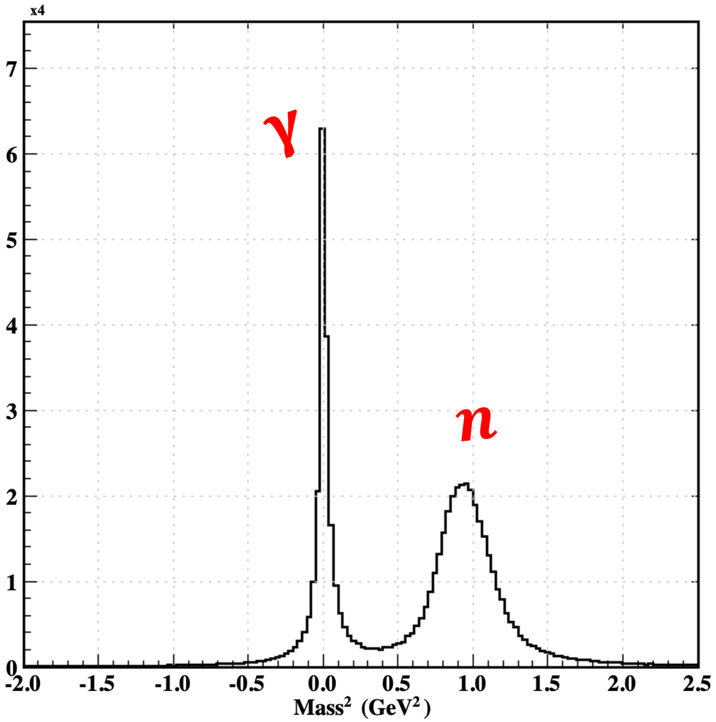
Neutral Particles Measured in PCAL/ECAL

$\beta_{neutral}$ vs p_{mm}



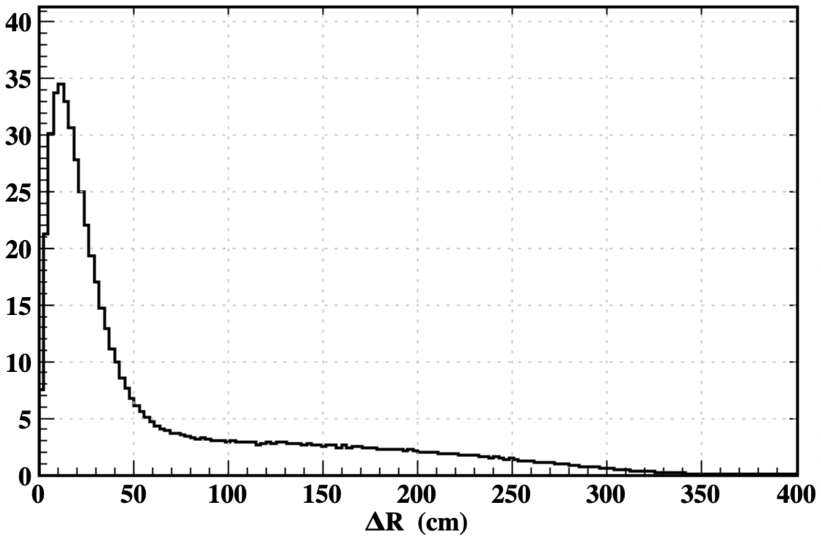
$\beta_{neutral}$ calculated from the path/time in PCAL/ECAL vs p_{mm}

mass^2 distribution of the neutral particles measured in PCAL/ECAL



mass^2 distribution of the neutral particles calculated from the measured β *neutral* and missing momentum

ΔR[cm]



ΔR is the distance between the intersection point of expected neutron and the intersection of detected neutral particles with the front face of PCAL/ ECAL

