Measurement of cross-section of the photoproduction of J/ψ on the proton

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13th of March 2024

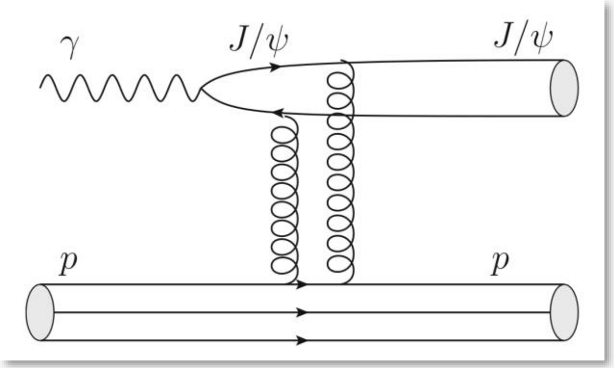
Jefferson Lab clas

Outline

Motivations for dilepton final state measurement

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) and mass radius of the nucleon close to threshold, and gluon GPDs at higher energies (under 2-gluon exchange assumption and no open-charm contributions)
- Model-dependent limit on the branching ration of the Pc pentaquark.

Publications at JLab

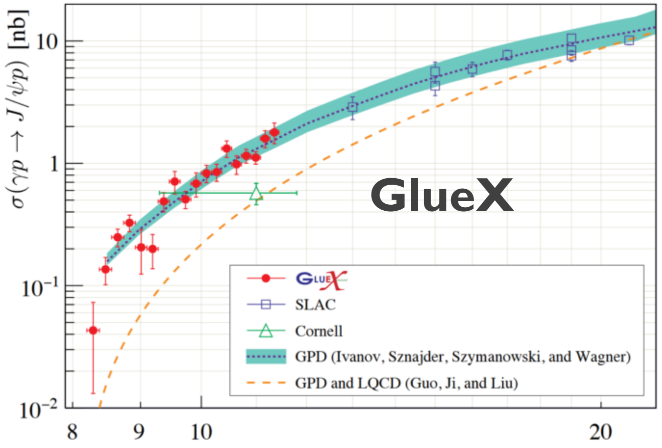


Figure in, Measurement of the J/ψ photoproduction cross section, S. Adhikari *et al.* (GlueX Collaboration) arXiv:2304.03845

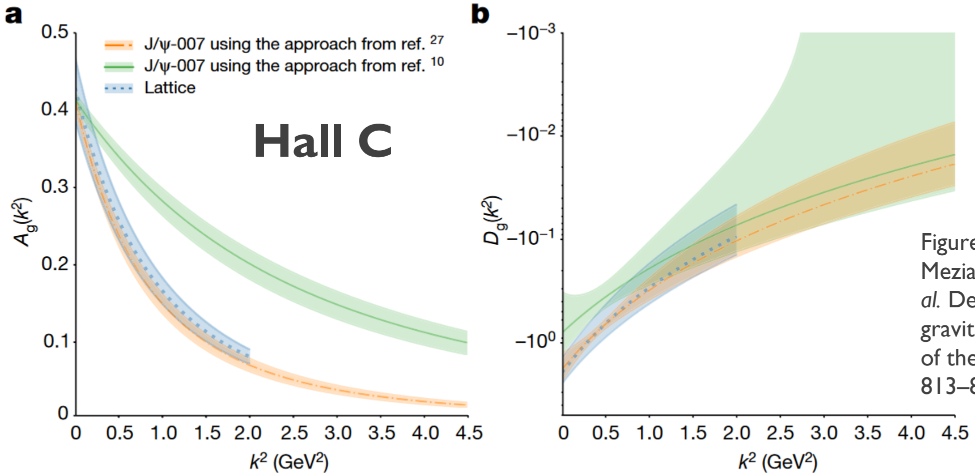


Figure in Duran, B., Meziani, ZE., Joosten, S. *et al.* Determining the gluonic gravitational form factors of the proton. *Nature* 615, 813–816 (2023)

General analysis strategy

1) CLAS12 PID + Positron NN PID

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

$p_X = p_{beam} + p_p - p_{e^+} - p_{e^+} - p_{p'}$ → 2) $|M_X^2| < 0.4 GeV^2$ → 3) $Q^2 < 0.5$ GeV^2

Event selection

- Event topology:
  - exactly one electron in FD
  - exactly one positron in FD
  - exactly one proton
  - anything else
- HTCC and ECAL hits in the same sector
- HTCC lepton time within 4 ns
- Lepton momenta > 1.7 GeV
- Proton in the FD
- Sampling Fraction > 0.15
- Lepton AI PID score > 0.05 (trained on pass 2 simulation)
- Exclusivity cuts:
  - $|MM^2|<0.4$ GeV^2
  - $|Q^2|<0.5$ GeV^2

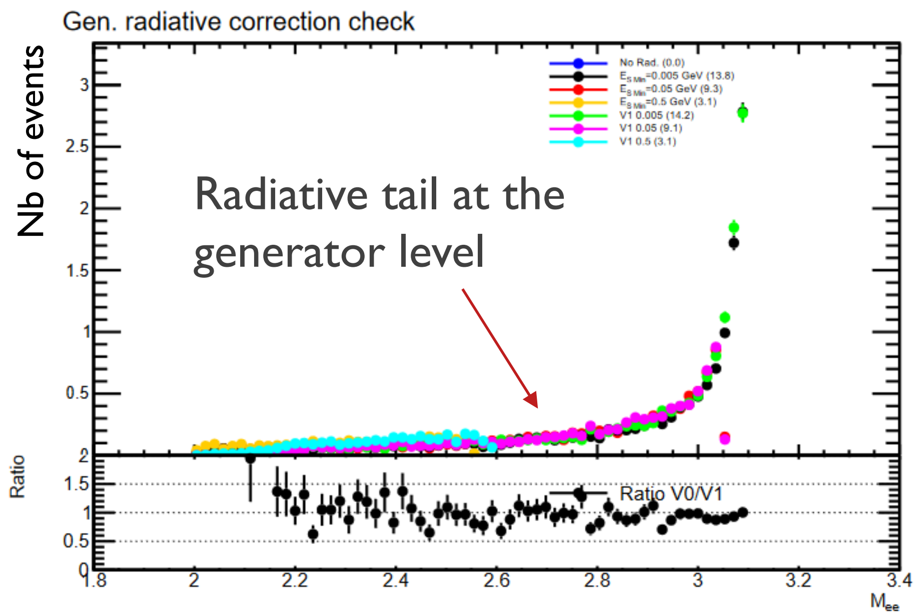
Data and MC samples

- Analysis on Pass 2 data. All *main* Fall 18 (Inbending and outbending) and Spring 19 runs are processed.
- Simulations are processed through OSG with pass 2 configuration
- The QADB tool is used to clean-up data and retrieve the accumulated charge per DST files
- The RCDB interface of clas12root is used to retrieve the beam current for each run
- Accumulated charge is computed per beam current for each configuration

	Config / Beam currents / Charge					
	Fall 18 In.			Fall 18 Out.		Sp. 19
Generator	45 nA 26.312 mC	50 nA 4.000 mC	55 nA 5.355 mC	40 nA 11.831 mC	50 nA 20.620 mC	50 nA 45.994 mC
Grape	8.2M each					6.7 M
TCSGen	2M each					1.5 M
JPsiGen	2M each					
JPsiGen (No rad.)	3M each					
Total of 24 MC samples and 3 Data samples						

Radiative effects

- Inclusion of radiative effect is done in all generators according to formulas in: *Matthias Heller et al. Soft-photon corrections to the bethe-heitler process in the γp → l+l−p reaction. PRD*
- The JpsiGen, TCSGen generator with radiative effect are on Github, as well as an event converter for Grape
  …not yet on OSG
- A full note on the algorithm is ready and will be included in the analysis note.
- The work was presented at the CLAS collaboration meeting in July 23.



Other analysis tools

https://github.com/PChatagnon/TCS_Analysis

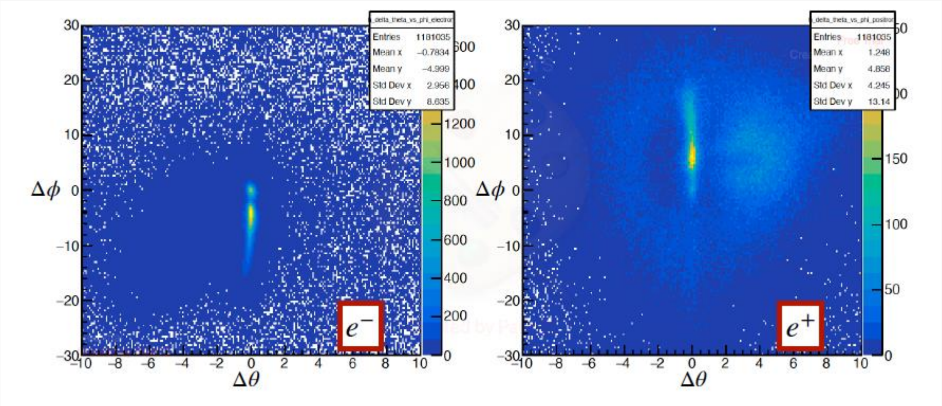
Fiducial cuts/dead paddle cuts

- Pass1 fiducial cuts on the PCAL (~ 8-9cm on V and W)
- Additional dead paddle cut, cross-check with Valerii Klimenko

Radiated photon correction

- Loop over photons in the event
- Add 4-vectors to the lepton if Δθ<1.5 deg.

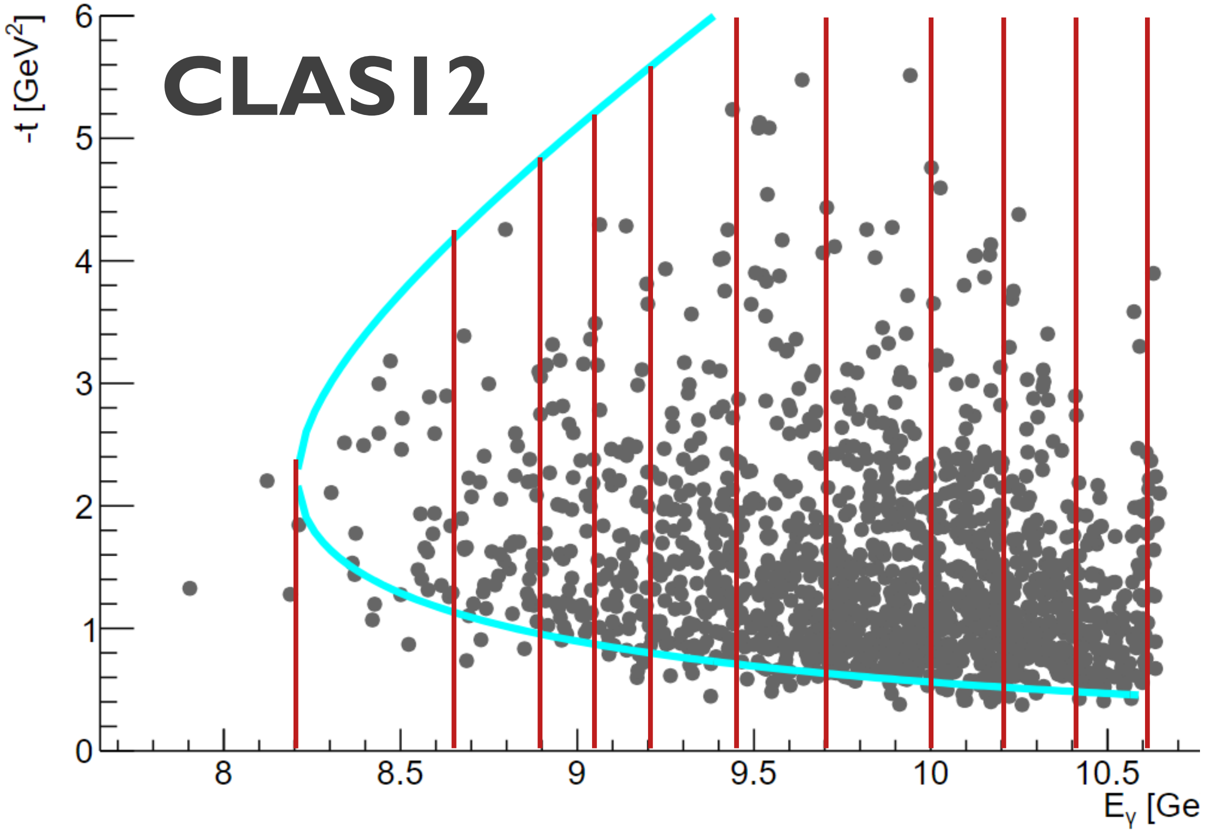
Plots from Mariana Tenorio

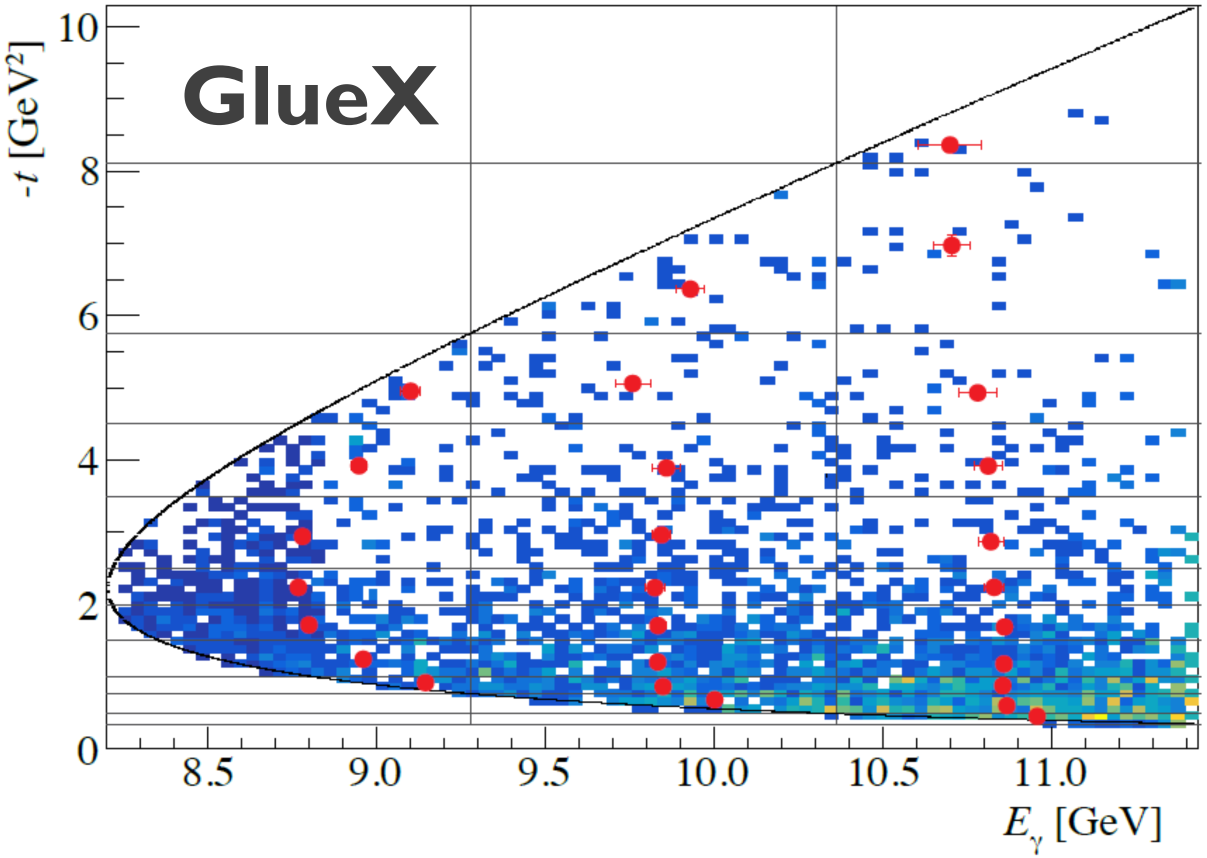


- Not included in the following:
  - Energy loss / Momentum corrections
  - Momentum smearing
  - *Edge*-based fiducial cuts

Results

Kinematic coverage and binning





Cross-section computation

$$\sigma_j = \frac{N_{J/\psi j}}{\mathcal{F}_j \cdot \mathcal{L} \cdot \omega_{cj} \cdot B_r \cdot \epsilon_j \cdot \epsilon_{Rad/j}}$$

