



Massachusetts Institute of Technology

# Efficiency Calculations and Run Period Consistency for RGA DVCS Cross Section Extraction

Timothy B. Hayward

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# Run Periods

- Five periods: two reconstruction software versions, two polarities, 2(~3) beam energies, 2 DC HV settings.
- Goal: measure the cross section completely independently for all five periods and then compare.

Table 1: Reconstruction version by run period.

coatjava 10.0.7 (no DAF)	coatjava 11.1.0 (DAF)
Fa18 Out	Sp18 Out
Fa18 Inb, Sp19 Inb	Sp18 Inb

Table 2: Torus polarity by run period.

Torus +1	Torus -1
Fa18 Out	Fa18 Inb, Sp19 Inb
Sp18 Out	Sp18 Inb

Table 3: Beam energy by run period.

10.200 GeV	10.594 GeV	10.604 GeV
Sp19 Inb	Sp18 Inb	Fa18 Inb
	Sp18 Out	Fa18 Out

Table 4: DC HV settings by run period.

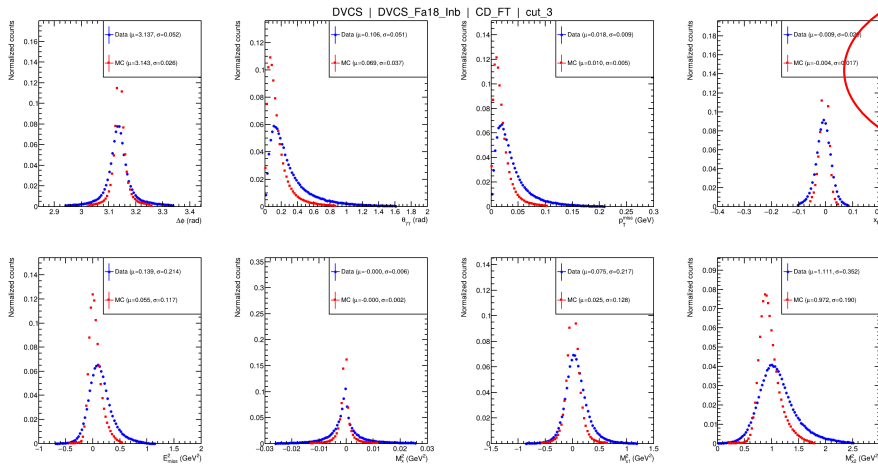
DC HV 8/10/9	DC HV 9/10/10
R2 > 60 mV	R2 > 45 mV
Sp18 Inb	Fa18 Inb, Fa18 Out
Sp18 Out	Sp19 Inb

# Cross Section Extraction

$$\frac{d\sigma}{dx_B dQ^2 d|t| d\phi} = \frac{(N_{e'p'\gamma} - N_{DVp\pi^0, \text{mis}})}{\mathcal{L} V_{\text{bin}} A \epsilon F_{\text{bin}} F_{\text{rad}}}$$

# Cross Section Extraction; $N_{e'p'\gamma}$

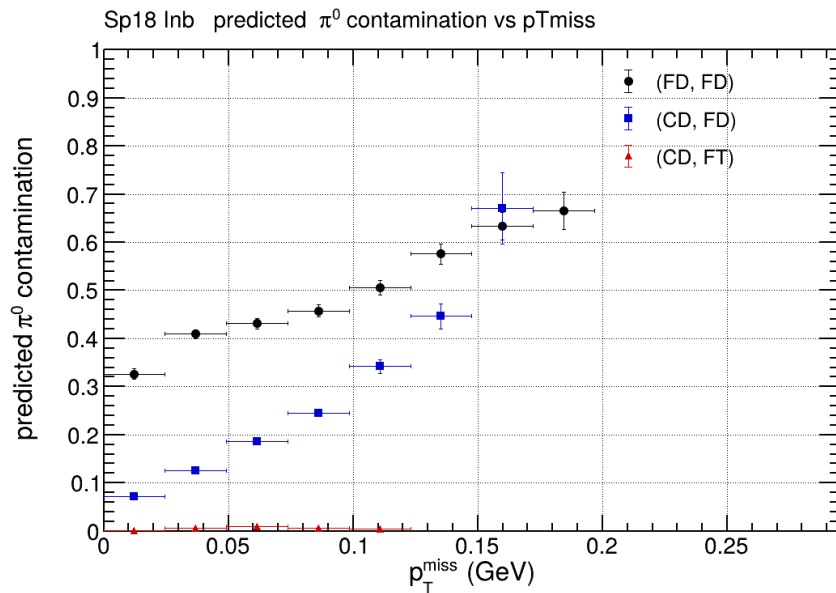
Number of  $e'p'\gamma$  final state particles passing exclusivity cuts ( $3\sigma$  on  $\Delta\phi$ ,  $M_x^2$ ,  $M_{xp}^2$ ,  $M_{xy}^2$ ,  $x_F$ ; 99% survival on  $P_{T(\text{miss})}$  and  $\theta_{\gamma\gamma}$ ) separately for all five run periods, data/MC and all three detector topologies (FD-FD, CD-FD, CD-FT).



$$\frac{(N_{e'p'\gamma} - N_{DVp\pi^0, \text{mis}})}{\mathcal{L} V_{\text{bin}} A \epsilon F_{\text{bin}} F_{\text{rad}}}$$

# Cross Section Extraction; $N_{DVP\pi^0,mis}$

Number of  $ep \rightarrow e'p'\pi^0 \rightarrow e'p'\gamma(\gamma)$  events passing DVCS exclusivity cuts. Determined through combination of reconstructed  $e'p'\gamma$  and  $e'p'\pi^0$  data/MC yields and the number of  $e'p'\pi^0$  MC events passing DVCS exclusivity cuts.



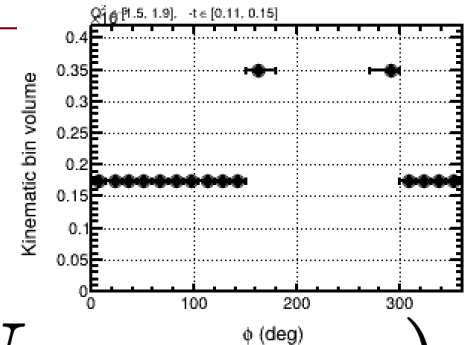
$$\frac{(N_{e'p'\gamma} - N_{DVP\pi^0,mis})}{\mathcal{L}V_{bin}A\epsilon F_{bin}F_{rad}}$$

# Cross Section Extraction; Corrections

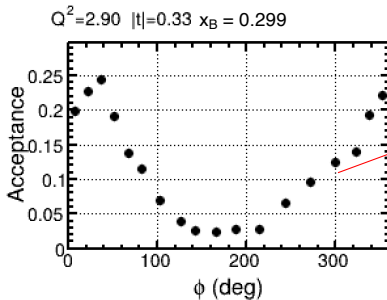
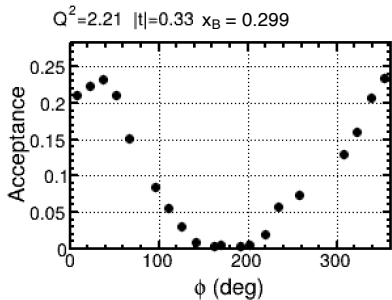
Luminosity (charge, target length, density, etc.):

1. Fa18 Inb: 30.3 mC
2. Fa18 Out: 34.2 mC
3. Sp19 Inb: 45.9 mC
4. Sp18 Inb: 56.4 mC
5. Sp18 Out: 16.2 mC

Bin volume, bounded by the allowed phase space

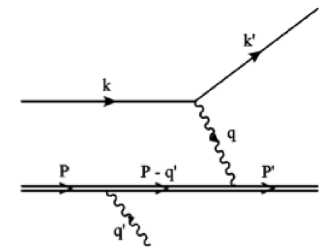


$$\frac{d\sigma}{dx_B dQ^2 d|t| d\phi} = \frac{(N_{e'p'\gamma} - N_{DVp\pi^0, \text{mis}})}{\mathcal{L} V_{\text{bin}} A \epsilon F_{\text{bin}} F_{\text{rad}}}$$



acceptance, rec/gen MC

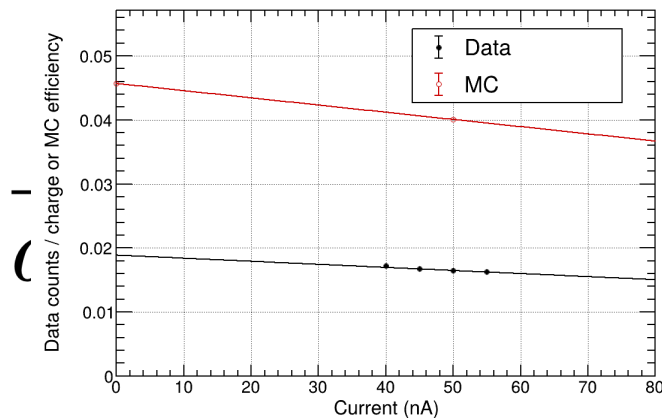
radiative corrections



correction for measurement at a single point instead of over the whole bin

# Cross Section Extraction; $\epsilon$ (efficiency)

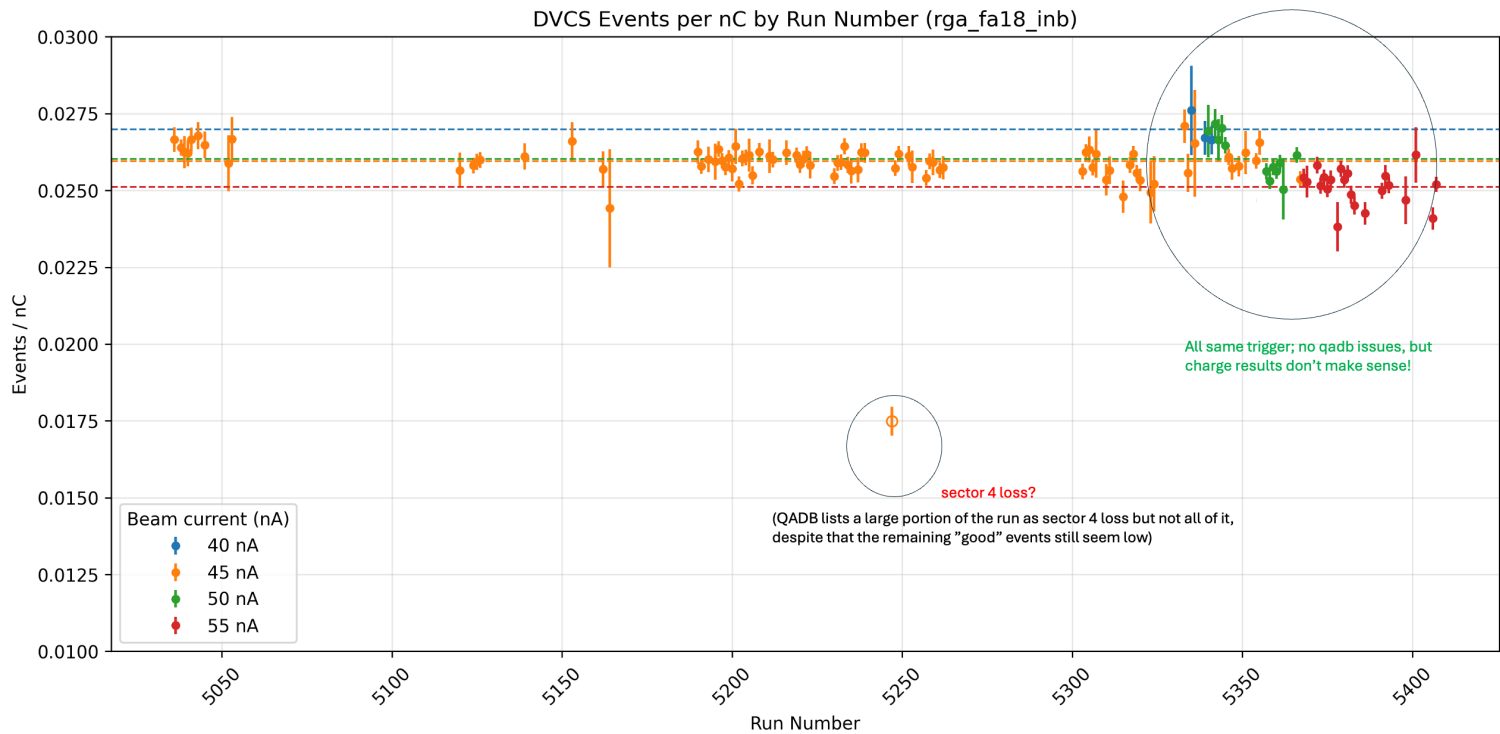
- CLAS12 reconstruction efficiency decreases as a function of current.
- Different effect per channel, run period, and between data/MC.
- Number of events = number of measured events / channel efficiency.



