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Quarkonium Production in Cold QCD: From JLab to an EIC

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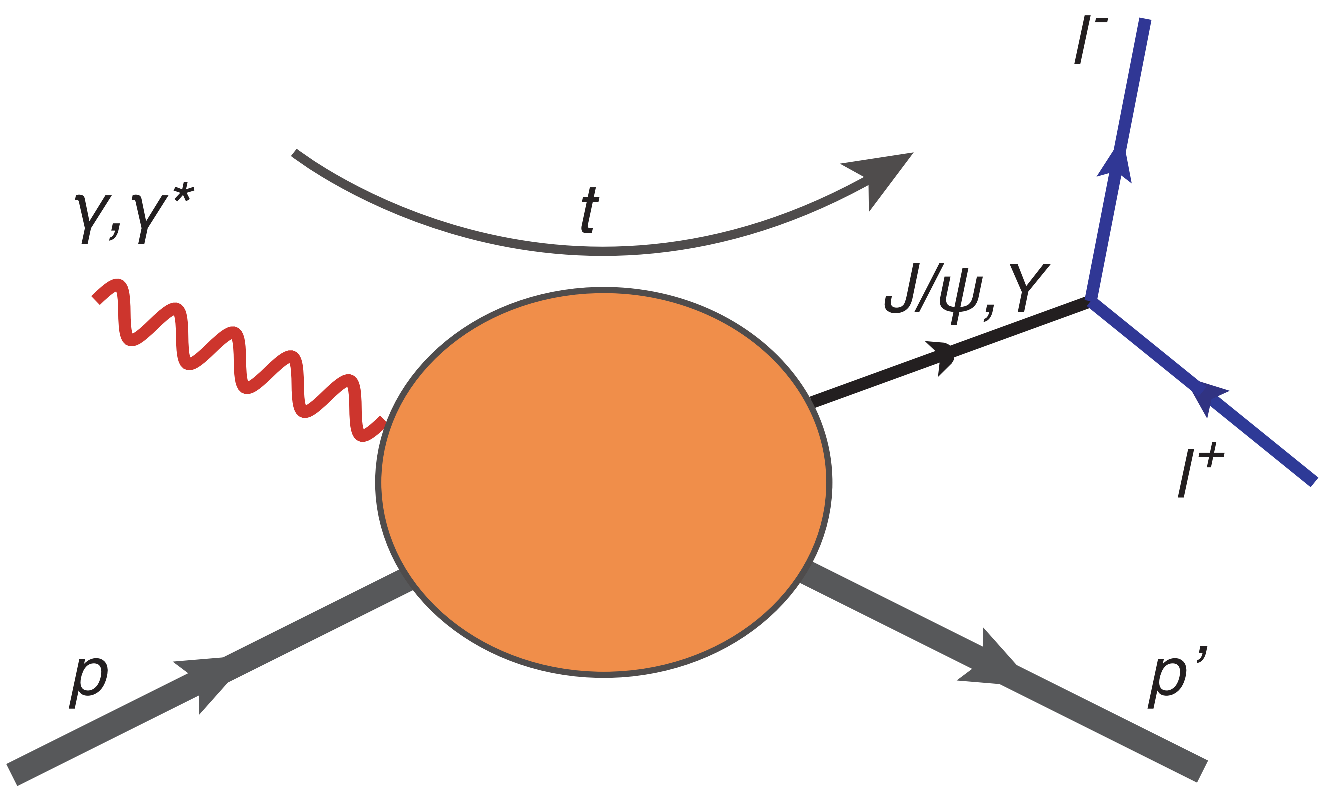
Quarkonium in **electro- and photo-production**

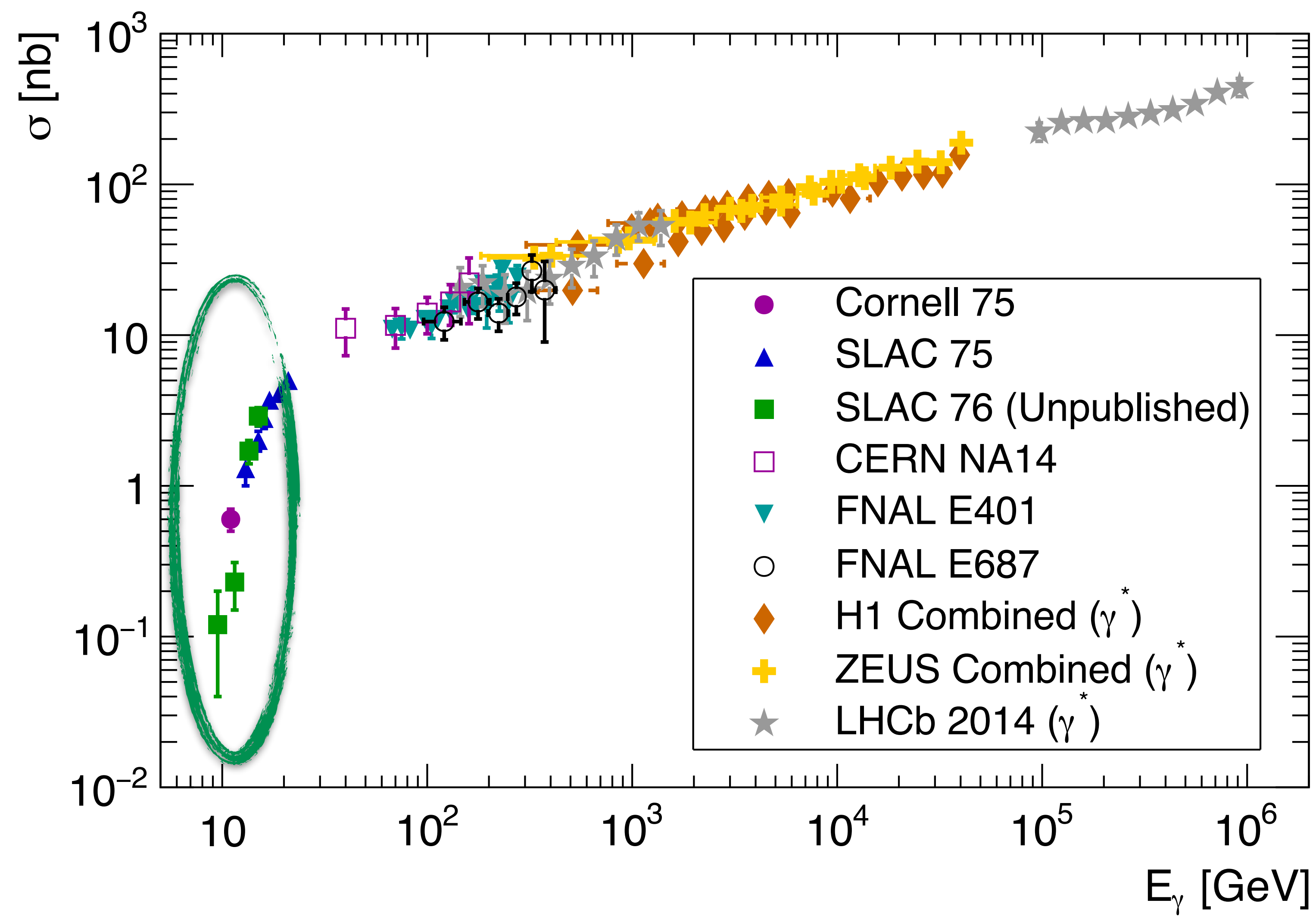


- Strong gluonic interaction between color neutral objects
- Minimal quark exchange
- **Quarkonium as a probe to study the gluonic structure of the nucleon**

Quarkonium in **electro- and photo-production**

Near Threshold:

- **Gluonic Van der Waals force**, possible quarkonium-nucleon/nucleus **bound states**
- **Origin of proton mass**, trace anomaly of the QCD energy-momentum tensor.
- **Mechanism** for quarkonium production

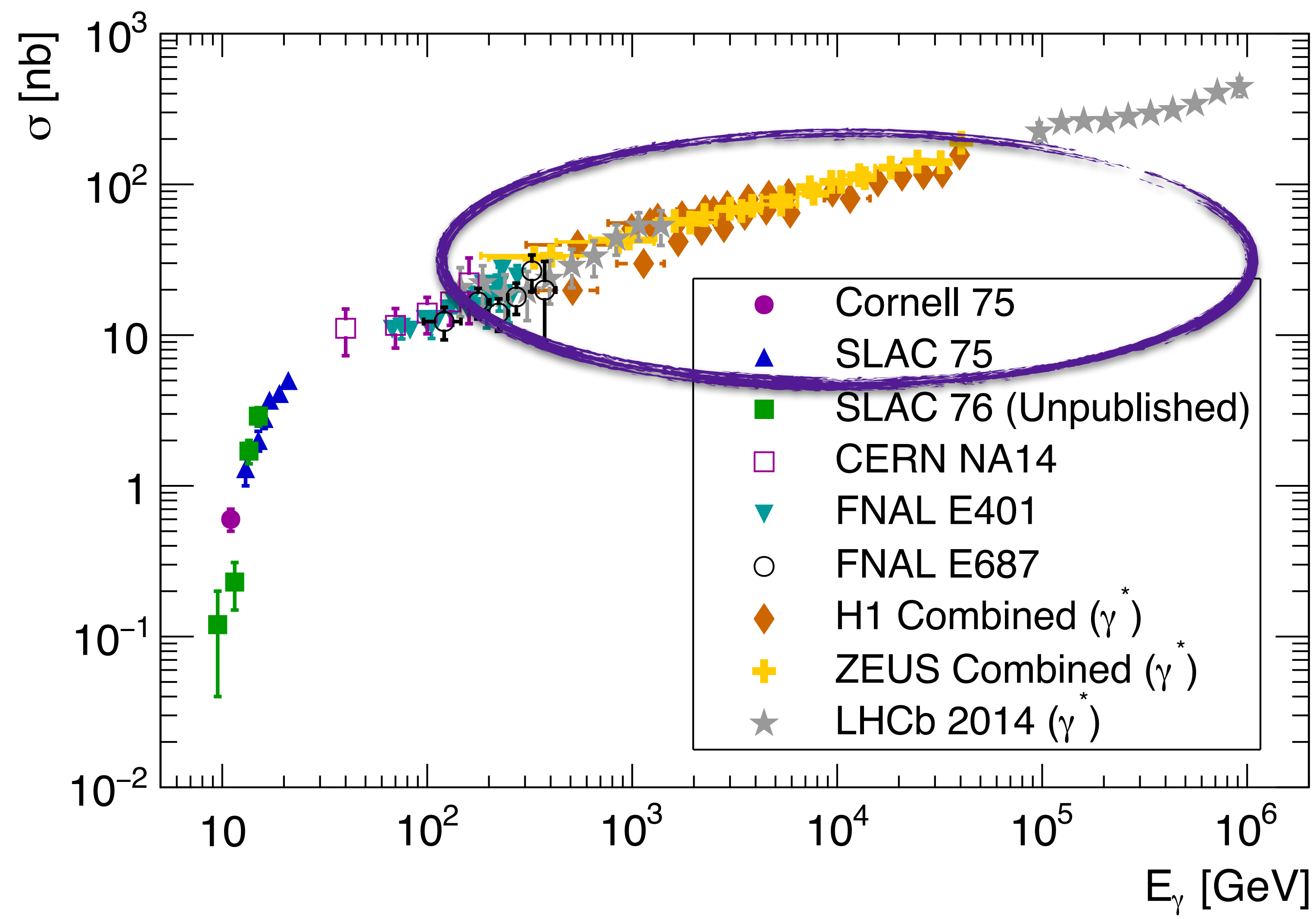


- ***J/ψ* program at Jefferson Lab**
- ***Υ(1s)* production at an EIC**

Quarkonium in **electro- and photo-production**

High Energies

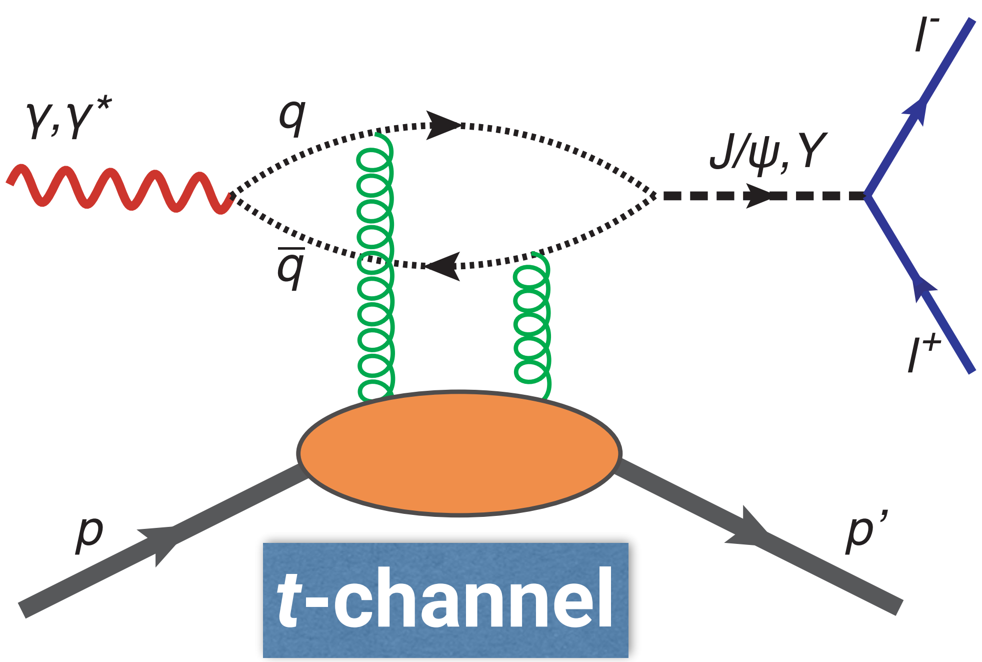
- Dominated by 2-gluon exchange
- **Gluon GPD:** Full 3D tomography of the gluonic structure of the nucleon



Quarkonium production at an EIC

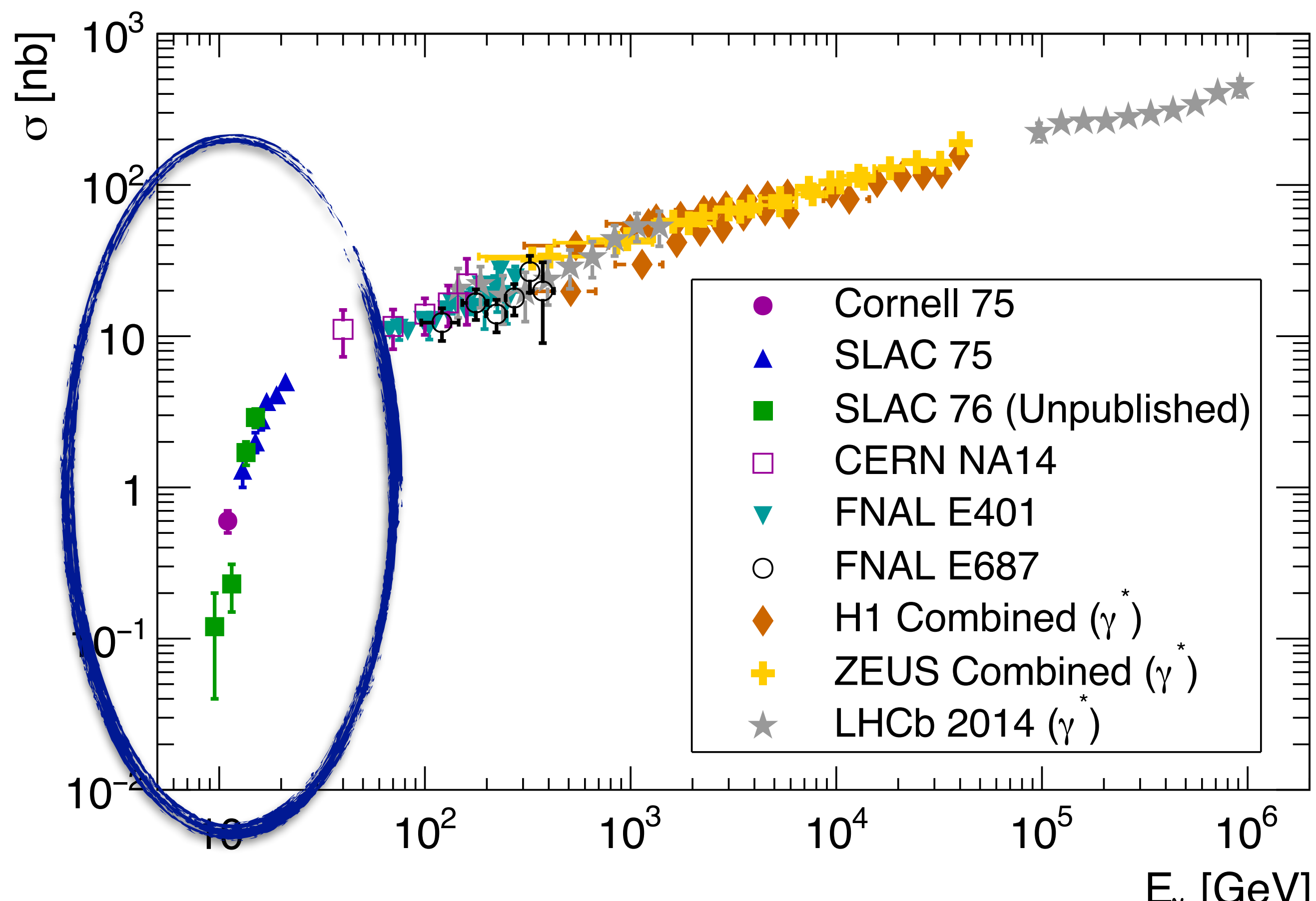
J/ψ production near threshold

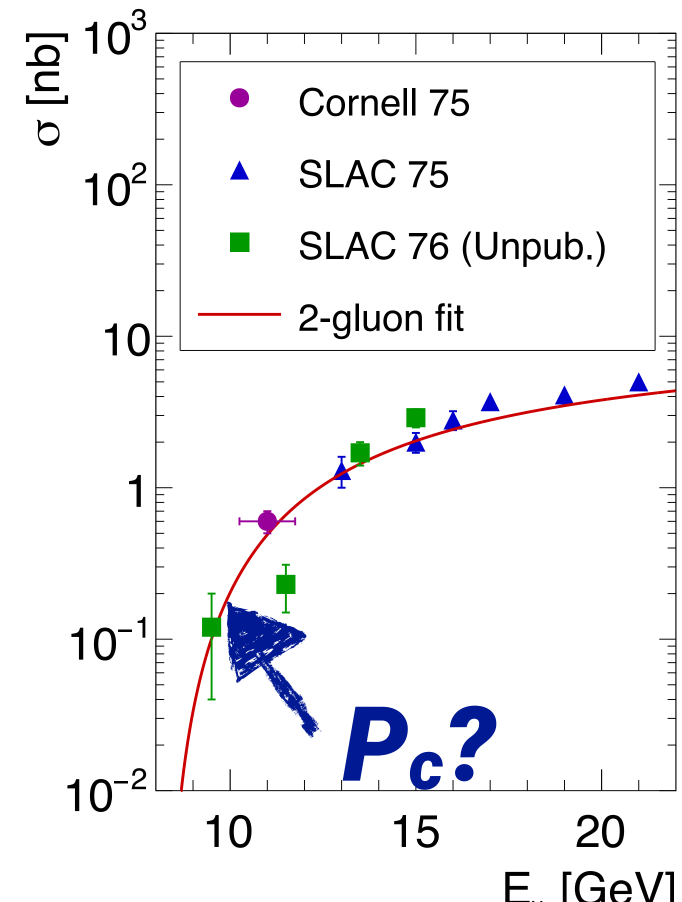
J/ψ photo-production: **what do we know?**



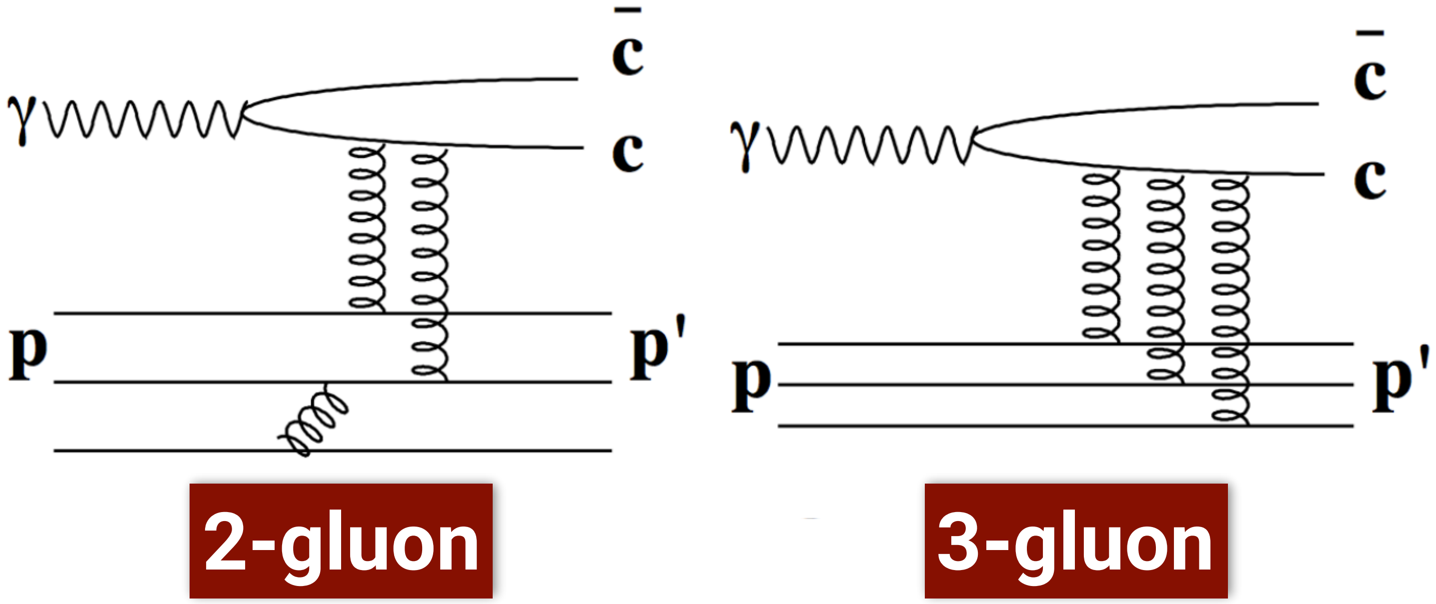
Brodsky S J, *et al.*, PLB 498-1 (2001), p23

- Cross section well constrained above 100 GeV
- **Almost no data near-threshold**
- Resolution of the existing measurements too low
- 2 of the 3 lowest points unpublished!





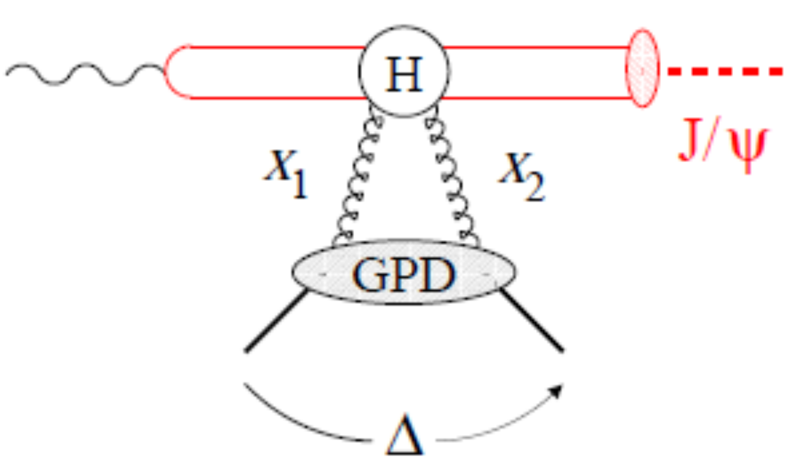
Production mechanism near threshold?



