Near-threshold photoproduction of J/ψ on the proton with CLAS12

Pierre Chatagnon (DPhN, CEA Saclay)

CLAS Collaboration Meeting

5th of March 2024

Analysis note

- The following material is extracted from the note of this analysis.
- With contributions from Stepan, Mariana, Richard and myself.
- Under review since the 18^{th} of February.

CLAS12 analysis note:
Measurement of the cross-section of the photoproduction of the J/ψ meson near the production threshold with the CLAS12 detector.

Pierre Chatagnon[1]*,
Stepan Stepanyan[2],
Mariana Tenorio-Pita[3],
Richard Tyson[2]

[1]Irfu/DPhN, CEA, F91191 Gif-sur-Yvette, France
[2]Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606
[3]Old Dominion University, Norfolk, Virginia

February 18, 2025

Abstract

This analysis note details the steps performed to extract the total and differential cross-section of the photoproduction of J/ψ near the production threshold. The data used for this analysis were taken in 2018 and 2019, with a 10.6 and 10.2 GeV electron beam scattering on a liquid hydrogen target. The aim of this analysis is to publish both the integrated and t-differential cross-sections, as well as the interpretation of these data in terms of gluonic content of the proton.

Link to the analysis note

Motivations

Near-threshold photoproduction of the J/ψ meson

Quasi-photoproduction of J/ψ

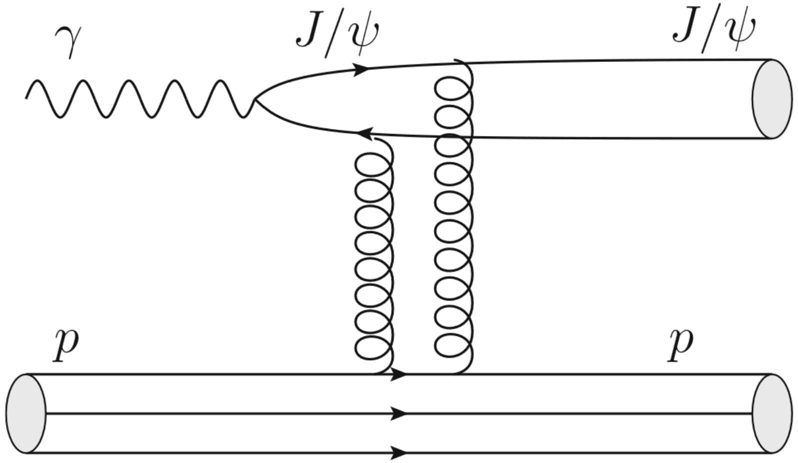
$$ep \to (e')\gamma p \to (X) J/\psi\, p' \to (X) e^+ e^- p'$$

Cross-section

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

Amplitude

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



Matrix element

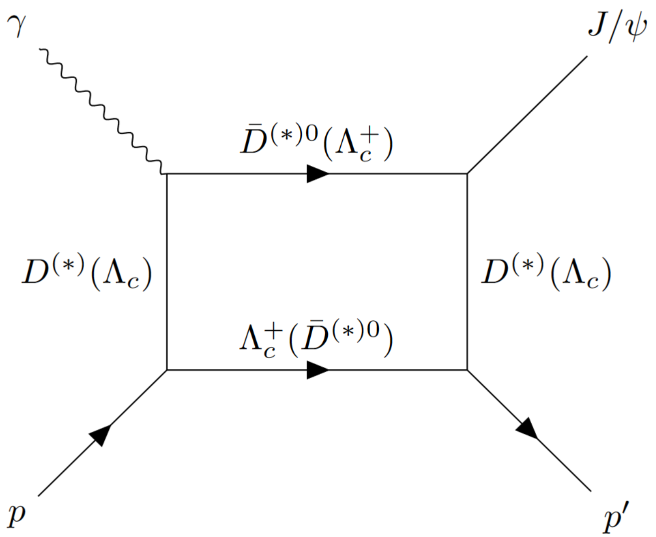
$$\langle p', s' | \hat{T}^a_{\mu\nu}(x) | p, s\rangle = \bar{u}' \left[A^a(t)\frac{\gamma_{\{\mu}P_{\nu\}}}{2} + B^a(t)\frac{iP_{\{\mu}\sigma_{\nu\}\rho}\Delta^\rho}{4m} + D^a(t)\frac{\Delta_\mu\Delta_\nu - g_{\mu\nu}\Delta^2}{4m} + m\bar{c}^a(t) g_{\mu\nu}\right] u e^{i(p'-p)x}$$

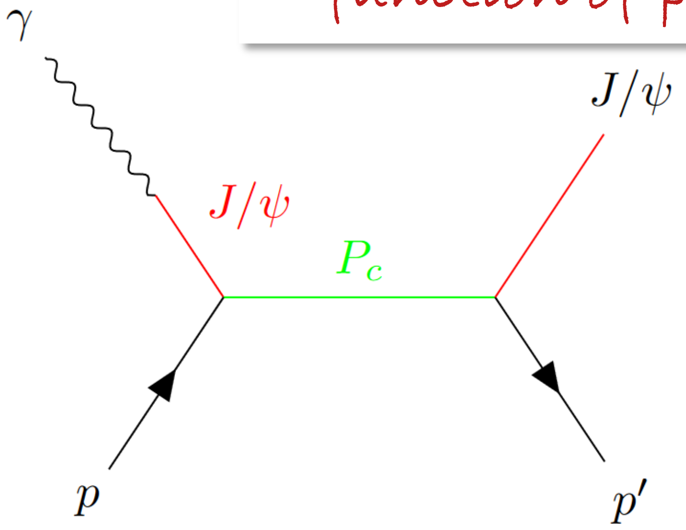
Near-threshold photoproduction of the J/ψ meson

… one big caveat: the coupled channels and pentaquarks

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

→ Total cross-section as a function of photon energy





Previous results from JLab

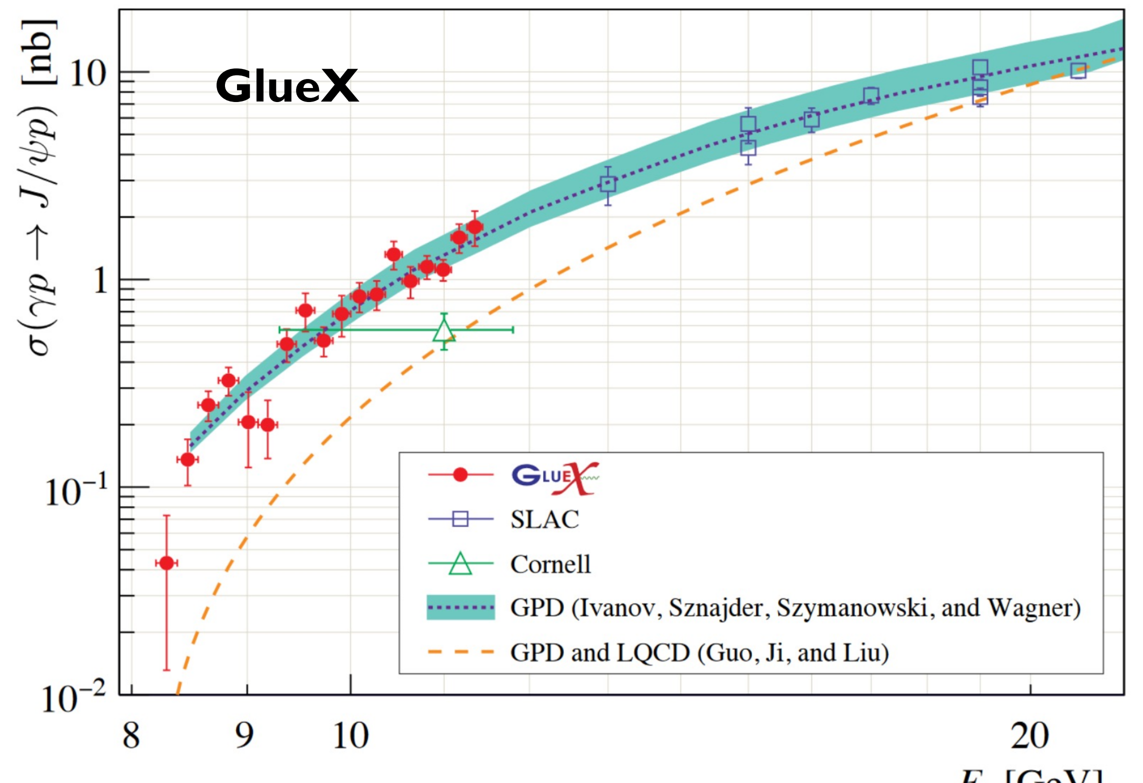


Figure from "Measurement of the J/ψ photoproduction cross section", S. Adhikari *et al.* (GlueX Collaboration). Phys. Rev. C 108, 025201, 2023, arXiv:2304.03845

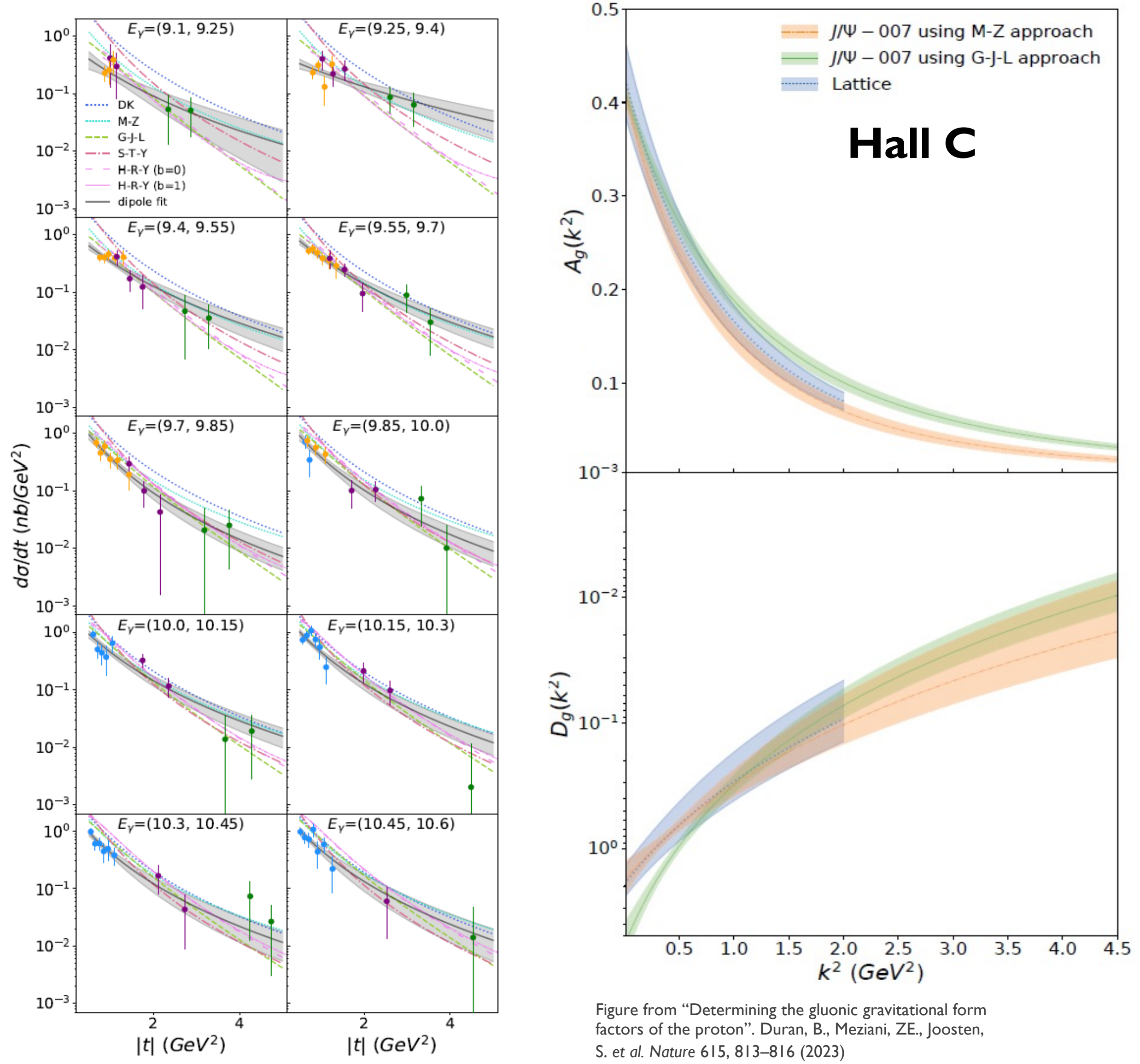


Figure from "Determining the gluonic gravitational form factors of the proton". Duran, B., Meziani, ZE., Joosten, S. *et al. Nature* 615, 813–816 (2023).

Data, MC & analysis tools

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.

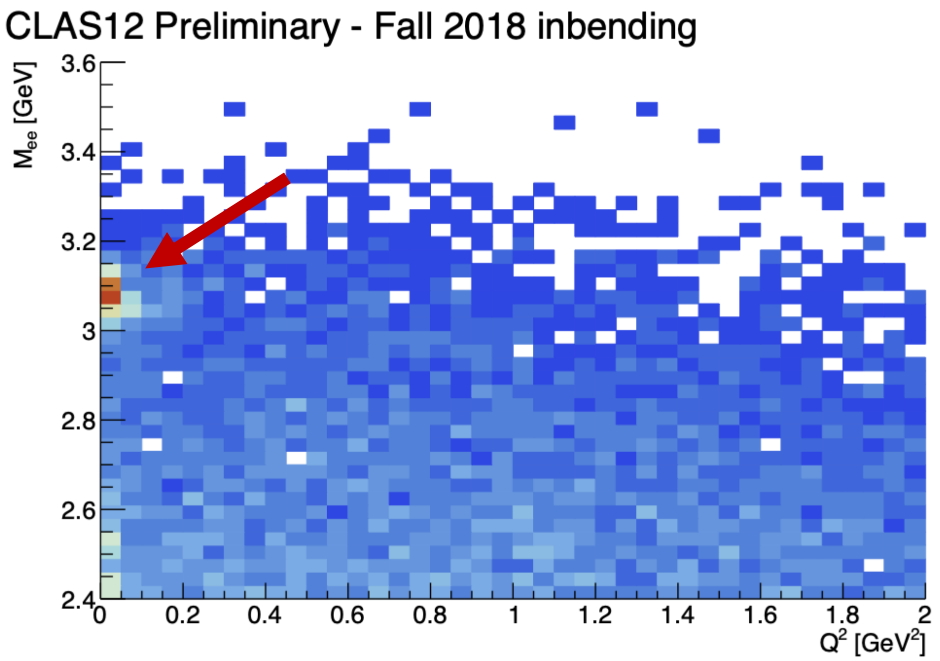
	Config / Beam currents / Charge					
	Fall 18 In.			Fall 18 Out.		Sp. 19
Generator	45 nA 26.312 mC	50 nA 4.000 mC	55 nA 5.355 mC	40 nA 11.831 mC	50 nA 20.620 mC	50 nA 45.994 mC
Grape	8.2M each					6.7 M
TCSGen	2M each					1.5 M
JPsiGen	2M each					
JPsiGen (No rad.)	3M each					
Total of 24 MC samples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

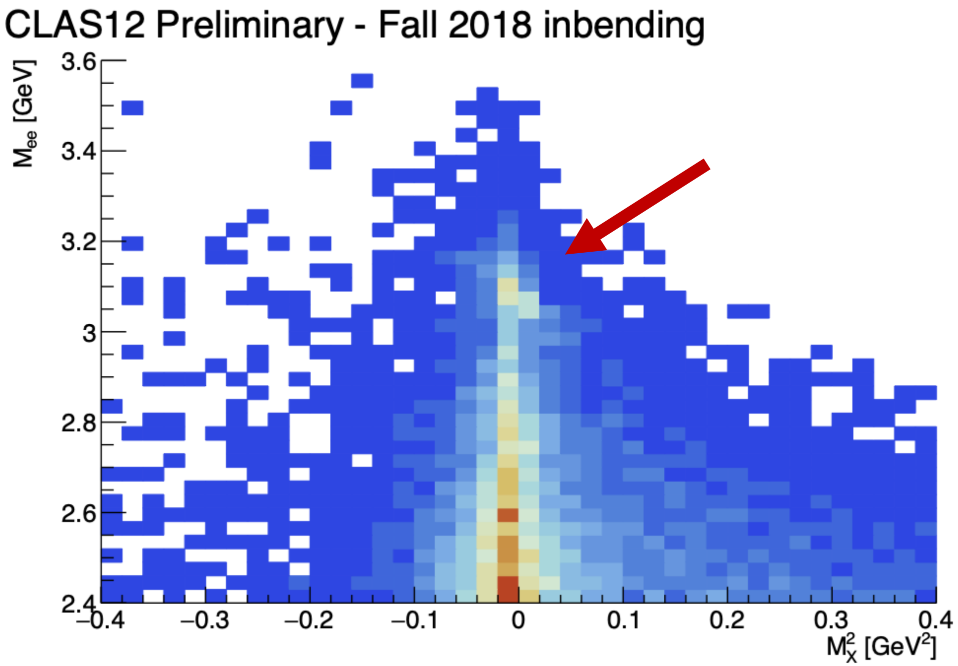
Event selection

CLAS12 EB PID + Lepton BDT PID

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

$p_X = p_{beam} + p_p - p_{e^+} - p_{e^+} - p_{p'}$ → Cuts on $|M_X^2|$ and Q^2





Summary of the analysis tools

- Fiducial cuts + dead paddle cuts,
- Proton energy loss correction,
- Lepton momentum correction,
- Radiated photon correction,
- BDT-based PID for the leptons above 4.5 GeV (see Mariana's note)

