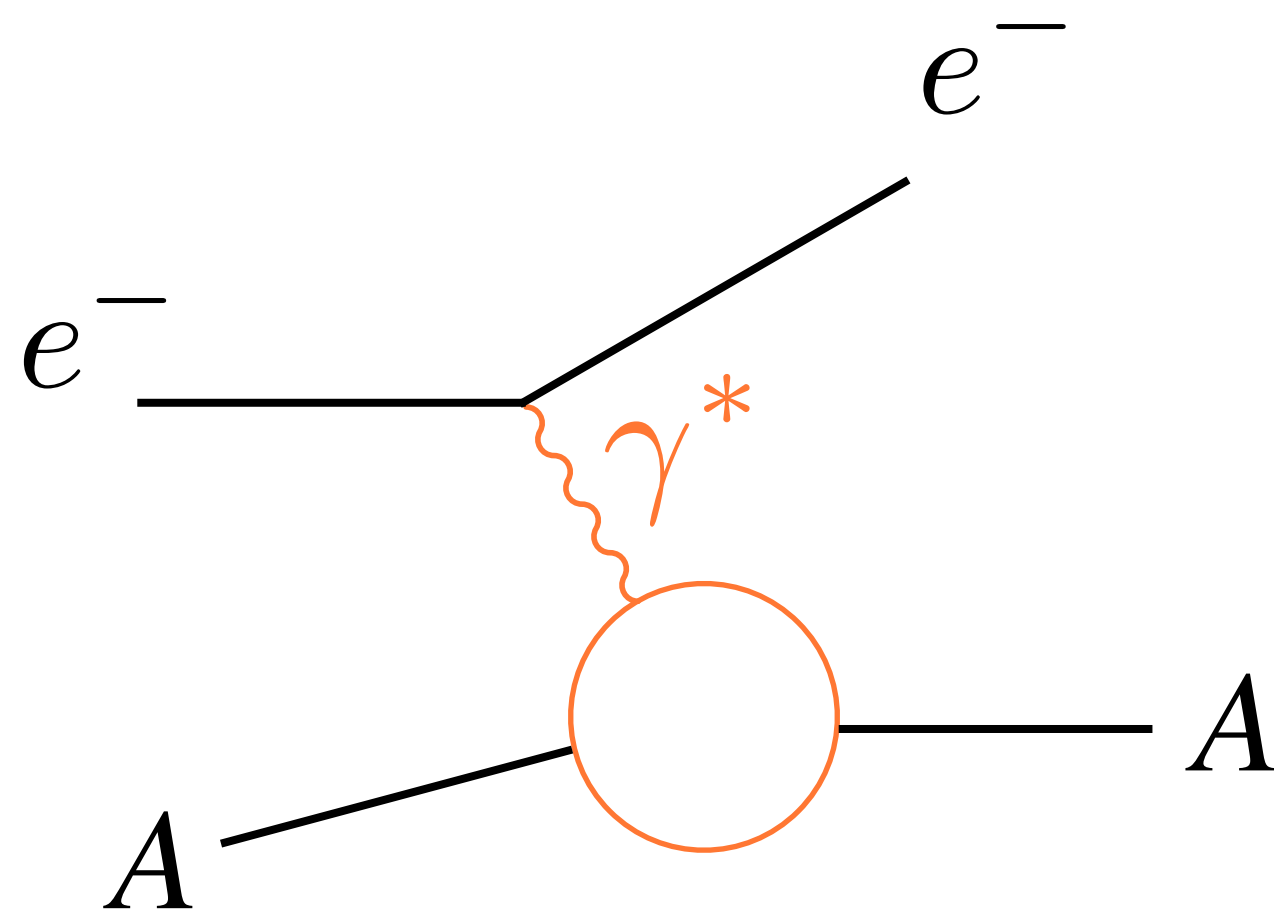


Near-Threshold Vector-Meson Photoproduction: Gravitational Form Factors and Exotic Hadrons

Keigo Mizutani
RCNP, The University of Osaka

New Perspectives on Exotic and Heavy Hadrons
Inha University, South Korea
26-Aug-2026



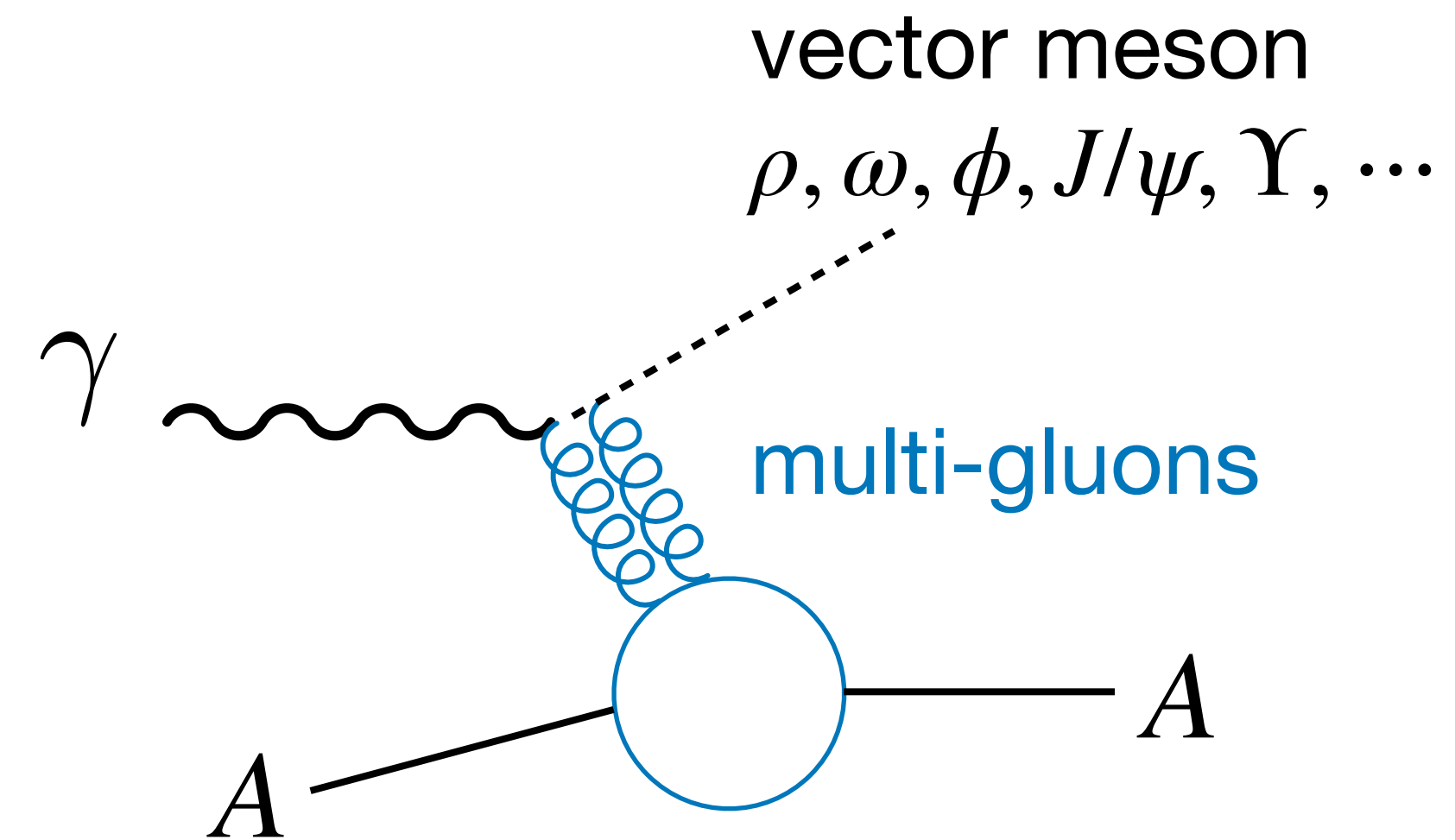
charge radius

spatial distribution of **quarks**

$$\langle R_C^2 \rangle = -6 \frac{dG_{\text{EM}}}{dQ^2} \Big|_{Q^2=0}$$

electromagnetic form factor

Electron scattering:
well-established probe of charge structure



mass radius

spatial distribution of **gluons** (& quarks)

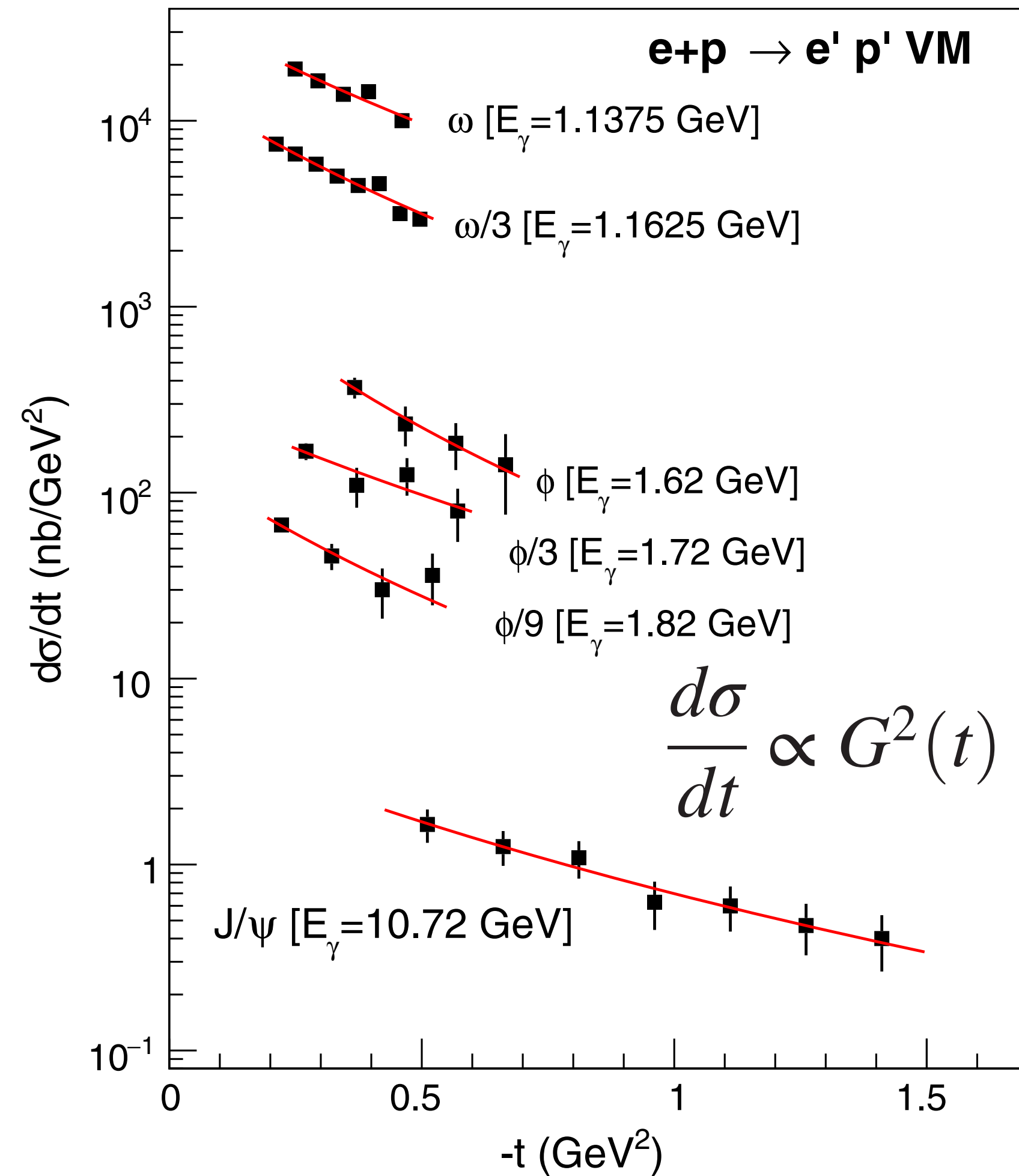
$$\langle R_m^2 \rangle = \frac{6}{M} \frac{dG}{dt} \Big|_{t=0}$$

nucleus mass

scalar gravitational form factor

Vector-meson photoproduction:
potential probe of gluonic / gravitational structure

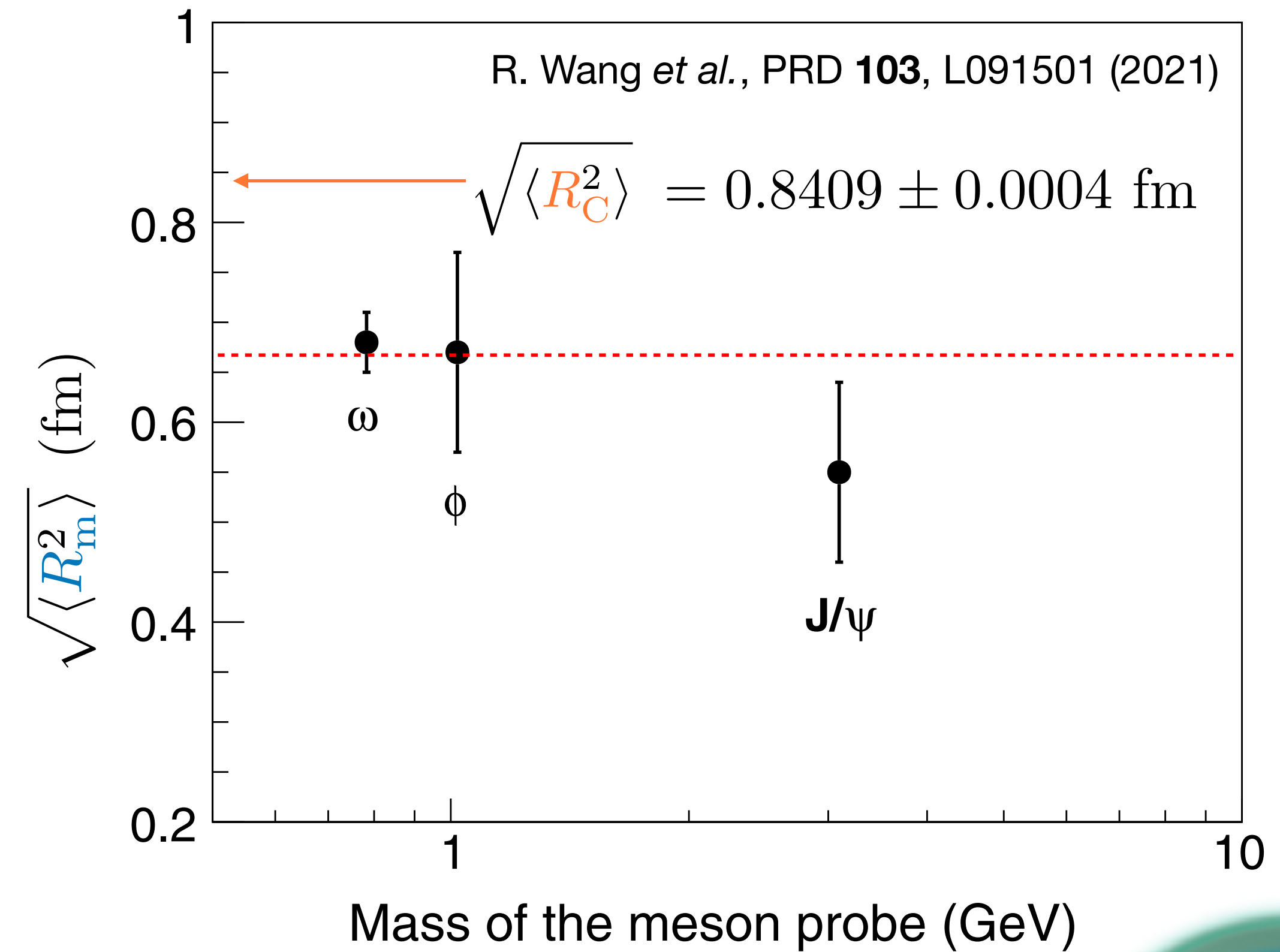
But only if the production mechanism is under control.



