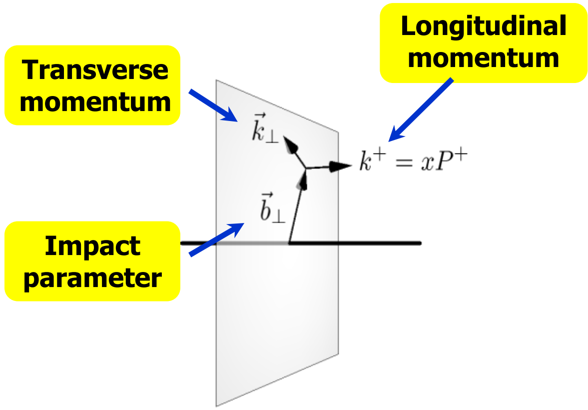
CLAS12 Run Group B
Electroproduction on deuterium with CLAS12

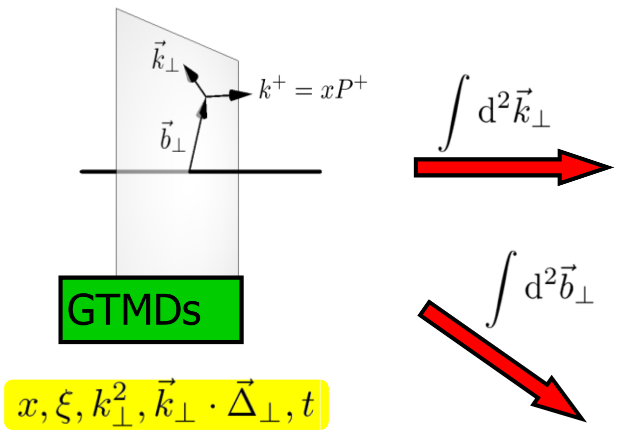
- Physics goals
- RG-B experiments
- Overview of the data taking
- Analysis updates and preliminary results
- Beam time request

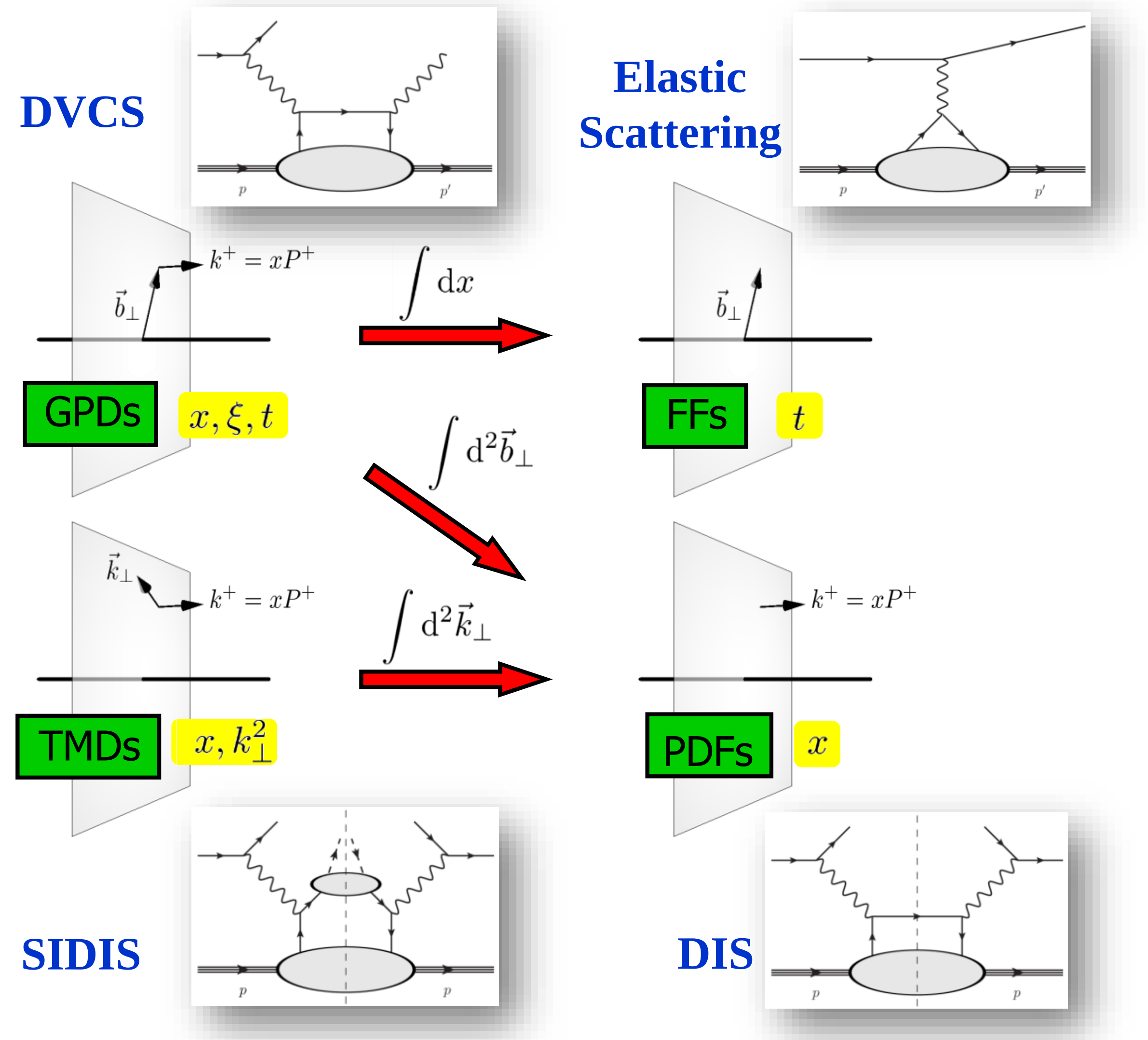
Silvia Niccolai, IJCLab Orsay
PAC48, 9/25/2020

Multi-dimensional mapping of the nucleon



A complete picture of nucleon structure requires the **measurement of all these distributions**.

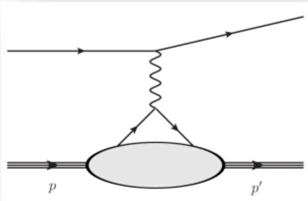




Run-Group B aims to measure all these distributions, using **deuteron** as a **neutron target**
→ Quark-flavor separation, combining with proton results

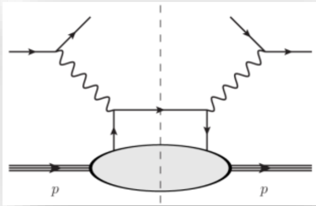
+ EMC effect, SRC
+ J/ψ photoproduction on deuteron

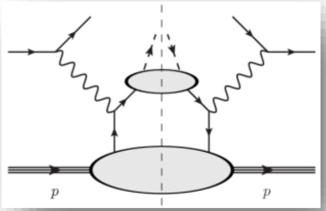
CLAS12 Run Group B: experiments



Elastic Scattering (G^n_M)

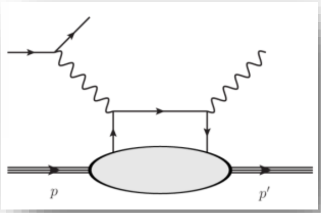
DIS (for SRC and EMC effect)

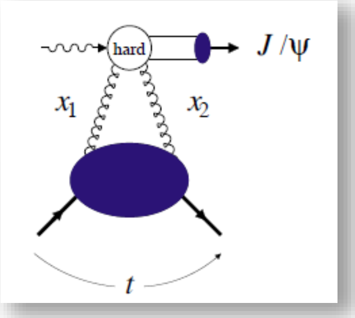




SIDIS (for PDFs and TMDs

nDVCS





J/ψ photoproduction

E12-07-104	Neutron magnetic form factor	G. Gilfoyle	A- 30
E12-09-007a	Study of parton distributions in K SIDIS	W. Armstrong	A- 56
E12-09-008	Boer-Mulders asymmetry in K SIDIS	M. Contalbrigo	A- 56
E12-11-003	Deeply virtual Compton scattering on the neutron	S. Niccolai	A **(HI) 90**
E12-09-008b	Collinear nucleon structure at twist-3 in dihadron SIDIS	M. Mirazita	RG
E12-11-003a	In medium structure functions, SRC, and the EMC effect	O. Hen	RG
E12-11-003b	Study of J/ψ photoproduction off the deuteron	Y. Ilieva	RG
E12-11-003c	Quasi-real photoproduction on deuterium	F. Hauenstein	RG (*)

(*) Joined RGB from fall run onwards

Common features to all experiments of RG-B:

- **Liquid deuterium target**
- **Beam energy: « 11 » GeV**

Run Group B running time

Scheduled beam time:
Spring: Febuary 6th - March 25th 2019
Fall: December 3rd –20th 2019
Winter: January 6th – 30th 2020

38.9 total PAC days according to ABUs
→ **43.2% of the approved 90 PAC days**
51 days requested for Jeopardy PAC

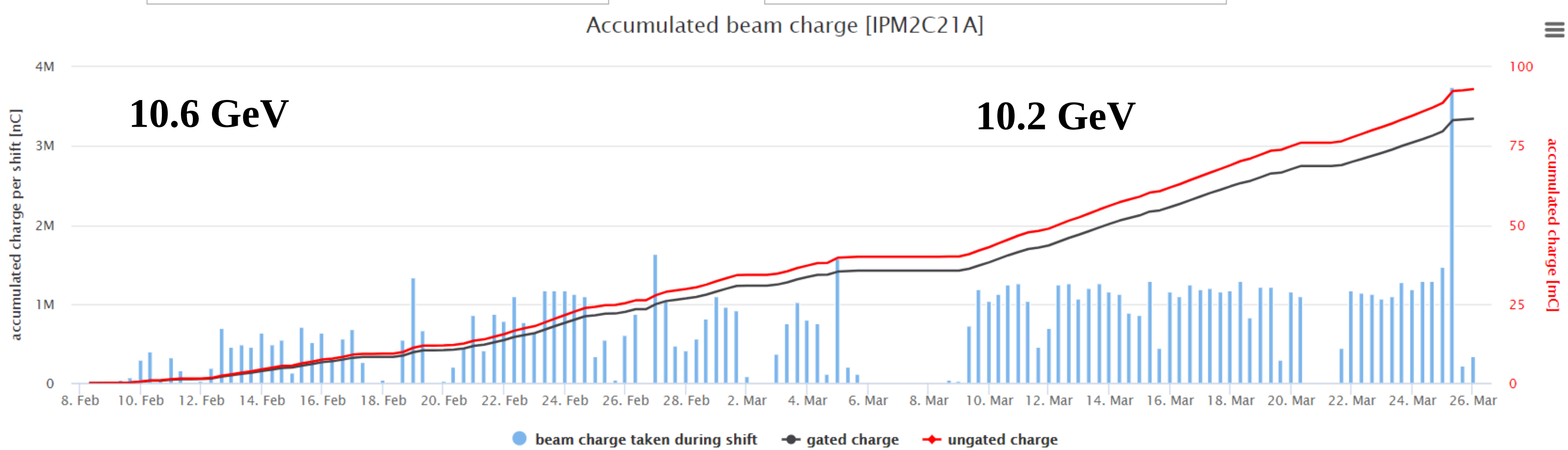
Status of data processing:
- spring dataset calibrated
- “cooking” completed
- fall “final” calibrations underway
- winter: preliminary calibrations

43.3 B triggers collected at 3 different beam energies:
- 10.6 GeV (9.7 B) **spring**
- 10.2 GeV (11.7 B) **spring**
- 10.4 GeV (21.9 B – with 9 B torus outbending) **fall, winter**

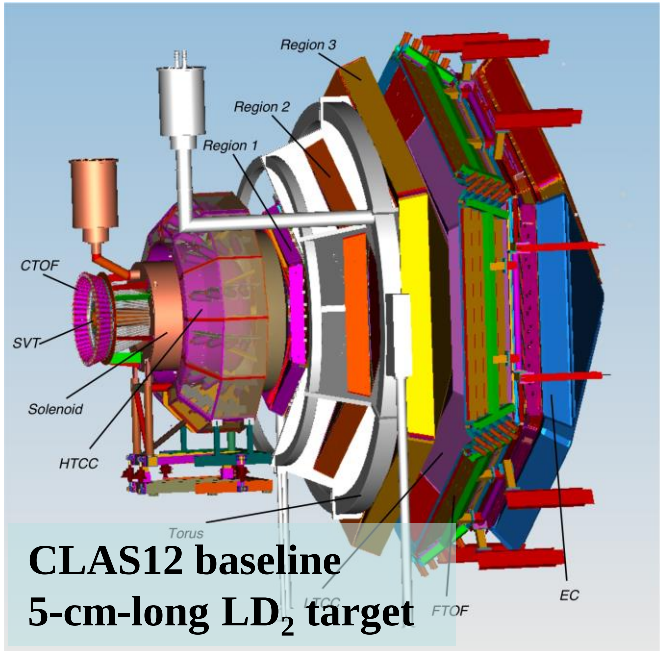
Average beam polarization ~86%

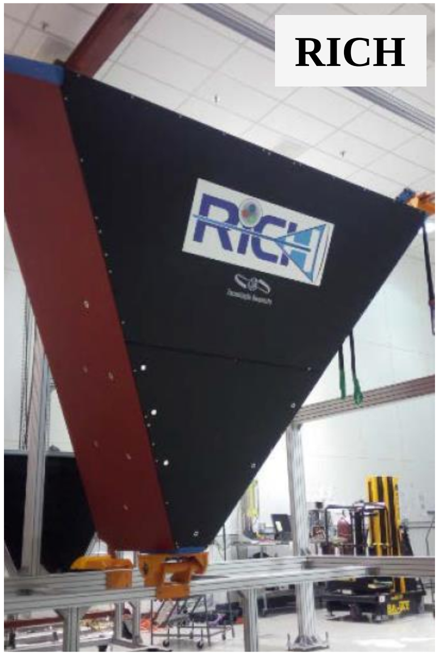
*All results presented here come from the **spring** dataset*
~50% of all the data taken