$$\frac{(N_{e'p'\gamma} - N_{DVp\pi^0, \text{mis}})}{\mathcal{L} V_{\text{bin}} A \epsilon F_{\text{bin}} F_{\text{rad}}}$$

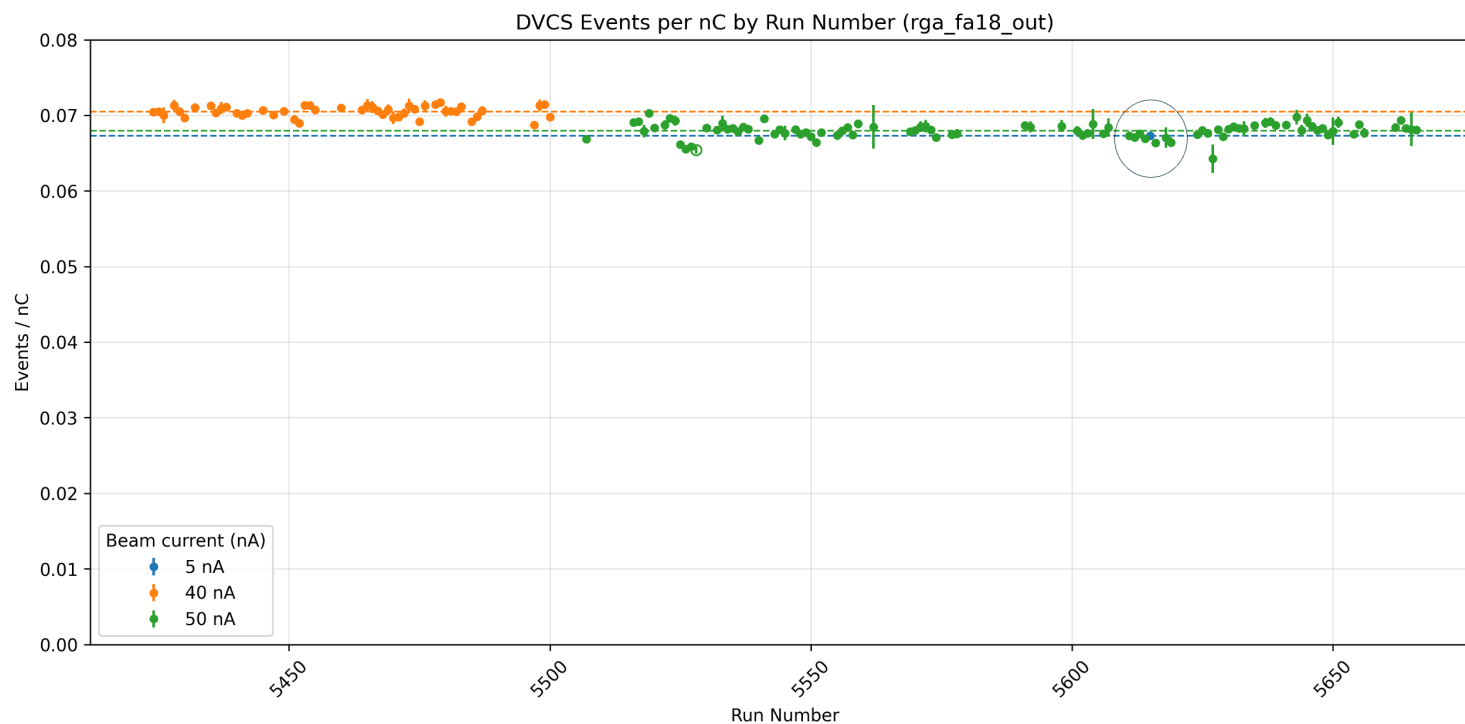
- Data efficiency estimated by measuring counts/charge as a function of current and extrapolating to 0 background. Serves as a useful run-by-run quality check!
- MC efficiency calculated as reconstructed/generated as a function of current and extrapolating to 0 background (possibly would have been better to use nobkg MC!).

# Efficiency as Counts/Charge; RGA Fa18 Inb



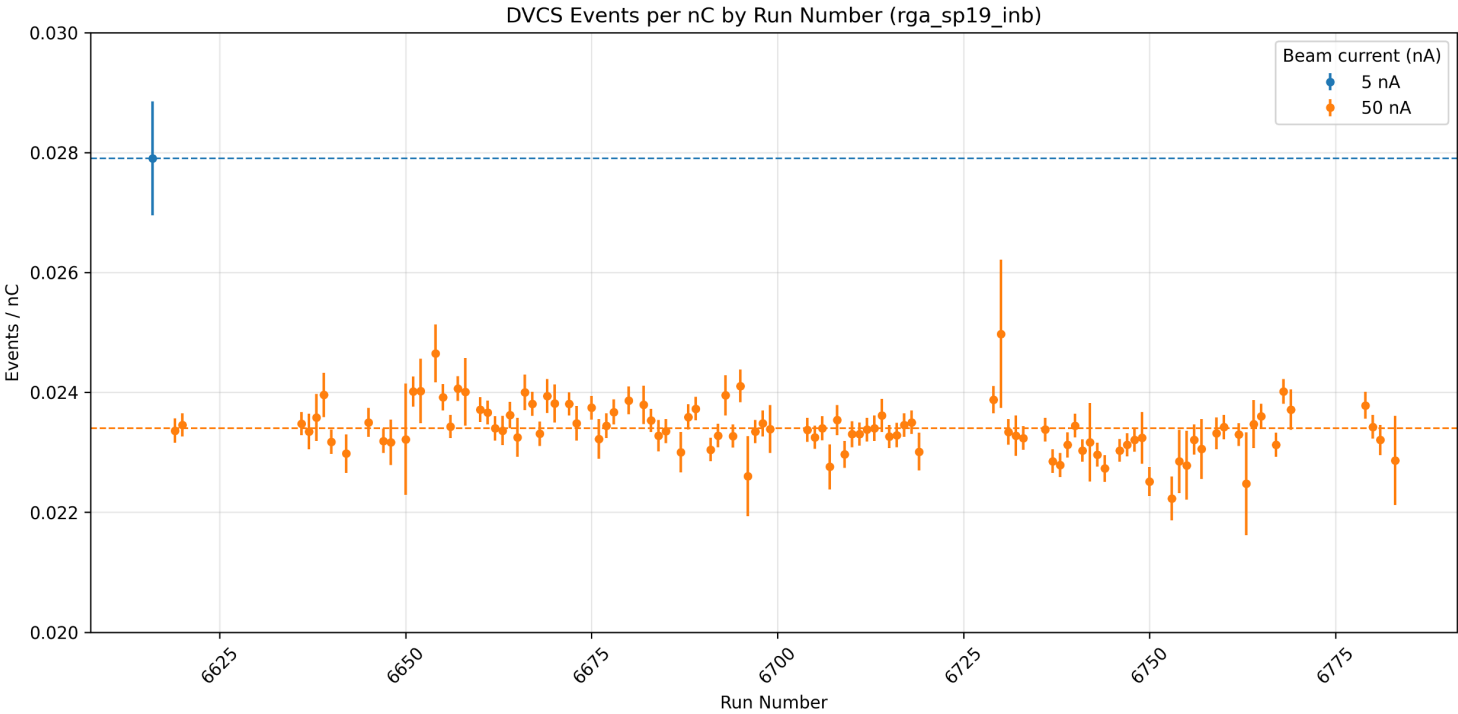
- 5333; [logbook entry](#); "40 nA"
- 5333-5340; [logbook entry](#); "40 nA", "MCC explain high Hall A current is causing instability"
- 5341-5345; [logbook entry](#); "50 nA" "beam very unstable", "frequent trips"
- 5345-5347; [logbook entry](#); "45 nA", "[during run 5345] MCC lowered beam to 20 nA to test stability".
- **Runs 5340-5345 reclassified as 40 n.**
- **Run 5345 removed.**
- **Run 5247 removed.**

# Efficiency as Counts/Charge; RGA Fa18 Out



- 5615: [logbook entry](#); “21:34 new run 5615 started, 5 nA at the beginning. Reached stable position conditions at 21:50, asked for 50 nA.”
- 
- 5615 reclassified as 50 nA run.

# Efficiency as Counts/Charge; RGA Sp19 Inb



- Two low luminosity runs: 6616 (5 nA), 6618 (10 nA); (only 5nA plotted here, see next slide for discussion).

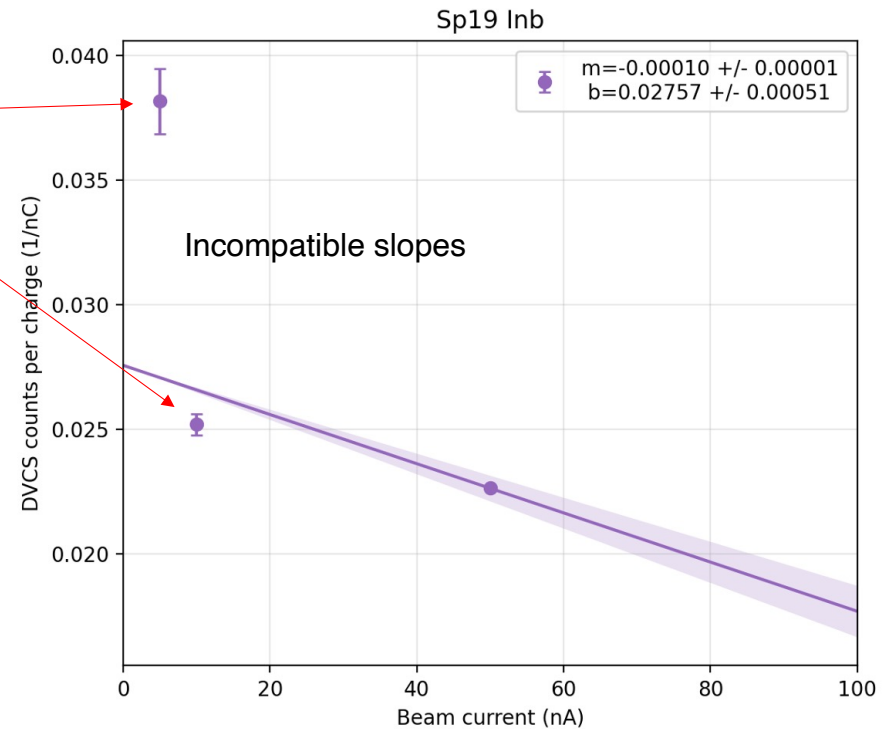
# Luminosity Scan – Sp19 Inb

- RGA Sp19 Inb has only two runs at non-production currents: 6616 (5nA), 6618 (10nA).

