OLD DOMINION UNIVERSITY

CLAS12 Run Group F Summary

(E12-06-113 and E12-06-113A)

Feb. 12th – Sep. 21st , 2020

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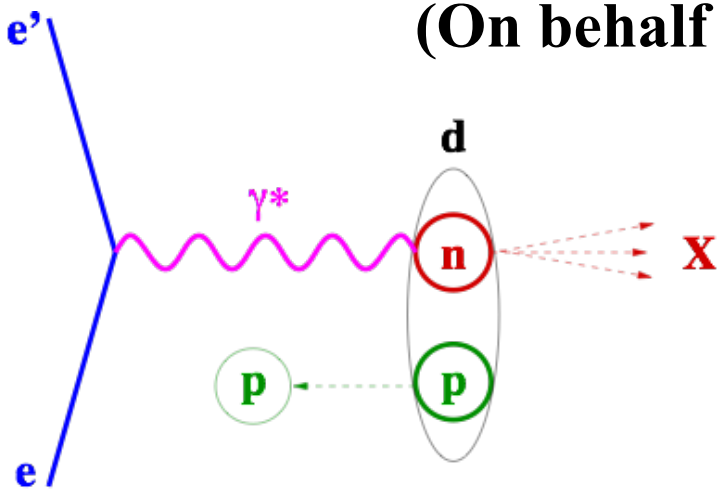
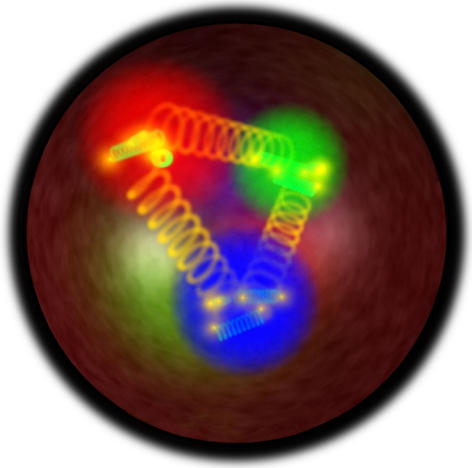
Old Dominion University

(On behalf of the CLAS Collaboration)





Outline

- Physics Motivations
- Experimental Setup and Recoil Detector.
- RG-F Physics Beam Time Accounting
- RG-F Data Summary
- First Look into the Data.
- Future Work and Manpower
- Conclusions

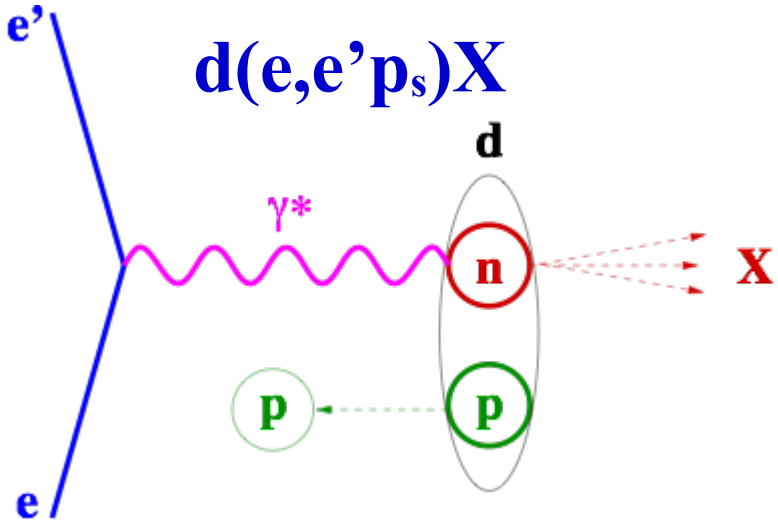
BONuS12: Quasi-Free Neutron Structure at Large x_B

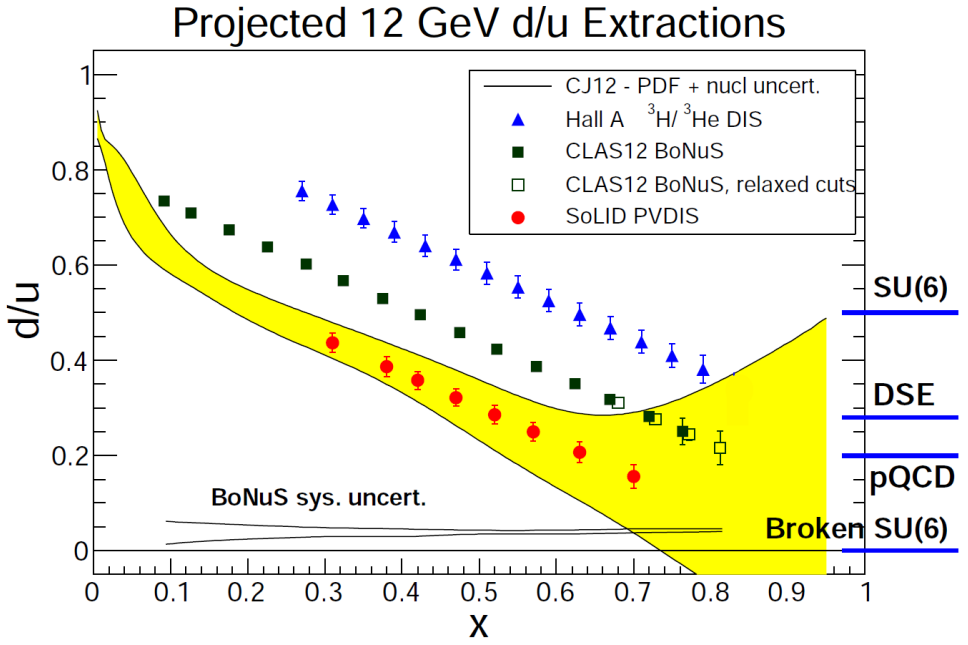
Parton Distribution Functions (PDFs)

→ Provide information on the partons longitudinal momentum distributions

→ Measurable via Deep Inelastic Scattering (DIS).

- For nucleons, the unpolarized DIS cross section is parametrized by two PDFs: $F_{1,2}(x)$, with $\mathcal{F}_1(x) = \frac{1}{2}\sum_q e_q^2 f_q(x)$ and $\mathcal{F}_2(x) = x\sum_q e_q^2 f_q(x)$





$$\frac{F_{2n}}{F_{2p}} \approx \frac{1+4d/u}{4+d/u} \Rightarrow \frac{d}{u} \approx \frac{4F_{2n}/F_{2p} - 1}{4 - F_{2n}/F_{2p}}$$

BONuS12 Nuclear Uncertainties

Final State Interactions:

- Struck neutron interacts with the spectator p.
- Proton momentum is enhanced.
- FSIs are small at low p_s and large θ_{pq}.

Target Fragmentation:

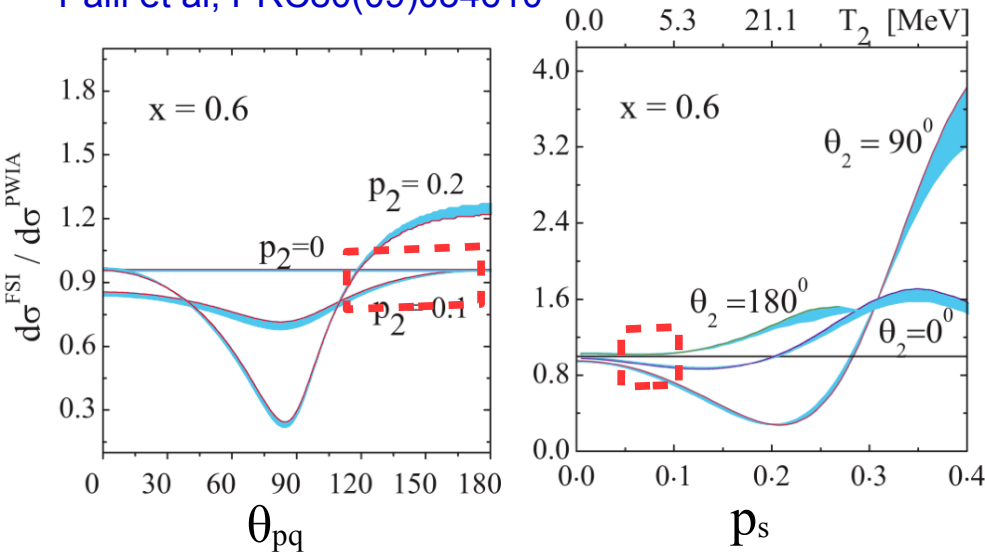
- e n → e p X (where n → π^- p) and
  e p → e p X (where p → π^0 p).
- TF enhances the proton yield only at forward angles ($\cos\theta_{pq} > 0.6$).

Off-Shell Corrections:

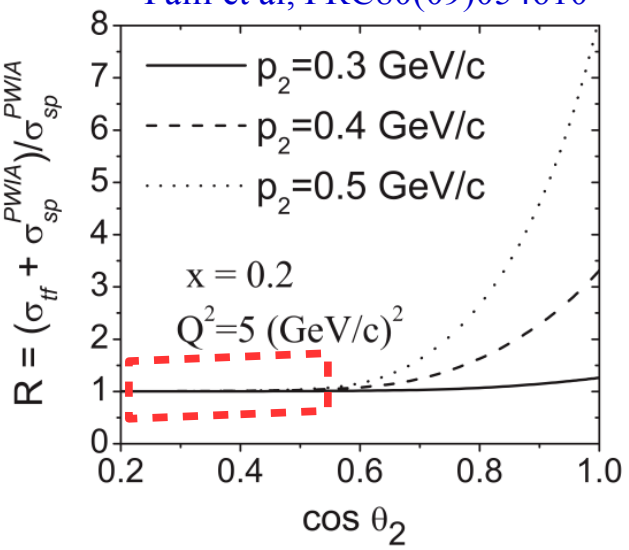
- Less than 2% in our region.