Cross-section computation

Number of photons and Number of targets

Number of J/Psi from data

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

Radiative corrections from MC

Normalization factor

Branching ratio

Reconstruction efficiency from MC

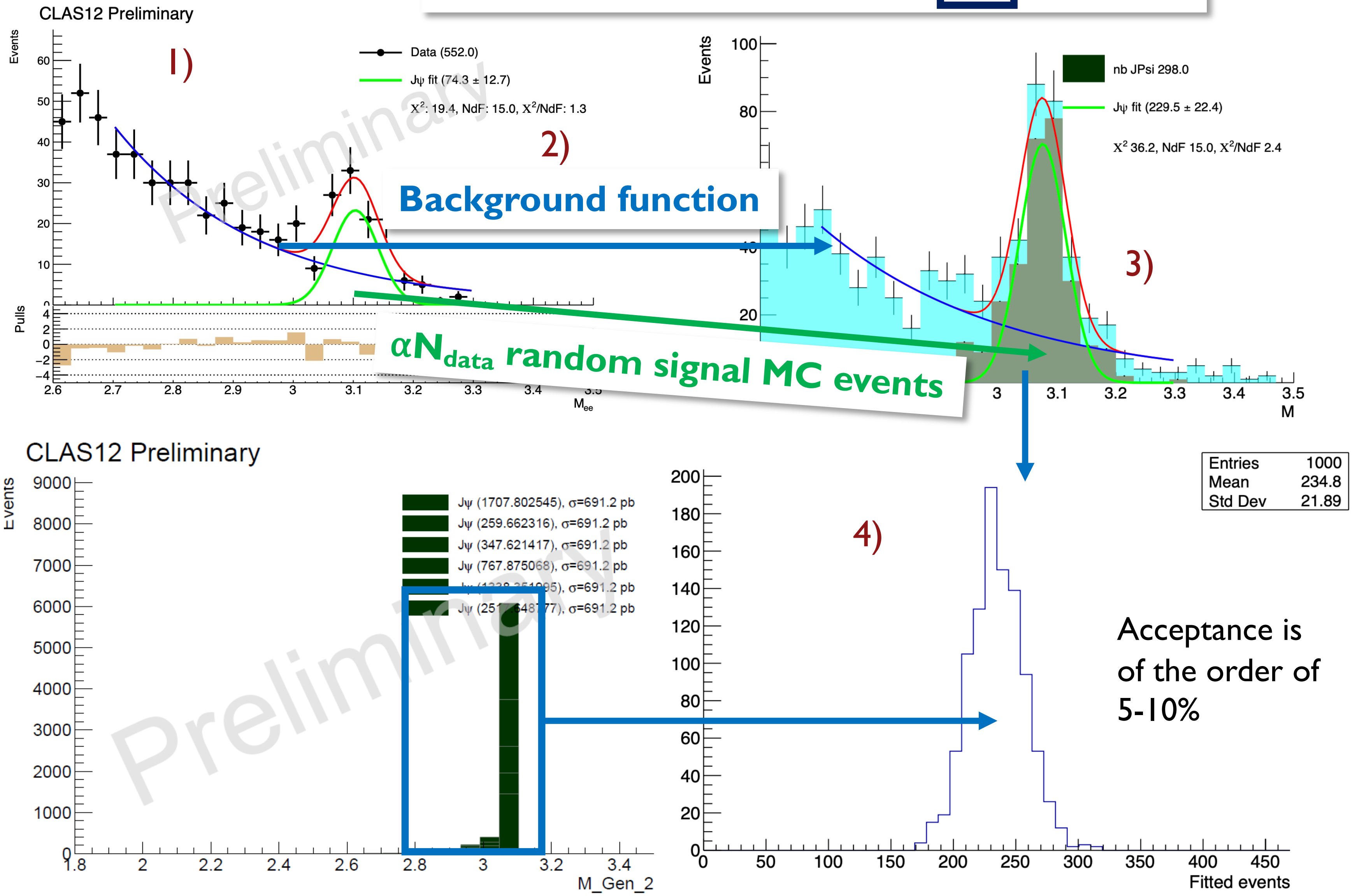
- Presentation at the March 2024 Collaboration Meeting
- Presentation at the RGA meeting (9/11/2024)

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 the number of J/ψ in the data (N_{data}) and a background function is extracted
2) BG events are generated according to this background function and added to αN_{data} random MC J/ψ events.
3) The obtained distribution is fitted with the same function as the data
4) The detection efficiency is then:

$$\epsilon_j = \frac{N_{Fit/MC}\big|_j}{\alpha \cdot N_{Fit/Data}\big|_j} \frac{N_{REC/MC}\big|_j}{N_{GEN+RAD/MC}\big|_j}$$



Acceptance is of the order of 5-10%

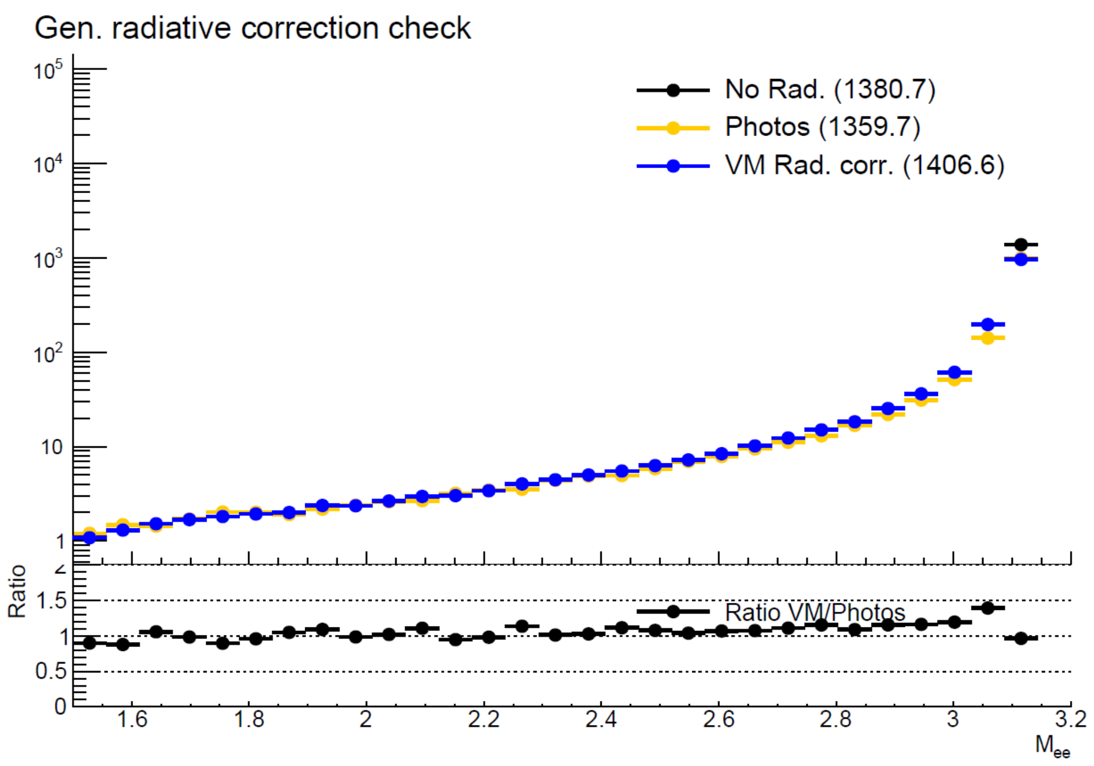
Radiative effects and correction

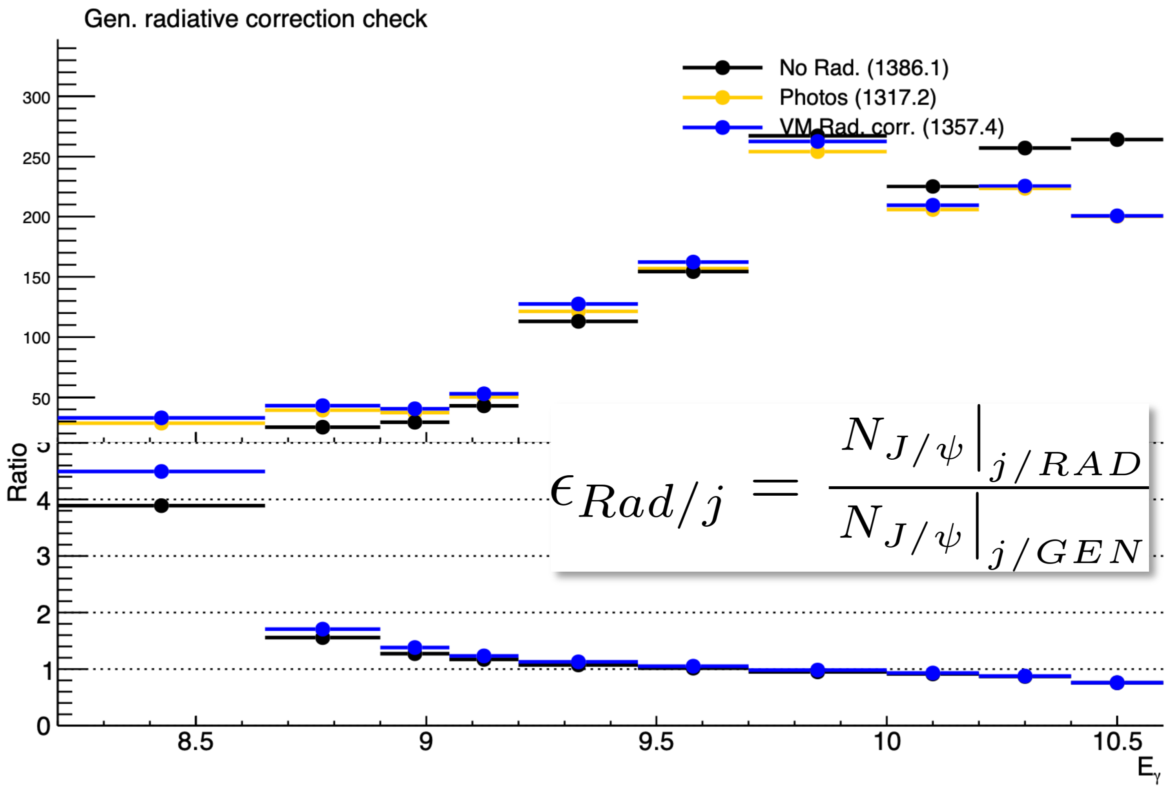
$$\sigma_j = \frac{N_{J/\psi j}}{\mathcal{F}_j \cdot \mathcal{L} \cdot \omega_{cj} \cdot B_r \cdot \epsilon_j \, \epsilon_{Rad/j}}$$

- Radiative corrections for BH: *Matthias Heller et al. Soft-photon corrections to the bethe-heitler process in the γp → l+l−p reaction. PRD*
- Radiative effects for J/ψ: *F. Ehlotzky and H.Mitter, Radiative corrections to the leptonic decay modes of the neutral vector mesons, Nuovo Cim., 55A: 181-92,1968*

  → Cross-check using *Photos*

- The JpsiGen, TCSGen generator with radiative effect are on Github, as well as an event converter for Grape.
- A full note on this algorithm is included in the analysis note.
- The work on the BH radiative corrections was presented at the CLAS collaboration meeting in July 23.

