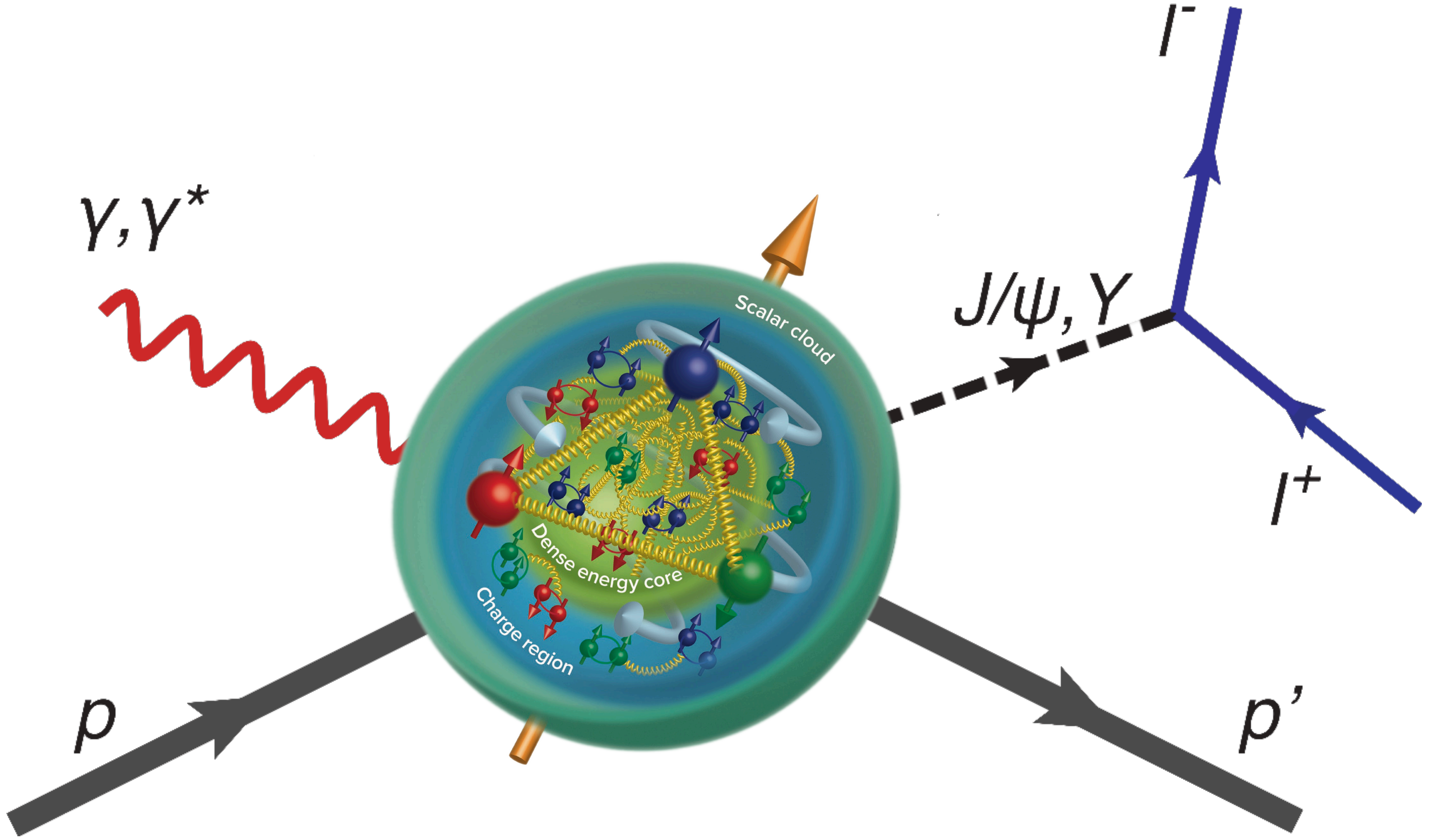
NEW RESULTS FROM THE HALL C J/Ψ-007 EXPERIMENT AND FUTURE PROSPECTS

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

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

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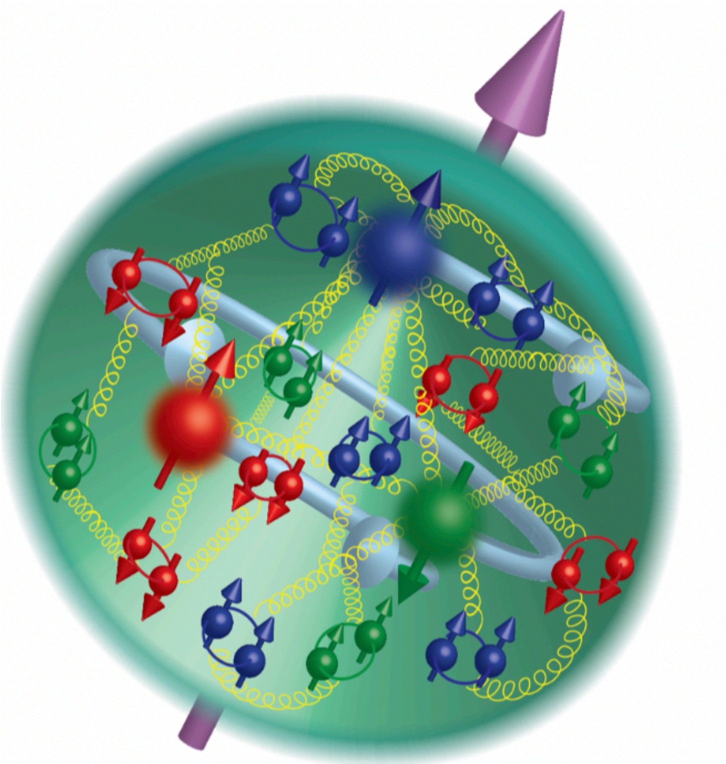
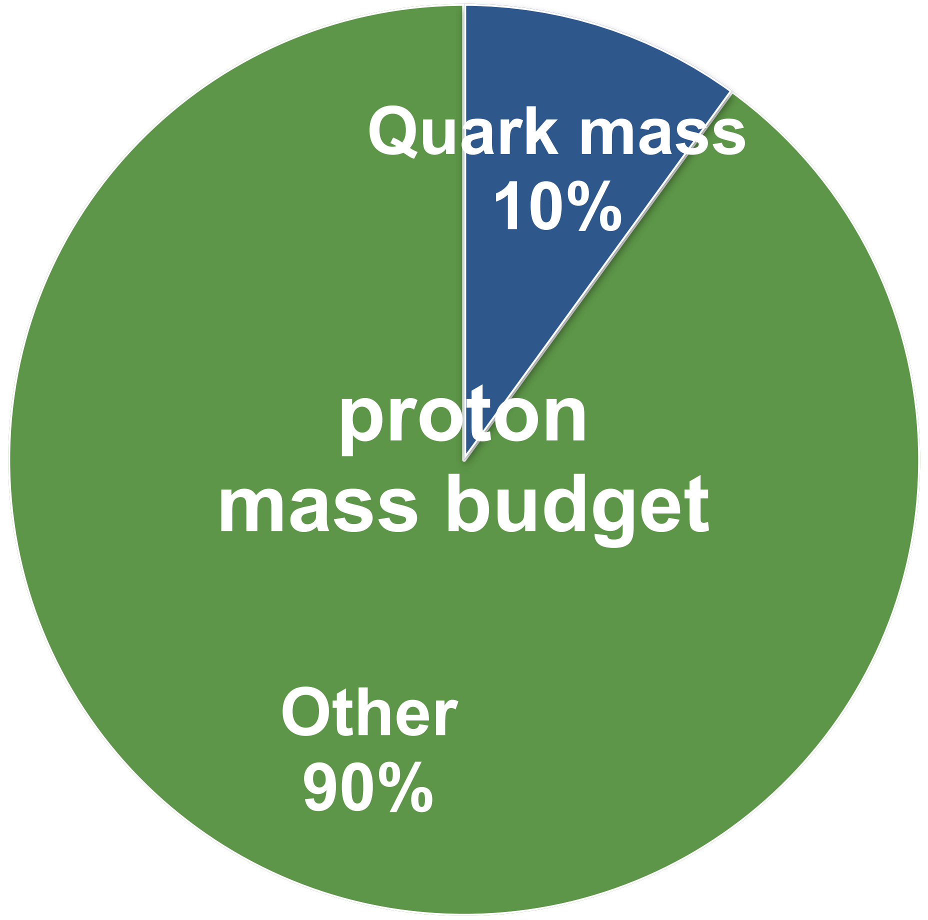
SoLID Science Workshop, Argonne, 2024

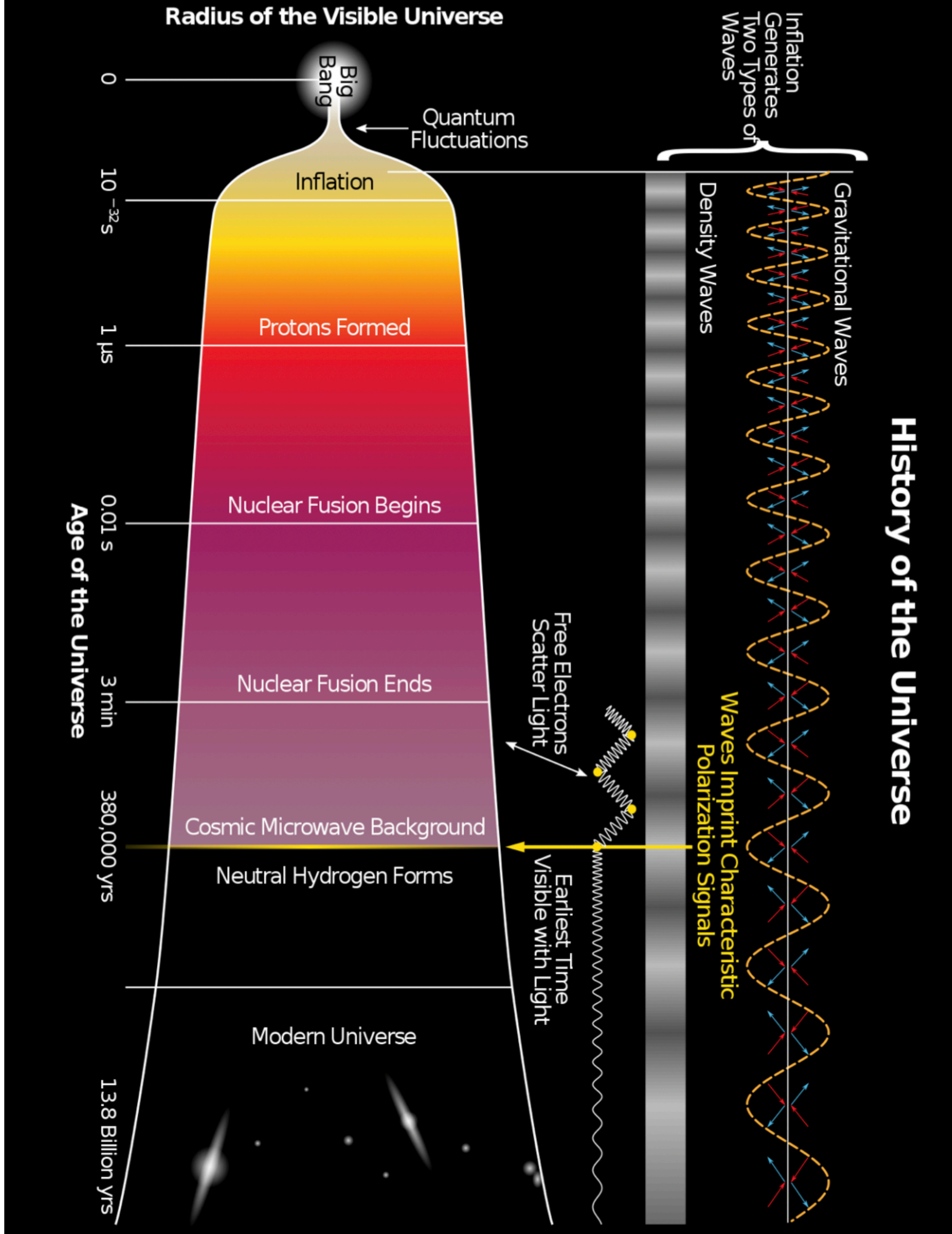
The emergence of nucleon mass

QCD IN THE STANDARD MODEL



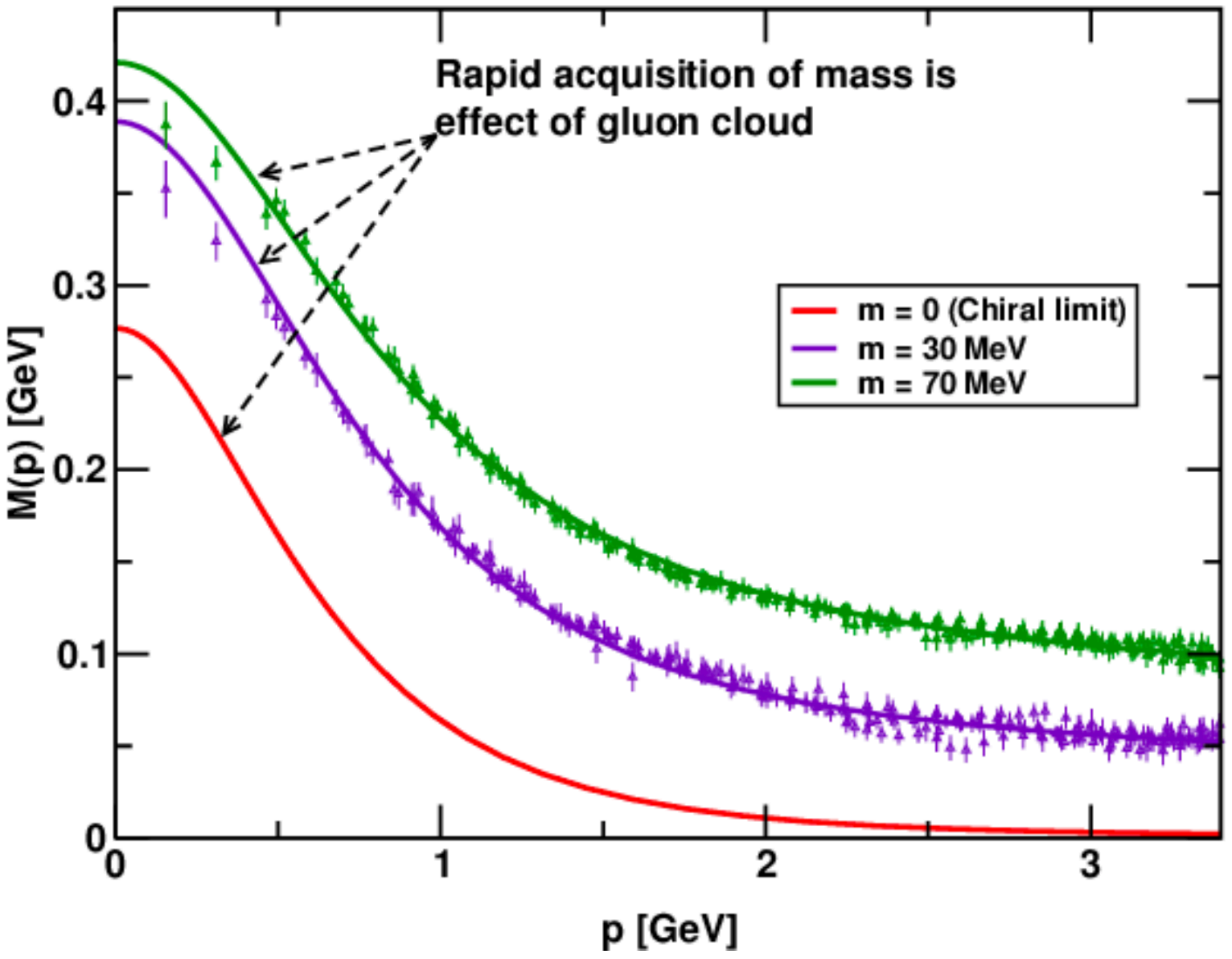


- Since the formation of protons and neutrons, most of the mass of the visible universe encapsulated in protons, neutrons, and nuclei.
- Surprising: nucleon mass much larger than sum of quark masses.
- *How does QCD give rise to the 1GeV proton?*
- *How is the proton mass distributed in its confinement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



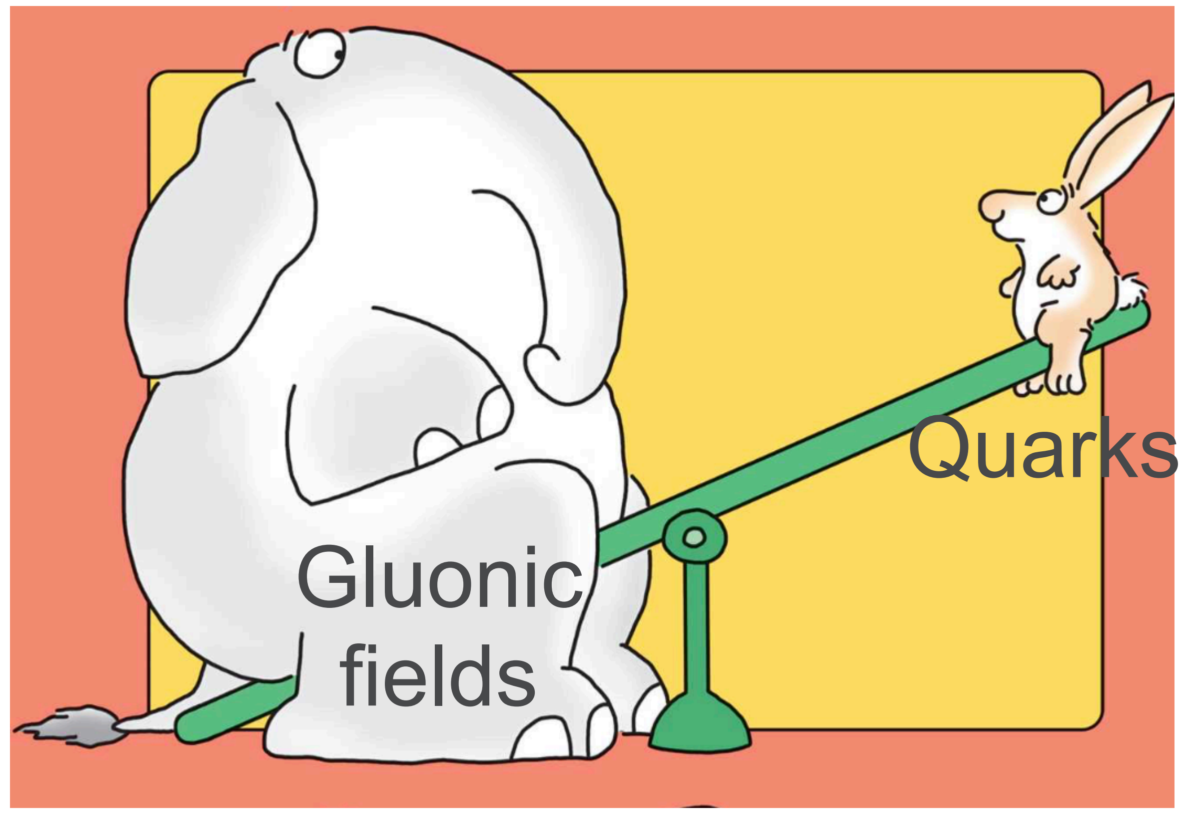
PROTON MASS IS AN EMERGENT PHENOMENON

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)

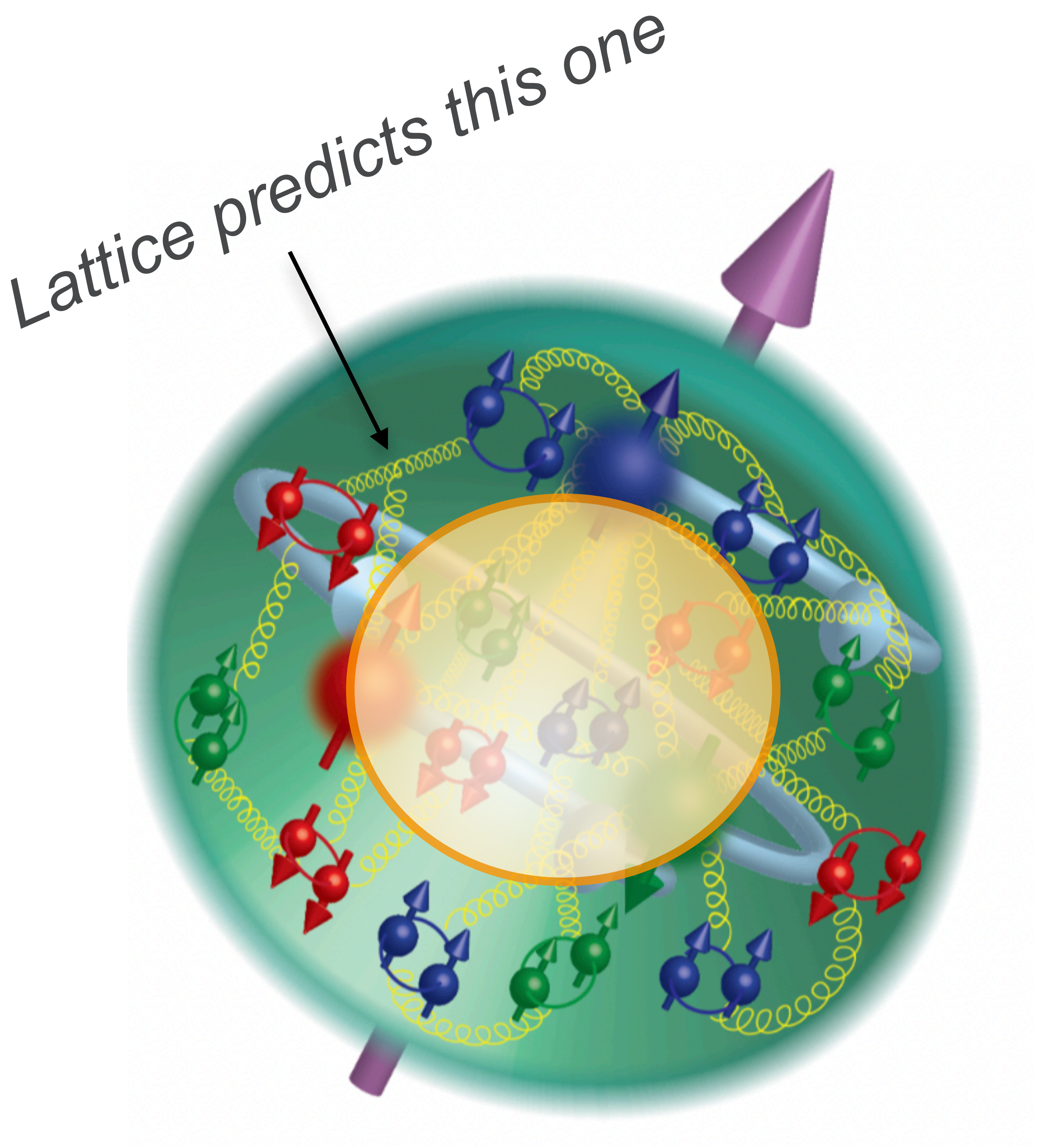
Most of the proton mass originates in the energy enclosed in the gluonic fields of the Strong Interaction itself



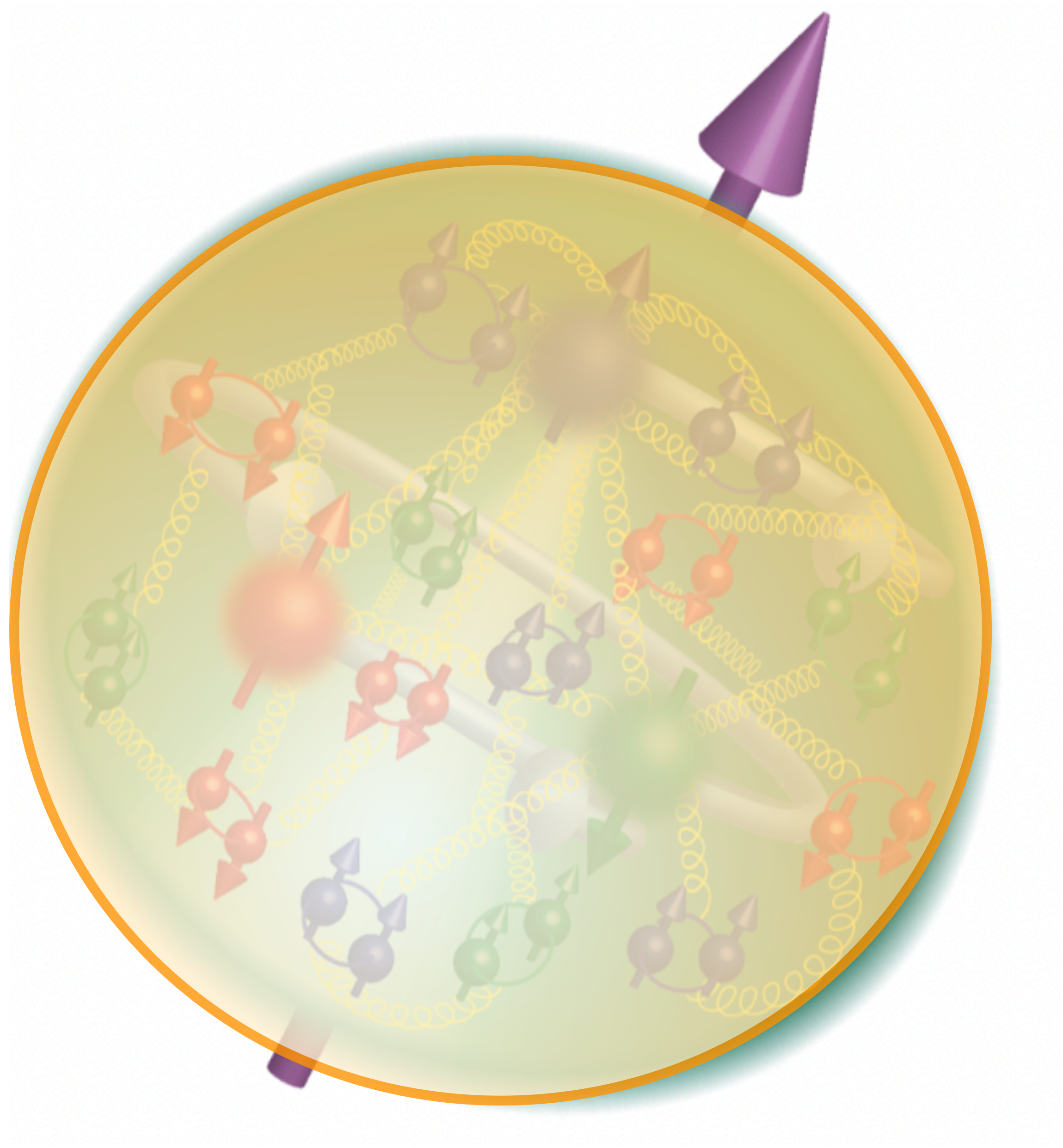
Bottom line: The Higgs mechanism is largely irrelevant for most of “normal” visible matter!

WHERE IS THE ENERGY INSIDE THE PROTON?

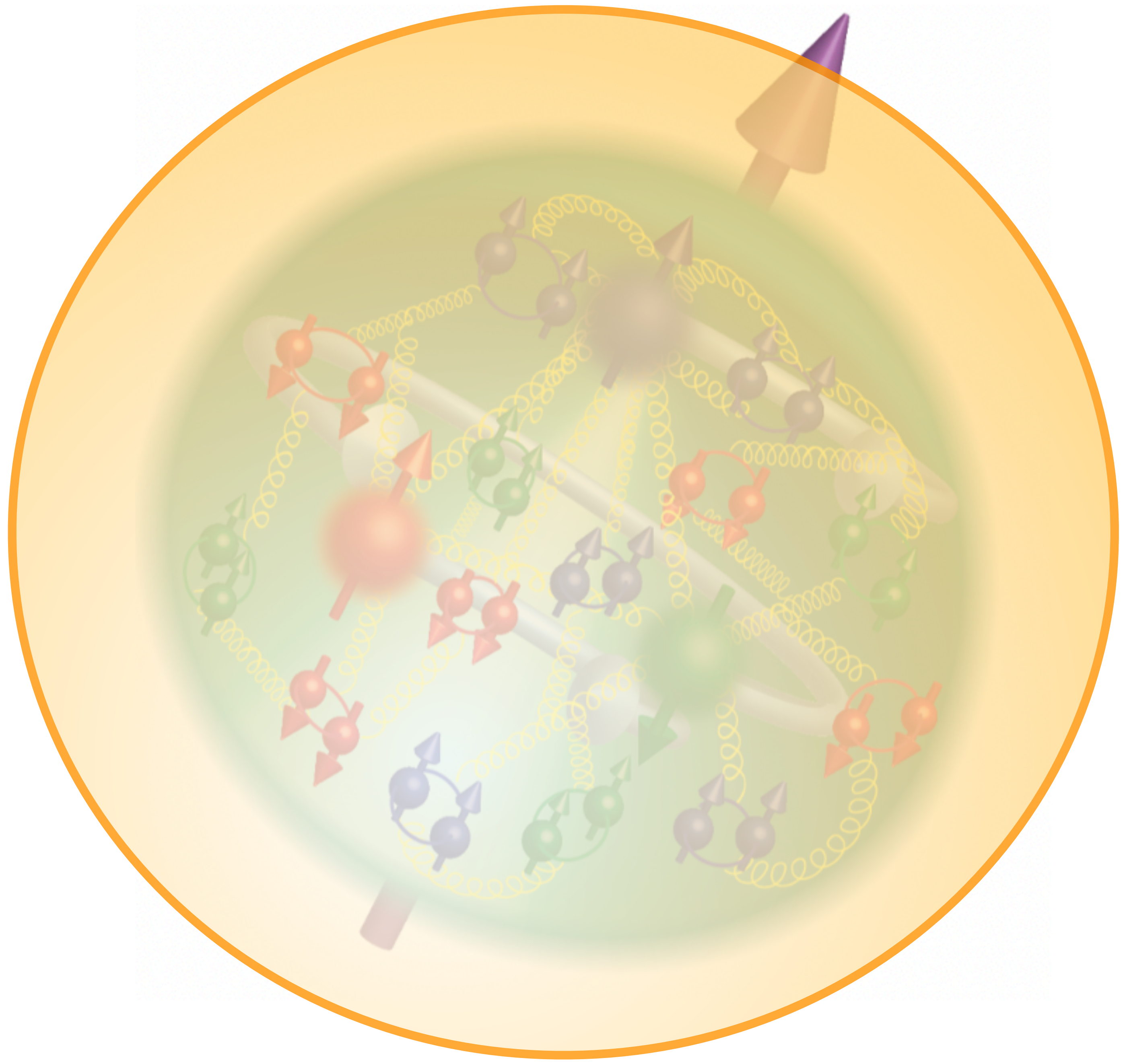
How does the mass radius compare to the charge radius?



