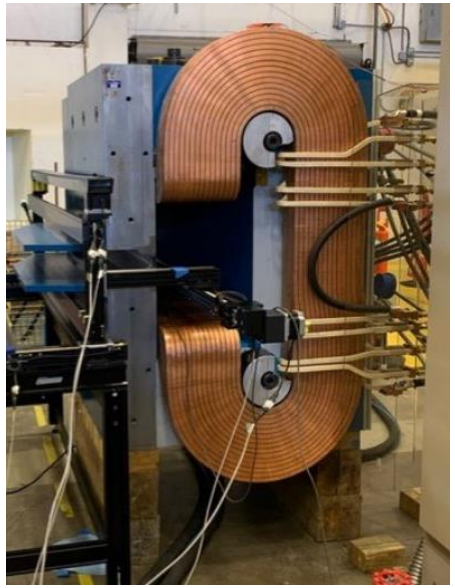
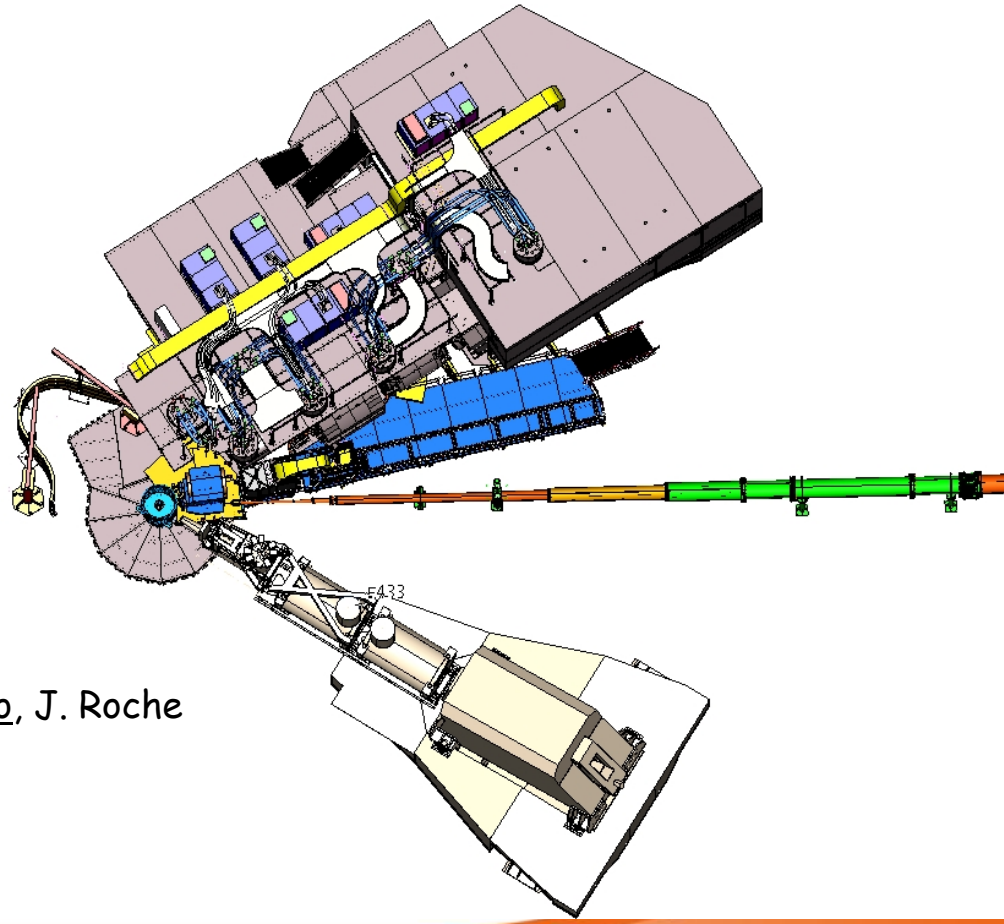
PR12-22-006:

Deeply Virtual Compton Scattering off the neutron with the Neutral Particle Spectrometer in Hall C



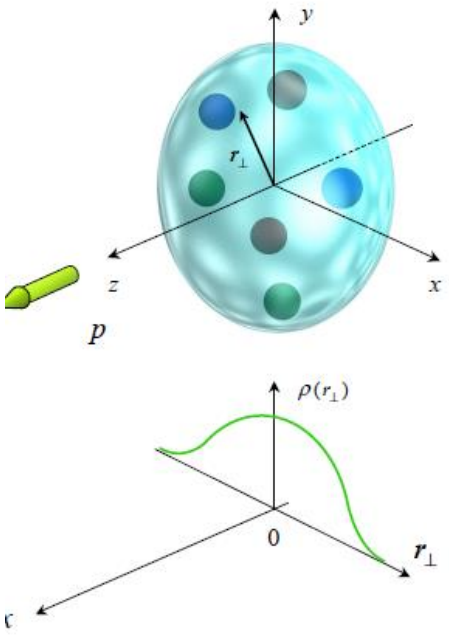


C. Hyde, M. Mazouz, C. Muñoz Camacho, J. Roche
(for the NPS Collaboration)

PAC 50 (July 11-14, 2022)

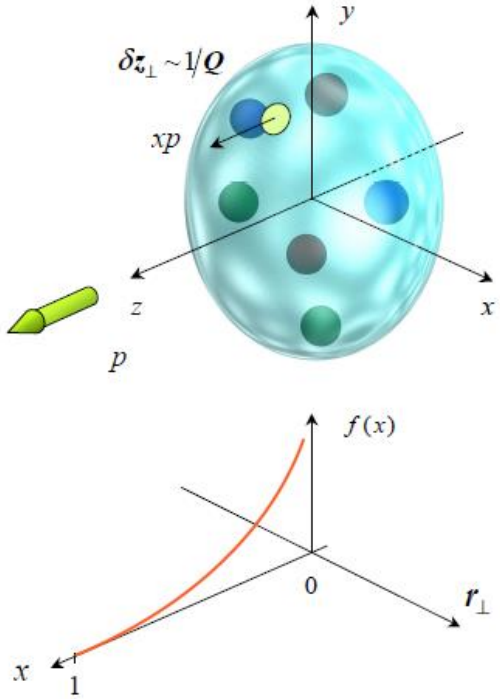
3D imaging of quarks and gluons

Elastic scattering



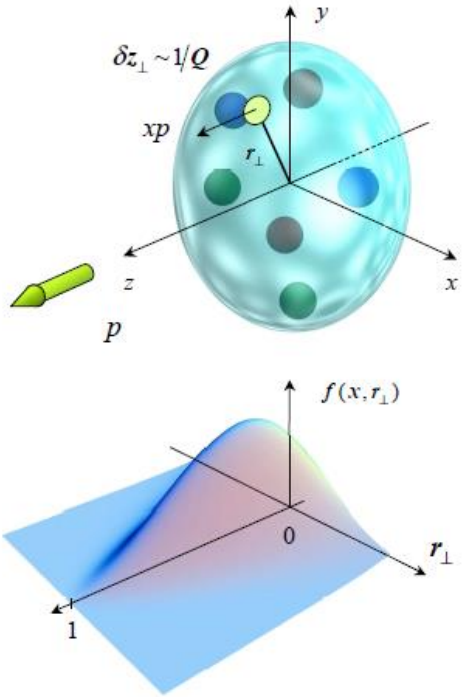
Form factors

Deeply Inelastic Scattering



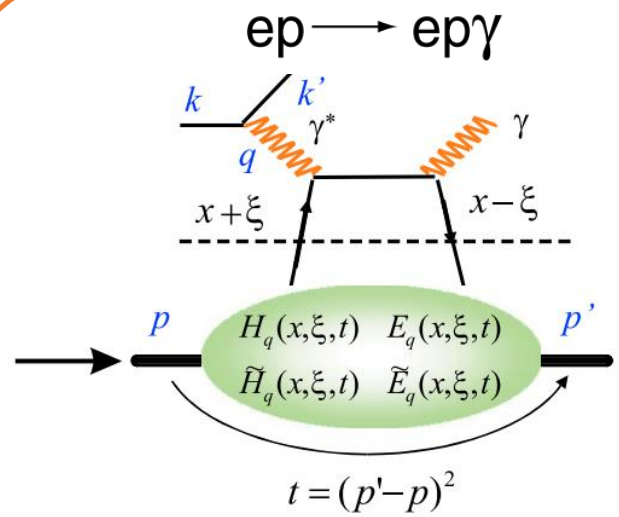
Parton distributions

Hard exclusive processes

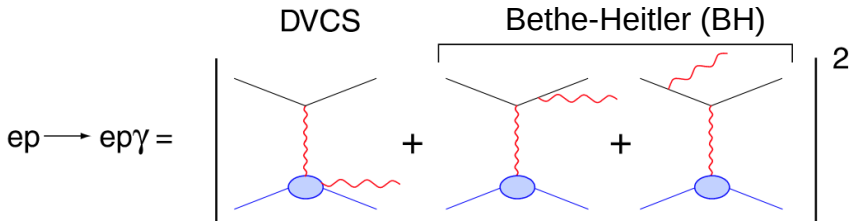


Generalized Parton Distributions (GPDs)

Golden channel



- All order QCD factorization
- Simplest GPD process
- Sensitive to all flavor of GPDs



Motivation

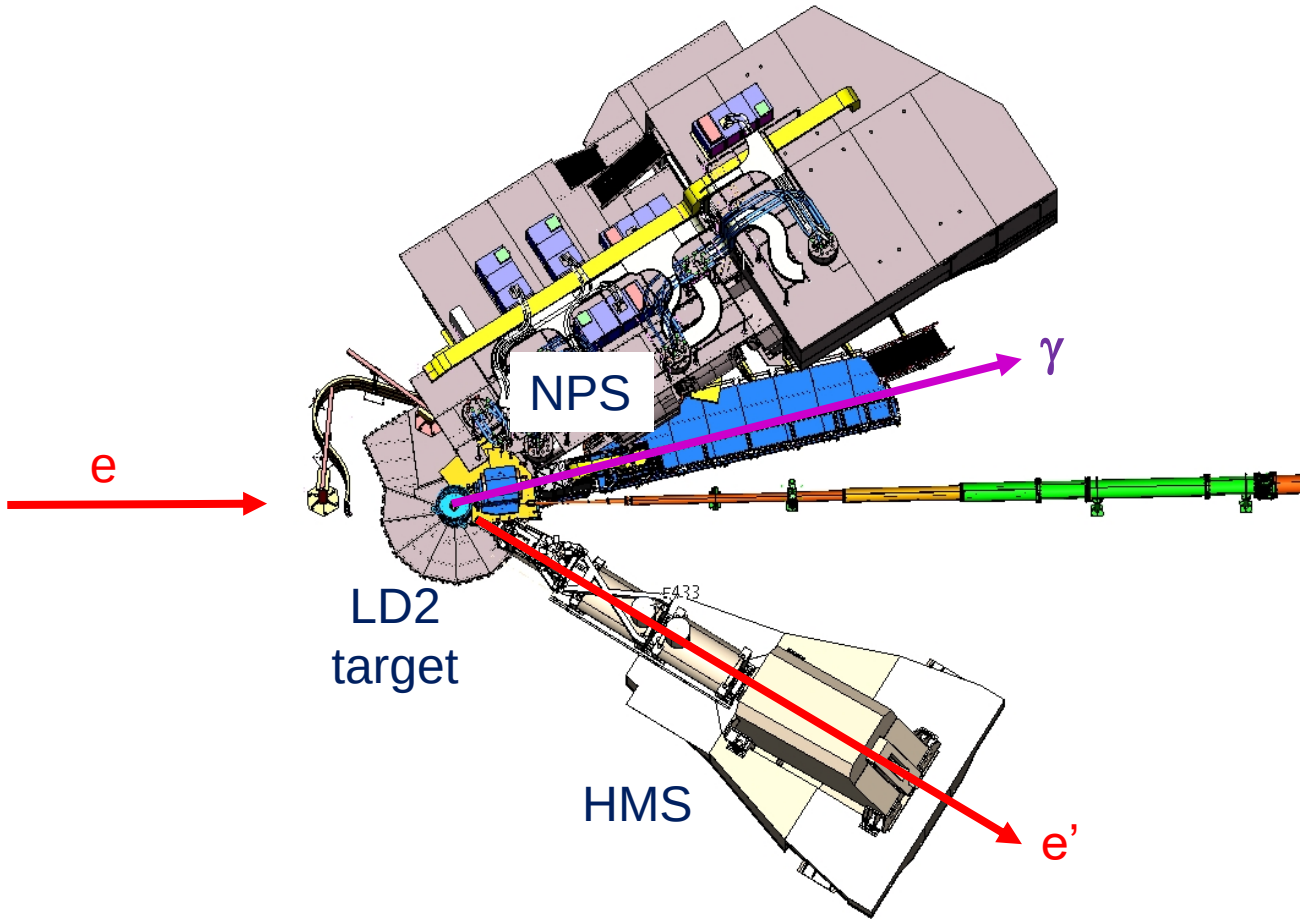
- Neutron DVCS (nDVCS) is the best and necessary reaction to probe flavor dependence of GPDs
- Accurate cross section measurements are needed for high sensitivity results
- Extensive program of DVCS measurements on proton targets approved at JLab12
- No experiment yet proposed to measure the nDVCS cross sections at JLab12

  (only 2 experiments for BSA in Hall B)

- 12 GeV kinematics and the high resolution of the NPS system offer several advantages over pioneer measurements at 6 GeV:
  - Better separation of nDVCS from coherent DVCS off deuteron, due to the larger values of momentum transfer *t*
  - Natural suppression of coherent DVCS off deuteron (sharp drop of *d* form factor)
  - Higher energy resolution of NPS wrt previous measurements using an PbF_2 calorimeter