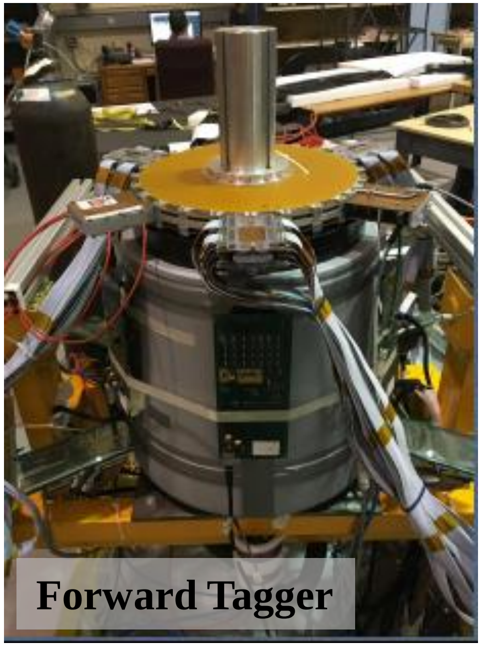
start date: 02/08/2019 end date: 03/25/2019



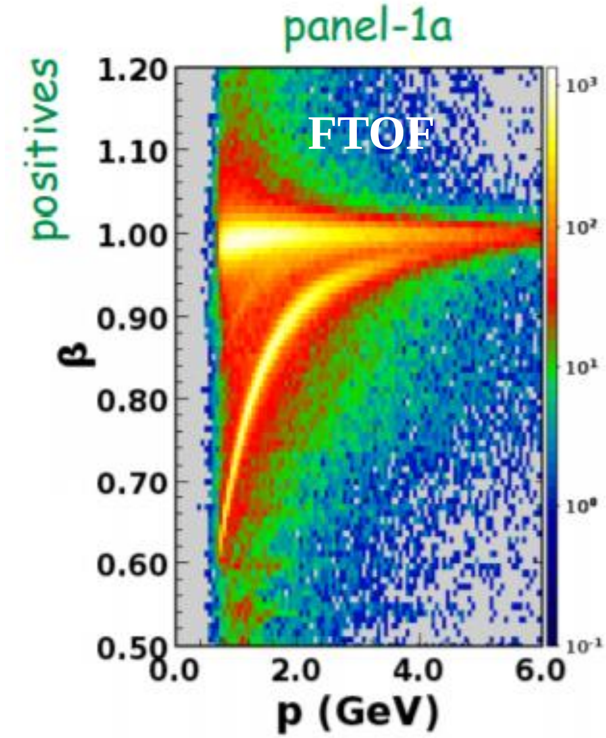
Experimental setup

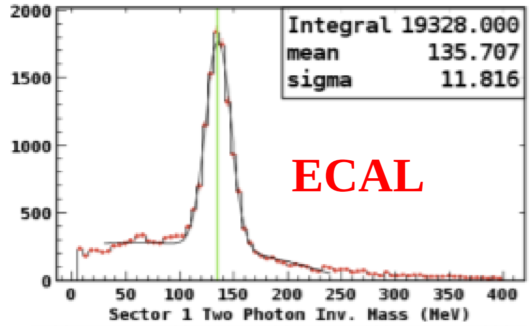




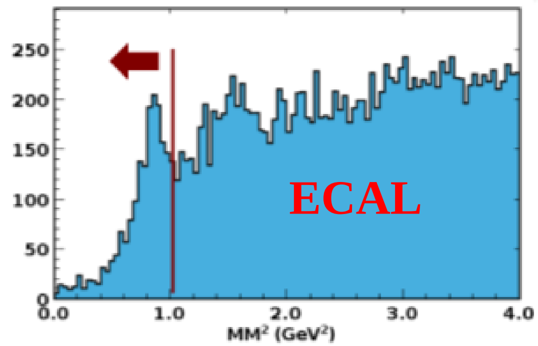


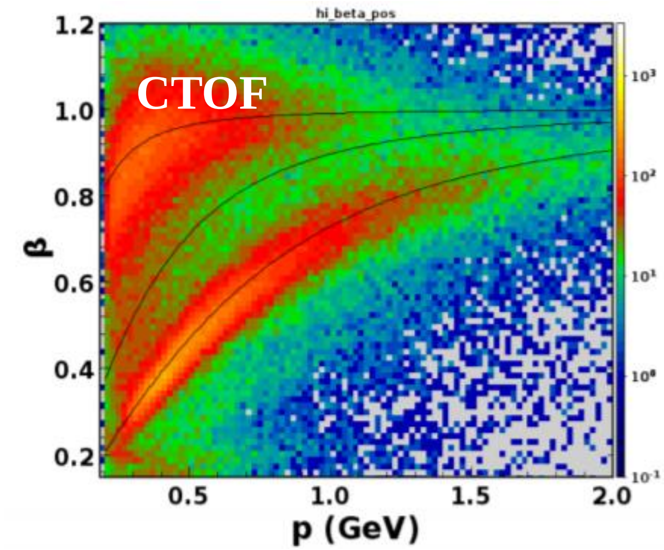
Data quality of RGB data

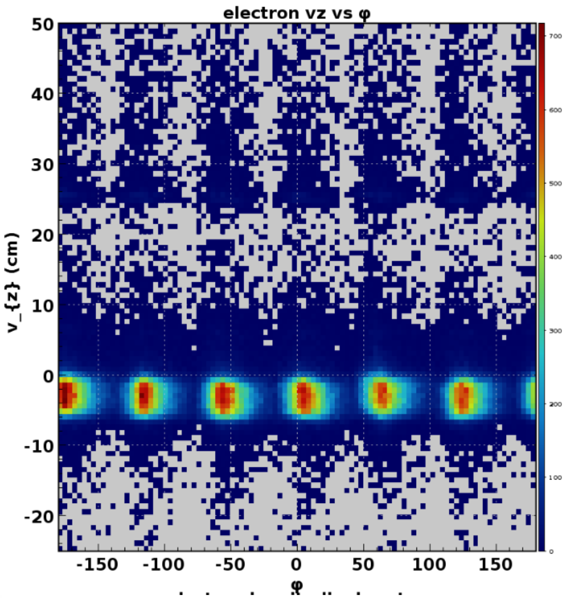


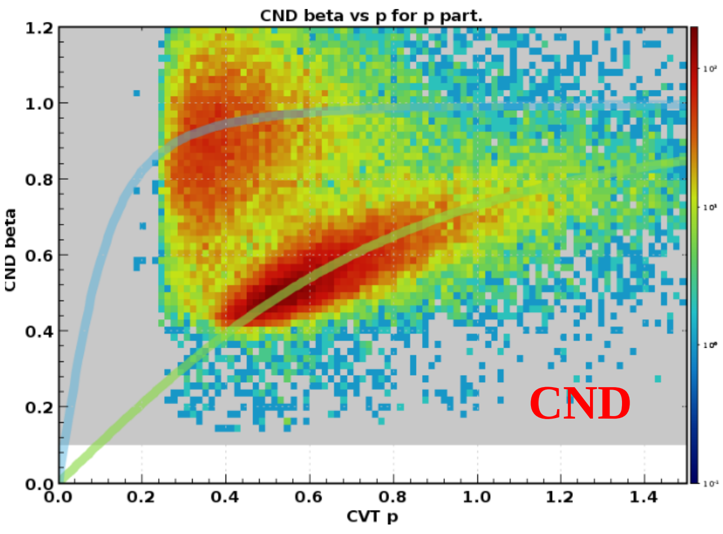


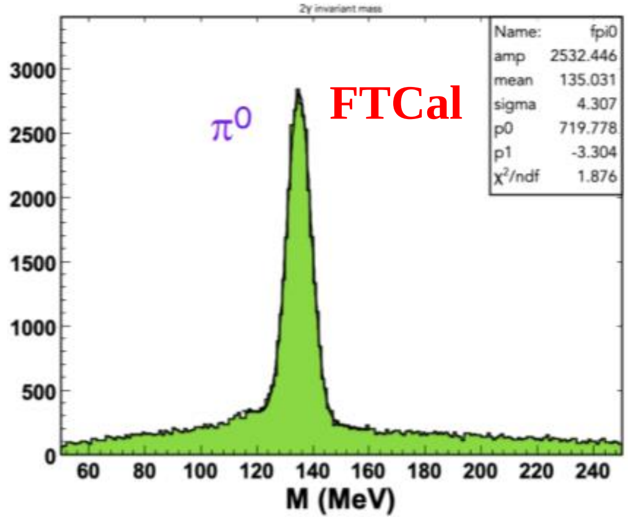
tagged neutrons d(e,e′π⁺)nn











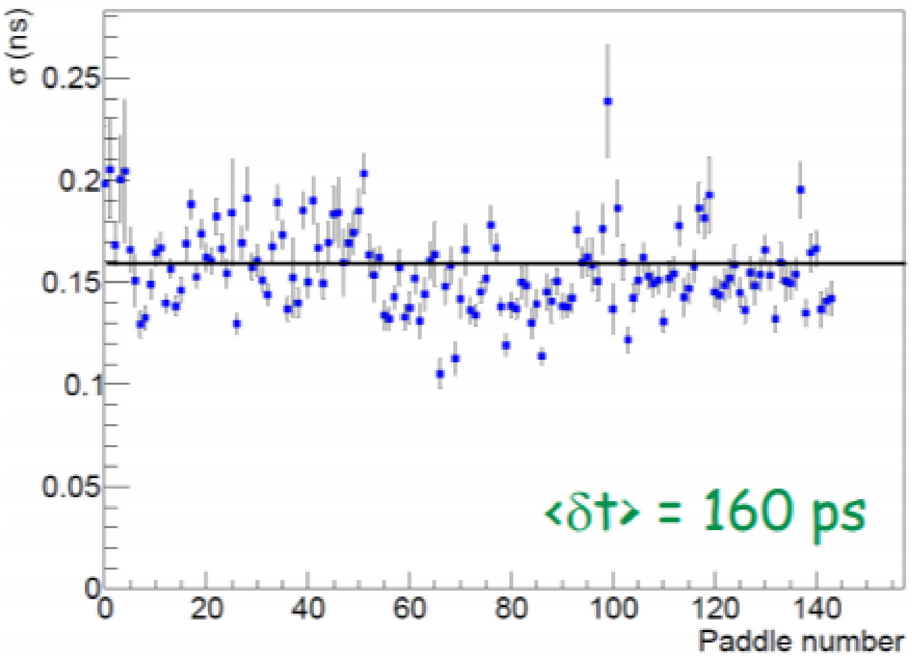
CND: performances with CLAS12 data

Purpose: detect the **recoiling neutron in nDVCS**
Requirements/performances**:**
- good neutron/photon separation for $0.2<p_n<1$ GeV/c
→ ~150 ps time resolution ✓ (~160 ps)
- momentum resolution $\delta p/p < 10\%$ ✓
- neutron detection efficiency ~10% ✓

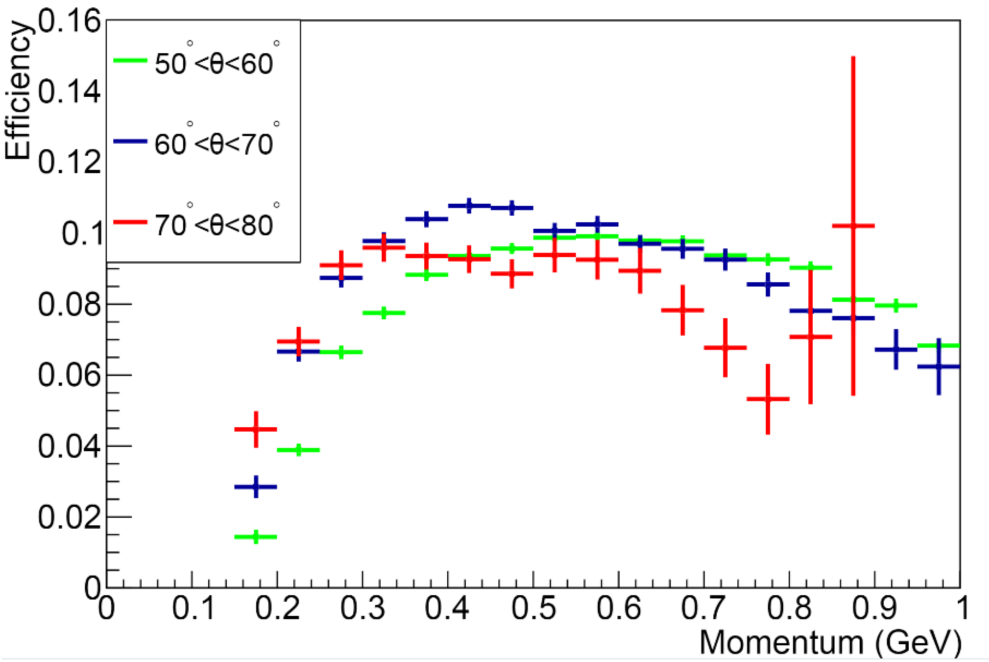
CND design: **scintillator barrel** - 3 radial layers, 48 bars per layer **coupled two-by-two** downstream by a **"u-turn" lightguide,** 144 long light guides with **PMTs** upstream

S.N. *et al.*, NIM A 904, 81 (2018)
P. Chatagnon *et al.*, NIM A 959 (2020) 163441

Timing resolution per paddle (RGB data)



