# J/ψ Near-Threshold Photoproduction off the Proton and Neutron with CLAS12

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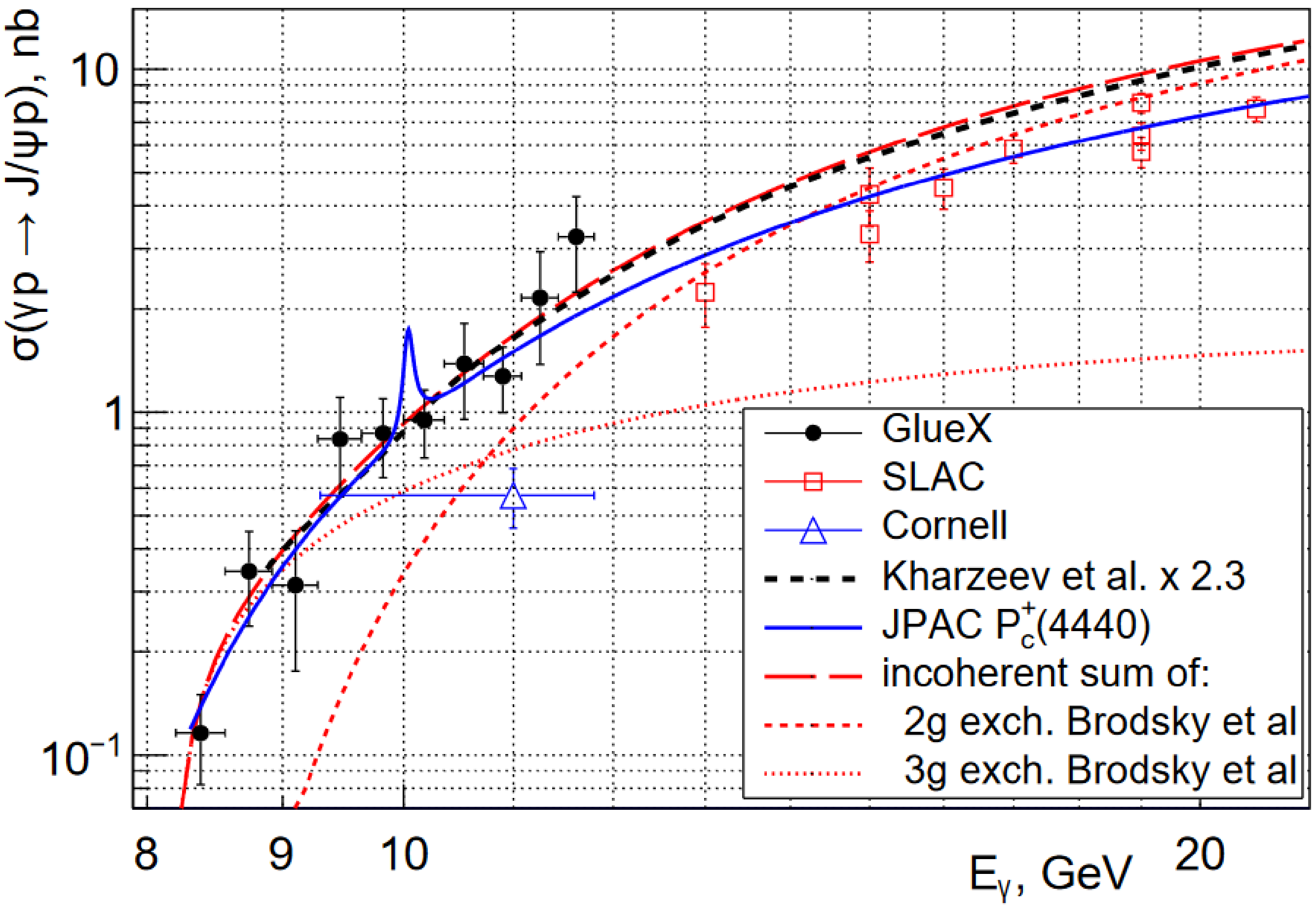
# J/ψ Near Threshold Photoproduction

- CLAS12 operates close to the 8.2 GeV J/ψ ($c\bar{c}$ meson) photoproduction threshold.
- Near threshold, all the valence quarks of the nucleon are predicted to participate in the reaction compared to one or two at higher energies [2].
- [3] relates the nucleon gluonic form-factor to the *t* dependency of the differential cross section.
- CLAS12 will make a first measurement of J/ψ photoproduction on the neutron.




Measurements of the J/ψ total cross section as a function of the photon beam energy and theoretical predictions scaled to GlueX data [1].

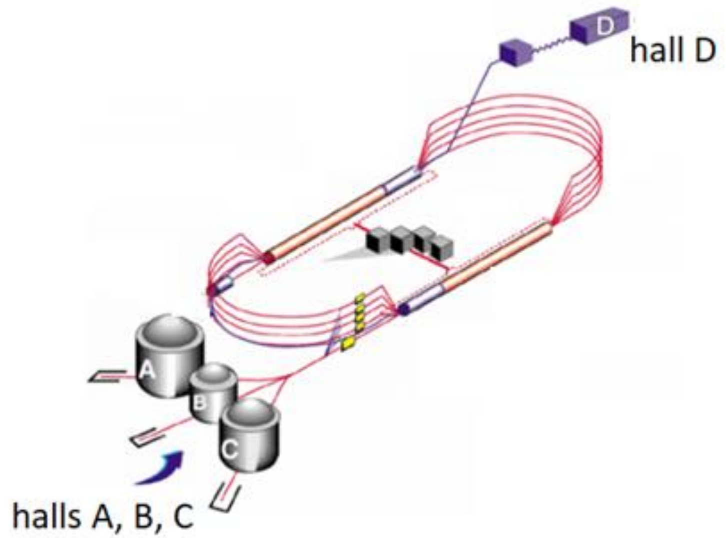

[1] A. Ali, *et. al.* (GlueX Collaboration), *Phys. Rev. Lett.* **123,** 072001 (2019).
[2] S. Brodsky, E. Chudakov, P. Hoyer, J. Laget, *Phys. Lett. B.* **498**, 23 (2001).
[3] L. Frankfurt, M. Strikman, Phys. Rev. D. 66, 031502 (2002)

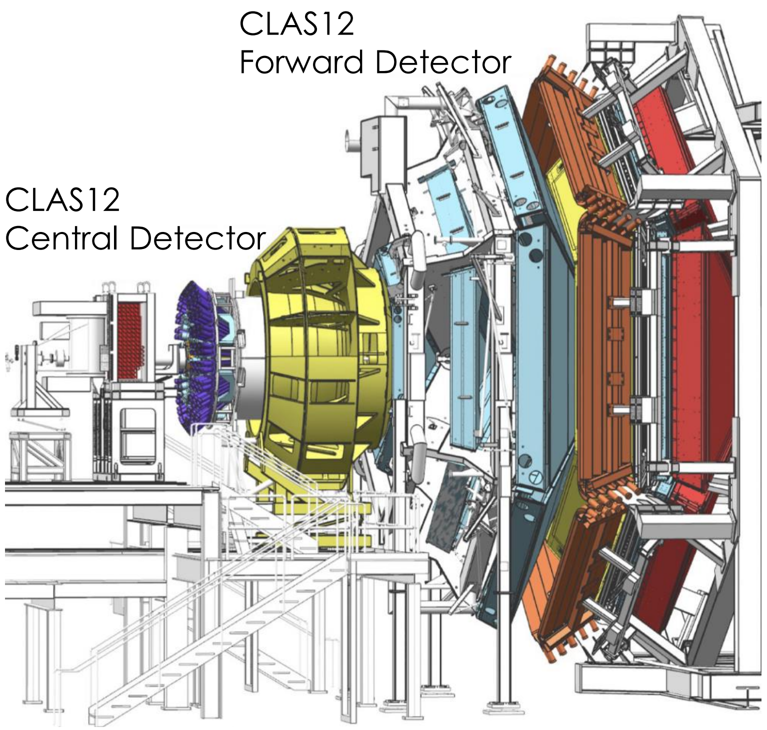
# The CLAS12 Detector

- The CLAS12 Detector is located in Jefferson Lab's Hall B, in Newport News, Virginia.
- The GlueX detector is located in Hall D.

# The CLAS12 Detector

- The CLAS12 Detector is located in Jefferson Lab's Hall B, in Newport News, Virginia.
- The recently upgraded CEBAF accelerator facility produces a 12 GeV electron beam, with beam energies up to 11 GeV delivered to Hall B.
- The Forward Detector has polar angle coverage of 5 to 35 degrees.
- The Central Detector has polar angle coverage of 35 to 125 degrees.



# Experiment Overview

- J/ψ decays to a lepton pair, with $l^+l^-$ denoting either $e^+e^-$ or $\mu^+\mu^-$.

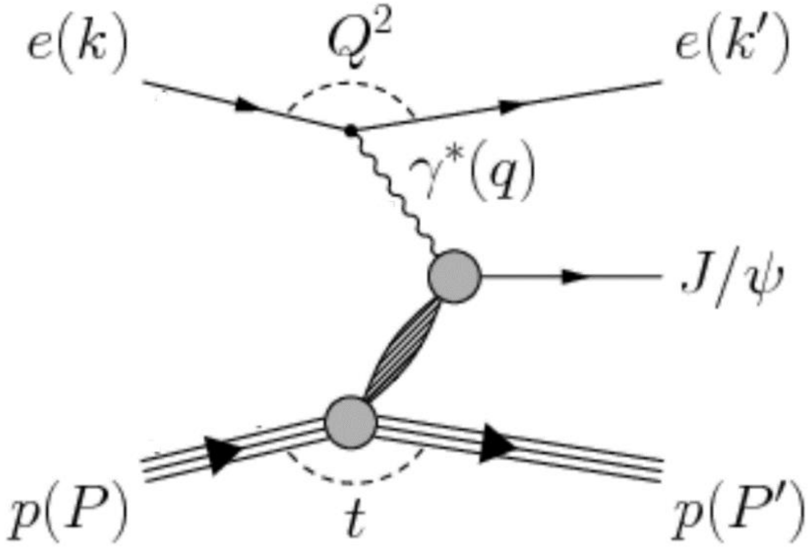
- CLAS12 took data with both a proton and a deuterium target offering several potential final states:

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

$$e\ p_{bound} \rightarrow e' J/\psi\ p \rightarrow (e')l^+l^-p$$

$$e\ n_{bound} \rightarrow e' J/\psi\ n \rightarrow (e')l^+l^-n$$

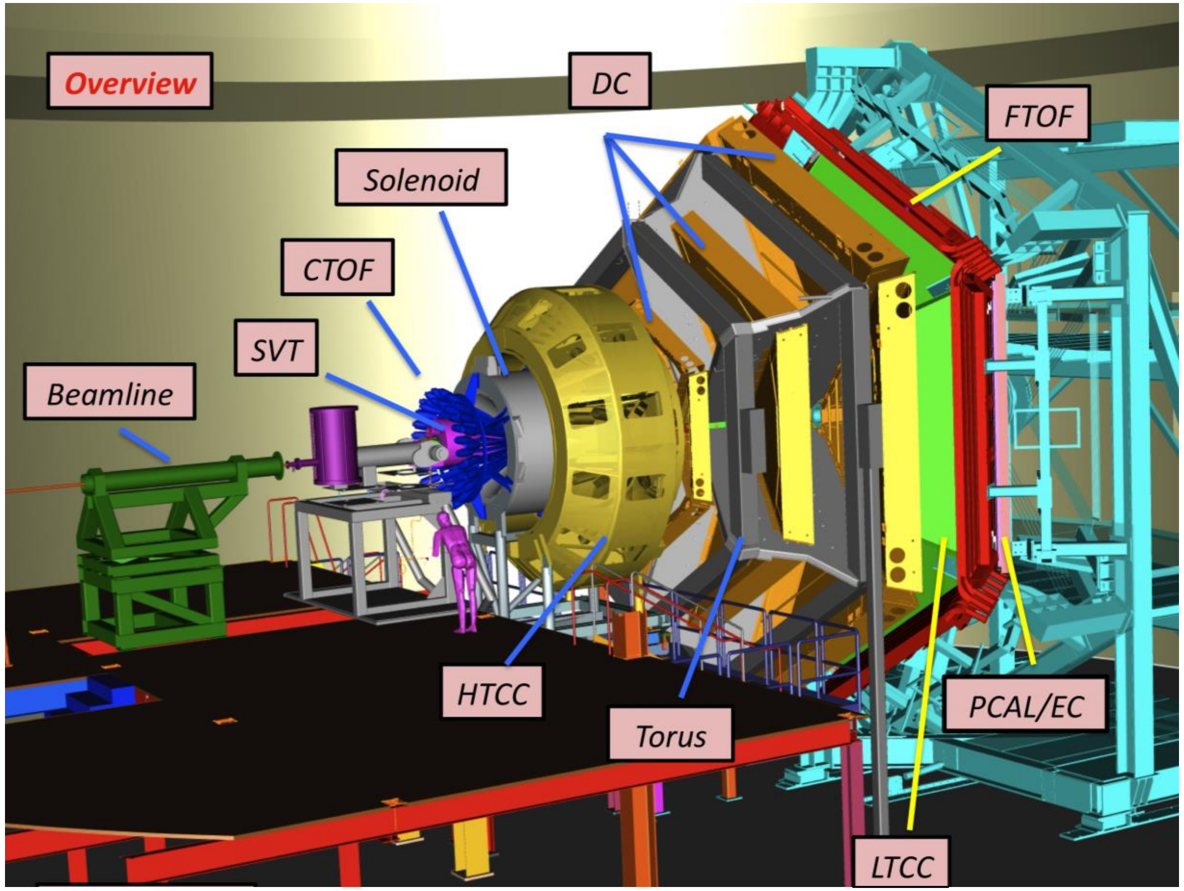
$$ed \rightarrow e' J/\psi\ d \rightarrow (e')l^+l^-d$$