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

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

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

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

Scalar (0++ glueball-like) radius

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

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

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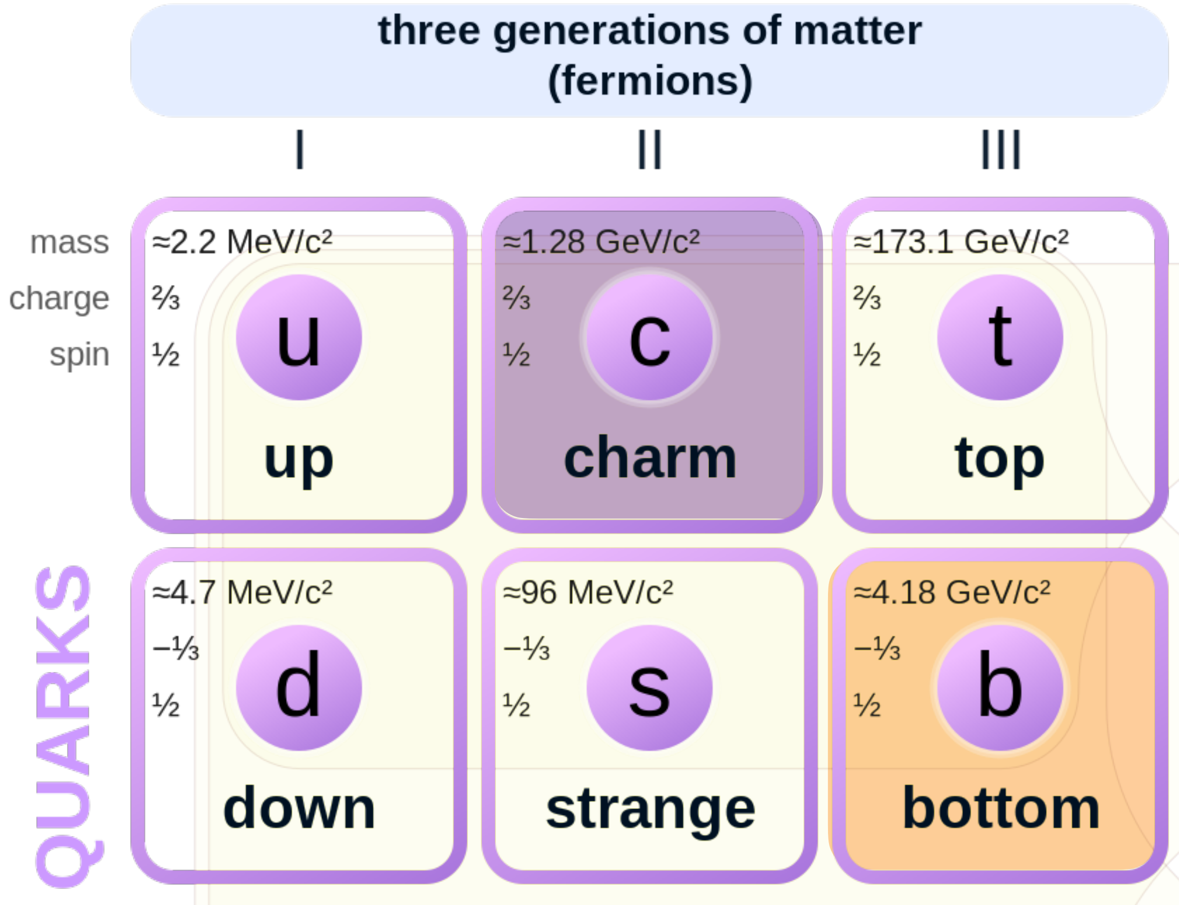
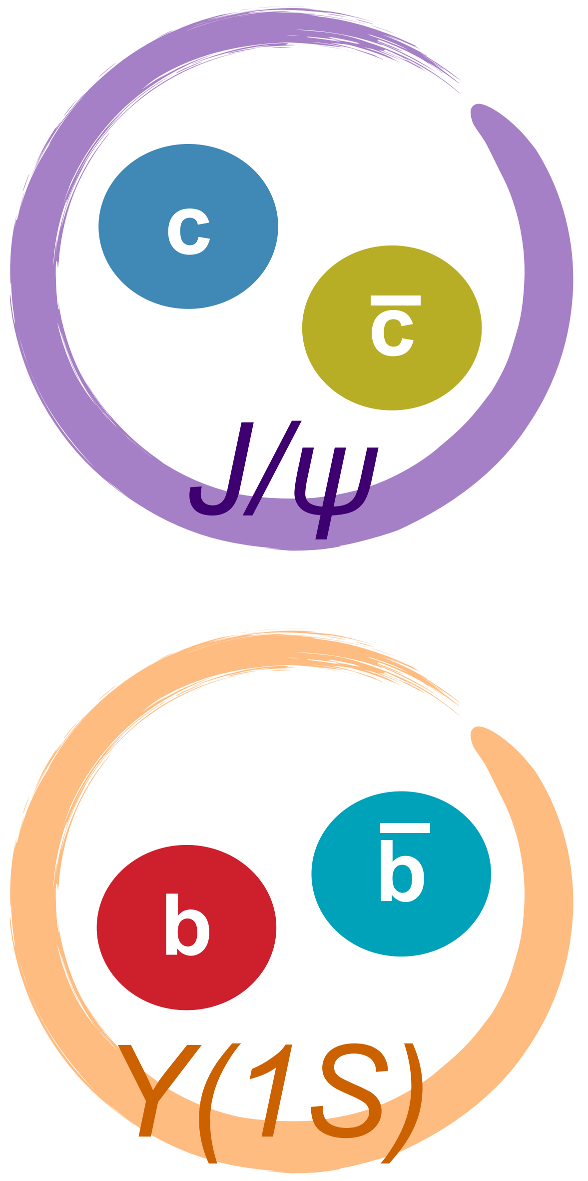
- Small “color” dipole made of heavy quarks well-suited to study gluons





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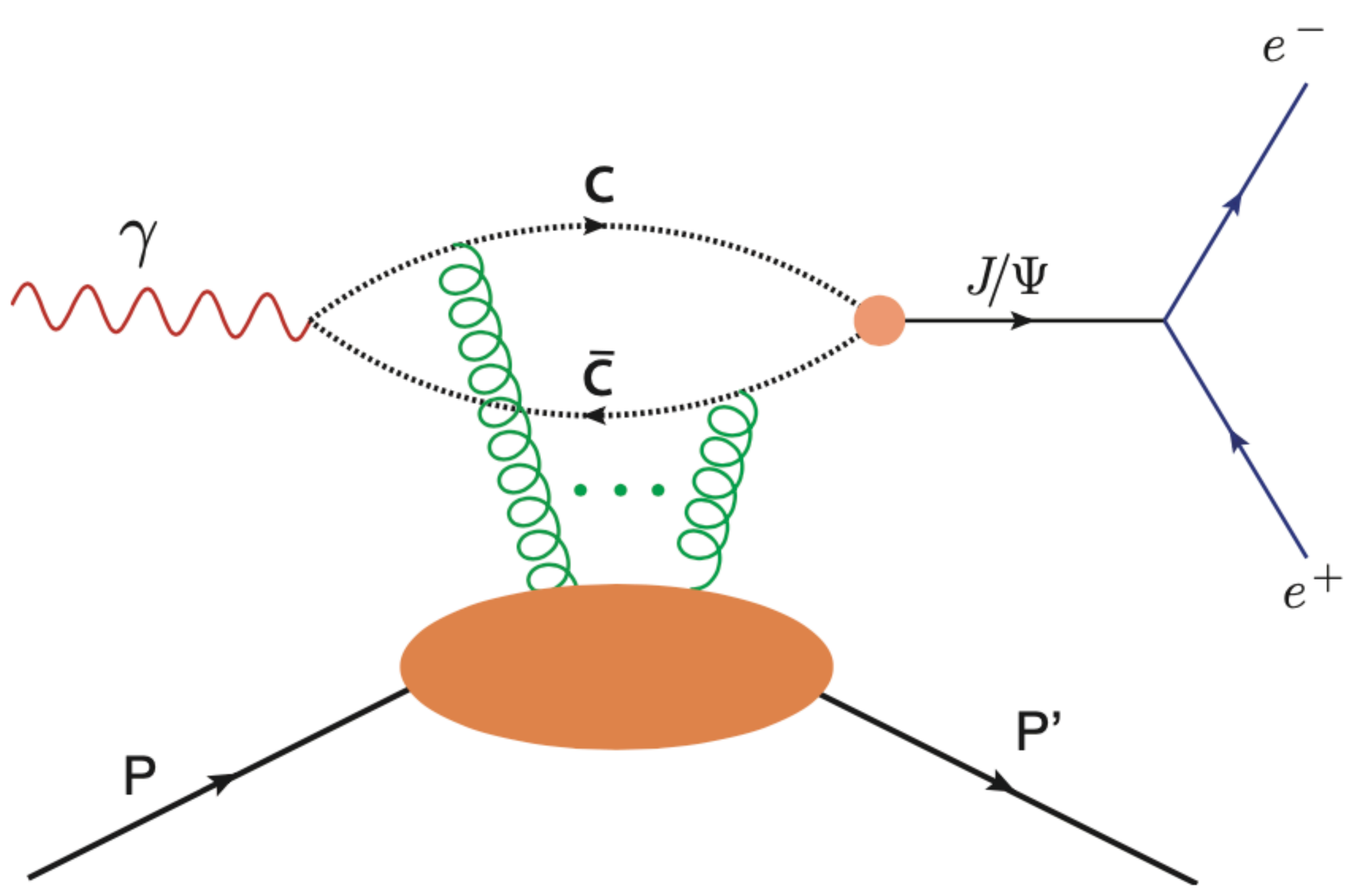
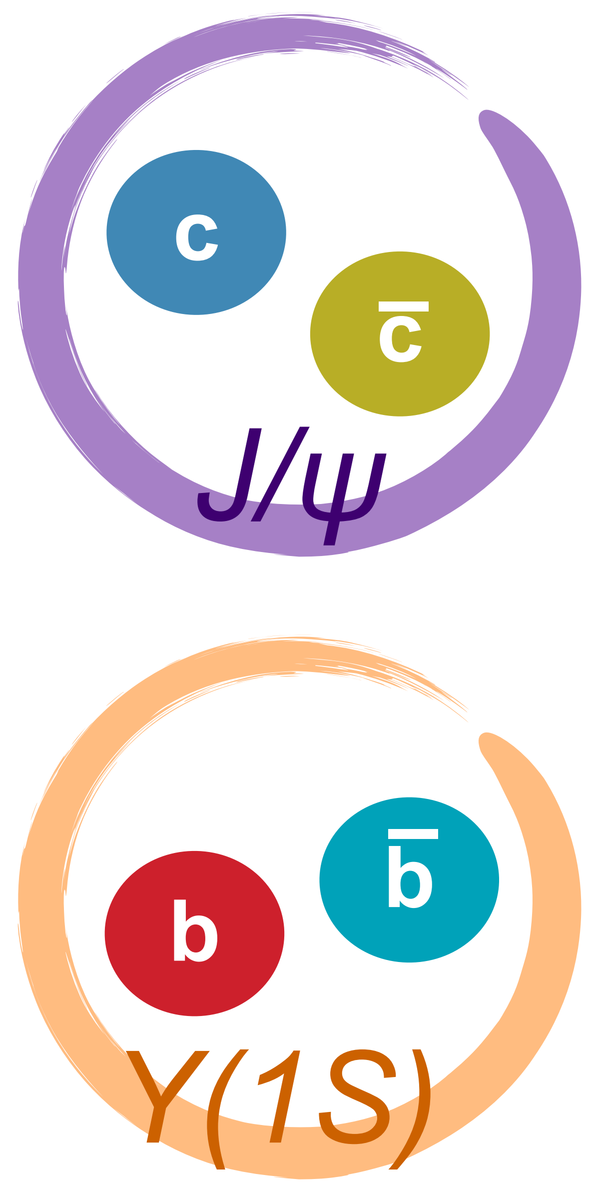
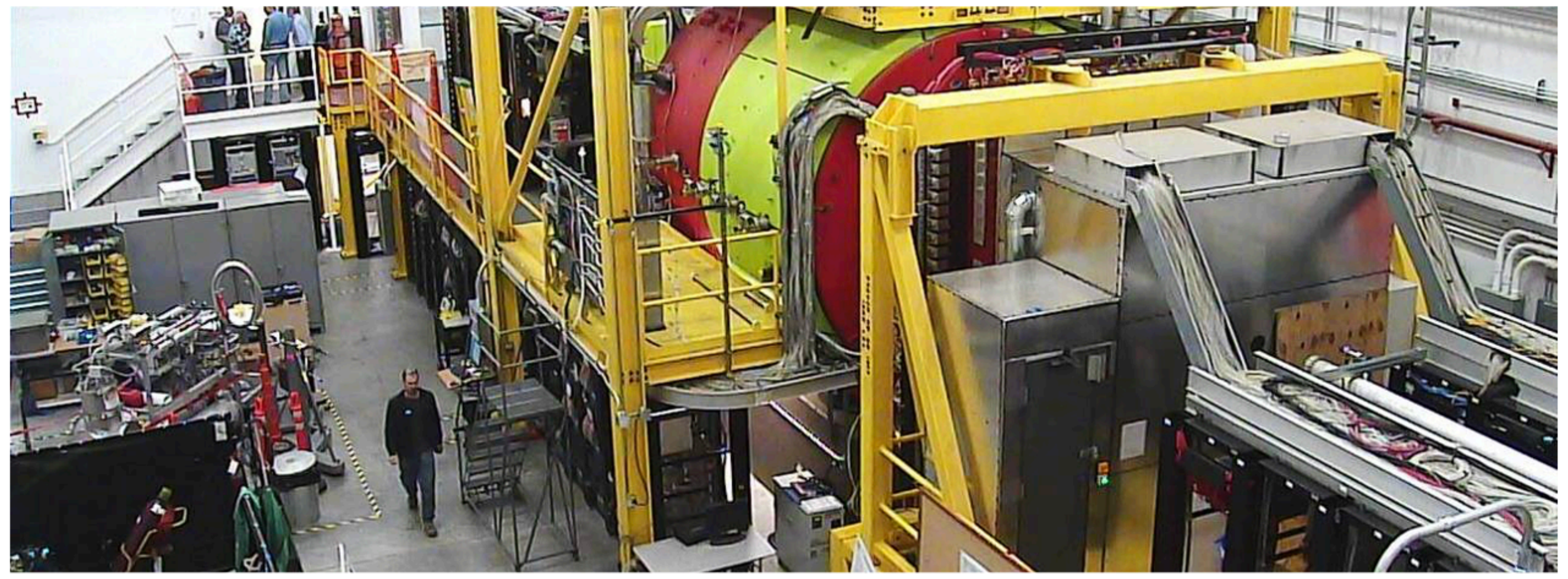


Gravitational form factors constrained by near-threshold exclusive J/ψ and Y photoproduction

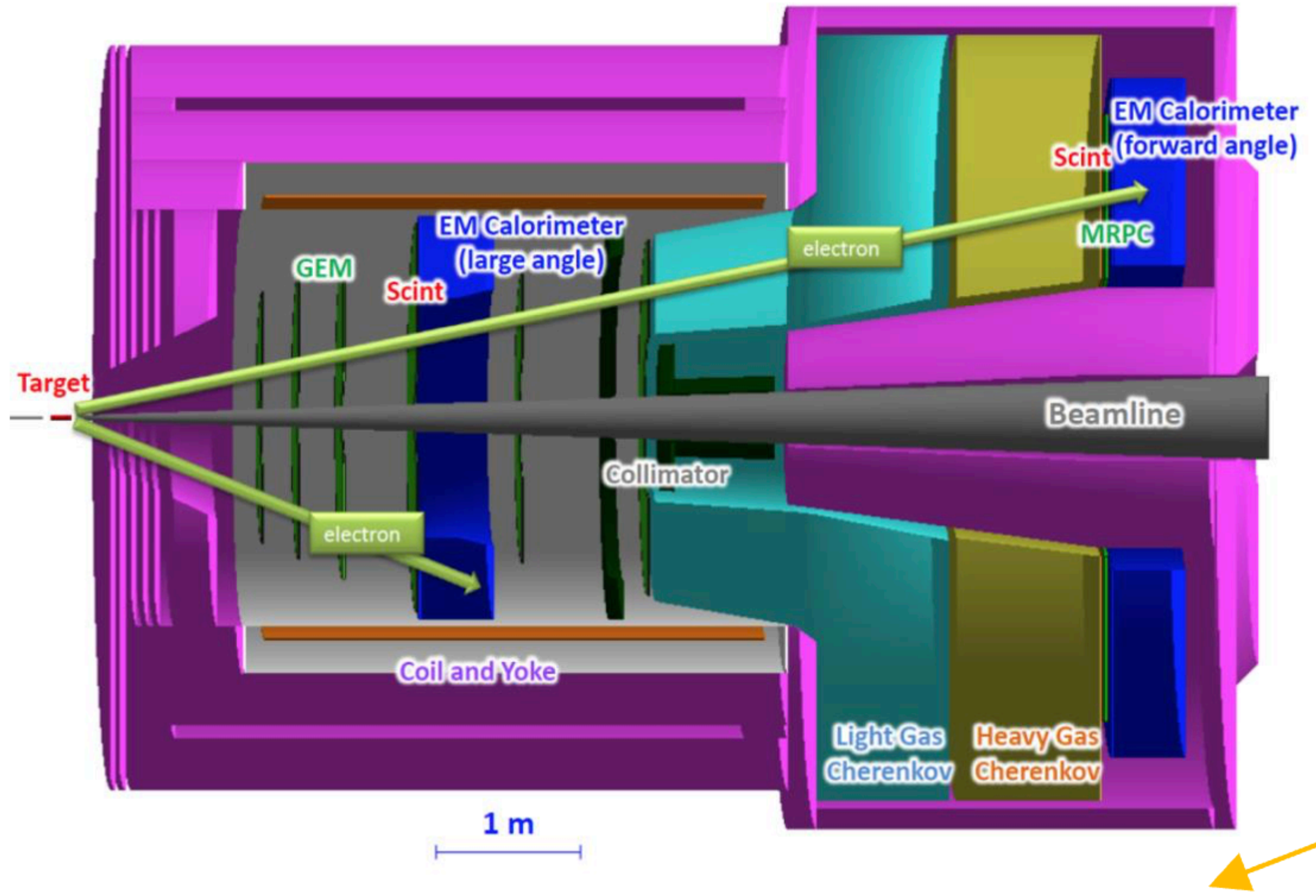
Beyond GFFs: 3-D gluonic structure of nucleons and nuclei constrained by exclusive J/ψ and Y electro-production at higher energies



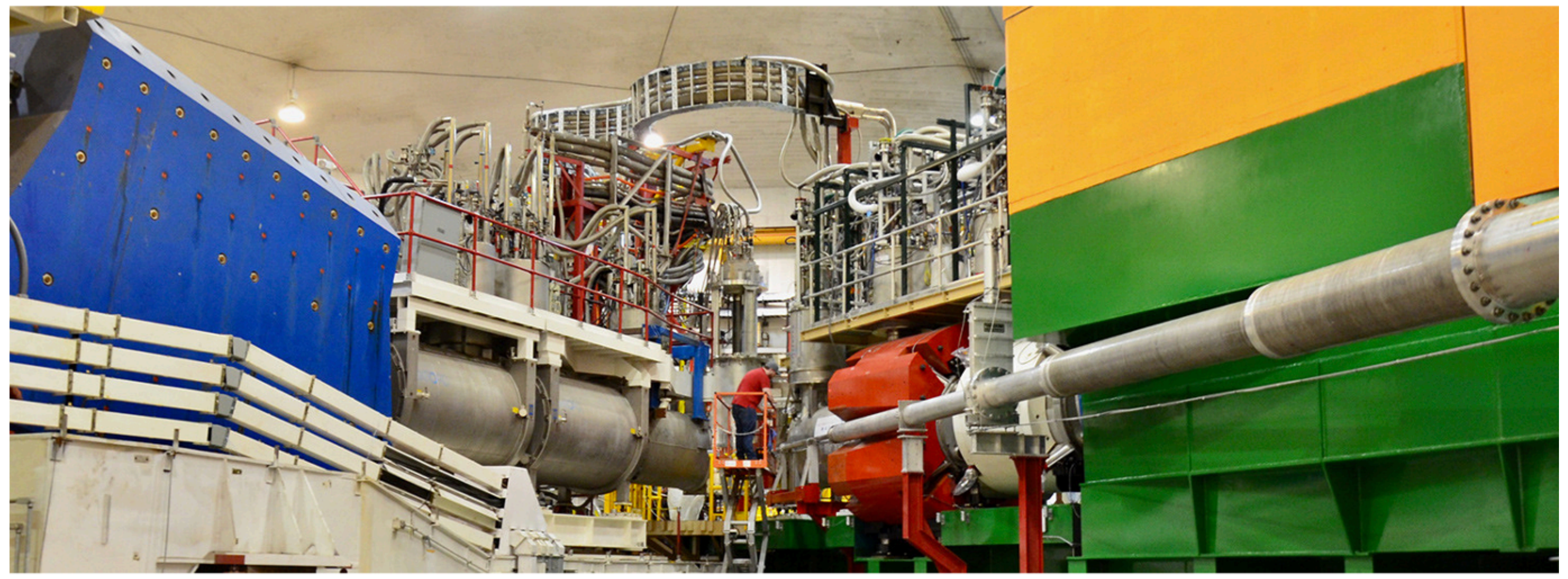
12 GEV J/ψ EXPERIMENTS AT JEFFERSON LAB



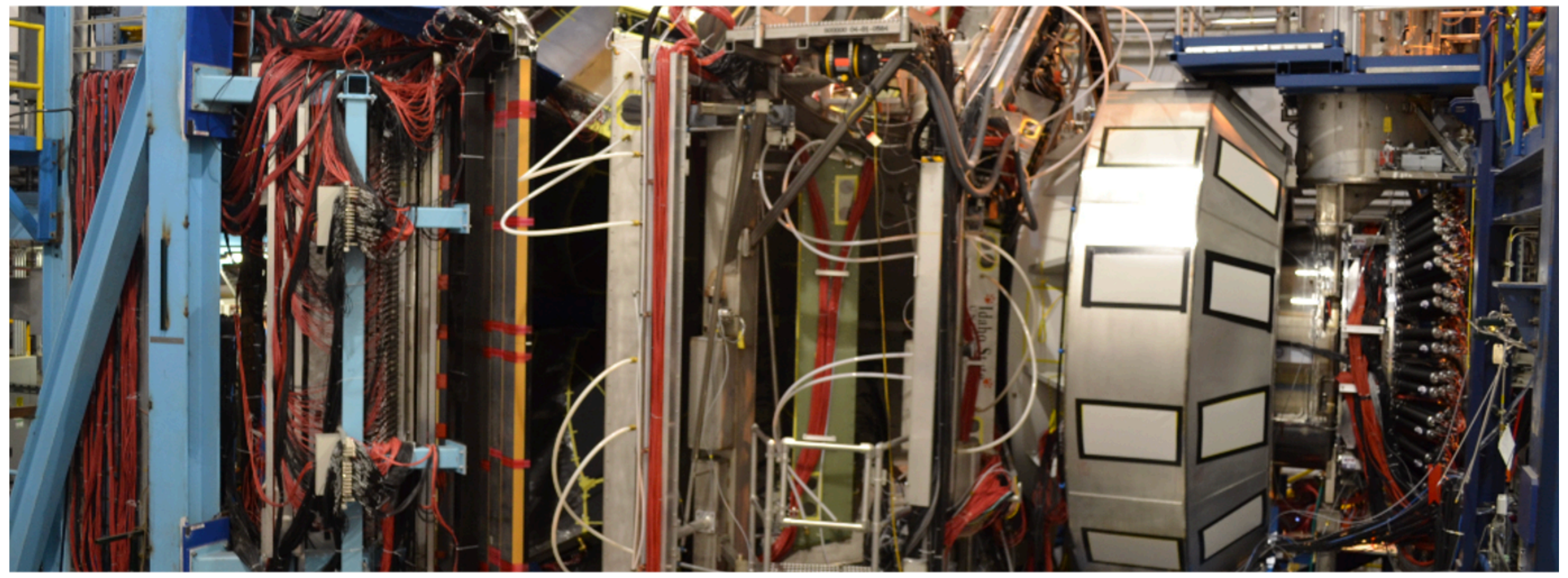
Hall D - GlueX observer the first J/ψ at JLab
A. Ali *et al.*, PRL 123, 072001 (2019)



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



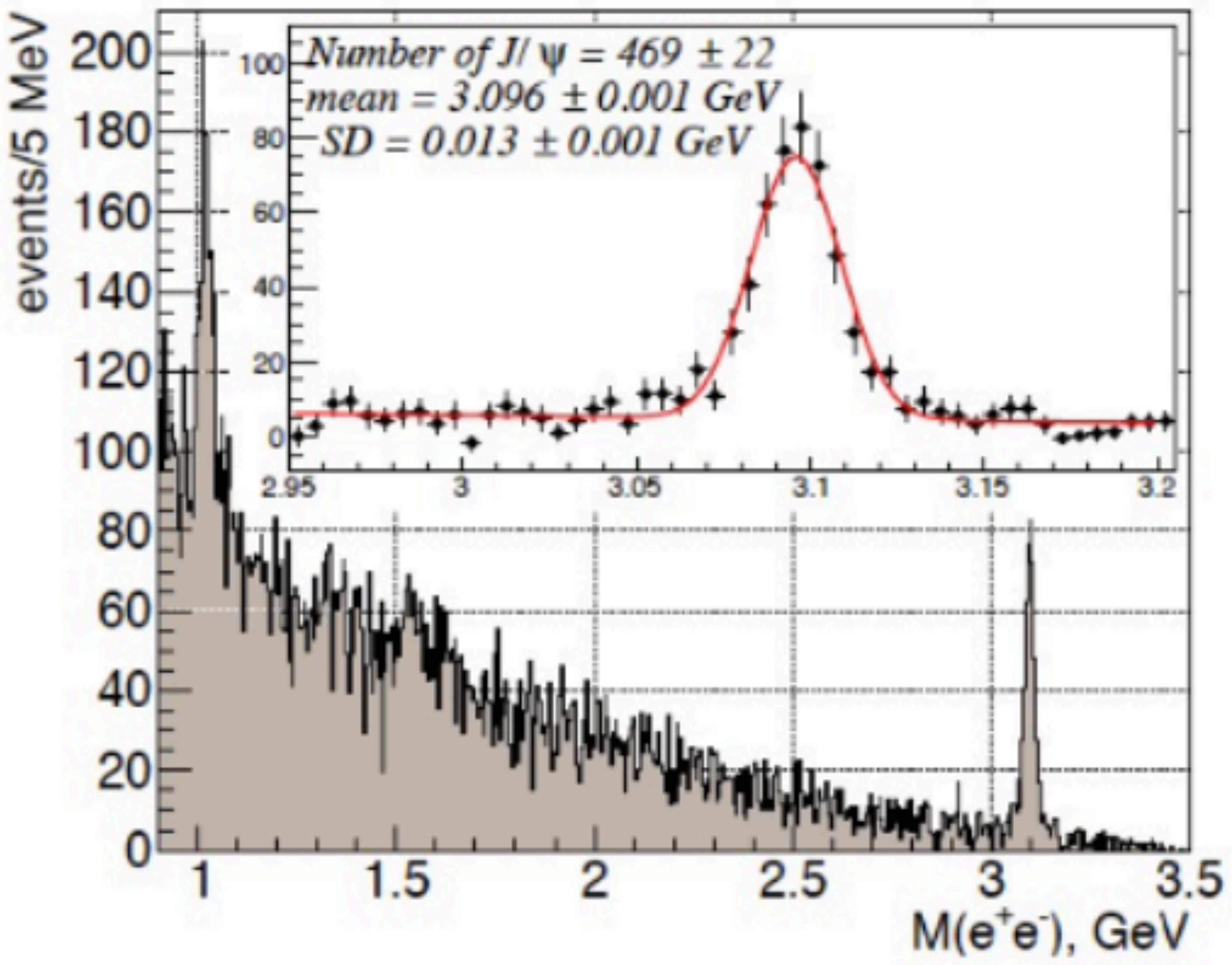
Hall B - CLAS12 has experiments to measure TCS + J/ψ in photoproduction as part of Run Groups A (hydrogen) and B (deuterium): E12-12-001, E12-12-001A, E12-11-003B

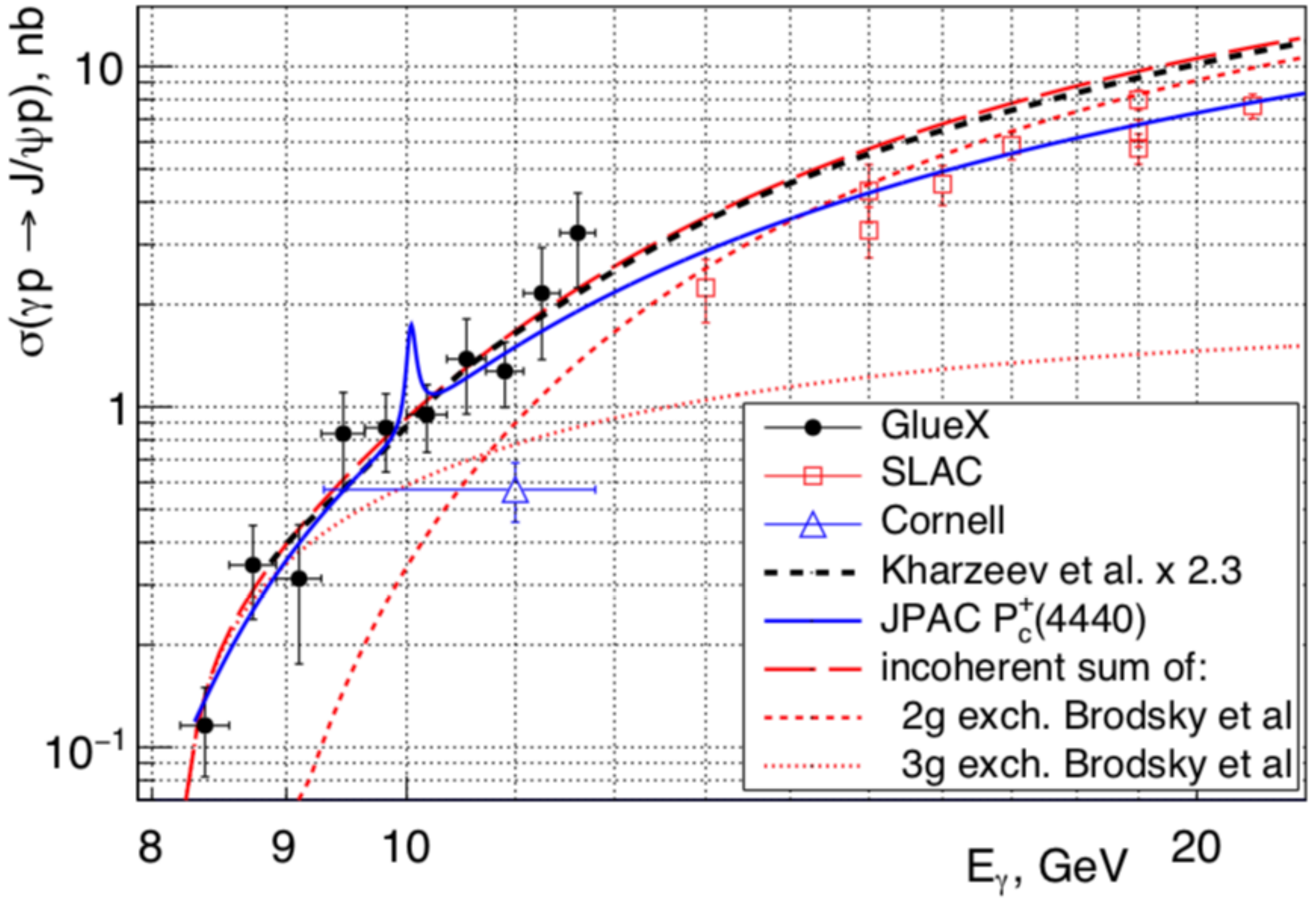
J/Ψ NEAR THRESHOLD IN HALL D

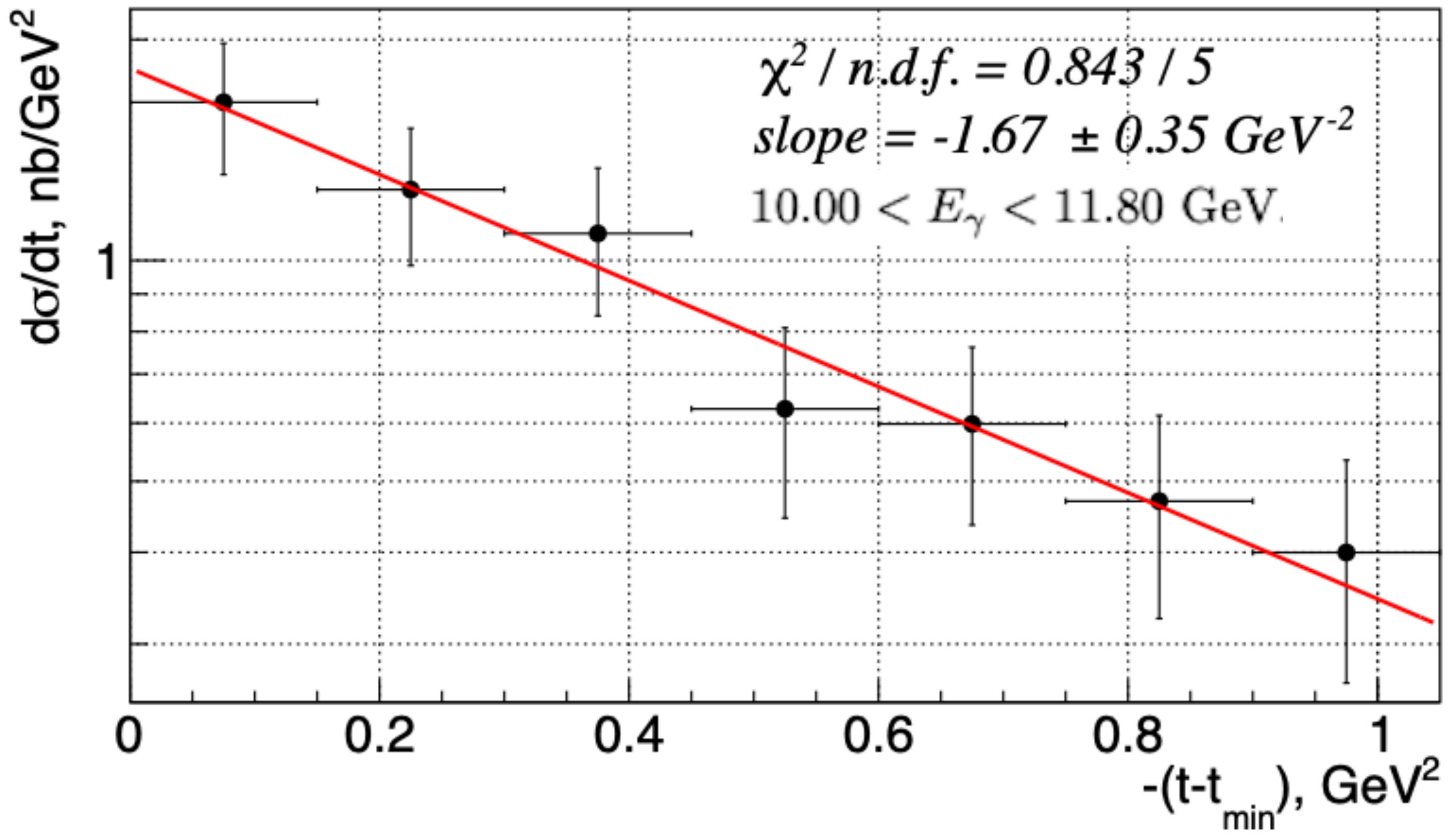
First J/ψ results from JLab, published in PRL 123, 072001 (2019)

