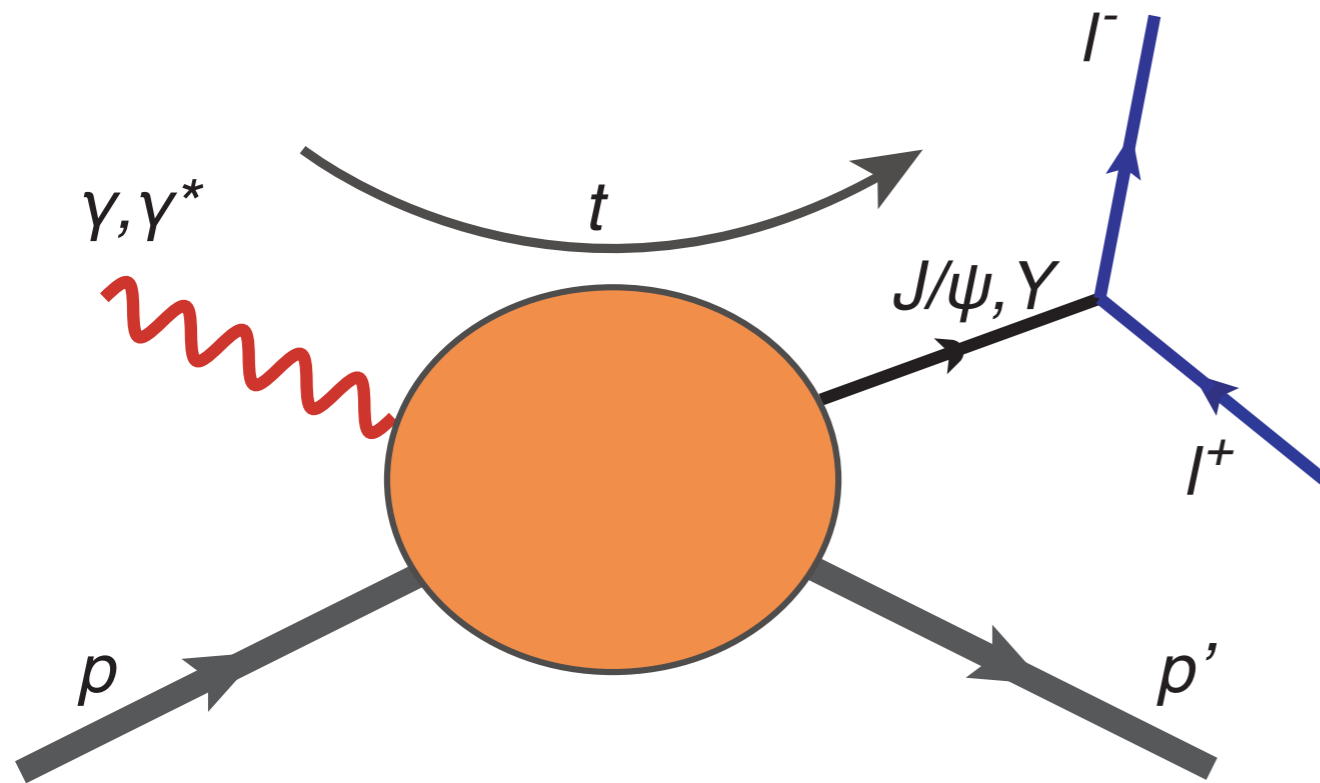


# Quarkonium Production in Cold QCD: From JLab to an EIC

**Sylvester Joosten**

sylvester.joosten@temple.edu

# Quarkonium in electro- and photo-production

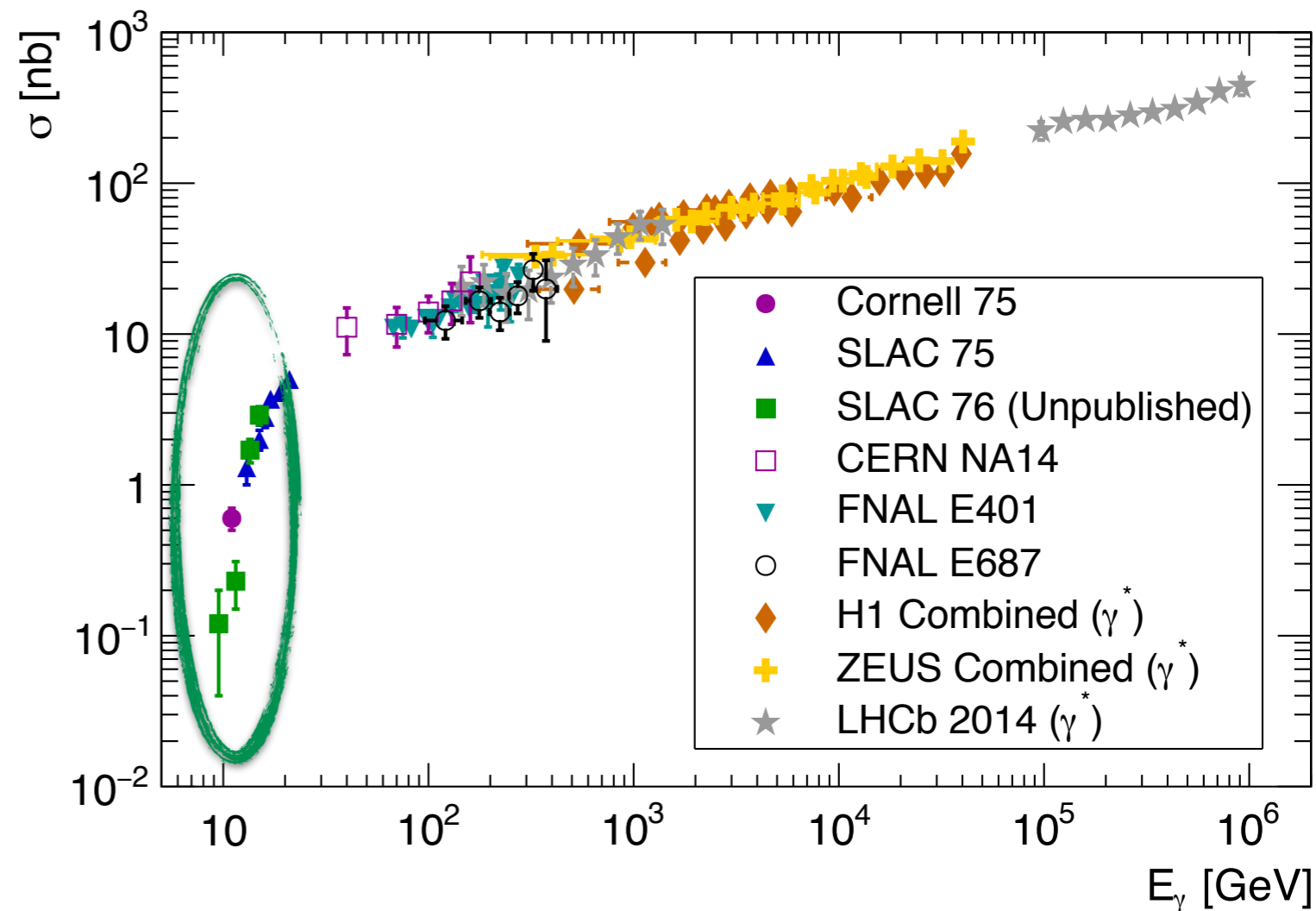


- Strong gluonic interaction between color neutral objects
- Minimal quark exchange
- **Quarkonium as a probe to study the gluonic structure of the nucleon**

# 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

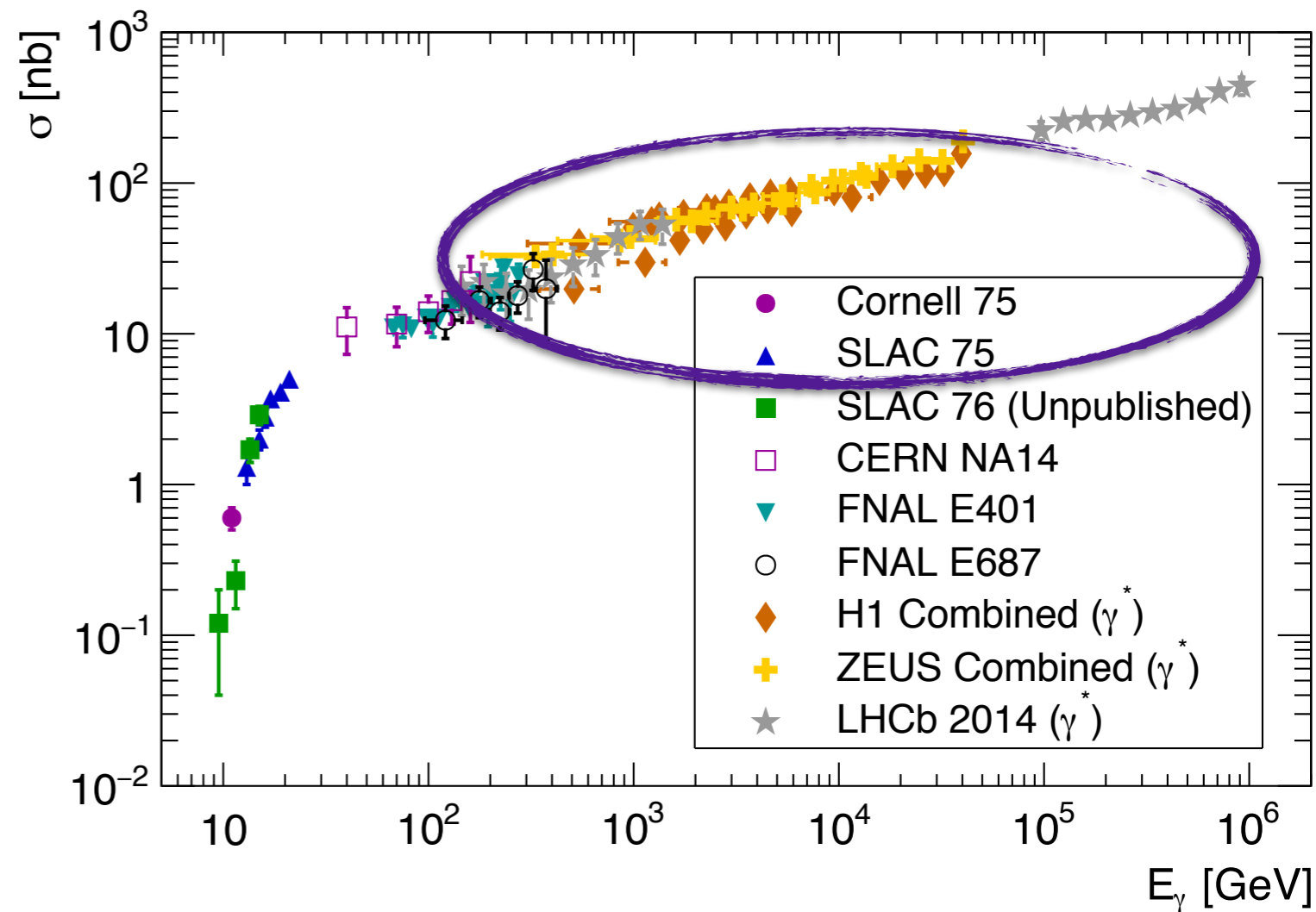


- ★  **$J/\psi$  program at Jefferson Lab**
- ★  **$Y(1s)$  production at an EIC**

# Quarkonium in electro- and photo-production

## High Energies

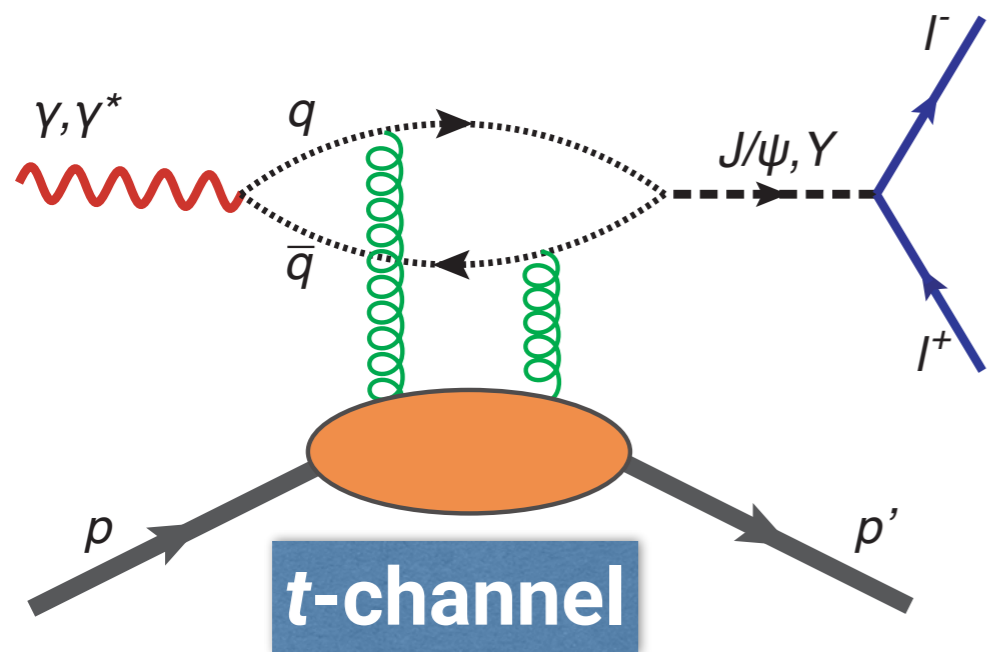
- ☆ Dominated by 2-gluon exchange
- ☆ **Gluon GPD: Full 3D** tomography of the gluonic structure of the nucleon



☆ Quarkonium production at an EIC

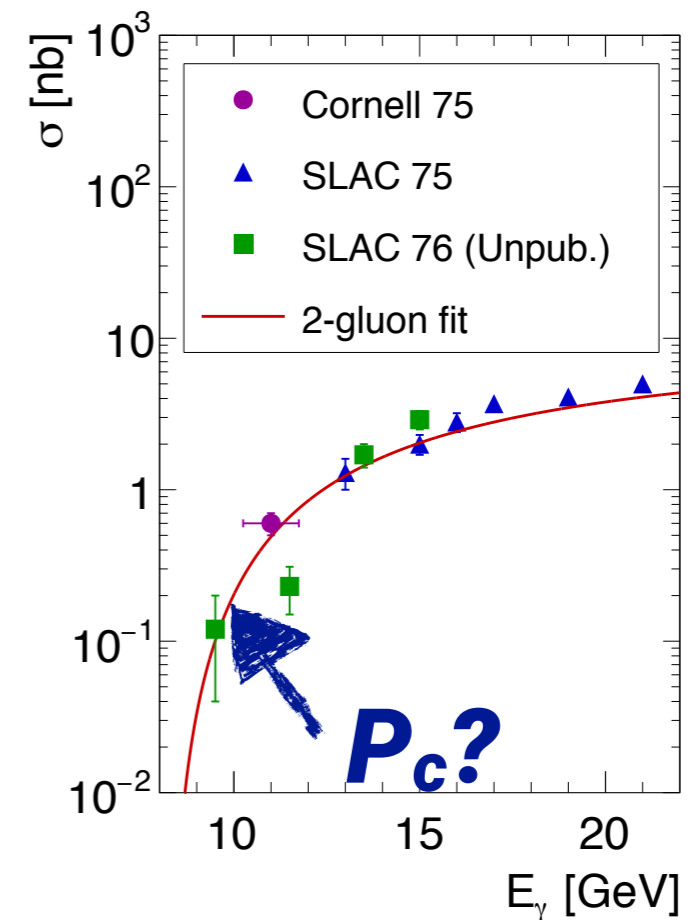
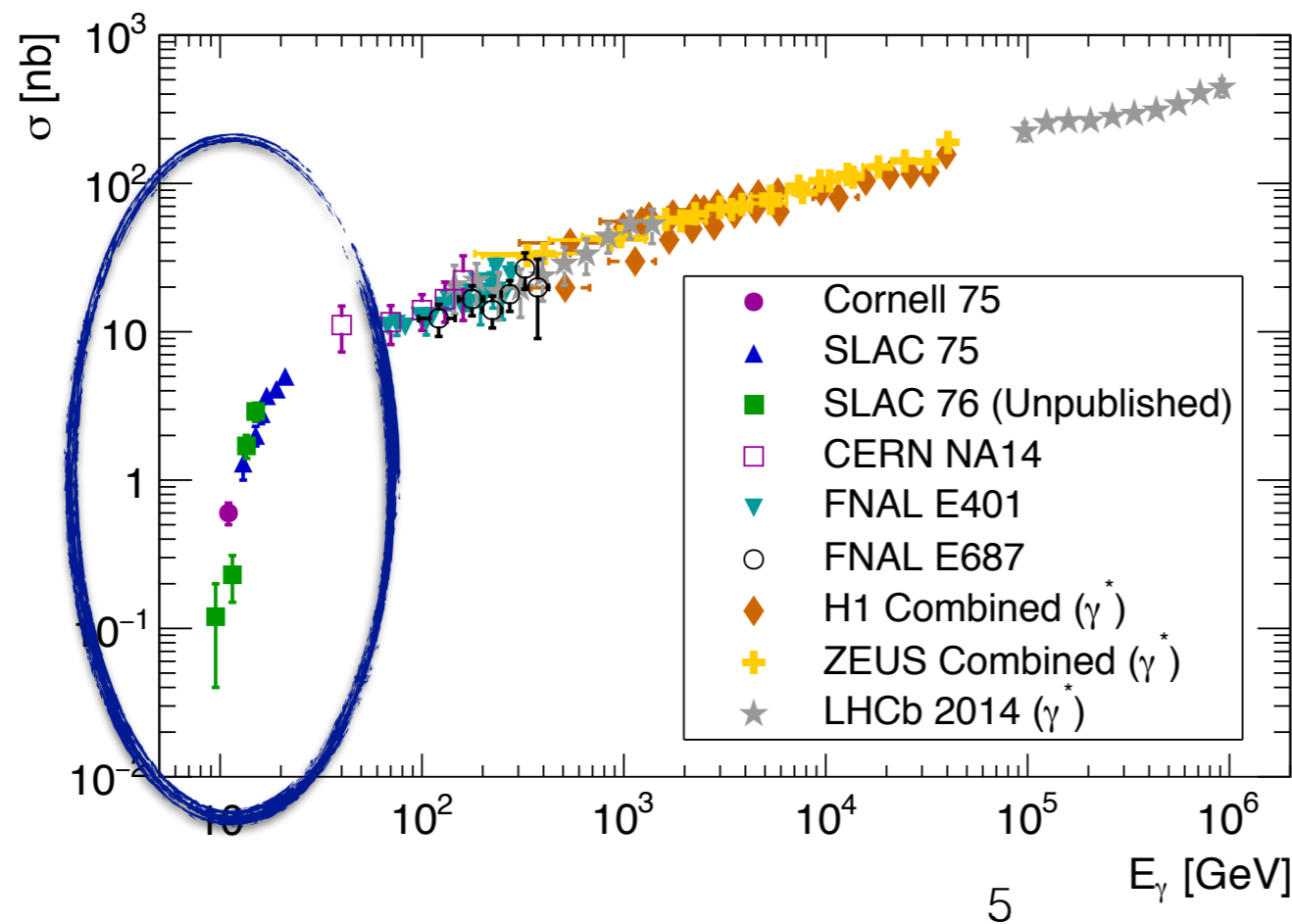
# $J/\psi$ production near threshold

# $J/\psi$ photo-production: what do we know?

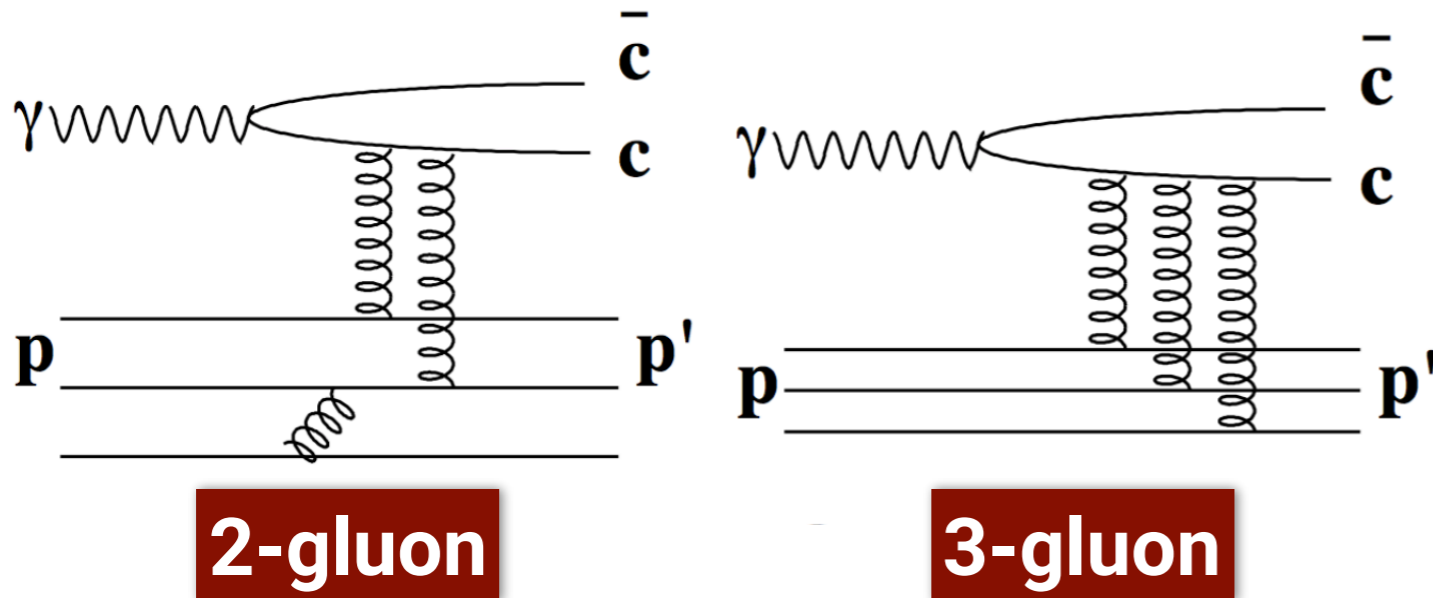


Brodsky S J, et al., PLB 498-1 (2001), p23

- 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?

