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

Quarkonium Production:
From JLab to an EIC

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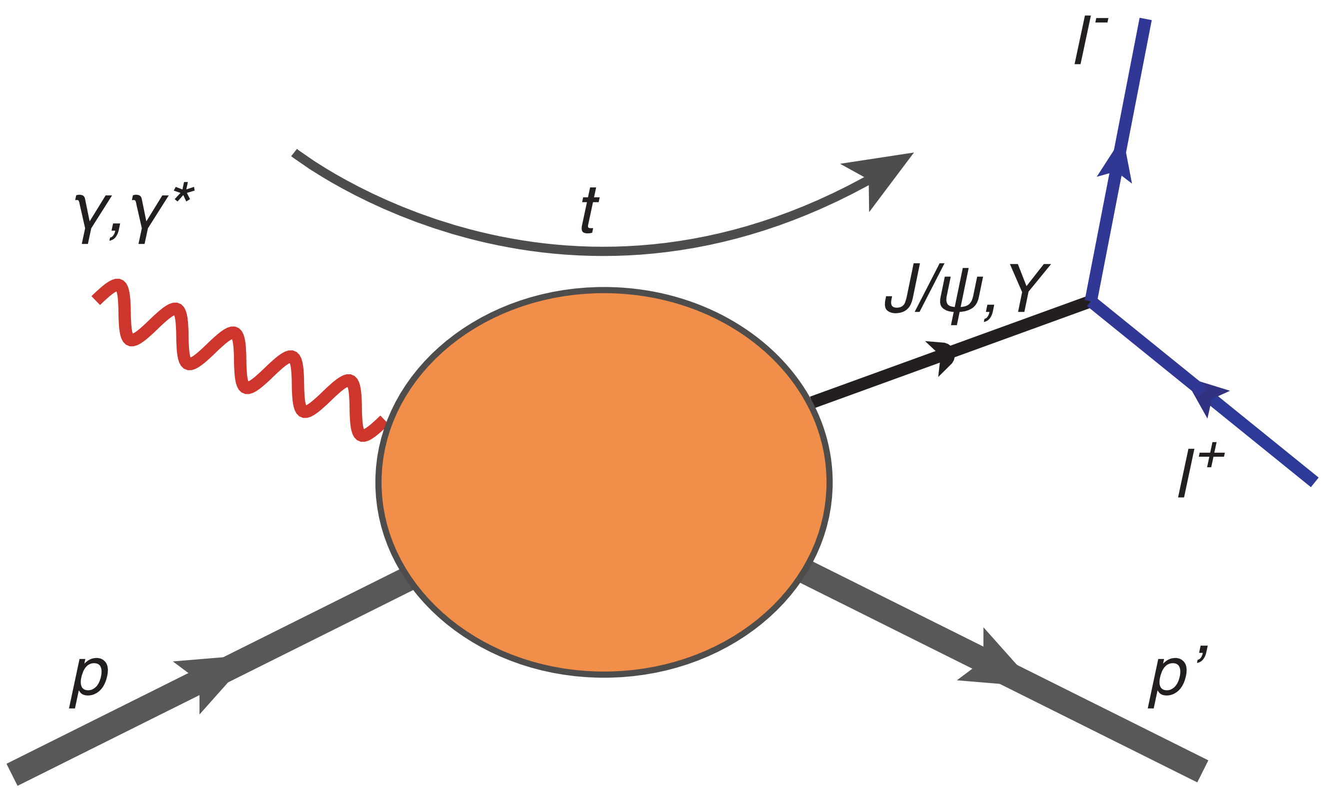
TEMPLE UNIVERSITY

QCD Evolution 2018 (Santa Fe, NM)

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 photo-production: **what do we know?**

J/ψ photo-production:

- **Direct photo-production**

  Cornell ’75,

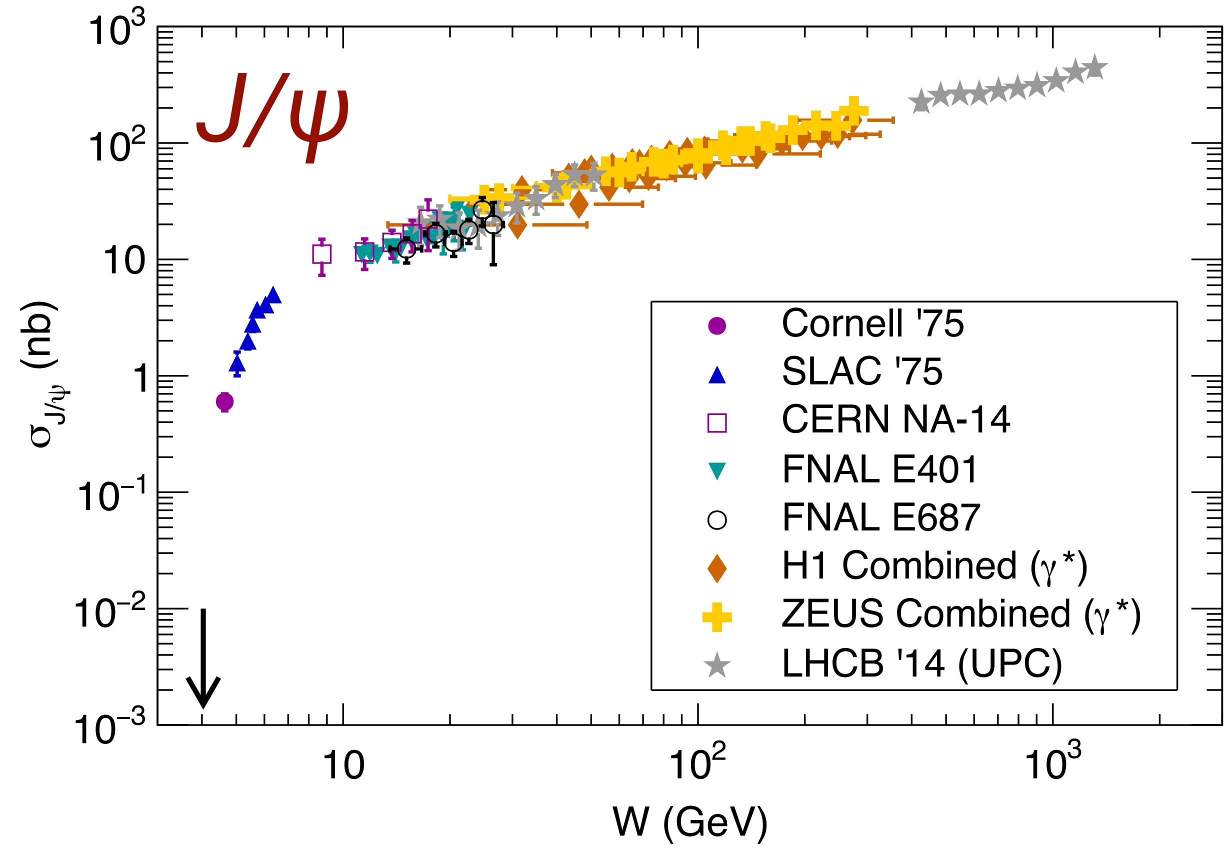
  SLAC ’75,

  CERN NA-14,

  FNAL E401, E687
- **Electro-production (quasi-real)**

  H1 and ZEUS
- **Ultra-peripheral *pp* collisions**

  LHCb ’14

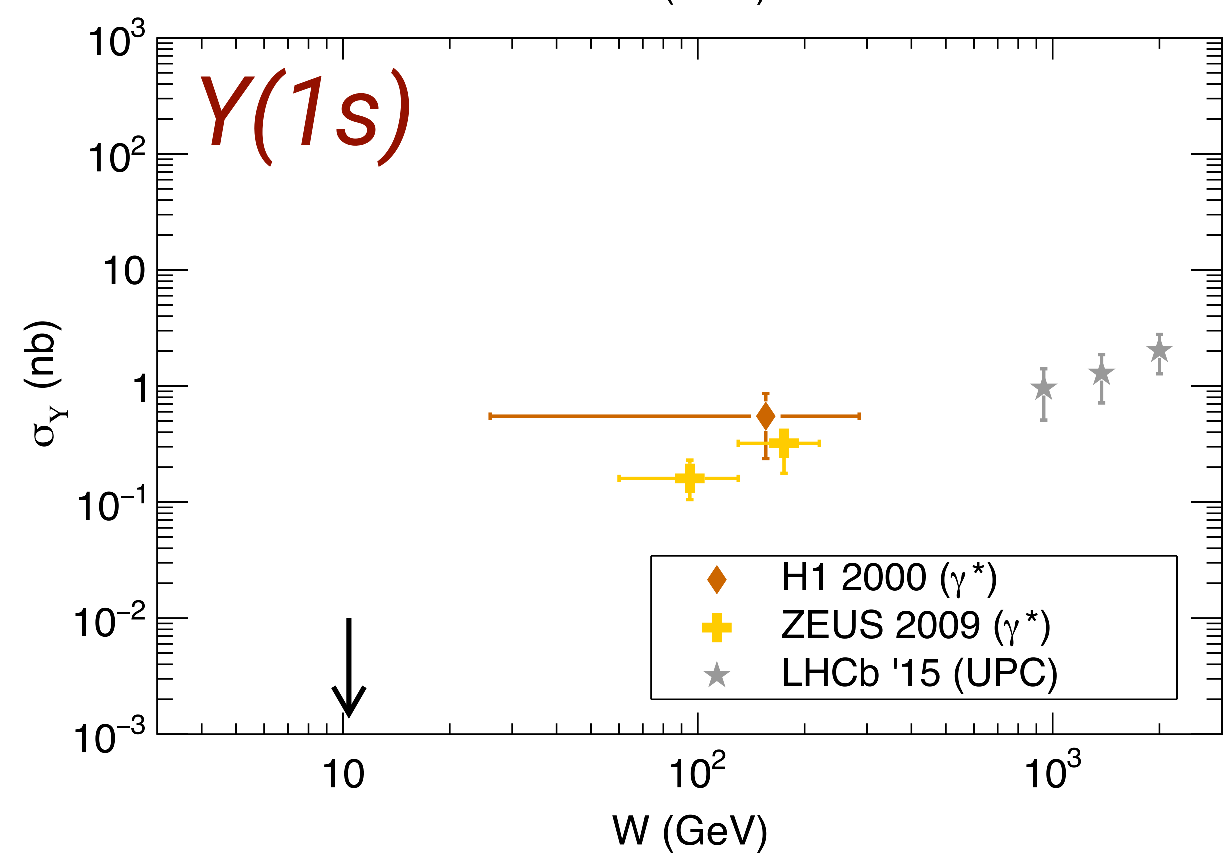


Υ(1s) photo-production:

- **Electro-production (quasi-real)**

  H1 and ZEUS
- **Ultra-peripheral *pp* collisions**

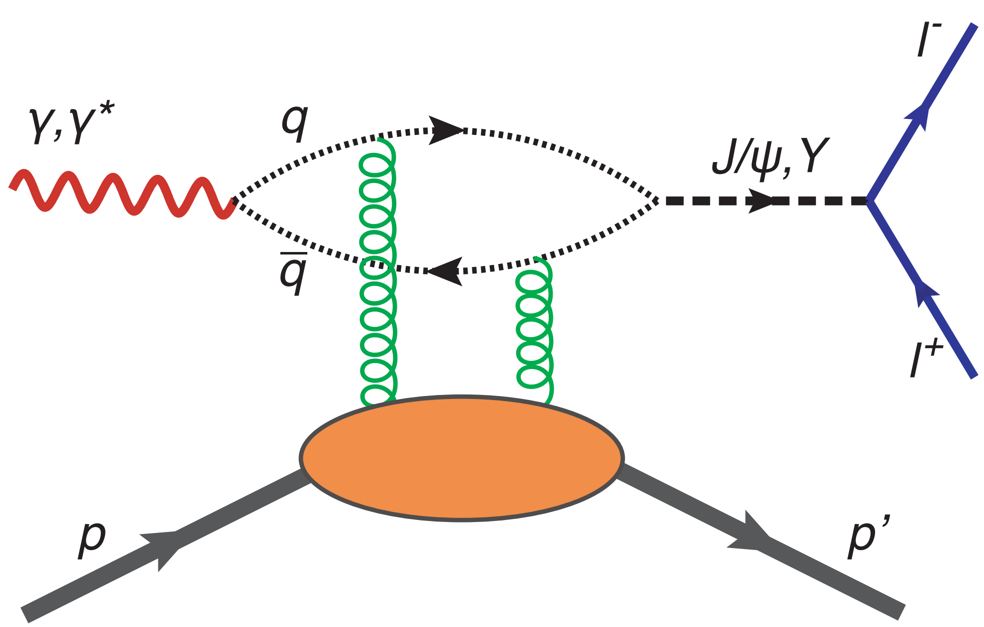
  LHCb ’15



Quarkonium photo-production: **what do we know?**

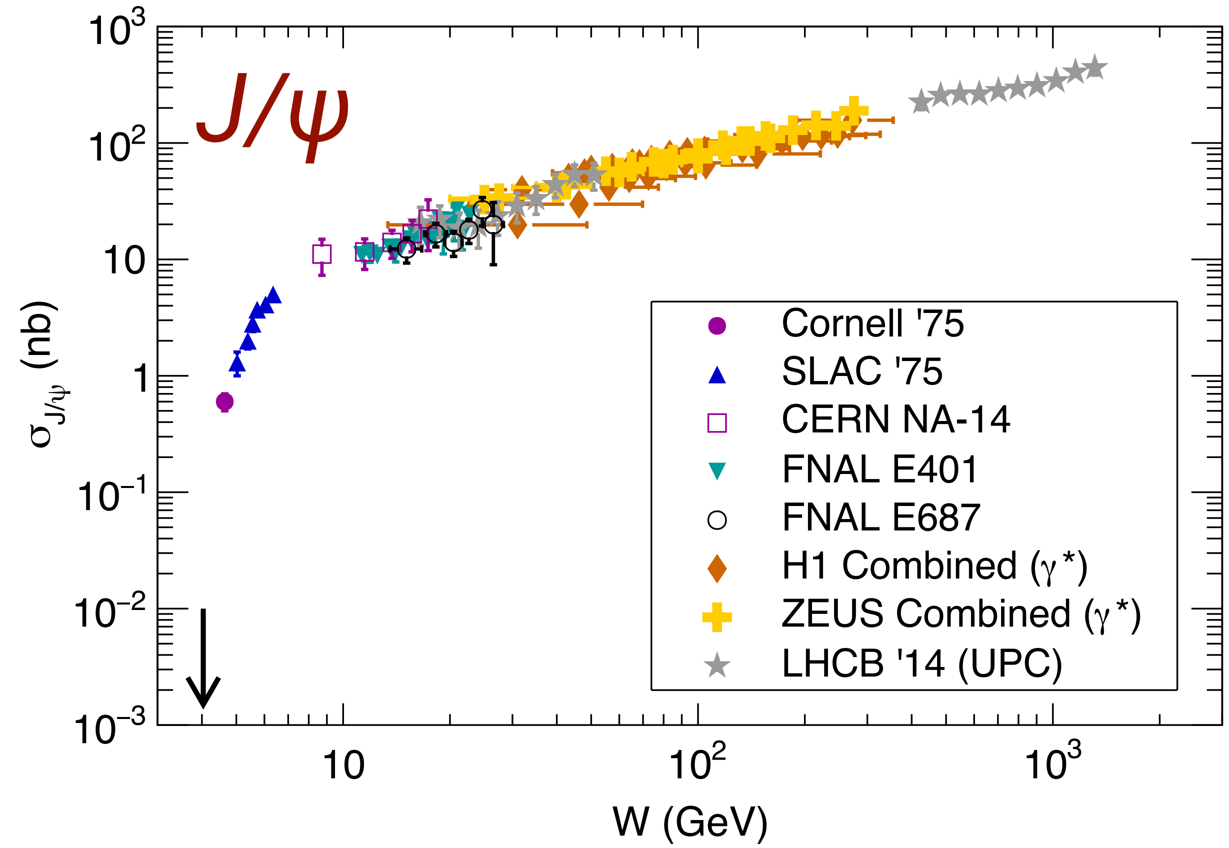
J/ψ photo-production:

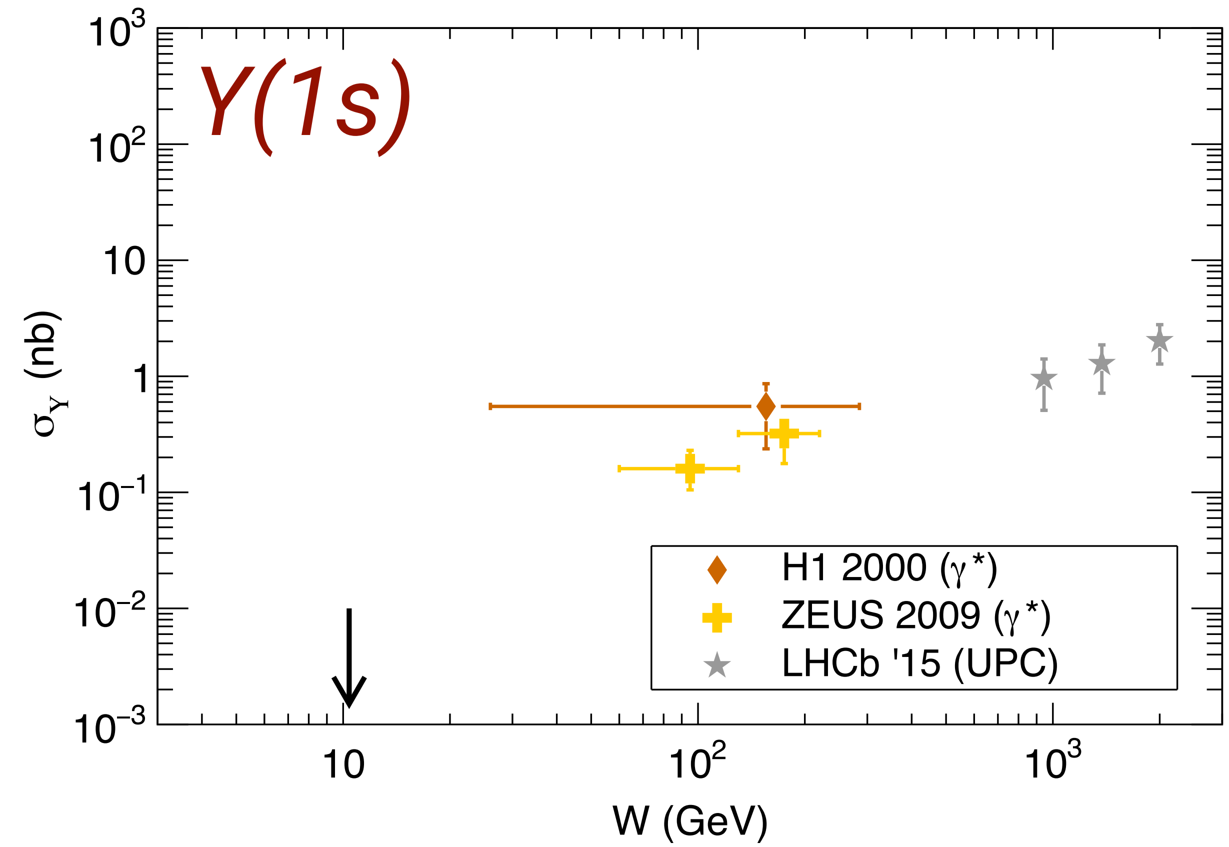
- Well constrained above $W > 15$ GeV
  - Dominated by ***t*-channel 2-gluon exchange**
- **Almost no data near threshold**



Υ(1s) photo-production:

- **Not much available**
  - ZEUS measured 62 ± 12 events total!

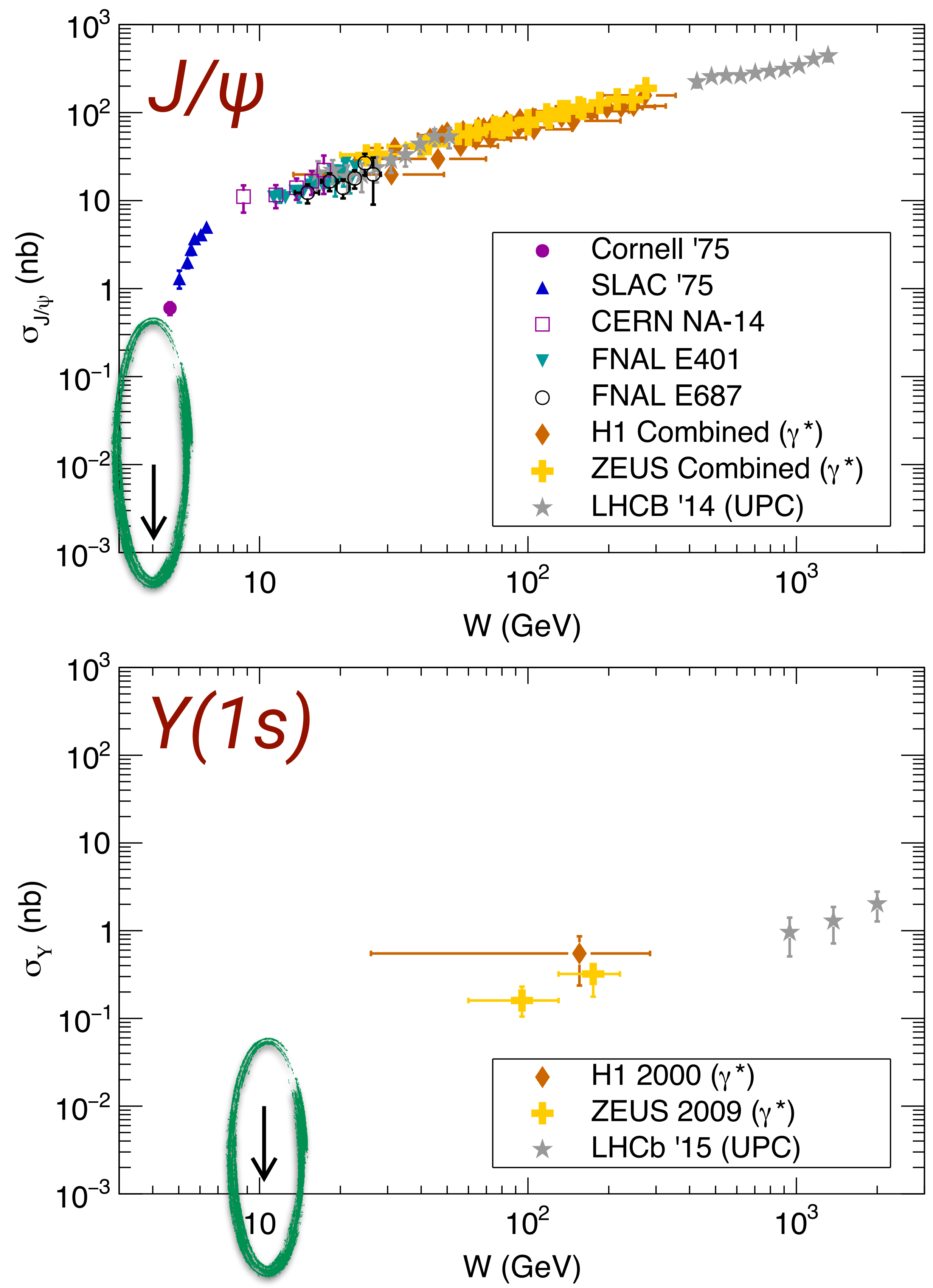




Why the **threshold region?**

Near Threshold:

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



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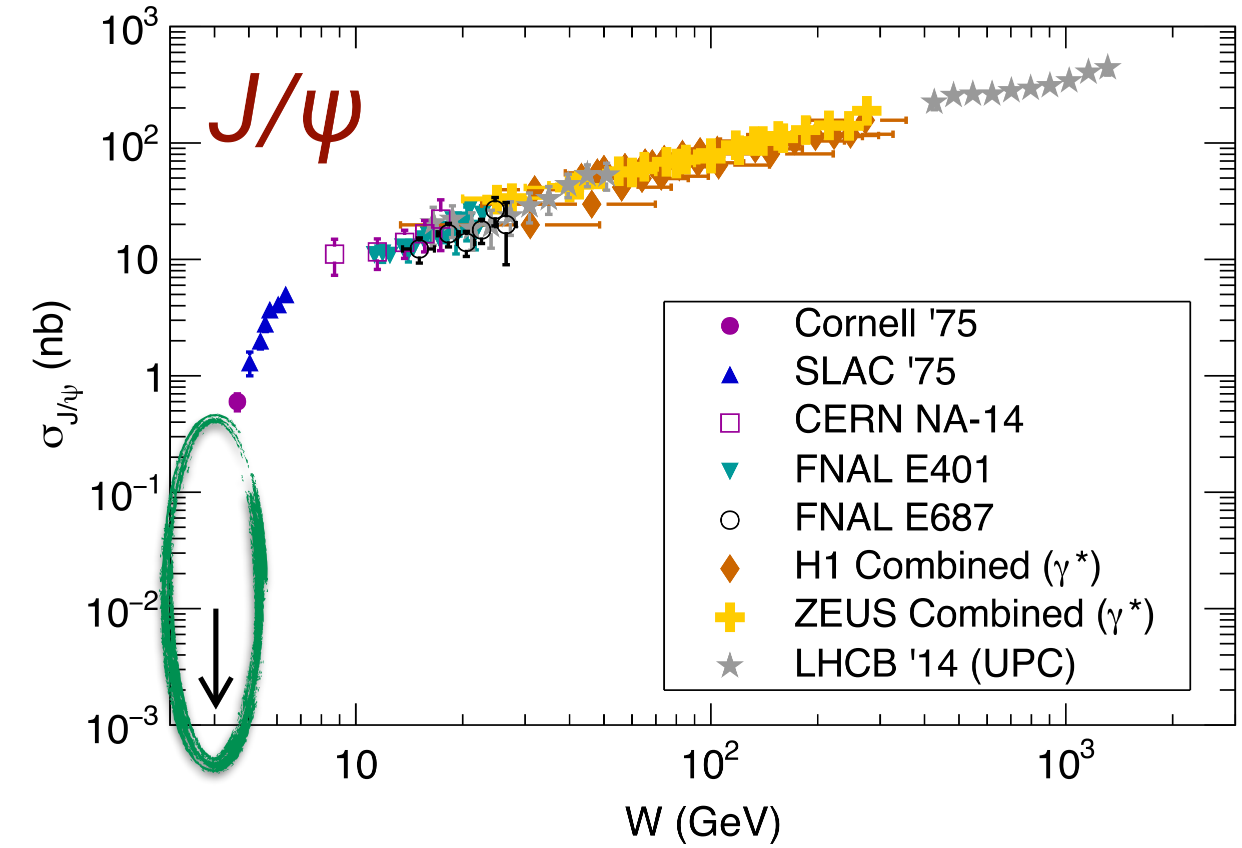
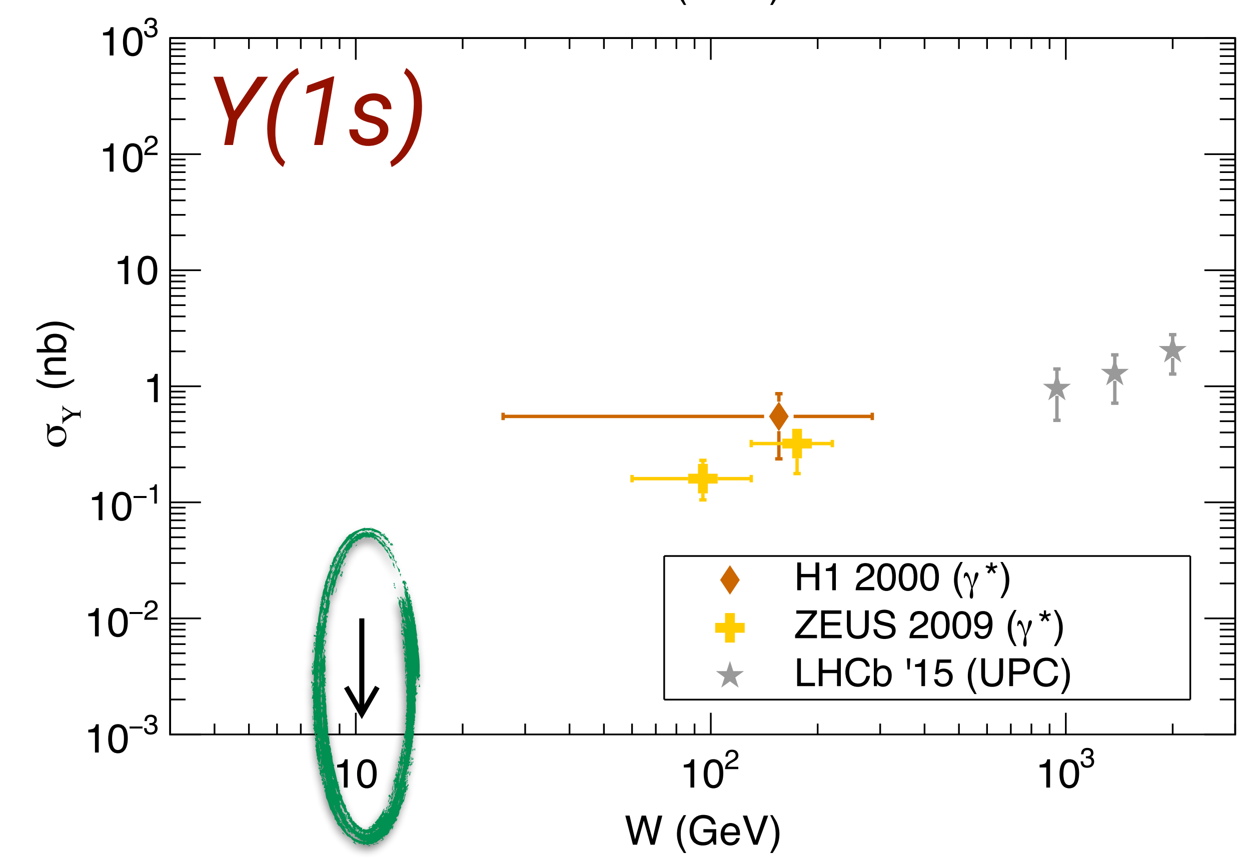


