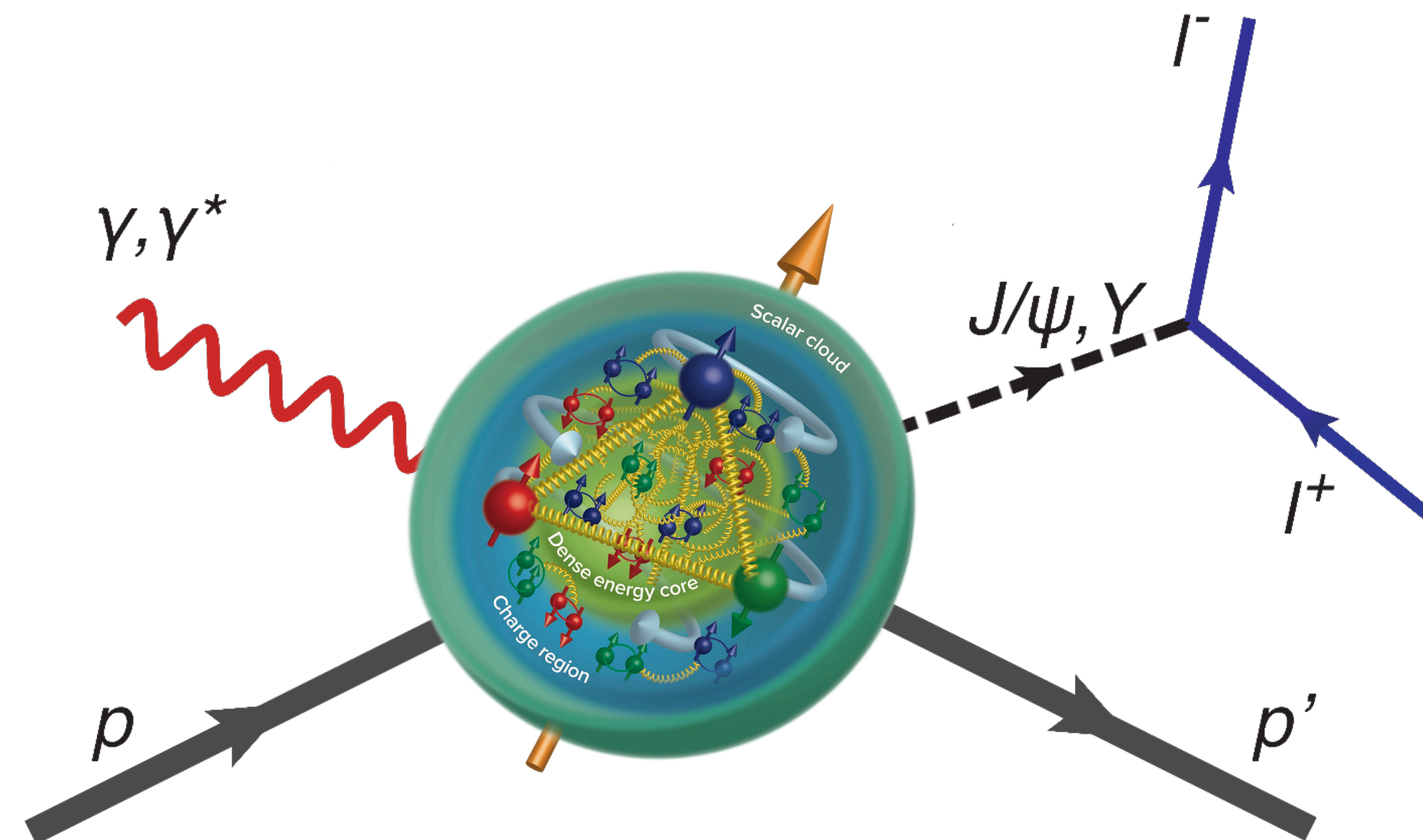


NEW RESULTS FROM THE JLAB J/ψ PROGRAM AND FUTURE PROSPECTS

MEASUREMENTS TOWARDS THE GLUONIC GRAVITATIONAL FORM FACTORS



SYLVESTER JOOSTEN

sjoosten@anl.gov

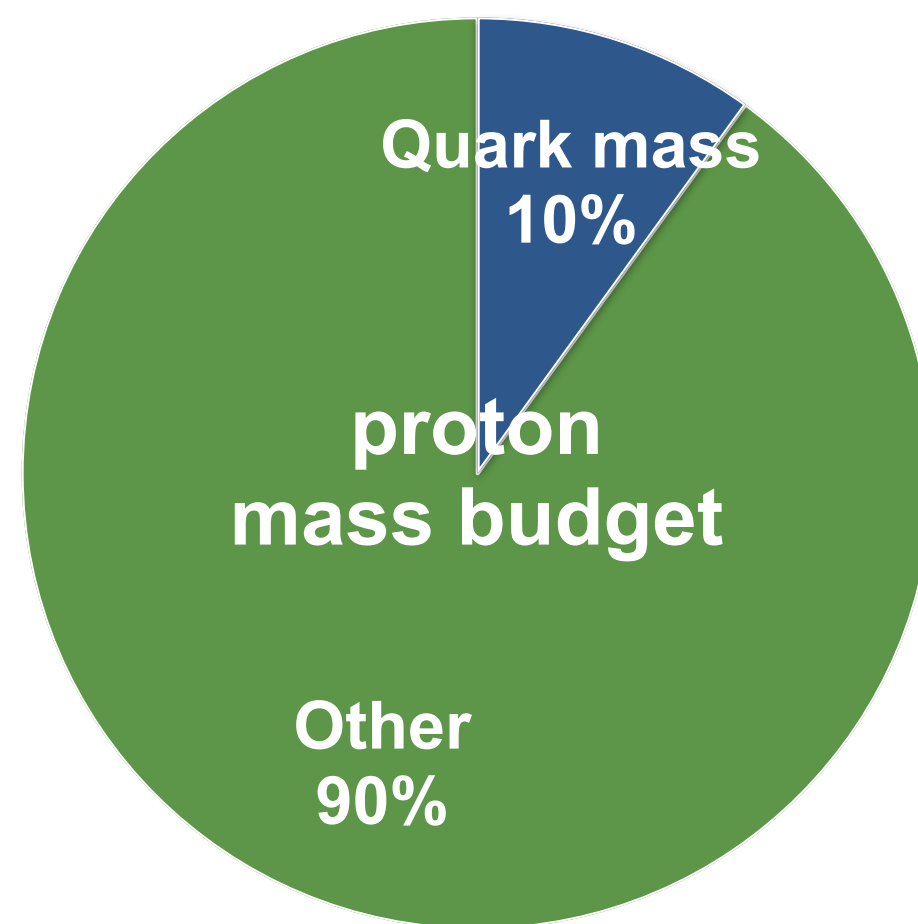
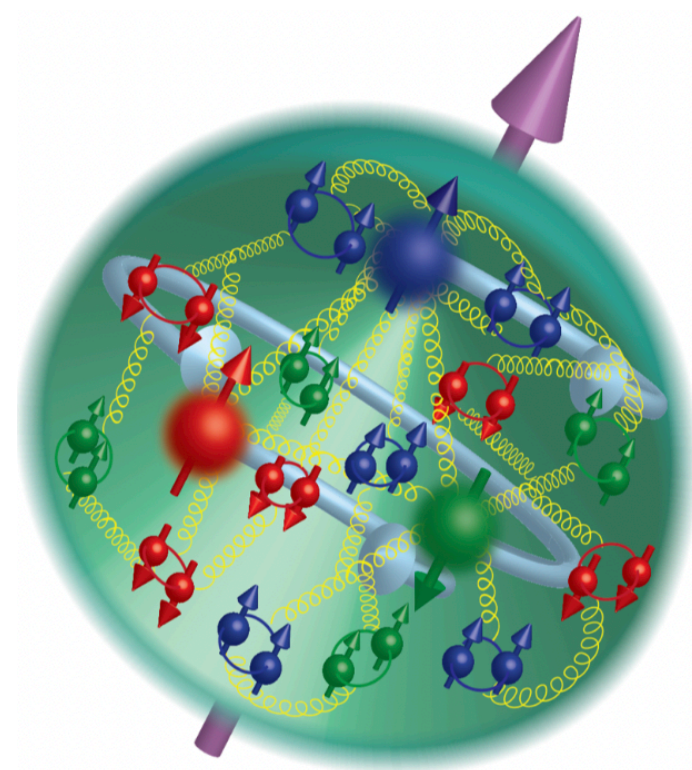
With special thanks to:

*Burcu Duran, Mark Jones, Shivangi Prasad,
Zein-Eddine Meziani, Chao Peng
and the Hall C J/ψ -007 collaboration*

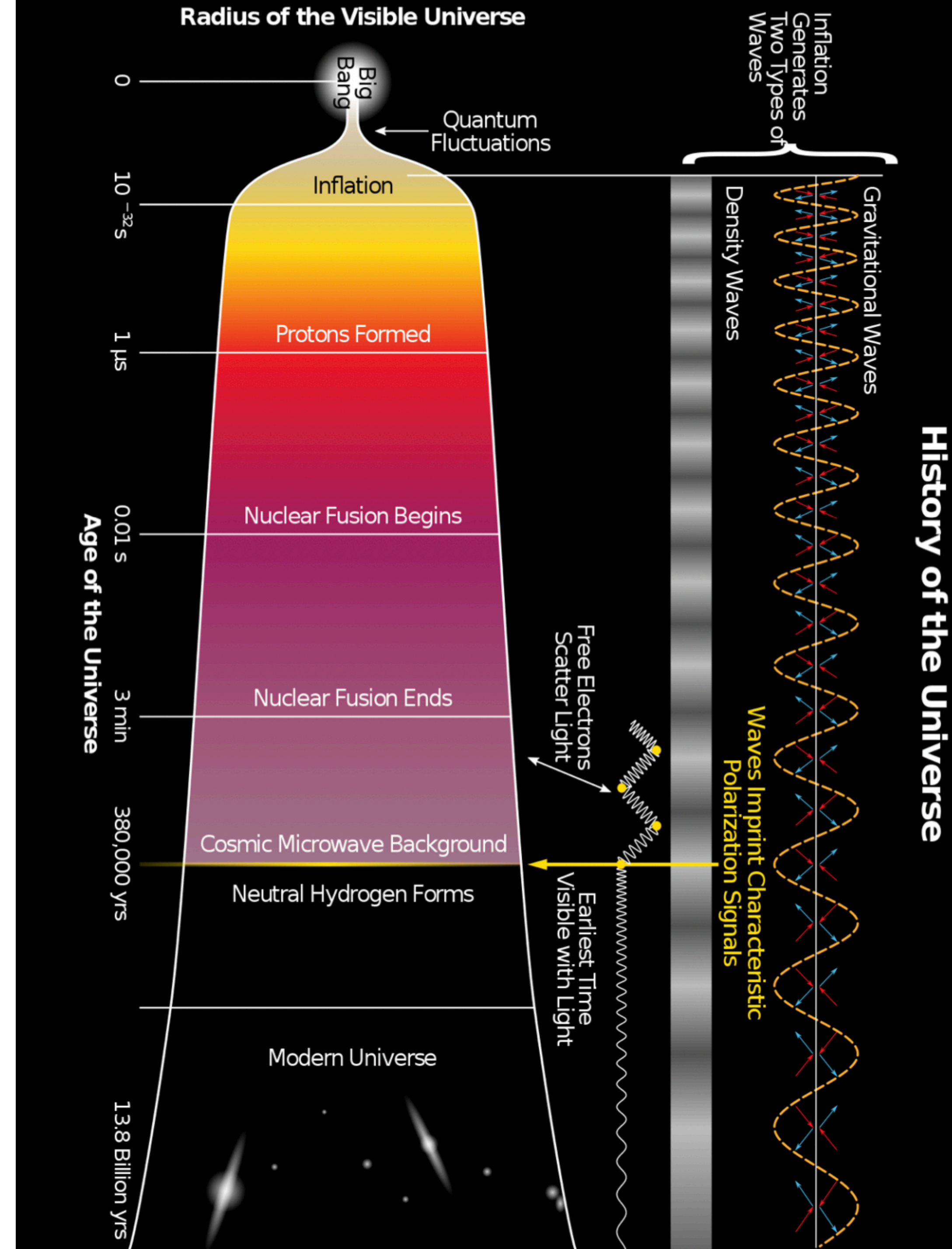
007 J/ψ

The emergence of nucleon mass

QCD IN THE STANDARD MODEL

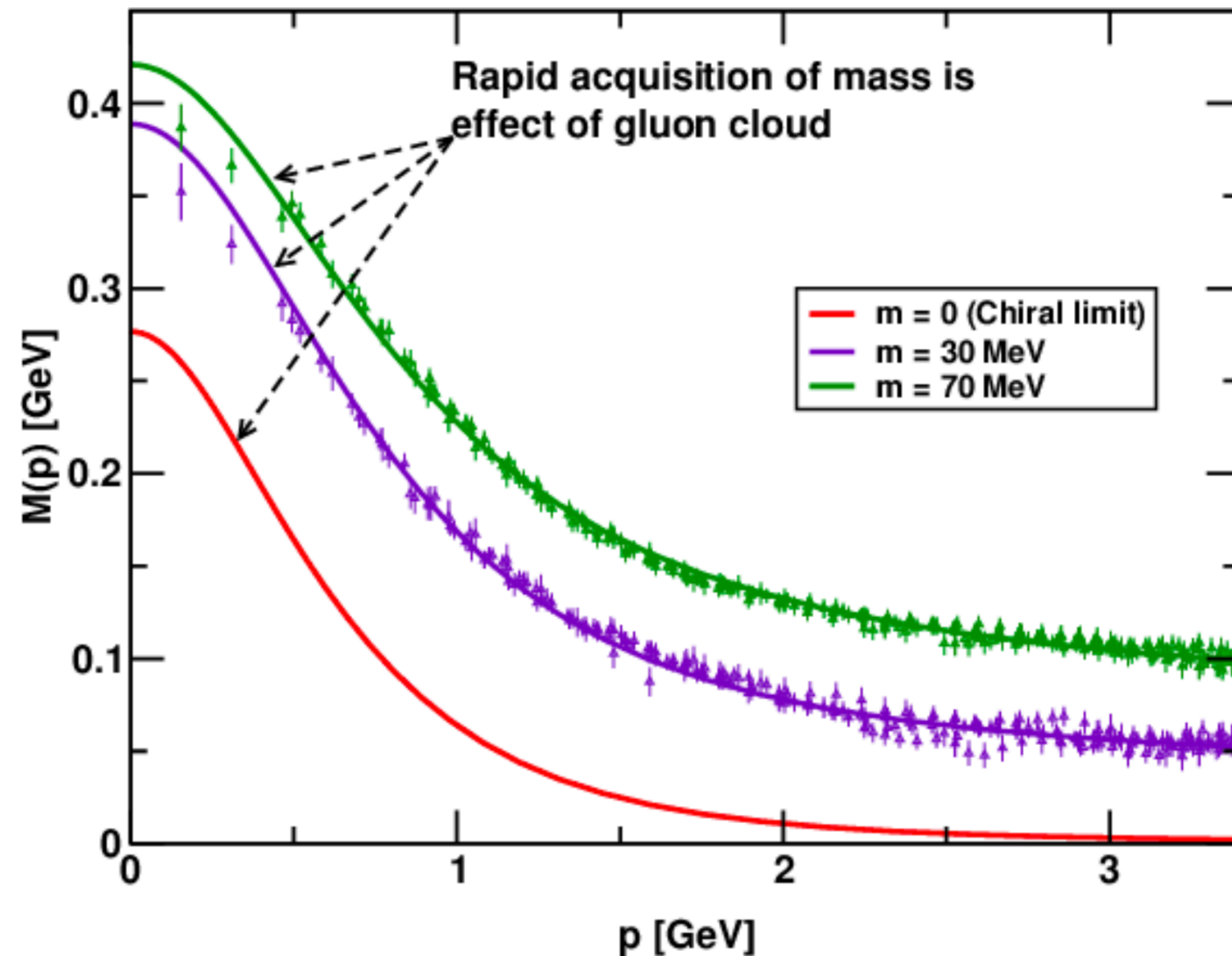


- Since the formation of protons and neutrons, most of the mass of the visible universe encapsulated in protons, neutrons, and nuclei.
- Surprising: nucleon mass much larger than sum of quark masses.
- *How does QCD give rise to the 1GeV proton?*
- *How is the proton mass distributed in its confinement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



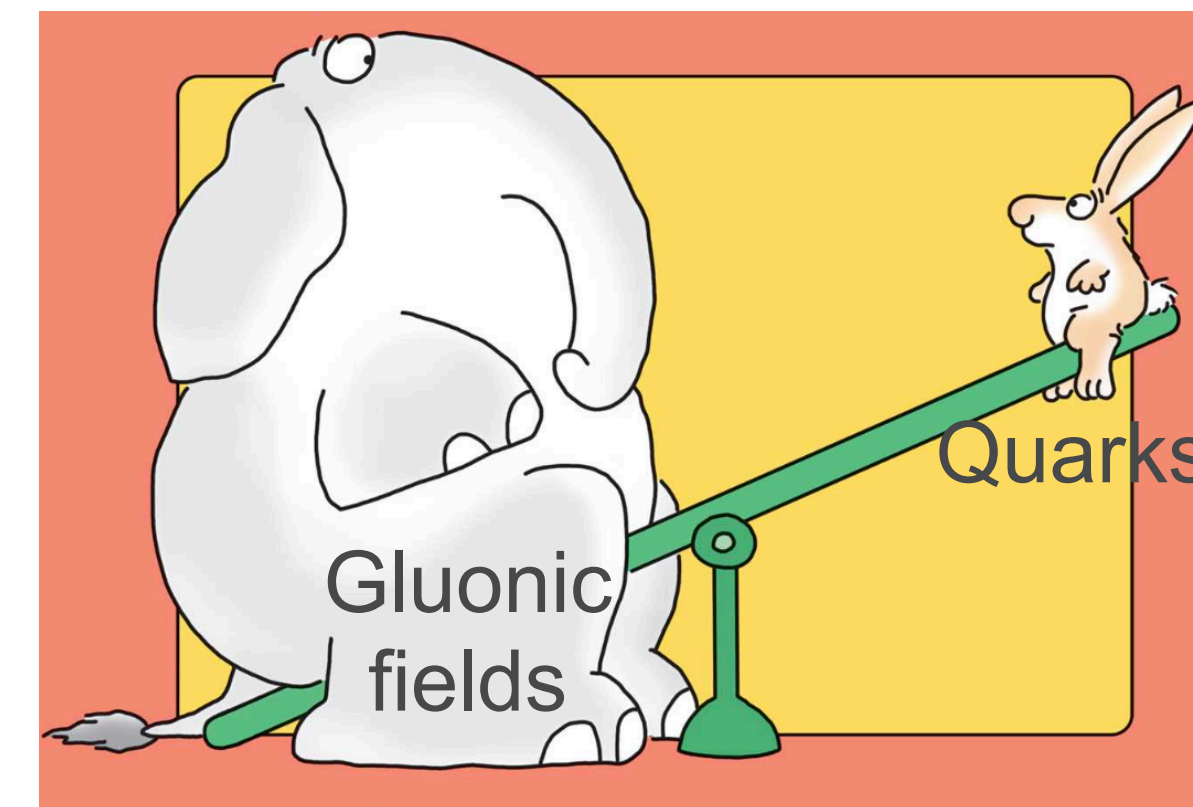
PROTON MASS IS AN EMERGENT PHENOMENON

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)

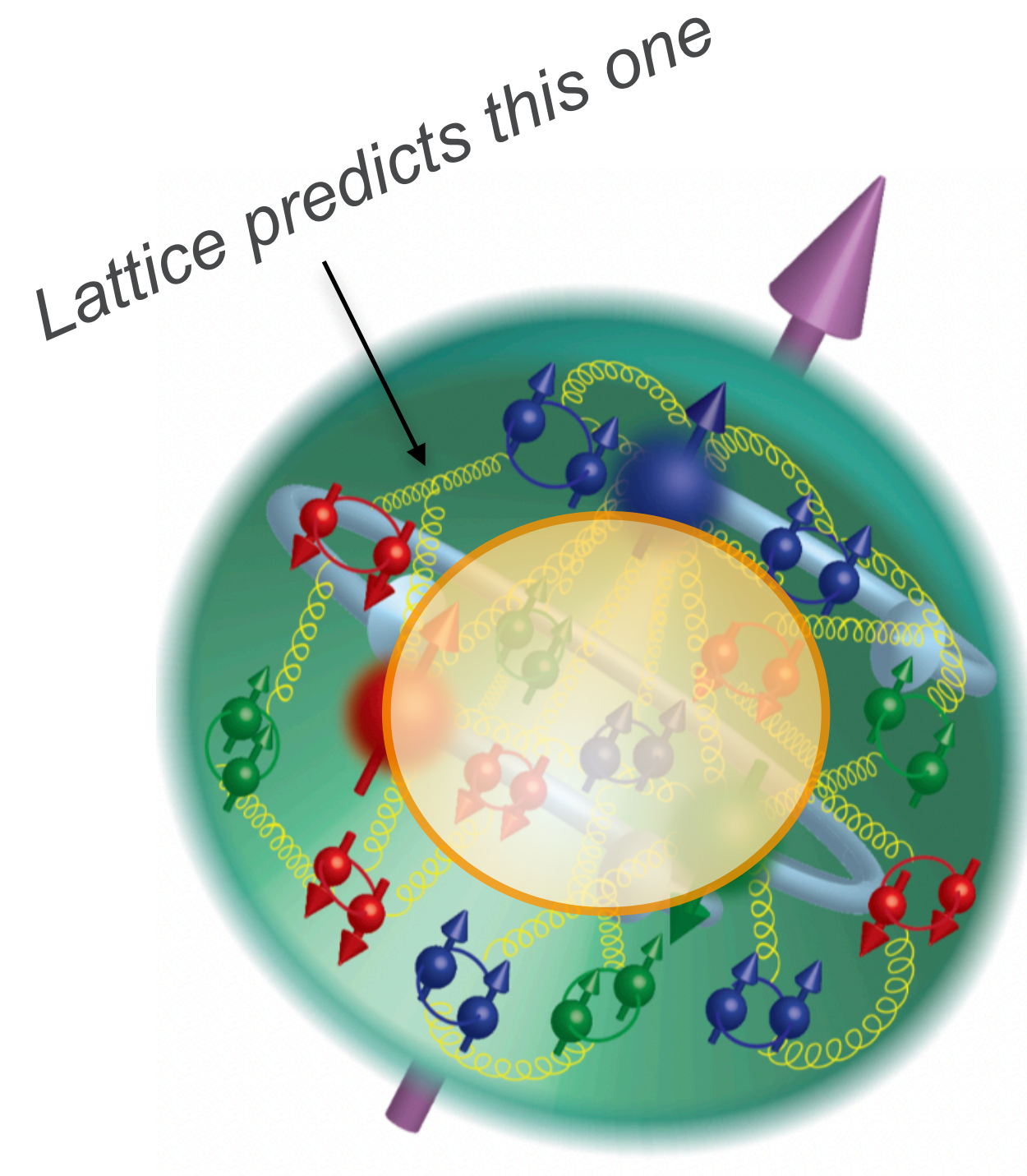
Most of the proton mass originates in the energy enclosed in the gluonic fields of the Strong Interaction itself



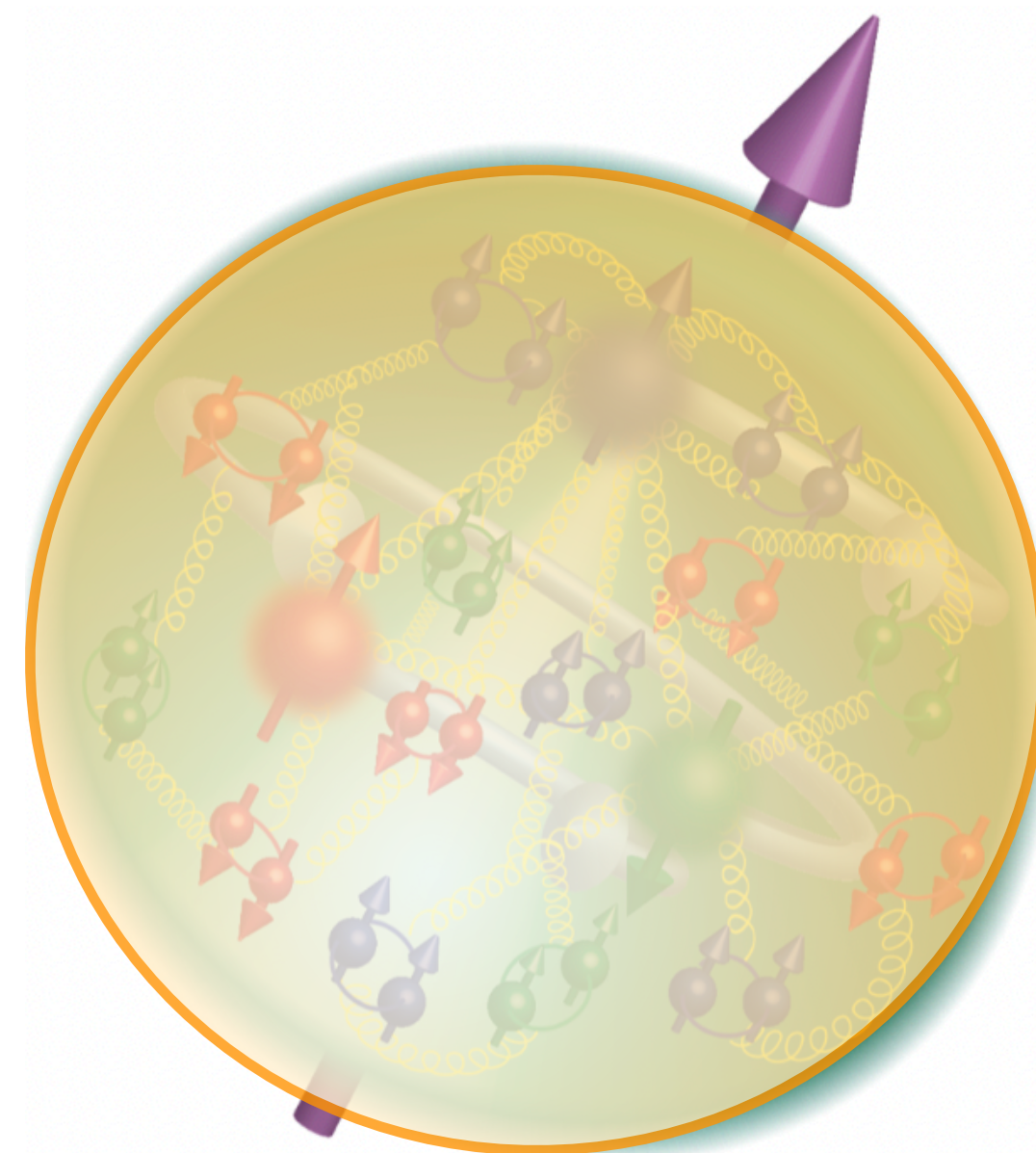
Bottom line: The Higgs mechanism is largely irrelevant for most of "normal" visible matter!

WHERE IS THE ENERGY INSIDE THE PROTON?

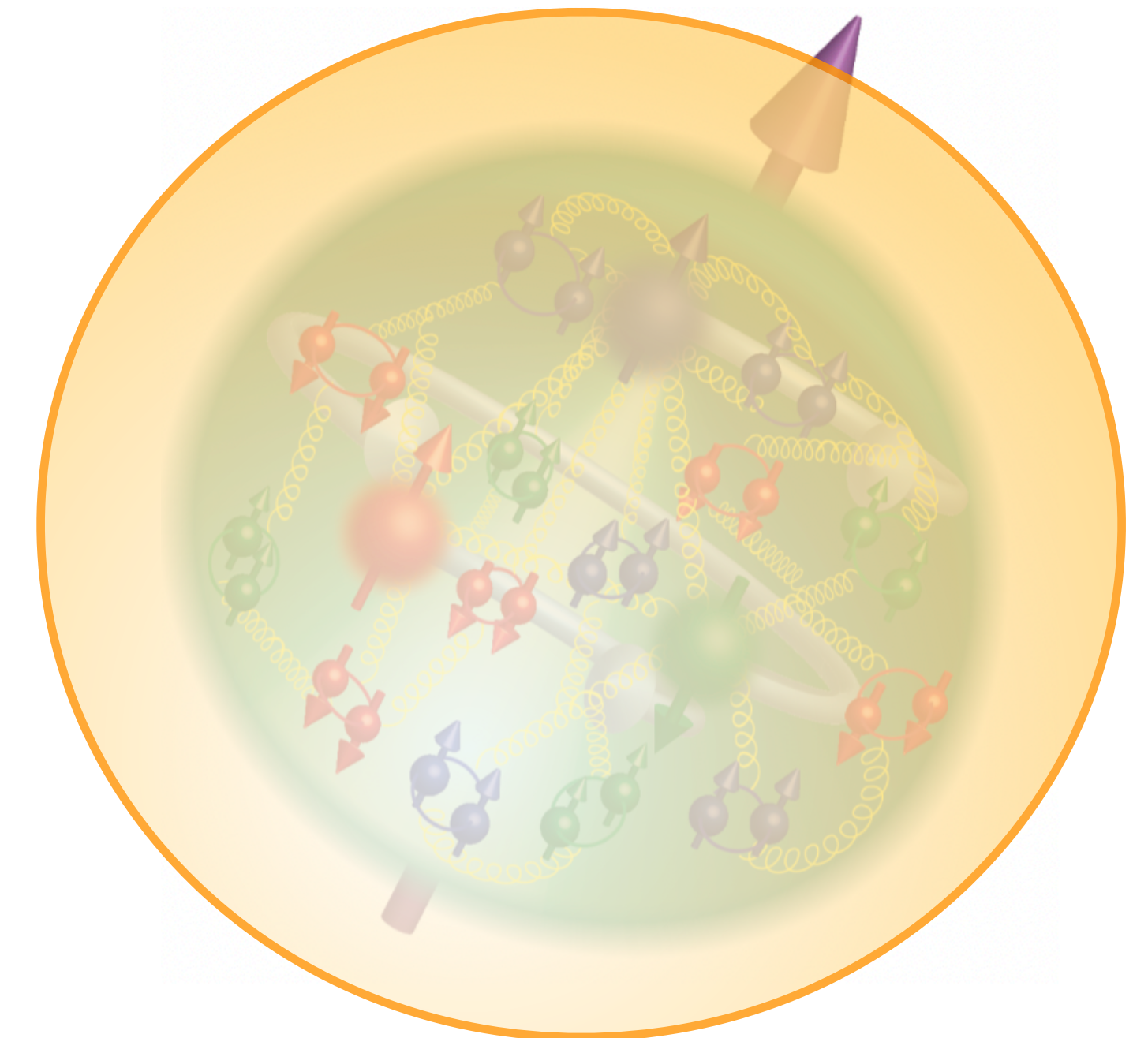
How does the mass radius compare to the charge radius?



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

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

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

Tensor (2++ graviton-like, mass) radius

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

Scalar (0++ glueball-like) radius

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

Both radii depend on the functional form of the gluonic A and C form factors at the origin.

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

HOW TO MEASURE THE GLUONIC GFFS

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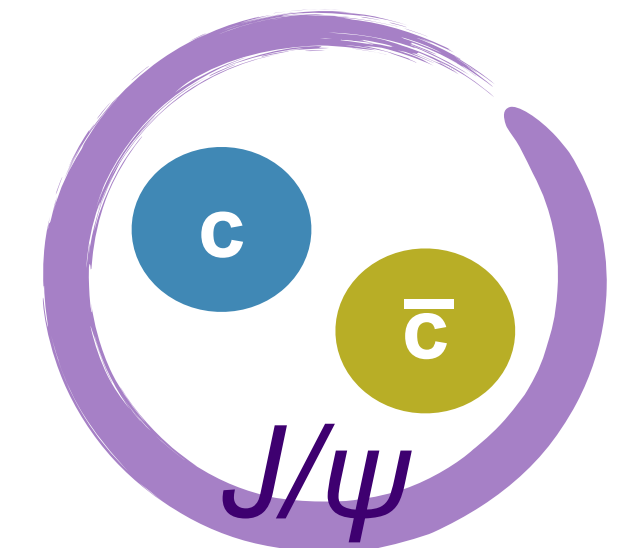
Cannot use direct gravitational probe: interaction too weak

Small “color” dipole made of heavy quarks well-suited to study gluons

three generations of matter (fermions)

	I	II	III
mass	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$
	u up	c charm	t top
	d down	s strange	b bottom

QUARKS

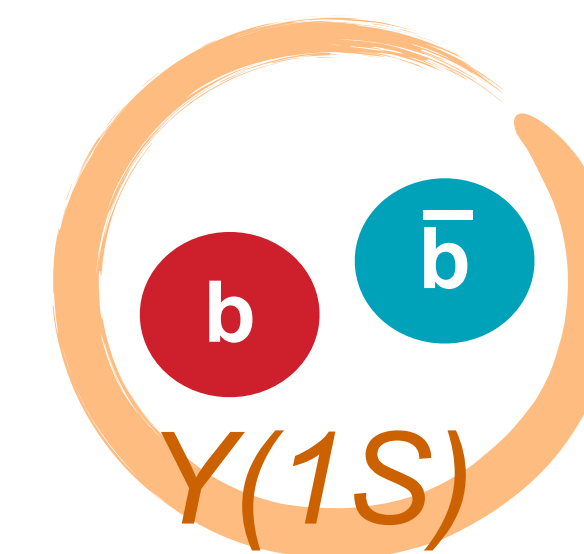
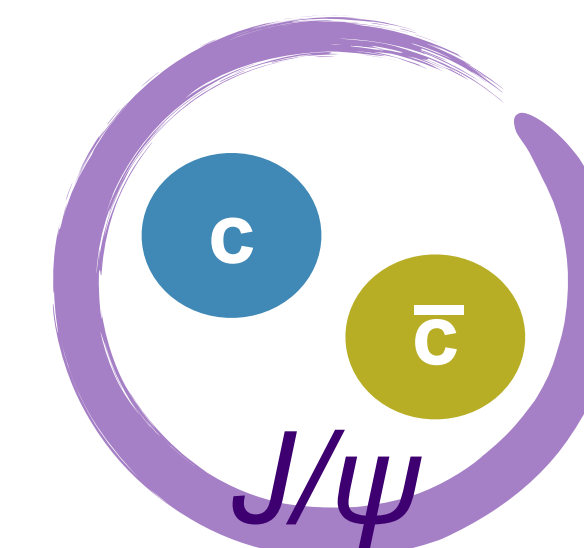
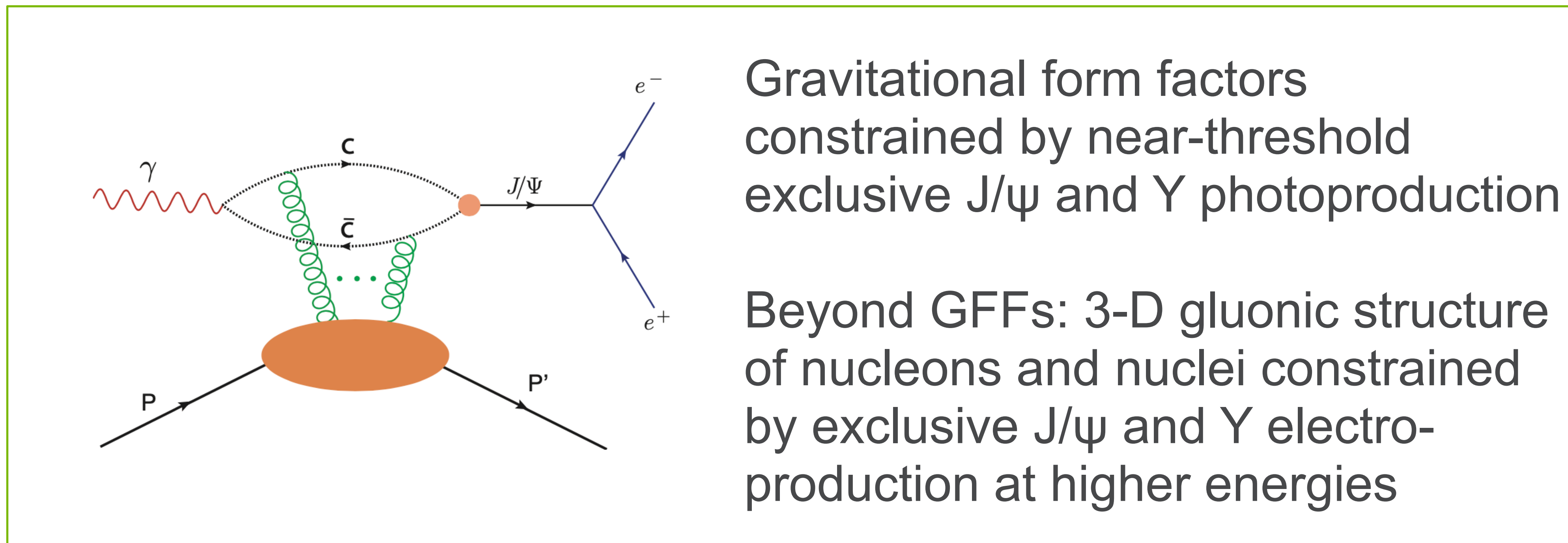


HOW TO MEASURE THE GLUONIC GFFS

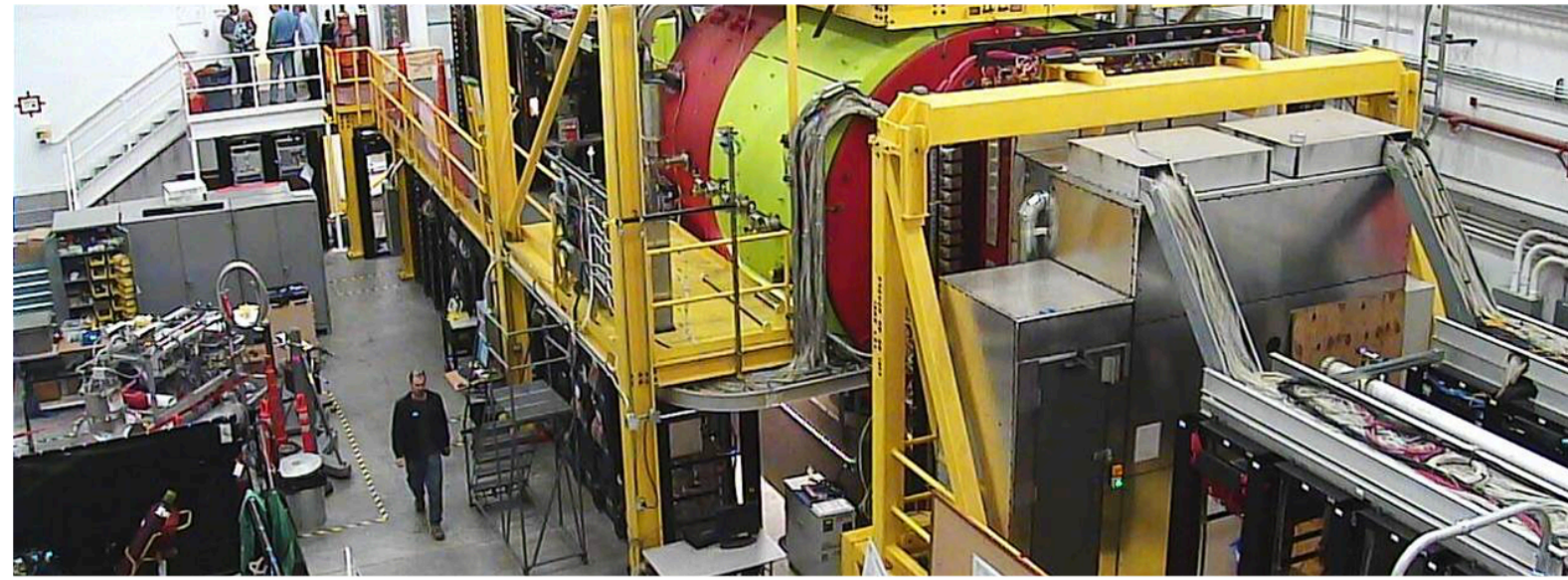
Gluons are elusive!