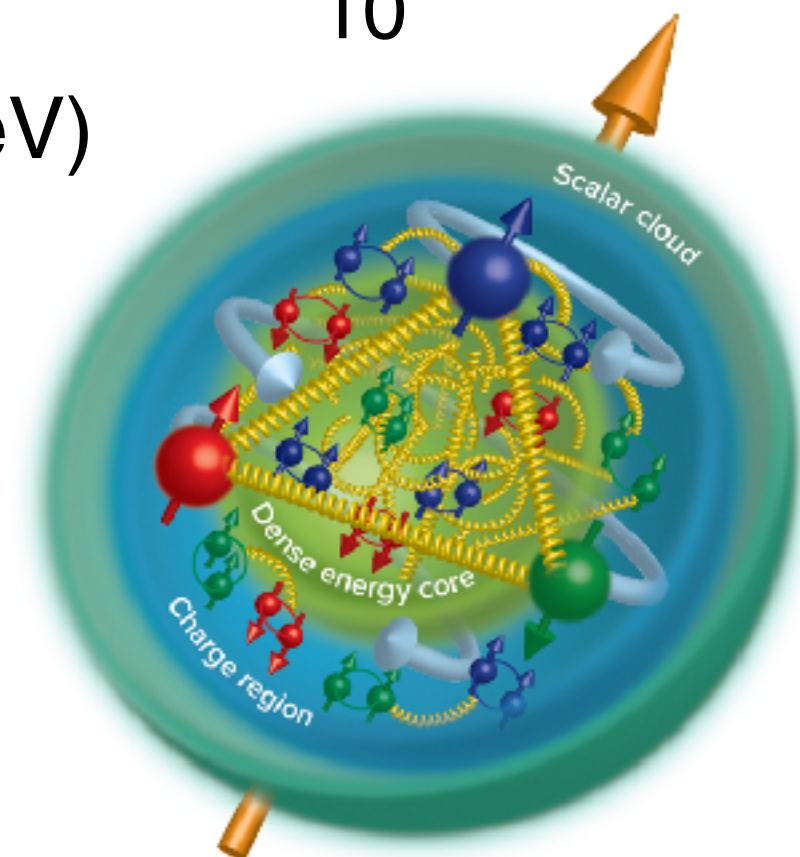
dipole-type scalar gravitational form factor

$$G(t) = \frac{M}{(1 - t/m_s^2)^2} \quad \langle R_m^2 \rangle = \frac{12}{m_s^2}$$

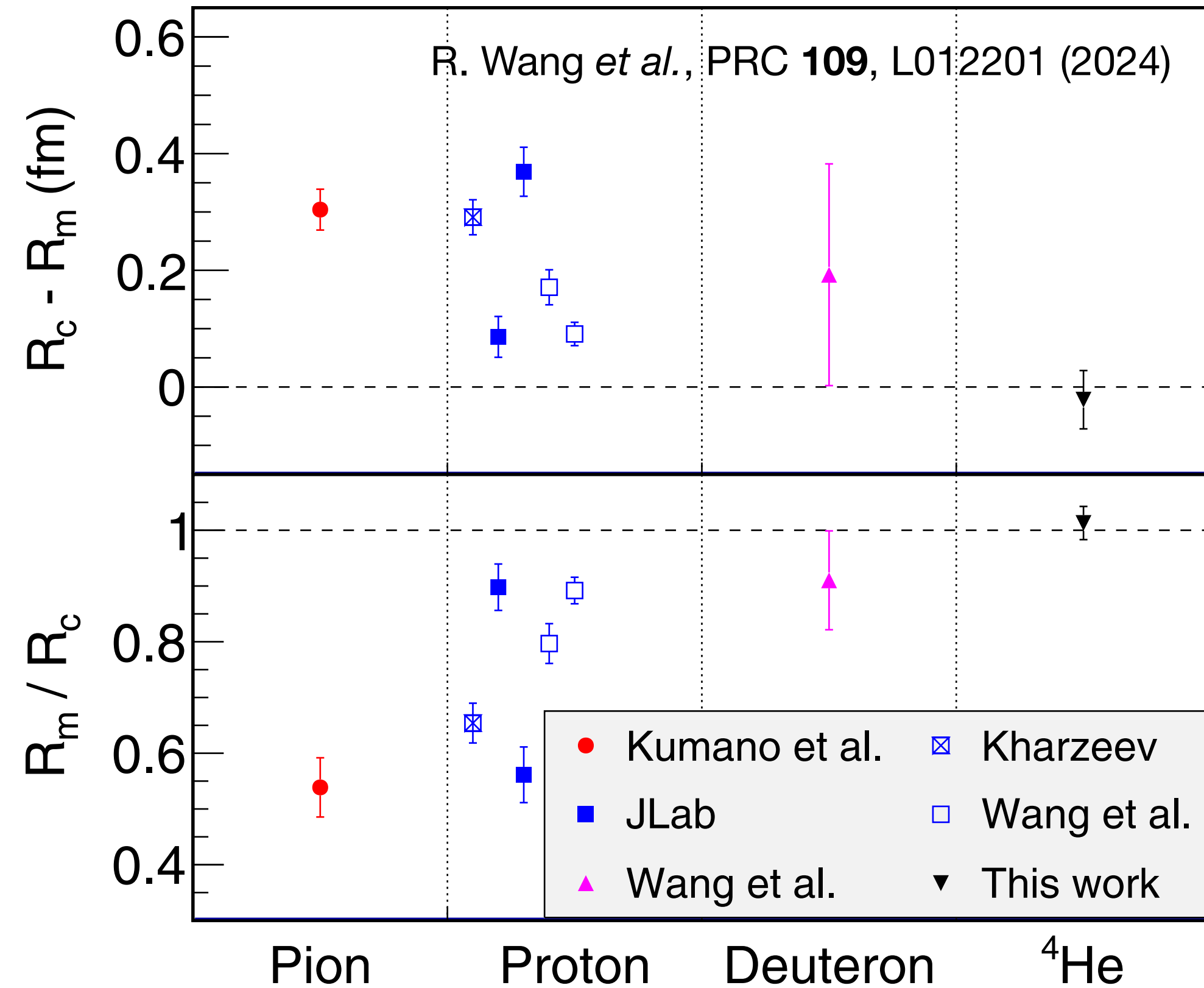
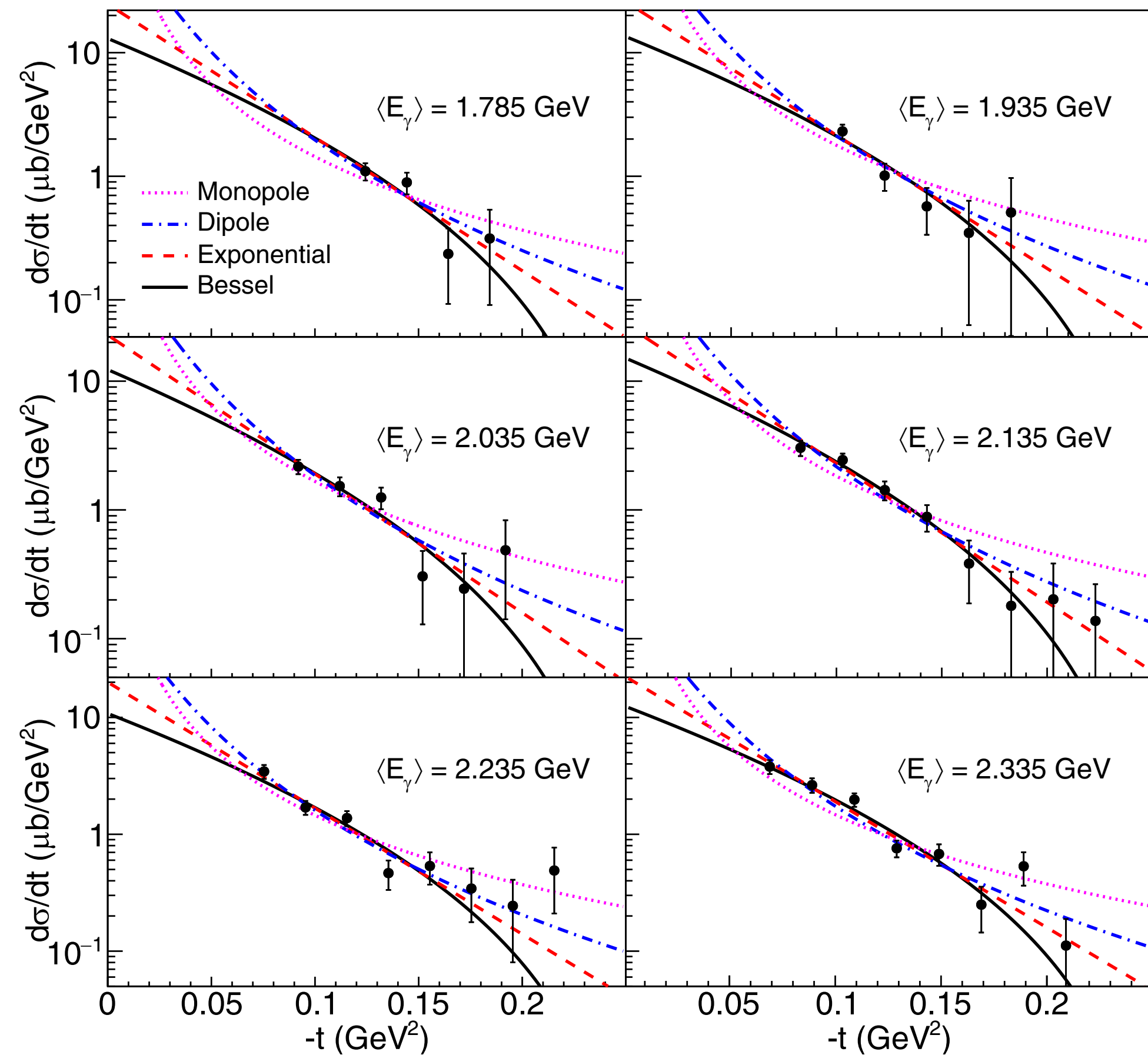
proton mass radius from different meson production channels



$$\langle R_m^2 \rangle < \langle R_C^2 \rangle \quad \text{gluon core?}$$

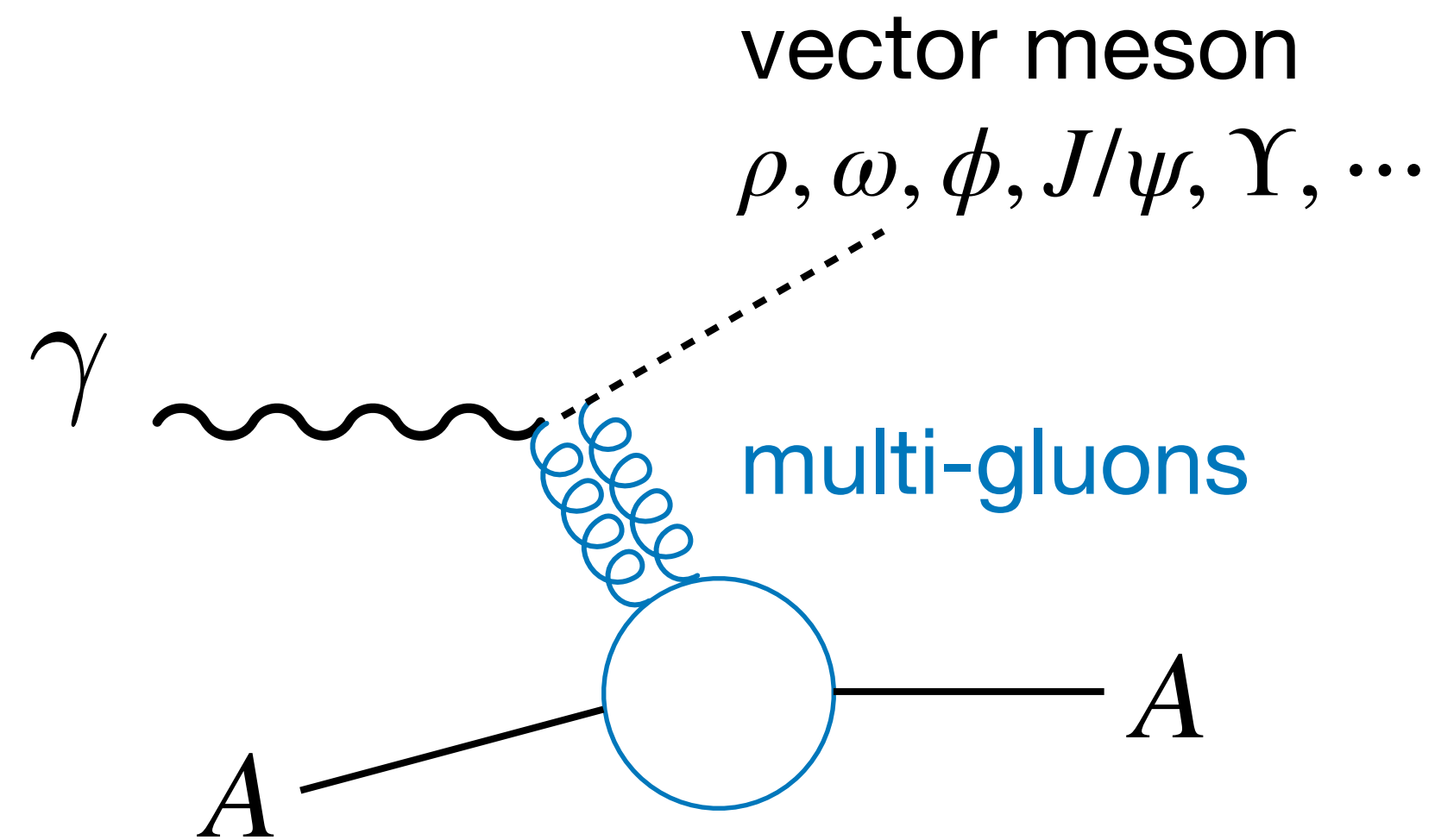


$$\gamma + {}^4\text{He} \rightarrow \phi + {}^4\text{He}$$



The same strategy can be extended to coherent production on nuclei.
 $\gamma A \rightarrow VA$ t -dep. $\rightarrow$ nuclear GFF $\rightarrow$ nuclear mass radius

- How does the mass distribution evolve from a nucleon to a nucleus?
- How does the mass radius compare with the charge radius?
- Is the nuclear gravitational structure simply inherited from nucleons?