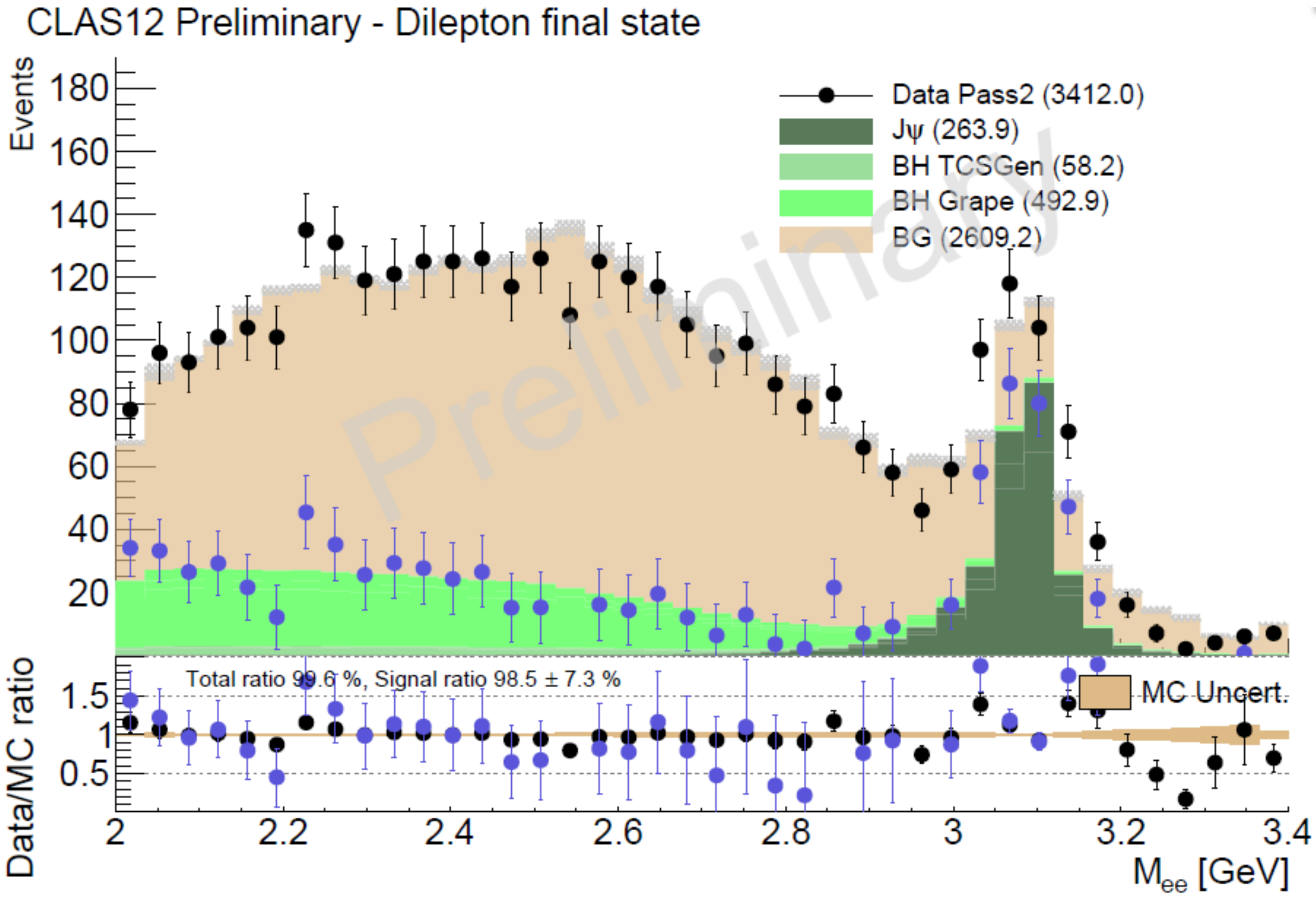


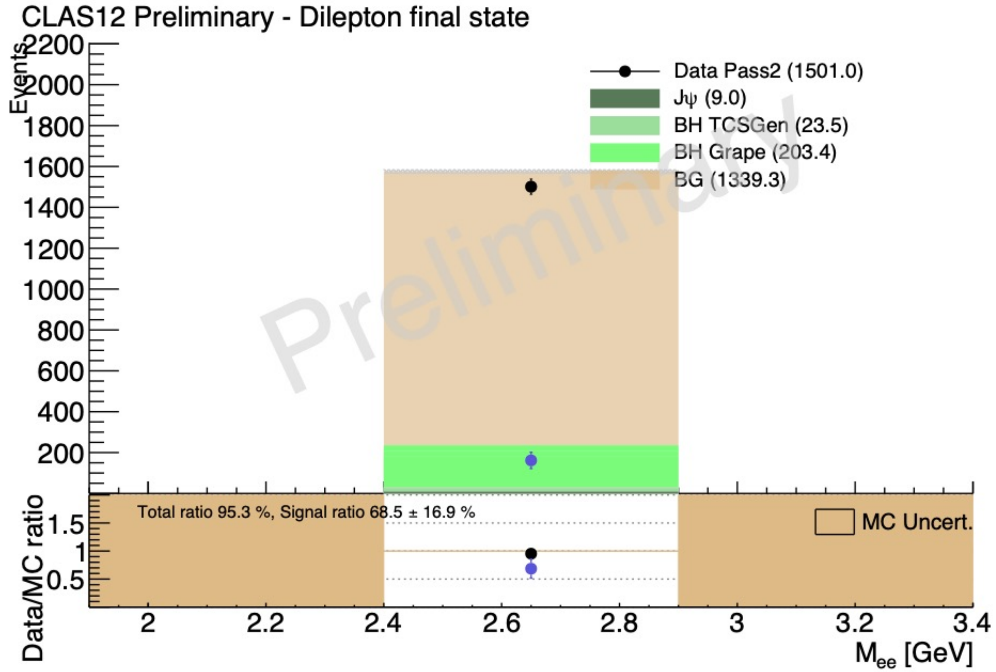


$$\epsilon_{Rad/j} = \frac{N_{J/\psi}\big|_{j/RAD}}{N_{J/\psi}\big|_{j/GEN}}$$

Normalization factor

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

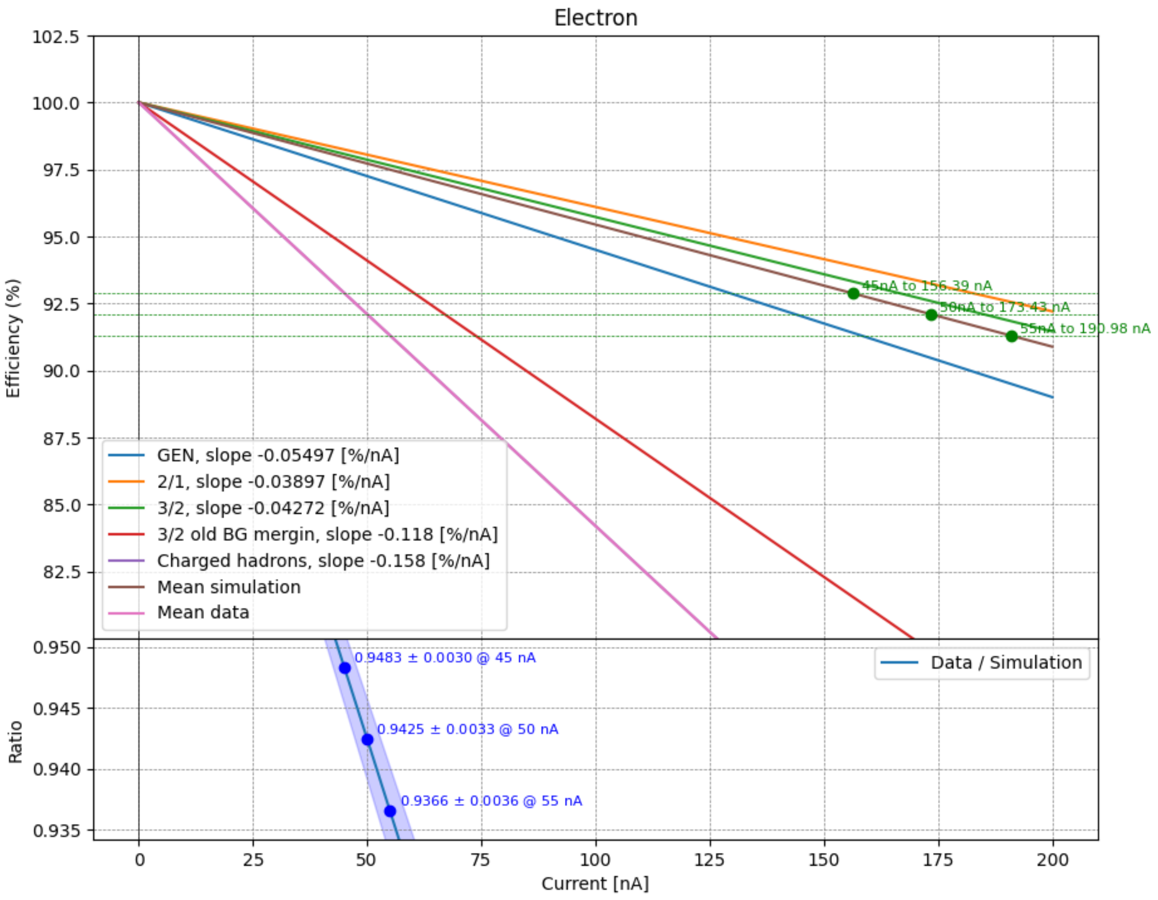


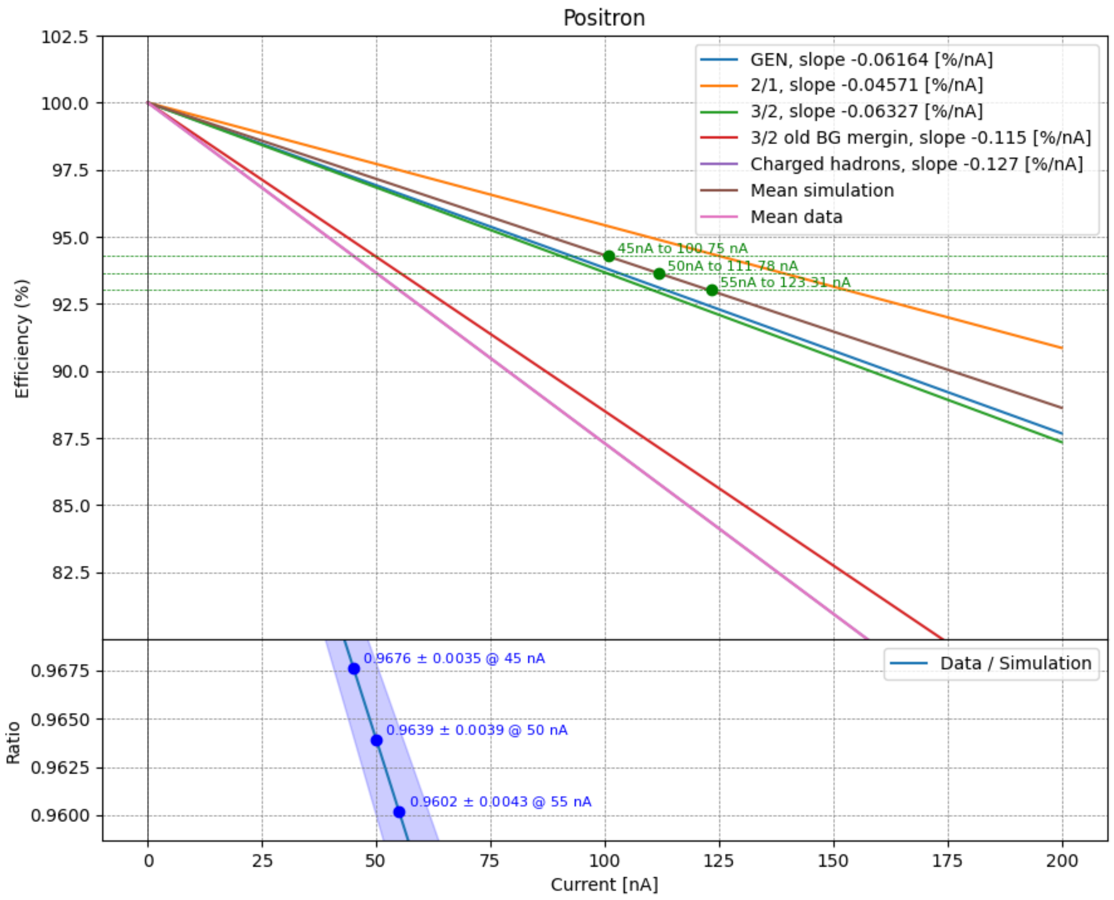


- Normalization factor for Fall Inbending 2018 :

$$\omega_c = \frac{N_{Data} - N_{BG}}{N_{SIM\ \ BH}} = 69\%$$

Normalization factor (2nd method)





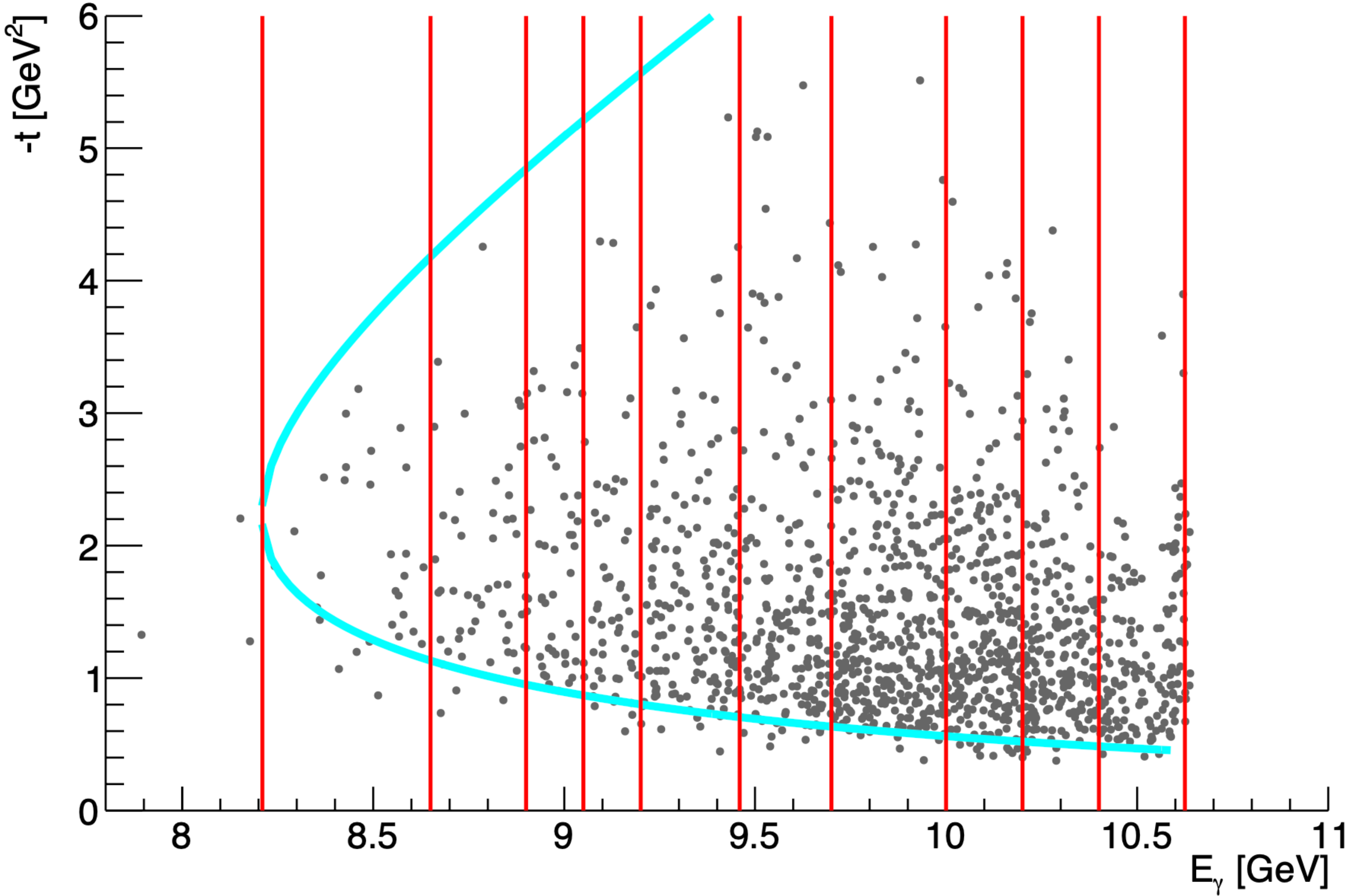
$$\omega_c = \bar{\epsilon}_{e^+} \cdot \bar{\epsilon}_{e^-} \cdot R^{PID}_{e^+} \cdot R^{PID}_{e^-} \cdot (n_{Std.\ PID} + n_{e^-} R^{BDT}_{e^-} + n_{e^+} R^{BDT}_{e^+} + n_{e^- e^+} R^{BDT}_{e^+} R^{BDT}_{e^-})$$

$$\omega_c^{tot} = 0.849$$ → 16% systematic uncertainty on the normalization

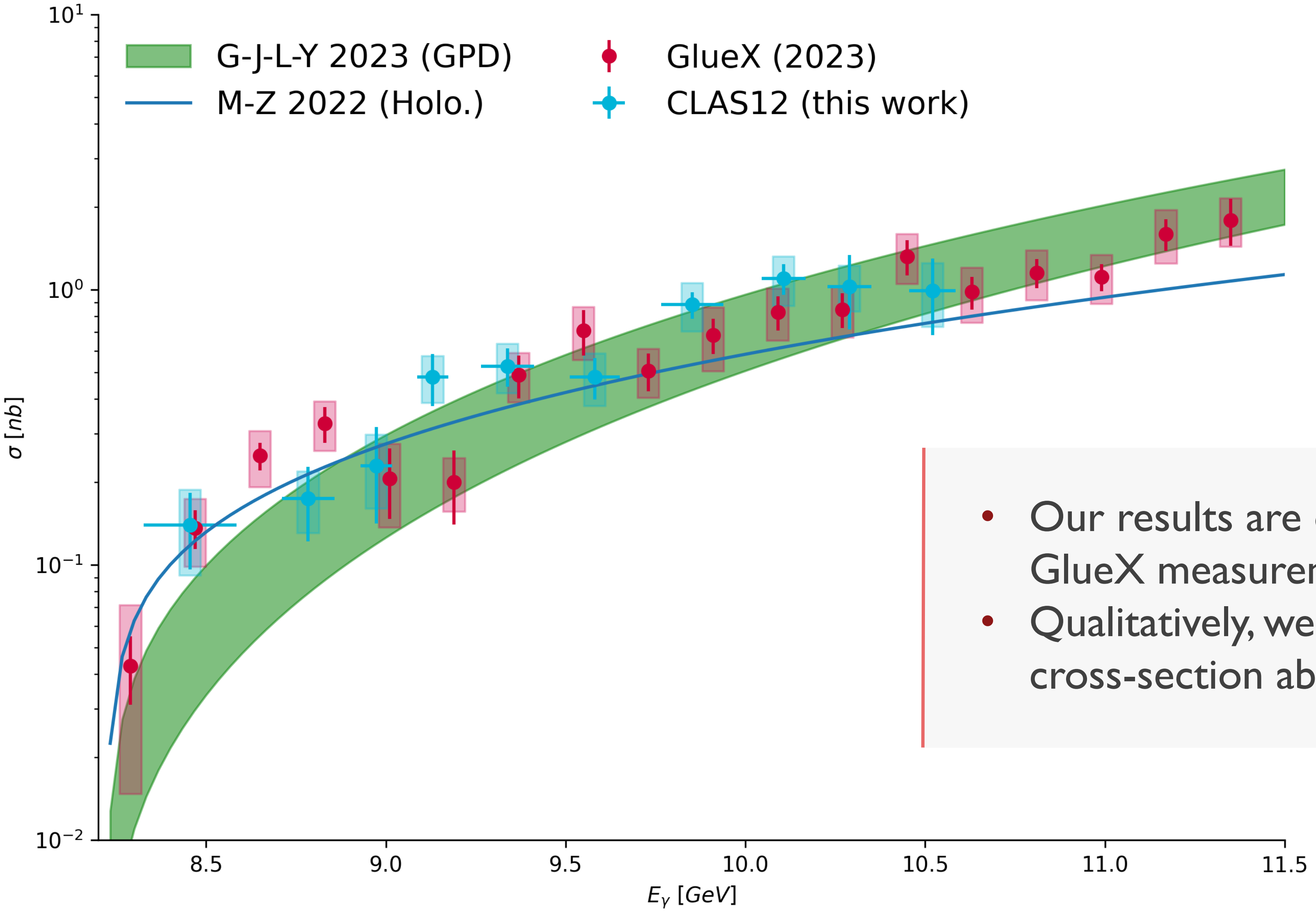
Results
& interpretation

Kinematic coverage and binning

Bin	1	2	3	4	5	6	7	8	9	10
Energy min. [GeV]	8.2	8.65	8.9	9.05	9.2	9.46	9.7	10.	10.2	10.4
Energy max. [GeV]	8.65	8.9	9.05	9.2	9.46	9.7	10.	10.2	10.4	10.6



Integrated cross-section

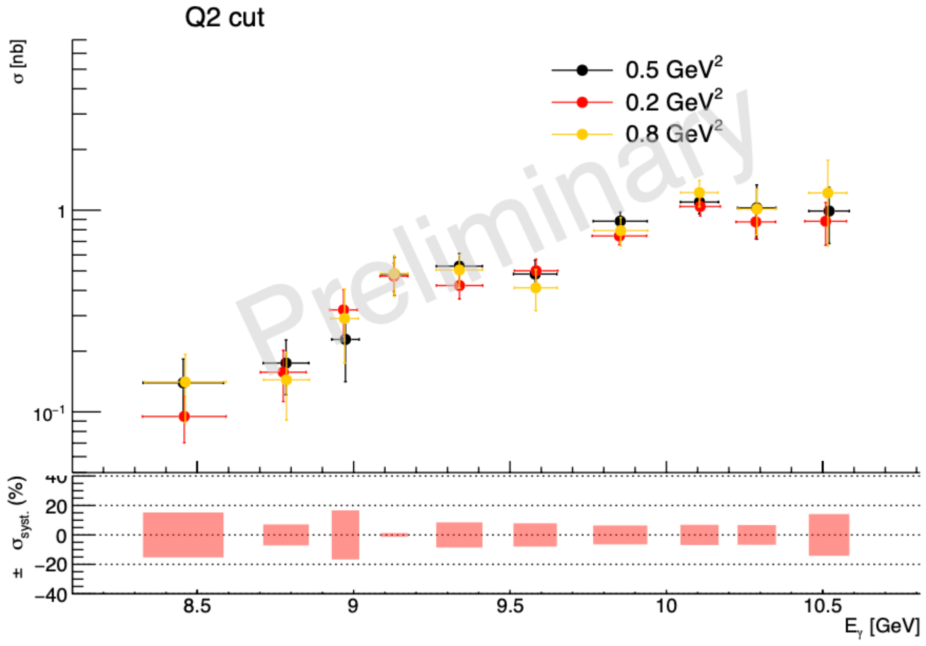


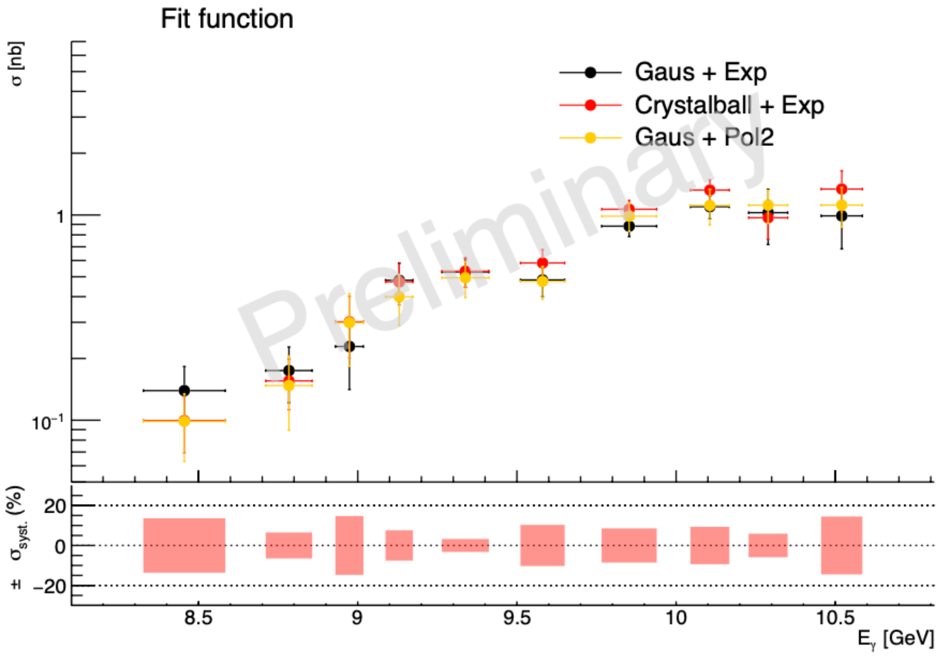
- Our results are overall in agreement with the GlueX measurement.
- Qualitatively, we do not see the reduction of the cross-section above 9 GeV.