- 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

$\gamma p \rightarrow p\, J/\psi \rightarrow p e^+ e^-$

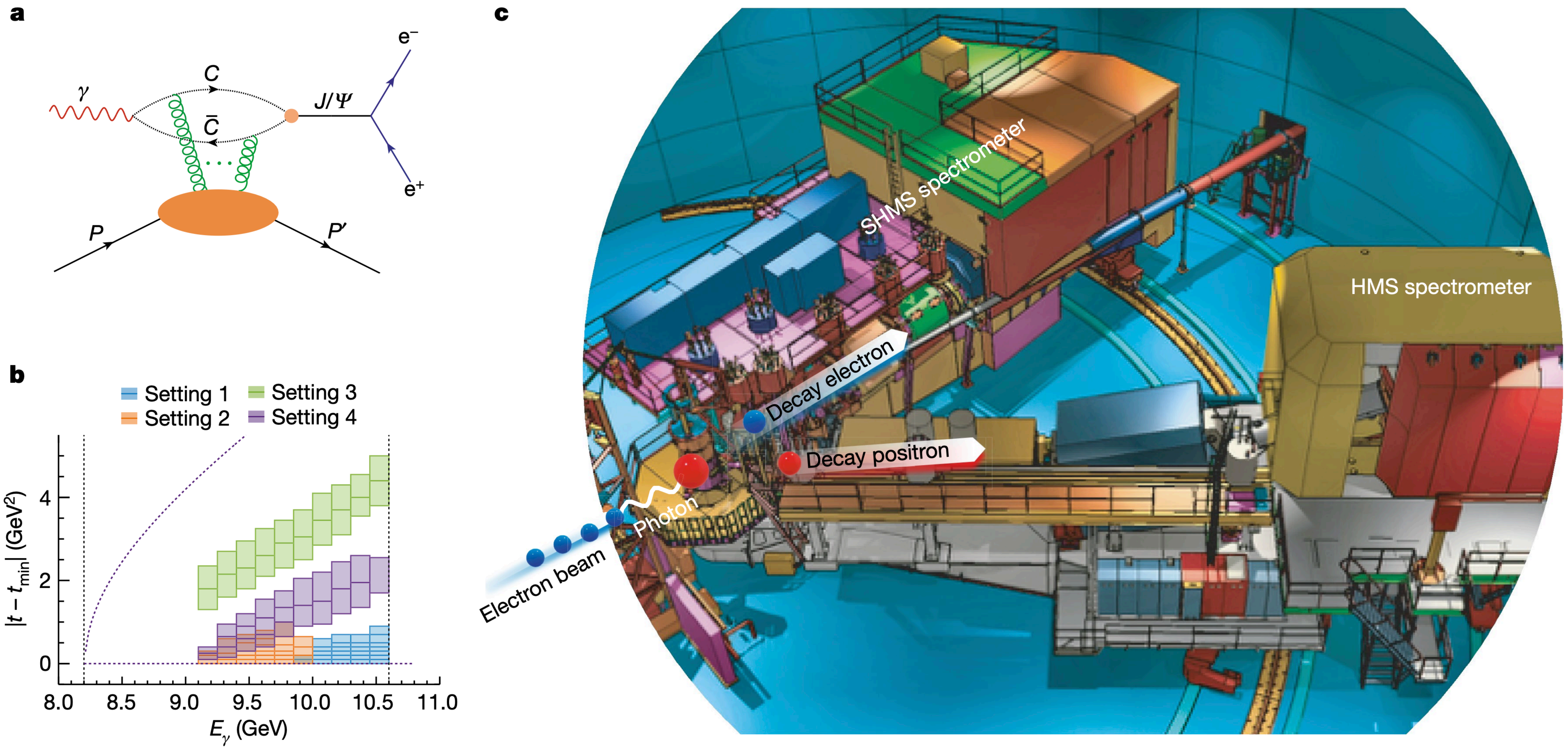






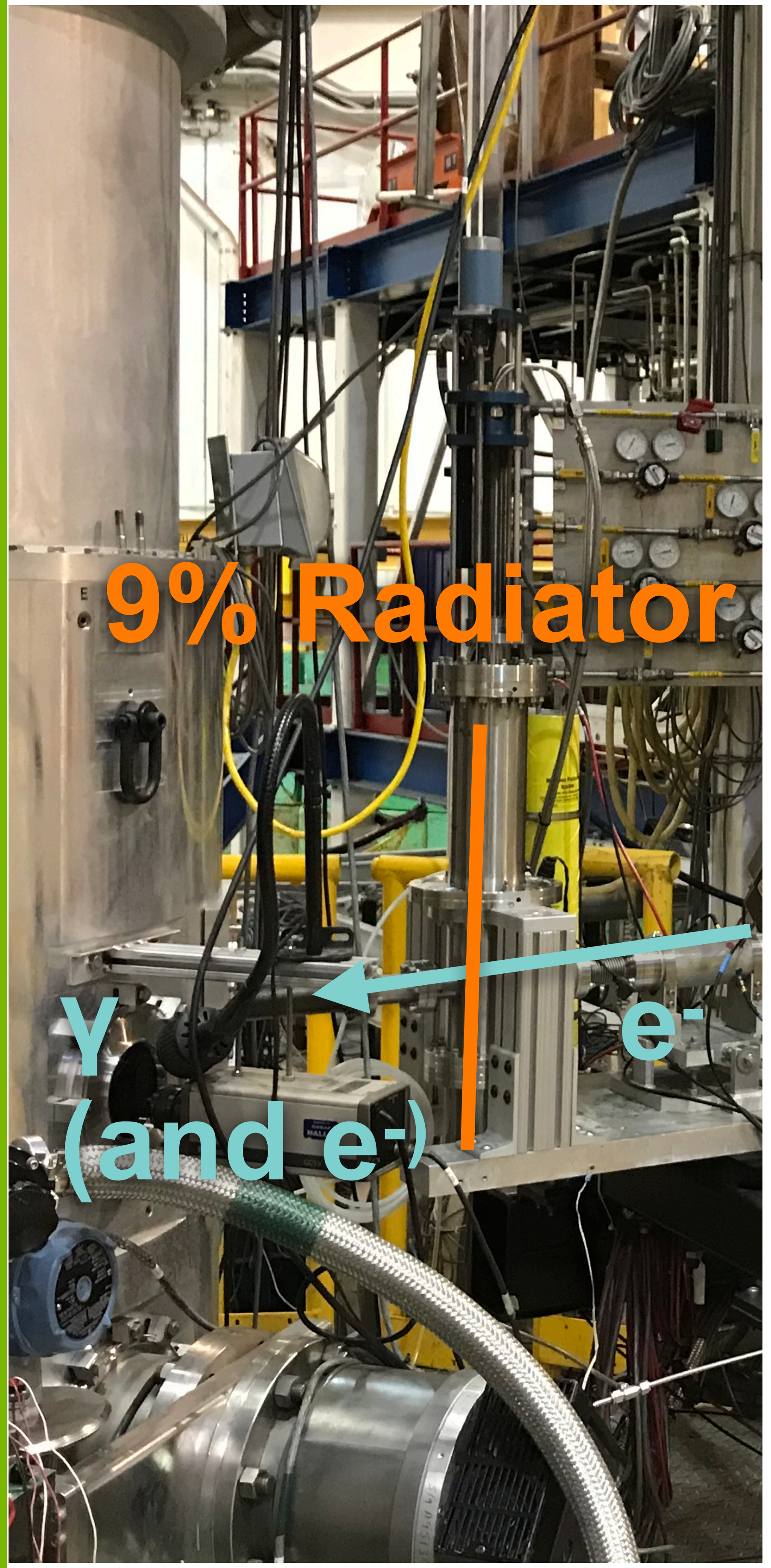
Near-threshold J/ψ photoproduction

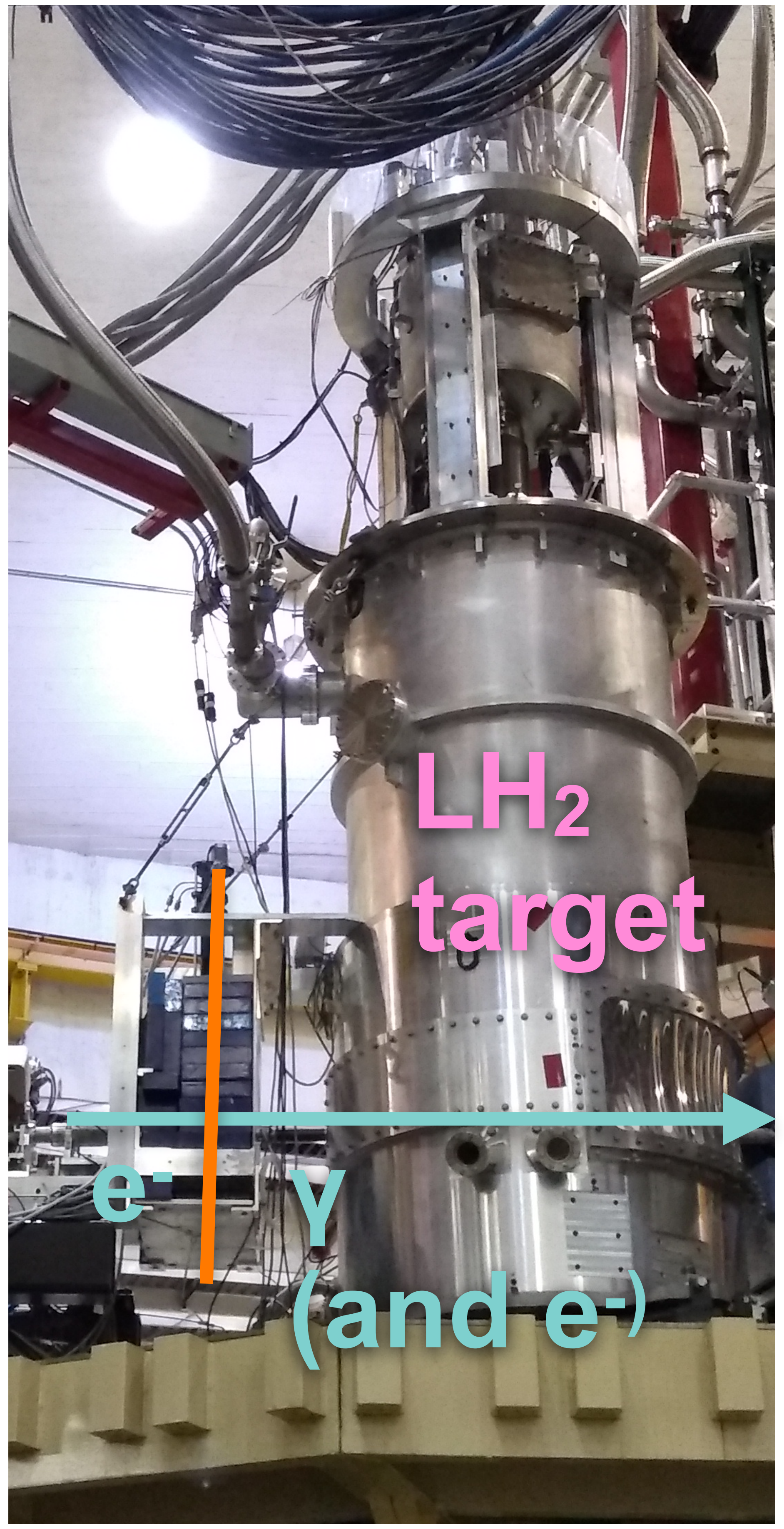
HALL C EXPERIMENT E12-16-007



HALL C EXPERIMENT E12-16-007

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





THE J/Ψ-007 COLLABORATION

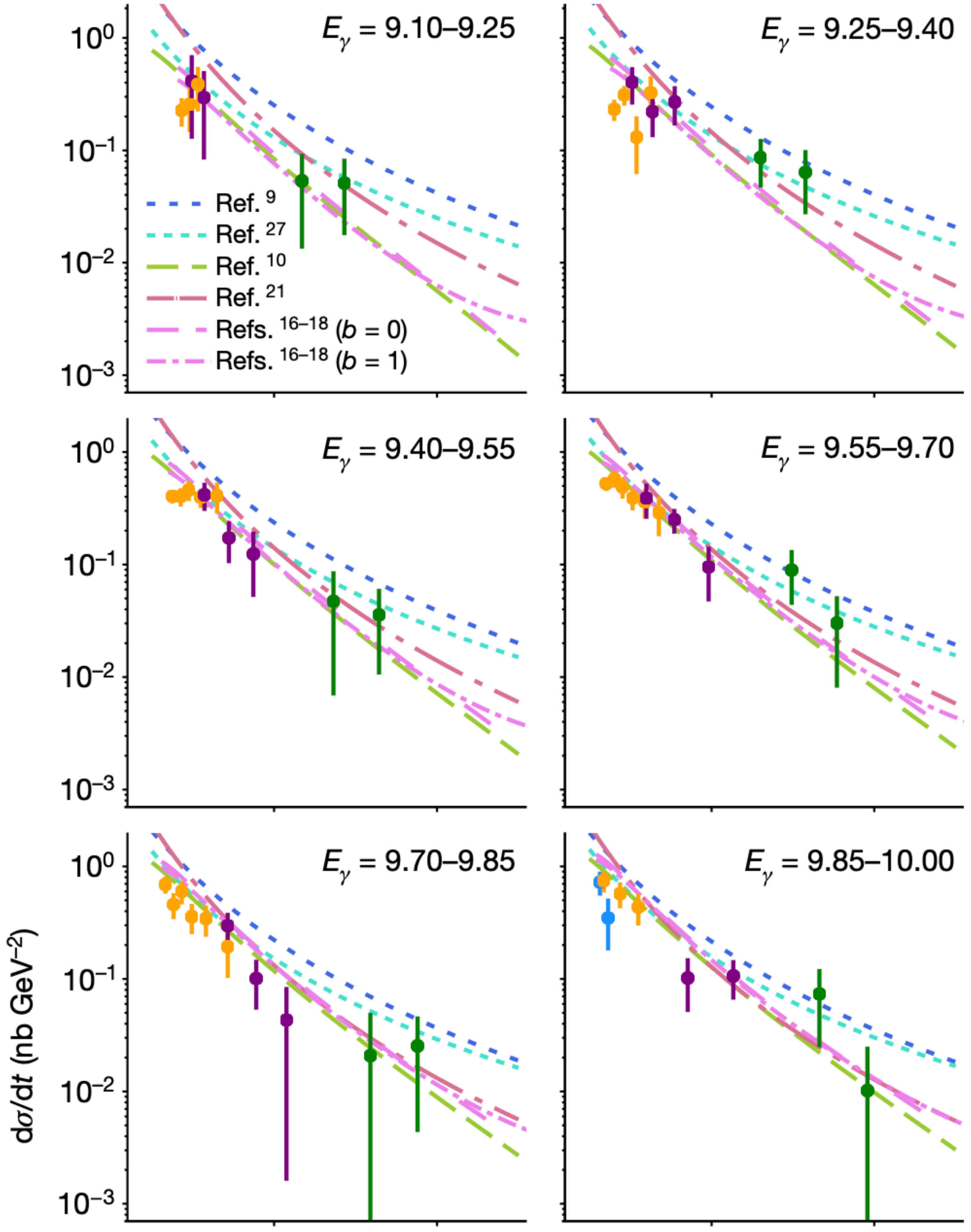
…and many others!

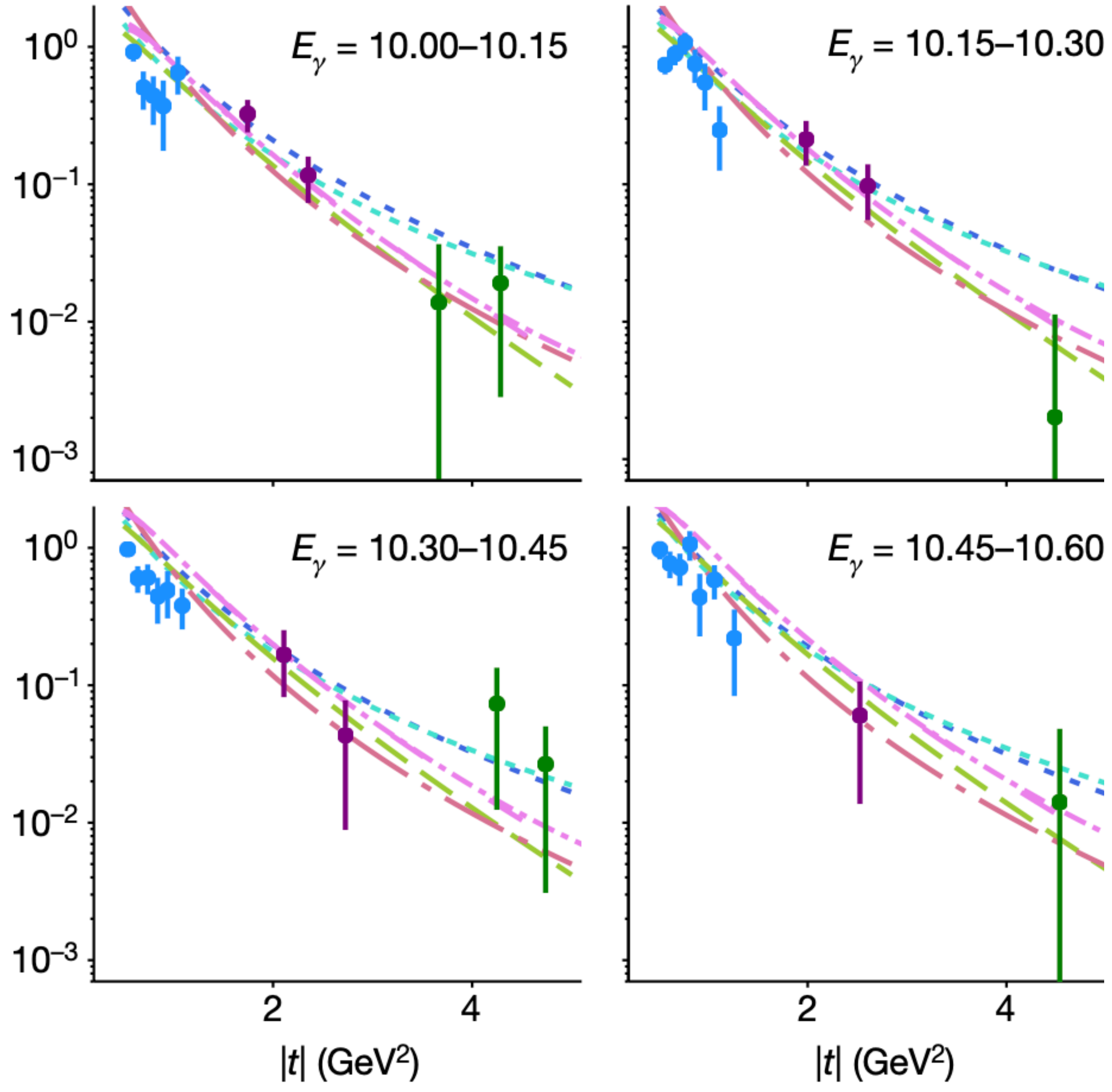
B. Duran[1,2], Z.-E. Meziani[1,2]✉, S. Joosten[1], M. K. Jones[3], S. Prasad[1], C. Peng[1], W. Armstrong[1], H. Atac[2], E. Chudakov[3], H. Bhatt[4], D. Bhetuwal[4], M. Boer[5], A. Camsonne[3], J.-P. Chen[3], M. M. Dalton[3], N. Deokar[2], M. Diefenthaler[3], J. Dunne[4], L. El Fassi[4], E. Fuchey[6], H. Gao[7], D. Gaskell[3], O. Hansen[3], F. Hauenstein[8], D. Higinbotham[3], S. Jia[2], A. Karki[4], C. Keppel[3], P. King[9], H. S. Ko[10], X. Li[7], R. Li[2], D. Mack[3], S. Malace[3], M. McCaughan[3], R. E. McClellan[11], R. Michaels[3], D. Meekins[3], Michael Paolone[2], L. Pentchev[3], E. Pooser[3], A. Puckett[6], R. Radloff[9], M. Rehfuss[2], P. E. Reimer[1], S. Riordan[1], B. Sawatzky[3], A. Smith[7], N. Sparveris[2], H. Szumila-Vance[3], S. Wood[3], J. Xie[1], Z. Ye[1], C. Yero[8] & Z. Zhao[7]

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

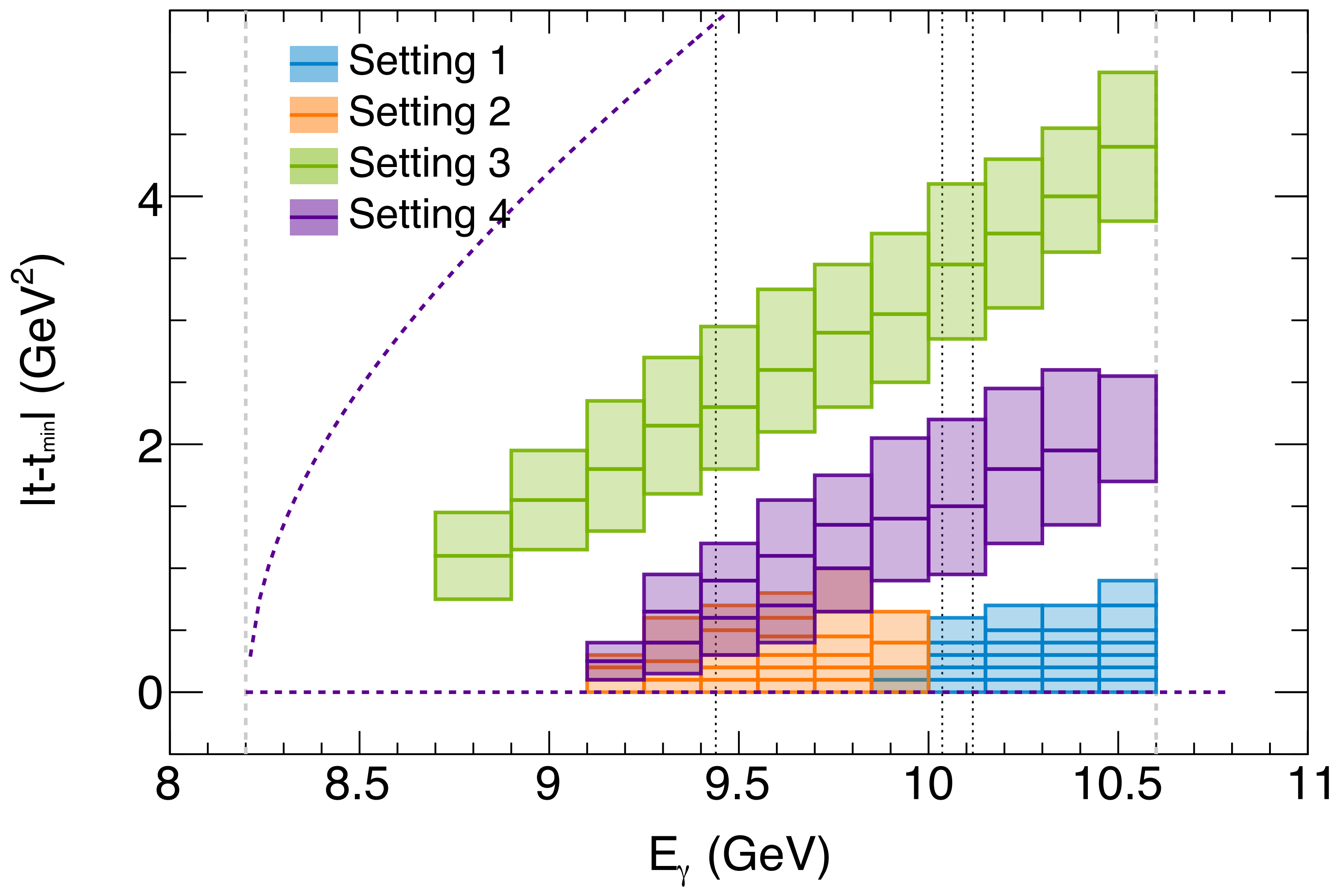
First results published in Nature!

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

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)

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

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

GPD Model

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

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

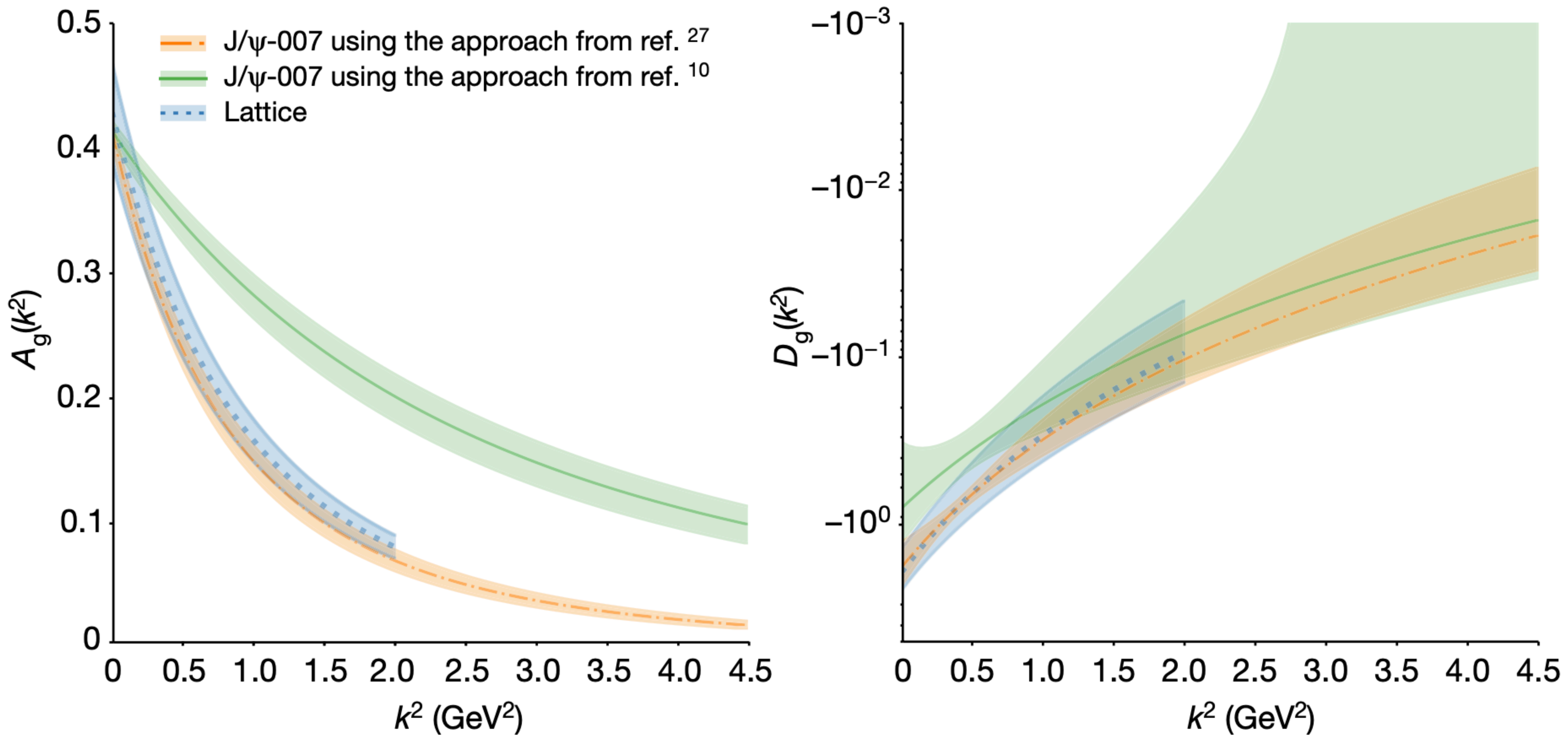
Assume $\xi \sim 1$ (it is less than 0.5 for most of the experimental data)

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

007 J/ψ

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).

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

007[J/ψ]

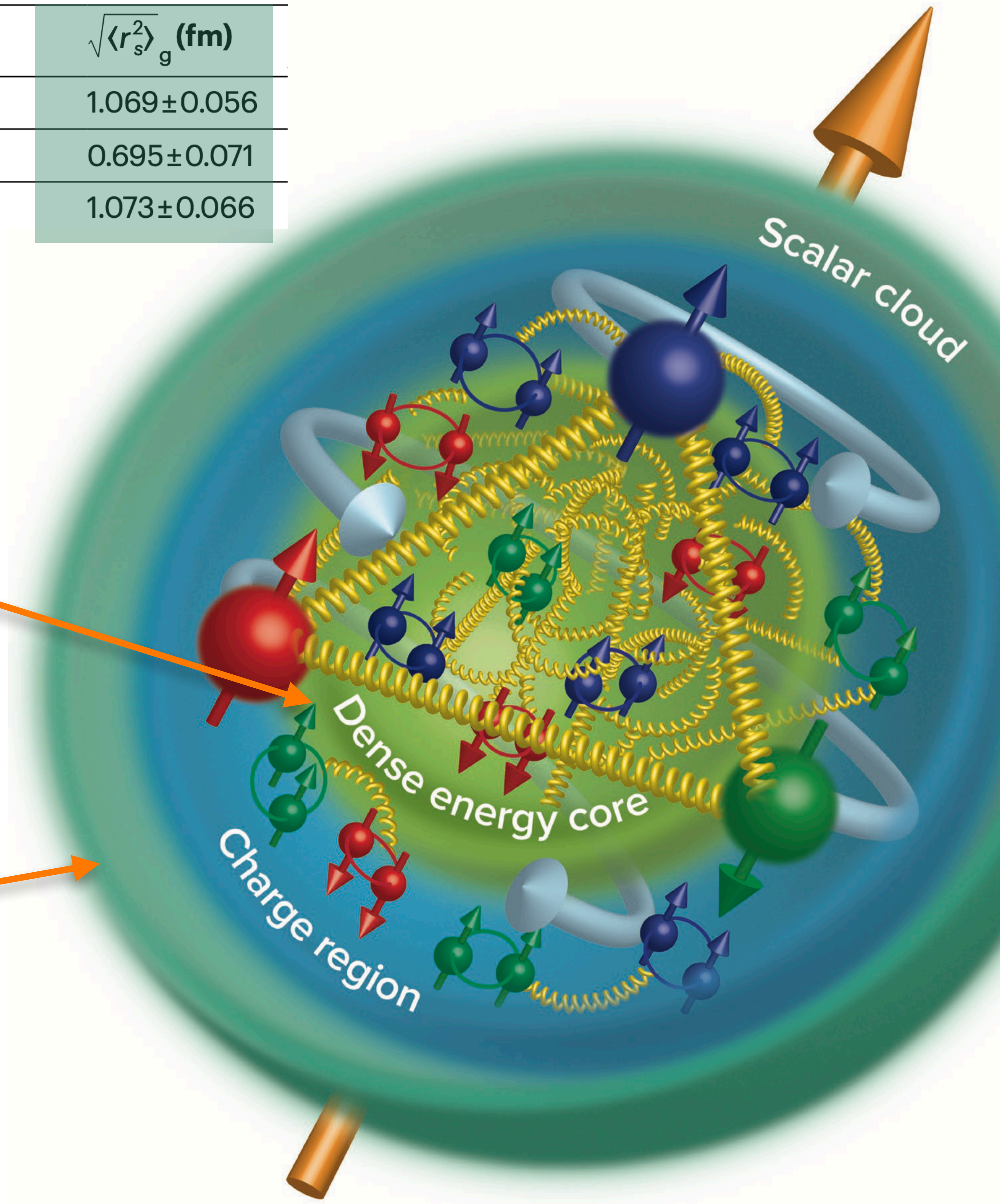
THE PROTON IN THREE REGIONS

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

Theoretical approach	χ^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

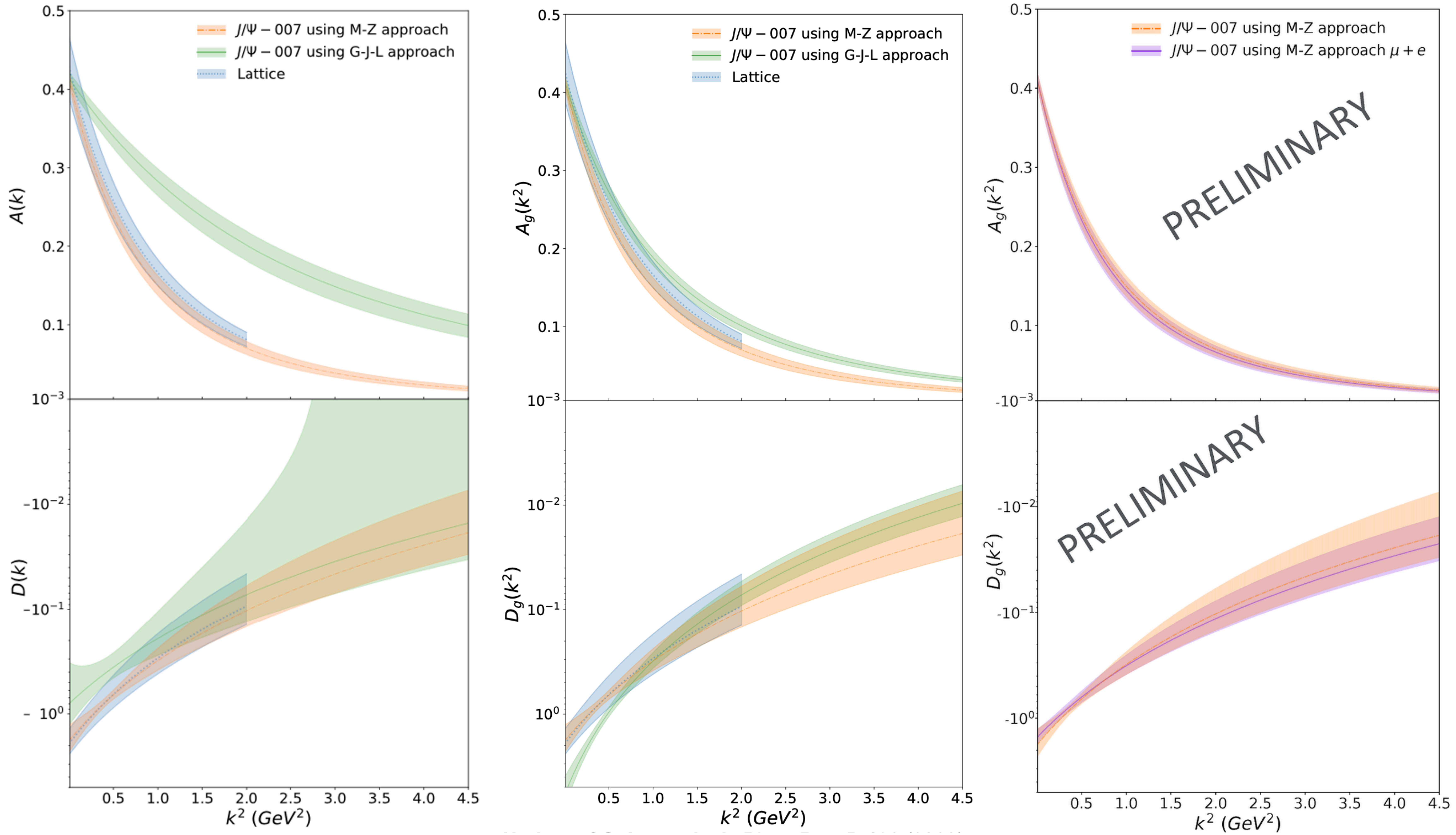
The proton's mass radius seems substantially smaller than its charge

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



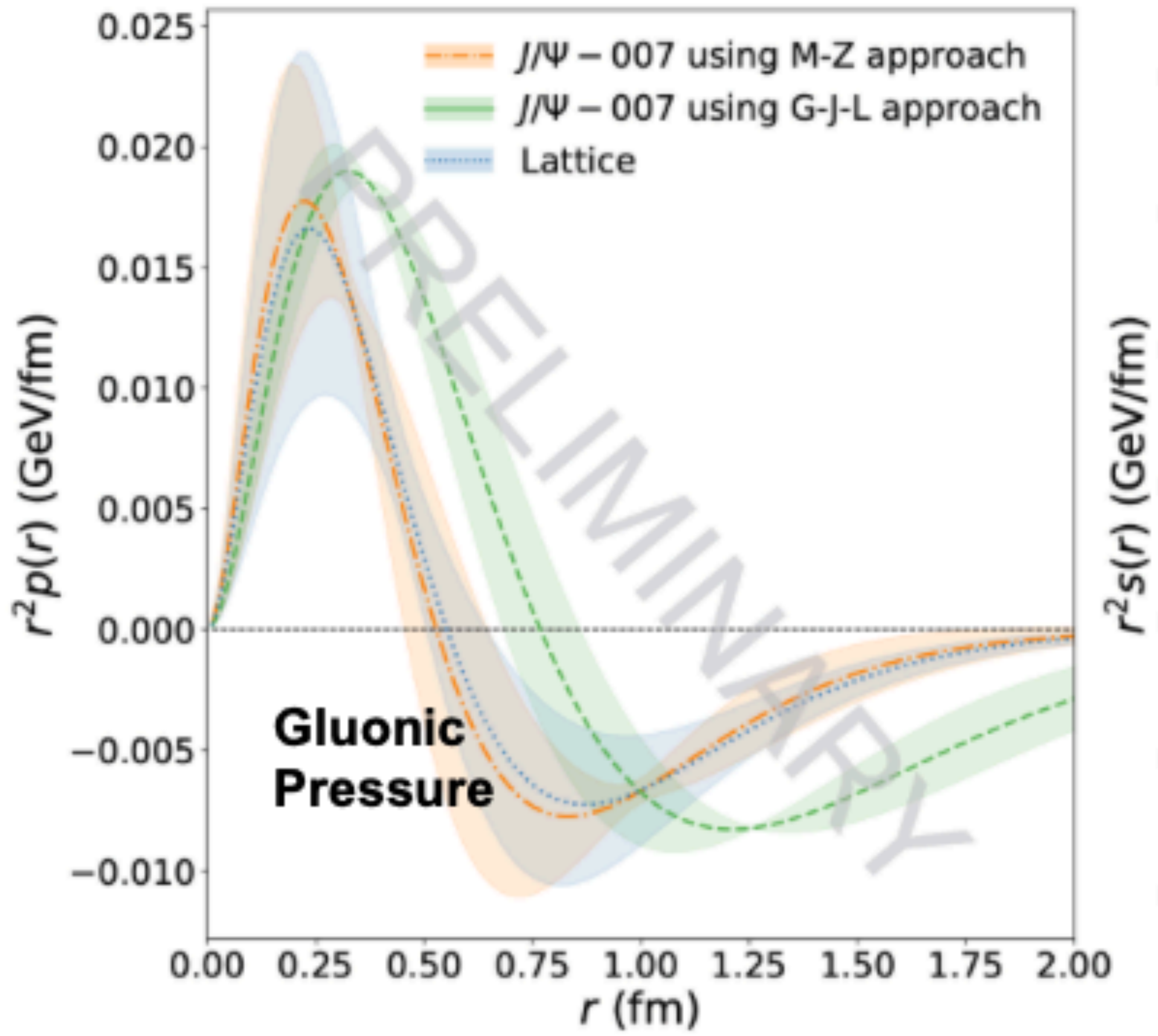
- Analysis with the muons decay channel results , doubling the statistics

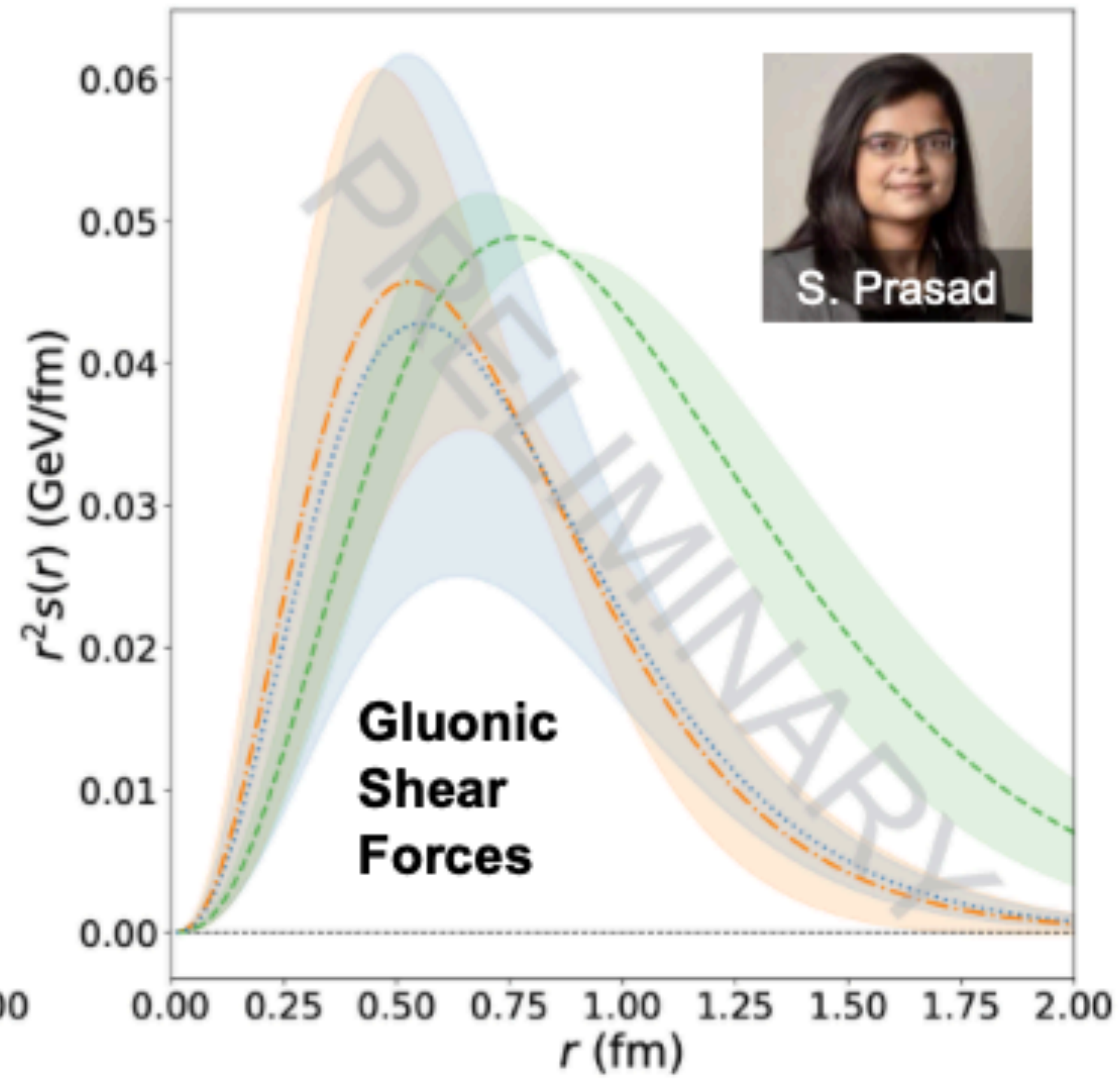
- Consistent with the electron results.