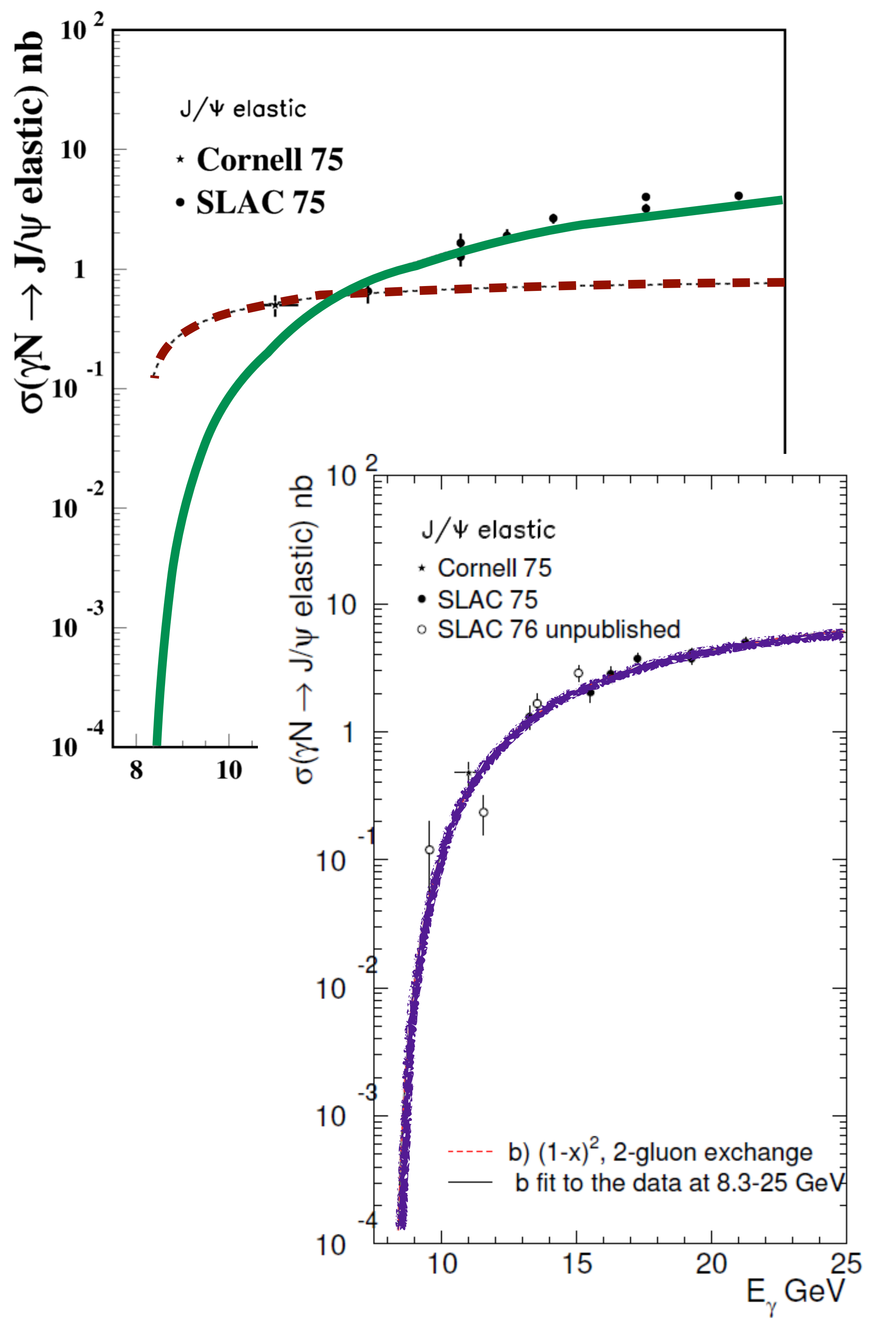
- Same as hard scattering (**2-gluon**)?
- Or does **3-gluon** exchange become dominant?

S.J. Brodsky, *et al.*, Phys.Lett. B498, 23-28 (2001)

- Or a **partonic soft mechanism** (power law 2-gluon form-factor)?



Frankfurt and Strikman., PRD66 (2002), 031502



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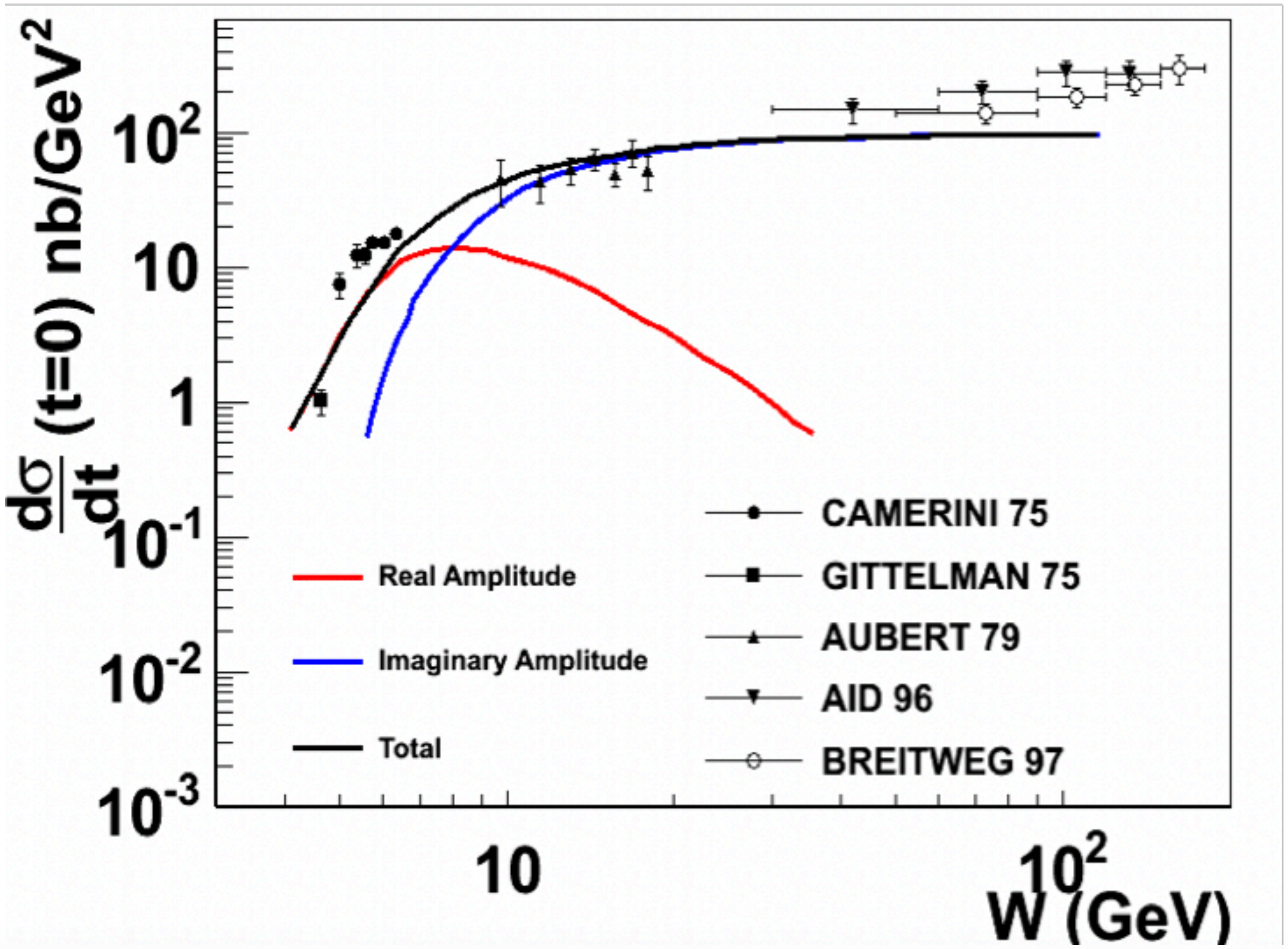
Production mechanism near threshold?

D. Kharzeev, Proc.Int.Sch.Phys.Fermi 130 (1996) 105-131
D. Kharzeev *et al.*, EPJ-C9 (1999) 459-462



- **Real part** of the scattering amplitude **dominates near threshold**
- Mostly constrained through dispersive relations.

Binding energy of the J/ψ - nucleon potential

O. Gryniuk and M. Vanderhaeghen, Phys. Rev. D 94, 074001 (2016)

- Color neutral objects:
  gluonic Van der Waals force

- **At threshold**, spin-averaged scattering amplitude related to **s-wave scattering length $a_{\psi p}$**

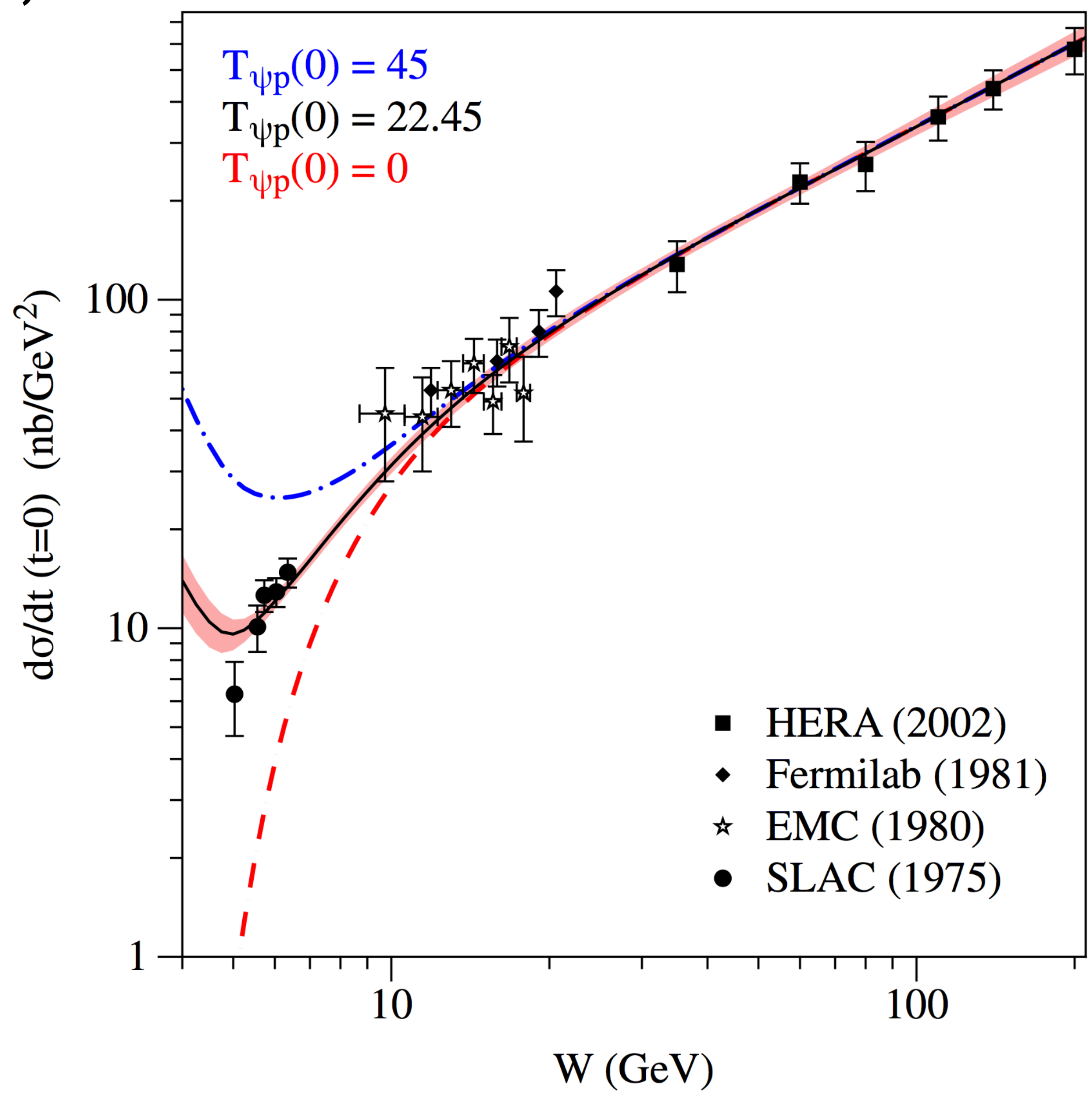
$$T_{\psi p} = 8\pi(M + M_\psi)a_{\psi p}$$

- **Binding $B_{\psi p}$** can be **derived from $a_{\psi p}$**

Binding energy of the J/ψ - nucleon potential

O. Gryniuk and M. Vanderhaeghen, Phys. Rev. D 94, 074001 (2016)

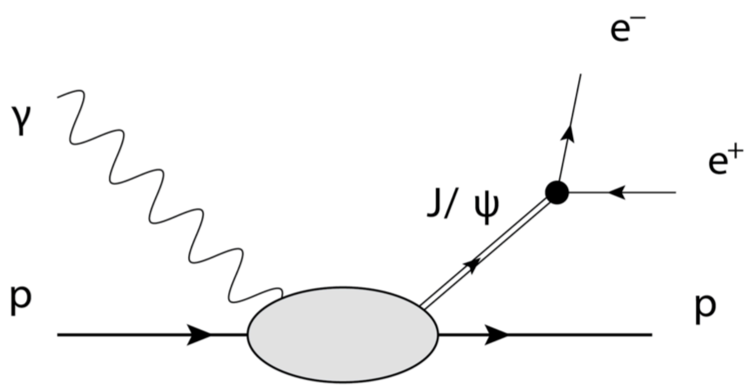
- Current estimates ranging from 0.05-0.30 fm, corresponding to $B_{\psi p}$ < 20 MeV
- LQCD: $B_{\psi p}$ < 40 MeV
- Fit to existing data: $a_{\psi p}$ = 0.05 fm ($B_{\psi p}$ = 3 MeV)



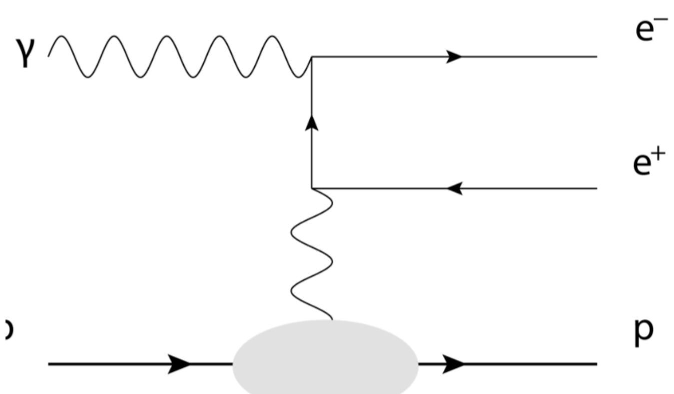
- Photo-production near threshold constrained with dispersion relations
- **Threshold data needed to really constrain $B_{\psi p}$**

B-H asymmetry: **access scattering length $a_{\psi p}$**

- **Interference** between elastic ***J/ψ* production** near threshold and **Bethe-Heitler**
- **Forward-backward asymmetry** near the *J/ψ* invariant mass peak
- Sensitive to real part of the scattering amplitude, hence $a_{\psi p}$ and $B_{\psi p}$



J/ψ

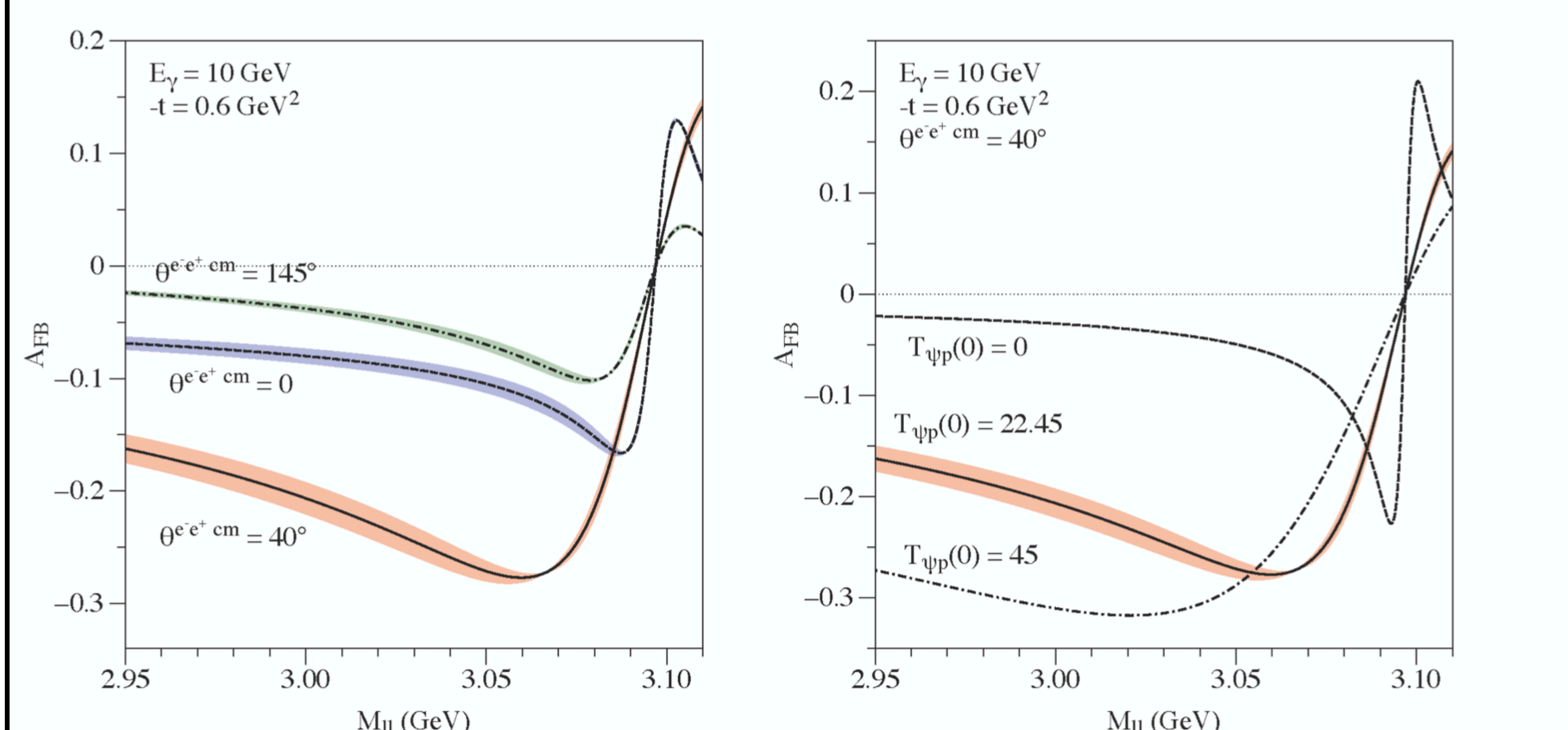


B-H

interference term

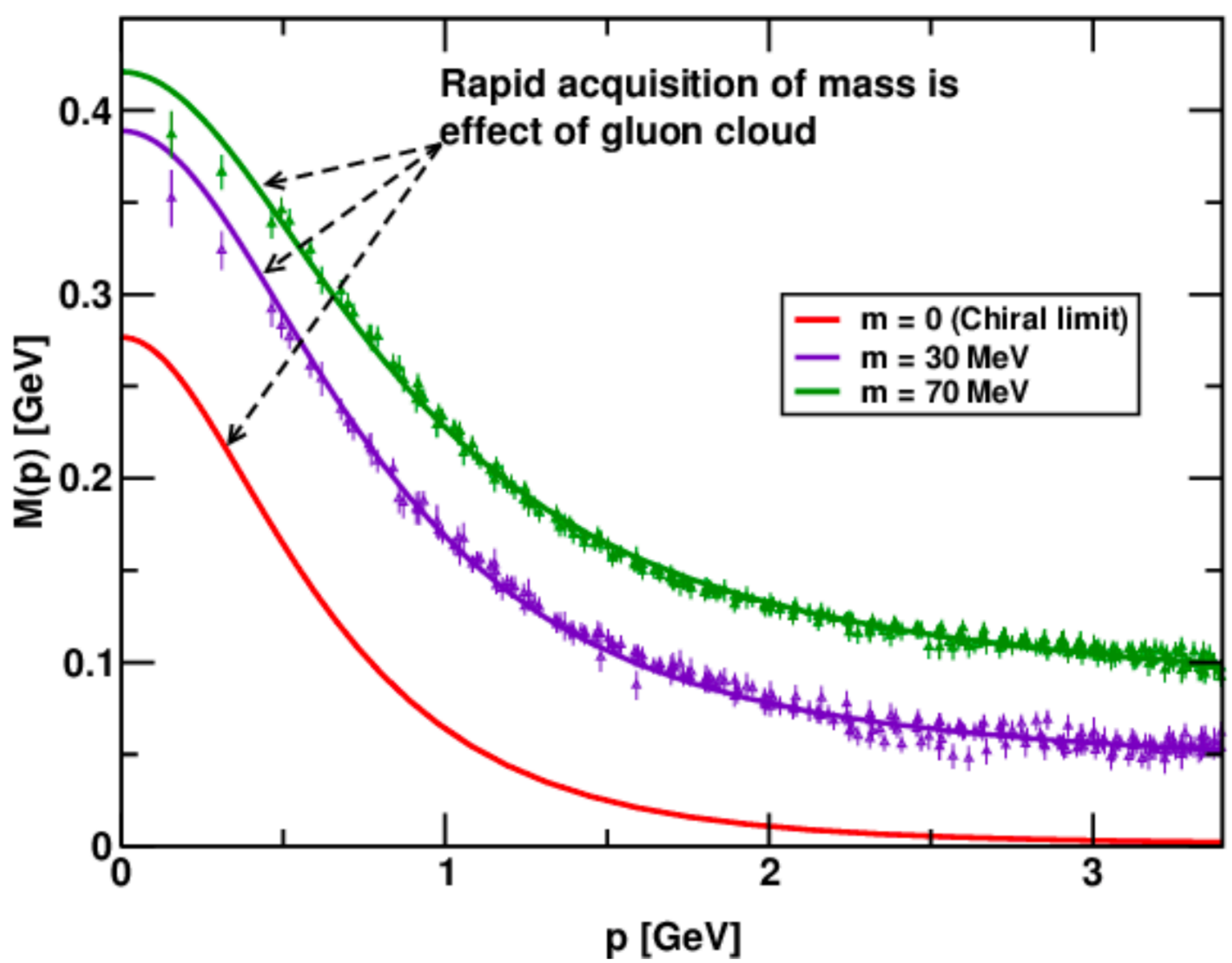
$$A_{\rm FB} \equiv \frac{\frac{d\sigma}{d\Omega}(\theta_{cm}) - \frac{d\sigma}{d\Omega}(\theta_{cm}-\pi)}{\frac{d\sigma}{d\Omega}(\theta_{cm}) + \frac{d\sigma}{d\Omega}(\theta_{cm}-\pi)} = \frac{\sum_s 2\,{\rm Re}T_\psi\, T_{BH}}{\sum_s |T_\psi|^2 + \sum_s |T_{BH}|^2}$$

$\theta_{\rm cm}$ — scattering angle in a lepton pair CM frame



The proton mass is an emergent phenomenon

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



Constituent quark mass from DSE and Lattice

- ☆ Low momentum gluons attach to the current quark (DSCB)
- ☆ **Gluon field accumulates ~300MeV/constituent quark**
- ☆ Even in the chiral limit **(mass from nothing)!**

