Deeply Virtual Compton Scattering on Polarized Protons and Neutrons with CLAS12

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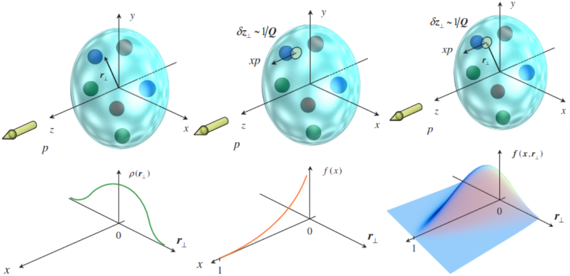
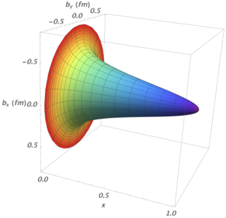
Nucleon structure studies, Generalized Parton Distributions

GPDs: partonic structure of nucleons in terms of transverse position, longitudinal momentum and their correlations.

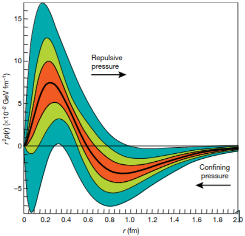


Big picture: Tomography of the nucleon? Nucleon spin origin? Forces inside the nucleon?

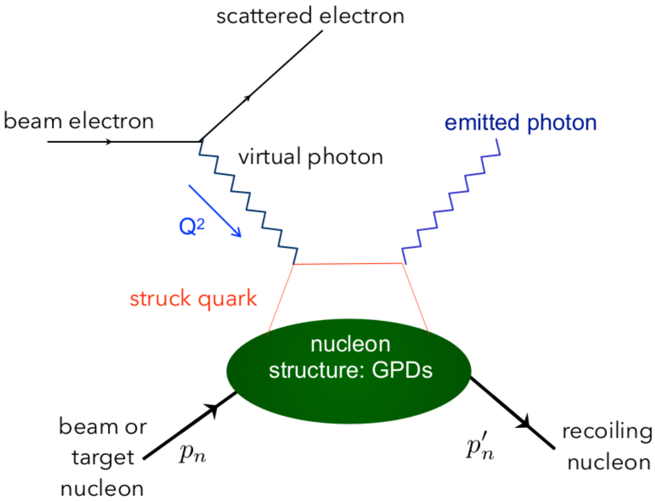


$$J_N = \frac{1}{2} = \frac{1}{2}\Sigma_q + L_q + J_g$$

Ji's relation: $J^q = \frac{1}{2} - J^g = \frac{1}{2}\int_{-1}^{1} x\,dx \left\{H^q(x,\xi,0) + E^q(x,\xi,0)\right\}$



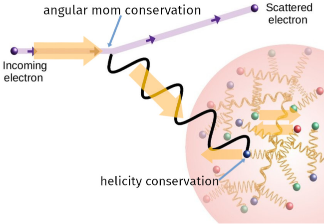
Deeply Virtual Compton Scattering (DVCS)



Accessing the nucleon structure by measuring asymmetries

A comment for Brynne and our MOLLER friends that use electron polarization to measure a very different kind of asymmetry 😉

Why do we measure asymmetries using polarized beams? Get an idea of it with the example of the nucleon spin structure in 1D.



- Beam e^- polarization $\rightarrow$ probing γ polarization
- Coupling between opposite γ and quark helicities
- Electron polarization $\rightarrow$ probes the quark helicity/spin distribution in the nucleon.

Difference in probability of scattering for each polarization state $\Delta\sigma = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \propto$ difference in population of quarks of different helicity states.

Same idea for DVCS and GPDs, but in 3D!

Accessing GPDs

Four quark GPDs can be accessed with DVCS by combining polarized beams and targets.

