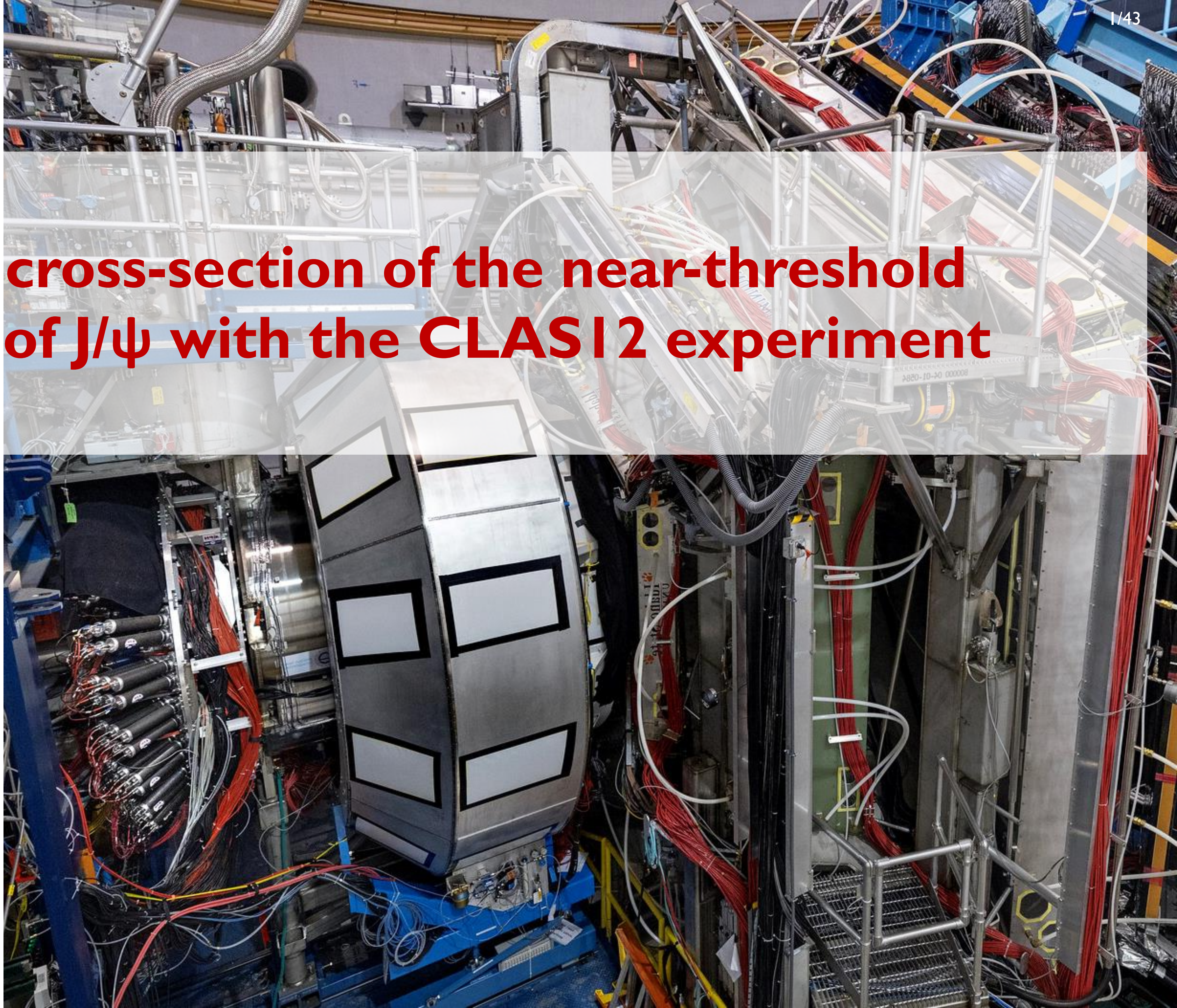
Extraction of the cross-section of the near-threshold photoproduction of J/ψ with the CLAS12 experiment



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SoLID Opportunities and Challenges of Nuclear Physics at the luminosity frontier

Argonne National Laboratory

June 17th 2024

Motivations and previous results

Photoproduction of the J/ψ meson near its production threshold

J/ψ photoproduction near the energy threshold

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

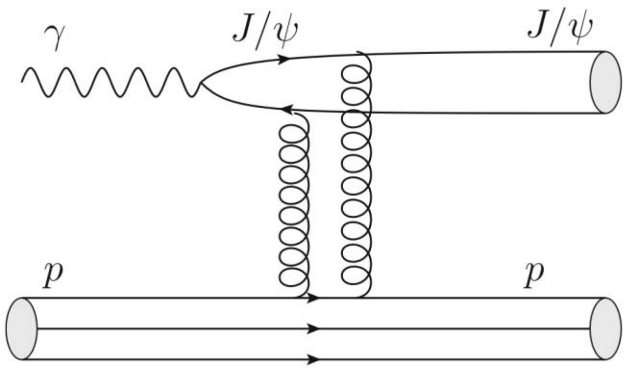
- At the energy production threshold, the t-dependence of the cross-section allows to access gluon Gravitational Form Factors (GFFs) and the mass radius of the nucleon.

Cross-section

$$\frac{d\sigma_{\gamma p\to J/\Psi p}}{dt} = \frac{1}{64\pi s}\frac{1}{|p_{\mathrm{cm}}|^2}|\mathcal{M}_{\gamma p\to J/\Psi p}(t)|^2$$

Amplitude

$$\mathcal{M}_{\gamma p\to J/\Psi p}(t) \propto \langle p'|T^g_{\mu\mu}|p\rangle$$



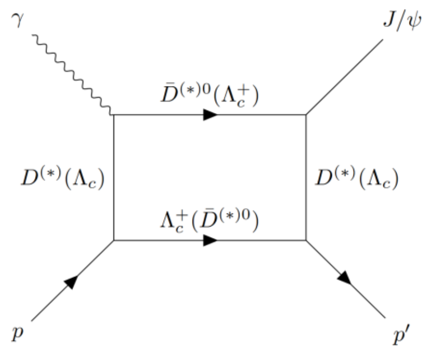
Matrix element

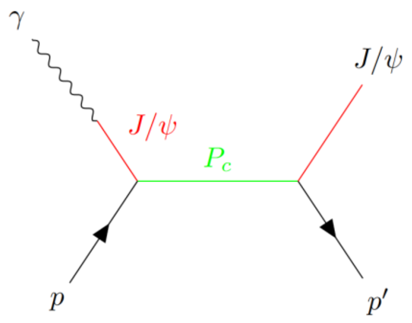
$$\langle p', s'|\hat{T}^a_{\mu\nu}(x)|p, s\rangle = \bar{u}'\left[A^a(t)\frac{\gamma_{\{\mu}P_{\nu\}}}{2} + B^a(t)\frac{iP_{\{\mu}\sigma_{\nu\}\rho}\Delta^\rho}{4m} + D^a(t)\frac{\Delta_\mu\Delta_\nu - g_{\mu\nu}\Delta^2}{4m} + m\bar{c}^a(t)g_{\mu\nu}\right]ue^{i(p'-p)x}$$

Coupled channels and pentaquarks

- The previous considerations rely on the application of Vector Meson Dominance.
- Thus the contribution from open-charm meson channels and potential pentaquark must understood or ruled-out.

→ *Total cross-section as a function of photon energy*





See Y. Guo, X. Ji, Y. Liu, "QCD analysis of near-threshold photon-proton production of heavy quarkonium", PRD (2021) and D. E. Kharzeev, "Mass radius of the proton", PRD (2021)

Recent results from JLab

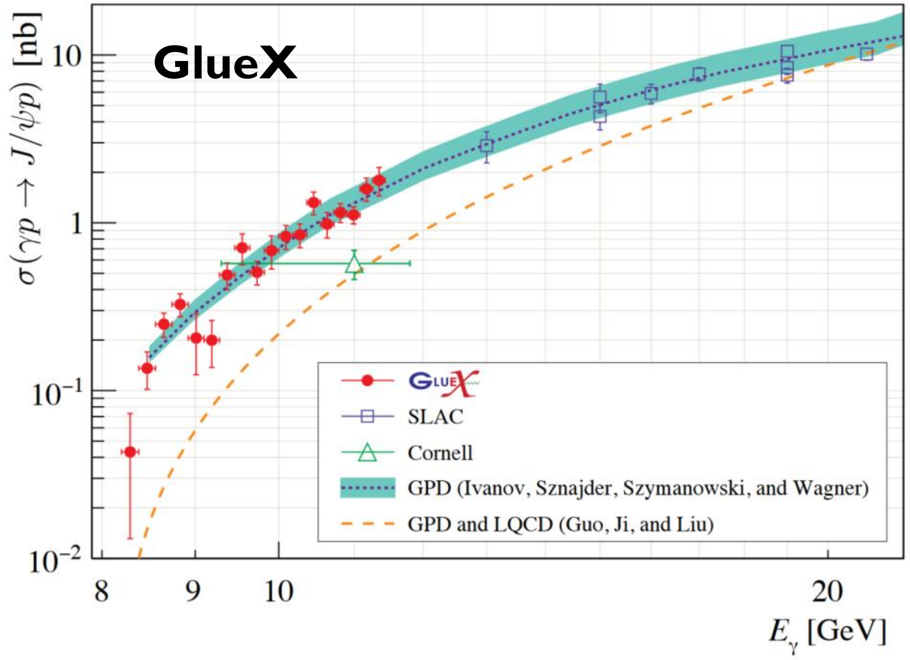


Figure from "Measurement of the J/ψ photoproduction cross section", S. Adhikari *et al.* (GlueX Collaboration). Phys. Rev. C 108, 025201, 2023, arXiv:2304.03845

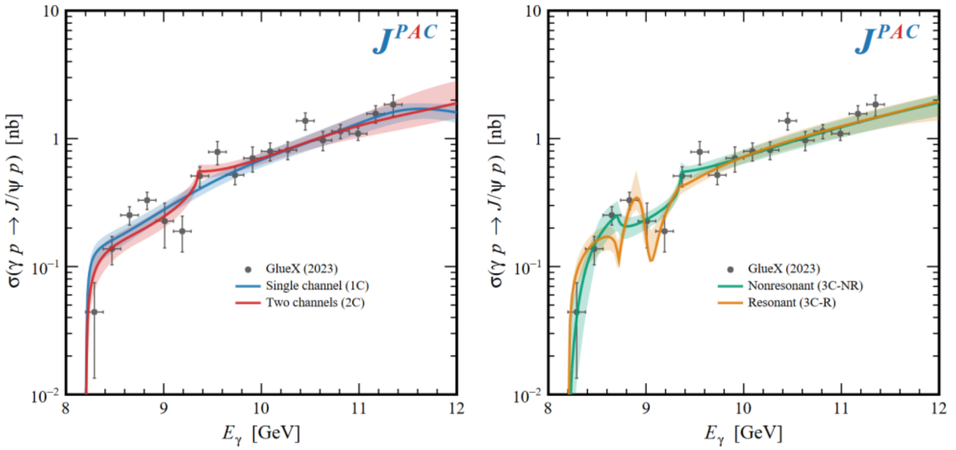
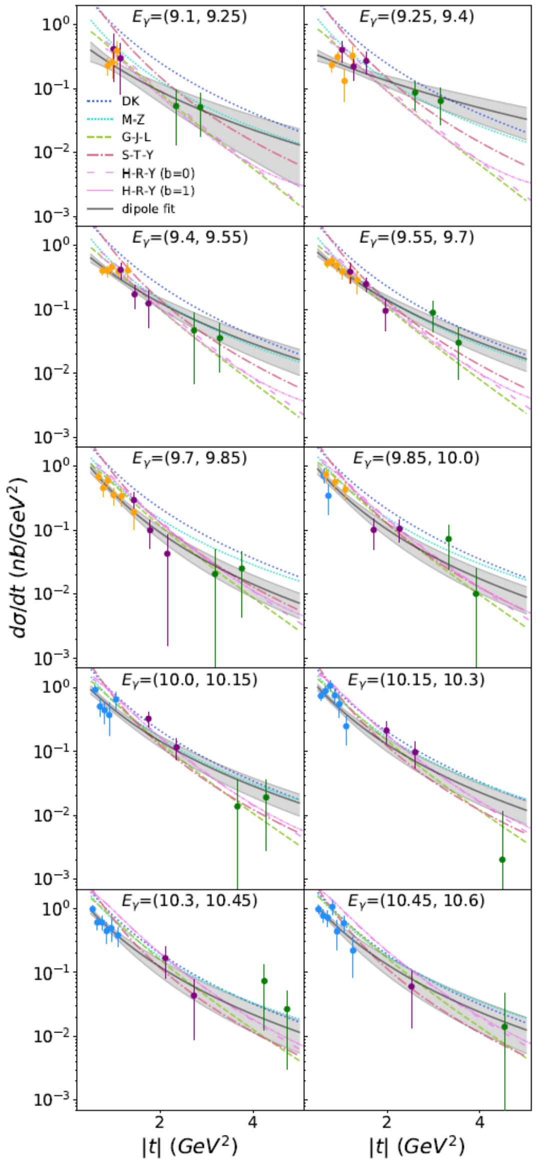
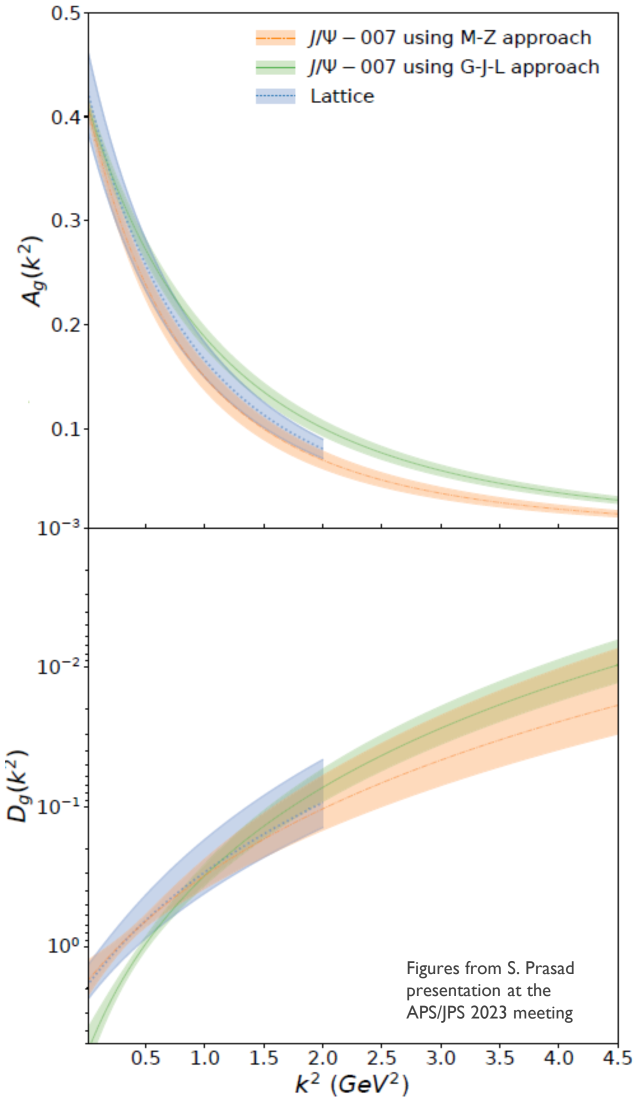


Figure in "Dynamics in near-threshold J/ψ photoproduction", D. Winney, C. Fernandez-Ramirez, A. Pilloni, A. N. Hiller Blin et al. (JPAC), Phys. Rev. D 108 (2023) 5, 054018 arXiv:2305.01449





Figures from S. Prasad presentation at the APS/JPS 2023 meeting

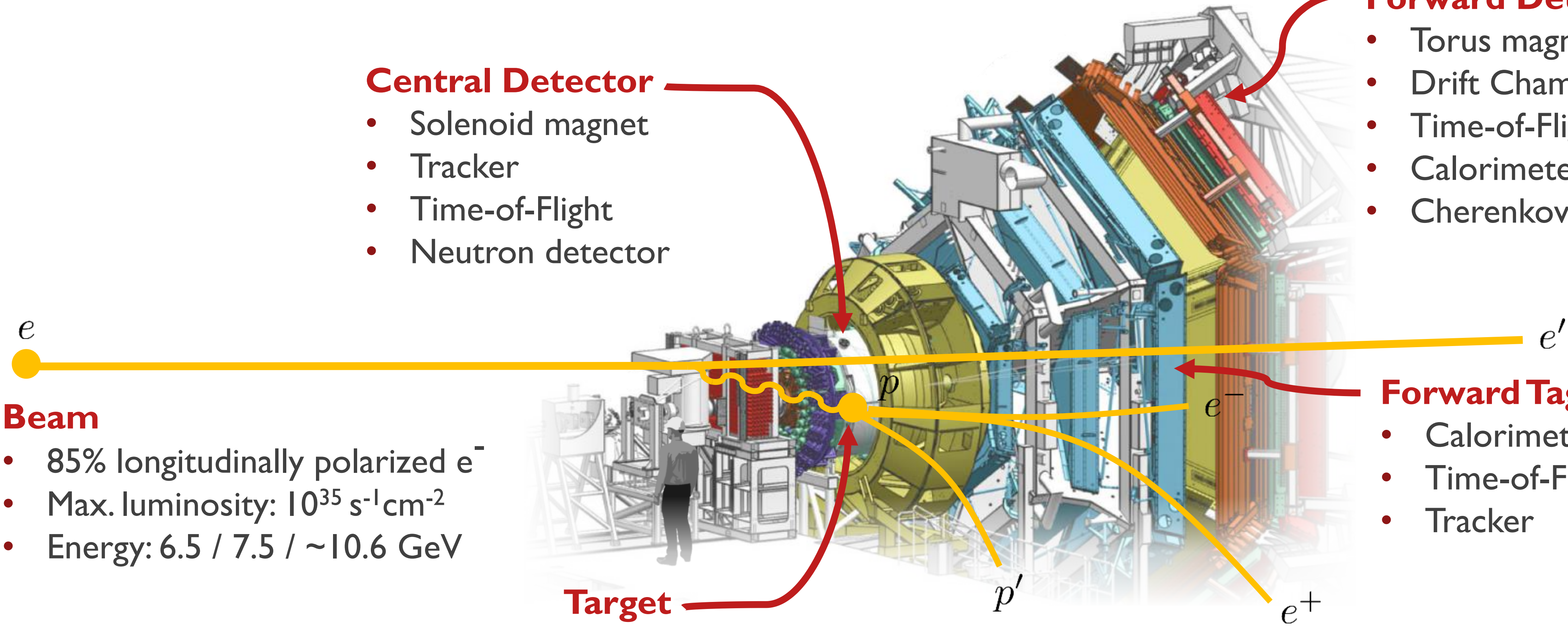
Figure from "Determining the gluonic gravitational form factors of the proton". Duran, B., Meziani, ZE., Joosten, S. *et al. Nature* 615, 813–816 (2023).