Systematics

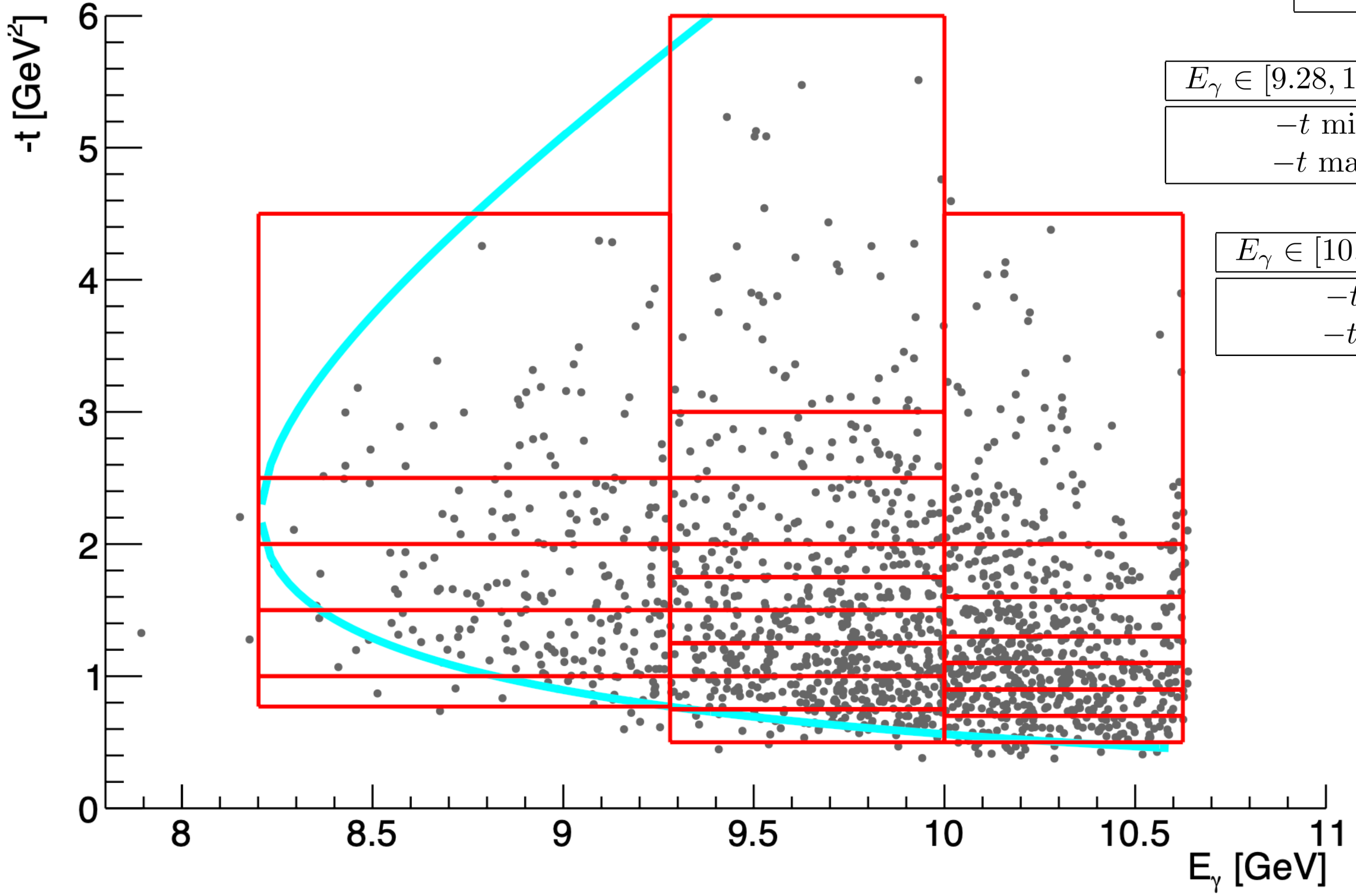
Variation	Q^2 [GeV^2]	MM^2 [GeV^2]	Fit function	AI PID	Prot. PID	Lepton mom. [GeV]
Standard	0.5	0.4	Gauss + Int.	0.0	No cuts	1.7
Down	0.2	0.2	CB + int.	-0.05	2σ	1.5
Up	0.8	0.8	Gauss + Pol.2	0.05	3σ	1.9

Variation	Norm.	Accumulated charge	Radiative correction
Standard	Mixed BG	Upper bound from inclusive CS analysis: 1.2%	-
Alternative	Single particle eff.		-





Differential cross-section binning



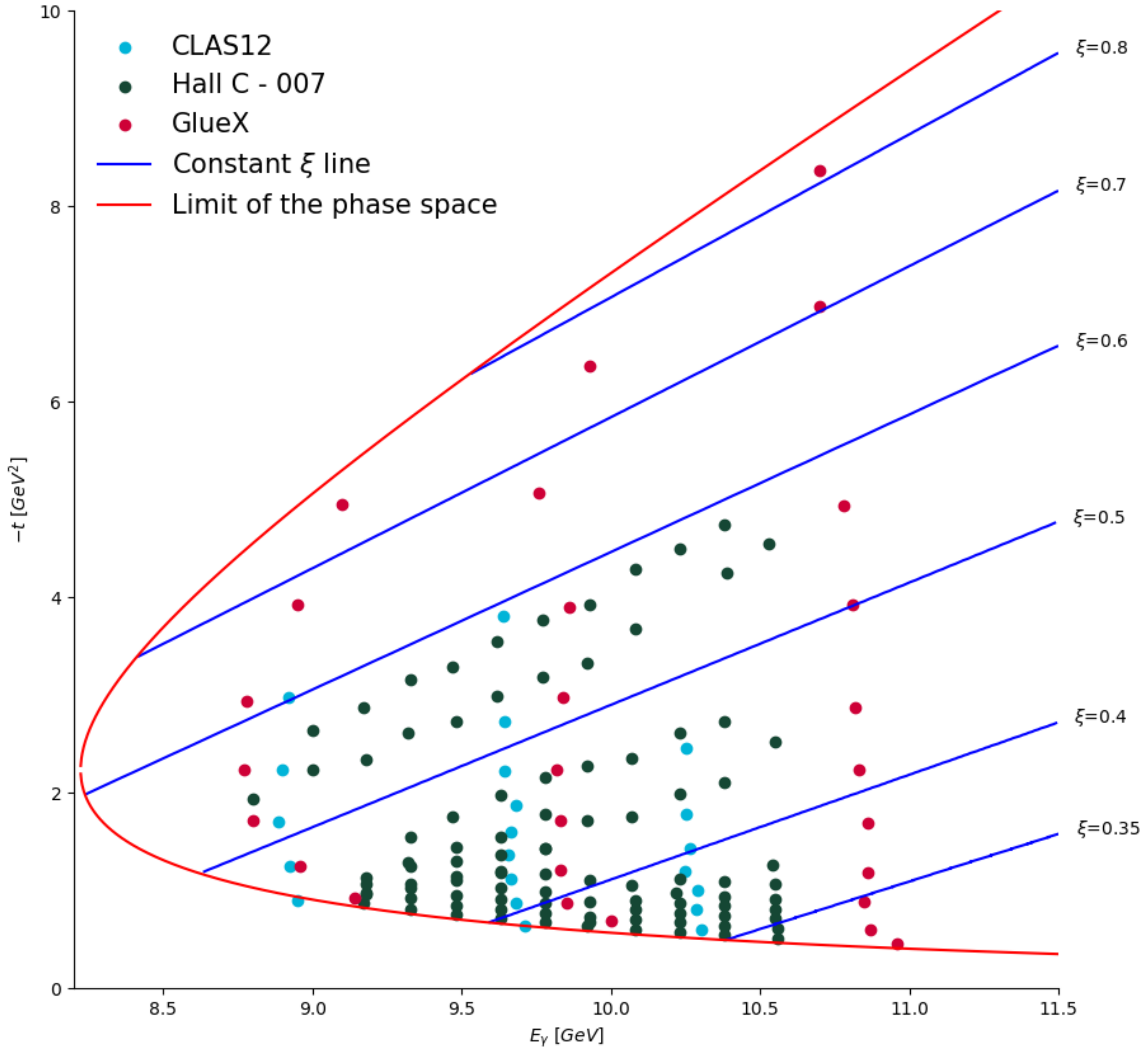
$E_\gamma \in [8.2, 9.28]$ GeV / Bin	1	2	3	4	5
$-t$ min. [GeV^2]	0.77	1.00	1.5	2.0	2.5
$-t$ max. [GeV^2]	1.00	1.5	2.0	2.5	4.5

$E_\gamma \in [9.28, 10.00]$ GeV / Bin	1	2	3	4	5	6	7	8	9
$-t$ min. [GeV^2]	0.5	0.75	1.0	1.25	1.5	1.75	2.0	2.5	3.0
$-t$ max. [GeV^2]	0.75	1.0	1.25	1.5	1.75	2.0	2.5	3.0	6.0

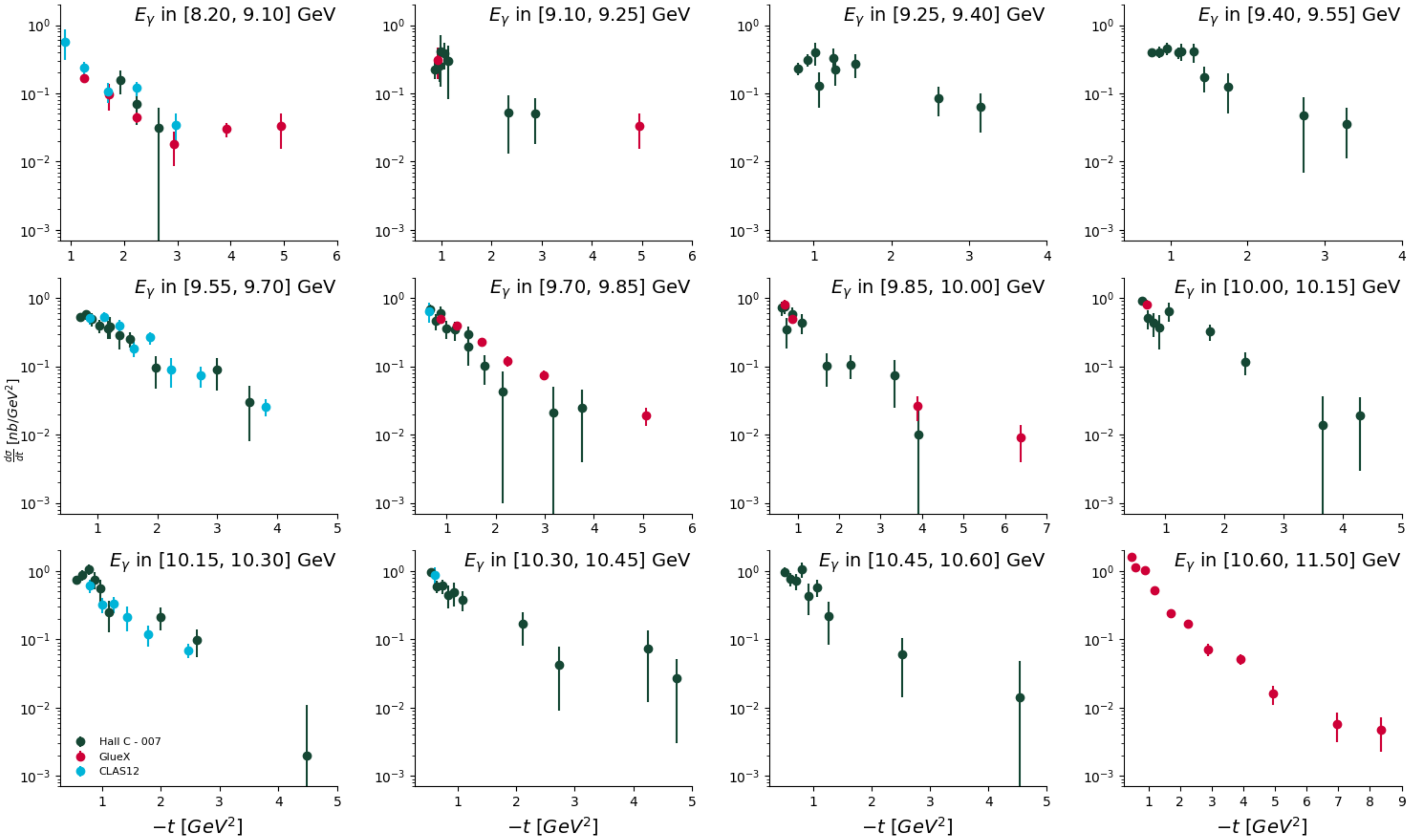
$E_\gamma \in [10.00, 10.6]$ GeV / Bin	1	2	3	4	5	6	7
$-t$ min. [GeV^2]	0.5	0.7	0.9	1.1	1.3	1.6	2.0
$-t$ max. [GeV^2]	0.7	0.9	1.1	1.3	1.6	2.0	4.5

- Limits set to have similar number of J/ψ per bin.
- Bin volume correction implemented for bins close to the $t_{min/max}$ boundaries.

Differential cross-section binning

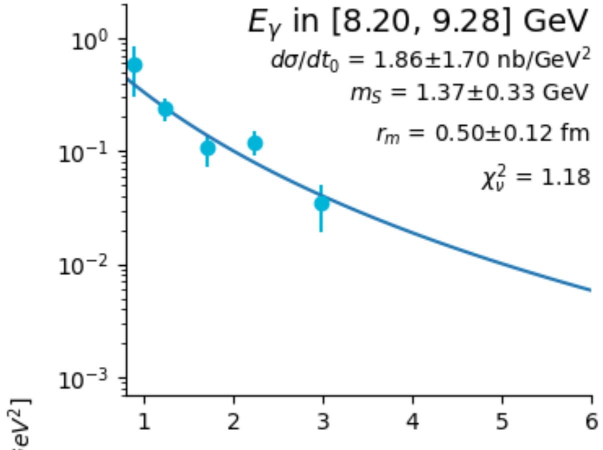


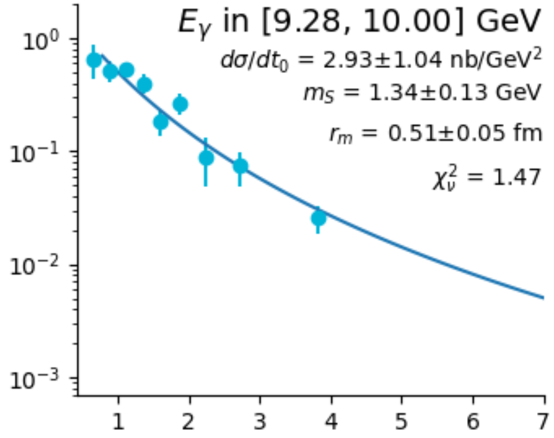
Differential cross-section results

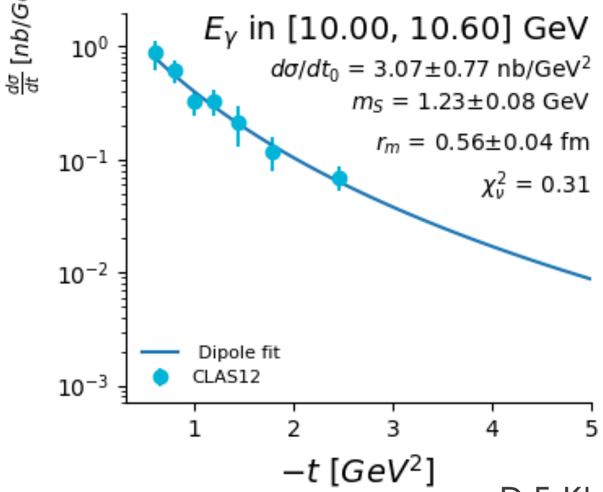


GlueX
Hall C - 007
CLAS12

Dipole fit and interpretation in term of mass radius



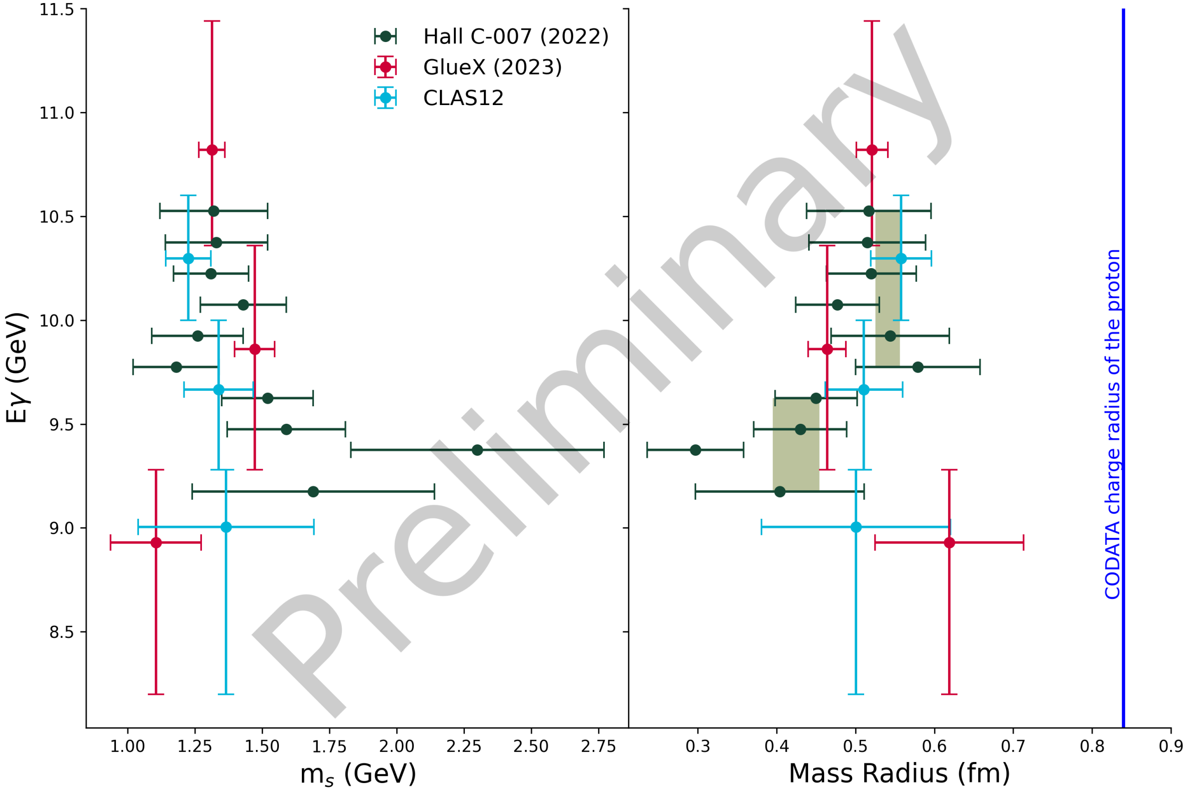




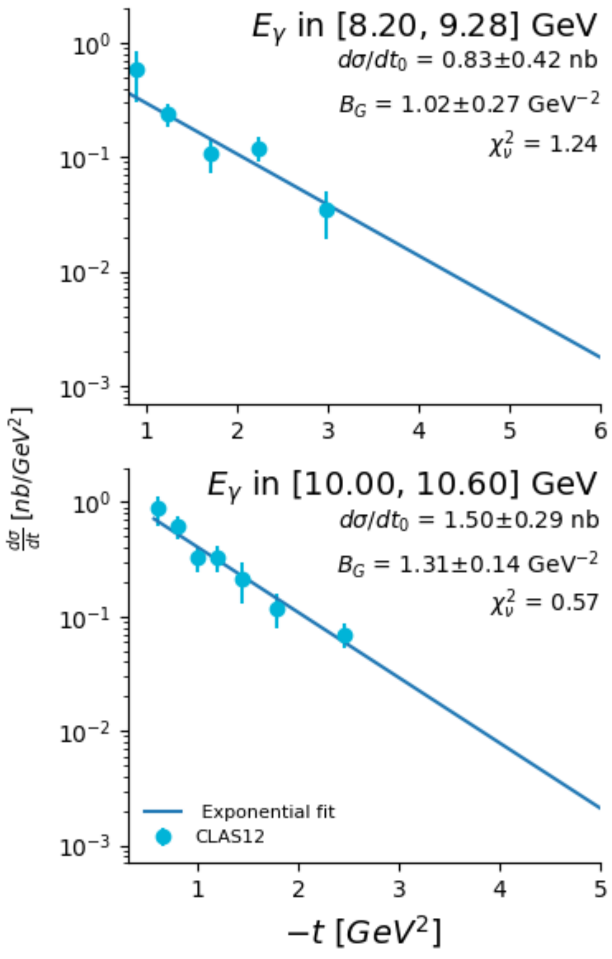
$$\frac{d\sigma}{dt} = \frac{d\sigma}{dt}\Big|_0 \cdot \frac{1}{(1-t/m_S^2)^4}$$