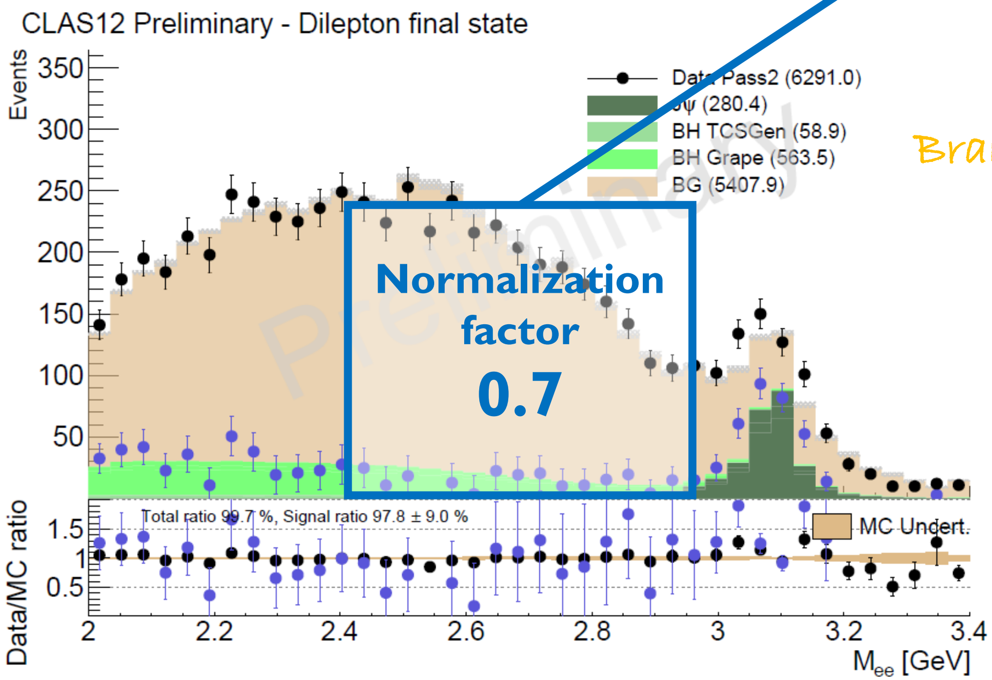
Number of photons and Number of targets

Number of J/Psi from data

Radiative corrections from MC

Branching ratio: 6%

Reconstruction efficiency from MC



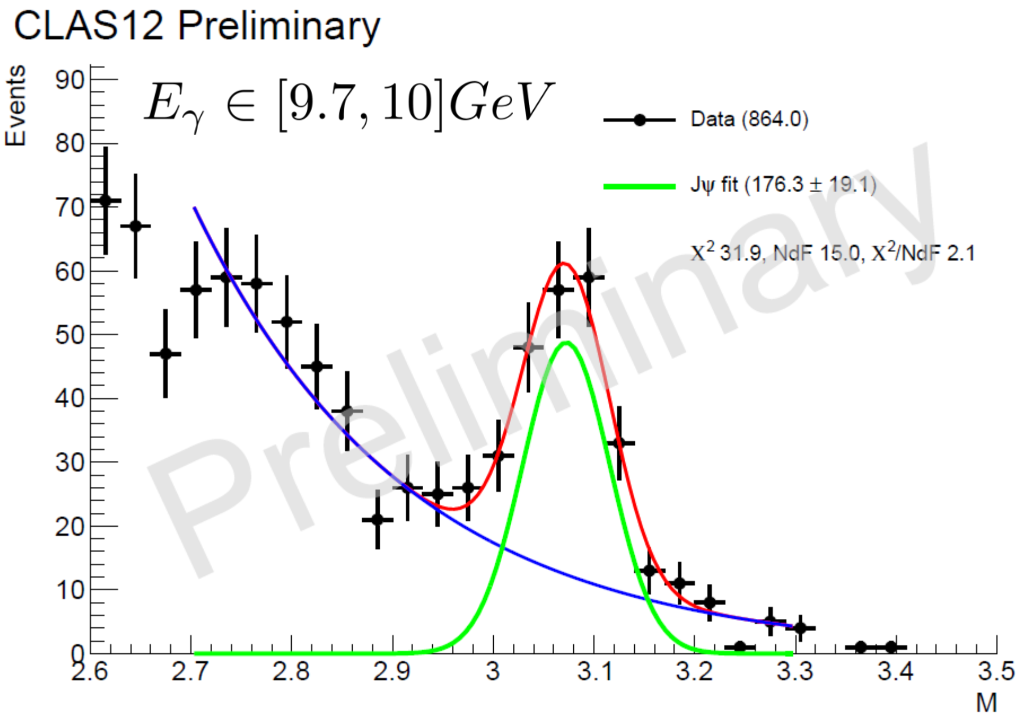
Normalization factor 0.7

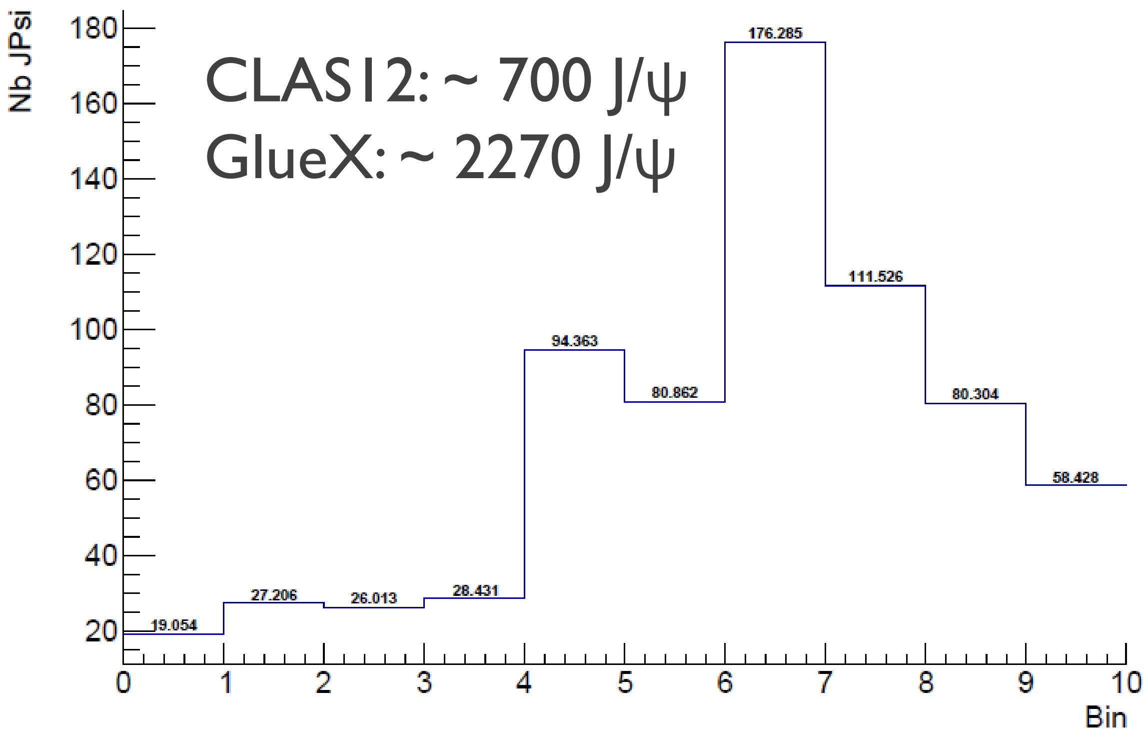
→ See Modeling Dilepton Background using Boosted Decision Trees talk tomorrow

Number of J/Psi

$$\sigma_j = \frac{N_{J/\psi j}}{\mathcal{F}_j \cdot \mathcal{L} \cdot \omega_{cj} \cdot B_r \cdot \epsilon_j \cdot \epsilon_{Rad/j}}$$

- All data samples are combined and **fitted together.**
- Gaussian + exponential background fit is used.
- Systematic study is performed on the fit function.





Photon flux

$$\sigma_j = \frac{N_{J/\psi j}}{\boxed{\mathcal{F}_j \cdot \mathcal{L}} \cdot \omega_{cj} \cdot B_r \cdot \epsilon_j \cdot \epsilon_{Rad/j}}$$

1) Real and virtual flux are provided event by event by the JPsiGen Generator.

2) The integral over the range of energy of the bin j is done using the integral/mean theorem:

$$\mathcal{F}_{c/j} = \int_j \mathcal{F}_c dE = \Delta E \frac{\sum_{i=1}^{N} \mathcal{F}_c(E_{GEN/i}) \cdot \omega_i}{\sum_{i=1}^{N} \omega_i}$$

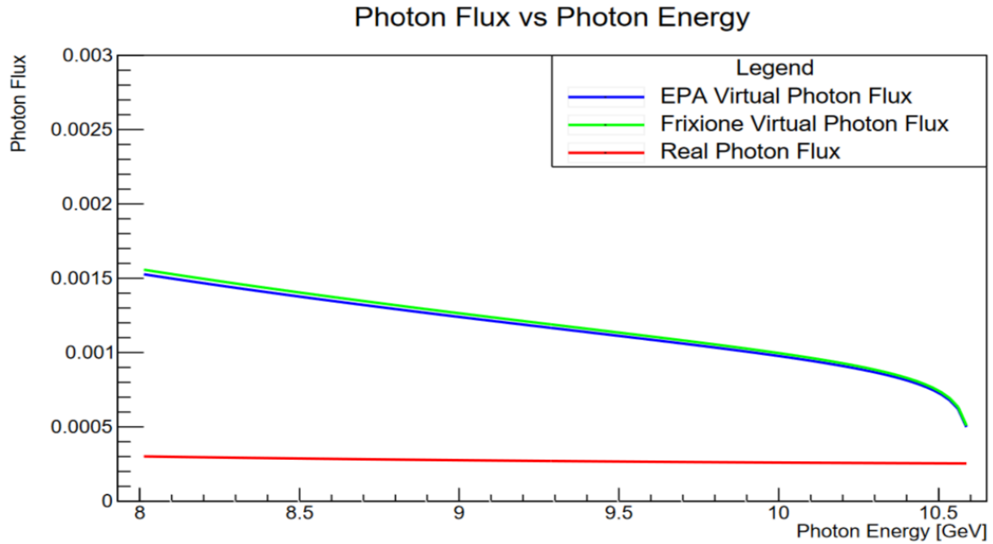
3) Each flux (one per configuration) is multiplied by the corresponding accumulated charge:

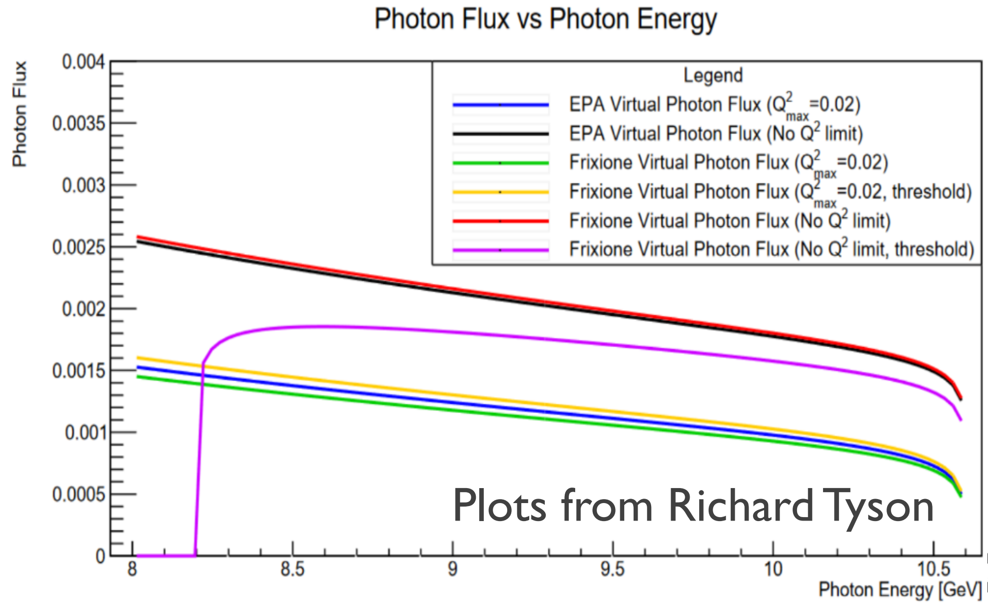
$$\mathcal{F}_j = \sum_c C_c \cdot \mathcal{F}_{c/j}$$

Total number of photon in the bin j in unit of e

4) The results is multiplied by the luminosity factor to recover the correct normalizing factor:

$$\mathcal{L} = \frac{l \cdot \rho \cdot N_A \cdot C}{e}$$



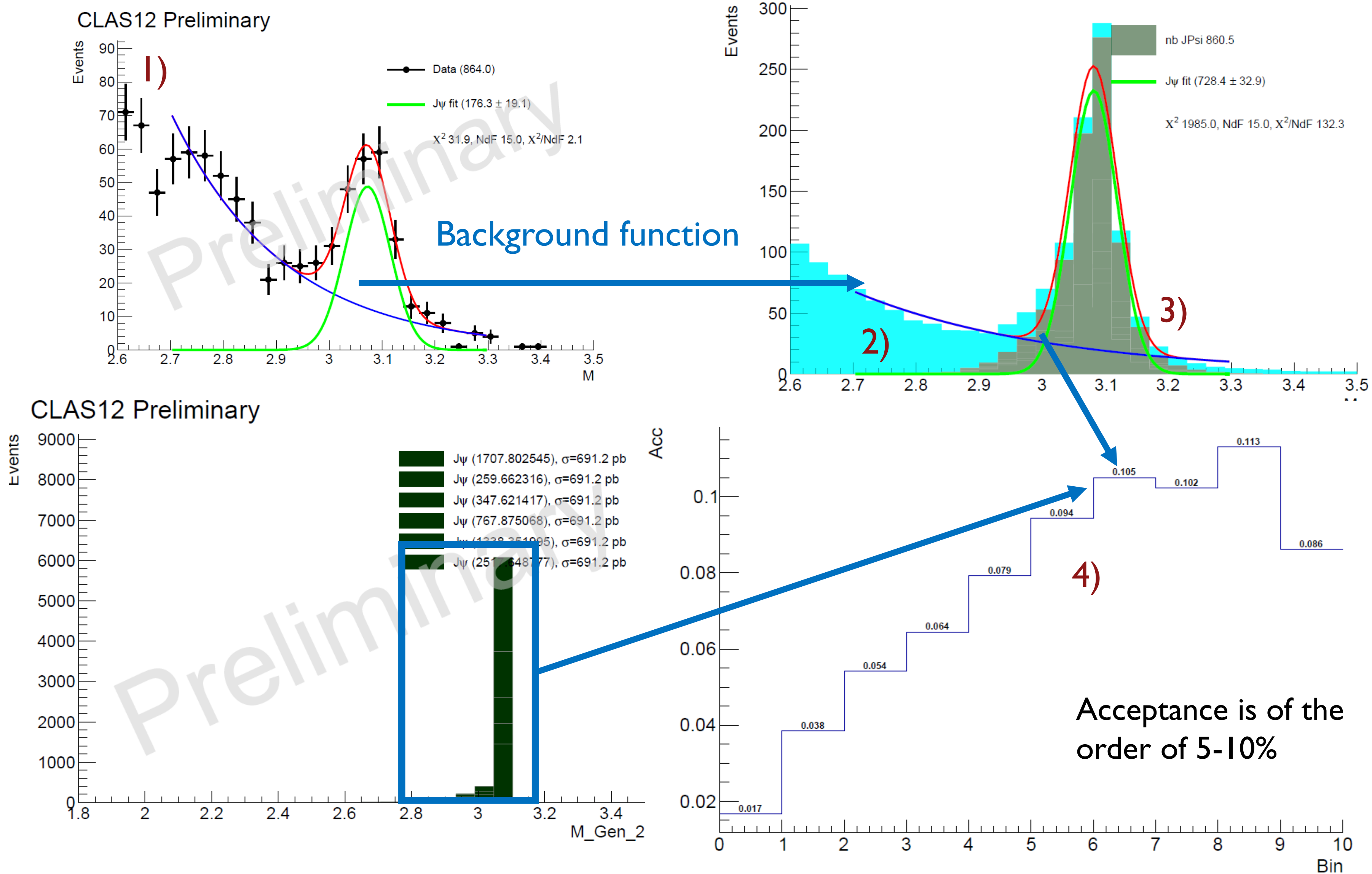


Detection efficiency

$$\sigma_j = \frac{N_{J/\psi j}}{\mathcal{F}_j \cdot \mathcal{L} \cdot \omega_{cj} \cdot B_r \cdot \epsilon_j \cdot \epsilon_{Rad/j}}$$