Beam, target polarisation		Proton / Neutron
$\vec{e}^-$ p/n	$\Delta\sigma_{LU} \sim \sin\phi\, \Im(F_1 H + \xi G_M \tilde{H} - \frac{t}{4M^2} F_2 E)\, d\phi$	$Im\{\boldsymbol{H_p}, \tilde{H}_p, E_p\}$ $Im\{H_n, \tilde{H}_n, \boldsymbol{E_n}\}$
e^- $\vec{p}$	$\Delta\sigma_{UL} \sim \sin\phi\, \Im(F_1 \tilde{H} + \xi G_M (H + \frac{x_B}{2} E) - \xi \frac{t}{4M^2} F_2 \tilde{E} + ...)\, d\phi$	$Im\{\boldsymbol{H_p}, \boldsymbol{\tilde{H}_p}\}$ $Im\{\boldsymbol{H_n}, E_n, \tilde{E}_n\}$
e^- $p^{\uparrow}$	$\Delta\sigma_{UT} \sim \cos\phi\, \Im(\frac{t}{4M^2}(F_2 H - F_1 E) + ...) d\phi$	$Im\{\boldsymbol{H_p}, \boldsymbol{E_p}\}$ $Im\{\boldsymbol{H_n}\}$
$\vec{e}^-$ $\vec{p}$	$\Delta\sigma_{LL} \sim (A + B\cos\phi)\, \Re(F_1 \tilde{H} + \xi G_M (H + \frac{x_B}{2} E) + ...) d\phi$	$Re\{\boldsymbol{H_p}, \boldsymbol{\tilde{H}_p}\}$ $Re\{\boldsymbol{H_n}, E_n, \tilde{E}_n\}$

Complete program for GPD extraction?

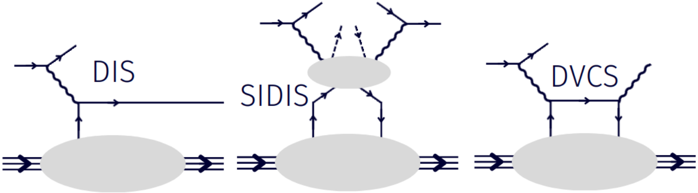
- Polarized beams (CEBAF)
- DVCS measurements (CLAS12)
- Polarized targets, p and n → Run Group C (CLAS12, Hall B)

The Run Group C (RGC) Experimental Program

RGC main feature: longitudinally polarized NH_3 and ND_3 targets.

+ 10.5 GeV highly-polarized electron beam

A complete program of experiments to study nucleons' structure.



Data taking: 11th June 2022 - 20th March 2023 with a 3 months break due to a major hardware failure.

- My work: DVCS on polarized protons and neutrons in D
- This presentation: DVCS on polarized protons in H.

Disclaimer: VERY preliminary results! Not fully calibrated data, (very) small fraction of the expected statistics.

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Run Group C at CLAS12

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+ 10.5 GeV highly-polarized electron beam

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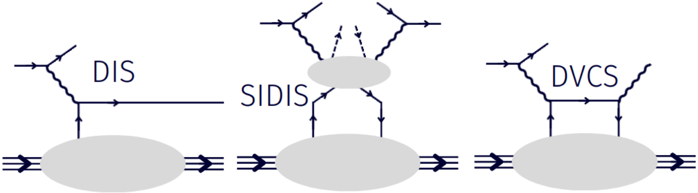

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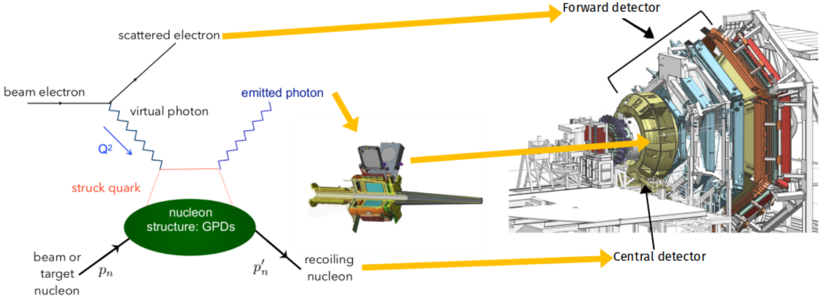
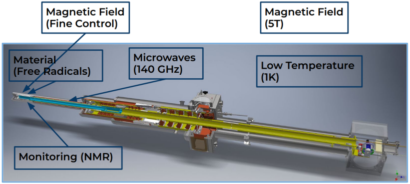
DVCS with CLAS12