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

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



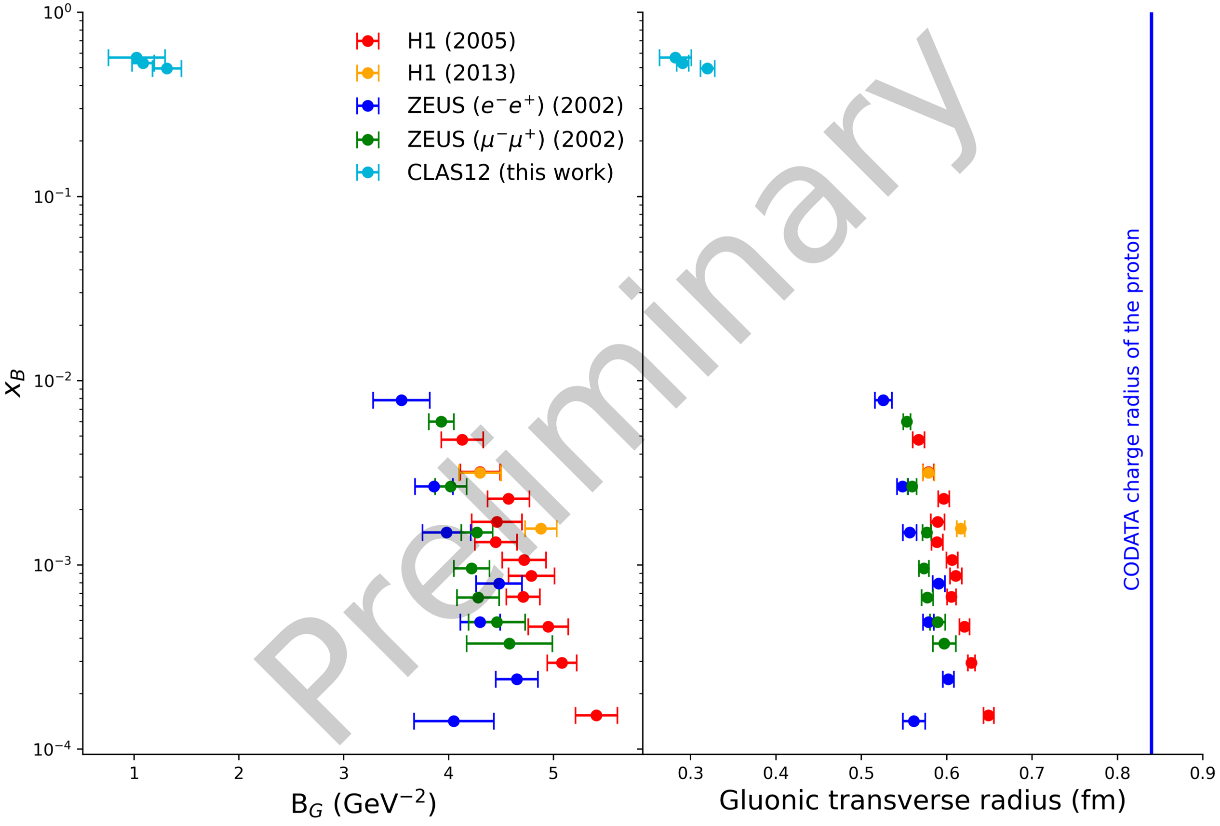
Exponential fit



$$\frac{d\sigma}{dt} = \left.\frac{d\sigma}{dt}\right|_0 e^{-B_G|t|}$$

$$r_g = \sqrt{2B_G}$$

$$x_B = \frac{M^2_{J/\psi}}{W^2 - m_p^2}$$



GFF extraction with CLAS12 data

Model dependent extraction of GFFs

- **Holographic QCD model**

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

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

- **Generalized Parton Distribution model**

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

Yuxun Guo, Xiangdong Ji, Yizhuang Liu, and Jinghong Yang. Updated analysis of near-threshold heavy quarkonium production for probe of proton's gluonic gravitational form factors. Phys. Rev.D, 108(3):034003, 2023

Cut at ξ<0.4 applied

- **GFF parametrization**

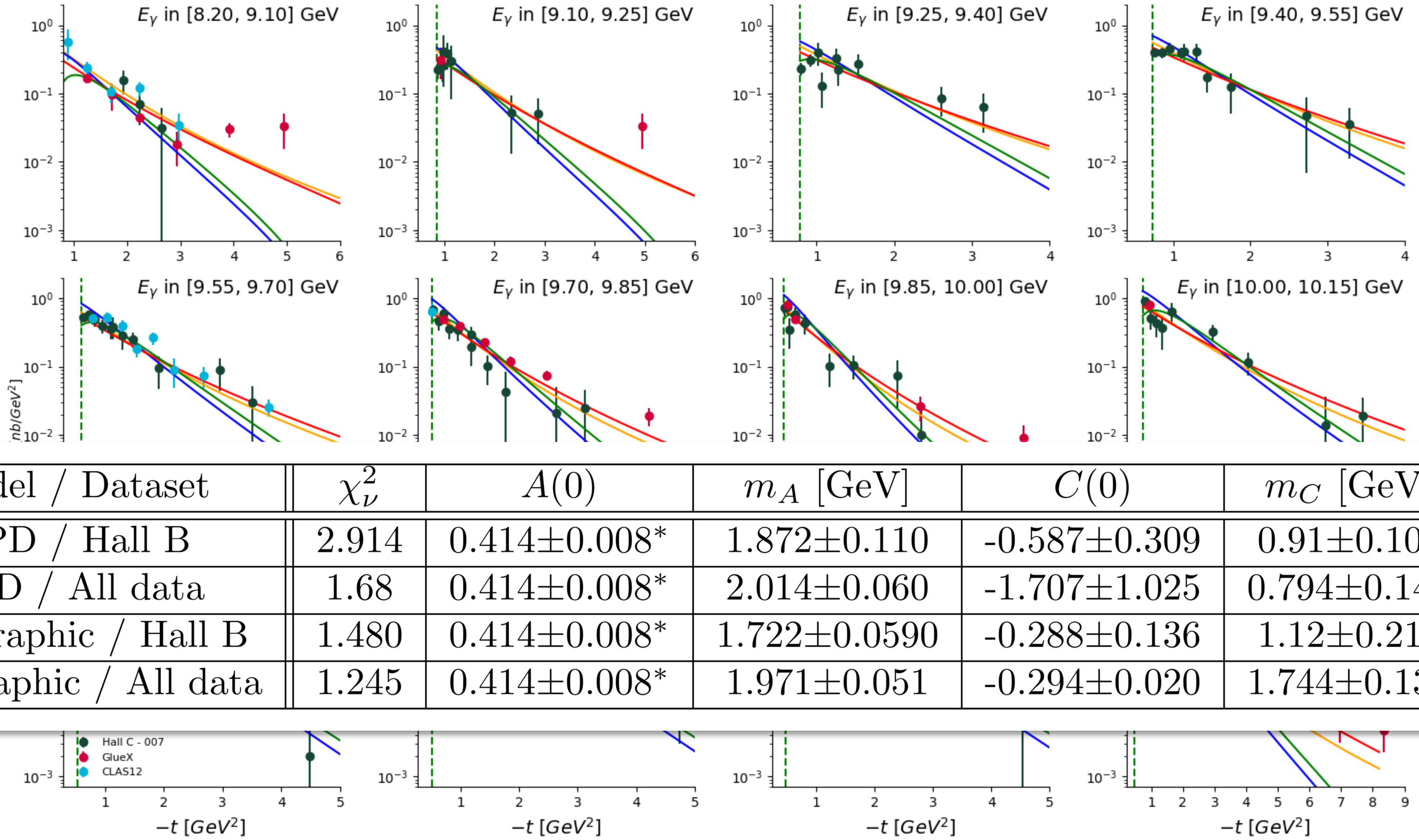
$$C(t) = \frac{1}{4}D(t) = \frac{C(0)}{(1-\frac{t}{m_C^2})^3} \qquad A(t) = \frac{A(0)}{(1-\frac{t}{m_A^2})^3}$$

Fixed parameters

Model / Dataset	$A(0)$	m_C [GeV]
GPD / Hall B	0.414±0.008	0.91±0.10
GPD / All data	0.414±0.008	-
Holographic / Hall B	0.414±0.008	1.12±0.21
Holographic / All data	0.414±0.008	-

- Duran, B., Meziani, ZE., Joosten, S. *et al.* Determining the gluonic gravitational form factors of the proton. *Nature* 615, 813–816 (2023)
- Yuxun Guo, Xiangdong Ji, Yizhuang Liu, and Jinghong Yang. Updated analysis of near-threshold heavy quarkonium production for probe of proton's gluonic gravitational form factors. Phys. Rev.D, 108(3):034003, 2023
- Tie-Jiun Hou et al. New CTEQ global analysis of quantum chromodynamics with high-precision data from the LHC. Phys. Rev. D, 103(1):014013, 2021

Toward GFF extraction including CLAS12 data



Model / Dataset	χ^2_ν	$A(0)$	m_A [GeV]	$C(0)$	m_C [GeV]
GPD / Hall B	2.914	0.414±0.008*	1.872±0.110	-0.587±0.309	0.91±0.10*
GPD / All data	1.68	0.414±0.008*	2.014±0.060	-1.707±1.025	0.794±0.148
Holographic / Hall B	1.480	0.414±0.008*	1.722±0.0590	-0.288±0.136	1.12±0.21*
Holographic / All data	1.245	0.414±0.008*	1.971±0.051	-0.294±0.020	1.744±0.135

GFF using CLAS12 data, and all available data

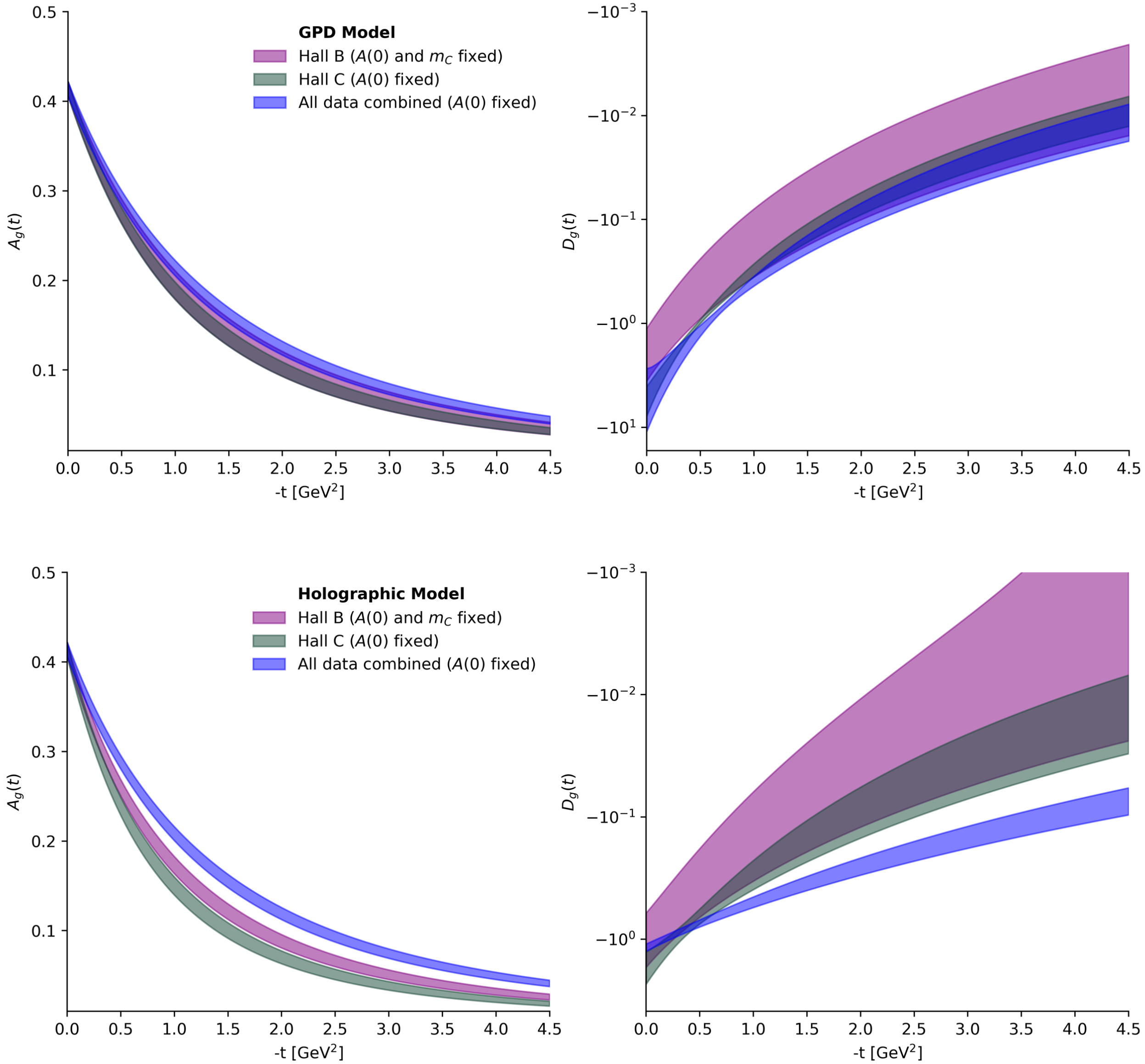
- Use the tripole ansatz for the GFFs:

$$C(t) = \frac{1}{4}D(t) = \frac{C(0)}{(1-\frac{t}{m_C^2})^3}$$

$$A(t) = \frac{A(0)}{(1-\frac{t}{m_A^2})^3}$$

- Error bars include correlations between fitted variables.

- Inclusion of Hall D data in the fit lead to flatter t-dependance of D.



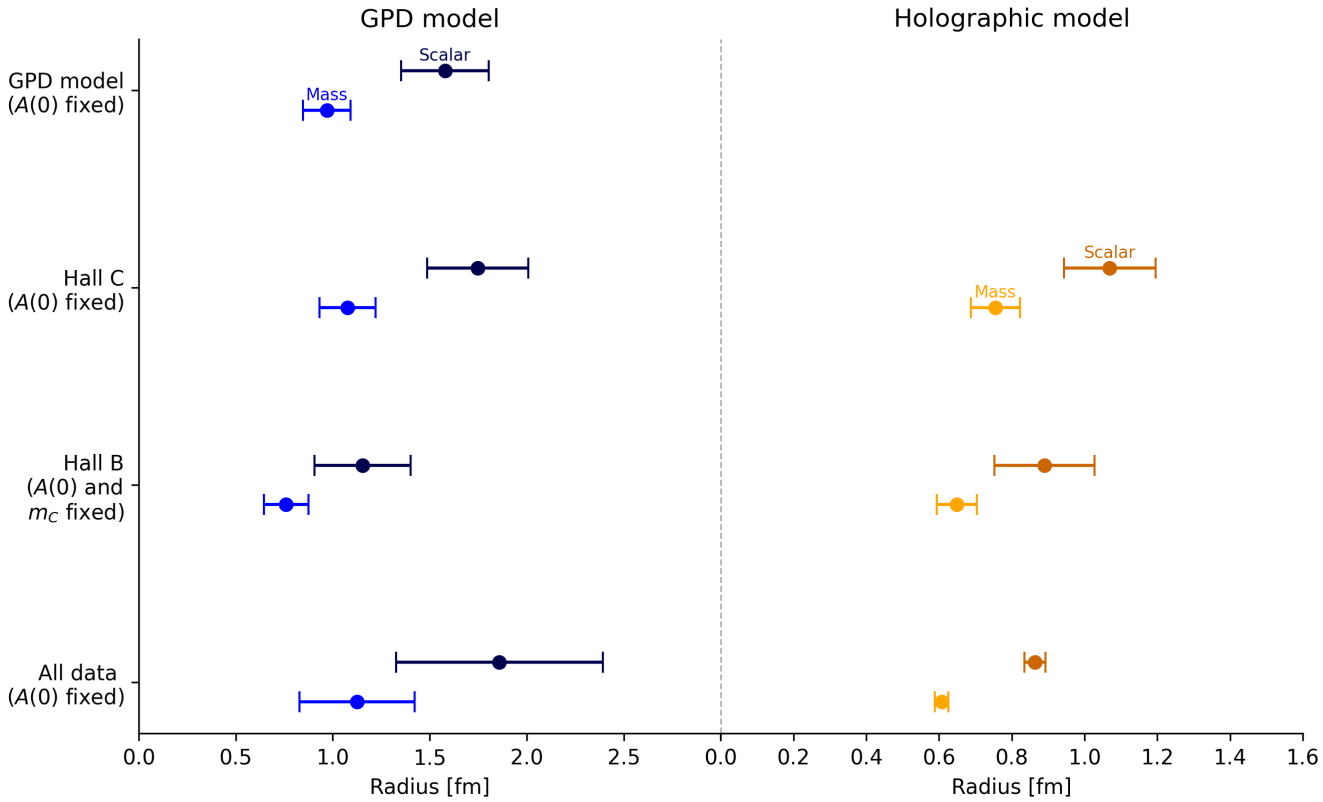
Mass and scalar radii

- From the GFFs, one can extract:
  - the gluon mass radius

$$\langle r_m^2\rangle_g = 6\frac{1}{A_g(0)}\frac{dA_g(t)}{dt}\bigg|_{t=0} - 6\frac{1}{A_g(0)}\frac{C_g(0)}{M_N^2} = \frac{18}{m_A^2} - 6\frac{1}{A_g(0)}\frac{C_g(0)}{M_N^2}$$

  - and the gluon scalar radius of the proton

$$\langle r_s^2\rangle_g = 6\frac{1}{A_g(0)}\frac{dA_g(t)}{dt}\bigg|_{t=0} - 18\frac{1}{A_g(0)}\frac{C_g(0)}{M_N^2} = \frac{18}{m_A^2} - 18\frac{1}{A_g(0)}\frac{C_g(0)}{M_N^2}$$