★ **The Higgs mechanism is largely irrelevant in “normal” matter!**

The proton mass: **covariant decomposition**

D. Kharzeev, Proc.Int.Sch.Phys.Fermi 130 (1996) 105-131

- Access **nucleon mass through trace of energy-momentum tensor (EMT)** at zero momentum transfer

$$\langle P|T^{\mu}_{\mu}|P\rangle = 2P^{\mu}P_{\mu} = 2M_p^2$$

- Trace of EMT **proportional to quarkonium-proton scattering amplitude**

M. Luke *et al.*, PLB 288 (1992) 355-359

- At low momentum transfer: heavy quarks decouple

$$T^{\mu}_{\mu} = \underbrace{\frac{\tilde{\beta}(g)}{2g}G^2}_{\text{Trace Anomaly}} + \underbrace{\sum_{q=u,d,s} m_q(1+\gamma_m)\bar{\psi}_q\psi_q}_{\text{Light Quark Mass}}$$

Trace Anomaly **Light Quark Mass**

- **Proton mass result of the vacuum polarization induced by the presence of the proton**

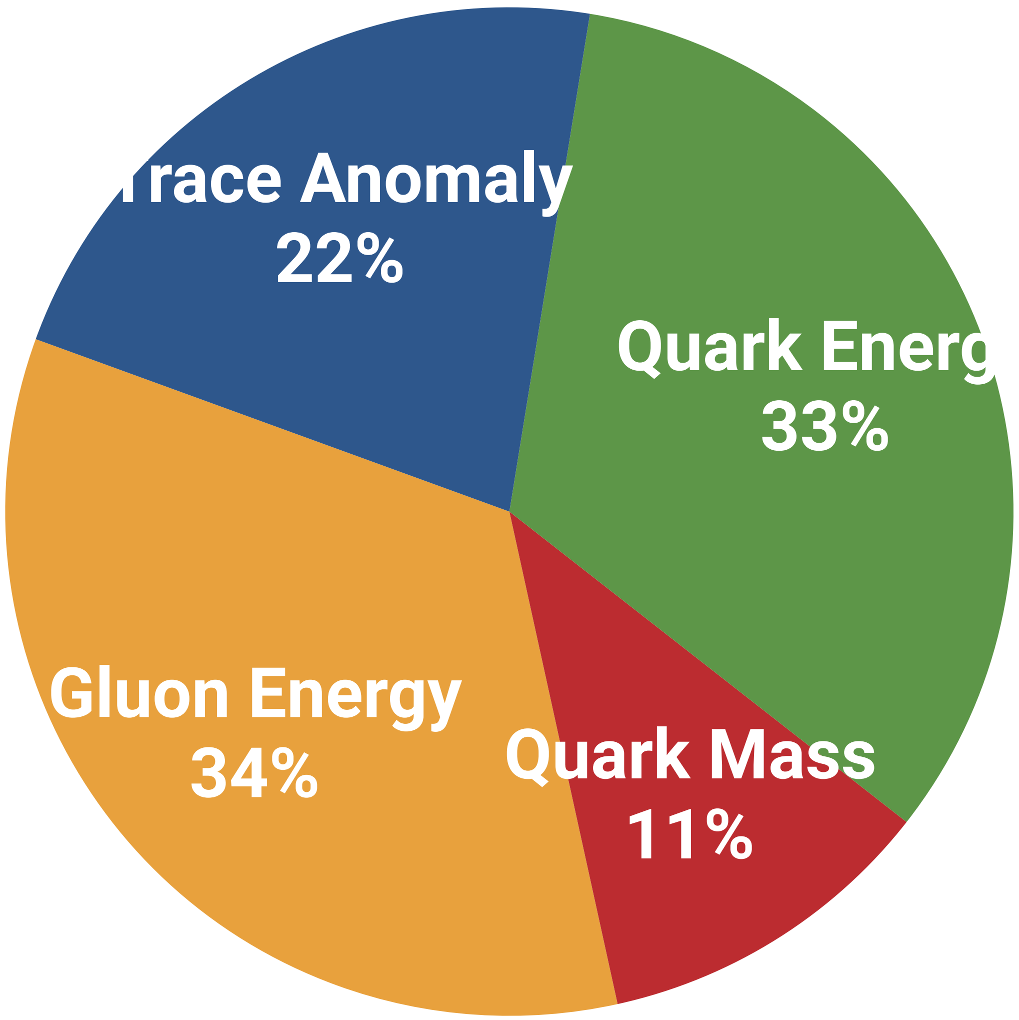
The proton mass: **rest-frame decomposition**

X. Ji, PRL 74, 1071 (1995) & PRD 52, 271 (1995)

- Matrix element of the **QCD Hamiltonian in the rest frame** gives the proton mass

$$H_{\mathrm{QCD}} = \int d^3x T^{00}(0,\vec{x})$$

$$= H_q + H_m + H_g + H_a$$



- In leading order:

$$M_q = \frac{3}{4}\left(a - \frac{b}{1+\gamma_m}\right)M$$

$$M_m = \frac{4+\gamma_m}{4(1+\gamma_m)}bM$$

$$M_g = \frac{3}{4}(1-a)M$$

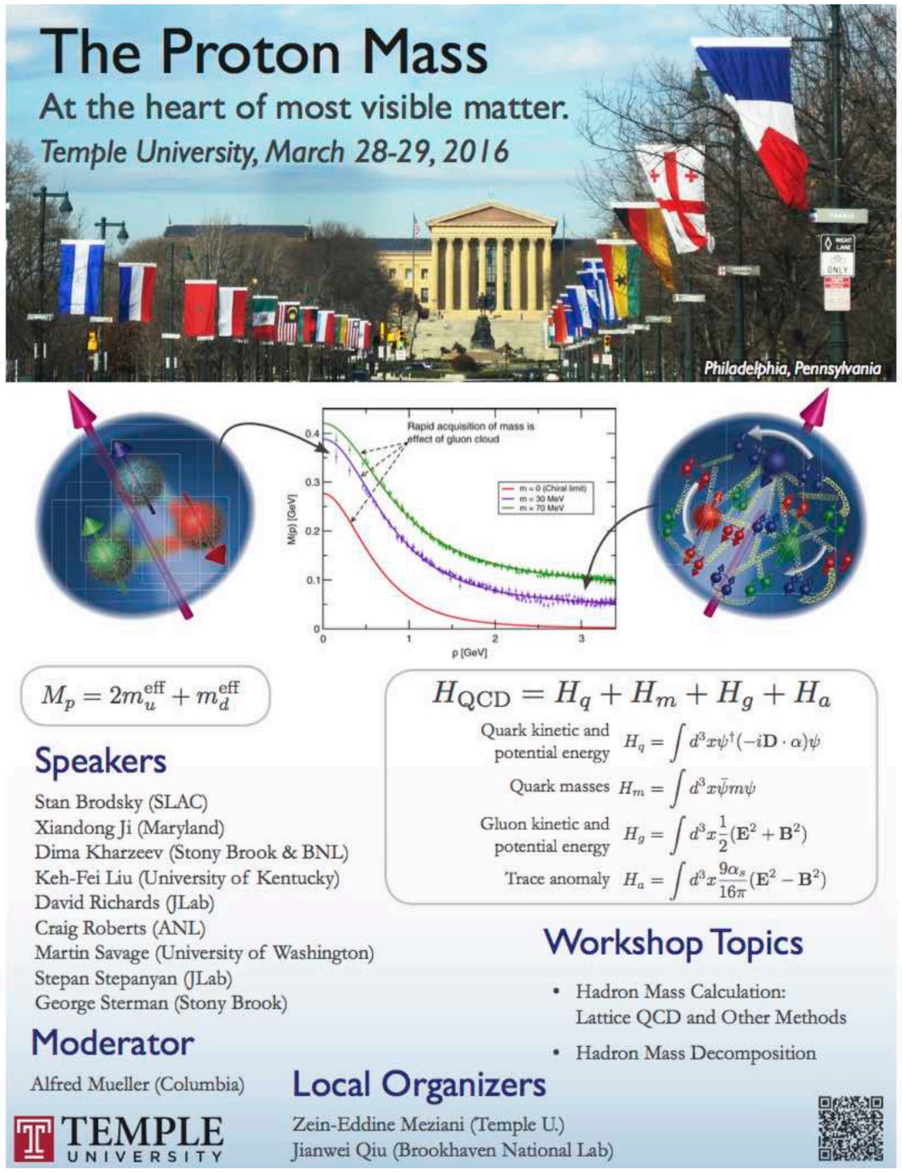
$$M_a = \frac{1}{4}(1-b)M$$

- *a(μ)* related to PDFs, well constrained
- ***b(μ)* related to quarkonium-proton scattering amplitude near-threshold**

The proton mass … **a hot topic!**

"… The vast majority of the nucleon's mass is due to quantum fluctuations of quark- antiquark pairs, the gluons, and the energy associated with quarks moving around at close to the speed of light. …"

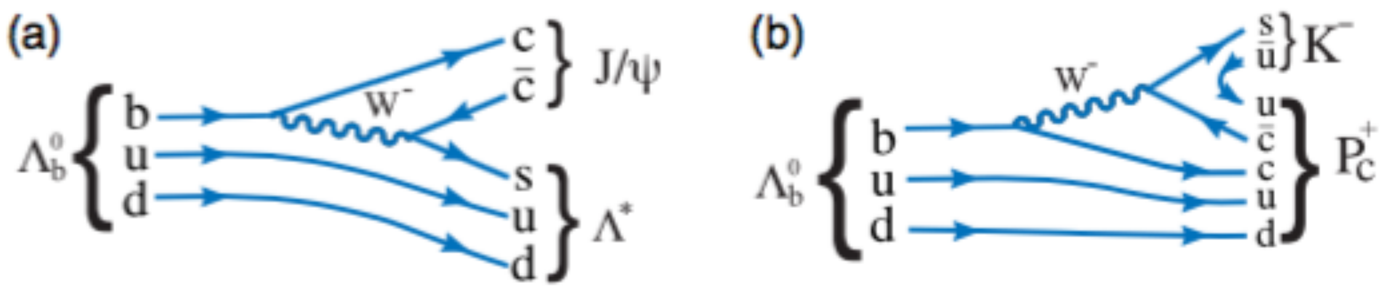
(The 2015 Long Range Plan for Nuclear Science)

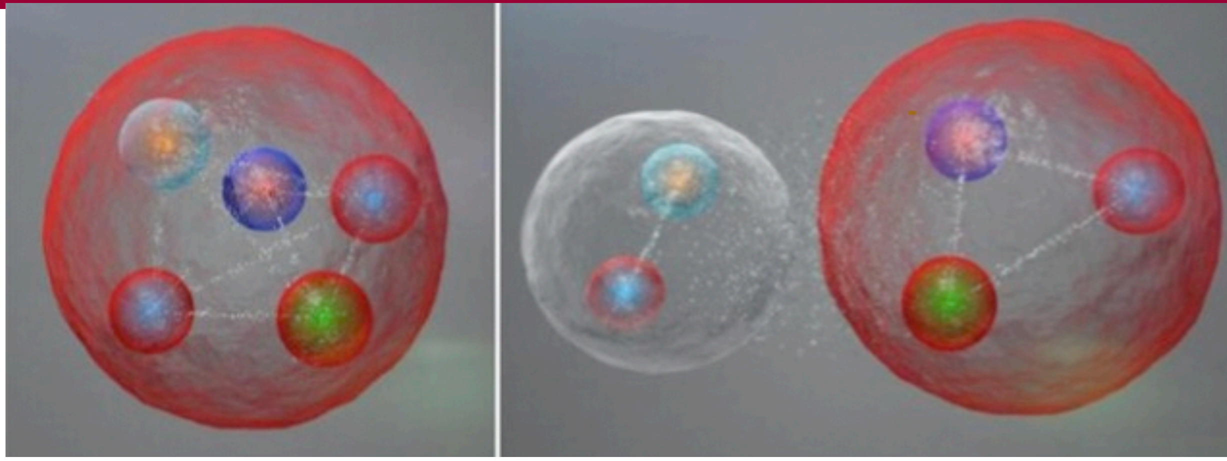


JLab will play a leading role:

Access trace anomaly through elastic J/ψ production near threshold

charmed "pentaquark" in **photo-production**





- Possible explanations for LHCb observations:
  - **LHCb**: 2 new **charmed "pentaquark"** (P_c) states
  - **alternative: kinematic enhancements** through anomalous triangle singularity **(ATS)**

Lui X-H, *et al.*, PLB 757 (2016), p231 (and references therein)

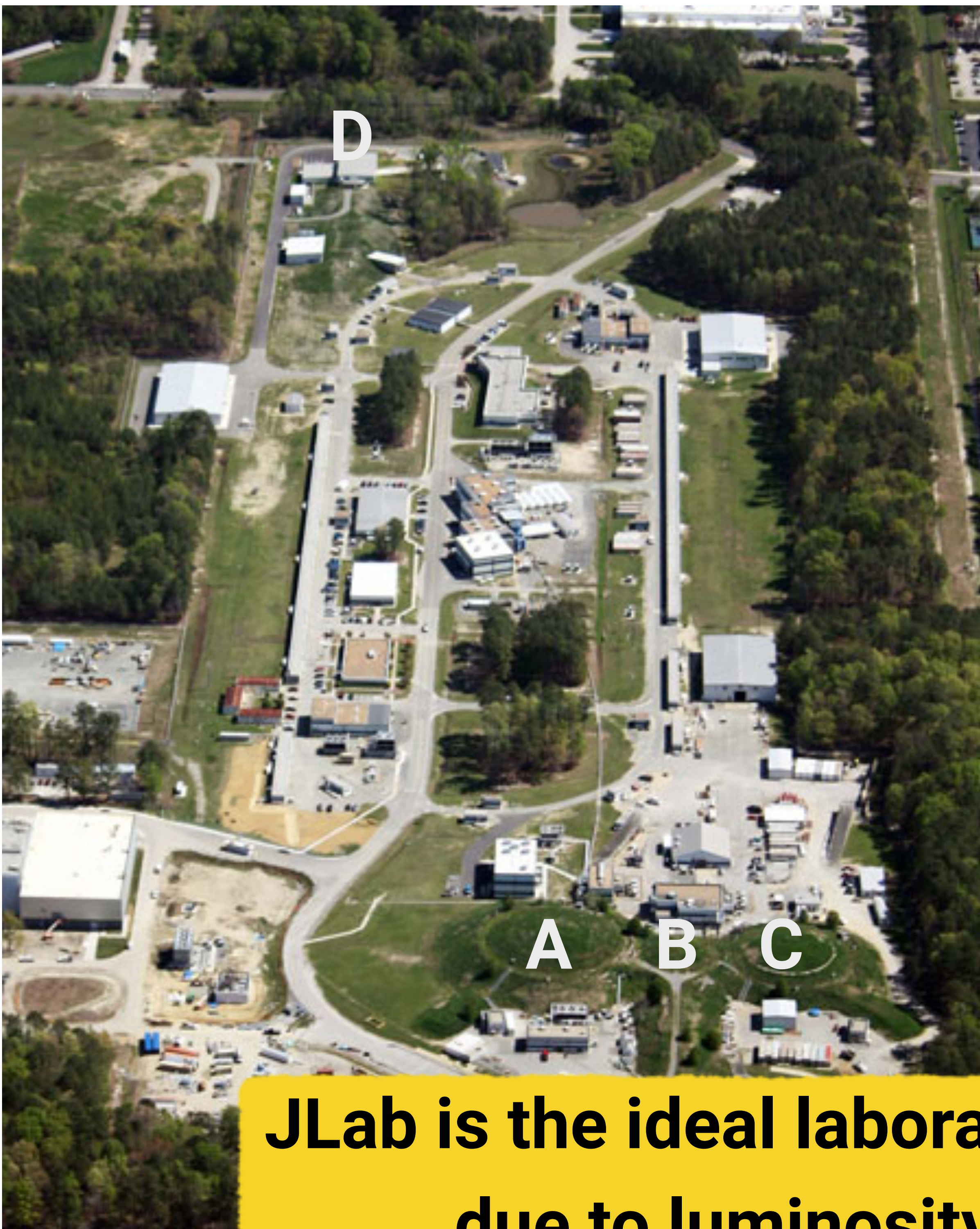
- **Photo-production** ideal tool to **distinguish** between both explanations
  - if P_c real states, **also created in photo-production**
  - kinematic enhancement through **ATS not possible**

Wang Q., *et al.*, PRD 92-3 (2015) 034022 (and references therein)

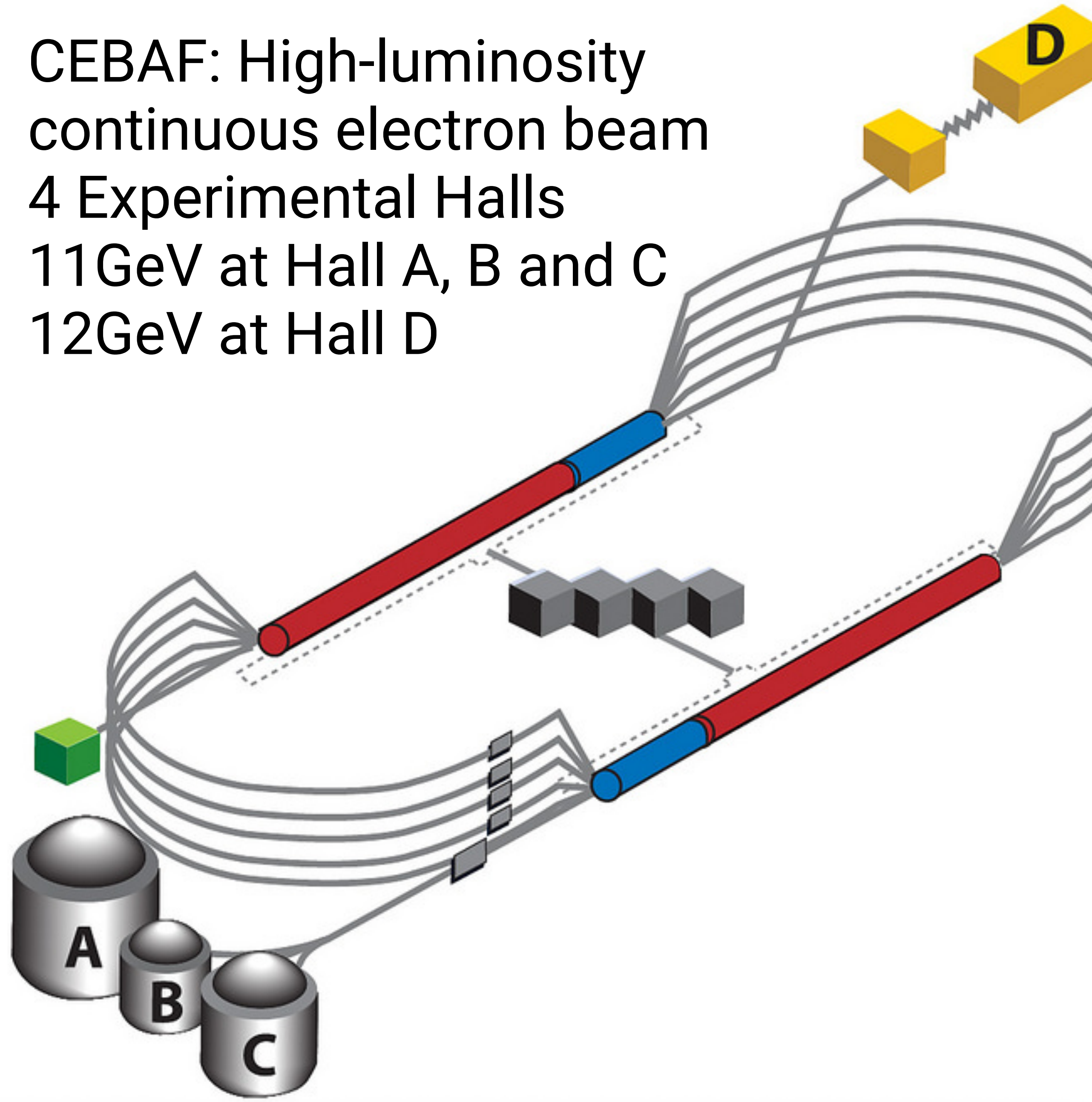
- P_c(4450) translates to **narrow peak around E_γ = 10 GeV**

JLab perfect place for this measurement!