1) From the data fit a second order polynomial background function is extracted
2) Events are generated according to this background function and added to the Jpsi signal MC sample
3) The obtained distribution is fitted with the same function as the data
4) The acceptance correction is then:

$$\epsilon_j = \frac{N_{J/\psi}\big|_{j/REC}}{N_{J/\psi}\big|_{j/RAD}}$$

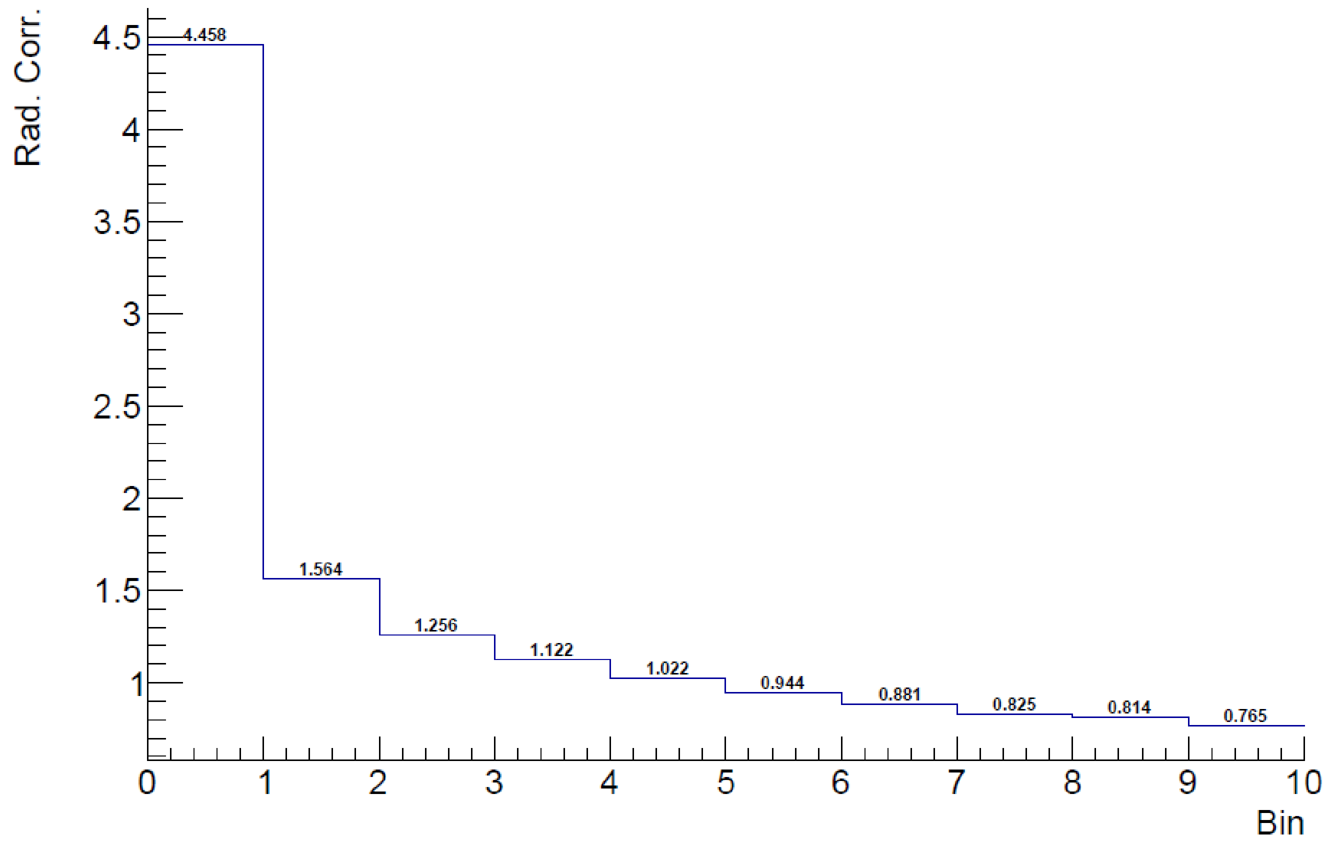


Radiative correction

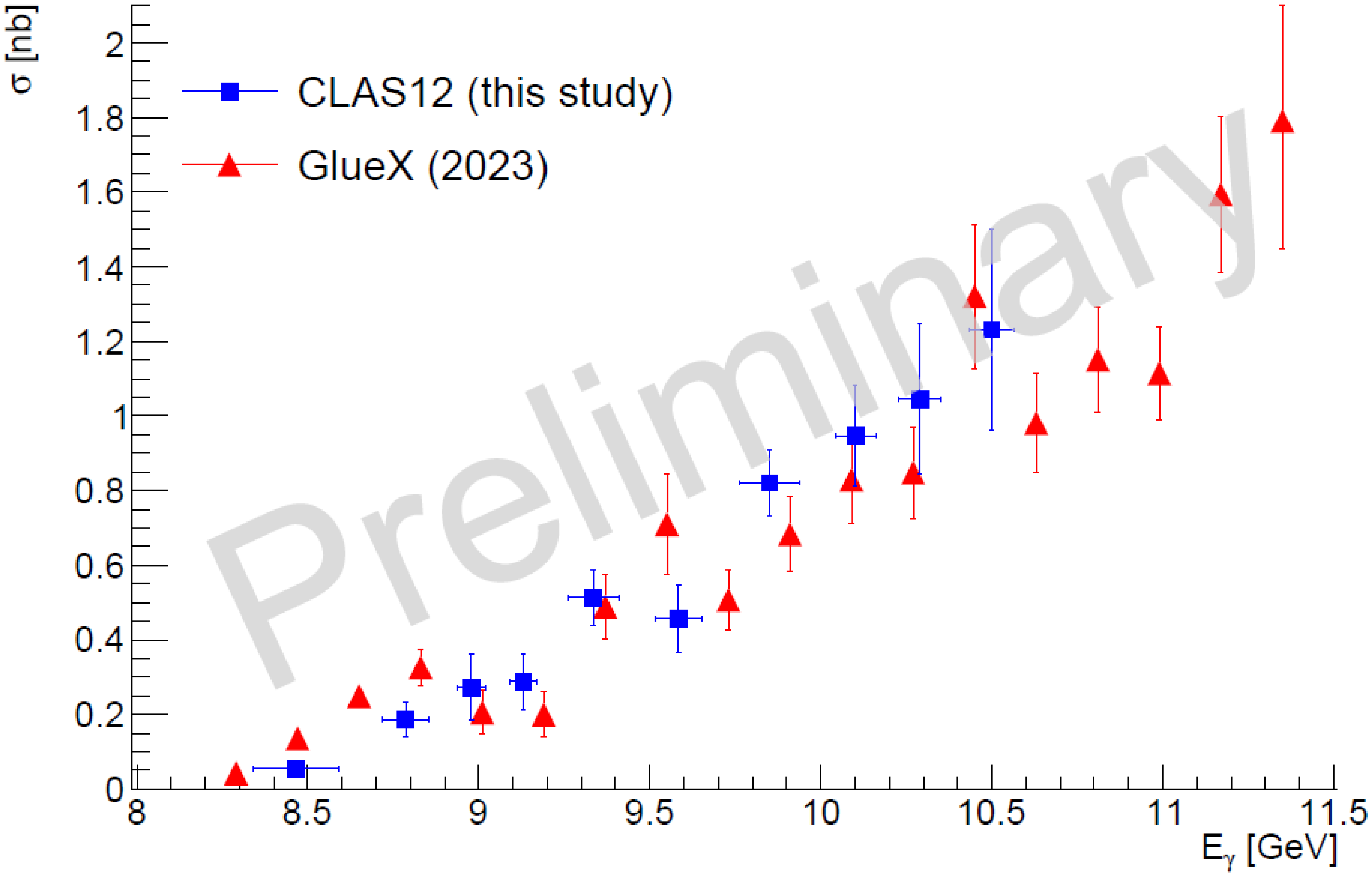
$$\sigma_j = \frac{N_{J/\psi j}}{\mathcal{F}_j \cdot \mathcal{L} \cdot \omega_{cj} \cdot B_r \cdot \epsilon_j \cdot \epsilon_{Rad/j}}$$

1) Jpsi samples without radiative effects are produced
2) The radiative correction is defined using the GEN kinematics as:

$$\epsilon_{Rad/j} = \frac{N_{J/\psi}\big|_{j/RAD}}{N_{J/\psi}\big|_{j/GEN}}$$

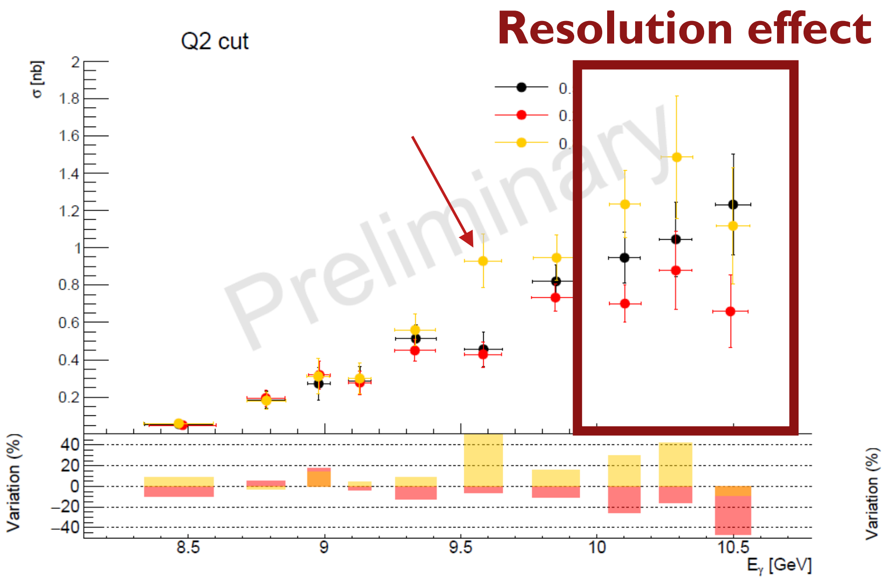


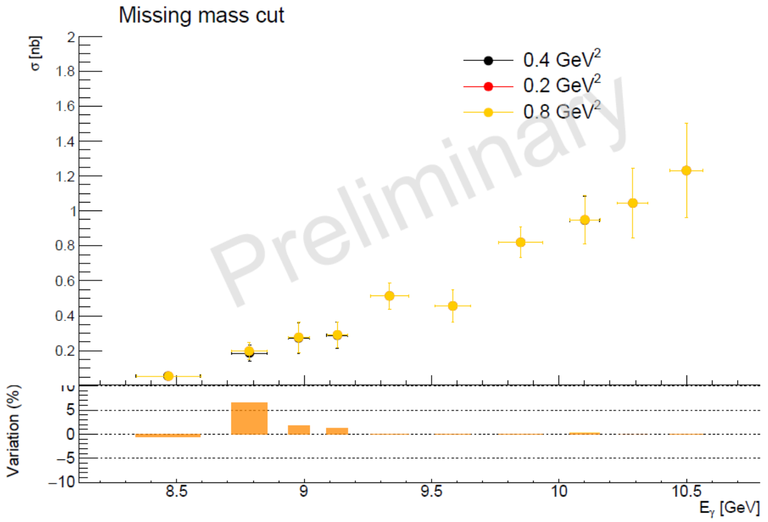
Preliminary cross-section as a function of Eγ

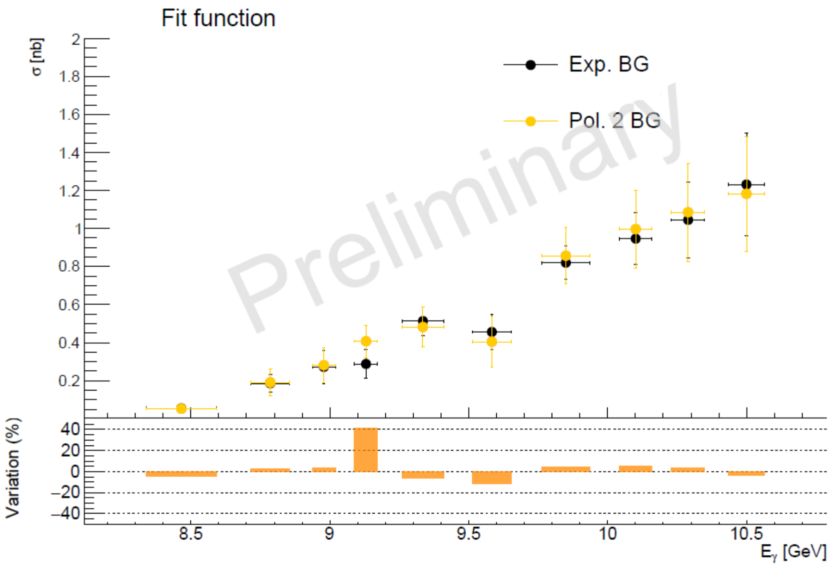


Selection cut systematics

- Every step of the analysis, except normalization factor, is repeated with different cuts:
  - Q^2 **DONE**
  - $|MM|^2$ **DONE**
  - Fit function **DONE**
  - Lepton momenta cut **To be done**
  - Lepton ID cut **To be done**
  - Proton PID **To be done**





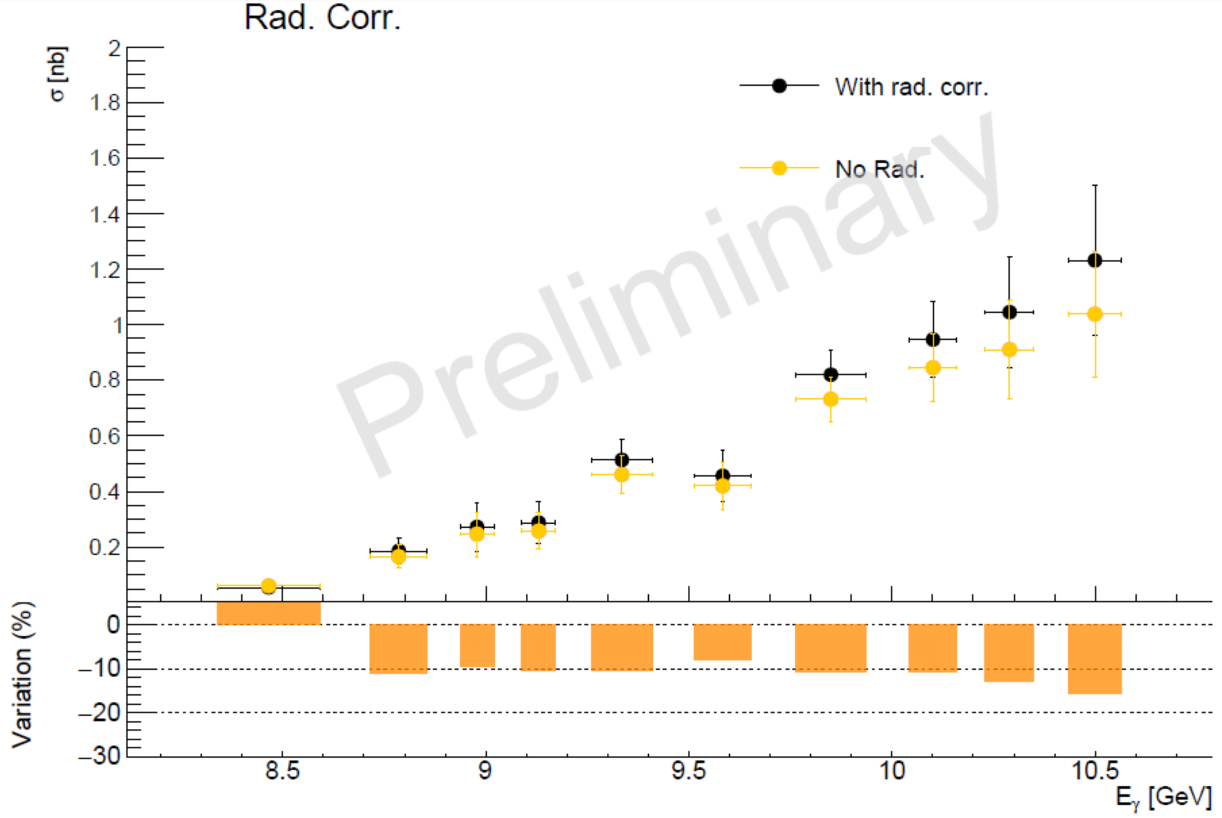


→ Implementation of ad-hoc smearing to reproduce resolution in MC and reduce this systematic

→ Variation of the signal function to be added

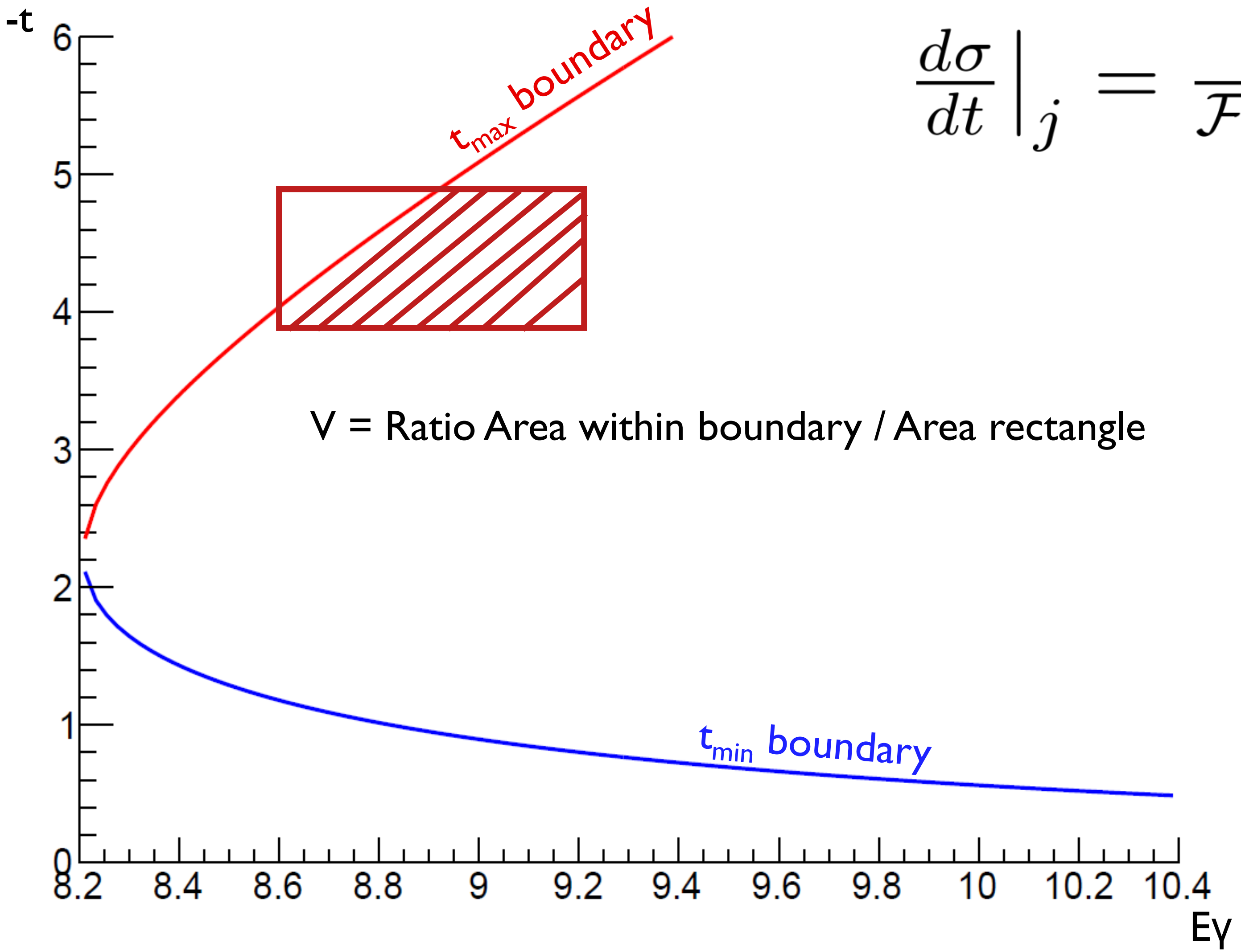
Radiative correction effect

- The standard CS is extracted using the Radiated Jpsi MC samples and radiative correction
- The alternate is using non-radiated MC samples
- The effect is of the order of 10% (GlueX quoted 8.5%)