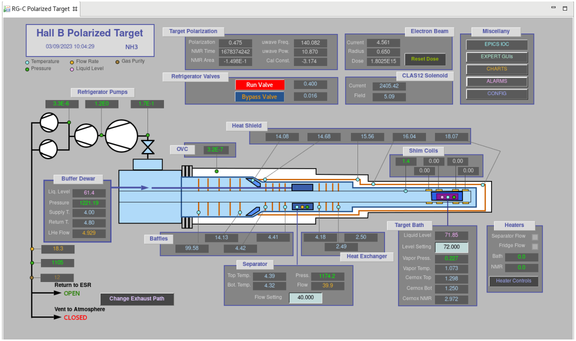
Target overview



Ingredients for a polarized target:

- Under 5T solenoid magnetic field
- Inside a 1K cryostat
- Samples are polarized with microwaves

- NH_3
- ND_3
- Background targets: empty, C, CH_2, CD_2



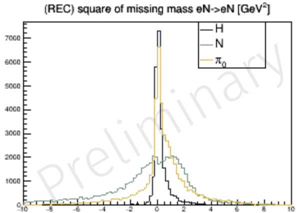
DVCS Measurement

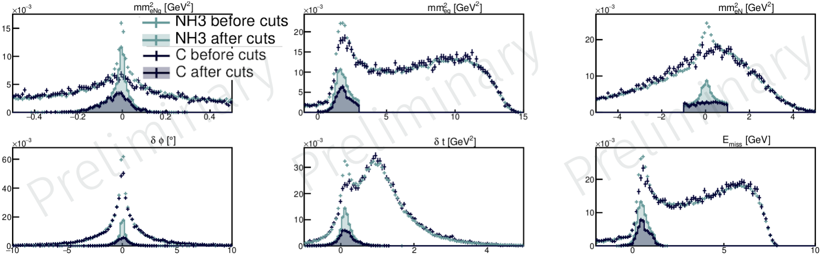
pDVCS events selection $ep \to ep\gamma$

- All $ep\gamma$ events on NH3.
- Goal is to select pDVCS on H.
- Exclusivity variables: missing masses, angles, etc.
- Background: pDVCS on N, $ep \to ep\pi^0(\gamma\gamma)$

$\to$ Yields extracted for each beam/target polarisation combinations.

Genepi: GPD-based BH, DVCS and DVMP event generator





What we measure: asymmetries

From the extracted $N^{beam,target}$ yields.

- Beam Spin Asymmetry (BSA):

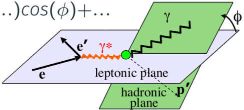
$$A_{LU} = \frac{(N^{++}+N^{+-})-(N^{-+}+N^{--})}{(N^{++}+N^{+-})+(N^{-+}+N^{--})} \simeq \frac{\overbrace{s^{I}_{1,unp}}^{\Im(\mathrm{H}_p),\ \Im(\mathcal{E}_n)} \sin(\phi)}{c^{BH}_{0,unp}+(c^{BH}_{1,unp}+c^{I}_{1,unp}+\ldots)\cos(\phi)+\ldots}$$

- Target Spin Asymmetry (TSA):

$$A_{UL} = \frac{(N^{++}+N^{-+})-(N^{+-}+N^{--})}{(N^{++}+N^{-+})+(N^{+-}+N^{--})} \simeq \frac{\overbrace{s^{I}_{1,LP}}^{\Im(\widetilde{\mathcal{H}_p}),\ \Im(\mathcal{H}_p),\ \Im(\mathcal{H}_n)} \sin(\phi)}{c^{BH}_{0,unp}+(c^{BH}_{1,unp}+c^{I}_{1,unp}+\ldots)\cos(\phi)+\ldots}$$

- Double Spin Asymmetry (DSA):

$$A_{LL} = \frac{(N^{++}+N^{--})-(N^{+-}+N^{-+})}{(N^{++}+N^{--})+(N^{+-}+N^{-+})} \simeq \frac{c^{BH}_{0,LP}+\overbrace{c^{I}_{0,LP}}^{\Re(\widetilde{\mathcal{H}_p}),\ \Re(\mathcal{H}_p)}+(c^{BH}_{1,LP}+\overbrace{c^{I}_{1,LP}}^{\Re(\mathcal{H}_n)})\cos(\phi)}{c^{BH}_{0,unp}+(c^{BH}_{1,unp}+c^{I}_{1,unp}+\ldots)\cos(\phi)+\ldots}$$



What we measure: asymmetries

From the extracted $N^{beam,target}$ yields.

