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

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CLAS collaboration meeting – Jefferson Lab

8th of November 2023

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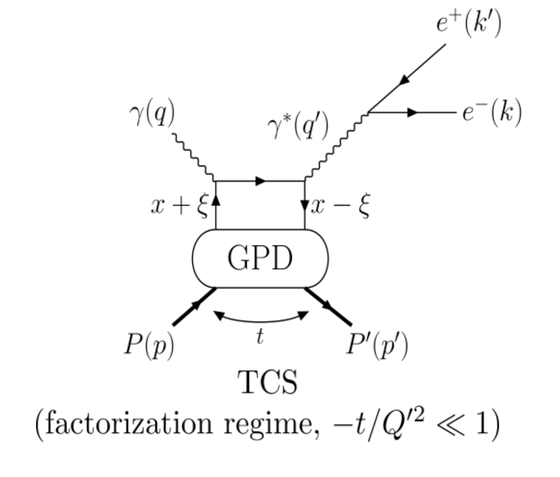
Outline

Motivations for dilepton final state measurement

Timelike Compton Scattering

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



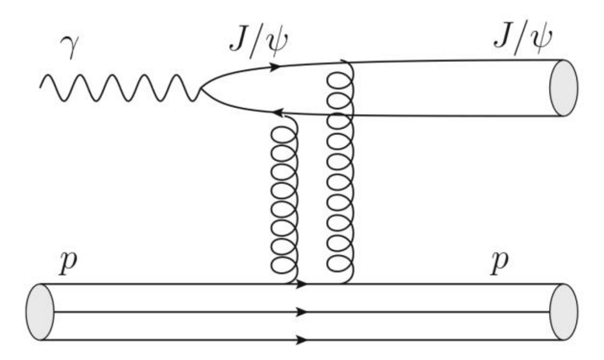
$$\frac{d^4\sigma_{INT}}{dQ'^2 dt d\Omega} \propto \frac{L_0}{L}\left[\cos(\phi)\frac{1+\cos^2(\theta)}{\sin(\theta)}\text{Re}\mathcal{H} + ...\right]$$

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

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

J/ψ photoproduction at threshold

$$\gamma p \to J/\psi\, p \to e^+ e^- p'$$

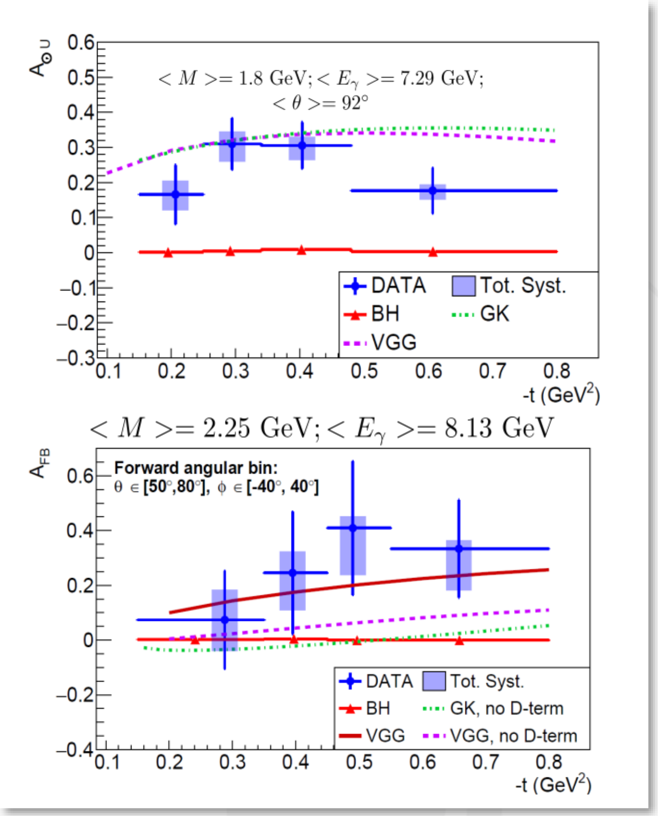


- The t-dependence of the cross-section allow to access gluon Gravitational Form Factors (GFFs), mass radius of the nucleon and gluon GPDs (under 2-gluon exchange assumption and no open-charm contributions)
- Model-dependent limit on the branching ration of the Pc pentaquark.

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

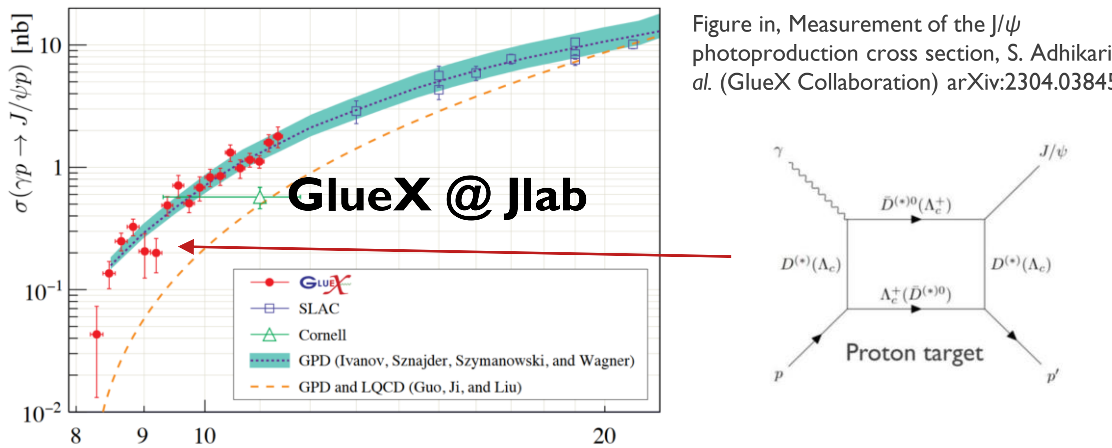


Figure in, Measurement of the J/ψ photoproduction cross section, S. Adhikari *et al.* (GlueX Collaboration) arXiv:2304.03845

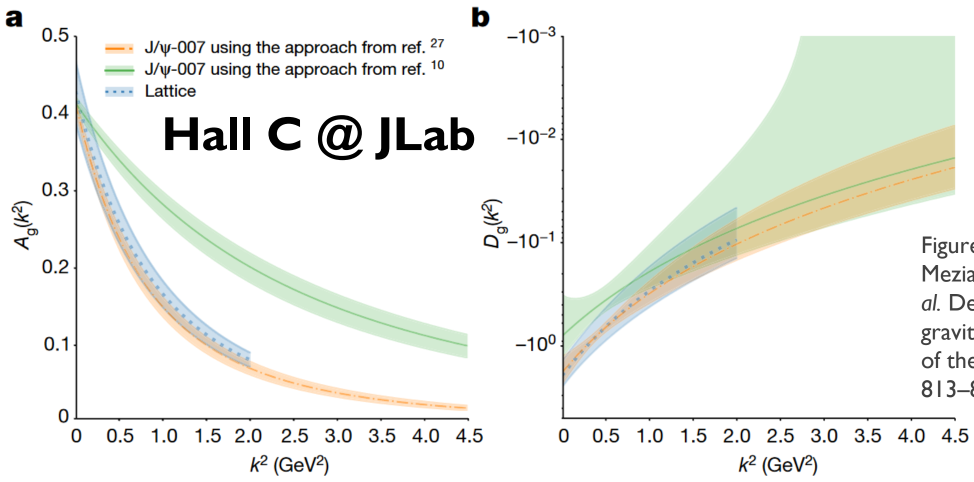
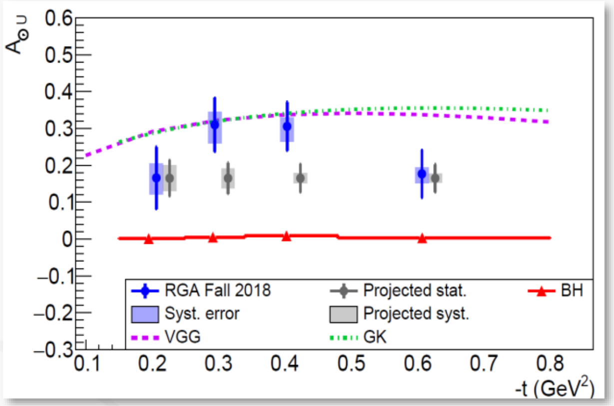


Figure in Duran, B., Meziani, ZE., Joosten, S. *et al.* Determining the gluonic gravitational form factors of the proton. *Nature* 615, 813–816 (2023)

Goals and plans

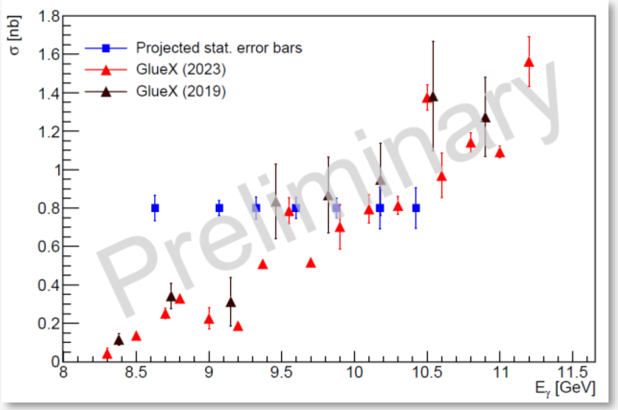
Timelike Compton Scattering

- Full statistics of RG-A will allow to divide error bars by factor 2.
- Potentially use them in GPD fit.