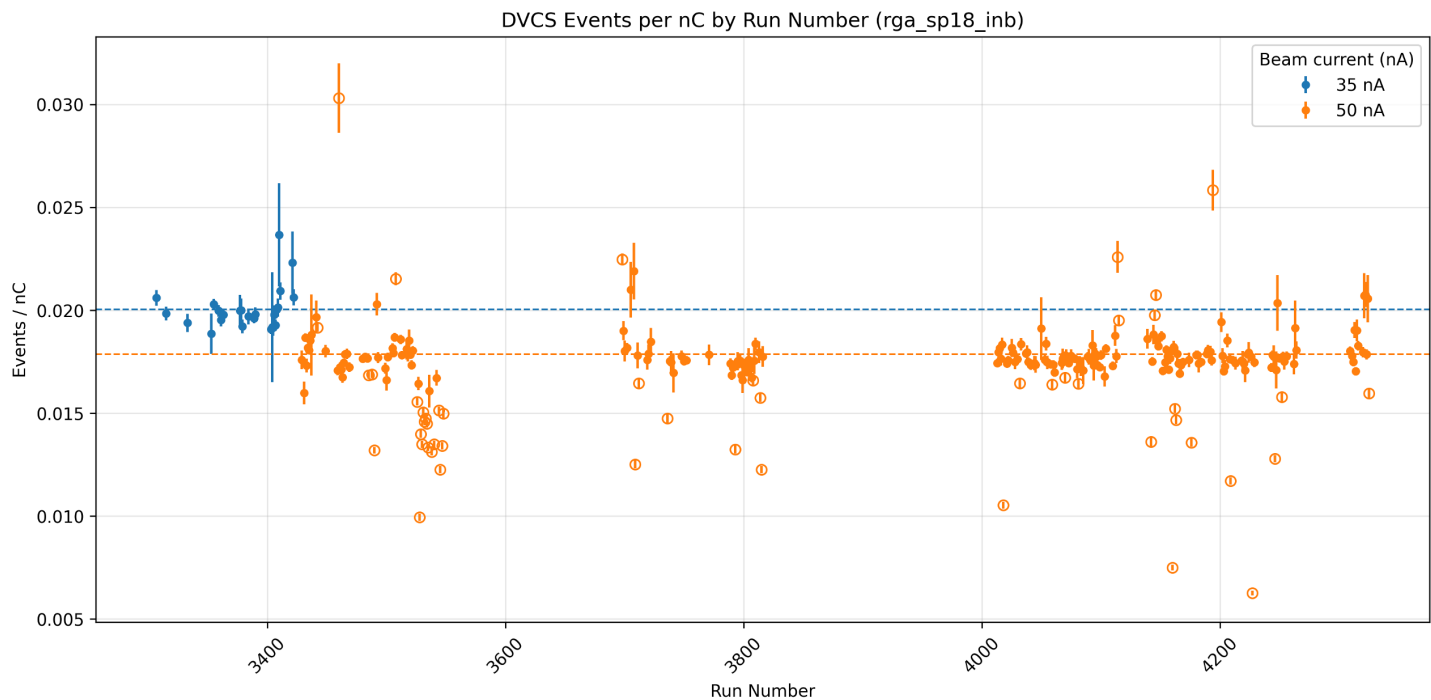
Table 1: Comparison of scaler charge totals for selected runs.

Quantity	Run 6616	Run 6618
RUN::Scaler (nC)	30,861	126,675
HEL::Scaler (nC)	20,680	124,616
HEL/RUN	0.670	0.984
QA Gated (nC)	30,926	126,662
QAHL (nC)	22,726	136,908
QAHL/QA Gated	0.735	1.081

- Relationship between two scalers different between both runs.
- One single low current run provides limited lever arm for fit and correspondingly large uncertainty on efficiency factor.
- For now: use RGA Fa18 Inb (broader number of currents) for Sp19 Inb efficiency; drop all <10nA runs from efficiency determination.

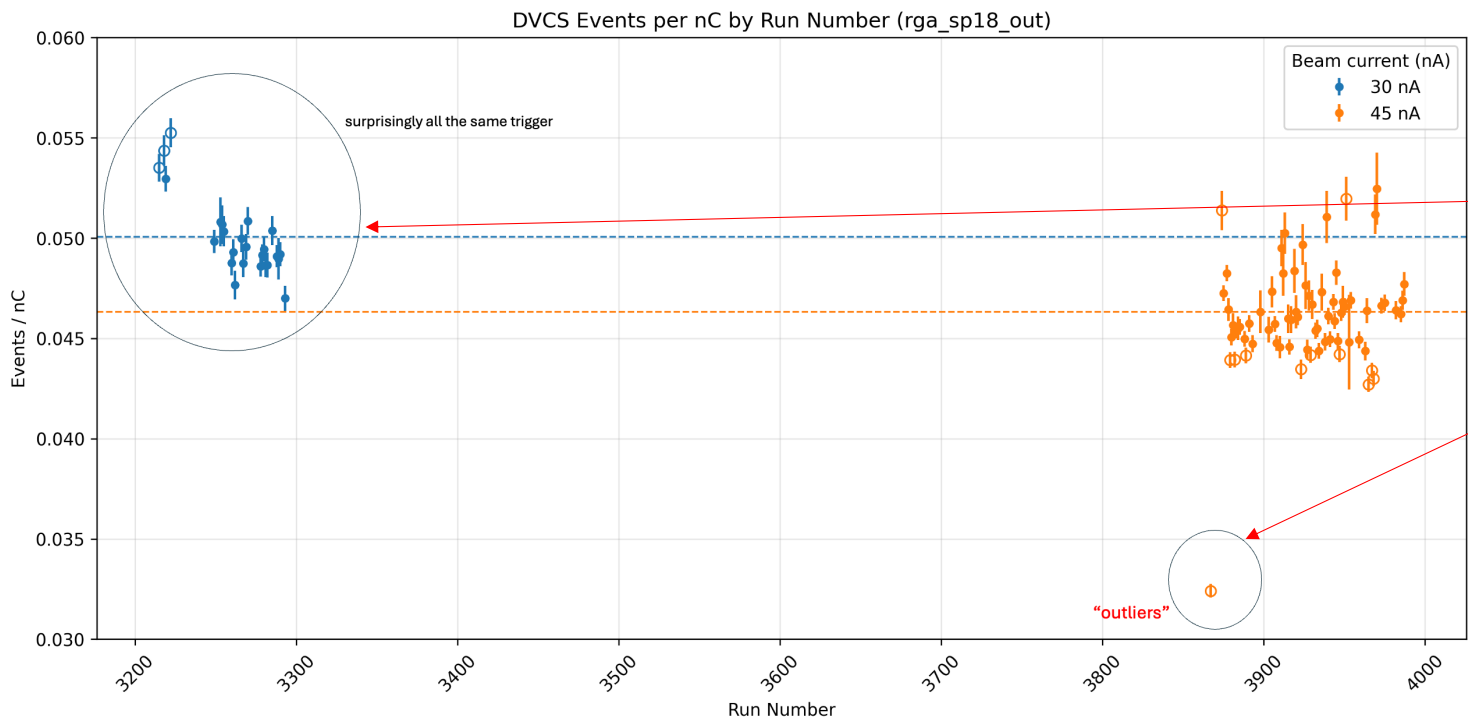


# Efficiency as Counts/Charge; RGA Sp18 Inb



- Many outlier runs in Sp18. Remove runs outside  $5\sigma$ .
- Remove: 3490, 3508, 3526, 3528, 3529, 3530, 3531, 3532, 3533, 3534, 3535, 3538, 3540, 3544, 3545, 3547, 3548, 3698, 3709, 3736, 3793, 3814, 3815, 4018, 4142, 4145, 4146, 4160, 4162, 4163, 4176, 4209, 4227, 4246, 4252.

# Efficiency as Counts/Charge; RGA Sp18 Out



- 3215, 3218, 3219, 3222: frequent “possibly no beam”, “charge unknown” periods but so too do the runs grouped together immediately after them. Logbook entry ([logbook entry](#)) does mention frequent trips, consistent with higher efficiency.
- 3867: large portion of run has marginal or total outlier, should be handled by qadb but run seems problematic.
- **Remove: 3215, 3218, 3219, 3222, 3867.**

# Summary of Removed and Adjusted Runs

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- RGA Fa18 Inb

- Removed: 5247, 5345
- Reclassified as 40nA instead of 50nA: 5340-5344

- RGA Fa18 Out

- Reclassified as 50nA instead of 5nA: 5615

- RGA Sp19 Inb

- 6616 (5nA), 6618 (10nA) temporarily removed while charge is being investigated.