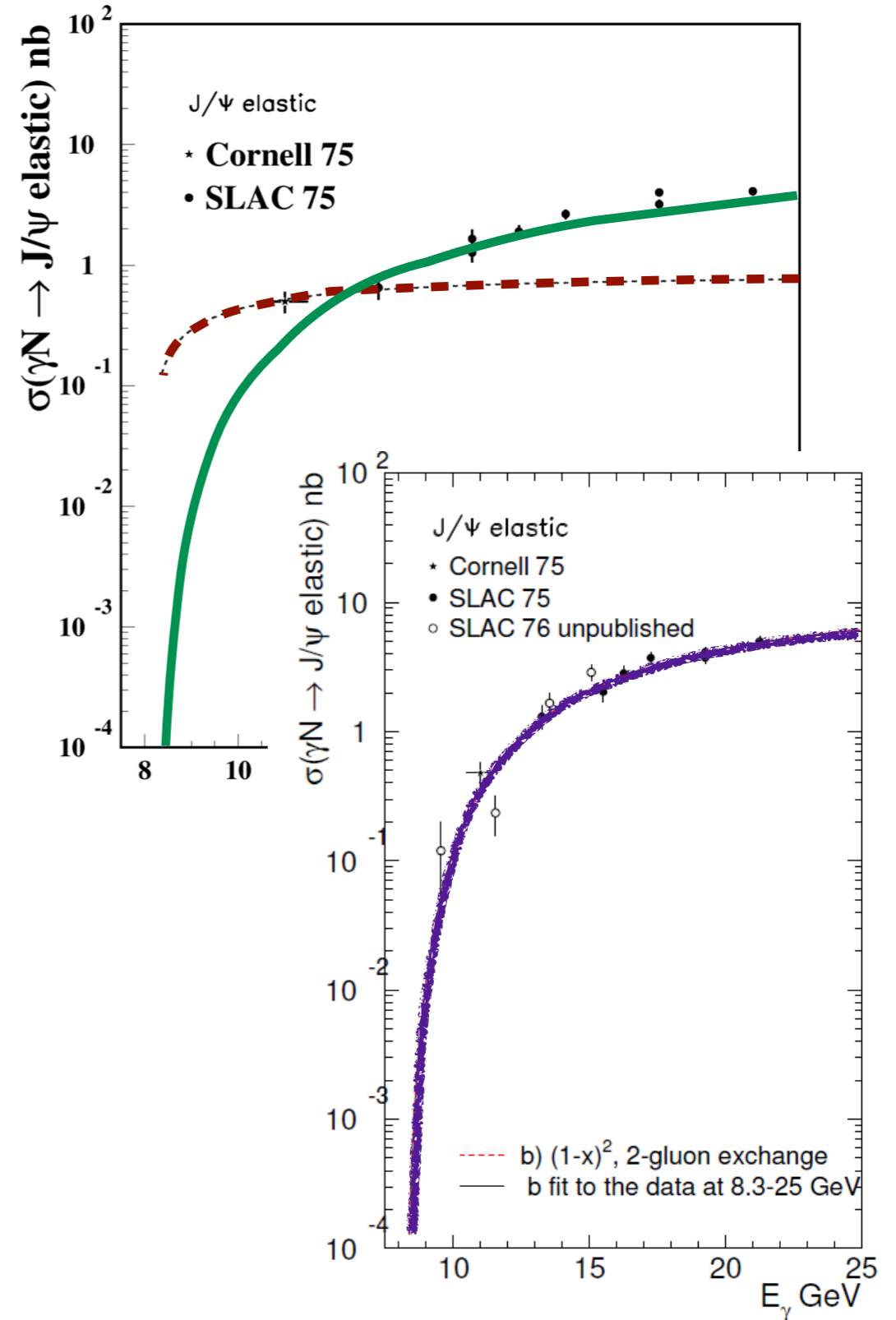
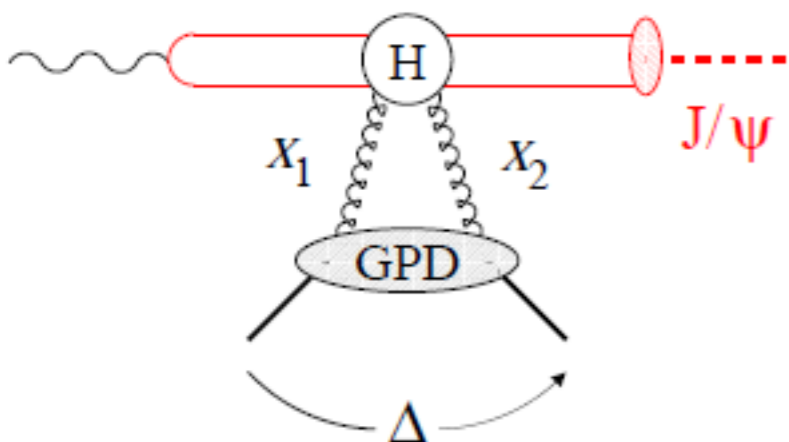


- ☆ Same as hard scattering (**2-gluon**)?
- ☆ Or does **3-gluon** exchange become dominant?

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

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

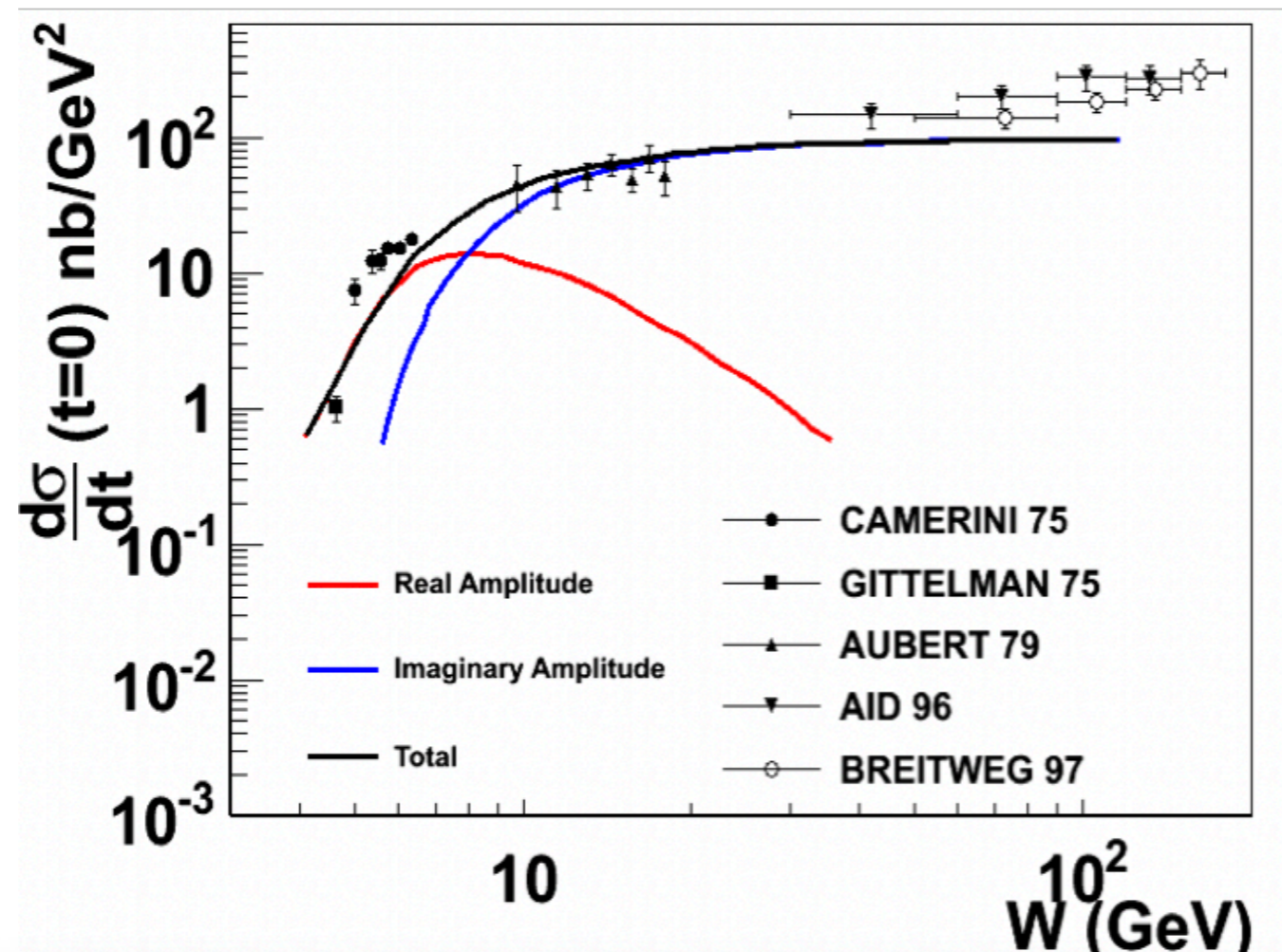
Frankfurt and Strikman., PRD66 (2002), 031502



# 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 $J/\psi$ - 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  $a_{\psi p}$**

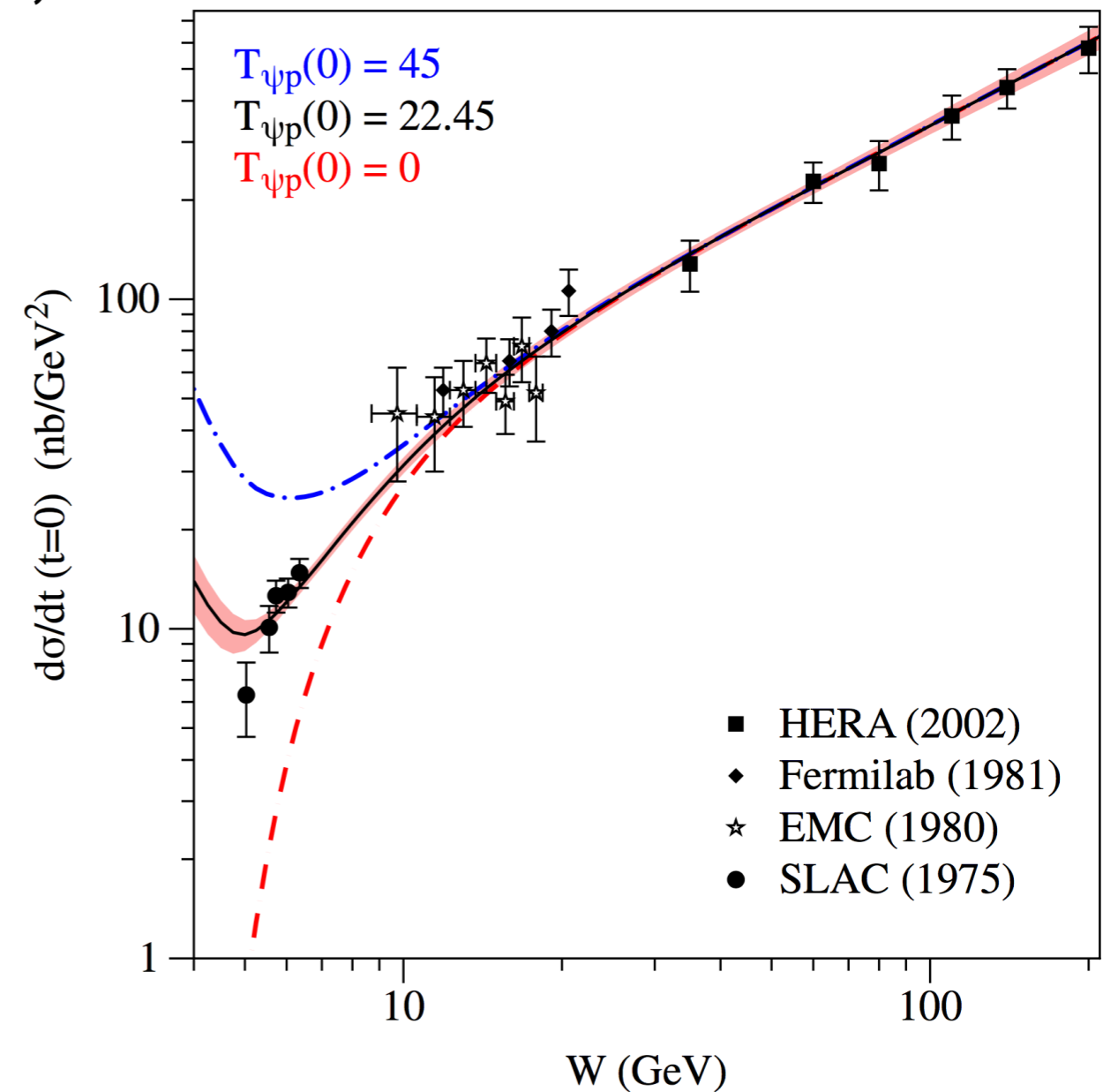
$$T_{\psi p} = 8\pi(M + M_{\psi})a_{\psi p}$$

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

# Binding energy of the $J/\psi$ - nucleon potential

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

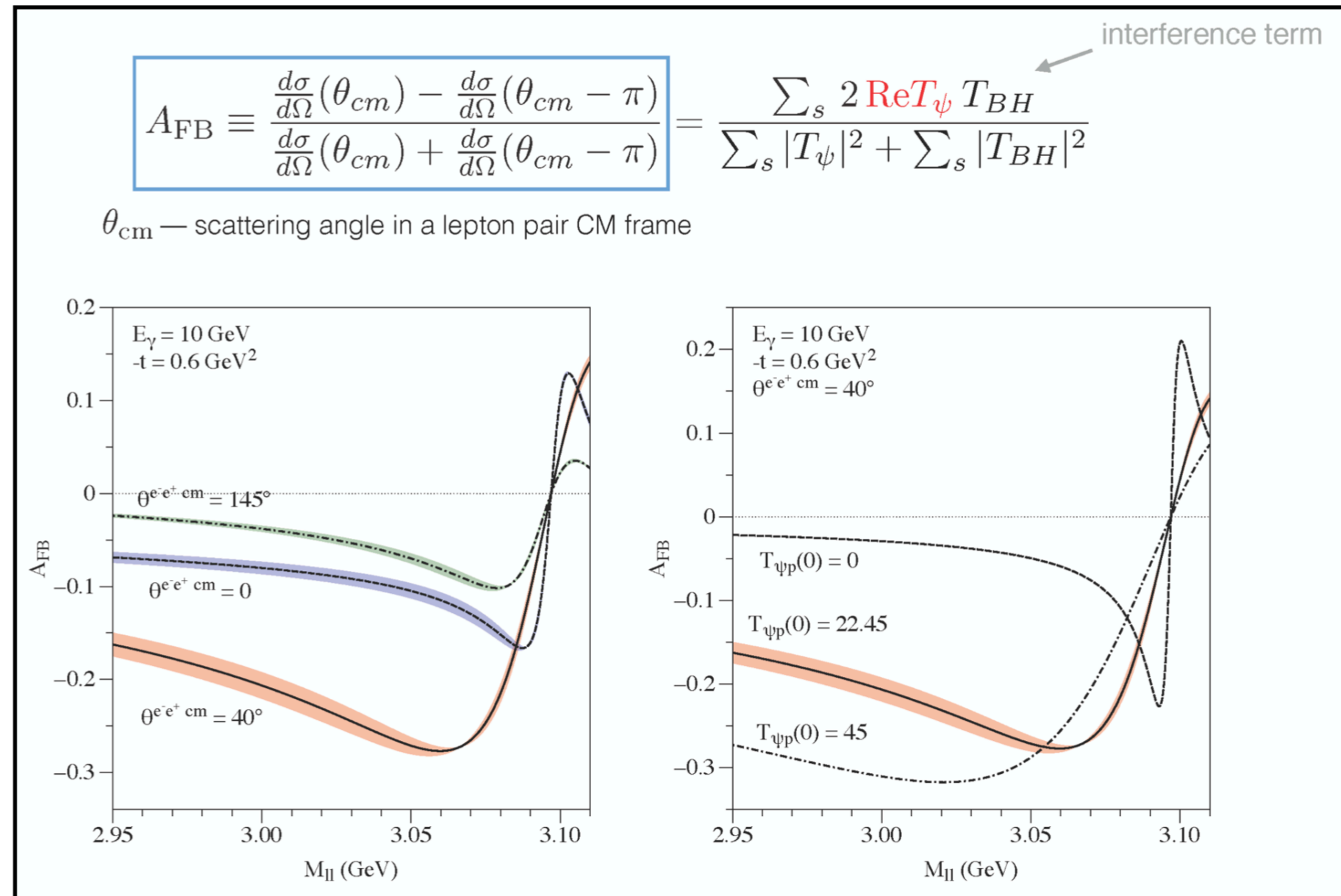
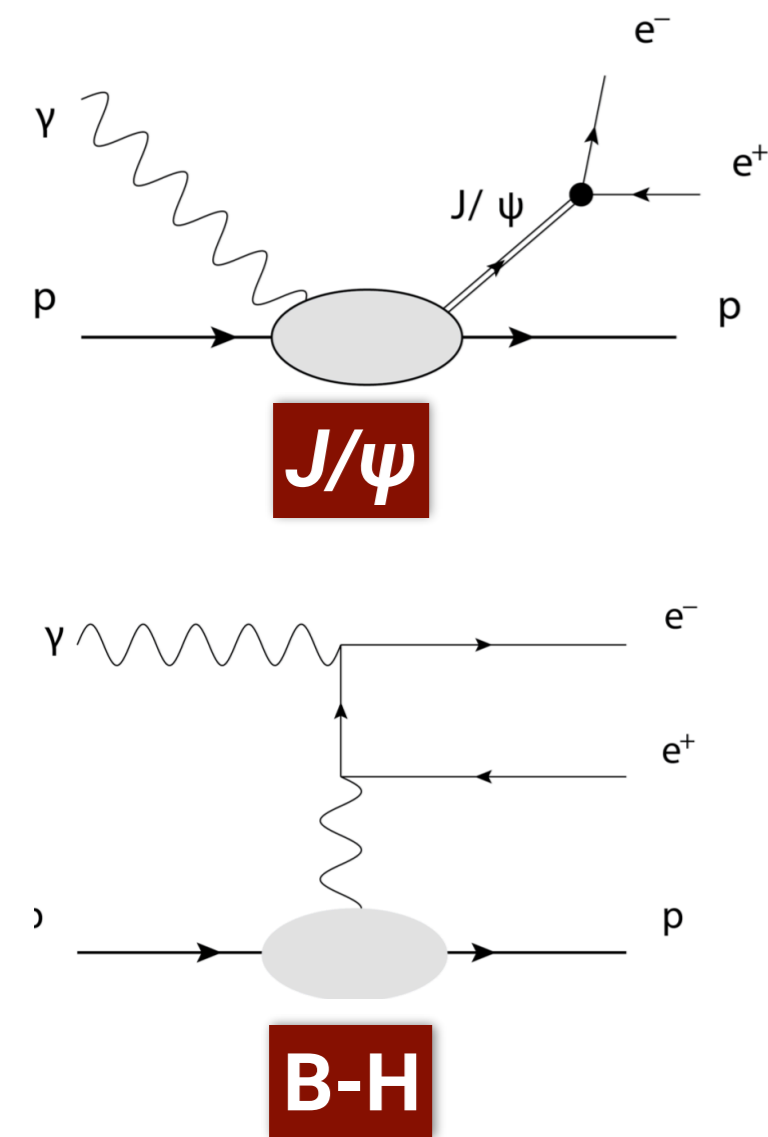
- ★ Current estimates ranging from 0.05-0.30 fm, corresponding to  $B_{\psi p} < 20$  MeV
- ★ LQCD:  $B_{\psi p} < 40$  MeV
- ★ Fit to existing data:  $a_{\psi p} = 0.05$  fm ( $B_{\psi p} = 3$  MeV)