Experimental setup

Measurement of the e N → e' γ X reaction (N=p,n,d) using an LD2 target in Hall C



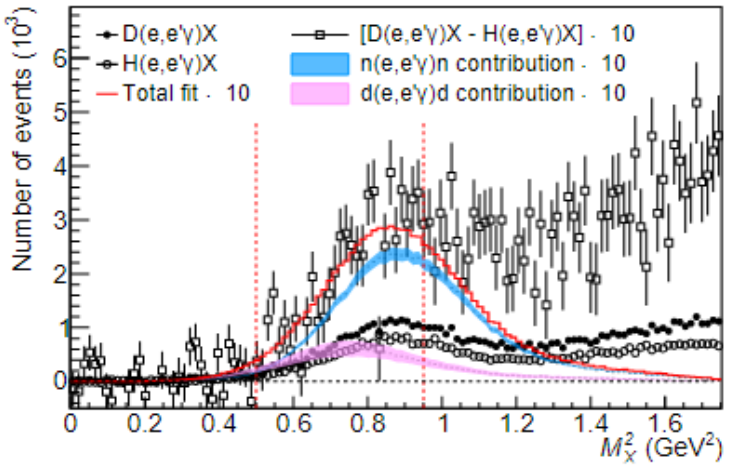
Analysis technique (impulse approximation):

$$D(e,e'\gamma)X = d(e,e'\gamma)d + n(e,e'\gamma)n + p(e,e'\gamma)p$$

Separated by missing mass

$$\left(\Delta M_X^2 = t(1 - M_N/M_d) \approx t/2\right)$$

Subtracted using interleaved data on LH2 (approved experiment E12-13-010)

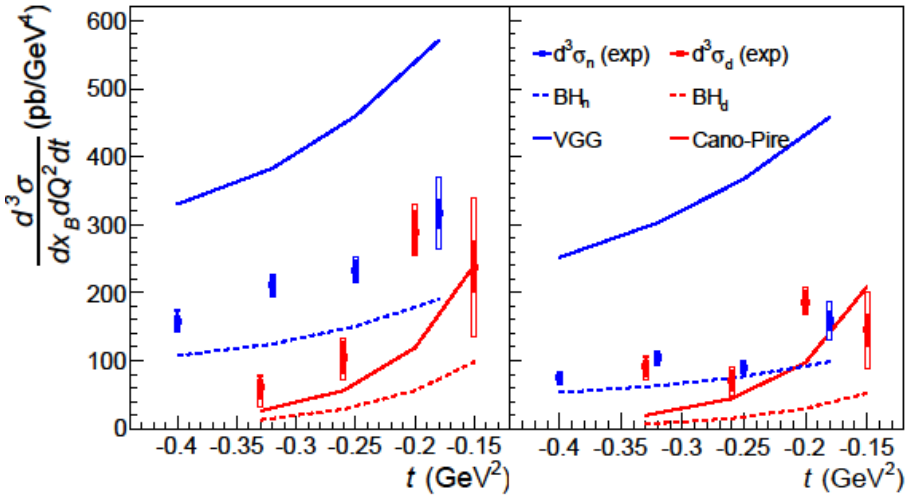


Results from 6 GeV experiment E08-025

High impact measurements to flavor separate GPDs

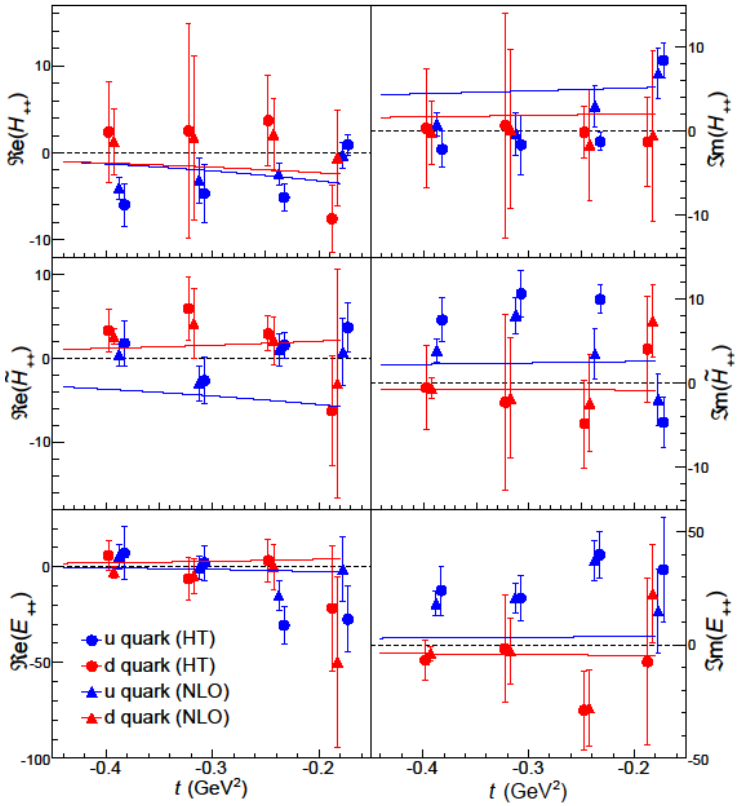
Cross section measurements from E08-205

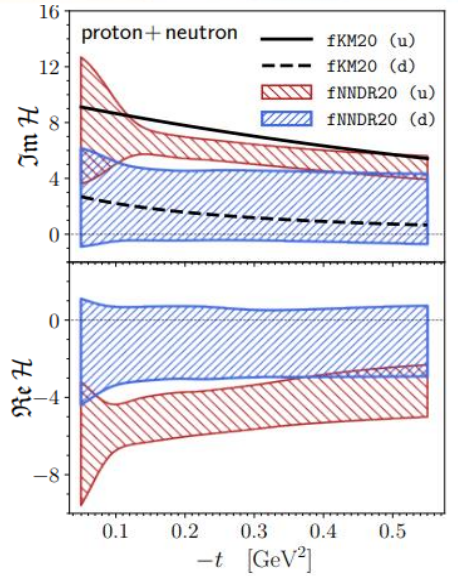
E_b =4.45 GeV E_b =5.55 GeV

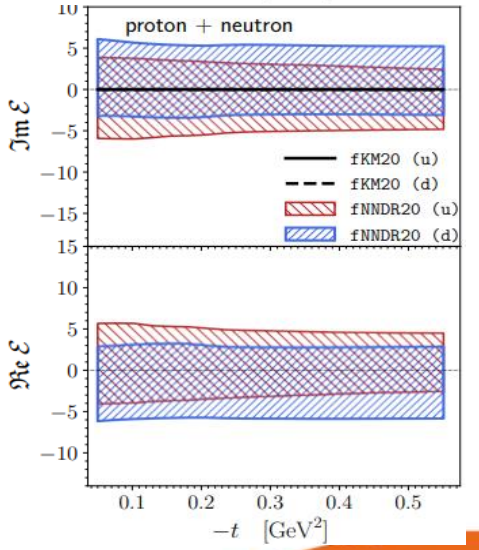


Benali et al, Nature Phys. 16, 191 (2020)

Flavor separation of Compton Form Factors







M. Čuić et al., Phys. Rev. Lett. 125 (2020)

$$\mathcal{T}^{DVCS} = \int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x-\xi+i\epsilon} + \cdots = \underbrace{\mathcal{P}\int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x-\xi}}_{\text{Access in helicity-independent cross section}} \overbrace{i\pi\, H(x=\xi,\xi,t)}^{\text{Access in helicity-dependent cross-section}} + \ldots$$

12 GeV DVCS kinematics

Approved proton DVCS E12-13-010

x_B	0.2					0.36					0.5			0.6			
Q^2 (GeV)^2	2.0			3.0		3.0		4.0		5.5	3.4		4.8	5.1			6.0
E_b (GeV)	6.6	8.8	11		6.6	8.8	11	8.8	11		8.8	11		6.6	8.8	11	
k' (GeV)	1.3	3.5	5.7	3.0	2.2	4.4	6.6	2.9	5.1	2.9	5.2	7.4	5.9	2.1	4.3	6.5	5.7
θ_{Calo} (deg)	6.3	9.2	10.6	6.3	11.7	14.7	16.2	10.3	12.4	7.9	20.2	21.7	16.6	13.8	17.8	19.8	17.2
D_{Calo} (m)	6	4		6		3		4	3	4	3						
I_{beam} (μA)	11	5	50	11		28		50	28	50	28						
$\sigma_{M_X^2}$ (GeV^2)	0.17			0.22	0.13		0.12	0.15		0.19	0.09		0.11	0.09			
$-t_{min}$ (GeV^2)	0.04				0.16			0.17			0.37		0.39	0.65			0.67
$-t_{min}/(2\sigma_{M_X^2})$	0.1				0.6			0.55		0.4	2		1.7	3.6			3.7
LH_2 Days	1	1	1	1	1	2	1	1	3	5	3	2	5	5	1	5	10
LD_2 Days					1	2	1	1	3	5	3	2	5	5	1	5	10
					This Proposal: 44 days on LD_2												

Typical 6 GeV kinematics

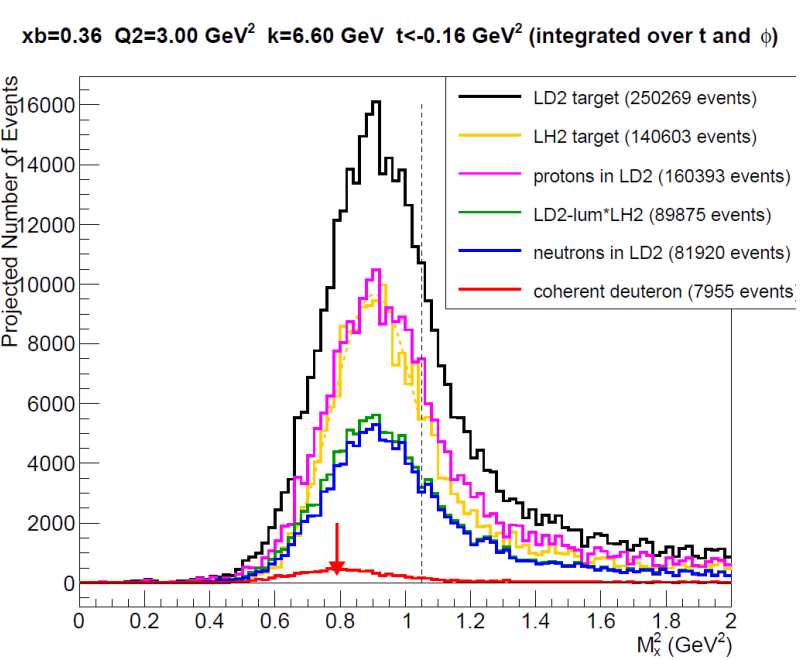
Previous 6 GeV experiment:
$\sigma_{M_X^2}$ =0.23 GeV^2 & $-t_{min}/(2\,\sigma_{M_X^2})$=0.35

~ ×2–12 better nDVCS & dDVCS separation than previous 6 GeV experiment

- 12 GeV → higher x_B → higher t_{min}
- NPS: higher energy resolution → smaller (~$\frac{1}{2}$) $\sigma_{M_X^2}$

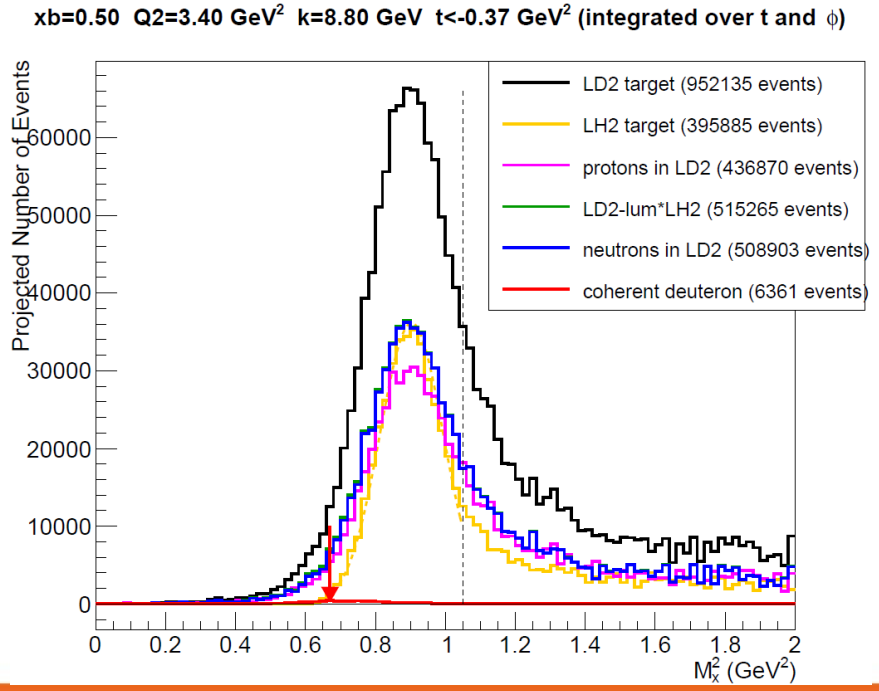
Projections: missing mass distributions

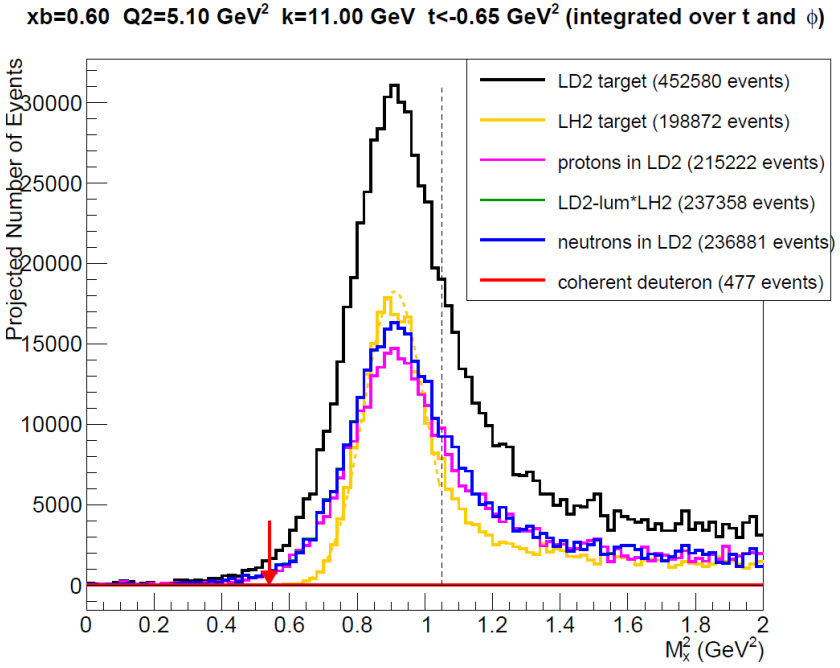
- Full Geant4 simulation of pDVCS, nDVCS and pDVCS through experimental setup
- pDVCS and nDVCS weighted by DVCS cross section model KM15 by Kumericki & Mueller [1512.09014]
- dDVCS model by W. Cosyn & B. Pire [PRD98 (2018)], with GPDs from Kroll-Goloskokov [Eur.Phy. J A (2014)]