❖ Cannot use Electromagnetic probe: primarily couples to quarks

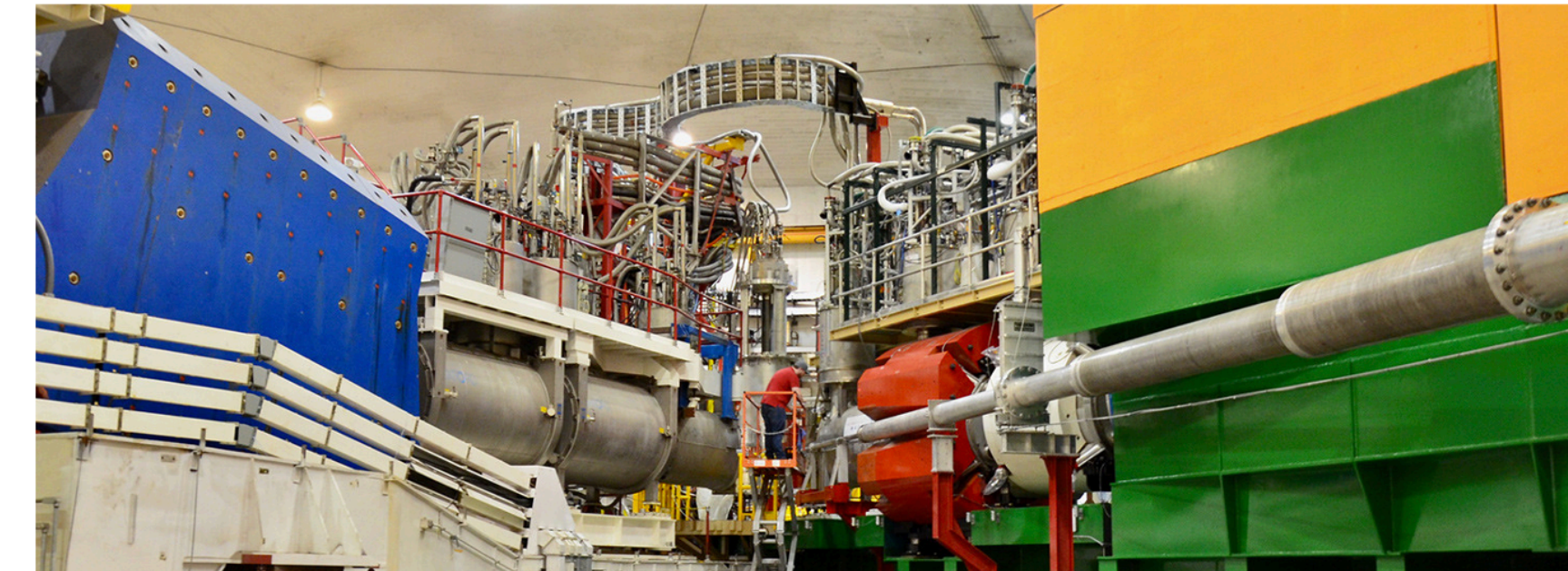
● Small “color” dipole made of heavy quarks well-suited to study gluons



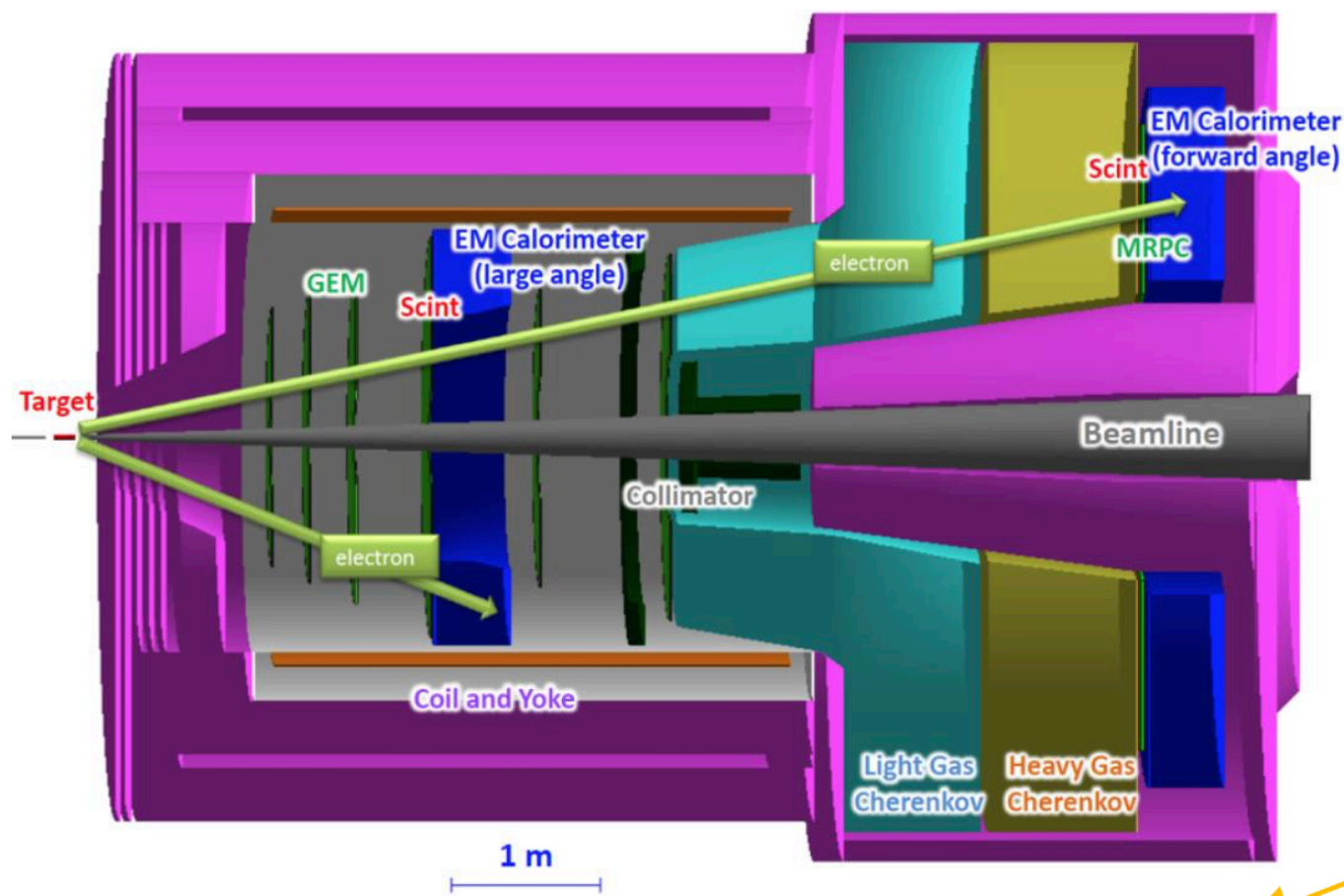
12 GEV J/ψ EXPERIMENTS AT JEFFERSON LAB



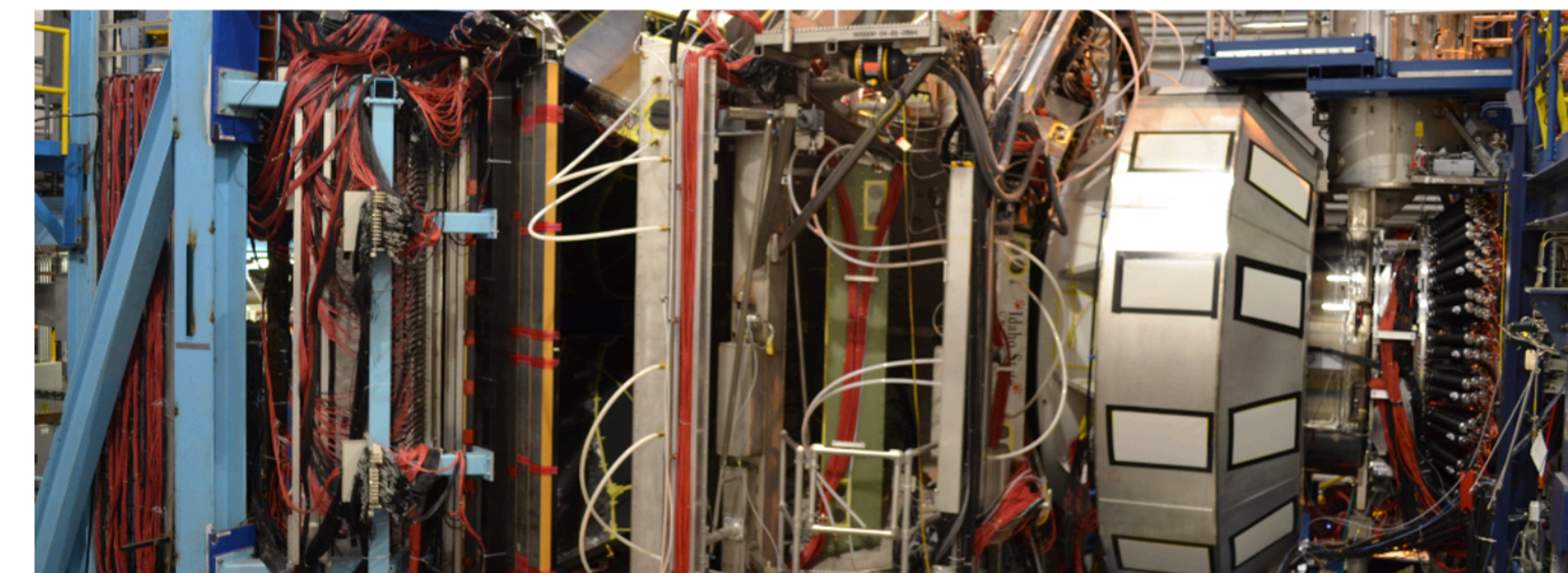
Hall D - GlueX observer the first J/ψ at JLab
A. Ali *et al.*, PRL 123, 072001 (2019)



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



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**

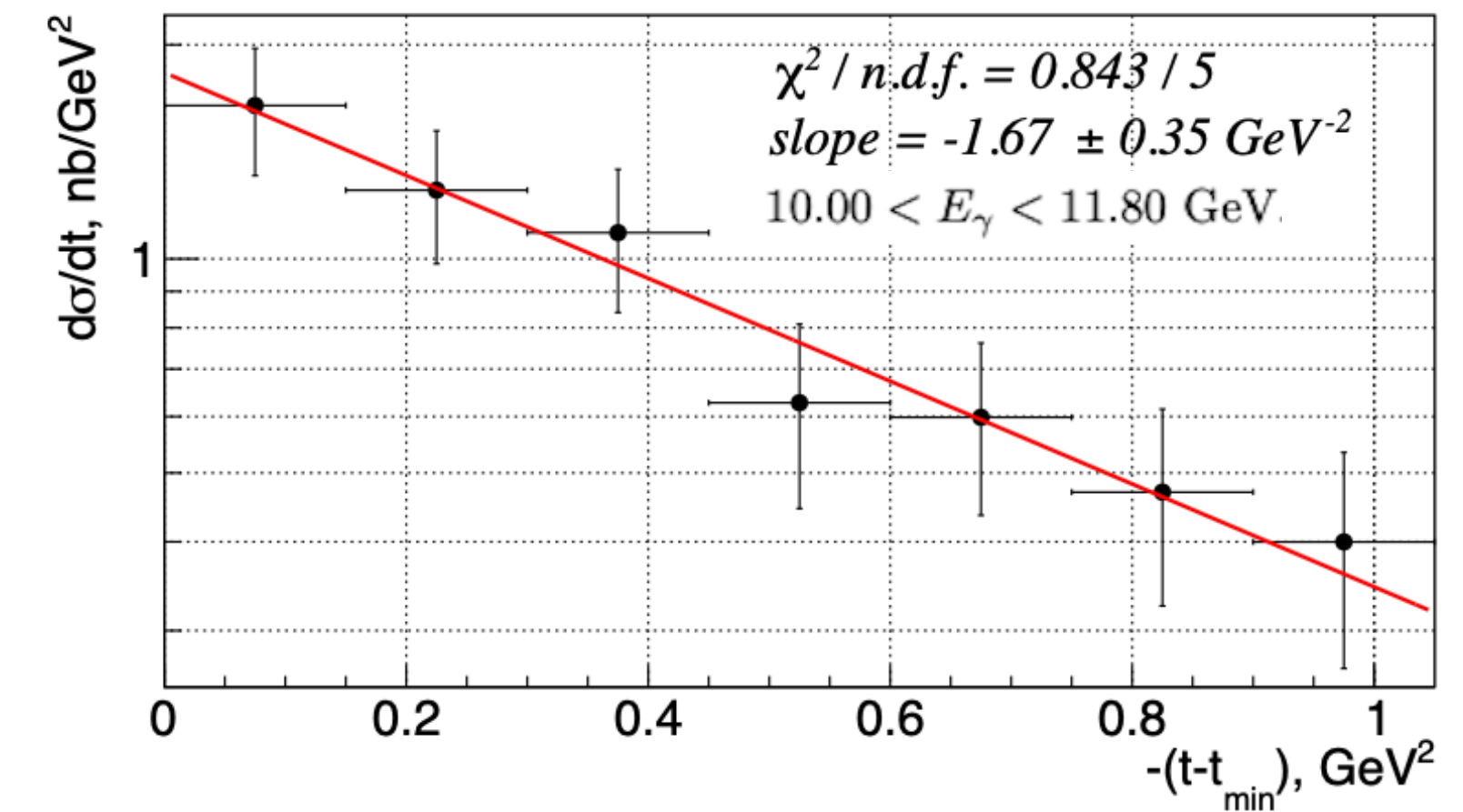
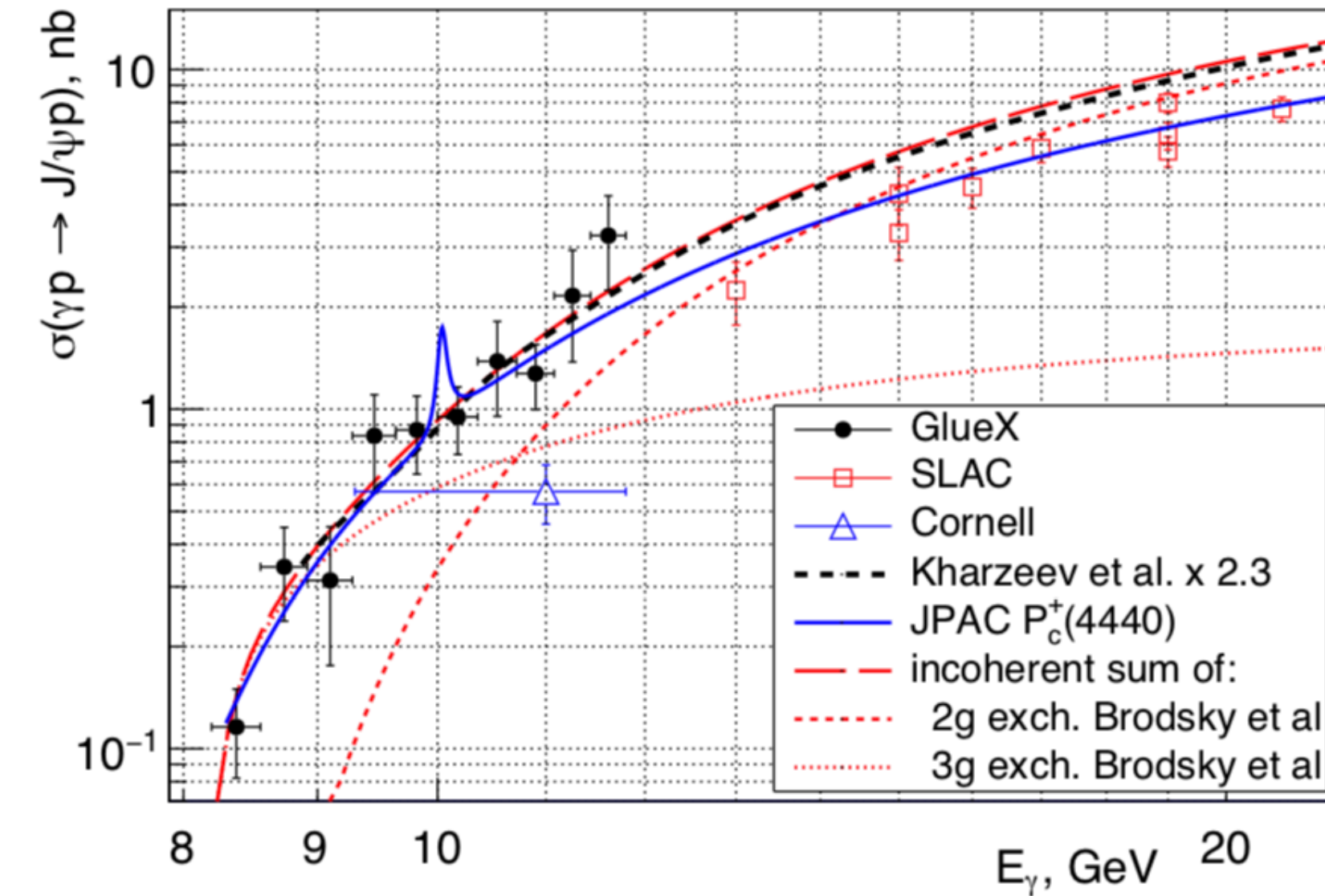
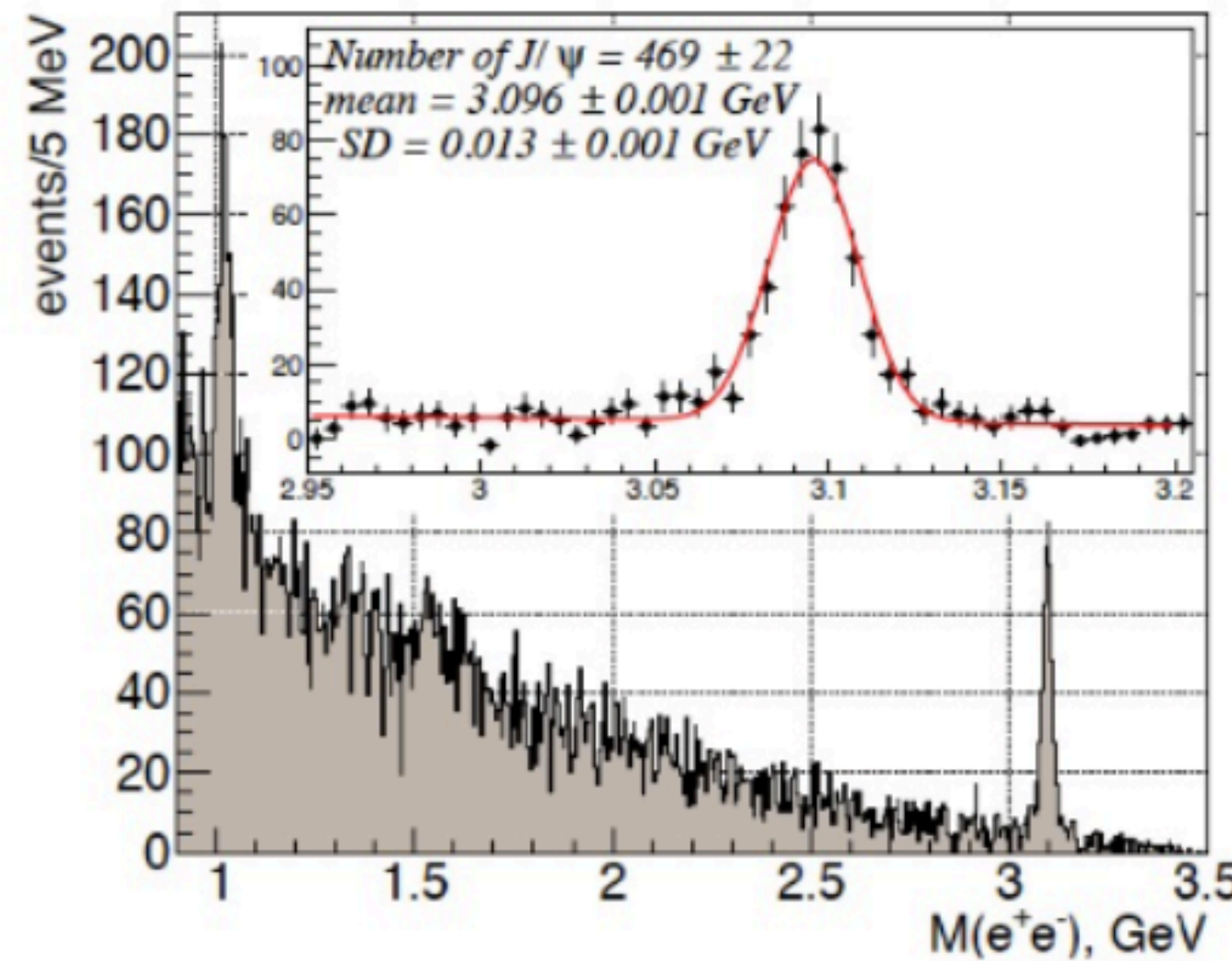


Hall B - **CLAS12** has experiments to measure TCS + J/ψ in photoproduction as part of Run Groups A (hydrogen) and B (deuterium): E12-12-001, E12-12-001A, E12-11-003B

J/Ψ NEAR THRESHOLD IN HALL D

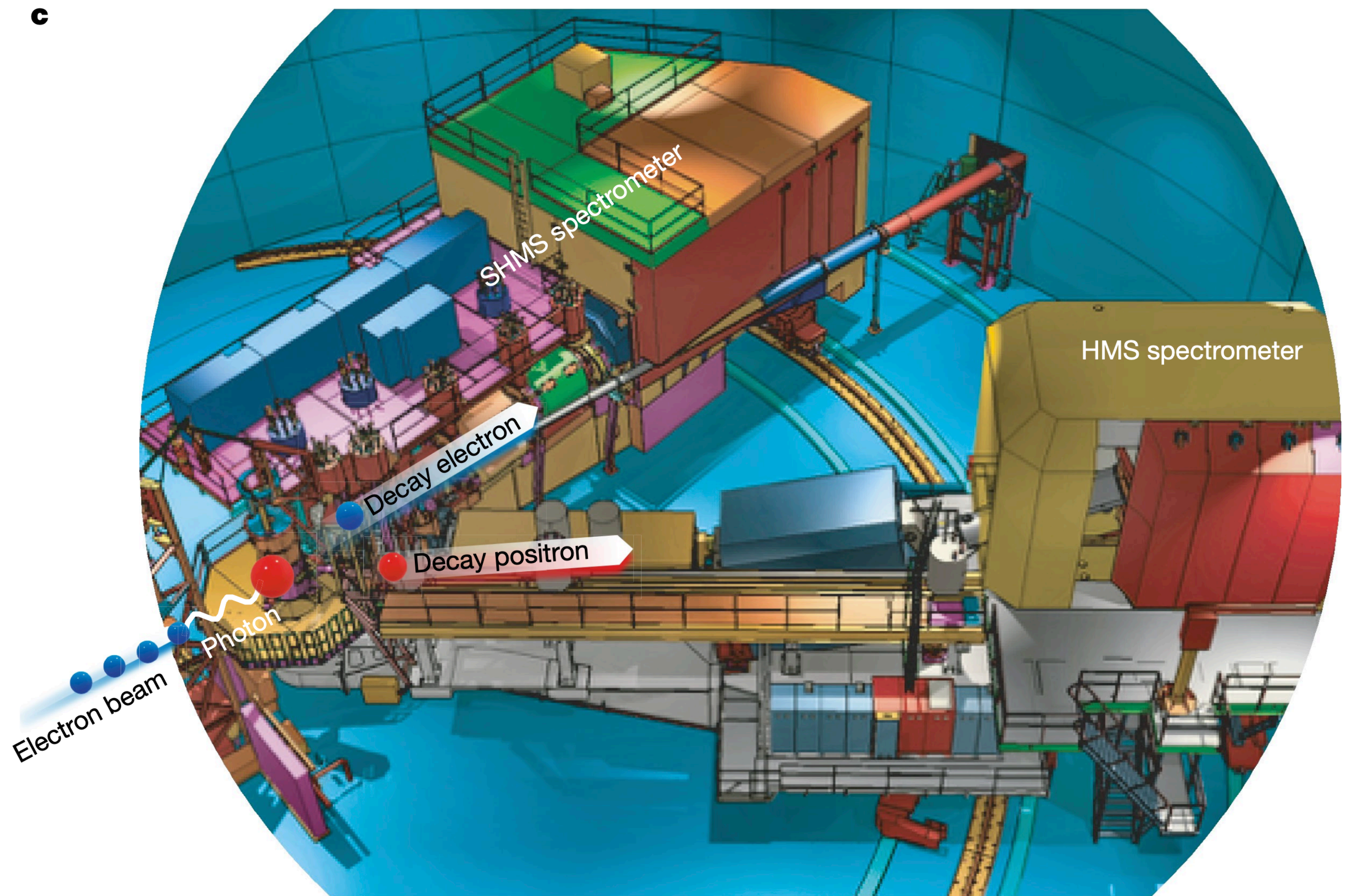
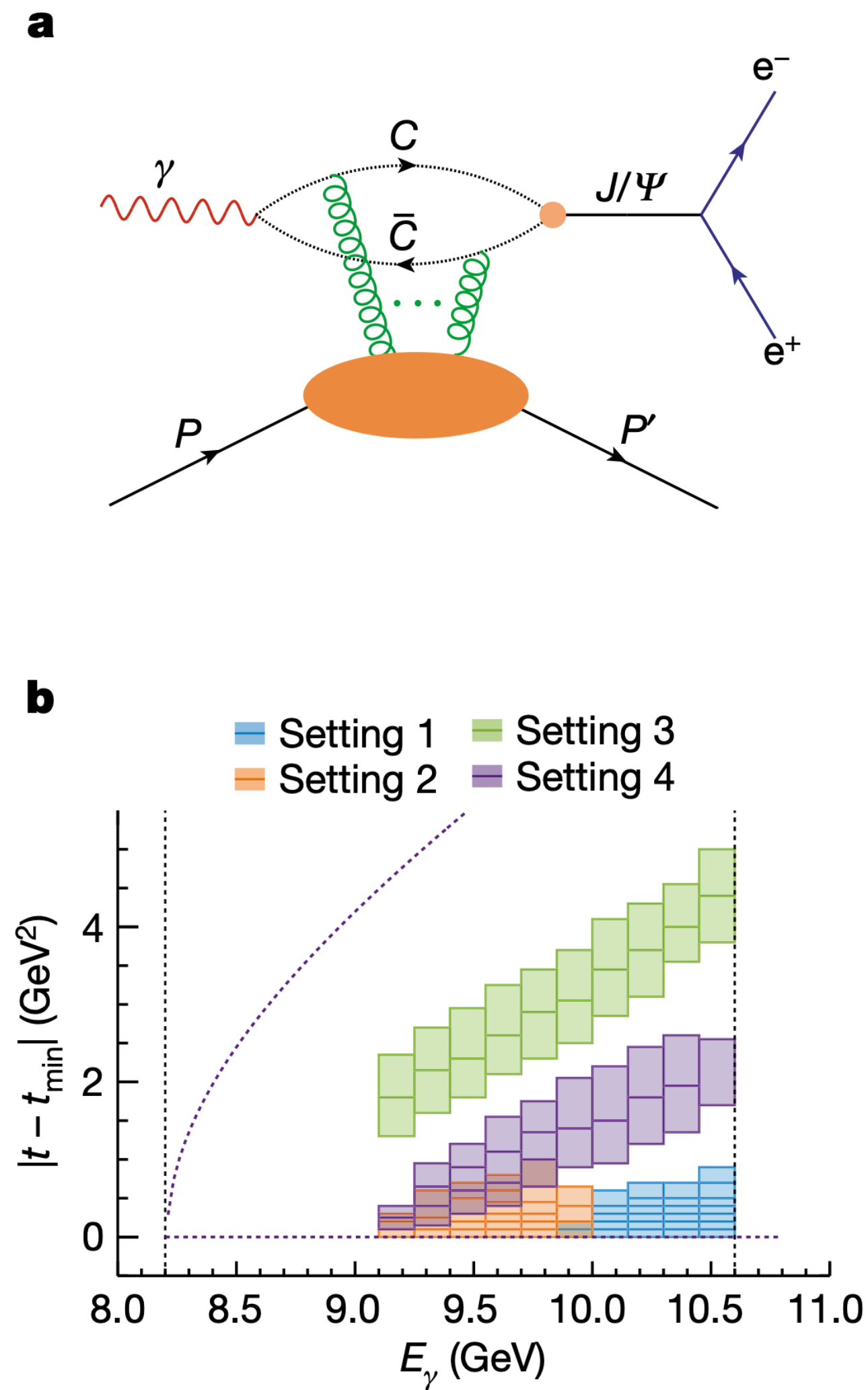
First J/ψ results from JLab, published in PRL 123, 072001 (2019)

- 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



Near-threshold J/ψ photoproduction

HALL C EXPERIMENT E12-16-007



THE J/Ψ-007 COLLABORATION

007^{J/Ψ}

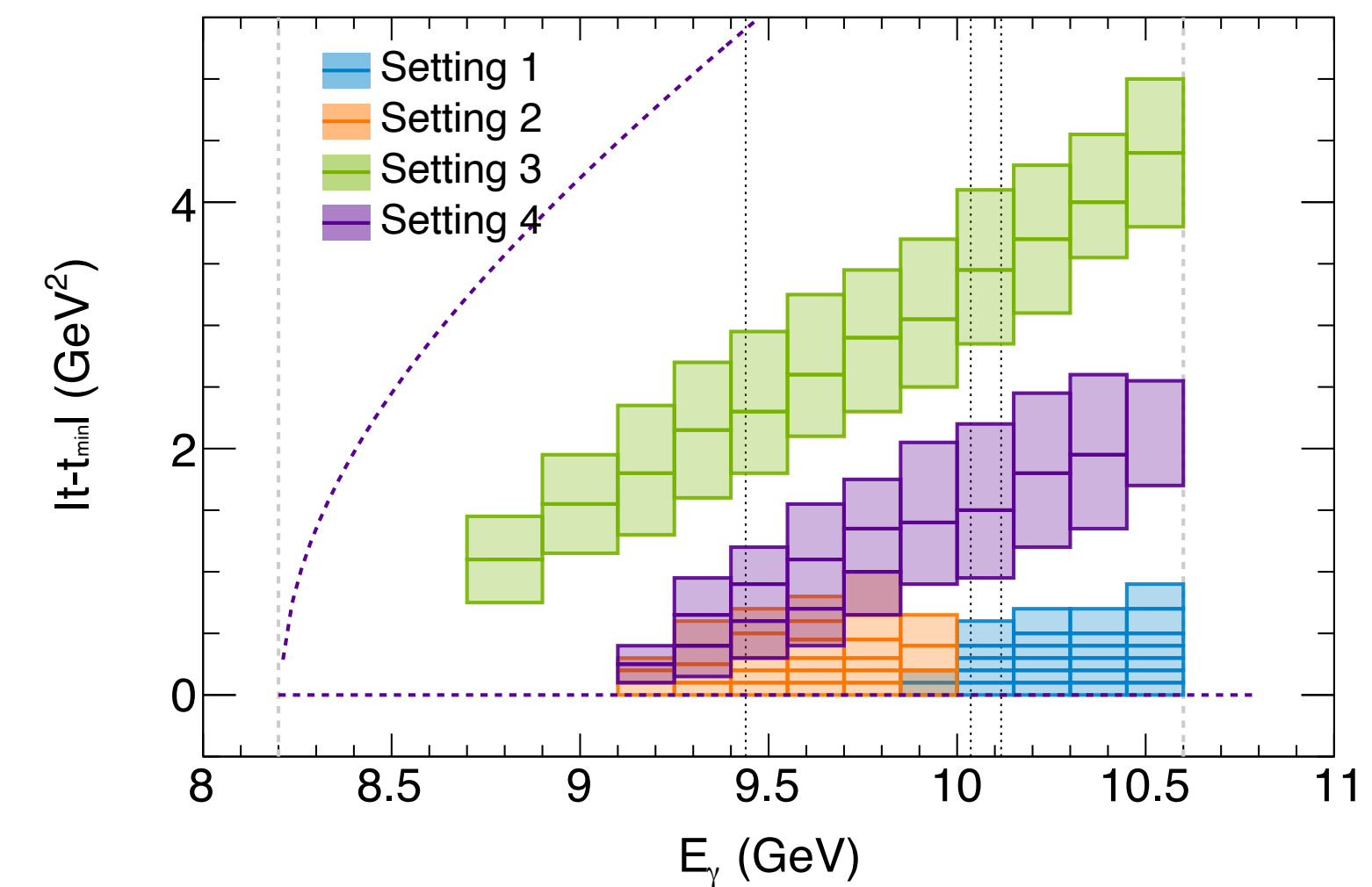
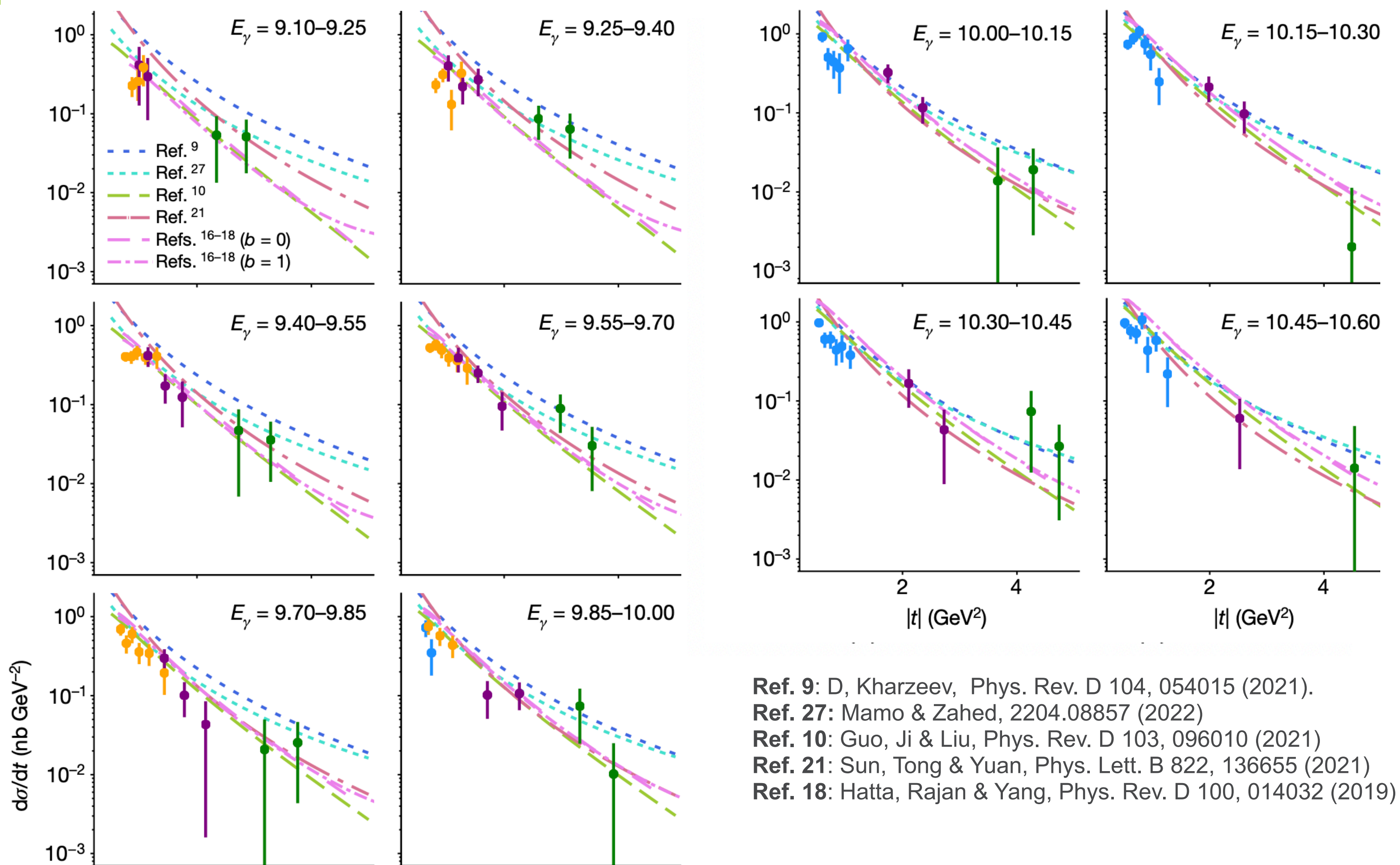


...and many others!

B. Duran^{1,2}, Z.-E. Meziani^{1,2}✉, S. Joosten¹, M. K. Jones³, S. Prasad¹, C. Peng¹, W. Armstrong¹, H. Atac², E. Chudakov³, H. Bhatt⁴, D. Bhetuwal⁴, M. Boer⁵, A. Camsonne³, J.-P. Chen³, M. M. Dalton³, N. Deokar², M. Diefenthaler³, J. Dunne⁴, L. El Fassi⁴, E. Fuchey⁶, H. Gao⁷, D. Gaskell³, O. Hansen³, F. Hauenstein⁸, D. Higinbotham³, S. Jia², A. Karki⁴, C. Keppel³, P. King⁹, H. S. Ko¹⁰, X. Li⁷, R. Li², D. Mack³, S. Malace³, M. McCaughan³, R. E. McClellan¹¹, R. Michaels³, D. Meekins³, Michael Paolone², L. Pentchev³, E. Pooser³, A. Puckett⁶, R. Radloff⁹, M. Rehfuss², P. E. Reimer¹, S. Riordan¹, B. Sawatzky³, A. Smith⁷, N. Sparveris², H. Szumila-Vance³, S. Wood³, J. Xie¹, Z. Ye¹, C. Yero⁸ & Z. Zhao⁷

First results published in Nature!

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)

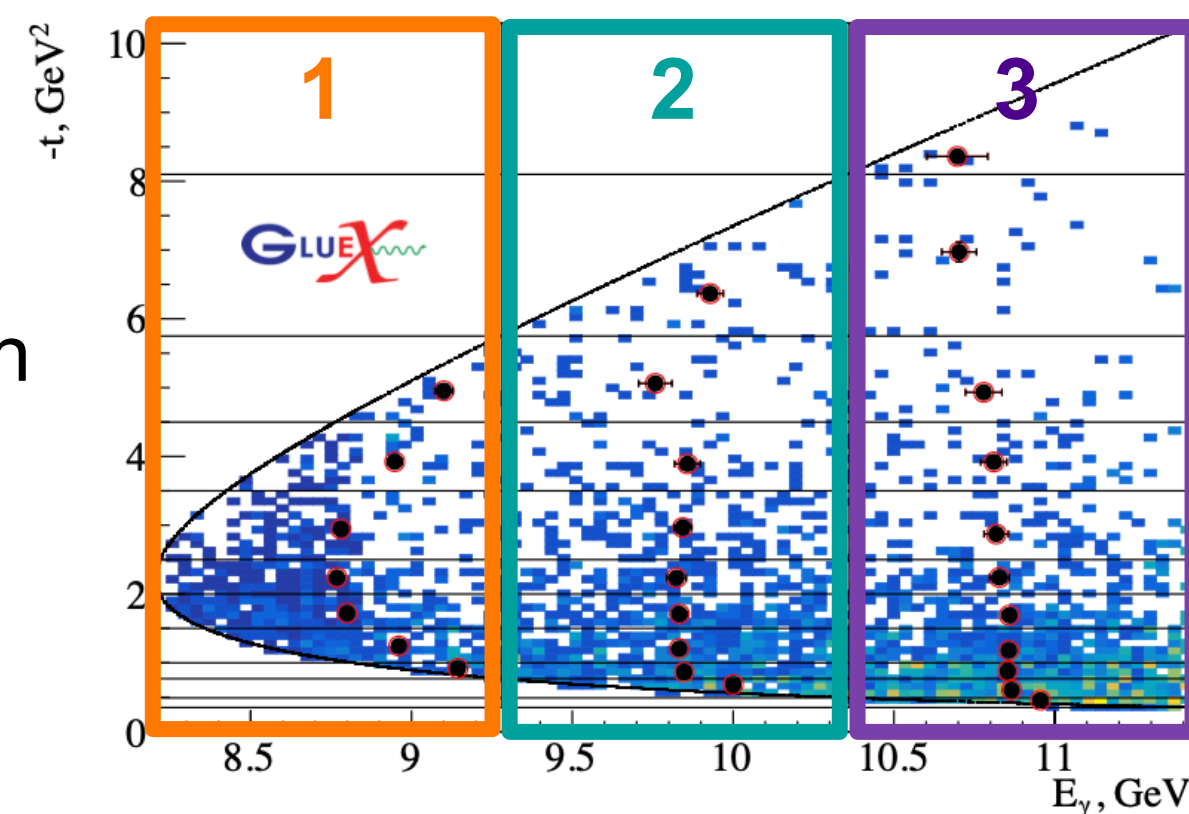
Unfolded 2D cross section results compared to various model predictions informed by the 2019 1D GlueX results
 All models work reasonably well at higher energies but deviate at lower energies