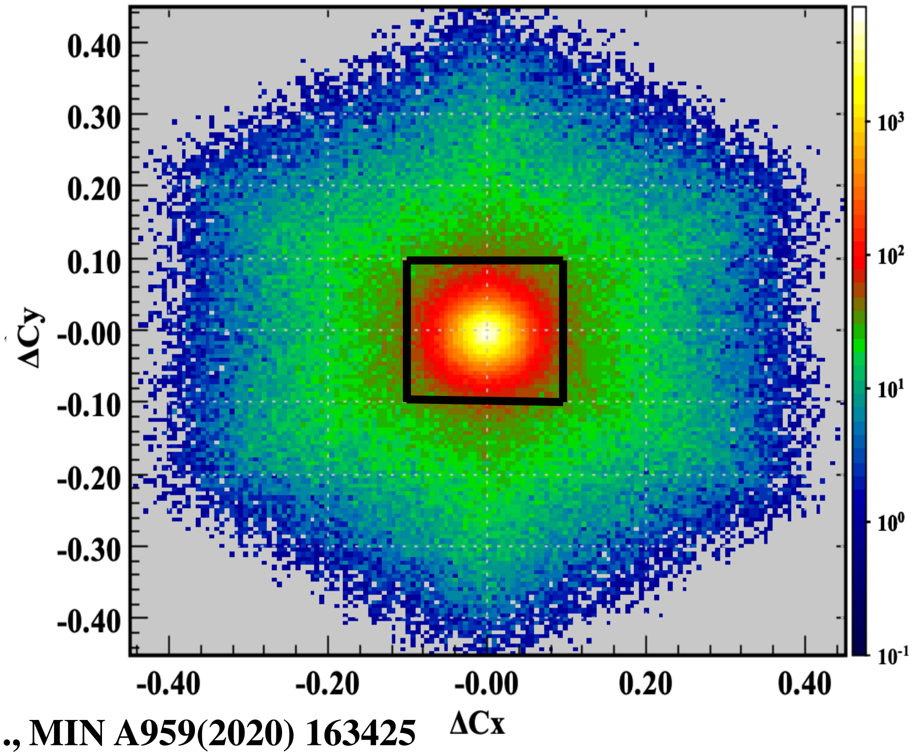
Identifying Neutron in PCAL/ECAL

To identify neutron hits:

Required the direction cosine of the expected neutron C_{exp} to coincide with the direction of the measured neutral particles C_{meas}

$\Delta C = C_{exp} - C_{meas}$

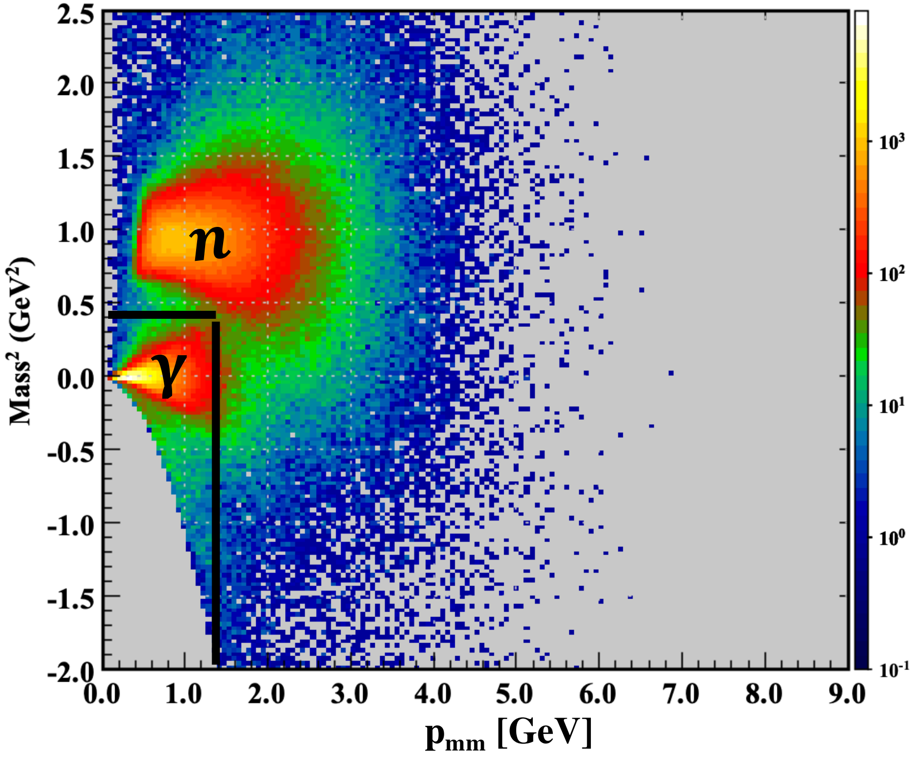
$-0.1 < \Delta Cx < 0.1$ && $-0.1 < \Delta Cy < 0.1$