J/ψ quasi-real photoproduction on a proton target

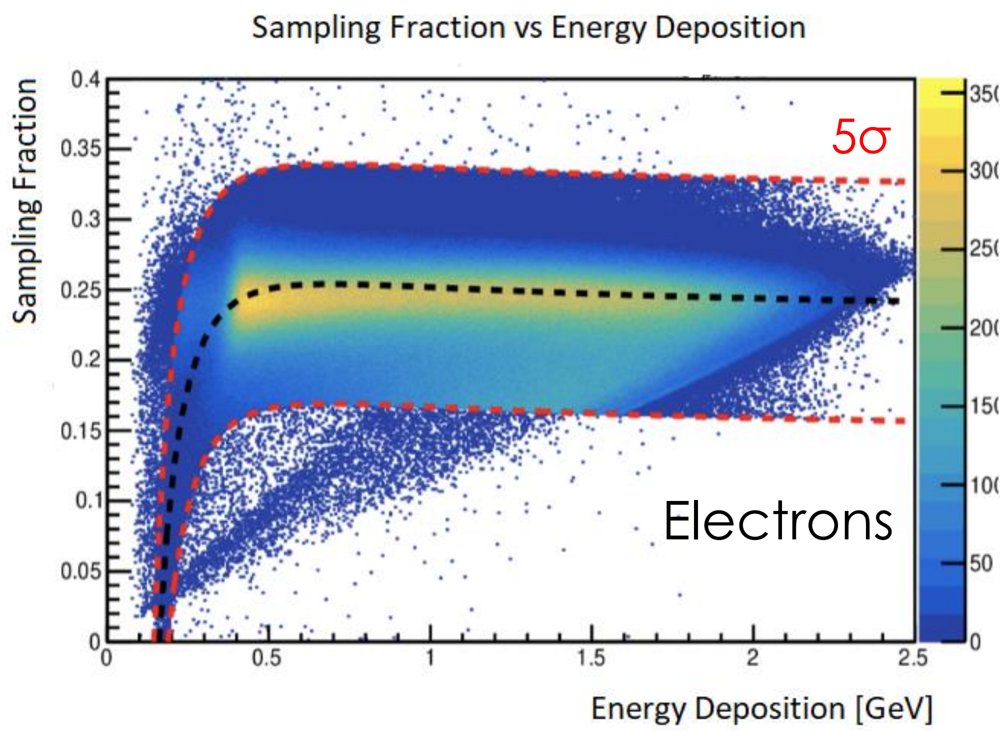
# CLAS12 Forward Detector

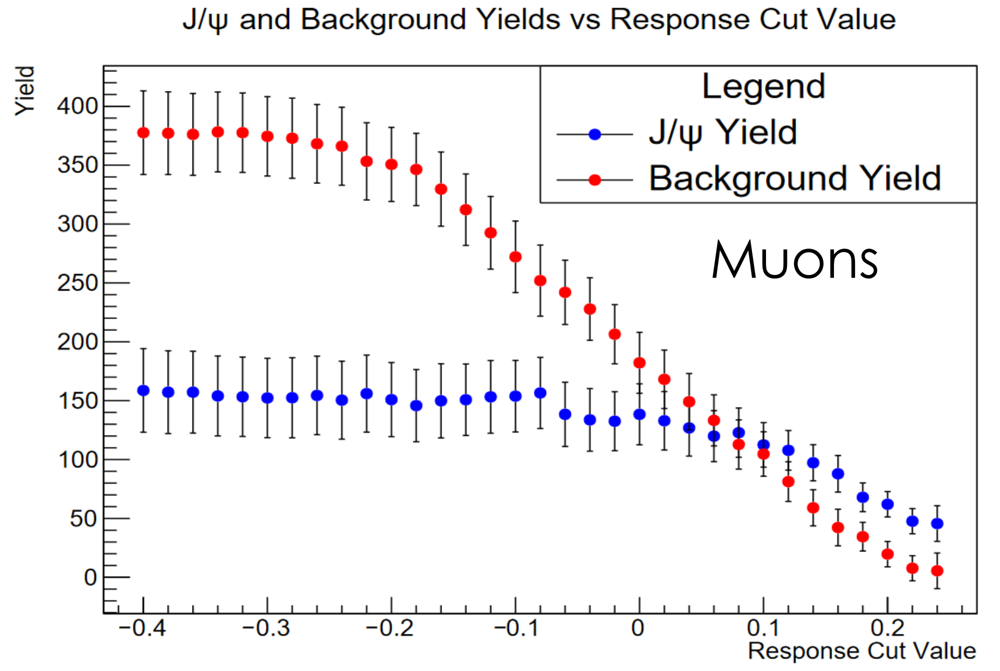
- All final state particles are detected with the Forward Detector.
- The High Threshold Cherenkov Counter (HTCC) was built to identify electrons.
- The tracking system and Drift Chambers (DC) measure the charge and momentum of particles.
- The Forward Time Of Flight (FTOF) counters were designed to resolve charged hadrons.
- The Electromagnetic Calorimeters (PCAL and EC) are used to detect neutrals and identify electrons and muons.



# Lepton Identification

- Electrons and positrons are required to produce a signal in the HTCC and high energy deposition in the calorimeter. Their main source of background is due to high momentum pions firing the HTCC.
- Muons are minimum ionising particles which we select with cuts on their energy deposition in the calorimeters. These are susceptible to a significant charged pion contamination.
- We refine leptons PID by training a machine learning classifier on variables from several CLAS12 detector subsystems to remove the pion background.
- The PID process is then reduced to a cut on the response of the classifier.

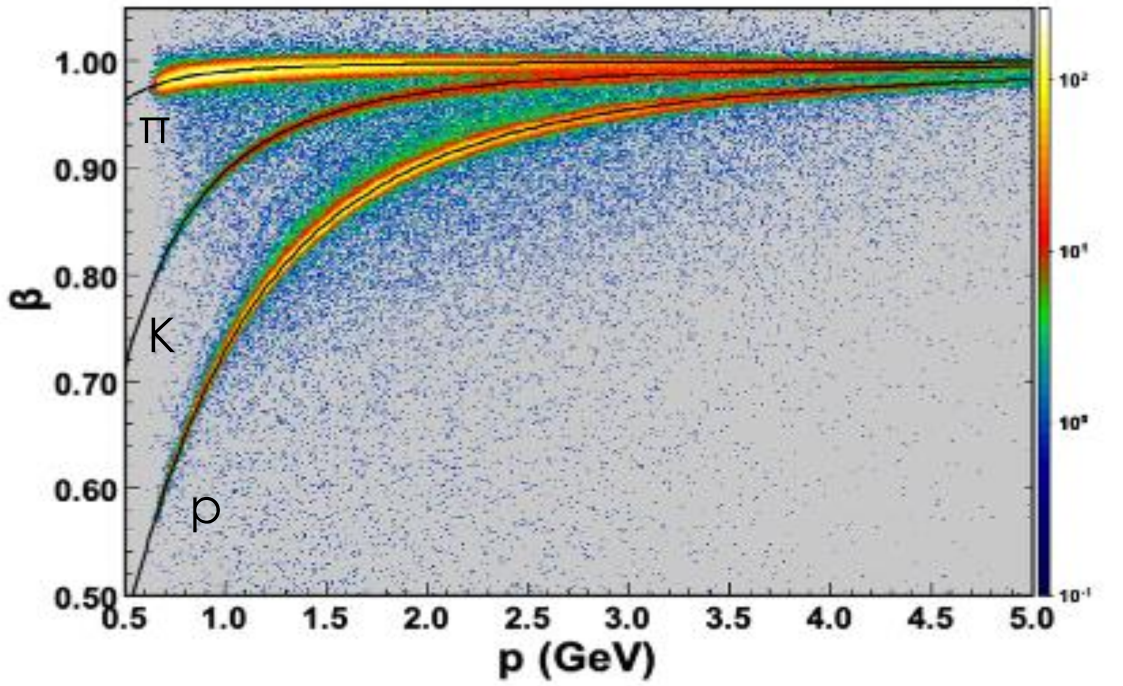


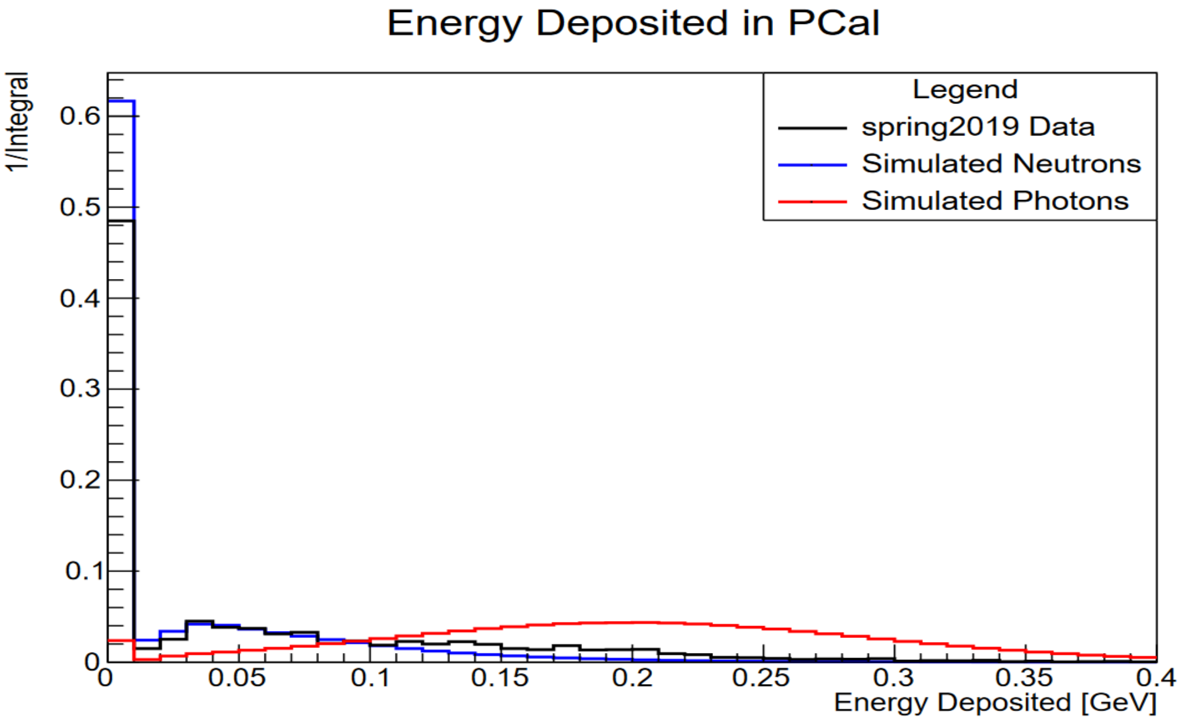



# Hadron Identification

- For protons (and charged hadrons in general) a cut is made on the Beta versus Momentum parametrization.

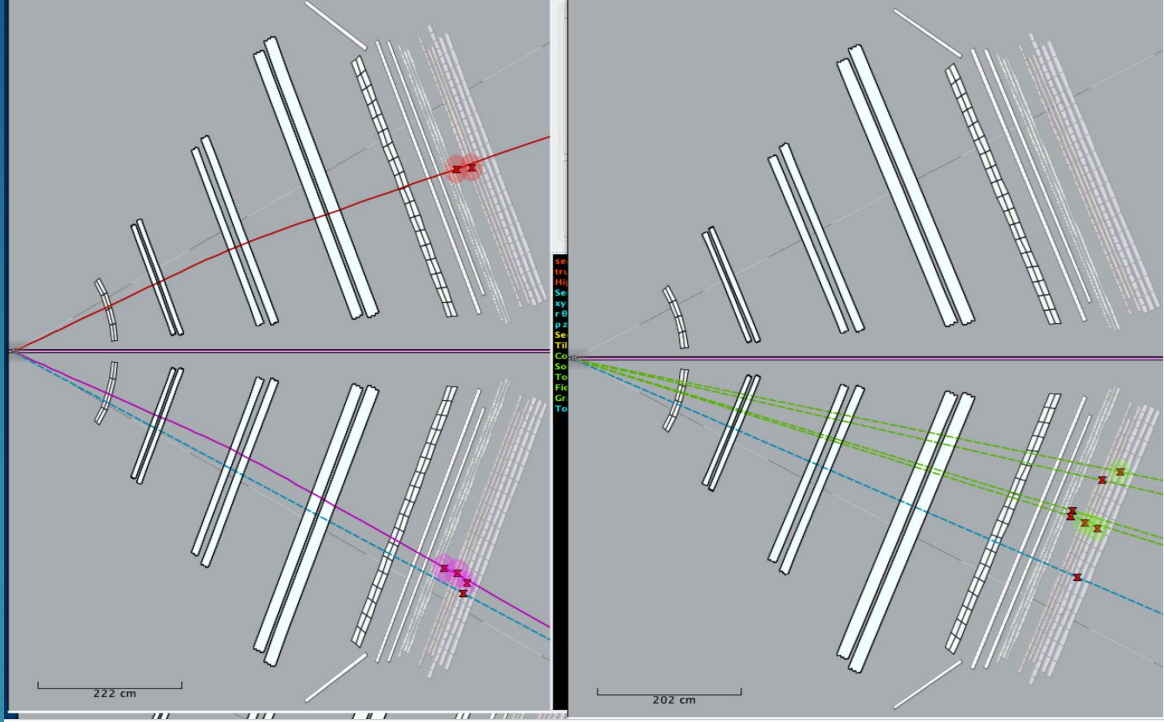
- For neutrons we require a neutral charge. No further cuts were applied as there isn't any strong evidence of photon contamination.

