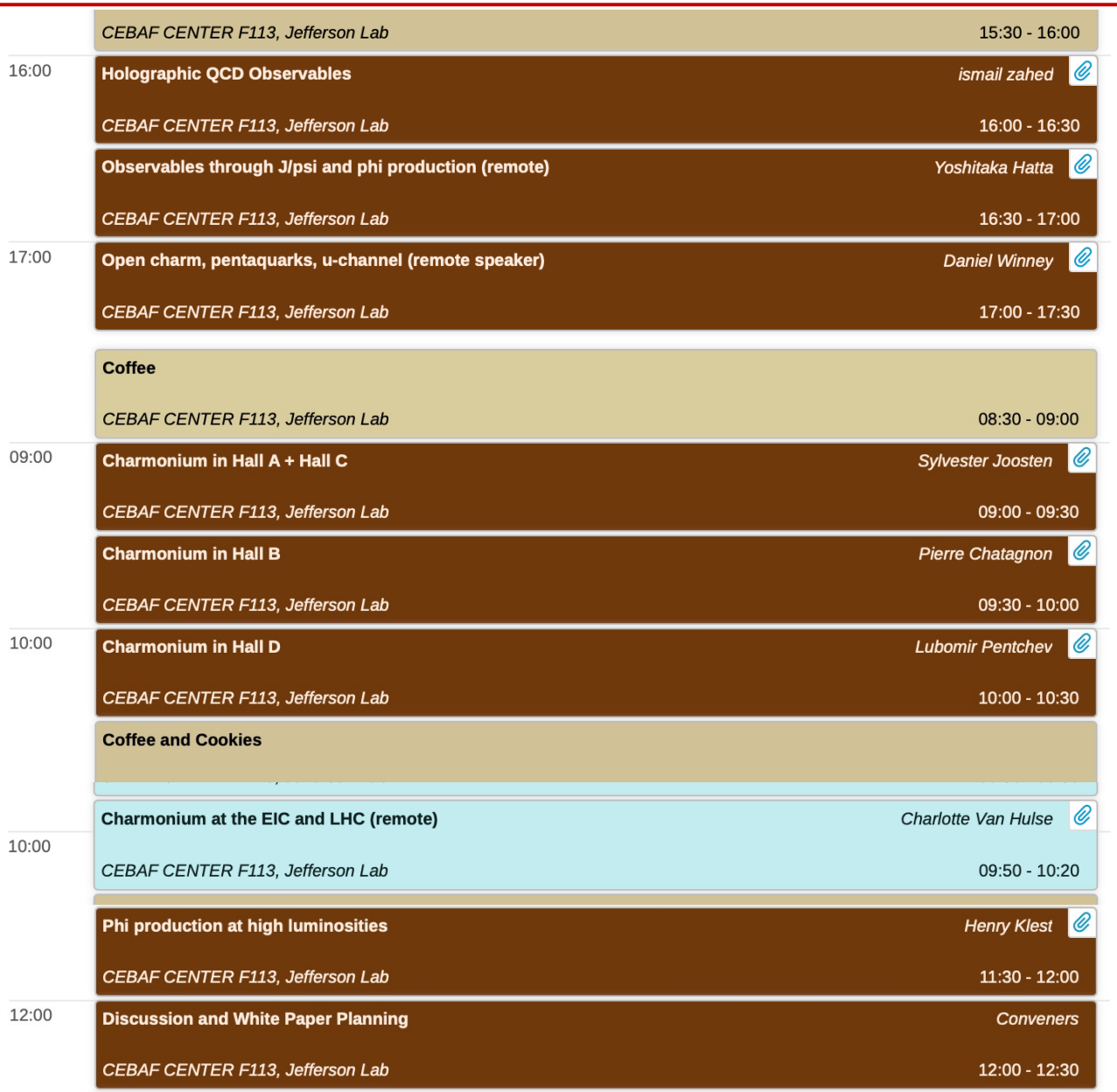


High-luminosity workshop highlights: Quarkonia

Pierre Chatagnon, CEA Saclay
CLAS Collaboration meeting, 19th of November 2026

Overview



Theory session

Measurements at JLab

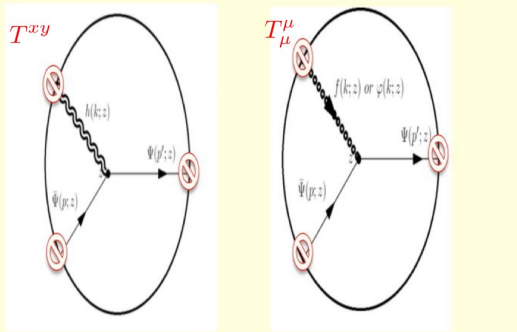
Complementarity

Theory overview

Holographic and GPD-models overview – I. Zahed & Y. Hatta

Holographic model

$$\langle p_2|T^{\mu\nu}(0)|p_1\rangle = \bar{u}(p_2)\left(A(k)\gamma^{(\mu}p^{\nu)} + B(k)\frac{ip^{(\mu}\sigma^{\nu)\alpha}k_\alpha}{2m_N} + C(k)\frac{k^\mu k^\nu - \eta^{\mu\nu}k^2}{m_N}\right)u(p_1)$$



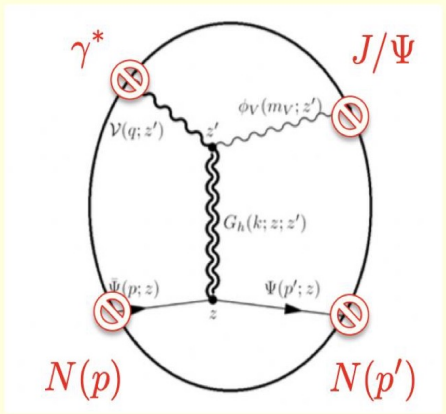
Spin-2 : $\langle p_2|T^{xy}(0)|p_1\rangle$ Spin-0 : $\langle p_2|T^{\mu}_{\mu}(0)|p_1\rangle$

$$h_{\mu\nu}(k,z) = \left[\epsilon^{TT}_{\mu\nu}h(k,z) + k_\mu k_\nu H(k,z)\right] + \left[k_\mu A^{\perp}_{\nu}(k,z) + k_\nu A^{\perp}_{\mu}(k,z)\right] + \left[\frac{1}{3}\eta_{\mu\nu}f(k,z)\right]$$

Mamo-Zahed 20

Figure from I. Zahed

$$\gamma^*(q,\epsilon) + N(p) \to V(q',\epsilon') + N(p')$$



$$\left(\frac{d\sigma}{dt}\right) = \mathcal{N}^2 \times \frac{e^2}{64\pi(s-m_N^2)^2} \times \frac{\left[A(K,\kappa_T) + \eta^2 D(K,\kappa_T,\kappa_S)\right]^2}{A^2(0)} \times \tilde{F}(s) \times 8,$$

Mamo-Zahed 20

See also Kharzeev 96',
Hatta et al. 19, 20',
Guo, Ji and Liu 21'
Yuan et al. 21, 22'

GPD models

Threshold approximation

YH, Strikman 2102.12631 (Mellin moment)
Guo, Ji, Liu 2103.11506 (Mellin moment)
Guo, Ji, Yuan 2308.13006 (conformal moment)

what is measurable — what we want

$$\int_{-1}^{1} dx \frac{1}{\xi - x - i\epsilon}\begin{cases}\frac{1}{2}H^{q(+)}(x,\xi,t,\mu^2)\\ \frac{1}{x}H^{g}(x,\xi,t,\mu^2),\end{cases} \approx \frac{2}{\xi^2}\frac{5}{4}(A^a(t,\mu^2) + \xi^2 D^a(t,\mu^2))$$

Keep only the first term in the conformal partial wave expansion

Very good approximation when $\xi = \mathcal{O}(1)$ and for gluon and strangeness GPDs

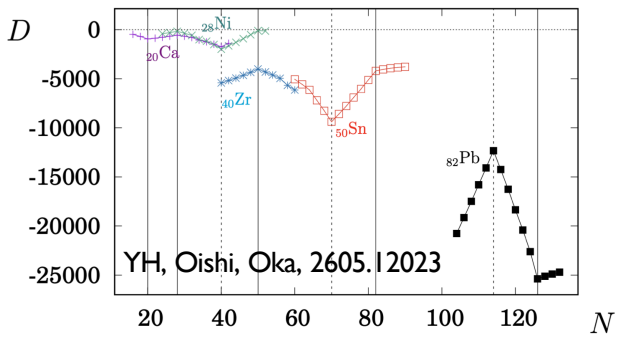
Recently extended to NLO Guo, Yuan, Zhao, 2501.10532; YH, Klest, Passek-K, Schoenleber, 2501.12343
YH, Schoenleber 2502.12061

However, ξ cannot be too large (factorization breakdown)

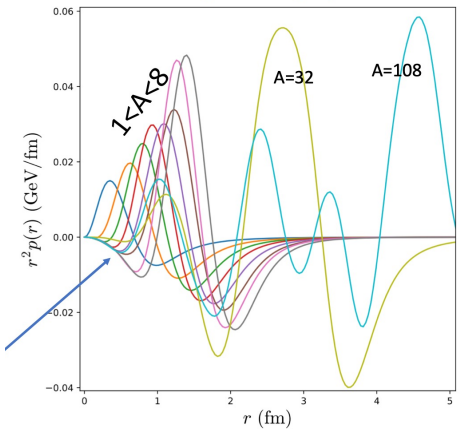
In electro-production, $\frac{1-\xi}{2\xi}Q^2 \gg |t|, M^2$ YH, Klest, Passek, Schoenleber (2025)

Slide from Y. Hatta

- D-term and pressure distributions inside nuclei



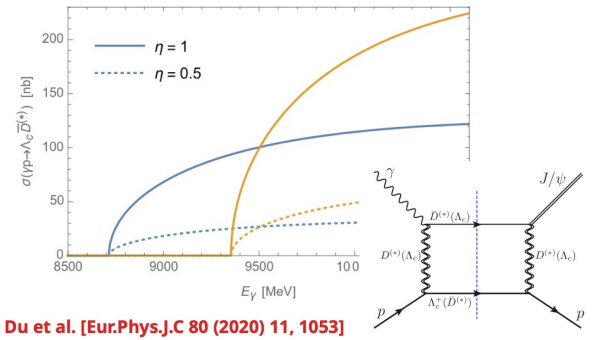
Martin-Caro, Huidobro, YH, 2312.12984



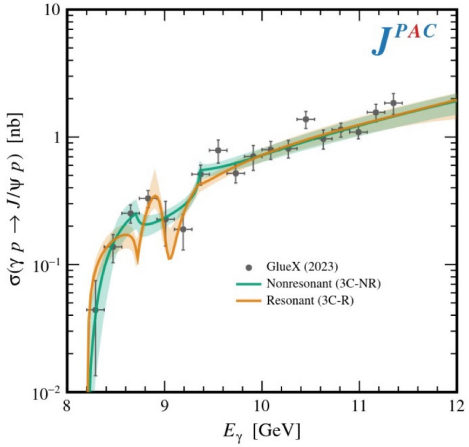
Theory prospects – Y. Guo & D. Winney

JPAC model (data-driven coupled-channel model)

JPAC [Phys.Rev.D 108 (2023) 5, 054018]



Du et al. [Eur.Phys.J.C 80 (2020) 11, 1053]



In progress: more tests!

Model claim: A spin-0 and/or spin-2 exchange in t-channel is a good approximation.
First principles: s-channel partial wave expansion, analyticity, and unitarity **+ crossing**
Under-construction systematically-improvable, first-principles-constrained model:

Reanalysis including full spin degrees of freedom to relate s-channel expansion to the t-channel.