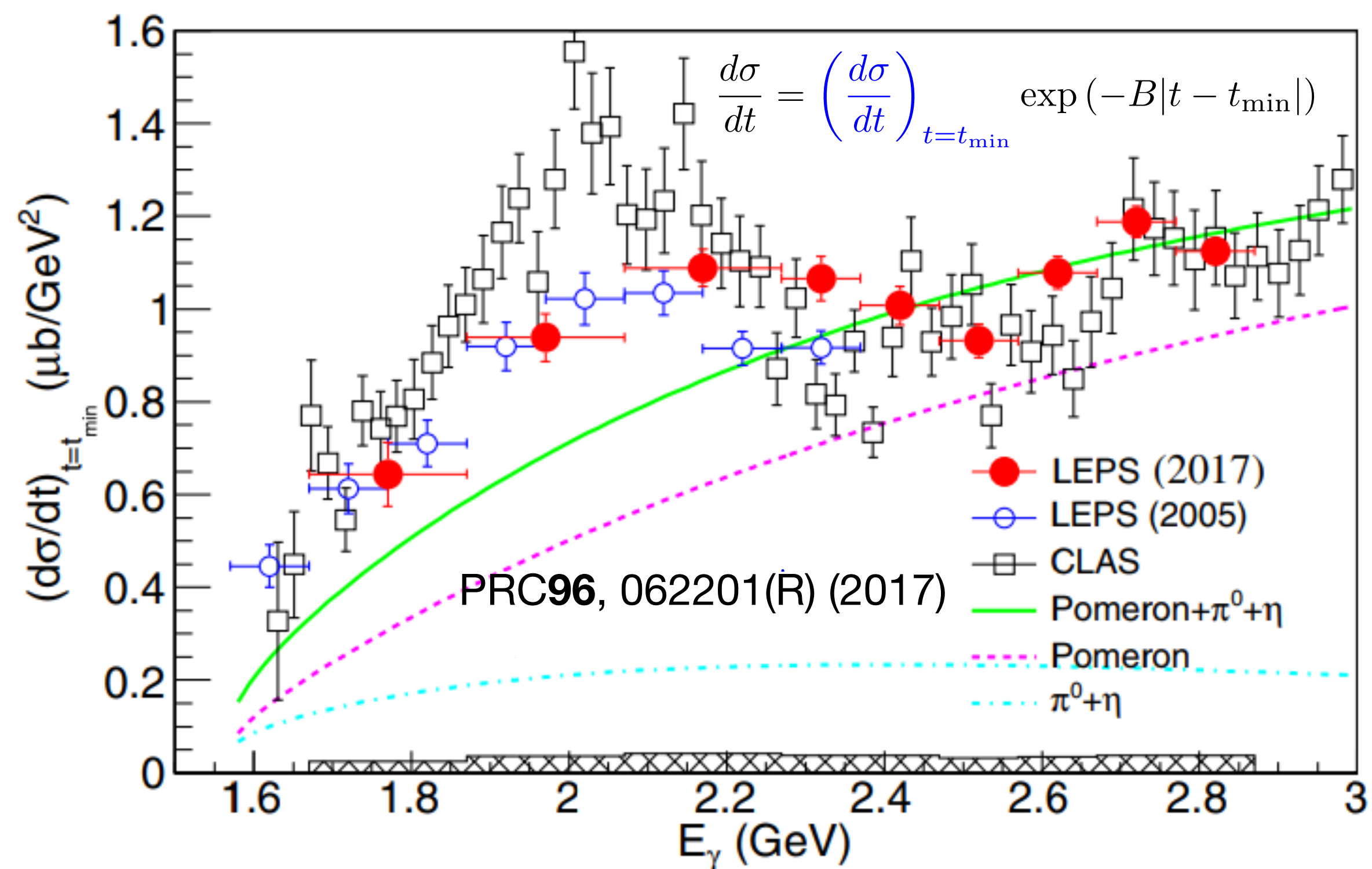


Does this mechanism really dominate near threshold?

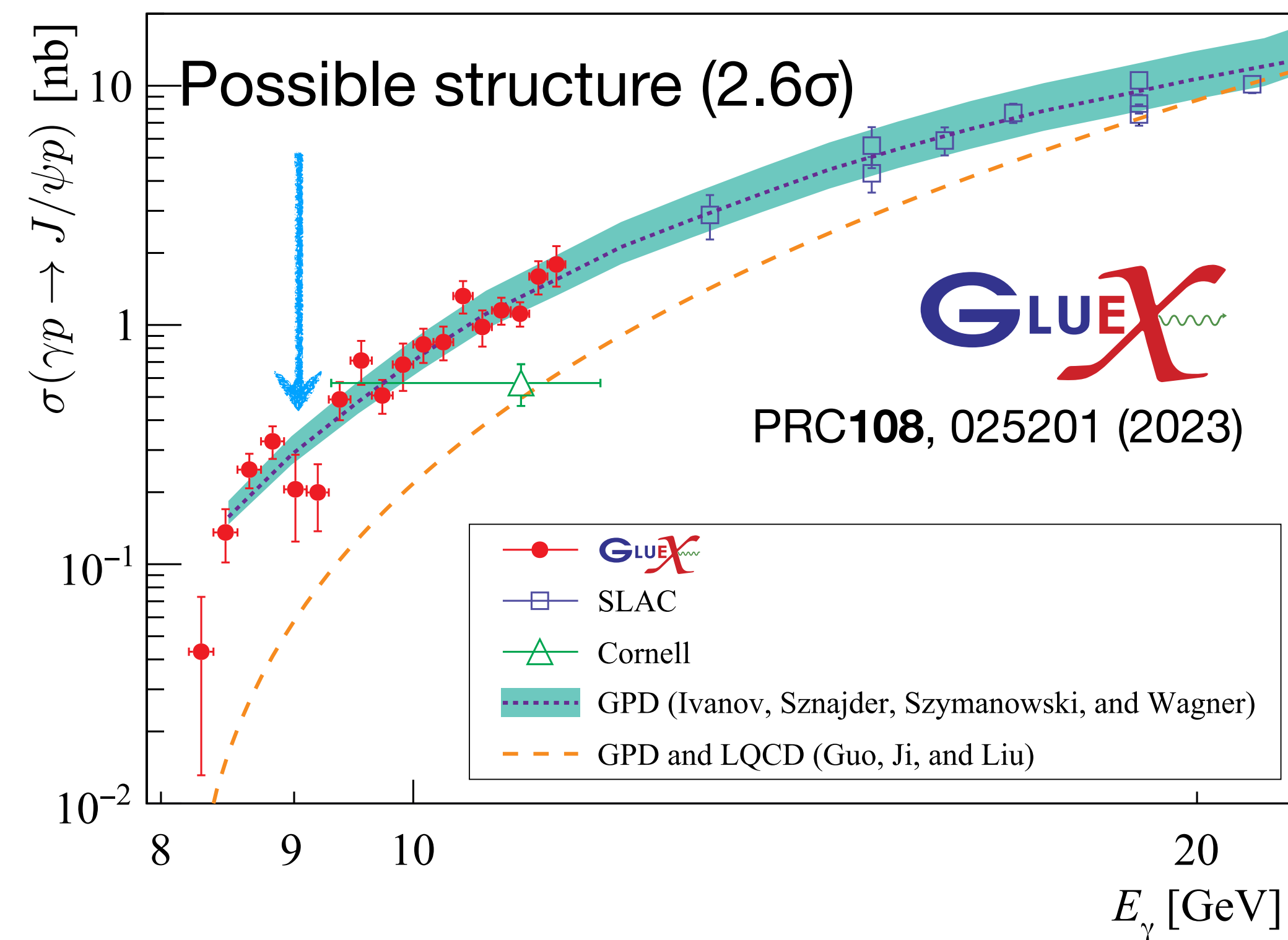
The interpretation of vector-meson photoproduction in terms of GFFs relies on assumptions about the production mechanism. Near threshold, other contributions may not be negligible.

How can we test the production mechanism experimentally?

$$\gamma p \rightarrow \phi p$$

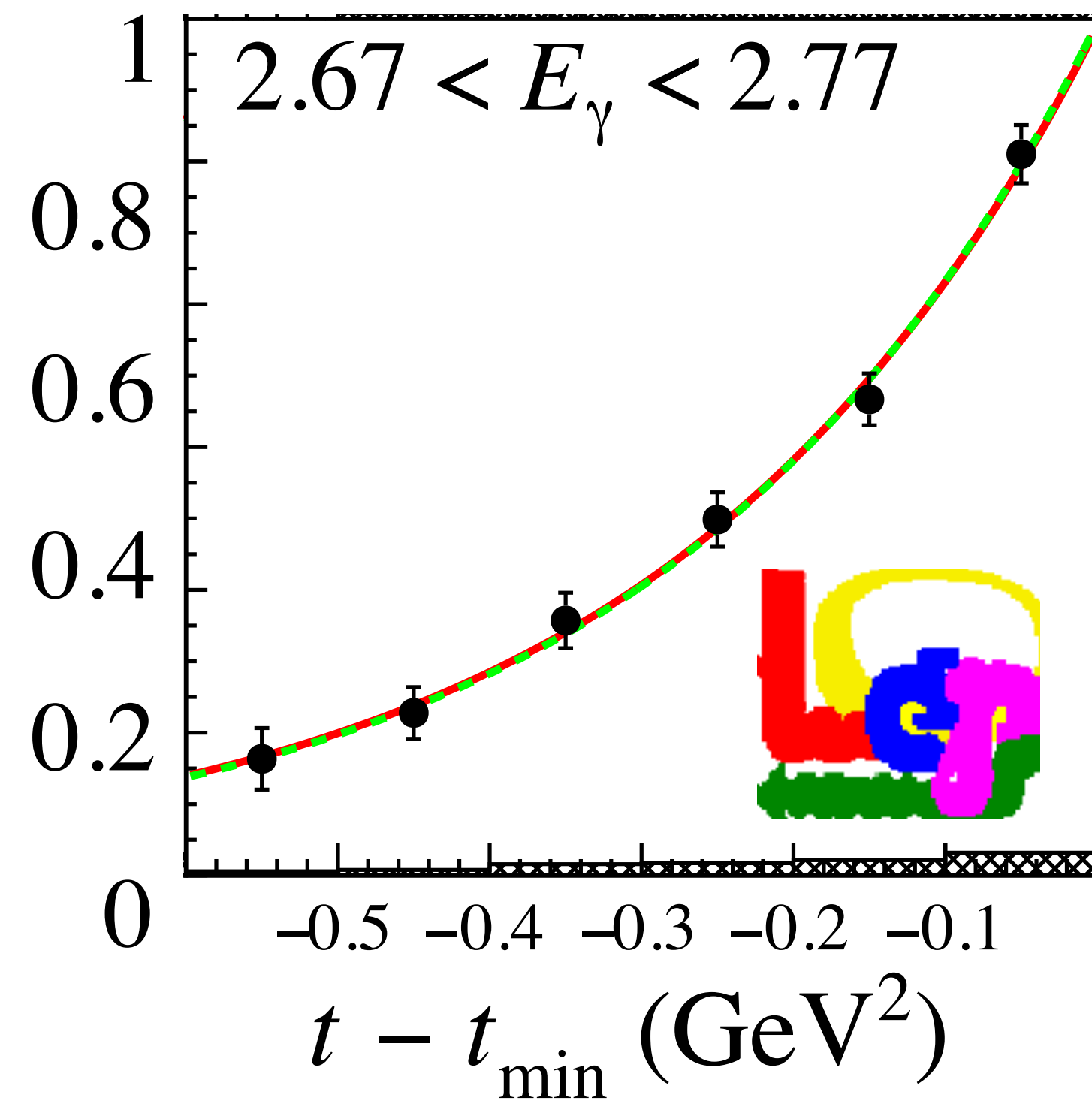


$$\gamma p \rightarrow J/\psi p$$

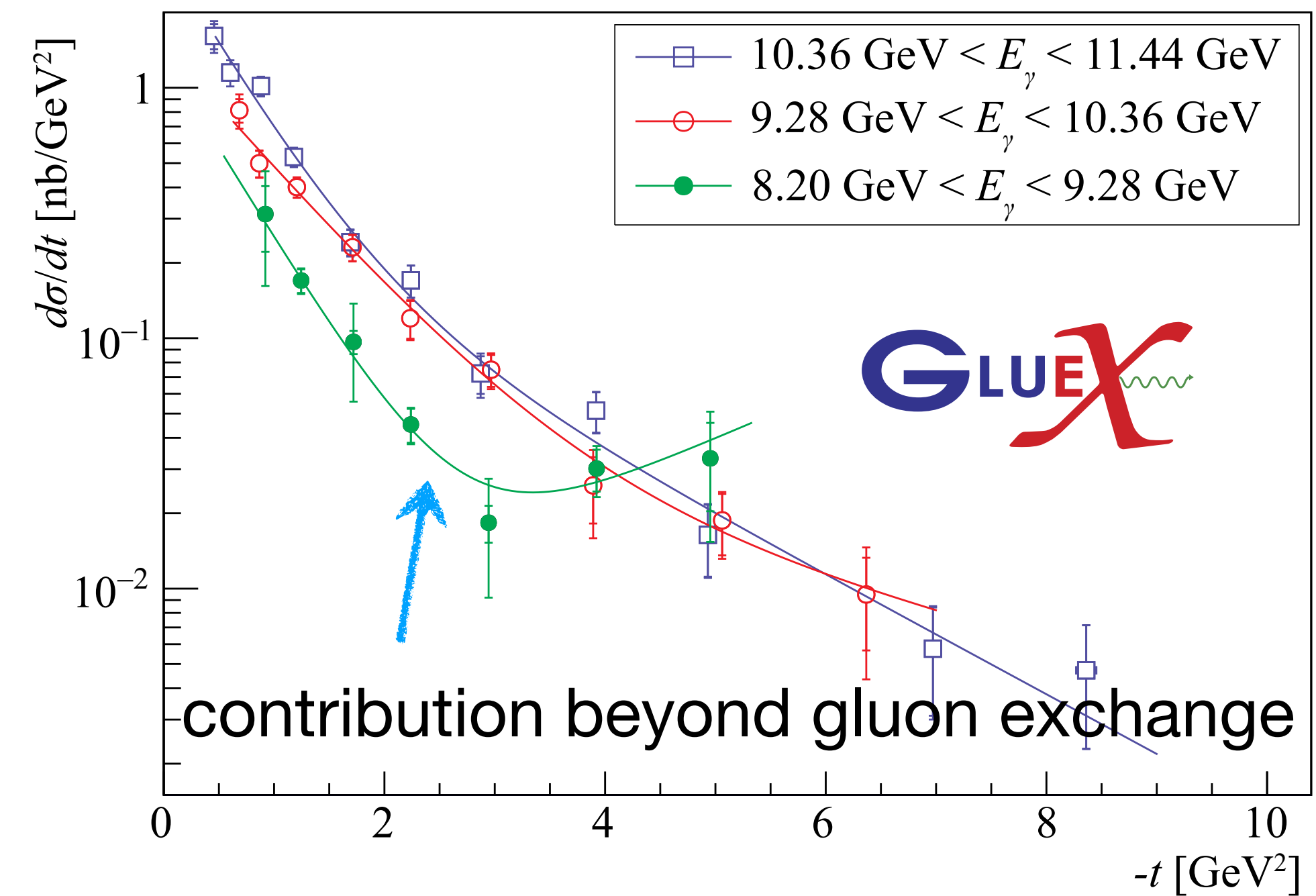


The threshold region may contain dynamics beyond a simple smooth multi-gluon-exchange picture.