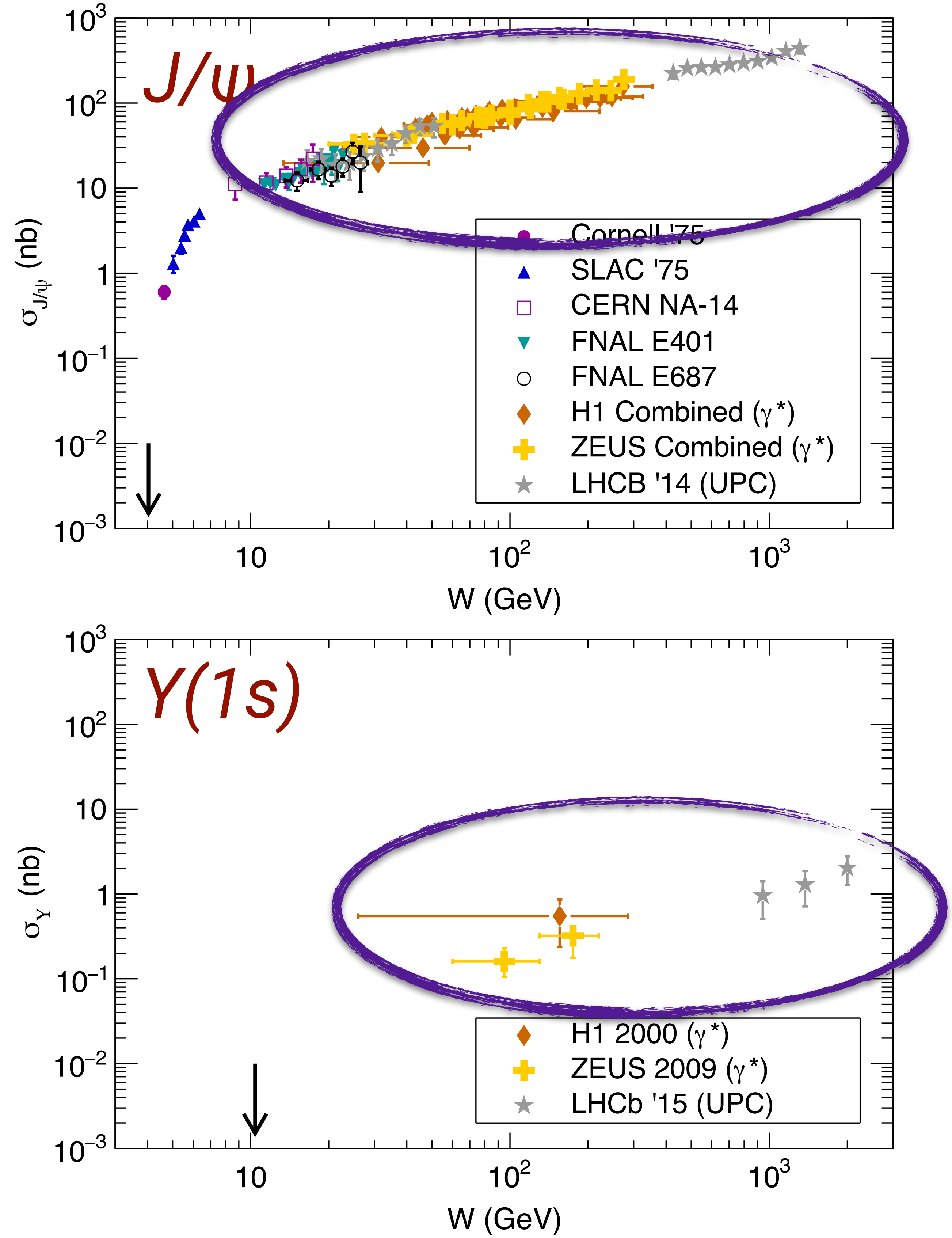


- ☆ ***J/ψ* program at Jefferson Lab**
- ☆ ***Υ(1s)* production at an EIC**

Why **electro-production** at **high energies?**

High Energies

- Access **Gluon GPD**: Full 3D tomography of the gluonic structure of the nucleon
- L-T separation and the Q^2 dependence of R for quarkonium production



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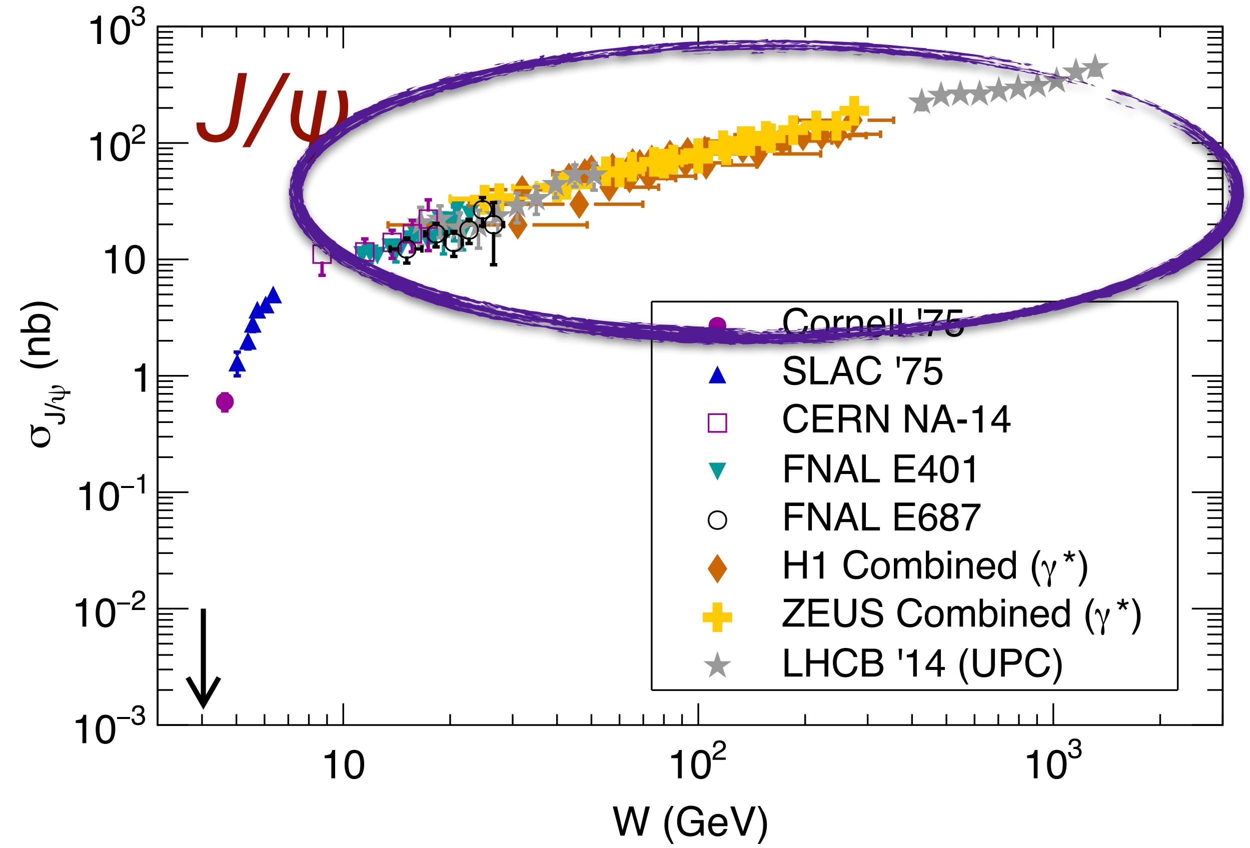
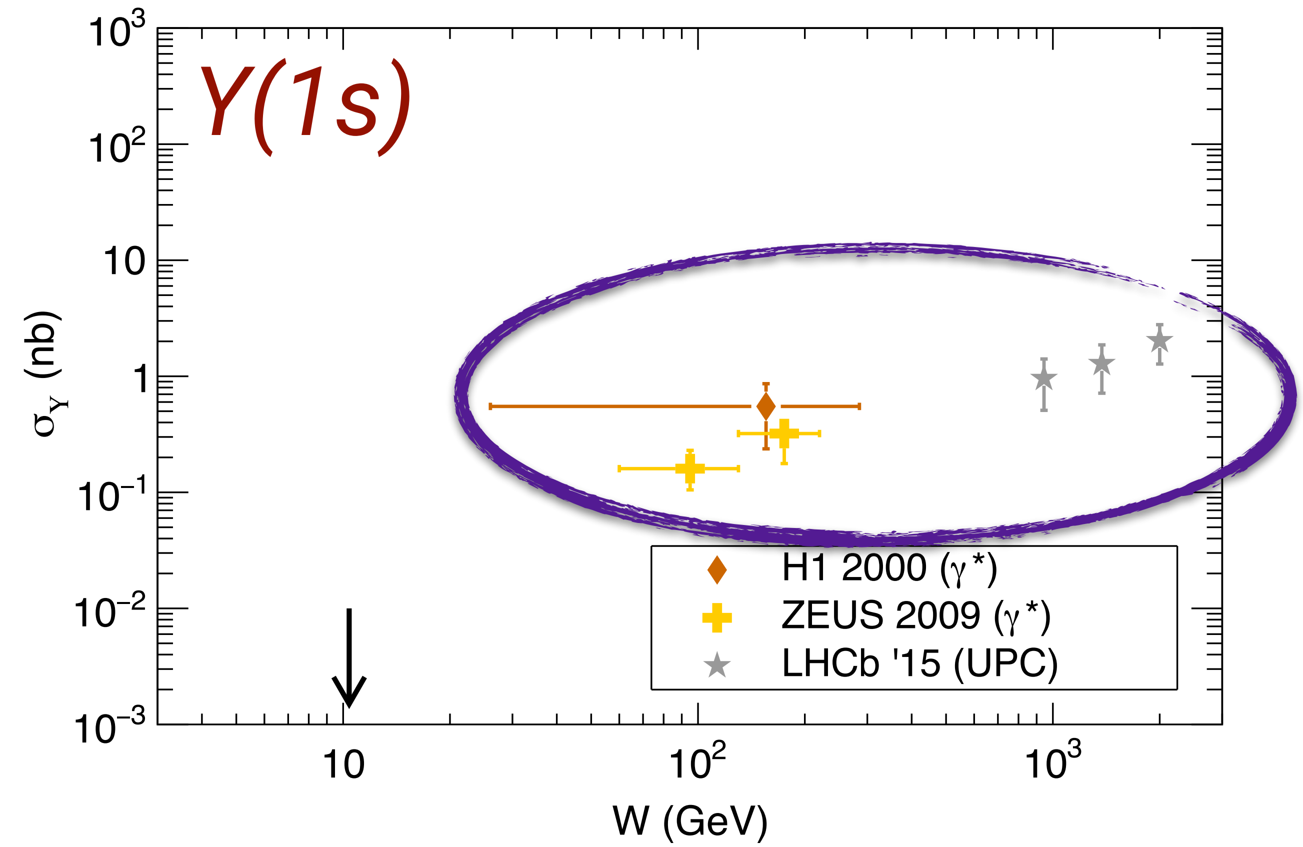
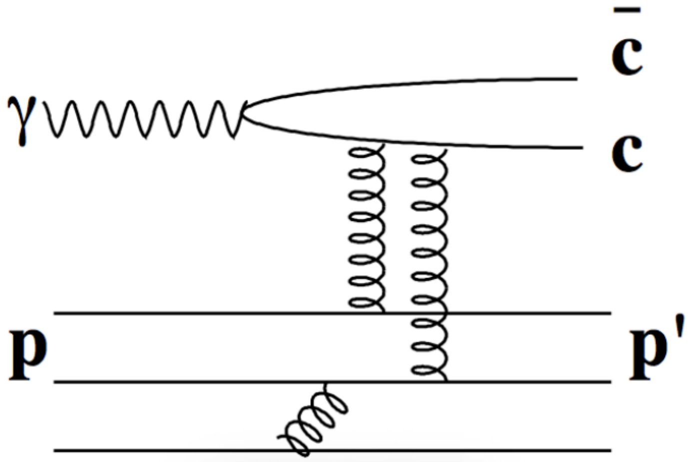




- ***J/ψ* production at an EIC**
- ***Υ(1s)* production at an EIC**

Quarkonium production **near threshold**

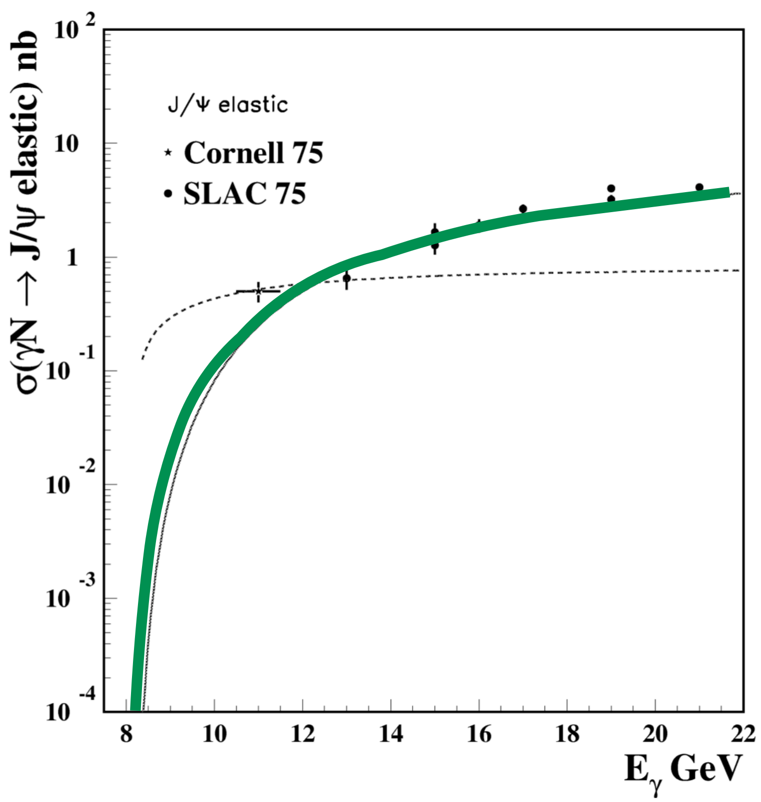
Production mechanism near threshold unknown



2-gluon

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

- ☆ Same as high energies (**2-gluon**)?



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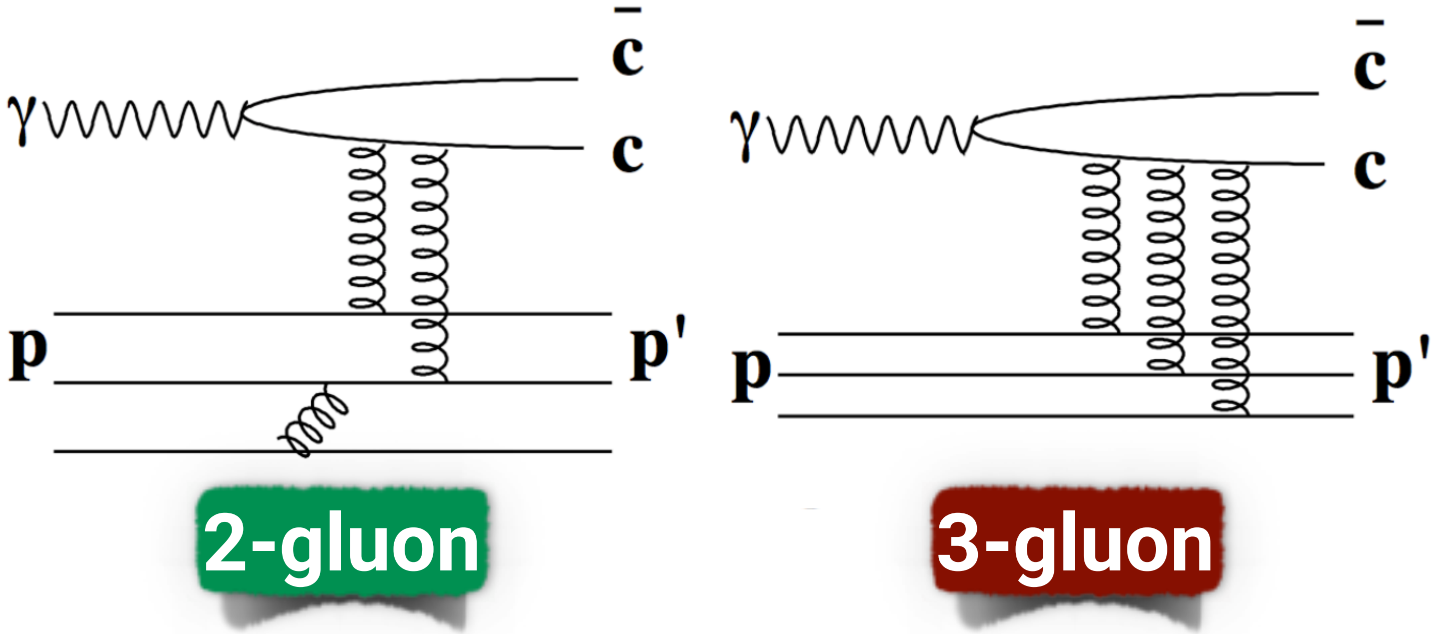

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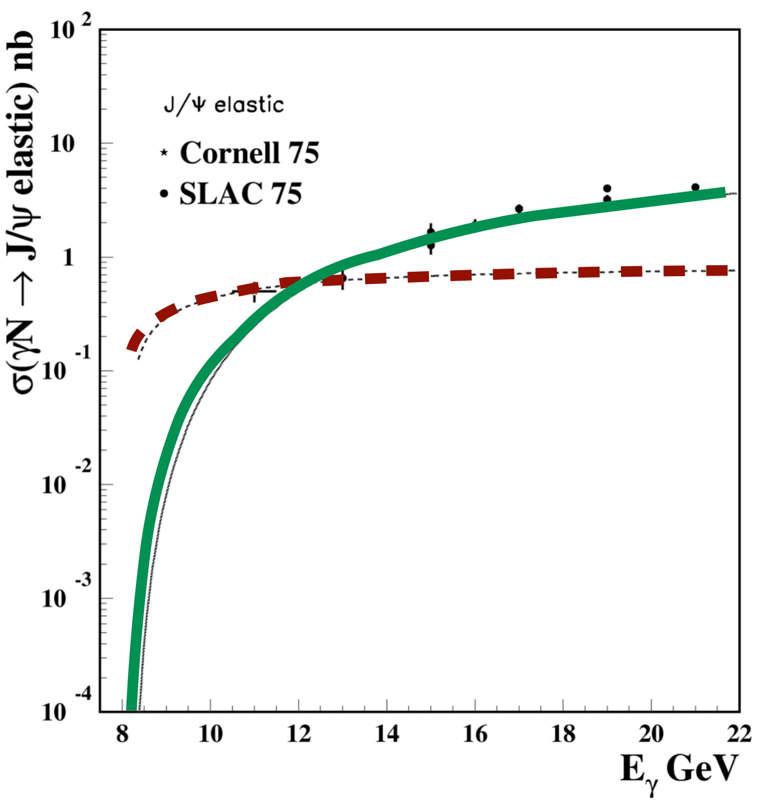
- Same as high energies (2-gluon)?
- Maybe 3-gluon exchange dominant?



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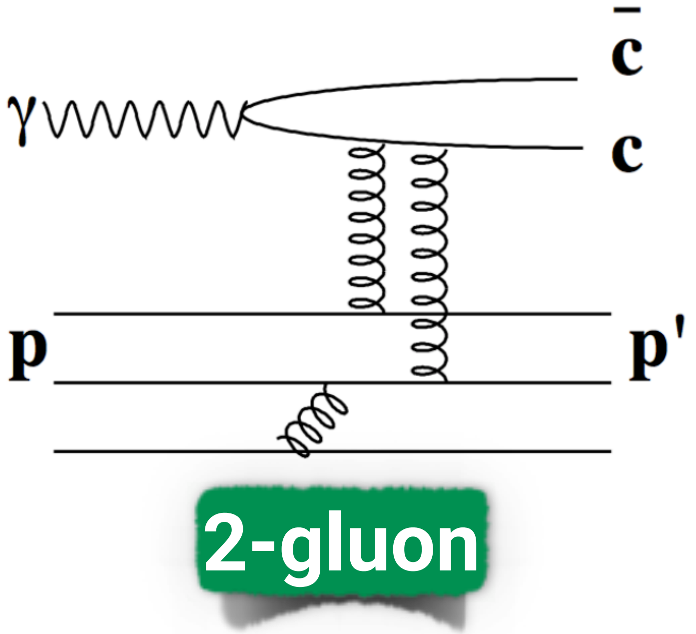

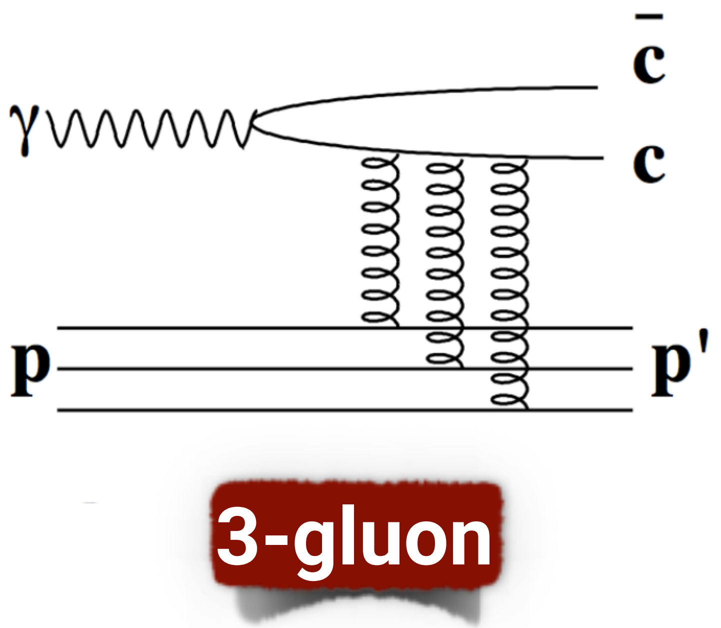

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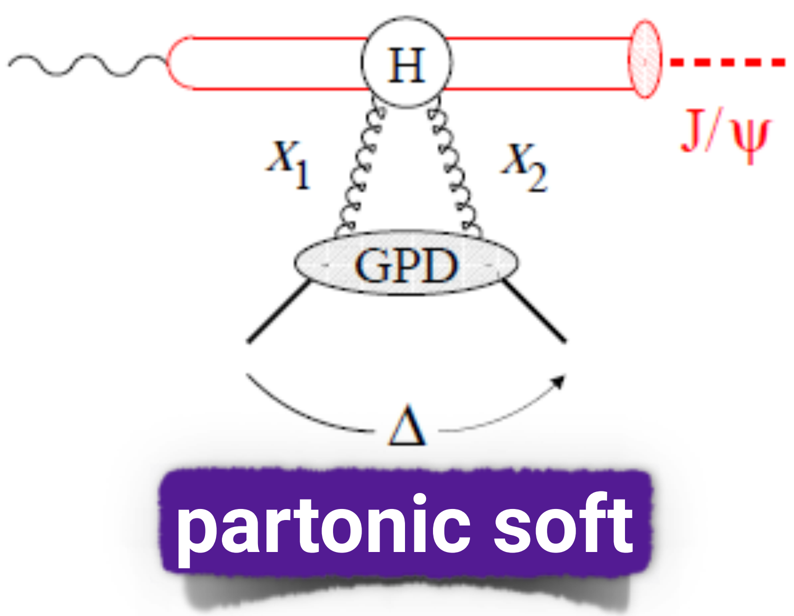

Frankfurt and Strikman., PRD66 (2002), 031502

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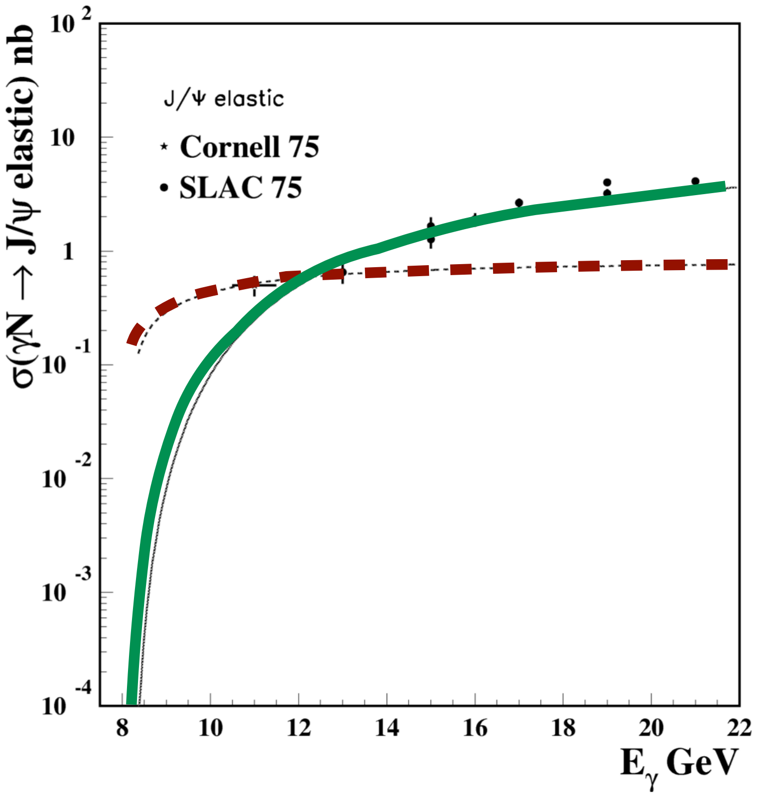
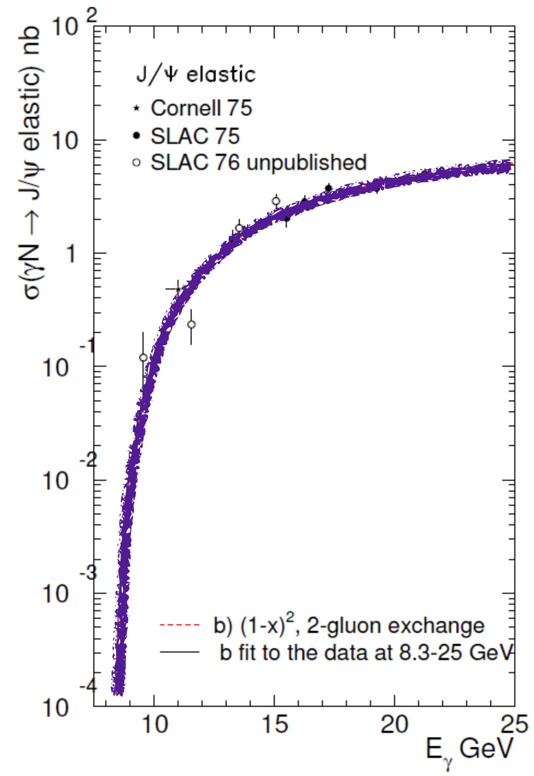
- Or a **partonic soft mechanism** (power law 2-gluon form-factor)?





