Update on the dilepton analysis on RGA: TCS and photoproduction of J/ψ

Pierre Chatagnon, for the dilepton group
CLAS collaboration meeting – Jefferson Lab

8th of November 2023

Jefferson Lab clas

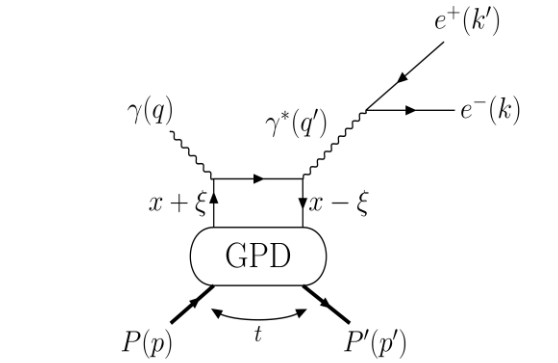
Outline

I	Motivations, general considerations and planning
II	Spring 2019 Pass 2: Comparison with pass 1 and first look at MC/data comparison
III	Lepton PID using machine learning
IV	J/ψ event selection and resolution
V	Maximum likelihood fit for the extraction of the TCS parameters
VI	Take-aways and timeline for future work

Motivations for dilepton final state measurement

Timelike Compton Scattering

$$\text{TCS: } \gamma p \rightarrow e^+ e^- p'$$



TCS
(factorization regime, $-t/Q'^2 \ll 1$)

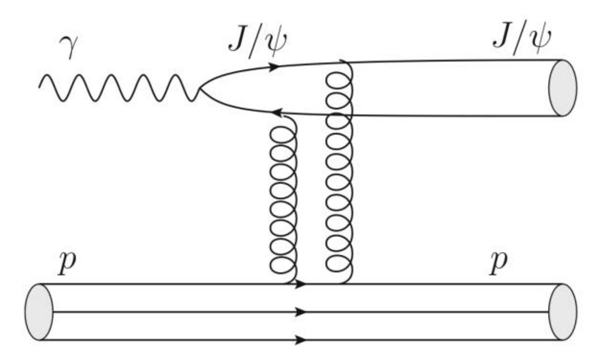
$$\frac{d^4\sigma_{INT}}{dQ'^2 dt d\Omega} \propto \frac{L_0}{L}\left[\cos(\phi)\frac{1+\cos^2(\theta)}{\sin(\theta)}\text{Re}\mathcal{H} + ...\right]$$

$$\frac{d^4\sigma_{INT}}{dQ'^2 dt d\Omega} = \frac{d^4\sigma_{INT}\,|_{\text{unpol.}}}{dQ'^2 dt d\Omega} - \nu \cdot A\frac{L_0}{L}\left[\sin(\phi)\frac{1+\cos^2(\theta)}{\sin(\theta)}\text{Im}\mathcal{H} + ...\right]$$

Formulae and notations of Berger, Diehl, Pire, Eur.Phys.J.C23:675-689,2002

J/ψ photoproduction at threshold

$$\gamma p \rightarrow J/\psi\; p \rightarrow e^+ e^- p'$$



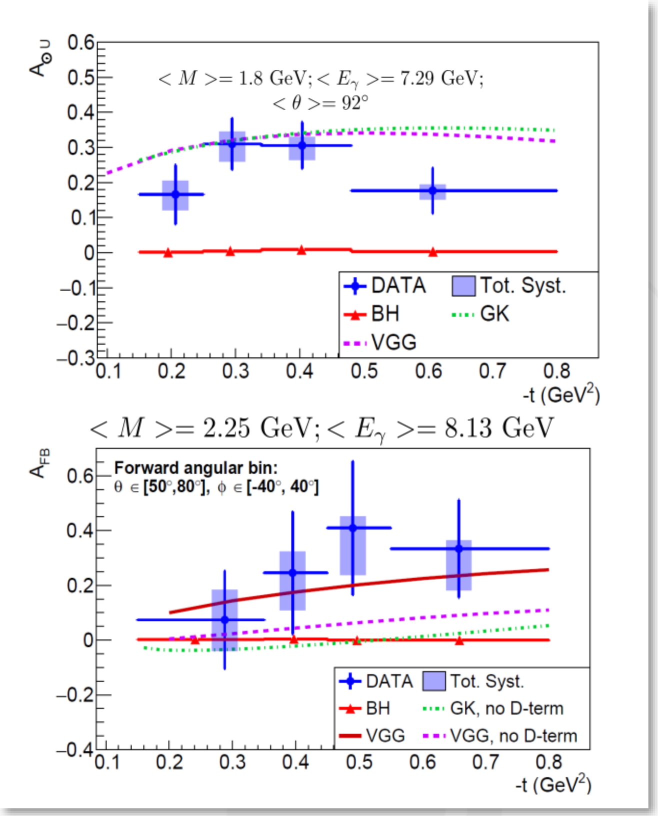
- The t-dependence of the cross-section allow to access gluon Gravitational Form Factors (GFFs), mass radius of the nucleon and gluon GPDs (under 2-gluon exchange assumption and no open-charm contributions)
- Model-dependent limit on the branching ration of the Pc pentaquark.

Jefferson Lab clas

Publication status

Timelike Compton Scattering

First Measurement of Timelike Compton Scattering, P. Chatagnon *et al.* (CLAS Collaboration), Phys. Rev. Lett. 127, 262501 (2021)



- Hint for the universality of GPDs
- Importance of the D-term in the GPD parametrization

J/ψ photoproduction at threshold

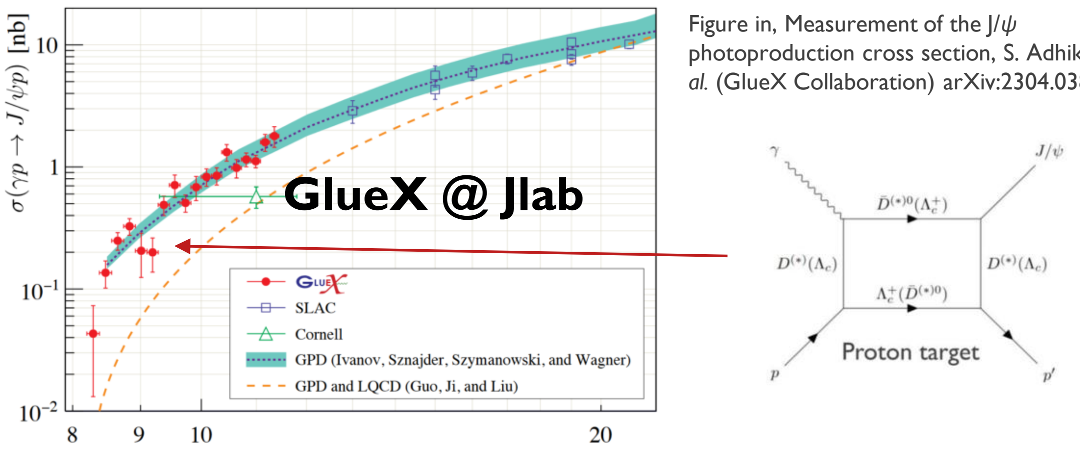


Figure in, Measurement of the J/ψ photoproduction cross section, S. Adhikari *et al.* (GlueX Collaboration) arXiv:2304.03845

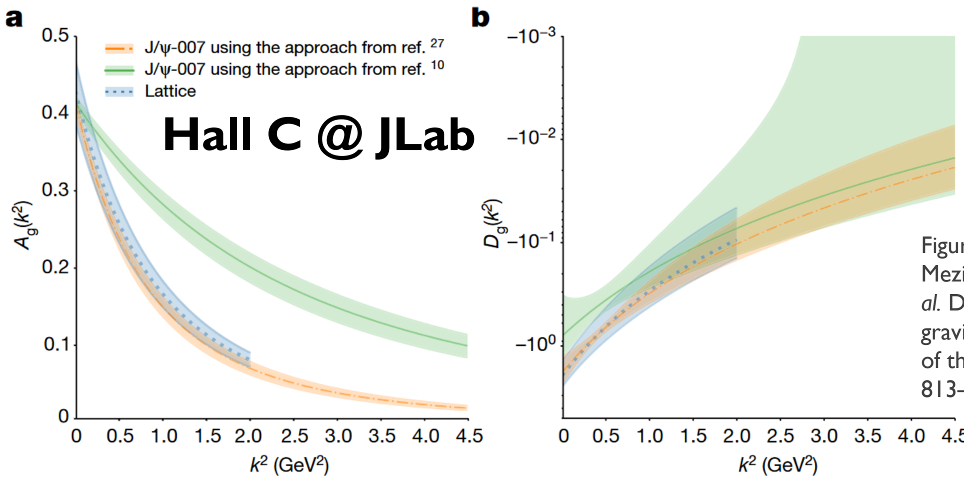
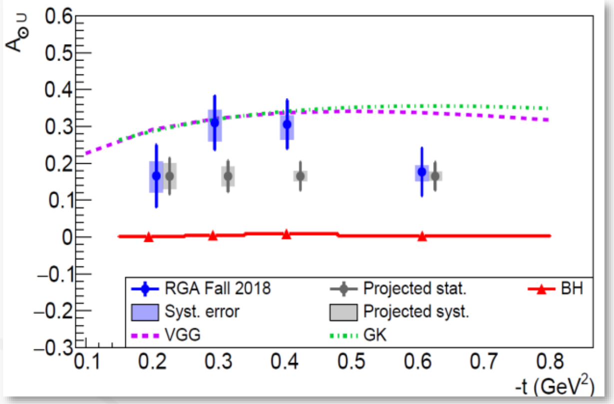


Figure in Duran, B., Meziani, ZE., Joosten, S. *et al.* Determining the gluonic gravitational form factors of the proton. *Nature* 615, 813–816 (2023)

Goals and plans

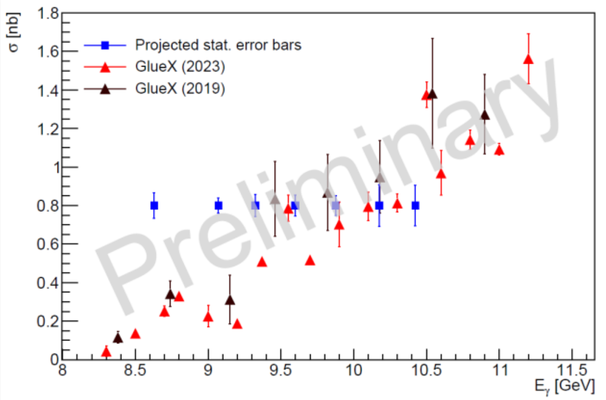
Timelike Compton Scattering

- Full statistics of RG-A will improve statistical accuracy by factor 2.
- Goal: use these results in GPD fits.

