Exclusive photoproduction of lepton pairs with CLAS12

Rafayel Paremuzyan for the dilepton group

CLAS12 Run Group A - Retreat

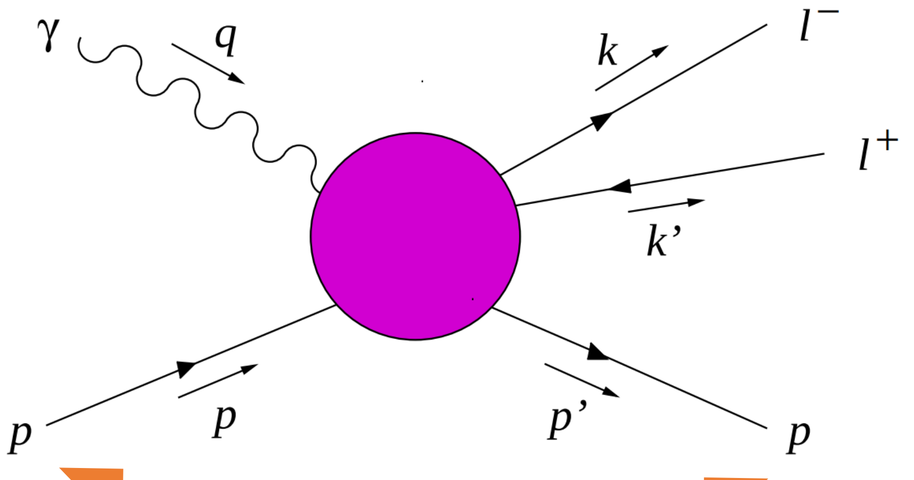
October 18, 2023, Christopher Newport University

Two main physics reactions

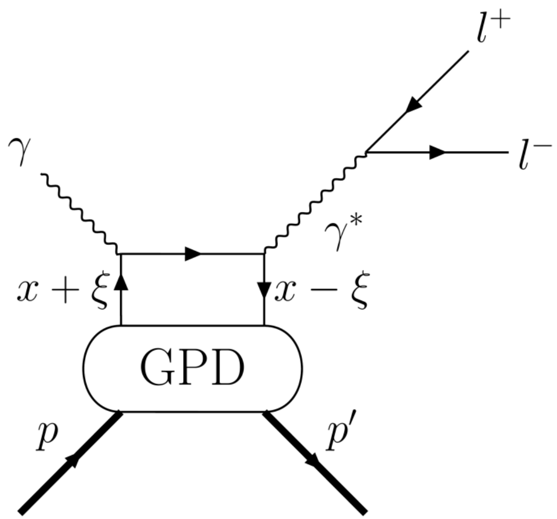
Photoproduction of lepton pairs

Two main physics reactions with the same final state.

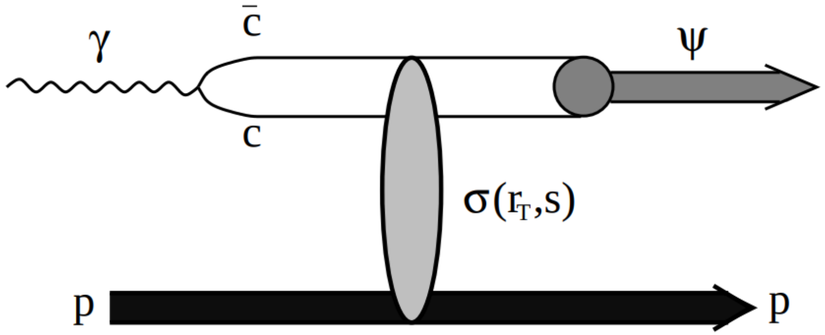
$ep \rightarrow e^- e^+ p(X)$



Timelike Compton Scattering (TCS)

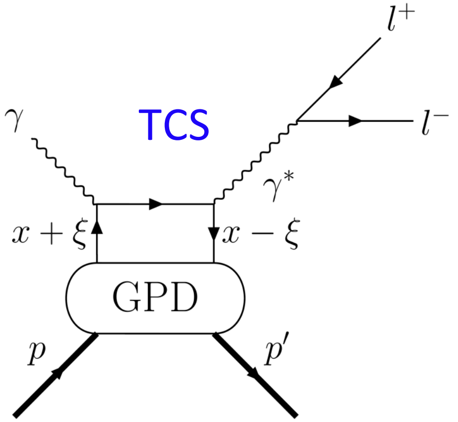


Photoproduction of J/Ψ near the threshold



TCS

- TCS is an inverse to DVCS process



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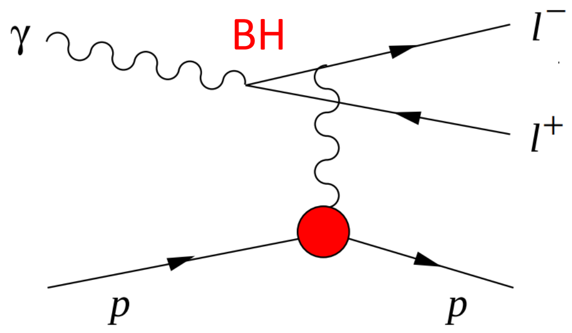
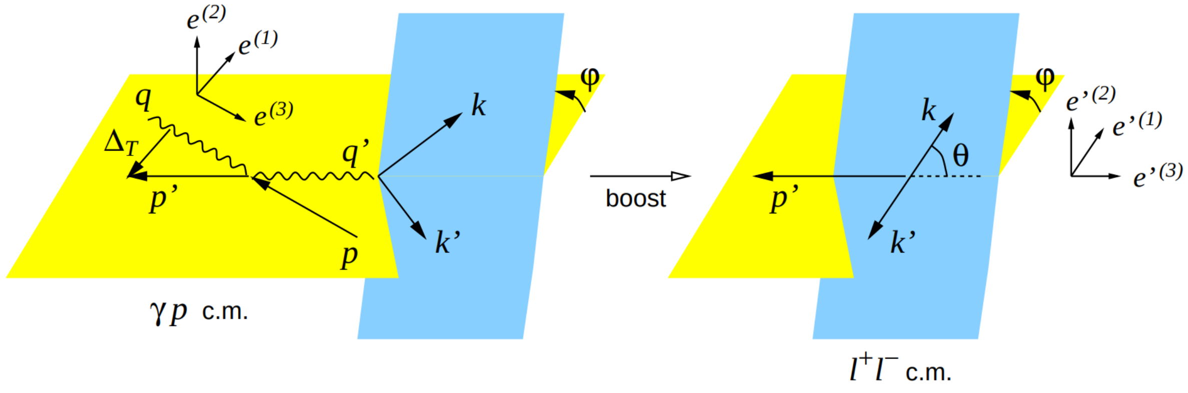




$$\frac{d^4\sigma_{\mathrm{INT}}}{dQ'^2\,dt\,d\Omega} = A\,\frac{1+\cos^2\theta}{\sin\theta} \times \left[\cos\phi\,\mathrm{Re}\tilde{M}^{--} - \nu\sin\phi\,\mathrm{Im}\,\tilde{M}^{--}\right]$$

$$\tilde{M}^{--} \sim \left[F_1\mathcal{H}_1 - \eta(F_1+F_2)\tilde{\mathcal{H}}_1 - \frac{t}{4M^2}F_2\mathcal{E}_1\right]$$

$$A_{\mathrm{FB}}(\theta,\phi) = \frac{d\sigma(\theta,\phi) - d\sigma(180^\circ-\theta, 180^\circ+\phi)}{d\sigma(\theta,\phi) + d\sigma(180^\circ-\theta, 180^\circ+\phi)}$$

Forward-Backward asymmetry projects out the cosine moment of the interference term and hence the Re. Part of M⁻⁻.

$$A_{\odot U} = \frac{\sigma_{\mathrm{LH}} - \sigma_{\mathrm{RH}}}{\sigma_{\mathrm{LH}} + \sigma_{\mathrm{RH}}}$$

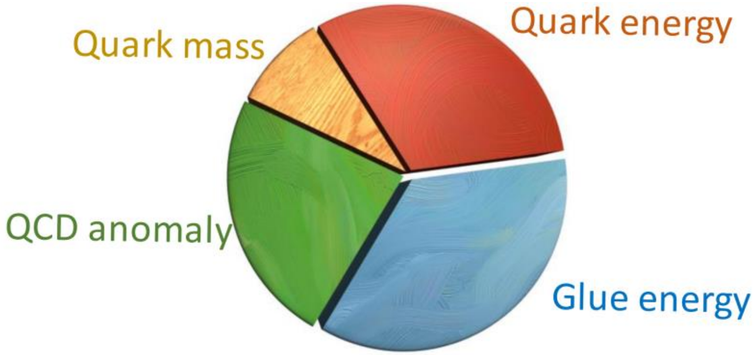
Polarization asymmetry projects out the sin moment of the interference term and hence the Im. part of M⁻⁻.

Photoproduction of J/ψ near the threshold

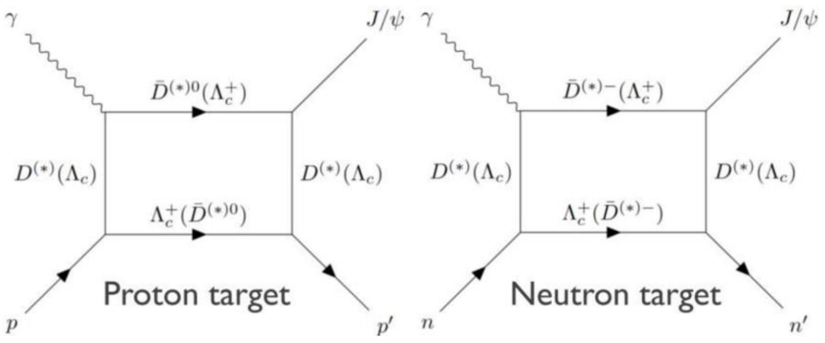
- Cross-section measurement near the threshold gives important insight of the production mechanism

- Access to the gluonic GPDs of the nucleon

- Trace anomaly. Decomposition of the proton mass
- Mass radius of the proton
- Access Gravitational Form factors (or EMT form factors)



- Production on Deuterium target
  - Comparing J/ψ cross-sections on the proton and neutron can shed more light on the production mechanism, if only gluon exchange, cross sections should be identical.



