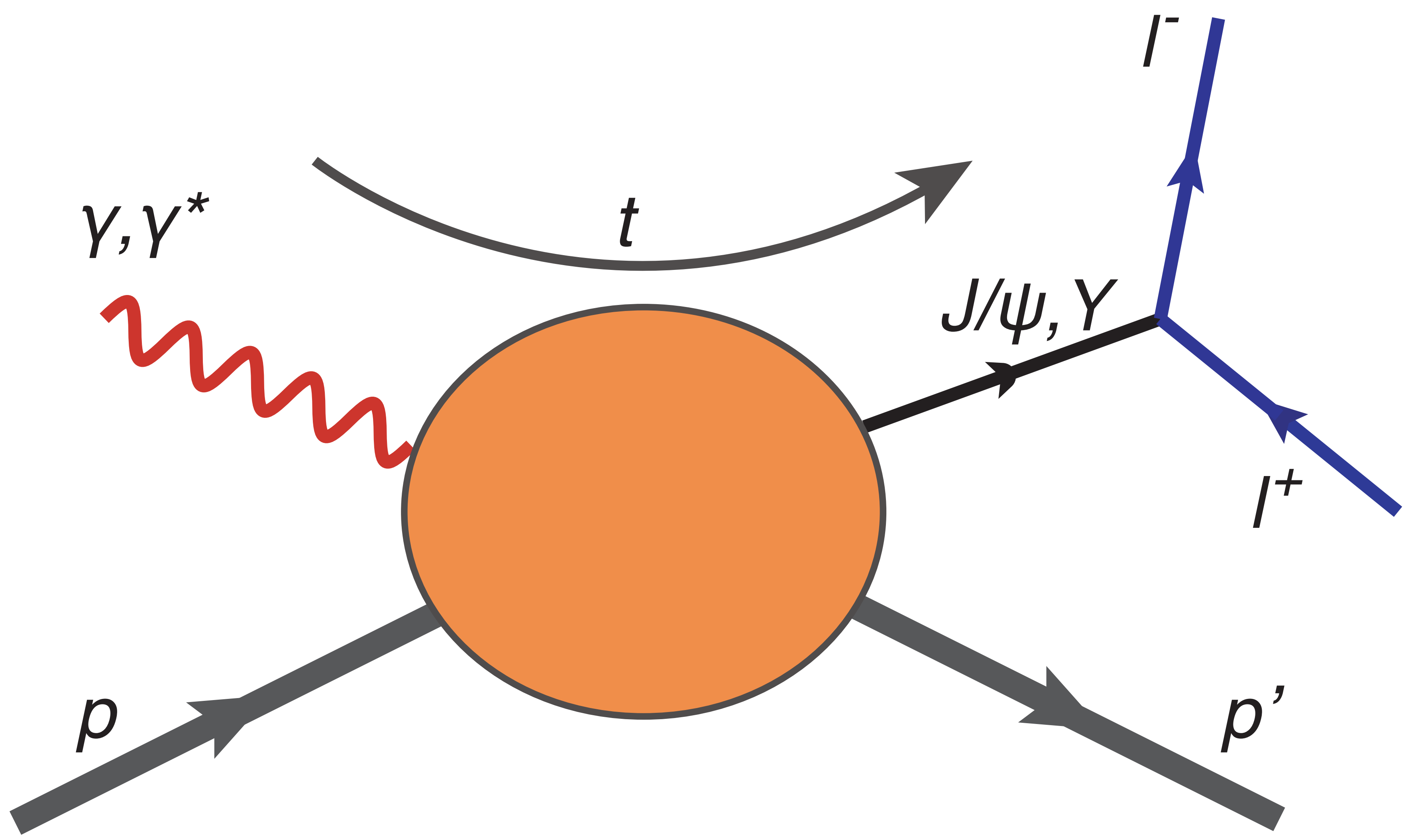
NEAR-THRESHOLD EXCLUSIVE QUARKONIUM PRODUCTION AT JLAB AND EIC

PROBES FOR THE ORIGIN OF HADRON MASS



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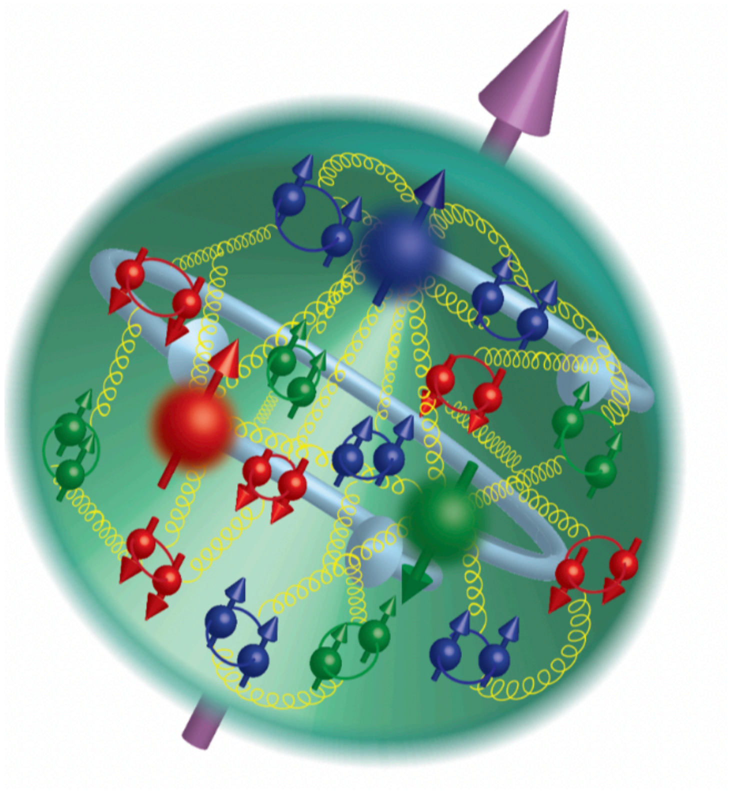
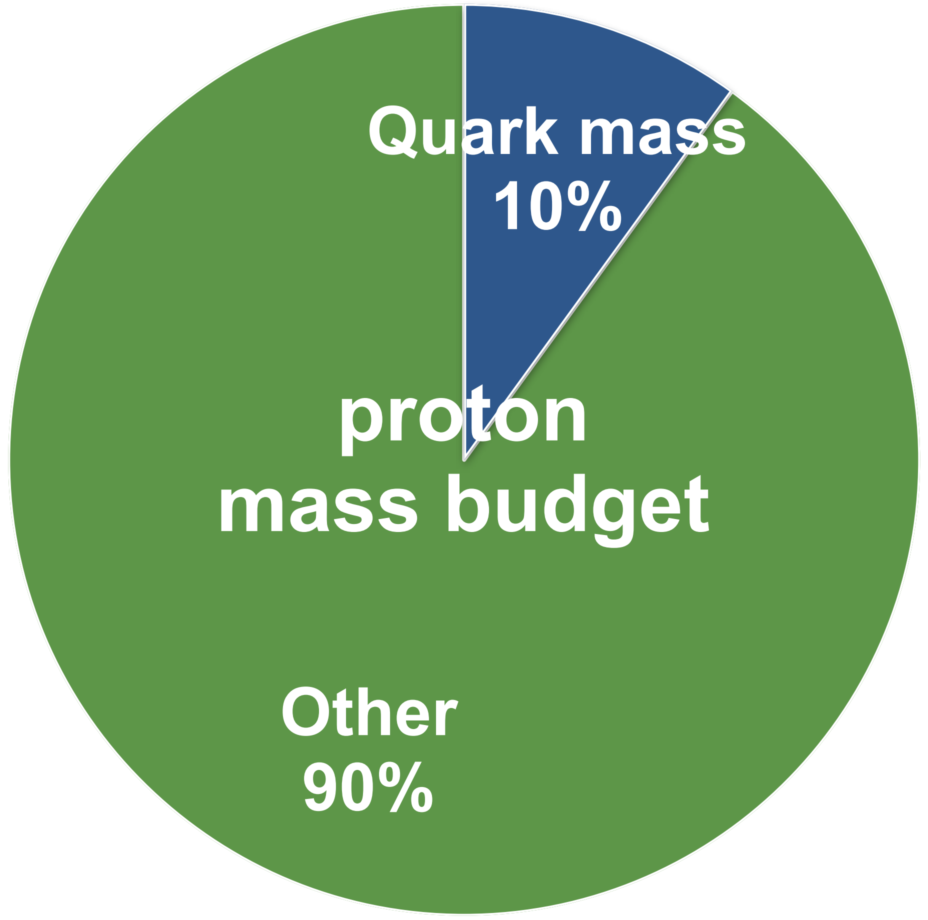
Town Hall Meeting on Hot and Cold QCD
MIT, September 23, 2022

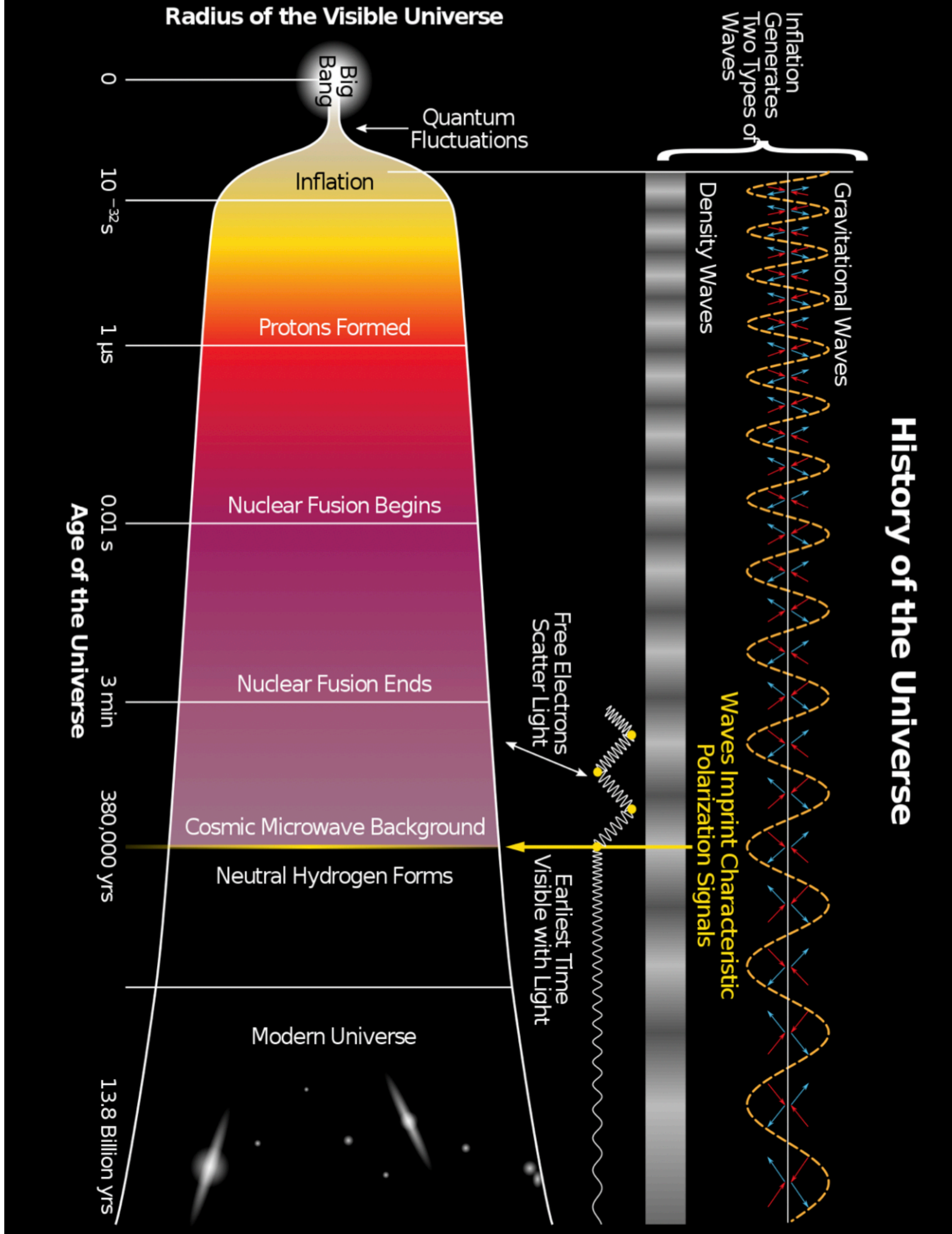
The emergence of nucleon mass

QCD IN THE STANDARD MODEL



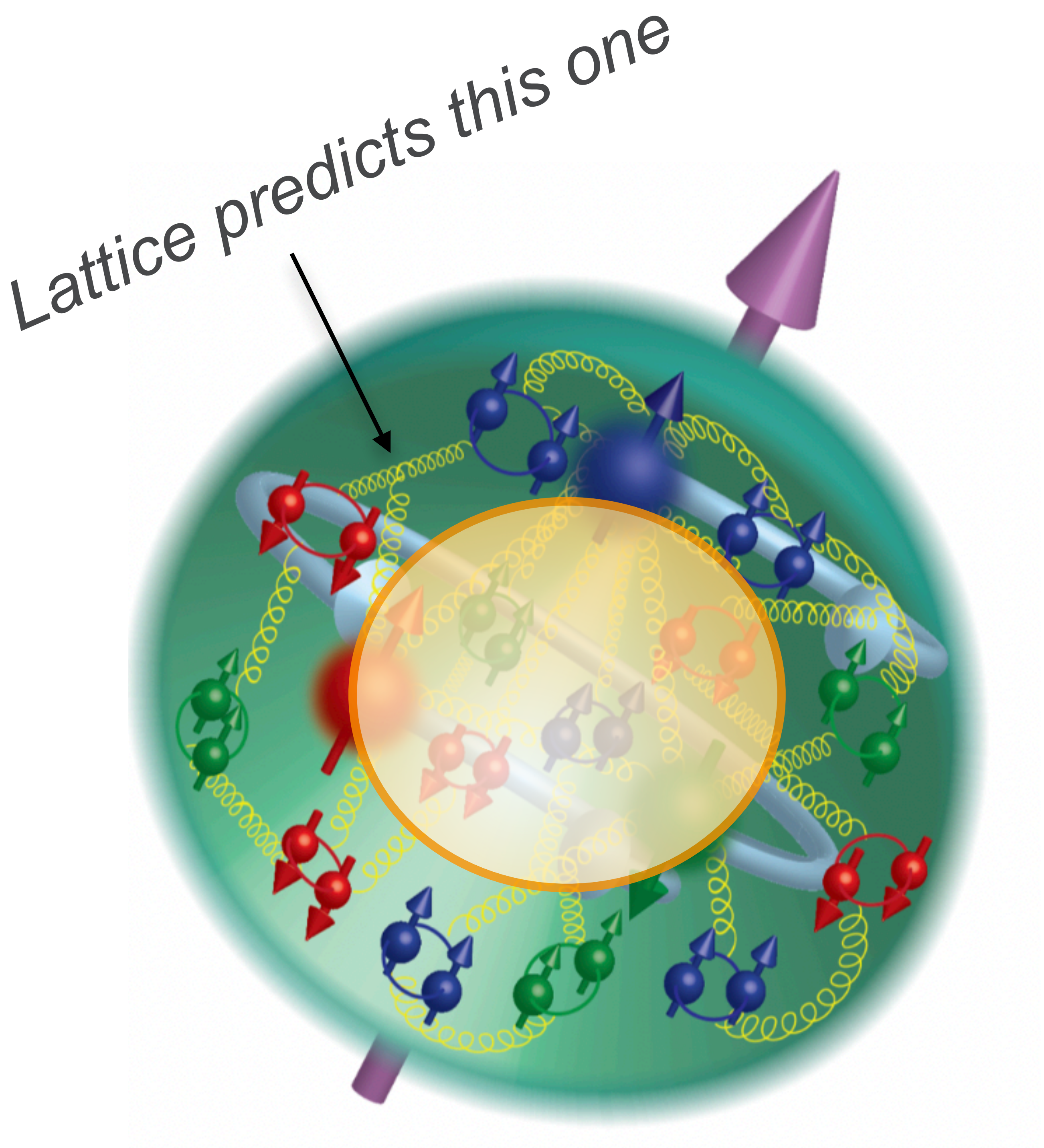


- Since the formation of protons and neutrons, most of the mass of the visible universe encapsulated in protons, neutrons, and nuclei.
- Surprising: nucleon mass much larger than sum of quark masses.
- *How does QCD give rise to the 1GeV proton?*
- *How is the proton mass distributed in its confinement size?*

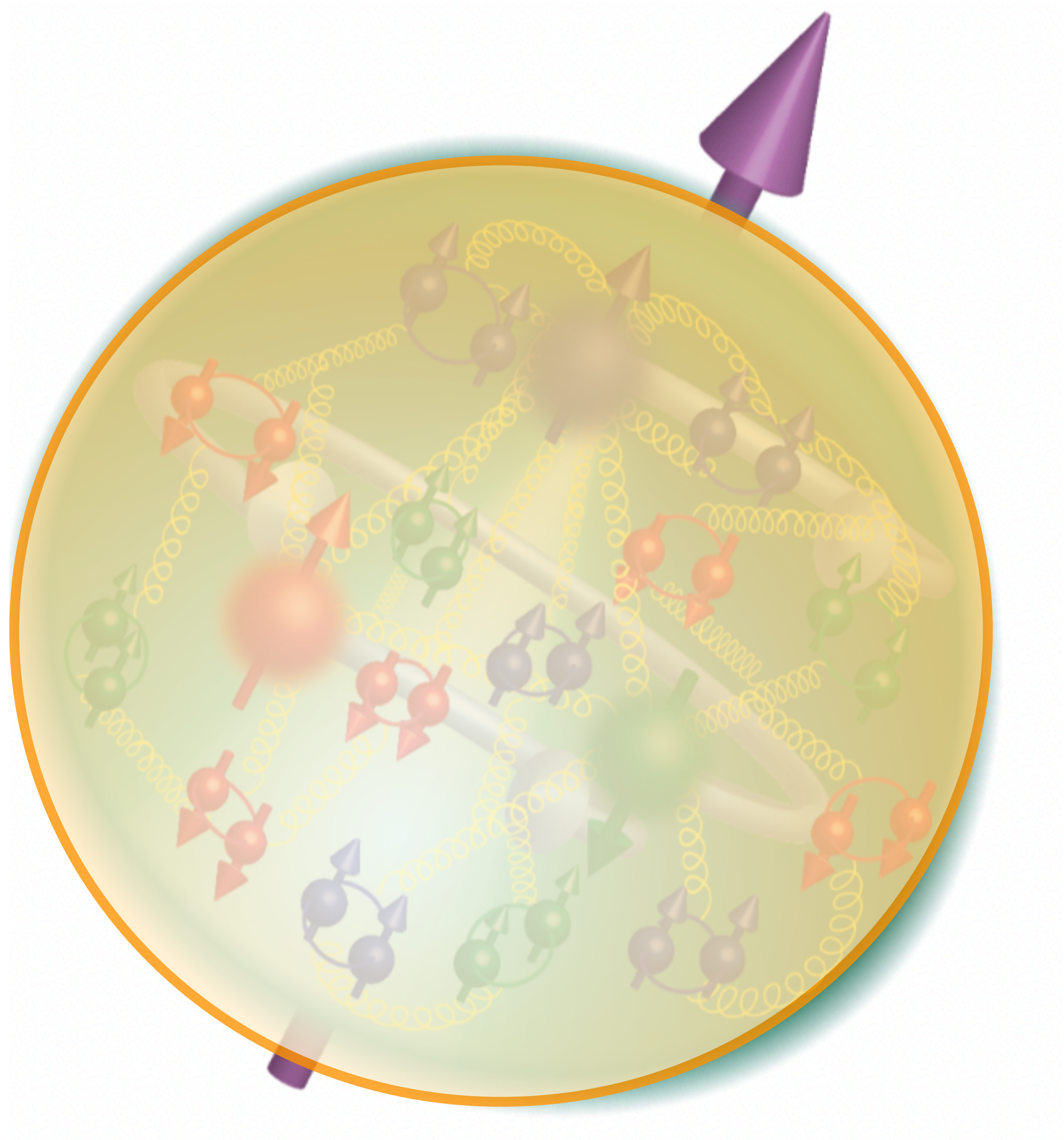


WHERE IS THE ENERGY INSIDE THE PROTON?