$$\gamma p \rightarrow \phi p$$

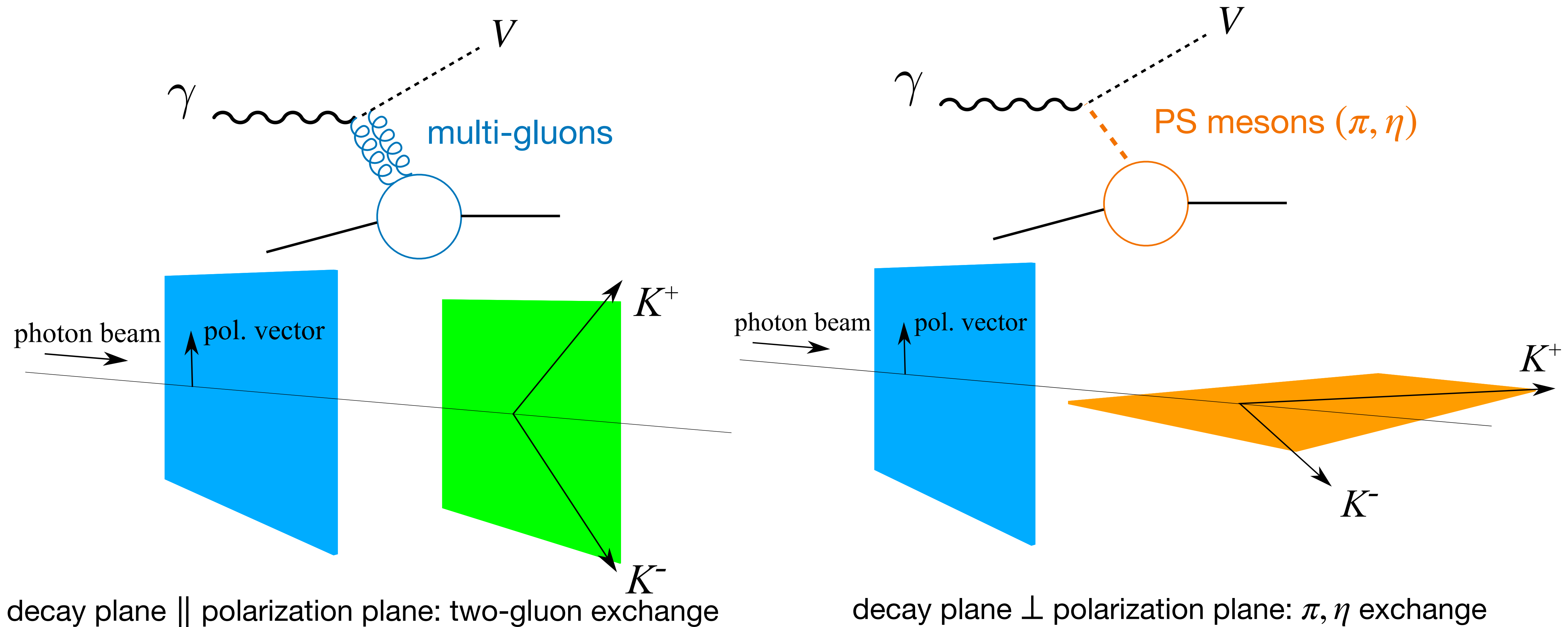


$$\gamma p \rightarrow J/\psi p$$



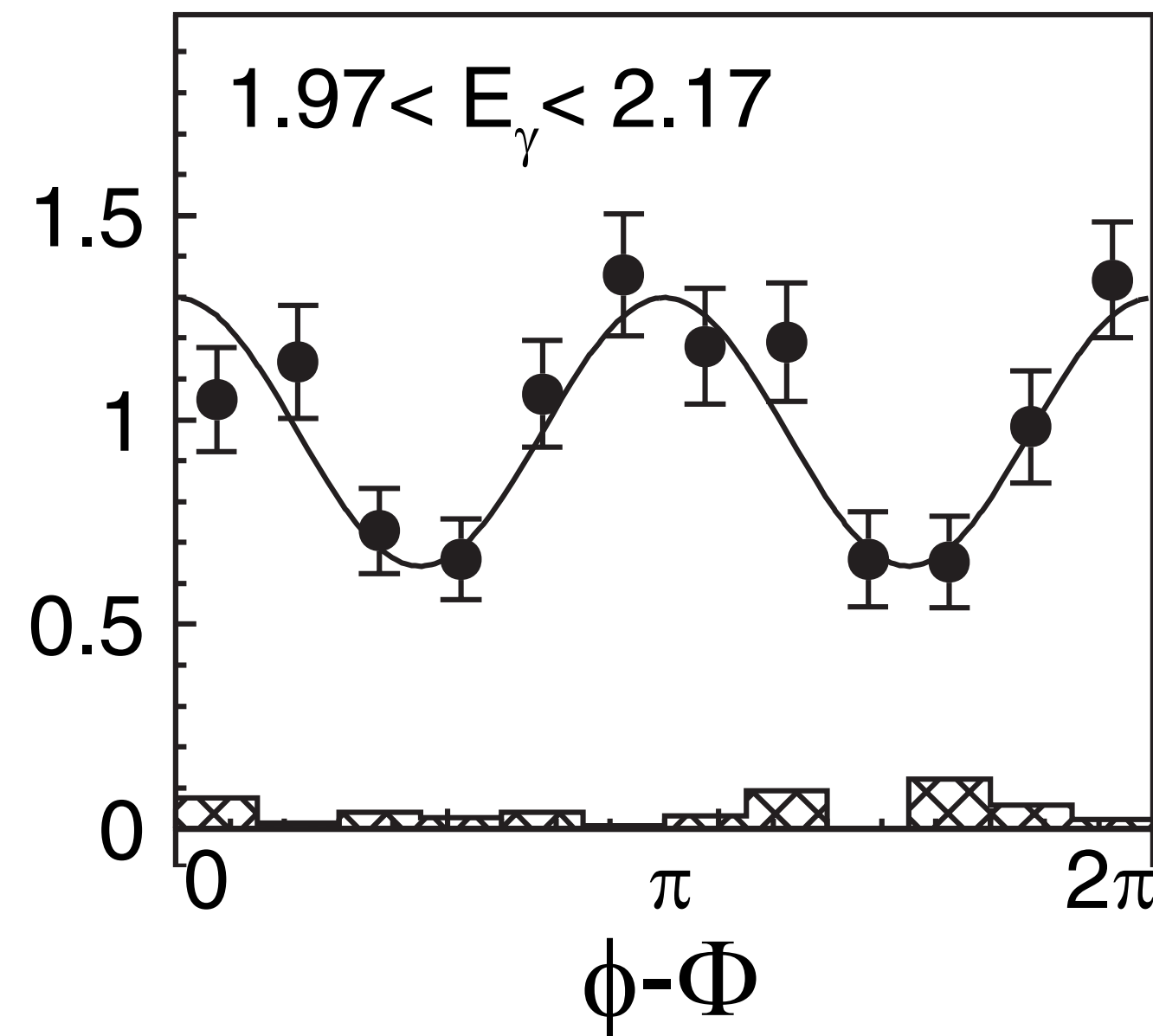
A forward t -channel picture works reasonably well.

Near threshold, the data indicate contributions beyond a simple forward t -channel production mechanism.



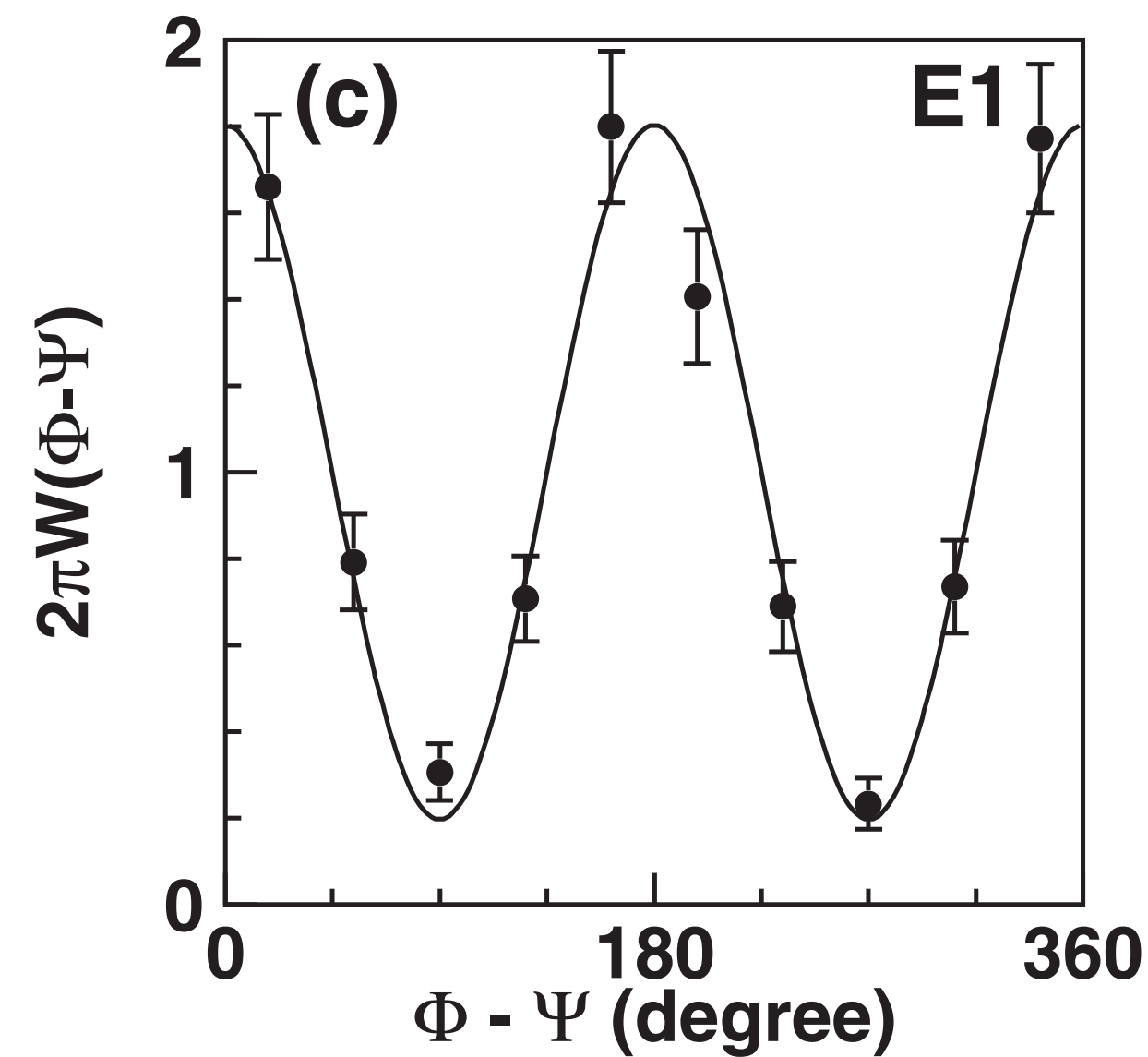
With linearly polarized photons, the vector-meson decay angular distribution is sensitive to the naturality of the exchanged amplitude.

$$\gamma p \rightarrow \phi p$$



70% natural-parity exch.
30% unnatural-parity exch.

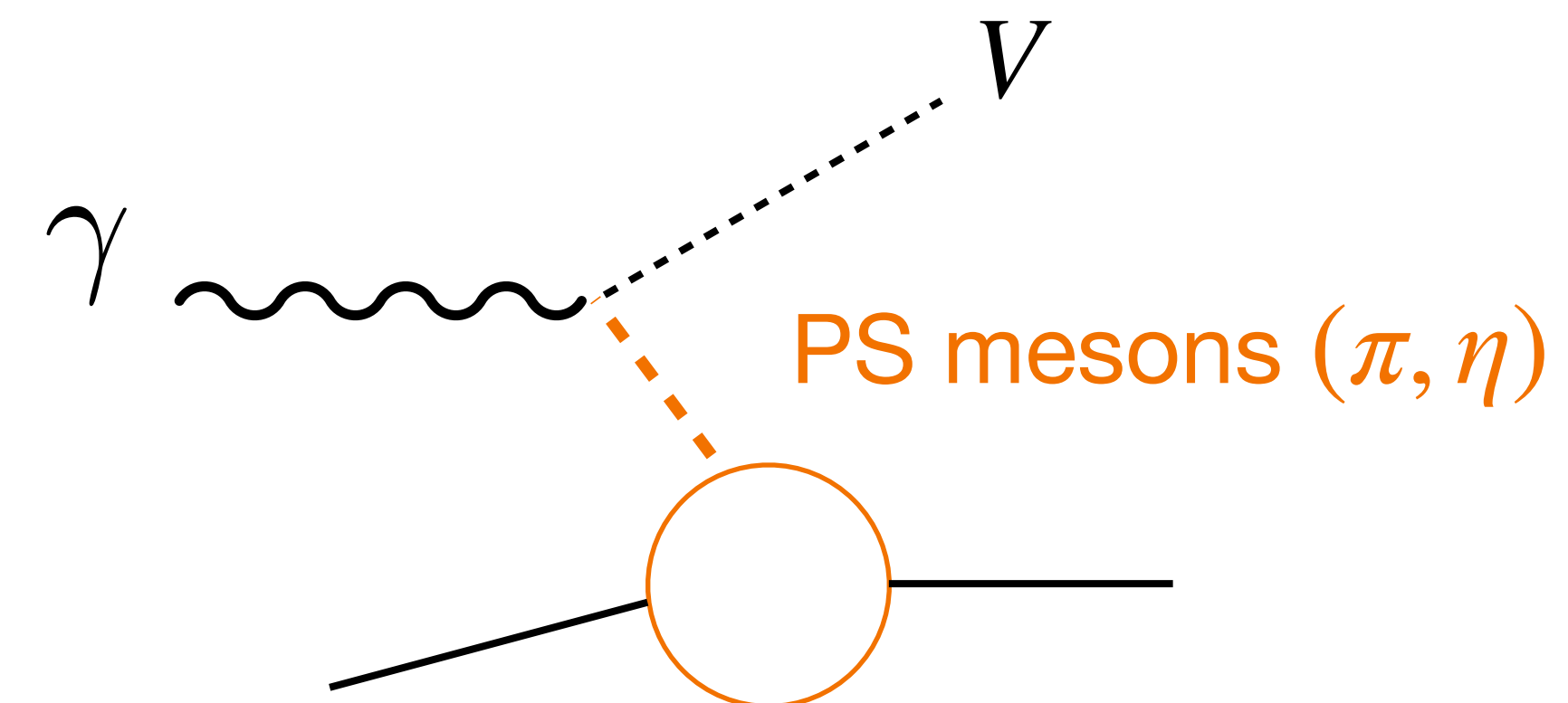
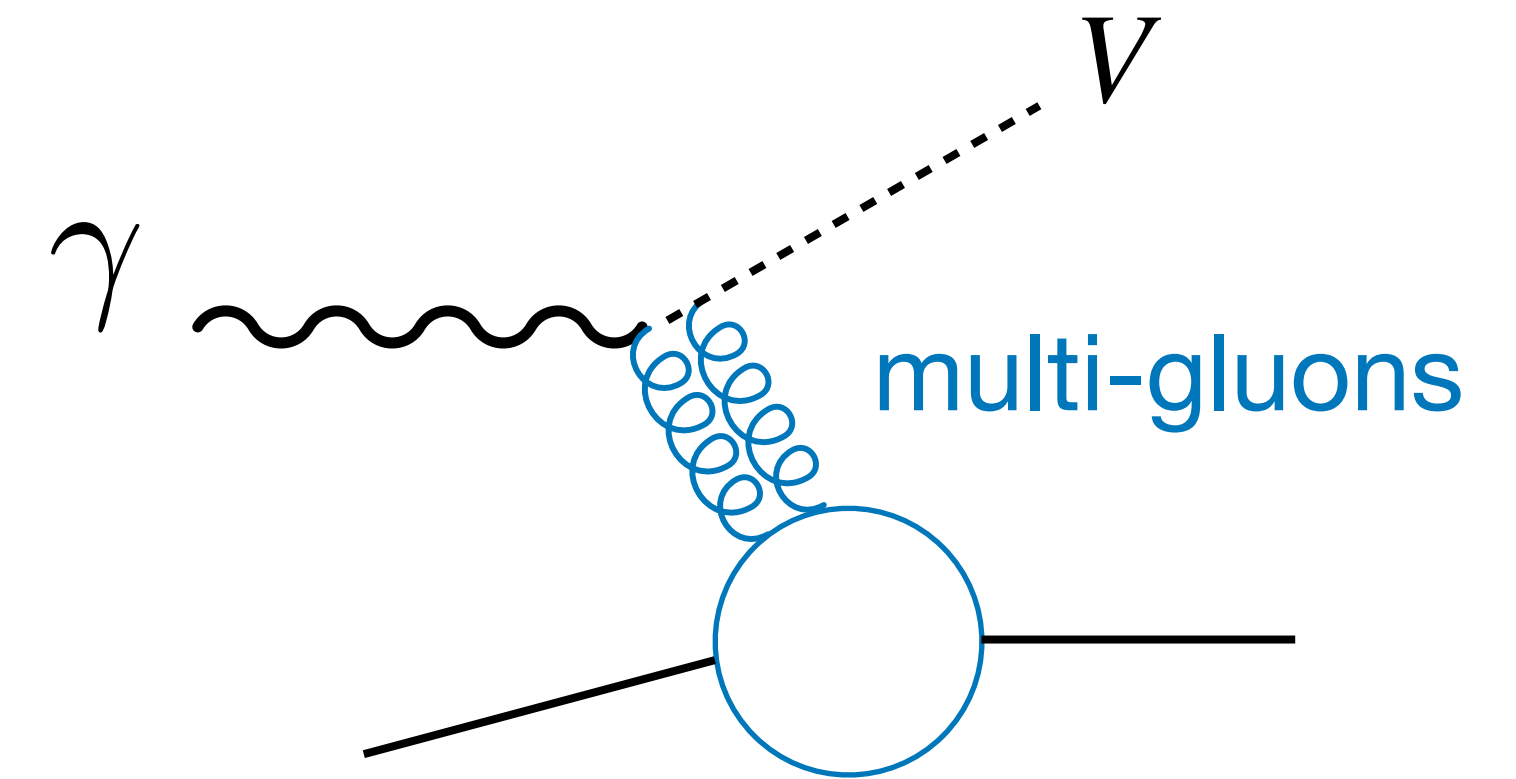
$$\gamma {}^4\text{He} \rightarrow \phi {}^4\text{He}$$