List of experiments and spokespersons

- **E12-12-001** Timelike Compton Scattering and J/psi photoproduction on the proton in e^+e^- pair production with CLAS12 at 11 GeV
  - P. Nadel-Turonski, M. Guidal, T. Horn, R. Paremuzyan, S. Stepanyan

- **E12-12-001A** Near threshold J/psi photoproduction and study of LHCb pentaquarks with CLAS12
  - S. Stepanyan, M. Battaglieri, A. Celentano, R. De Vita, V. Kubarovsky

- **E12-11-003B** Study of J/psi Photoproduction off the Deuteron
  - Y. Ilieva, V. Kubarovsky, B. McKinnon, P. Nadel-Turonski, S. Stepanyan, Z. Zhao

RG-B

List any new idea of CAA

Analysis by Kayieigh Gates,
Working on the preparation for CAA

TCS on linearly polarized target

RG-C

List of PhD students and subject of thesis topic completed and in progress

Pierre Chatagnon	Nucleon Structure studies with CLAS12 at Jefferson Lab: Timelike Compton Scattering and the Central Neutron Detector (October 2020)	
Joseph Newton	J/ψ Photoproduction Near Threshold with CLAS12 (August 2021)	
Richard Tyson	J/ψ Near Threshold Photoproduction at CLAS12 (August 2023)	RG-B
Davit Martiryan	Study of J/Ψ photoproduction using CLAS12 detector (January 2022)	
Mariana Tenorio Pita	J/ψ Production off a Proton Target at CLAS12 (In progress)	
Kayleigh Gates	Timelike Compton Scattering on linearly polarized target with CLAS12 (in progress)	RG-C

Analyses based on pass1 data

Analysis note:

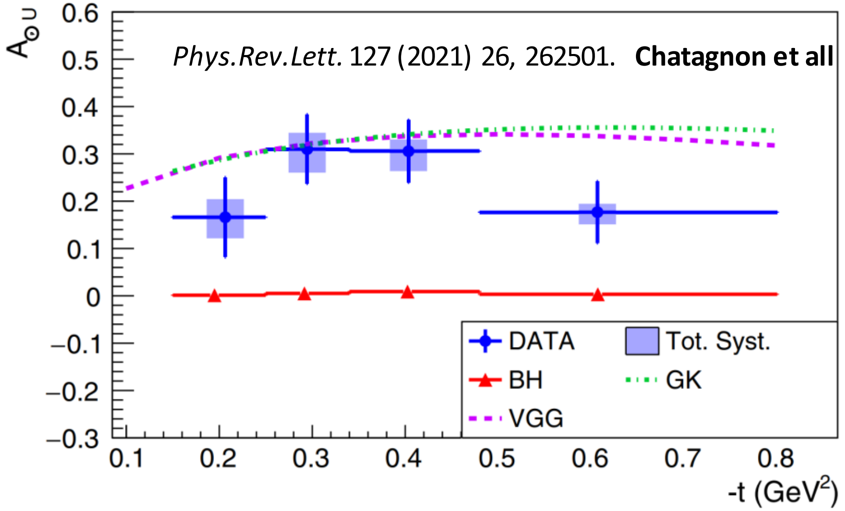
- Title: "Timelike Compton Scattering with CLAS12"
- Lead authors: P. Chatagnon, S. Nicollai and S. Stepanyan
- Data set: F18 Inbending
- Observables: Forward backward asymmetry and polarization asymmetry

Publication:

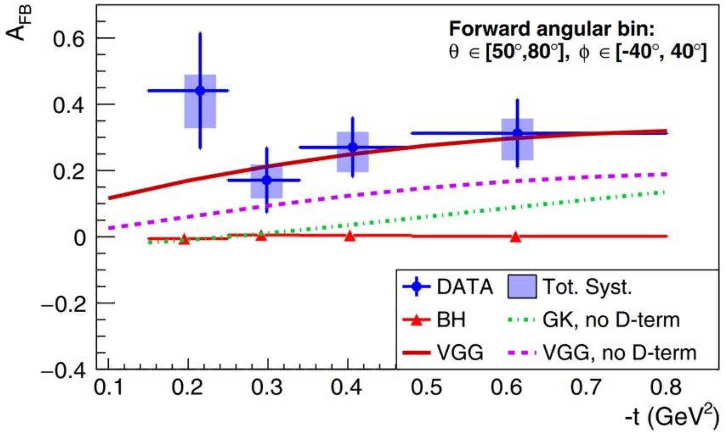
- Title: "First-time observation of Timelike Compton Scattering", based on the above analysis note
- Journal: *Phys.Rev.Lett.* 127 (2021) 26, 262501.

$$A_{FB}(\theta,\phi) = \frac{d\sigma(\theta,\phi) - d\sigma(180^\circ-\theta, 180^\circ+\phi)}{d\sigma(\theta,\phi) + d\sigma(180^\circ-\theta, 180^\circ+\phi)}$$

$$A_{\odot U} = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-} \qquad E_\gamma = 7.29 \pm 1.55 \text{ GeV} \quad M = 1.80 \pm 0.26 \text{ GeV}$$



$E_\gamma = 7.23 \pm 1.61$ GeV
$M = 1.81 \pm 0.26$ GeV



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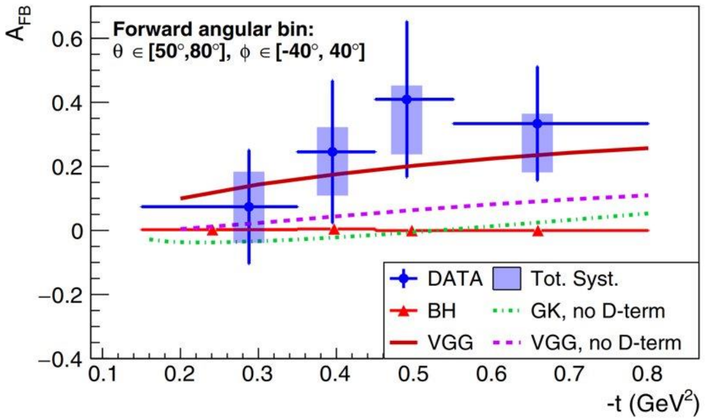


No plans to release another analysis based on pass1 data.

Photoproduction with electron beam

Common in TCS and J/Ψ analyses.

Two photon sources:

Real photons + Virtual photons

Electroproduction cross-section can be expressed as:

$$\frac{d\sigma}{dt} = \Gamma_\gamma \cdot \frac{d\sigma_\gamma}{dt} + \Gamma_{\gamma *} \cdot (\frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt})$$

Real photon flux Virtual photon flux

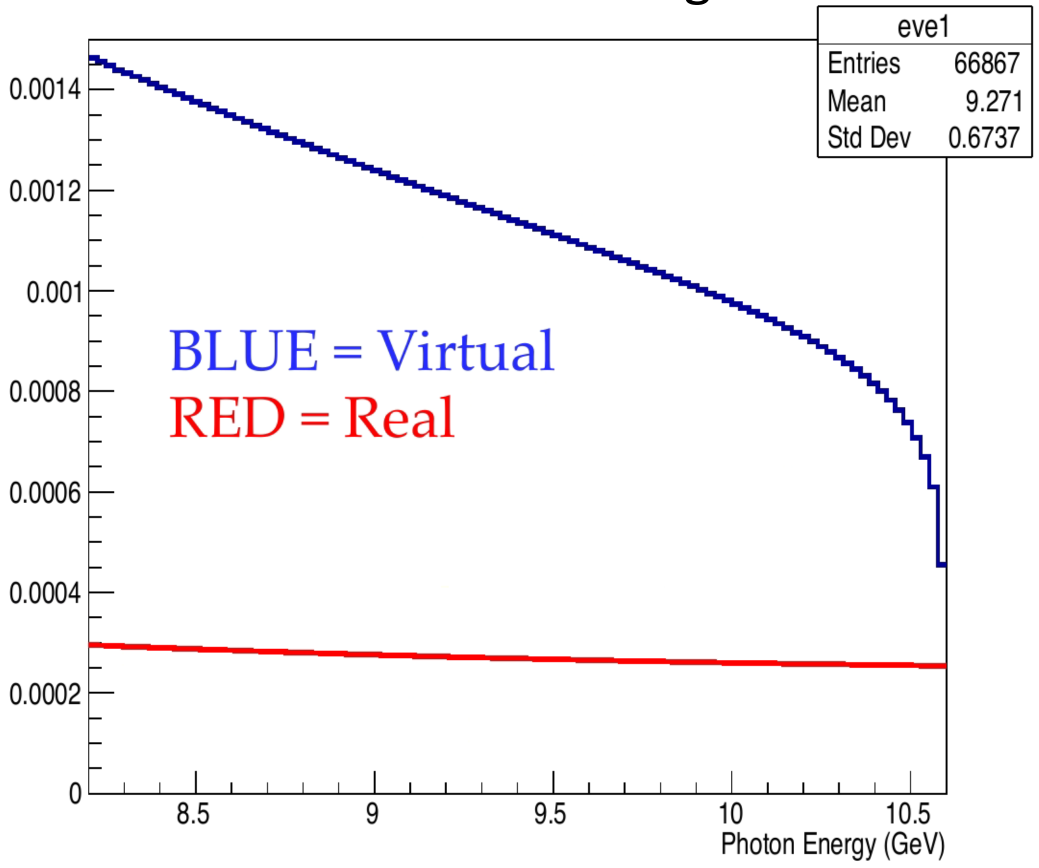
At small Q^2, $\boldsymbol{\sigma}_L$ approaches to 0.

$$\frac{d\sigma}{dt} = (\Gamma_\gamma + \Gamma_{\gamma *}) \cdot \frac{d\sigma_\gamma}{dt}$$

$$n(E_\gamma) = \frac{l}{2 \cdot X_0} \frac{1}{E_\gamma} \cdot \left(\frac{4}{3} - \frac{4}{3} \frac{E_\gamma}{E_b} + \frac{E_\gamma^2}{E_b^2} \right) dE$$ Real photon flux