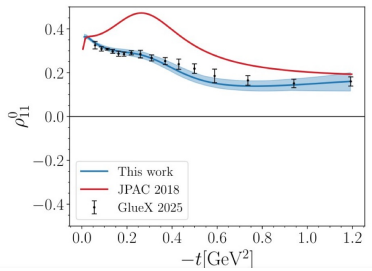
$$\mathcal{F}_{\{\lambda\}}(s,\cos\theta_s) = \sum_{J=M_s}^{J_{\max}} (2J+1)\, d^J_{\lambda\lambda'}(\theta_s)\, F^J_{\{\lambda\}}(s)$$

$$\mathcal{G}_{\{\mu\}}(t,\cos\theta_t) = \sum_{\{\lambda\}} \mathbb{C}_{\{\mu,\lambda\}}(s,t)\, \mathcal{F}_{\{\lambda\}}(s,\cos\theta_s)$$

Martin & Spearman [Ch. 7.2]

Polarization observables needed for robust constraints on helicity amplitudes! See e.g. JPAC [arXiv:2604.22719]

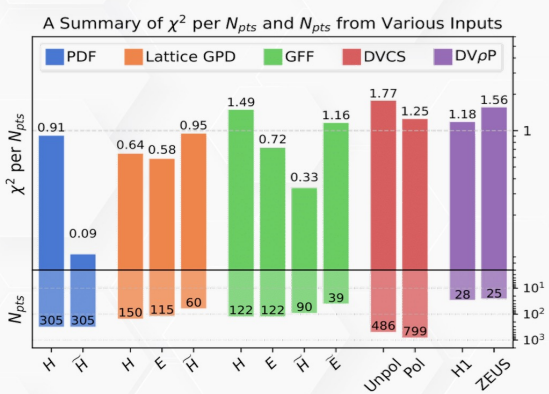
Also see t-channel spin re-summation analysis in holography. Mamo, Tezgin, & Weiss [arXiv:2607.25099]



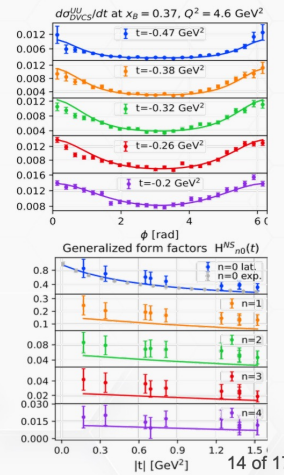
Slide from D. Winney

Opportunities of (gluonic) GPDs at High Luminosity Facilities

Generally, we observe excellent agreement across various inputs:



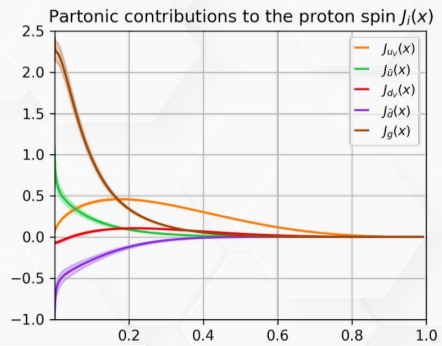
Reduced chi squared of 1.09 for 2,646 data points



Yuxun Guo @ JLab High Lumi. 14 of 17

The partonic contributions to the proton spin can also be obtained from the extracted GUMP1.0 GPDs. Specifically, they are given by

$$J_{q/g}(x) = \frac{1}{2}\left(H_{q/g} + E_{q/g}\right)(x, \xi = 0, t = 0)$$



- Parametric biases/errors not considered
- Consistent with most existing constraints
- Some tension with the lattice GFFs
- Proton spin sum rule satisfied!

Yuxun Guo @ JLab High Lumi. 16 of 17

Slides from Y. Guo

Theory overview

- Production of J/ is viewed as a way to **access the gluon dynamics inside the nucleon** at JLab energy…
- …under **strong hypothesis that still need to be demonstrated**.

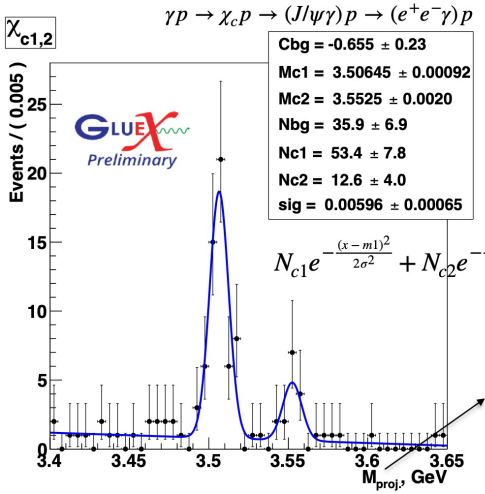
- Many models have been (and are still being actively) developed:
  - GPD-based
  - Holographic-QCD based
  - Based on Pomeron exchange
  - Data-driven coupled-channel K-matrix model

- **Many remaining theoretical challenges**:
  - GPD factorization has not been proven for J/ photoproduction
  - "Exotic" production mechanisms yet to be fully constrained.

Measurements at JLab

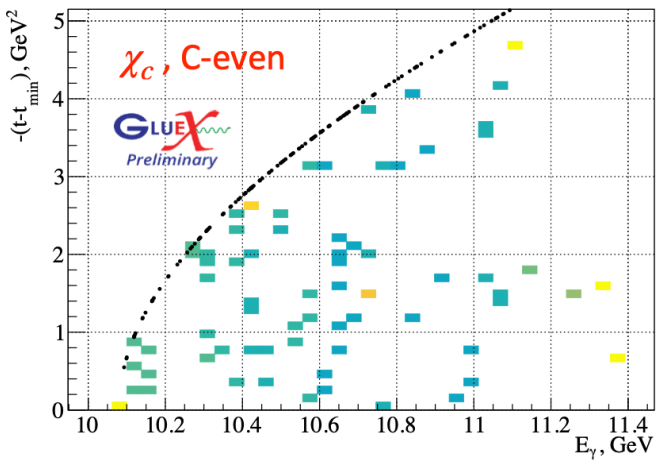
Perspectives for charmonium in Hall D – L. Pentchev

χ_c with GlueX

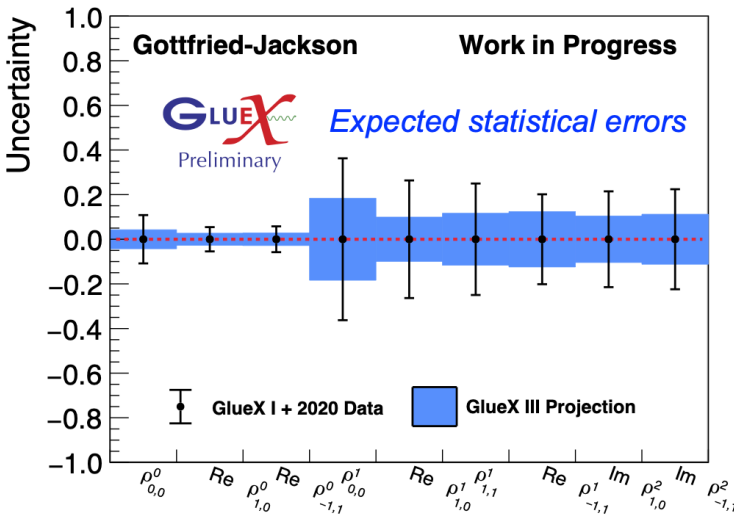


- $\chi_{c1}(3511)$, 1^{++} $BR(\chi_{c1} \to \gamma J/\psi) = 33.9\,\%$ $E_\gamma^{thr} = 10.1$ GeV
- $\chi_{c2}(3556)$, 2^{++} $BR(\chi_{c2} \to \gamma J/\psi) = 19.0\,\%$ $E_\gamma^{thr} = 10.2$ GeV
- $\chi_{c0}(3415)$, 0^{++} $BR(\chi_{c0} \to \gamma J/\psi) = 1.35\,\%$ - not visible yet in our data

- Current Data set allow to see Xc1 and Xc2
- 3-gluon exchange needed to produce these states

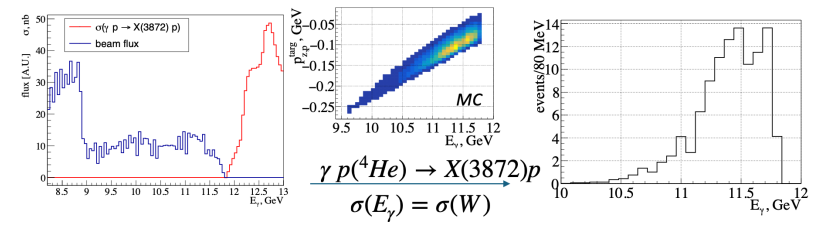


Perspectives with GlueX



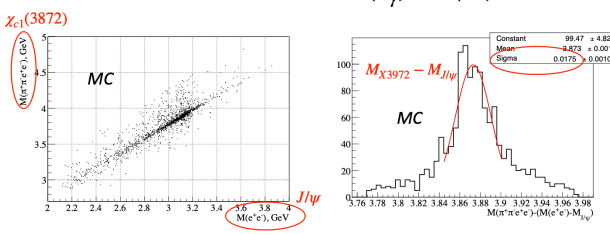
- GlueX-III will allow for precise SDME measurement
- Measurement on He4 could open the phase space for X(3872)

$\chi_{c1}(3872)$ production off ^4He with 12 GeV



$\gamma\, p(^4He) \to X(3872)p$

$\sigma(E_\gamma) = \sigma(W)$



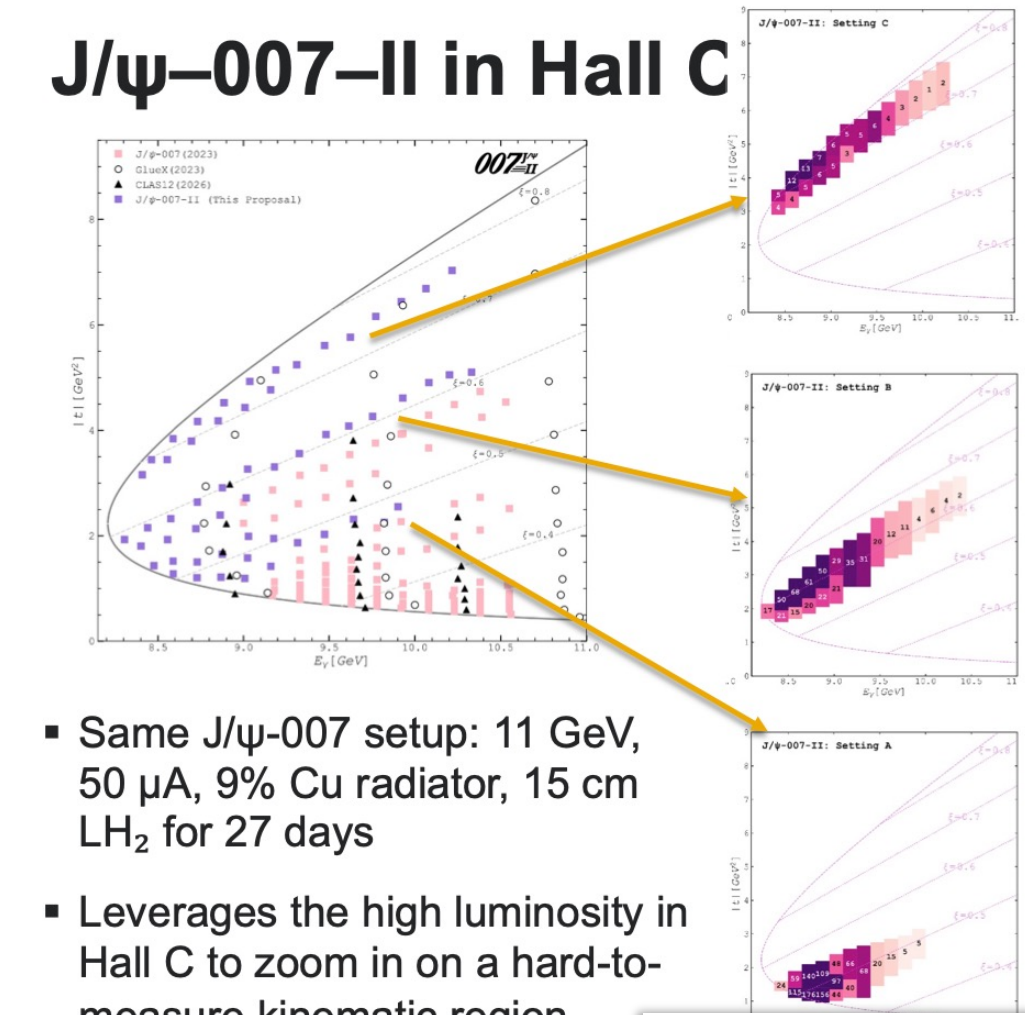
Assuming same luminosity (67 PAC days) and 12 GeV electron beam

