# Near threshold J/$\psi$ production at JLAB

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Seminar at INFN Genoa

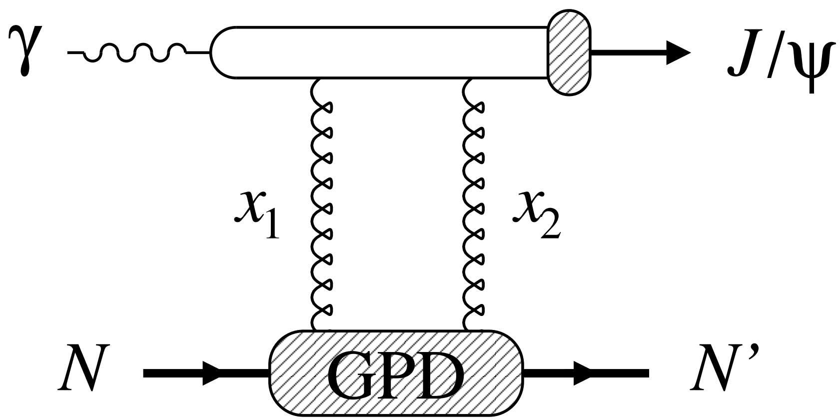
May 22, 2017

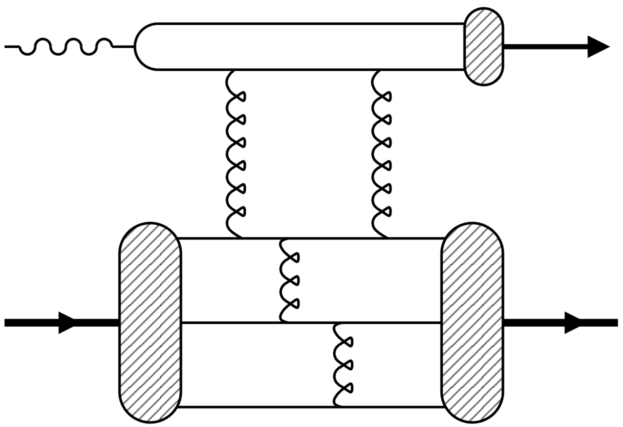
- Why *J/ψ* photoproduction near threshold
- LHCb (*J/ψ* p) pentaquarks in photoproduction
- JLAB12 – a new energy regime
- Planed and ongoing experiments
- CLAS12 detector in Hall-B
- Untagged and tagged photoproduction
- *J/ψ* measurements with CLAS12
- Cross section and expected results
- Summary

# Why study $J/\psi$ photoproduction?

- There are "*almost*" no $c\bar{c}$ in the nucleon, production of $J/\psi$ goes via gluon exchange
- Small size $Q\bar{Q}$ state due to large mass of *c*-quark

Unique probe of the gluon field of the target



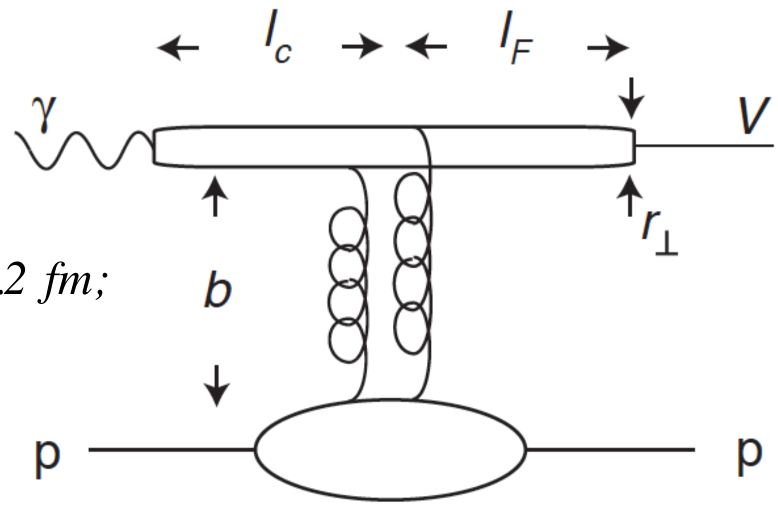



At high energies (HERA, FNAL) probes gluon GPDs. Considerable amount of data at W > 10 GeV, in good agreement with 2-gluon exchange mechanism

Near threshold (large momentum transferred) probes gluonic form factor. No data below $E\gamma$=11 GeV, enhancement near threshold is expected due to multi-gluon exchange

# VDM picture of the production

$$E_\gamma \approx 10\ GeV \Rightarrow b \sim \frac{1}{\sqrt{-t}} \sim 0.2\ fm;$$




$$m_c \approx 1.5\ GeV;$$

$$r_\perp \sim \frac{1}{m_c} = 0.13\ fm$$

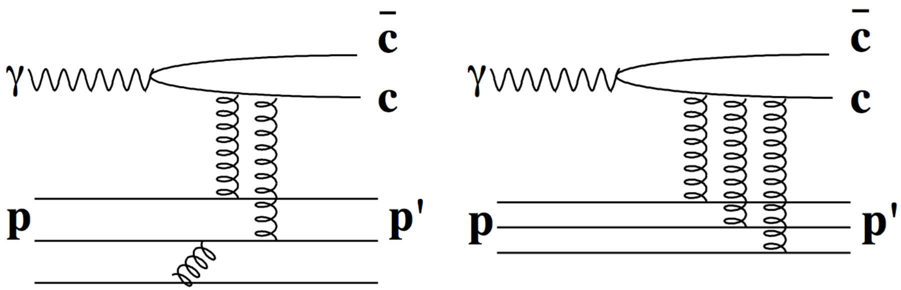
$$E_\gamma \approx 10\ GeV \Rightarrow l_c = \frac{2E_\gamma}{4m_c^2} \approx 0.4\ fm;\ l_F \approx \frac{2E_{J/\psi}}{2m_c\left(m_{\psi'} - m_{J/\psi}\right)} \sim 1-2\ fm;$$

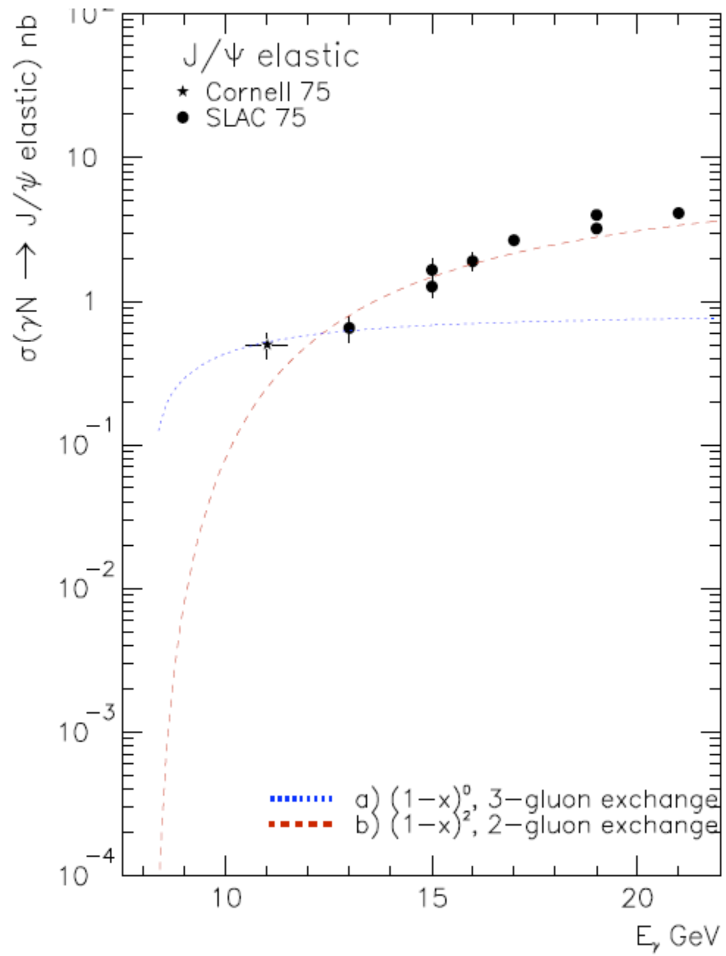
Favorable kinematics for studying

- production mechanism near threshold
- nucleons' local gluon field distribution, *b, r* << 1 fm
- J/ψN scattering, $l_c$ and $l_F$ ~ fm

