Probing Nuclear Color States with J/Ψ and φ

Michael Paolone
Temple University

Nuclear Photoproduction with GlueX Workshop

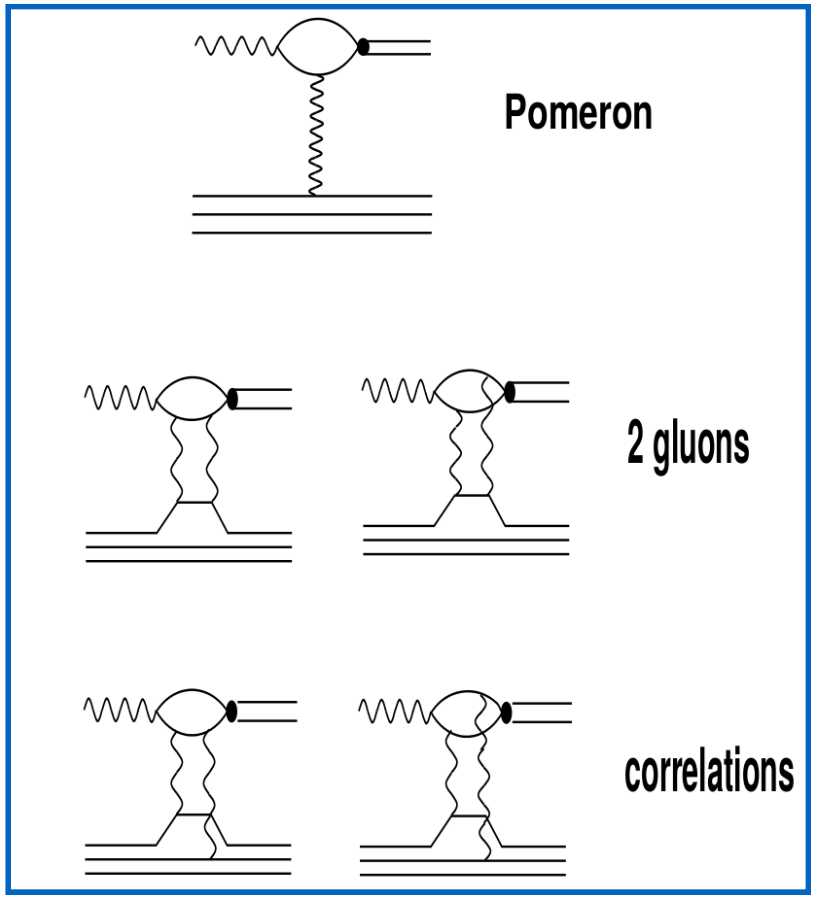
Jefferson Lab
April 29th 2016

Why J/Ψ and ϕ?

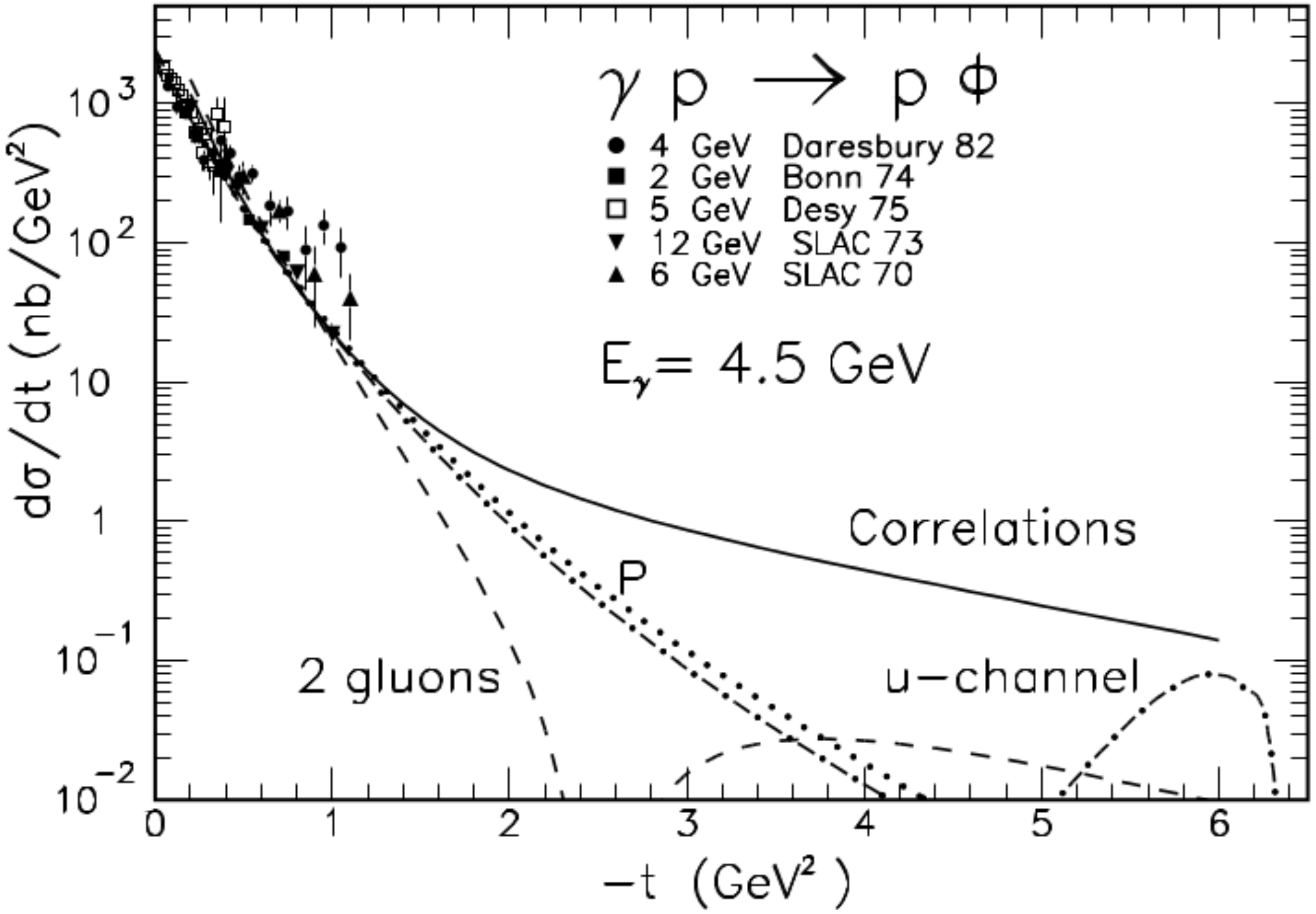
- Interesting because of flavor disparity with target (nucleon or nuclear) which restricts available interaction channels.
    - Suppression of meson / quark exchange!
        - ϕ (mostly strange) interacts with nucleons (mostly up-down) primarily via pomeron / 2+ gluon exchange.
        - J/Ψ (mostly charmed) interactions should be even cleaner via pomeron / gluons.

What do we know about ϕ photo production (nucleon and nuclear)?

$\gamma + p \rightarrow p + \phi$ (theory)



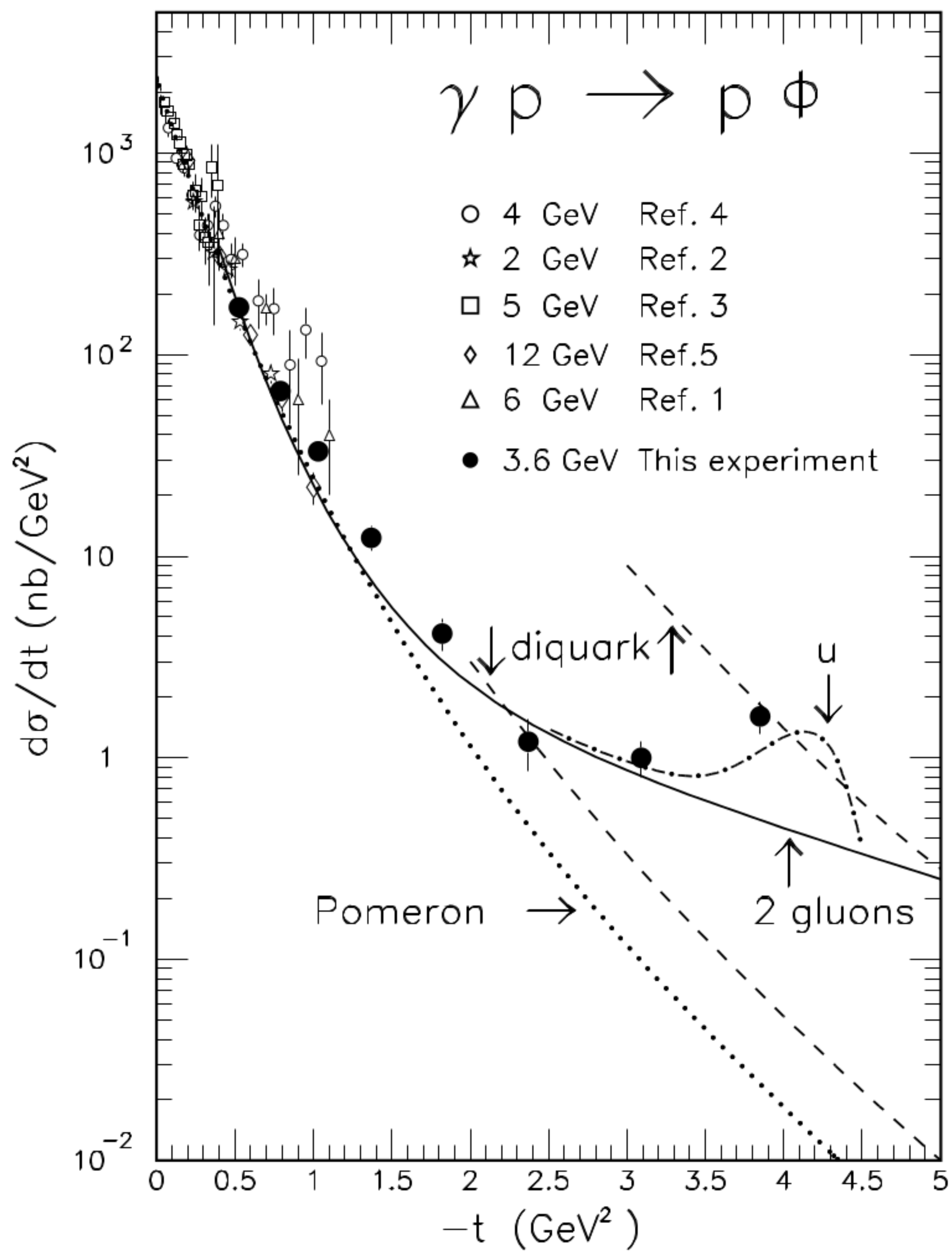
- Laget Description:
  - Since ϕ is mostly strange, meson exchange is highly suppressed (OZI rule)
  - Considering this suppression, Pomeron exchange explains the observed production very well at small |t|.
  - At intermediate |t| when the scattering parameter b becomes comparable to the gluon correlation length, the two-gluon exchange channel opens up.
    - At higher |t|, the gluons can couple to different quarks in the nucleon (correlations)
  - At large angles (and small u), u-channel nucleon exchange is also possible.



Laget, Phys.Lett. B489 (2000) 313-318

$\gamma + p \rightarrow p + \phi$ (CLAS6)

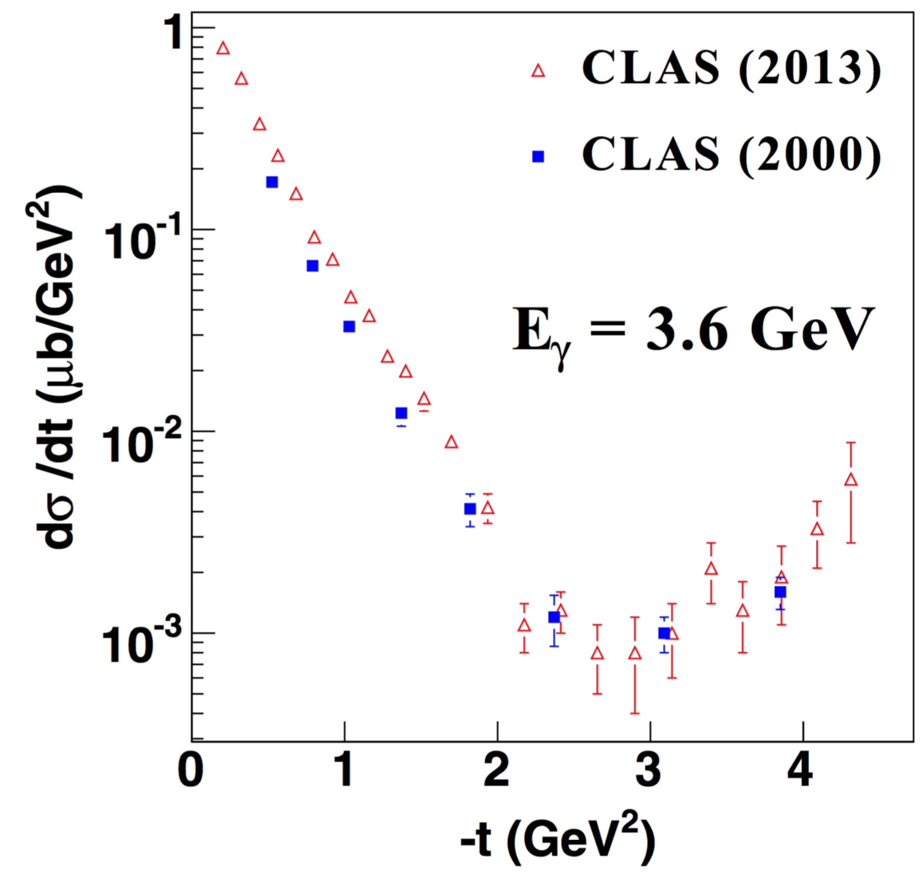
- Anciant, et al. found strong evidence for a two-gluon contribution.
  - A u-channel contribution is also evident. The dash-dot curve uses a $g_{\phi NN} = 3$ (higher than predicted from SU(3) mass splitting, but in line with observations of nucleon-nucleon and nucleon-hyperon scattering).
  - A larger $g_{\phi NN}$ implies a larger strange contribution to the nucleon sea.



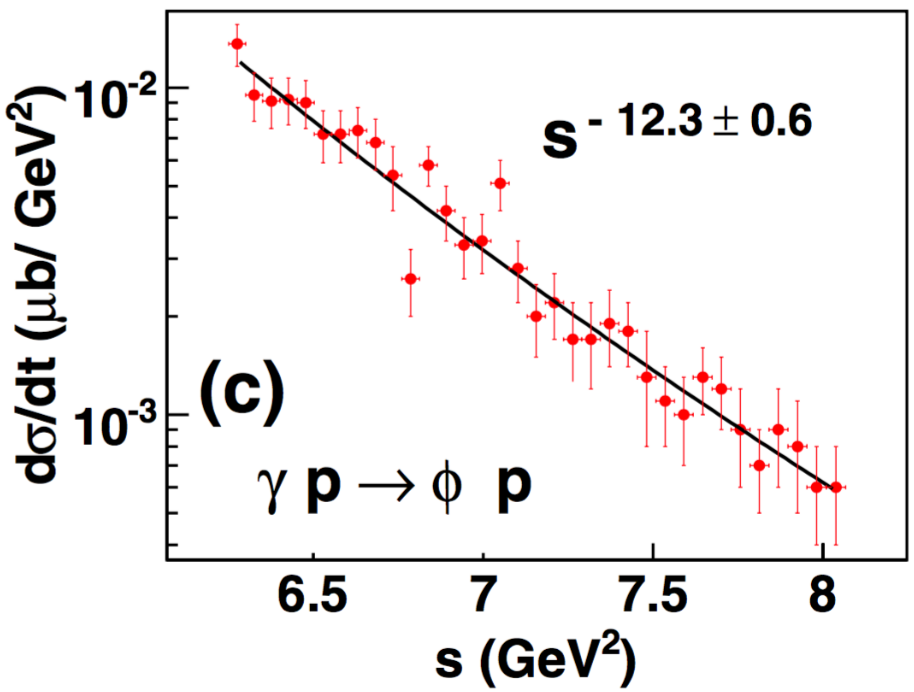
Anciant et al., Phys.Rev.Lett. 85 (2000) 4682-4686

$\gamma + p \rightarrow p + \phi$ (CLAS6 cont.)

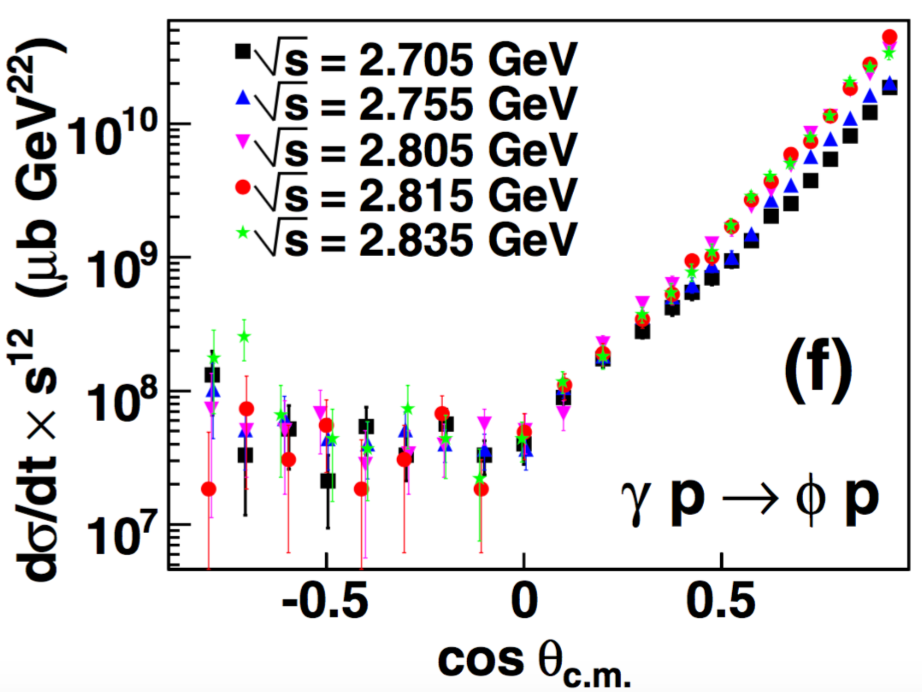
- Dey, et al. gives most recent CLAS6 results. Agrees with previous studies at CLAS.



Dey et al., Phys.Rev. D90 (2014)



Dey et al., Phys.Rev. C89 (2014)



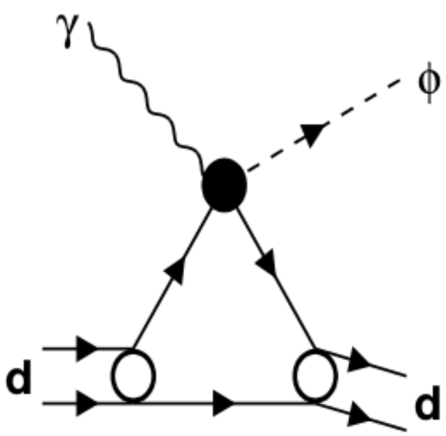
We expect s-scaling like:

$$\frac{d\sigma}{dt} \approx s^{-n+2} f(\cos\theta_{c.m.})$$

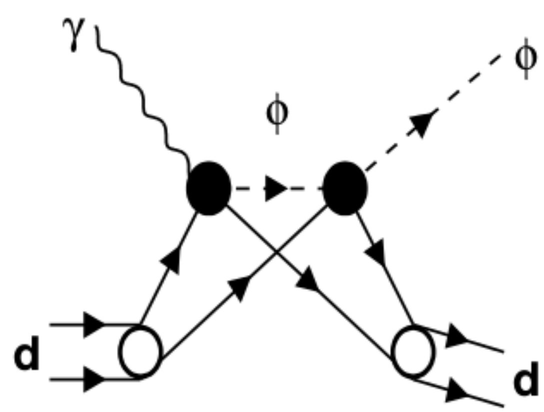
One way to get s^{-12}:

$$n = 2 \times |s\bar{s}g\rangle + 2 \times |uudg\rangle = 14$$

γ + d → d + ϕ (CLAS6)

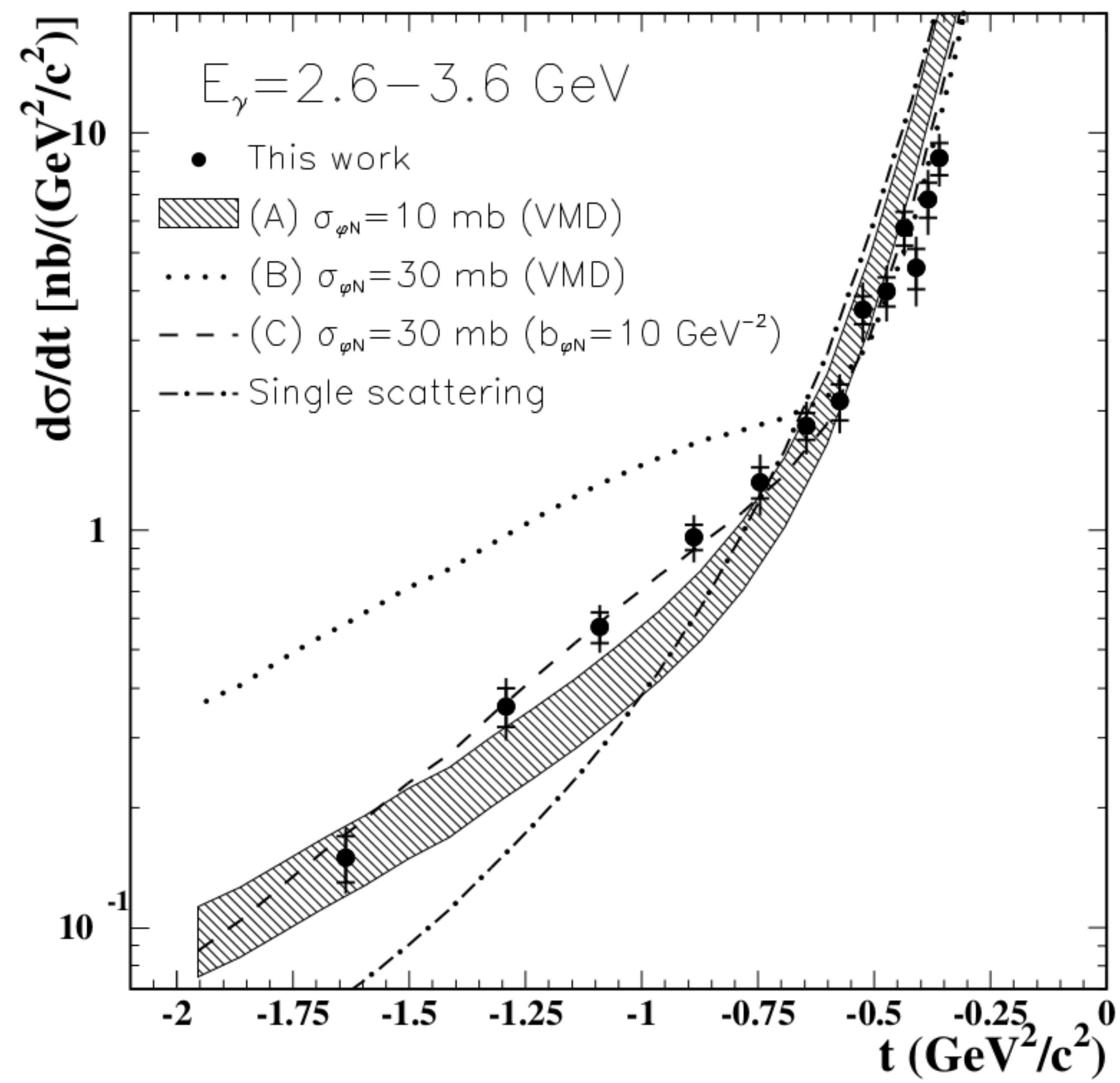


Single Scattering



Double Scattering

- Single scattering underestimates the cross-section at larger |t|
- Using the pure VMD prediction and the expected ϕ-N cross-section does not agree well (Shaded band)
- Increasing the ϕ-N cross-section (due to A > 1) to 30mb agrees well at low |t| but overestimates at high |t| (dotted curve)
- Assuming that the phi can also fluctuate into K pairs before the re-scatter (with a new slope parameter, b = 10 GeV^{-2}) gives good-agreement.