G.Asryan et al., MIN A959(2020) 163425

mass² distribution of the neutral particles vs missing momentum

$mass^2 > 0.45$ If $p_{mm} < 1.2$

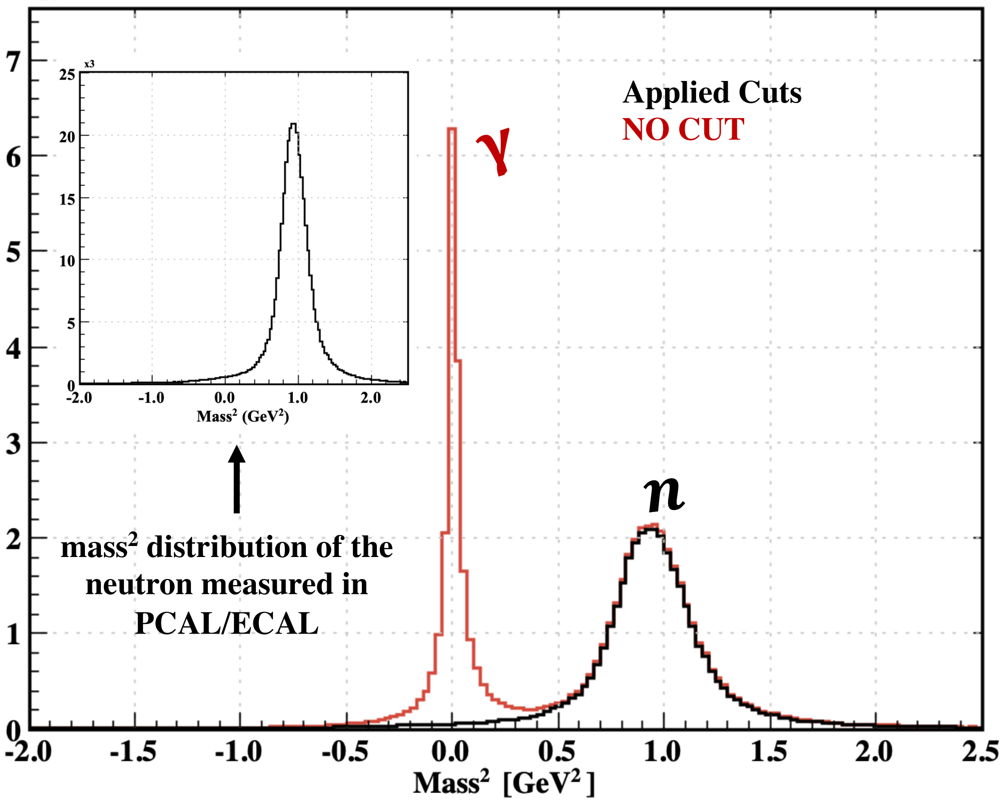


Neutral Particles Measured in PCAL/ECAL

Cuts Applied:

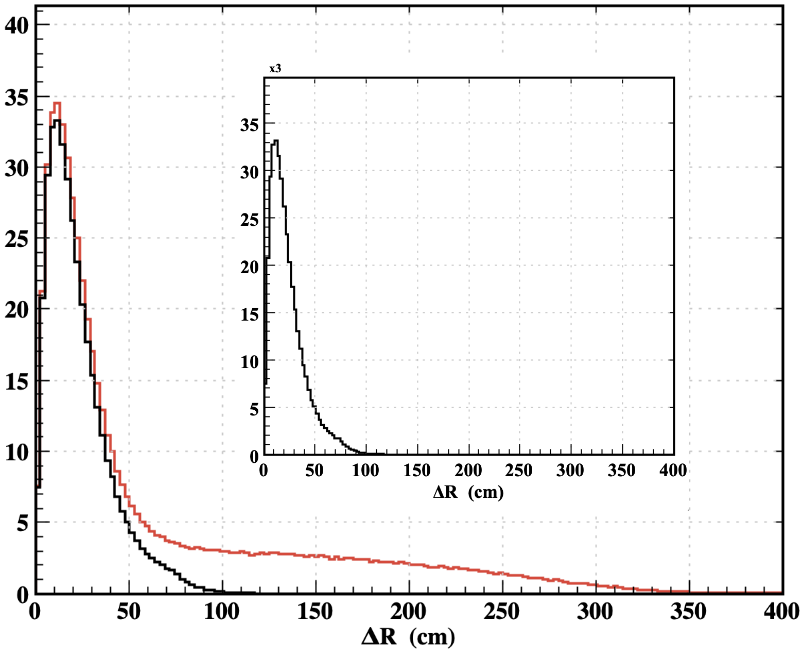
$-0.1 < \Delta Cx < 0.1$
$-0.1 < \Delta Cy < 0.1$
$mass^2 > 0.45$ If $p\_mm < 1.2$