# $J/\psi$ photoproduction near threshold

- The lowest published energy point is at $E_\gamma$=11 GeV
- Production mechanisms, 2-gluon or 3-gluon exchange
- Need precision data to sort this out




$$\frac{d\sigma}{dt} = \mathcal{N}_{2g} v \frac{(1-x)^2}{R^2 \mathcal{M}^2} F_{2g}^2(t)(s-m_p^2)^2$$

$$\frac{d\sigma}{dt} = \mathcal{N}_{3g} v \frac{(1-x)^0}{R^4 \mathcal{M}^4} F_{3g}^2(t)(s-m_p^2)^2$$

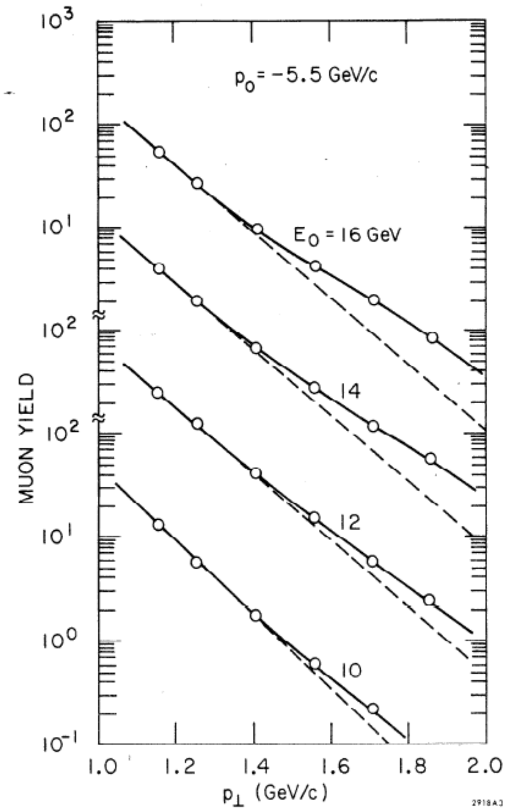
S.J. Brodsky, E. Chudakov, P. Hoyer, and J-M. Laget, Phys.Lett. B498, 23-28 (2001)

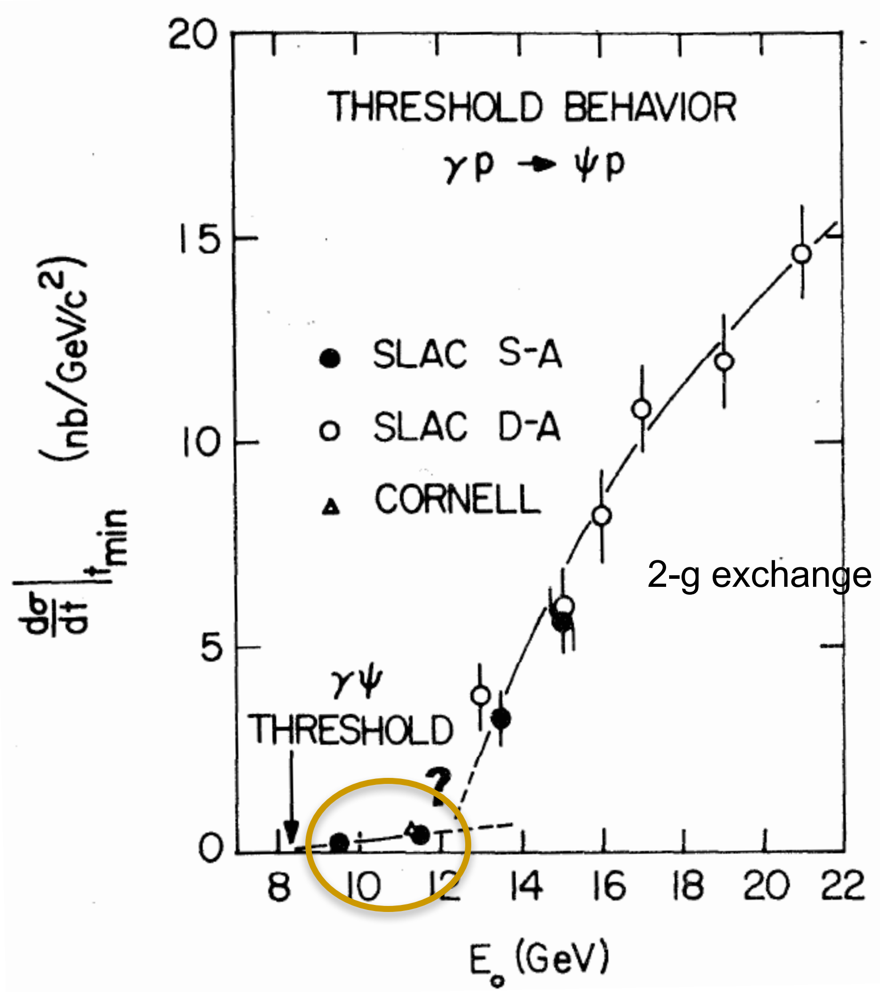
# SLAC single arm measurements

Flattening of cross section near the threshold – can it be due to a resonance?

