DVCS off the neutron with Super BigBite Spectrometer

Eric Fuchey
William & Mary

Towards Improved Hadron Tomography with Hard Exclusive Reactions
ECT*, Trento, Italy, August 5th-9th, 2024

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Nucleon Spin Puzzle and GPDs

$$S_N = \tfrac{1}{2} = \tfrac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

Well known | known | unknown

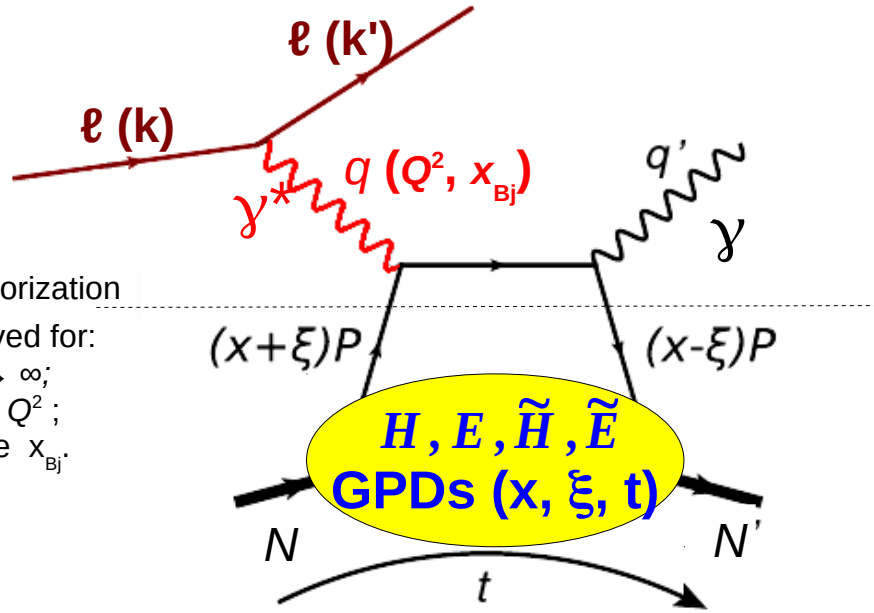
Static quark model: $\Delta\Sigma = 1$

EMC: small $\Delta\Sigma$
[Phys. Lett. B 206 (1988) 364]

Compass: **$0.26 < \Delta\Sigma < 0.36$**
[Phys. Lett. B 753, pp 18-28, 2016]

$L_{q,g}$? => needs "3D" parameterization

Exclusive reactions:
(DVCS: $\ell N \to \ell N\gamma$, HEMP: $\ell N \to \ell N h$)



Ji sum rule: $\int dx\, x\, [H+E](t=0) = 2J$
[Phys. Rev. Lett. 78, 610 (1997)]

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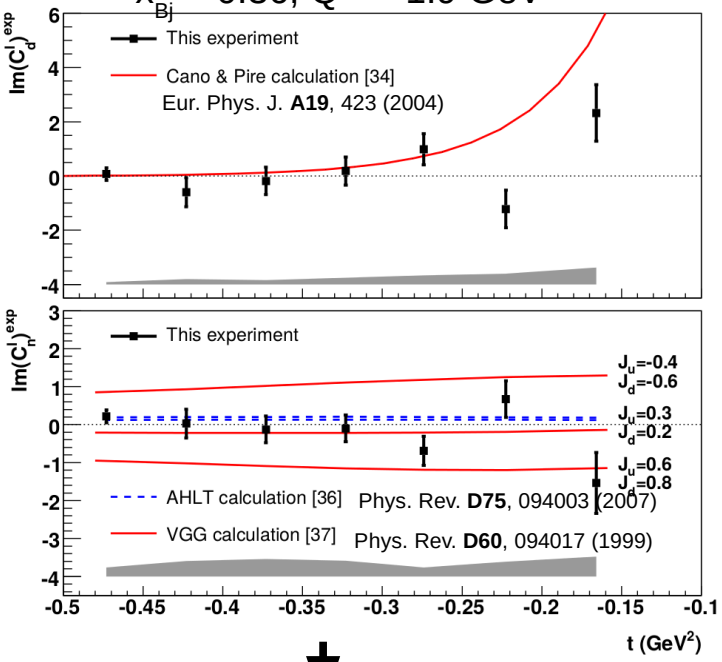
DVCS Off Neutron: Constraint on Quark AM

DVCS on neutron: => GPD E => quark AM J

Reminder: **Ji sum rule**: $\int dx\, x\, [H+E](t=0) = 2J$

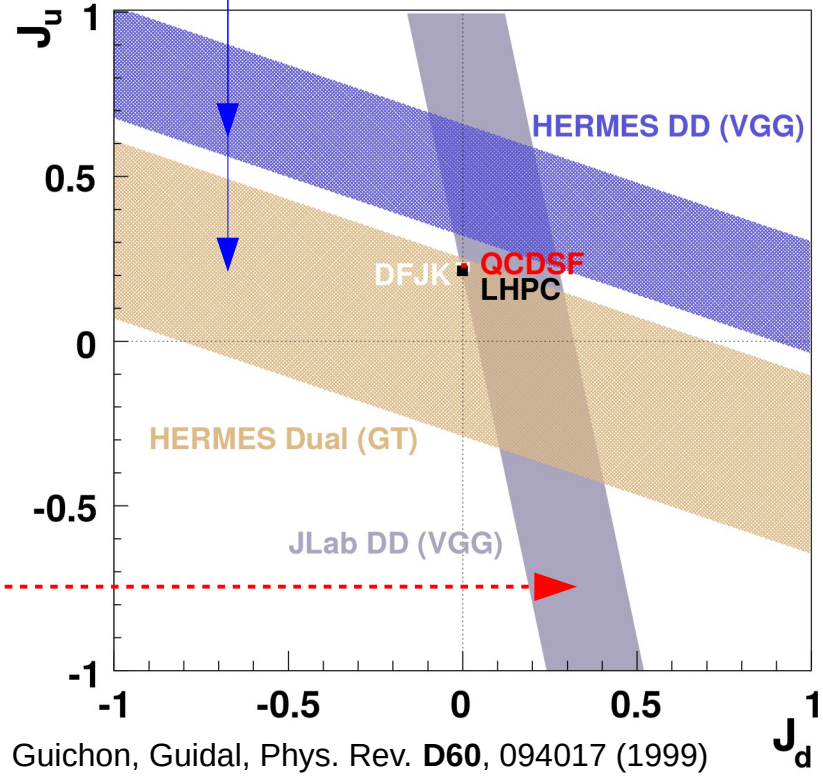
Compton Form Factors extracted from cross sections
[Mazouz and Hall A coll. : Phys. Rev. Lett. **99**, (2007) 242501]

x_{Bj} = 0.36, Q^2 = 1.9 GeV^2



constraint $J_{d,u}$

+HERMES TTSA on proton: ($J_{u,d}$)
[HERMES coll.: J. High Energy Phys. **0806** (2008) 066]

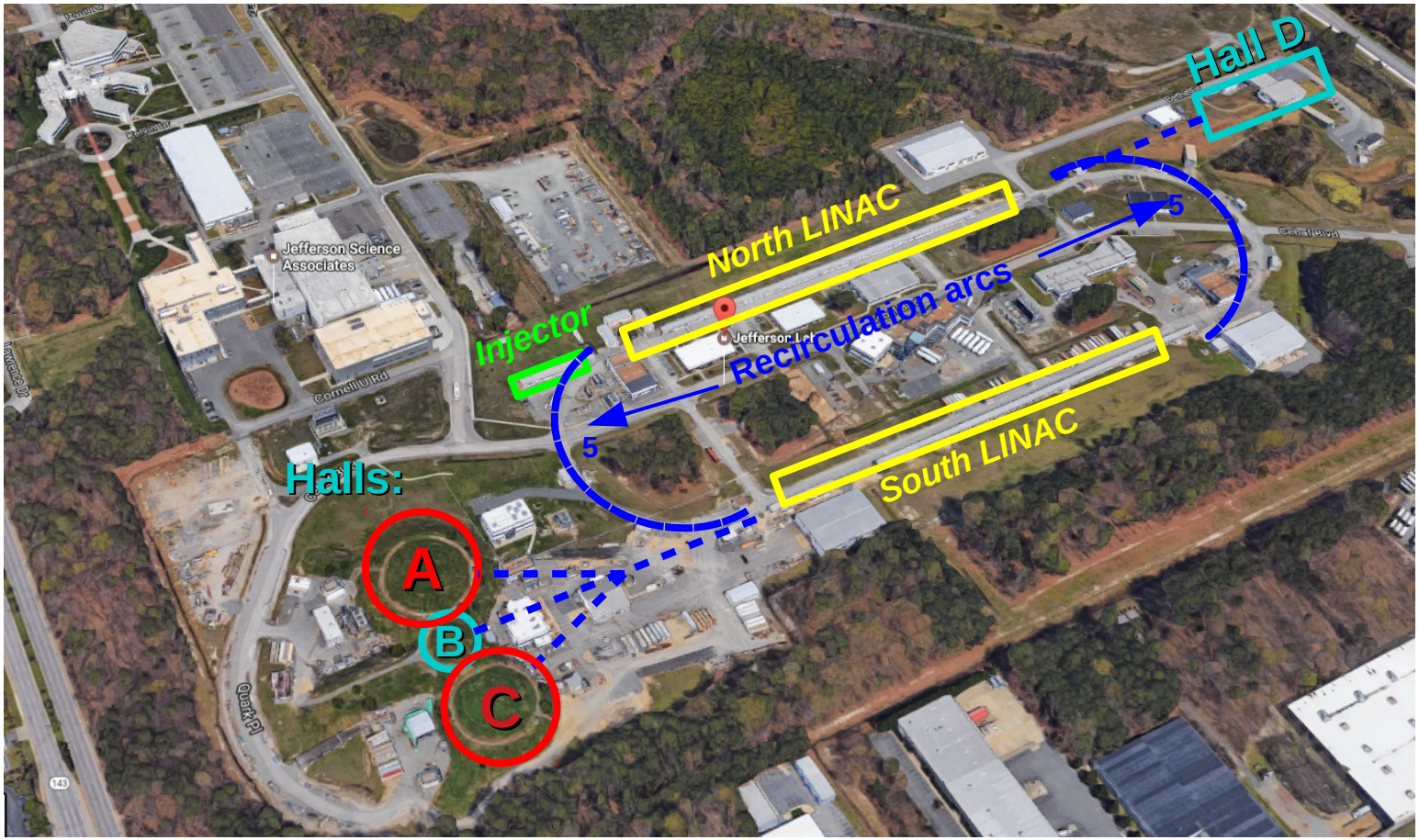


VGG: Vanderhaeghen, Guichon, Guidal, Phys. Rev. **D60**, 094017 (1999)
GT: Guzey, Teckentrup, Phys. Rev. **D74** (2006) 054027.
QCDSF/UKQCD Coll.: Eur. Phys. J. **A32** (2007) 445.
LHPC Coll.: Phys. Rev. **D77** (2008) 094502.
Diehl, Feldmann, Jakob, Kroll, Eur. Phys. J. **C39** (2005) 1.
} L-QCD

Additional nDVCS data will narrow down the experimental constraint

Hall A/C at Jefferson Lab 12 GeV

Jefferson Lab @ 12 GeV:
Continuous wave electron beam, I_{max}~70 μA, $Pol_{beam\ max}$ ≥ 80 %,
E_{max} = 11 GeV in Halls A, B, C (12 GeV for Hall D only).