Mibe et al., Phys.Rev. C76 (2007) 052202

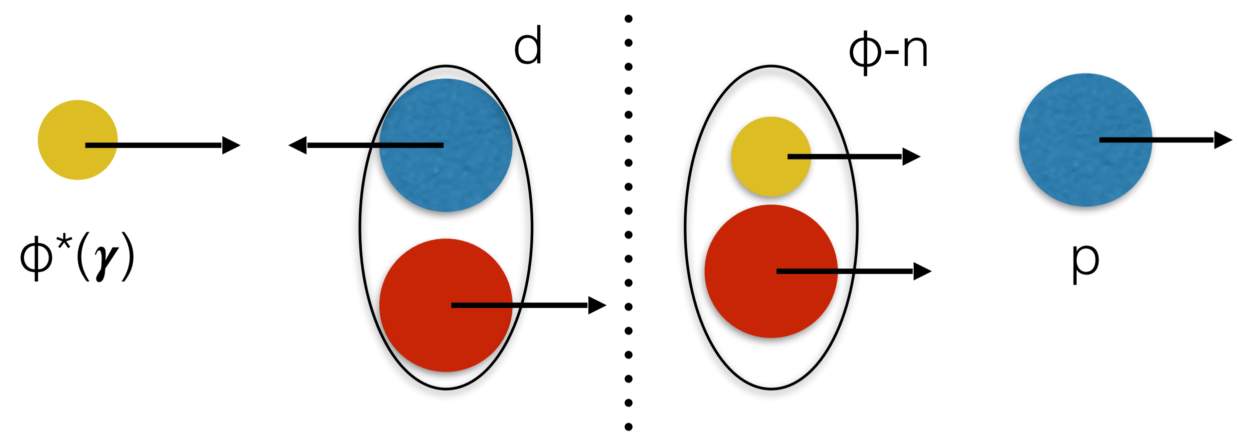
$\gamma + d \rightarrow p + [n\phi]$

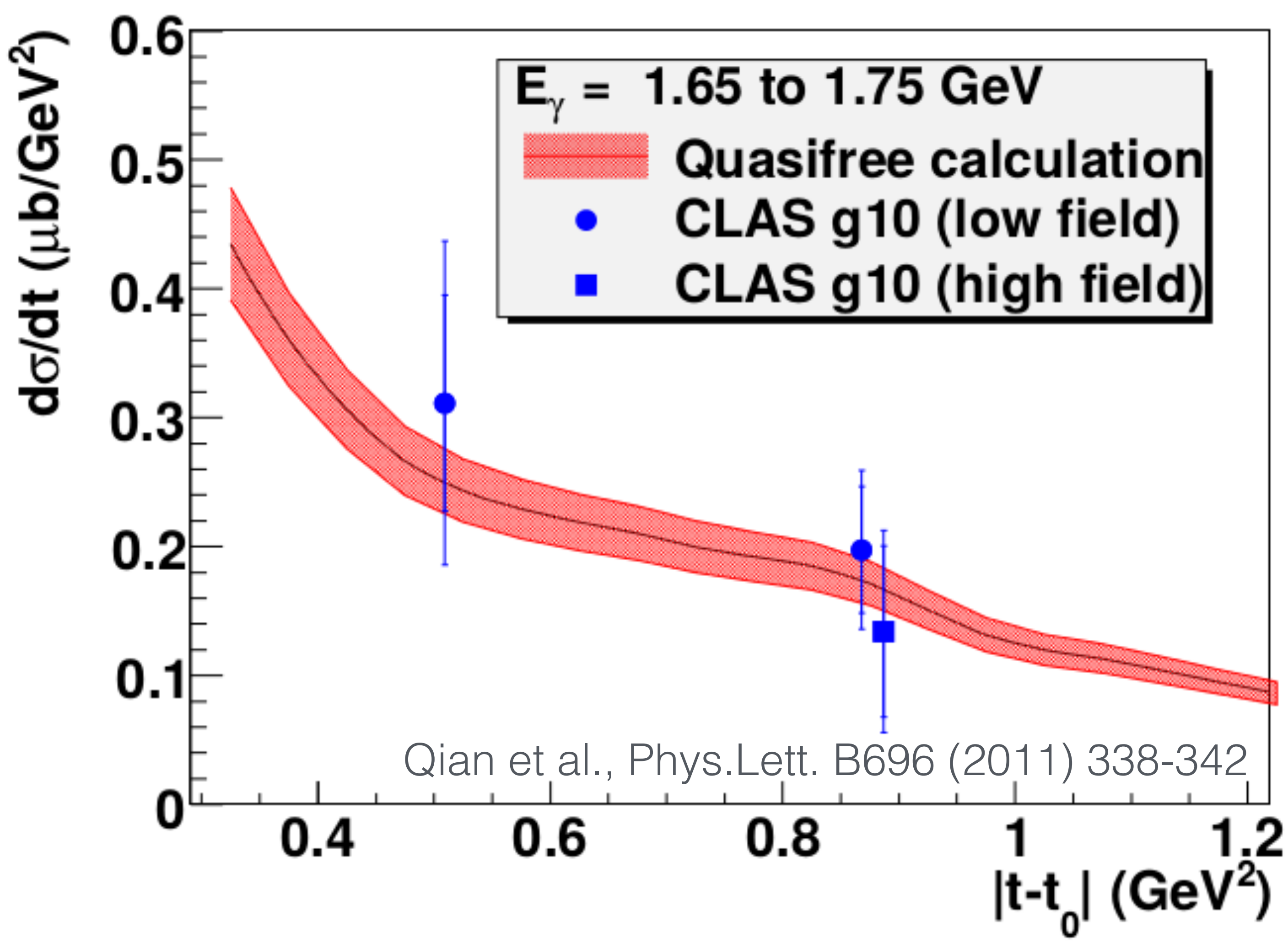
- At sub-threshold phi production on deuterium, you gain a handle on the momentum of the recoil neutron and phi.
- At the right kinematics, the phi and the neutron will travel together at the same speed, increasing the likelihood of a bound state.
- Gao, Lee, and Marinov predict a ϕ-N bound state with a QCD van der Waals attraction with:

$$V_{(s\bar{s}),N} = -\alpha e^{\mu r}/r$$

α = 1.25 and μ = 0.6 GeV
The binding energy will be 1.8 MeV

Phys.Rev. C63 (2001) 022201

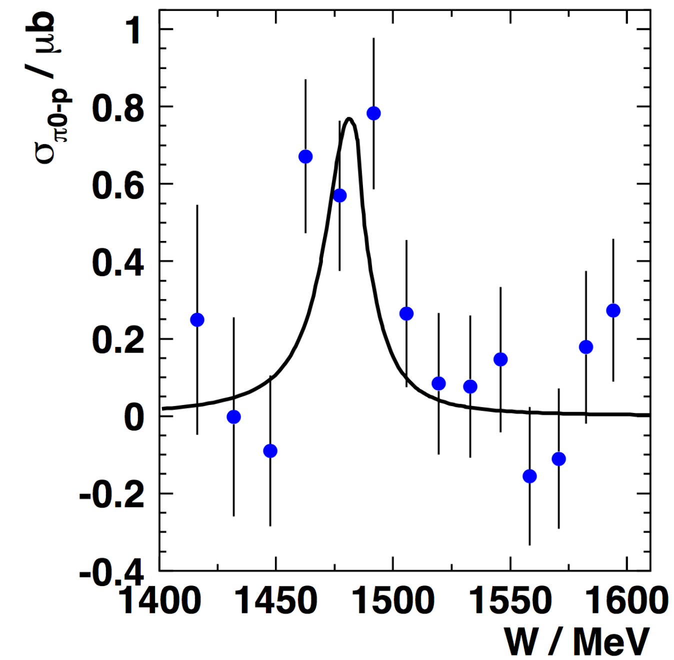


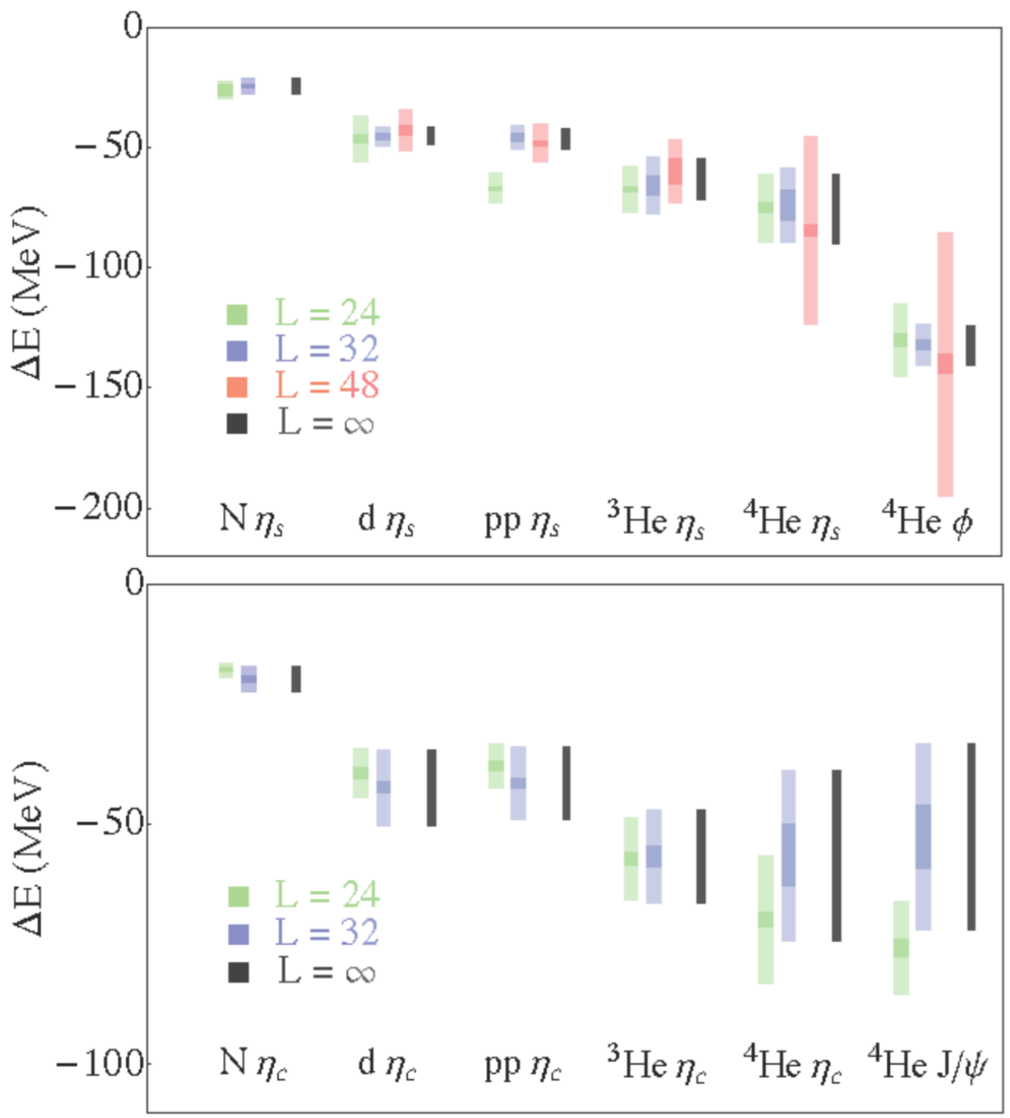


Qian et al., Phys.Lett. B696 (2011) 338-342

Mesic bound states

- **Published results for a η-^{3}He with TAPS at MAIMI**
  - Binding energy of (-4.4 ± 4.2) MeV and full width (25.6 ± 6.1) MeV
    M. Pfeiffer, et al. Phys.Rev.Lett. 92 (arxiv.org/abs/nucl-ex/0312011)

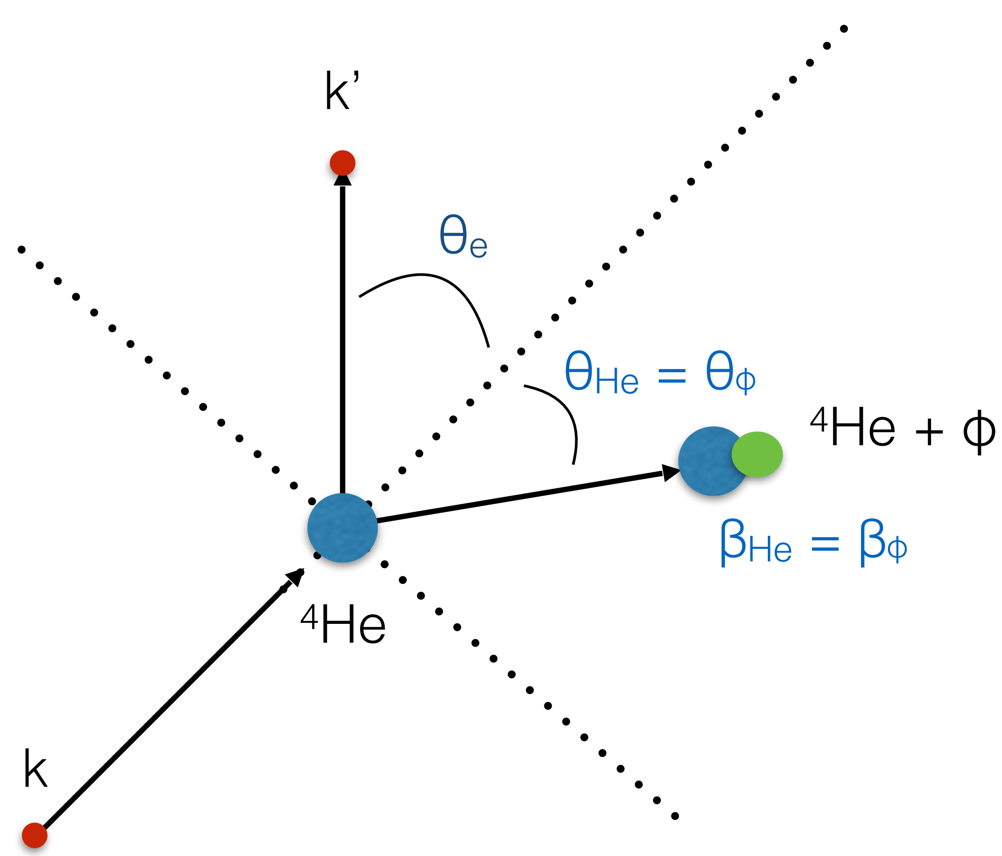




Recent lattice calculations from NPLQCD group predict a strong binding with ϕ-^{4}He!

ϕ electroproduction on ^{4}He at threshold

- Two-arm coincidence between scattered electron and ^{4}He. ϕ and η are selected with missing mass.
- With careful selection of kinematics, the relative velocity between the phi and ^{4}He can be centered at zero.
- Maximizes the possibility of a bound state.



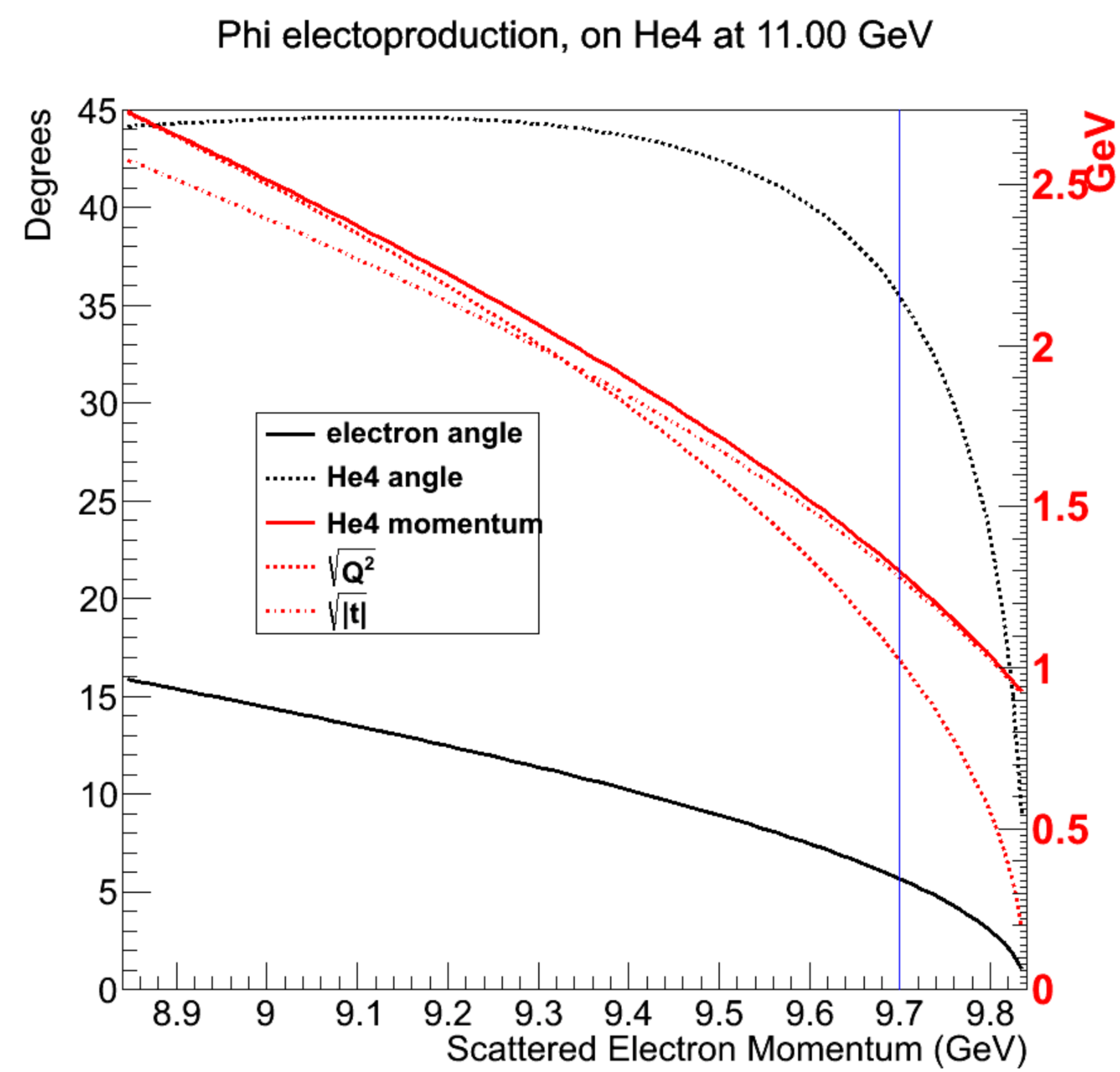
Investigating neutral meson-nuclei bound states with coherent electroproduction of η and ϕ mesons off of ^{4}He in Hall-C

A Letter of Intent to PAC 42

M. Paolone, S. Joosten, Z.-E. Meziani, N. Sparveris
Temple University
Philadelphia, Pennsylvania USA

M. Jones
Thomas Jefferson National Accelerator Facility
Newport News, Virginia USA

May 29, 2014



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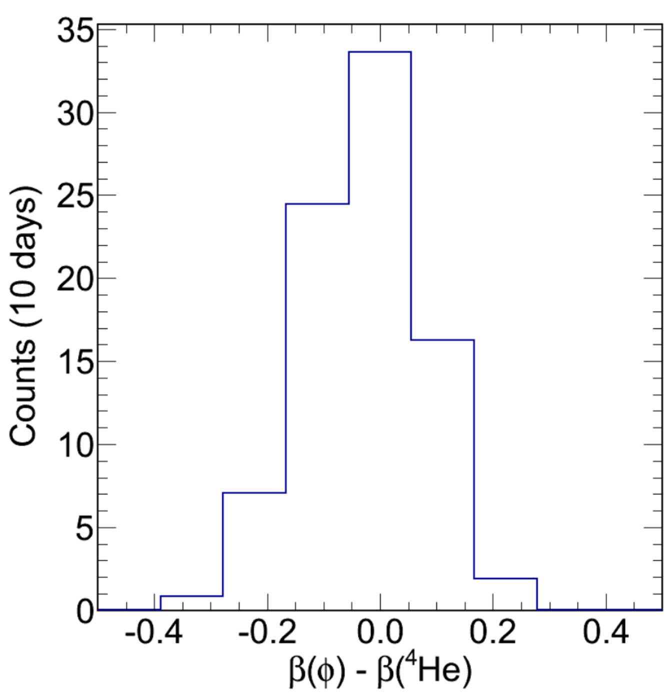

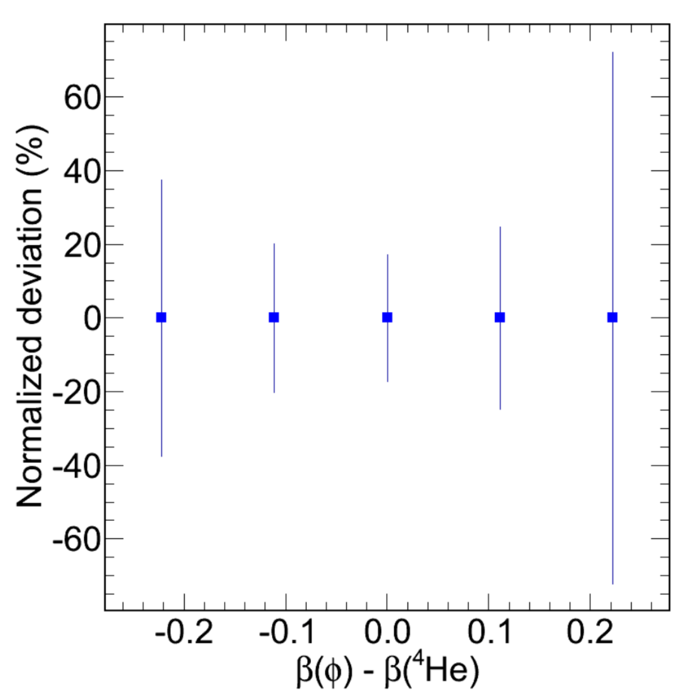

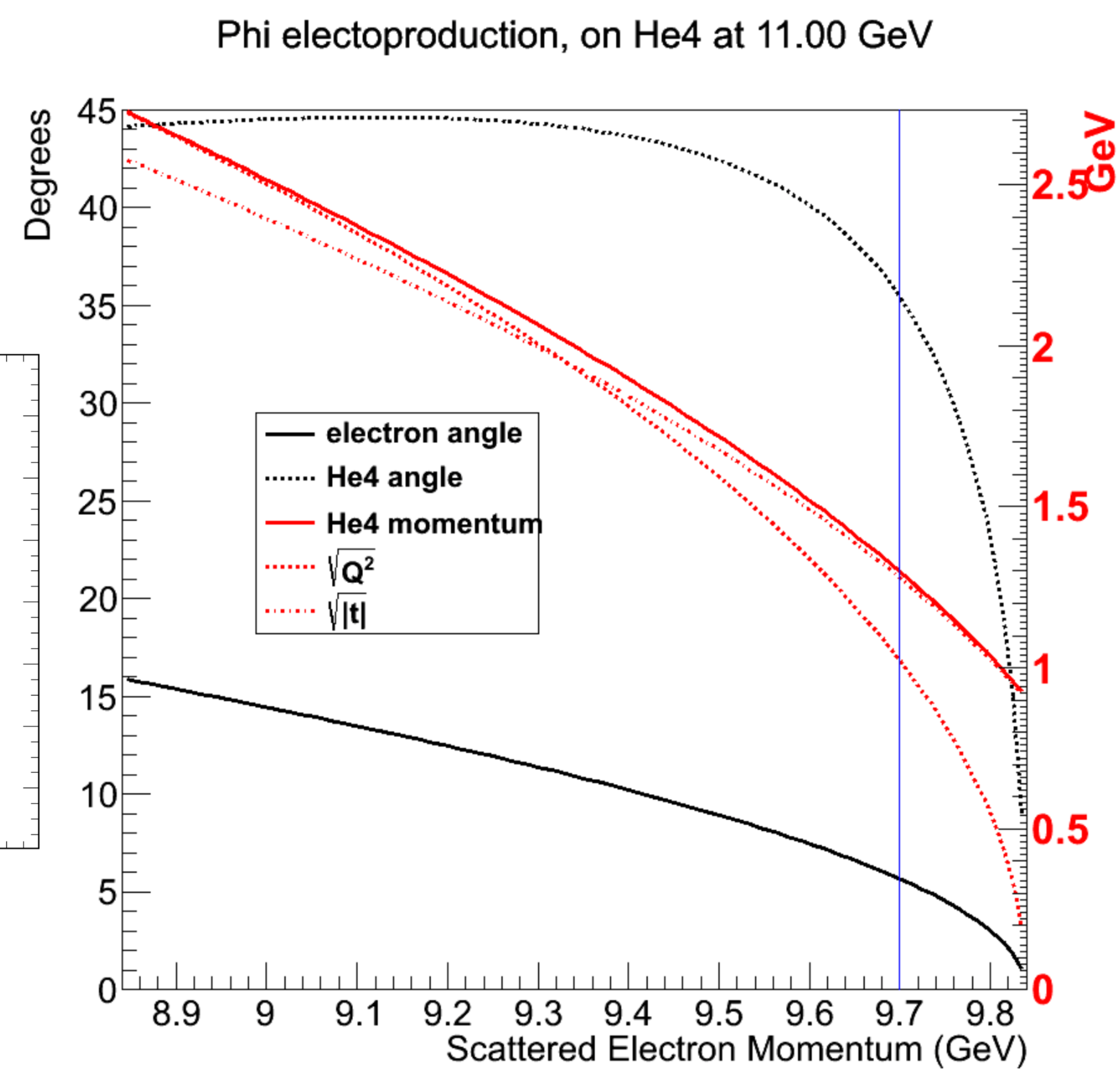

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★ **Need theoretical calculations for bound states!**

- J/Ψ - ^{3}He binding energies were predicted by J.J. Wu and H. Lee (arXiv:1210.6009v1)
- 3 and 4 body binding calculations exist.
- No direct ϕ-^{4}He calculations available!