$x_B \sim 0.36$

$x_B \sim 0.50$



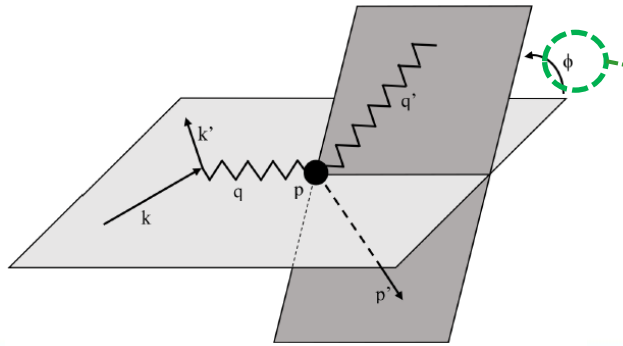


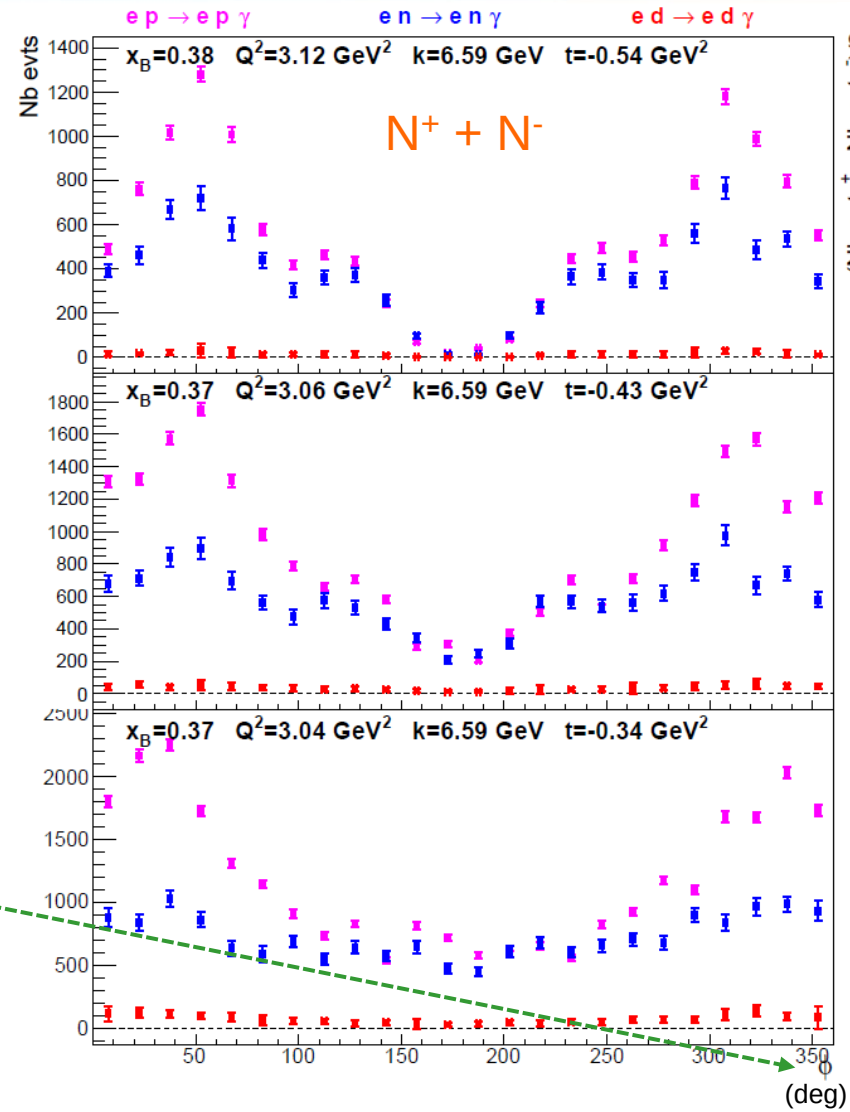
$x_B \sim 0.60$

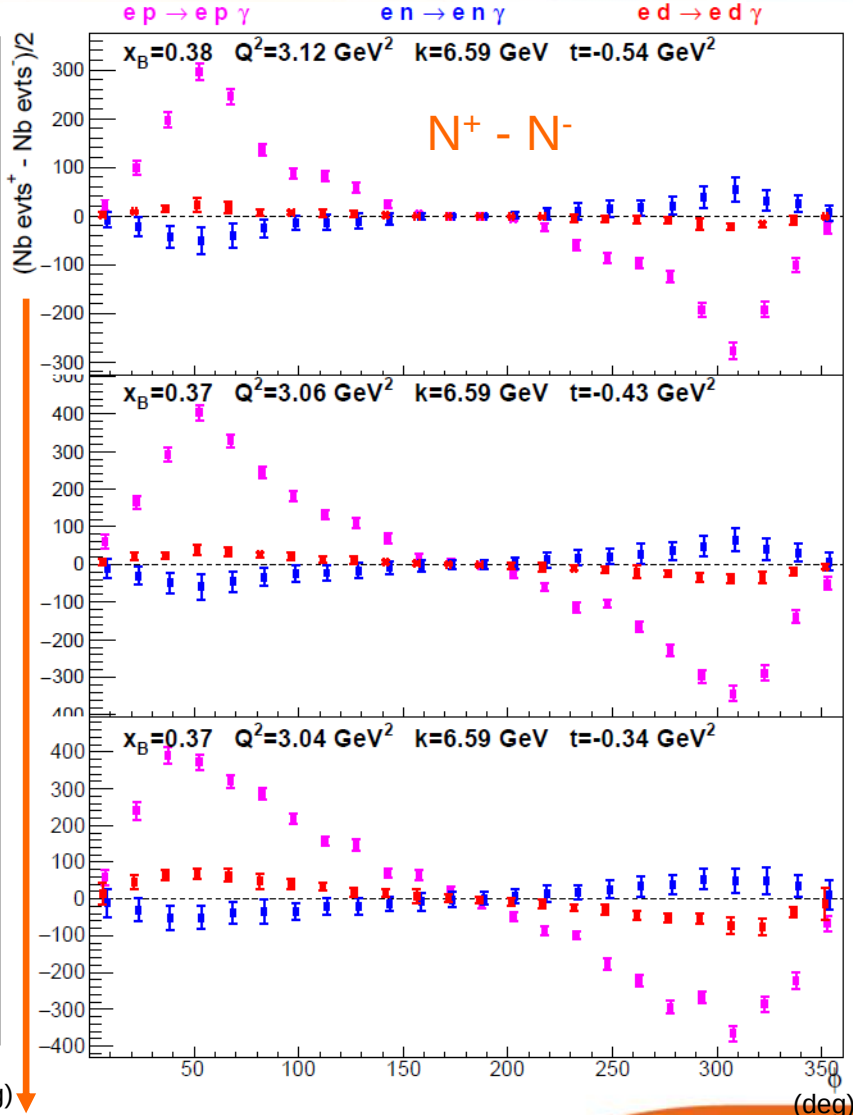
Projections: number of counts

- Beam time request such as to match the beam time of the proton data (to statistically optimize the subtraction of the incoherent proton channel)

- Proton beam time request (E12-13-010) was driven by helicity-dependent cross sections, and such that systematic and statistical uncertainties are comparable (3-4%)







decreasing values of |t|

Projections: cross section measurements

Models

- KM15: K. Kumericki, D. Mueller [1512.09014 & PRL125 (2020)]
- UVA: B. Kriesten, S. Liuti et al. [PRD 101 (2020)]
- VGG: M. Vandergheuagen, P. Guichon, M.Guidal [PRD60 (1999)]
- CCP: Cano, Cosyn, Pire [PRD98 (2018) & Eur.Phys.J.A 19 (2004)]