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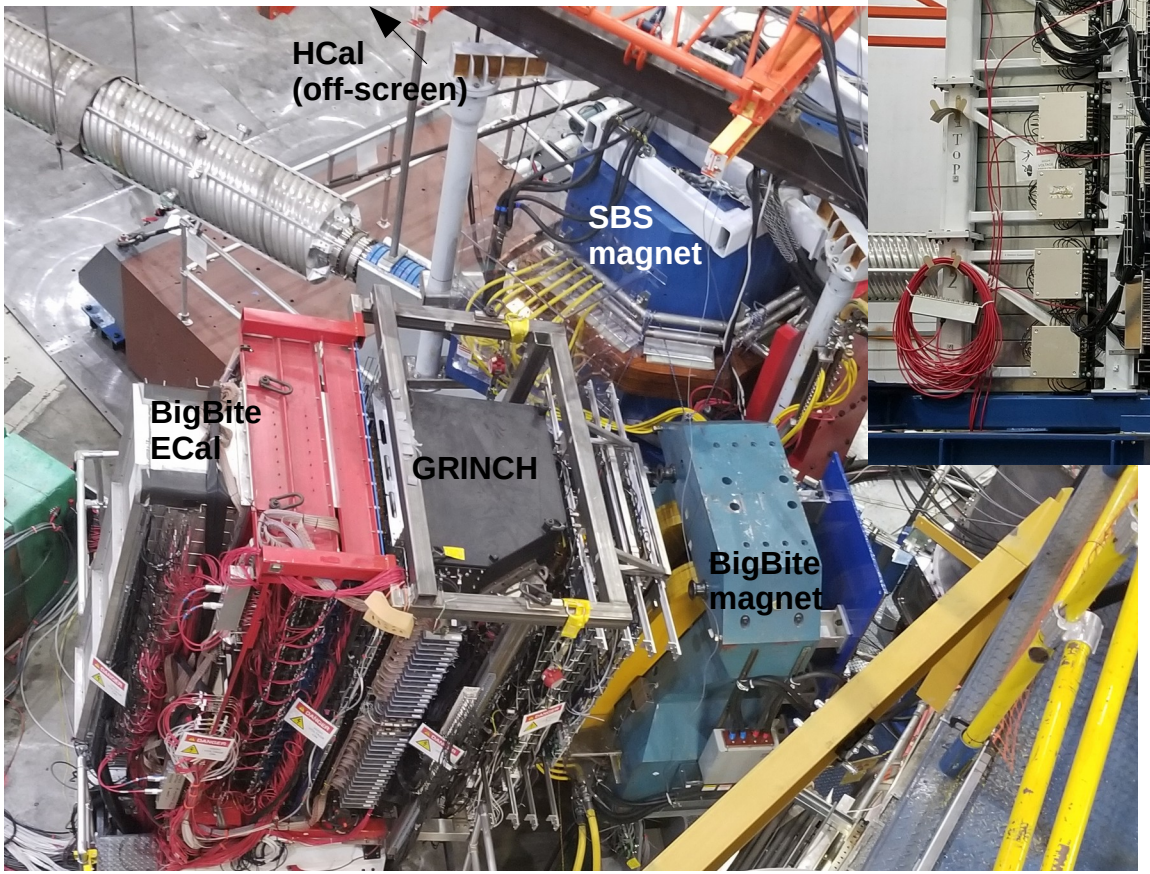
Super BigBite Spectrometer

Super BigBite spectrometer (SBS):

**** Major new project* for Hall A @ Jefferson Lab 12 GeV**;
* Modular detector package behind a dipole magnet.
* Program started in Fall 2021 with GMn, nTPE
*** May need to be relocated in Hall C after 2025**



Physics programs:

- *Form factors at high Q^2*:
  * G_E^p (LH_2, recoil pol);
  * G_M^n , G_e^n-RP (LD_2), G_E^n (pol. ^{3}He);
  * nTPE (two-photon exchange in *e-n* elastic scattering)
- Transverse Momentum Distributions:
  Semi-Inclusive DIS off pol. ^{3}He
- Structure functions w tagged *p*:
  * TDIS (mesons (π, K))
  * TDISn (neutron PDFs)
- **Generalized Parton Distributions: n-DVCS on deuterium with *spectator proton tagging***

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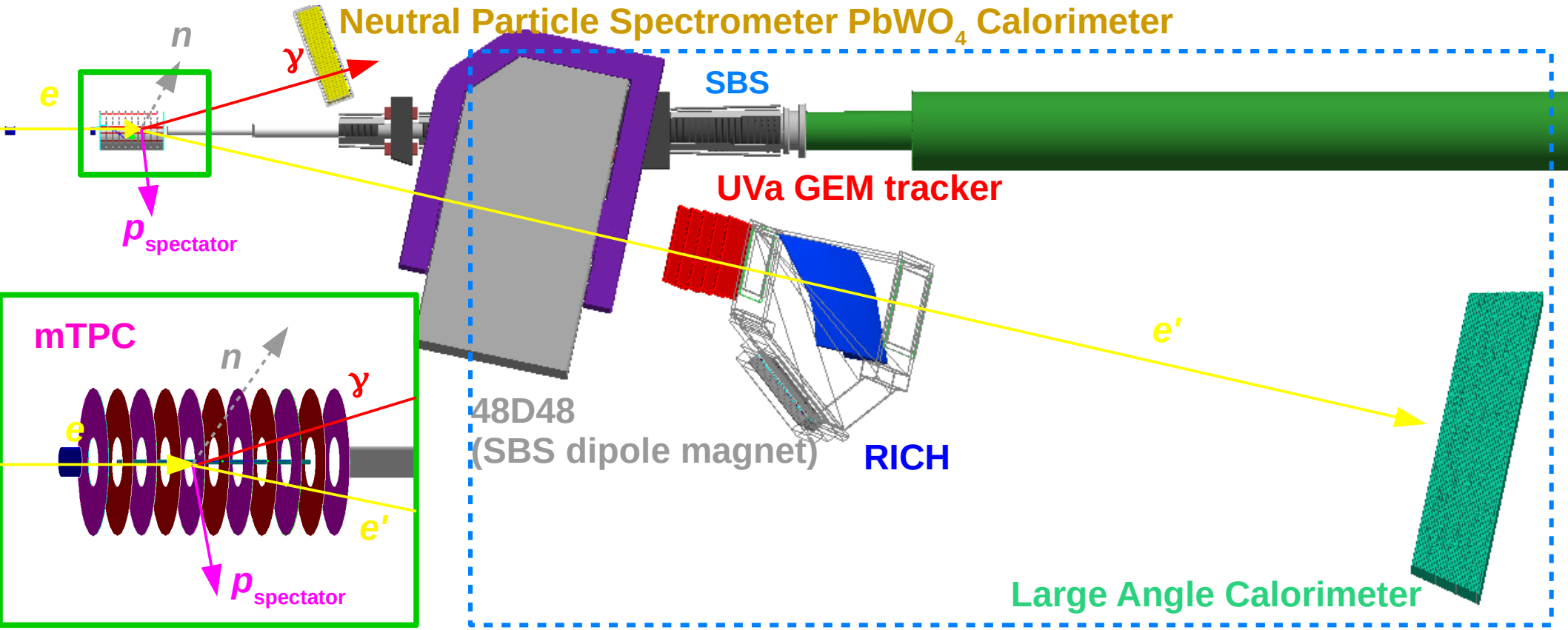
n-DVCS with Spectator Proton Tagging

LOI12-24-007 "Deeply Virtual Compton Scattering using the Tagged Deeply Inelastic Scattering Experimental Setup" (A. Camsonne, R. Montgomery, Z. Ye, *E.F.*)

* Run concurently with the TDIS experiment at 11 GeV, 25 μA on 40 cm, 4 atm gas D_2;
* Extend run with DVCS data at additional beam energies (8.8, 6.6 GeV)

nDVCS: **D(*e*,*e'*γ*p*$_{spec}$)*n***



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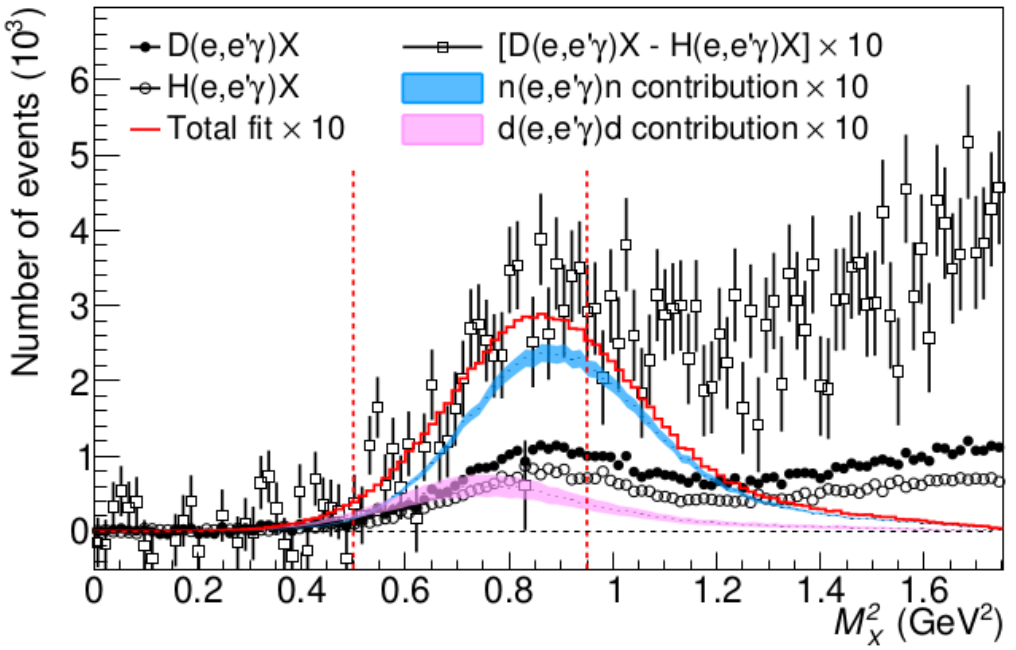
Advantages of Spectator Proton Tagging Technique

* **Unambiguous identification of *en*→*enγ* among *D(e, e'γ)X***
(highly desirable: without it, systematic uncertainty on n/p/d separation can be huge.)

* detection of spectator proton may provide better vertex and momentum resolution than e.g. detection of a neutron

=> spectator proton information may improve the resolution on the reconstructed missing mass of the system D(e, e'γ p_{spec})n



Example of D(e, e'γ)X data with no p/n disambiguation: data from Hall A 6 GeV
[M. Benali *et al.*, Nature Phys. 16 (2020) 2, 191-198]

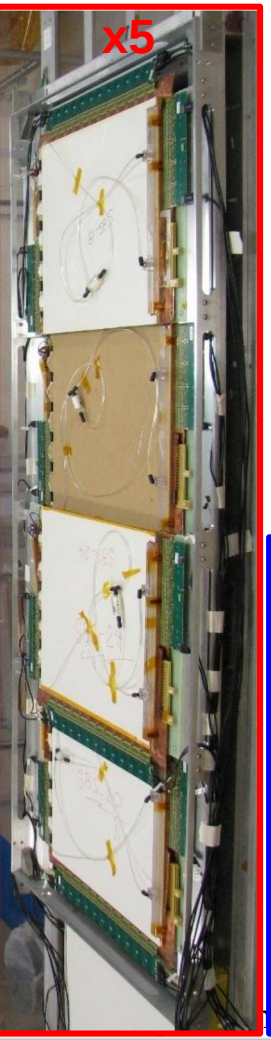
$$M_X^2 = (k + N(\vec{p} = \vec{0}) + k' - q')$$

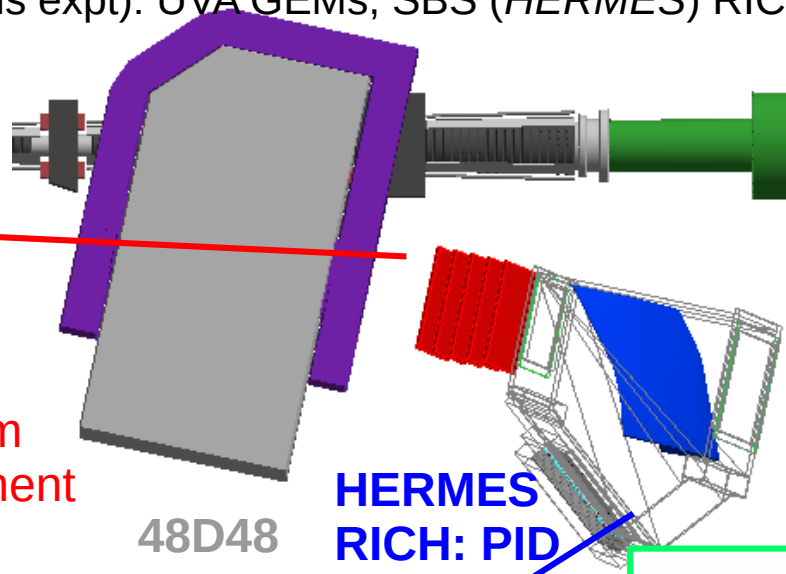
SBS configuration for TDIS/nDVCS

Super BigBite Spectrometer: medium solid angle dipole with modular detector package.