4% scale uncertainty

NEW 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

$E_\gamma \sim 8.2 - 11.44$ GeV

(compared to 10 E_γ slices

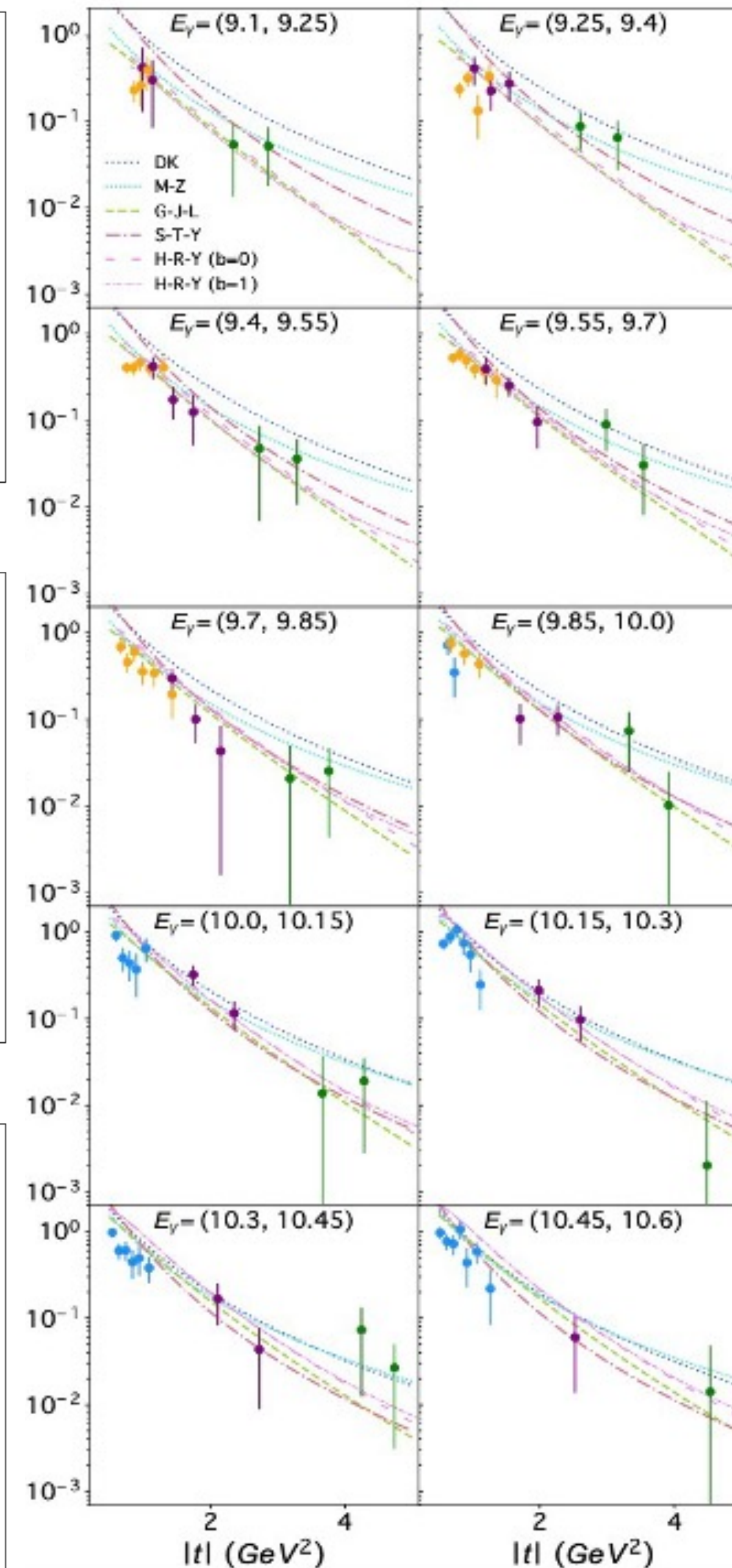
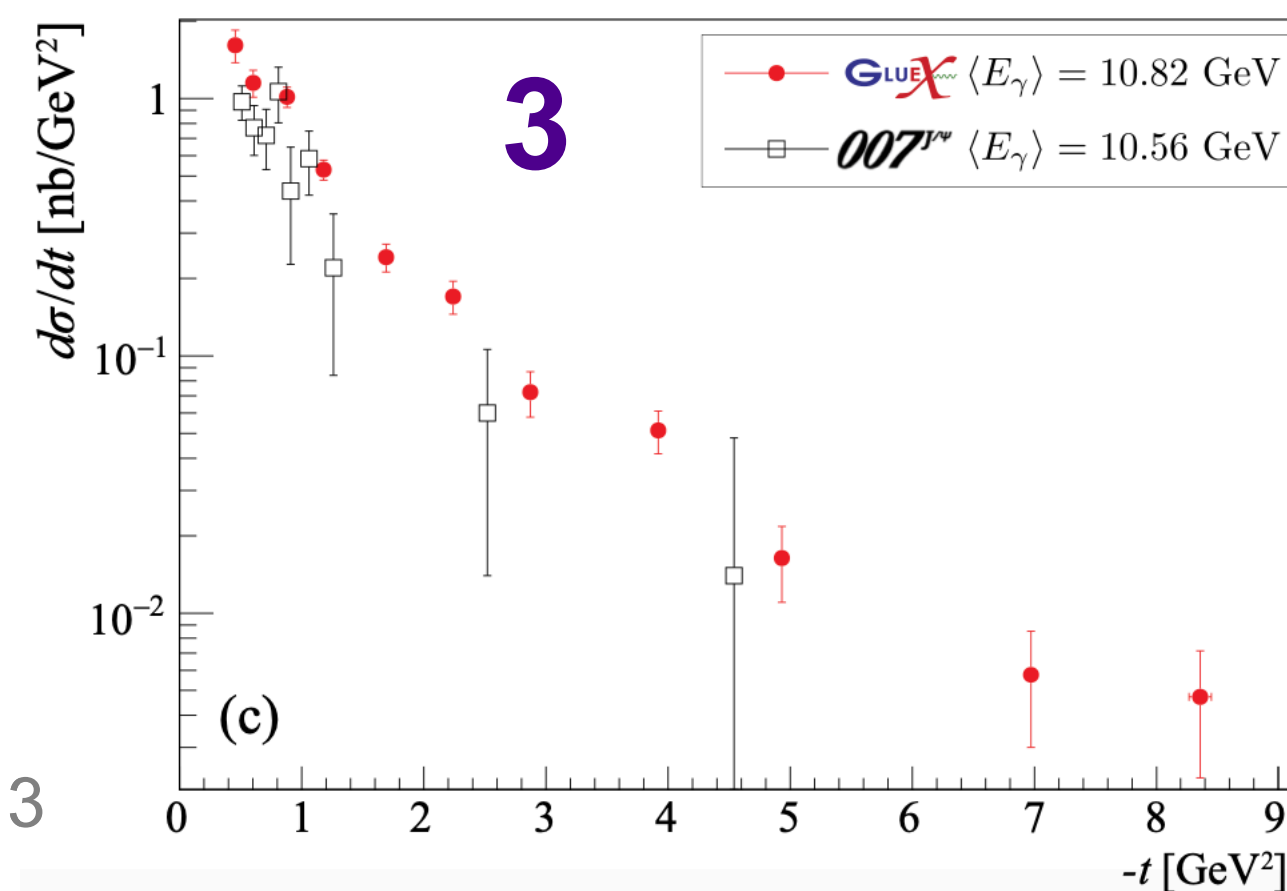
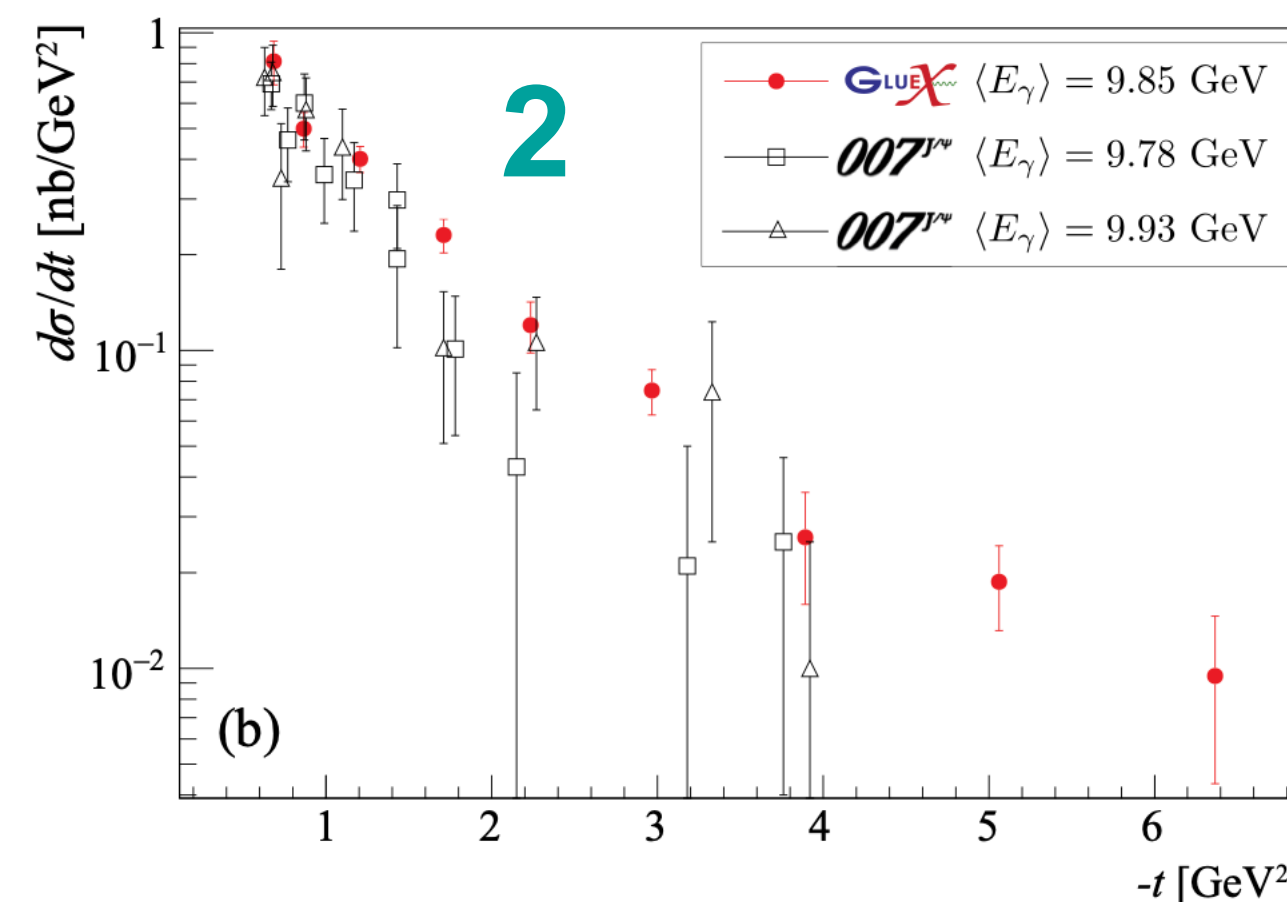
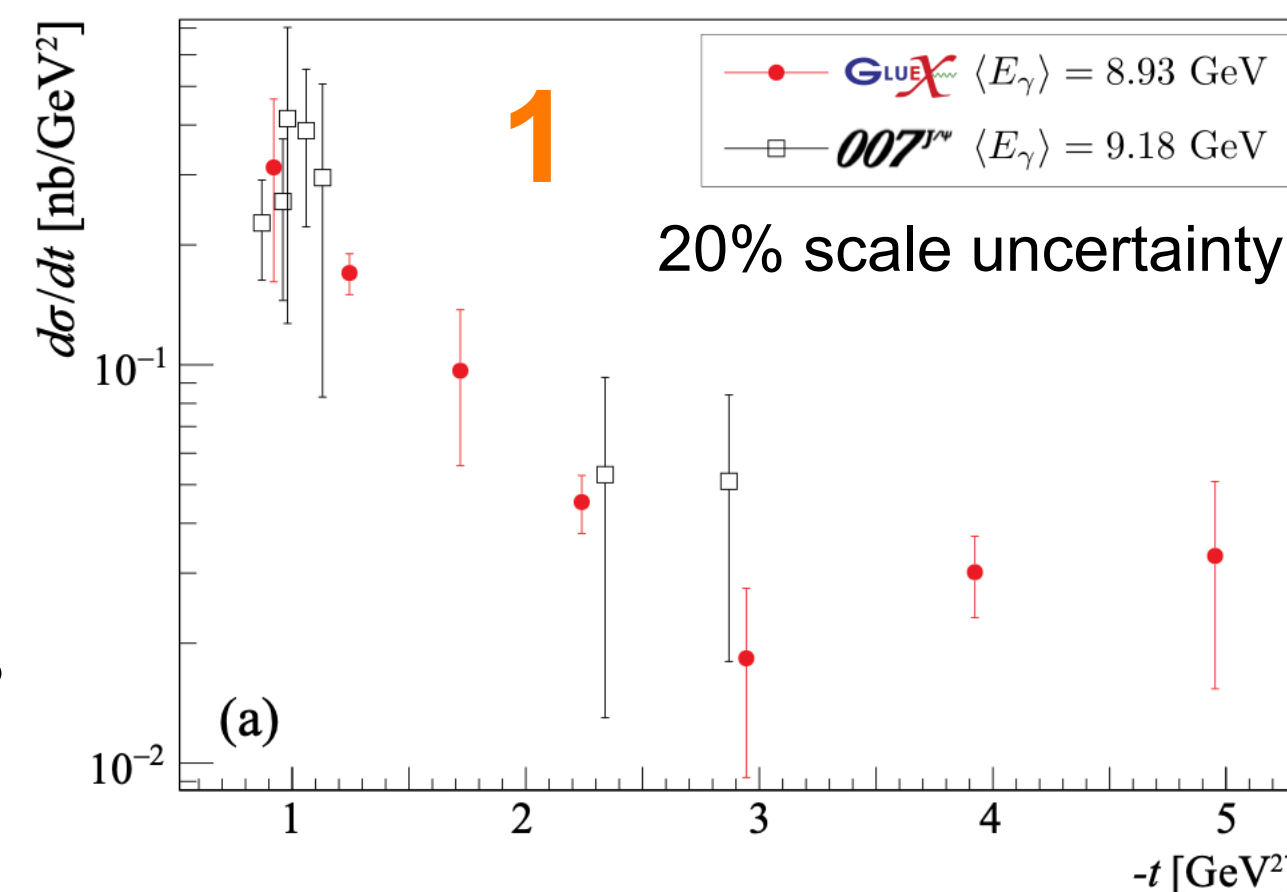
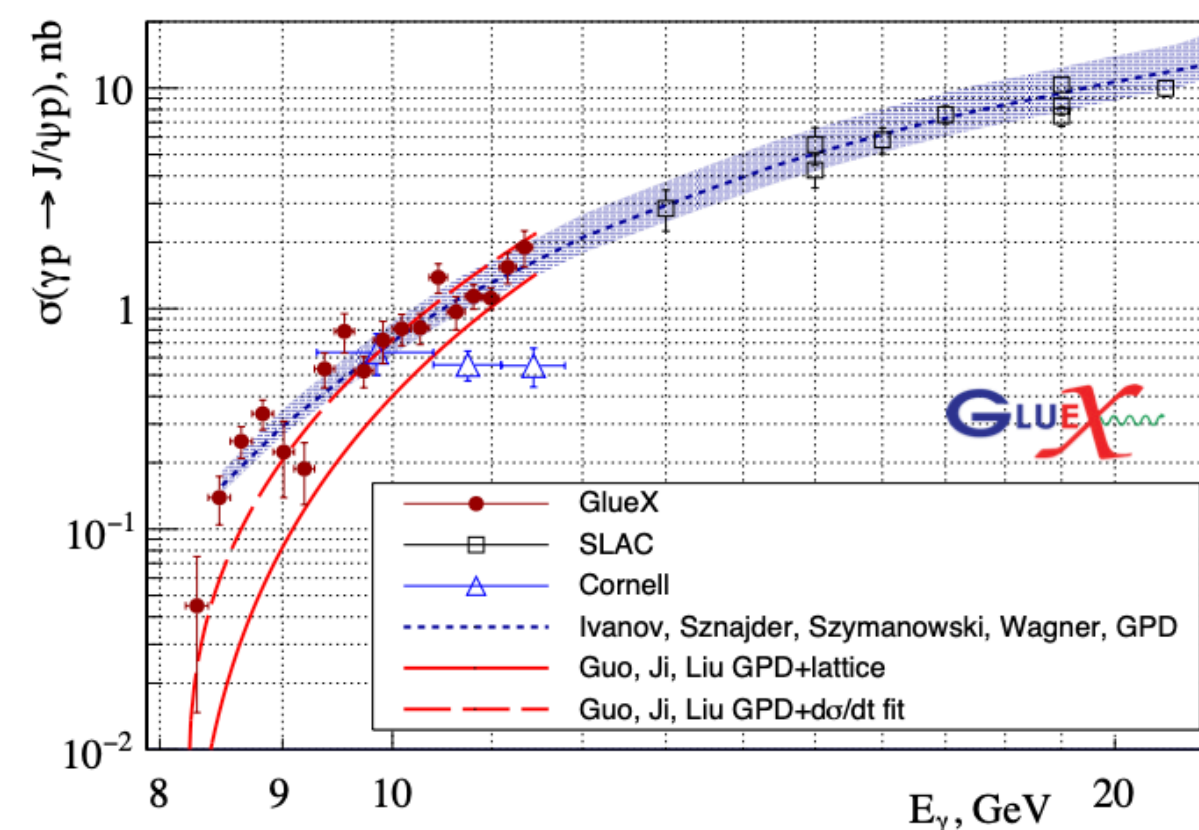
$E_\gamma \sim 9.1 - 10.6$ GeV

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



MODEL ASSUMPTIONS AND CAVEATS

First model-dependent attempt to determine the GFFs from experiment

Assumptions

Neglect $B(t)$ - in concordance with both models and lattice QCD

Neglect \bar{C}_g when evaluating the cross section and radii (*)

Assume tripole shape for $A(t)$ and $C(t)$ (**)

Fix $A(0)$ to the average gluon PDF from CT18

Both models fit the data well ($\chi^2 \sim 1$)

(*) This is appropriate for the holographic model but not the GPD model. See Hatta et al. JHEP 12 (2018) 008 & Tanaka, K. JHEP 03 (2023) 013 for a calculation of $\bar{C}_g = -\bar{C}_q$

(**) Doing the same extraction with a dipole shape, or does not impact our results

Holographic Model

K. Mamo & I. Zahed, PRD 103, 094010 (2021) and 2204.08857 (2022)

$$\frac{d\sigma}{dt} = \mathcal{N} \times \frac{e^2}{64\pi(s - m_N^2)^2} \times \frac{[A(-t, \kappa_T) + \eta^2 D(-t, \kappa_T, \kappa_S)]^2}{A^2(0)} \times F_{\tilde{J}/\psi}(s) \times 8$$

\mathcal{N} normalized to the previous world data (not given by the model)

GPD Model

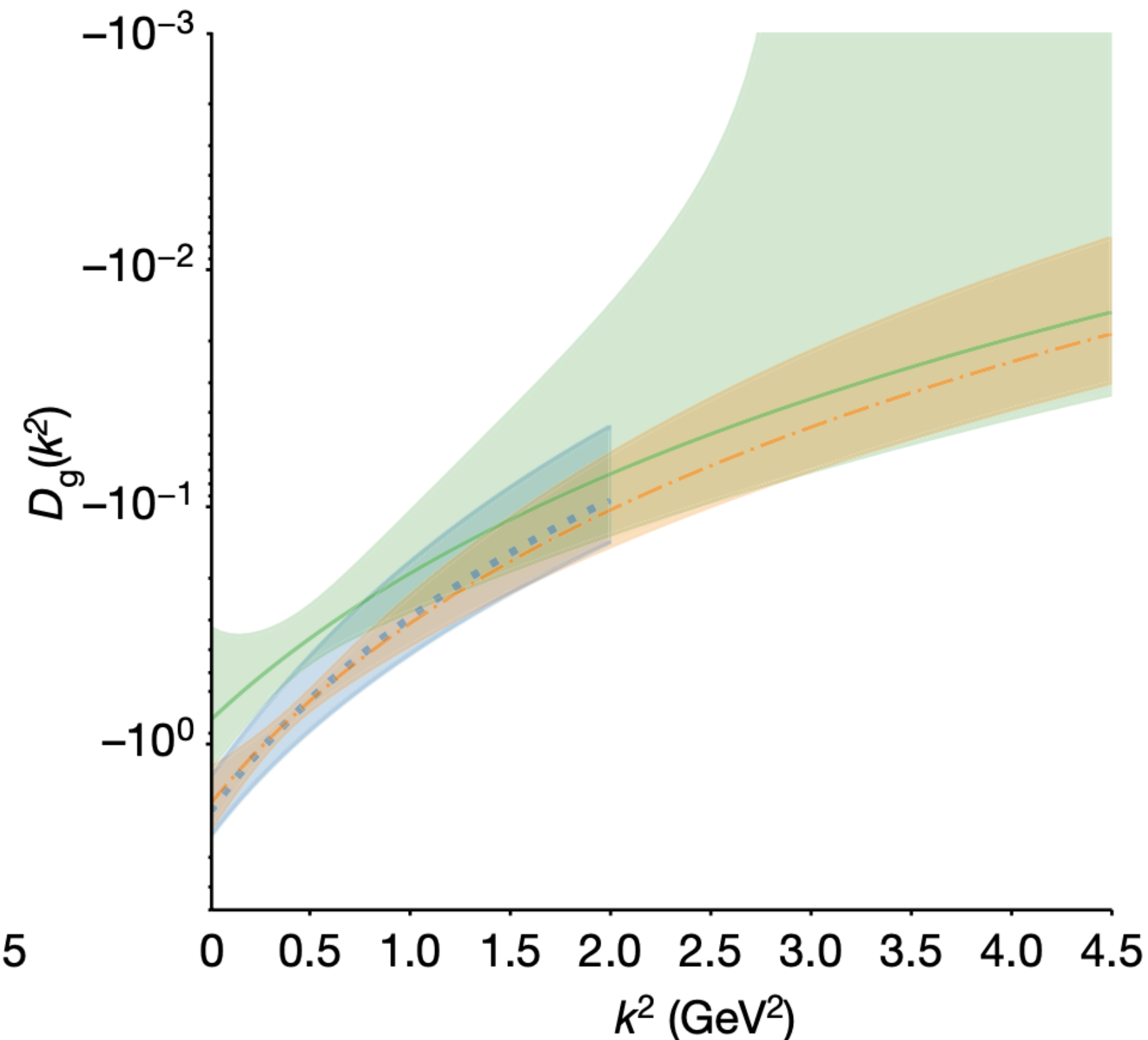
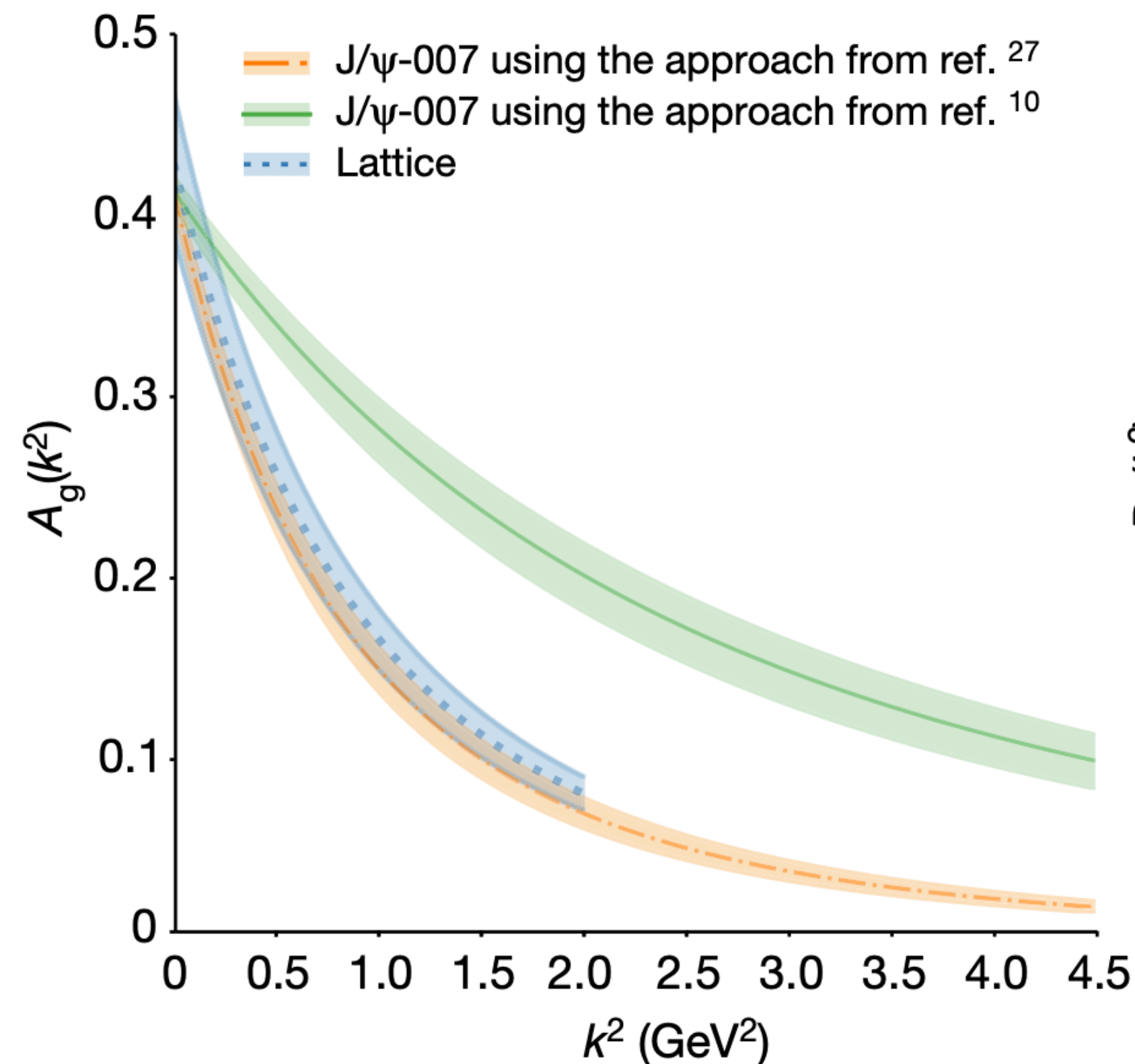
Y. Guo, X. Ji, Y. Liu, PRD 103, 096010 (2021)

$$\frac{d\sigma}{dt} = \frac{\alpha_e m e_Q^2}{4(W^2 - m_N^2)^2} \frac{(16\pi\alpha_s)^2}{3M_V^2} |\psi_{NR}|^2 |G(t, \xi)|^2$$

Assume $\xi \sim 1$ (it is less than 0.5 for most of the experimental data)

GLUONIC GFFS FROM EXPERIMENTAL DATA

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).

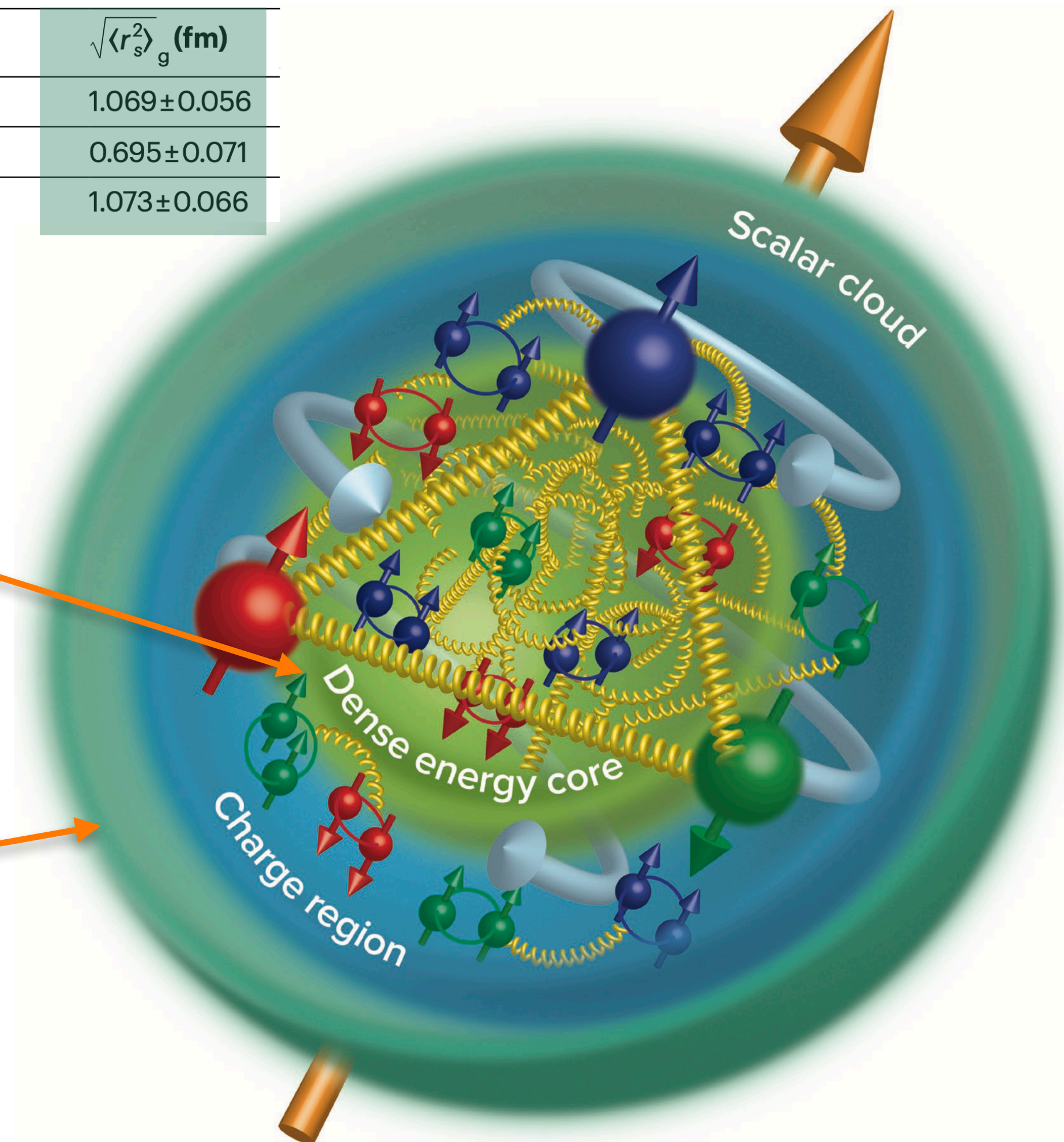
THE PROTON IN THREE REGIONS

Table 1 | The gluonic GFF fit parameters, proton mass radius and scalar radius

Theoretical approach	$\chi^2/n.d.f.$	m_A (GeV)	m_c (GeV)	$C_g(0)$	$\sqrt{\langle r_m^2 \rangle_g}$ (fm)	$\sqrt{\langle r_s^2 \rangle_g}$ (fm)
Holographic QCD	0.925	1.575±0.059	1.12±0.21	-0.45±0.132	0.755±0.035	1.069±0.056
GPD	0.924	2.71±0.19	1.28±0.5	-0.20±0.11	0.472±0.042	0.695±0.071
Lattice		1.641±0.043	1.07±0.12	-0.483±0.133	0.7464±0.025	1.073±0.066

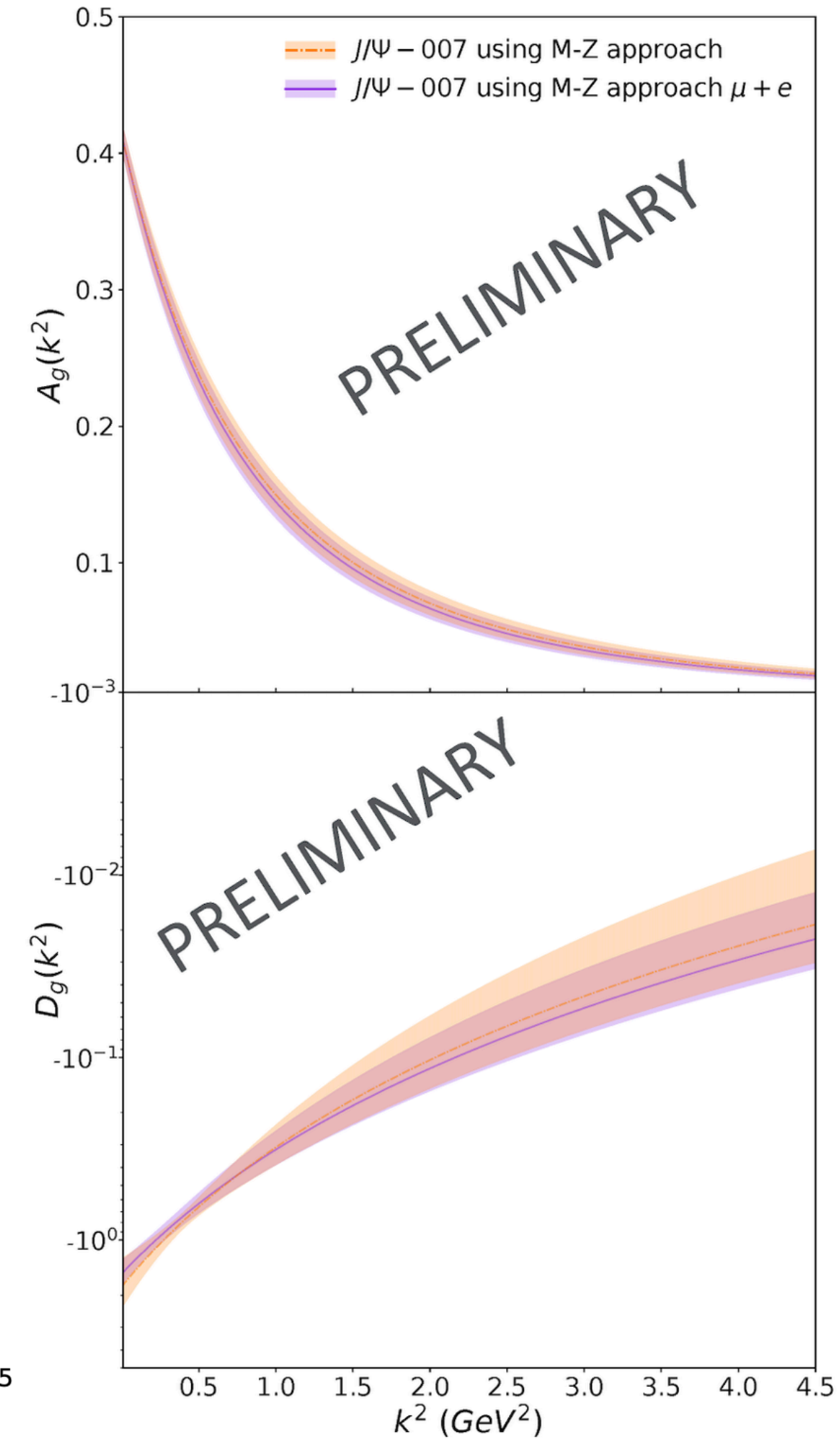
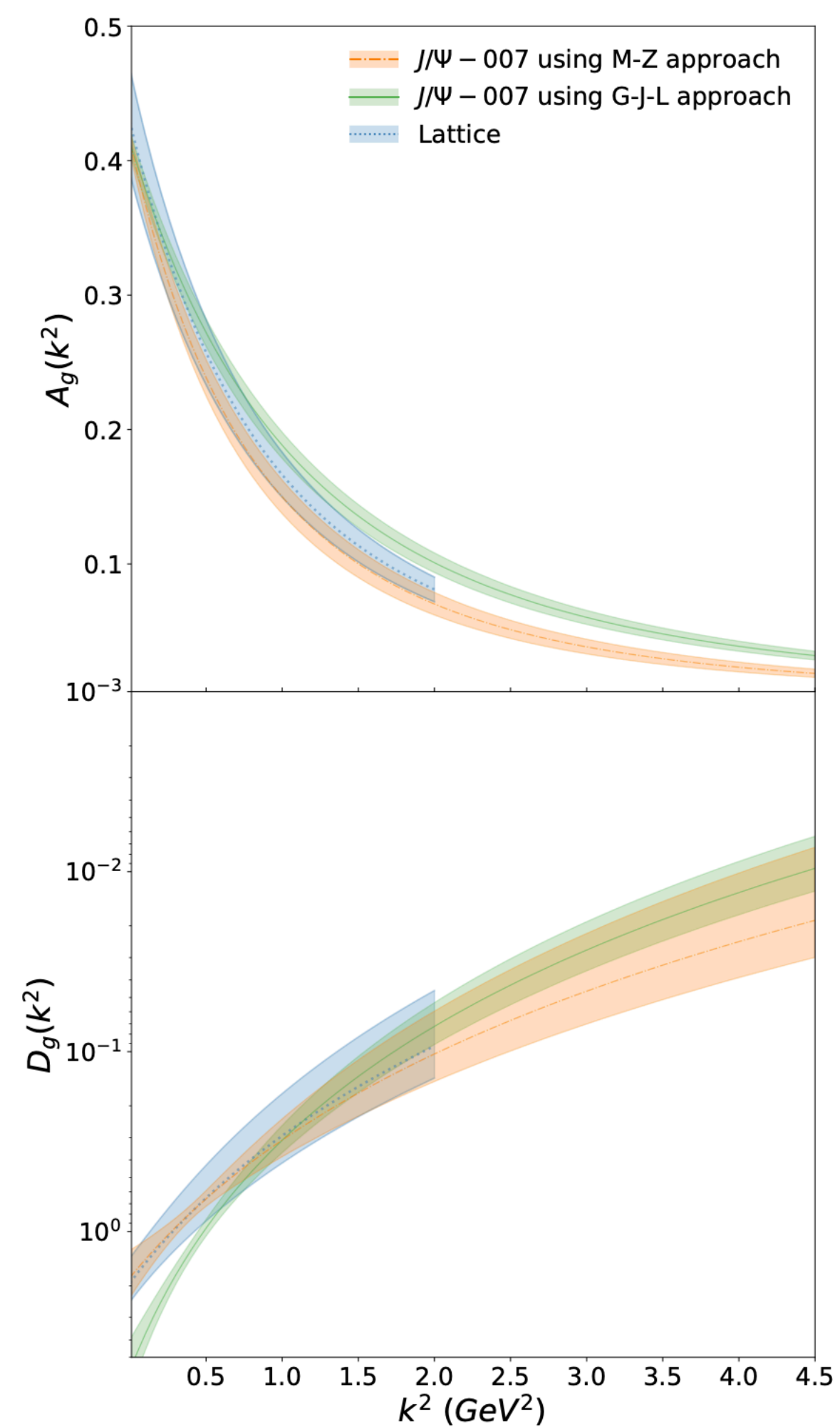
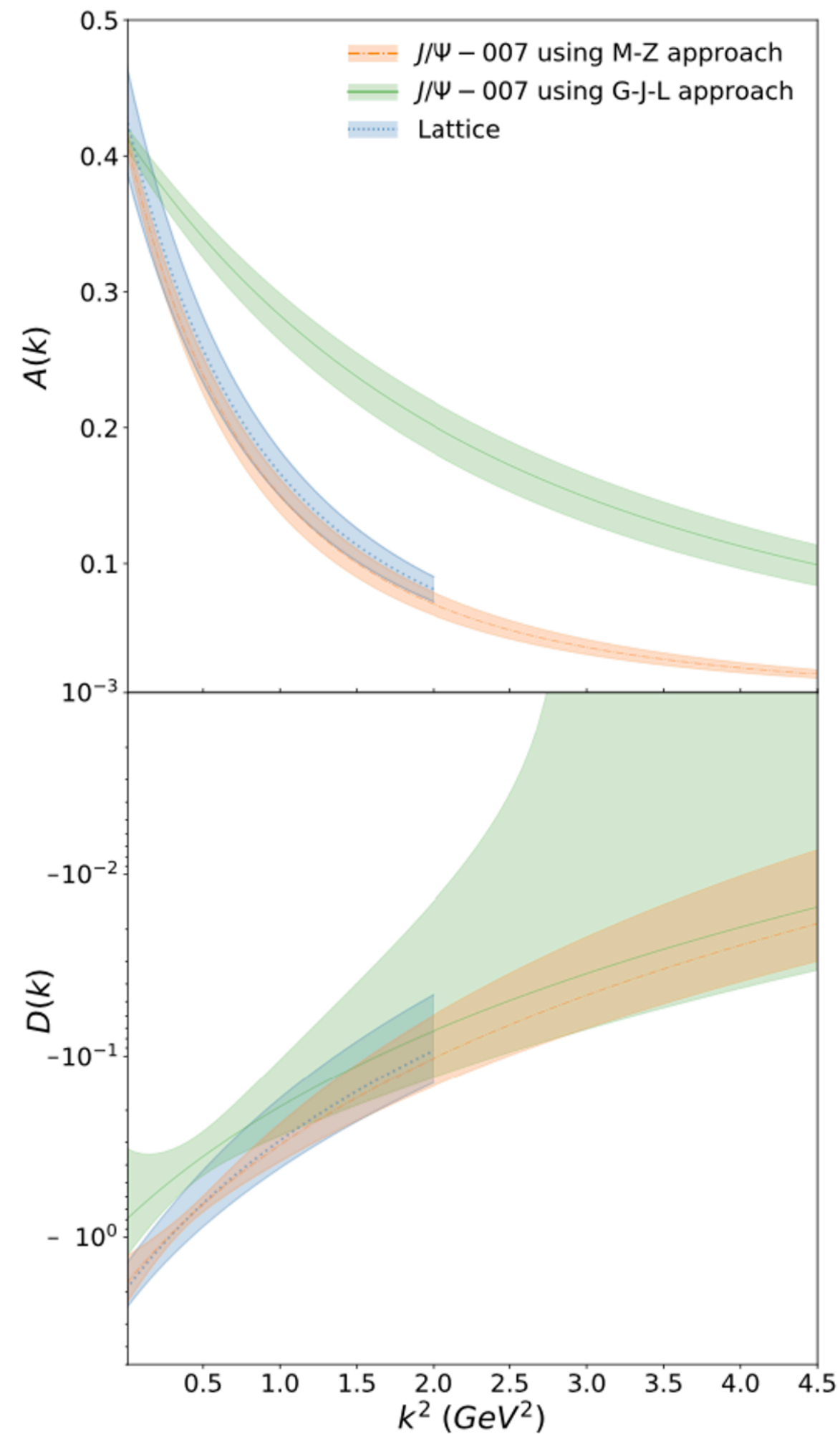
The proton's mass radius seems substantially smaller than its charge

The holographic QCD fit to our data and the latest Lattice calculations find a scalar gluonic cloud surrounding the charge region at about 1 fermi



UPDATES SINCE THE J/ ψ -007 PAPER

Update of G-J-L analysis PRD 108
(2023) no.3, 034003 arXiv:2305.06992



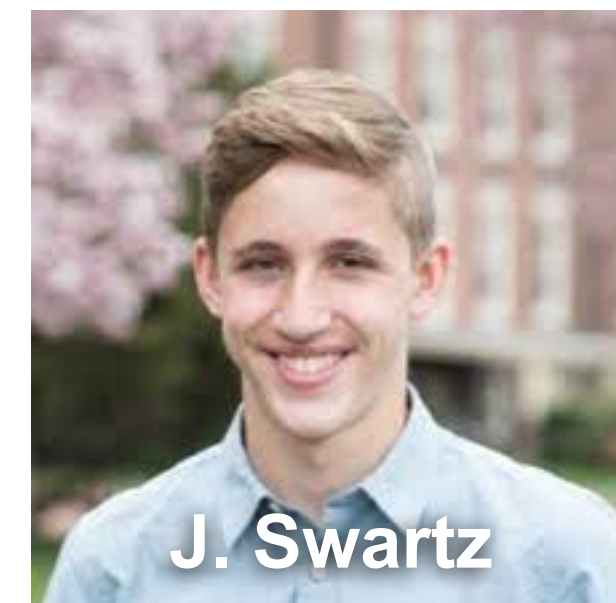
- Analysis with the muons decay channel results, doubling the statistics

- Consistent with the electron results.