~100% natural-parity exch.

$${}^4\text{He} : J = I = 0$$

π, η cannot couple to He-4.

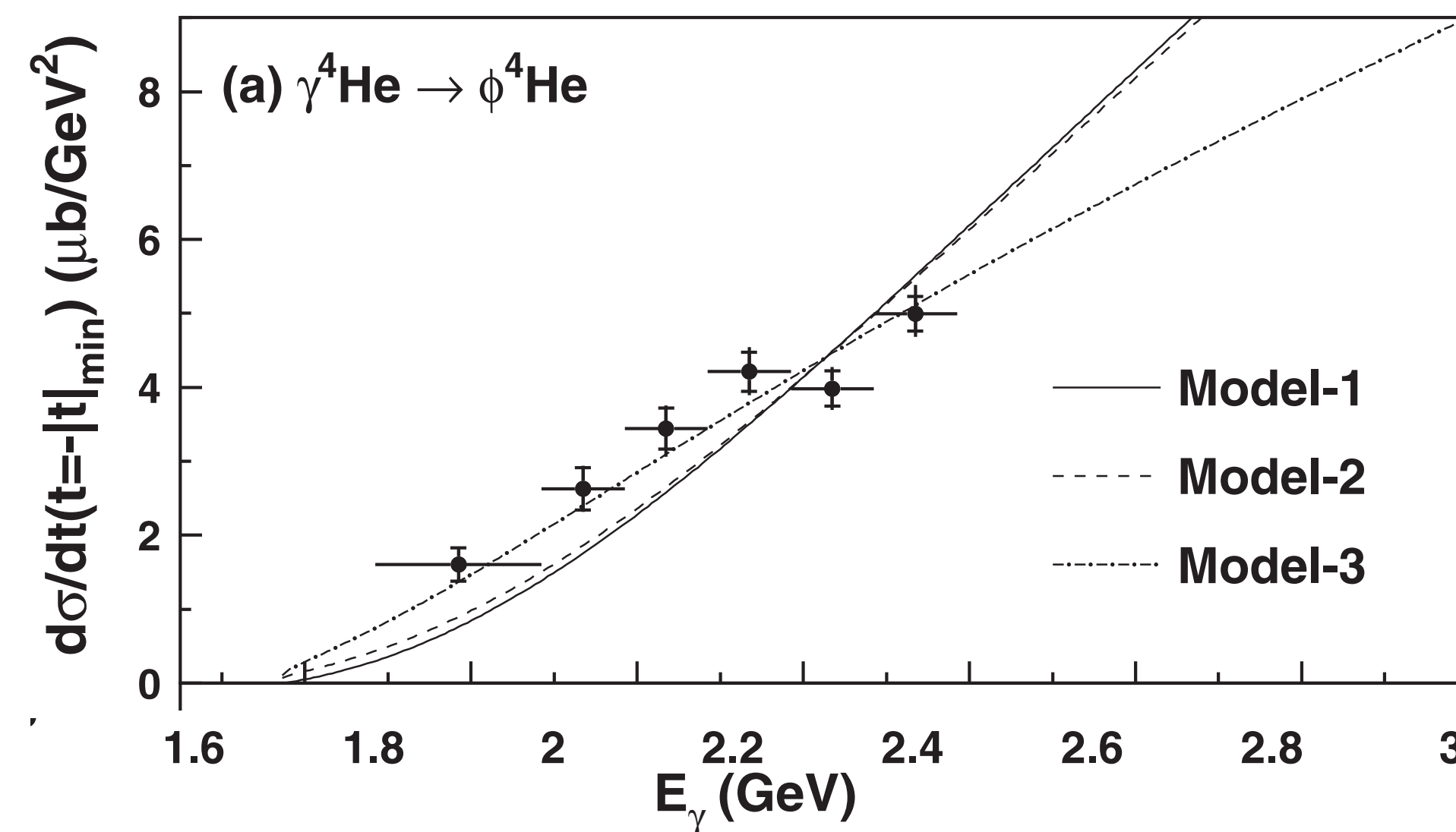
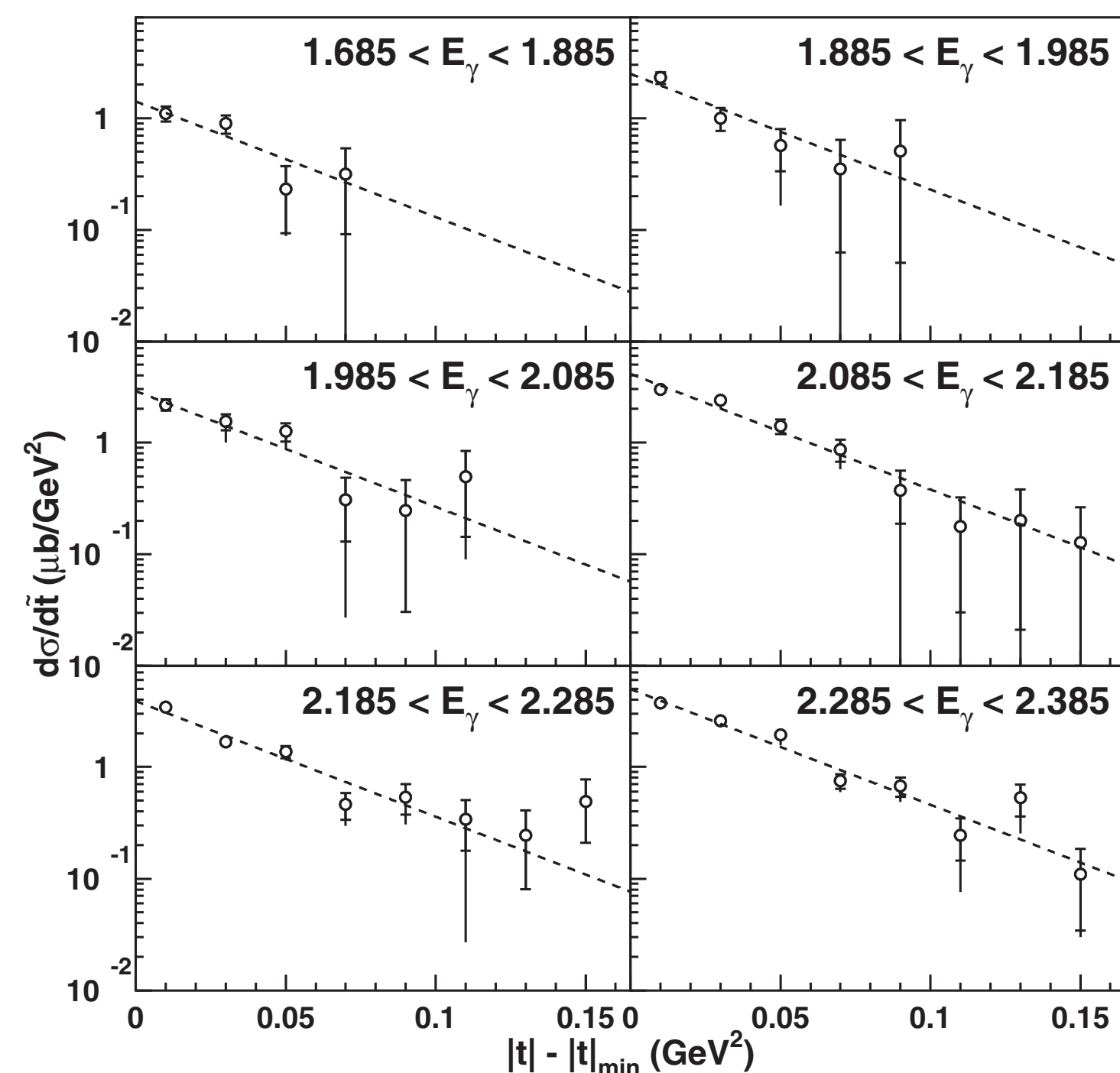
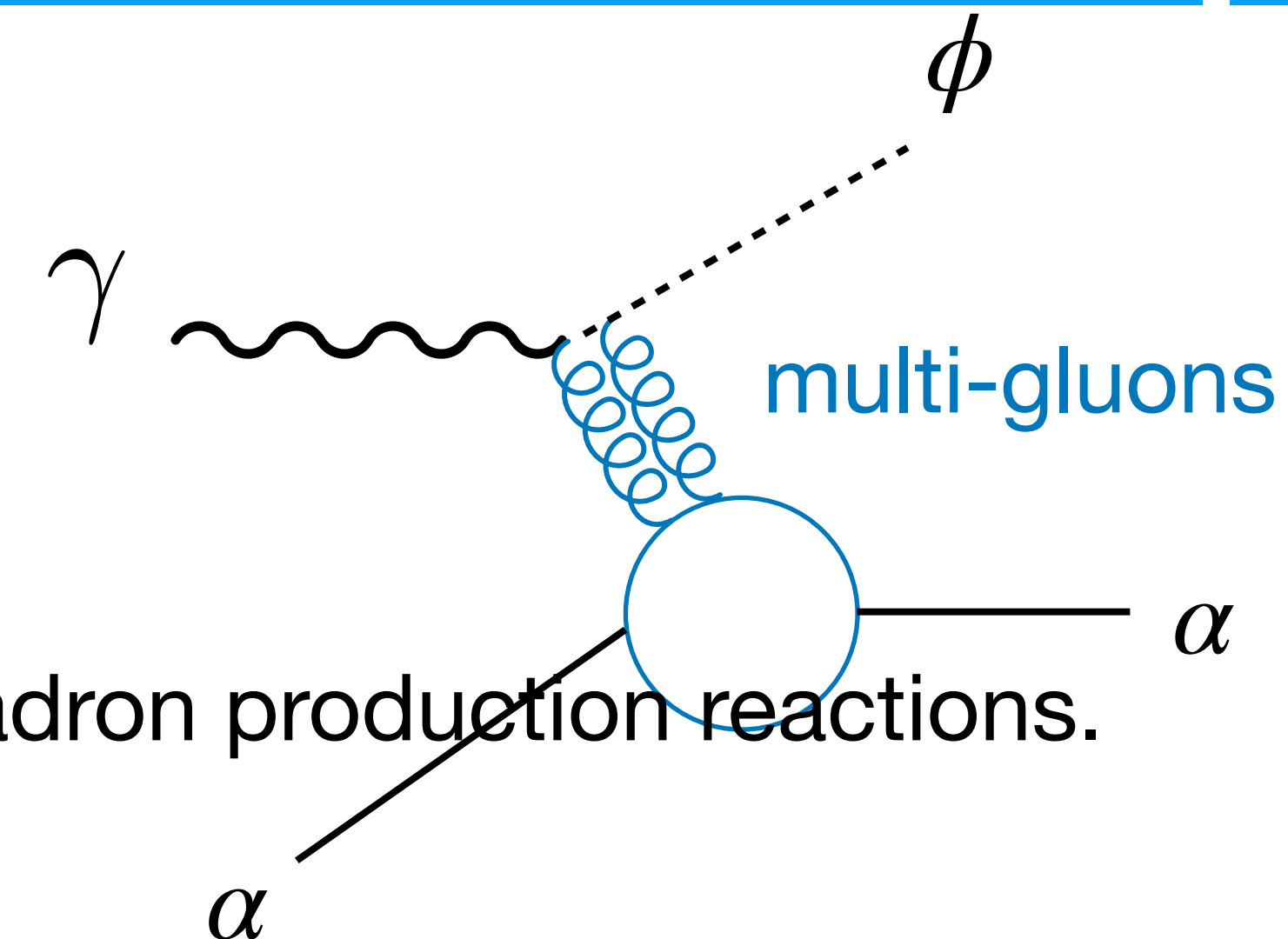


This is the experimental evidence that helium-4 acts as a spin/parity filter.