J/ψ at JLab in **the 12GeV era**

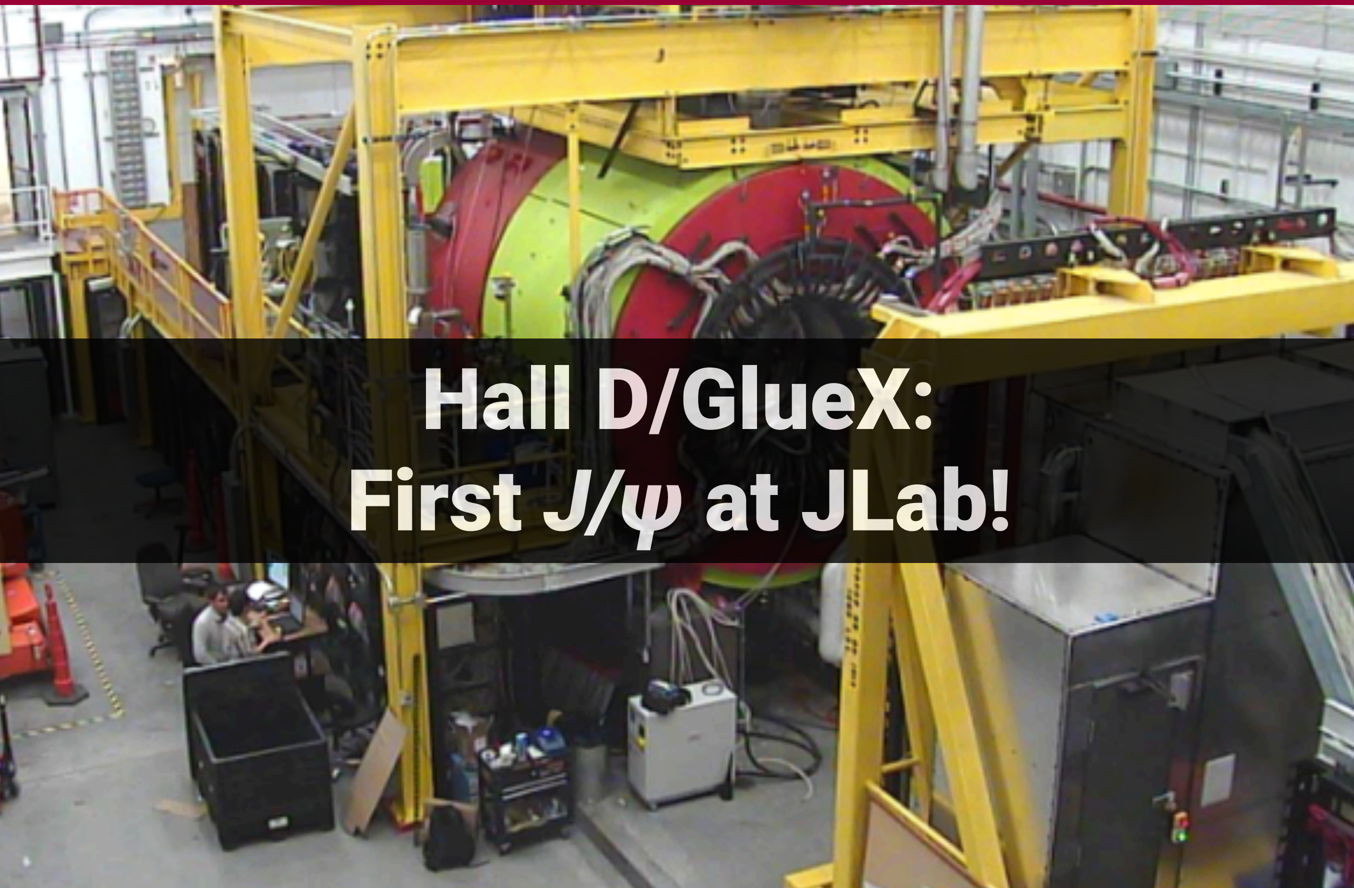


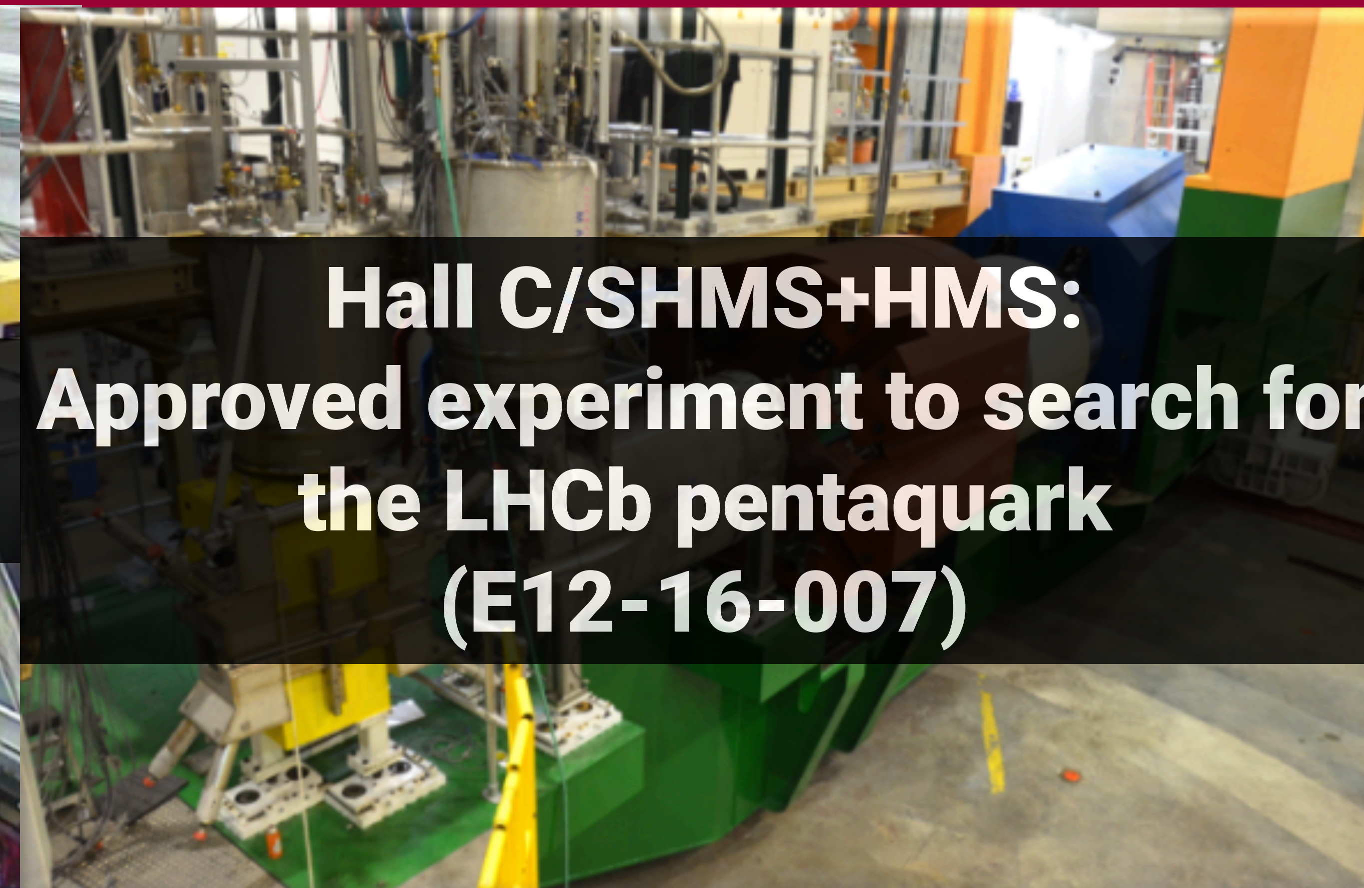
- CEBAF: High-luminosity continuous electron beam
- 4 Experimental Halls
- 11GeV at Hall A, B and C
- 12GeV at Hall D

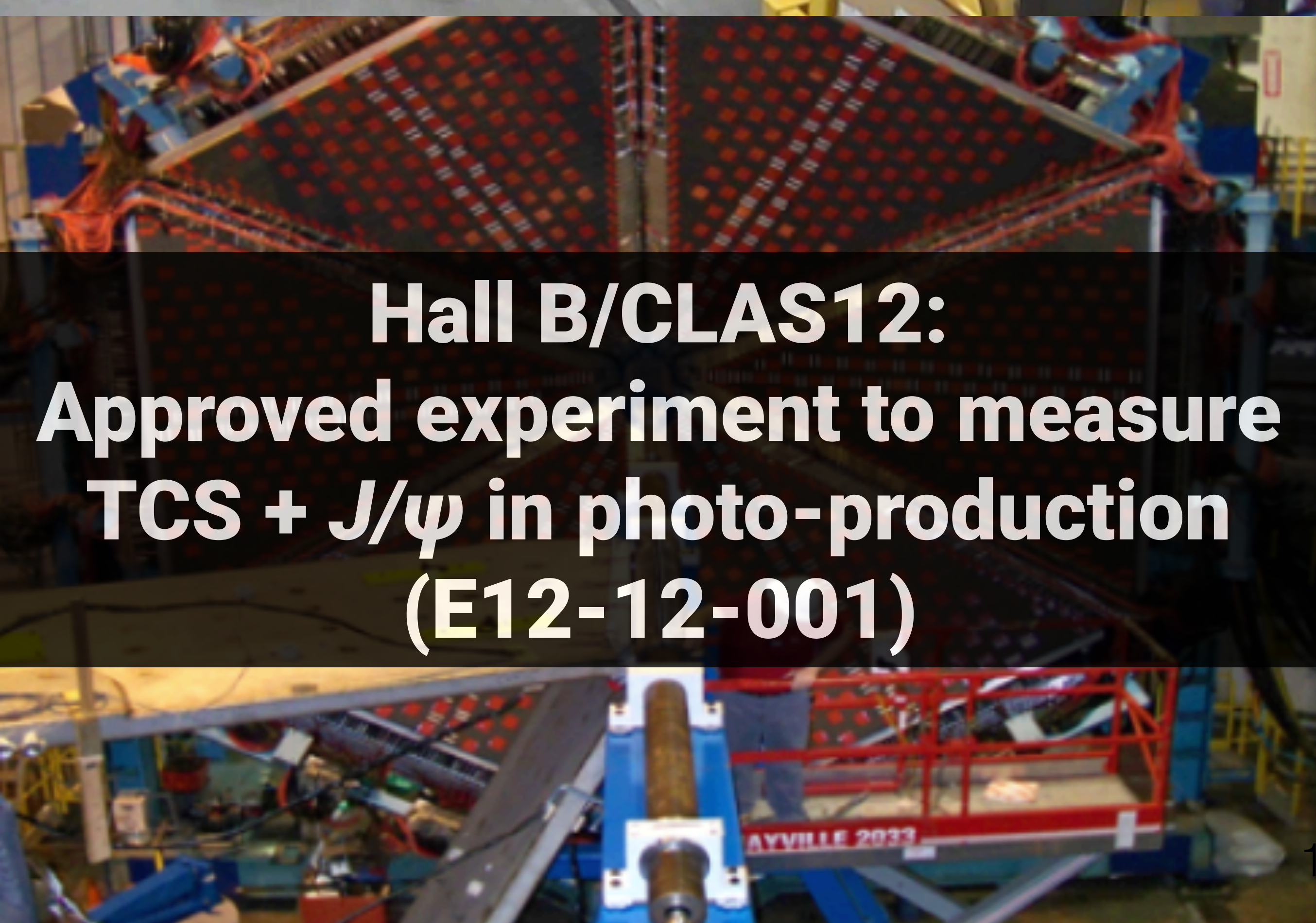


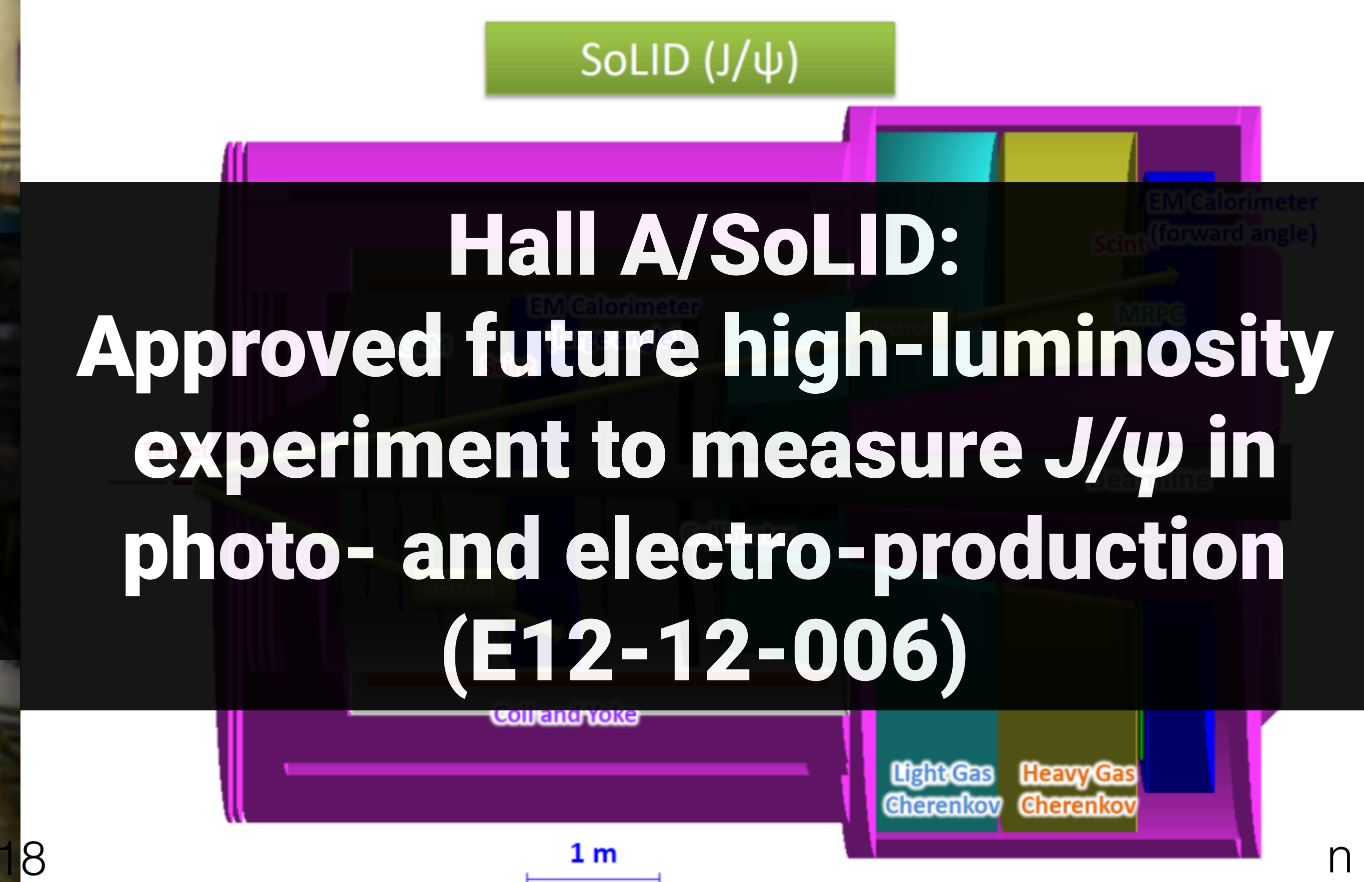
JLab is the ideal laboratory to measure *J/ψ* near threshold, due to luminosity, resolution and energy reach!

12 GeV *J/ψ* experiments at JLab





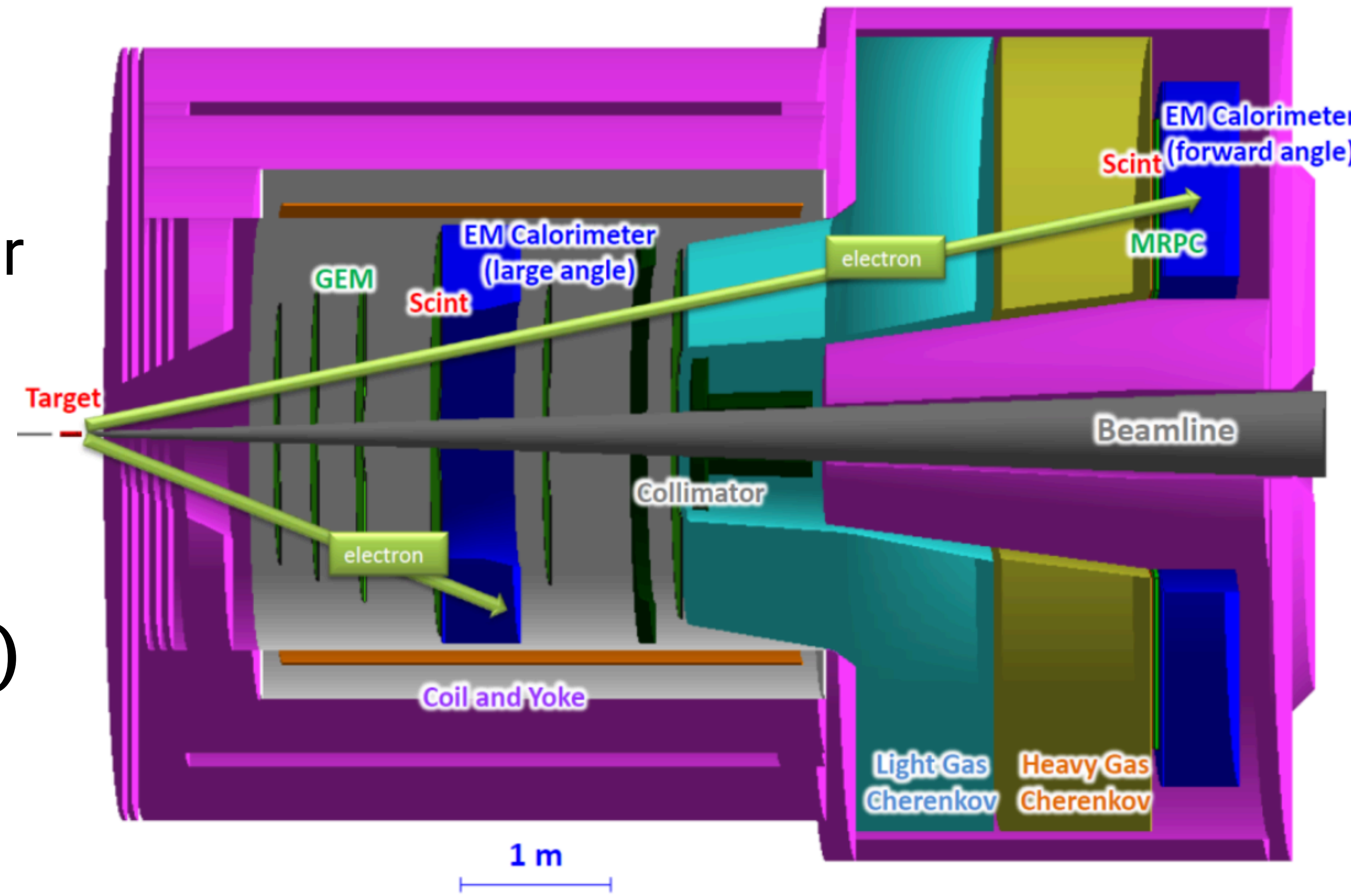




J/ψ experiment E12-12-006 at SoLID

ATHENNA Collaboration

- 3μA electron beam at 11 GeV for **50 days**
- 11 GeV beam 15cm **liquid hydrogen target**
- **Ultra-high luminosity (43.2 ab^{-1})**
- General purpose **large-acceptance** spectrometer
- Symmetric acceptance for electrons and positrons



$$\gamma/\gamma^* + N \rightarrow N + J/\psi$$

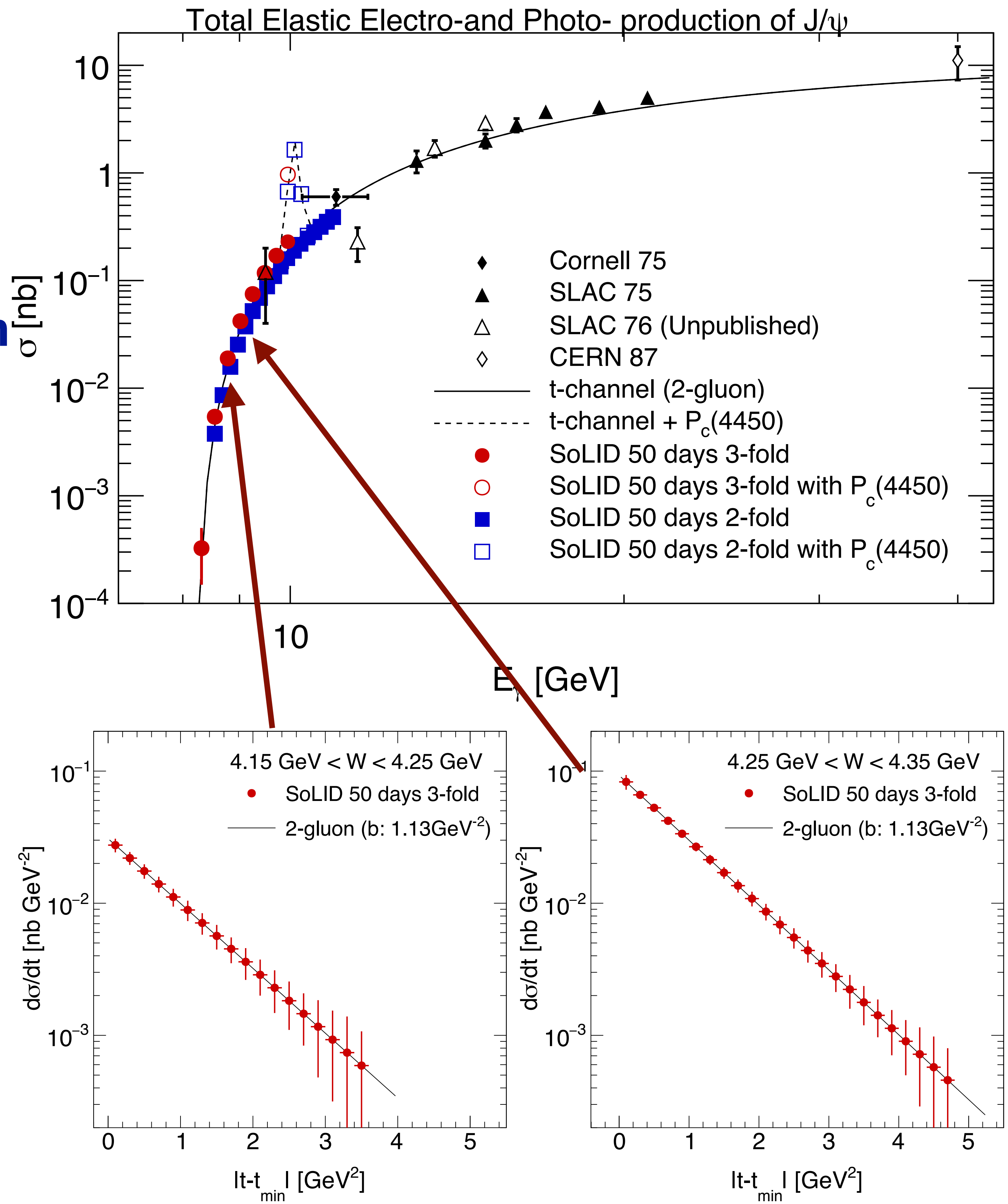
- Electro-production
- Real photo-production through bremsstrahlung in the target cell

K. Hafidi, S. Joosten *et al.*, Few Body Syst. 58 (2017) no.4, 141 and references therein

J/ψ experiment E12-12-006 at SoLID

ATHENNA Collaboration

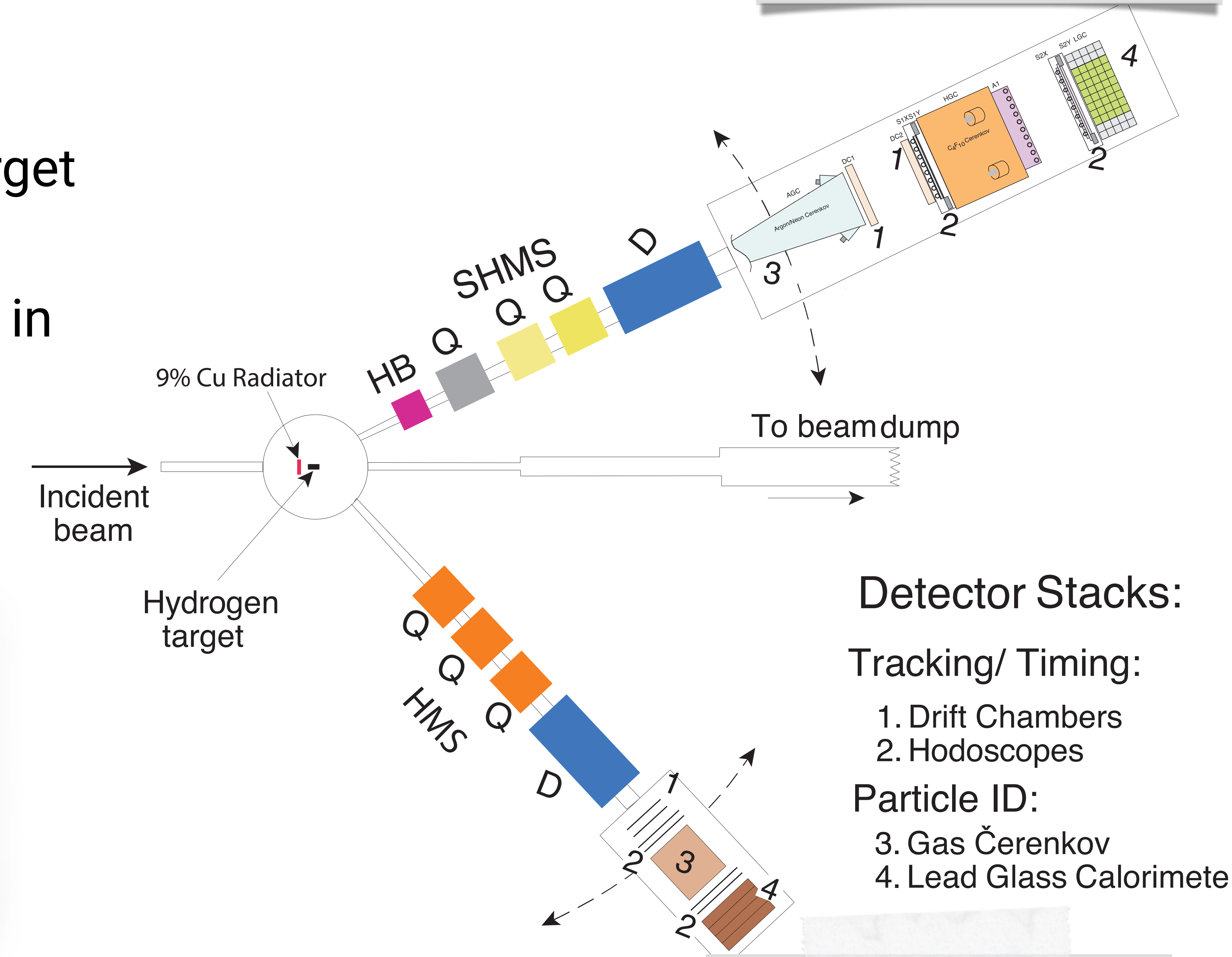
- **Photo-production**
  - **2-fold** coincidence + **recoil** proton
  - *t*-channel J/ψ rate: **1627 per day**
  - **Advantage over electro-production**
    - Energy reach in charmed pentaquark region
    - High rate
- **Electro-production**
  - **3-fold** coincidence (3 leptons)
  - *t*-channel J/ψ rate: **86 per day**
  - **Advantage over photo-production:**
    - Better resolution
    - Less background
    - Closer to threshold



Pentaquark search E12-16-007 in **Hall C**

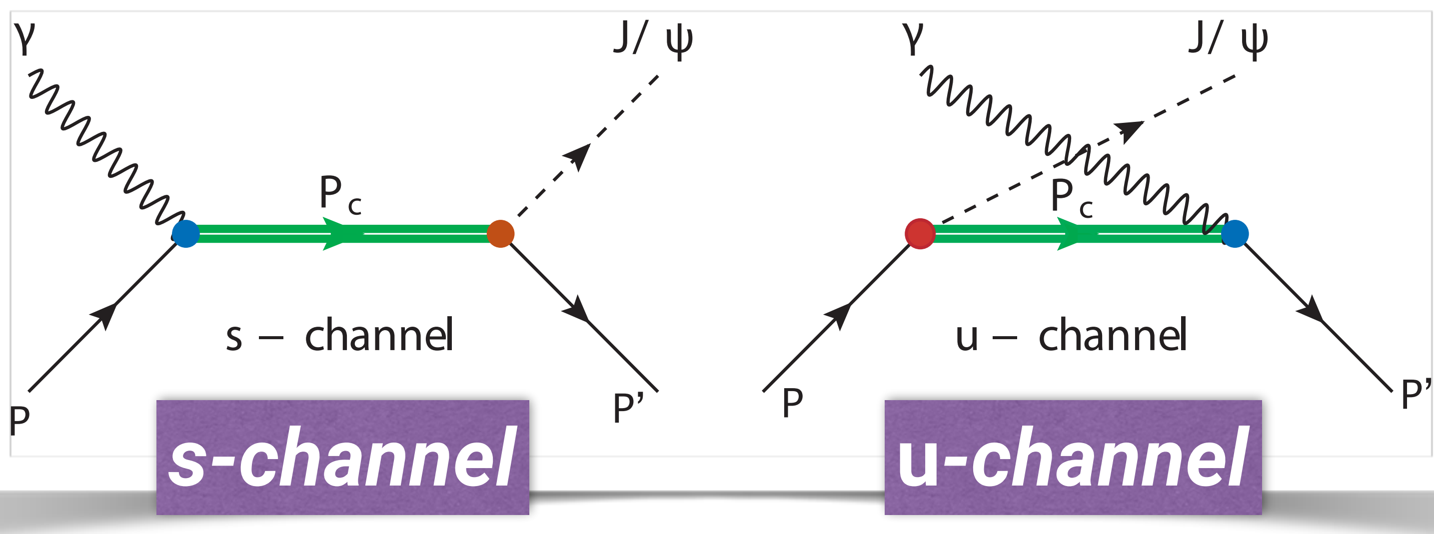
- 50μA electron beam at 11 GeV for **11 days**
- 9% copper radiator
- 15cm liquid hydrogen target
- **total 10% RL**
- Detect *J/ψ* decay leptons in coincidence
  - Bremsstrahlung photon energy fully constrained

Approved high-impact experiment …will run soon (and fast)!