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

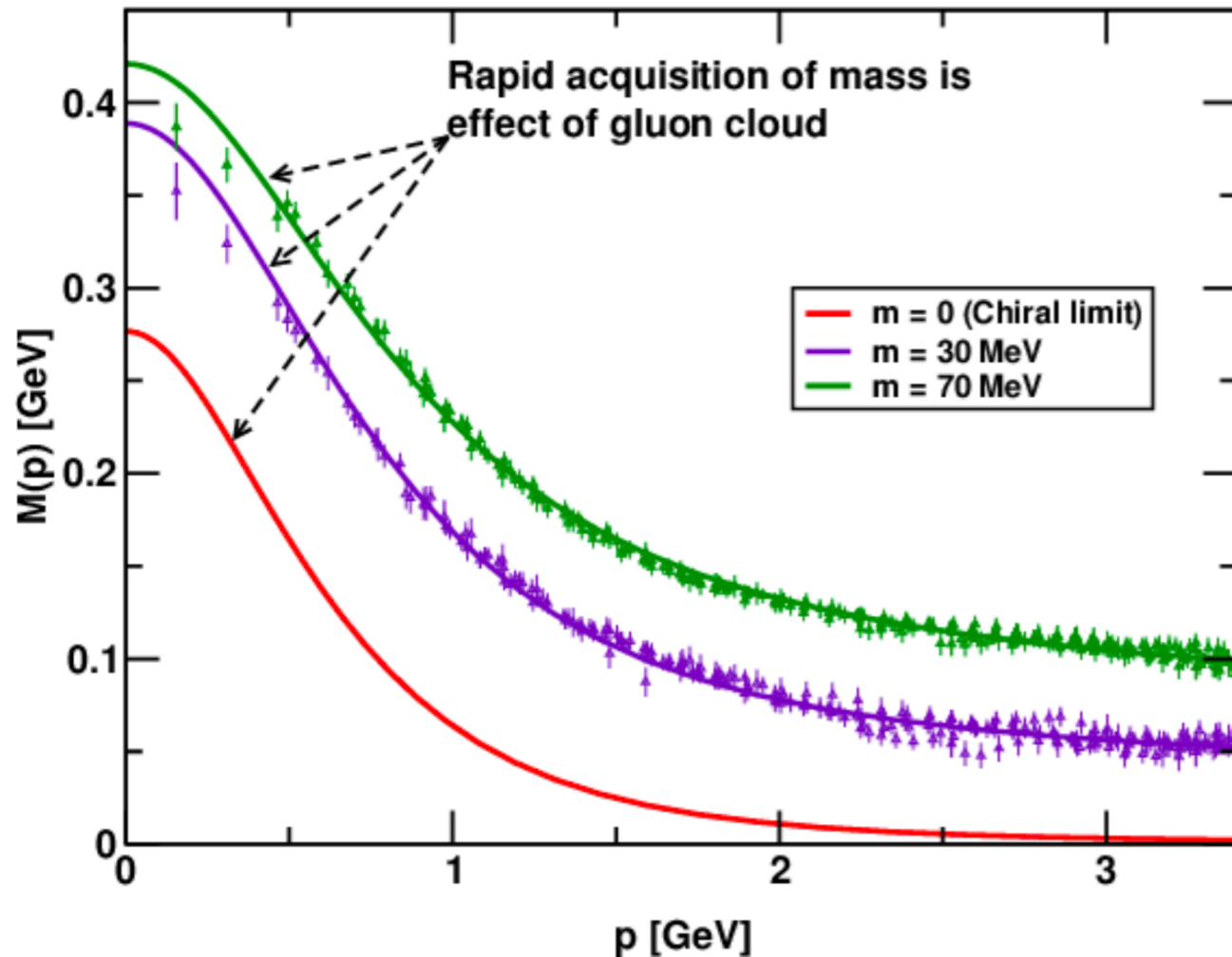
# B-H asymmetry: access scattering length $a_{\psi p}$

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



# 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**  
 **$\sim 300$  MeV/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

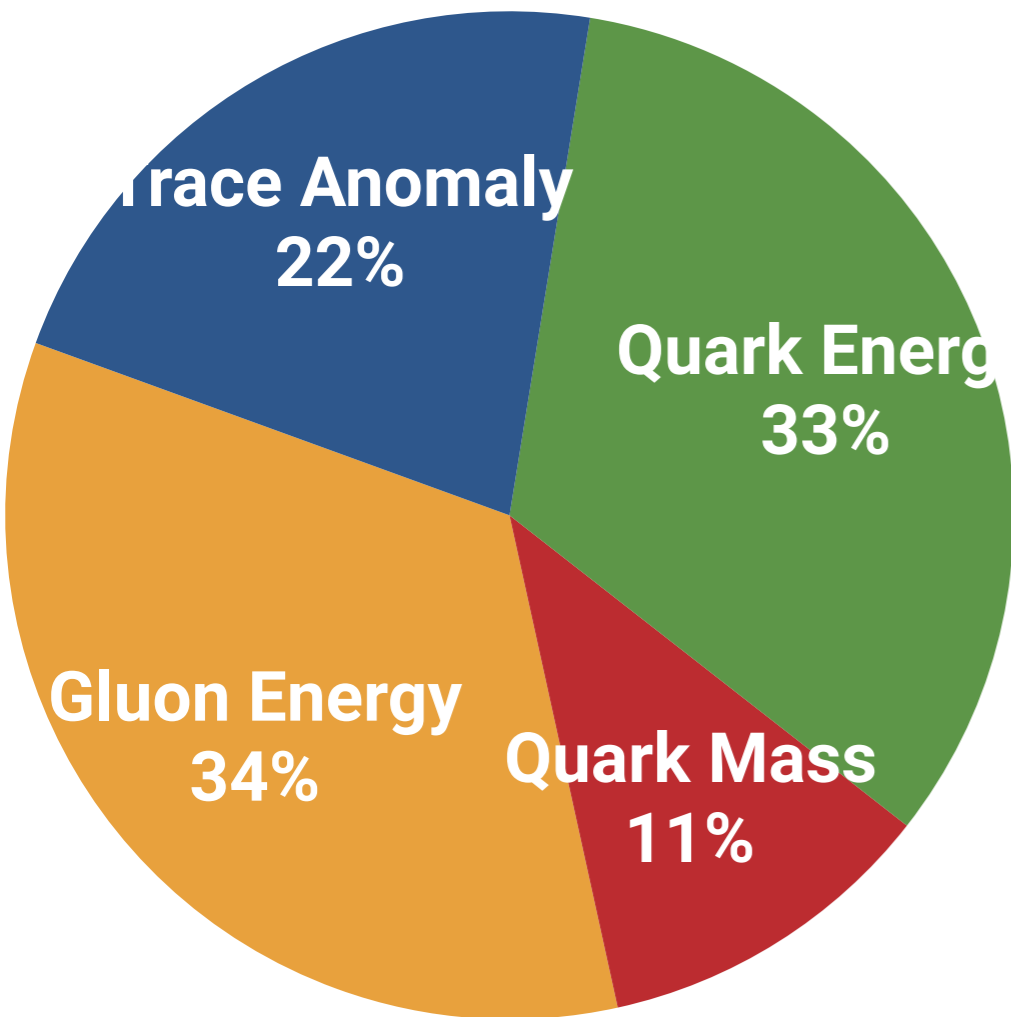
# The proton mass: rest-frame decomposition

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

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

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

$$= \underbrace{H_q}_{\text{green}} + \underbrace{H_m}_{\text{red}} + \underbrace{H_g}_{\text{orange}} + \underbrace{H_a}_{\text{blue}}$$



- ★ In leading order:

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

$$\underbrace{M_m}_{\text{red}} = \frac{4 + \gamma_m}{4(1 + \gamma_m)} b M$$

$$\underbrace{M_g}_{\text{orange}} = \frac{3}{4} (1 - a) M$$

$$\underbrace{M_a}_{\text{blue}} = \frac{1}{4} (1 - b) M$$

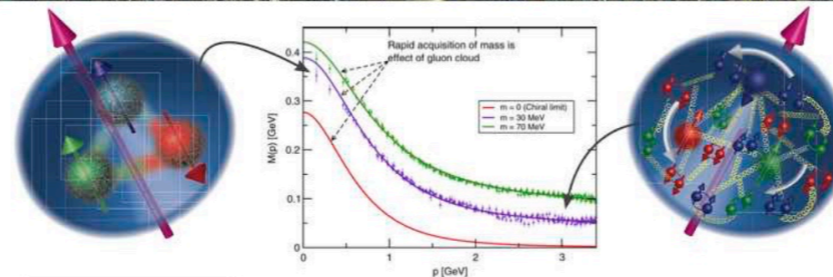
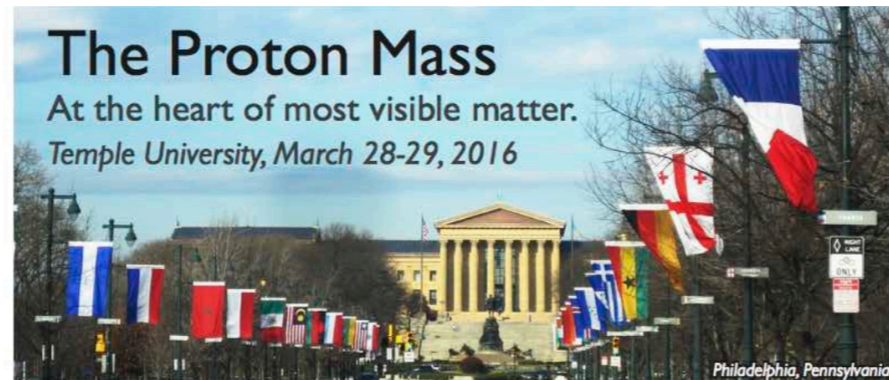
★  $a(\mu)$  related to PDFs, well constrained

★  $b(\mu)$  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)



$$M_p = 2m_u^{\text{eff}} + m_d^{\text{eff}}$$

### Speakers

- Stan Brodsky (SLAC)
- Xiangdong Ji (Maryland)
- Dima Kharzeev (Stony Brook & BNL)
- Keh-Fei Liu (University of Kentucky)
- David Richards (JLab)
- Craig Roberts (ANL)
- Martin Savage (University of Washington)
- Stepan Stepanyan (JLab)
- George Sterman (Stony Brook)

### Moderator

Alfred Mueller (Columbia)

$$H_{\text{QCD}} = H_q + H_m + H_g + H_a$$

Quark kinetic and potential energy  $H_q = \int d^3x \psi^\dagger (-i\mathbf{D} \cdot \boldsymbol{\alpha}) \psi$

Quark masses  $H_m = \int d^3x \bar{\psi} m \psi$

Gluon kinetic and potential energy  $H_g = \int d^3x \frac{1}{2} (\mathbf{E}^2 + \mathbf{B}^2)$

Trace anomaly  $H_a = \int d^3x \frac{9\alpha_s}{16\pi} (\mathbf{E}^2 - \mathbf{B}^2)$

### Workshop Topics

- Hadron Mass Calculation: Lattice QCD and Other Methods
- Hadron Mass Decomposition



### Local Organizers

Zein-Eddine Meziani (Temple U)  
Jianwei Qiu (Brookhaven National Lab)



ECT\*

EUROPEAN CENTRE FOR THEORETICAL STUDIES  
IN NUCLEAR PHYSICS AND RELATED AREAS  
TRENTO, ITALY  
Institutional Member of the European Expert Committee NUPECC

Castello di Trento ("Trin"), watercolor 19.8 x 27.7, painted by A. Dürer on his way back from Venice (1495). British Museum, London

## The Proton Mass: At the Heart of Most Visible Matter

Trento, April 3 - 7, 2017

**Main Topics**

**Hadron mass decomposition in terms of constituents:**  
Uniqueness of the decomposition, Quark mass, and quark and gluon energy contribution, Anomaly contribution, ...

**Hadron mass calculations:**  
Lattice QCD (total & individual mass components), Approximated analytical methods, Phenomenological model approaches, ...

**Experimental access to hadron mass components:**  
Exclusive heavy quarkonium production at threshold, nuclear gluonometry through polarized nuclear structure function, ...

**Confirmed speakers and participants**

Alexandrou Constantia (Cyprus University), Brodsky Stan (SLAC), Burkardt Matthias (New Mexico State University), Chen Jian-Ping (Jefferson Lab), Chudakov Eugene (Jefferson Lab), Cloët Ian (Argonne National Lab), de Teramond Guy (University Costa Rica), Deshpande Abhay (Stony Brook University), Eichmann Gernot (Giessen University), Hafidi Kawtar (Argonne National Lab), Hoellbling Christian (University of Wuppertal), Lin Huey-Wen (Michigan State University), Liu Keh-Fei (University of Kentucky), Loeck Cedric (Ecole Polytechnique, Palaiseau), Mulders Piet (Rijke University of Amsterdam), Papanastasiou Ioannis (Yale University), Pascalisia Vladimir (Johannes Gutenberg University of Mainz), Richards David (Jefferson Lab), Roberts Craig (Argonne National Lab), Sliker Karl (University of New Hampshire), Mauro Anselmino (University of Torino & INFN), Bob Jaffe (Massachusetts Institute of Technology), Dima Kharzeev (Stony Brook University), Xiangdong Ji (University of Maryland).

**Organizers**

Zein-Eddine Meziani (Temple University)  
Barbara Pasquini (University of Pavia)  
Jianwei Qiu (Jefferson Lab)  
Marc Vanderhaeghen (Universität Mainz)

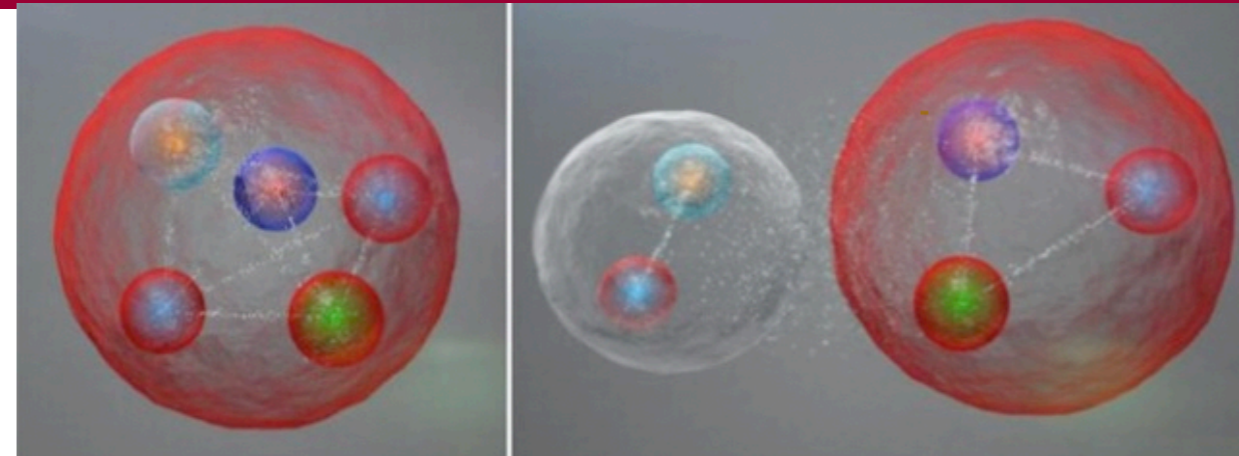
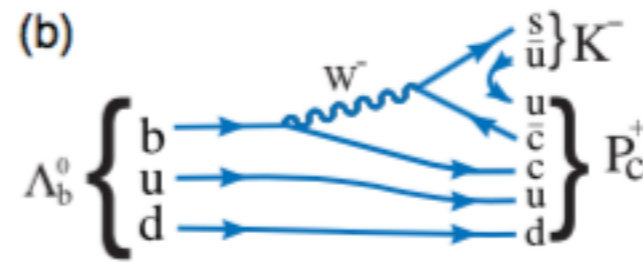
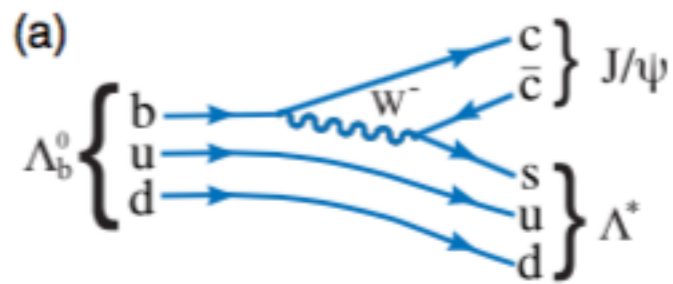
**Director of the ECT\*:** Professor Jochen Wambach (ECT\*)

The ECT\* is sponsored by the "Fondazione Bruno Kessler" in collaboration with the "Assessorato alla Cultura" (Provincia Autonoma di Trento), funding agencies of EU Member and Associated States and has the support of the Department of Physics of the University of Trento.

For local organization please contact: Gianmaria Ziglio - ECT\* Secretariat - Villa Tambosi - Strada delle Tabarelle 286 - 38123 Villazzano (Trento) - Italy  
Tel.:(+39-0461) 314721 Fax:(+39-0461) 314750, E-mail: ect@ectstar.eu or visit <http://www.ectstar.eu>

JLab will play a leading role:  
Access trace anomaly through elastic  
 $J/\psi$  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  $E_\gamma = 10$  GeV**

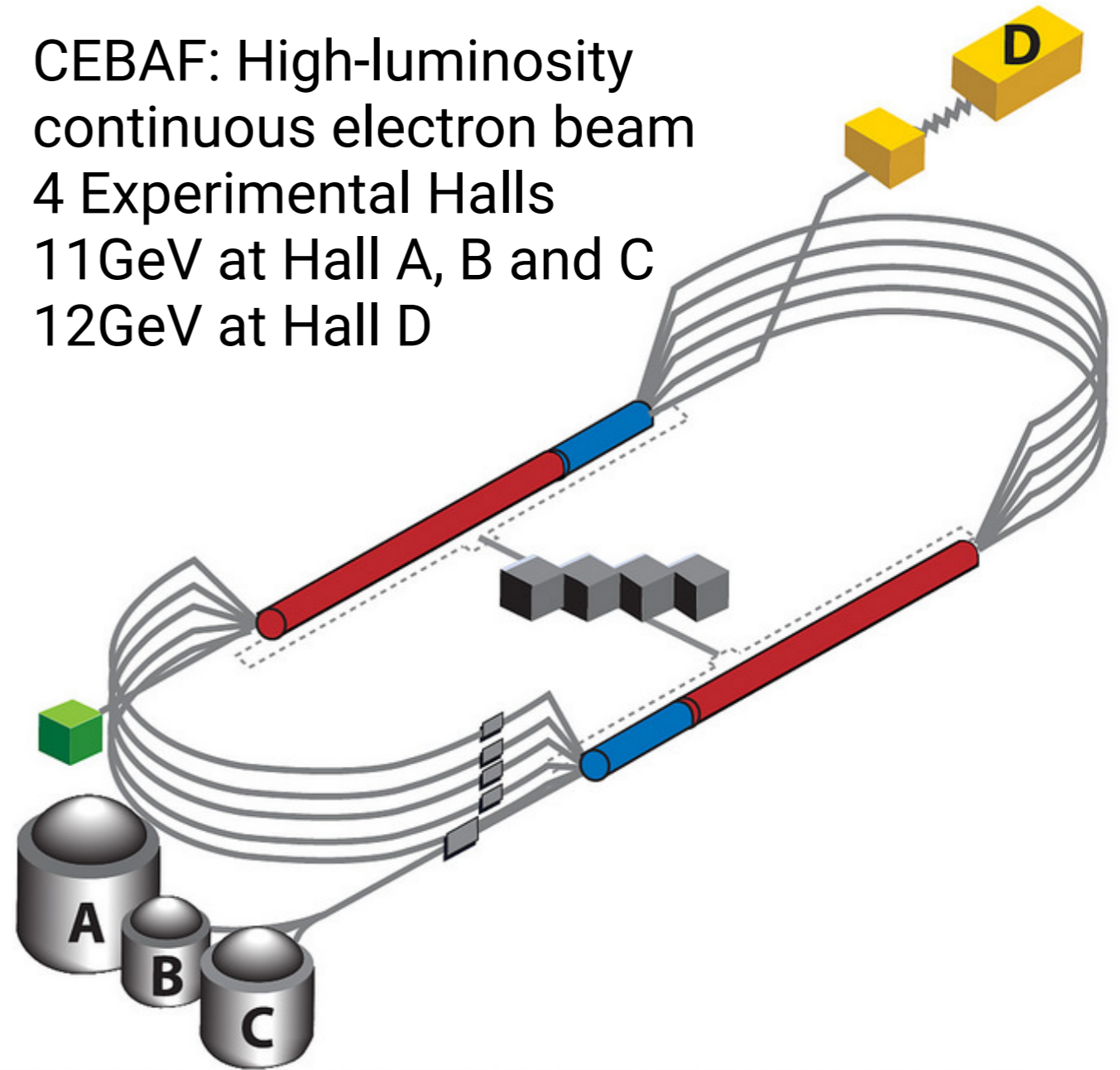
**JLab perfect place for this measurement!**



# $J/\psi$ 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  $J/\psi$  near threshold, due to luminosity, resolution and energy reach!**