- RGA Sp18 Inb

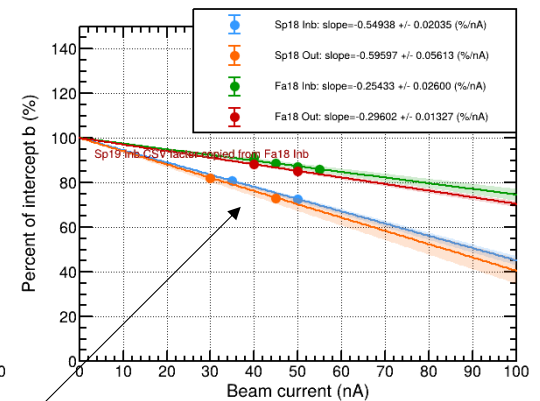
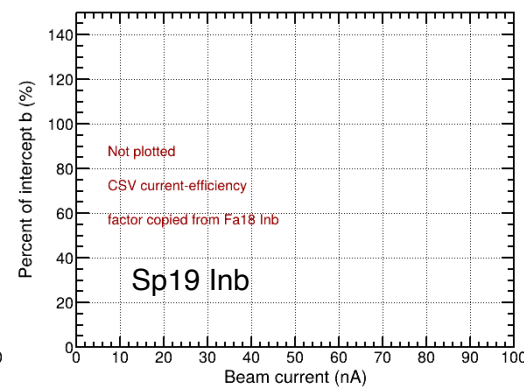
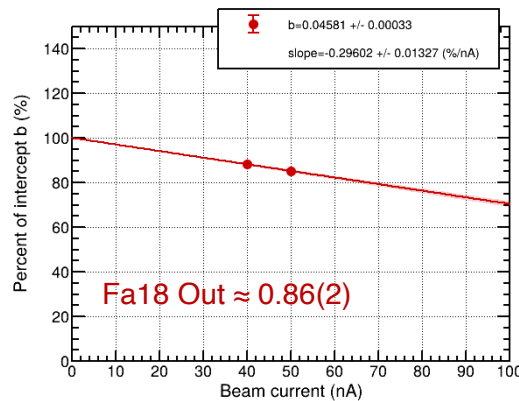
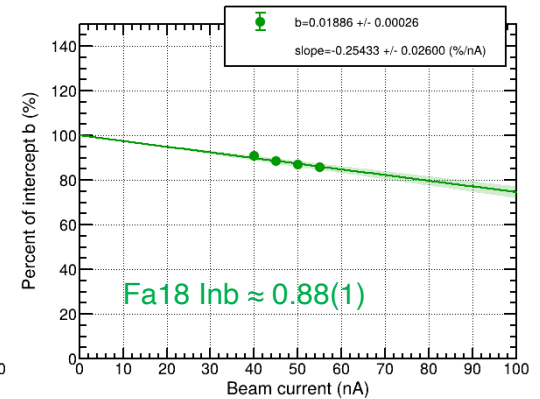
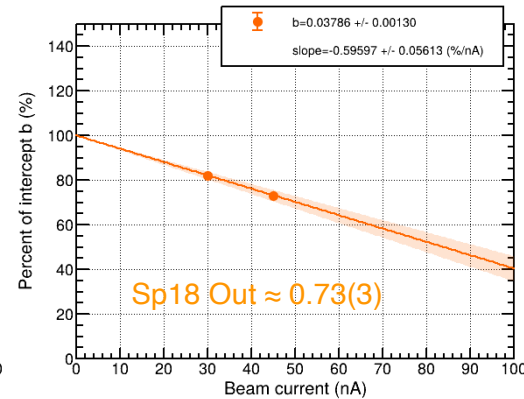
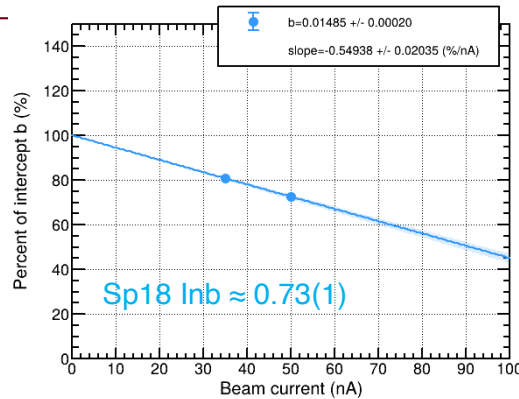
- Removed: 3355, 3404, 3408, 3449, 3490, 3499, 3500, 3505, 3508, 3526, 3527, 3528, 3529, 3530, 3531, 3532, 3533, 3534, 3535, 3536, 3538, 3540, 3544, 3545, 3547, 3548, 3698, 3709, 3712, 3736, 3793, 3800, 3801, 3807, 3808, 3809, 3810, 3813, 3814, 3815, 3817, 3867, 3877, 3879, 3882, 3923, 3927, 3929, 3947, 3951, 3953, 3965, 3967, 3968, 4018, 4059, 4142, 4145, 4146, 4159, 4160, 4162, 4163, 4176, 4209, 4227, 4246, 4252, 4325

- RGA Sp18 Out

- Removed: 3267, 3867, 3877, 3879, 3882, 3923, 3927, 3929, 3947, 3951, 3953, 3965, 3967, 3968

# Data Efficiency Results

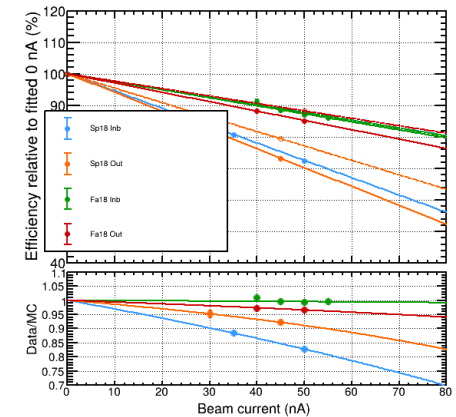
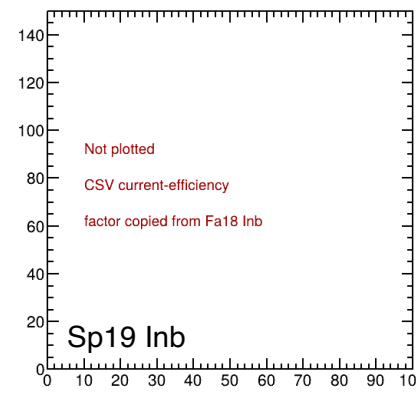
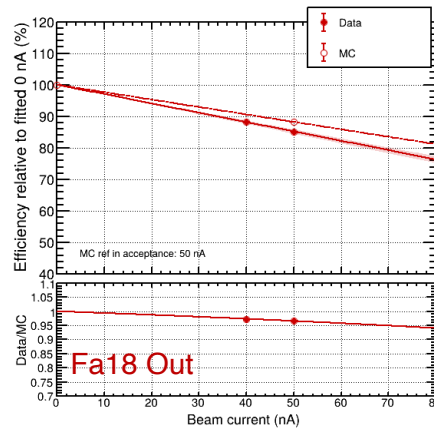
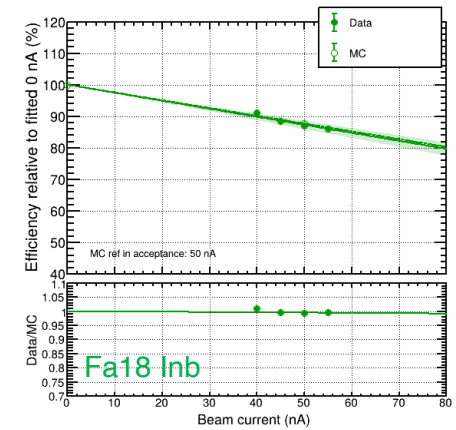
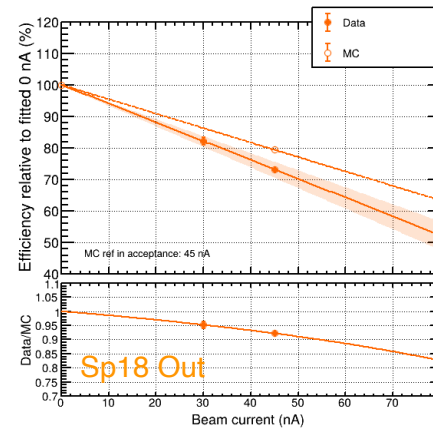
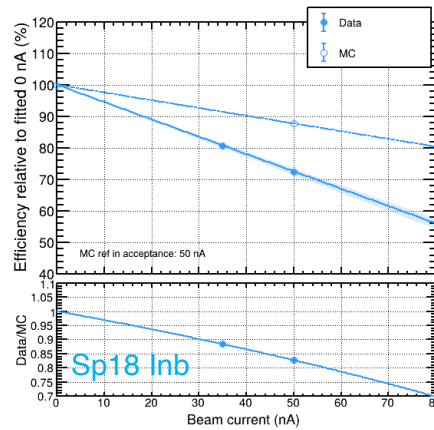
- Efficiency loss determined as a function of current.
- Data divided by  $e(I_{nom})$ , where  $I_{nom}$  is the weighted average current of the run period.



Observed run period difference consistent with  
cj/DC HV effect, not torus polarity.

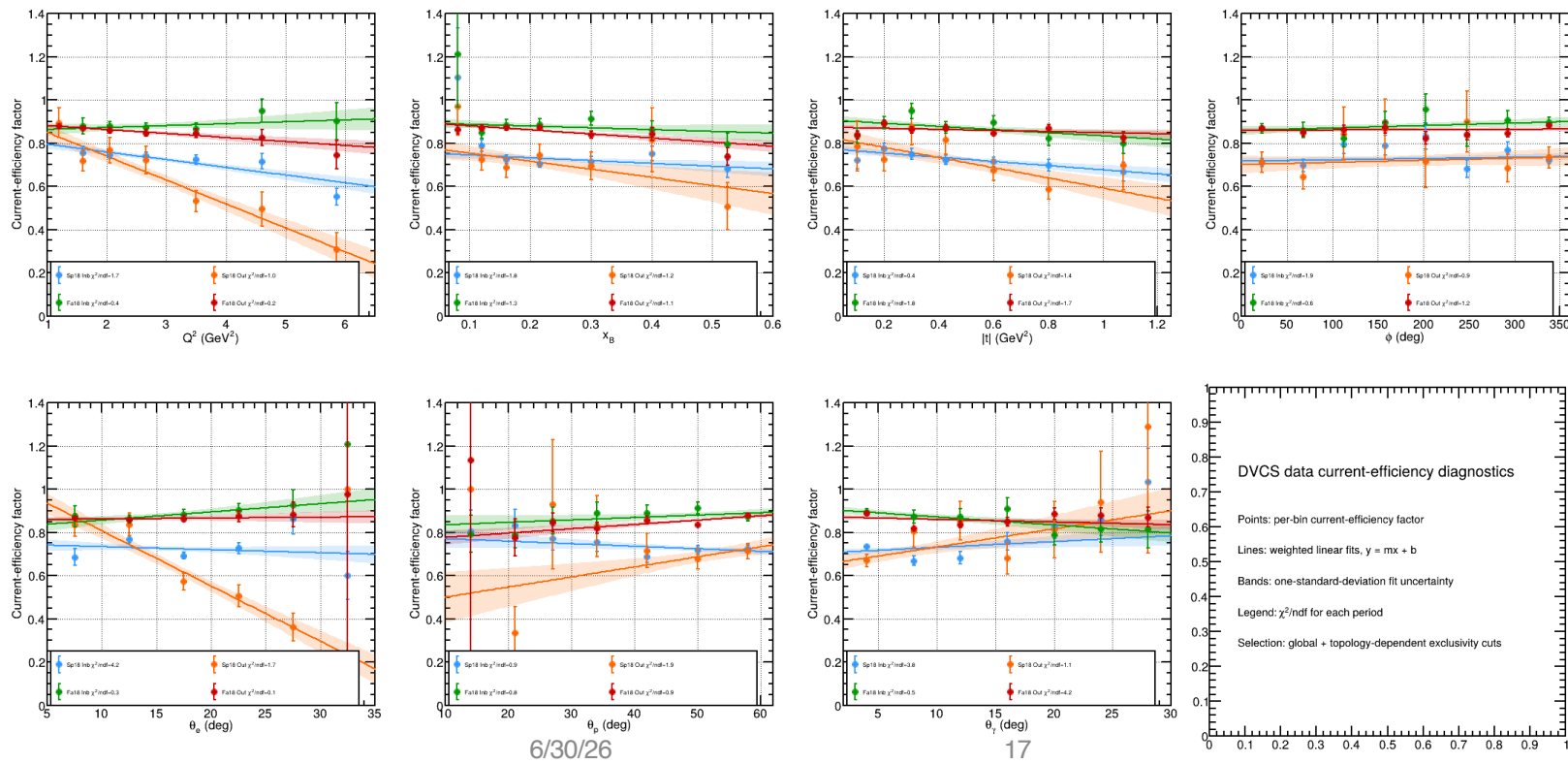
# MC Efficiency Results

- Fa18 data/MC efficiency very close to 1 (after considerable effort!!).
- Sp18 data less efficient than gemc simulation (lower HV effect not properly simulated in gemc?).
- Sp18 Inb/Out MC slopes not consistent unlike Fa18 Inb/Out.
- Sp18 out likely the outlier (Sp18 Inb is close to Fa18 Inb/Fa18 Out).



