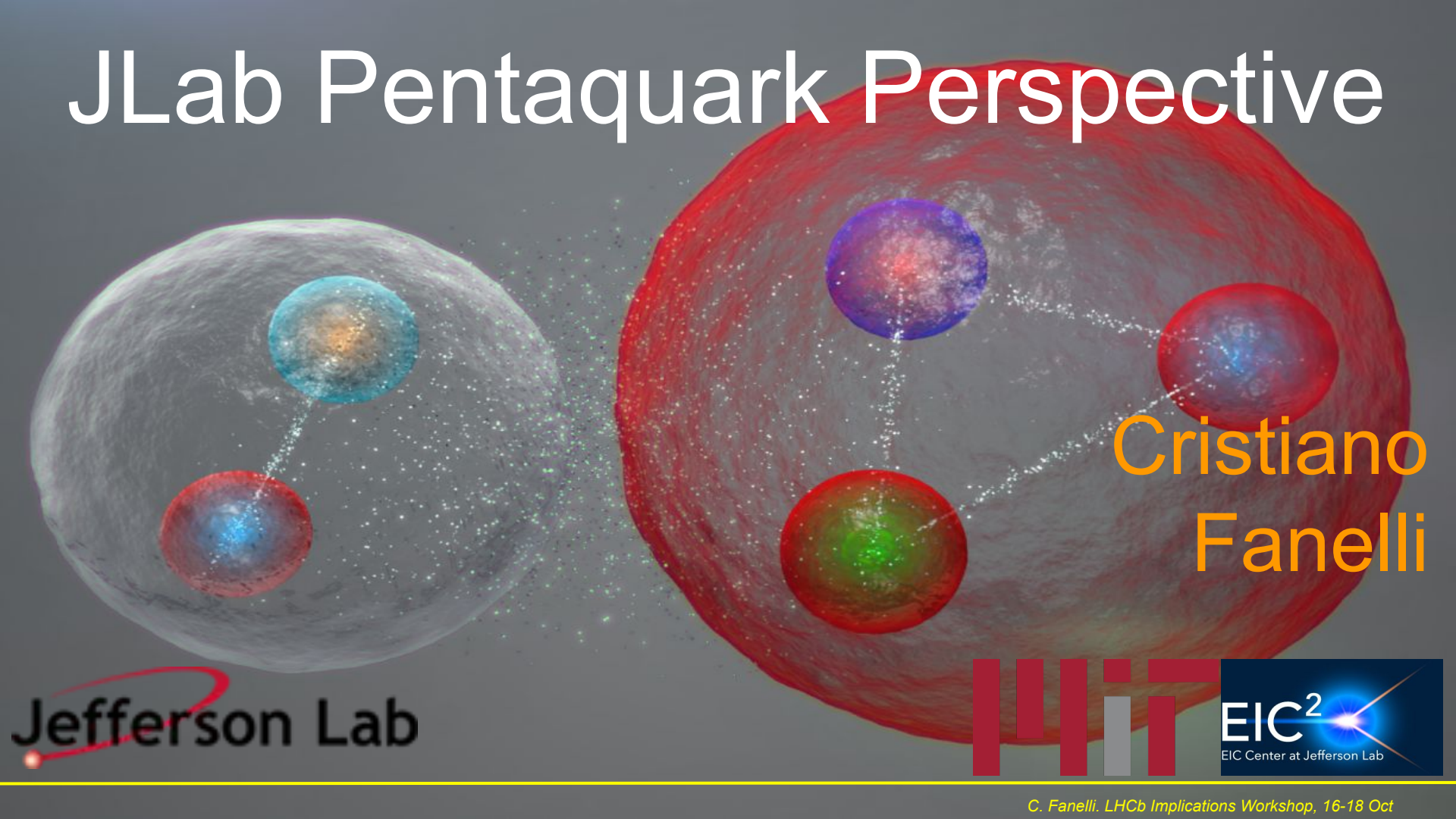
JLab Pentaquark Perspective



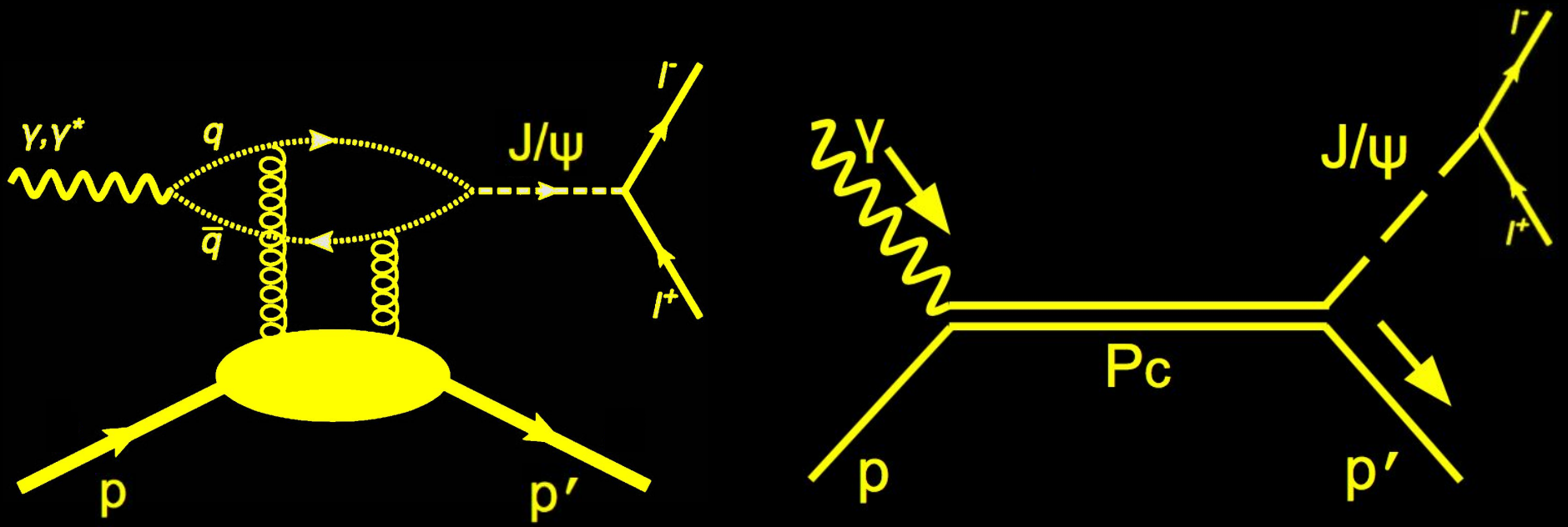
Cristiano Fanelli

Jefferson Lab

MIT

EIC^2 EIC Center at Jefferson Lab

Physics Motivation



As the title should suggest, the main motivation is to access the properties of pentaquark states... through photoproduction at Jefferson Lab

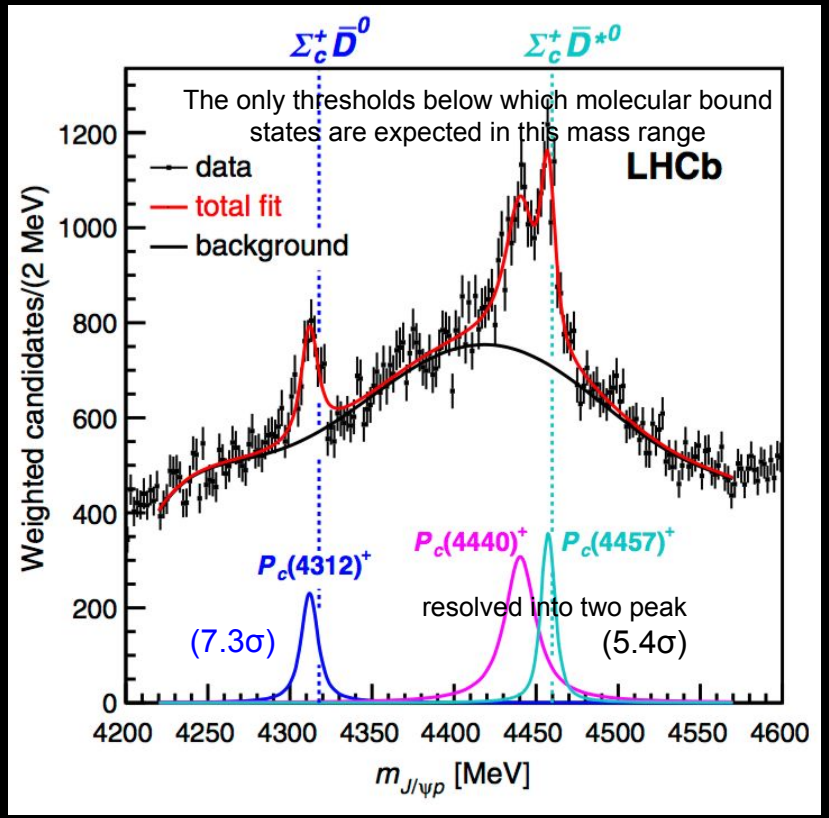
Physics Motivation

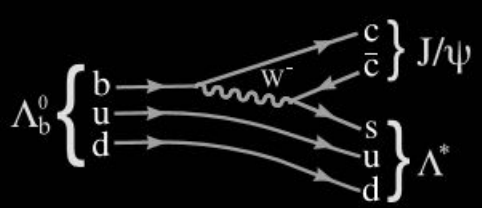
- Phys. Rev. Lett. 115, 072001 (2015) - LHCb
- Phys. Rev. Lett. 122, 222001 (2019) - LHCb
- arXiv:1609.00676v2 [hep-ex] - Hall C
- Phys. Rev. Lett. 123, 072001 (2019) - GlueX
- JLab proposal PR12-12-006.pdf - SoLID

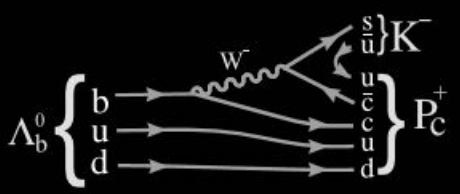
- Near threshold J/ψ photo-production off a nucleon was an important subject in nonperturbative QCD and experimental proposals at JLab appeared even before LHCb results.
- Obviously the first LHCb experimental observations of resonances consistent with Pc "*spurred a sense of urgency to carry out measurements*" at JLab
- This has been further revitalized in 2019 after the LHCb discovery of three new states.
- All experimental Halls at JLab involved in this physics program:
  - Current analyses in Hall D, C, B (details later)
  - Future electroproduction program in Hall A
  - Possibility of measurement of polarization

LHCb Discovery

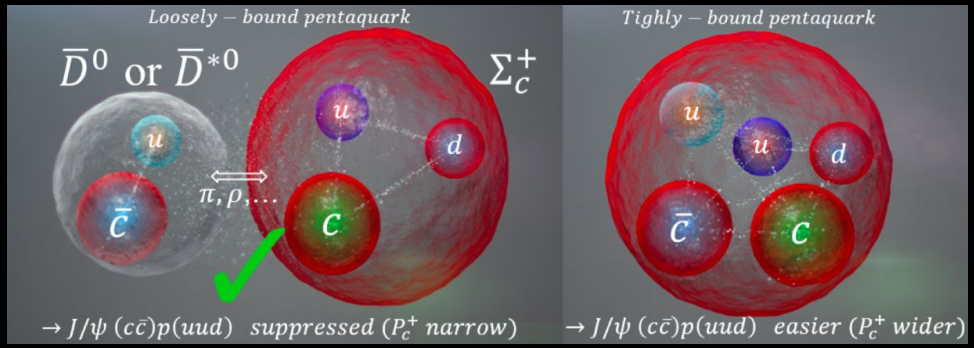
R. Aaij *et al.* (LHCb), Phys.Rev.Lett. 122 (2019) no.22, 222001







The near threshold masses and the narrow widths favor molecular pentaquarks with meson-baryon substructure



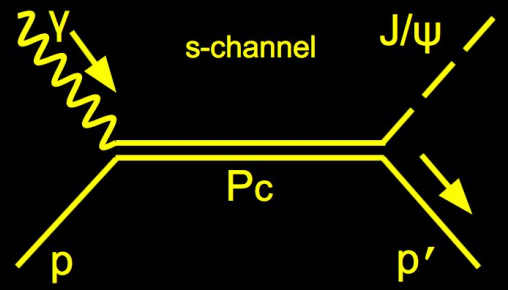
We need to measure J^P to confirm molecular hypothesis, find isospin partners… Can di-quark substructure separated by a potential barrier produce width suppression? Are masses near thresholds just by coincidence?