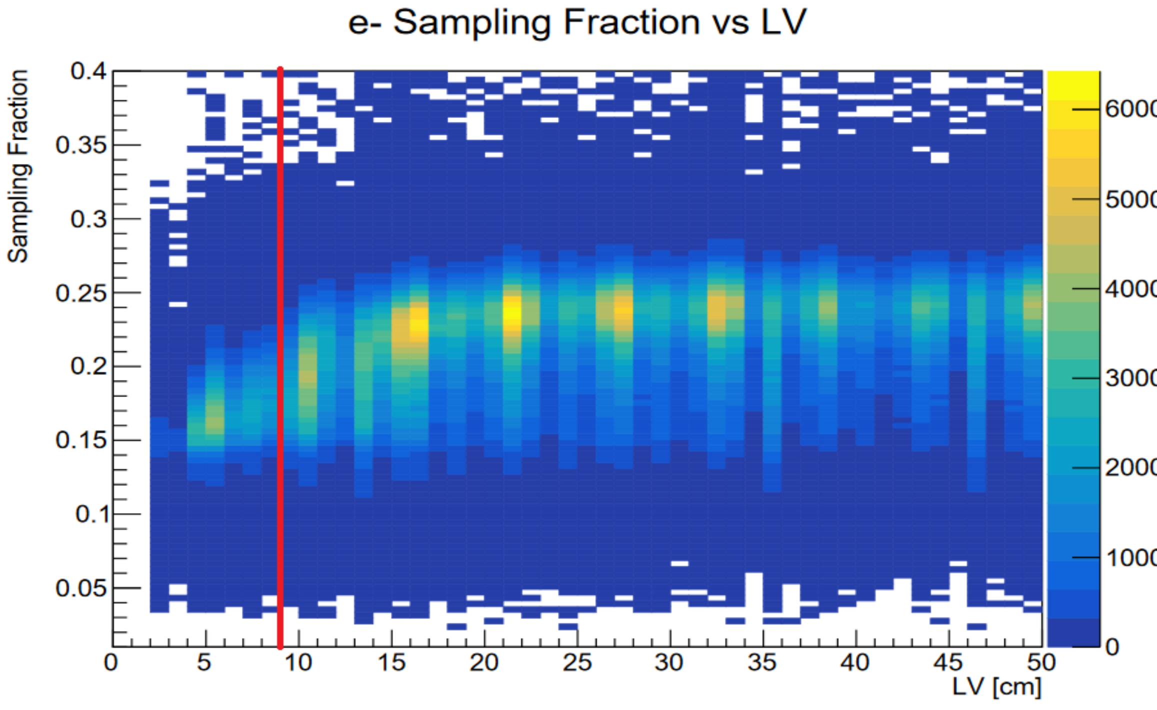


# Particle Corrections

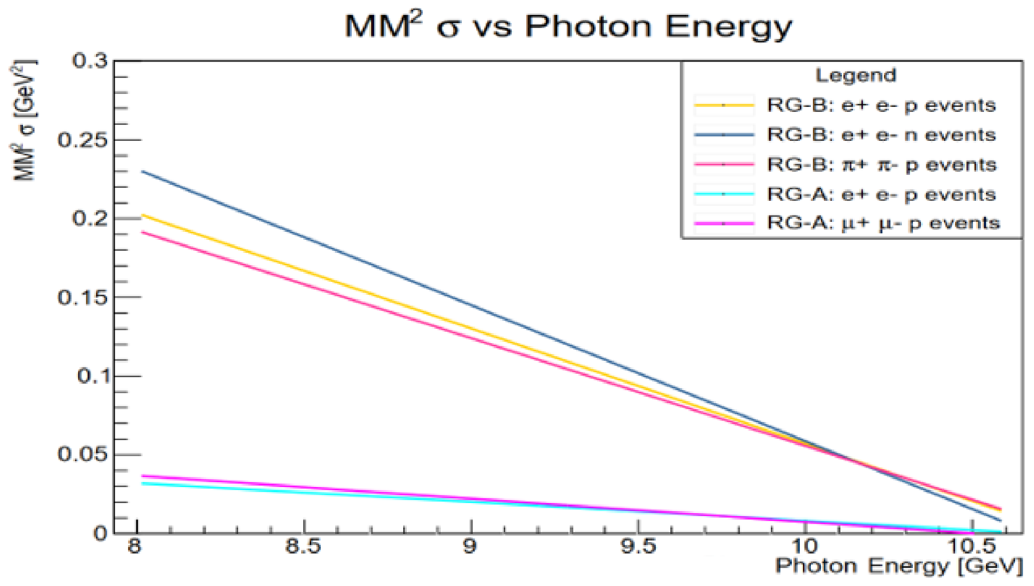
- Radiative corrections for electrons/positrons add the momentum of radiated photons.
- Neutrons also produce secondary clusters. These are removed by taking the earliest neutral in a given sector.
- The reconstructed path length for neutrons is corrected for a more accurate calculation of the momentum.
- We apply fiducial cuts to remove e+/e- hits close to the edges of the PCAL where the shower is not fully contained within the calorimeter.
- Fiducial cuts in the drift chambers are applied to electrons, positrons, protons and muons by removing hits at the edge of the layers.

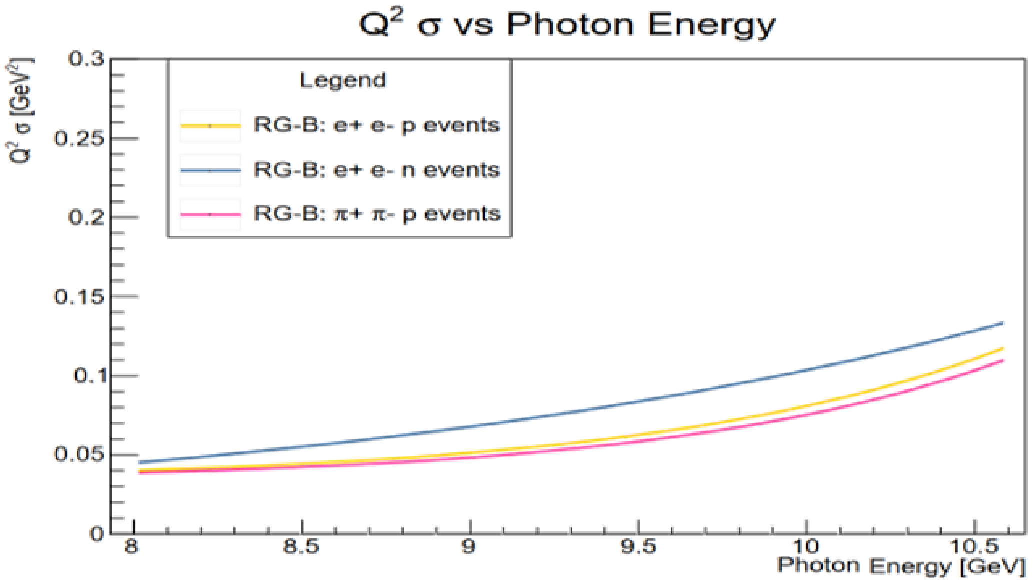


# Initial Event Selection

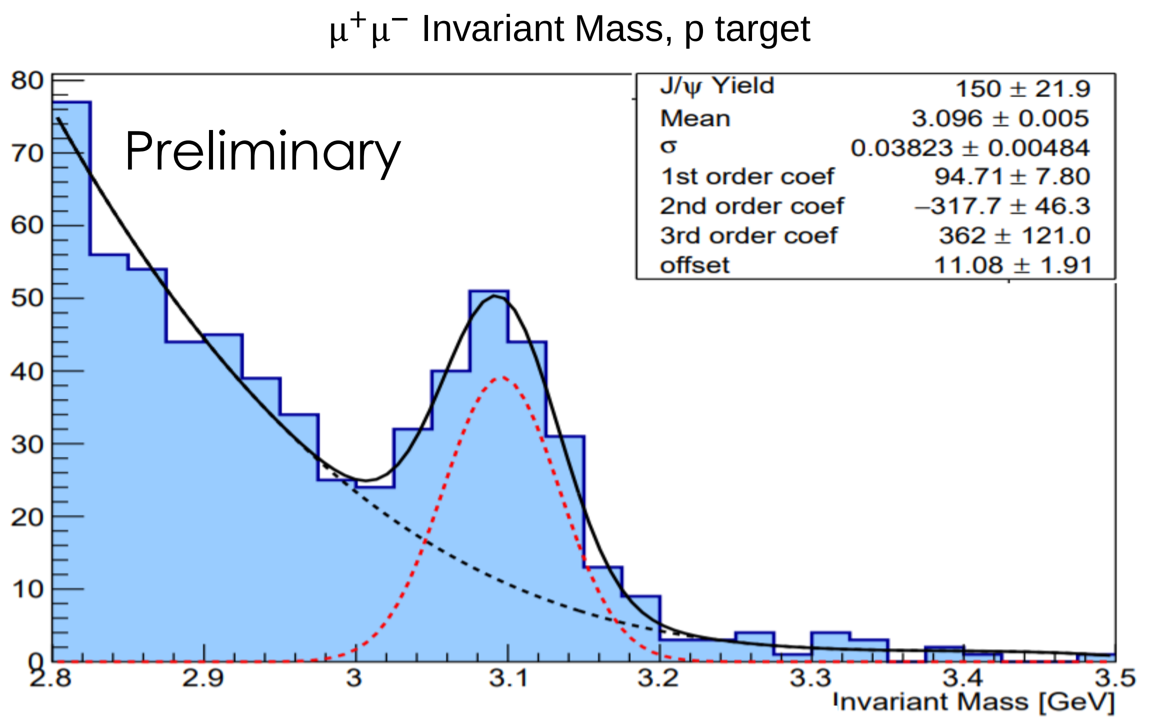
- We minimize $Q^2$ to select only quasi-real photoproduction events.
- Similarly, we want the missing mass close to the mass of the scattered electron (which is effectively 0).
- The widths of these distributions can be parametrised as a function of the photon energy.
- The labels RG-A and RG-B refer to a proton or deuterium target respectively.

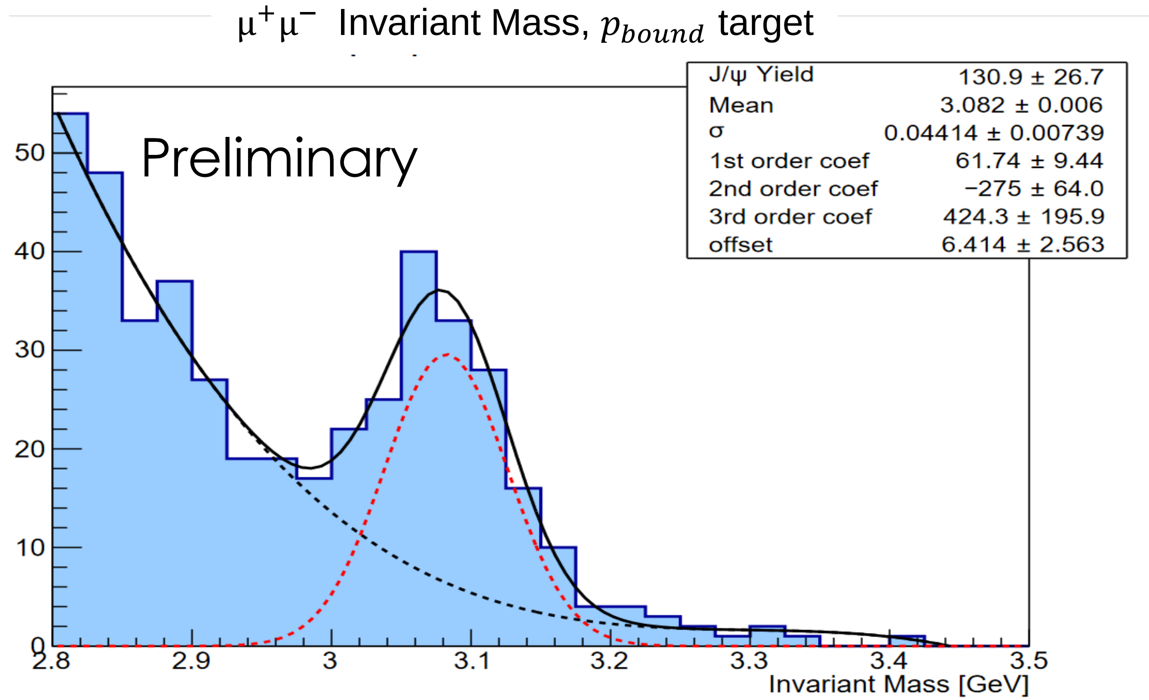


# Di-Muon Invariant Mass

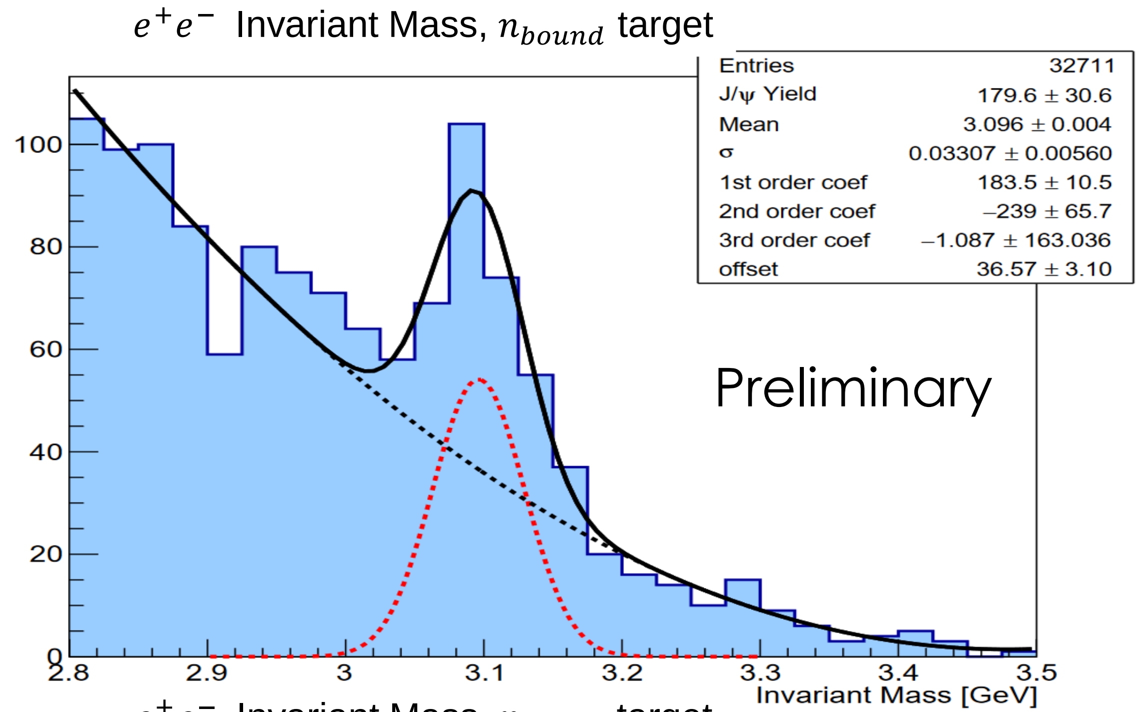
- Plotted here are the invariant mass distributions of:
  - $\mu^+\mu^-$ produced on a proton target.
  - $\mu^+\mu^-$ produced on a bound proton in the deuteron target.
- These are preliminary and produced with only a subset of all available data.