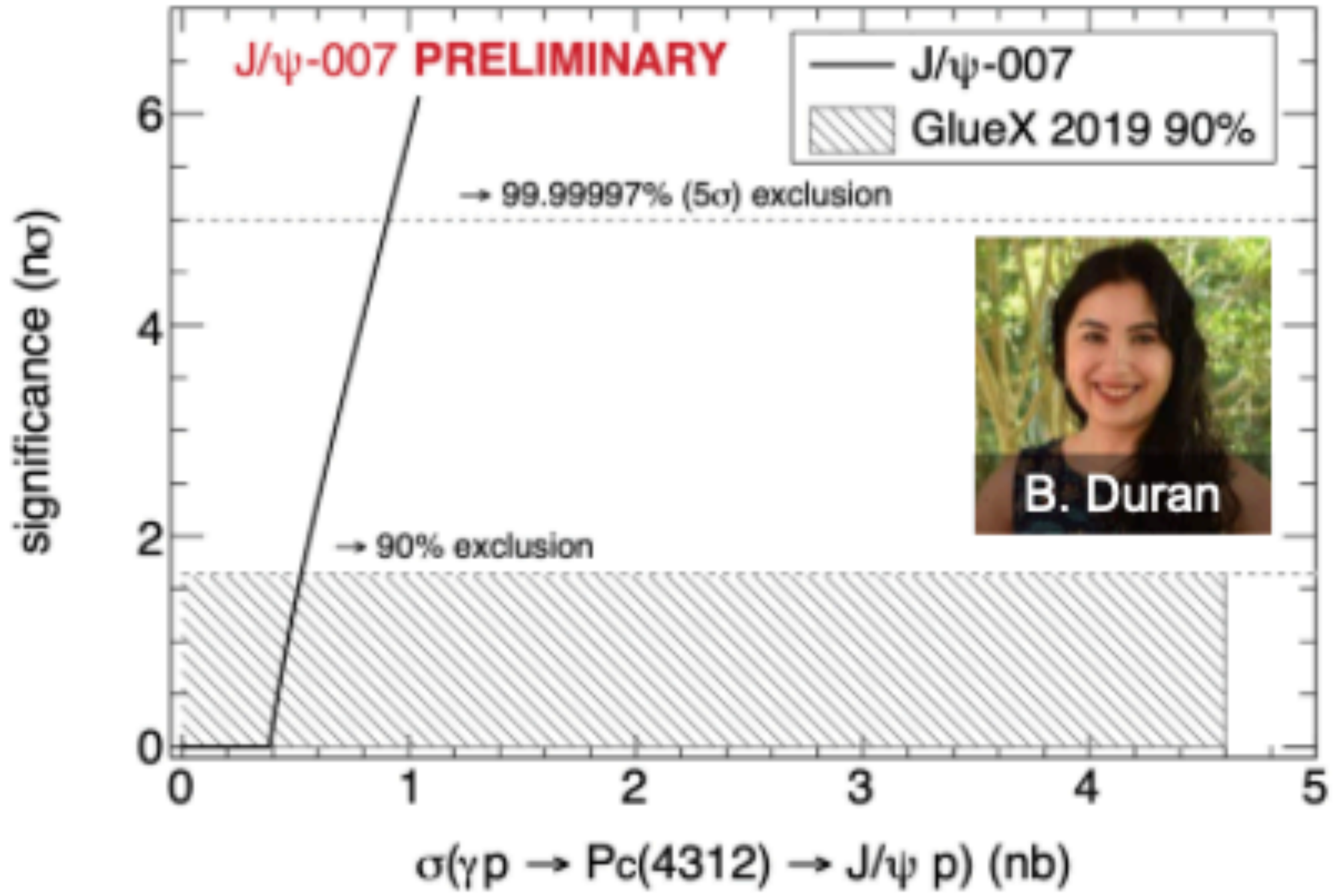
- Largest impact on the *C(t)* form factor with improved precision

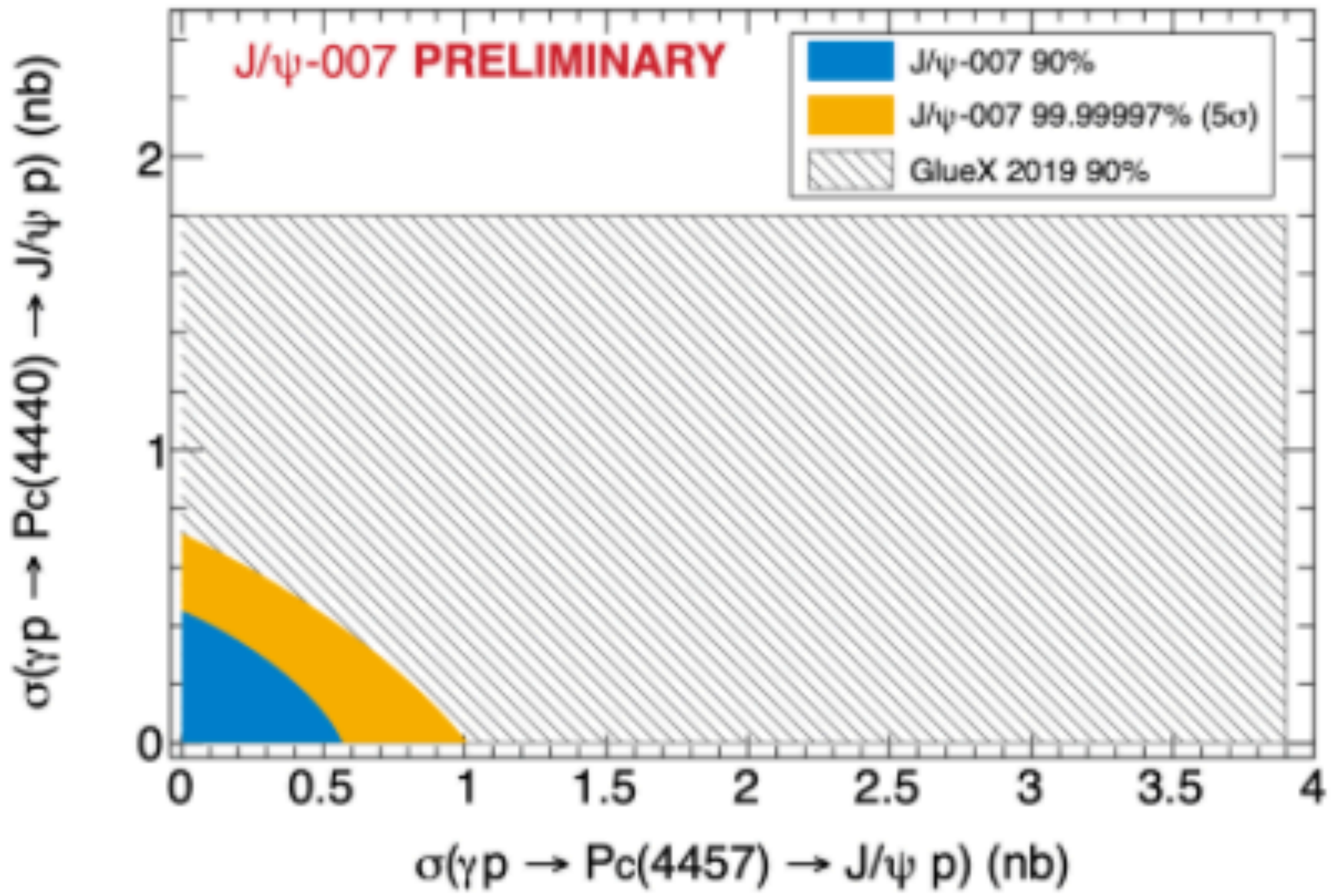
Upcoming J/ψ-007 Results

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



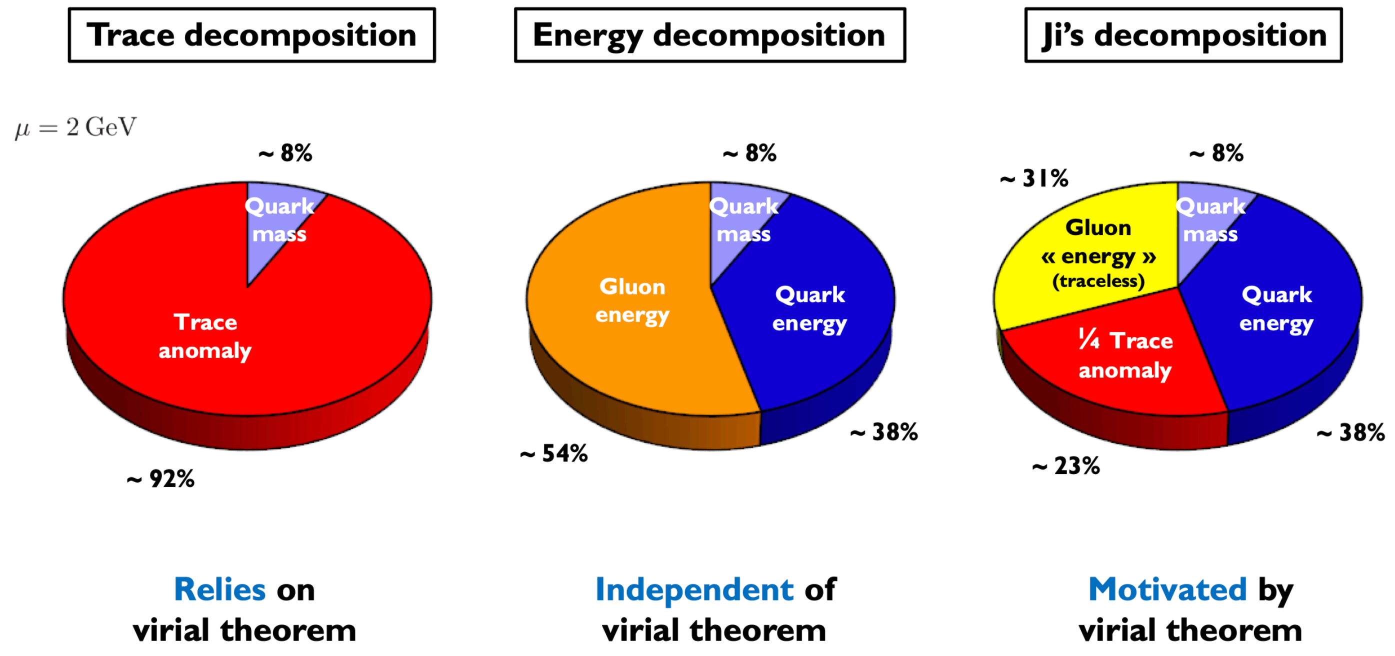




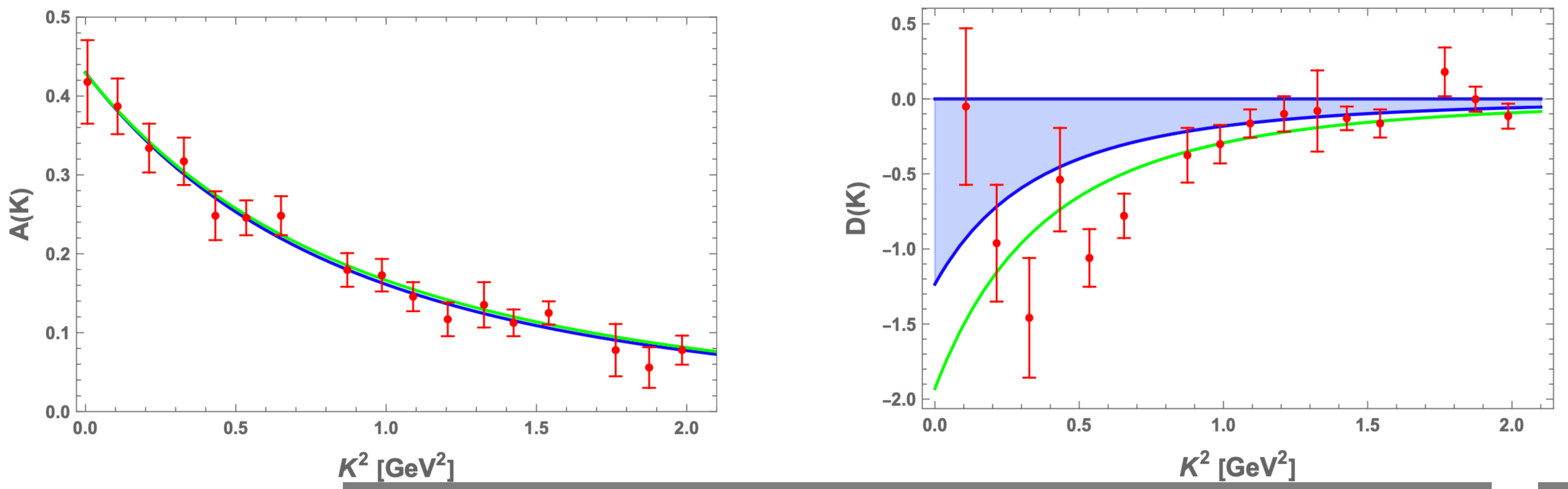


Expect more results soon: Finalizing systematics on the di-muon decay channel, preparing two new manuscripts: on the 2D cross section, and on the LHCb hidden-charm pentaquark

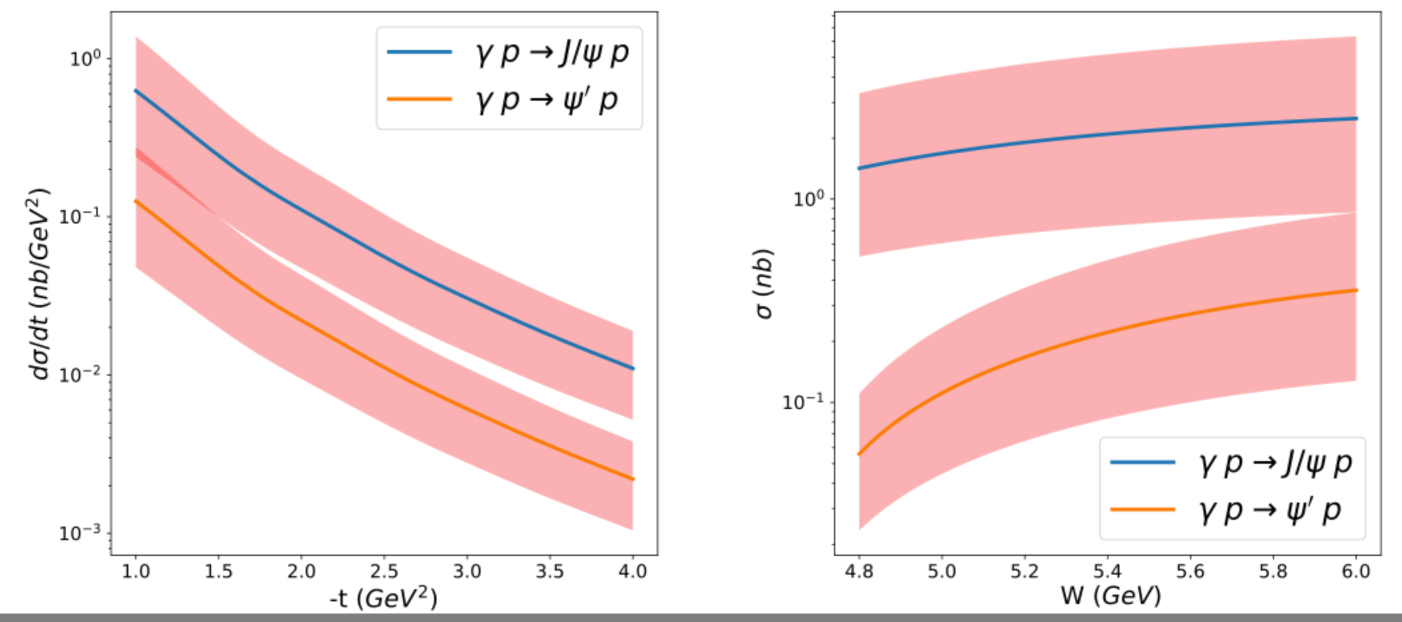
PROMINENT RECENT DEVELOPMENTS



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

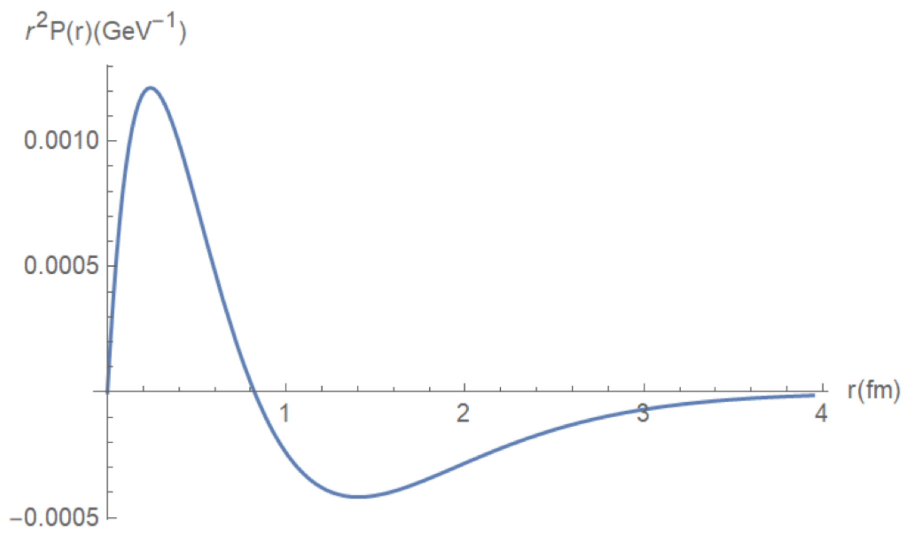


Proton gravitational form factors holographic QCD compared with Lattice, K. Mamo & I. Zahed (2022)

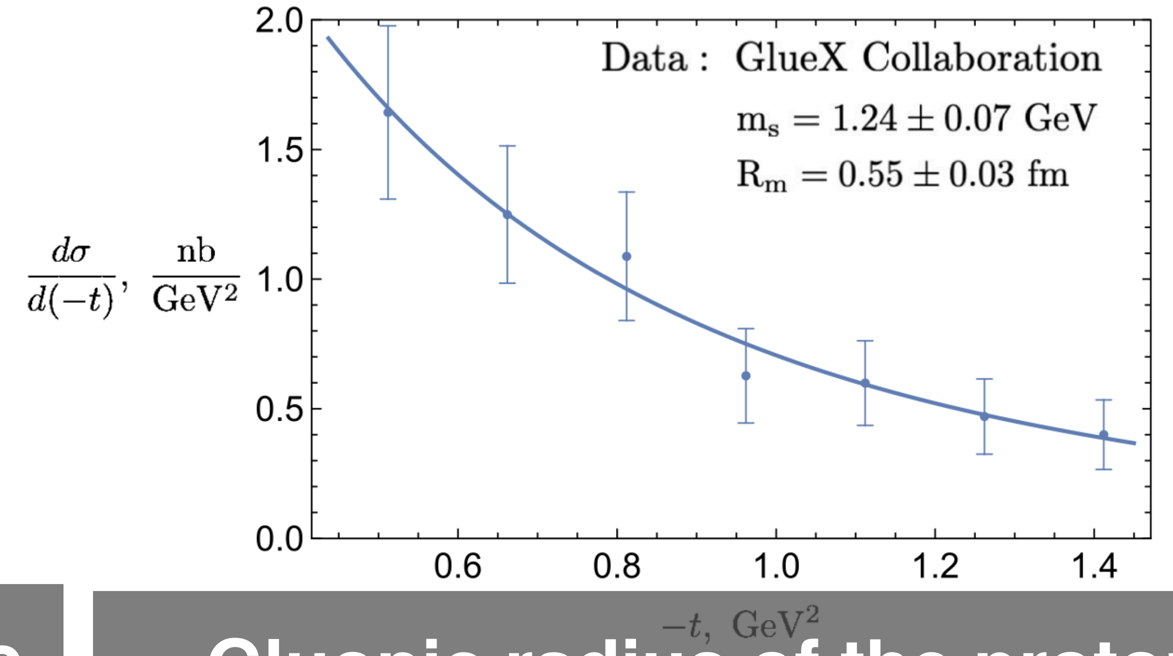


Near-threshold heavy quarkonium production at large momentum transfer, P. Sun, X-B. Tong, F. Yuan (PRD 2022)

- 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)

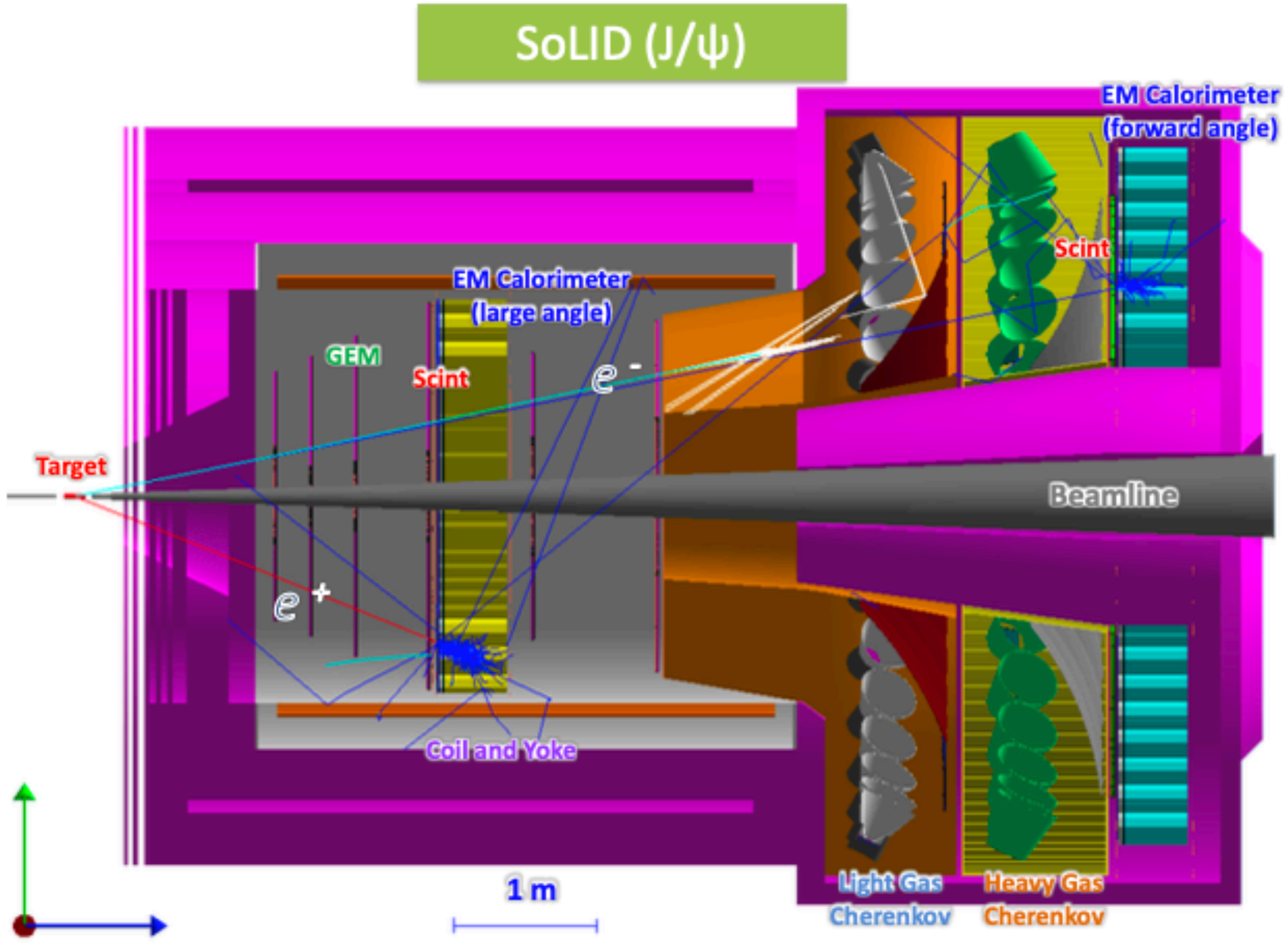


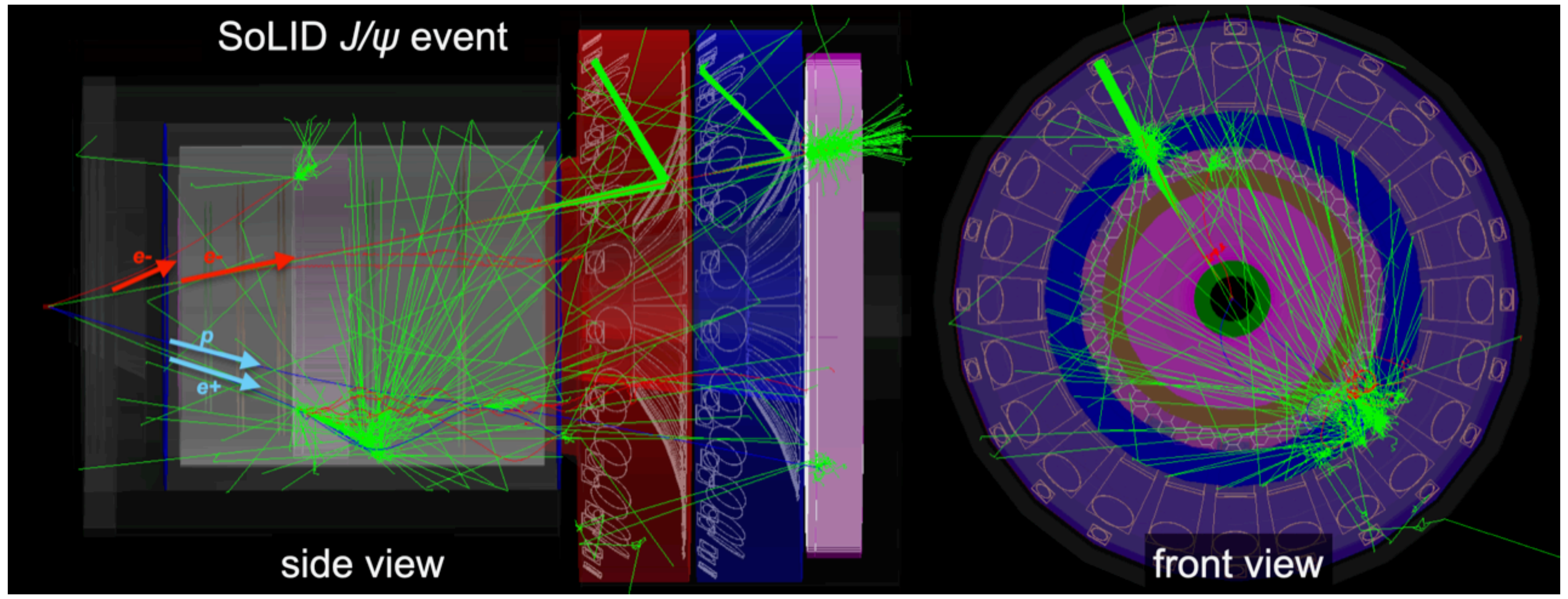
Gluonic radius of the proton based on 1D GlueX results, D. Kharzeev (PRD 2021)

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**: $43.2 ab^{-1}$
- **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

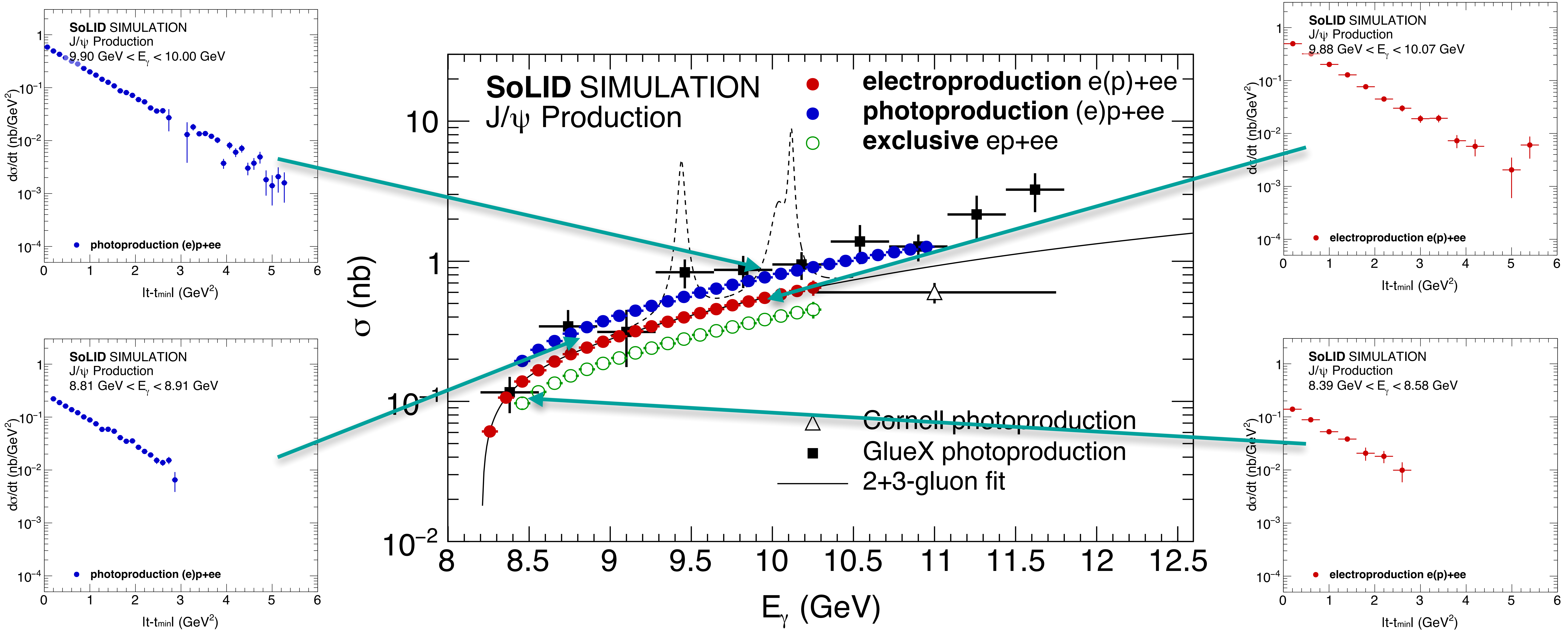




SOLENOIDAL LARGE INTENSITY DEVICE

SOLID-J/Ψ PROJECTIONS

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



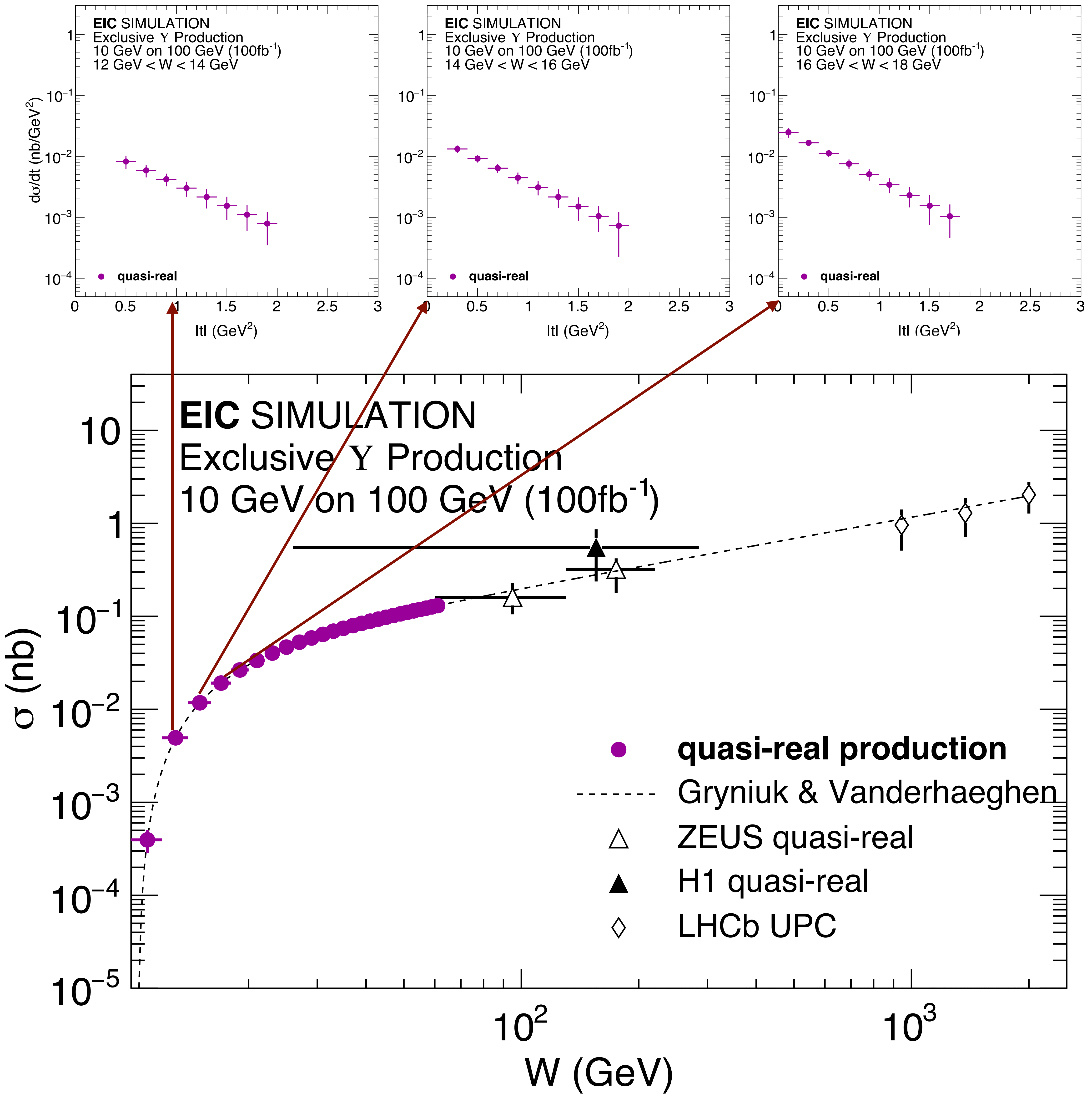
S. Joosten

S. Joosten, Z.-E. Meziani, PoS QCDEV2017 017 (2018)
O. Grynyuk, S. Joosten, Z.-E. Meziani, M. Vanderhaeghen PRD 102, 014016 (2020)