Overall systematic uncertainities will be less than 6%

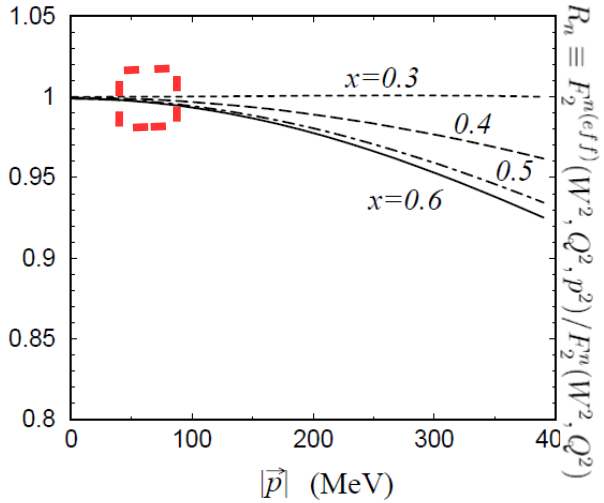
Palli et al, PRC80(09)054610



Palli et al, PRC80(09)054610

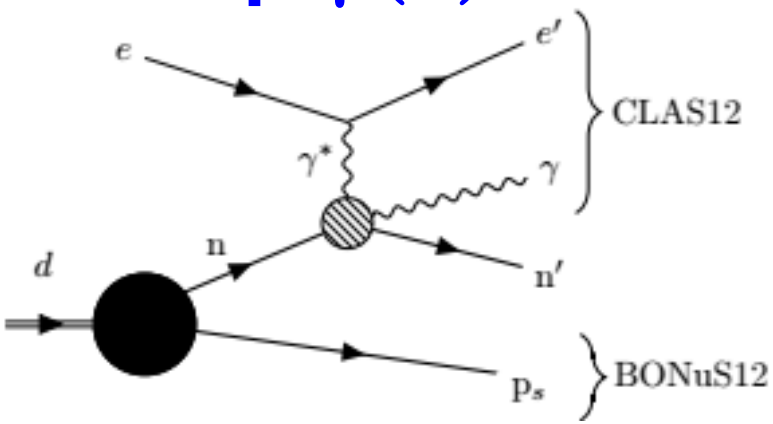


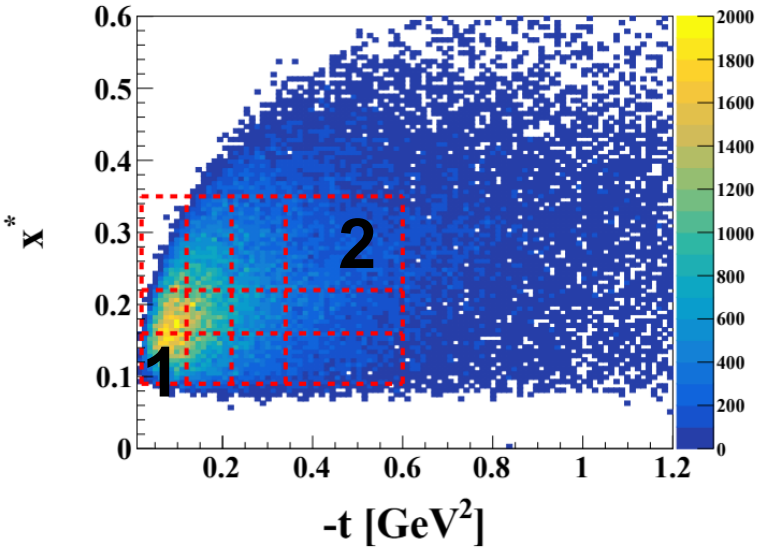
Melnitchoul et al, PRL B335,11(1994)



Tagged-proton nDVCS

$e^- D \rightarrow e^- p \gamma (n)$

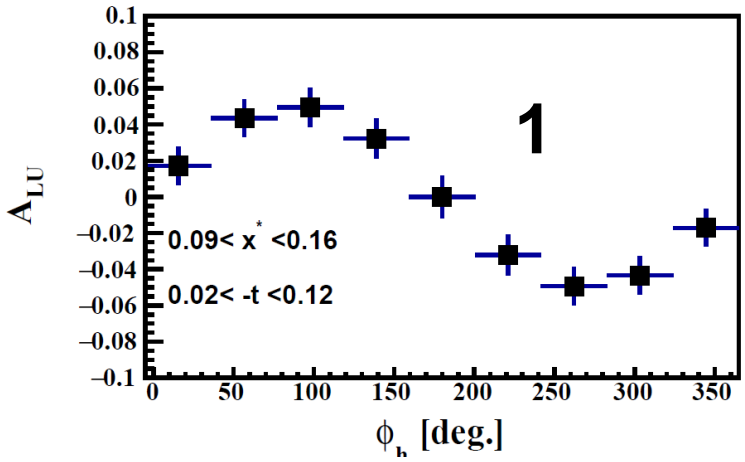


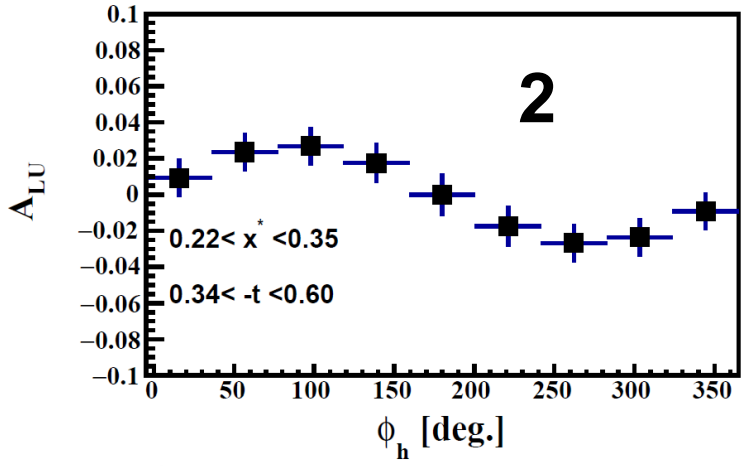


$$x^* = \frac{Q^2}{2M_N E y(2-\alpha_{sp})} = \frac{x_B}{2-\alpha_{sp}},$$

$$\alpha_{sp} = \frac{E_s - p_s^z}{M_N}$$

◊ 9M expected events.
◊ Total of 108 bins in x* vs. t vs. phi
◊ 20% conservative sys. Uncertainities.
◊ **Exploring the neutron's CFF via the BSA.**
◊ **Compare the nDVCS to Free proton DVCS.**

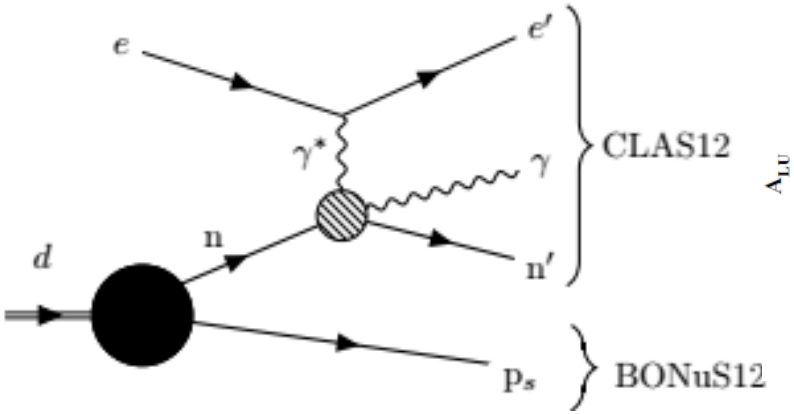


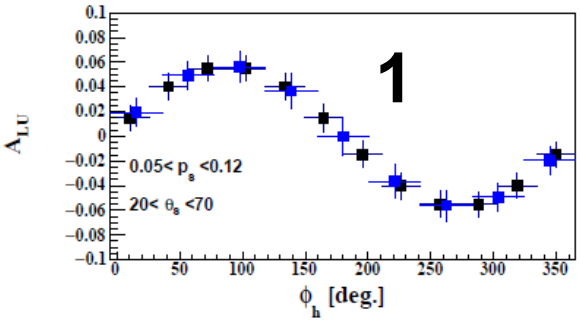


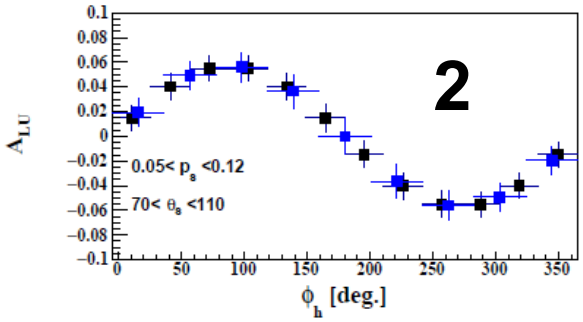
Fully exclusive nDVCS

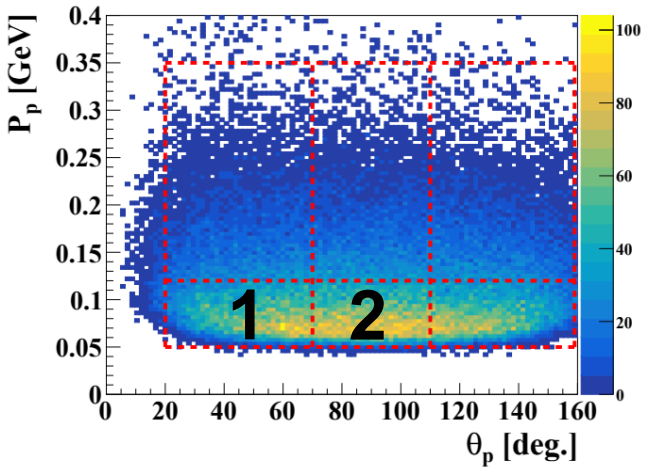
$e^- D \rightarrow e^- n \gamma p$

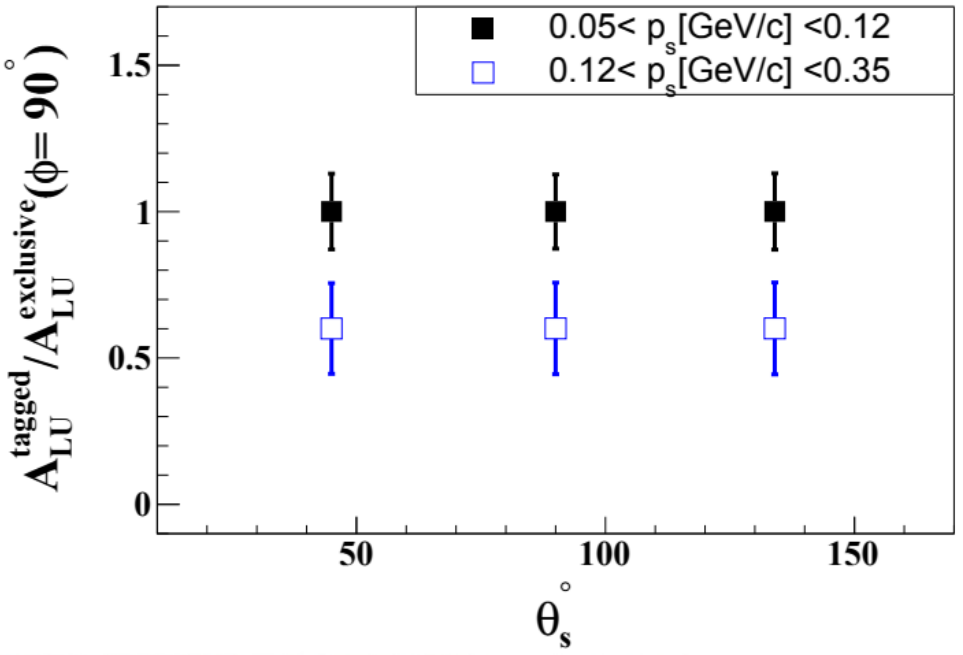
◊ 9M tagged nDVCS events (**black**)
~ 0.8M fully exclusive nDVCS (**blue**).
◊ **Exploring the Fermi motion and FSI effects on BSA.**











Other Physics Topics Accessible with BONuS12

The neutron PDF measurement is at the heart of the physics that will be achieved by successfully analyzing BONuS12 dataset, while a whole list of physics topics will be explored from this future golden data:

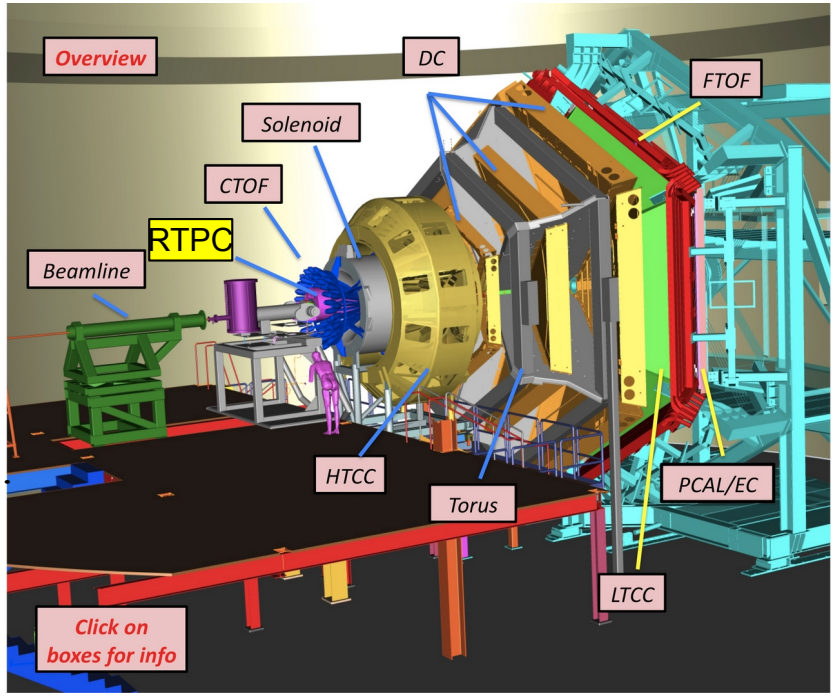
- **Neutron Elastic Scattering**
  - Access to neutron form factors.
- **Coherent DVCS off D**
  - Access to new GPDs, H_3 , with relationships to dueteron charge form factors.
- **Coherent DVMP off D**
  - π^0 , φ, ω and ρ mesons.
- **Semi-inclusive reaction p(e,e`p)X**
  - Study the π^0 cloud of the proton.
- **D(e, e`pp$_s$)X**
  - Study the π^- cloud of the neutron.
- **More Physics:**
  - DVCS off bound nucleons.
  - DVMP off bound nucleons.
  - The role of the final state interaction in hadronization and medium modified fragmentation functions.
  - The medium modification of the transverse momentum dependent parton distributions.
  - ... and more

BONuS12 Experimental Setup

10.4 GeV

$e^- D \rightarrow e\ p\ \gamma\ (n)$

- **CLAS12 Forward Detector:**
  - → Superconducting Torus magnet.
  - → 6 independent sectors:
    - → HTCC: identifying e^- ($p < 5.0$ GeV/c).
    - → 3 regions of DCs: tracking charged particles.
    - → (LTCC and RICH): π^- identification ($p > 3.0$ GeV/c).
    - → FTOF Counters: identifying hadrons.
    - → PCAL and EC: detecting γ, e^- and n [5°,40°].

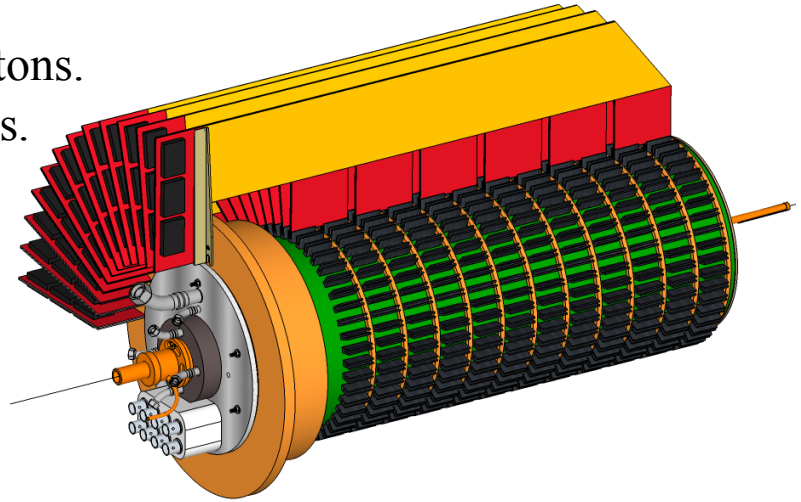


- **Central Detector:**
  - **Target:** D_2 gas @ 7.5 atm, 293 K
  - **BONuS12 RTPC:** Detects low energy spectator protons.
  - **Solenoid:** - Shields the detectors from Møller electrons.
    - Enables tracking in the RTPC.
  - **CTOF, CND, and FMT**

37 days on D_2

5 days on H_2

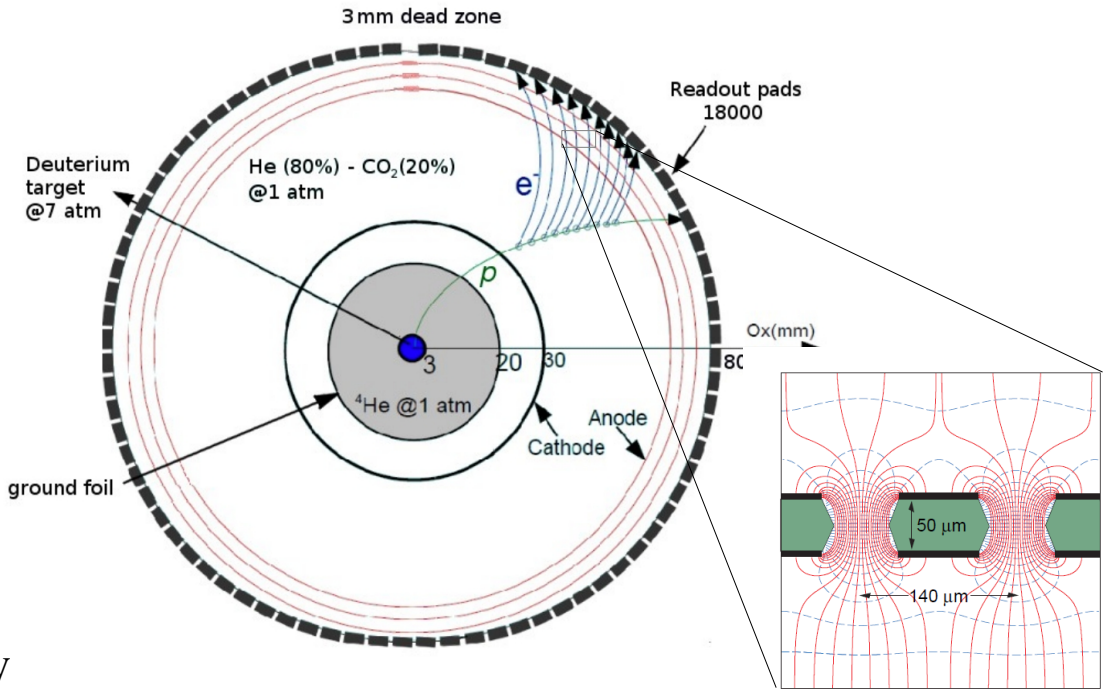
with $L = 2 \cdot 10^{34}$ cm^{-2} sec^{-1}



BONuS12 RTPC

- Design:

- 100% azimuthal coverage.
- 400 mm long , 160 mm Ø.
- 60 mm diameter target with 50 μm Kapton wall.
- 30 mm radius of cathode foil (4 μm thick).
- 40 mm drift region with total drift voltage of 4.3 kV.
  $|\vec{B}|$ = 3.7-4 T
- 3 GEMs layers, gain of 100/layer
- 17280 readout elements (2.7 mm x 3.9 mm).



- Work principle:

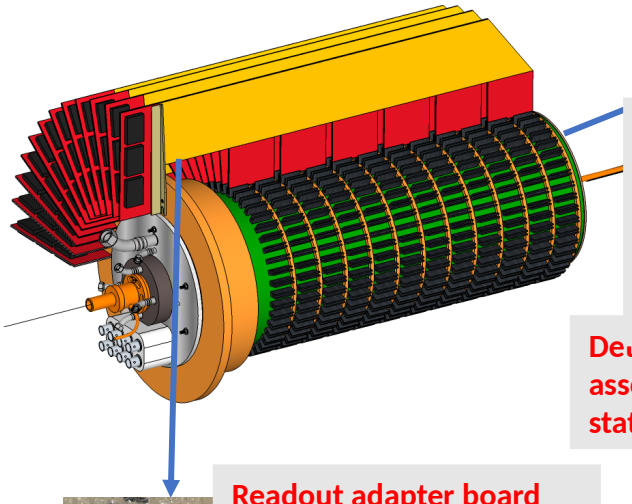
Charged particle ionizes the gas atoms
→ Under EM field, released electrons follow their drift paths at a certain drift speed
→ Amplifications via the 3 GEM layers
→ Readout board → MVT FEU electronics → Signal height vs. Time bin

- Offline reconstruction:

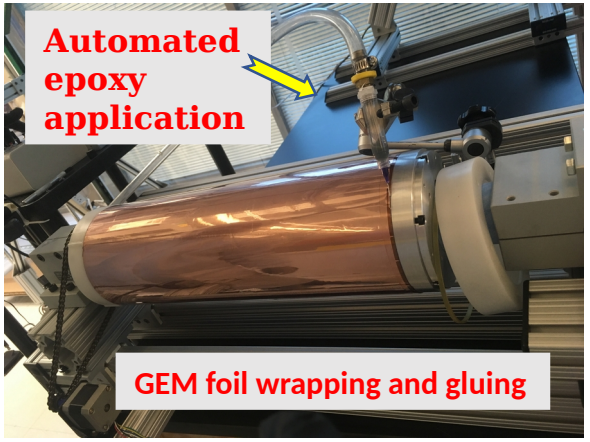
Signal height $\xrightarrow{\text{Pads' gains } (G_i)}$ $\left\langle \frac{dE}{dX} \right\rangle = \frac{\sum_i \frac{ADC_i}{Gi}}{vtl}$ → **PID**