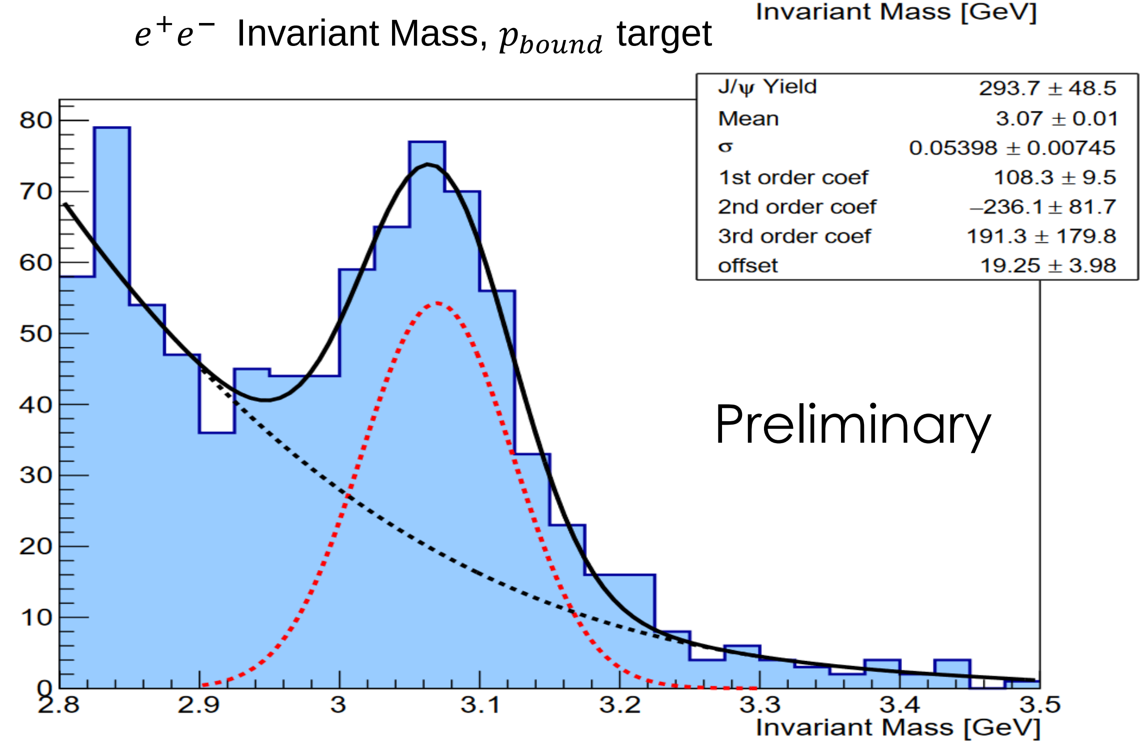


# Di-Electron Invariant Mass

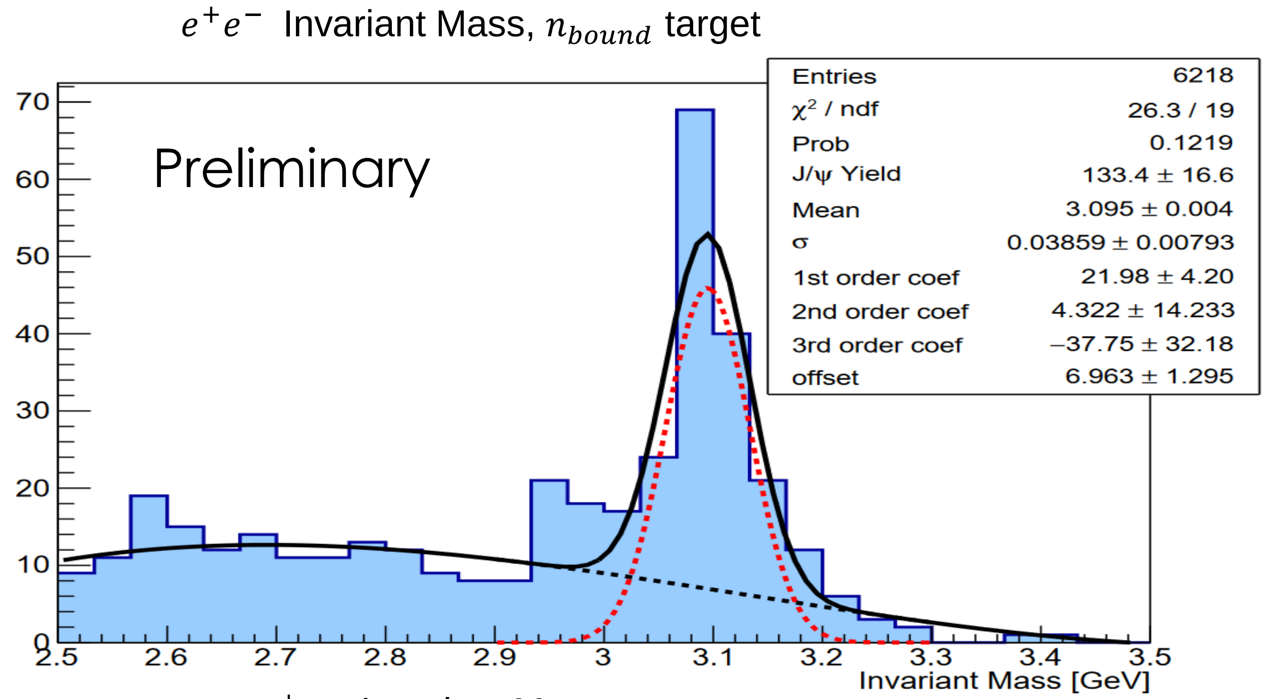
- Plotted here are the invariant mass distributions of:
  - $e^+e^-$ produced on a bound neutron in the deuteron target.
  - $e^+e^-$ produced on a bound proton in the deuteron target.
- The decrease in yield in the neutron channel compared to the proton channel is due to a lower detection efficiency for neutrons.
- These are preliminary and produced with only a subset of all available data.

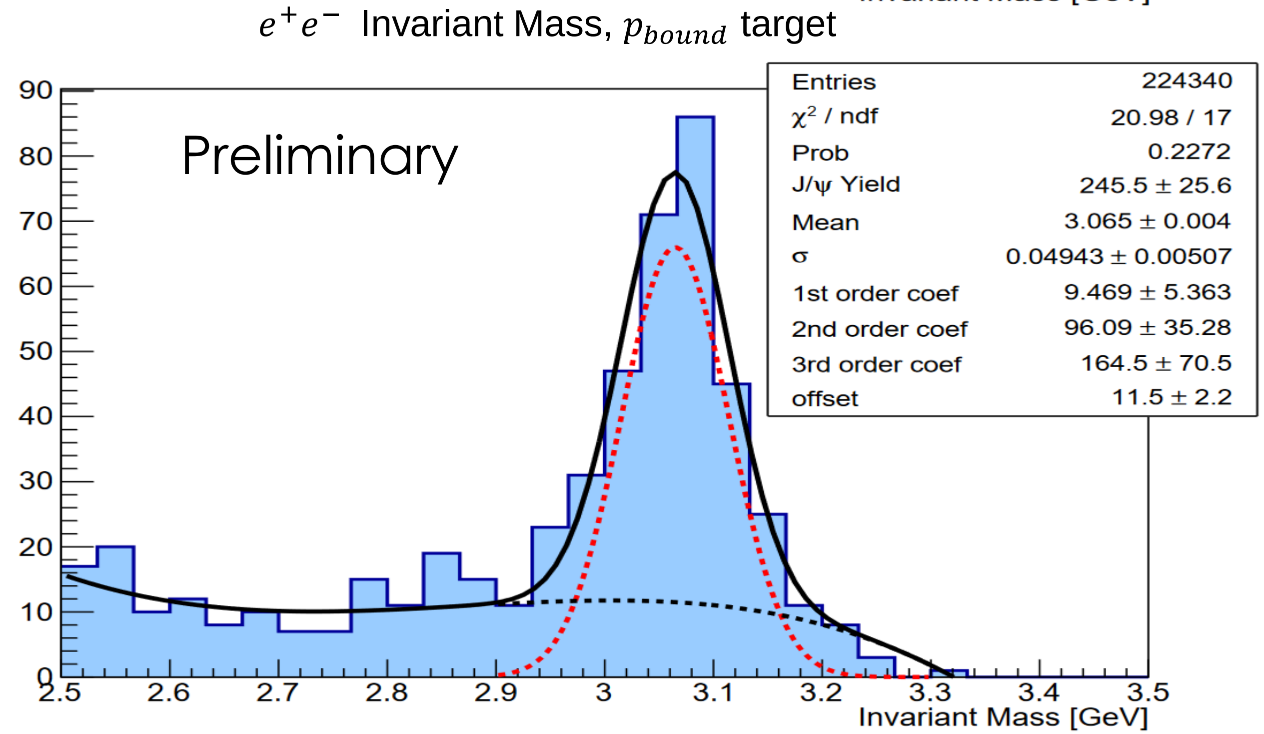


# ML Based Reaction ID

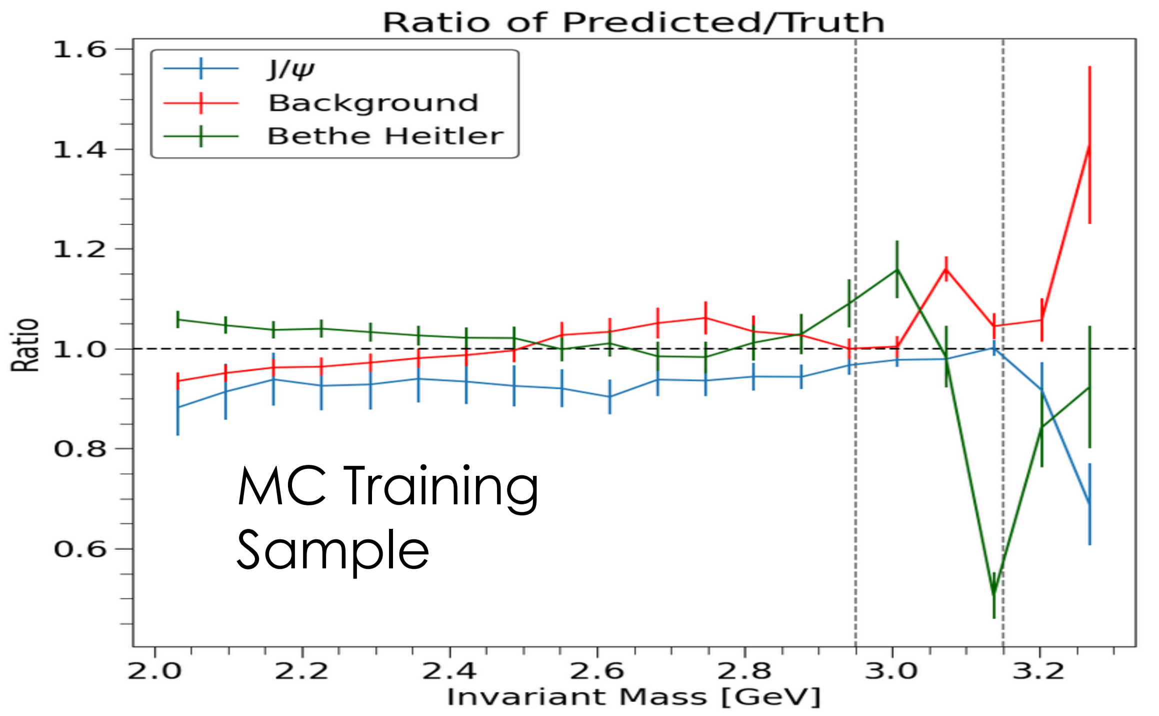
- We can extract a very clean $J/\psi$ signal using a neural network trained on P/Theta/Phi of our final state particles.
- The training samples are:
  - $J/\psi$ simulation.
  - Mismatched particles from different events of the above.
- In practice we need Bethe Heitler for normalisation.

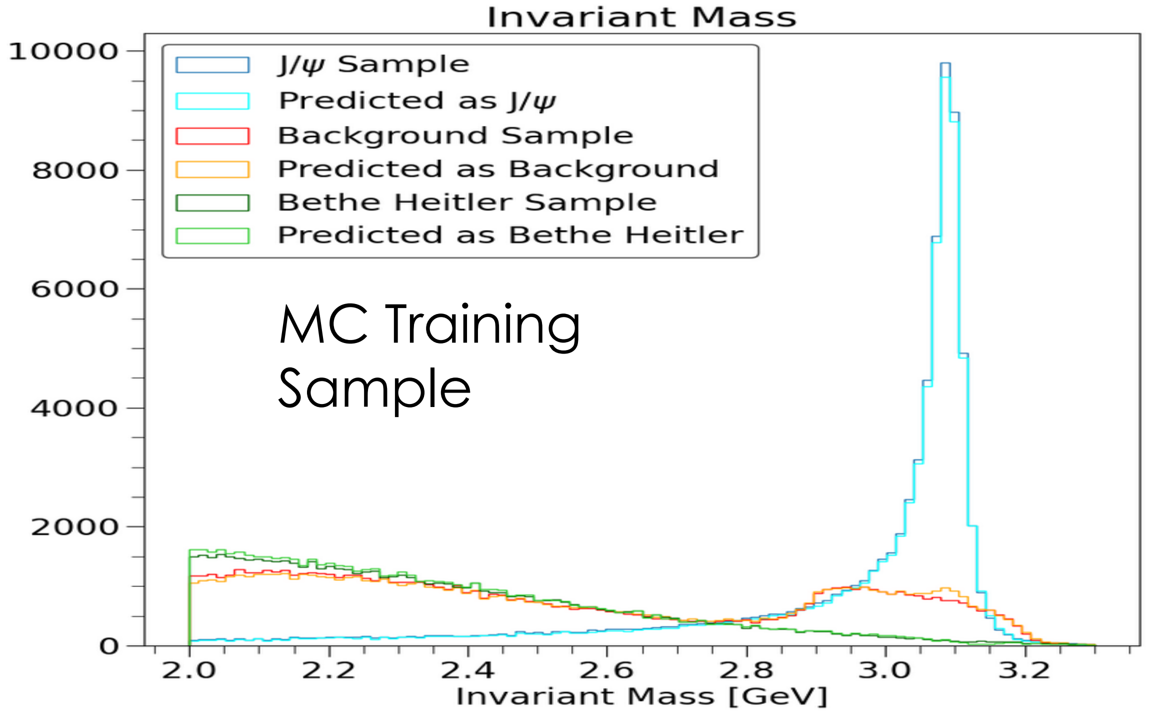


# Multiple Reactions

- Bethe Heitler has different kinematics to $J/\psi$ and is removed by the classifier shown in the previous slide.
- We can train a classifier to ID 3 reactions:
  - J/psi as before
  - Bethe Heitler photo/electroproduction
  - Mismatched particles from events in both above
- The principal can be applied to any analysis to disentangle different physical processes and sources of background.
- This is very much work in progress and we still have to validate this on data taken with CLAS12.