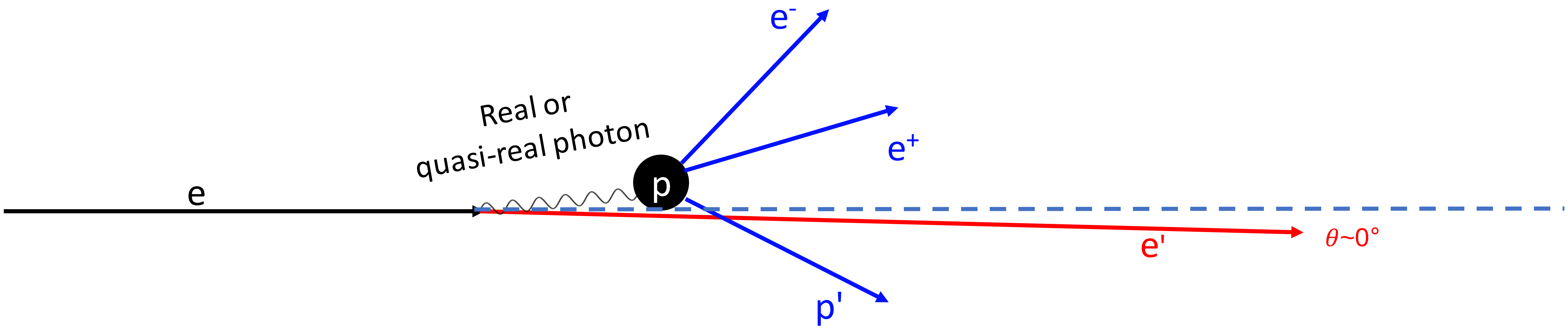
$$\Gamma(E_\gamma) = \frac{1}{E_b} \frac{\alpha}{\pi \cdot x} \cdot \left((1 - x + \frac{x^2}{2}) \cdot log(\frac{Q^2_{max}}{Q^2_{min}}) - (1-x) \right) dE$$ Virtual photon flux

Flux for 5cm LH2 target



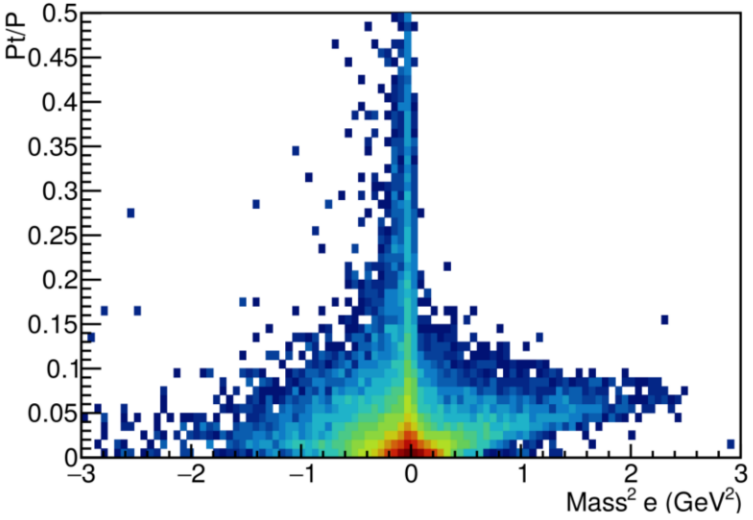
Selection of events with quasi-real photoproduction

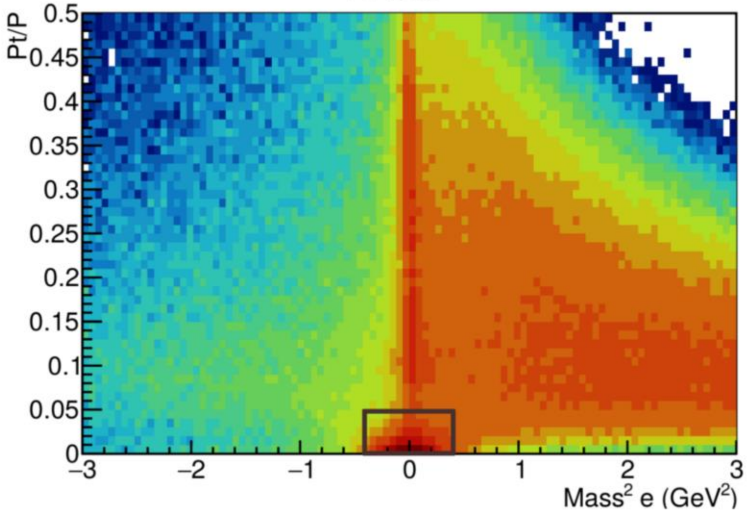
Common in TCS and J/Ψ analyses.



The kinematics of the scattered beam electron is identified as the missing 4 momentum of the e^-e^+p' system with Q^2~0 and M_{mis}~0

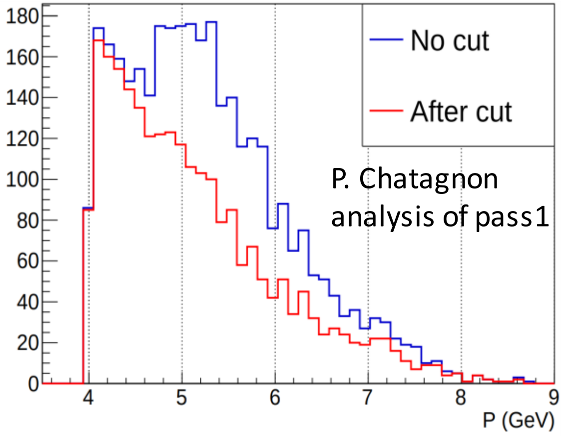
Add a clear label

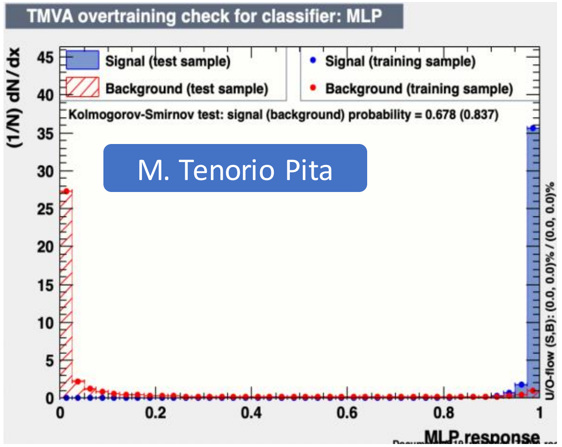


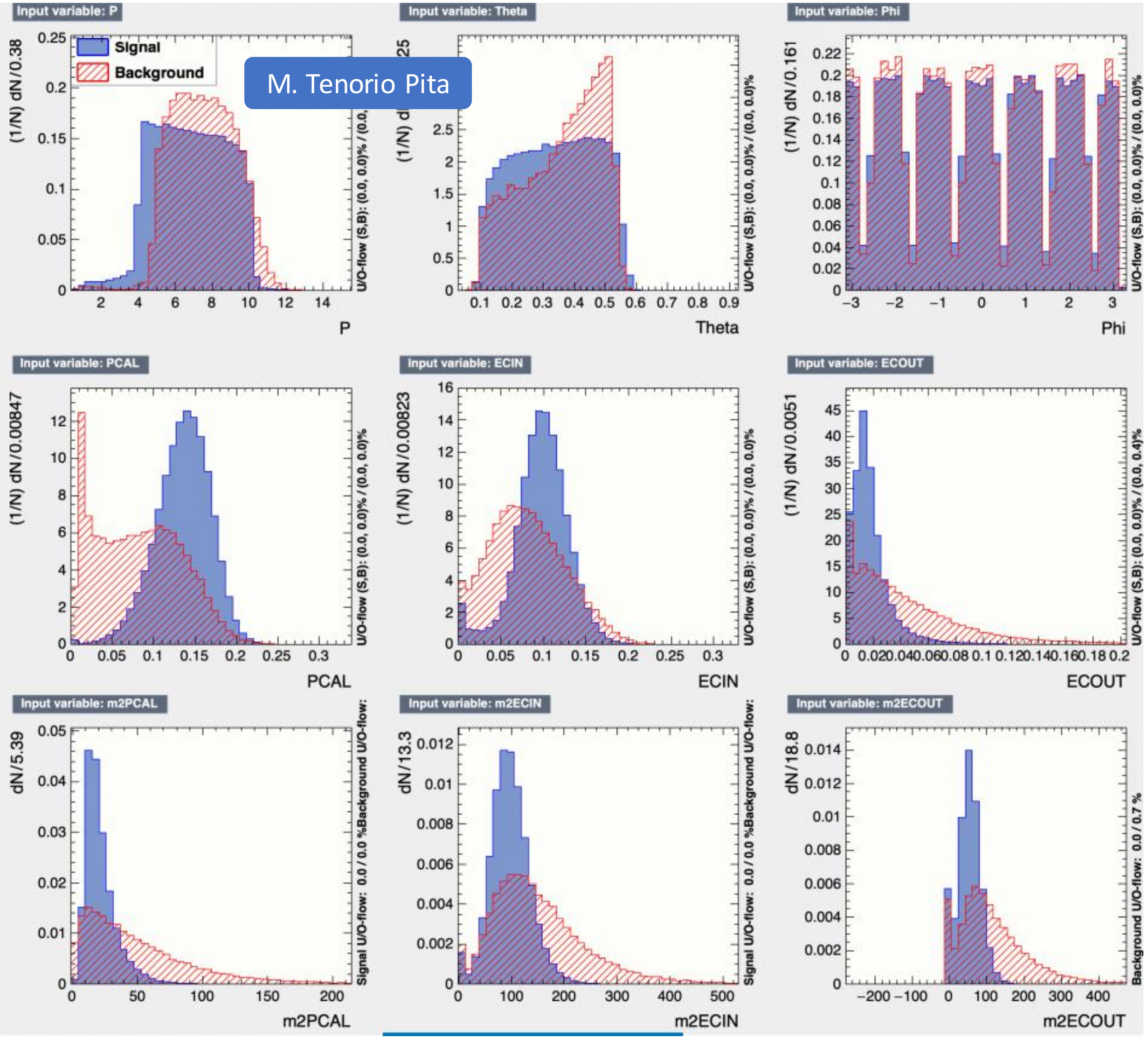


Positron identification w/ AI

In addition to EB PID, positrons need additional cleaning.
In pass1, Root TMVA package was used to clean pion pi+ contamination.