J/ψ photoproduction at threshold

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



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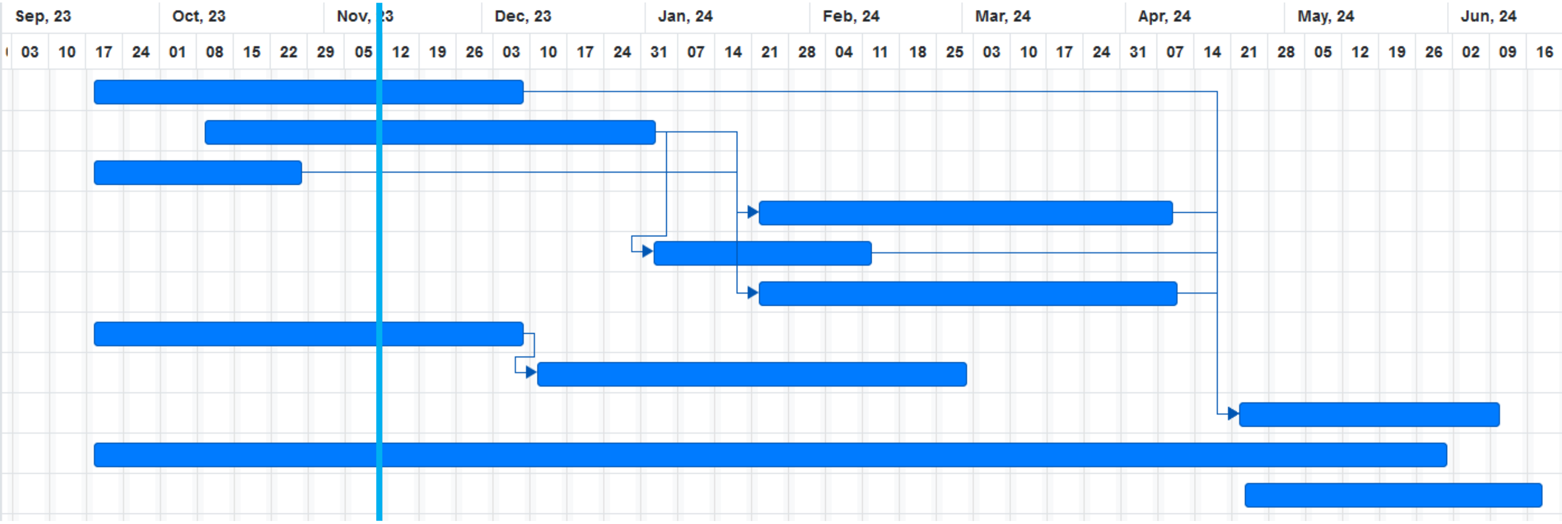

Objective: summer 2024

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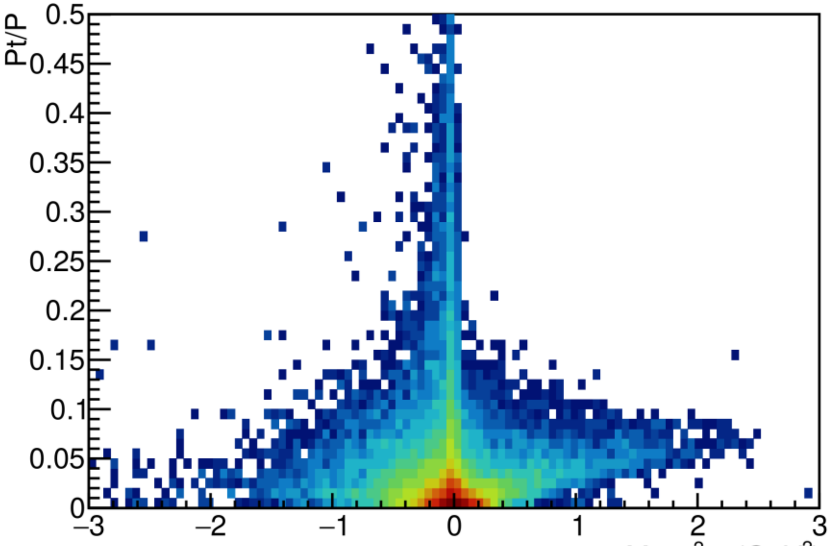
General analysis strategy

1) CLAS12 PID + Positron NN PID

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

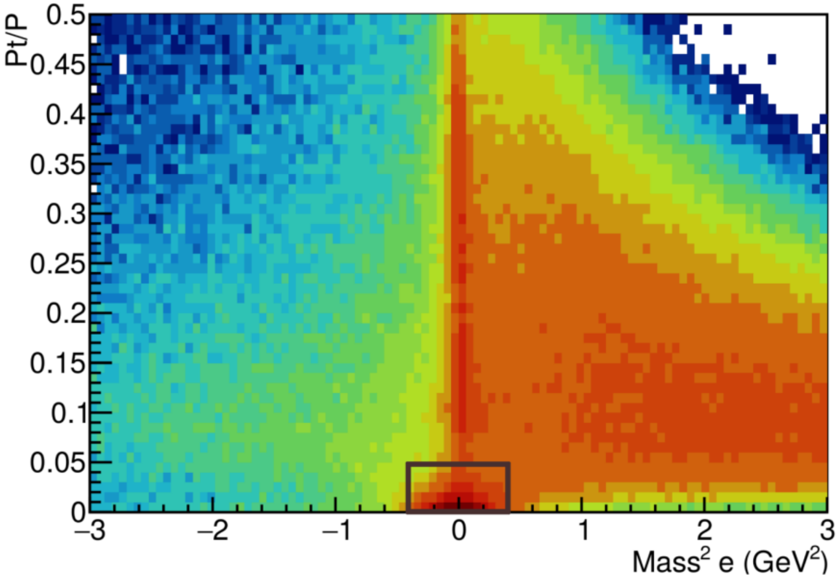
$p_X = p_{beam} + p_p - p_{e^+} - p_{e^+} - p_{p'}$ → 2) $|M_X^2| < 0.4 GeV^2$ → 3) $|\frac{Pt_X}{P_X}| < 0.05$ or $Q^2 < 0.1$ GeV^2

Simulation



Plots from the Pass 1 TCS analysis note

Data

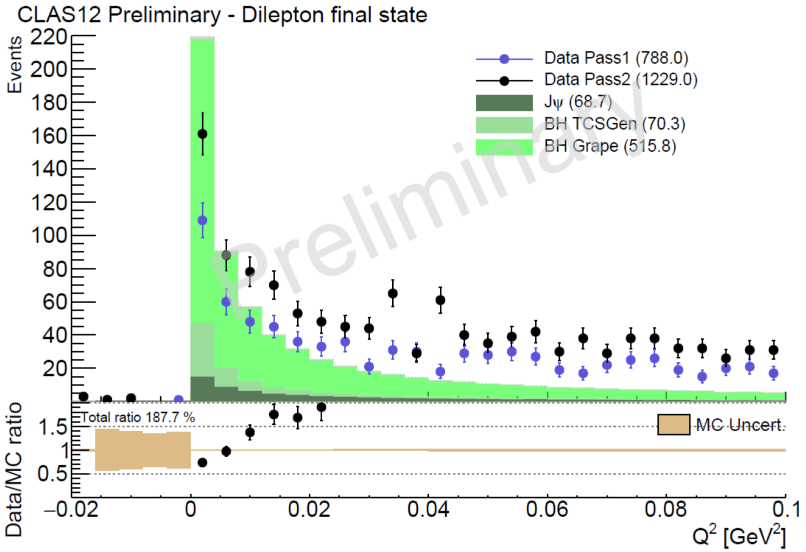


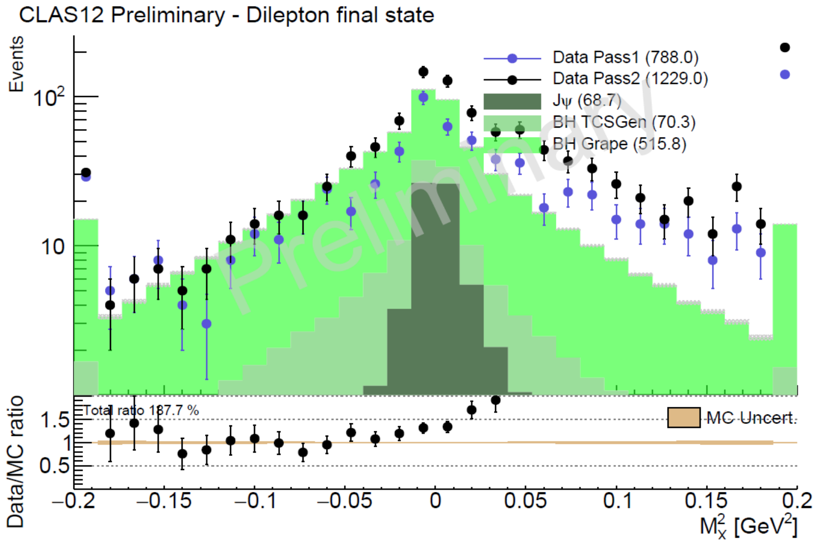
II - Pass 2 data: first look at Spring 2019

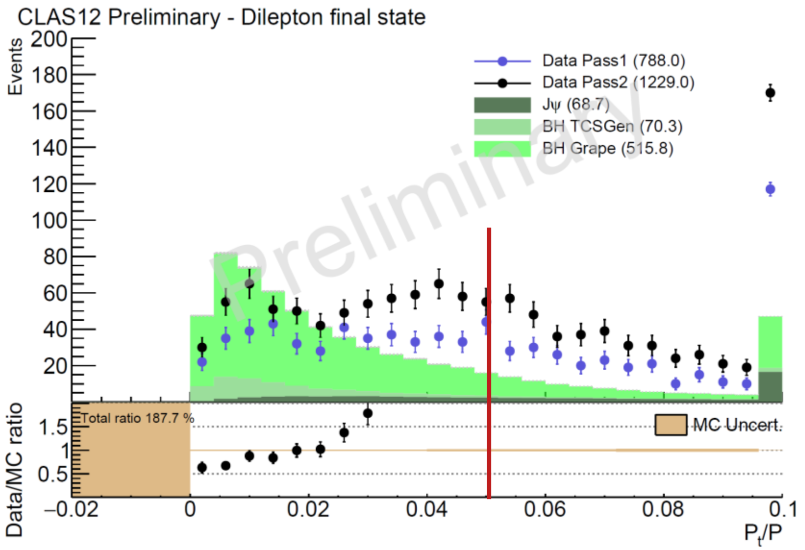
Comparison of data and MC (I)