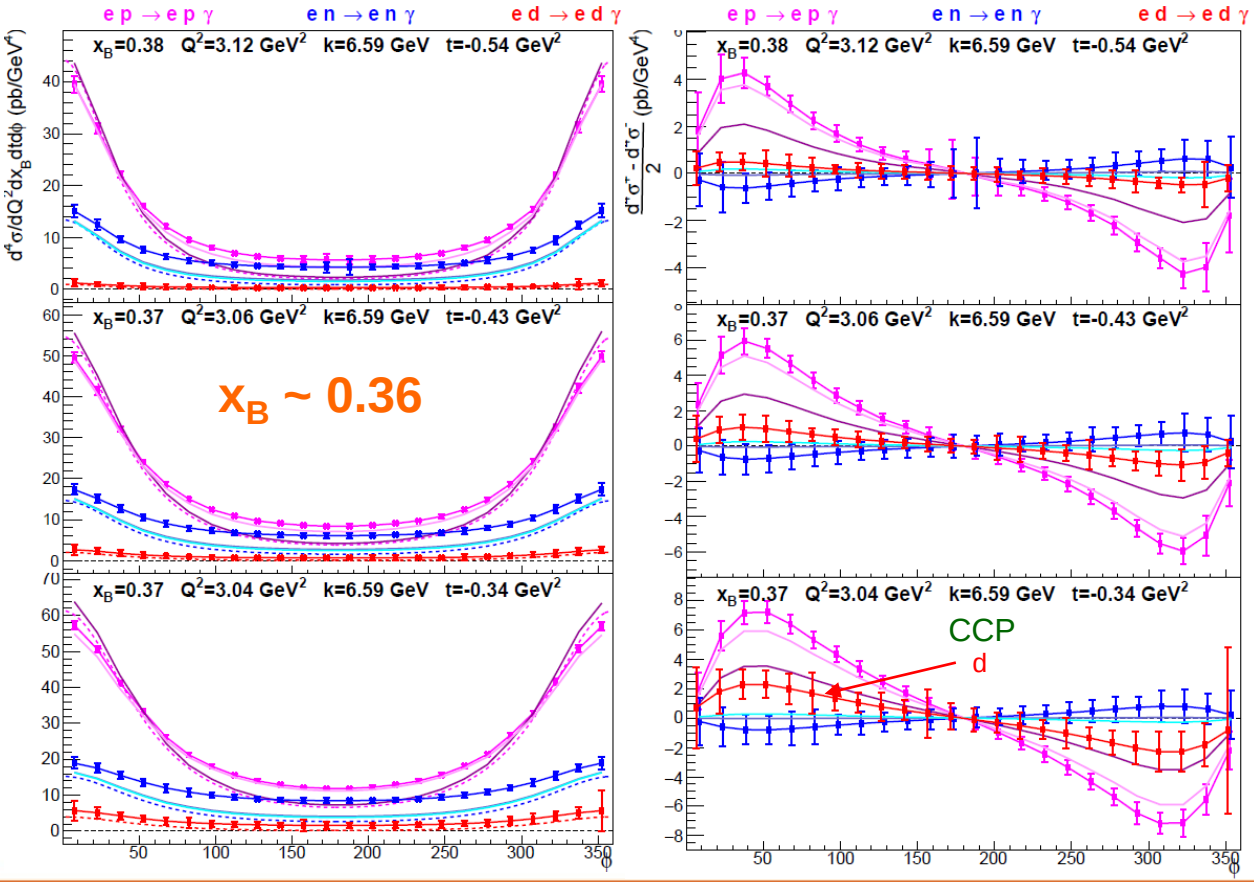
proton, neutron DVCS

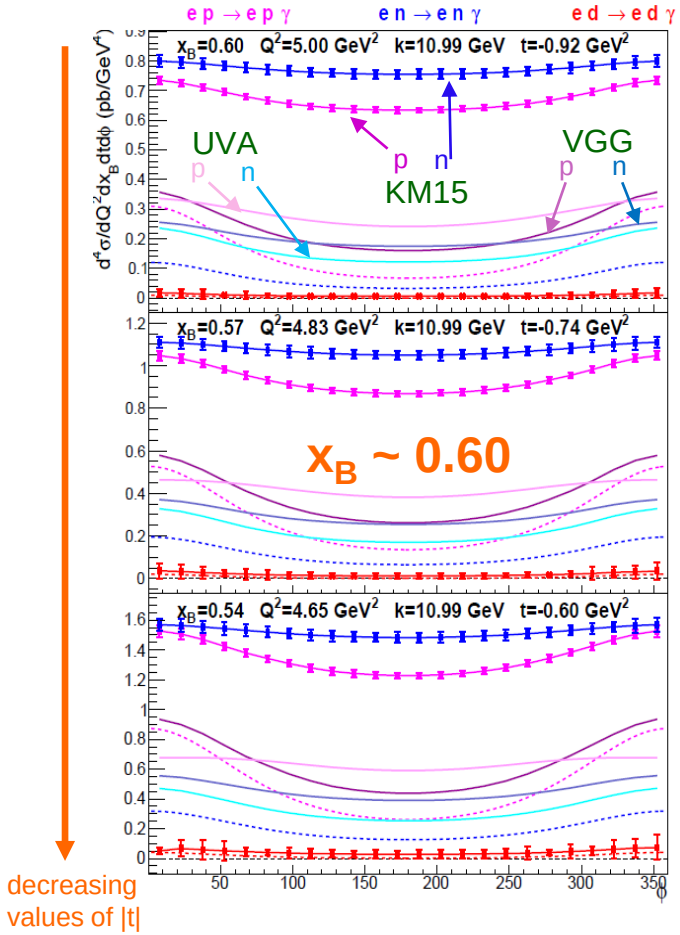
coherent deuteron DVCS

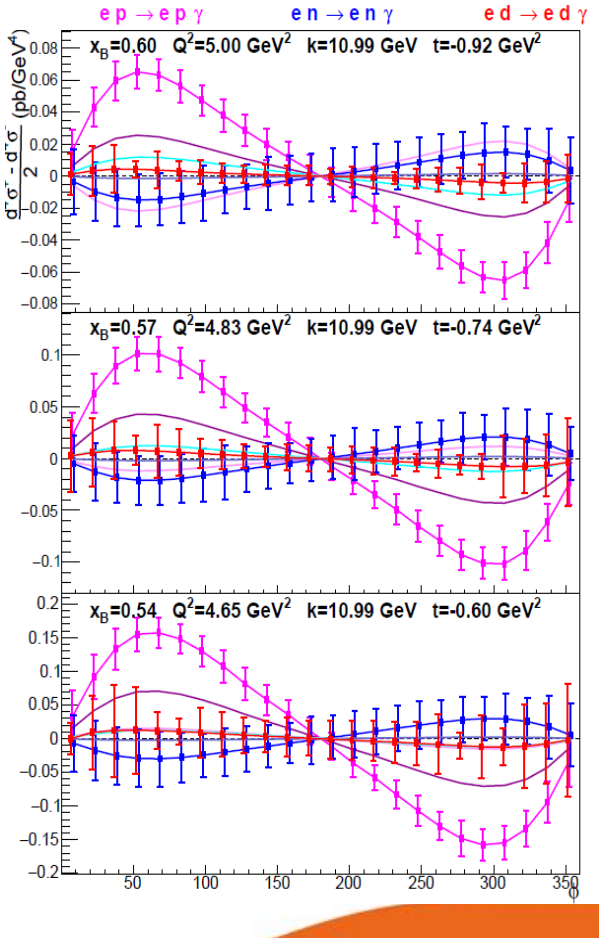
More kinematic bins in backup slides

$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi}$$

$$\frac{d^4\sigma^+ - d^4\sigma^-}{dQ^2 dx_B dt d\phi}$$





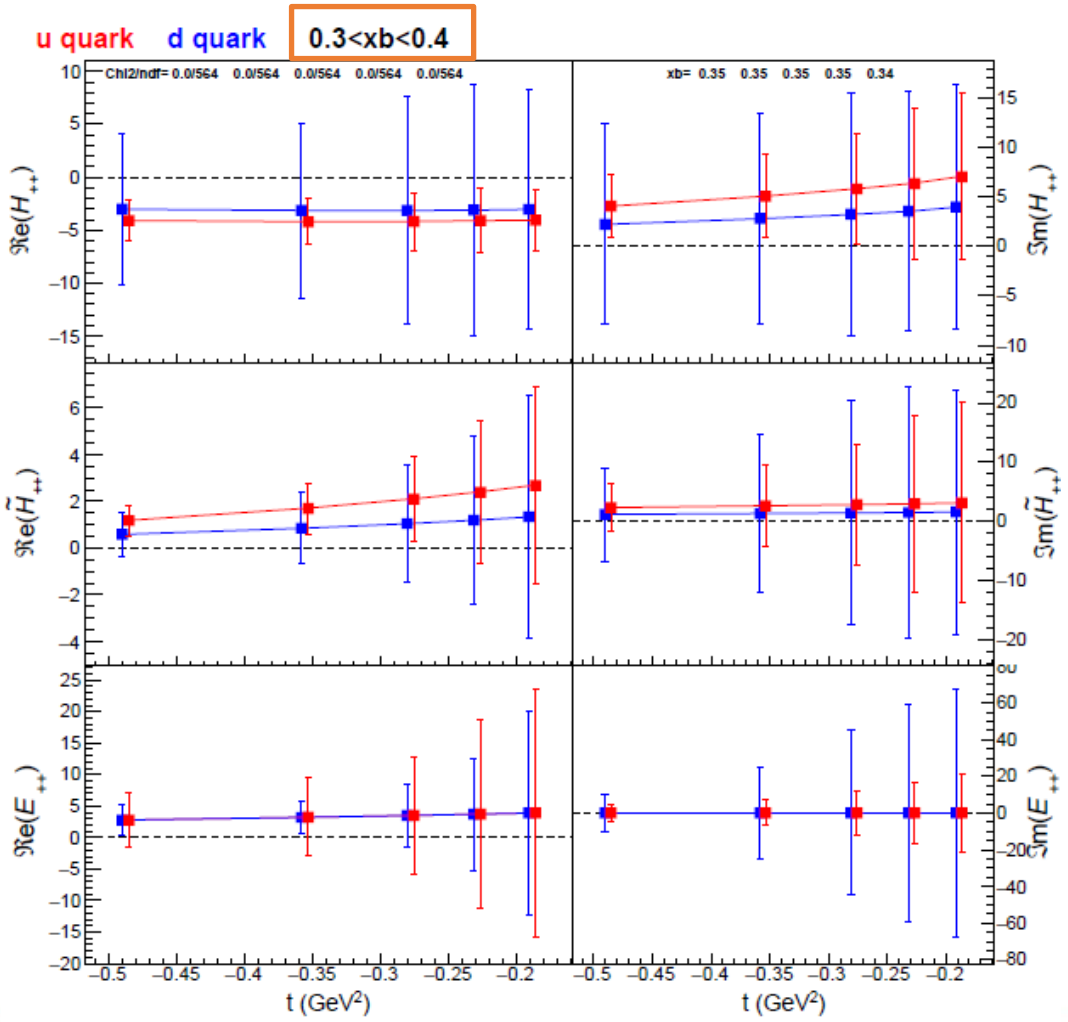


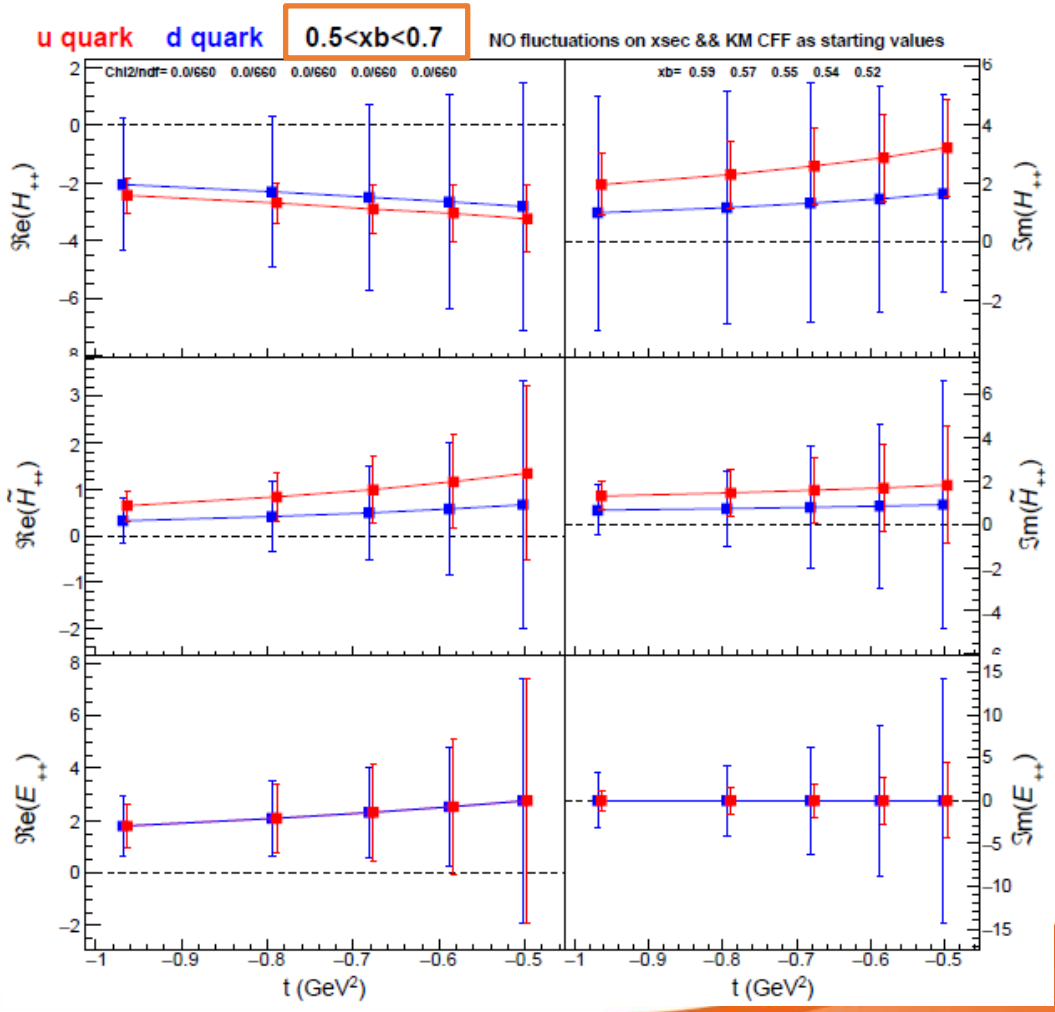
decreasing values of |t|

Dotted lines: Bethe-Heitler (p, n, d)

Impact on flavor dependence of CFFs

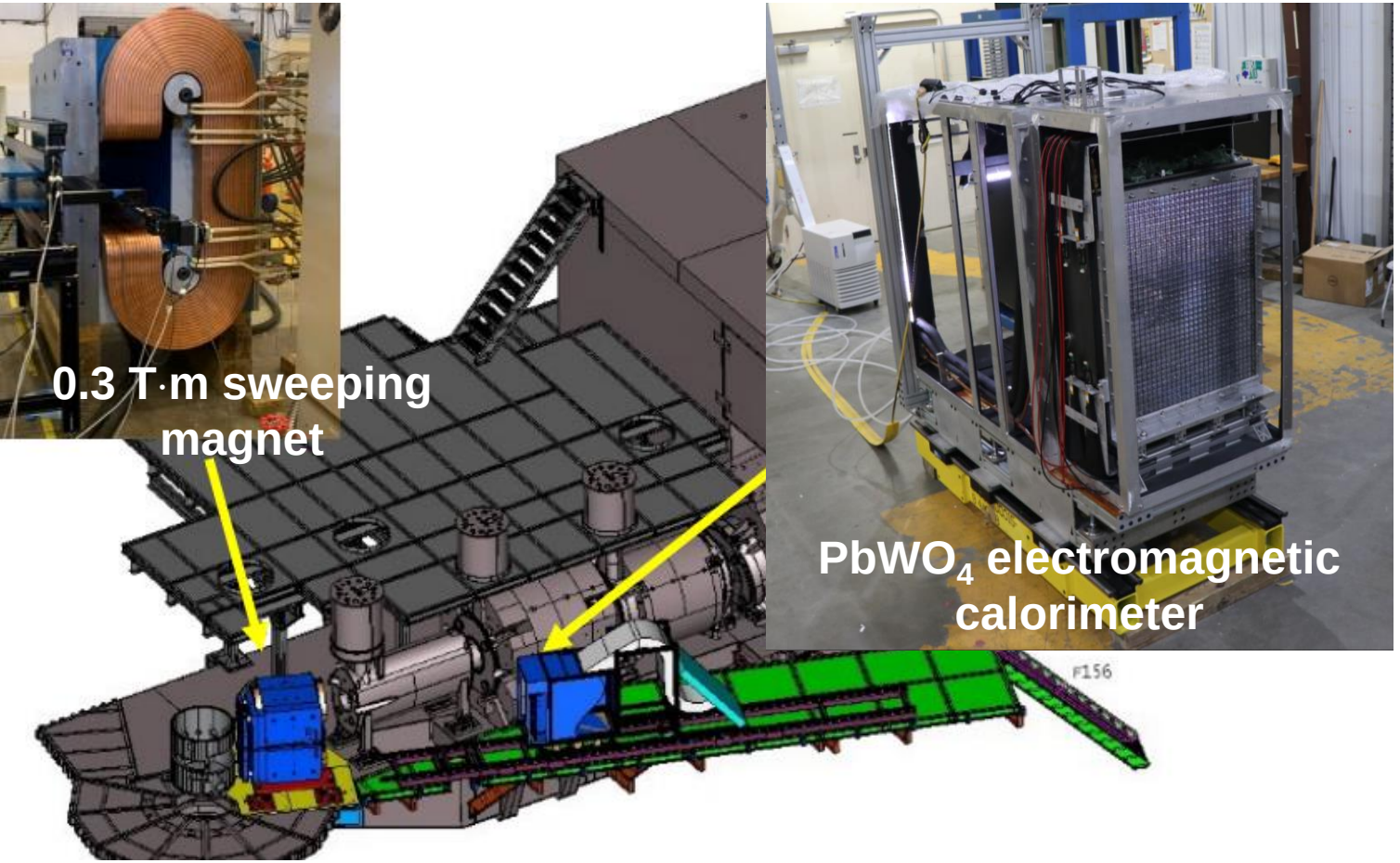
- Simultaneous fit of E12-13-010 (proton) and PR12-22-006 (neutron) projected data
- Real and imaginary parts of CFFs H, $\widetilde{H}$ and E (u & d) as free parameters (nDVCS not sensitive to $\widetilde{E}$)