- Largest impact on the $C(t)$ form factor with improved precision



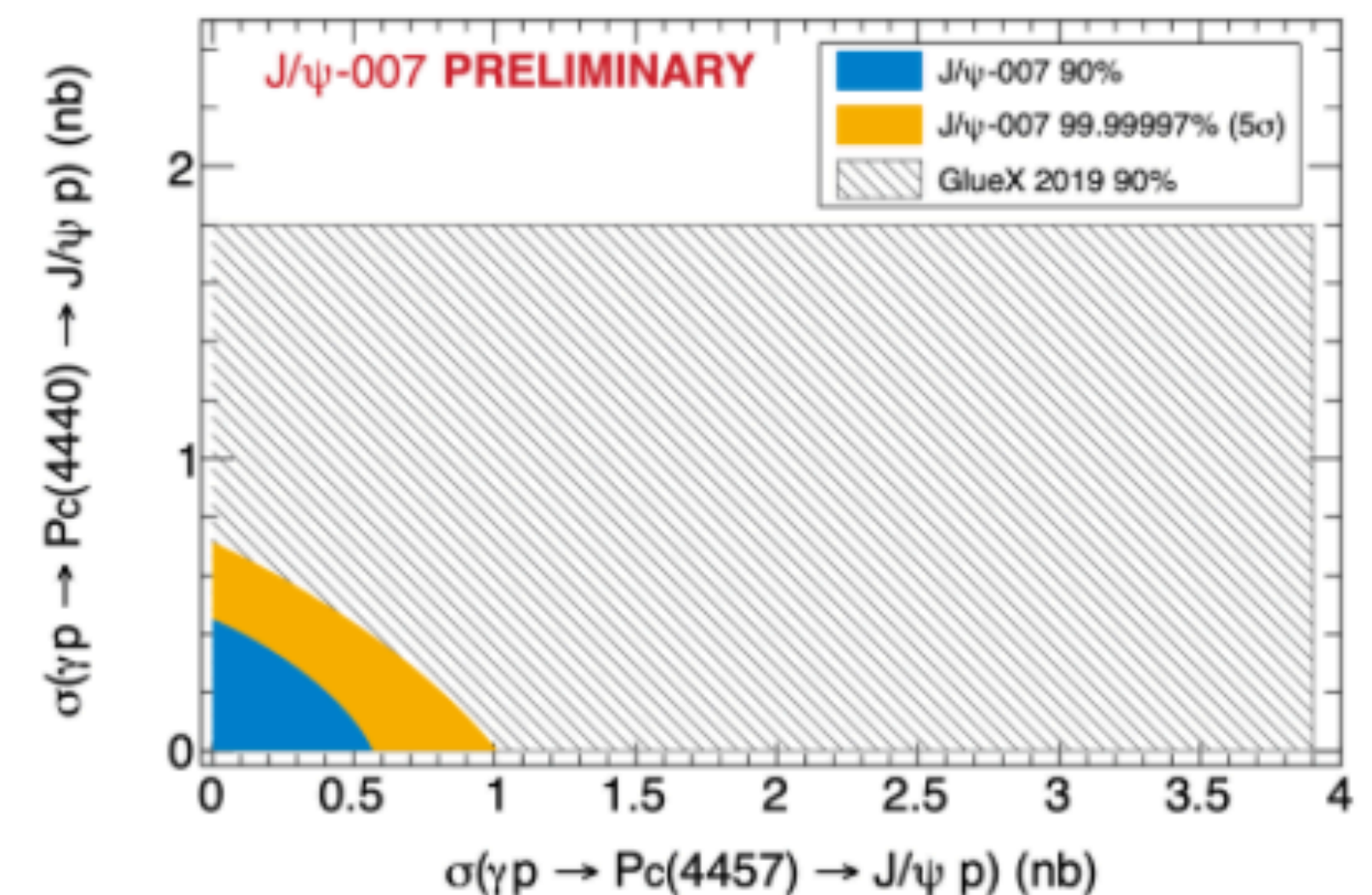
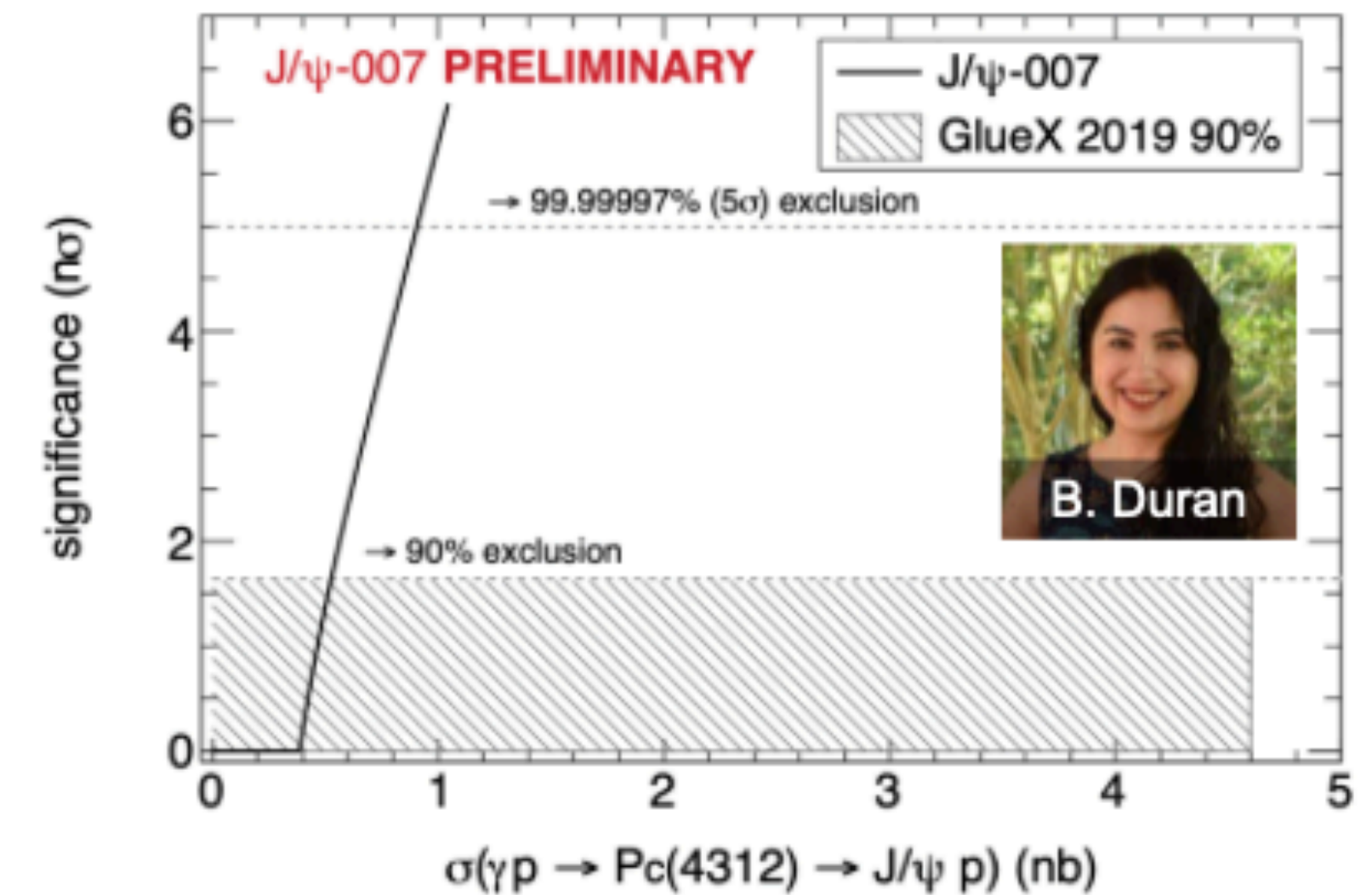
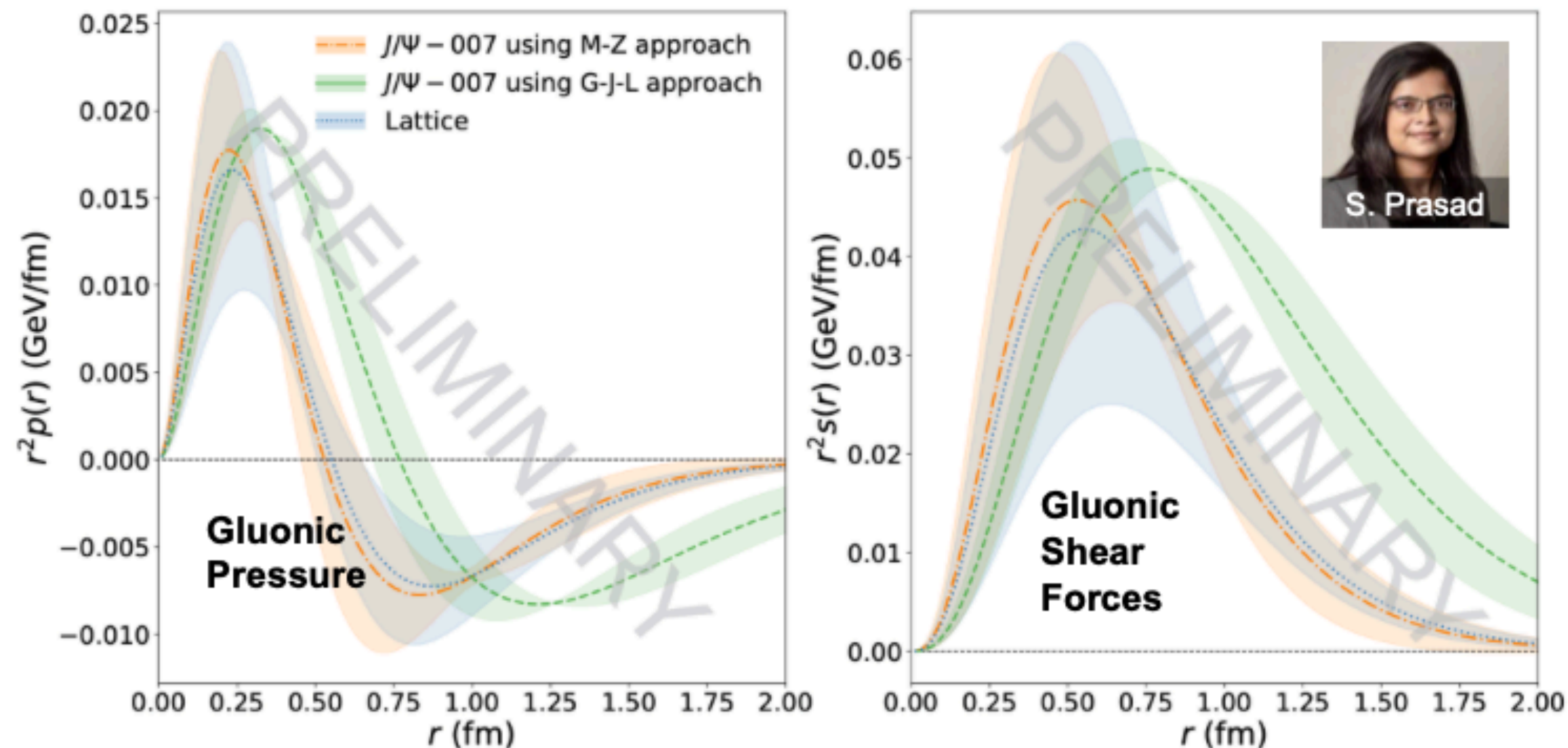
S. Prasad



J. Swartz

Upcoming J/ψ-007 Results

From near-threshold J/ψ in 2-D to gluonic gravitational form factors



- Expect more results in FY24: the gluonic pressure and shear forces in the proton, hidden-charm pentaquarks, and di-muon decay channel

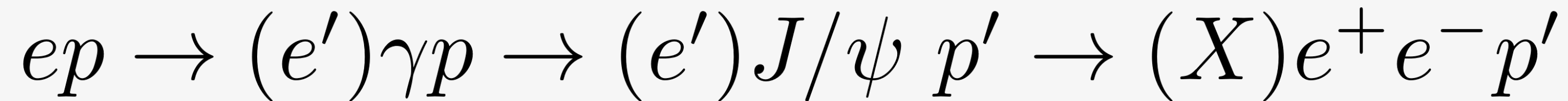
Slide from Pierre Chatagnon

NEW CLAS12 RESULTS AND OUTLOOK

From TCS to near-threshold J/ψ photoproduction

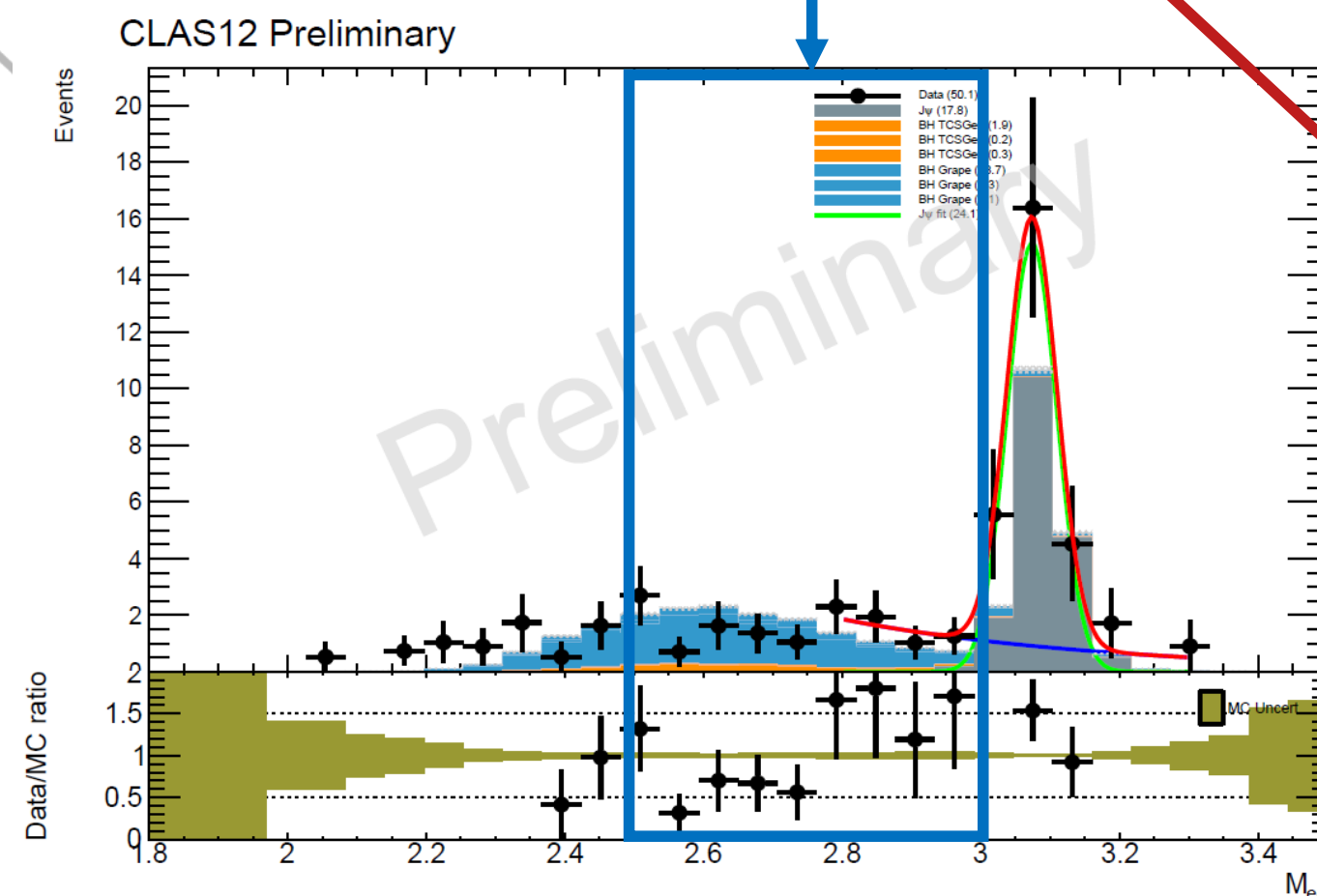
14/16

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



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

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



Number of J/ψ

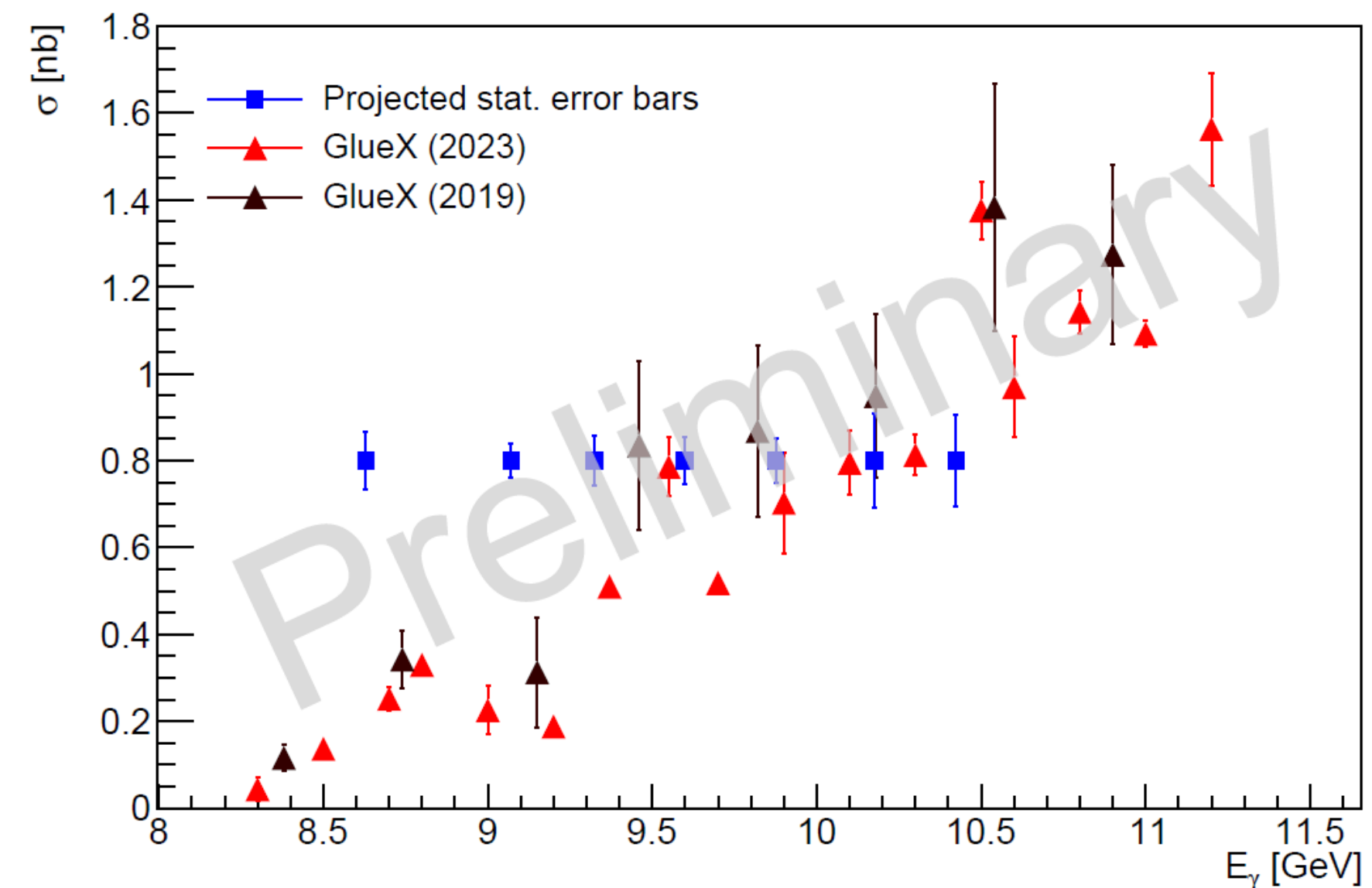
Reconstruction efficiency of the J/ψ
→ from MC

Branching ratio of $J/\psi \rightarrow e^+e^-$
→ 6%

NEW CLAS12 RESULTS AND OUTLOOK

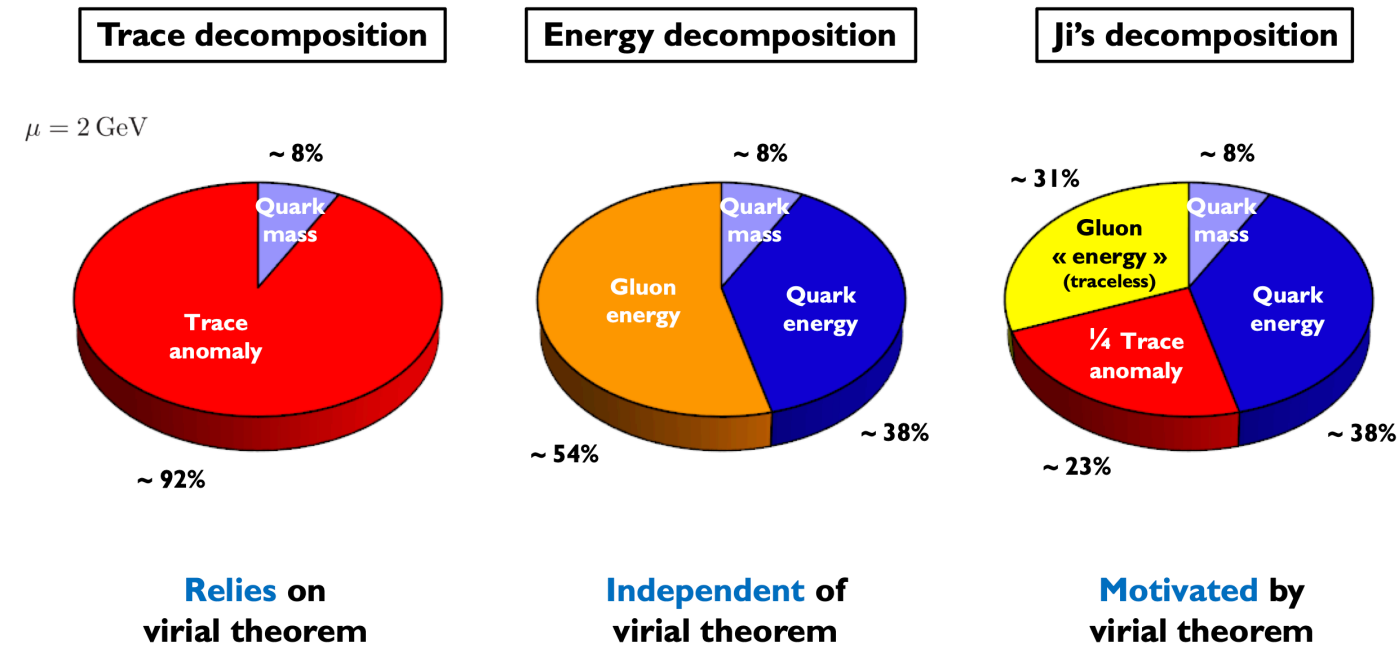
Projections for the full CLAS12 proton target dataset

- 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).

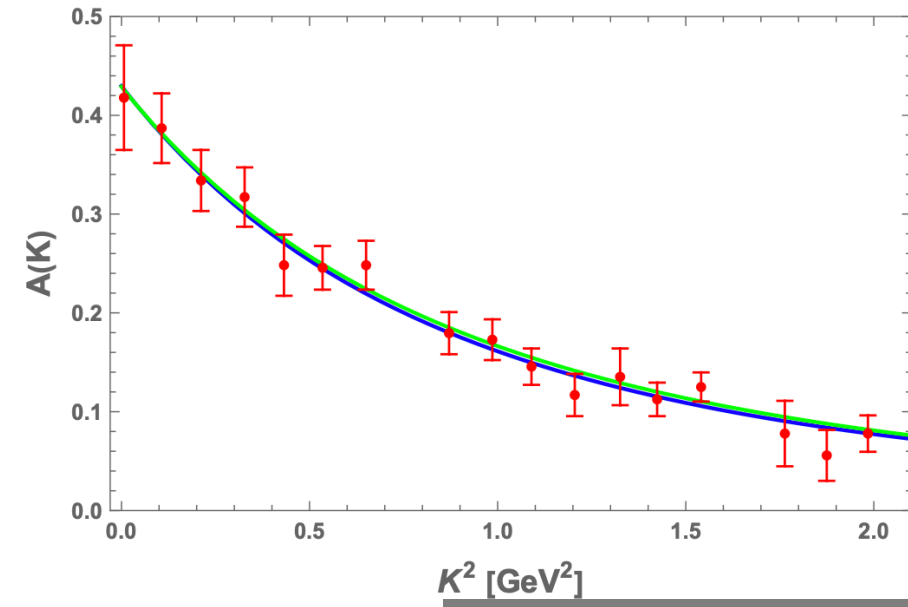


Including all data taken on unpolarized proton and improved tracking efficiency

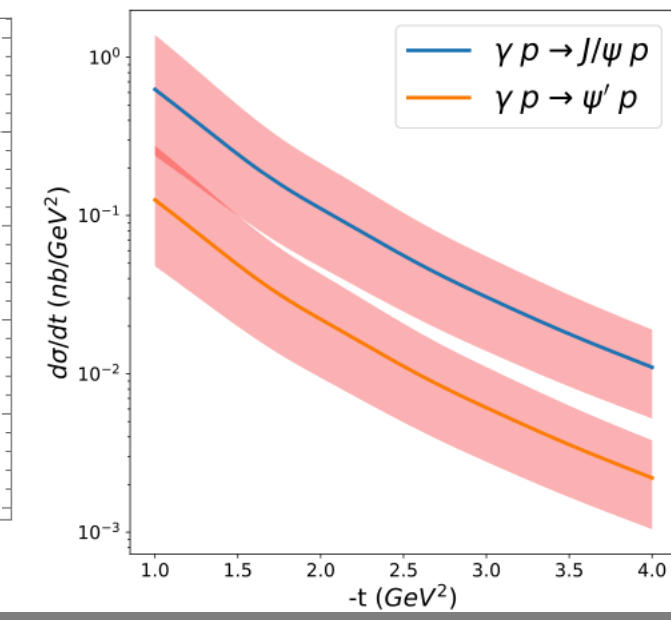
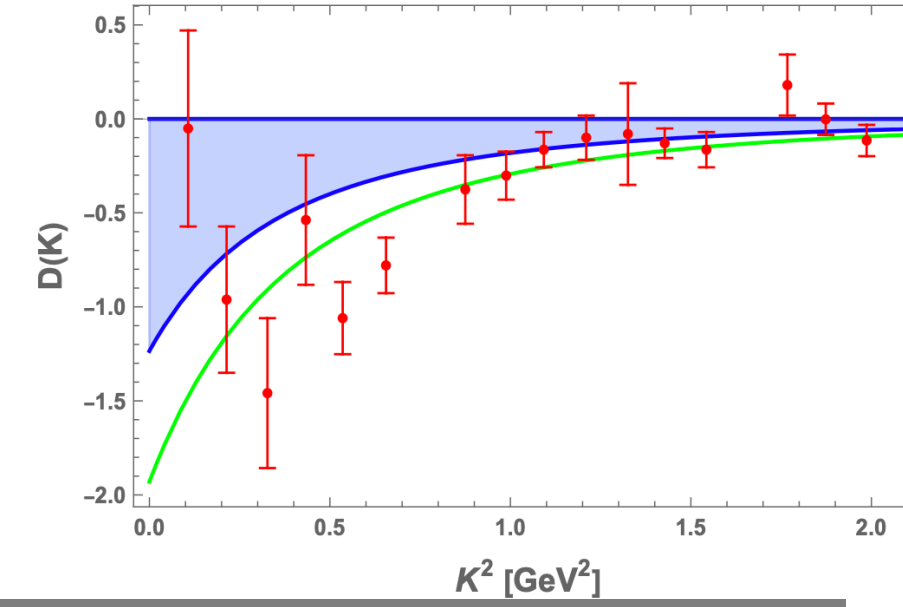
PROMINENT RECENT DEVELOPMENTS



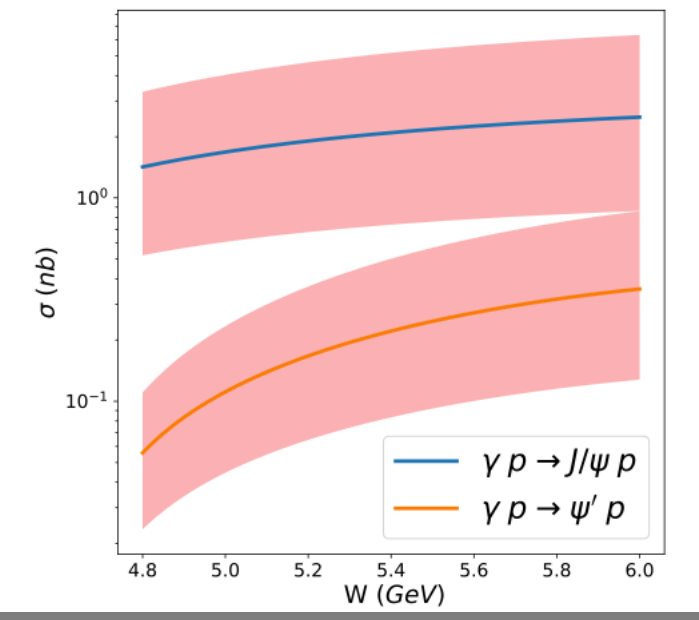
Proton mass budget decompositions, C. Lorce (from 2022 INT workshop)



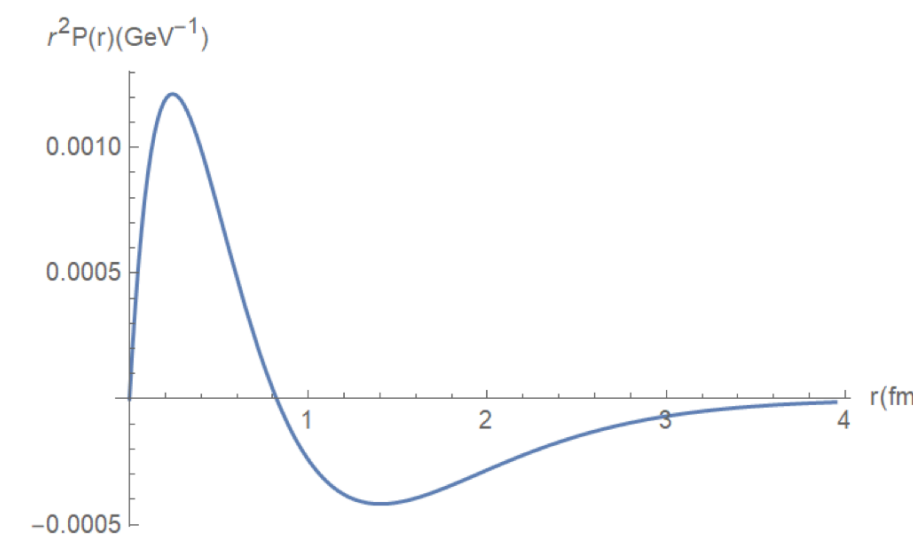
Proton gravitational form factors holographic QCD compared with Lattice, K. Mamo & I. Zahed (2022)



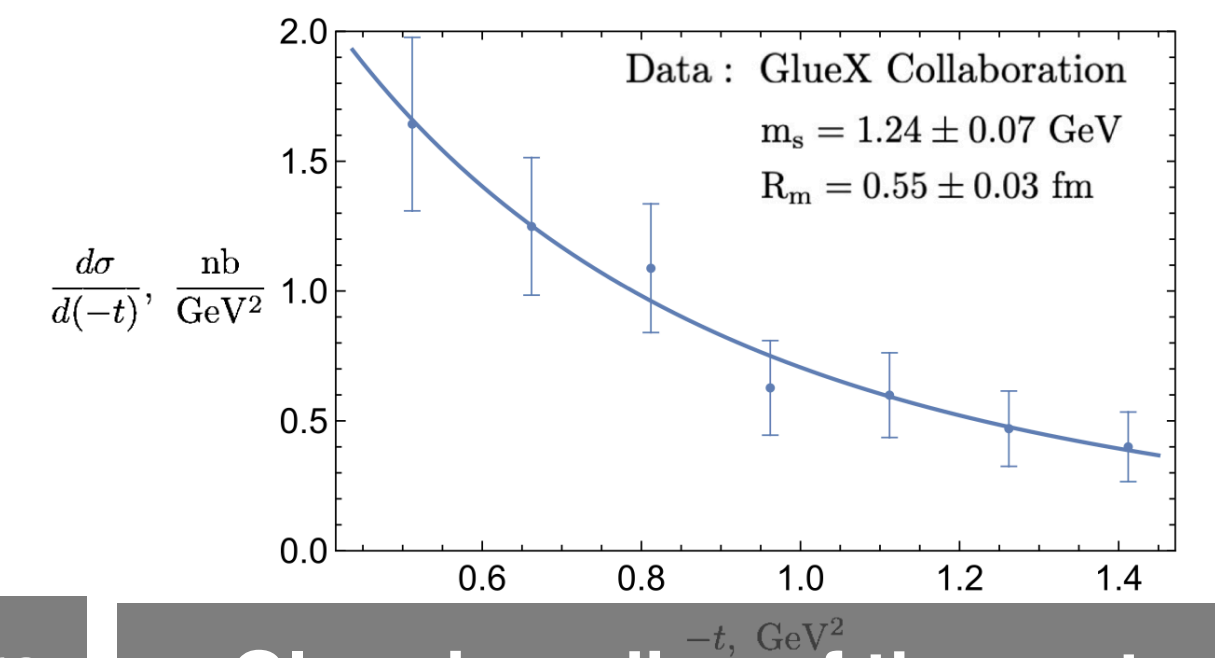
Near-threshold heavy quarkonium production at large momentum transfer, P. Sun, X-B. Tong, F. Yuan (PRD 2022)



- 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)

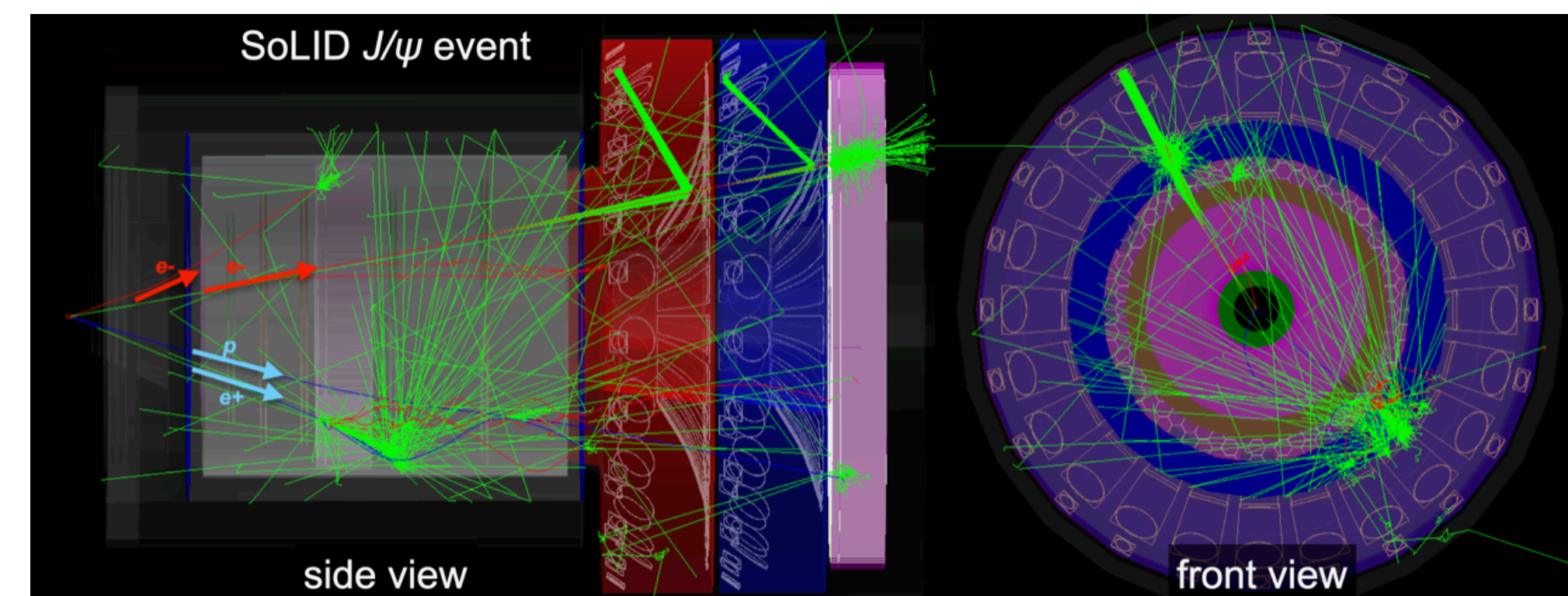
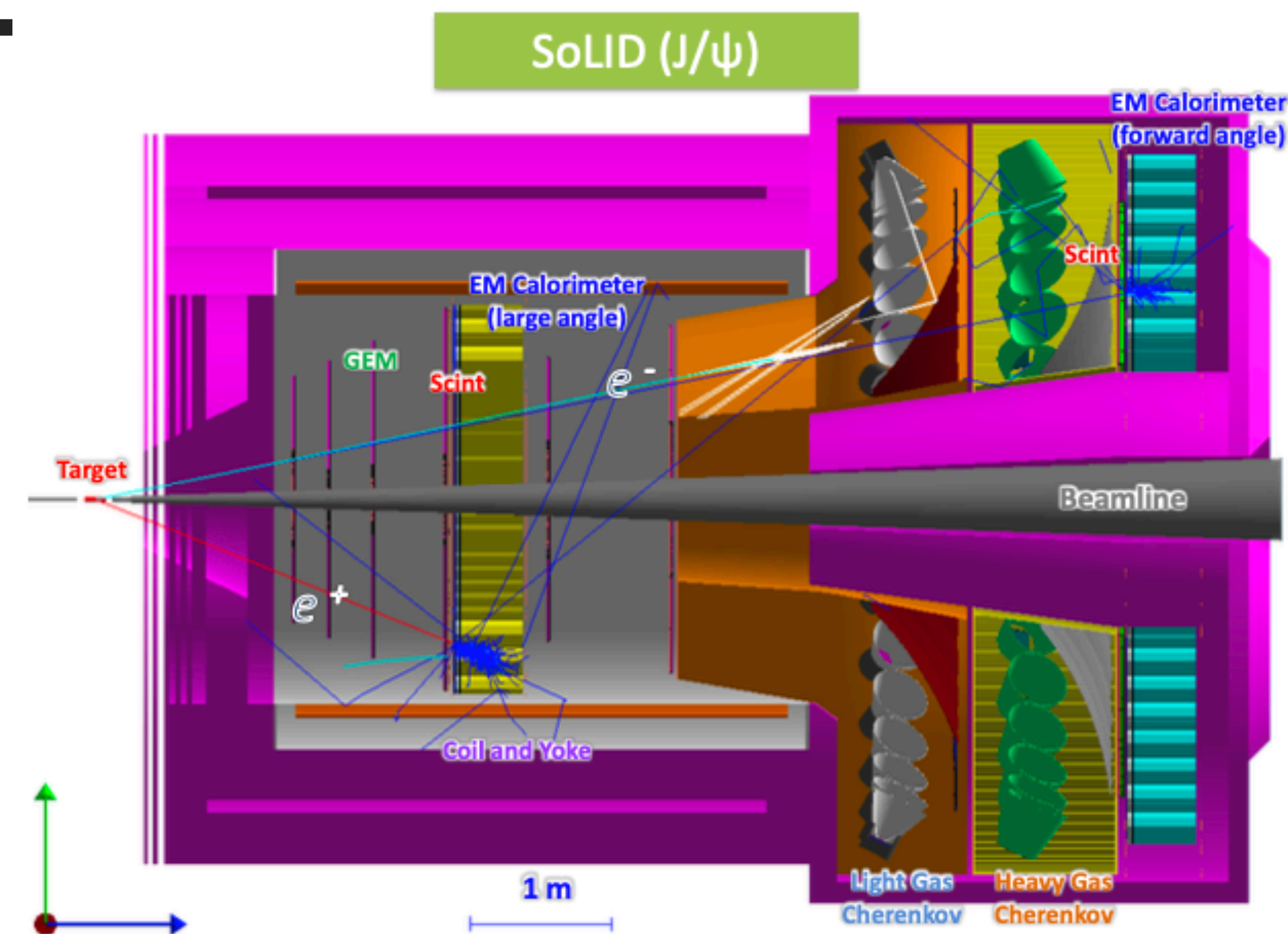


Gluonic radius of the proton based on 1D GlueX results, D. Kharzeev (PRD 2021)