Maiani, Polosa, Riquer, PLB778,247 (2018)

J/ψ photo-production near threshold

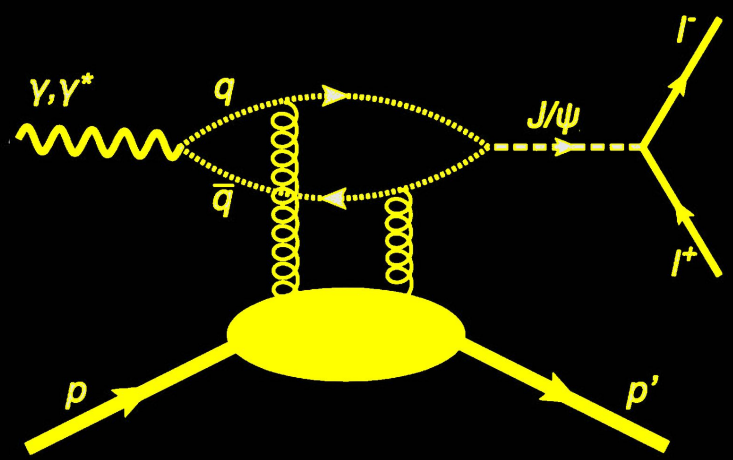
	Threshold E [GeV]
J/ψ	8.2
$Pc^+(4312)$	9.44
$Pc^+(4440)$	10.04
$Pc^+(4457)$	10.12

- JLab ideal place to search for photo-produced Pc
- Photo-production ideal to distinguish truly new states
  - e.g., ATS is not possible
  - J/ψ angular distribution differs between t-channel and s(u)-channel, the latter being more isotropic

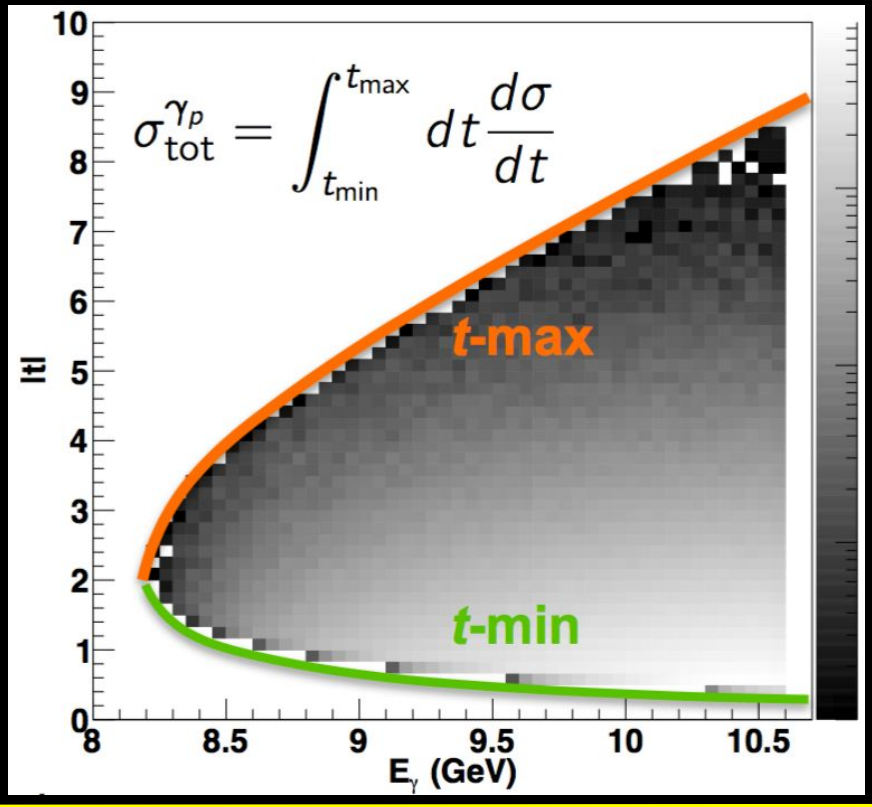


- Observations from LHCb combined to physics information accessible at JLab can confirm states and narrow down interpretations.

Kinematics



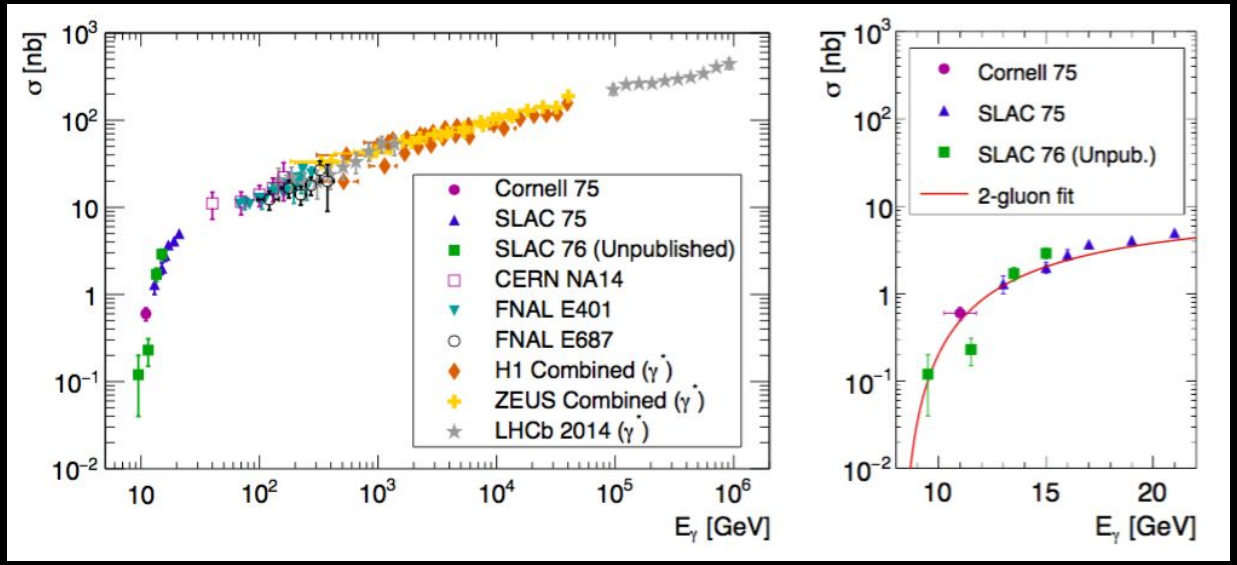
	W	E	t
J/ψ threshold	~4.0 GeV	~8.2 GeV	~-1.5 GeV^2



- Phase space limits defined by J/ψ direction
  - Forward (with photon): $t = t_{min}$
  - Backward (with proton): $t = t_{max}$
- Forward preferred:
  t-dependence ~ exponential

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

- arXiv:1609.00676v2 [hep-ex] and references therein



Direct photo-production
- Cornell '75
- SLAC '75
- CERN NA-14
- FNAL E401, E687

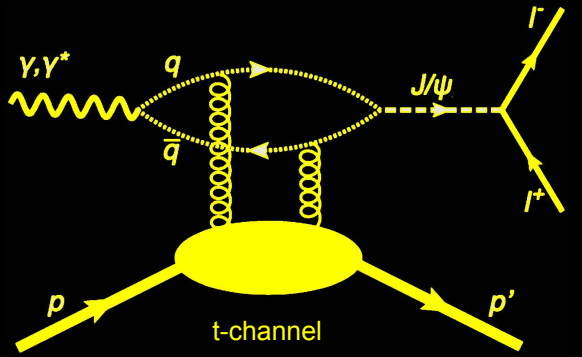
Electro-production (quasi-real)
- H1 and ZEUS

Ultra-peripheral pp collisions
- LHCb '14

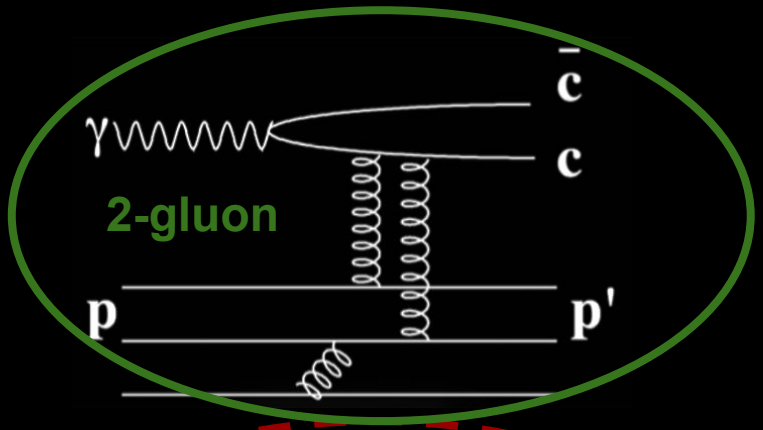
Well constrained at large E.

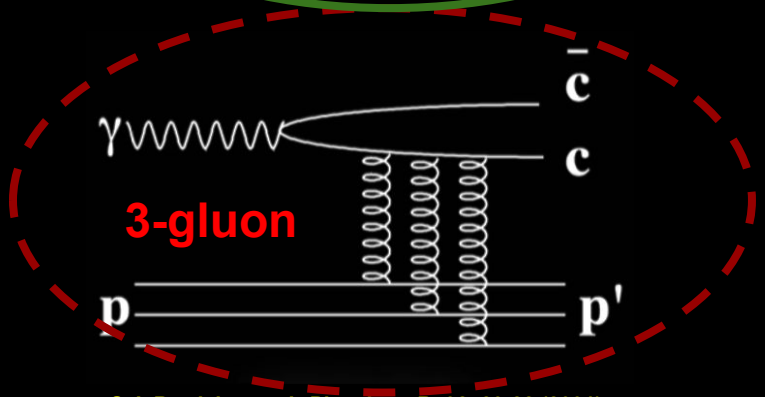
Dominated by t-channel 2 gluon exchange.

Almost no data near threshold before JLab…

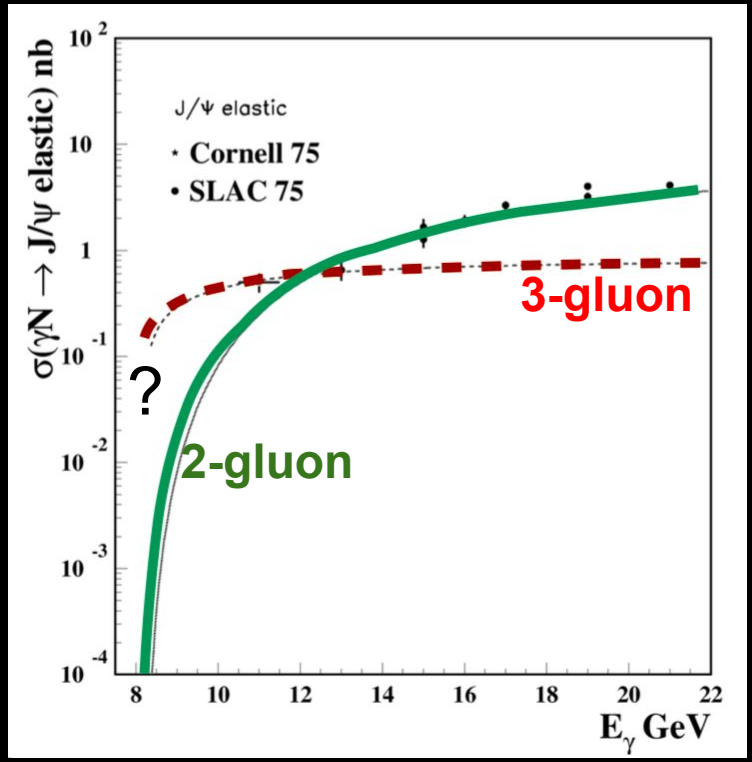


J/ψ near-threshold production unknown (before JLab)