S. Brodsky, SLAC-PUB-14985

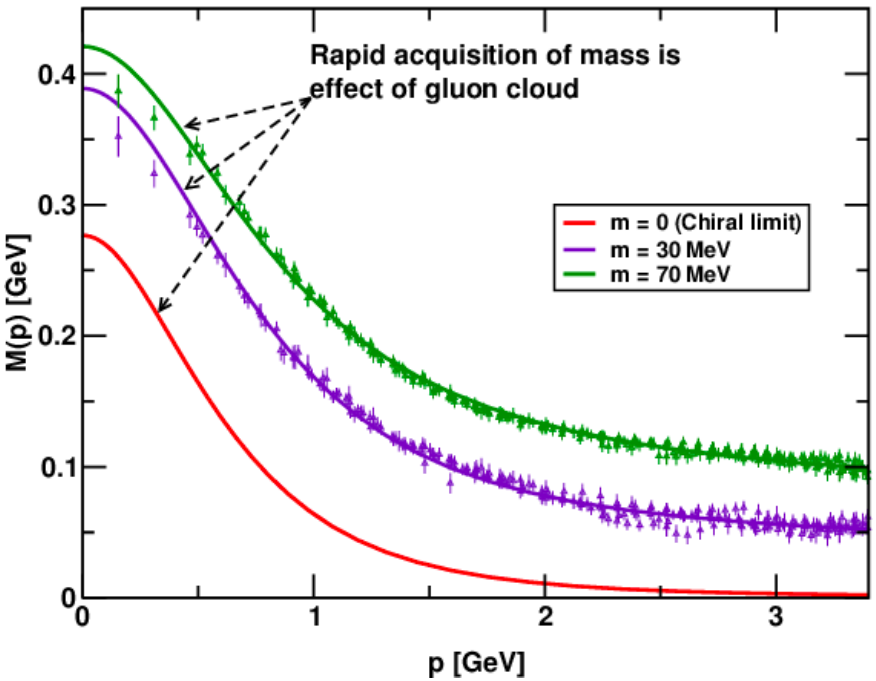
R.L. Anderson, SLAC-PUB-1741

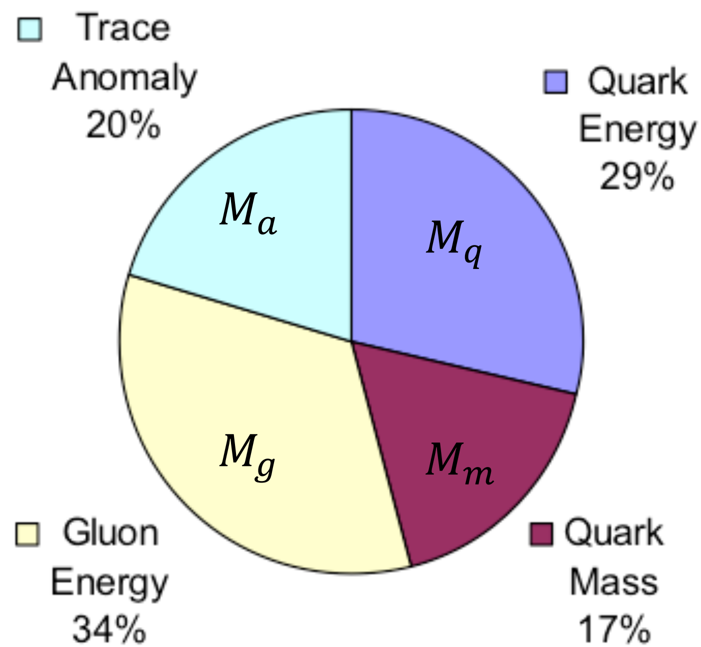


# Proton mass

- Current quark mass accounts only for ~1% of proton's mass
- The mass of the nucleon is due to quantum fluctuations, the gluons, and the kinetic energy of quarks




$$M_p = \frac{\langle P | \int d^3x T^{00} | P \rangle}{\langle P | P \rangle} \Big|_{at\ rest} = M_q + M_g + M_m + M_a$$

X. Ji, PRL (1995)

# Quarkonium scattering and trace anomaly

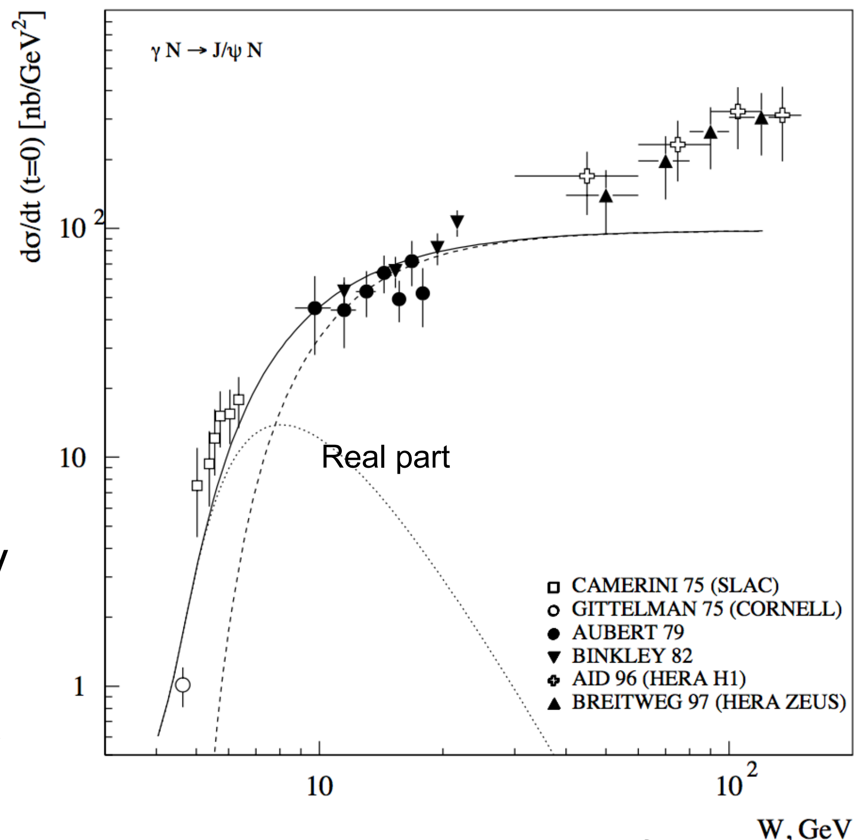
- The elastic photoproduction of a vector meson can be related to the vector-meson nucleon scattering

$$\frac{d\sigma_{\gamma N\to\psi N}}{dt} = \mathcal{K}\cdot\frac{3\cdot\Gamma(V\to e^+e^-)}{\alpha\cdot m_V}\cdot\frac{d\sigma_{\psi N\to\psi N}}{dt}$$

$$\frac{d\sigma_{\psi N\to\psi N}}{dt}\Big|_{t=0} = \frac{1}{64\pi}\cdot\frac{1}{m_\psi^2(\lambda^2-m_N^2)}\left|M_{\psi N}\right|^2$$

- Through optical theorem, the imaginary part is related to the total cross section
- The real part, with a large contribution near threshold, contains trace anomaly

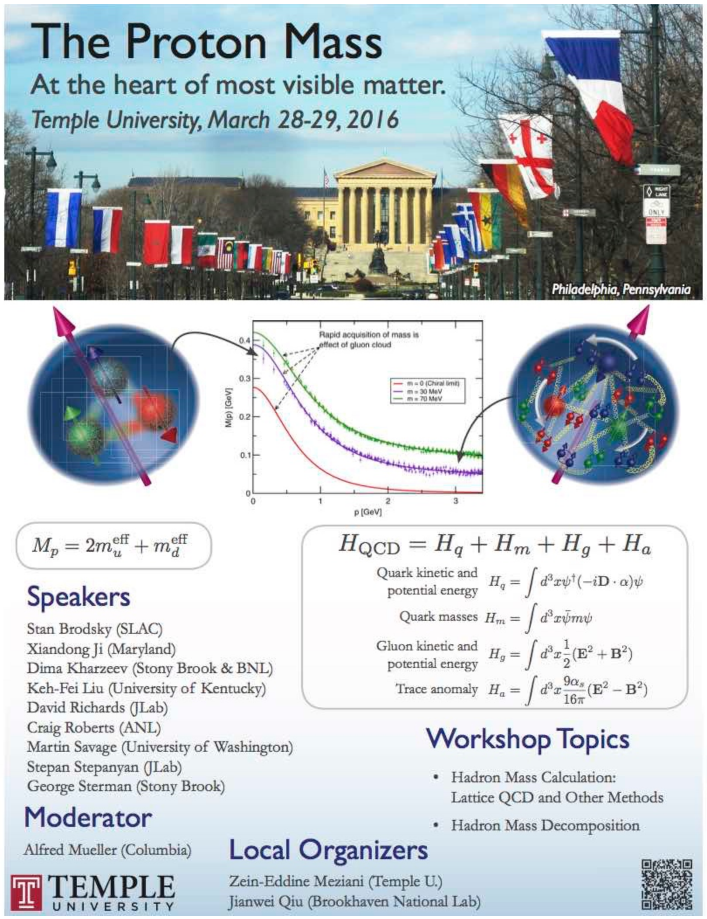
D. Kharzeev. Quarkonium interactions in QCD, 1995 nucl-th/9601029
D. Kharzeev, H. Satz, A. Syamtomov, and G. Zinovjev, Eur.Phys.J., C9:459–462, 1999




Quarkonium-proton interaction at low energy probes the distribution of mass inside the proton.