Purpose:* measure scattered electrons:** (D(*e*,e'γp***$_{spec}$*n*)

Detector package (for this expt): UVA GEMs, SBS (*HERMES*) RICH, Large Angle Calorimeter (Hall B CLAS6)





UVA GEM tracker: momentum measurement

48D48

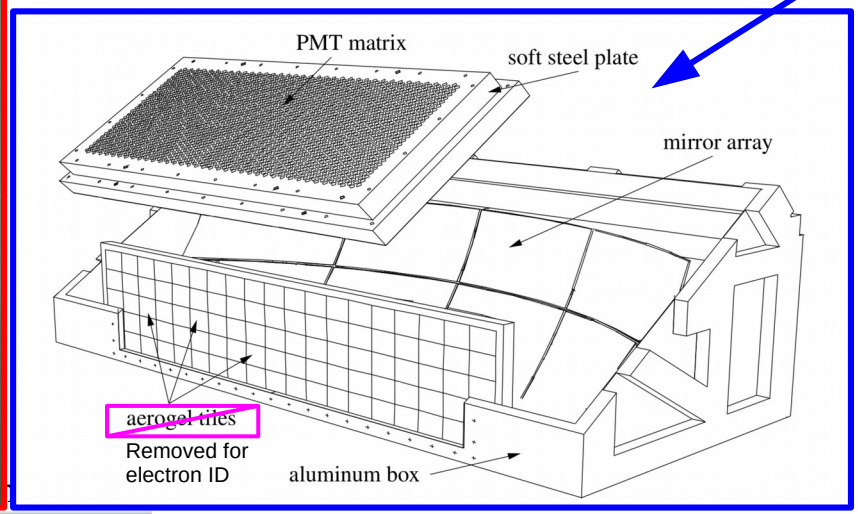
HERMES RICH: PID

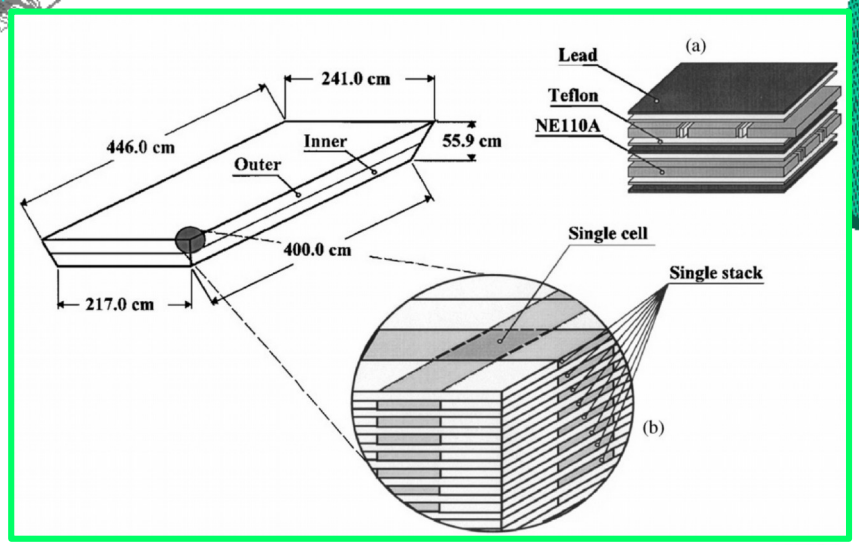
SBS: ~60 msr at 2.5 m

$\sigma_p/p < 3\ 10^{-4}\ p + 2.9\ 10^{-3}$

σ_v (mm) = (0.53 + 4.49 / p) / sinθ

Large Angle Calorimeter from CLAS6: PID, Trigger





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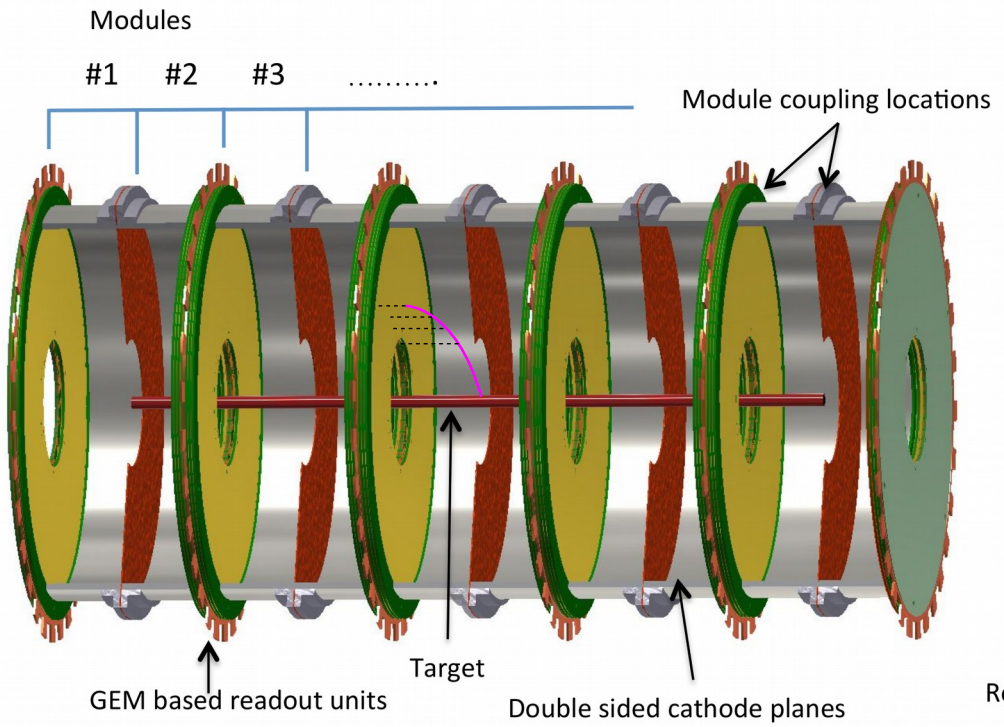
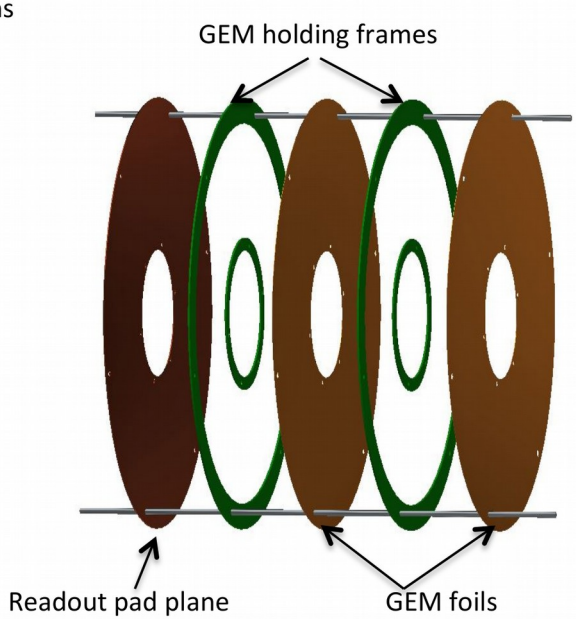
Multiple Time Projection Chamber (mTPC)

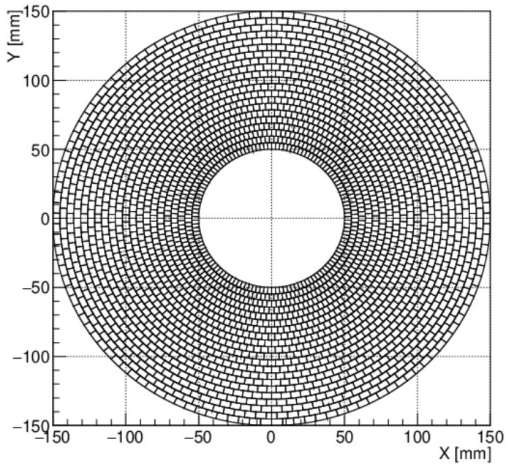
Purpose: **detect low momentum spectator proton** (D(e,$e'$$\gamma$$p_{spec}$)$n$) in ***high background***

Actively developed for Tagged DIS experiment (H/D(e, e' p_{spec})X) by UVA.

* Split into 10 modules => drift time ~ 1-2 μs => "high" luminosity ~ 3.0 10^{36} cm^{-2} s^{-1}.
* Electric field // magnetic field;
* Drift electron amplified by GEM foils
* Readout by pads.