Experimental equipment readiness

[JLab experiment schedule (6/10/2022)]



- **NPS (Neutral Particle Spectrometer)** experiment readiness review passed on 2019
- Equipment (calorimeter and sweeping magnet) ready and being tested
- Installation in Hall C during Spring 2023
- NPS run (E12-13-010) scheduled from July 17 (2023) to Feb 15 (2024)

Collaboration track record

	Experiment	PAC	Goal	Results
6 GeV	E00-110	PAC18	1st dedicated DVCS experiment at JLab	PRL97 (2006), PRC83 (2011), PRC92 (2015)
	E03-106	PAC24	1st neutron DVCS experiment	PRL99 (2007)
	E07-007	PAC31	DVCS Rosenbluth-like separation (proton)	PRL117 (2016), Nature Commun. 8 (2017)
	E08-025	PAC33	DVCS Rosenbluth-like separation (neutron)	PRL118 (2017), Nature Physics 16 (2020)
12 GeV	E12-06-114	PAC30+38+41+47	1st 12 GeV experiment	PRL127 (2021), PRL128 (2022)
	E12-13-010	PAC40	DVCS Rosenbluth-like separation (proton)	*Scheduled 2023-2024*

Summary

- We propose to measure the DVCS cross section off quasi-free neutrons with an LD2 target & NPS in Hall C
- Accurate cross section measurements off neutron are a necessary complement to the approved proton DVCS program at JLab12
- Essential measurements for probing the flavor dependence of GPDs
- 12GeV kinematics and NPS will significantly improve initial results at 6 GeV
- *Interleaved measurements with approved LH2 experiment (E12-13-010) will reduce systematics uncertainties*
- Exclusive π^0 electroproduction cross section off the neutron will also be measured

Beam time request: 44 days

Back-up

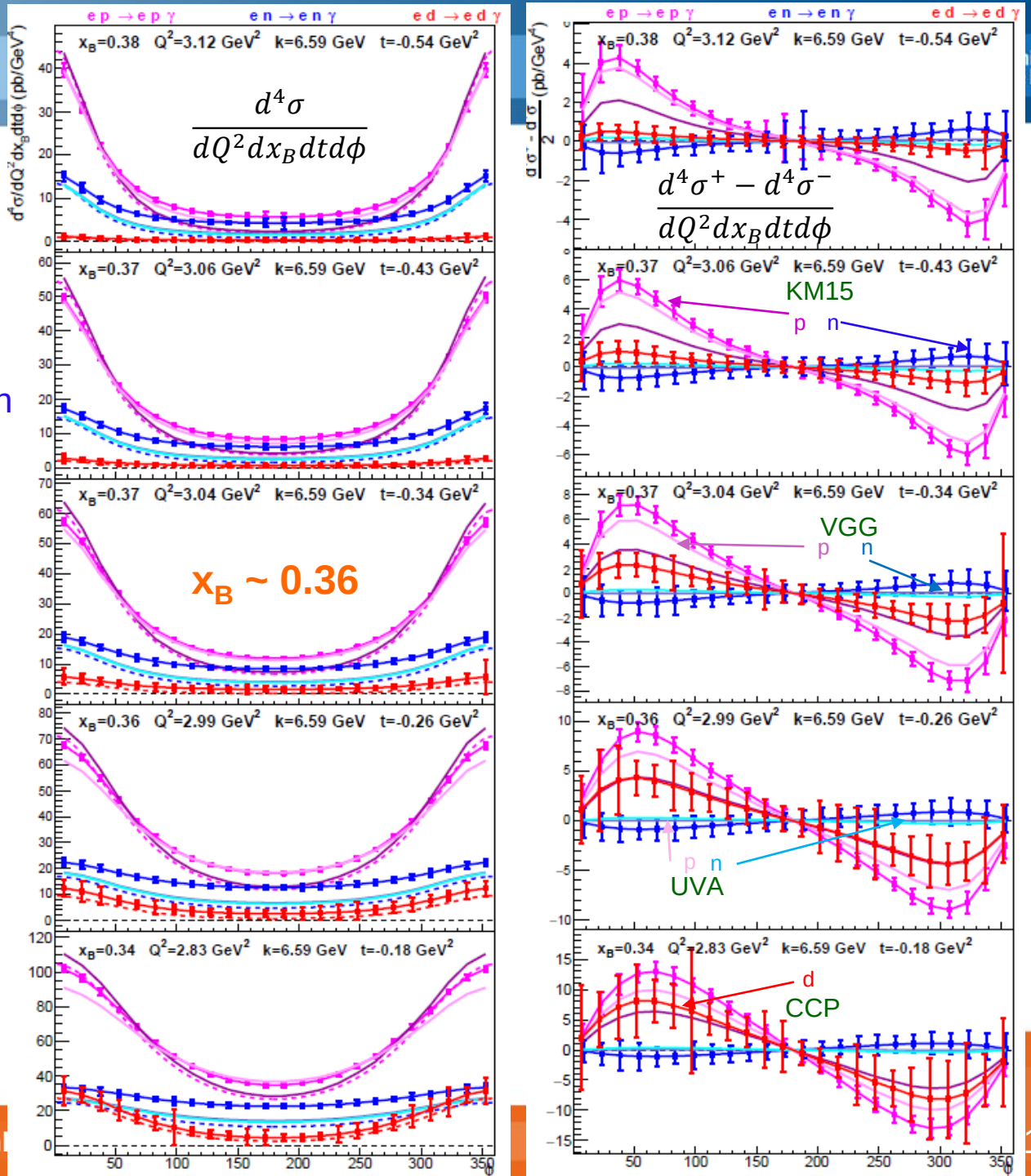
X-section projections

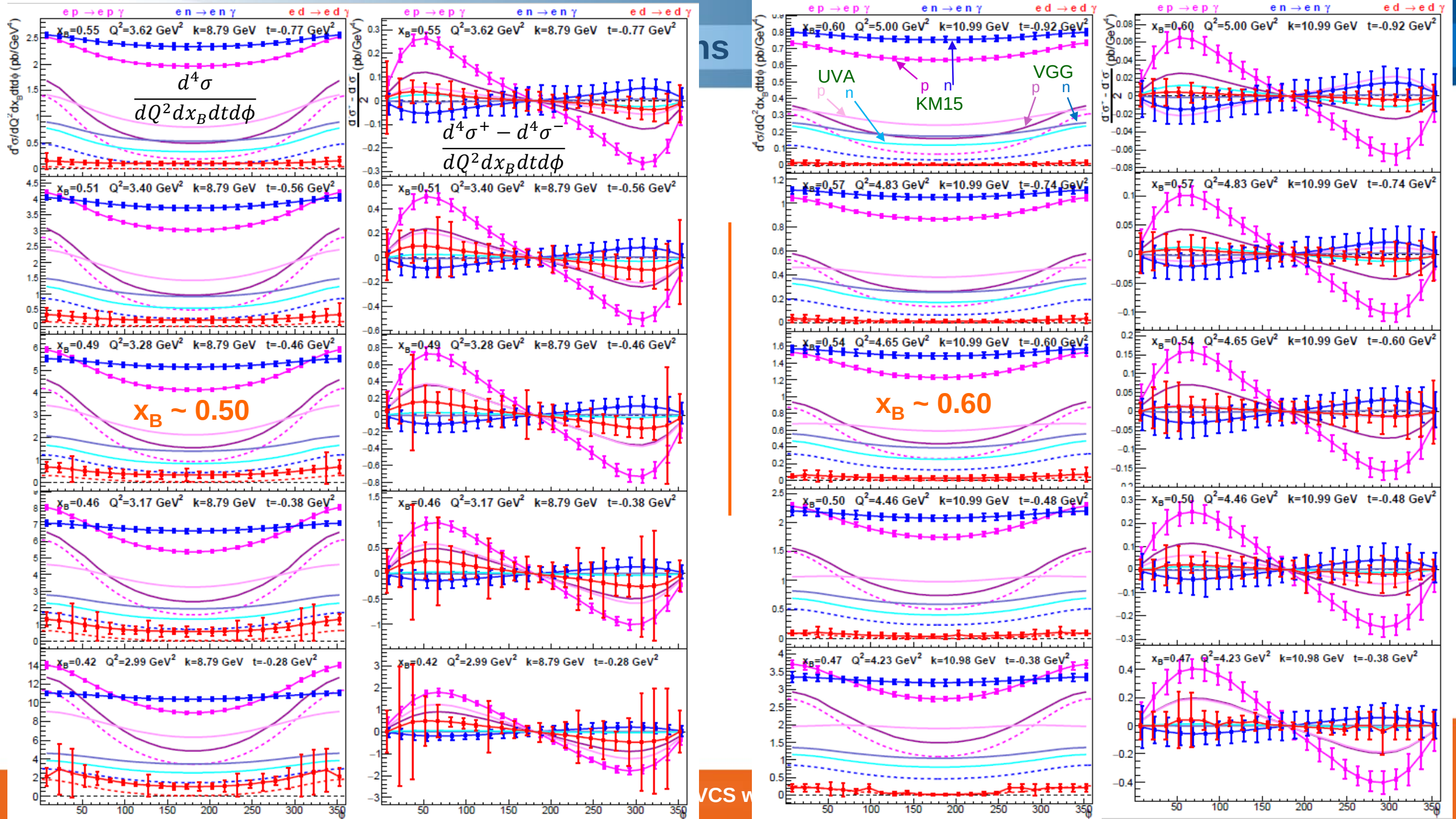
- KM15: K. Kumericki, D. Mueller [1512.09014 & PRL125 (2020)]
- UVA: B. Kriesten, S. Liuti et al. [PRD 101 (2020)]
- VGG: M. Vandergheuagen, P. Guichon, M.Guidal [PRD60 (1999)]
- CCP: Cano, Cosyn, Pire [PRD98 (2018) & Eur.Phys.J.A 19 (2004)]

proton, neutron DVCS

coherent deuteron DVCS

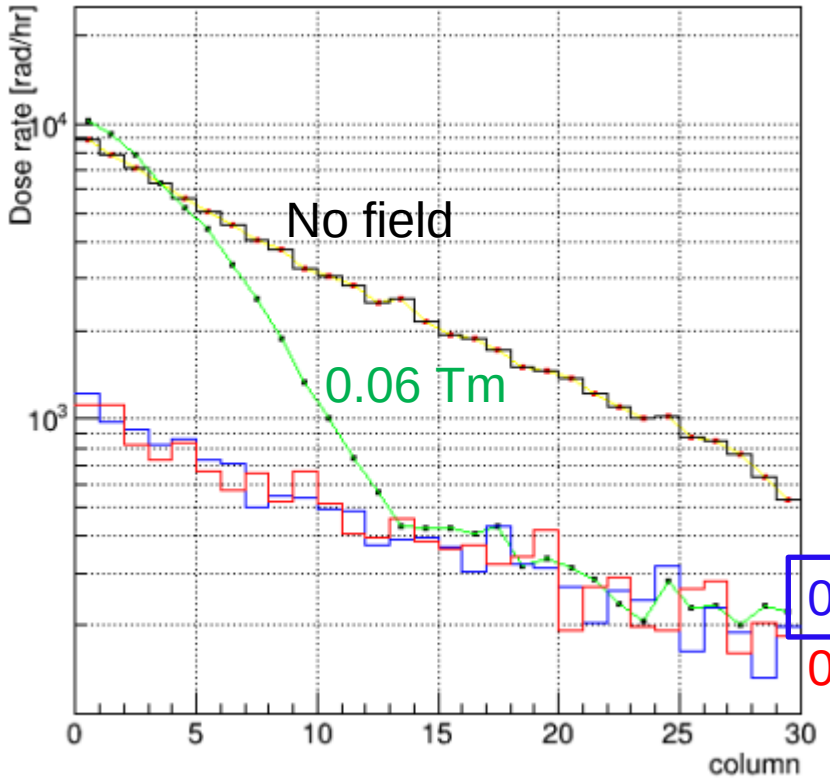
Dotted lines: Bethe-Heitler (p, n, d)




ep → ep γ
en → en γ
ed → ed γ
$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi}$
$\frac{d^4\sigma^+ - d^4\sigma^-}{dQ^2 dx_B dt d\phi}$
x_B ~ 0.50
x_B ~ 0.60
UVA
p n
KM15
p n
VGG
p n
x_B=0.55 Q^2=3.62 GeV^2 k=8.79 GeV t=-0.77 GeV^2
x_B=0.51 Q^2=3.40 GeV^2 k=8.79 GeV t=-0.56 GeV^2
x_B=0.49 Q^2=3.28 GeV^2 k=8.79 GeV t=-0.46 GeV^2
x_B=0.46 Q^2=3.17 GeV^2 k=8.79 GeV t=-0.38 GeV^2
x_B=0.42 Q^2=2.99 GeV^2 k=8.79 GeV t=-0.28 GeV^2
x_B=0.60 Q^2=5.00 GeV^2 k=10.99 GeV t=-0.92 GeV^2
x_B=0.57 Q^2=4.83 GeV^2 k=10.99 GeV t=-0.74 GeV^2
x_B=0.54 Q^2=4.65 GeV^2 k=10.99 GeV t=-0.60 GeV^2
x_B=0.50 Q^2=4.46 GeV^2 k=10.99 GeV t=-0.48 GeV^2
x_B=0.47 Q^2=4.23 GeV^2 k=10.98 GeV t=-0.38 GeV^2
$d^4\sigma/dQ^2 dx_B dt d\phi$ (pb/GeV^4)
$\frac{d\sigma^+ - d\sigma^-}{2}$ (pb/GeV^4)
ϕ