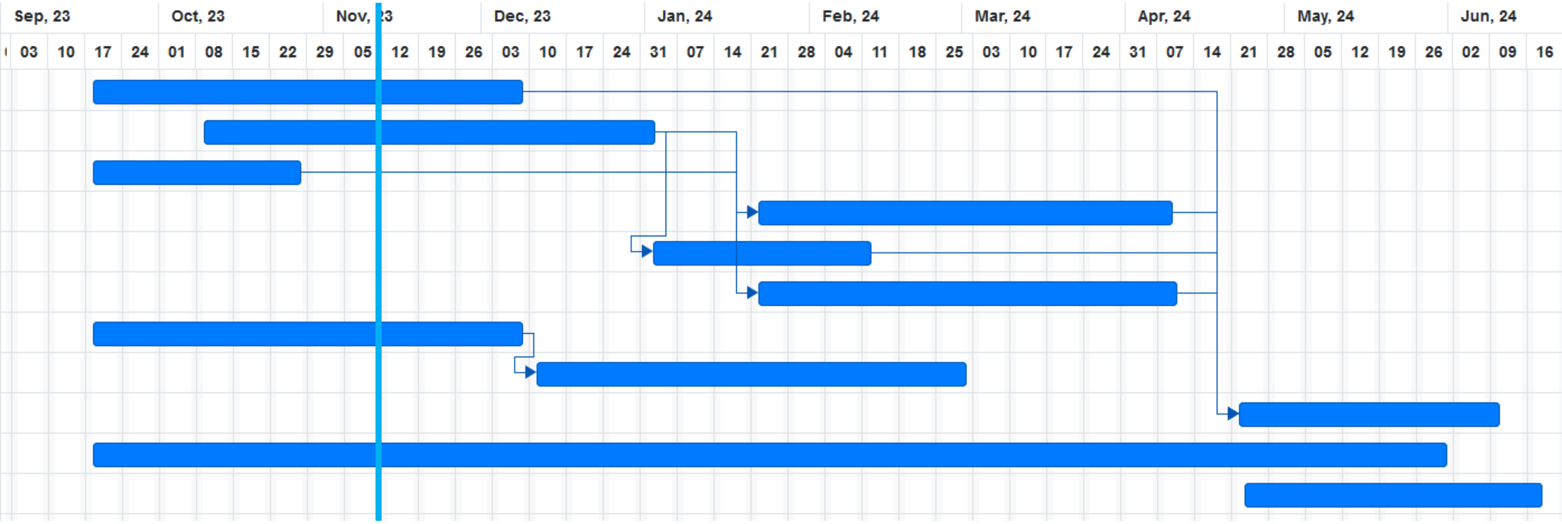


J/ψ photoproduction at threshold

- Statistics comparable with GlueX 2019 analysis
- Independent cross-check of the ~9 GeV cusp
- Enough statistics to extract t-dependence and GFFs



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



Objective: summer 2024

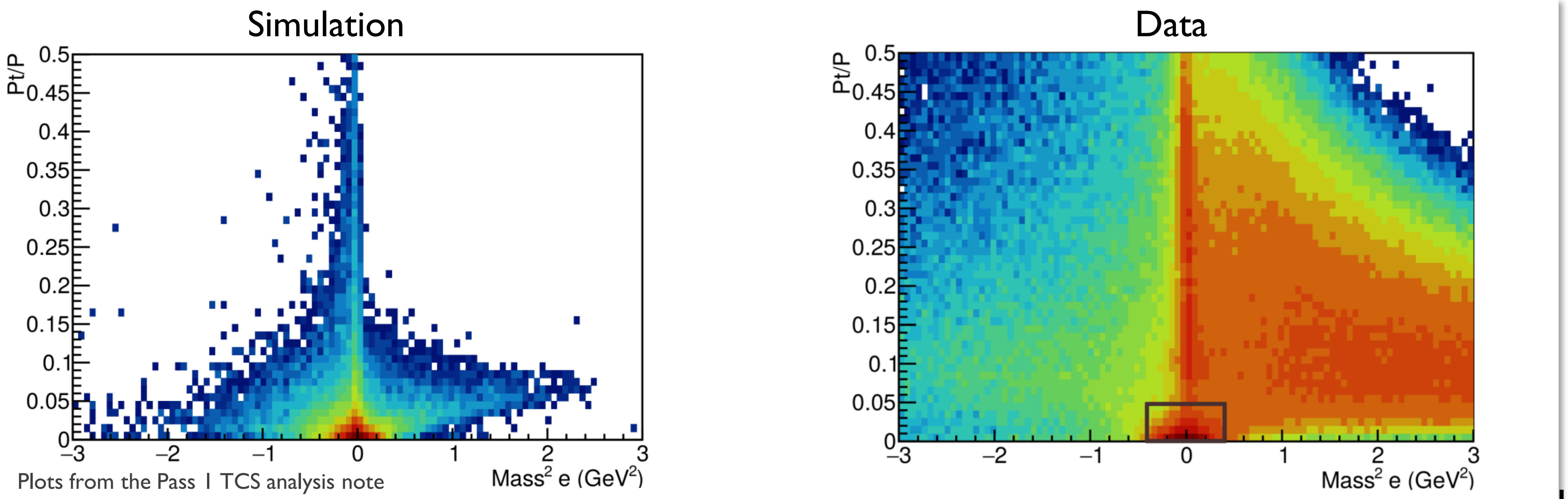
Jefferson Lab clas

General analysis strategy

1) CLAS12 PID + Positron NN PID

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

$p_X = p_{beam} + p_p - p_{e^+} - p_{e^+} - p_{p'}$ → 2) $|M_X^2| < 0.4GeV^2$ Missing particle is an electron… → 3) $|\frac{Pt_X}{P_X}| < 0.05$ or $Q^2 < 0.1$ GeV^2 …scattered at small angle



Plots from the Pass 1 TCS analysis note

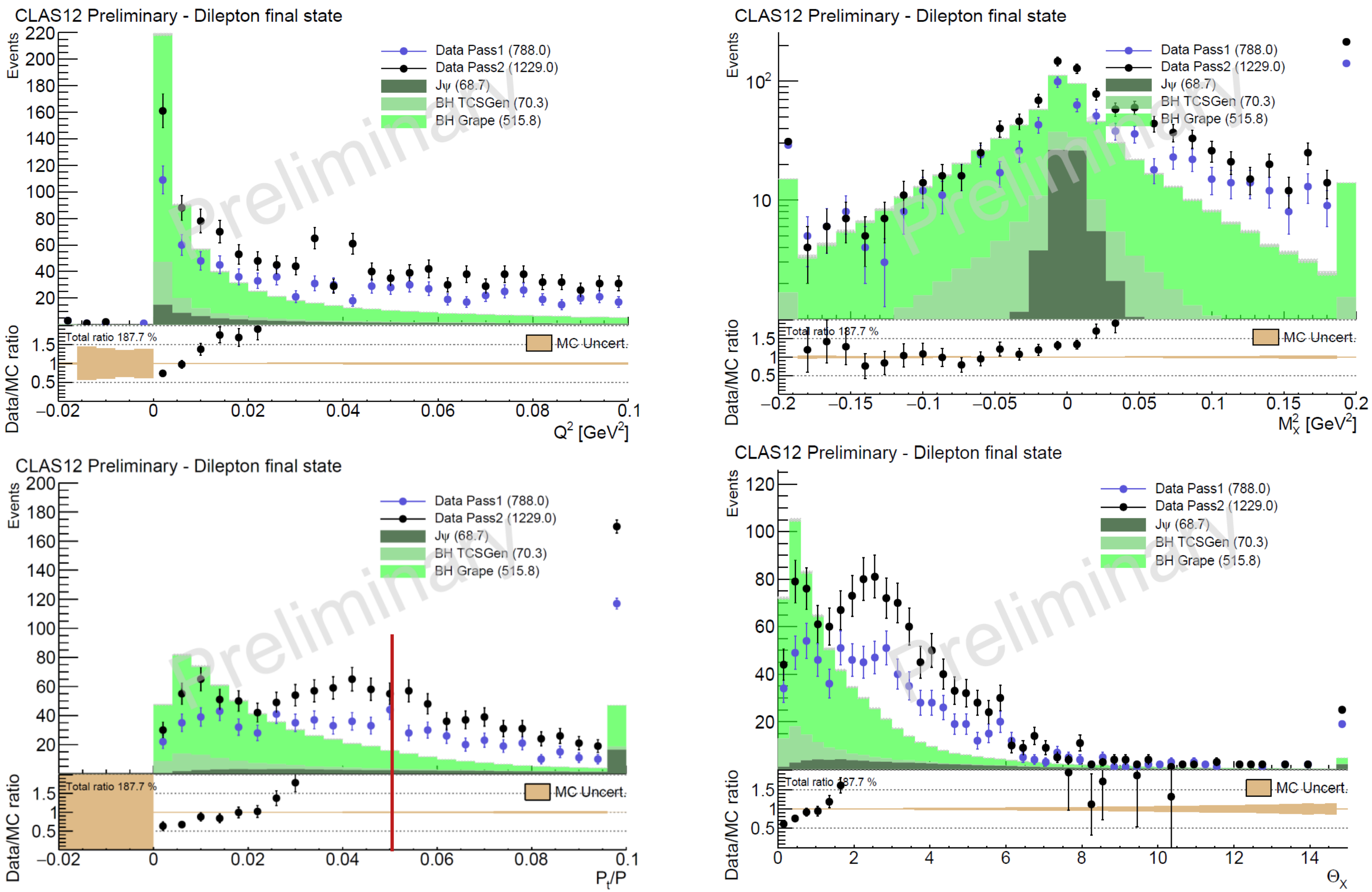
II - Pass 2 data: first look at Spring 2019