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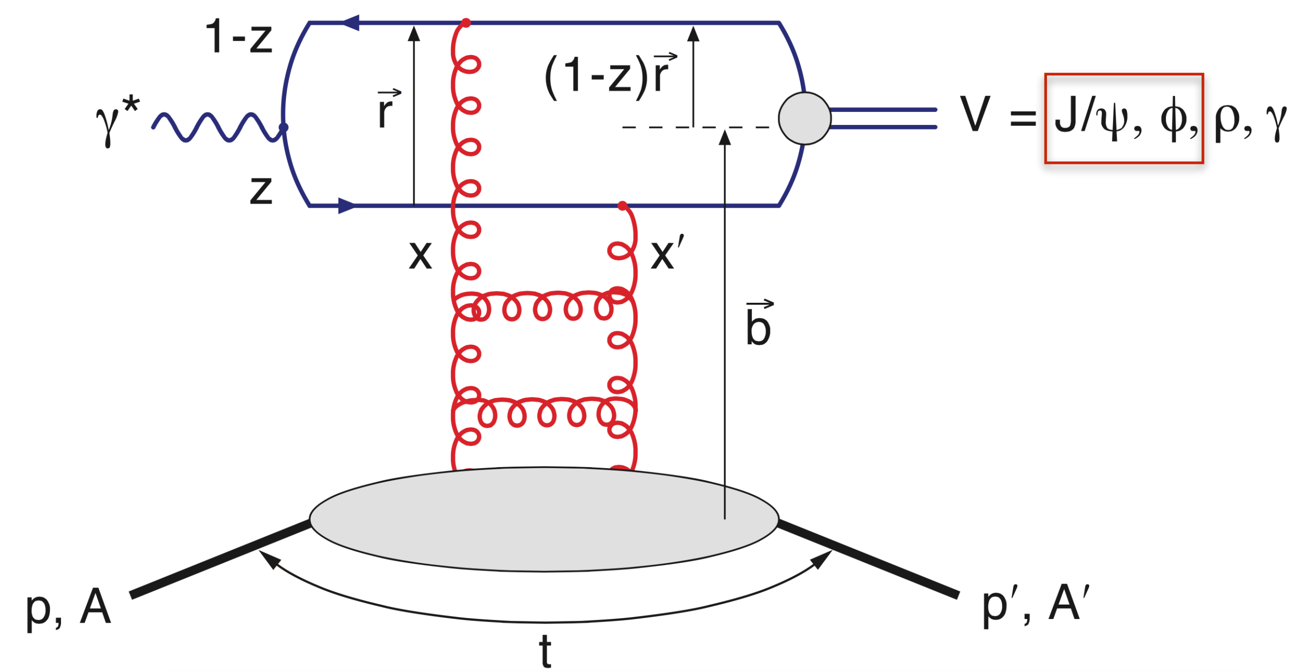
What can we learn above threshold?

$c\bar{c}$ or $s\bar{s}$ electroproduction to probe gluon distributions

- Diffractive scattering occurs when the DIS electron interacts with a color-neutral vacuum excitation:
  - Within a perturbative QCD framework, this vacuum excitation can be represented by a combination of 2+ gluons (Pomeron).
- Hard diffractive cross-section is proportional to the square of the gluon density.
  - Most sensitive tool to access gluon density distributions



For J/Ψ and ϕ production, flavor disparity between target and meson suppresses direct quark exchange!

Tull, Ullrich dipole model formalism for diffractive DIS production amplitude on protons:

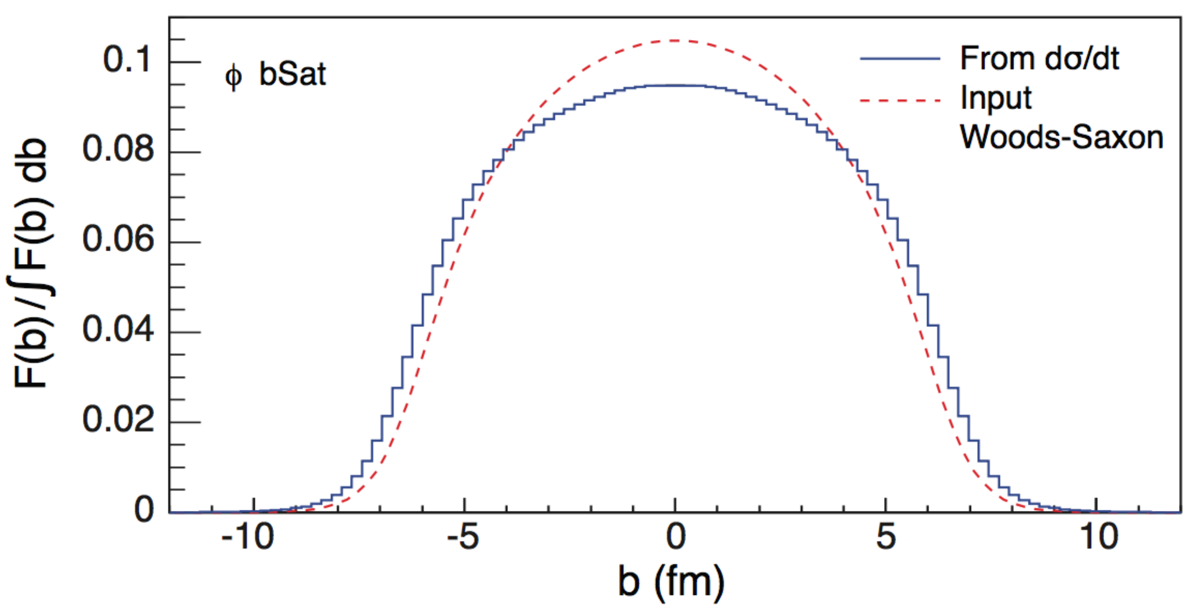
$$\mathcal{A}_{T,L}^{\gamma^* p \to V p}(x, Q, \Delta) = i \int \mathrm{d}r \int \frac{\mathrm{d}z}{4\pi} \int \mathrm{d}^2\mathbf{b}\, (\Psi_V^* \Psi)(r, z) \times 2\pi r J_0([1-z]r\Delta) e^{-i\mathbf{b}\cdot\Delta} \frac{\mathrm{d}\sigma_{q\bar{q}}^{(p)}}{\mathrm{d}^2\mathbf{b}}(x, r, \mathbf{b}) \quad (1)$$

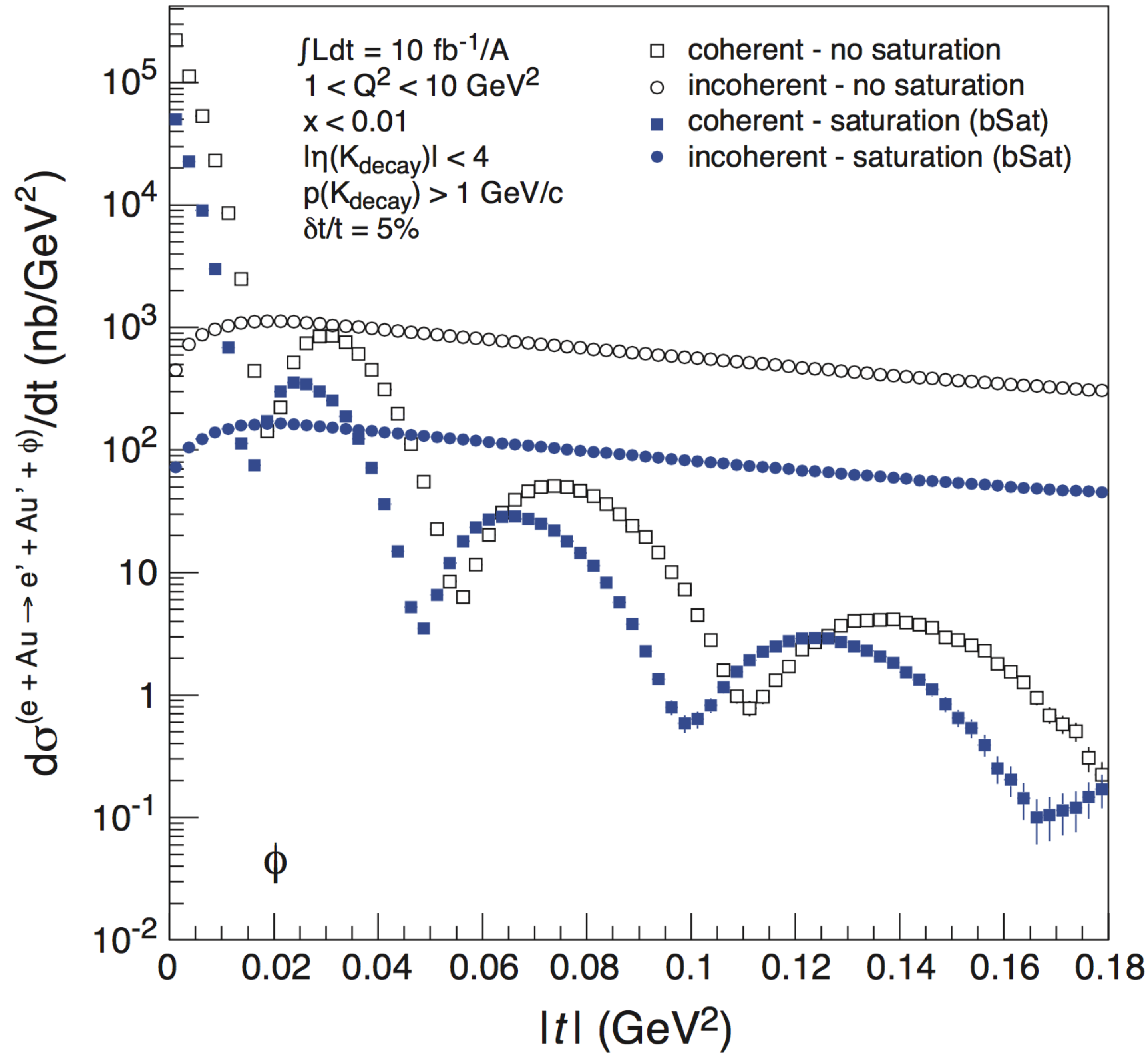
Coherent electroproduction of ϕ off heavy nuclei at EIC

- **EIC White Paper**: Tull and Ullrich[1,2]: Measurements of Diffractive Events (p.83)

- Uses convention of Munier, Stasto, and Mueller[3]:
  - Fourier transform of cross section can give information on gluon distribution in impact parameter (b) space!

$$F(b) = \int_0^\infty \frac{dq\, q}{2\pi} J_0(q\, b) \sqrt{\frac{d\sigma_{coherent}}{dt}}$$

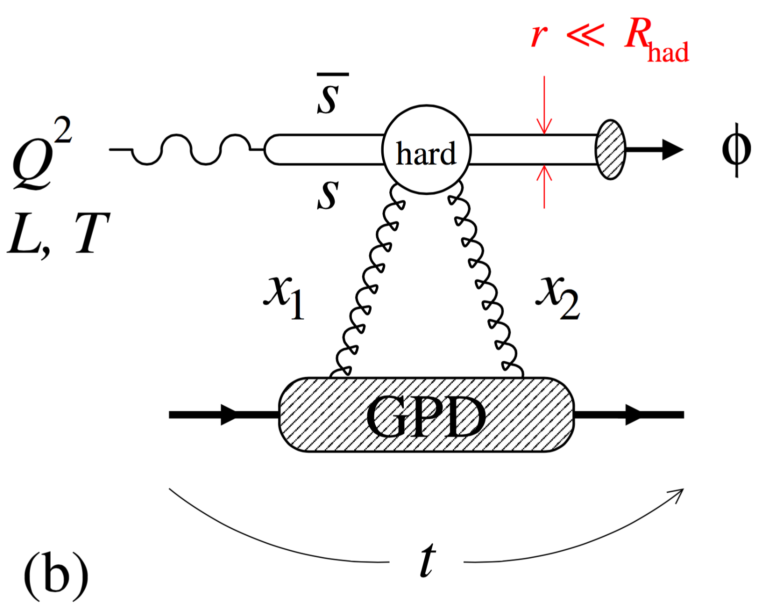




[1]EIC white paper (arXiv:1212.1701)
[2]Phys. Rev. C 87, 024913 (2013) (arXiv:1211.3048)
[3]Nucl.Phys. B603 (2001) 427-445 (arXiv:hep-ph/0102291)

$\gamma^* + p \rightarrow p + \phi$ (CLAS12 proposed)

- Recent proposal in CLAS12 approved with a "B+" rating to study the gluonic density distribution on Hydrogen.



Proposal to Jefferson Lab PAC39
Exclusive Phi Meson Electroproduction with CLAS12

H. Avakian,[1] J. Ball,[2] A. Biselli,[3] V. Burkert,[1] R. Dupr,[2] L. Elouadrhiri,[1] R. Ent,[1] F.–X. Girod,[1,*] S. Goloskokov,[4] B. Guegan,[5,6] M. Guidal,[5,*] H.–S. Jo,[5] K. Joo,[7] P. Kroll,[8] A Marti,[5] H. Moutarde,[2] A. Kubarovsky,[6,*] V. Kubarovsky,[1,*] C. Munoz Camacho,[5] S. Niccolai,[5] K. Park,[1] R. Paremuzyan,[5] S. Procureur,[2] F. Sabatié,[2] N. Saylor,[6,5] D. Sokhan,[5] S. Stepanyan,[1] P. Stoler,[6,†] M. Ungaro,[7] E. Voutier,[9] C. Weiss,[1,†] D. Weygand,[1] and the CLAS Collaboration

[1]*Jefferson Lab, Newport News, VA 23606, USA*
[2]*IRFU/SPhN, Saclay, France*
[3]*Fairfield University*
[4]*Joint Institute for Nuclear Research, Dubna, Russia*
[5]*Institut de Physique Nucleaire Orsay, France*
[6]*Rensselaer Polytechnic Institute*
[7]*Department of Physics, University of Connecticut, Storrs, CT 06269, USA*
[8]*Wuppertal University, Wuppertal, Germany*
[9]*LPSC Grenoble, France*

- In the GPD framework, the light-cone momentum fractions are: $x_{1,2} = x \pm \xi$
- The momentum transfer is then: $\xi = x_B/(2 - x_B)$
- and the gluon GPD is written: $H_g(x, \xi; t)$ with $H_g(x, \xi = 0, t = 0) = xg(x)$
- The longitudinal cross-section is then written:

$$\frac{d\sigma_L}{dt} = \frac{\alpha_{\mathrm{em}}}{Q^2} \frac{x_B^2}{1 - x_B} \left[(1 - \xi^2)|\langle H_g \rangle|^2 + \text{ terms in } \langle E_g \rangle\right]$$

$\gamma^* + p \rightarrow p + \phi$ (CLAS12 proposed)

- A useful parameter to describe the gluon density distribution is the reduced gluon distribution:

$$\rho_g(x,b) \equiv g(x,b)/g(x)$$

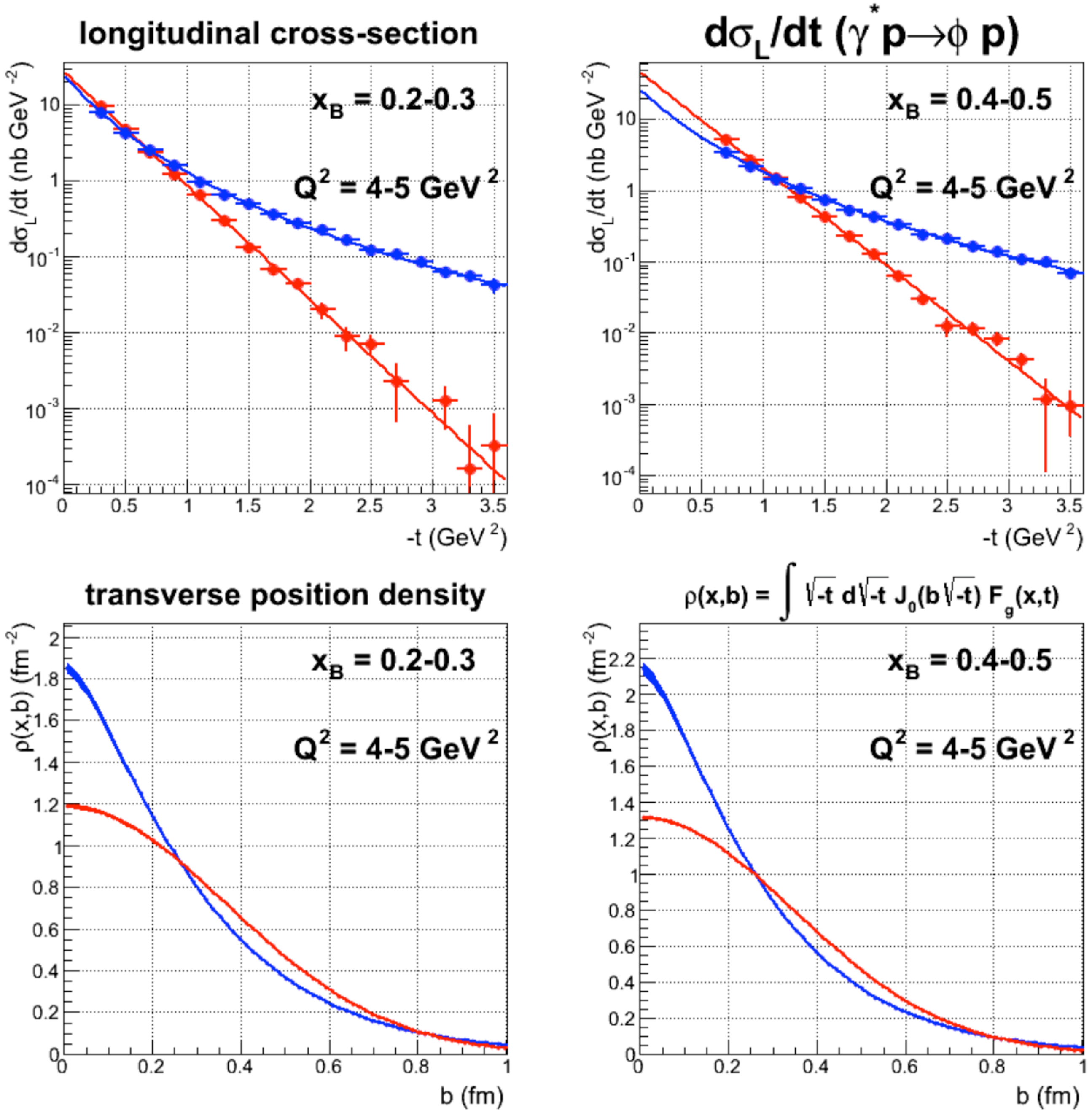
- Then, defining a gluonic form-factor as:

$$F_g(x,t) \equiv H_g(x,\xi=0,t)/H_g(x,\xi=0,t=0)$$

- One can extract the gluon distribution via Fourier transform:

$$\rho_g(x,b) = \int \frac{d^2\Delta_T}{(2\pi)^2} e^{i(\boldsymbol{\Delta}_T \boldsymbol{b})} F_g(x,t=-\boldsymbol{\Delta}_T^2)$$

The red and blue curves correspond respectively to an exponential or dipole parameterization of the cross-section.



$\gamma^* + {}^4He \rightarrow {}^4He + \phi$ (new CLAS12 working proposal)

- ^{4}He is nice place to search for medium effects: relatively light, dense, and the 4-nucleon system is not overly complicated.