+ Closure test (Implemented but not presented here)

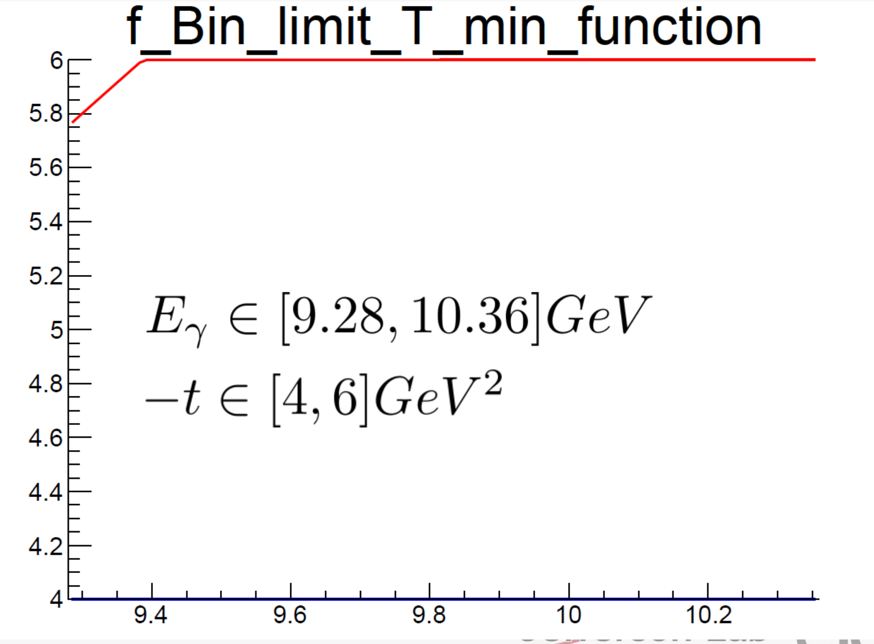
Bin volume correction



V = Ratio Area within boundary / Area rectangle

$$\frac{d\sigma}{dt}\Big|_j = \frac{N_{J/\psi/j}}{\mathcal{F}_j \cdot \mathcal{L} \cdot \omega_{c/j} \cdot B_r \cdot \epsilon_j \cdot \epsilon_{Rad/j} \cdot \mathcal{V}_j \cdot \Delta t_j}$$

- In practice is this readily done using integral of functions in root



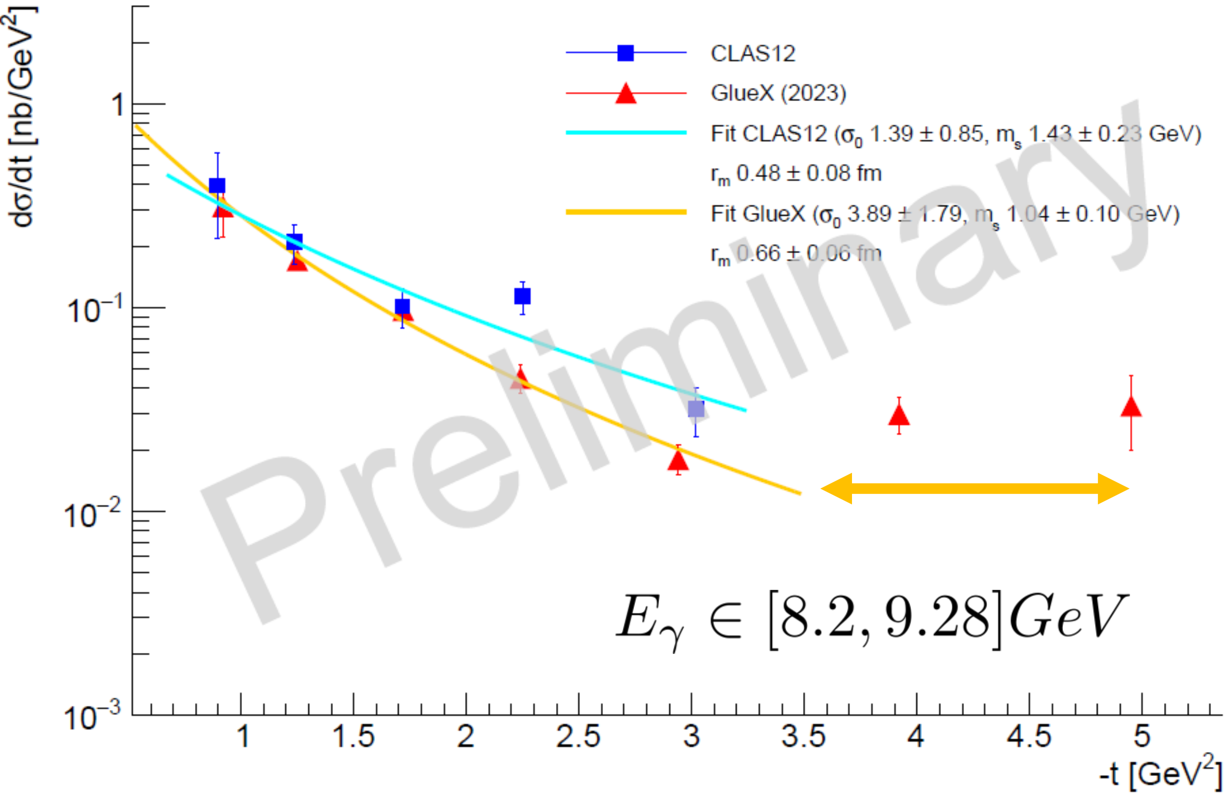
t-dependence of the cross-section

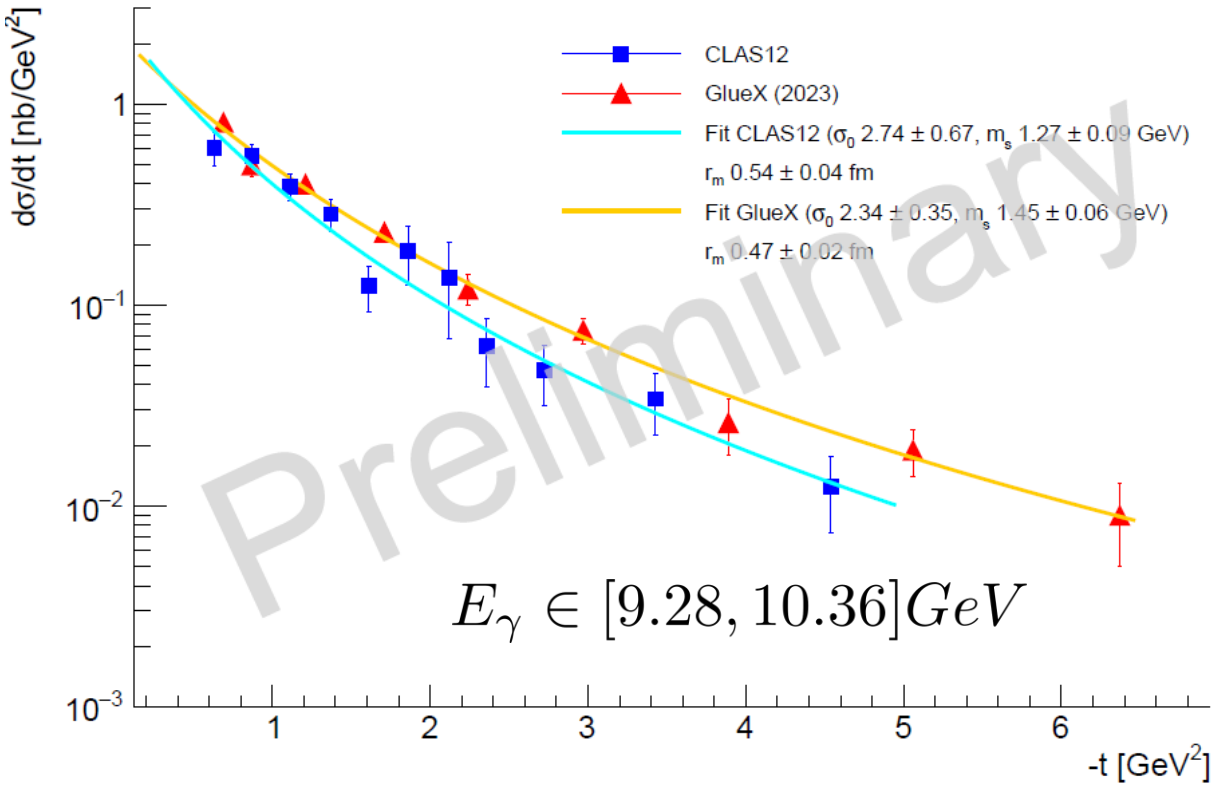
- The t-dependent cross-section can be parametrized as:

$$\frac{d\sigma}{dt} = \frac{d\sigma}{dt}\Big|_0 \cdot \frac{1}{(1-t/m_S^2)^4}$$

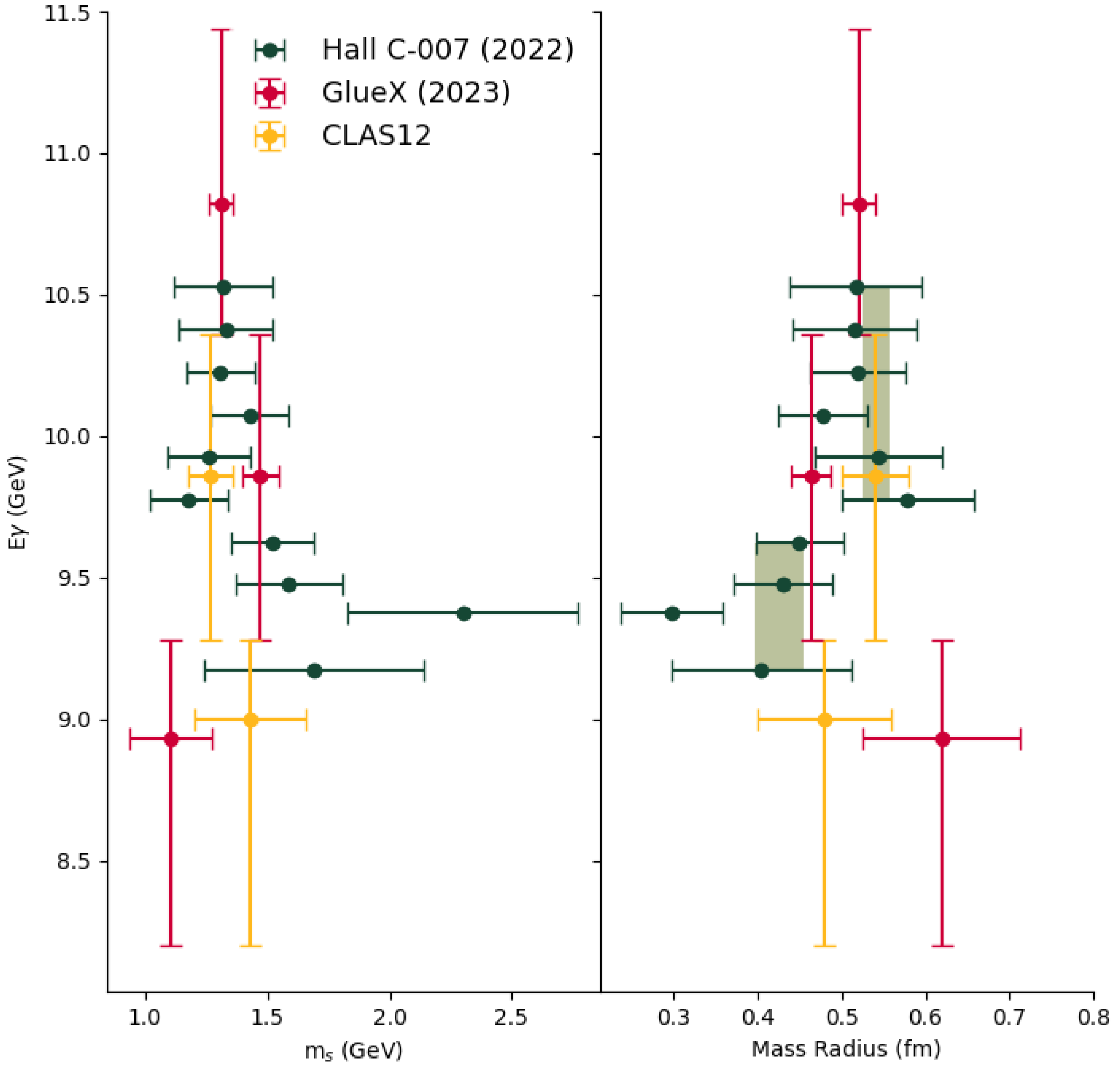
- ms can be interpreted as the mass radius of the proton. $\sqrt{\langle r_m^2 \rangle} = \frac{\sqrt{12}}{ms}$

- Our results are not sensitive to the flattening at small Eγ and large t seen by GlueX.