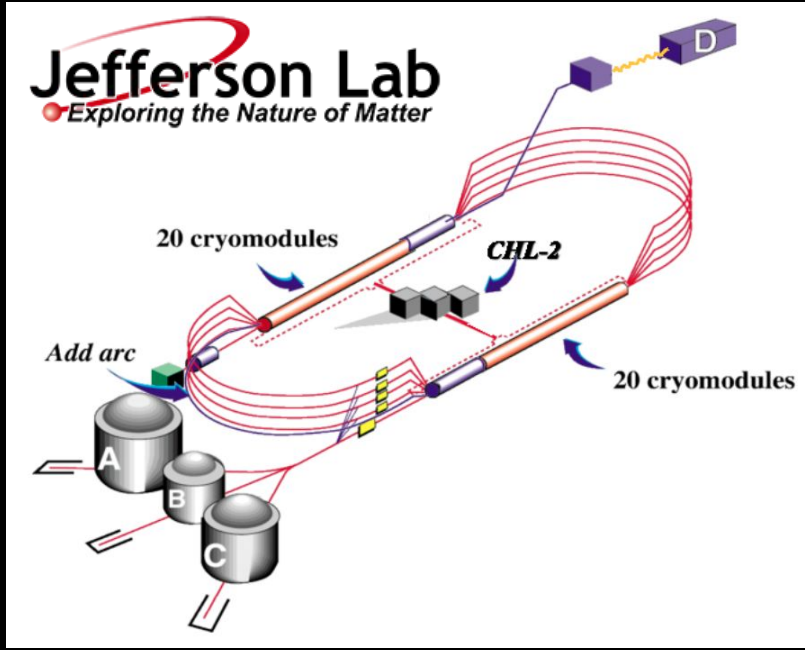




S.J. Brodsky, *et al.*, Phys.Lett. B498, 23-28 (2001)



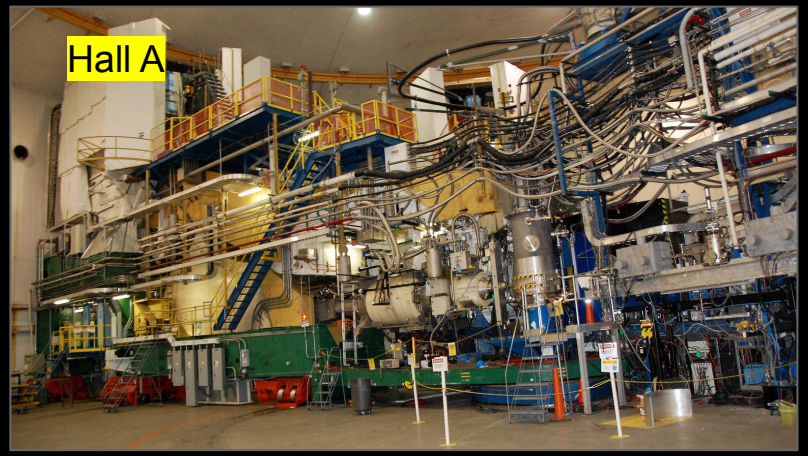
The Jefferson Lab National Accelerator Facility

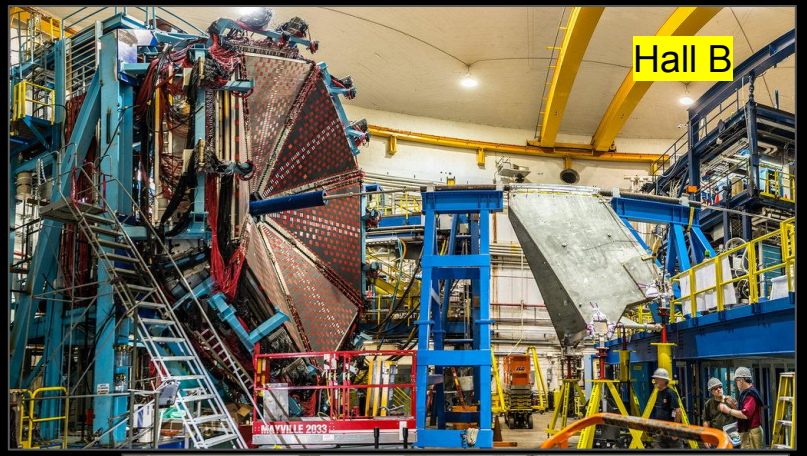


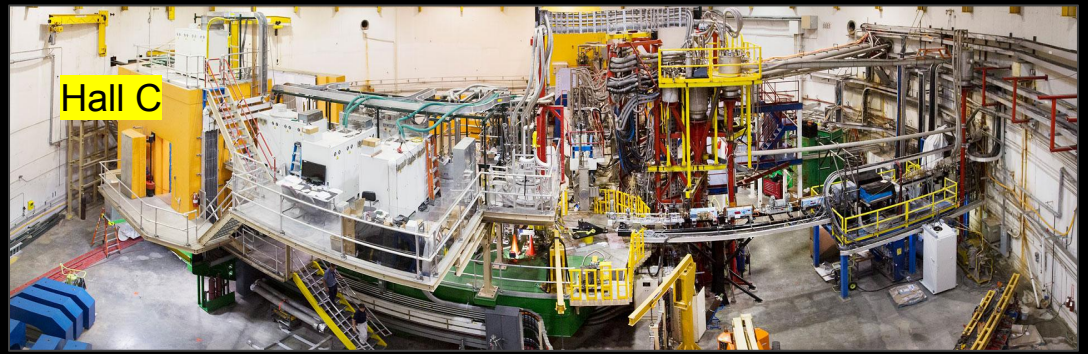
- JLab is a US national laboratory located in Newport News, VA.
- World-leading facility endowed with a continuous polarized beam with max energy 12 GeV.
- Beam delivered to four Halls to explore the nuclear and hadron physics.
- Flagship experimental physics program.

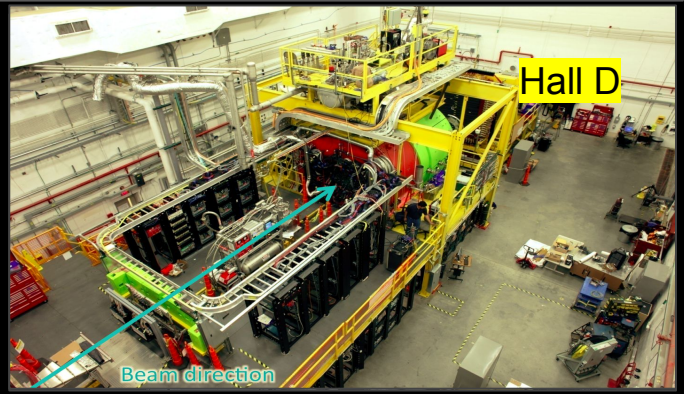
The Jefferson Lab National Accelerator Facility

Exploring the Nature of Matter





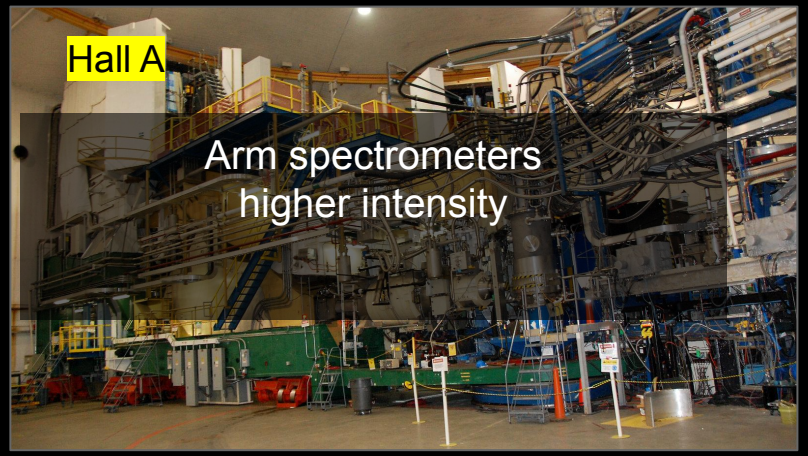


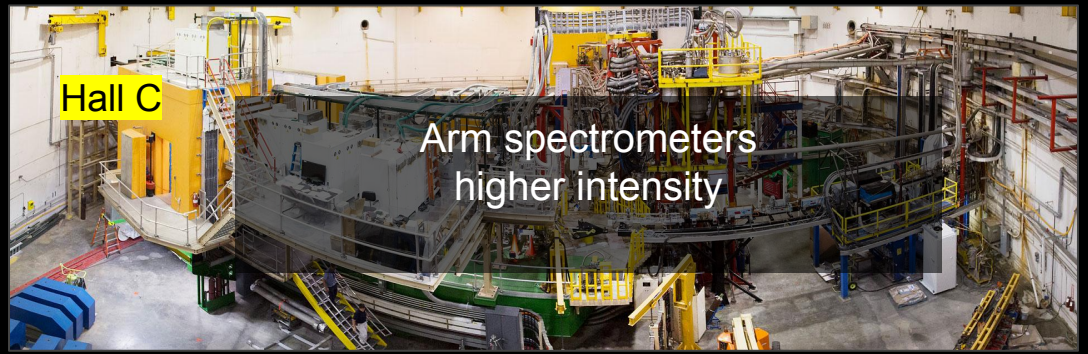


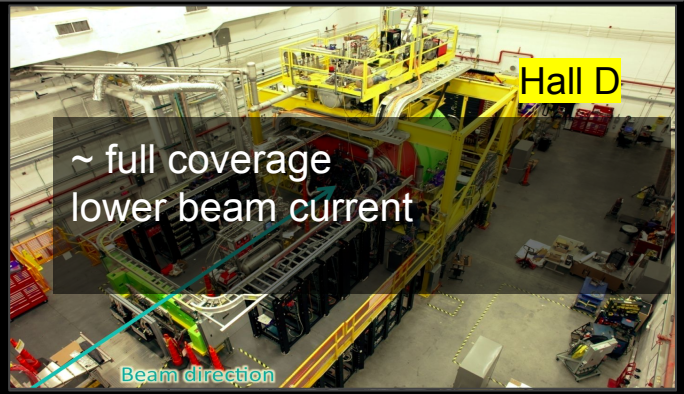
The Jefferson Lab National Accelerator Facility