# 12 GeV $J/\psi$ experiments at JLab



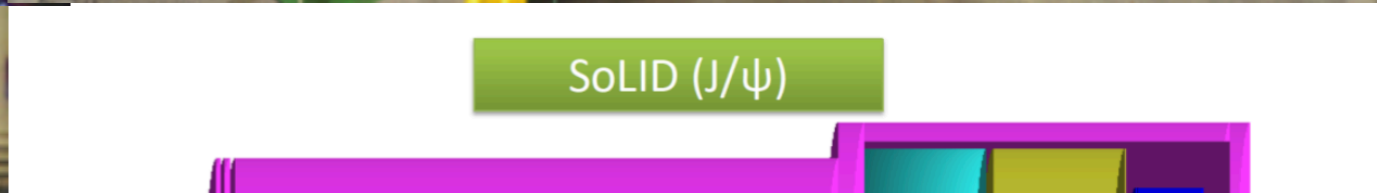
**Hall D/SHMS+HMS:  
First  $J/\psi$  at JLab!**



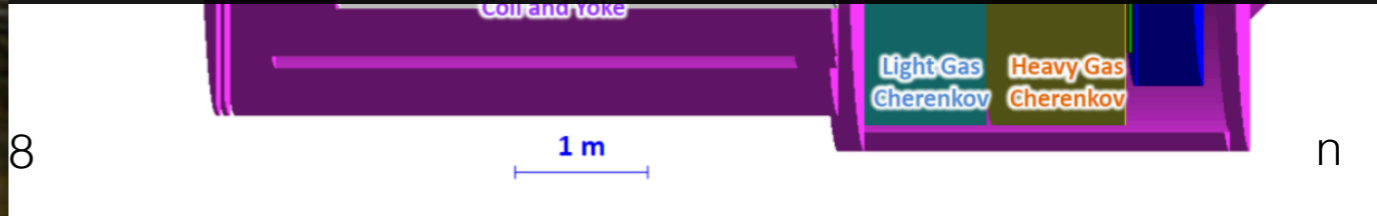
**Hall C/SHMS+HMS:  
Approved experiment to search for  
the LHCb pentaquark  
(E12-16-007)**



**Hall B/CLAS12:  
Approved experiment to measure  
TCS +  $J/\psi$  in photo-production  
(E12-12-001)**



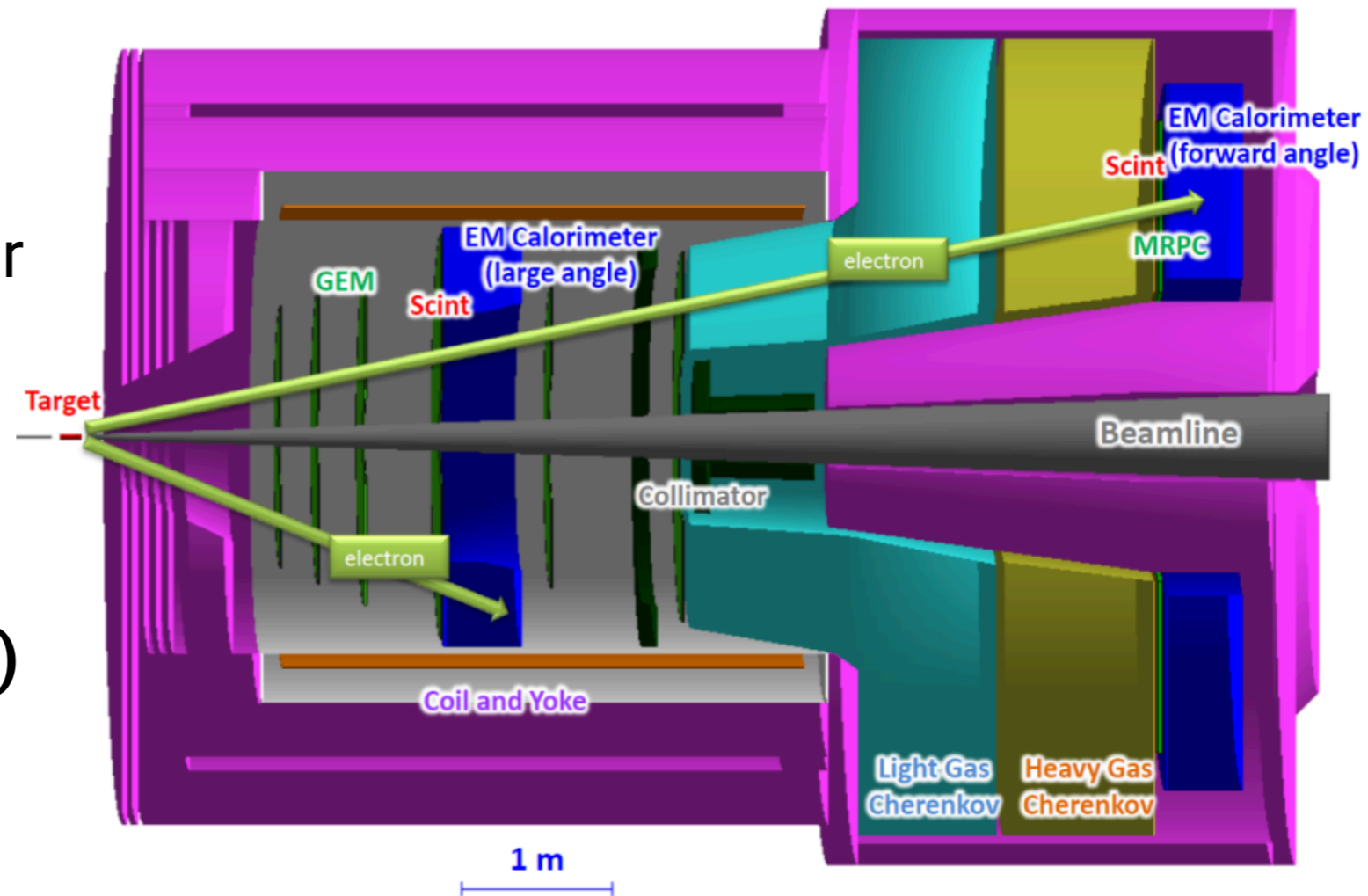
**Hall A/SoLID:  
Approved future high-luminosity  
experiment to measure  $J/\psi$  in  
photo- and electro-production  
(E12-12-006)**



# $J/\psi$ experiment E12-12-006 at SoLID

ATHENNA Collaboration

- $3\mu\text{A}$  electron beam at 11 GeV for **50 days**
- 11 GeV beam 15cm **liquid hydrogen target**
- **Ultra-high luminosity** ( $43.2 \text{ ab}^{-1}$ )
- 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

# $J/\psi$ experiment E12-12-006 at SoLID

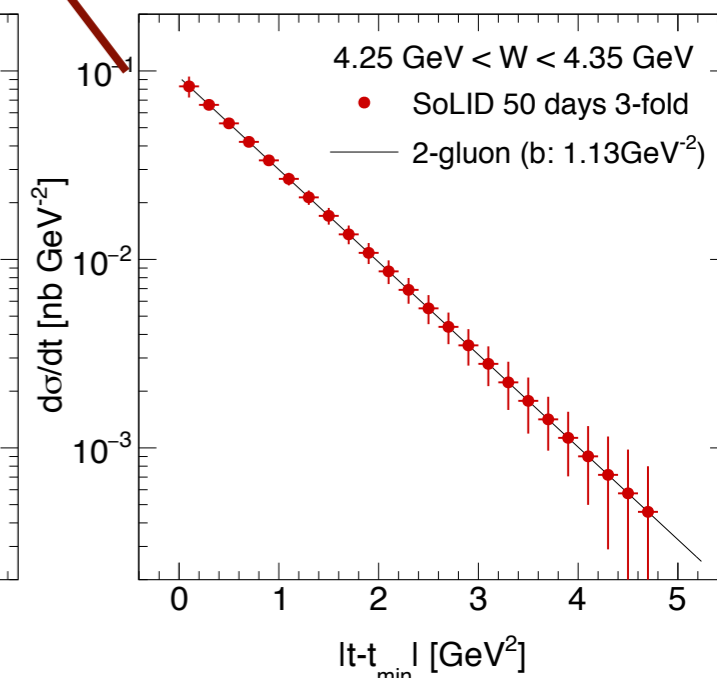
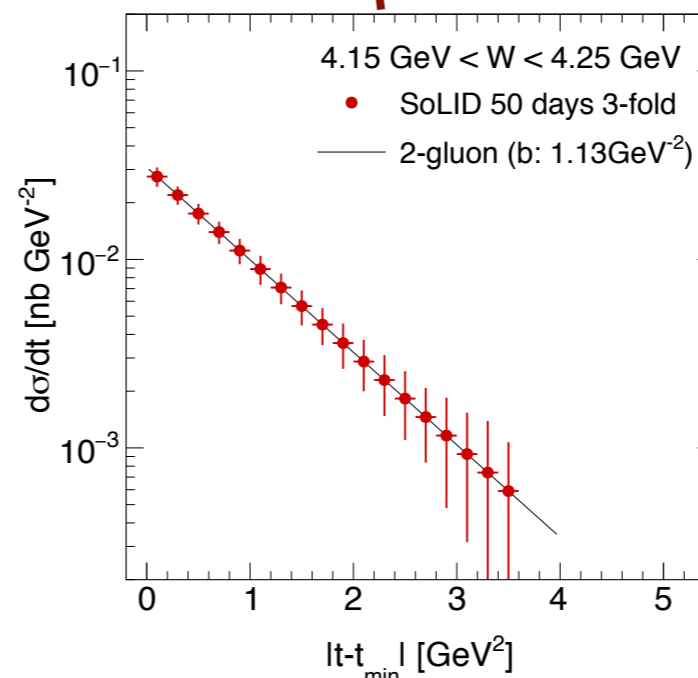
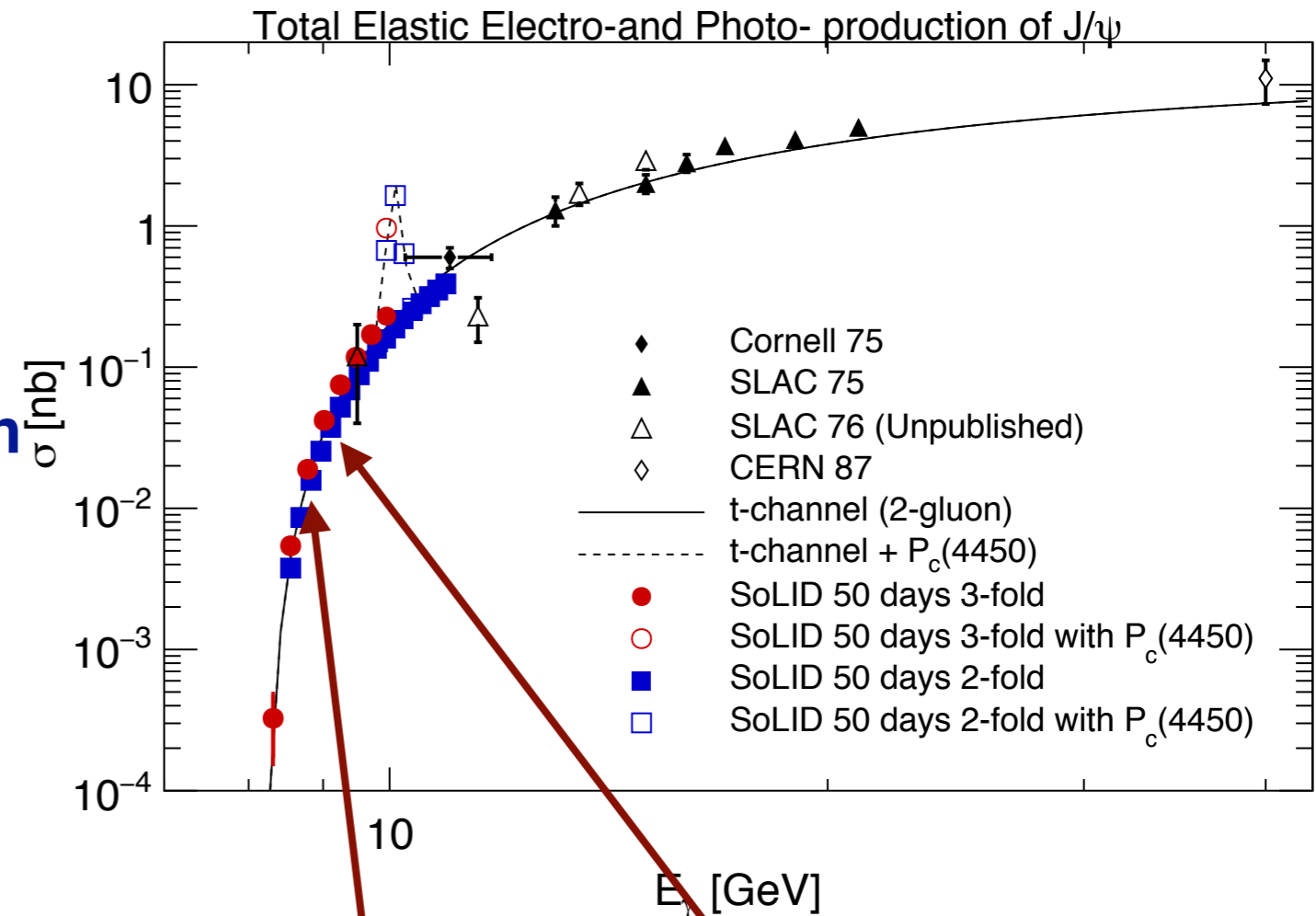
ATHENNA Collaboration

## Photo-production

- 2-fold coincidence + recoil proton
- $t$ -channel  $J/\psi$  rate: **1627 per day**
- Advantage over electro-production**
  - Energy reach in charmed pentaquark region
  - High rate

## Electro-production

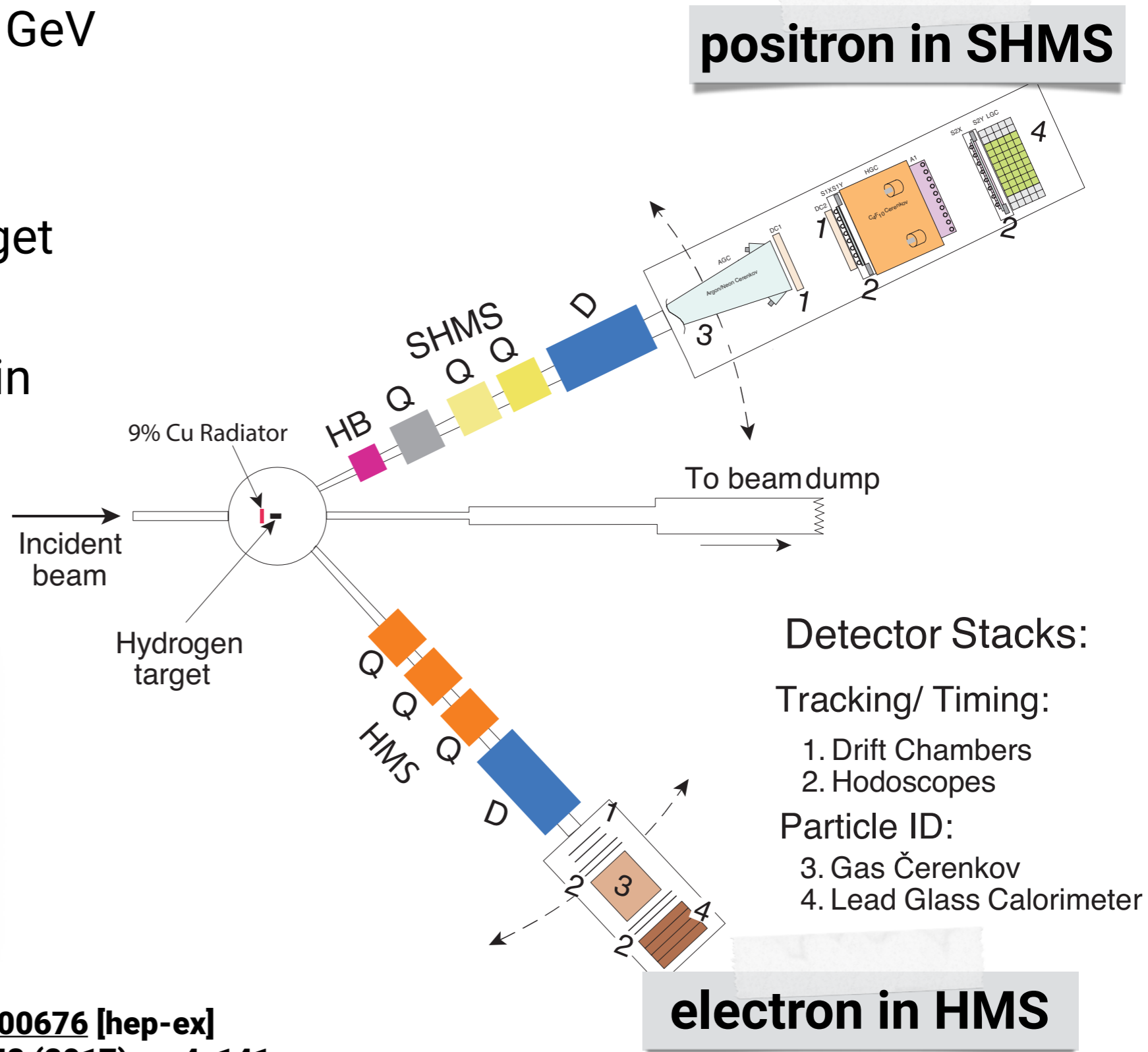
- 3-fold coincidence (3 leptons)
- $t$ -channel  $J/\psi$  rate: **86 per day**
- Advantage over photo-production:**
  - Better resolution
  - Less background
  - Closer to threshold



# Pentaquark search E12-16-007 in Hall C

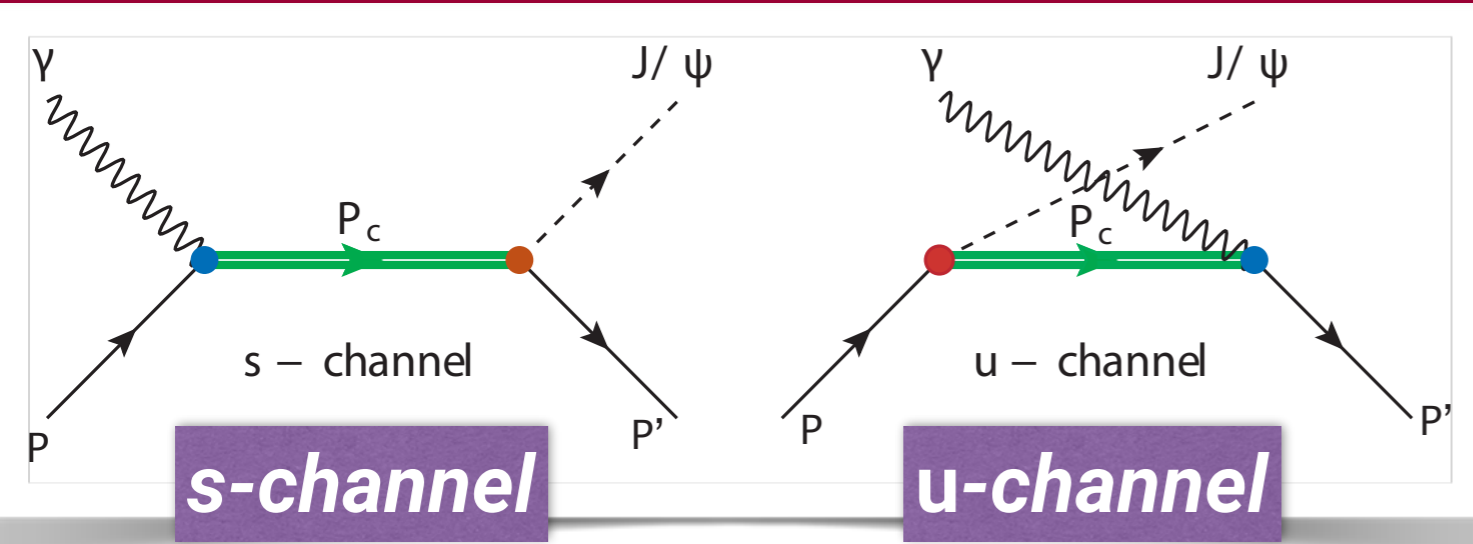
- ☆  $50\mu\text{A}$  electron beam at 11 GeV for **11 days**
- ☆ 9% copper radiator
- ☆ 15cm liquid hydrogen target
- ☆ **total 10% RL**
- ☆ Detect  $J/\psi$  decay leptons in coincidence
- ☆ Bremsstrahlung photon energy fully constrained