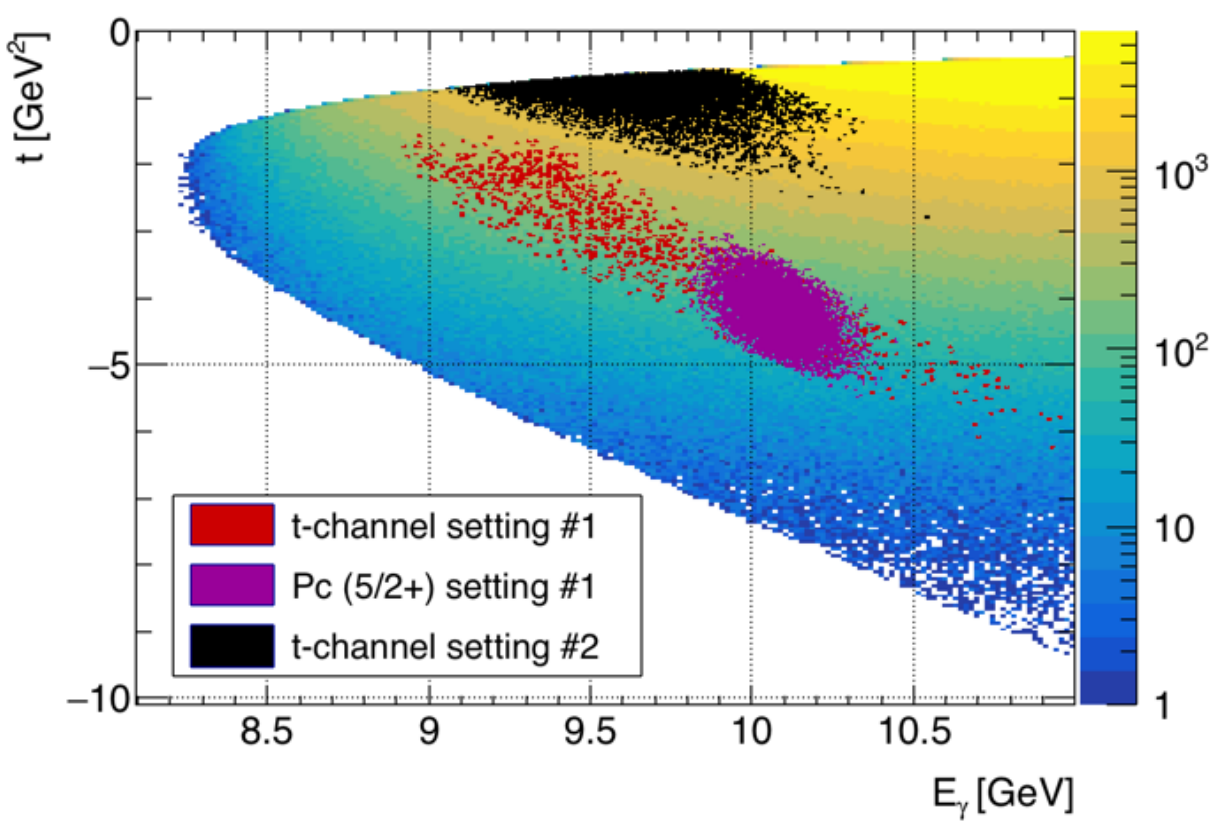


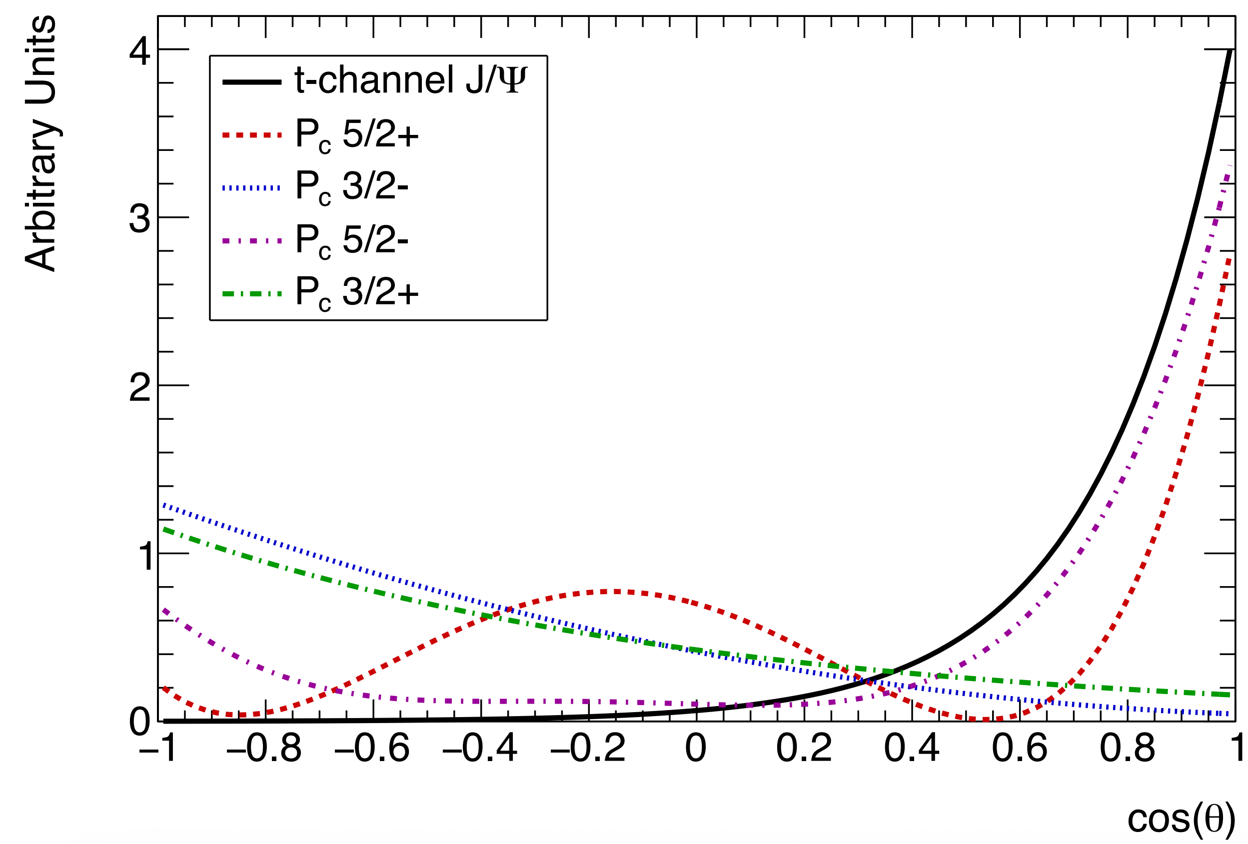
Z.-E. Meziani, S. Joosten *et al.*, arXiv:1609.00676 [hep-ex]
K. Hafidi, S. Joosten *et al.*, Few Body Syst. 58 (2017) no.4, 141

Resonant J/ψ production through P_c decay



- Cross section depends on **coupling to (J/ψ, p) channel**
- ***J/ψ* angular distribution** depends on P_c **spin/parity**





$$\frac{d\sigma}{d\cos\theta_{J/\psi}}(\gamma p \to P_c \to J/\psi p)$$

Leverage cos(*θ*) dependence to maximize S/B at low coupling!

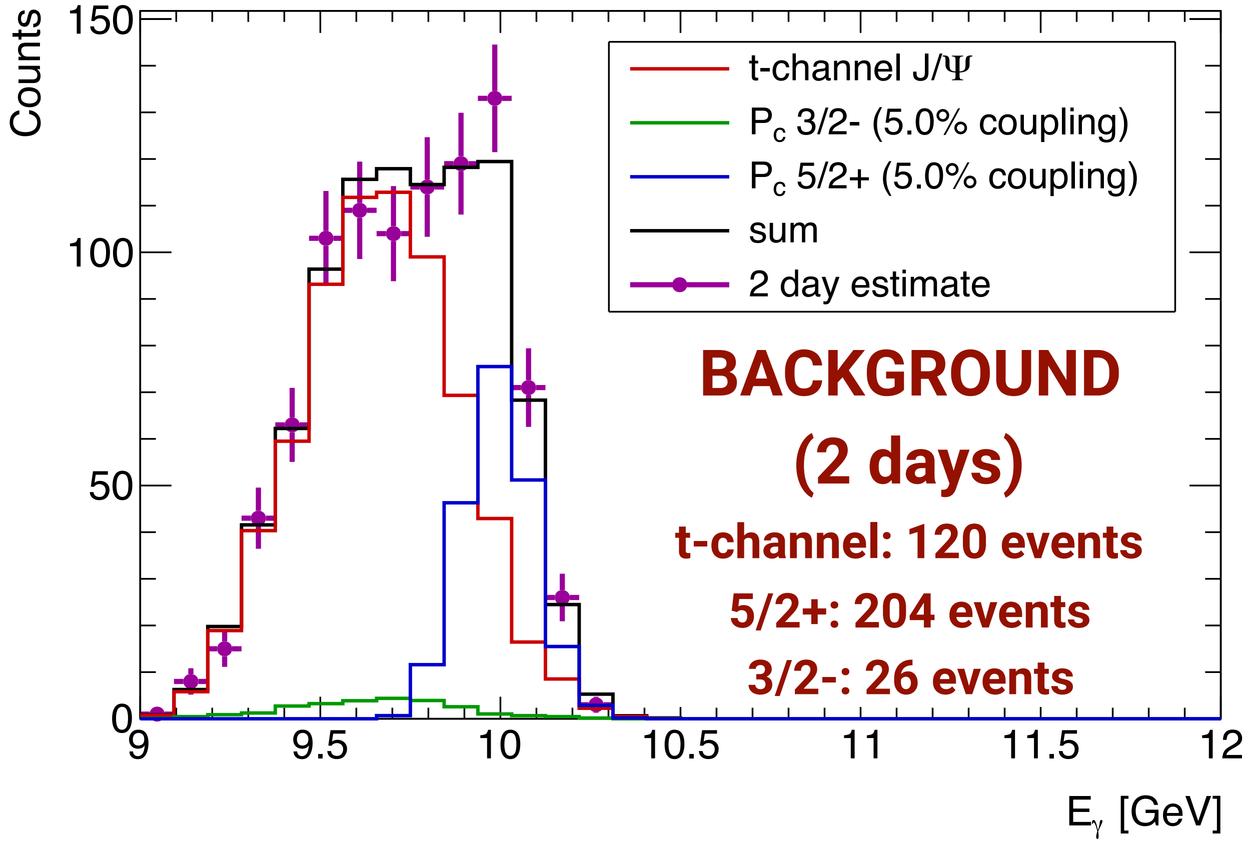
Wang Q., *et al.*, PRD 92-3 (2015) 034022-7

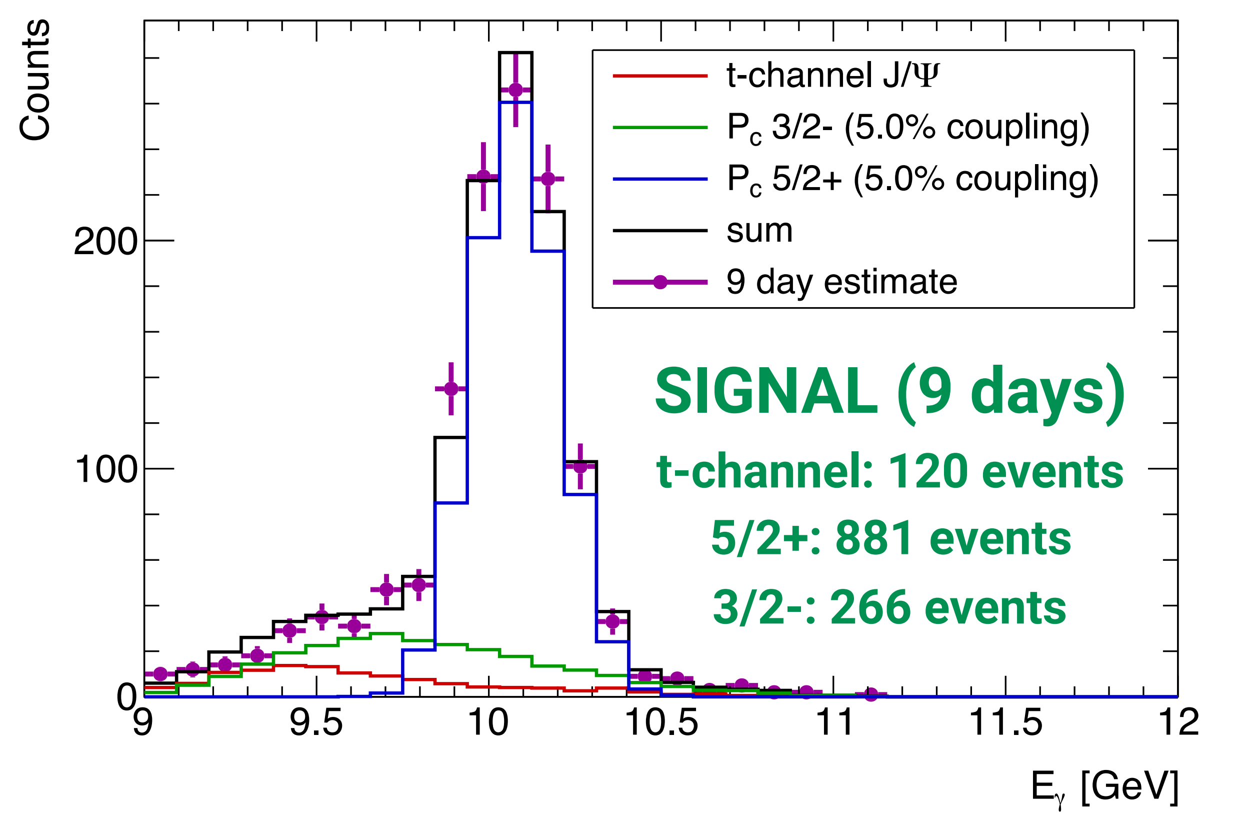
Projected results for P_c search in Hall C

- **assuming 5% coupling** (value favored by existing photo-production data) **Wang Q., *et al.*, PRD 92-3 (2015) 034022-7**
- 9+2 days of beam time at 50μA
- **5/2+ peak dominates the spectrum**
- able to separate 5/2+ from ***t*-channel at low Eγ**
- will provide **first-hand information about *t*-channel production near threshold**

Only 11 days!

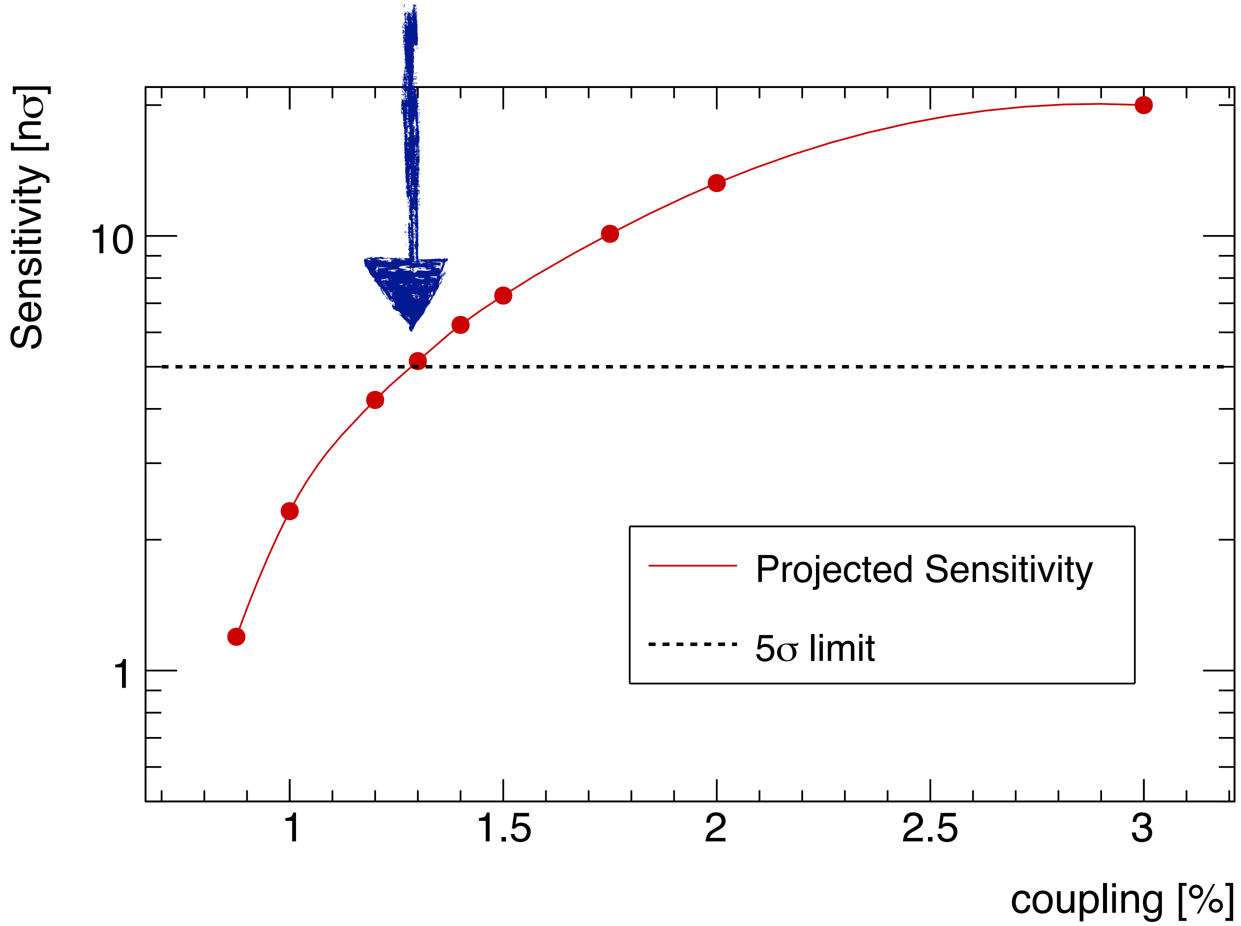
Significance > 20σ!