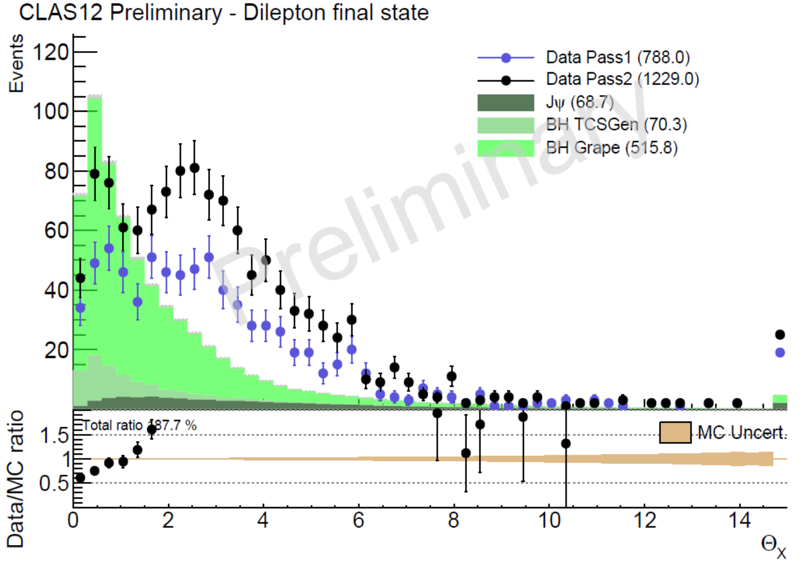
Event selection

- 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

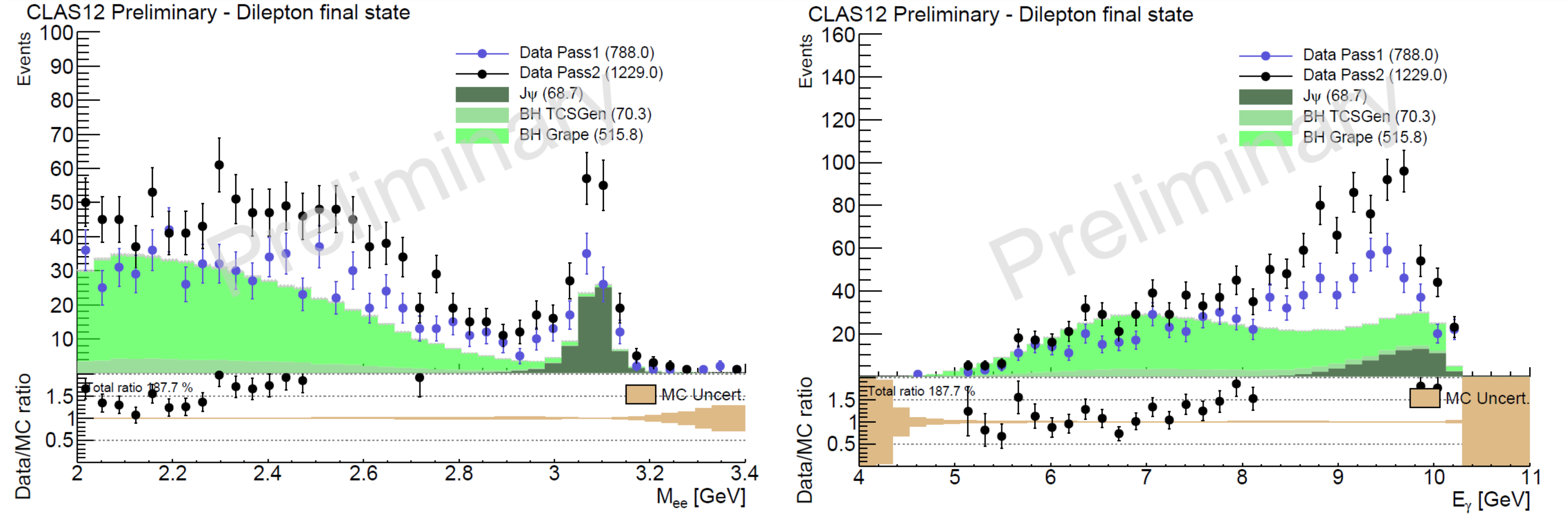






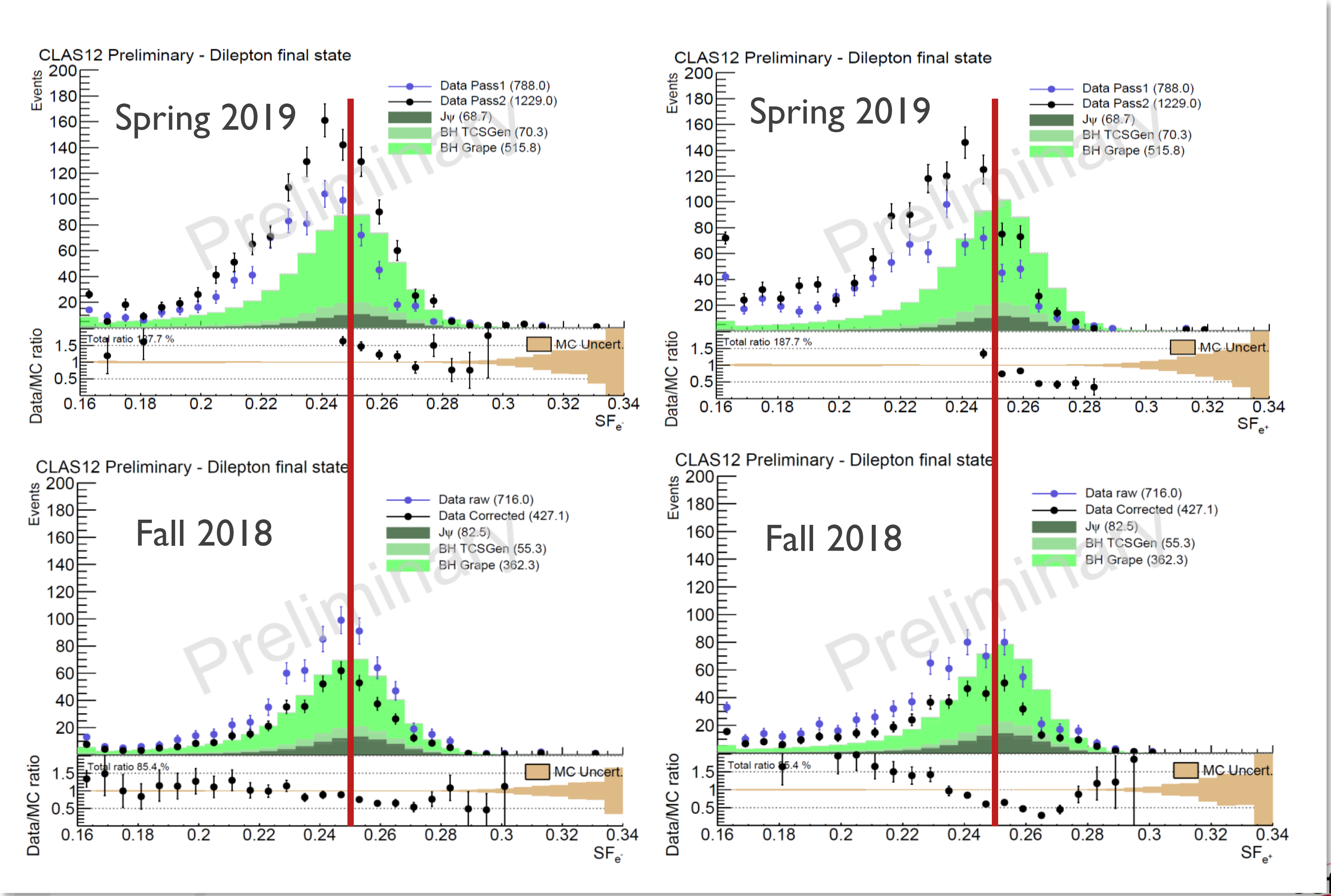


Comparison of data and MC (2)