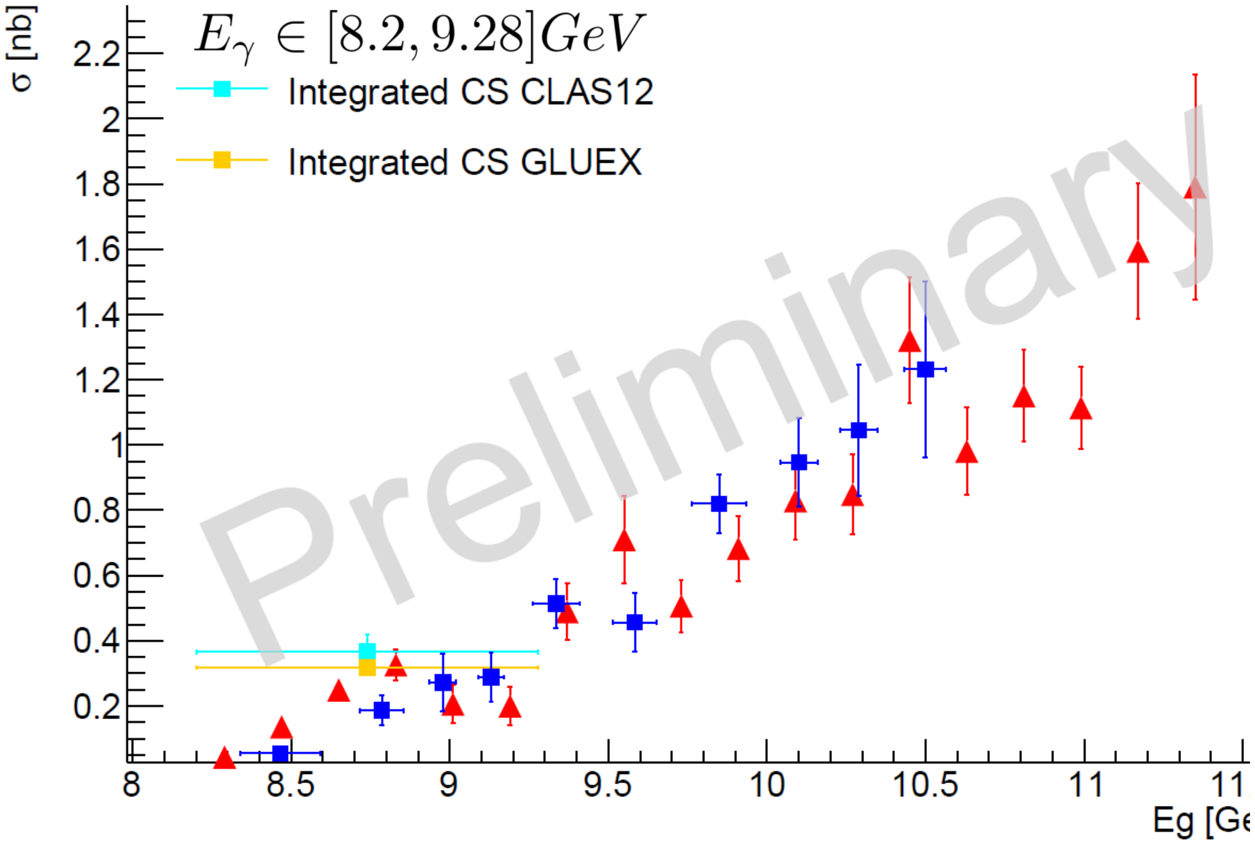


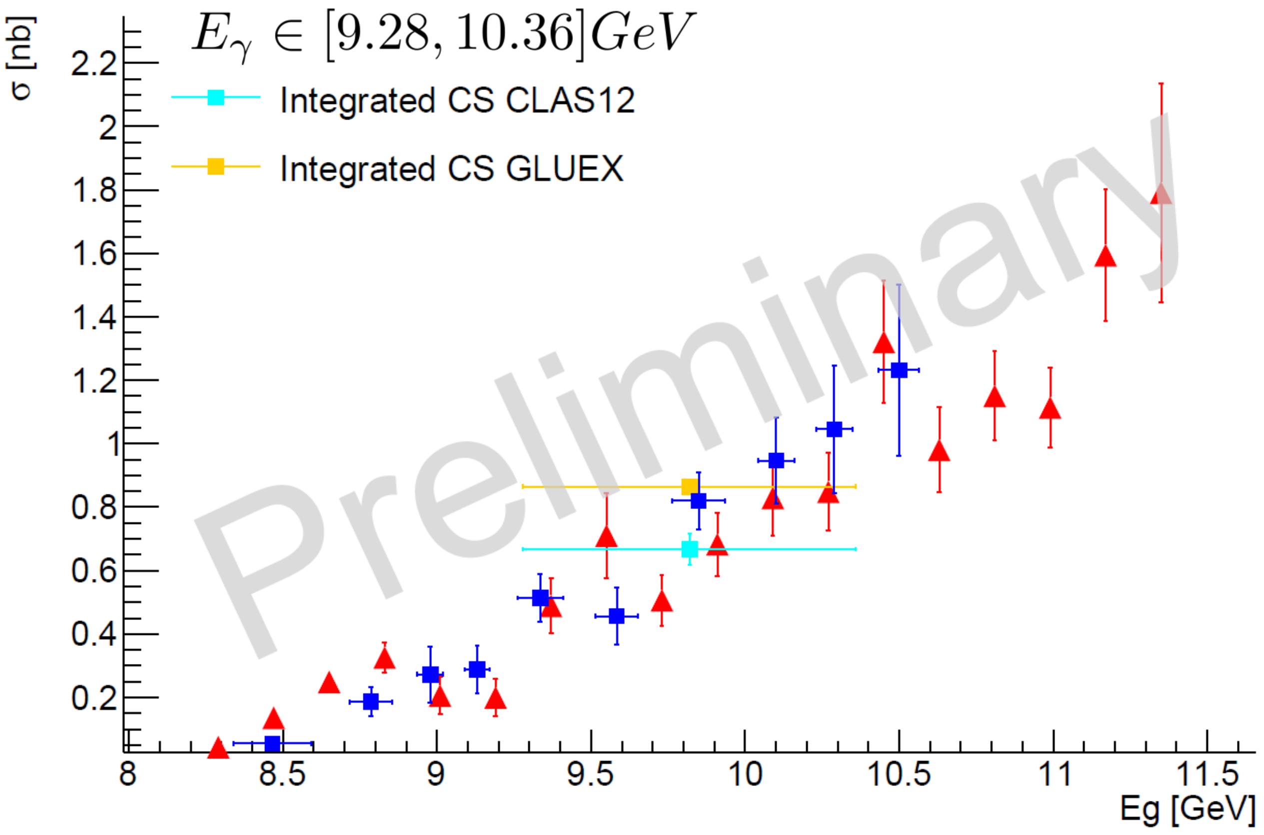
Comparison with previous experiments



Integrated t-dependent cross-section

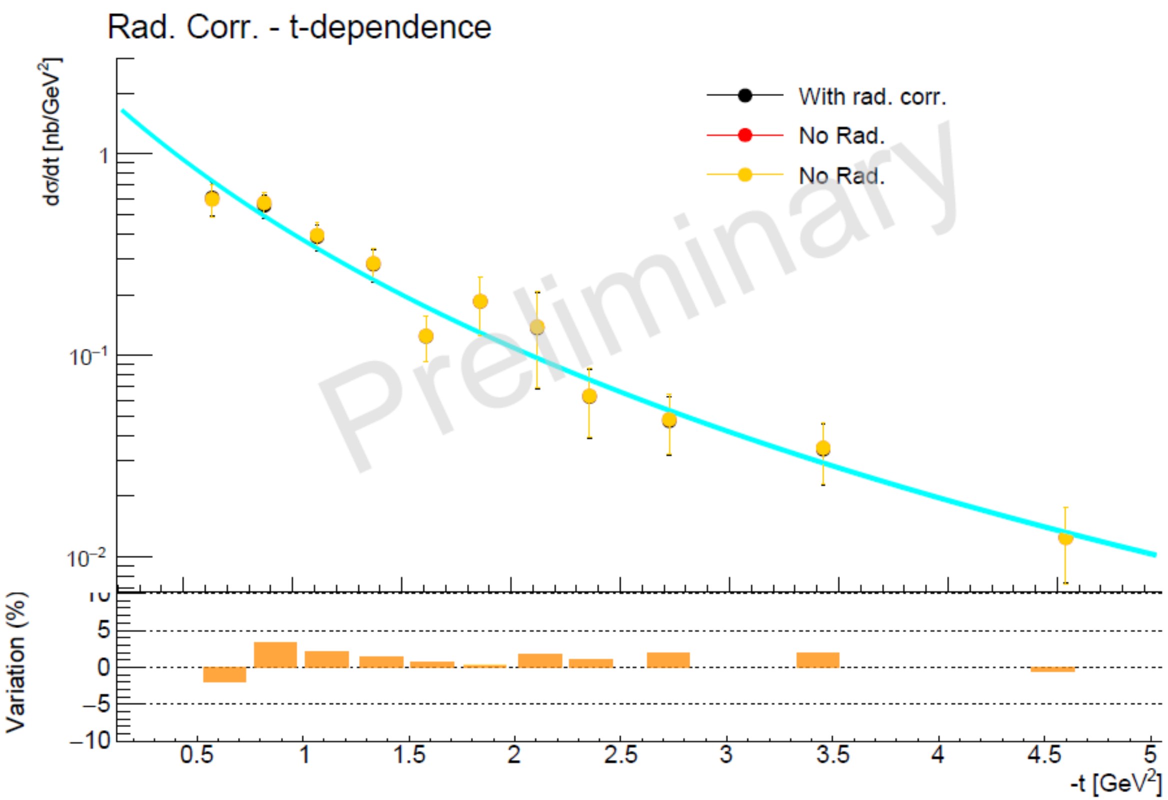
- The integral of the t-dependent cross section is done bin-by-bin: $\sigma = \sum_j \left.\frac{d\sigma}{dt}\right|_j \cdot \Delta t_j$
- And compared to the total CS



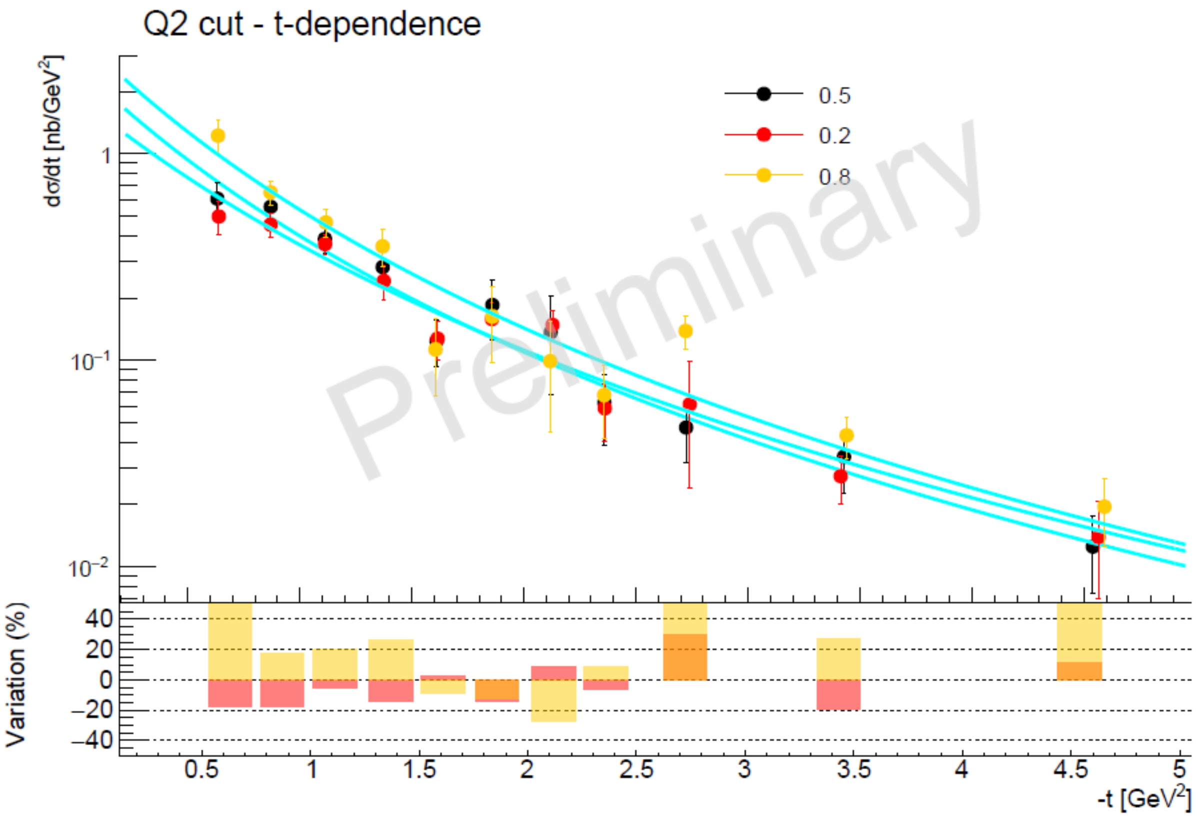


- Good agreement between integrated t-dependent CS and Eγ-dependent CS

Systematic studies



- Little dependence on –t (expected)
- ~2-3% variation



- Large variation mostly due to the fitting
  → Systematic way to choose the binning

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Take-aways and path going forward

I The JPsi analysis is at an advanced stage.

II Data and MC samples have been produced, the framework to analyze them is final.

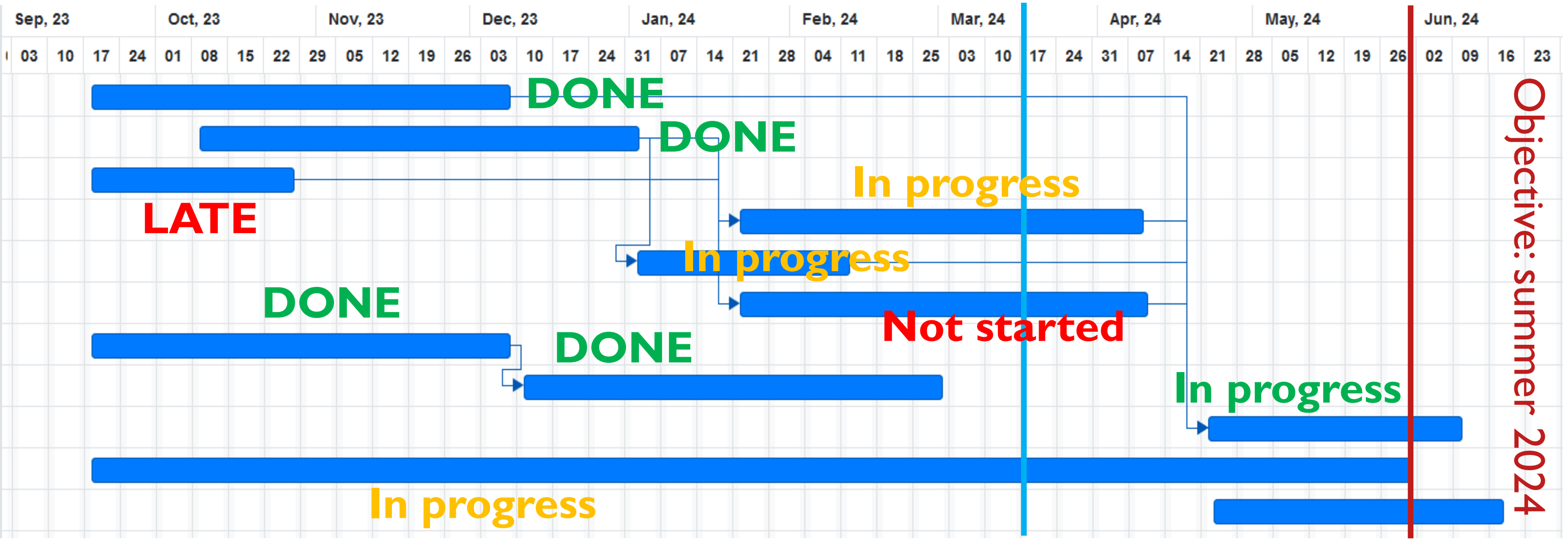
III Some common tools remain to be developed and used in the analysis.

V **A release note will be ready by early April at the latest. An analysis note will be ready for the summer**

Back-up

Timeline for the tools and task for a dilepton publication

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



- On time for PID, Data processing and radiative corrections
- Still some tools required/preferred for the analysis (Momentum corrections/smearing)
- Still on track for analysis note submission by the summer

Data/MC normalization

- Each event is weighted by:

$$\omega = \frac{\mathcal{L} \cdot \sigma_{tot}}{nb_{GEN}}$$ for generator providing integrated CS,

$$\omega = \frac{\mathcal{L} \cdot w_{GEN}}{nb_{GEN}}$$ for weighted generator.

- Where the luminosity is obtained from target specification:

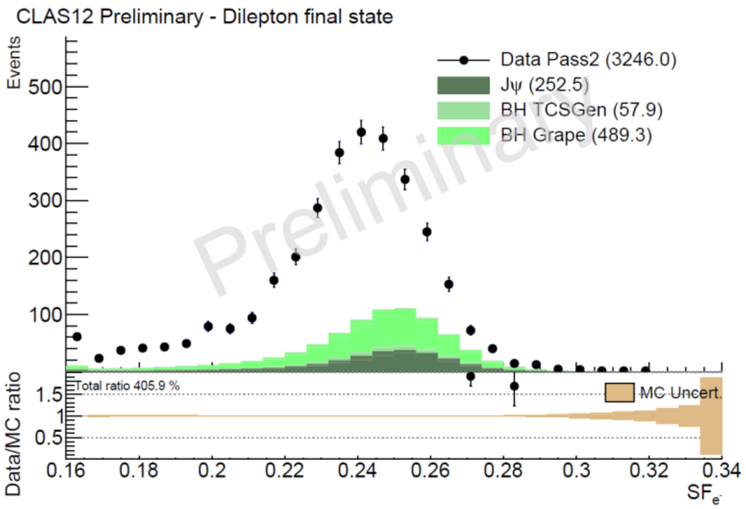
$$\mathcal{L} = \frac{l \cdot \rho \cdot N_A \cdot C \cdot Q}{e} = 1316.875 \cdot Q(\text{in mC})$$

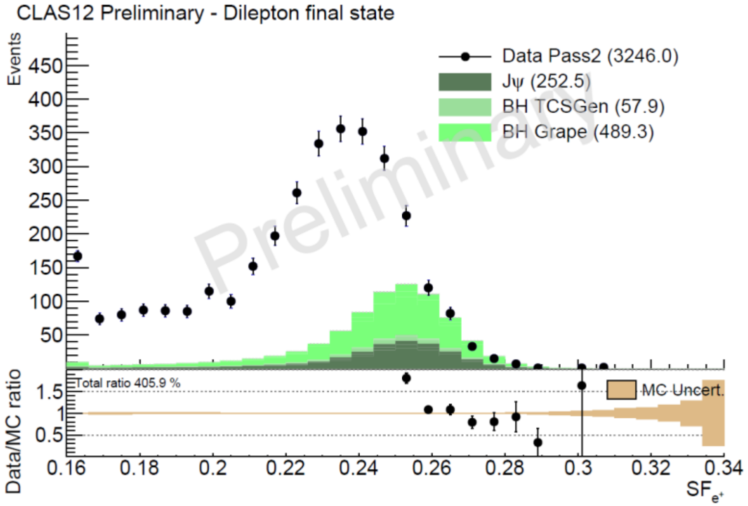
Length of the target $l = 5$ cm
Density of the target $\rho = 0.07$ g/cm^3
Avogadro constant $N_A = 6.02 \times 10^{23}$ mol^{-1}
Unit charge $e = 1.6 \times 10^{-19}$ C
Conversion to pb $C = 10^{-36}$

https://clasweb.jlab.org/rungroups/tlc/wiki/images/e/e7/Normalization_MC_Data-5.pdf