Exploring the Nature of Matter

*Current configurations

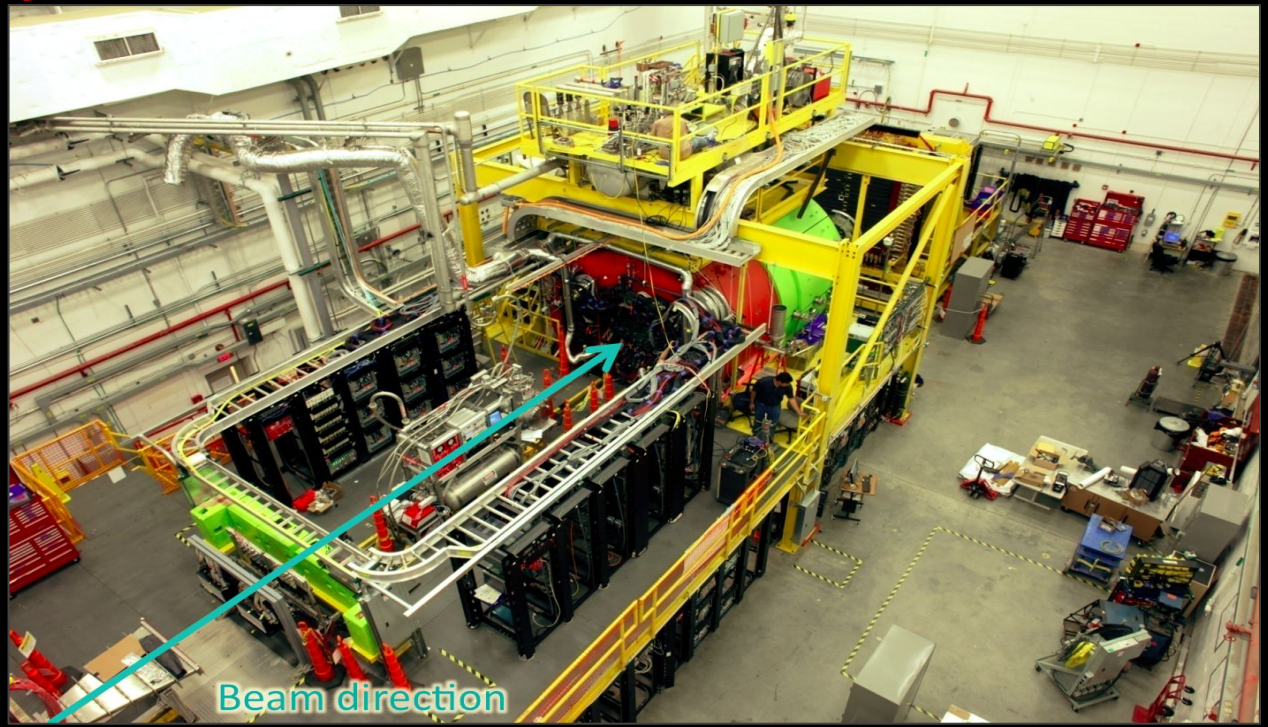






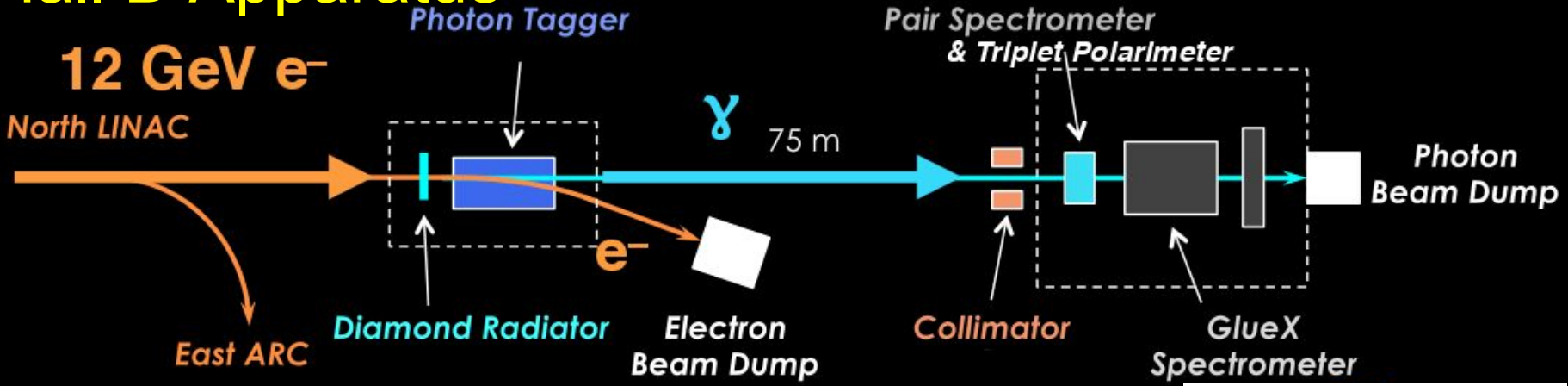
GlueX @ Hall D

Credits: L. Pentchev, Hall D
https://www.jlab.org/user_resources/meetings/JLUO_6_19/Pentchev.pdf

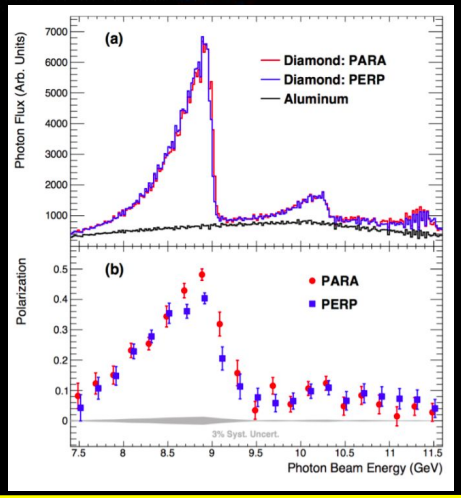


"First measurements of near-threshold J/ψ exclusive photoproduction off the proton" PRL 123, 072001 (Aug 2019)

Hall D Apparatus

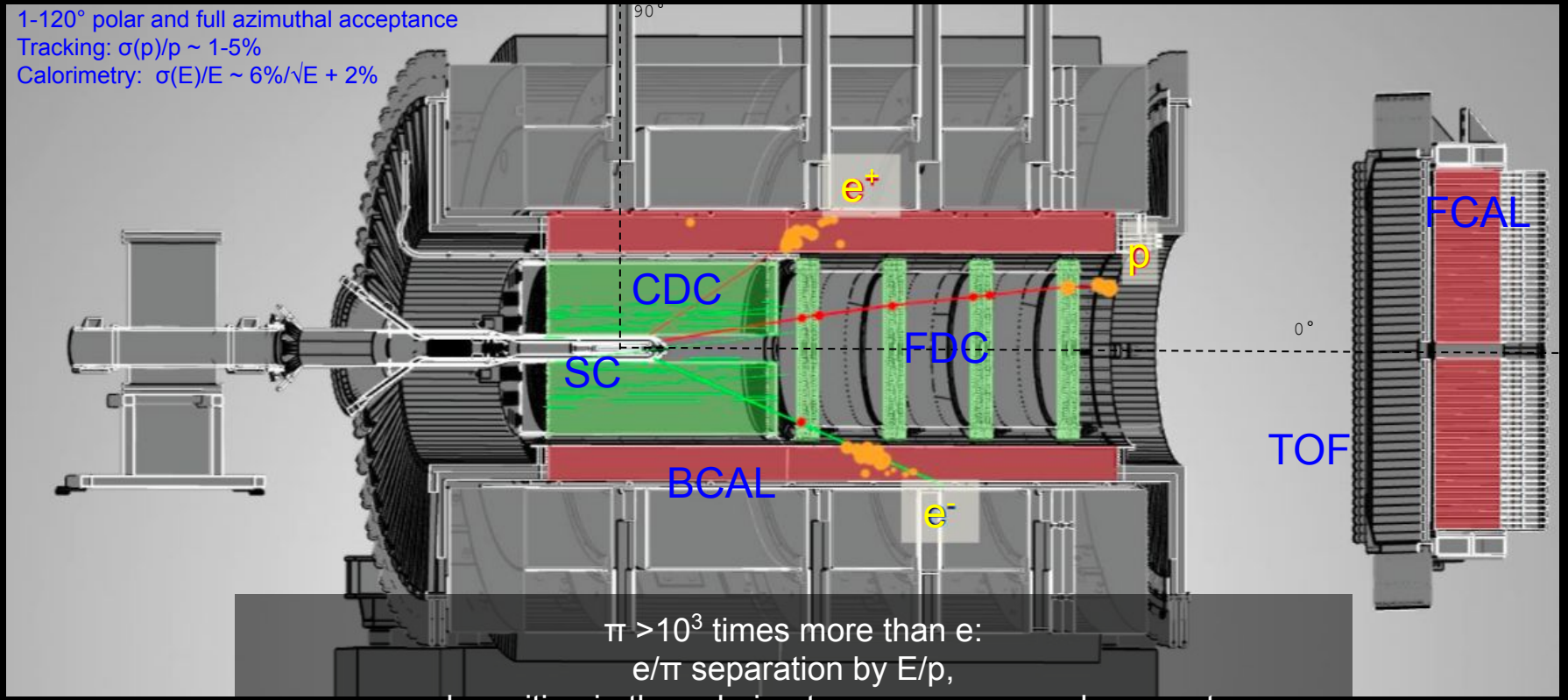


- Photon beam from coherent Bremsstrahlung off thin diamond
- Photon energy tagged by scattered electron: 0.2% resolution
- Beam collimated at 75m, <35 μrad
- Intensity: ~ $2 \cdot 10^7$ - $5 \cdot 10^7$ γ/sec above J/ψ threshold (8.2 GeV) – total ~ 68 pb^{-1} in 2016-2017 runs (25% of total statistics up to date)
- Photons are linearly polarized (~ 40% at peak); polarization not used – runs with perp. polarization planes mixed, also using amorphous radiators



Signature of γp->J/ψ(e^+e^-)p

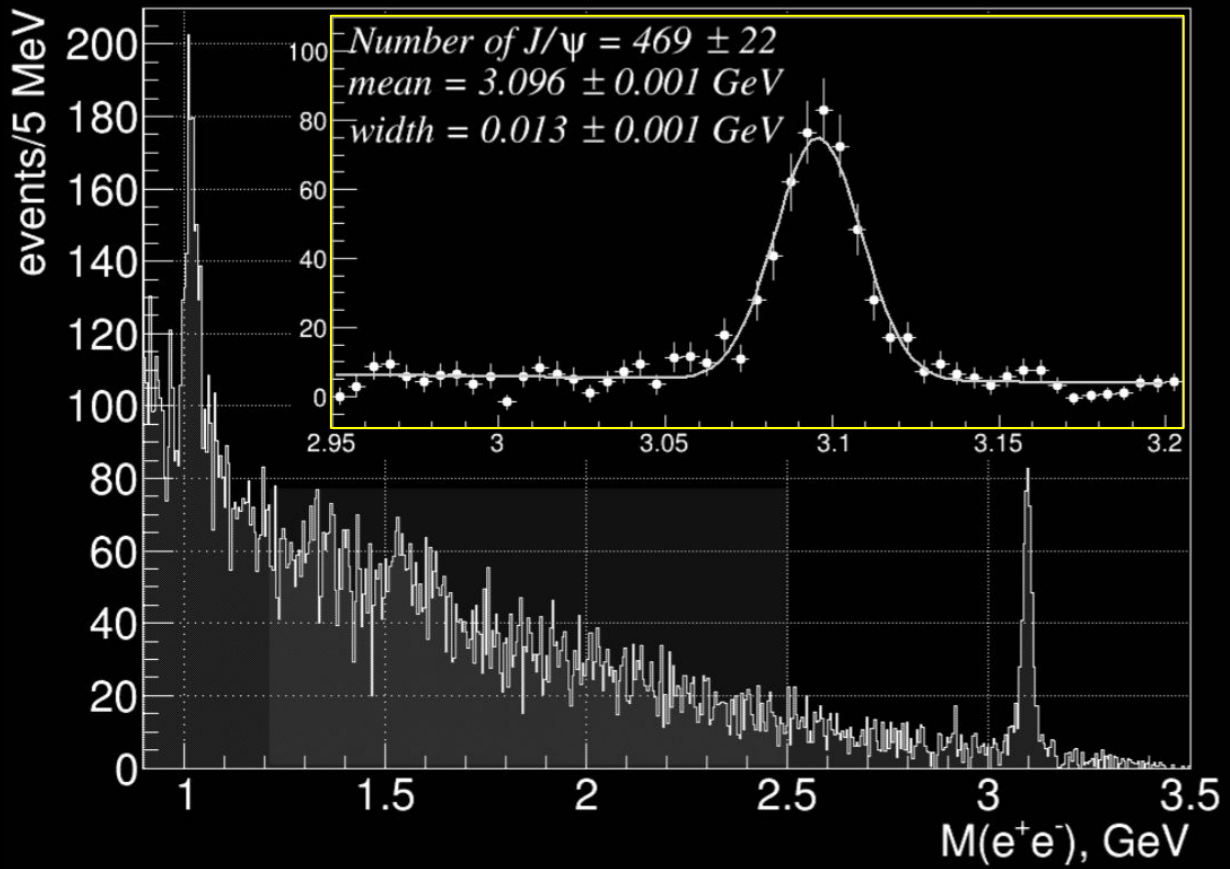
2T-solenoid, LH target
Tracking (FDC, CDC)
Calorimetry (BCAL, FCAL),
Timing (TOF, SC)



π >10^3 times more than e:
e/π separation by E/p,
energy deposition in the calorimeters over measured momentum

Di-lepton Invariant Mass Spectrum

Phys. Rev. Lett. 123, 072001 (2019)

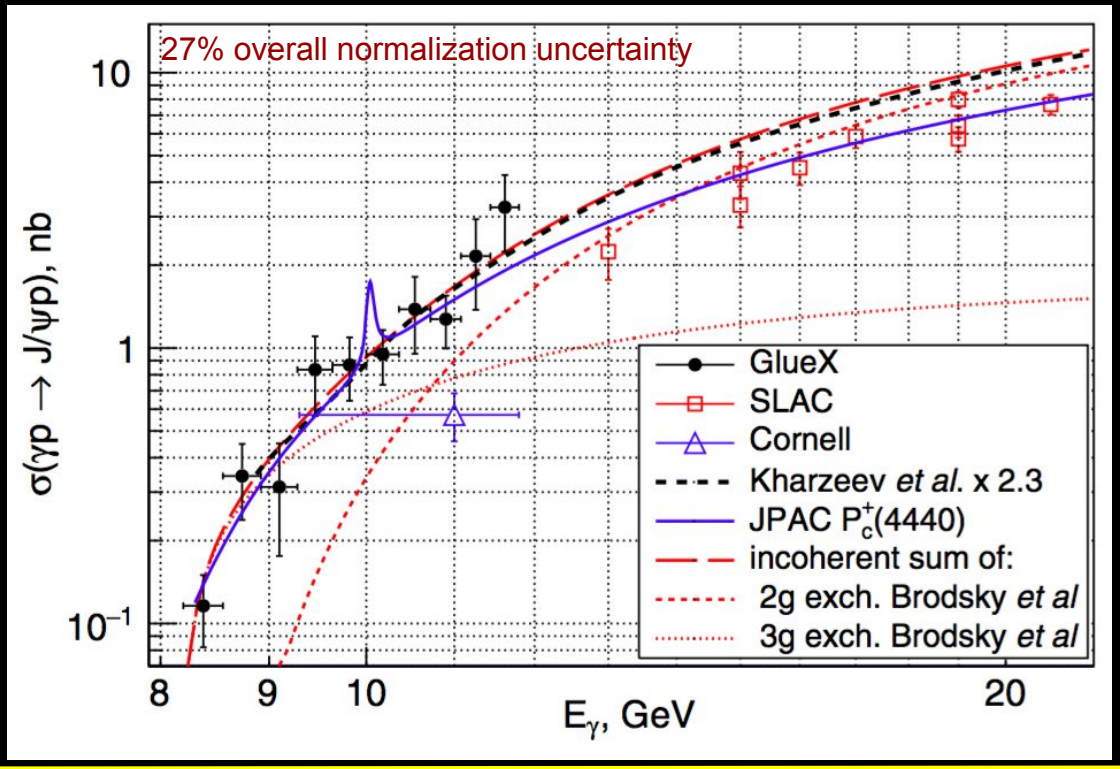


- Tagged photon beam (0.2% energy resolution) and exclusivity of the reaction.
- Kinematic fit (constrained mostly by the recoil proton): 13 MeV mass resolution; no radiative tail
- Pion contamination ~50% in the continuum (using E/p fits to estimate it)