Time and Pad location → 3D reconstruction of track → vector p/q, vz, vertex time

BONuS12 RTPC Construction

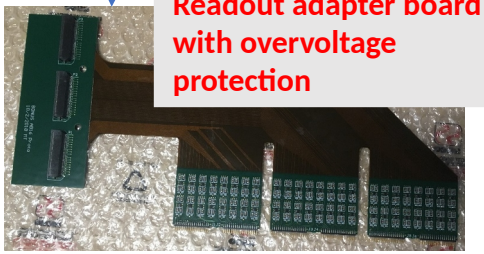


Completed outer shell of RTPC with readout board

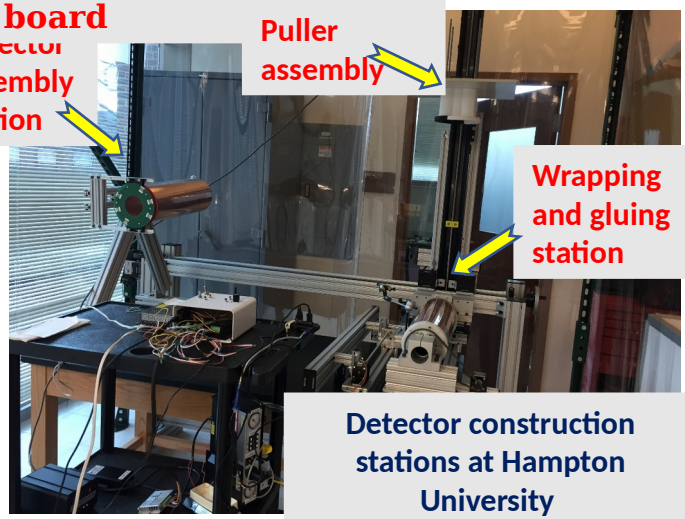


Automated epoxy application

GEM foil wrapping and gluing



Readout adapter board with overvoltage protection



Detector assembly station

Puller assembly

Wrapping and gluing station

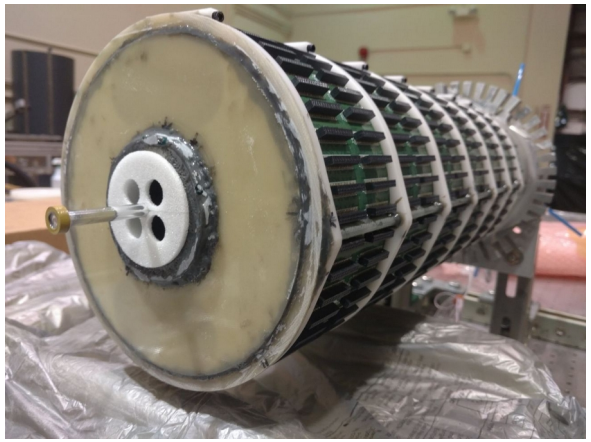
Detector construction stations at Hampton University

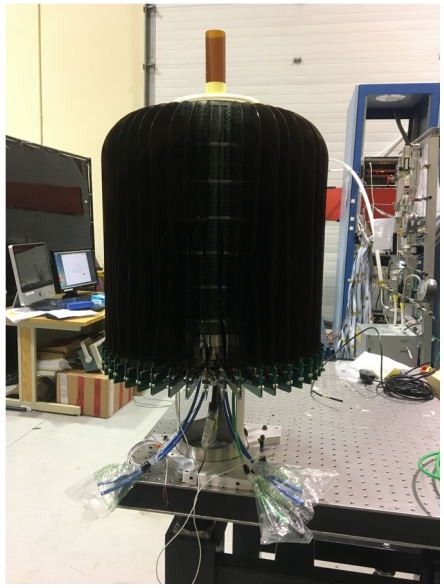
Readout board being installed on triple-GEM assembly

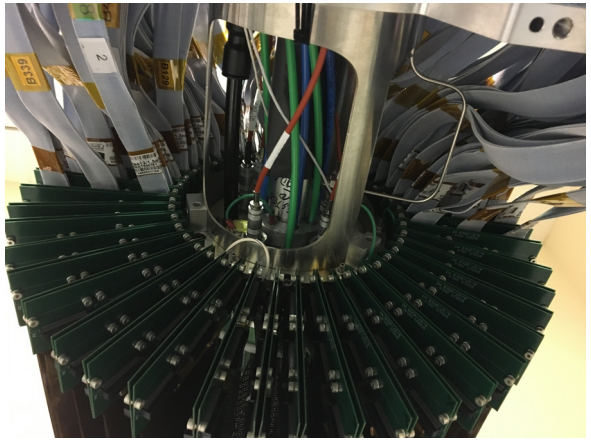
@ **ODU**: Individual testing for all BONuS12 RTPC parts, DAQ, and Target straws.
@ **HU**: Assembly station for the detectors.
- We built 3 complete RTPCs and several prototypes.

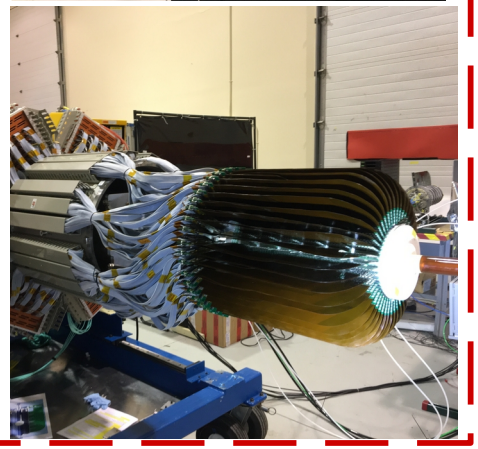
BONuS12 RTPCs

RTPC1

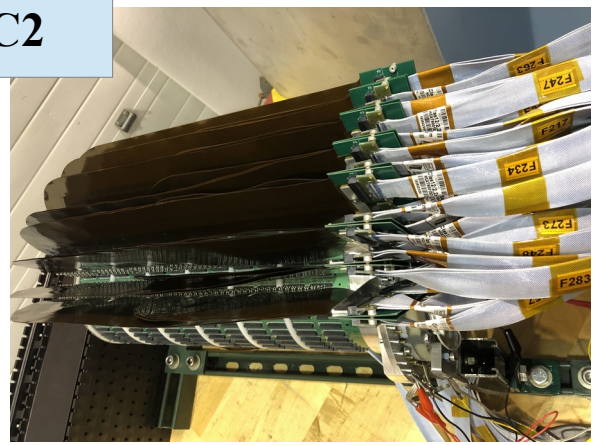




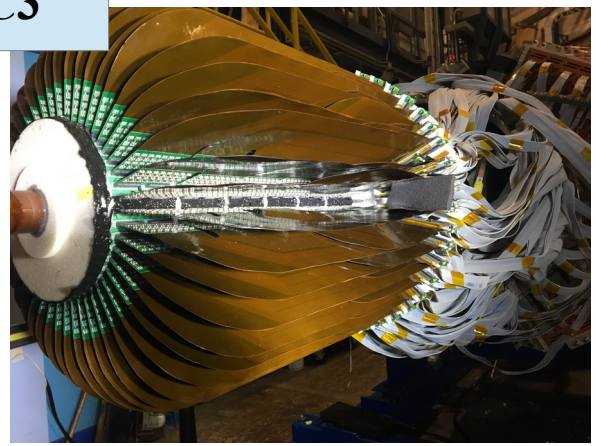




RTPC2



RTPC3

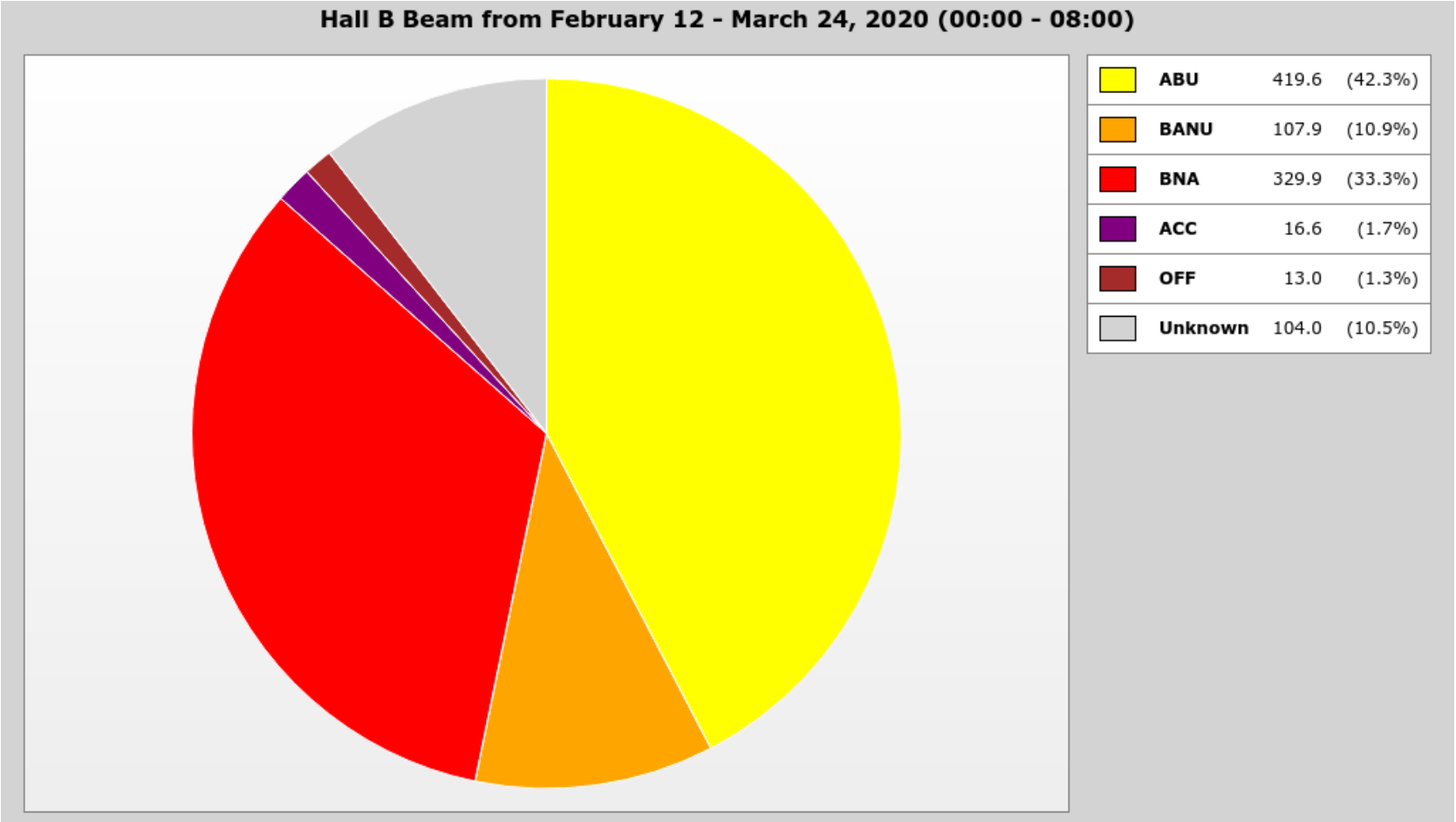


- **RTPC1**: Developed unstable detection effiency by time. Used at the beginning of the **Spring run**.
- **RTPC2**: Built and tested, but some repairs are needed (1 out of 16 sectors on GEM2 is shorted).
- **RTPC3**: Very stable performance. **Used at the end of the Spring Run and all the Summer Run**.