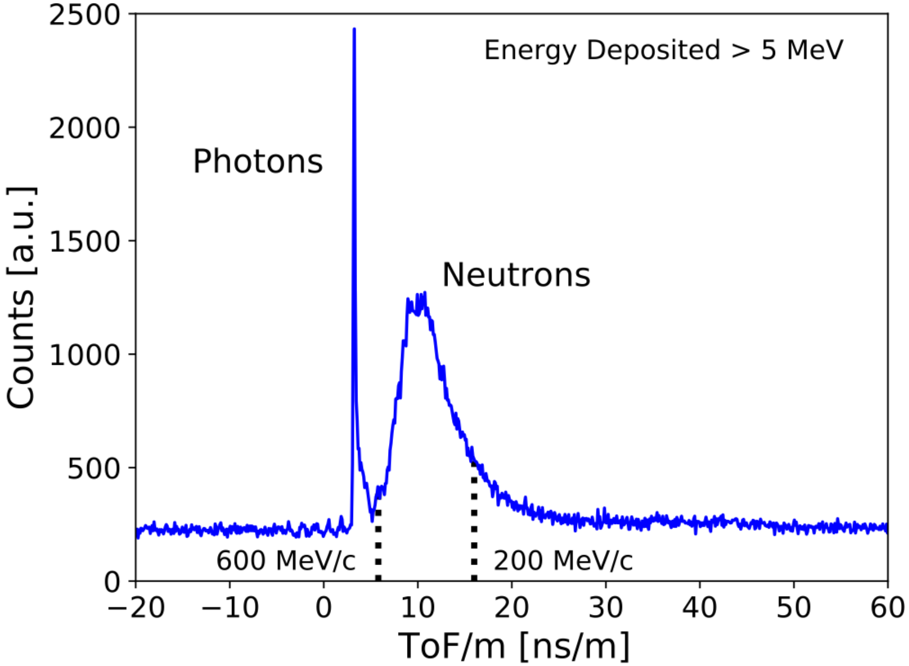
Neutron efficiency from ep→e'nπ+ (RGA data)

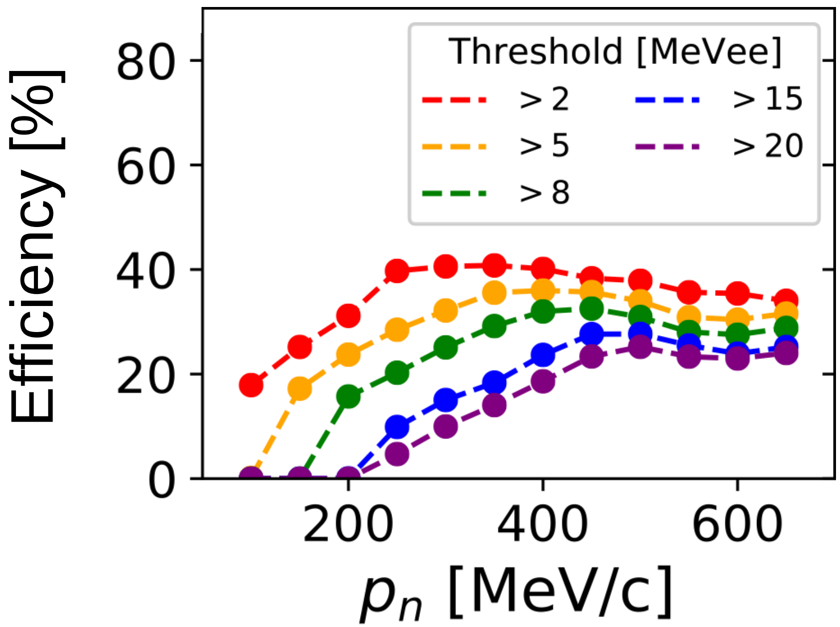


BAND: performance with CLAS12

Goal: detect recoil spectator neutrons from DIS on proton in deuterium

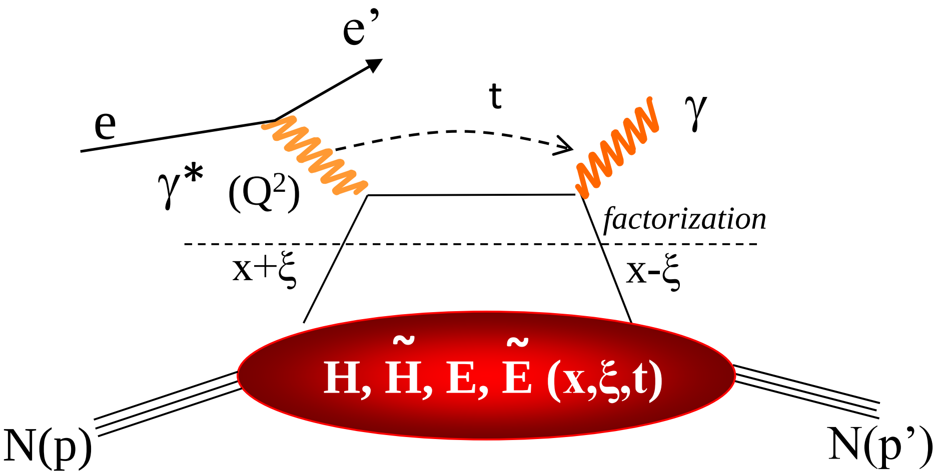
- requires photon separation for $p_n \in [0.2, 0.6]$ GeV/c
- requires neutron efficiency ~30%





E.P. Segarra et al., NIM A 978 (2020)

Interest of DVCS on the neutron



A combined analysis of DVCS observables for proton and neutron targets is necessary for flavor separation of GPDs

$$(H,E)_u(\xi,\xi,t) = \tfrac{9}{15}\left[4(H,E)_p(\xi,\xi,t) - (H,E)_n(\xi,\xi,t)\right]$$

$$(H,E)_d(\xi,\xi,t) = \tfrac{9}{15}\left[4(H,E)_n(\xi,\xi,t) - (H,E)_p(\xi,\xi,t)\right]$$

$$\frac{1}{2}\int_{-1}^{1} x dx (H(x,\xi,t=0) + E(x,\xi,t=0)) = J = \frac{1}{2}\Delta\Sigma + \Delta L$$

The beam-spin asymmetry for nDVCS is the most sensitive observable to the GPD E → Ji's sum rule for Quarks' Angular Momentum

Polarized beam, unpolarized target:

$$\Delta\sigma_{LU} \sim \sin\phi \,\mathrm{Im}\{F_1\mathcal{H} + \xi(F_1+F_2)\tilde{\mathcal{H}} + kF_2\mathcal{E}\}d\phi \Rightarrow \mathrm{Im}\{\mathcal{H}_n, \tilde{\mathcal{H}}_n, \mathcal{E}_n\}$$

Unpolarized beam, transversely polarized target:

$$\Delta\sigma_{UT} \sim \cos\phi \,\mathrm{Im}\{k(F_2\mathcal{H} - F_1\mathcal{E}) + \ldots\}d\phi \Rightarrow \mathrm{Im}\{\mathcal{H}_p, \mathcal{E}_p\}$$

Neutron
Proton

The BSA for nDVCS:

- is complementary to the TSA for pDVCS on transverse target, aiming at *E*
- depends strongly on the kinematics → wide coverage needed
- is smaller than for pDVCS → more beam time needed to achieve reasonable statistics

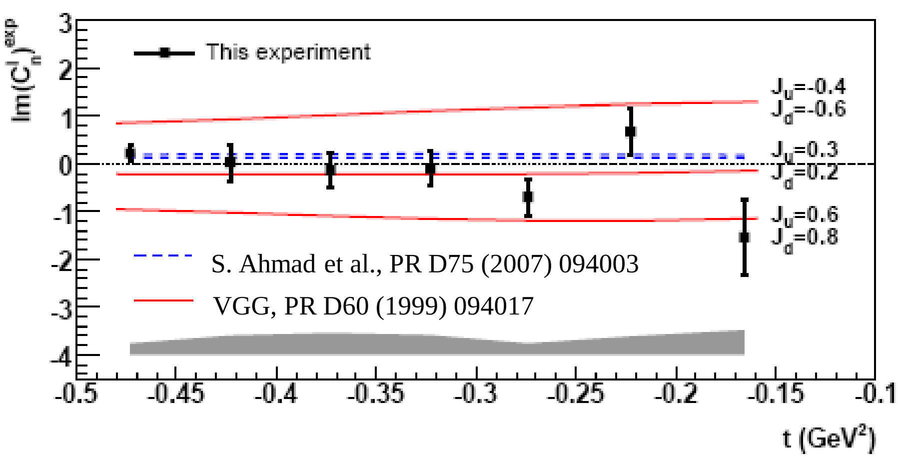
$\vec{e}d \rightarrow e\gamma(np)$

DVCS on the neutron in Hall A at 6 GeV

$$D(e,e'\gamma)X - H(e,e'\gamma)X = n(e,e'\gamma)n + d(e,e'\gamma)d + \ldots$$

$$\Delta\sigma_{LU} \sim \sin\phi \; \mathrm{Im}\{F_1\mathcal{H} + \xi(F_1+F_2)\widetilde{\mathcal{H}} - kF_2\mathcal{E}\}$$

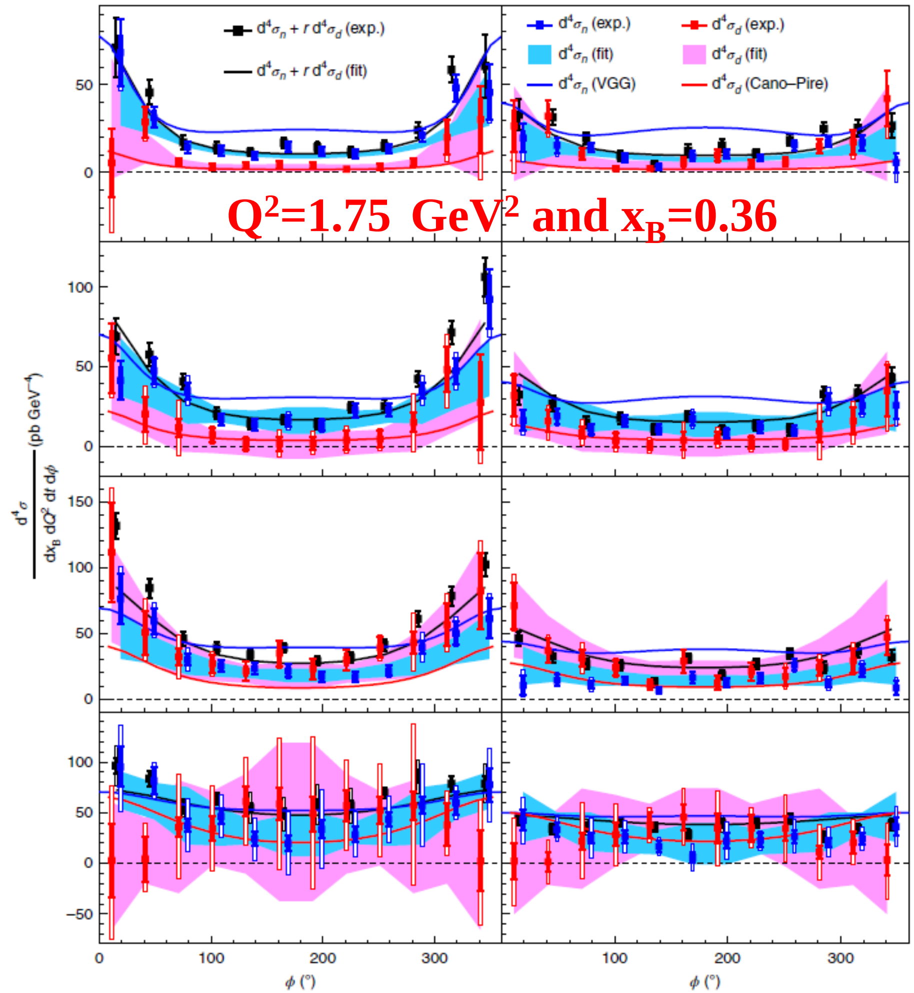
M. Mazouz et al., PRL 99 (2007) 242501



Q^2=1.9 GeV^2 and x_B=0.36

- **E03-106**: **First-time measurement of $\Delta\sigma_{LU}$ for nDVCS, *no neutron detection***
- **model-dependent extraction of J_u, J_d**

$$\frac{1}{2}\int_{-1}^{1} x dx (H(x,\xi,t=0) + E(x,\xi,t=0)) = J$$



Q^2=1.75 GeV^2 and x_B=0.36

Hall-A experiment E08-025 (2010)

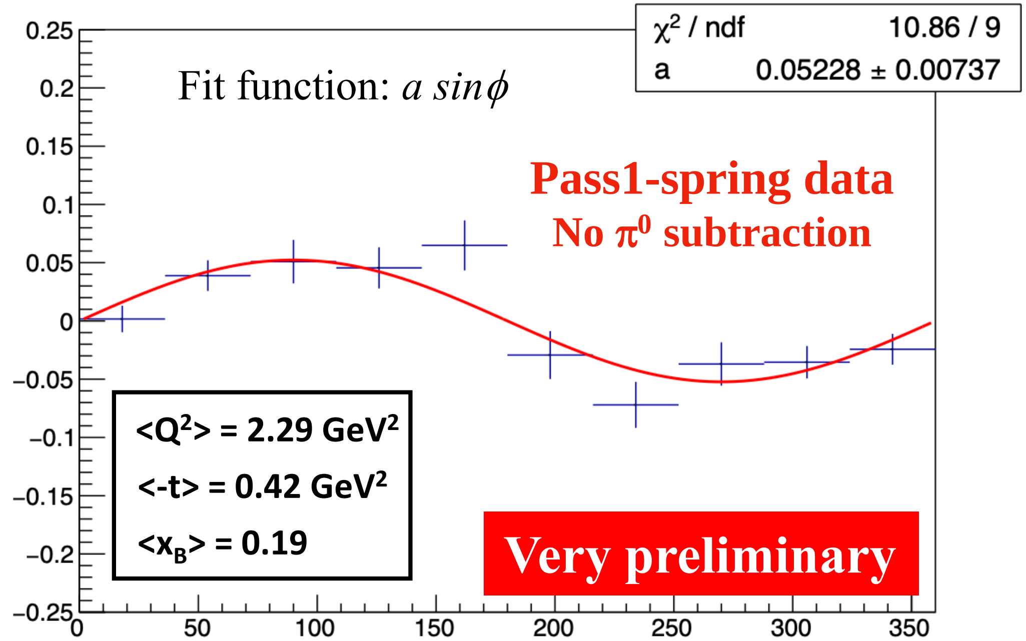
- Beam-energy « Rosenbluth » separation of nDVCS CS using an LD2 target and two different beam energies
- First observation of non-zero nDVCS CS
- **M. Benali et al., Nature 16 (2020)**