# Charmonium photoproduction and the proton mass

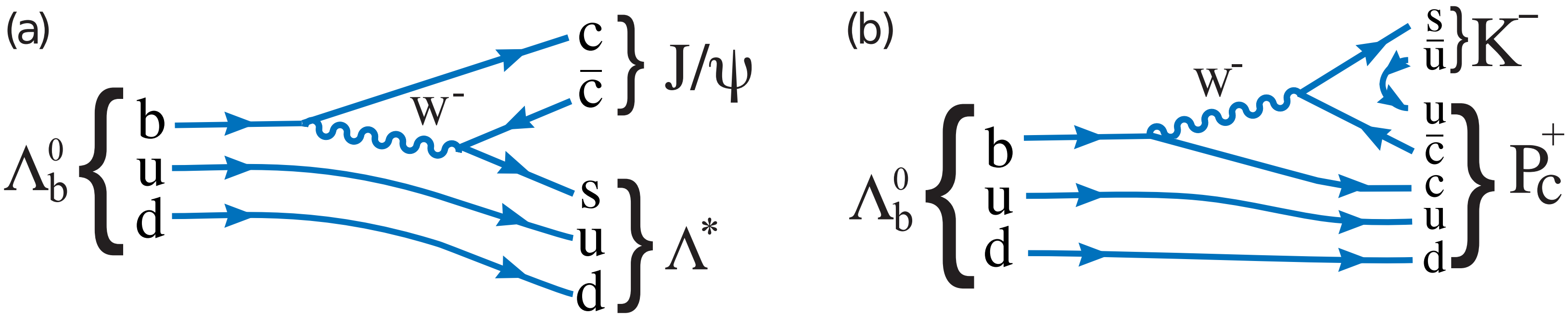
## Hot topic- JLAB experiments will have significant contribution




# LHCb hidden charmed pentaquarks

Amplitude analysis of the decay $\Lambda_b^0 \to K^- p J/\psi$ with two interfering modes of $\Lambda_b^0$ decay (with 14 $\Lambda^*$ states listed by PDG)

$\Lambda_b^0 \to \Lambda^* J/\psi$ $\qquad\qquad$ $\Lambda_b^0 \to K^- P_c^+$




Two exotic $c\bar{c}uud$ 5-quark states, $P_c^+$, were needed to converge

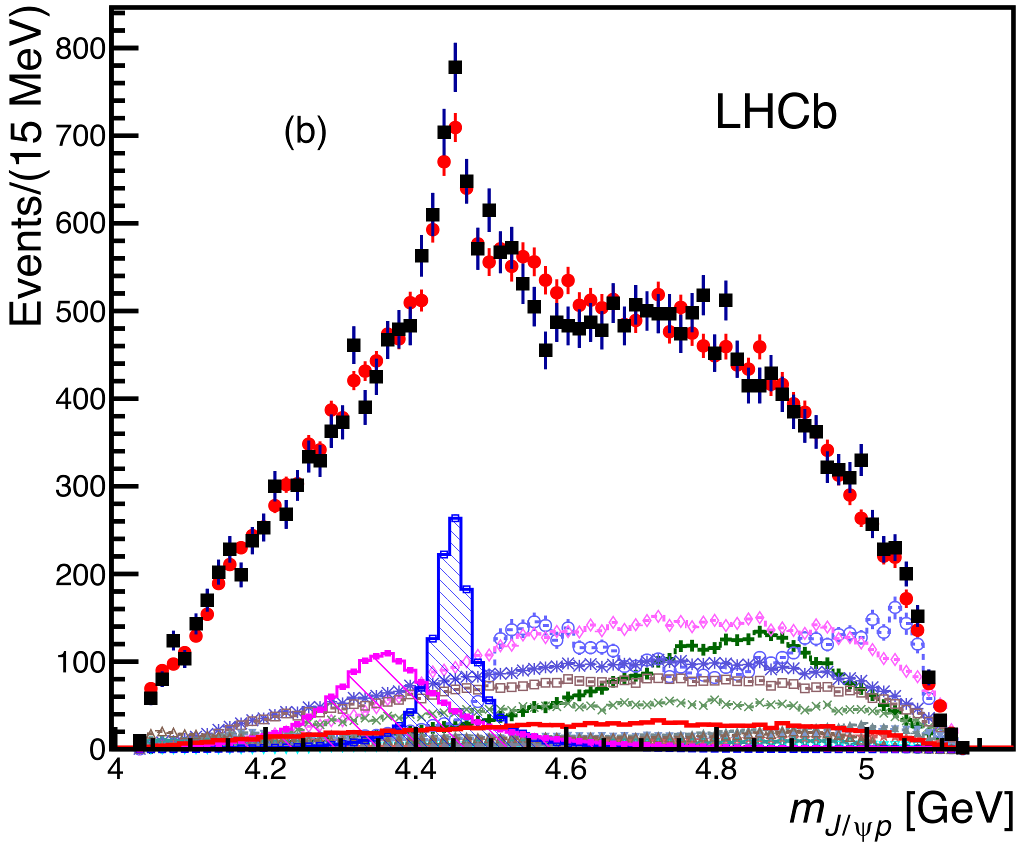
The significance of each of these resonances is more than 9σ.

R. Aaij et al. [LHCb Collaboration], Phys. Rev. Lett. 115, 072001

# The new J/ψp pentaquark states, $P_c^+$

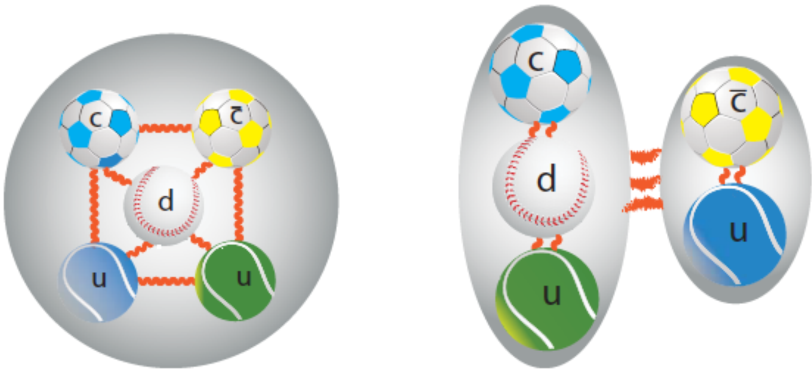
$M_-$=4380±8±29 MeV
$\Gamma_-$=205±18±86 MeV
$J^P=3/2^-$

$M_+$=4449.8±1.7±2.5 MeV
$\Gamma_+$=39±5±19 MeV,
$J^P= 5/2^+$.