Jefferson Lab

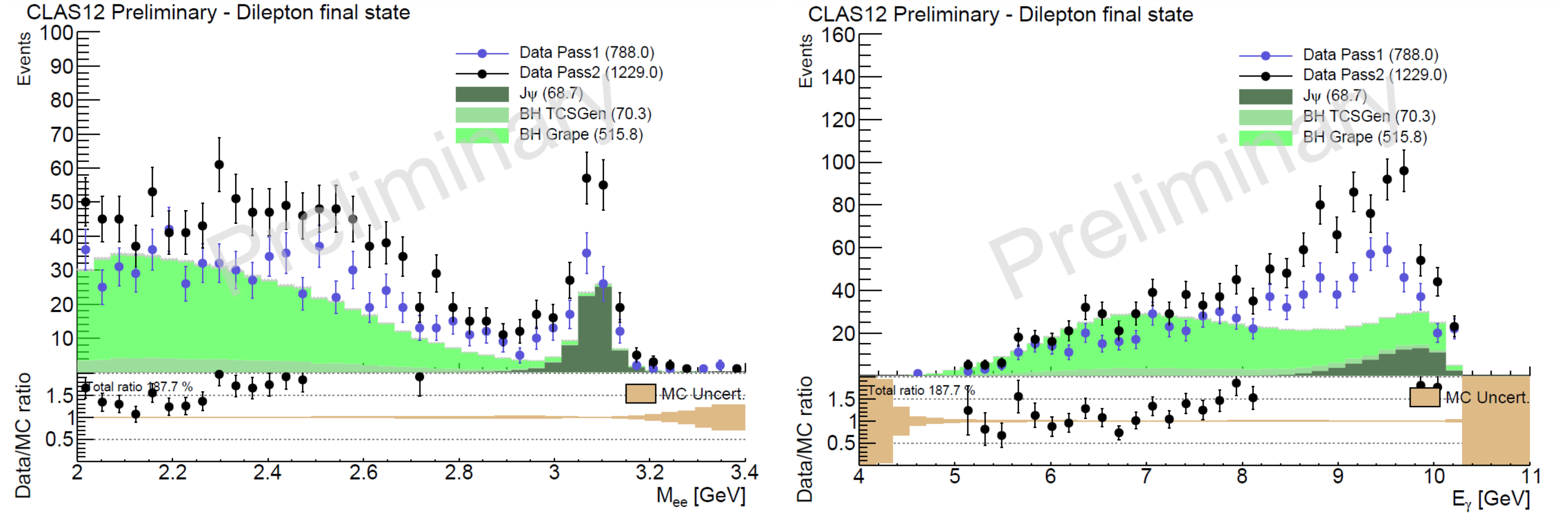
Comparison of data and MC (I)

Event selection

- Event topology:
  - exactly one electron in FD
  - exactly one positron in FD
  - exactly one proton
  - anything else
- Lepton momenta > 1.7 GeV
- Sampling Fraction > 0.15
-
- Lepton AI PID score > 0.05 (trained on pass1 simulation)
- Exclusivity cuts:
  - $|MM^2|<0.4$ GeV^2
  - $|Q^2|<0.1$ GeV^2

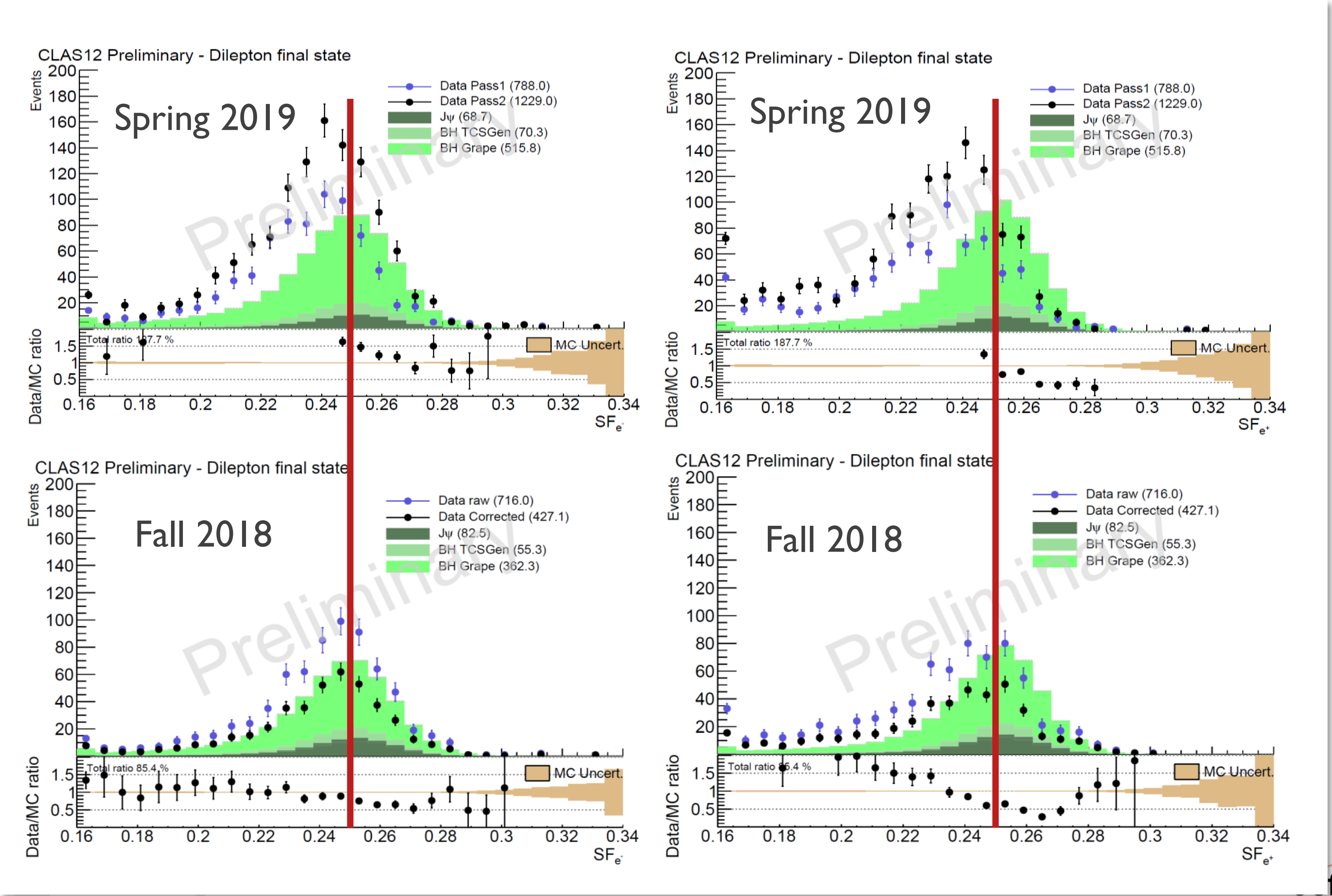


Comparison of data and MC (2)



- Same behavior is seen in Spring 19 and Fall 18 data: the large Q2 background must be subtracted before calculating any cross-section
- We will use the same-charge lepton event method to do so
  → outbending dataset is essential

Sampling fraction MC/Data mismatch



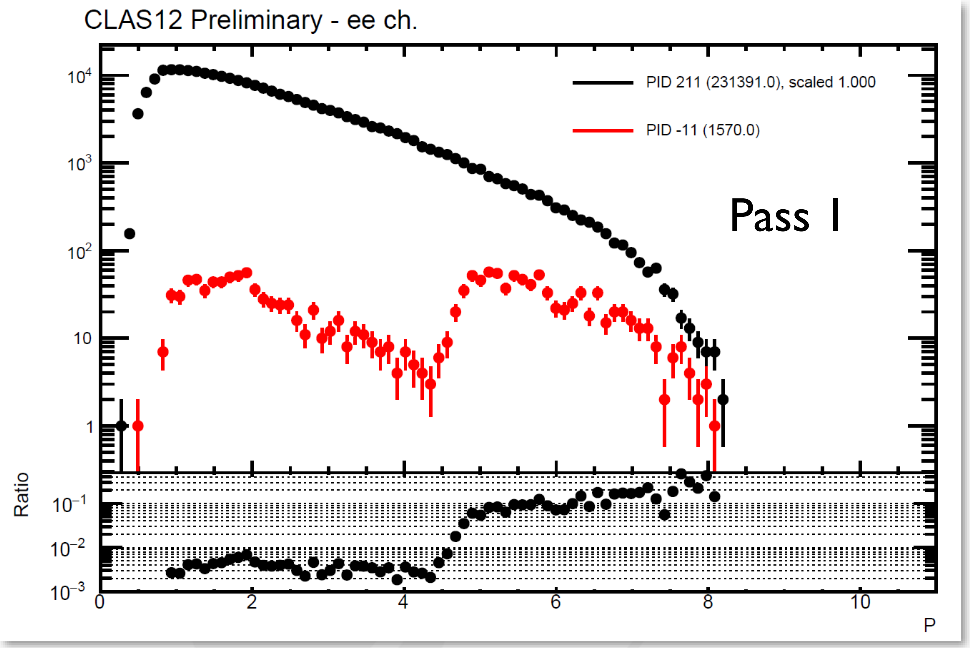
III - Lepton PID using machine learning

Motivations and previous work

Motivations

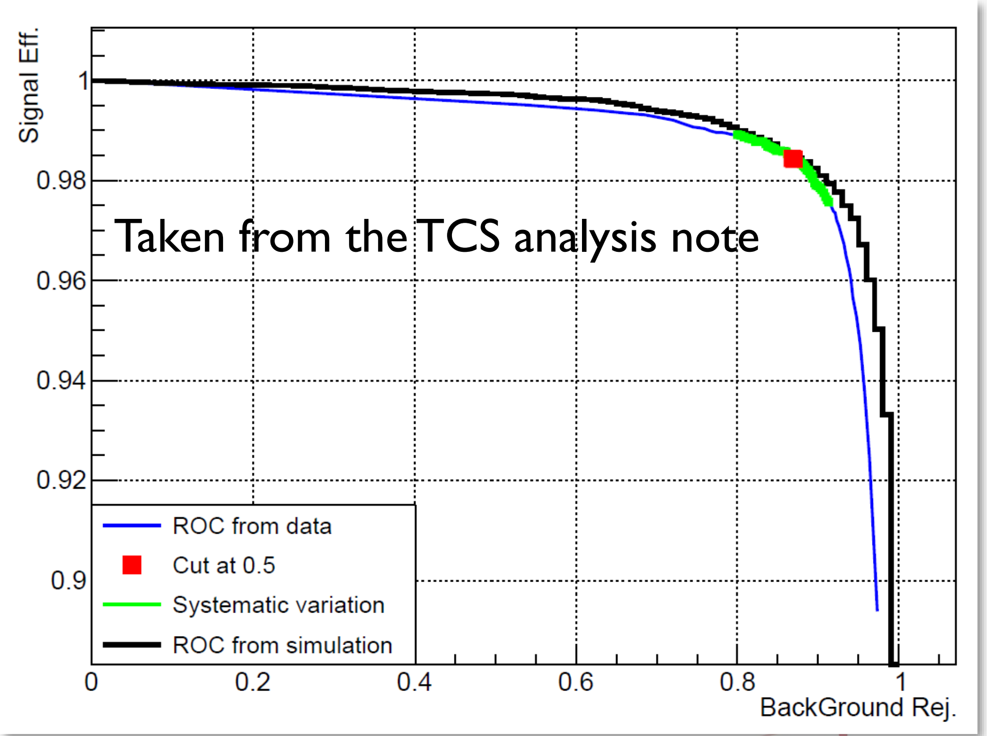
- Above the HTCC, threshold both pions and leptons produce a HTCC signal. In the EB, only ECAL provide a separation between the two.
- ep → epπ$^+$(π$^-$) is a large background at large positron momenta

$$ep \to ep\pi^+\pi^- \text{ VS } ep \to epe^+\pi^-$$



Previous work and motivations

- Long standing feature, already solved for the TCS publication
- Use the layer segmentation of the ECAL to provide separation
  - Variables used: SFs and m2 of PCAL, ECIN, ECOUT
  - Method tested: **NN**, BDT