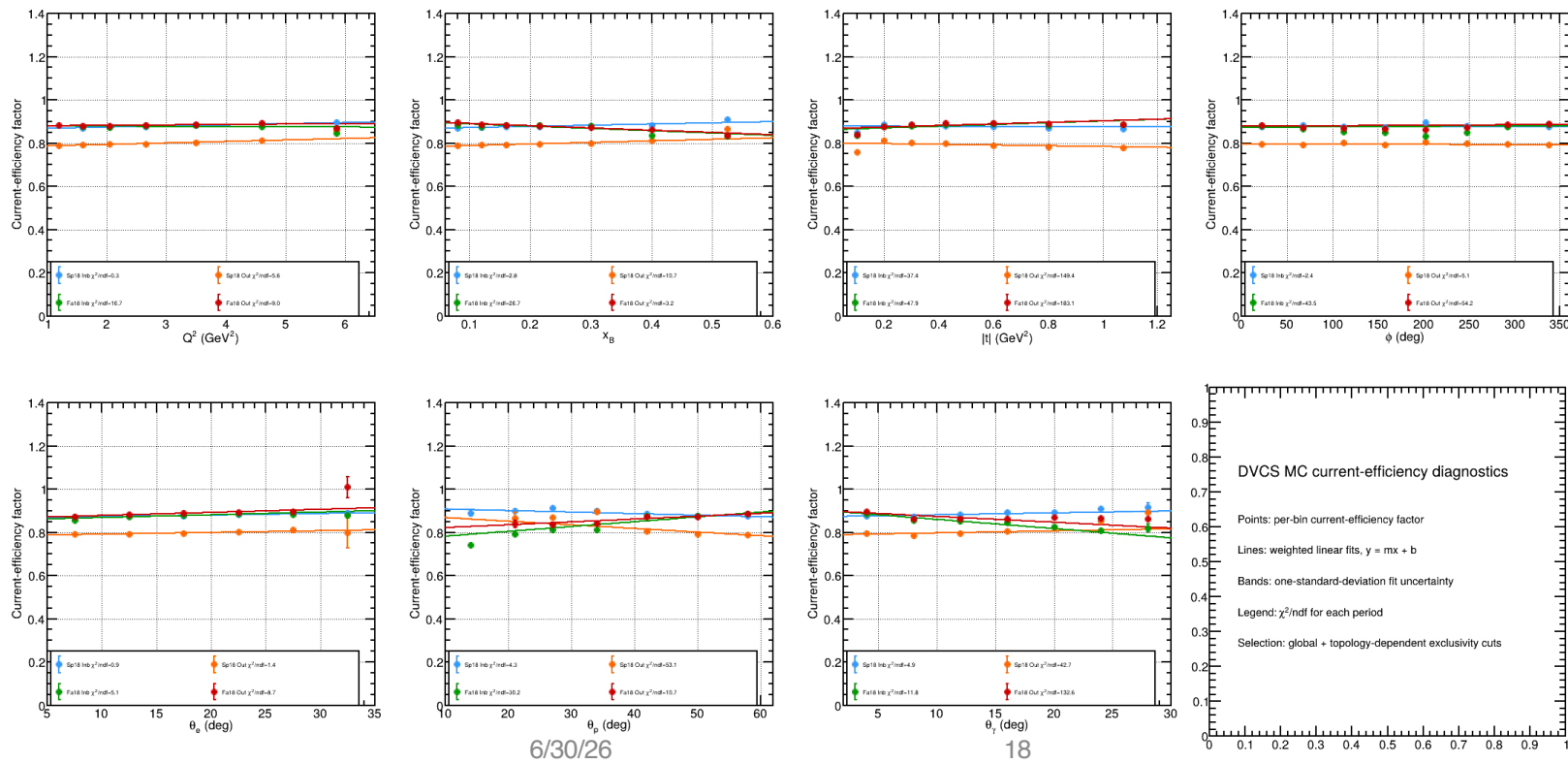
# Kinematic Dependence of Data Efficiency

- Strong kinematic dependence in Sp18 Out (and to a lesser extent Sp18 Inb) likely correlated with electron polar angle.
- Efficiency fit as a function of  $e_\theta$  and each bin is corrected based on its  $\varepsilon(e_\theta)$



# No Kinematic Dependence of MC Efficiency

- Strong kinematic dependence in Sp18 Out (and to a lesser extent Sp18 Inb) likely correlated with electron polar angle.
- Efficiency fit as a function of  $e_\theta$  and each bin is corrected based on its  $\varepsilon(e_\theta)$



6/30/26

18



# Overall Period Comparison

- Comparison of run periods to weighted average on a bin-by-bin basis.

$$\bar{\sigma}_b = \frac{\sum_i w_{i,b} \sigma_{i,b}}{\sum_i w_{i,b}} \quad R_{i,b} = \frac{\sigma_{i,b}}{\bar{\sigma}_b} \quad \langle R_i \rangle = \frac{\sum_b W_{i,b} R_{i,b}}{\sum_b W_{i,b}}$$

- No obvious correlation between torus polarity / software version.

$$s_{\text{obs}} = \sqrt{\frac{1}{N} \sum_i (\langle R_i \rangle - 1)^2}$$

- Current overall run period combination systematic ~8%.
- Fa18 Inb(Sp19 Inb) largest outlier.

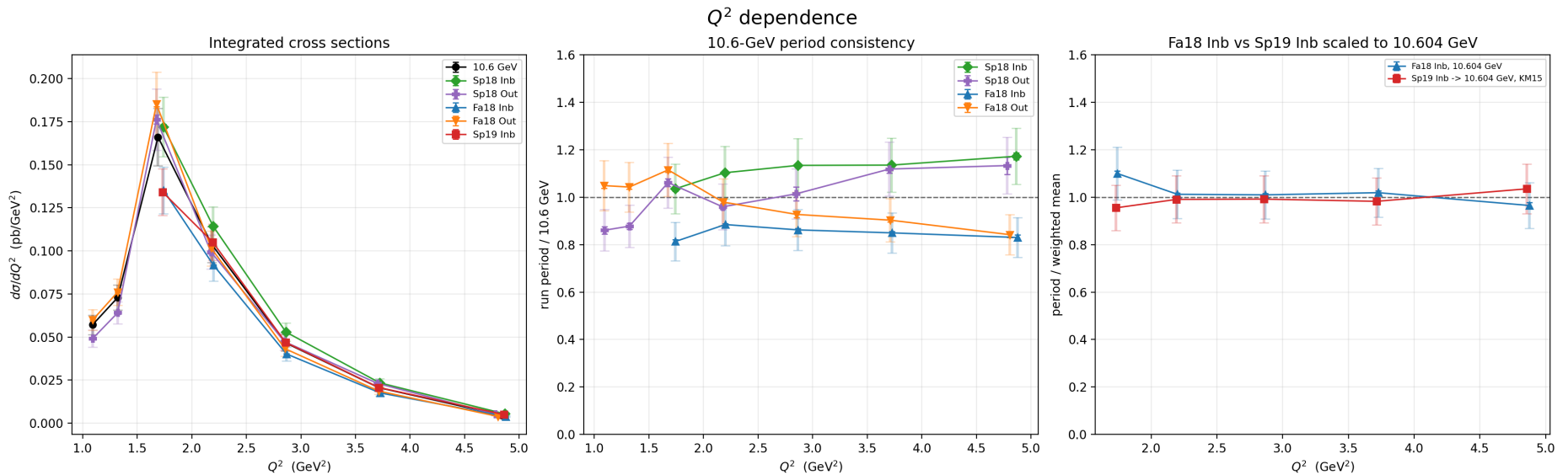
10.6 GeV unpolarized combination		
Period	$\langle R_i \rangle$	$\delta \langle R_i \rangle_{\text{stat}}$
Fa18 Inb	0.8973	0.0018
Fa18 Out	1.0303	0.0014
Sp18 Inb	1.1178	0.0023
Sp18 Out	0.9467	0.0030
Systematic estimates		
$s_{\text{comb}}$	8.39%	
$s_{\text{half}}$	11.02%	
$s_{\text{stat}}$	0.22%	

Inb vs Out unpolarized comparison		
Polarity	$\langle R_i \rangle$	$\delta \langle R_i \rangle_{\text{stat}}$
Inbending	0.9810	0.0014
Outbending	1.0155	0.0013
Systematic estimates		
$s_{\text{comb}}$	1.73%	
$s_{\text{half}}$	1.72%	
$s_{\text{stat}}$	0.13%	

Fa18 vs Sp18 unpolarized comparison		
Polarity	$\langle R_i \rangle$	$\delta \langle R_i \rangle_{\text{stat}}$
Fall 2018	0.9796	0.0010
Spring 2018	1.0555	0.0018
Systematic estimates		
$s_{\text{comb}}$	4.18%	
$s_{\text{half}}$	3.79%	
$s_{\text{stat}}$	0.10%	

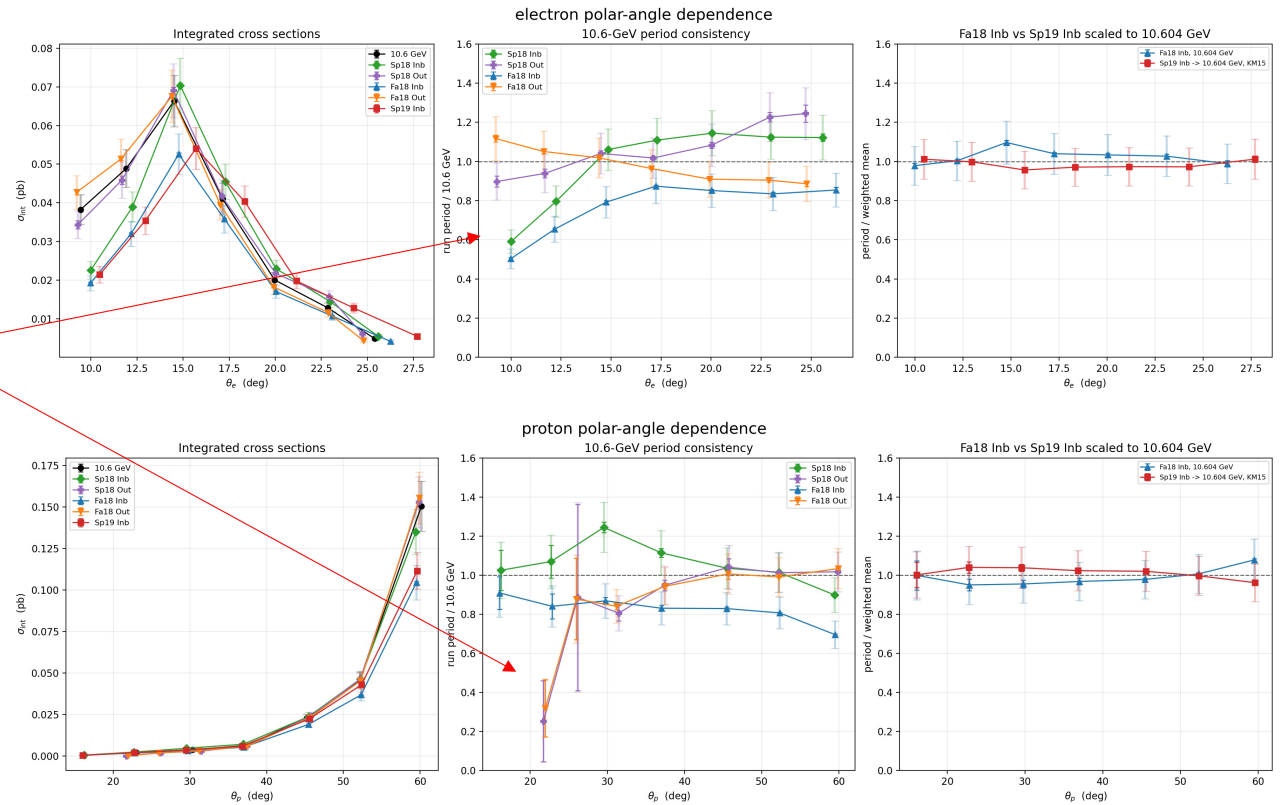
# Kinematic Period Dependence

- Relatively little kinematic dependence in physics variables.
- Very good agreement between Fa18 Inb/Sp19 Inb (scaled to 10.6 GeV).