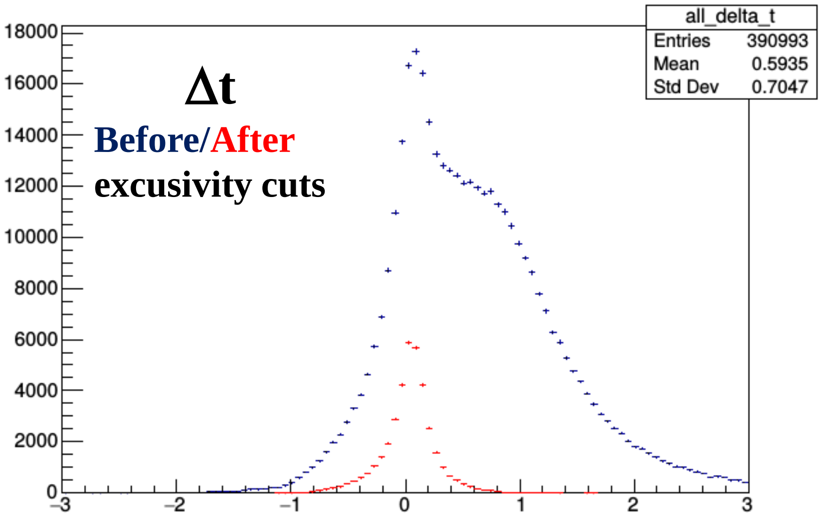
nDVCS with RGB data

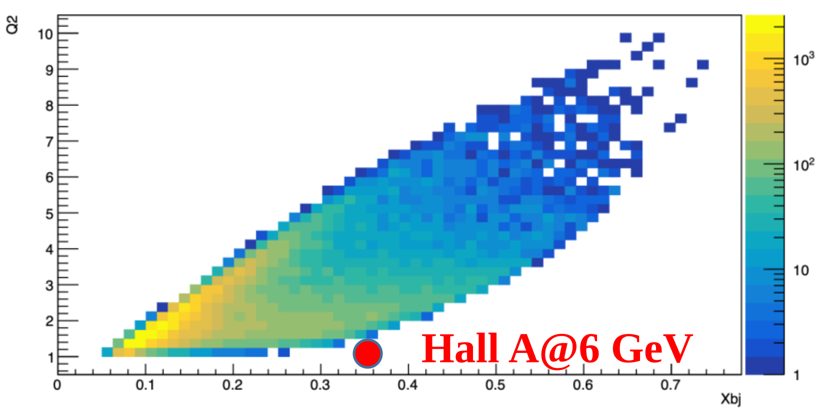
$\vec{e}d \to en\gamma(p)$

- Exclusive final state selection: events with at least one **electron, neutron, photon** (PID + kinematic cuts)
- The chosen combination in each event is the one satisfying at best the exclusivity criteria on:

M_X, p_X, E_X ($ed \to en\gamma X$), Δt, $\Delta\phi$, $\theta_{\gamma X}$





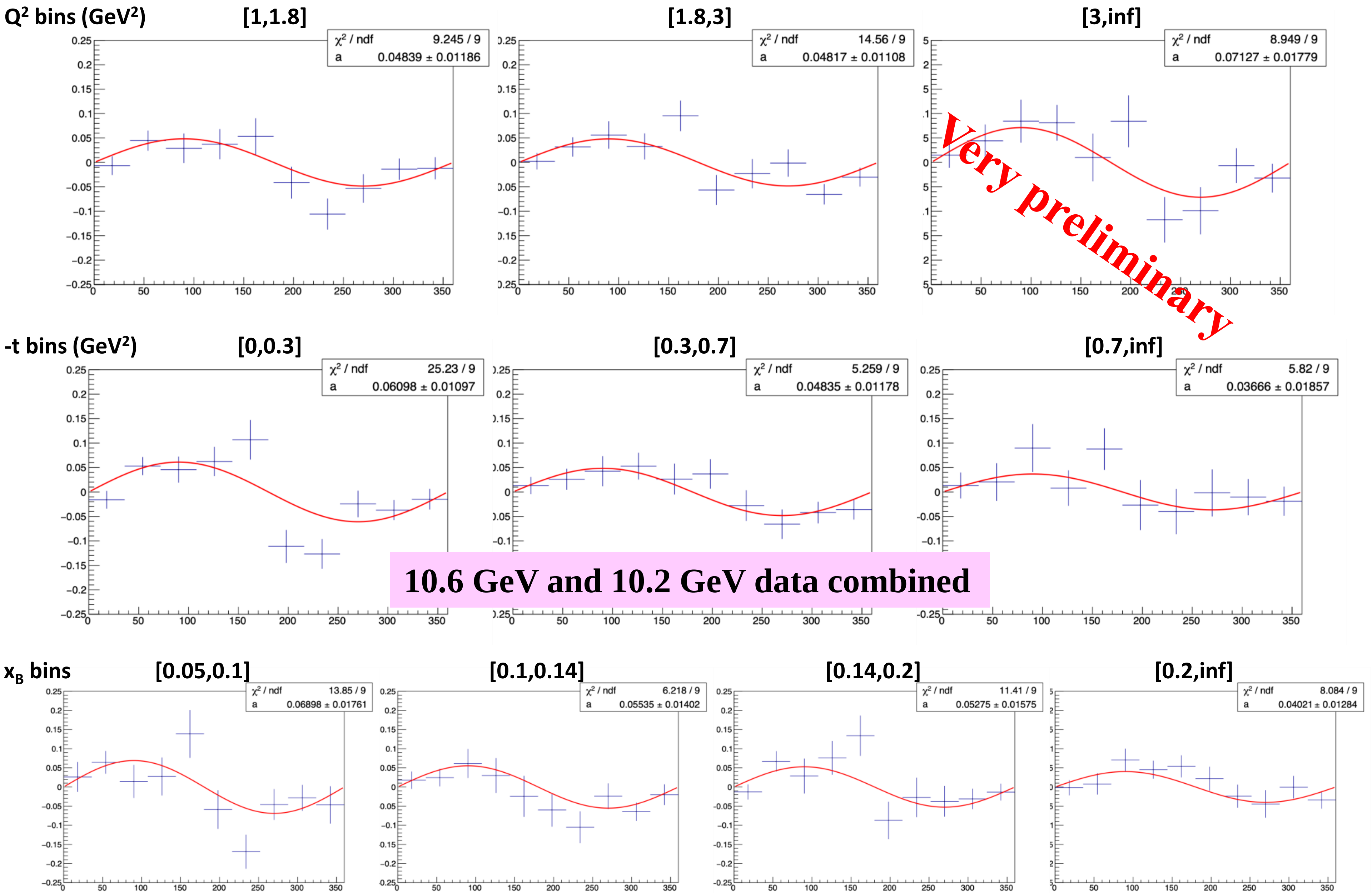


- 55188 nDVCS event candidates
- Raw BSA integrated over all kinematics and topologies
- Includes **a charged particle veto** based on CND and CTOF information: remove proton contamination, due to CVT inefficiencies, from neutrals sample (tests and improvements are ongoing)
- Work ongoing on π^0 subtraction, fiducial cuts, etc…

A. Hobart, K. Price, S. N. (IJCLab Orsay)

nDVCS raw BSA vs ϕ in 1-dim. bins

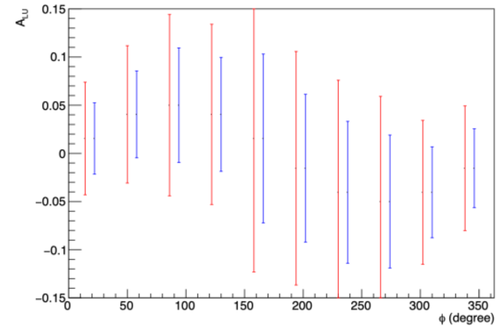
First-time measurement



Q^2 bins

Projections for nDVCS vs ϕ in 3-dim. bins

[4,inf]

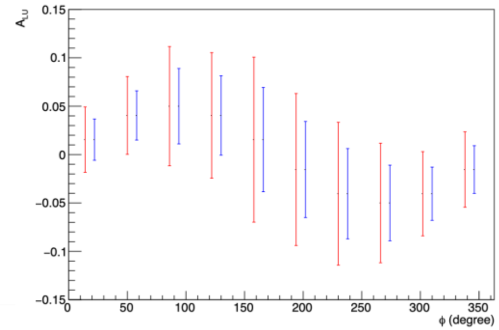


-t bin [0,0.35] GeV^2

Data-driven projections for the expected uncertainties, starting from current yield per bin (Y):

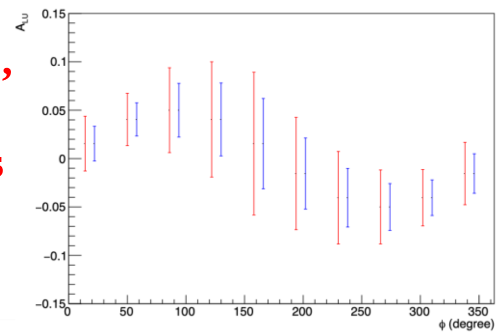
- **expected yield for all existing RGB data (Y*2)**
- **expected yield for 90 PAC days (Y*4)**
- **$A^{\sin\phi}$=0.05 for all (Q^2, x_B, -t) bins**

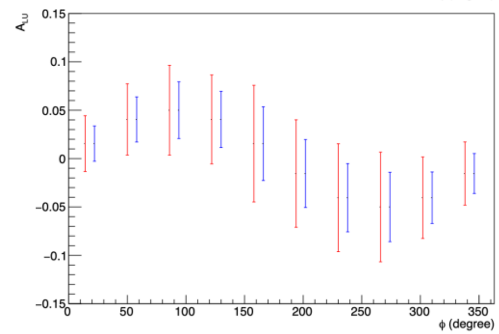
[3,4]



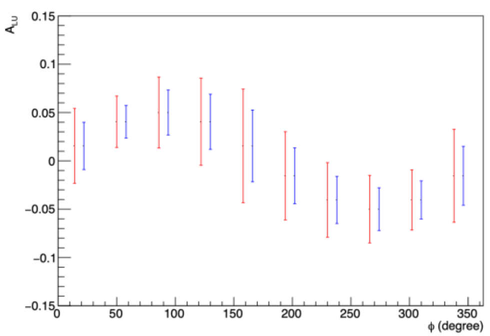
Existing data:
Relative uncertainty >100%, worse at high Q^2, low –t, central ϕ, crucial kinematics for GPDs and Ji’s sum rule

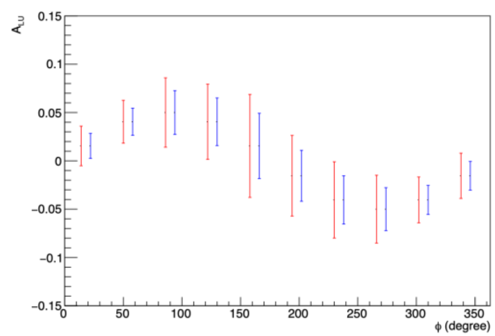
[2,3]

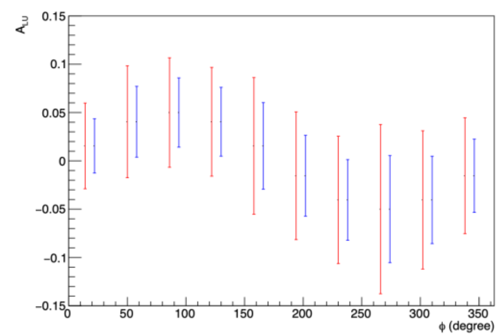




[1,2]







[0.05,0.1] [0.1,0.17] [0.17,inf] **x_B bins**

Q² bins

Projections for nDVCS vs ϕ in 3-dim. bins

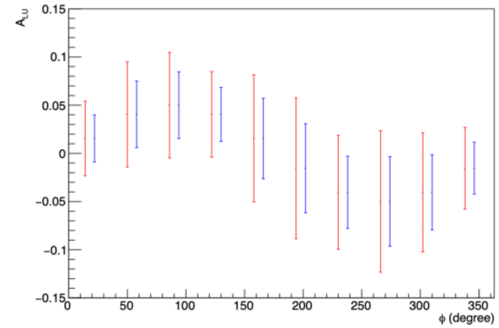
-t bin [0.35,inf] GeV²

Data-driven projections for the expected uncertainties, starting from current yield per bin (Y):

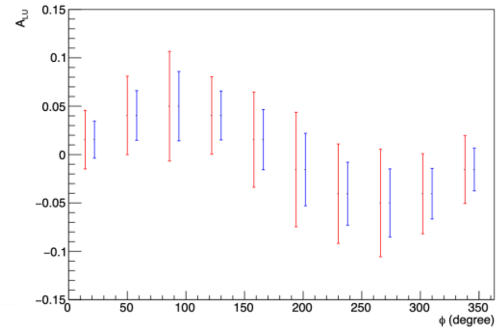
- **expected yield for all existing RGB data (Y*2)**
- **expected yield for 90 PAC days (Y*4)**
- **$A^{\sin\phi}$=0.05 for all (Q^2, x_B, -t) bins**

Existing data:
Relative uncertainty >100%, worse at high Q^2, low –t, central ϕ, crucial kinematics for GPDs and Ji's sum rule

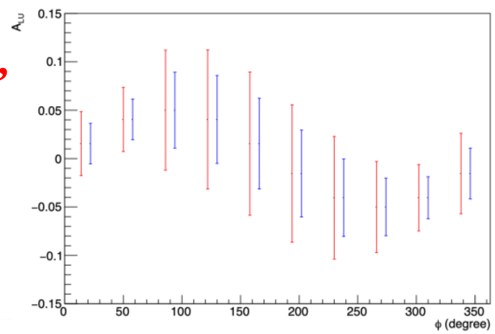
[4,inf]

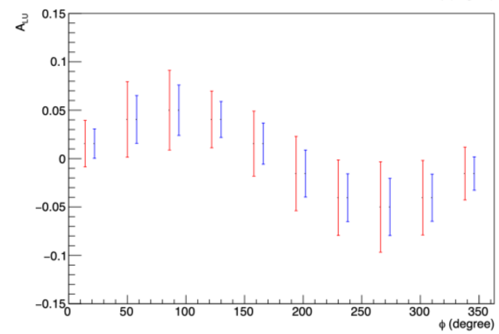


[3,4]