Model / Dataset	$\sqrt{< r_m^2 >_g}$ [fm]	$\sqrt{< r_s^2 >_g}$ [fm]
GPD / Hall B	0.759±0.115	1.153±0.248
GPD / All data	1.126±0.297	1.859±0.533
Holographic / Hall B	0.649±0.055	0.889±0.138
Holographic / All data	0.607±0.019	0.863±0.029

Pressure distributions

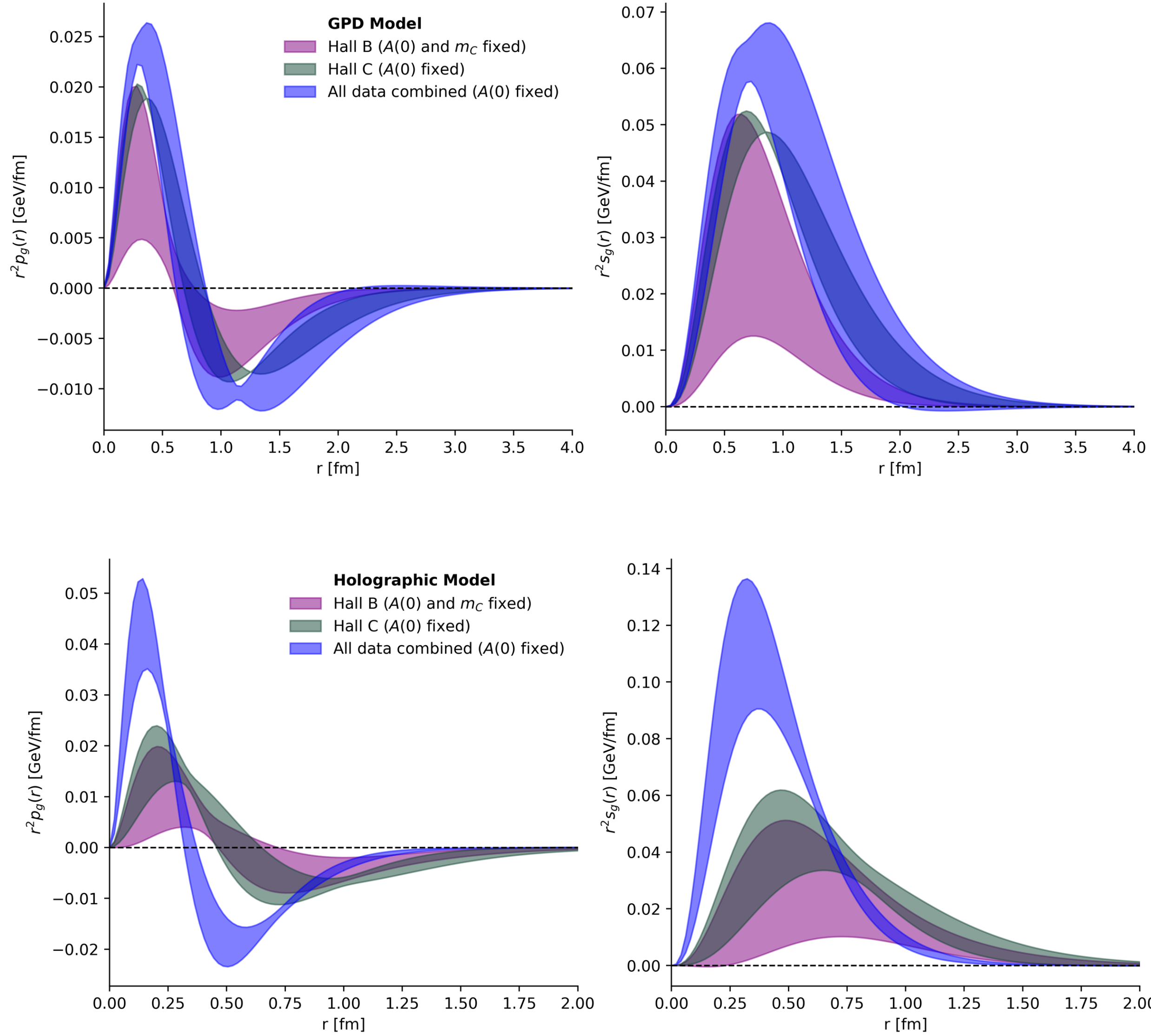
- From the Fourier transform of the D GFF…

$$\tilde{D}(r) = \int \frac{d^3\Delta}{(2\pi)^3} e^{-i\Delta\cdot r} D(\Delta, m_C)$$
$$= D(0)\frac{m_C^3}{32\pi}(1 + m_C r)e^{-m_C r}$$

- … it is possible to derive transverse and shear pressure profiles:

$$r^2 p(r) = \frac{1}{6m_N}\frac{d}{dr}\left(r^2 \frac{d}{dr}\tilde{D}(r)\right)$$
$$= \frac{1}{6m_p}\frac{4C(0)m_C^5}{32\pi} r^2(m_C r - 3)e^{-m_C r}$$

$$r^2 s(r) = -\frac{1}{4m_N} r^3 \frac{d}{dr}\left(\frac{1}{r}\frac{d}{dr}\tilde{D}(r)\right)$$
$$= -\frac{1}{4m_p}\frac{4C(0)m_C^6}{32\pi} r^3 e^{-m_C r}$$



Take-aways and path going forward

- The total and differential cross-section of the near threshold photoproduction of J/ψ has been measured with RG-A data.
- An interpretation of these data only, and combined with existing data has been done in terms of GFFs.

- The analysis is under review.
- An article (PLB or PRC) is being drafted.

Back-up

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 ρ = 0.07 g/cm^3
Avogadro constant N_A = 6.02x10^{23} mol^{-1}
Unit charge e = 1.6x10^{-19} C
Conversion to pb C = 10^{-36}

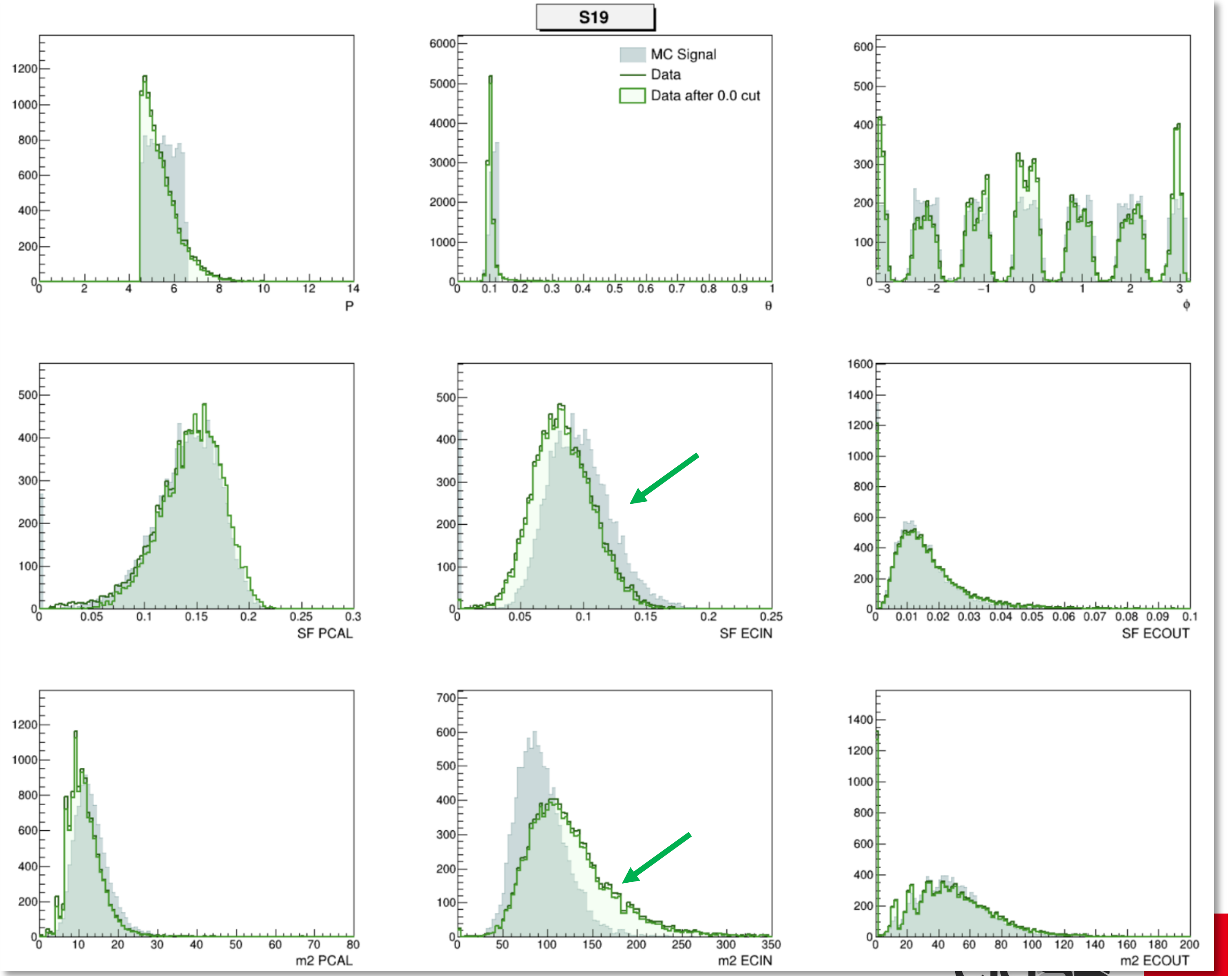
https://clasweb.jlab.org/rungroups/tlc/wiki/images/e/e7/Normalization_MC_Data-5.pdf

Lepton ID at high momenta

Figures from M.Tenorio

- Used BDT approach for leptons PID at high momenta > 4.5 GeV
- Similar approach as for the TCS analysis of 2020
- One BDT per particle per era (6 BDT in total).

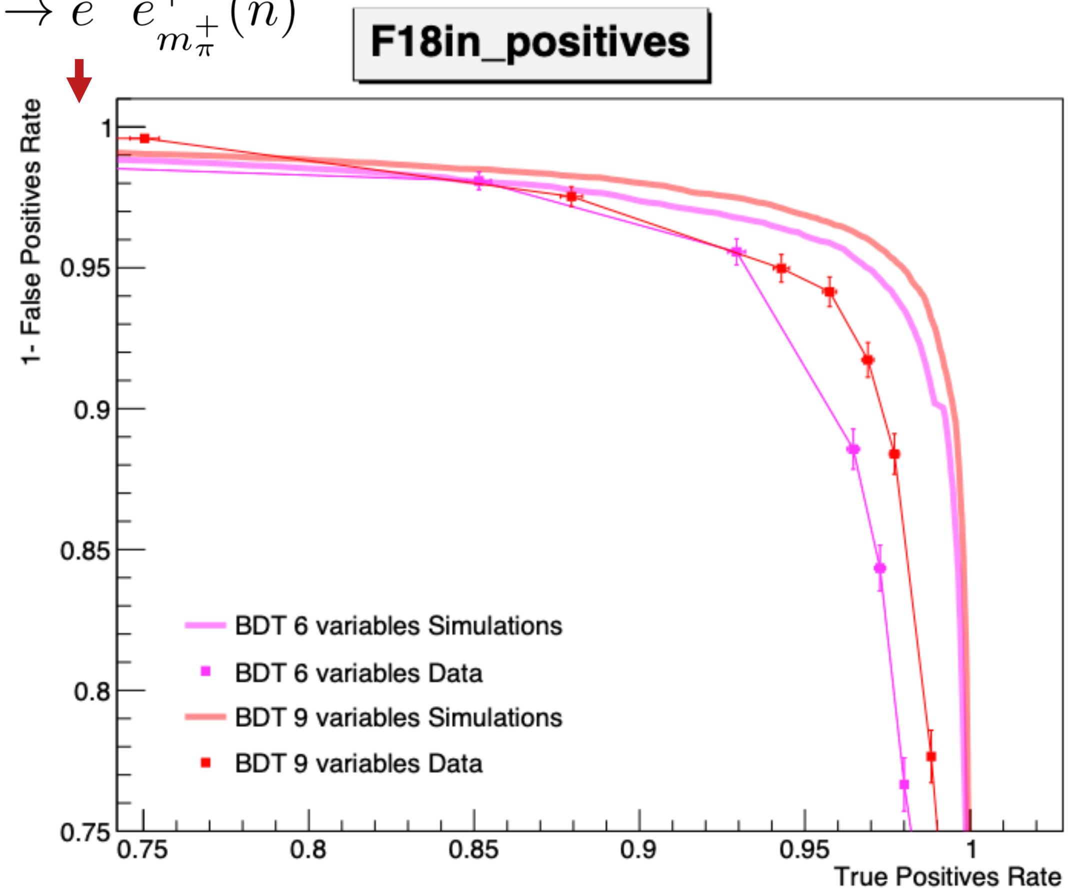
- Used kinematic variables, and high-level calorimeter variables.
- Trained on MC, validated on MC and data.