THE SOLID-J/ ψ EXPERIMENT

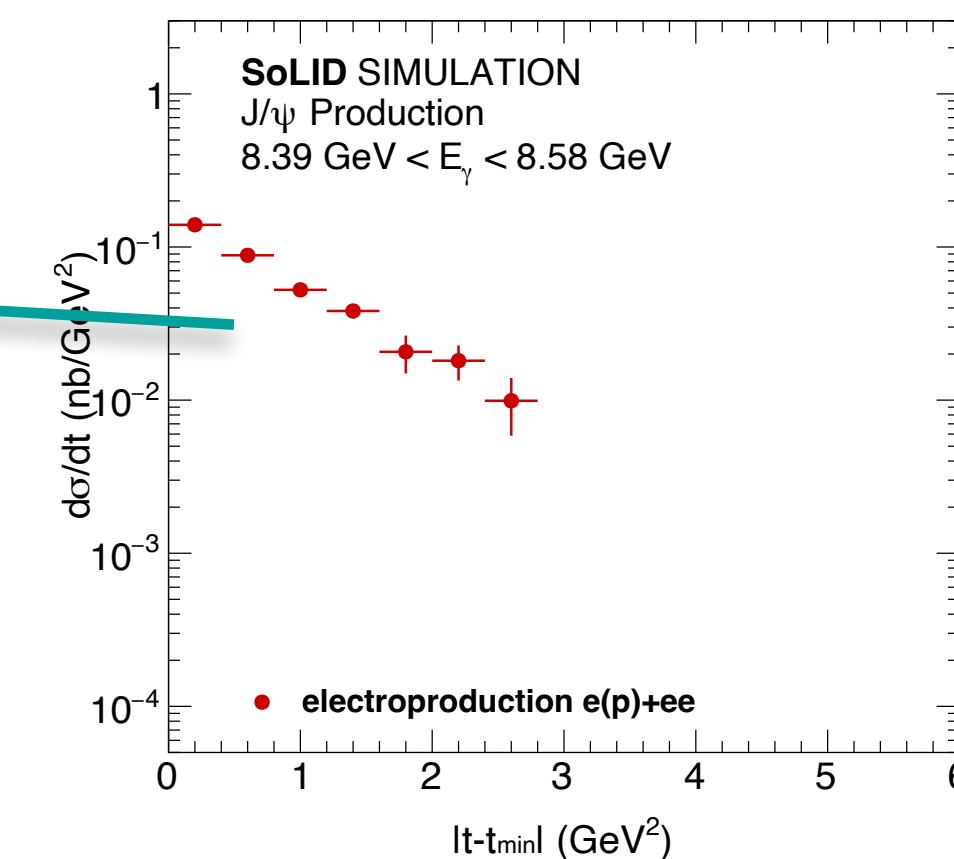
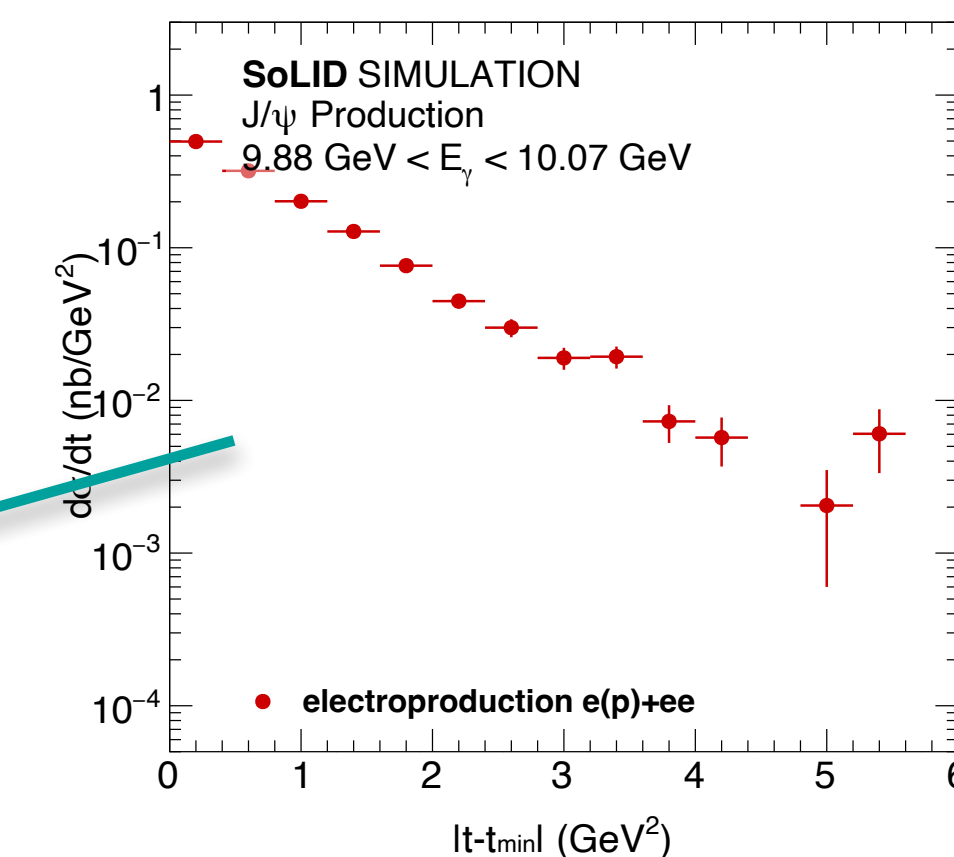
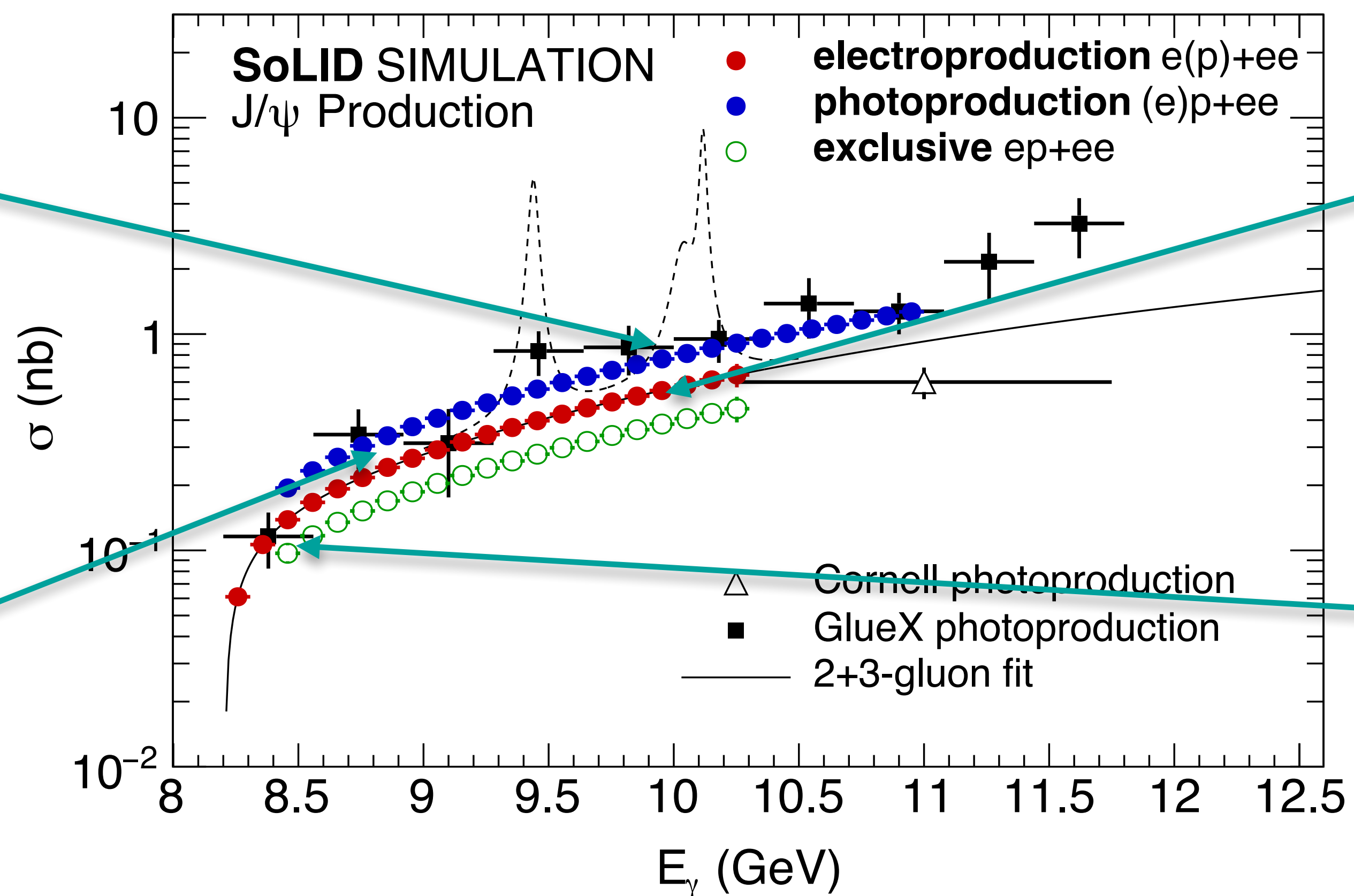
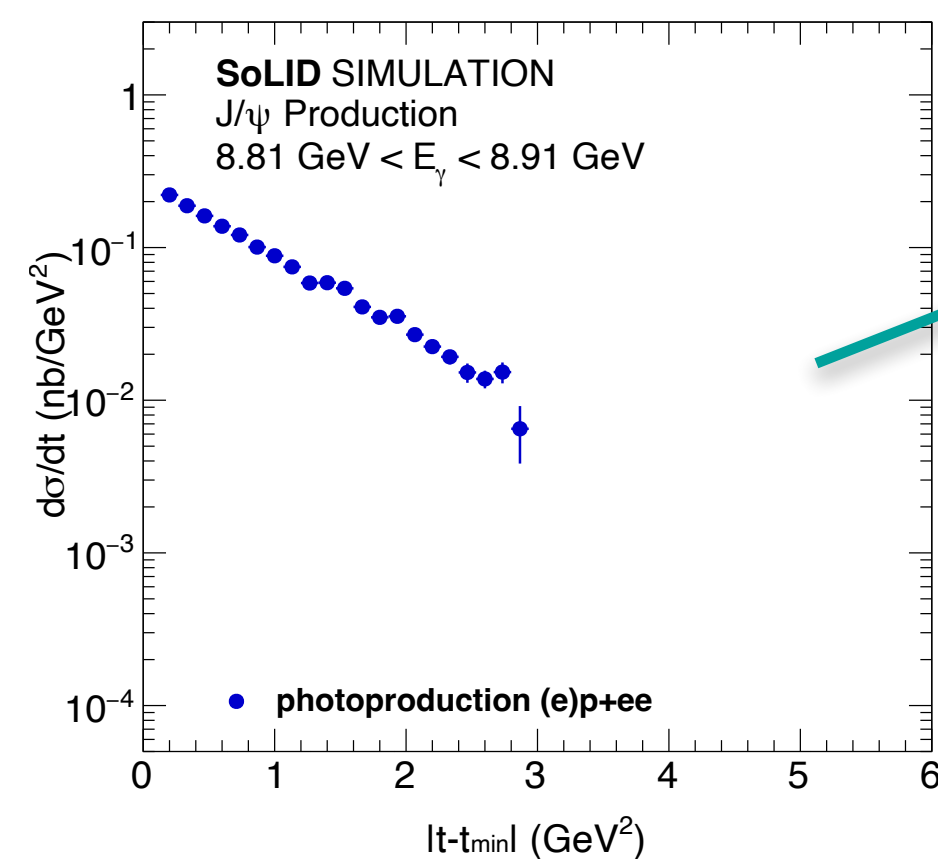
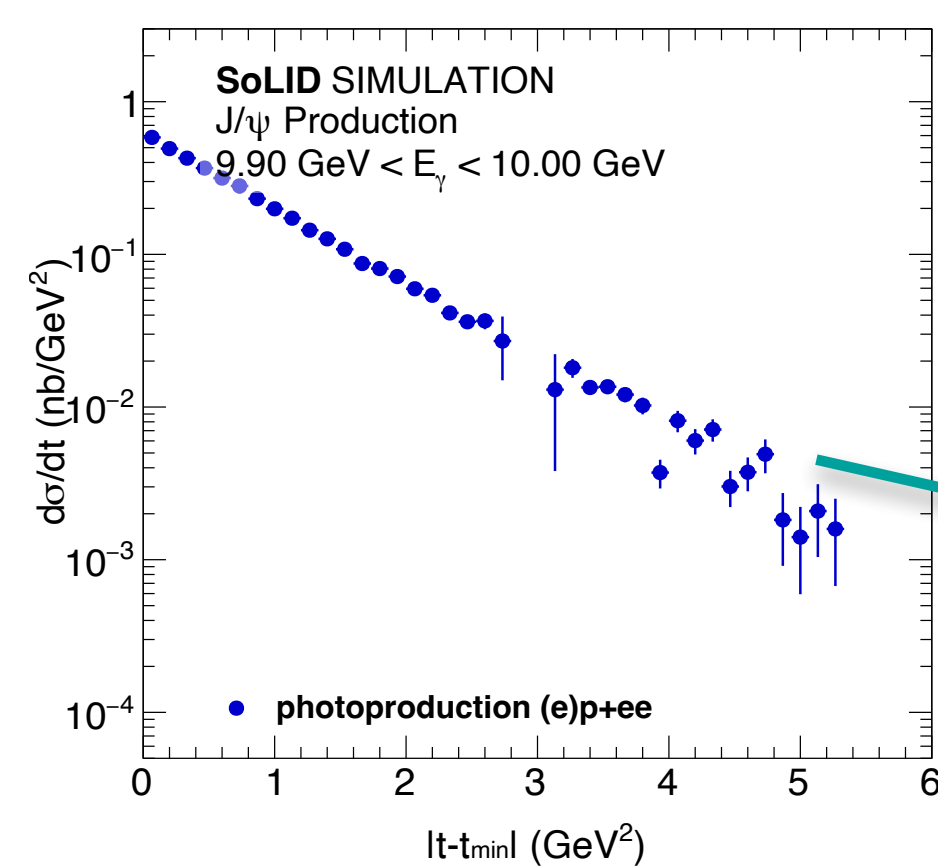
Ultimate factory for near-threshold J/ ψ

- General purpose large-acceptance spectrometer
- 50+10 days of 3 μ A beam on a 15cm long LH2 target ($10^{37}/\text{cm}^2/\text{s}$)
- **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 electroproduction channel provides for a modest lever-arm in Q² near threshold



SOLID-J/ ψ PROJECTIONS

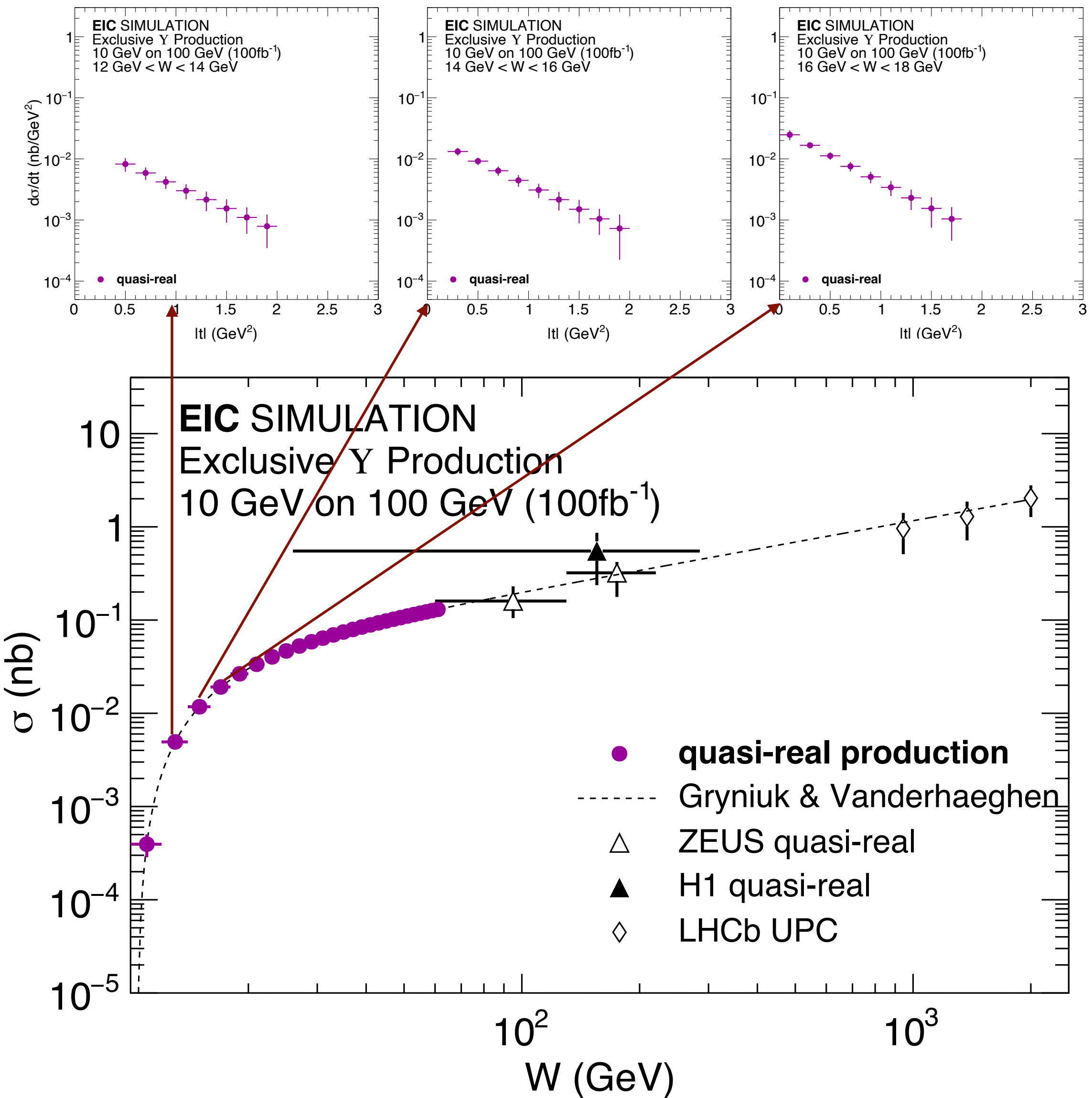
High-precision 2-D cross section crucial to really connect GFFs to data



Y(1S) NEAR THRESHOLD

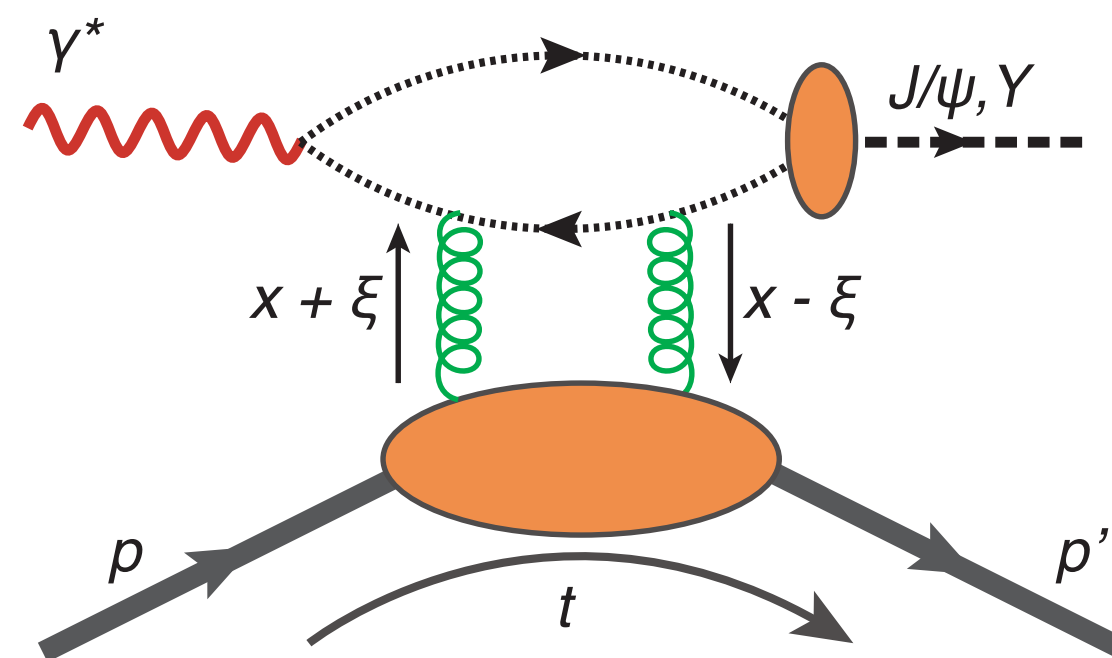
Y(1S) with the ePIC detector

- Y(1S) at EIC trades statistical precision of J/ψ at SoLID for lower theoretical uncertainties and extra channel to study universality.
- Large Q² reach at EIC an additional knob to study production



DEEPLY-VIRTUAL QUARKONIUM PRODUCTION

Accessing the 3-D gluon structure

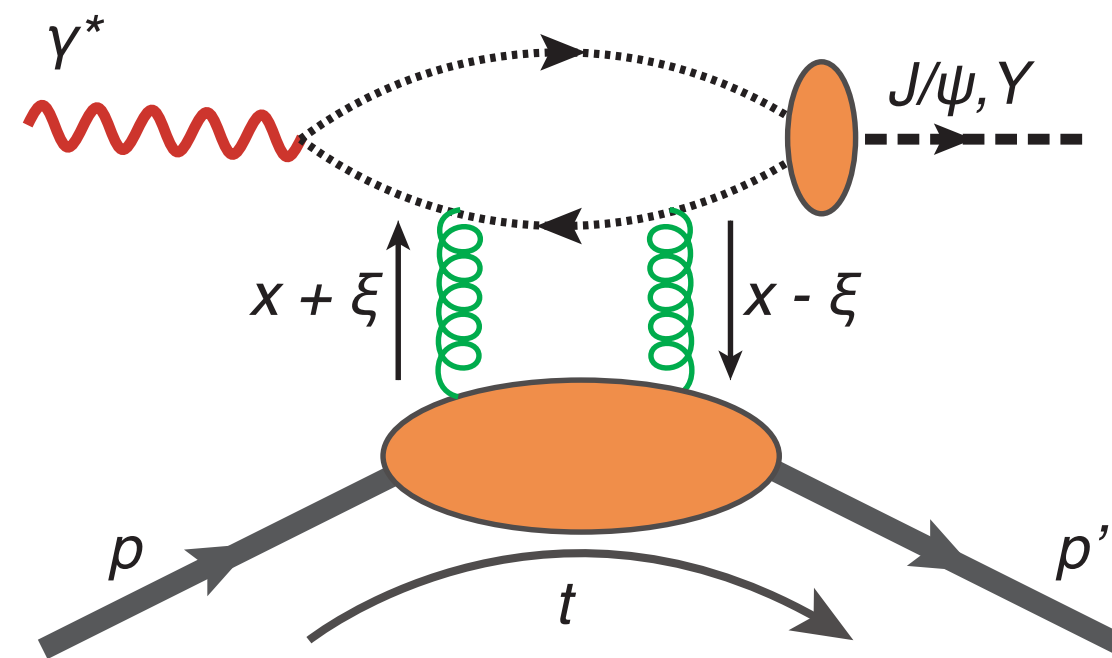


Hard scale: $Q^2 + M_V^2$

Modified Bjorken- x : $x_V = \frac{Q^2 + M_V^2}{2p \cdot q}$

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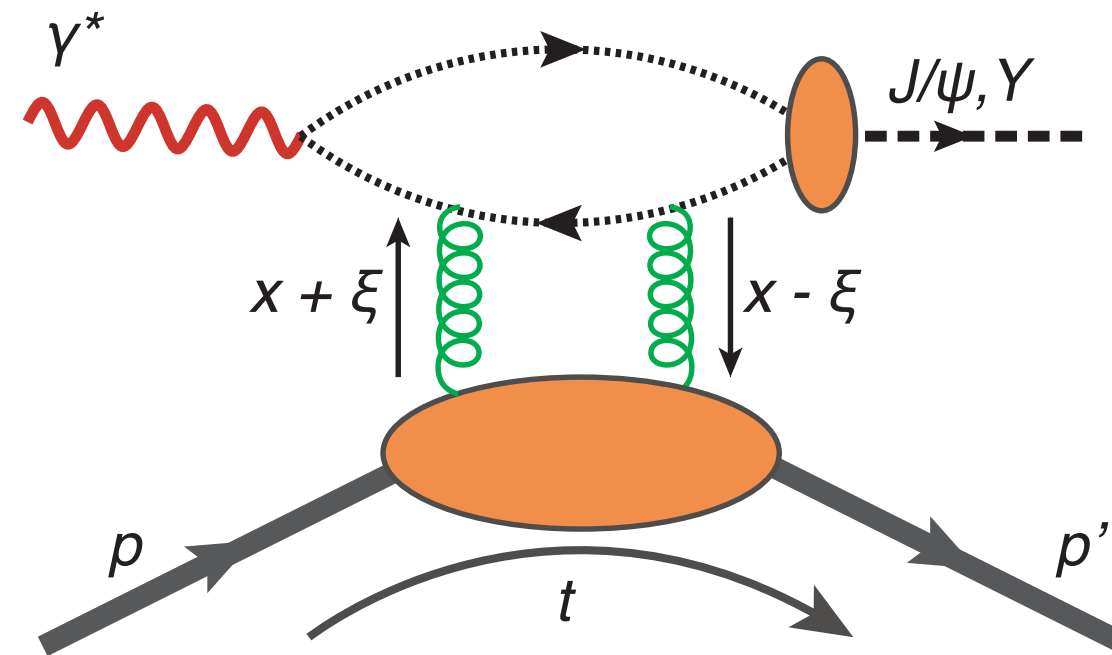
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average unpolarized gluon GPD related to t -dependent cross section (LO)

$$|\langle \mathcal{H}_g \rangle|(t) \propto \sqrt{\frac{d\sigma}{dt}(t) / \frac{d\sigma}{dt}(t=0)}$$

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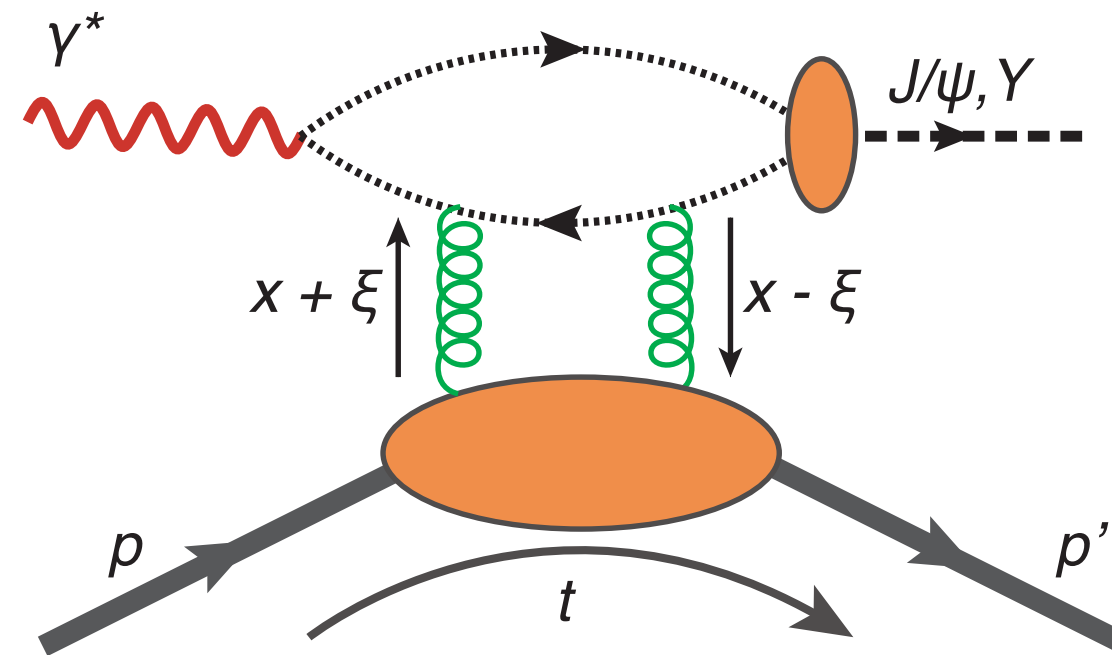


Fourier transform:
3-D transverse gluonic density

$$\rho(|\vec{b}_T|, x_V) = \int \frac{d^2 \vec{\Delta}_T}{(2\pi)^2} e^{i\vec{\Delta}_T \vec{b}_T} |\langle \mathcal{H}_g \rangle|(t = -\vec{\Delta}_T^2)$$

DEEPLY-VIRTUAL QUARKONIUM PRODUCTION

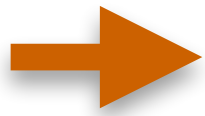
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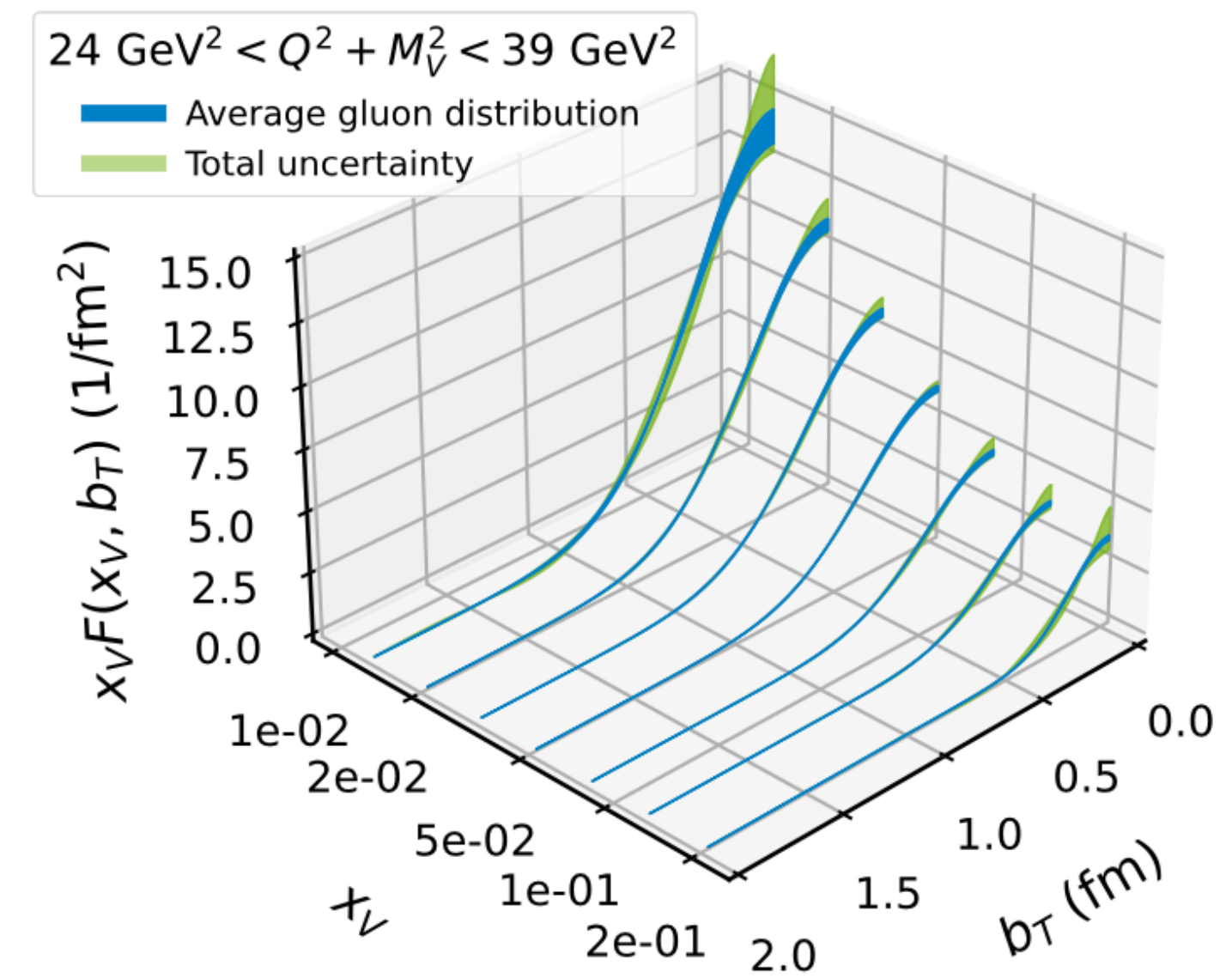
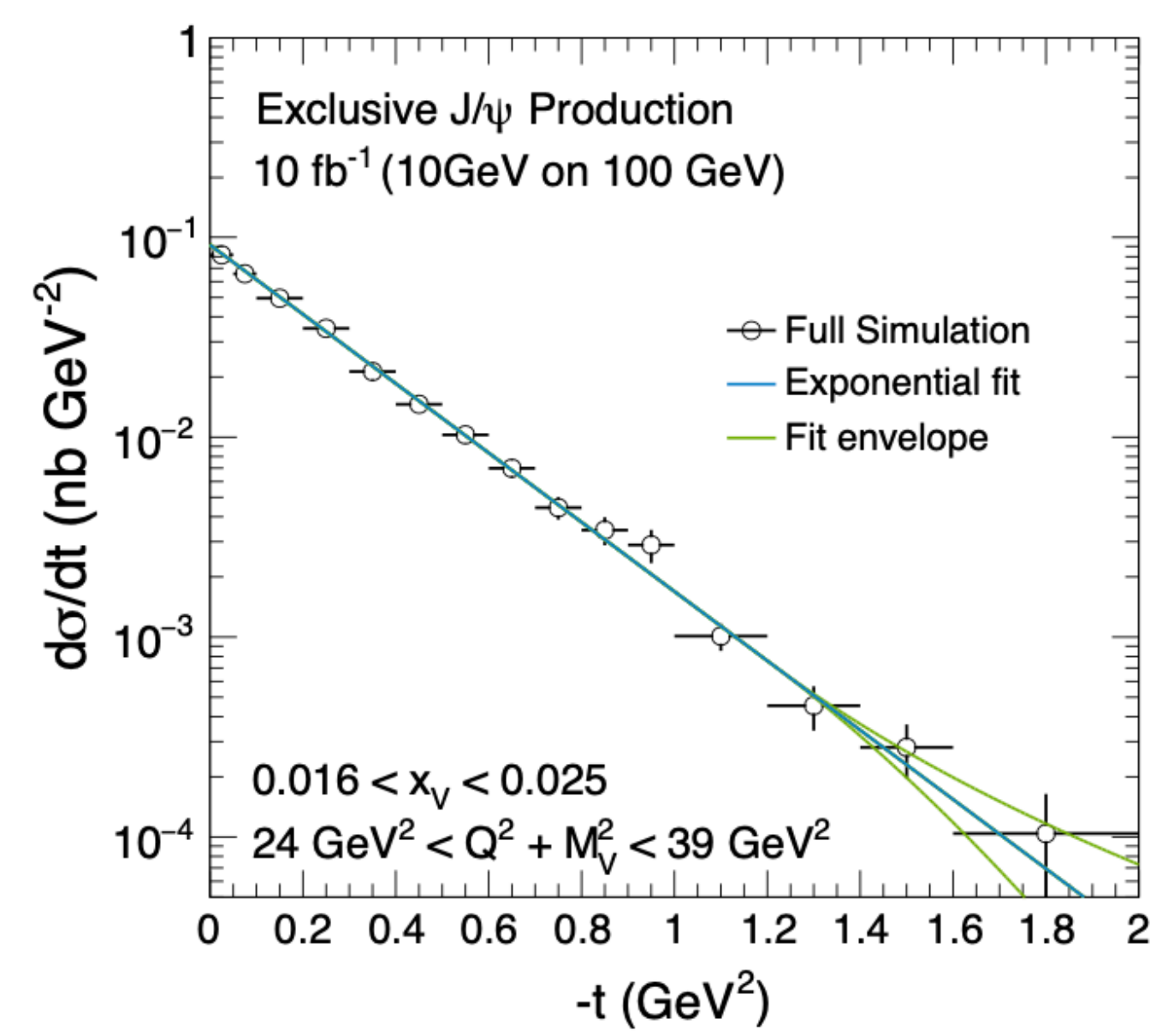
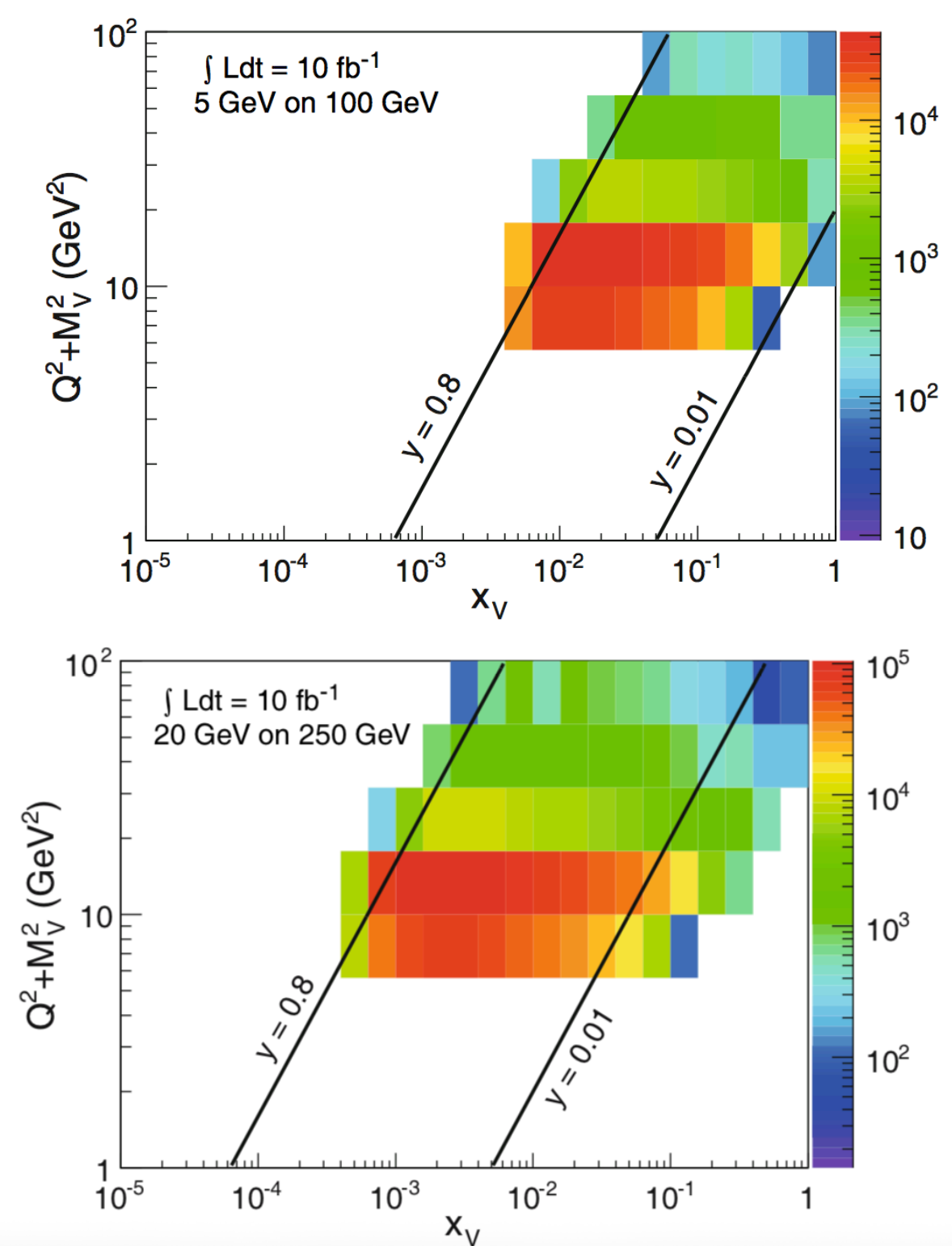
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3-D GPDs can be related to 2-D Gravitational Form Factors

GLUON TOMOGRAPHY WITH J/Ψ



***t*-spectra**

Normalized average gluon density

**Only possible at an EIC:
 from the valence region
 deep into the sea!**

Same can be done with Y(1S) at EIC!

CONCLUSION

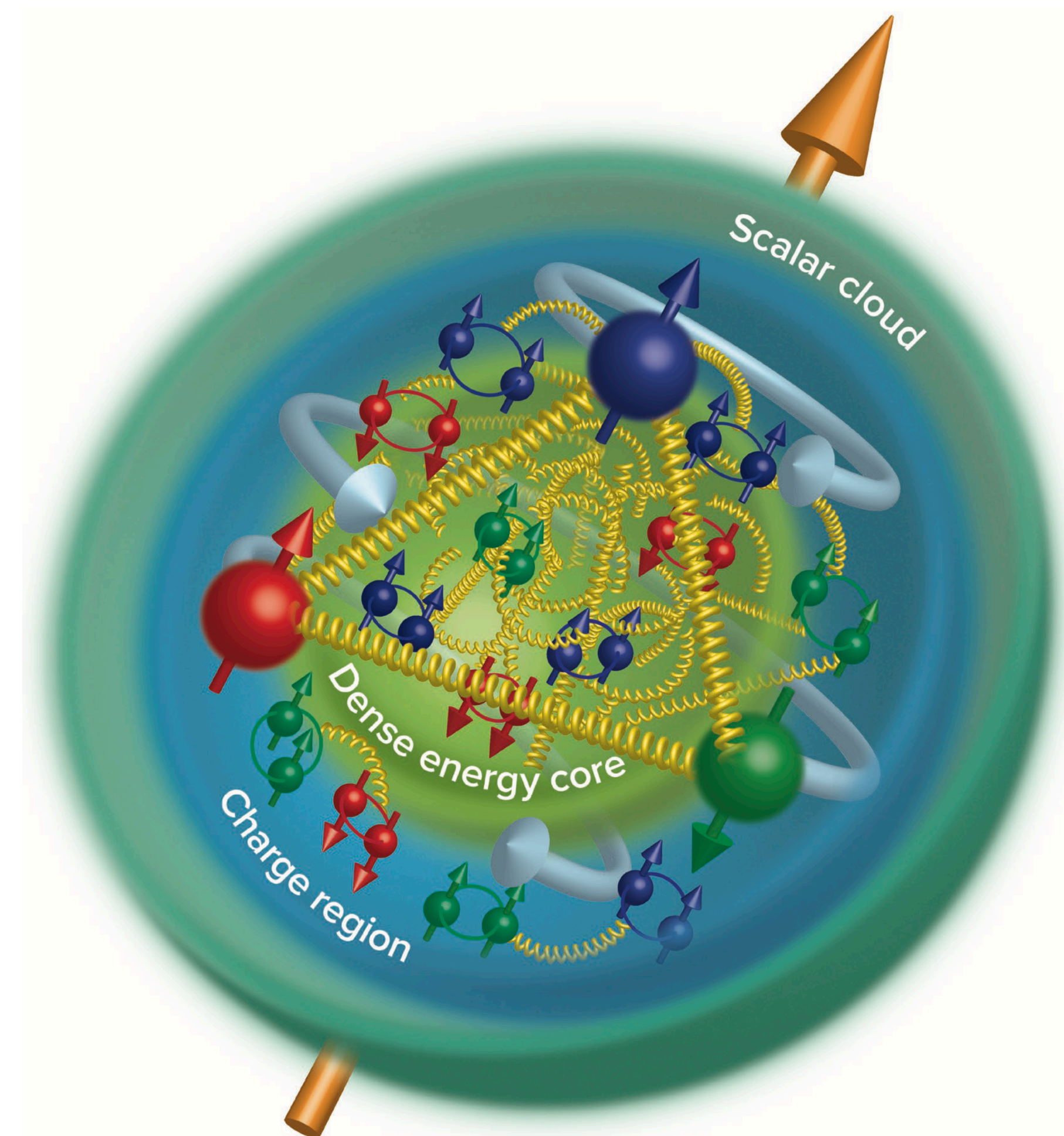
The JLab 12-GeV program has delivered important first results on near-threshold J/ψ production from GlueX and Hall C (J/ψ -007)

- 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 at Jefferson Lab 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

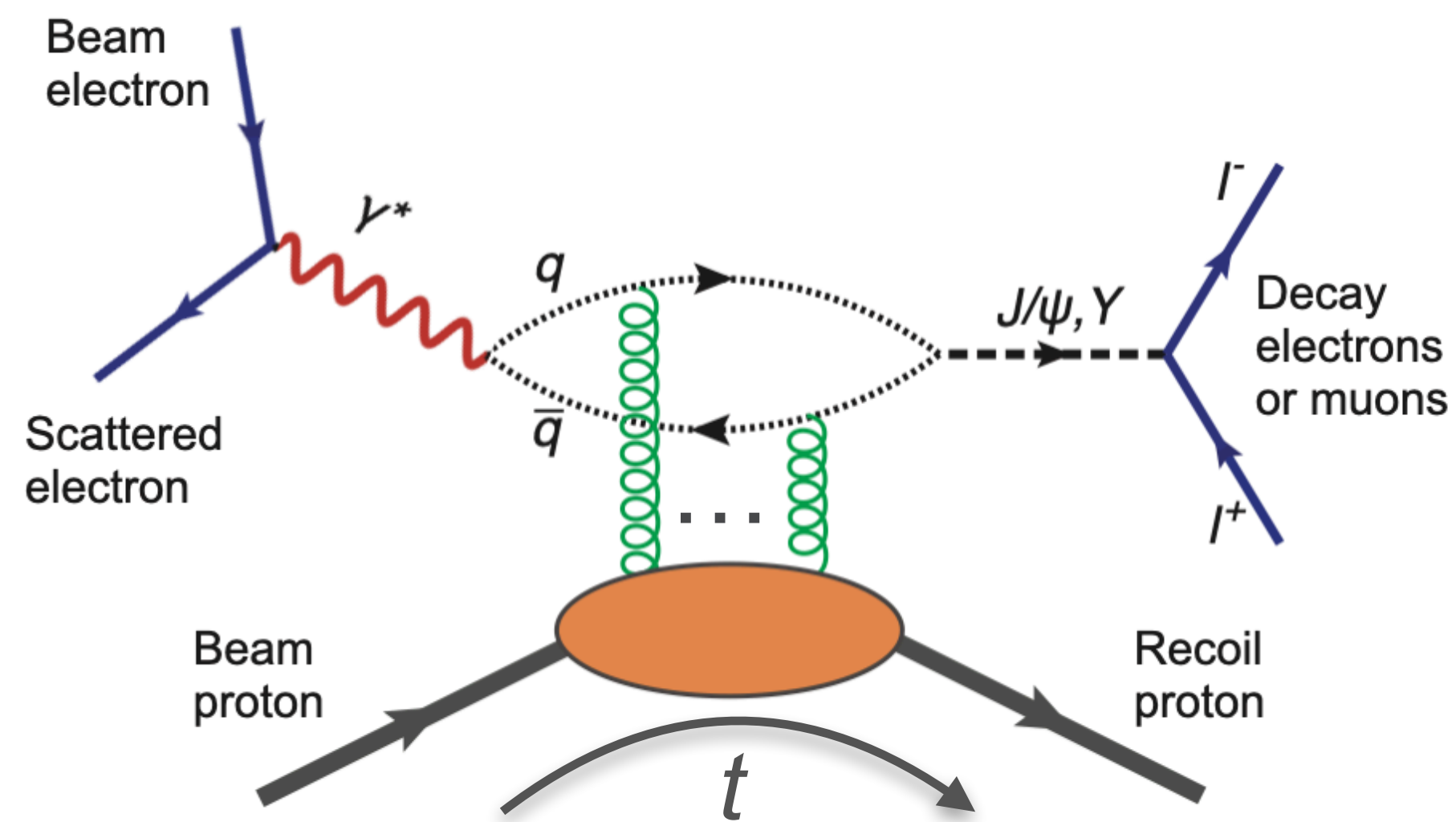


An illustration on a teal background. On the left, a hand in a black suit sleeve reaches out. On the right, a hand in a grey suit sleeve reaches out. Three glowing yellow lightbulbs with radiating lines are positioned between the hands. Three large black question marks are scattered in the upper left area.