Total Cross-Section

Phys. Rev. Lett. 123, 072001 (2019)

$$\sigma_{J/\psi}(E_\gamma) = \frac{N_{J/\psi}(E_\gamma)}{N_{\rm BH}(E_\gamma)} \frac{\sigma_{\rm BH}(E_\gamma)}{\mathcal{B}_{J/\psi}} \frac{\varepsilon_{\rm BH}(E_\gamma)}{\varepsilon_{J/\psi}(E_\gamma)}$$



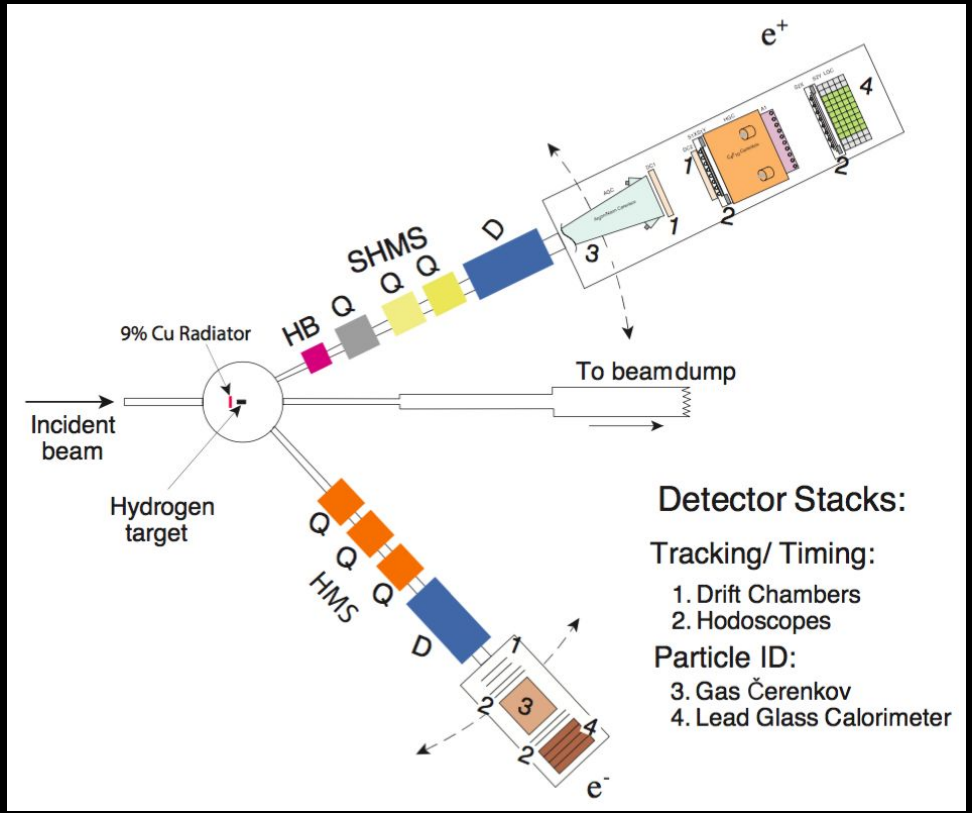
- Yields extracted from fits of M(e^+e^-) and E/p in bins of energy
- σ_{BH} calculated using analytical and numerical calculation of e.m. tree level diagrams
- Syst. uncertainties as max deviation when varying fitting methods
- Uncertainties dominated by statistics
- Our data are compatible with a combination of 2-gluon and 3-gluon exchange. The shape of the curve agrees with the Kharzeev curve multiplied by a factor ~2.
- No evidence for Pc structures.

	M(4312)	M(4440)	M(4457)
BR(J/ψp) 90% C.L. upper limit	4.6%	2.3%	3.8%

Hall C, PR12-16-007

Credits: S. Joosten, Hall C
https://www.jlab.org/user_resources/meetings/JLUO_6_19/Joosten.pdf

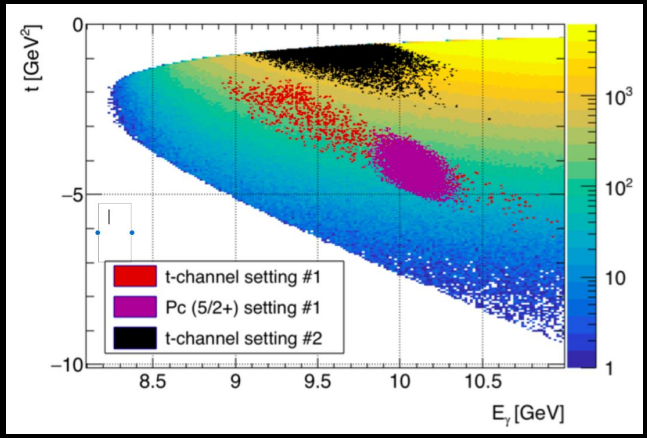
007 $^{J/\psi}$ Experiment



- High intensity real photon beam (9% copper radiator) from I_e ~ 50 μA
- 10cm liquid hydrogen target
- Detect J/ψ decay leptons in coincidence
- Bremsstrahlung photon energy fully constrained

Ran Feb 8 - Mar 7 2019

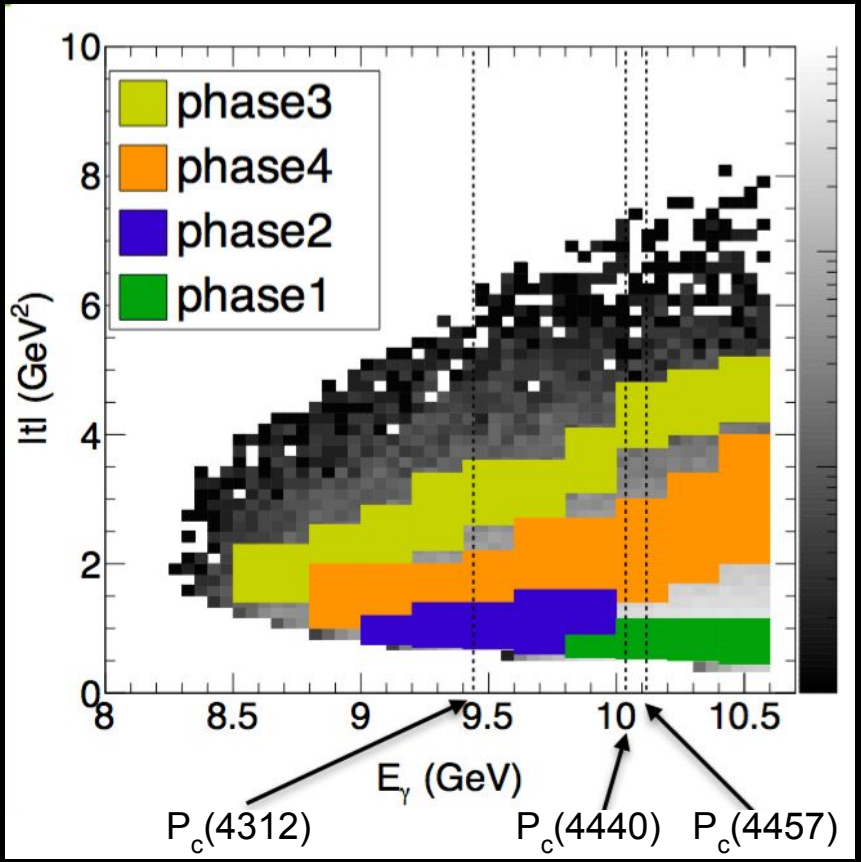
Meziani et al., arXiv:1609.00676v2 [hep-ex]



- Experiment tuned to provide best S/B for resonant J/ψ production at high t
- “Symmetric” configuration for t-channel x-sec measurements
- “Asymmetric” configuration for s-channel

007$^{J/\Psi}$ Experiment

https://www.jlab.org/user_resources/meetings/JLUO_6_19/Joosten.pdf

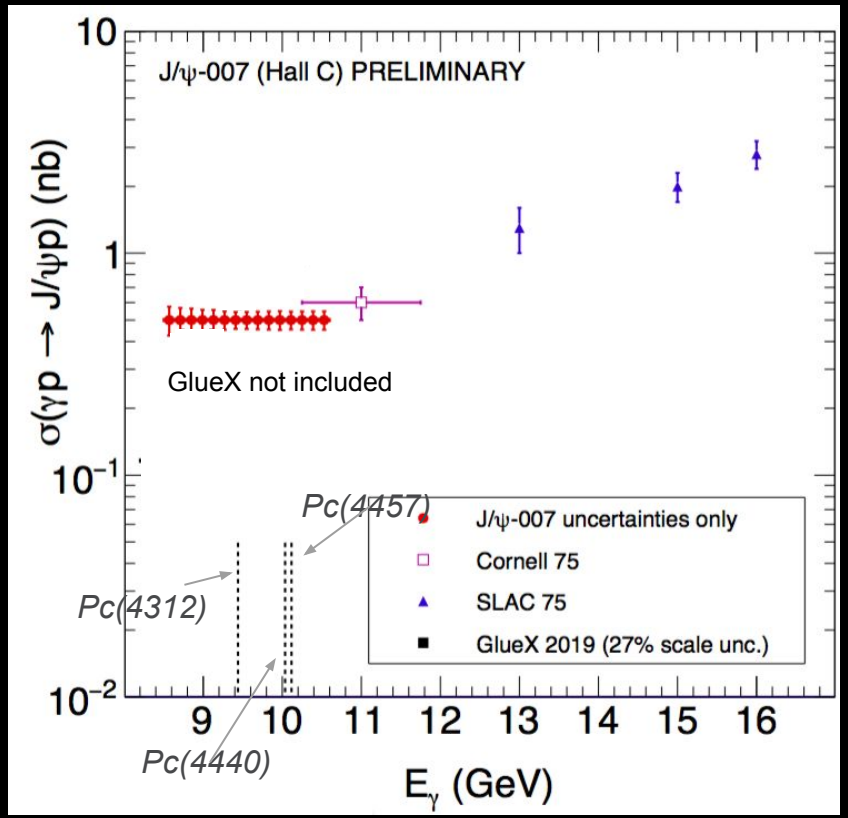


- Largest dataset of *J/ψ* produced with a real photon beam.
- 2D photo-production cross section between 8.5-10.6 GeV
- Used 4 settings to cover entire phase space
- High-*t* "enriched" sample, only possible at Hall C!
- Combine data from all settings for maximal sensitivity to LHCb pentaquark
- Covers energy range the three new LHCb pentaquark candidates

Best signal-to-background for resonant *J/ψ* production (*P*) **at high *t***

Absolute Cross Section

https://www.jlab.org/user_resources/meetings/JLUO_6_19/Joosten.pdf



Only showing (preliminary) uncertainties!