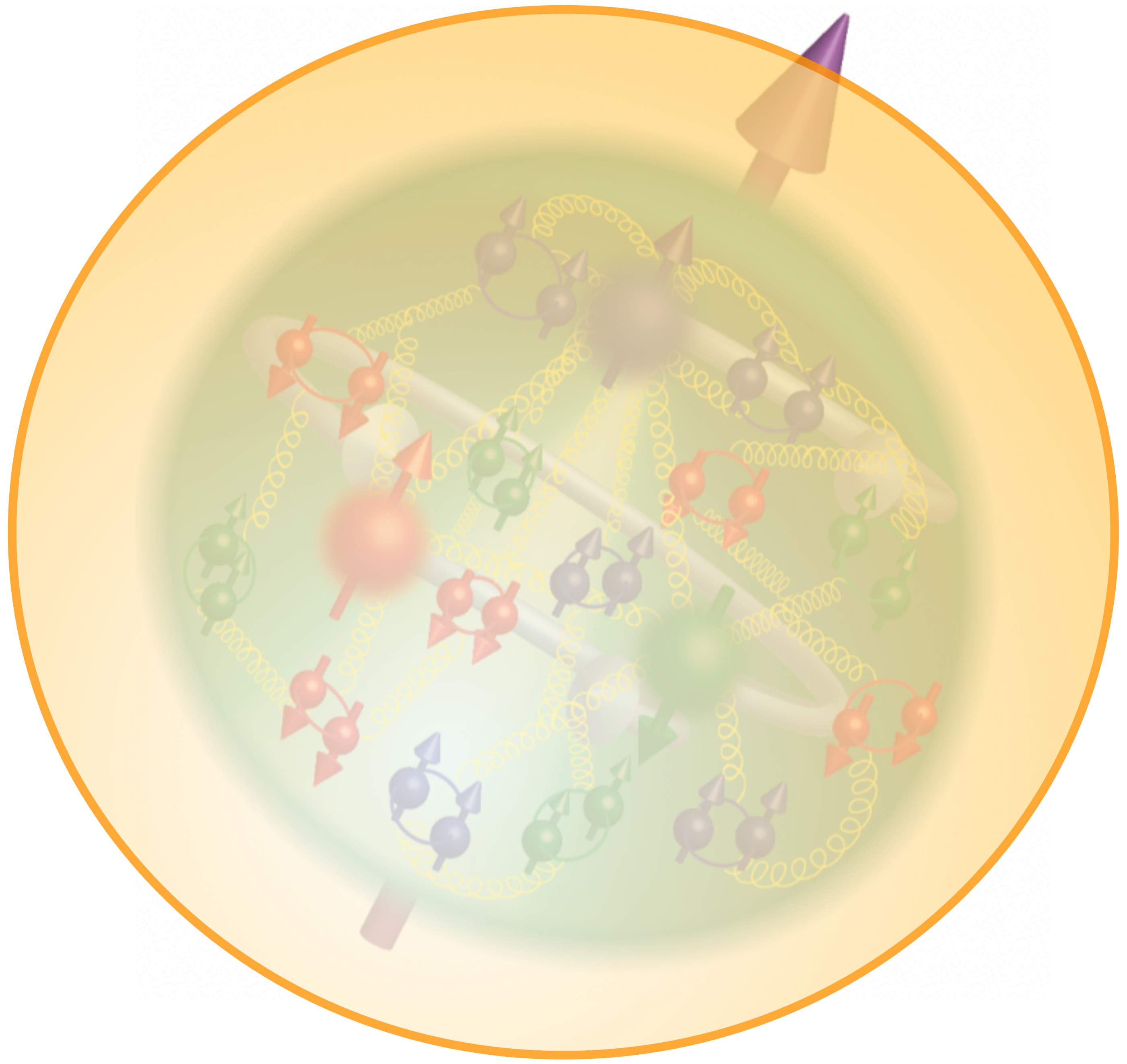
How does the mass radius compare to the charge radius?



Vs



Vs



Dense energetic core?

Same as charge radius?

Energy halo beyond charge radius?

GRAVITATIONAL FORM FACTORS (GFFS)

Towards observables of the matter structure of the proton

GFFs are the form factors of the QCD energy-momentum tensor (EMT) for quarks and gluons

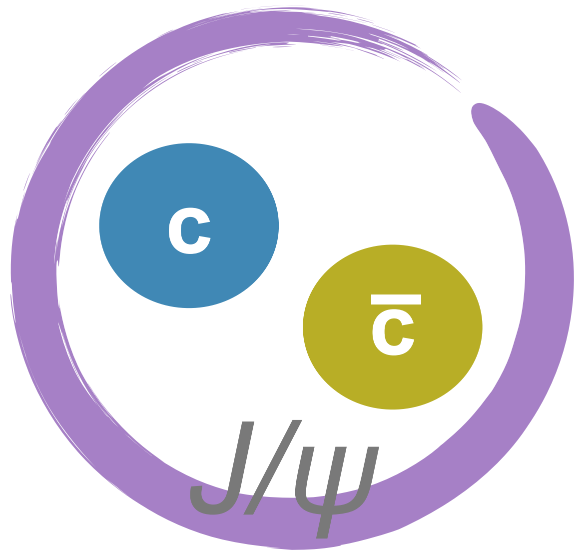
$$\langle N' \mid T^{\mu,\nu}_{q,g} \mid N \rangle = \bar{u}(N')\left(A_{g,q}(t)\gamma^{\{\mu}P^{\nu\}} + B_{g,q}(t)\frac{iP^{\{\mu}\sigma^{\nu\}\rho}\Delta_\rho}{2M} + C_{g,q}(t)\frac{\Delta^\mu\Delta^\nu - g^{\mu\nu}\Delta^2}{M} + \bar{C}_{g,q}(t)Mg^{\mu\nu} \right) u(N)$$

EMT physics encoded in these GFFs:

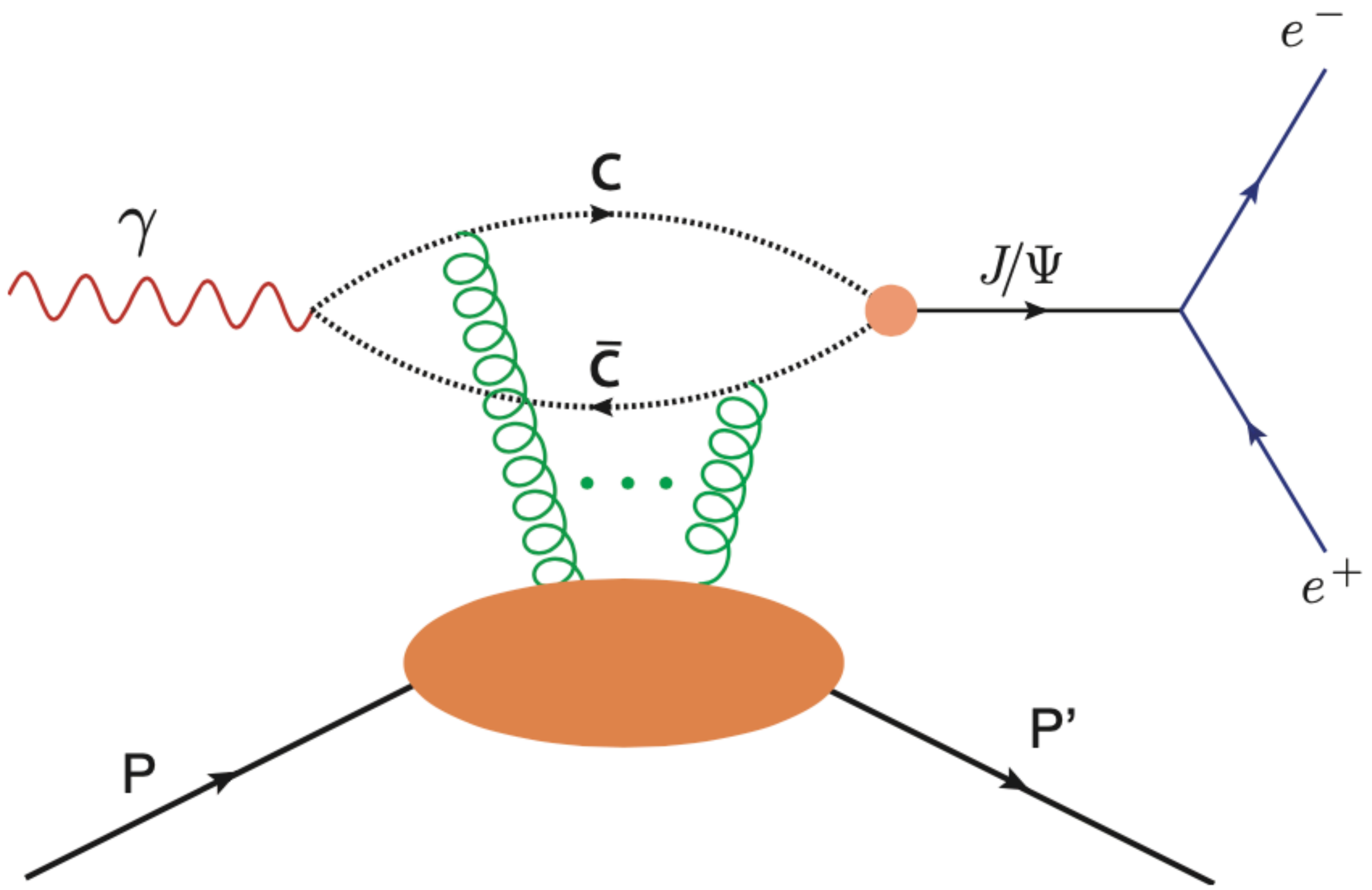
- $A_{g,q}(t)$: Related to quark and gluon momenta, $A_{g,q}(0) = \langle x_{q,g} \rangle$
- $J_{g,q}(t) = 1/2 \left(A_{g,q}(t) + B_{g,q}(t) \right)$: Related to angular momentum, $J_{\text{tot}}(0) = 1/2$
- $D_{g,q}(t) = 4C_{g,q}(t)$: Related to pressure and shear forces

PROBING THE GLUONS

Exclusive quarkonium production near the threshold

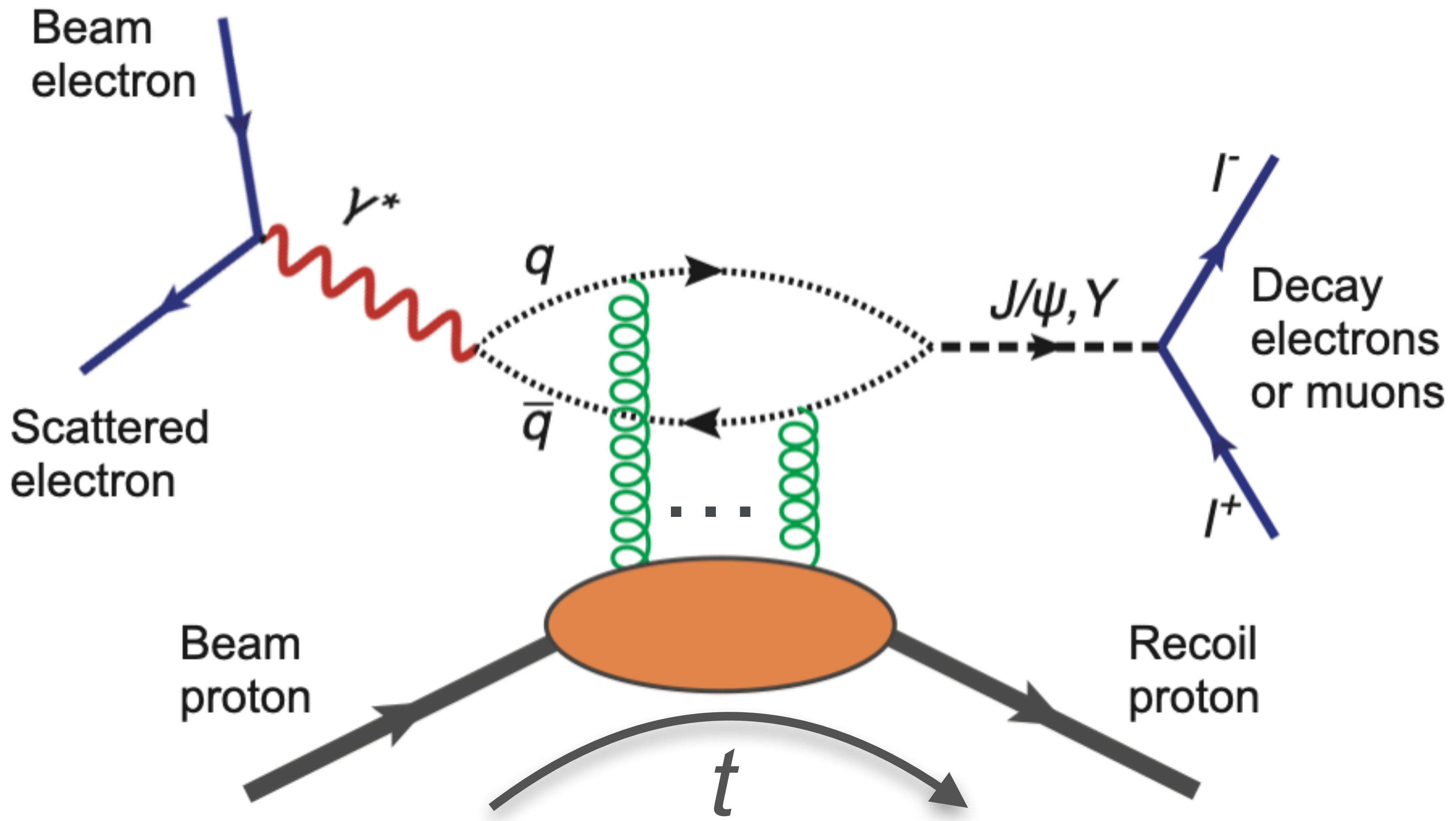


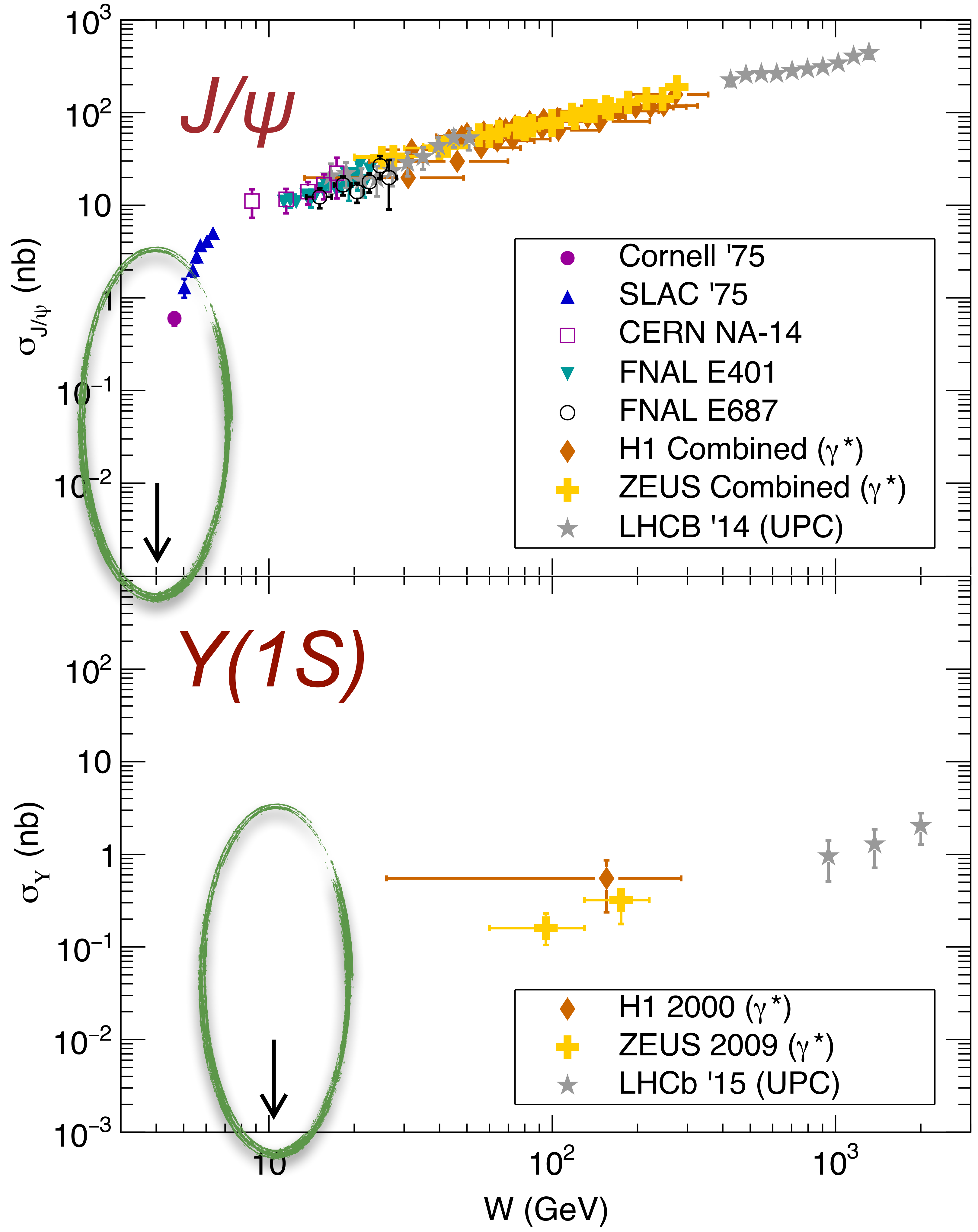
- Electromagnetic charge and spin of the proton well-studied through electron scattering
- Electromagnetic neutral gluons harder to access directly
  - Quarkonium uniquely sensitive to gluons: they do not couple to light quarks
  - Differential cross section of quarkonium near threshold promising channel to directly probe gluons
  - Sufficient data at different photon energies can constrain the GFF slopes and magnitudes in the forward limit (t=0)
  - **Access the matter distribution, mass radius, and potentially the trace anomaly of the EMT.**



EXCLUSIVE QUARKONIUM PRODUCTION

Before Jefferson Lab 12 GeV





- No near-threshold data available
- In case of Y(1S): not much available overall
- **Almost no data near threshold before JLab 12 GeV**