R. Aaij et al. [LHCb Collaboration], Phys. Rev. Lett. 115, 072001

# Interpretation of new states




## Charmed Baryon and anti-charmed meson molecule:

- M. Karliner and J. L. Rosner, arXiv:1506.06386
- L. Roca, J. Nieves, and E. Oset, arXiv:1507.04249
- R. Chen, X. Liu, X.-Q. Li, and S.-L. Zhu, arXiv:1507.03704
- H-X. Chen, W. Chen, X. Liu, T.G. Steele, and S-L. Zhu, arXiv:1507.0317
- J. He, arXiv:1507.05200
- U.-G. Meiner and J. A. Oller,, arXiv:1507.07478. For P(4550) $\chi_{c1}p$
- A. Mironov and A. Morozov, arXiv:1507.04694. Is NOT a molecule

$$\bar{D}^{*}\Sigma_{c} - \bar{D}^{*}\Sigma_{c}^{*}$$

## A resonance state or reflection:

- F.-K. Guo, U.-G. Meiner, W. Wang, and Z. Yang, arXiv:1507.04950; Dominant decay to $\chi_{c1}p$ if real
- M. Mikhasenko, arXiv:1507.06552. Possible reflection in the complicated decay chain

**Need independent verification with a different production mechanism**

# JLAB12 – a new energy regime

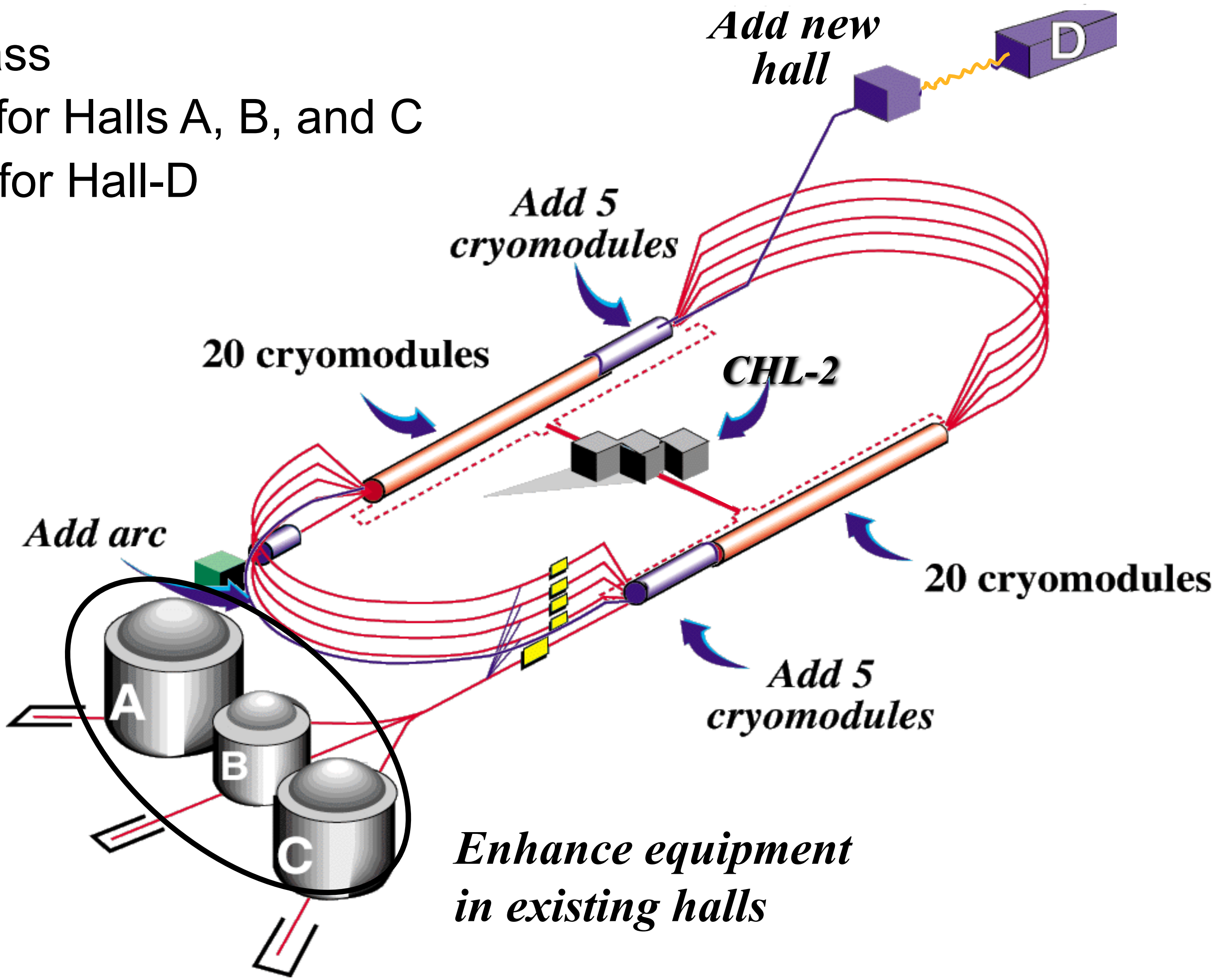
- The energy of upgraded JLAB machine, CEBAF, is well above J/$\psi$ production threshold energy, 8.2 GeV, on a free nucleon
- With up to 12 GeV electron beam, the threshold region will be studied in great detail using high luminosity detectors in all Halls
- The same experiments are well positioned to search and study LHCb hidden charm pentaquarks
- Currently three experiments have been approved and one is running:
  - Gluex data analysis (no approved experiment)
  - E12-16-007 using spectrometers in Hall-C,
  - E12-12-006 using future SoLID detector in Hall-A, 50 days approved
  - **E12-12-001 on CLAS12 in Hall-B, 130 days approved and the new proposal PR12-17-001**
- A new proposal has been submitted to PAC45 for extended studies of the J/$\psi$ and charmed pentaquark photoproduction