Experimental setup and analysis strategy

The CLAS12 detector package

Central Detector
- Solenoid magnet
- Tracker
- Time-of-Flight
- Neutron detector

Forward Detector
- Torus magnet
- Drift Chambers
- Time-of-Flight
- Calorimeters
- Cherenkov counters



Beam
- 85% longitudinally polarized e^-
- Max. luminosity: 10^{35} $s^{-1}cm^{-2}$
- Energy: 6.5 / 7.5 / ~10.6 GeV

Forward Tagger
- Calorimeter
- Time-of-Flight
- Tracker

Target
- **Proton**
- **Deuterium**
- Longitudinally pol. H/D
- Nuclear targets (Cu, Sn, He)

Exclusive dilepton event selection

What we want to measure

$$\gamma p \to e^+ e^- p'$$

What we can measure with CLAS12

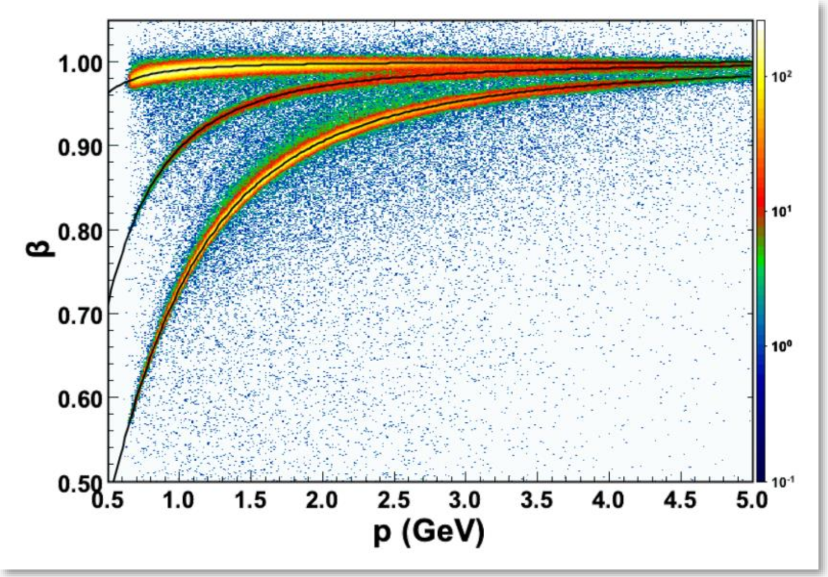
$$ep \to (e')\gamma p \to (e')e^+ e^- p'$$

Exclusive dilepton event selection: Particle identification

1) CLAS12 PID + Positron NN PID

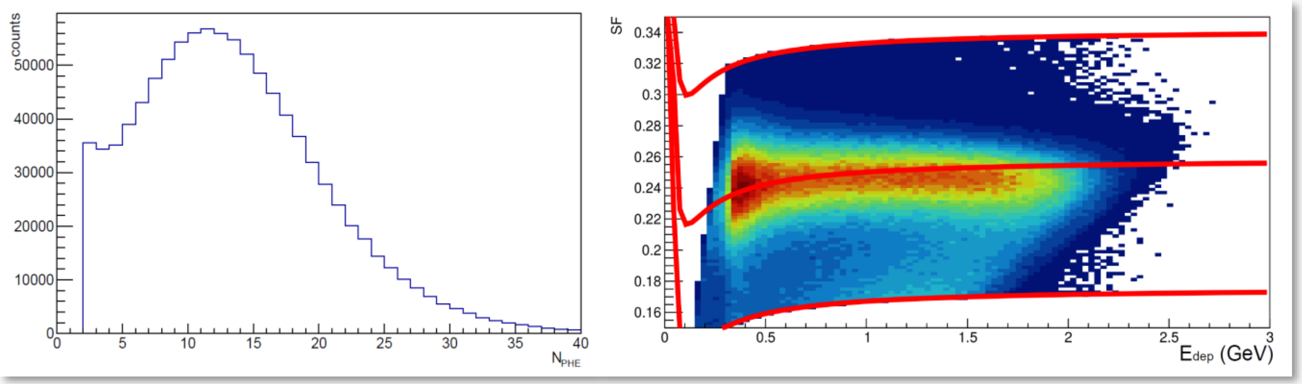
$$ep \to (e')\gamma p \to (X)e^+e^-p'$$

Proton identification



Lepton identification

Cherenkov counters + Calorimeter energy deposition



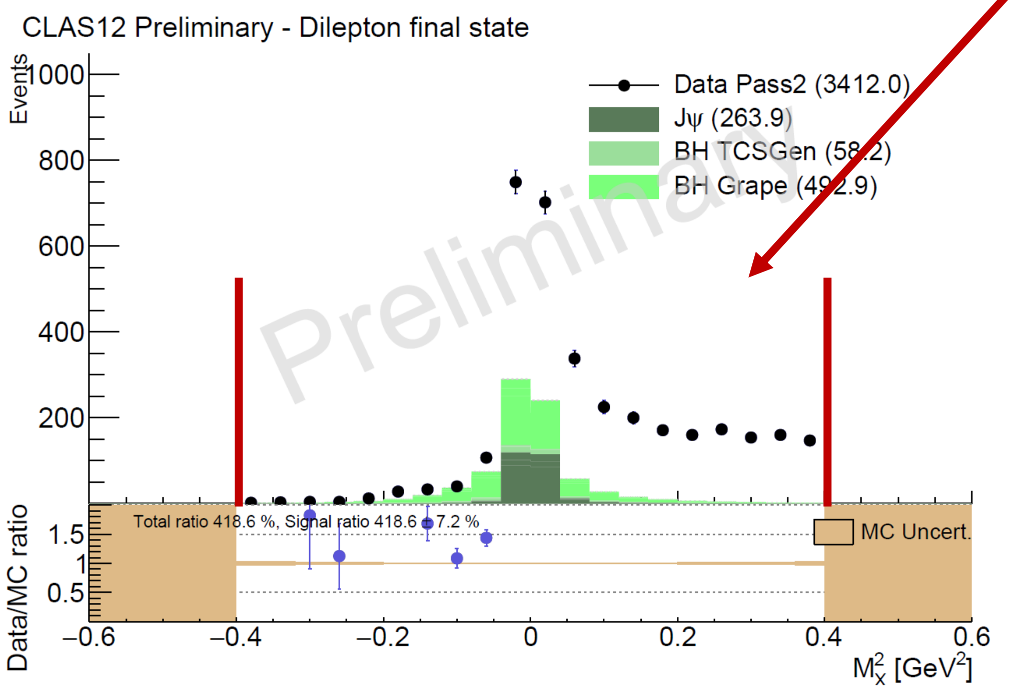
$$Sampling\ Fraction = \frac{E_{dep}}{P}$$

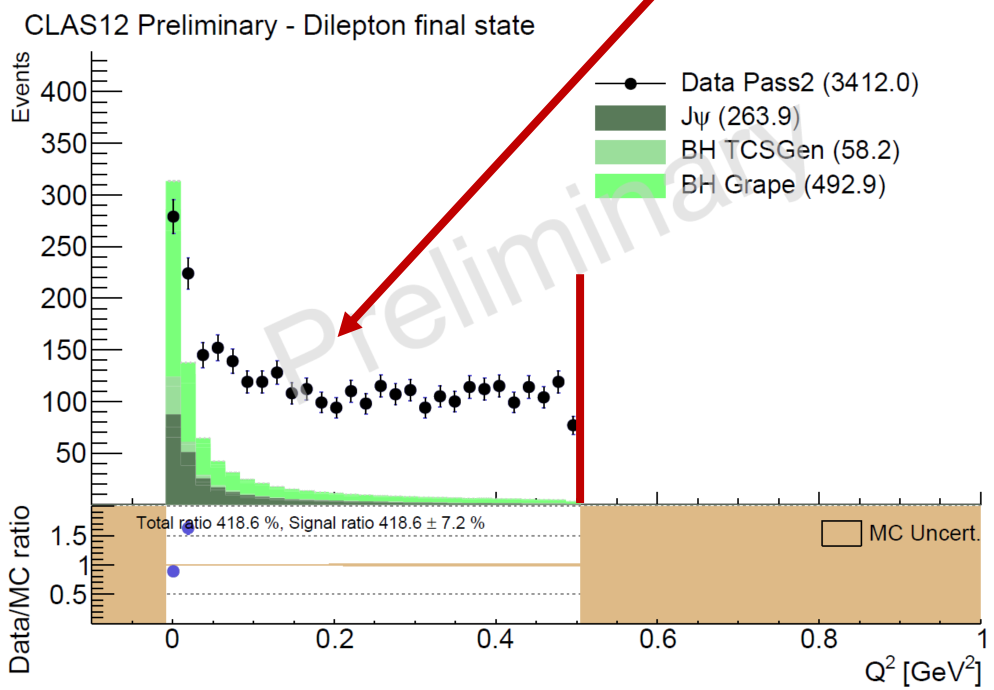
Exclusive dilepton event selection: Exclusivity variables

1) CLAS12 PID + Positron NN PID

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

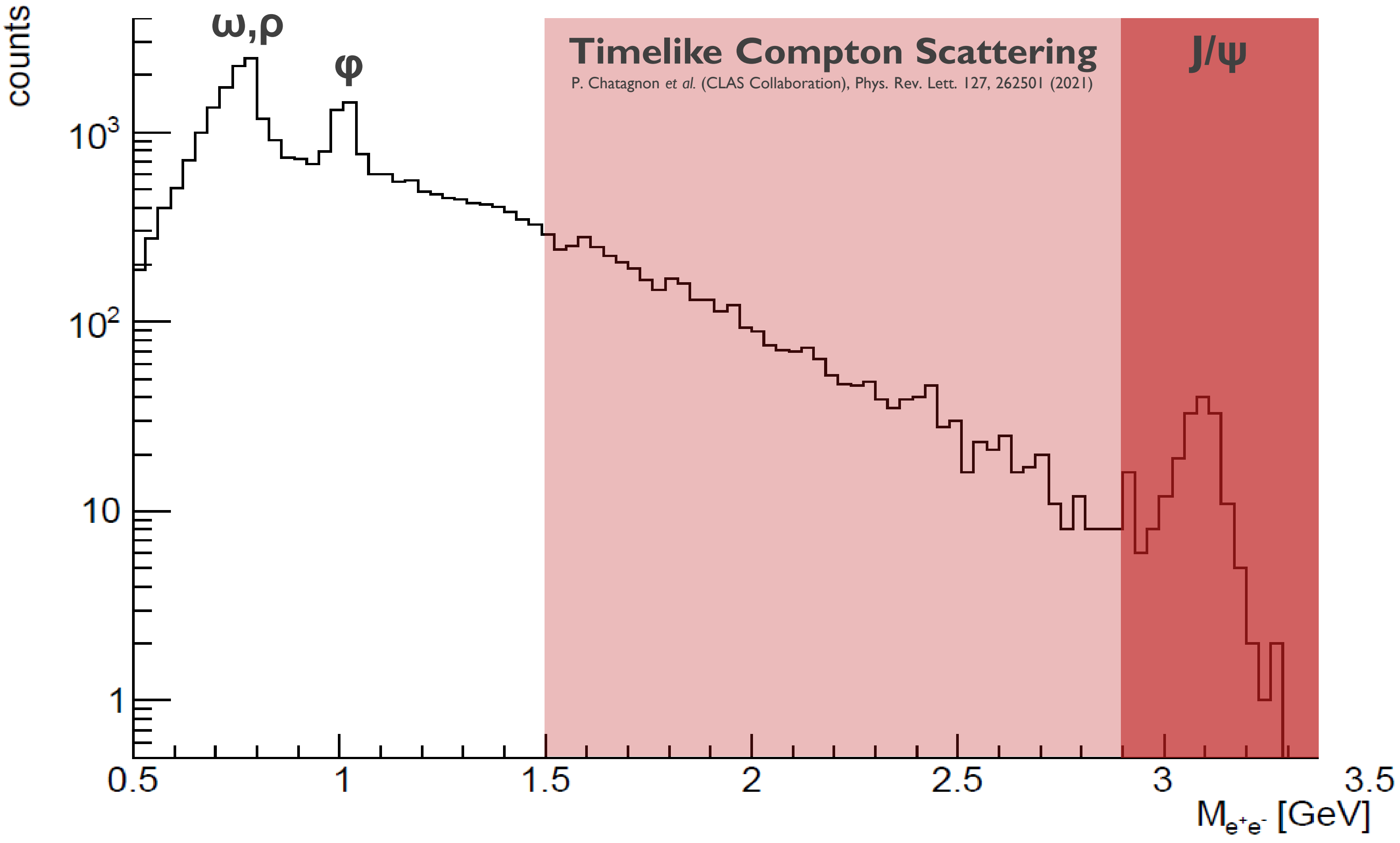
$$p_X = p_{beam} + p_p - p_{e^+} - p_{e^+} - p_{p'} \longrightarrow 2)\ |M_X^2| < 0.4GeV^2 \longrightarrow 3\ )\ Q^2 < 0.5\ \mathrm{GeV}^2$$





Exclusive dilepton invariant mass spectrum

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



Total cross section computation

I)

Number of J/Psi from data

Number of photons and Number of targets

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

Radiative corrections from MC

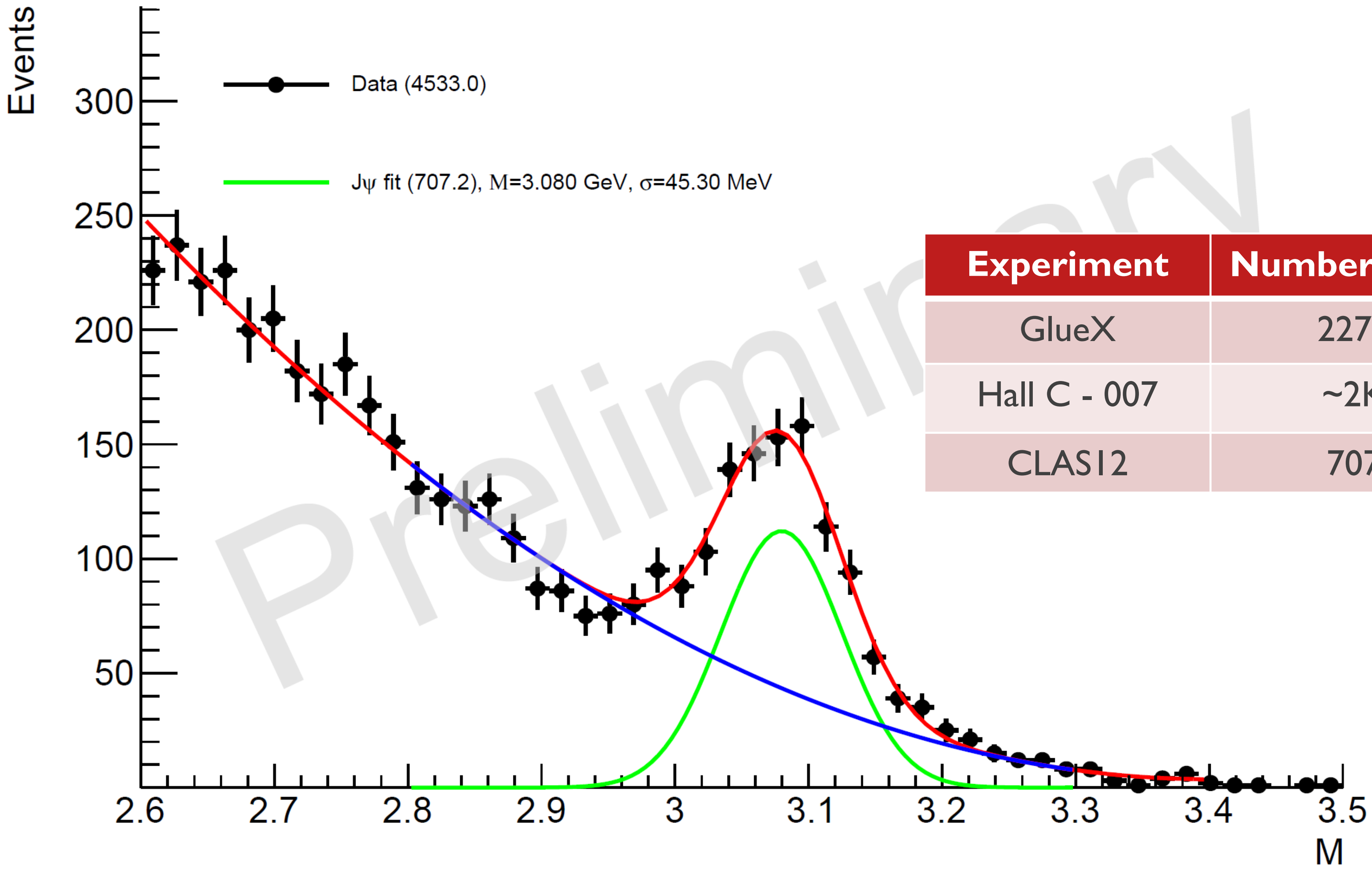
II)

Normalization factor

Branching ratio

Reconstruction efficiency from MC

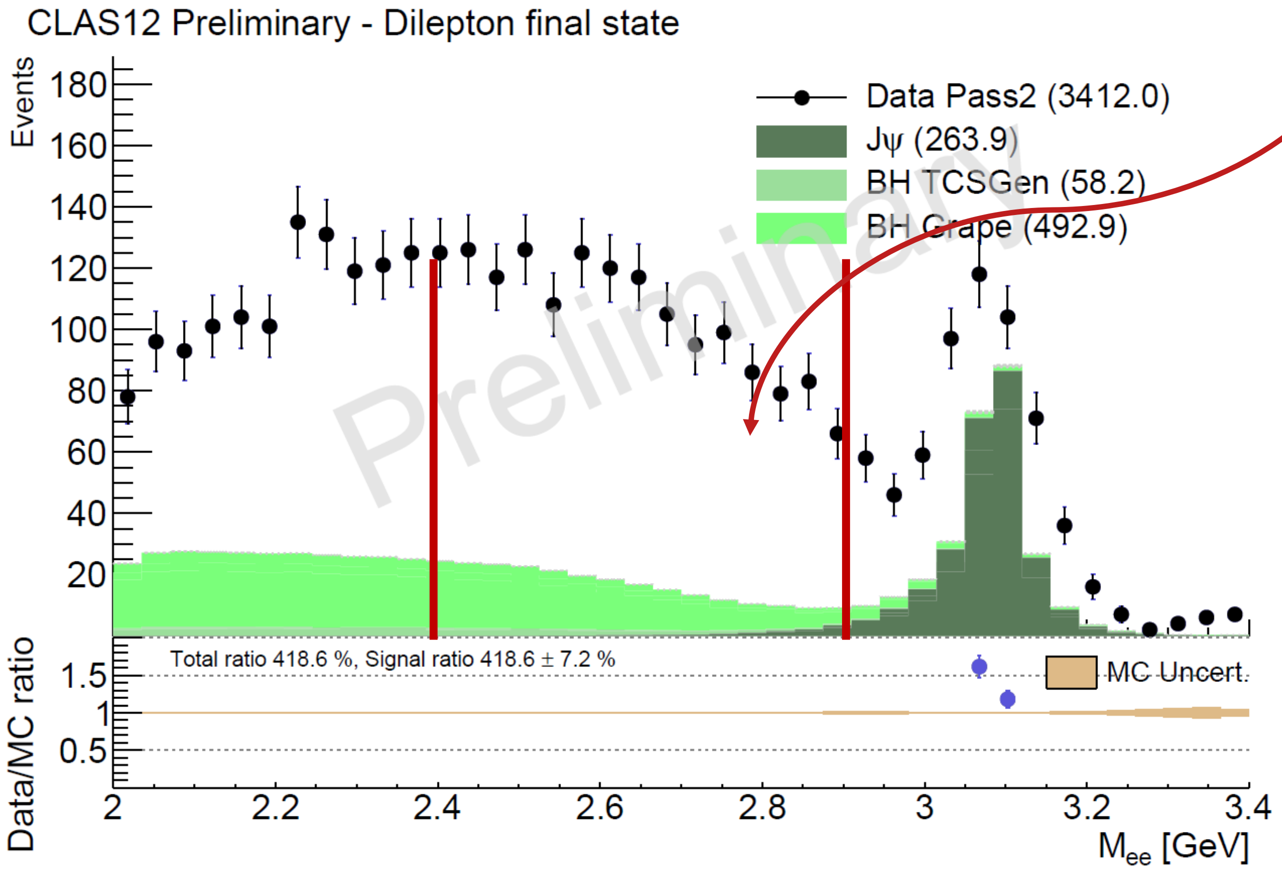
1) Number of J/ψ from data

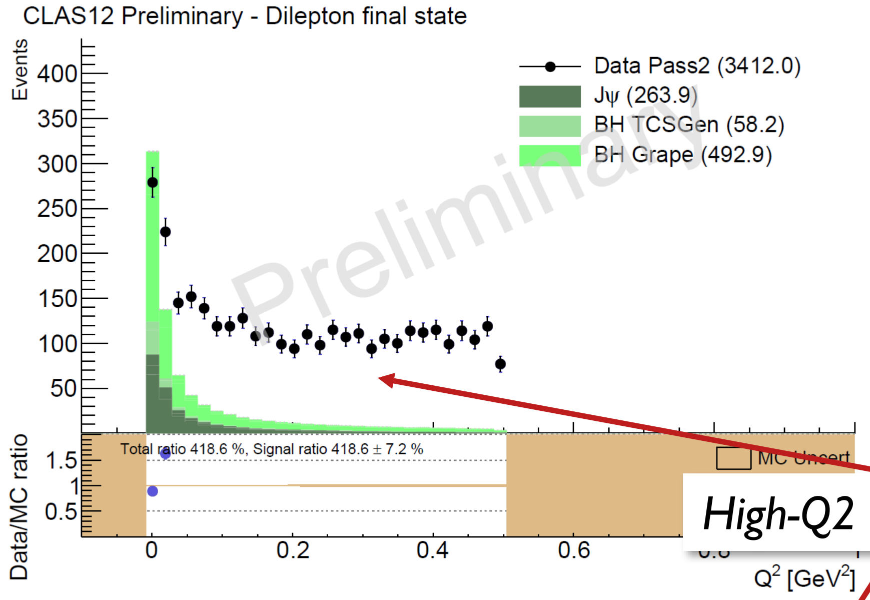


Experiment	Number of J/ψ	Integrated $\mathcal{L}$ (pb^{-1})
GlueX	2270	320.3
Hall C - 007	~2K	
CLAS12	707	113.768

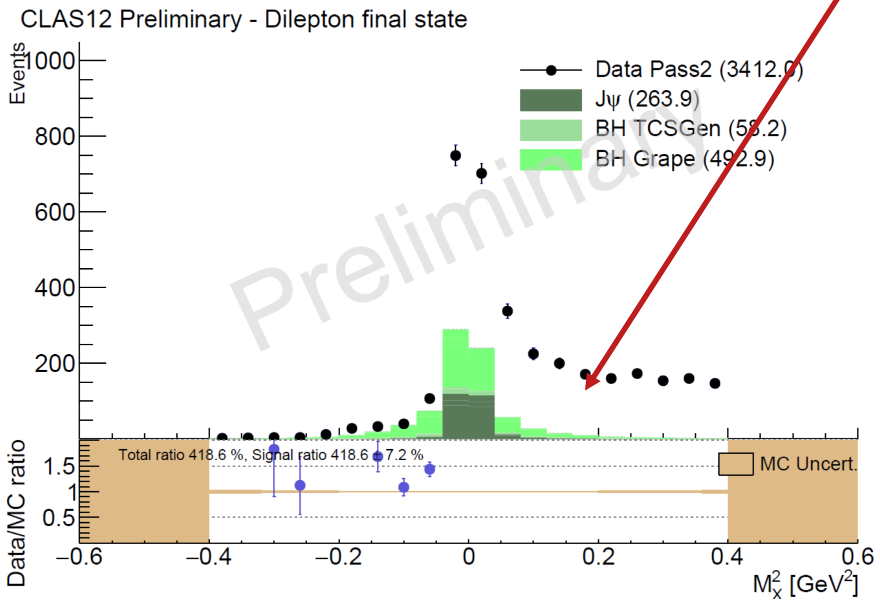
II) Normalization factor - Comparison Data/MC