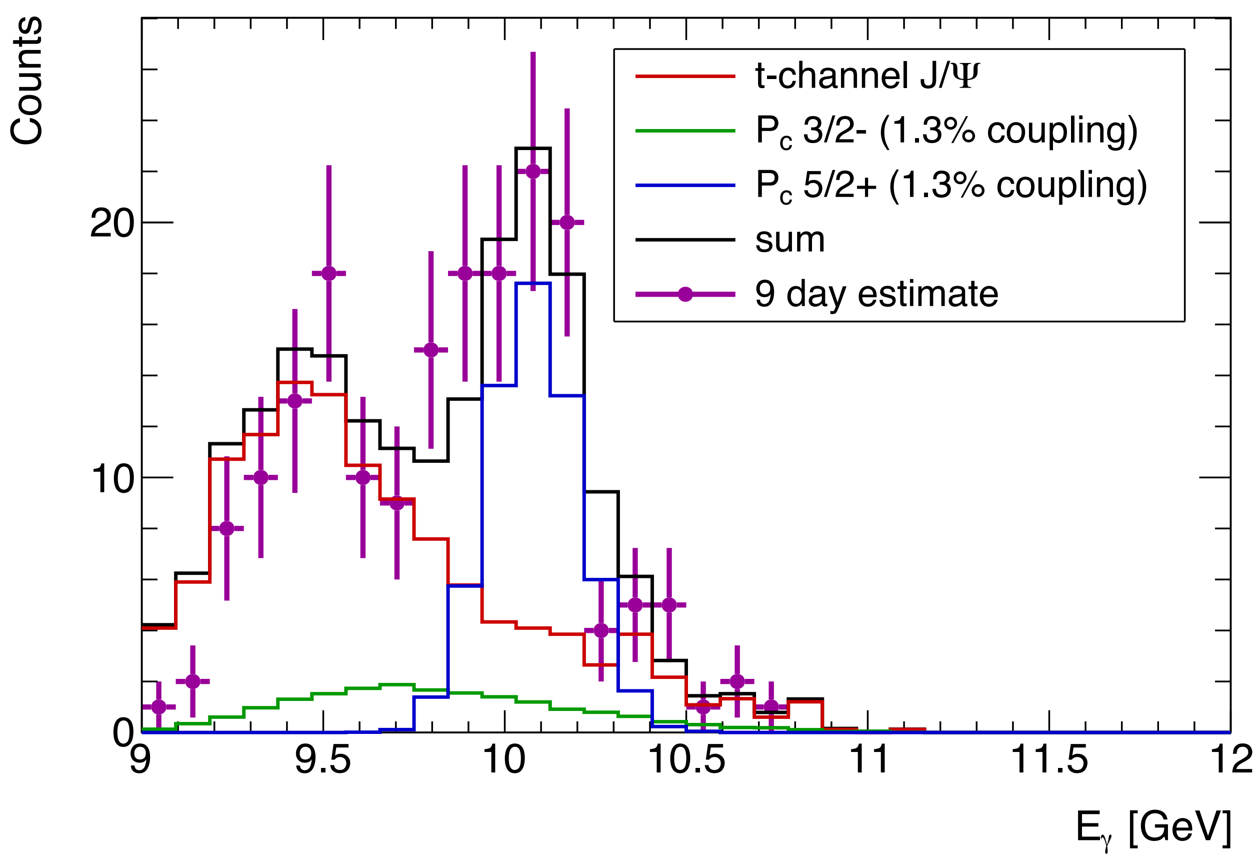




Sensitivity for **Discovery**

- sensitivity calculated using a Δ-log-likelihood formalism
- **5 standard deviation** level of sensitivity **starting from 1.3% coupling!**





J/ψ experiments at JLab

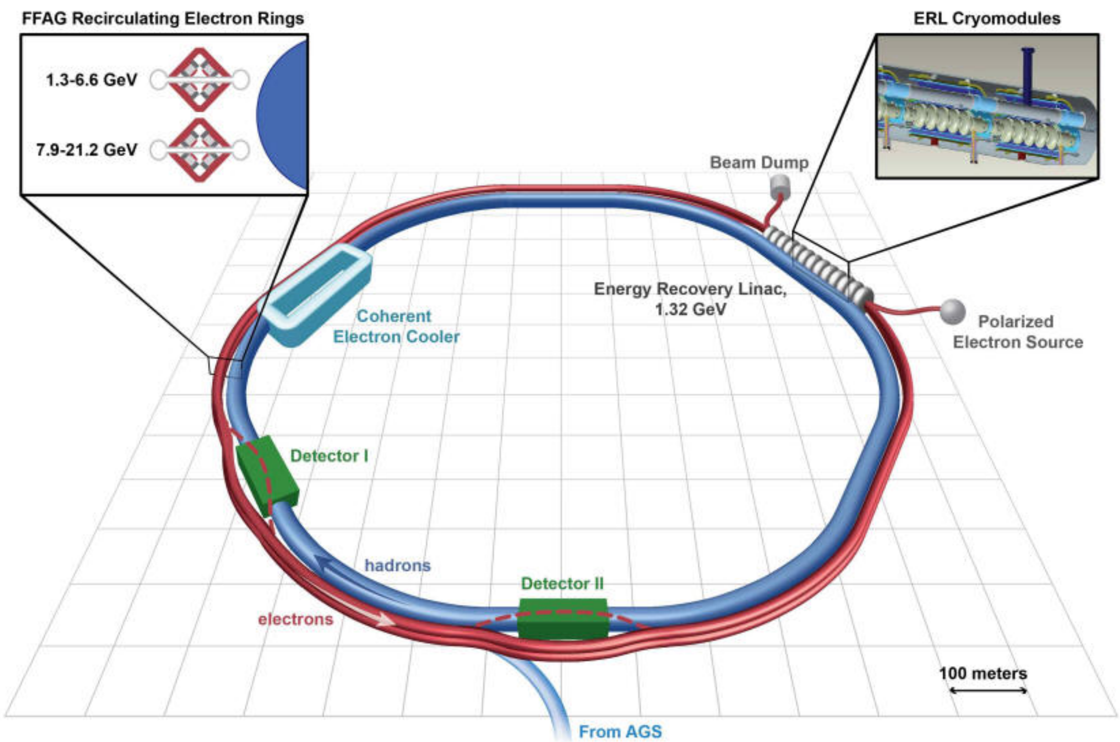
	GlueX HALL D	HMS+SHMS HALL C	CLAS 12 HALL B	SoLID HALL A
J/ψ Rate (photo-prod.)	**5-10/day**	#1: 13/day #2: **341/day**	**45/day**	**1627/day**
J/ψ Rate (electro-prod.)				**86/day**
Experiment		E12-16-007	E12-12-001	E12-12-006
PAC		9+2 days **high-impact**	130 days	50 days
When?	Now	Soon!	Next years	5-10 years

Time

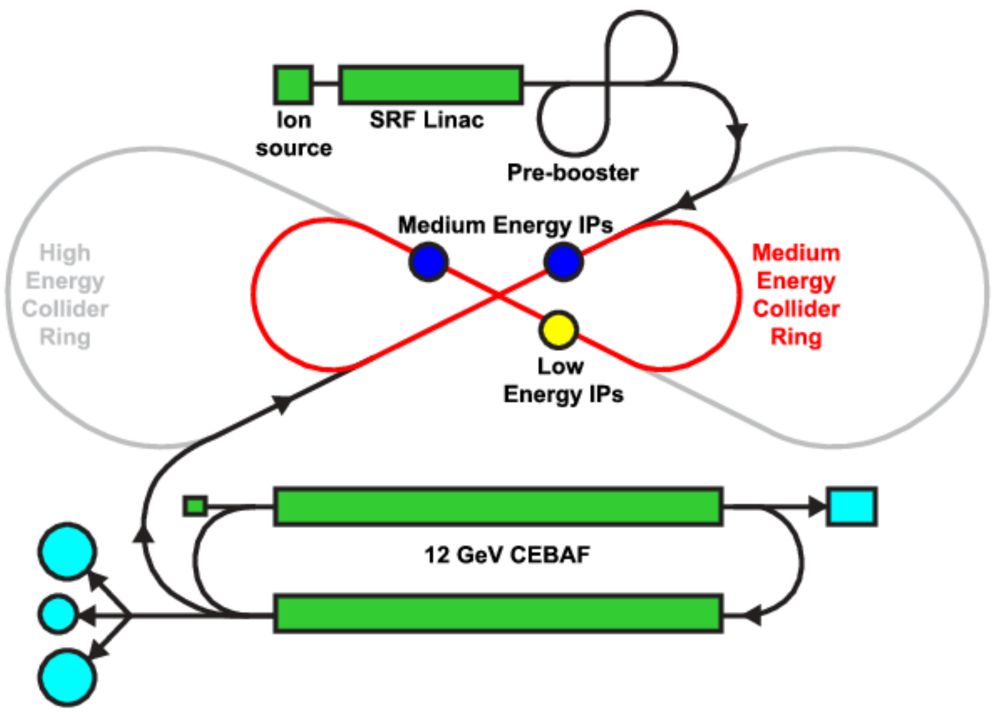
Elastic quarkonium production **at an EIC**

US Based EIC: **The Machines**

eRHIC (BNL)



JLEIC (JLab)



- First polarized electron-proton/ion collider in the world
- First electron-nucleus collider in the world
- Both make use of existing infrastructure

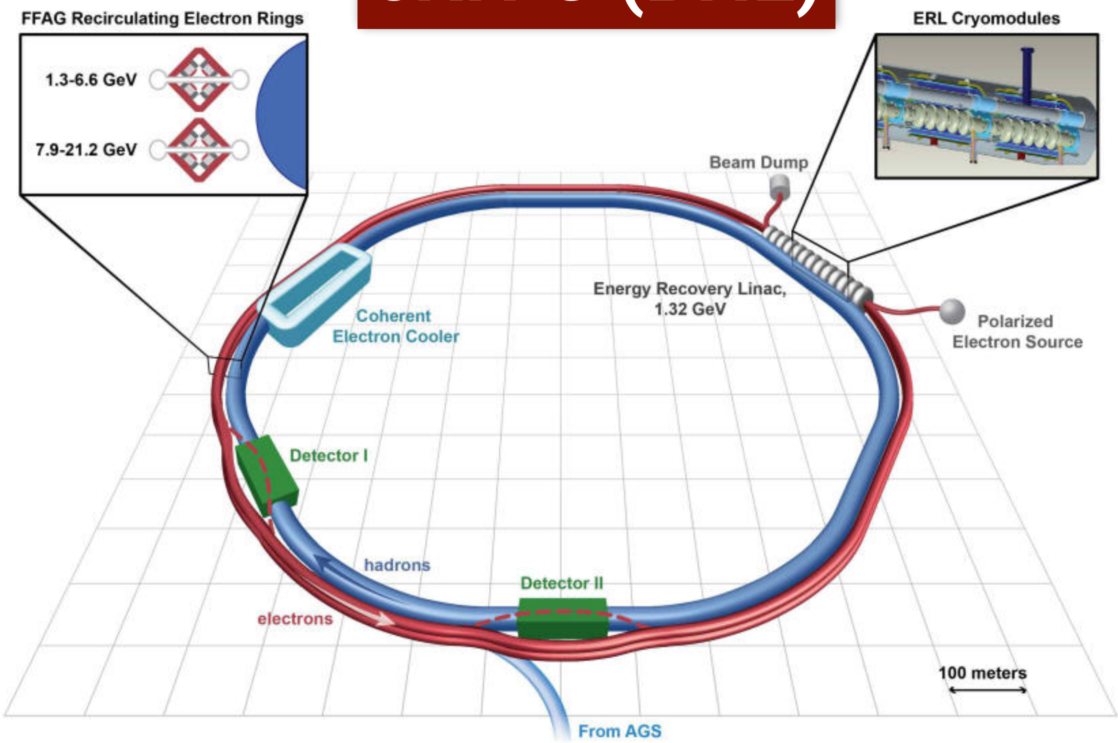
Quarkonia at an EIC **complimentary to JLab**

- J/ψ production at high W tool for **gluon imaging** not possible at JLab12
- Access to **Q^2 dependence close to J/ψ threshold**

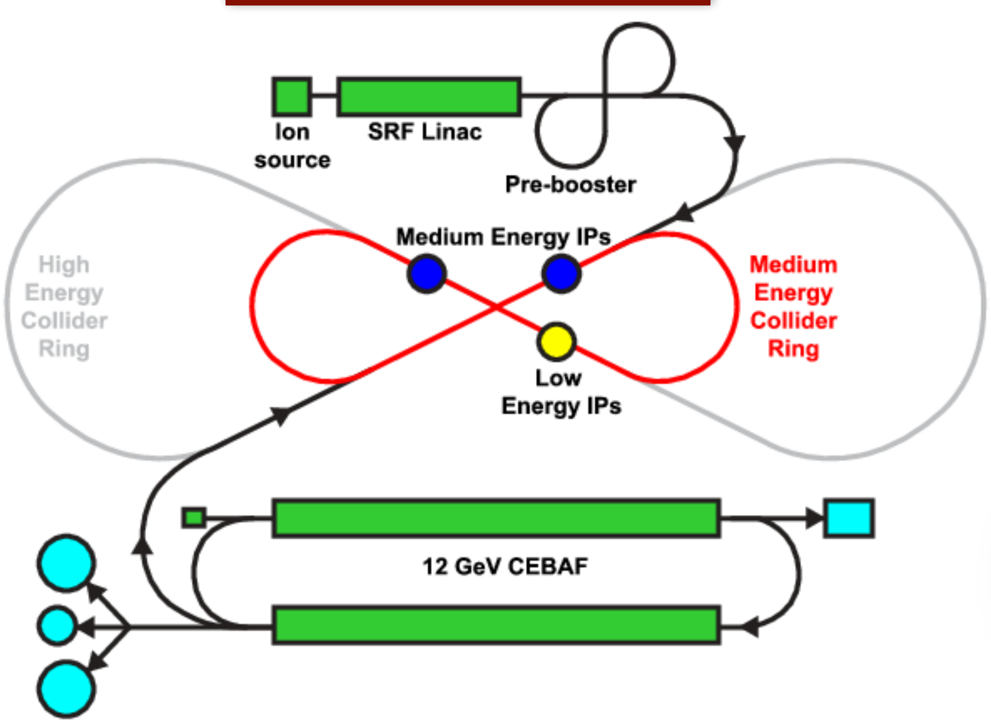
- **$\Upsilon(1s)$** production possible at threshold and high W
- Important cross check for **universality** due to smaller higher-order corrections
  - For gluon GPDs extracted with J/ψ at the EIC
  - For J/ψ threshold physics at JLab12
- Is there a “bottom pentaquark?”

Accelerator and **detector parameters**

eRHIC (BNL)



JLEIC (JLab)

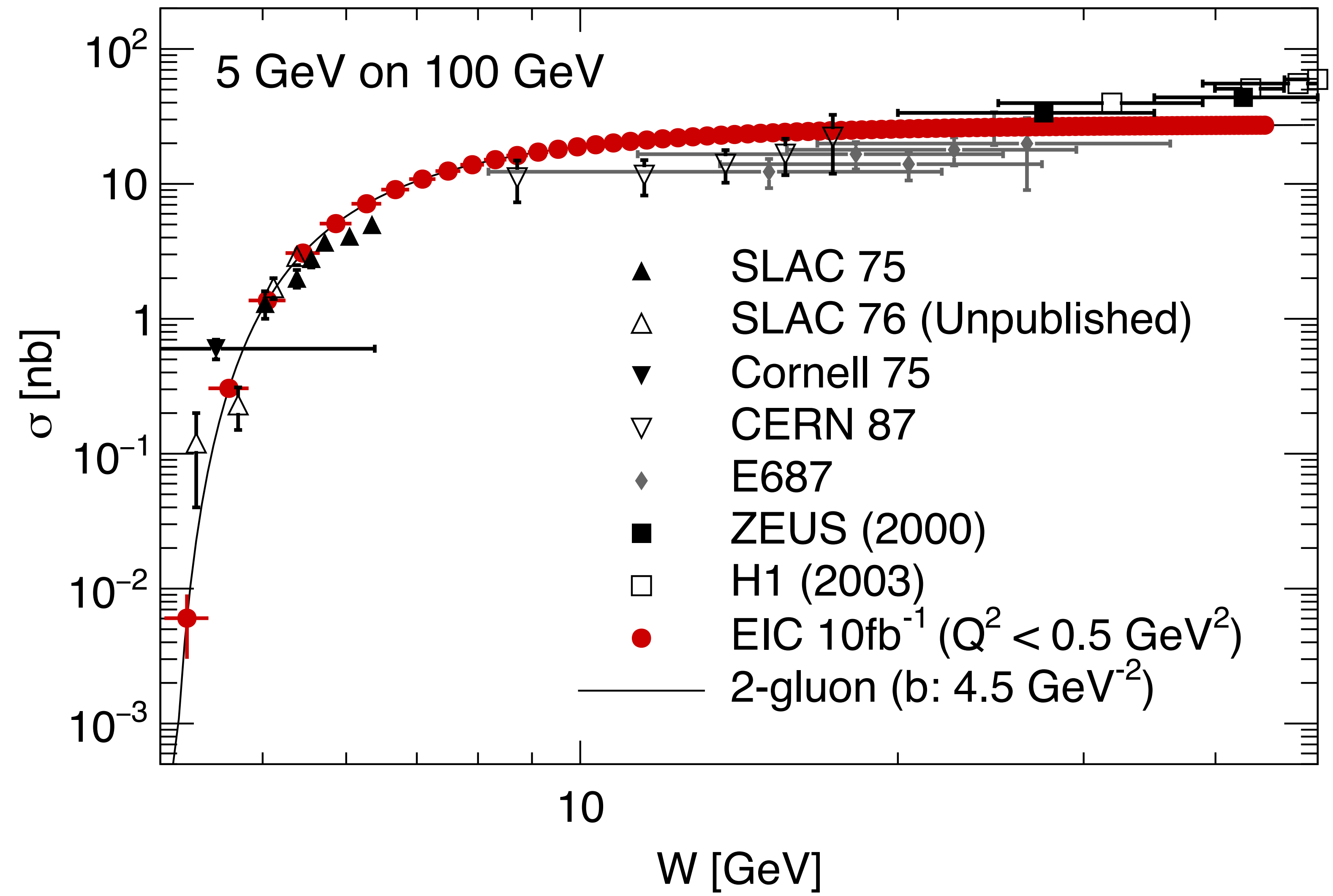


- Nominal parameters relevant to DVMP:
  - (Consistent with accelerator/ detector specs from white-paper)
  - **5 GeV electron beam on 100 GeV proton beam** in range of both designs
  - **Luminosity: 10-100 fb^{-1}**
  - **Acceptance** (conservative!):
    - **Leptons**: pseudo-rapidity $|\eta| < 5$
    - **Recoil proton:** scattering angle $\theta > 2$ mrad
  - Resolution:
    - Angular < 0.5 mrad
    - Momentum < 1%

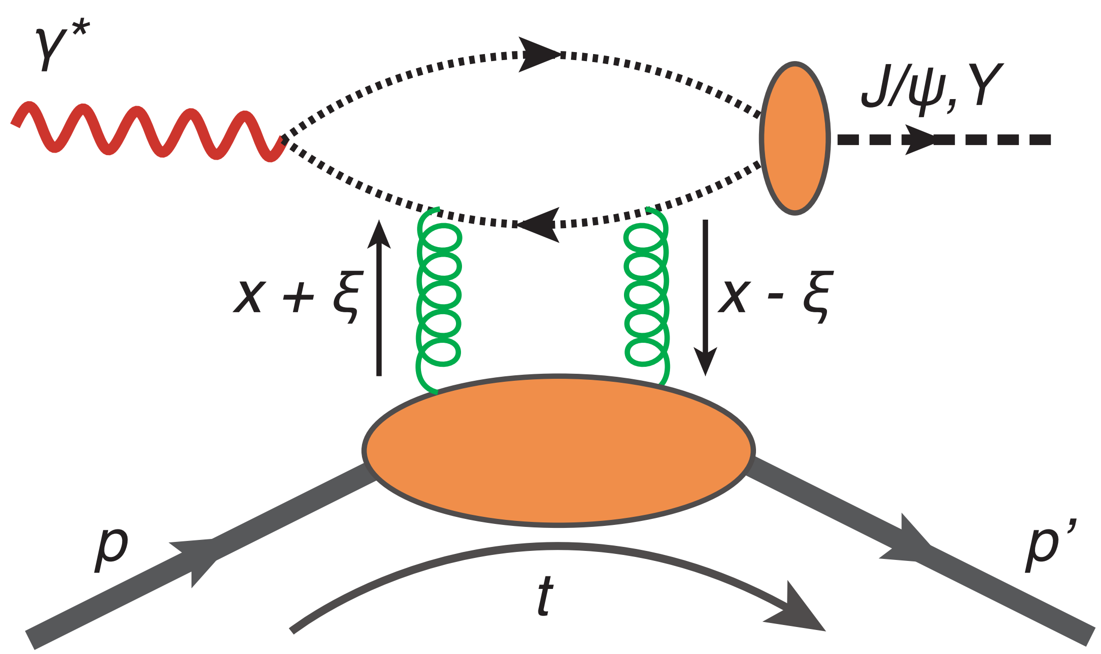
Only looking at electron-positron channels!

J/ψ photo-production cross section

- **Quasi-real production** at an EIC
- Simulation based on a 2-gluon fit to the world data
- **Fully exclusive** reaction
- Can go **close to threshold**



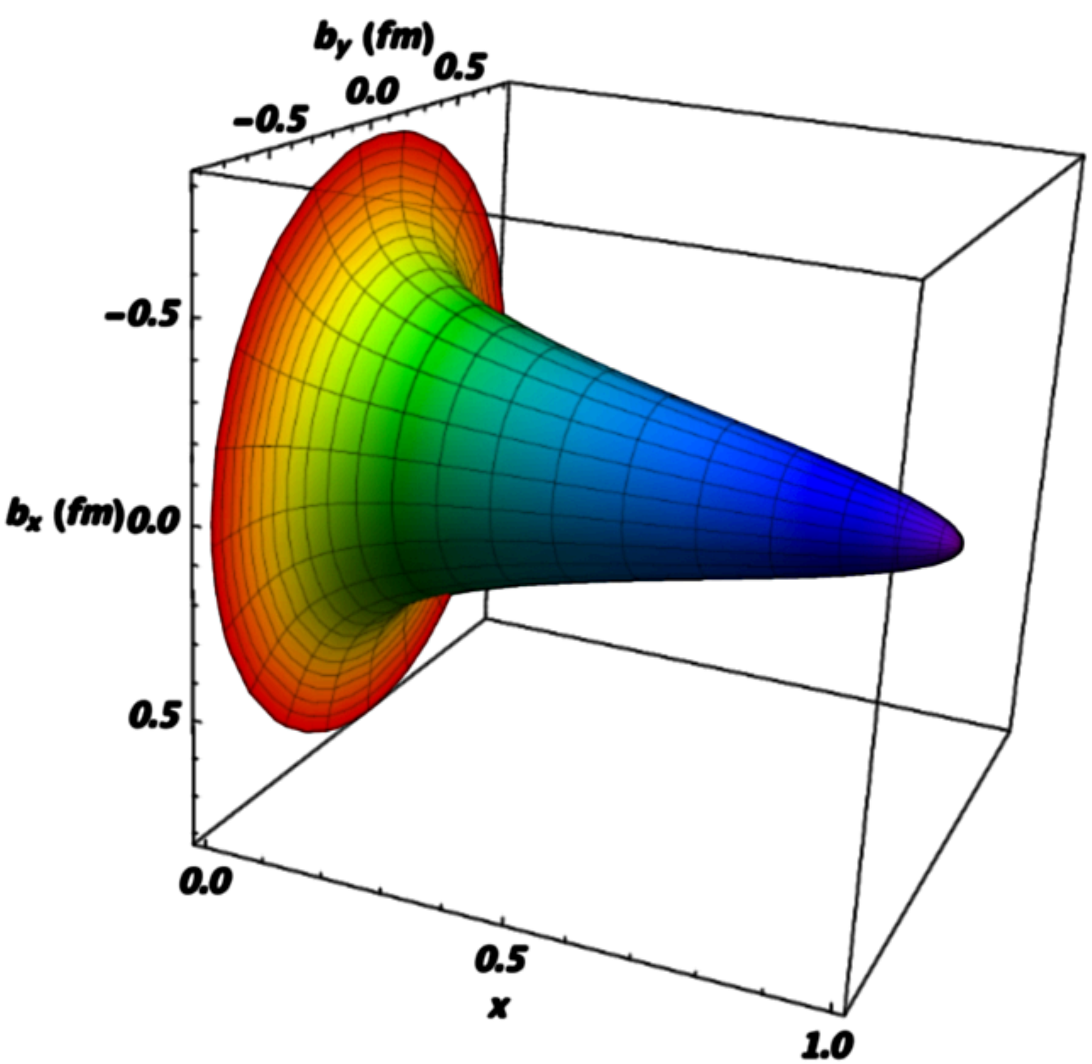
Deeply-virtual meson production and the gluon GPD



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

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

***t* related to transverse momentum transfer** $$-t = \frac{x_V^2 M_P^2 + \vec{\Delta}_T^2}{1 - x_V}$$



Leading order: **unpolarized gluon GPD related to *t*-dependent cross section**

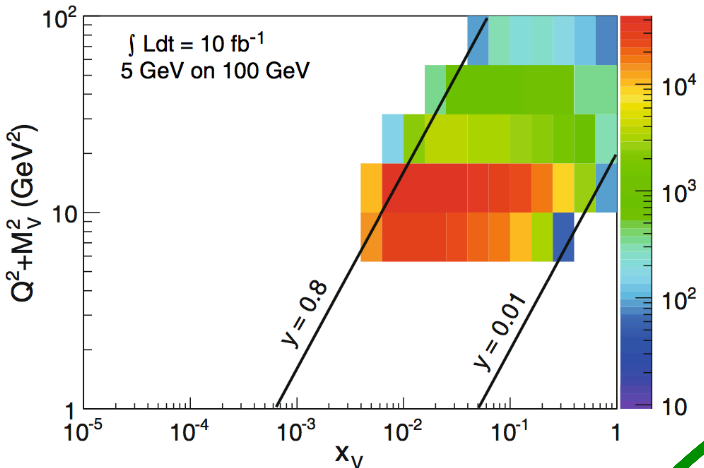
$$|\langle \mathcal{H}_g \rangle|(t) \propto \sqrt{\frac{d\sigma}{dt}(t) / \frac{d\sigma}{dt}(t=0)}$$