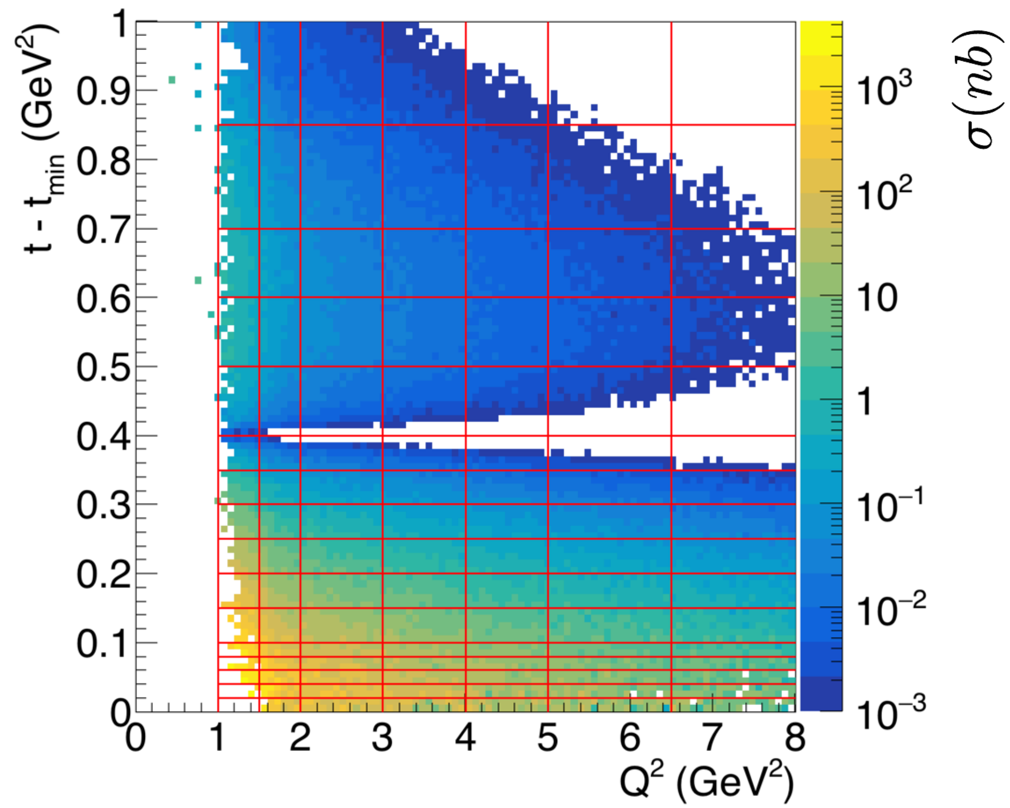
$$\frac{d\sigma_L}{dt}[{}^4He] \propto |\langle H_g \rangle|^2$$

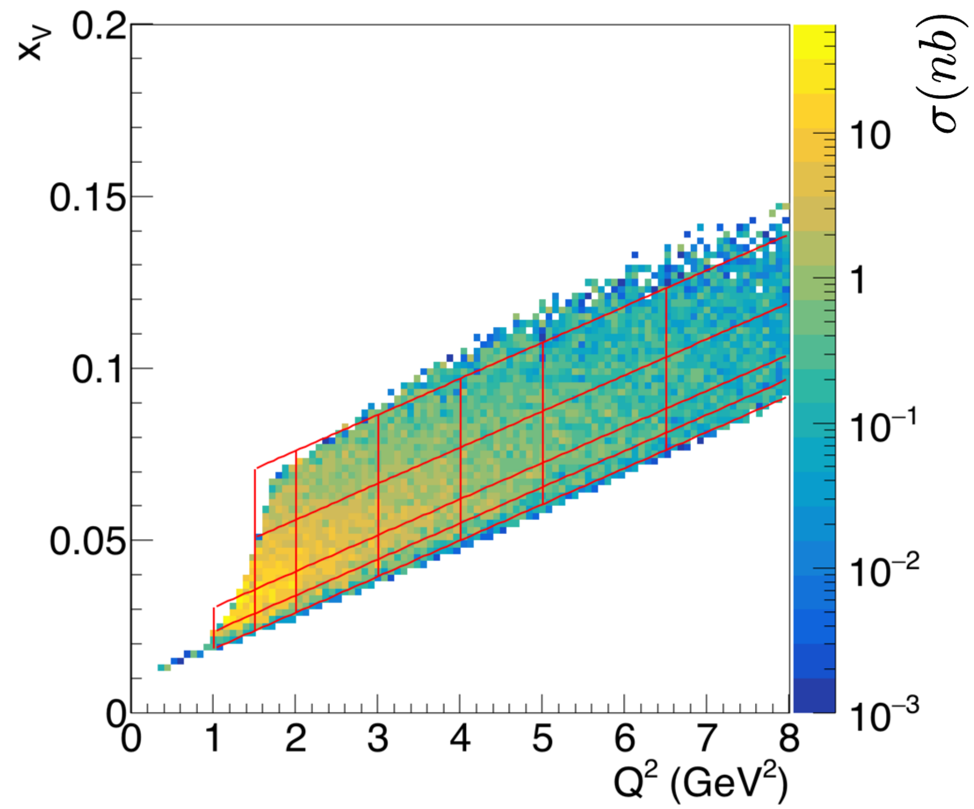
- In combination with the ALERT detector collaboration, a proposal is being prepared for PAC 44. Proposes to investigate DVCS and DVMP off a ^{4}He target using a newly designed ALERT recoil detector.

- How are partons / gluons distributed in a nucleus? First steps toward a global analysis.

We can compare x_V in DVMP (gluon GPD) to x_B in DVCS (parton GPD)

$$x_V = \frac{Q^2 + M_\phi^2}{W^2 + Q^2 + M_{He}^2} = x_B \left(\frac{Q^2 + M_\phi^2}{Q^2} \right)$$



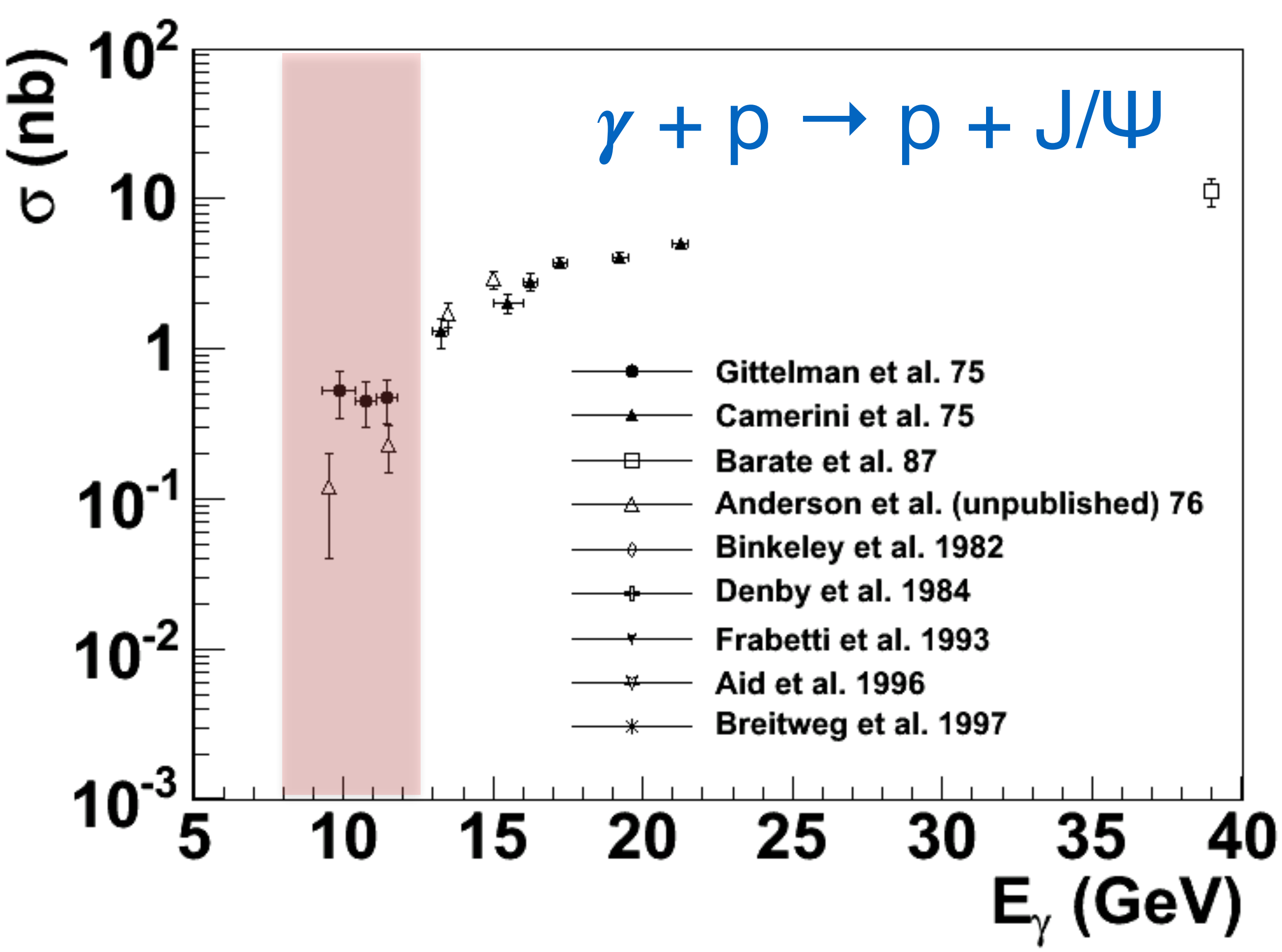


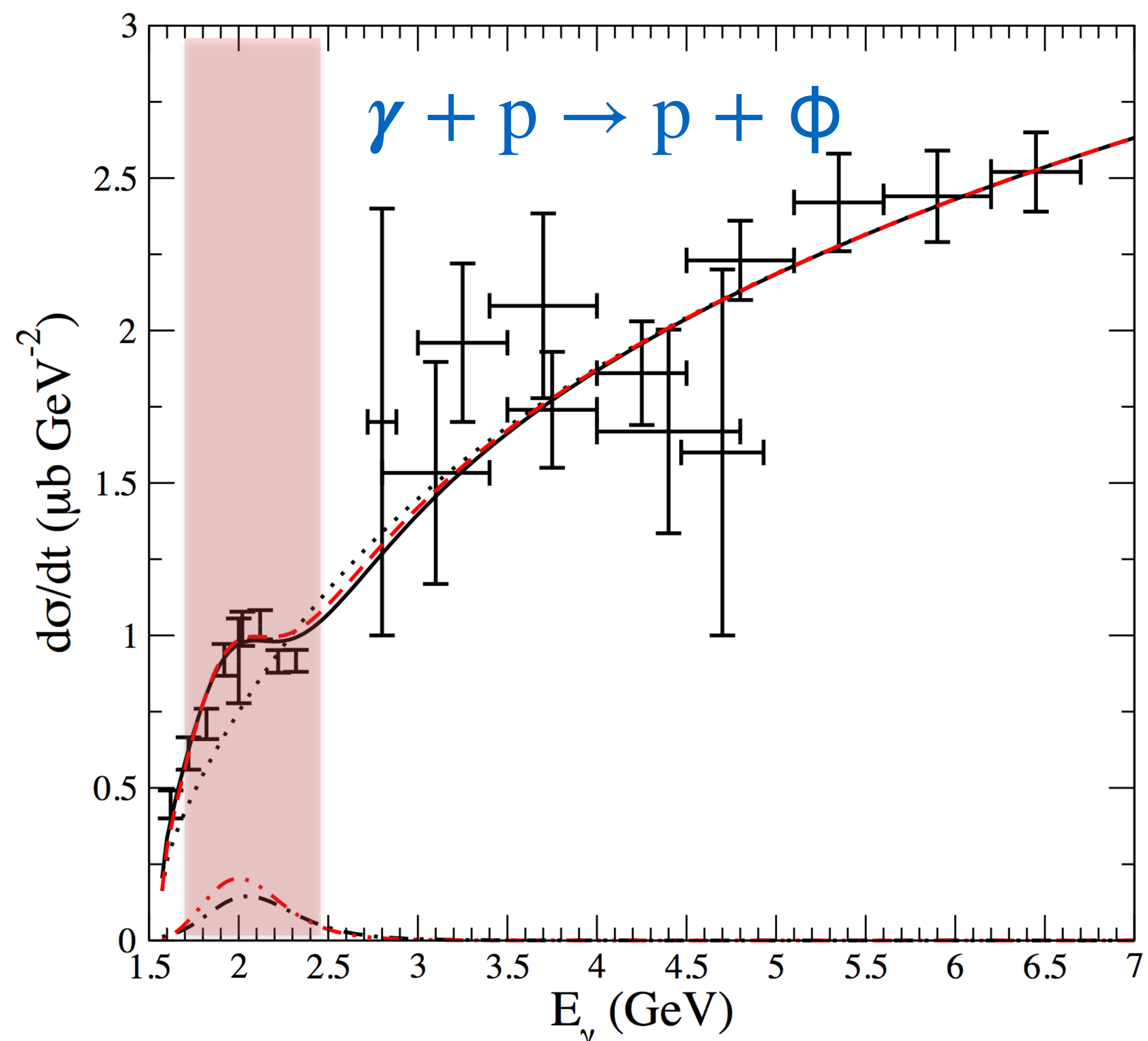
What can we learn from J/Ψ production at JLAB

- We now have opportunities in Hall-A/SoLID, Hall-C, and Hall-B/CLAS12 to study J/Ψ production / decay.
    - Small cross-section (at energies JLAB can reach) means we need decent luminosity.
        - CLAS12 was able to overcome luminosity restrictions with clever experiment design.
        - Hall-D will need some creativity to come up with a solution.

Electroproduction of J/Ψ off a proton target near threshold

- An 11 GeV electron beam allows one to reach just beyond threshold for J/Ψ production.
  - The threshold region is very rich in physics.
    - Enhancements in J/Ψ and ϕ??





Kiswhandi, Yang. Phys.Rev. C86 (2012)

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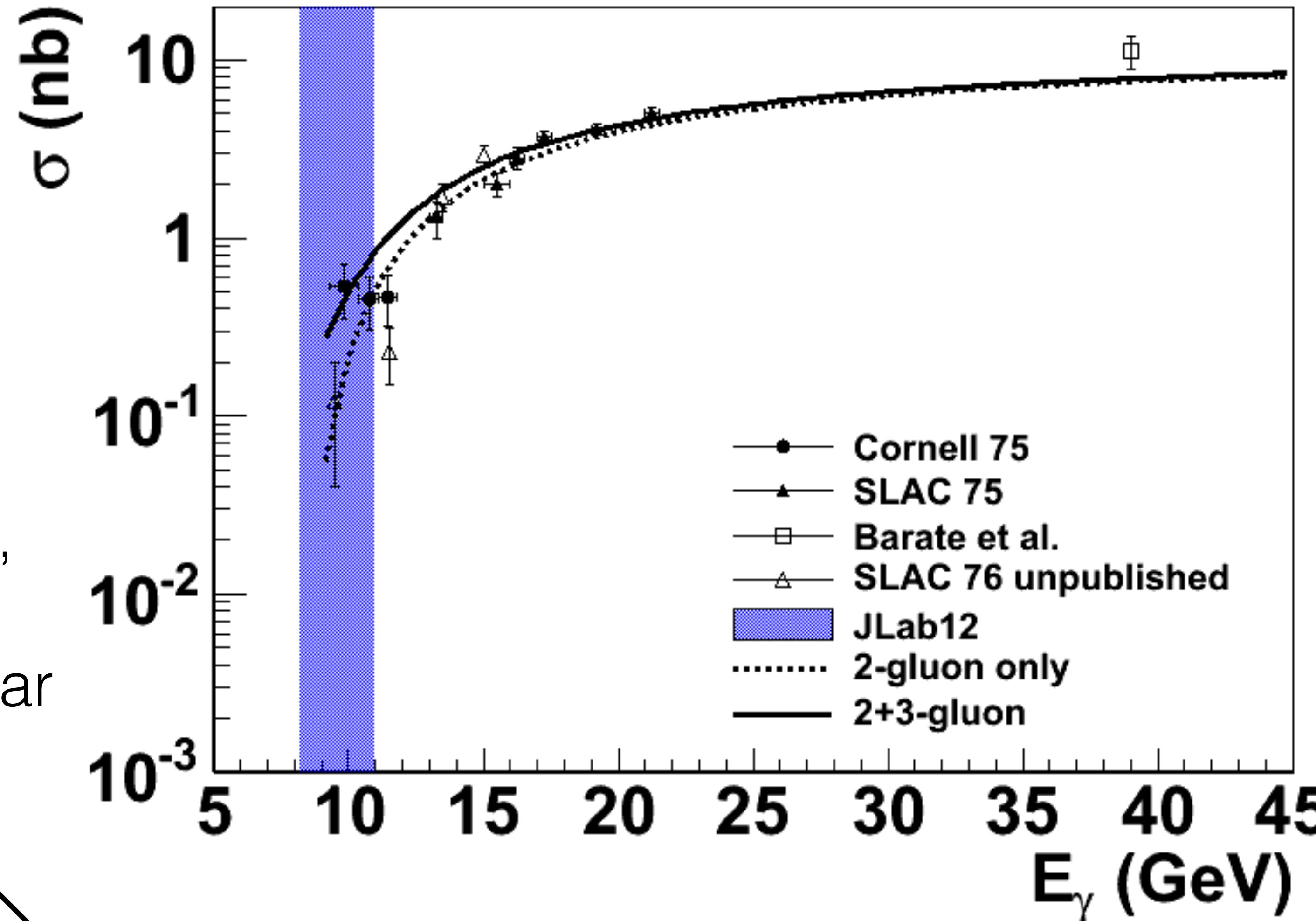
  - According to a hard scattering model, the J/Ψ is produced via 2-gluon exchange, with a possible 3-gluon near threshold from Brodsky, Chudakov, Hoyer, Laget (PLB 498, 23 [2001])

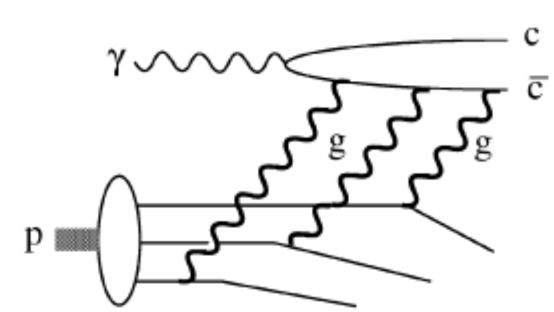


$$2-g:(1-x)^2 F(t)$$

$$3-g:(1-x)^0 F(t)$$

$$F(t) \propto \exp(1.13t)$$

$$x = \frac{2M_p M_{J/\psi} + M_{J/\psi}^2}{2E_\gamma M_p}$$



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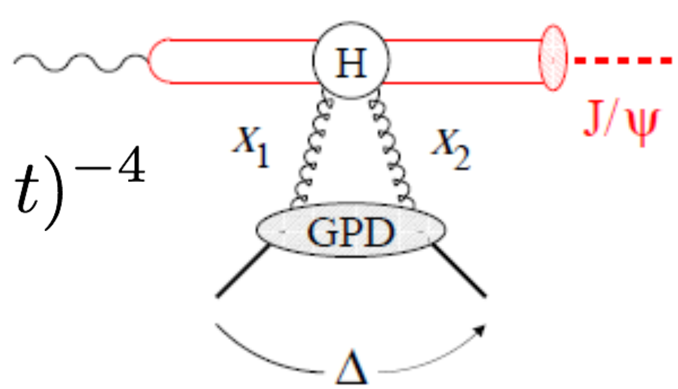
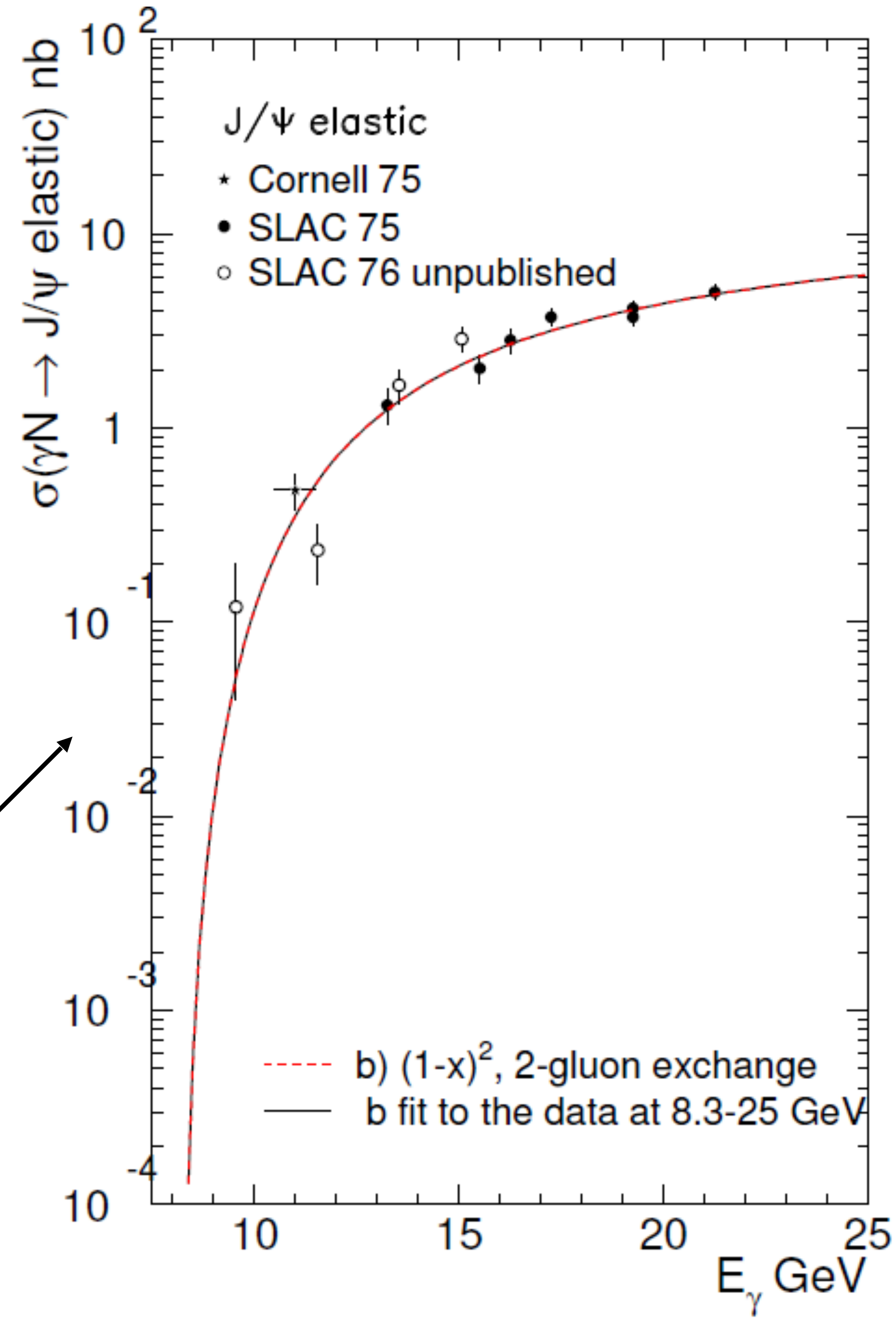
  - According to a hard scattering model, the J/Ψ is produced via 2-gluon exchange, with a possible 3-gluon near threshold from Brodsky, Chudakov, Hoyer, Laget (PLB 498, 23 [2001])
  - A prediction of a partonic soft mechanism using a 2-gluon form factor also is available from Frankfurt and Strikman, (PRD 66, 031502 [2002])

$$FF \propto (1-t)^{-4}$$





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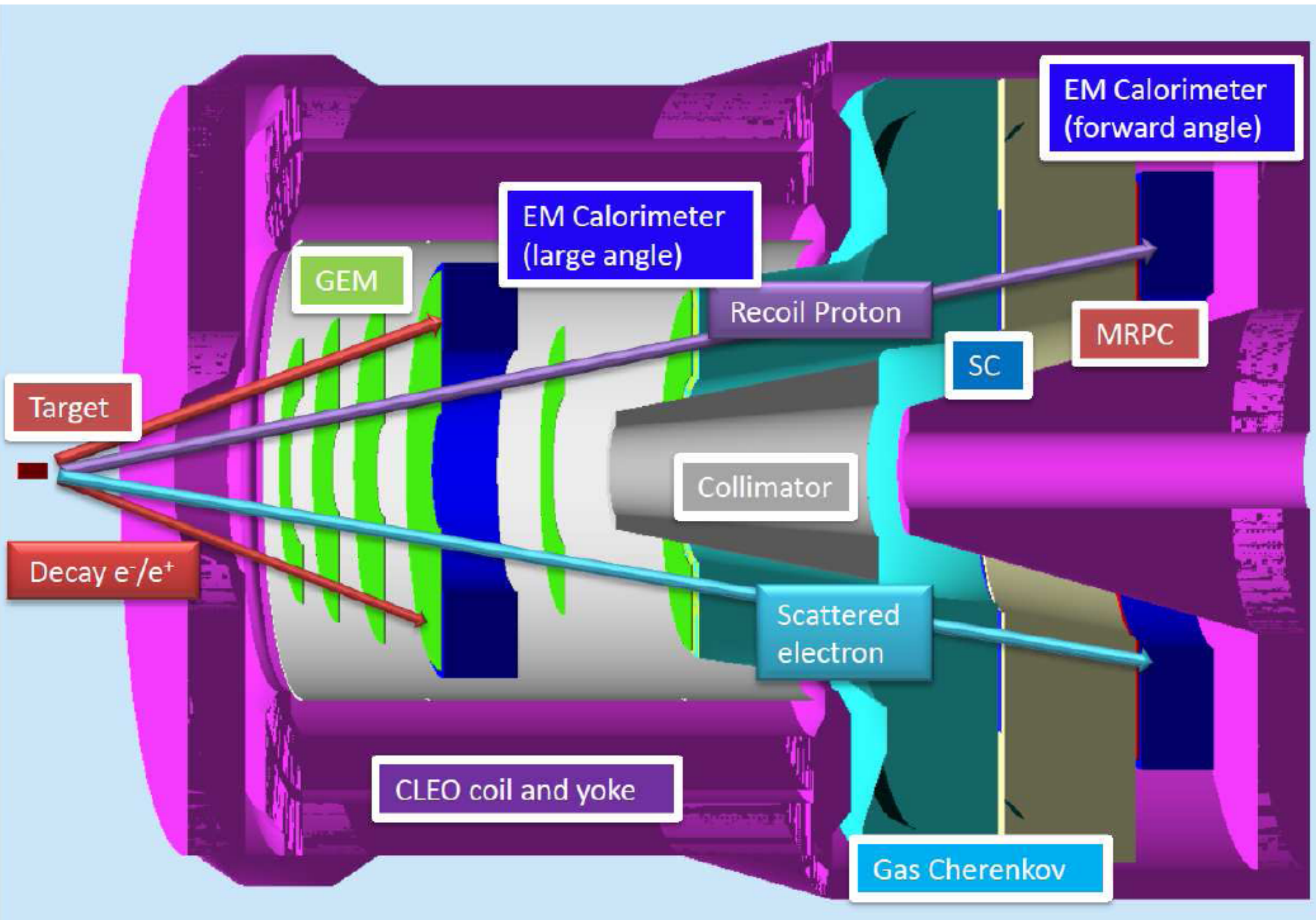