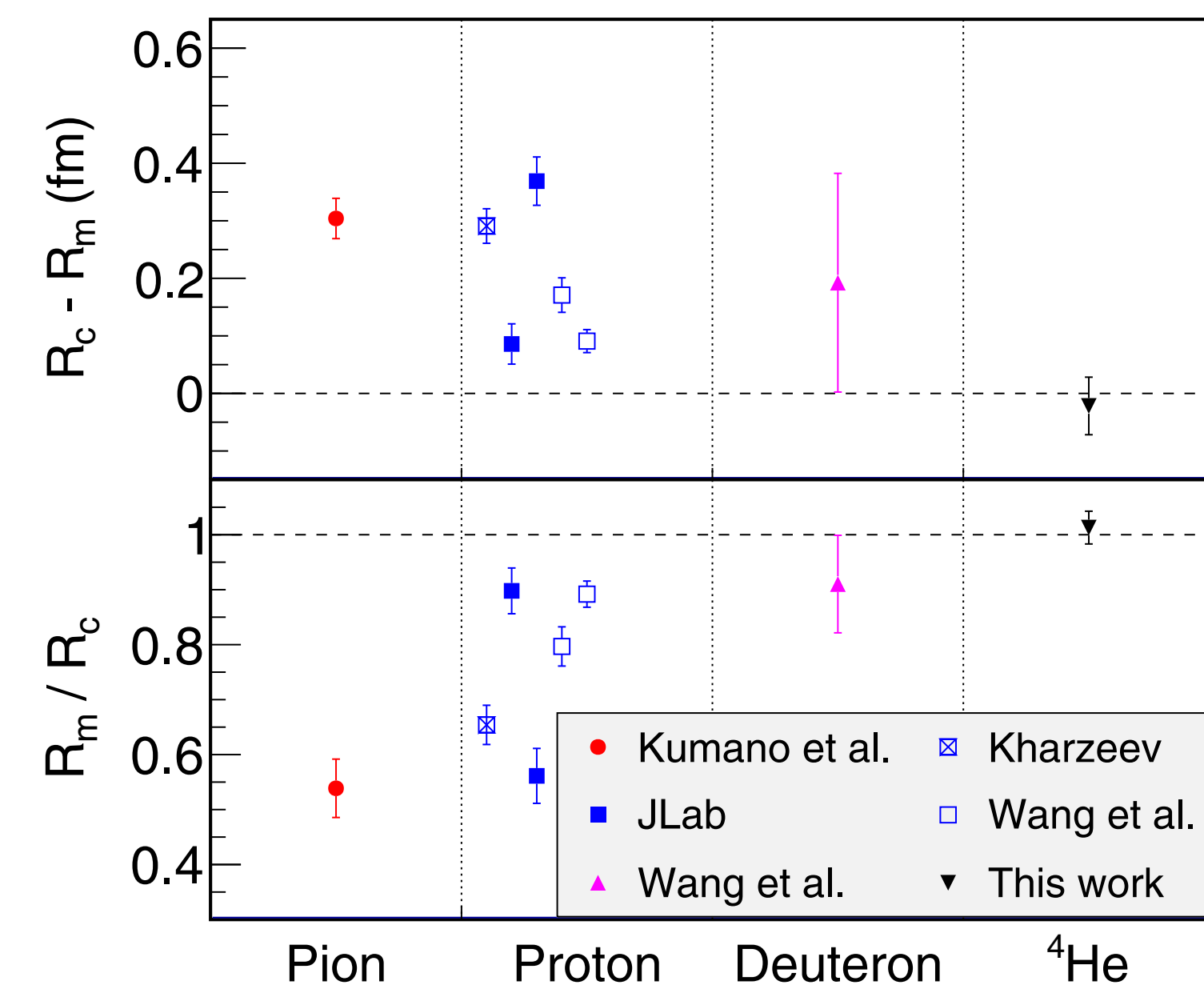
Simple in terms of production mechanisms:

- Few contributing mechanisms
- Few diagrams
- Minimal resonance contributions

→ $\gamma^4\text{He} \rightarrow \phi^4\text{He}$ (or $\gamma^4\text{He} \rightarrow V^4\text{He}$) is one of the “simplest” hadron production reactions.



Coh. vector meson photoprod. on He-4: **Clean baseline data** for understanding hadron production



Among these systems, the ⁴He extraction is particularly well controlled from the reaction-mechanism point of view.

- More statistics are still needed.
- The present fit does not explicitly include the vector-meson size.
- Measurements with different vector mesons are therefore particularly important.

A Measurement of ⁴He Coherent J/Ψ Photo-production at threshold in Hall C at Jefferson Lab; Towards a determination of ⁴He Gluonic Radius

W. Armstrong, I. Cloët, T.-S. H. Lee, S. Joosten, Z.-E. Meziani
Physics Division, Argonne National Laboratory, Argonne, IL 60439, USA

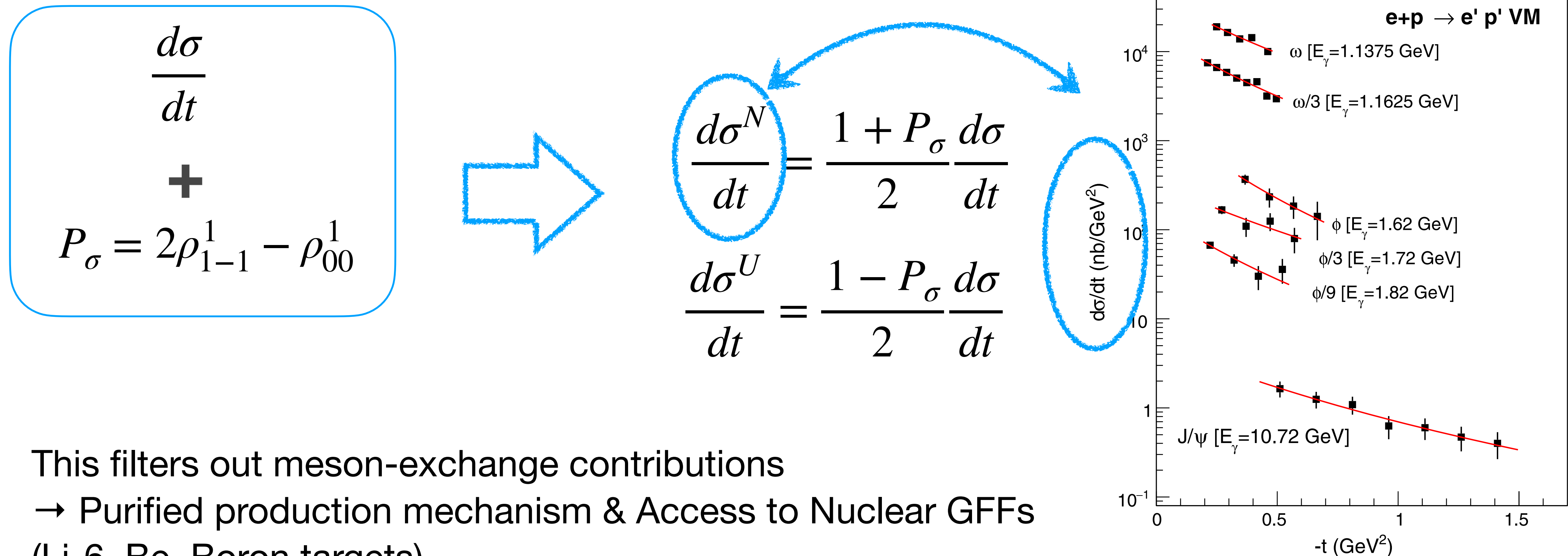
M. Jones
Jefferson Lab, Newport News, VA 23606, USA

A Letter of Intent to PAC47

$\gamma^4\text{He} \rightarrow \omega^4\text{He}$ can be accessed at LEPS and RARiS.

For nuclei where both natural- and unnatural-parity exchange contribute:

- Decay asymmetries (SDMEs) allow us to separate the two components.
- The t dependence of the natural-parity component can then be studied independently.



This filters out meson-exchange contributions

→ Purified production mechanism & Access to Nuclear GFFs
(Li-6, Be, Boron targets)

Ongoing: Application of this N/U separation to existing LEPS data.

1. Simple coherent systems

e.g. ^4He

→ use the target itself as a reaction filter

2. Polarization / decay-asymmetry measurements

→ separate natural- and unnatural-parity components

→ study $d\sigma^N/dt$

3. Different vector mesons

$\omega, \phi, J/\psi$ → test probe dependence

→ check the robustness of the extracted GFF / mass radius

Experiment + reaction theory → constrain the production mechanism

- Near-threshold vector-meson photoproduction is a promising probe of hadron and nuclear structure, including gravitational form factors.
- Near threshold, the energy and t dependences indicate that a simple production picture is not always sufficient.
- Coherent production on simple nuclei such as He-4 can strongly filter the reaction mechanism.
- Decay asymmetries provide information beyond $d\sigma/dt$ and allow natural- and unnatural-parity contributions to be separated.
- Measurements with different vector mesons provide an important consistency check of the extracted GFF / mass radius.

Cross sections + decay asymmetries + target dependence
→ **constrain the production mechanism**
→ **more reliable structure extraction**

The same reaction-mechanism control is also essential for exotic-hadron searches.

PHYSICAL REVIEW D **103**, L091501 (2021)

Letter

Extraction of the proton mass radius from the vector meson photoproductions near thresholds

Rong Wang^{1,2,*}, Wei Kou^{1,2,†}, Ya-Ping Xie^{1,2,‡} and Xurong Chen^{1,2,3,§}

¹*Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China*

²*University of Chinese Academy of Sciences, Beijing 100049, China*

³*Guangdong Provincial Key Laboratory of Nuclear Science, Institute of Quantum Matter, South China Normal University, Guangzhou 510006, China*

 (Received 10 March 2021; accepted 15 April 2021; published 11 May 2021)

We present an analysis of the proton mass radius by studying the t dependence of the differential cross sections of the vector meson photoproductions near the thresholds. At low energy, the photoproduction of a quarkonium off the proton is connected to the scalar gravitational form factor of the proton, which is sensitive to the proton mass distribution from the quantum chromodynamics trace anomaly. Under an assumption of the scalar form factor of dipole form, the proton mass radius is extracted via the near-threshold photoproduction data of J/ψ , ϕ , and ω vector mesons. The average value of the proton mass radius is estimated to be $\sqrt{\langle R_m^2 \rangle} = 0.67 \pm 0.03$ fm, with the dipole cutoff $m_s = 1.01 \pm 0.04$ GeV.

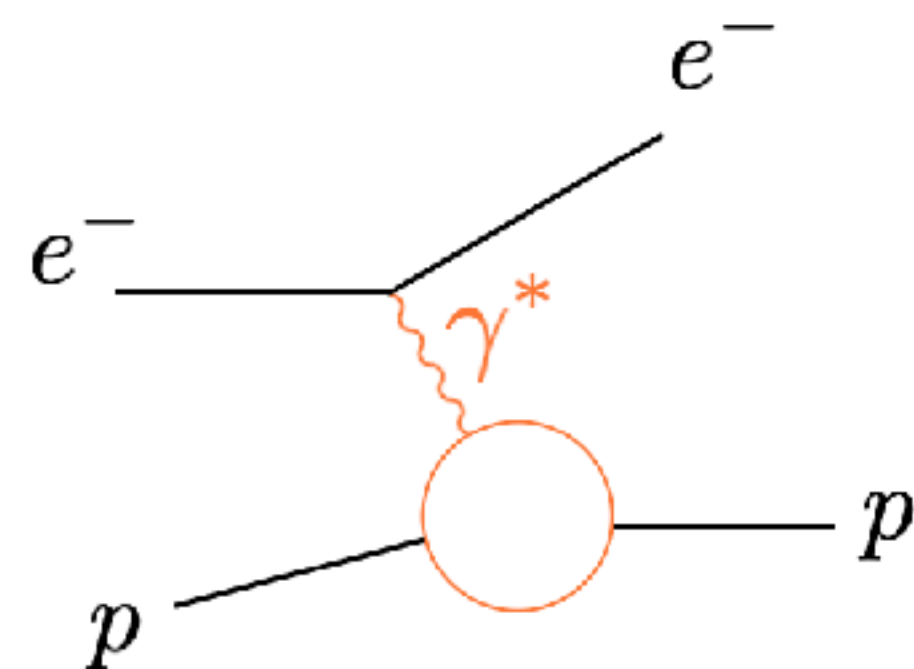
DOI: [10.1103/PhysRevD.103.L091501](https://doi.org/10.1103/PhysRevD.103.L091501)

The proton matrix element of EMT contains three gravitational form factors (GFFs) $[A(t), B(t), D(t)]$ [3,4,15–18], which is written as

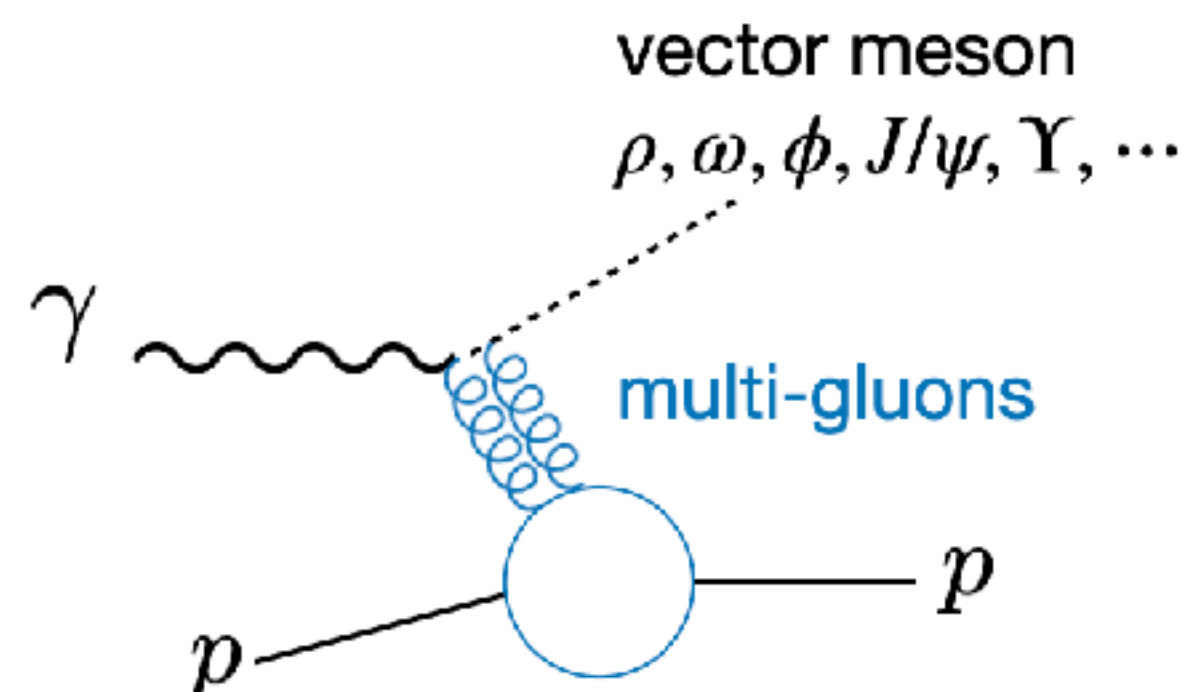
$$\langle p' | T_{\mu\nu} | p \rangle = \bar{u}' \left[A(t) \frac{\gamma_{\{\mu} P_{\nu\}}}{2} + B(t) \frac{i P_{\{\mu} \sigma_{\nu\} \rho} \Delta^\rho}{4m} + D(t) \frac{\Delta_\mu \Delta_\nu - g_{\mu\nu} \Delta^2}{4m} + m \bar{c}(t) g_{\mu\nu} \right] u e^{i(p'-p)x}, \quad (1)$$

where the kinematic variables are $P = \frac{1}{2}(p' + p)$, $\Delta = p' - p$, $t = \Delta^2$, and the covariant normalization is expressed as $\langle p' | p \rangle = 2p^0 (2\pi)^3 \delta^{(3)}(\mathbf{p}' - \mathbf{p})$. Using the Gordon identity $2m \bar{u}' \gamma^\alpha u = \bar{u}' (2P^\alpha + i\sigma^{\alpha\kappa} \Delta_\kappa) u$ an alternative decomposition is given by [18]

$$\langle p' | T_{\mu\nu} | p \rangle = \bar{u}' \left[A(t) \frac{P_\mu P_\nu}{m} + J(t) \frac{i P_{\{\mu} \sigma_{\nu\} \rho} \Delta^\rho}{2m} + D(t) \frac{\Delta_\mu \Delta_\nu - g_{\mu\nu} \Delta^2}{4m} + m \bar{c}(t) g_{\mu\nu} \right] u e^{i(p'-p)x}. \quad (2)$$



charge radius
spatial distribution of **quarks**



mass radius
spatial distribution of **gluons** (& quarks)