Expect 50-100 $\chi_{c1}(3872)$ events

$\gamma\, p(^4He) \to X(3872)\, p + X \to \pi^+\pi^- J/\psi p + X \to \pi^+\pi^- e^+e^- p + X$ inclusive

Perspectives for charmonium in Hall A & C – S.Joosten

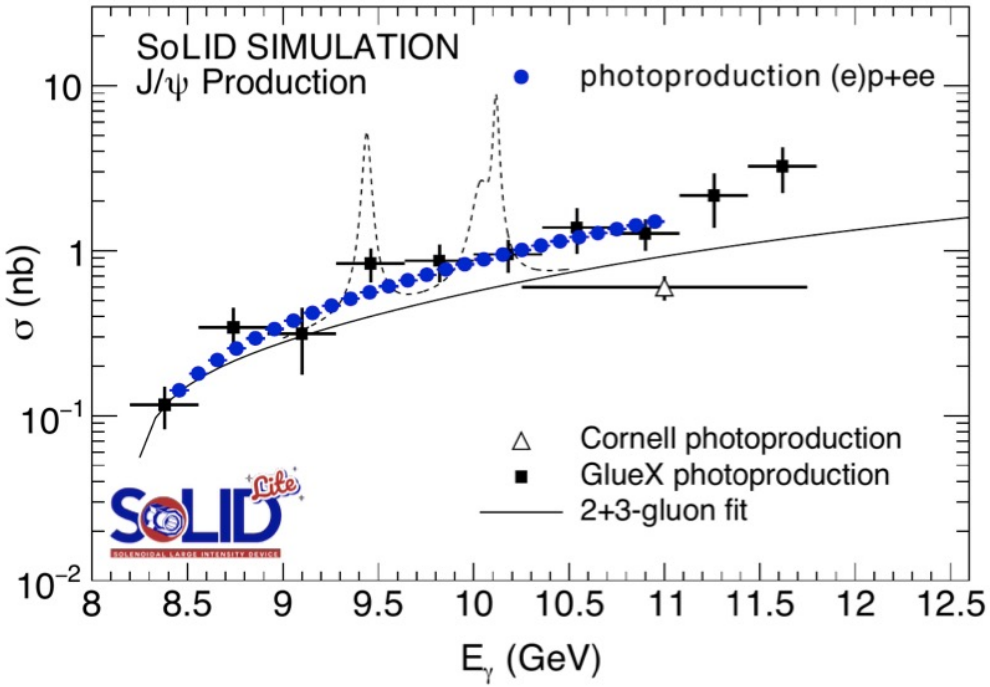
J/ψ-007 II in Hall C



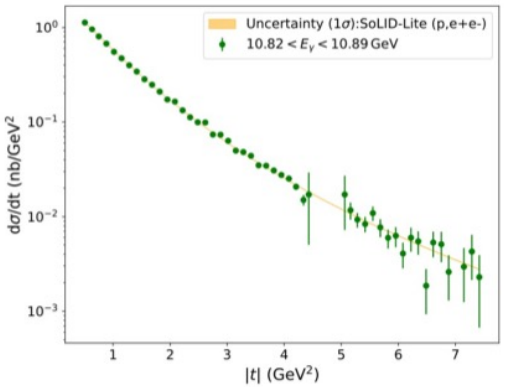
- Same J/ψ-007 setup: 11 GeV, 50 μA, 9% Cu radiator, 15 cm LH_2 for 27 days
- Leverages the high luminosity in Hall C to zoom in on a hard-to-measure kinematic region

Approved by PAC54 with A-

Measurement with "SoliD-lite"



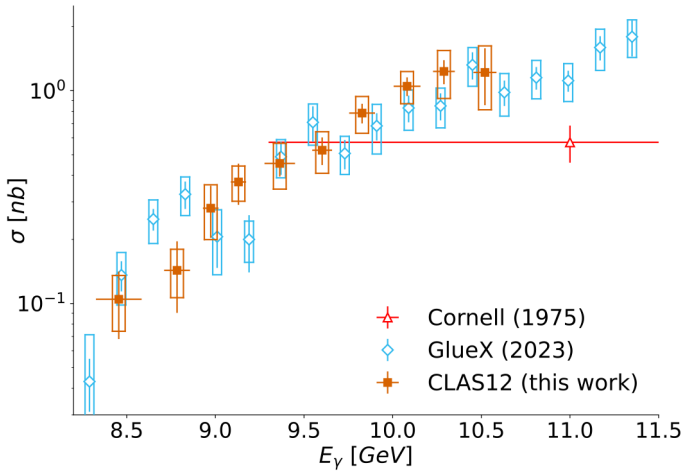
- Projection for both SoLID and SoLID-lite have been produced.
- Latter option still provides great physics reach

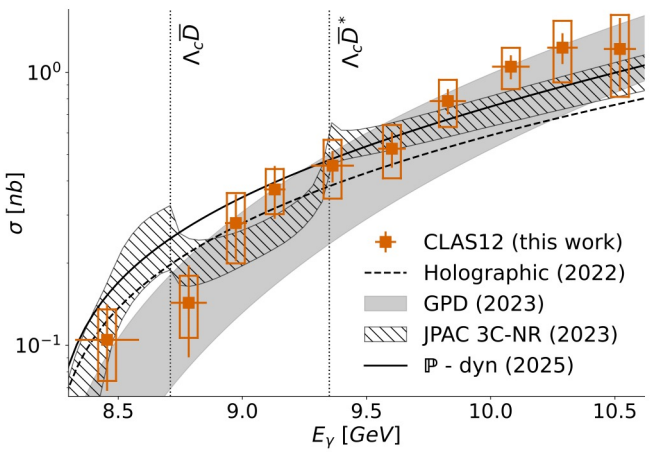


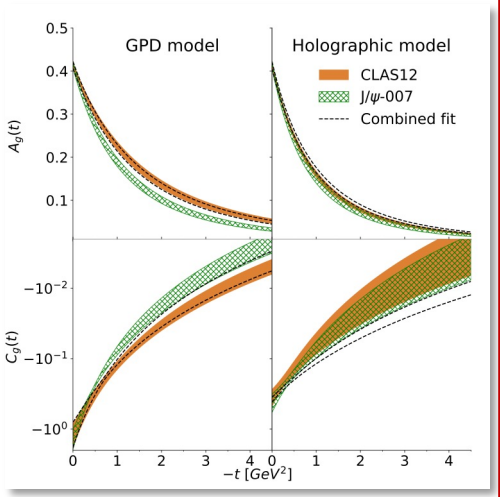
Charmonium in Hall B – P.Chatagnon

J/ψ photoproduction on proton

- Measurement on RG-A data.
- No clear structure at ~9 GeV.
- Published in PRC

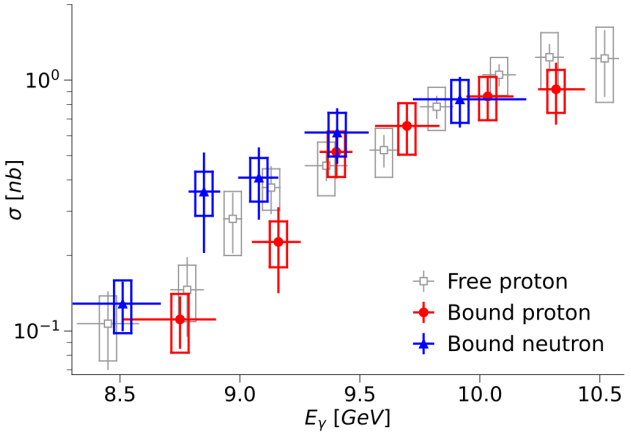


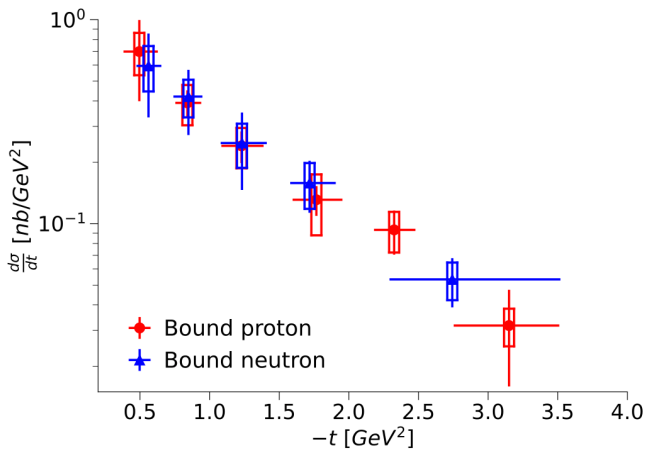


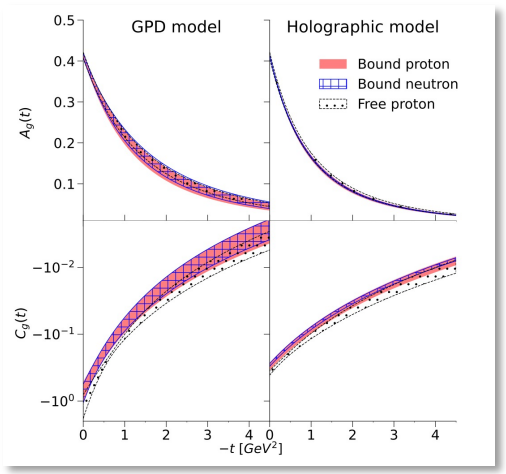


J/ψ photoproduction on neutron

- Measurement on deuterium target, CS extracted for bound proton and bound neutron.
- Submitted to PRL