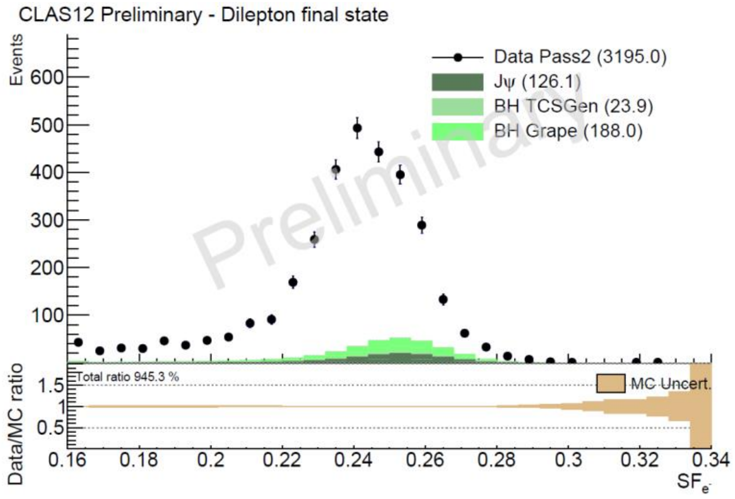
Sampling fraction MC/Data mismatch

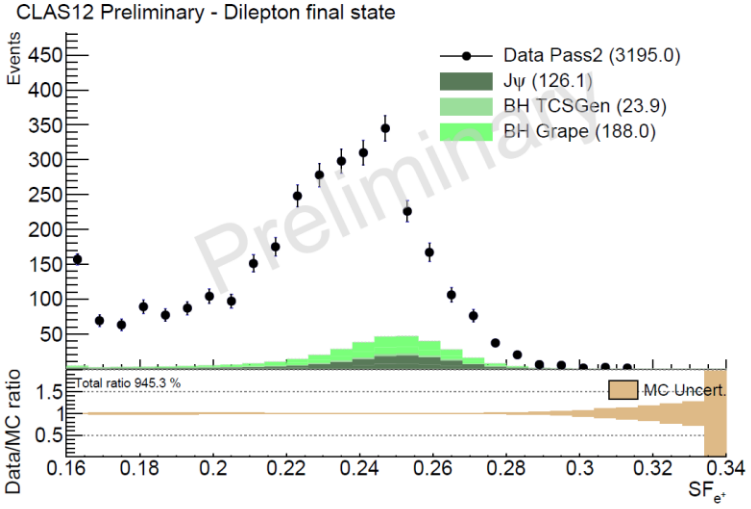
Inbending Fall 2018





Outbending Fall 2018





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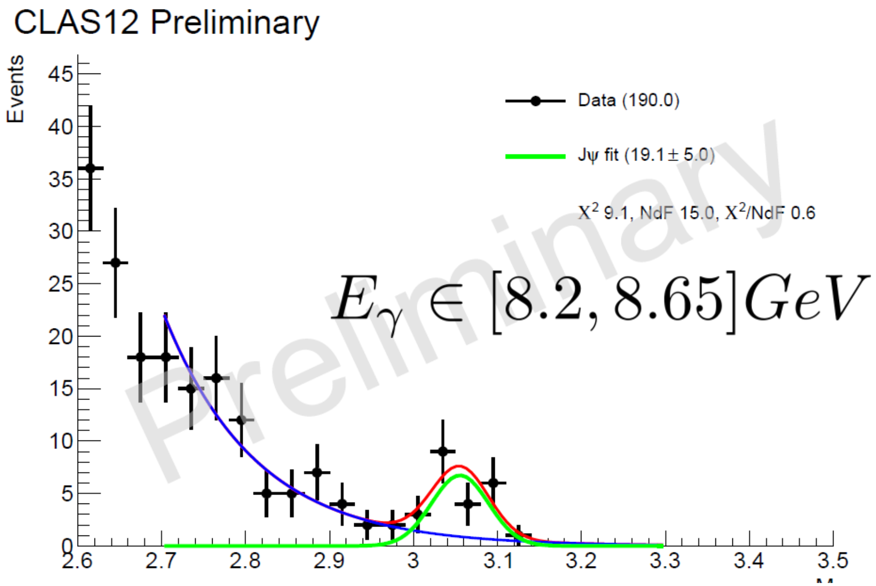
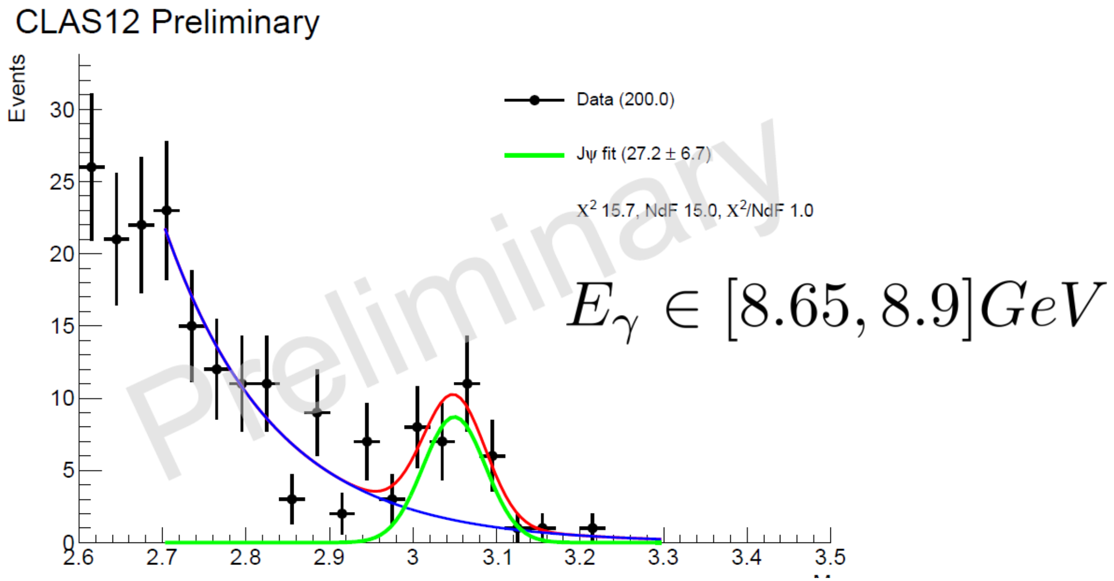
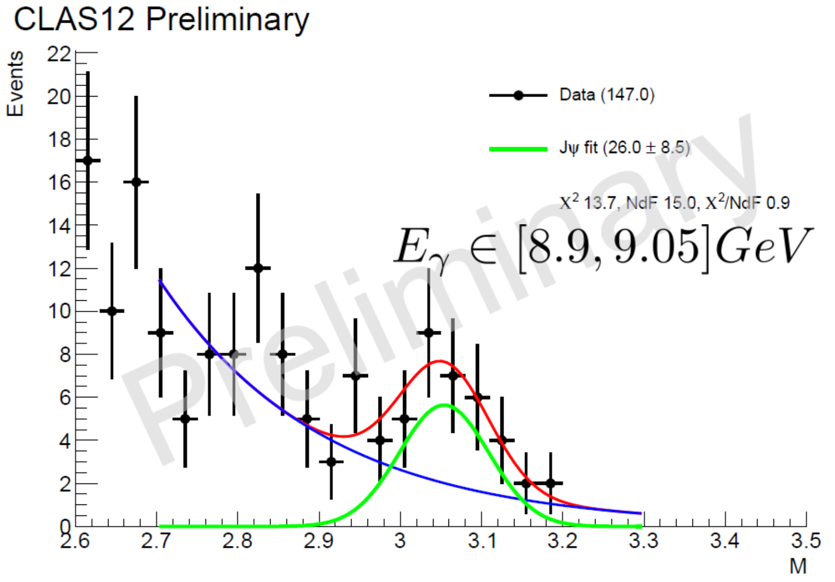
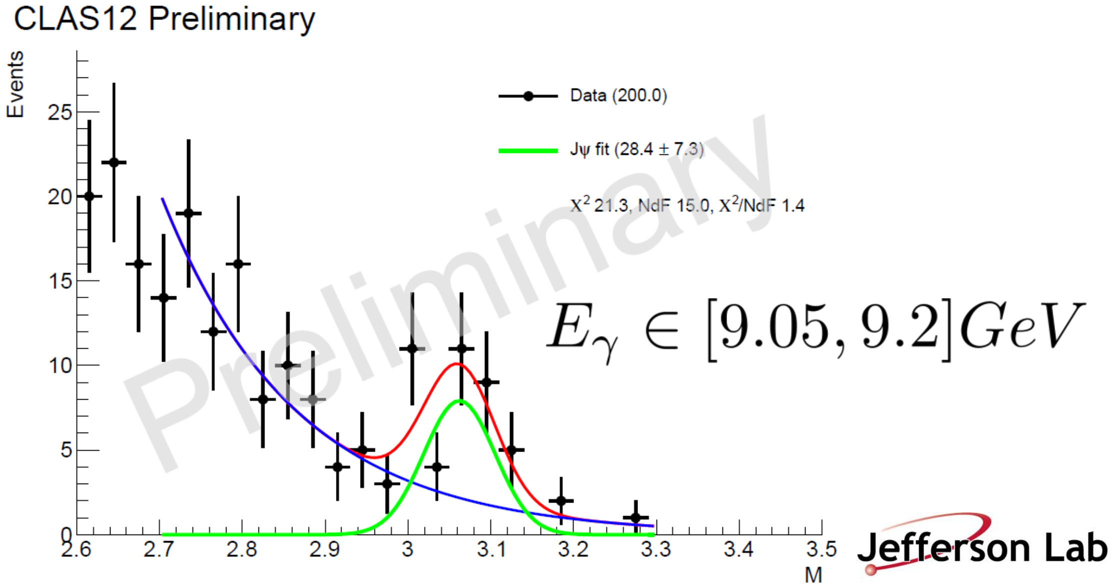
All Data fits









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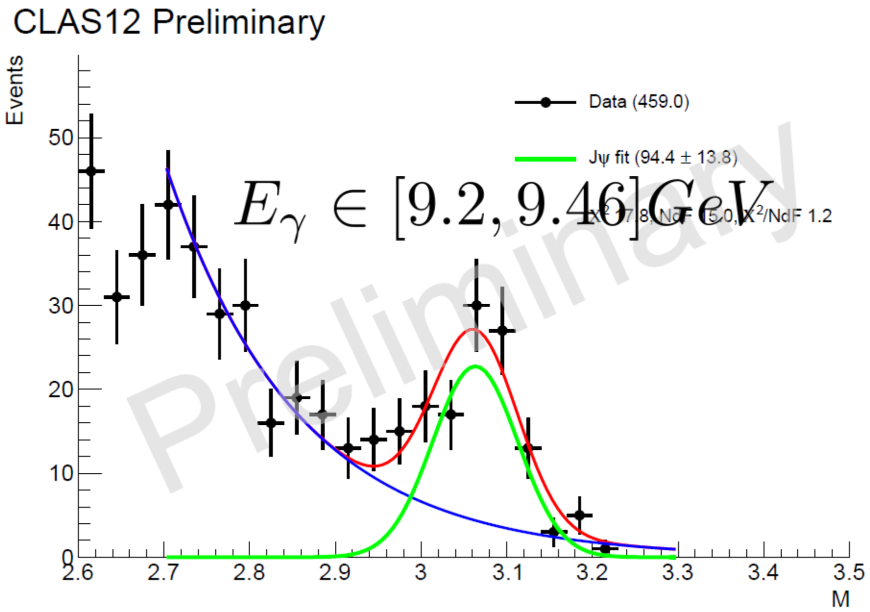