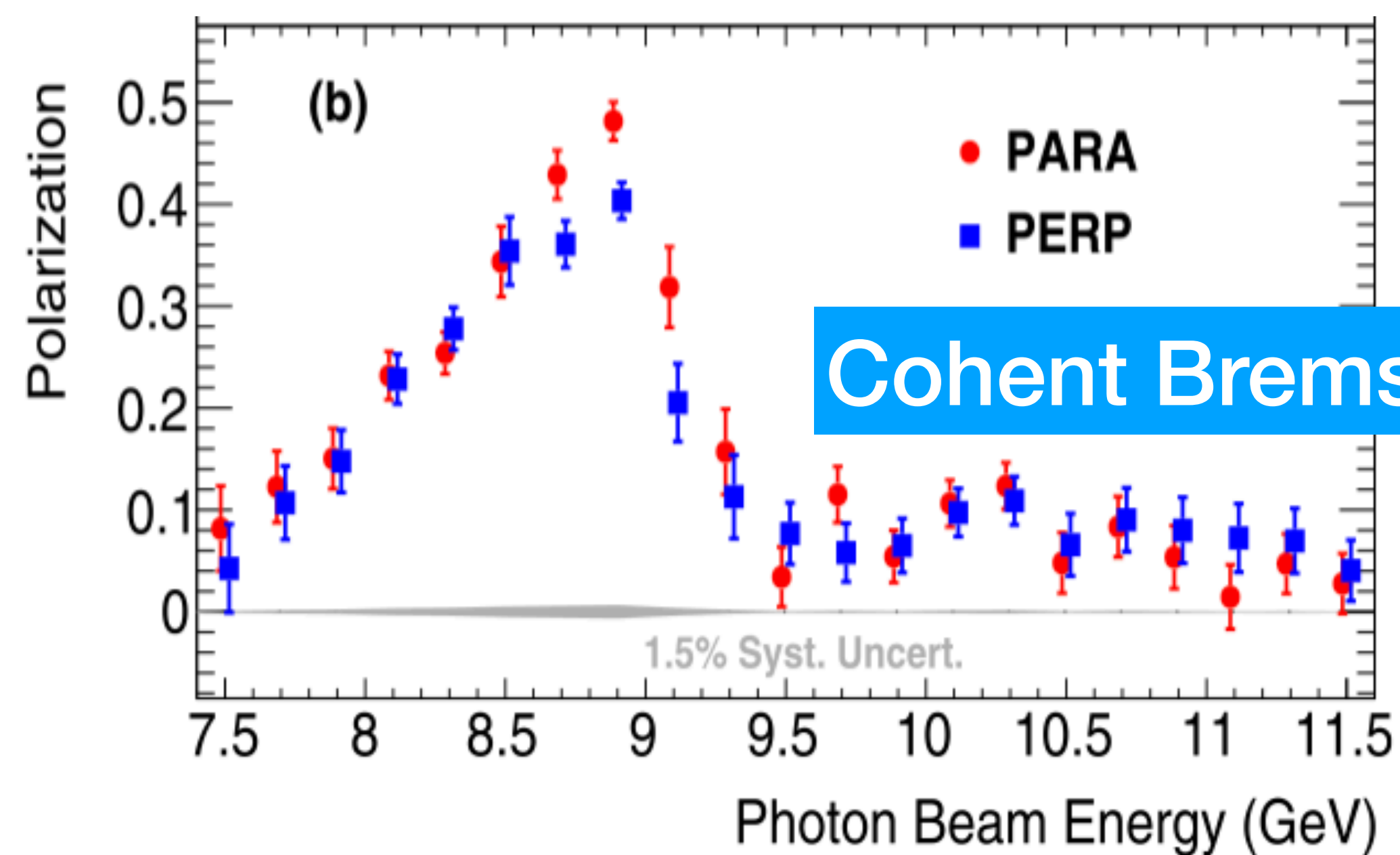
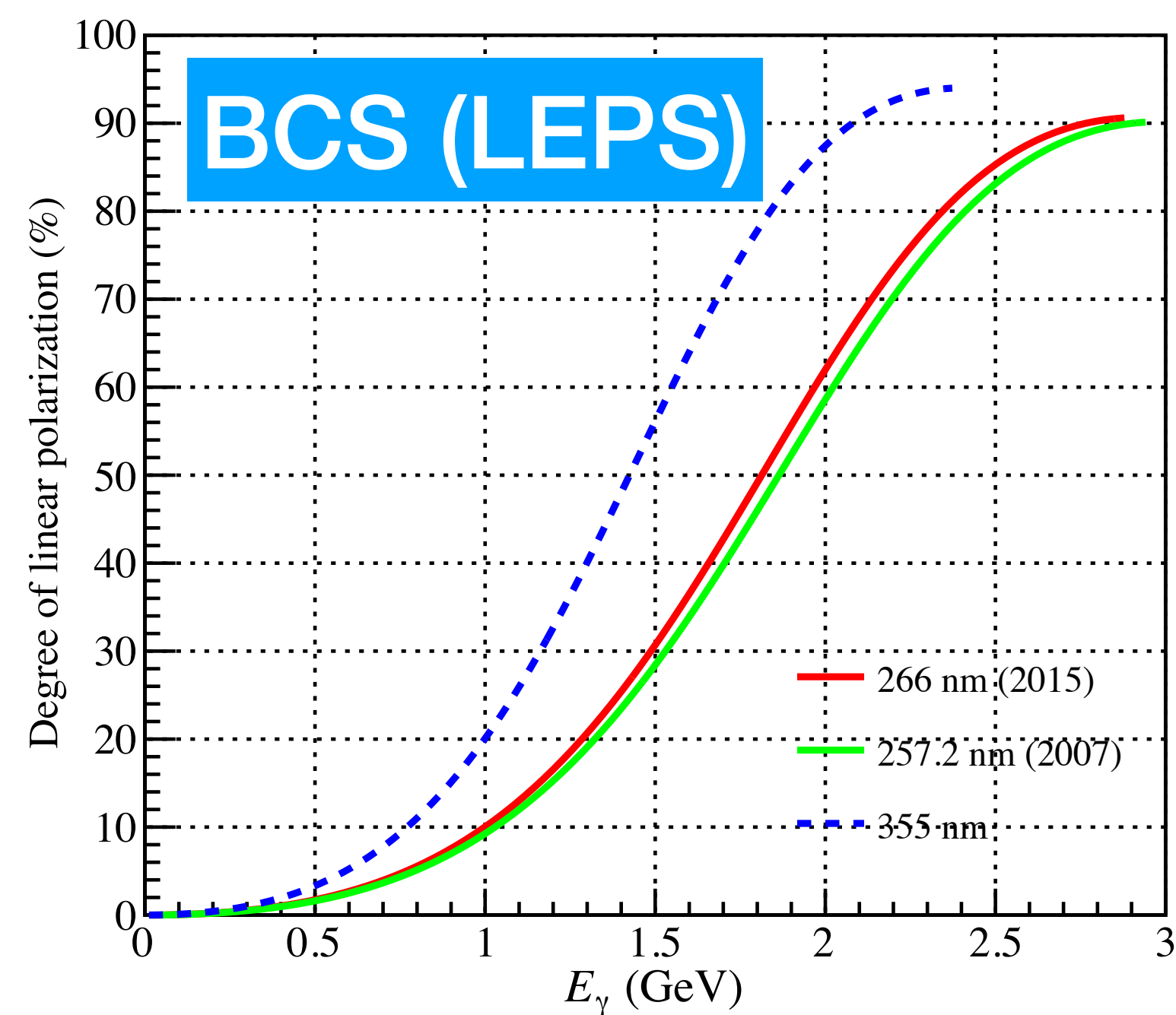
$$G(t) = A(t)M - B(t) \frac{t}{4M} + D(t) \frac{3t}{M}. \quad (4)$$