- Cross-normalization using the continuum Bethe-Heitler events just below the J/ψ peak (from 2.4 GeV to 2.9 GeV).
- ***Requires the complete understanding of all signal and background contributions !***





High-Q2 background



II) Normalization factor - Overall strategy for the background modelization

1) Event mixing procedure:
   - 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)

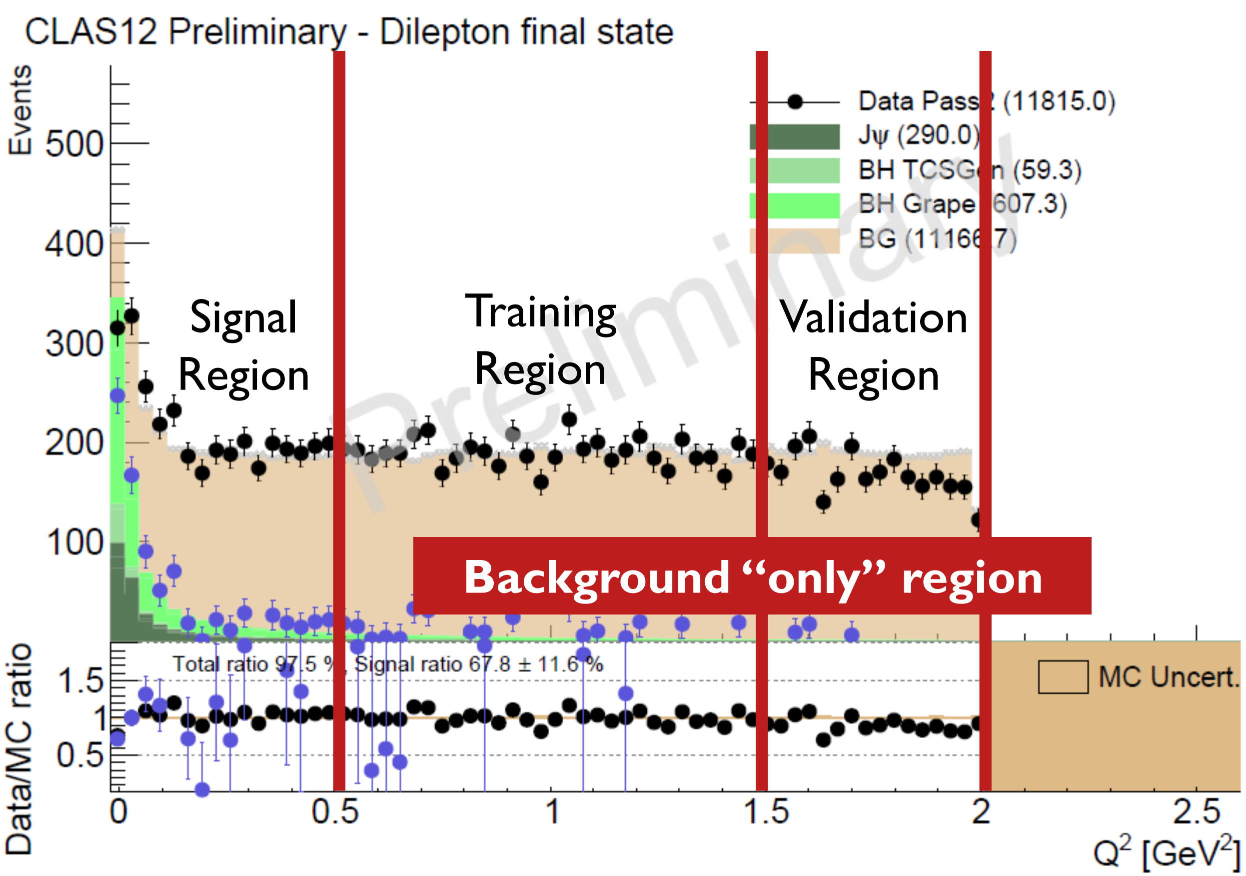
   → *Source sample*

2) Reweight events to match *data in the training region*

   → *Target sample*

3) Validate the weights on the validation region.

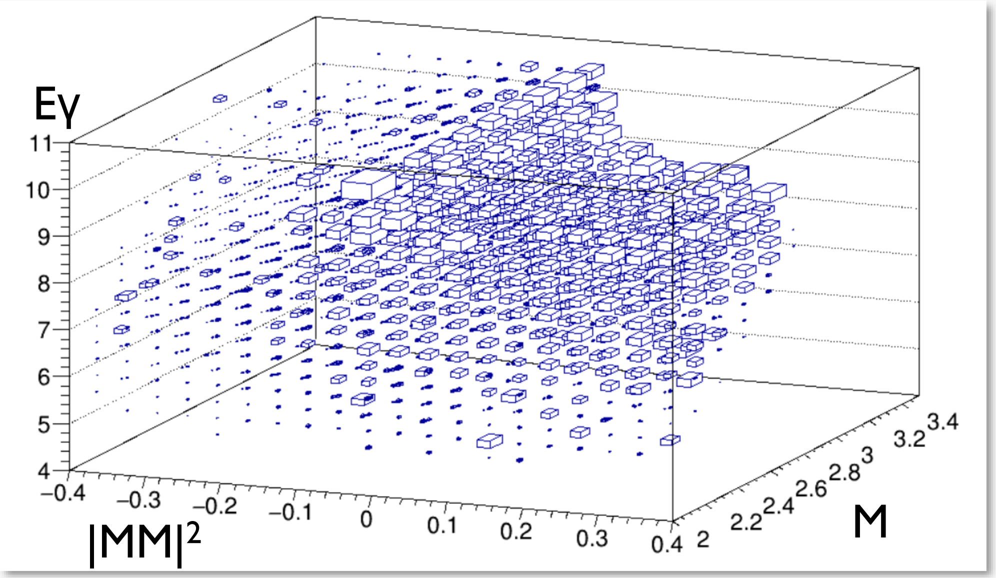
4) Apply weights on the signal region and obtained BG-subtracted yields



II) Normalization factor - Reweighting methods

Binned weights

- Compute ratio $\omega = \frac{N_{target}|bin}{N_{source}|bin}$ and apply to event from the mixed BG sample.
- Inconvenient method
  1) Need to track bin indices
  2) Which variable to use ?
  3) Curse of dimensionality: the more variable, the less events per bins



Boosted decision trees

- Use a ML method to compute a weight event-by-event so that source and target distribution match
- Weights are obtained by optimizing a ML algorithm to distinguish target from source:

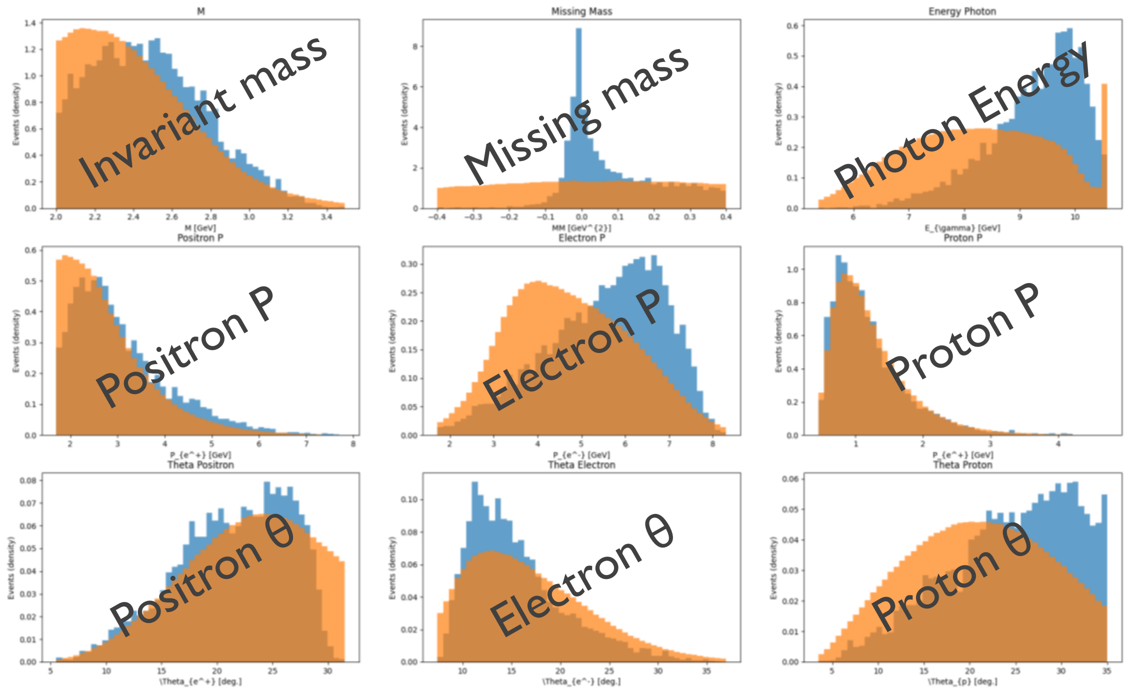
$$\omega = \frac{f_{target}(\mathbf{x})}{f_{source}(\mathbf{x})} = \frac{p_{target}(\mathbf{x})}{p_{source}(\mathbf{x})}$$

- Using method from Alex Rogozhnikov 2016 *J. Phys.: Conf. Ser.* **762** 012036. Code available here.

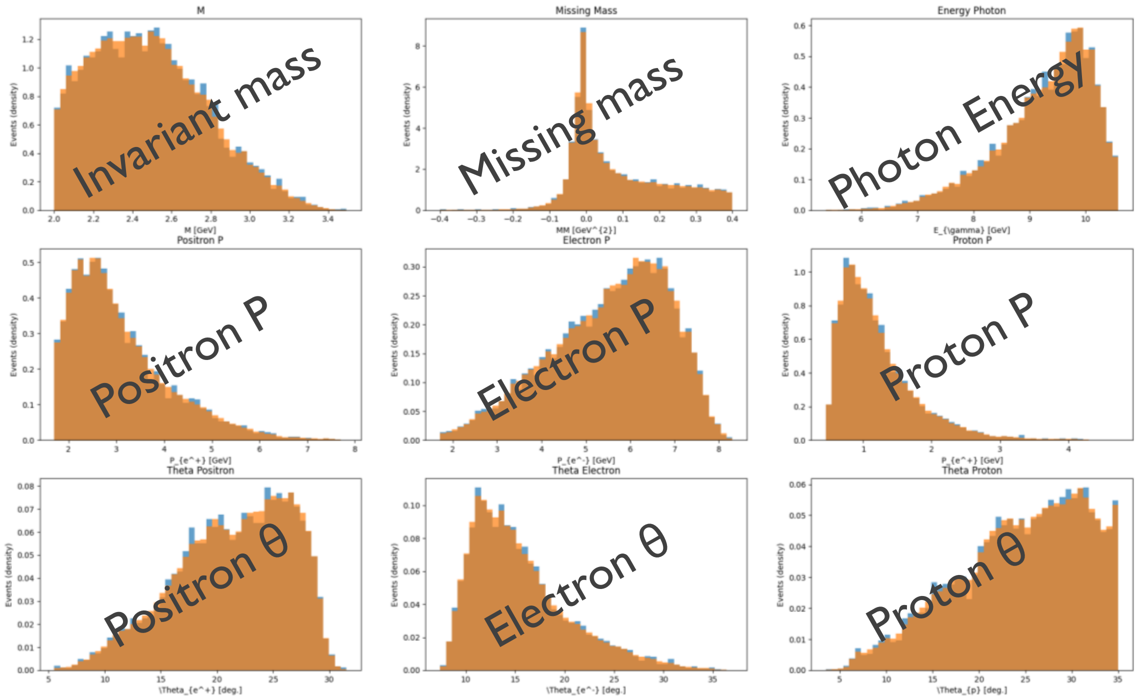
- Advantages:
  1) As many variables as needed can be matched
  2) No/less of a dimensionality curse
  3) Easy to use, no need to handle complex bin indexing

II) Normalization factor - Reweighting using Boosted Decision Trees

Before reweighting



After reweighting



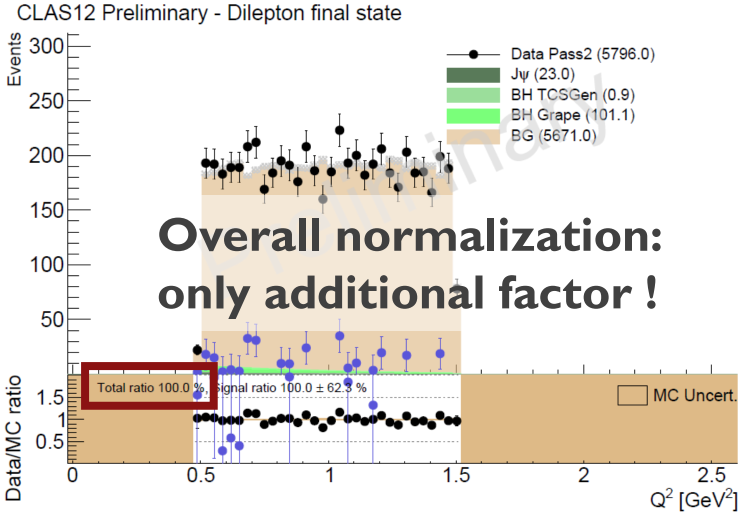
Events in the training region (Target)

Mixed background (Source)

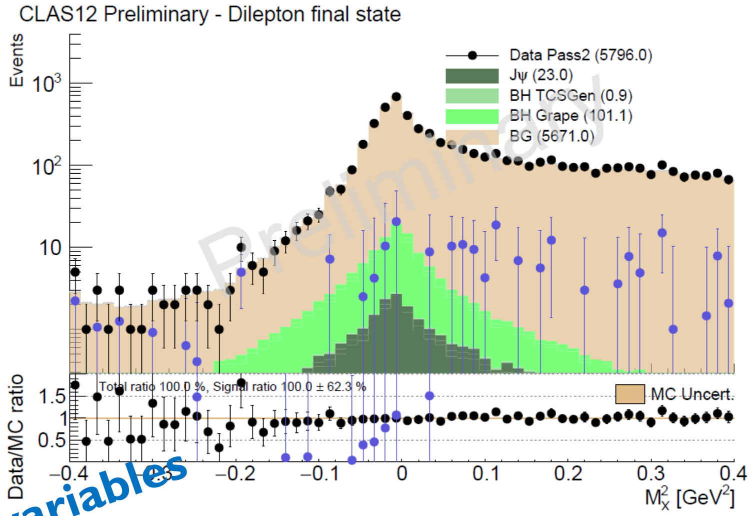
II) Normalization factor - Reweighting in the training region

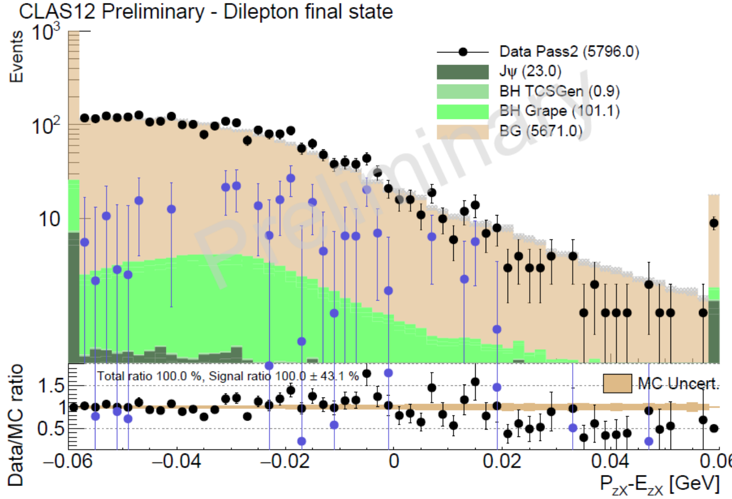
$Q^2 \in [0.5, 1.5] GeV^2$

Training region

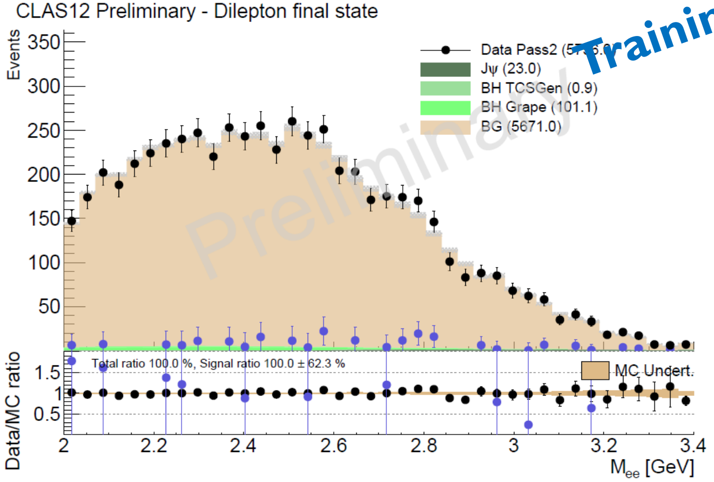


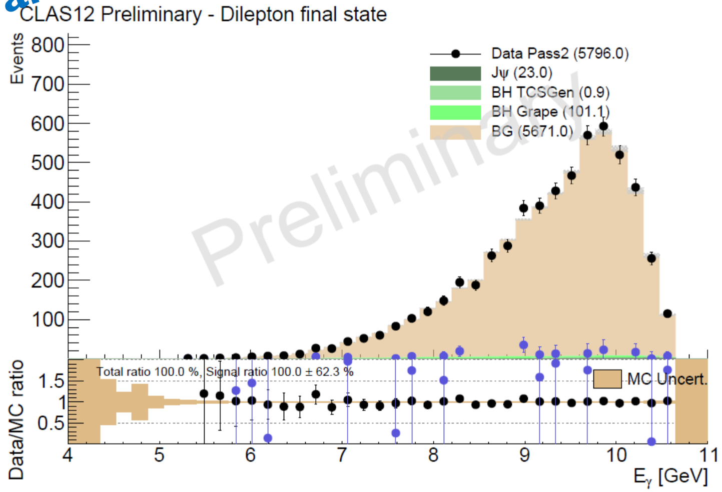
Overall normalization: only additional factor !