Current status

All material of this section provided by M. Tenorio Pita

Approach

- For both electrons and positrons, and for each RGA configuration:

2 (e^+/e^-) x 3 (Spring19/Fall18 in/out) = 6 classifiers

- Use the layer segmentation of the ECAL to provide separation

Variables used: P, θ, ϕ, SFs and m2 of PCAL, ECIN, ECOUT

Method tested: NN, BDT

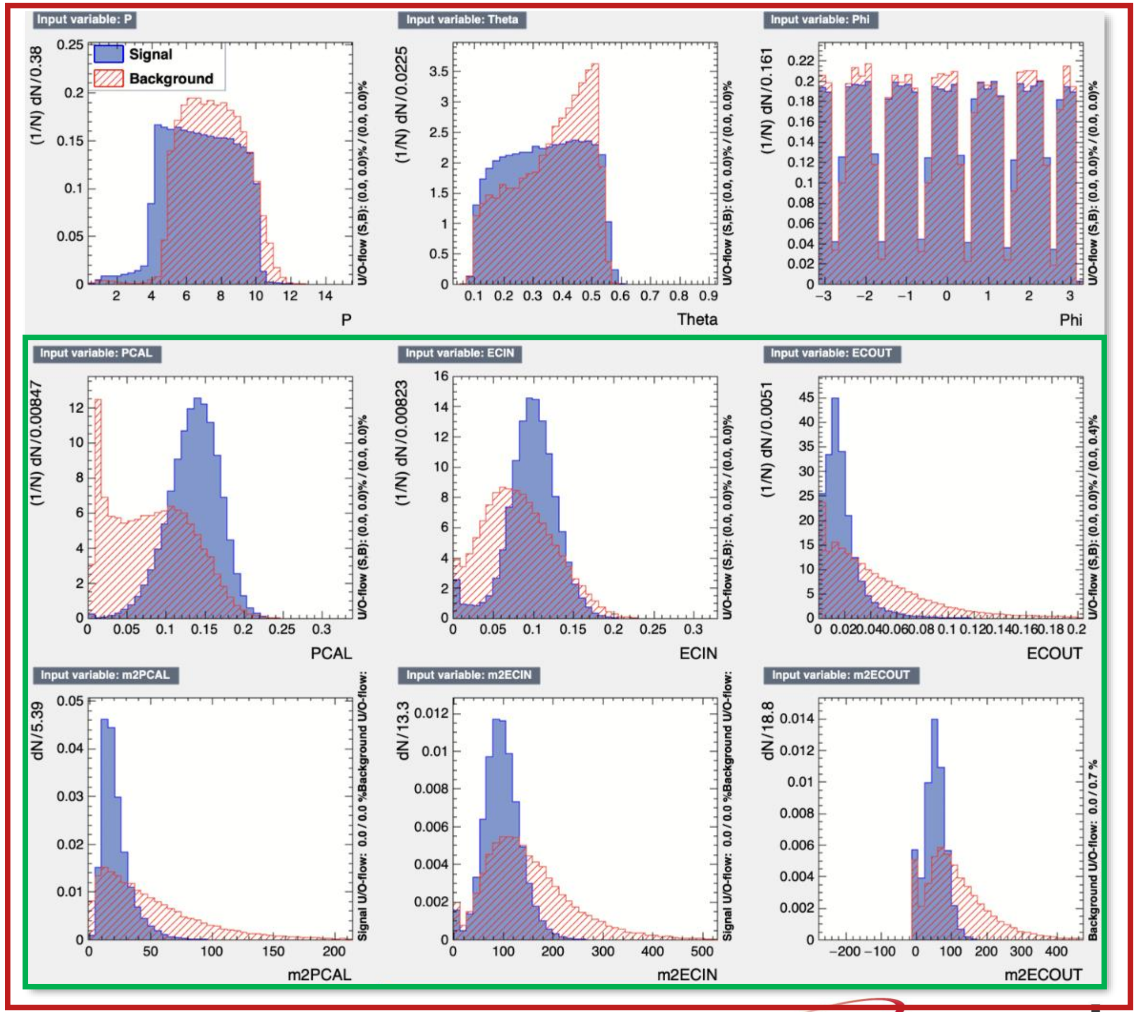
- Trained on simulation:

Signal: flat $e^{+/-}$ distribution, reconstructed as $e^{+/-}$

Background: flat $\pi^{+/-}$ distribution, reconstructed as $e^{+/-}$

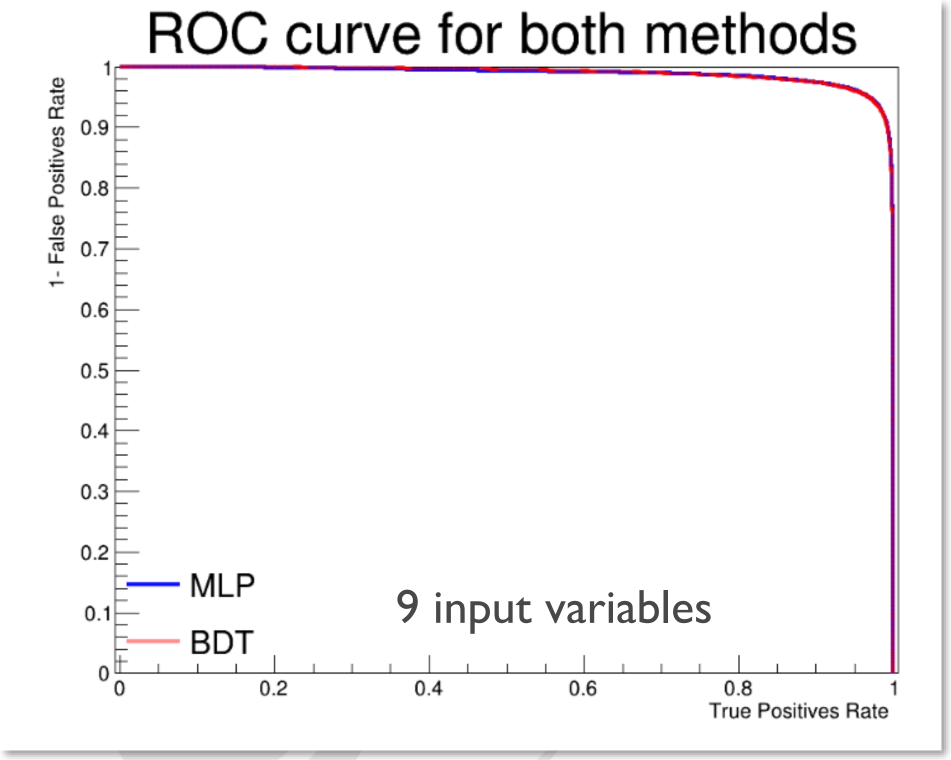
- Only RGA Spring 2019 for now

Input variables for signal (blue) and background (red)



Performances

- We tested both 6 and **9 input variables**, for 2 methods **NN** and BDT.
- Signal efficiency: 99.4 %
- Background rate: 10%



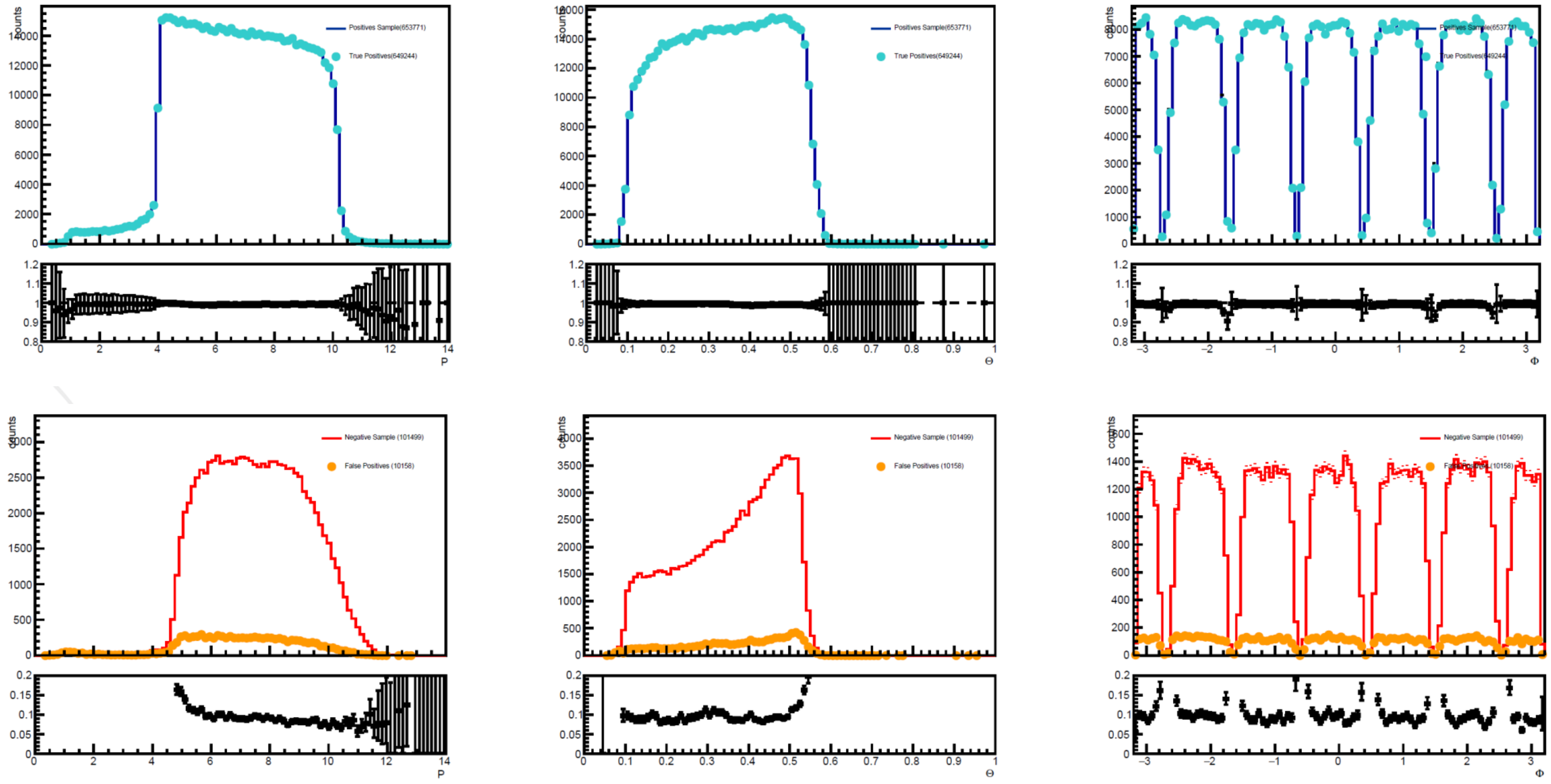
NN 6 var.	Actual e+ (653771)	Actual π+ (101499)
Predicted e+	647688	12805
Predicted π+	6083	88694
	TPR 99.1 %	FPR 12.6 %