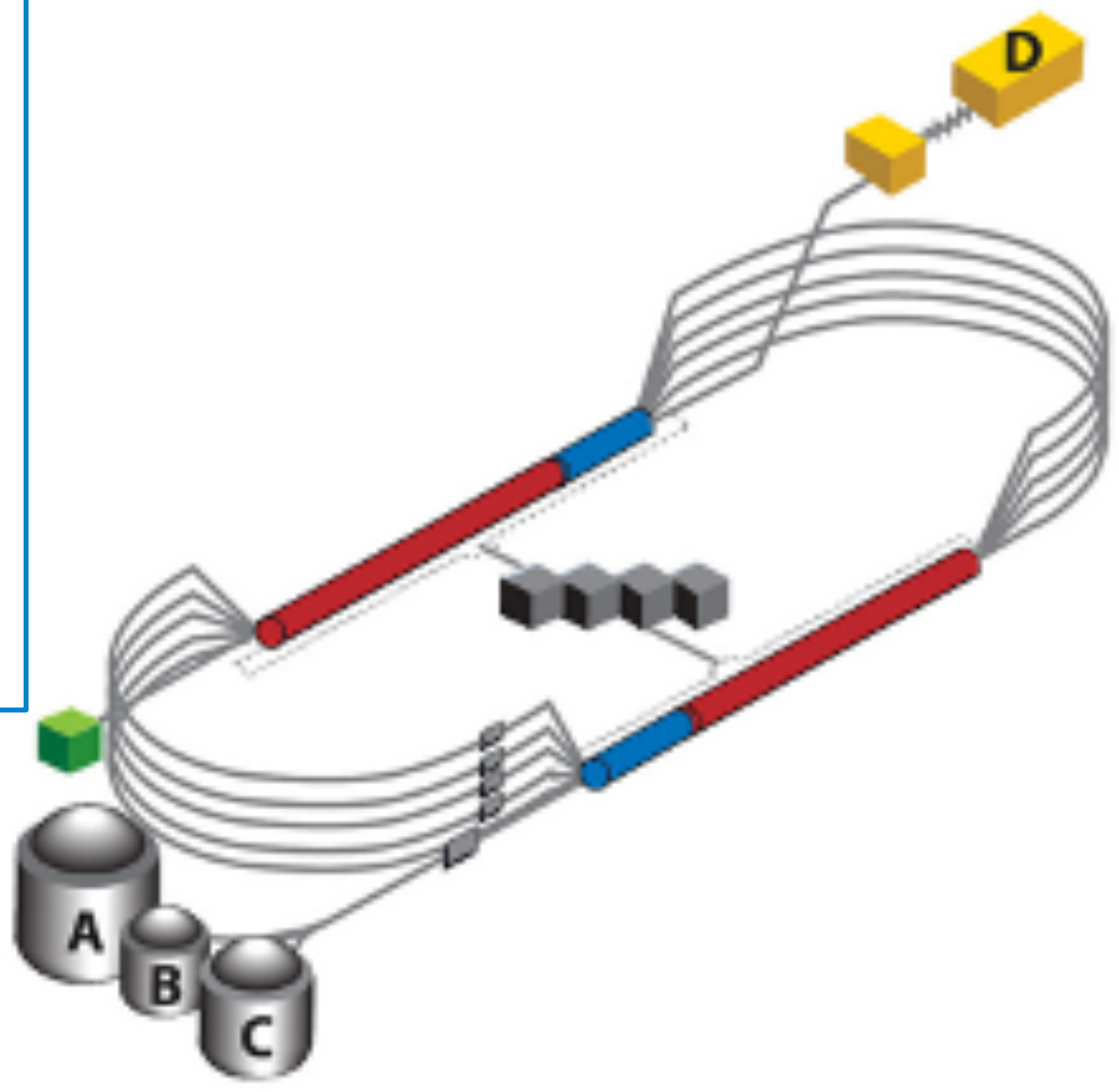
QUARKONIUM AT JEFFERSON LAB AND EIC

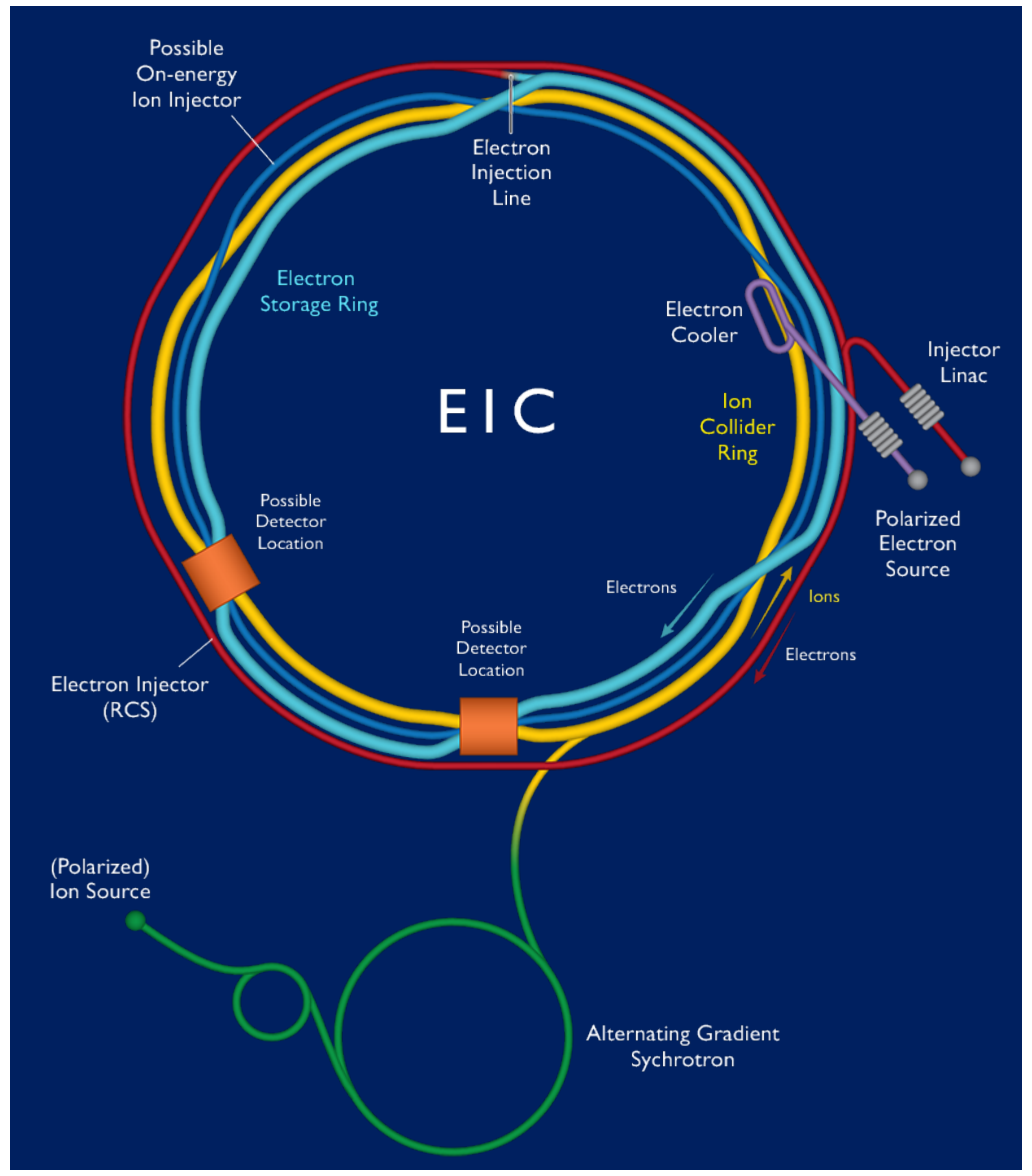
Jefferson Lab

CEBAF: very high luminosity (10^{35}-10^{39} $cm^{-2}s^{-1}$) continuous electron beam on fixed target

4 experimental halls:
- 11GeV in Hall A, B &C
- 12GeV in Hall D

Jefferson Lab is the ideal laboratory to measure J/ψ near threshold,
due to luminosity, resolution and energy reach





Electron-ion Collider

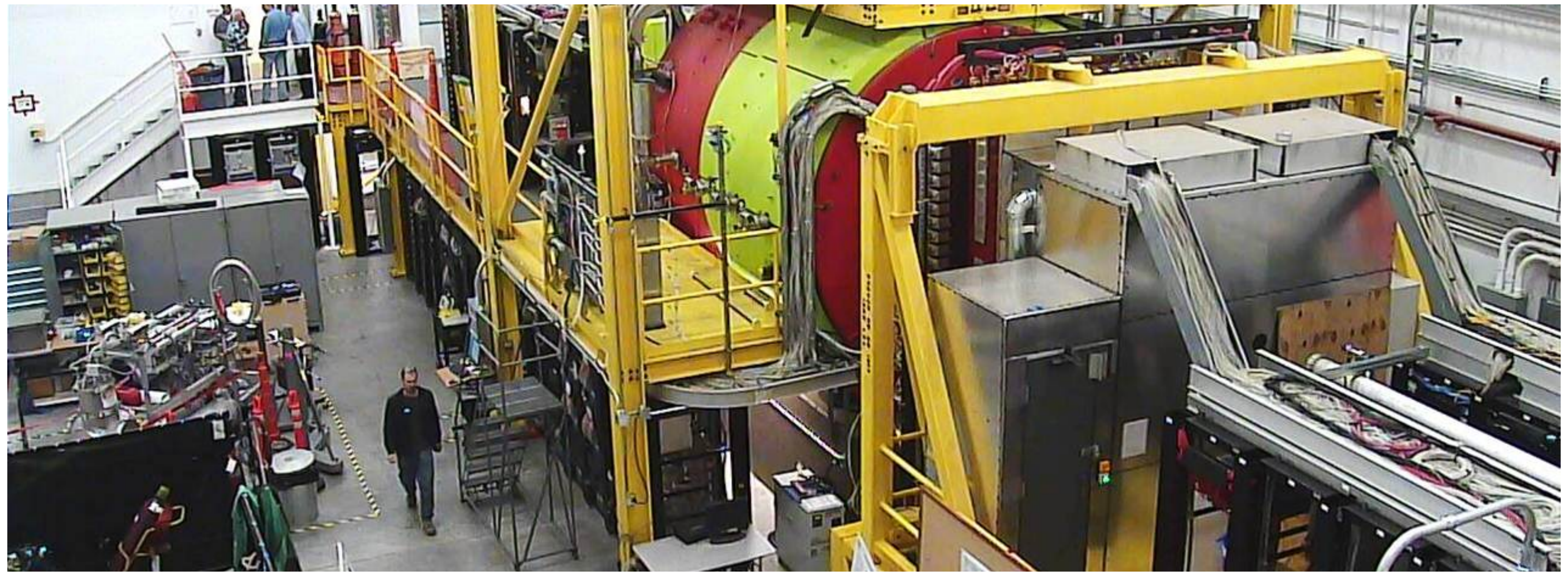
EIC: high luminosity (10^{33}-10^{34} $cm^{-2}s^{-1}$) polarized electron polarized ion collider

Variable CM energies: 29-140 GeV with 2 possible interactions regions

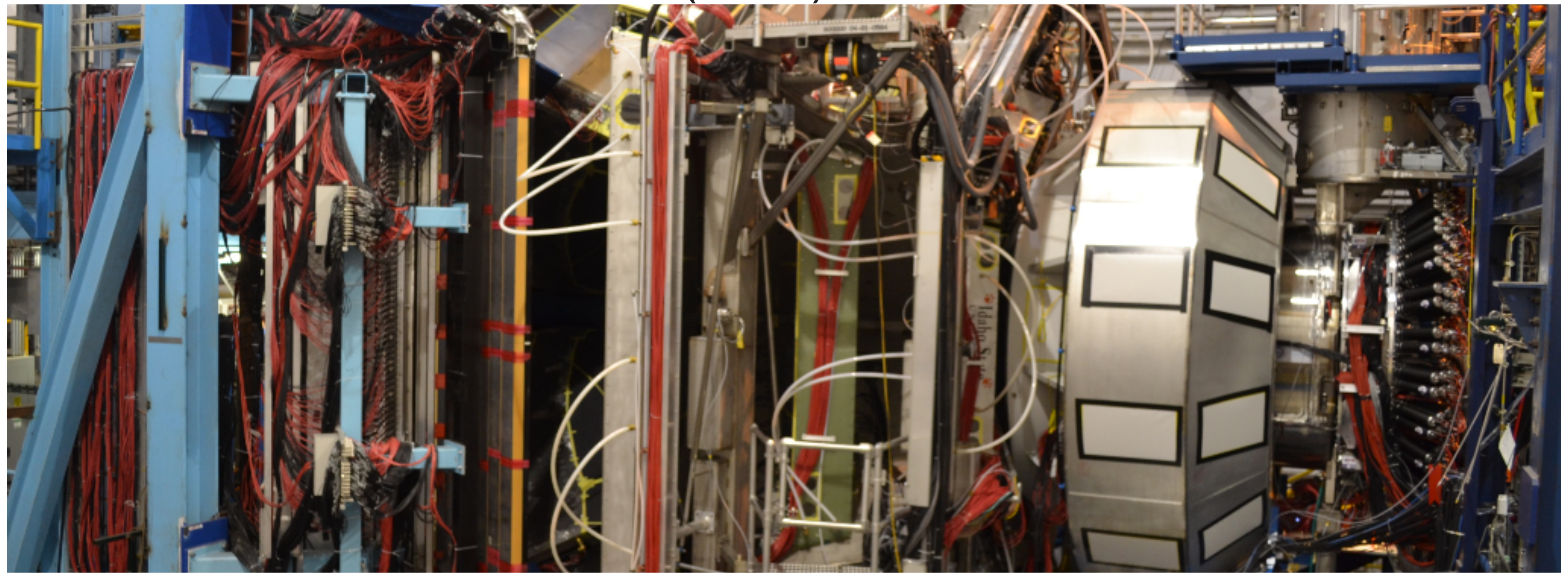
Reach to J/ψ threshold in photo more difficult (in principle feasible at larger Q^2), sufficient energy and luminosity to study Υ near threshold.

Complementary programs: Jefferson Lab is the ideal laboratory to measure J/ψ near threshold, and EIC has sufficient luminosity to measure Υ near threshold

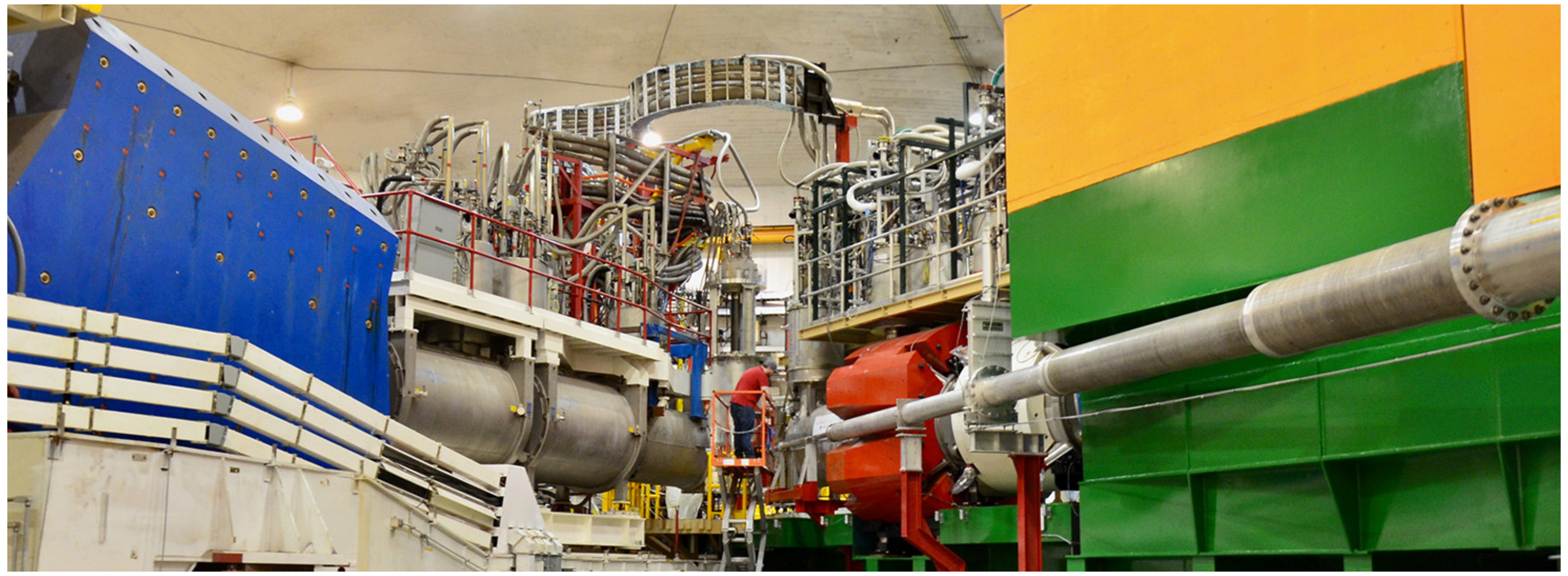
12 GEV J/Ψ EXPERIMENTS AT JEFFERSON LAB



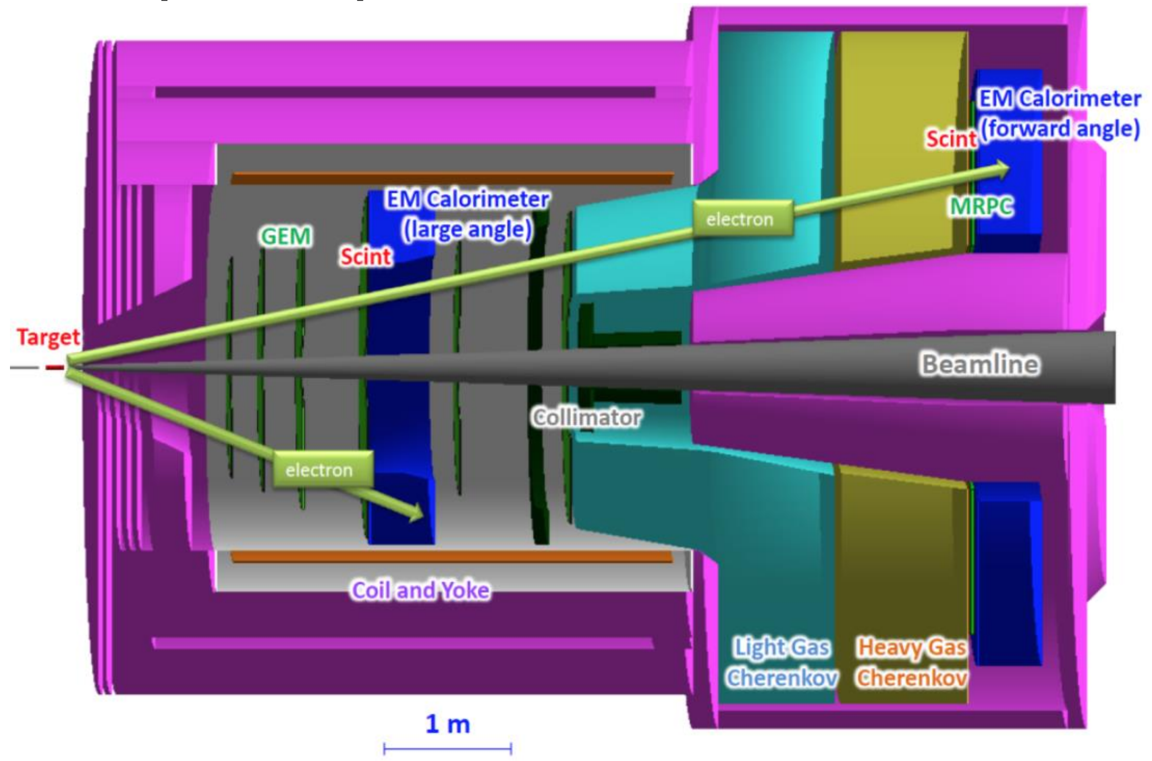
Hall D - GlueX observer the first J/ψ at JLab
A. Ali *et al.*, PRL 123, 072001 (2019)



Hall B - CLAS12 has experiments to measure TCS + J/ψ in photoproduction as part of Run Groups A (hydrogen) and B (deuterium): E12-12-001, E12-12-001A, E12-11-003B



Hall C has the **J/ψ-007** experiment (E12-16-007) to search for the LHCb hidden-charm pentaquark