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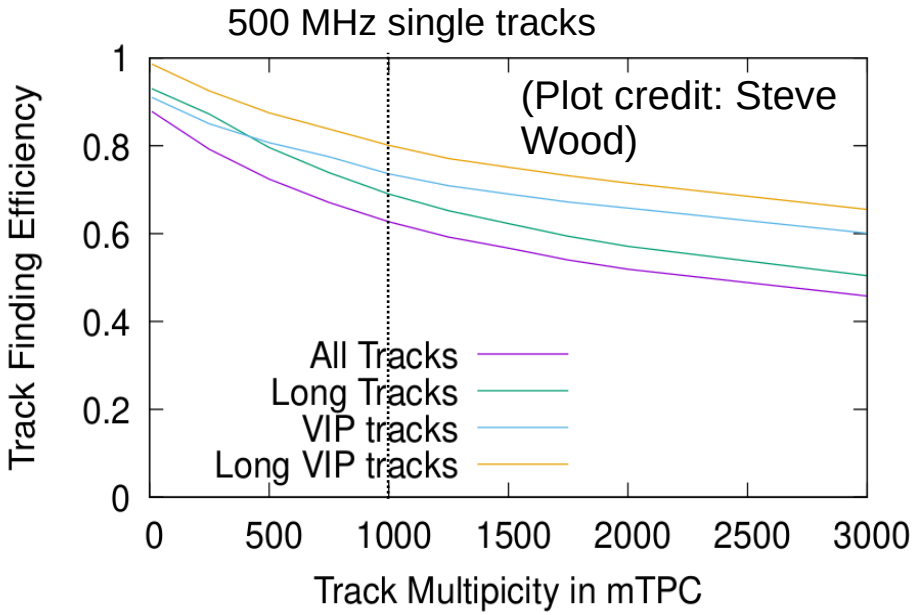
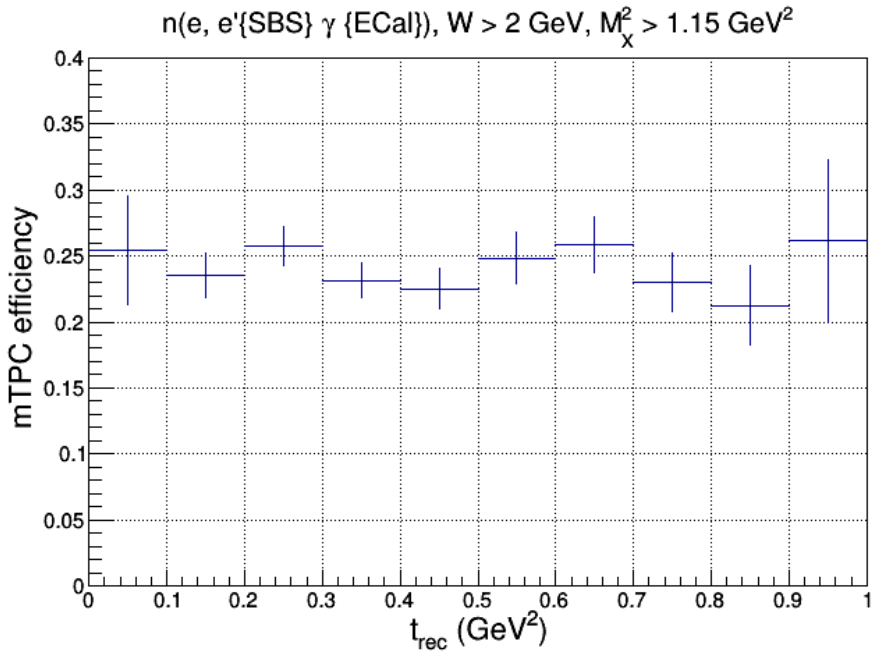
mTPC projected performance

Purpose: **detect low momentum spectator proton** (D(*e*,*e'*$\gamma$$p_{spec}$)*n*) in ***high background***

Expected single tracks rate *over the full mTPC* for 25 uA on 40 cm D_2 at 300K, 4 atm: **550 tracks**
mTPC design combined with appropriate tracking algorithm => ≥60% tracking efficiency.

~25 % n(e, e' γ)X events correctly tagged with spectator proton
(*no dependence in t*)





Long tracks: tracks with ≥4 pads hit
VIP tracks: protons, 70<p<400MeV/c 30<θ<80 deg

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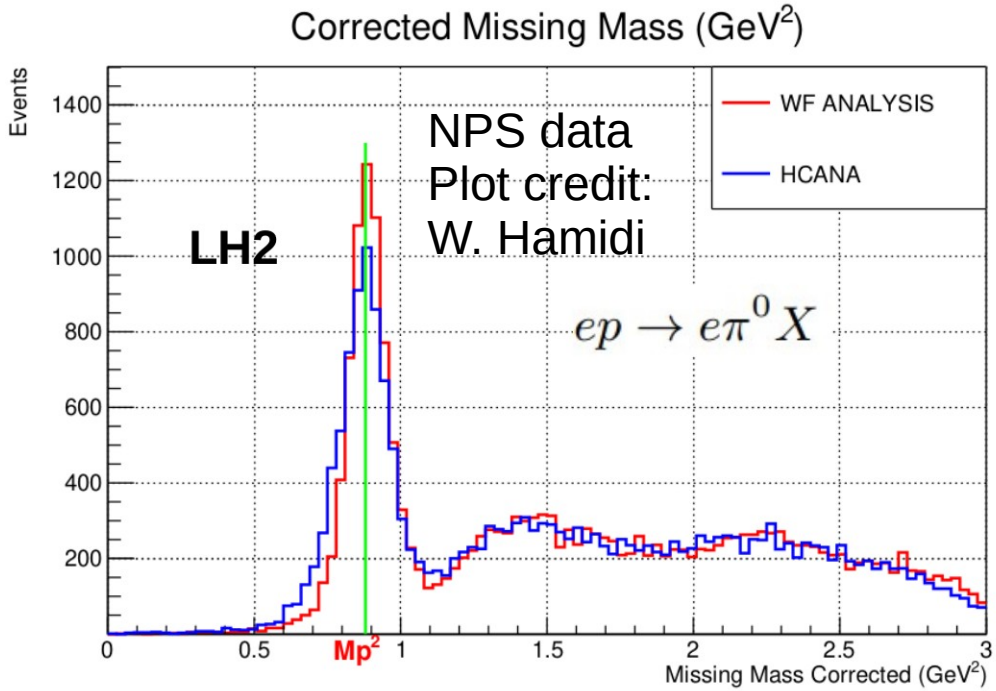
NPS Electromagnetic Calorimeter

NPS Calorimeter:

Purpose: **detect the high energy photon** (D(*e*,*e'*γp_{spec})*n*)

NPS $PbWO_4$ calorimeter:

1116 (36x31) $PbWO_4$ blocks, 2.05x2.05*18 cm^3.



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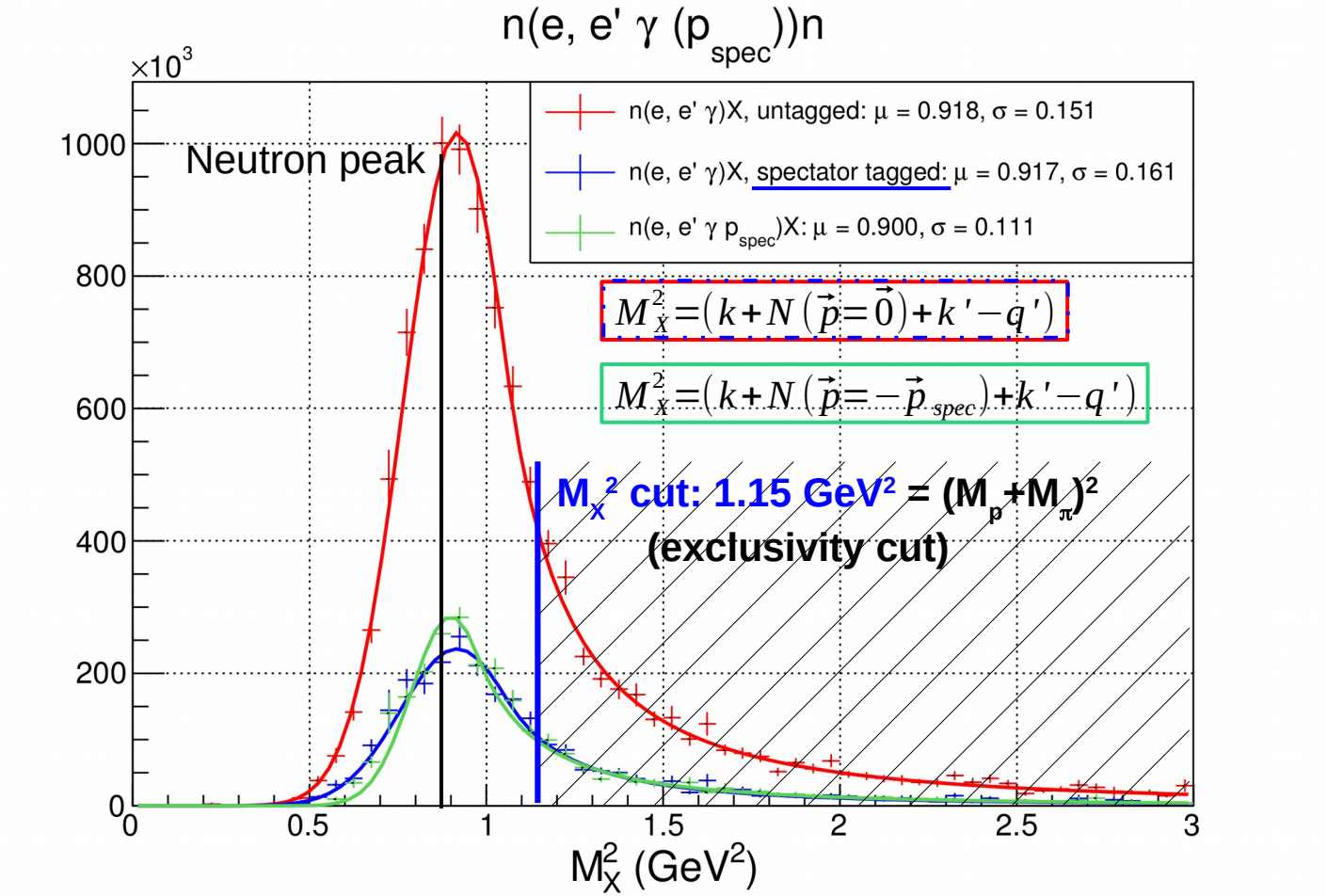
Missing Mass Resolution

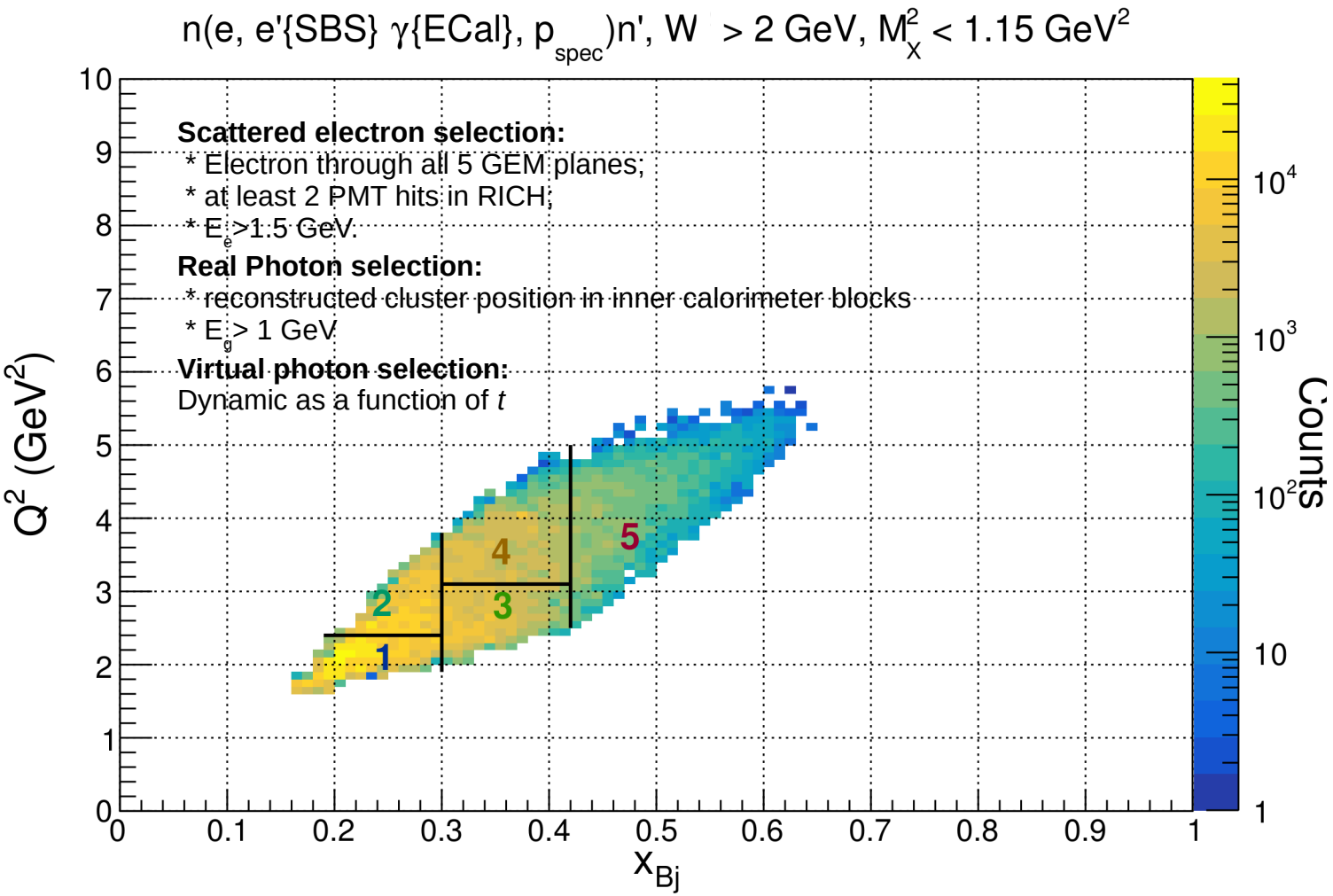
Reconstructed missing mass squared:
After inclusion of SBS (preliminary) resolutions: σ_p~0.5 %, σ_v~6.6 mm
and $PbWO_4$ calorimeter (preliminary) resolutions: σ_E~2.5 %, σ_X~5.0 mm