- 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



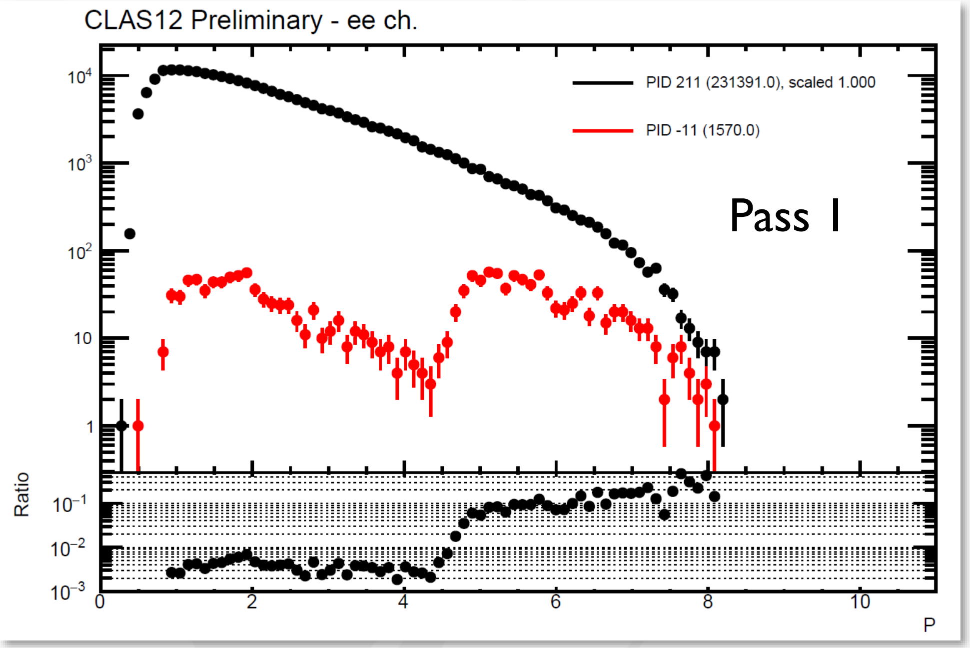
III - Lepton PID using machine learning

Motivations and previous work

Motivations

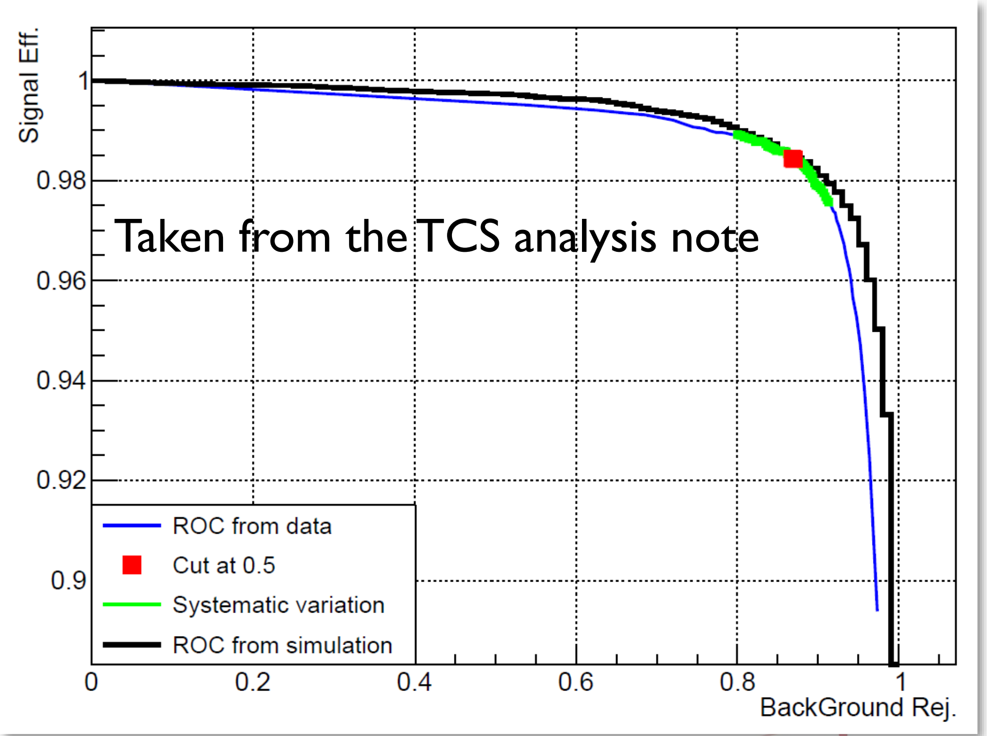
- Above the HTCC, threshold both pions and leptons produce a HTCC signal. In the EB, only ECAL provide a separation between the two.
- ep → epπ$^+$(π$^-$) is a large background at large positron momenta

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



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

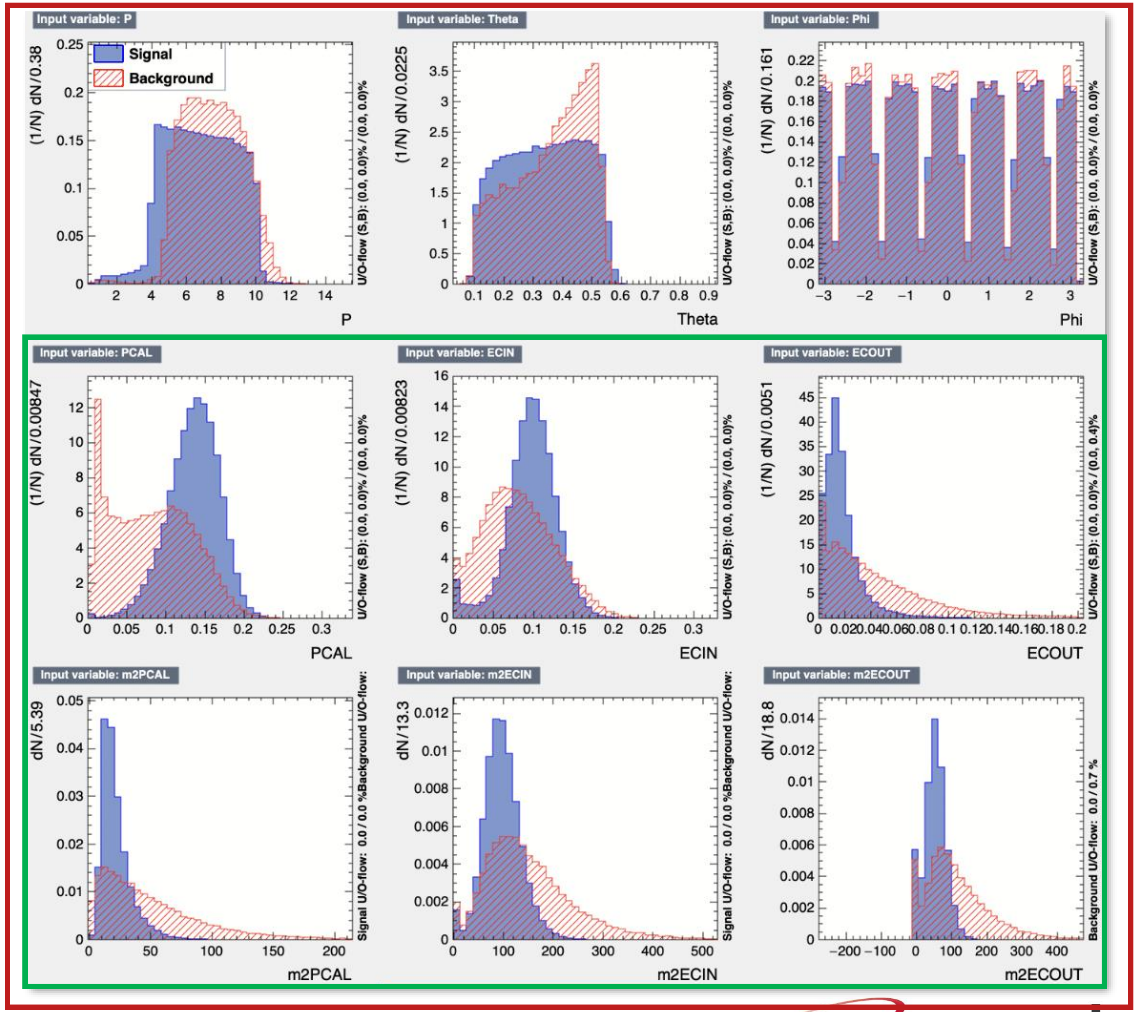
- Trained on simulation:

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

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

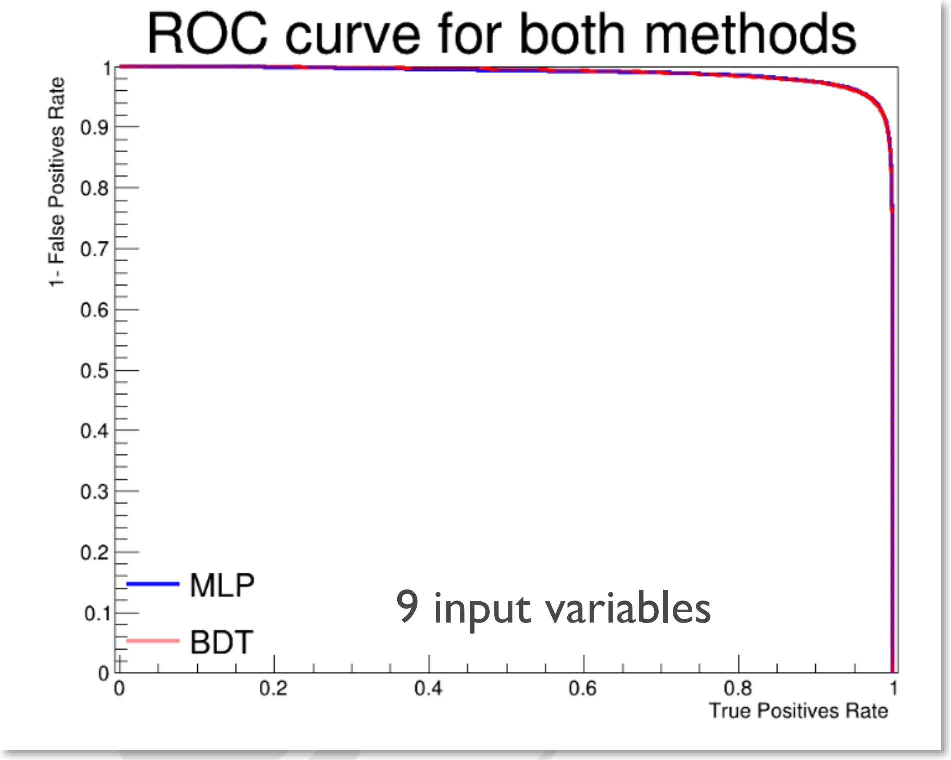
- Only RGA Spring 2019 for now

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 reduction: 10%

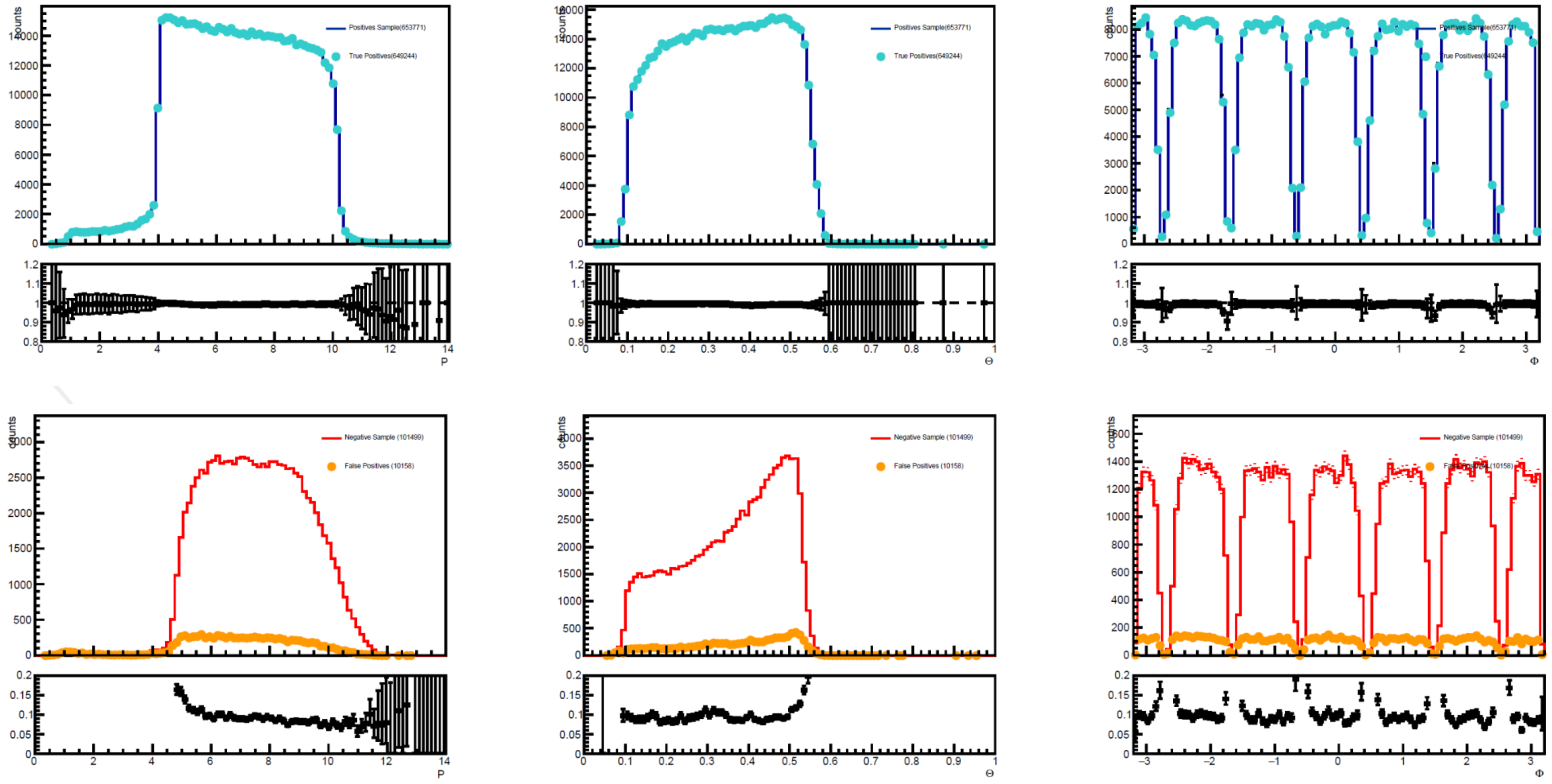


NN 6 var.	Actual e+ (653771)	Actual π+ (101499)
Predicted e+	647688	12805
Predicted π+	6083	88694
	TPR 99.1 %	FPR 12.6 %

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

Validation

NN. 9 Variables



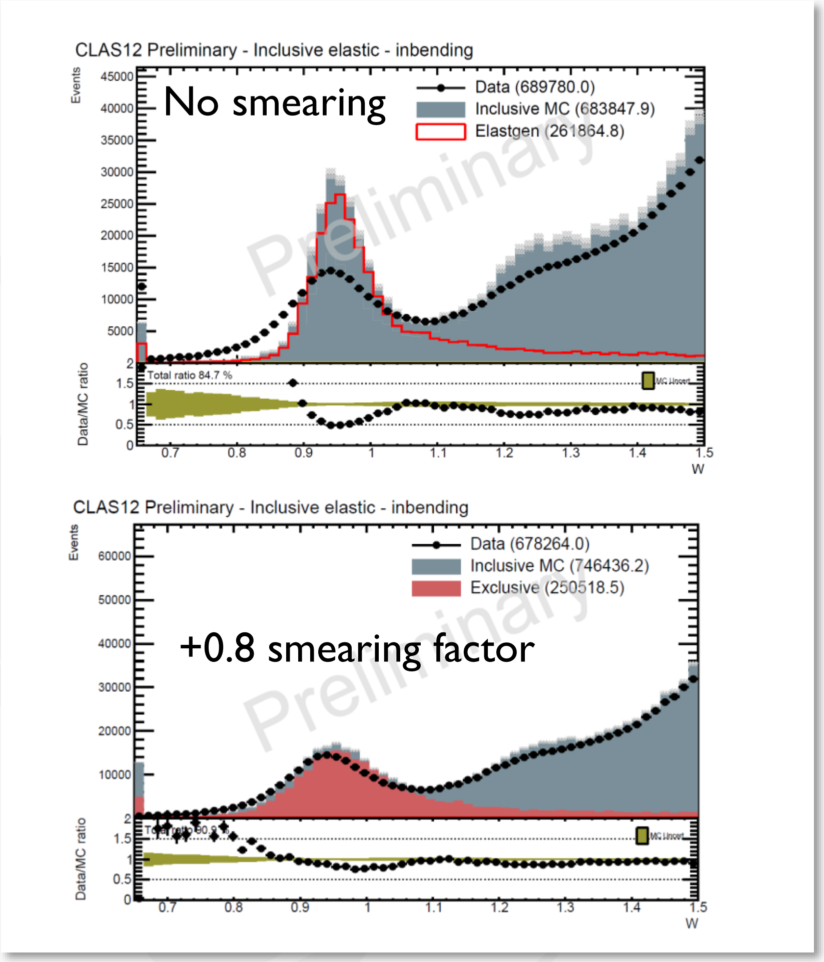
- Signal efficiency and background reduction as a function of particle kinematics
- Done on separate samples