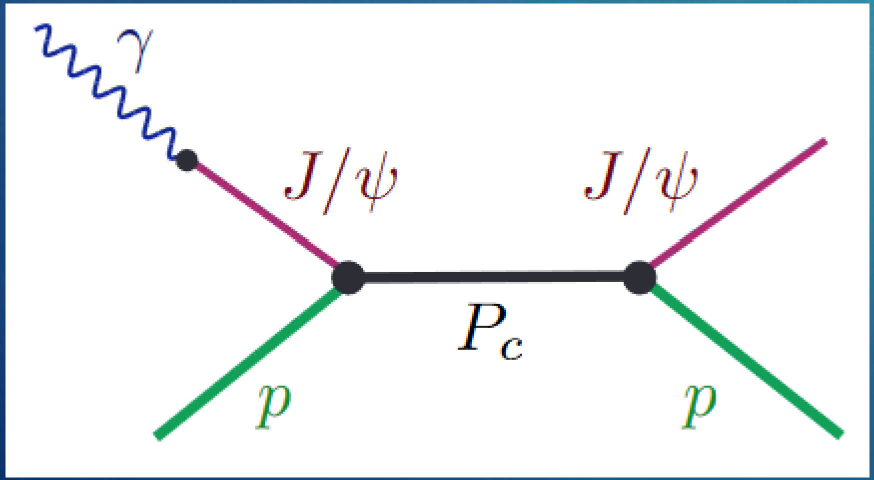
# Conclusion

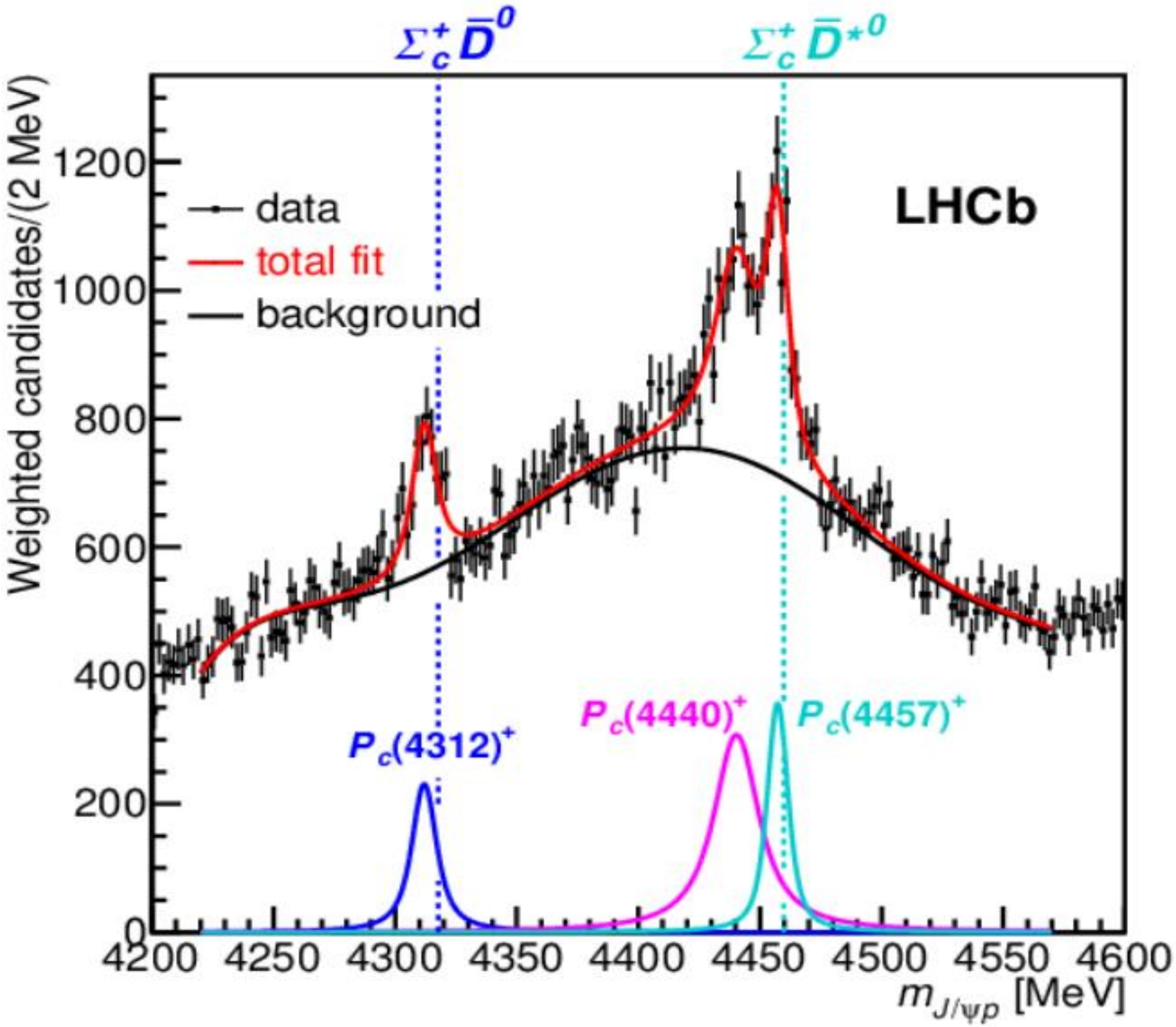
- The total and differential $J/\psi$ photoproduction cross section provide unique insight on the $J/\psi$ production mechanism and the nucleon gluonic form factor.
- CLAS12 will make a first measurement of the $J/\psi$ photoproduction cross section ratio on proton and neutron.
- The analyses aiming for these measurements are ongoing and well developed.
- Next: total and differential cross sections for the proton and deuterium targets.

# Backup Slides

# $P_C^+$ resonances with CLAS12

- CLAS12 should be able to place upper limits on the branching fraction $\mathrm{B}(P_C^+ \to J/\psi\ p)$ and $\mathrm{B}(P_C^+ \to J/\psi\ n)$.




The J/ψ p invariant mass distribution measured at the LHCb. Taken from:

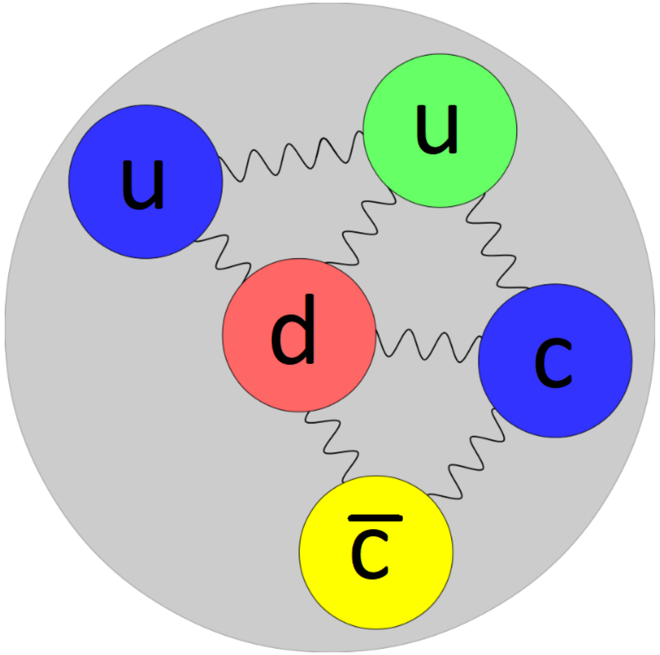
R. Aaij, *et. al.* (LHCb Collaboration), *Phys. Rev. Lett.* **122**, 22 (2019).

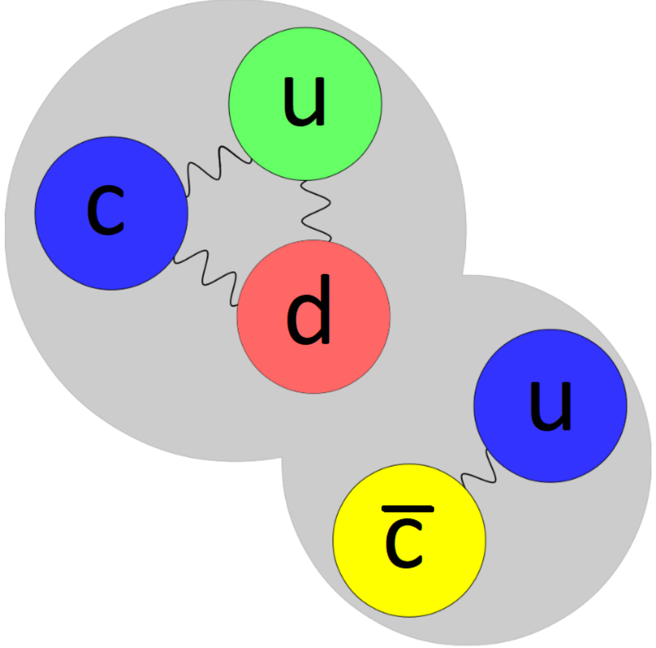
# $P_c^+$ Models

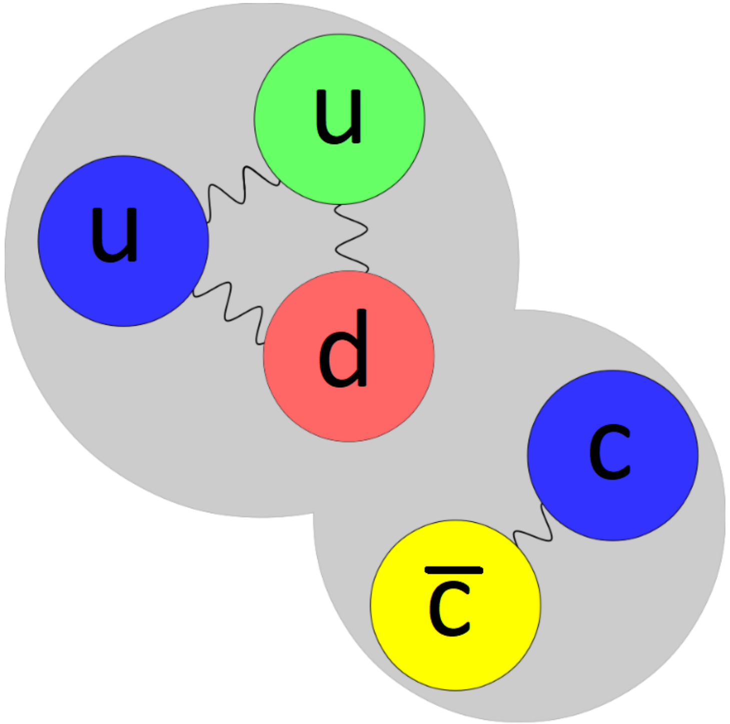
- Hadronic molecules: Weekly coupled charmed baryon and charmed meson.

- Hadro-charmonium states: compact bound $\mathbf{c\bar{c}}$ state and light quarks.

- Quarks in a bag: Two tightly correlated di-quarks and an anti-quark.