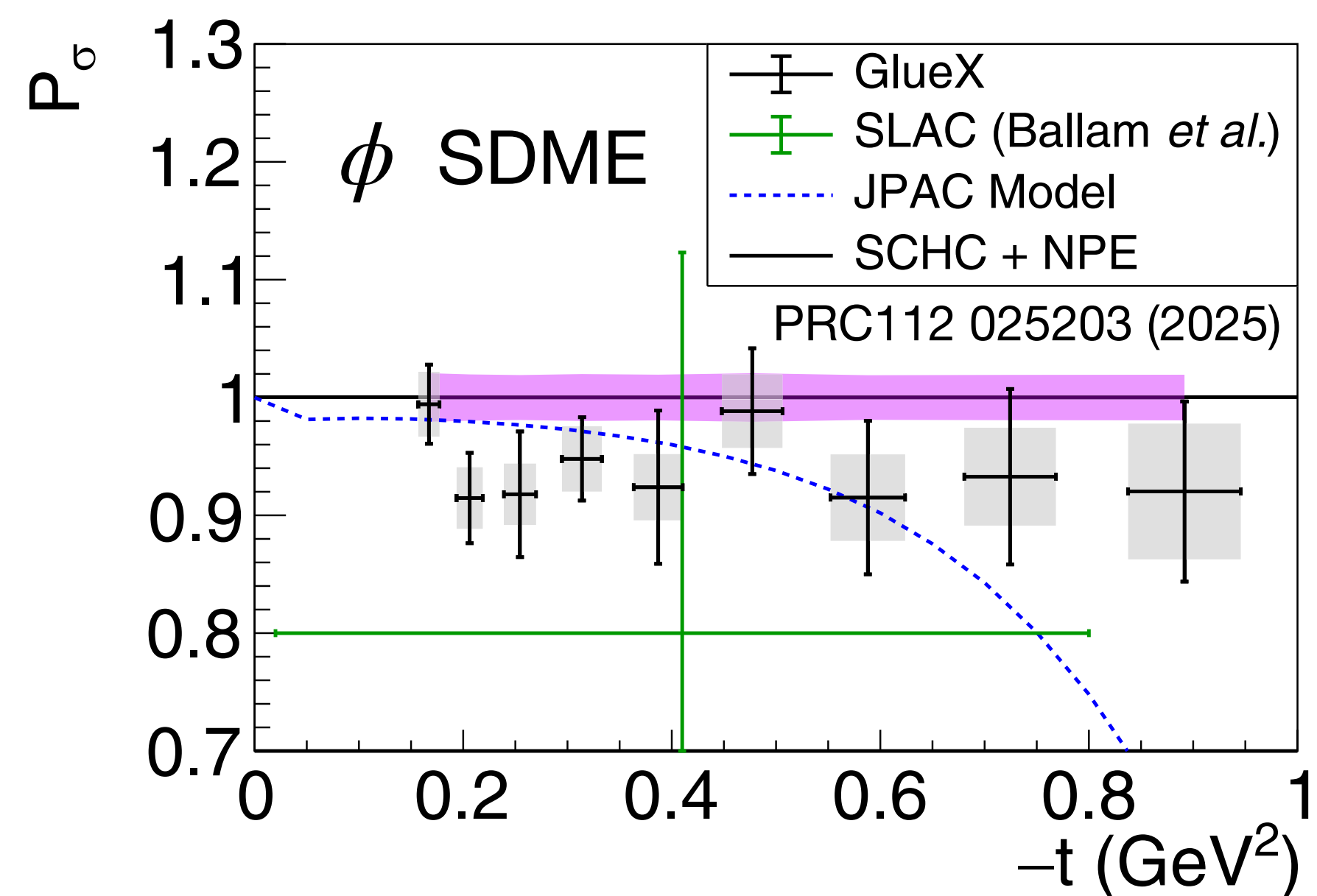
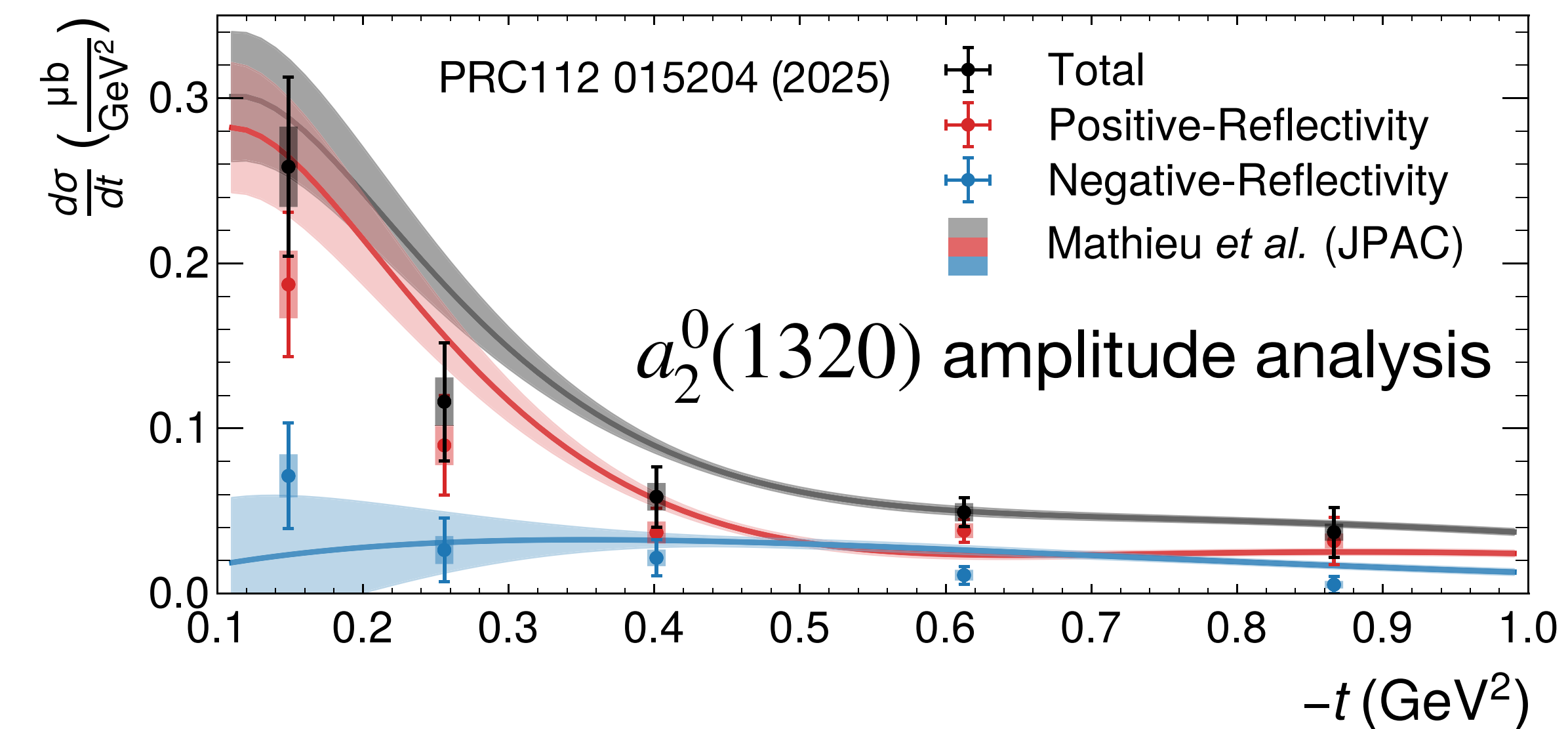
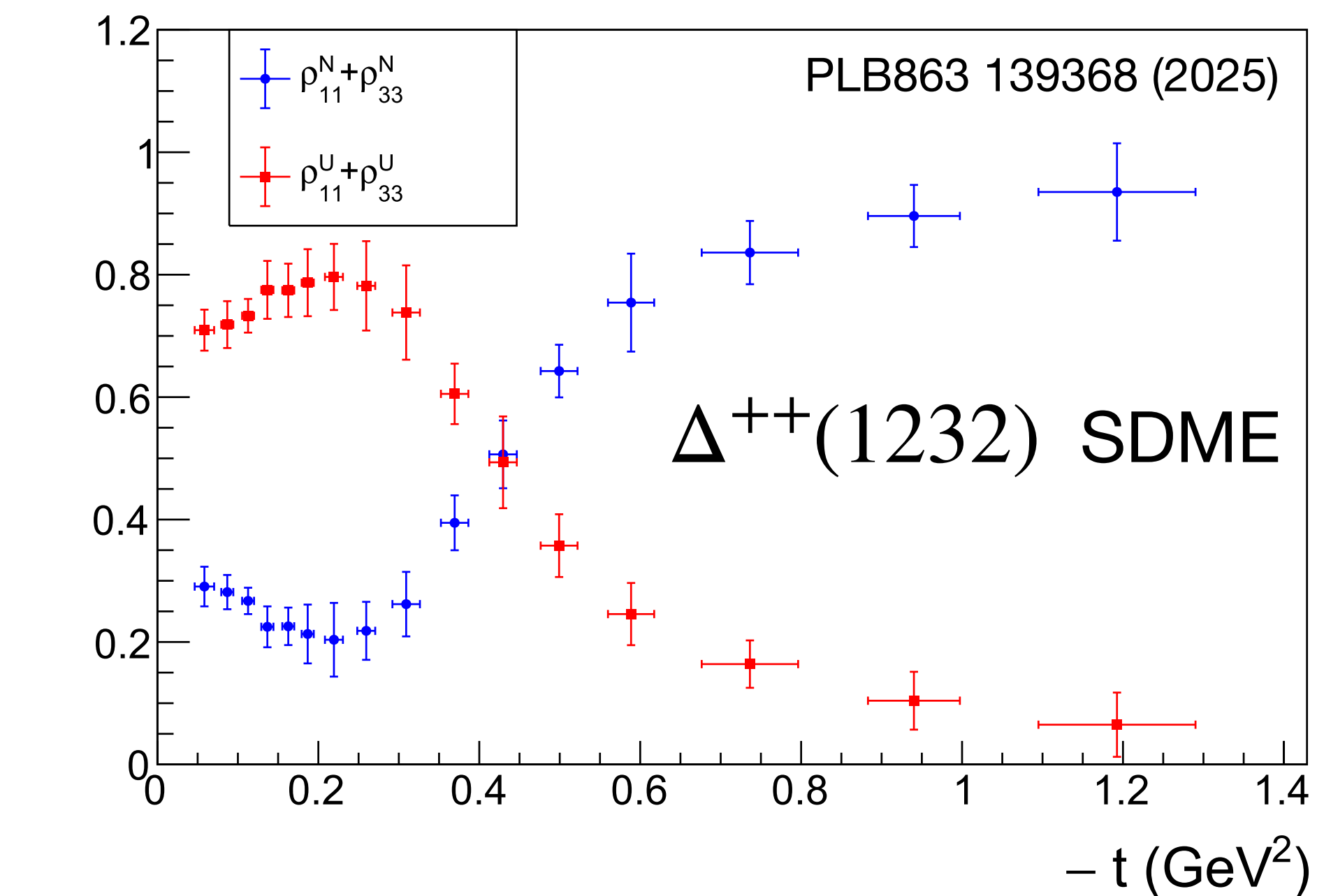
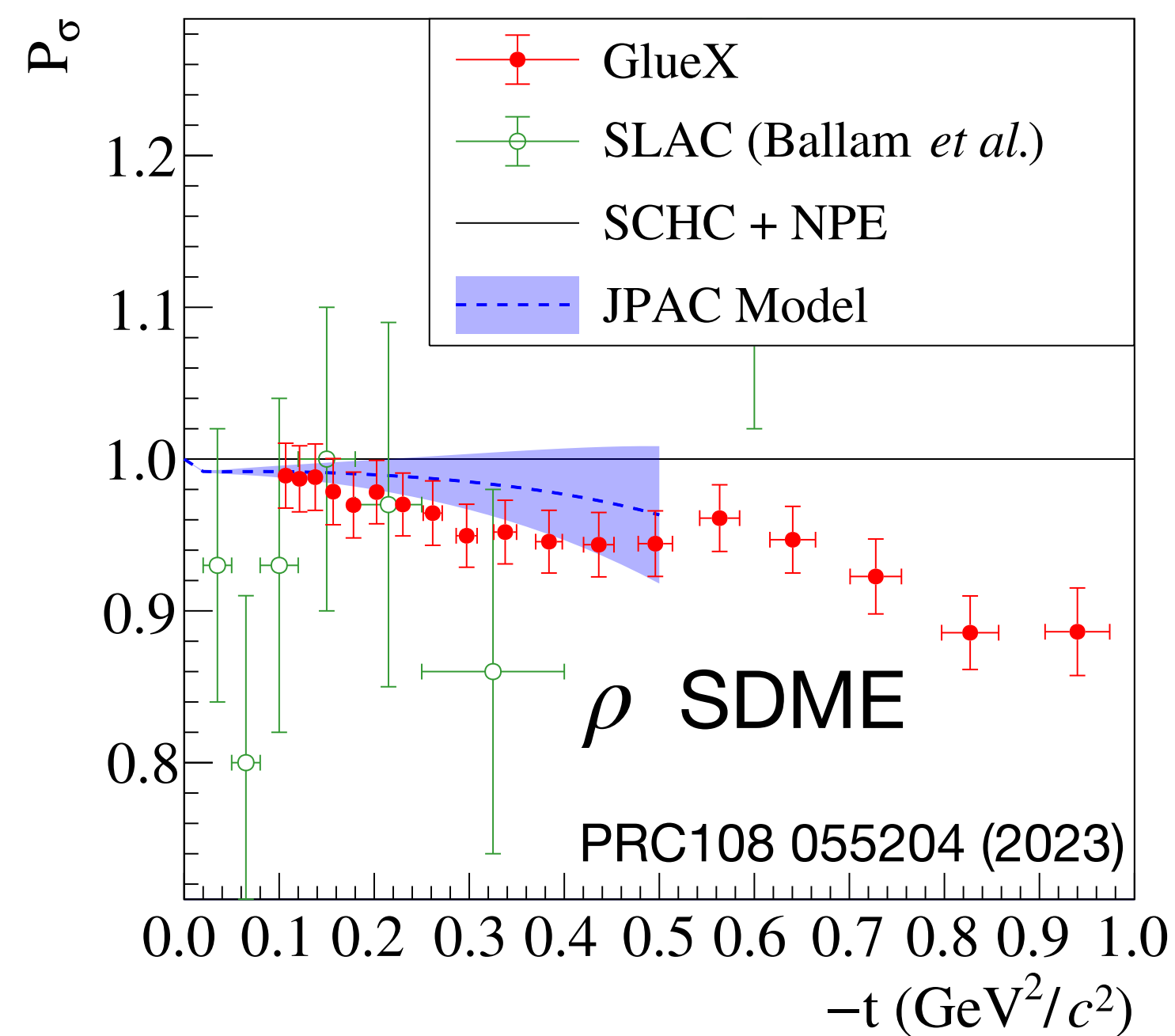
The gravitational form factors are usually parametrized as the dipole form. Therefore we have

$$G(t) = \frac{M}{(1 - t/m_s^2)^2}, \quad (5)$$

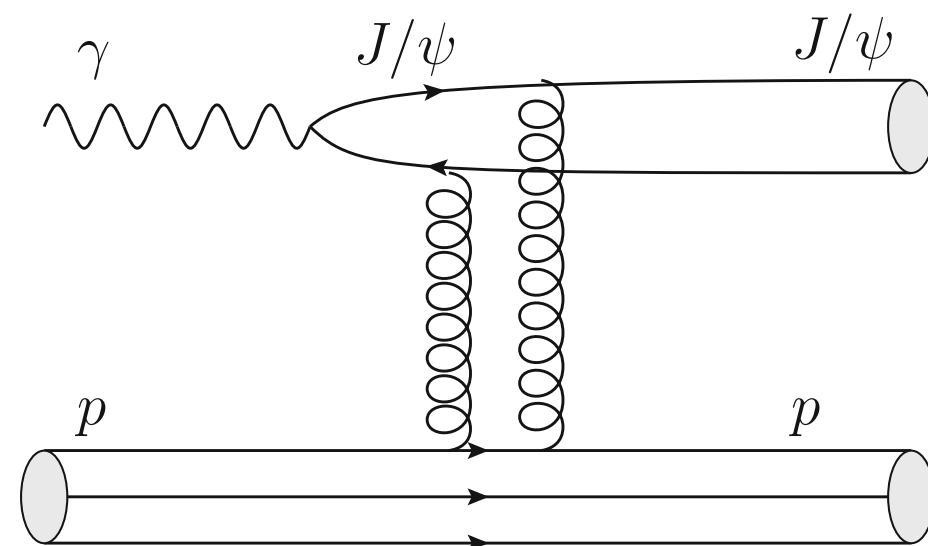
in which m_s is a free parameter to be determined experimentally. According to the definition, the mass radius is connected to the dipole parameter m_s as

$$\langle R_m^2 \rangle = \frac{12}{m_s^2}. \quad (6)$$

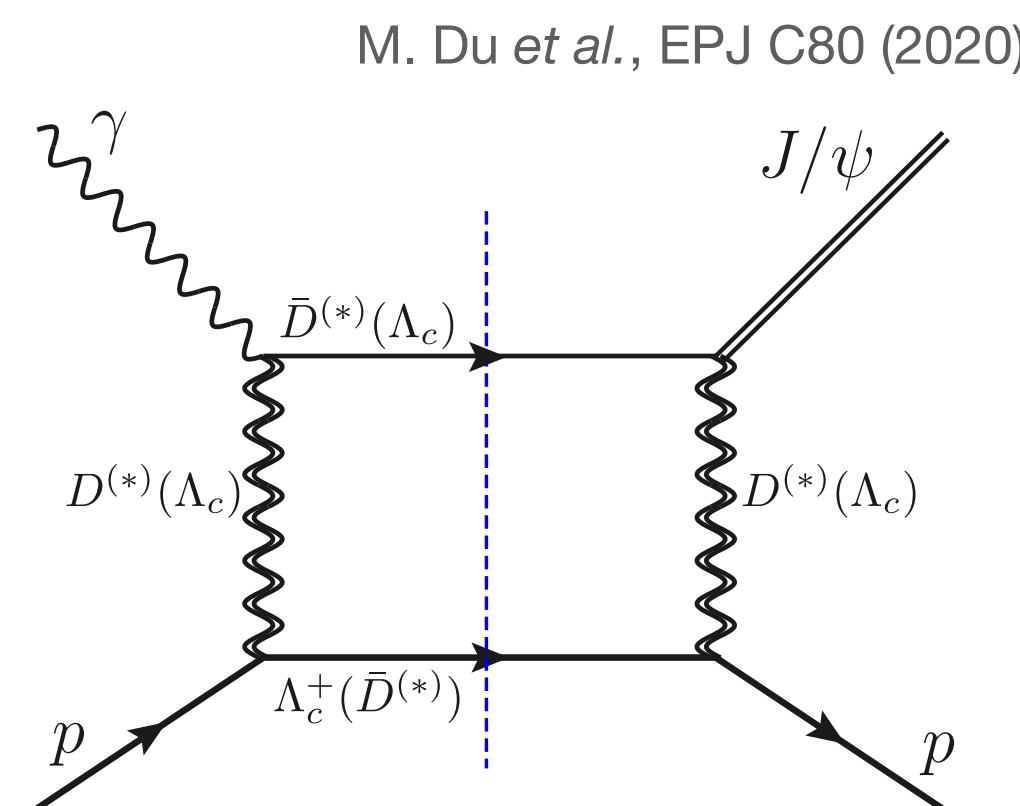




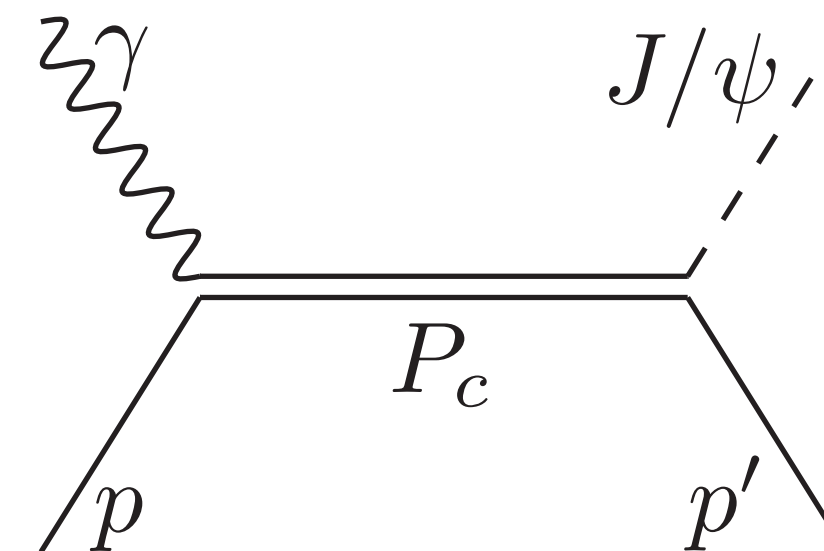
- Threshold J/ψ photoproduction $\rightarrow$ properties of proton mass?
- High E_γ region is well explained by Pomeron model.
- Understanding of production mechanism near threshold is desired.



Gluon exchange?



Open-charm?



Pentaquark?

In addition to σ_{total} and $d\sigma/dt$ measurements,
Spin observables (SDME) place stringent constraints on models!