Near Threshold Electroproduction of J/Ψ at 11 GeV

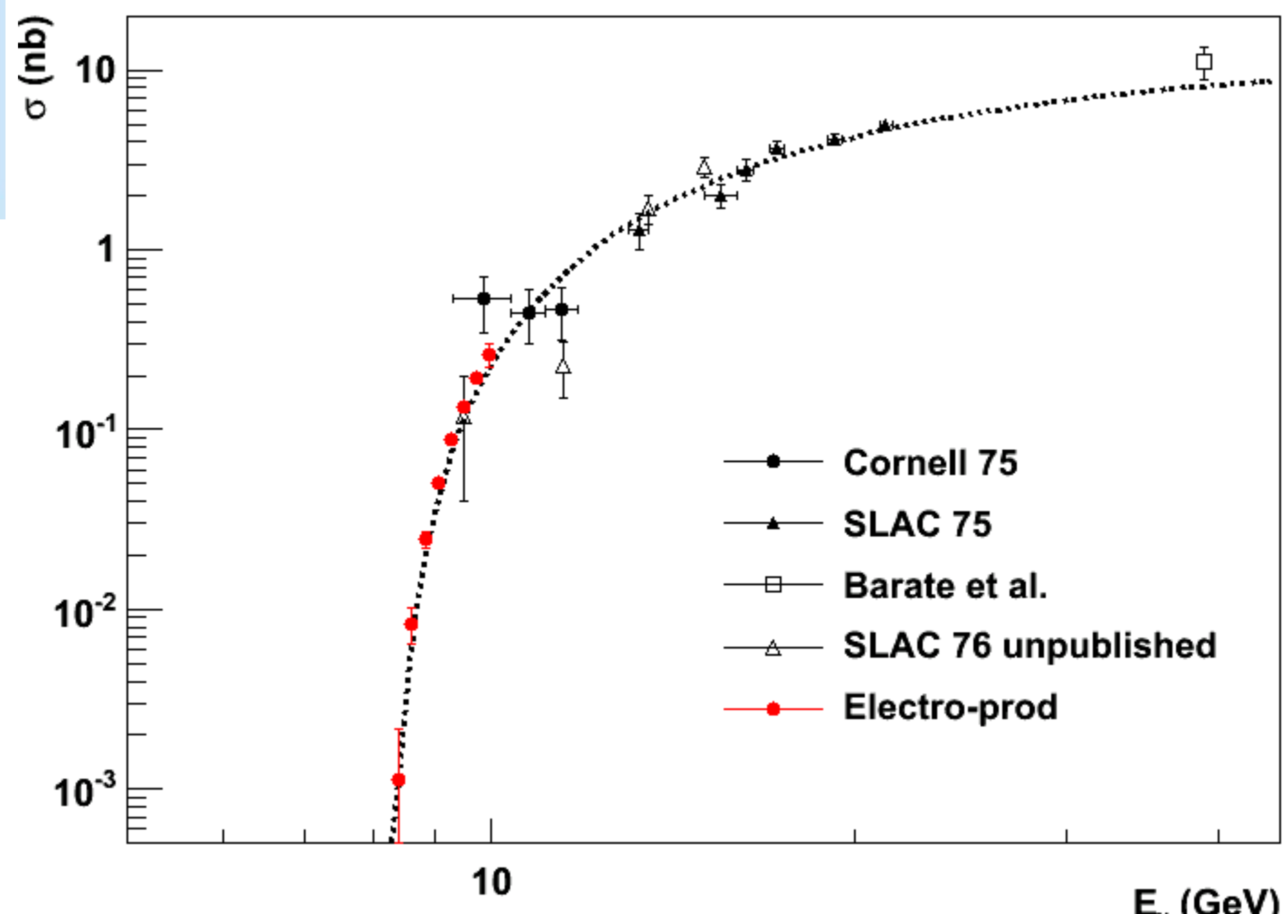
May 4, 2012

the ATHENNA Collaboration [1]

(A new experiment proposal to JLab-PAC39)

Approved with an A rating.
To be run with the SoLID detector in JLab's Hall-A.

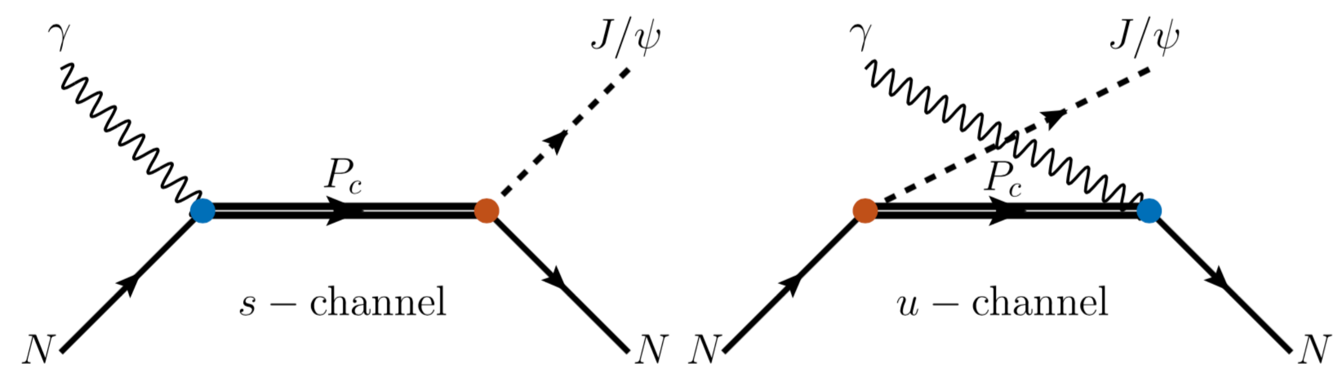
Expected measurement for 1200 hours, triple coincidence (e+, e-, e-) is 2.1k events with 2-g exchange (shown), or 8.08k events with 2-g and 3-g exchange:

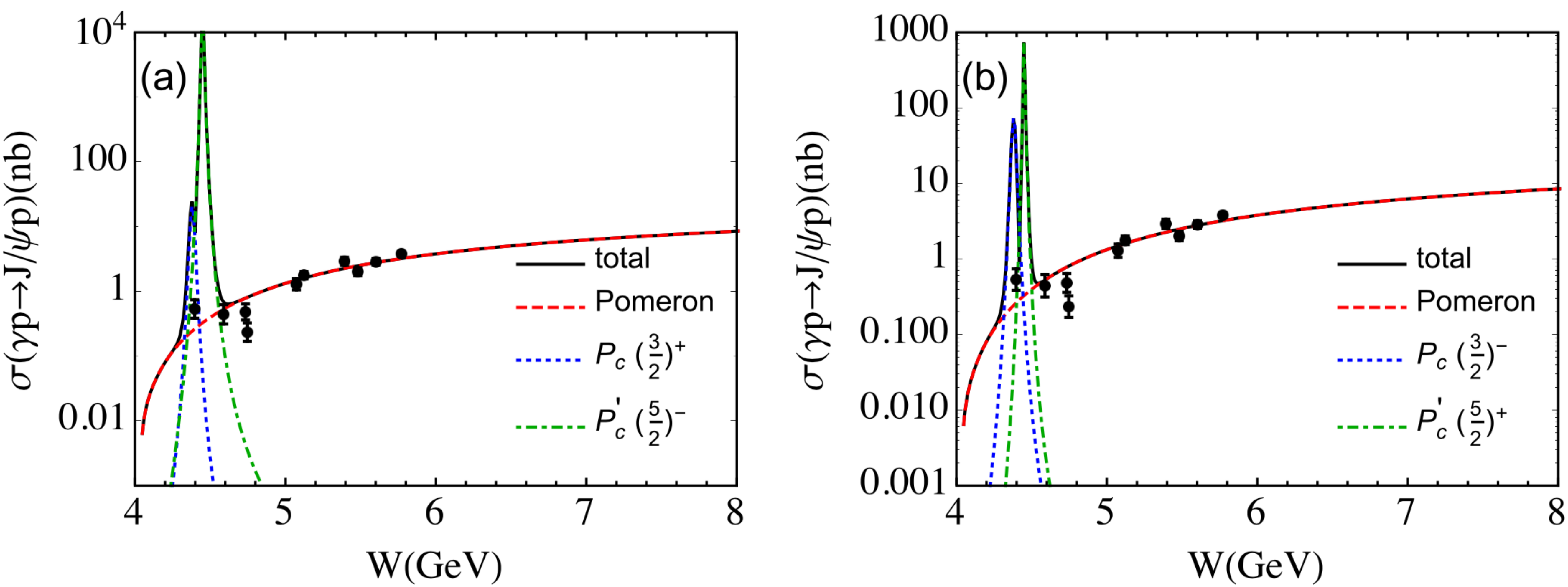


LHCb Pentaquark → J/Ψ + p

- The $P_c^+(4450)$ [Mass = 4449.8 ± 1.7 ± 2.5 MeV, Width = 39 ± 5 ± 19 MeV]
- The $P_c^+(4380)$ [Mass = 4380 ± 8 ± 29 MeV, Width = 205 ± 18 ± 86 MeV]

- Q. Wang, X.-H. Liu, Q. Zhao, *Phys.Rev.D 92*
  - Only s + u production, VMD coupling, hadron typical off-shell form factor, lower order partial waves.





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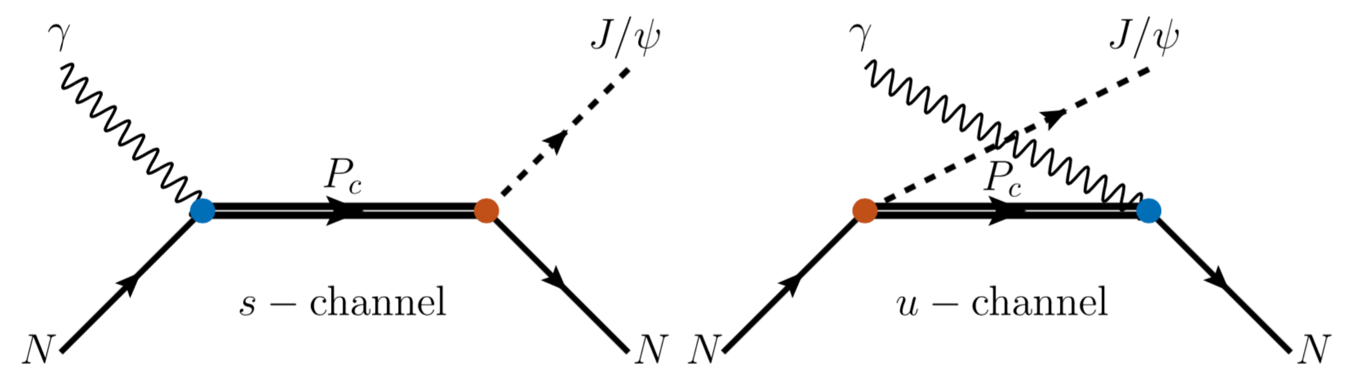
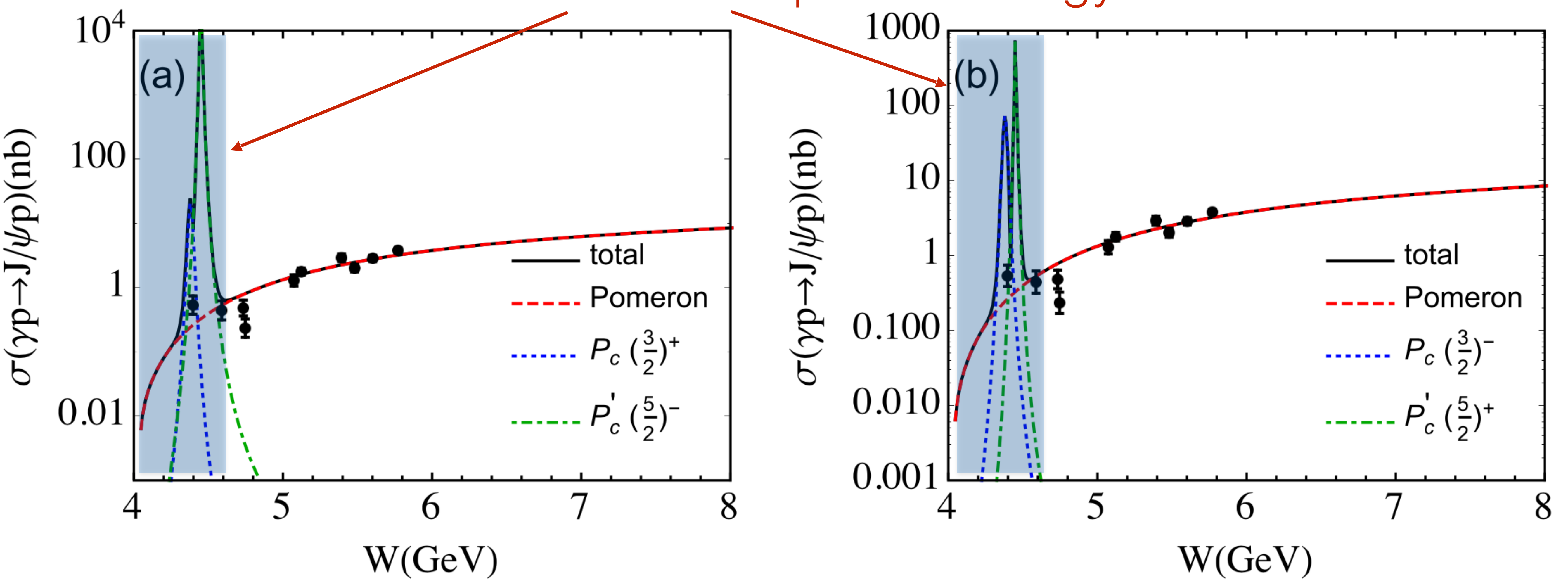
- The $P_c^+(4450)$ [Mass = 4449.8 ± 1.7 ± 2.5 MeV, Width = 39 ± 5 ± 19 MeV]
- The $P_c^+(4380)$ [Mass = 4380 ± 8 ± 29 MeV, Width = 205 ± 18 ± 86 MeV]

- Q. Wang, X.-H. Liu, Q. Zhao, *Phys.Rev.D 92*
  - Only s + u production, VMD coupling, hadron typical off-shell form factor, lower order partial waves.



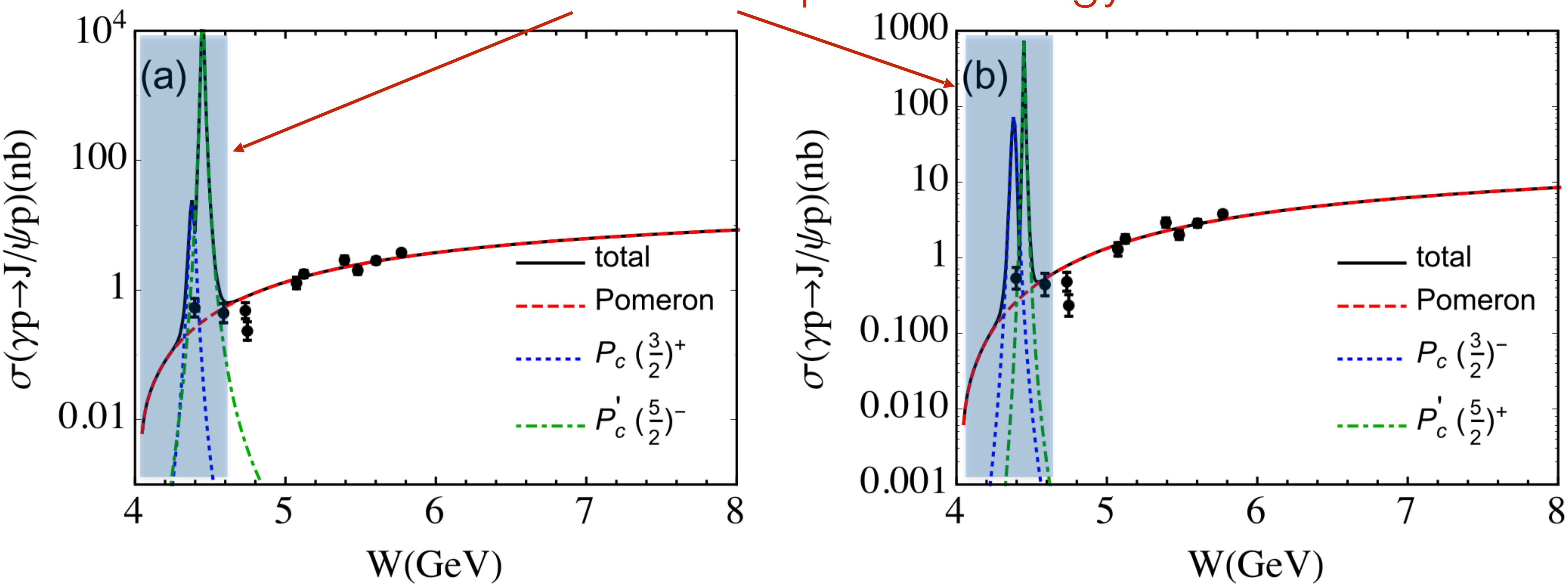
Accessible with 11 GeV photon energy



LHCb Pentaquark → J/Ψ + p

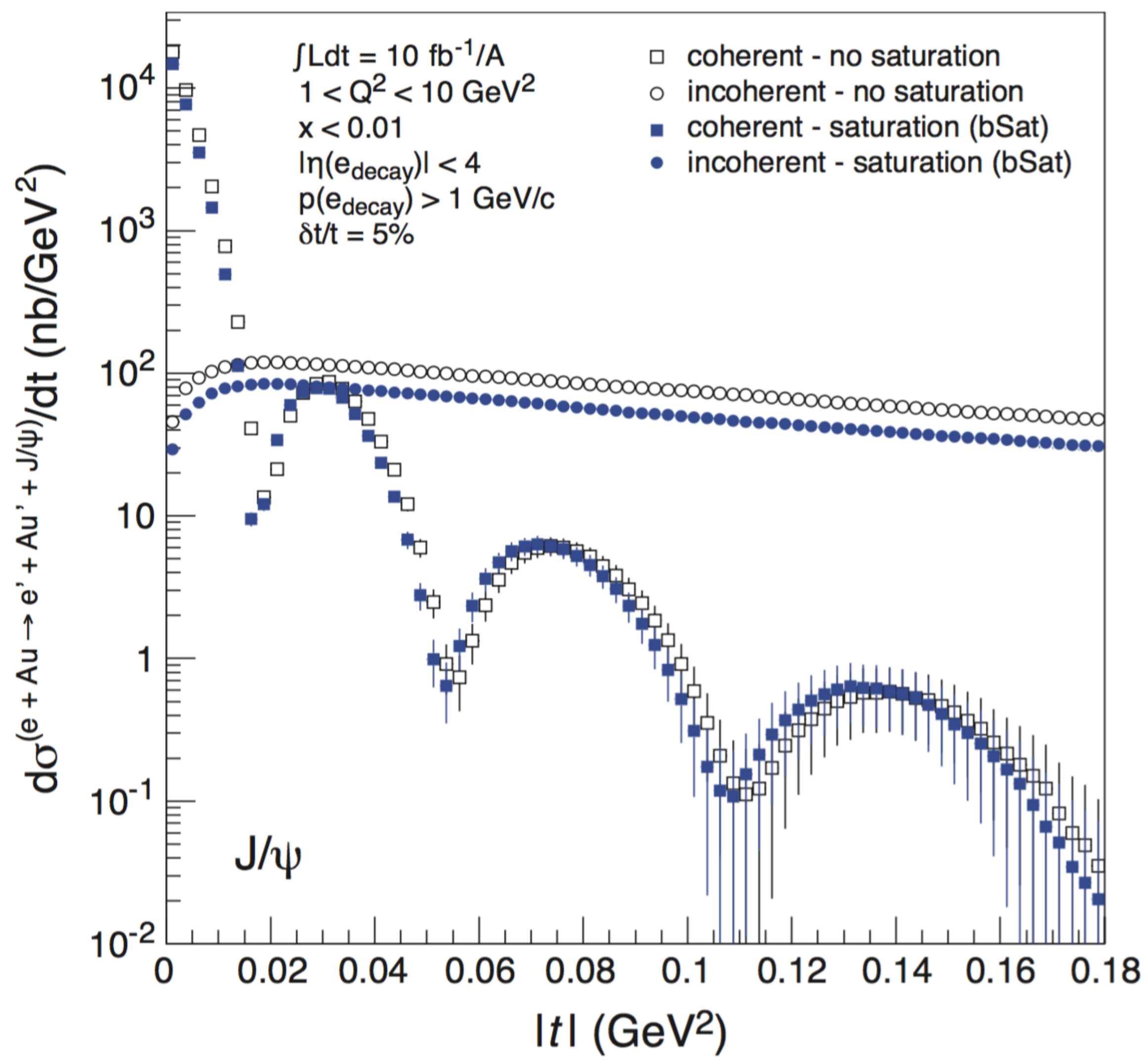
- **At Temple University we are working on a proposal for Hall-C:**
  - e+ e- decay of J/Ψ detected in coincidence (p undetected)
  - radiated real-photon beam (untagged)
  - W control with electron beam energy tuning.