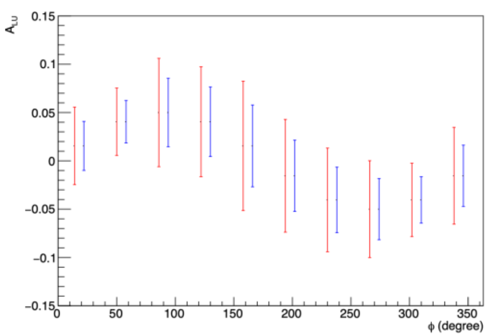


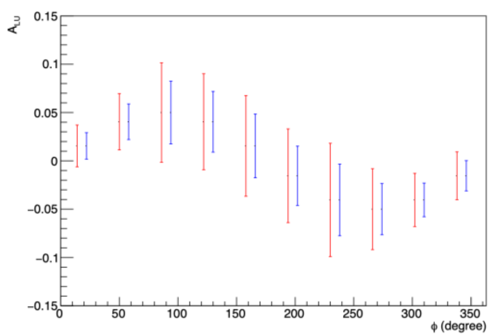
[2,3]

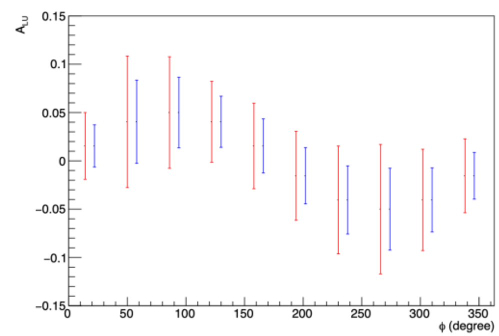




[1,2]







[0.05,0.1] [0.1,0.17] [0.17,inf]

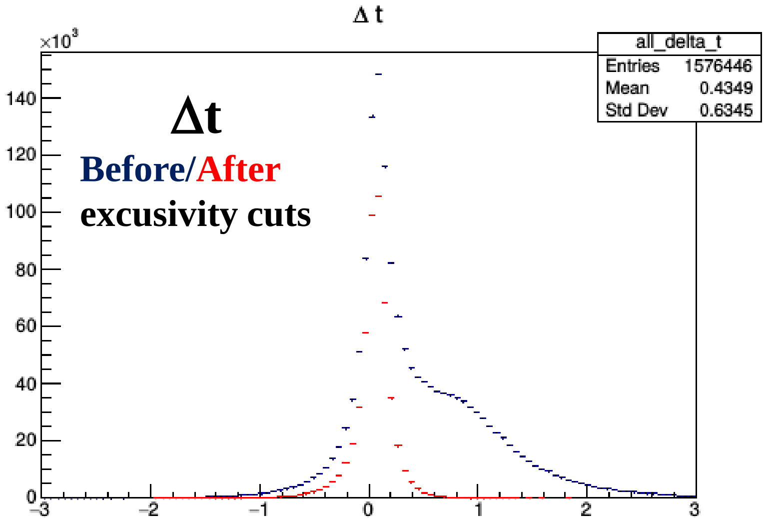
x_B bins

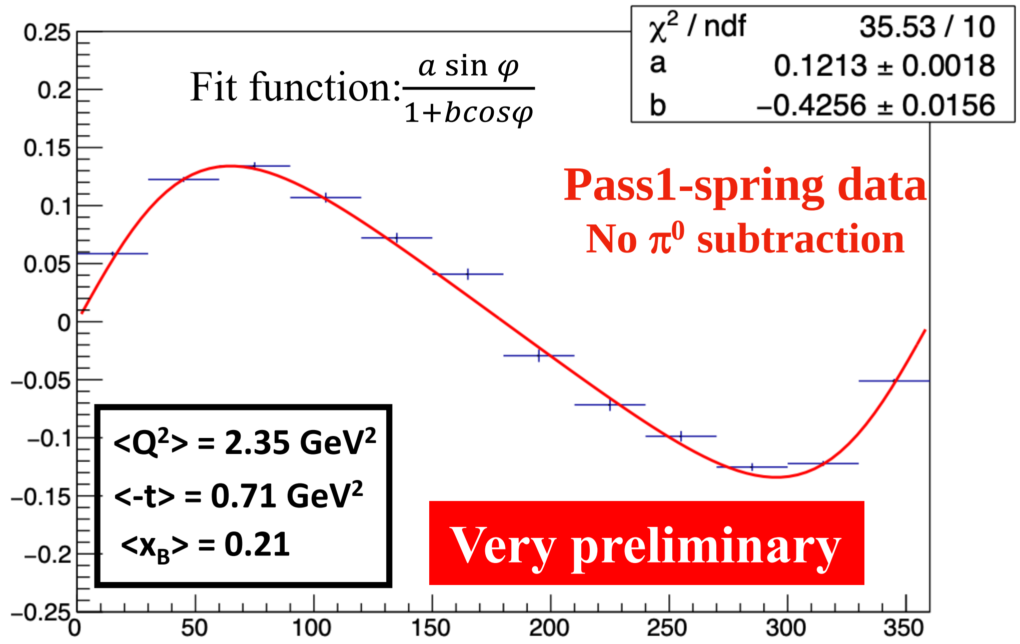
Incoherent pDVCS on deuterium

$\vec{e}d \rightarrow ep\gamma(n)$

- Events with at least one **electron, proton, photon** are selected (PID + kinematic cuts)
- The chosen combination in each event is the one satisfying at best the exclusivity criteria:

M_X, p_X, E_X ($ed \rightarrow ep\gamma X$), Δt, $\Delta\phi$, $\theta_{\gamma X}$





- 2020720 identified pDVCS candidates
- Raw BSA integrated over all kinematics and detection topologies
- **Compatible with raw BSA from pDVCS in RGA**
- **nDVCS and pDVCS yields scale as expected (CS, efficiency)**
- Work ongoing on π^0 subtraction, fiducial cuts, etc…

Interest of pDVCS on deuterium:

- In itself: nuclear medium effects on proton structure
- To evaluate FSI for nDVCS, comparing to free pDVCS

A. Hobart, S. N. (IJCLab Orsay)

pDVCS raw BSA vs ϕ in 3-dim. bins

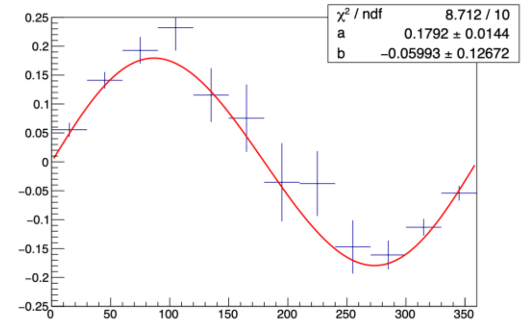
Q^2 bins (GeV^2)

First-time measurement

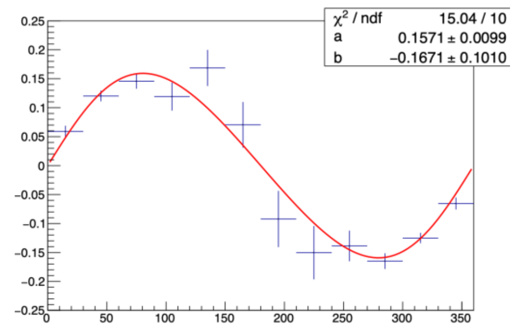
-t bin [0,0.2] (GeV^2)

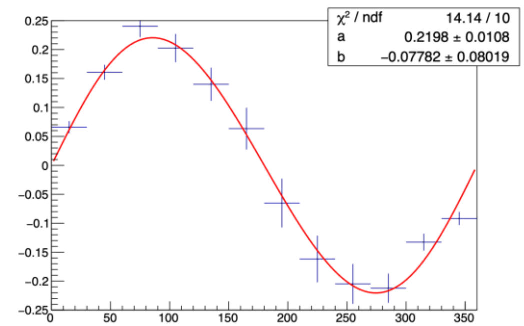
Very preliminary

[3,inf]

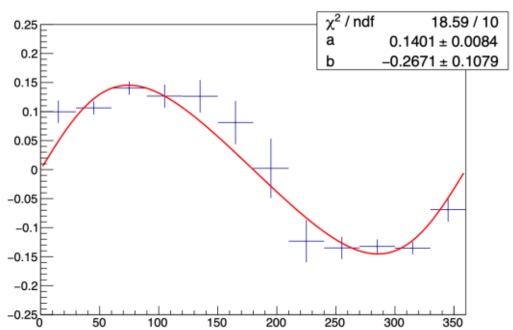


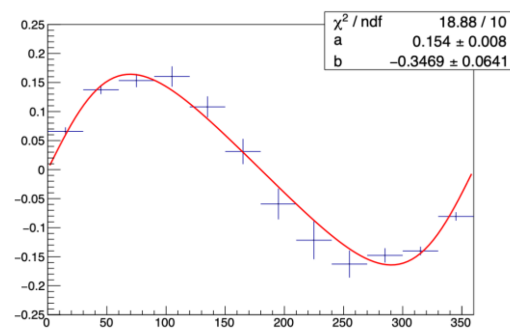
[2,3]

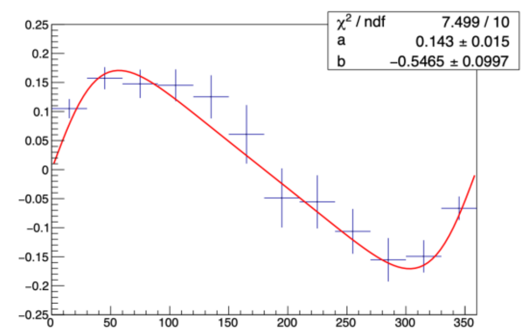




[1,2]







[0.05,0.1] [0.1,0.17] [0.17,inf] **x_B bins**

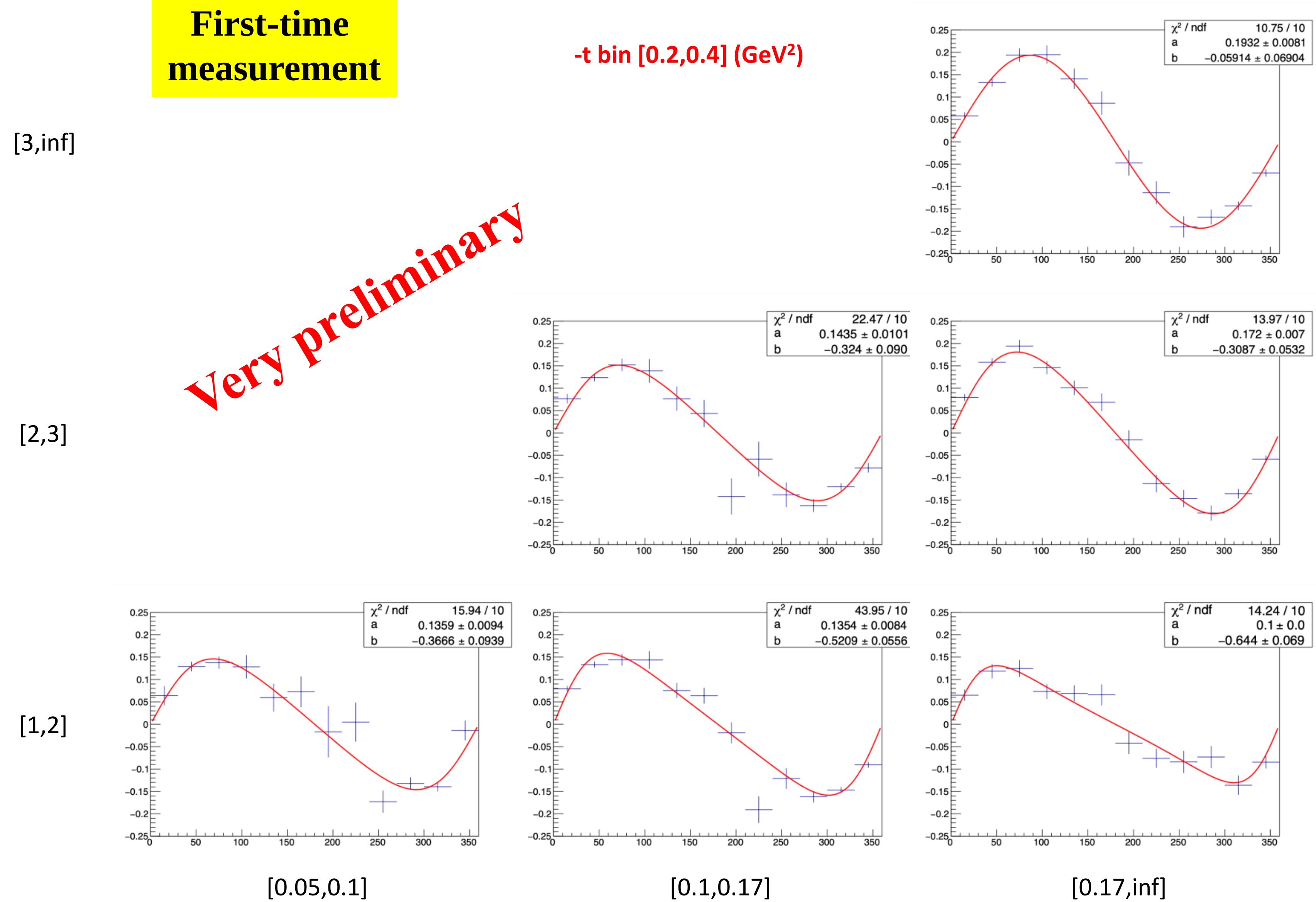
pDVCS raw BSA vs ϕ in 3-dim. bins

Q^2 bins (GeV^2)

First-time measurement

-t bin [0.2,0.4] (GeV^2)

Very preliminary



x_B bins

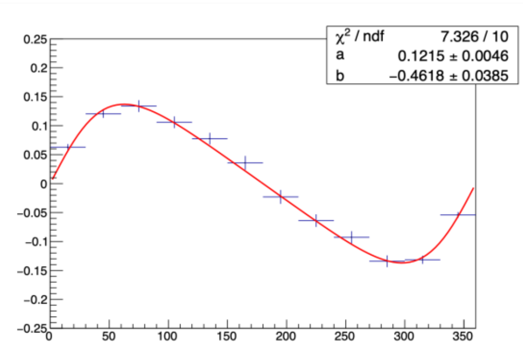
pDVCS raw BSA vs ϕ in 3-dim. bins

Q^2 bins (GeV^2)

