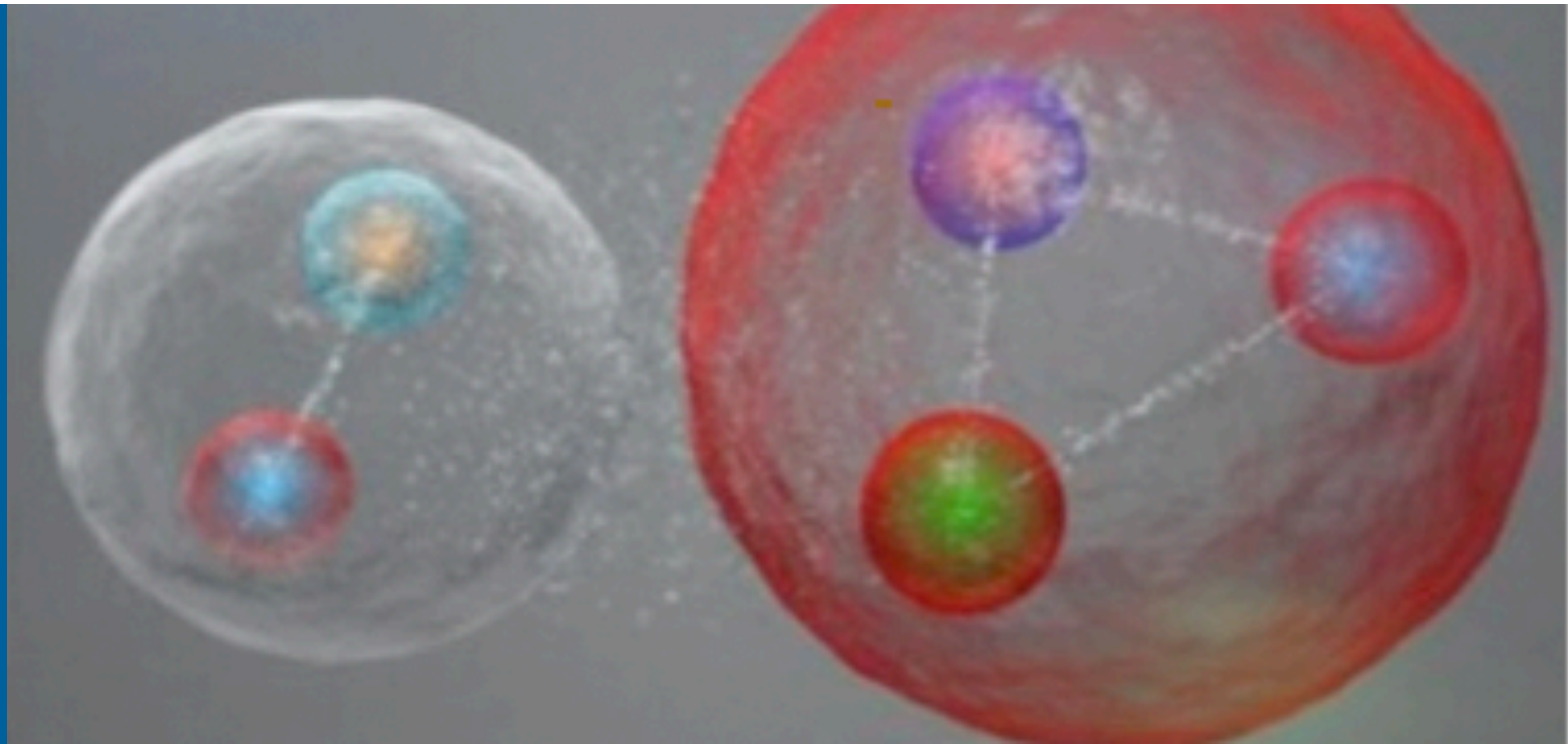
This work is supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under contract DE-AC02-06CH11357.

Argonne NATIONAL LABORATORY

Near-threshold Electroproduction of J/ψ at 11 GeV



SYLVESTER JOOSTEN
sjoosten@anl.gov

ON BEHALF OF SOLID-J/Ψ

SoLID
SOLENOIDAL LARGE INTENSITY DEVICE

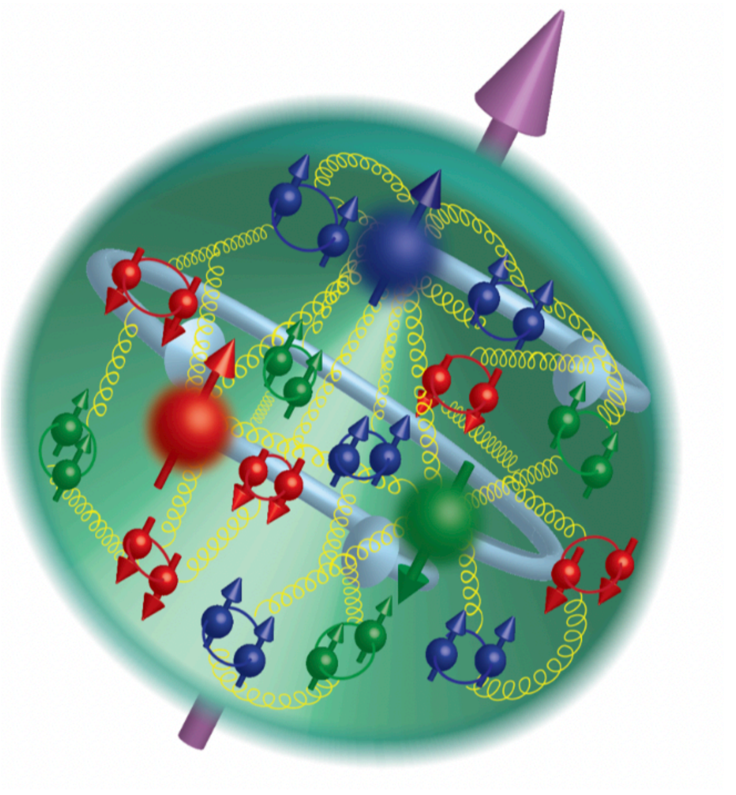
U.S. DEPARTMENT OF ENERGY
Argonne National Laboratory is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC.

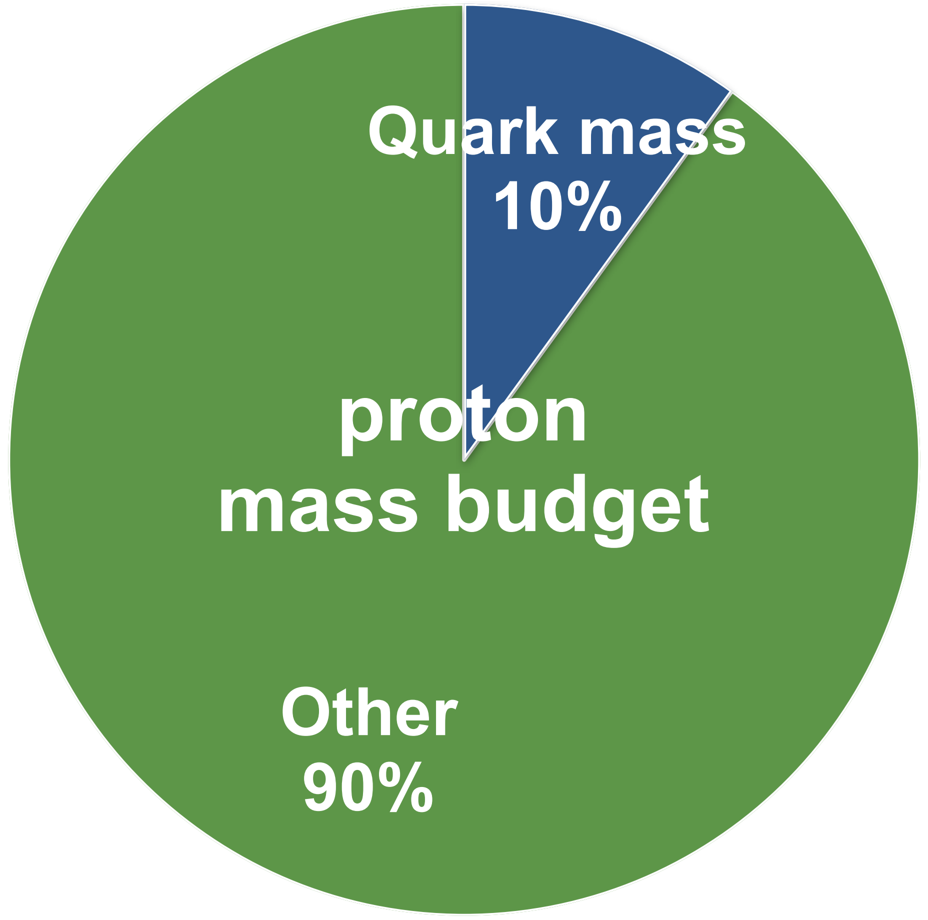
This work is supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under contract DE-AC02-06CH11357.

Hall A Collaboration Meeting
Jefferson Lab, January 17, 2024

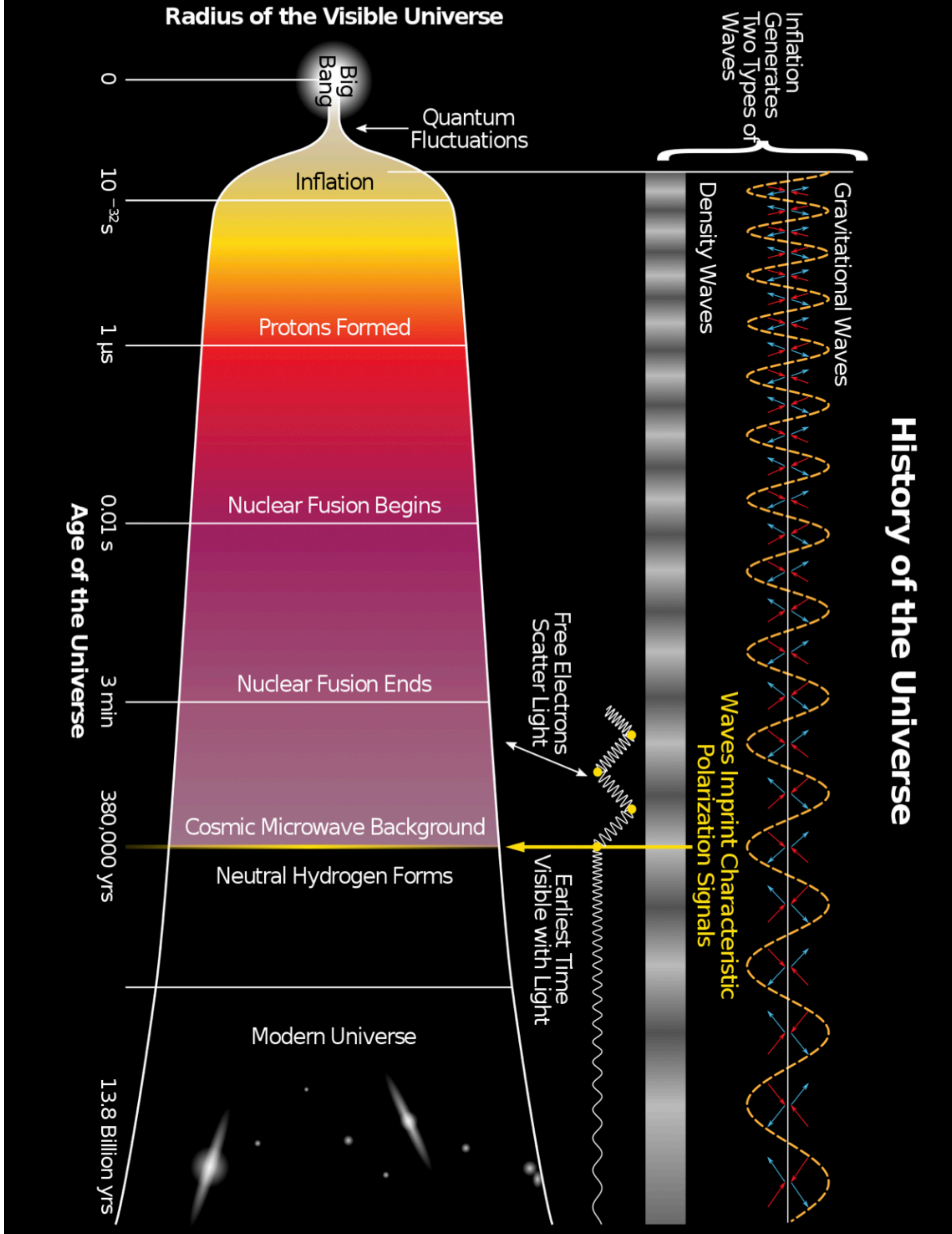
The emergence of nucleon mass

QCD IN THE STANDARD MODEL



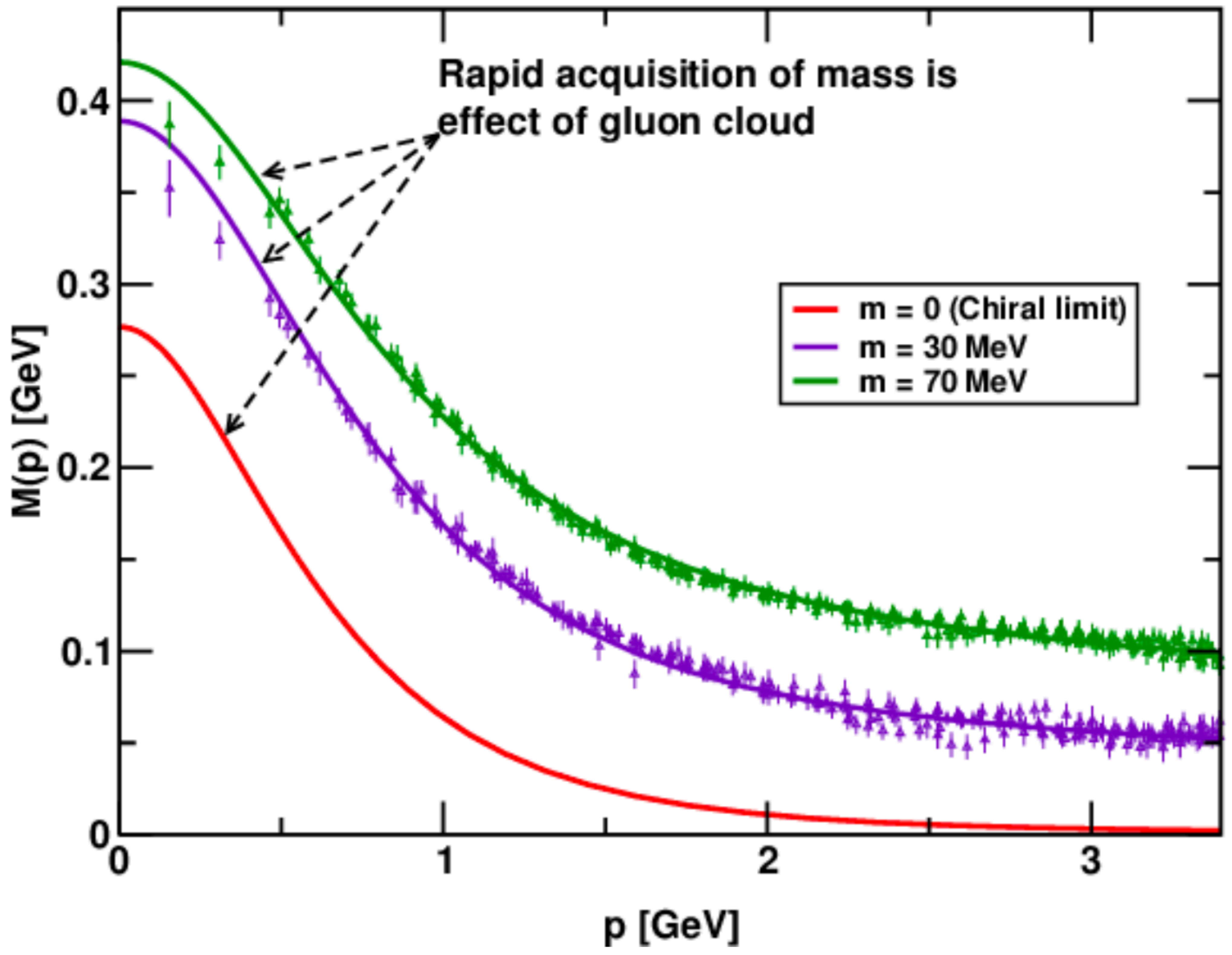


- Since the formation of protons and neutrons, most of the mass of the visible universe encapsulated in protons, neutrons, and nuclei.
- Surprising: nucleon mass much larger than sum of quark masses.
- *How does QCD give rise to the 1GeV proton?*
- *How is the proton mass distributed in its confinement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



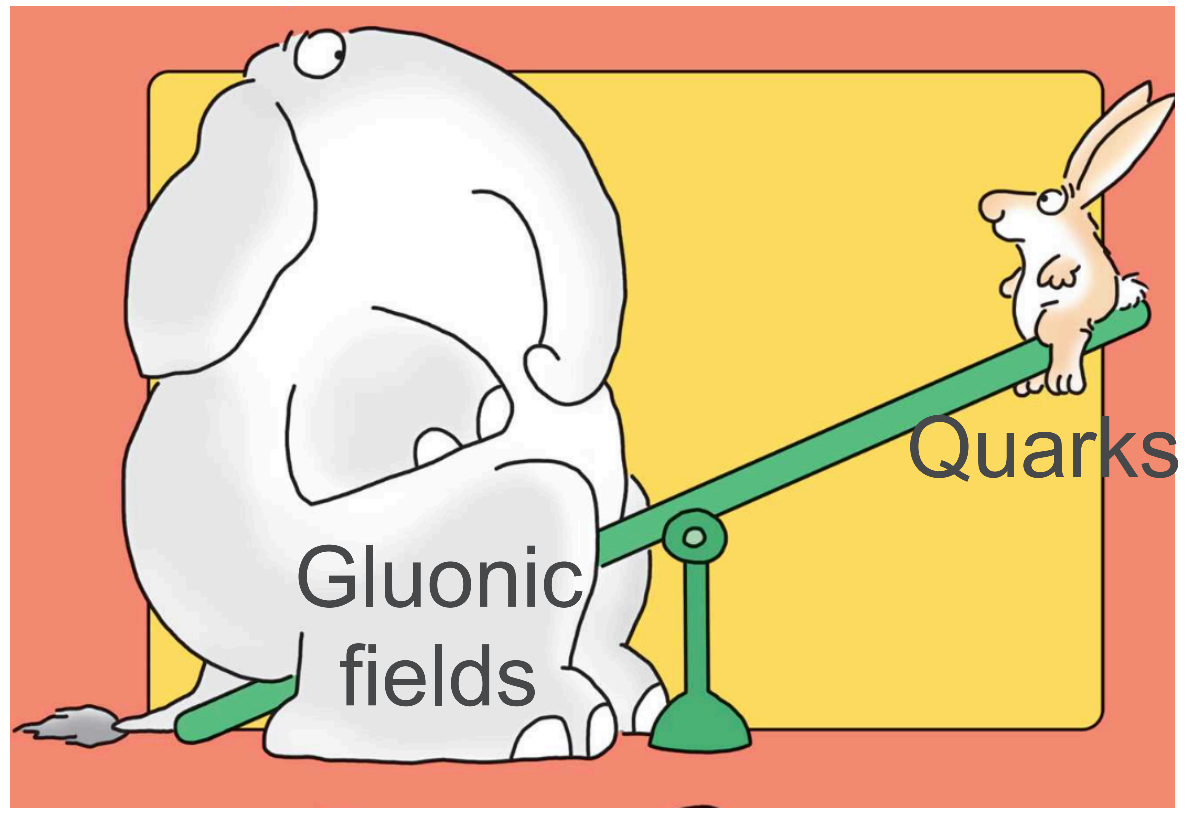
PROTON MASS IS AN EMERGENT PHENOMENON

QCD responsible for the proton mass



M. S. Bhagwat et al., Phys. Rev. C 68, 015203 (2003)
I. C. Cloet et al., Prog. Part. Nucl. Phys. 77, 1-69 (2014)

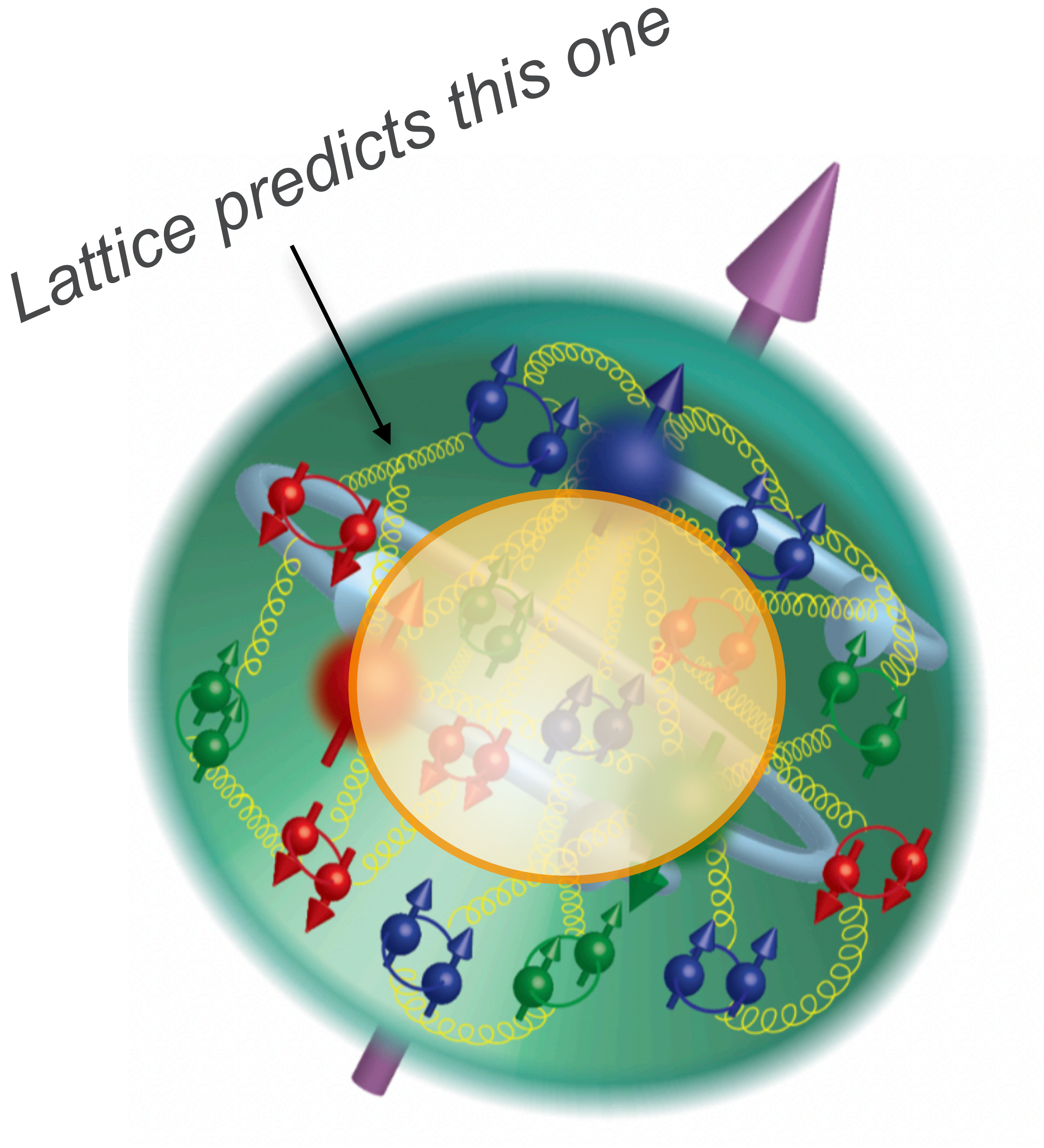
Most of the proton mass originates in the energy enclosed in the gluonic fields of the Strong Interaction itself



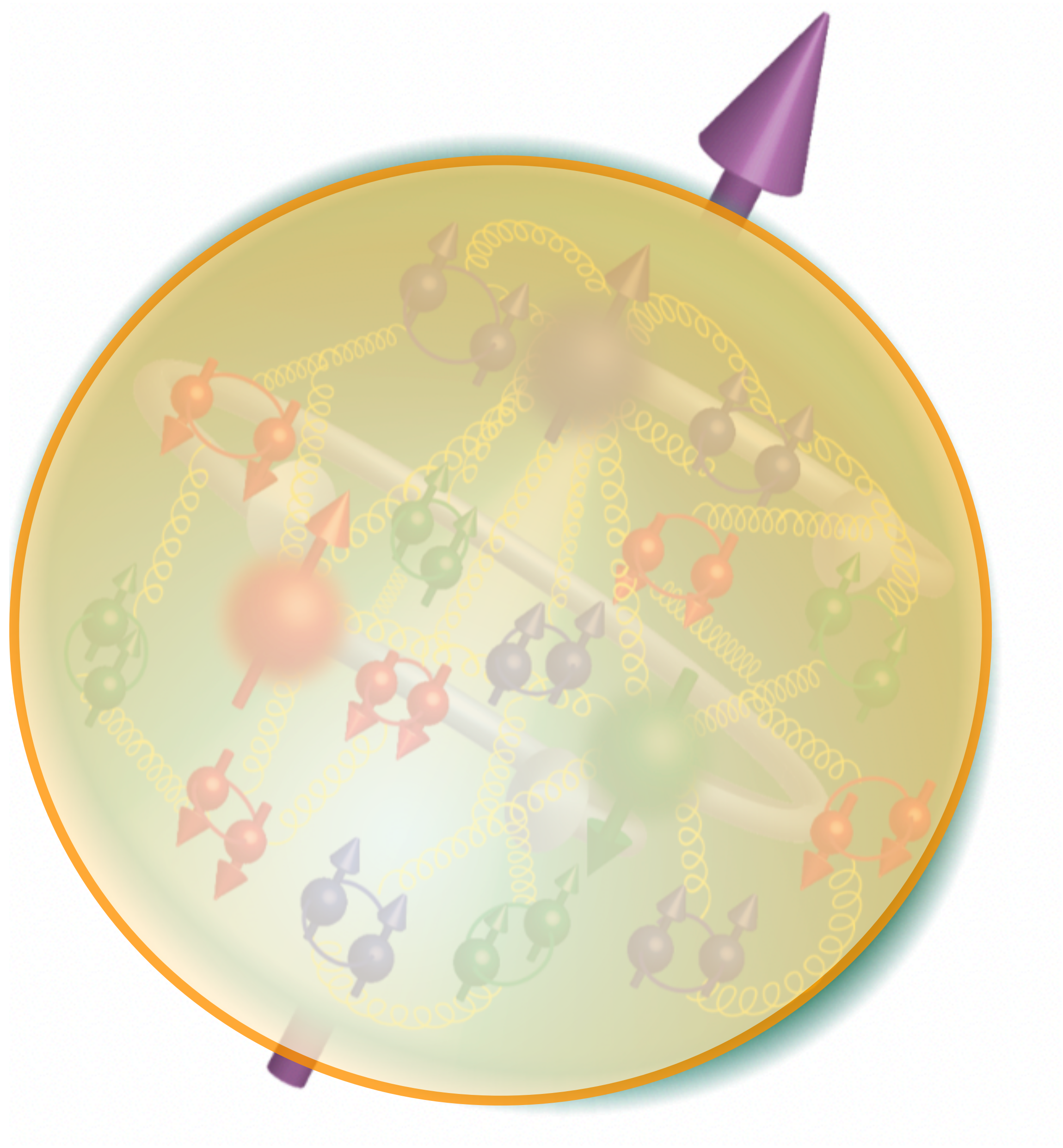
Bottom line: The Higgs mechanism is largely irrelevant for most of "normal" visible matter!