NN 9 var.	Actual e+	Actual π+
Predicted e+	649244	10158
Predicted π+	4527	91341
Performances	TPR 99.4%	FPR 10%

Validation

- Signal efficiency and background reduction as a function of particle kinematics
- Done on separate samples

NN. 9 Variables



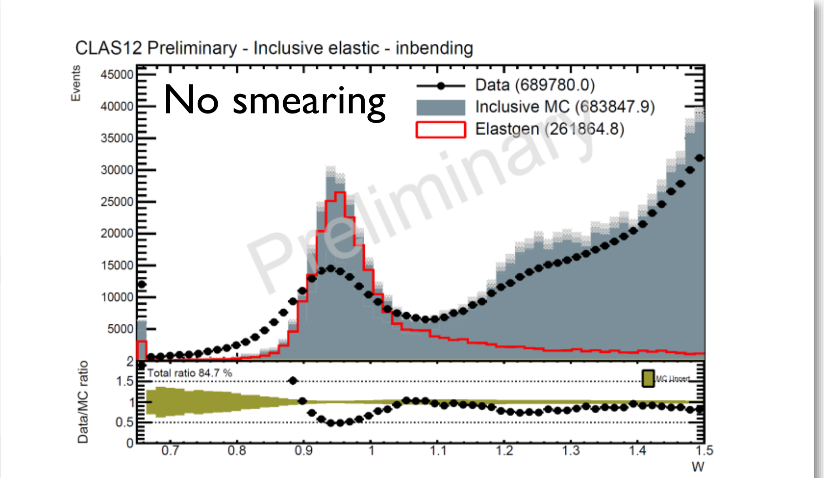
IV - J/ψ event selection, resolution and cross-section

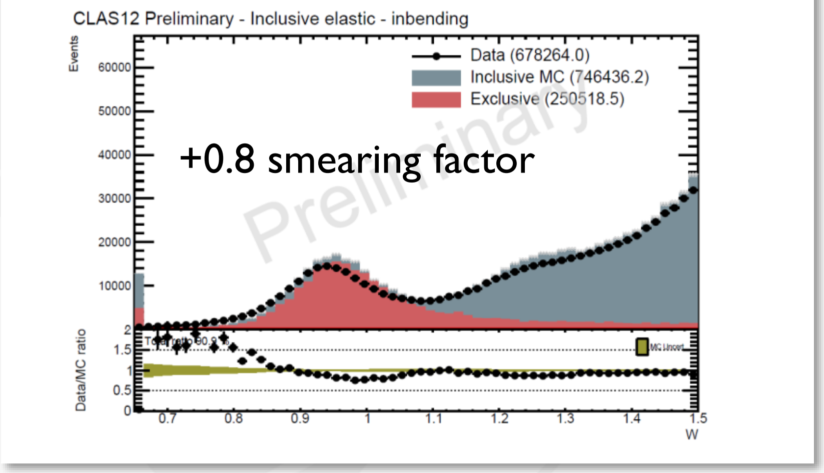
Jefferson Lab clas

Motivations

Inclusive elastic events

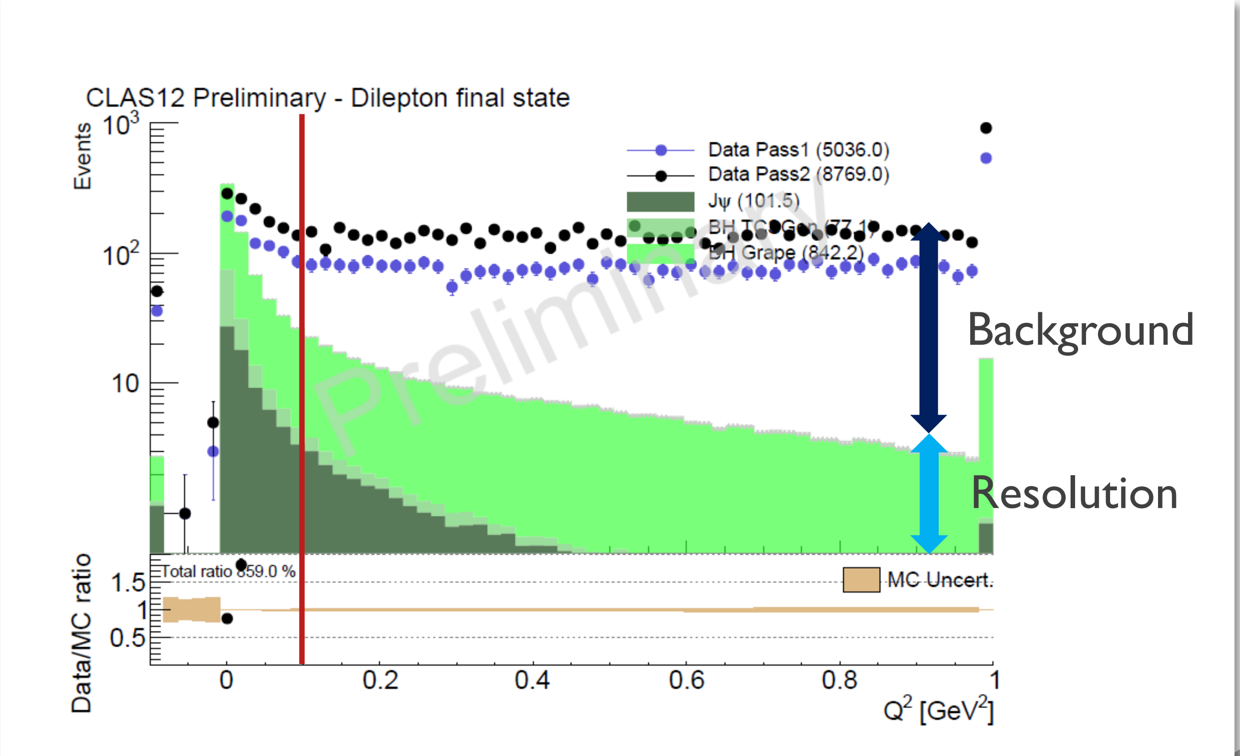
- In Pass 1 data, the smearing of the MC is key to understand the elastic peak resolution





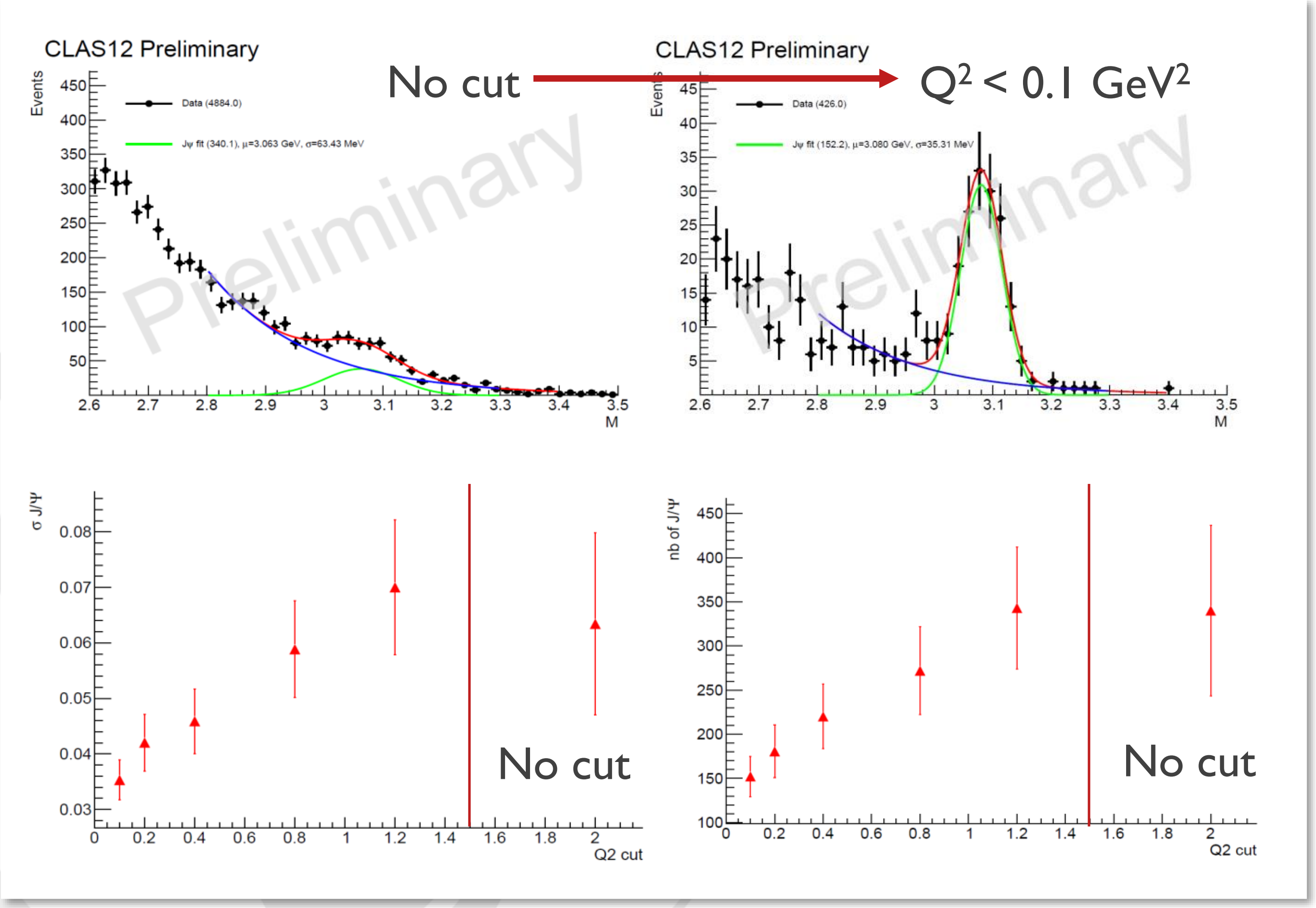
Inclusive elastic events

- Although photo-production events are generated (Q^2=0 GeV), the reconstructed virtuality of the incoming photon is large
- If the data resolution is not well reproduced by MC, the tail will be mis-reproduced and thus the extracted efficiency