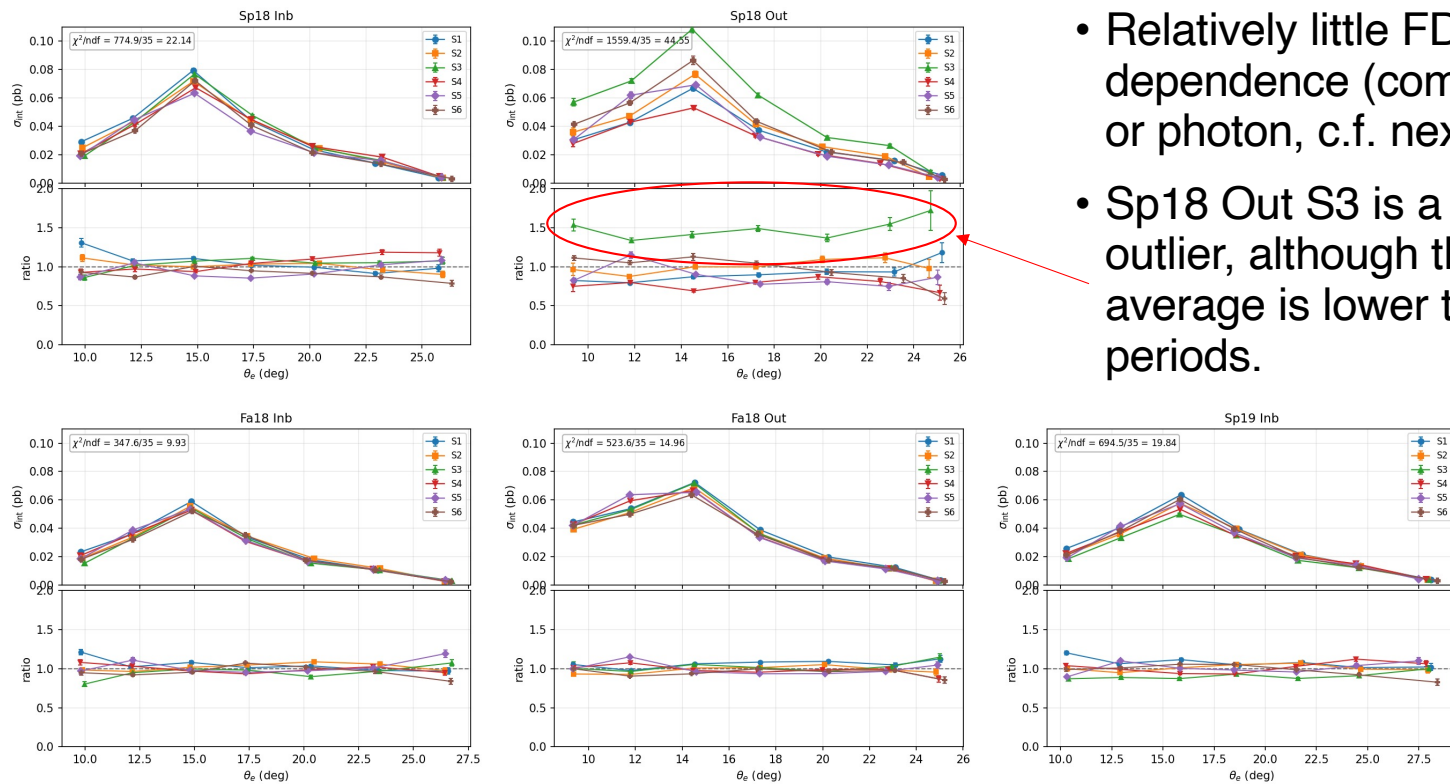
# Kinematic Period Dependence

- Drop off for inbending tracks (electron in torus-1 data, proton in torus+1 data) at small polar angles.



# Electron FD Sector Dependence

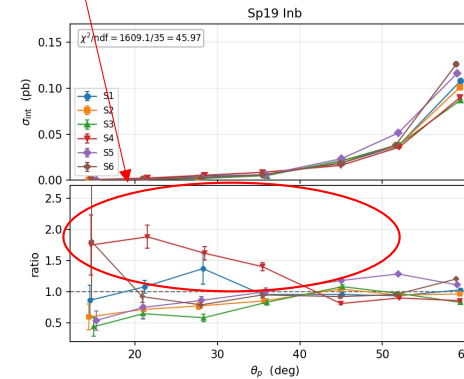
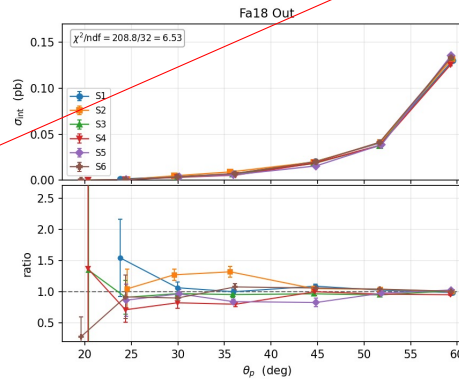
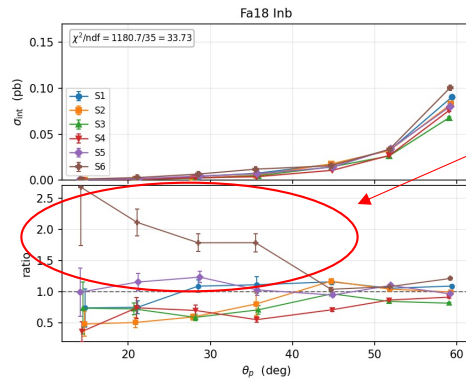
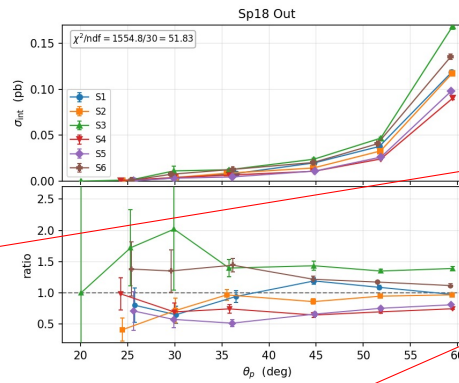
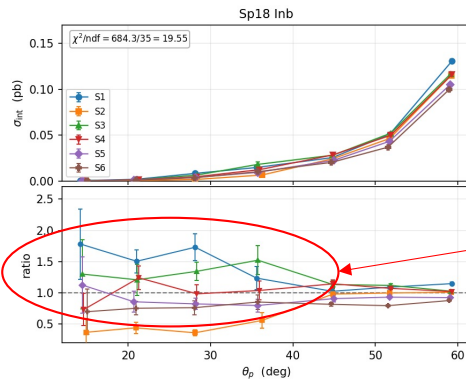
normed DVCS cross section: electron polar-angle dependence by electron FD sector



- Relatively little FD electron sector dependence (compared to proton or photon, c.f. next slides).
- Sp18 Out S3 is a large high outlier, although the run period on average is lower than other periods.

# Electron FD Sector Dependence

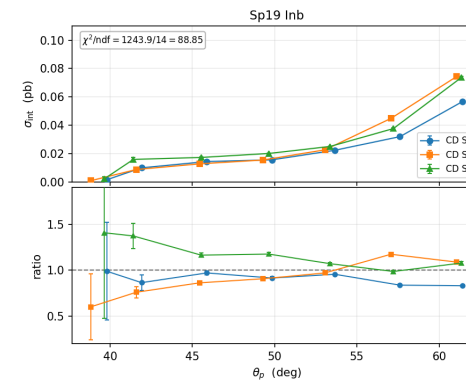
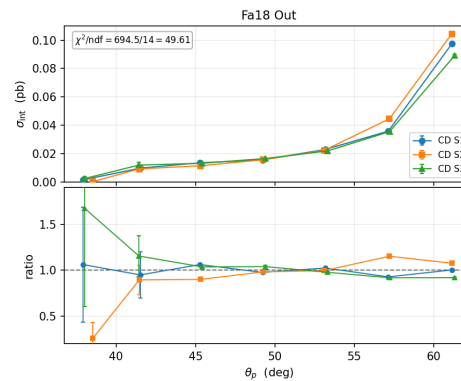
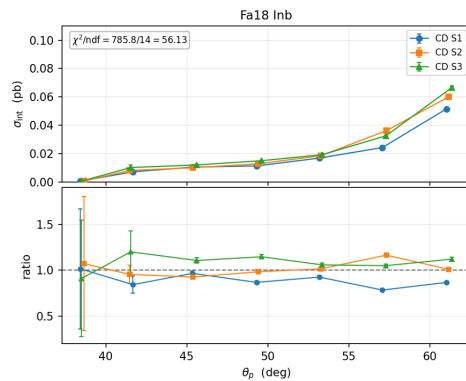
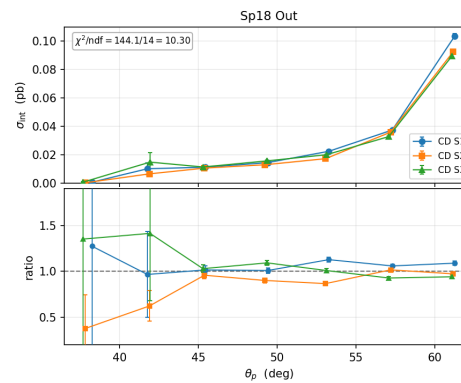
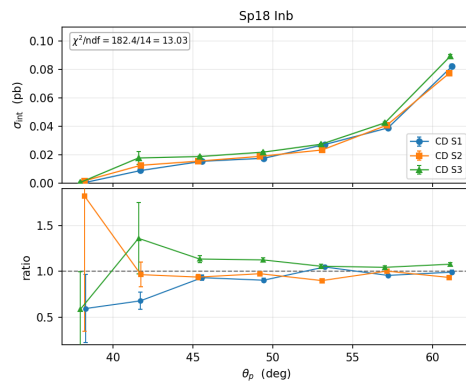
proton polar-angle dependence by electron FD sector



- Noticeable divergence happens when the electron sector dependence is plotted as a function of proton or photon polar angle. But only for FD.
- Fa18 Inb sector 6 and Sp19 Inb sector 4 particularly bad.