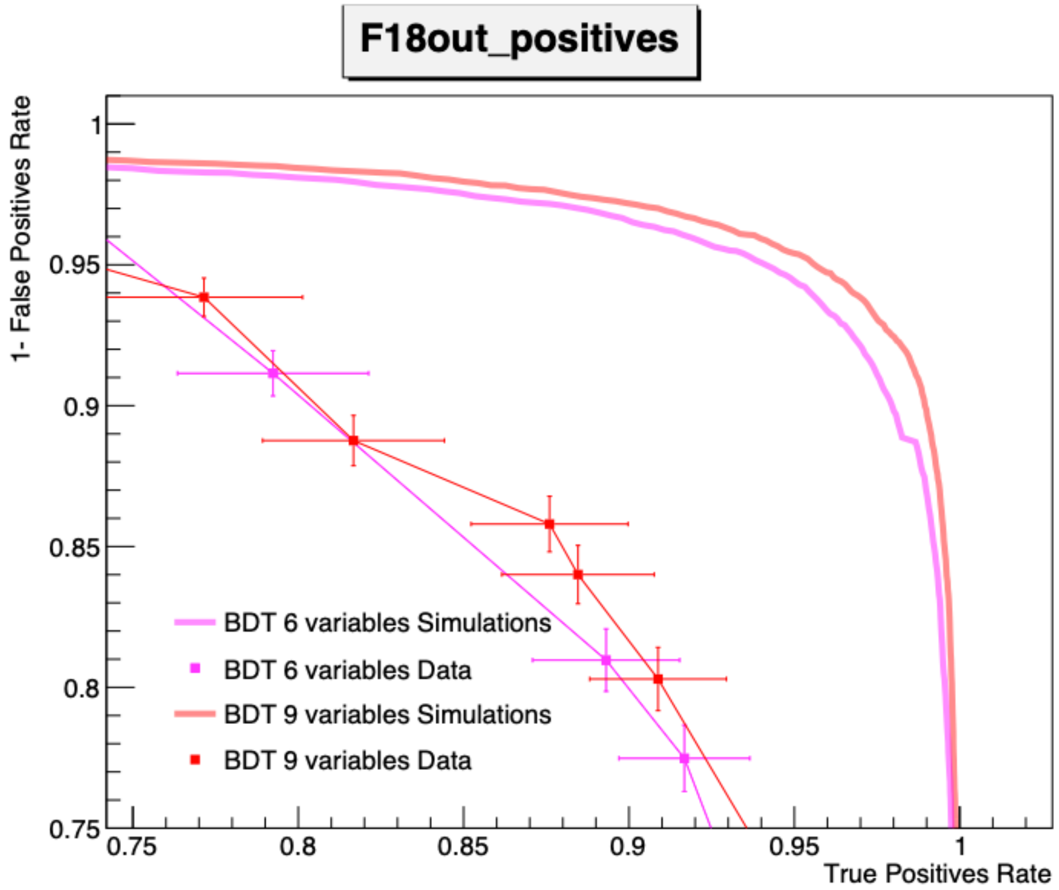


Lepton ID at high momenta

Figures from M.Tenorio

$ep \to e^- e^+_{m_\pi^+}(n)$





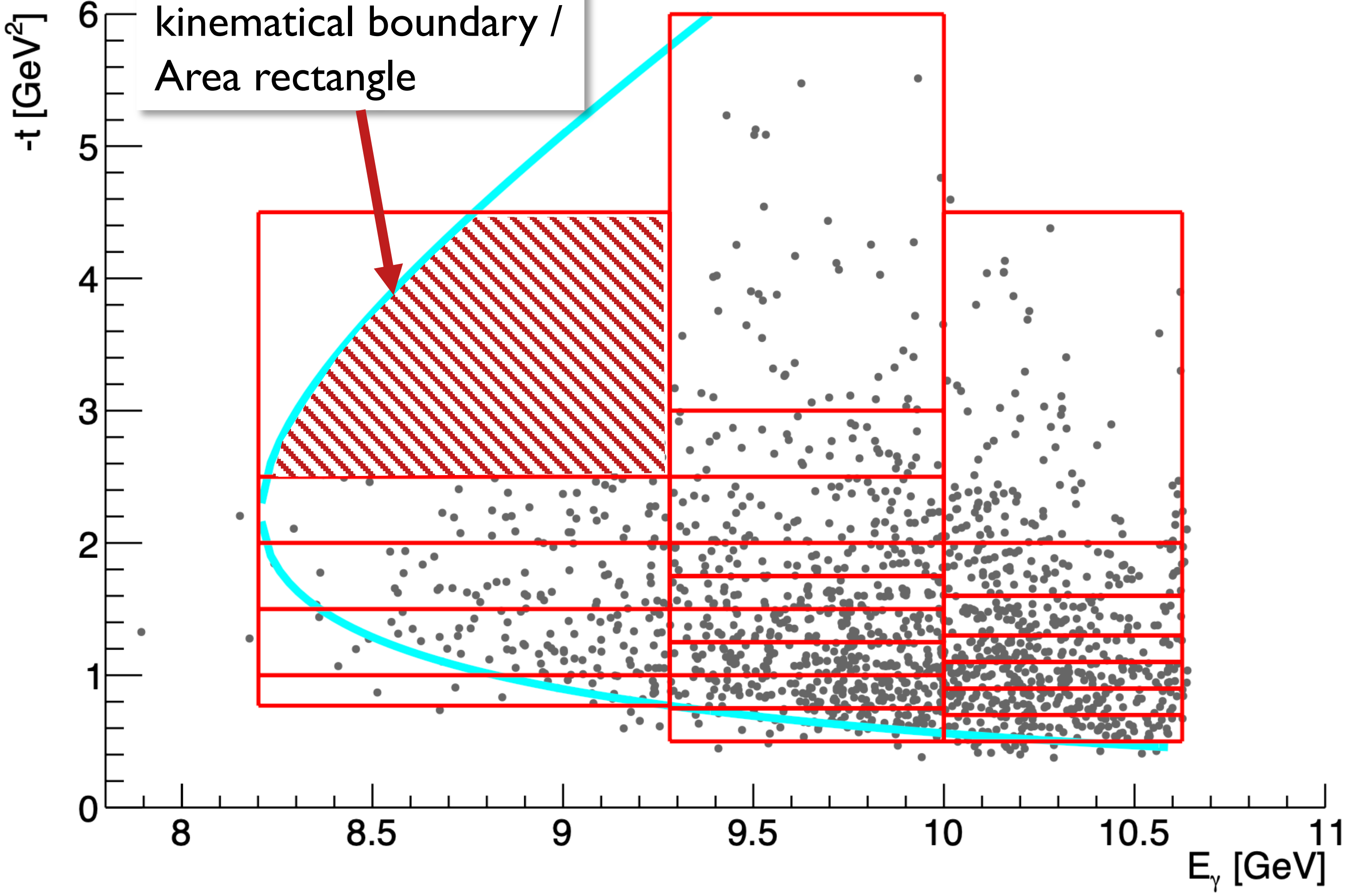
$e^+ \to e^+\gamma$

This work has a dedicated analysis note and is implemented in Iguana

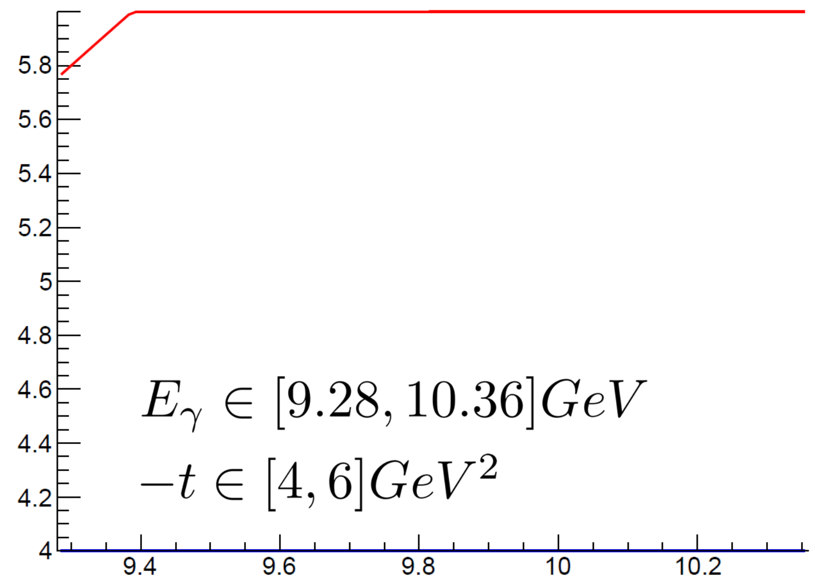
Bin volume correction

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

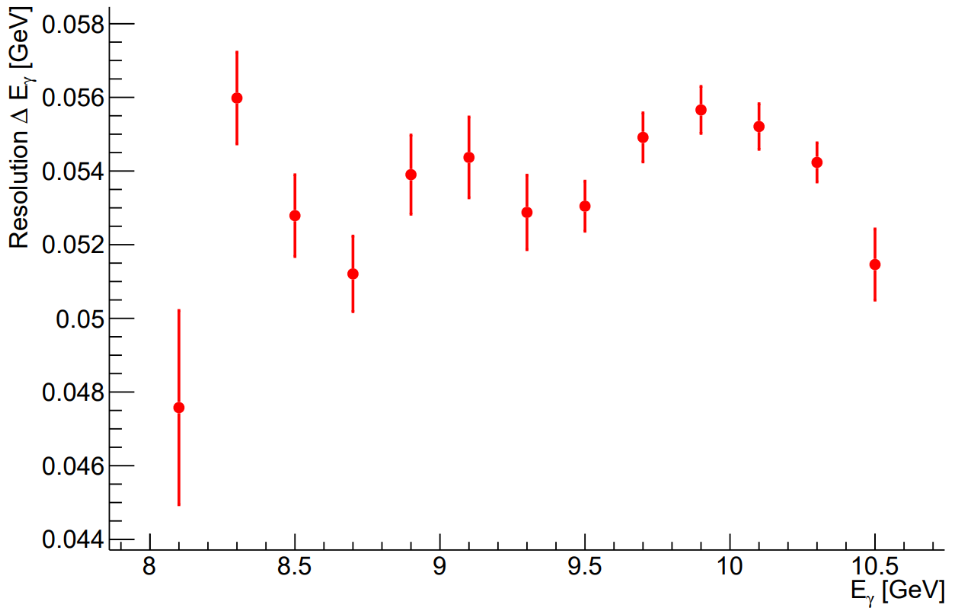
V = Ratio Area within kinematical boundary / Area rectangle



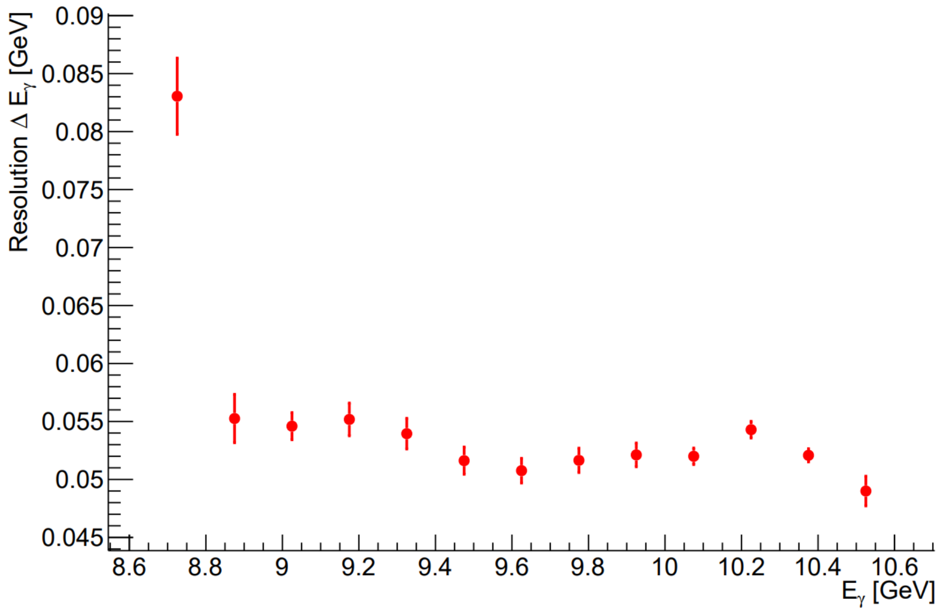
- In practice is this readily done using integral of functions in root



Photon energy resolutions

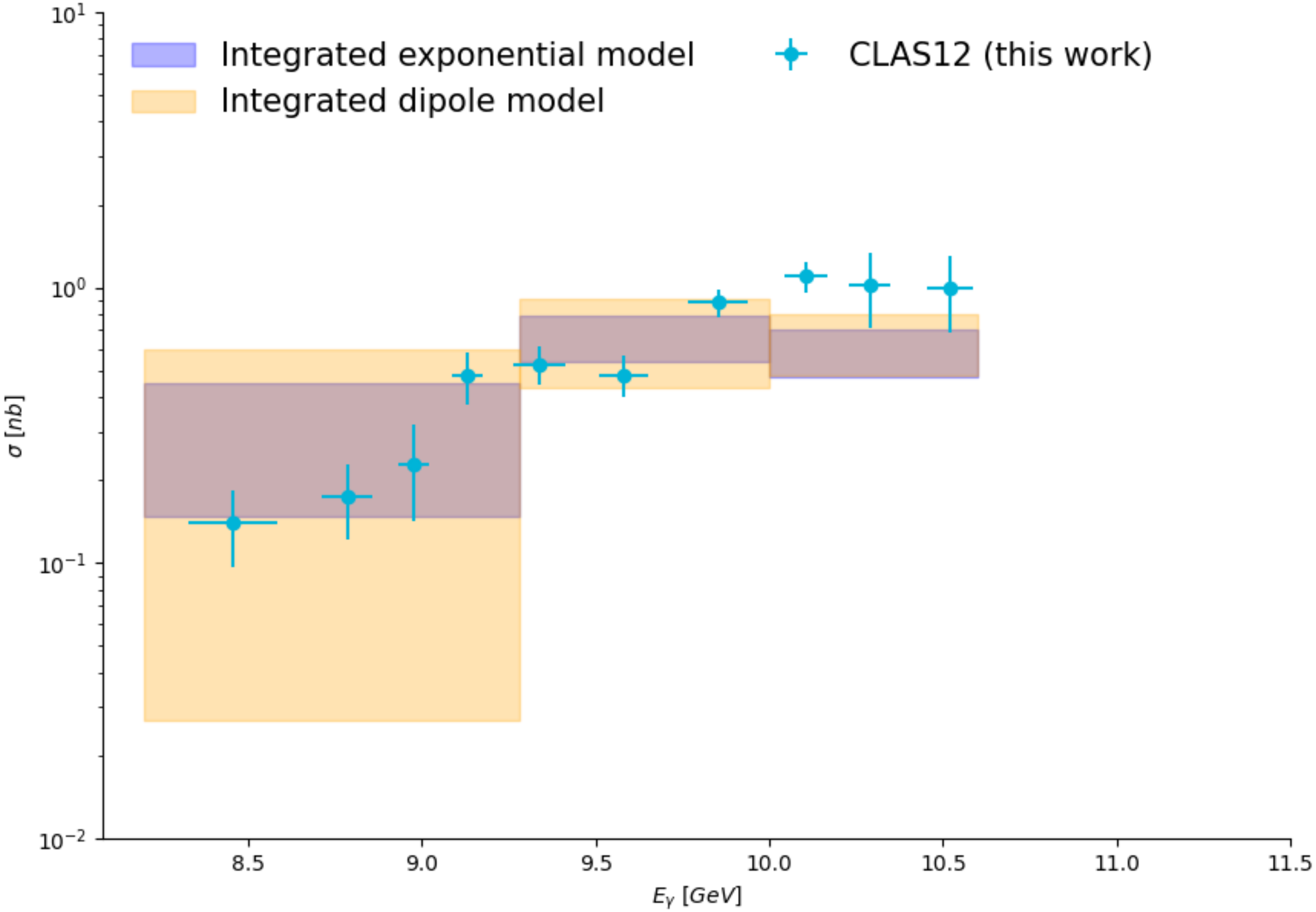


(a) Resolution of the initial photon energy for the Fall 2018 inbending configuration.



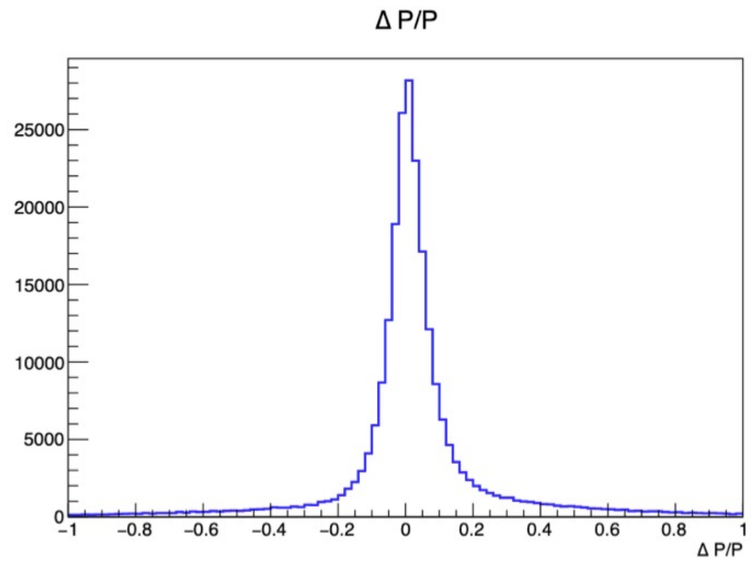
(b) Resolution of the initial photon energy for the Fall 2018 outbending configuration.

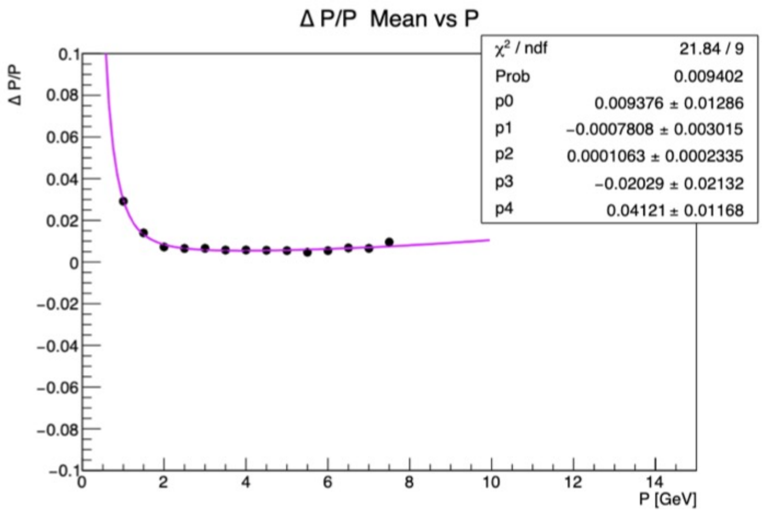
Integrated differential CS

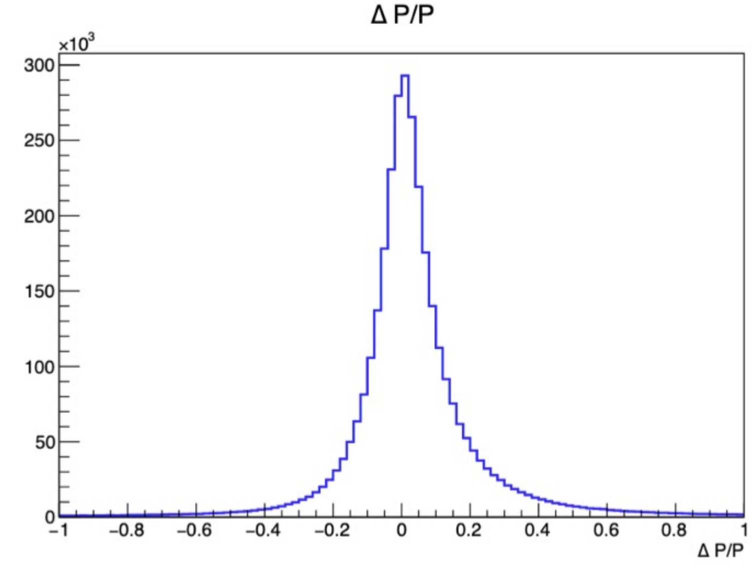


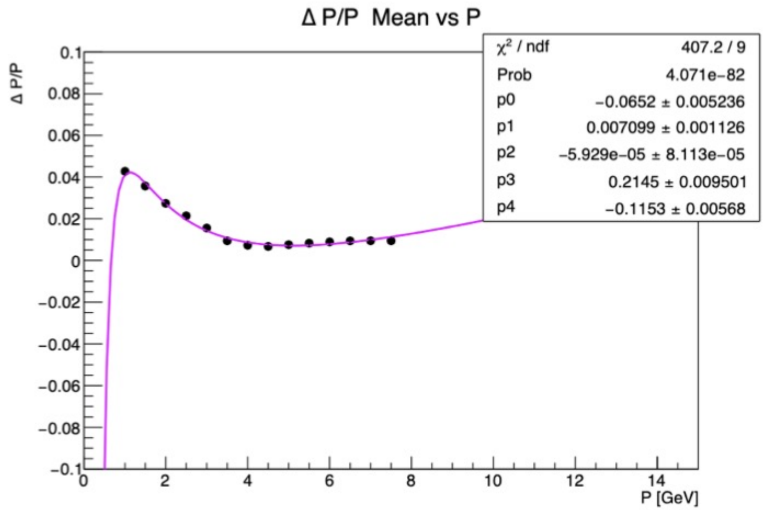
Lepton momentum corrections

Figures from R.Tyson









$$e_{beam} \rightarrow e_i \gamma_r p \rightarrow e_f p X$$

$$p_i = \frac{M_p}{1-\cos\theta_{e^-}}\left(\cos\theta_{e^-} + \sin\theta_{e^-}\frac{\cos\theta_p}{\sin\theta_p} - 1\right)$$