WHERE IS THE ENERGY INSIDE THE PROTON?

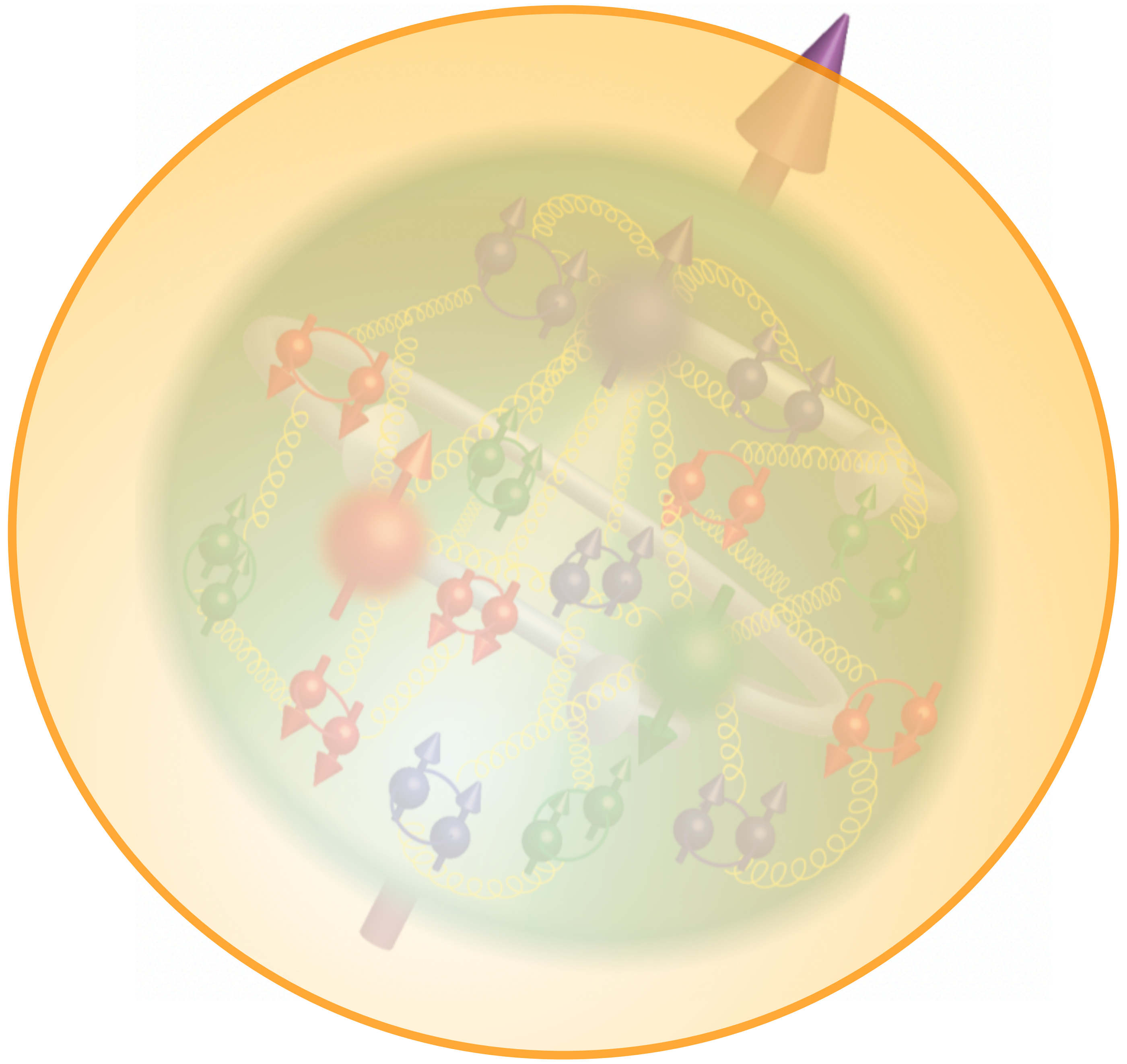
How does the mass radius compare to the charge radius?



Vs



Vs



Dense energetic core?

Same as charge radius?

Energy halo beyond charge radius?

GRAVITATIONAL FORM FACTORS (GFFS)

Towards observables for the matter structure of the proton

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

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

GFFs encode mechanical properties of the proton:

- $A_{g,q}(t)$: 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

HOW TO MEASURE THE GLUONIC GFFS

Gluons are elusive!

🛑 Cannot use Electromagnetic probe: primarily couples to quarks

🛑 Cannot use Weak probe: also primarily couples to quarks

🛑 Cannot use hadronic probe made of light quarks: primarily sensitive to quark structure

🛑 Cannot use direct gravitational probe: interaction too weak

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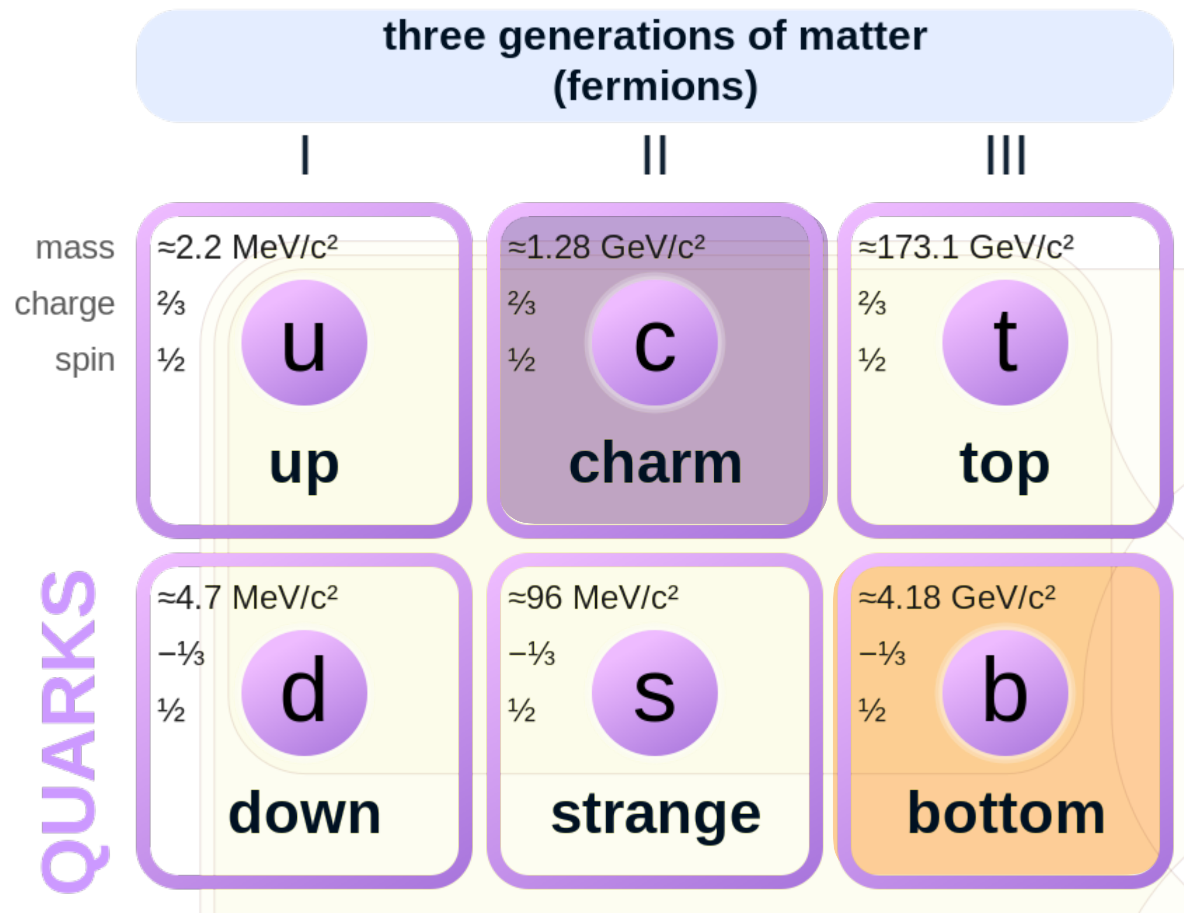

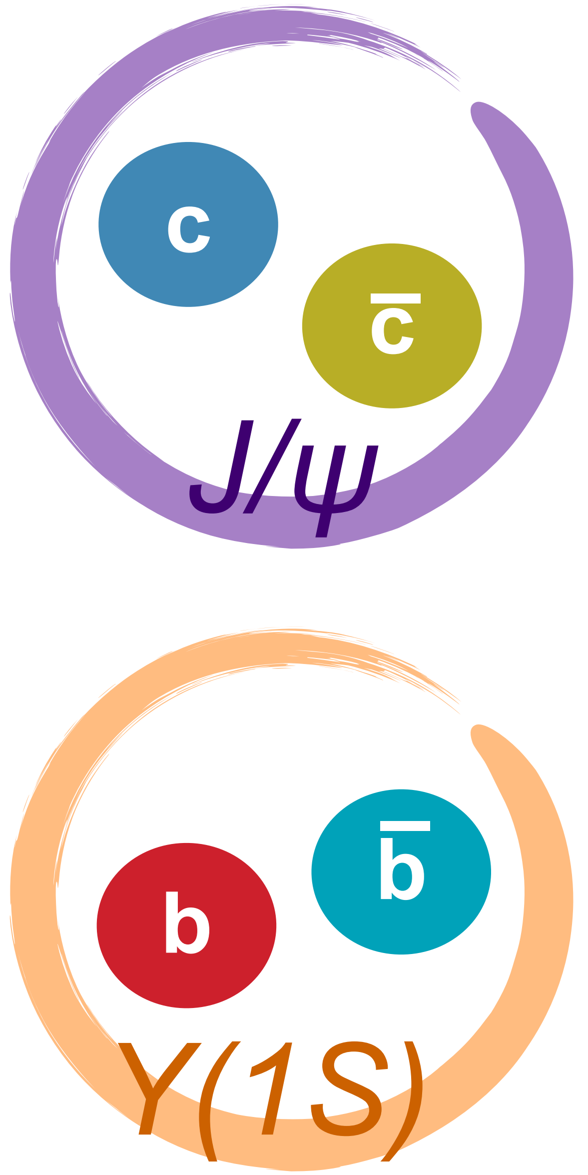

HOW TO MEASURE THE GLUONIC GFFS

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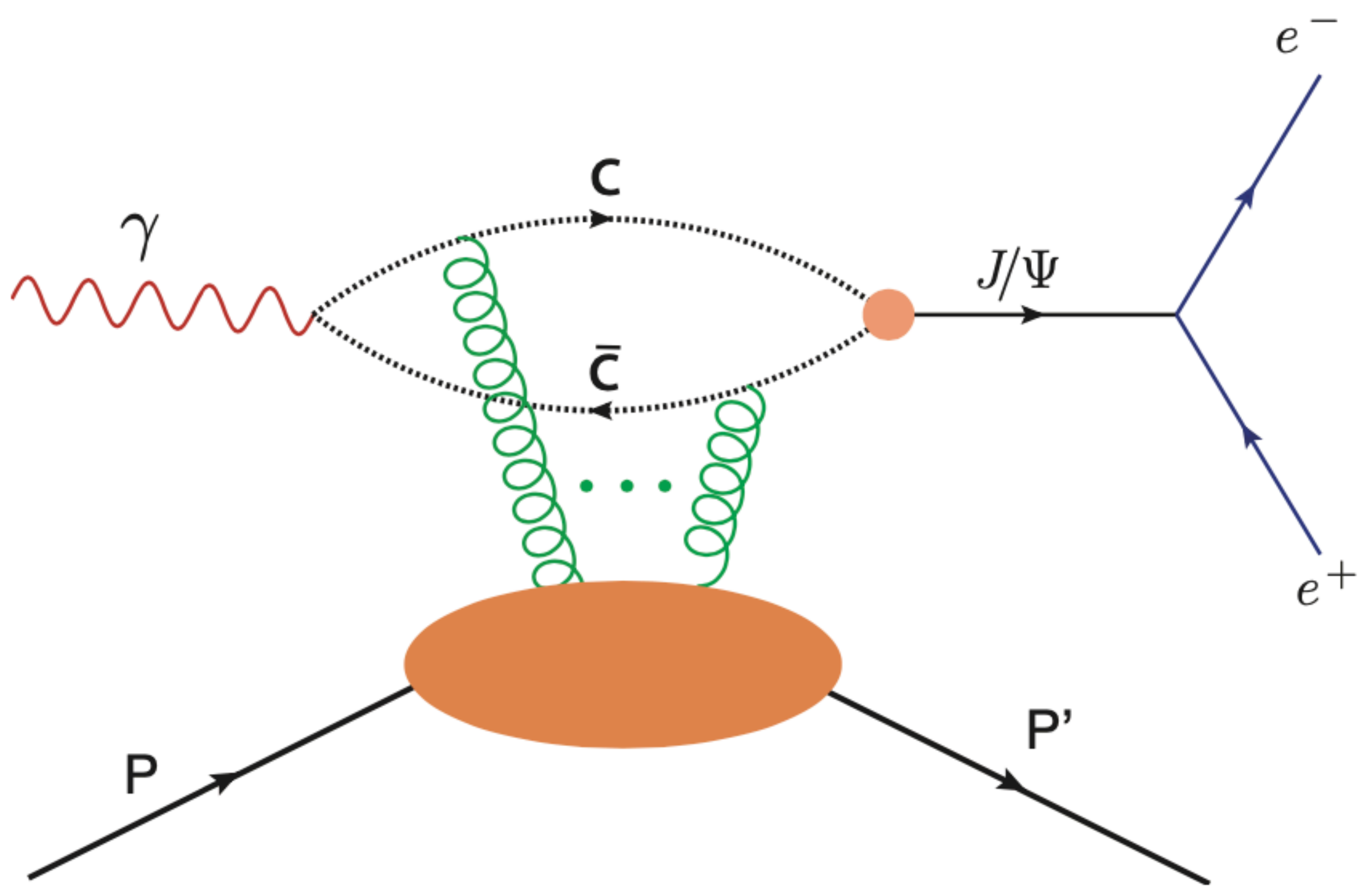
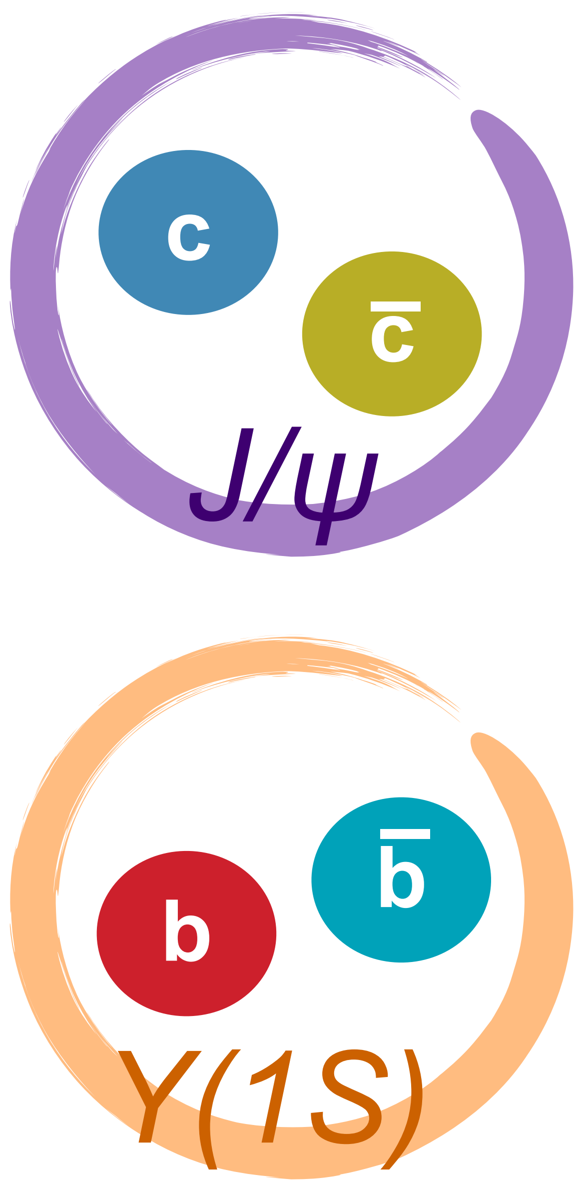


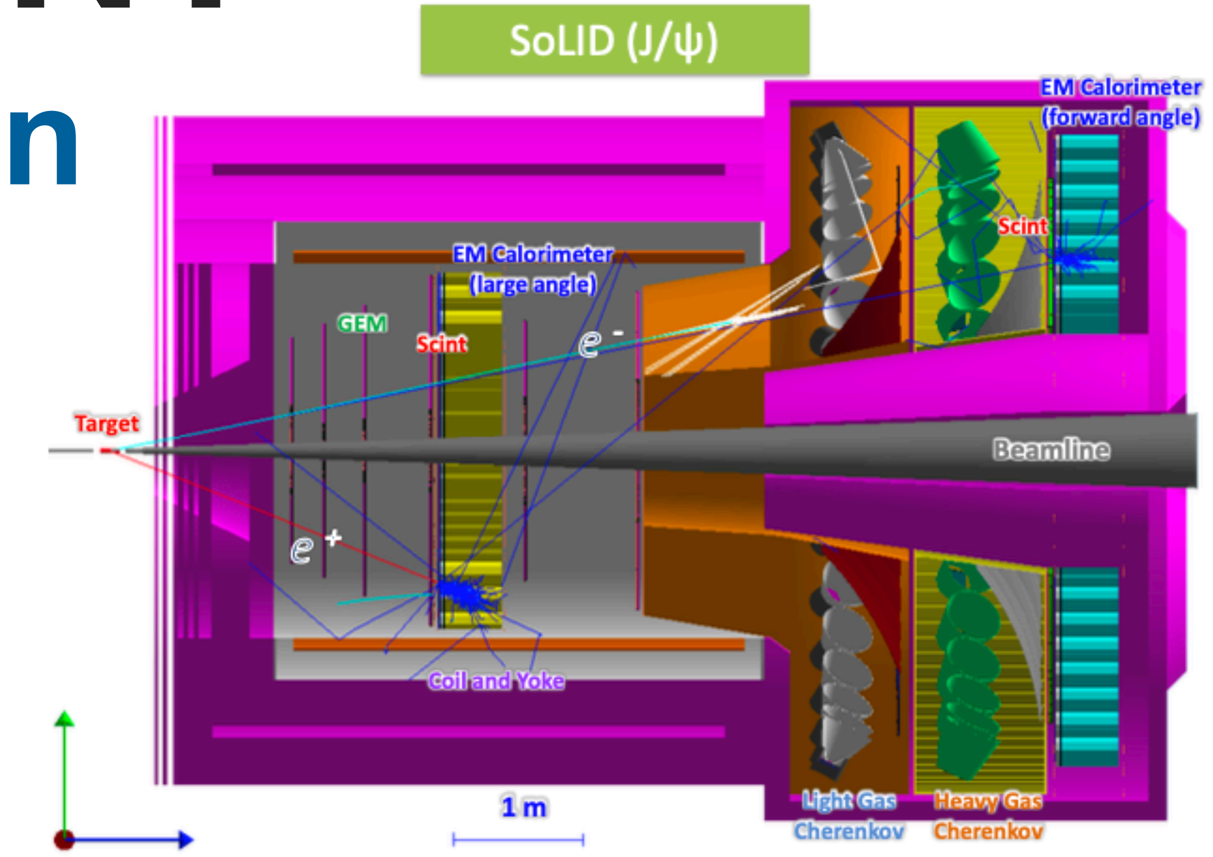
Gravitational form factors constrained by near-threshold exclusive J/ψ and Υ photoproduction

Beyond GFFs: 3-D gluonic structure of nucleons and nuclei constrained by exclusive J/ψ and Υ electro-production at higher energies

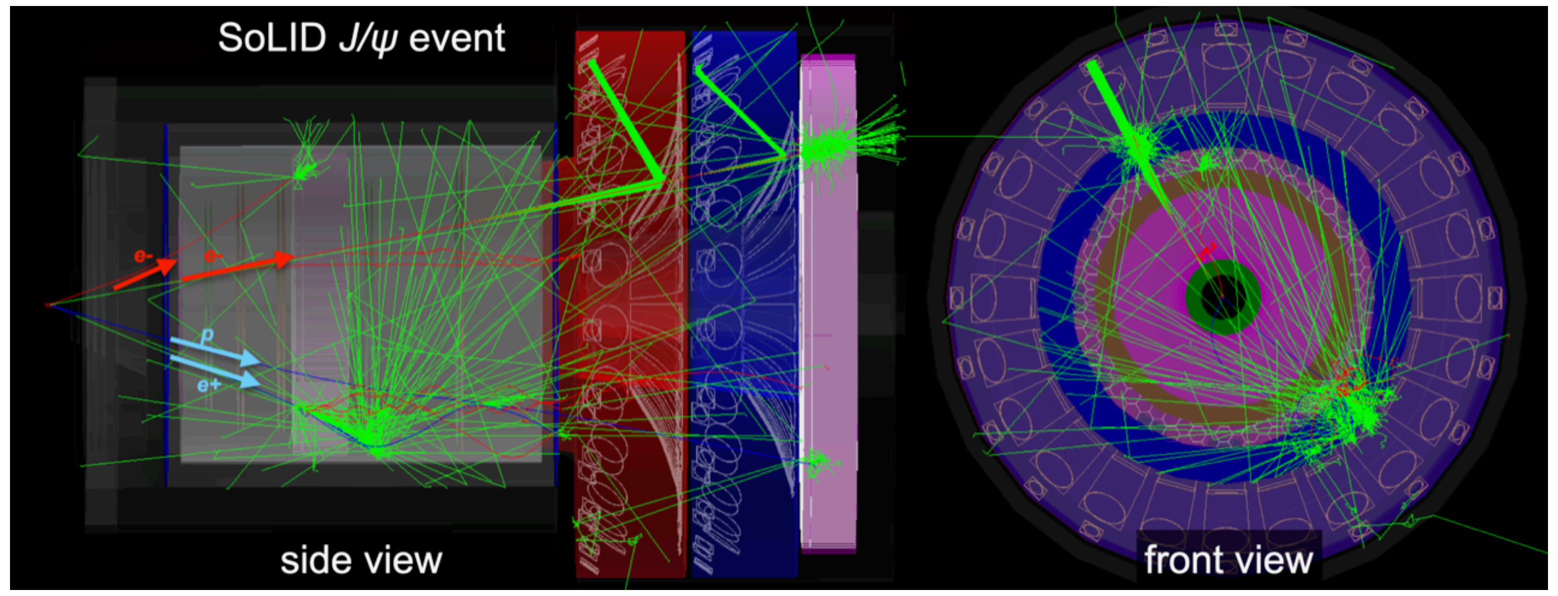


THE UPDATED SOLID-J/Ψ EXPERIMENT

Ultimate experiment for near-threshold J/ψ production



- 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$^+$)