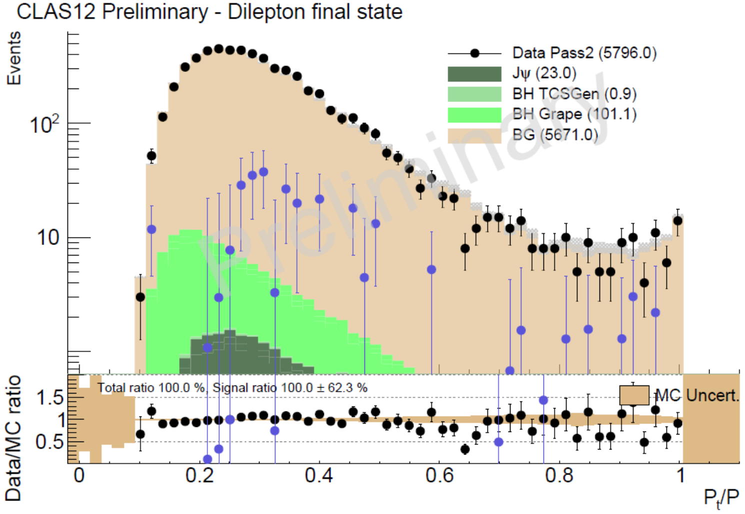




Training variables



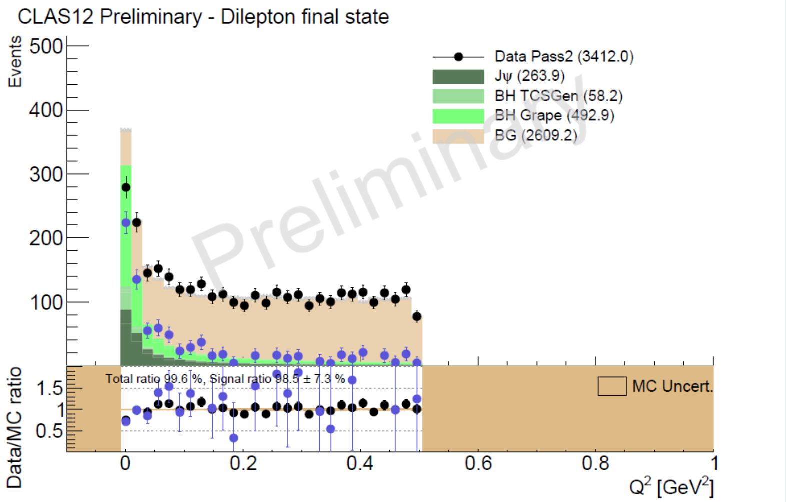


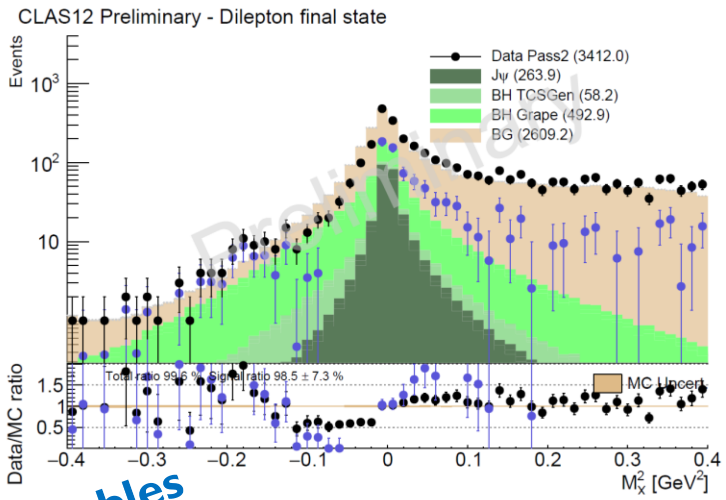


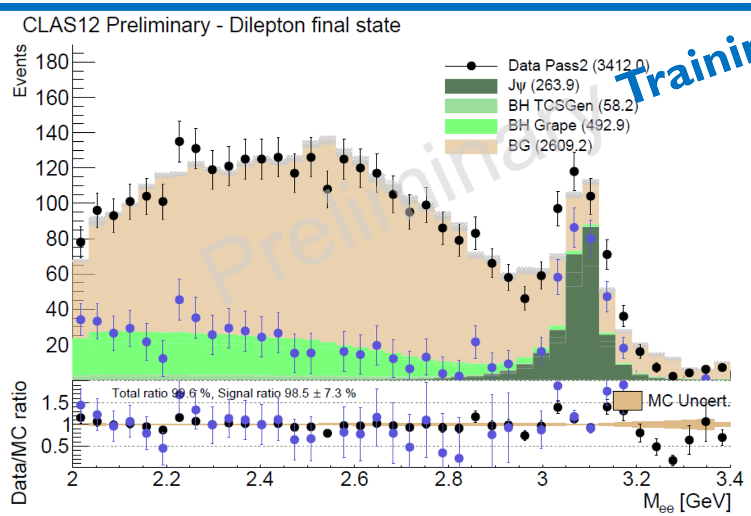
II) Normalization factor - Data/MC comparison in the signal region

$Q^2 \in [0.0, 0.5] GeV^2$

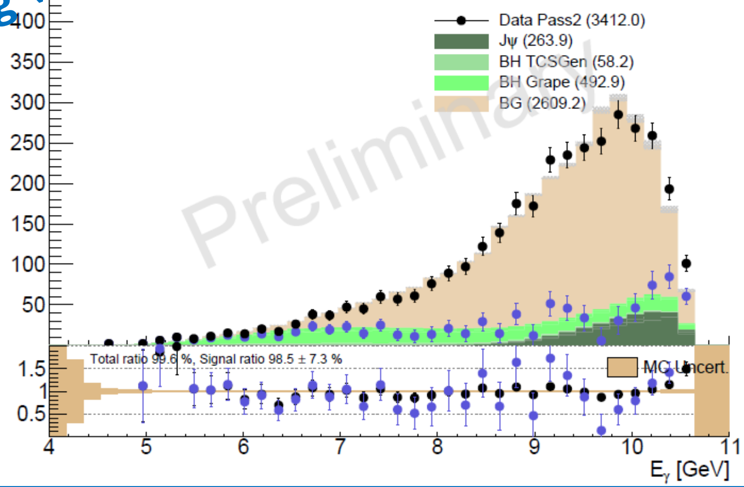
Signal region

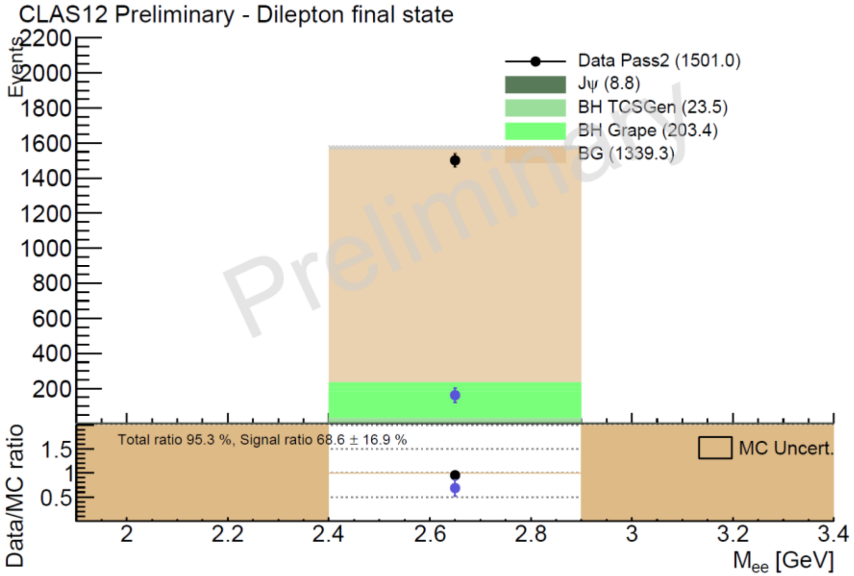






Training variables





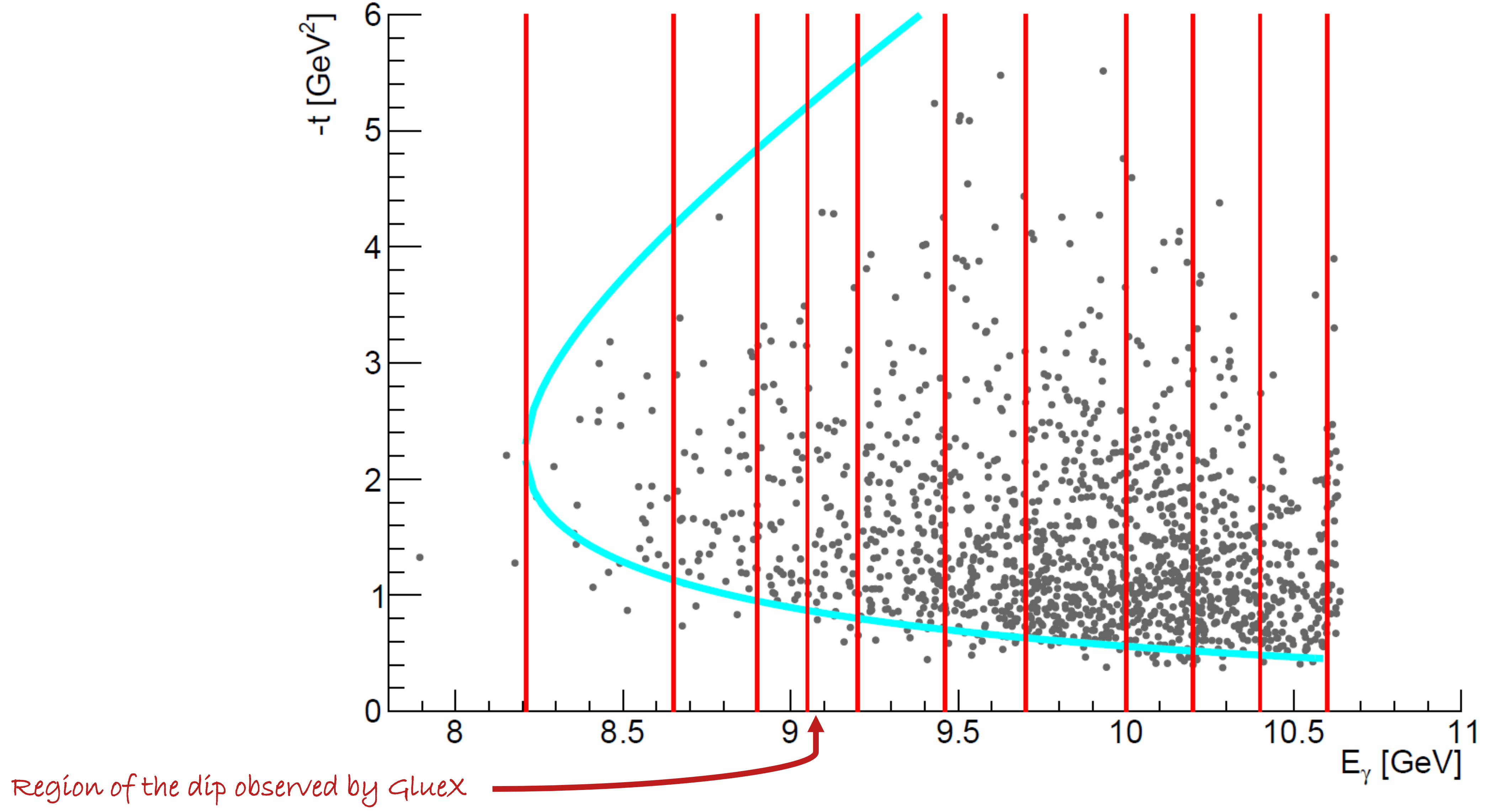
- Normalization factor can be computed as:

$$\omega_c = \frac{N_{Data} - N_{BG}}{N_{SIM\ BH}} = 68,6\% \pm 16.9\%$$

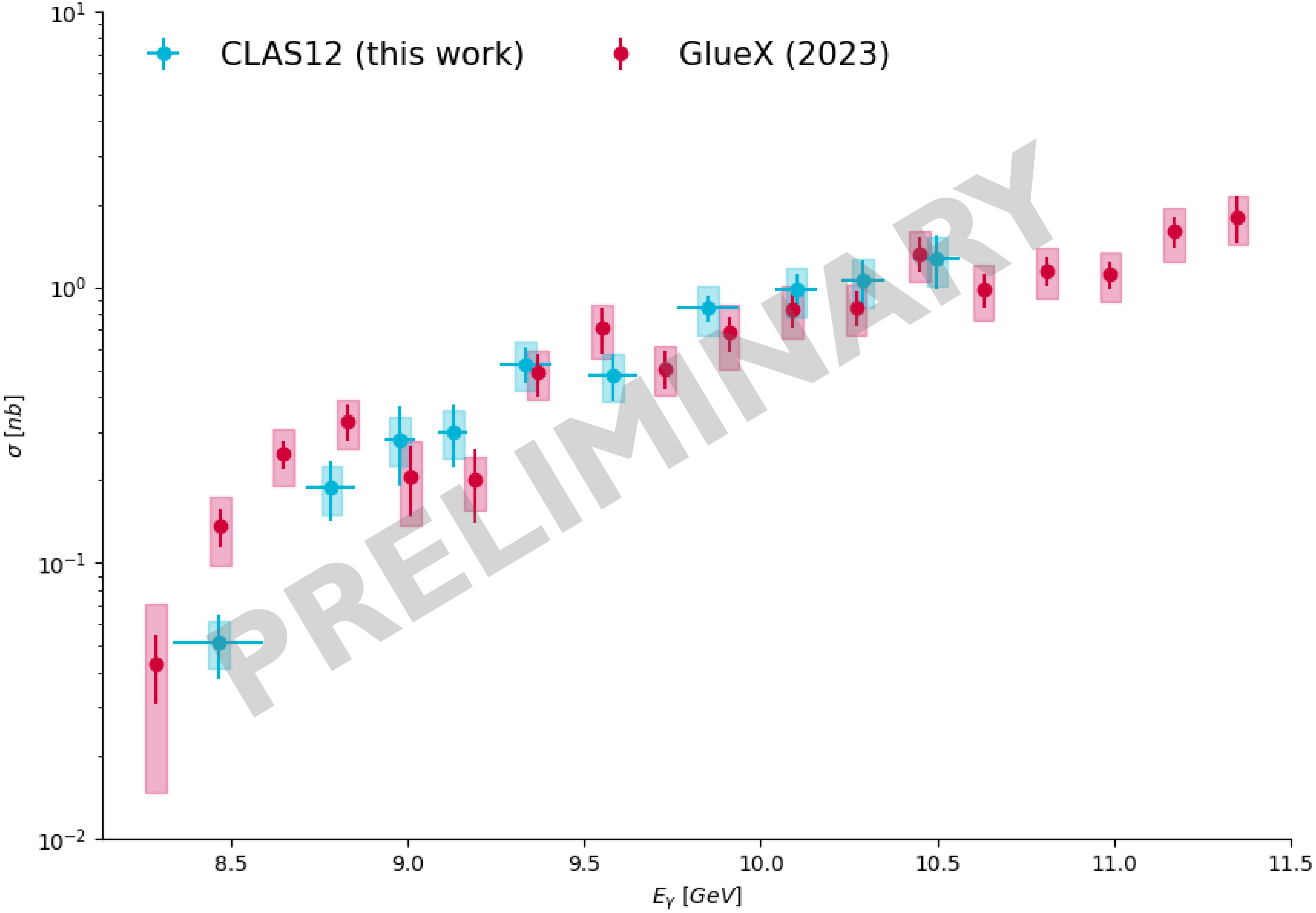
Assigned as systematic error on normalization

Results from the CLAS12 experiment

Kinematic coverage and binning

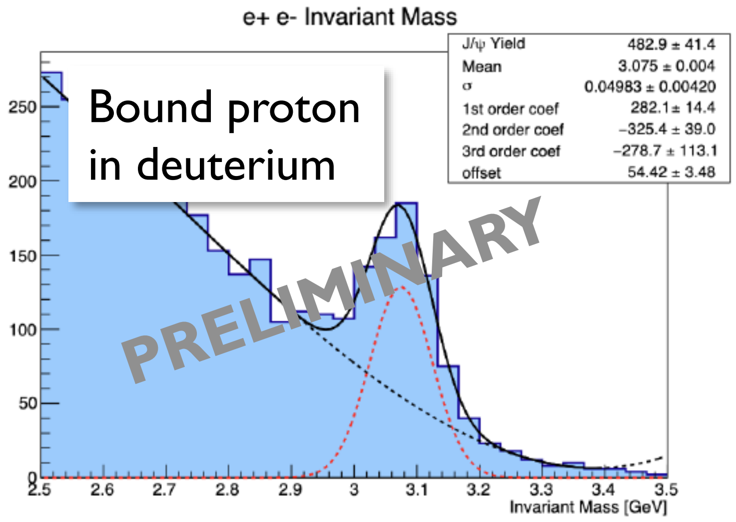


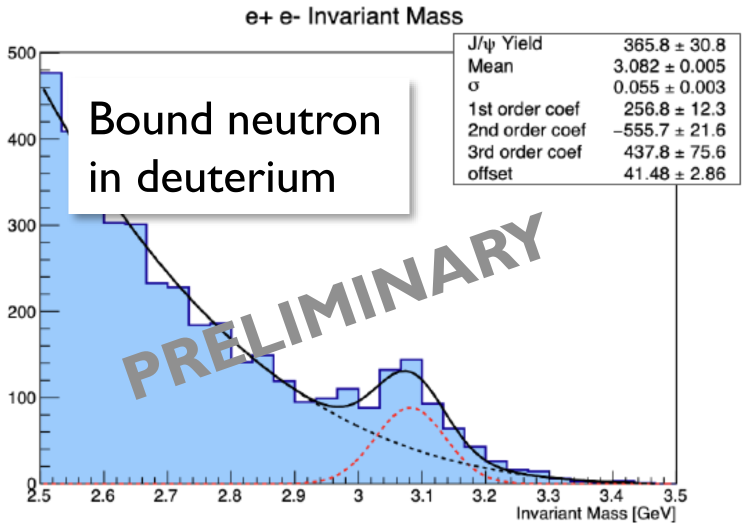
Preliminary total cross-section results



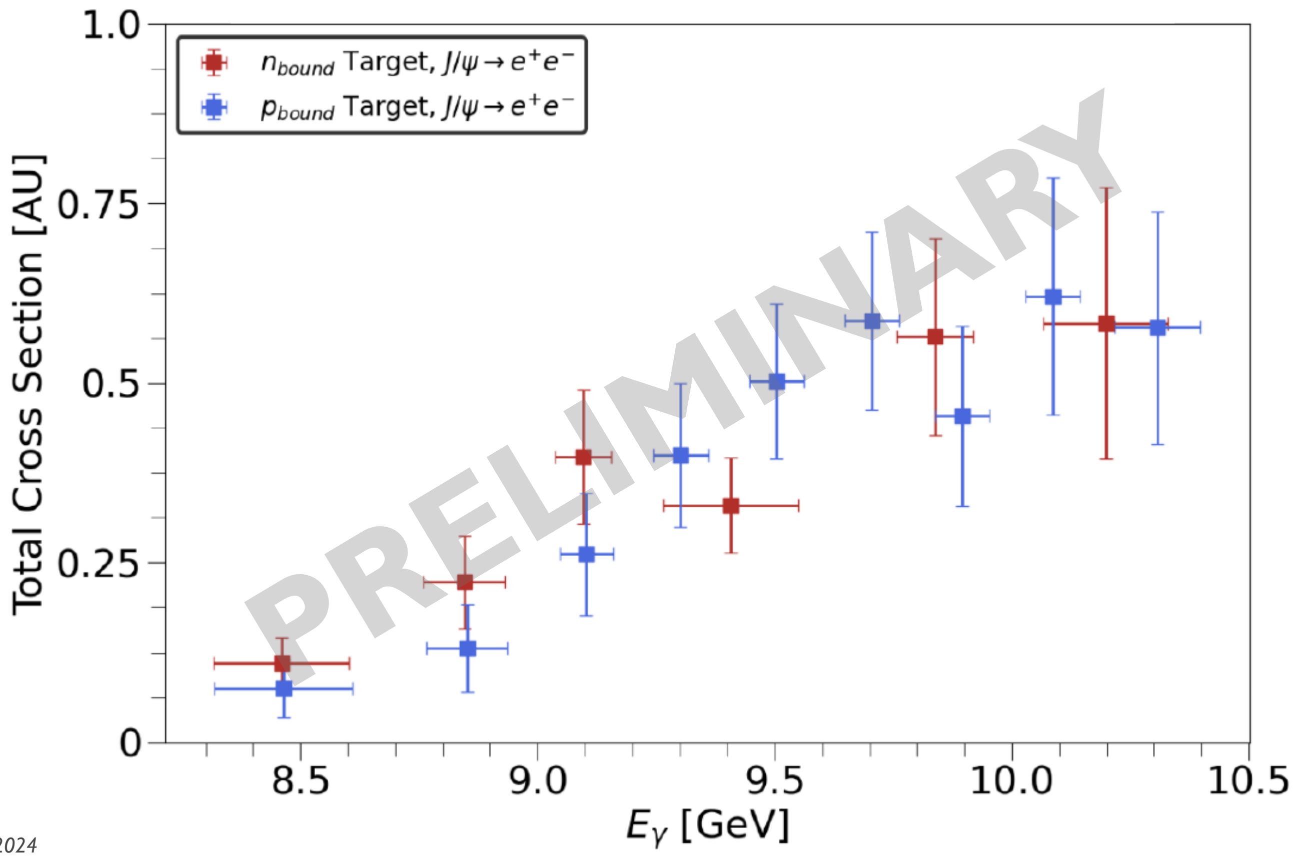
- Only the dominant normalization systematic (17%) is included in the CLAS12 results.
- Both cross-sections are in agreement and errors (statistical and systematics) are of similar size.
- No clear conclusion concerning a potential dip in the open charm threshold region.