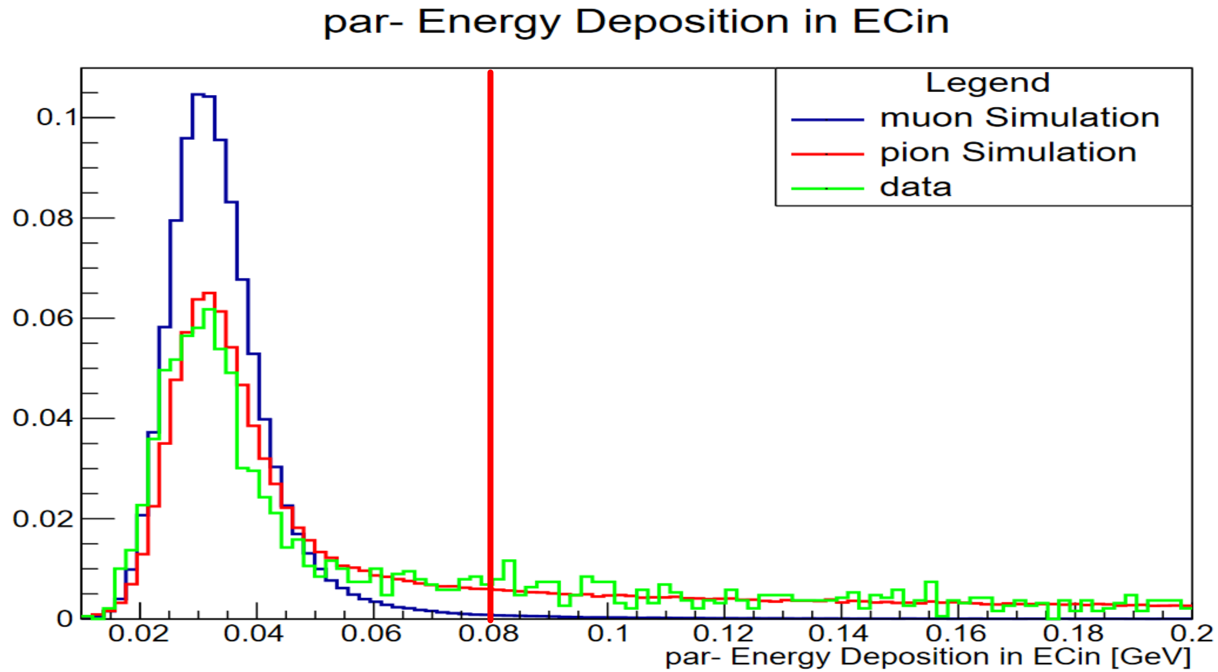


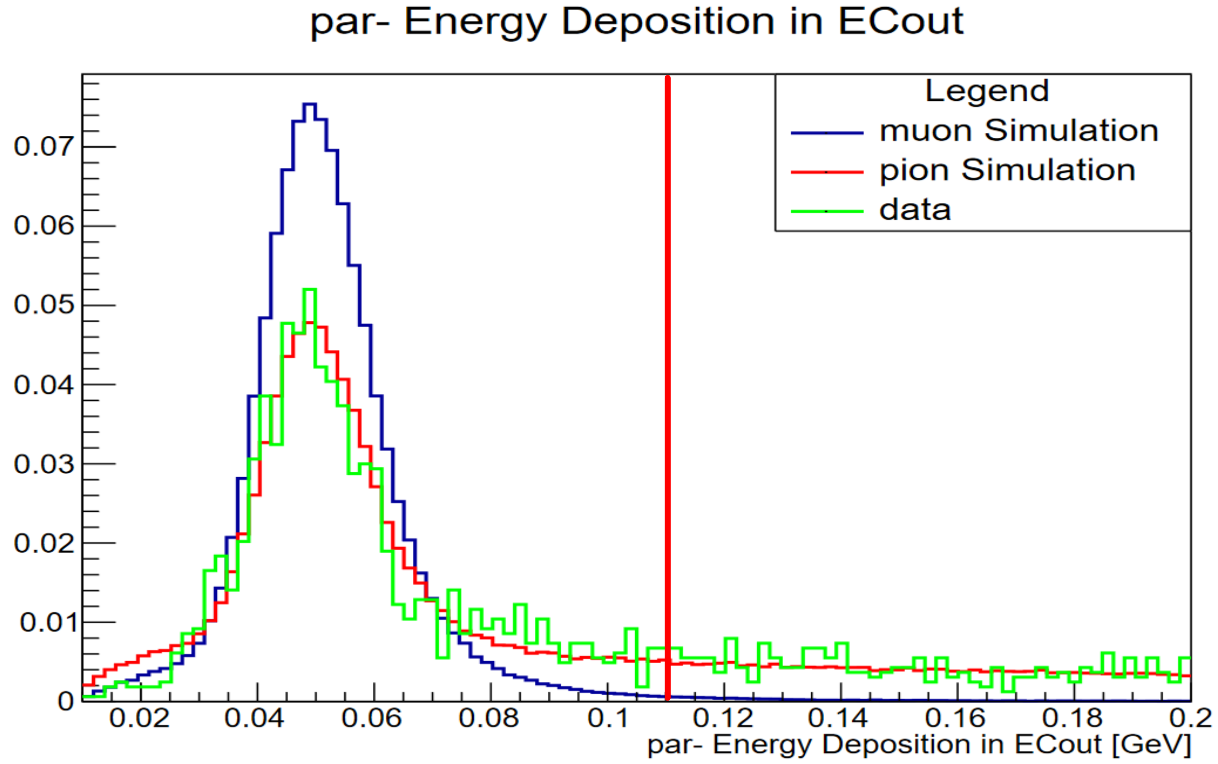



# Muon Identification

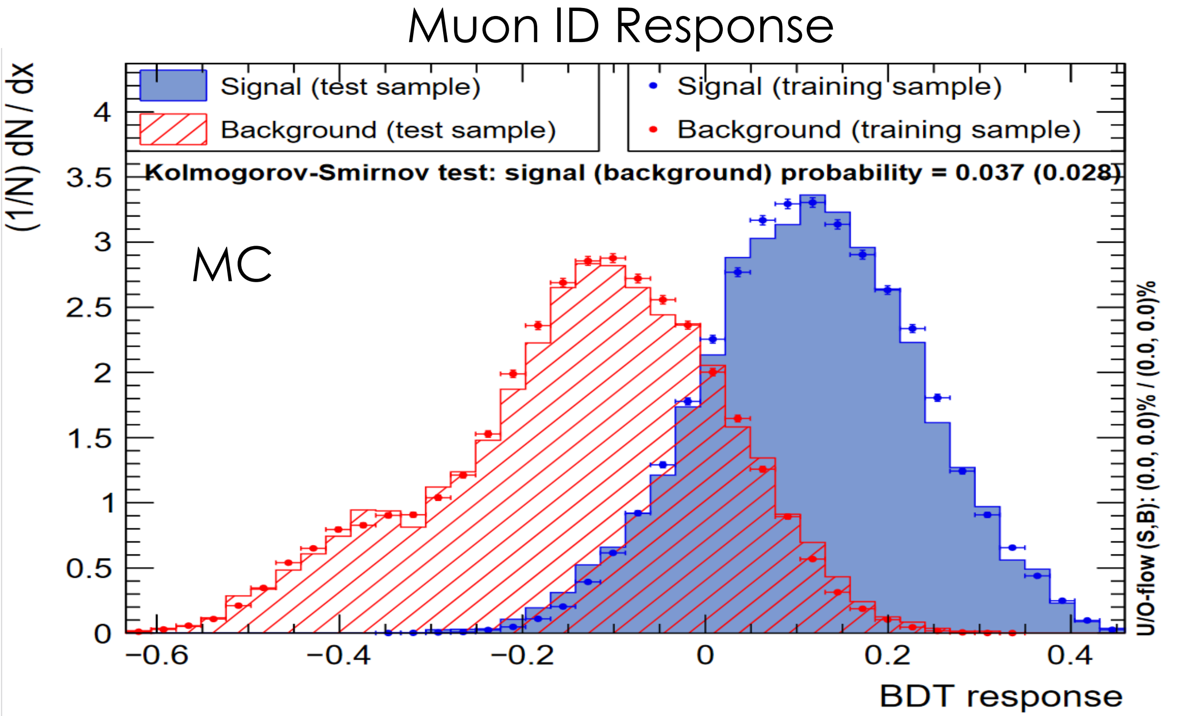
- Muons are minimum ionising particles which we select with cuts on their energy deposition in the CLAS12 calorimeters.
- Train a decision tree on MC data with training sample:
  - $\mu^+\mu^-$ past energy deposition cuts.
  - $\pi^+\pi^-$ past energy deposition cuts.

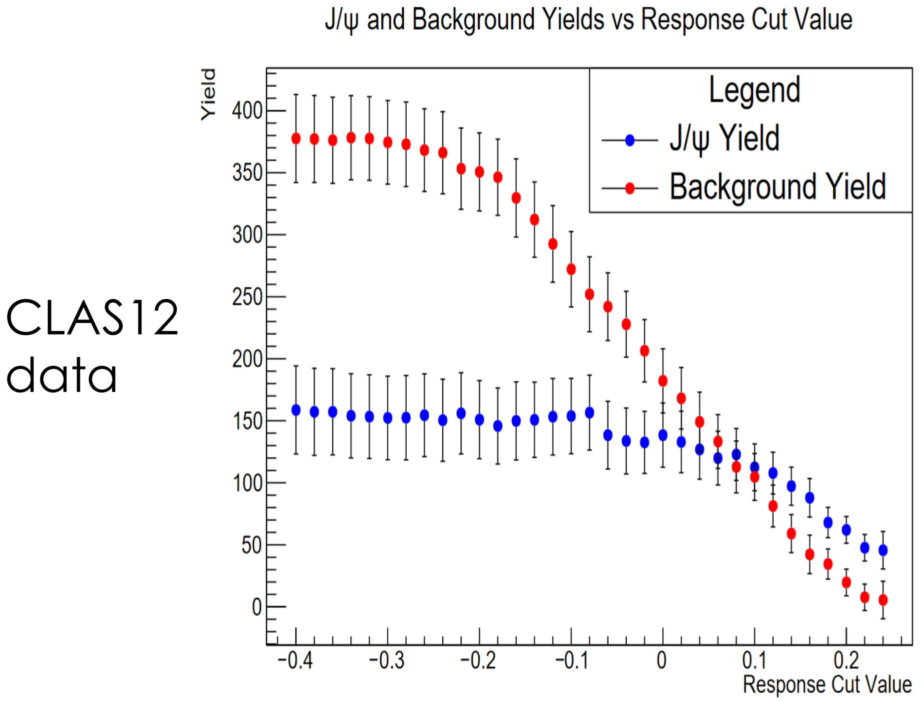


# Muon ID Response

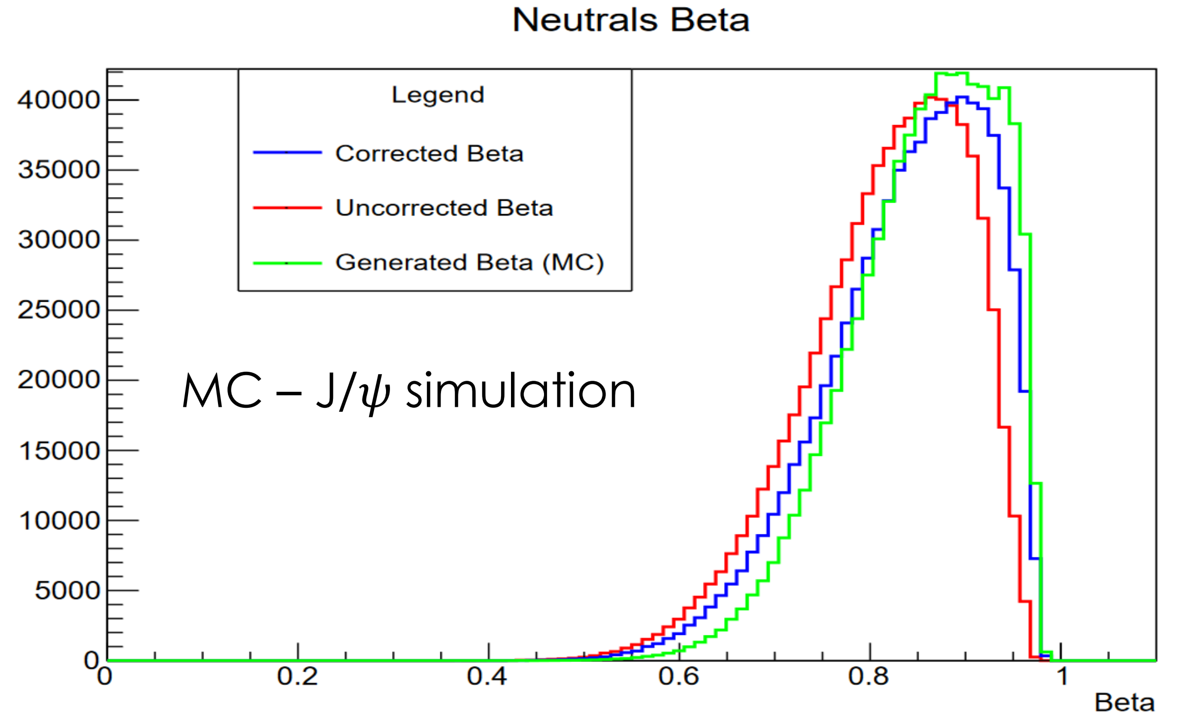
- The classifier output is given as a probability of being a signal event, called the response.
- The PID process is effectively reduced down to a cut on the response.
- This cut can be varied to study the systematic effect introduced by the classifiers.

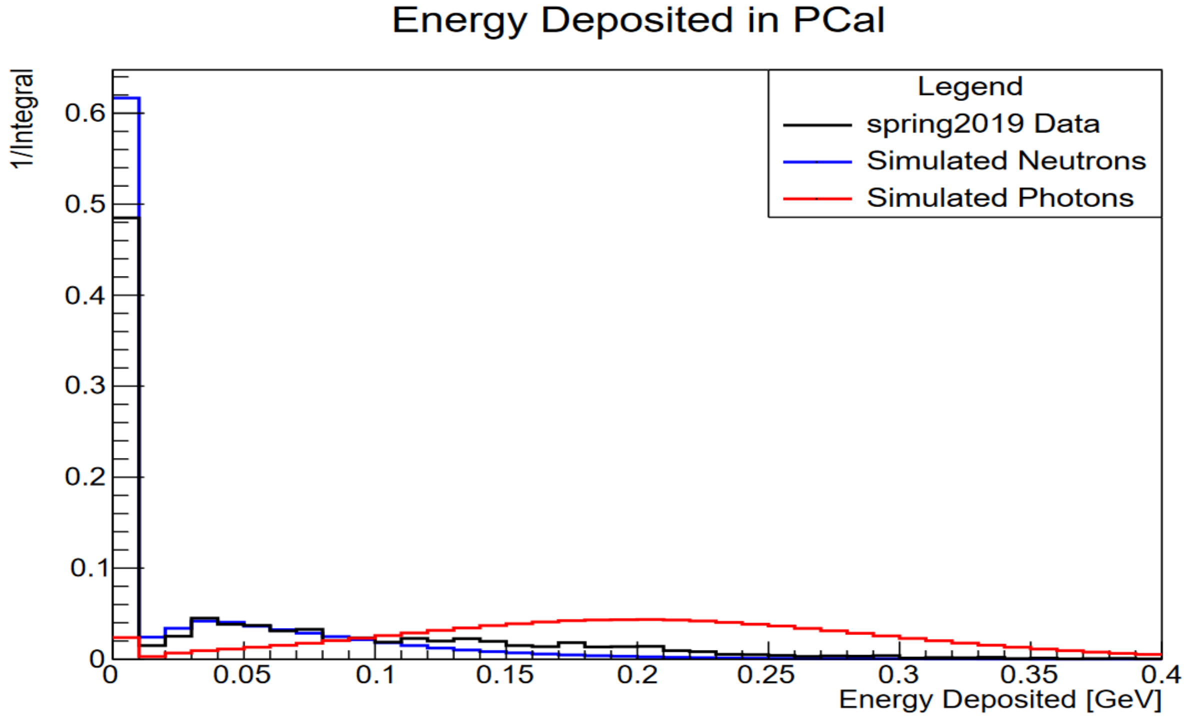


# Neutral ID

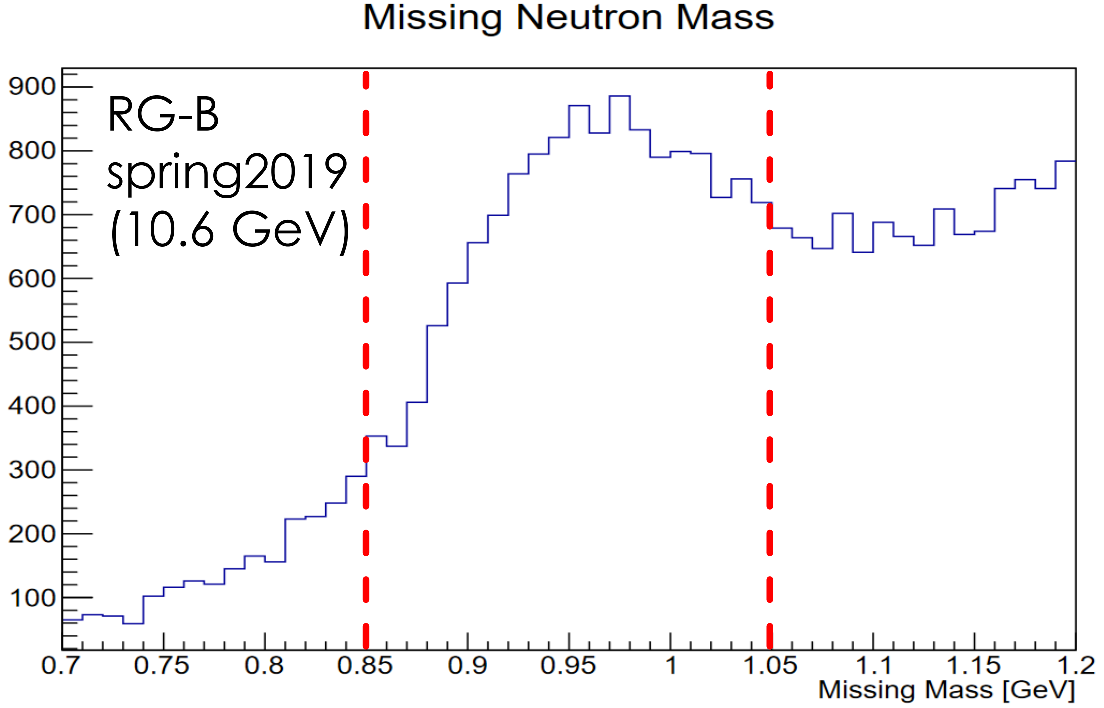
- We have neutrons with high beta, making it hard to cut on Beta to ID neutrals.
- From simulation however it doesn't look like we have large photon contamination past our exclusivity cuts.
- We therefore don't apply any neutral PID.