First-time measurement

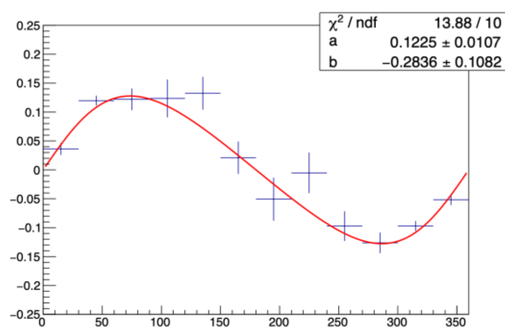
-t bin [0.4,inf] (GeV^2)

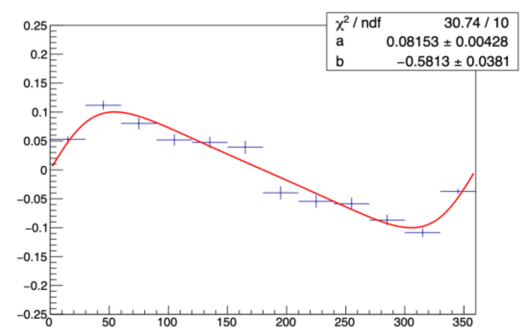
[3,inf]



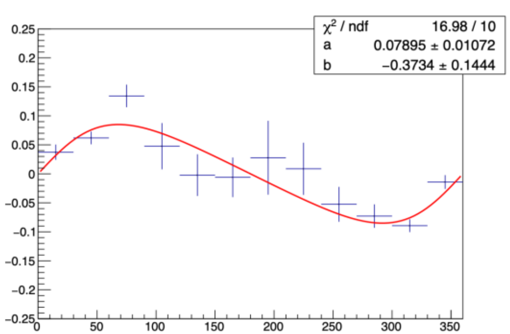
Very preliminary

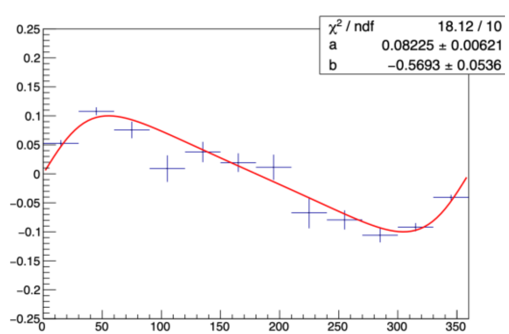
[2,3]

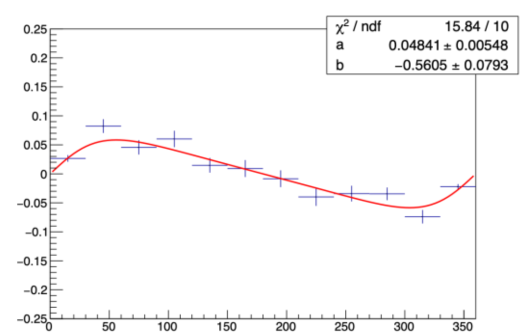




[1,2]







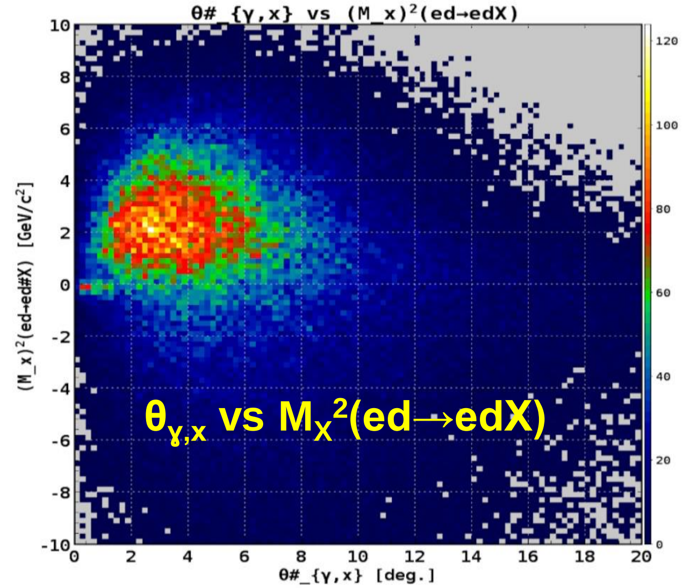
[0.05,0.1] [0.1,0.17] [0.17,inf] **x_B bins**

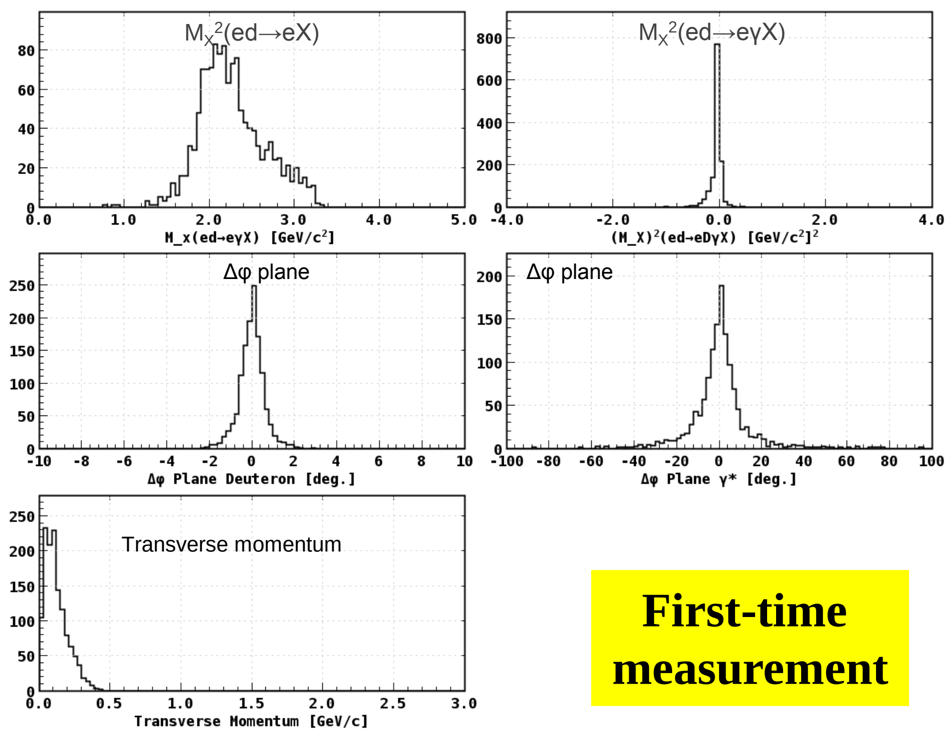
J. Dickovick,
A. Biselli
B. (Fairfield U.)

Coherent Deuteron DVCS

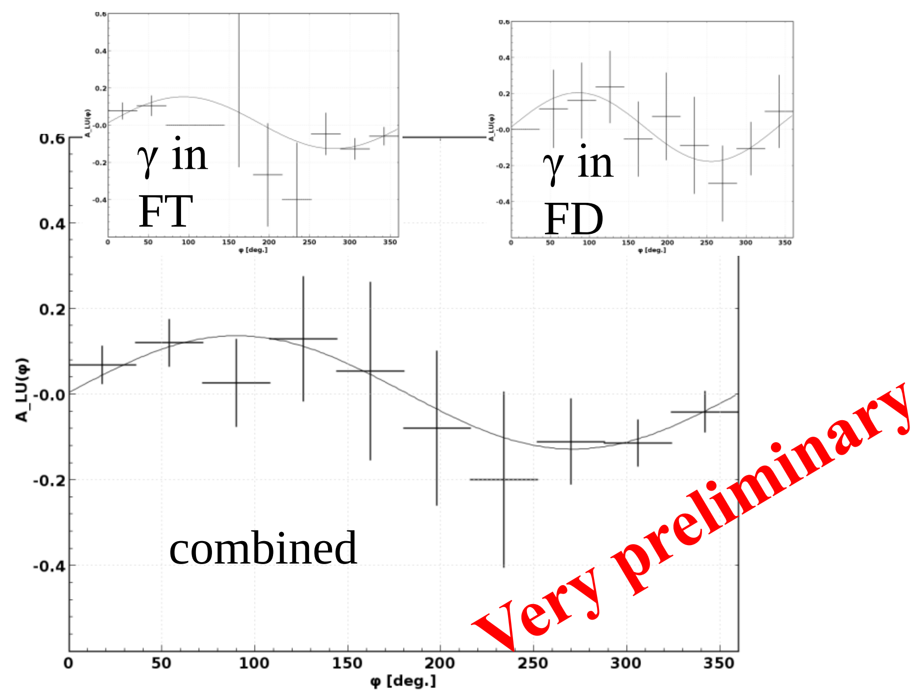
$\vec{e}d \rightarrow ed\gamma$

- 35 runs - pass0v16 ("**DNP cooking", ~25% of spring)**
- $ed \rightarrow ed\gamma$
- Exclusivity cuts for events with γ in FT:
  - $E_X(ed \rightarrow ed\gamma X) < 2$ GeV
  - $p_t < 0.5$ GeV/c
  - 2-dimensional cut on $\theta_{\gamma,x}$ vs $M_X^2(ed \rightarrow edX)$
- Similar cuts for FD





First-time measurement

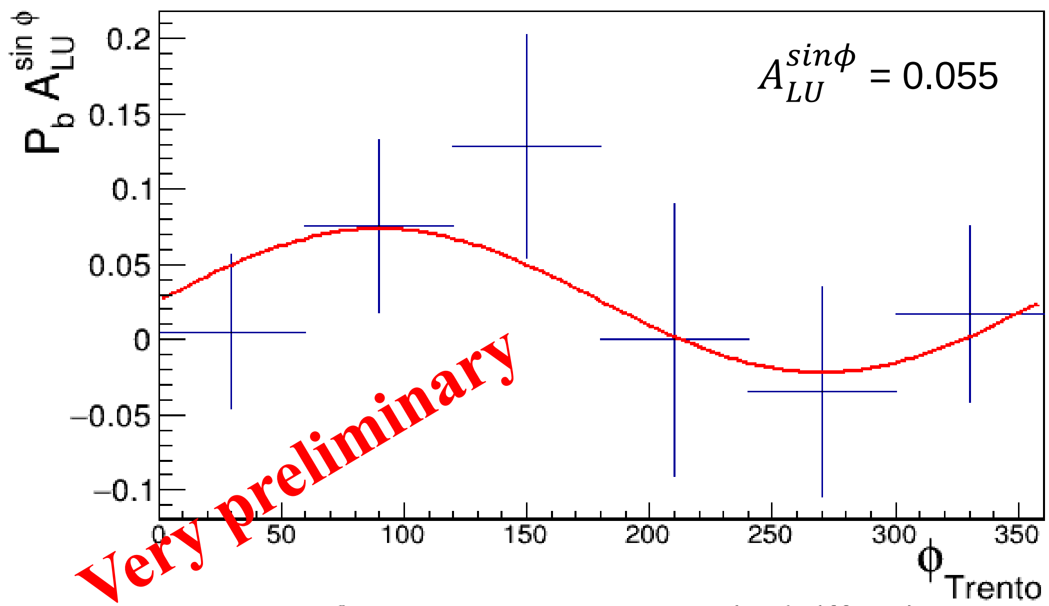


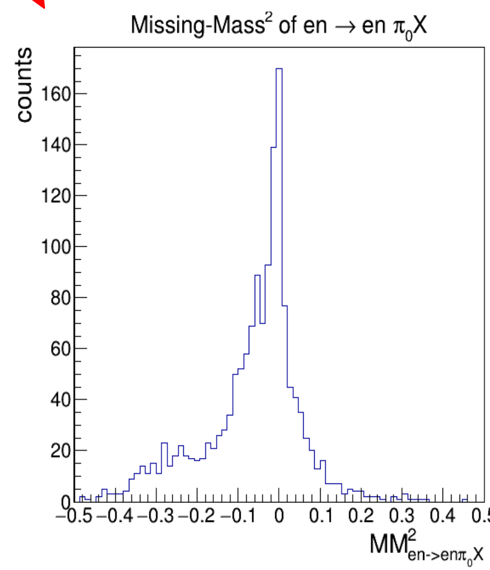
Hard exclusive π_0 production on the neutron

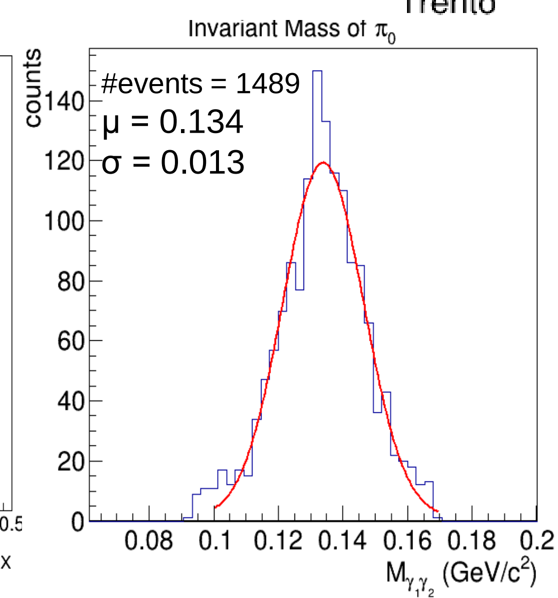
Paul Naidoo & Daria Sokhan – University of Glasgow

- **Channel: eD → e'n'π_0($p_{spect.}$)**
- Motivation:
  - DVCS and DVMP with proton and neutron targets needed for **flavour separation of GPDs**
  - Exclusive π_0 production is sensitive to **transversity** GPDs
- Cuts (work in progress):
  - 3σ π_0 mass
  - $\theta_{e\gamma} > 8^{\circ}$
  - $\delta\Phi_{Trento} < 5^{\circ}$
  - $MP_{eD\to e'p'\gamma\gamma} < 0.7$GeV
  - $Q^2 > 1$ GeV^2/c^4
  - $-t < 1$ GeV^2/c^4
- Optimisation of exclusivity cuts ongoing.
- More statistics needed for higher-precision result.