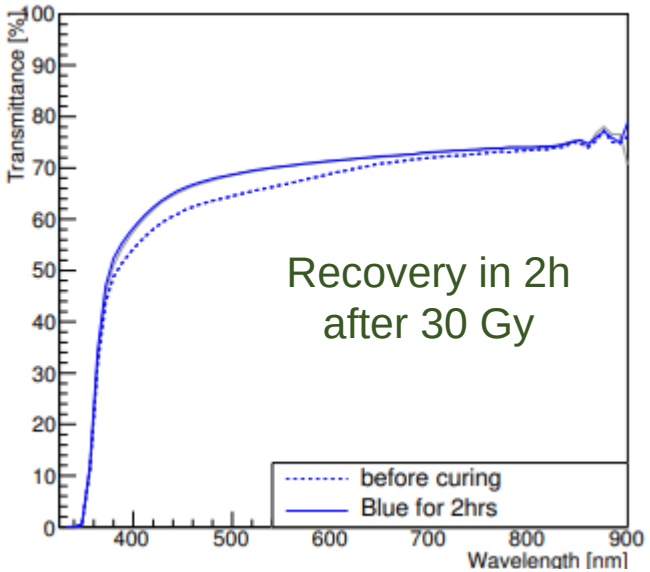
TAC report: radiation damage

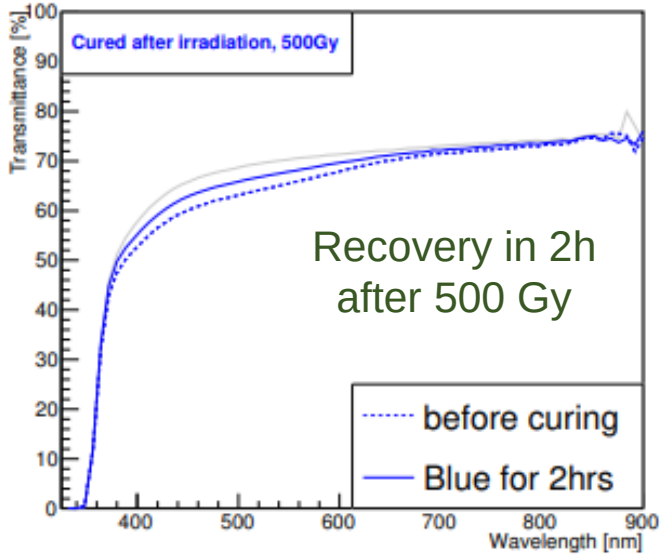
Dose rate in rad/h (0.01 Gy/h) as a function of calorimeter column wrt the beamline in the highest radiation setting



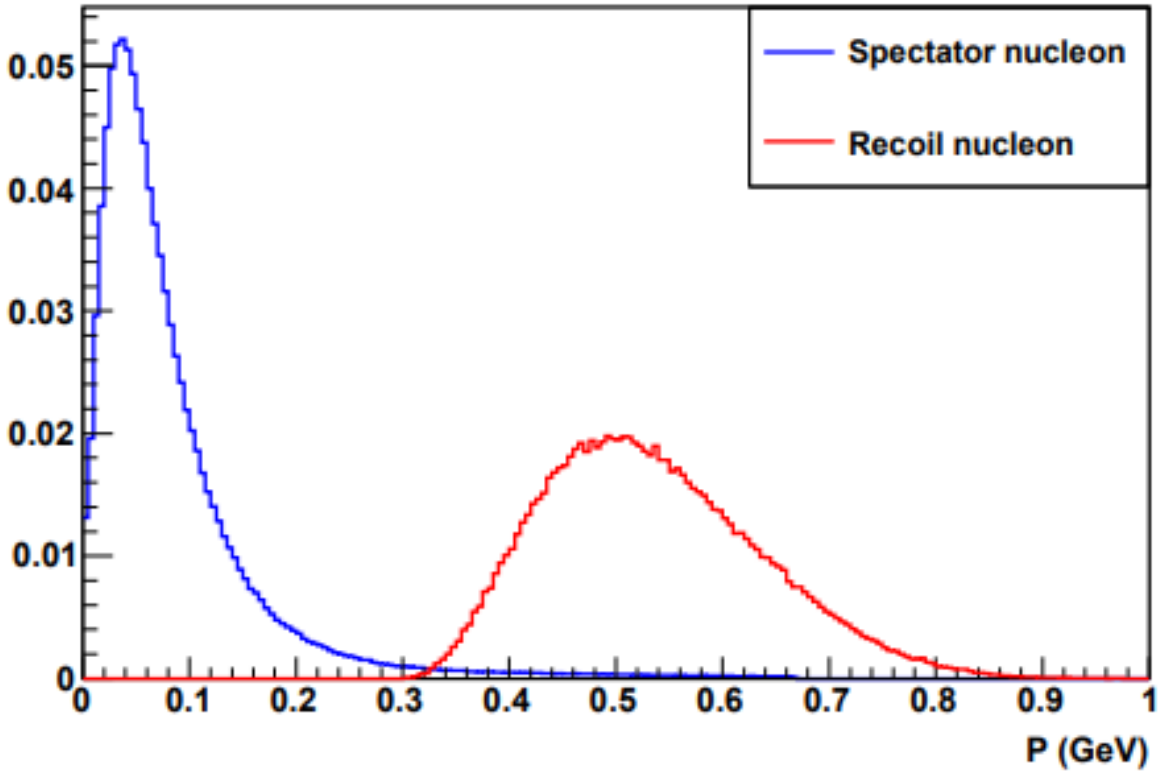
Max. rate: 10 Gy/h

Anticipated field in sweeping magnet





Impulse approximation: justification



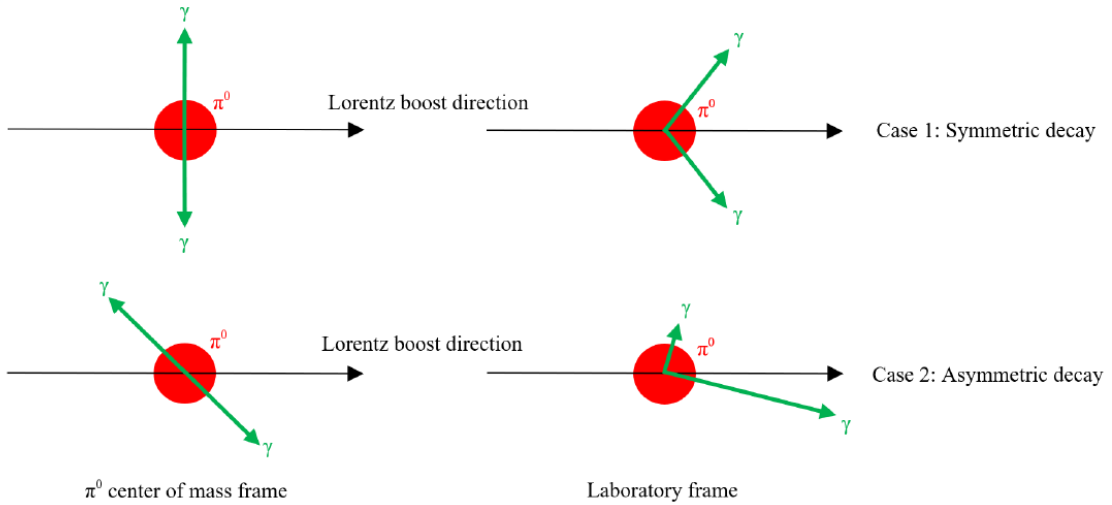
Momentum distribution of spectator proton (blue) in the deuteron (Fermi momentum distribution) and the n-DVCS recoil neutron (red) in the proposed kinematics (x_B=0.36 setting).
Overlap is less than 3%.

Systematic uncertainties

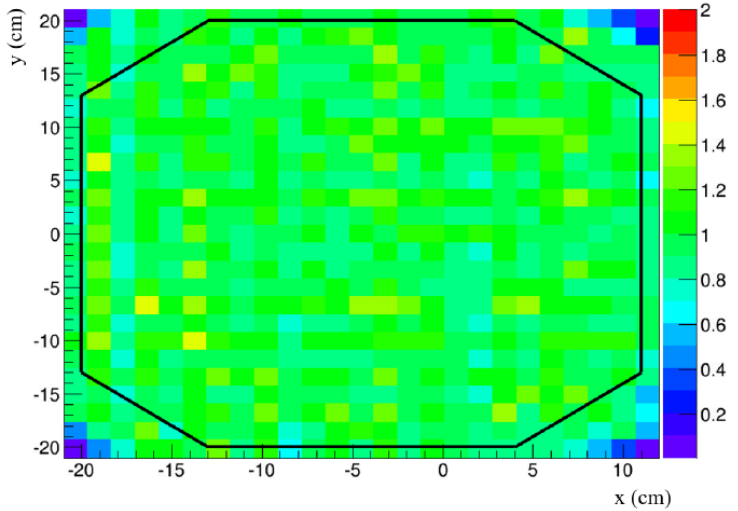
Source	pt-to-pt (%)	scale (%)
Acceptance	0.4	1.0
Electron ID	< 0.1	< 0.1
Efficiency	0.5	1.0
Electron tracking efficiency	0.1	0.5
Integrated luminosity	0.5	2.0
Target thickness	0.2	0.5
Kinematics	0.4	< 0.1
Exclusivity	1.0	2.0
π^0 subtraction (for DVCS)	0.5	1.0
Radiative corrections	1.2	2.0
Total	1.8 1.9	3.8 3.9

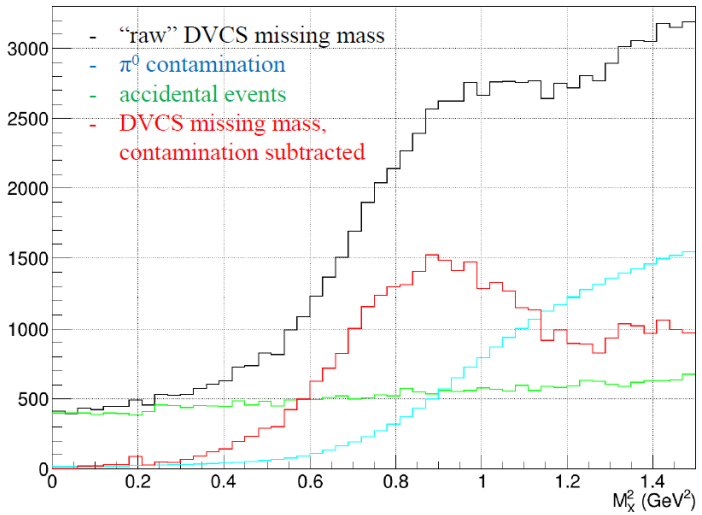
Estimated systematic uncertainties for the proposed experiment based on previous Hall C and Hall A experiments

π^0 subtraction



π^0 subtraction efficiency depending on the position in the calorimeter.