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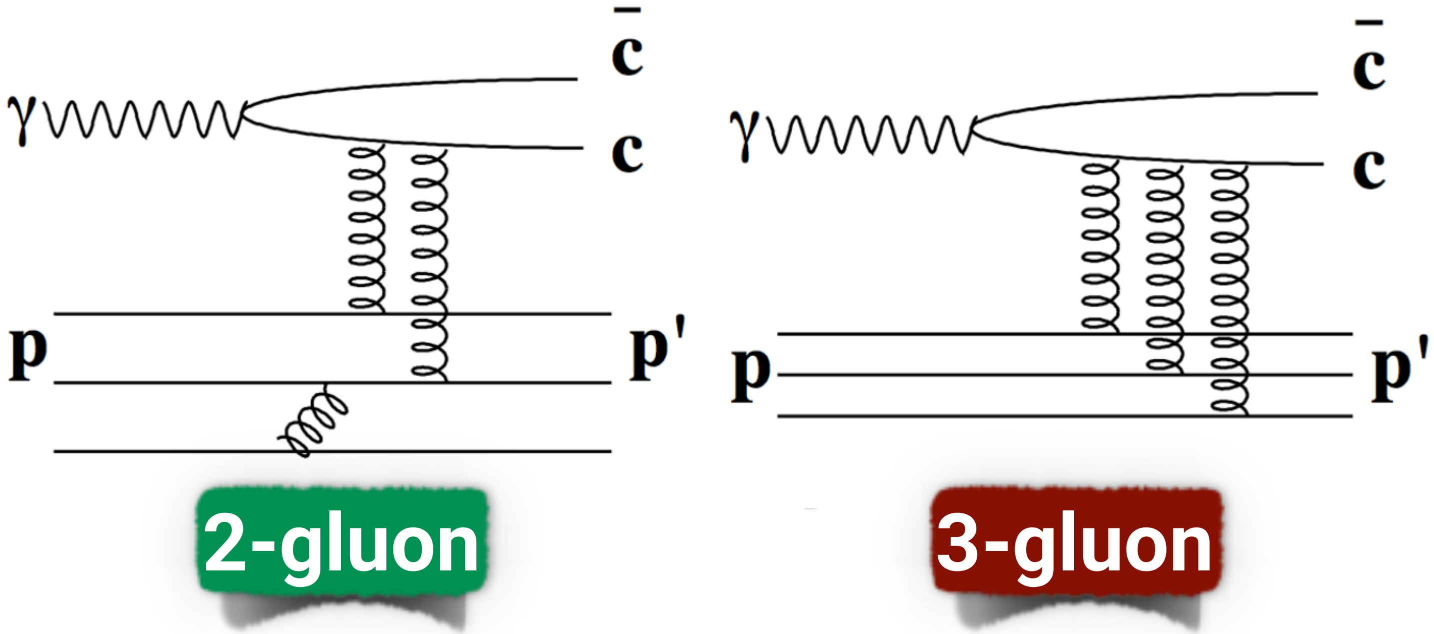

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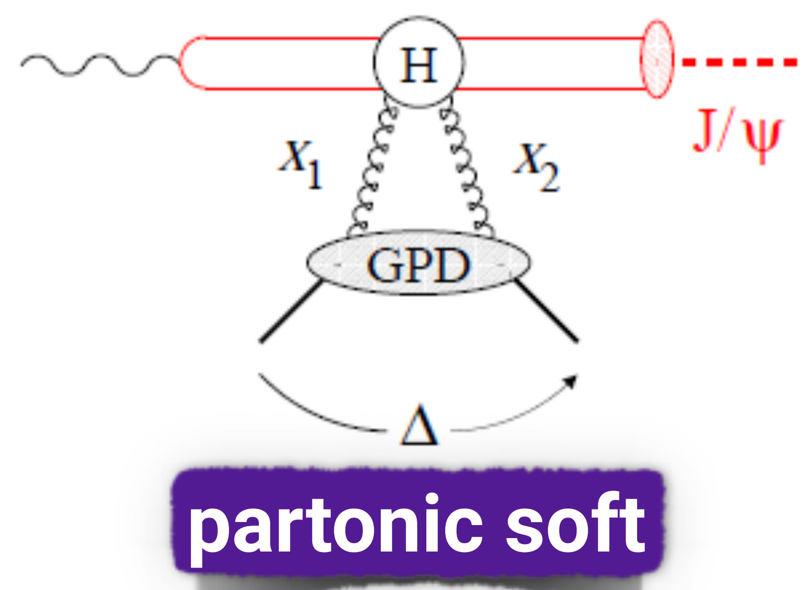

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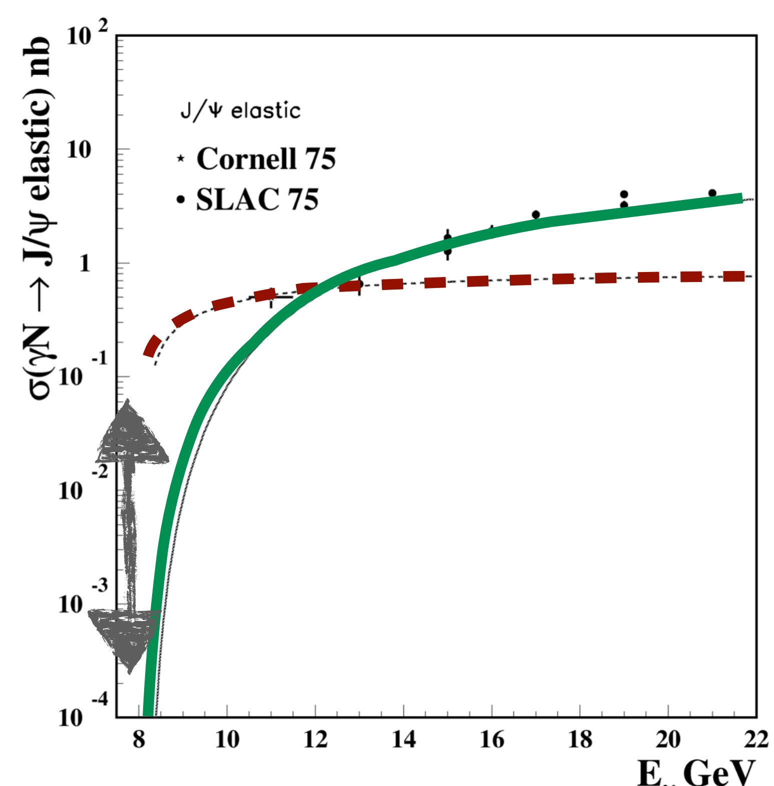
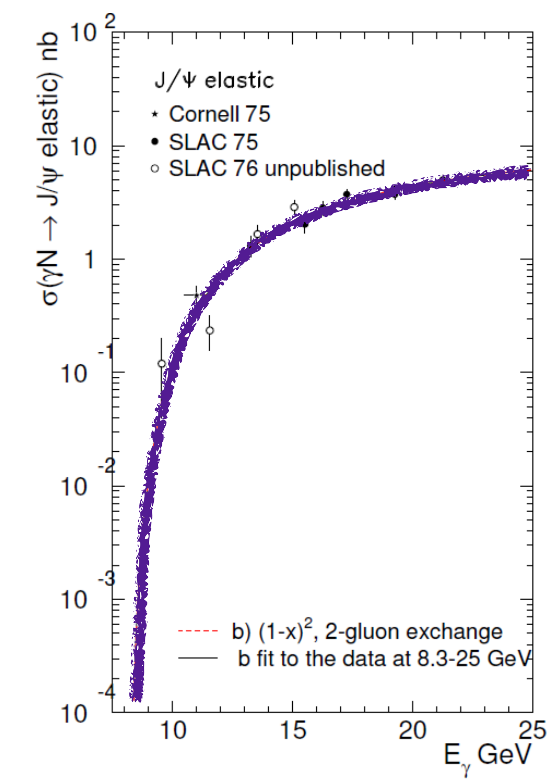
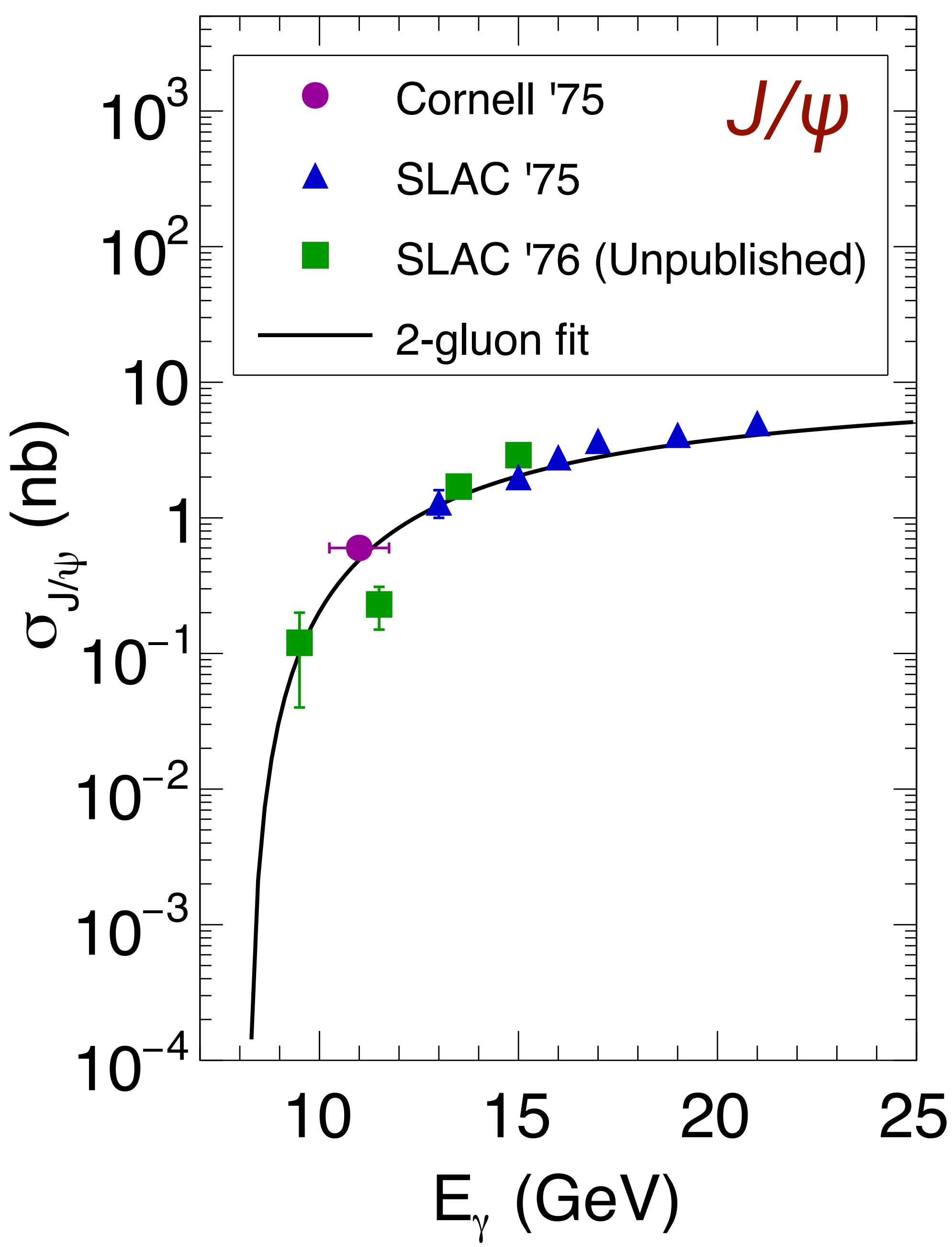
- ★ Orders of magnitude difference
- ★ **2-gluon** fastest drop-off
  - ★ **Drives required luminosity** for threshold measurement

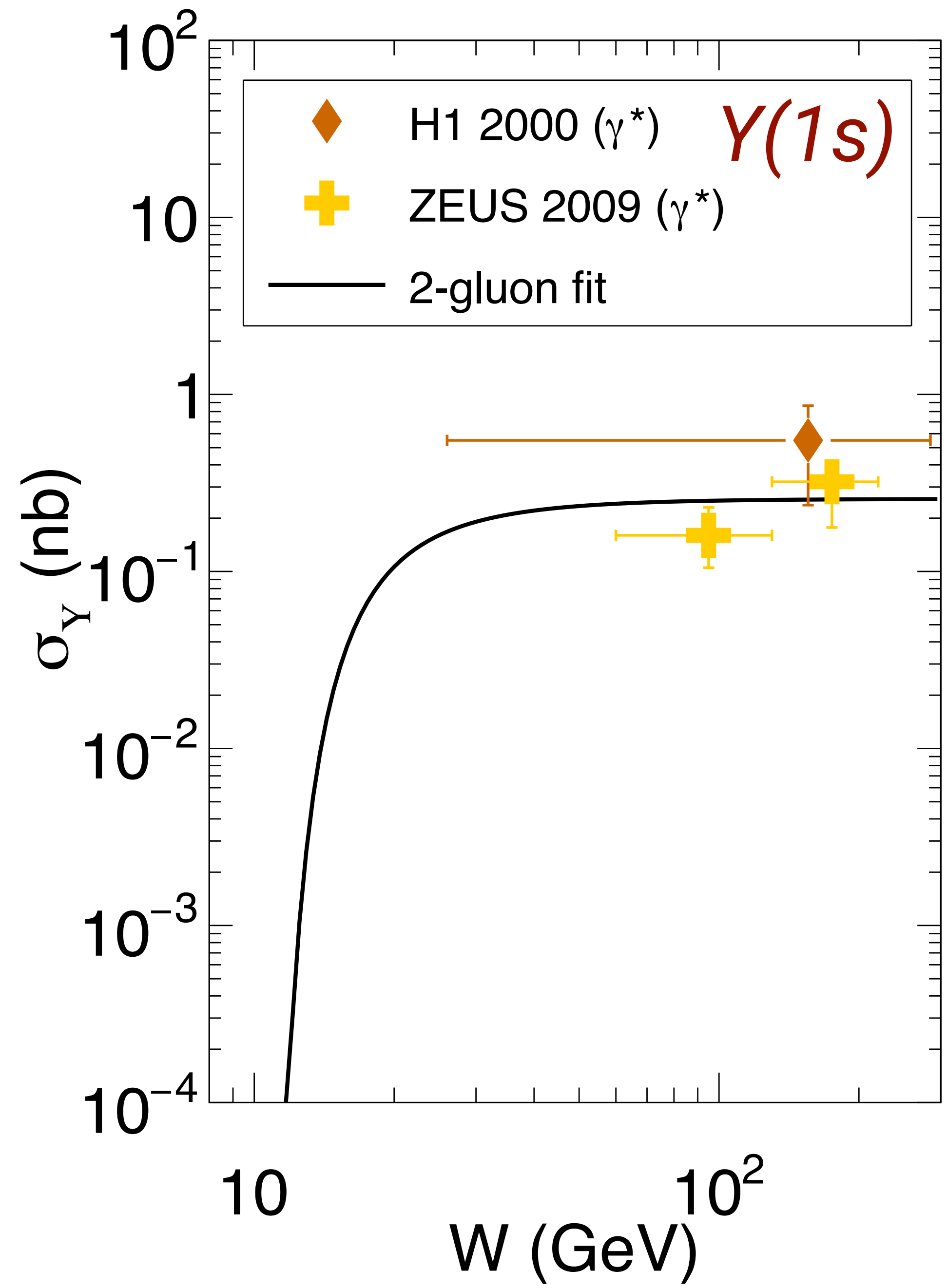




2-gluon fit near threshold

- Smallest cross section drives required precision and luminosity
  - Use **2-gluon estimate for experimental projections** near threshold





Quarkonium-nucleon **scattering amplitude**

- VMD relates photo-production cross section to quarkonium-nucleon scattering amplitude $T_{\psi p}$.

Quarkonium-nucleon **scattering amplitude**

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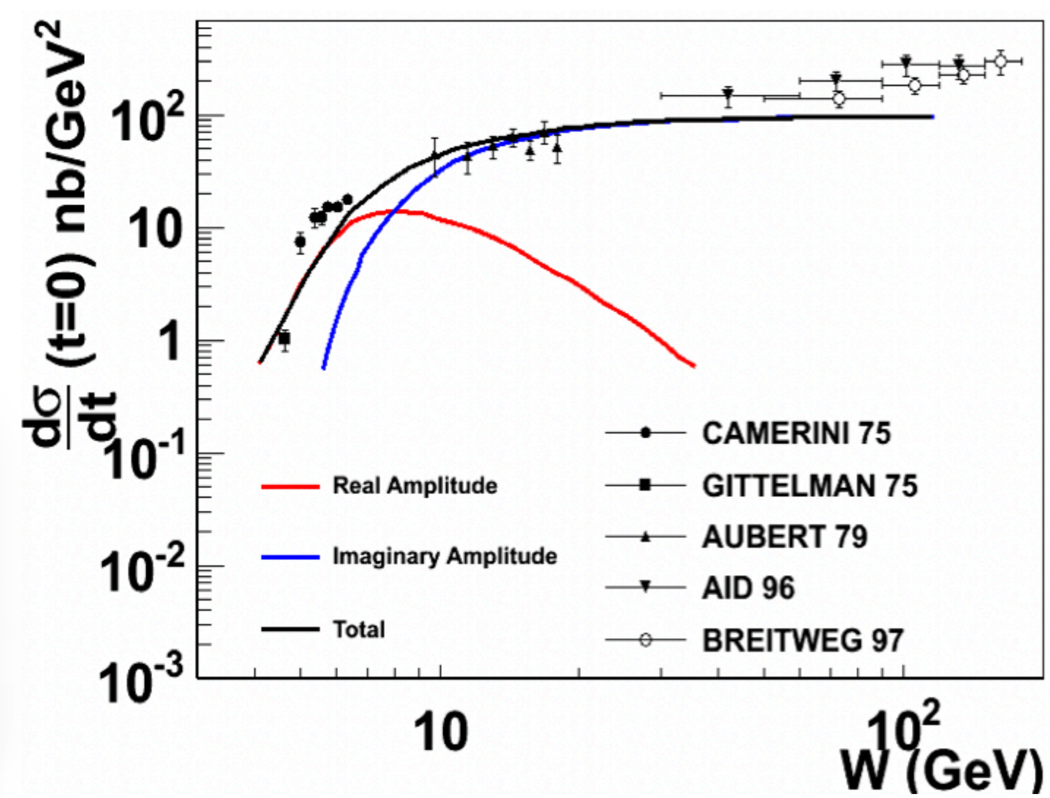
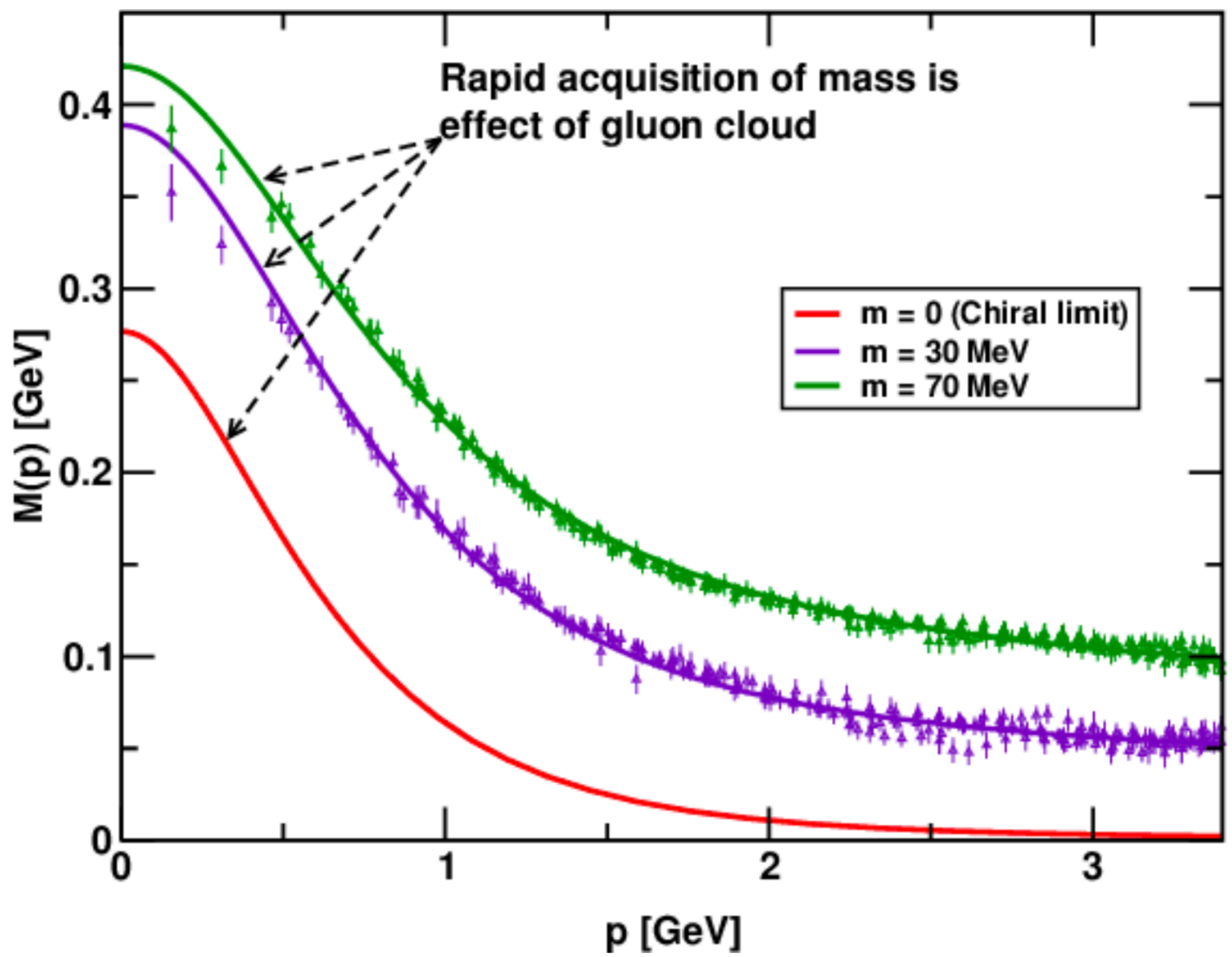
- **Real part $T_{\psi p}$ dominates near threshold**
- Mostly constrained through dispersive relations, not data.



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

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 (DCSB)
- ☆ **Gluon field accumulates ~300MeV/constituent quark**
- ☆ Even in the chiral limit **(mass from nothing)!**

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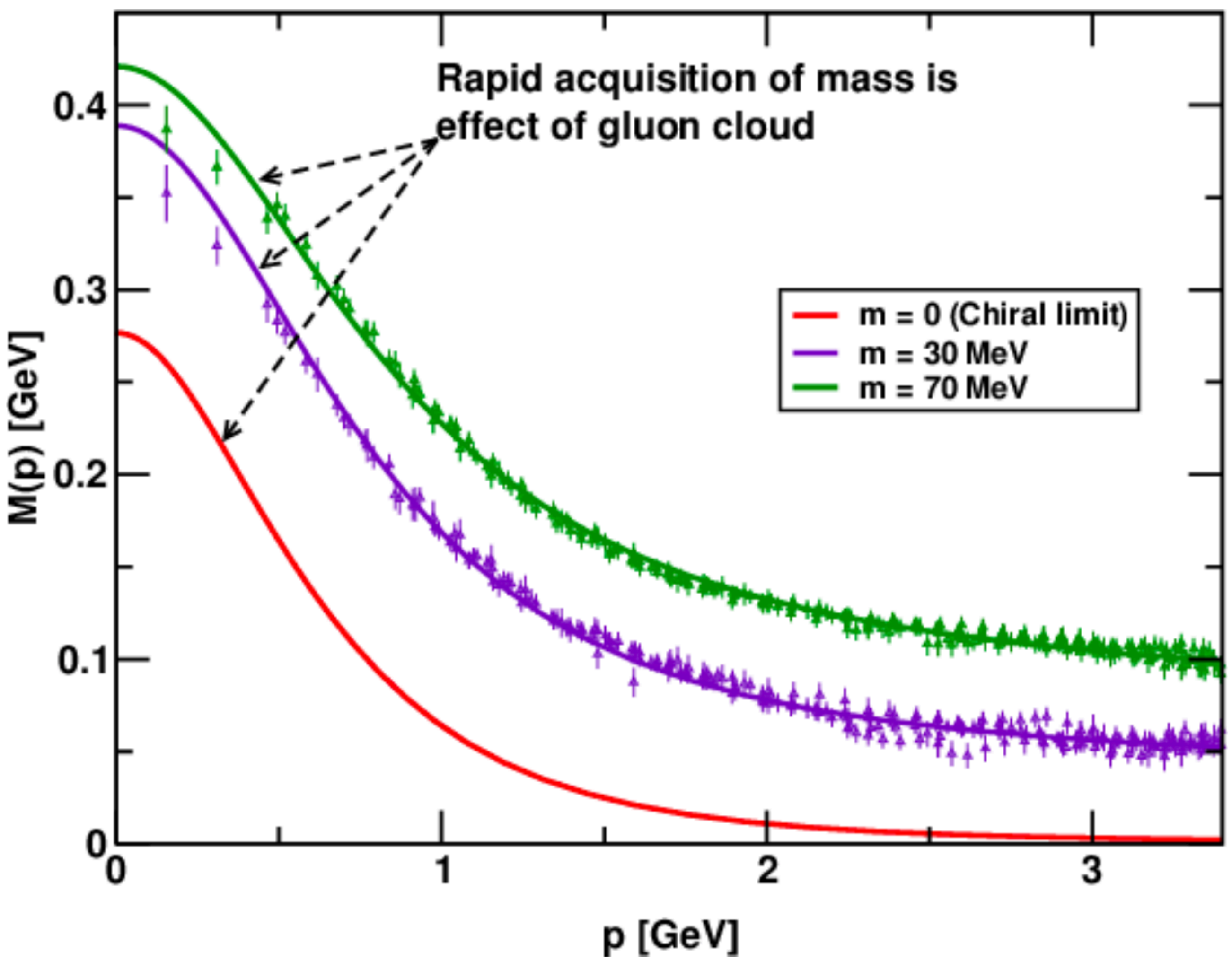

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- **The Higgs mechanism is largely irrelevant in "normal" matter!**

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

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

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- At low momentum transfer: heavy quarks decouple

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

Trace Anomaly **Light Quark Mass**

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Trace Anomaly **Light Quark Mass**

- **Trace anomaly term dominant:**
  "Proton mass result of the vacuum polarization induced by the presence of the proton."

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Trace Anomaly **Light Quark Mass**

- **Experimental access:**
  - Trace of EMT proportional to **quarkonium-proton scattering amplitude $T_{\psi p}$**

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

- **Lattice QCD:**
  - Possible to evaluate <G^2> directly

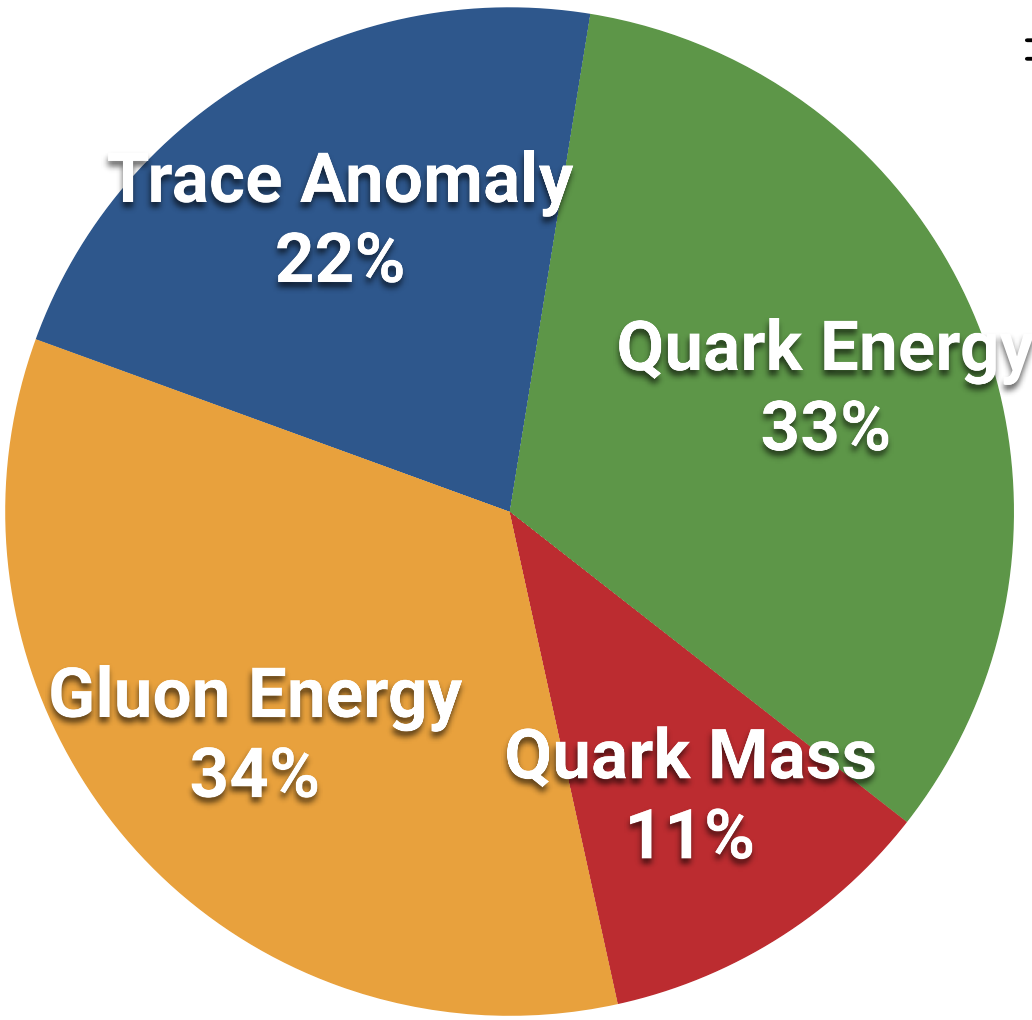
The proton mass: **rest-frame decomposition**

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:

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

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

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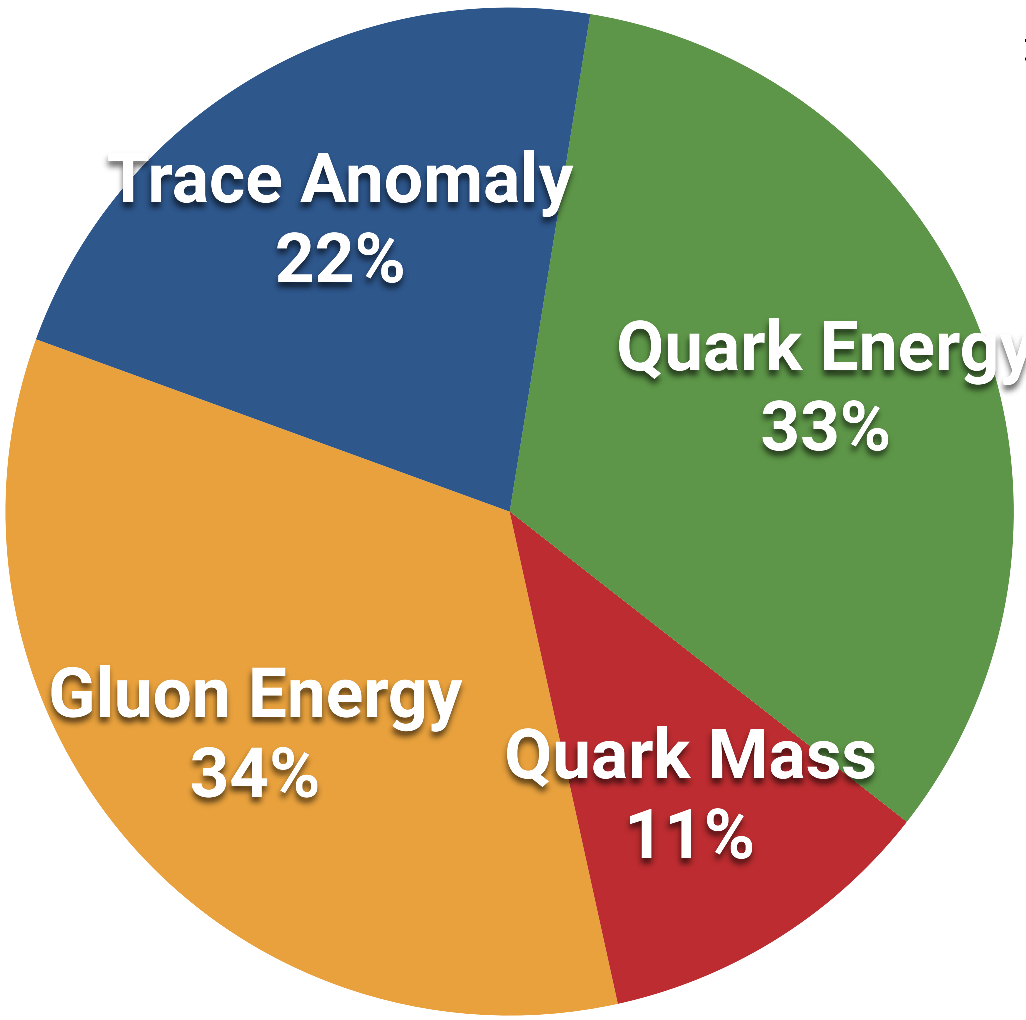