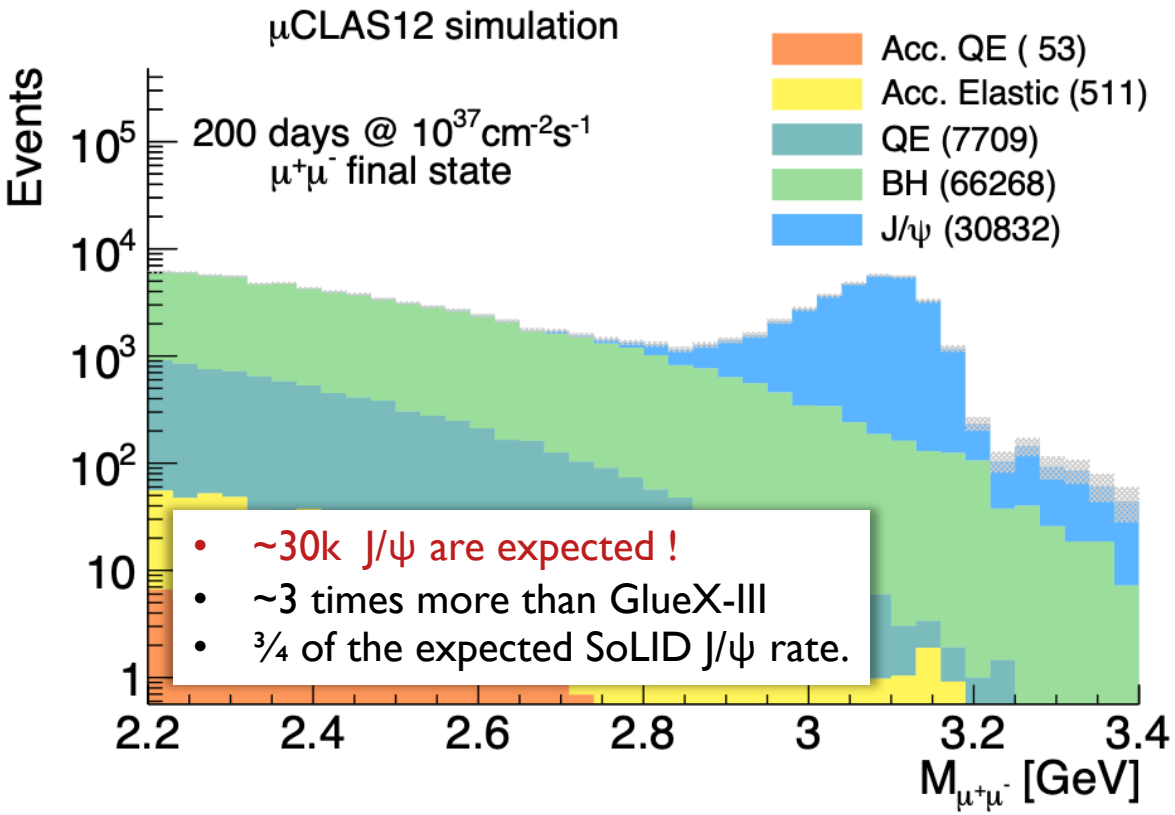


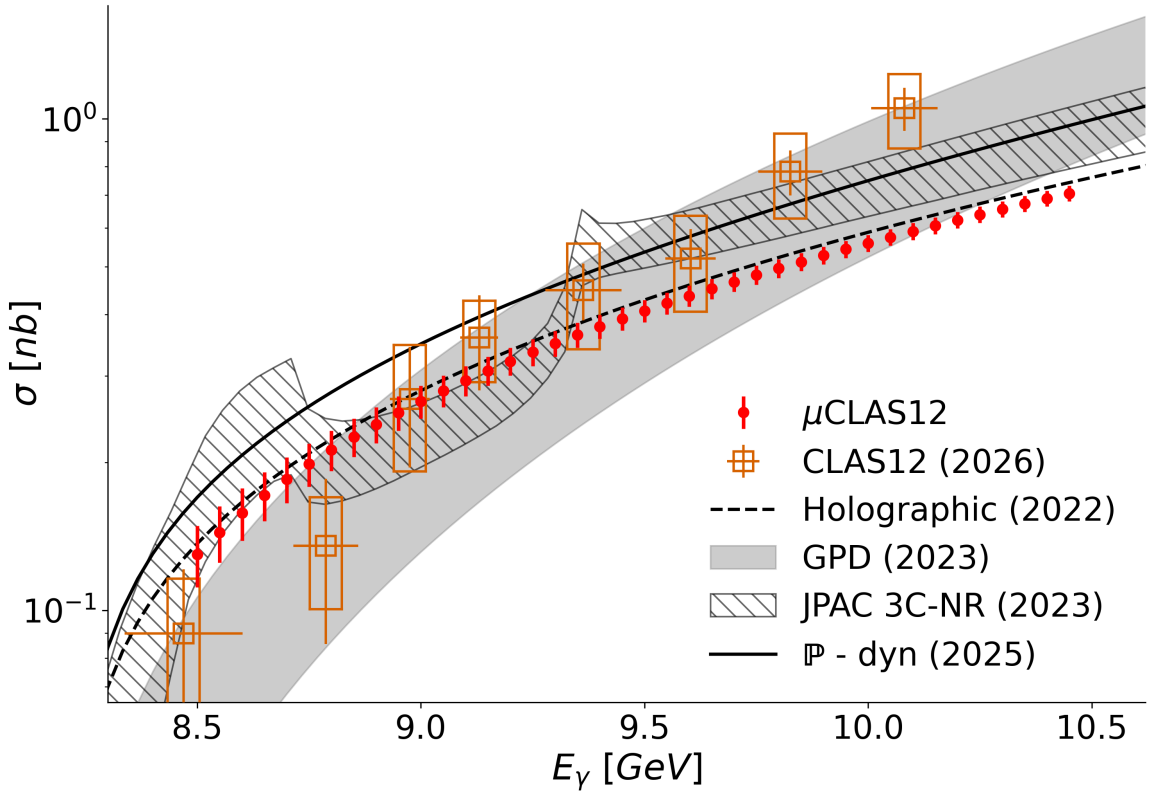


Charmonium in Hall B – P.Chatagnon

- μCLAS12 presented at the PAC53, accepted with rating A.
- Article published in EPJA in 2026.
- Extensive physics program, including very competitive J/ψ measurement.

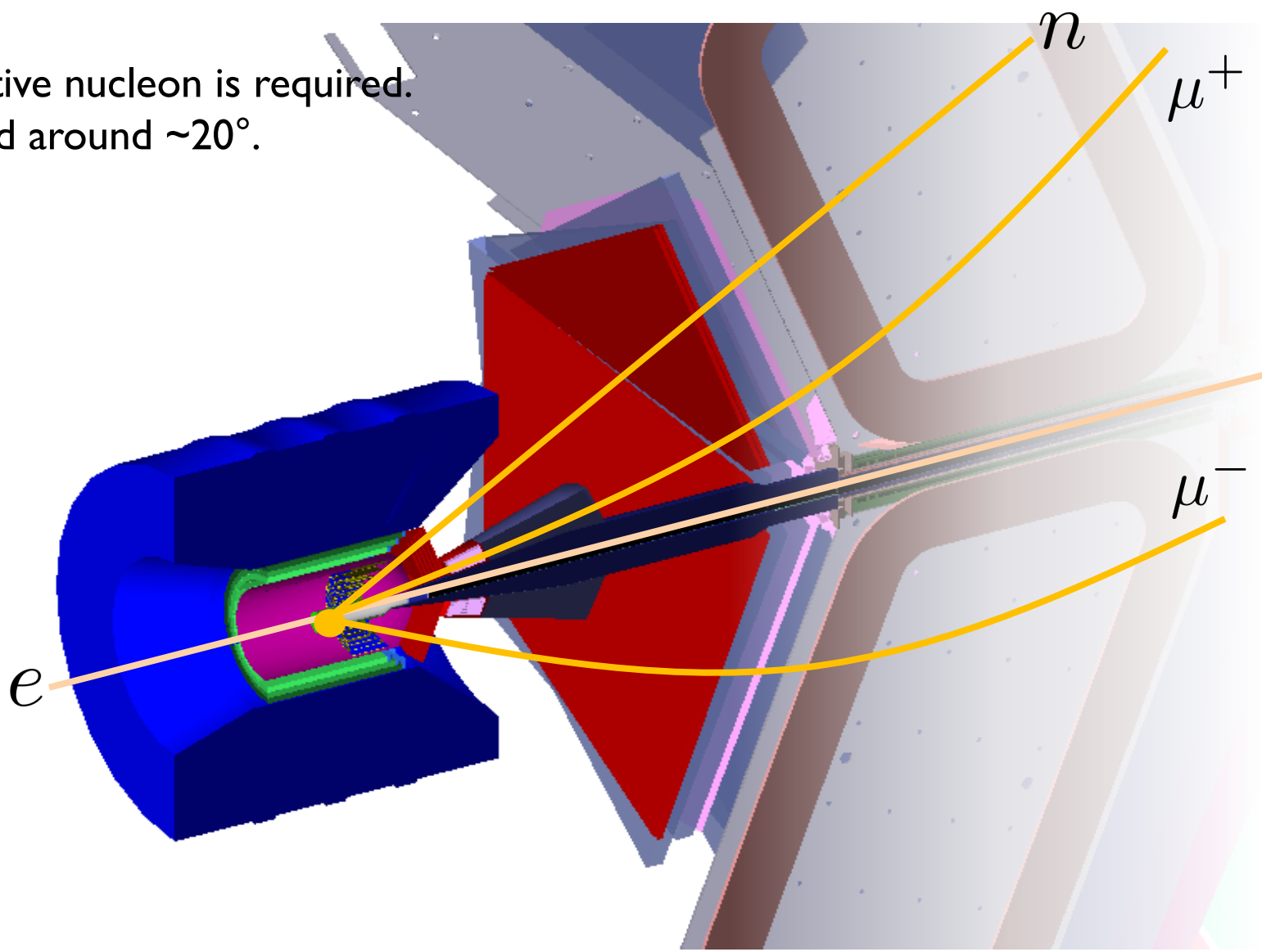
μCLAS12 article
2605.11690
Published in EPJA





Stage 2 - μCLAS12: the neutron and nuclear target case

- For nuclear target, the detection of the active nucleon is required.
- In the CLAS12 kinematics, they are emitted around ~20°.



Analysis strategy

- Deuterium target
- At least one muon polar angle within 15 degrees
- One cleanly IDed muon should enable to reconstruct J/ψ in $\mu^+\mu^-$ invariant mass.
- Shielding decreases neutron polar angle acceptance (~ >15 degrees)
- Assume 90% tracking efficiency per charged particle at 450nA.

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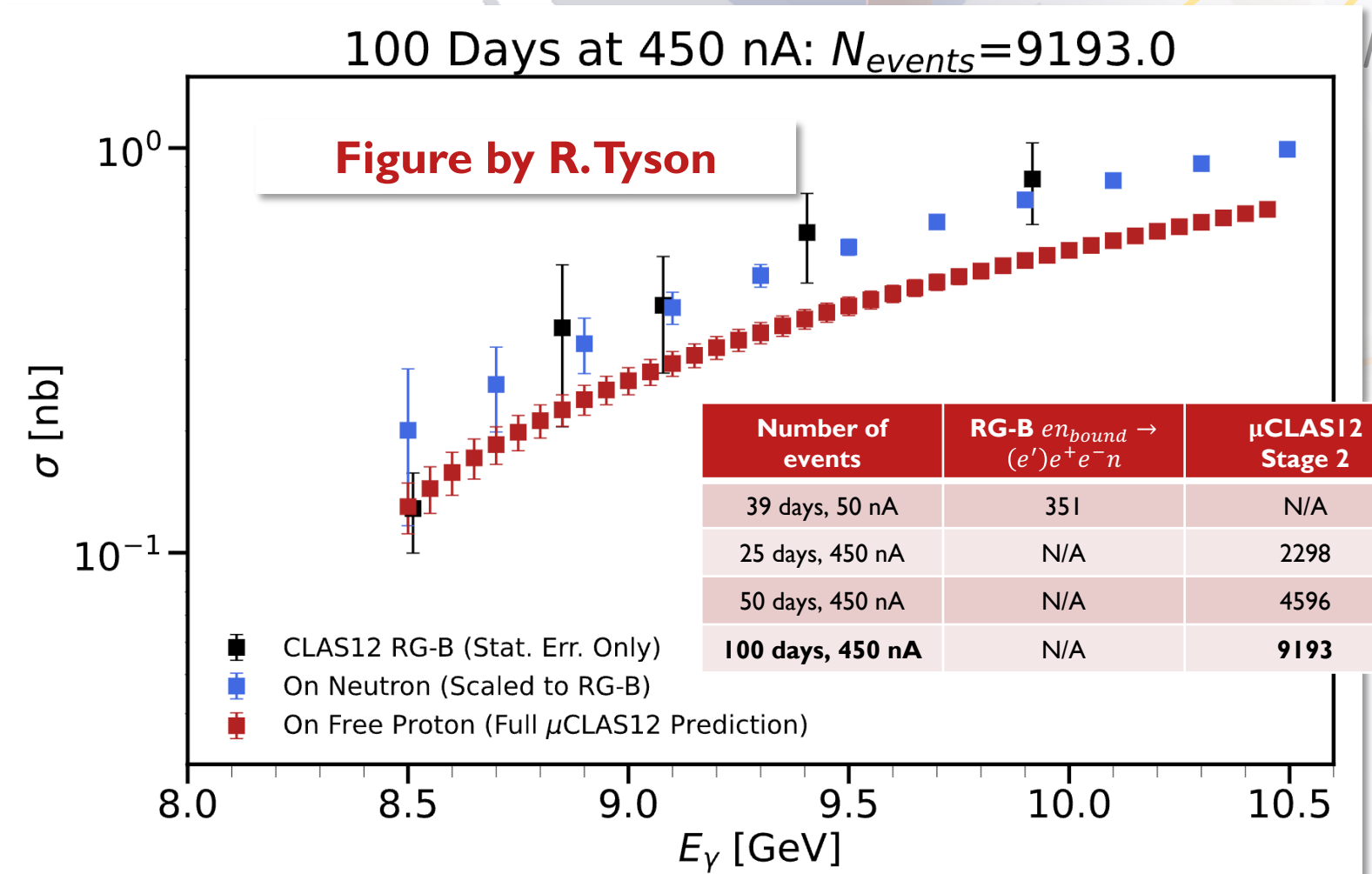


Number of events	RG-B $en_{bound} \rightarrow (e')e^+e^-n$	μCLAS12 Stage 2
39 days, 50 nA	351	N/A
25 days, 450 nA	N/A	2298
50 days, 450 nA	N/A	4596
100 days, 450 nA	N/A	**9193**

Measurements at JLab

- JLab is the only place where near threshold J/ψ can me measured, thanks to:
  → the **energy range** accessible,
  → and the **large luminosity** available.