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

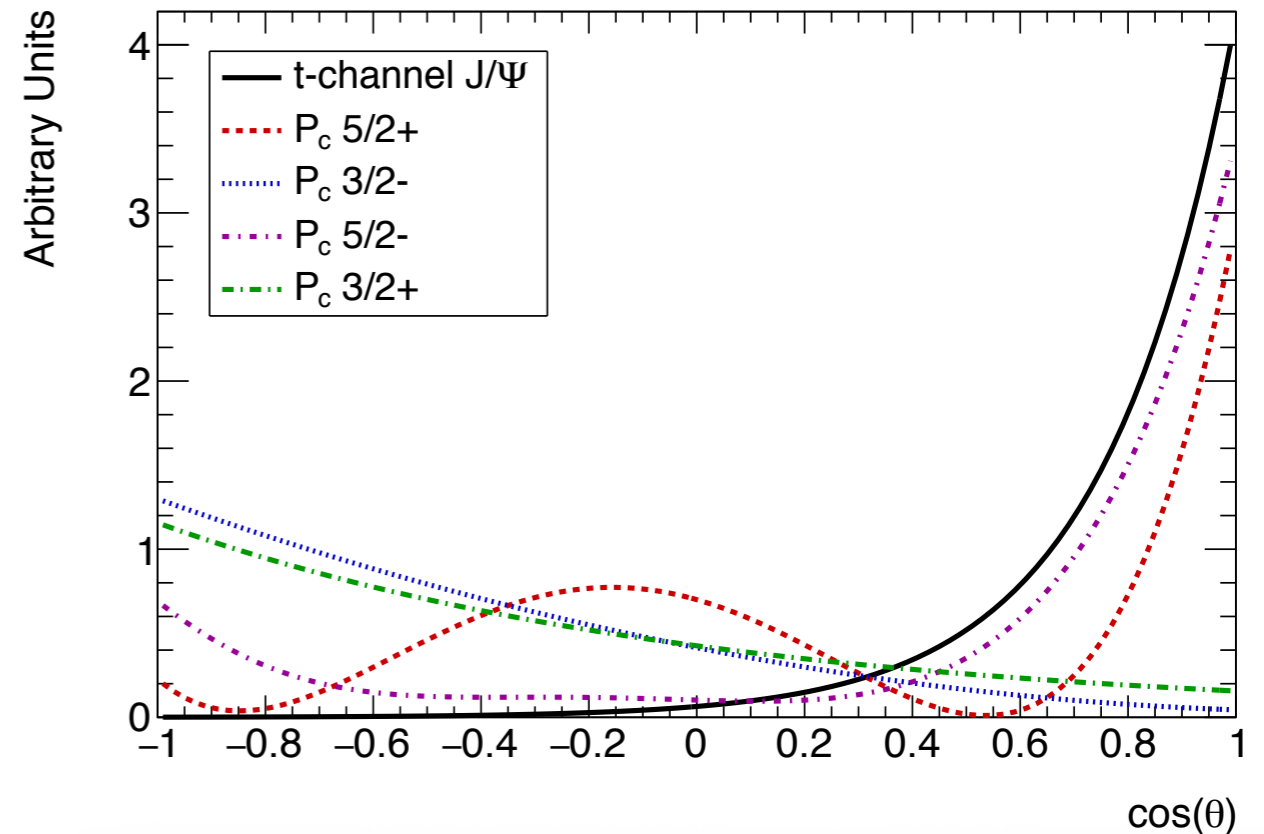
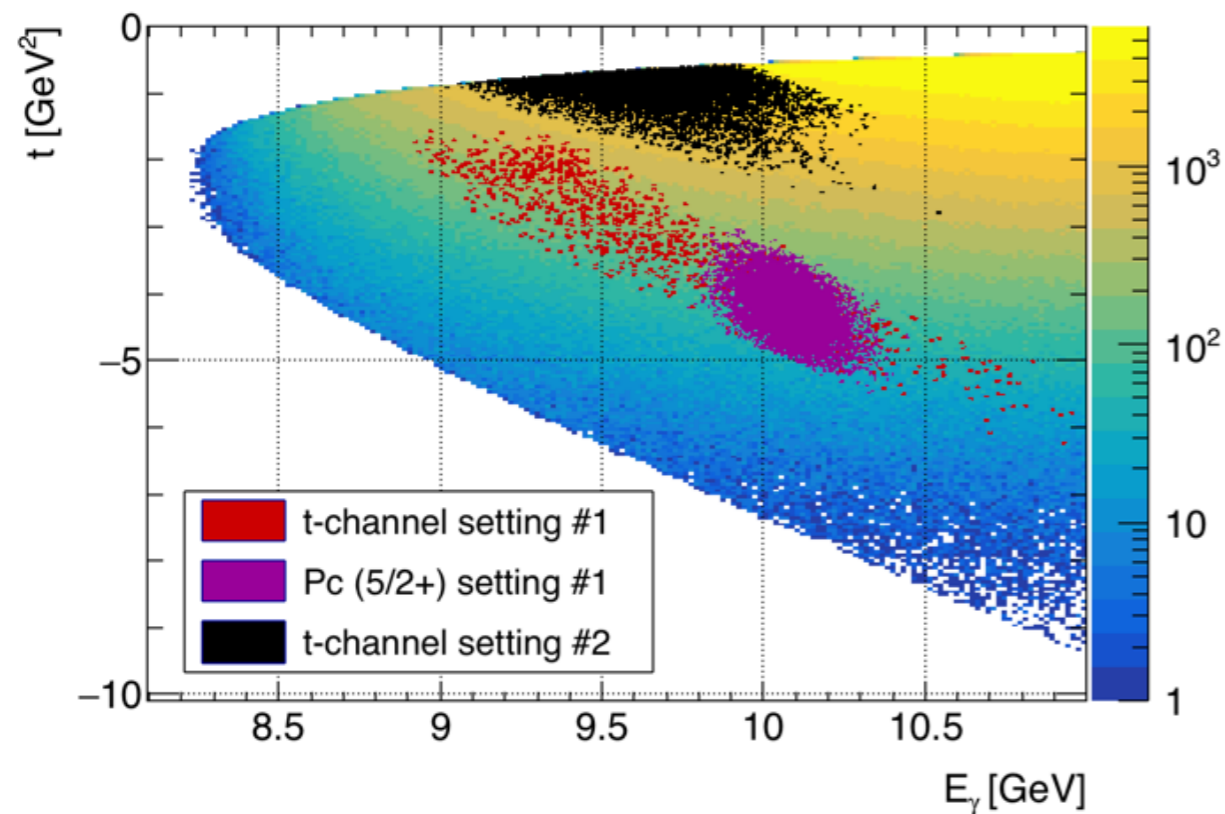


Z.-E. Meziani, S. Joosten *et al.*, [arXiv:1609.00676](https://arxiv.org/abs/1609.00676) [hep-ex]  
 K. Hafidi, S. Joosten *et al.*, *Few Body Syst.* **58** (2017) no.4, 141

# Resonant $J/\psi$ production through $P_c$ decay



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



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

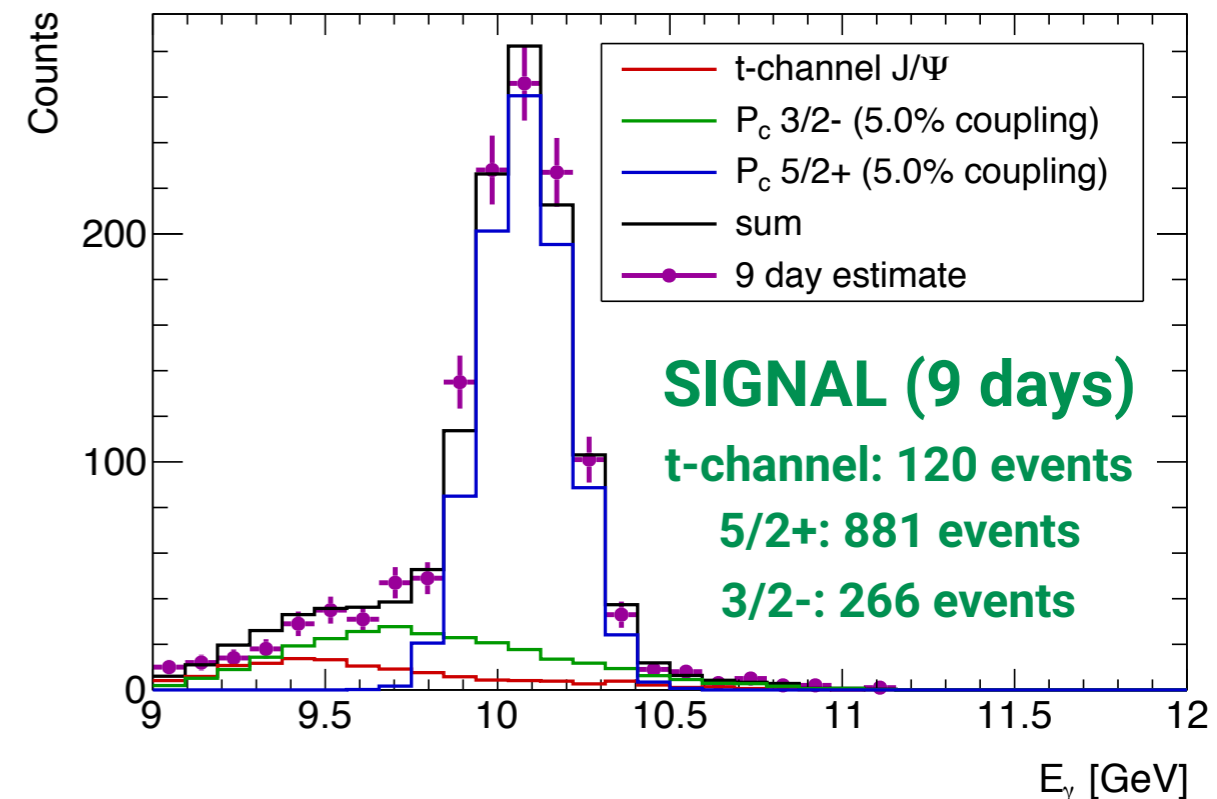
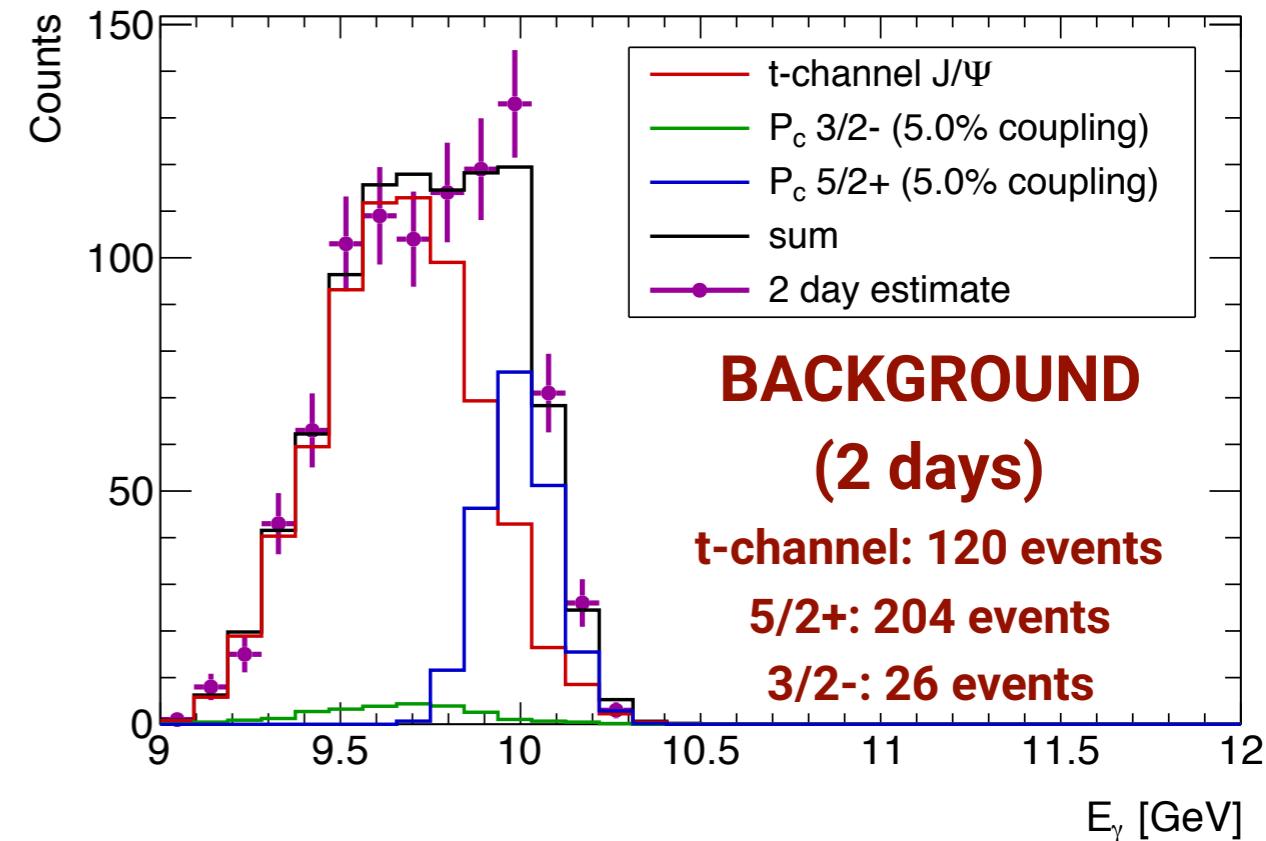
**Leverage  $\cos(\theta)$  dependence to maximize S/B at low coupling!**

# 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  $50\mu\text{A}$
- 5/2+ peak dominates the spectrum
- able to separate 5/2+ from ***t*-channel** at low  $E_\gamma$
- will provide **first-hand information** about ***t*-channel** production near threshold

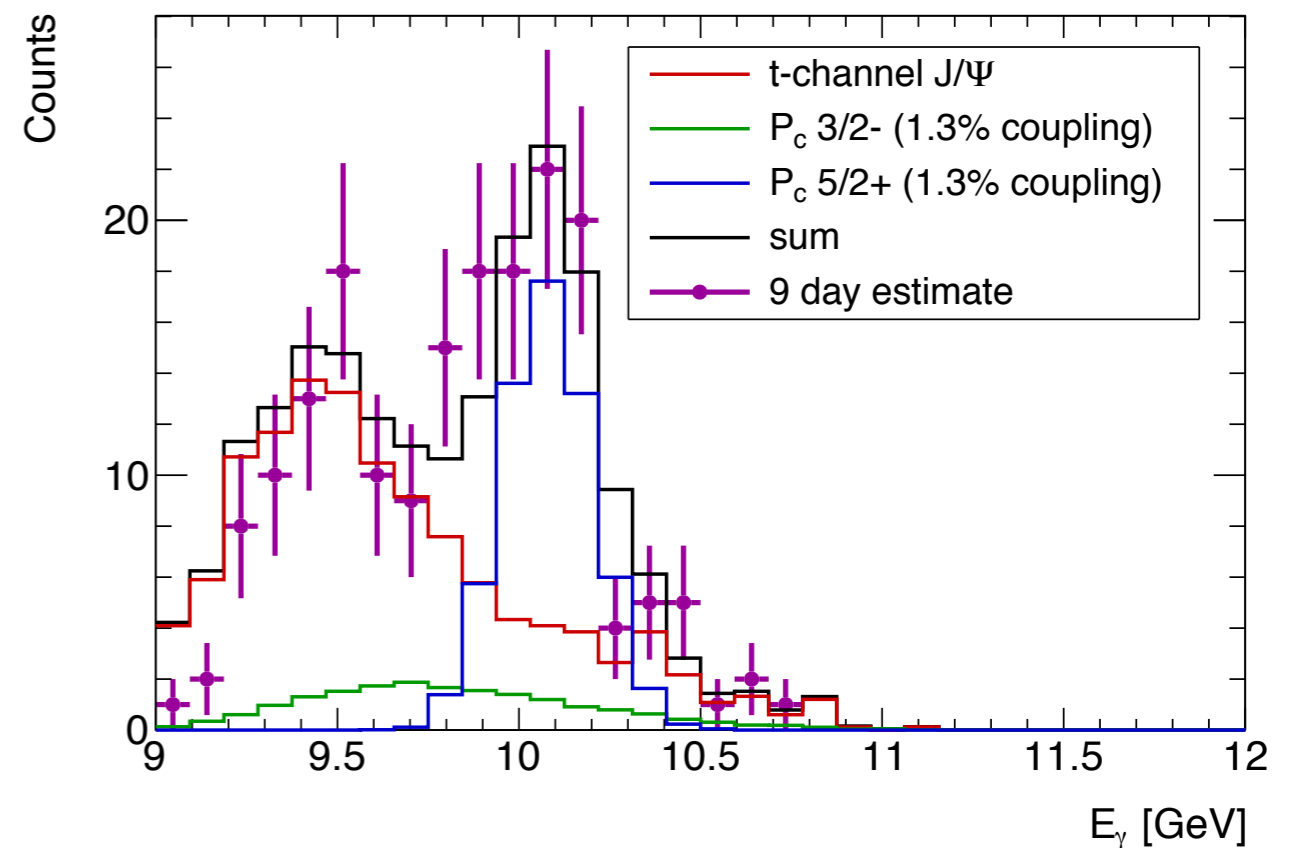
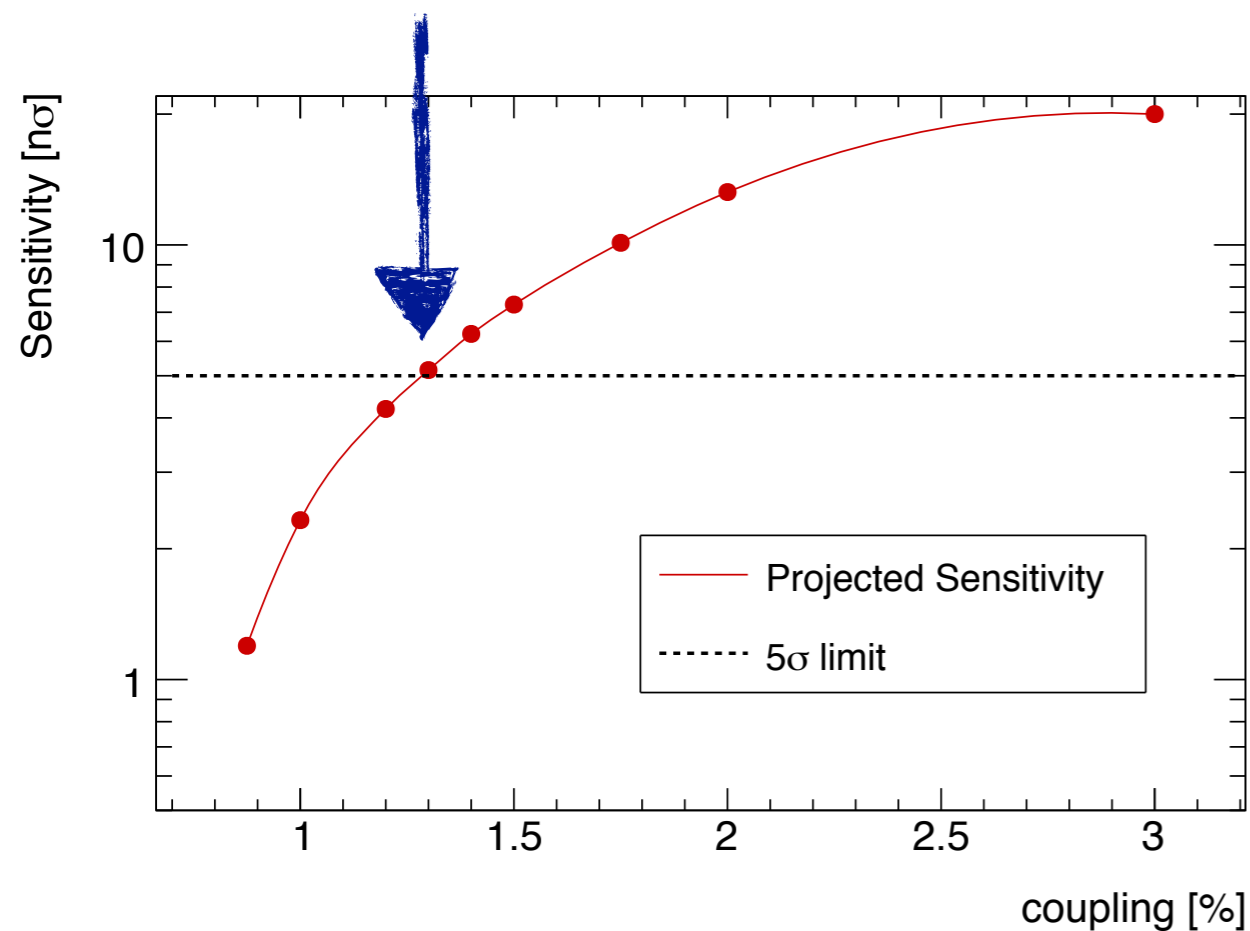
Only 11 days!

Significance  $> 20\sigma$ !