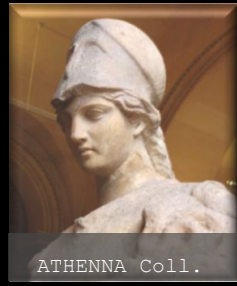
- High-precision measurement of the *t*-dependent cross section between 8.5-10.6 GeV
- Precise (~5%) absolute cross section possible due to calibration measurements of elastic and inelastic cross sections

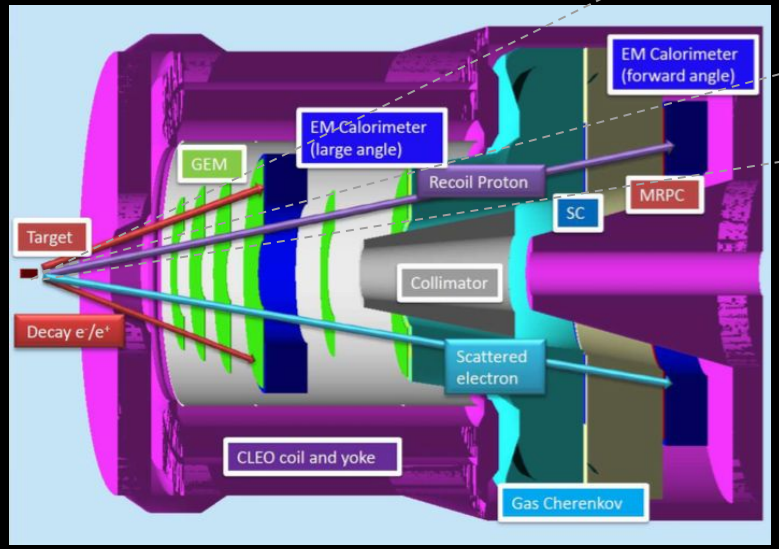
New results will be shown soon…

Absolute cross section ~5% precision

Hall A, SoLID ATHENNA Coll.

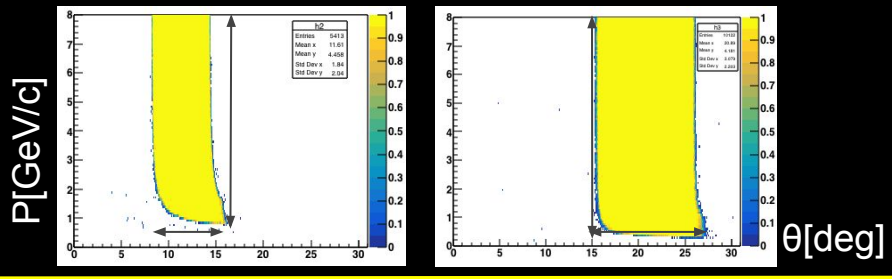
J/ψ Experiment E12-12-006 at SoLID





K. Hafidi *et al.*, Few Body Syst. 58 (2017) 4, 141

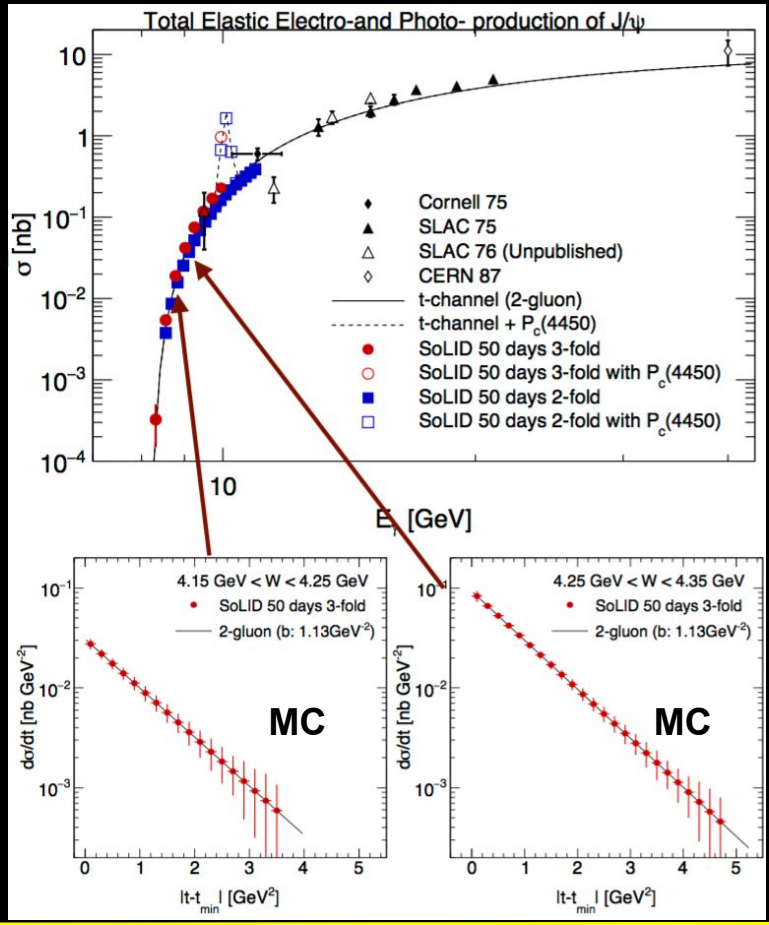
- 3μA electron beam at 11 GeV for 50 days
- 11 GeV beam 15cm liquid hydrogen target
- Ultra-high luminosity (43.2 ab^{-1})
- General purpose large-acceptance spectrometer
- Symmetric acceptance for electrons and positrons
  - Electro-production
  - Real photo-production through bremsstrahlung in the target cell



J/ψ Experiment E12-12-006 at SoLID (in ~ 10 years from now)

- Photo-production
  - 2-fold coincidence + recoil proton
  - t-channel J/ψ rate: 1.6k per day
  - Advantage over electro-production
    - Energy reach in charmed Pc region
    - High rate
- Electro-production
  - 3-fold coincidence (3 leptons)
  - t-channel J/ψ rate: 80/day
  - Advantage over photo-production
    - Less background
    - Closer to threshold

Sensitivity below 10^{-3} nb



Hall B CLAS12

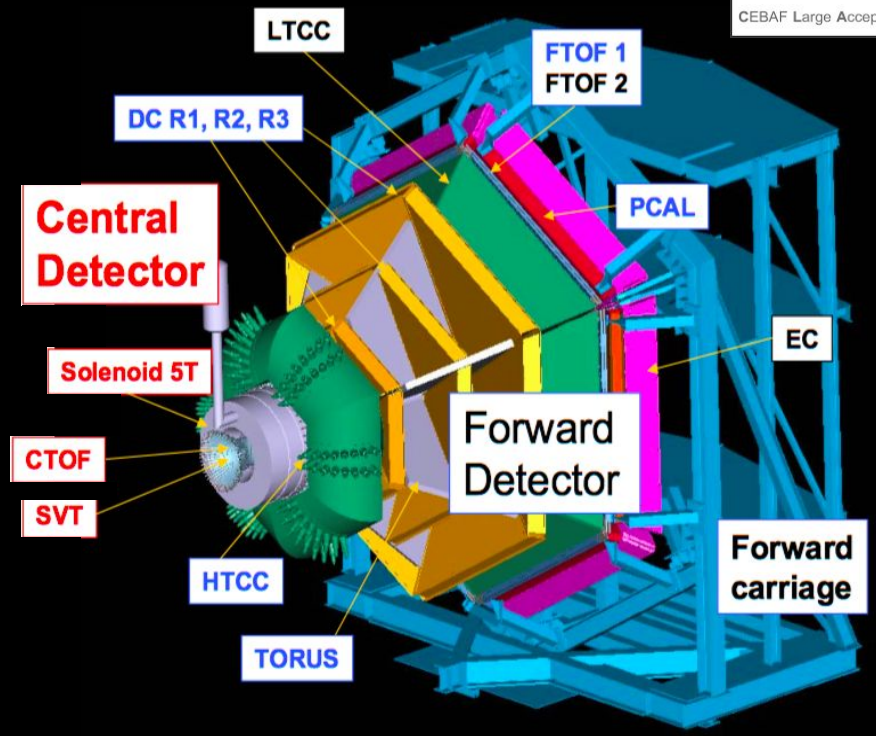
Hall B CLAS12

Electrons scatter off a LH target at low scattering angles through the exchange of a quasi-real photon at $Q^2 \sim 0$

Can detect the recoil p and the e^+e^- from the decay of J/ψ (with tagged and untagged scattered electron e')

Experiment 12-12-001 was approved for 120 days of beamtime on CLAS12 at a luminosity of 10^{35} $cm^{-2}s^{-1}$.

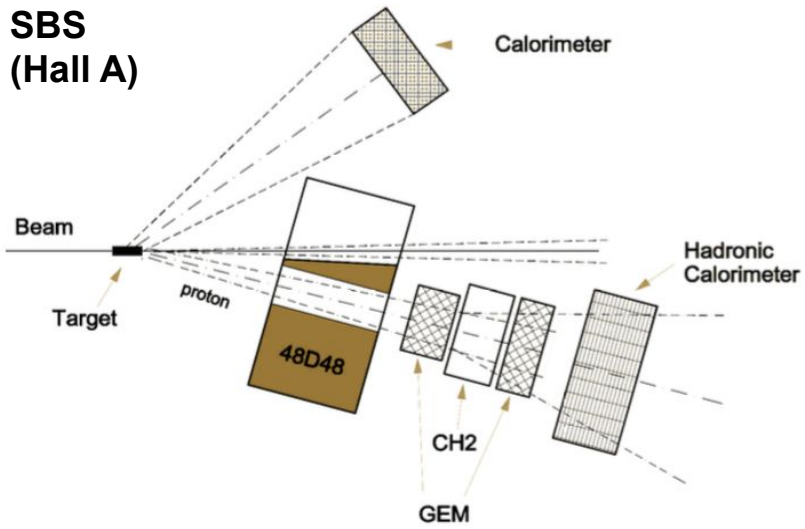
Approximately 40% of data collected.



Analysis ongoing…

Novel Directions: Polarization Observables

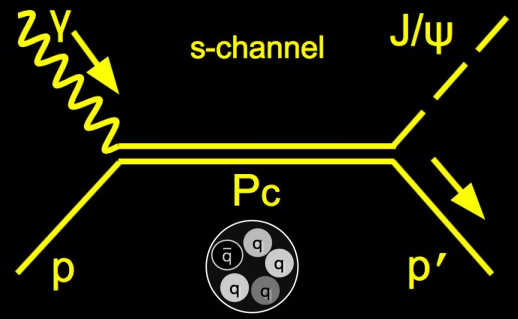
SBS (Hall A)



	I_e [μA]	X0	$\rho_{free} \cdot l$ [g/cm^2]
K_{LL} (SBS)	5.0	$6 \cdot 10^{-2}$	1.08
A_{LL} (SBS)	0.1	$10 \cdot 10^{-2}$	0.32

JLab, PAC 46, LOI 12-18-001, CF, L. Pentchev, B. Wojtsekhowski

$$A(K)_{LL} = \frac{1}{2}\left[\frac{d\sigma(++) - d\sigma(+-)}{d\sigma(++) + d\sigma(+-)} - \frac{d\sigma(-+) - d\sigma(--)}{d\sigma(-+) + d\sigma(--)}\right]$$

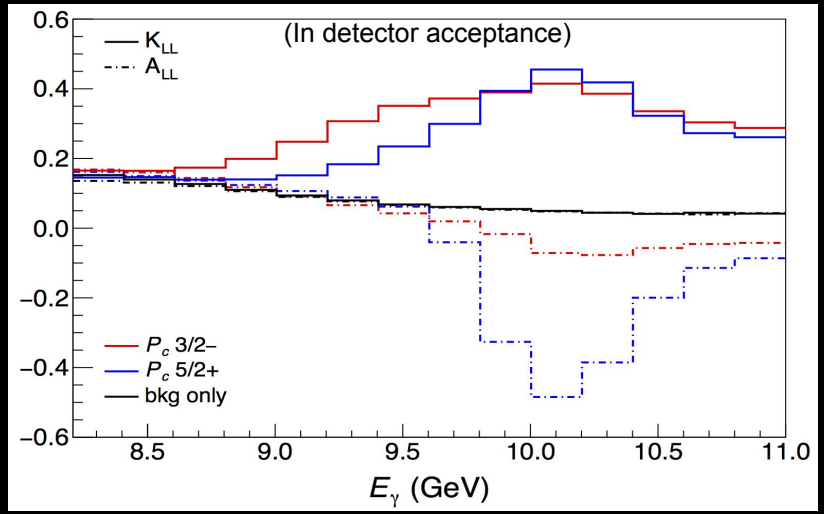


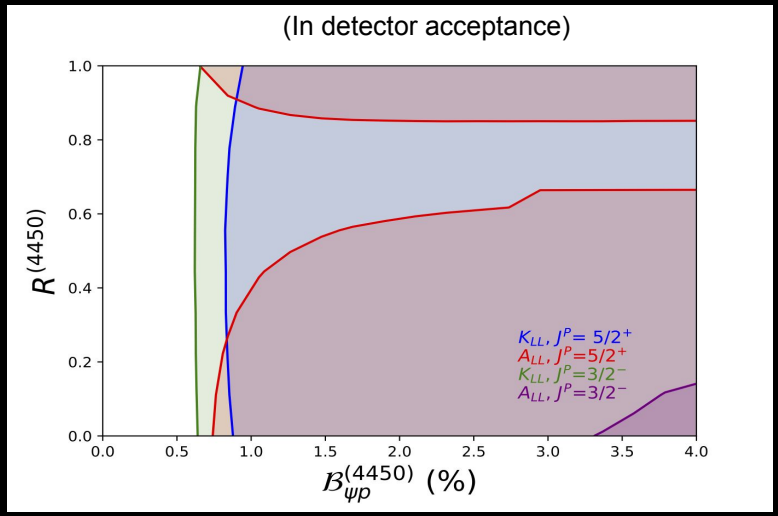
Summary: The measurement of polarization observables will be a novel and innovative way to probe the parameters of the newly discovered pentaquark states. The PAC encourages submission of a full proposal after observation through photoproduction is confirmed by an approved JLAB experiment. **(LOI 12-18-001, PAC 46)**

Polarization Observables

Phys. Rev. D 100, D. Winney, CF, A. Pilloni et al 034019 (2019)

- We thus analyzed the possibility of observing these exotic structures, treating the Pc (4440) and Pc (4457) states as one combined Pc(4450) peak, since there is as of now no information on the quantum numbers of the individual states.
- Pomeron-like background added coherently to the two resonances Pc(4450) and Pc(4380) data on J/ψ photoproduction close to threshold including the new GlueX results.