Fourier transform: unpolarized gluon GPD

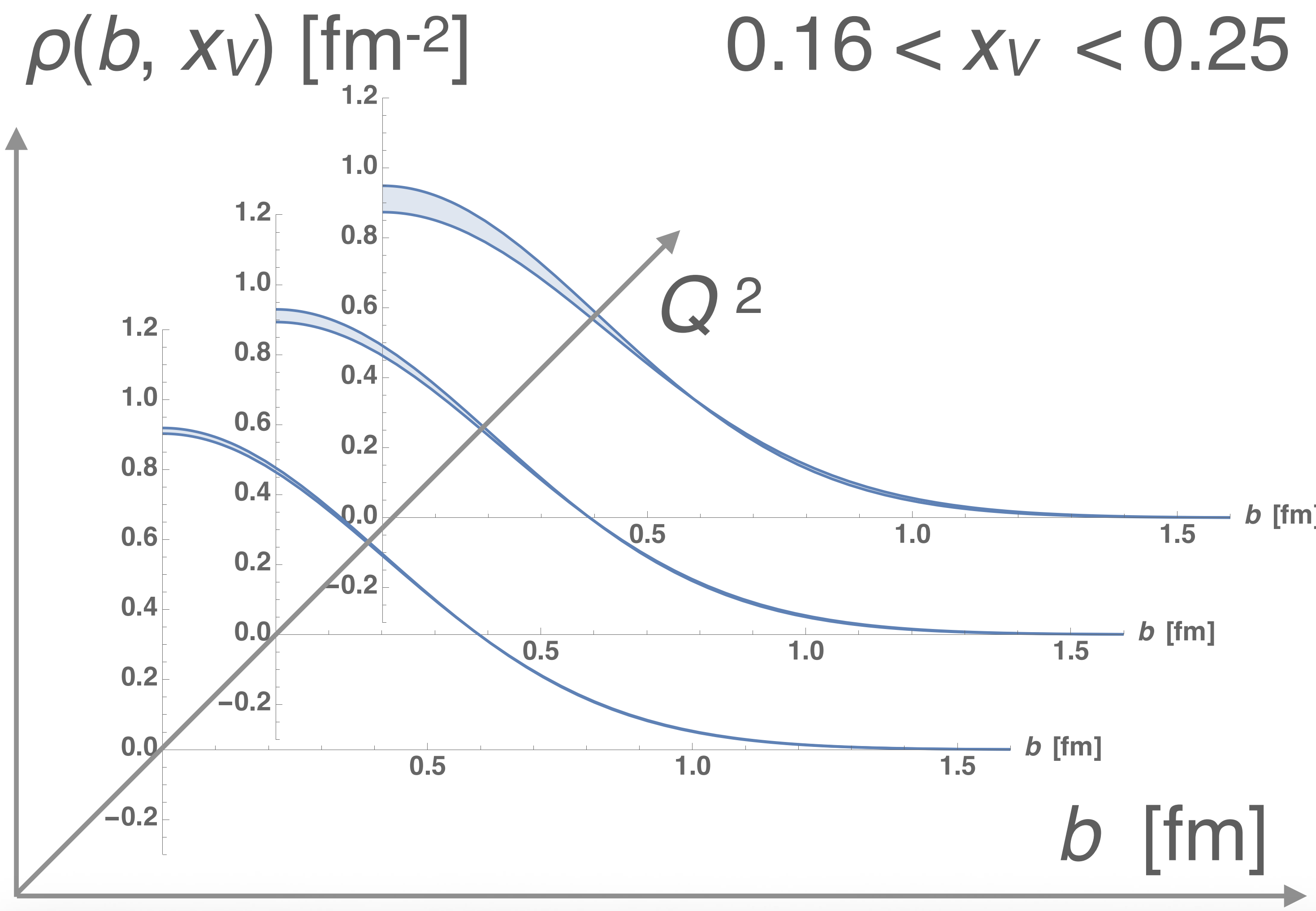
$$\rho(|\vec{b}_T|, x_V) = \int \frac{d^2\vec{\Delta}_T}{(2\pi)^2} e^{i\vec{\Delta}_T \vec{b}_T} |\langle H_g \rangle|(t = -\vec{\Delta}_T^2)$$

Spatial **Imaging of gluon density** with J/ψ

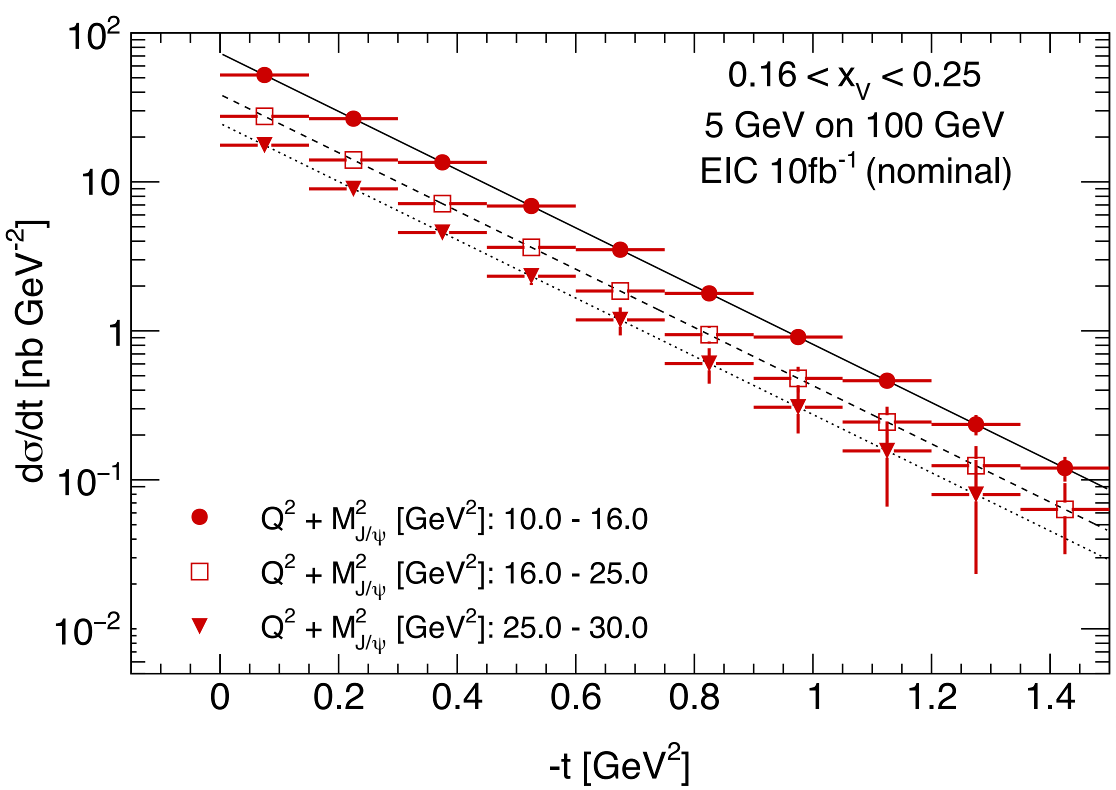
Gluon GPD in fine bins of x_V and Q^2



Normalized average gluon density:



***t*-spectrum**



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

TEMPLE UNIVERSITY
S. Joosten

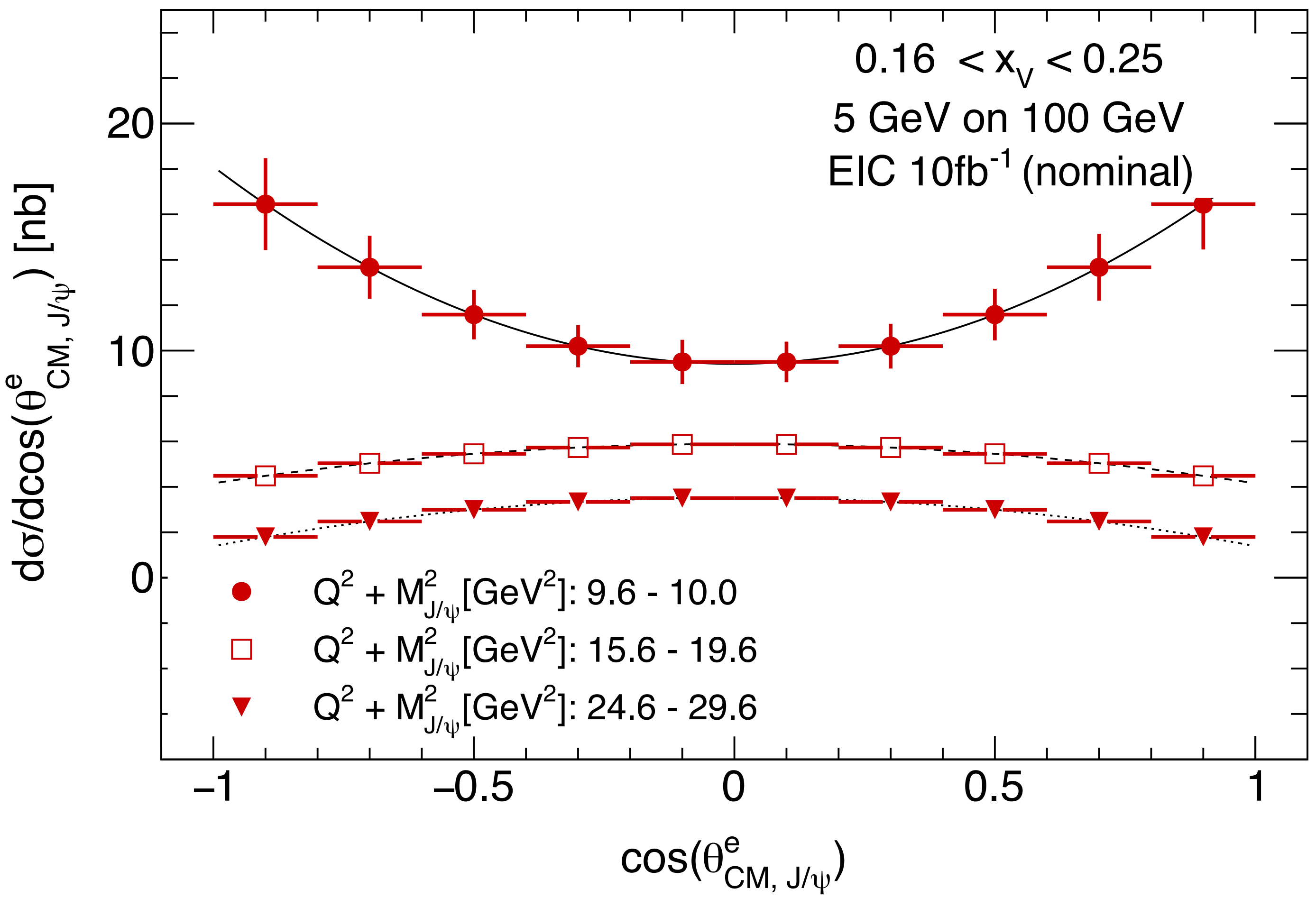
L-T separation and the Q^2 dependence of R

- **s-channel helicity conservation** (SCHC):
  - J/ψ takes on (virtual) photon polarization
  - **Angular distribution of the decay pair**

$$\mathcal{W}(\cos\theta_{\rm CM}) = \frac{3}{8}\left(1 + r^{04}_{00} + (1 - 3r^{04}_{00})\cos^2\theta_{\rm CM}\right)$$

- Can extract ***R* in 3D** (Q^2, x_V, t)

$$R \equiv \frac{\sigma_L}{\sigma_T} = \frac{1}{\epsilon}\frac{r^{04}_{00}}{1 - r^{04}_{00}}$$

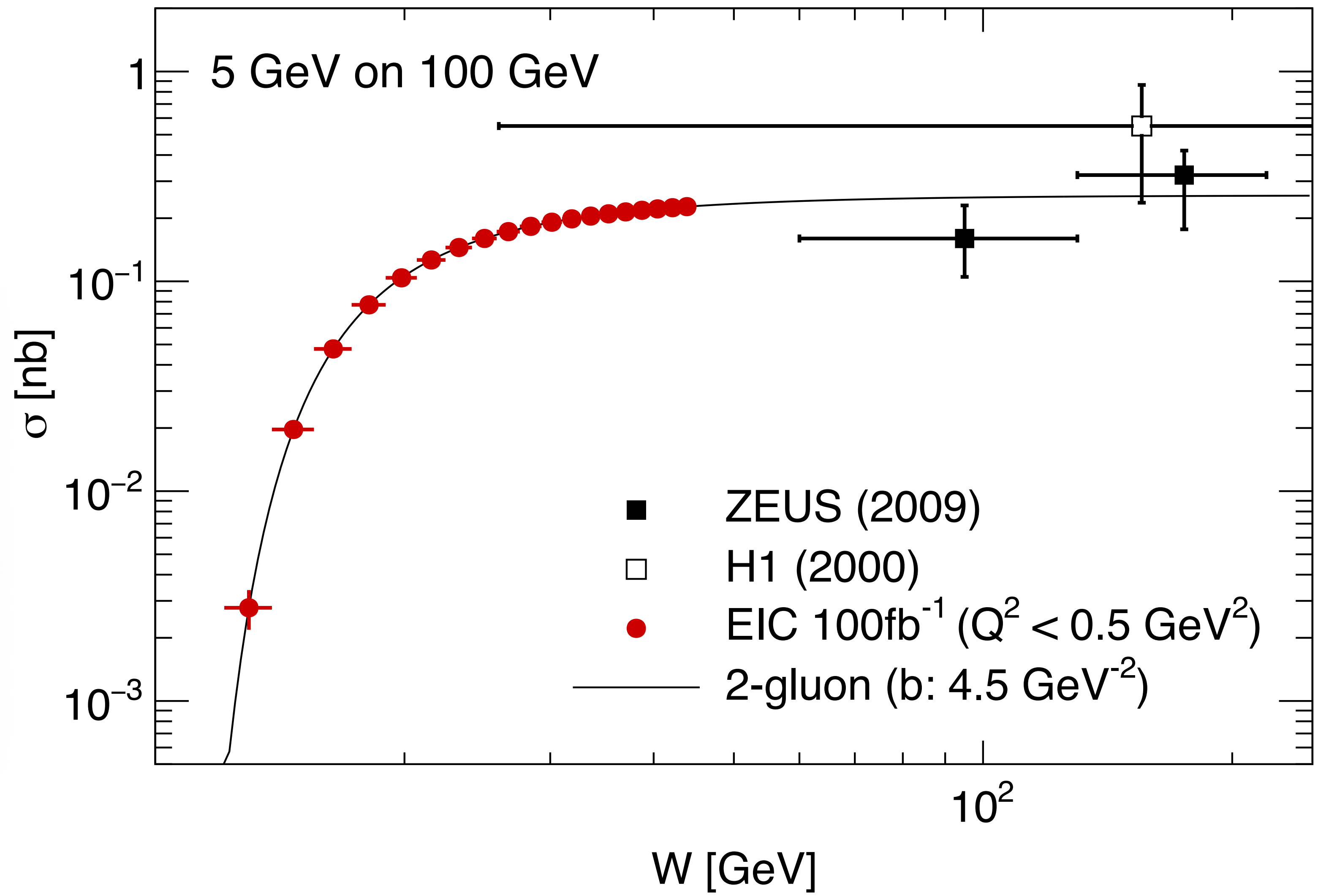


Υ **photo-production** cross section

- **Quasi-real production** at an EIC
- Simulation based on a 2-gluon fit to the HERA data
- **Fully exclusive** reaction
- Can go **to near-threshold region**

Υ cross section ~100x lower than *J/ψ*.

Reasonable precision with 10x more luminosity

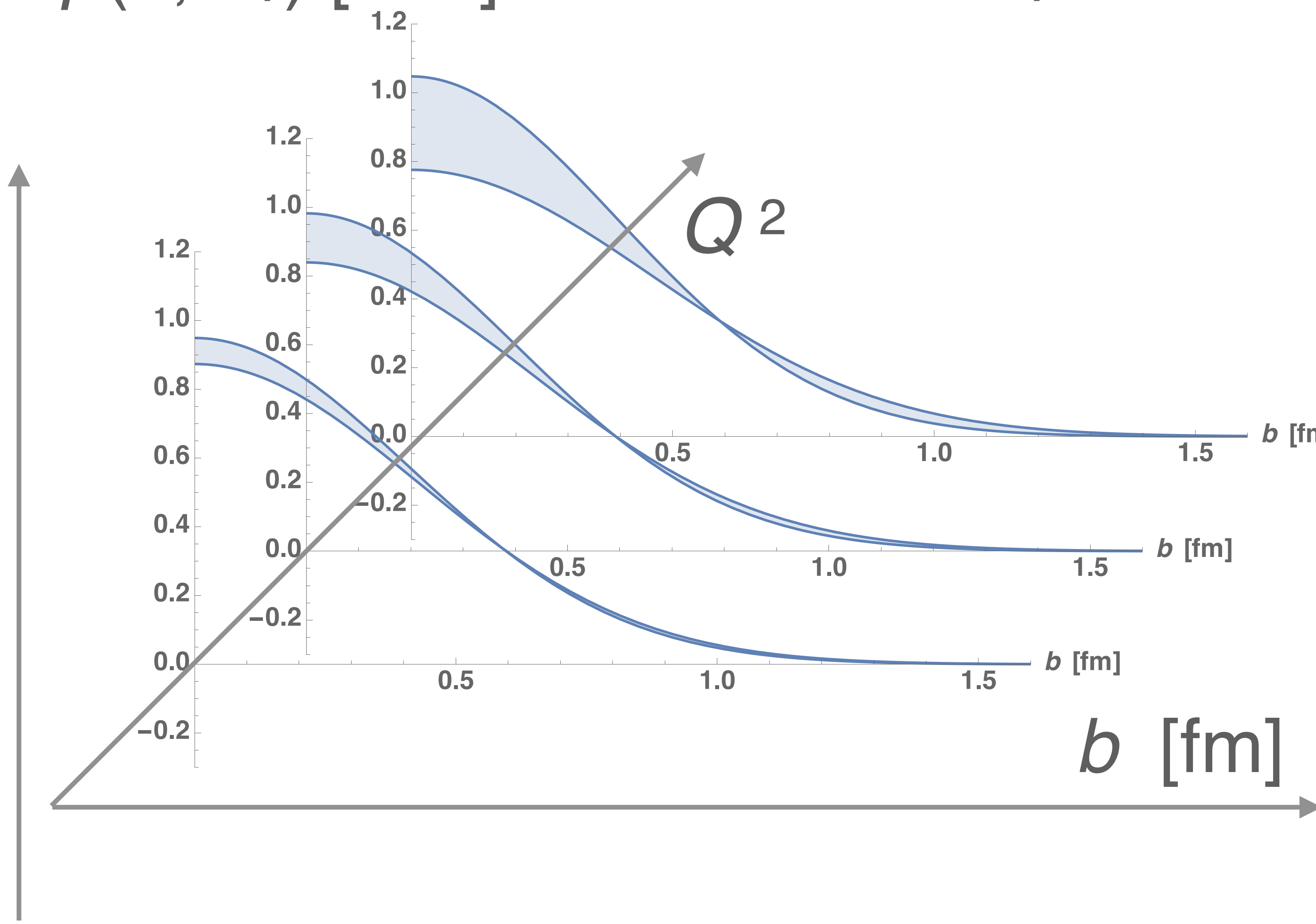


Spatial **Imaging of gluon density** with *Υ(1s)*

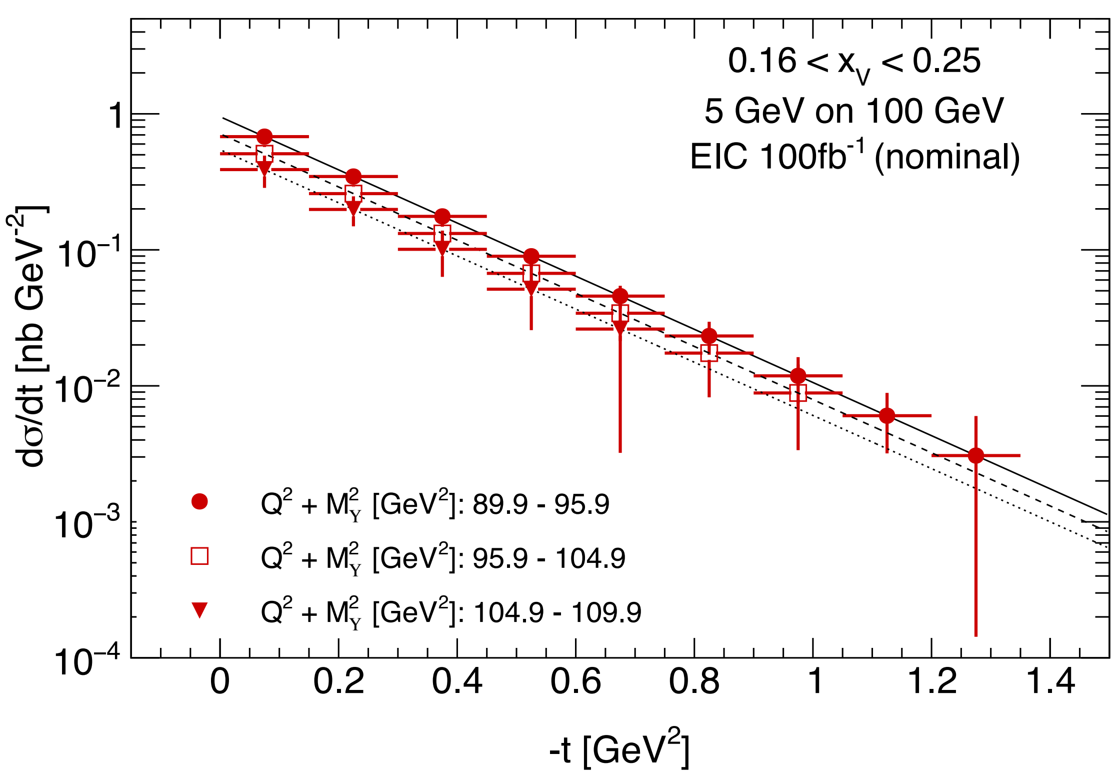
Υ(1s) a viable tool to check Universality!

Normalized average gluon density:

$\rho(b, x_V)$ [fm^{-2}] $\quad 0.16 < x_V < 0.25$



***t*-spectrum**



Conclusion

- **Quarkonium** production an important tool to study the **gluonic fields** in the nucleon
- **Threshold production** of quarkonium can shed light on the **trace anomaly,** quarkonium-nucleon **binding** and **proton mass**
- Possible to study charm (and bottom?) pentaquarks
- At **high energies**: possible to access **gluon GPDs**
- Can **test universality by comparing** ***Υ*** **to** ***J/ψ*** results
- **JLab12 and the EIC** are (will be) perfectly positioned to **significantly contribute to these topics**

This work is supported by DOE grant DE-FG02-94ER4084

BACKUP SLIDES

$$\frac{d\sigma}{dQ^2 dy dt} = \Gamma_T(1+\epsilon R) D \frac{d\sigma_\gamma}{dt}$$

$$R = \left(\frac{AM_V^2 + Q^2}{AM_V^2}\right)^{n_1} - 1$$

- Martynov, et. al., “Photoproduction of Vector Mesons in the Soft Dipole Pomeron Model.” PRD 67 (7), 2003. doi:10.1103/PhysRevD.67.074023
- R. Fiore et al., "Exclusive Jpsi electroproduction in a dual model.” PRD80:116001, 2009"

$$D = \left(\frac{M_V^2}{M_V^2 + Q^2}\right)^{n_2}$$

- A. Airapetian et al, "Exclusive Leptoproduction of rho0 Mesons on Hydrogen at Intermediate W Values", EPJ C 17 (2000) 389-398
- Adams et al., "Diffractive production of ρ0 mesons in muon–proton interactions 470 GeV", ZPC74 (1997) 237-261.
- M Tytgat, "Diffractive production of ρ0 and ω vector mesons at HERMES” DESY-Thesis 2001-018 (2001)
- P. Liebing, “Can the Gluon Polarization be Extracted From HERMES Data”, DESY-Thesis (2004)

$$\frac{d\sigma_\gamma}{dt}$$

- Brodsky, S J, E Chudakov, P Hoyer, and J M Laget. 2001. “Photoproduction of Charm Near Threshold.” Physics Letters B 498 (1-2): 23–28. doi:10.1016/S0370-2693(00)01373-3.