Consequence for the number of J/ψ

- The J/ψ photoproduction yield should depend on the Q2 cut similarly in data and simulation

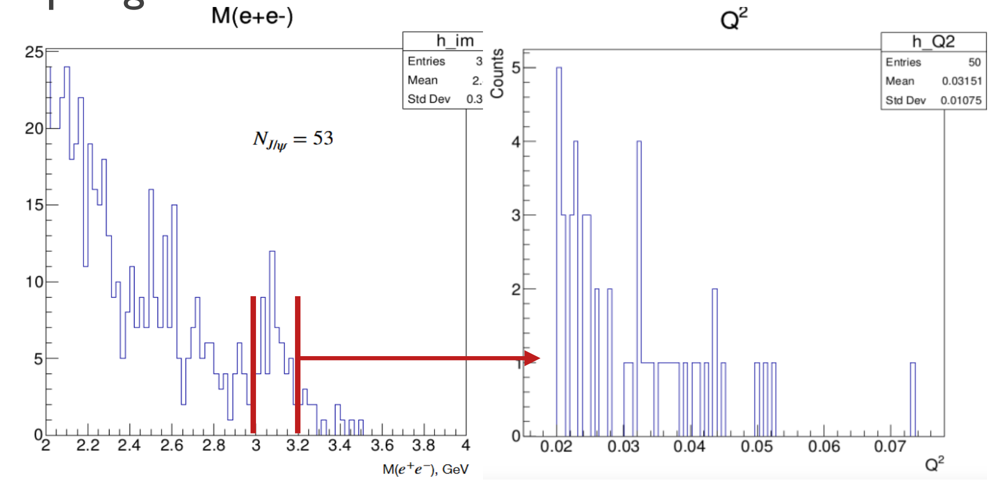


Maximum virtuality of the incoming photon

$$ep \to e' J/\psi\ p' \to e' l^+ l^- (X)$$

- Using tagged photo-production events, one can measure the virtuality of the incoming photon with only the FT resolution involved
- The large Q2 events in the untagged case are solely due to FD resolution effects

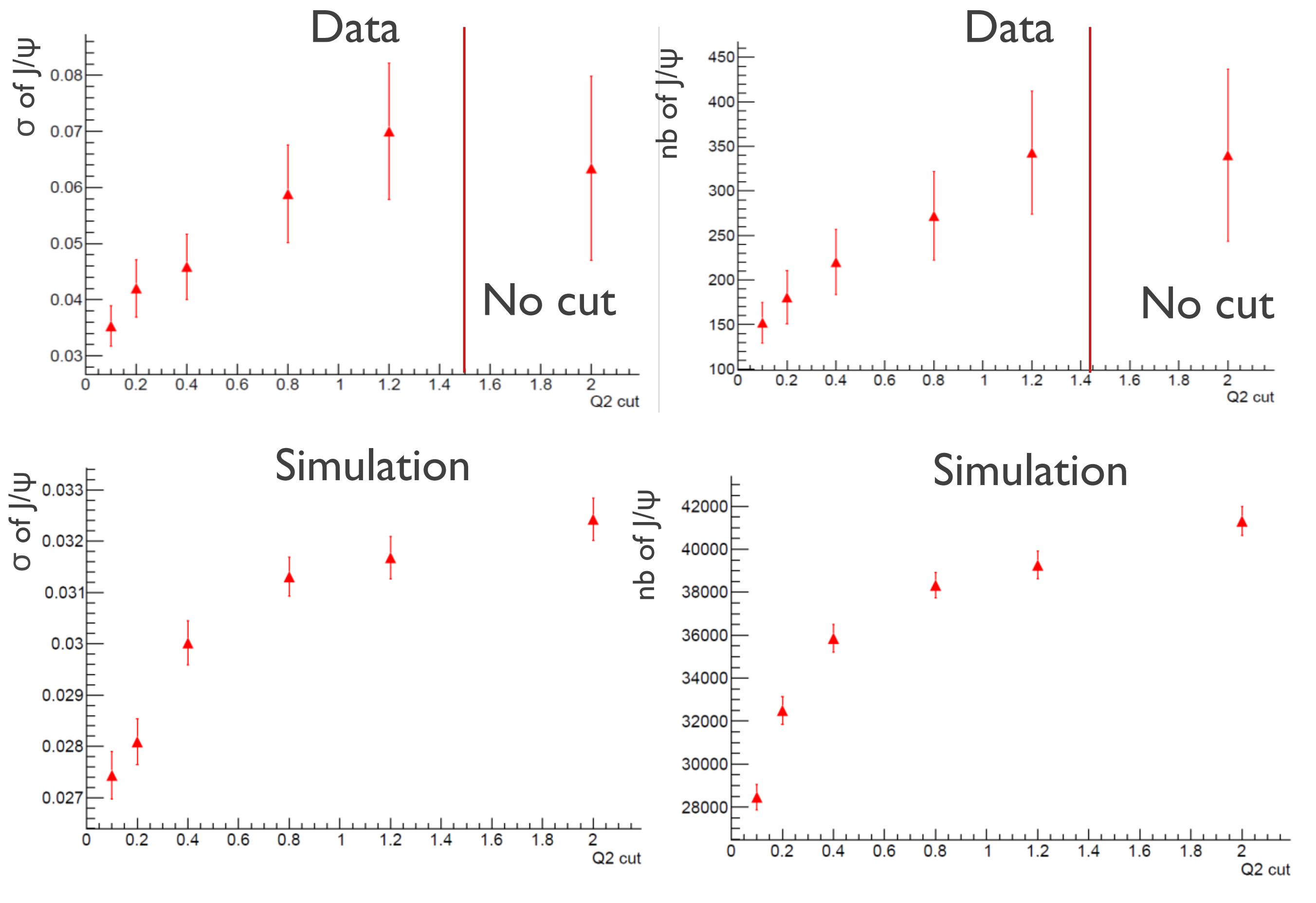
Spring 2019 – Full statistics



Material provided by M. Tenorio Pita

Consequence for the number of J/ψ

- The J/ψ photoproduction yield should depend on the Q2 cut similarly in data and simulation