Y(1S) NEAR THRESHOLD

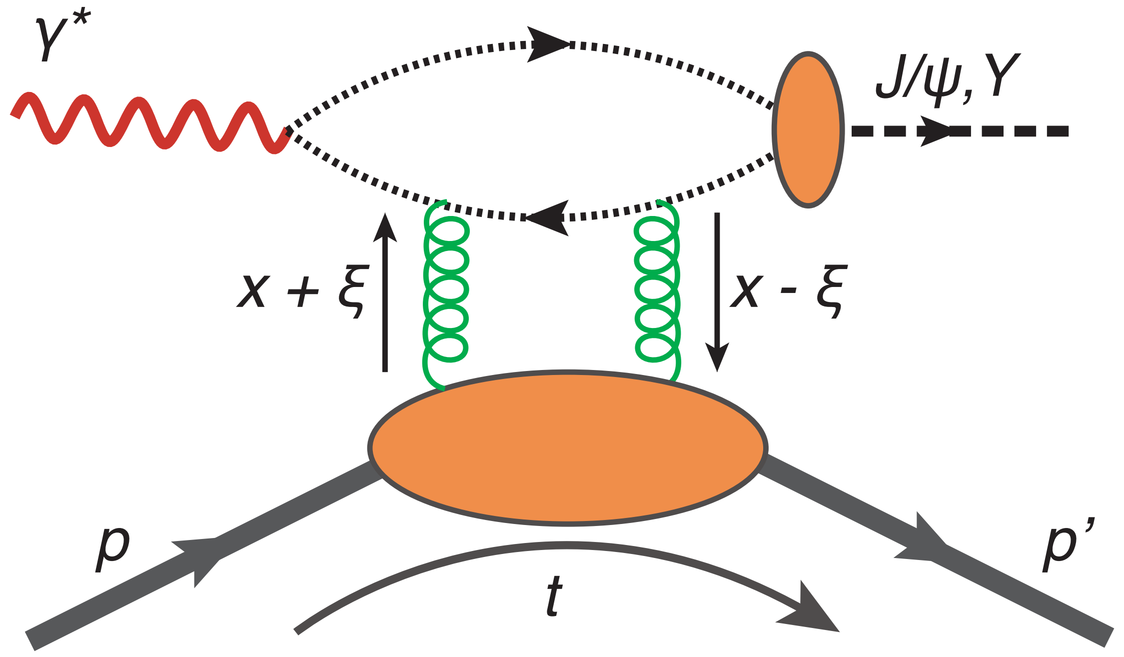
Y(1S) with the ePIC detector

- Y(1S) at EIC trades statistical precision of J/ψ at SoLID for lower theoretical uncertainties and extra channel to study universality.
- Large Q^2 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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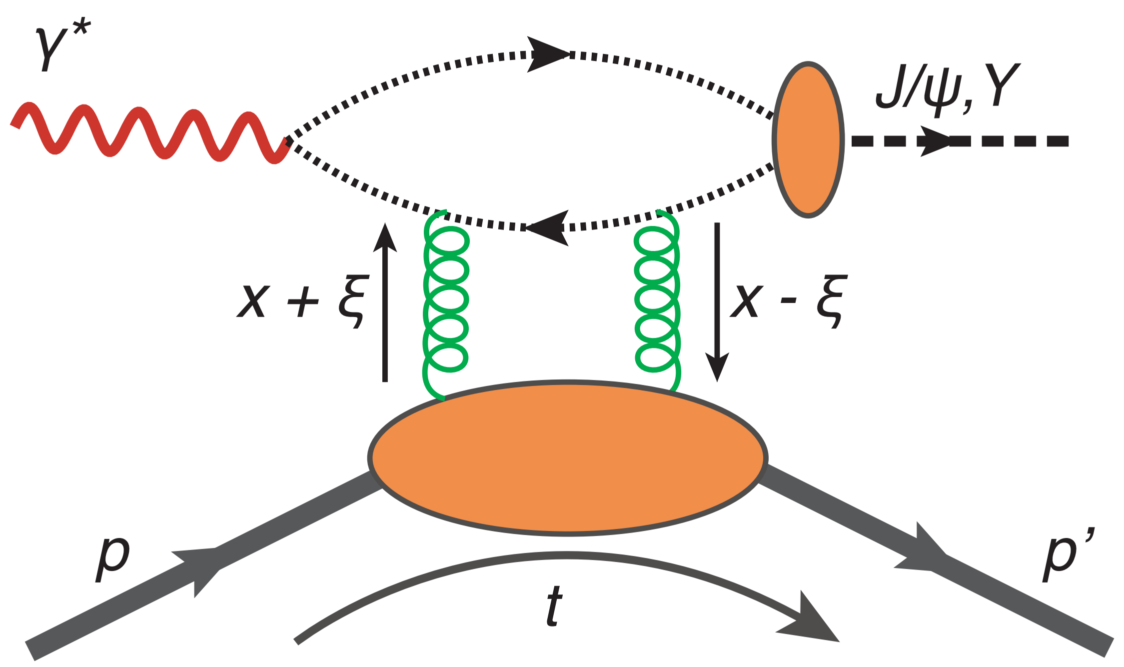

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average unpolarized gluon GPD related to *t*-dependent cross section (LO)

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

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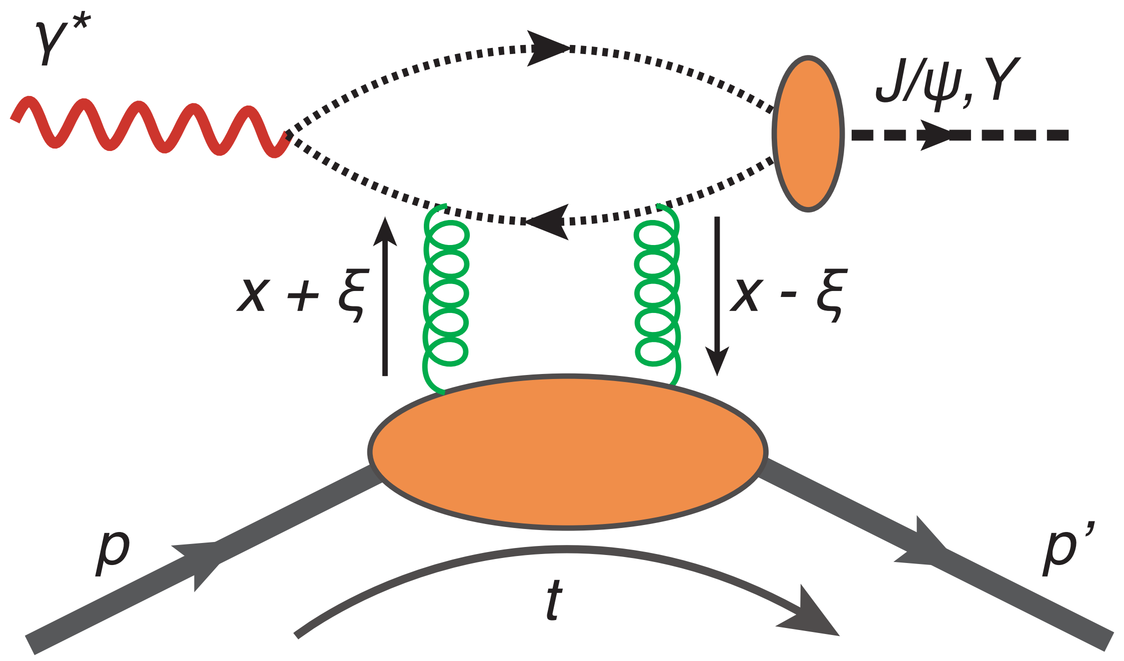

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→

Fourier transform:
3-D transverse gluonic density

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

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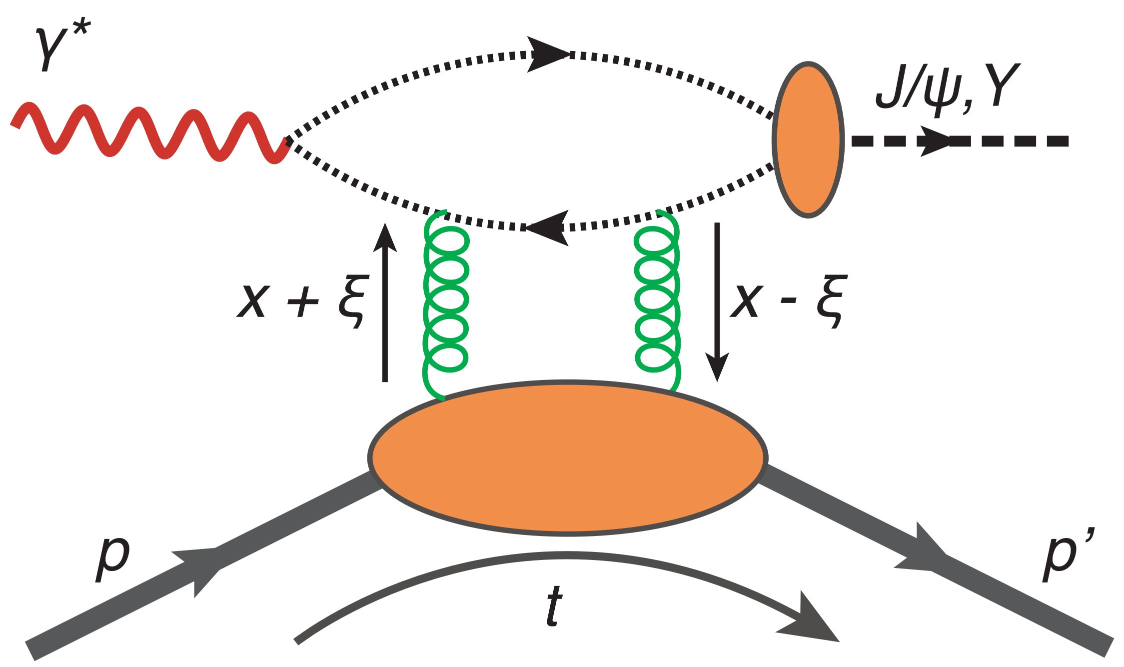

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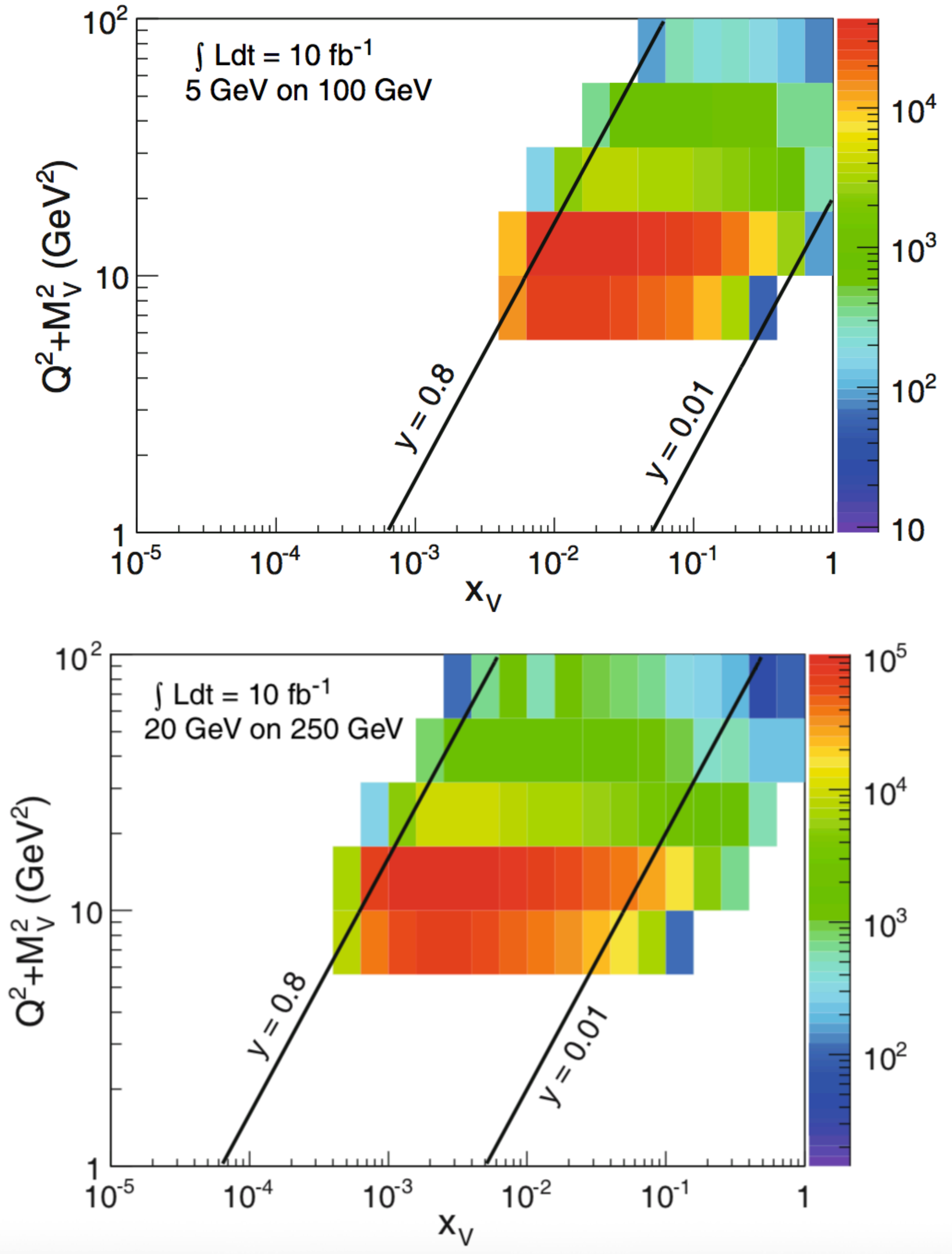
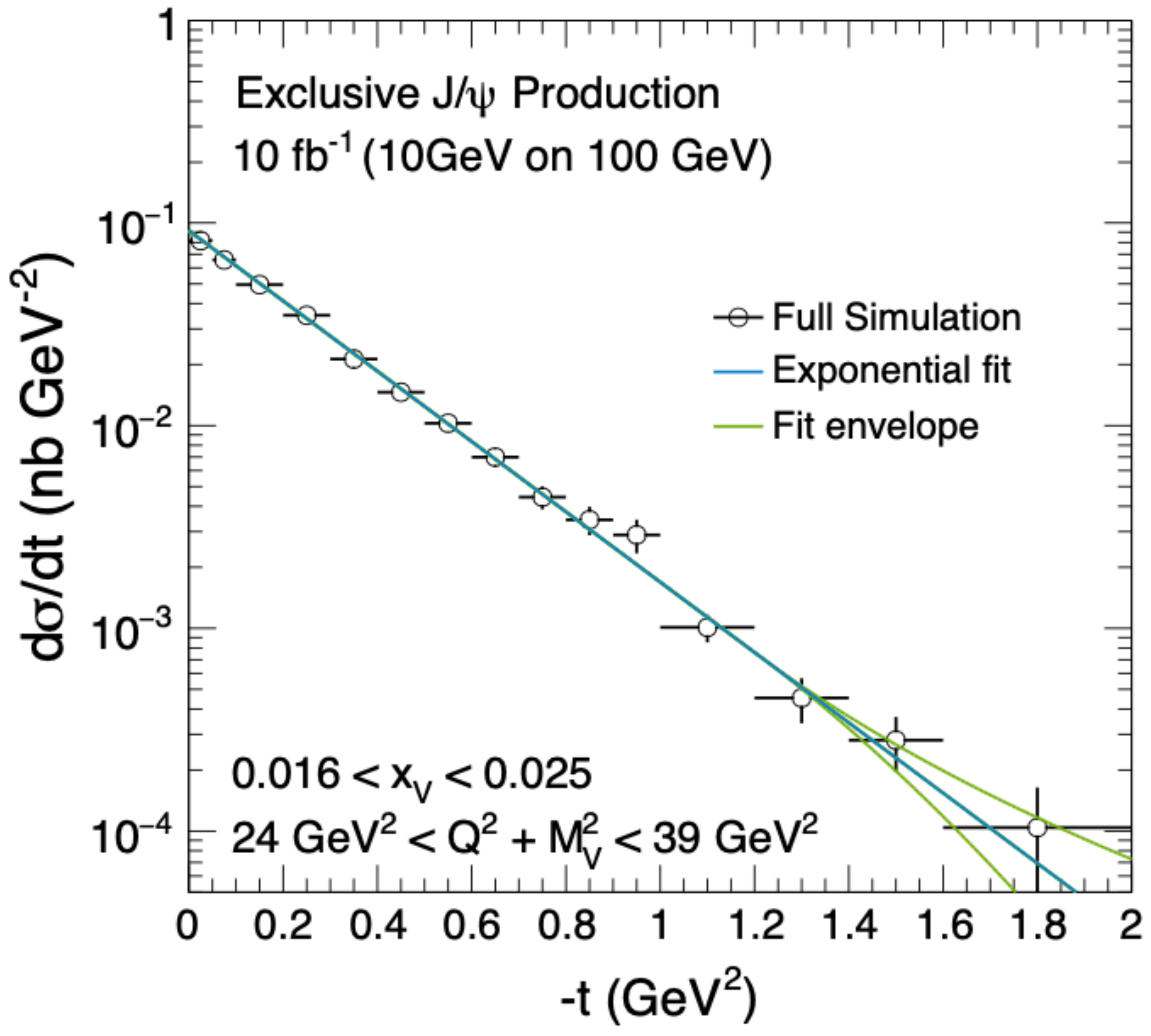
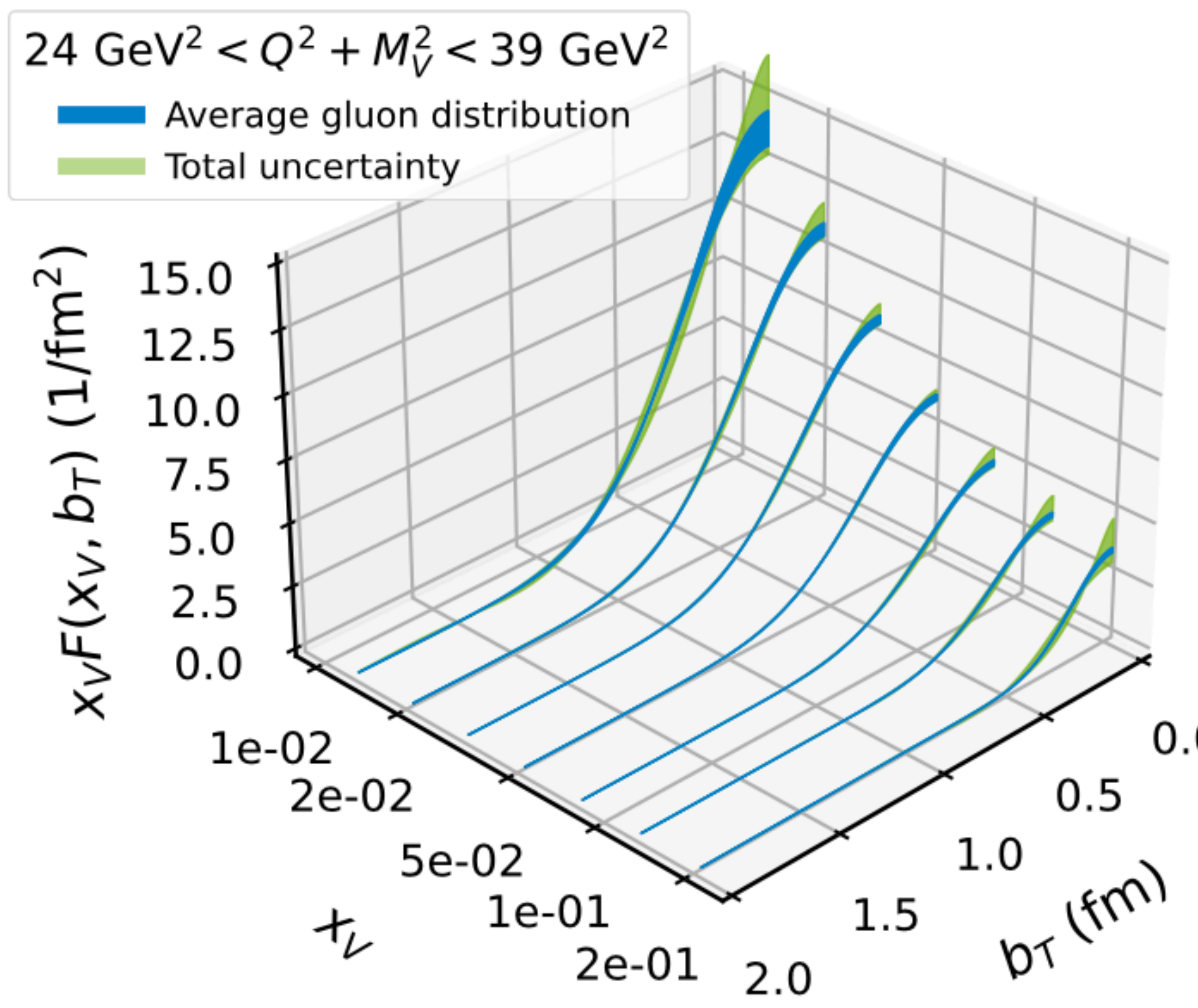
3-D GPDs can be related to 2-D Gravitational Form Factors

Eur.Phys.J.A 52 (2016) 9, 268
JINST 17 (2022) 10, P10019

GLUON TOMOGRAPHY WITH J/Ψ







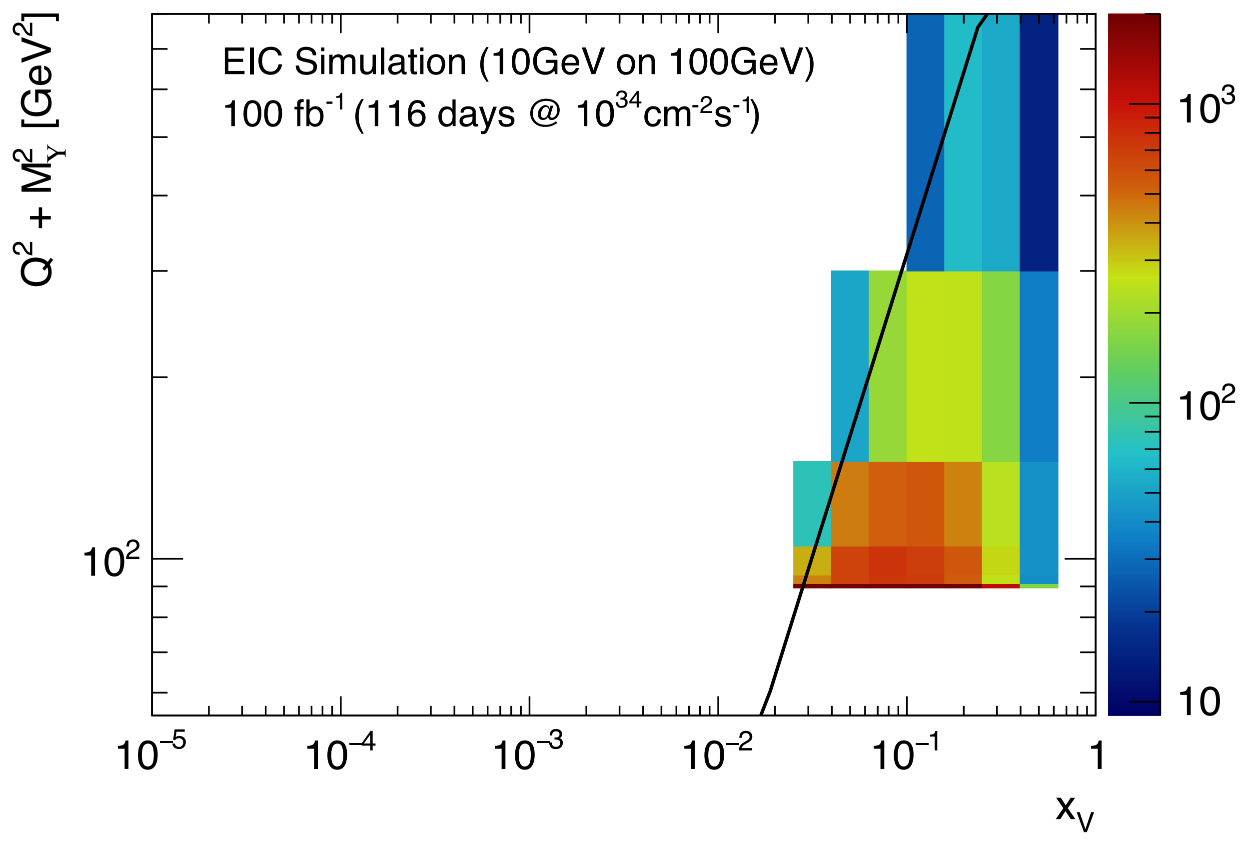
***t*-spectra** → **Normalized average gluon density**

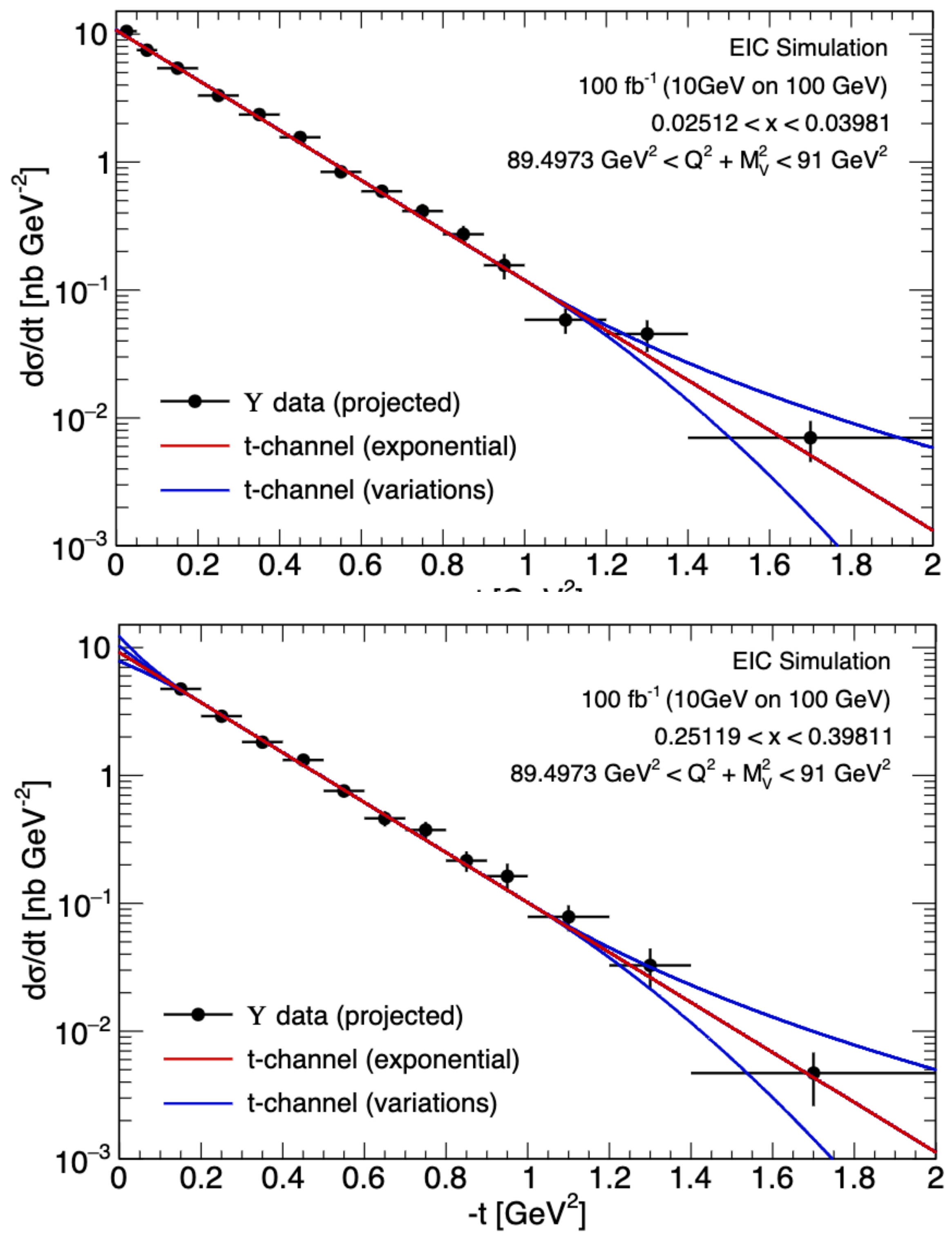
Only possible at an EIC:
from the valence region
deep into the sea!

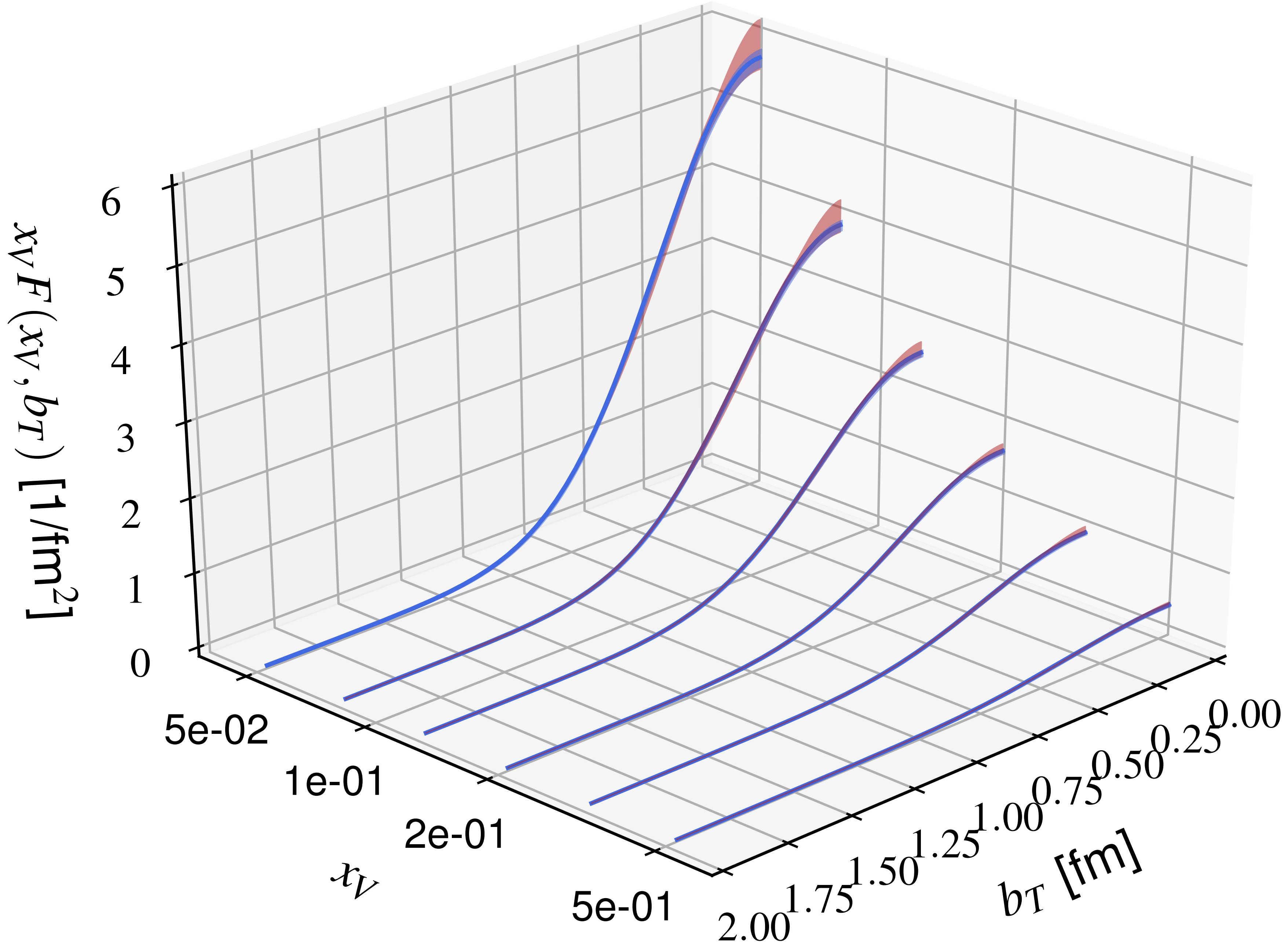
Same can be done with Y(1S) at EIC!