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

Motivations

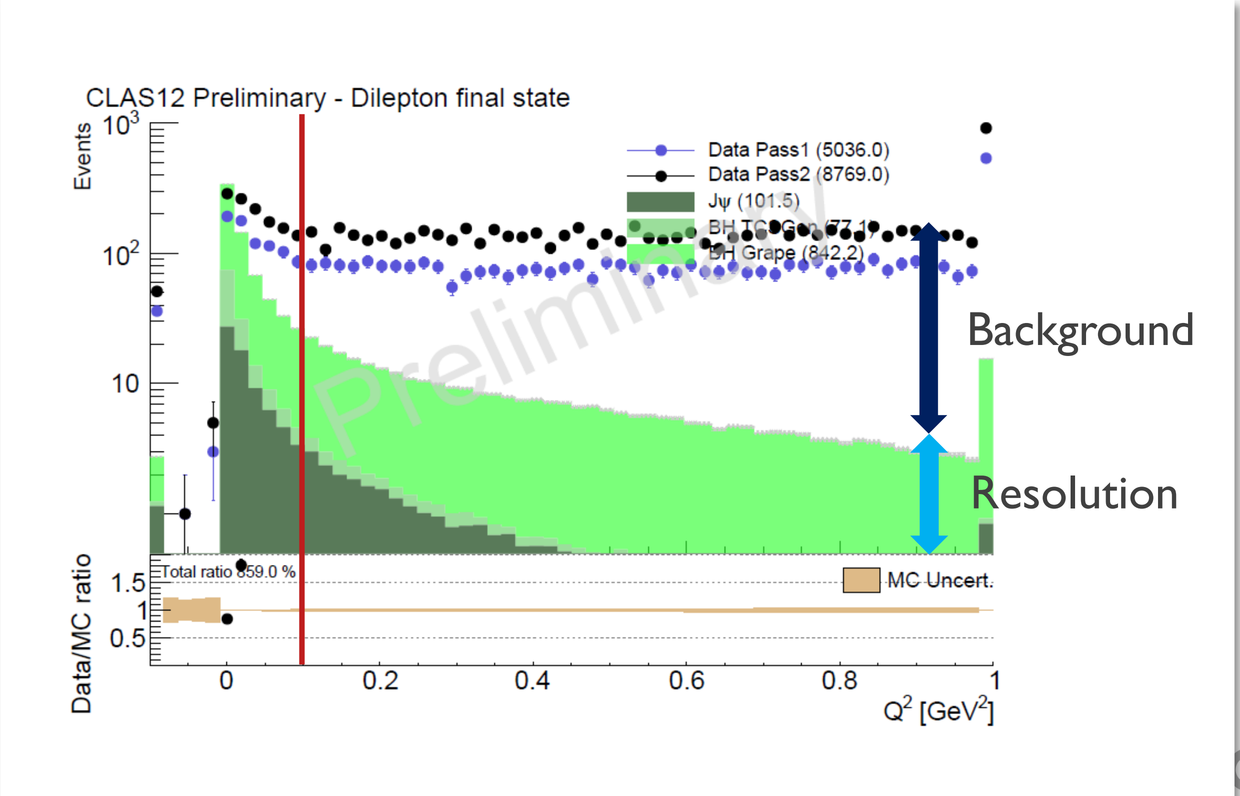
Inclusive elastic events

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



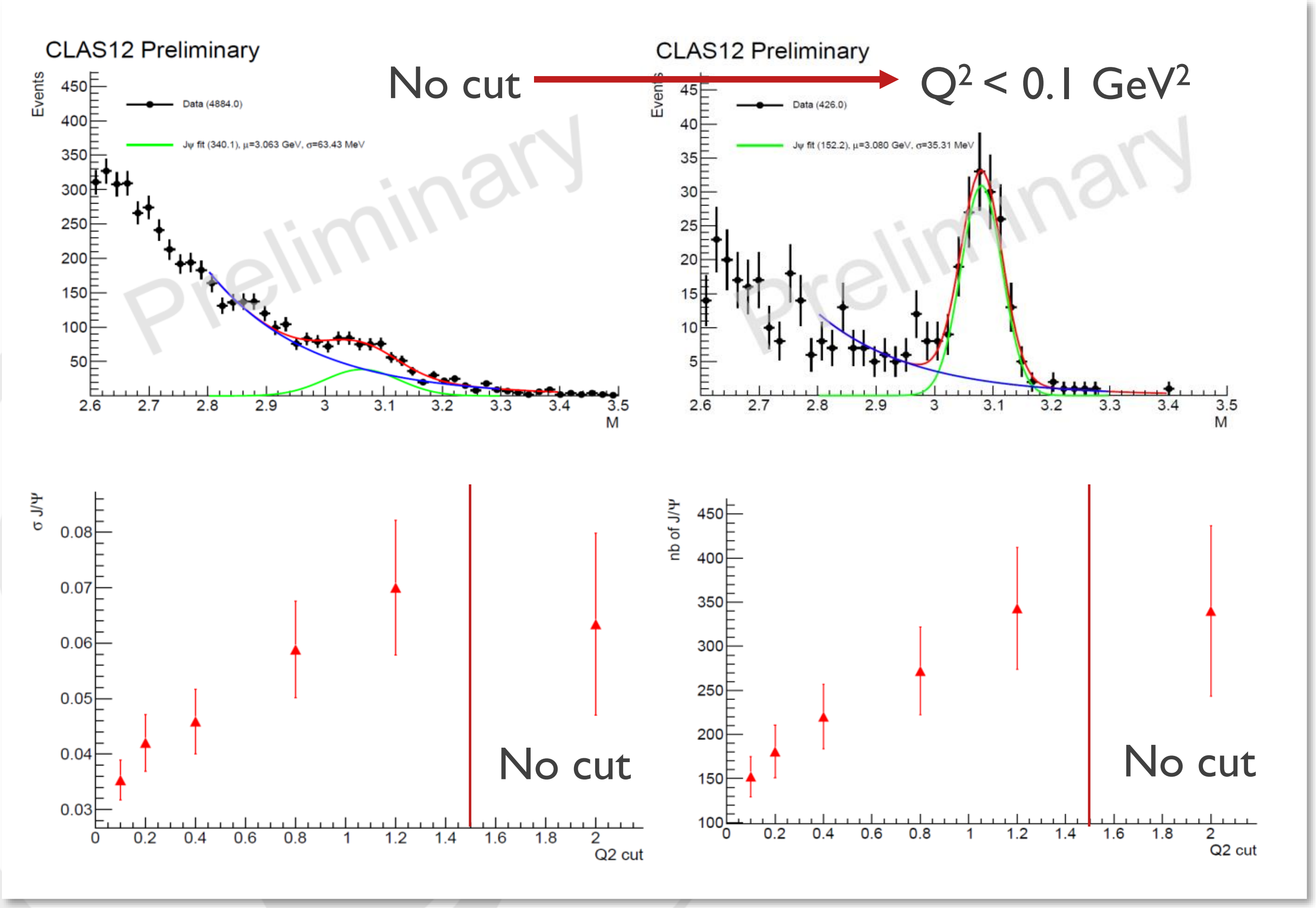
Inclusive elastic events

- 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

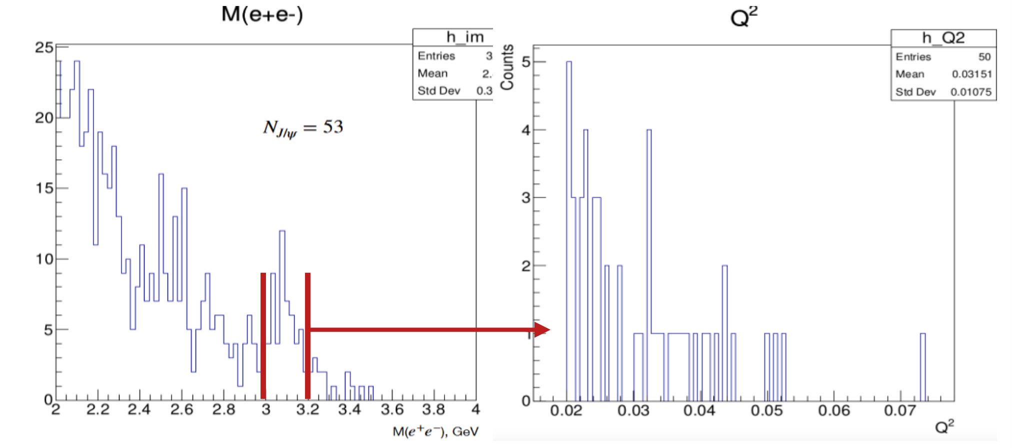


Maximum virtuality of the incoming photon

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

- Using tagged photo-production events, one can measure the virtuality of the incoming photon with only the FT resolution involved

Spring 2019 – Full statistics



Material provided by M.Tenorio Pita

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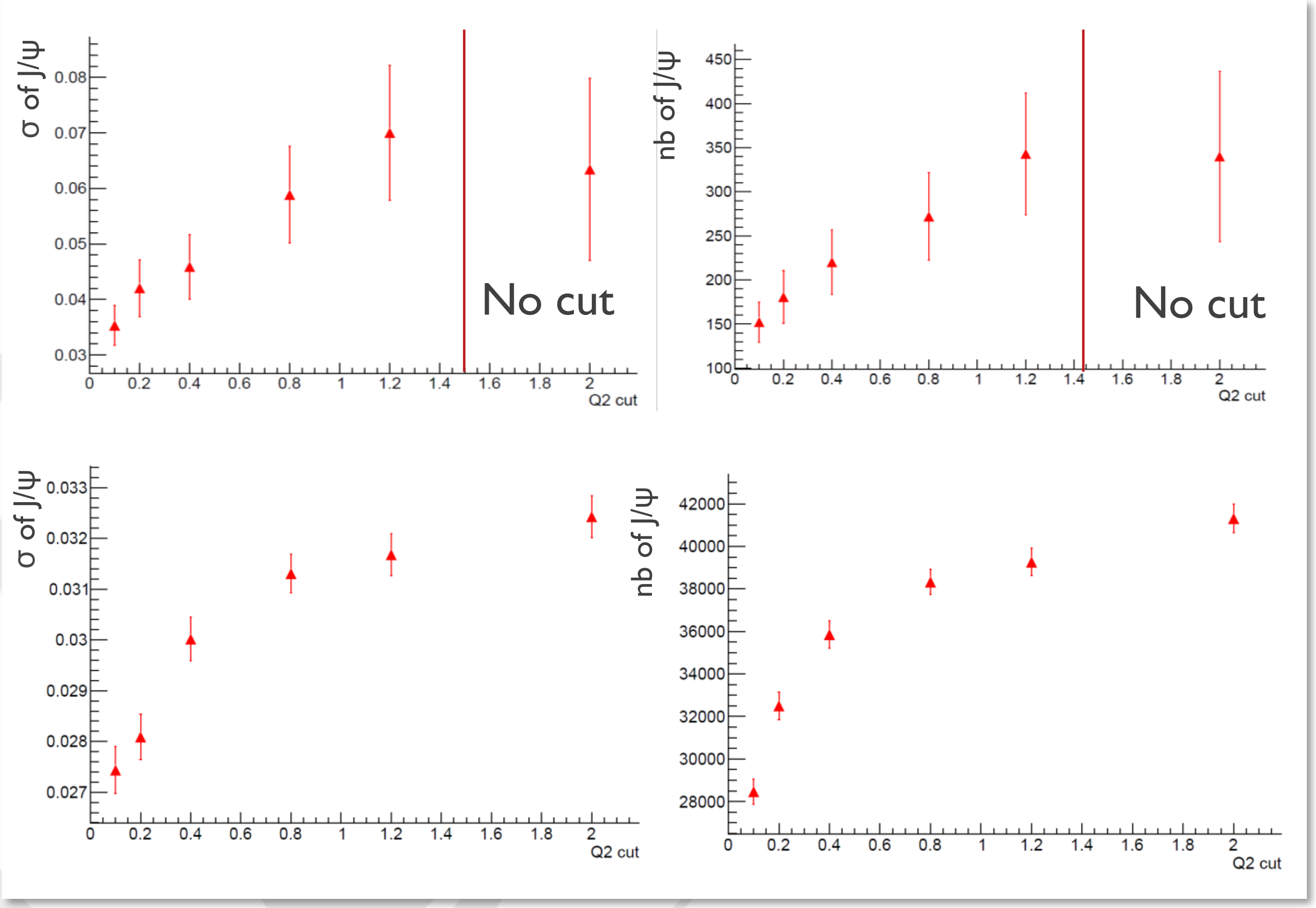