- Beam Spin Asymmetry (BSA):

$$A_{LU} = \frac{P_t^-(N^{++}-N^{-+})+P_t^+(N^{+-}-N^{--})}{Pb\times(P_t^-(N^{++}+N^{-+})+P_t^+(N^{+-}+N^{--}))} \simeq \frac{\overbrace{s^I_{1,unp}}^{\Im(\mathrm{H}_p),\,\Im(\mathcal{E}_n)} sin(\phi)}{c^{BH}_{0,unp}+(c^{BH}_{1,unp}+c^I_{1,unp}+\ldots)cos(\phi)+\ldots}$$

- Target Spin Asymmetry (TSA):

$$A_{UL} = \frac{N^{++}+N^{-+}-N^{+-}-N^{--}}{Df\times(P_t^-(N^{++}+N^{-+})+P_t^+(N^{+-}+N^{--}))} \simeq \frac{\overbrace{s^I_{1,LP}}^{\Im(\widetilde{\mathcal{H}_p}),\,\Im(\mathcal{H}_p),\,\Im(\mathcal{H}_n)} sin(\phi)}{c^{BH}_{0,unp}+(c^{BH}_{1,unp}+c^I_{1,unp}+\ldots)cos(\phi)+\ldots}$$

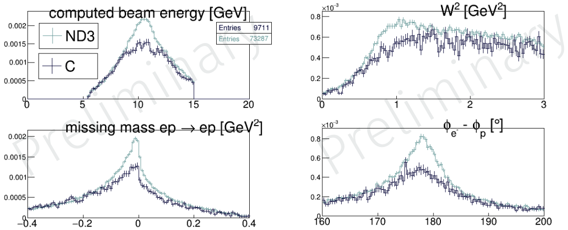
- Double Spin Asymmetry (DSA):

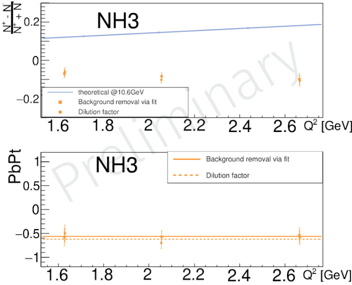
$$A_{LL} = \frac{N^{++}+N^{--}-N^{+-}-N^{-+}}{P_b\times Df\times(P_t^-(N^{++}+N^{-+})+P_t^+(N^{+-}+N^{--}))} \simeq \frac{c^{BH}_{0,LP}+\overbrace{c^I_{0,LP}}^{\Re(\widetilde{\mathcal{H}_p}),\,\Re(\mathcal{H}_p),}+(c^{BH}_{1,LP}+\overbrace{c^I_{1,LP}}^{\Re(\mathcal{H}_n)})cos(\phi)}{c^{BH}_{0,unp}+(c^{BH}_{1,unp}+c^I_{1,unp}+\ldots)cos(\phi)+\ldots}$$

Reality: no 100% polarizations, unpolarized N background.

Measuring the target polarization

Measuring the target polarization is not trivial. Necessitates full analysis of (quasi-)elastic $ep \to ep$ events.