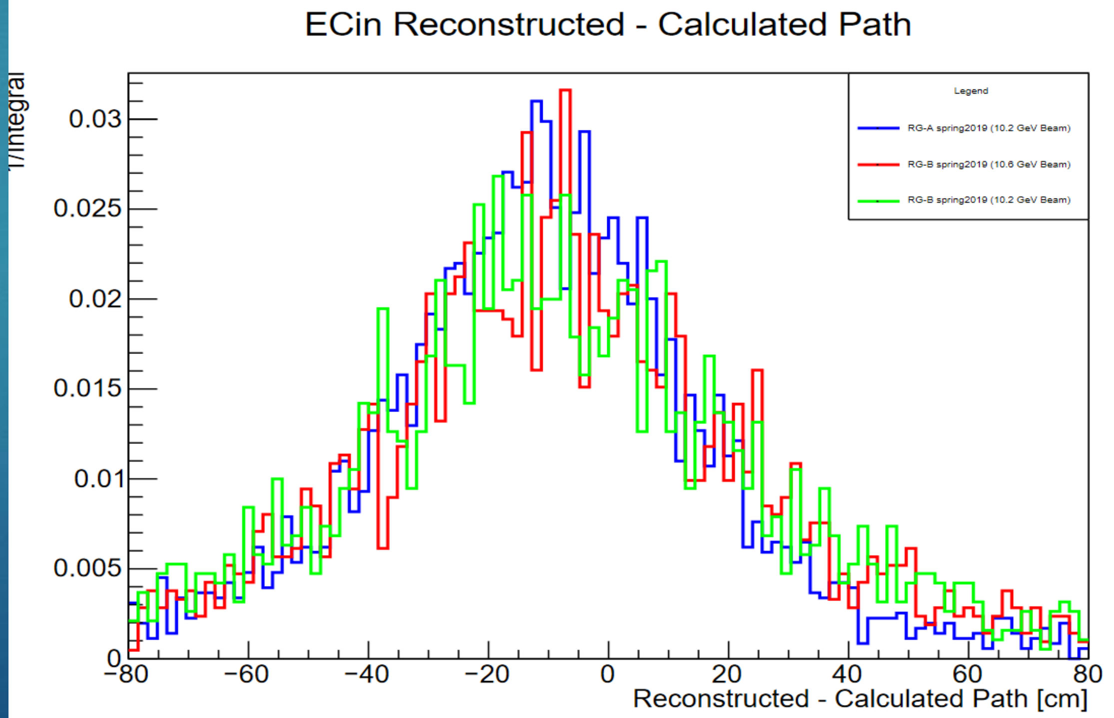


# Neutron Path Corrections

- In the data reconstruction the neutron interaction point is set to the front face of the calorimeter when it should be within.
- Idea is to use ep->e'nπ+ and compare calculated to reconstructed neutron path.
- Here we check three datasets:
    - RG-A spring2019 (10.2 GeV beam) – proton target
    - RG-B spring2019 (10.6 GeV beam) – deuterium target
    - RG-B spring2019 (10.2 GeV beam) – deuterium target

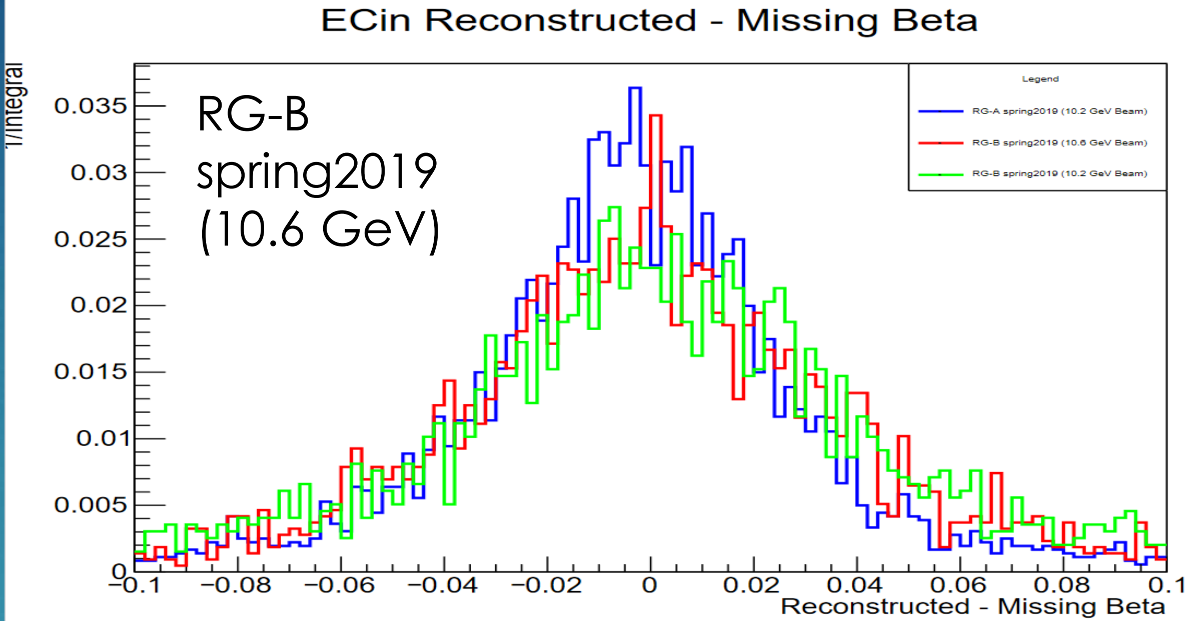


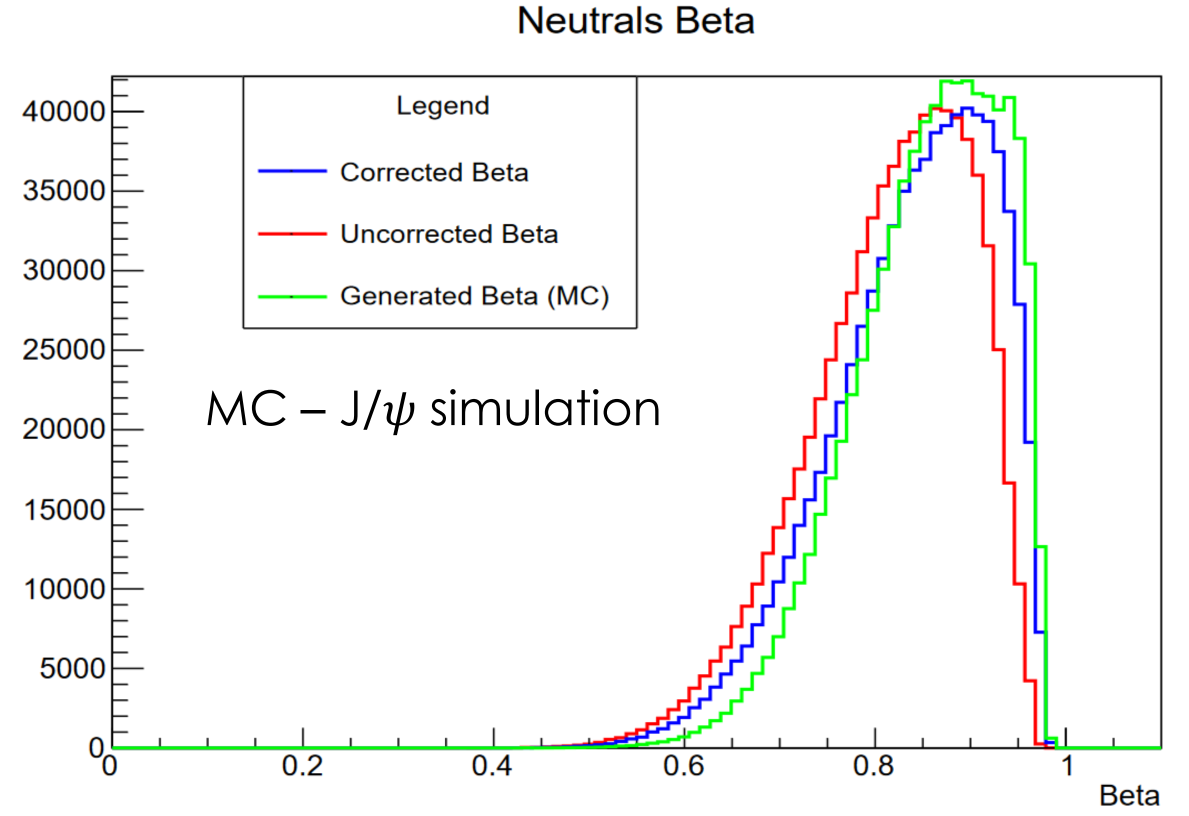



# Neutron Path Corrections

- Correcting the path length means we can then correct the neutron Beta/momentum.

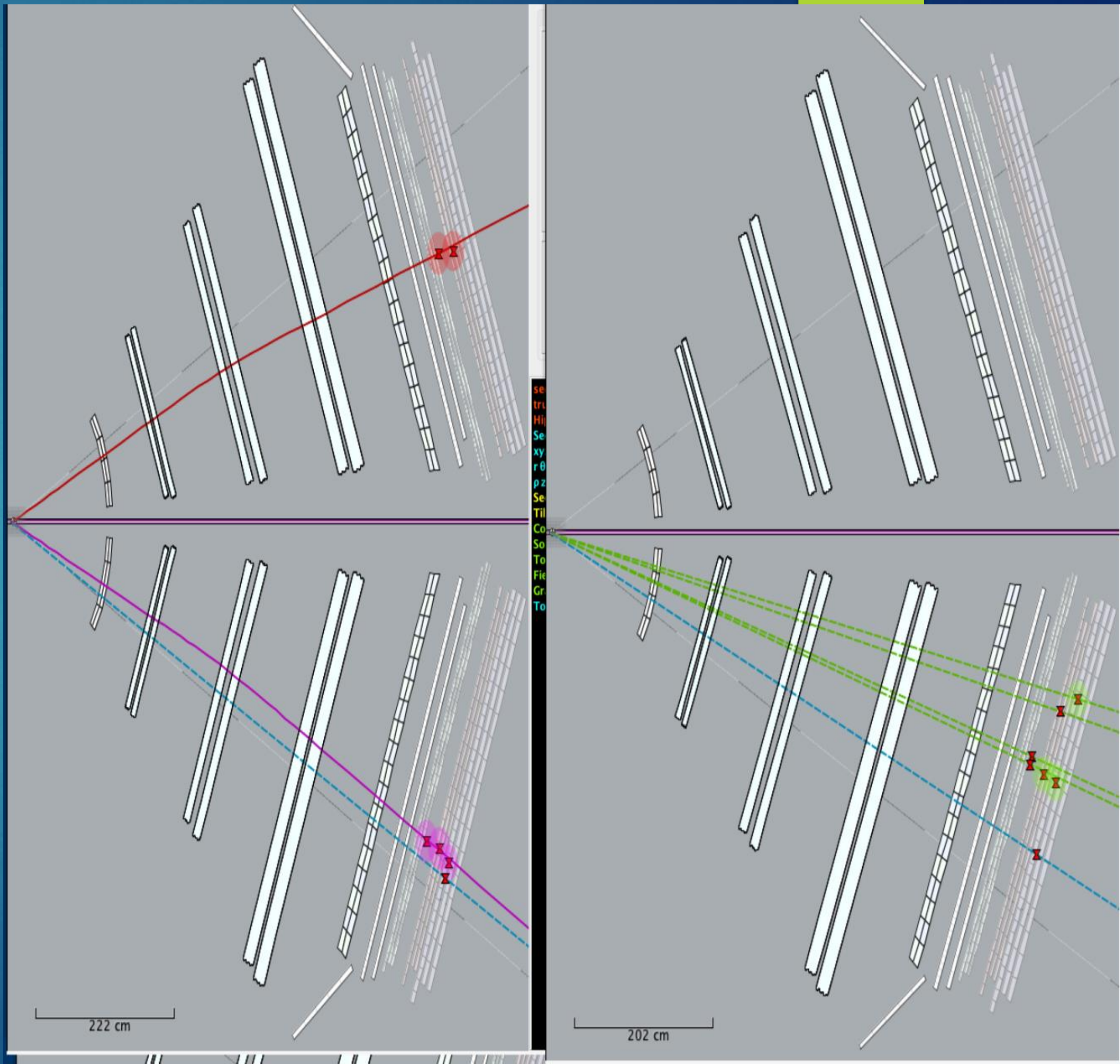
- We can use the same procedure to derive corrections for MC and data.