Photoproduction on neutron target - *Analysis by R.Tyson (Jefferson Lab)*

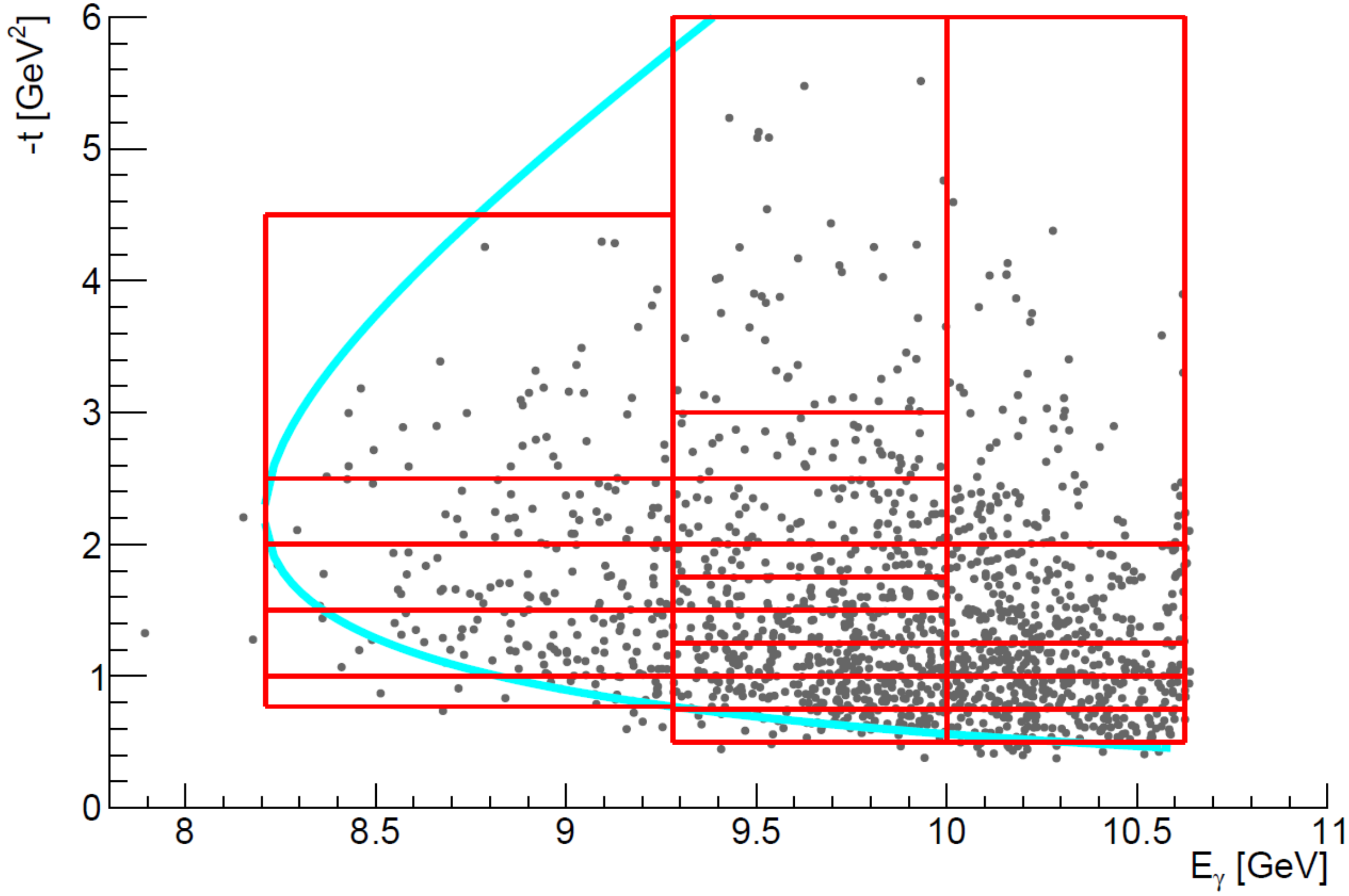


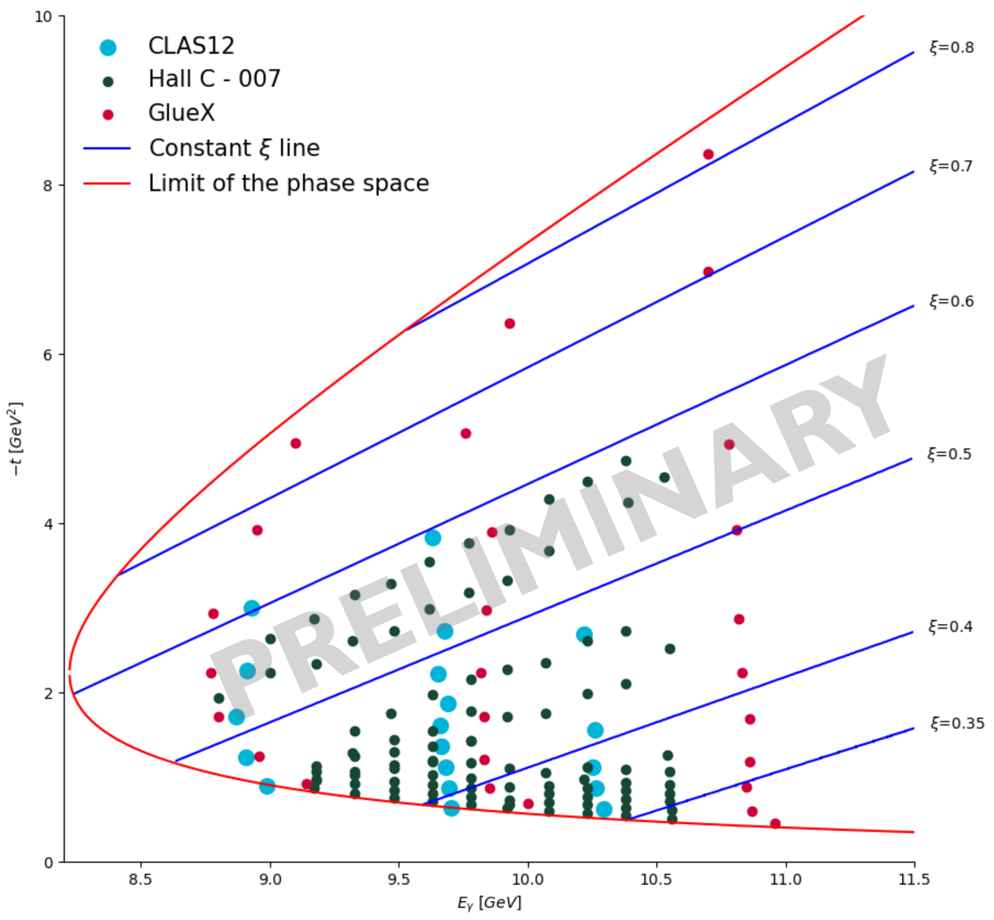


- Main goal: test isospin invariance of the process, access to the gluon content of neutrons.
- Understanding both the proton and neutron efficiency is the main challenge of this analysis.

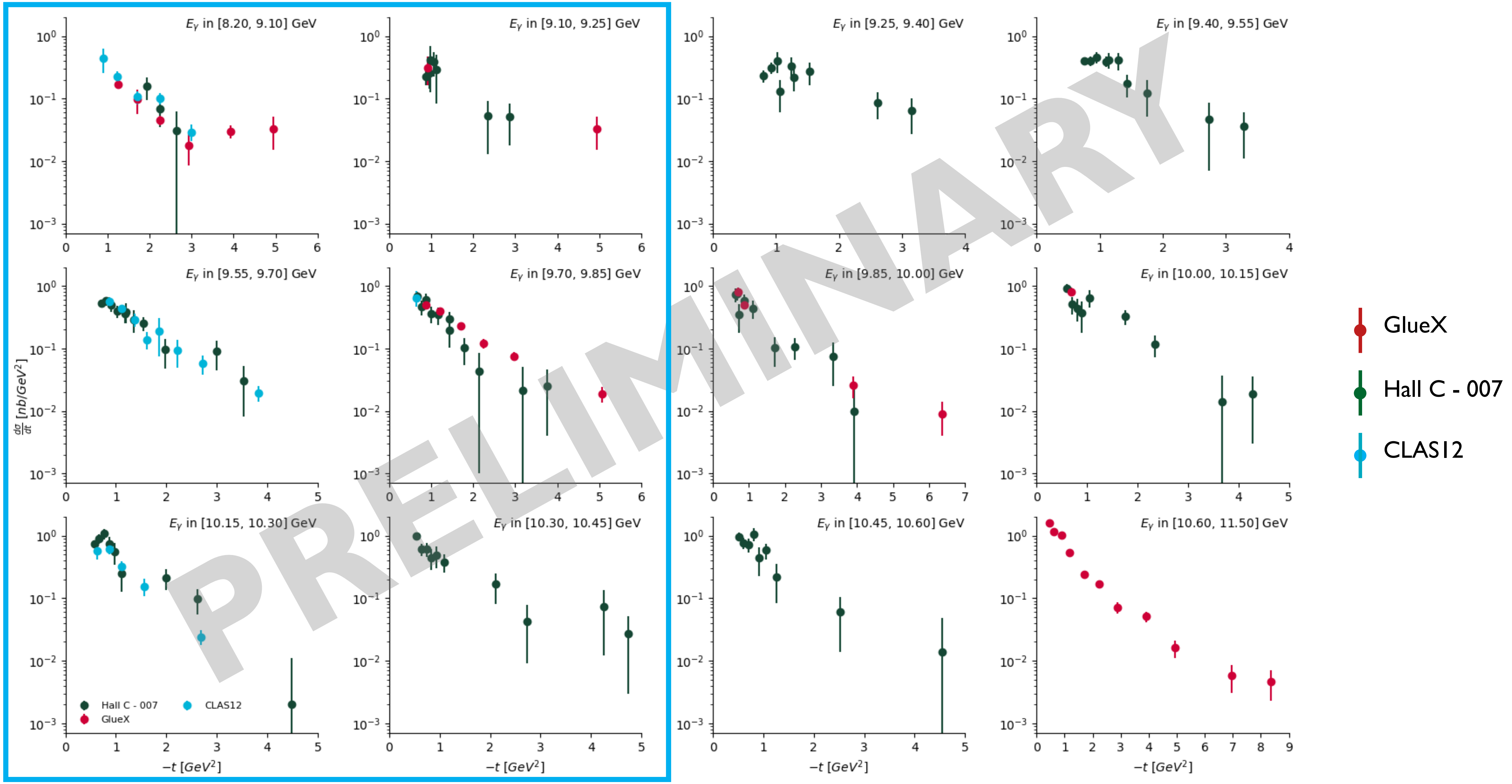


Differential cross section coverage and binning

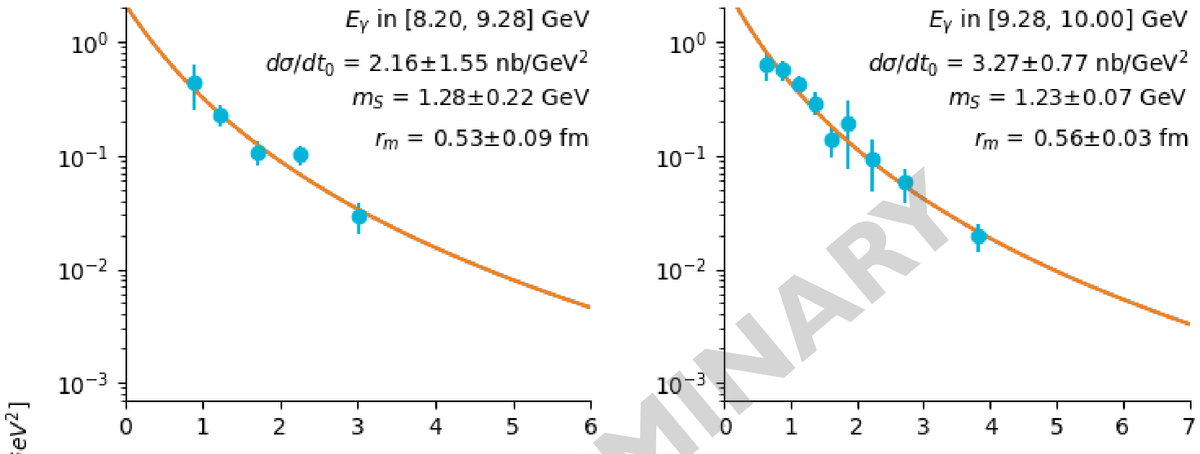


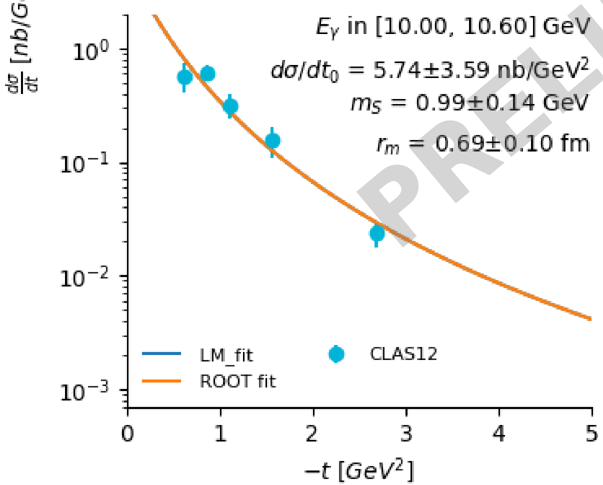


Preliminary differential cross-section results



Dipole fit and interpretation in term of mass radius

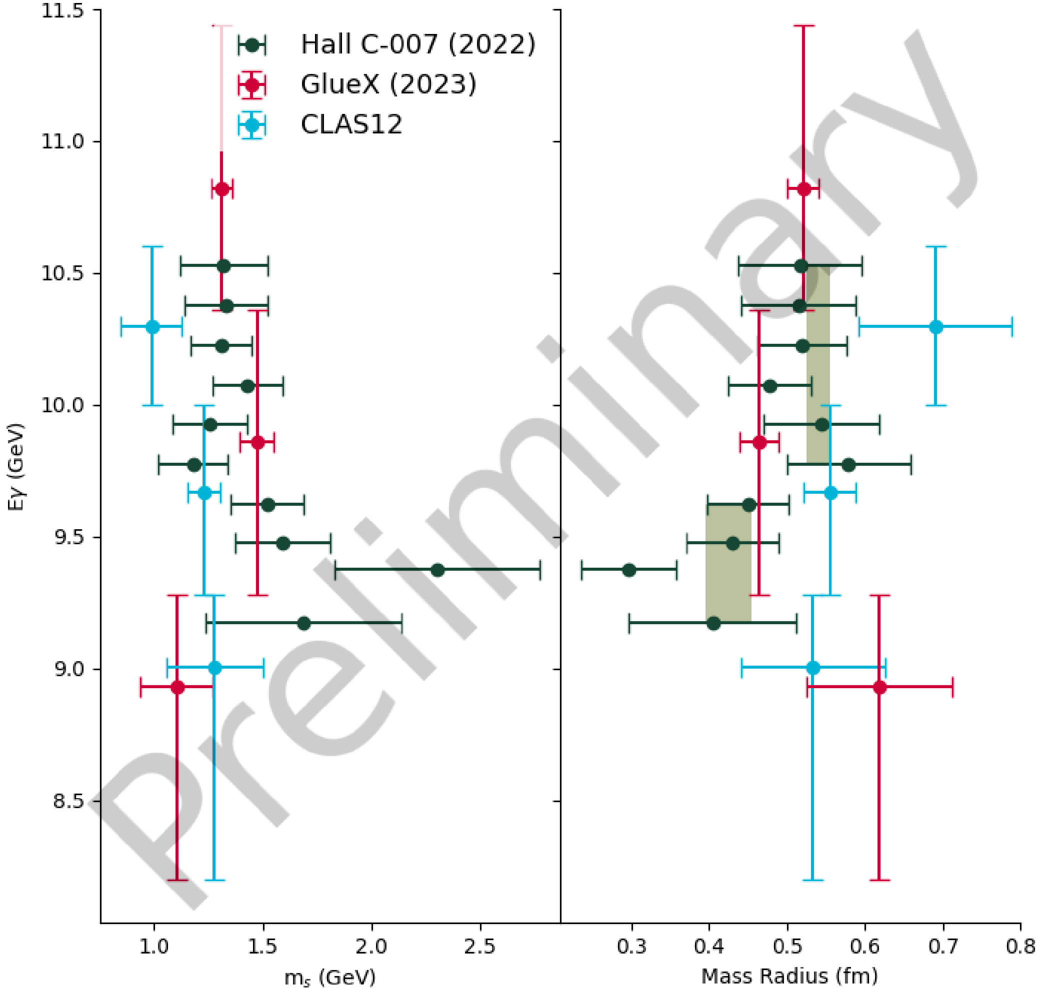




$$\frac{d\sigma}{dt} = \frac{d\sigma}{dt}\Big|_0 \cdot \frac{1}{(1-t/m_S^2)^4}$$

$$\sqrt{\langle r_m^2 \rangle} = \frac{\sqrt{12}}{ms}$$

See D. E. Kharzeev, "Mass radius of the proton", PRD (2021)



Toward GFF extraction including CLAS12 data (work in progress)

Model dependent extraction of GFFs

- **Holographic QCD model**

J/ψ near threshold in holographic QCD: A and D gravitational form factors, Kiminad A. Mamo and Ismail Zahed, Phys. Rev. D 106, 086004,2022

$$\frac{d\sigma}{dt} = \mathcal{N}^2 \frac{e^2}{64\pi(s-M_N^2)^2} \frac{[A(t)+\eta^2 D(t)]^2}{A^2(0)} \cdot \tilde{F}(s) \cdot 8$$

- **Generalized Parton Distribution model**

QCD analysis of near-threshold photon-proton production of heavy quarkonium, Yuxun Guo, Xiangdong Ji, and Yizhuang Liu, Phys. Rev. D 103, 096010, 2021

$$\frac{d\sigma}{dt} = \frac{\alpha_{EM} e_Q^2}{4(W^2-M_N^2)^2} \frac{(16\pi\alpha_S)^2}{3M_V^3} |\phi_{NR}(0)|^2 |G(t,\xi)|^2$$

GFFs in $G(t,\xi)$

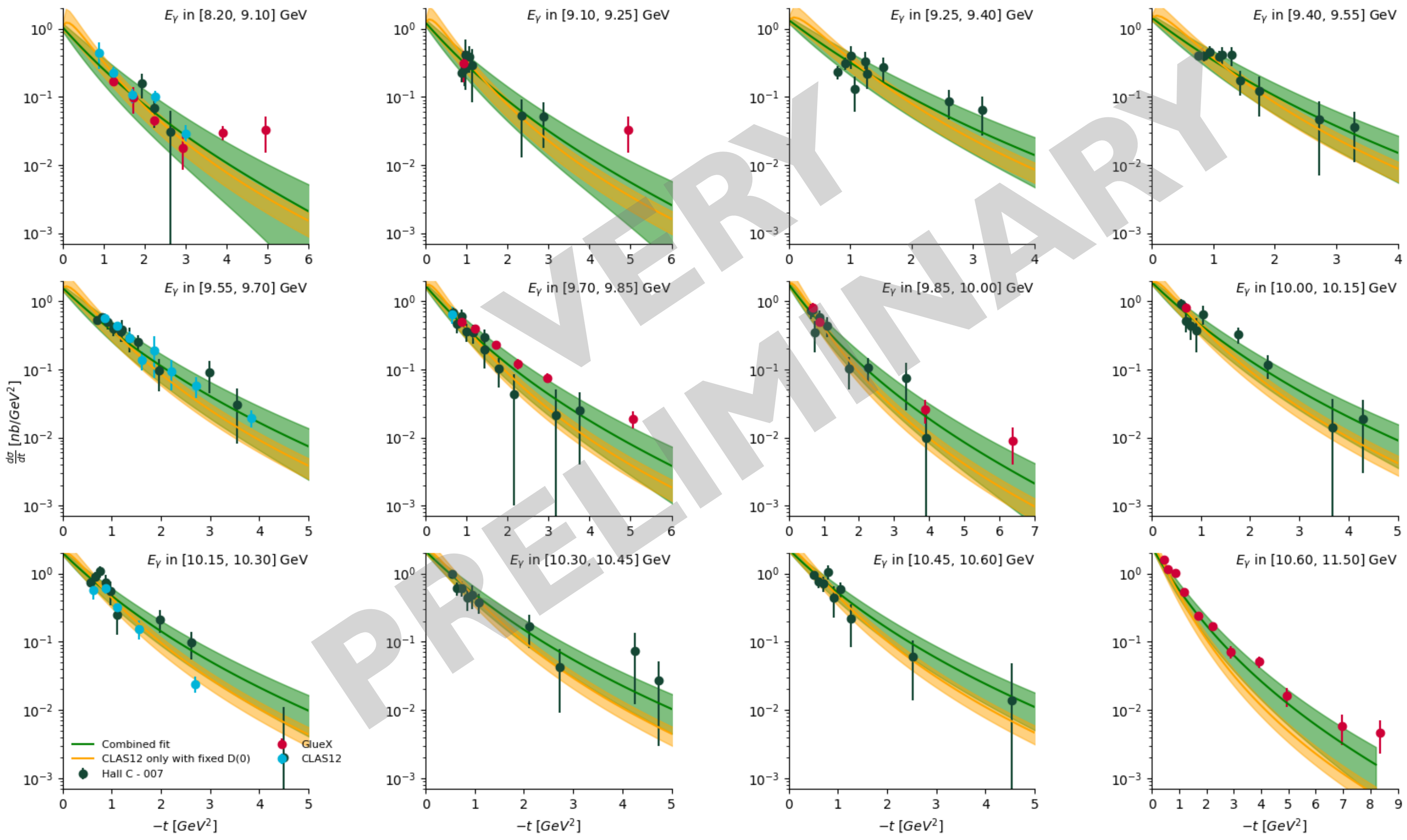
- **GFF parametrization**

$$D(t) = \frac{D(0)}{(1-\frac{t}{m_D})^3} \qquad A(t) = \frac{A(0)}{(1-\frac{t}{m_A})^3}$$

$$A(0) = 0.414$$

Equal to gluon momentum fraction

See T.-J. Hou et al., Phys. Rev. D 103, 014013 (2021) for A(0) value



Take-aways and outlook

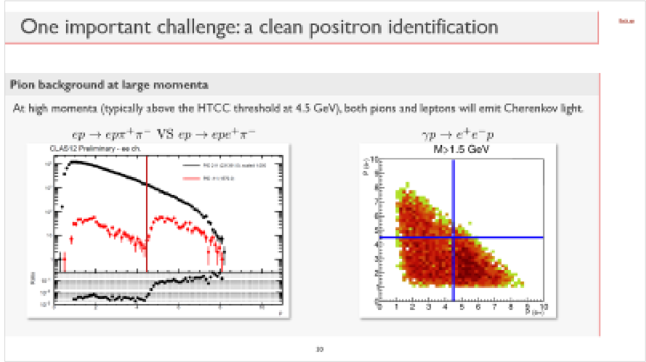
- Photoproduction of J/ψ has become a *flagship* measurement for *current and future* JLab experiments.
- *New cross-section results* from the CLAS12 experiment have now been released.
- Current work is dedicated to wrapping-up the analysis note for *publication in the **next few months***.
- Strong efforts to *interpret these data*, and *expend upon the capabilities of CLAS12* (measurement on deuterium target and muon final state analysis).