S. Joosten, Z.-E. Meziani, PoS QCDEV2017 017 (2018)

GLUON TOMOGRAPHY WITH Υ(1S)







Average gluon density:

t-spectra

1 **year** at peak luminosity

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

CONCLUSION

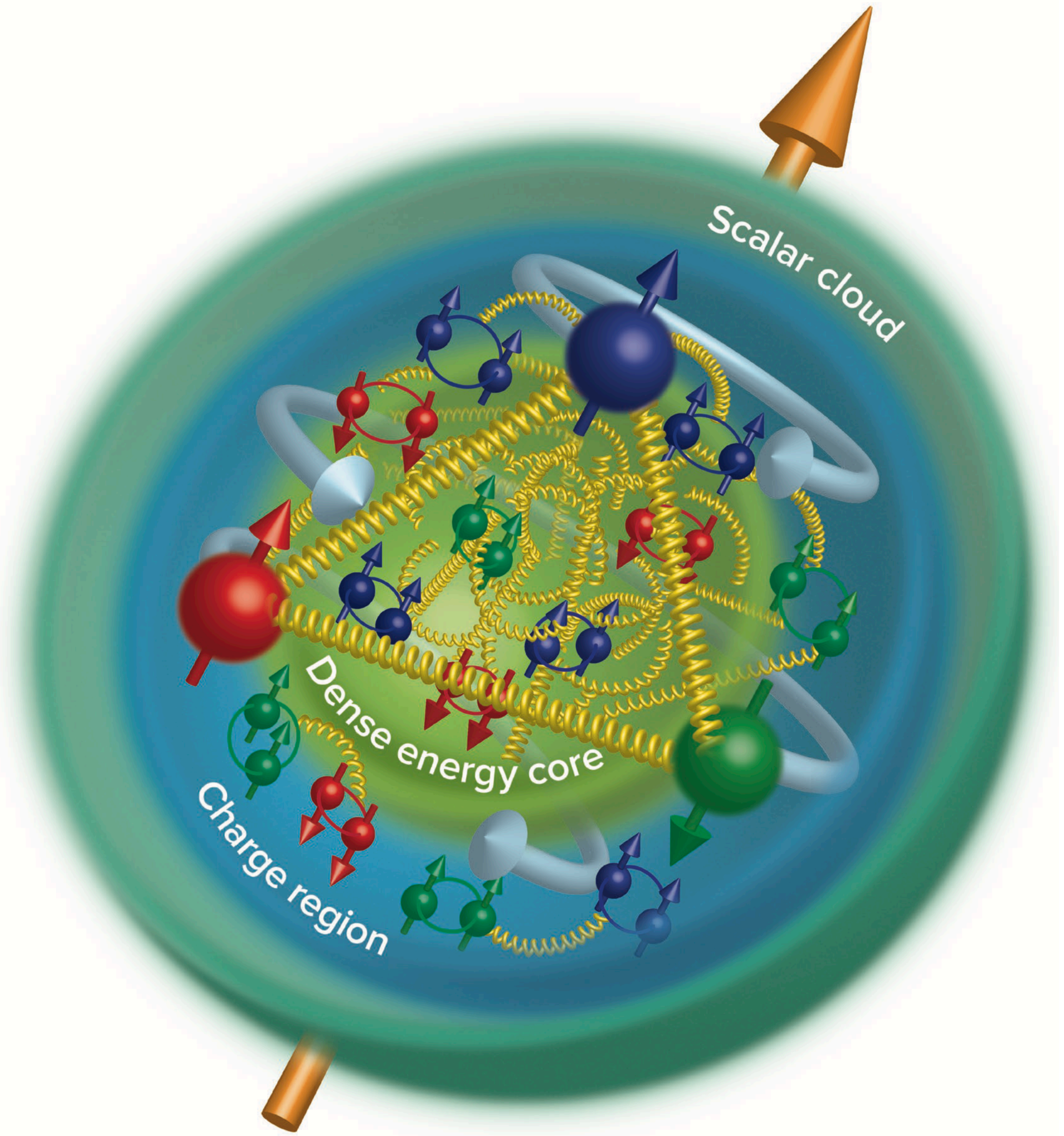
The JLab 12-GeV program has delivered important first results on near-threshold J/ψ production from GlueX and Hall C (J/ψ-007)

- A new window on the gluonic structure of the proton
- Does the proton 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.

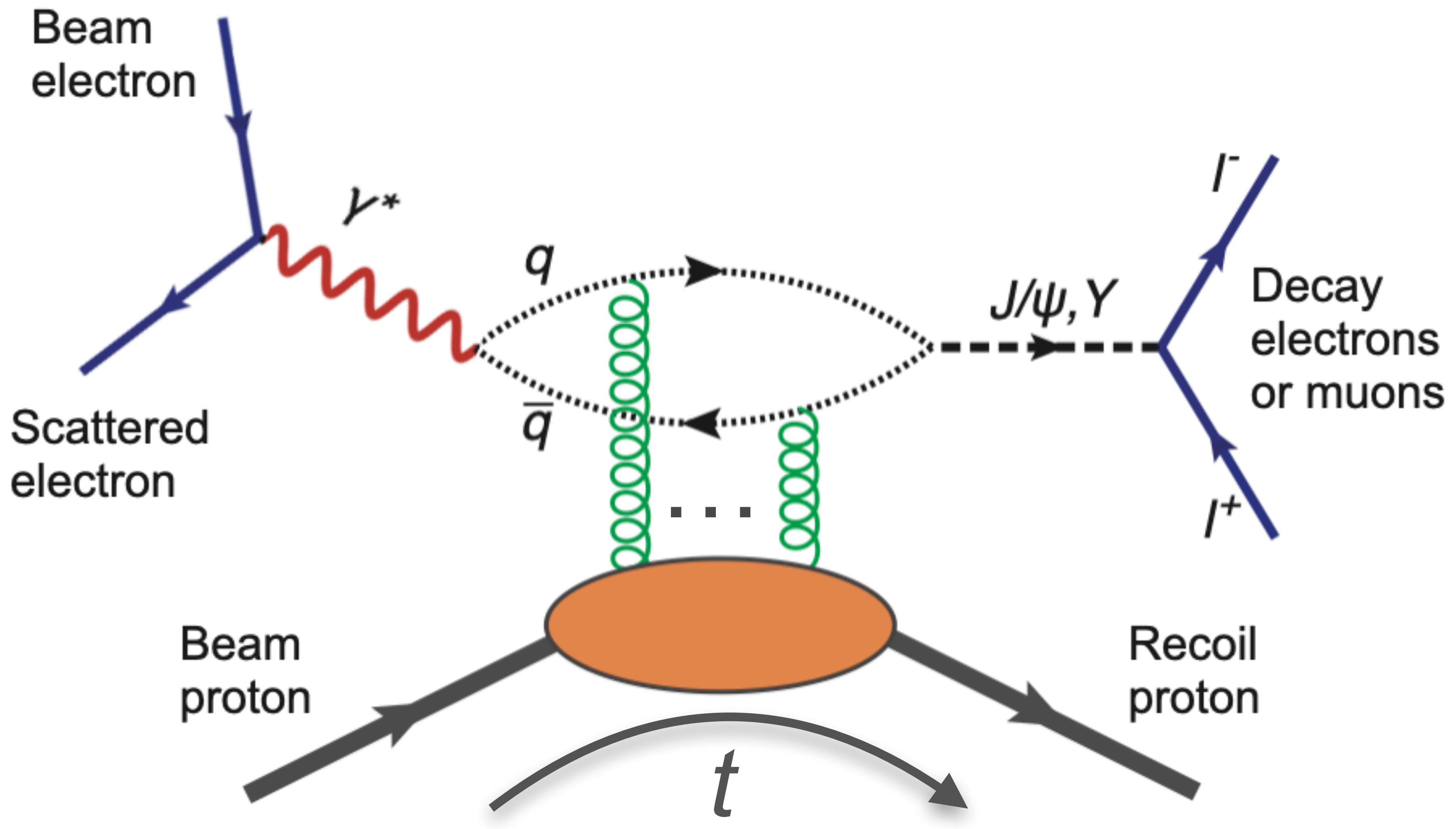
The mass structure of the nucleons and nuclei is a rapidly evolving topic, reaching from Jefferson Lab to the EIC

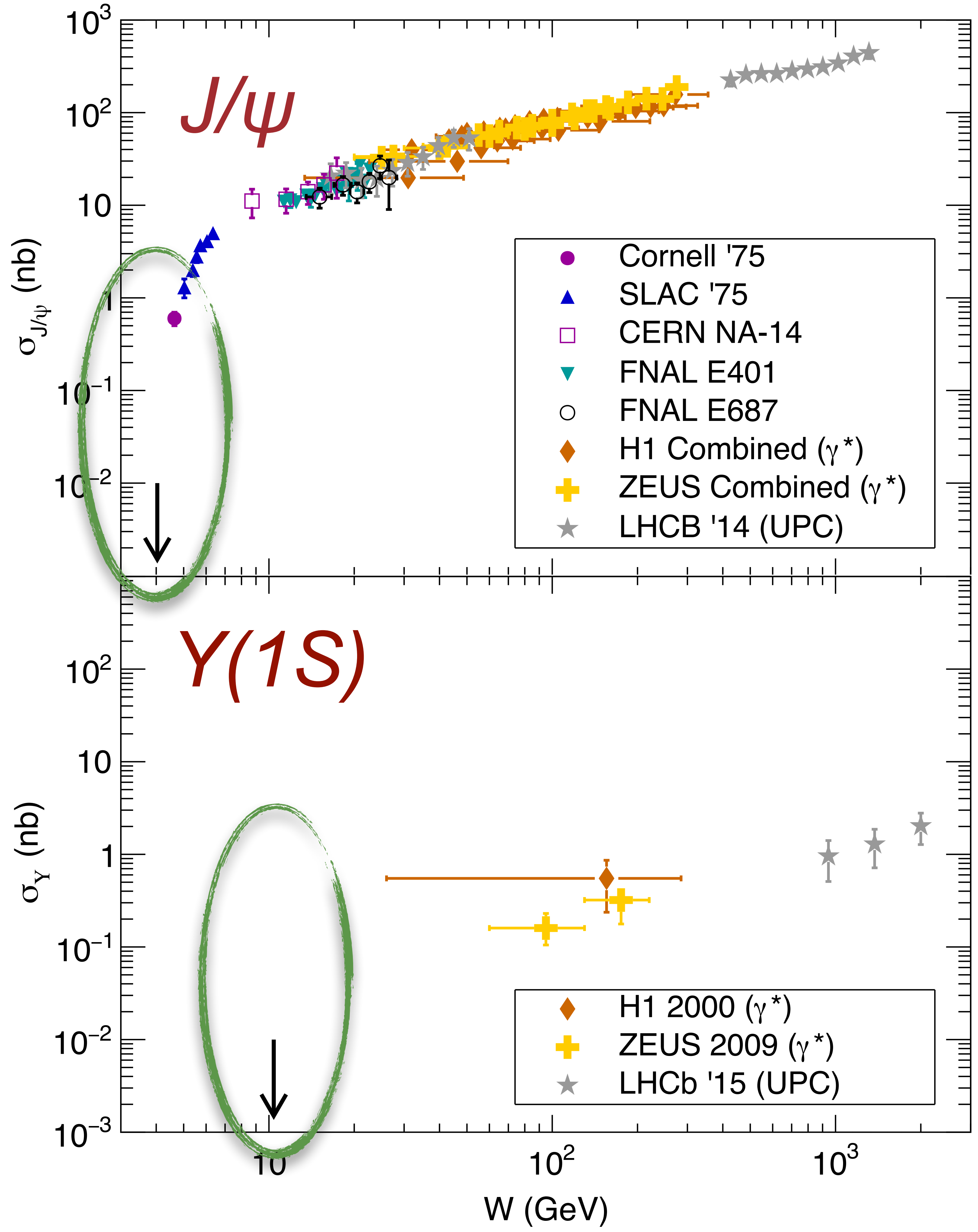


QUESTIONS?

WHAT DID WE KNOW BEFORE 12 GEV AT JLAB?

Exclusive quarkonium photoproduction





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

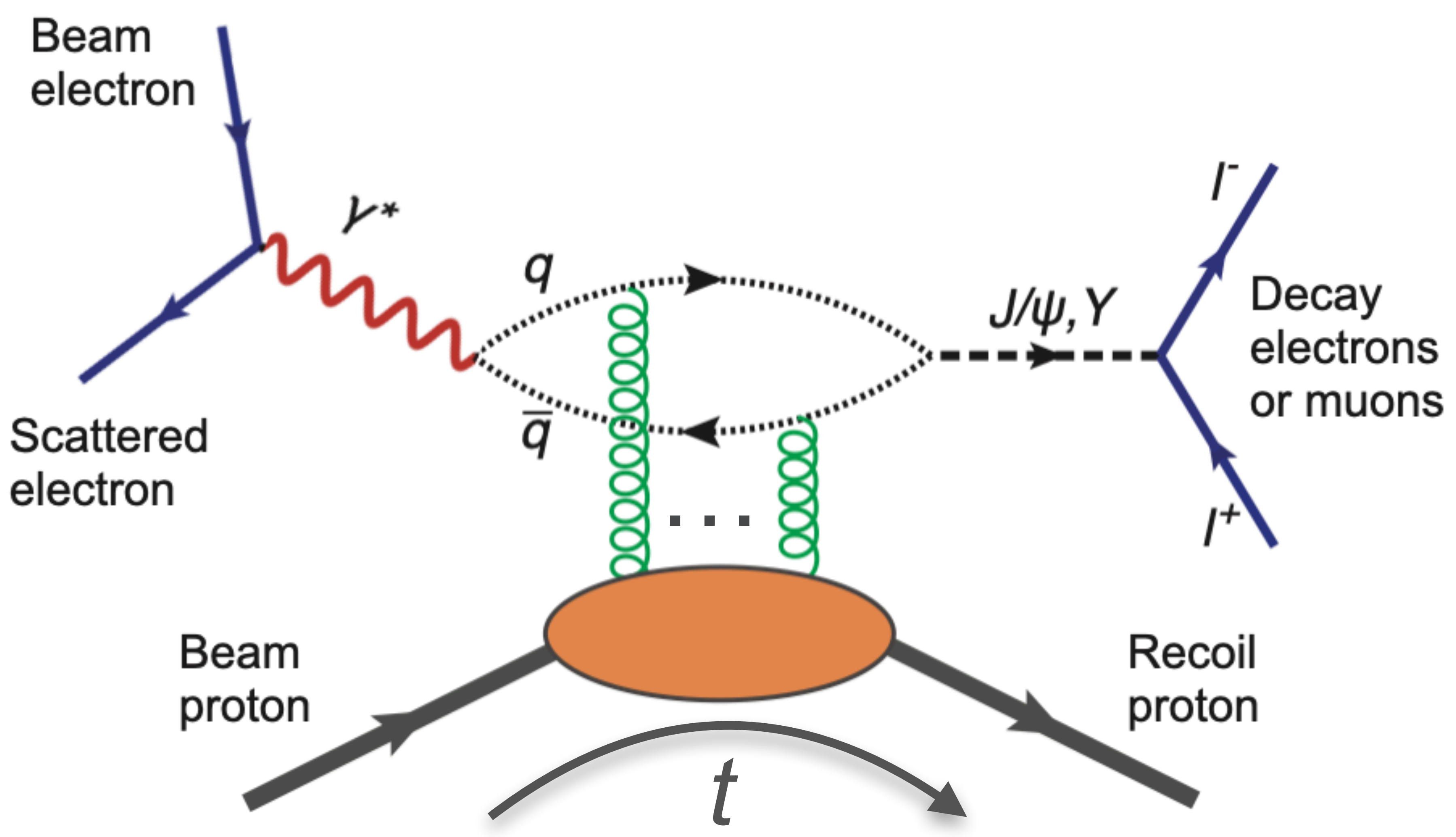
J/Ψ EXPERIMENTS AT JLAB COMPARED

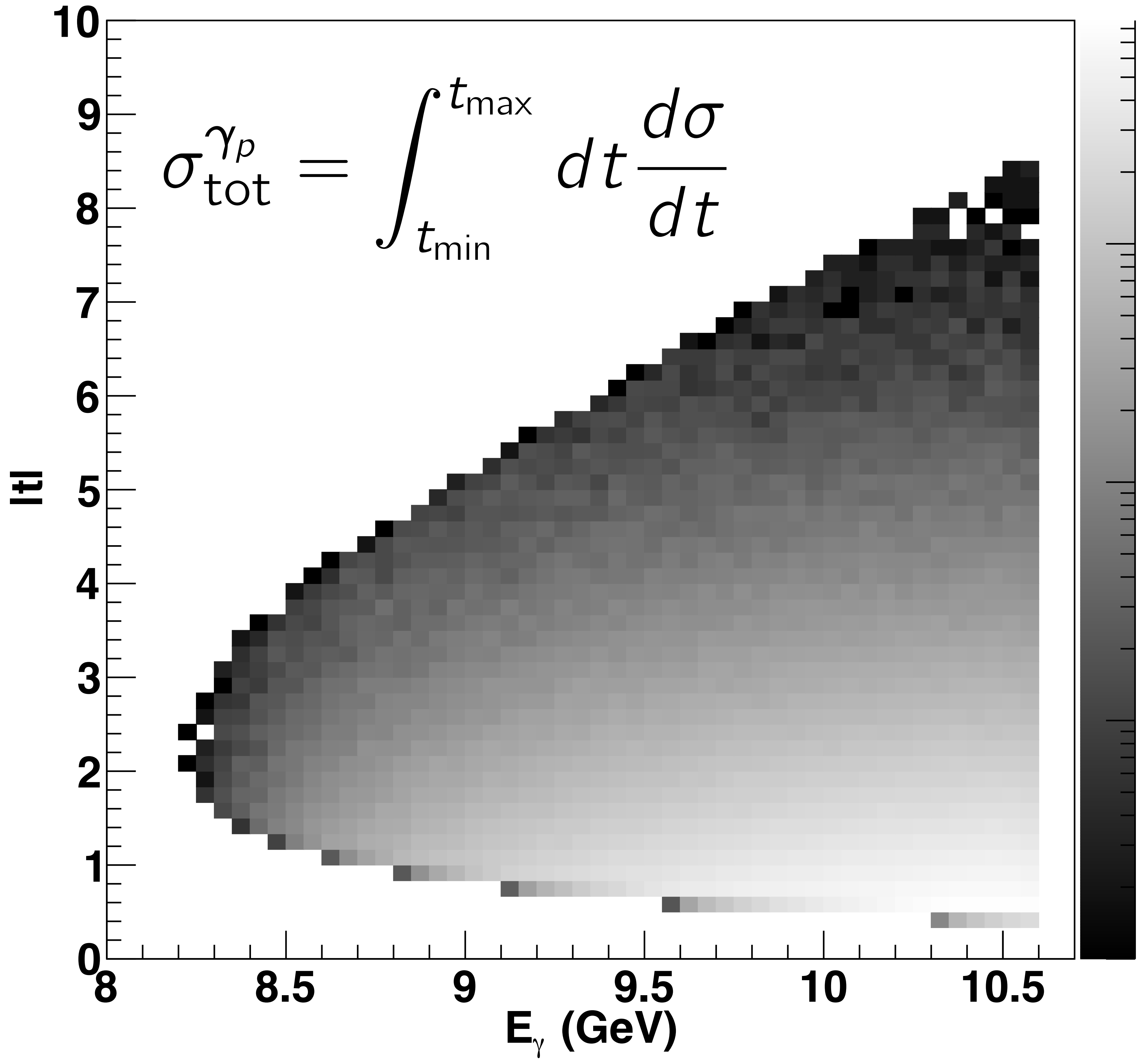
	GlueX HALL D	HMS+SHMS HALL C	CLAS 12 with upgrade[1] HALL B	SoLID HALL A
J/ψ counts (photo-prod.)	**469 published ~10k phase I + II**	**2k electron channel 2k muon channel**	**14k**	**804k**
J/ψ Rate (electro-prod.)	**N/A**	**N/A**	**1k**	**21k**
Features	Good reach to threshold. No high-t reach.	Can 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

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

EXCLUSIVE QUARKONIUM PRODUCTION

The basics





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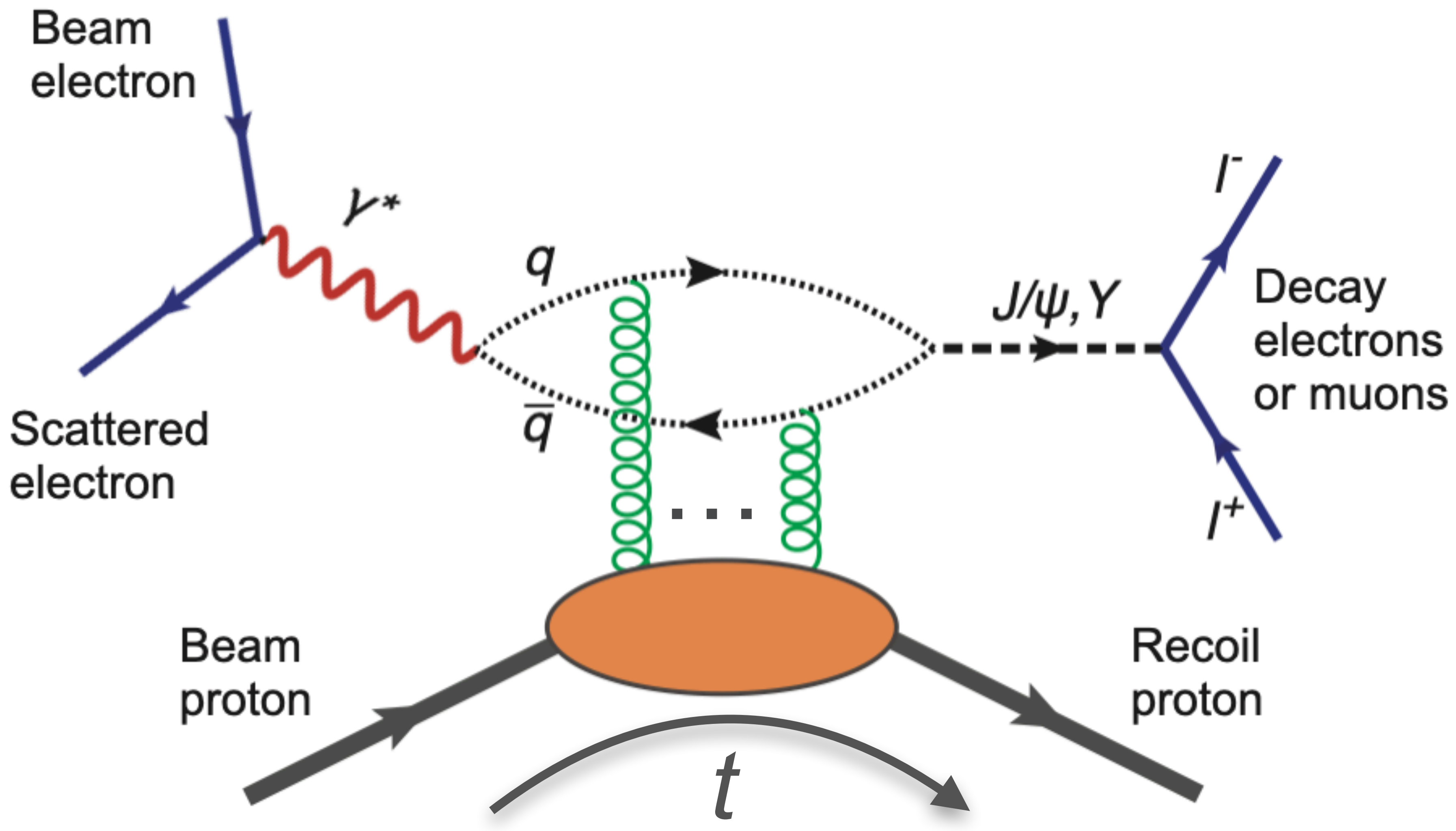

J/ψ threshold:

$W \approx 4.04\text{GeV}$

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

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

$Y(1S)$ threshold:

$W \approx 10.4\text{GeV}$

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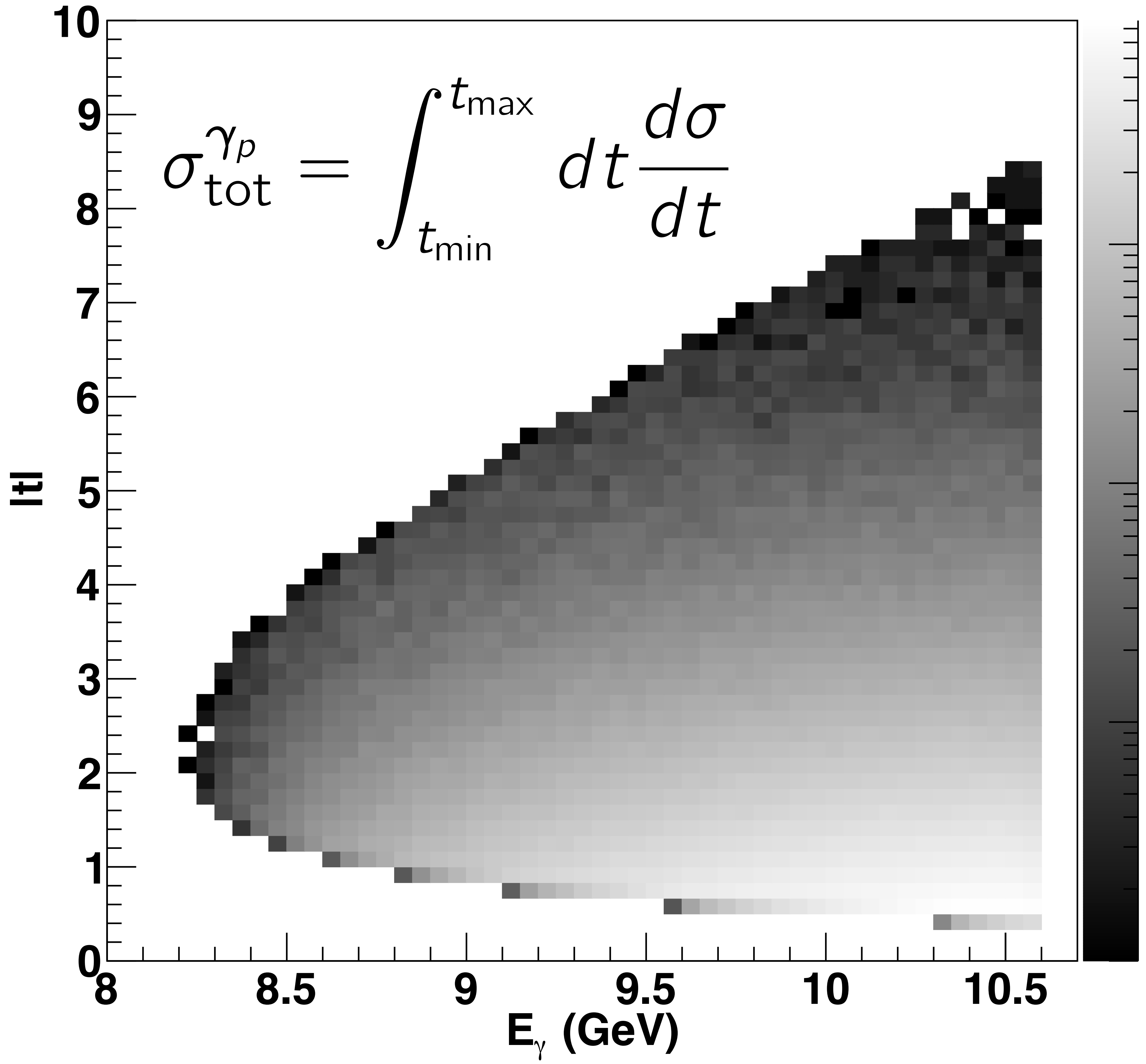

- Phase space limits defined by quarkonium direction

EXCLUSIVE QUARKONIUM PRODUCTION

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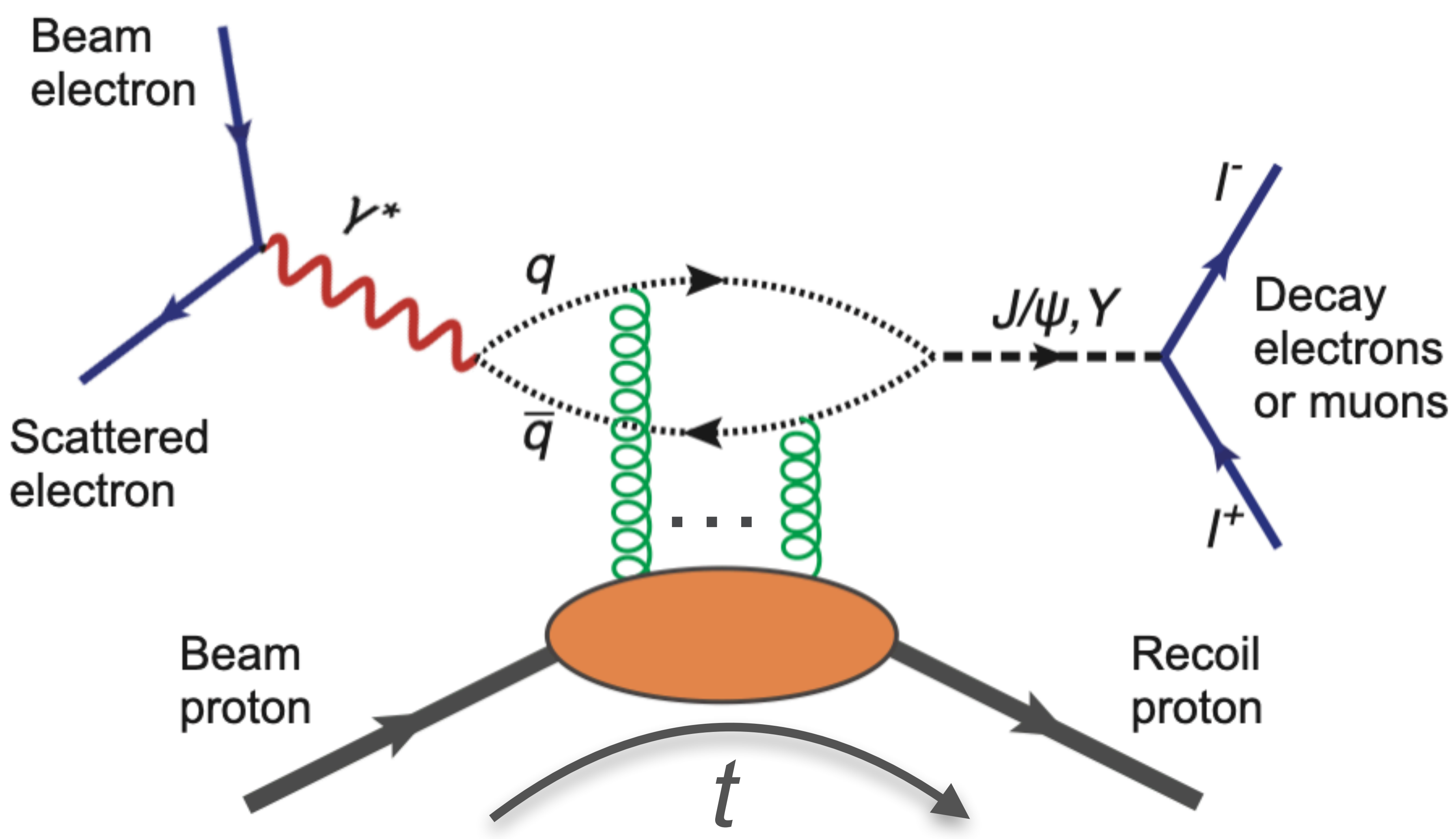

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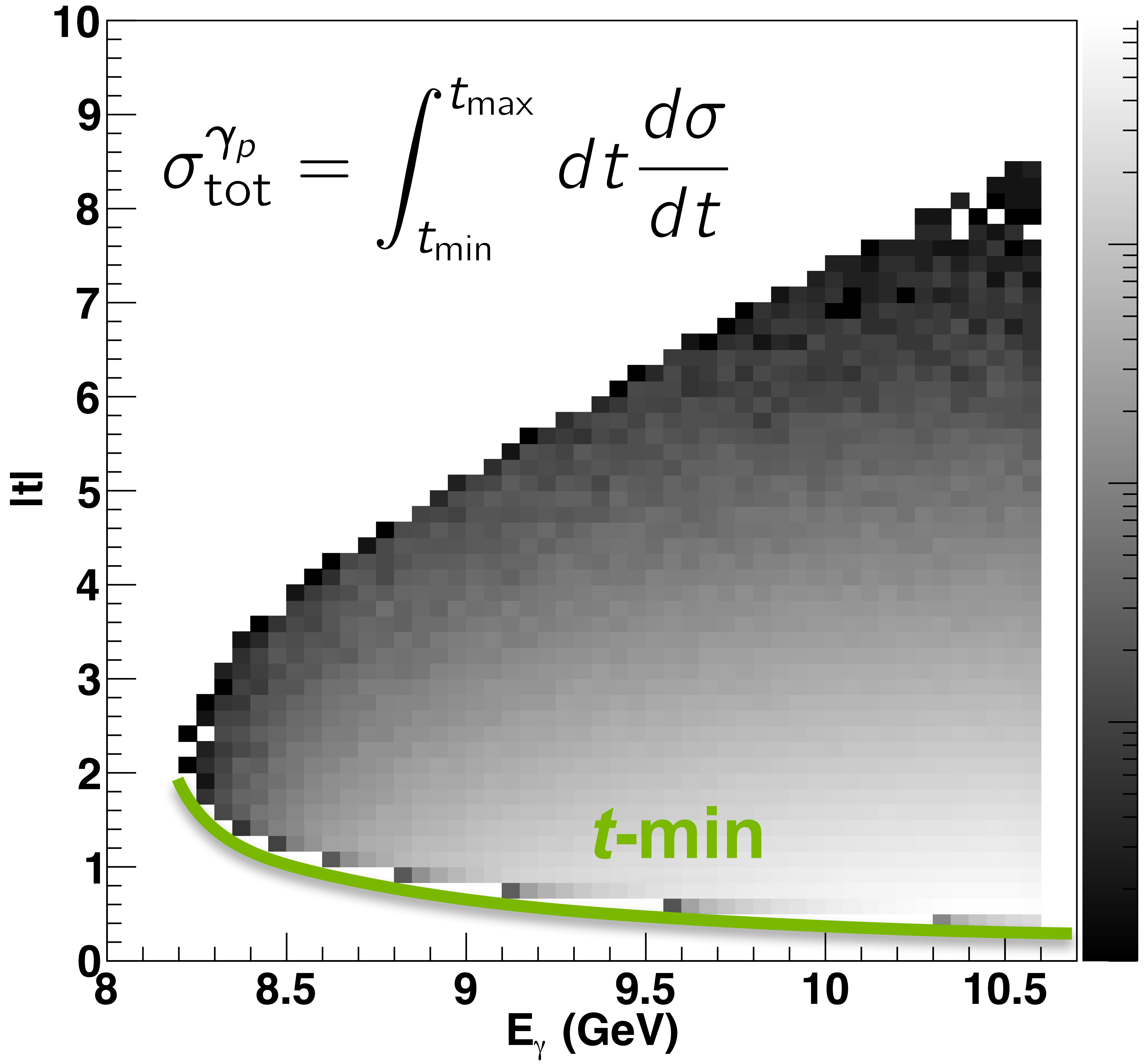

- Phase space limits defined by quarkonium direction
  - Forward (with photon): $t = t_{\min}$