Inclusion of spectator proton in final state gives modest improvement on missing mass squared likely due to magnitude of radiative tail

Kinematic Coverage

Q^2, x_{Bj} coverage at **11 GeV**, 25 μA on 40 cm, 4 atm gas D_2
after selection on SBS and calorimeter, spectator proton association, exclusivity cut



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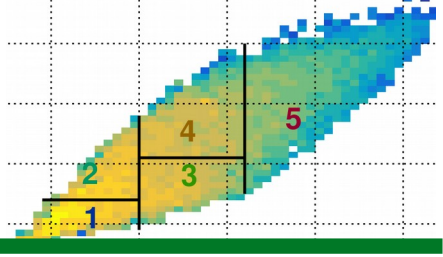
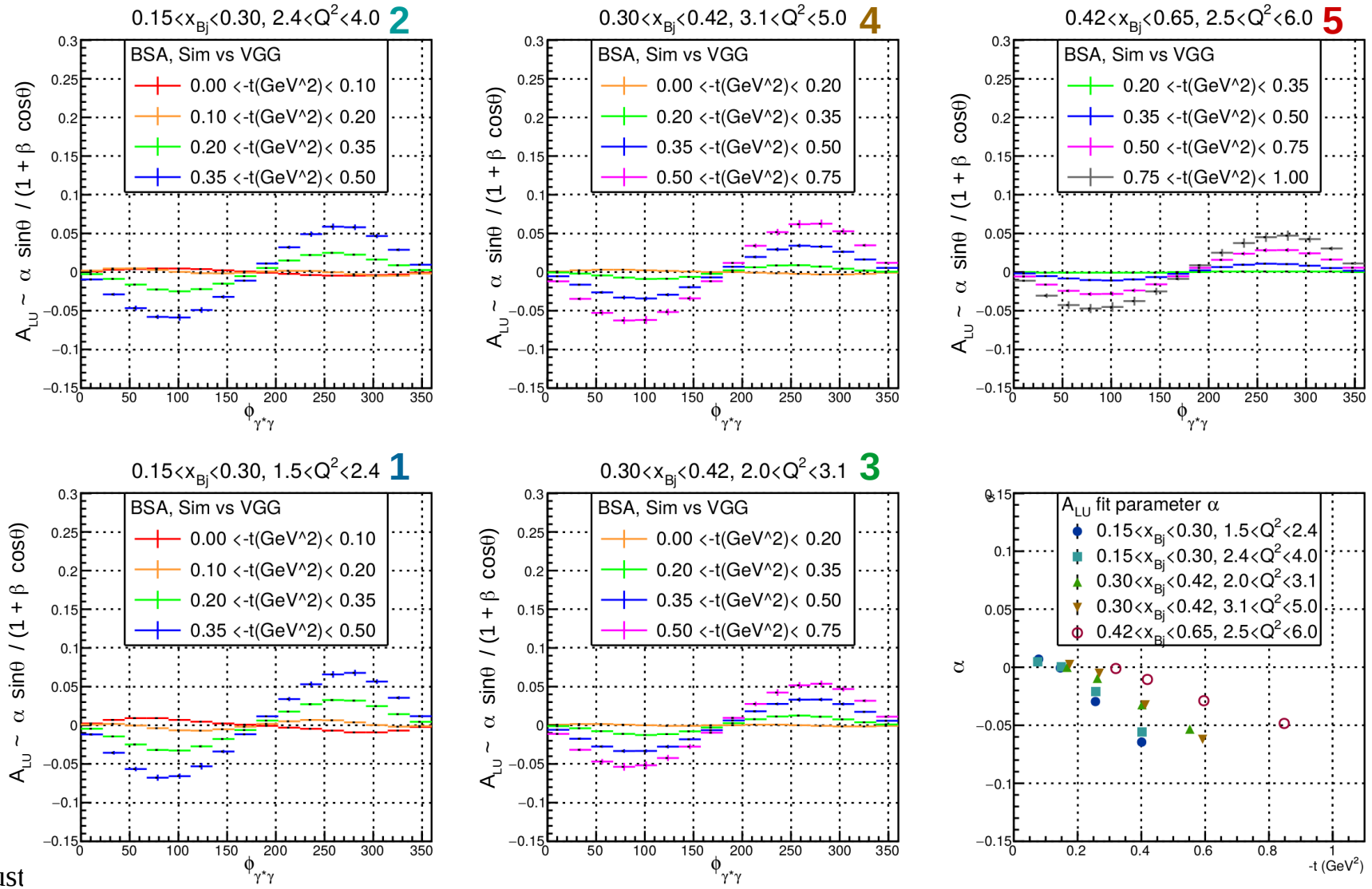
Beam Spin Asymmetries



11 GeV, 5 days beam at 25 μA on 4atm D_2 gas target: **$1.5\ 10^{36}$ cm^{-2} s^{-1} n^{-1}.**



> 700 k tagged $en \rightarrow en\gamma$ events (estimations with VGG)

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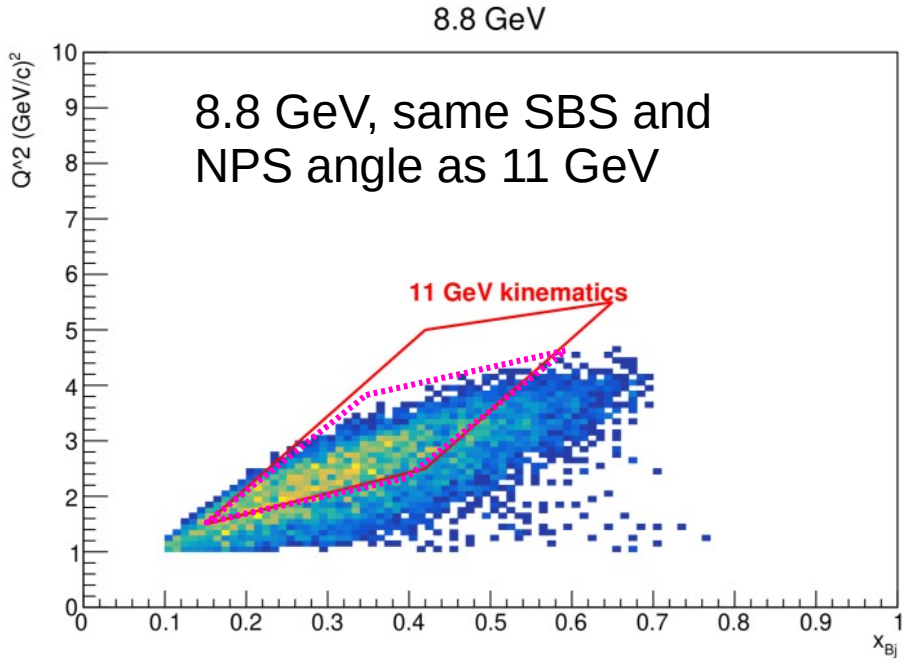
Additional Settings
DVCS data at different beam energies

* Extend run at other beam energies (8.8, 6.6 GeV) for $DVCS^2$/DVCS-BH interference

* Requires enough overlap between respective x_{Bj}-Q^2 coverages of different beam energies;
  - may require moving SBS i.e. may require input from Hall A/C engineers

*** Work In Progress:**
  - settings may be adjusted for 8.8 GeV
  - rates for 8.8 GeV, 6.6 GeV to be evaluated

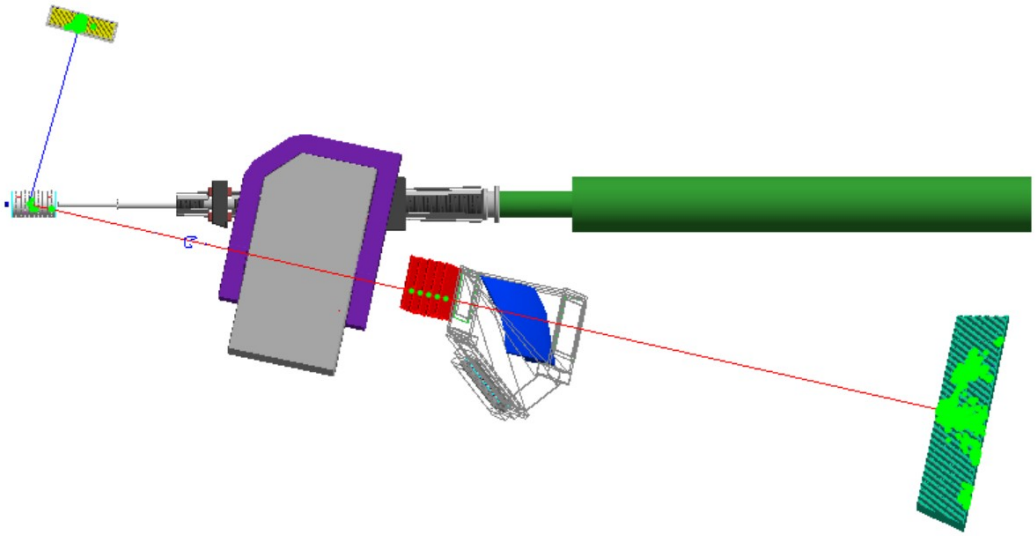


Additional Settings:
NPS calorimeter calibration

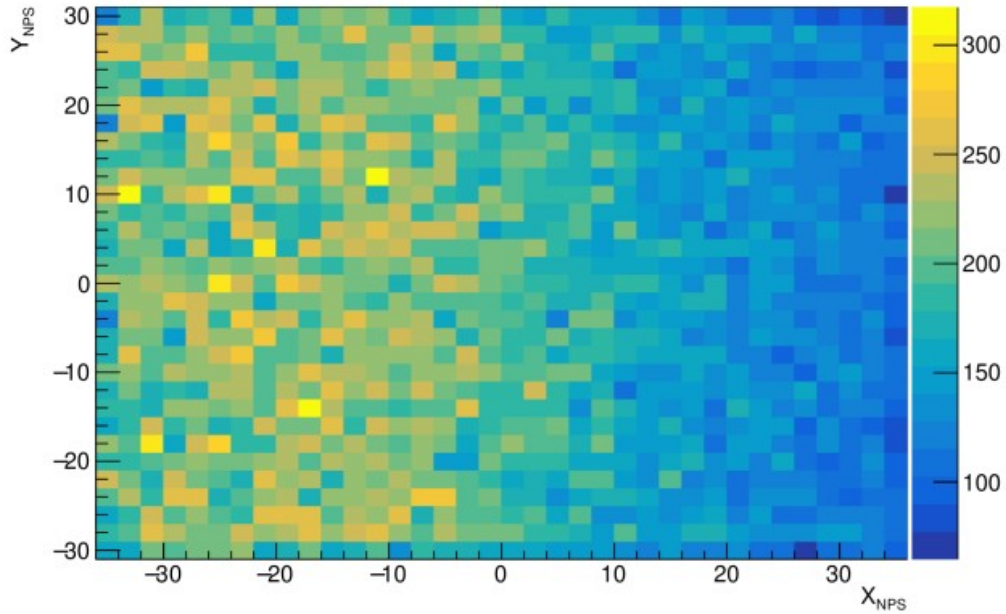
* Electron arm at the same angle, SBS polarity reversed to measure protons;