mass² distribution of the neutral particles



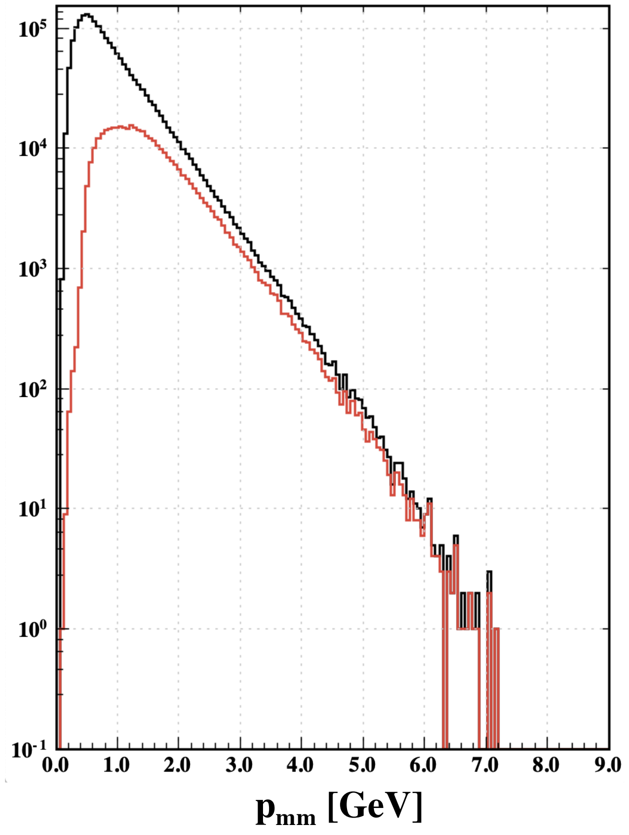
mass² distribution of the neutral particles calculated from the measured β *neutral* and missing momentum

ΔR[cm]