# JLab Upgrade to 12 GeV

E = 2.2 GeV/pass

$E_{max}$ = 11 GeV for Halls A, B, and C

$E_{max}$ = 12 GeV for Hall-D



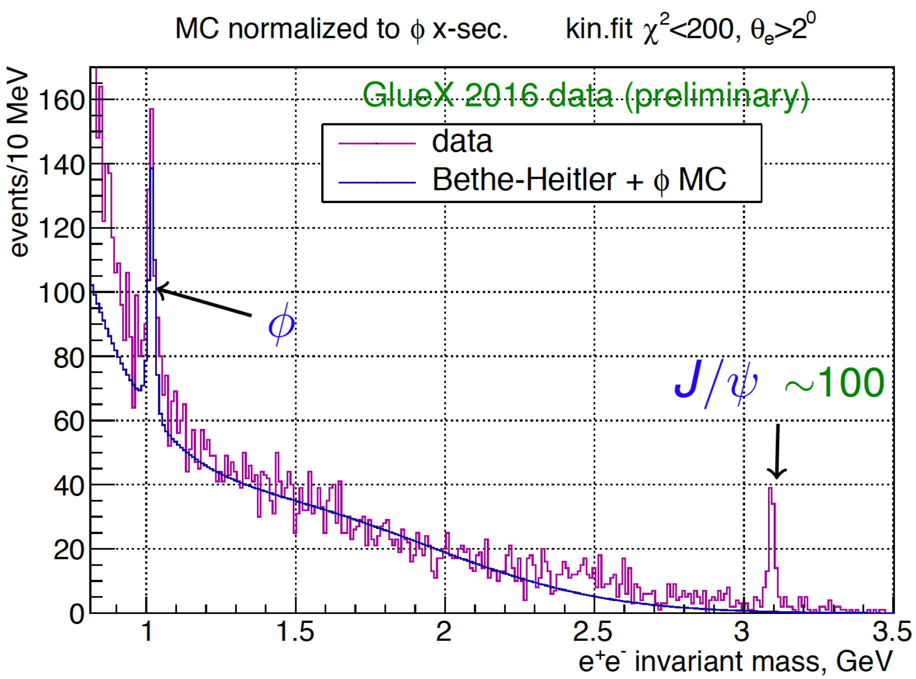

$I_{max}$ = 100 $\mu$A

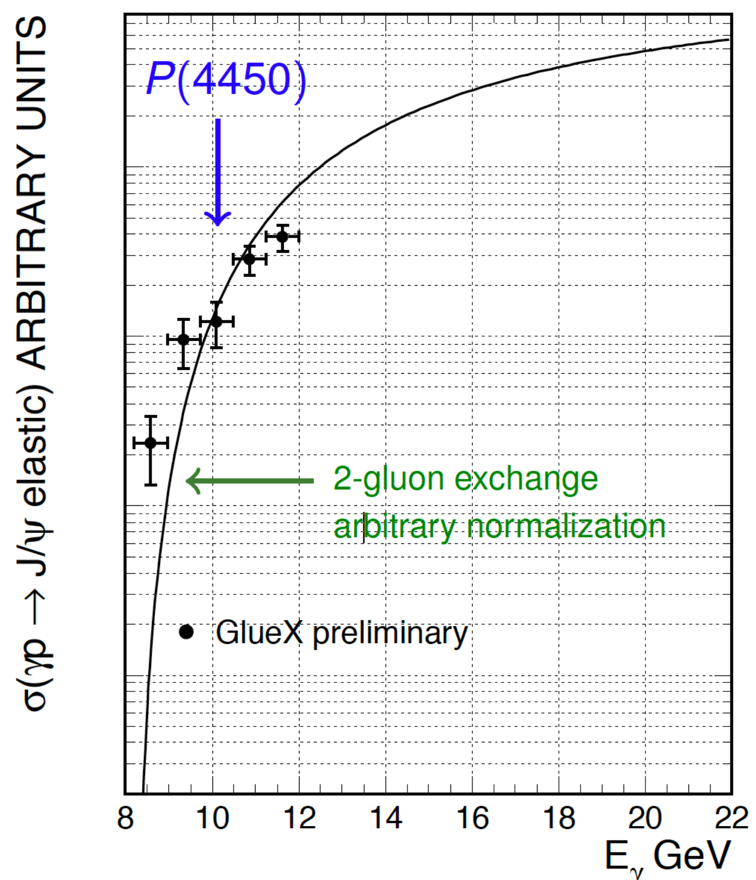
P = 85%

3-Hall operations (499 MHz/Hall)

# Hall-D Gluex results

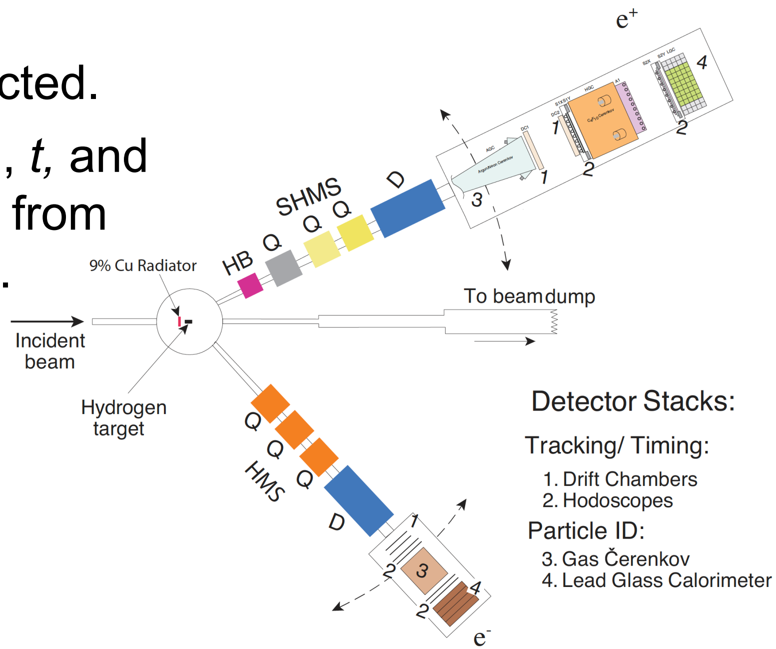
- All 2016 data: exclusive events $pe^+e$, the $e^+e^-$ PID using the electromagnetic calorimeters BCAL and FCAL. Kinematic fit with the beam energy from the tagger
- Planned measurements, after adding the 2017 Spring data will limit the pentaquark yield (the mass resolution 6 MeV/c² )

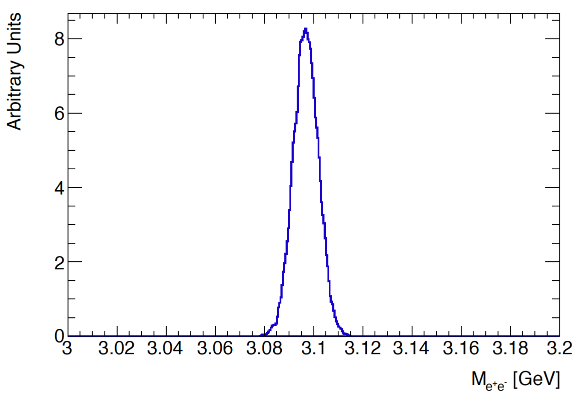


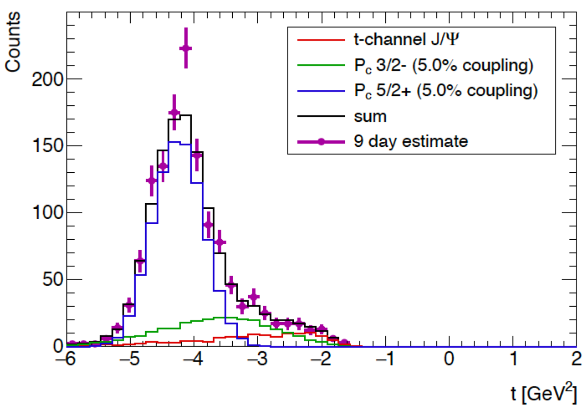



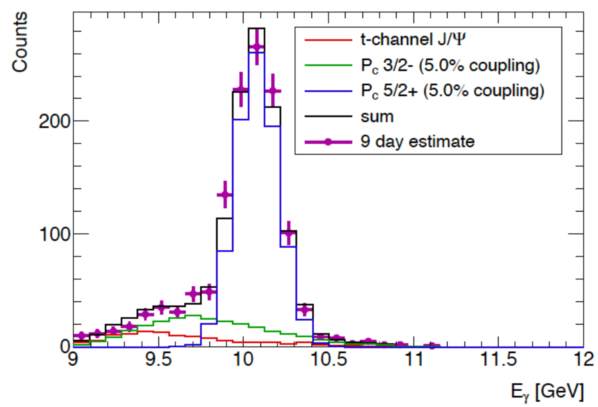
# Hall-C experiment E12-16-007

- Only $e^+e^-$ pair from $J/\psi$ decay will be detected.
- The four momentum transfer to the proton, *t*, and the real photon energy $E\gamma$ are determined from reconstructed three-momentum of the $J/\psi$.
- The region of kinematics where $J/\psi$ t-channel production is suppressed
- Total of 9 days of beam time is requested for measurements