M. Tenorio Pita is currently working on training and validating this AI on pass2 data.

Expected to be finished and validated with data within 1-2 months.

Physics backgrounds

Two main physics backgrounds

- ep→e'e$^+$p'(e$^-$) decay electron escapes detection, while beam electron is detected
- ep→e'π$^+$p'(π$^-$) π$^+$ is misidentified as e$^+$, and π$^-$ escapes

$$N(e^-e^+p') = N_S(e^-e^+) + N_{BG}(e'e^+/\pi^+)$$

Same charge dilepton final states ep→e'e$^-$p'(e$^+$) and ep→e'π$^-$p'(π$^+$) contribute only to the background.

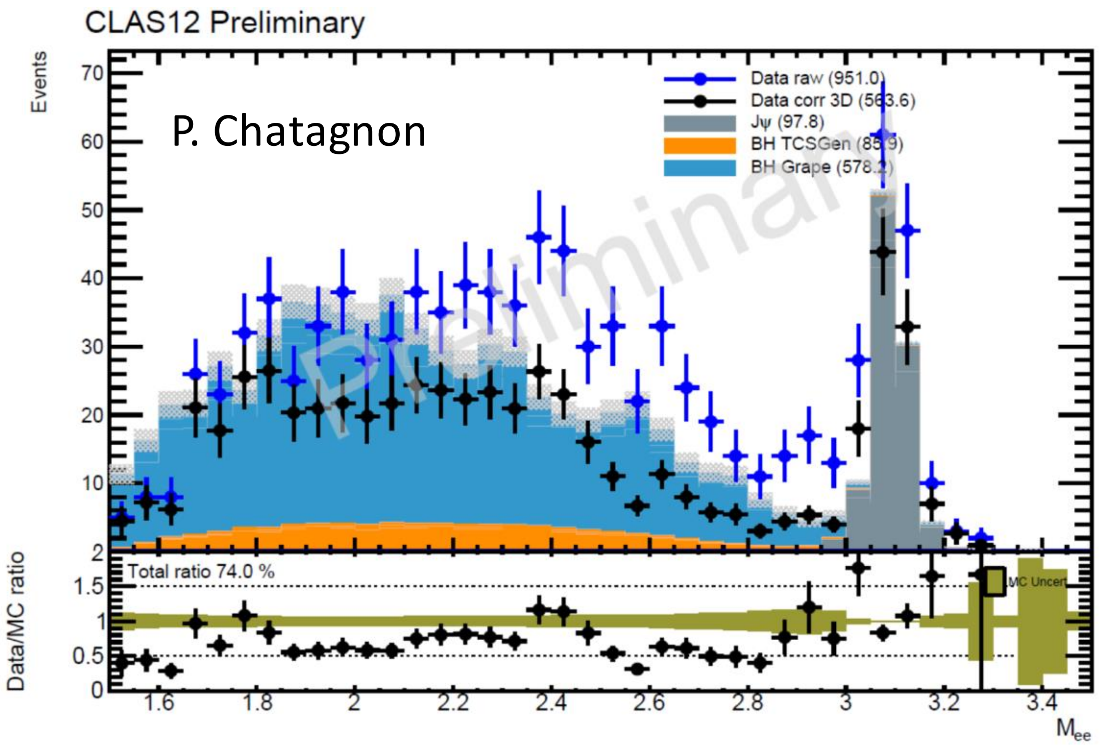
Bg topologies of course don't produce equal number of same and opposite charge lepton pairs in CLAS12, however using the inbending and outbending data one can estimate the contribution of the background in the total sample.

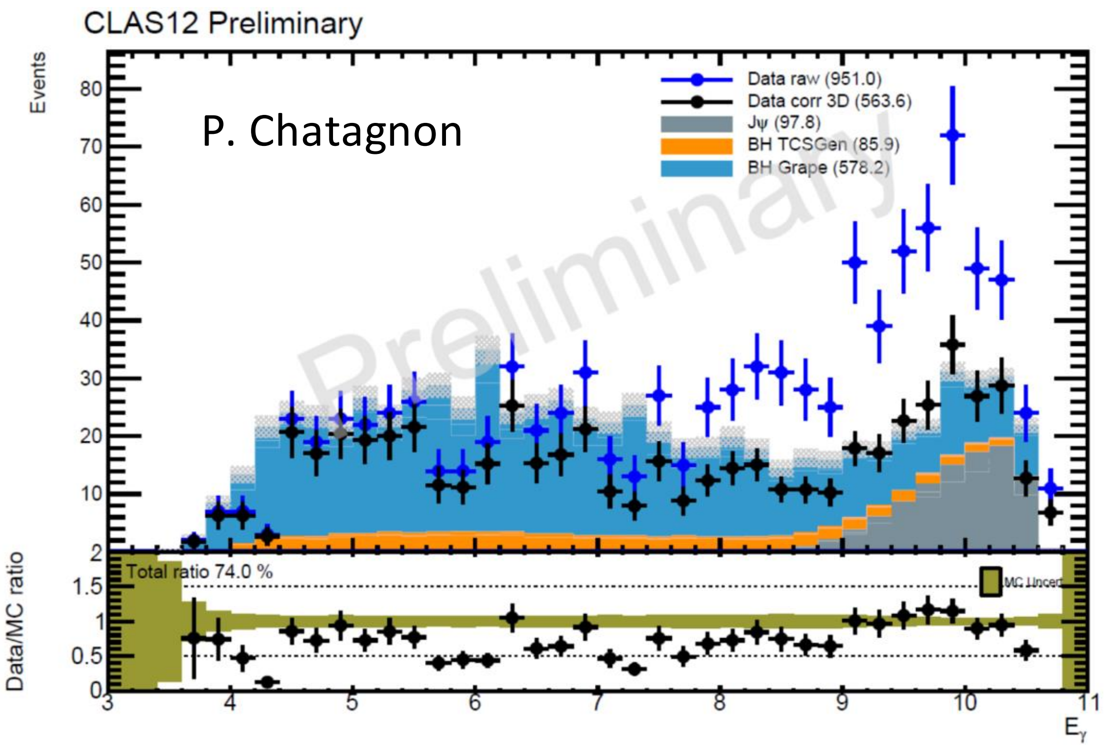
$$\begin{aligned} R^{in} &= \frac{N^{in}(e'e^-p')}{N^{in}(e^+e^-p')} = \frac{a^2\cdot\sigma_{BG}}{a\cdot b\cdot\sigma_{BG+S}} = \frac{a\cdot\sigma_{BG}}{b\cdot\sigma_{BG+S}} \\ R^{out} &= \frac{N^{out}(e'e^-p')}{N^{out}(e^+e^-p')} = \frac{b^2\cdot\sigma_{BG}}{a\cdot b\cdot\sigma_{BG+S}} = \frac{b\cdot\sigma_{BG}}{a\cdot\sigma_{BG+S}} \\ r^2 &= \frac{R^{in}}{R^{out}} = \frac{a^2}{b^2} \\ r &= \frac{a}{b} \end{aligned}$$

$$\frac{N_S}{N_S+N_{Bg}} = 1-\sqrt{\frac{N^{In}(e^-e'p')}{N^{In}(e^-e^+p')}\frac{N^{Out}(e^-e'p')}{N^{Out}(e^-e^+p')}}$$

"a" CLAS12 efficiency for inbending track
"b" CLAS12 efficiency for Outbending track

Correcting the data for the background



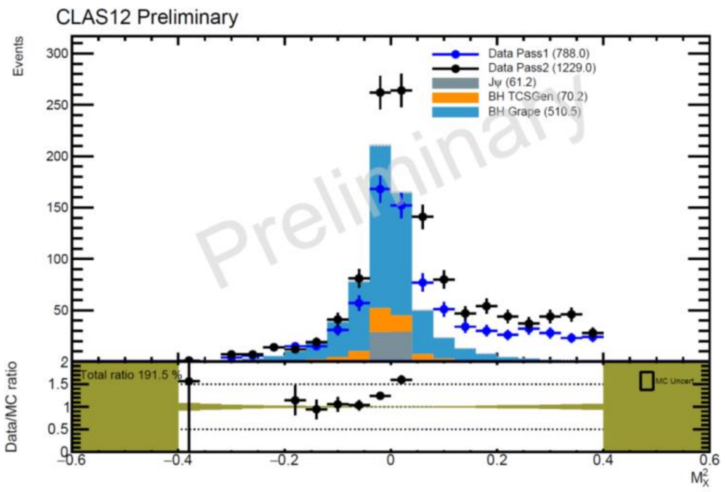


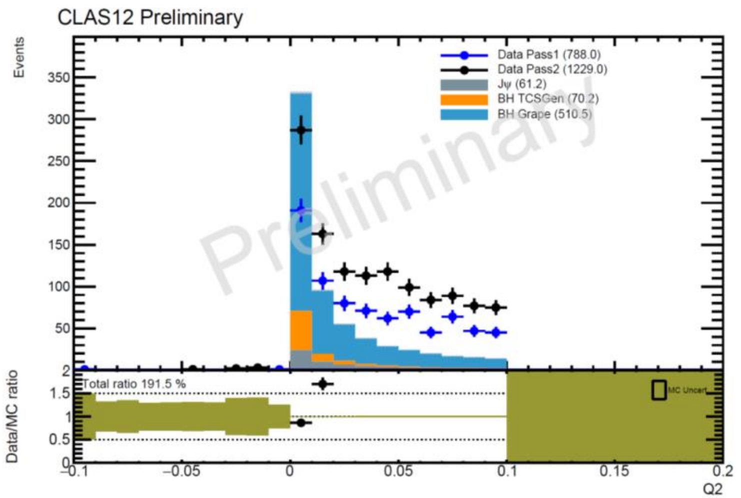
Especially at higher (above 8 GeV) photon energies the contribution from background processes become significant.

After background subtraction, the data and MC agreement is reasonable.