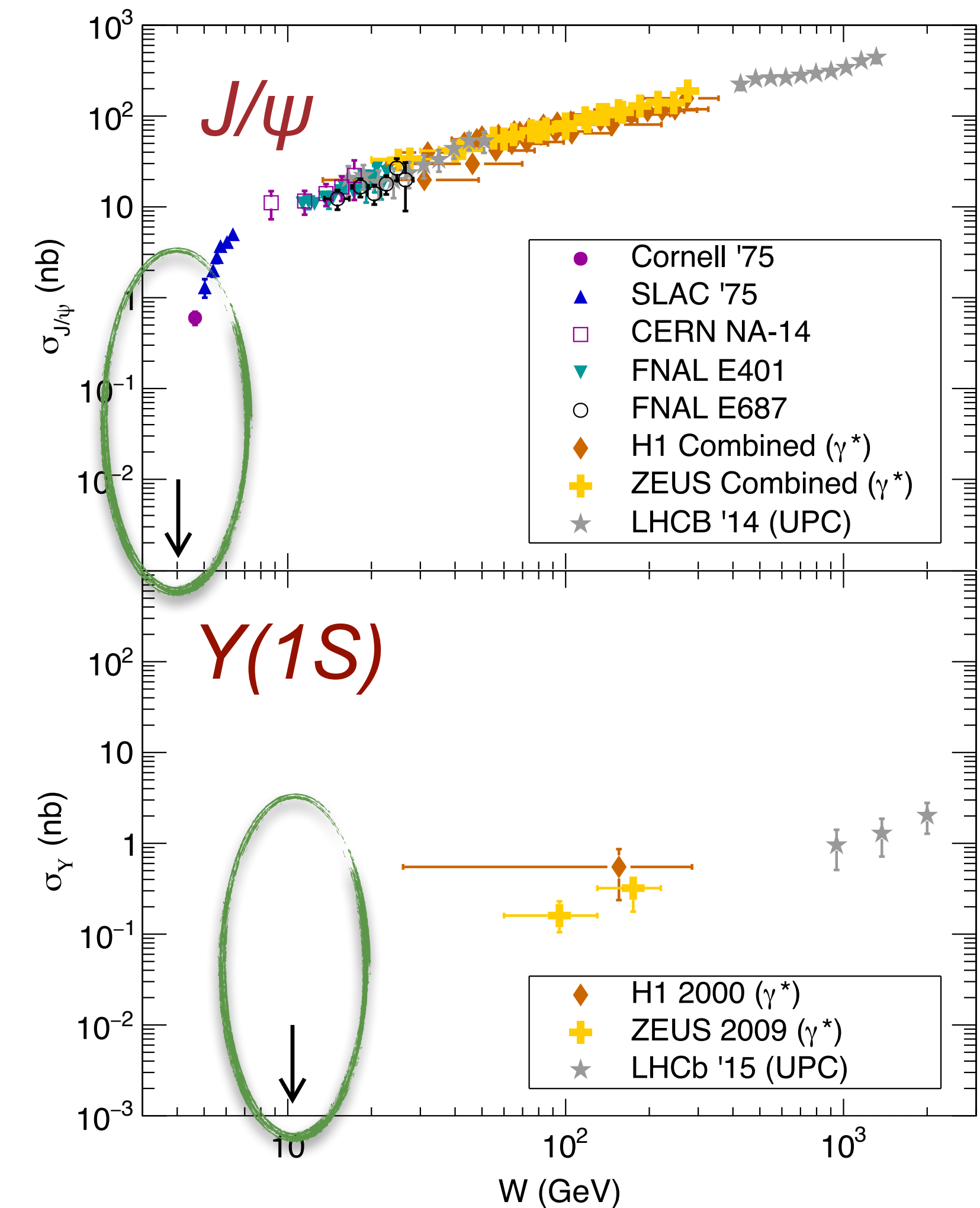
QUESTIONS?

WHAT DID WE KNOW BEFORE 12 GEV AT JLAB?

Exclusive quarkonium photoproduction



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



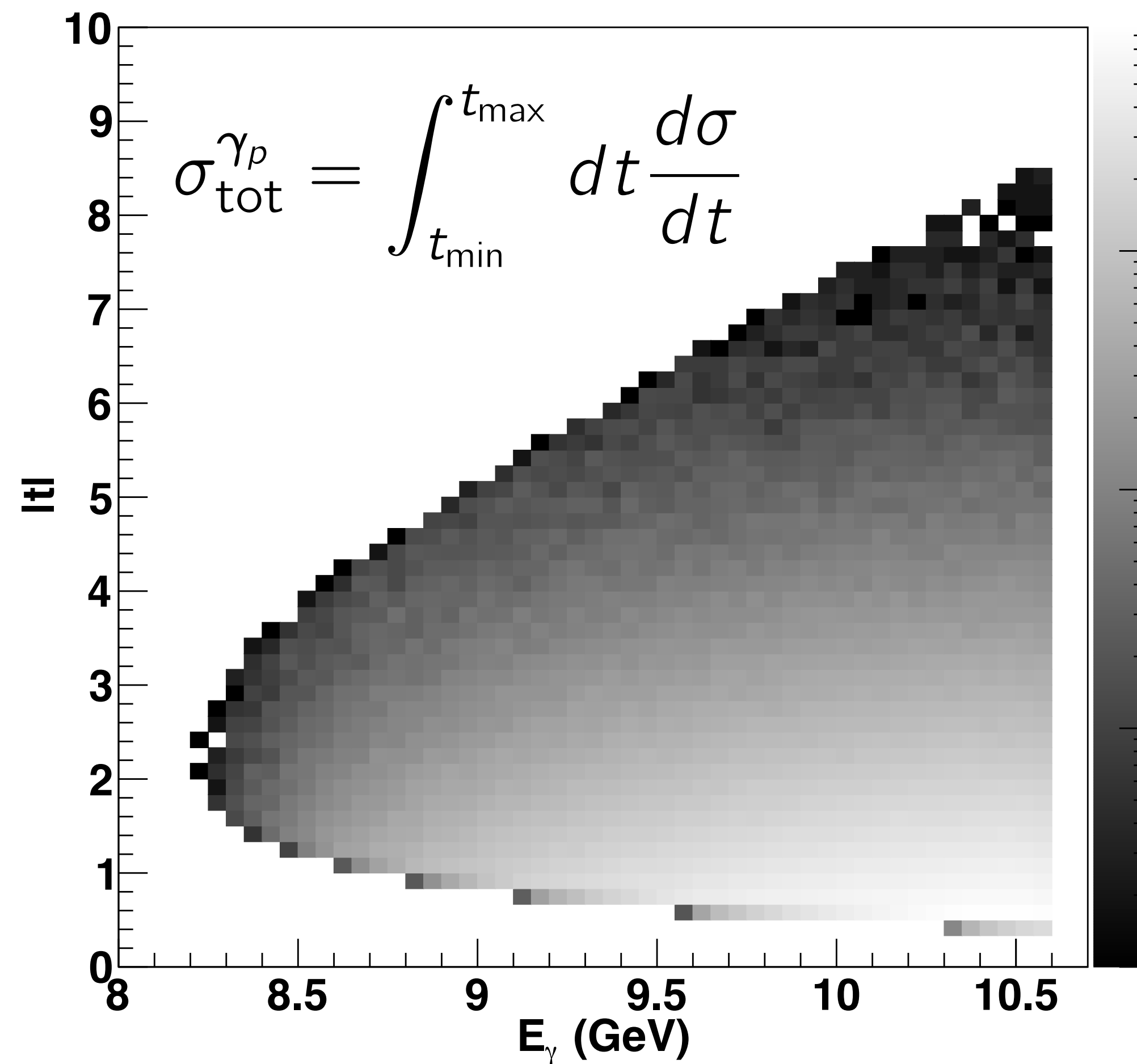
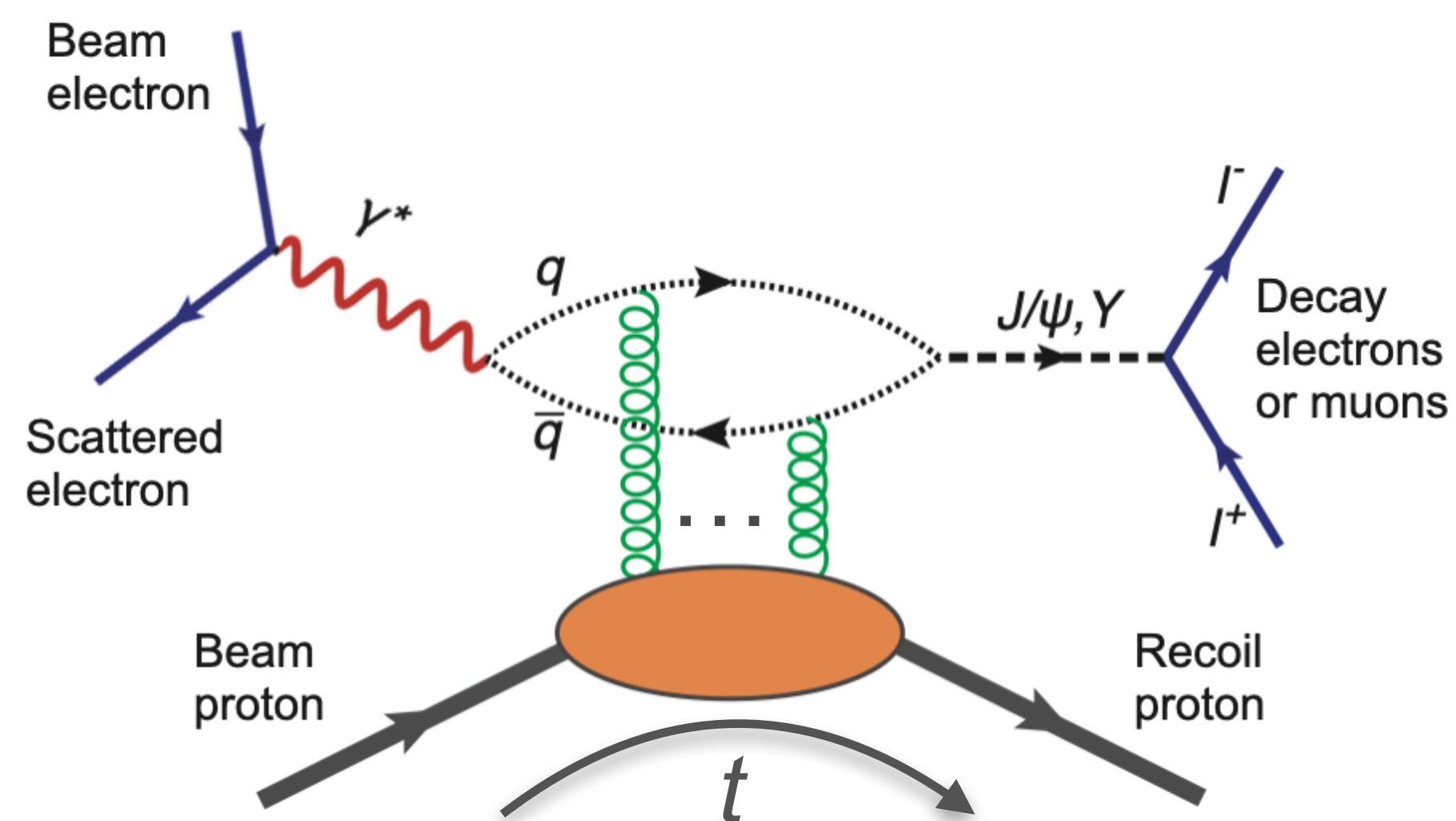
J/Ψ EXPERIMENTS AT JLAB COMPARED

	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

¹The CLAS12 projected count rates assume the proposed CLAS12 luminosity upgrade to $2 \times 10^{35} / \text{cm}^2 / \text{s}$

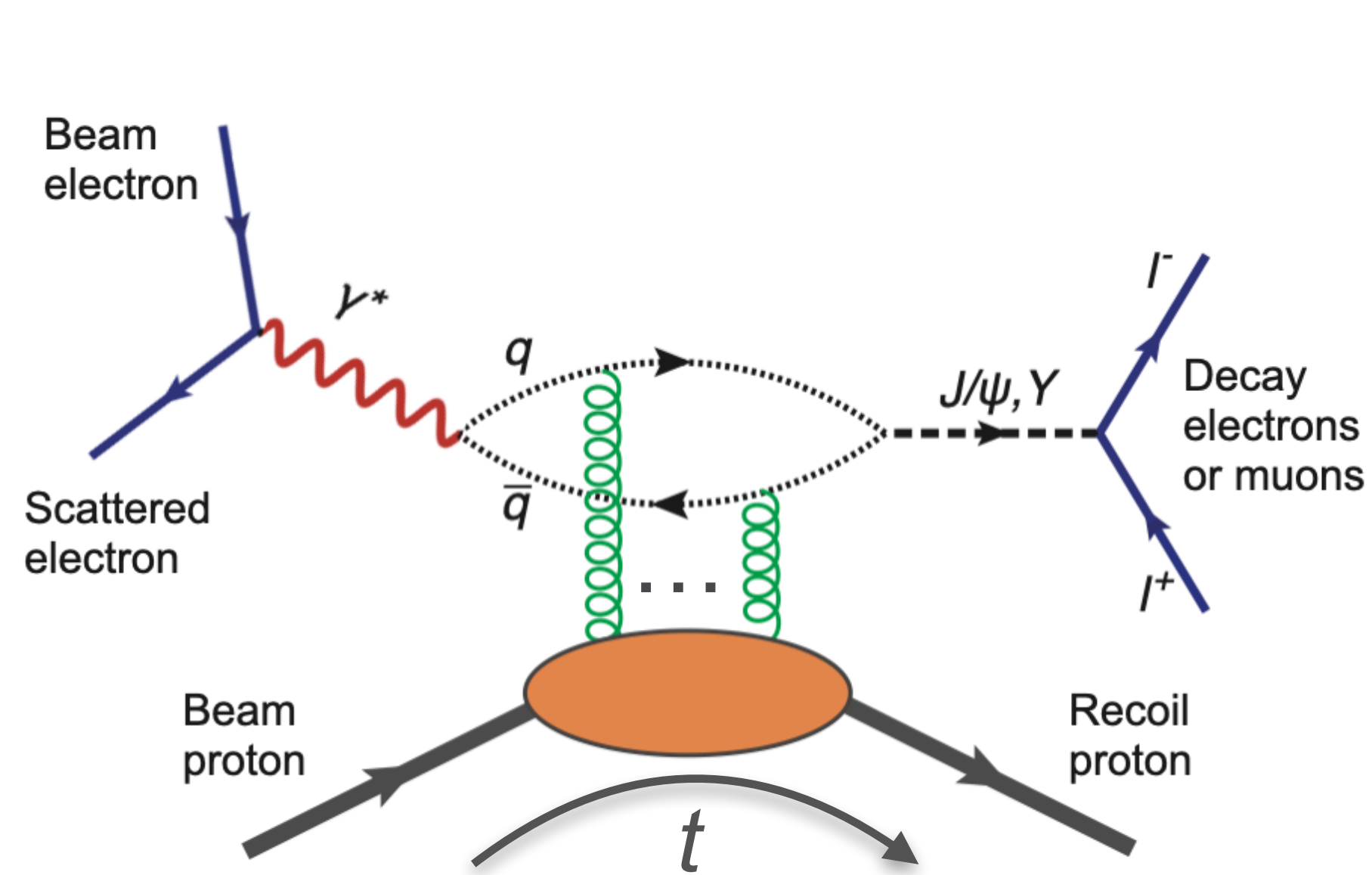
EXCLUSIVE QUARKONIUM PRODUCTION

The basics



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The basics



J/ψ threshold:

$$W \approx 4.04 \text{ GeV}$$

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

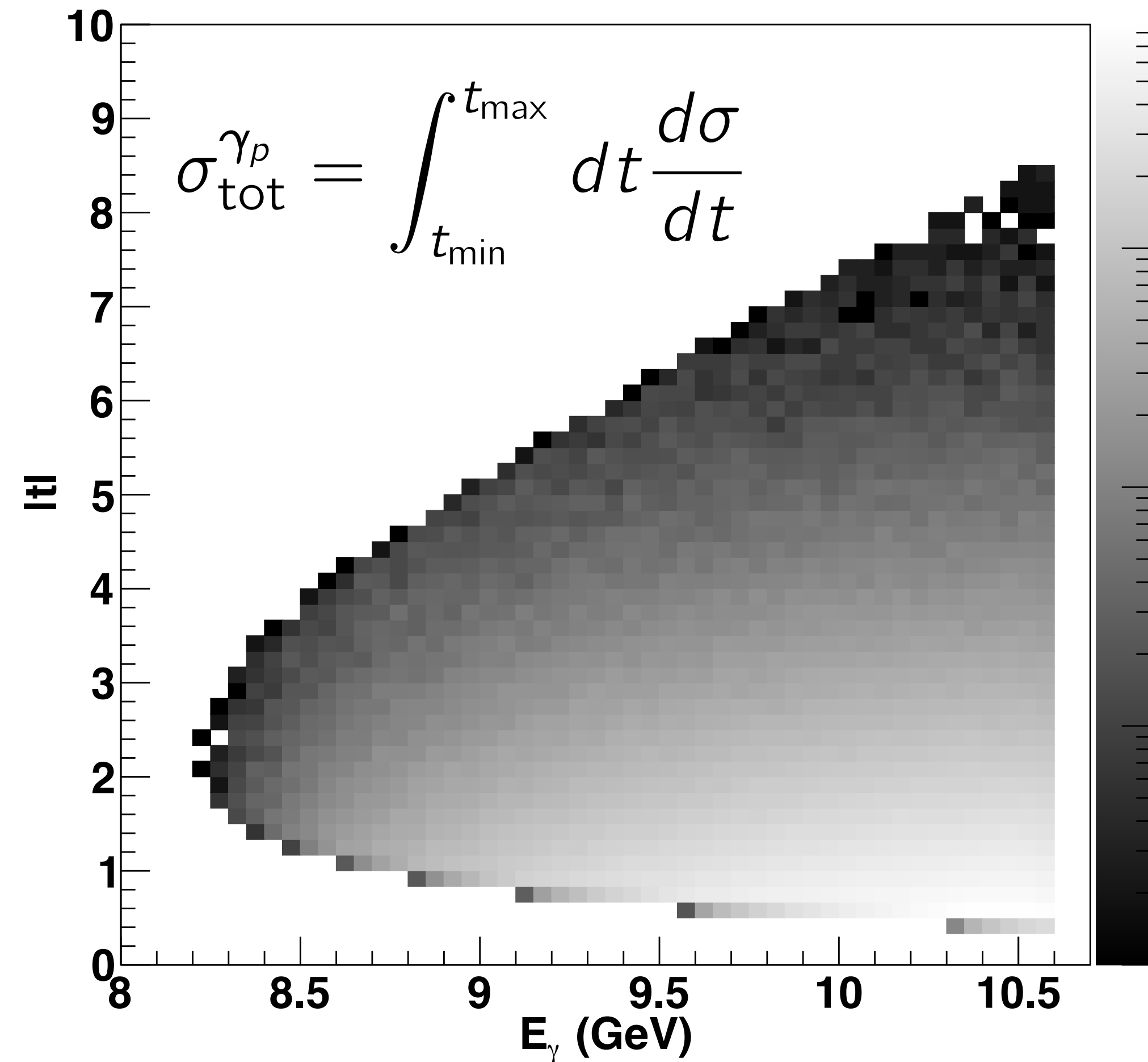
$$t \approx -1.5 \text{ GeV}^2$$

$Y(1S)$ threshold:

$$W \approx 10.4 \text{ GeV}$$

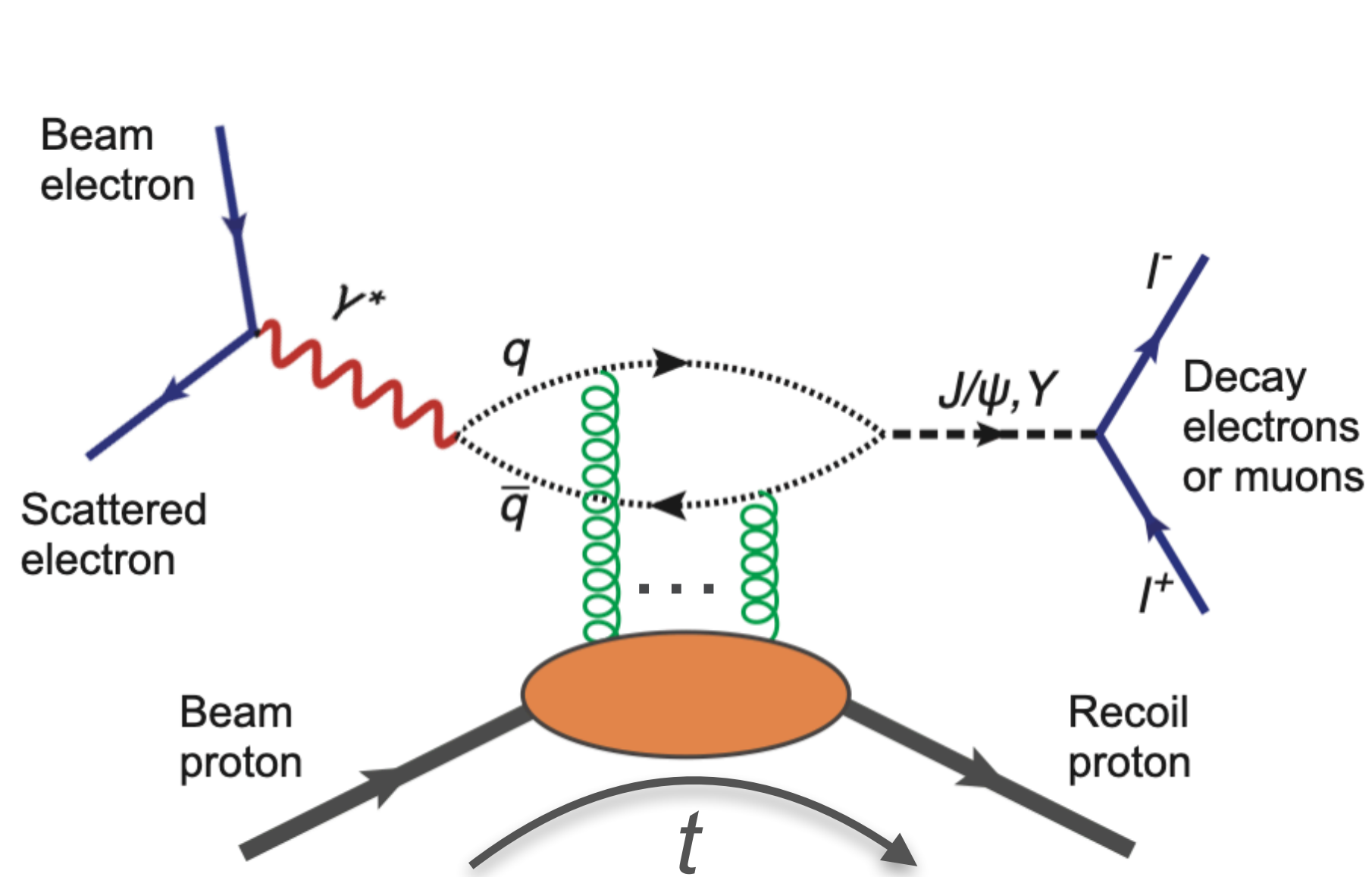
$$t \approx -8.1 \text{ GeV}^2$$

- Phase space limits defined by quarkonium direction



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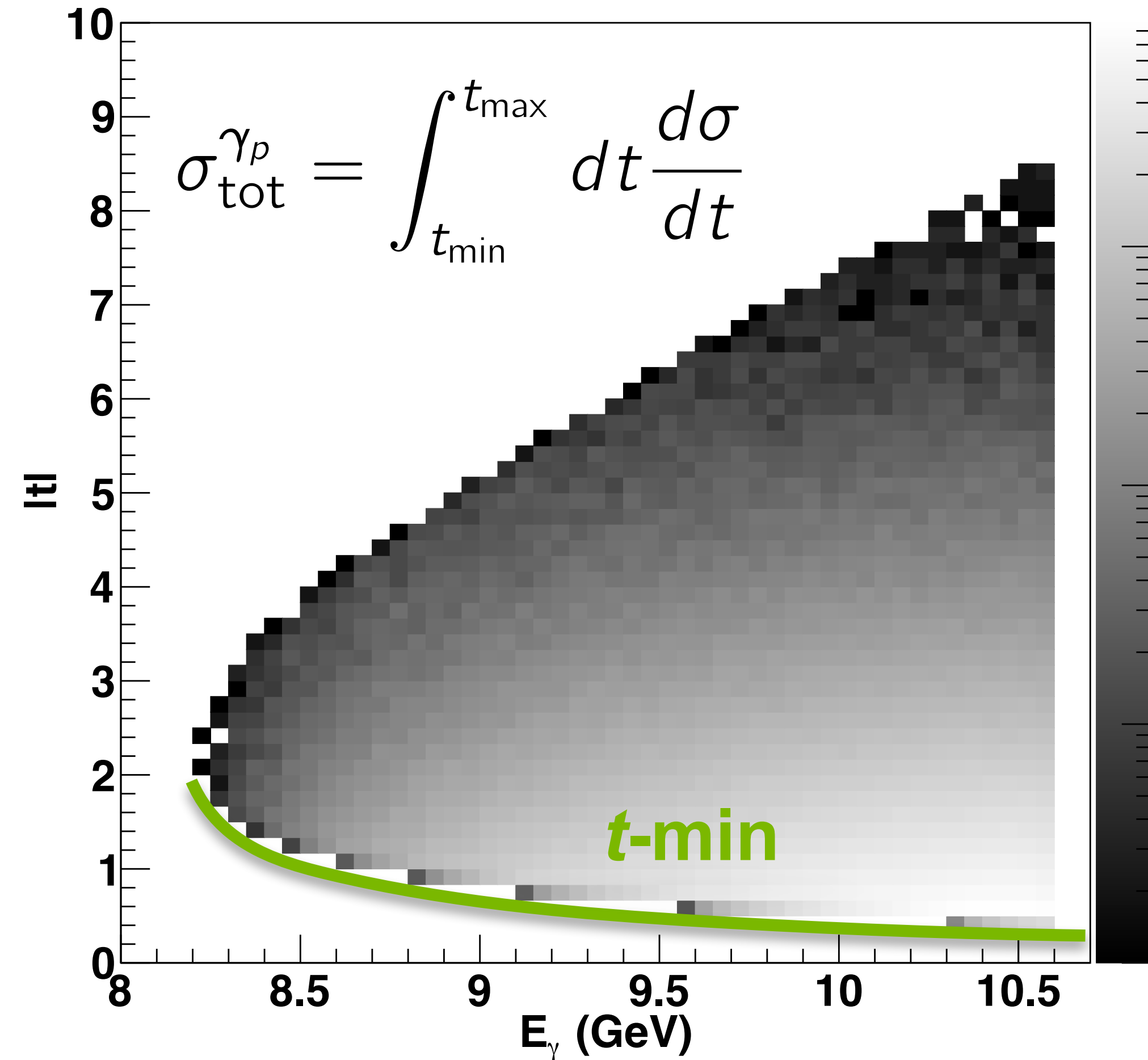
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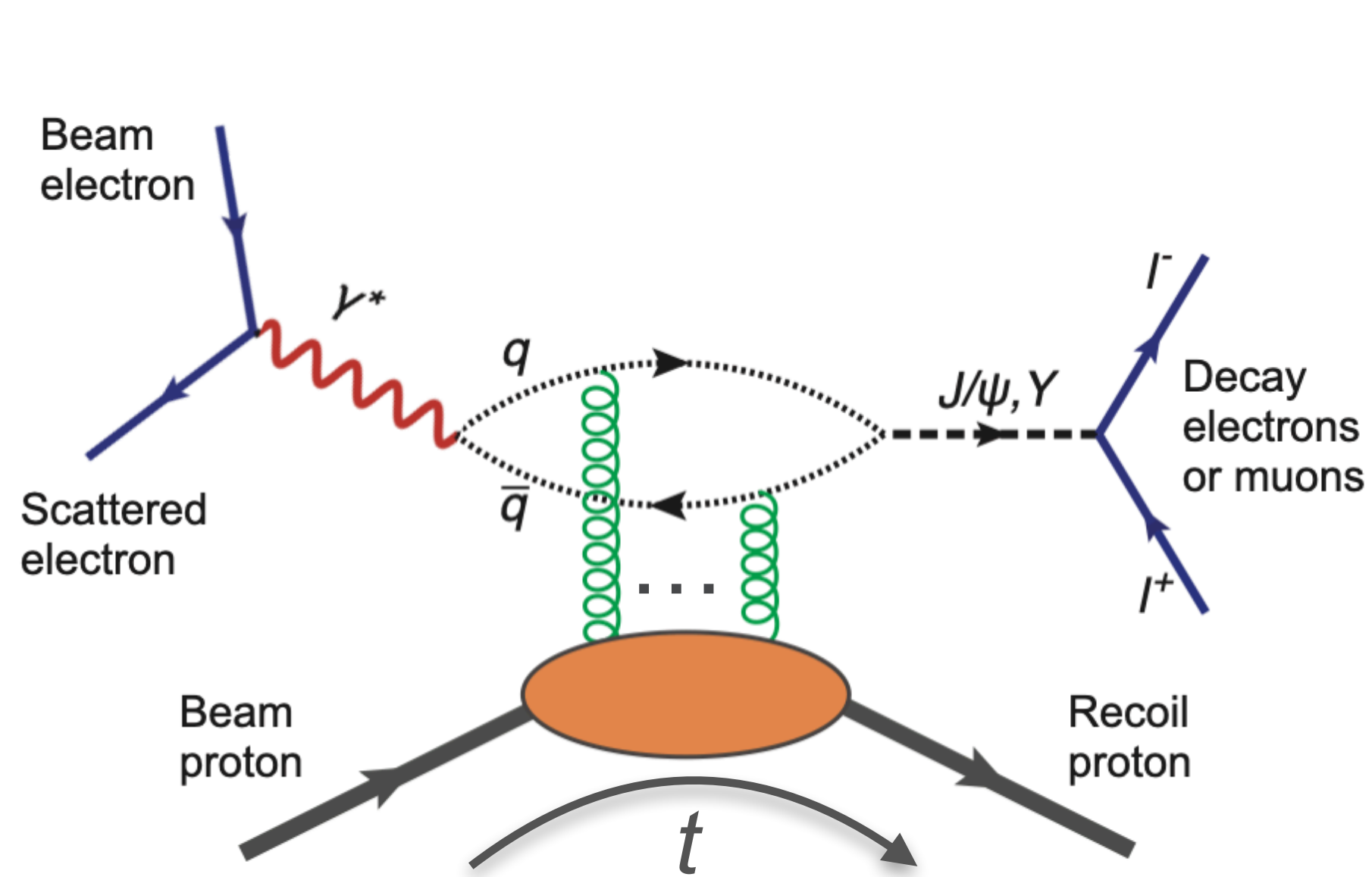
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- Phase space limits defined by quarkonium direction
- Forward (with photon): $t = t_{\min}$



EXCLUSIVE QUARKONIUM PRODUCTION

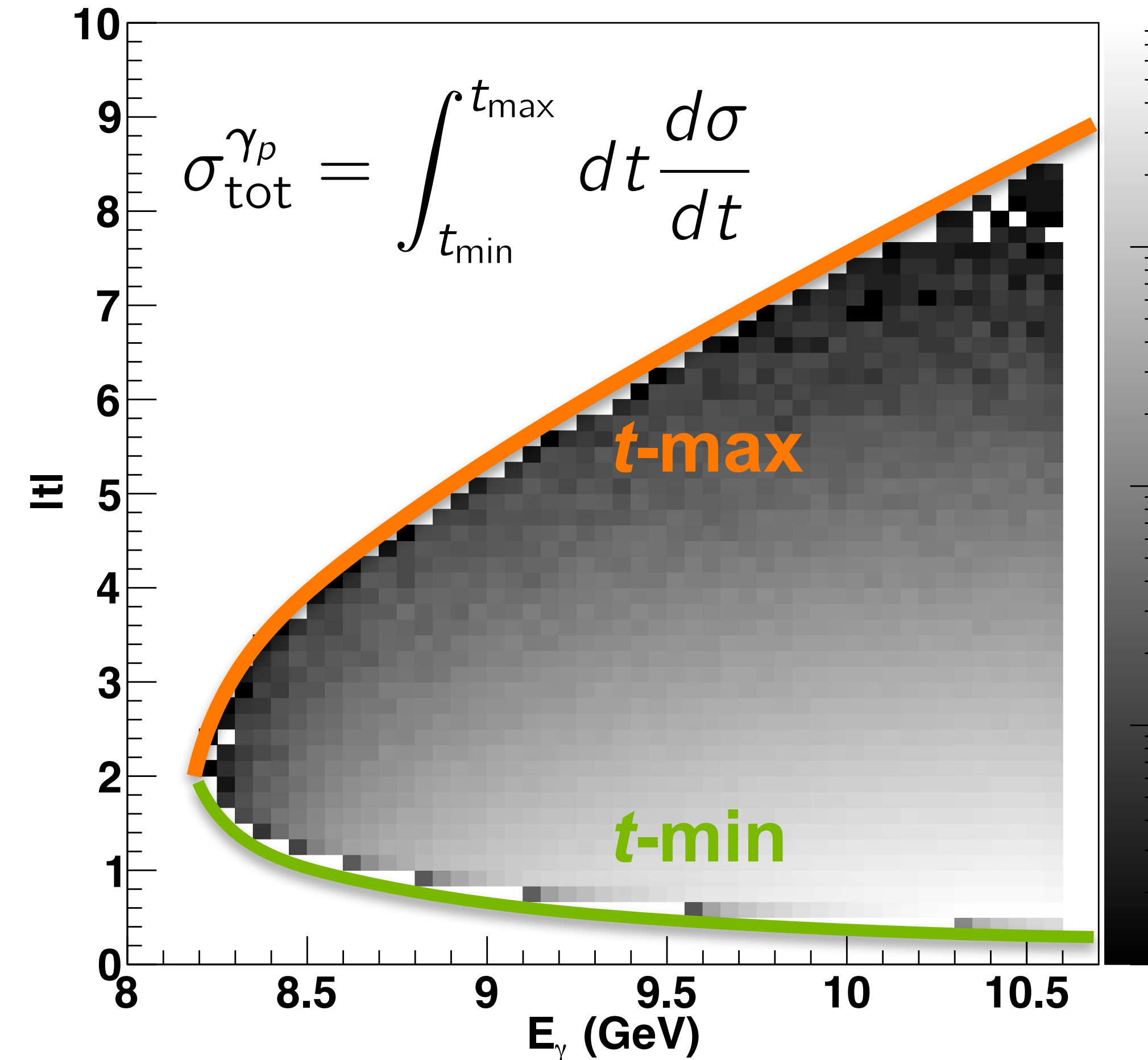
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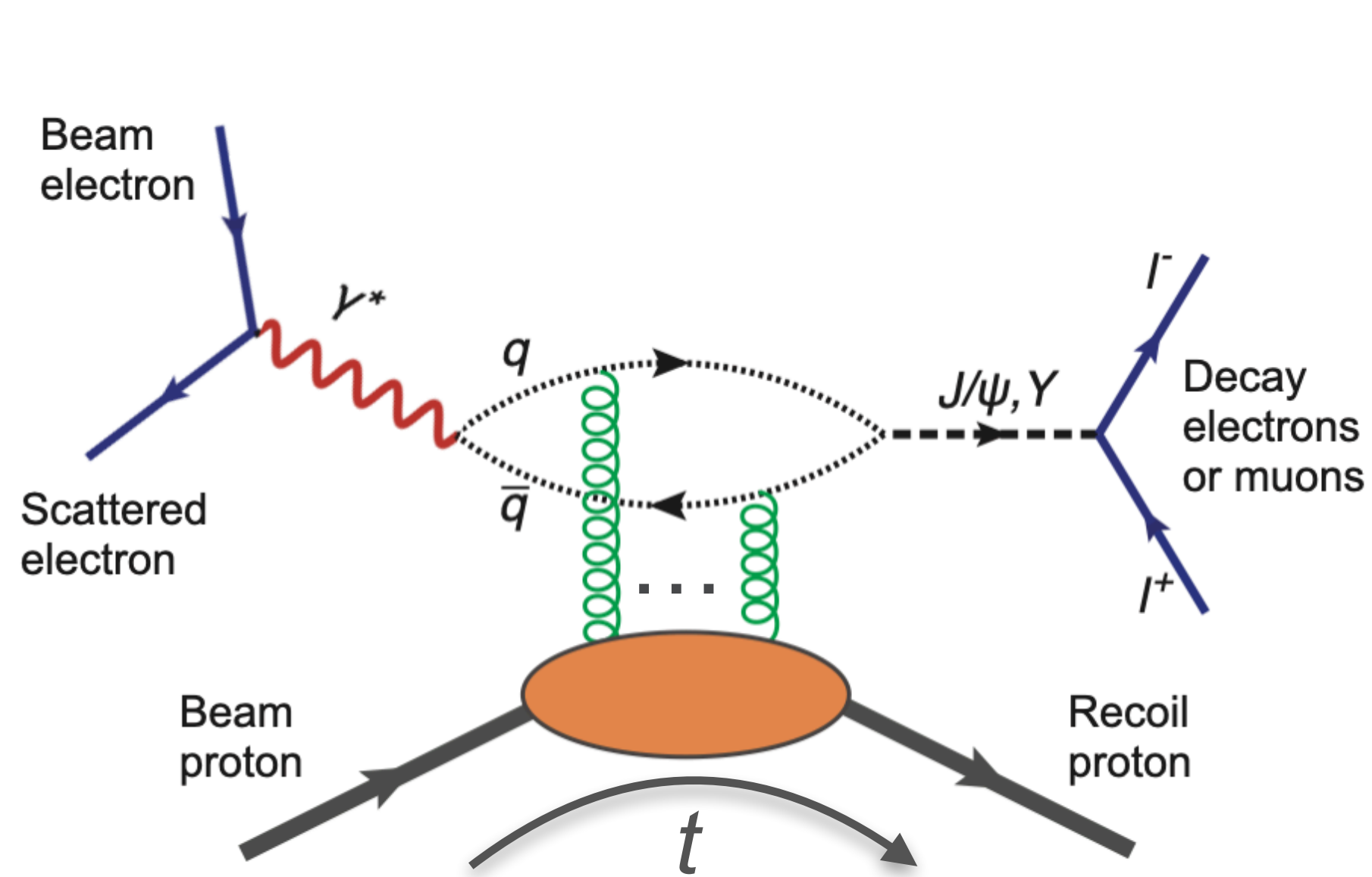
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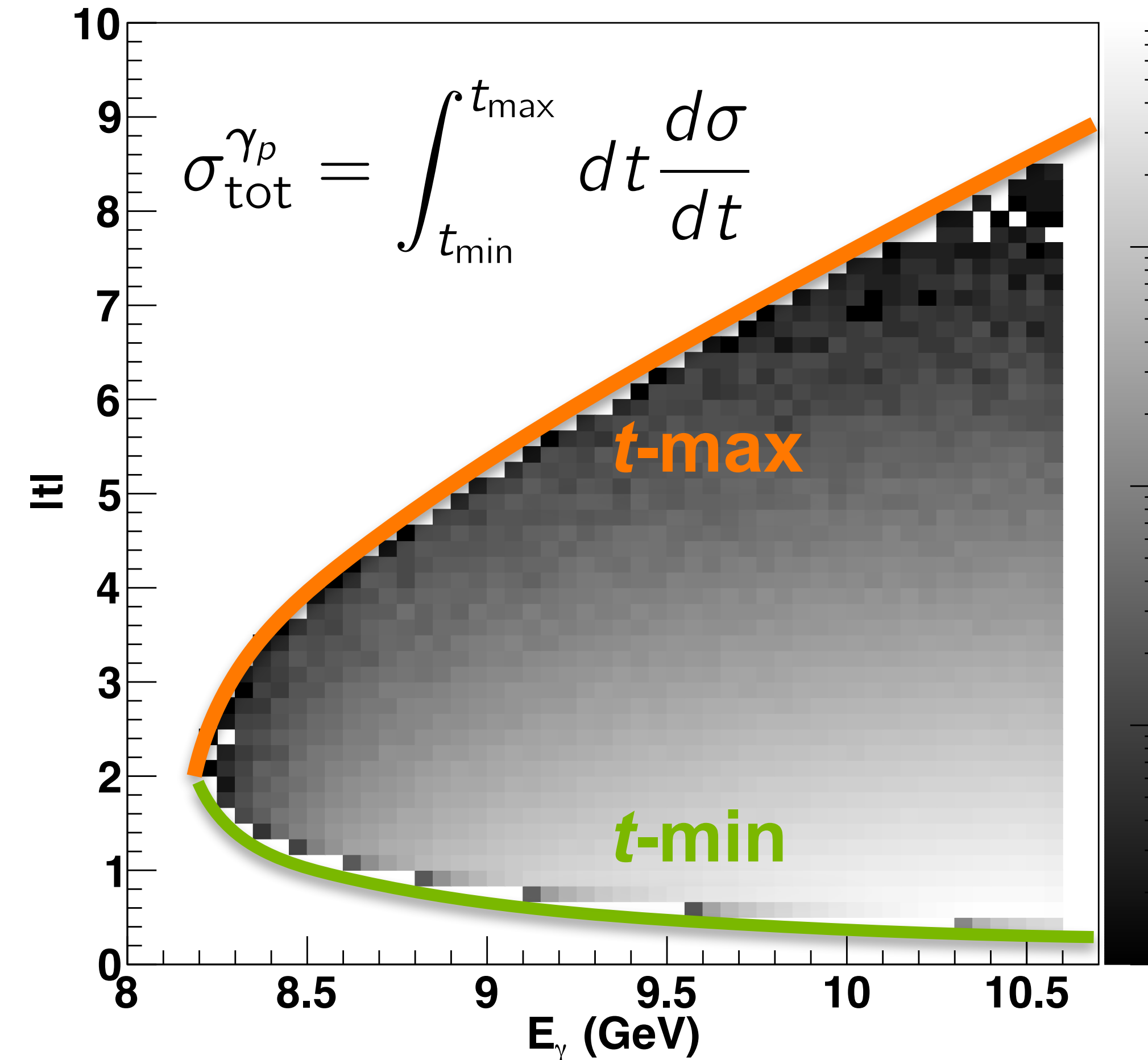
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- Forward direction preferred: t -dependence \sim exponential