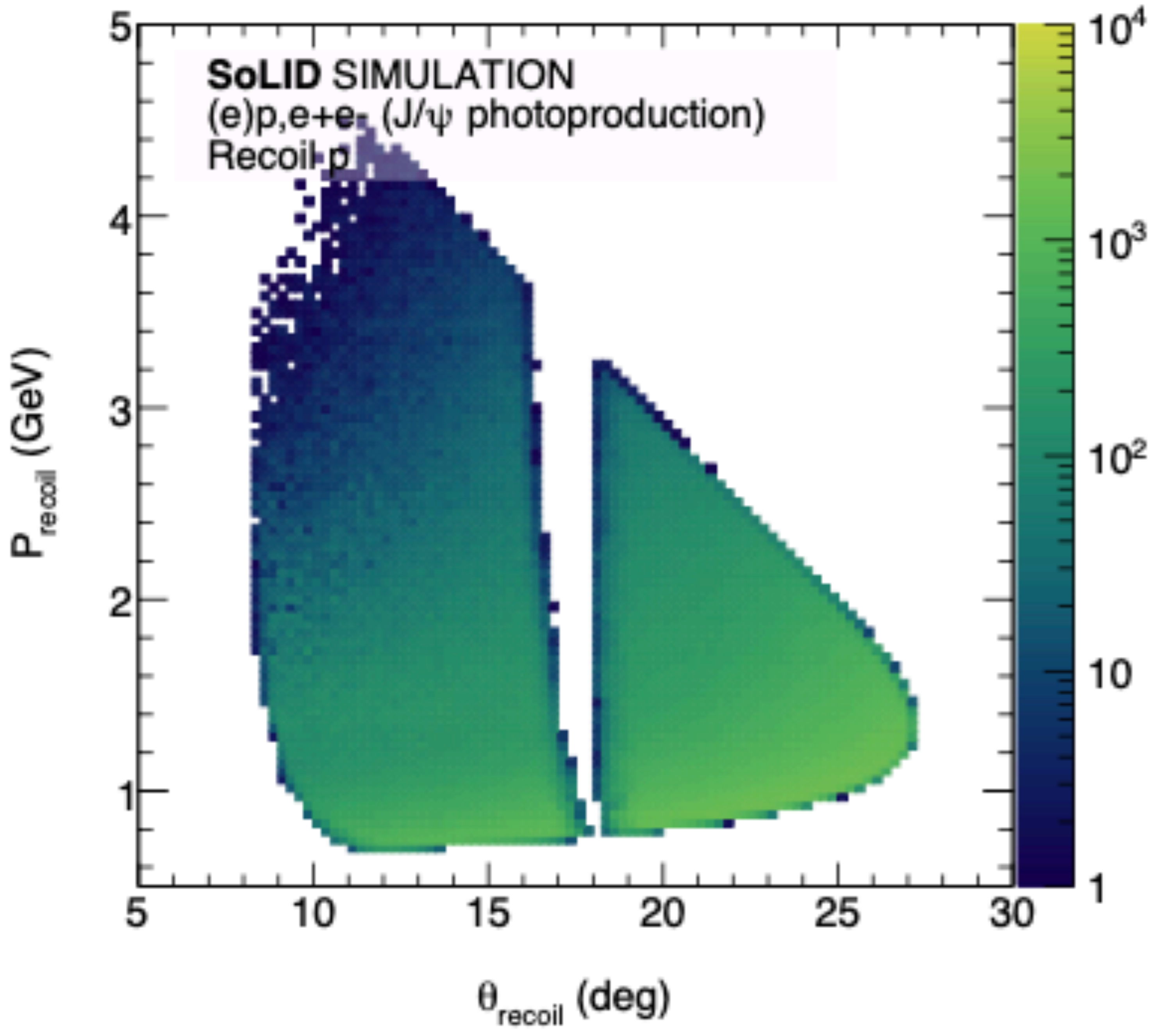


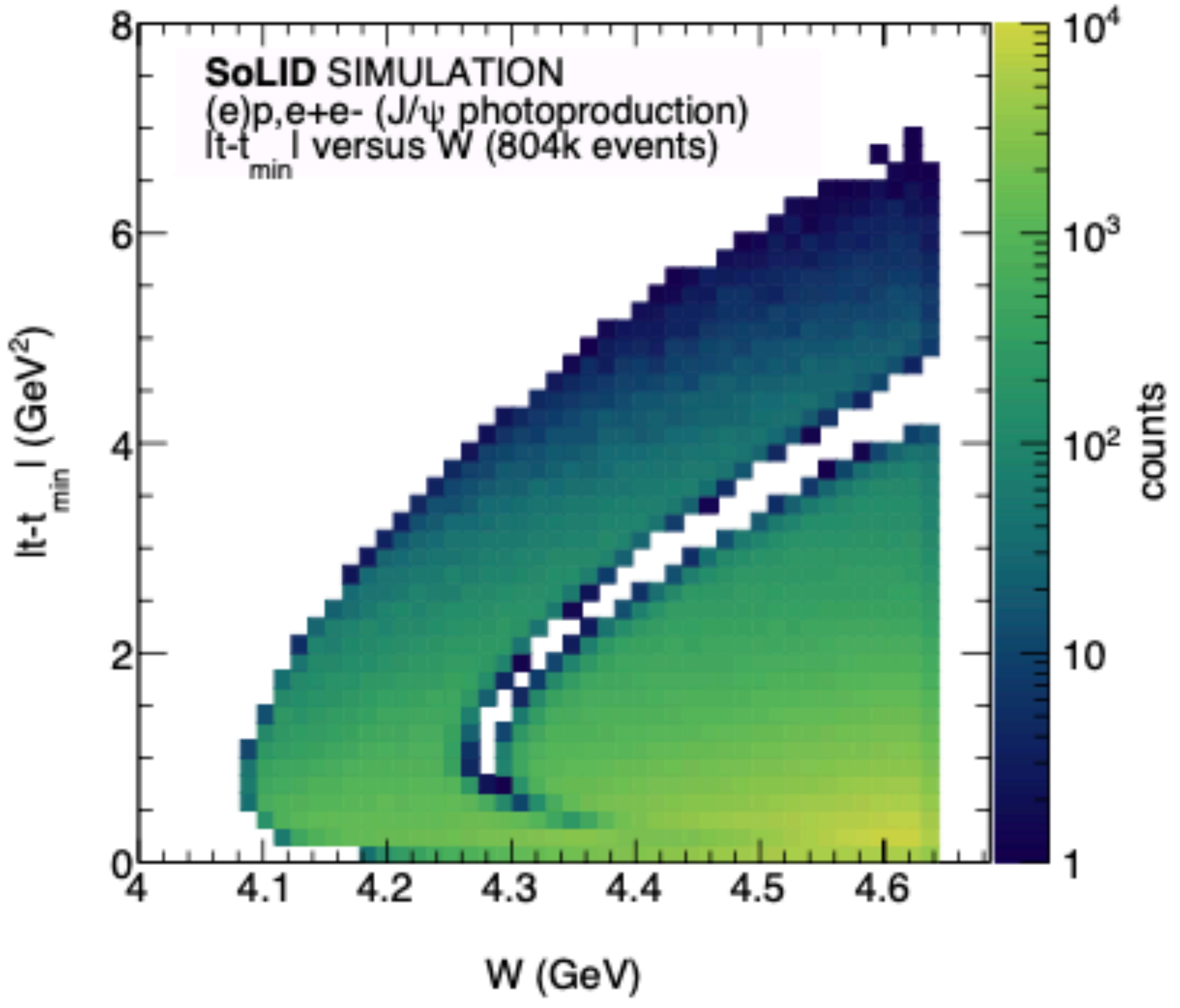
SoLID-J/ψ received an upgraded rating of A at the 2022 PAC Jeopardy Review

PHOTOPRODUCTION

Ultra-high statistics and best reach to high energies

- Production through quasi-real photons, and bremsstrahlung in the extended target.
- Measure J/ψ decay pair in forward and/or wide-angle detectors
- Identify recoil proton (which is slow) through time-of-flight with the SPDs and MRPCs.
- Can make measurement up to very large values of *t*.

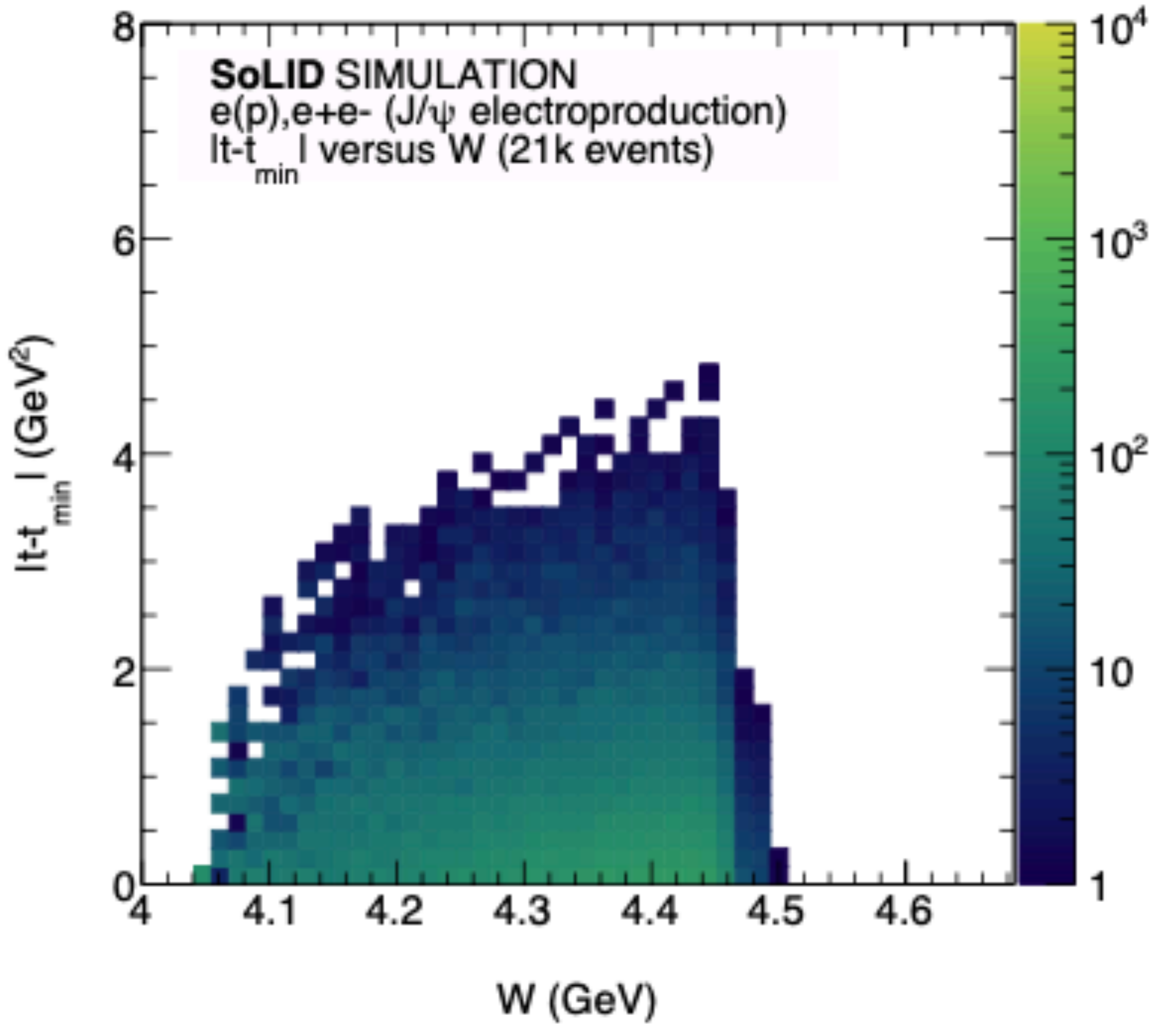


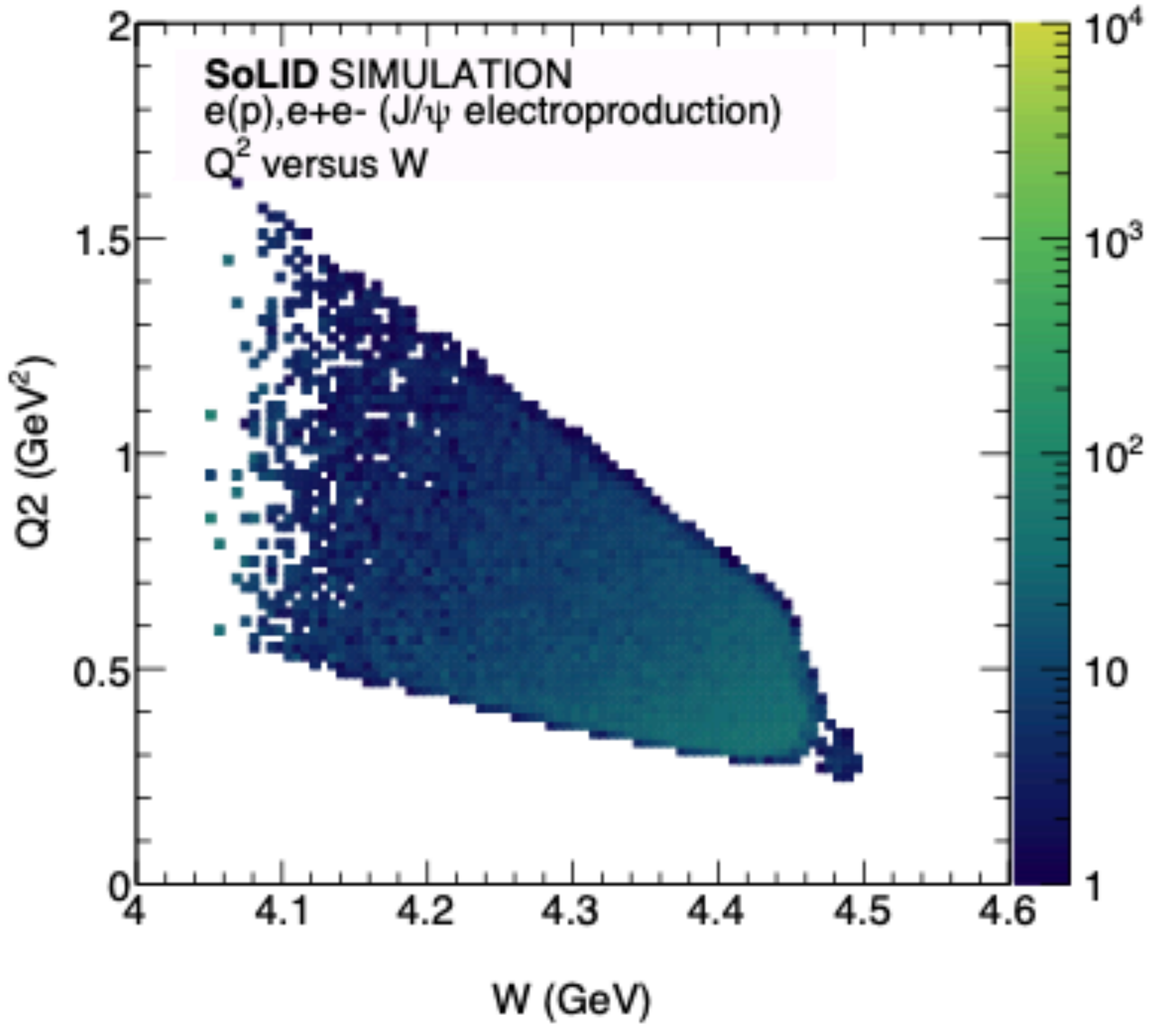


ELECTROPRODUCTION

Unrivaled reach towards the threshold and modest lever-arm in Q^2

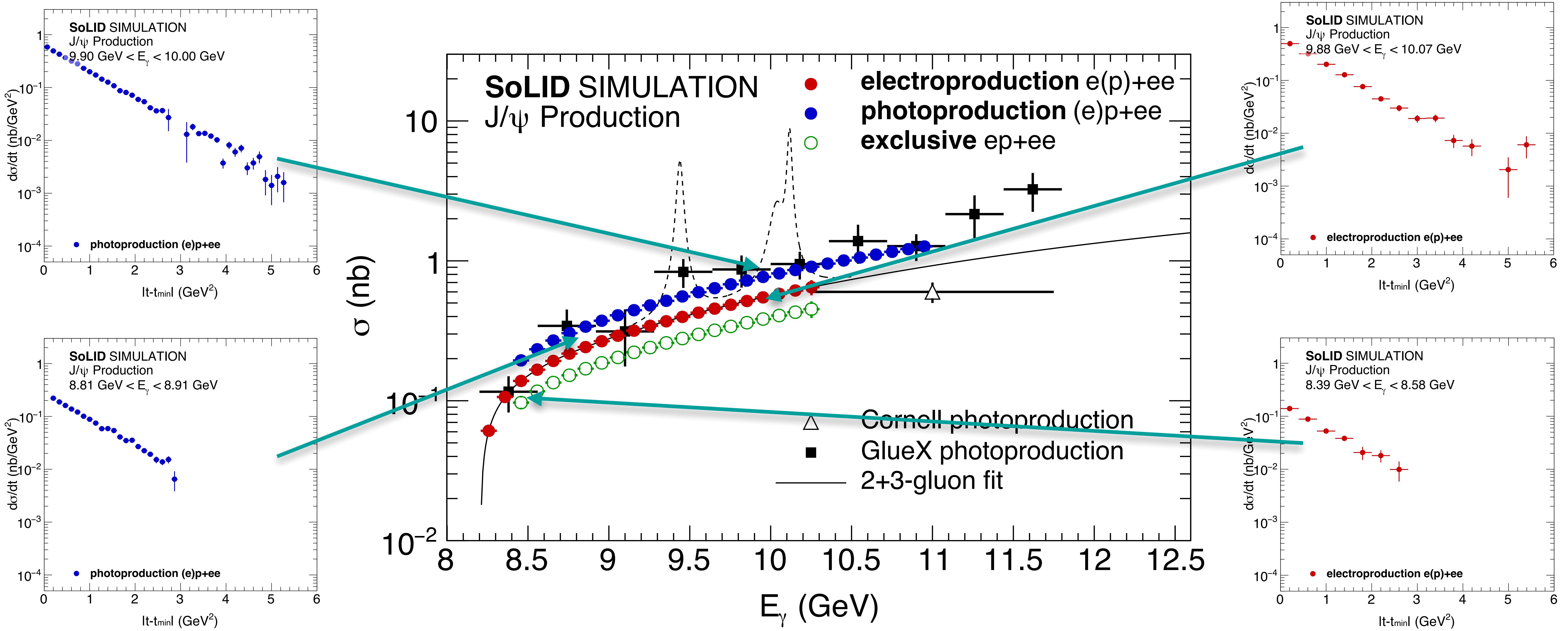
- Production through virtual photons
- Measure J/ψ decay pair in forward and/or wide-angle detectors
- Identify scattered electron in the forward spectrometer.
- Coverage up to larger values of t very close to threshold.





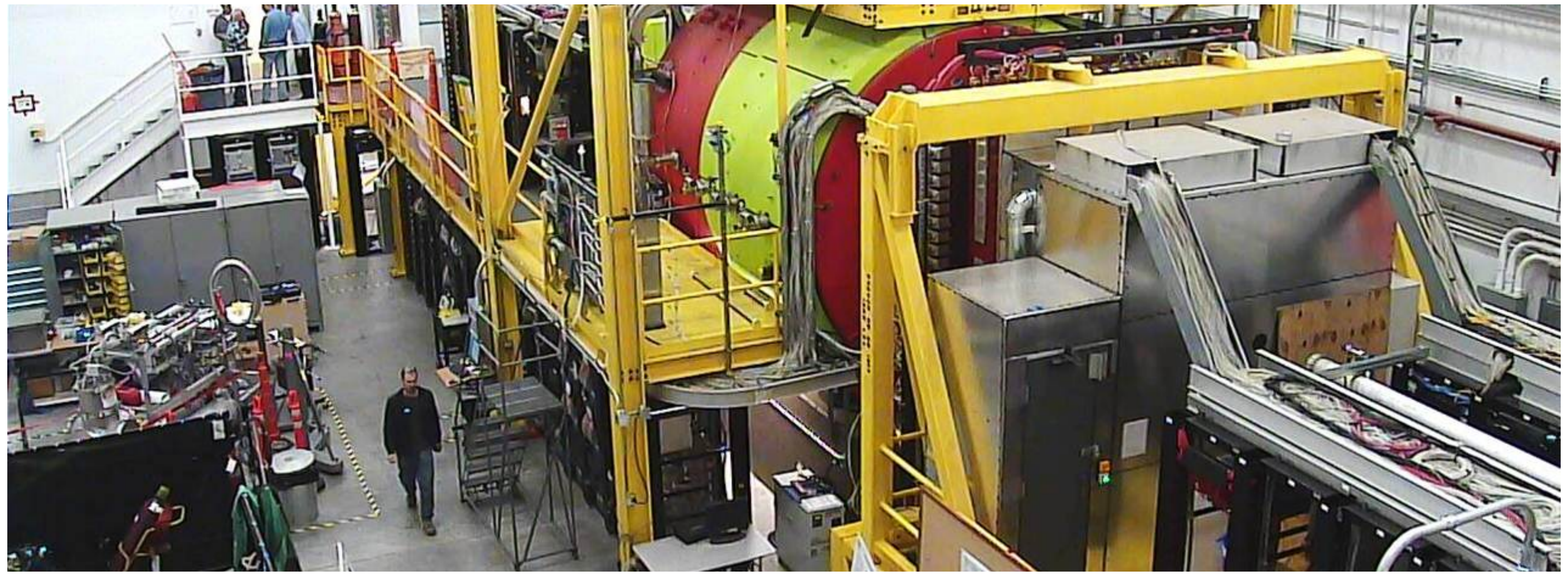
SOLID-J/Ψ PROJECTIONS AT 11 GEV

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

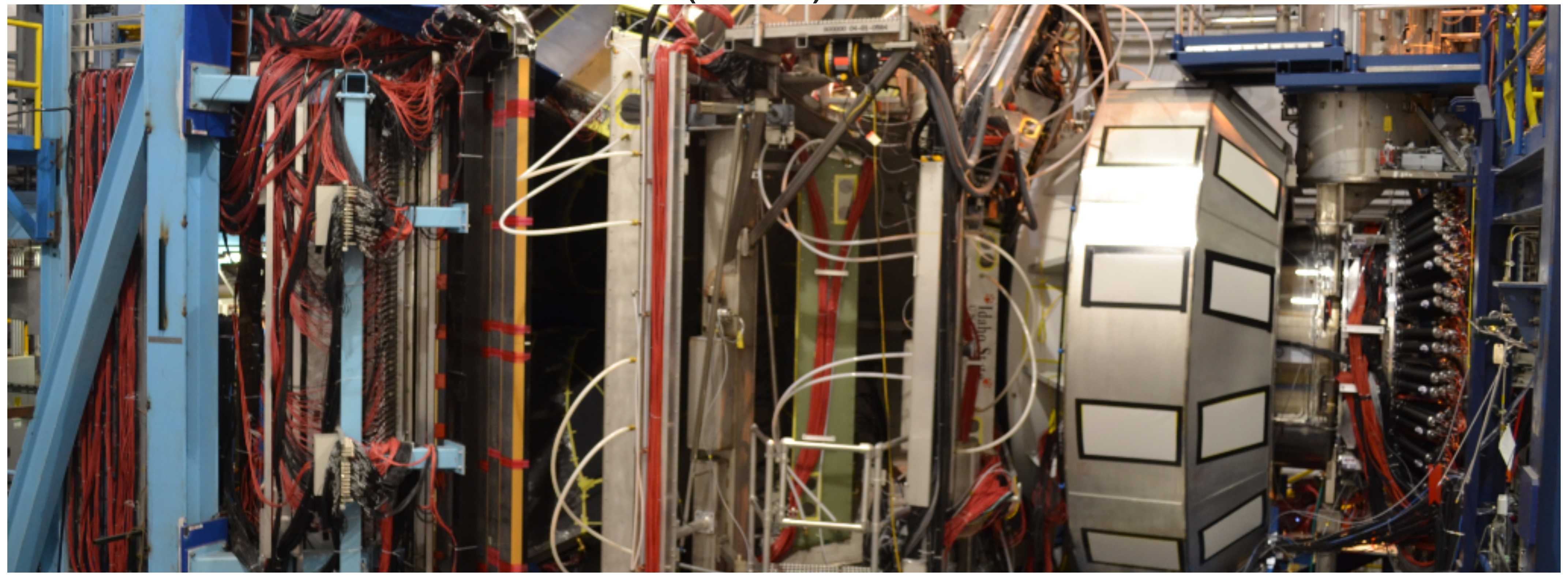


J/Ψ EXPERIMENTS IN THE 12 GEV ERA

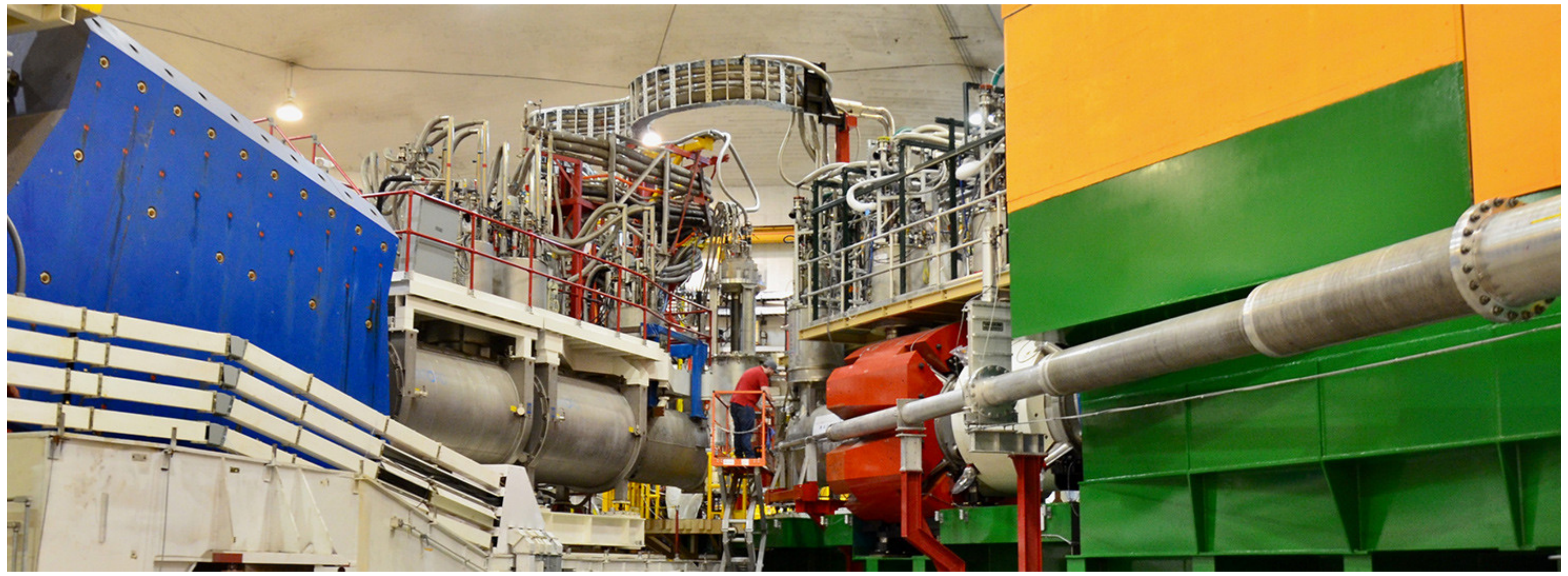
How does SoLID-J/ψ fit with the other 12 GeV experiments?