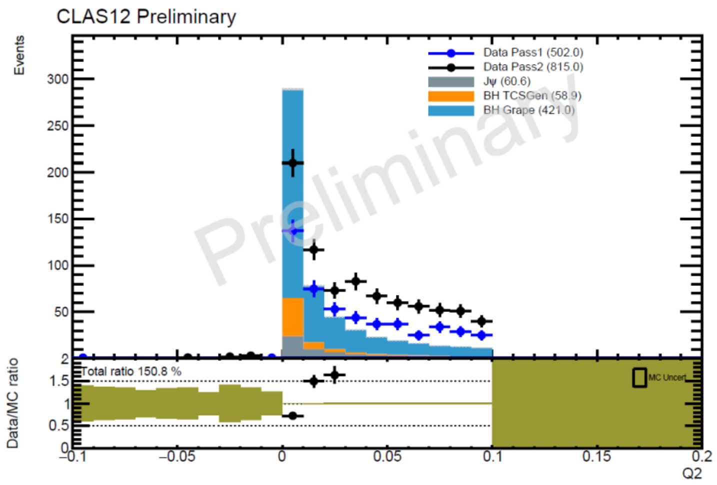
Momentum resolutions: Data vs MC

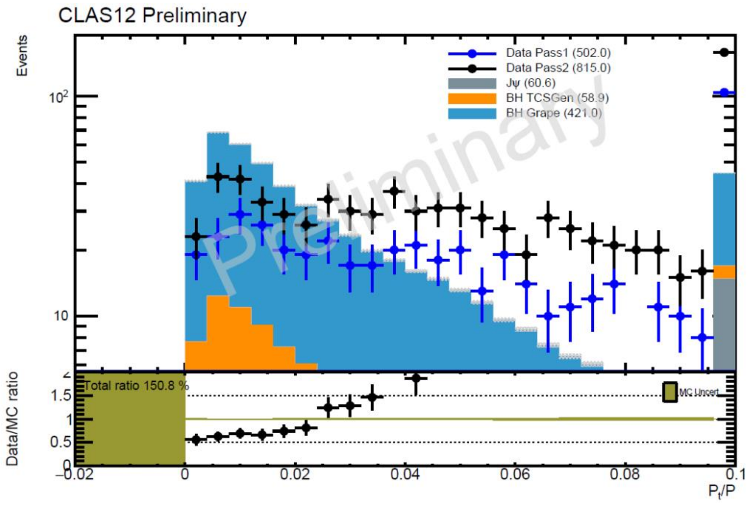
P. Chatagnon





After $|M_X|^2 < 0.1$ GeV^2





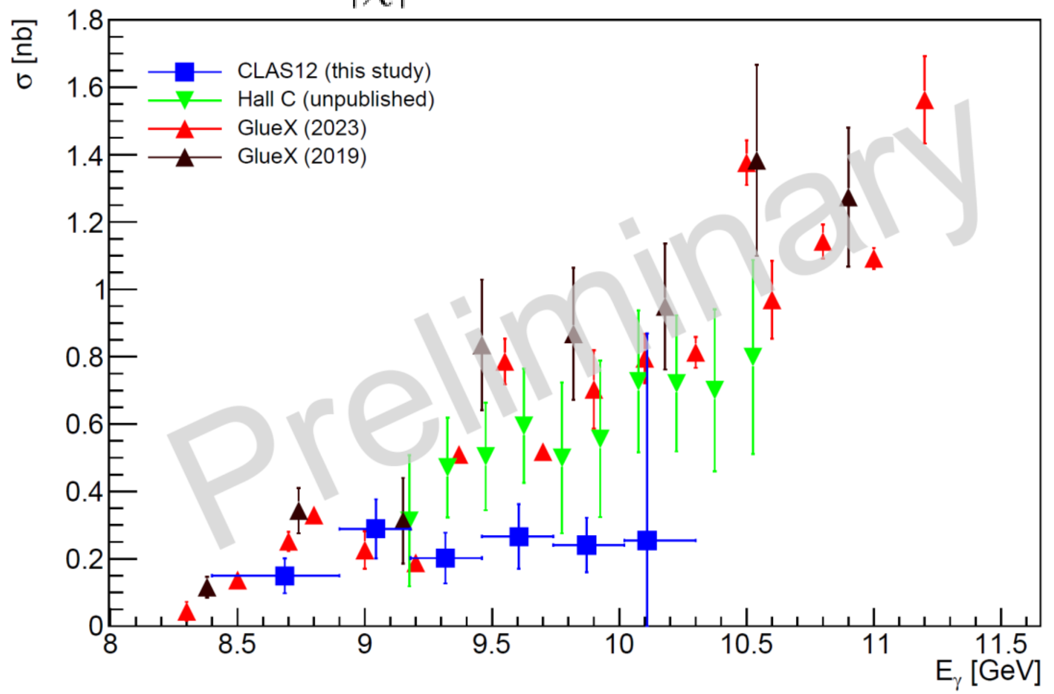
- Widths of Exclusivity variables don't quite match in MC and Data.
- This has significant impact on J/psi cross-section.

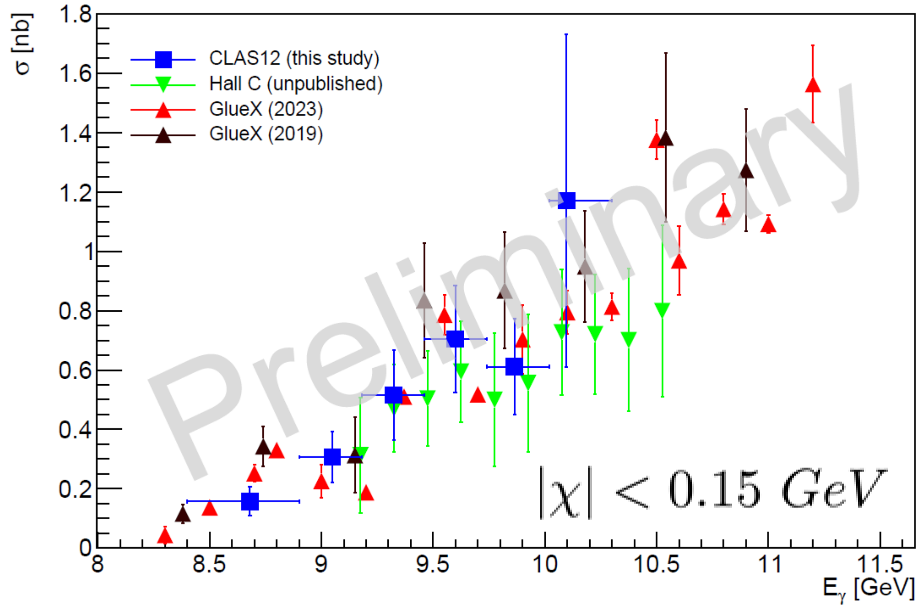
Momentum resolutions: Data vs MC

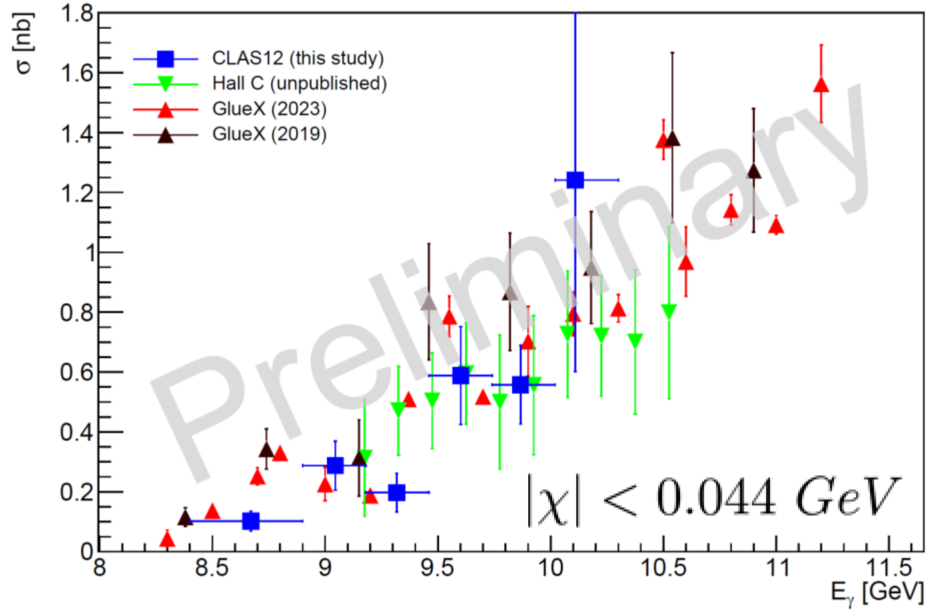
P. Chatagnon's analysis

$$\chi = P_X - P_X^Z \qquad |M_X^2| < 0.4\ GeV^2$$

$$|\chi| < 0.005\ GeV$$



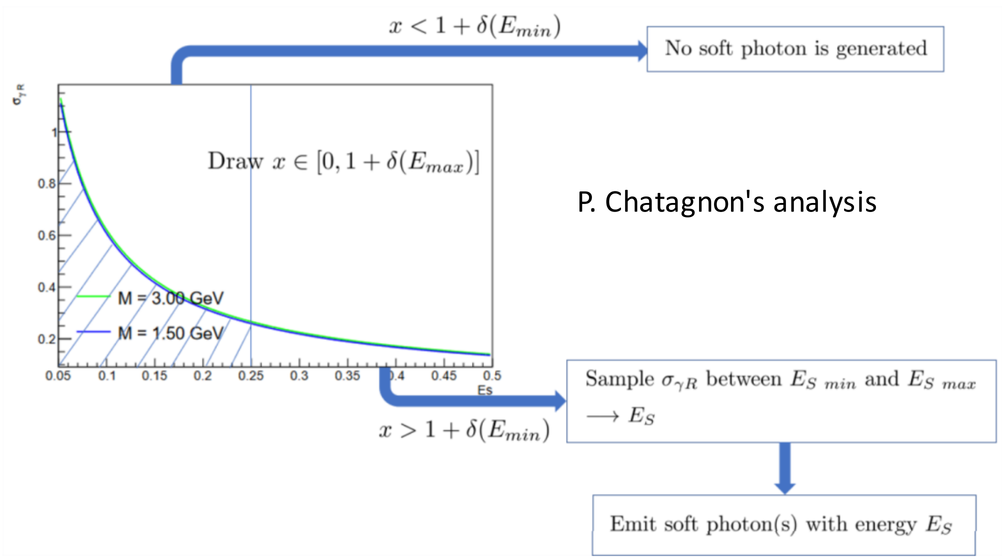




Apparently significant amount of J/Ψ (or events w/ high photon energy) gets high Q^2 (transverse missing momentum) which is not reproducible with MC.