# Sensitivity for **Discovery**

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





# $J/\psi$ experiments at JLab

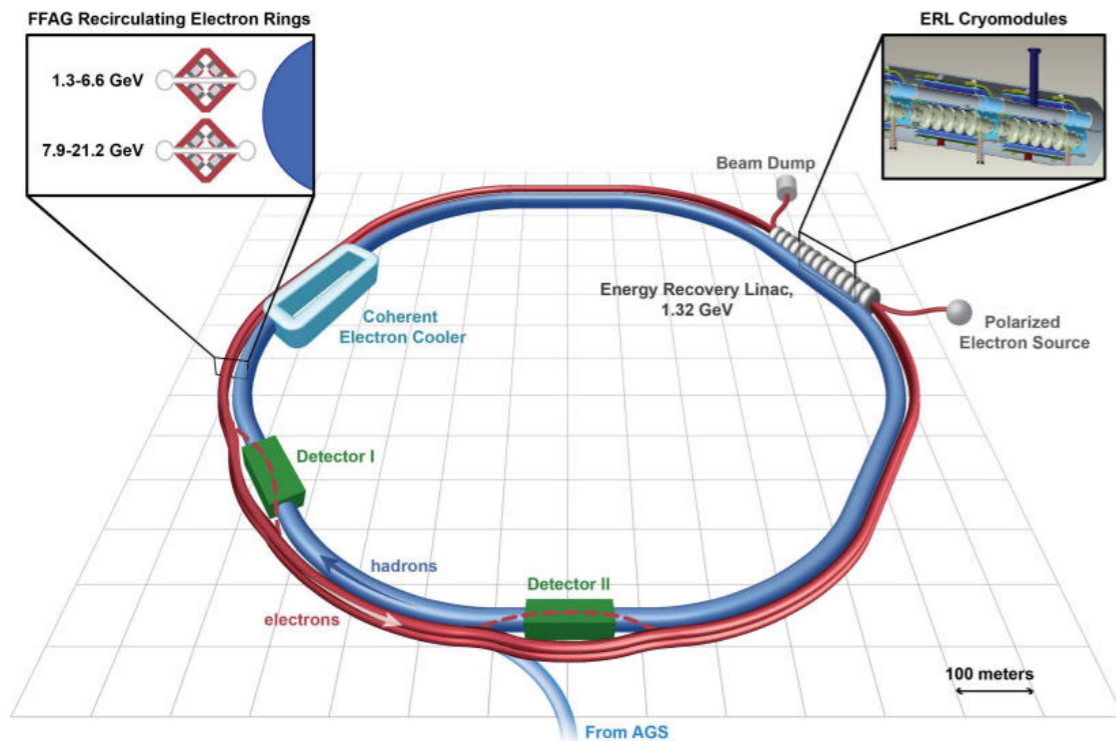
	GlueX HALL D	HMS+SHMS HALL C	CLAS 12 HALL B	SoLID HALL A
$J/\psi$ Rate (photo-prod.)	<b>5-10/day</b>	#1: 13/day #2: <b>341/day</b>	<b>45/day</b>	<b>1627/day</b>
$J/\psi$ Rate (electro-prod.)				<b>86/day</b>
Experiment		E12-16-007	E12-12-001	E12-12-006
PAC		9+2 days <b>high-impact</b>	130 days	50 days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

**Time** 

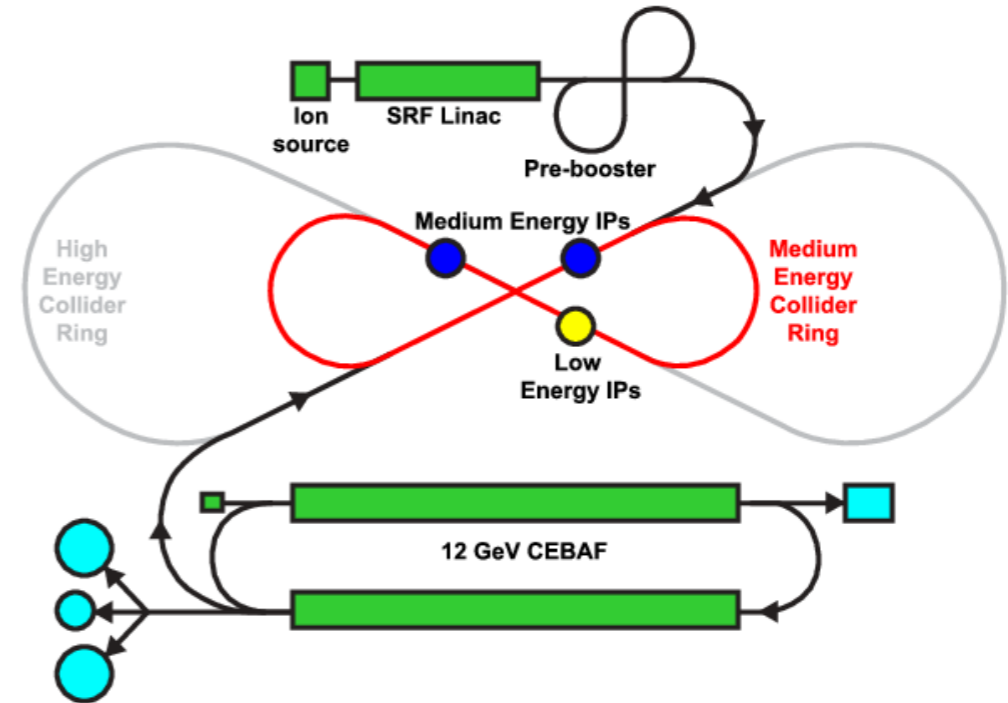
# Elastic quarkonium production **at an EIC**

# 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

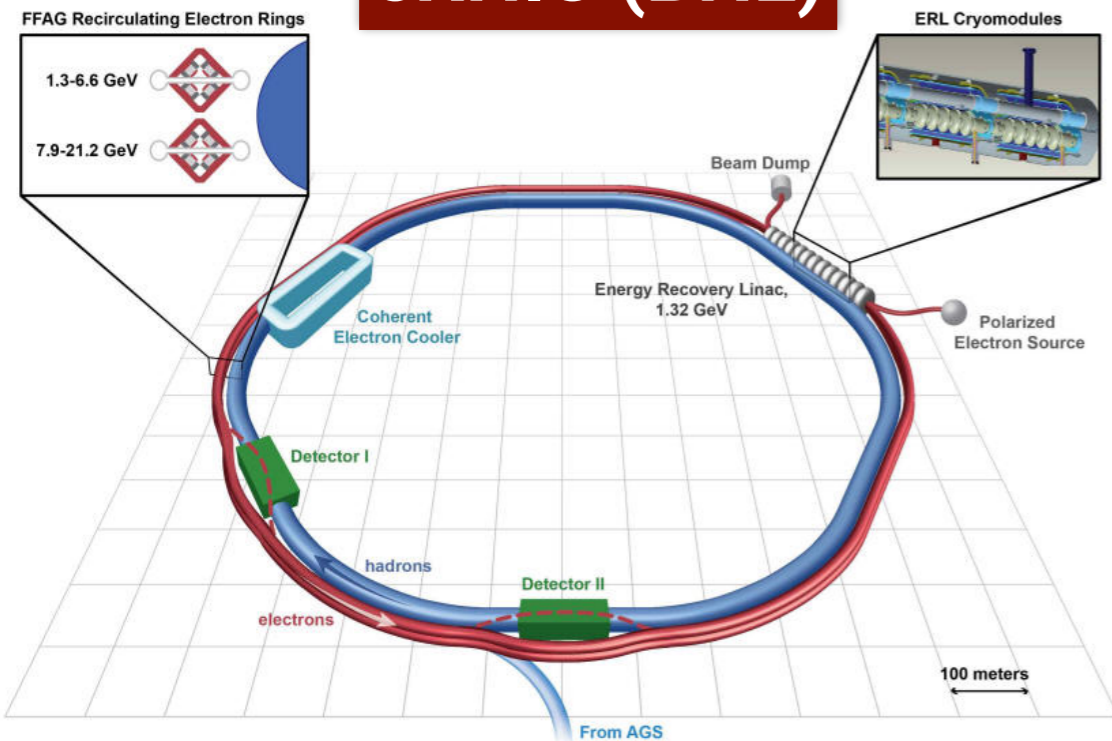
# Quarkonia at an EIC **complimentary** to JLab

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

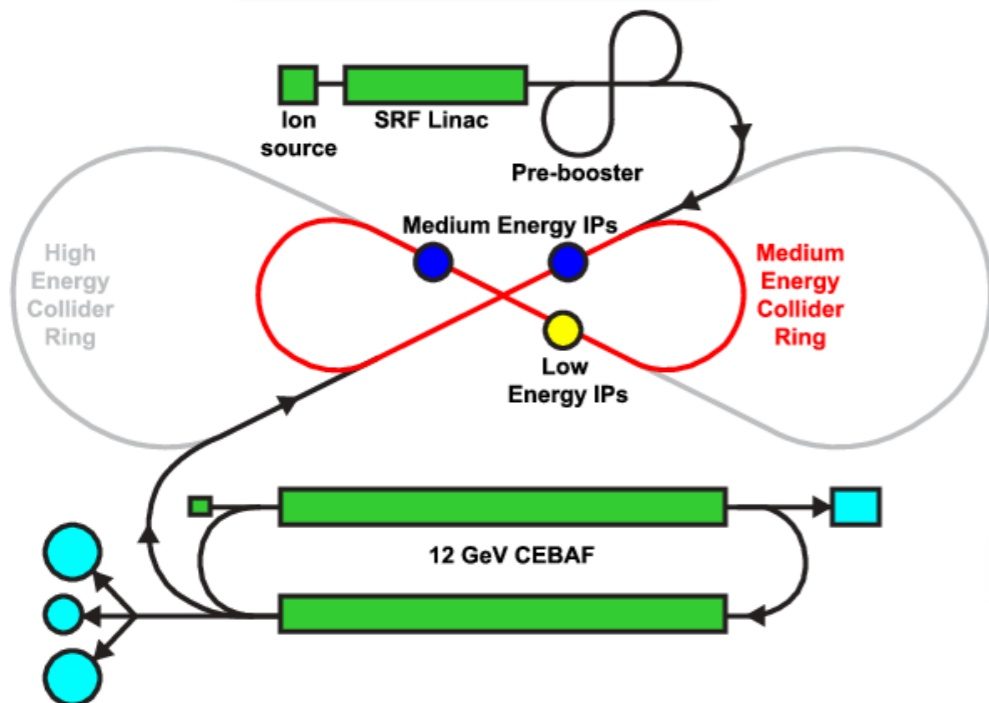
- $Y(1s)$  production possible at threshold and high  $W$
- Important cross check for **universality** due to smaller higher-order corrections
  - For gluon GPDs extracted with  $J/\psi$  at the EIC
  - For  $J/\psi$  threshold physics at JLab12
- Is there a “bottom pentaquark?”

# Accelerator and detector parameters

## eRHIC (BNL)



## JLEIC (JLab)

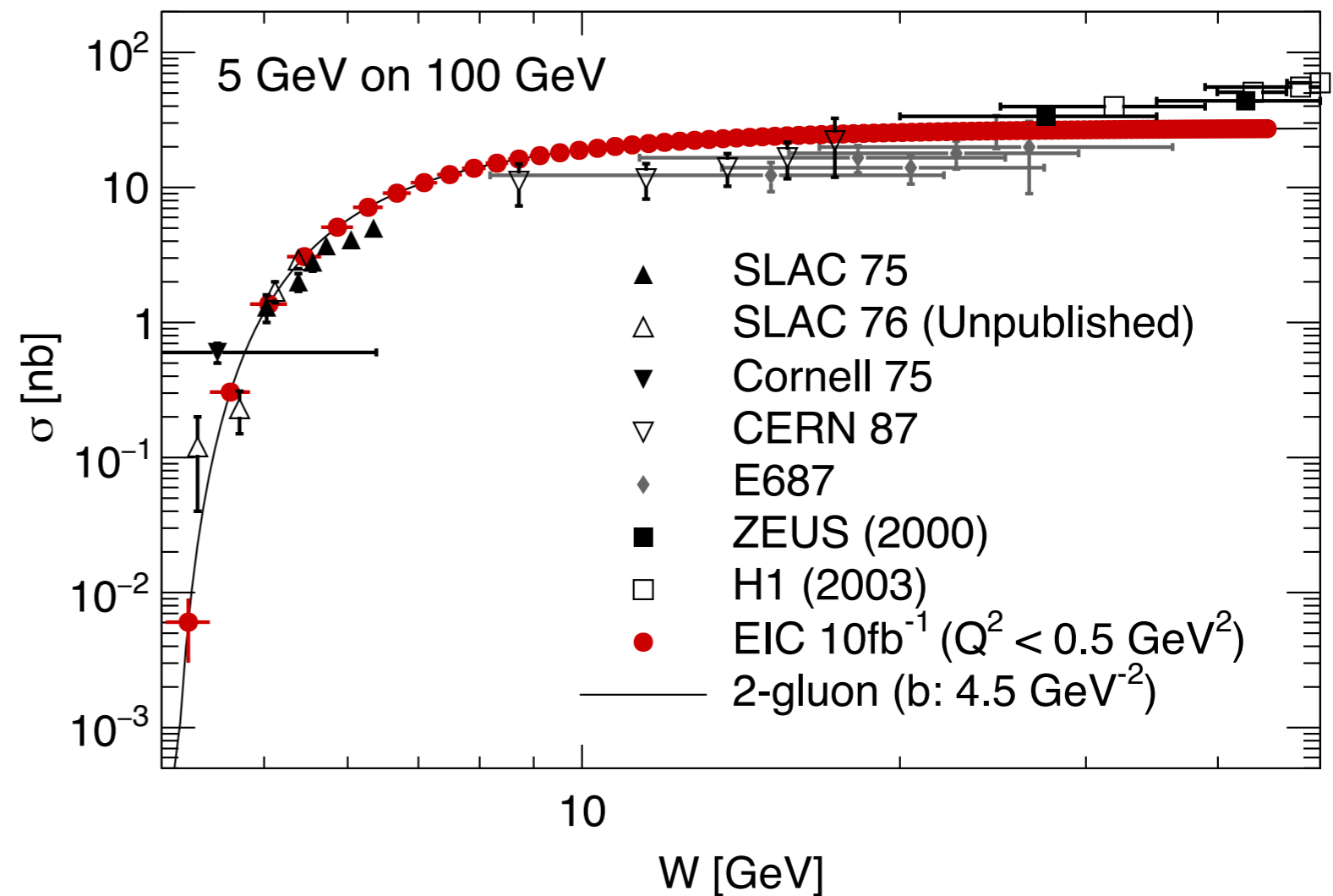


- Nominal parameters relevant to DVMP:
  - (Consistent with accelerator/detector specs from white-paper)
  - 5 GeV electron beam on 100 GeV proton beam** in range of both designs
  - Luminosity:  $10-100 \text{ fb}^{-1}$**
  - Acceptance** (conservative!):
    - Leptons:** pseudo-rapidity  $|\eta| <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

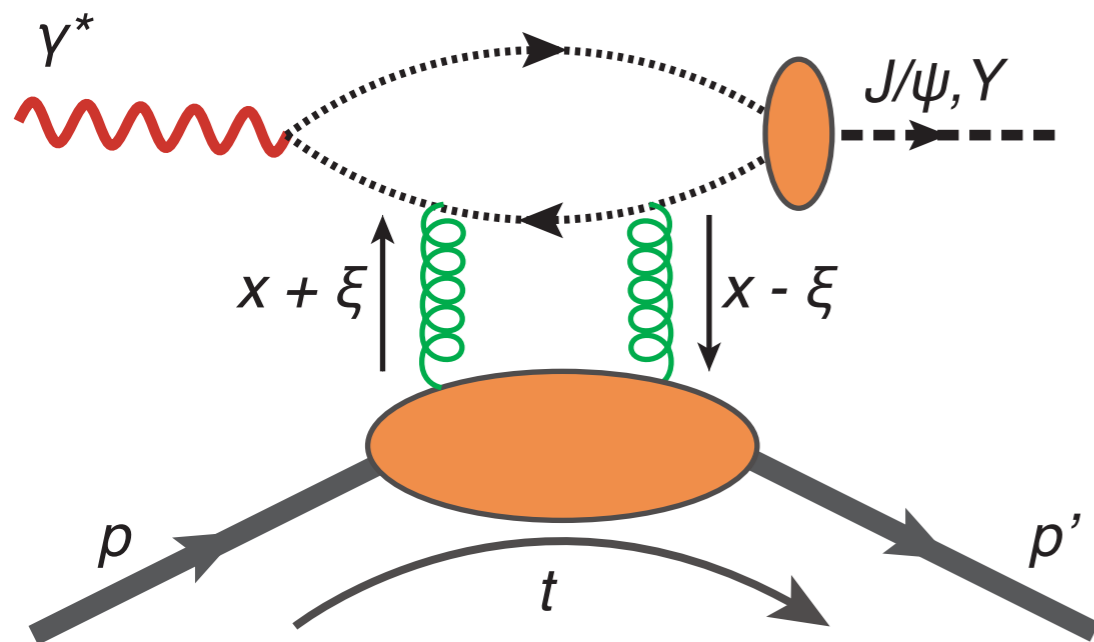
Only looking at electron-positron channels!

# $J/\psi$ 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**

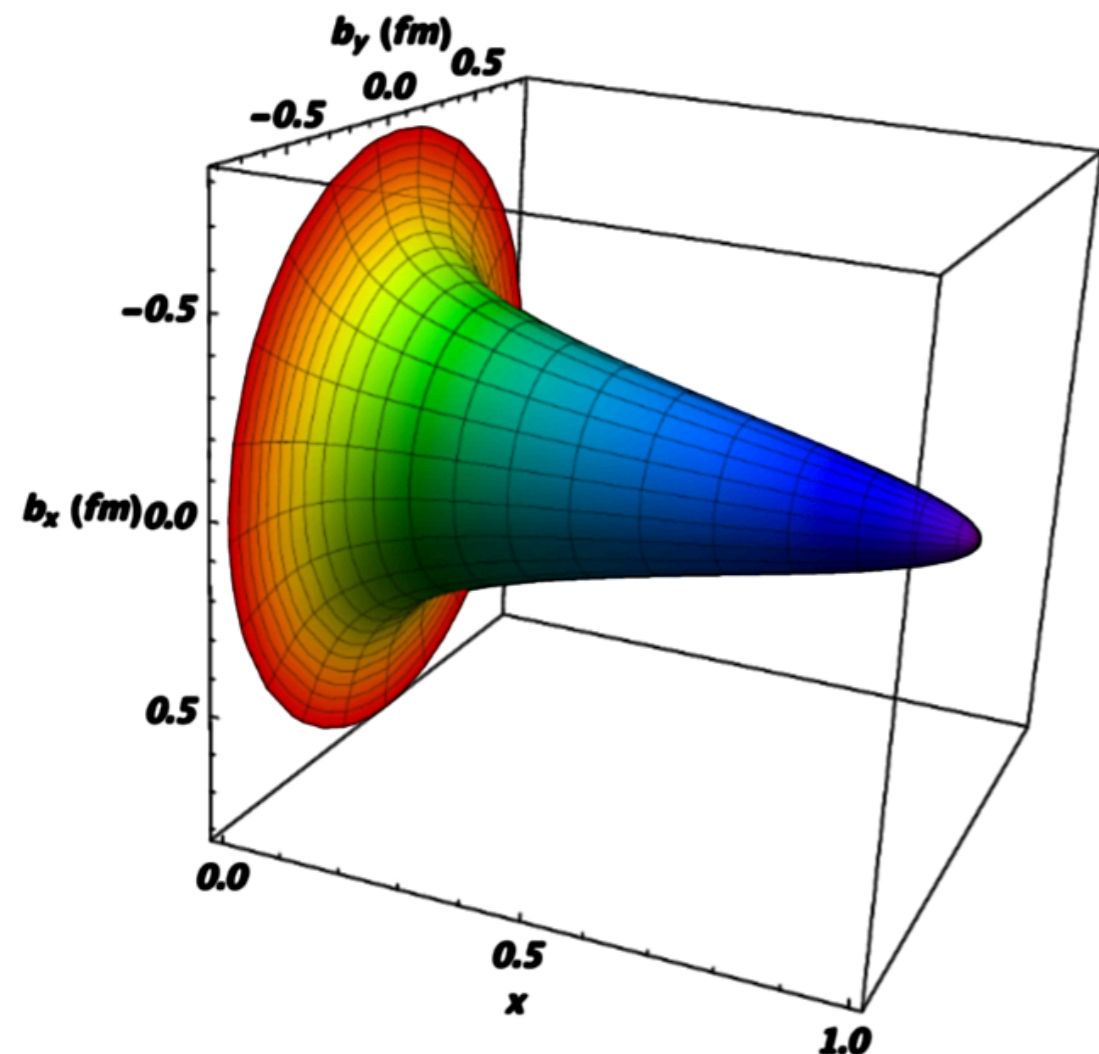
$$-t = \frac{x_V^2 M_P^2 + \vec{\Delta}_T^2}{1 - x_V}$$

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

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

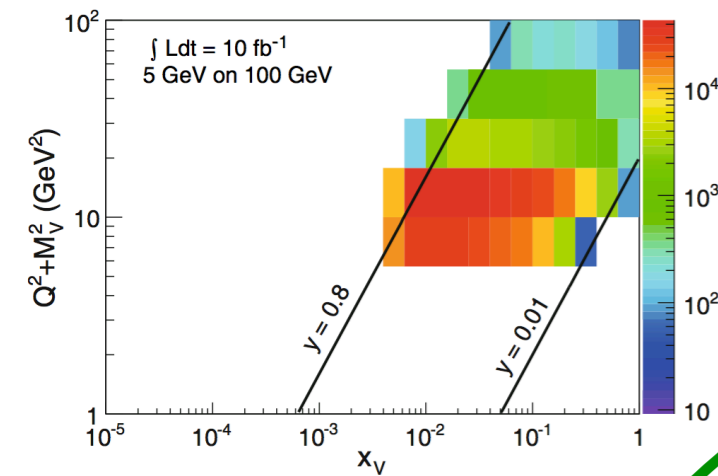
**Fourier transform: unpolarized gluon GPD**