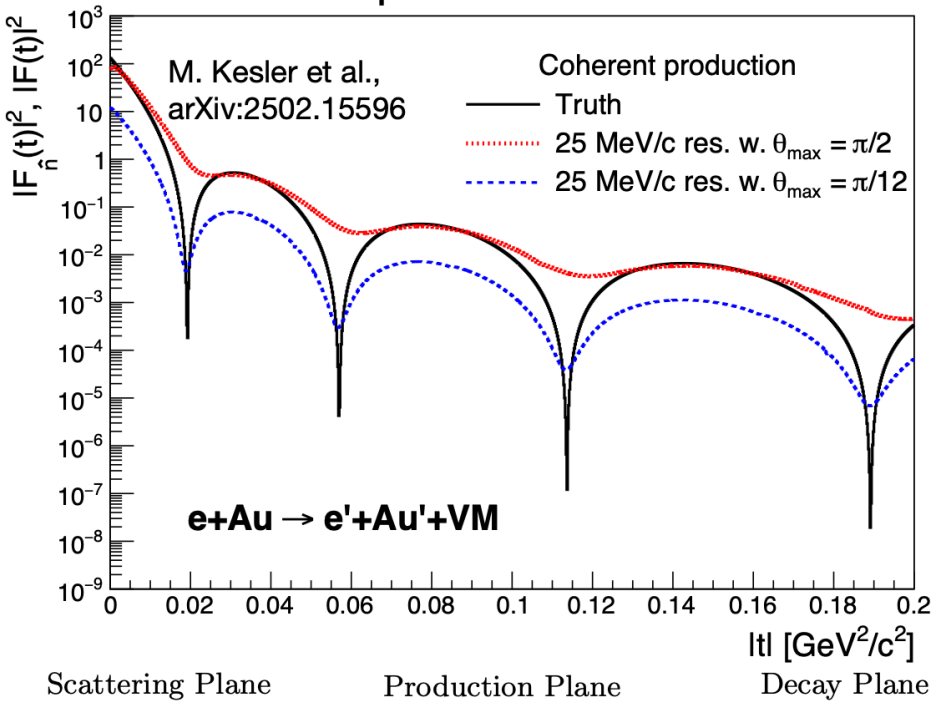
- Exclusive J/ψ has now become one of the **flagship measurements** at Jefferson Lab:
  → with **published results** in all halls,
  → on **various targets** (proton, neutron, heavy nuclei).

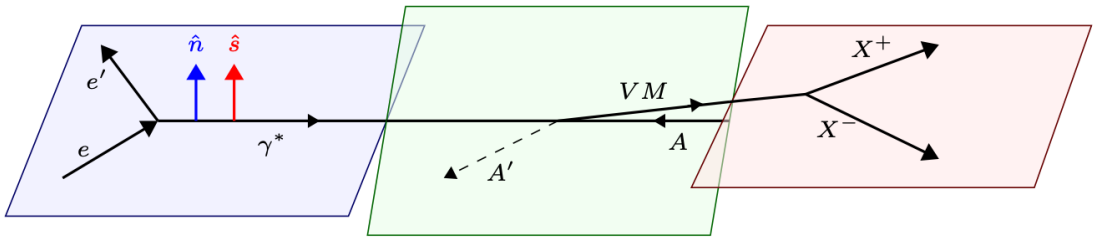
- Future short-term and long-term experiments have been proposed and accepted by the PAC,
  → relying on **high beam current combined with large acceptance detectors**.

Complementarity with other facilities

Exclusive quarkonia at the EIC and the LHC – C.Van Hulse

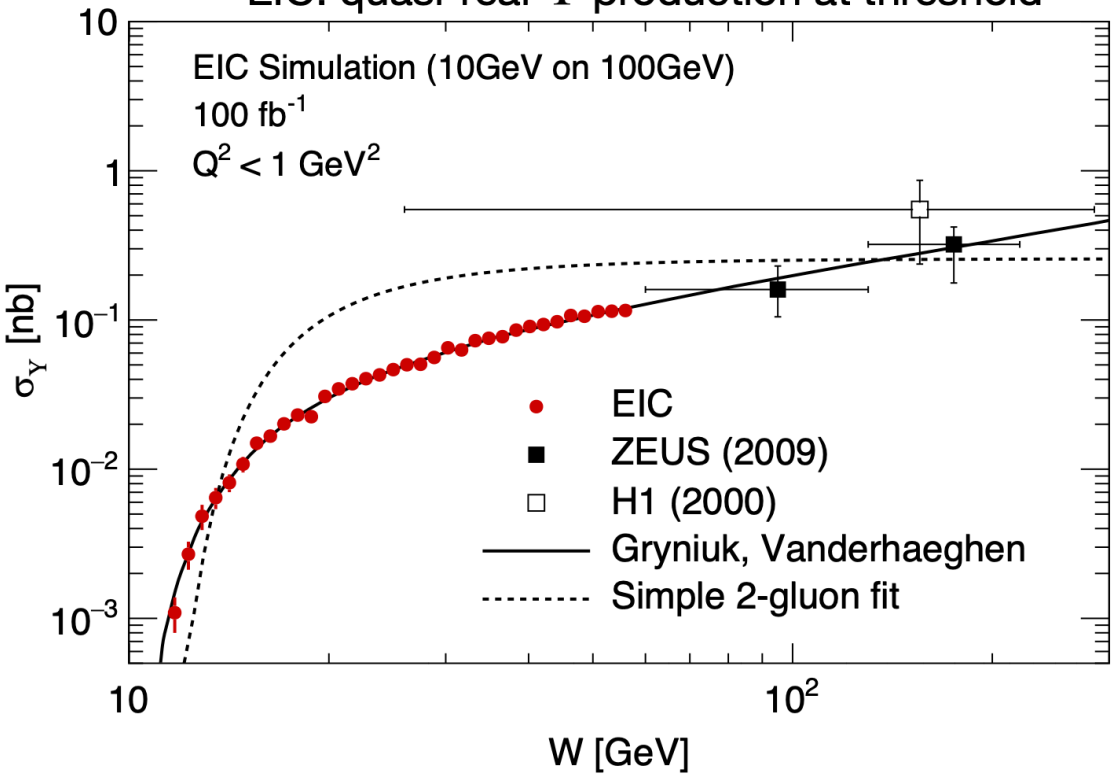
Development of new method





project t along $\hat{n}$

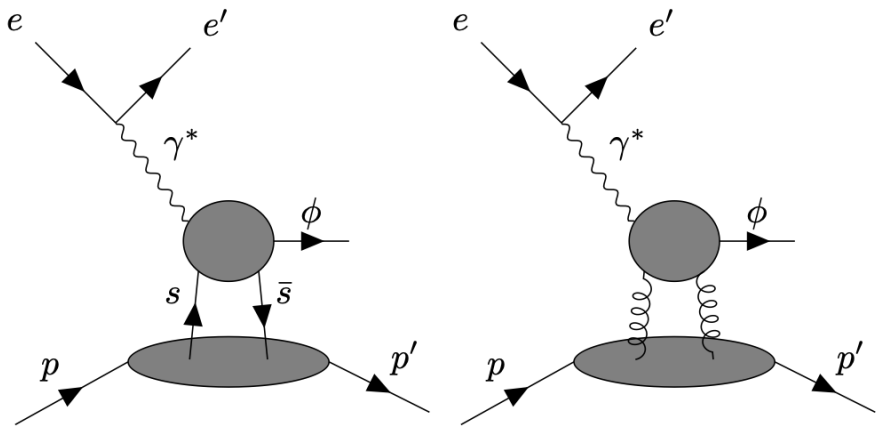
EIC: quasi-real Υ production at threshold



- Exclusive quarkonia production will be one of the flagship measurement at the EIC…
- …both on the proton and nuclei.
- **JLab quarkonia programs will constitute a baseline** for these future measurements.

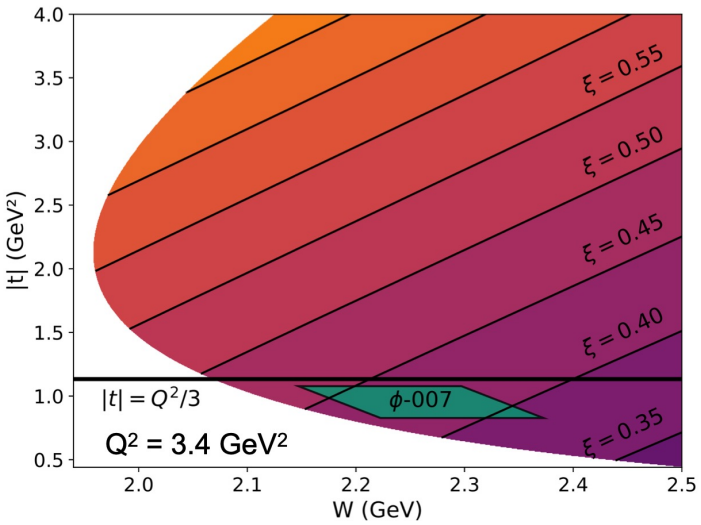
Electro-production of in Hall C – H. Klest

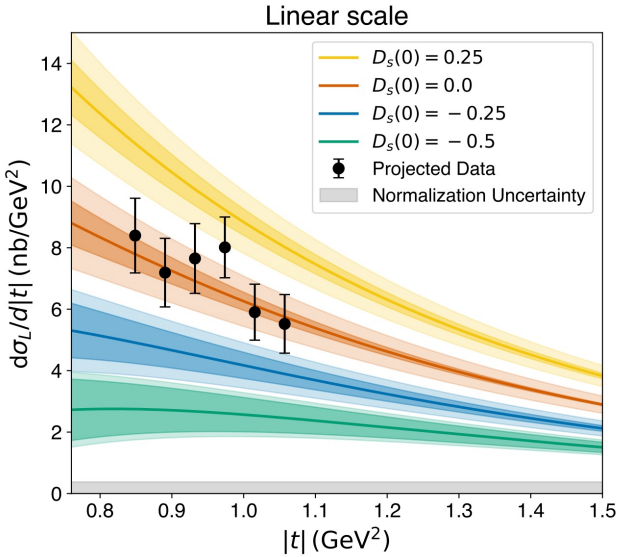
Strangeness and gluons in the nucleon



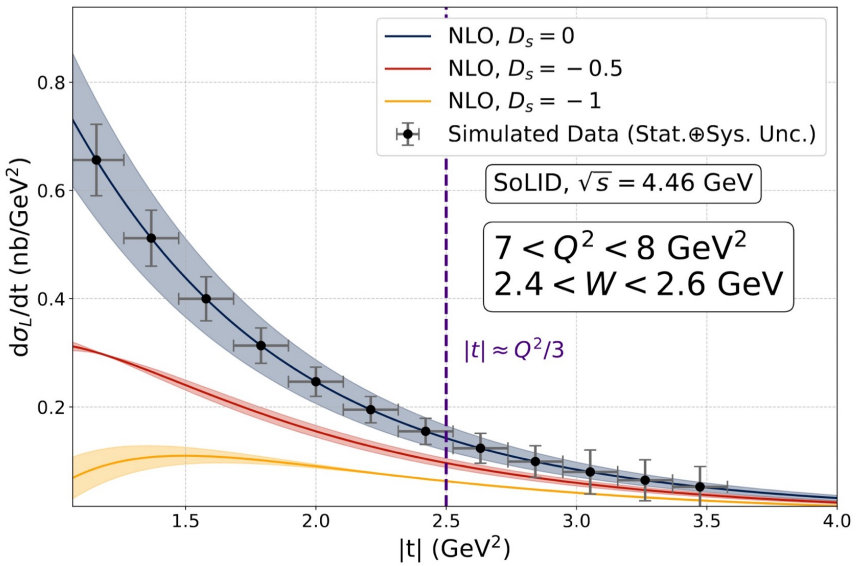
$$\mathcal{H}(\xi,t,Q^2) \approx \frac{2\kappa}{\xi^2}\frac{15}{2}\left[\left\{\alpha_s(\mu)+\frac{\alpha_s^2(\mu)}{2\pi}\left(25.7309-2n_f+\left(-\frac{131}{18}+\frac{n_f}{3}\right)\ln\frac{Q^2}{\mu^2}\right)\right\}(A_s(t,\mu)+\xi^2 D_s(t,\mu)) \quad (35)$$
$$+\frac{\alpha_s^2}{2\pi}\left(-2.3889+\frac{2}{3}\ln\frac{Q^2}{\mu^2}\right)\sum_q(A_q+\xi^2 D_q)+\frac{3}{8}\left\{\alpha_s+\frac{\alpha_s^2}{2\pi}\left(13.8682-\frac{83}{18}\ln\frac{Q^2}{\mu^2}\right)\right\}(A_g+\xi^2 D_g)\Big],$$

- ϕ electro-production gives access to the gluon and strange GPDs/GFFs.
- **Extremely complementary to J/ψ program**, to constrain gluons





- Experiment approved in Hall C during PAC53.
- Projections made for SoLID-lite detector.