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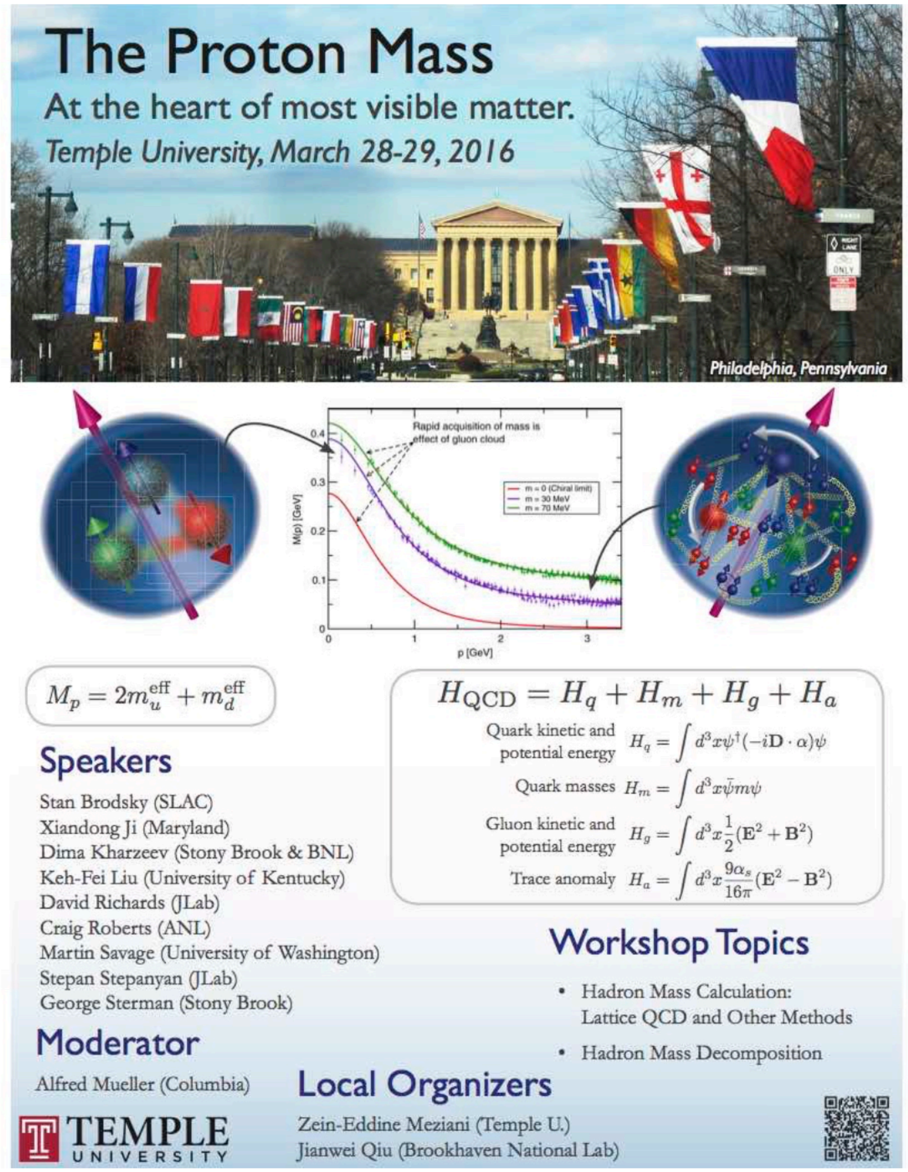
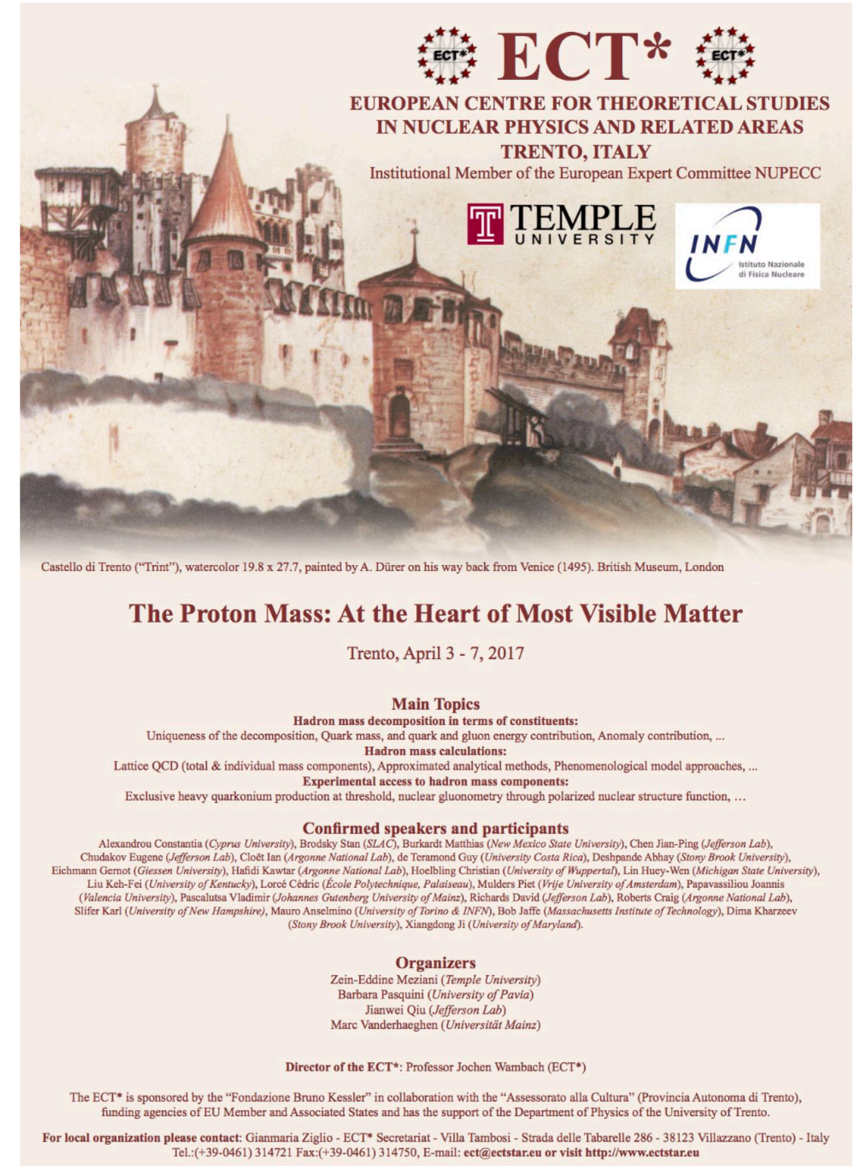
- *a(μ)* related to PDFs, well constrained
- ***b(μ)*** **related to quarkonium-proton scattering amplitude** $T_{\psi p}$ **near-threshold**

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)





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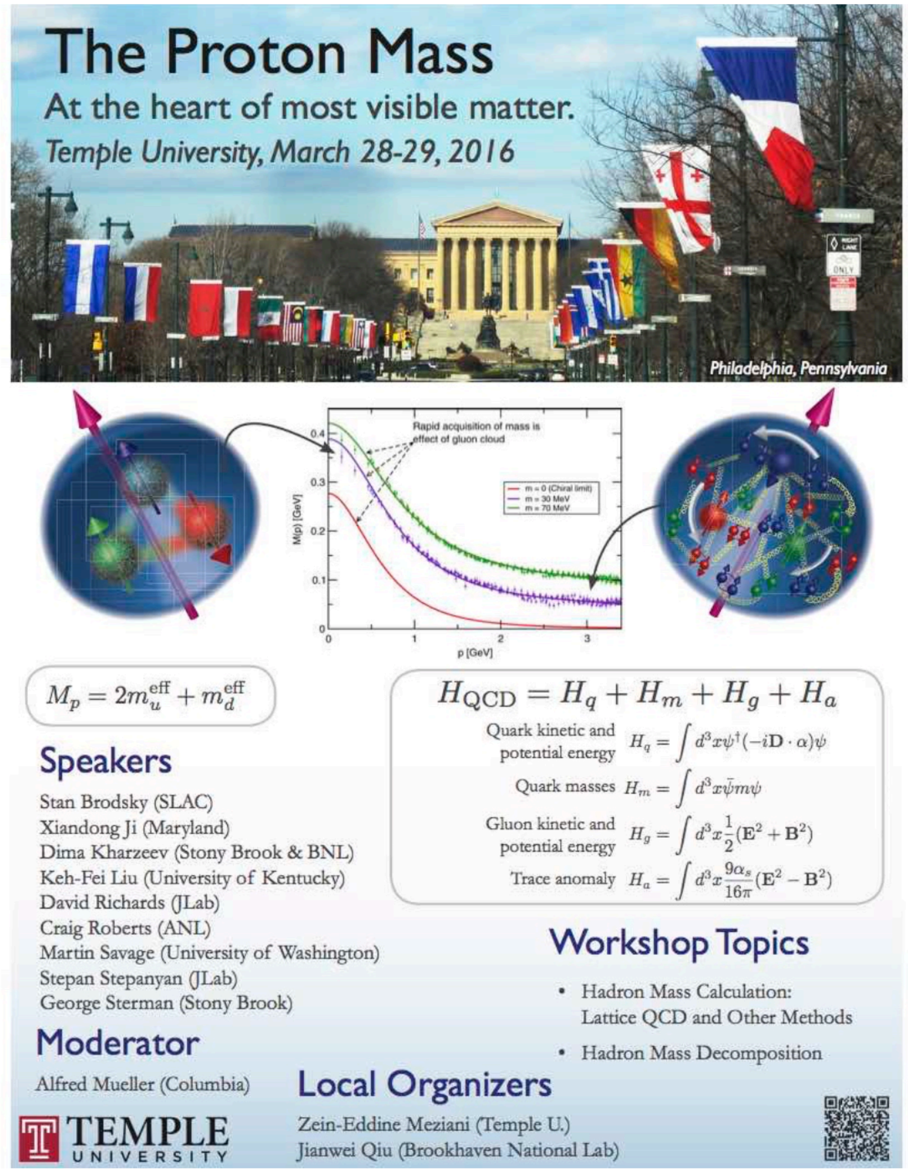

JLab will play a leading role:

Access trace anomaly through elastic J/ψ production near threshold

Binding energy of the J/ψ - nucleon potential

- 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 $a_{\psi p}$**

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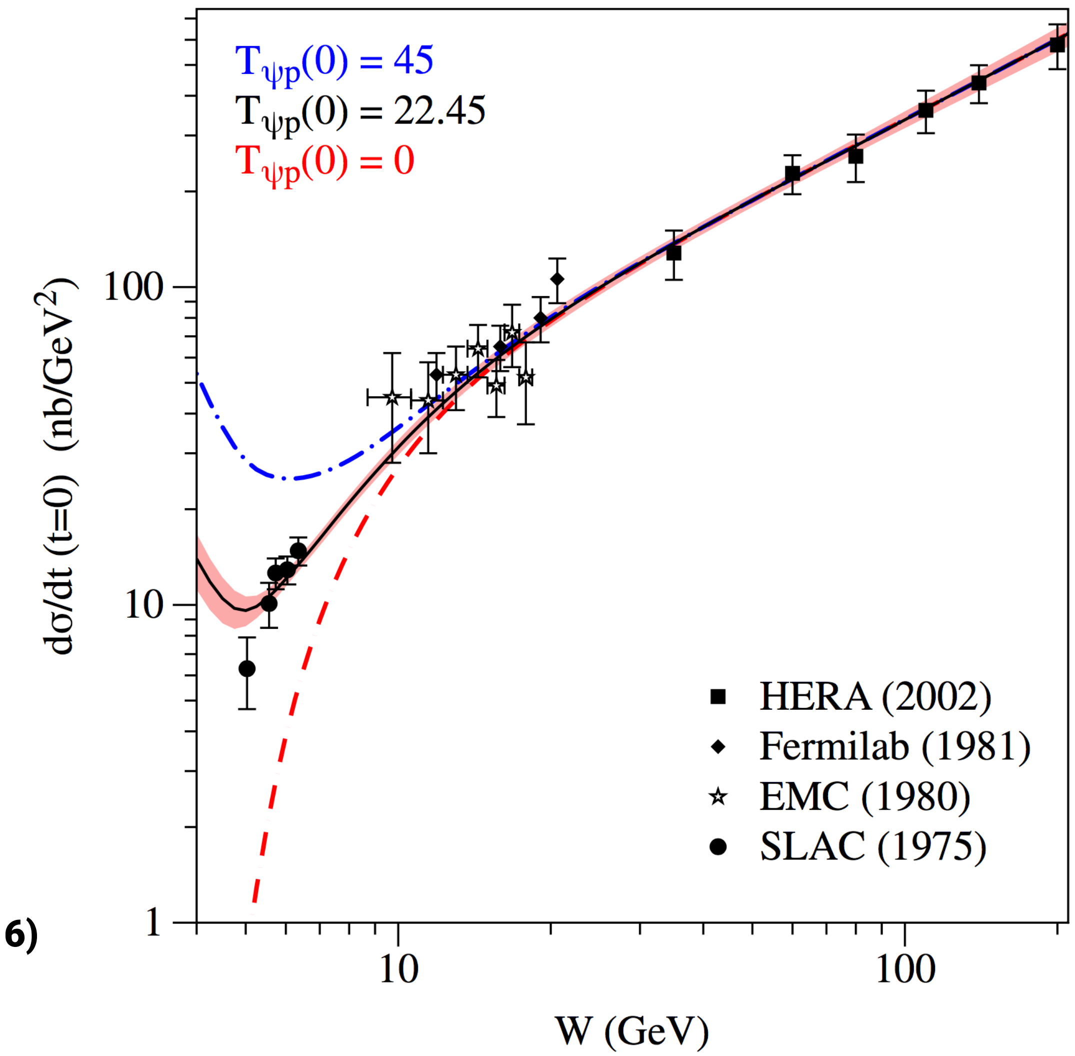
  - **Binding $B_{\psi p}$** can be **derived from $a_{\psi p}$**
    - Estimates between 0.05-0.30 fm, corresponding to $B_{\psi p}$ < 20 MeV
    - LQCD: $B_{\psi p}$ < 40 MeV

      S. R. Beane *et al.*, Phys. Rev. D 91, 114503 (2015)
    - Recent fit to existing data in a dispersive framework:
      - $a_{\psi p}$ ~ 0.05 fm ($B_{\psi p}$ ~ 3 MeV)

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



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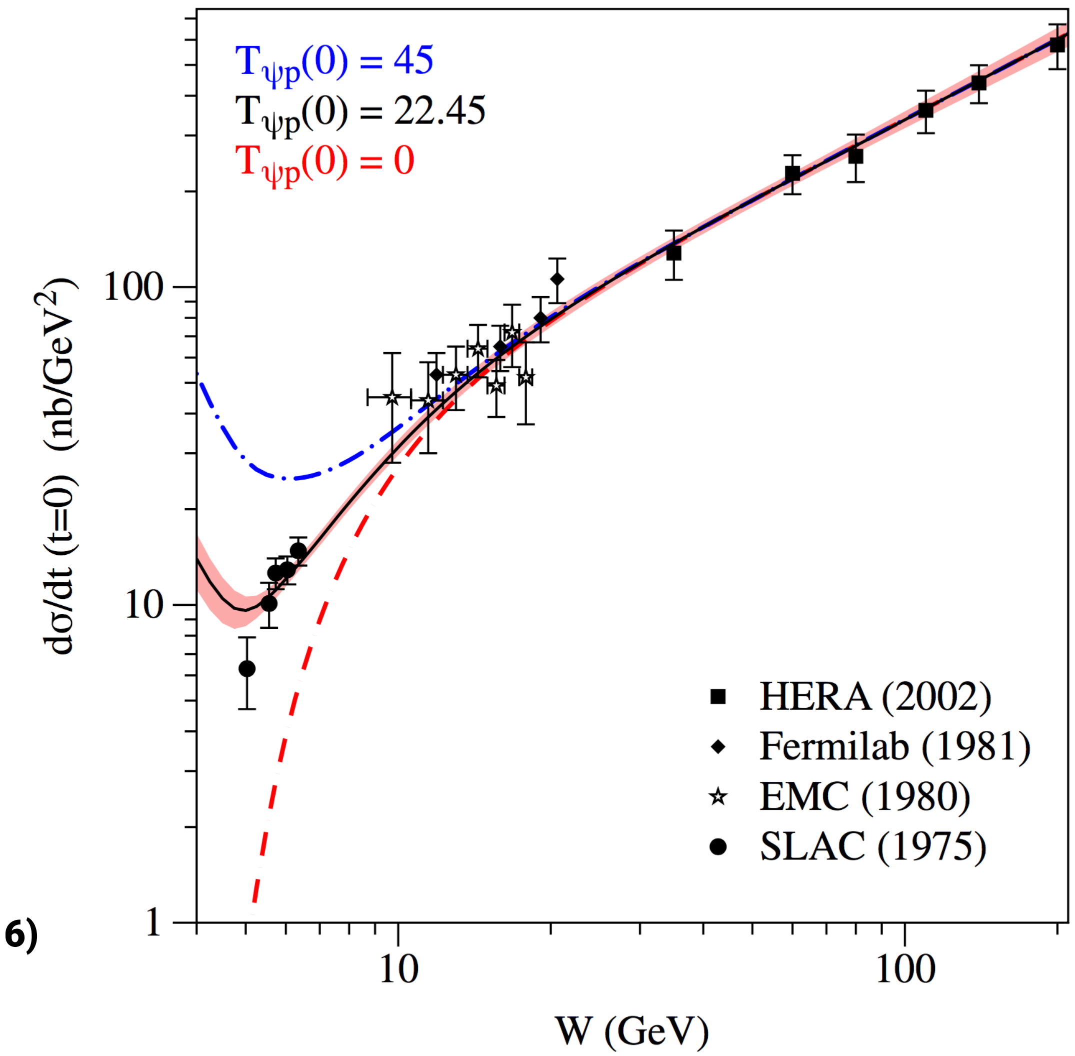
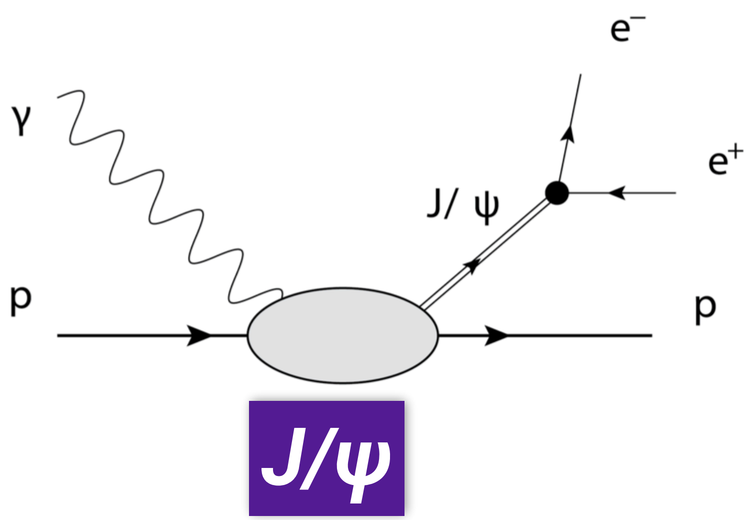
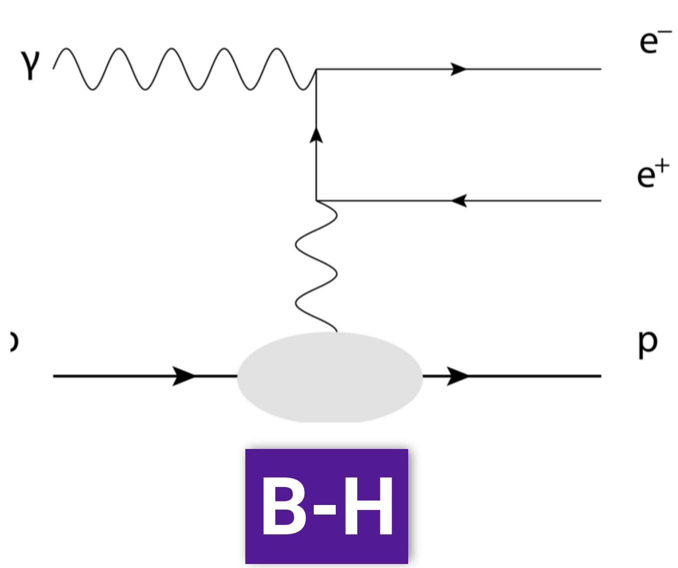
- Photo-production near threshold constrained through dispersion relations, not data
- **Threshold experiments needed!**



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 $B_{\psi p}$

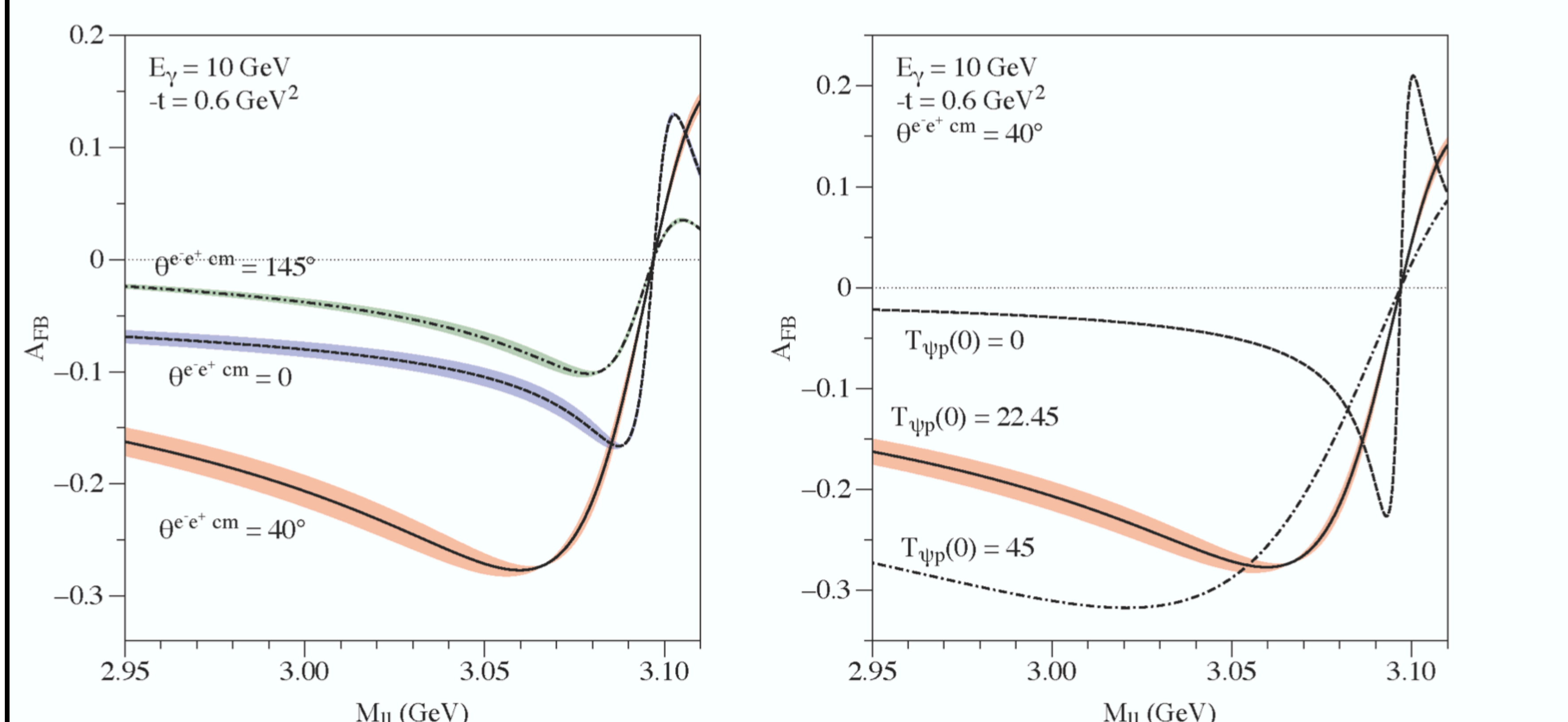




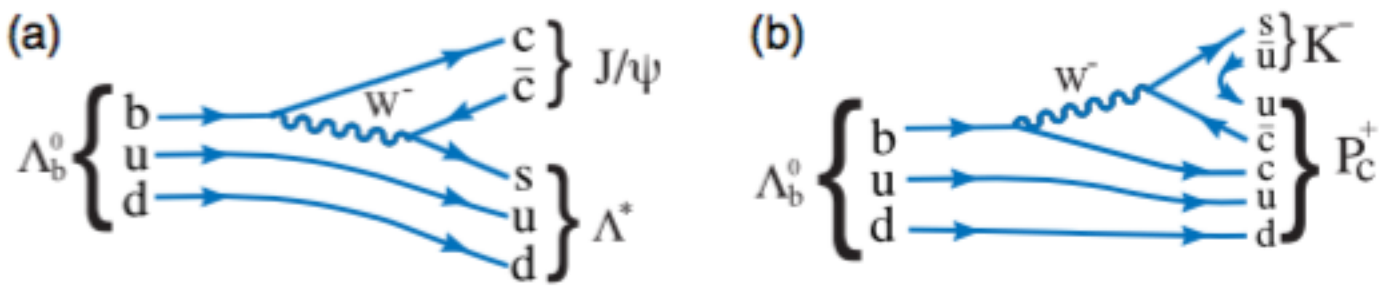
interference term

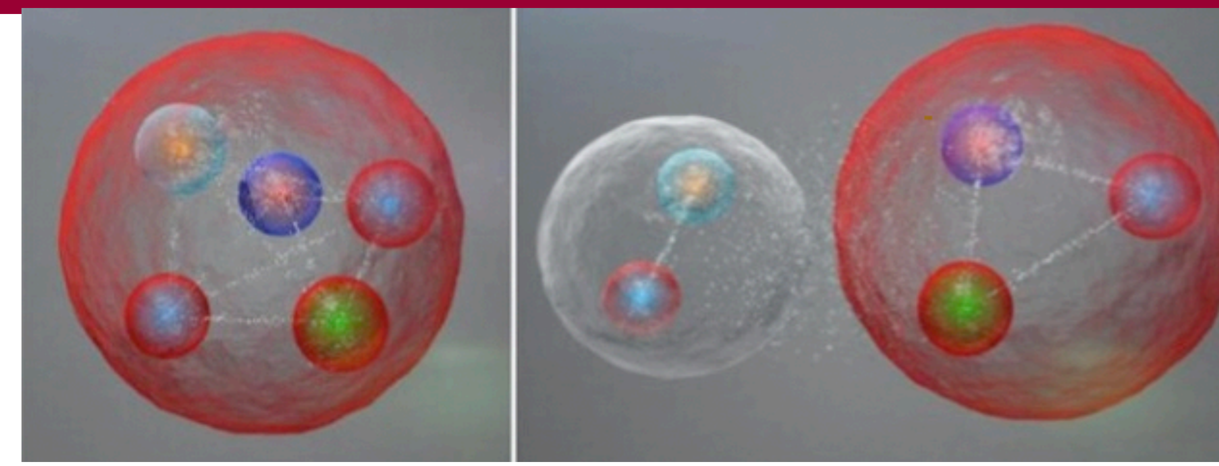
$$A_{\mathrm{FB}} \equiv \frac{\frac{d\sigma}{d\Omega}(\theta_{cm}) - \frac{d\sigma}{d\Omega}(\theta_{cm}-\pi)}{\frac{d\sigma}{d\Omega}(\theta_{cm}) + \frac{d\sigma}{d\Omega}(\theta_{cm}-\pi)} = \frac{\sum_s 2\,\mathrm{Re}T_\psi\, T_{BH}}{\sum_s |T_\psi|^2 + \sum_s |T_{BH}|^2}$$

θ_{cm} — scattering angle in a lepton pair CM frame



charmed “pentaquark” in **photo-production**





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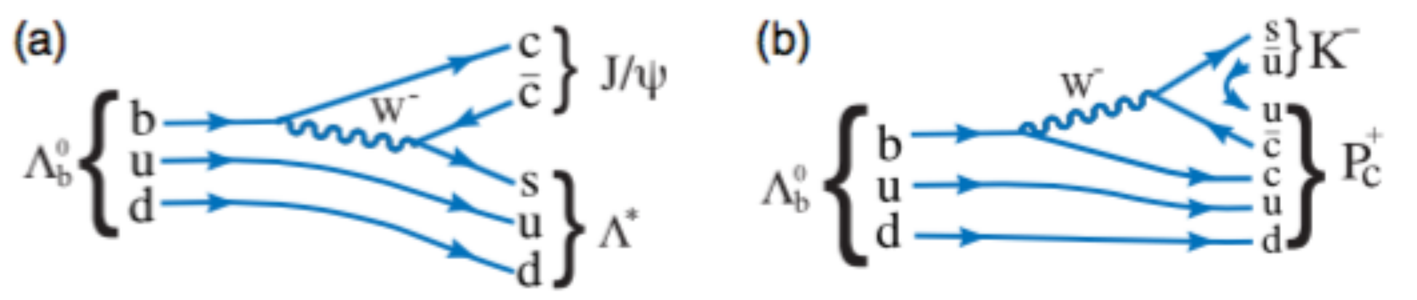

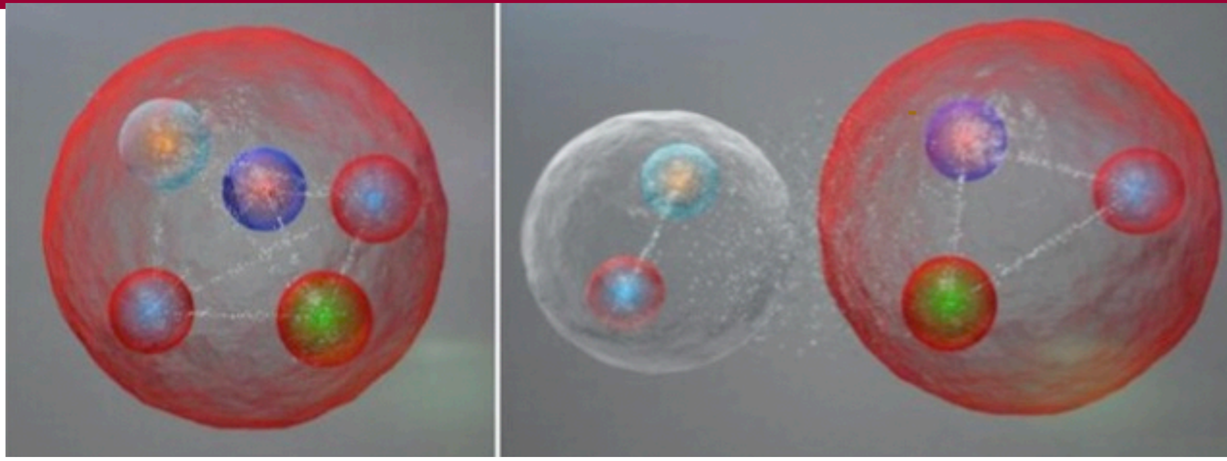

- Possible explanations for LHCb observations:
  - **LHCb**: 2 new **charmed "pentaquark"** (P_c) states
  - **alternative: kinematic enhancements** through anomalous triangle singularity **(ATS)**