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

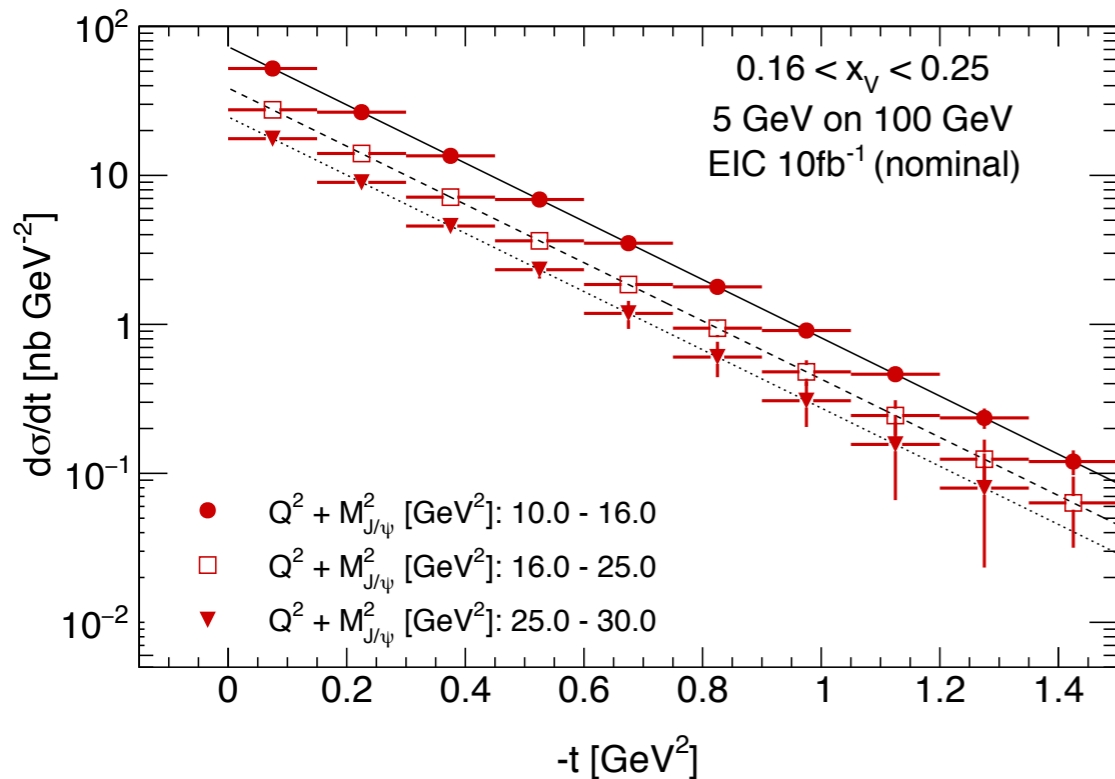


# Spatial Imaging of gluon density with $J/\psi$

## Gluon GPD in fine bins of $x_V$ and $Q^2$



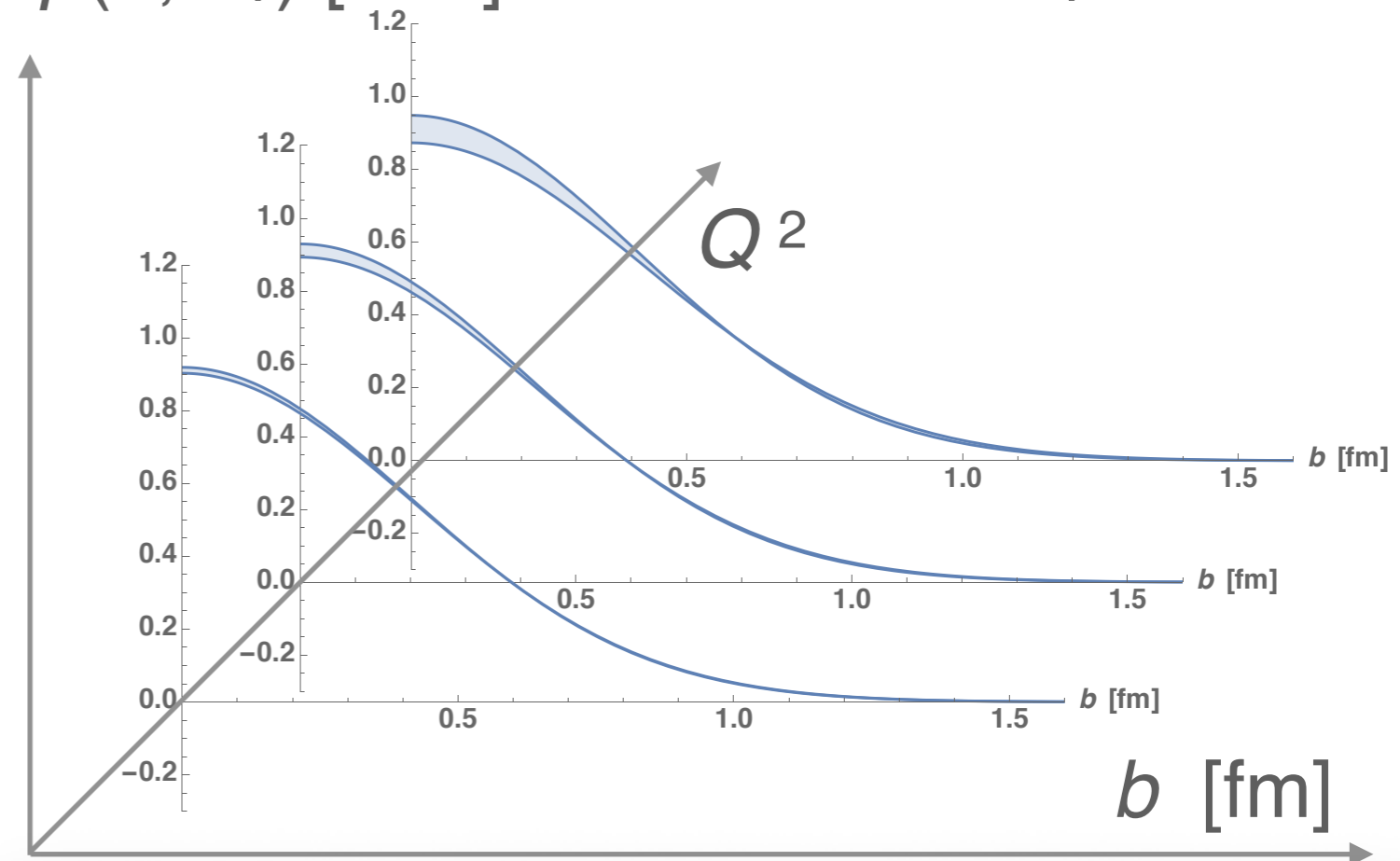
**t-spectrum**



**Normalized average gluon density:**

$\rho(b, x_V)$  [fm<sup>-2</sup>]

$0.16 < x_V < 0.25$



**Only possible at an EIC:**

**from the valence region deep into the sea!**



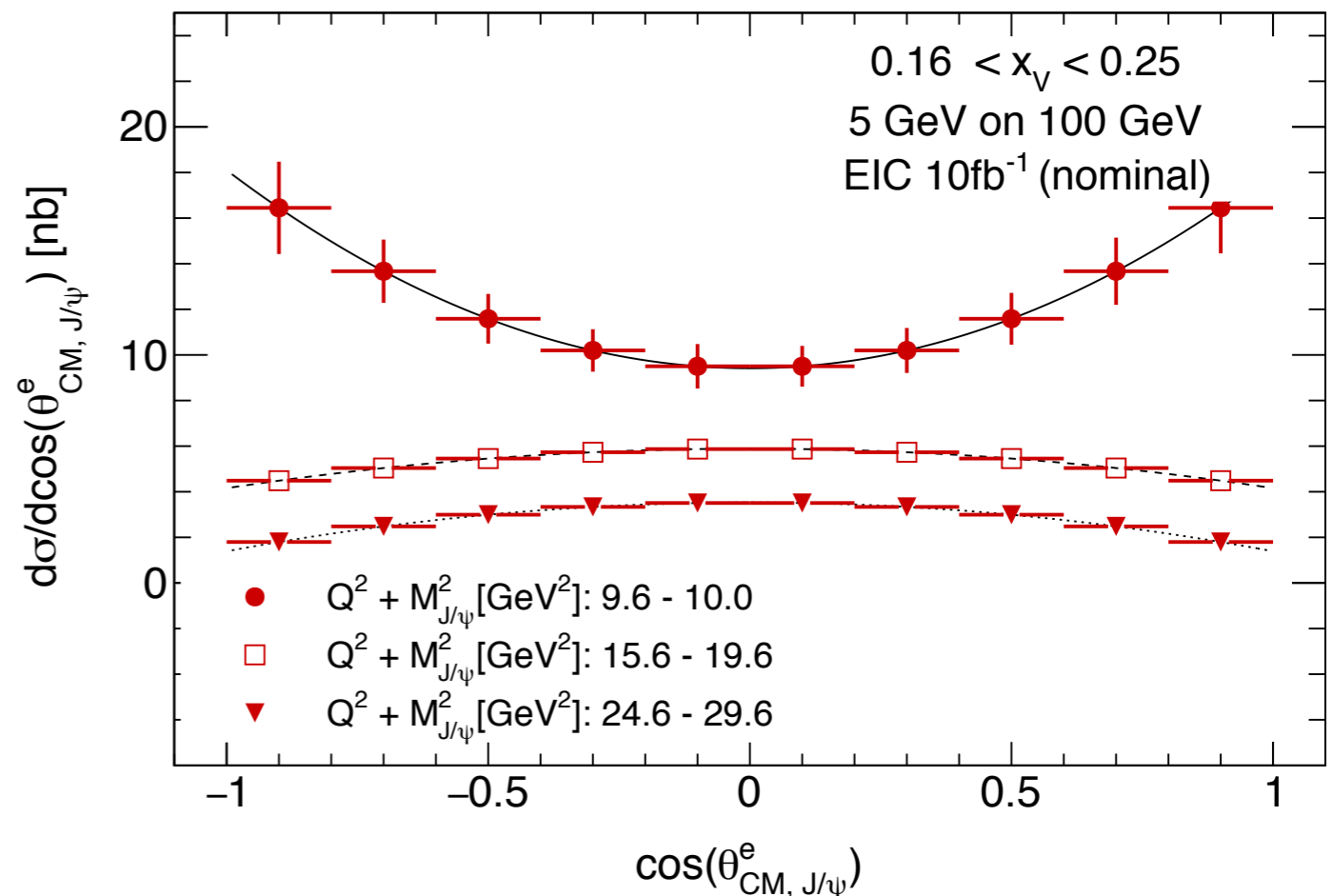
# L-T separation and the $Q^2$ dependence of $R$

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

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

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

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

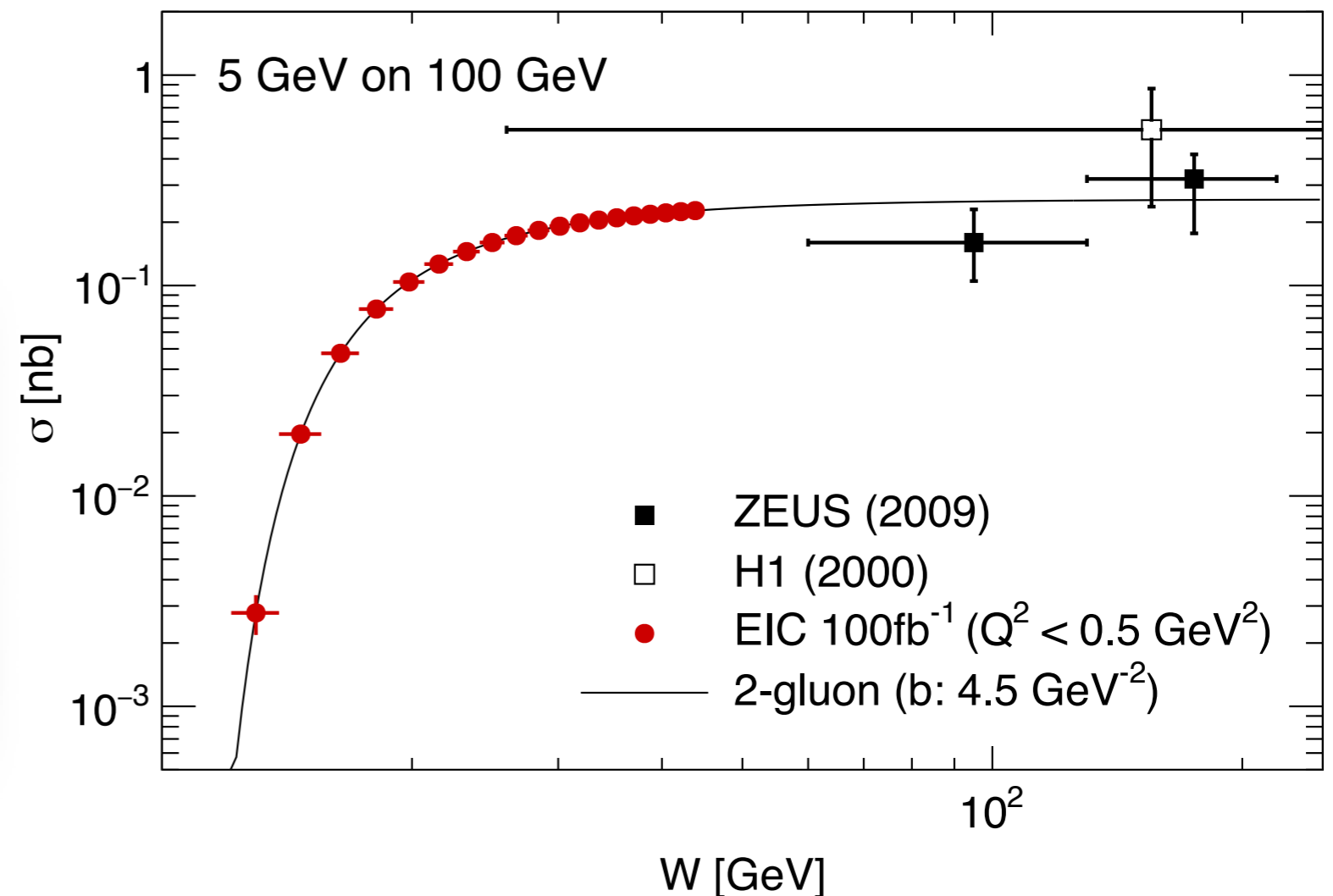


# $\Upsilon$ photo-production cross section

- **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**

$\Upsilon$  cross section  $\sim 100x$  lower than  $J/\psi$ .

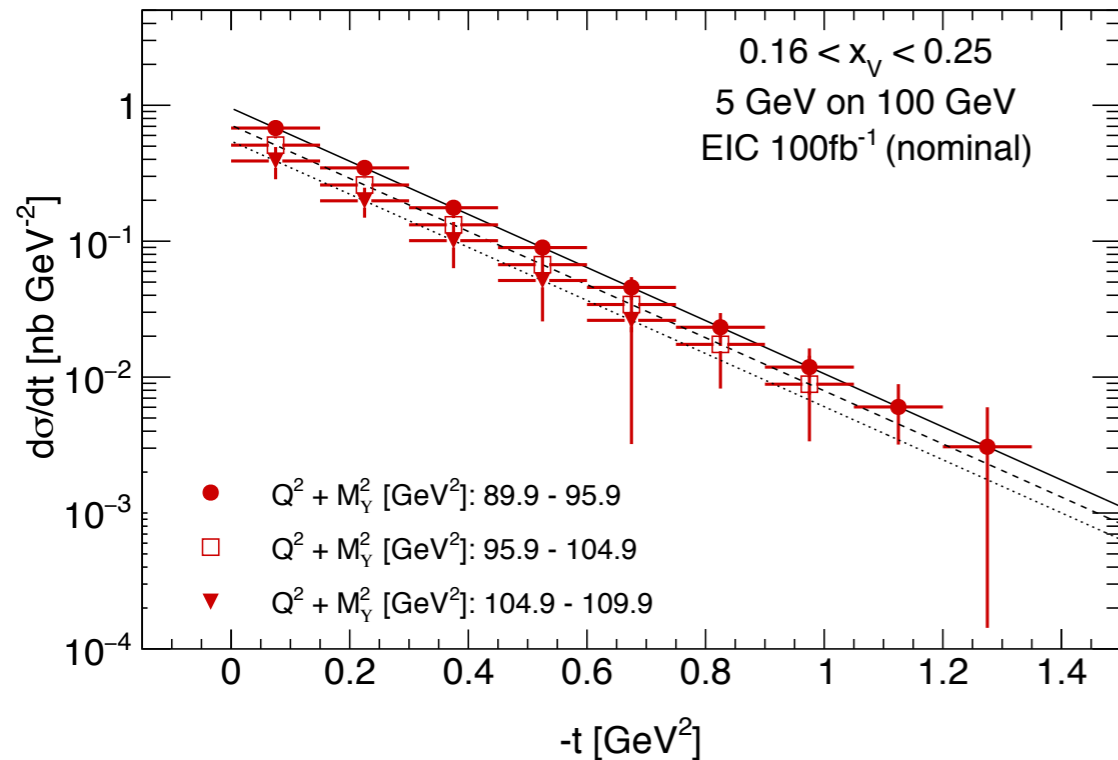
**Reasonable precision with 10x more luminosity**



# Spatial Imaging of gluon density with $Y(1s)$

$Y(1s)$  a viable tool to check Universality!

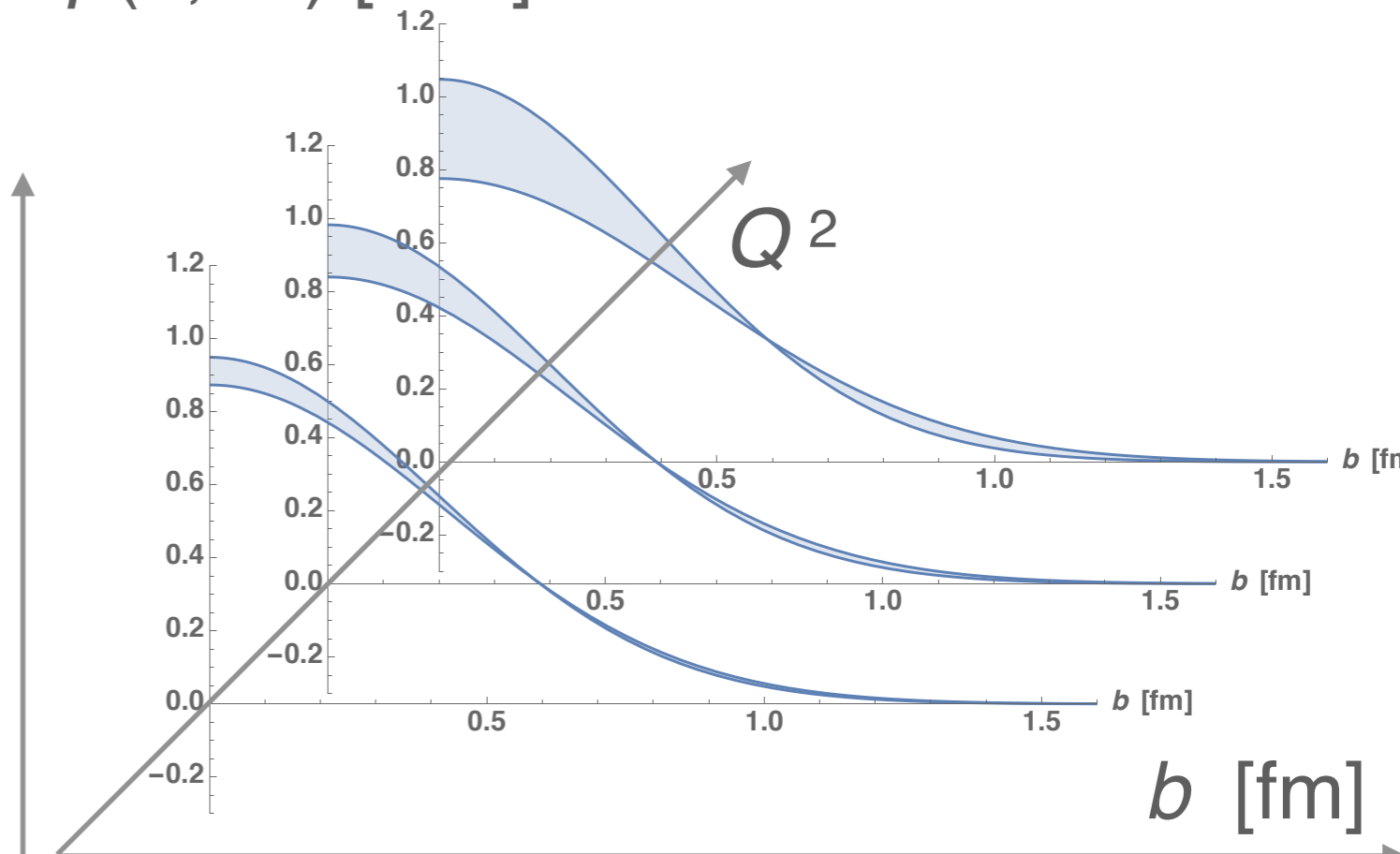
**t-spectrum**



**Normalized average gluon density:**

$\rho(b, x_V)$  [fm<sup>-2</sup>]

0.16 <  $x_V$  < 0.25



# 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  $Y$  to  $J/\psi$  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