Summary and key take-aways

- J/ψ production is now at the center of a large theoretical effort,
  → Many models have been developed to interpret the data
  → **Challenges remains and precision data will play an important role to solve them**.

- Exclusive J/ψ production has now become one of the **flagship measurement** at Jefferson Lab:
  → with **published measurement** in all halls,
  → on **various targets** (proton, neutron, heavy nuclei).

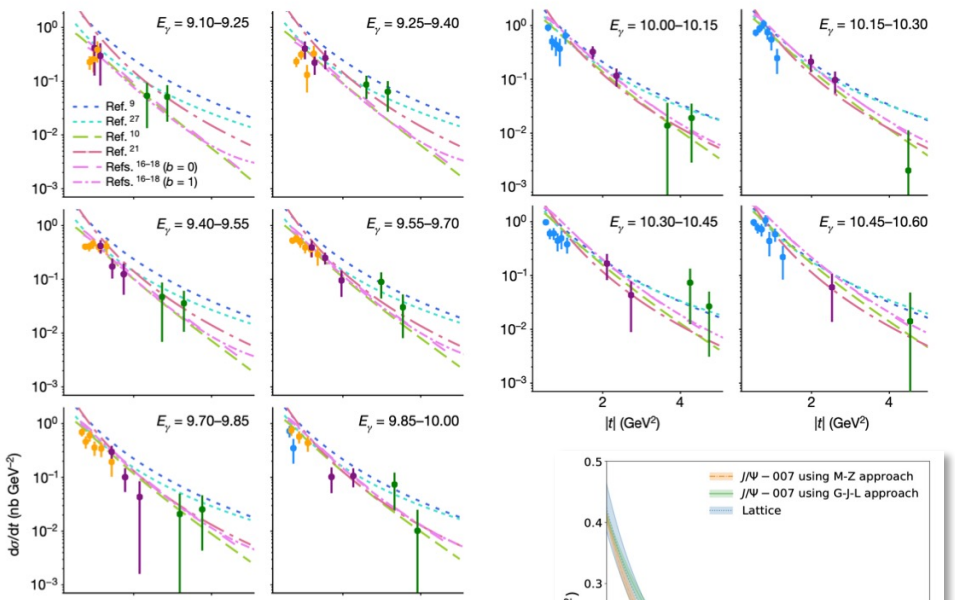
- Future short term and long term have been proposed, and accepted by the PAC,
  → relying on **high beam current combined with large acceptance detectors**.

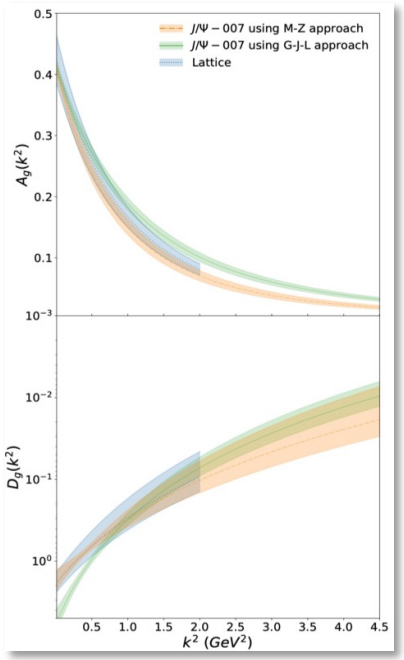
- Exclusive production of quarkonia will be at the center of the EIC program,
  → JLab has the potential to timely deliver on this topic
  → with precision data, **setting baseline** for these future experiments.

Back up

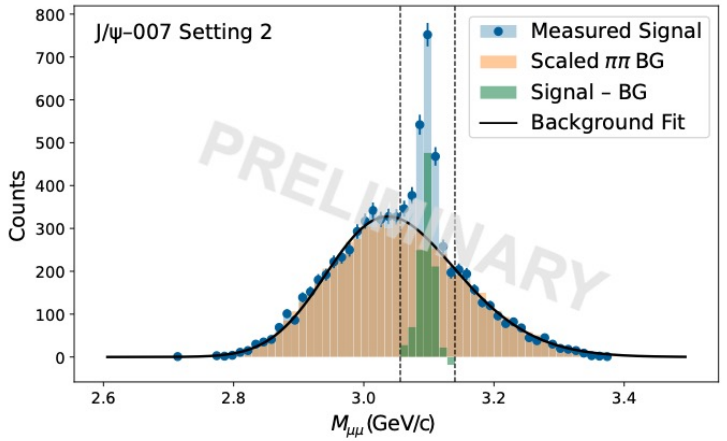
Charmonium in Hall A & C – S.Joosten

First extraction of the gluon GFFs

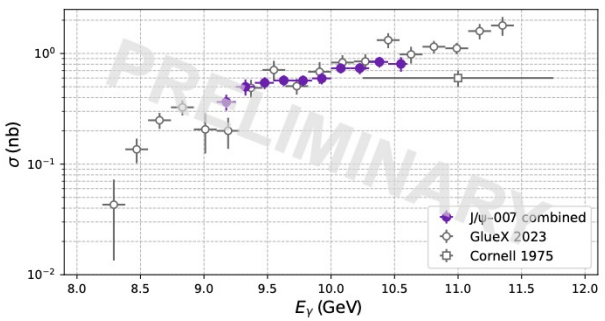


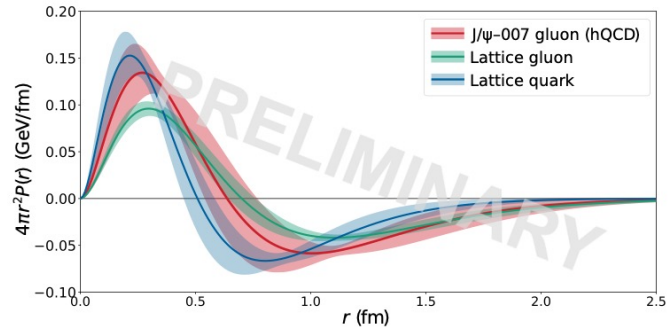


New paper, using the di-muon final state



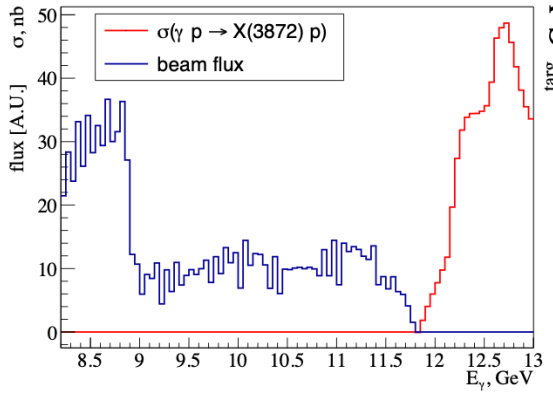
- Near-threshold J/ψ di-muon channel photoproduction cross section

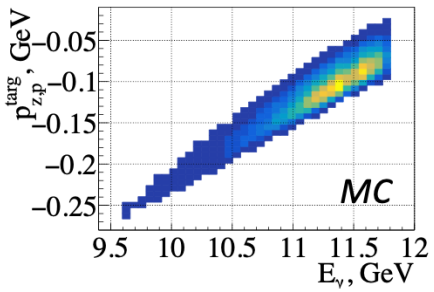




X(3872) in Hall D – Slide from L. Pentchev

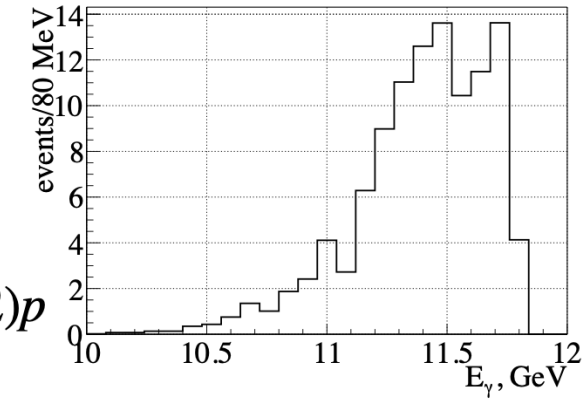
$\chi_{c1}(3872)$ production off ^4He with 12 GeV



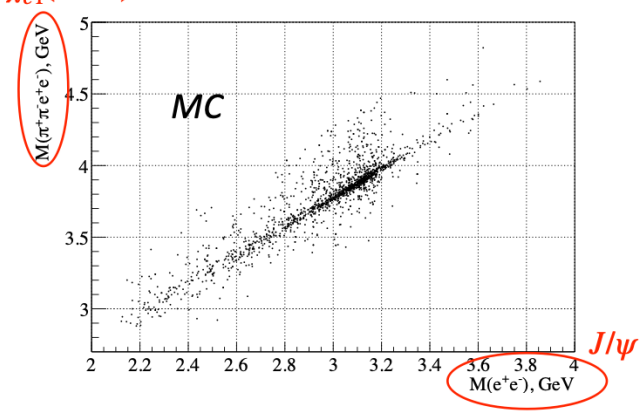


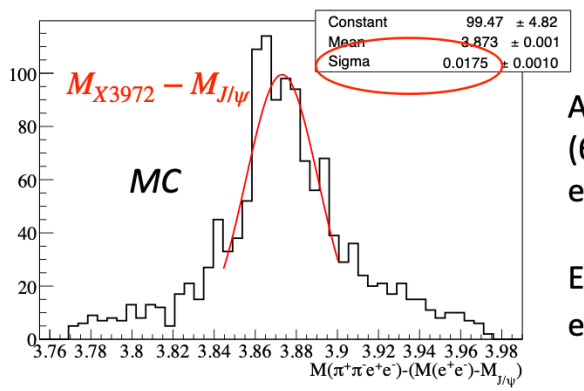
$$\gamma\, p(^4He) \rightarrow X(3872)p$$

$$\sigma(E_\gamma) = \sigma(W)$$



$\chi_{c1}(3872)$





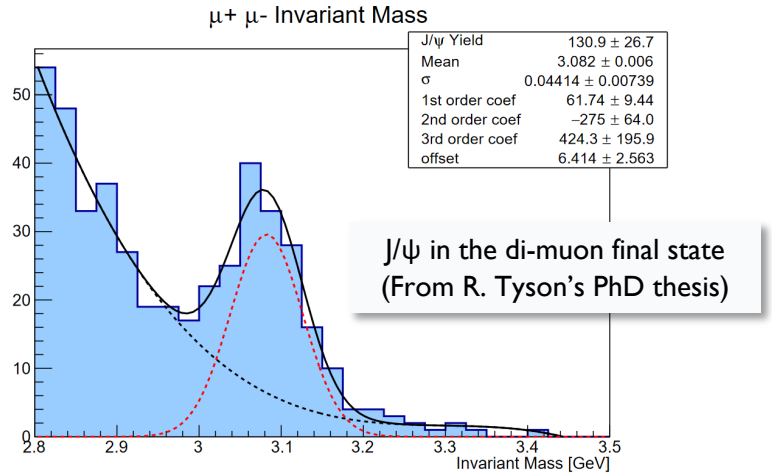
Assuming same luminosity (67 PAC days) and 12 GeV electron beam