* NPS at 80 degrees to detect electron (electron calcuated from proton info);

* 4.4 GeV beam, 5 μA on 40 cm water target;



Elastic counts for 24h



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List of items for a full proposal

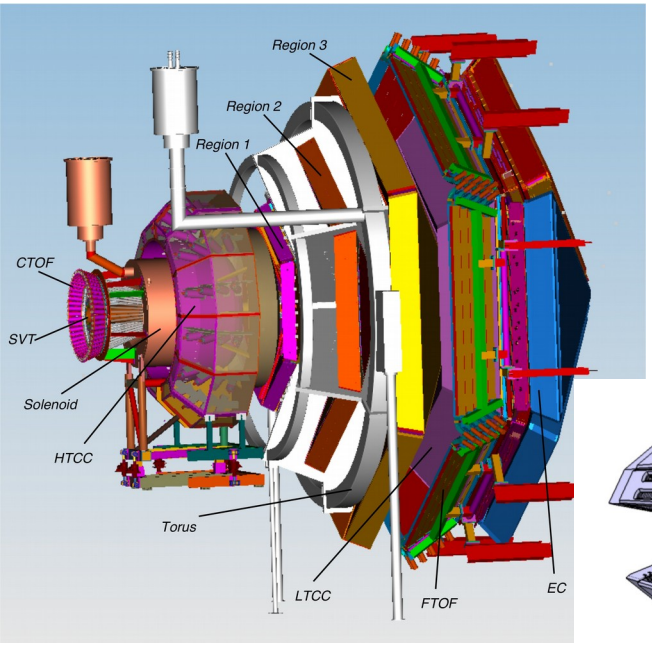
* Input from Hall A/C engineers to ensure mechanical compatibility between the exisiting TDIS setup and the NPS calorimeter (and stand)

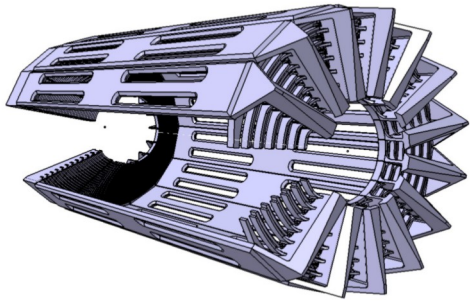
* Comprehensive rate calculations for 8.8 and 6.6 GeV:
  - moving SBS may be needed to ensure significant overlap in Q^2, x_{Bj} between all 3 beam energies;
  - requires input from engineers;

* Evaluation of π^0 background with inclusive π^0 generator from P. Bosted updated with NPS data;

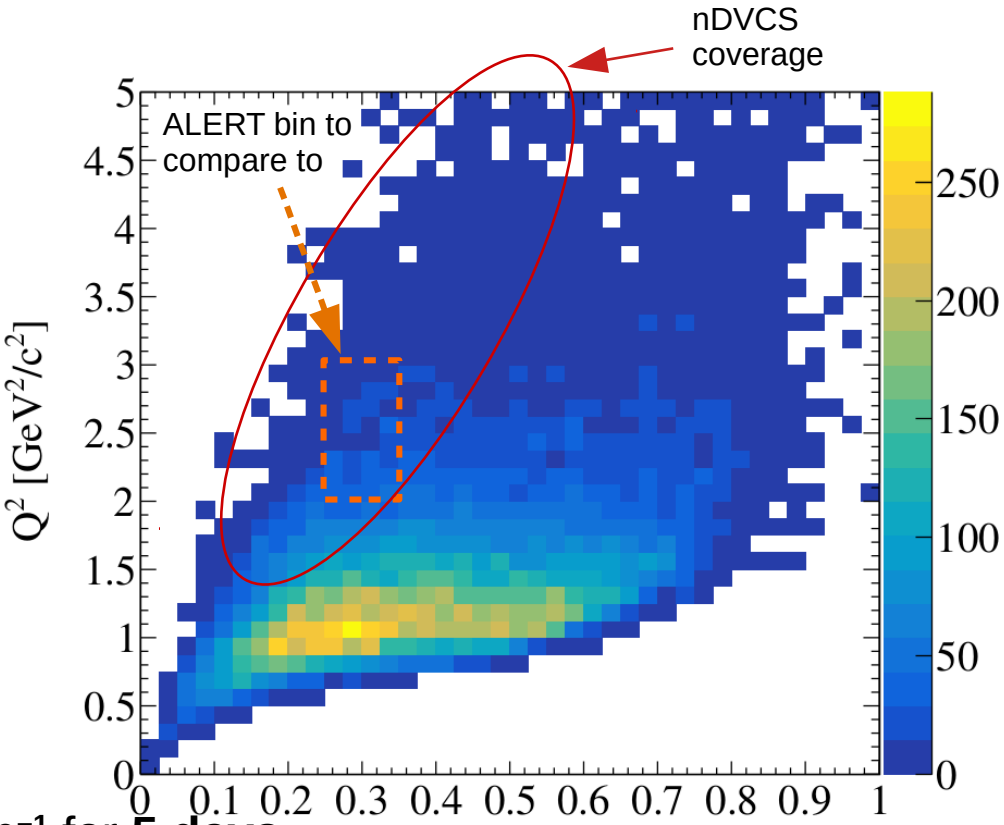
Comparison with ALERT

ALERT (A Low Energy Recoil Tracker) will measure DVCS off ^{4}He and D with CLAS12





Direct comparison between ALERT and n-DVCS on: $0.25 < x_{Bj} < 0.35$, $2\ \text{GeV}^2 < Q^2 < 3\ \text{GeV}^2$



ALERT CLAS12 vs nDVCS Hall A SBS:

Wider kinematic coverage for ALERT

nDVCS with SBS: Luminosity **1.5×10^{36} cm^{-2} s^{-1} n^{-1}** for **5 days**

ALERT with CLAS12 in Hall B: Luminosity **3×10^{34} cm^{-2} s^{-1} n^{-1}** for **20 days** at 11 GeV.

* Additional beam energies for nDVCS with SBS;

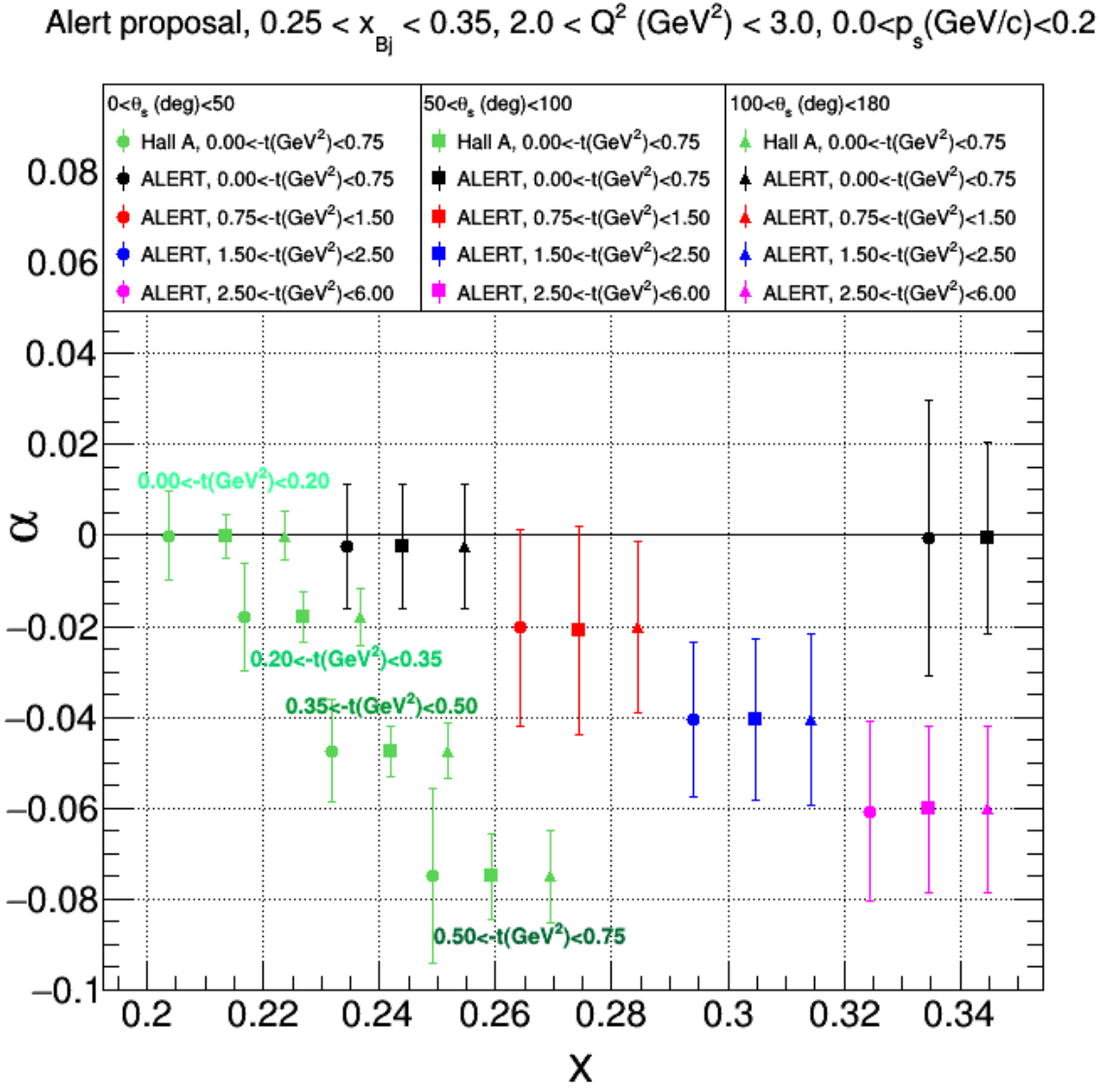
* 10x more statistics on the region of overlap for nDVCS with SBS (higher Q^2 at x~0.3);

Comparison with ALERT

(0.25 < x_{Bj} < 0.35,
0.0 < P_s (GeV/c) < 0.2)

Bin	x	Q^2	t	θ_s	P_s
units		GeV^2	GeV^2	°	GeV/c
	0.05	1	0	0.0	0.0
	0.25	1.5	0.75	50	0.2
	0.35	2.0	1.5	100	0.35
	0.5	3.0	2.5	180	0.5
	0.8	10	6.0		

Our projections are in green



nDVCS Hall A SBS vs ALERT CLAS12:
Lower kinematic coverage but higher statistics

Summary

* nDVCS with spectator proton tagging constitutes a great addition to the existing and future nDVCS experiments:

- *unambiguous* nDVCS detection;

* Proposed experiment would run jointly with TDIS on deuterium for 5 days, and take additional beam time for NPS calibration (1 day) and nDVCS at other beam energies (5 days per beam energy):

- estimated ~700 k tagged $en \rightarrow en\gamma$ counts total at 11 GeV;
- 8.8, 6.6 GeV to be prepared;

* **Complementarity** with ALERT and other neutron DVCS experiments such as *n*DVCS with recoil neutron detection:

- Hall B experiments have better kinematic coverage;
- nDVCS has sigificantly better statistics namely at higher Q^2 and will record several beam energies

* Overall positive feedback from PAC!