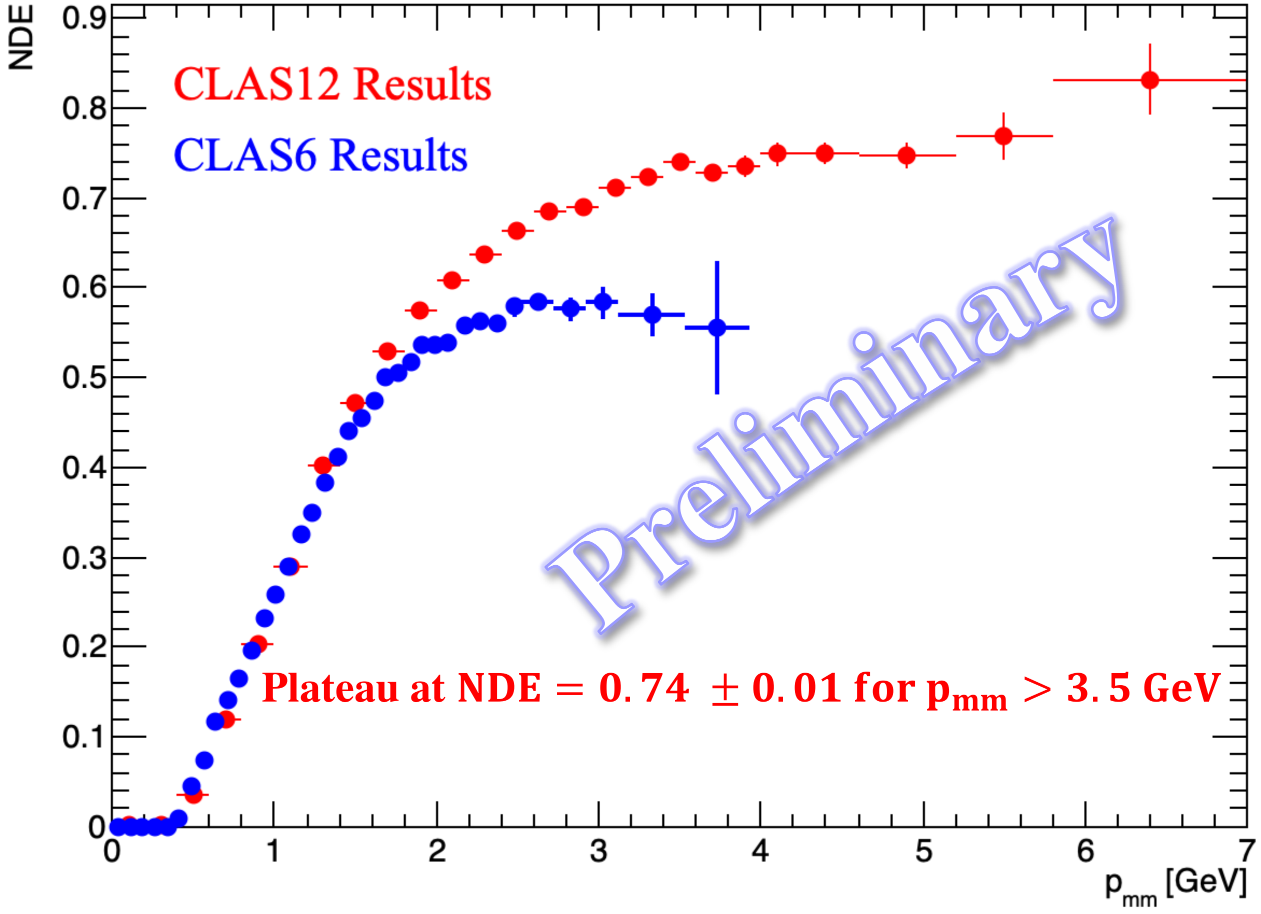


ΔR is the distance between the Intersection point of expected neutron and the intersection of detected neutral particles with the front face of PCAL/ ECAL

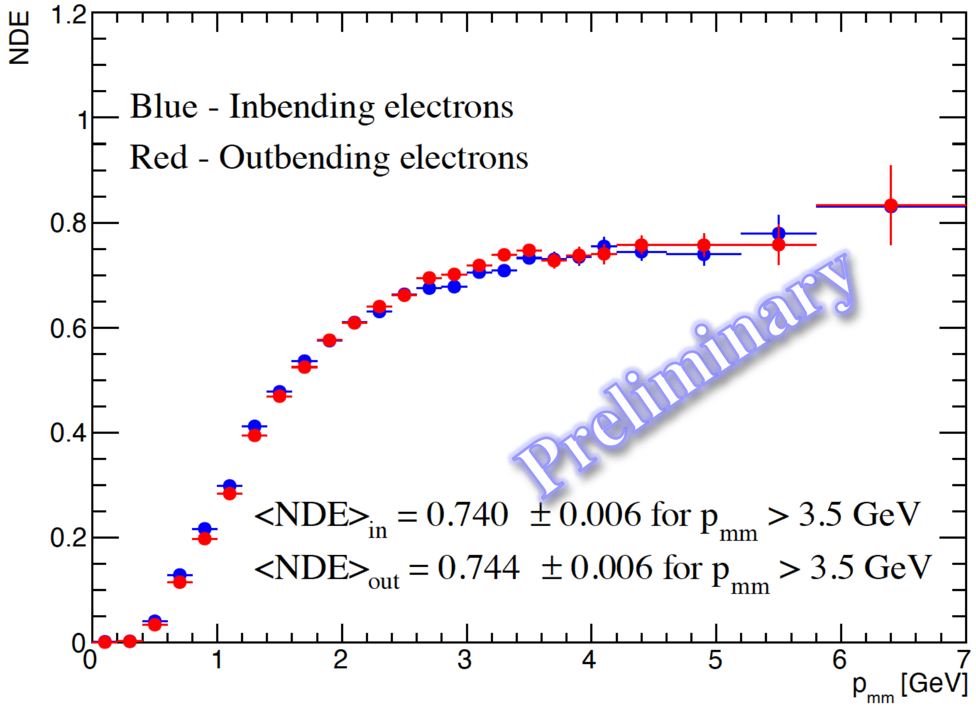
Missing Momentum of Expected neutron
Missing Momentum of Detected neutron



Preliminary Results of NDE



Plateau at NDE = 0.74 ± 0.01 for $p_{mm} > 3.5$ GeV



$\langle NDE \rangle_{in} = 0.740 \pm 0.006$ for $p_{mm} > 3.5$ GeV

$\langle NDE \rangle_{out} = 0.744 \pm 0.006$ for $p_{mm} > 3.5$ GeV

Summary

- The neutron magnetic form factor G_M^n is a fundamental quantity related to the transverse distribution of magnetization in the nucleon.
- The upgraded CEBAF provides the opportunities to measure the neutron magnetic G_M^n form factor to high Q^2.
- Ratio method on deuteron will be used to reduce the systematic uncertainty and extract a precise G_M^n measurement with systematic uncertainty to less than 3%.
- Precise measurement of NDE is a major challenge in this analysis.
- More statistics will be coming from the data processing of the Spring run.
- Data analysis in progress for deuteron-target data:
  - ✓ Select quasi-elastic e-p and e-n events

Thank you ..