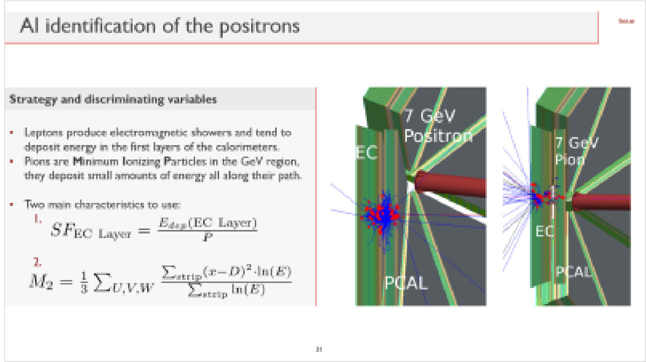
Thank you for your attention

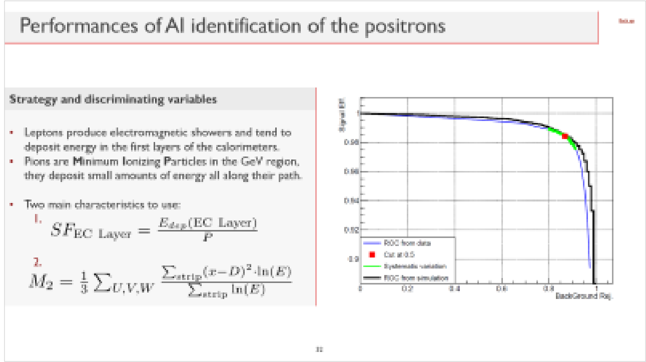
BACK-UPs

Back up

Positron PID







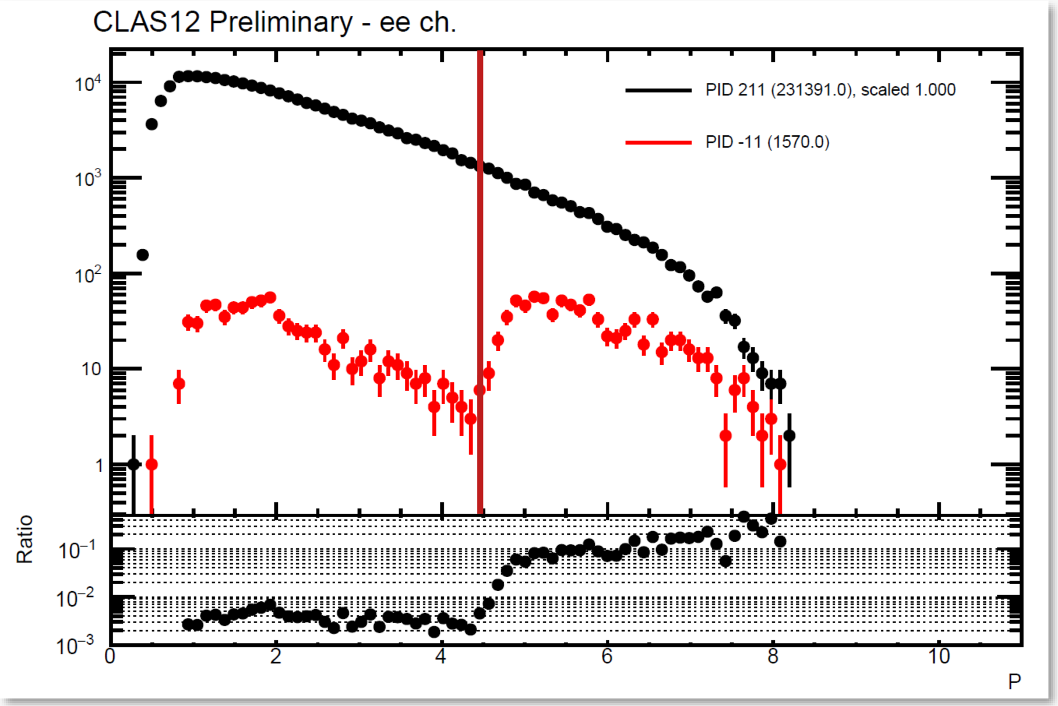
One important challenge: a clean positron identification

Back up

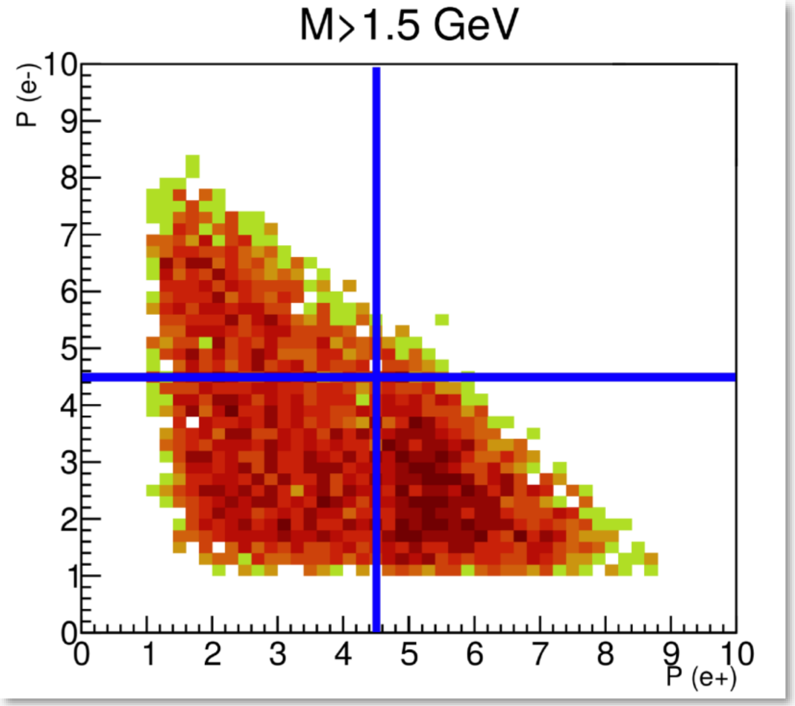
Pion background at large momenta

At high momenta (typically above the HTCC threshold at 4.5 GeV), both pions and leptons will emit Cherenkov light.

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



$$\gamma p \to e^+e^-p$$



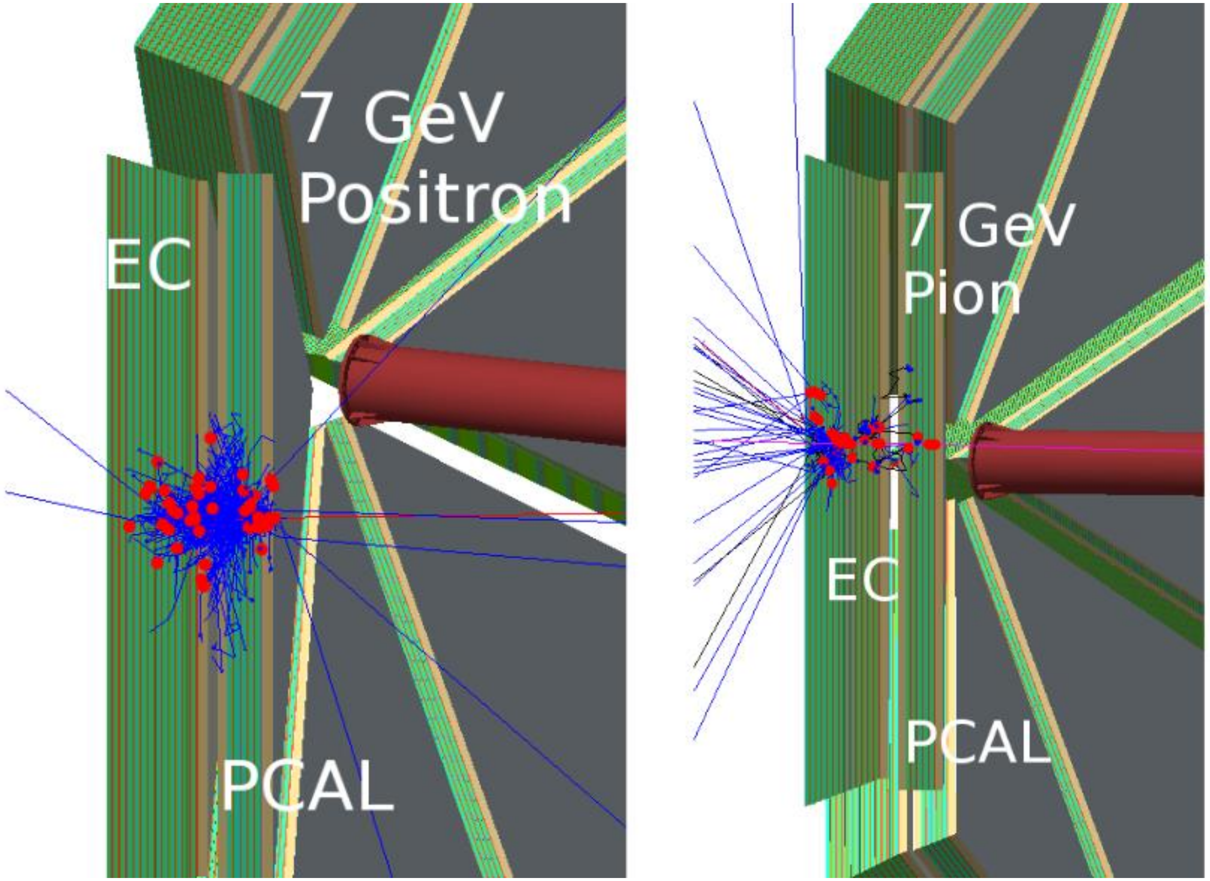
AI identification of the positrons

Back up

Strategy and discriminating variables

- Leptons produce electromagnetic showers and tend to deposit energy in the first layers of the calorimeters.
- Pions are **M**inimum **I**onizing **P**articles in the GeV region, they deposit small amounts of energy all along their path.

- Two main characteristics to use:
  1. $$SF_{\text{EC Layer}} = \frac{E_{dep}(\text{EC Layer})}{P}$$
  2. $$M_2 = \frac{1}{3}\sum_{U,V,W} \frac{\sum_{\text{strip}}(x-D)^2 \cdot \ln(E)}{\sum_{\text{strip}} \ln(E)}$$



Performances of AI identification of the positrons

Back up

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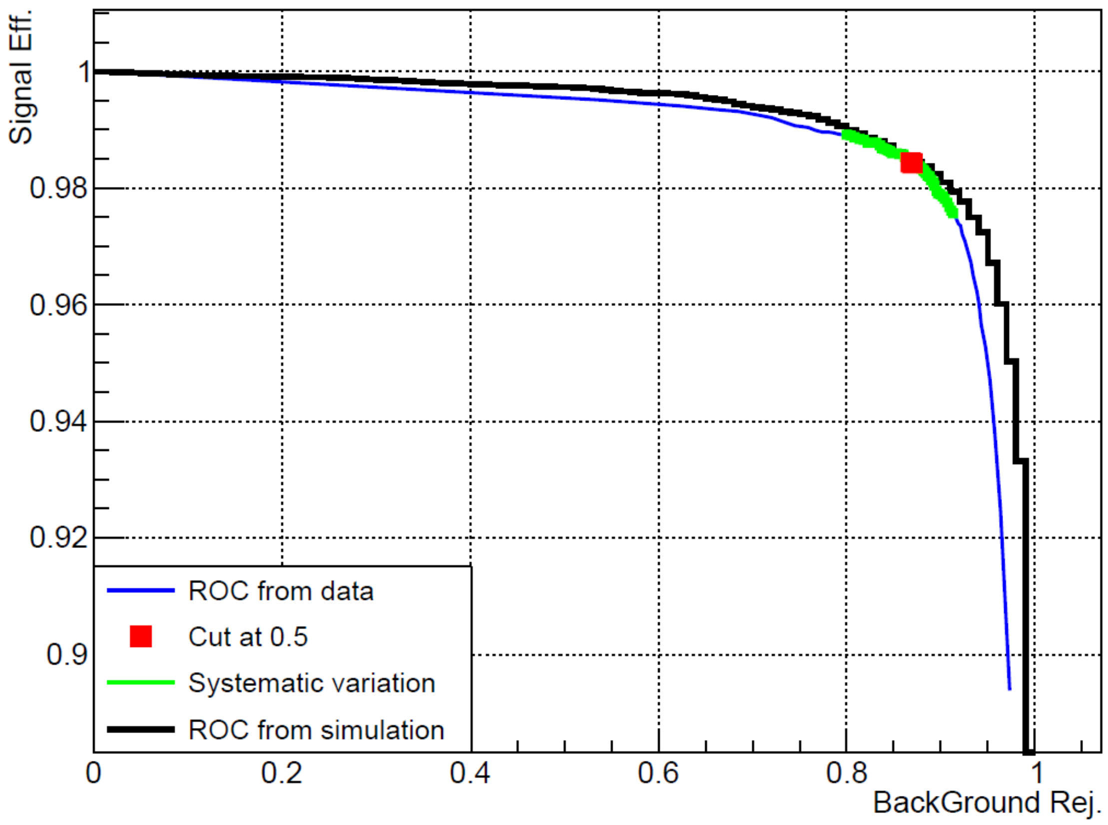
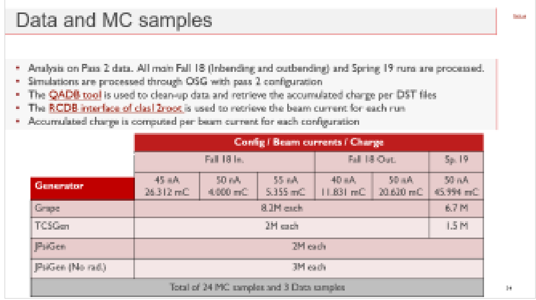
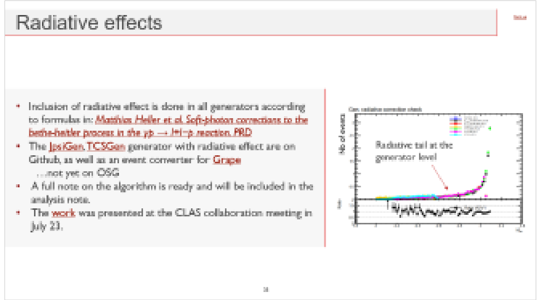
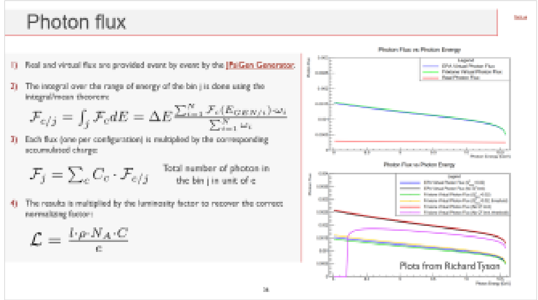


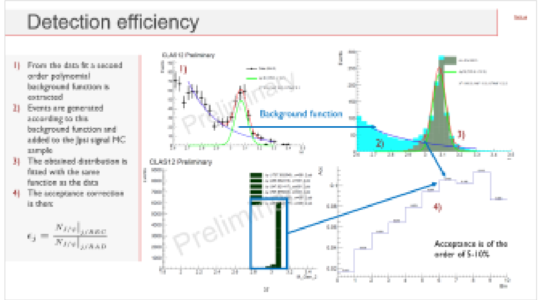
Back up

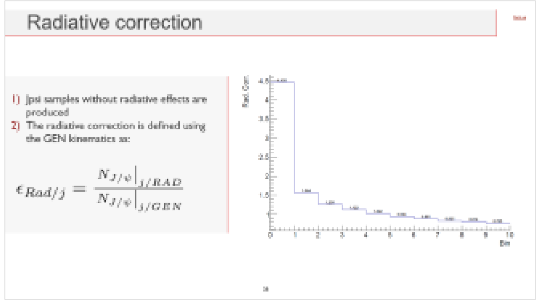
J/ψ analysis

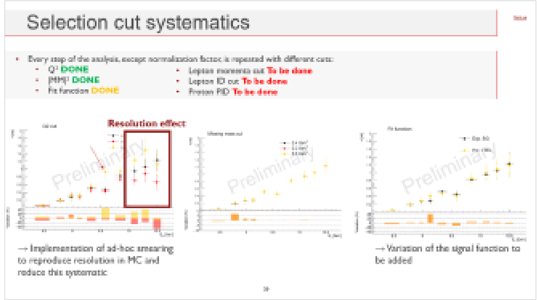


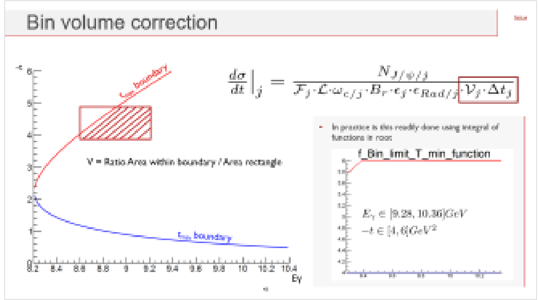


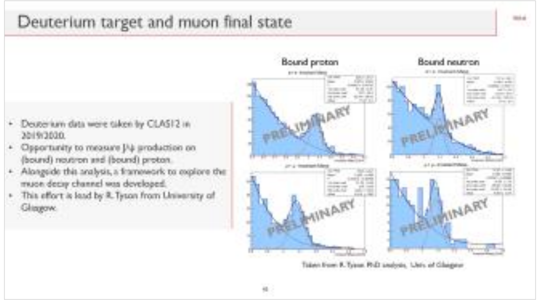


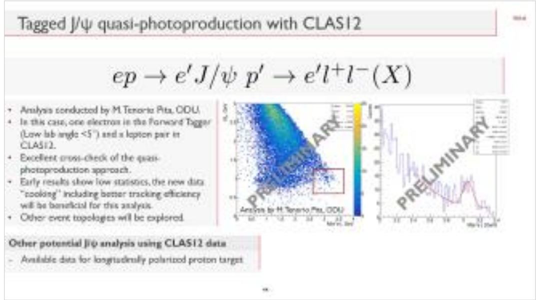












Data and MC samples

Back up

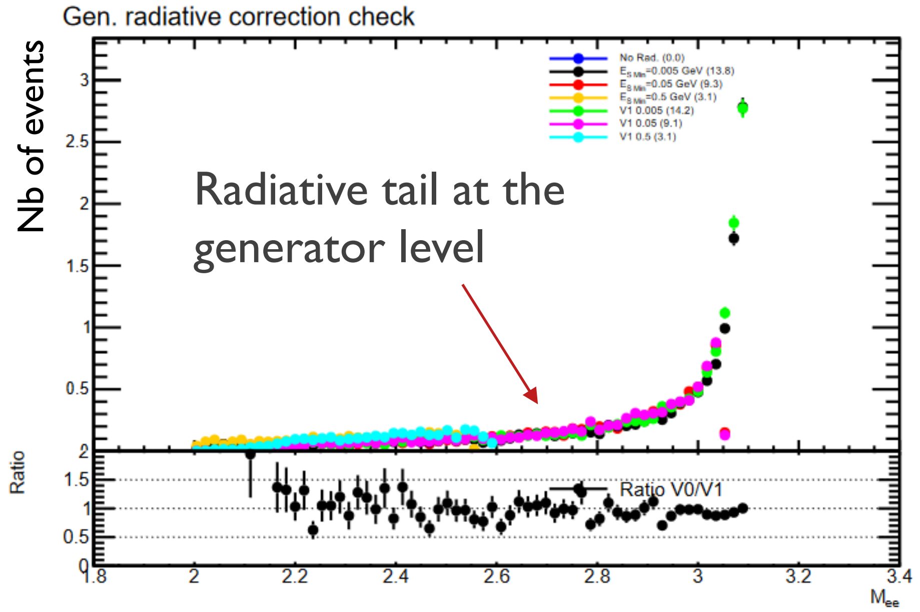
- Analysis on Pass 2 data. All *main* Fall 18 (Inbending and outbending) and Spring 19 runs are processed.
- Simulations are processed through OSG with pass 2 configuration
- The QADB tool is used to clean-up data and retrieve the accumulated charge per DST files
- The RCDB interface of clas12root is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

Back up

- 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 $\gamma p \to l^+l^-p$ 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.