QUARKONIUM AT JEFFERSON LAB AND EIC

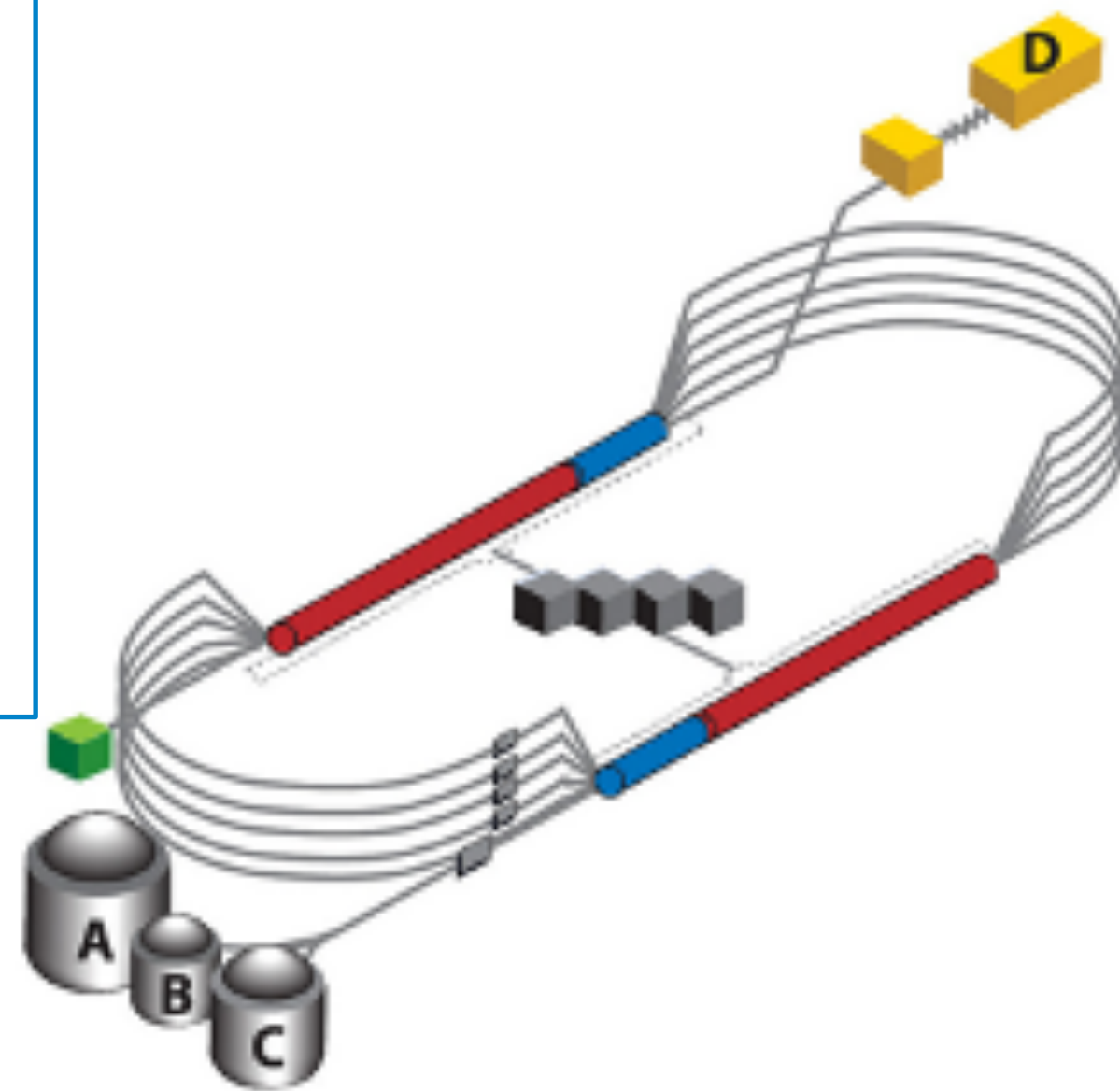
Jefferson Lab

CEBAF: very high luminosity (10^{35} - 10^{39} cm⁻²s⁻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



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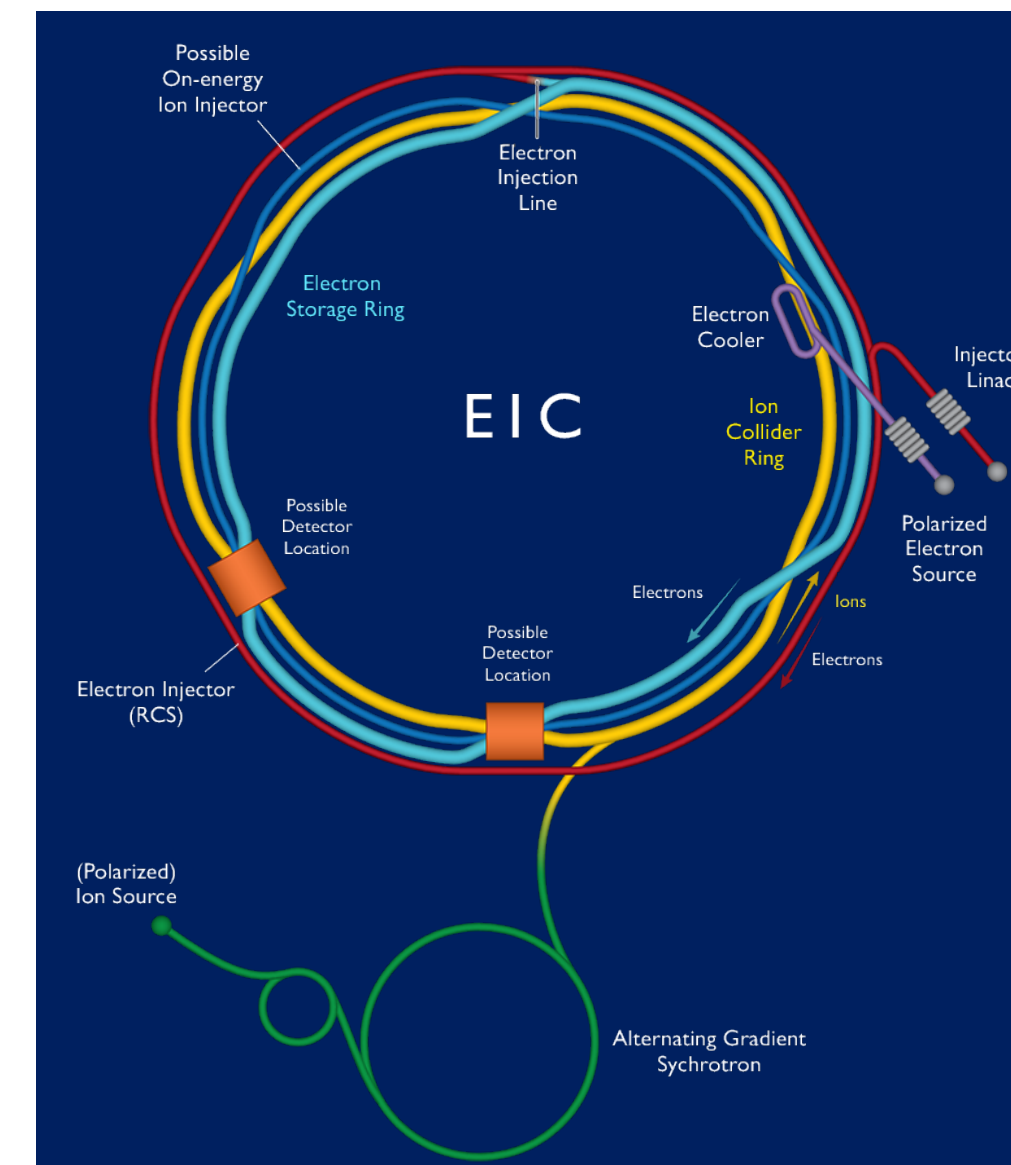
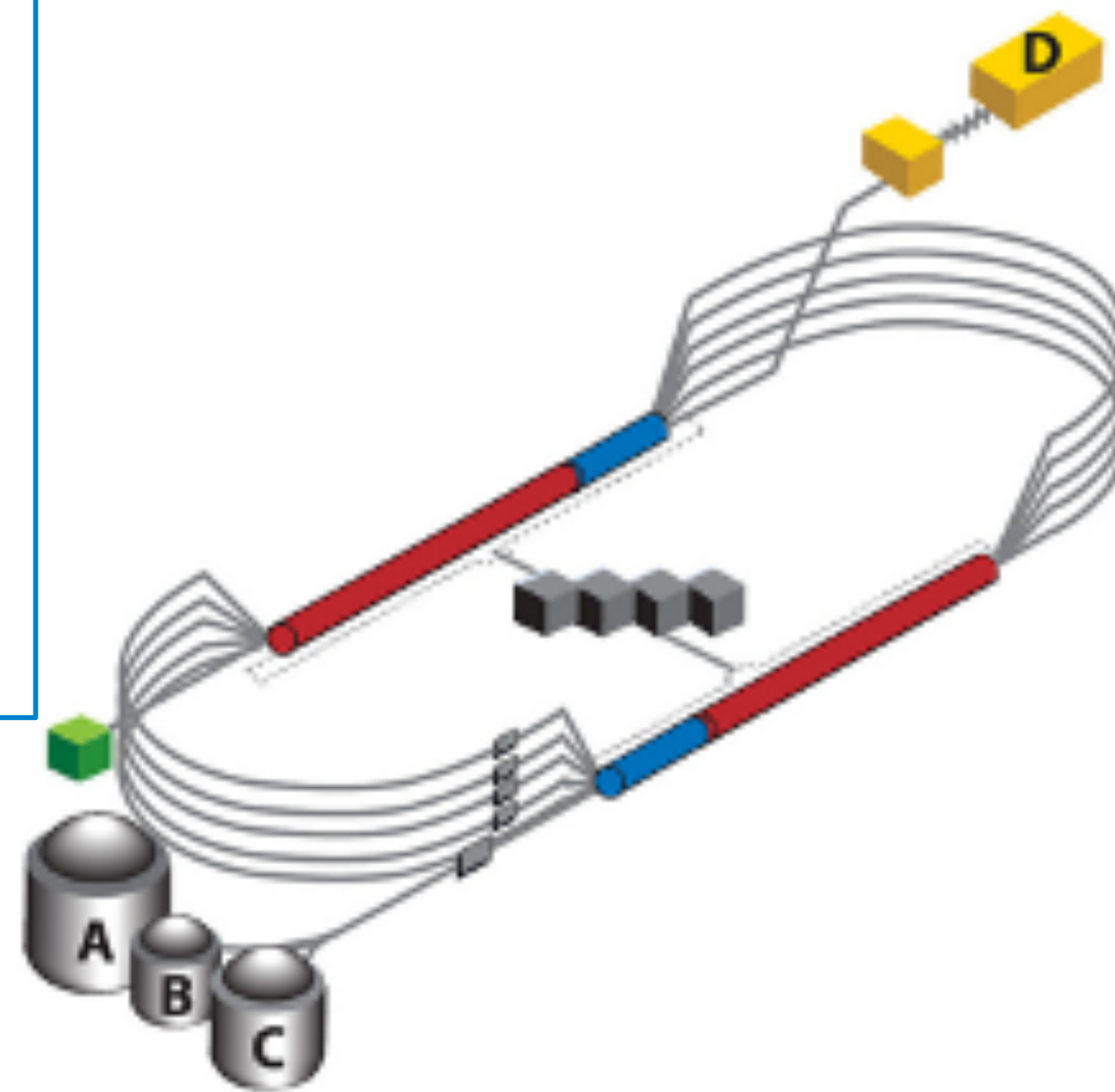
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Electron-ion Collider

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

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

Ideally suited to study J/ψ electroproduction at higher energies, sufficient energy and luminosity to produce $Y(1S)$.

QUARKONIUM AT JEFFERSON LAB AND EIC

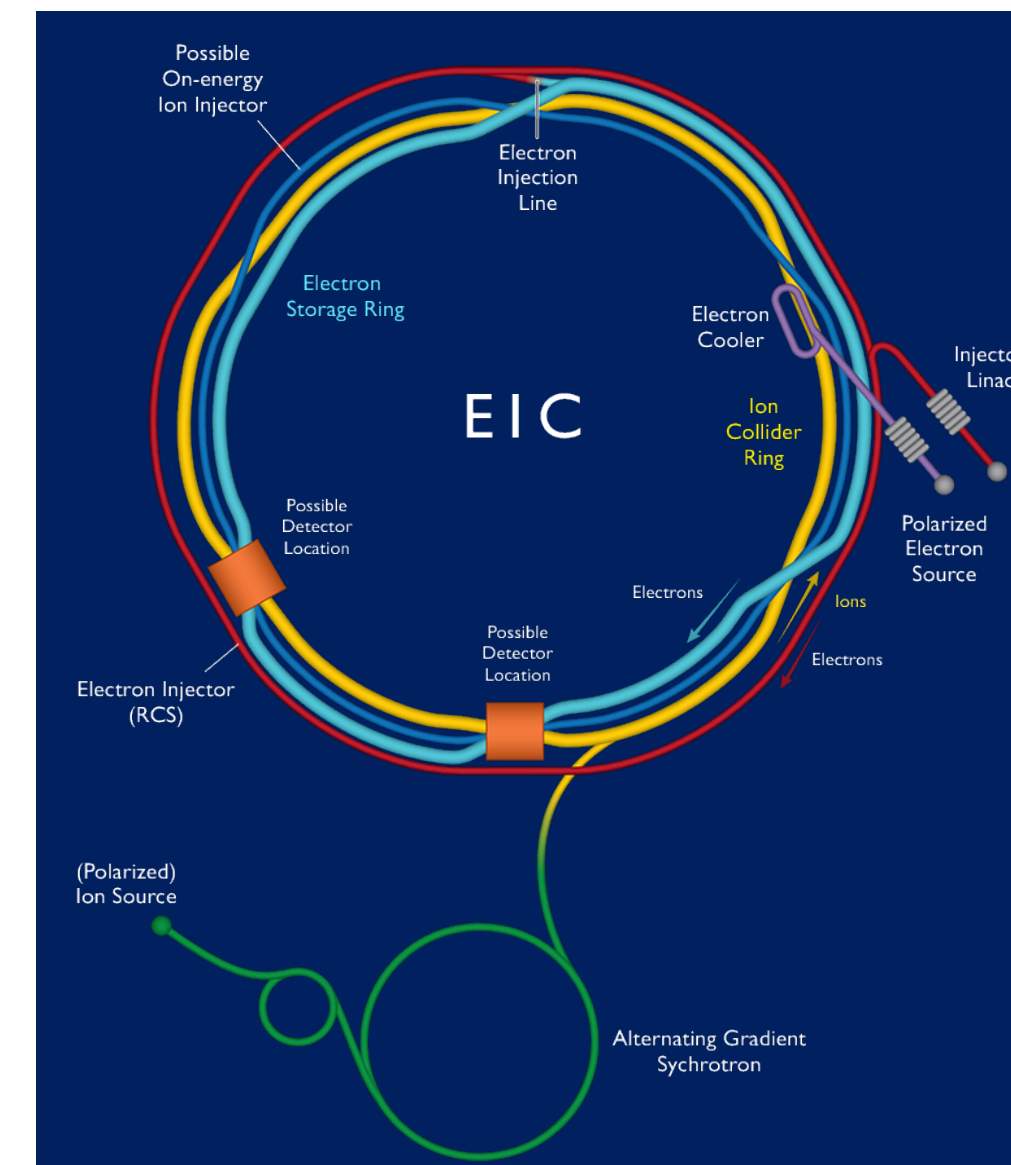
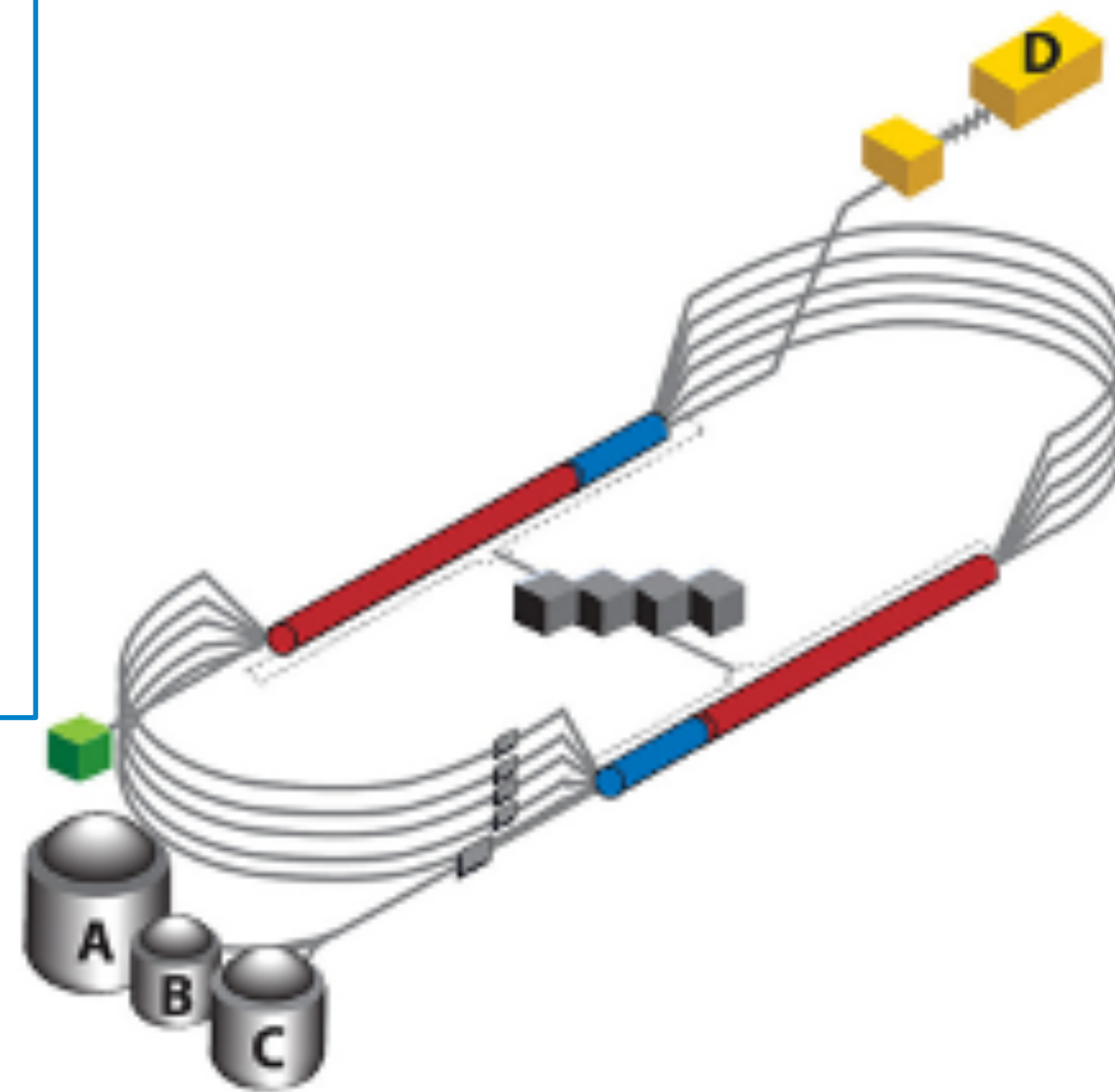
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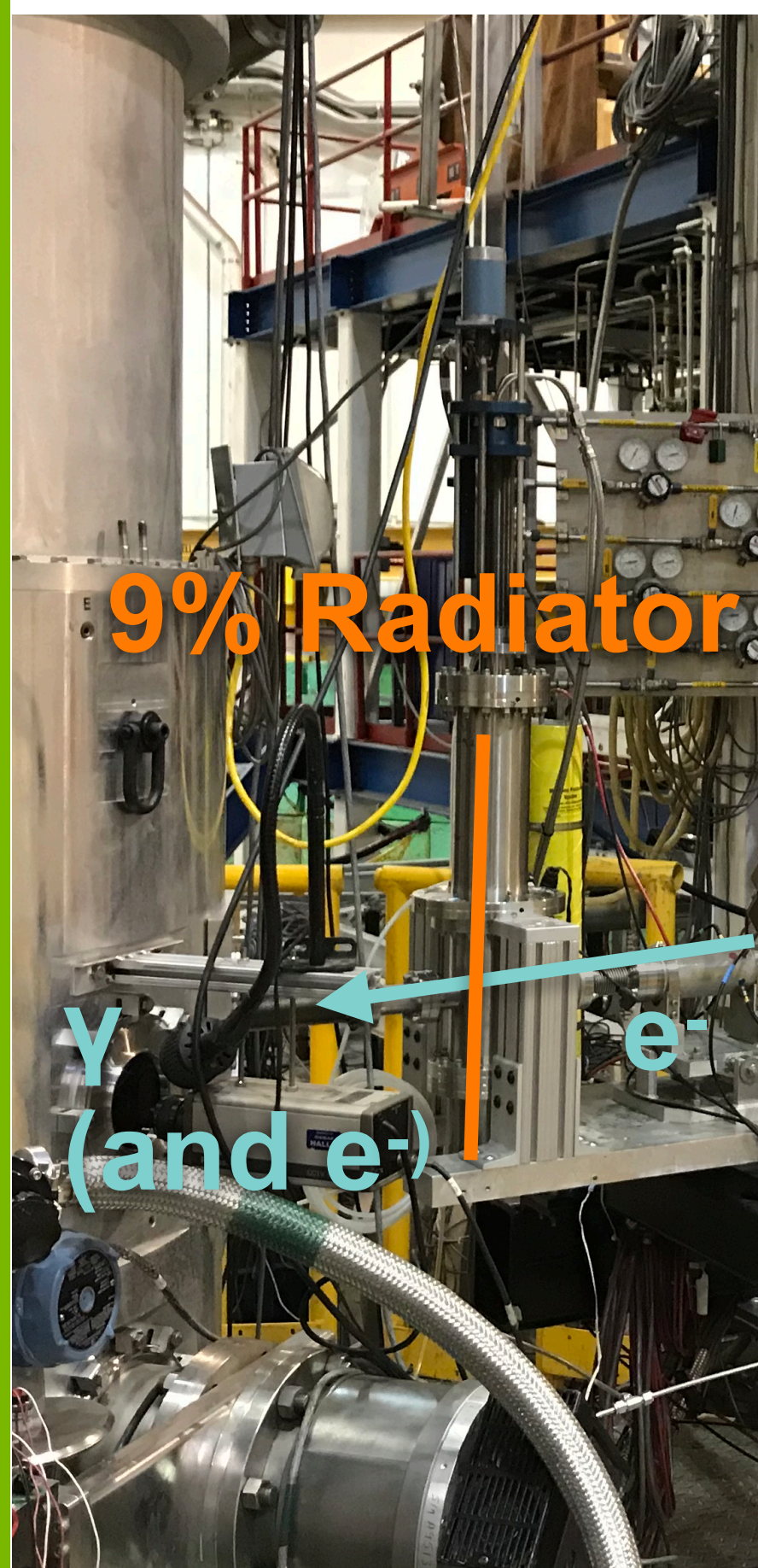
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Complementary programs: Jefferson Lab is the ideal laboratory to access GFFs with J/ψ production, and EIC has sufficient luminosity and energy for 3-D gluonic imaging.

HALL C EXPERIMENT E12-16-007

J/ψ-007: “Search for the LHCb Pentaquark”, ran in 2019

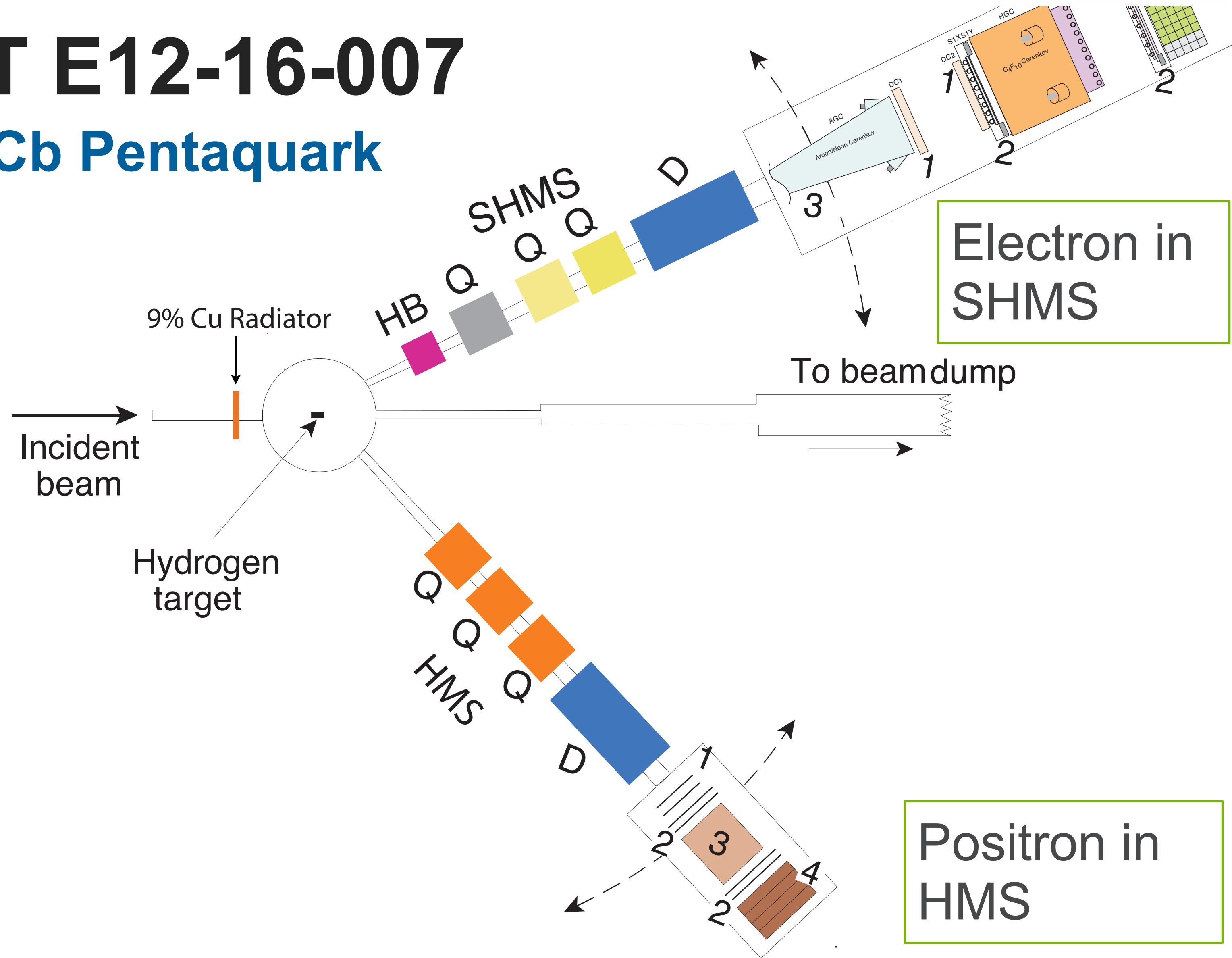
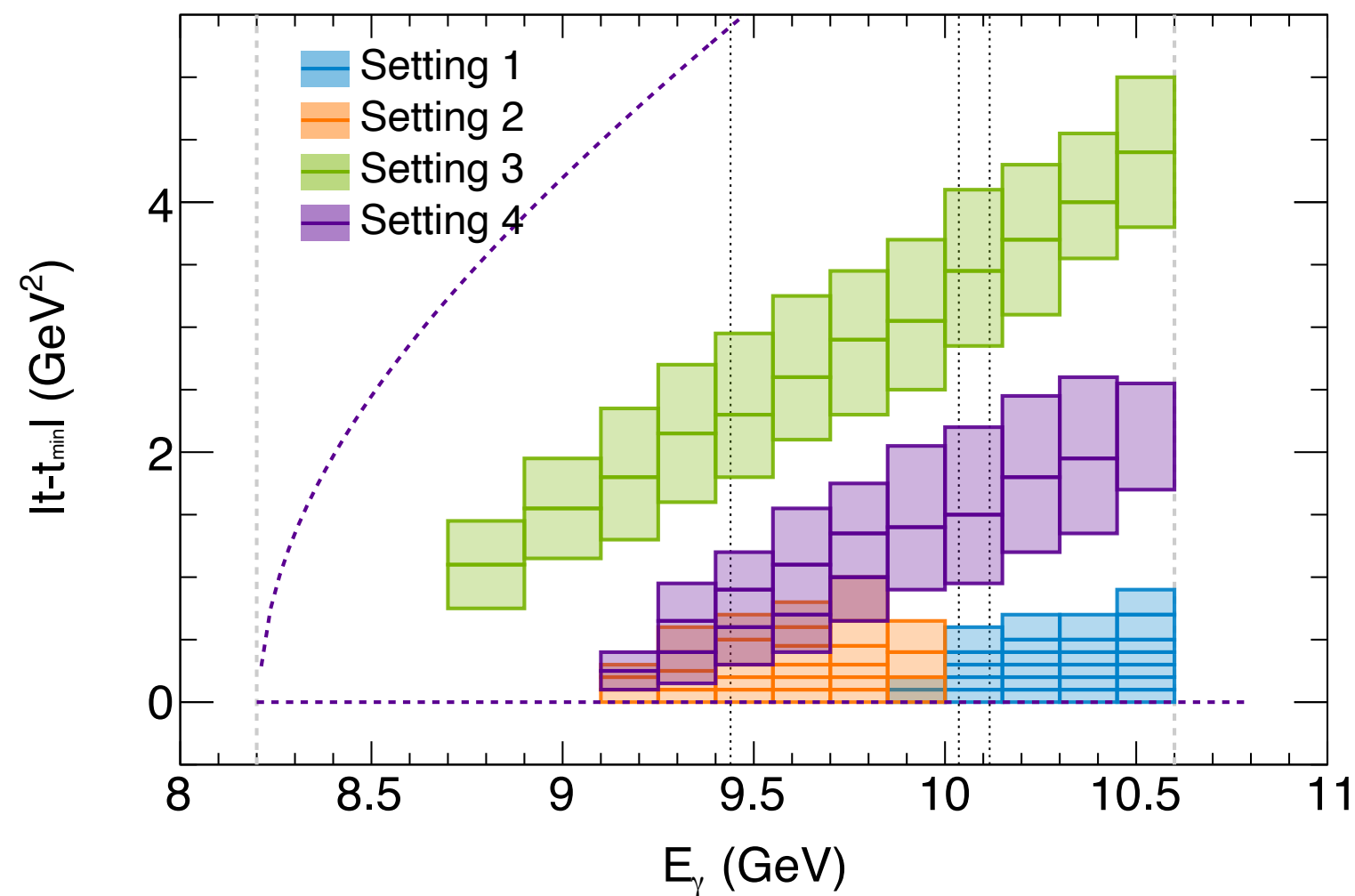




JLAB EXPERIMENT E12-16-007

J/ψ-007: Search for the LHCb Pentaquark

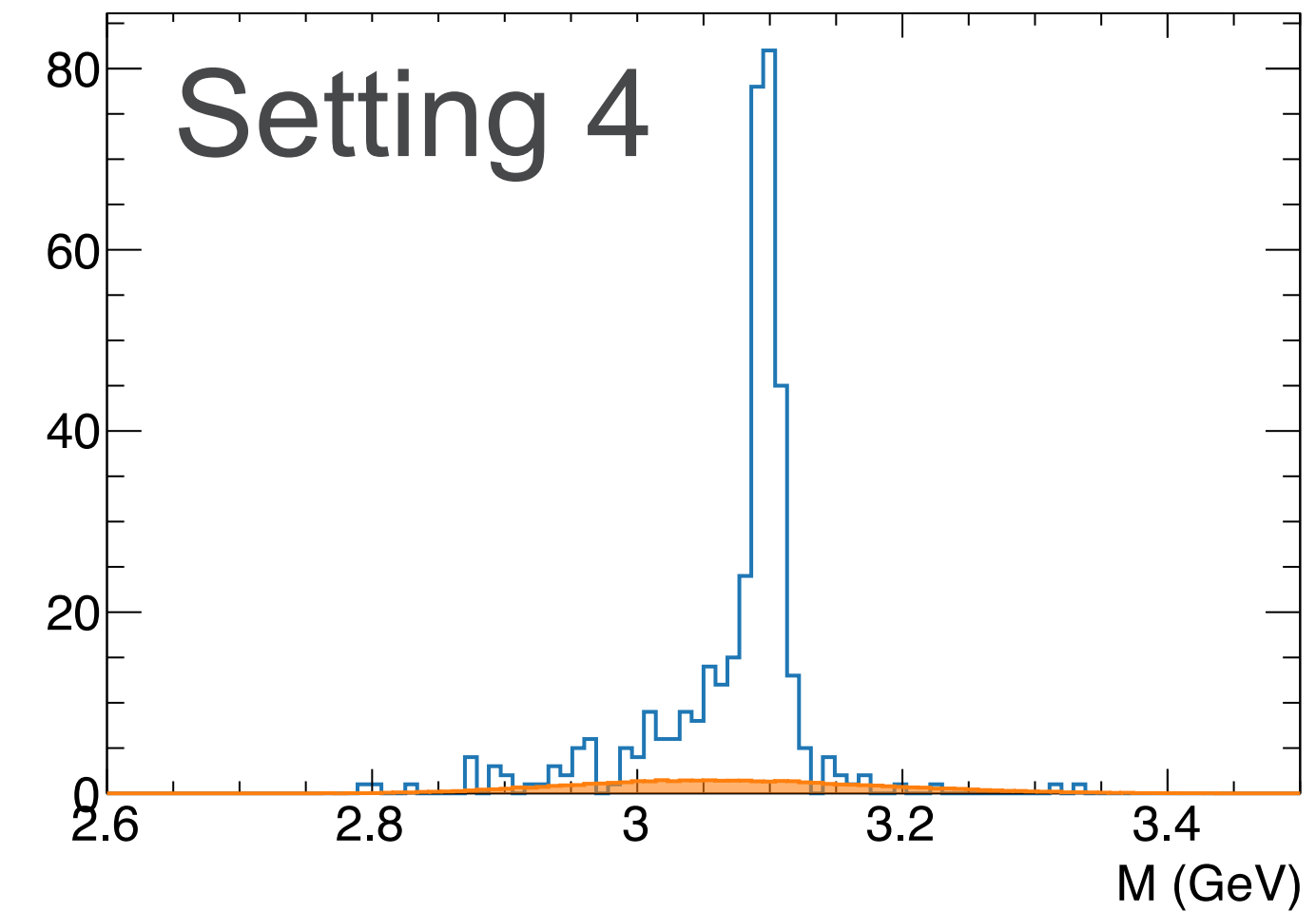
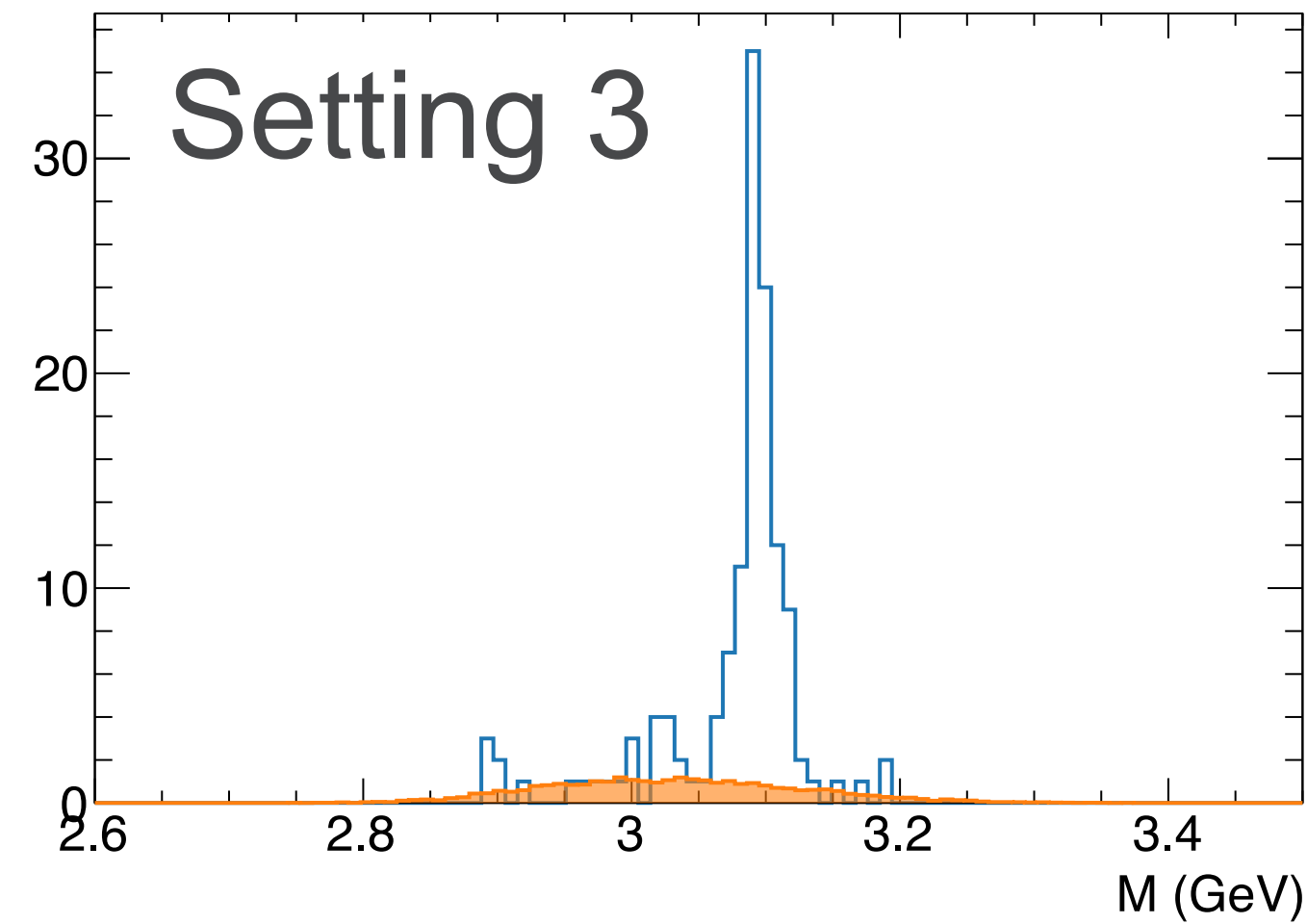
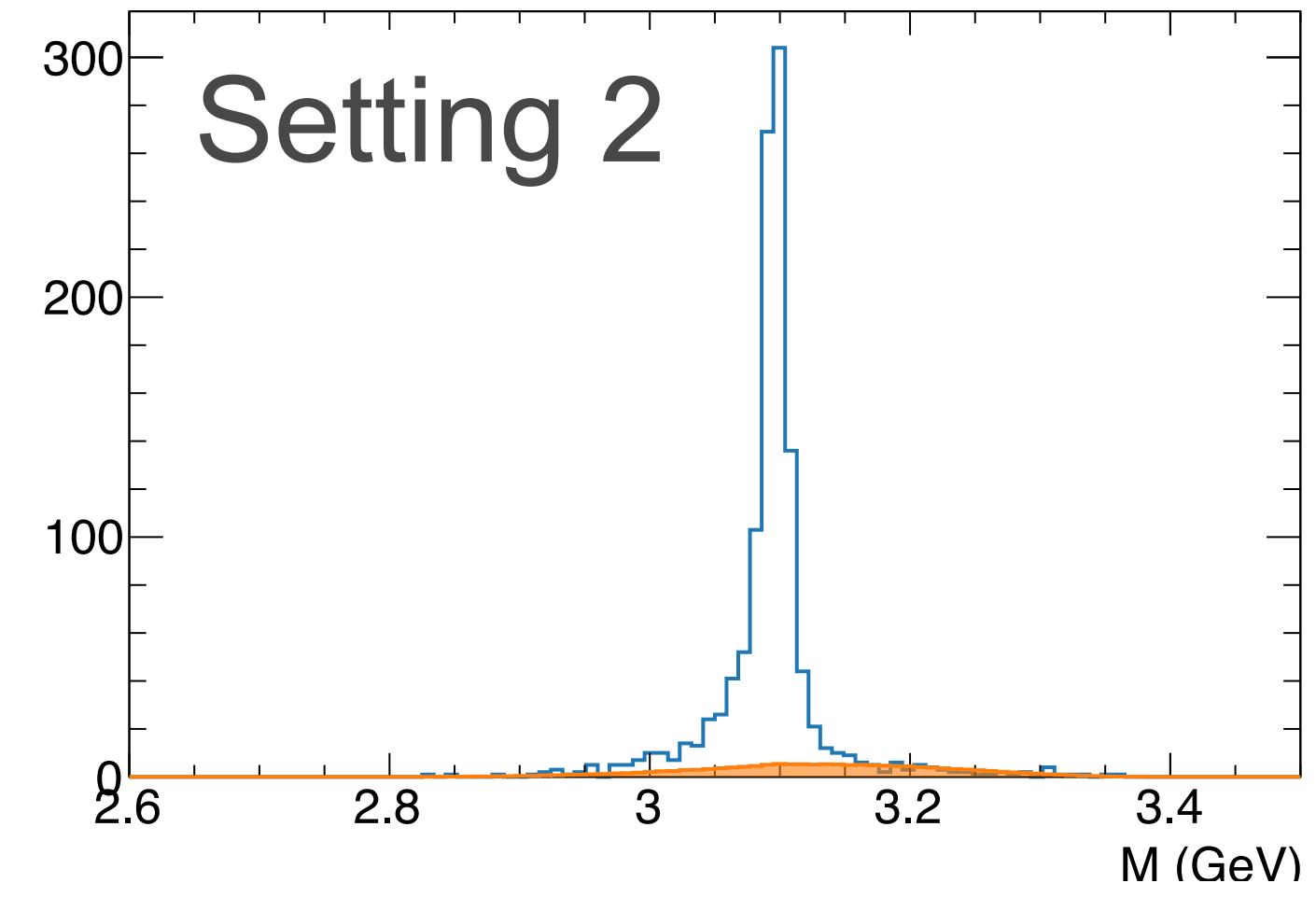
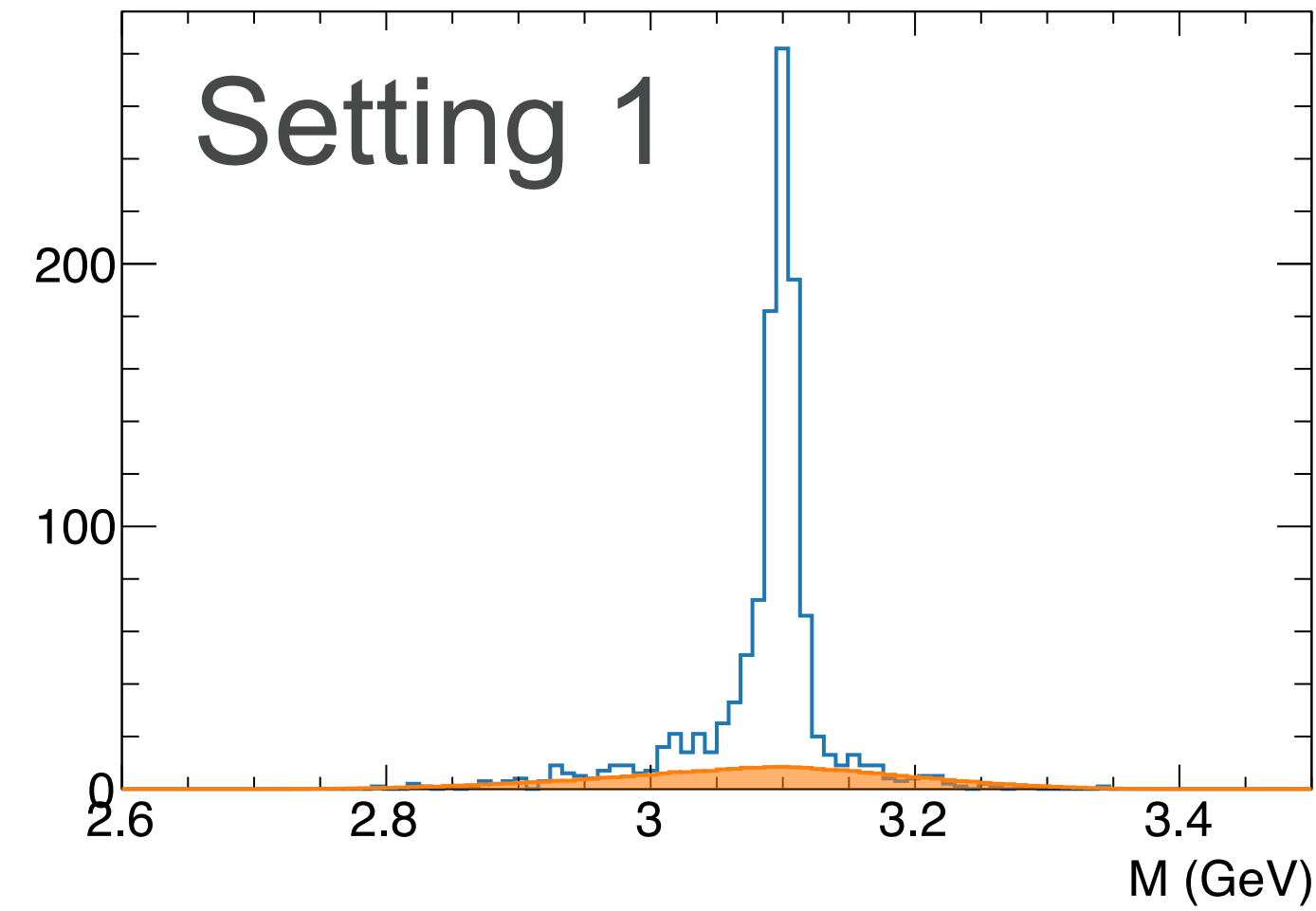
- Ran February 2019 for ~8 PAC days
- High intensity real photon beam (50μA electron beam on a 9% copper radiator)
- 10cm liquid hydrogen target
- Detect J/ψ decay leptons in coincidence
 - Bremsstrahlung photon energy fully constrained