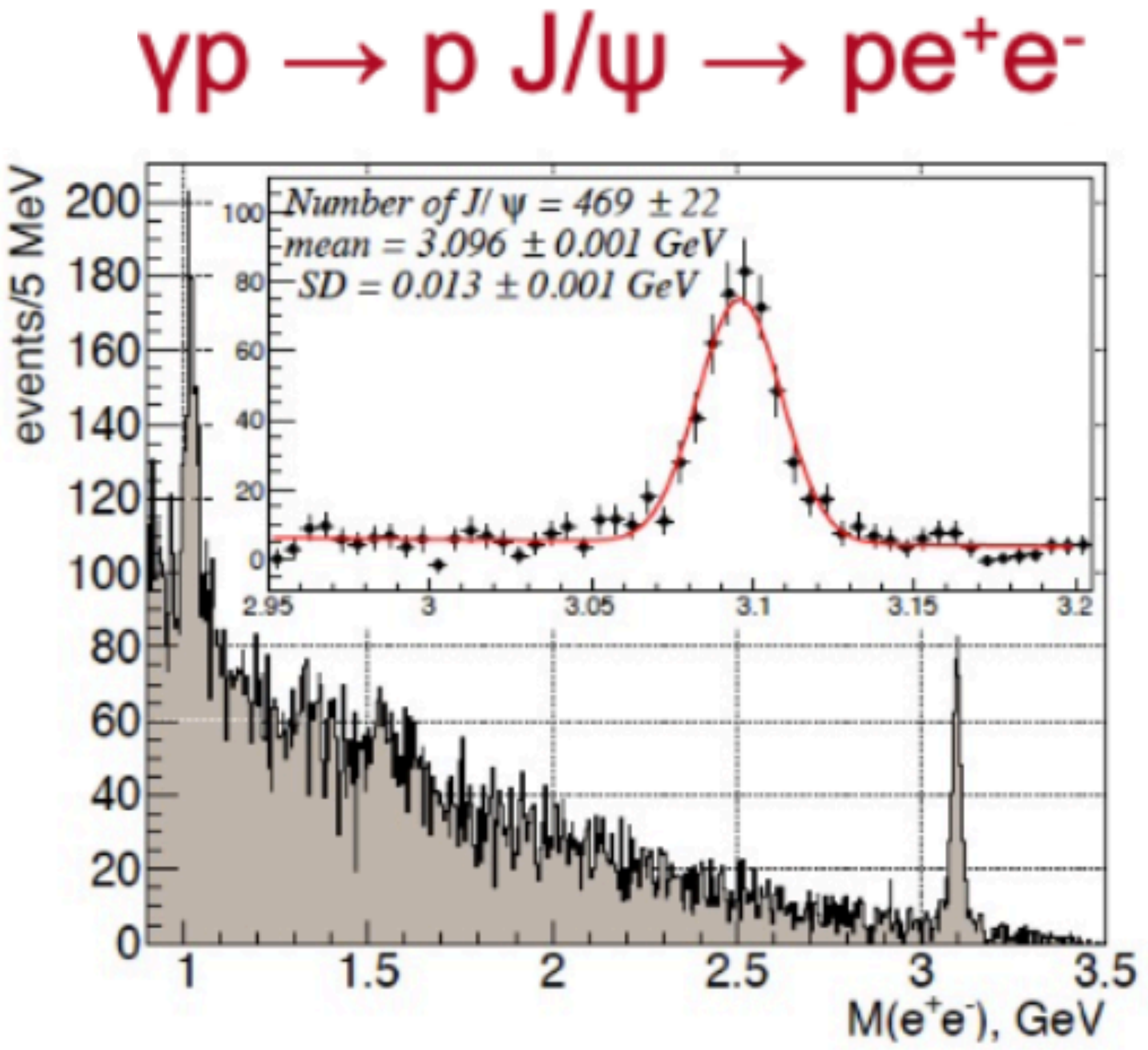


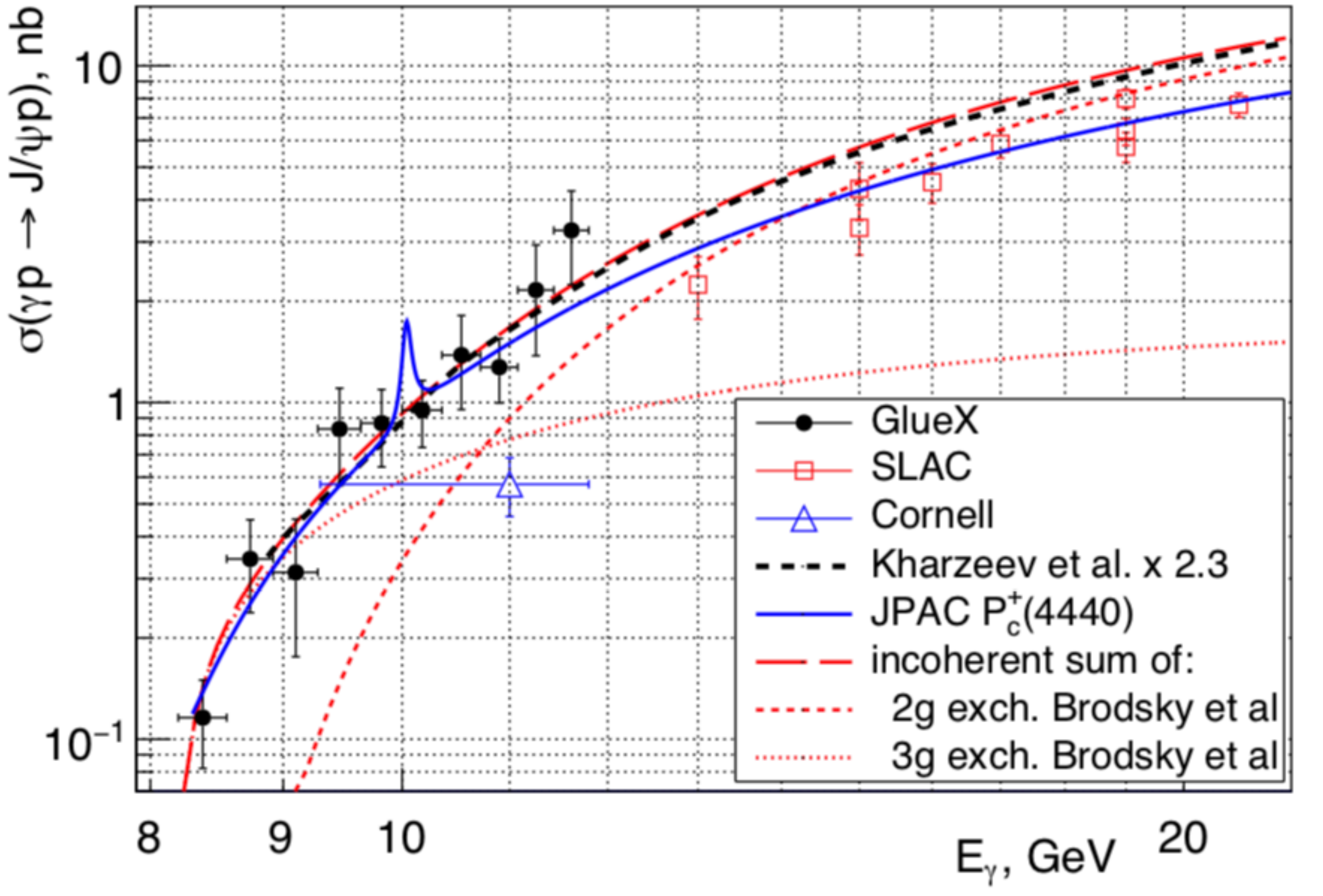
Hall A has experiment E12-12-006 at **SoLID** to measure J/ψ in electro- and photoproduction, and an LOI to measure double polarization using **SBS**

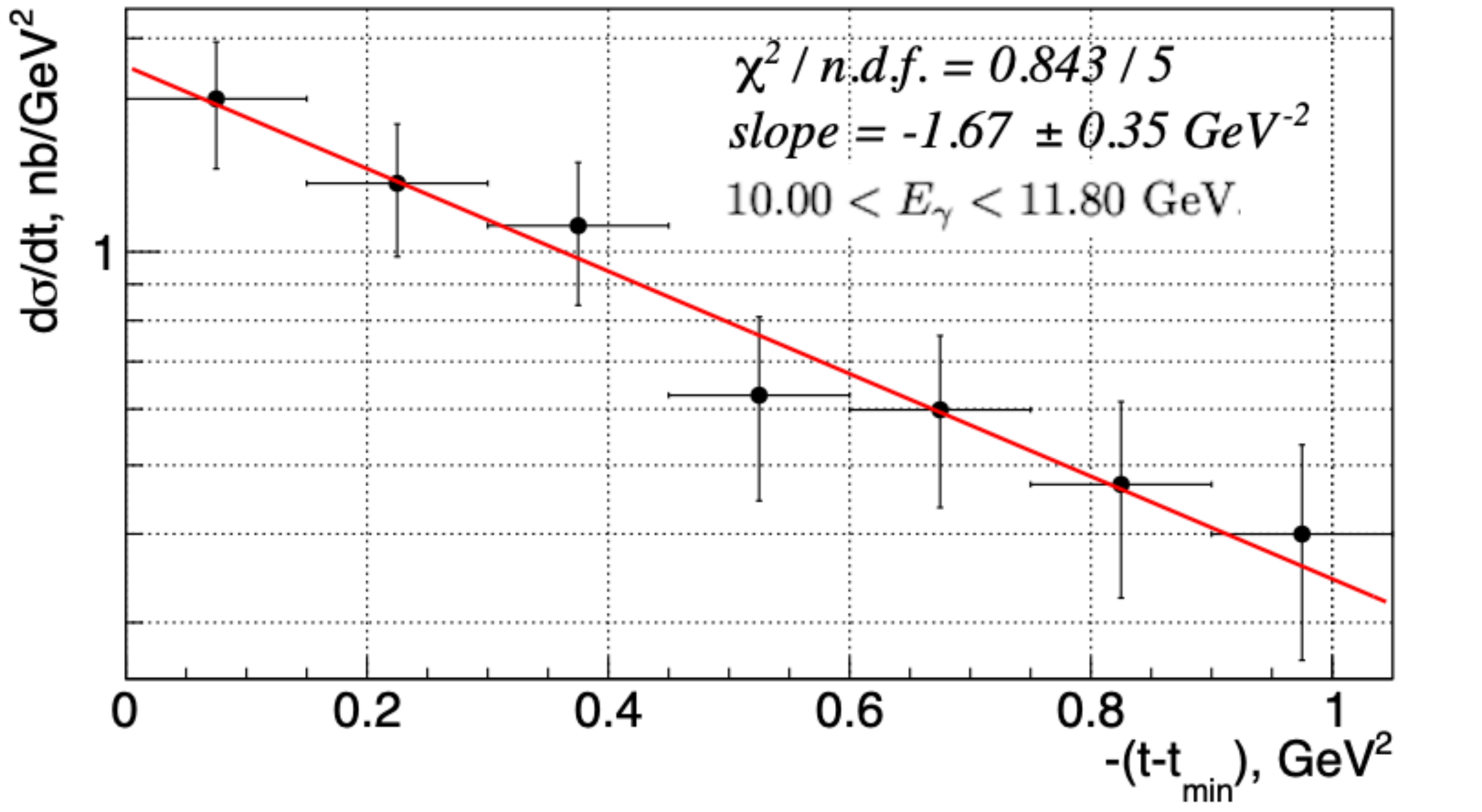
J/Ψ NEAR THRESHOLD IN HALL D

First J/ψ results from JLab, published in PRL 123, 072001 (2019)

- 1D cross section (~469 counts)
- Trends significantly higher than old measurements
- Single 1D t-profile spurred on many new theoretical calculations
- Did not see evidence for hidden-charm pentaquarks





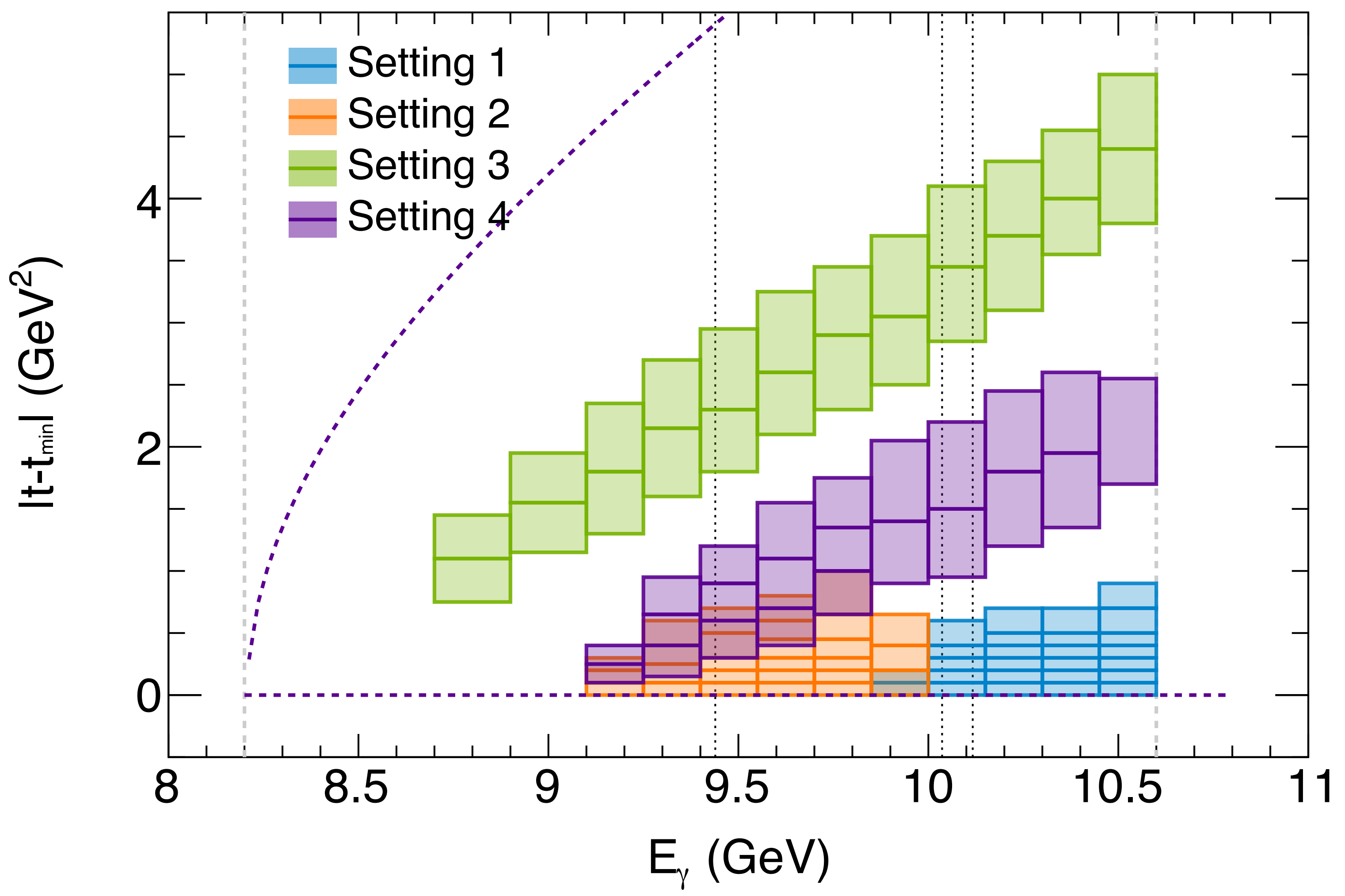


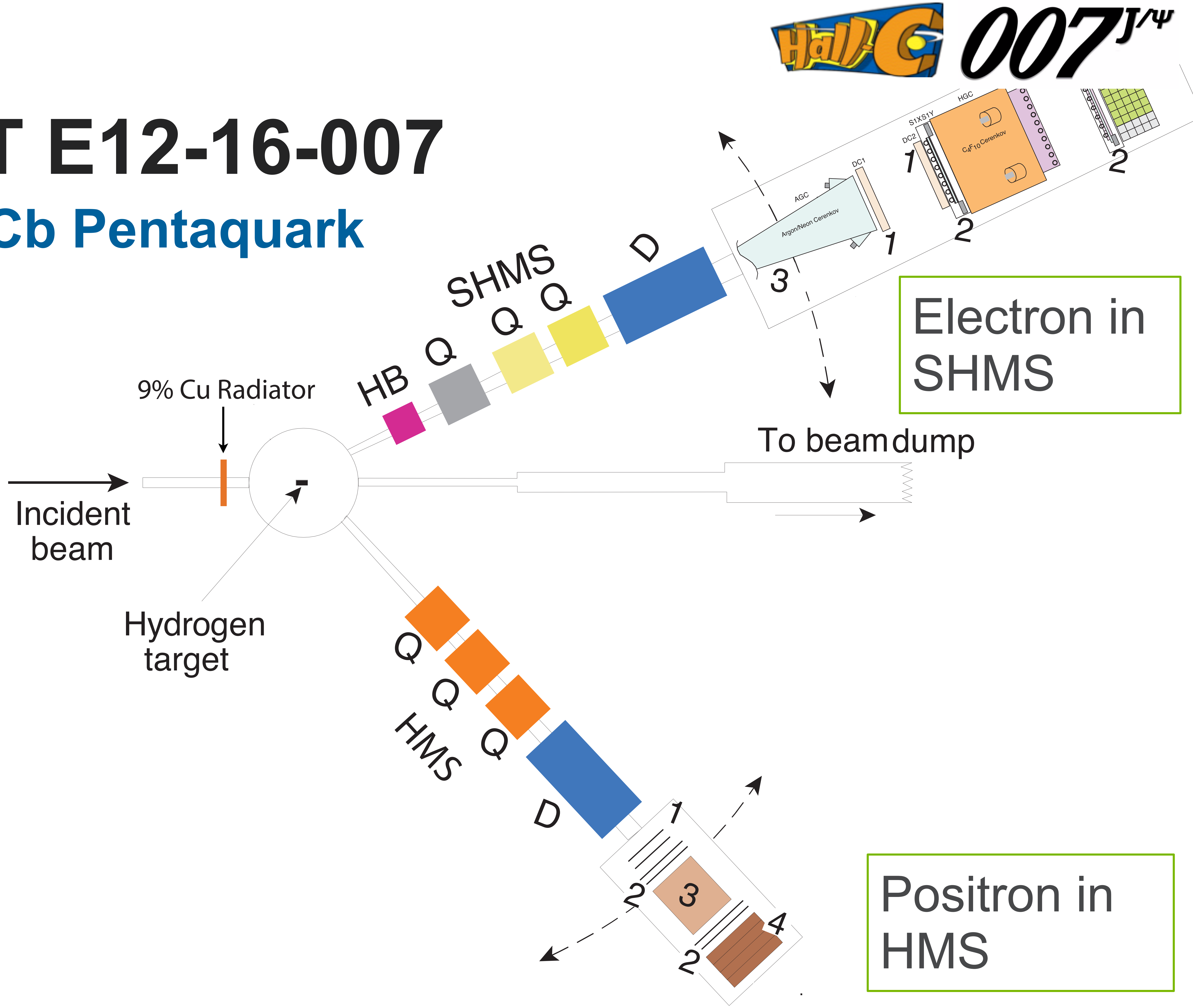
Z.-E. Meziani, S. Joosten *et al.*, arXiv:1609.00676 [hep-ex]
K. Hafidi, S. Joosten *et al.*, Few Body Syst. 58 (2017) no.4, 141

JLAB EXPERIMENT E12-16-007

J/ψ-007: Search for the LHCb Pentaquark

- Ran February 2019 for ~8 PAC days
- High intensity real photon beam (50μA electron beam on a 9% copper radiator)
- 10cm liquid hydrogen target
- Detect J/ψ decay leptons in coincidence
  - Bremsstrahlung photon energy fully constrained