# Proton CD Sector Dependence

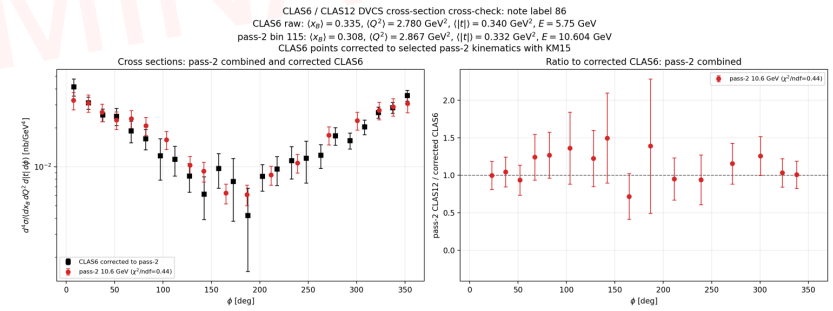
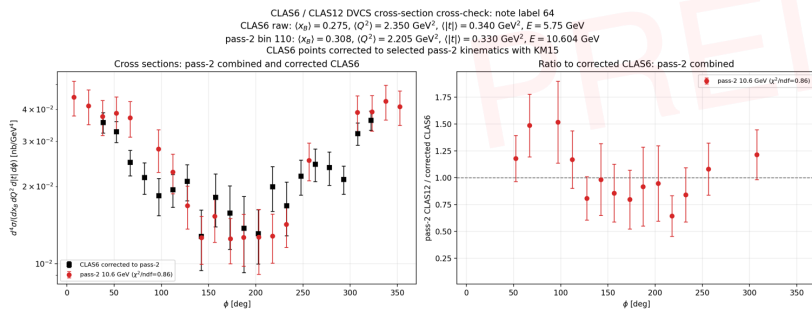
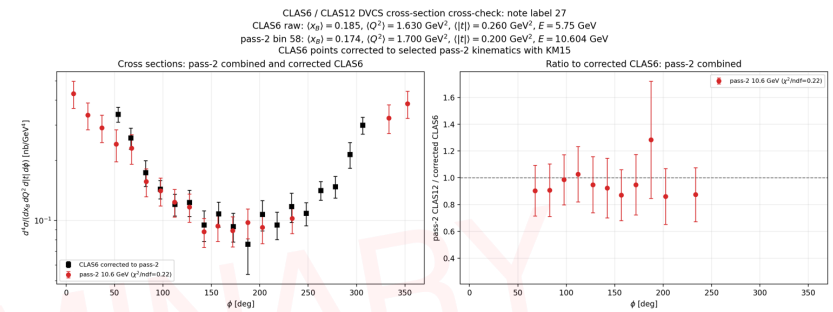
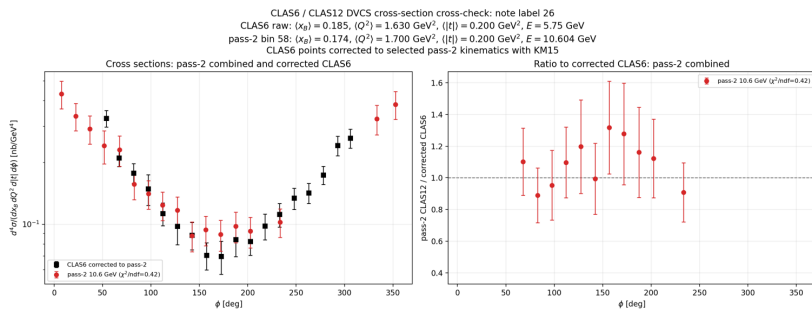
proton polar-angle dependence by proton CD sector



- CD is comparatively well behaved.

# CLAS6 Cross Check

- Comparison in closest kinematic bins to CLAS6 scaled-to-10.6-GeV show very good agreement.



CLAS6: H. S. Jo *et al.*, Physical Review Letters 115, 212003 (2015)

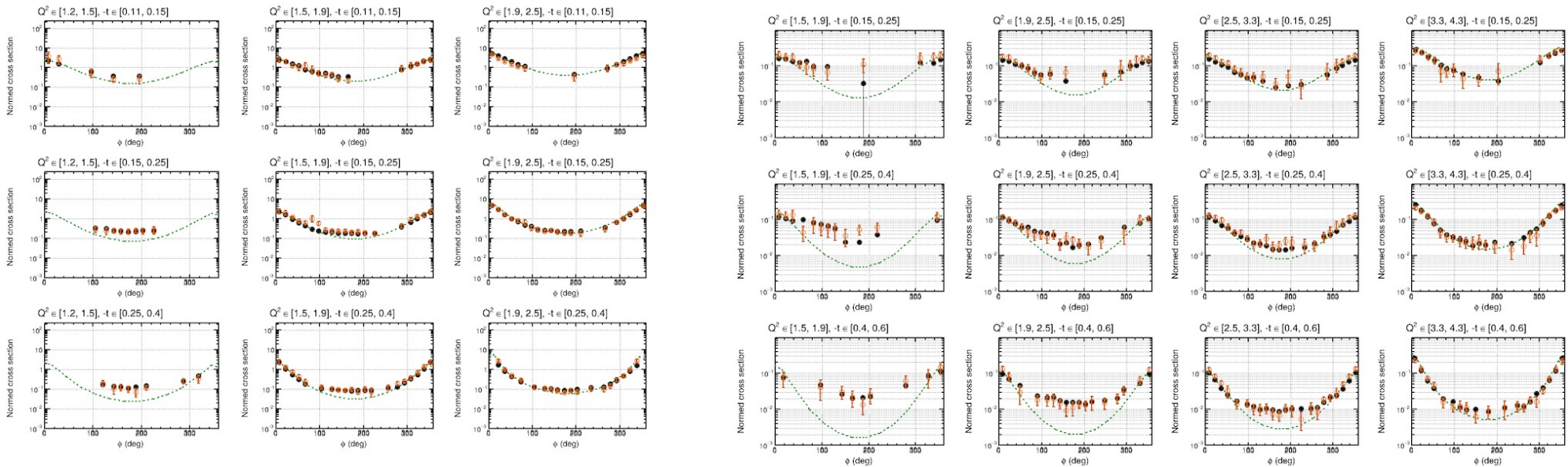


# CLAS12 Cross Check

- Pass-1 paper approved by review committee last week and headed to author check.
- Consistent results to pass-1 analysis.

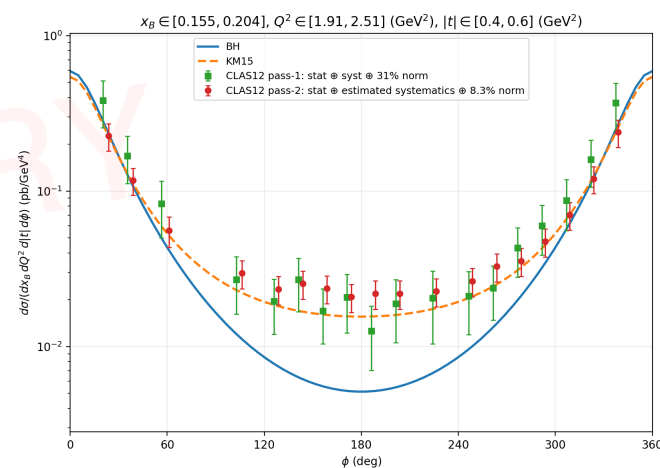
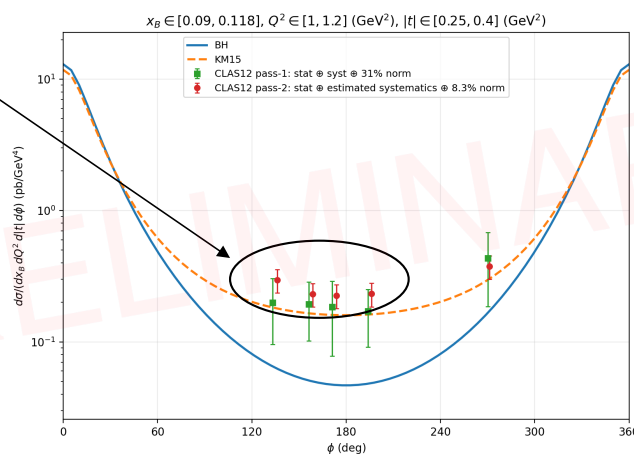
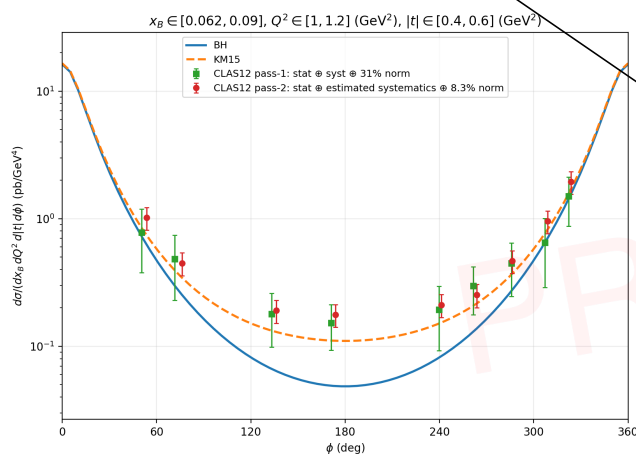
$x_b \in [0.118, 0.155]$   
 pass-1, pass-2, BH

$x_b \in [0.204, 0.268]$   
 pass-1, pass-2, BH



# Improvements compared to pass-1

- Final statistics improved by  $\sim 2x$  (addition of Sp18 data but also improvements to reconstruction in Fa18).
- Point-to-point systematics improved slightly. No global normalization with accompanying 31% uncertainty necessary but possible combination systematic currently estimated at 8.3%.
- Improved discriminatory power. Conservative preliminary statement: RGA pass-2 measurement  $>$  KM15.



# Conclusions

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- $ep \rightarrow e'p\gamma$  cross section has been determined independently for all five periods of RGA data taking.
- Results are consistent with CLAS6 and CLAS12 pass-1 measurements (without the need for external normalization and accompanying 31% pass-1 normalization uncertainty).
- Both statistical and total systematic uncertainties (including normalization) improved by a factor of  $\sim 2$  compared to pass-1.
- Significantly improved discriminatory power compared to model predictions. Potential measurement  $> KM15$ , consistent with observation of BSAs.
- Run periods are in slight tension with a potential median scale systematic of  $\sim 8\%$ .
- Strong FD sector-to-sector dependence for protons and photons but relatively little for electrons or CD protons.

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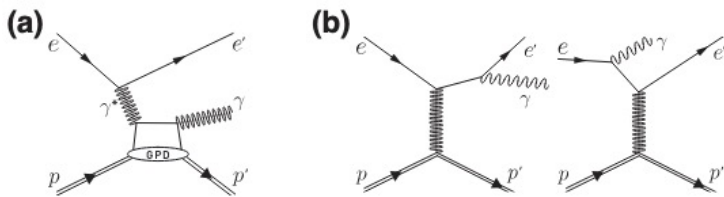
# Ancillary Slides

# Nucleon Structure through DVCS and accessing GPDs

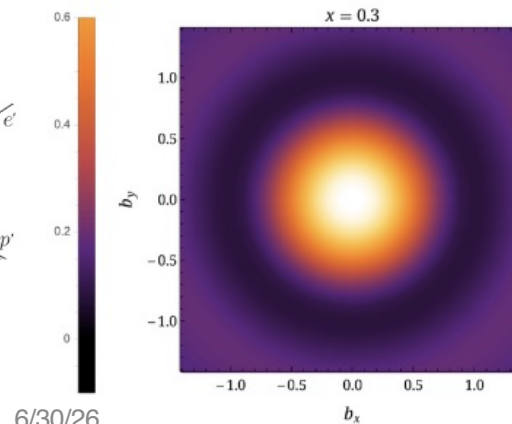
- Generalized Parton Distributions (GPDs) unify form factors and parton distribution functions and provide a more complete 3D picture of the nucleus.
- Give access to information on the correlations between transverse position and longitudinal momentum of quarks and gluons inside the nucleus.
- Accessible experimentally through measurements of exclusive processes such as Deeply Virtual Compton Scattering (DVCS) or Deeply Virtual Meson Production (DVMP).