Accessible with 11 GeV photon energy



J/Ψ production off nuclei

- Already proposed for EIC (coherent electroproduction)
- Possible at JLab12 (no proposals, yet…)
    - Gluon distribution?
    - Threshold effects?
    - Mesic bound states?
    - in-medium modification?
- Needs creative work on both theoretical and experimental side to make a reality, but the interest is there!



Summary

- Many opportunities to probe protons and nuclei with J/Ψ and ϕ production.
  - Transverse gluon distributions can be measured.
  - Experiments on the free proton are approved. Proposals are being prepared to study coherent ϕ off the nucleus at JLab.
  - Threshold production of J/Ψ off proton should come (relatively) soon at JLab.
    - A LHCb pentaquark search is fairly straight-forward at JLab. A proposal is being put together using Hall-C.
  - A ϕ - ^{4}He bound states search would be interesting and is possible at JLab.
  - Feasibility of coherent J/Ψ production on nuclei at JLab needs to be investigated.

Backup Slides

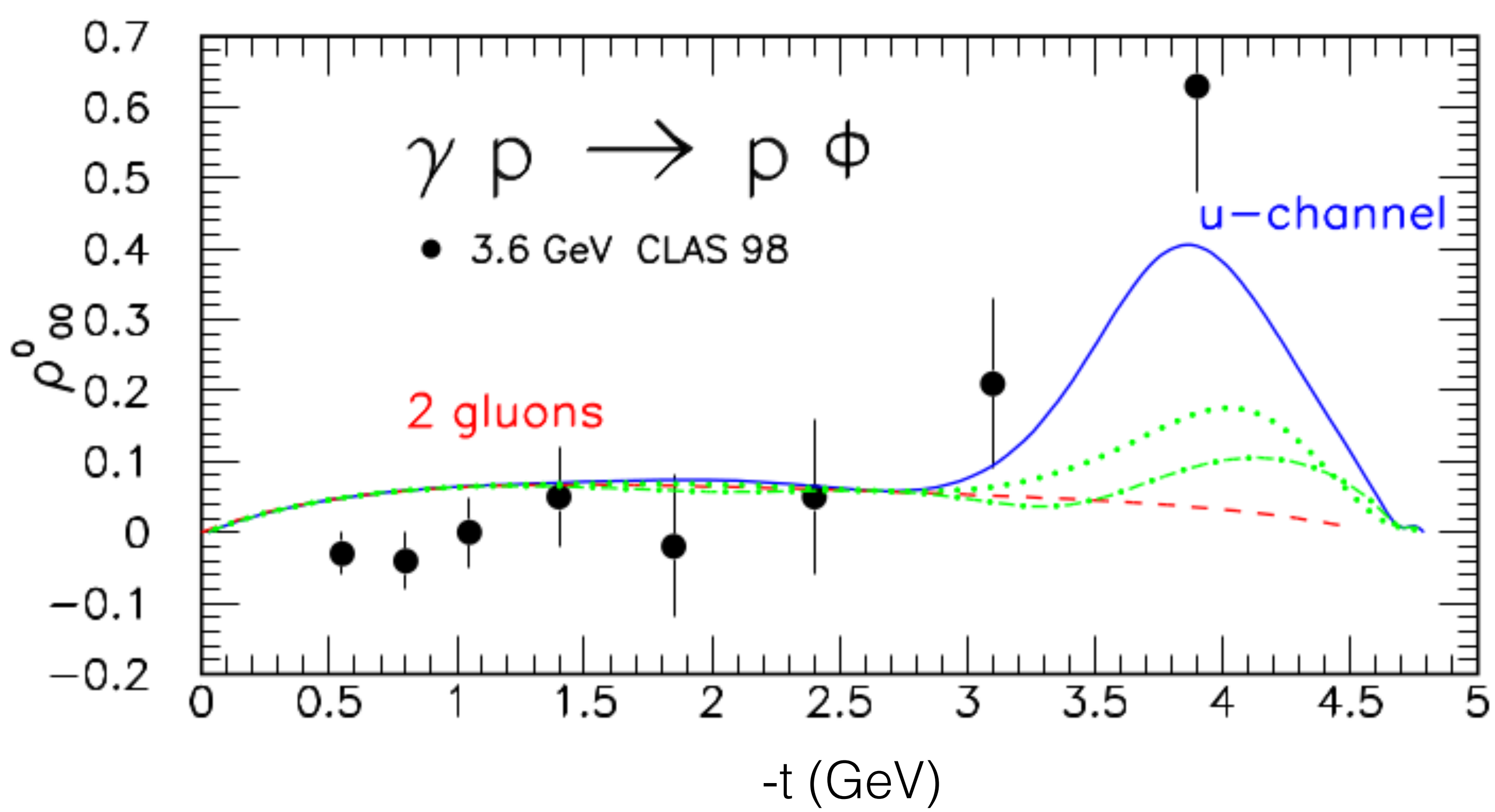
$\gamma + p \rightarrow p + \varphi$ (Spin Density Matrix)

- If s-Channel helicity conservation (SCHC) holds for vector mesons with Pomeron/two-gluon exchange (early rho studies showed this), and the u-channel process breaks SCHC, then angular information about the ϕ decay can help separate processes.

- With an unpolarized beam only the first term of the spin density matrix survives. The angular distribution can be written as:

$$\frac{dN}{d\theta} = \frac{3}{4}\sin\theta\left[\left(1-\rho^0_{00}\right)\sin^2\theta + 2\rho^0_{00}\cos^2\theta\right]$$

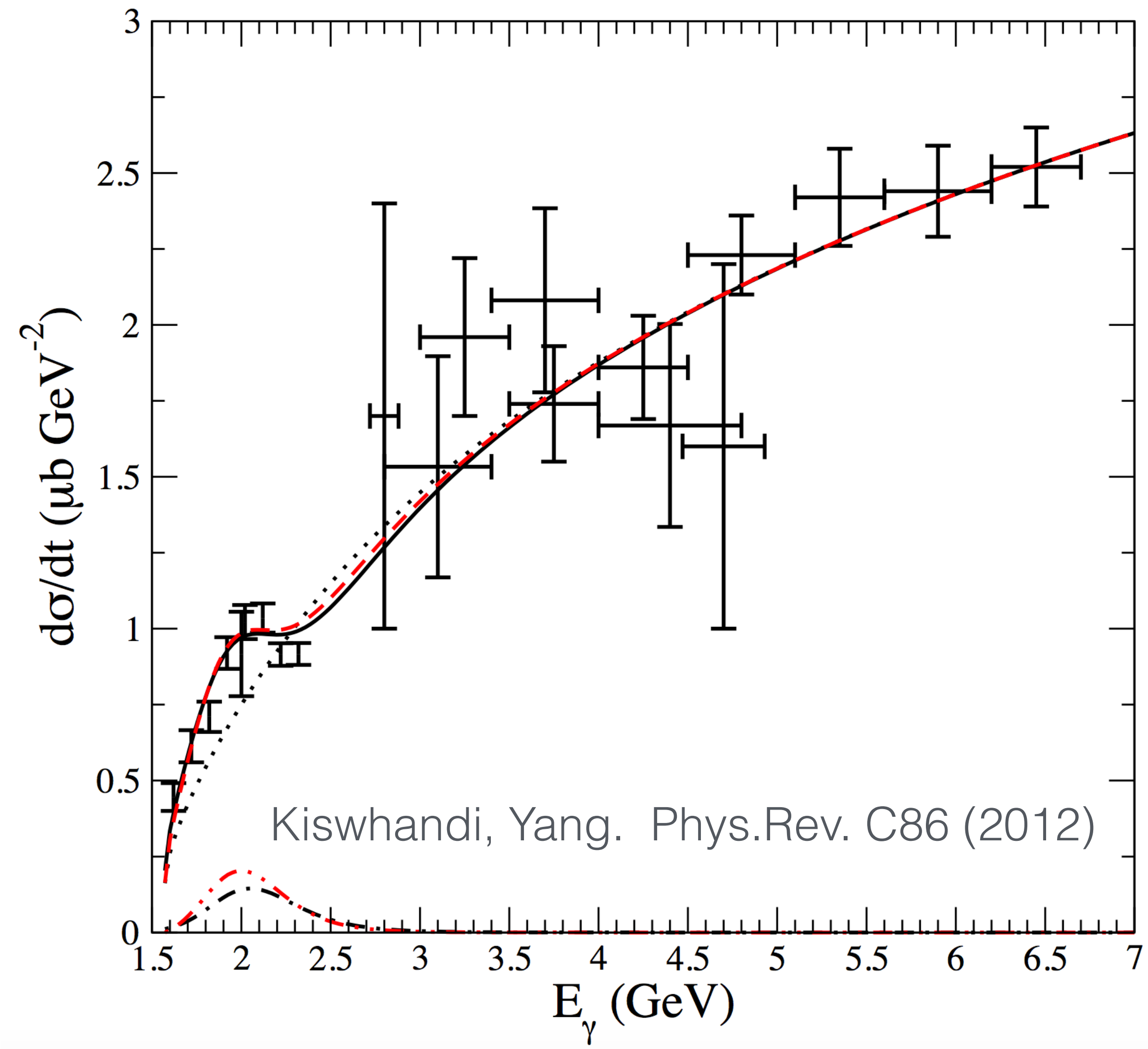
- ρ^0_{00} describes the probability that a longitudinally polarized ϕ meson is produced by a transverse real photon.
  - If this term is much larger than zero then SCHC is broken.

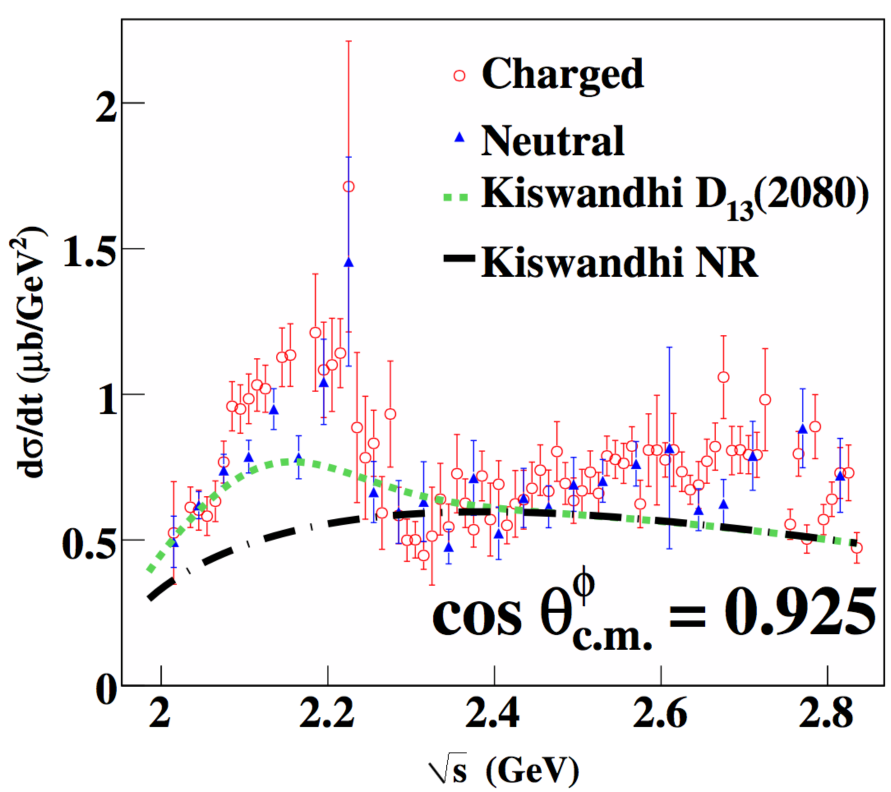


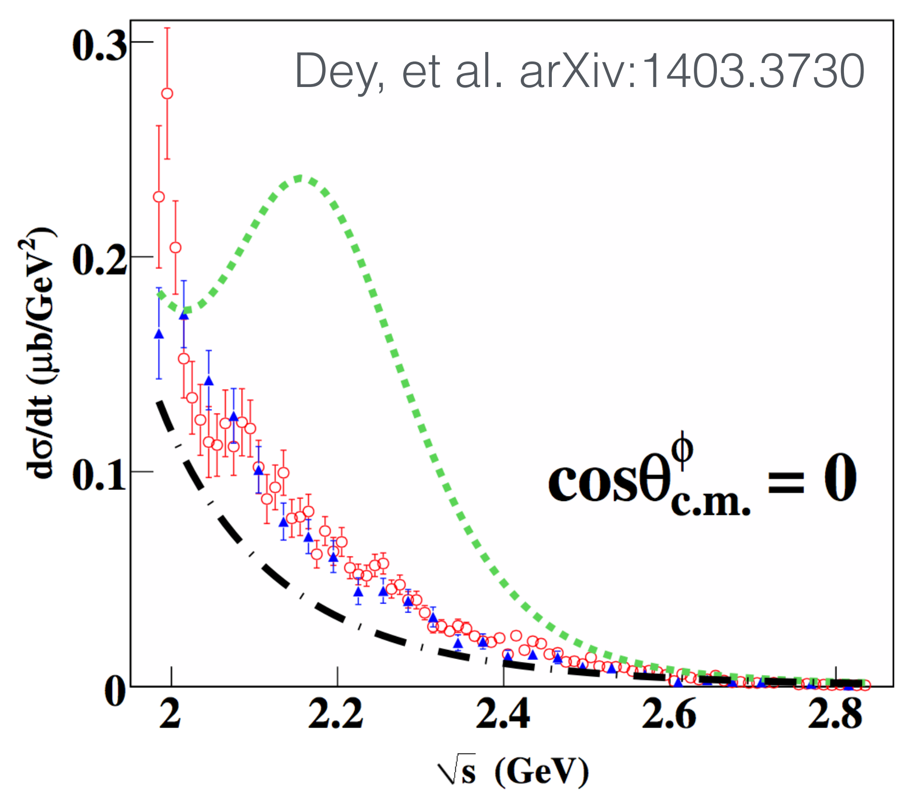
McCormick et al., Phys.Rev. C69 (2004) 032203

$\gamma + p \rightarrow p + \varphi$
($J^P = 3/2^\pm$ resonance?)

- One of the more interesting puzzles to come out of angular studies of ϕ production is the mysterious peaking nature near 2 GeV photon energies.
  - **Possible solution**: $J^P = 3/2^\pm$ resonance [$D_{13}(2080)$] contributions?
    - **Unlikely**: resonance structure disappears at low angle.
  - **Possible Solution**: Re-scattering from Lambda-K production?
    - **Unlikely**: Neutral (K^0K^0) channel shows exact same structure.

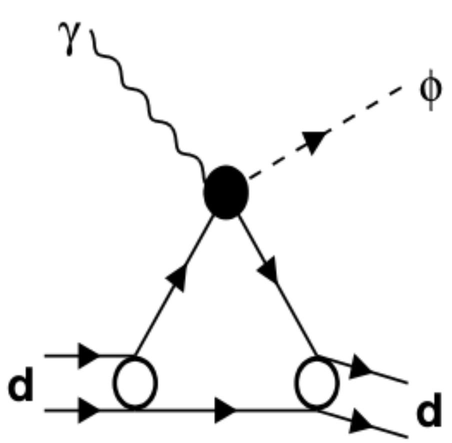




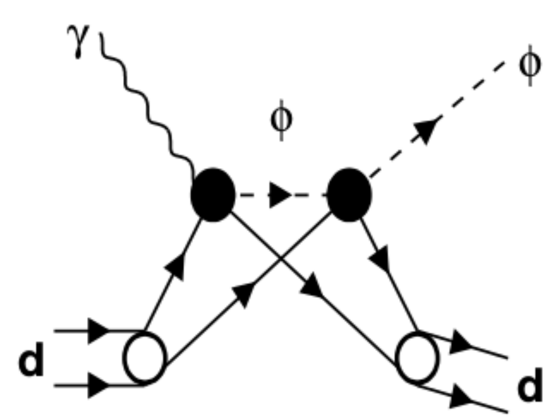


$\gamma + d \rightarrow d + \varphi$

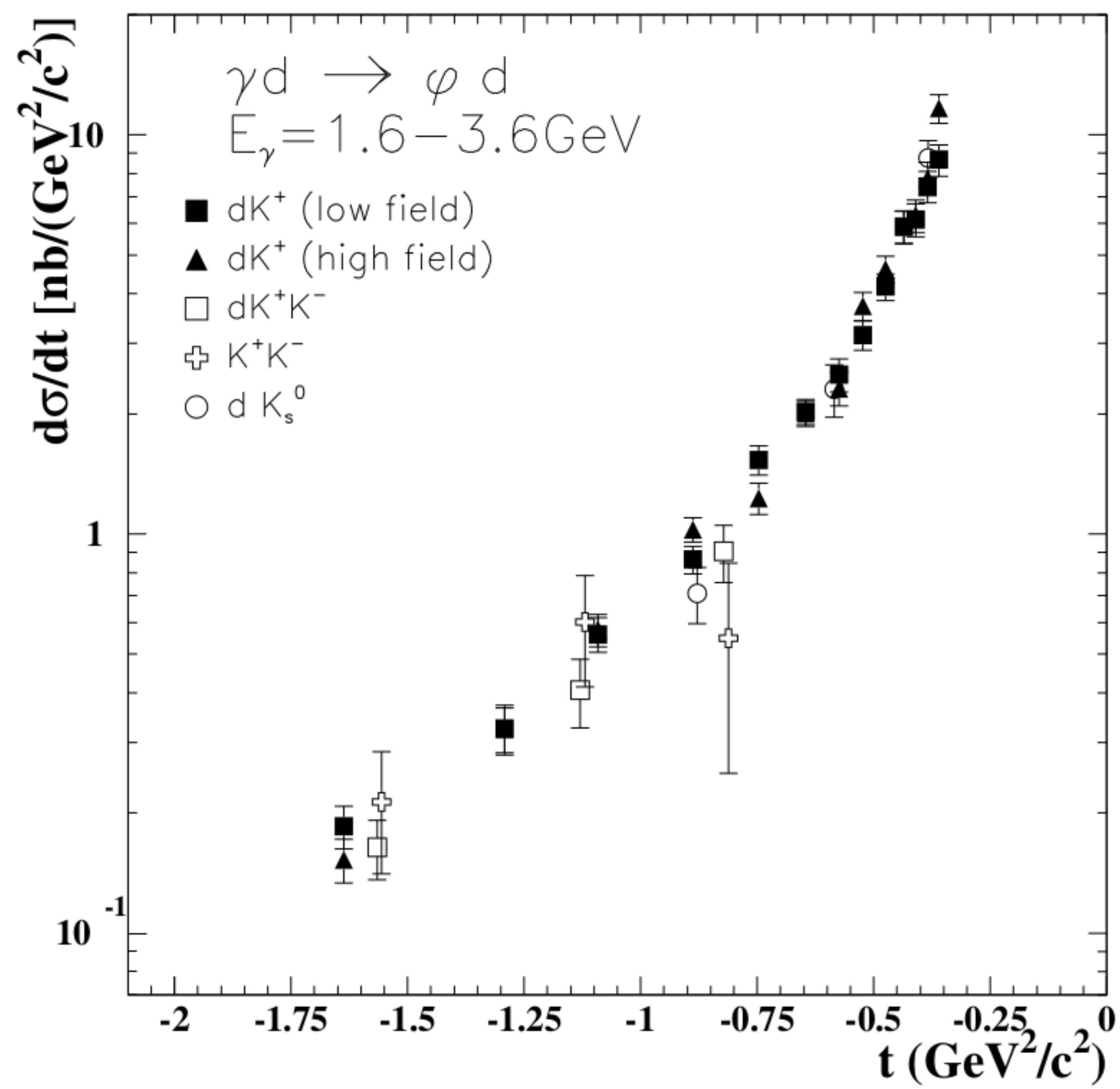
- In deuteron coherent scattering, one must consider re-scattering processes, bound states, and possible in-medium modifications.
- Re-scattering:



Single Scattering



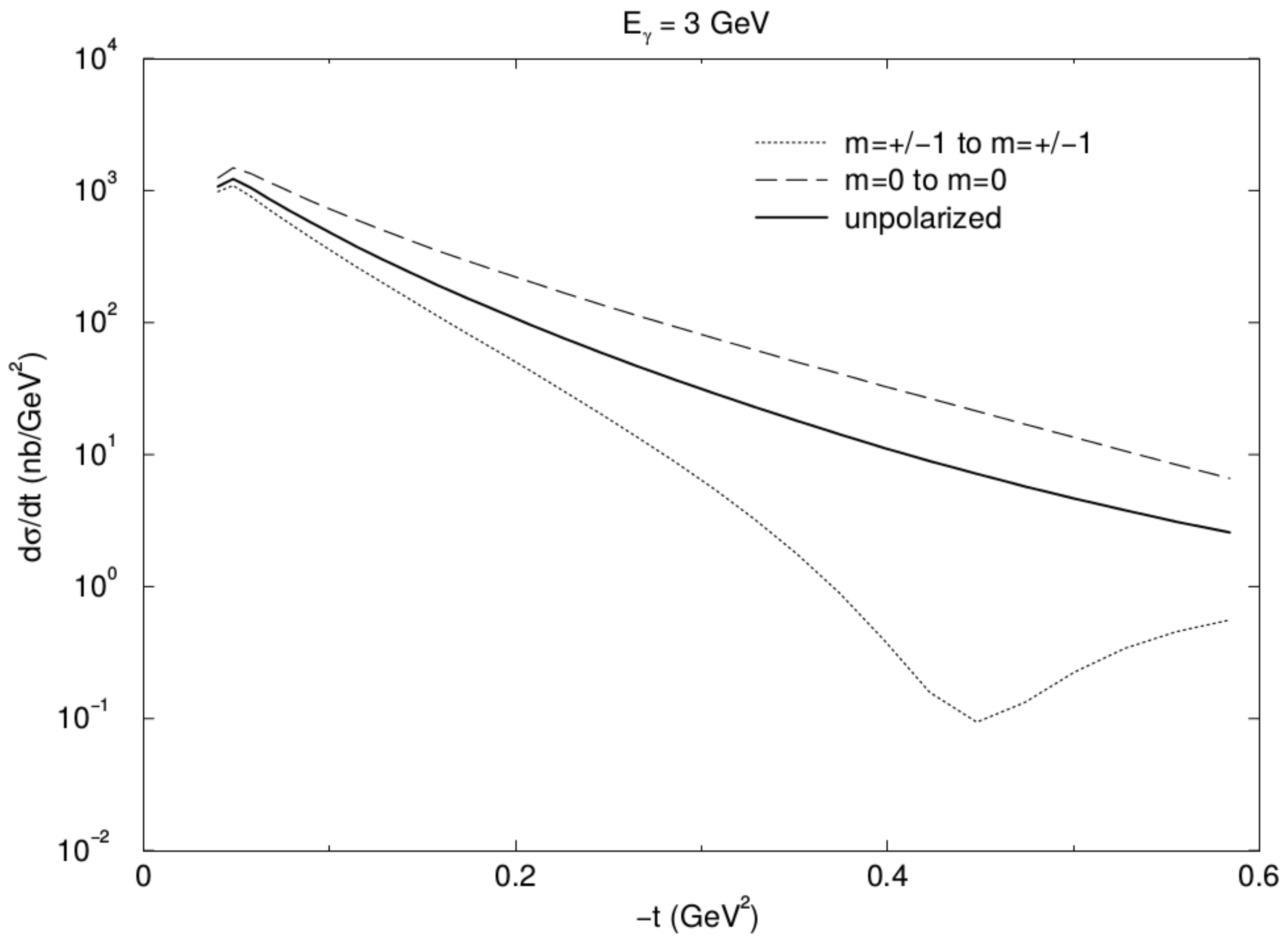
Double Scattering



Mibe et al., Phys.Rev. C76 (2007) 052202

$\gamma + d \rightarrow d + \phi$

- At intermediate energies, the eikonal approximation will still hold, but Glauber theory assumptions, like factorization and ultra-relativistic simplifications, can break down.
- Rogers, Sargsian, and Strikman used GEA and Feynman rules to calculate the coherent cross-section at these energies.