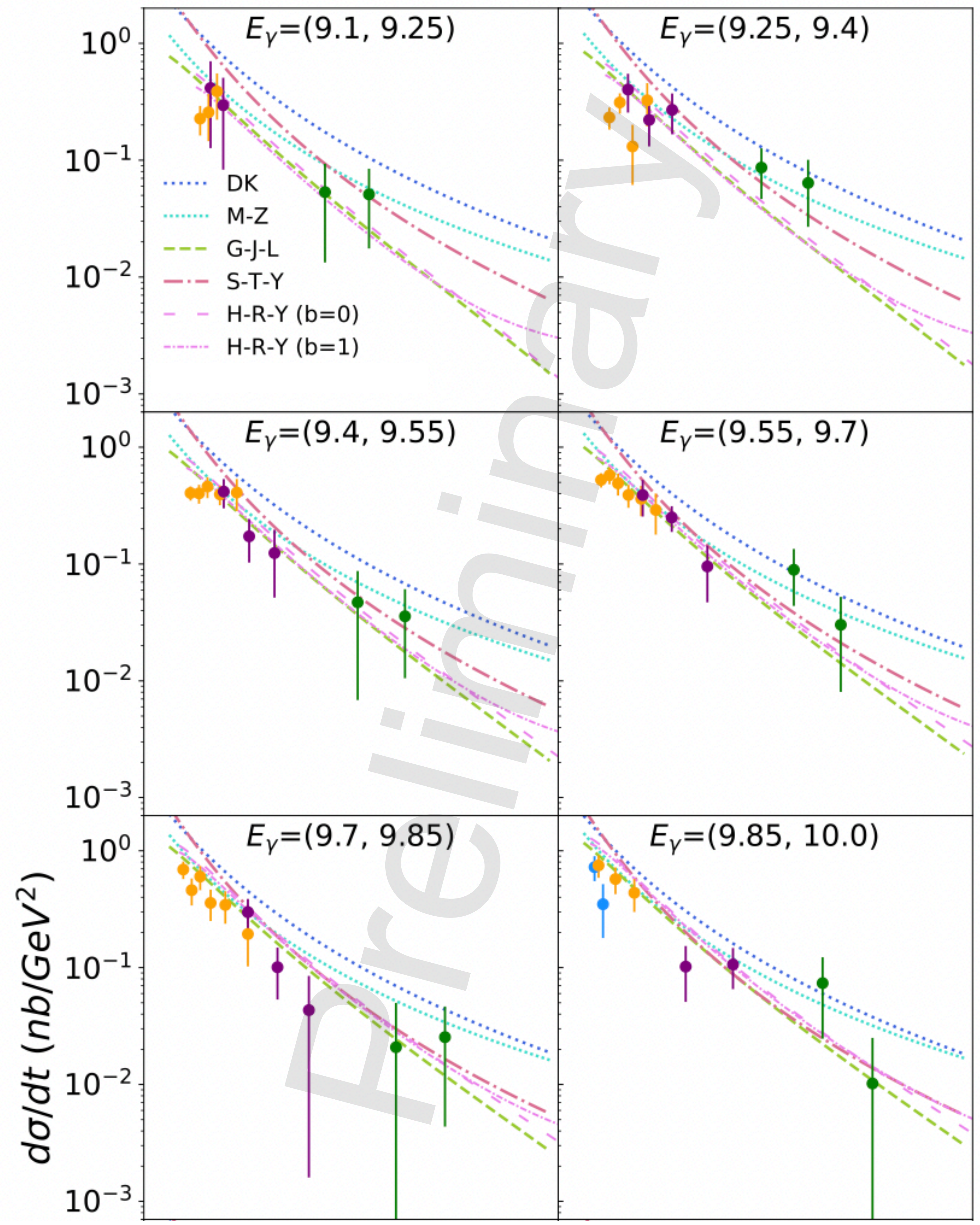


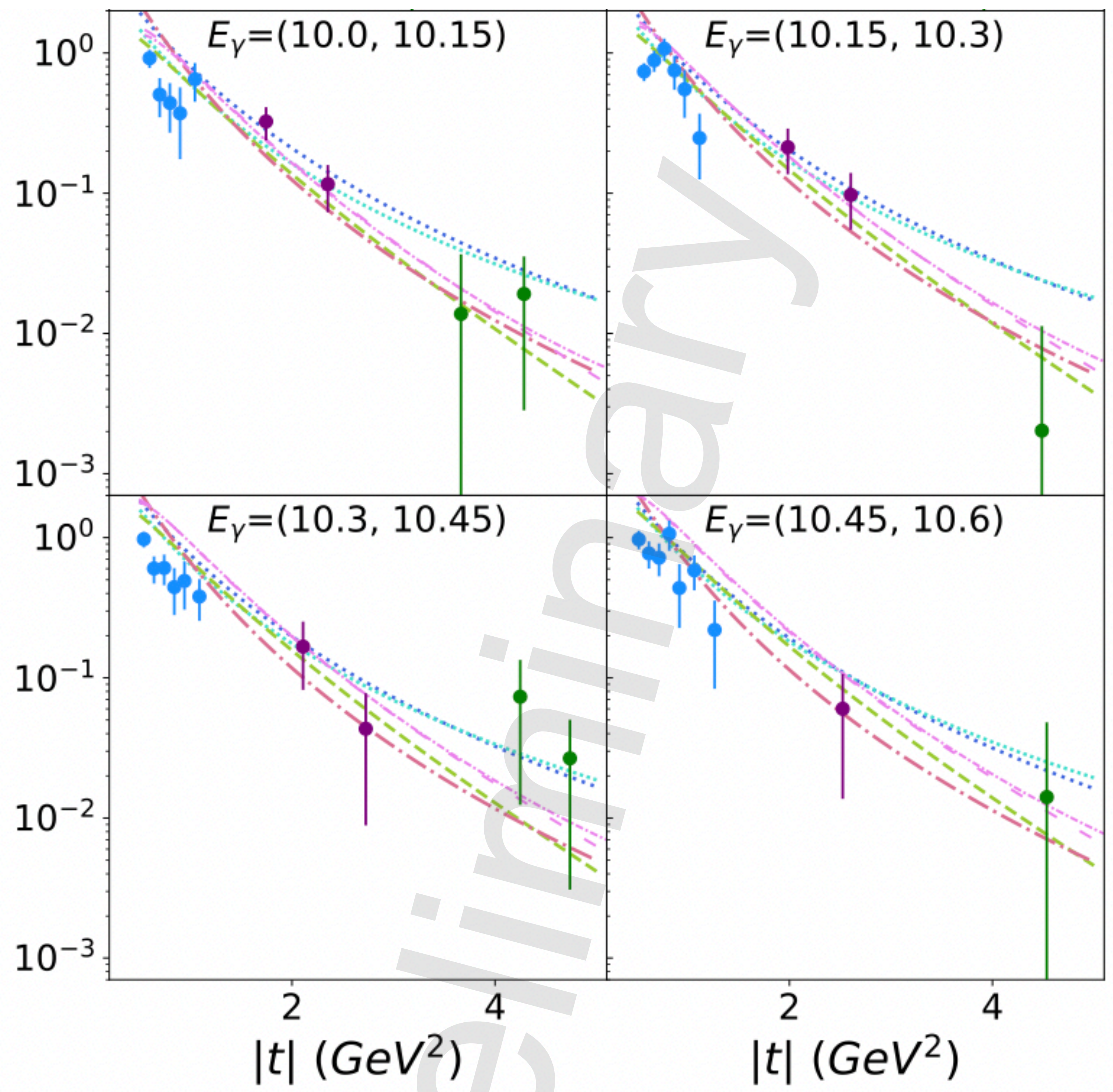


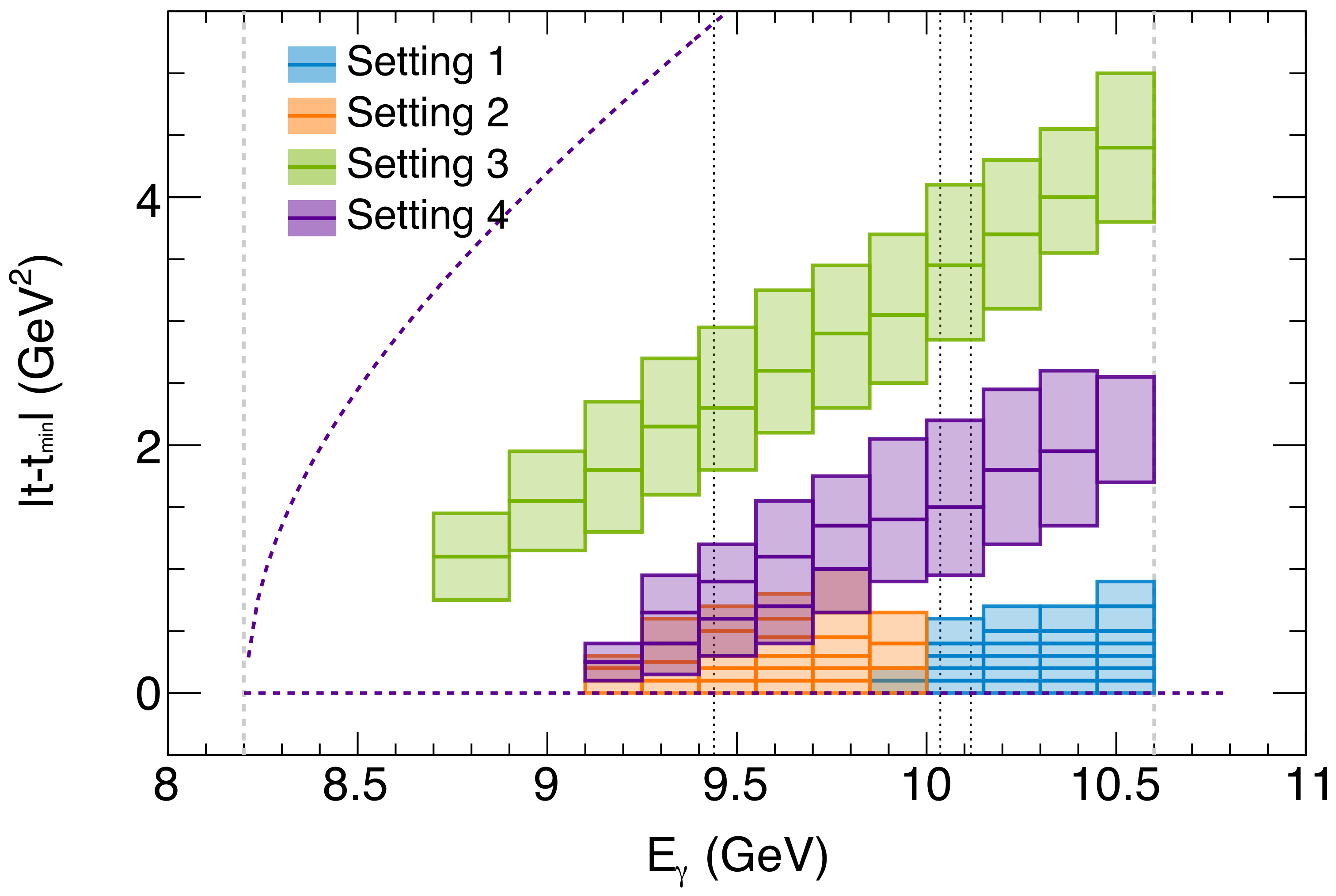
Preprint: https://arxiv.org/abs/2207.05212

Results currently under peer-review

PRELIMINARY 2D J/Ψ CROSS SECTION RESULTS







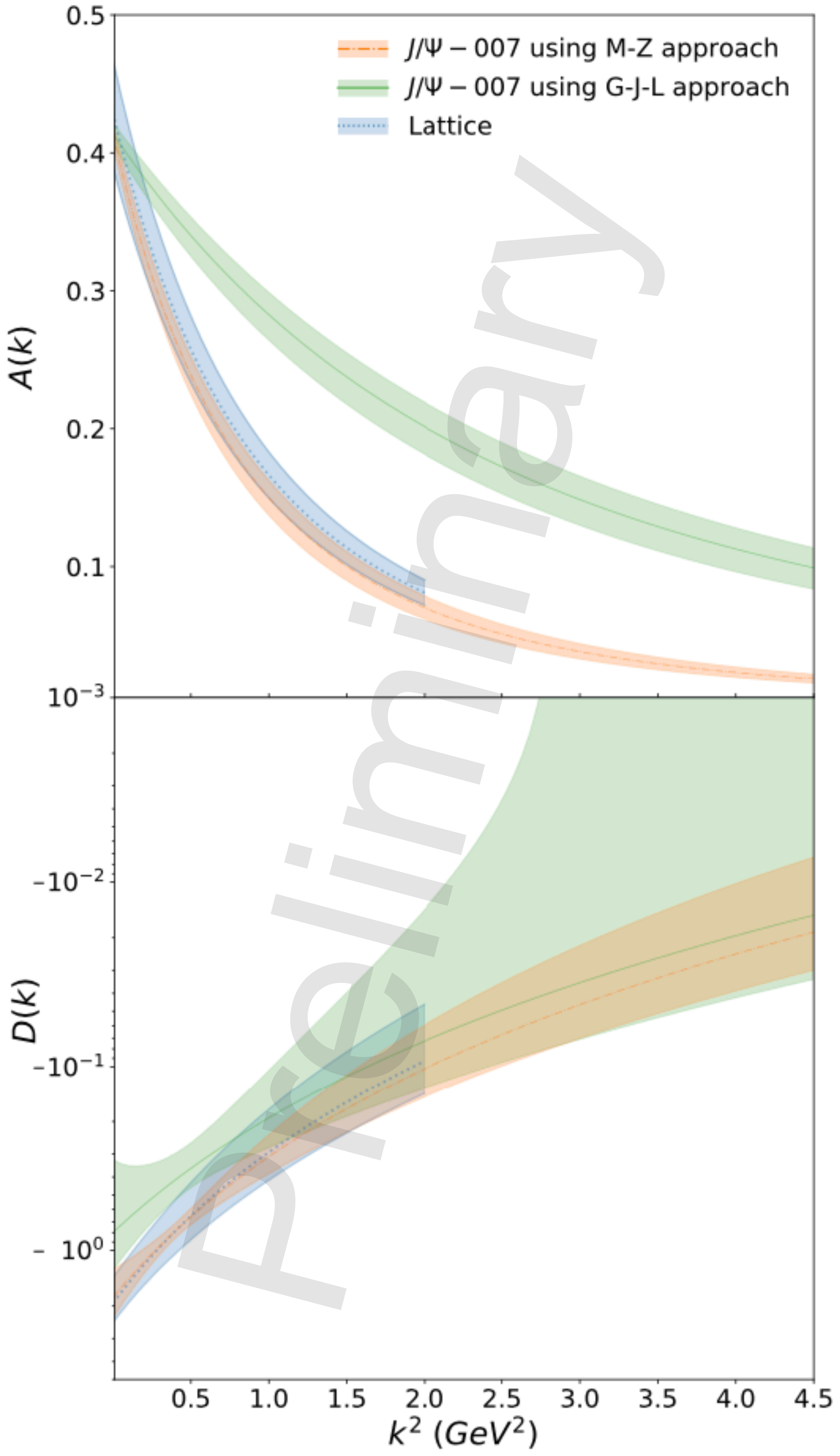
DK: D, Kharzeev, Phys. Rev. D 104, 054015 (2021).
M-Z: Mamo & Zahed, 2204.08857 (2022)
G-J-L: Guo, Ji & Liu, Phys. Rev. D 103, 096010 (2021)
S-T-Y: Sun, Tong & Yuan, Phys. Lett. B 822, 136655 (2021)
H-R-Y: Hatta, Rajan & Yang, Phys. Rev. D 100, 014032 (2019)

- Unfolded 2D cross section results compared to various model predictions informed by the 2019 1D GlueX results
- All models work reasonably well at higher energies but deviate at lower energies

Preprint: https://arxiv.org/abs/2207.05212

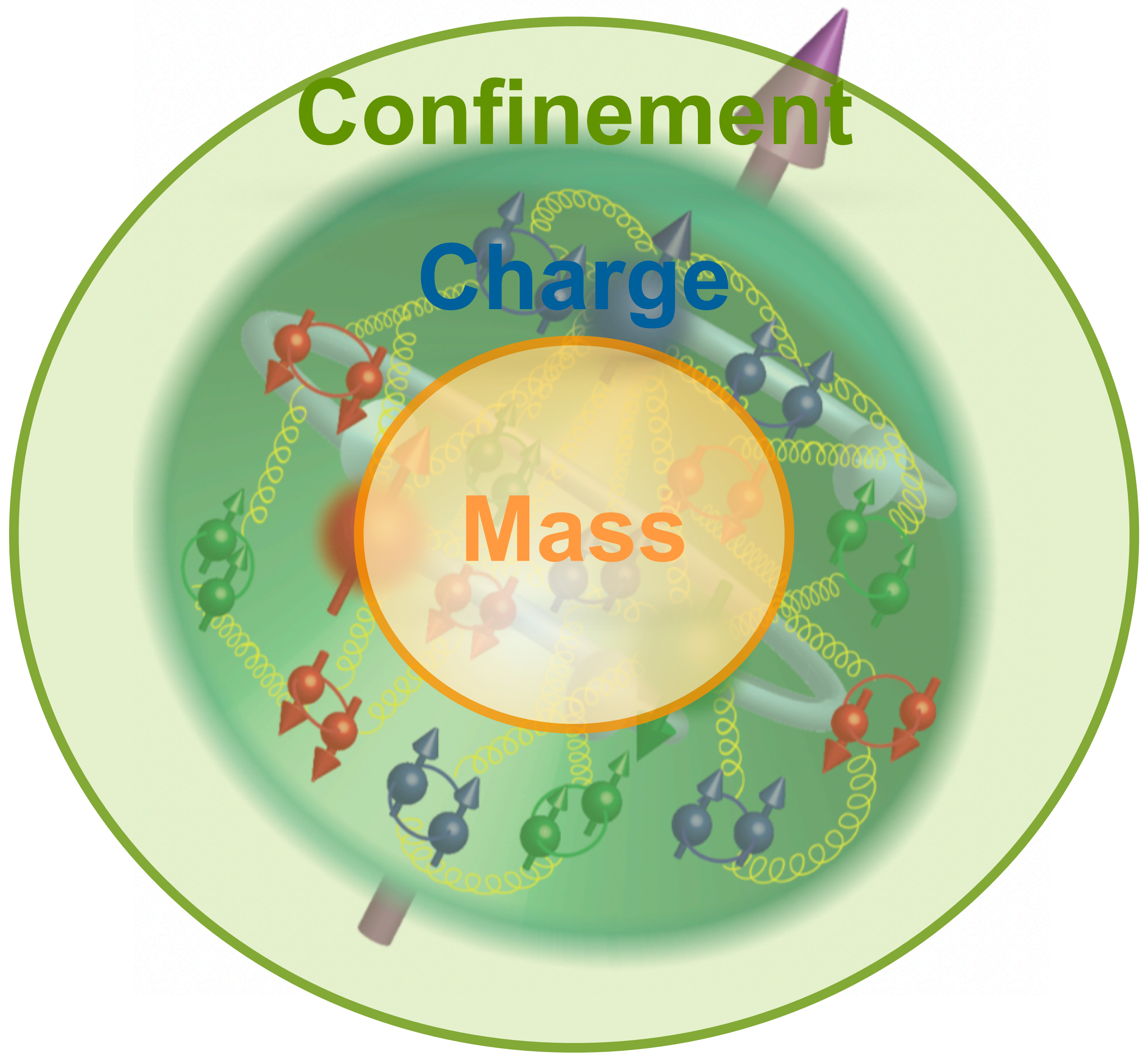
GLUONIC GFF RESULTS

Good agreement between Holographic QCD and Lattice results!



- Results from the 2D gluonic GFF fits
- Gluonic $A_g(t)$ and $D_g(t) = 4C_g(t)$ form factors
- χ^2/n.d.f. in both cases very close to 1
- M-Z (holographic QCD) approach fit to only experimental data gives results very close to the latest lattice results!
- GPD approach gives very different values, may indicate (expected) issues with the factorization assumption

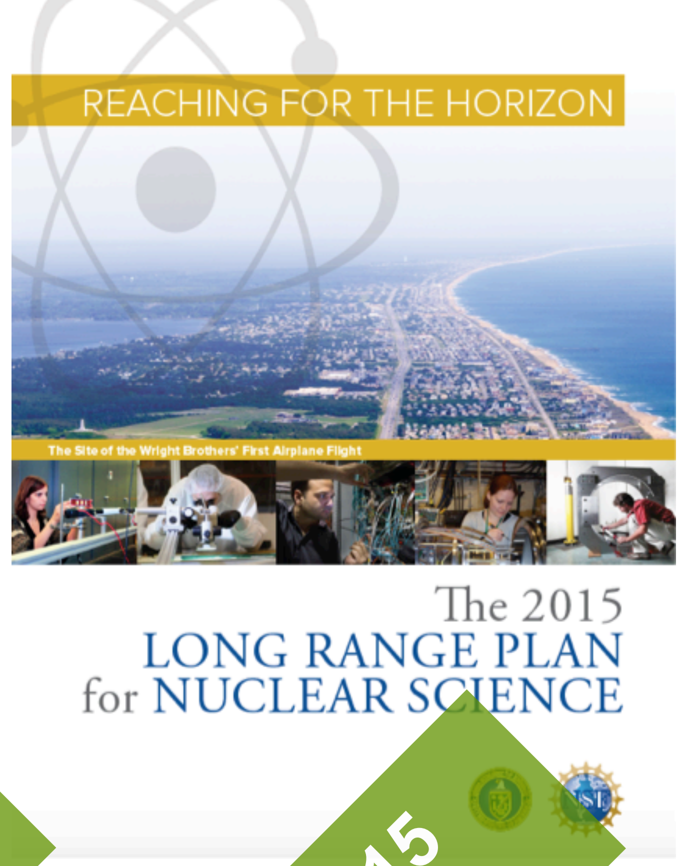
A picture of three zones?