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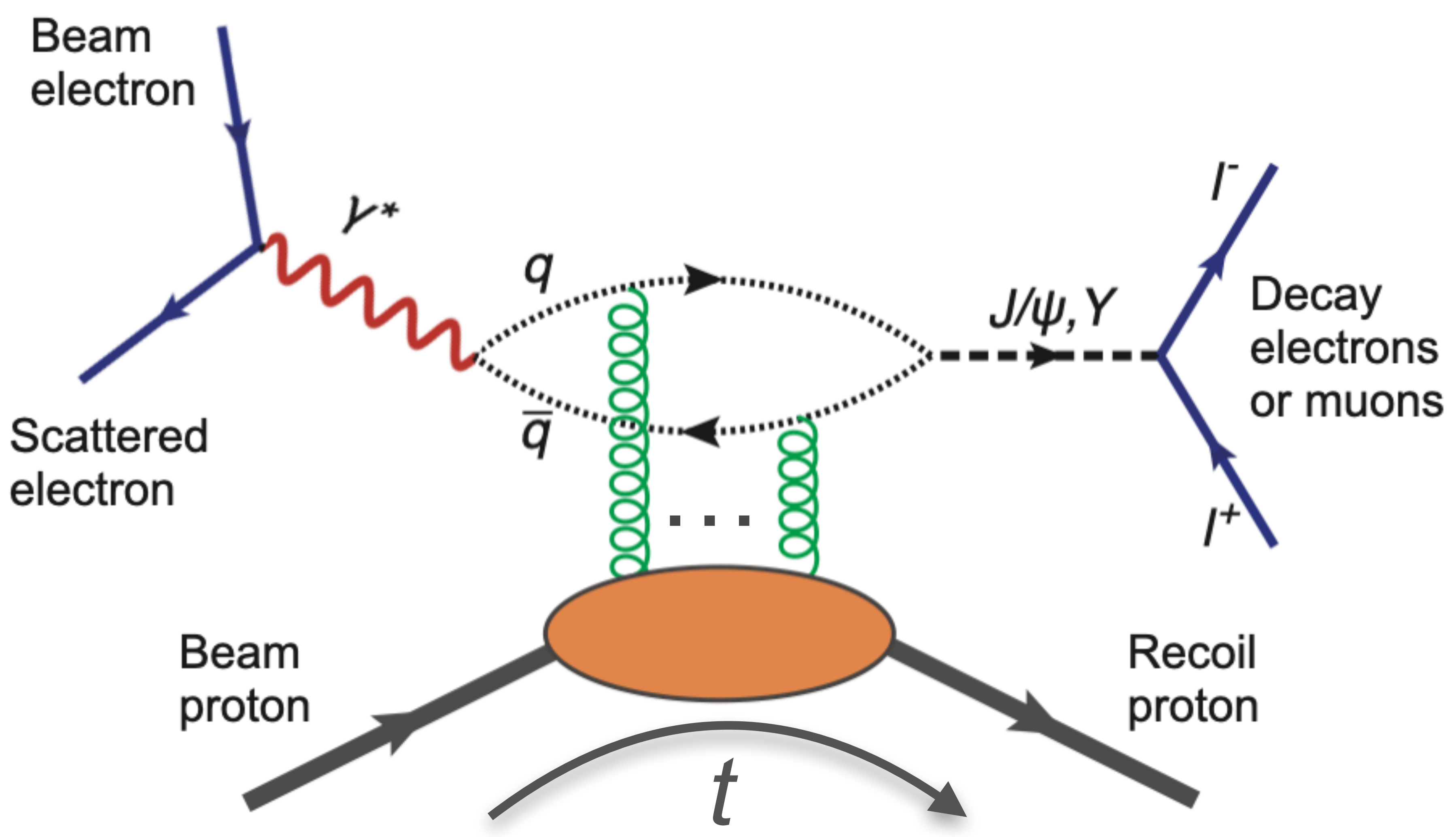

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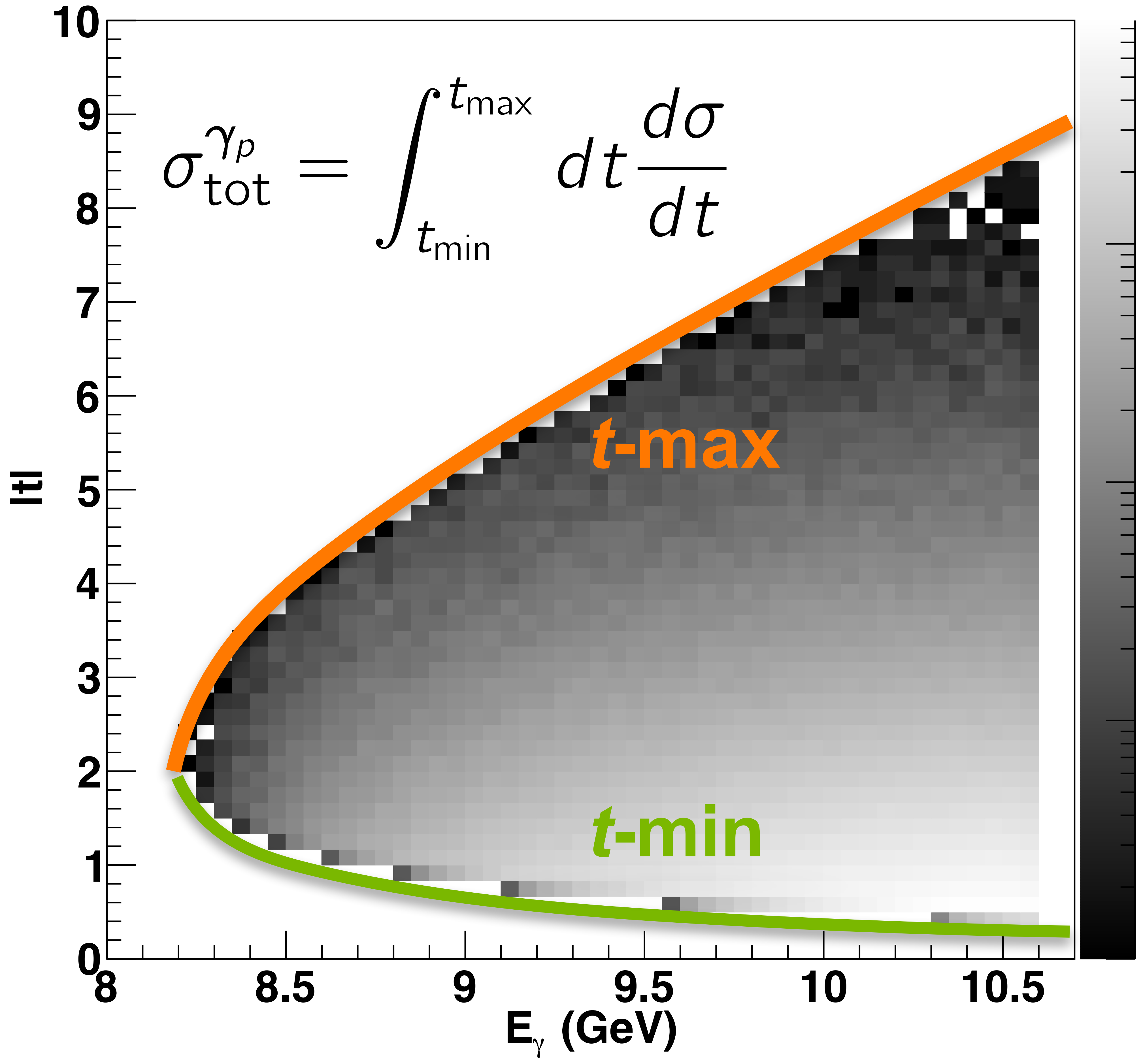
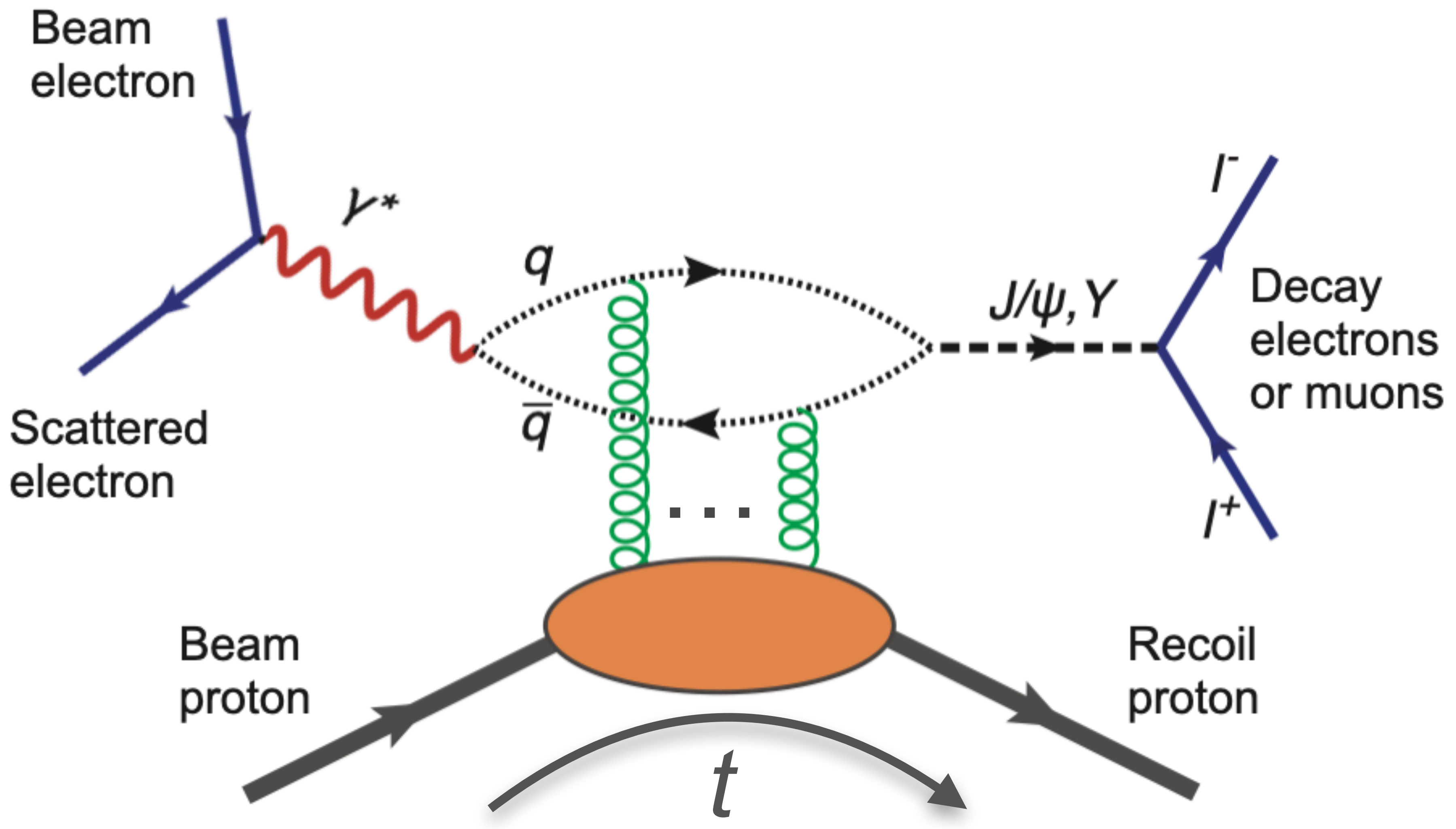


- Phase space limits defined by quarkonium direction
  - Forward (with photon): $t = t_{\text{min}}$
  - Backward (with proton): $t = t_{\text{max}}$

EXCLUSIVE QUARKONIUM PRODUCTION

The basics



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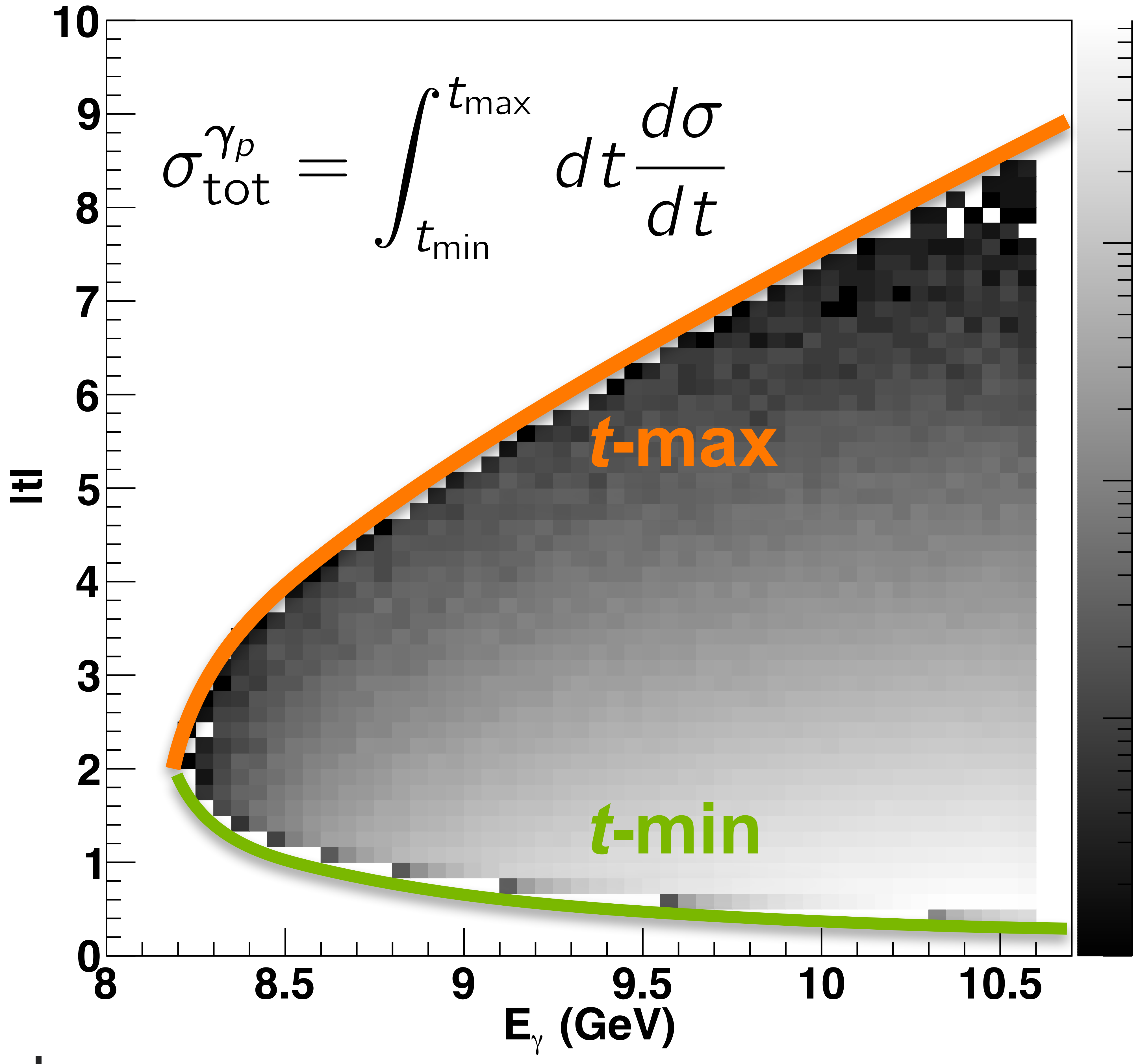


- Phase space limits defined by quarkonium direction
  - Forward (with photon): $t = t_{min}$
  - Backward (with proton): $t = t_{max}$
- Forward direction preferred: *t*-dependence ~exponential

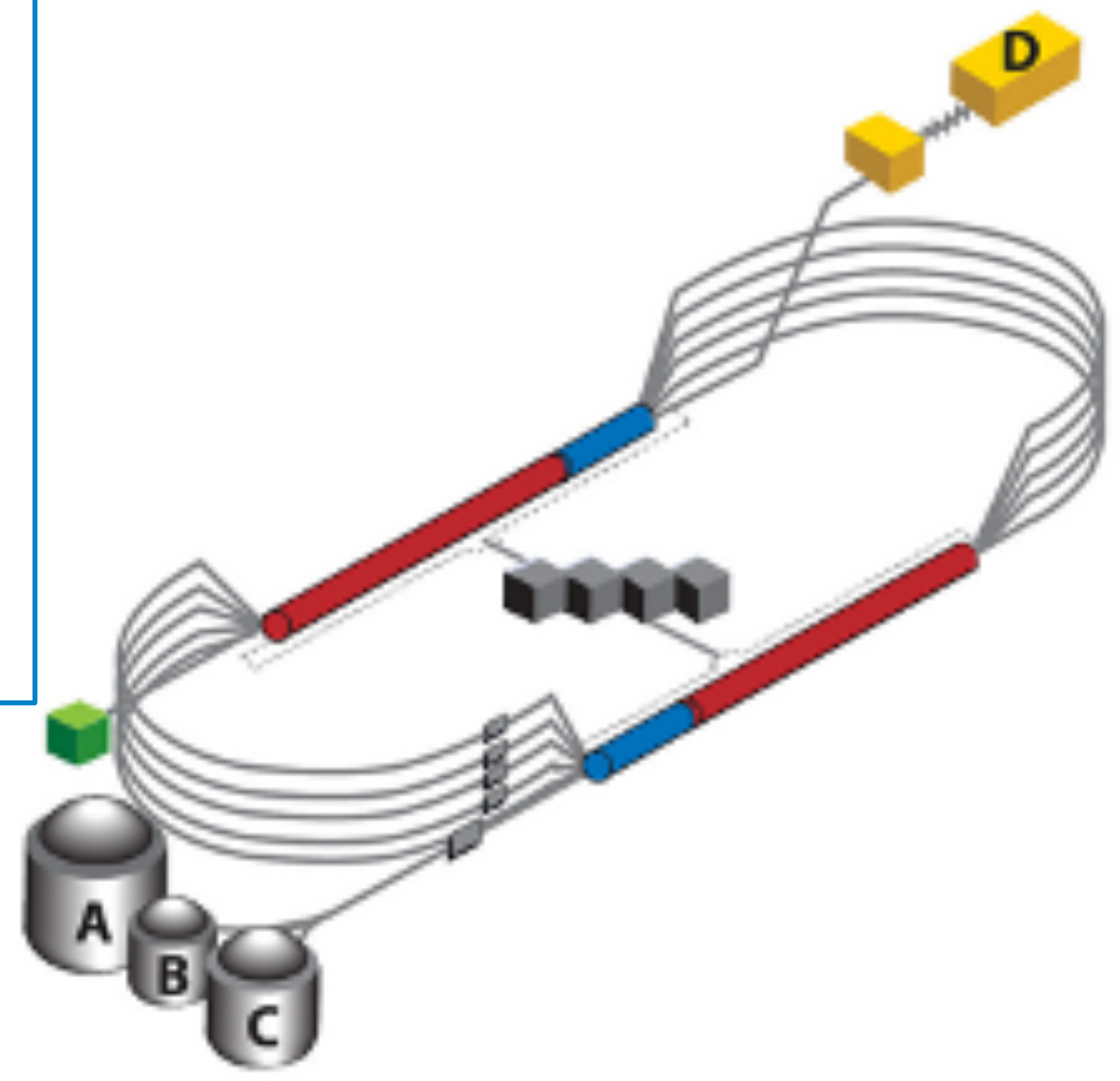
QUARKONIUM AT JEFFERSON LAB AND EIC

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



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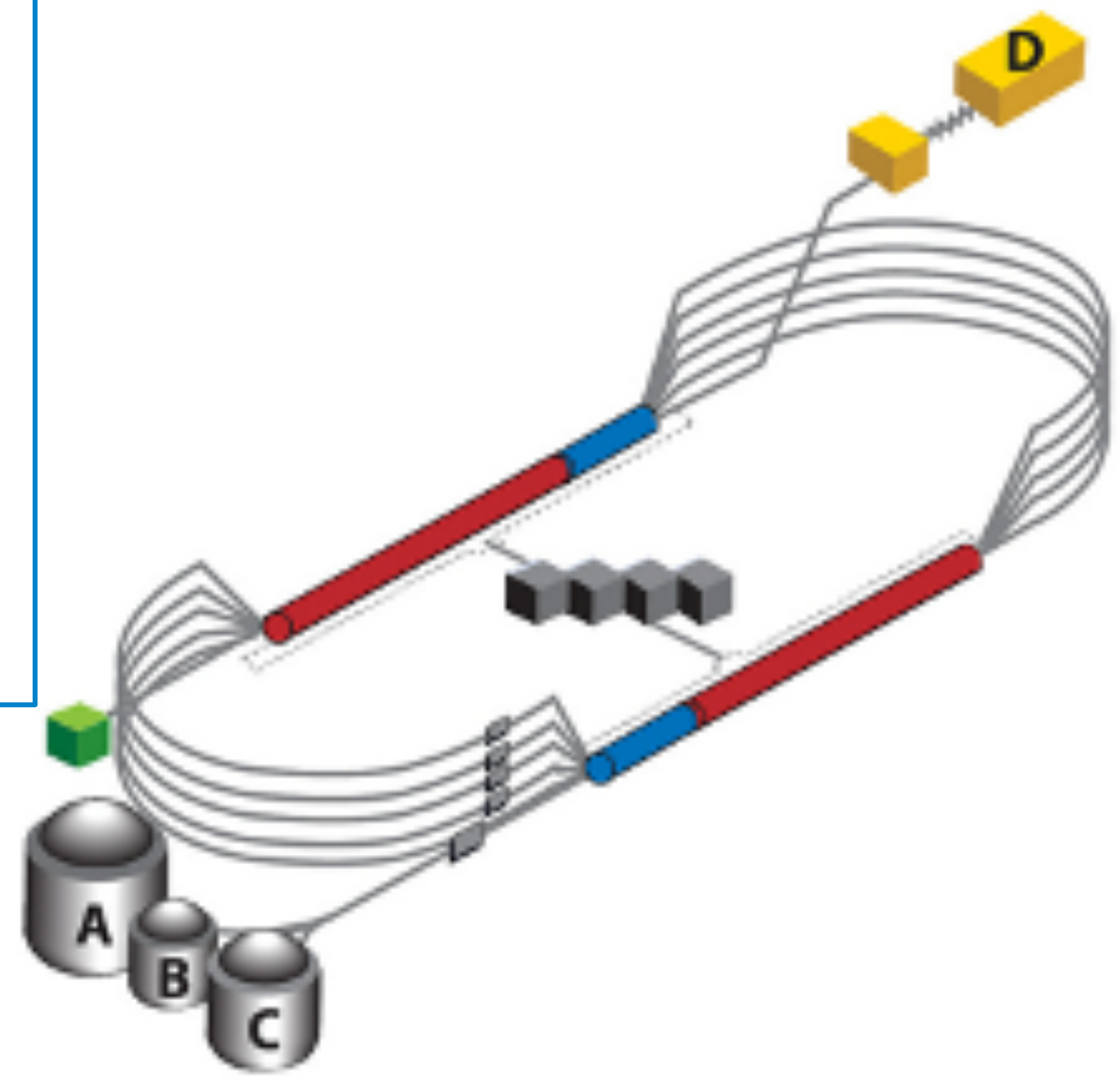

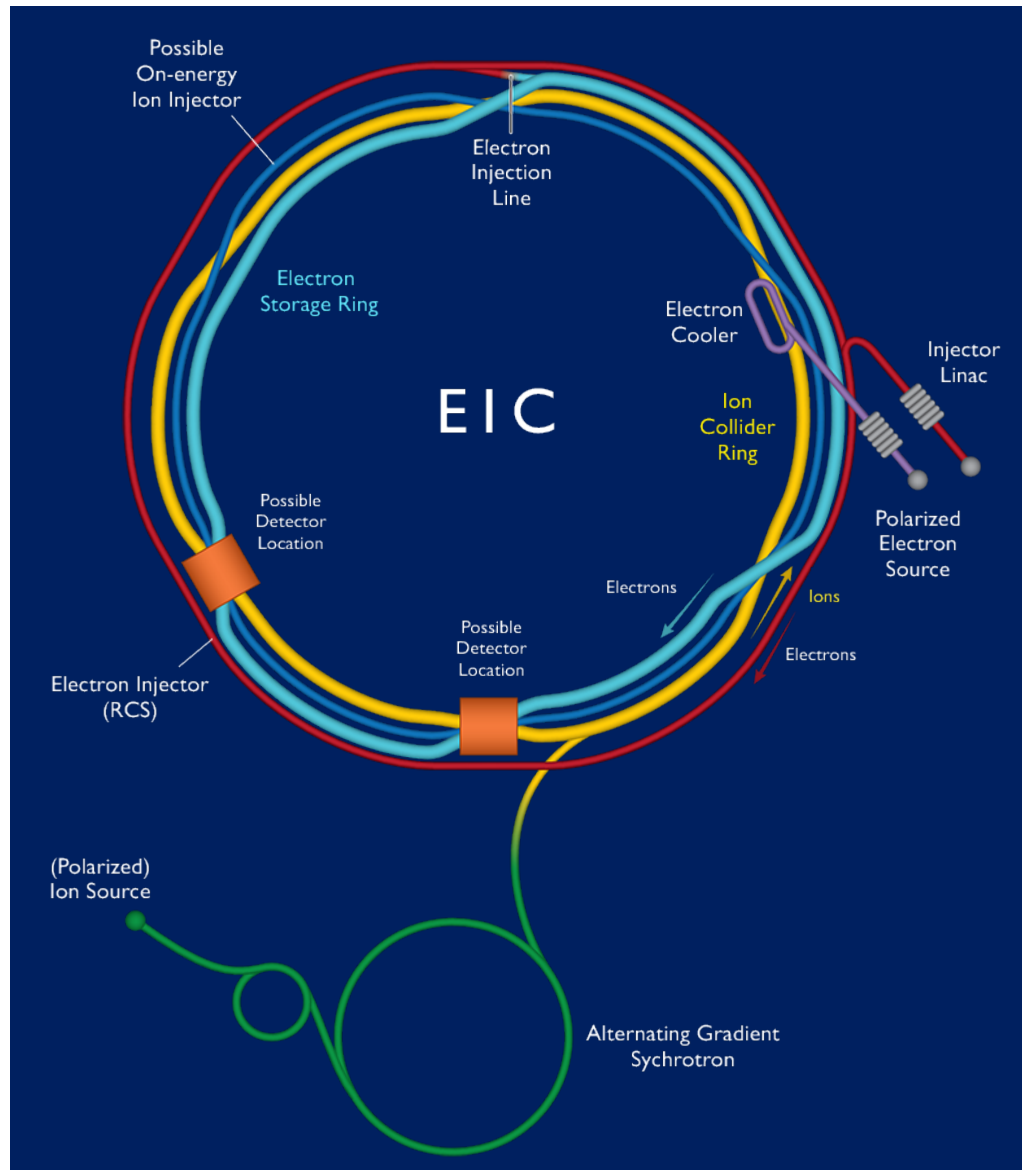

Electron-ion Collider

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

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

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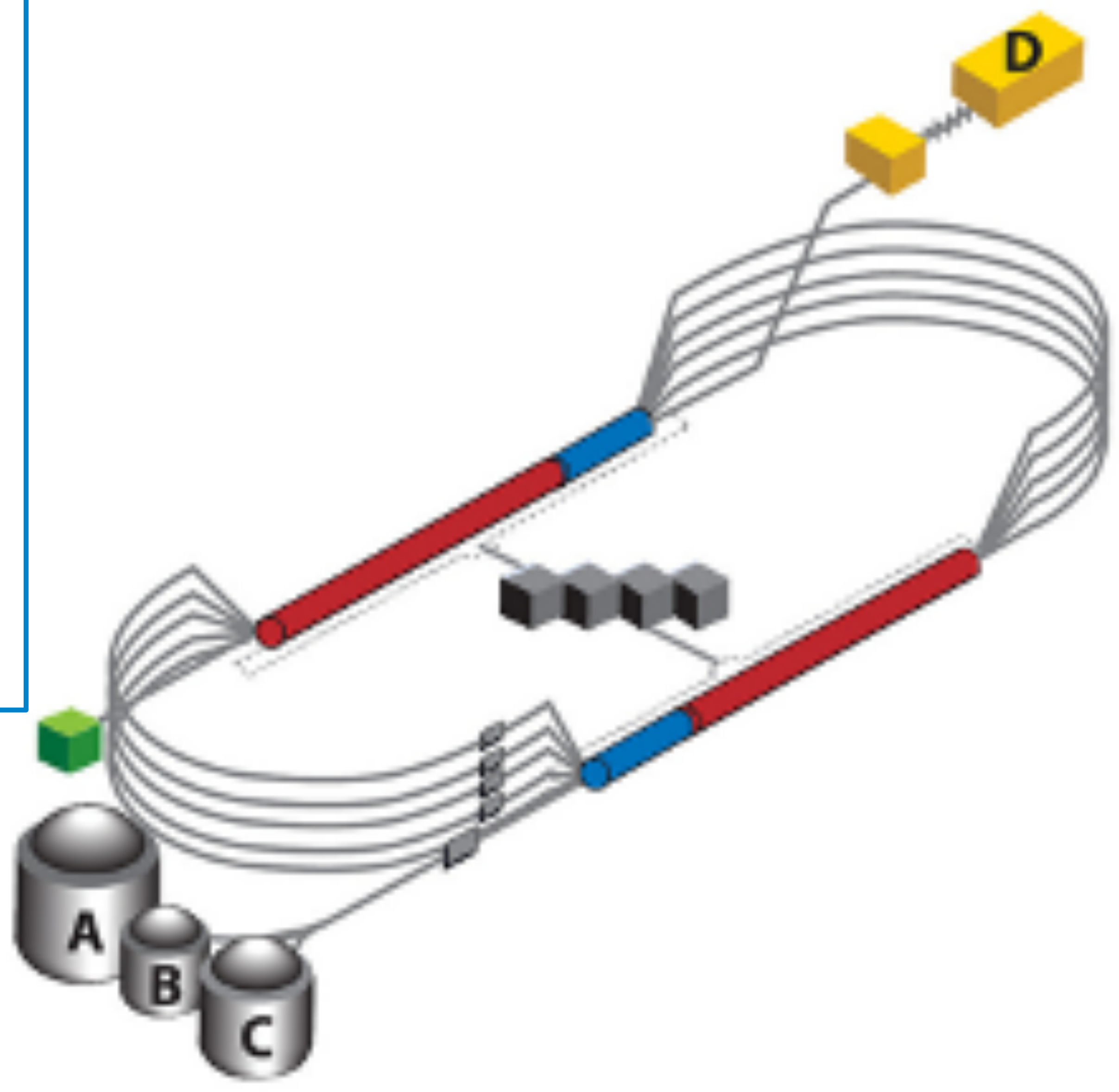

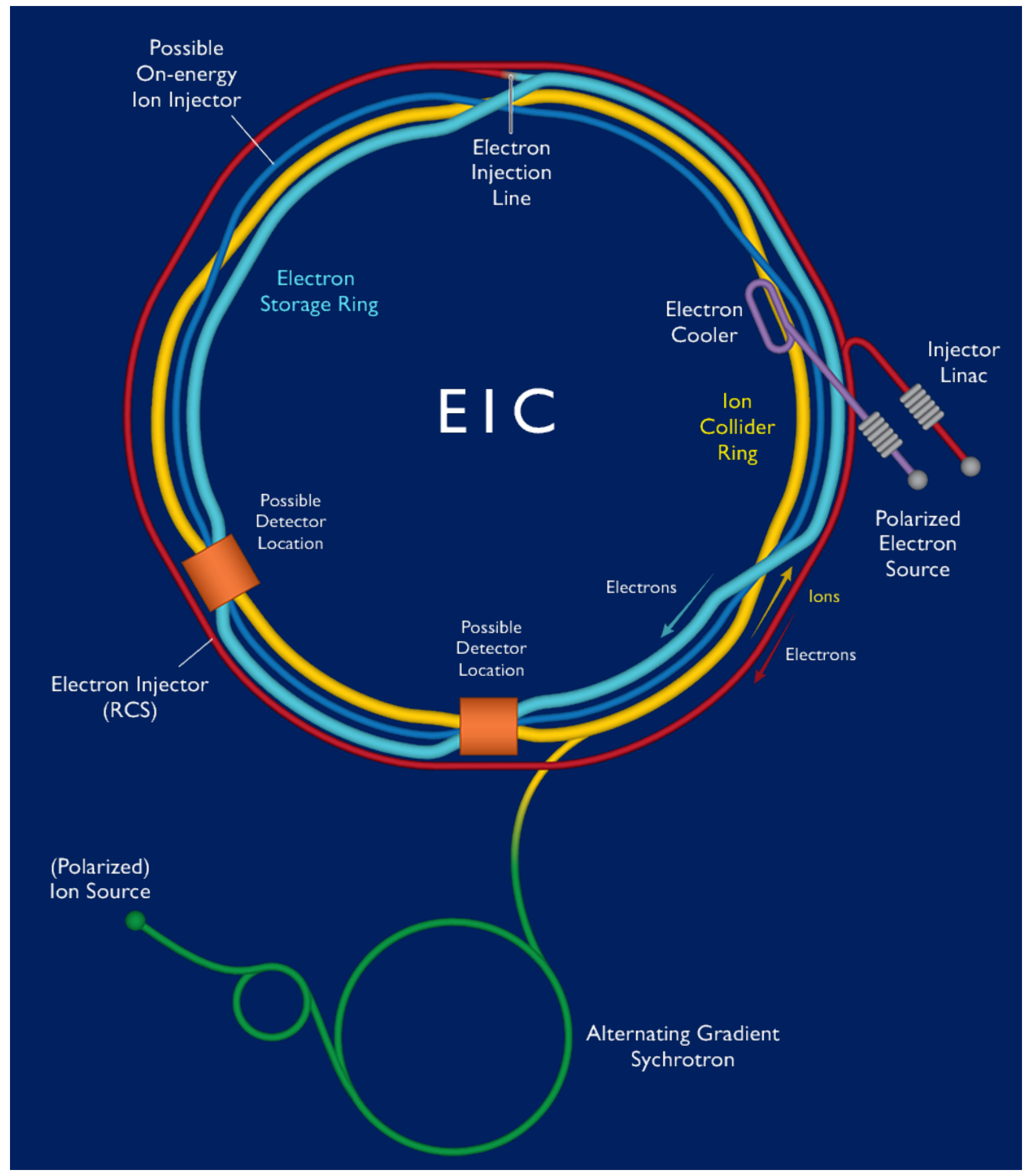

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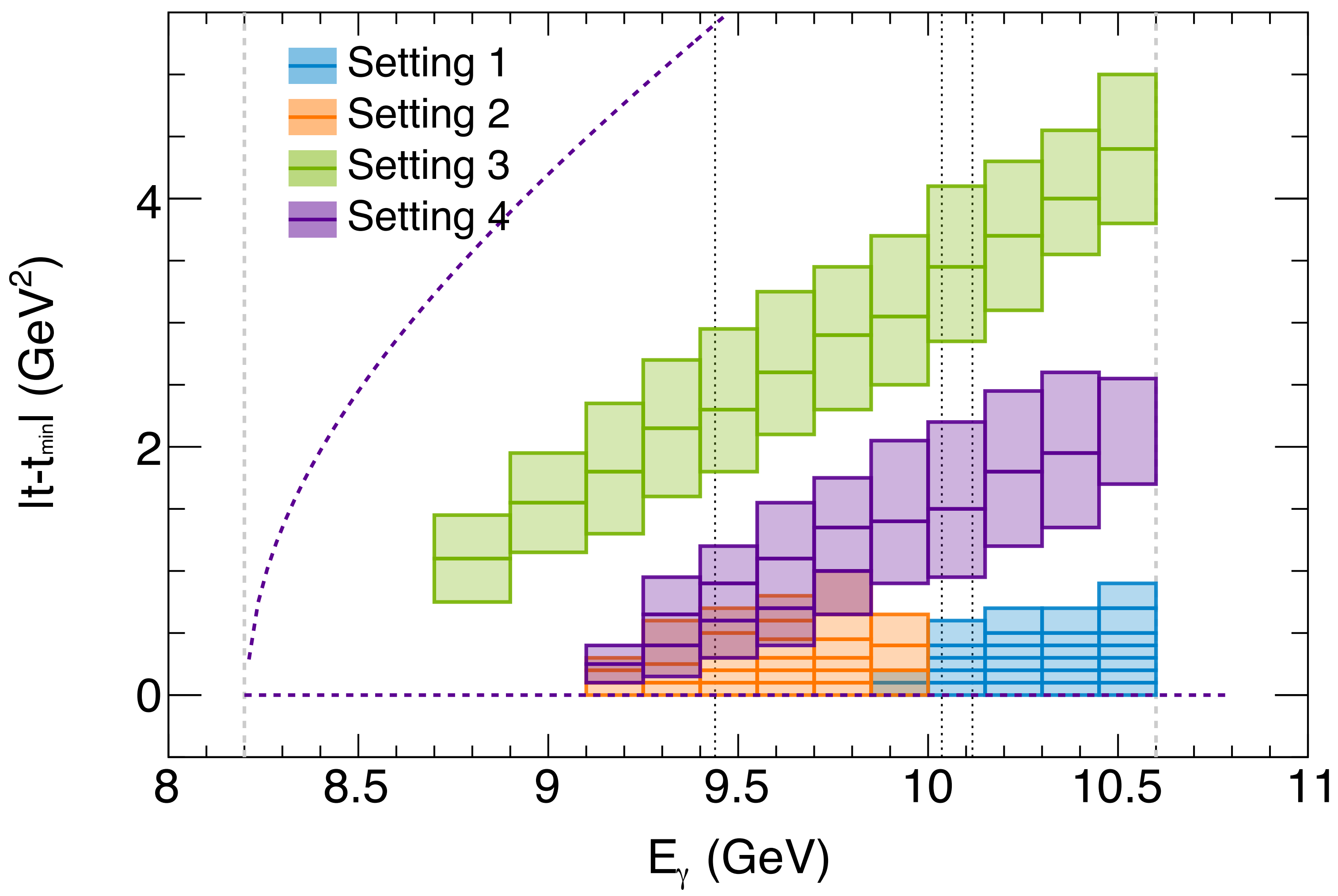
Complementary programs: Jefferson Lab is the ideal laboratory to access GFFs with J/ψ production, and EIC has sufficient luminosity and energy for 3-D gluonic imaging.