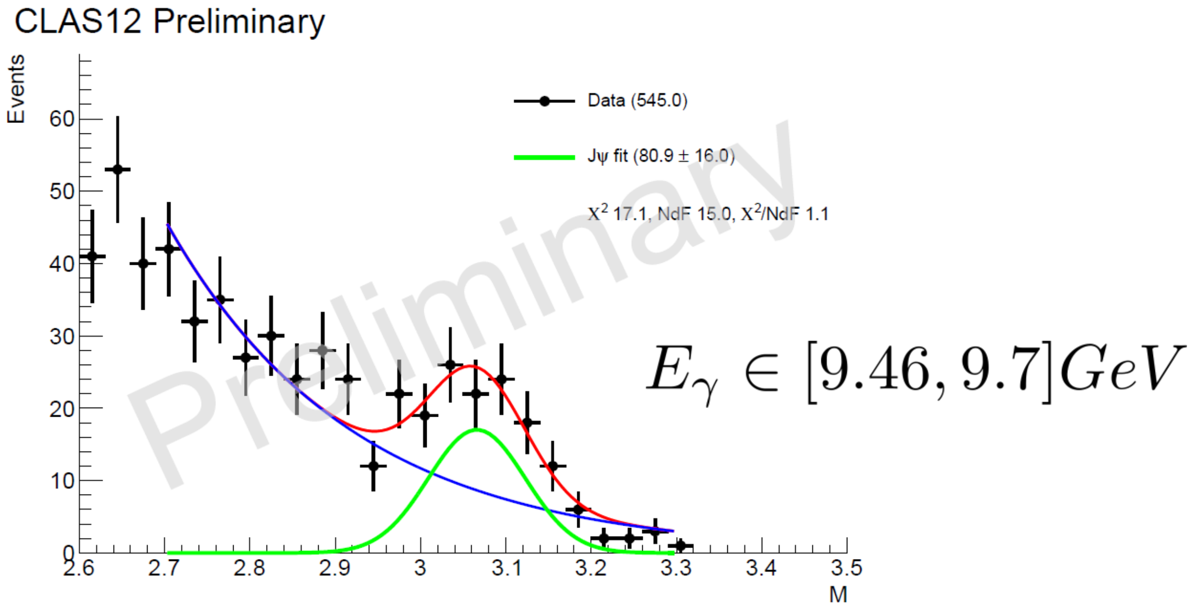

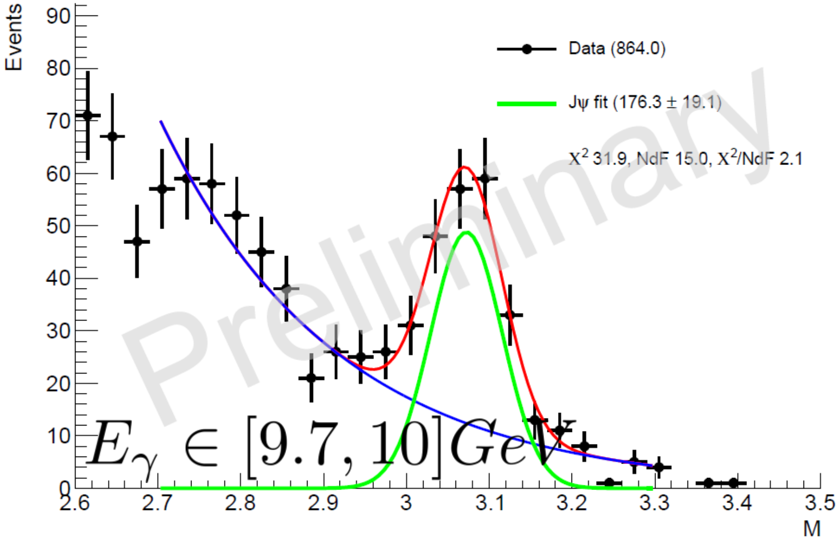

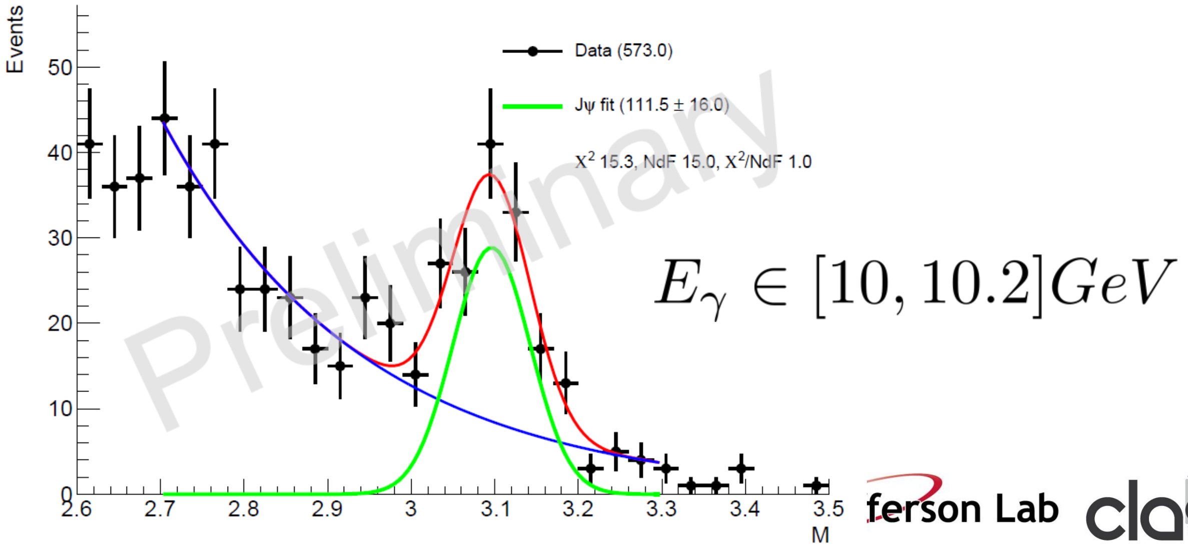

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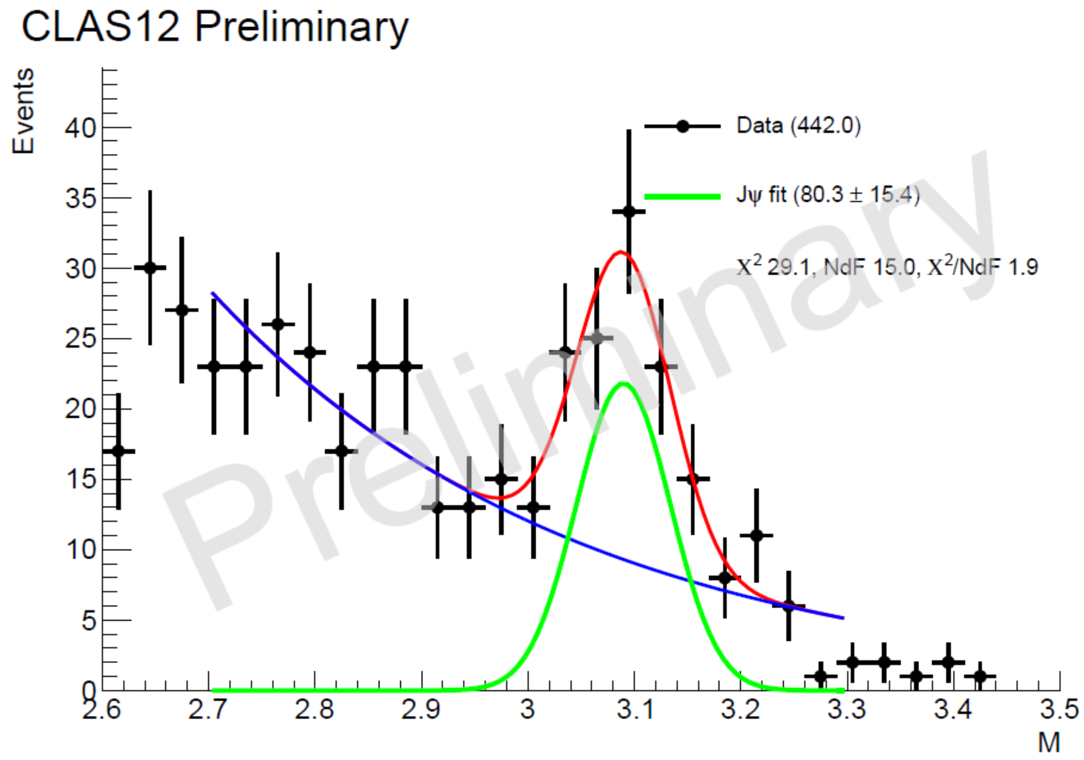
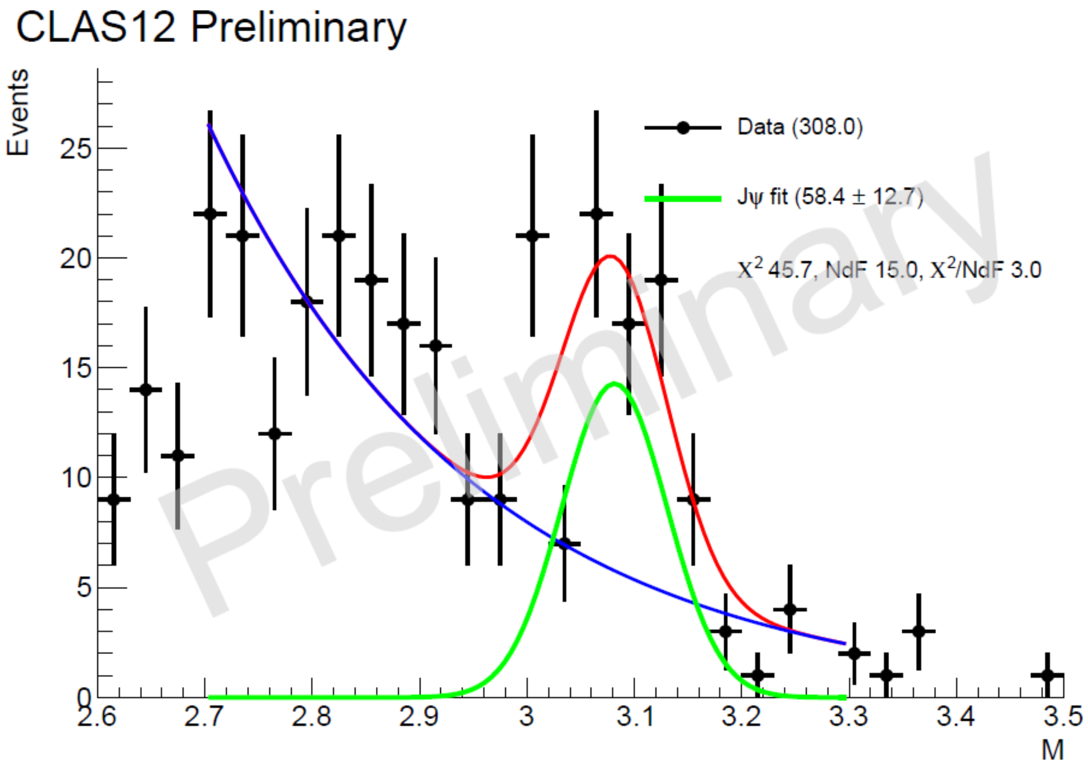
All Data fits



$E_\gamma \in [10.2, 10.4] GeV$



$E_\gamma \in [10.4, 10.6] GeV$

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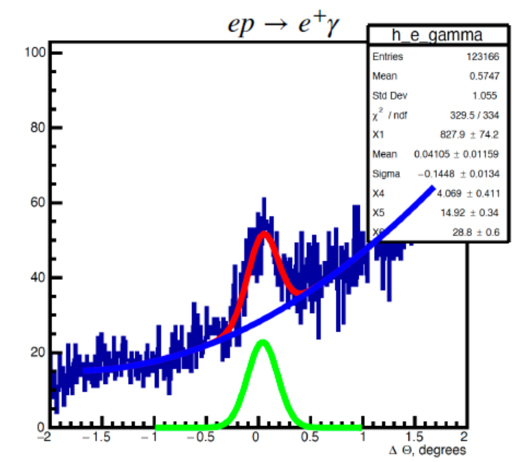
Lepton PID using AI

- Multiple evidences for large contamination from pions in the positron sample at high momenta (P>4.5 GeV)
- We developed a PID algorithm to use on top of the EB PID for leptons (electron, positron, muon(soon))
- Multivariate classifier using calorimeter responses only
  - Extension to Pass2 to the work that was done for the Pass1 TCS analysis

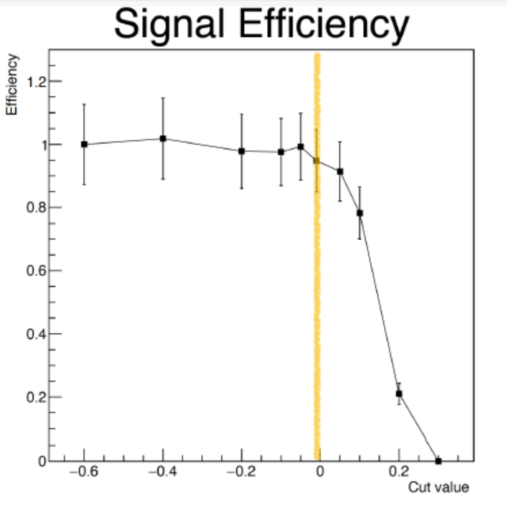
- One classifier per configuration and lepton flavor (6 in total)
- Soon available through Iguana
- Trained on simulation and validated on data