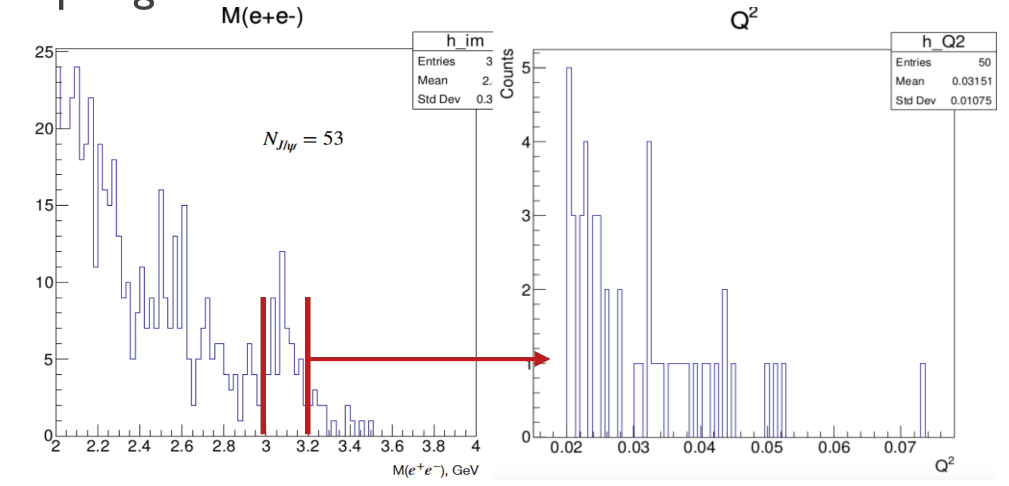


Maximum virtuality of the incoming photon

$$ep \rightarrow e' J/\psi\ p' \rightarrow e' l^+ l^- (X)$$

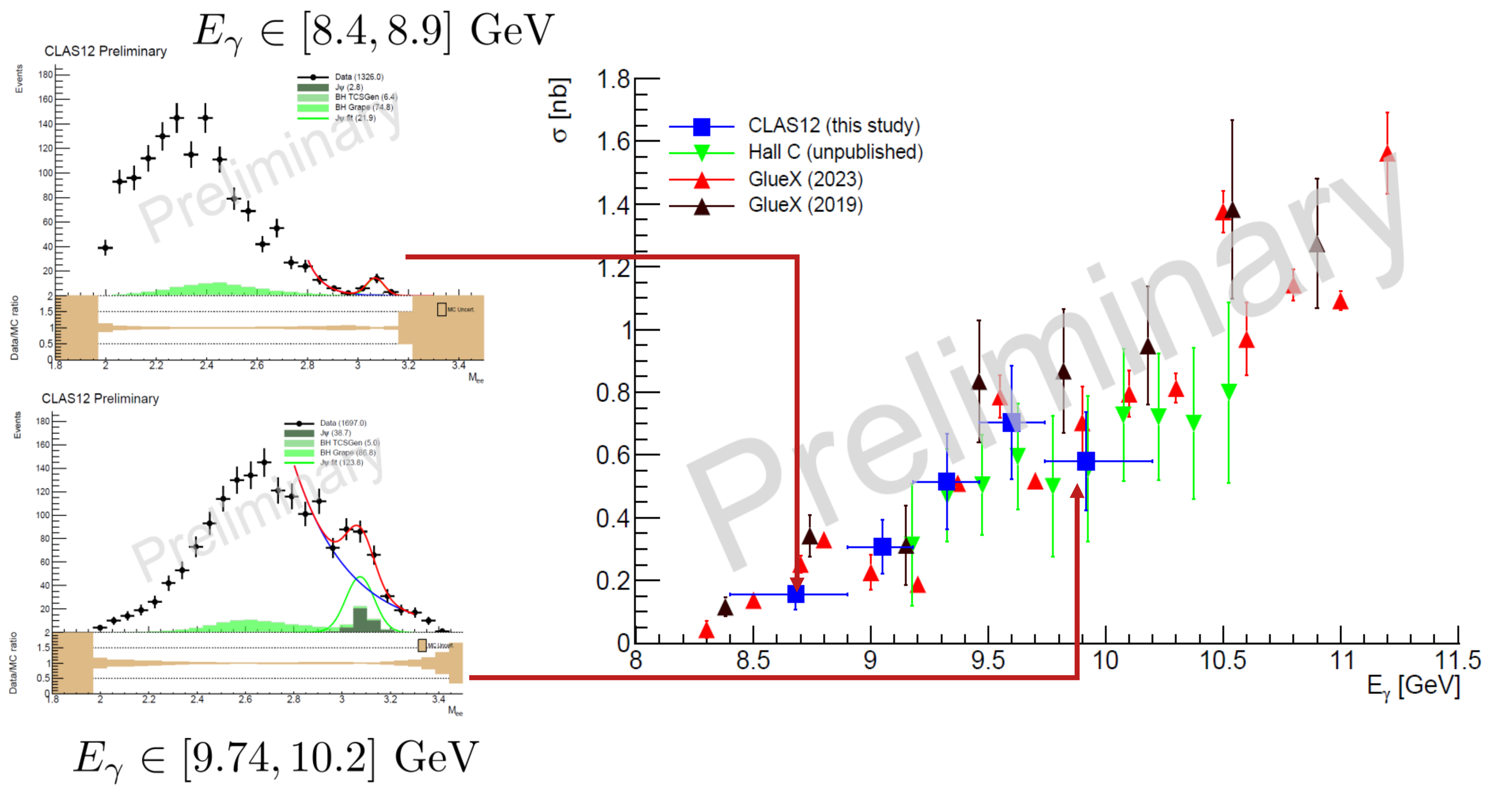
- Using tagged photo-production events, one can measure the virtuality of the incoming photon with only the FT resolution involved
- The large Q2 events in the untagged case are solely due to FD resolution effects

Spring 2019 – Full statistics



Material provided by M. Tenorio Pita

Effect on the CS extraction



- Acceptance calculated using J/ψ photoproduction MC events and no Q^2 cut
- No cross-normalization with BH
- Fit using gaussian + exponential

V-TCS observable extraction: maximum likelihood approach

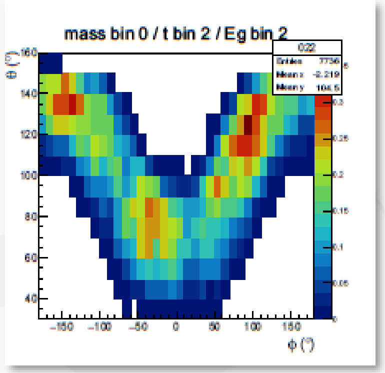
Motivations and formalism

All material provided by D. Glazier

Limitation of the current approach

- Both non-trivial angle dependence and non-trivial angular integration…

$$\frac{d^4\sigma_{INT}}{dQ'^2dtd\Omega} = \frac{d^4\sigma_{INT}\,|_{\text{unpol.}}}{dQ'^2dtd\Omega} - \nu\cdot A\frac{L_0}{L}\left[\sin(\phi)\frac{1+\cos^2(\theta)}{\sin(\theta)}\text{Im}\mathcal{H} + \ldots\right]$$



… makes the naive fitting procedure not straight forward to interpret

- What about the pure TCS contribution ?

$$\sigma(\gamma p \to e^+e^-p) = \sigma_{BH} + \sigma_{INT} + \sigma_{TCS}$$

Maximum likelihood fit

$$I(\theta,\phi,hP) = \sigma_{BH} + \sigma_{TCS} + \sigma_{INT}$$

$$I(\theta,\phi,hP) = B\frac{1+\cos^2(\theta)}{\sin^2(\theta)} + T(1+\cos^2(\theta)) + A\frac{1+\cos^2(\theta)}{\sin(\theta)}(ReM\cos(\phi) - hP.ImM\sin(\phi))$$

If our data distribution, f, depends on an acceptance function $\eta(x_i)$ and a physics model $I(x_i:\theta_j)$:

$$f(x_i:\theta_j) = I(x_i:\theta_j).\eta(x_i)$$

Then we can approximate p by summing over M accepted Monte-Carlo events,

$$p(x_i:\theta_j) = \frac{I(x_i:\theta_j)\eta(x_i)}{\sum_s^M I(x_{i,s}:\theta_j)}$$

$$L(\theta_j, Y) = \prod_k^N p(x_{i,k}:\theta_j)e^{-Y}\frac{Y^N}{N!}$$

$$-\ln L(\theta_j,Y) = -\sum_k^N \ln\left[\frac{I(x_{i,k}:\theta_j)}{\sum_s^M I(x_{i,s}:\theta_j)}\right] + Y - N\ln Y - \sum_k^N \ln\eta(x_{i,k})$$

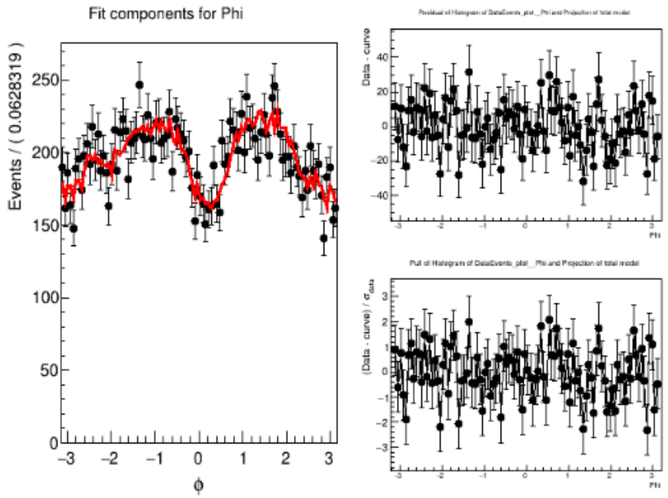
$$\mathcal{L}(\theta_j,Y) = -\ln L(\theta_j,Y) = -\sum_k^N \ln\frac{I(x_{i,k}:\theta_j)}{\sum_s^M I(x_{i,s}:\theta_j)} + Y - N\ln Y$$

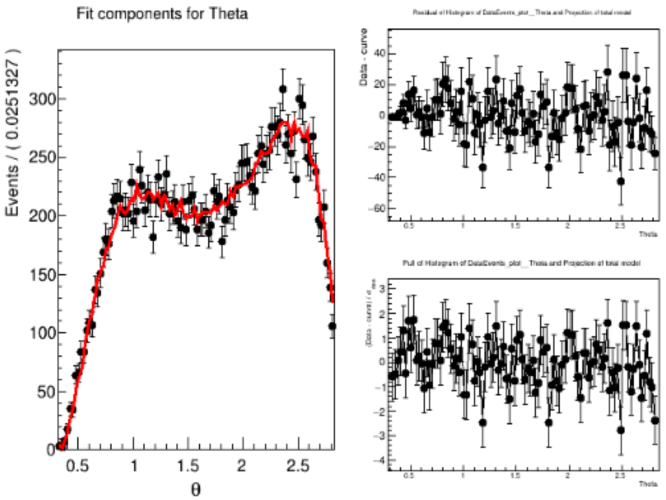
Current status of brufit for TCS

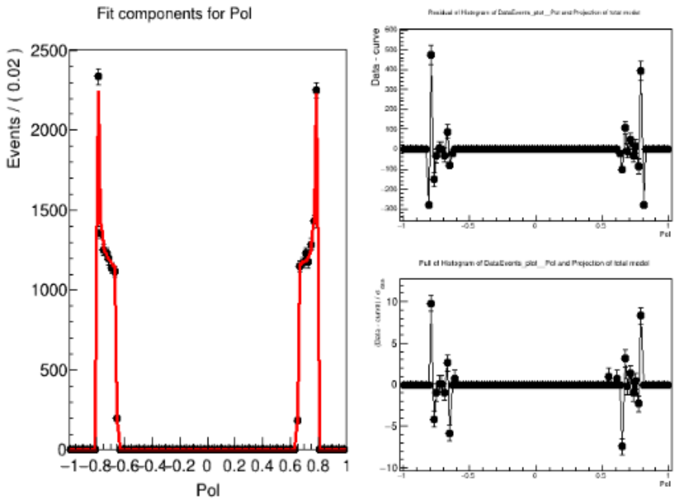
Brufit tutorial: https://indico.jlab.org/event/343/contributions/5450/attachments/4585/5691/GlazierBruFit

Maximum Likelihood Approach
Gen with truth

```
Reproduce input parameters ?
BH = 0.6 ; ImM = 0.8 ; TCS = 0.2
Results
BH      5.5324e-01 +/-  1.60e-02
ImM     8.1496e-01 +/-  3.21e-02
TCS     2.5344e-01 +/-  1.72e-02
Slight bias from BH to TCS ?
```