Expect 50-100 $\chi_{c1}(3872)$ events

$$\gamma\, p(^4He) \rightarrow X(3872)\, p + X \rightarrow \pi^+\pi^- J/\psi p + X \rightarrow \pi^+\pi^- e^+ e^- p + X \text{ inclusive}$$

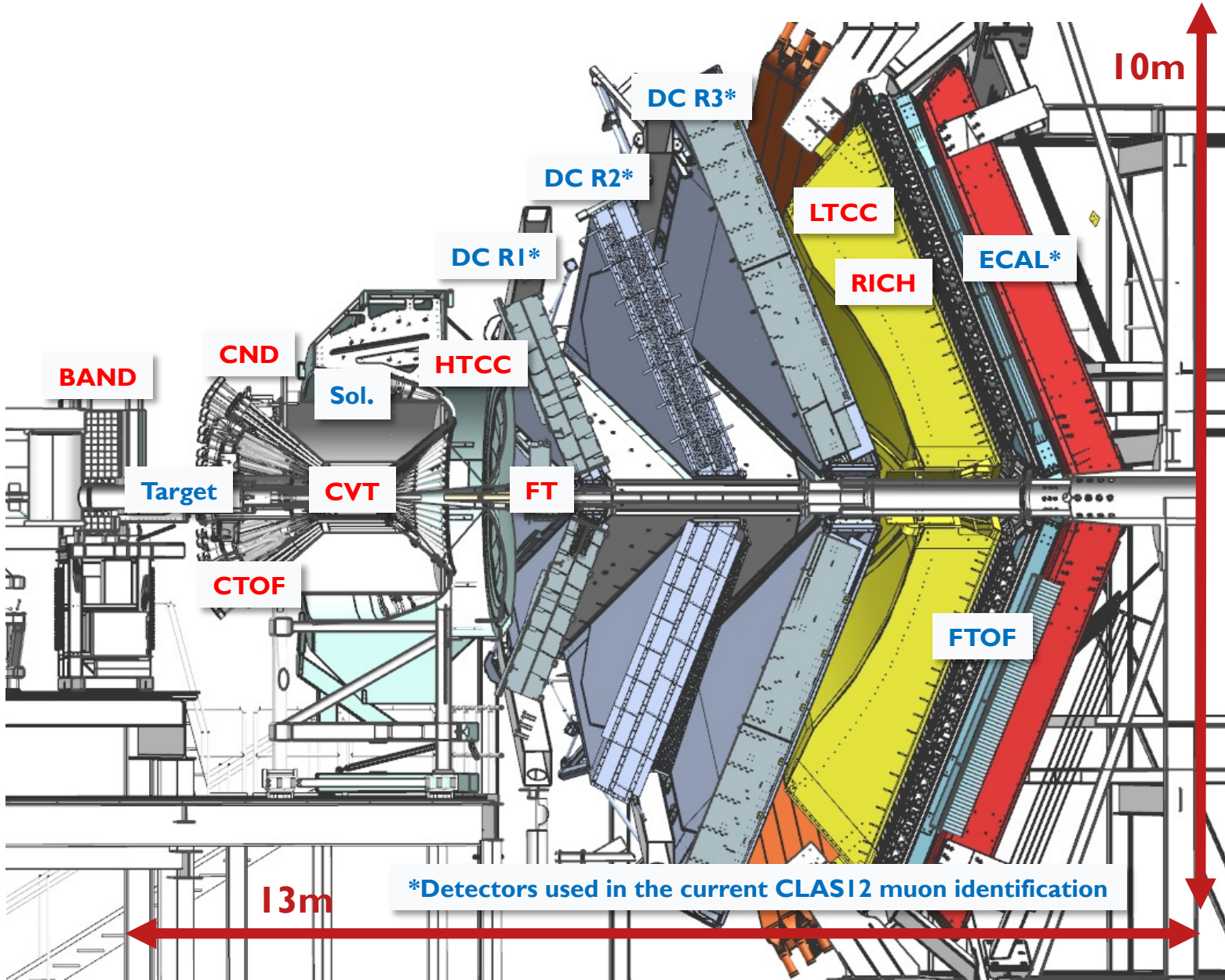
From the CLAS12 configuration…

- The μCLAS12 setup will **mostly use existing CLAS12 detectors**.



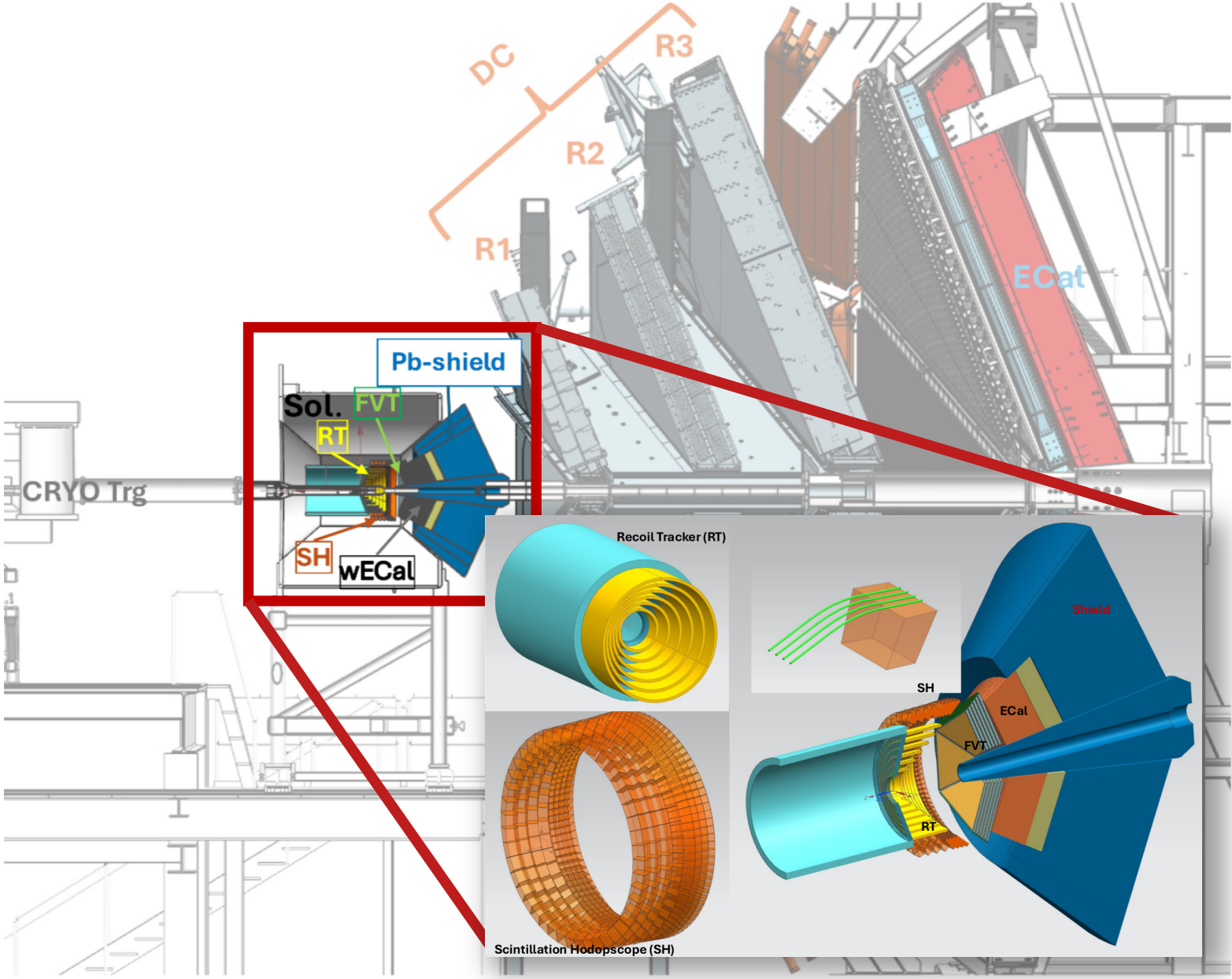
J/ψ in the di-muon final state (From R. Tyson's PhD thesis)

- The CLAS12 FD detector will be effectively used as a muon detector.
- The CTOF, CND, CVT, HTCC, FT, LTCC, RICH and BAND will be removed.

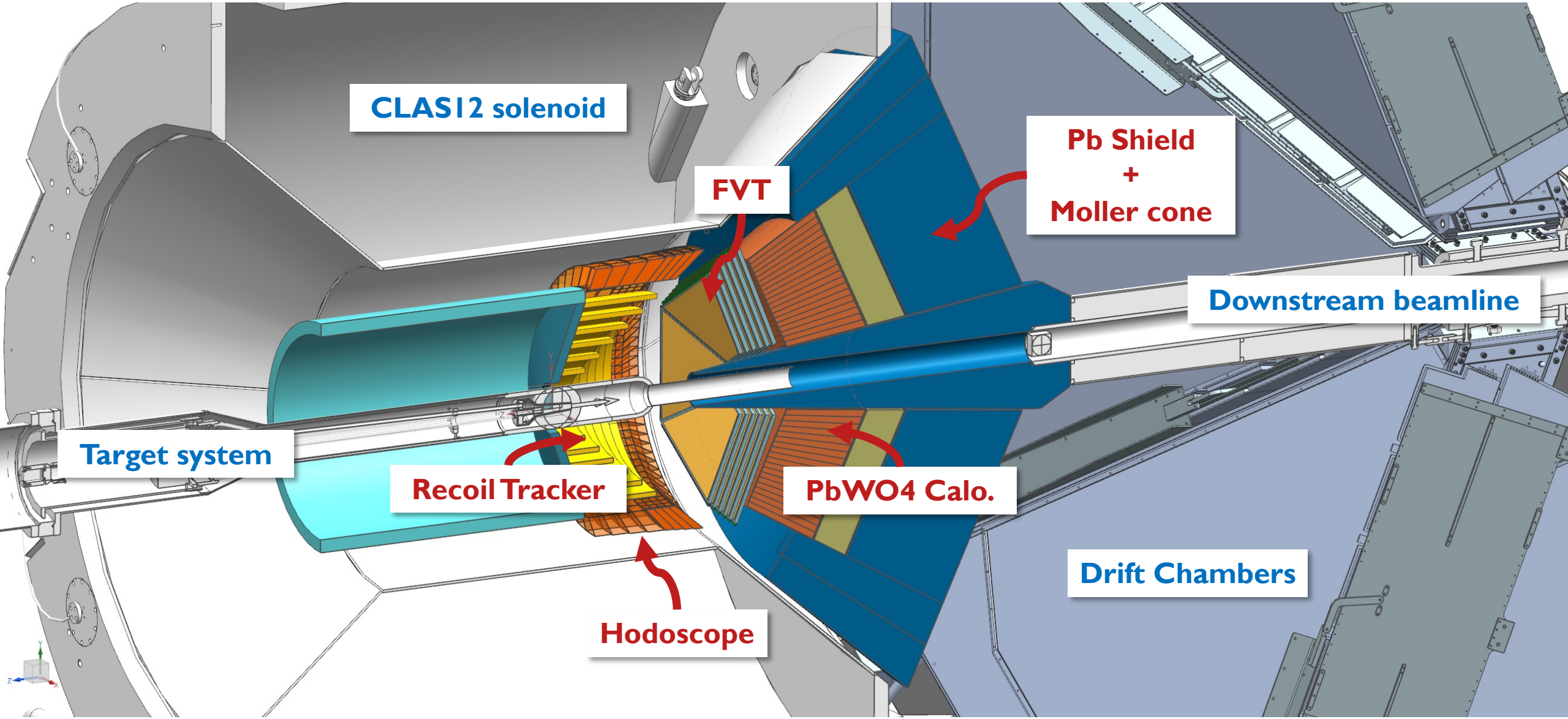


… to the µCLAS12 configuration

- A **lead shield** to reduce pion background in the FD.
- A **PbWO4 calorimeter** will identify scattered electron.
- A **GEM Forward Vertex tracker** will be used for vertexing.
- A **recoil tracker** surrounds the target to detect recoil proton,
- associated with a **Central Scintillator Hodoscope** for timing.