- PAC values the scientific case and recommends preparation of a full proposal;
- very constructive discussions with PAC referee (Kresimir);
- working to transform it into a full proposal *next year!*

Thank you for your attention !

Expected results:
Projections

Beam time, luminosity:

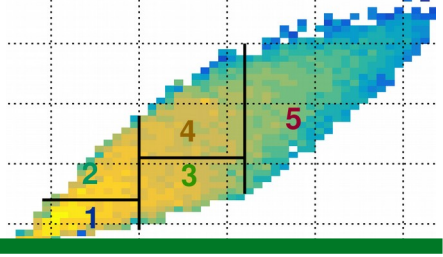
We wish to run at the same time as Tagged DIS experiment in Hall A
=> 5 days beam on deuterium target at 25μA on 4atm D_2 gas= **$1.5\ 10^{36}$ cm^{-2} s^{-1} n^{-1}.**

TDIS existing beam time request				
Target	Current (μA)	Beam Energy (GeV)	Beam Time (hrs)	Notes
Hydrogen	50	11	264	includes 1 day for commissioning
Deuterium	25	11	144	includes 1 day for commissioning
Hydrogen Deuterium	5 5	11 4.4	120 16 8	 mTPC calibration with HCAL Beam Energy Changes
Total (TDIS)			552	23 days
Preliminary additional beam time request for n-DVCS				
Hydrogen Total (n-DVCS only)	6	4.4	24 24 12 60	SBS move DVCS calorimeter calibration Møller measurements 2.5 days
Total (TDIS + nDVCS)			612	25.5 days

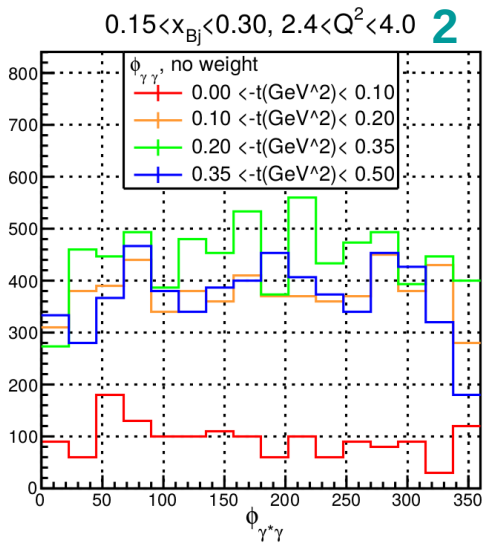
NB: additional time requested for:

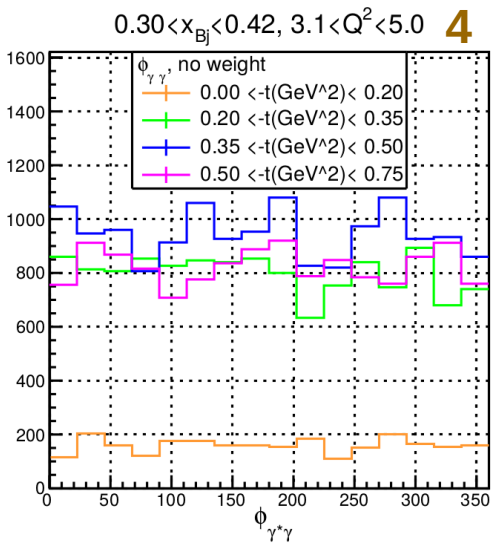
- DVCS calorimeter calibration (implies SBS movement...)
- Beam Polarimetry (2-3 Møller runs, 4 hours each)

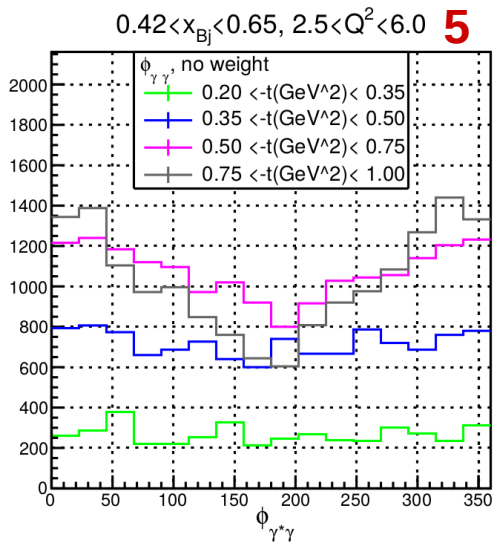
Kinematic coverage

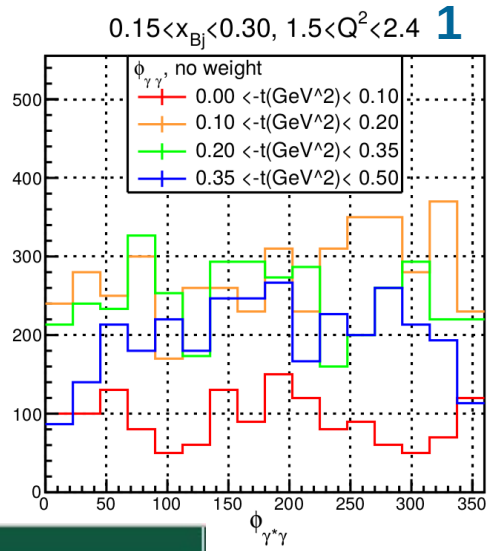


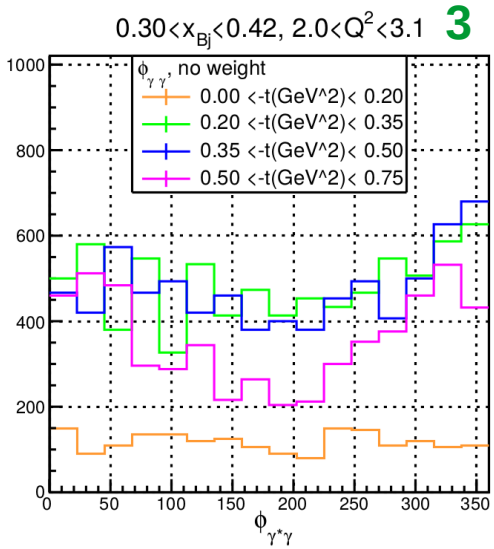
***t*, ϕ coverage** (no XS weight) after selection on SBS and calorimeter, spectator proton association, exclusivity cut for each x_{Bj}, Q^2 bin





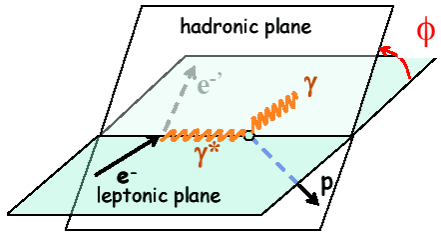






Real Photon selection:
* reconstructed cluster position in inner calorimeter blocks
* $E_g > 1$ GeV

Virtual photon selection:
Dynamic as a function of *t*



Phi distribution ~uniform in *t*

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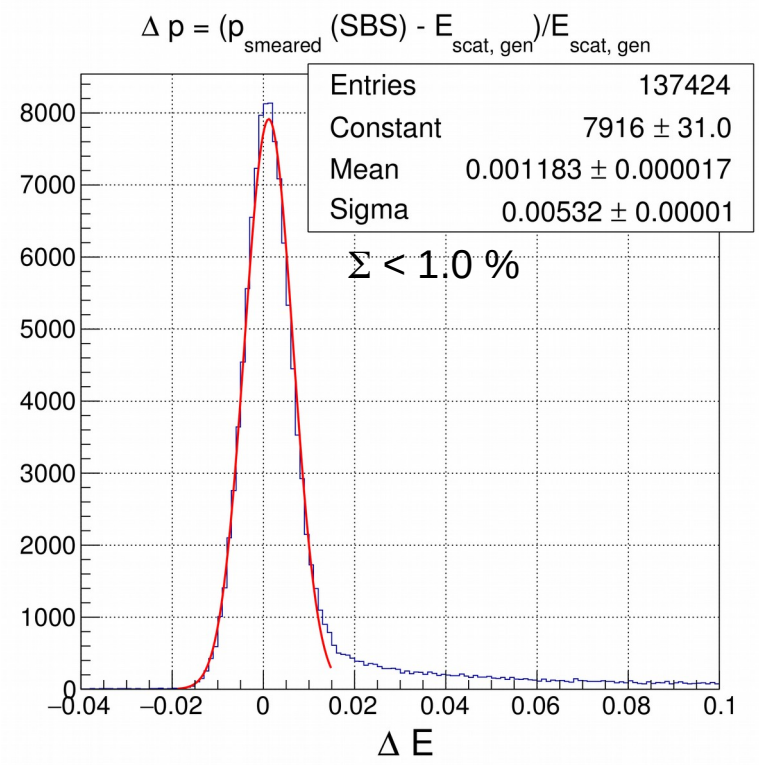
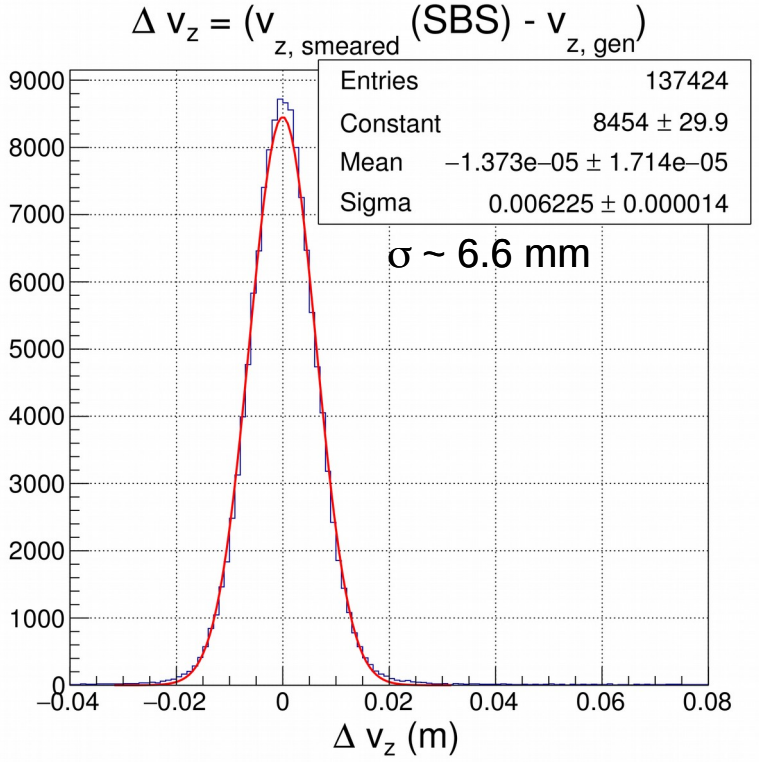
Expected results:
Experimental effects: SBS resolution

Electron reconstruction:

Smearing "by-hand" with SBS claimed resolutions:
- does not include reconstruction/optics model ;
- includes electron energy loss between vertex and GEMs

(uses the GEM hit mometum info for the scattered electron)





"by-hand smearing" might be a tad too clean, but an independent study showed that it was not completely unreasonable.