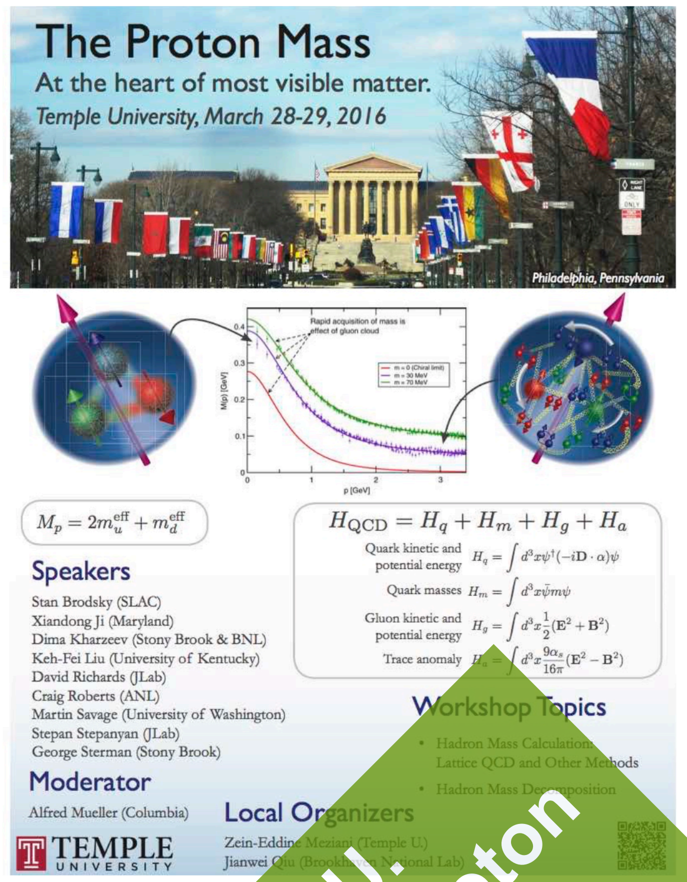


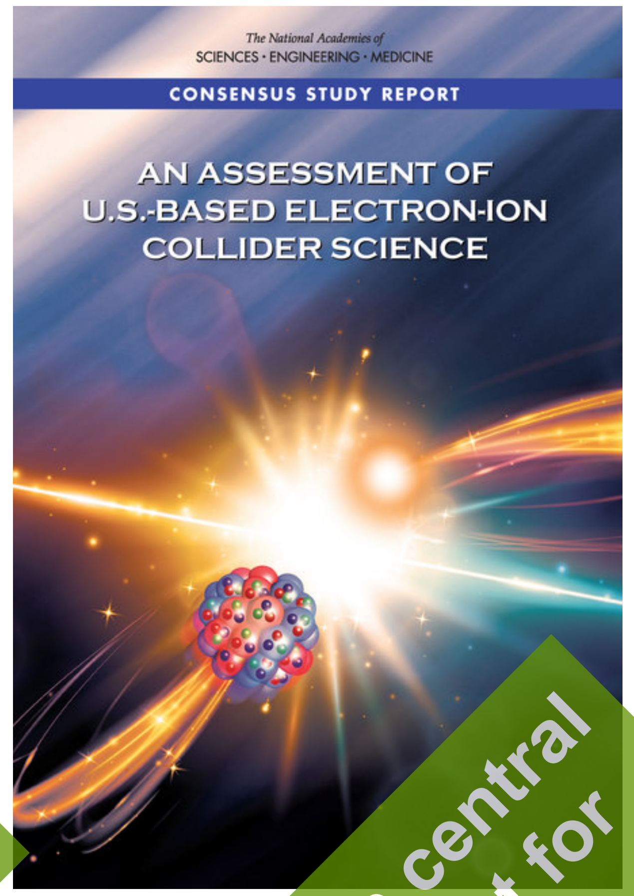
M-Z: K. Mamo & I. Zahed, PRD 103, 094010 (2021) and 2204.08857 (2022)
G-J-L: Y. Guo, X. Ji, Y. Liu, PRD 103, 096010 (2021)
Lattice: D. Pefkou, D, Hackett, P. Shanahan, Phys. Rev. D 105, 054509 (2022).

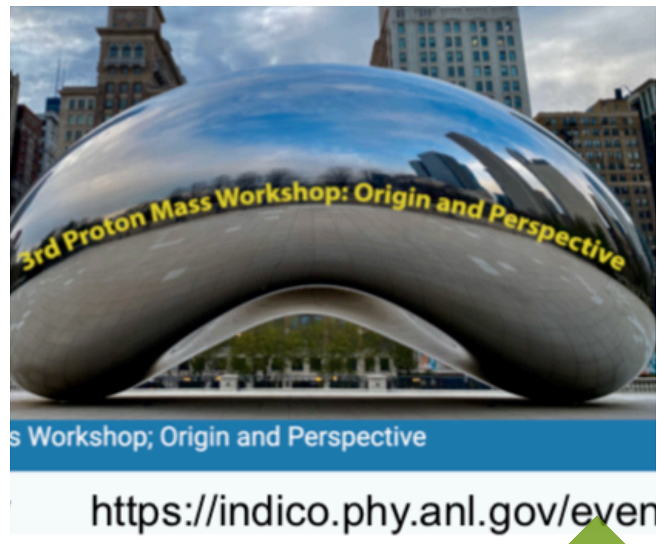
The proton mass: An important topic in contemporary hadronic physics!

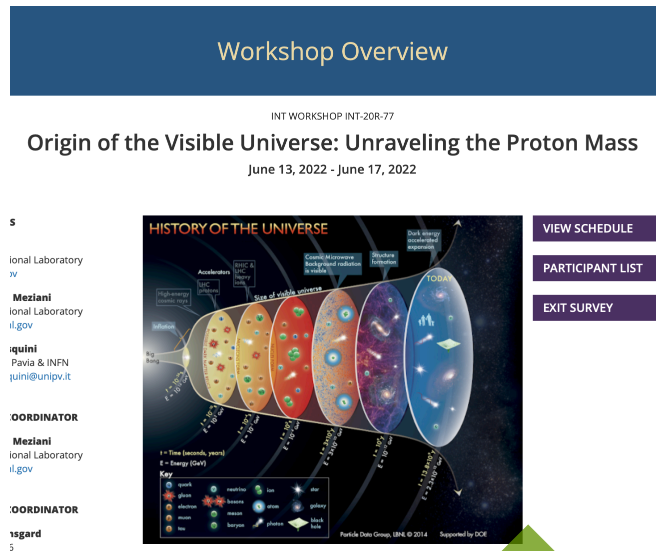
RAPIDLY EVOLVING











- 2012 Temple U. Workshop on heavy quarkonia
- 2015 LHCb finds resonance in J/ψ-p channel consistent with pentaquarks
- Featured in the 2015 Long Range plan
- 2016 Temple U. Workshop on the proton mass
- 2016 Proposal for Hall C Pentaquark search
- 2017 ECT* Workshop on the proton mass
- 2018 Proton mass central in NAS assessment for EIC
- 2019 First GlueX near-threshold J/ψ results
- 2021 Remote Workshop on the proton mass
- 2021 First Hall C results on the pentaquark search
- 2022 INT Workshop on the proton mass
- 2022 First 2D near-threshold J/ψ results from Hall C

➡️ See Tanja Horn's talk on meson structure tomorrow

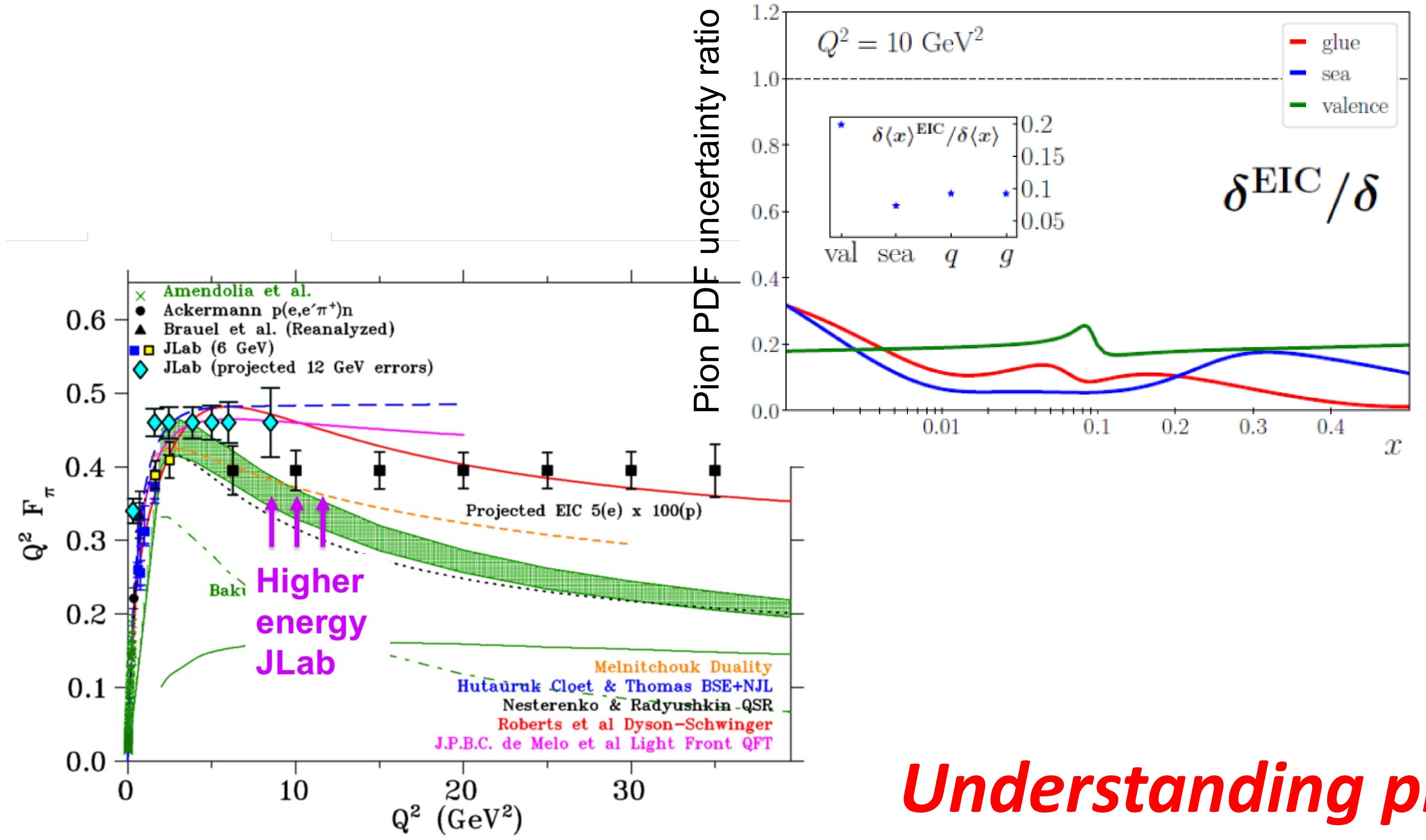
Slide by Tanja Horn and Rolf Ent

Light Meson Structure Programs at JLab and EIC

Beyond protons and neutrons, pions and kaons are the necessary main building blocks of nuclear matter.
If we really want to claim we understand QCD dynamics, we have to understand their structure.

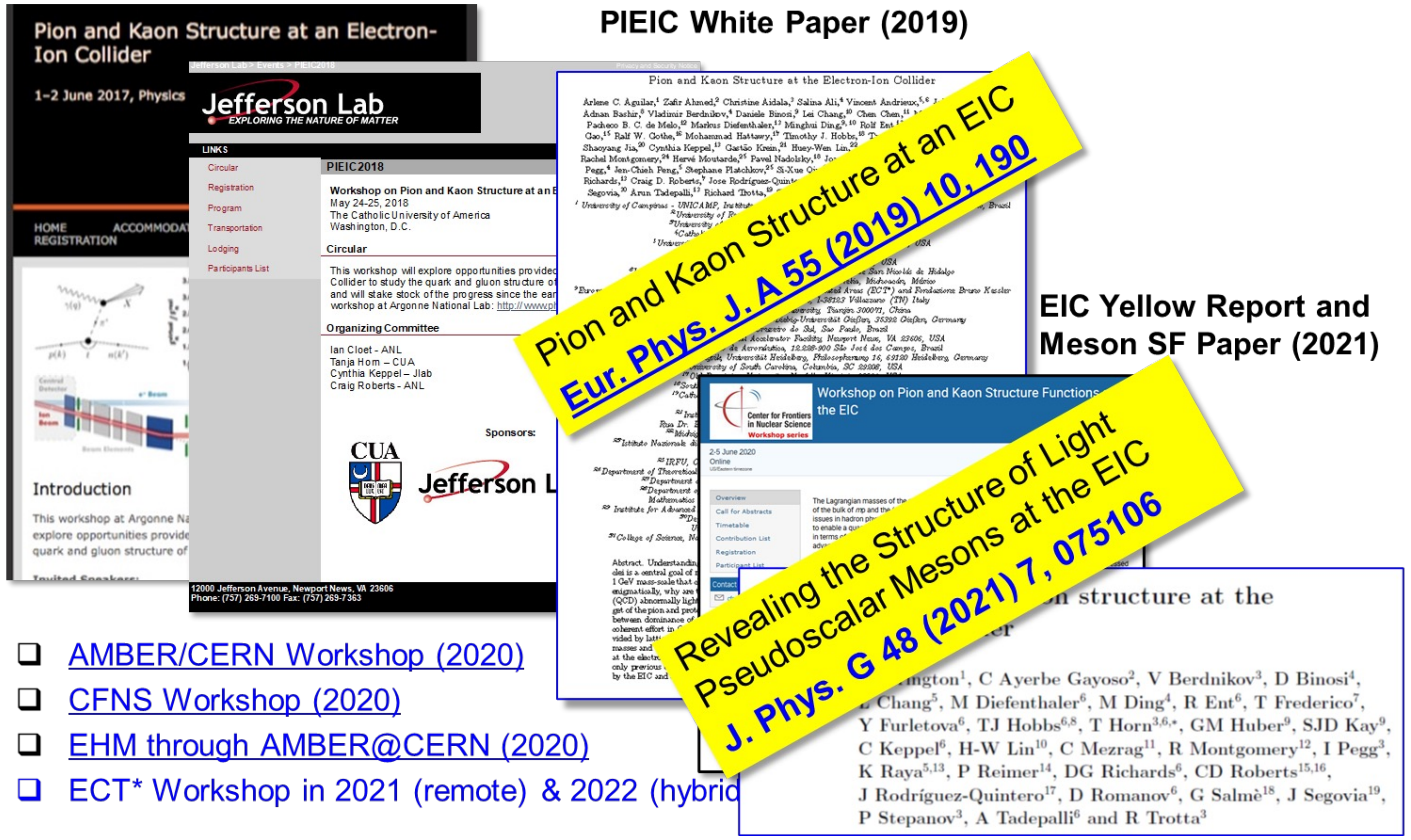
Proton Mass ~ 940 MeV versus Pion Mass ~140 MeV

Paradoxically, the lightest pseudoscalar mesons – the pions and kaons – appear to be key to the further understanding of the emergent mass and structure mechanisms.



Pion and Kaon Structure at the EIC – History

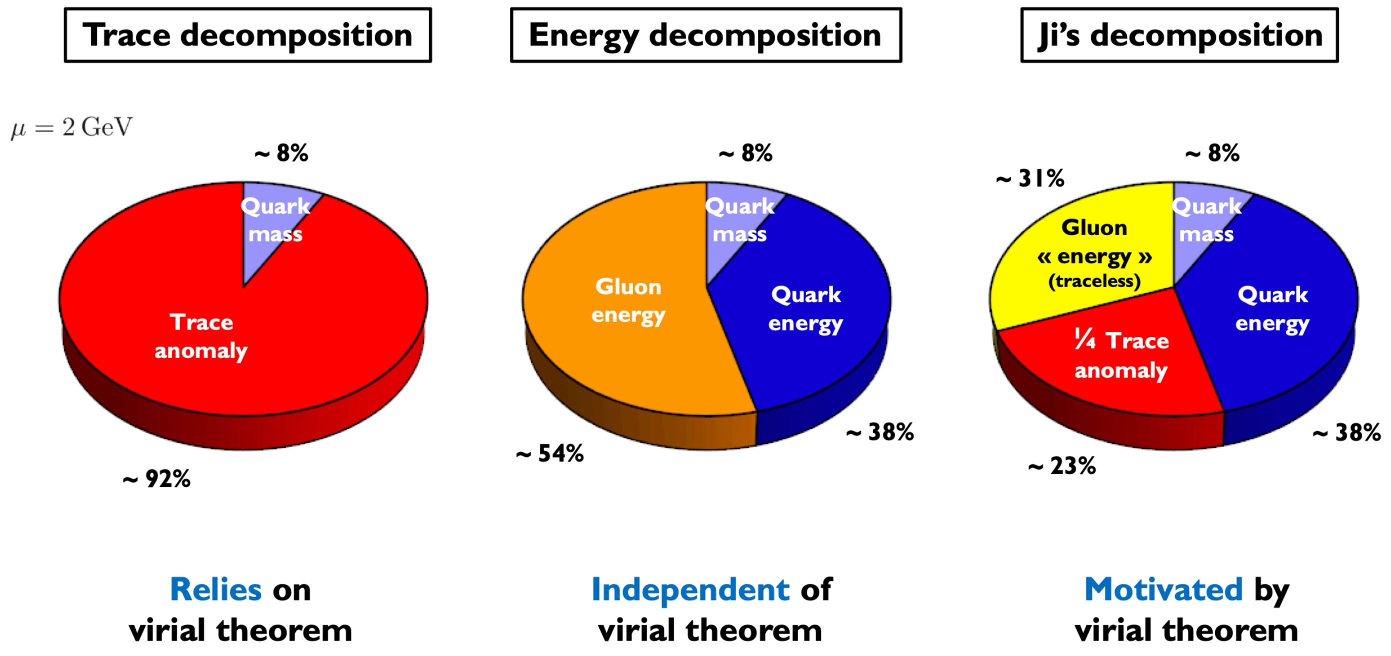
- ❑ PIEIC Workshops hosted at ANL (2017) and CUA (2018)
- ❑ ECT* Workshop: Emergent Mass and its Consequences (2018)



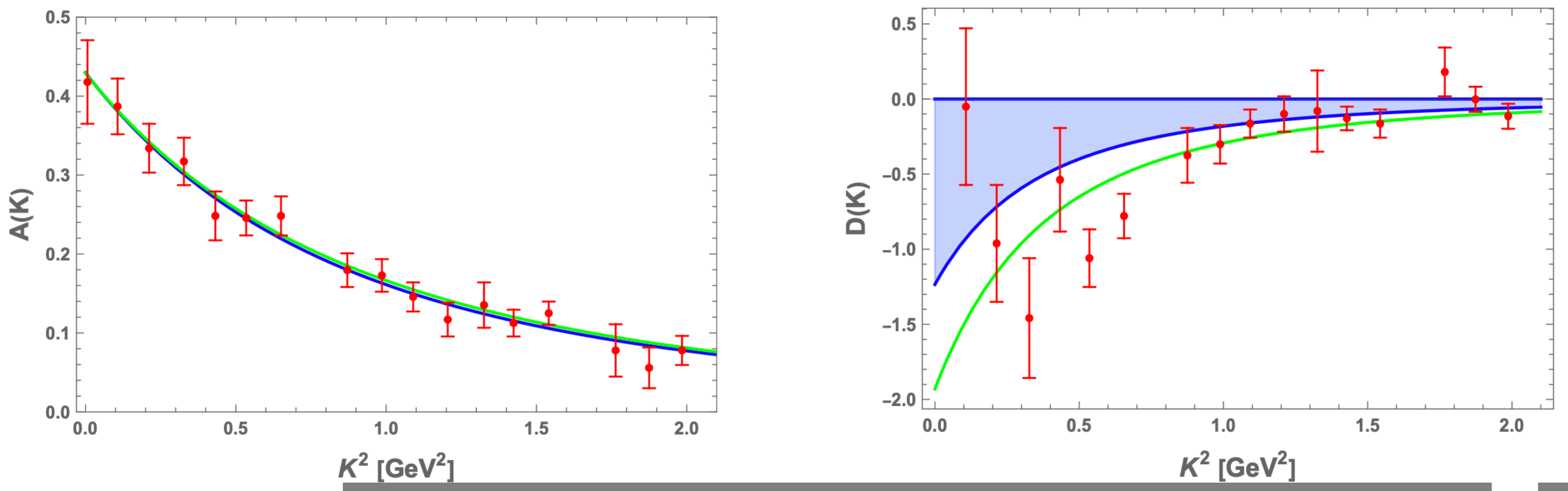
- ❑ AMBER/CERN Workshop (2020)
- ❑ CFNS Workshop (2020)
- ❑ EHM through AMBER@CERN (2020)
- ❑ ECT* Workshop in 2021 (remote) & 2022 (hybrid)

Understanding pion/kaon is vital to our understanding of hadron structure and dynamic generation of hadron mass