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

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

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

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

- 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"
- 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 rho0 mesons in muon-proton interactions 470 GeV", ZPC74 (1997) 237-261.
- M Tytgat, "Diffractive production of rho0 and omega vector mesons at HERMES" DESY-Thesis 2001-018 (2001)
- P. Liebing, "Can the Gluon Polarization be Extracted From HERMES Data", DESY-Thesis (2004)
- 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

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

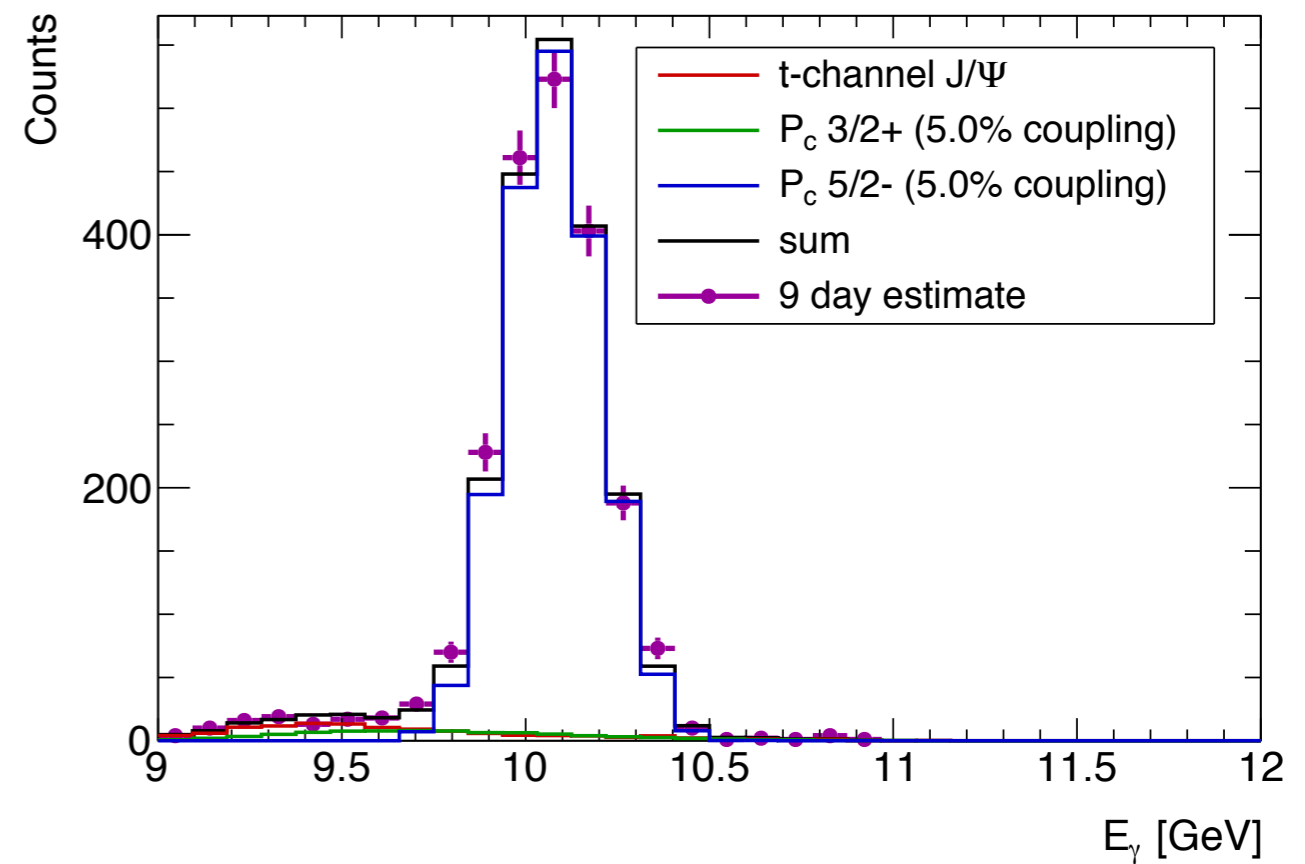
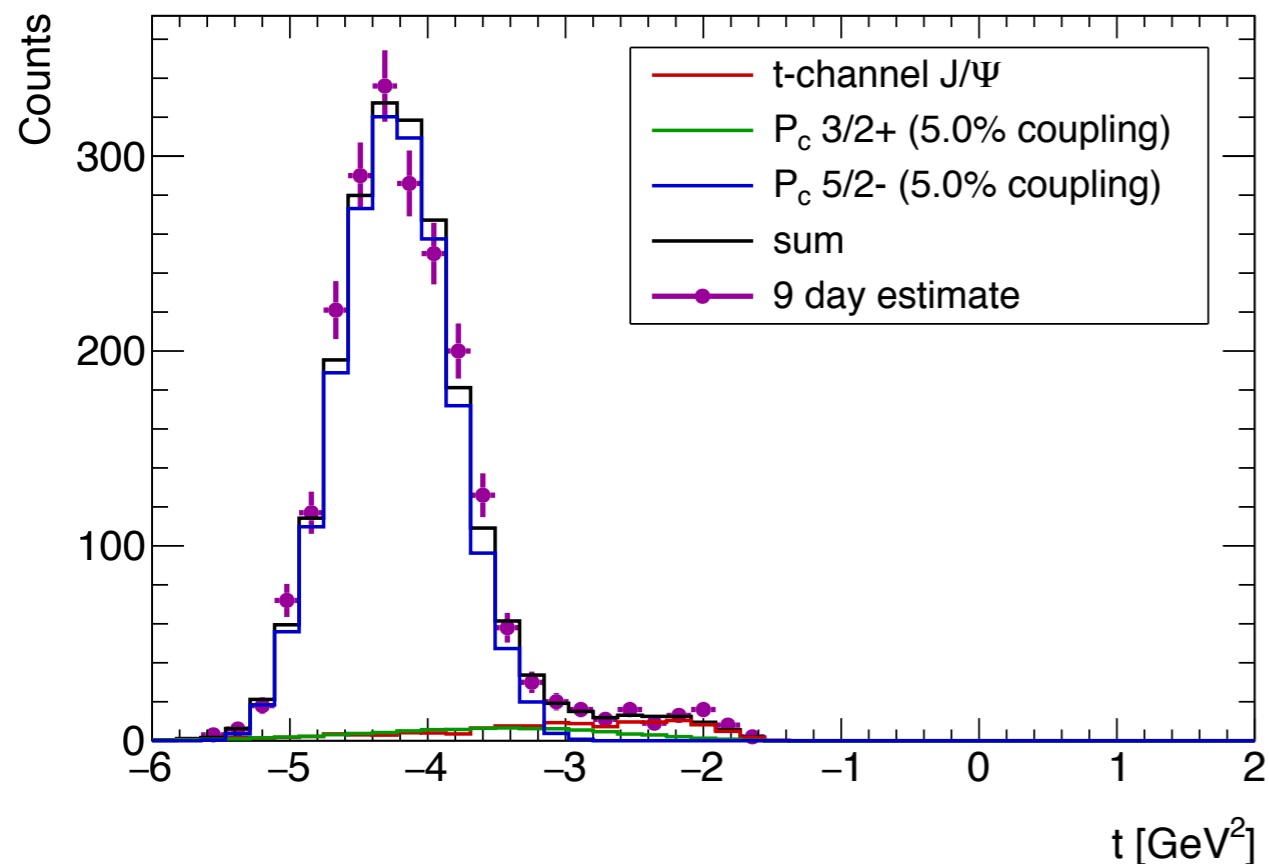
- **FORMULA FOR TWO FERMION DECAY**
- J. Breitweg et al. (ZEUS), Exclusive electro-production of rho0 and J/psi mesons at HERA, EPJ-C 6-4 (1999)
- Chekanov et al. (ZEUS), Exclusive photo production of J/psi mesons at HERA (2002)
- K. Schilling et. Al, Nucl.Phys. B 61, 381 (1973)

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

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

# Alternate $P_c$ Assumption (Setting "SIGNAL")

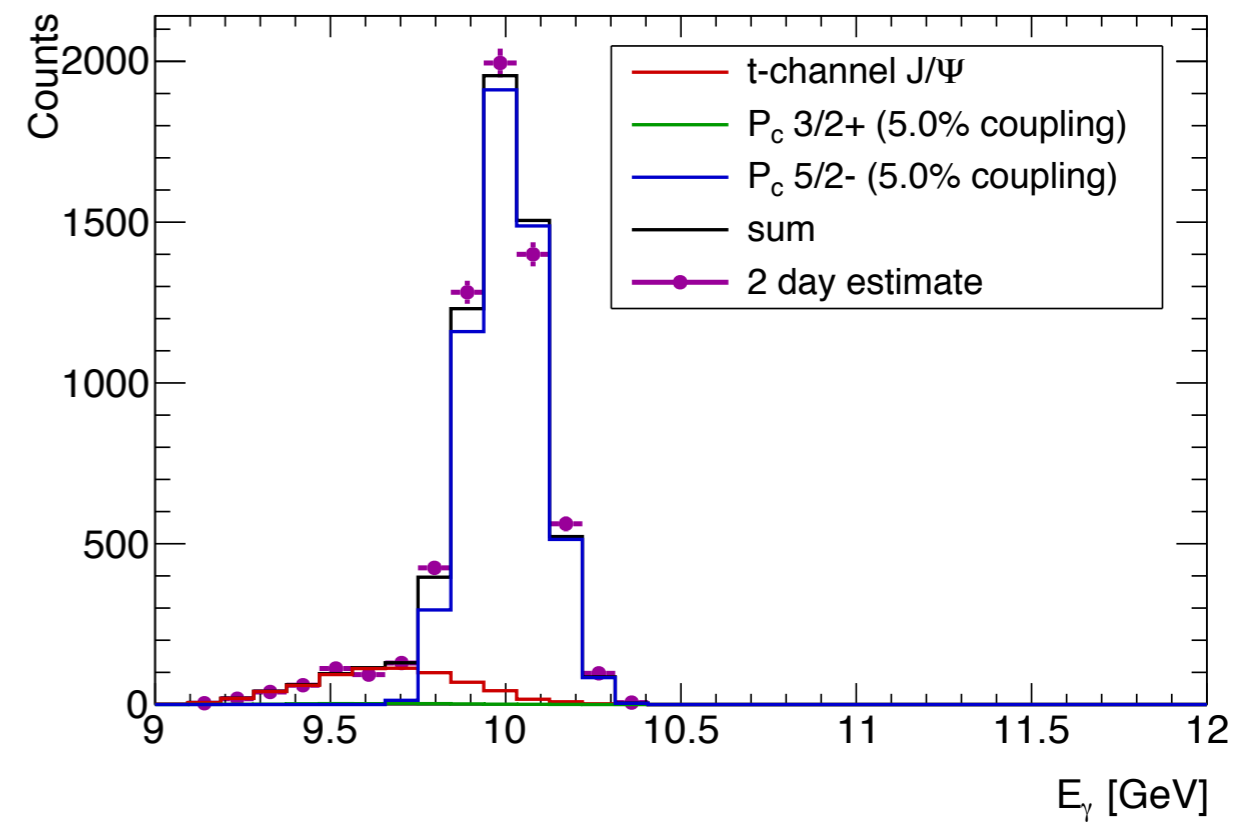
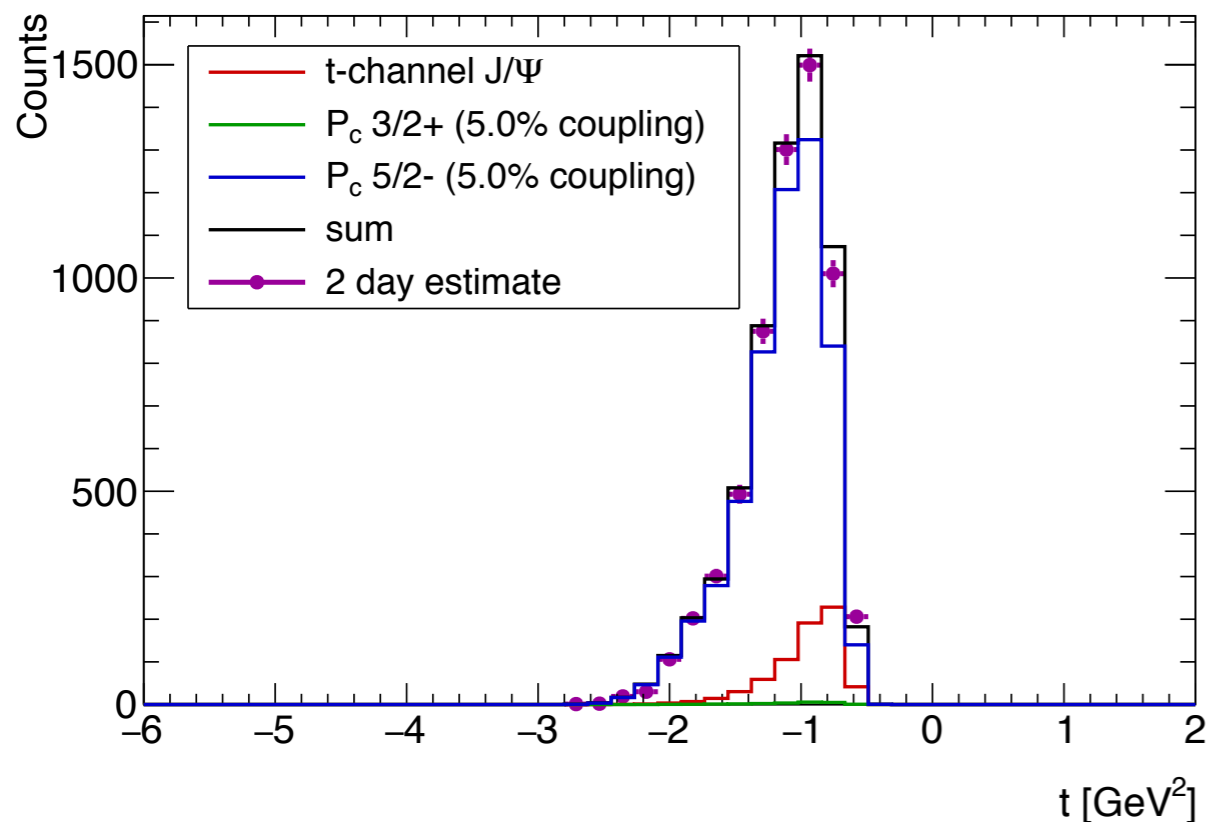
- **Alternate (5/2-, 3/2+)  $P_c$  assumption**
- assuming 5% coupling for the (5/2-, 3/2+)  $P_c$  assumption
- 9 days of beam time at 50 $\mu$ A
- 5/2- peak **dominates the spectrum** (even larger than the 5/2+ peak!)





# Alternate $P_c$ Assumption (“BACKGROUND” Setting)

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

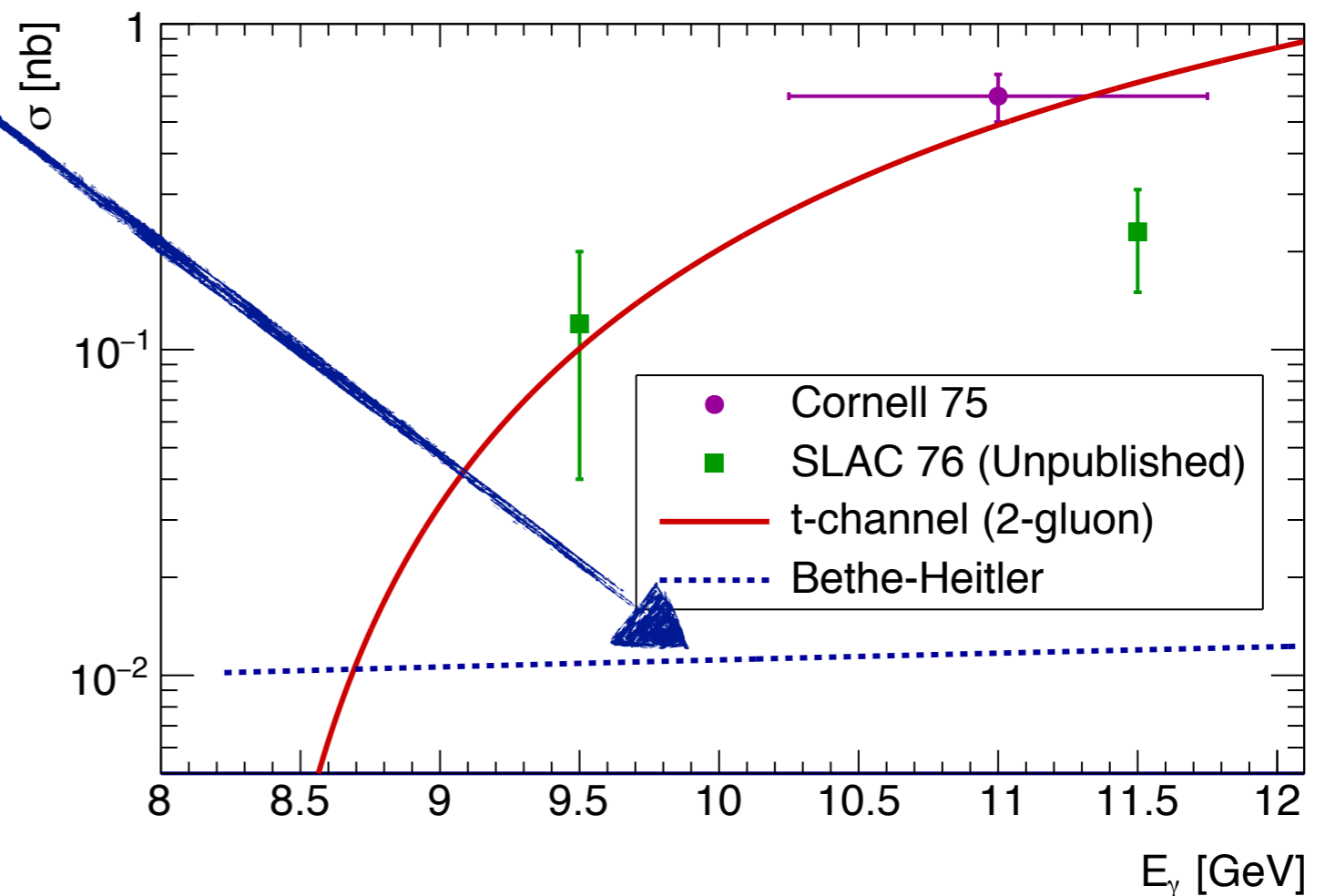
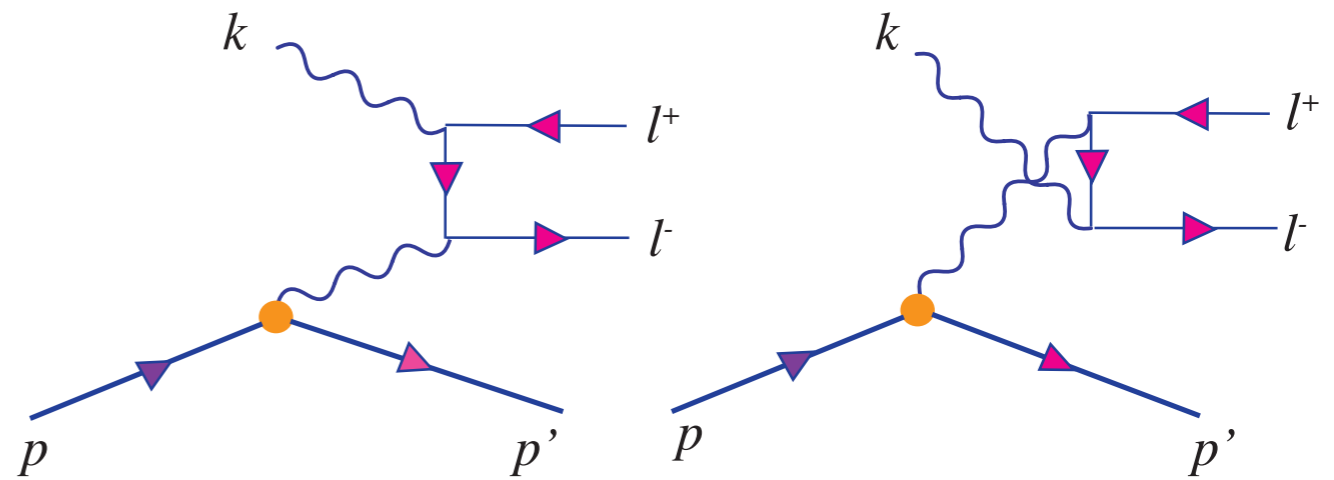


# Background: Bethe-Heitler pair production



**Not an issue!**

- Estimated using calculations from Pauk and Vanderhaeghen
- Constant background < 10% of the  $t$ -channel  $J/\psi$
- 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  $\sim 1$  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  $P_c(4450)$  ( $\underline{E}_{rc} > 9.7$  GeV)!**

**not an issue for the  $P_c$ !**

# Photon Energy Reconstruction

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

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

# Properties of the Hall C Spectrometers

	$P$ GeV/ $c$	$\Delta P/P$ %	$\sigma P/P$ %	$\theta^{\text{in}}$	$\Delta\theta^{\text{in}}$ 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), 50 $\mu$ A, 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!**