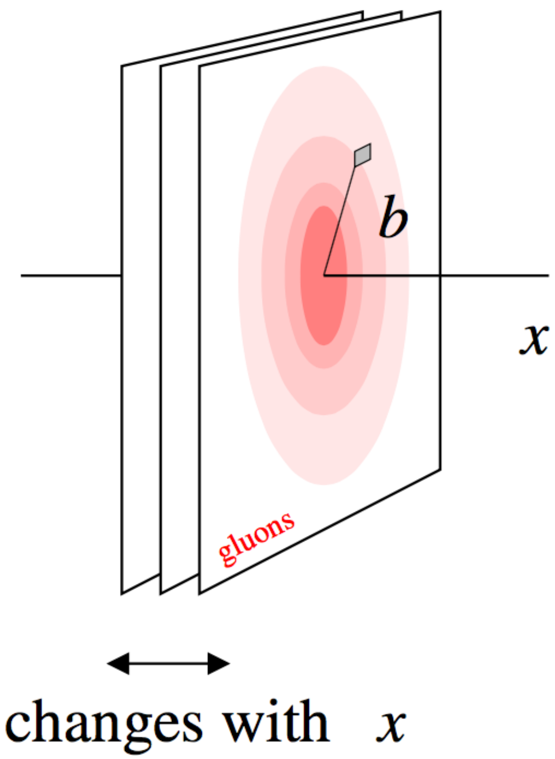
Rogers, Sargsian, and Strikman. Phys.Rev. C73 (2006) 045202

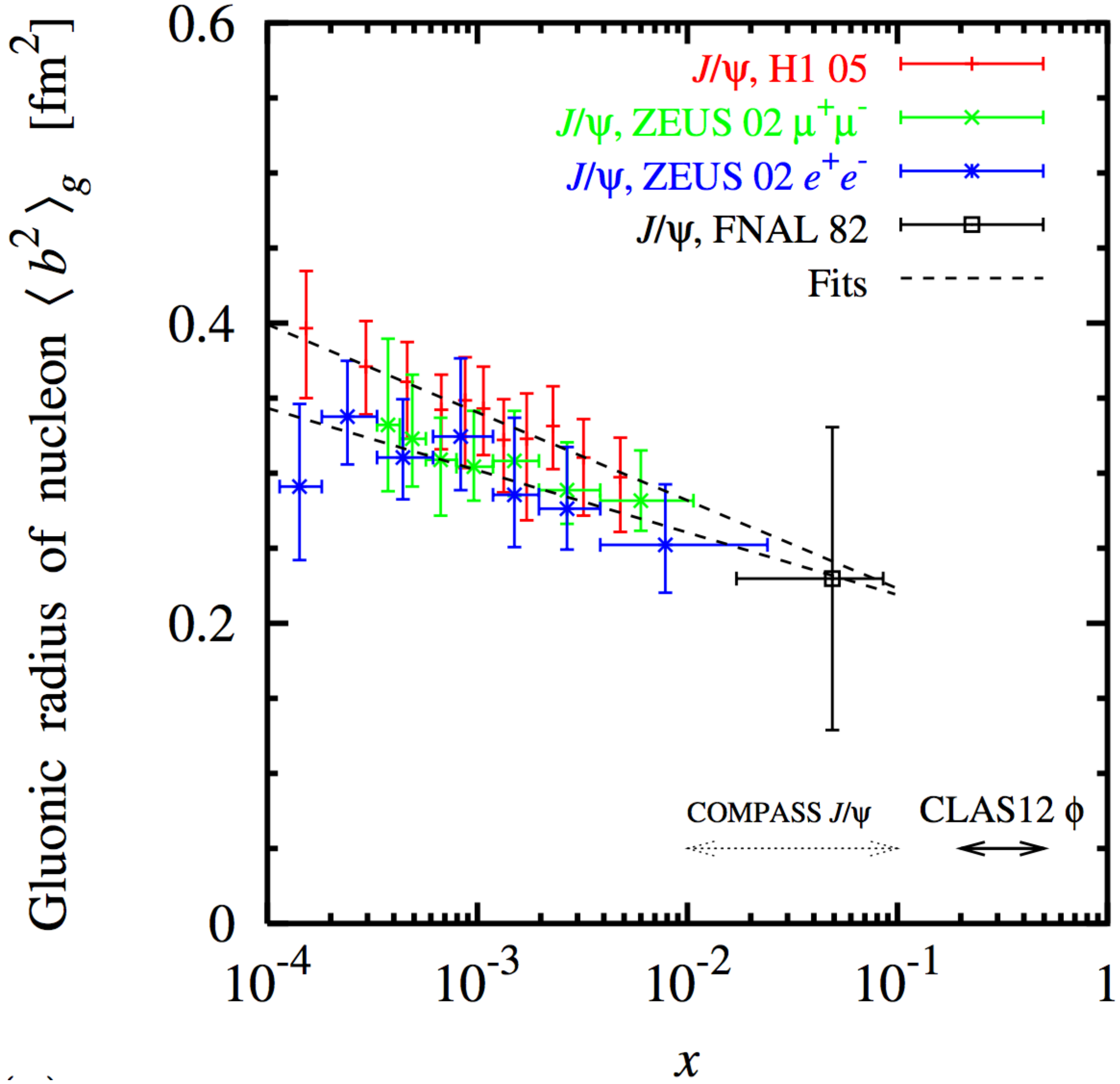
$\gamma^* + p \to p + \phi$ (CLAS12 proposed)

- One can also access the gluonic radius in x-space by defining the average gluonic transverse radius as:

$$\langle b^2 \rangle_g \equiv \int d^2b\, b^2\, \rho_g(b,x) = 4\,\frac{\partial F_g}{\partial t}(t=0)$$

- J/Ψ studies have been performed at HERA and FNAL to extract the gluon radius.





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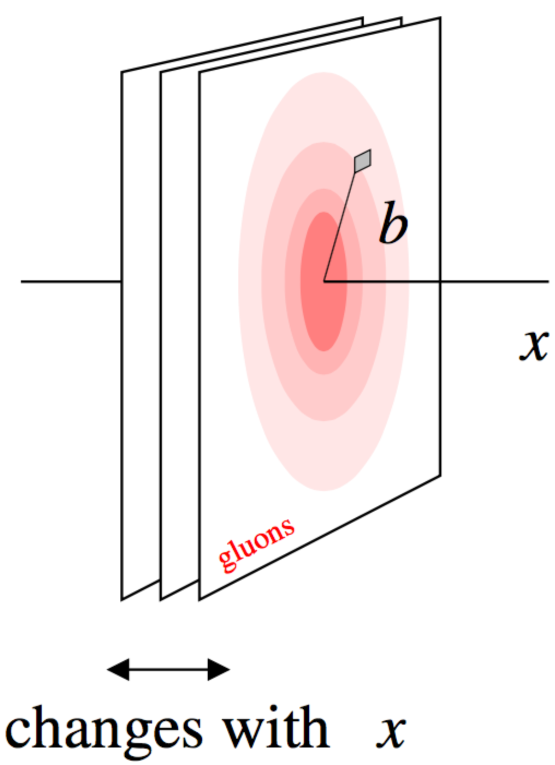
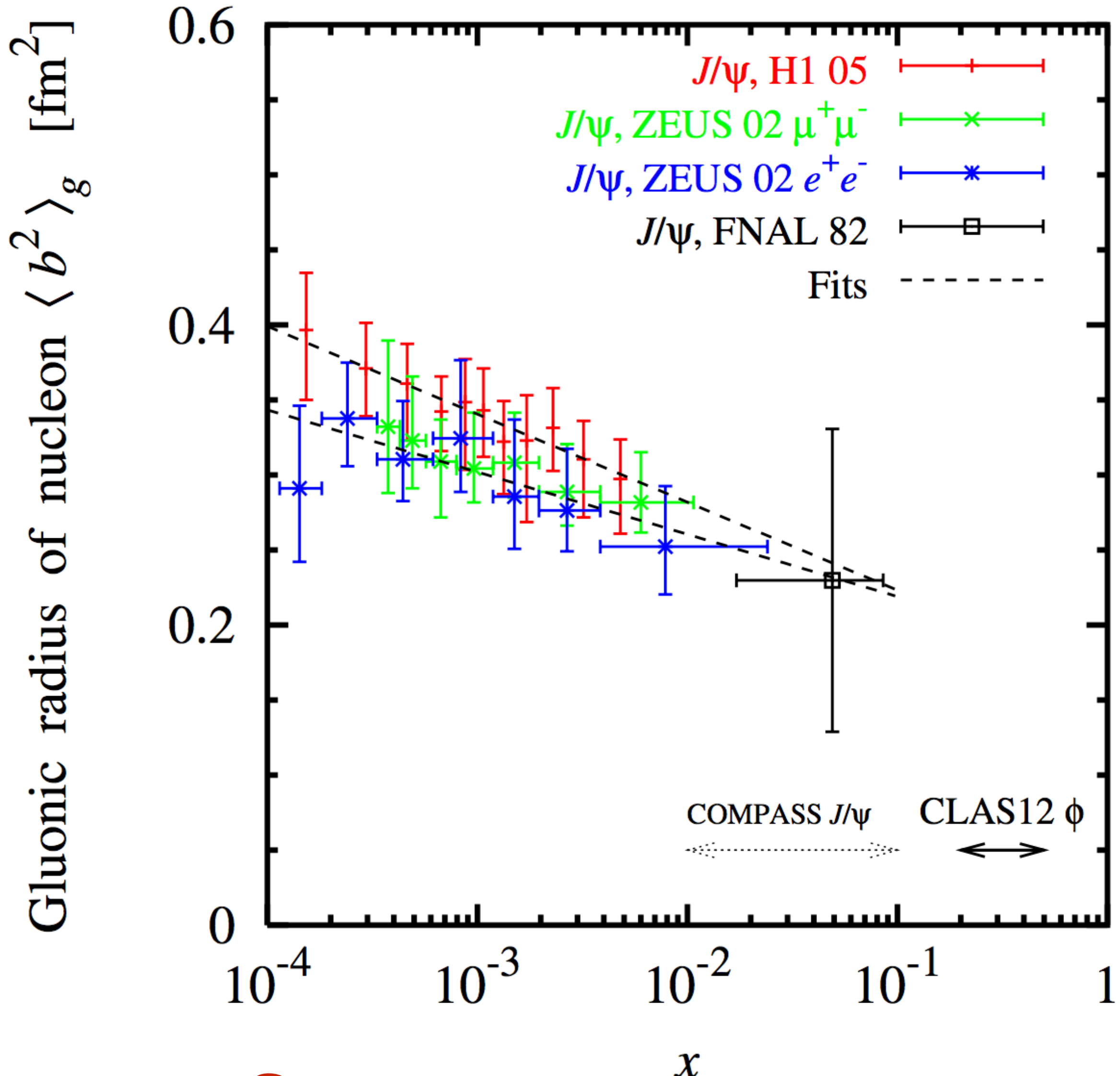
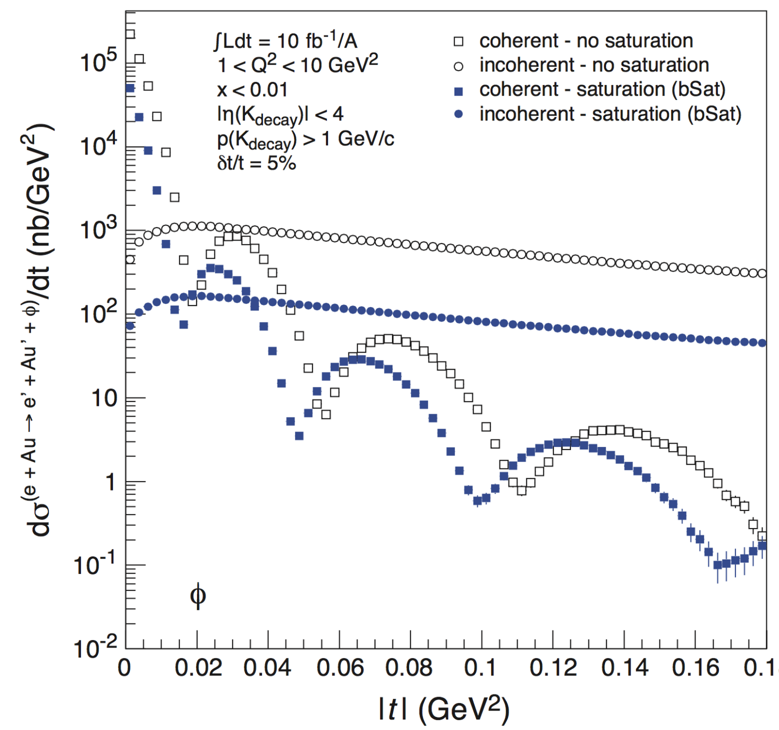


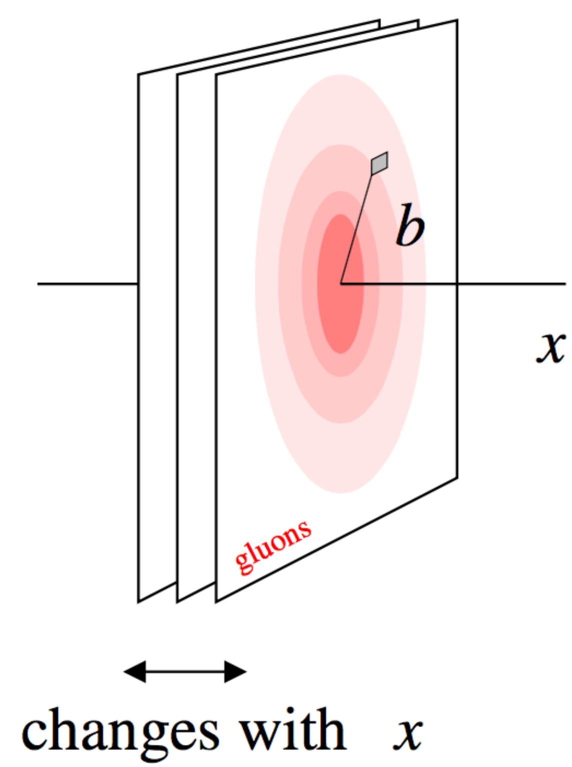


What can we learn with nuclear targets?

Value in $\gamma^* + {}^4He \rightarrow {}^4He + \phi$?

- What does the gluon distribution look like for nuclei?
- Does the phi-production process sample individual nucleons, or the nucleus as a whole?
    - A diffractive pattern would indicate an interaction with the gluon field of a nucleon. No diffractive pattern would indicate an interaction with the gluon field of the entire nucleus.
    - Would high-x reveal an average gluon radius near that of a nucleon, and low-x give the radius of the nucleus?
- Re-scattering? Other medium effects?





Estimating the coherent ϕ electroproduction cross-section off ^{4}He

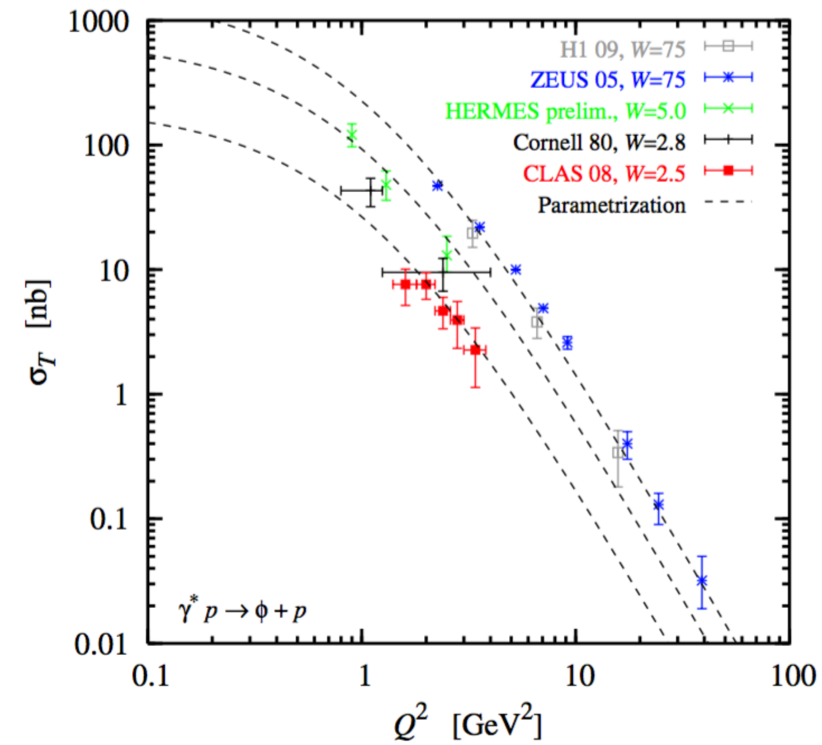
- Phenomenological approach to production off proton:

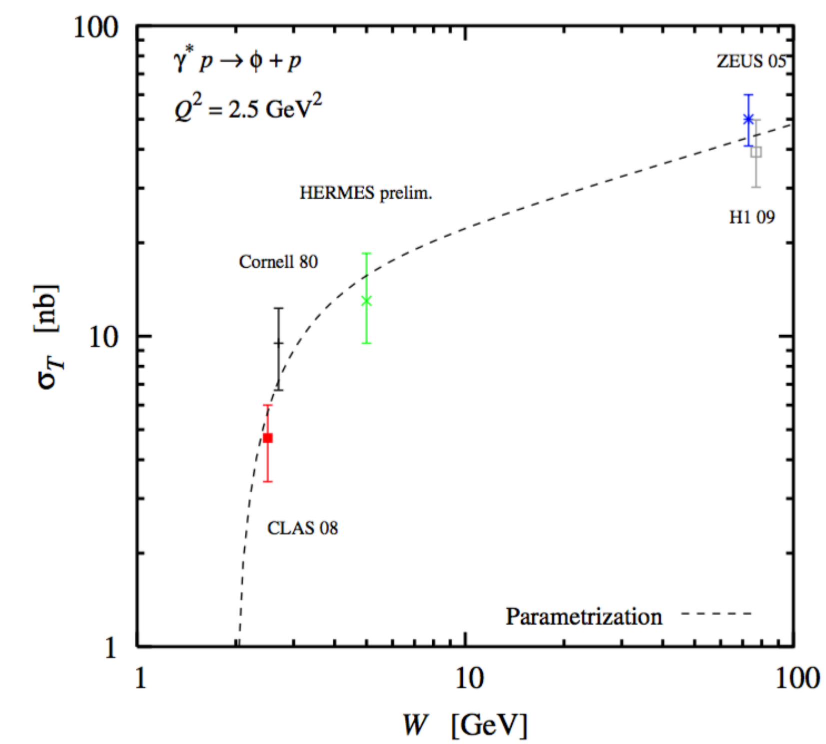
$$\frac{d\sigma}{dx_B dQ^2 dt} = \Gamma(Q^2, x_B, E)\left(\frac{d\sigma_T}{dt}(Q^2, x_B, t) + \epsilon\frac{d\sigma_L}{dt}(Q^2, x_B, t)\right)$$

  - Longitudinal and transverse response functions
  - Exponential t-dependance of ϕ
  - W, Q^2 dependence parameterized to world data.
- Kinematics are restricted to e + ^{4}He → e’ + ^{4}He + ϕ.
  - Cross-section is calculated with (naively) modified “t” and “W”:
    - “target nucleon” has random isotropically distributed fermi-momentum
    - “recoil nucleon” has (^{4}He momentum)/4 + random fermi-momentum
- Helium charge form factor $F_{c,4He}$ is calculated with both a Fourier-Bessel transform and DQSM for large Q^2.
  - $Q^2 \rightarrow |t - t_{min}| = t'$, for calculation of all form-factors.
- Cross-section goes like:

$$\frac{d\sigma_{^4He}}{dx_B dQ^2 dt} = \frac{d\sigma_p}{dx_B dQ^2 dt}\left|\frac{A\, F_C(t')_{^4He}}{F_C(t')_p}\right|^2$$