Photon flux

Back up

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:

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

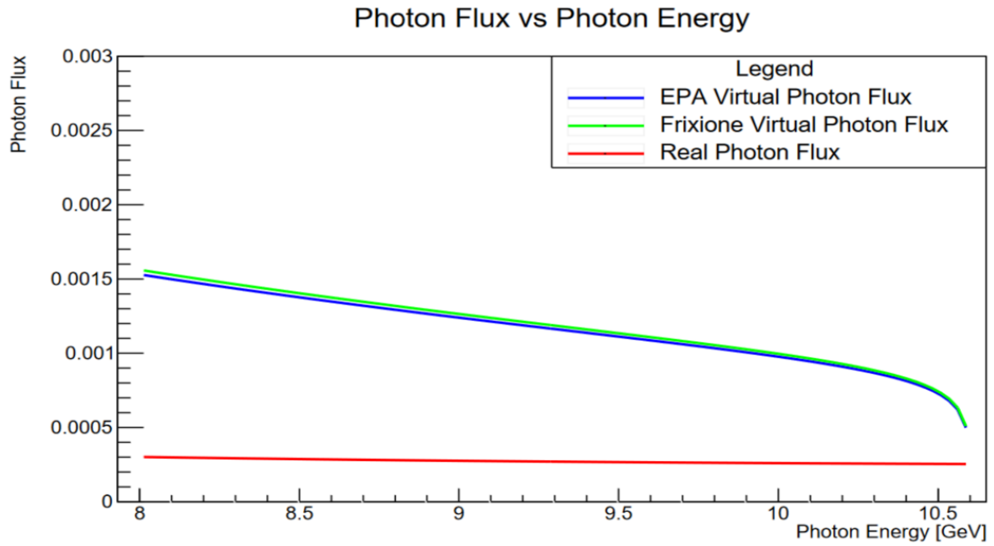
3) Each flux (one per configuration) is multiplied by the corresponding accumulated charge:

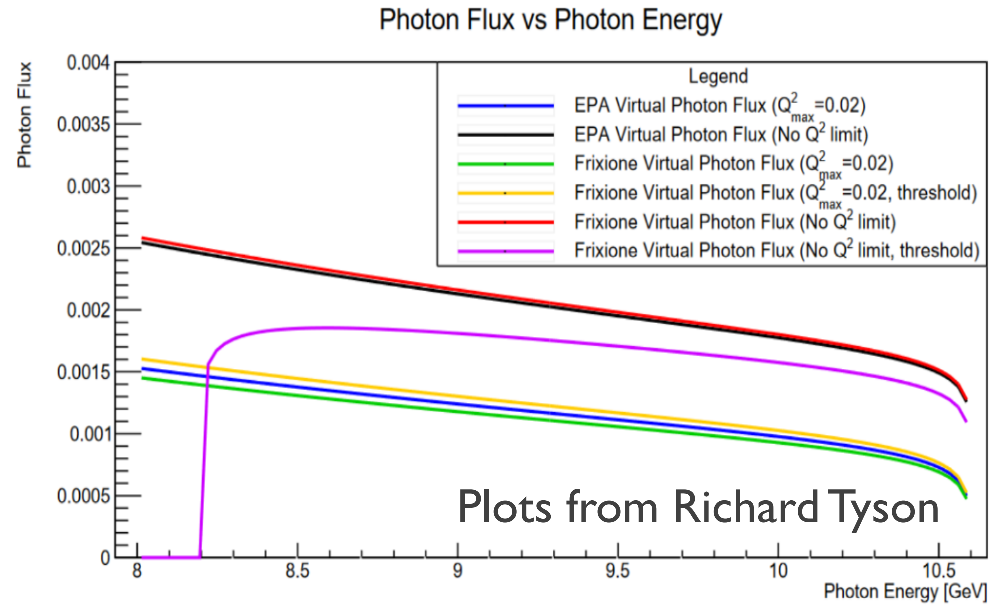
$$\mathcal{F}_j = \sum_c C_c \cdot \mathcal{F}_{c/j}$$

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:

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



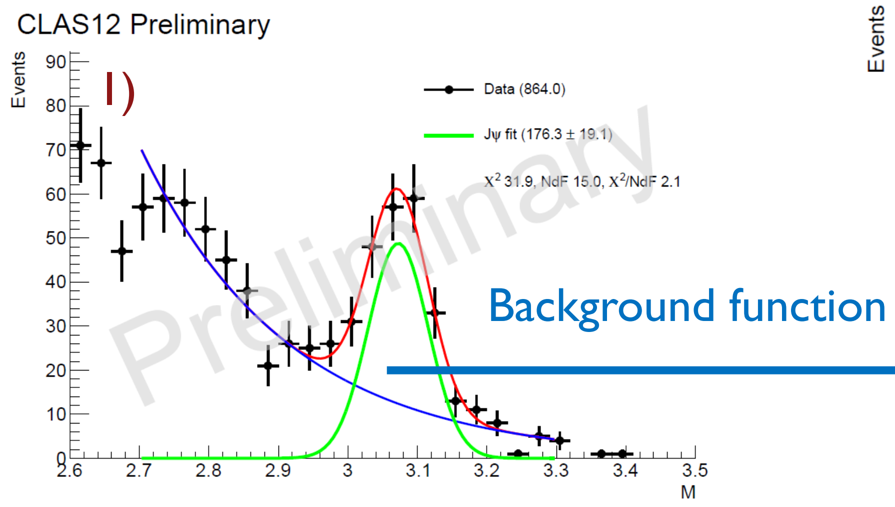


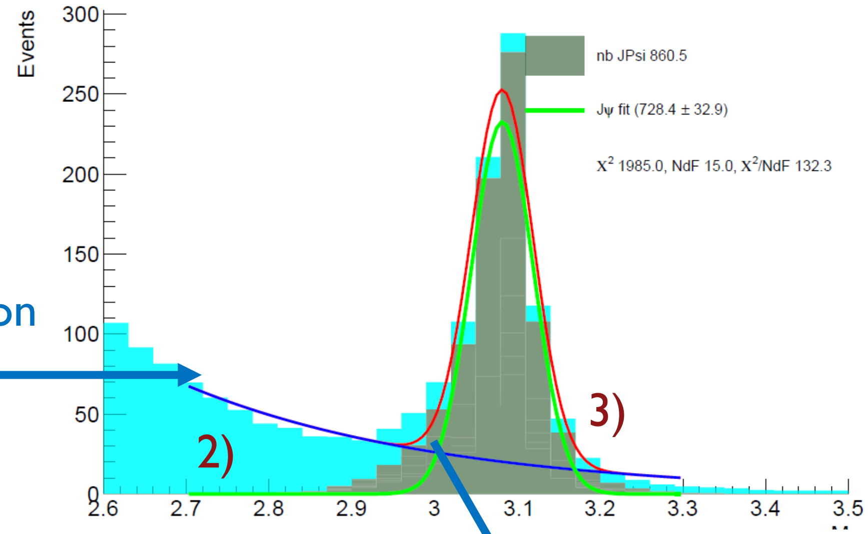
Detection efficiency

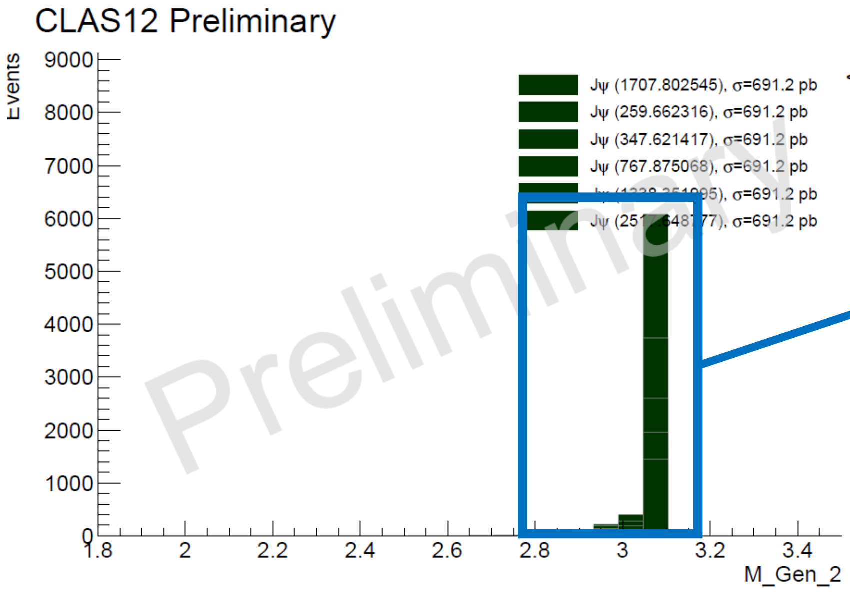
Back up

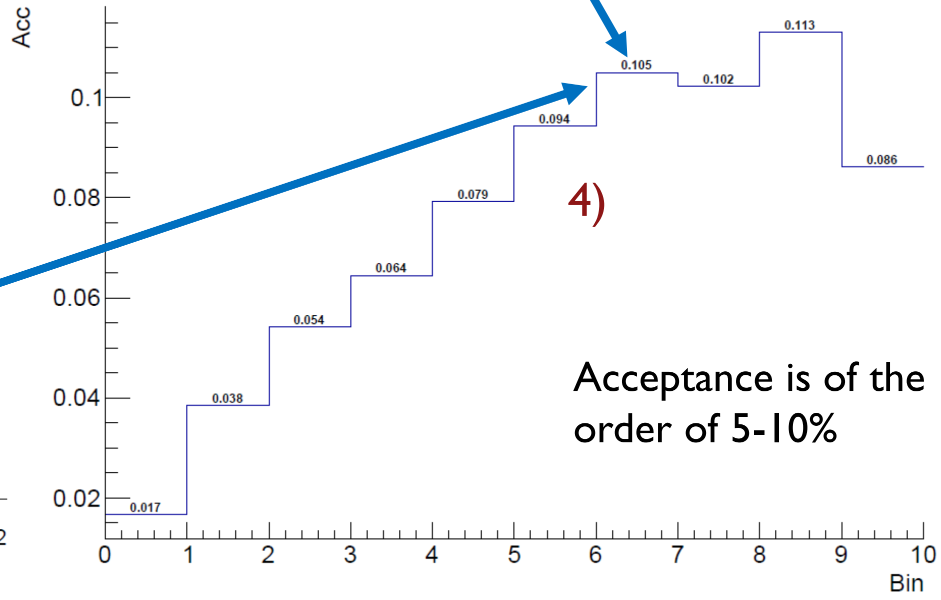
1) From the data fit a second order polynomial background function is extracted
2) Events are generated according to this background function and added to the Jpsi signal MC sample
3) The obtained distribution is fitted with the same function as the data
4) The acceptance correction is then:

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







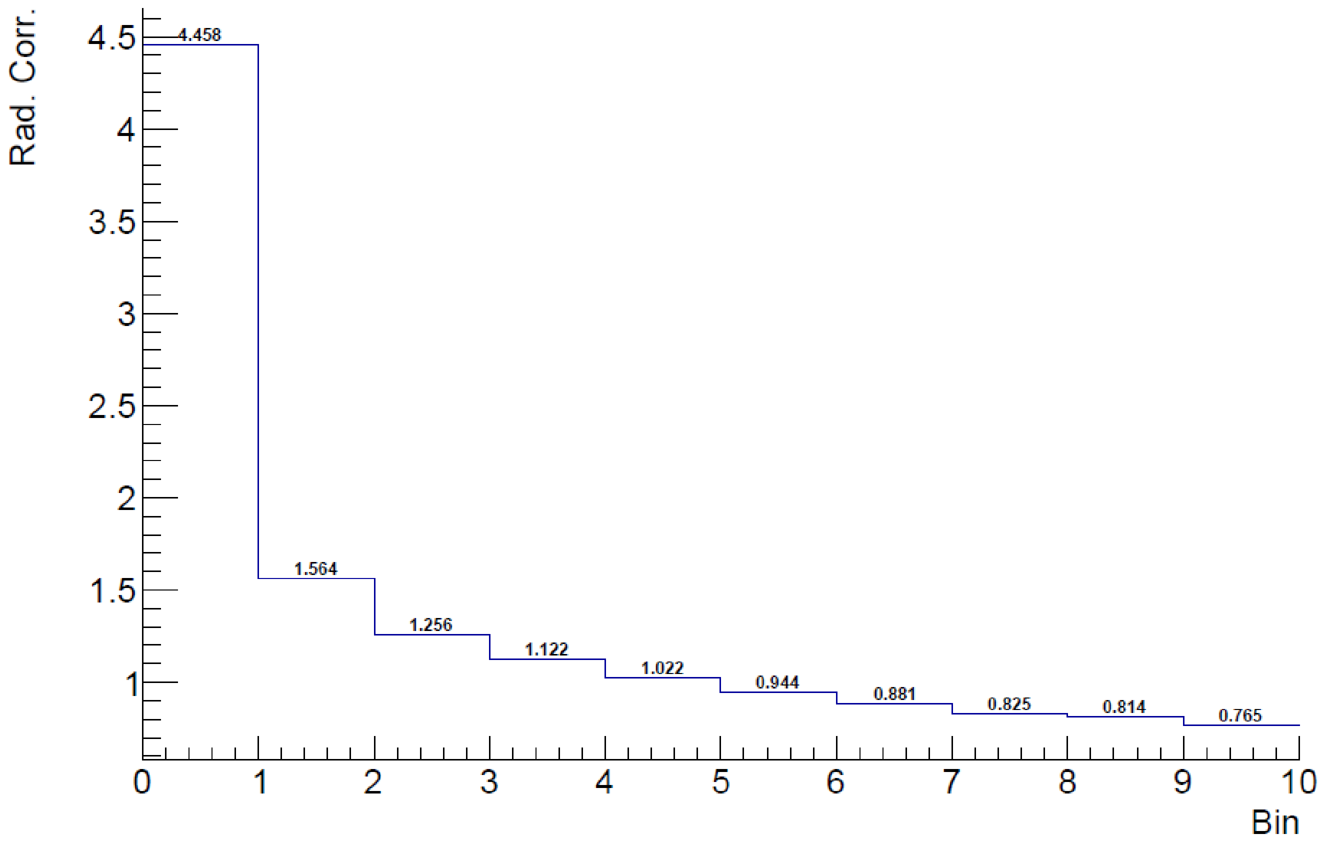


Radiative correction

Back up

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

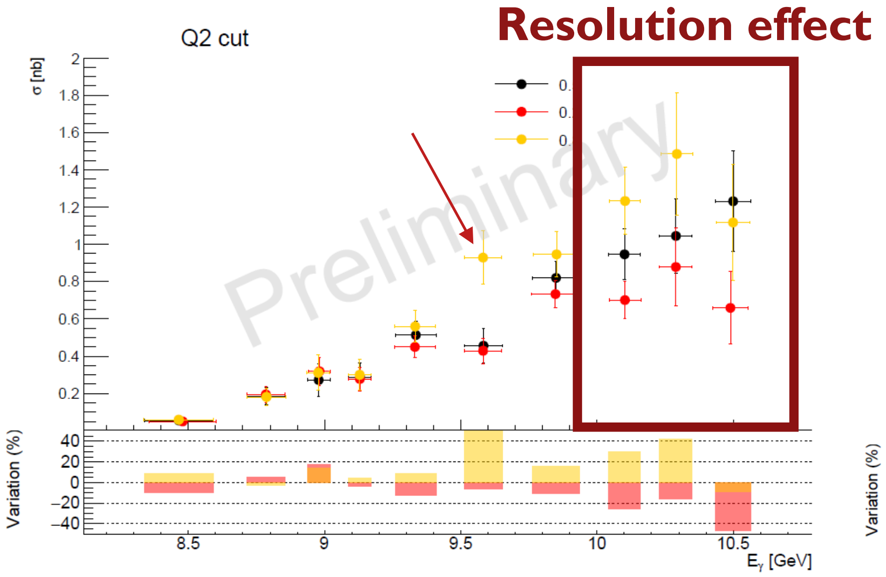
$$\epsilon_{Rad/j} = \frac{N_{J/\psi}\big|_{j/RAD}}{N_{J/\psi}\big|_{j/GEN}}$$

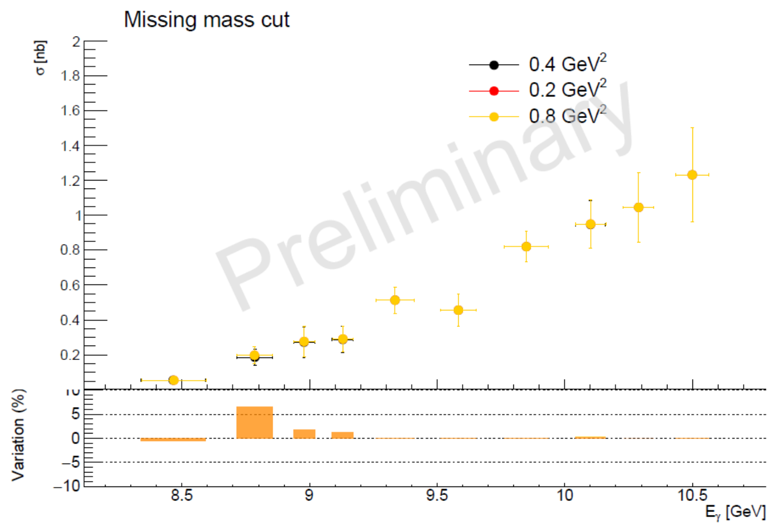


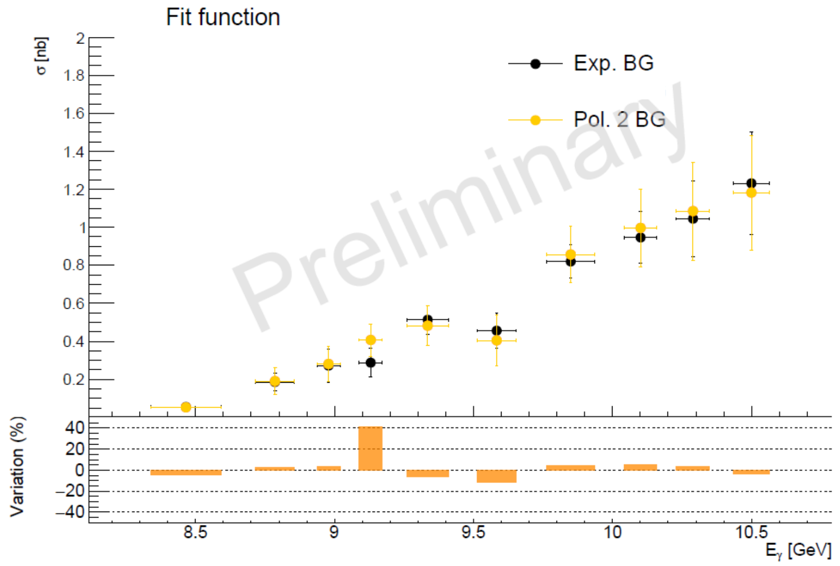
Selection cut systematics

Back up

- 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**





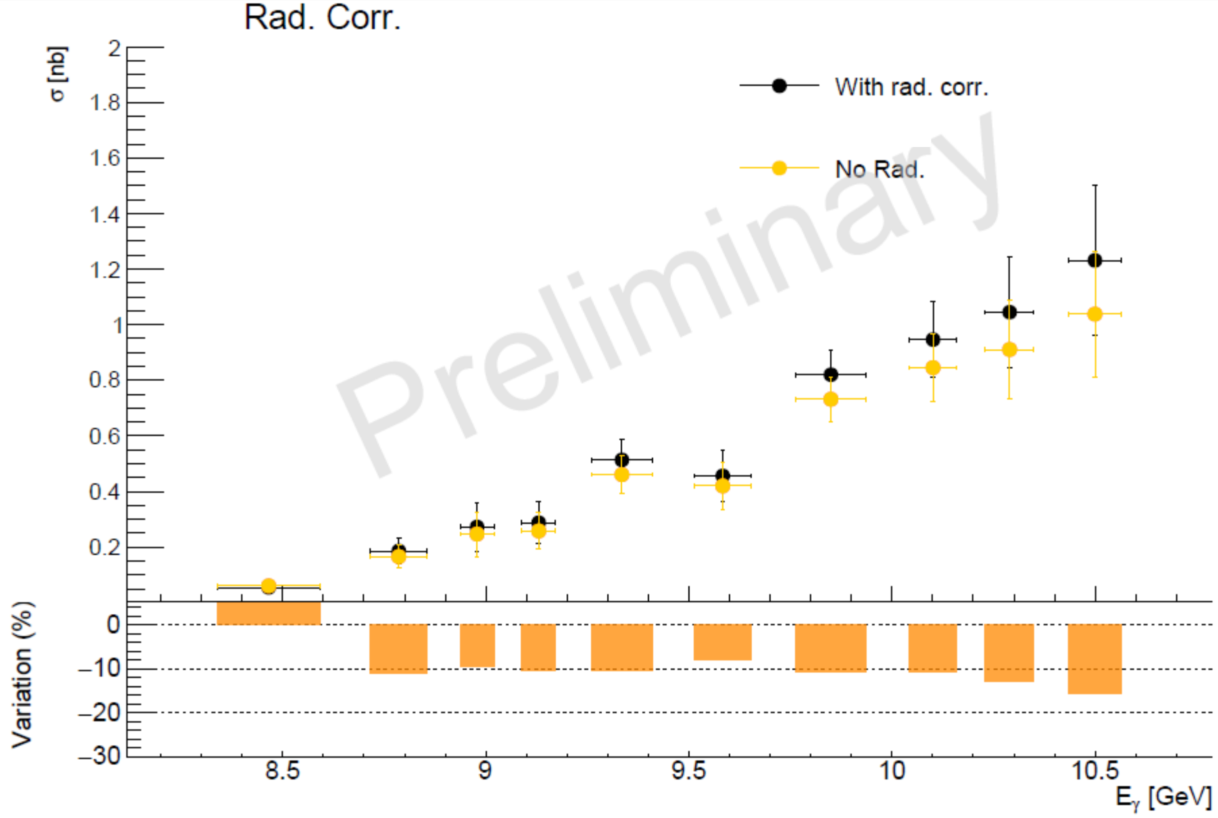


→ Implementation of ad-hoc smearing to reproduce resolution in MC and reduce this systematic