A Short History of RG-F

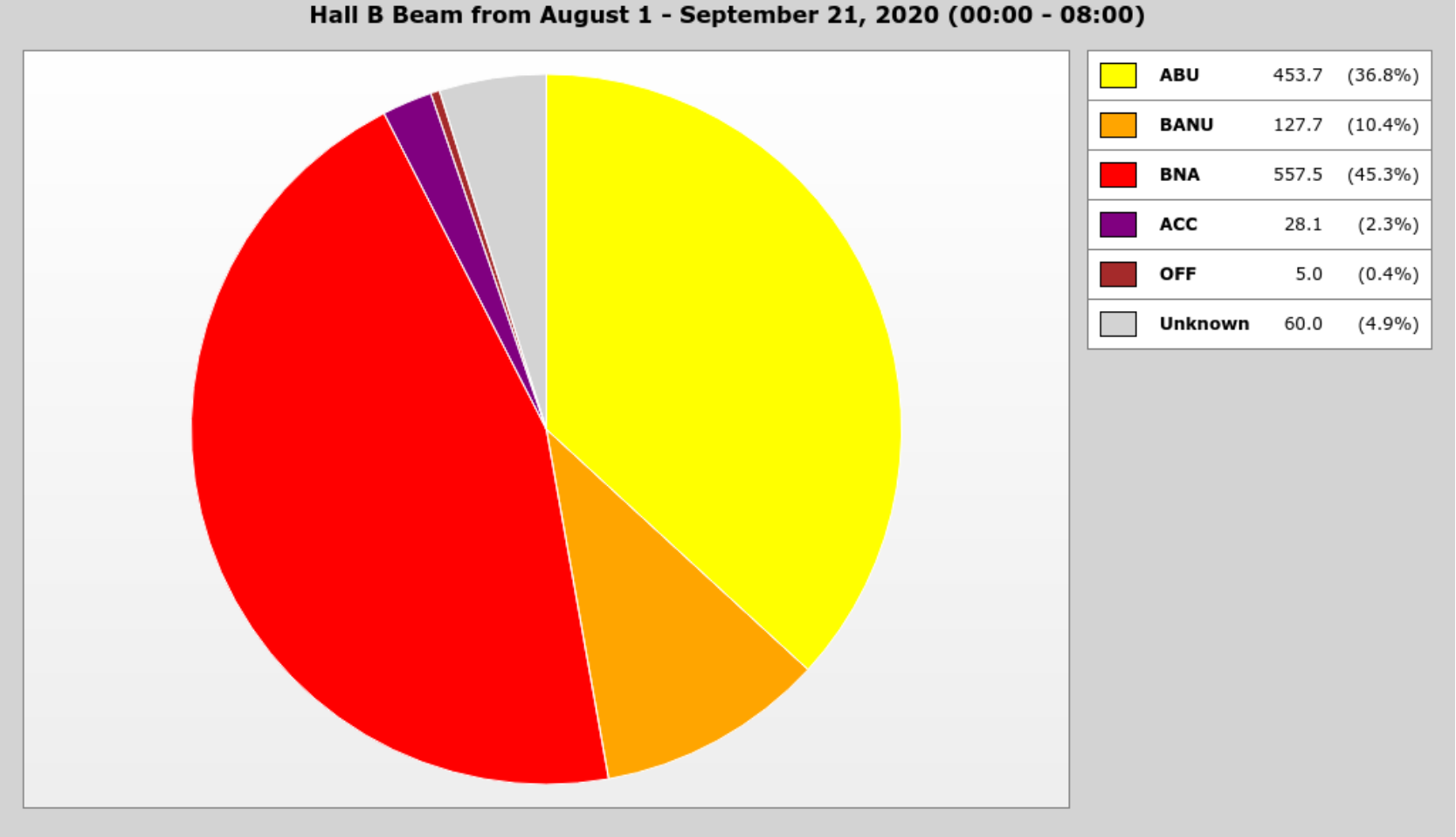
- 2/10-12: RTPC1/FMT installed in Hall, Cosmic Runs.
- 2/12-14: Accelerator startup and beam tuning
- 2/14-15: 2.1 GeV outbending run on all the target types (H_2, empty, D_2 and ^4He) (calibration).
- 2/16-3/9: 10.4 GeV inbending production running on all the targets
- 3/9-14: 10.4 GeV outbending production running on all thetargets
- 3/14-16: Brief return to 10.4 GeV inbending production running on D_2
- 3/16-20: Swap RTPC1 against RTPC3
- 3/20-24: 10.4 GeV inbending production running on all the targets.
- 3/24-06/08: Run halted (MEDCON-6).
- 06/08-07/17: Sealing RTPC3 (along the seam, first using Silicon on SL1, then DP-190 on SL0) and changing the target straw (15um → 30 um target windows).
- 07/17- 07/31: Cosmic data (maps in B field and HV).
- 08/02-08/06: 2.2 GeV outbending and inbending (half torus field) run on all the target types (calibration).
- 08/08-09/08: 10.4 GeV inbending (full torus field) run on all the target types.
- 09/08 – 09/10: Changed the beamline exit window (38 hours started on 09/08 @ 11:30 AM)
- 09/10-09/21: Back to 10.4 GeV inbending (full torus field) run on all the target types.
- 09/21 @ 7:00: Run is completed. We took another 4 hours of cosmic data.

RG-F Spring Run Time Accounting



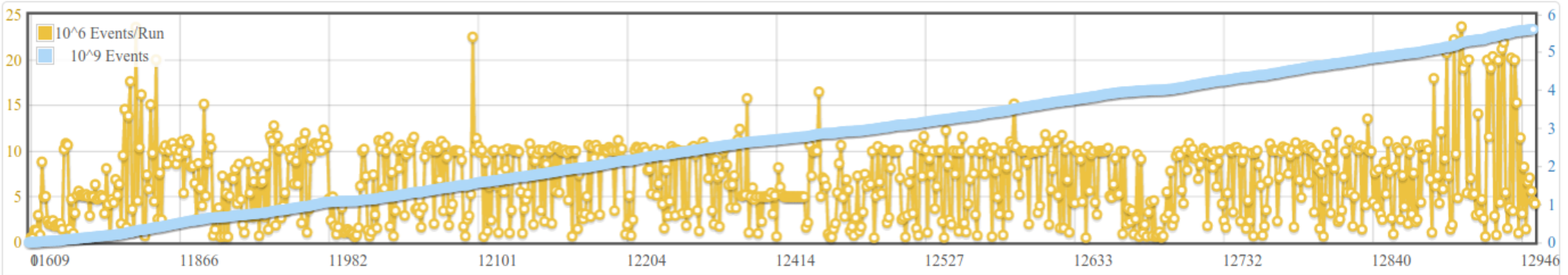
- ABU: 17.5 PAC days (1 @ 1 pass, 16.5 @ 5 pass)
- BANU: RTPC1→ RTPC3 Swap, Target gas changing and purging.
- 6 Moller runs (Avg. Beam Pol. (%) = 84.3 ±1.5)

RG-F Summer Run Time Accounting



- ABU: 19 PAC days (3 @ 1 pass, 16 @ 5 pass)
- BANU: Beamline exit window replacement, Target gas changing and purging.
- 8 Moller runs (Avg. Beam Pol. (%) = 83.1 ±1.5)

RG-F Data Summary

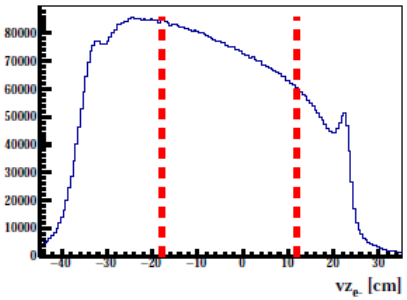


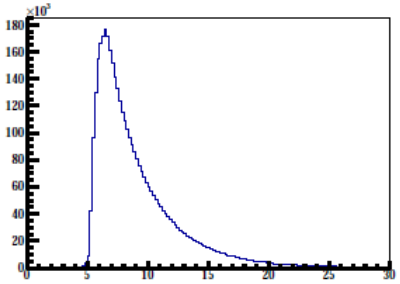
Showing runs: 11609 - 12955. 818 runs per page. Total runs: 818

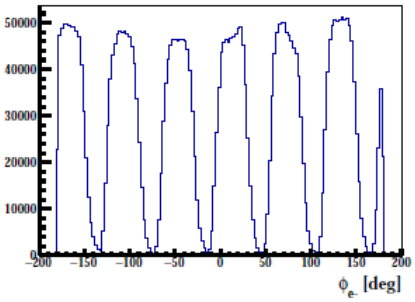
Beam Energy	Target	Spring 2020	Summer 2020
1 Pass Data	H2	81M	185M
	D2	37M	45M
	4He	19M	44M
	Empty	1M	22M
	Total	138M	296M
5 Pass Data	H2	151M	266M
	D2	2275M	2355M
	4He	77M	51M
	Empty	21M	45M
	Total	2524M	2717M

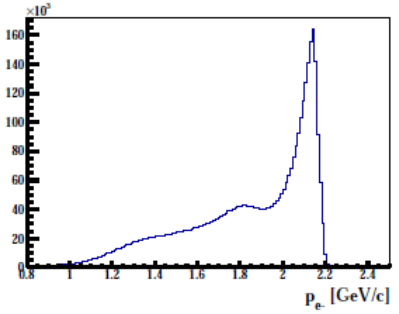
Preliminary Analysis – 1 Pass Data

Electron Selection : 2.14 GeV on H_2 target

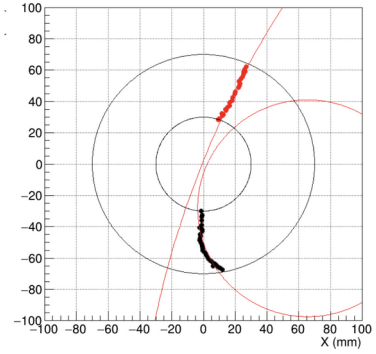


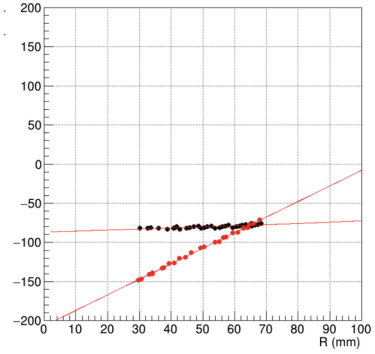


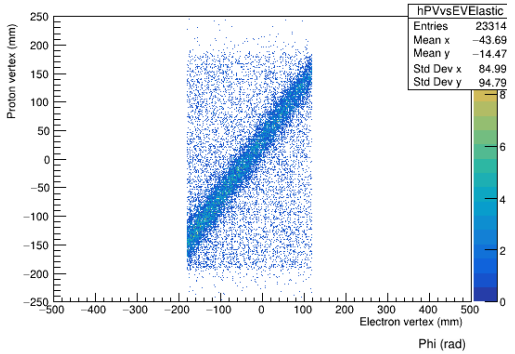


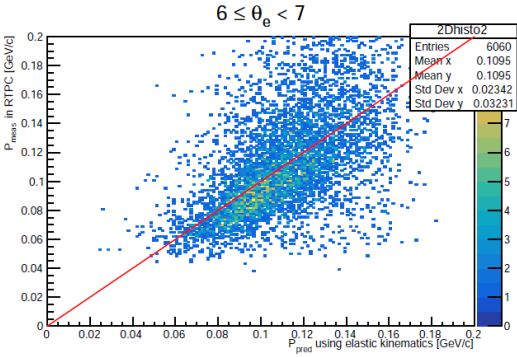


Radiative elastic e- in coincidence with good p tracks:

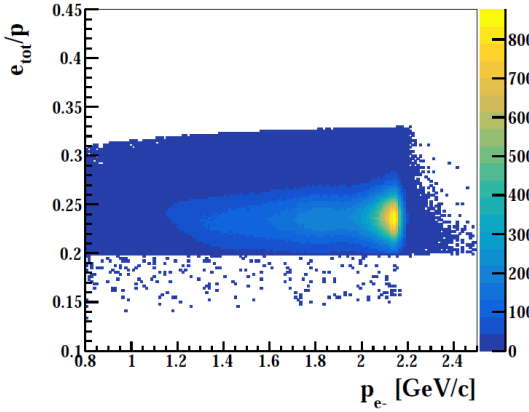


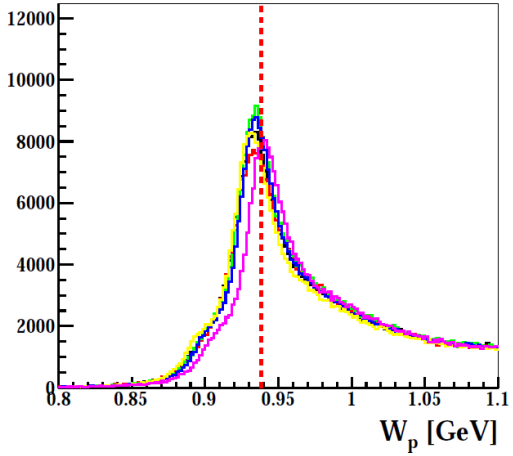


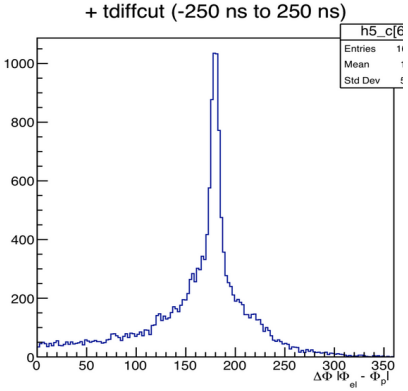


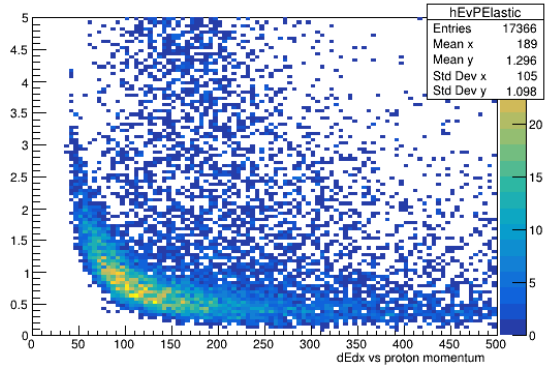


Phi (rad)









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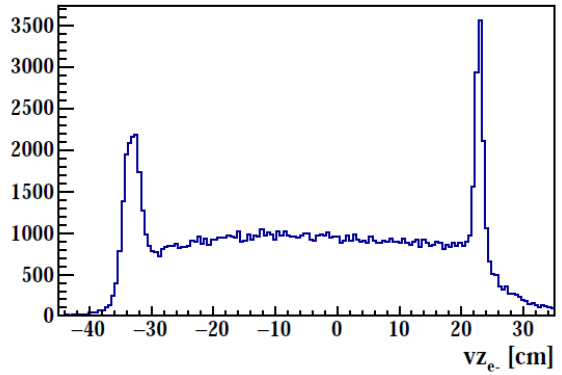
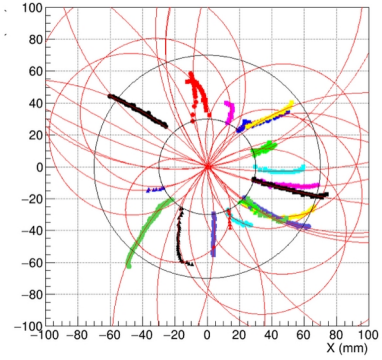
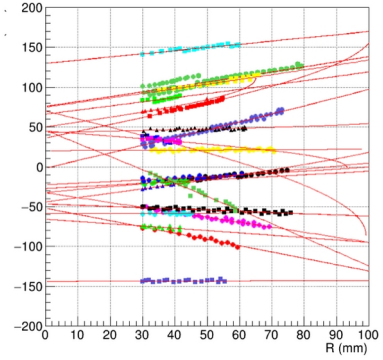
Preliminary Analysis – 5 Pass Data

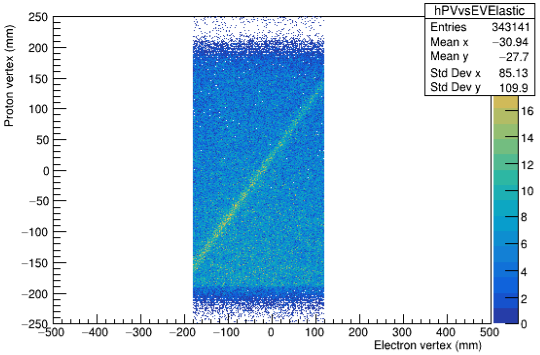
e- @10.4 GeV beam on D_2 target

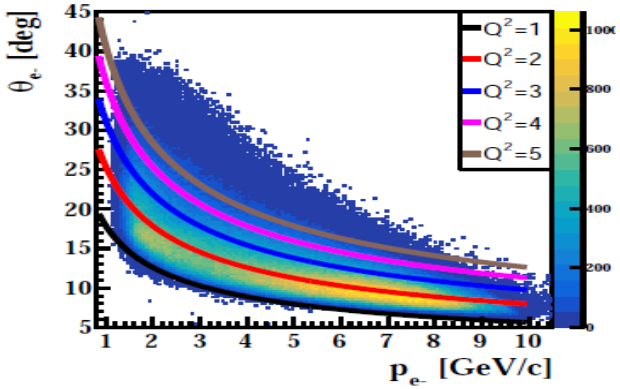
Proton Selection on D_2 target

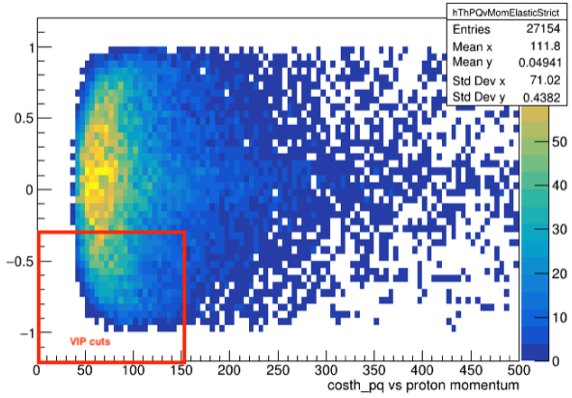


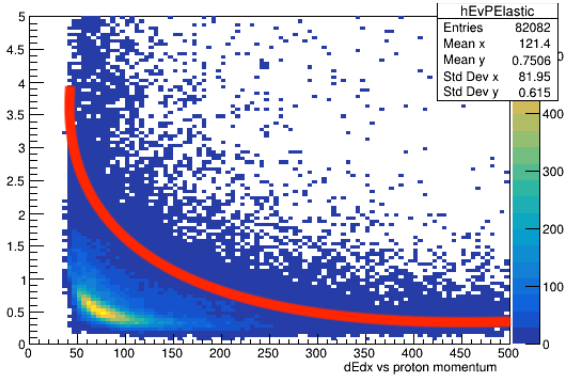


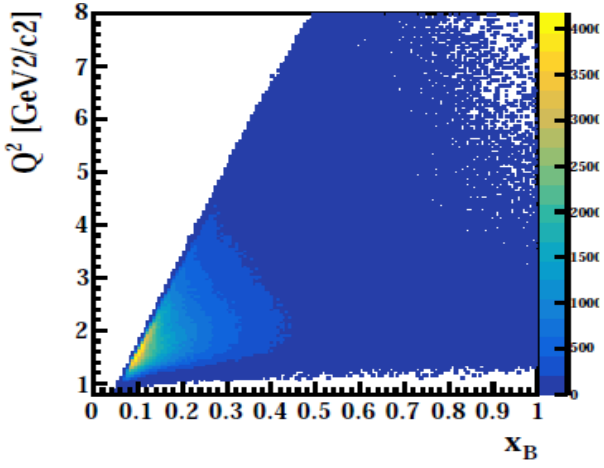


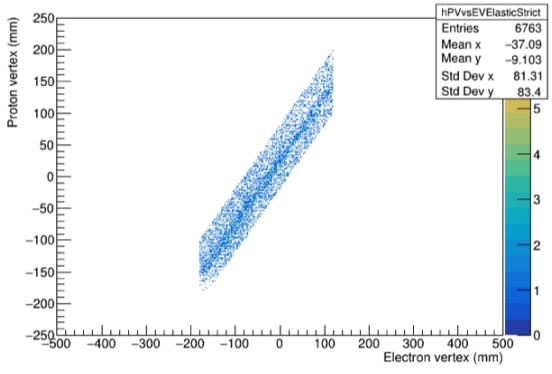


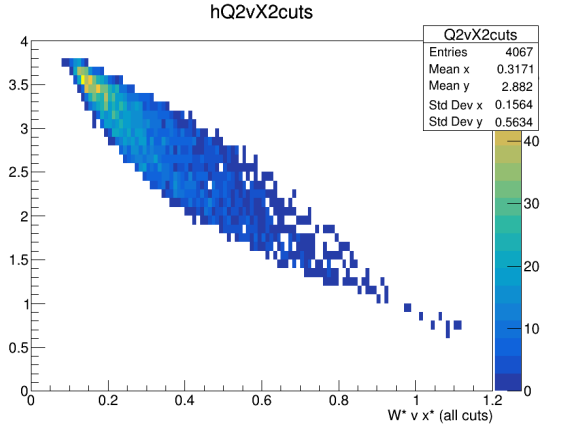












ODU

RG-F Future Work & Manpower

Work Item	Volunteer	Volunteer	Volunteer
1. Garfield++ studies	Yu-Chun Hung	Aruni Nadeeshani	
2. Maintaining and updating BONuS12 GEMC simulation	Yu-Chun Hung	Krishna Adhikari	
3. Radiative losses from simulation for different final state particles	Madhusudhan Pokhrel	Krishna Adhikari	Eric Christy (inclusive)
4. Analysis of simulated data, i.e., elastic and other channels (n-DIS, n-DVCS, n-DVMP, ...)	Madhusudhan Pokhrel	Mohammad Hattawy	
5. Implementing Kalman filter for BONuS12	Mathieu Ouillon	Sebastian Kuhn	
6. Improving BONuS12 code for track finding, merging, and disentangling	Mathieu Ouillon	Sebastian Kuhn	
7. Extracting resolutions and corrections in vertex, momentum, theta, phi; effiency using the elastic data	Madhusudhan pokhrel	Mohammad Hattawy	
8. Improving the gain calibration and the calculated dEdx	Madhusudhan pokhrel	Sebastian Kuhn	Mohammad Hattawy
9. Checking the CLAS12 alignment using the zero-field run, then re-do DC calibration if needed (DC expert)	Mohammad Hattawy		
10. Checking the energy calibration of PCAL+ECAL for e- and extracting corrections (through etot/p vs. time)	Jiwan Poudel	Mohammad Hattawy	
11. Checking the energy calibration for final photons through pi0 final state particles and extract corrections	Jiwan Poudel	Mohammad Hattawy	
12. Extract acceptance ratios and detection effiency from simulation for different final state particles (e-, p, n, photon, D2)	Mohammad Hattawy		
13. Checking the calibration of the neutron detection in the central CND and CToF from experimental data	Mohammad Hattawy	Daniel Carman	Silvia Niccolai
14. Contributing in the FMT reconstruction implementation	Bruno Benkel (software)	Jorge Lopez (validation)	Raffaella De Vita (supervisor)
15. Continue supporting cooking the BONuS12 data	Bradley Yale	Mohammad Hattawy	
16. Analyzing the elastic data on the four different targets (H2, D2, 4He, empty)	Sebastian Kuhn	Krishna Adhikari	Eric Christy
17. DIS analysis on D2 using the 10GeV data	Sebastian Kuhn	Krishna Adhikari	Eric Christy
18. n-DVCS analysis on D2 using the 10 GeV data	Mathieu Ouillon	Mohammad Hattawy	
19. Maintaining the database	Aruni Nadeeshani	Mohammad Hattawy	
20. Target Purity studies	Narbe Kalantarians		

Conclusions

◊ After the successful running of **BONuS6**, **BONuS12** continues to explore the higher x_B region of the neutron PDFs measurements in addition to many physics topics to be explored using this future golden dataset.