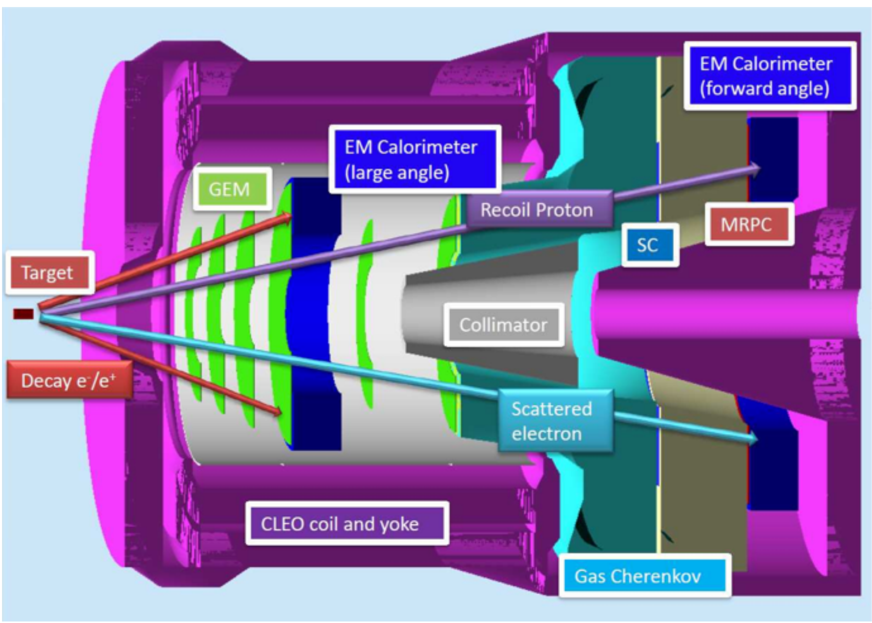



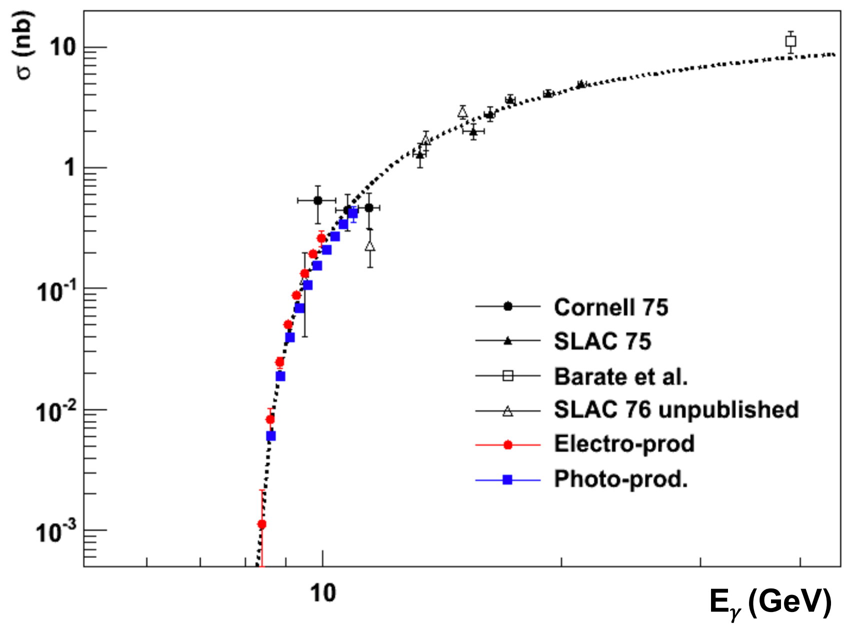



# Hall-A SoLID experiment

- 11GeV, 3uA $e^-$ beam on 15cm $LH_2$ target, luminosity $1.2 \times 10^{37}$ $cm^{-2}$ $s^{-1}$ for 50 days
- Measure the t- and energy dependence of the J/$\psi$ photo- and electroproduction cross sections near threshold
- J/$\psi$ will be identified through its decay to ($e^+e^-$)
- Measurement includes analysis of the decay angular distribution and the study of interference with Bethe-Heitler process (to separate real and imaginary parts of the amplitude)



# New proposal – JLAB PAC45

**Near threshold $J/\psi$ photoproduction and study of LHCb pentaquarks with CLAS12**

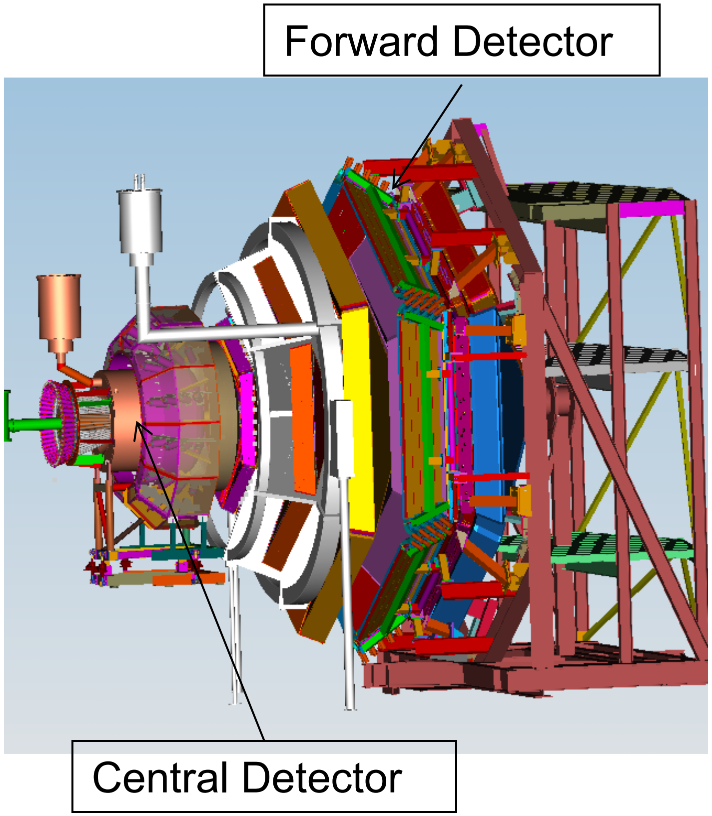
M. Battaglieri*, A. Celentano*, and R. De Vita*
*INFN, Sezione di Genova, 16146 Genova, Italy*

N. Baltzell, V. Burkert, V. Kubarovsky*, and S. Stepanyan*†
*Thomas Jefferson National Accelerator Facility, Newport News, VA 23606*

* Co-spokespersons

- Extends measurements of approved CLAS12 experiment E12-12-001
- Includes $J/\psi \to \mu^+\mu^-$ decay mode
- Will study charmed pentaquarks, $P_c(4380)$ and $P_c(4450)$.