μCLAS12 subsystems overview

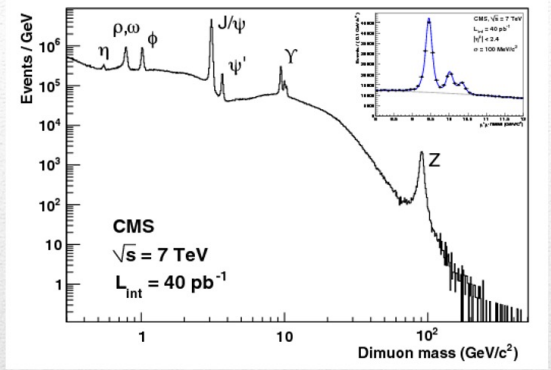


Charmonia spectroscopy with μCLAS12 – Alessandro Pilloni (Messina)

Spectroscopy with muons?

Pros:
- Cleaner than electrons
- Better signal/bkg
- Increase in luminosity with new run
- Peculiar signatures

Cons:
- Radiative/leptonic decays, small BR

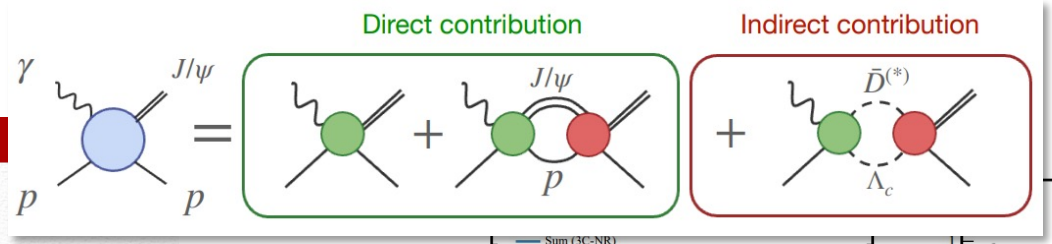


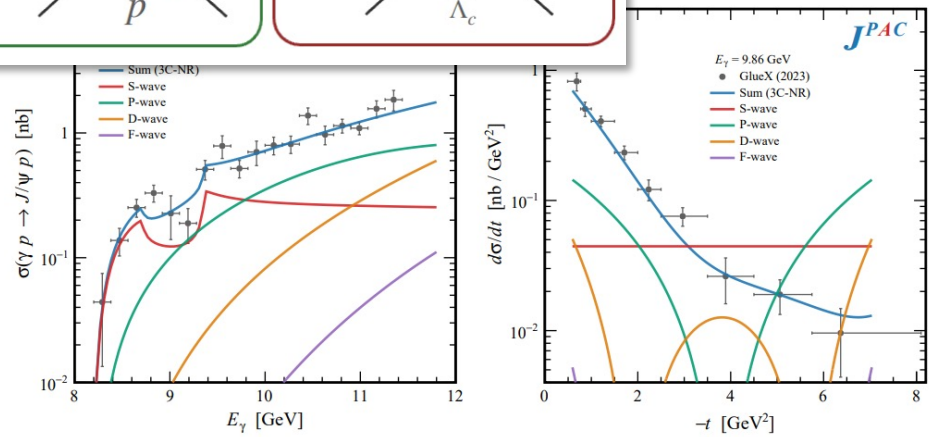
Light sector unfeasible

$$\frac{BR(\phi\to\mu^+\mu^-)}{BR(\phi\to K^+K^-)} = 5.7\times10^{-4}$$

Charmonium promising

$$\frac{BR(J/\psi\to\mu^+\mu^-)}{BR(J/\psi\to had)} = 7\%$$



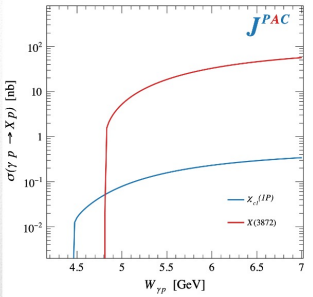


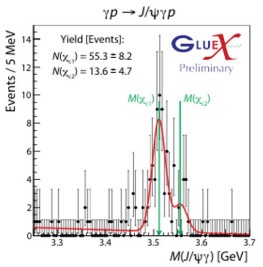
χ_{c1} photoproduction

Preliminary results from GlueX suggest that vector meson exchange underestimate the cross section

Possible contribution from $C = -$ 3-gluon exchange (Odderon-like)

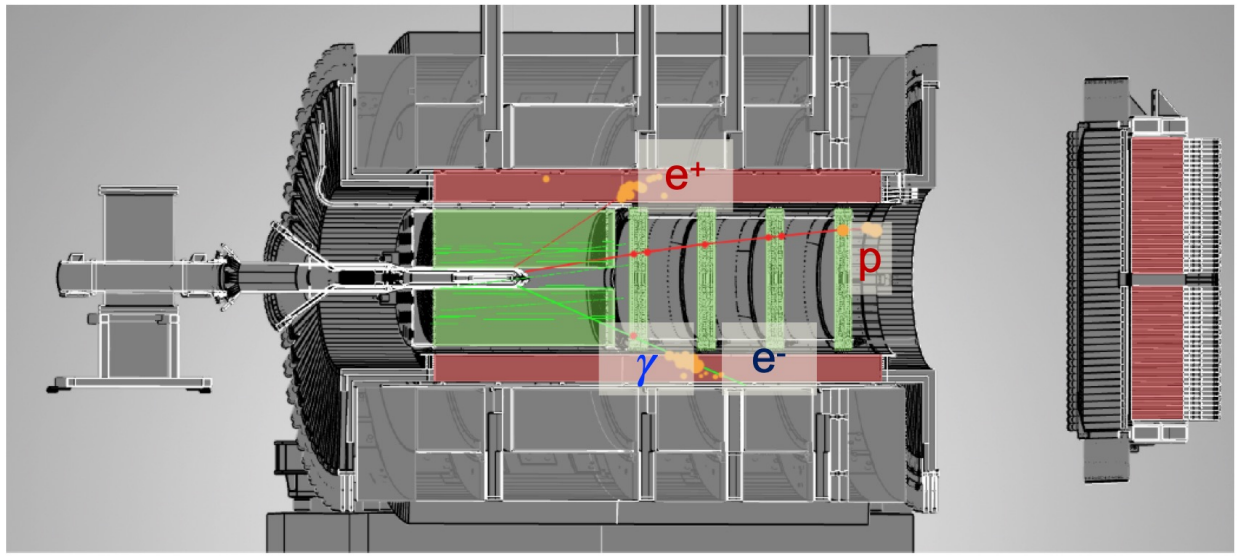
Needs further measurement and theory modeling, t and Q^2 dependence to be explored

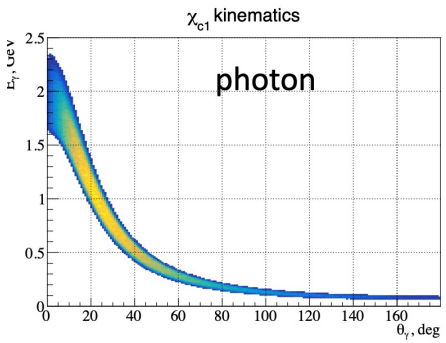


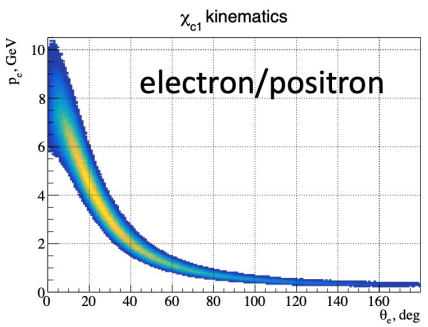


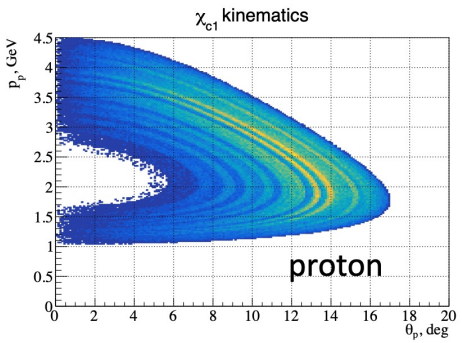
χ_c measurements with GlueX – Lubomir Pentchev (JLab)

$$\gamma p \to \chi_c p \to J/\psi\gamma\, p \to e^+e^-\gamma\, p \quad \textit{exclusive}$$



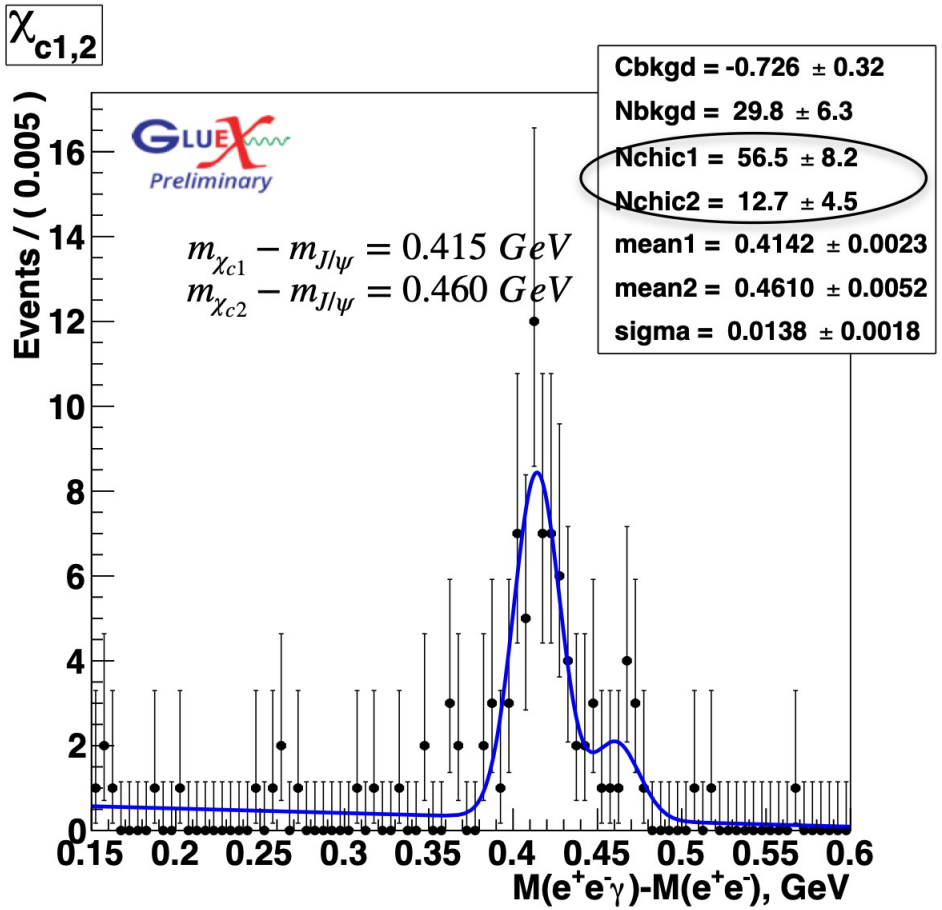






MC simulations

$$\gamma p \to \chi_c p \to (J/\psi\gamma)\, p \to (e^+e^-\gamma)\, p$$



- $\chi_{c1}(3511)$ and $\chi_{c2}(3556)$, 1^{++} and 2^{++} $(1P)$, $E_\gamma^{thr} = 10.1$ GeV