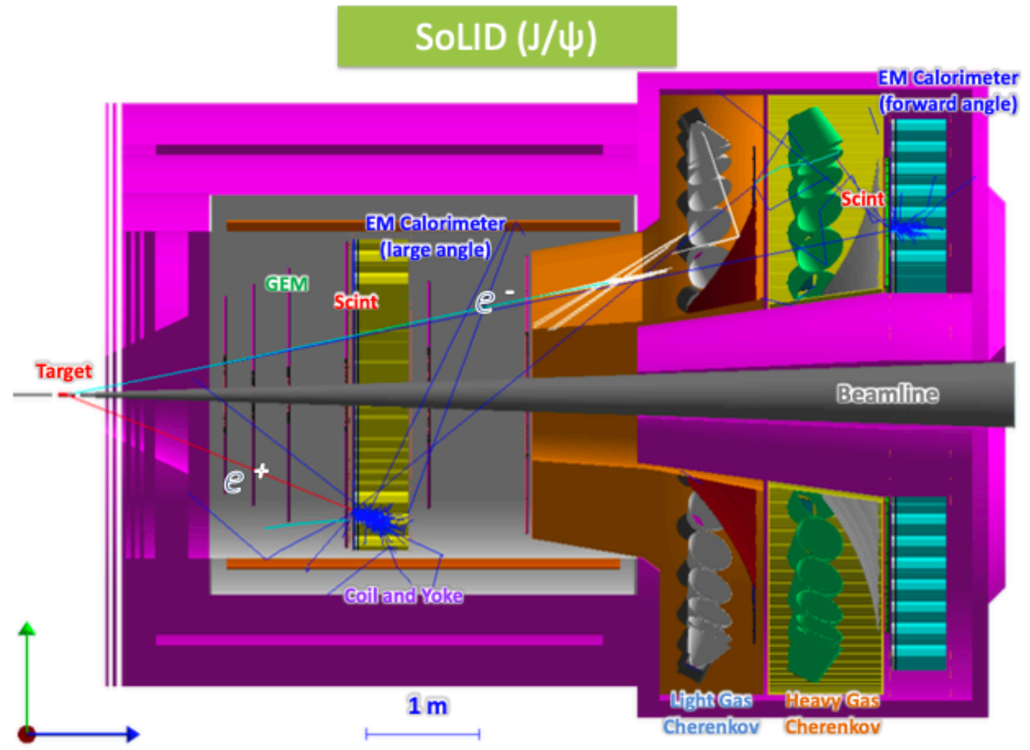
Hall D - GlueX observer the first J/ψ at JLab
A. Ali *et al.*, PRL 123, 072001 (2019)



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

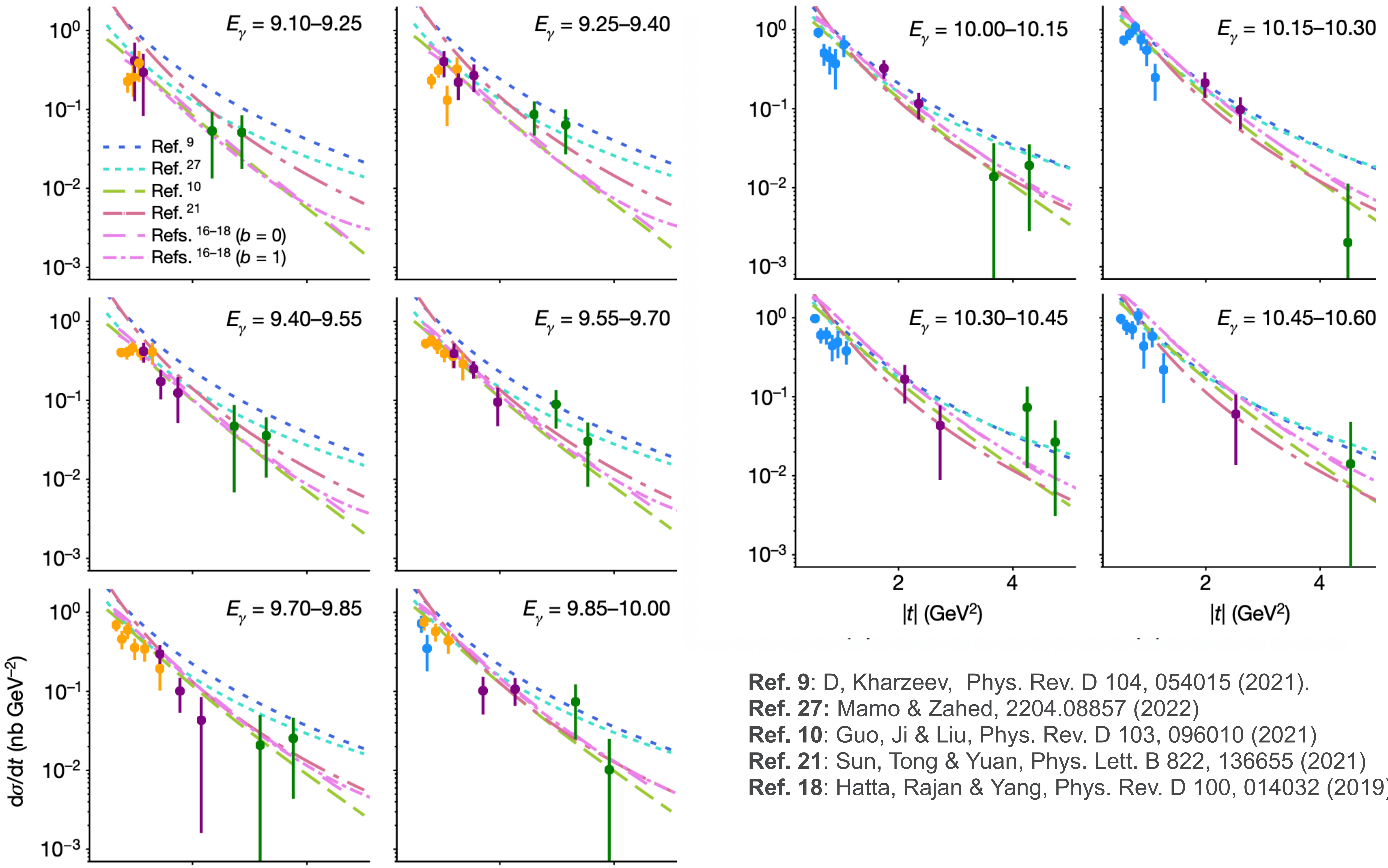


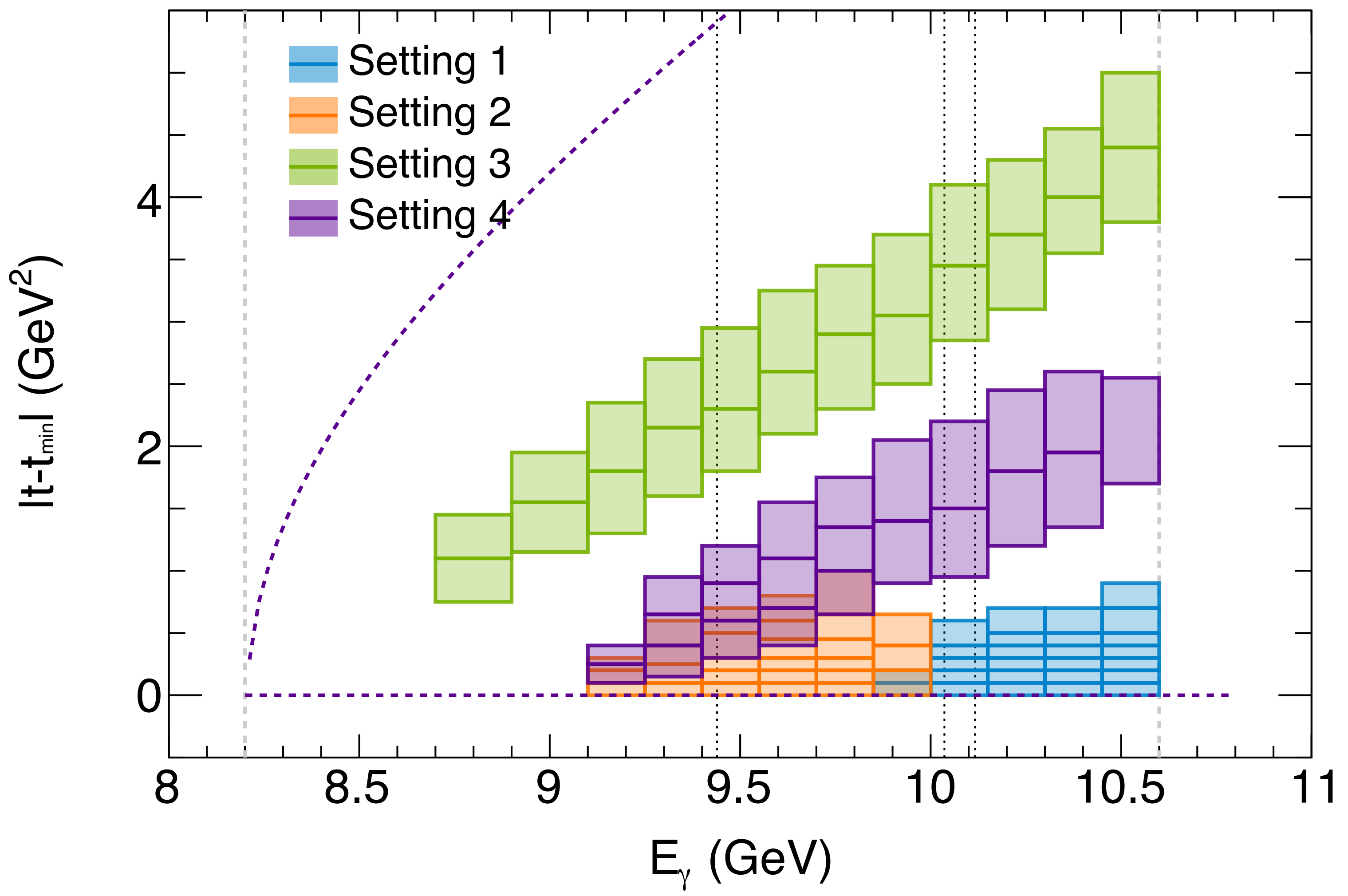
Hall A has experiment E12-12-006 at **SoLID** to measure J/ψ in electro- and photoproduction, and an LOI to measure double polarization using **SBS**

B. Duran *et al.*, Nature volume 615, pages 813–816 (2023)

First 2-D measurement near threshold from Hall C J/ψ-007

2-D J/Ψ CROSS SECTIONS NEAR THRESHOLD





Ref. 9: D, Kharzeev, Phys. Rev. D 104, 054015 (2021).
Ref. 27: Mamo & Zahed, 2204.08857 (2022)
Ref. 10: Guo, Ji & Liu, Phys. Rev. D 103, 096010 (2021)
Ref. 21: Sun, Tong & Yuan, Phys. Lett. B 822, 136655 (2021)
Ref. 18: 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

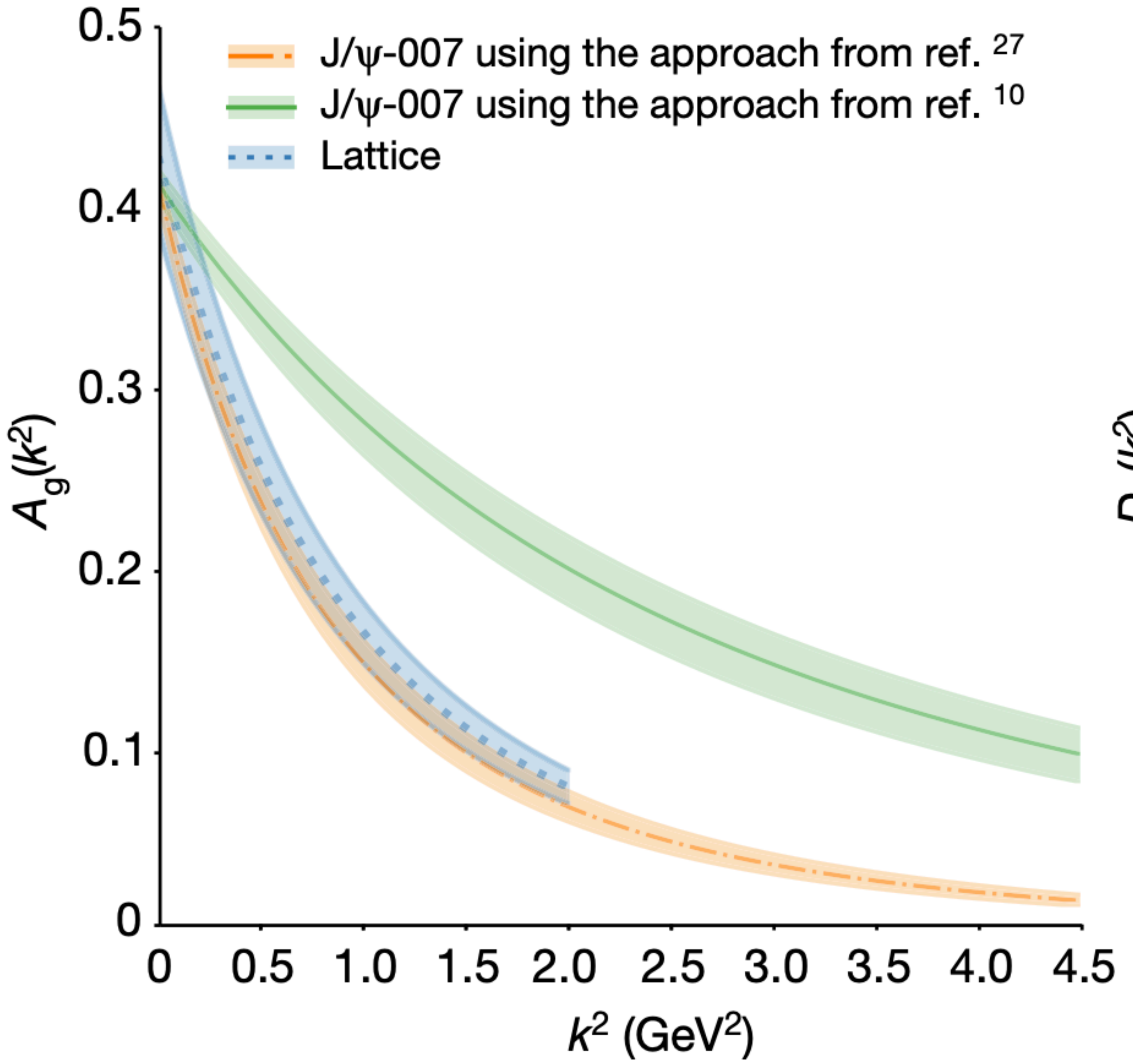
4% scale uncertainty

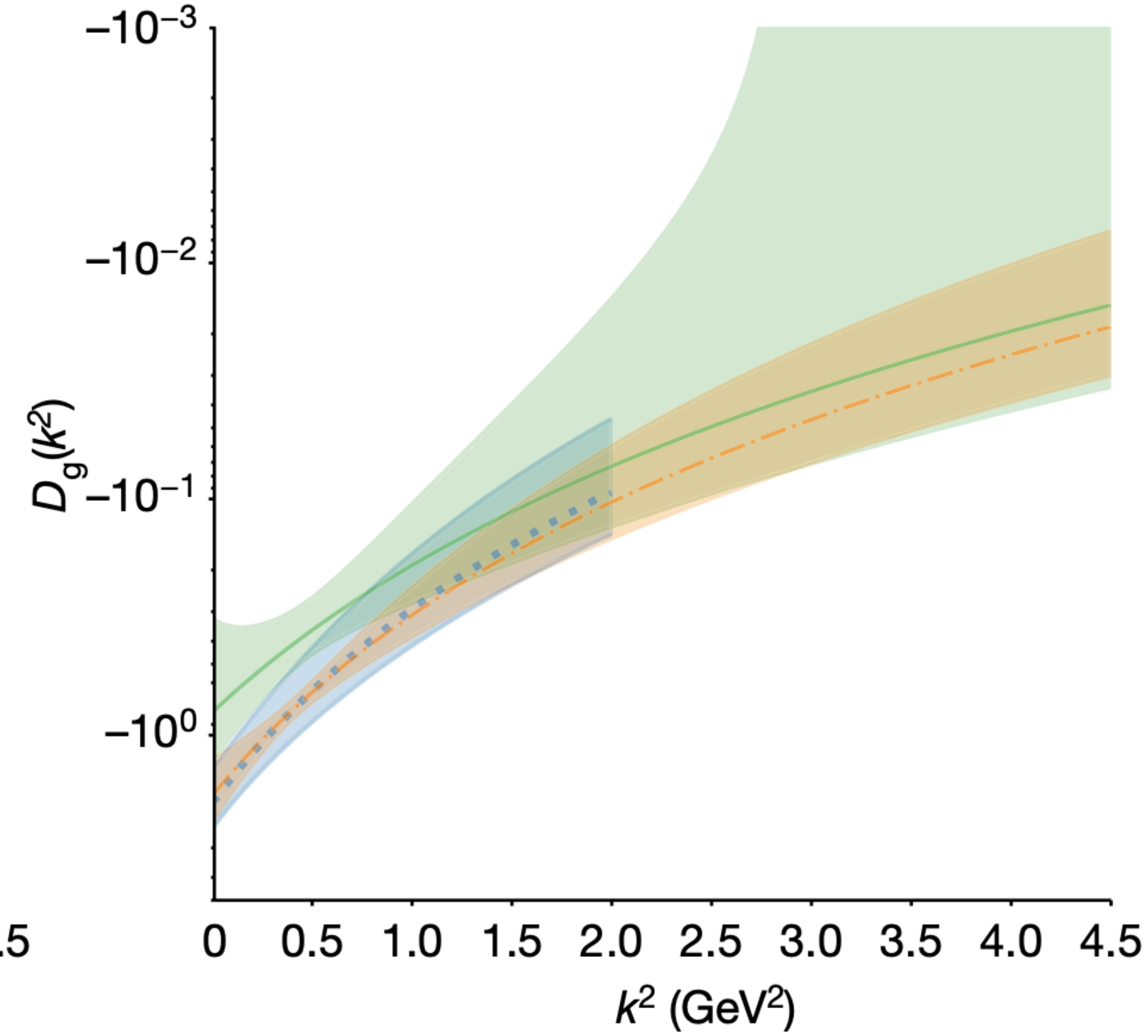
B. Duran *et* al., Nature volume 615, pages 813–816 (2023)

007[J/ψ]

A FIRST MODEL-DEPENDENT LOOK AT GFFS

Remarkable agreement between GFFs determined from data using the Holographic QCD approach and the direct Lattice QCD calculation!





Determined from experiment

Holographic QCD approach
GPD approach

Determined from theory

Lattice QCD calculation

Ref 27 (Holographic QCD): K. Mamo & I. Zahed, PRD 103, 094010 (2021) and 2204.08857 (2022)
Ref 10 (GPD Formalism): Y. Guo, X. Ji, Y. Liu, PRD 103, 096010 (2021)
Lattice: D. Pefkou, D, Hackett, P. Shanahan, Phys. Rev. D 105, 054509 (2022).

SoLID will be crucial to fully disentangle model assumptions from the underlying gluonic structure of the proton

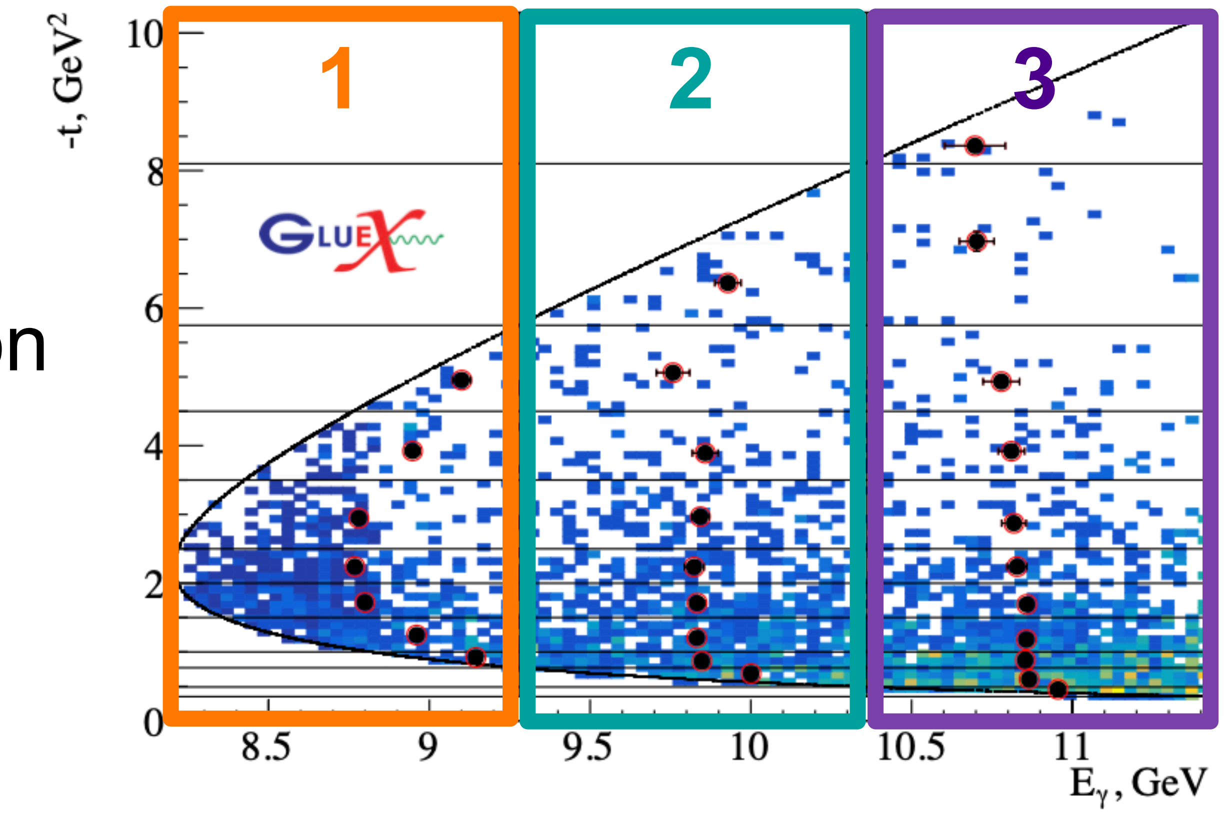
See talks by J. Swartz and S. Prasad tomorrow for latest preliminary results

S.Adhikari et al. (GlueX), Phys. Rev. C 108, 025201

LATEST GLUEX RESULTS

2.2k J/ψ (~ same as J/ψ-007 e+e- results)