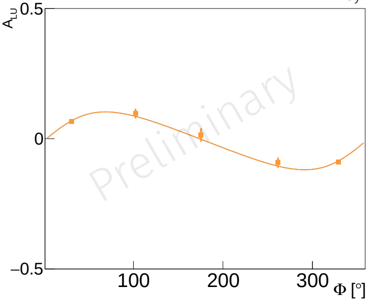


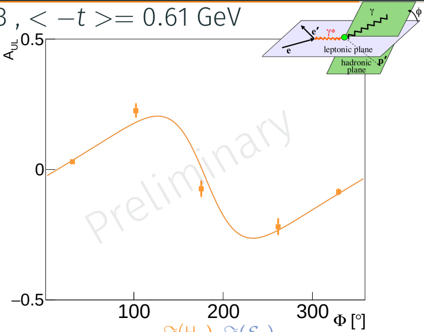


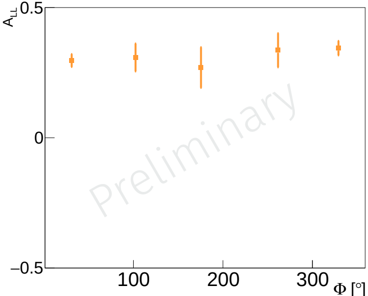
- $A = \frac{N^+ - N^-}{N^+ + N^-} = A_{\parallel}^{th} \times P_b \times P_t$
- $A_{\parallel}^{th} = \frac{2\tau G[\frac{M}{E} + G(\tau \frac{M}{E} + (1+\tau)\tan(\frac{\theta}{2})^2)]}{1 + G^2 \frac{\tau}{\epsilon}}$ very well known with $G = \frac{G_M}{G_E}$
- A very reliable way of knowing $P_b \times P_t$!

Preliminary asymmetries for pDVCS (NH3)

$< Q^2 >= 2.5\ \mathrm{GeV}^2$, $< X_{bj} >= 0.23$, $< -t >= 0.61$ GeV



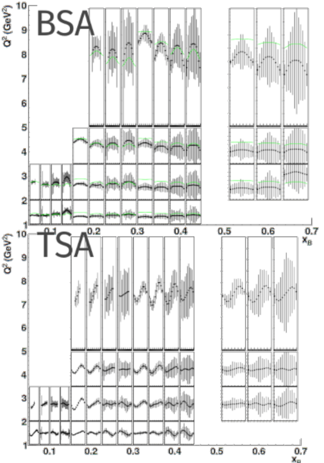


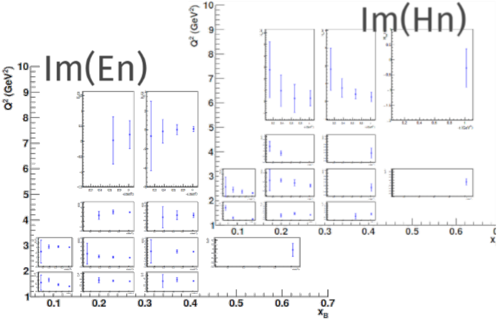


- $A_{LU}(\phi) \simeq \dfrac{\overbrace{s^I_{1,unp}}^{\Im(H_p),\ \Im(\mathcal{E}_n)} \sin(\phi)}{c^{BH}_{0,unp}+(c^{BH}_{1,unp}+c^I_{1,unp}+\ldots)\cos(\phi)+\ldots}$
- $A_{UL}(\phi) \simeq \dfrac{\overbrace{s^I_{1,LP}}^{\Im(\widetilde{\mathcal{H}}_p),\ \Im(\mathcal{H}_p),\ \Im(\mathcal{H}_n)} \sin(\phi)}{c^{BH}_{0,unp}+(c^{BH}_{1,unp}+c^I_{1,unp}+\ldots)\cos(\phi)+\ldots}$
- $A_{LL}(\phi) \simeq \dfrac{c^{BH}_{0,LP}+\overbrace{C^I_{0,LP}}^{\Re(\widetilde{\mathcal{H}}_p),\ \Re(\mathcal{H}_p)}+(c^{BH}_{1,LP}+\overbrace{C^I_{1,LP}}^{\Re(\mathcal{H}_n)})\cos(\phi)}{c^{BH}_{0,unp}+(c^{BH}_{1,unp}+c^I_{1,unp}+\ldots)\cos(\phi)+\ldots}$

Outlooks

- Data processing is on-going
- Final analysis: BSA, TSA, DSA on polarized p and n in ND3.
- Proton and neutron CFFs, flavor dependency, D effects.



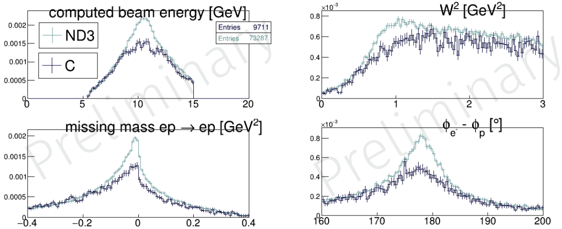


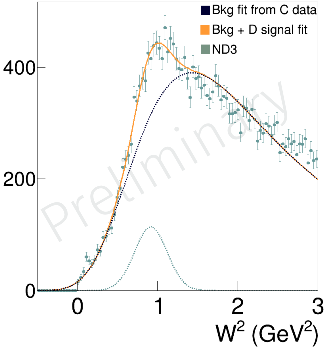
Backup

Measuring the target polarization

A crucial measurement that I will be using today as a warm-up for asymmetry measurements: elastic extraction of $P_b \times P_t$