Radiative corrections

Rad corrections are implemented based on PhysRev. D, 97:076012, Apr 2018, Soft-photon corrections to the Bethe-Heitler process in the $\gamma p \rightarrow l^- l^+ p$ reaction.

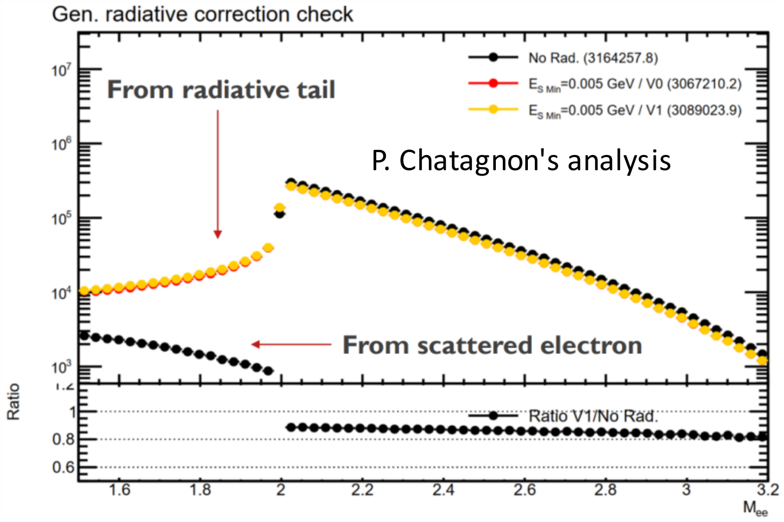


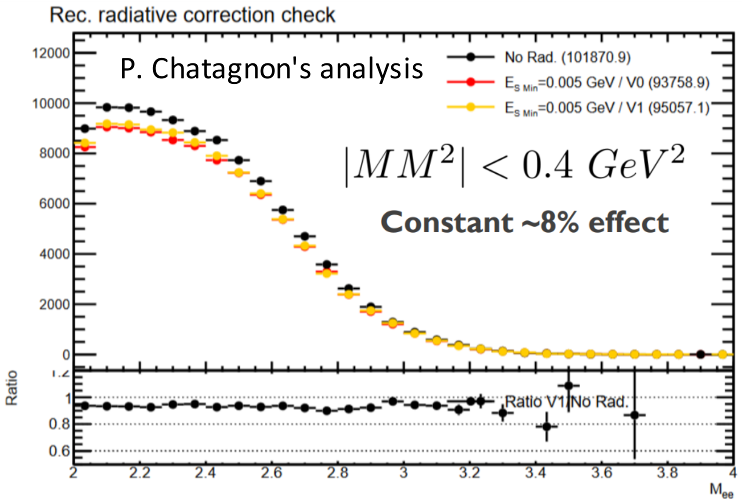
$$\left(\frac{d\sigma}{dt ds_{ll}}\right)_{rad} = \left(\frac{d\sigma}{dt ds_{ll}}\right)_0 (1+\delta)$$

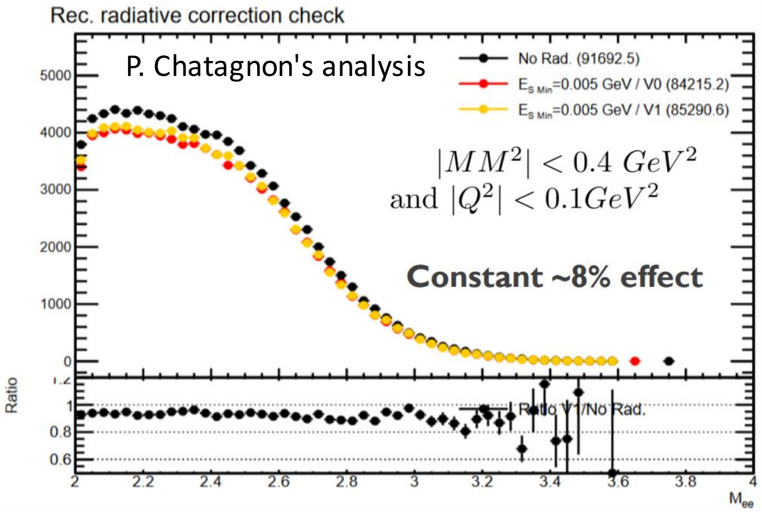
With $s_{ll} \gg 4m^2$ δ takes the form $\delta = -\left(\frac{\alpha}{\pi}\right)\left\{\ln\left(\frac{4\Delta E_s^2}{s_{ll}}\right)\left[1 + \ln\left(\frac{m^2}{s_{ll}}\right)\right] - \frac{\pi^2}{3}\right\}$

Pierre implemented radiative photon emission at the generator level.

About 8% constant effect across all the mass range.



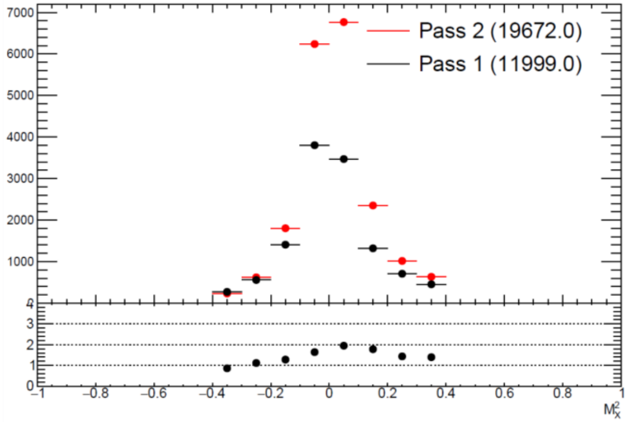




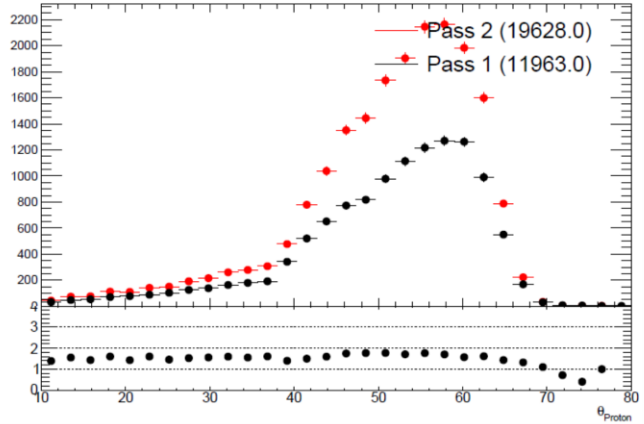
Pass 1 vs pass 2 comparisons

Same runs were compared from S19 pass1 and pass2.