Work by Mariana Tenorio

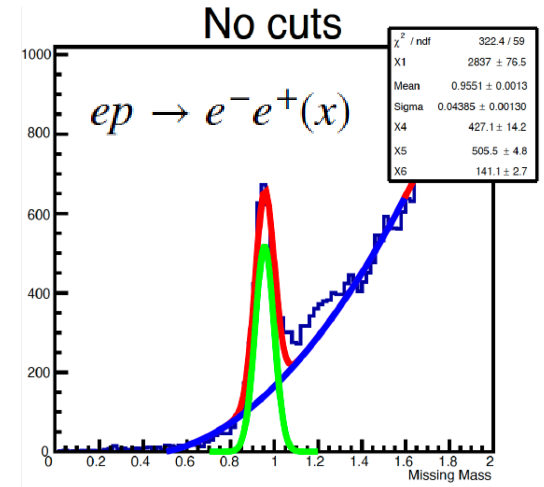
Signal efficiency validation on data

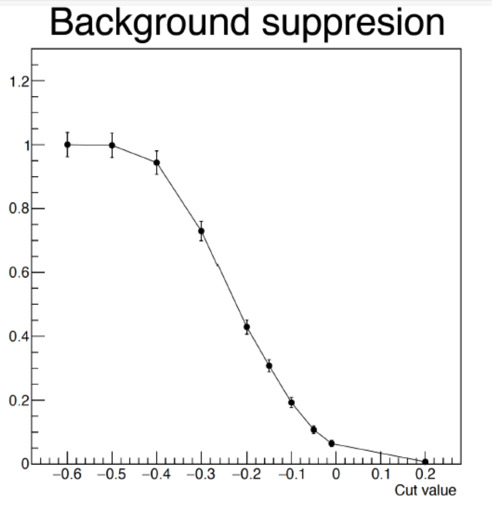


All plots from Mariana Tenorio

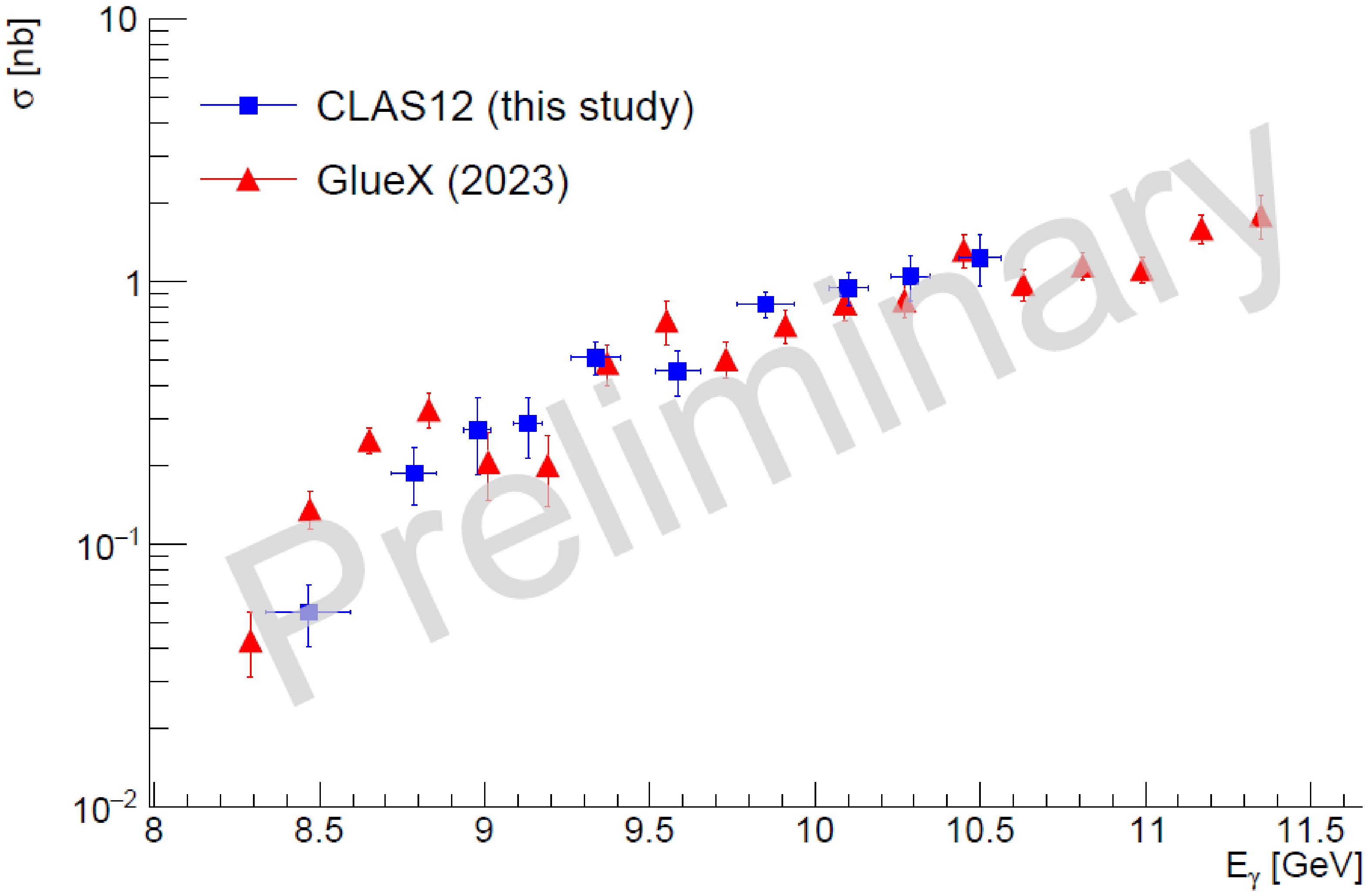


Background rejection validation on data

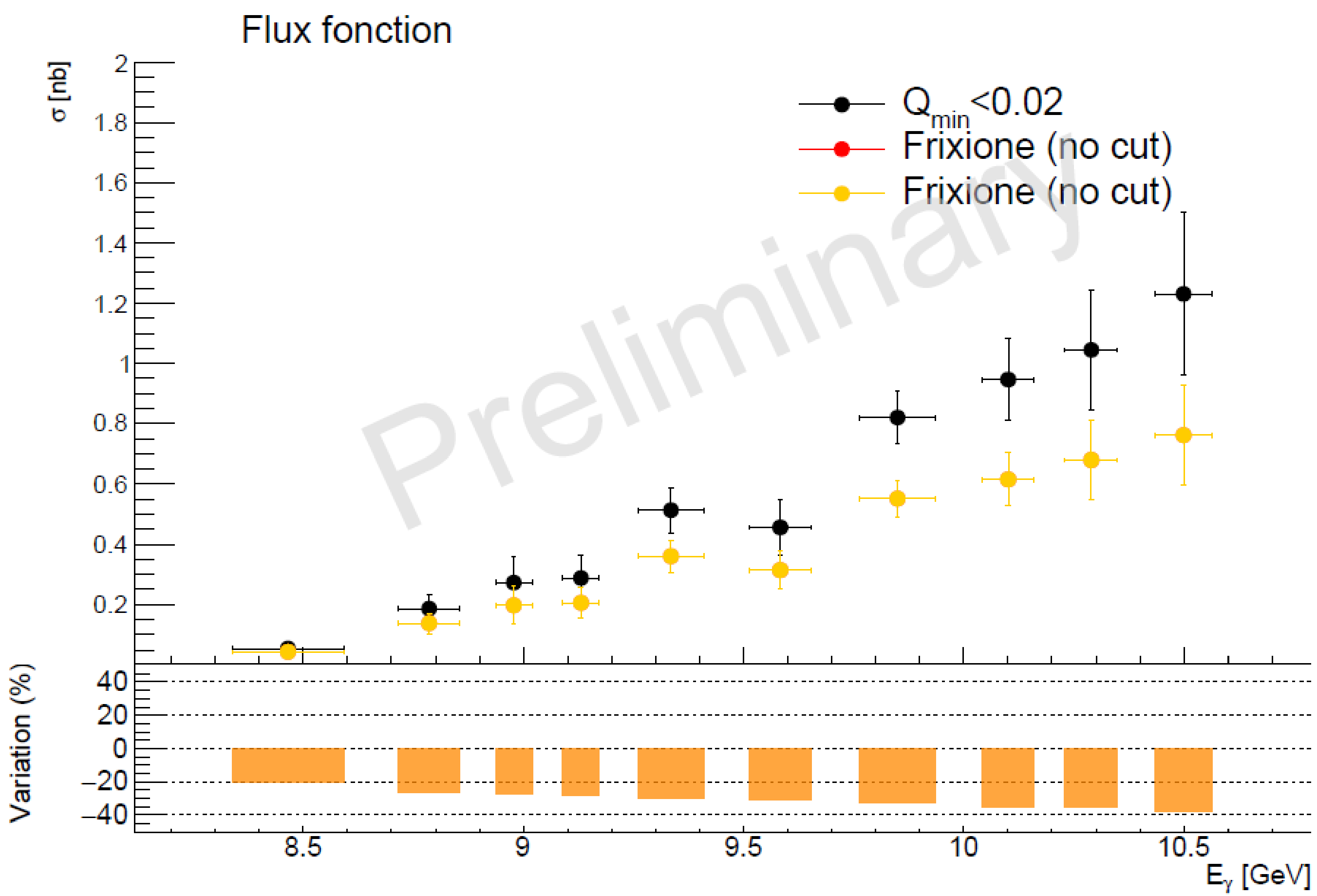


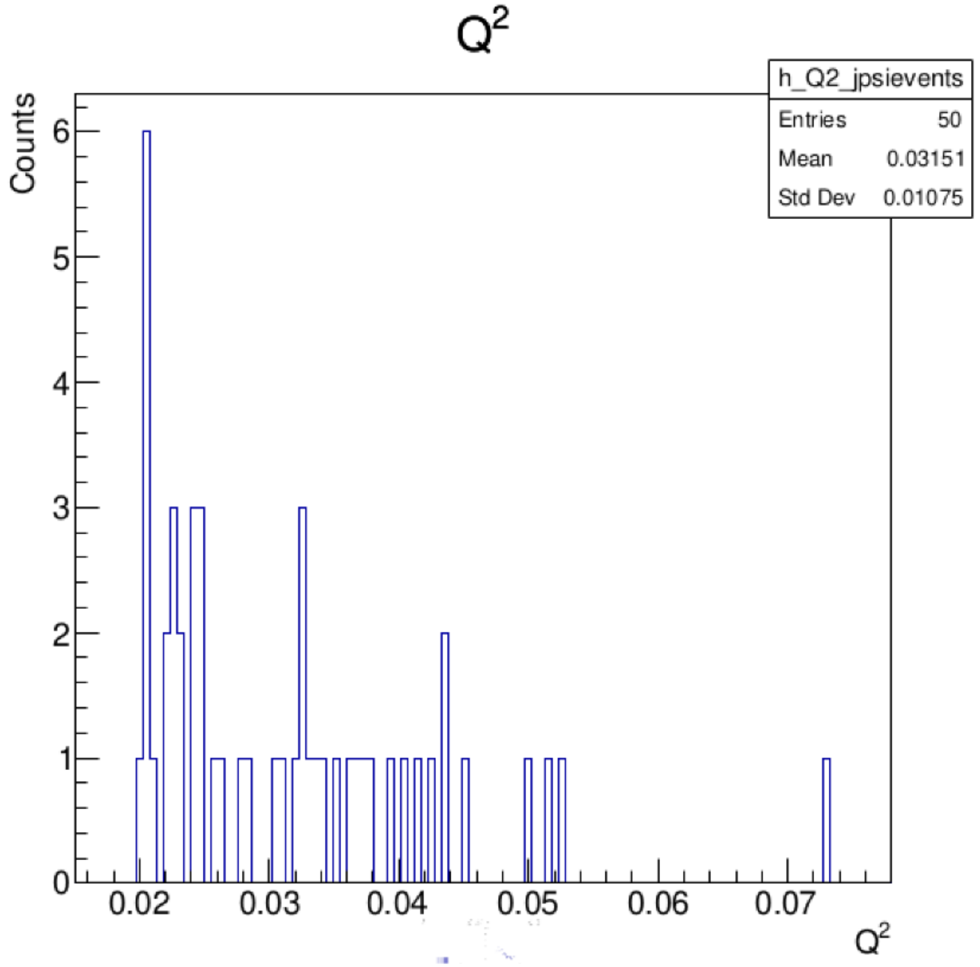


Log scale results



Effect of using Frixione Flux

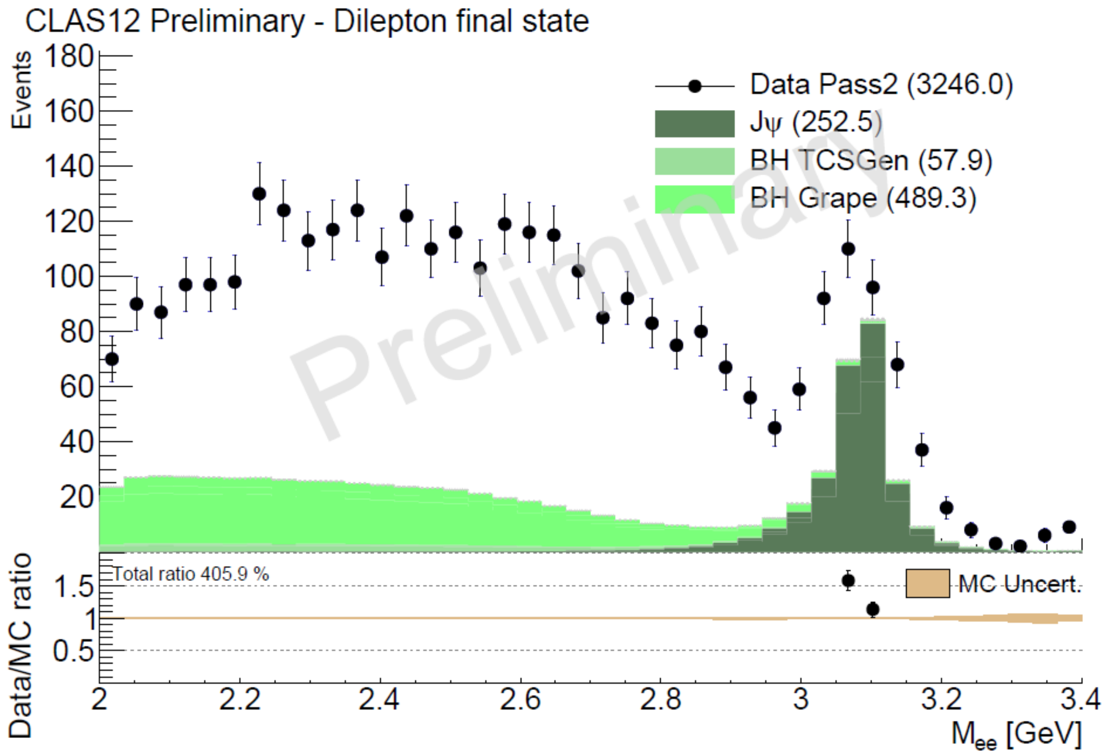


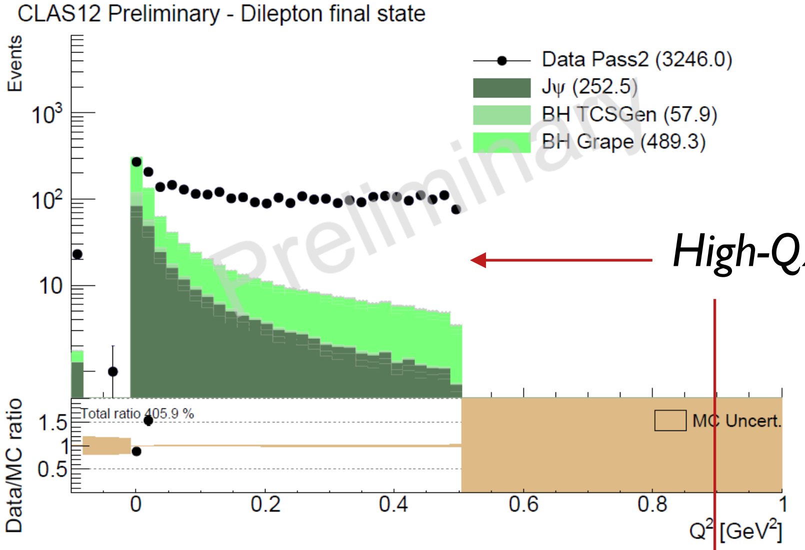


IV – Background modelisation and normalization

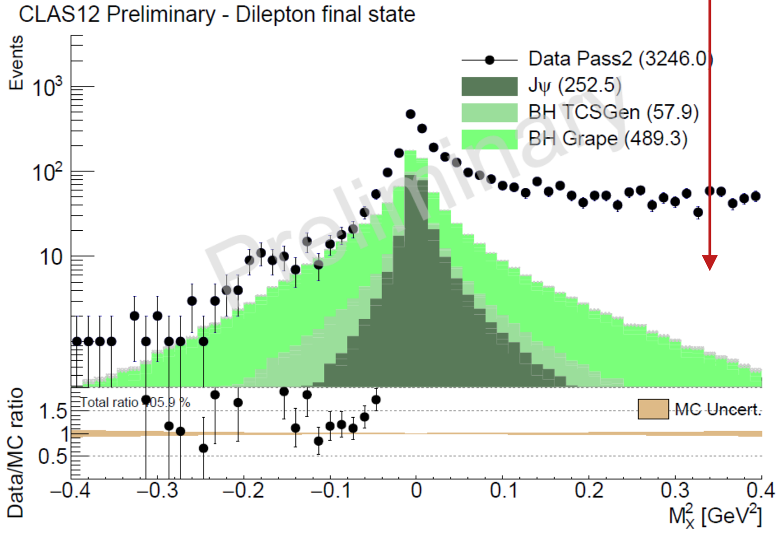
Comparison data/MC – Fall 2018 inbending

- Plotting conventions
  - Color-filled histograms are *stacked,* ie they show the total number of events with contributions for different channels "on top of each other"
  - Marker histograms are *not stacked* and simply superimposed





High-Q2 background

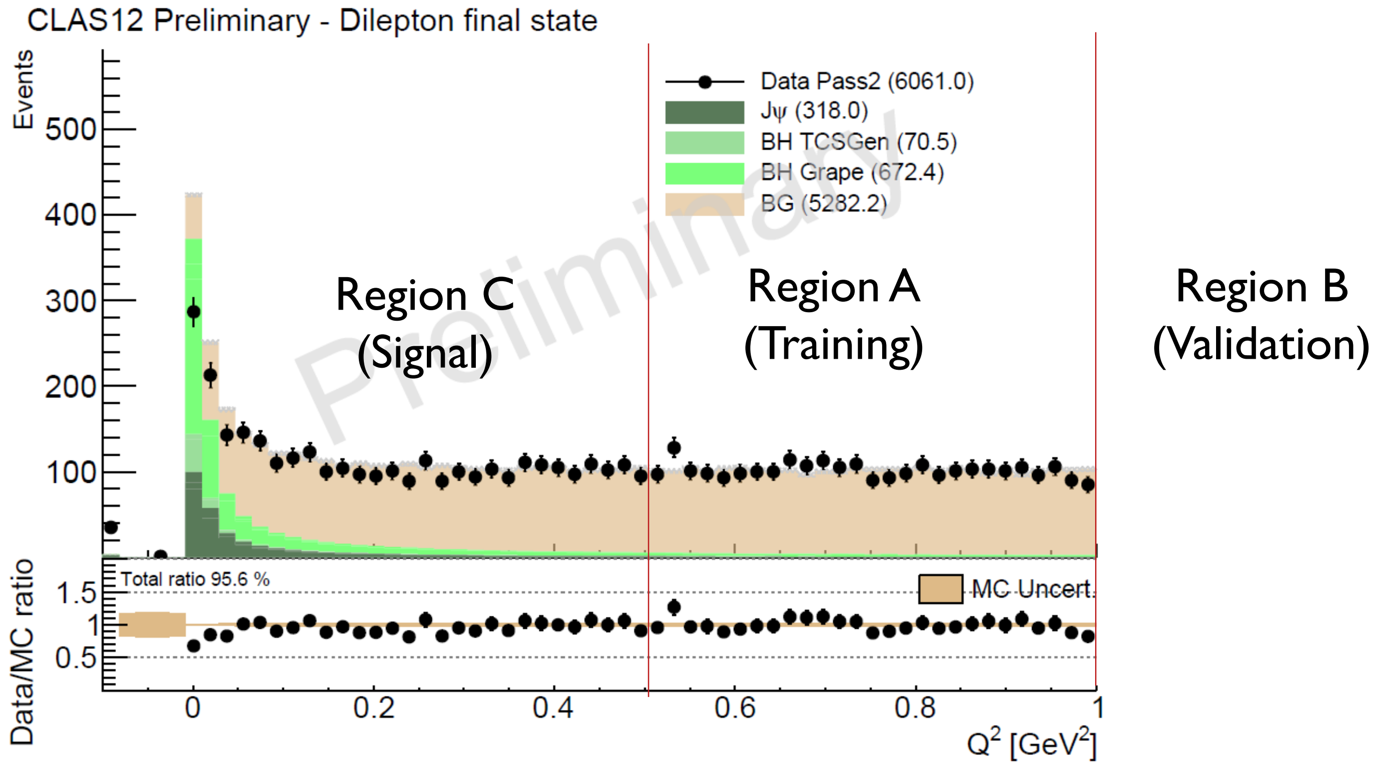


n Lab

Overall strategy for background modelization

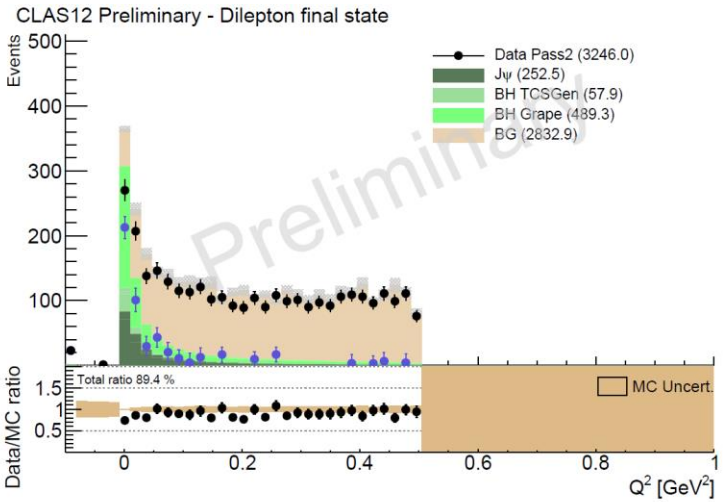
1) Event mixing
   - From data randomly select electron, positron, proton (from different events)
   - Construct kinematics and make sure they are within the region of interest

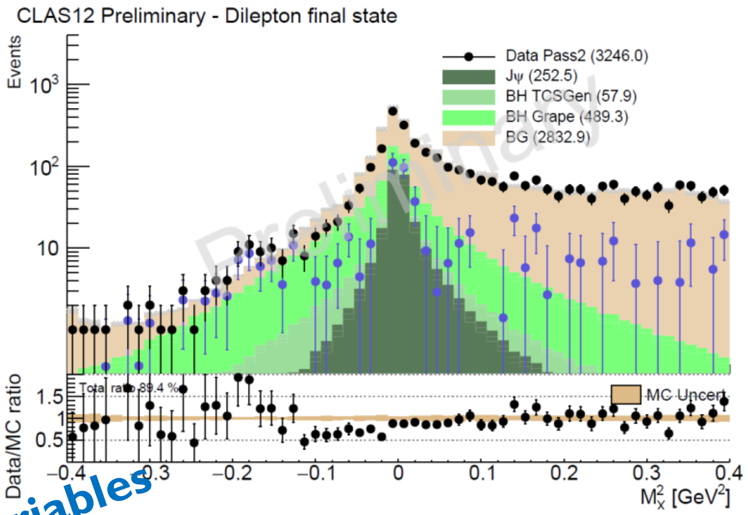
   (M_{ee}>2 GeV, $|MM|^2$<0.4 GeV^2, Q^2<2 GeV^2)
2) Reweight events to match data in the training region
3) Validate the weights on region B
4) Apply weights on region C and obtained BG-subtracted yields

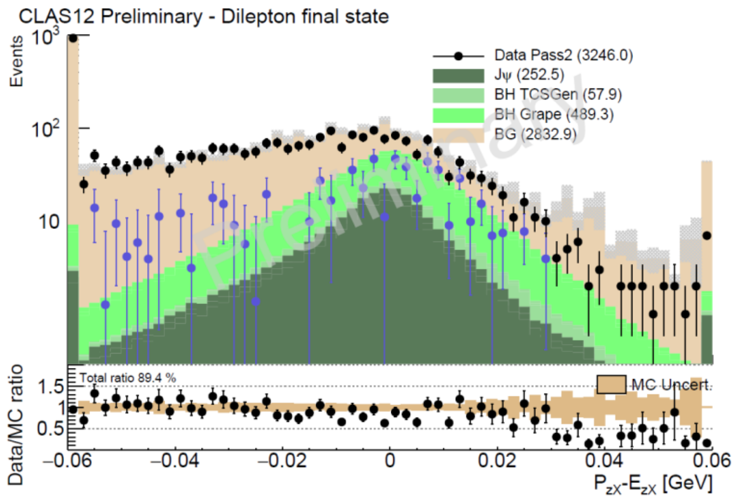


Full comparison data/MC – Fall 2018 inbending (1)

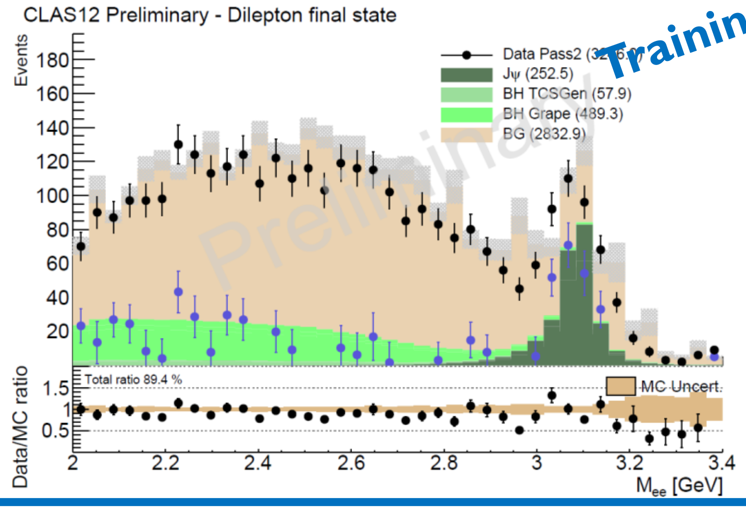
$Q^2 \in [0.0, 0.5] GeV^2$ Region C (Signal)

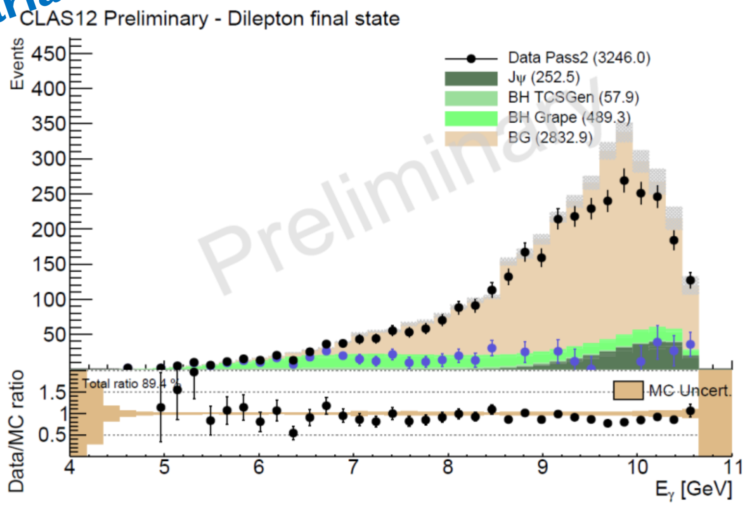


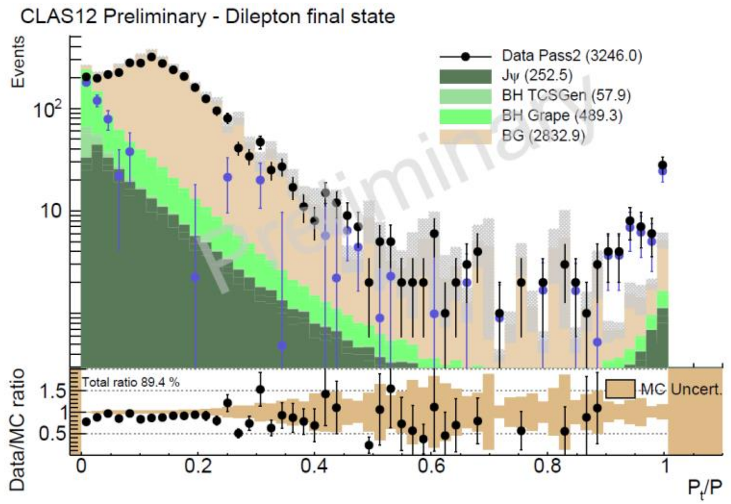




Training variables







Normalization factor

- Normalization factor can be computed as:

$$\omega_c = \frac{N_{Data} - N_{BG}}{N_{SIM\ \ BH}}$$

- Results:
  - Fall 2018 inbending – 68%
  - Spring 2019 inbending – 69%
  - Fall 2018 outbending – to be continued

- In the following, we use a normalization factor of 0.7

Spring 2019