→ Variation of the signal function to be added

Radiative correction effect

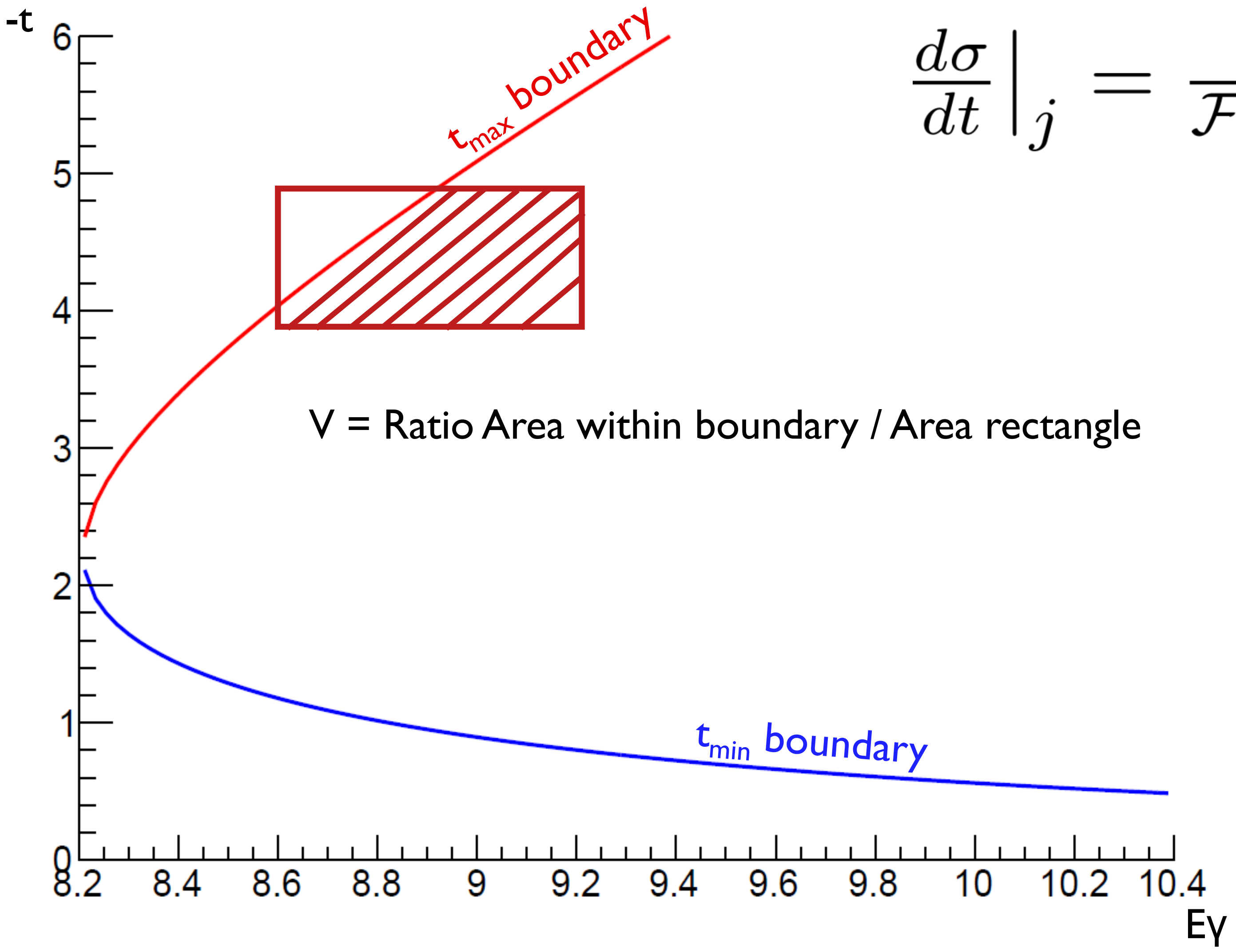
- The standard CS is extracted using the Radiated Jpsi MC samples and radiative correction
- The alternate is using non-radiated MC samples
- The effect is of the order of 10% (GlueX quoted 8.5%)



+ Closure test (Implemented but not presented here)

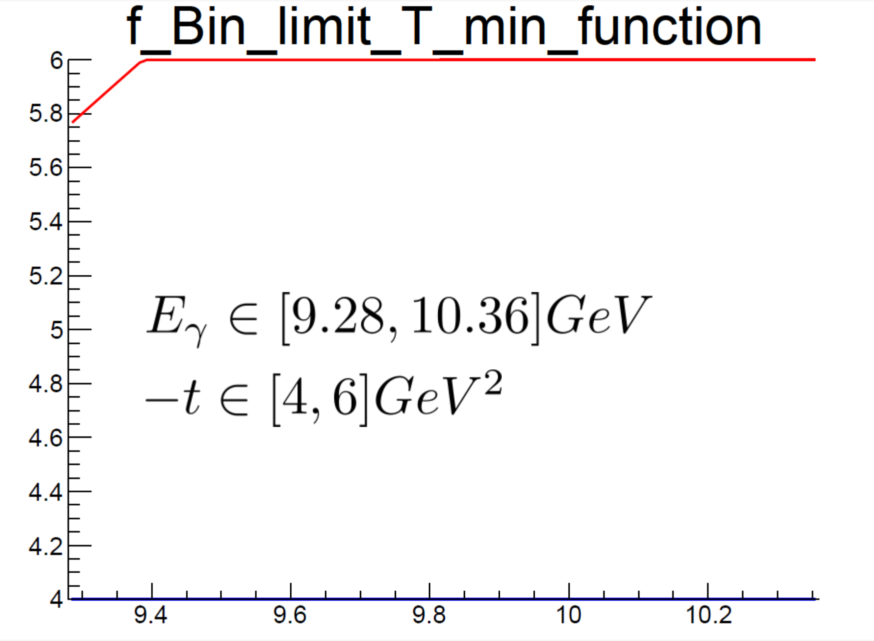
Bin volume correction

Back up



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

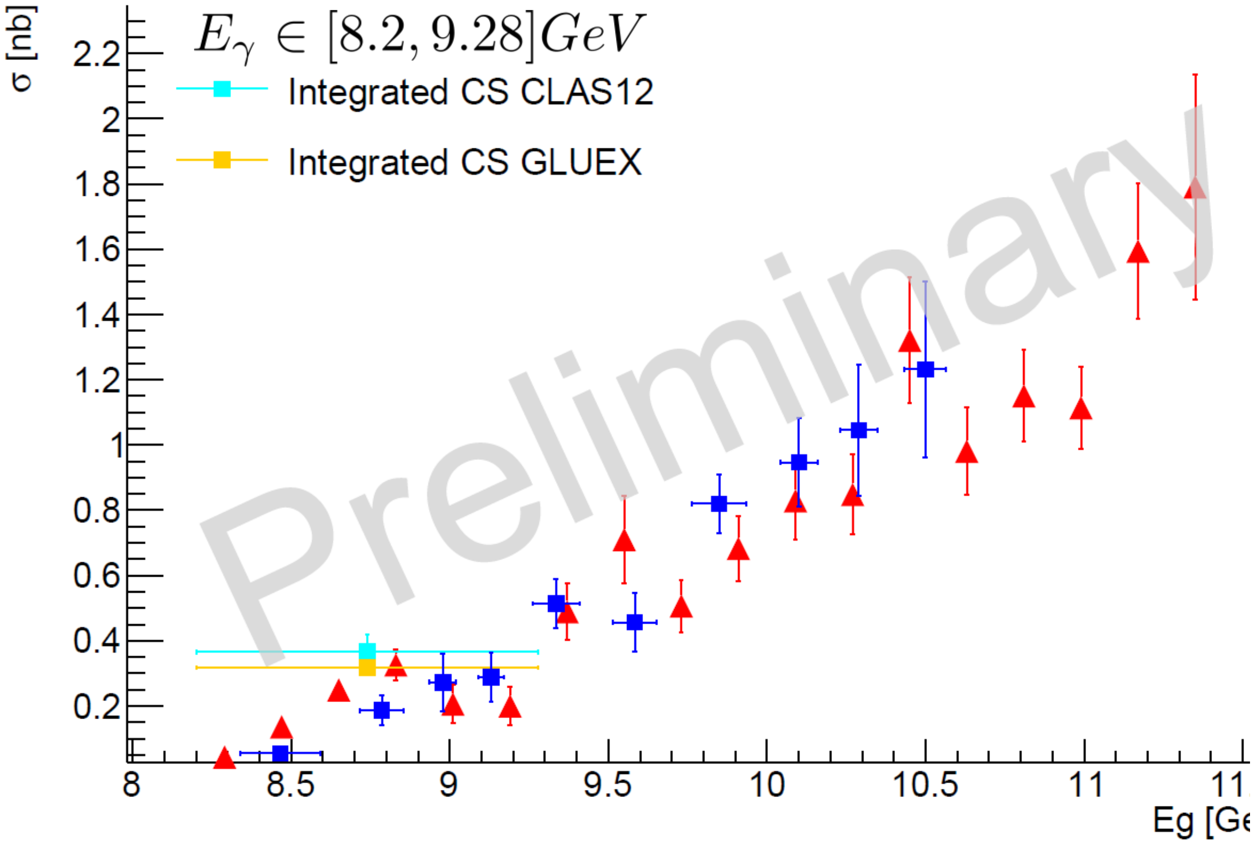
- In practice is this readily done using integral of functions in root

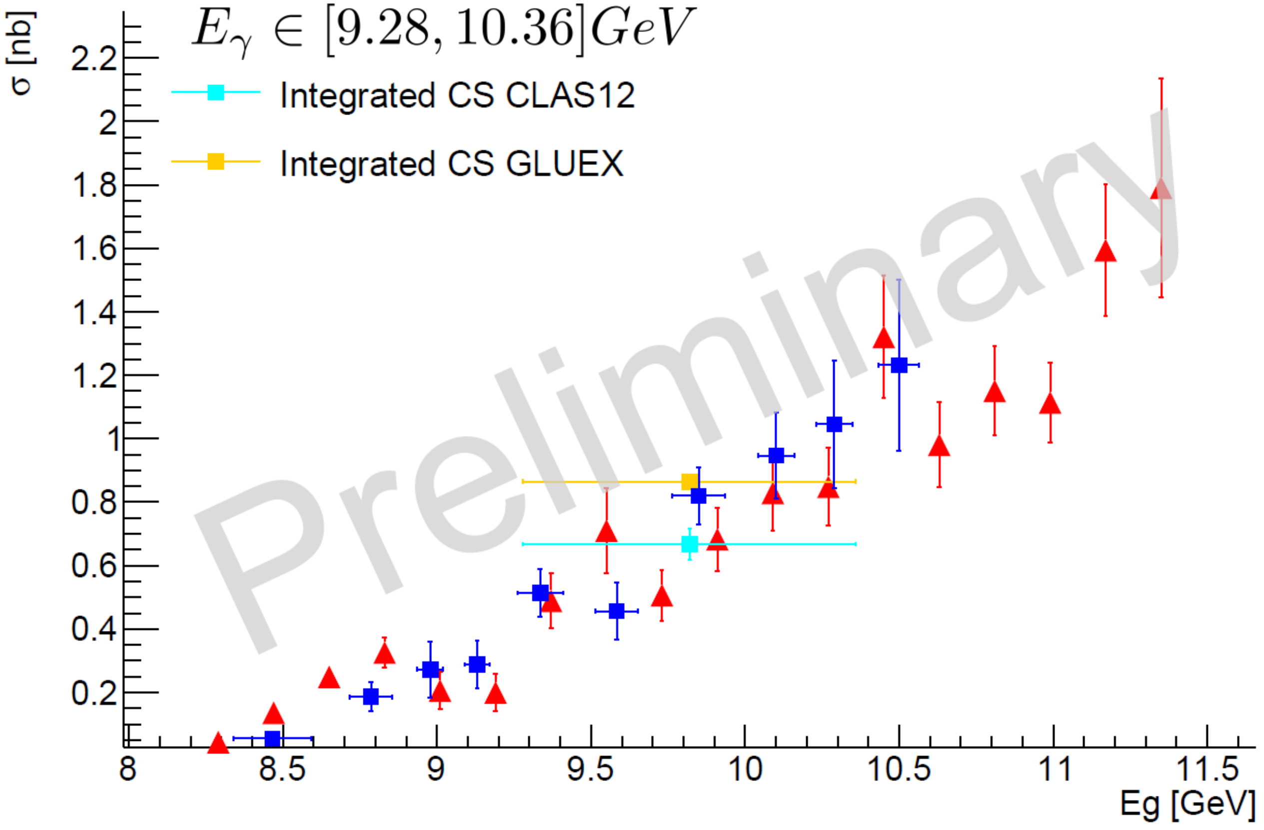


Integrated t-dependent cross-section

- The integral of the t-dependent cross section is done bin-by-bin:
- And compared to the total CS

$$\sigma = \sum_j \left.\frac{d\sigma}{dt}\right|_j \cdot \Delta t_j$$





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

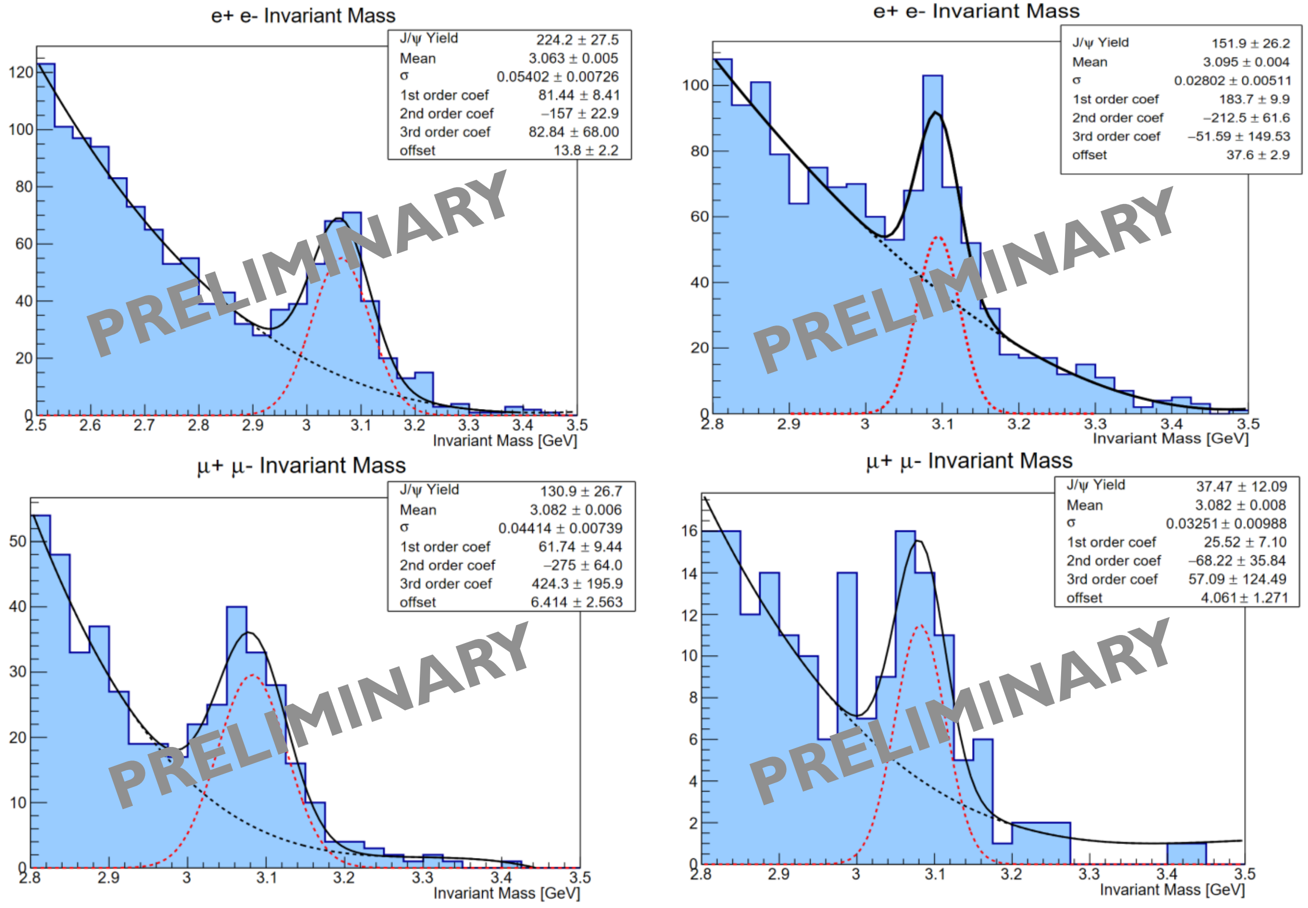
Deuterium target and muon final state

Back up

- Deuterium data were taken by CLAS12 in 2019/2020.
- Opportunity to measure J/ψ production on (bound) neutron and (bound) proton.
- Alongside this analysis, a framework to explore the muon decay channel was developed.
- This effort is lead by R. Tyson from University of Glasgow.

Bound proton

Bound neutron



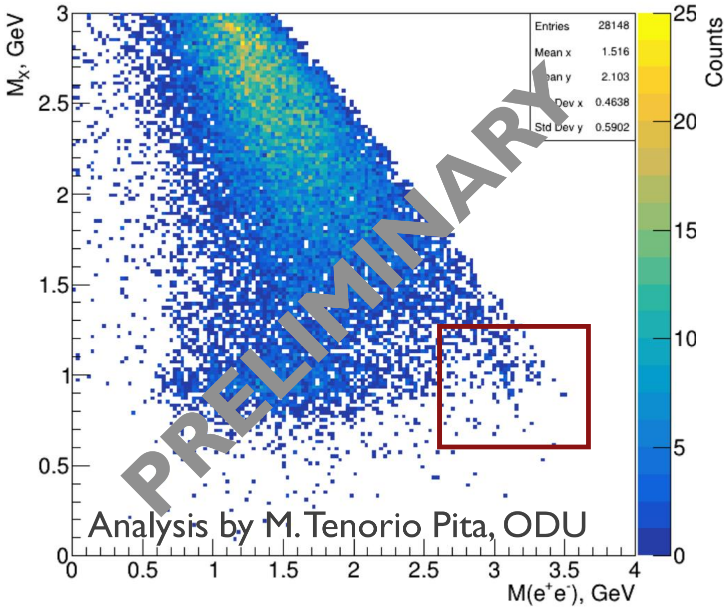
Taken from R. Tyson PhD analysis, Univ. of Glasgow

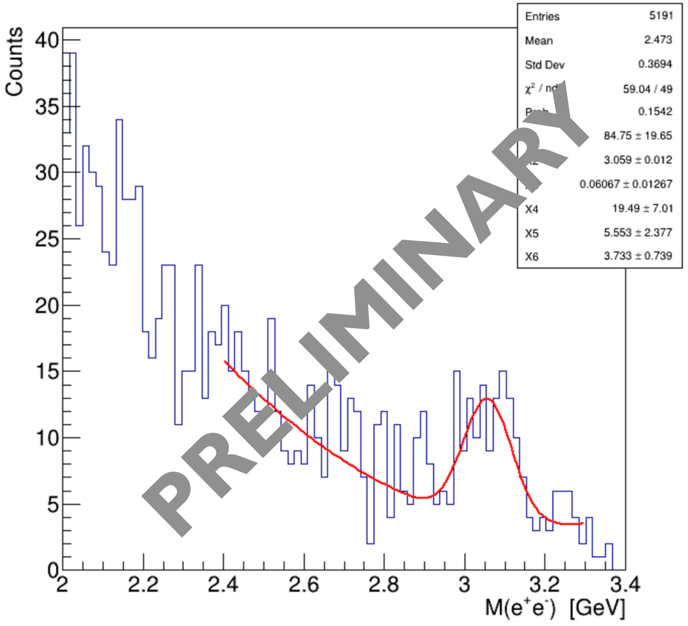
Tagged J/ψ quasi-photoproduction with CLAS12

Back up

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

- Analysis conducted by M. Tenorio Pita, ODU.
- In this case, one electron in the Forward Tagger (Low lab angle <5°) and a lepton pair in CLAS12.
- Excellent cross-check of the quasi-photoproduction approach.
- Early results show low statistics, the new data "cooking" including better tracking efficiency will be beneficial for this analysis.
- Other event topologies will be explored.





Other potential J/ψ analysis using CLAS12 data

- Available data for longitudinally polarized proton target