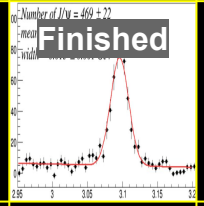


Sensitivity to photo-couplings and hadronic branching ratio

Summary Table

N.b. Only published results are from GlueX. Other numbers might change as the analyses progress.
Estimated number of J/ψ based on 2-gluon exchange.

time

Experiment	Production	When	Number of J/Ψ	Kinematics	Resolution	Physics
Hall D (GlueX) cf. Phys. Rev. Lett. 123, 072001 (2019)	$\gamma p \rightarrow J/\psi p'$ (e+e-p) Tagged beam		reco 469+/-22 (now ~ 2k) + ~1k (2020)	$E \in (8.2,11.8)$ GeV $-(t-t_{min}) \in (0.,1.05)$ GeV^2	$\sigma(M_{J/\psi})$=13 MeV $\sigma(E_\gamma)/E_\gamma$=0.2%	- J/ψ near thr. prod. σ,dσ/dt - Pc? - Spectroscopy - Beam asymmetry
Hall C (HMS+SHMS) cf. PR12-12-006, S. Joosten, JLUO 2019 Private comm. (✝)	$\gamma p \rightarrow J/\psi p'$ (e+e-)	Finished Ongoing analysis	~2100 (~4200 with μ)	$E \in (\sim 8.5.,10.6)$ GeV	$\sigma(M_{J/\psi}) \sim$ 5 MeV $\sigma(E_\gamma) \sim$ 5 MeV (✝)	- J/ψ near thr. prod. σ,dσ/dt - Pc?
Hall B (CLAS12) J. Newton, JLUO 2019. cf. E12-12-001A	$ep \rightarrow e'J/\psi p'$ untagged, tagged e'	Ongoing	<rate> ~45/day (tot) 120 PAC days 40% collected	$W \in (4.1,4.5)$ GeV	untagged: $\sigma(M_{e+e-p}) \sim$ 13 MeV tagged: $\sigma(M_W) \sim$5-8 MeV	- J/ψ near thr. prod. σ,dσ/dt - Pc? - timelike Compton
Hall A (SoLID) cf. PR12-12-006, S. Joosten, JLUO 2019	$\gamma p \rightarrow J/\psi p'$ (e+e-p) + $ep \rightarrow e'J/\psi p'$ (e+e-e'; e+e-p e')	~10 years	<rate> $\sim 1.6 \cdot 10^3$/day ~80/day 50 PAC days	$W \in (4.05,4.45)$ GeV $\lvert t-t_{min} \rvert < 2.5$ GeV^2	ongoing	- J/ψ near thr. prod. σ,dσ/dt - Pc?

Conclusions and Perspectives

- Quarkonium production an important tool to study the gluonic fields in the nucleon and LHCb pentaquarks

  (threshold production of quarkonium can shed light on the trace anomaly, the origin of the proton mass, quarkonium-nucleon binding...)

- JLab12 perfectly positioned to significantly contribute to these topics:
  - First GlueX results near threshold published
  - New results of Hall C J/ψ-007 experiment will be released soon: high precision absolute cross-section measurements
  - Ongoing analysis in Hall B

The largest dataset of J/ψ produced at JLab with real photon beam will either confirm Pc resonances, or place very strong limit on the photo-coupling.

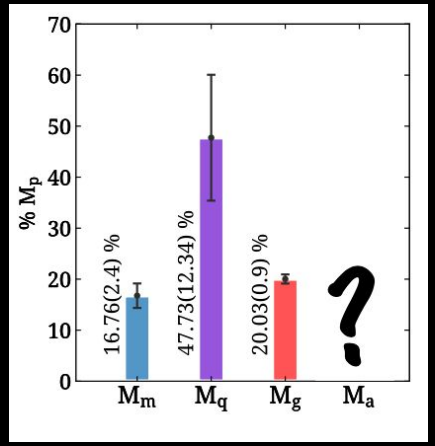
BACKUP

J/ψ near-threshold physics in addition to Pc searches

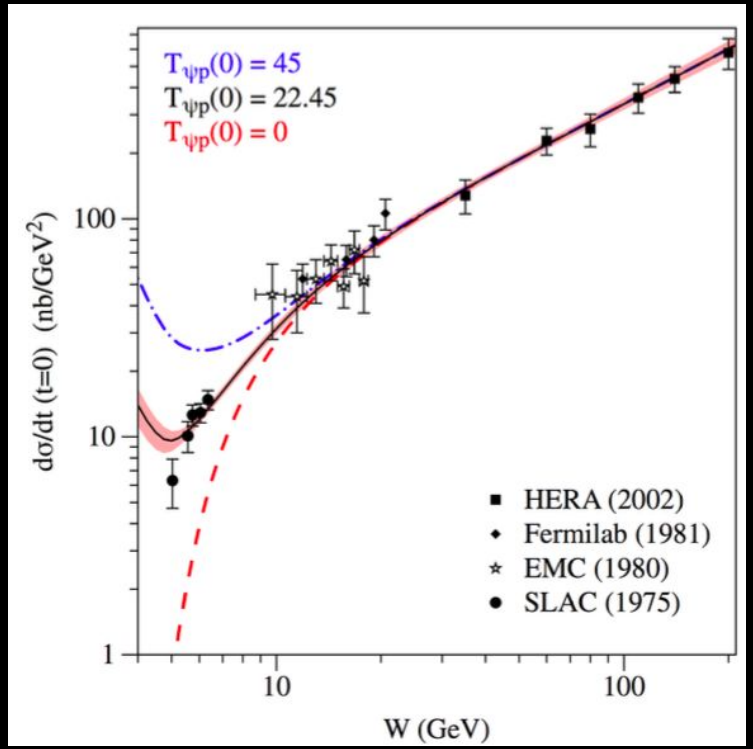
A lot of interesting physics potentially accessible:

- 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
- Bethe-Heitler Asymmetry

- Gryniuk, Vanderhaeghen, PRD 94, 105 (2016)
- S. R. Beane *et al.*, PRD 91, 114503 (2015)

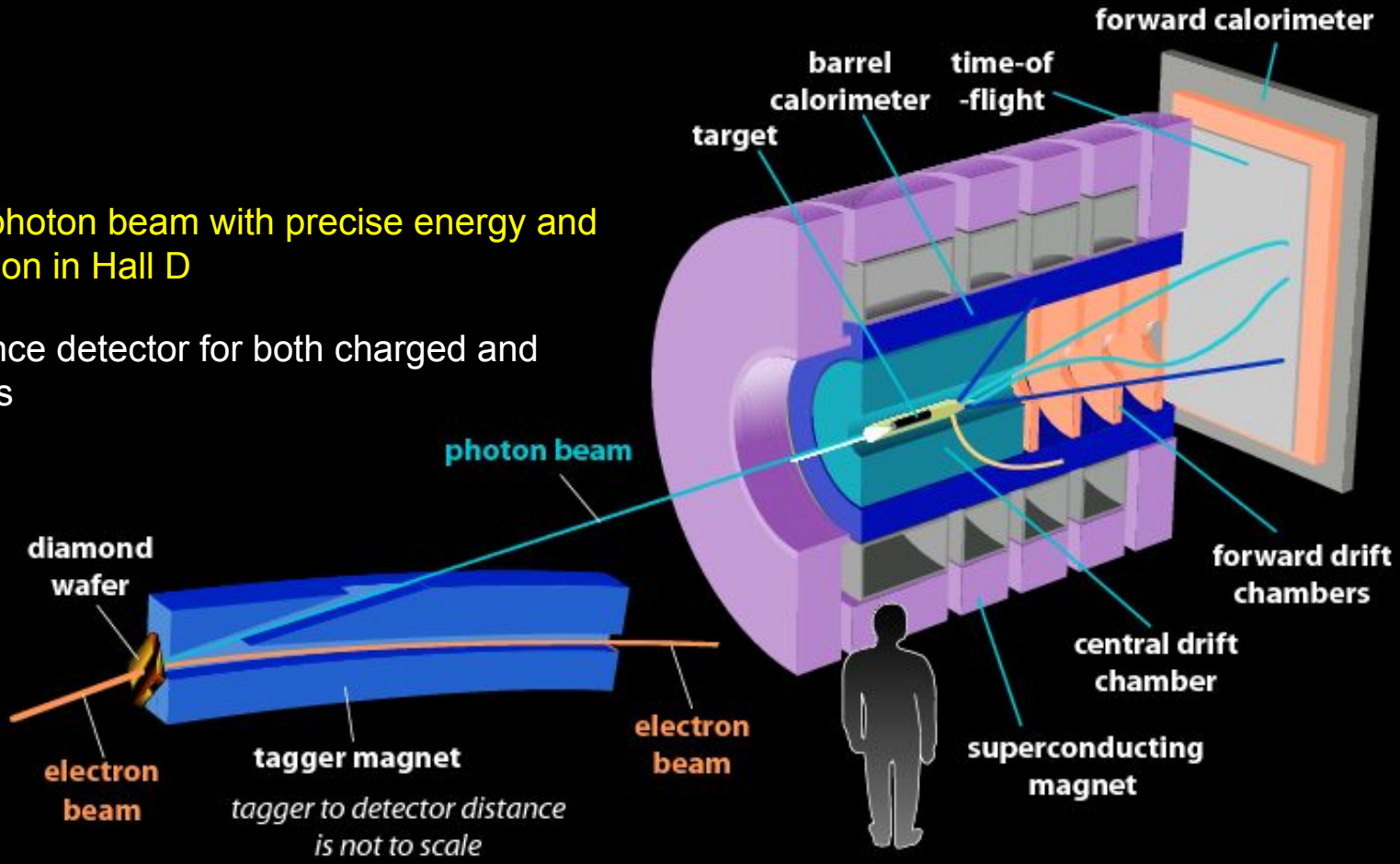


- C. Alexandrou *et al.*, (ETMC), PRL 116, 252001 (2016)