First-time measurement



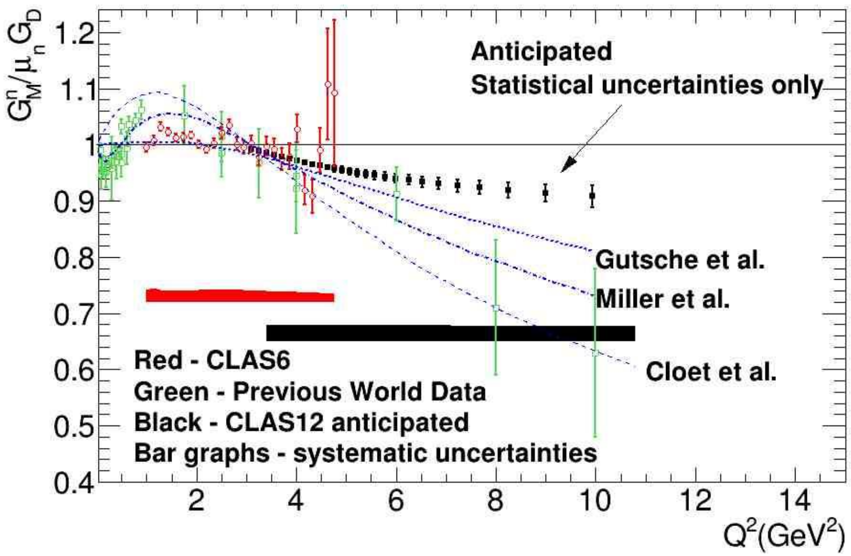




Measurement of the Neutron Magnetic Form Factor G_M^n at High Q^2 Using the Ratio Method on Deuterium

L.Baashen (FIU), B.A. Raue (FIU), G. Gilfoyle (Richmond), L.C. Smith (UVA)

Goal: **Extract G_M^n at high Q^2 using the ratio of quasi-elastic e-n and quasi-elastic e-p on deuteron:** $R = \frac{d(e,e'n)p}{d(e,e'p)n}$



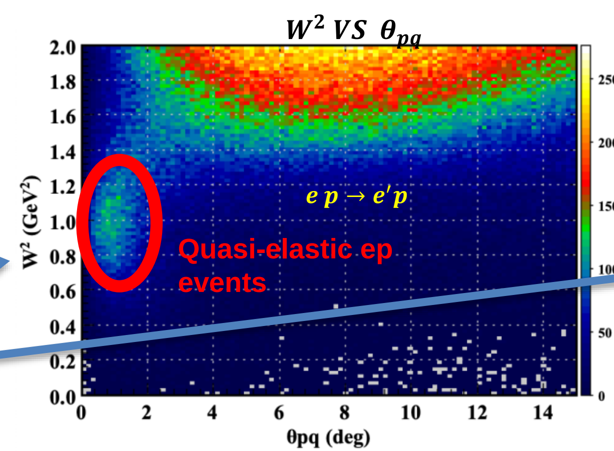
- The neutron magnetic form factor is a fundamental observable related to the distribution of magnetization in the nucleon.
- Figure to the left shows world's data for G^n_M including anticipated results.
- Curves show recent theoretical calculations from Gutsche et al. (PRD 97, 054011, 2018) and Miller et al. (arXiv 1912.07797 [nucl-th], 2020).
- Continued strong theory reported by JLab TAC.
- **Additional RGB run time will extend the reach in Q^2 and improve the statistical precision at high Q^2.**

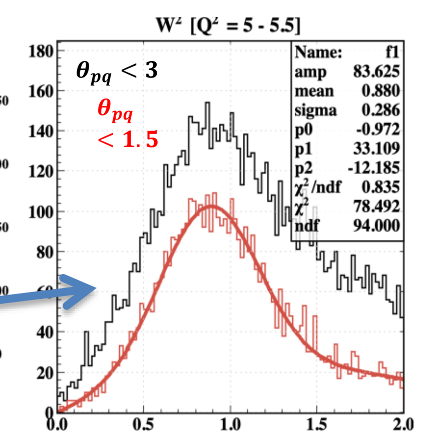
Analysis status for quasi-elastic e-p :

- Using RG-B data from spring 2019 (pass 1 cooking) ~ 223 production runs.
- Select tracks with one electron and one proton in Forward Detector.

Quasi-elastic event selection:

- Cut on $W^2 < 2$ GeV^2
- Cut on θ_{pq} (angle between the virtual photon and scattered nucleon 3-momenta) to reduce inelastic background.





Quasi-elastic ep event at Q^2 = 5.25 GeV^2

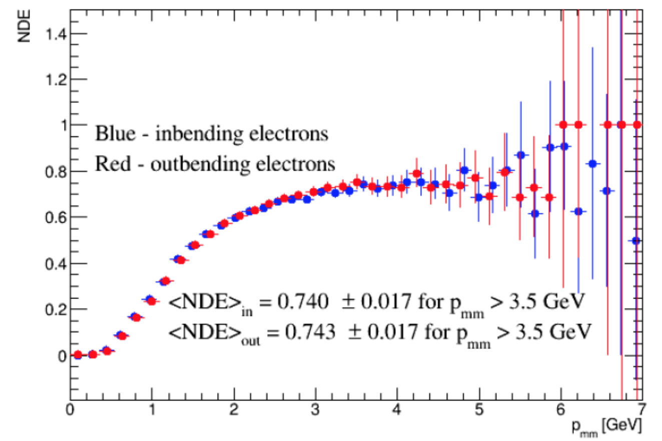
Measuring the neutron detection efficiency (NDE) needed for quasi-elastic e-n $e\,D \rightarrow e'\,n\,(p)$

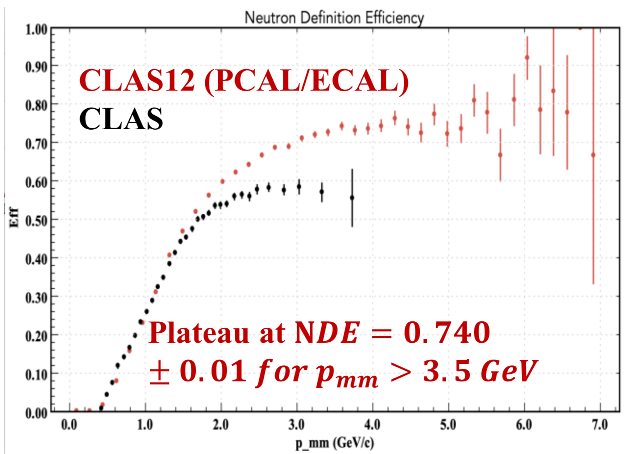
Analysis status:

- Using RG-A data from fall 2018 (pass 1 cooking) ~ 359 runs
- Use $ep \rightarrow e'\pi^{+}(n\,)$ as a source of tagged neutrons in the calorimeter
- NDE ~ 0.74 at the plateau (p_{mm} > 3.5 GeV) for outbending and inbending electrons
- CLAS12 measurement reaches higher efficiency thanks to PCAL.

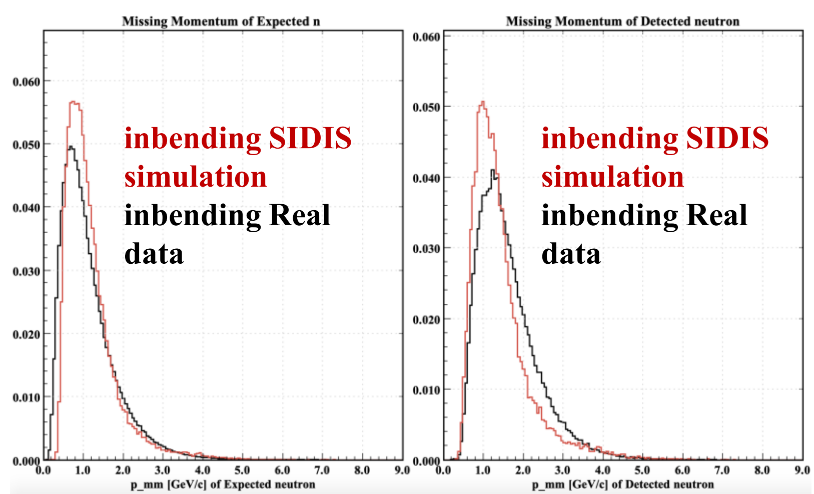
Next steps:

Investigating the accuracy of both the numerator and denominator of the efficiency ratio to determine the shape of the background in simulation.





Simulate events using SIDIS and A0/MAID2000 event generators. Preliminary comparison with data from the SIDIS simulation is shown here.

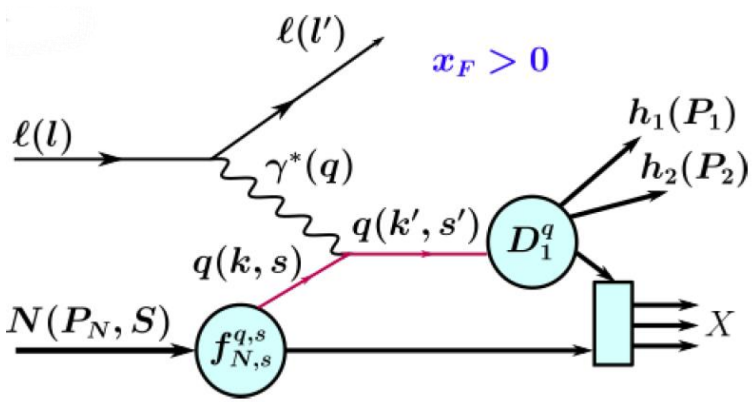


Di-hadron Multiplicity

e N → e' π+ π- X

Number of di-hadron pairs per DIS electron

$$M(x_B, z, M_{\pi\pi}; Q^2) = \frac{d\sigma^{dh} / dx_B dz dM_{\pi\pi} dQ^2}{d\sigma^{DIS} / dx_B dQ^2}$$



$$d\sigma^{dh} \propto \sum_q f_{1,q}(x_B) D_{1,q}^{dh}(z, M_{\pi\pi})$$

Di-hadron unpolarized Fragmentation Function (FF)
It enters in the denominator of every asymmetry

Assuming isospin symmetry, the analysis of hydrogen and deuterium data allows the extraction of u and d FF

$$D_{1,u}^{dh} = 3\frac{M^p\left(\frac{4}{9}f_{1,u} + \frac{1}{9}f_{1,d}\right) - \frac{1}{9}M^d\left(f_{1,u} + f_{1,d}\right)}{K_f f_{1,u}}$$

$$D_{1,d}^{dh} = 3\frac{\frac{4}{9}M^d\left(f_{1,u} + f_{1,d}\right) - M^p\left(\frac{4}{9}f_{1,u} + \frac{1}{9}f_{1,d}\right)}{K_f f_{1,d}}$$