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

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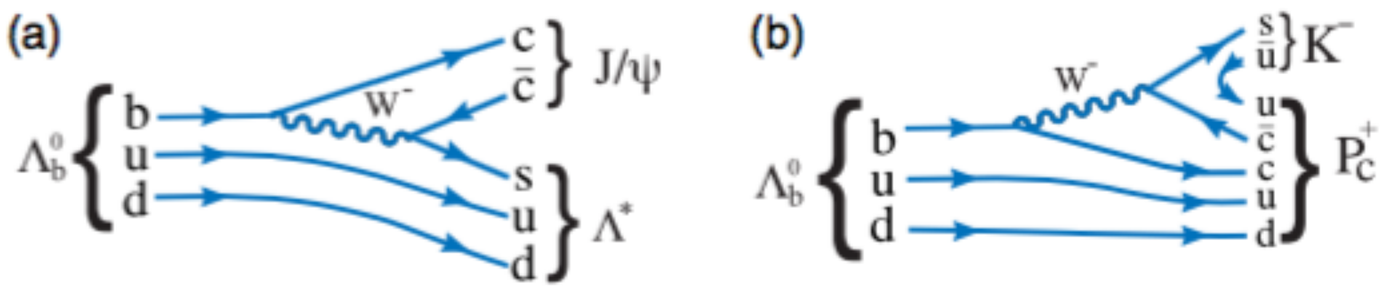

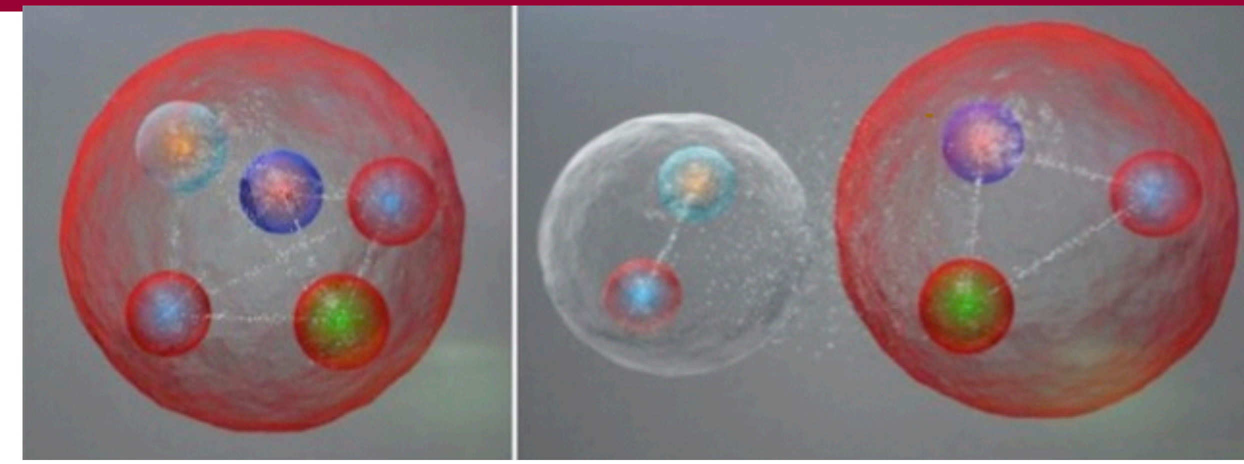

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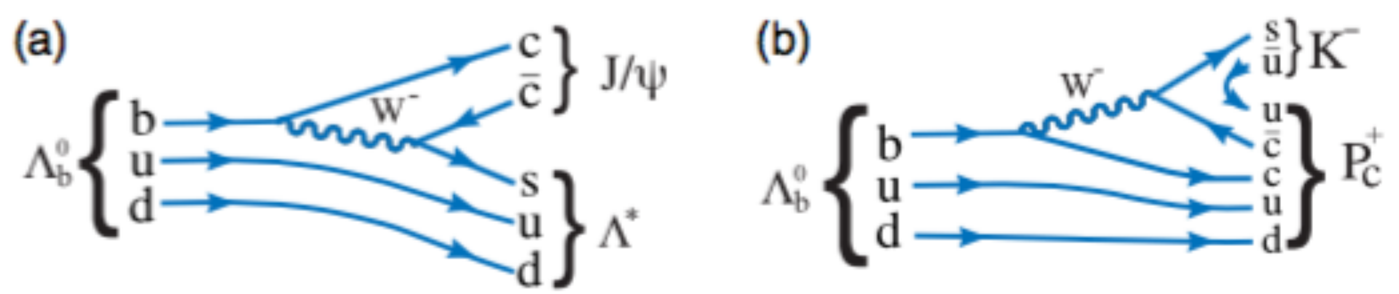
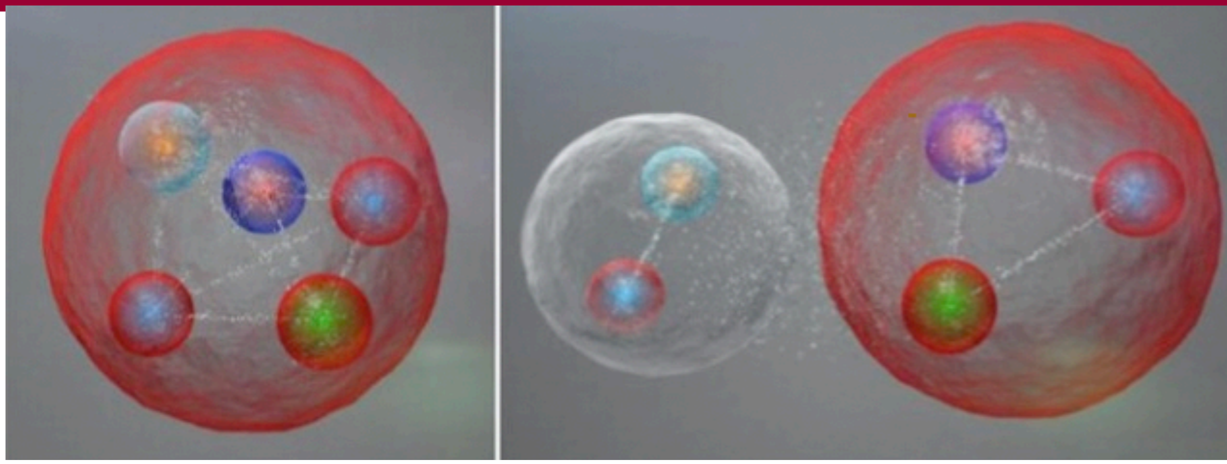
- **Photo-production** ideal tool to **distinguish** between both explanations
  - if P_c real states, **also created in photo-production**
  - kinematic enhancement through **ATS not possible**

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

charmed “pentaquark” in **photo-production**





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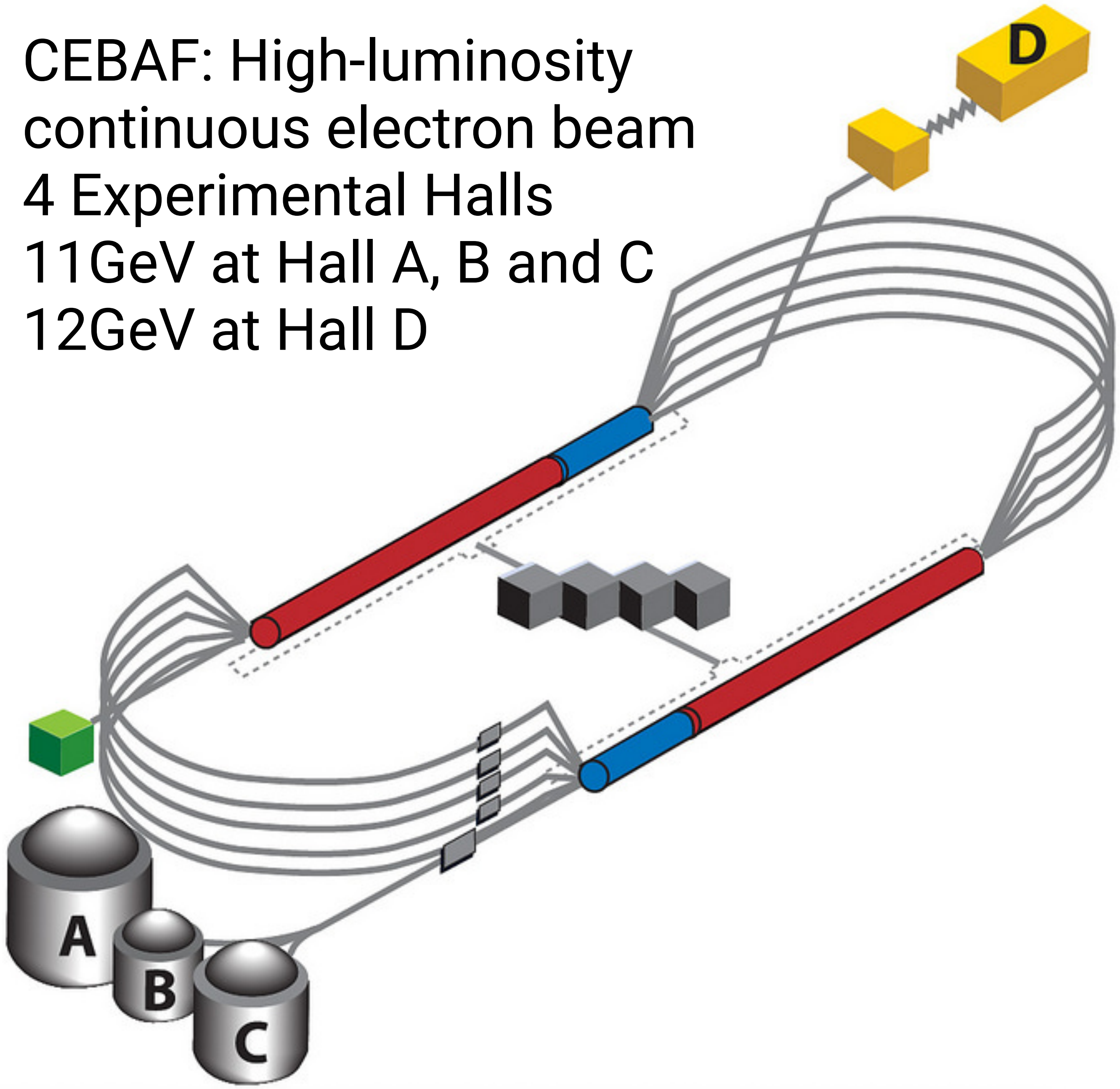
  Wang Q., *et al.*, PRD 92-3 (2015) 034022 (and references therein)
- P_c(4450) translates to **narrow peak around E_γ = 10 GeV**

JLab perfect place for this measurement!

J/ψ at JLab in **the 12GeV era**

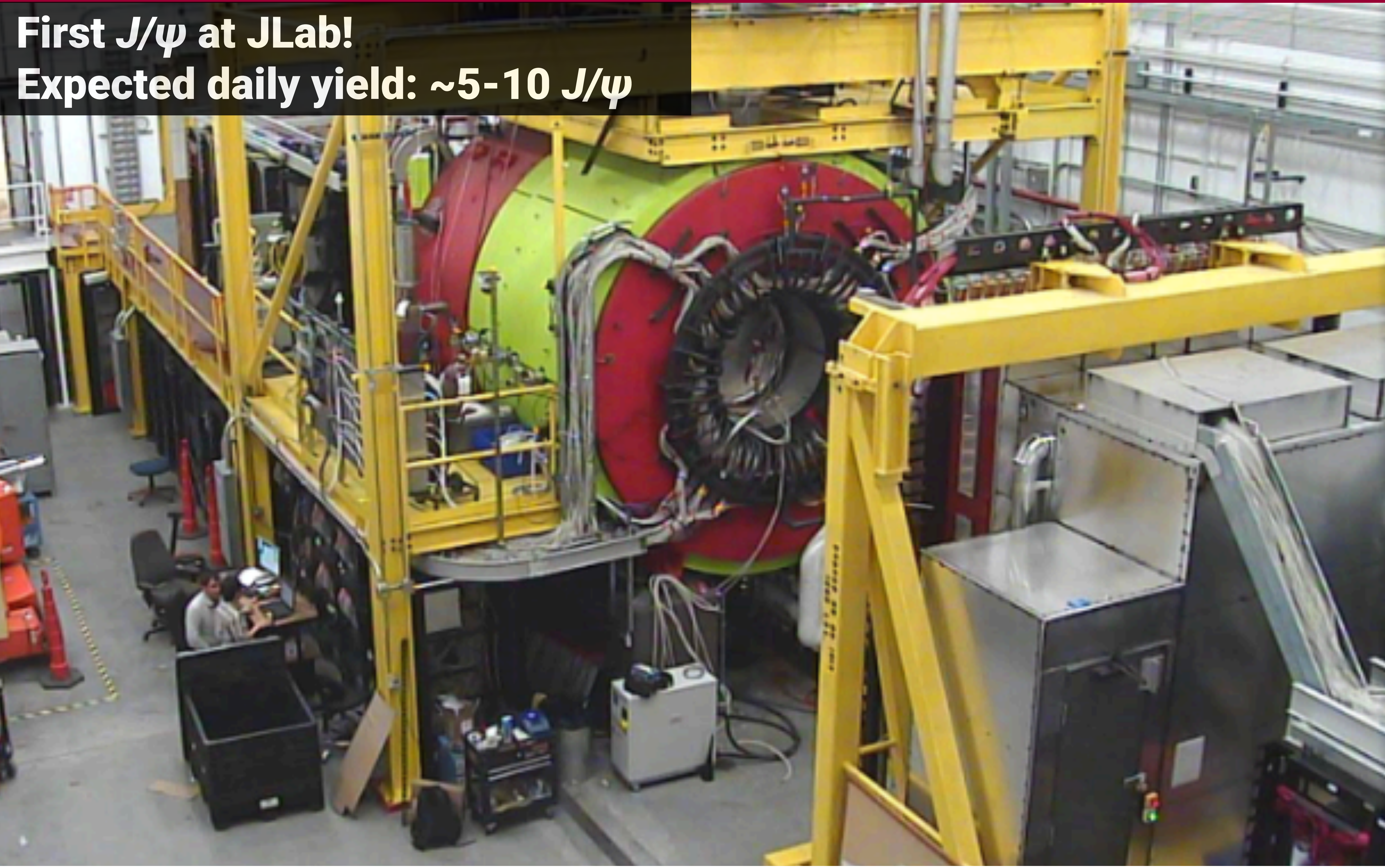
- CEBAF: High-luminosity continuous electron beam
- 4 Experimental Halls
- 11GeV at Hall A, B and C
- 12GeV at Hall D



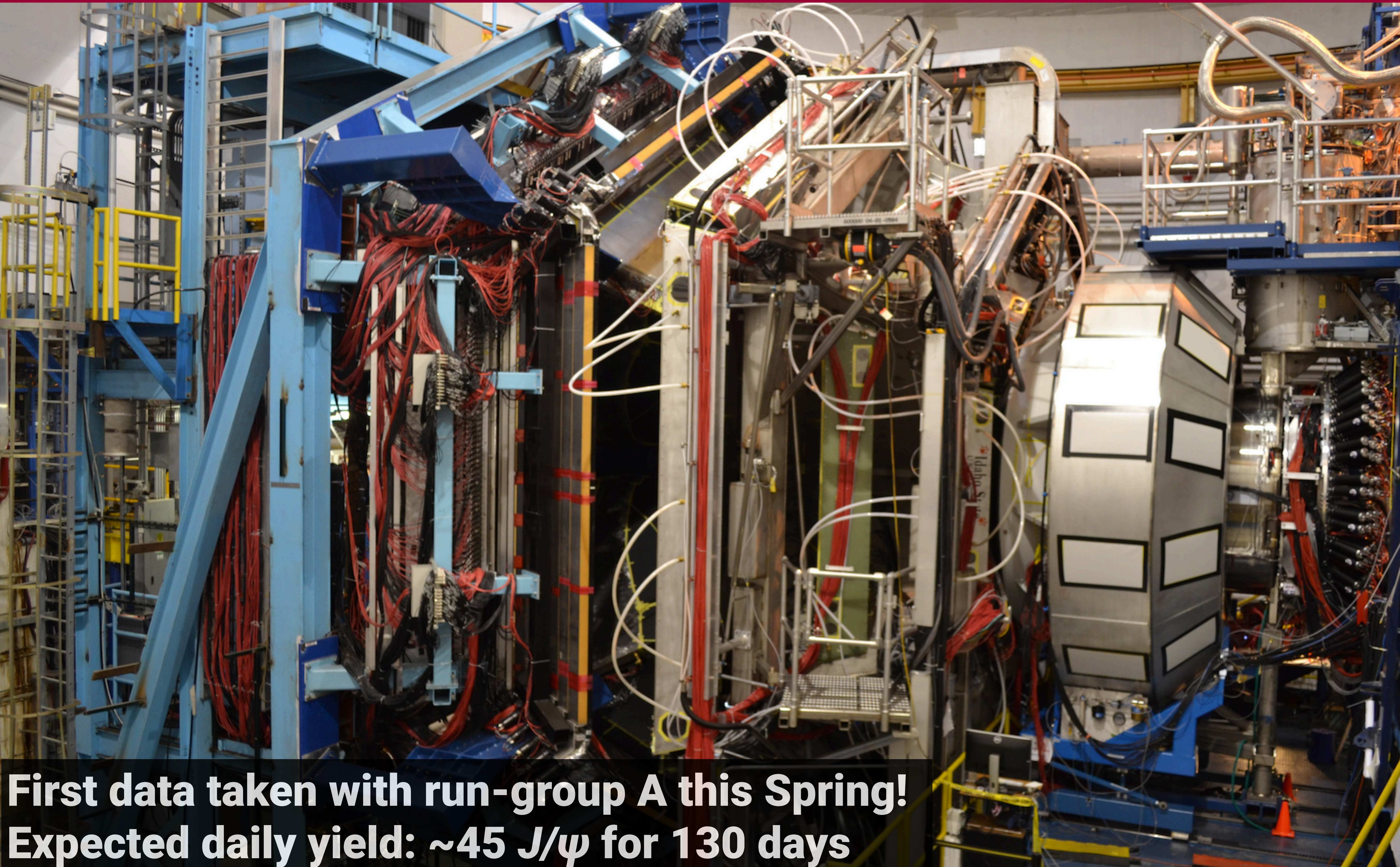
JLab is the ideal laboratory to measure *J/ψ* near threshold, due to luminosity, resolution and energy reach!

J/ψ in Hall D/**GlueX**

First J/ψ at JLab!
Expected daily yield: ~5-10 J/ψ



***J/ψ* experiment** E12-12-001 in Hall B/**CLAS12**

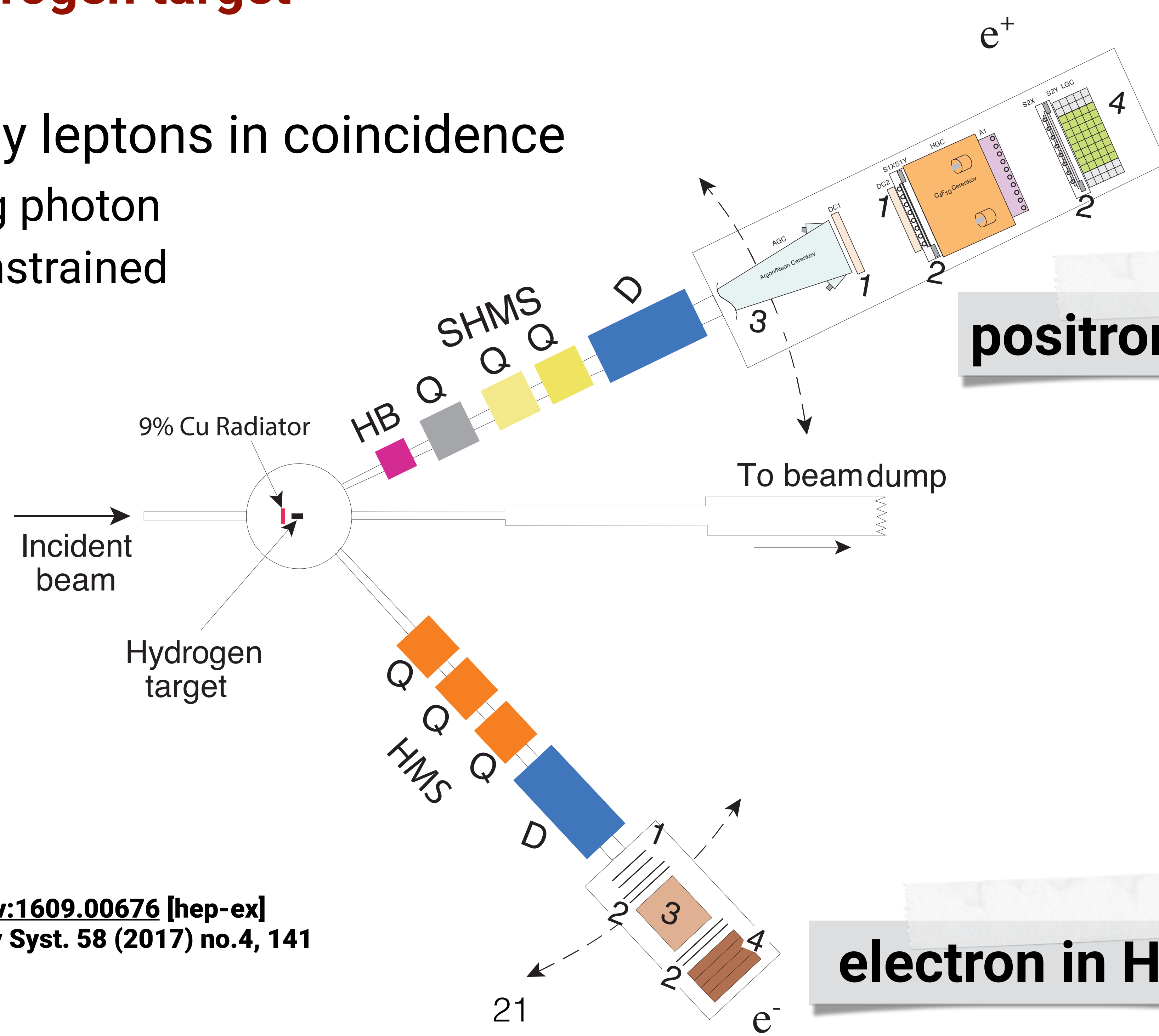


First data taken with run-group A this Spring!
Expected daily yield: ~45 *J/ψ* for 130 days

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

J/ψ–007

- 50μA electron beam at 10.6 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



positron in SHMS

electron in HMS

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

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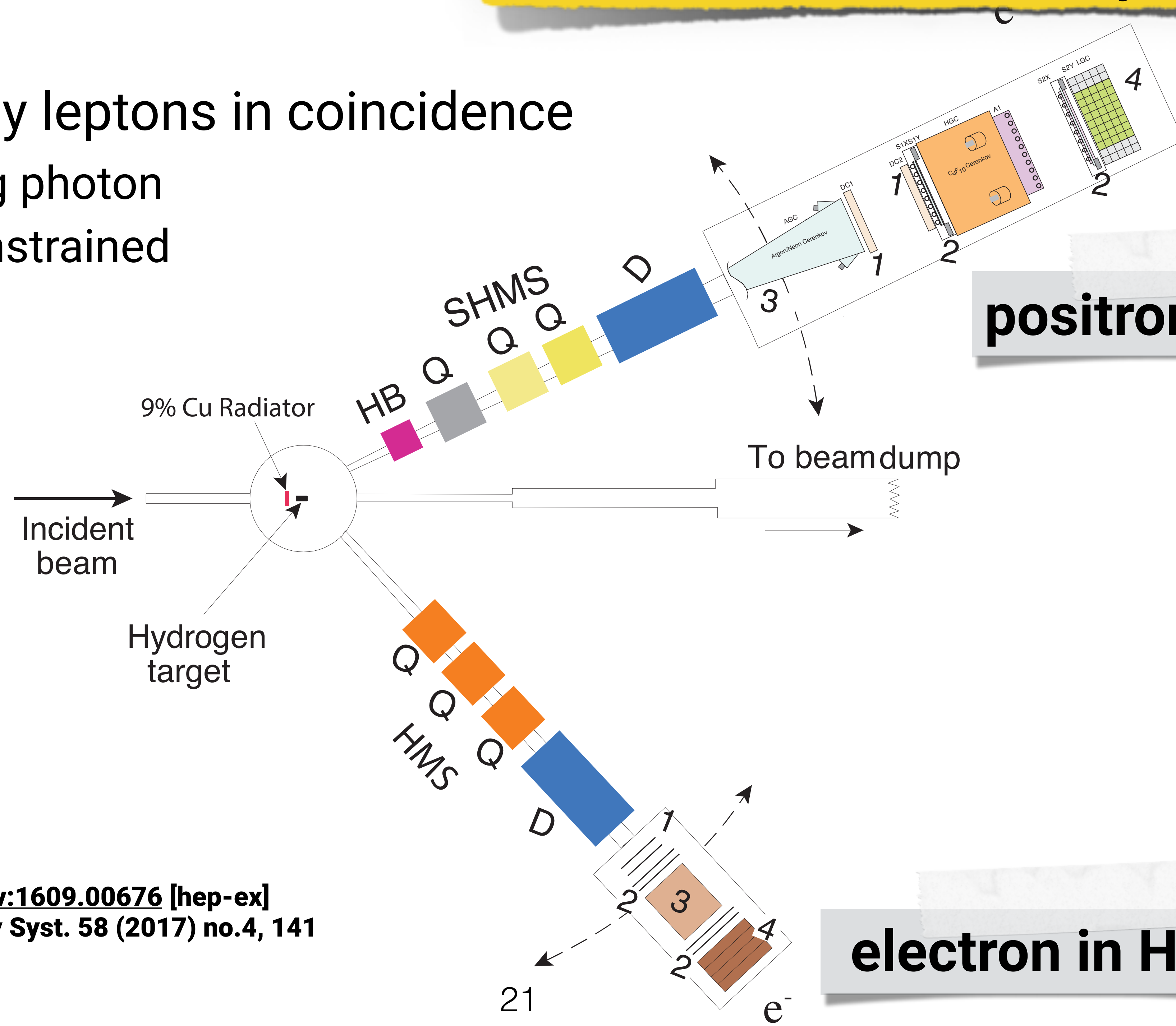
High-impact experiment ...will run February 2019!