Differential cross section in 3 E_γ slices



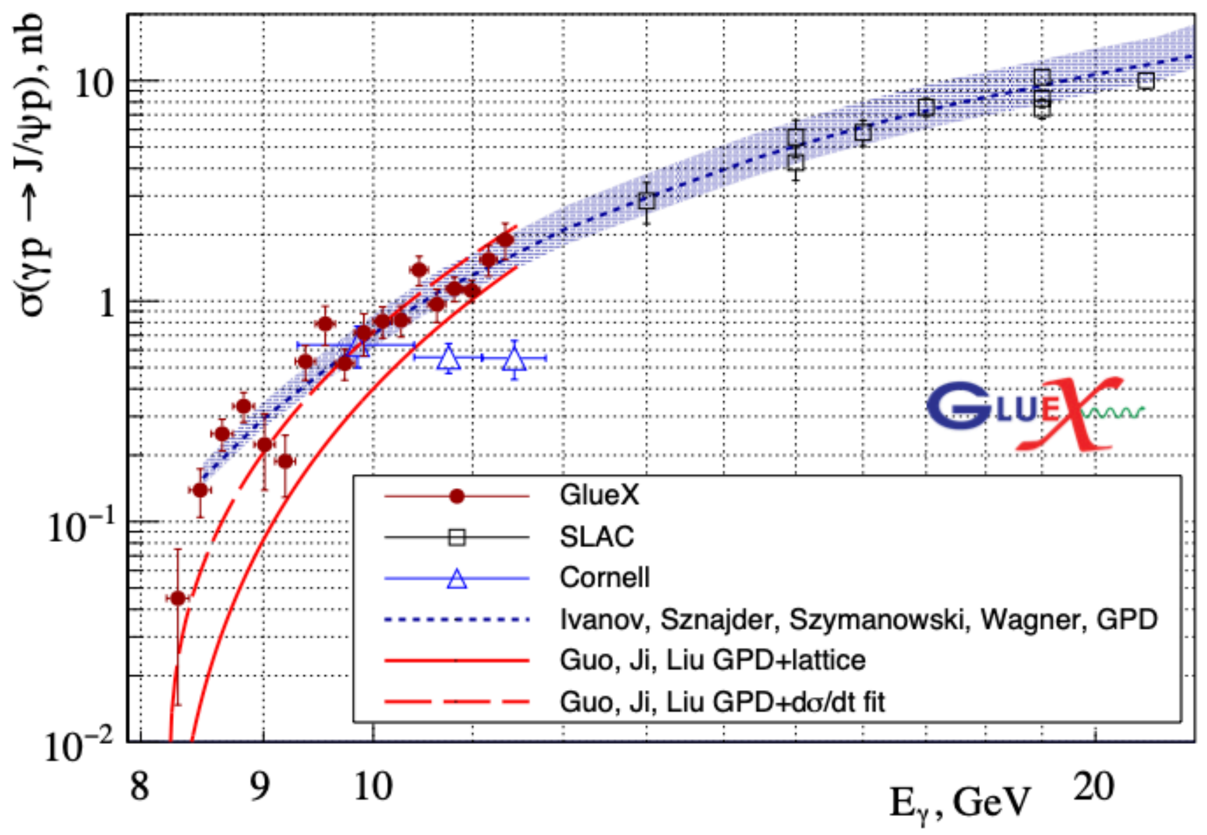
2-D differential cross section in 3 E_γ slices
E_γ ~ 8.2 - 11.44 GeV

(compared to 10 E_γ slices
E_γ ~ 9.1 - 10.6 GeV
for J/ψ-007)

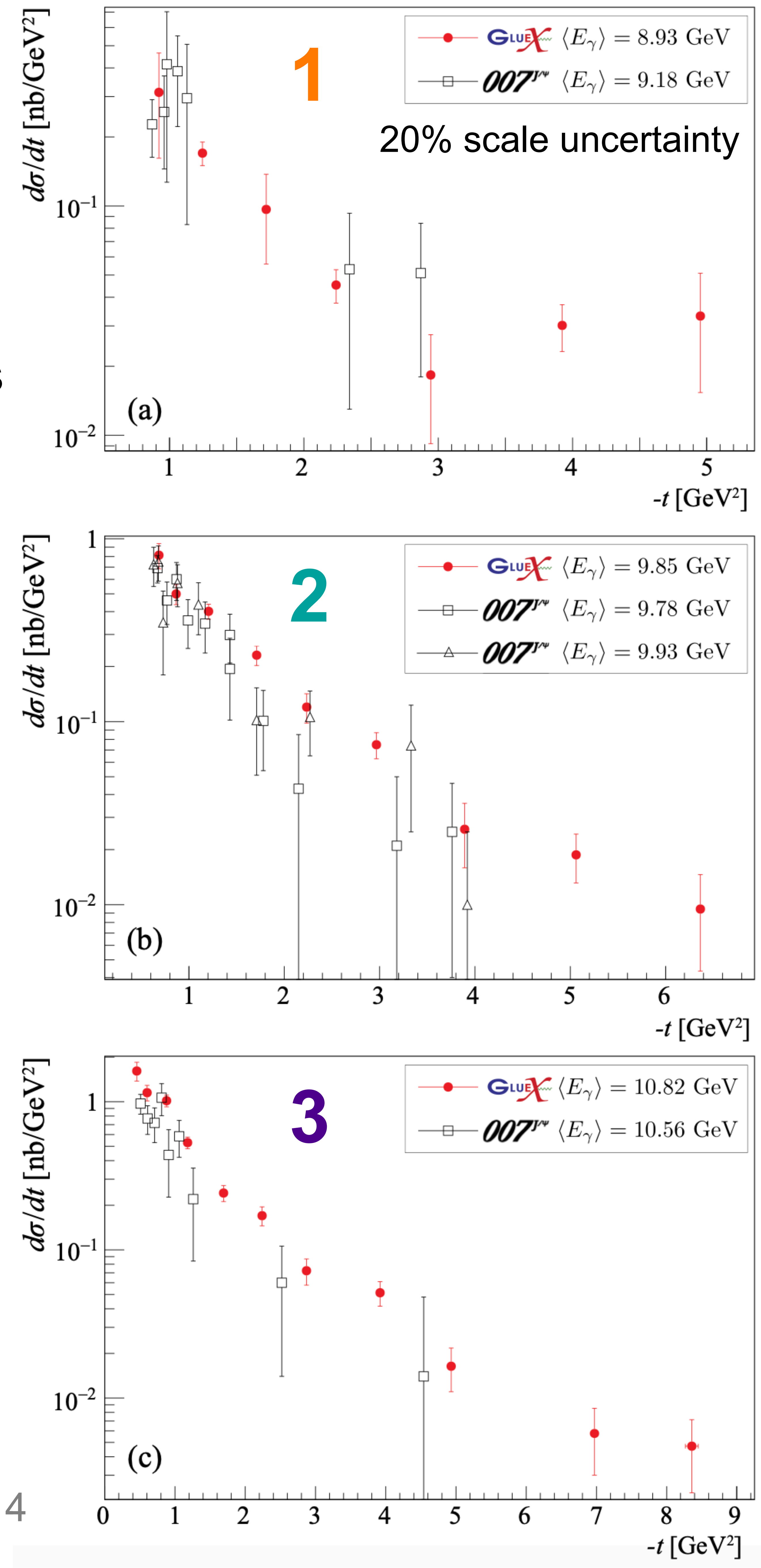
New GlueX results have 20% scale uncertainty.

Good agreement within errors with between GlueX and J/ψ-007

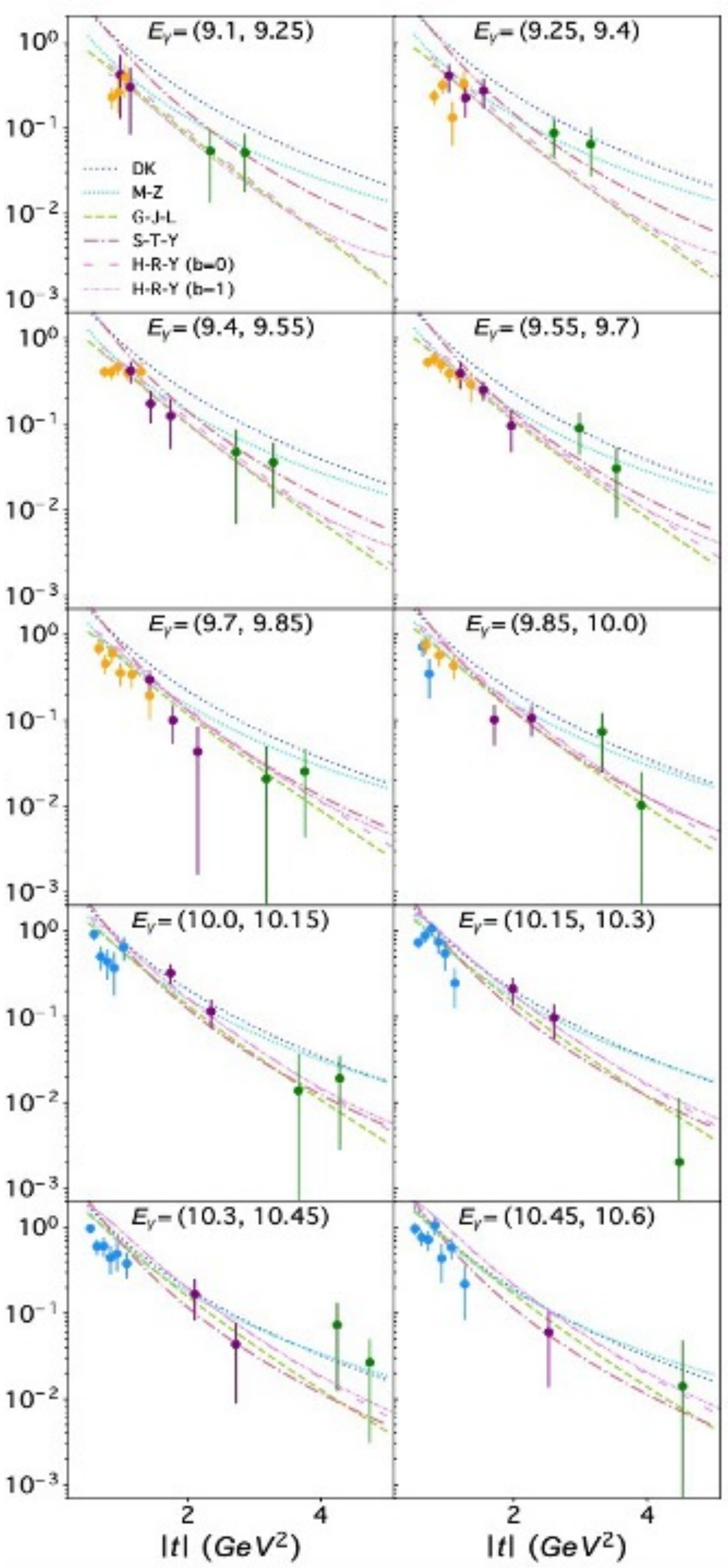
Integrated 1-D cross section



GlueX 2023



J/ψ-007 2023



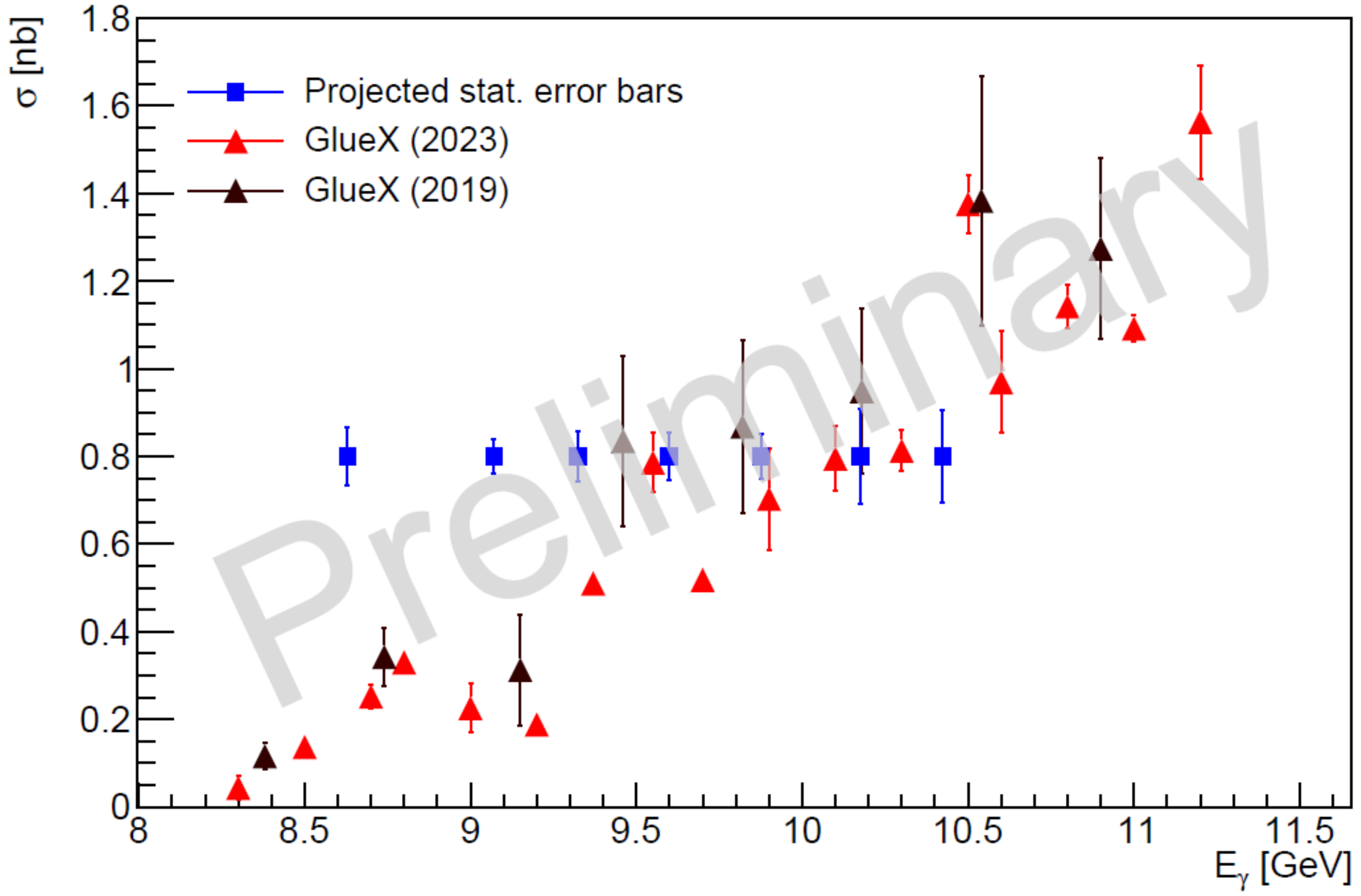
S. Joosten

Slide from Pierre Chatagnon

NEW CLAS12 RESULTS AND OUTLOOK

Projections for the full CLAS12 proton target dataset

- Projected statistics error bars based on full dataset available on proton target and expected 50% improvement for tracking.
- Maximum photon energy slightly smaller than GlueX.
- Projected error bars are competitive with GlueX.
- t-dependence will also be extracted.
- J/ψ photoproduction on neutron is also measured (Analysis by R. Tyson, U. of Glasgow).



Including all data taken on unpolarized proton and improved tracking efficiency

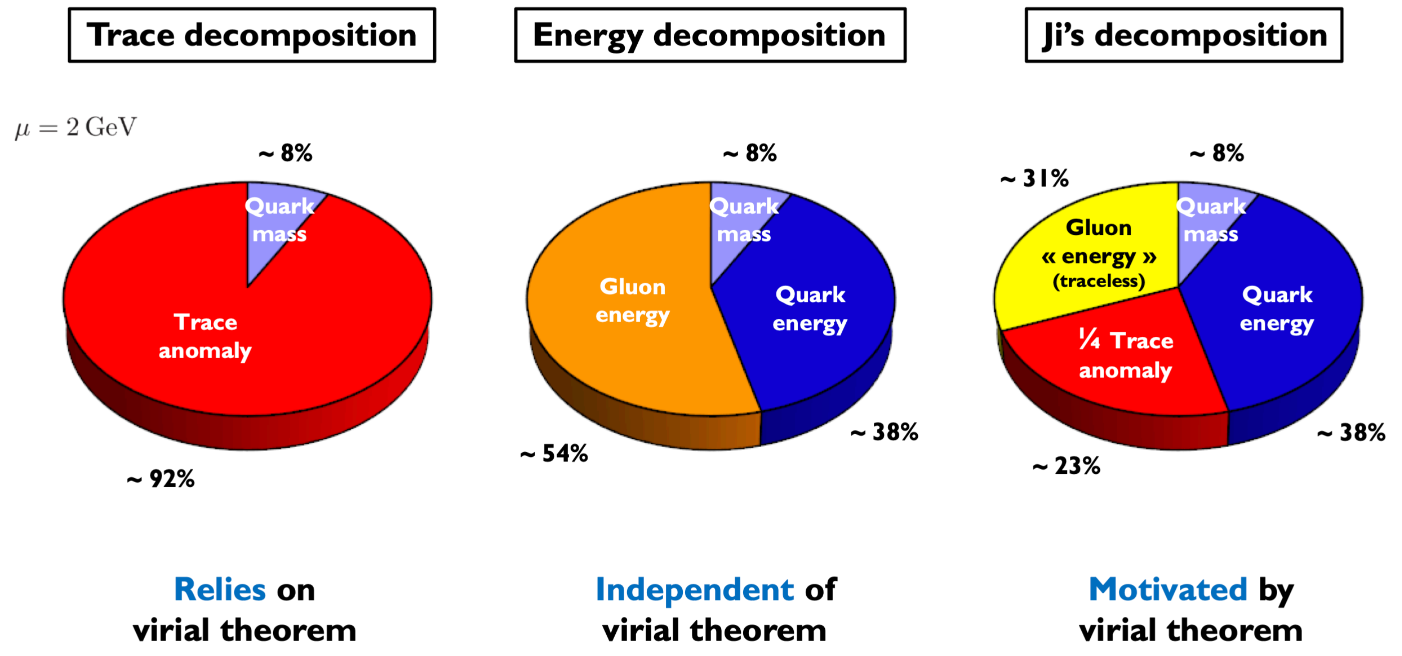
Jefferson Lab clas

J/Ψ EXPERIMENTS AT JLAB COMPARED

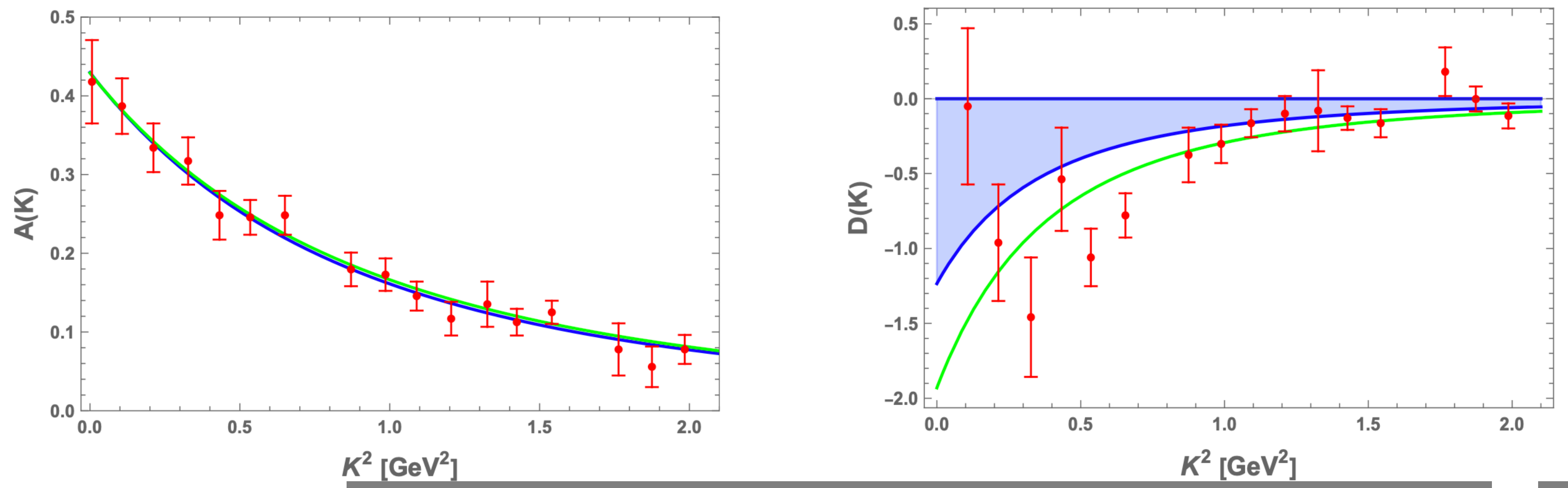
	GlueX HALL D	HMS+SHMS HALL C	CLAS 12 with upgrade[1] HALL B	SoLID HALL A
J/ψ counts (photo-prod.)	469 published ~10k phase I + II	2k electron channel 2k muon channel	14k	804k
J/ψ Rate (electro-prod.)	N/A	N/A	1k	21k
Features	Good reach to threshold.	Can reach high-t only at higher energies. Low statistics.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

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

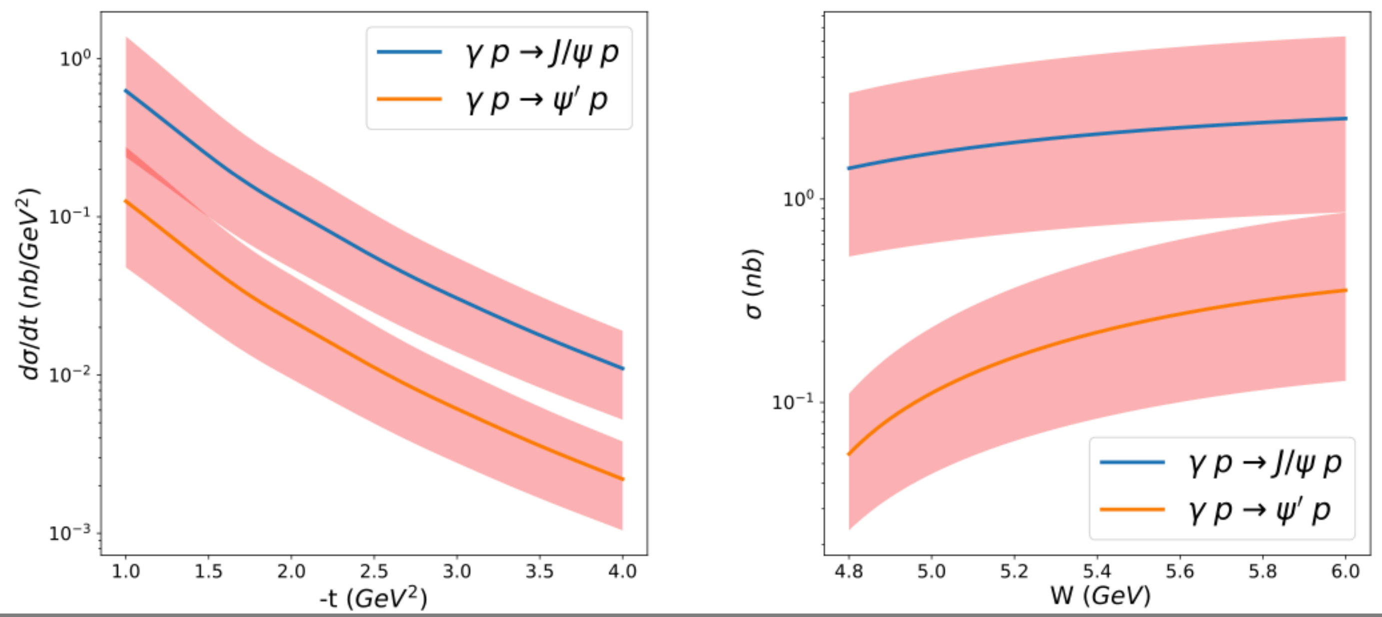
PROMINENT RECENT DEVELOPMENTS



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

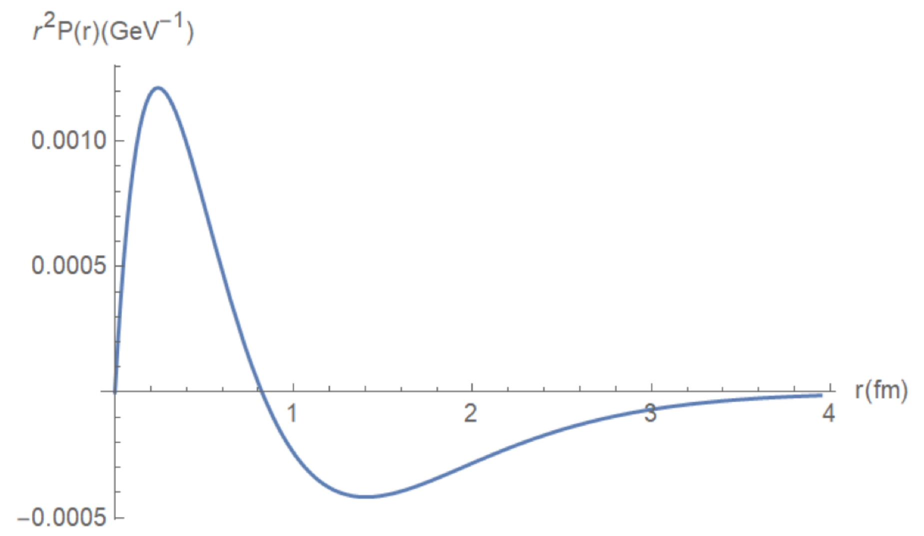


Proton gravitational form factors holographic QCD compared with Lattice, K. Mamo & I. Zahed (2022)