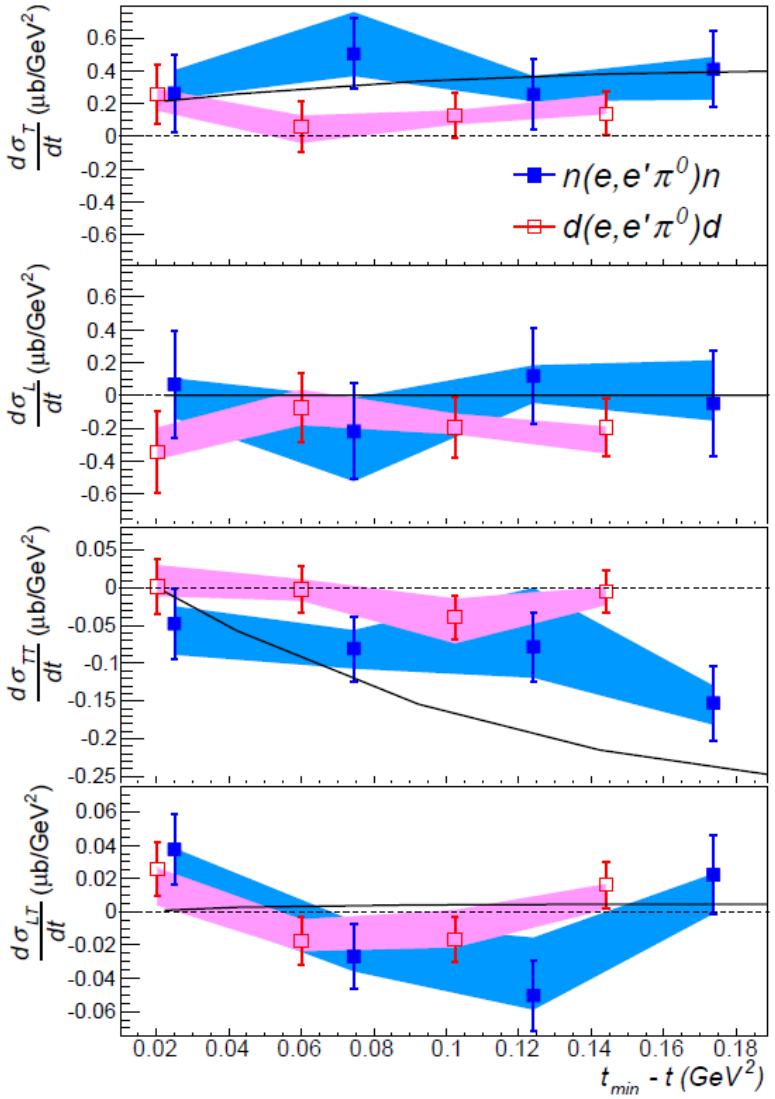


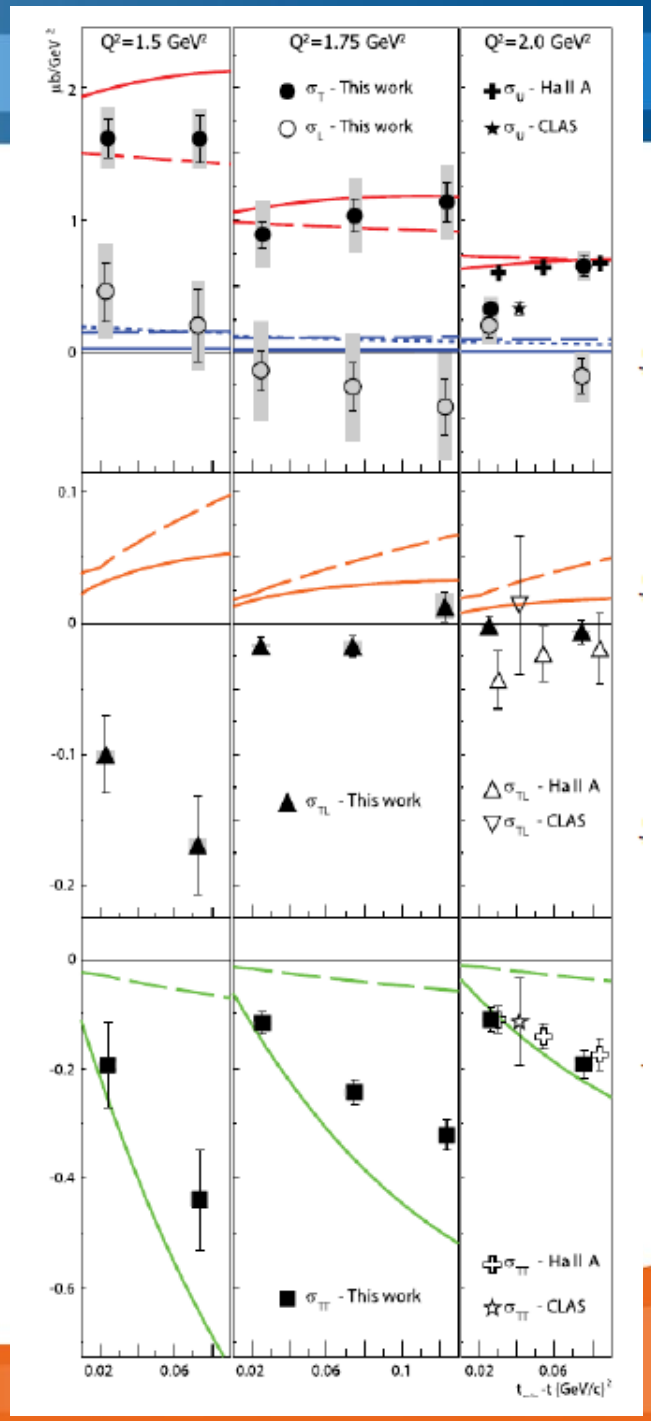


- **π^0 contamination** subtraction method:
  - **Identify π^0 in data**:
    - 2 photons.
    - Avoid calorimeter edges (energy leaks).
    - Invariant mass compatible with π^0.
  - For each π^0: MC simulation $\pi^0 \rightarrow \gamma\,\gamma$
  - **Subtract from DVCS data**:
    - Normalized MC events with only 1 photon detected.

→Advantage: **ep → e'p'π^0 cross section taken into account** by using π^0 data.

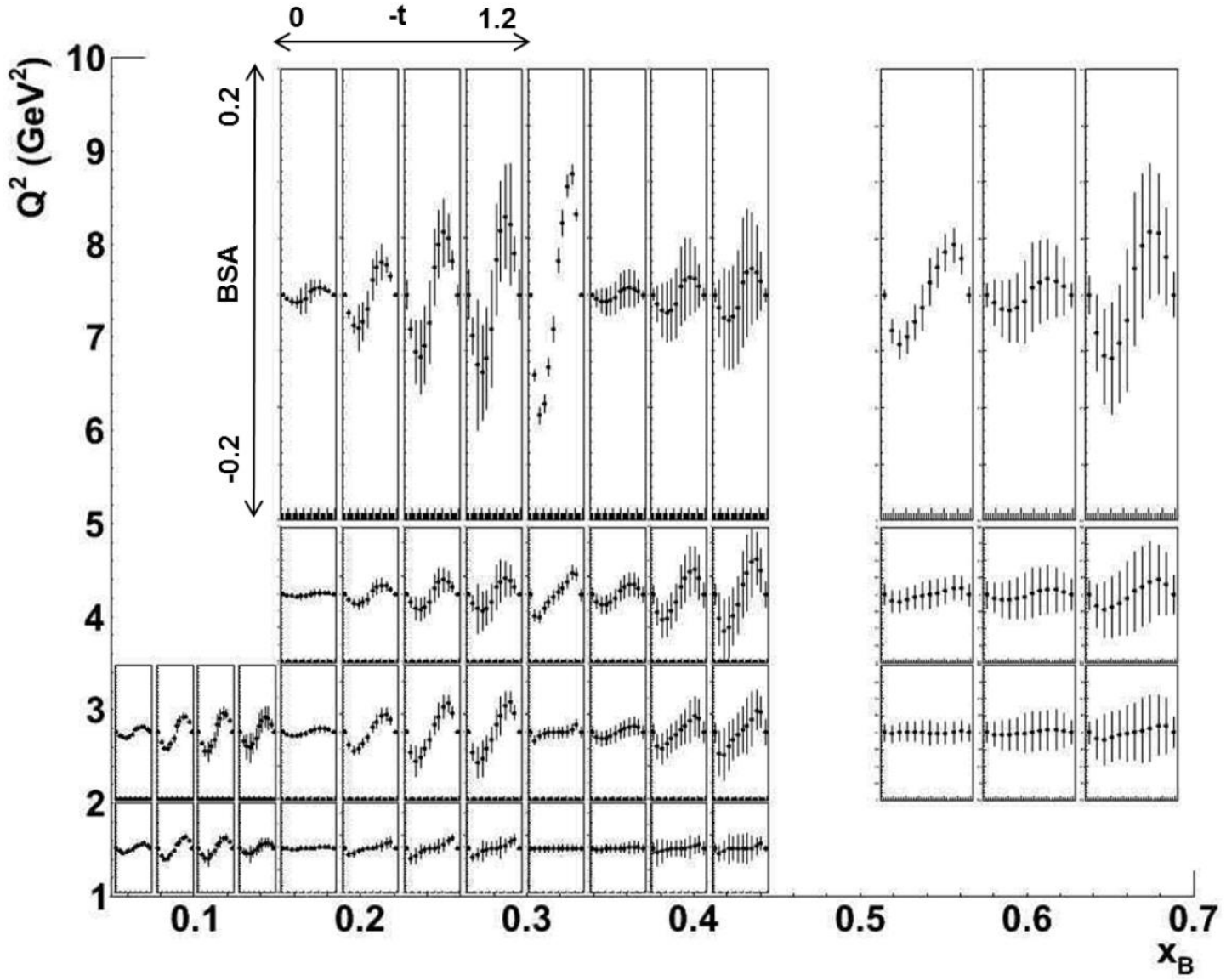
Exclusive π^0 electroproduction





nDVCS in Hall B

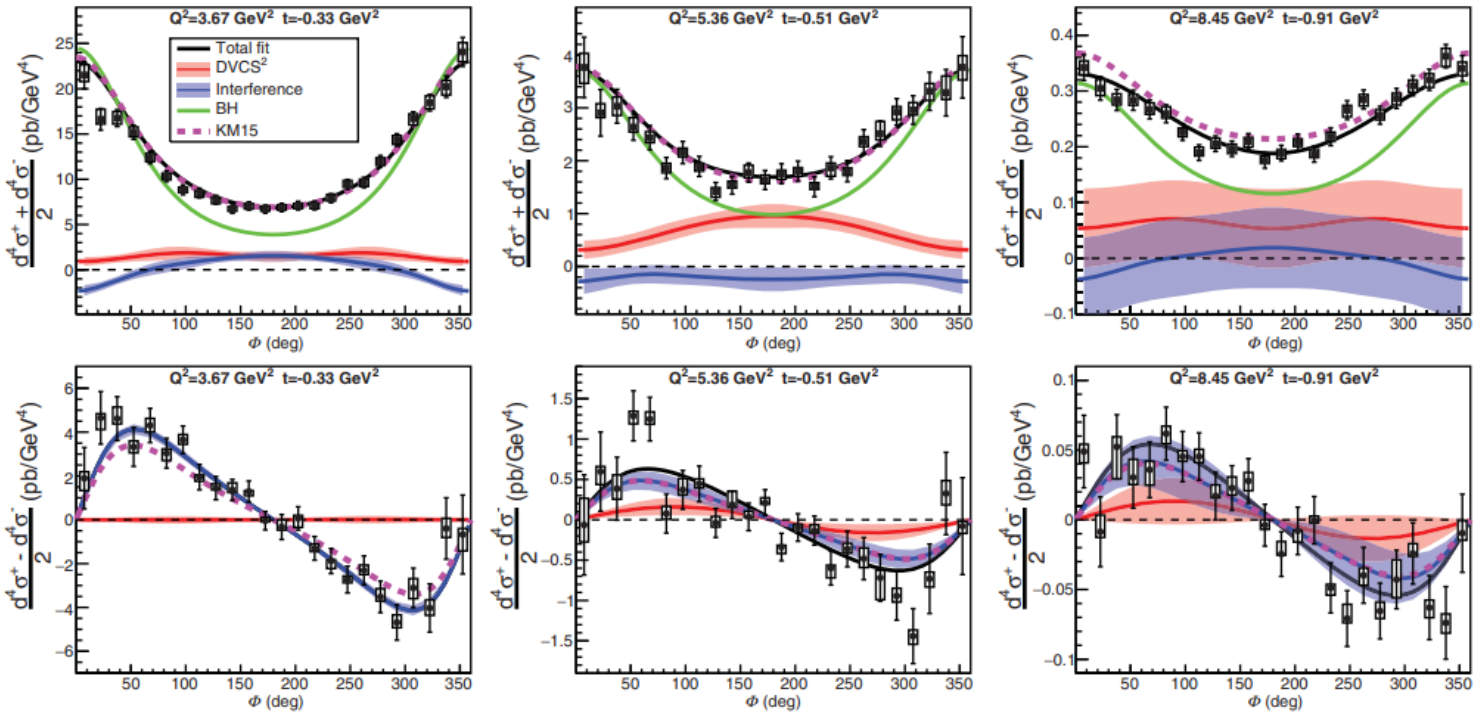
Beam spin asymmetries



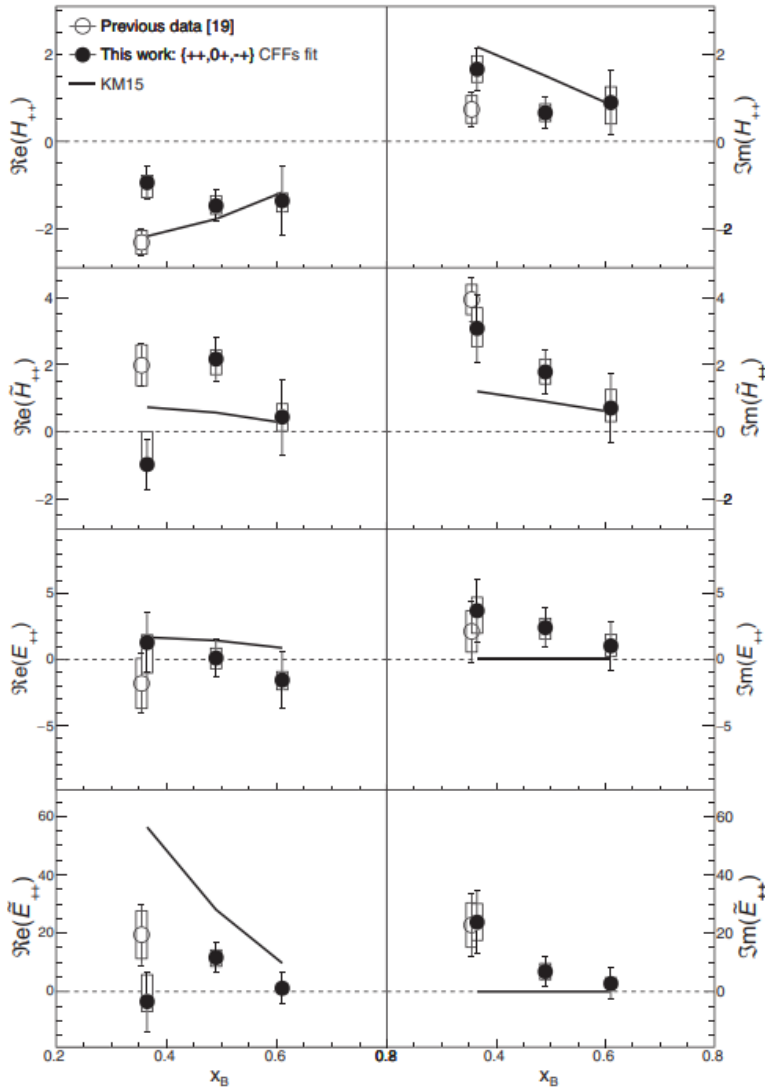
DVCS in Hall A at 12 GeV (E12-06-114)

Constraints in all 4 CFFs (Re & Im parts)

High precision
helicity-dependent & helicity-independent cross sections



$x_B \sim 0.36$ $x_B \sim 0.50$ $x_B \sim 0.60$



Phys. Rev. Lett. 128 (2022)