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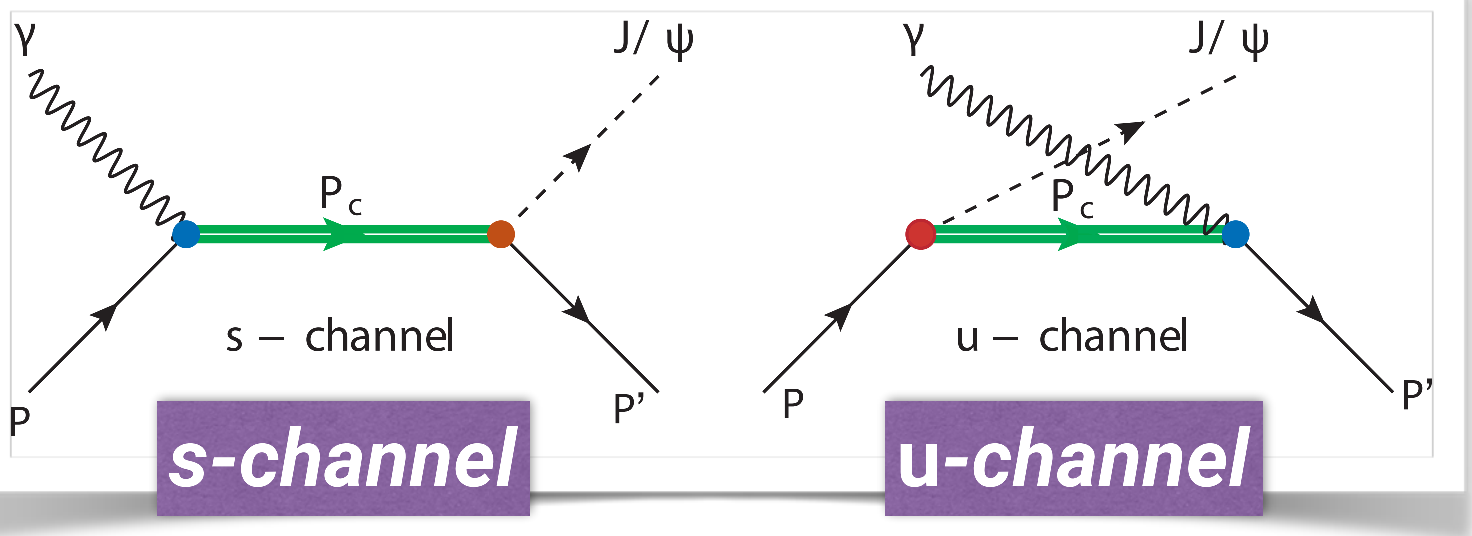
TEMPLE UNIVERSITY

S. Joosten

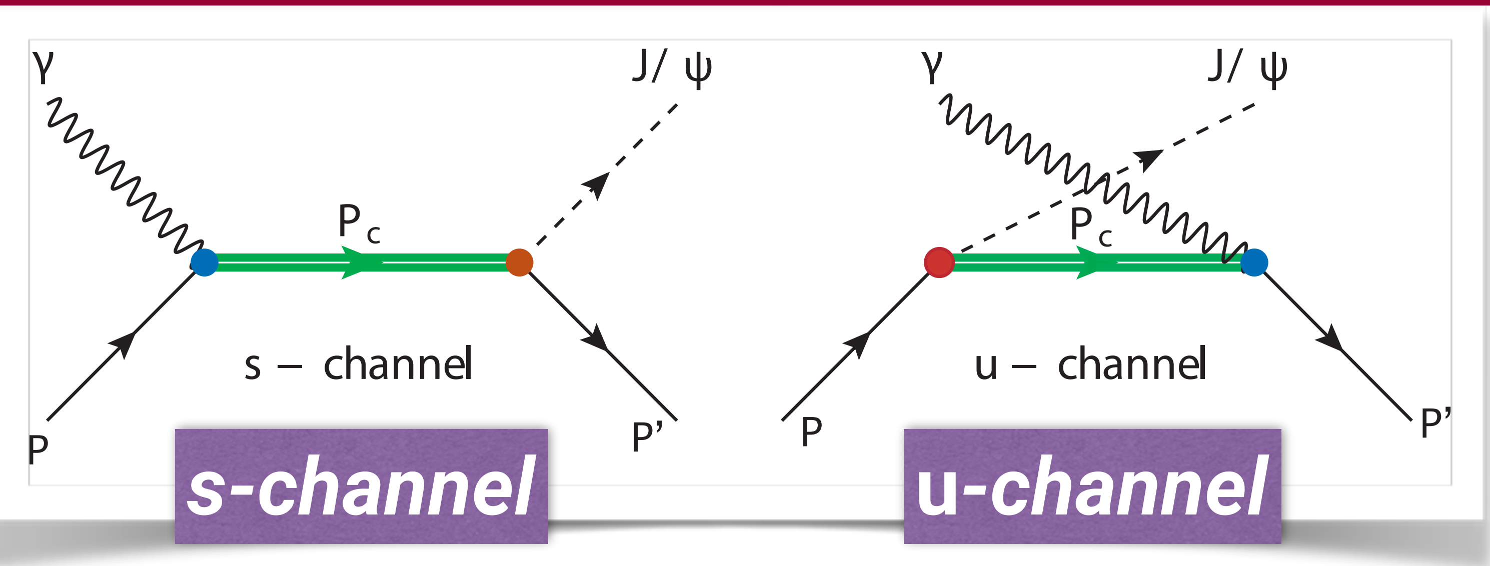
Resonant J/ψ production through P_c decay

J/ψ—007



Resonant J/ψ production through P_c decay

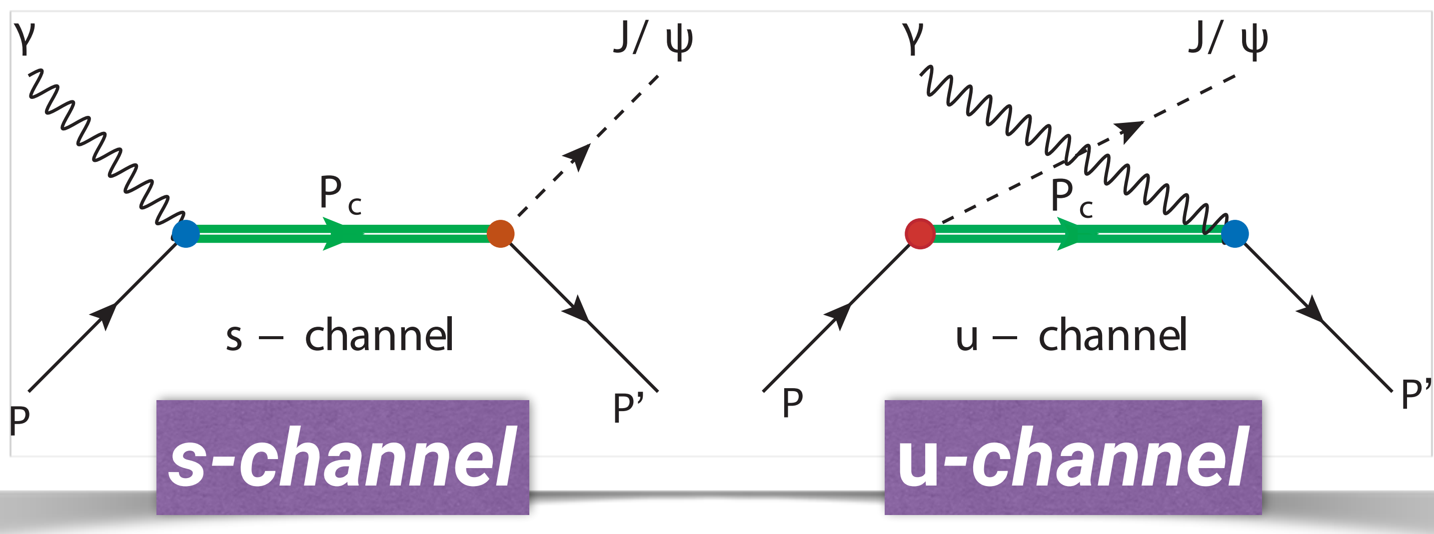
$J/\psi - 007$



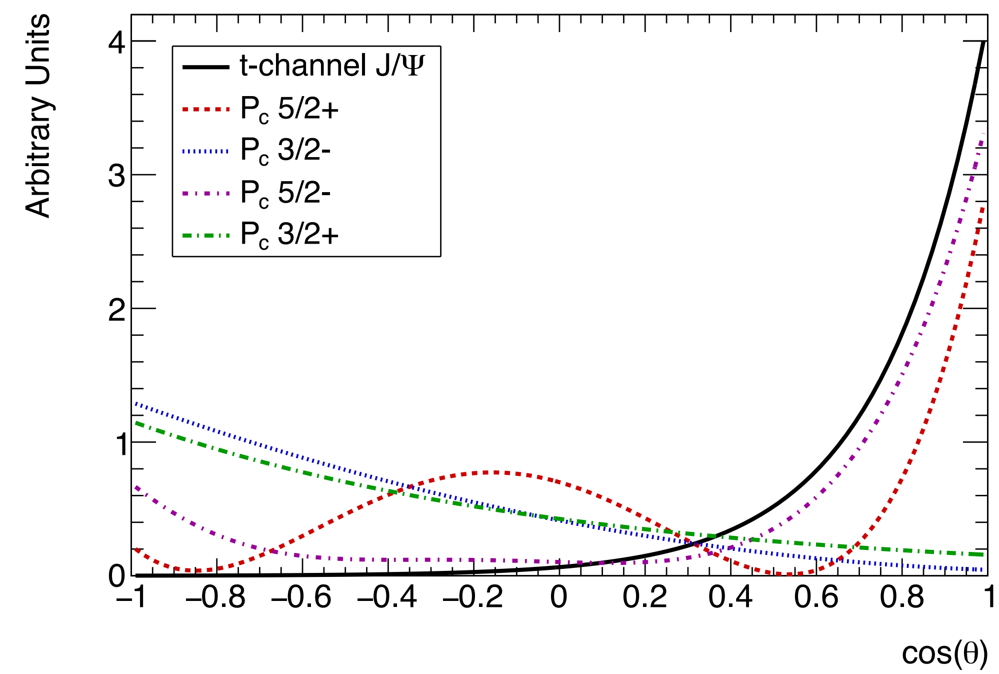
- Cross section depends on **coupling of P_c to (J/ψ, p) channel**

Resonant J/ψ production through P_c decay

J/ψ–007



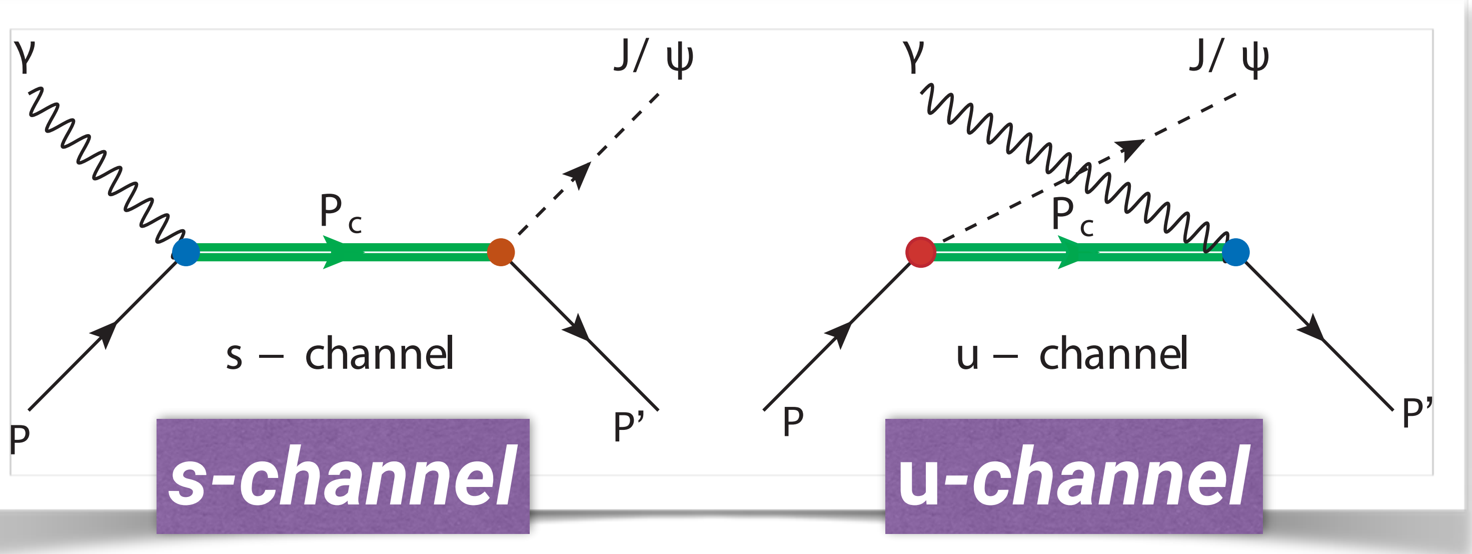
$$\frac{d\sigma}{d\cos\theta_{J/\psi}}(\gamma p \to P_c \to J/\psi p)$$



- Cross section depends on **coupling of *P_c* to (*J/ψ*, *p*) channel**
- ***J/ψ* angular distribution** differs between *t*-channel and *s*(*u*)-channel

Resonant J/ψ production through P_c decay

J/ψ–007

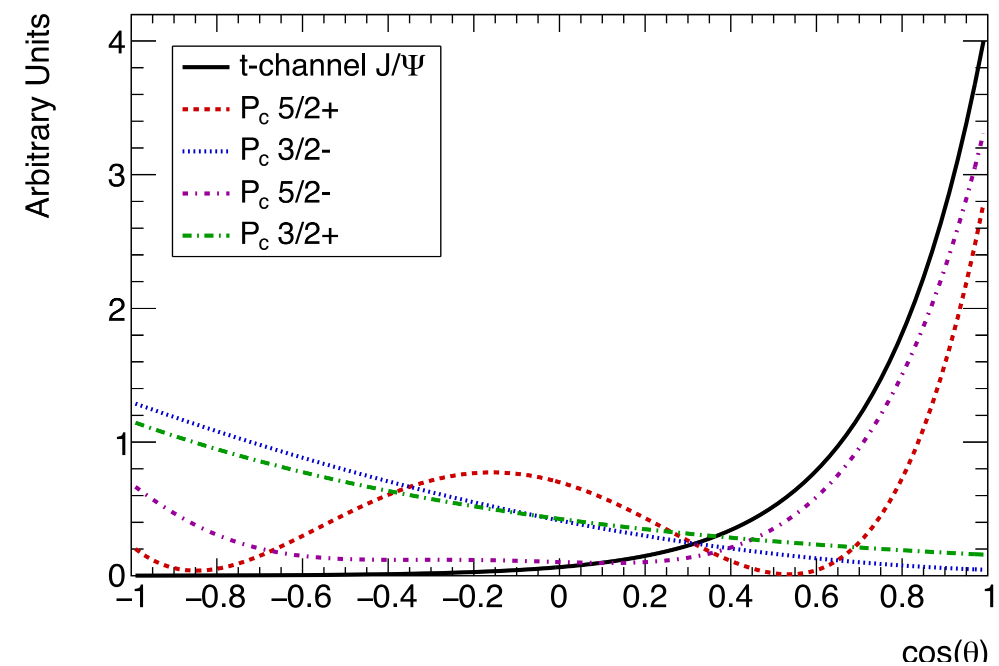


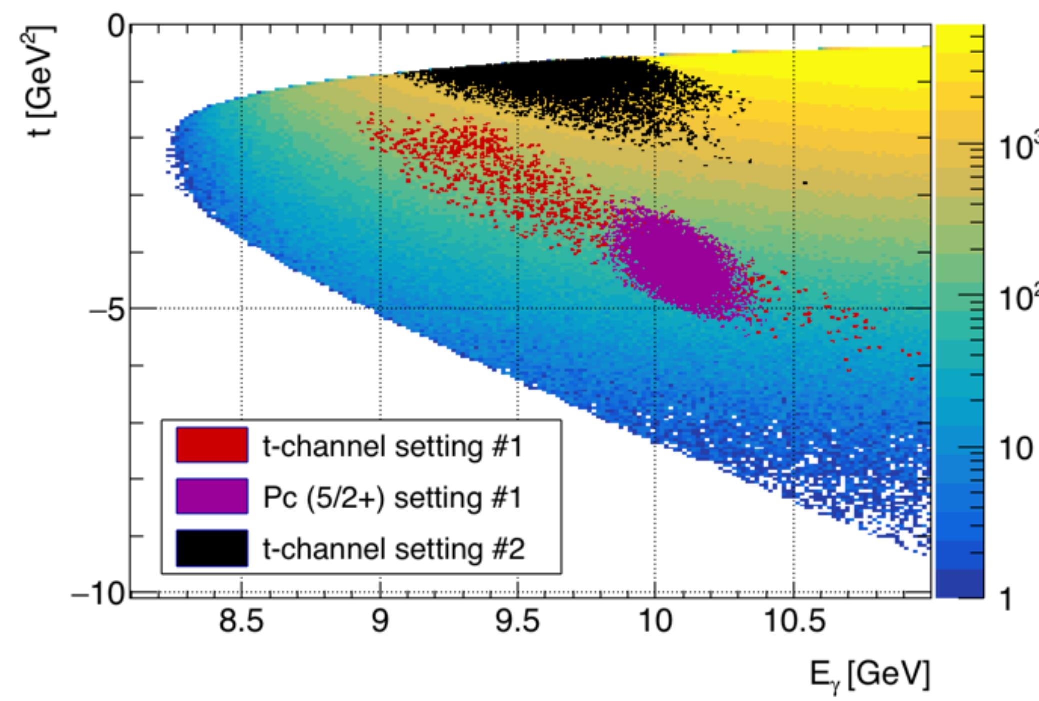
$$\frac{d\sigma}{d\cos\theta_{J/\psi}}(\gamma p \to P_c \to J/\psi p)$$

- Cross section depends on **coupling of P_c to (J/ψ, p) channel**
- ***J/ψ* angular distribution** differs between *t*-channel and *s*(*u*)-channel

Leverage angular dependence to maximize sensitivity at low coupling!

- 2 settings:
  - "**SIGNAL**" (#1) to maximize S/B
  - "**BACKGROUND**" (#2) to precisely determine *t*-channel J/ψ cross section

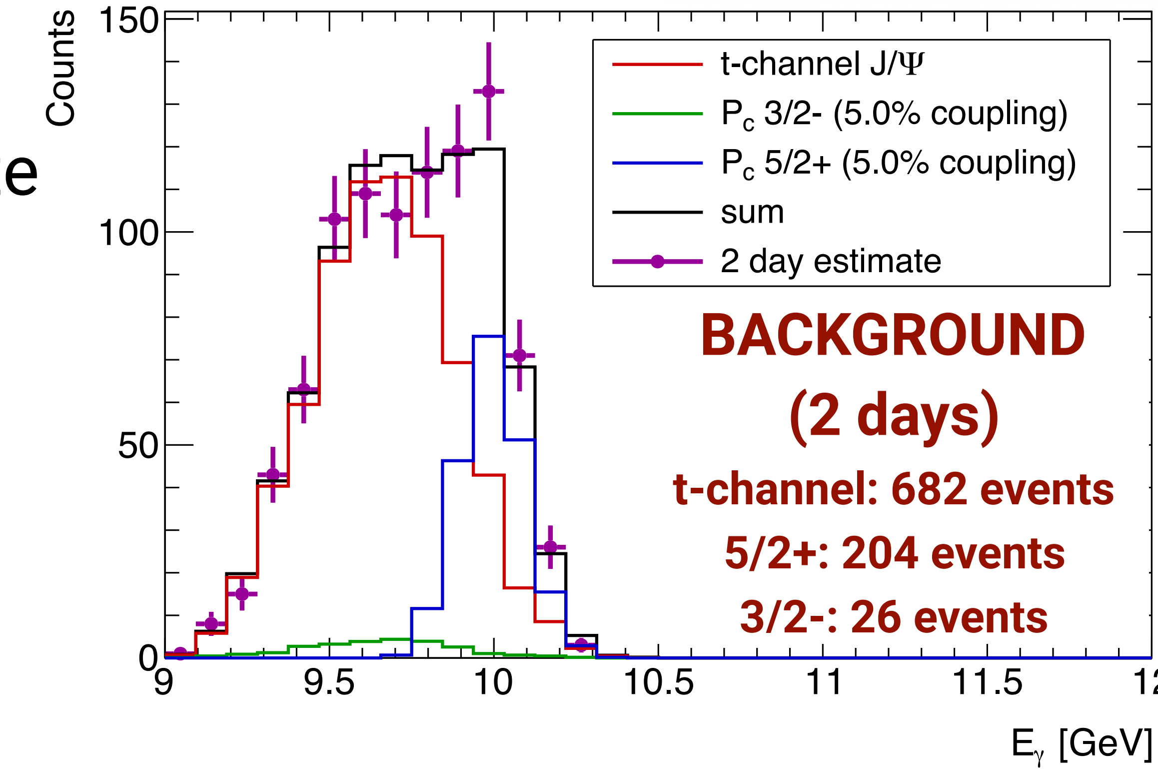


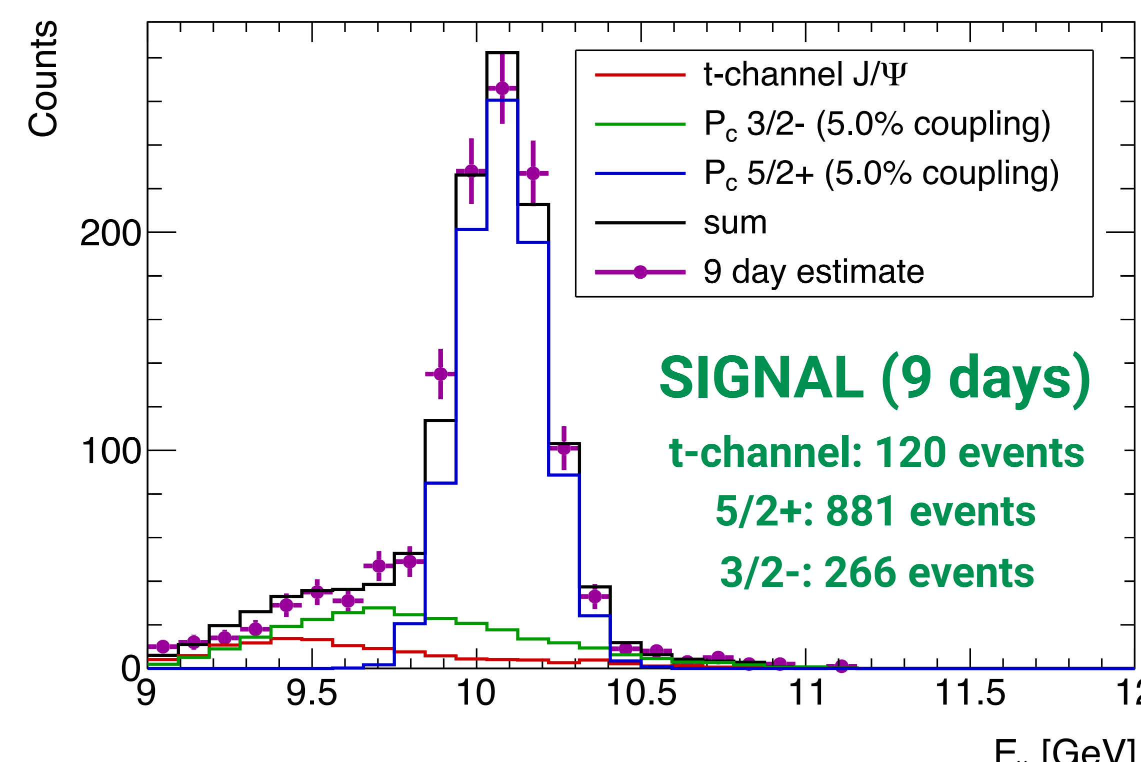


Projected results for P_c search in Hall C

J/ψ−007

- 2+9 days of beam time at 50μA
- **5/2+ peak dominates the spectrum**
  - 26x reduction in *t*-channel background rate
- Background measurement will provide **first-hand information about *t*-channel production near threshold**





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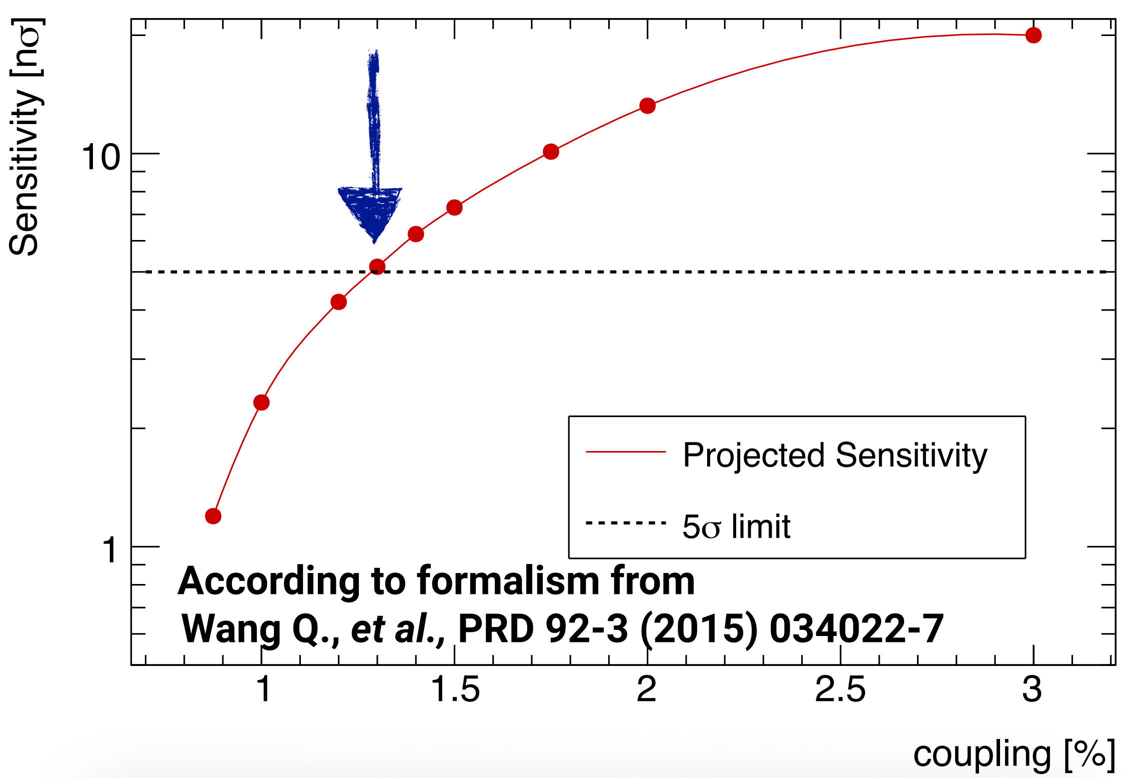
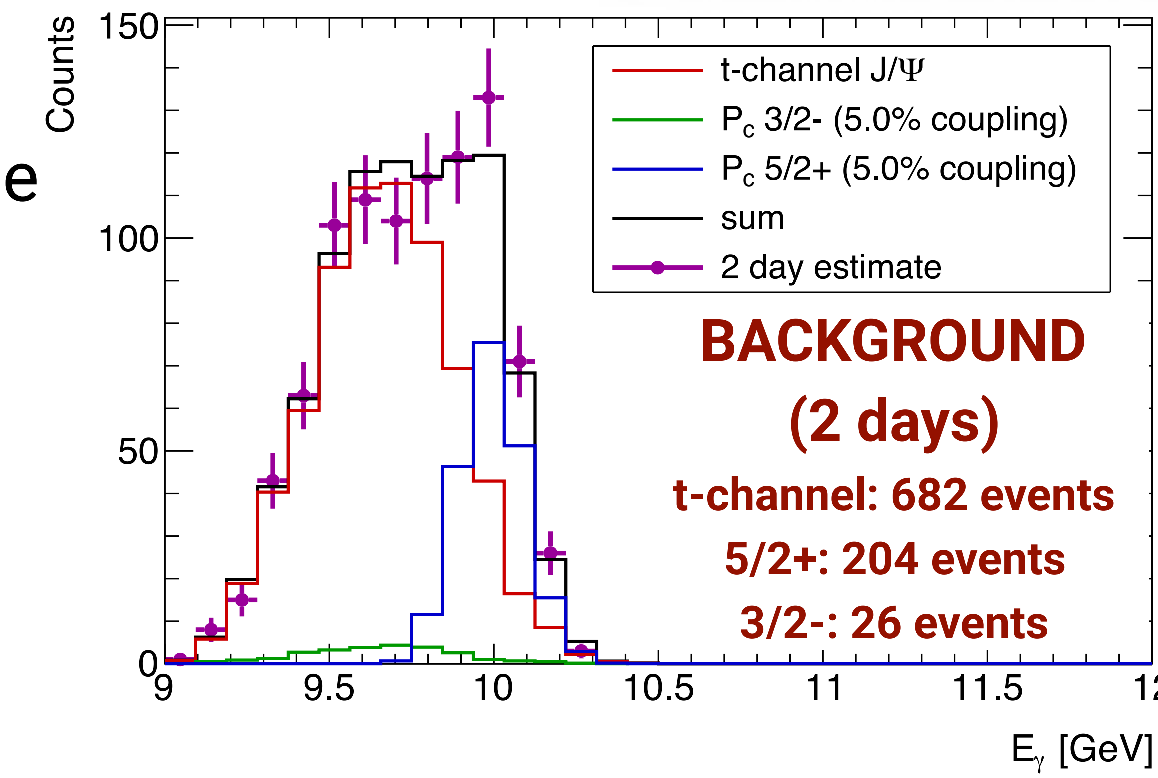
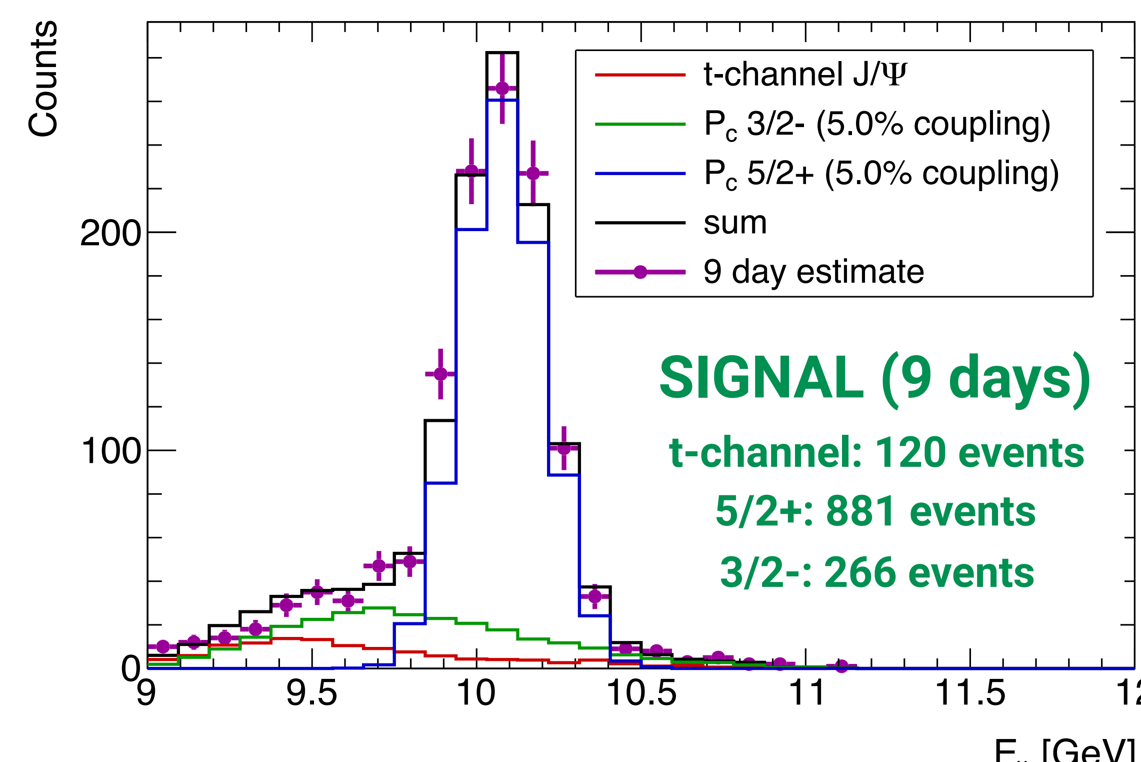