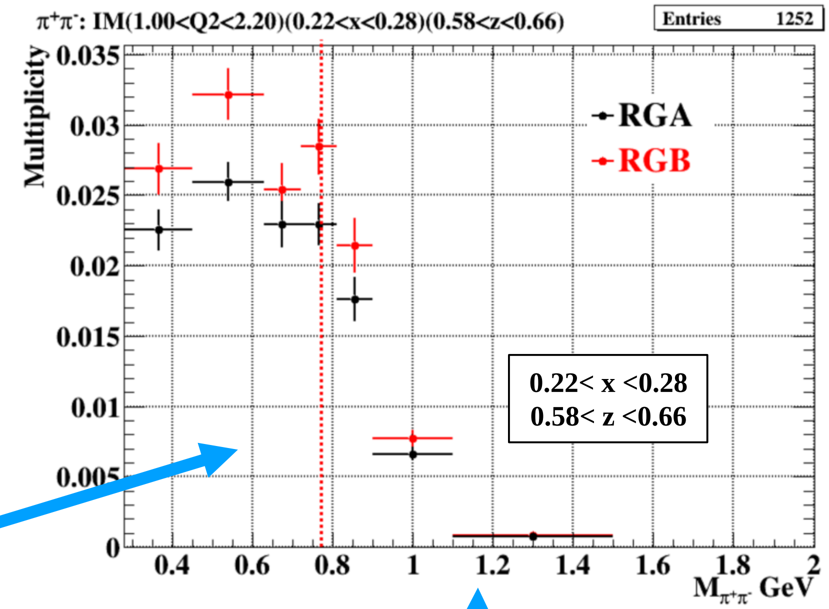
K_f → kinematic factors

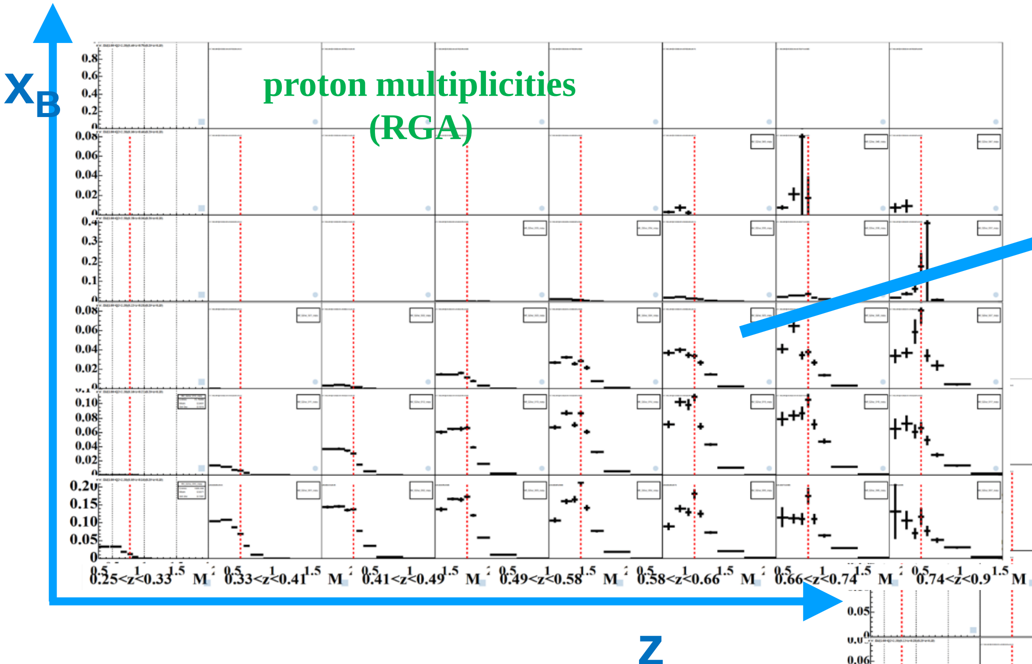
The PDF f_{1q} of the proton are known

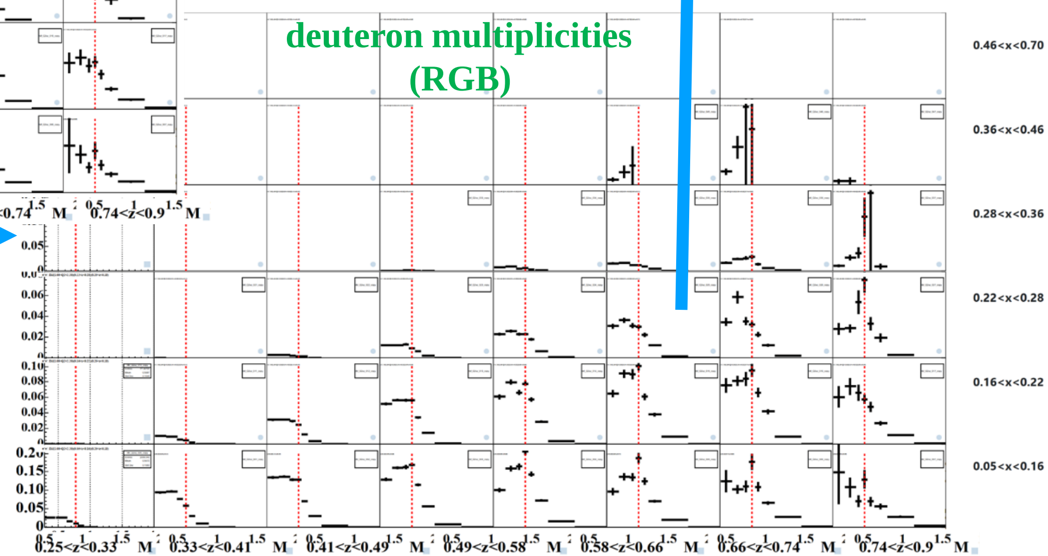
Multiplicities

DNP cooking

$1 < Q^2 < 2.2\ \mathrm{GeV}^2$





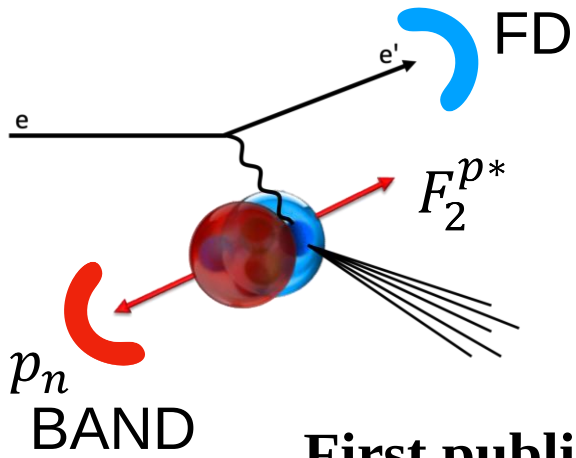


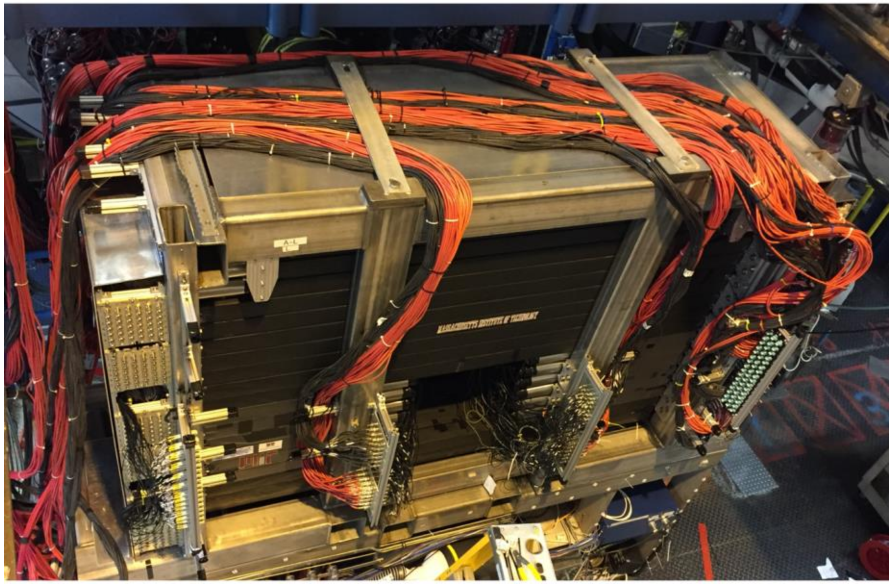
Very preliminary

- Fully unintegrated 4D analysis in x_B, z, $M_{\pi\pi}$ and Q^2
- DIS cuts: $Q^2 > 1$, $W > 2$, $y<0.8$
- SIDIS cuts: $x_F^{+/-} > 0$, $0.1 < z < 0.95$, $MM>1.1$

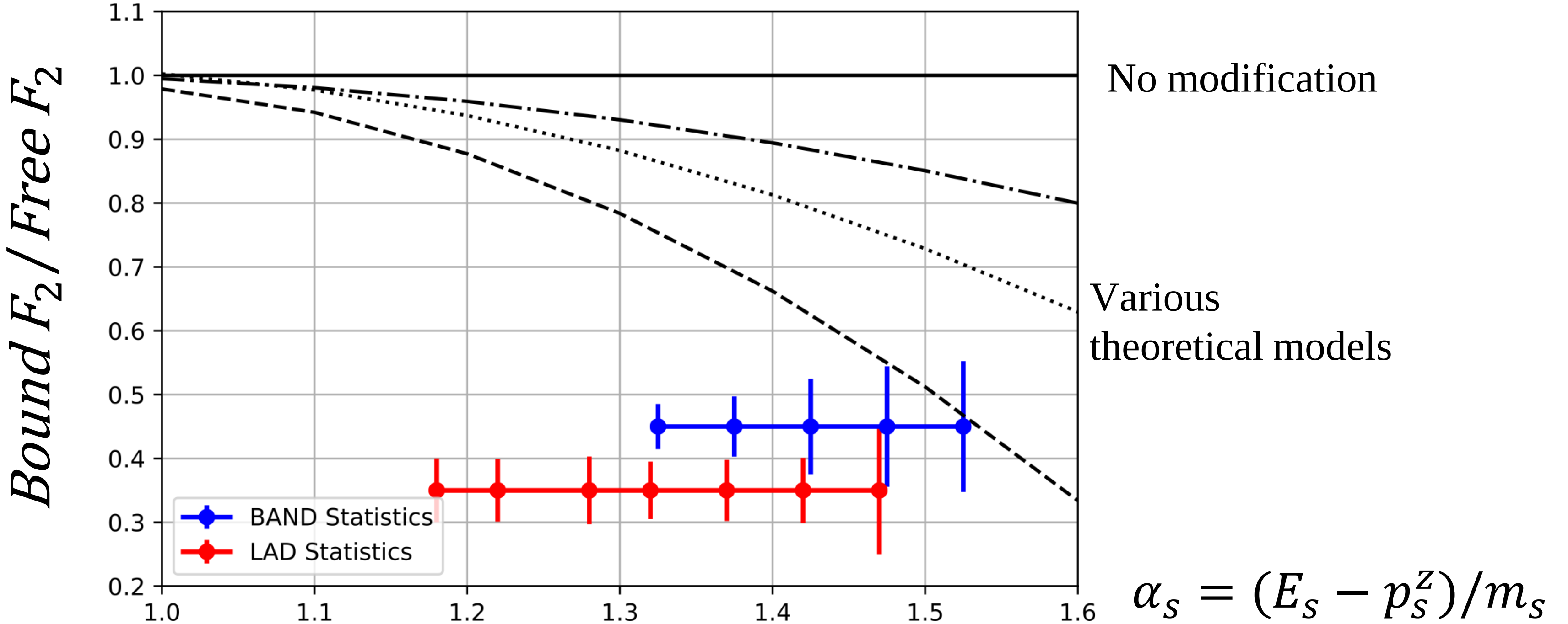
O. Soto, M. Mirazita (INFN-LNF)

Study bound proton structure by tagging neutron

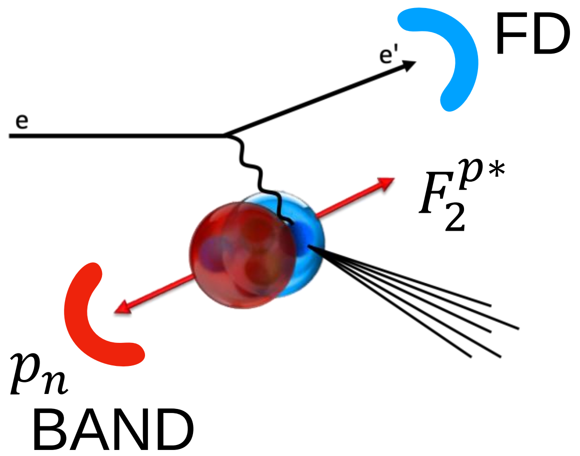




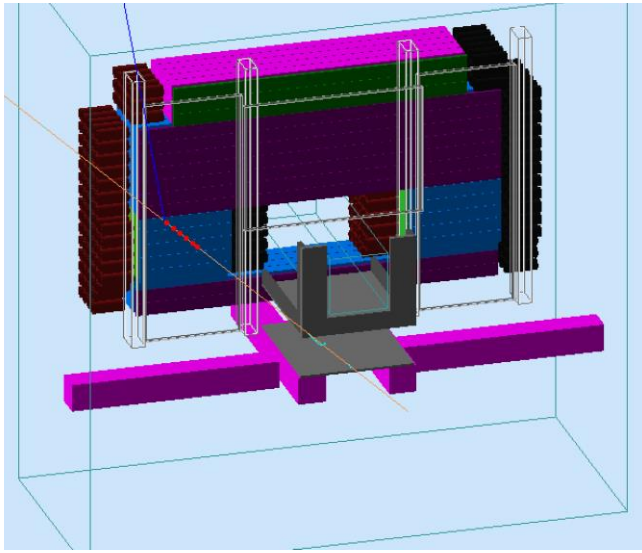
First publication goal

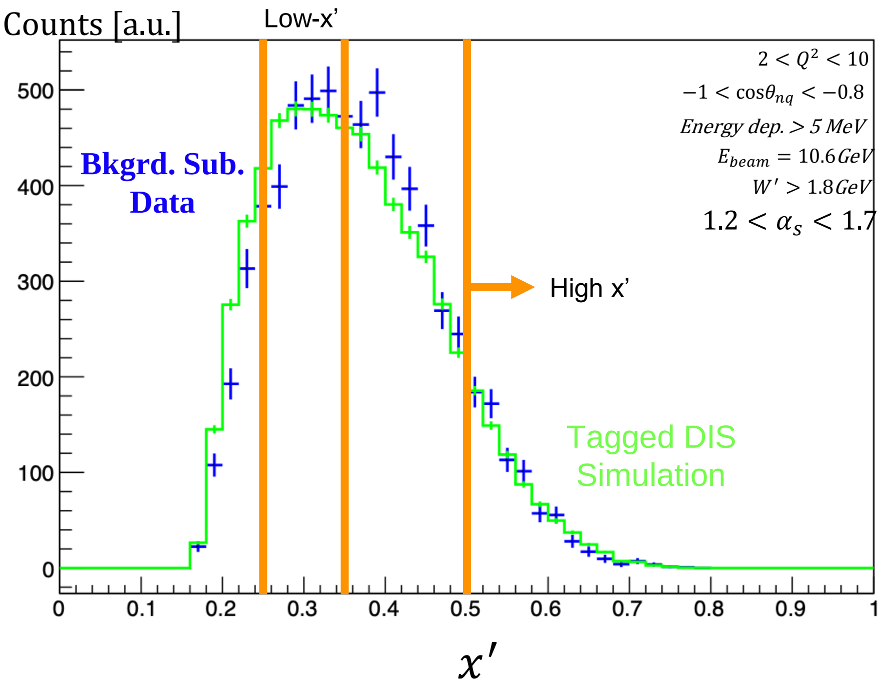


Study bound proton structure by tagging neutron



GEMC implementation





Path to first publication:

- GEMC simulation (neutron smearing, radiative effects, etc..)
- pass 1 validation
- ratio systematics

Conclusions and beam-time request

- RG-B aims at mapping the 3D structure of the neutron via electroproduction on deuterium
- Quark-flavor separation of the measured structure functions can be achieved combining with proton data
- The first « half » of RG-B running ended on January 30
- ~38.9 PAC days collected out of the 90 PAC days approved for nDVCS
- Three different beam energies for the 3 periods
- The Spring dataset has been calibrated and reconstructed (~50% of the collected statistics)
- Calibrations well advanced for Fall and Winter datasets
- Physics analyses in good progress: n/p/d-DVCS, n/p-DVMP(π^0), G^n_M, Di-hadron SIDIS, Tagged-DIS

- **We request the PAC to allow us to run the remainder 51 days of our approved beam time:**
  - ✓ **We will achieve (Q^2, x_B, -t, ϕ) binning for nDVCS BSA with acceptable statistical errors, and hopefully at a constant beam energy**
  - ✓ **We will achieve high precision at high Q^2 for G^n_M**
  - ✓ **We will provide first-time pioneering measurements for new channels (d-DVCS, n-DVMP(π^0)) which have low cross sections and efficiencies**
  - ✓ **…(any more arguments?)**