Exclusivity

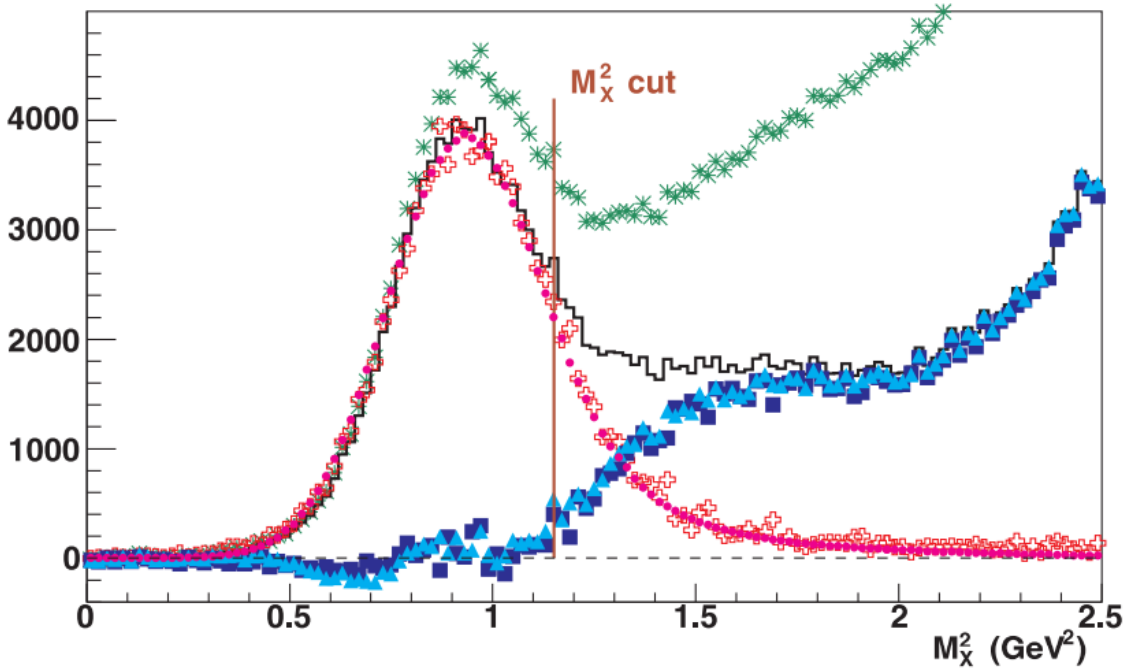
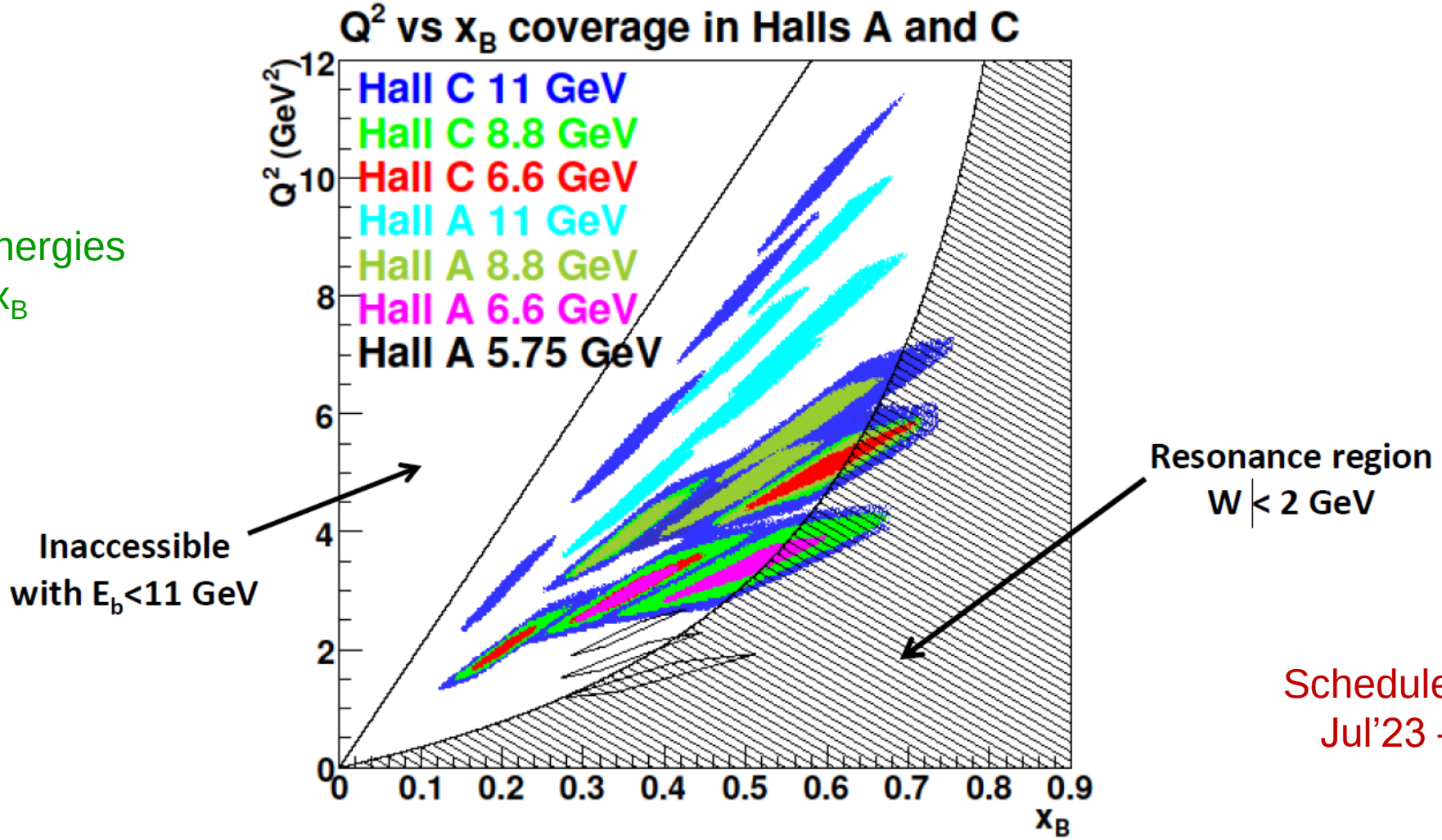


FIG. 2: (color online). Missing mass squared for $H(e, e'\gamma)X$ events (stars) at $Q^2 = 2.3$ GeV^2 and $-t \in [0.12, 0.4]$ GeV^2, integrated over the azimuthal angle of the photon $\phi_{\gamma\gamma}$. The solid histogram shows the data once the $H(e, e'\gamma)\gamma X'$ events have been subtracted. The other histograms are described in the text.

PRL97 (2006)

DVCS in Hall C

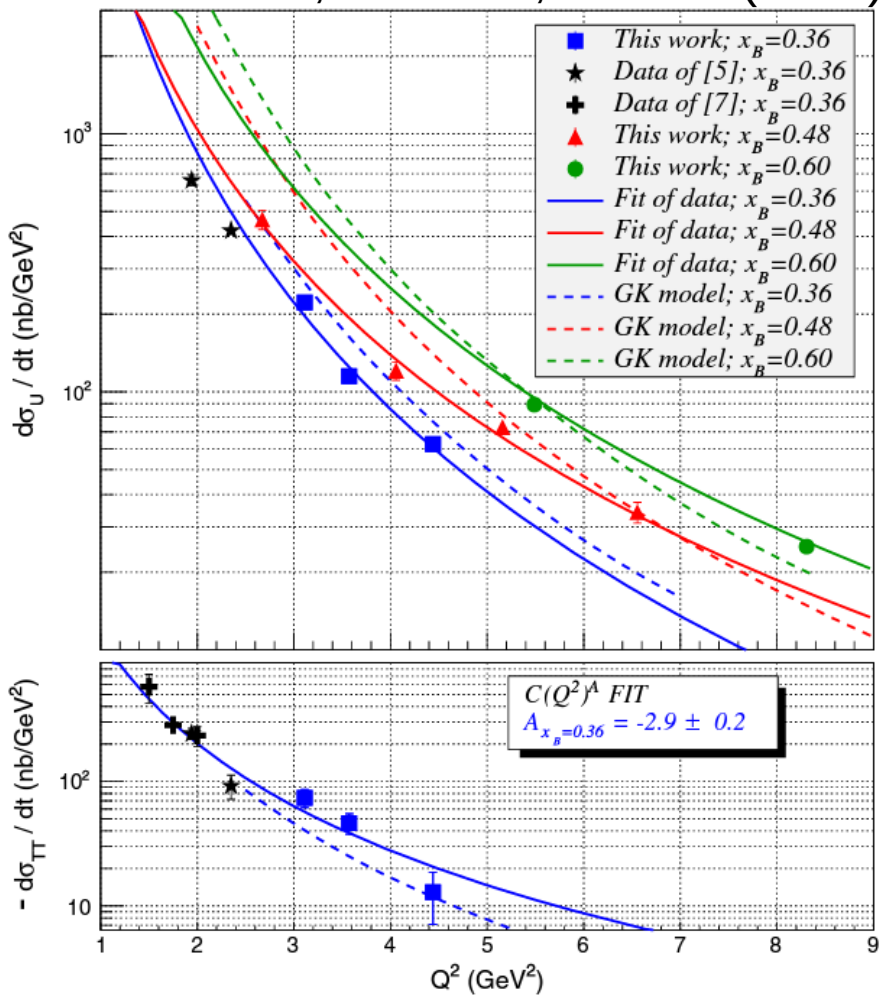
Different beam energies at fixed Q^2,x_B

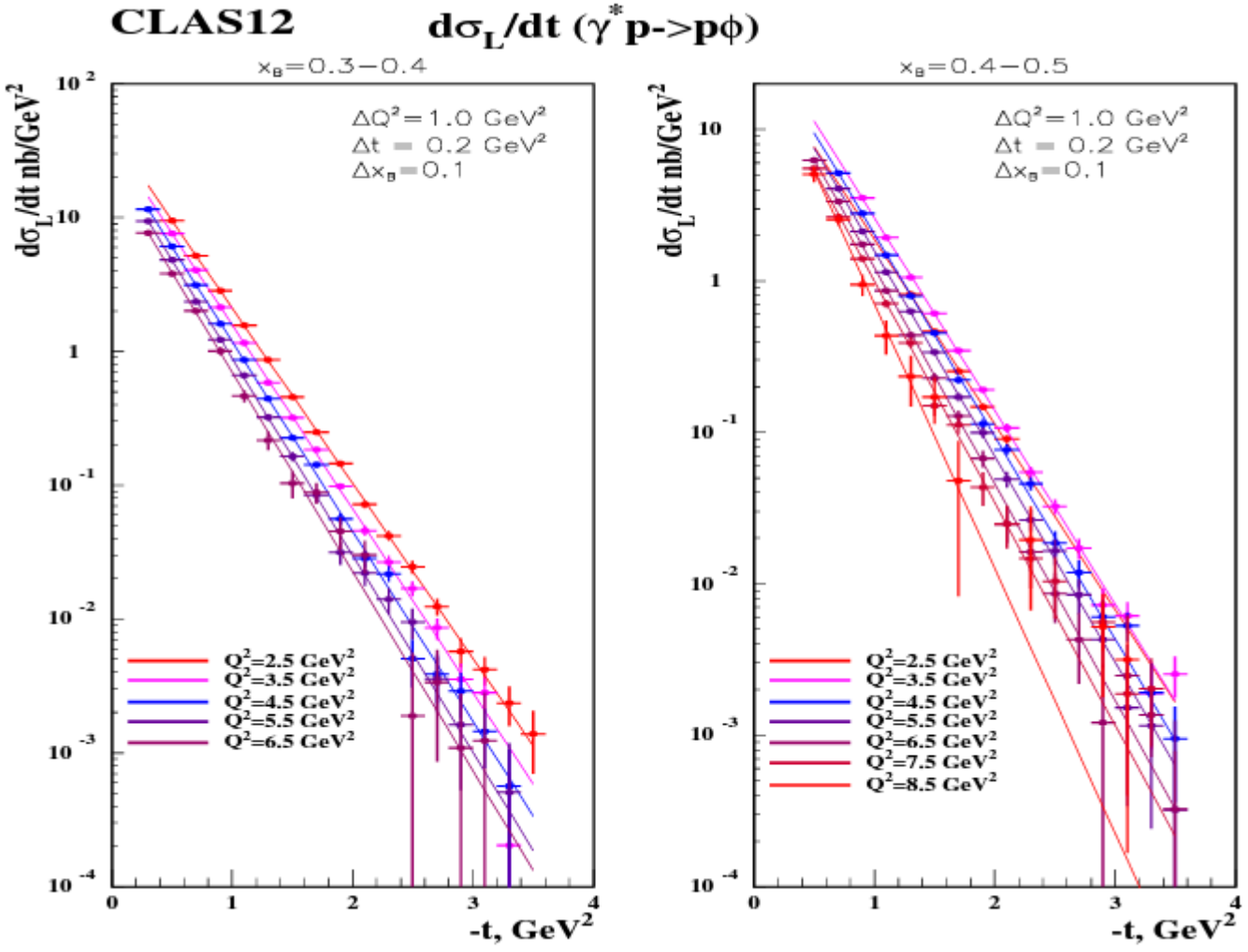


Scheduled to run in Jul'23 – Feb'24

Exclusive meson production

Hall A π^0, PRL 127, 152301 (2021)





Exclusive program experiments at JLab12

Measurement	Hall	Notes
DVCS	A,B,C	B includes long. & trans. target
nDVCS	B	Unp. & long. pol. target
DVCS w/ e+	B, C	
TCS	A (Solid), B, C	
Excl. π^0	A,B,C	
Excl. π^-	A (Solid), (B)	
Excl. ϕ, η	B	
L/T separation (K, π+)	C	
WACS (γ, π^0)	A, C	
Backwards π^0	C	