◊ BONuS12 team has built 3 complete RTPCs and several prototypes, where all the learned from **BONuS6** and **EG6 RTPCs** have been applied in these third generation RTPCs in HallB.

◊ RG-F has received 87% of the Approved PAC days. We are happy and no intentions to ask for beam time extension.

◊ Both the FD and RTPC calibrations are at an already advanced stage.

◊ Pass0 analysis is in progress for both datasets, i.e., the Summer Run and the Spring Run.
→ JOIN US (Mondays @ 12:00 PM on https://bluejeans.com/7576835804/)
(Mailing list https://mailman.jlab.org/mailman/listinfo/Bonuslist)

5.675 billion thanks go to all the people - in particular Hall B staff helping us, and volunteer shift takers - who worked incredibly hard under very challenging conditions to make this experiment happen.

Acknowledgments

- Hall B scientific staff: Daniel Carman, Eugene Pasyuk, Gagik Gavalian, Mac Mestayer, Marco Battaglieri, Nathan Baltzell, Sergey Boyarinov, Stepan Stepanyan, Valery Kubarovsk, Volker Burkert, Youri Sharabian, Yuri Gotra.
- Hall B engineering staff and technical staff: Bob Miller, Calvin Mealer, Cyril Wiggins, Denny Insley, Krister Bruhwel, Mike Zarecky, Morgan Cook, Todd Ewing.
- Electronics group: Armen Stepanyan, Ben Raydo, Chris cuevas, Mark Taylor.
- DSG group: Brian Eng, Marc Mcmullen, et al.
- Machine shop group: Vincent Pope, David Wallace, Alan Lewis, et al.
- Saclay group: Irakli Mandjavidze, Maxence Vandenbroucke, Maxime Defurne, Stephan Aune et al.,
- Alignment group: Chris Gould et al.,
- Software group: Raffaella De Vita et al.,
- The Procurement and Shipping & Receiving departments: Renee Carter and Donald Brown.
- BONuS12 students & Postdocs: Aruni Nadeeshani, David Payette, Jiwan Poudel, Madhu Pokhrel, Mathieu Ouillon, Nathan Dzbenski, Yu-Chun Hung & Bradley Yale, Gabriel Charles, Ibrahim Albayrak, Krishna Adhikari.

- RCs: Florian Hauenstein, Narbe Kalantarian, Carlos Ayerbe Gayoso.
- Shift takers: Achyut Khanal, Adam Thornton, Adrian Saina, Alessandra Filippi, Annalisa D'Angelo, Aron Kripko, Bradley Yale, Brandon Clary, Burcu Duran, Chan Kim, Charles Hyde, Christopher Dilks, Daniel Carman, David Payette, Dilini Bulumulla, Eugene Pasyuk, Florian Hauenstein, Gabriel Niculescu, Gagik Gavalian, Gary Hollis, Gerard Gilfoyle, Giovanni Angelini, Hamza Atac, Harut Avakian, Hayk Hakobyan, Hovanes Egiyan, Igor Strakovsky, Isabella Illari, Iuliia Skorodumina, Jiwan Poudel, Jixie Zhang, Jose Carvajal, Victoria Lagerquist, Joseph Newton, Joshua Artem Tan, Junqi Xie, Keith Griffioen, Kevin L. Giovanetti, Kevin Wei, Krishna Neupane, LamyaAbudaker A Baashen, Latifa Elouadrhiri, Lawrence Weinstein, Lucilla Lanza, Mac Mestayer, Madhusudhan Pokhrel, Charles Hyde, Marco Battaglieri, Mathieu Ehrhart, Maxime Defurne, Michael Wood, Mohammad Hattawy, Nathan Baltzell, Nicholas Tyler, Nikolay Markov, Noelie Cherrier, Orlando Soto, Pushpa Pandey, Rafayel Paremuzyan, Raffaella De Vita, Robert Fersch, Sebastian Kuhn, Stepan Stepanyan, Stephen Bueltmann, Stuart Fegan, Susan Schadmand, Taya Chetry, Timothy Hayward, Torri Roark, Tsuneo Kageya, Tyler Viducic, Utsav Shrestha, Valery Kubarovsky, Veronique Ziegler, Victor Mokeev, Victoria Lagerquist, Vitali Baturin, Volker Burkert, William Phelps, Yulia Furletova, Yuri Gotra
- Special thanks to Jay Benesh, Steve Suhring, Mike Tiefenback and all the MCC people.

- RG-F Spokespersons: Cynthia Keppel, Eric Christy, Howerd Fenker, Keith Griffioen, Mohammad Hattawy*‡, Raphael Dupre, Sebastian Kuhn†, Stephan Bueltmann*, Vladas Tvaskis, Wally Melnitchouk.
(*Proposal contact person, ‡ Analysis coordinator, † Experiment contact person)

ODU

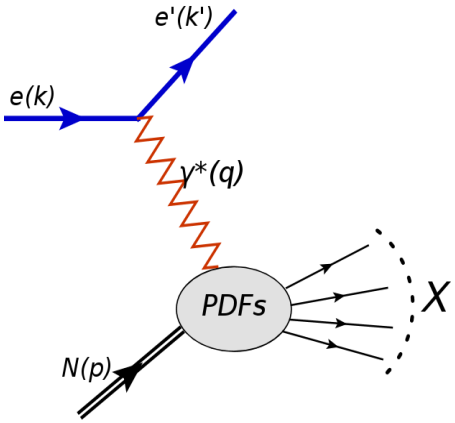
Backup Slides!

Nucleon Structure (1/2)

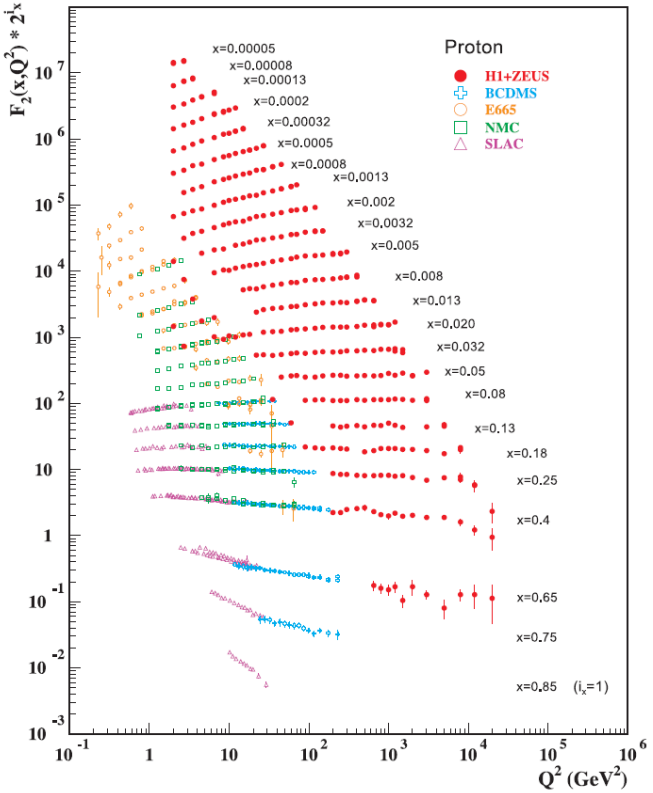
Parton Distribution Functions (PDFs)

→ Provide information on the partons longitudinal momentum distributions

→ Measurable via Deep Inelastic Scattering (DIS).



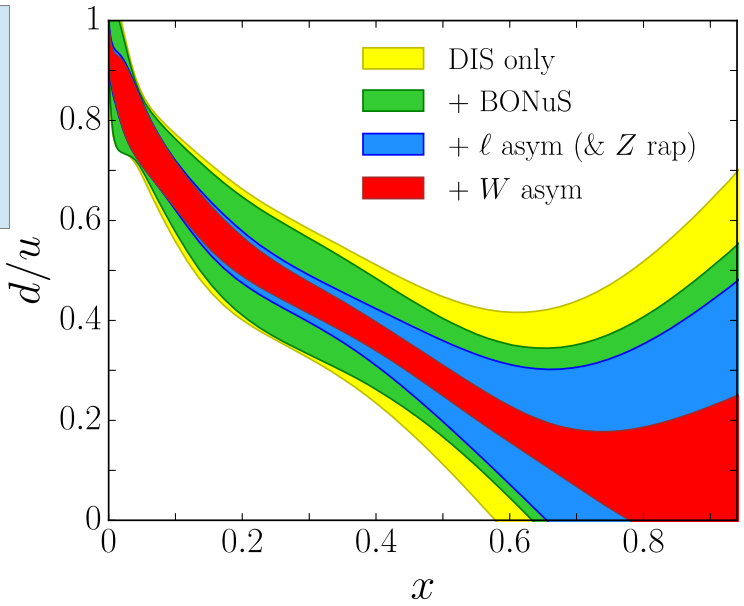
- For nucleons, the unpolarized DIS cross section is parametrized by two PDFs: $F_{1,2}(x)$, with $\mathcal{F}_1(x) = \frac{1}{2}\sum_q e_q^2 f_q(x)$ and $\mathcal{F}_2(x) = x\sum_q e_q^2 f_q(x)$



- J. Beringer et al. (Particle Data Group), Phys. Rev. D 86, 010001, page241, 2012.

$$F_2^p(x) = x\sum_q e_q^2\,(q(x)+\bar{q}(x)) \approx x\left(\frac{4}{9}u(x)+\frac{1}{9}d(x)\right)$$