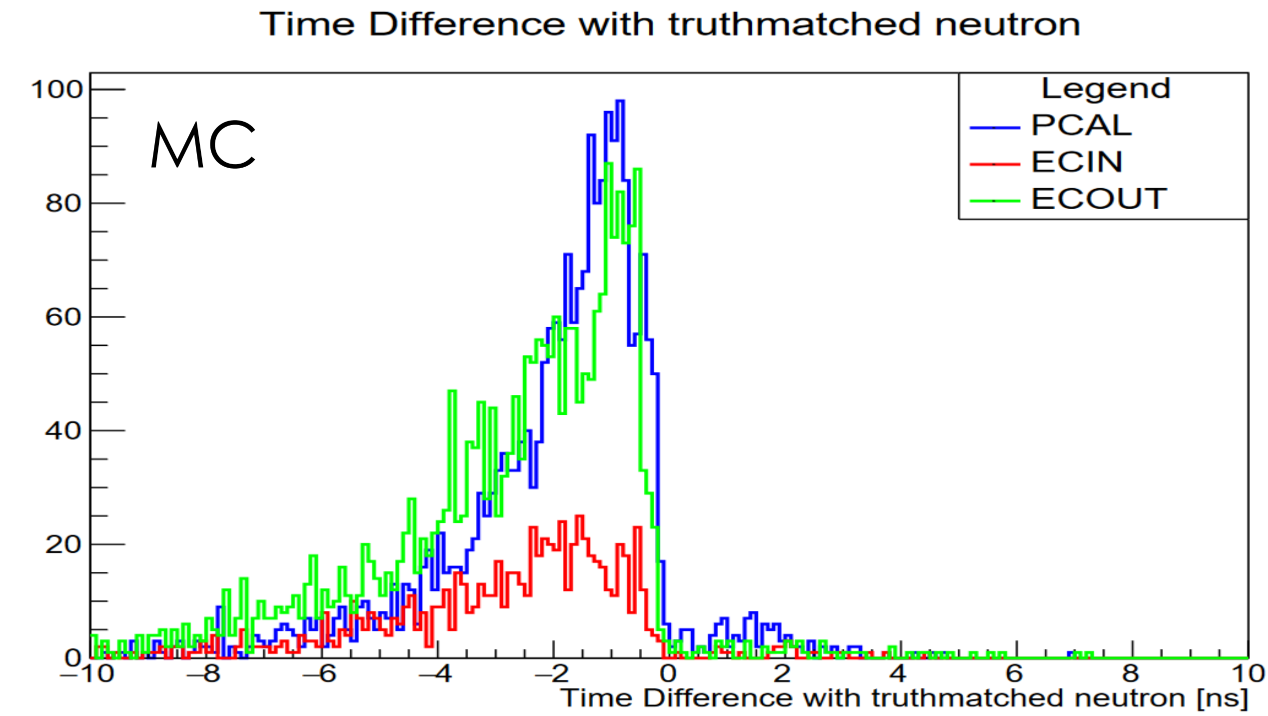
# Secondary Neutrons

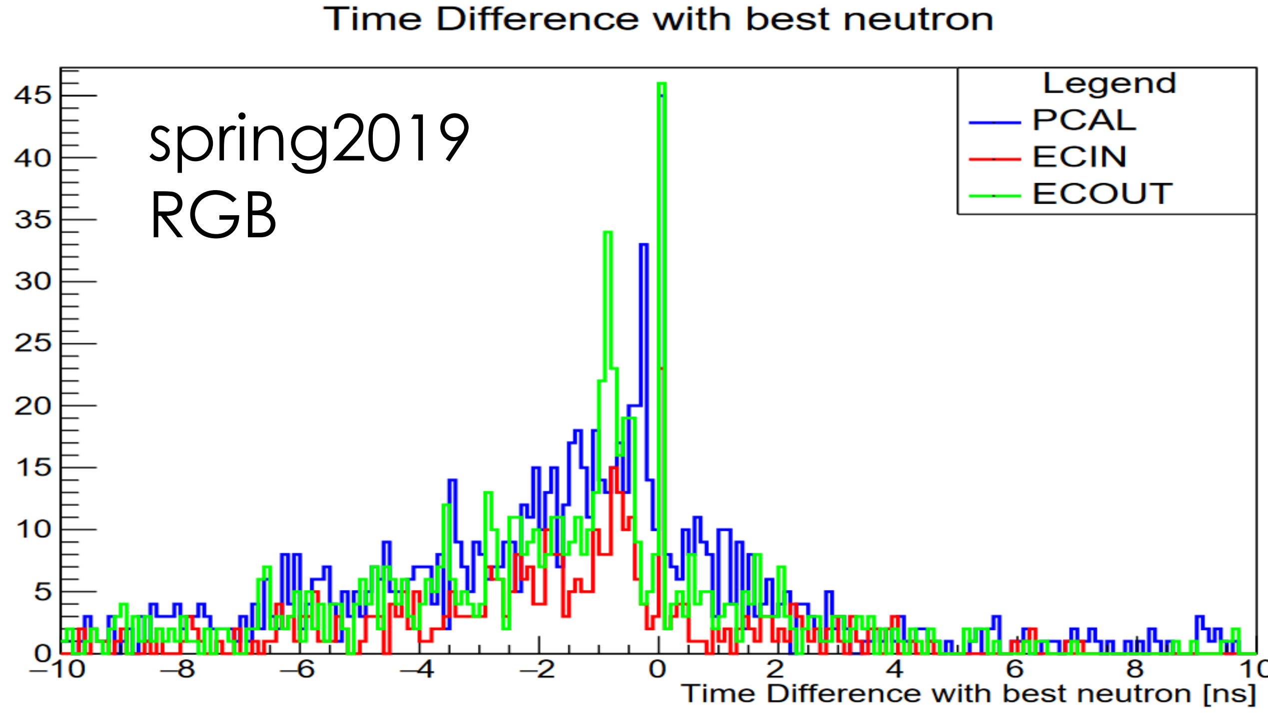
- Neutrons often produce secondary neutrons, due to:
  - real physical processes
  - Issues in reconstruction? Peak finding algorithm creates two clusters?
- This effect is seen in similar rates in both CLAS12 and MC (~30% of entries) with usual cuts and analysis procedures applied.



# Secondary Neutrons

- Initial neutrons tend to occur first:
  - Earliest time when in same calorimeter layer
  - In layer closest to target when in different layers
- A couple of things left to iron out:
  - What happens when I have more than one particle in a sector (ie photons that are faster than neutrons)?
  - What happens if I have neutrons from another beam bunch?



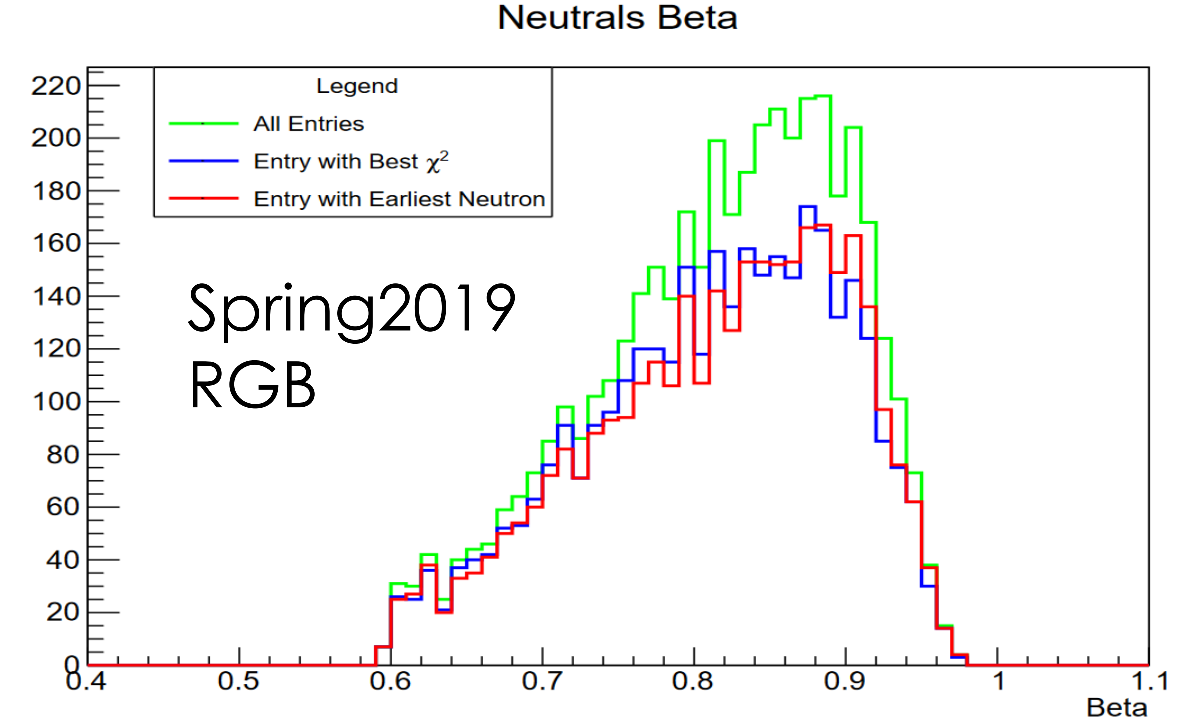



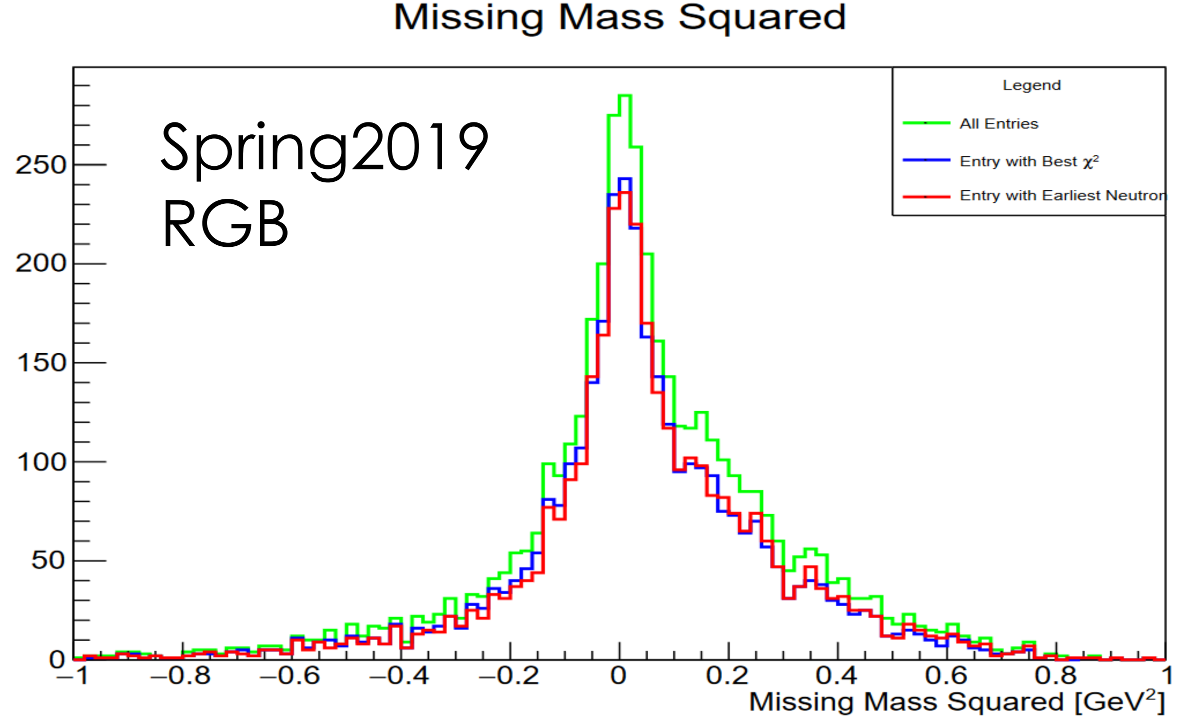
# Neutron Selection

- We have two selection procedures:
  - Only consider the earliest neutral in each sector as our main candidate.
  - Otherwise rank by $\chi^2$ value calculated from exclusivity variables ($MM^2/Q^2$).

- $\chi^2$ calculated as:

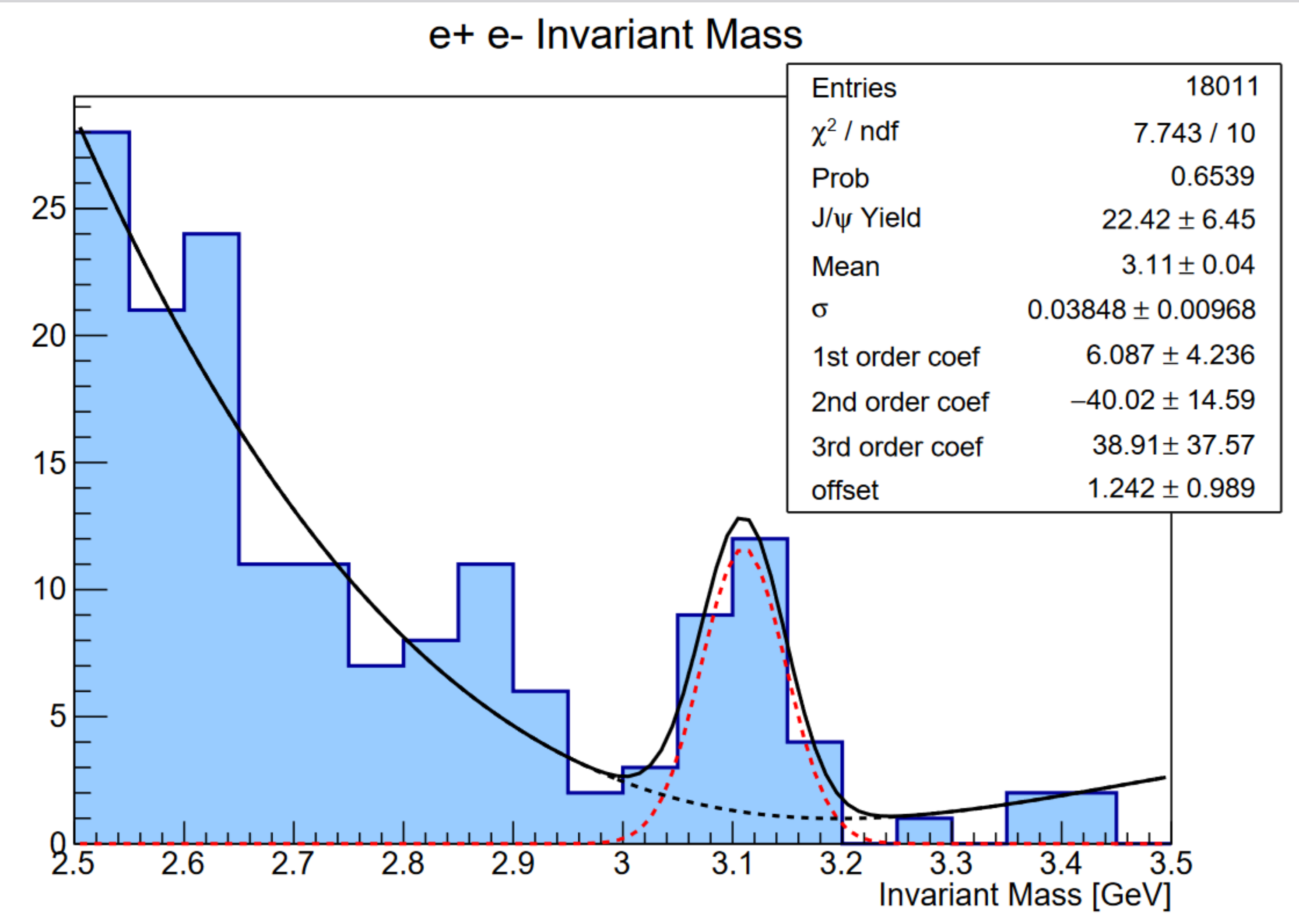
$$\chi^2 = \Sigma^{variables} \frac{(observed\ - expected)^2}{expected}$$



# $ed \to (e')e^+e^-d$

- Here the electron beam interacts with the deuteron as a whole.
- Deuteron ID isn't perfect at CLAS12 so we could possibly improve our statistics somewhat.
- This isn't a priority at the moment given low statistics.



# ρ, ω and φ mesons

- Plotted here is the invariant mass of $e^+e^-$ produced on a bound proton in the deuteron target.
- φ mesons are clearly resolved.
- ρ and ω mesons are unresolvable but clearly present.