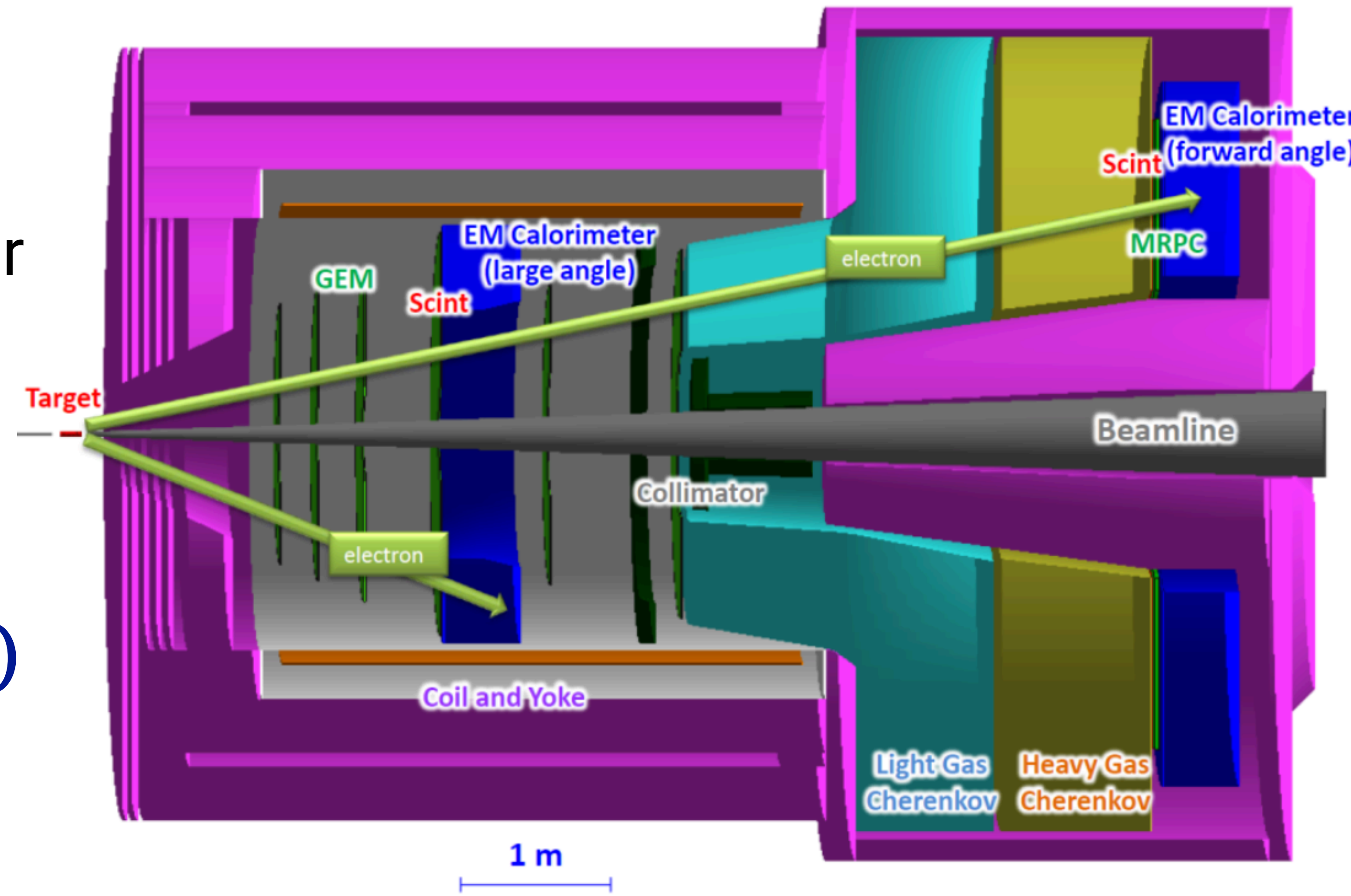


Significance > 20σ!
(in case of 5% coupling)

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



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

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

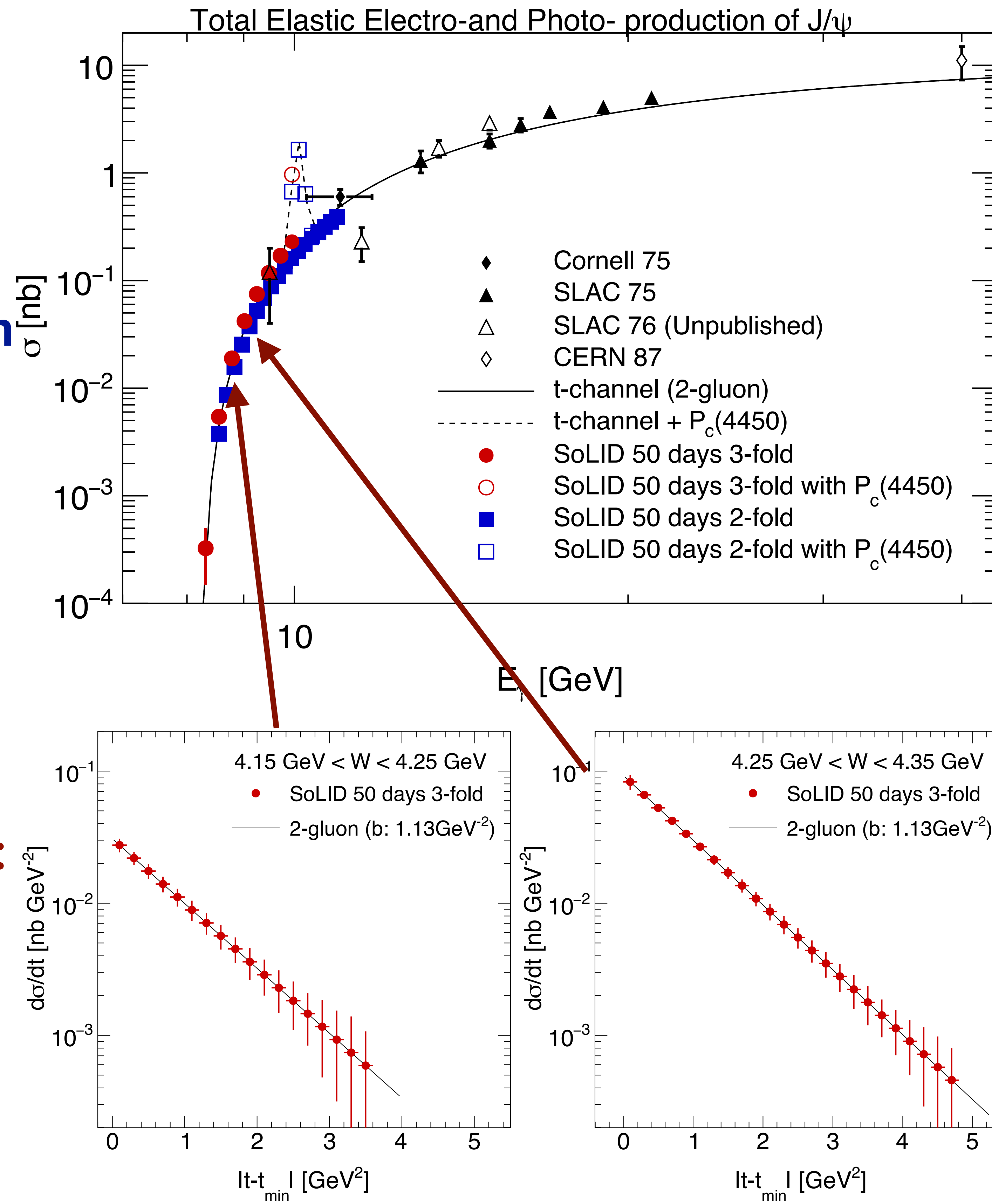
K. Hafidi, S. Joosten *et al.*, Few Body Syst. 58 (2017) no.4, 141 and references therein

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:**
    - Less background
    - Closer to threshold

Sensitivity below 10^{-3} nb !



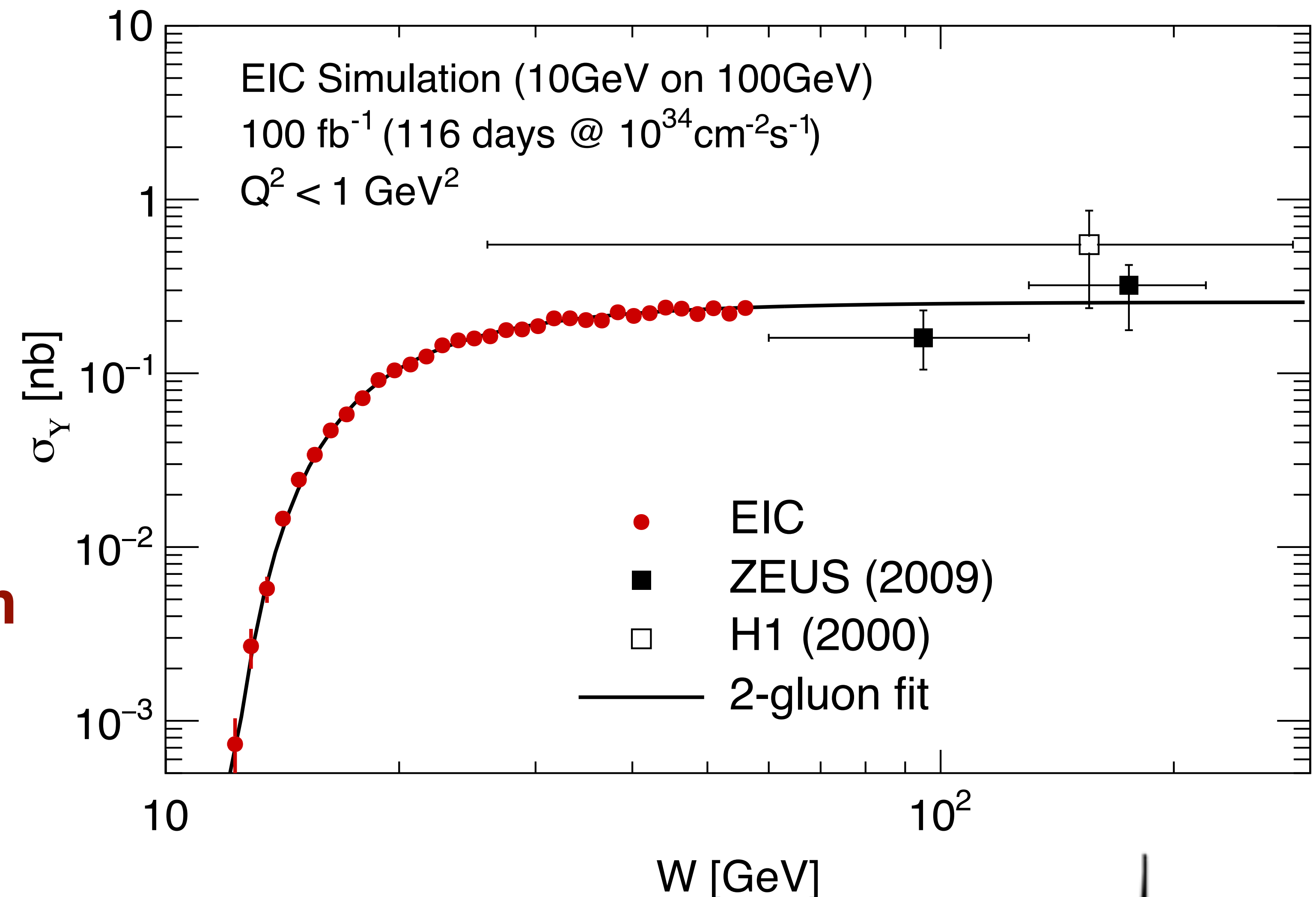
J/ψ experiments at JLab **in a nutshell**

	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 days		9+2	130	50
When?	Ongoing	Early 2019	Ongoing	~10 years?

Exciting times for near-threshold *J/ψ* production!

Υ photo-production at an EIC

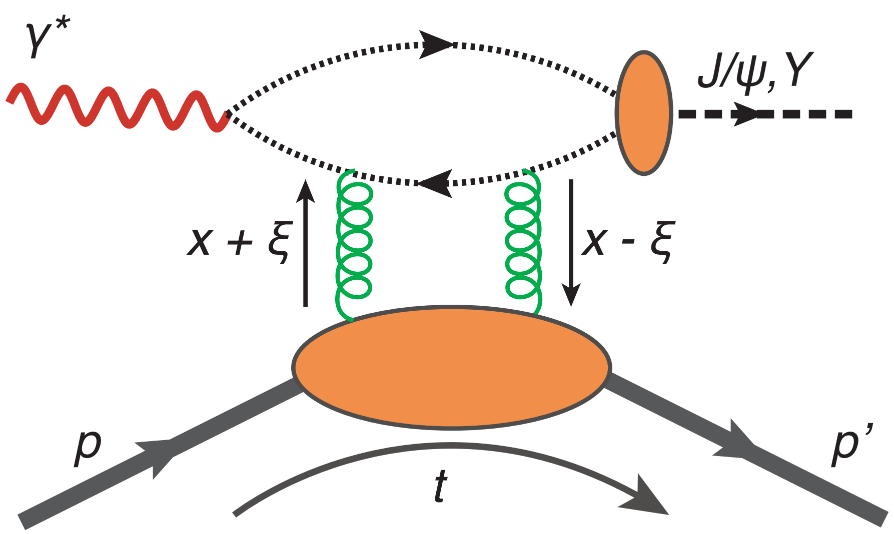
- **Quasi-real production** at an EIC
- Using nominal EIC detector (consistent with white paper)
  - Both electron and muon channel
- **Fully exclusive** reaction
- Can go **to near-threshold region**



- ***Υ(1s)*** **production possible at threshold!**
  - Provides measure for **universality,** complimentary to threshold *J/ψ* program at JLab12
  - Is there a "beautiful" pentaquark?
- **Sensitivity down to ~10^{-3} nb!**

quarkonium production **at high energies**

Deeply-virtual quarkonium production and the gluon GPD



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

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

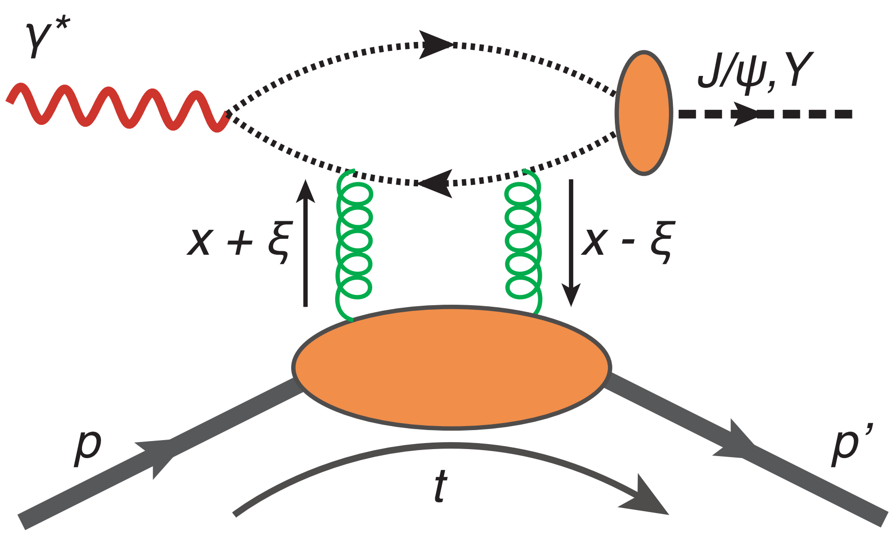
- **average unpolarized gluon GPD** related to *t*-dependent cross section (LO)

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

- **Fourier transform:** transverse gluonic profile

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

Deeply-virtual quarkonium production and the gluon GPD



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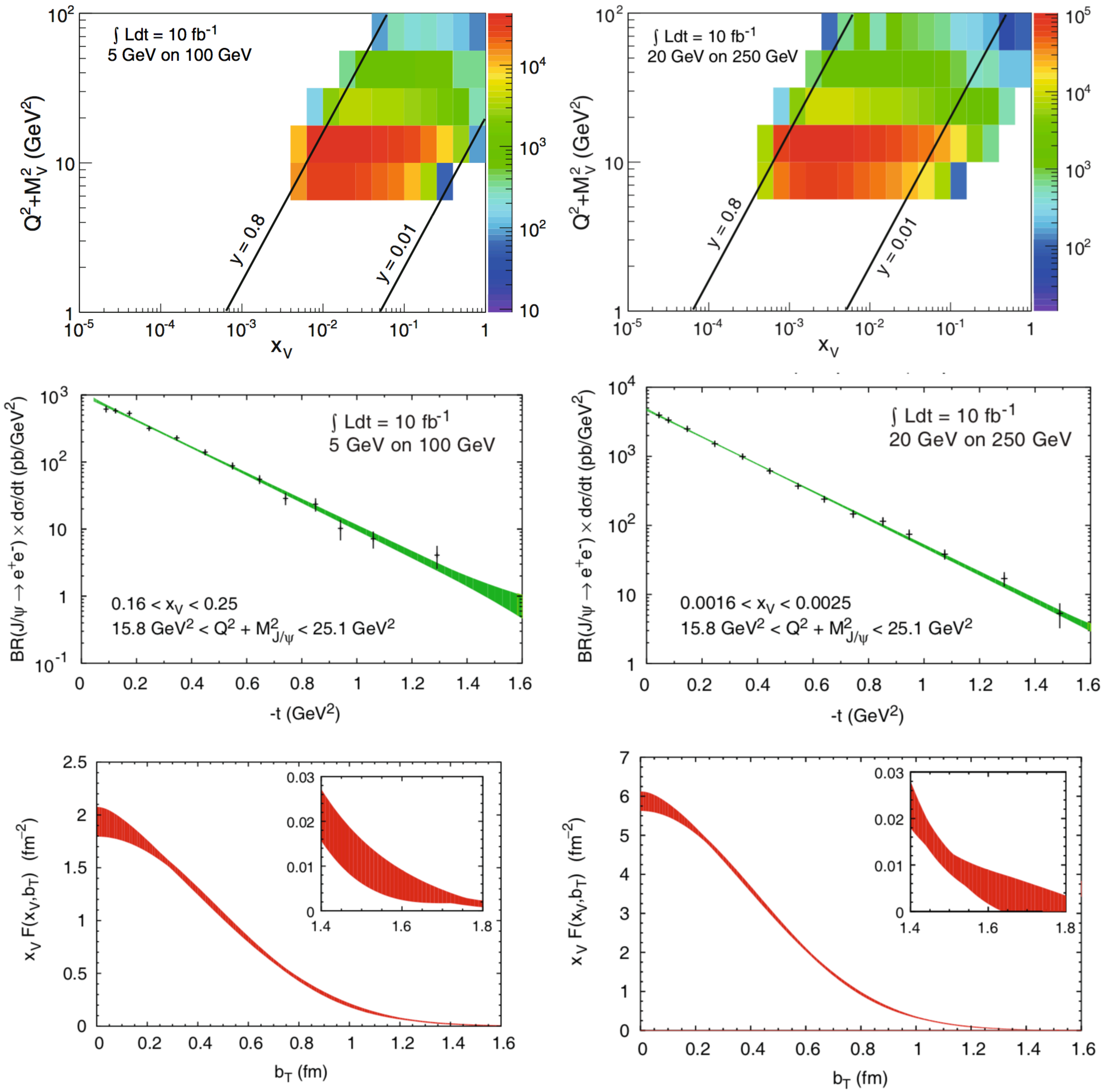
- **Remarks:**
  - **Simplest** possible GPD extraction
  - Intrinsic systematic uncertainty due to **extrapolation** outside of measured *t*-range
  - **NLO effects** could be significant
    - Corrections expected to be smaller for *Υ(1s)* than for *J/ψ*

Gluon tomography with J/ψ

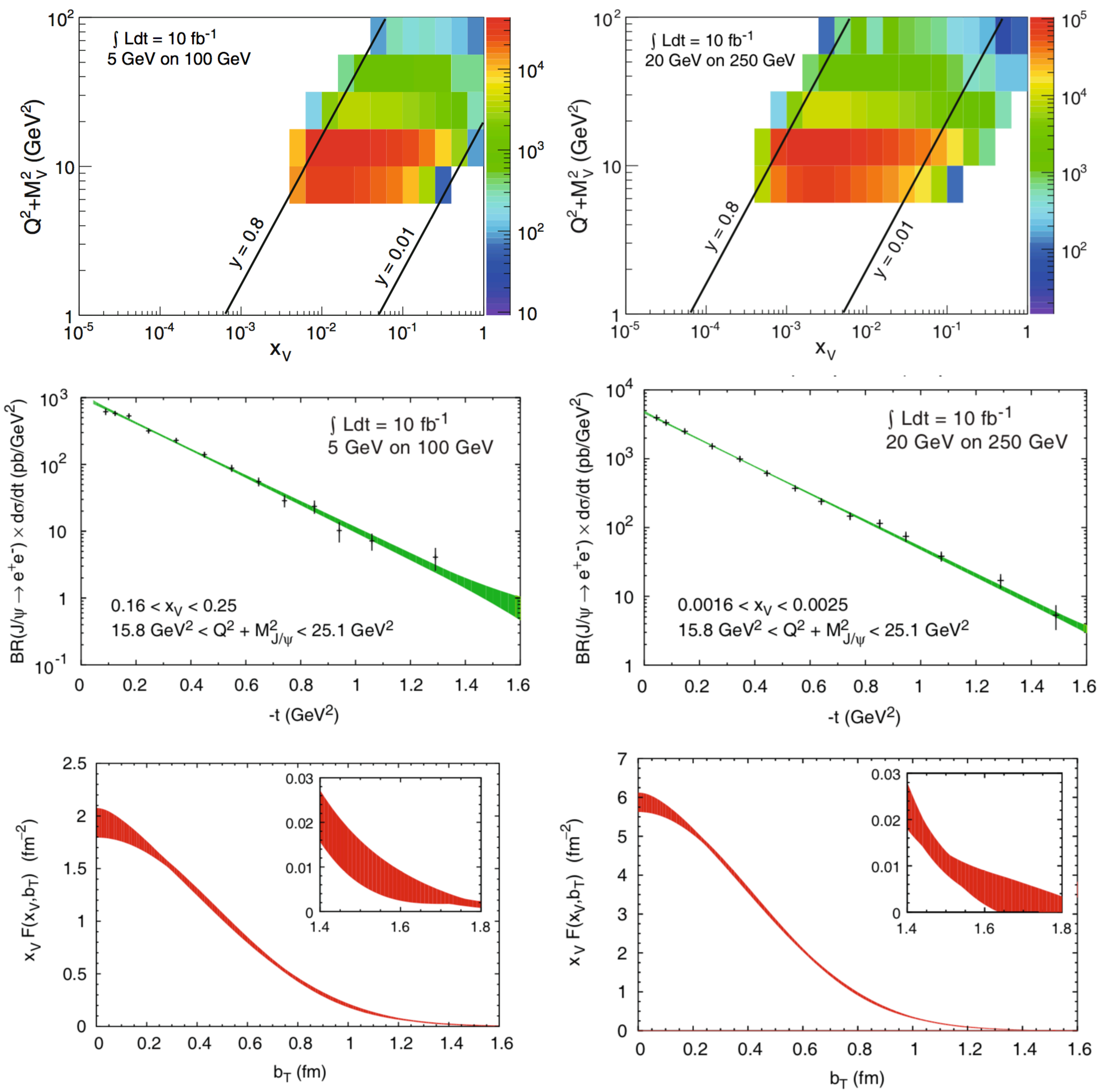


Gluon GPD in fine bins of x_V and Q^2 (from EIC white paper)

***t*-spectra**

Normalized average gluon density

Gluon tomography with J/ψ



Gluon GPD in fine bins of x_V and Q^2 (from EIC white paper)

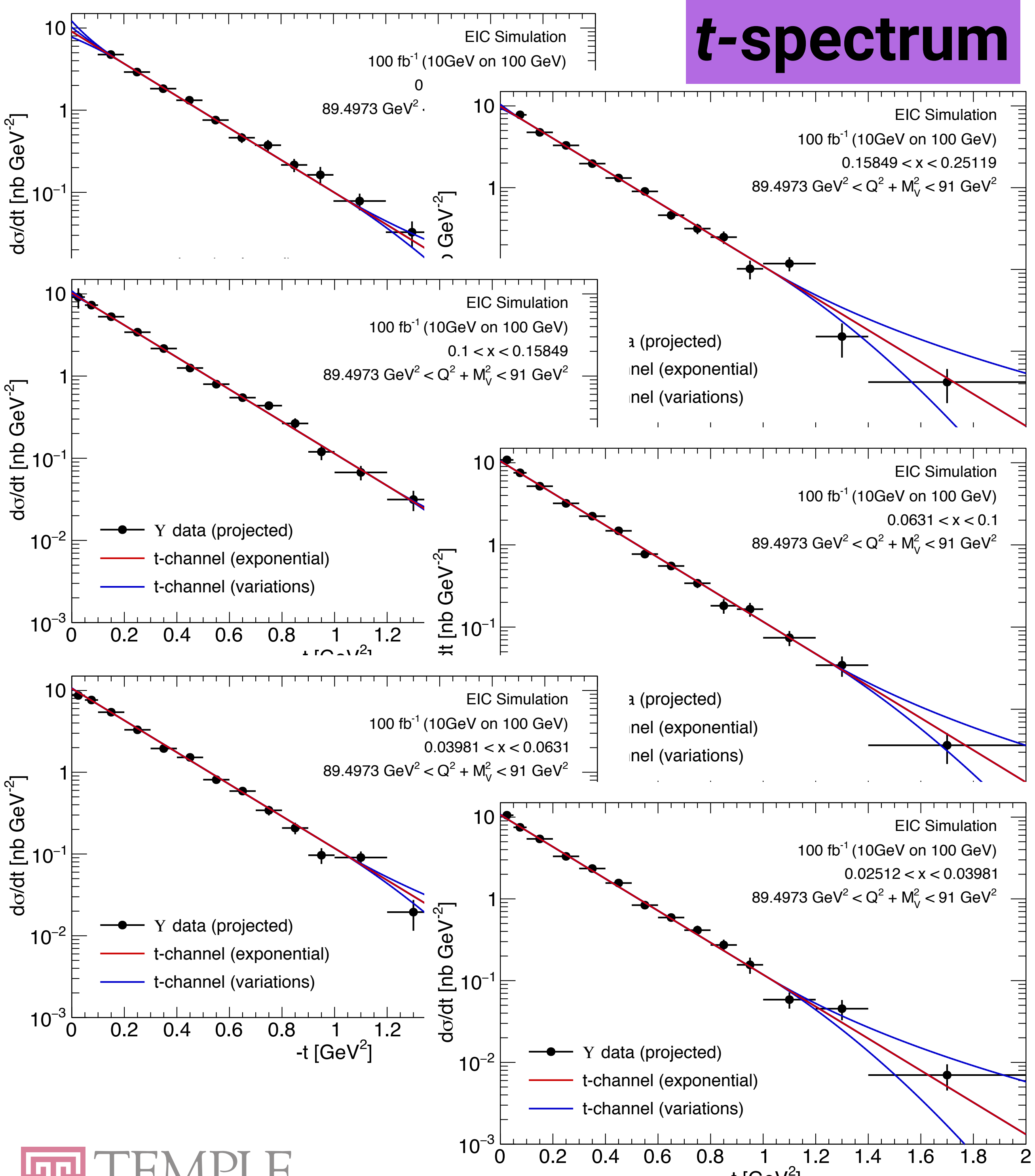
***t*-spectra**

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

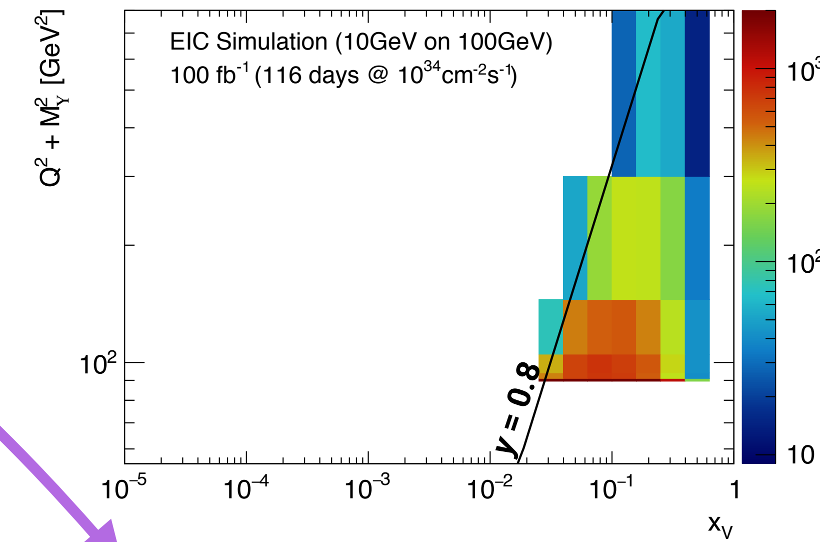
Normalized average gluon density

Gluon tomography with *Υ(1s)*

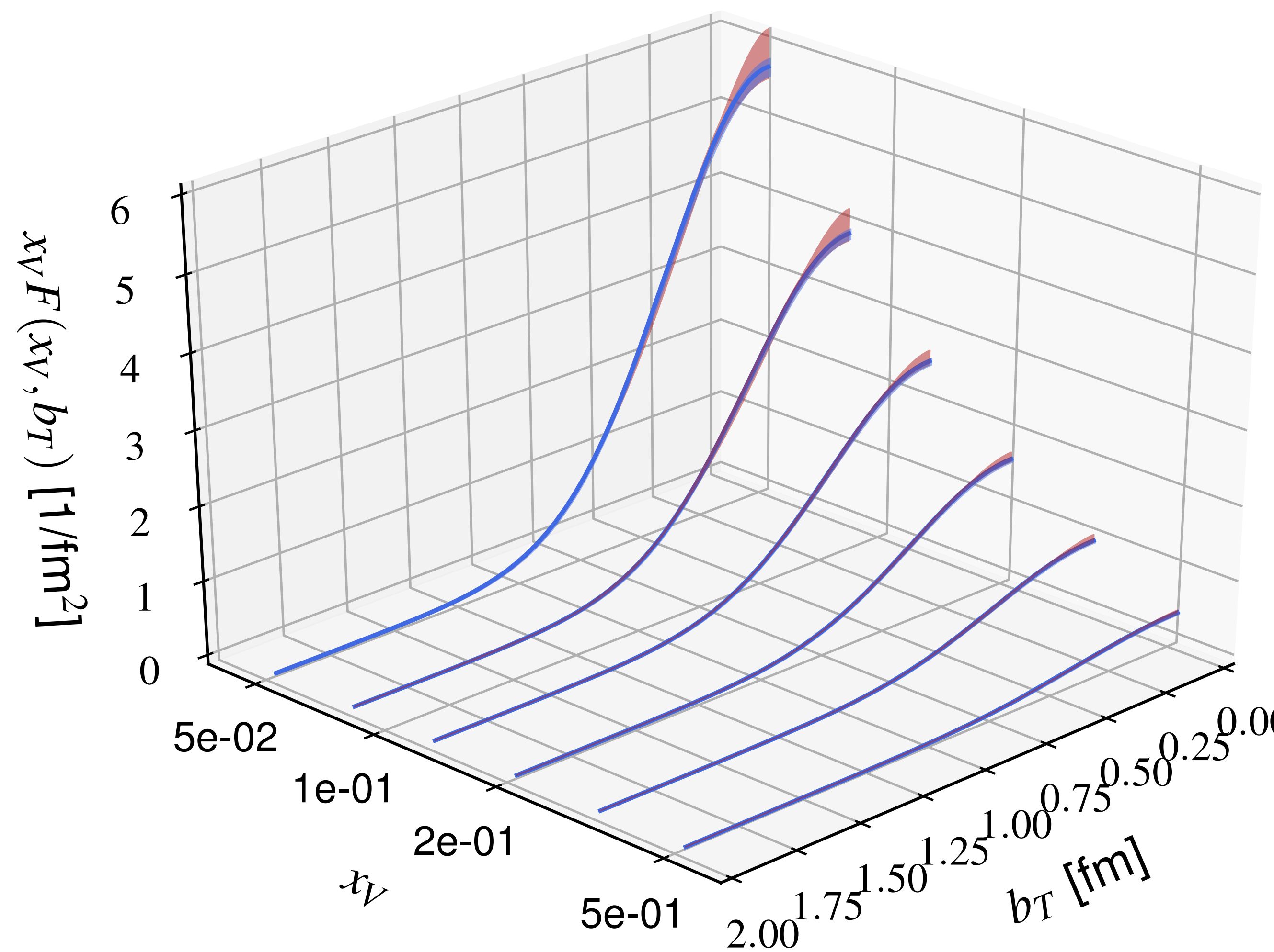
- Nominal EIC detector
- 10x more luminosity
- Electron and muon channels