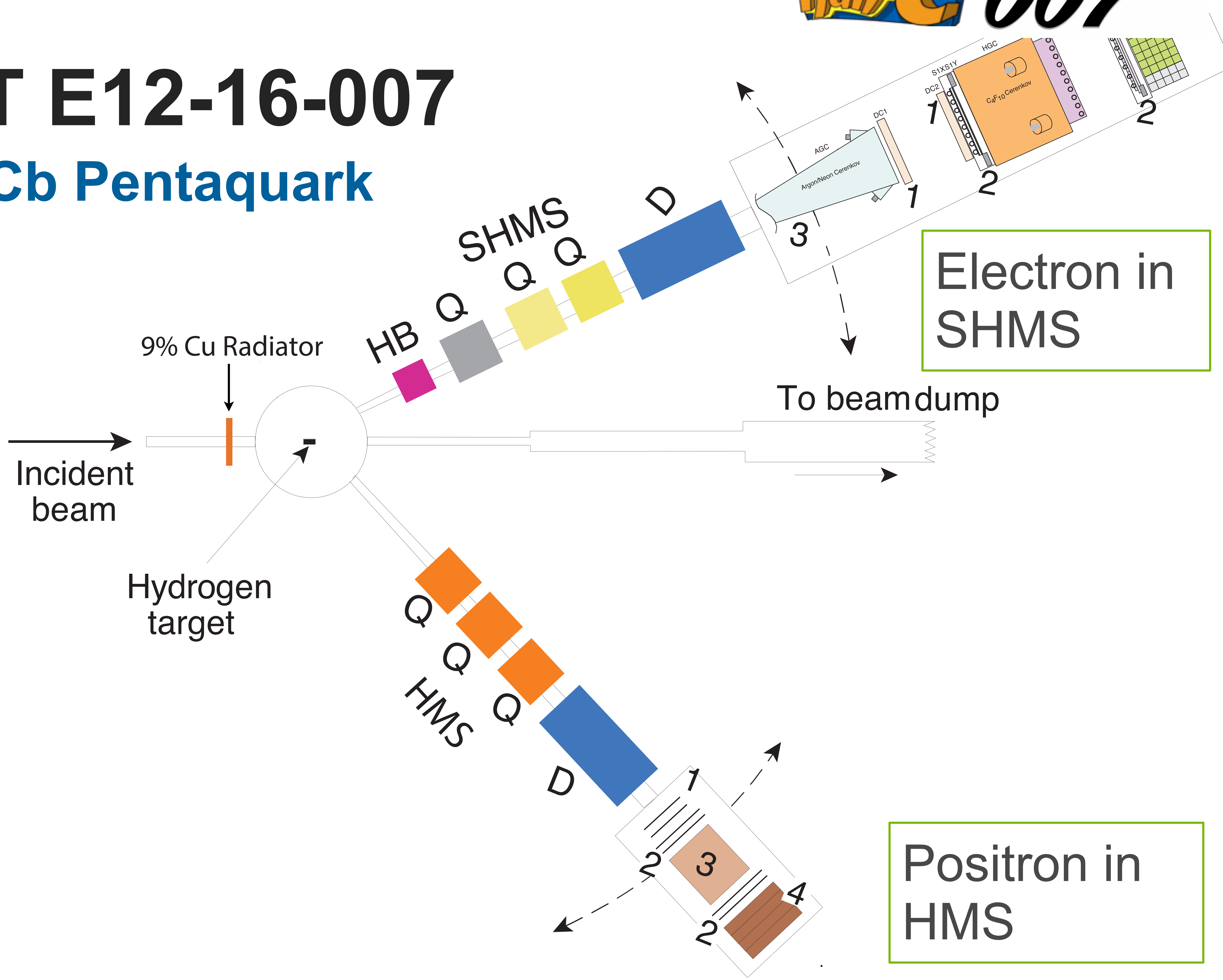
Z.-E. Meziani, S. Joosten *et al.*, arXiv:1609.00676 [hep-ex]
K. Hafidi, S. Joosten *et al.*, Few Body Syst. 58 (2017) no.4, 141

JLAB EXPERIMENT E12-16-007

J/ψ-007: Search for the LHCb Pentaquark

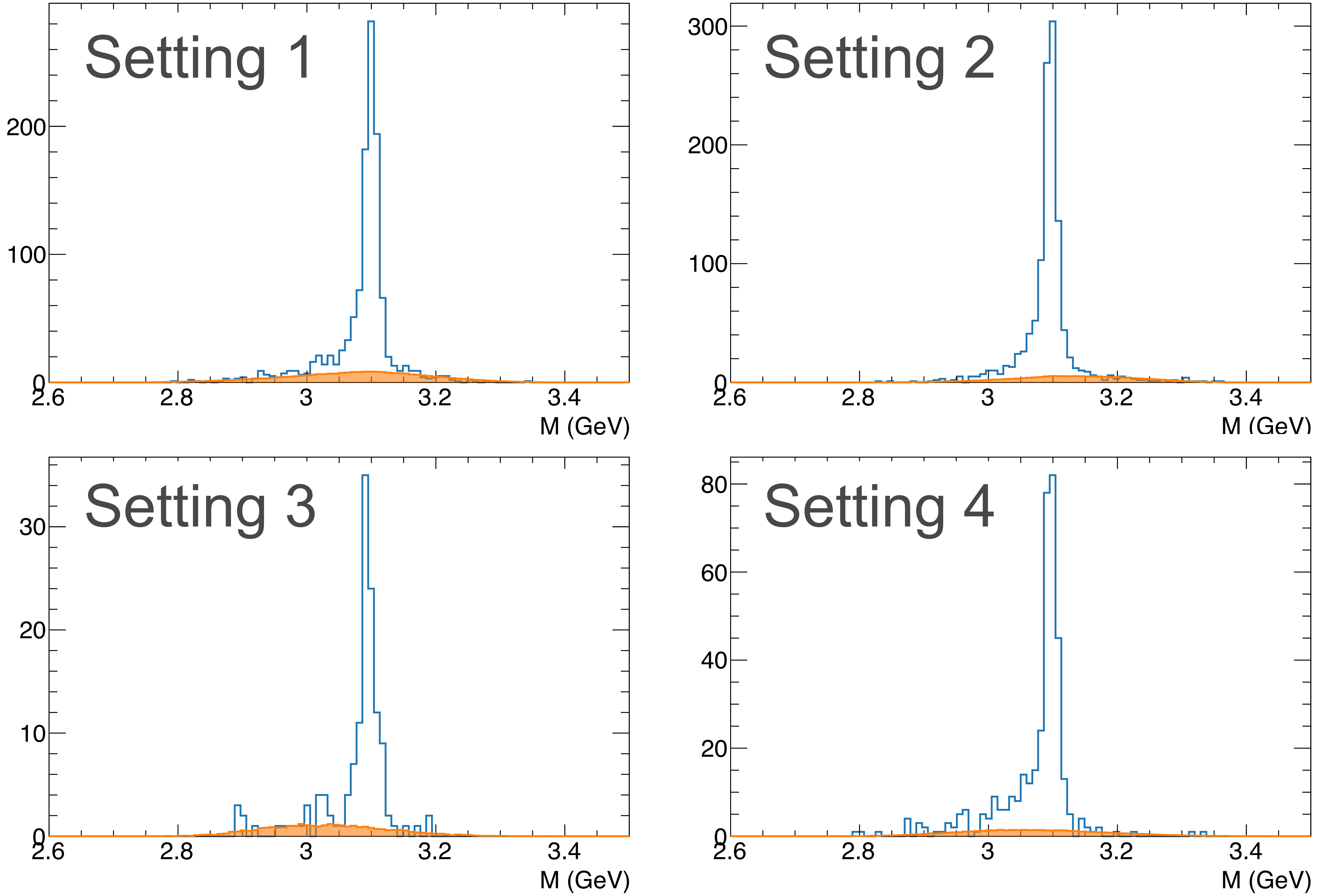
- Ran February 2019 for ~8 PAC days
- High intensity real photon beam (50μA electron beam on a 9% copper radiator)
- 10cm liquid hydrogen target
- Detect J/ψ decay leptons in coincidence
  - Bremsstrahlung photon energy fully constrained





CLEAR J/Ψ SIGNAL WITH MINIMAL BACKGROUND

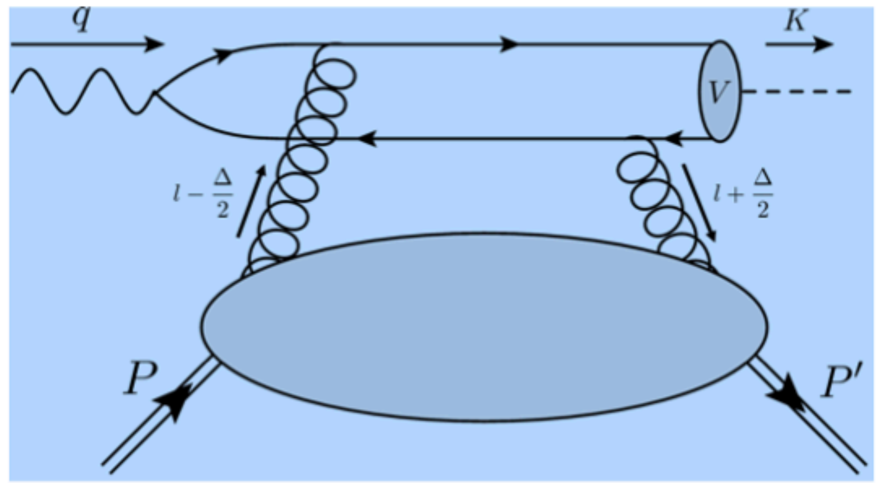
settings	HMS	SHMS	target	charge [C]	goal
setting 1	19.1^o at +4.95GeV	17.0^o at -4.835GeV	LH2 with radiator	5.2	low-t and high energy
			dummy with radiator	0.6	target wall
			LH2, no radiator	0.1	electroproduction
setting 2	19.9^o at +4.6GeV	20.1^o at -4.3GeV	LH2 with radiator	8.2	low-t and low energy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



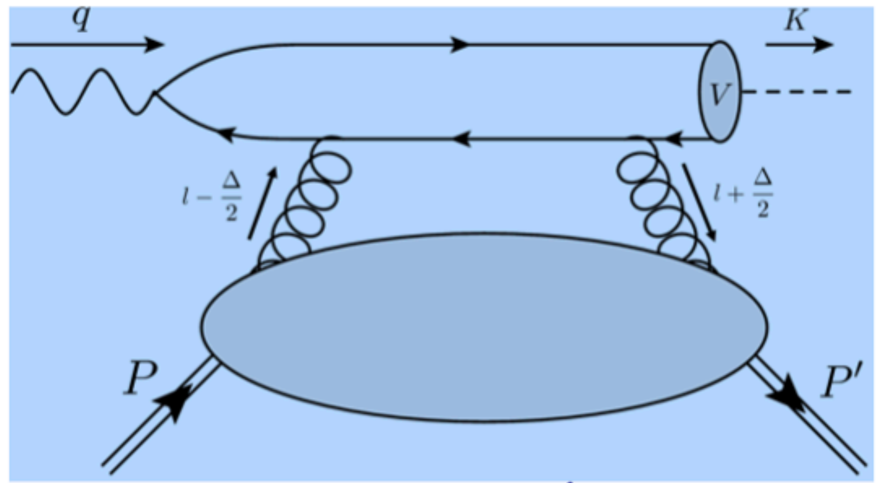
THE GENERALIZED PARTON DISTRIBUTION MODEL

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

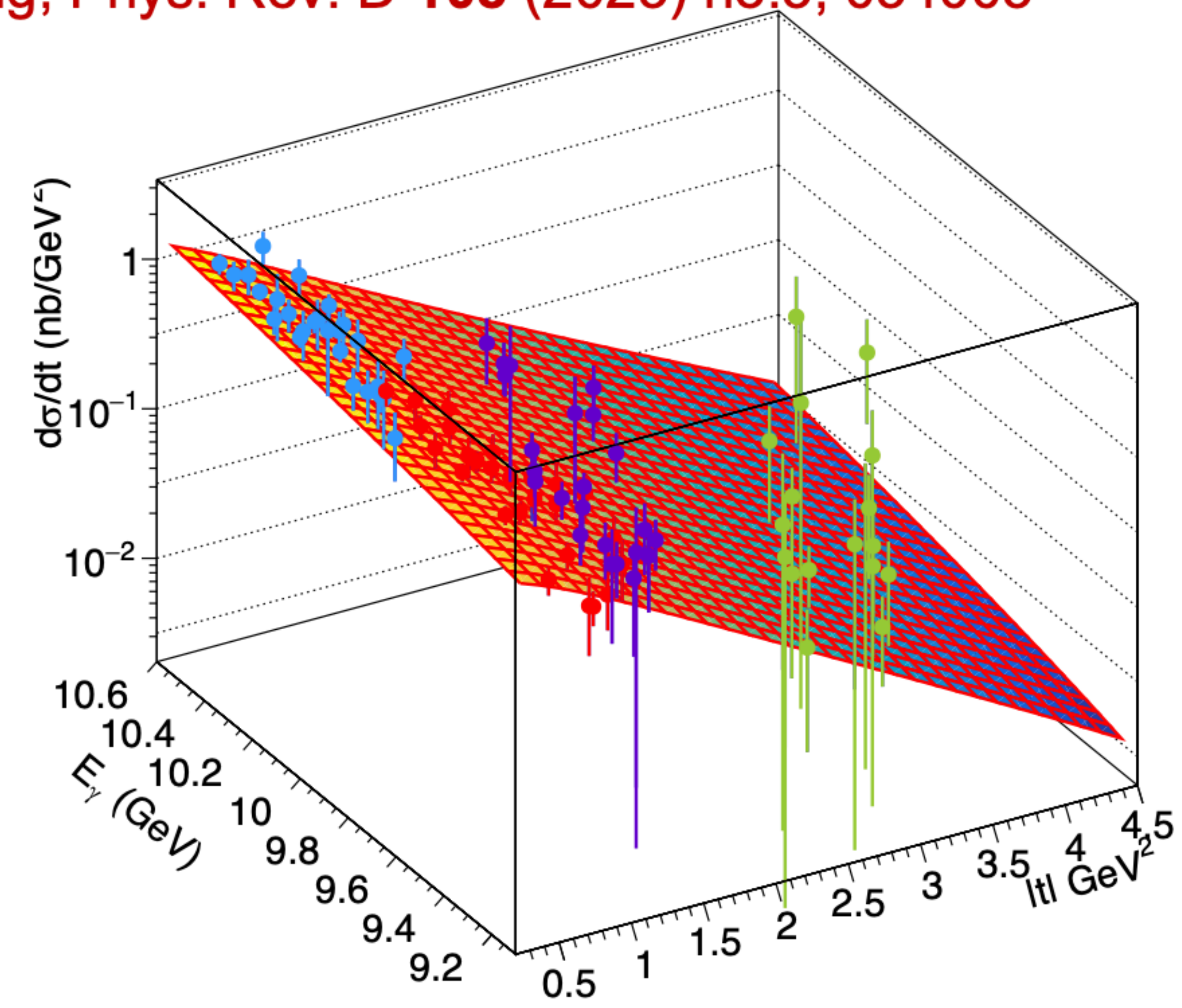


(a)



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

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



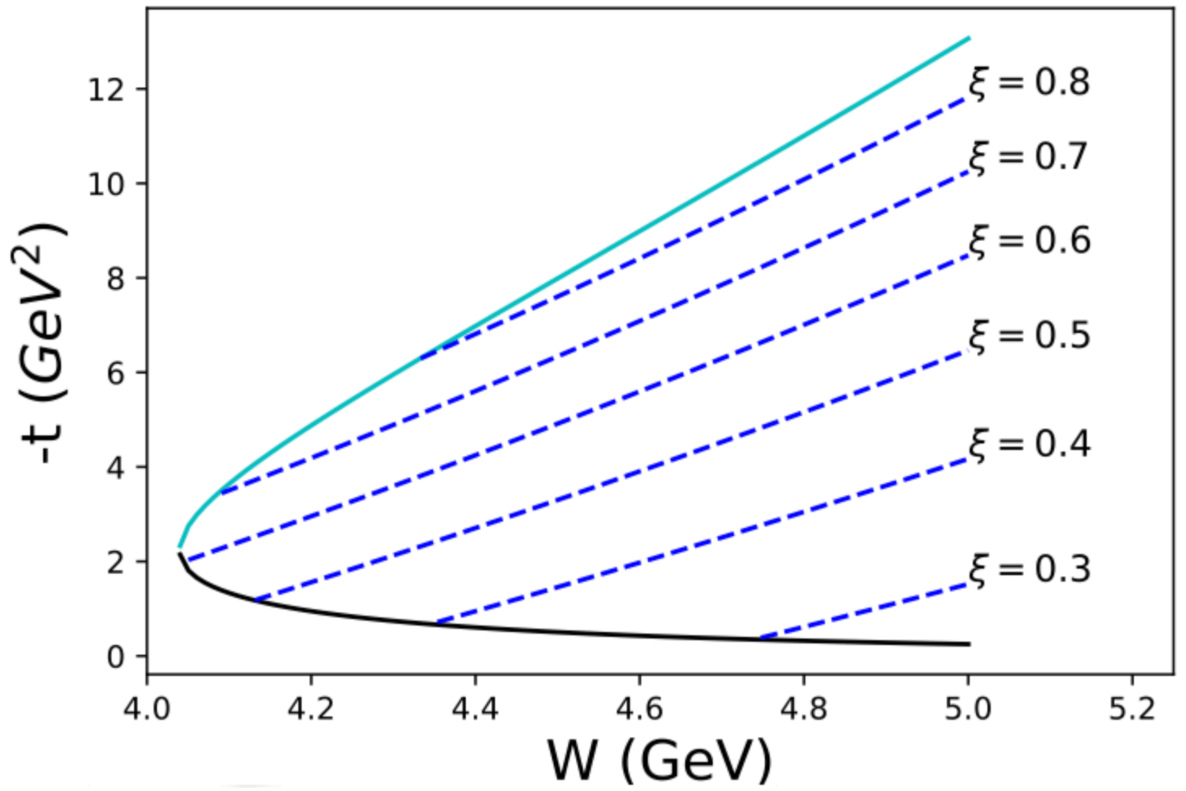
$$|G(t,\xi)|^2 = \frac{4}{\xi^4}\{(1 - \frac{t}{4m_N^2})E_2^2 - 2E_2(H_2 + E_2) + (1-\xi^2)(H_2+E_2)^2\}$$

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

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

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

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

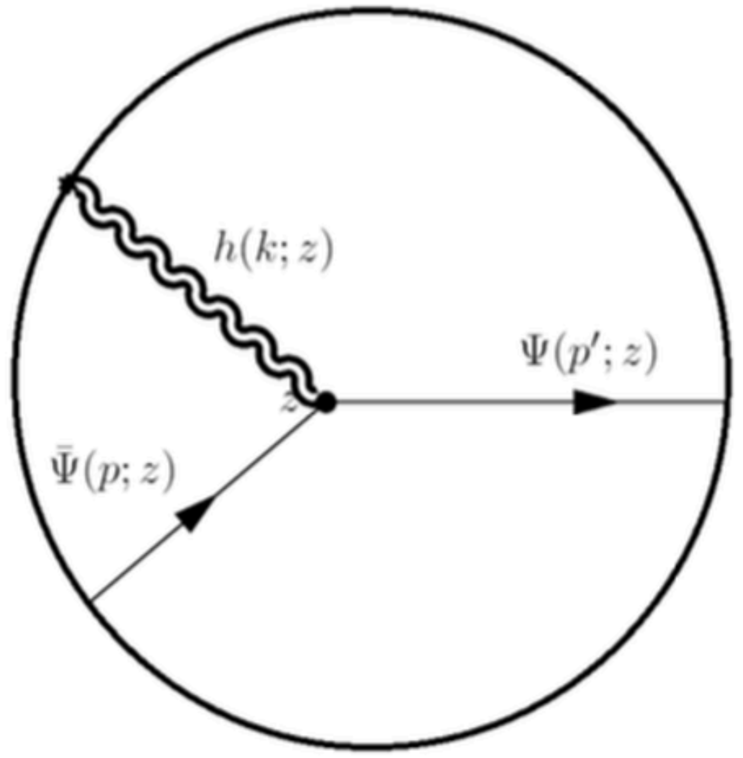


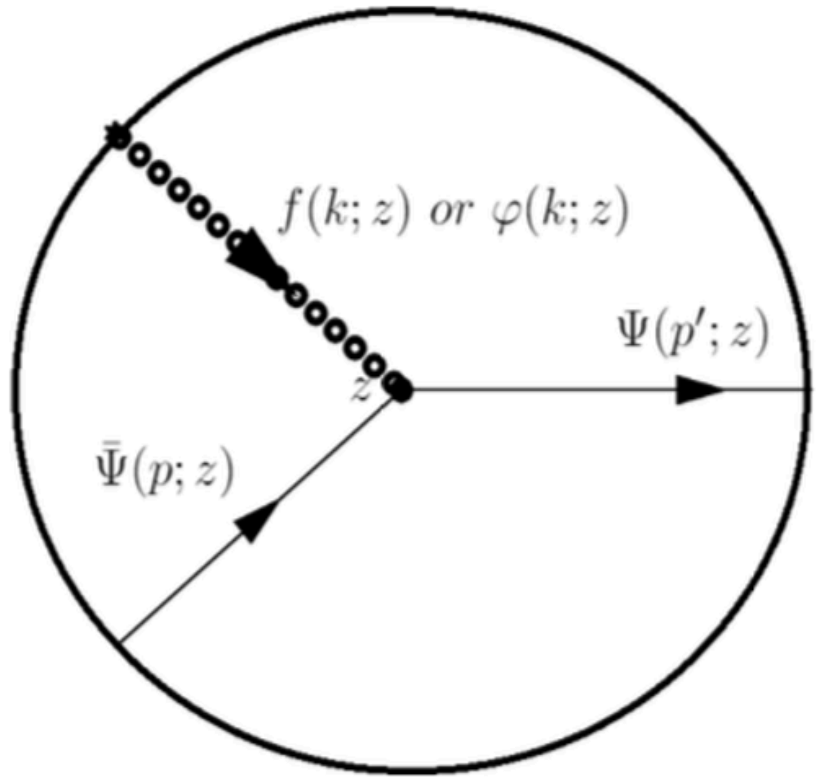
THE HOLOGRAPHIC QCD MODEL

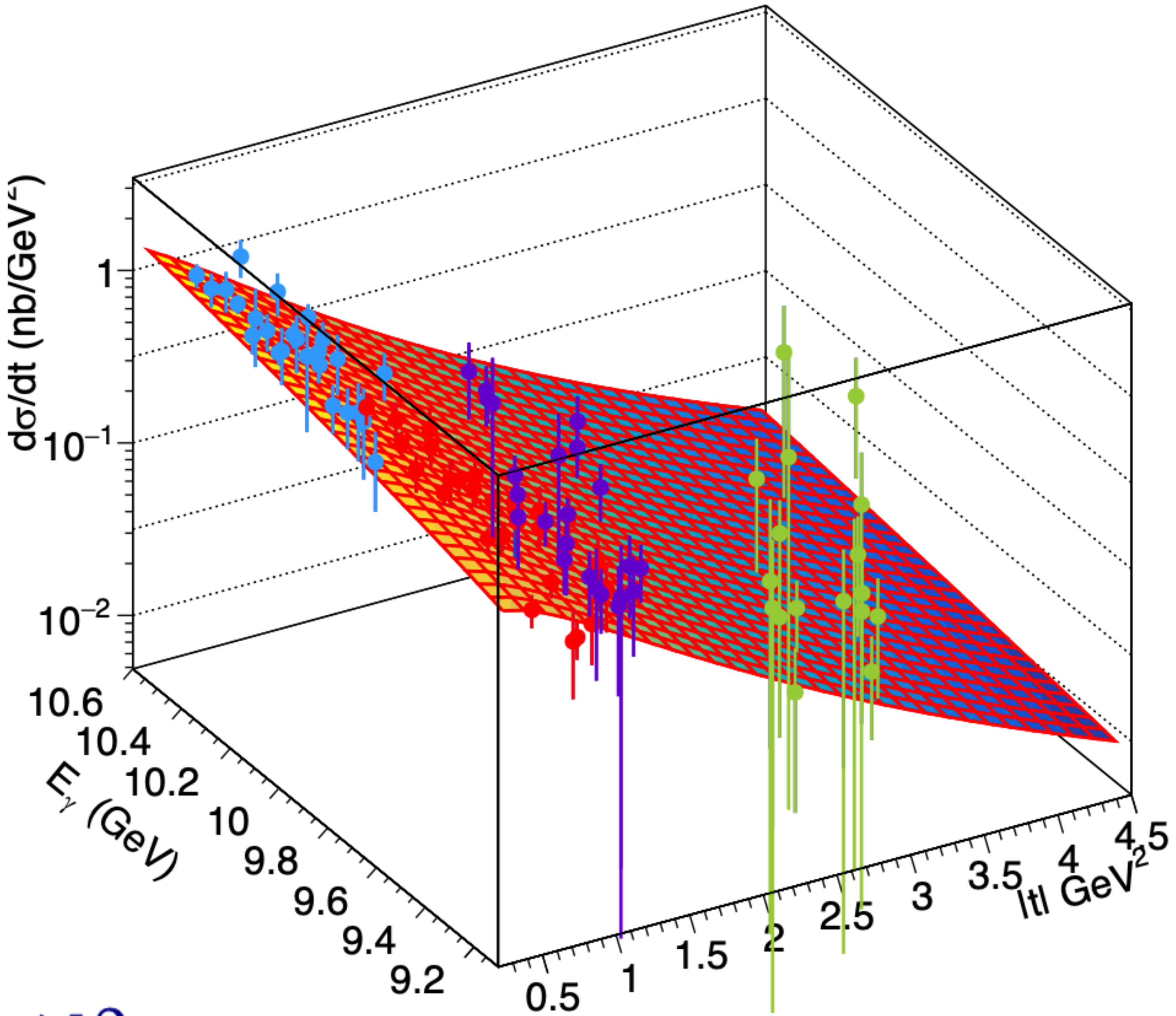
2D fit to extract the *A(t)* & *C(t)* assuming *B(t)* to be small

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

A tensor component and a scalar component







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

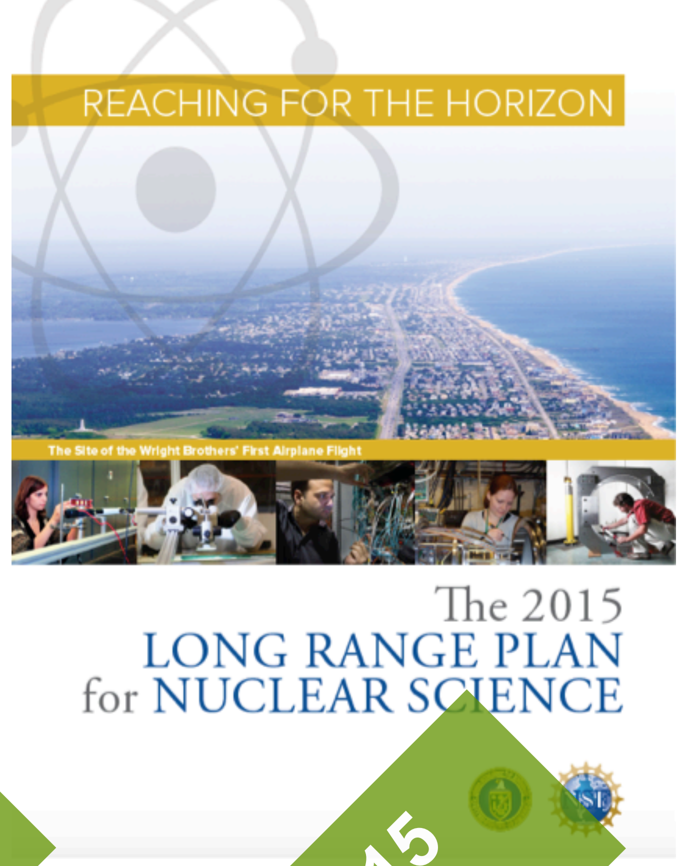
Spin-0 : $\langle p_2|T^{\mu}_{\mu}(0)|p_1\rangle$

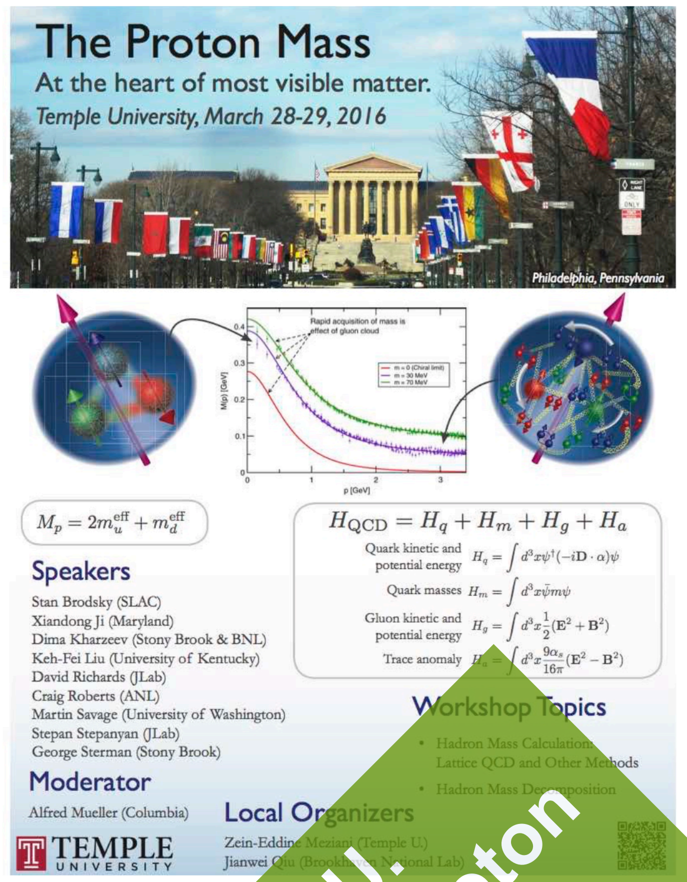
$$\frac{d\sigma}{dt} = \mathcal{N} \times \frac{e^2}{64\pi(s-m_N^2)^2} \times \frac{A(-t,\kappa_T)+\eta^2 D(-t,\kappa_T,\kappa_S)]^2}{A^2(0)} \times \tilde{F(s)} \times 8$$

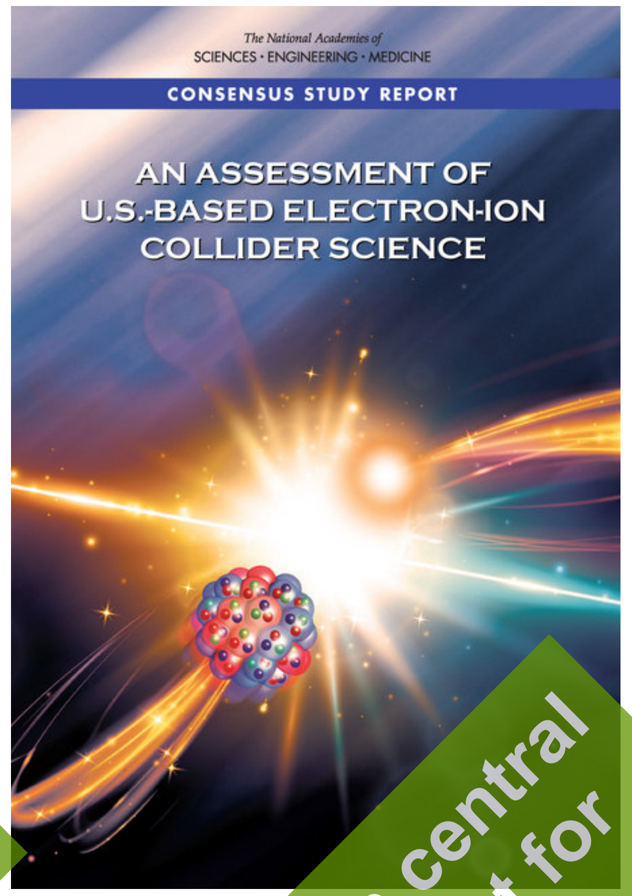
- *A(t)* and *D(t)* shapes are fully calculated; However, dipole forms are assumed as very good approximations and are used in the fits to the data. $A_g(0)= <x_g>$ is fixed to the DIS value from global fit CT18.
- *B(t)* is neglected and $\mathcal{N}$ is normalized to the cross section.

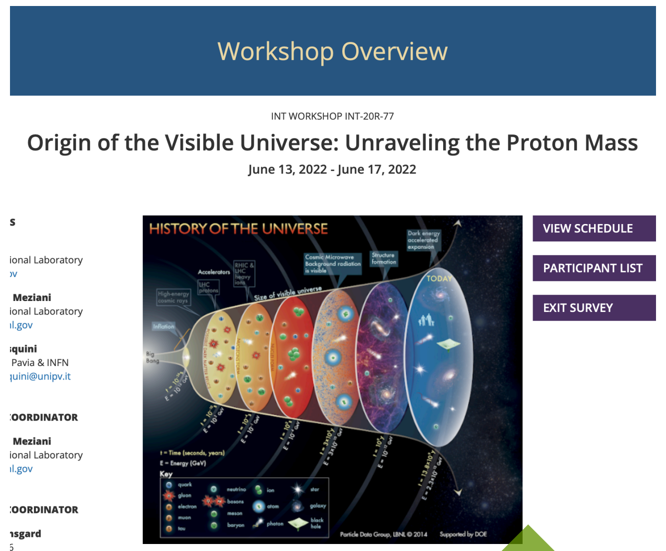
The proton mass: An important topic in contemporary hadronic physics!

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