DIS on proton provides strong constraints on the u quark distribution



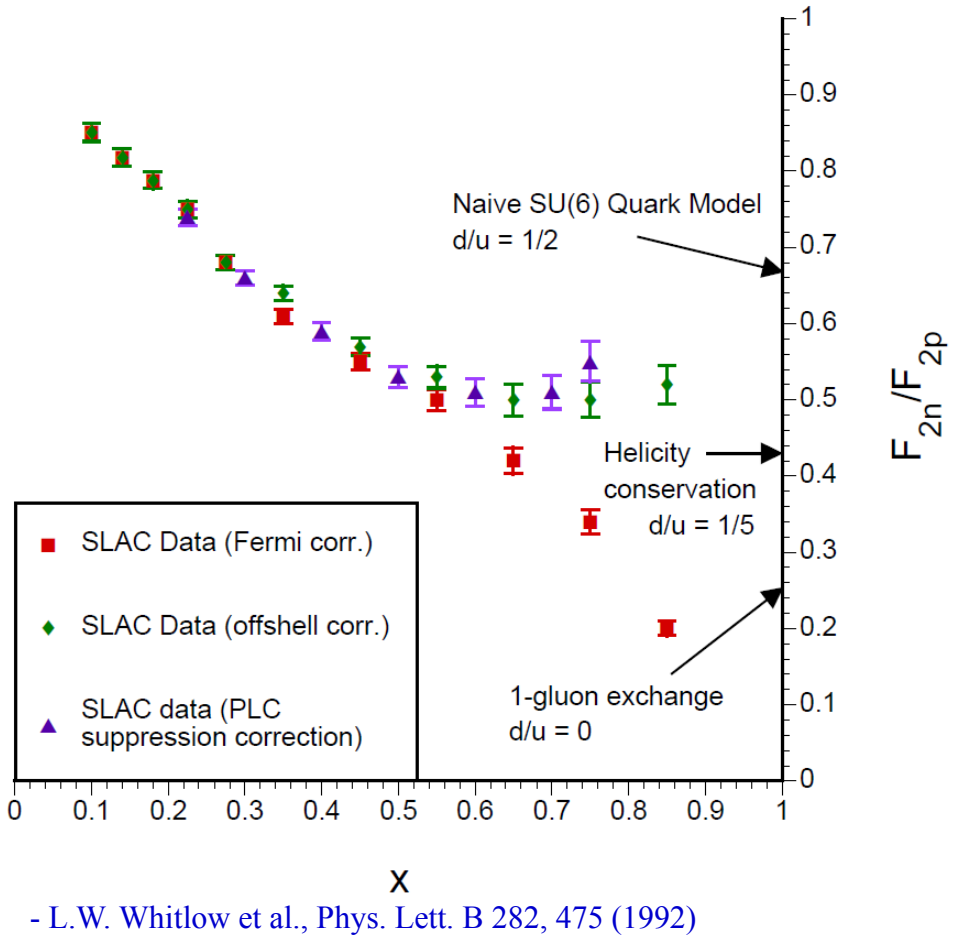
We need more precise determination of d quark distribution

Nucleon Structure (2/2)

- **What about Using Deuteron DIS to constrain the d quark distributions?**

$$\frac{F_{2n}}{F_{2p}} \approx \frac{1+4d/u}{4+d/u} \Rightarrow \frac{d}{u} \approx \frac{4F_{2n}/F_{2p} - 1}{4 - F_{2n}/F_{2p}}$$

$$F_{2n}/F_{2p} = F_{2d}/F_{2p} - 1$$



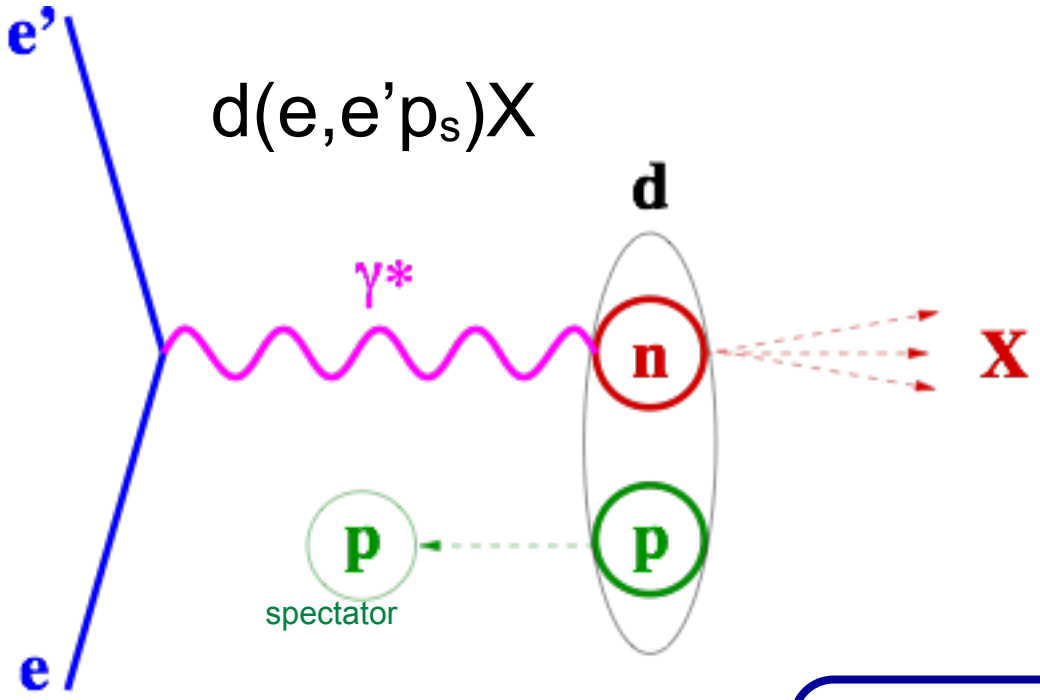
- L.W. Whitlow et al., Phys. Lett. B 282, 475 (1992)

- **Nuclear corrections led to ambiguities in the extracted F_{2n}.**

- **We need free neutron data, but ...**
  - Free neutrons decay in 15 minutes.
  - Radioactivity.
  - Difficulte to create dense target.

- **Alternative Solution:** Barely Off-shell Neutrons from Deuterons, Tritons and ^{3}He targets to minimize the nuclear model uncertainties associated with Fermi motion, off-shell effects (binding), structure modifications (EMC effect), ...

Minimizing Nuclear Uncertainties: "Spectator Tagging"



Initial hadronic state

$$p_N^\mu = (M_d - E_s, -\vec{p}_s)$$

$$E_p + E_n = M_d$$

$$E^* = M_d - \sqrt{M_s^2 + p_s^2}$$

$$M^{*2} = (M_d - E_s)^2 - \vec{p}_s^{\,2}$$

Final hadronic state

$$W^{*2} \approx M^{*2} - Q^2 + 2M\nu\,(2 - \alpha_s)$$

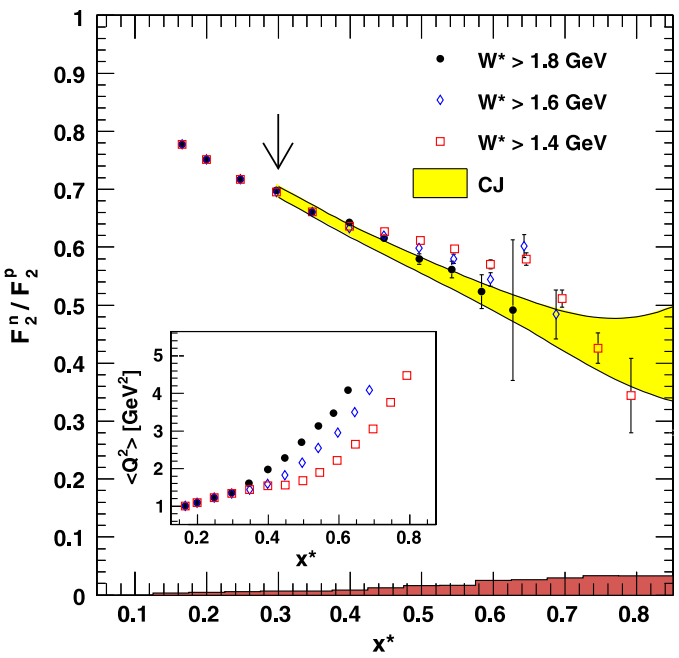
$$x^* = \frac{Q^2}{2p_N^\mu q^\mu} \approx \frac{Q^2}{2M\nu(2-\alpha_s)} = \frac{x}{2-\alpha_s}$$

$$\alpha_s = \frac{E_s - p_{s_{||}}}{M_s}$$

*** DIS region with:**

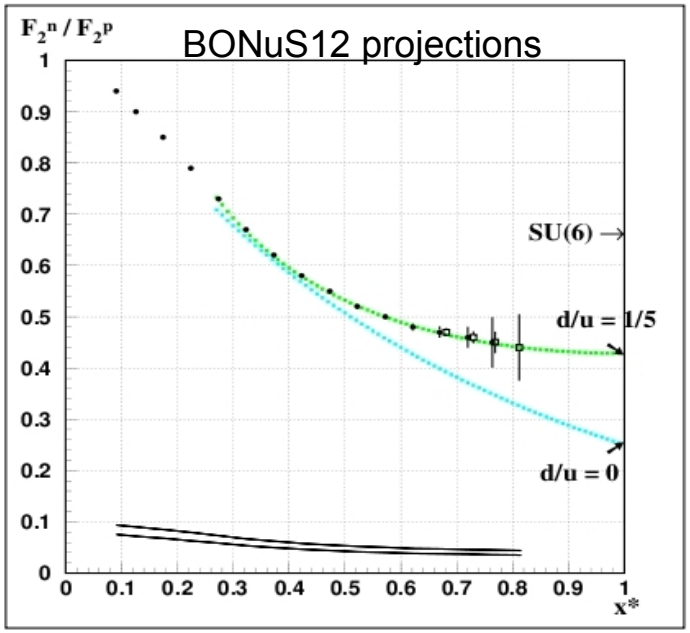
- $Q^2 > 1$ GeV$^2/c^2$
- $W^* > 2$ GeV
- $p_s > 70$ MeV/c
- $10° < \theta_{pq} < 170°$

JLab Previous & planned measurements



BONuS6

BONuS12



RG-F Moller Measurements

Moller Run #	Date	HWP	Beam Pol.	Uncer.	Logbook link
95	02/16/20	OUT	84.8	1.5	https://logbooks.jlab.org/entry/3784826
98	02/18/20	OUT	85.4	1.5	https://logbooks.jlab.org/entry/3786819
99	02/25/20	OUT	83.3	1.5	https://logbooks.jlab.org/entry/3791993
100	03/06/20	OUT	86	1.5	https://logbooks.jlab.org/entry/3796881
102	03/10/20	OUT	82.3	1.5	https://logbooks.jlab.org/entry/3801471
104	03/23/20	OUT	84.1	1.5	https://logbooks.jlab.org/entry/3808544
105	08/08/20	OUT	84.1	1.5	https://logbooks.jlab.org/entry/3822396
107	08/14/20	OUT	80.3	1.5	https://logbooks.jlab.org/entry/3827454
109	08/21/20	IN	82.5	1.5	https://logbooks.jlab.org/entry/3832089
110	08/21/20	OUT	84.4	1.5	https://logbooks.jlab.org/entry/3832117
111	08/31/20	IN	83.5	1.5	https://logbooks.jlab.org/entry/3838479
113	09/10/20	OUT	79.2	1.5	https://logbooks.jlab.org/entry/3845112
114	09/18/20	OUT	86.2	1.5	https://logbooks.jlab.org/entry/3851060
115	09/20/20	OUT	85.2	1.5	https://logbooks.jlab.org/entry/3852212