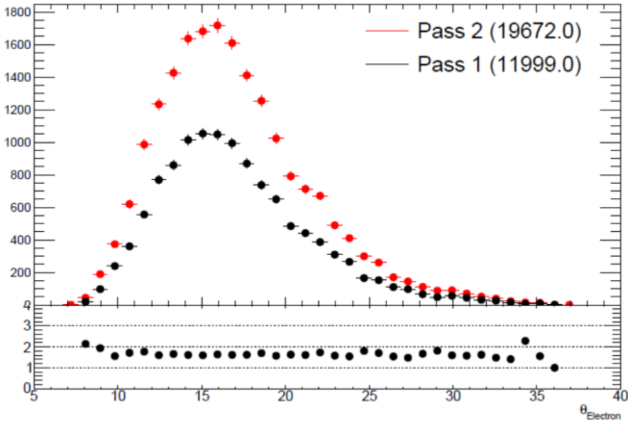
Mx^2



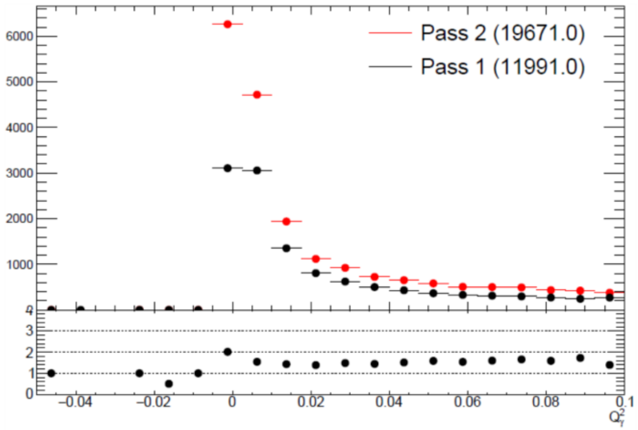
Proton polar angle



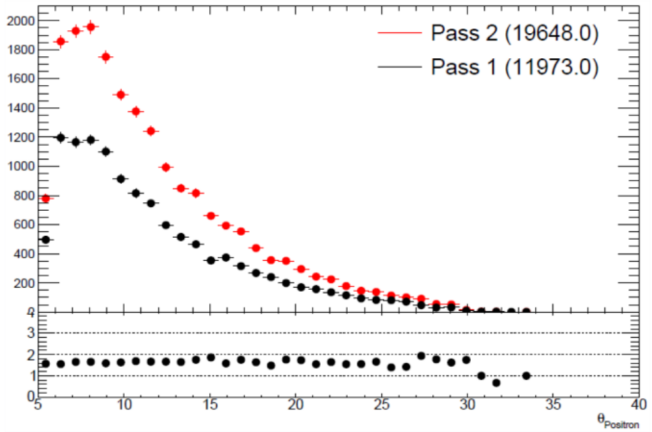
Electron polar angle



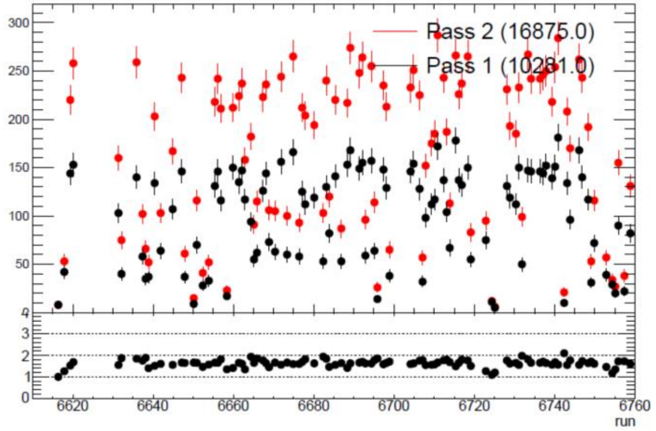
Q^2



Positron polar angle

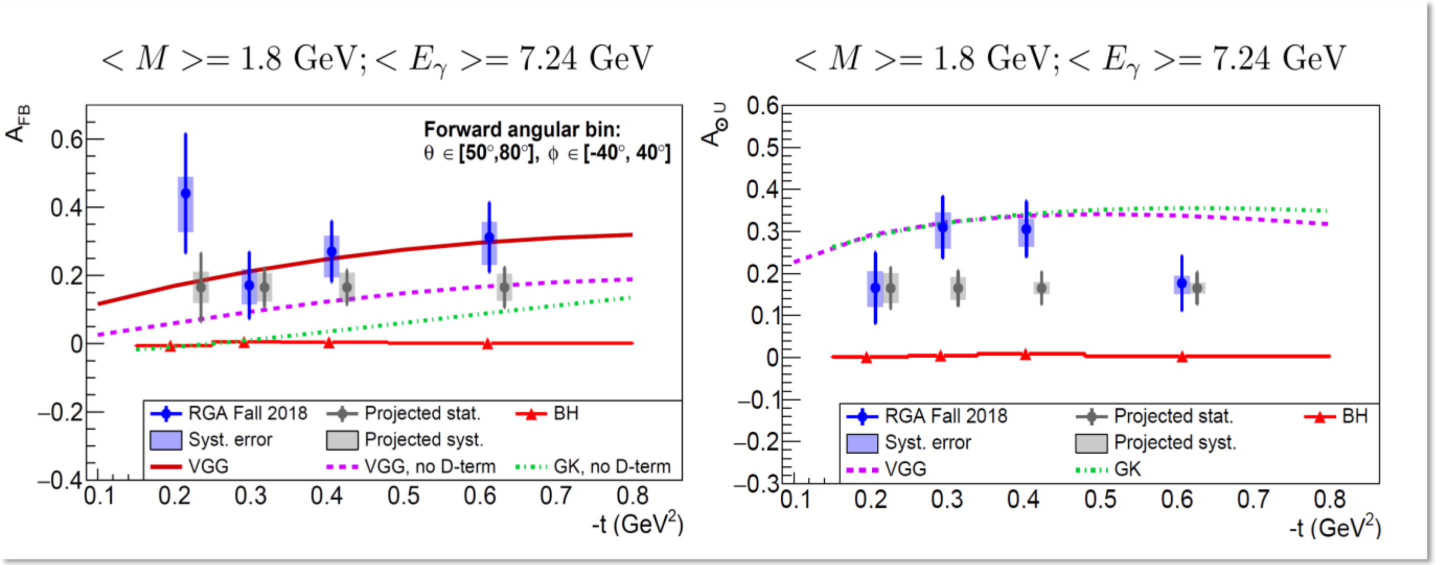


As a function of Run number



In average about x1.8 increase of statistics in S19 pass2.

Plans for publications in 2024

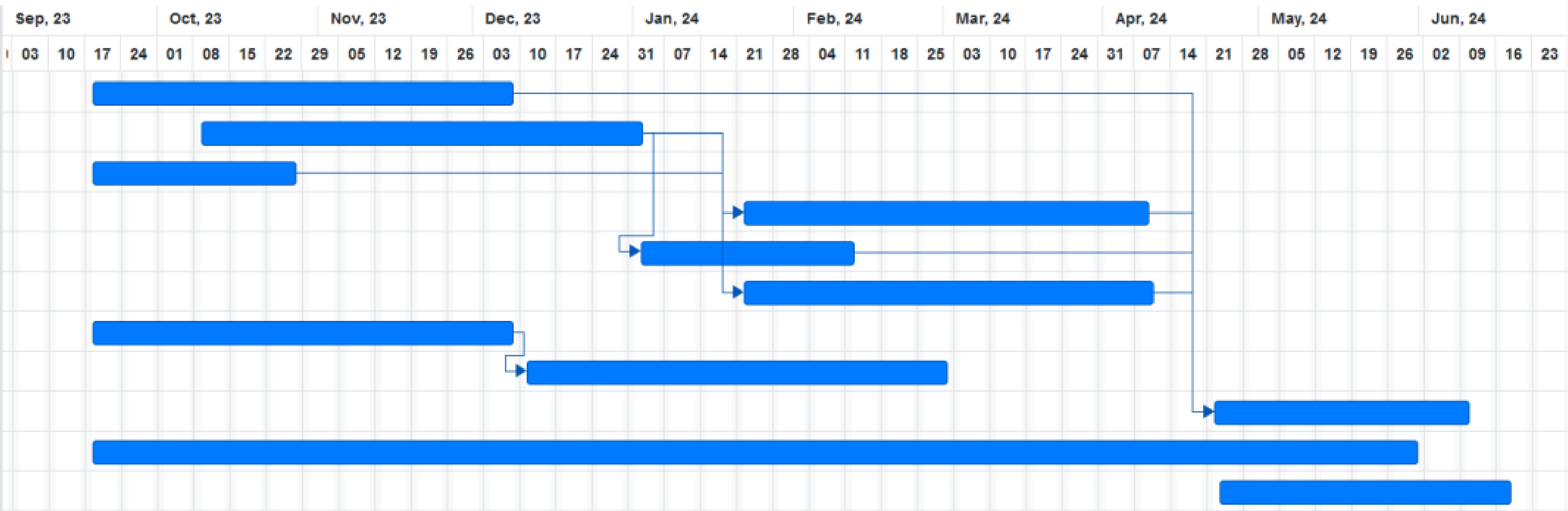


Projected results using only inbending data set.

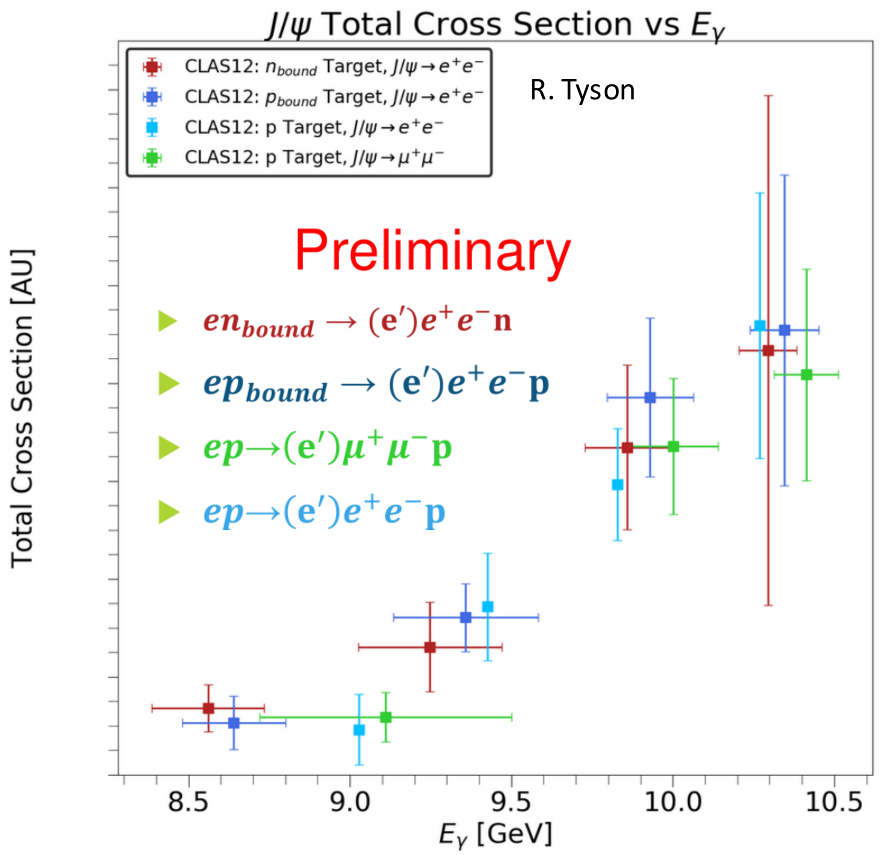
Exploring possibility to extract polarization asymmetry using a Maximum likelihood fit, suggested by Derek.

Derek is tuning a framework for TCS analysis (will take 1-2 months)

ID	Name	Start Date	End Date
1	Lepton AI PID	Sep 18, 2023	Dec 08, 2023
2	Data processing	Oct 09, 2023	Jan 02, 2024
4	Energy loss corrections	Sep 18, 2023	Oct 27, 2023
5	Momemtum correction	Jan 22, 2024	Apr 09, 2024
9	Fiducial cuts	Jan 02, 2024	Feb 12, 2024
6	Momentum smearing	Jan 22, 2024	Apr 10, 2024
7	Radiative correction validations	Sep 18, 2023	Dec 08, 2023
8	Radiative corrections	Dec 11, 2023	Mar 01, 2024
10	Systematics	Apr 22, 2024	Jun 10, 2024
11	Analysis note writting	Sep 18, 2023	May 31, 2024
12	Article writting	Apr 23, 2024	Jun 18, 2024



Summary and future plans



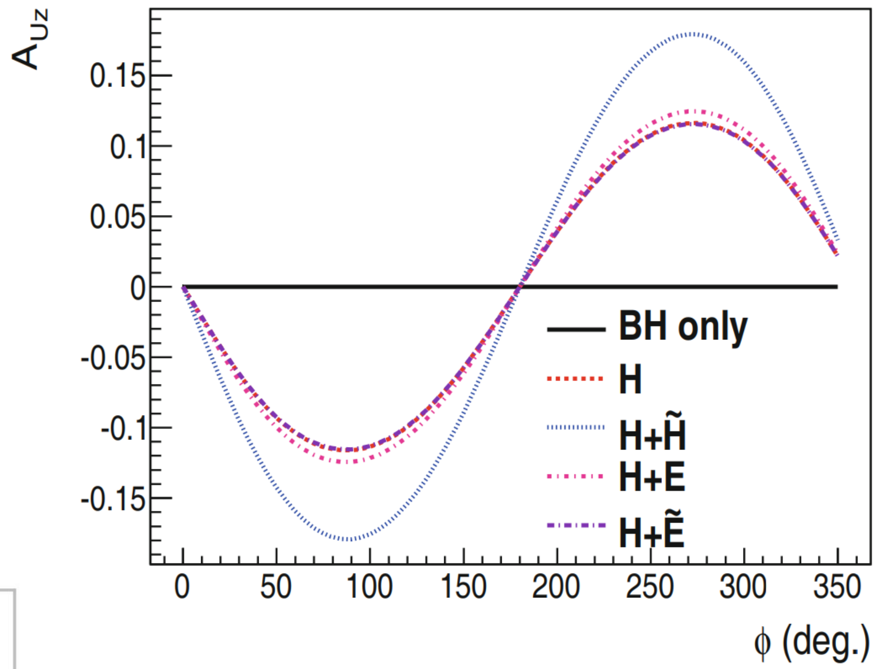
- Main analysis efforts are directed to the untagged J/psi and TCS measurements with the e^-e^+ channel.
- Based on pass1 data, we have published 1st TCS symmetries
- 4 PhD (3 based on RG-A) theses completed and 2 (1 based on RG-A) are in progress
- One of important questions is to have data and MC resolutions to be matched.
- During the next one year the main goal is to complete the TCS analysis on the whole RG-A data set.
- In a longer term we plan to have finish J/psi cross-section with muon channel as well.