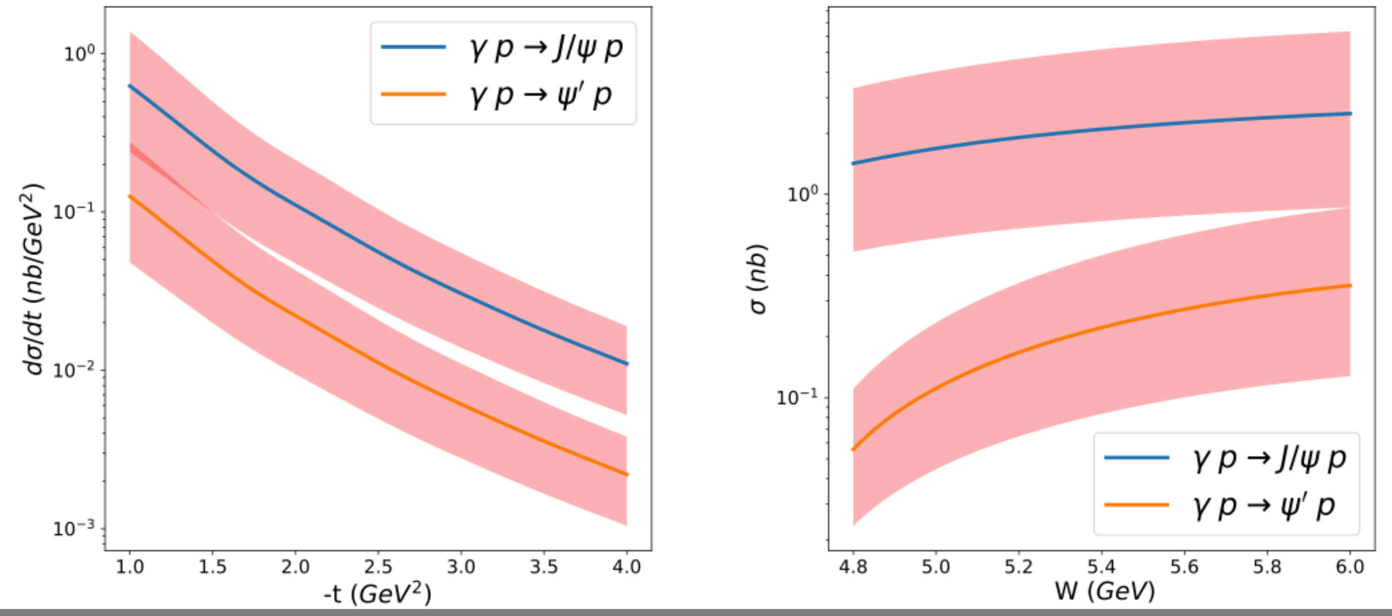
PROMINENT RECENT DEVELOPMENTS



Proton mass budget decompositions, C. Lorce (from 2022 INT workshop)

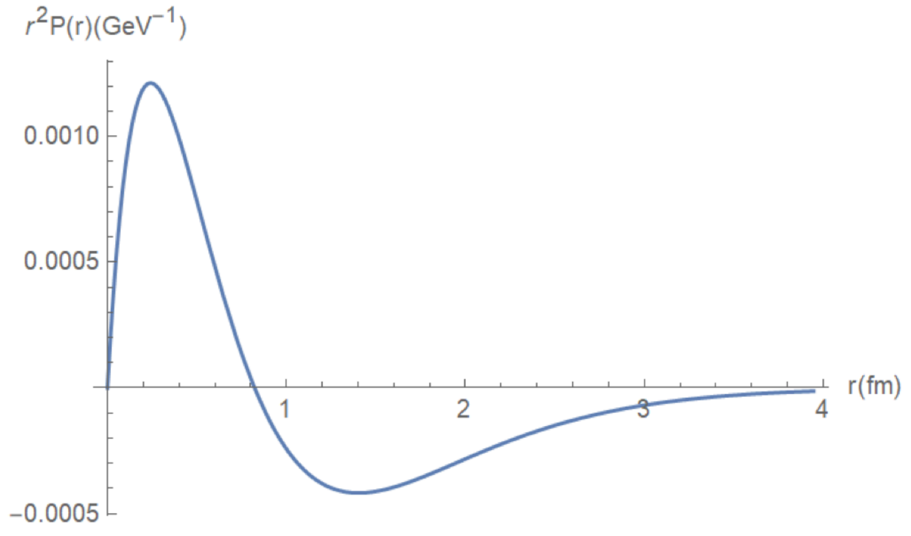


Proton gravitational form factors holographic QCD compared with Lattice, K. Mamo & I. Zahed (2022)

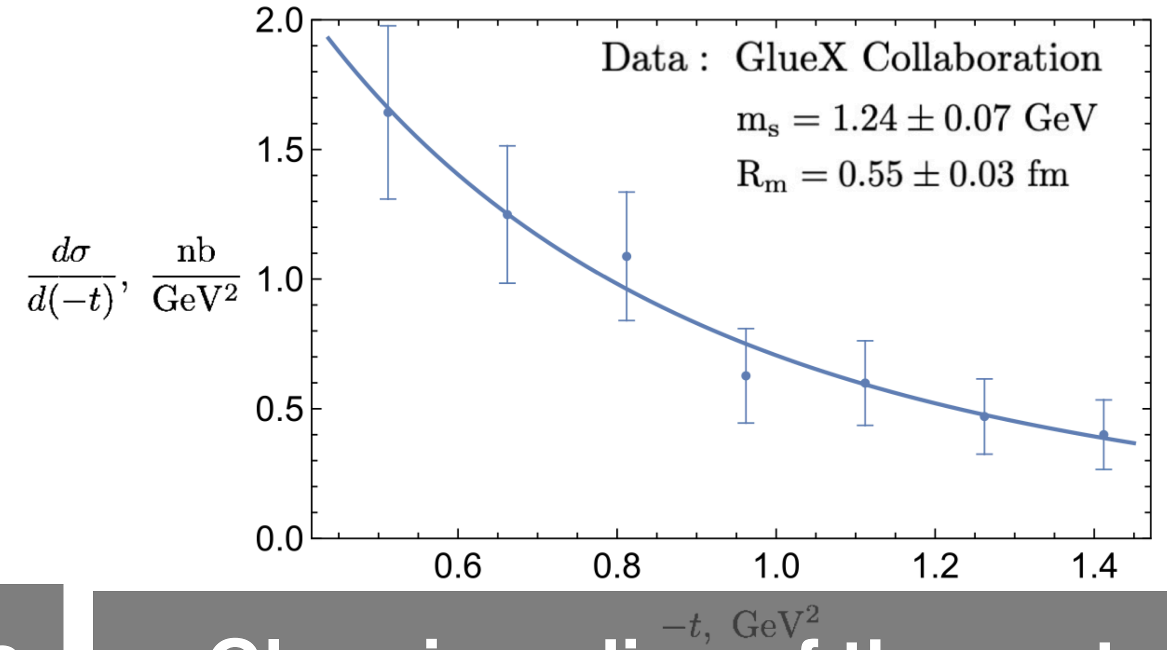


Near-threshold heavy quarkonium production at large momentum transfer, P. Sun, X-B. Tong, F. Yuan (PRD 2022)

- A hot topic: many theoretical developments, and pace of publications only speeding up!
- Many extractions depend on extrapolating to the forward limit (t=0), which introduces theoretical systematic uncertainties. Precise high-t as a function photon energy crucial.
- Other avenues for factorization include large-t region, large Q^2 region, or larger vector meson mass.



Gluon contribution to pressure in GPD formalism, Y. Guo, X. Ji, Y. Liu, (PRD 2021)

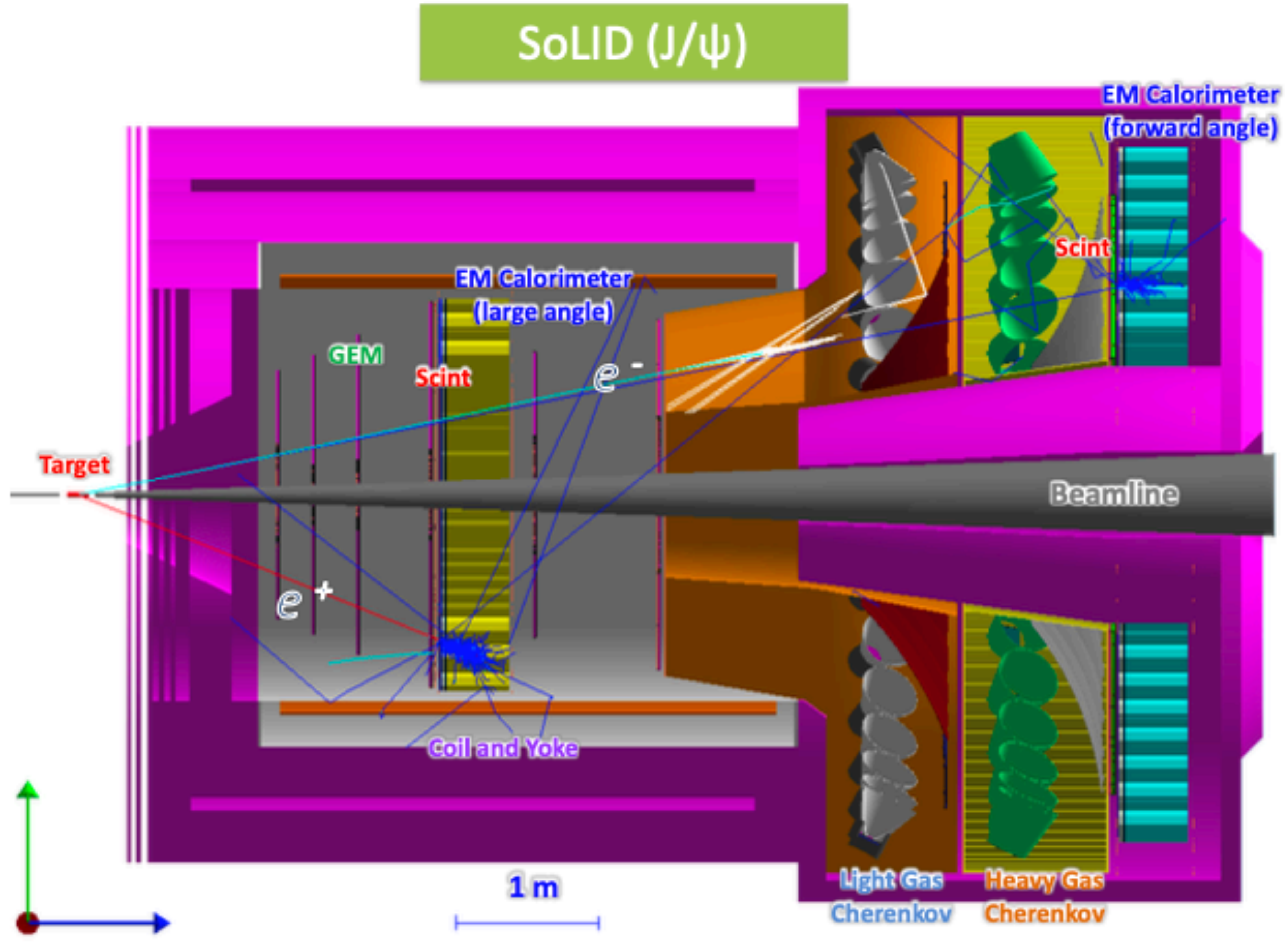


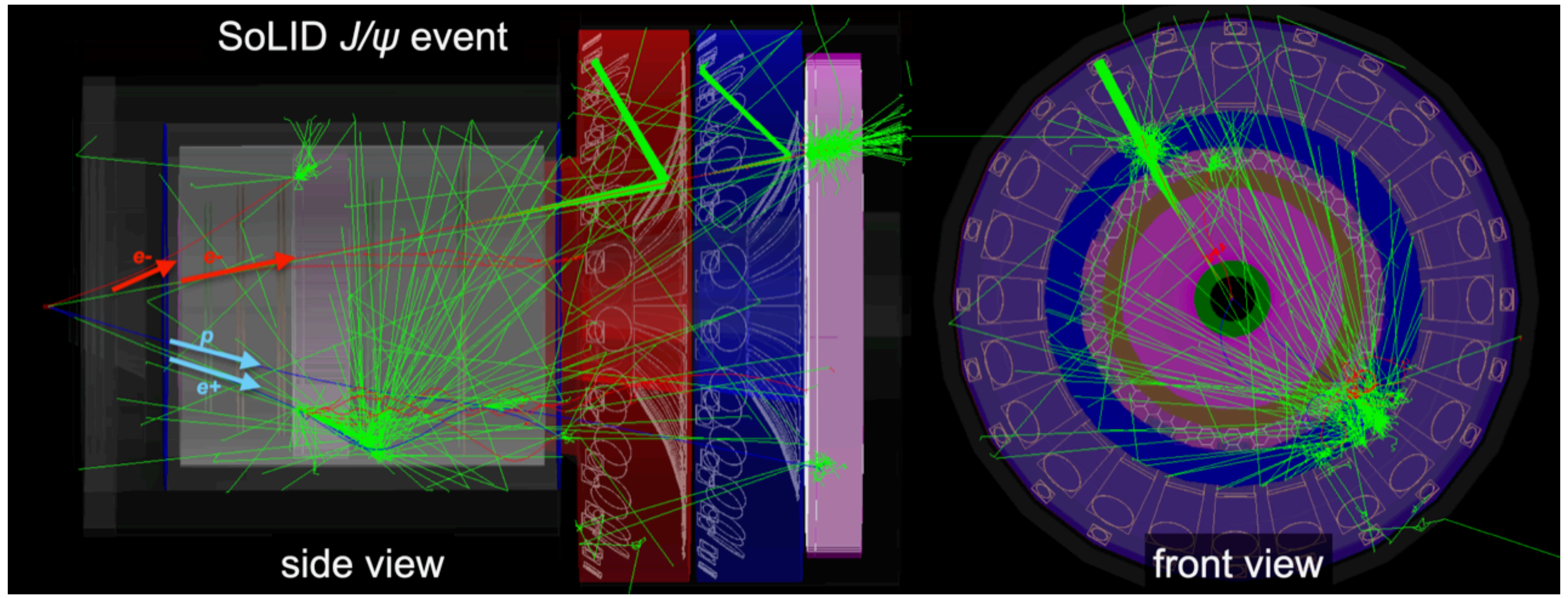
Gluonic radius of the proton based on 1D GlueX results, D. Kharzeev (PRD 2021)

THE SOLID-J/Ψ EXPERIMENT

Ultimate factory for near-threshold J/ψ

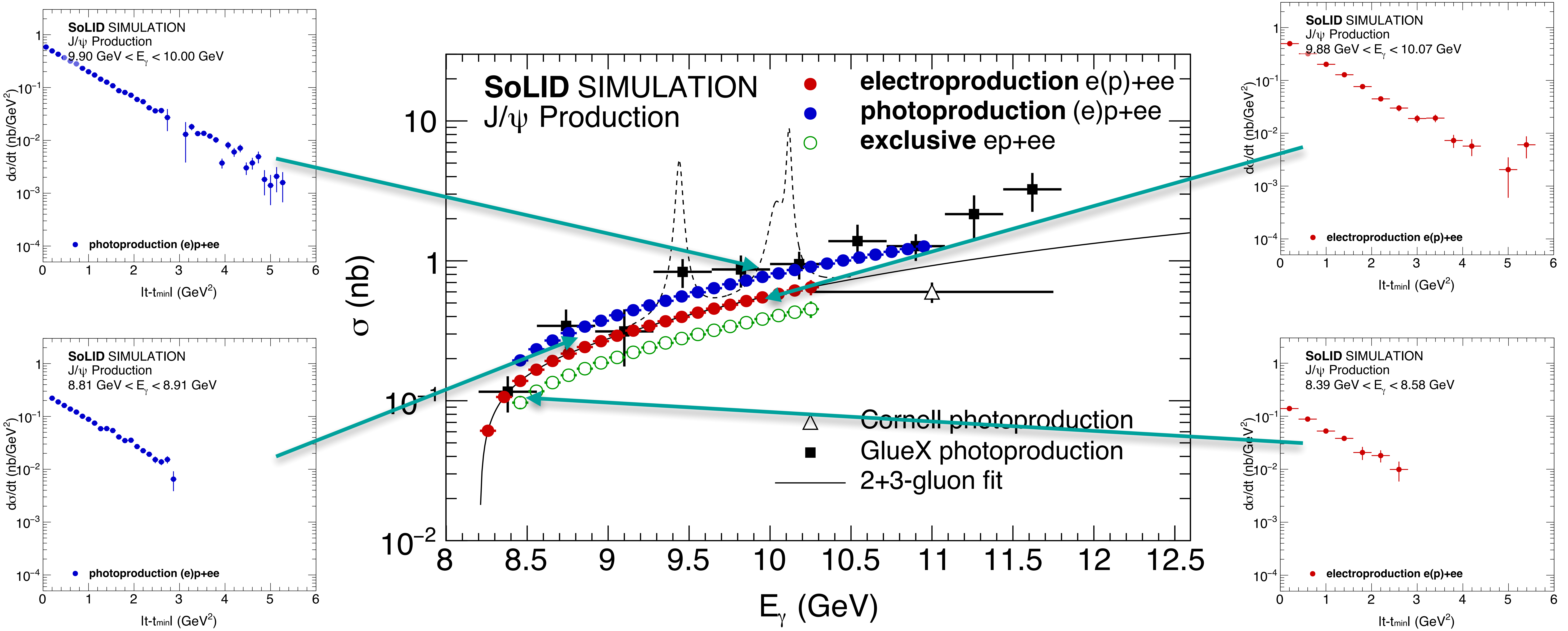
- General purpose large-acceptance spectrometer
- 50+10 days of 3μA beam on a 15cm long LH2 target (10^{37}/cm^2/s)
- **Ultra-high luminosity**: 43.2ab^{-1}
- **Open 2-particle trigger,** covering J/ψ production in four channels: Electroproduction (e,e$^-$e$^+$), photoproduction (p,e$^-$e$^+$), inclusive (e$^-$e$^+$), exclusive (ep,e$^-$e$^+$)
- The electoproduction channel provides for a modest lever-arm in Q^2 near threshold





SOLID-J/Ψ PROJECTIONS

Precision at high t crucial for extrapolations to the forward limit (exponential, dipole, triple, …)



J/Ψ EXPERIMENTS AT JLAB COMPARED

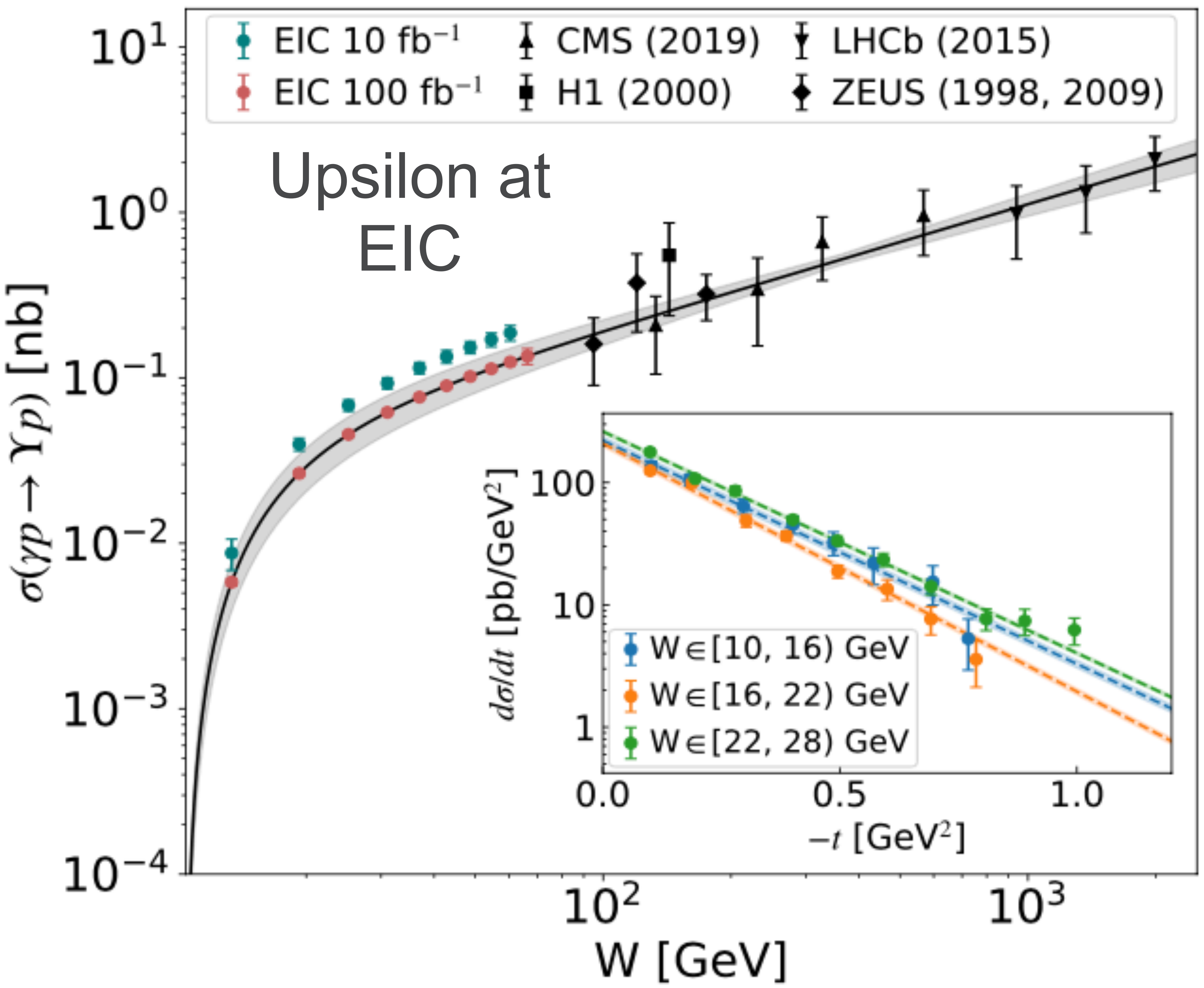
	GlueX HALL D	HMS+SHMS HALL C	CLAS 12 with upgrade[1] HALL B	SoLID HALL A
J/ψ counts (photo-prod.)	**469 published ~10k phase I + II**	**2k electron channel 2k muon channel**	**14k**	**804k**
J/ψ Rate (electro-prod.)	**N/A**	**N/A**	**1k**	**21k**
Features	Good reach to threshold. No high-t reach.	Can reach high-t only at higher energies. Low statistics.	No high-t reach. Electroproduction low statistics.	Enough luminosity to reach high t. High precision.
When?	Finished/Ongoing	Finished	Ongoing/Proposed	Future