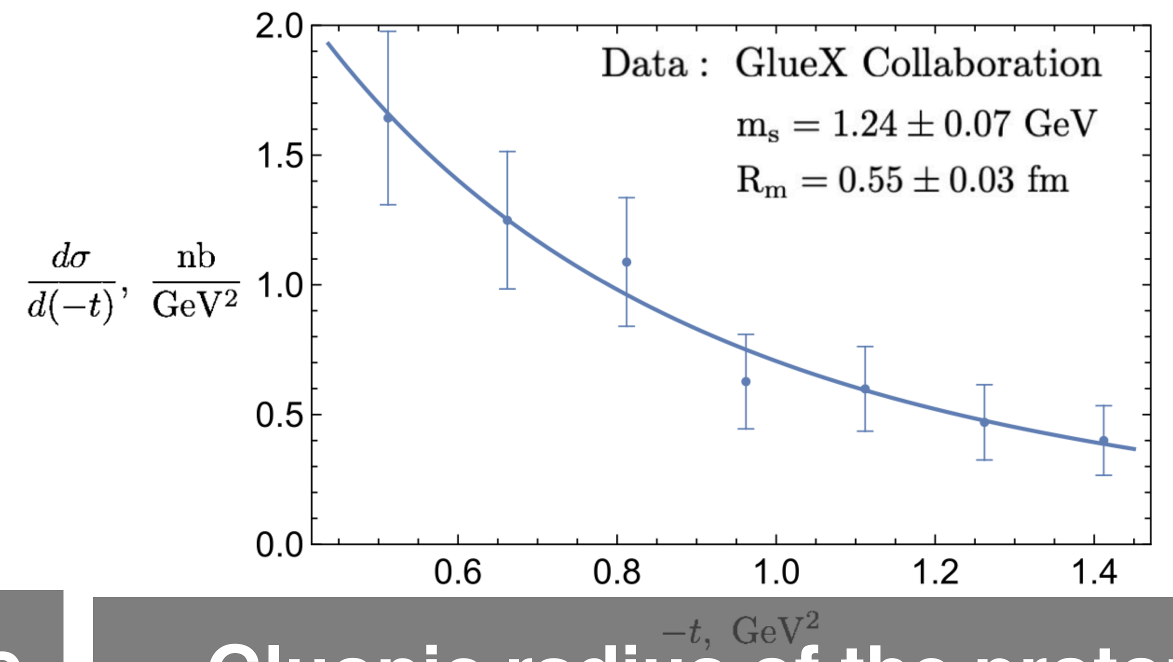


Near-threshold heavy quarkonium production at large momentum transfer, P. Sun, X-B. Tong, F. Yuan (PRD 2022)

- 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)

$\gamma\, p \rightarrow \gamma^*(e^- e^+)\, p'$

RUN GROUP: TIMELIKE COMPTON SCATTERING AT SOLID

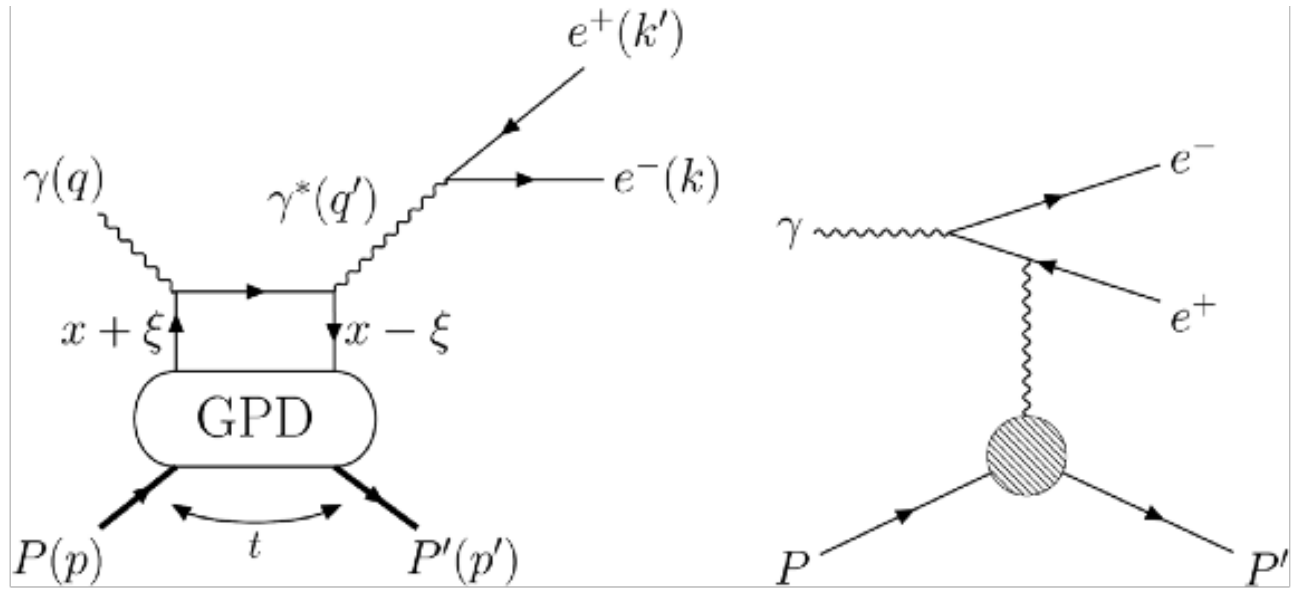
Run group proposal E12-12-006A, approved in 2015

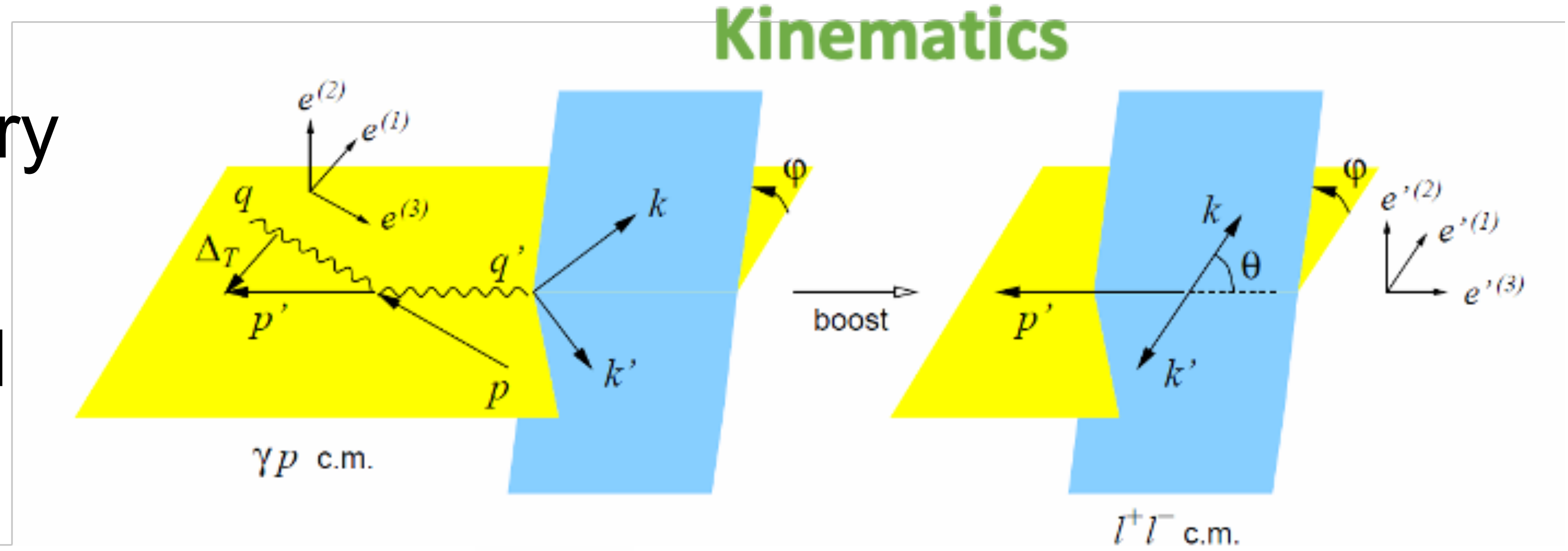
Motivation

- Channel to access GPDs complimentary to DVCS, can test universality
- New observables to better constrain global GPD fits

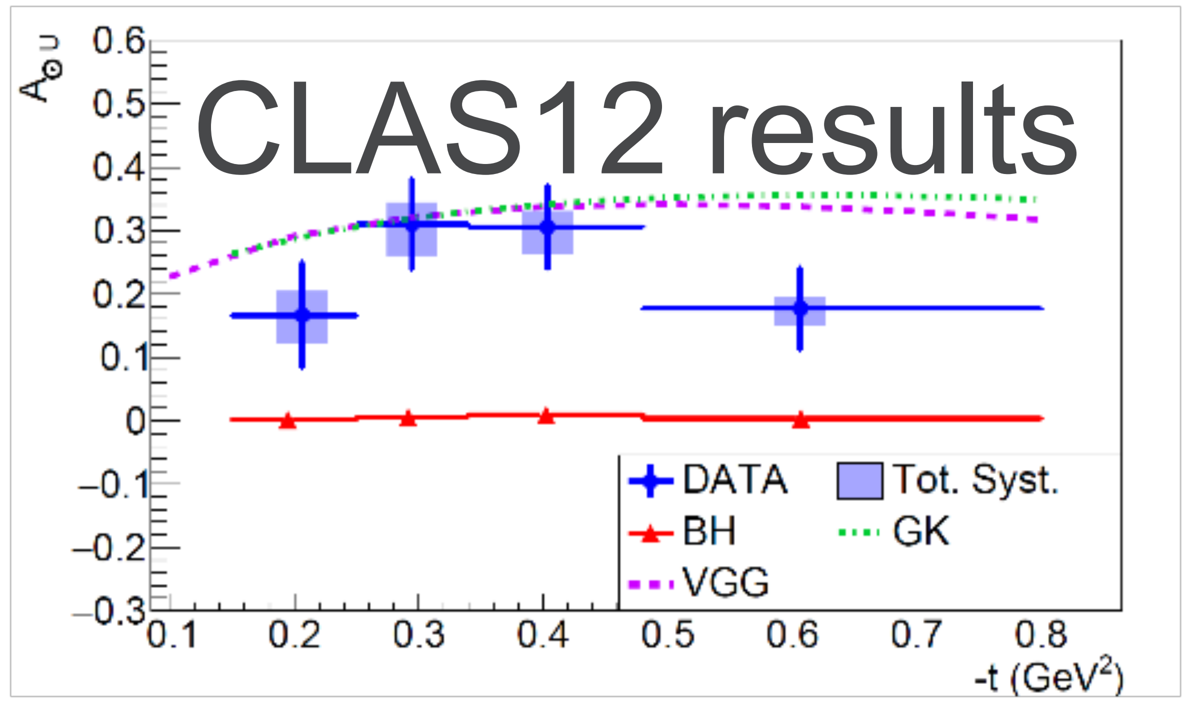
Current experimental status

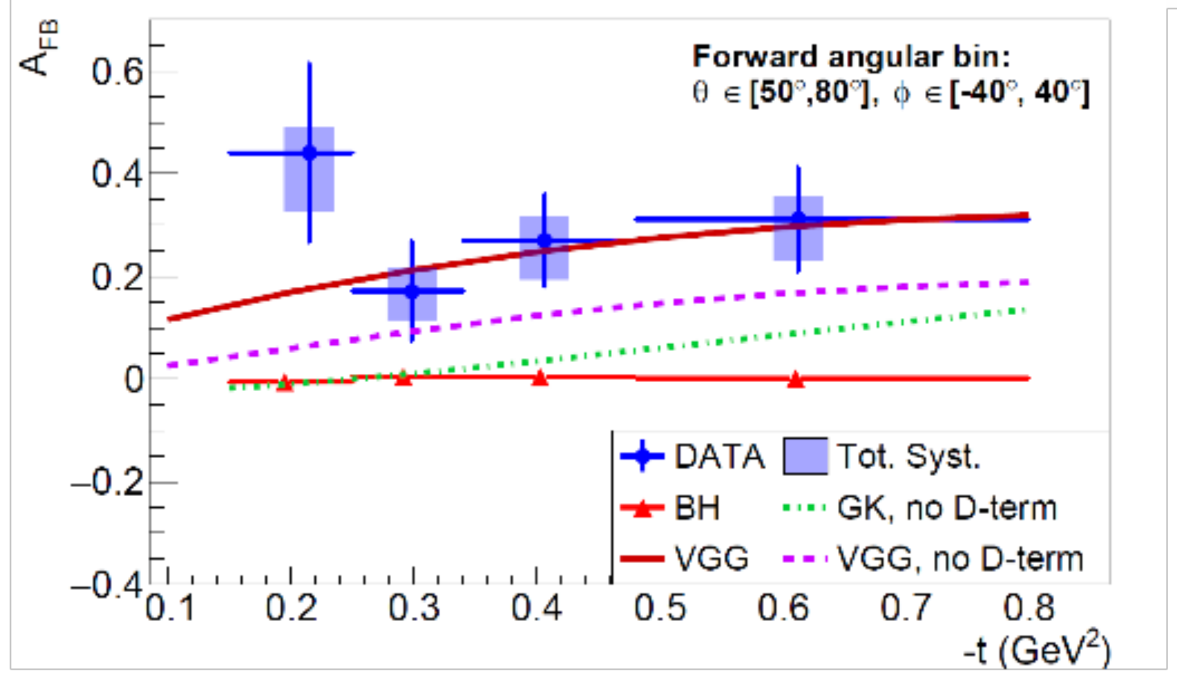
- Channel explored at CLAS6
- First results from CLAS12 published in PRL 127, 262501 (2021)
  - Used TCS and Bethe-Heitler interference to obtain nonzero beam polarized asymmetry A_{LU} and forward backward asymmetry A_{FB}
  - Consistent with DVCS-data-constrained GPD model predictions for the imaginary and real parts of GPD H and support universality
  - Limited by statistical precision

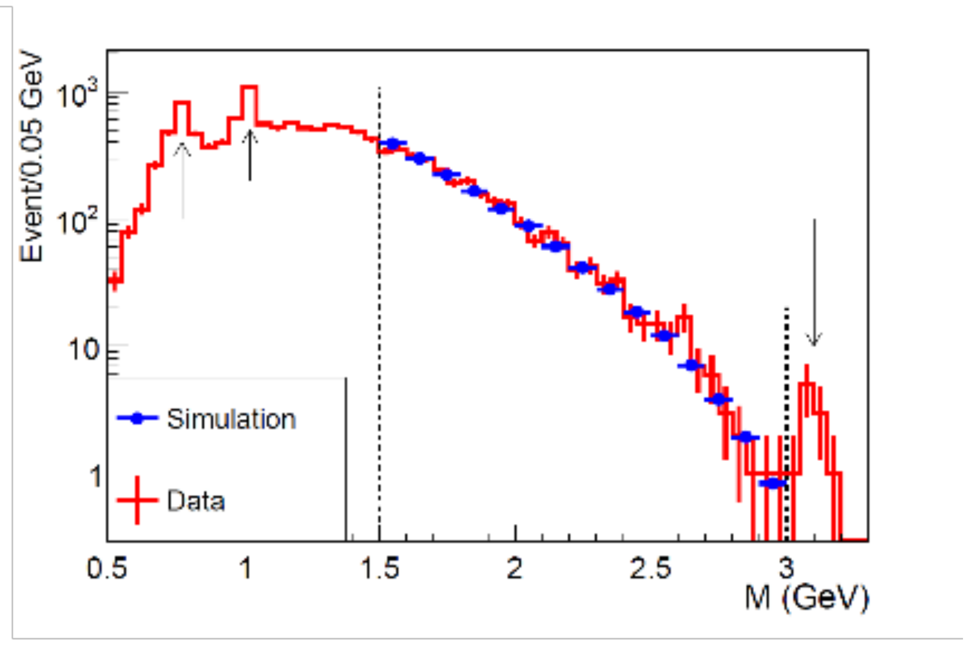




CLAS12 results







TCS Spokespeople: Marie Boer, Pawel Nadel-Turonski, Jixie Zhang, Zhiwen Zhao

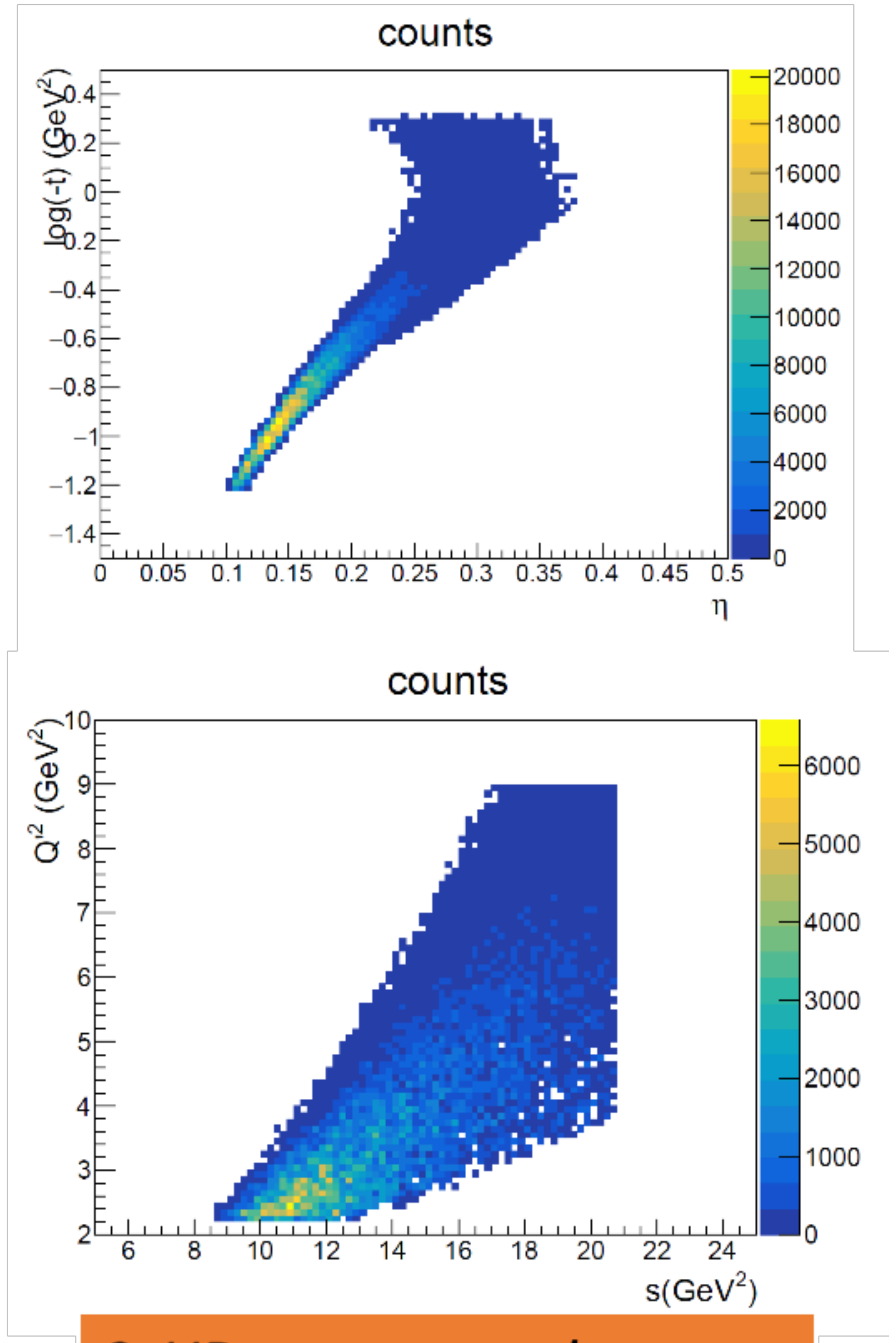
$\gamma\, p \rightarrow \gamma^*(e^- e^+)\, p'$

RUN GROUP: TIMELIKE COMPTON SCATTERING AT SOLID

Run group proposal E12-12-006A, approved in 2015

Advantages of measuring TCS at SoLID

- At least 1 order larger statistics than CLAS12
- Usher TCS study into precision era with multi-dimensional binning
  - SoLID TCS has 250 times more integrated luminosity than the CLAS12 TCS published result
  - SoLID acceptance for TCS events is about ¼ of CLAS12, But with full azimuthal symmetry
- SoLID TCS will allow NLO corrections to be studied and is in synergy with EIC at low x



SoLID coverage and counts

This work is supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under contract DE-AC02-06CH11357.

CONCLUSION

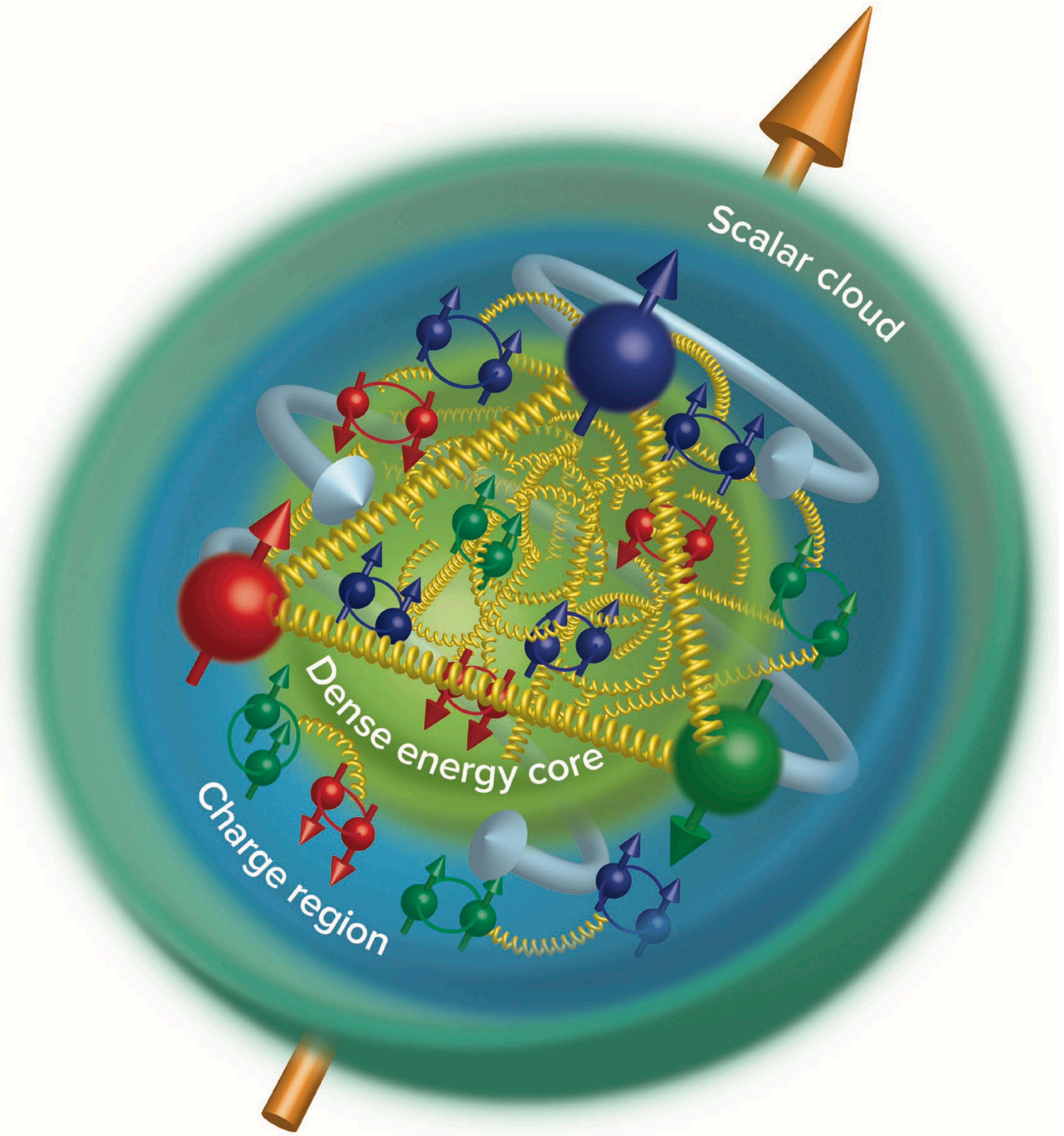
The JLab 12-GeV program has delivered important first results on near-threshold J/ψ production from GlueX and Hall C (J/ψ-007)

- A new window on the gluonic structure of the proton
- Does the proton appears to have a dense energy core
- What are the implications of a possible scalar gluonic cloud?

The planned near-threshold J/ψ production program with SoLID-J/ψ is crucial to further our understanding of the origin of mass.

- SoLID can reach J/ψ observables that cannot be achieved anywhere else, including precision measurements at high t and precision electroproduction near threshold.

The mass structure of the nucleons and nuclei is a rapidly evolving topic, reaching from Jefferson Lab to the EIC



QUESTIONS?

This work is supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under contract DE-AC02-06CH11357.

COLLABORATION

SoLID: a large collaboration!