Angular dependence of the decay lepton pair in the J/psi Helicity frame

$$\mathcal{W}(\cos\theta_{\rm CM}) = \frac{3}{8}\left(1 + r_{00}^{04} + (1 - 3r_{00}^{04})\cos^2\theta_{\rm CM}\right)$$

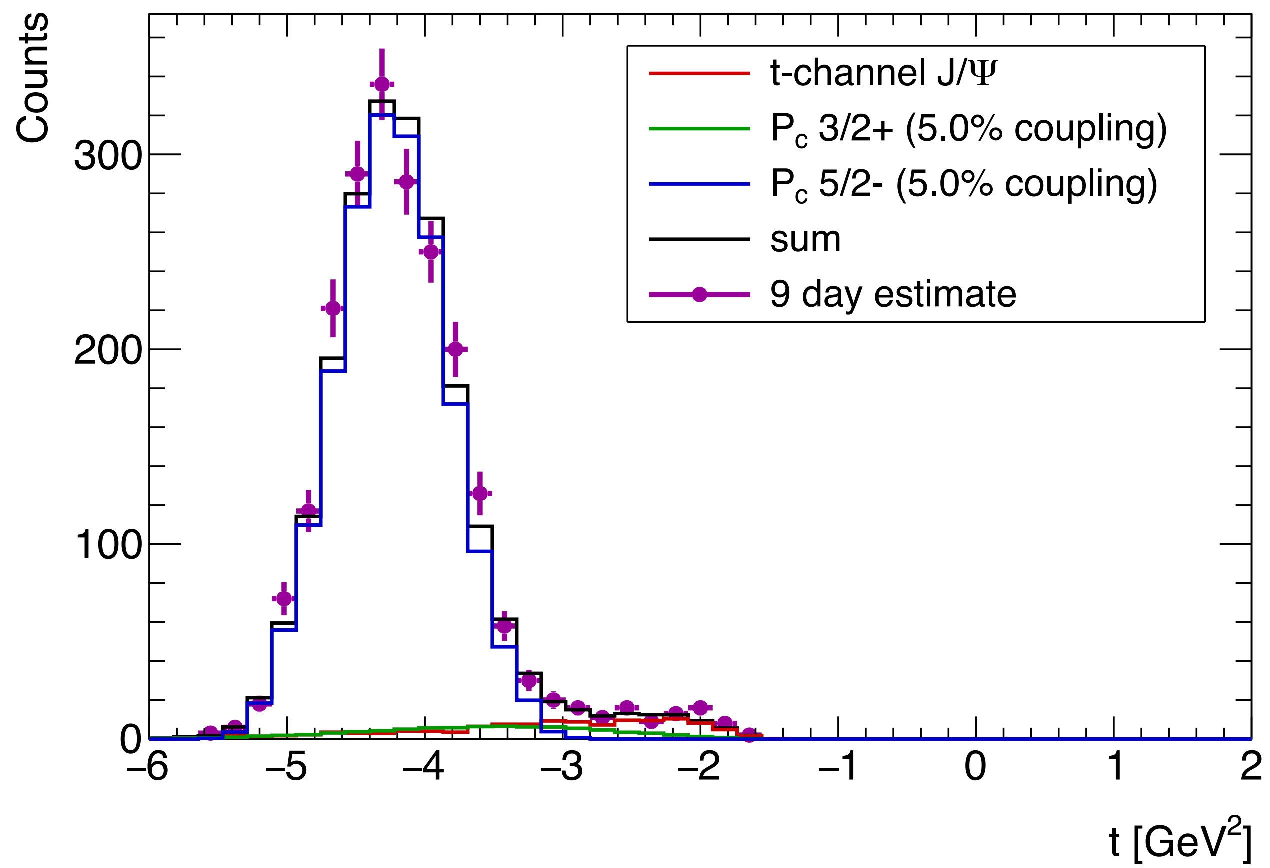
- **FORMULA FOR TWO FERMION DECAY**
- J. Breitweg et al. (ZEUS), Exclusive electro-production of rho0 and J/psi mesons at HERA, EPJ-C 6-4 (1999)
- Chekanov et al. (ZEUS), Exclusive photo production of J/psi mesons at HERA (2002)
- K. Schilling et. Al, Nucl.Phys. B 61, 381 (1973)

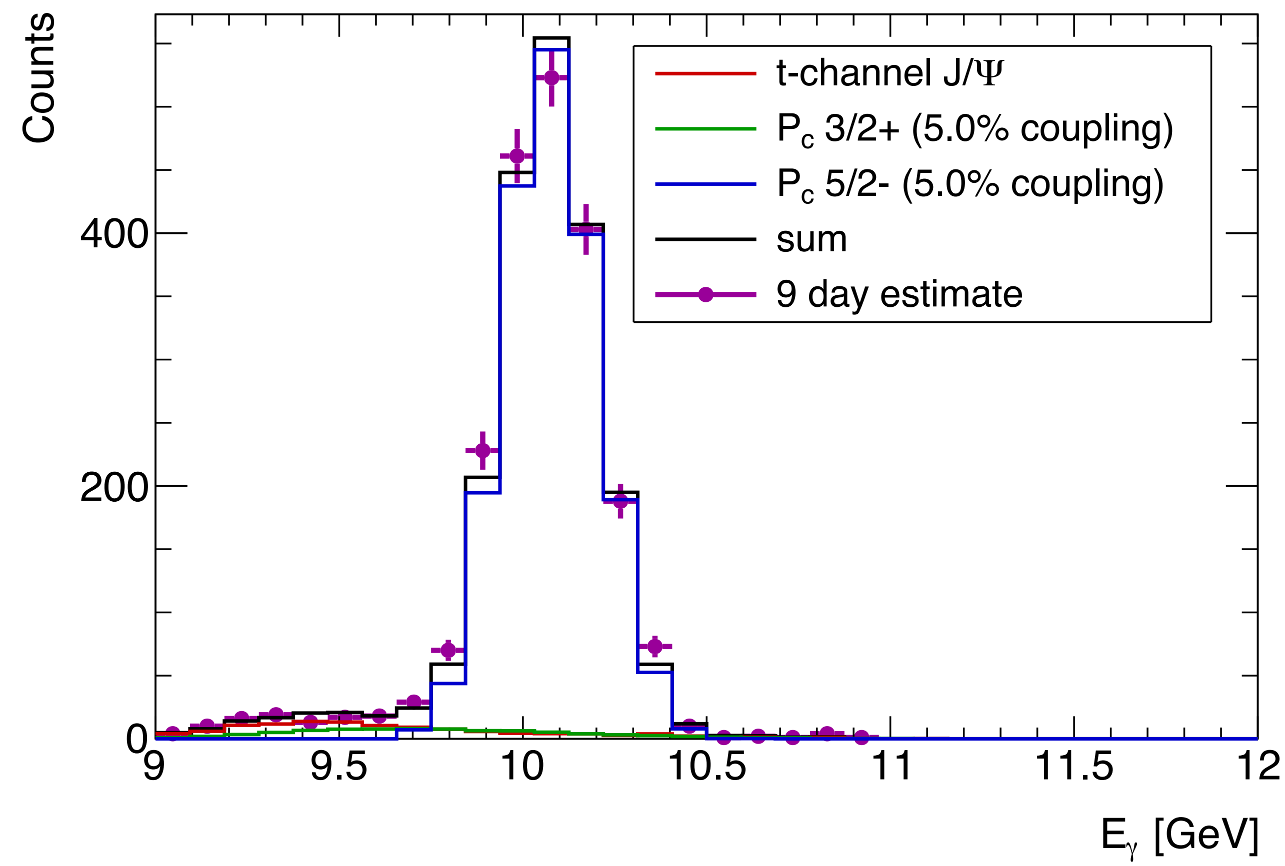
$$R = \frac{1}{\epsilon}\frac{r_{00}^{04}}{1 - r_{00}^{04}}$$

- **Extract r04 from the measured angular distribution**
- **Directly related to R!**

Alternate P_c Assumption (Setting "SIGNAL")

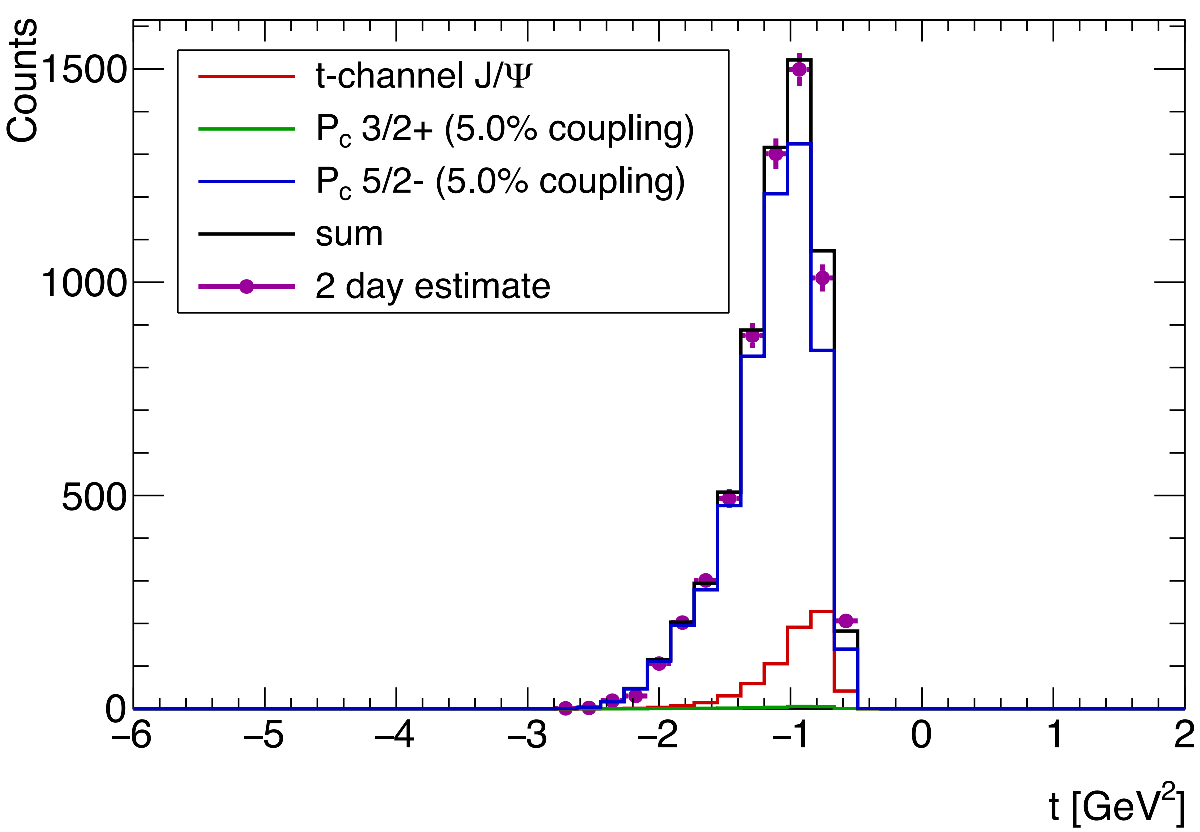
- **Alternate (5/2-, 3/2+) P_c assumption**
- assuming 5% coupling for the (5/2-, 3/2+) P_c assumption
- 9 days of beam time at 50µA
- 5/2- peak **dominates the spectrum** (even larger than the 5/2+ peak!)

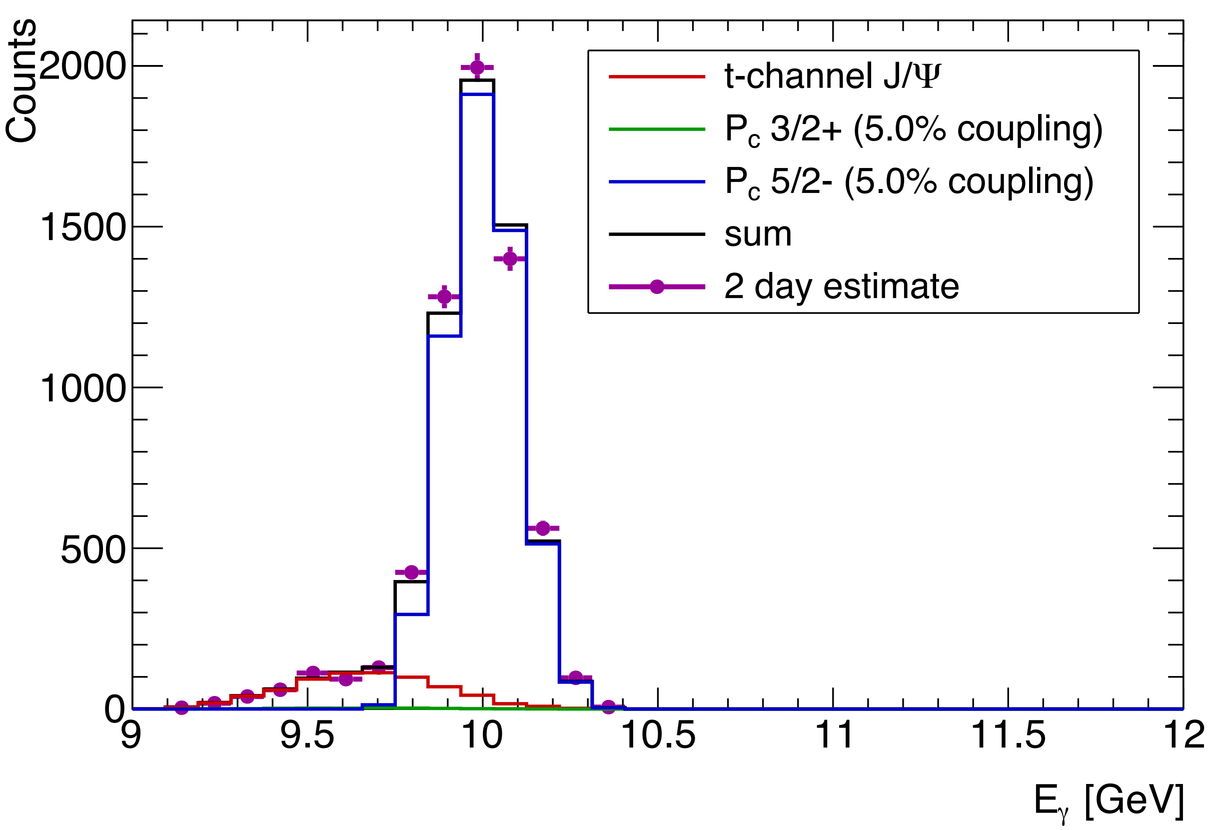




Alternate P_c Assumption ("BACKGROUND" Setting)

- **Alternate (5/2-, 3/2+) *P_c* assumption**
- 2 days of beam time at 50μA
- able to **separate** 5/2- from ***t*-channel at low E_γ**
- will provide **first-hand information about *t*-channel production near threshold**
- assuming 5% coupling for the (5/2-, 3/2+) P_c assumption

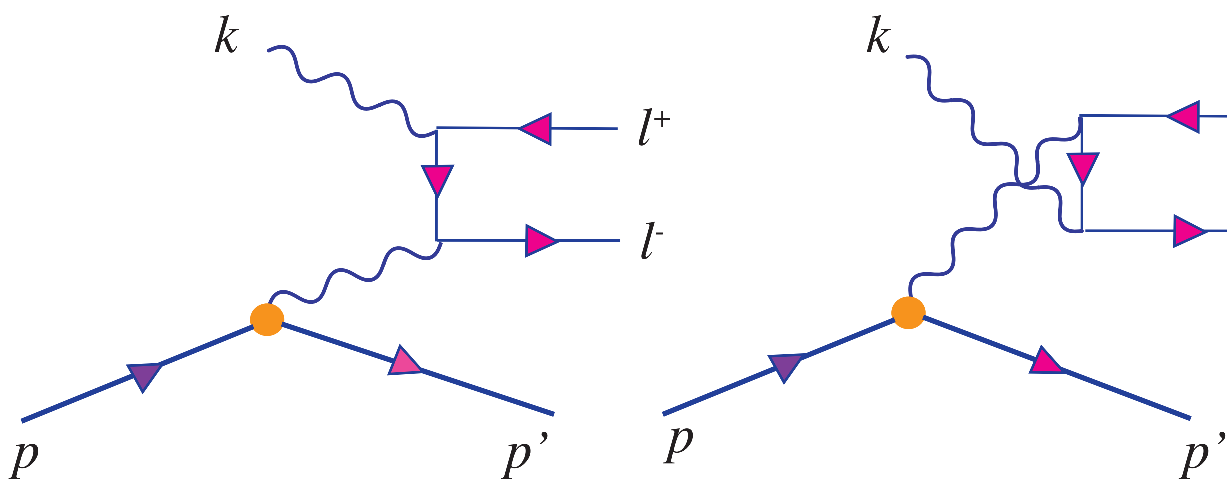




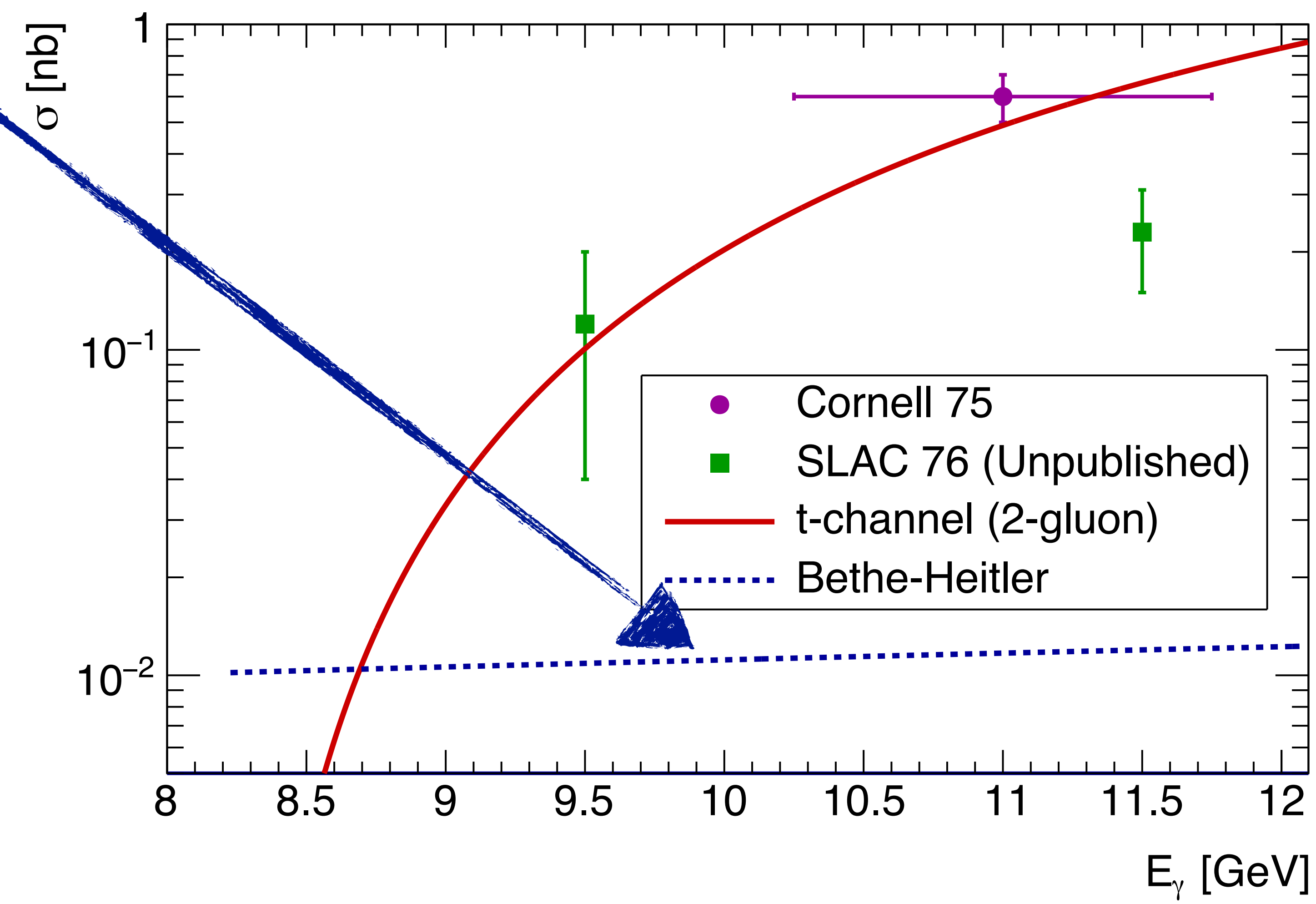
Background: **Bethe-Heitler pair production**

$$\gamma p \to e^+ e^- p$$

Not an issue!



- Estimated using calculations from Pauk and Vanderhaeghen
- Constant background < 10% of the *t*-channel J/ψ
- Can be **exactly calculated** and controlled for
- Interference negligible at the P_c(4450) peak



Pauk V and Vanderhaeghen M, PRL 115(22) (2015) 221804

Background: **inelastic *t*-channel** ($\gamma p \rightarrow J/\psi p \pi$)

- Threshold at 9 GeV
- Reconstructed photon energy $\underline{E}_{rc}$ is ~1 GeV too low
- **less than 30% of the elastic *t*-channel** background
- Contaminates the **8 GeV < $\underline{E}_{rc}$ < 9.7 GeV** range for a photon end-point energy of 10.7 GeV
  - **not an issue for the P_c(4450) ($\underline{E}_{rc}$ > 9.7GeV)!**

not an issue for the P_c!

Photon Energy Reconstruction

- Can **unambiguously** reconstruct the initial photon energy from the reconstructed J/ψ momentum and energy
- Assumptions:
  - photon beam along the *z*-axis
  - proton target at rest
  - 2 final state particles: a proton and a *J/ψ*

$$E_\gamma = \frac{M_J^2 - 2E_J M_P}{2(E_J - M_p - P_J \cos\theta)}$$

Properties of the Hall C Spectrometers

	P GeV/c	$\Delta P/P$ %	$\sigma P/P$ %	θ^{in}	$\Delta\theta^{\text{in}}$ mrad	$\Delta\theta^{\text{out}}$ mrad	$\Delta\Omega$ msr	$\sigma\theta^{\text{in}}$ mrad	$\sigma\theta^{\text{out}}$ mrad
HMS	0.4-7.4	-10 +10	0.1	10.5°-90°	±24	±70	8	0.8	1.0
SHMS	2.5-11.	-15 +25	0.1	5.5°-25°	±20	±50	4	1.0	1.0

Run Plan for E12-16-007

- **Total Beam Time Request:**
  - 11 days (264h), 10.7 GeV (or 11 GeV), 50μA, Hall C
- **Run Plan:**
  1. ***t*-channel "BACKGROUND": 40 hours**
  2. **radiator out: 8 hours (longer if needed)**
  3. **main "SIGNAL" measurement: 216 hours**

11 days,
standard equipment!