		Quark Polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$H$		$\bar{E} = 2\tilde{H}_T + E_T$
	L		$\tilde{H}$	$\tilde{E}_T$
	T	$E$	$\tilde{E}$	$H_T, \tilde{H}_T$

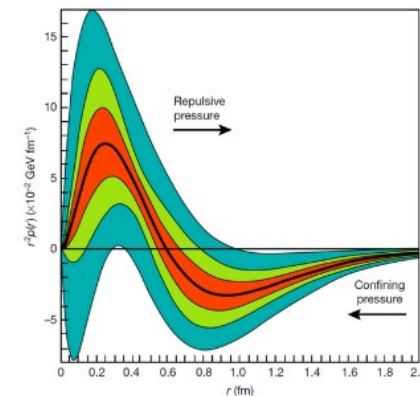
$$\sigma \propto |BH|^2 + |DVCS|^2 + \text{Interference}$$



Nucleon Tomography



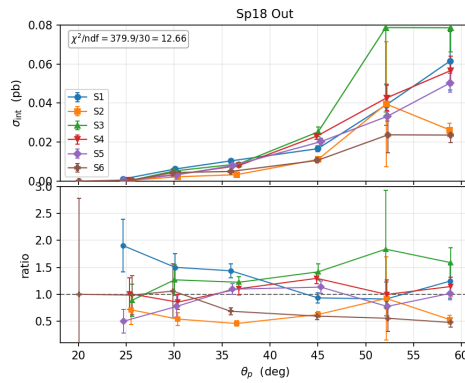
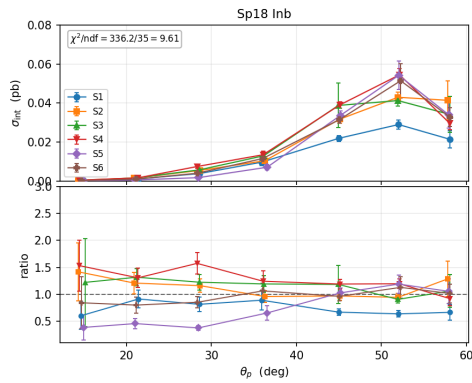
Gravitational Form Factors



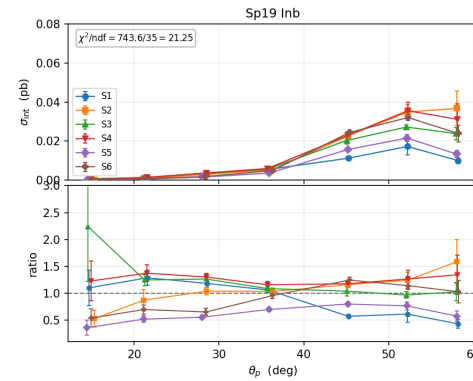
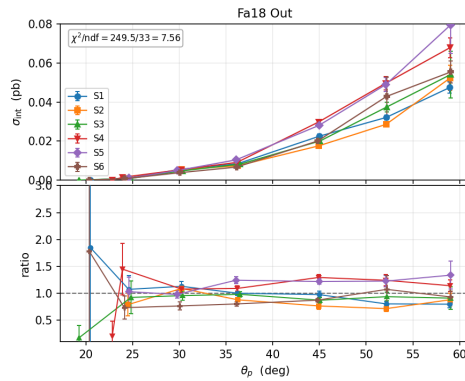
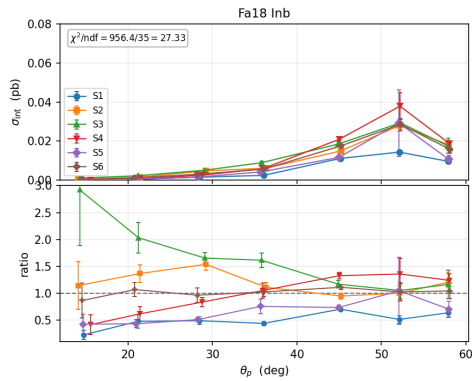
- Mass/energy distribution inside the nucleon
- Nucleon mass radius
- Shear forces and pressure distributions

# Proton FD Sector Dependence

proton polar-angle dependence by photon FD sector

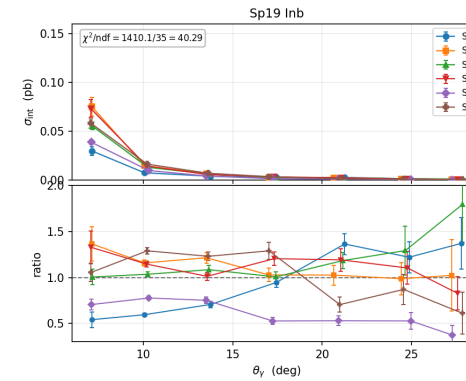
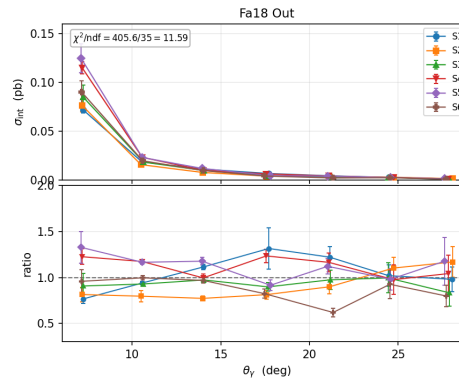
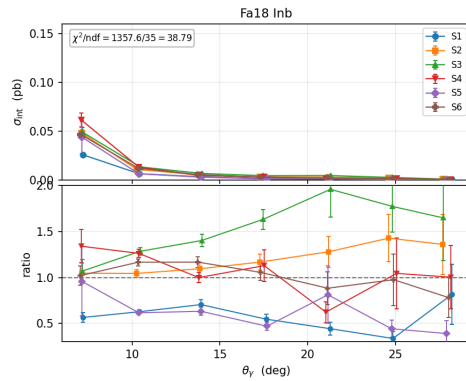
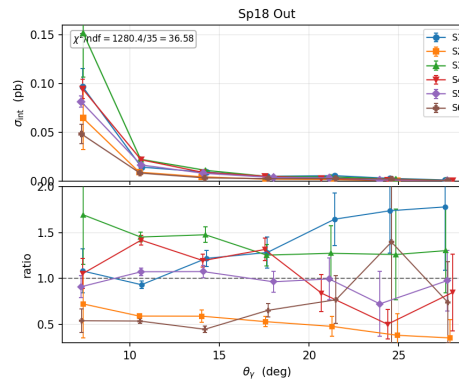
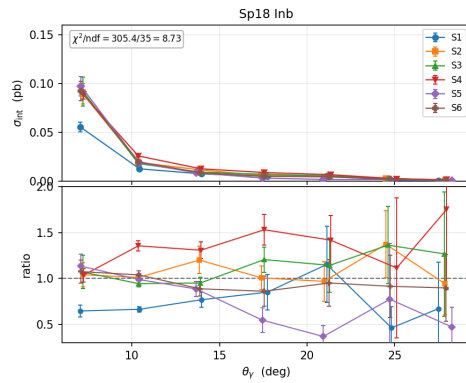


- Lower statistics for FD protons but larger sector-to-sector discrepancy.



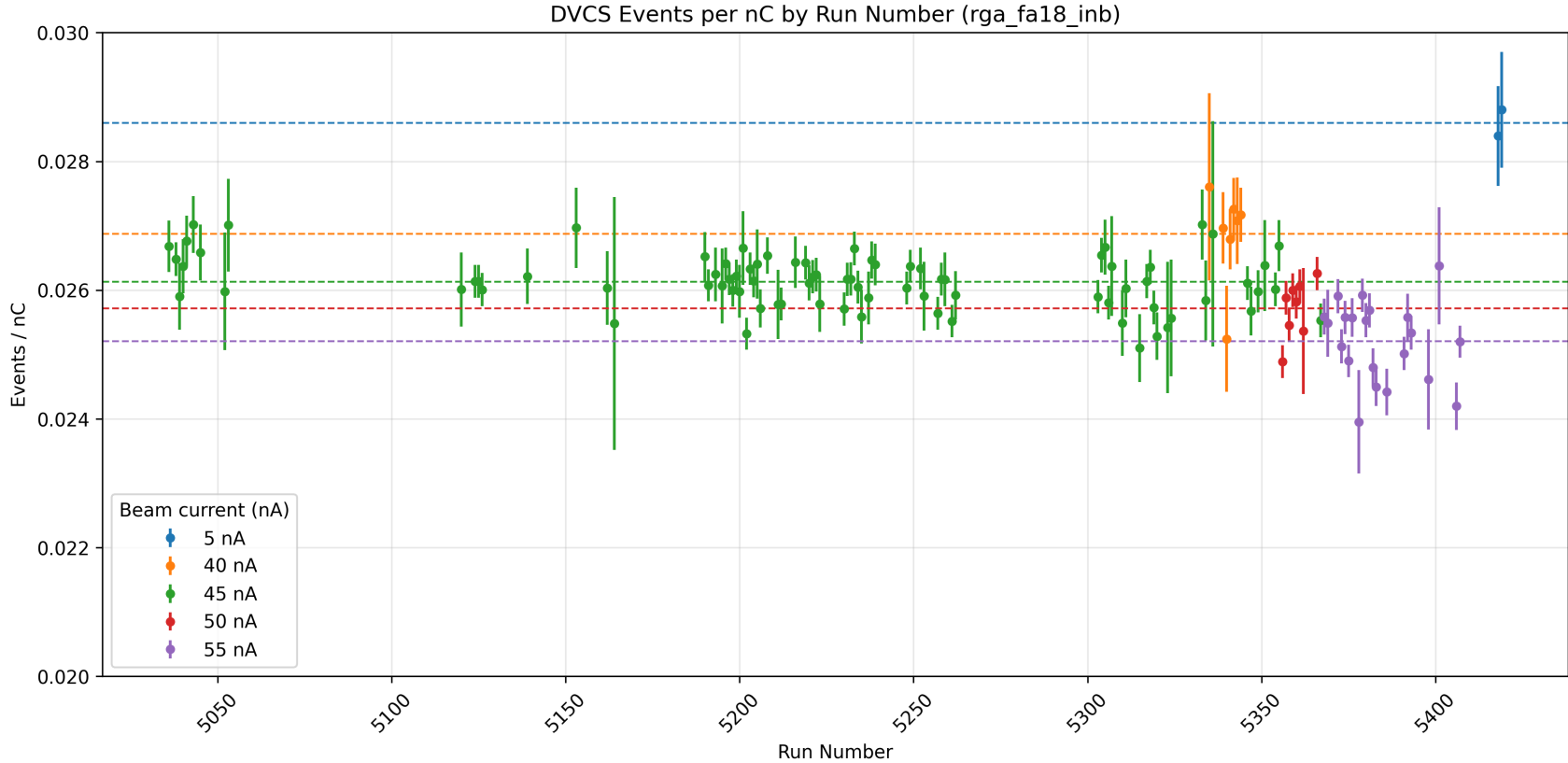
# Photon FD Sector Dependence

photon polar-angle dependence by photon FD sector



- Photon FD sector dependence is comparatively very high.

# Final RGA Fa18 Inb Events/nC





# Final RGA Sp19 Inb Events/nC