GlueX

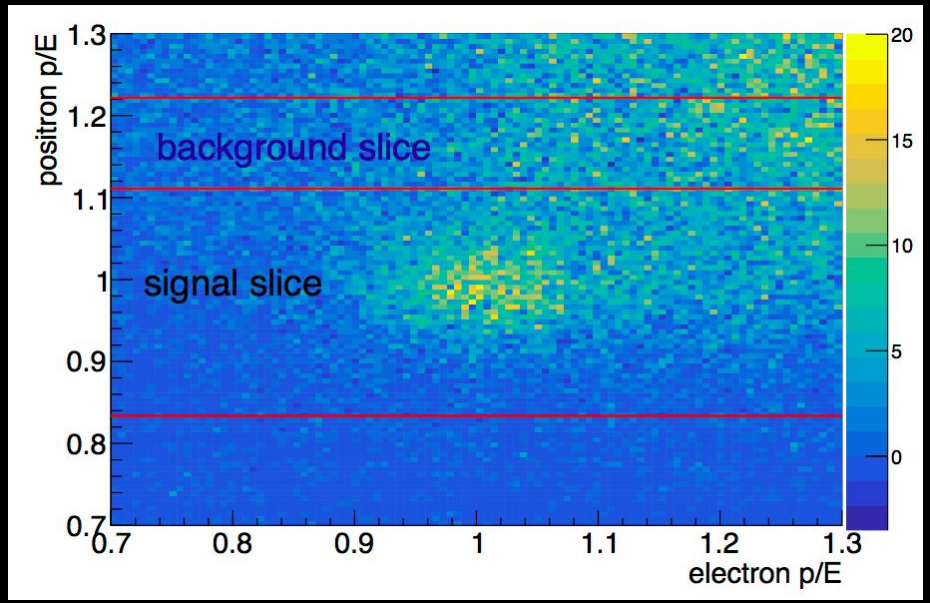
- High intensity photon beam with precise energy and linear polarization in Hall D
- Large acceptance detector for both charged and neutral particles

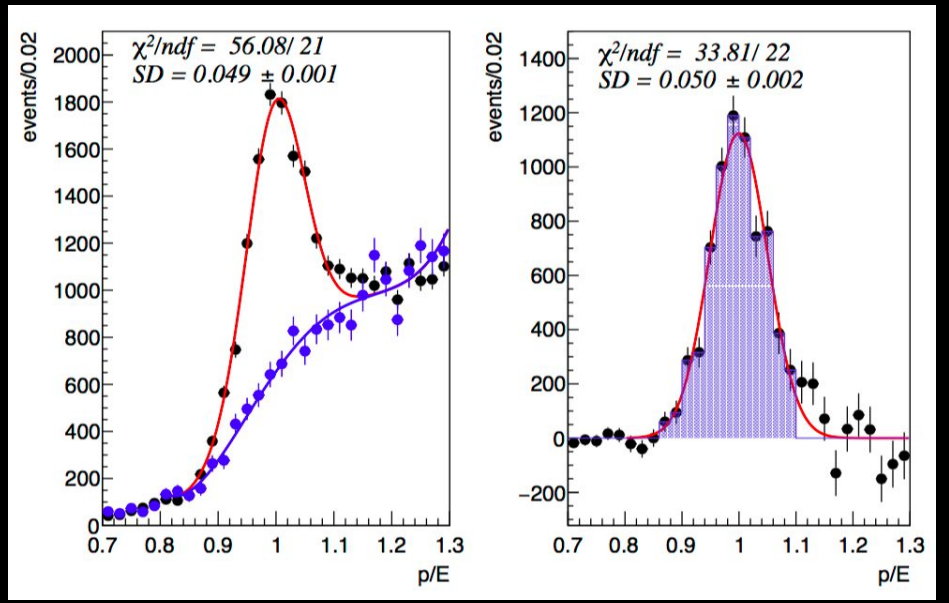


photoproduction of hybrids, light-quark mesons, and strangeonium states

Electron/Pion Separation

arXiv:1905.10811v2 [nucl-ex]





Hall D, GlueX

Perspectives: Accessible Charmonia at GlueX

Reaction	Threshold	Suggested Decays (Branching Fractions)
$\gamma p \to p\,\eta_c(1S)$	7.7 GeV	$\eta_c(1S) \to K_S K\pi(2.3\%), K^+K^-\pi^0(2.3\%),\ \eta\pi\pi(1.7\%)$
$\gamma p \to p\,J/\psi(1S)$	8.2 GeV	$J/\psi(1S) \to e^+e^-(6\%)$
$\gamma p \to p\,\chi_{c0}(1P)$	9.6 GeV	$\chi_c 0(1P) \to \pi^+\pi^-\pi^+\pi^-(2.3\%)$
$\gamma p \to p\,\chi_{c1}(1P)$	10.1 GeV	$\chi_{c1}(1P) \to \gamma J/\psi(34\%)$
$\gamma p \to p\,h_c(1P)$	10.1 GeV	$h_c(1P) \to \gamma\eta_c(1S)(51\%)$
$\gamma p \to p\,\chi_{c2}(1P)$	10.3 GeV	$\chi_{c2}(1P) \to \gamma J/\psi(19\%)$
$\gamma p \to p\,\psi(2S)$	10.9 GeV	$\psi(2S) \to \pi^+\pi^- J/\psi(35\%)$

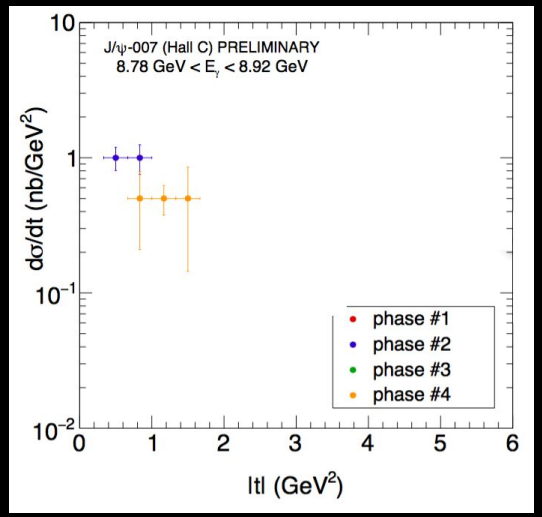
Courtesy of S. Dobbs

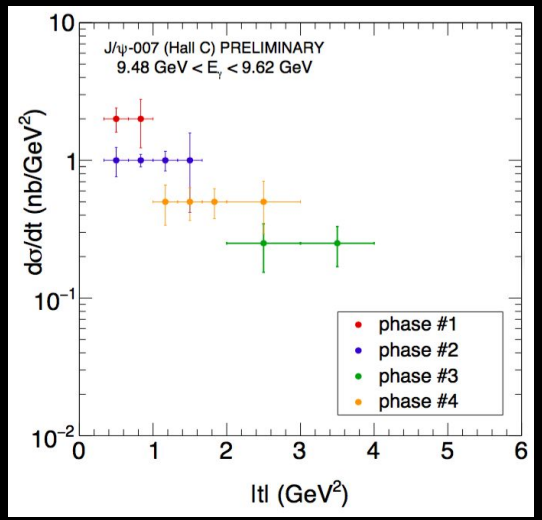
Hall D, GlueX

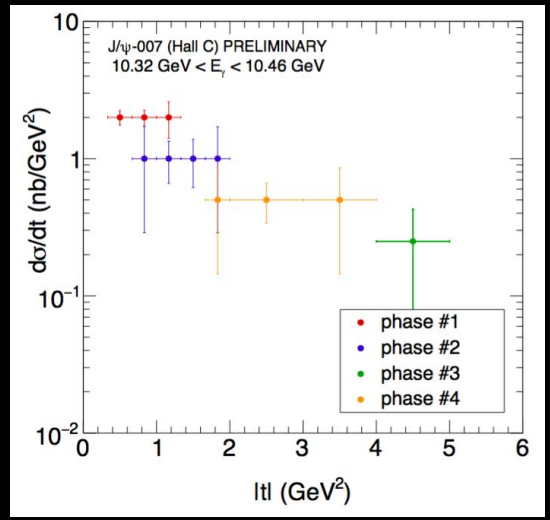
Absolute Cross Section

https://www.jlab.org/user_resources/meetings/JLUO_6_19/Joosten.pdf

Only showing uncertainties: y-position for each setting arbitrary for improved visibility)





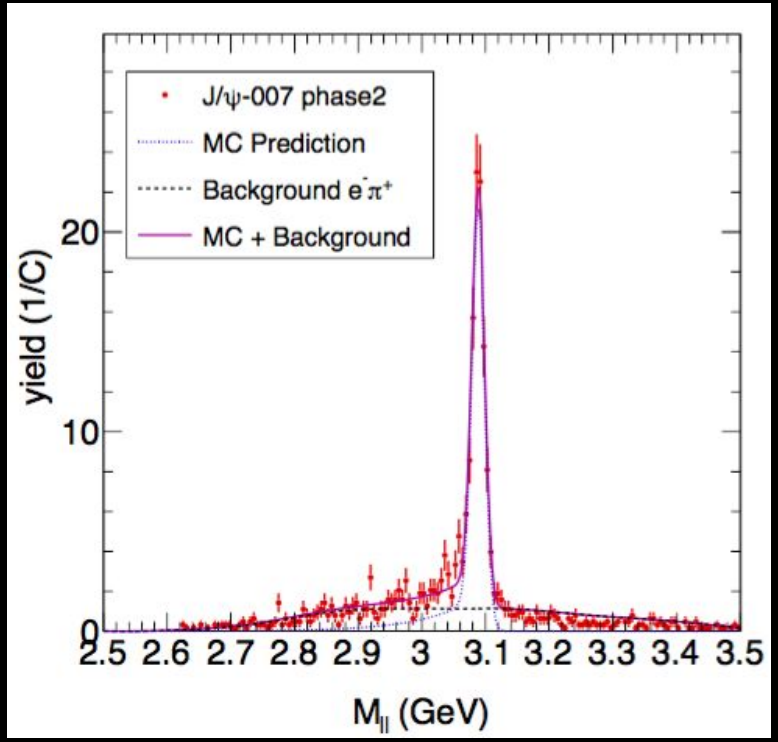


First 2D measurement near threshold: access Color van der Waals force and trace anomaly

Hall C, J/ψ-007

Signal shape well understood

Credits: S. Joosten, (Hall C)
https://www.jlab.org/user_resources/meetings/JLUO_6_19/Joosten.pdf

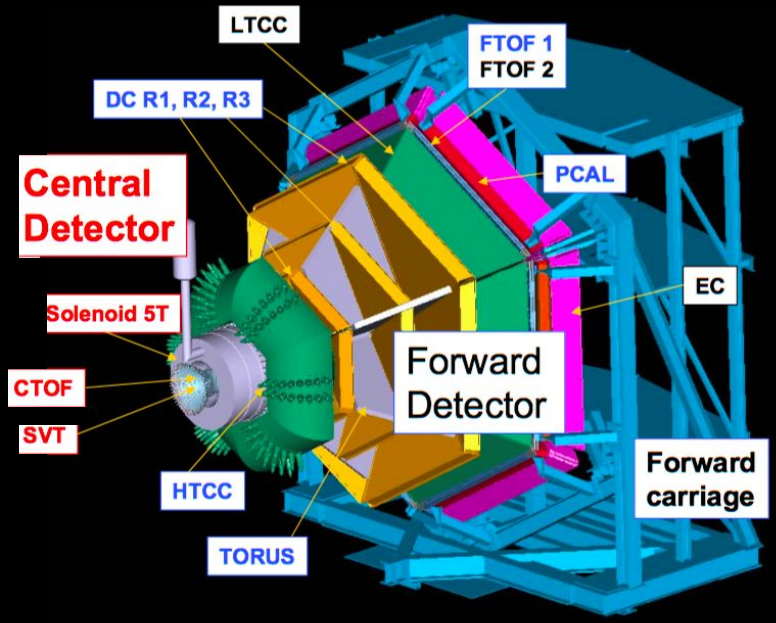


- MC has model of radiator, realistic target, detector and RC (using PHOTOS)
- Measured signal well described by MC for all settings.
- Background dominated by pion electro-production
- Bethe-Heitler contamination very small due to large spectrometer angles
- Took data with open trigger: **background shape from real data!**

Hall C, J/ψ-007

Credits: https://www.jlab.org/conferences/CLAS12/Burkert.pdf

Hall B CLAS12: exploded view



	Forward Detector	Central Detector
Angular range		
Charged Particles	$5^0 - 40^0$	$40^0 - 135^0$
Photons	$2^0 - 40^0$	N/A
Resolution		
$\delta p/p$ (%)	< 1 @ 5 GeV/c	< 3 @ 0.5 GeV/c
$\delta\Theta$ (mr)	< 0.5	< 10
$\delta\phi$ (mr)	< 0.5	< 6
Photon detection		
Energy (MeV)	>150	N/A
$\delta\Theta$ (mr)	4 (1GeV)	N/A
Neutron detection		
N_{eff}	0.1 – 0.6	0.05
Particle ID		
e/π	Full range	N/A
π/p	Full range	≤ 1.2 GeV/c
π/K	Full range	≤ 0.65 GeV/c
K/p	< 4 GeV/c	≤ 0.90 GeV/c
$\pi^0 \rightarrow \gamma\gamma$	Full range	N/A
$\eta \rightarrow \gamma\gamma$	Full range	N/A