SOLENOIDAL LARGE INTENSITY DEVICE

270+ collaborators from 70+ institutions in 13 countries

SoLID-J/ψ Spokespeople

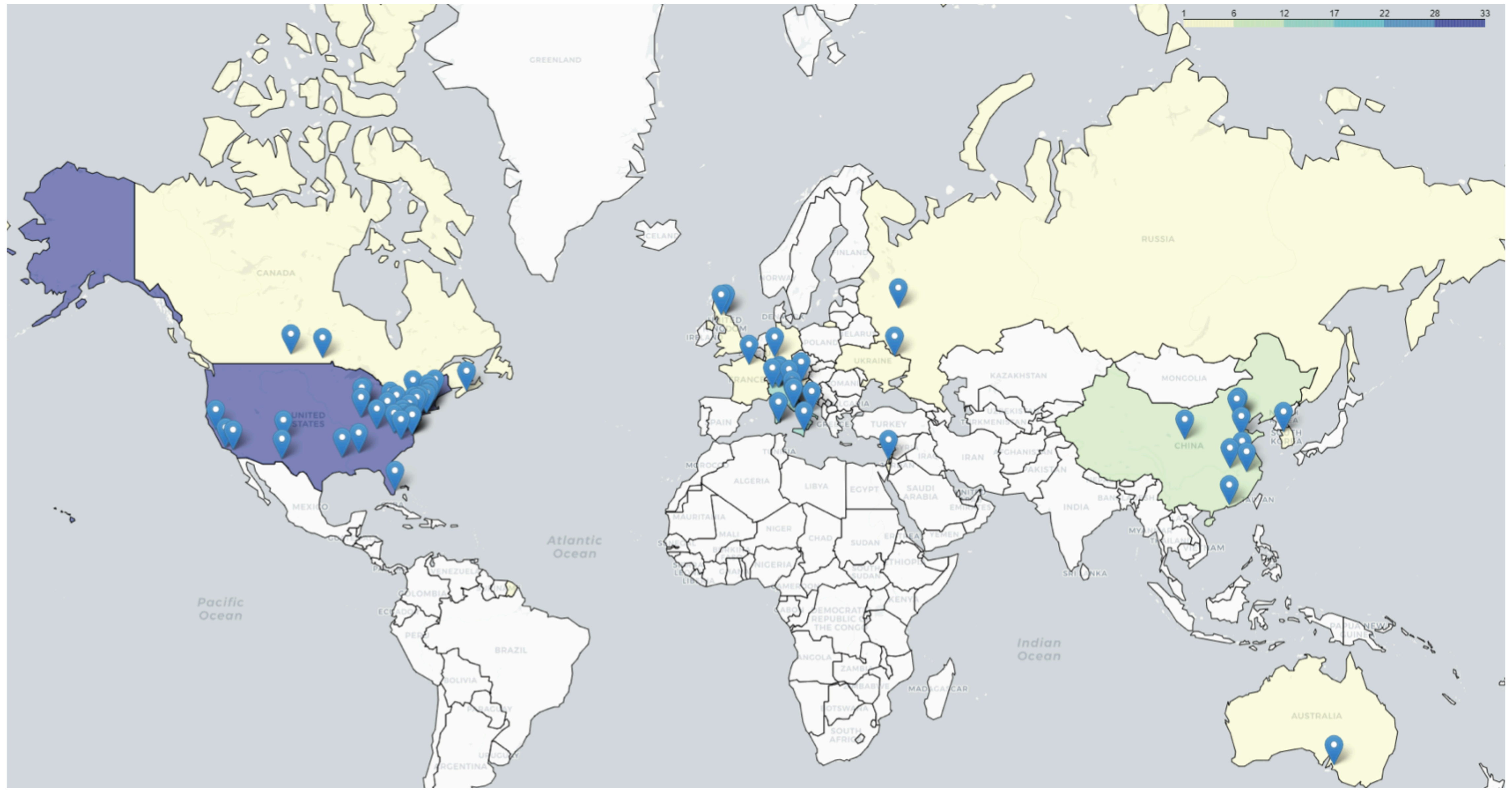
Sylvester Joosten (ANL)

Zein-Eddine Meziani (ANL)

Xin Qian (BNL)

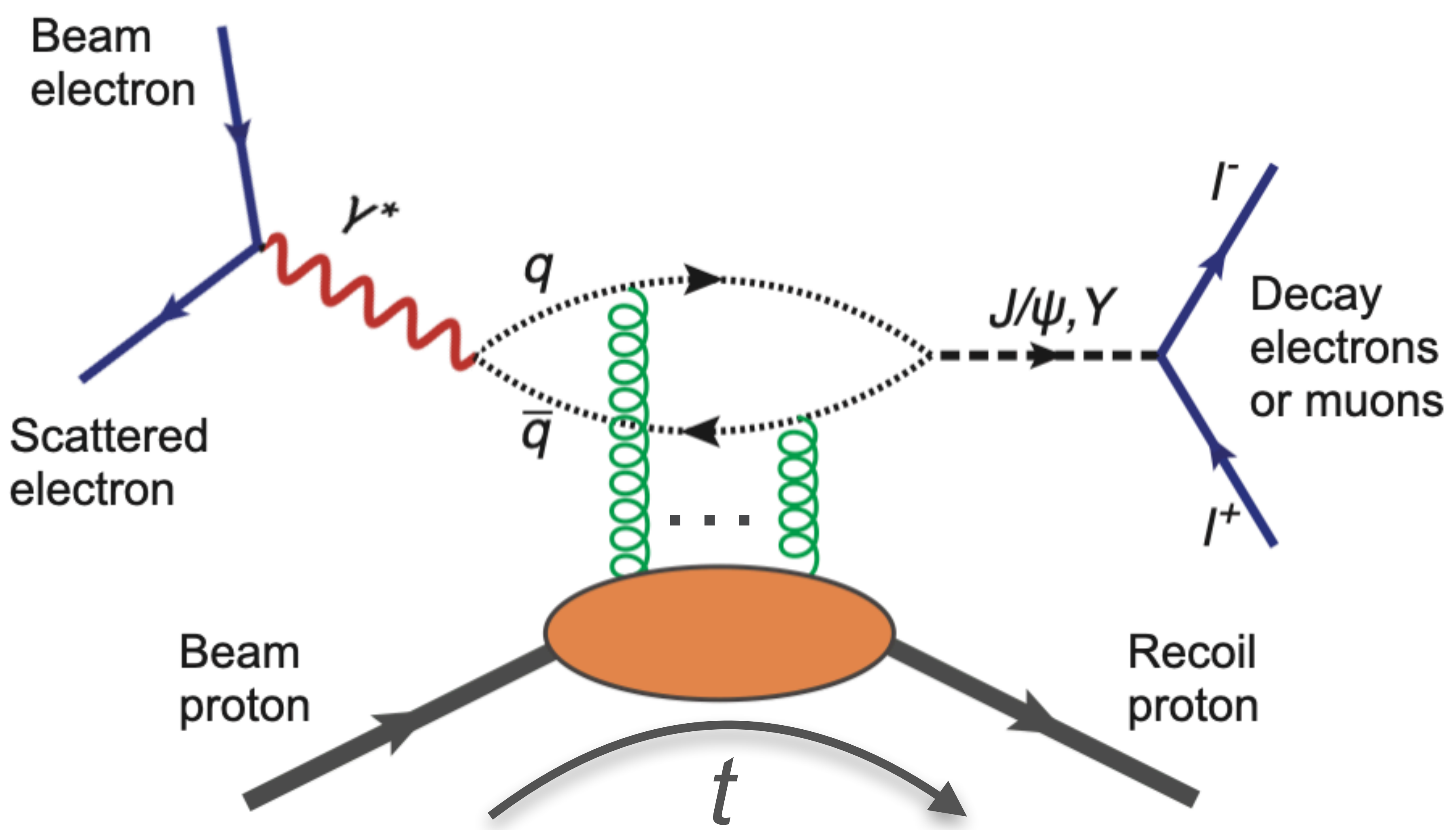
Nikos Sparveris (Temple University)

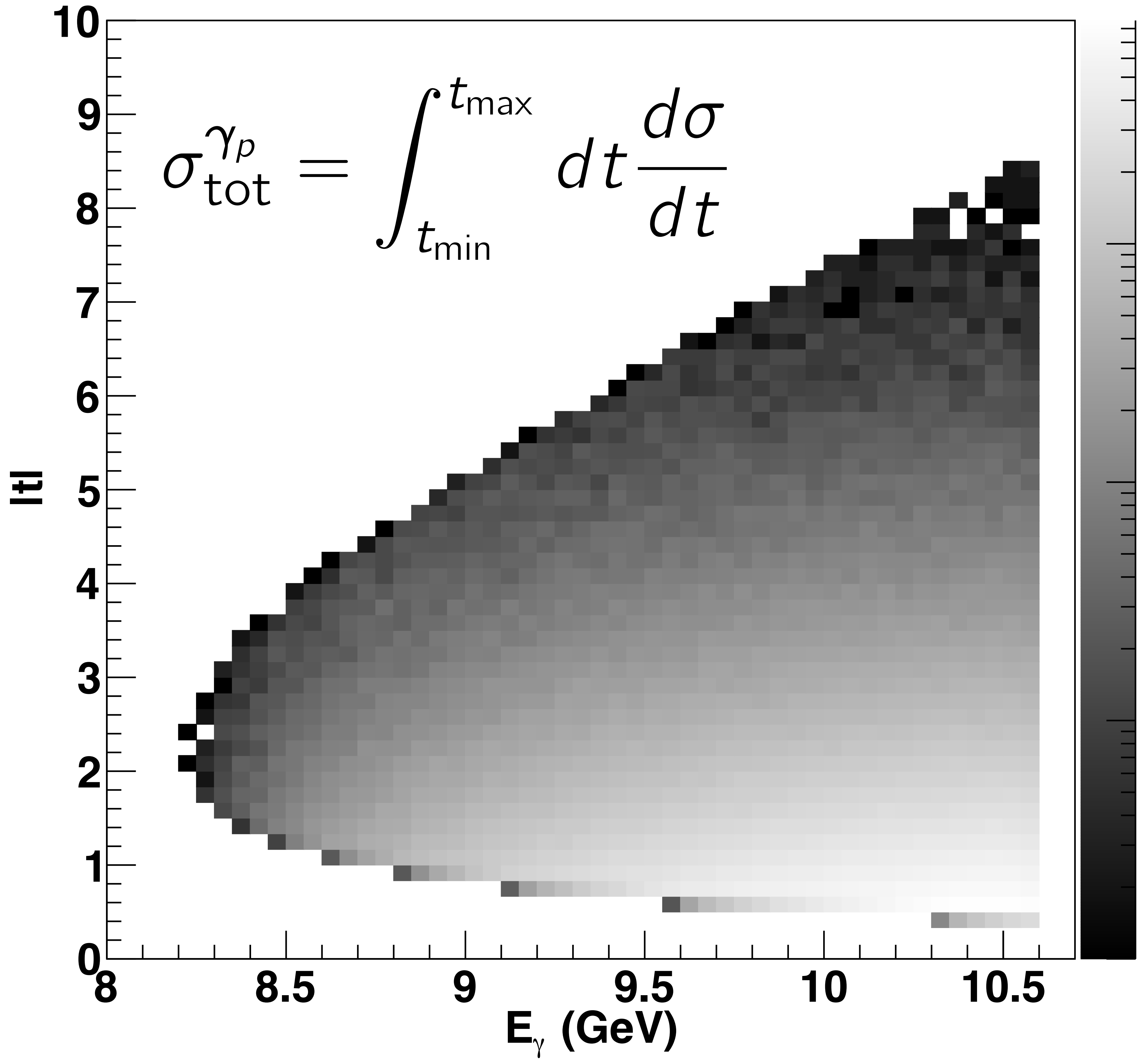
Zhiwen Zhao (Duke University)



EXCLUSIVE QUARKONIUM PRODUCTION

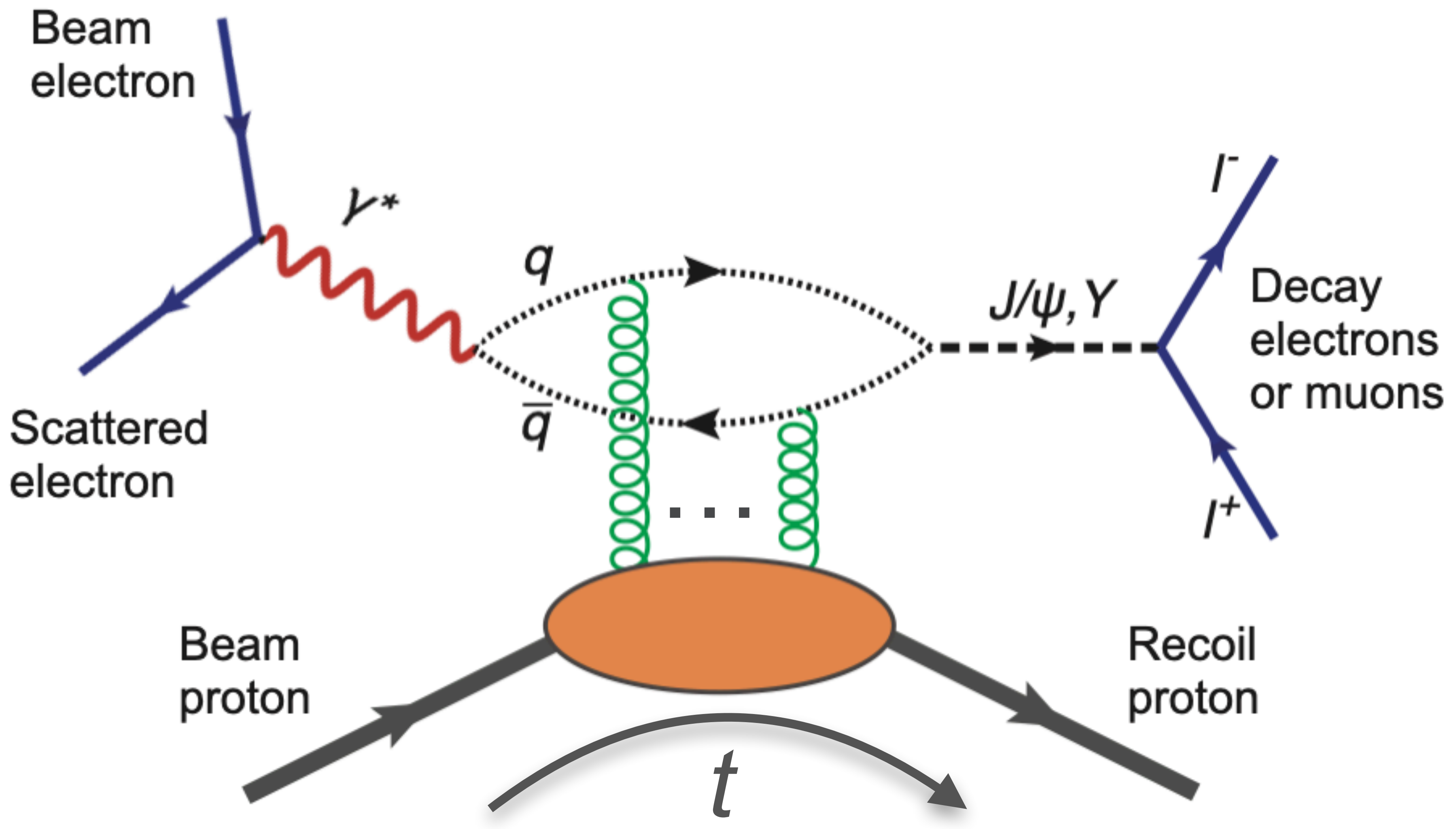
The basics





EXCLUSIVE QUARKONIUM PRODUCTION

The basics



J/ψ threshold:

$W \approx 4.04\text{GeV}$

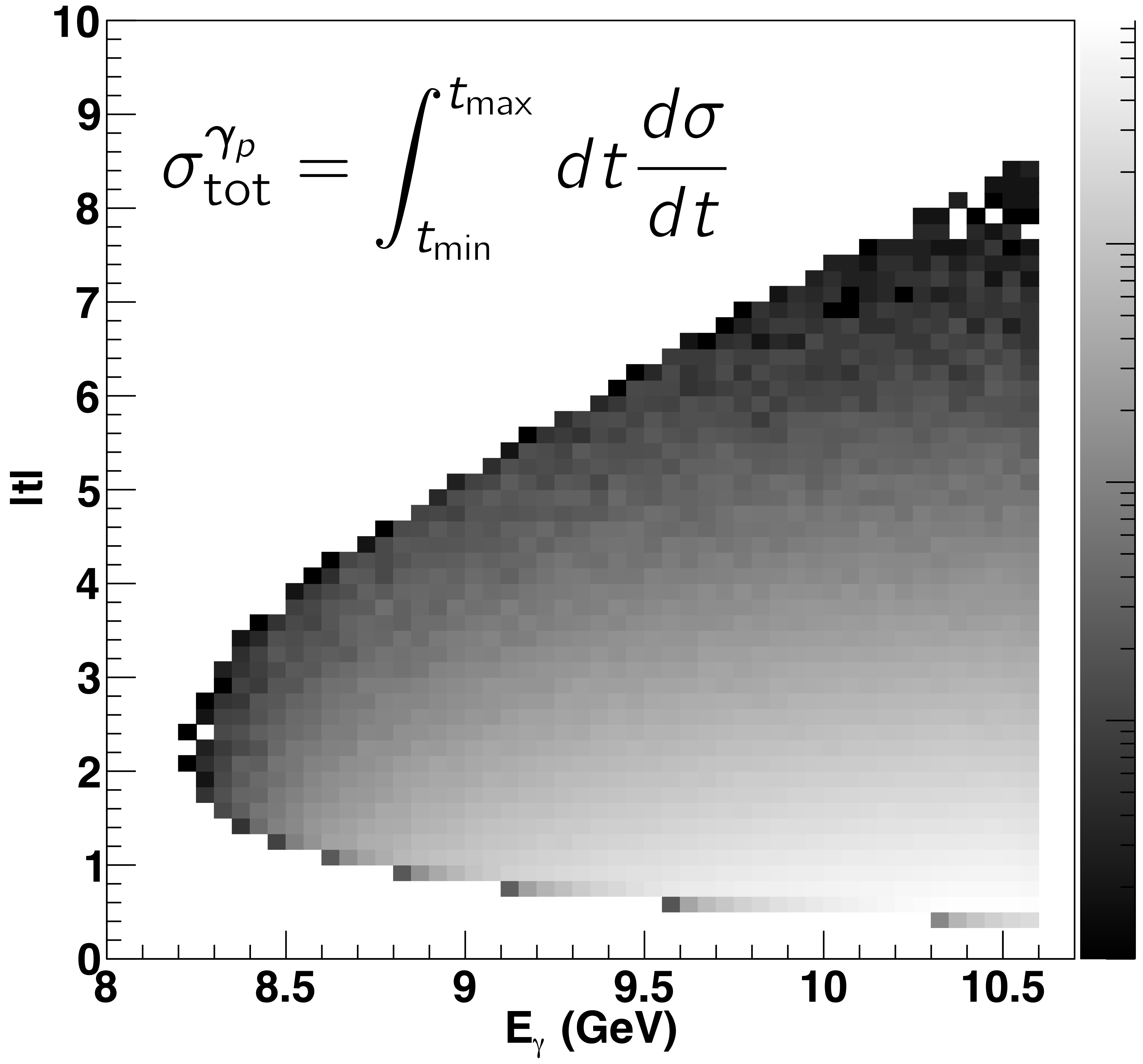
$E_\gamma^{\text{lab}} \approx 8.2\text{GeV}$

$t \approx -1.5\text{GeV}^2$

Υ(1S) threshold:

$W \approx 10.4\text{GeV}$

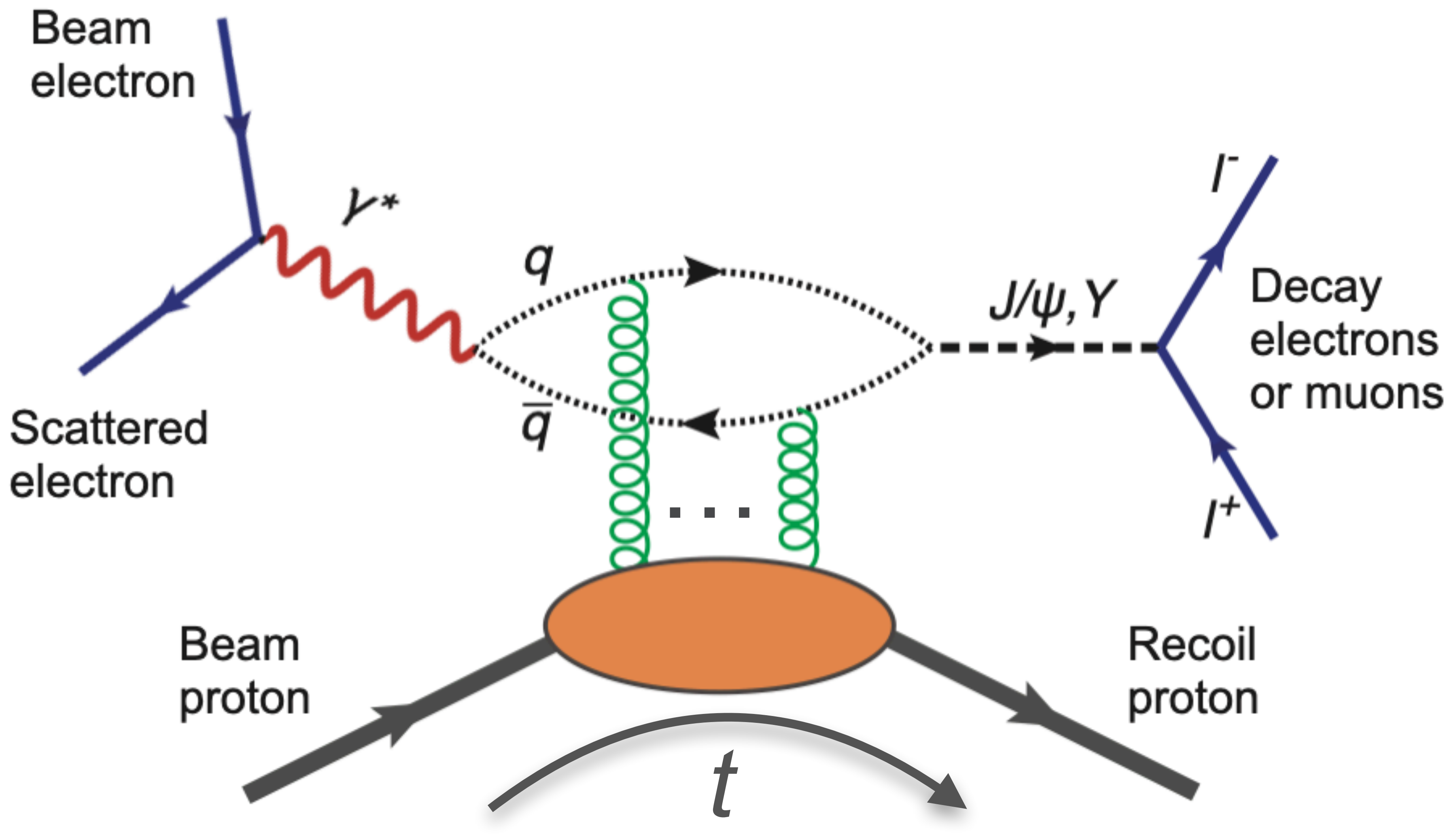
$t \approx -8.1\text{GeV}^2$



- Phase space limits defined by quarkonium direction

EXCLUSIVE QUARKONIUM PRODUCTION

The basics



J/ψ threshold:

$$W \approx 4.04\text{GeV}$$
$$E_\gamma^{\text{lab}} \approx 8.2\text{GeV}$$
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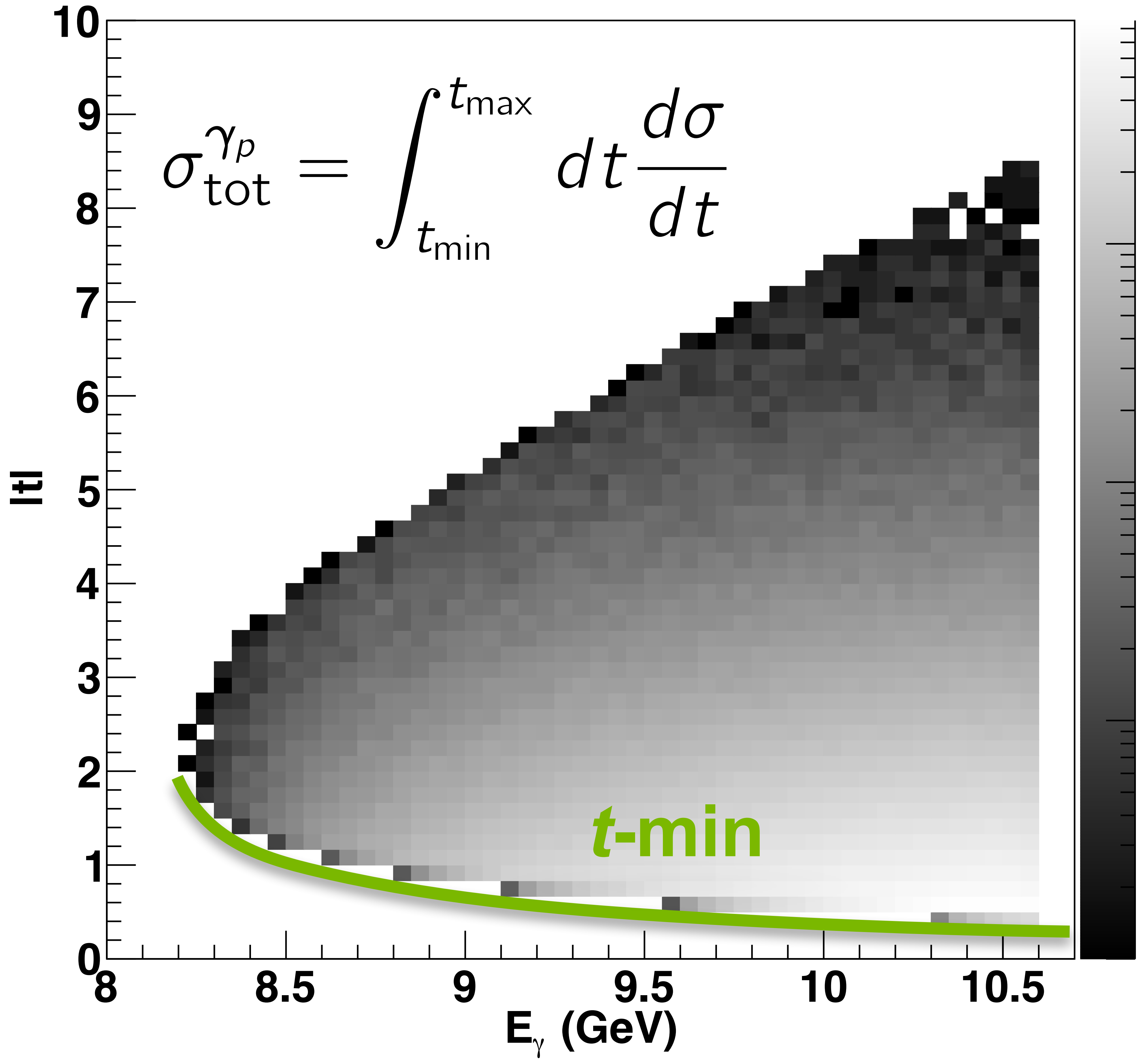
$\Upsilon(1S)$ threshold:

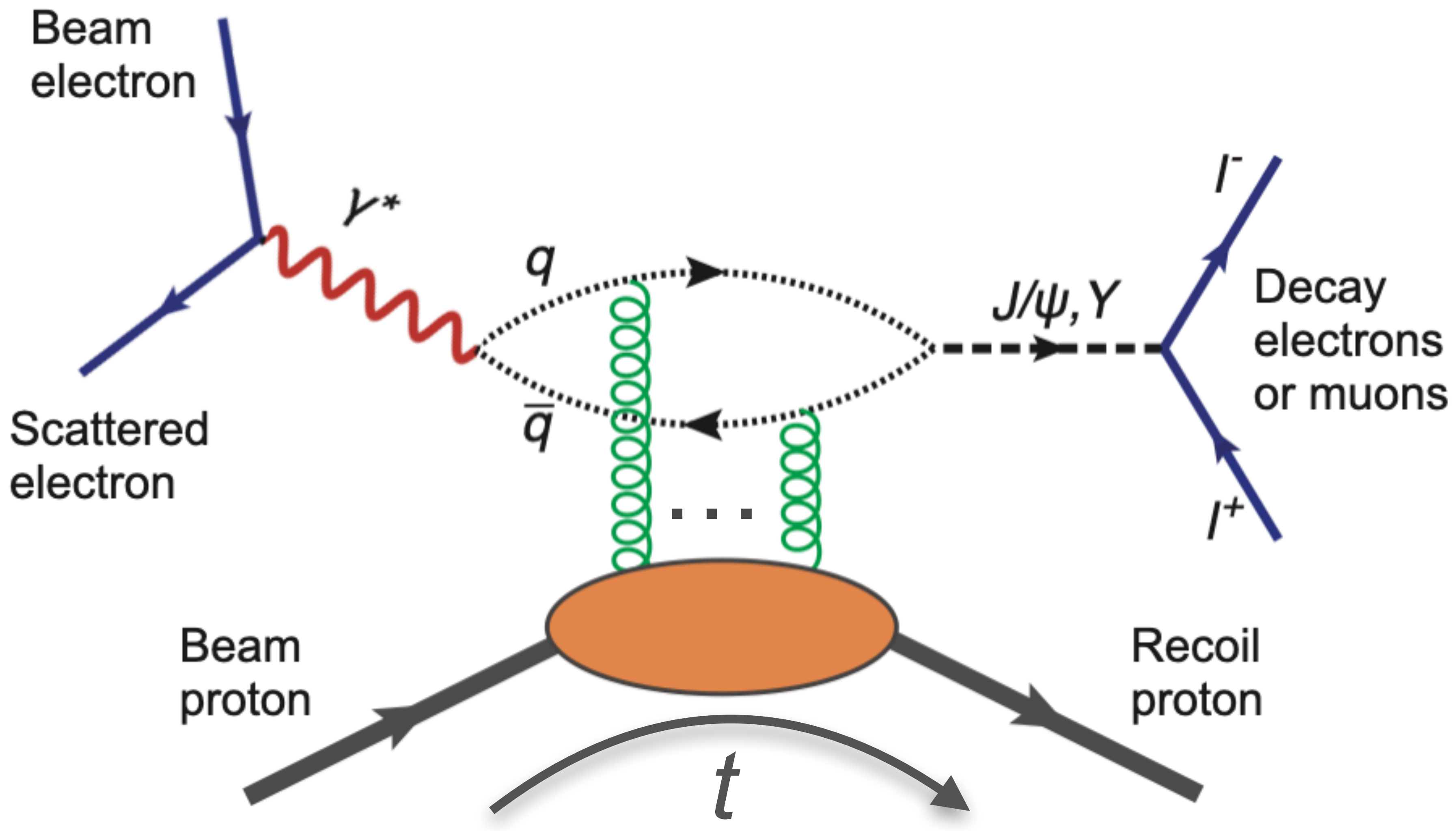
$$W \approx 10.4\text{GeV}$$
$$t \approx -8.1\text{GeV}^2$$



- Phase space limits defined by quarkonium direction
  - Forward (with photon): $t = t_{\text{min}}$

EXCLUSIVE QUARKONIUM PRODUCTION

The basics



J/ψ threshold:

$W \approx 4.04\text{GeV}$

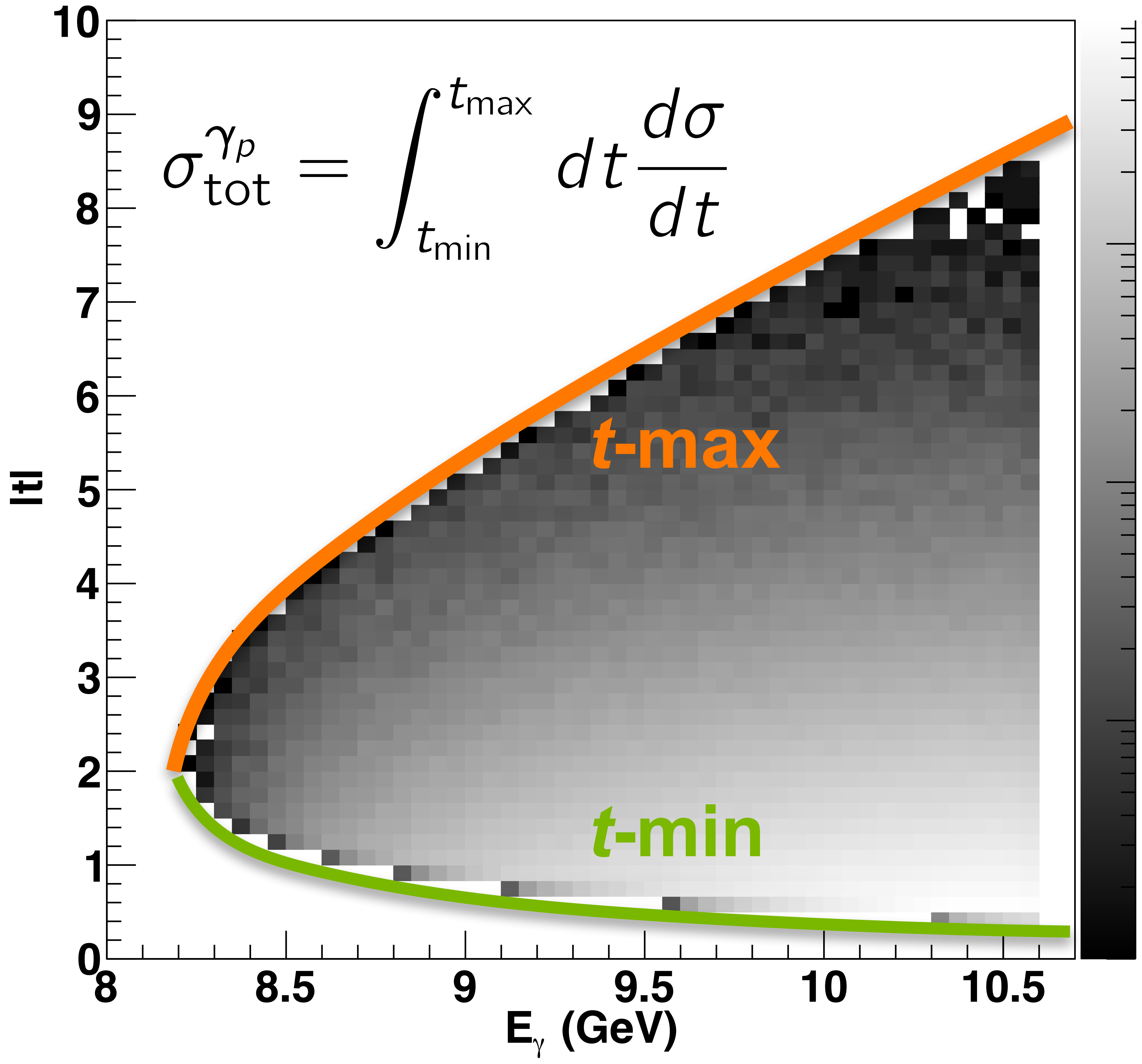
$E_\gamma^{\text{lab}} \approx 8.2\text{GeV}$

$t \approx -1.5\text{GeV}^2$

$Y(1S)$ threshold:

$W \approx 10.4\text{GeV}$

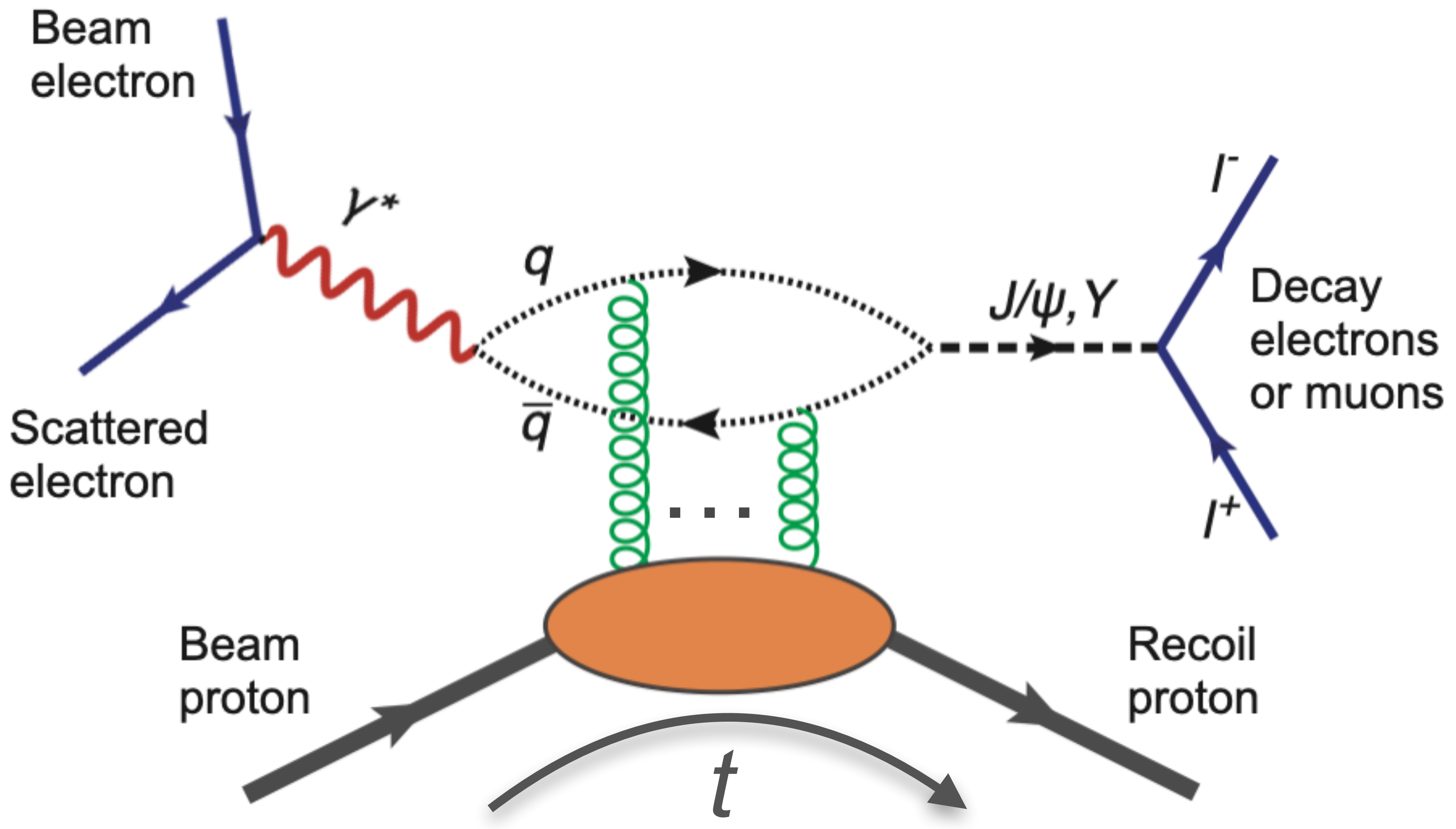
$t \approx -8.1\text{GeV}^2$



- Phase space limits defined by quarkonium direction
  - Forward (with photon): $t = t_{\text{min}}$
  - Backward (with proton): $t = t_{\text{max}}$

EXCLUSIVE QUARKONIUM PRODUCTION

The basics



J/ψ threshold:

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Υ(1S) threshold:

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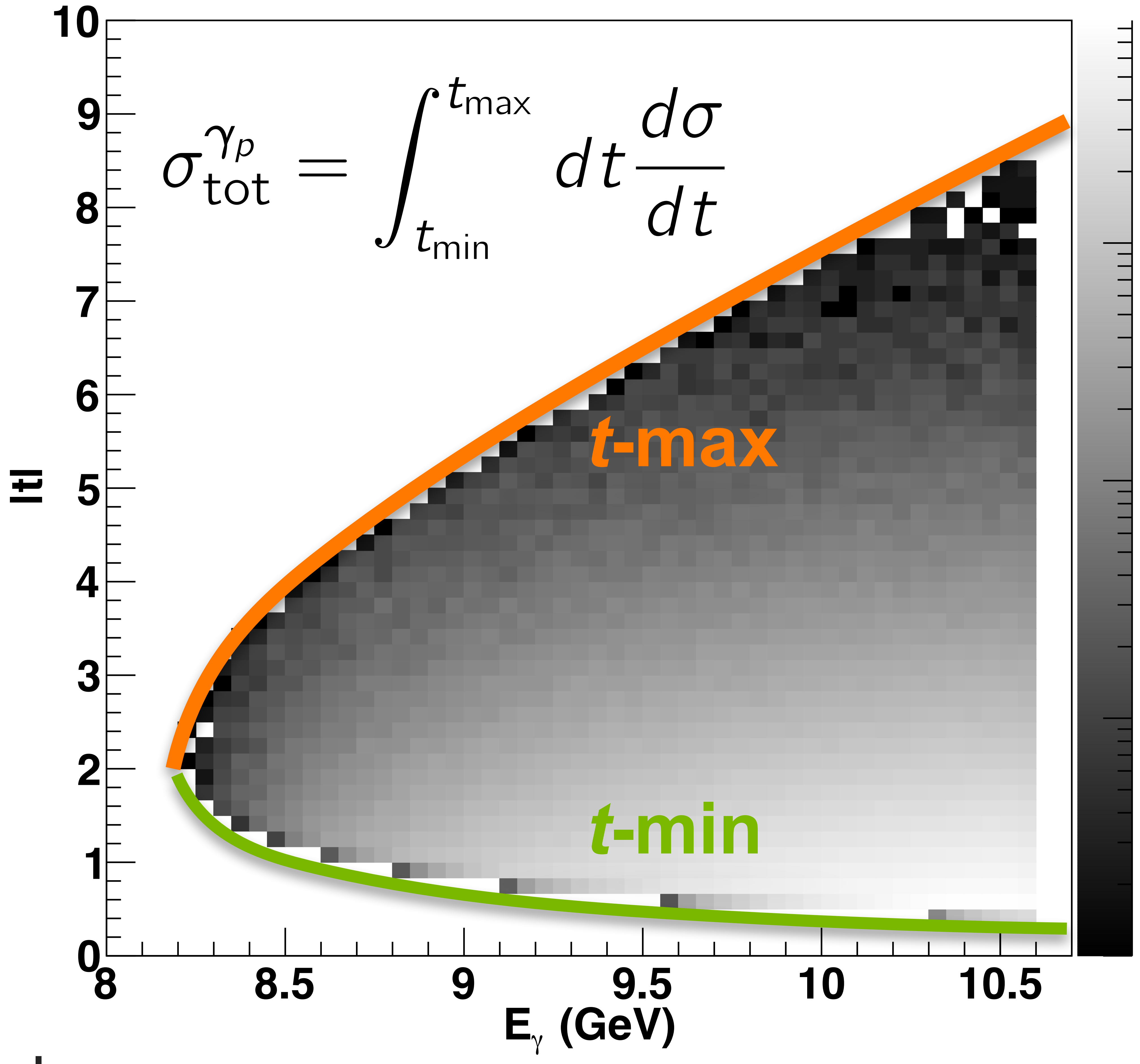
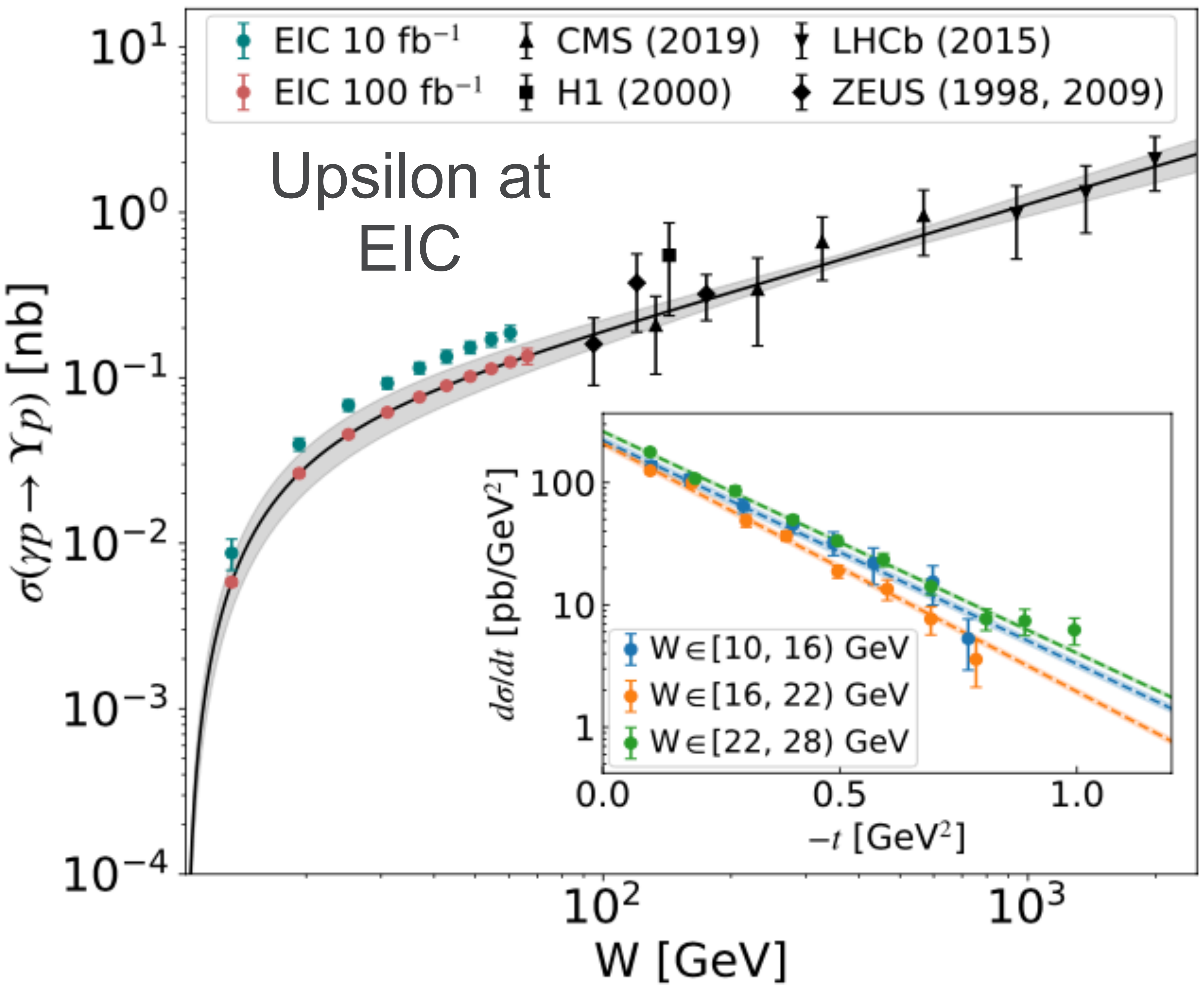


- Phase space limits defined by quarkonium direction
  - Forward (with photon): $t = t_{\min}$
  - Backward (with proton): $t = t_{\max}$
- Forward direction preferred: *t*-dependence ~exponential

COMPLEMENTARITY WITH EIC

J/ψ at SoLID and Υ at EIC

- 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



NEW CLAS12 RESULTS AND OUTLOOK

J/ψ (quasi-)photoproduction events selection & cross-section extraction

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

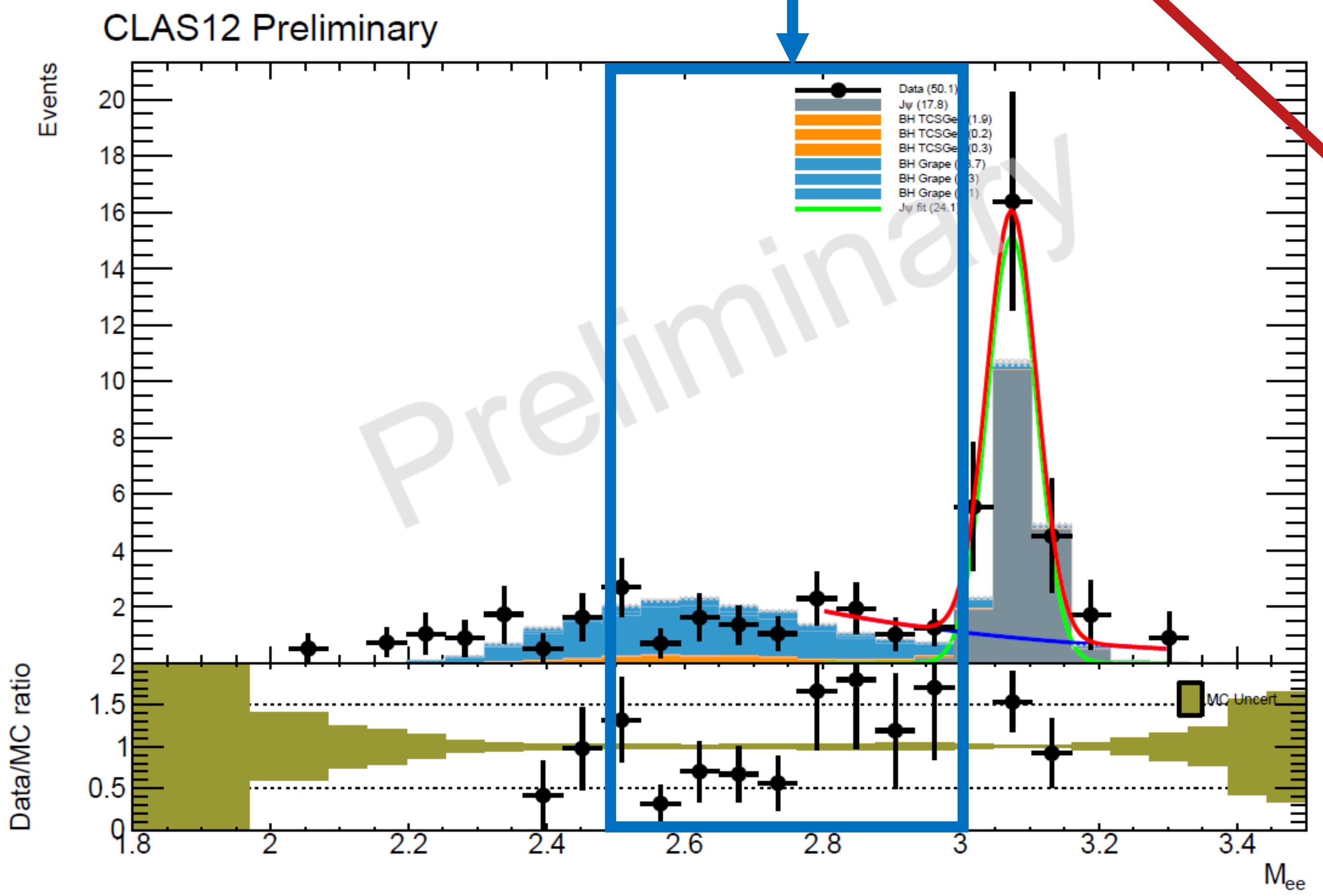
$$\sigma_0(E_\gamma) = \frac{N_{J/\psi}}{N_\gamma \cdot n_T \cdot \omega_c \cdot Br \cdot \epsilon(E_\gamma)}$$

Number of J/ψ

Reconstruction efficiency of the J/ψ → from MC

Branching ratio of J/ψ → e^+e^- → 6%

- Number of photons (from accumulated charge and photon flux from QED).
- Number of targets (from the density of dihydrogen and length of the target).



Jefferson Lab clas