Identical parametrization as CLAS12 proposal for ϕ production off p





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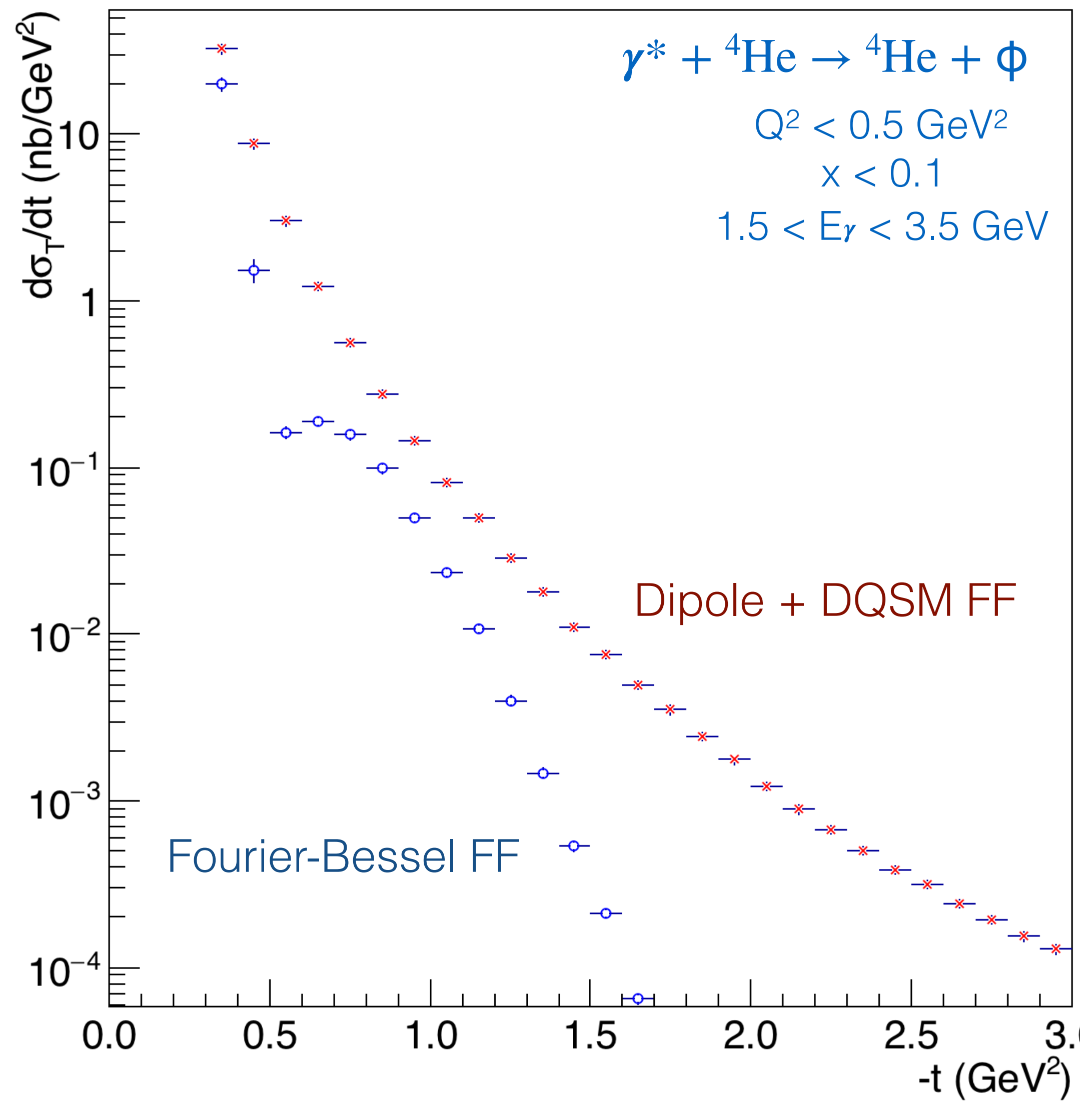
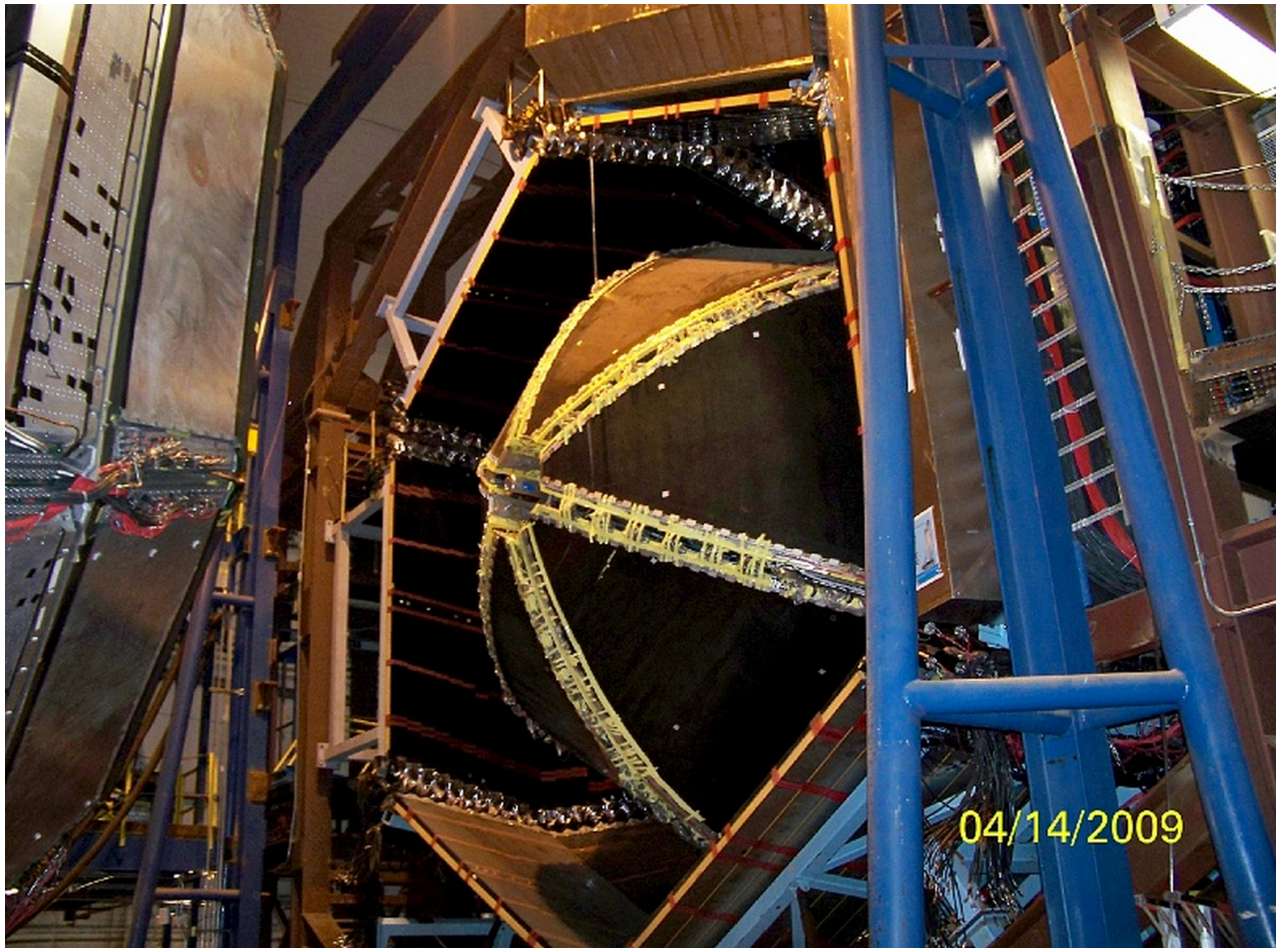


Preliminary study of $\gamma^* + {}^4He \rightarrow {}^4He + \phi$ at JLab 6GeV.

- The eg6 experiment at JLab gives us an opportunity to study ϕ electroproduction off ^4He.
- A CLAS experiment (2π phi coverage), with a recoil nucleon detector (BoNuS RTPC).
- Access to the exclusive reaction through many channels.
  - $e + {}^4He \rightarrow e' + K^+ + K^- + {}^4He$ (fully exclusive)
  - $e + {}^4He \rightarrow e' + K^+ + K^- + ({}^4He)$
  - $e + {}^4He \rightarrow e' + (K^+) + K^- + {}^4He$
  - $e + {}^4He \rightarrow (e') + e^+ + e^- + {}^4He$
  - $e + {}^4He \rightarrow e' + \pi^+ + \pi^- + (K^0) + {}^4He$



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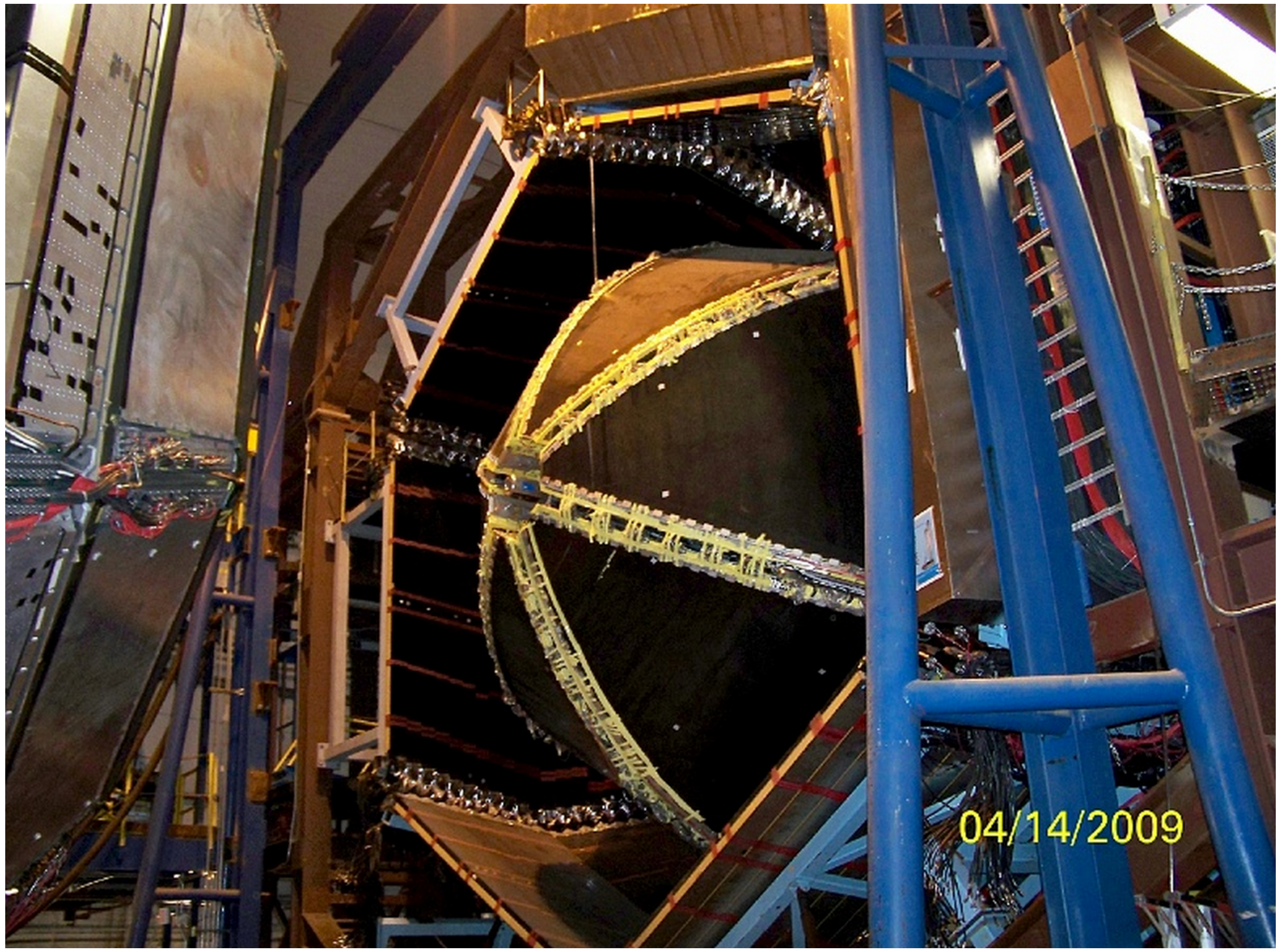
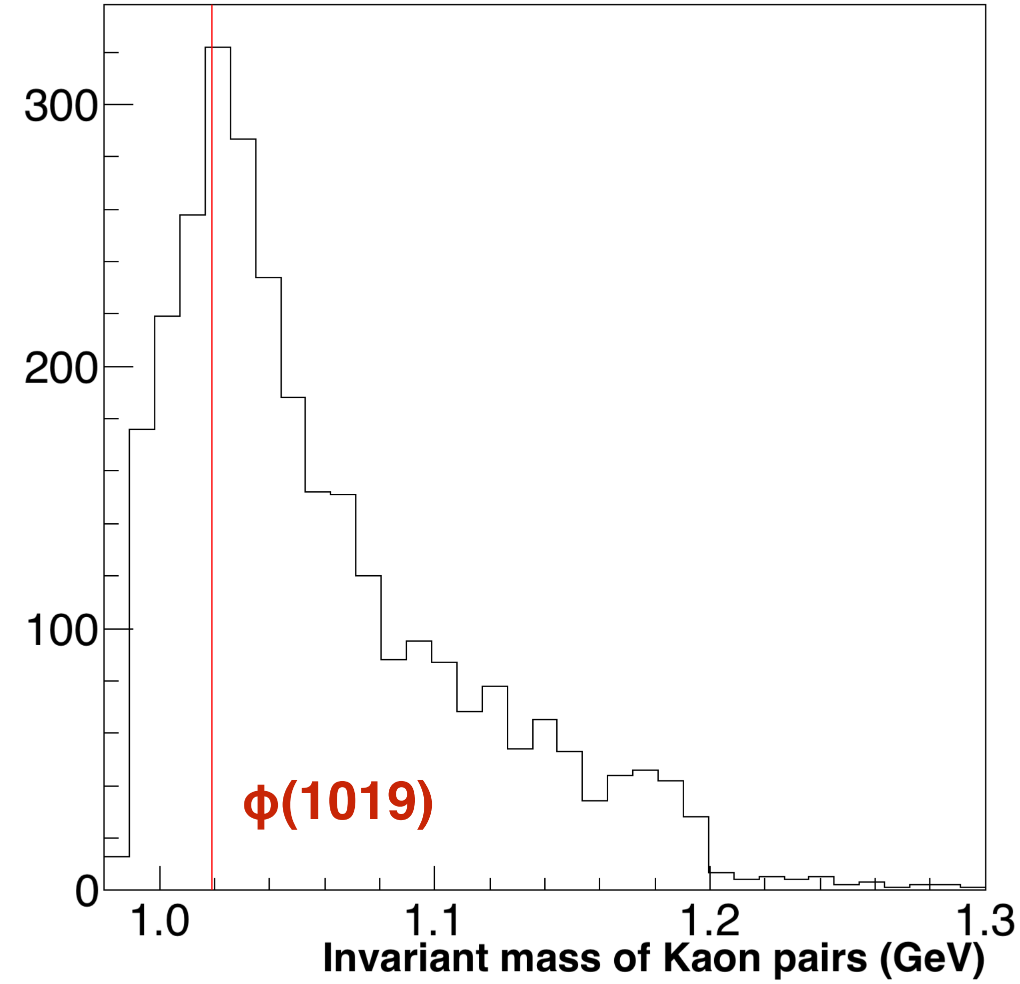
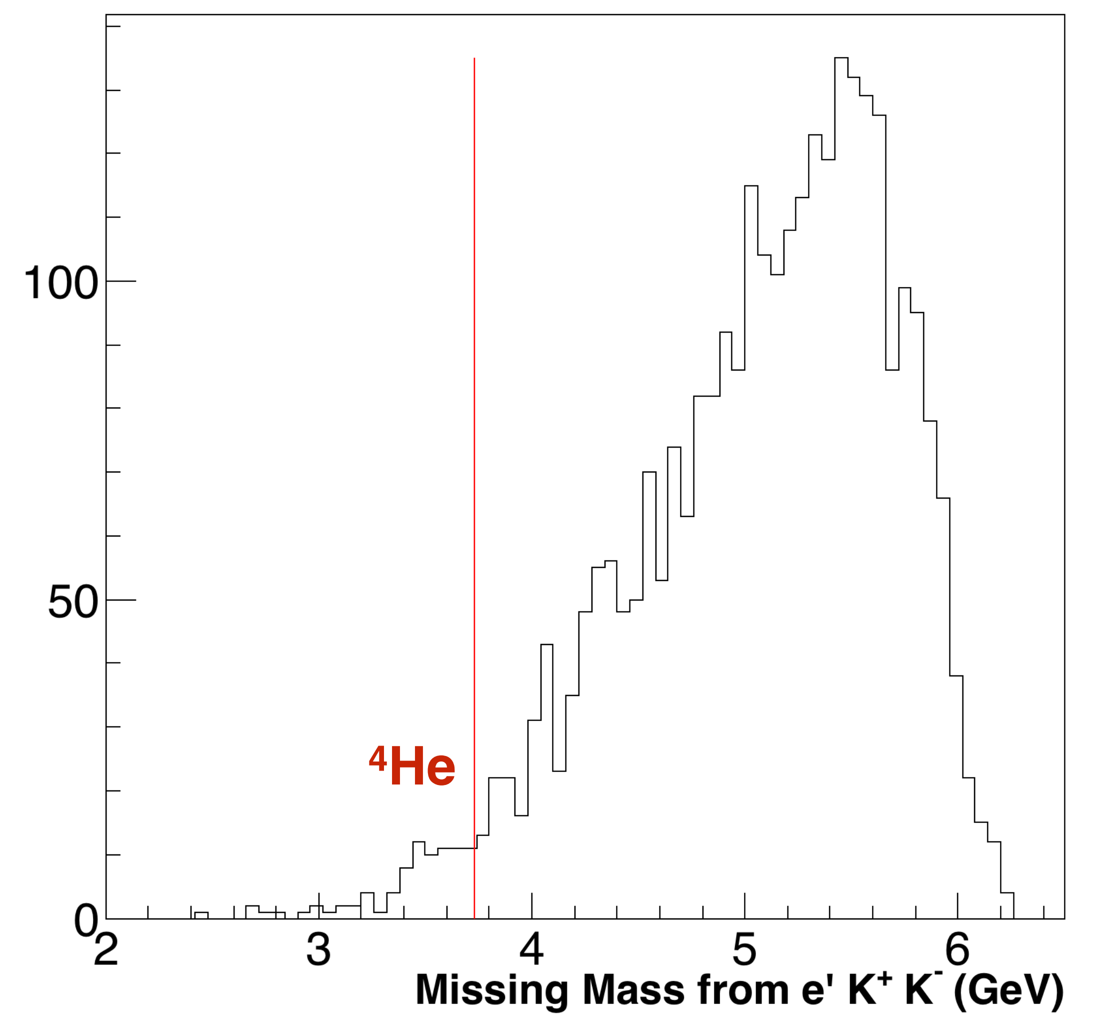
  - $e + {}^4He \rightarrow (e') + e^+ + e^- + {}^4He$
  - $e + {}^4He \rightarrow e' + \pi^+ + \pi^- + (K^0) + {}^4He$



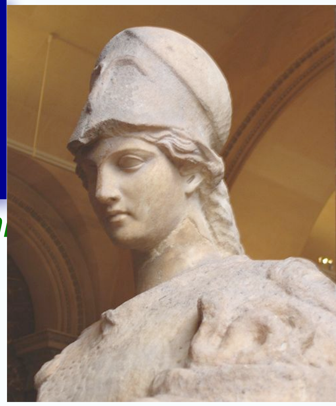
Preliminary study in eg6 of
e + ^{4}He → e’ + K^+ + K^- + (^{4}He)

- All eg6 6-GeV data is skimmed.
- ^{4}He is not detected: No RTPC needed.
- Good selection of electrons (standard EC/CC selection and fiducial cuts)
- Kaons are identified with timing (relative to good electron) and TOF scintillator energy deposit. Kaons in pairs are generally more clean than single kaons.
- Good ϕ identification.
- No visible coherent peak in MM.
  - Still to do:
    - Energy loss of Kaons through target.
    - Simulations of detector response.





ATHENNA Collaboration



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Laboratory, Argonne, IL)
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H. Badhdasaryan, G. D. Cates, M. Dalton, D. Day, D. Keller, V. V. Nelyubin, K. Paschke, A. Tobias, Z. W. Zhao *(Co-spokesperson)*, X. Zheng *(University of Virginia, Charlottesville, VA)*
F. R. Wesselmann *(Xavier University of Louisiana, New Orleans, LA)*

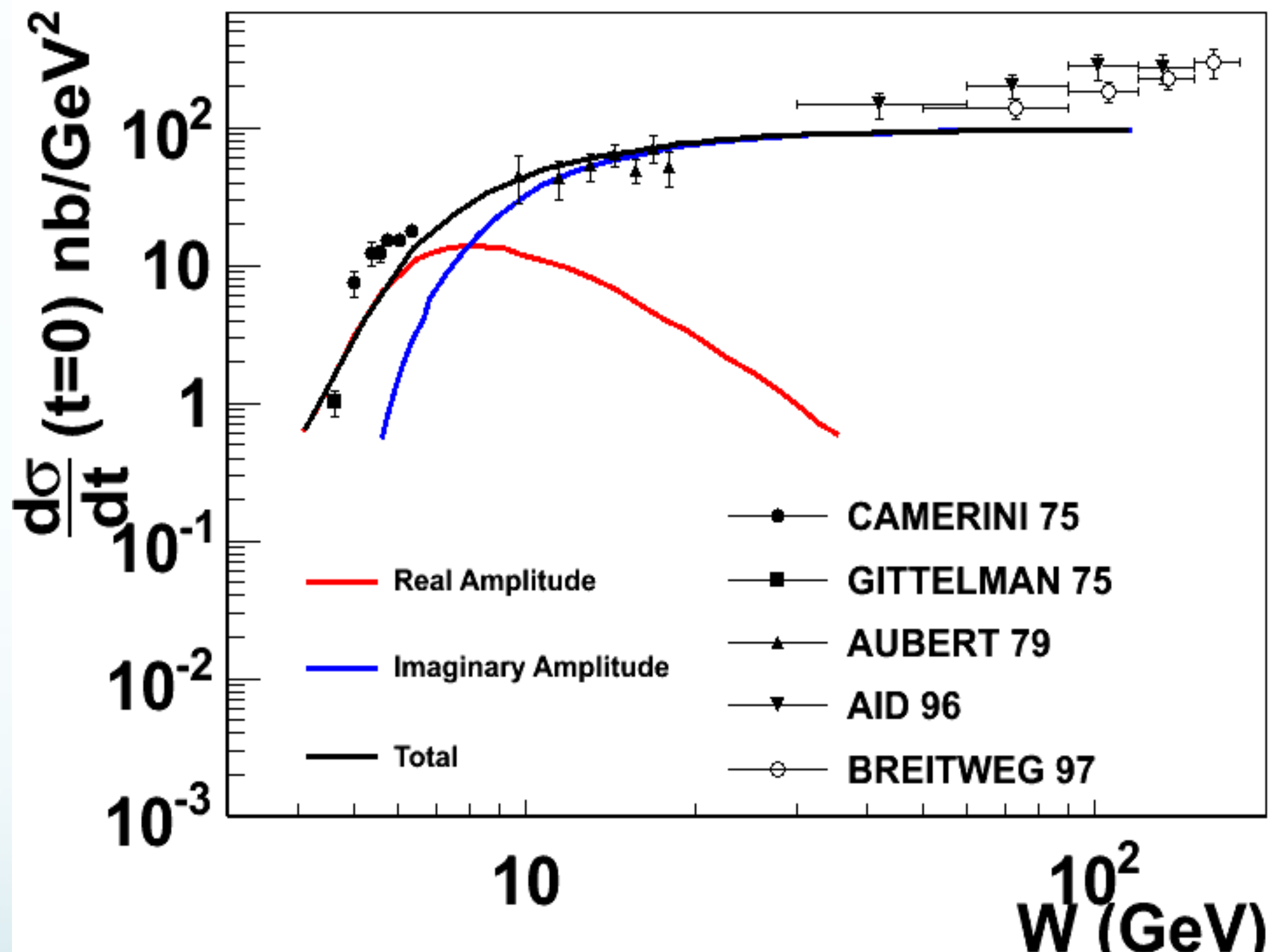
Another view: Reaction mechanism with FSI?

D. Kharzeev. Quarkonium interactions in QCD, 1995 nucl-th/9601029
D. Kharzeev, H. Satz, A. Syamtomov, and G. Zinovjev, Eur.Phys.J., C9:459–462, 1999

$$\frac{d\sigma_{\gamma N \to \psi N}}{dt}(s, t=0) = \frac{3\Gamma(\psi \to e^+e^-)}{\alpha m_\psi}\left(\frac{k_{\psi N}}{k_{\gamma N}}\right)^2 \frac{d\sigma_{\psi N \to \psi N}}{dt}(s, t=0)$$

$$\frac{d\sigma_{\psi N \to \psi N}}{dt}(s, t=0) = \frac{1}{64\pi}\frac{1}{m_\psi^2(\lambda^2 - m_N^2)}|\mathcal{M}_{\psi N}(s, t=0)|^2$$

- **Imaginary part** is related to the total cross section through optical theorem
- **Real part contains the conformal (trace) anomaly**
  - Dominate the near threshold region



A measurement near threshold could shed light on the conformal anomaly

$$xg(x,b) \equiv \int \frac{d^2\Delta_T}{(2\pi)^2}\, e^{i\boldsymbol{\Delta}_T \boldsymbol{b}}\, H_g(x,\xi=0,t=-\boldsymbol{\Delta}_T^2),$$

$$K(x,\xi,Q^2)_{\text{mod. hard scatt.}} = \int_0^1 dz \int d^2r\; \Psi_\phi(z,r)\, \alpha_S(\mu_R)\, C(z,x,\xi,Q^2)\, e^{-S(z,r,Q^2)},$$

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