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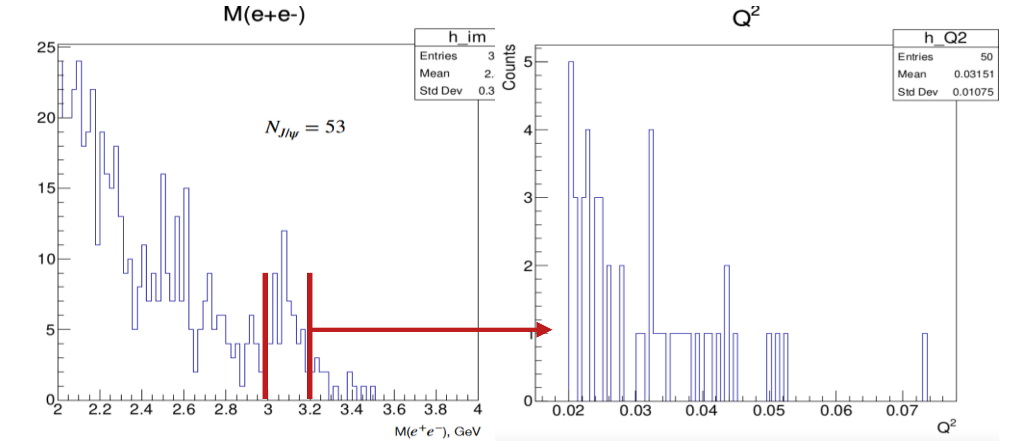
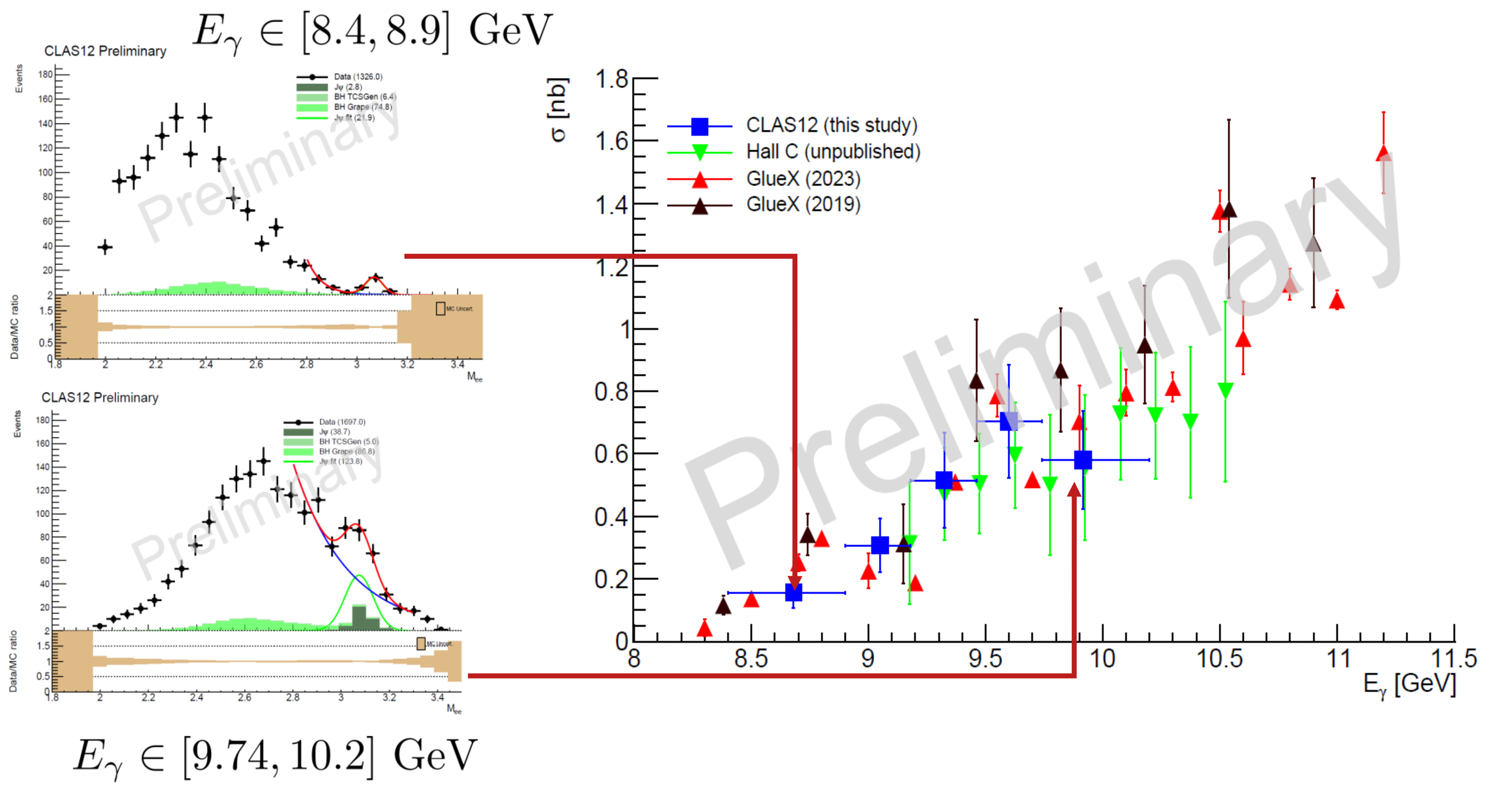


Material provided by M. Tenorio Pita

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

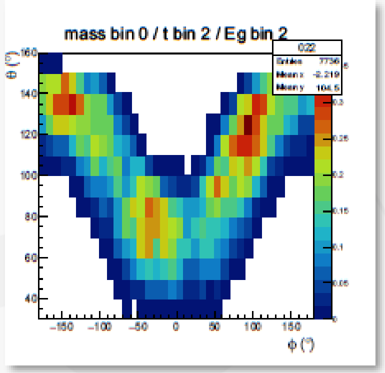
Motivations and formalism

All material provided by D. Glazier

Limitation of the current approach

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

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



… 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,

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

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

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

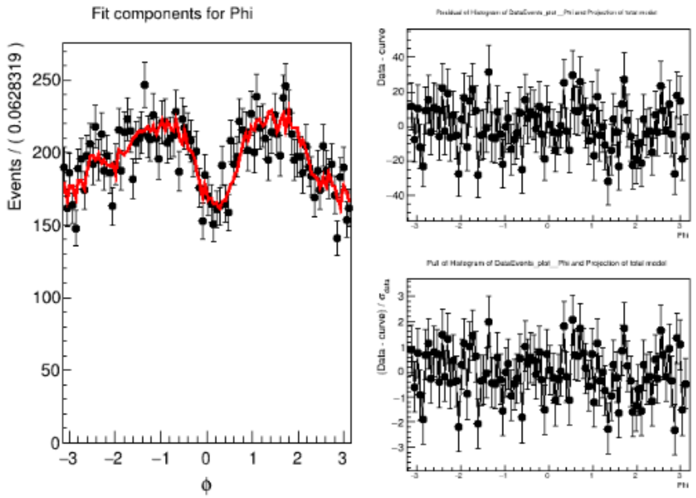
$$\mathcal{L}(\theta_j, Y) = -\ln L(\theta_j, Y) = -\sum_k^N \ln\frac{I(x_{i,k} : \theta_j)}{\sum_s^M I(x_{i,s} : \theta_j)} + Y - N\ln Y$$

Current status

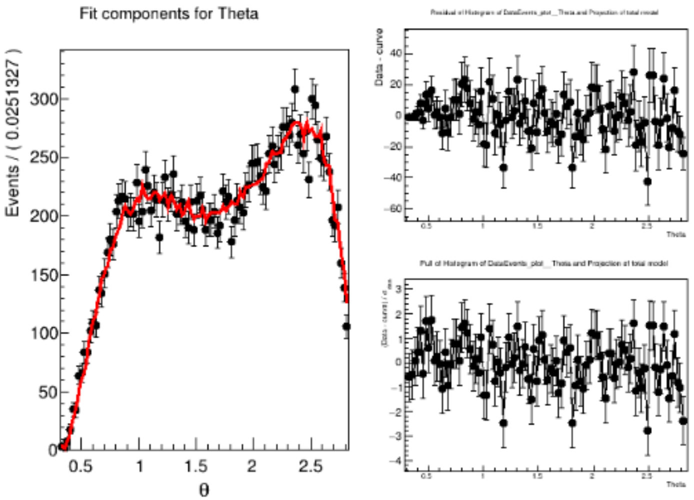
https://indico.jlab.org/event/343/contributions/5450/attachments/4585/5691/GlazierBruFit