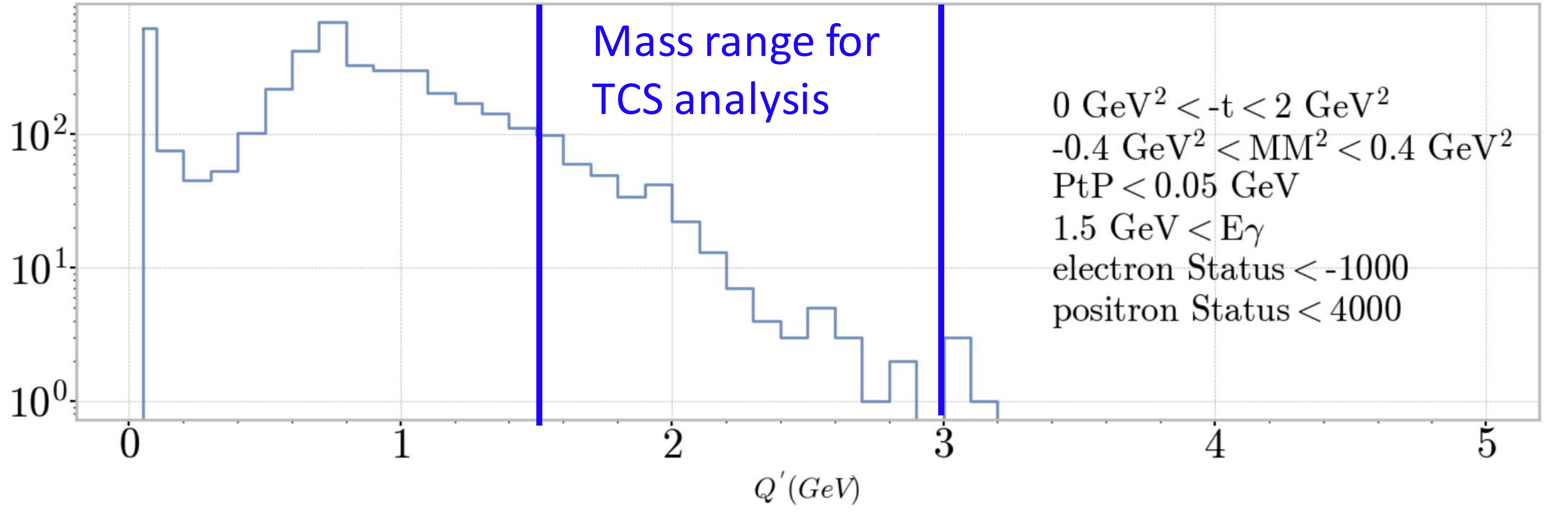
Backup

List any new idea of CAA

This however is for RG-C

- Kayleigh Gates (University Of Glasgow)
- TCS on linearly polarized target
- Gives access to H and H~(H~relatively less known)
- RG-C data is being analyzed





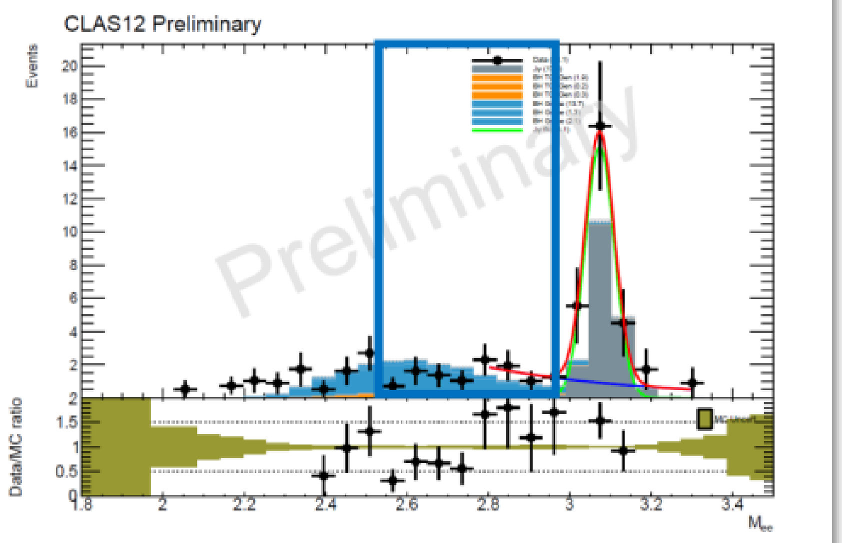
The radiative corrections are expected to play a role in two key ingredient of the cross-section calculation:

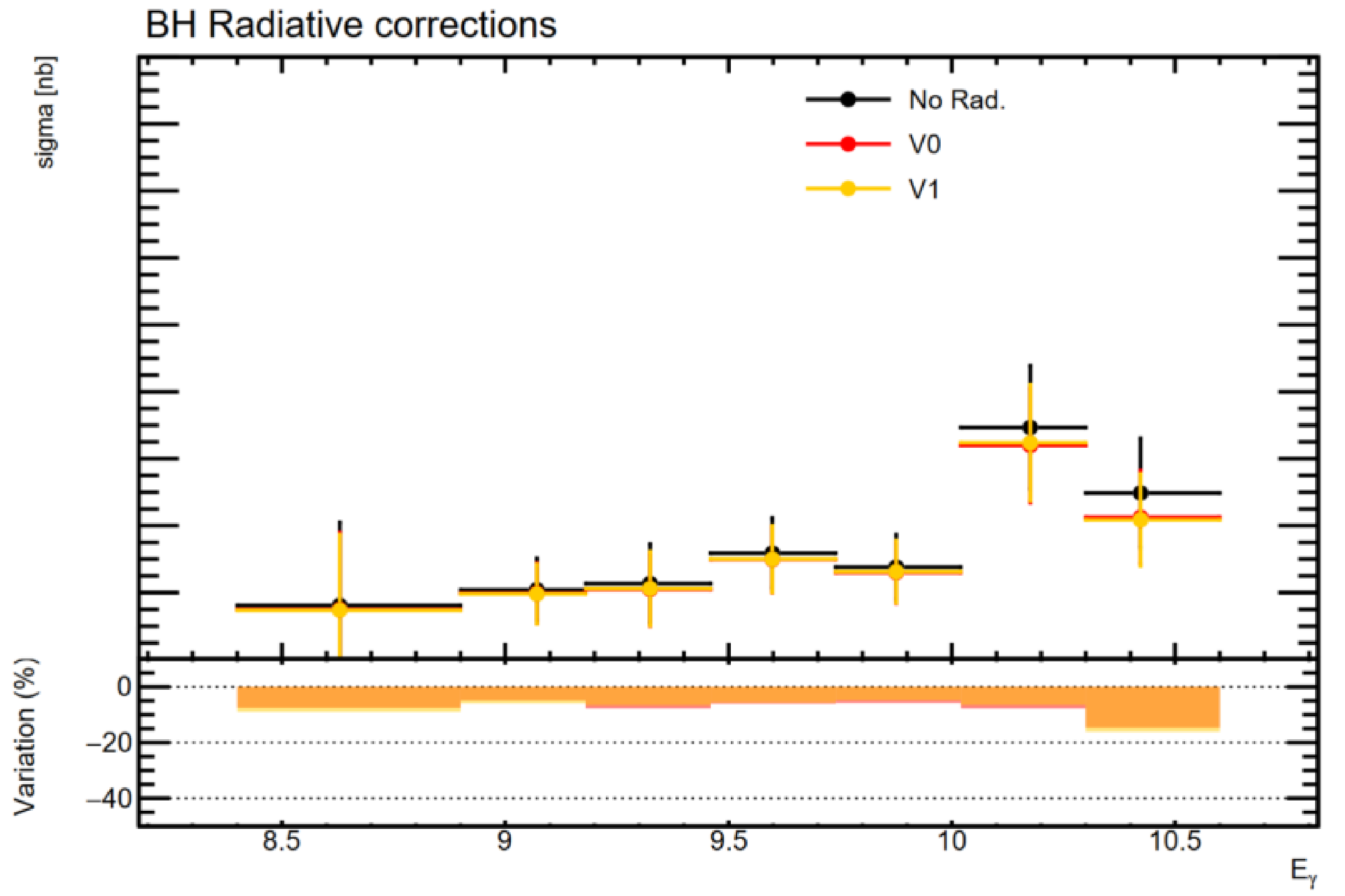
- In the acceptance: J/Psi simulation with radiated correction used to account for larger peak width.
- In the normalization factor: Grape generated events are passed through the radiative correction algorithm. Expect to be 10% effect.

P. Chatagnon's analysis

Cross-section calculations

$$\sigma_0(E_\gamma) = \frac{N_{J/\psi}}{N_\gamma \cdot n_T \cdot \omega_c \cdot Br \cdot \epsilon(E_\gamma)}$$





Tagged J/psi

ep->e$^-$e$^+$e'(X), no proton detection is required.

e$^-$: detected in FD
e$^+$: detected in FD
e': detected in FT

Full S19 pass2 data.

Missing mass vs invariant mass: ep->e$^-$e$^+$e'(X)