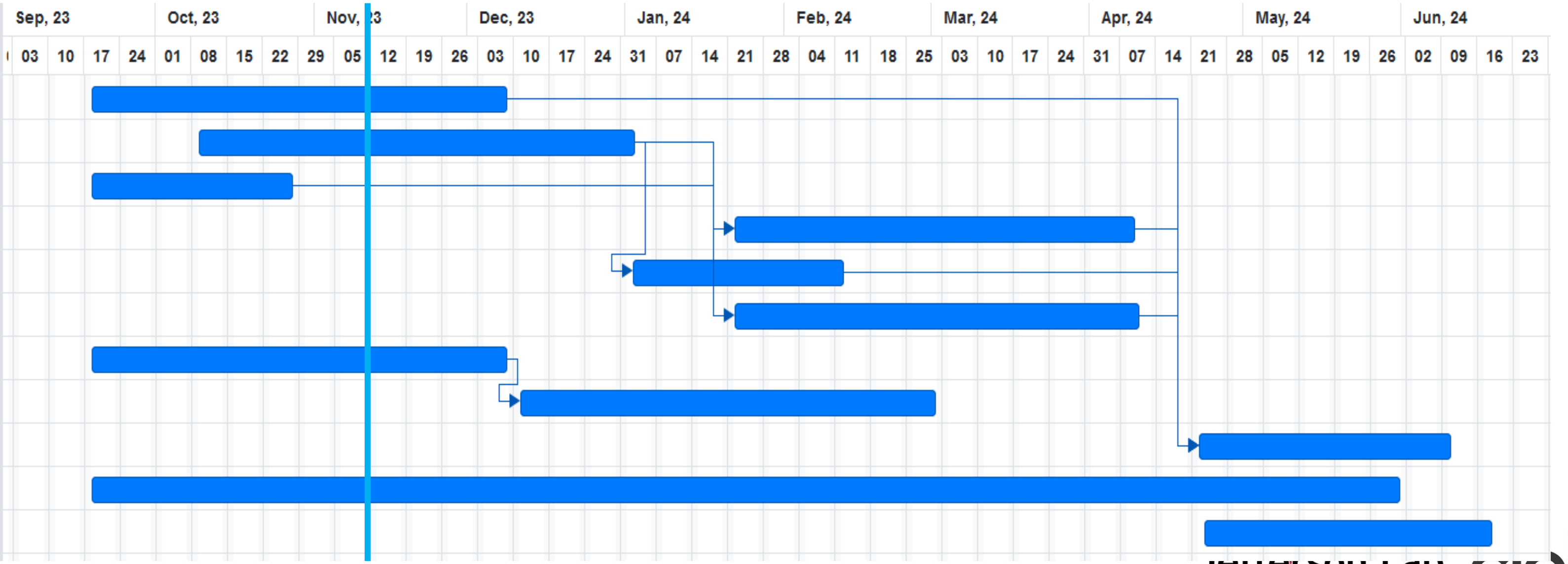
- Method based on brufit https://github.com/dglazier/brufit/tree/R6.28/tutorials/TCS
- Tested on MC event passed through GEMC (geometrical acceptance + resolution effects)

Jefferson Lab clas

Summary and outlook

- We have established a plan to reach both a new TCS and a first J/ψ publication on RGA.
- The work force matches the need: Derek (brufit for TCS), Kayleigh (TCS on RGC), Mariana (J/ψ on RGA), Pierre (TCS and J/ψ on RGA), Richard (J/ψ on RGA and RGB), Rafo (Simulation)
- Spring 19 Pass 2 dataset looks good, with similar issue than Pass 1 (Resolution and high-Q^2 background).
- AI PID for lepton is well underway and consistent with Pass 1 analysis.
- Maximum likelihood fit method is being developed for TCS observable extraction.

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

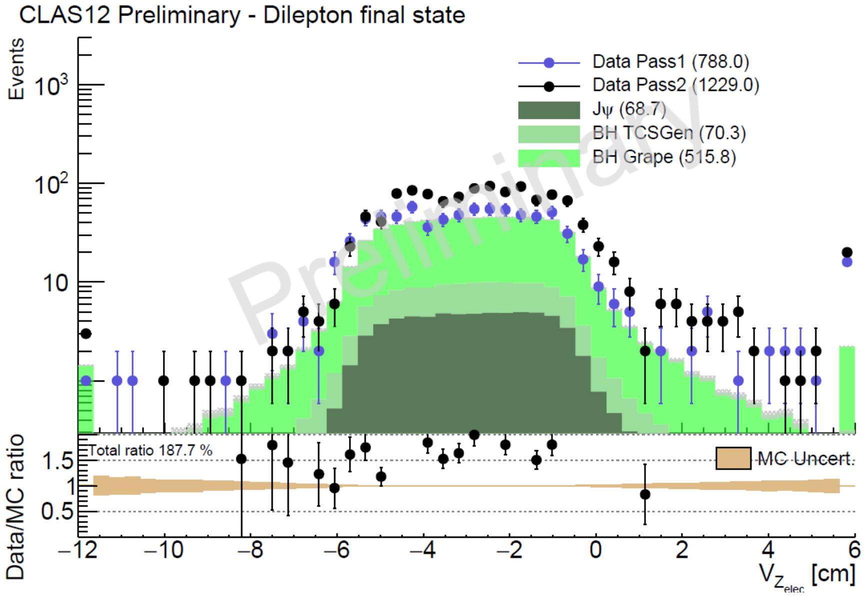


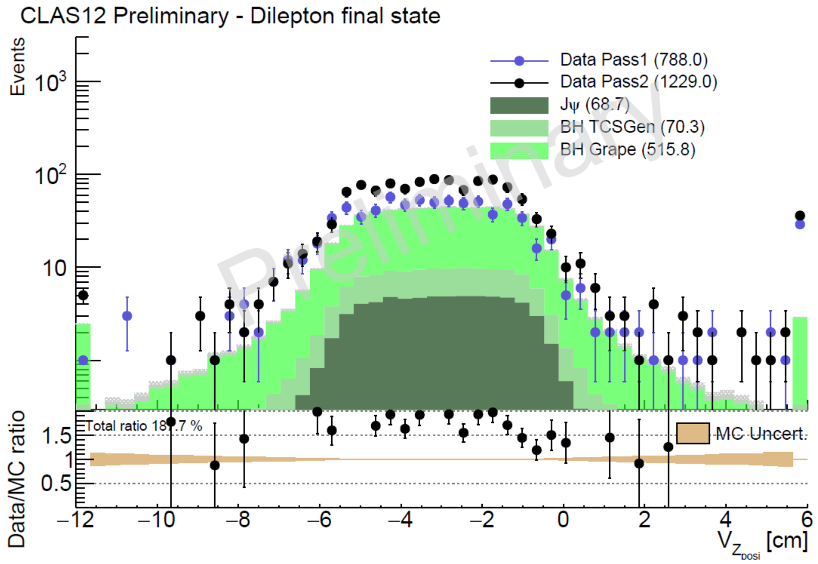
Back-up

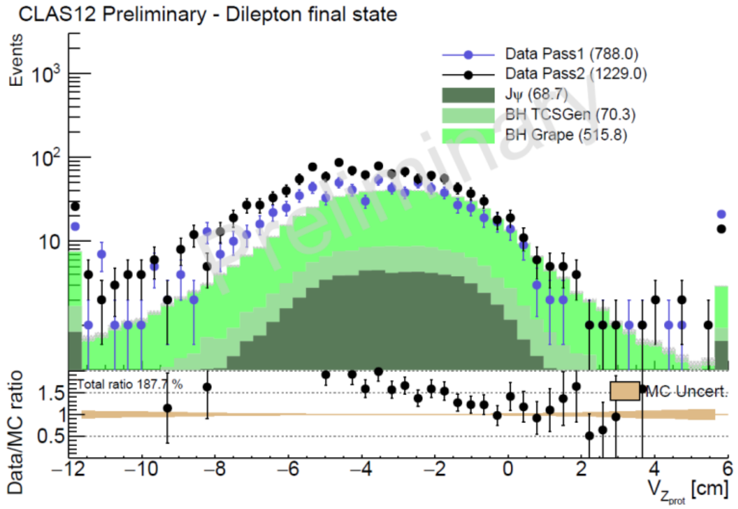
II - Pass 2 data: first look at Spring 2019

Jefferson Lab clas

Spring 19 Pass 2: Vertices





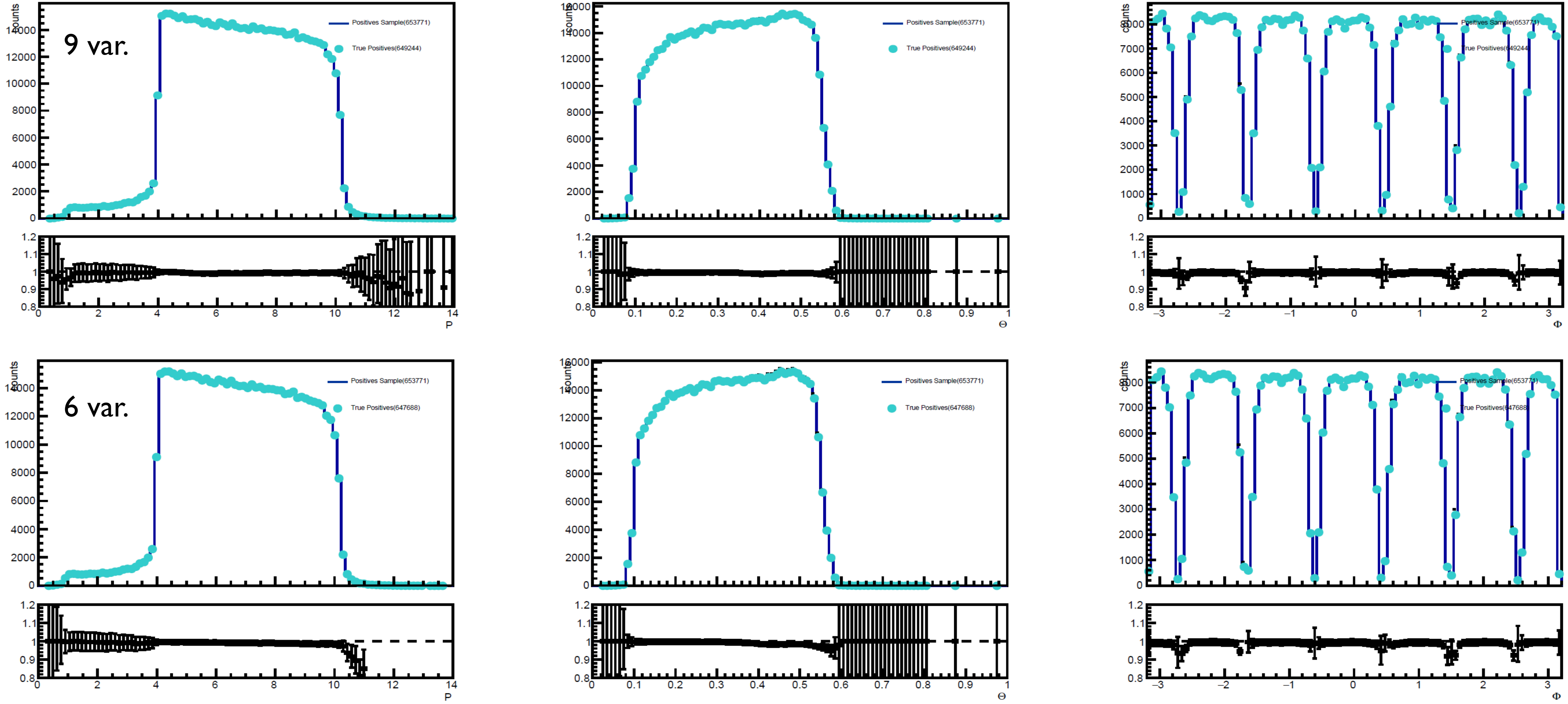


Jefferson Lab clas

III - Lepton PID using machine learning

Jefferson Lab clas

Validation - Efficiency



Validation - Contamination