***t*-spectrum**



Average gluon density:



S. Joosten

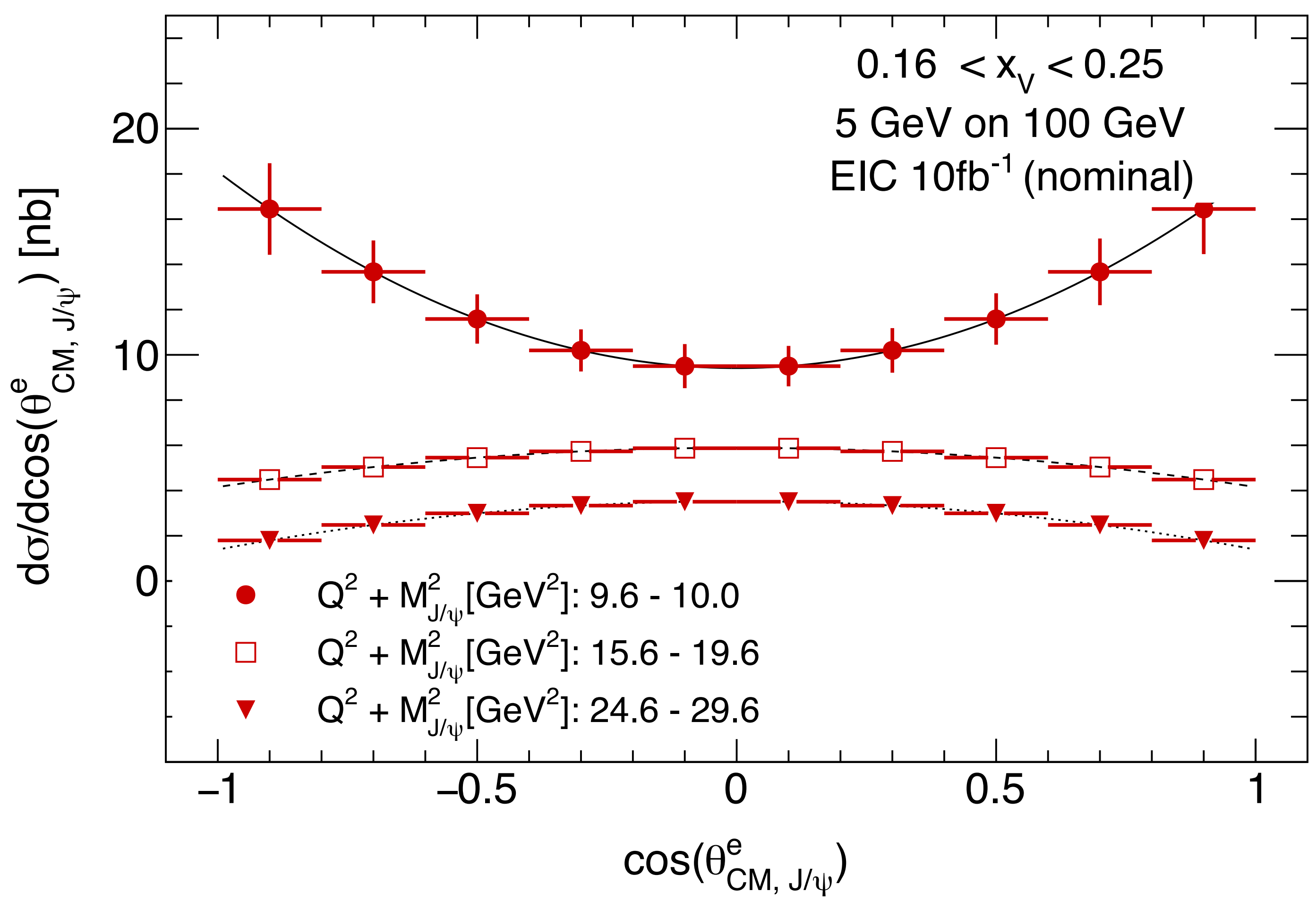
L-T separation and the Q^2 dependence of R

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

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

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

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



Conclusion

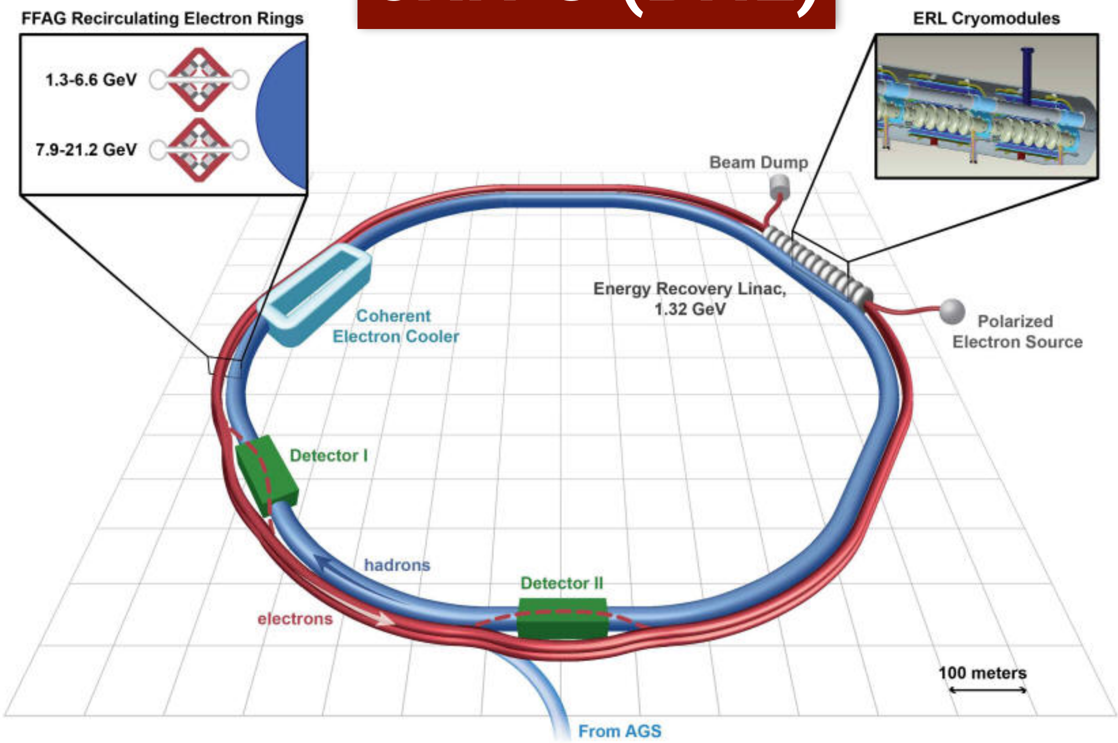
- **Quarkonium** production an important tool to study the **gluonic fields** in the nucleon
- **Threshold production** of quarkonium can shed light on the **trace anomaly,** quarkonium-nucleon **binding** and **proton mass**
- Possible to study “charming” (and “beautiful”?) pentaquarks
- At **high energies**: 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

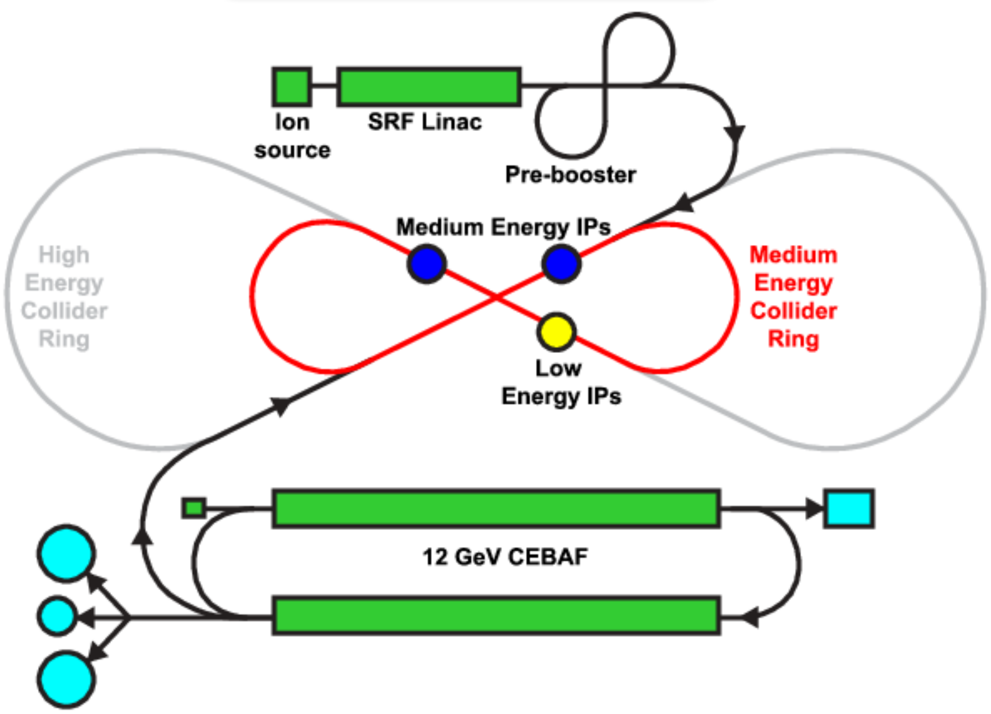
BACKUP SLIDES

Accelerator and **detector parameters**

eRHIC (BNL)



JLEIC (JLab)



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

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

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

- 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!**

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*

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

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

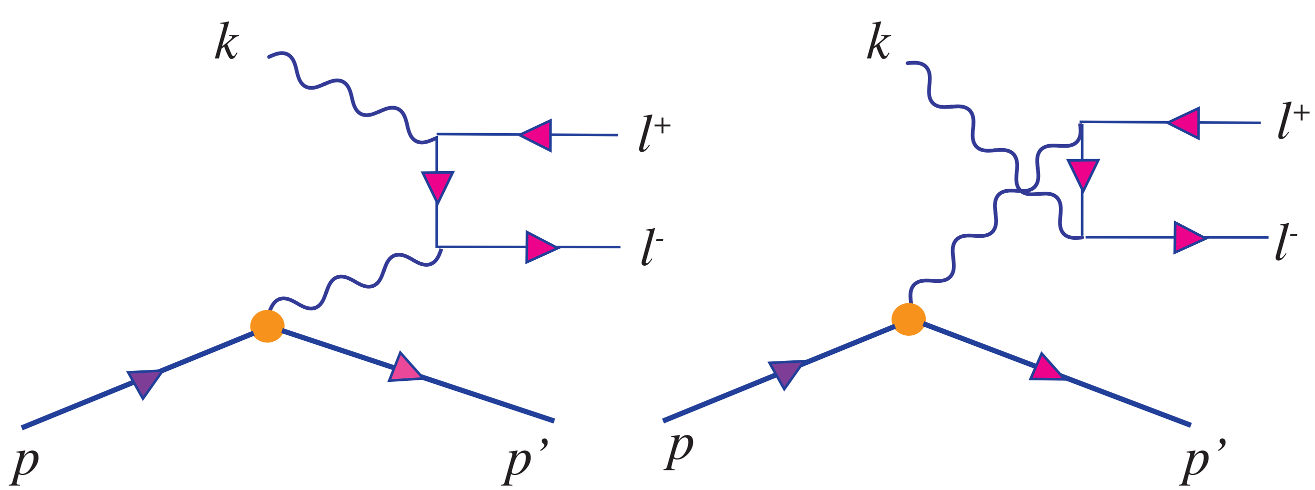
- Threshold at 9 GeV
- Reconstructed photon energy $\underline{E}_{rc}$ is ~1 GeV too low
- **less than 30% of the elastic *t*-channel** background
- Contaminates the **8 GeV < $\underline{E}_{rc}$ < 9.7 GeV** range for a photon end-point energy of 10.7 GeV
  - **not an issue for the P_c(4450) ($\underline{E}_{rc}$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

not an issue for the P_c!

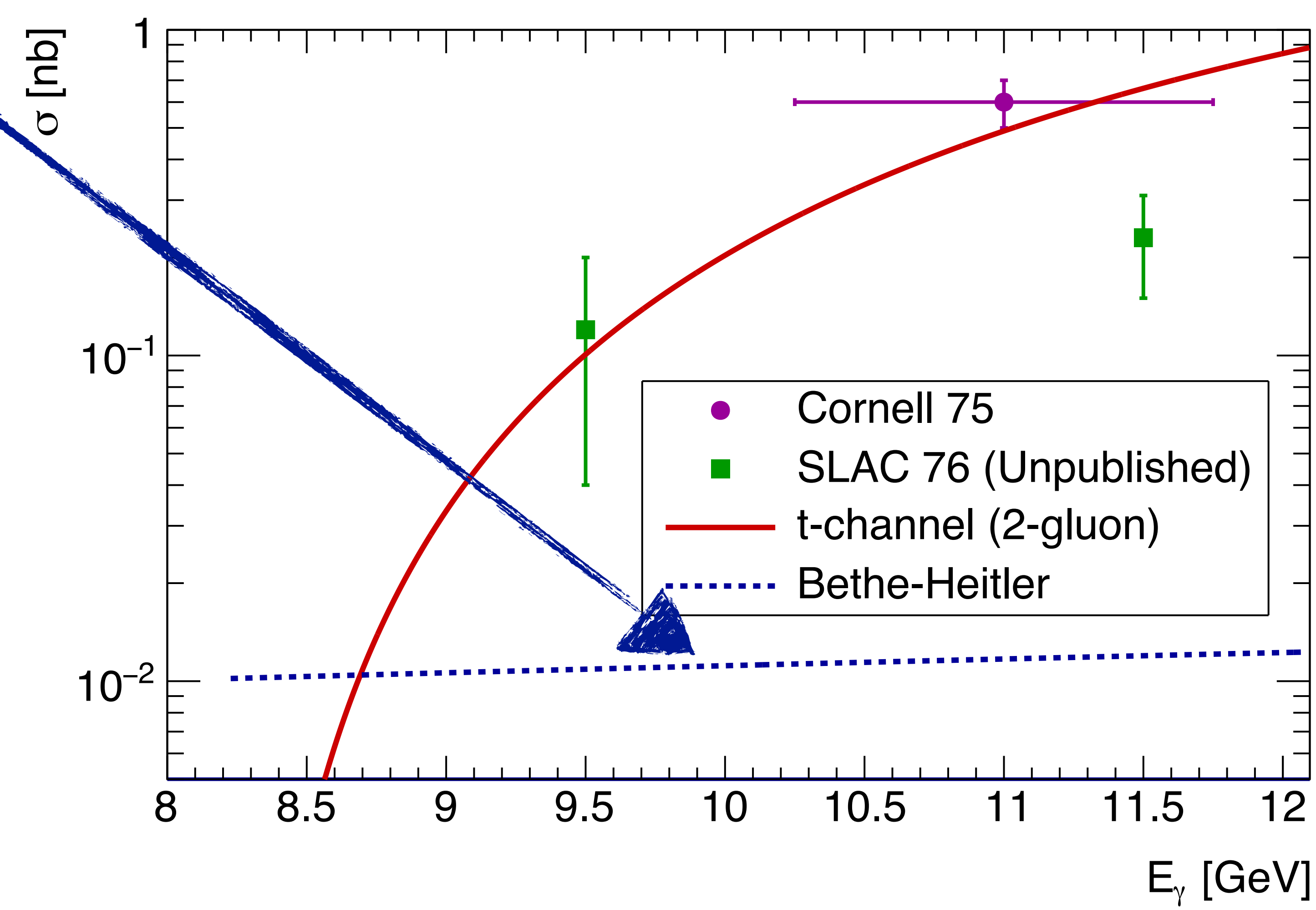
Background: **Bethe-Heitler pair production**

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

Not an issue!



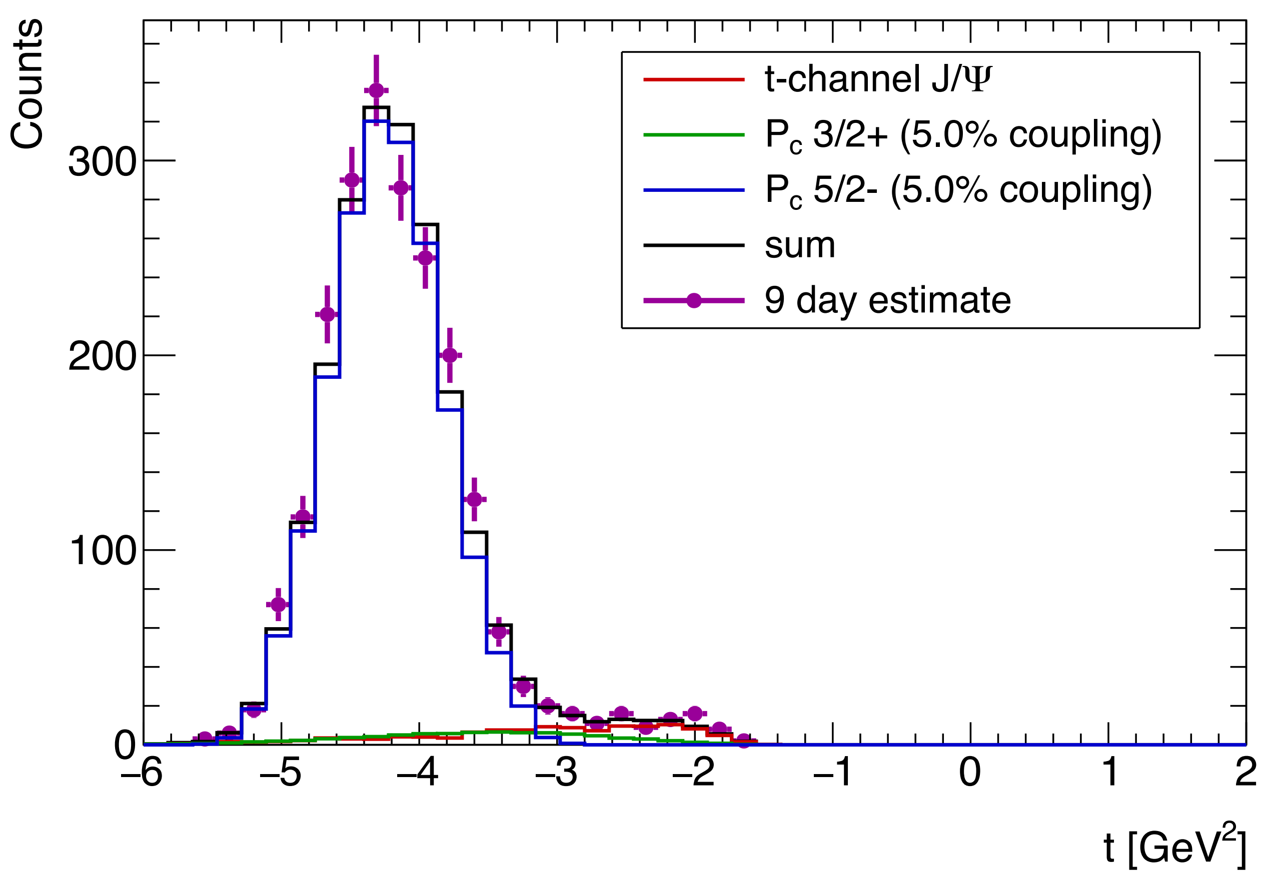
- Estimated using calculations from Pauk and Vanderhaeghen
- Constant background < 10% of the *t*-channel J/ψ
- Can be **exactly calculated** and controlled for
- Interference negligible at the P_c(4450) peak

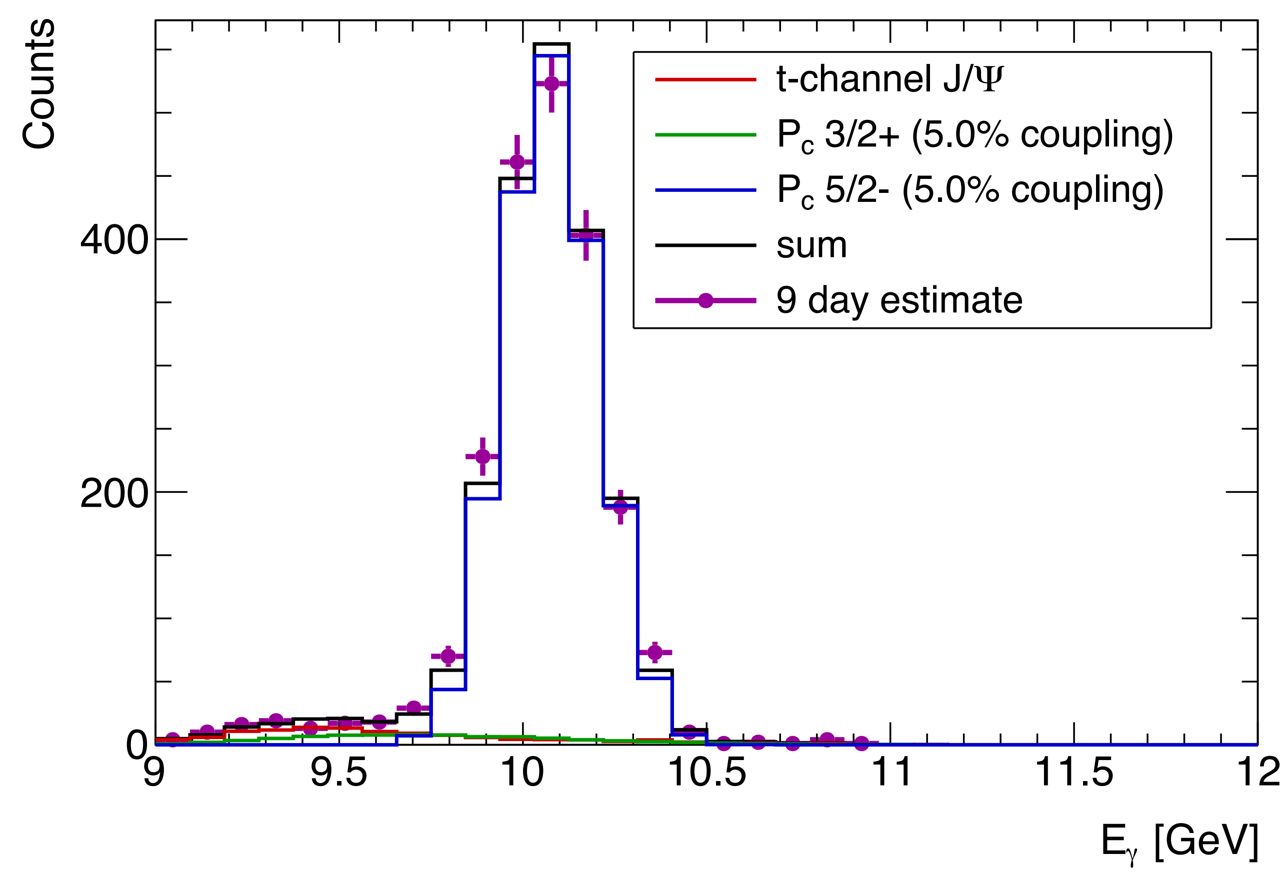


Pauk V and Vanderhaeghen M, PRL 115(22) (2015) 221804

Alternate P_c Assumption (Setting "SIGNAL")

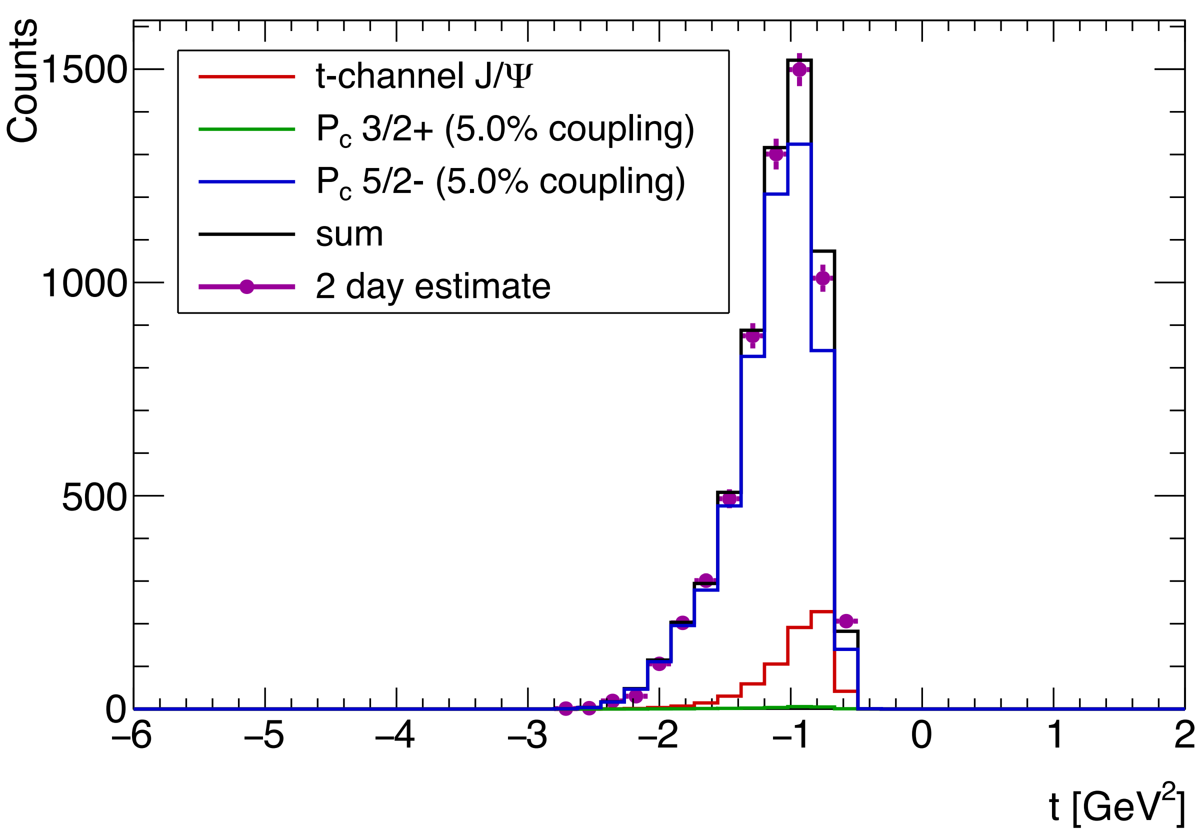
- **Alternate (5/2-, 3/2+) P_c assumption**
- assuming 5% coupling for the (5/2-, 3/2+) P_c assumption
- 9 days of beam time at 50μA
- 5/2- peak **dominates the spectrum** (even larger than the 5/2+ peak!)

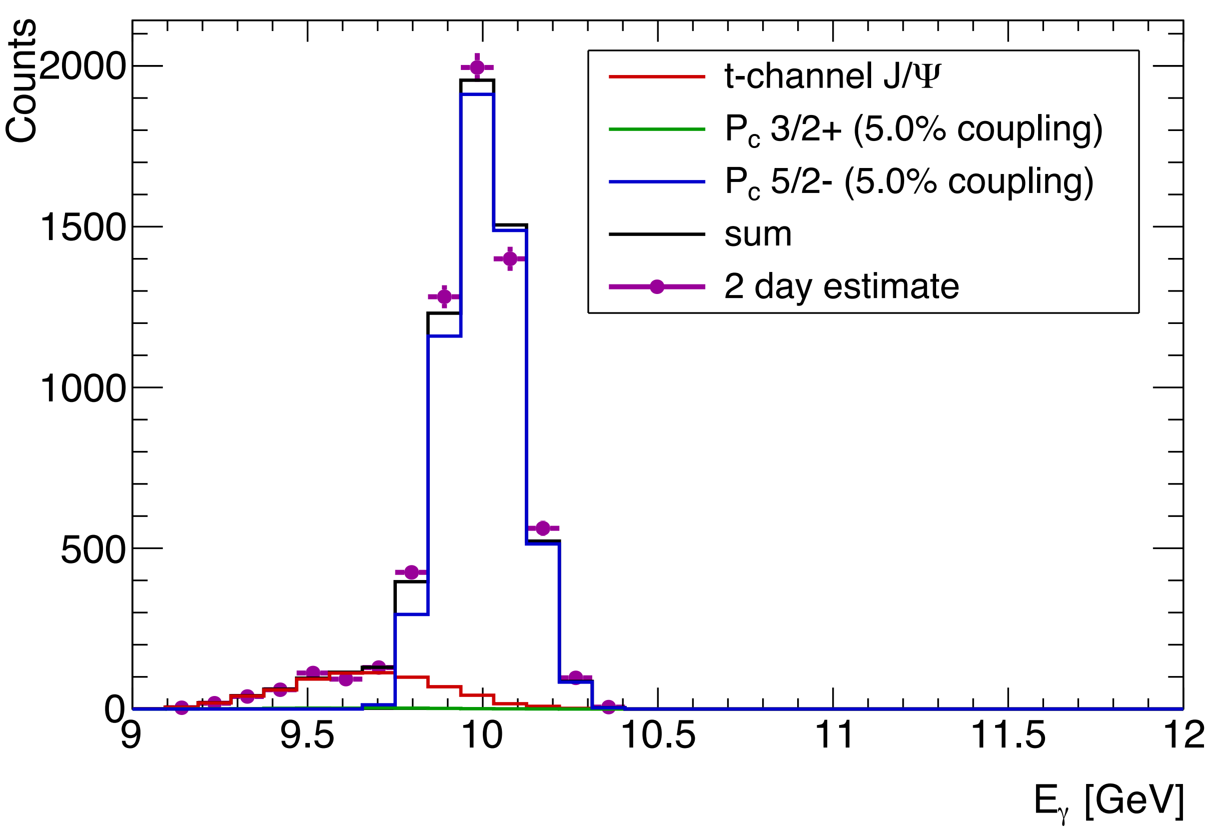




Alternate P_c Assumption ("BACKGROUND" Setting)

- **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





Sensitivity for **Discovery**

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