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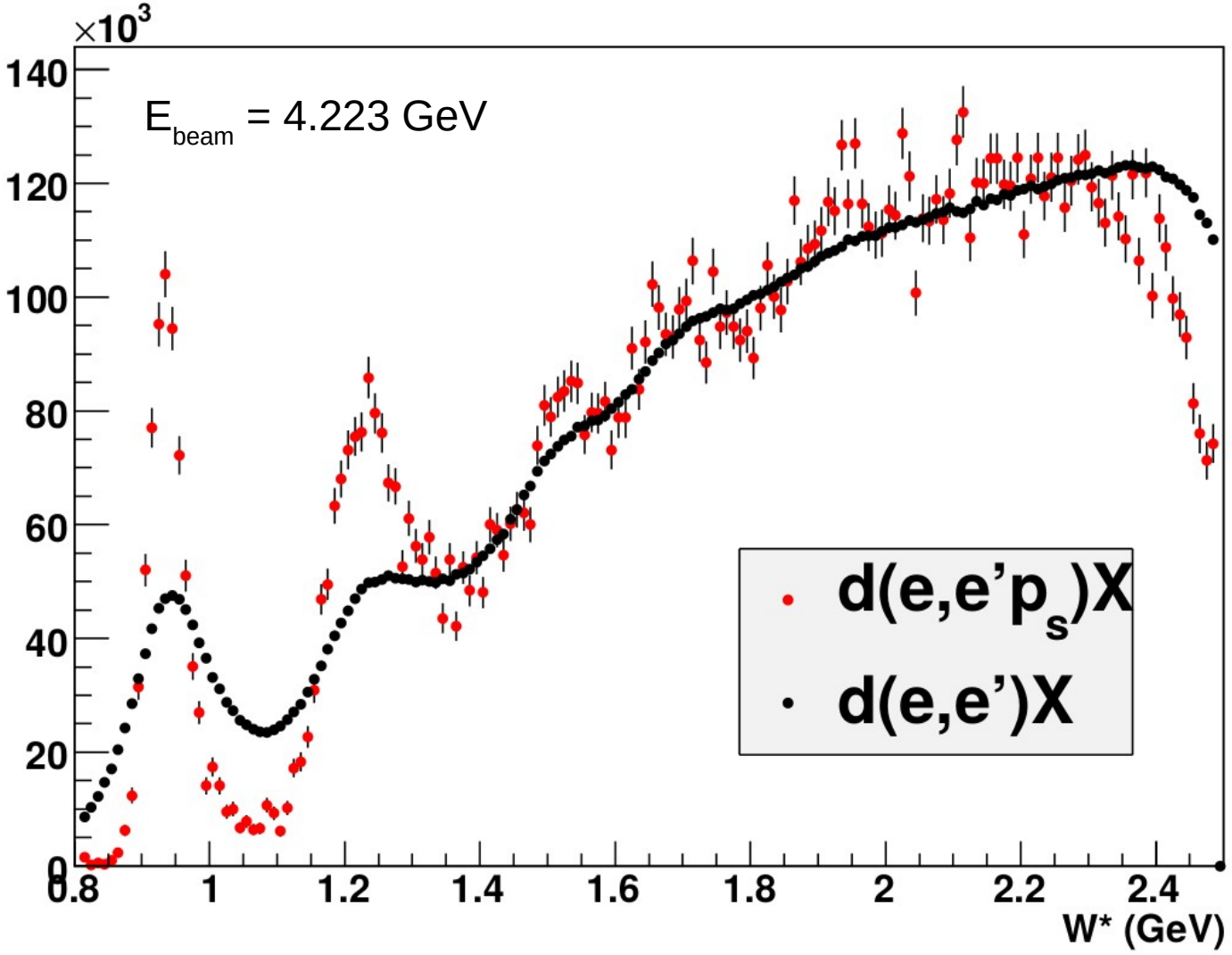
Expected results:
Fermi momentum correction for BoNuS



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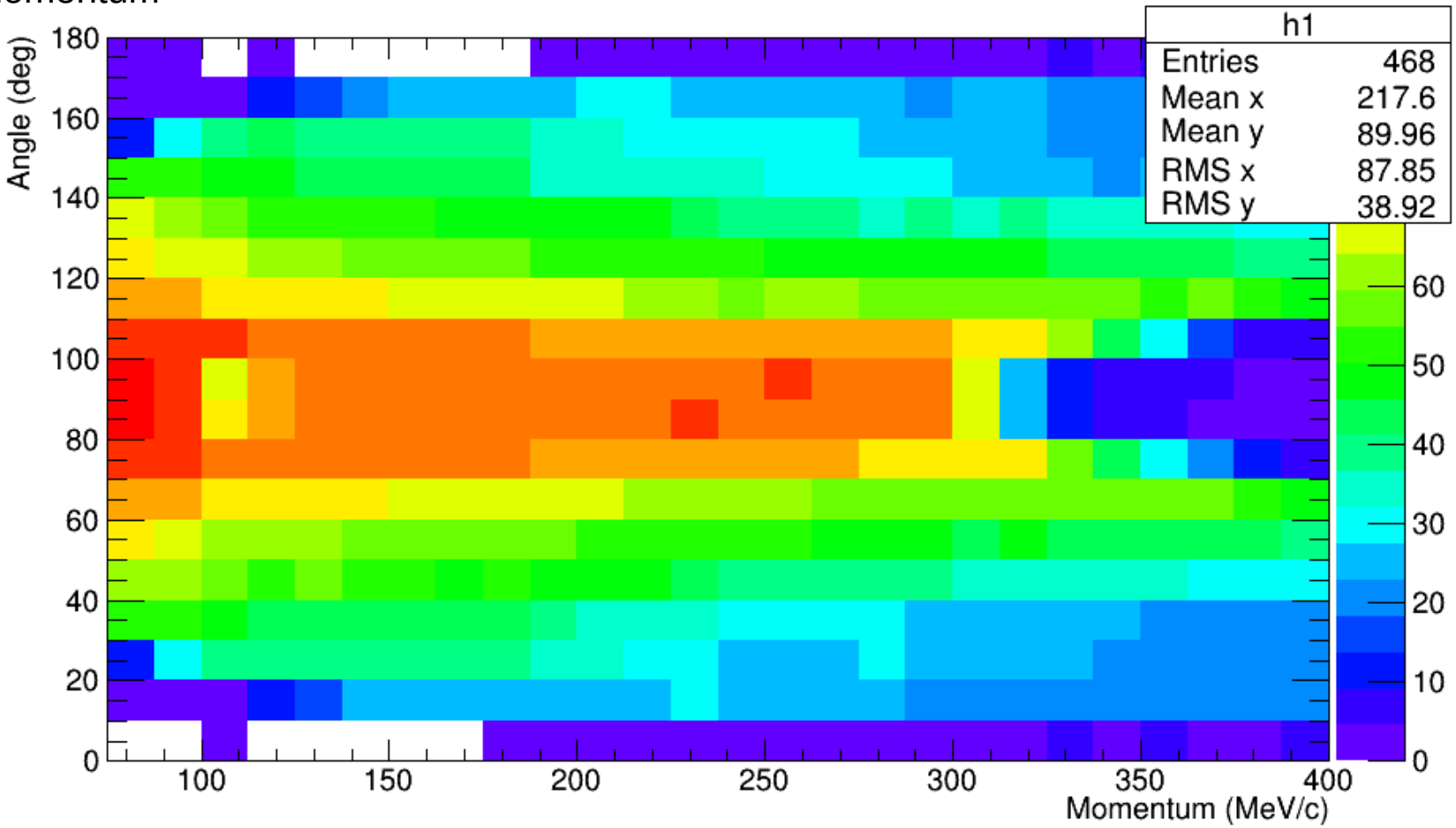
nDVCS experimental setup:
mTPC projected performance

mTPC efficiency: (Courtesy from Marco Carmignotto, JLab)

Semi-empirical efficiency:

proportion of protons reaching active gas volume and reconstructed within 10 % of generated momentum



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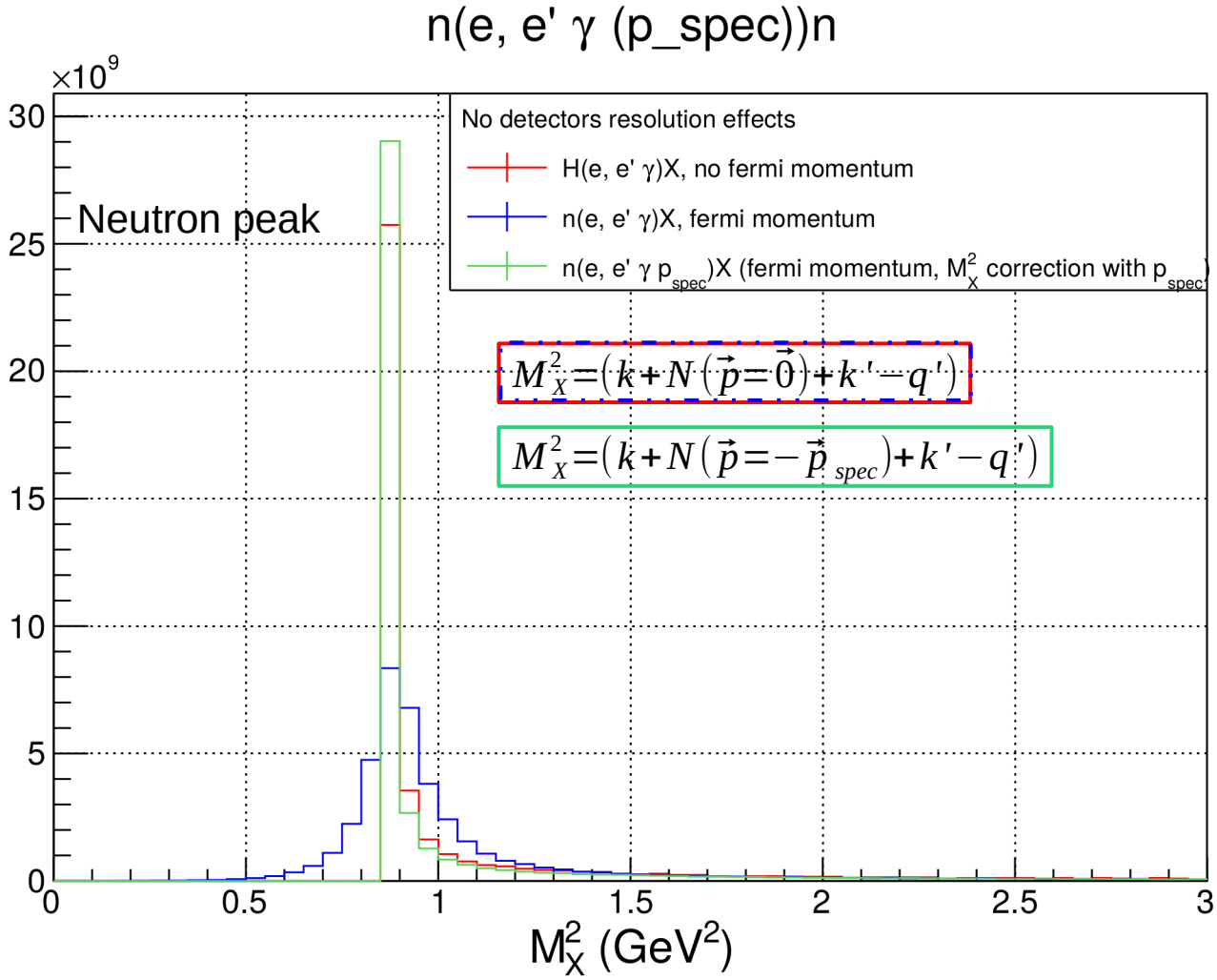
Expected results:
Experimental effects: Fermi Momentum/ radiative corrections

Missing mass squared, radiative effects (Mo/Tsai)
+ Fermi momentum only



Radiative tail past neutron peak not negligible wrt Fermi Momentum smearing