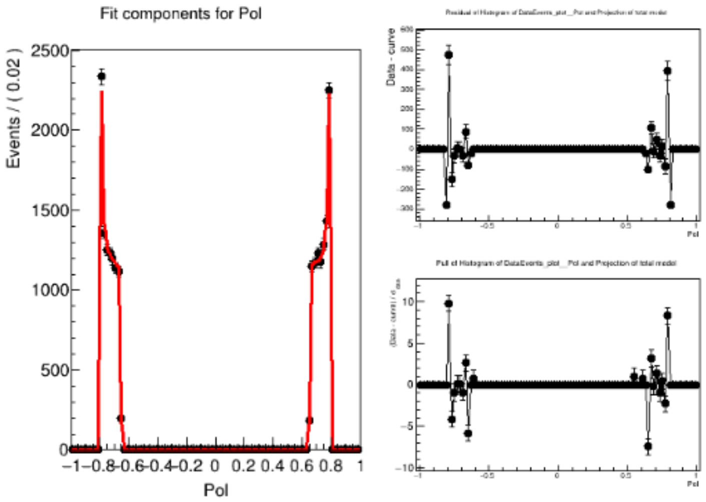
Maximum Likelihood Approach
Gen with truth

```
Reproduce input parameters ?
BH = 0.6 ; ImM = 0.7; 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
- Tested on MC only
- Fitted function





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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), Stepan (J/ψ on RGA).
- 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.

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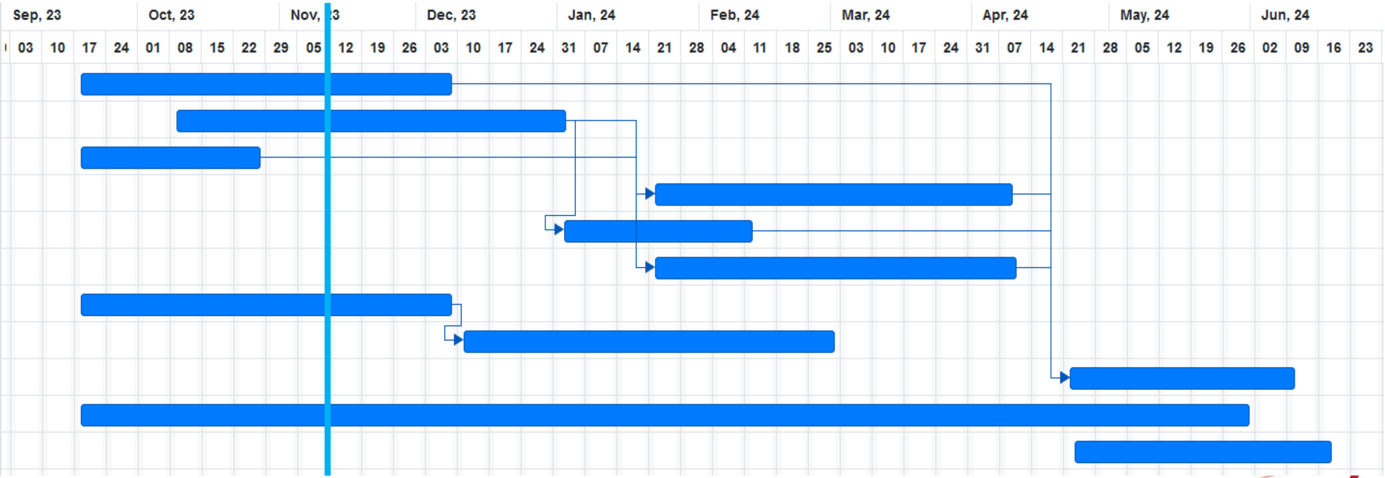
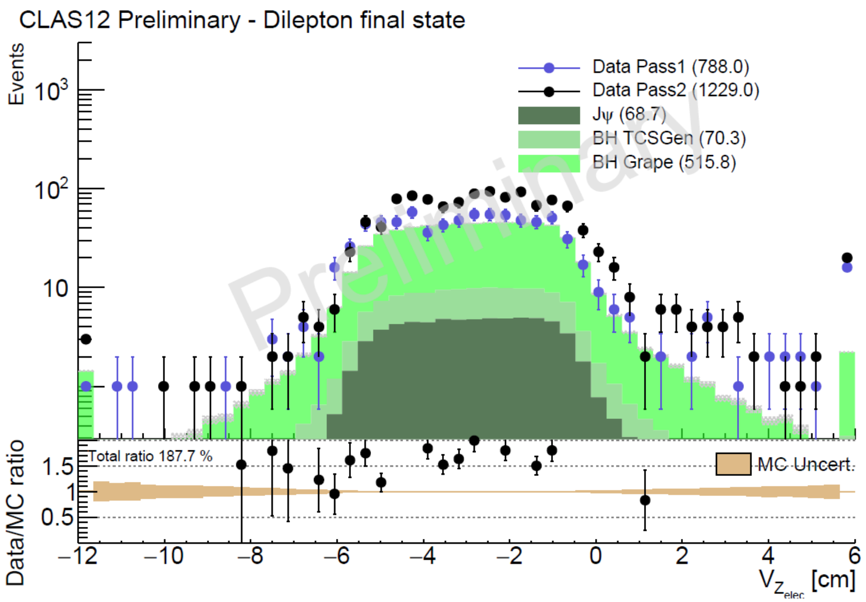
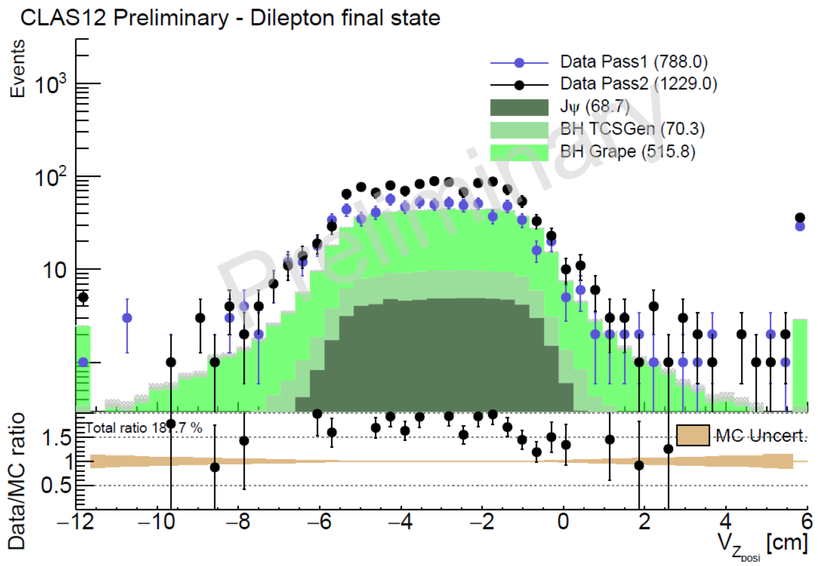


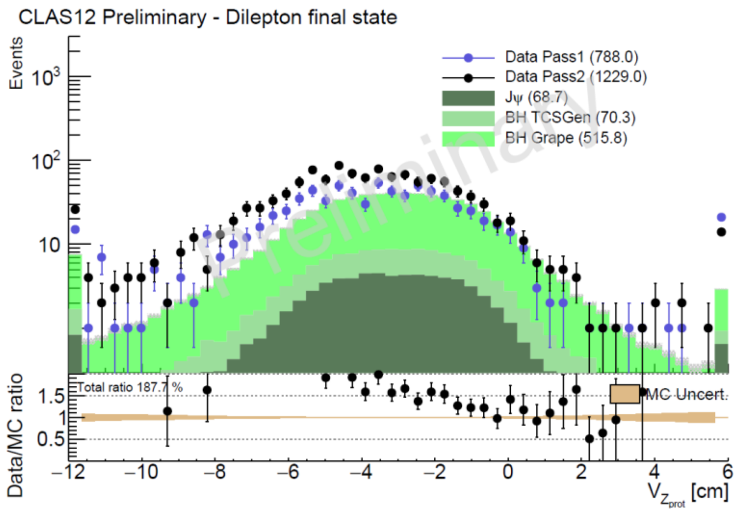
Back-up

II - Pass 2 data: first look at Spring 2019

Spring 19 Pass 2: Vertices







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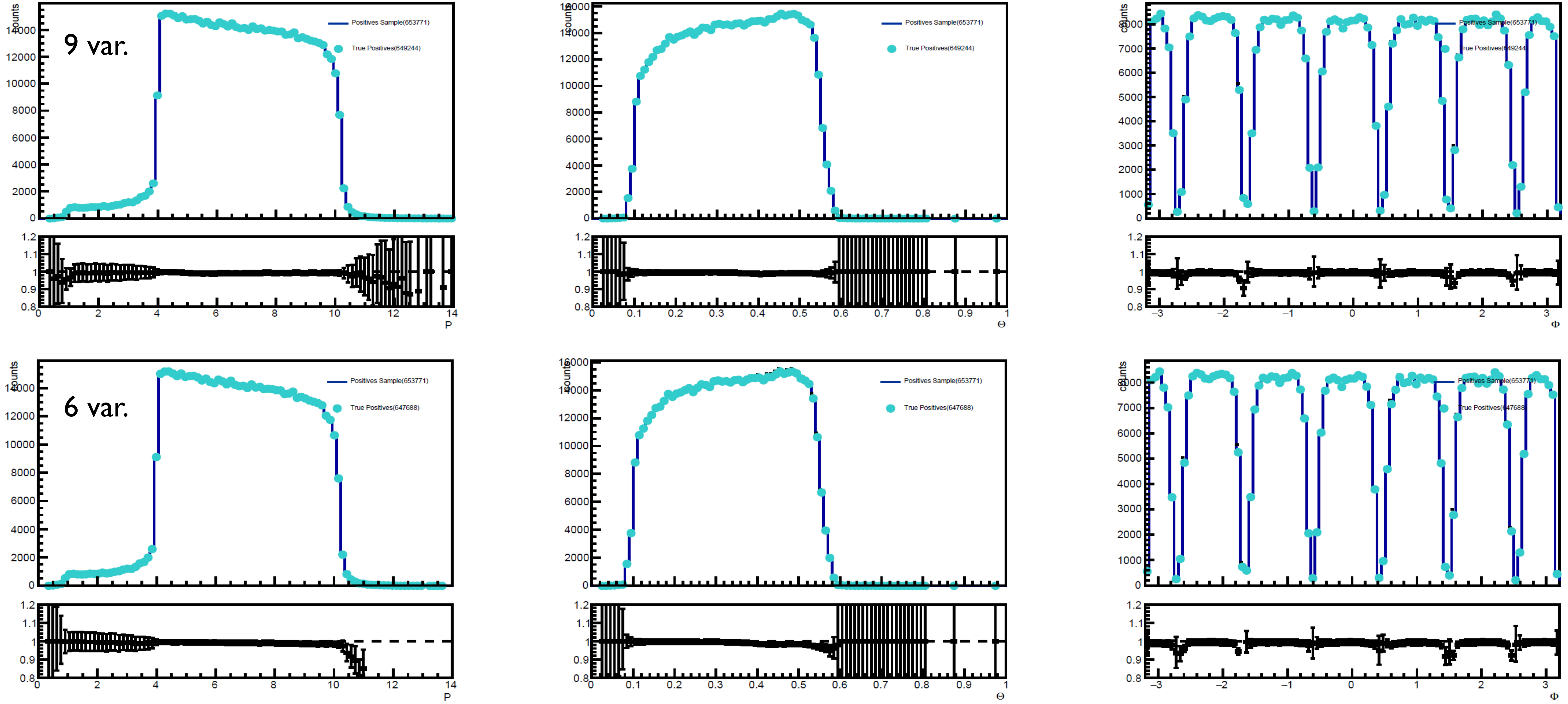
III - Lepton PID using machine learning

Validation - Efficiency



Validation - Contamination