CLEAR J/ Ψ SIGNAL WITH MINIMAL BACKGROUND

007^{J/ Ψ}

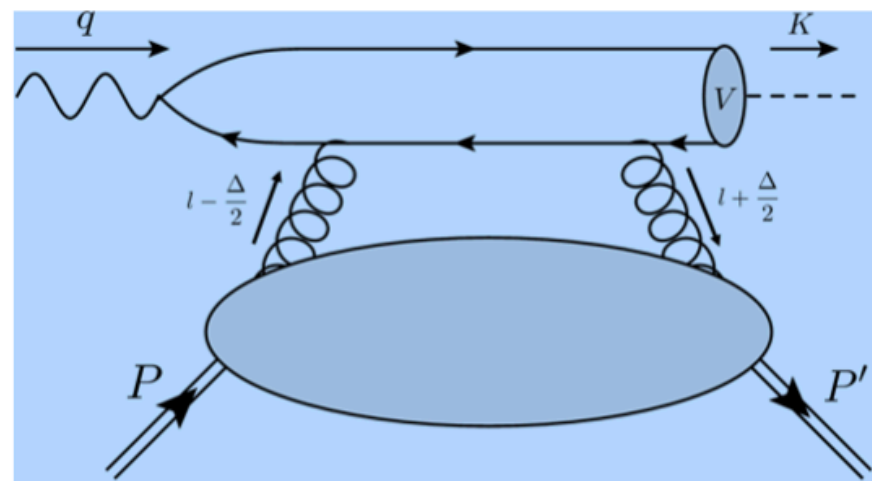
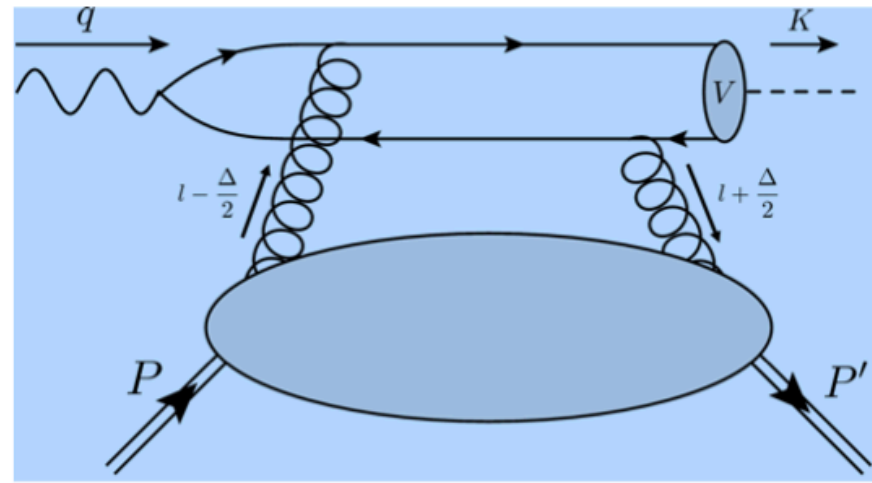
settings	HMS	SHMS	target	charge [C]	goal
setting 1	19.1° at +4.95GeV	17.0° at -4.835GeV	LH2 with radiator dummy with radiator LH2, no radiator	5.2 0.6 0.1	low- t and high energy target wall electroproduction
setting 2	19.9° at +4.6GeV	20.1° at -4.3GeV	LH2 with radiator dummy with radiator	8.2 0.3	low- t and low energy target wall
setting 3	16.4° at +4.08GeV	30.0° at -3.5GeV	LH2 with radiator	13.8	high- t
setting 4	16.5° at +4.4GeV	24.5° at -4.4GeV	LH2 with radiator dummy with radiator	6.9 0.2	medium- t target wall



THE GENERALIZED PARTON DISTRIBUTION MODEL

2D fit to extract $A(t)$ & $C(t)$ assuming $B(t)$ negligible

Y. Guo, X. Ji and Y. Liu, Phys. Rev. D **103**, no.9, 096010 (2021) and Y. Guo, X. Ji and Y. Liu, J. Yang, Phys. Rev. D **108** (2023) no.3, 034003



$$\frac{d\sigma}{dt} = \frac{\alpha_e m e_Q^2}{4(W^2 - m_N^2)^2} \frac{(16\pi\alpha_s)^2}{3M_V^2} |\psi_{NR}|^2 |G(t, \xi)|^2$$

$$G(t, \xi) = \sum_0^{\infty} \frac{1}{\xi^{2n+2}} \int_{-1}^1 dx x^{2n} F_g(x, \xi, t)$$

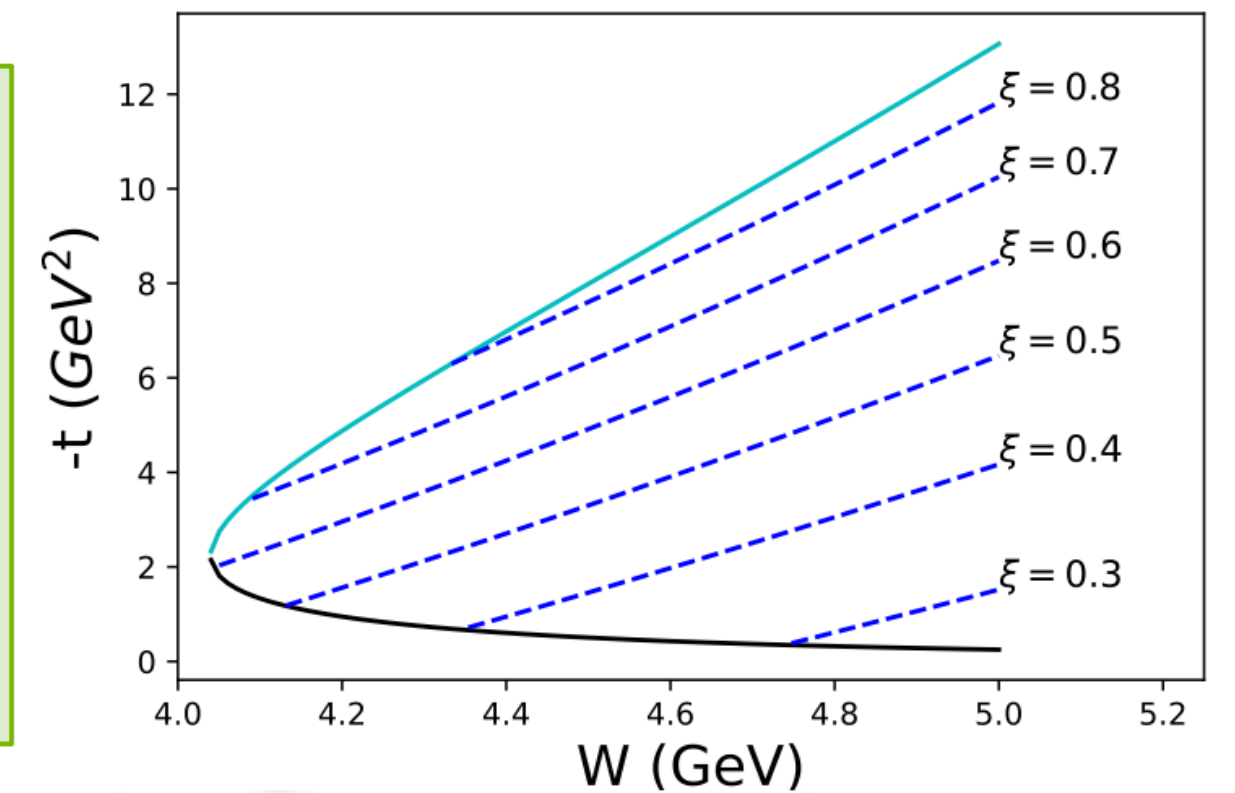
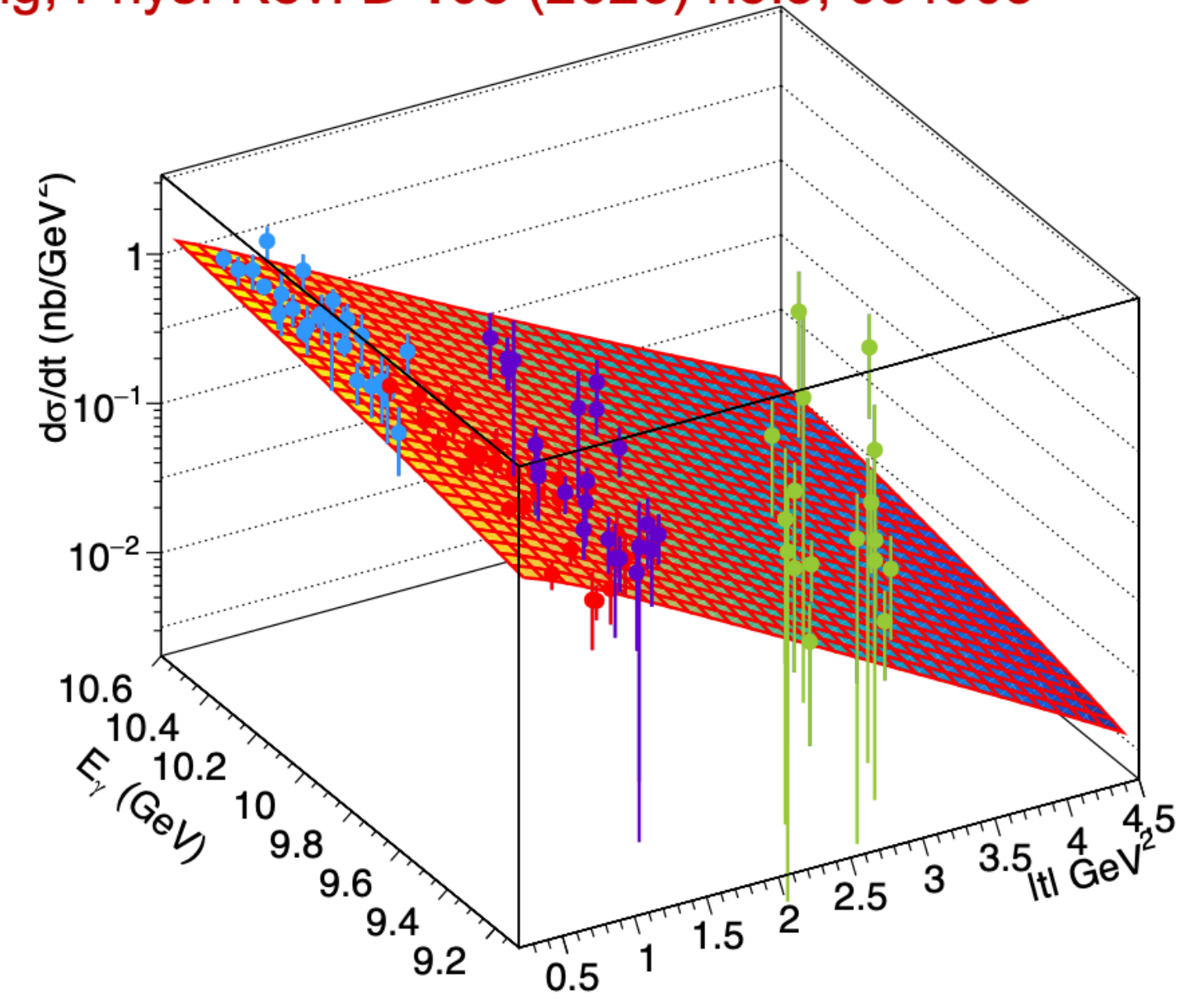
$$|G(t, \xi)|^2 = \frac{4}{\xi^4} \left\{ \left(1 - \frac{t}{4m_N^2}\right) E_2^2 - 2E_2(H_2 + E_2) + (1 - \xi^2)(H_2 + E_2)^2 \right\}$$

$$\int_0^1 dx H_g(x, \xi, t) = A_{2,0}^g(t) + (2\xi)^2 C_2^g \equiv H_2(t, \xi)$$

$$\int_0^1 dx E_g(x, \xi, t) = B_{2,0}^g(t) - (2\xi)^2 C_2^g \equiv E_2(t, \xi)$$

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

$$C_g(t) = \frac{C_g(0)}{\left(1 - \frac{t}{m_C^2}\right)^3}$$

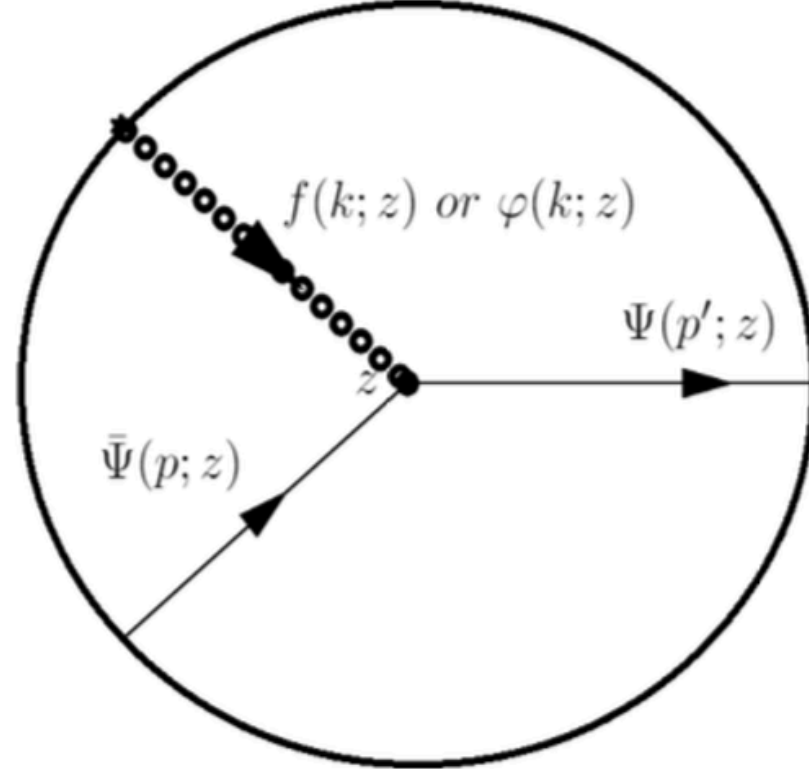
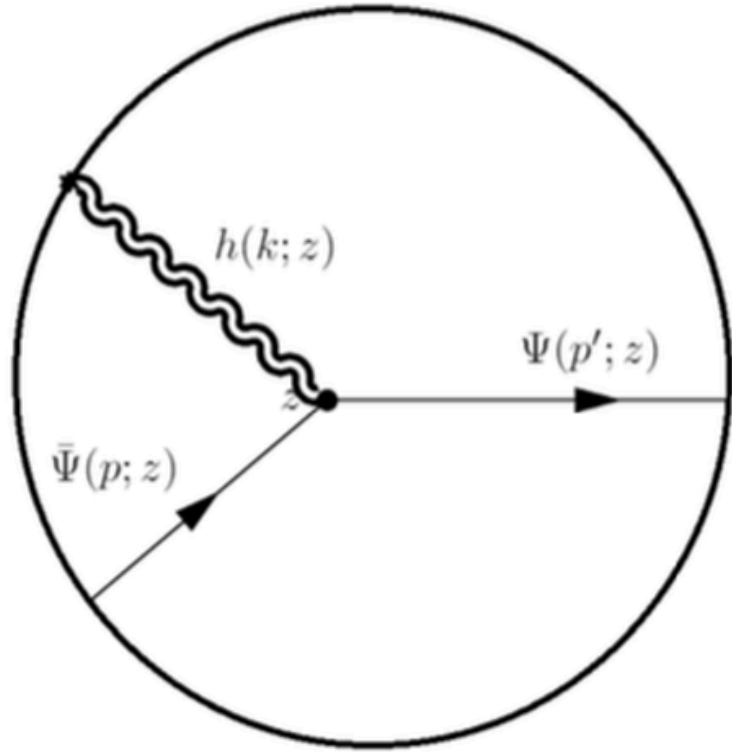


THE HOLOGRAPHIC QCD MODEL

2D fit to extract the $A(t)$ & $C(t)$ assuming $B(t)$ to be small

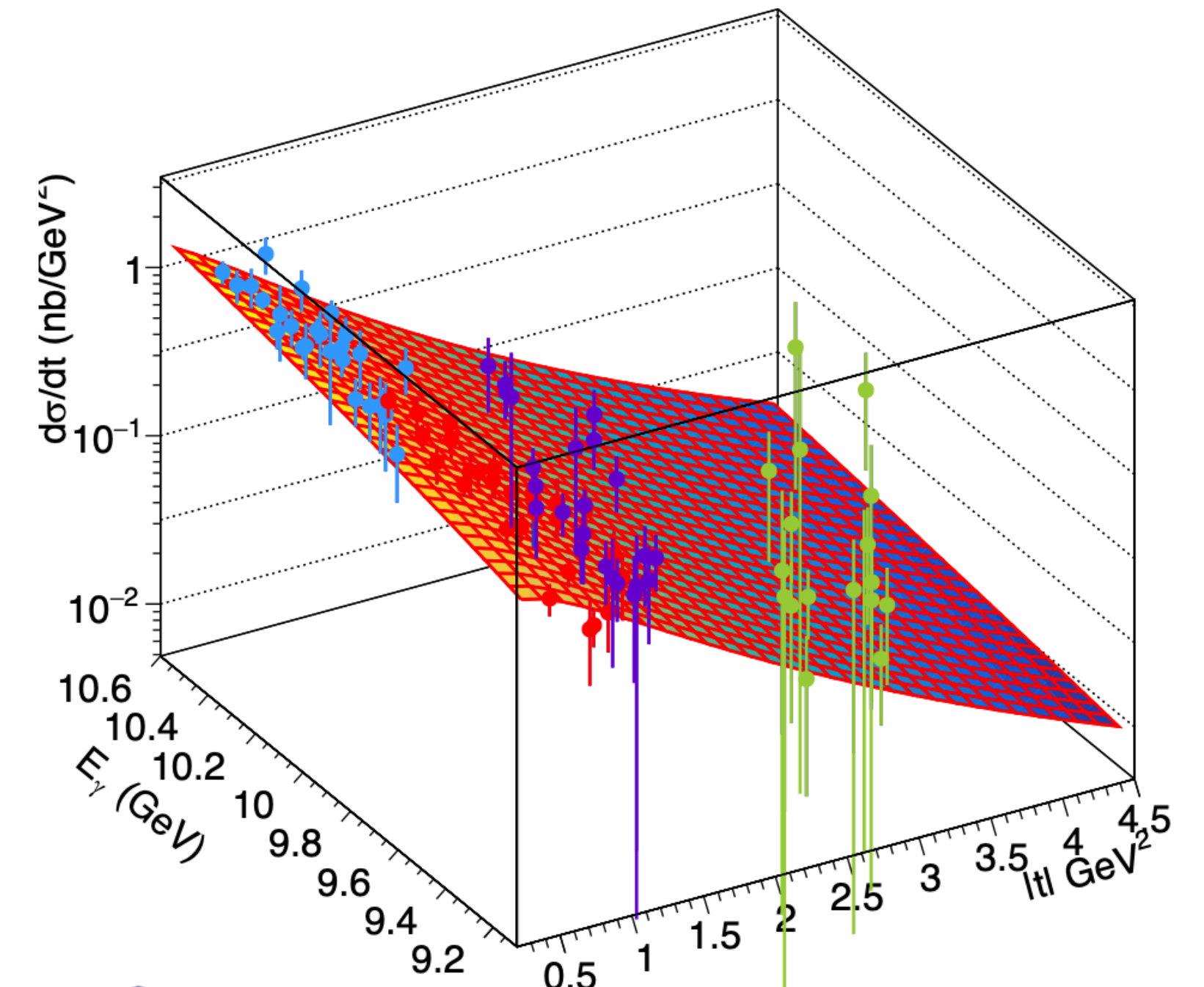
M-Z: K. Mamo & I. Zahed, PRD 103, 094010 (2021) and 2204.08857 (2022)

A tensor component and a scalar component



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

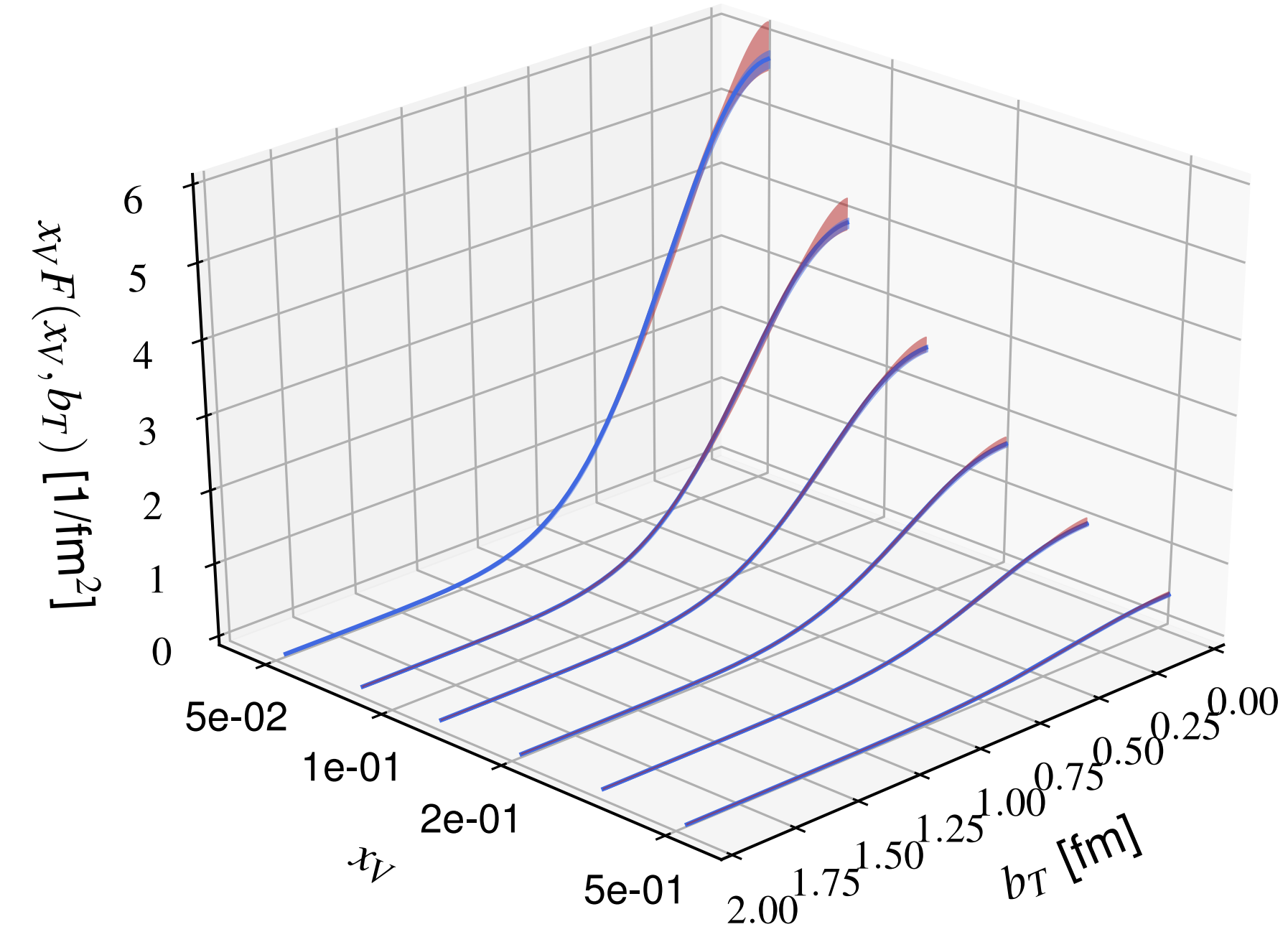
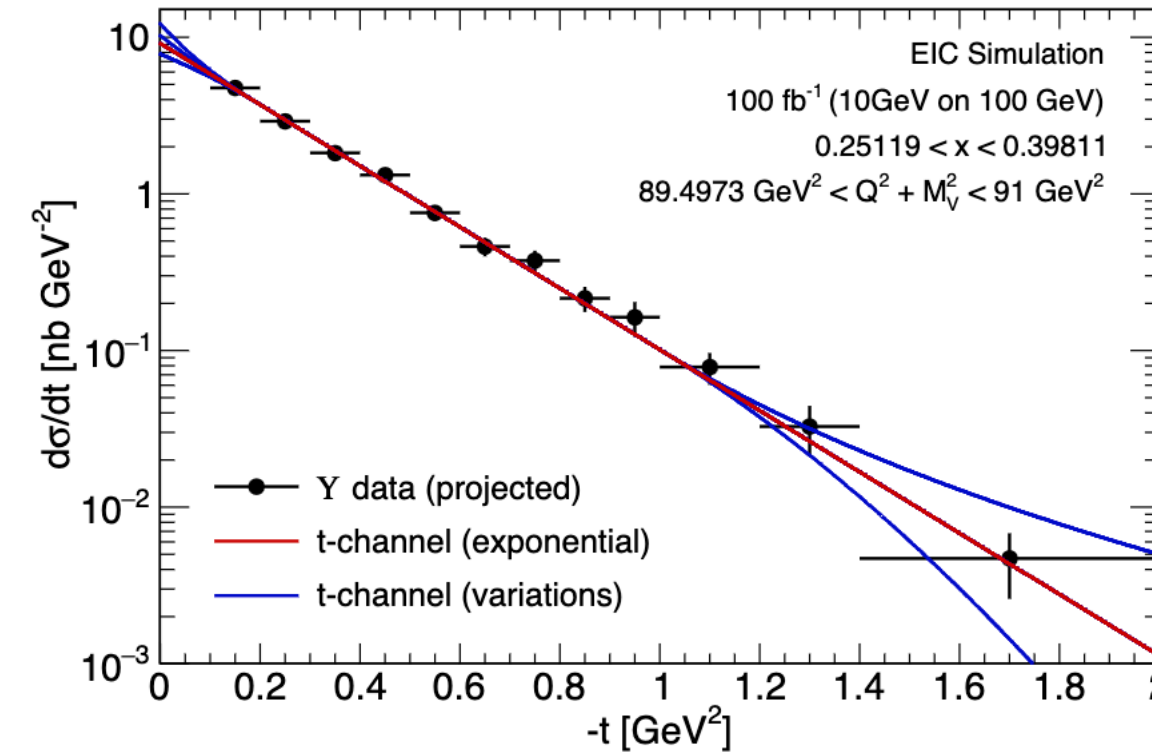
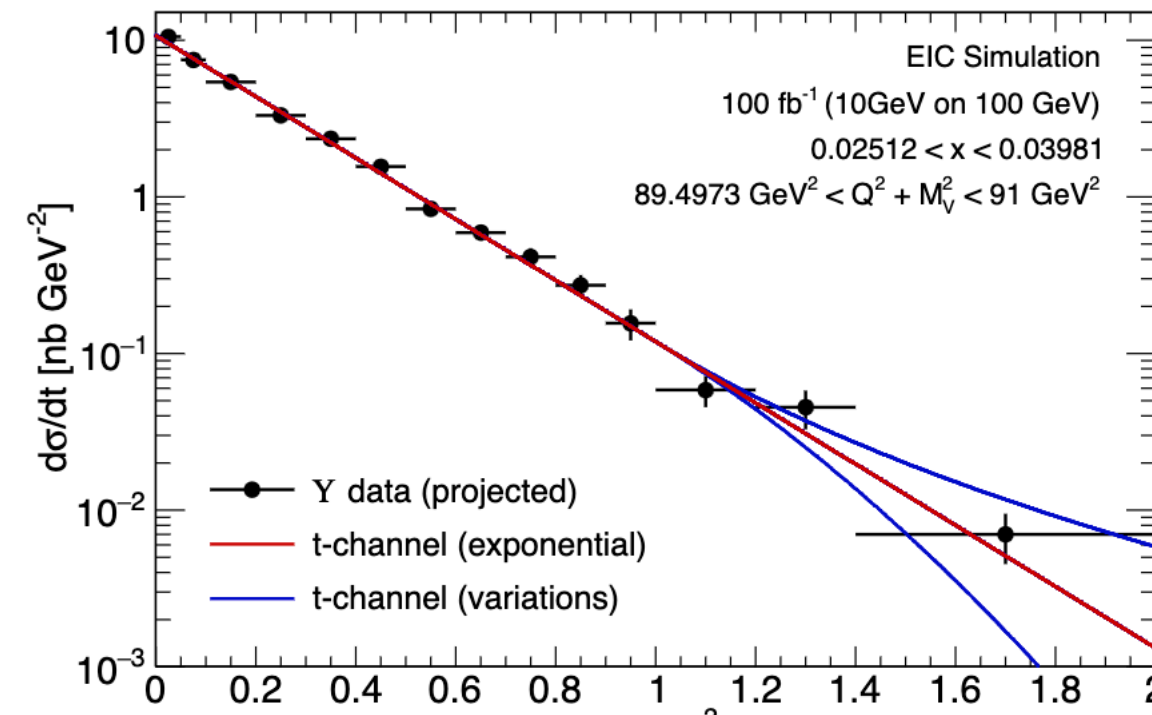
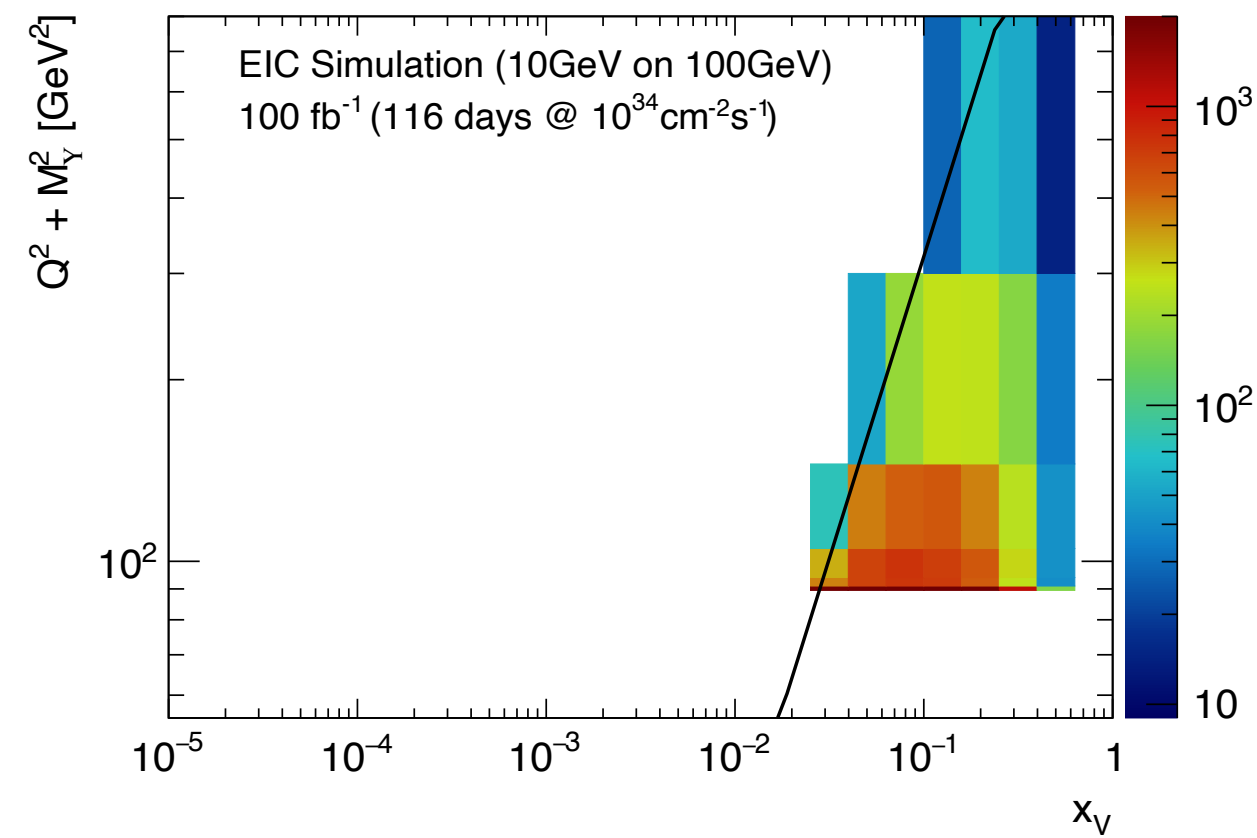
Spin-0 : $\langle p_2 | T_{\mu}^{\mu}(0) | p_1 \rangle$



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

- $A(t)$ and $D(t)$ shapes are fully calculated; However, dipole forms are assumed as very good approximations and are used in the fits to the data. $A_g(0) = \langle x_q \rangle$ is fixed to the DIS value from global fit CT18.
- $B(t)$ is neglected and \mathcal{N} is normalized to the cross section.

GLUON TOMOGRAPHY WITH $\Upsilon(1S)$



t-spectra

Average gluon density:

1 year at peak luminosity

Slide from Pierre Chatagnon

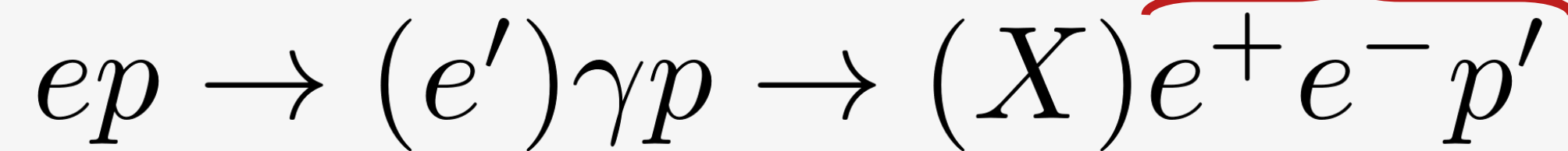
EVENT SELECTION WITH CLAS12

From TCS to near-threshold J/ψ photoproduction

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(Quasi-)Photoproduction events selection

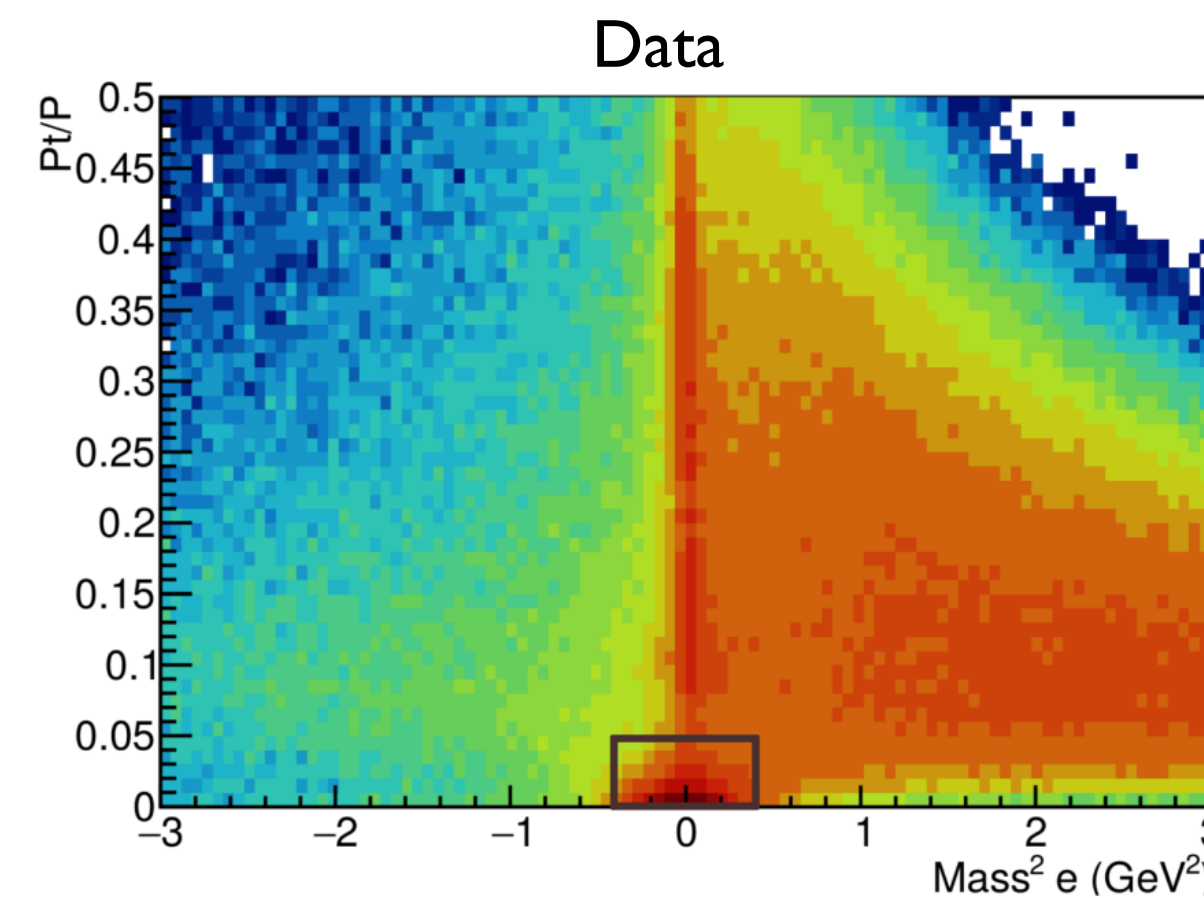
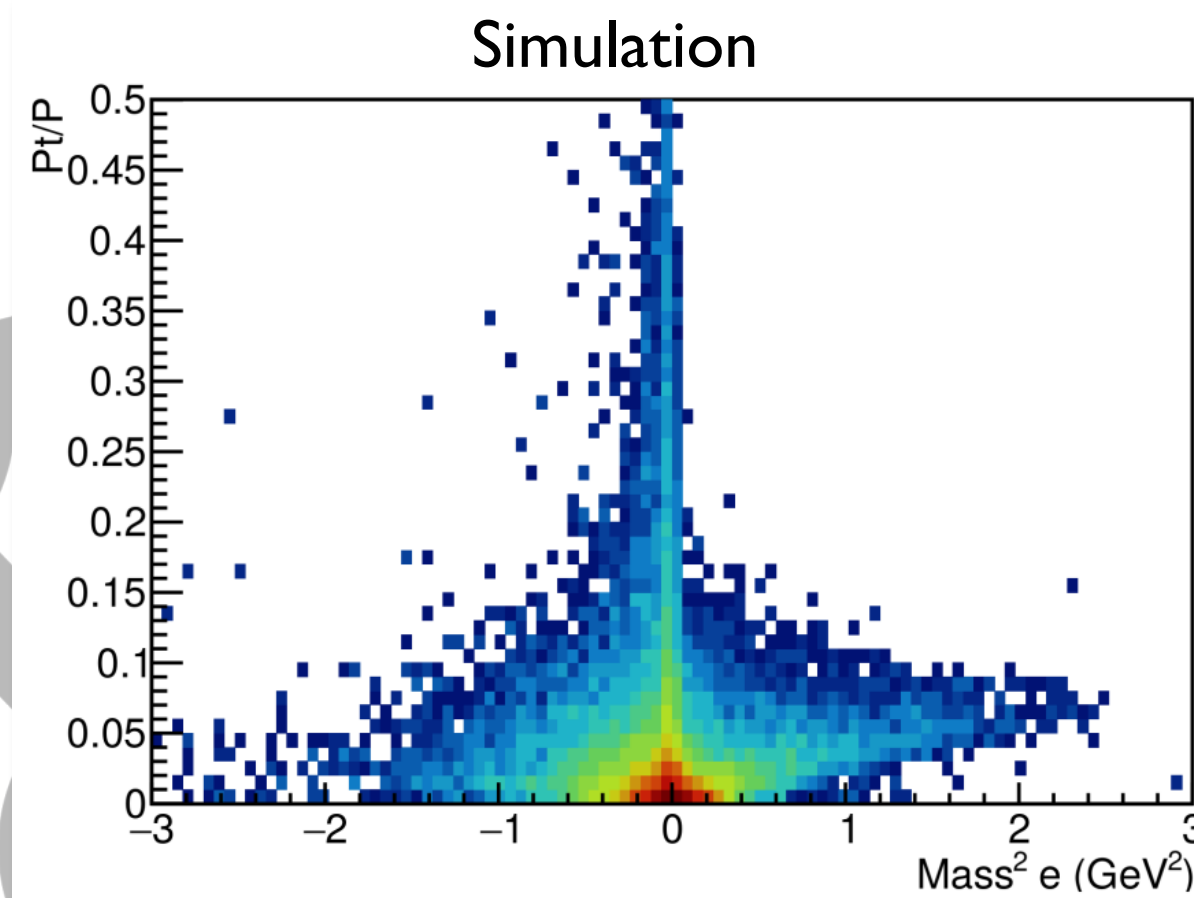
1) CLAS12 PID + Positron NN PID



$$p_X = p_{beam} + p_p - p_{e^+} - p_{e^-} - p_{p'}$$

2) $|M_X^2| < 0.4 \text{ GeV}^2$

3) $\frac{Pt_X}{P_X} < 0.05$
 $\rightarrow Q^2 < 0.1 \text{ GeV}^2$



Jefferson Lab **clas**