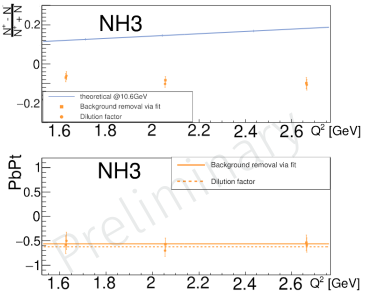
The only accurate way to measure the target polarization is by analysing (quasi-)elastic events $ep \to ep$.





Elastic extraction of $P_b \times P_t$

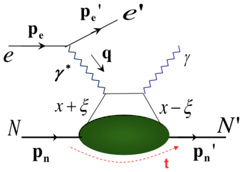
- $ep \rightarrow ep$
- Count events with + VS - e^- polarizations.
- Probes the polarization of p inside H or D.
- Observed asymmetry $A = A_{\|}^{th} \times P_b \times P_t$
- We know the proton electromagnetic form factor ratio $G = G_M/G_E$ very well.
- Theoretical DSA
  $A_{\|}^{th} = \frac{2\tau G[\frac{M}{E} + G(\tau\frac{M}{E} + (1+\tau)\tan(\frac{\theta}{2})^2)]}{1+G^2\frac{\tau}{\epsilon}}$
- A very reliable way of knowing $P_b \times P_t$!

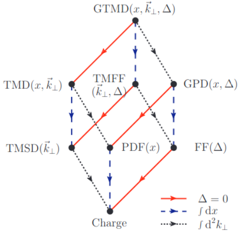


Of course the full story is more subtle:

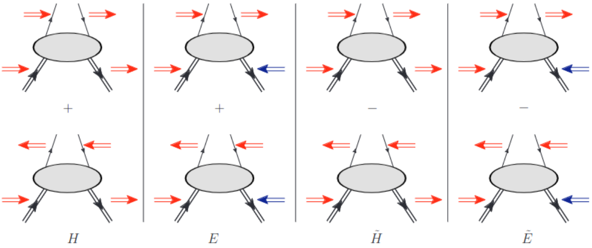
- Taking into account N background? Dilution factors.
- Max likelihood estimator for $P_b \times P_t$?
- Low statistics at 10.5 GeV
- Radiative effects? Resolution effects? Nuclear binding in D?

Miscellaneous DVCS and GPDs information





- $Q^2 = -q^2 = -(p_e - p_e')^2$
- $t = (p_n - p_n')^2$
- $x_{Bj} = \frac{Q^2}{2p_n q}$



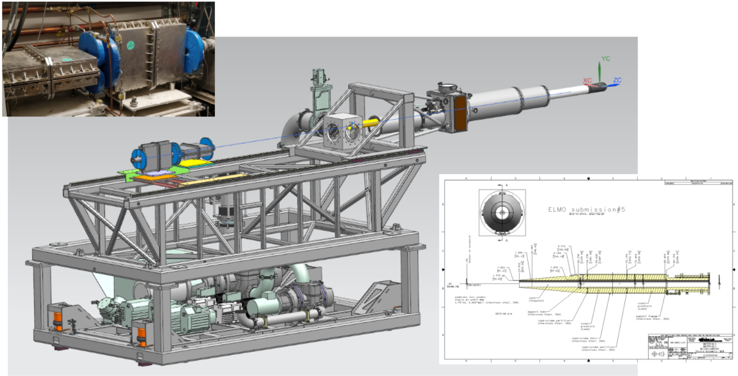
The RGC beamline

The raster magnets

- Target is depolarized by radiation damage
- Beam is moved uniformly on the surface
  = rastering

FTOn/ELMO configurations

- Beginning and end of RGC used the Forward Tagger
- Middle of the run used the ELMO Möller cone



The RGC schedule

Original plan: Run from June 8, 2022 to March 14, 2023 120 PAC days