[1]The CLAS12 projected count rates assume the proposed CLAS12 luminosity upgrade to $2x10^{35}/cm^2/s$

COMPLEMENTARITY WITH EIC

J/ψ at SoLID and Υ at EPIC

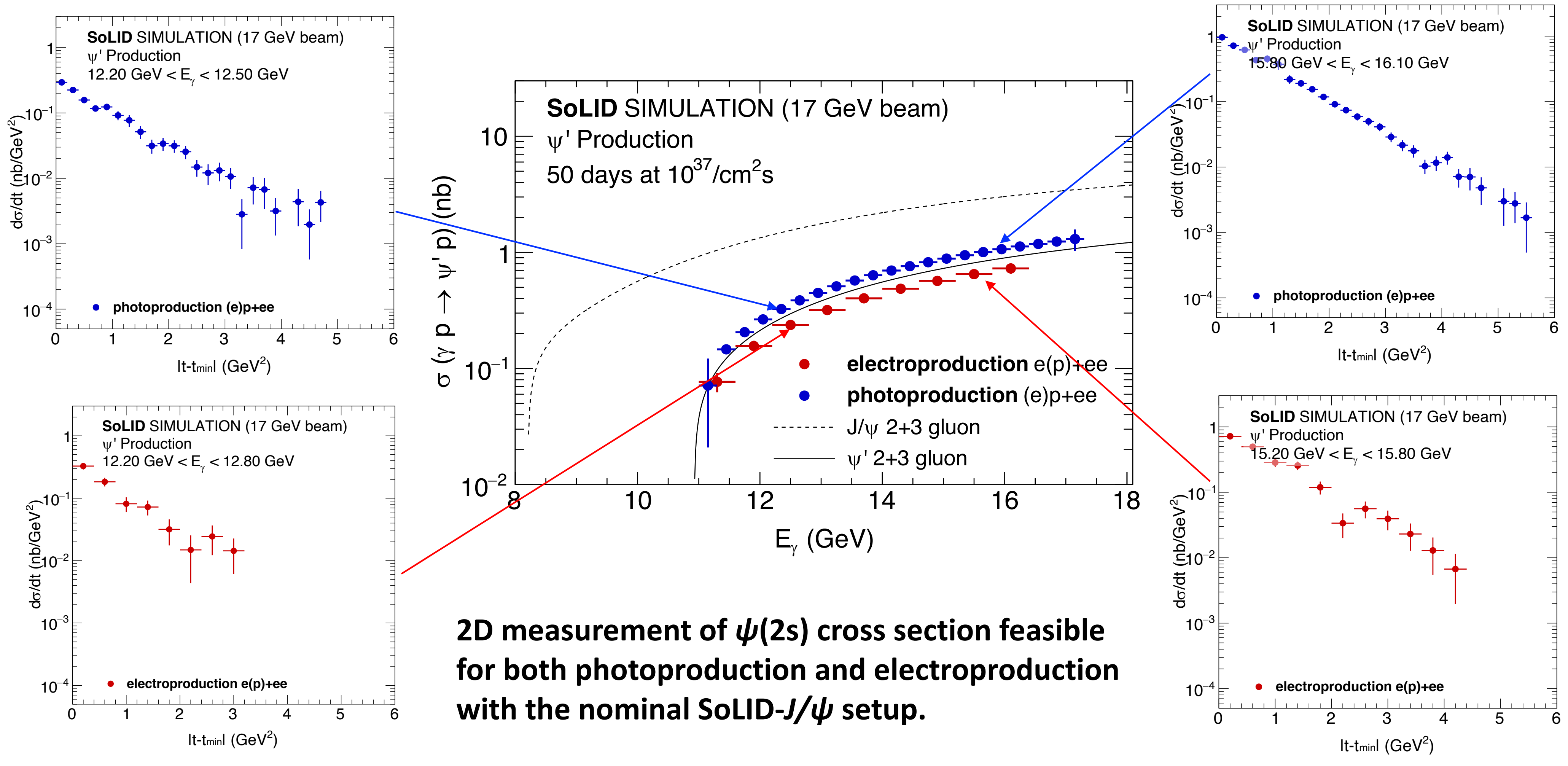
- Υ(1S) at EIC trades statistical precision of J/ψ at SoLID for lower theoretical uncertainties, and extra channel to study universality.
- Large Q^2 reach at EIC an additional knob to study production, near-threshold J/ψ production at large Q^2 may be experimentally feasible!



THOUGHTS ON “JLAB BEYOND”

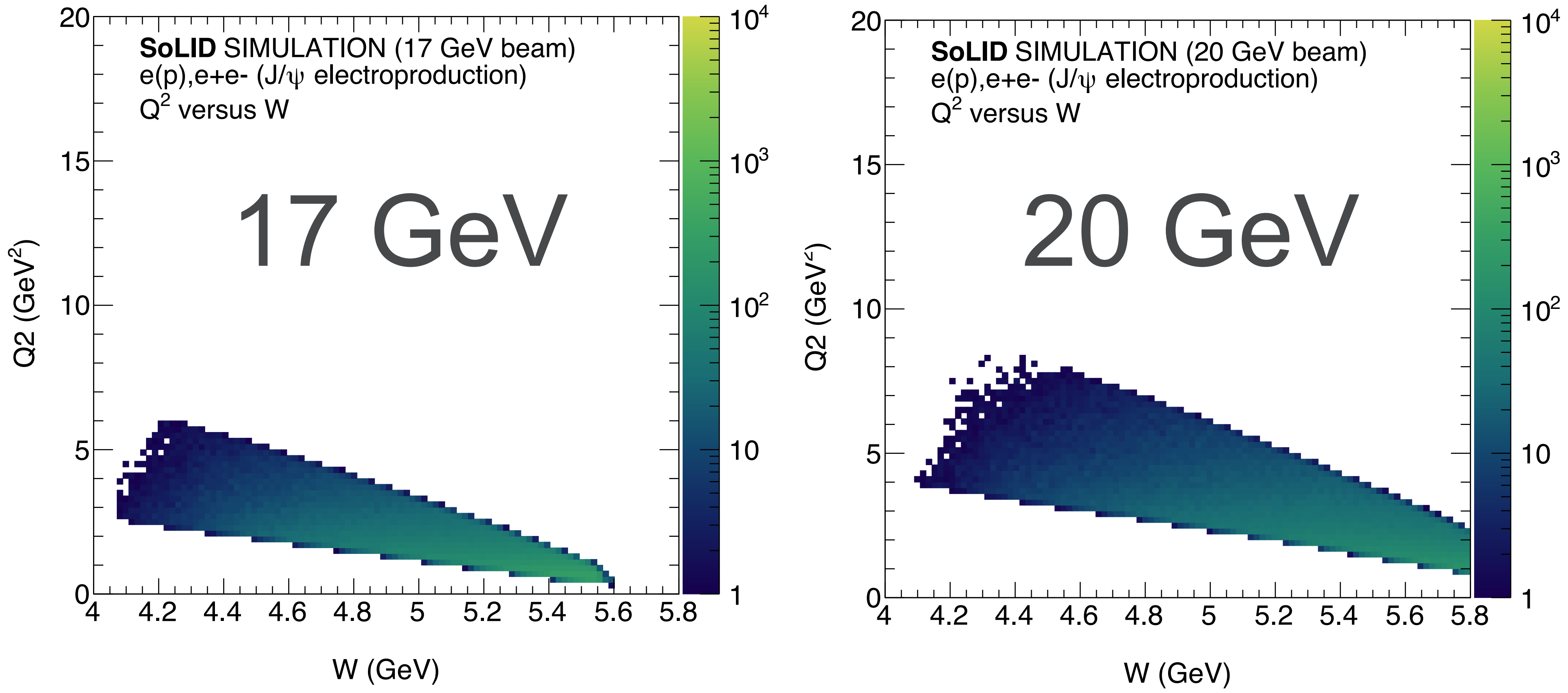
What can be done with a JLab energy upgrade at SoLID?

ψ(2s) at SoLID (17-20 GeV)



2D measurement of *ψ*(2s) cross section feasible for both photoproduction and electroproduction with the nominal SoLID-*J*/*ψ* setup.

Q2-reach for J/ψ at threshold up to ~10GeV2 for 20 GeV beam

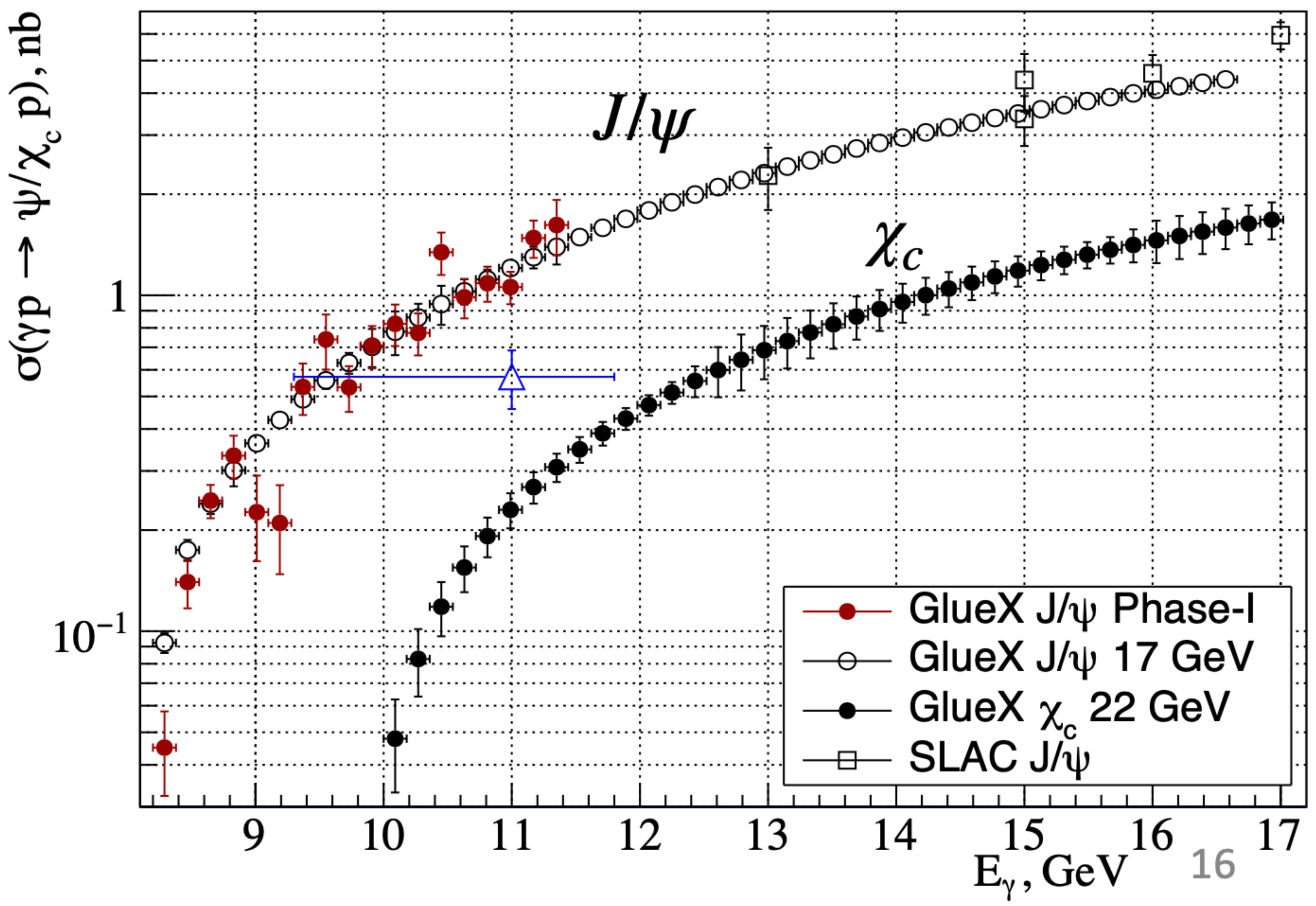


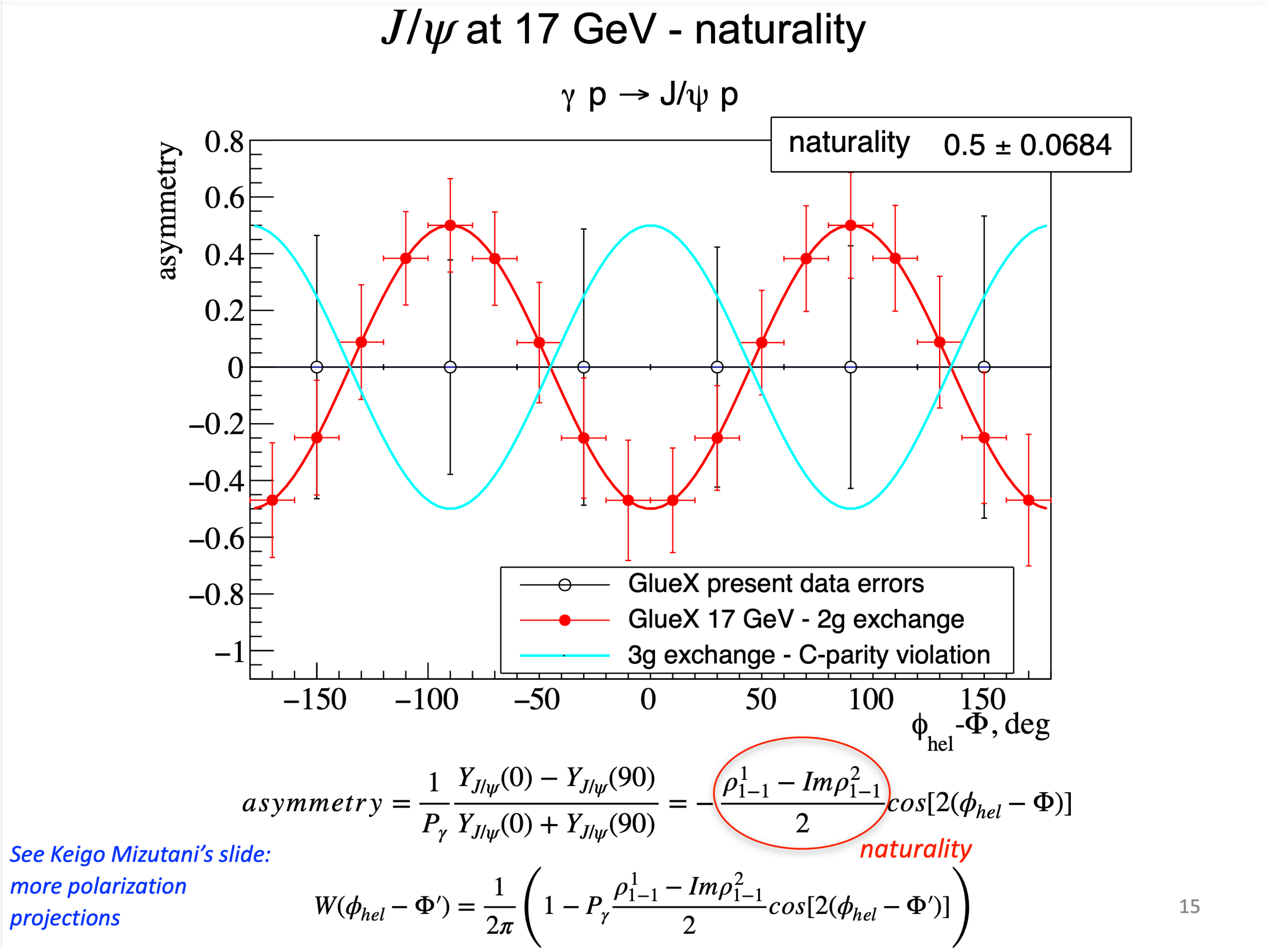
- Higher beam energy at SoLID can enable
  - Precision near-threshold **ψ(2s) production - larger color dipole** to probe the proton
  - Reach **larger values of Q^2** for J/ψ electroproduction. Modest Q^2 reach compared to EIC, but with much higher statistics near-threshold.

THOUGHTS ON "JLAB BEYOND"

What can be done with a JLab energy upgrade at GlueX?

- 17+GeV at GlueX will allow for **measurements of polarization observables** that can help separate different contributions to J/ψ production
- Energy upgrade would enable looking at C-even charmonium states





$$asymmetry = \frac{1}{P_\gamma}\frac{Y_{J/\psi}(0) - Y_{J/\psi}(90)}{Y_{J/\psi}(0) + Y_{J/\psi}(90)} = -\frac{\rho^1_{1-1} - Im\rho^2_{1-1}}{2} cos[2(\phi_{hel} - \Phi)]$$

$$W(\phi_{hel} - \Phi') = \frac{1}{2\pi}\left(1 - P_\gamma \frac{\rho^1_{1-1} - Im\rho^2_{1-1}}{2} cos[2(\phi_{hel} - \Phi')]\right)$$

Figures by Lubomir Pentchev (J/ψ Beyond workshop)

CONCLUSION

- The JLab 12-GeV program has delivered important first results on near-threshold J/ψ production from GlueX and Hall C (J/ψ-007)
  - New window on the gluonic GFFs in the proton
  - Does the proton have a dense energetic core?
- The planned near-threshold J/ψ production program at Jefferson Lab crucial to further our understanding of the origin of mass.
  - This includes the approved program at GlueX, CLAS12 with luminosity upgrade, and importantly SoLID-J/ψ in Hall A.
  - SoLID can reach J/ψ observables that cannot be achieved anywhere else, including precision measurements at high t, and precision electroproduction near threshold.
- The matter structure of the proton and threshold quarkonium production are rapidly evolving topics that reach from Jefferson Lab to the EIC
  - EIC is complimentary: enables measurement of high-mass vector mesons and production at high Q2, important to understand factorization. High-luminosity crucial for these measurements.
  - A possible JLab energy upgrade could expand its scientific reach for near-threshold quarkonium production without too much overlap with the EIC.

The origin of the proton's mass is one of the central questions in contemporary hadronic physics. The topic, highlighted in the 2015 Long Range Plan and the 2018 NAS assessment of the EIC, has seen many prominent experimental and theoretical developments in recent years. Completion of the planned near-threshold quarkonium production experiments at Jefferson Lab, including the SoLID experiment, is crucial to further our understanding of the matter distribution inside the proton. The complementary measurements with the EPIC detector at the EIC hold the key to come to a fully universal theoretical understanding of the origin of the proton mass. The program could be further strengthened and expanded through a Jefferson Lab energy upgrade.

QUESTIONS?