$$p_f = \frac{p_i}{1+\frac{p_i}{M_p}(1-\cos\theta_{e^-})}$$

Other analysis tools

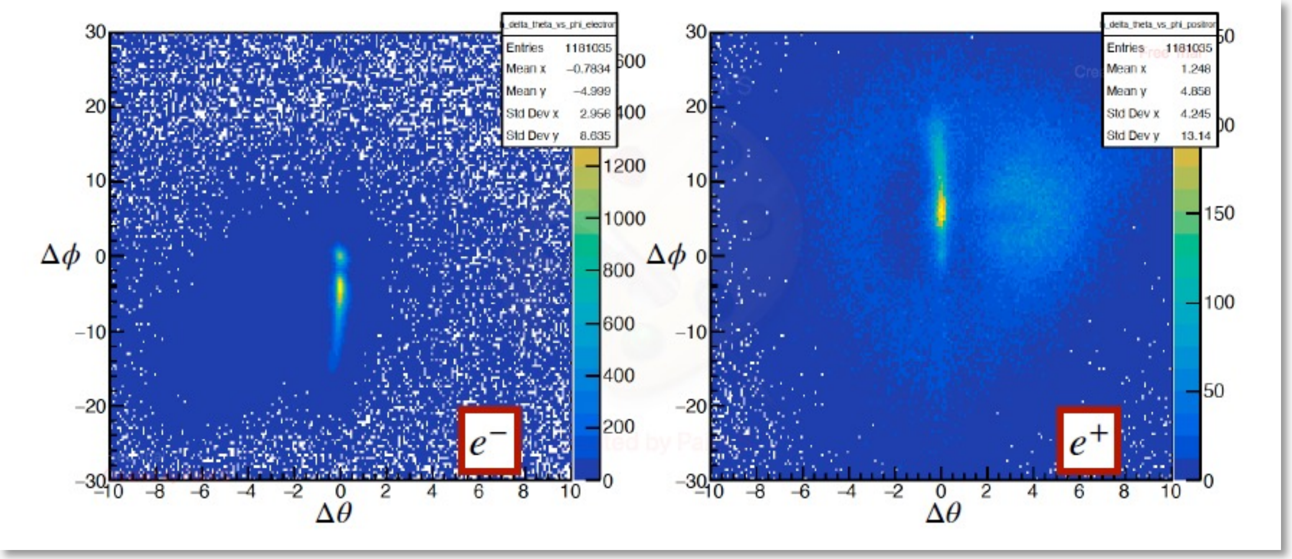
Fiducial cuts/dead paddle cuts

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

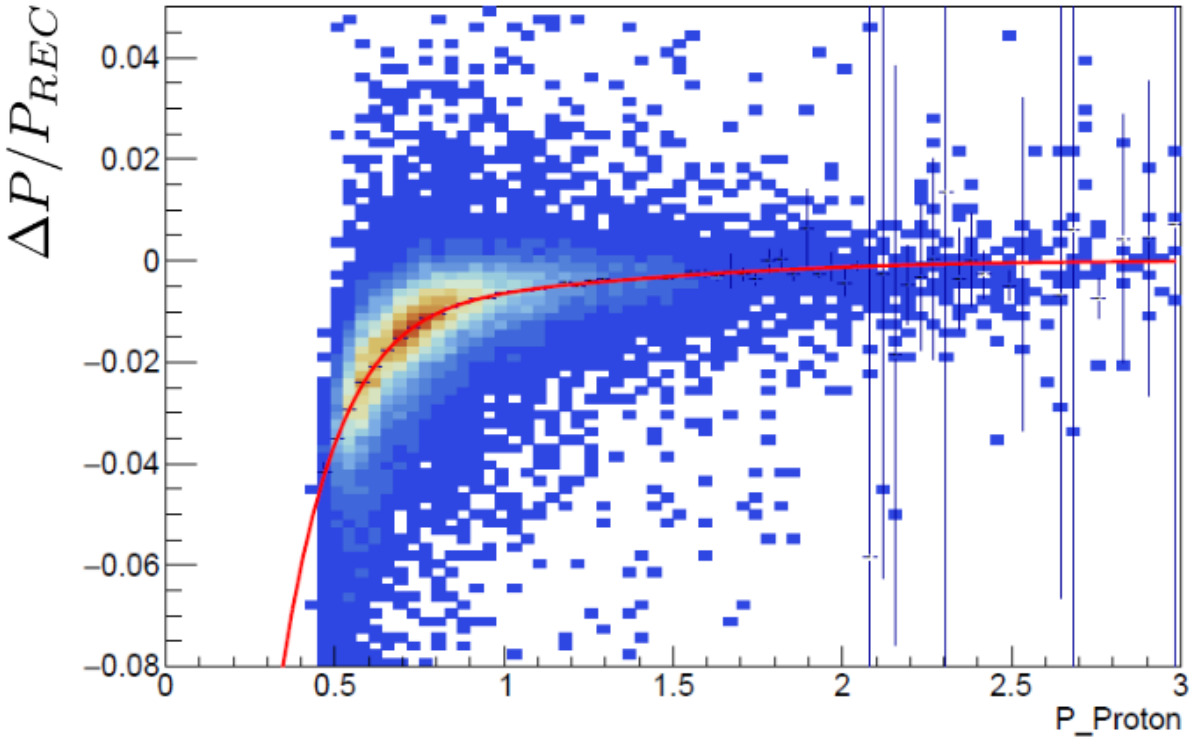
Radiated photon correction

Plots from M. Tenorio

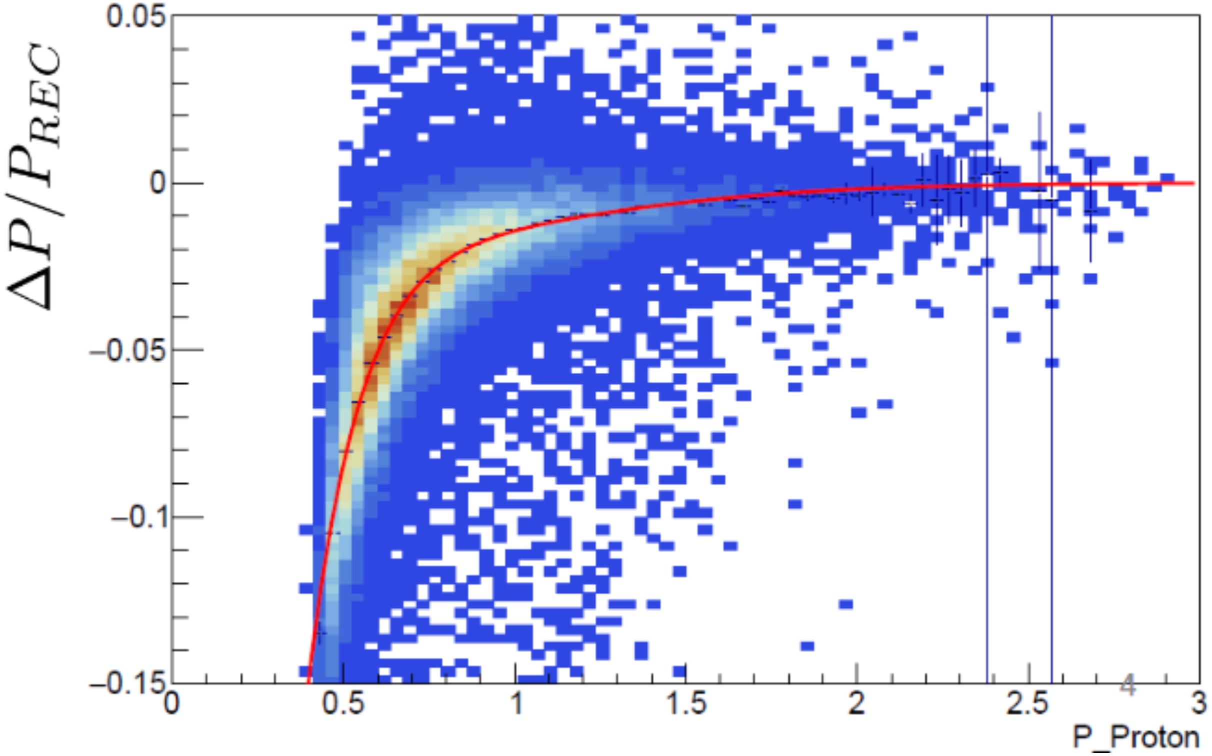
- Loop over photons in the event
- Add 4-vectors to the lepton if Δθ<1.5 deg.



Proton energy loss



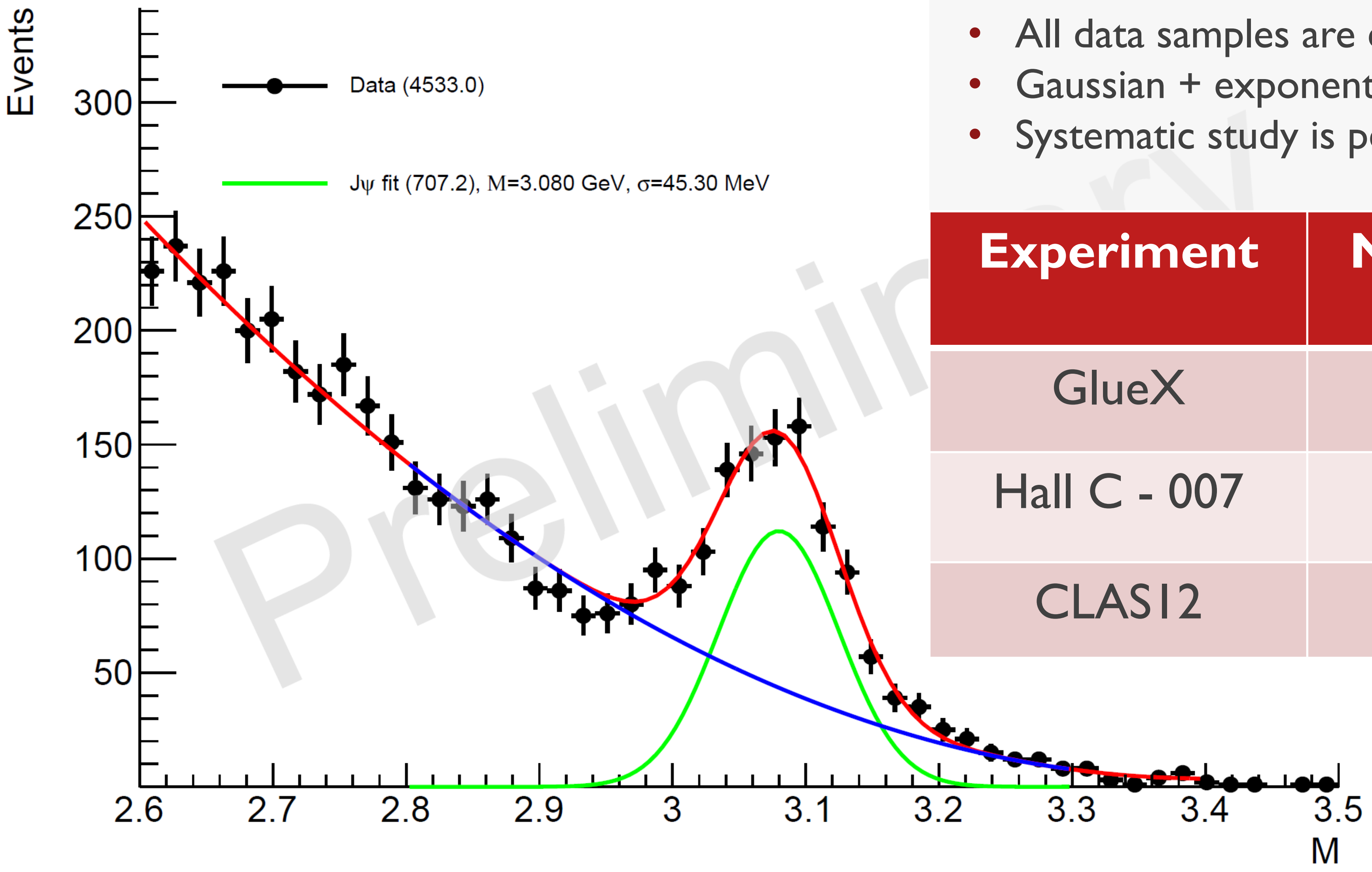
Theta < 27 deg.



Theta > 27 deg.

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.

Experiment	Number of J/ψ	Integrated $\mathcal{L}$ (pb^{-1})
GlueX	2270	320
Hall C - 007	~2K	
CLAS12	707	114

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:

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

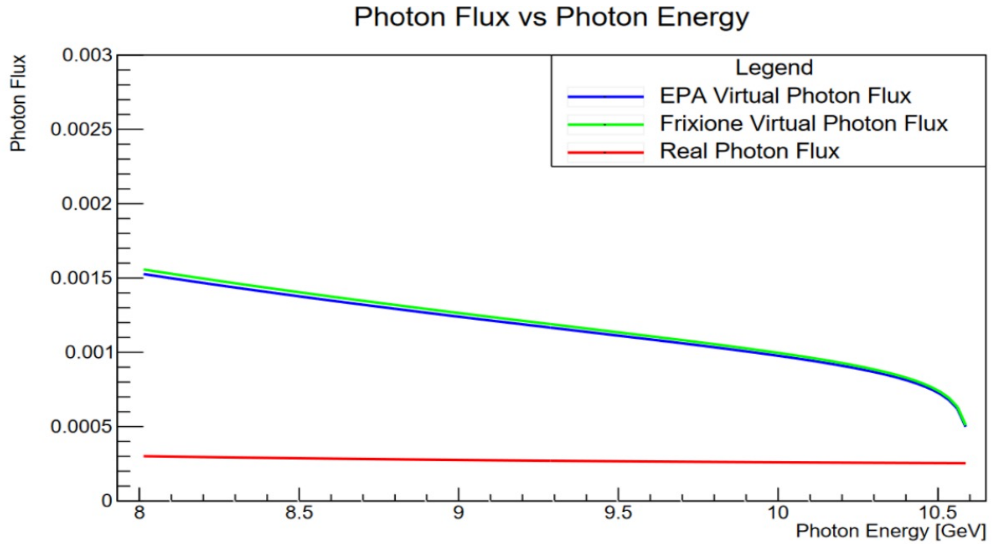
3) Each flux (one per configuration) is multiplied by the corresponding accumulated charge:

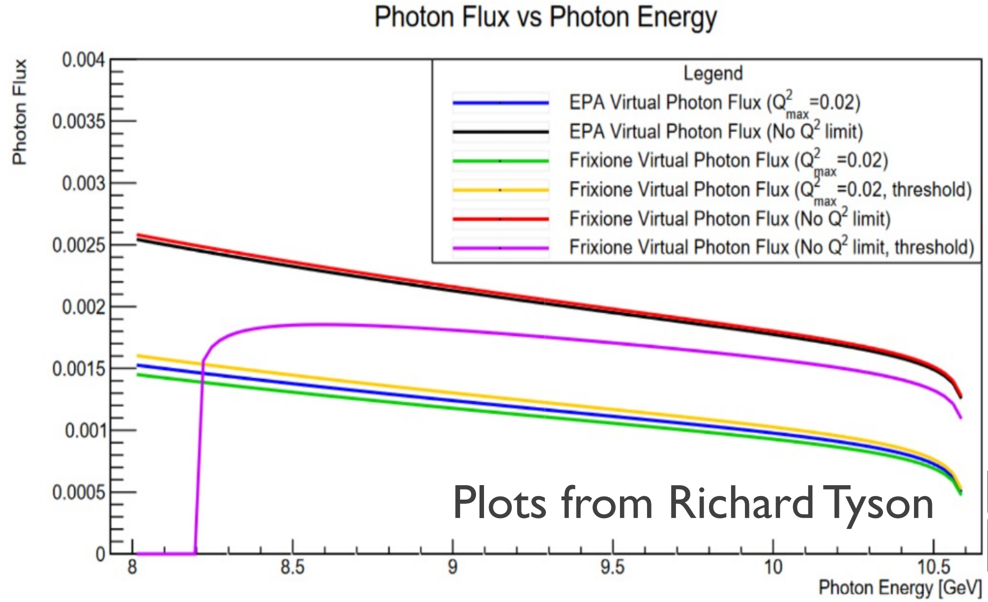
$$\mathcal{F}_j = \sum_c C_c \cdot \mathcal{F}_{c/j}$$

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:

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





Plots from Richard Tyson

Normalization factor

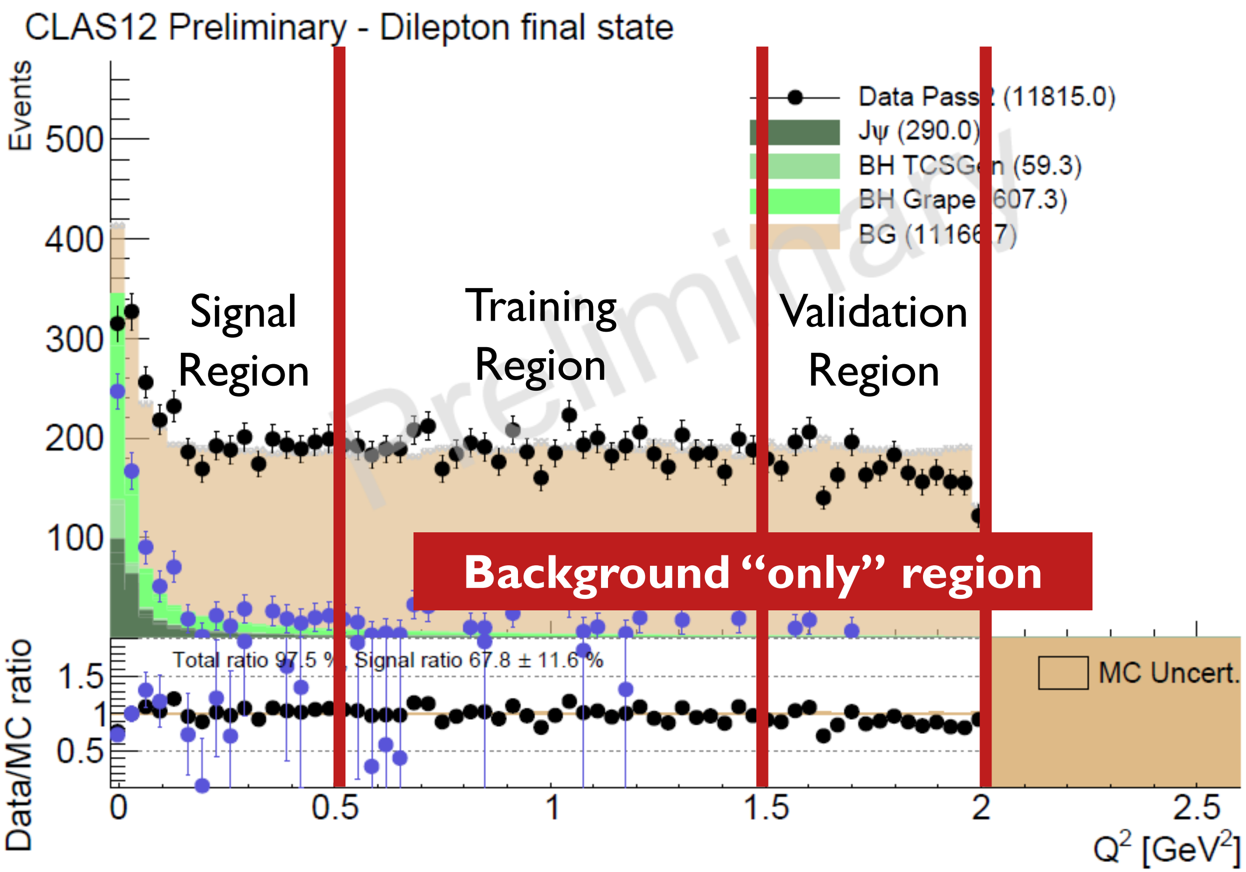
1) Event mixing procedure from data :
   - Randomly select electron, positron, proton (from different events)
   - Construct kinematics and make sure they are within the region of interest:

   (M_{ee}>2 GeV, $|MM|^2$<0.4 GeV^2, Q^2<2 GeV^2)

2) Reweight events to match data in the training region, using a BDT-based method from Alex Rogozhnikov 2016 J. Phys.: Conf. Ser. **762** 012036. Code available here.

3) Validate the weights on the validation region.

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



Initial state radiation

- The initial electron beam can also radiate a photon **before** emitting the real hard photon responsible for the J/ψ photoproduction.
- ISR are included in the BH MC sample.
- Using GRAPE, which include the ISR, only events in the J/ψ region, we quantified the effect of ISR on the number of photon emitted.