# CLAS12 in Hall-B



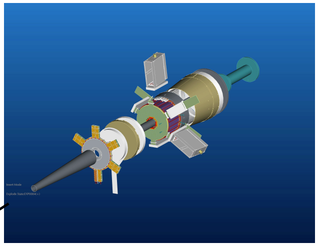

$$L = 10^{35} cm^{-2} s^{-1}$$

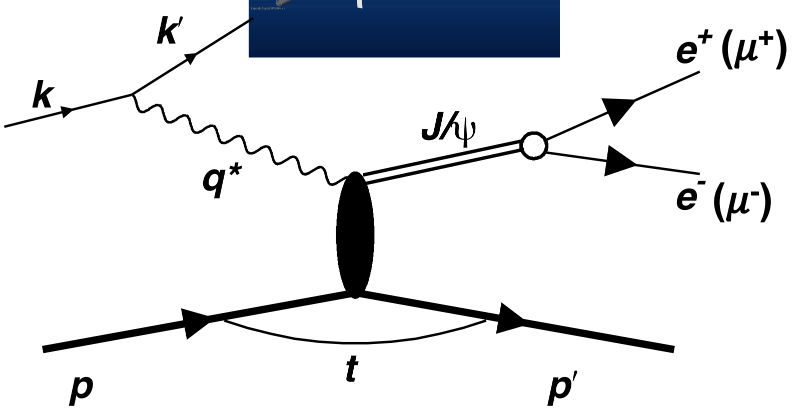
| | FD | CD |
|---|---|---|
| Angular range | | |
| Track | $5^0 - 40^0$ | $35^0 - 125^0$ |
| Photons | $2^0 - 40^0$ | --- |
| Resolution | | |
| dp/p (%) | < 1 @ 5 GeV/c | < 5 @ 1.5 GeV/c |
| $d\theta$ (mr) | < 1 | < 10 – 20 |
| $\Delta\phi$ (mr) | < 3 | < 5 |
| Photon detection | | |
| Energy (MeV) | >150 | --- |
| $\delta\theta$ (mr) | 4 @ 1 GeV | --- |
| Neutron detection | $N_{eff} < 0.7$ | $N_{eff} < 0.3$ |
| Particle ID | | |
| $e/\pi$ | Full range | --- |
| $\pi/p$ | < 5 GeV/c | < 1.25 GeV/c |
| $\pi/K$ | < 2.6 GeV/c | < 0.65 GeV/c |
| K/p | < 4 GeV/c | < 1.0 GeV/c |
| $\pi(\eta)\to\gamma\gamma$ | Full range | --- |

# Hall-B CLAS12 experiment

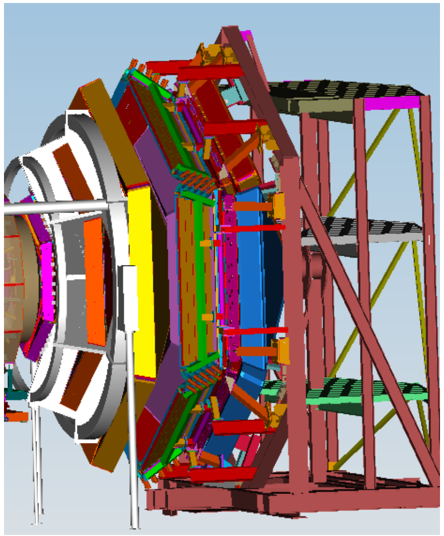
- Untagged photoproduction – àla CLAS and proposed E12-12-001 analysis:
  - Recoil proton and decay leptons will be detected
  - kinematcis of the scattered electron will be reconstructed in the missing momentum analysis
- Tagged photoproduction – as CLAS12 MesonX:
  - scattered electron will be detected in the CLAS12 FT, $Q^2$<0.02 GeV$^2$
  - Multiple combination of hadronic final state (the recoil proton and the J/$\psi$ decay leptons) will be detected in CLAS12 FD

**CLAS12 Forward Tagger**





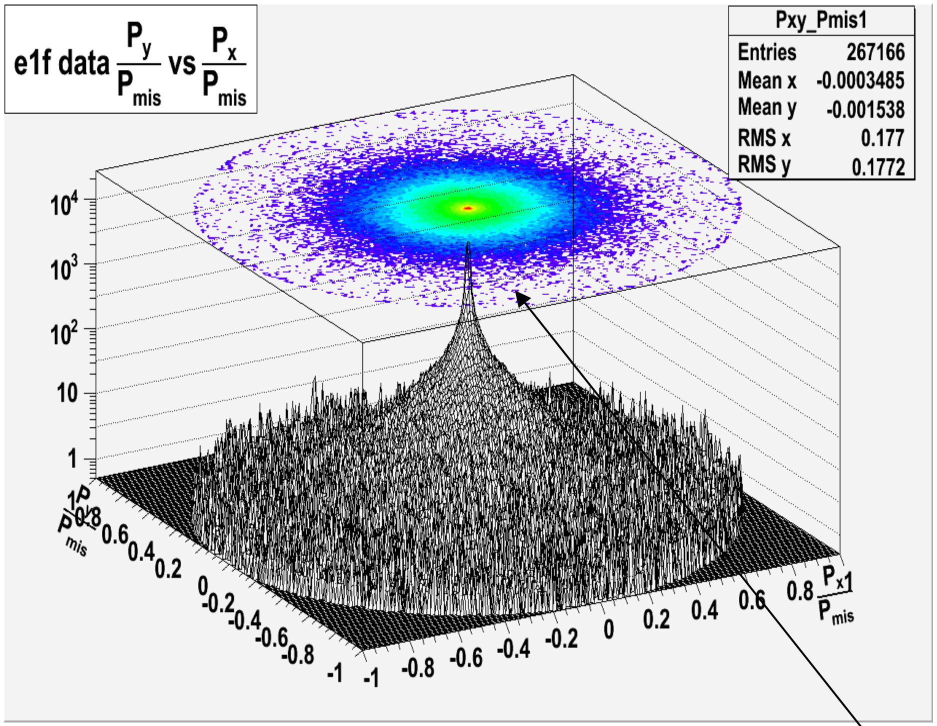

**CLAS12 Forward Detector**

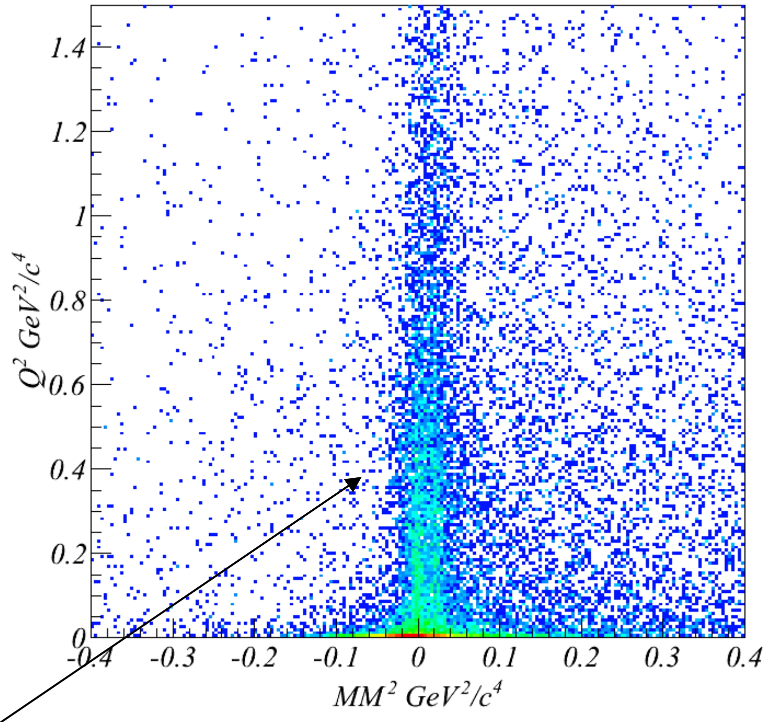


# $e^+e^-$ with CLAS at 6 GeV

Electron scattering at ~0 degree as a source of quasi-real photo-production events

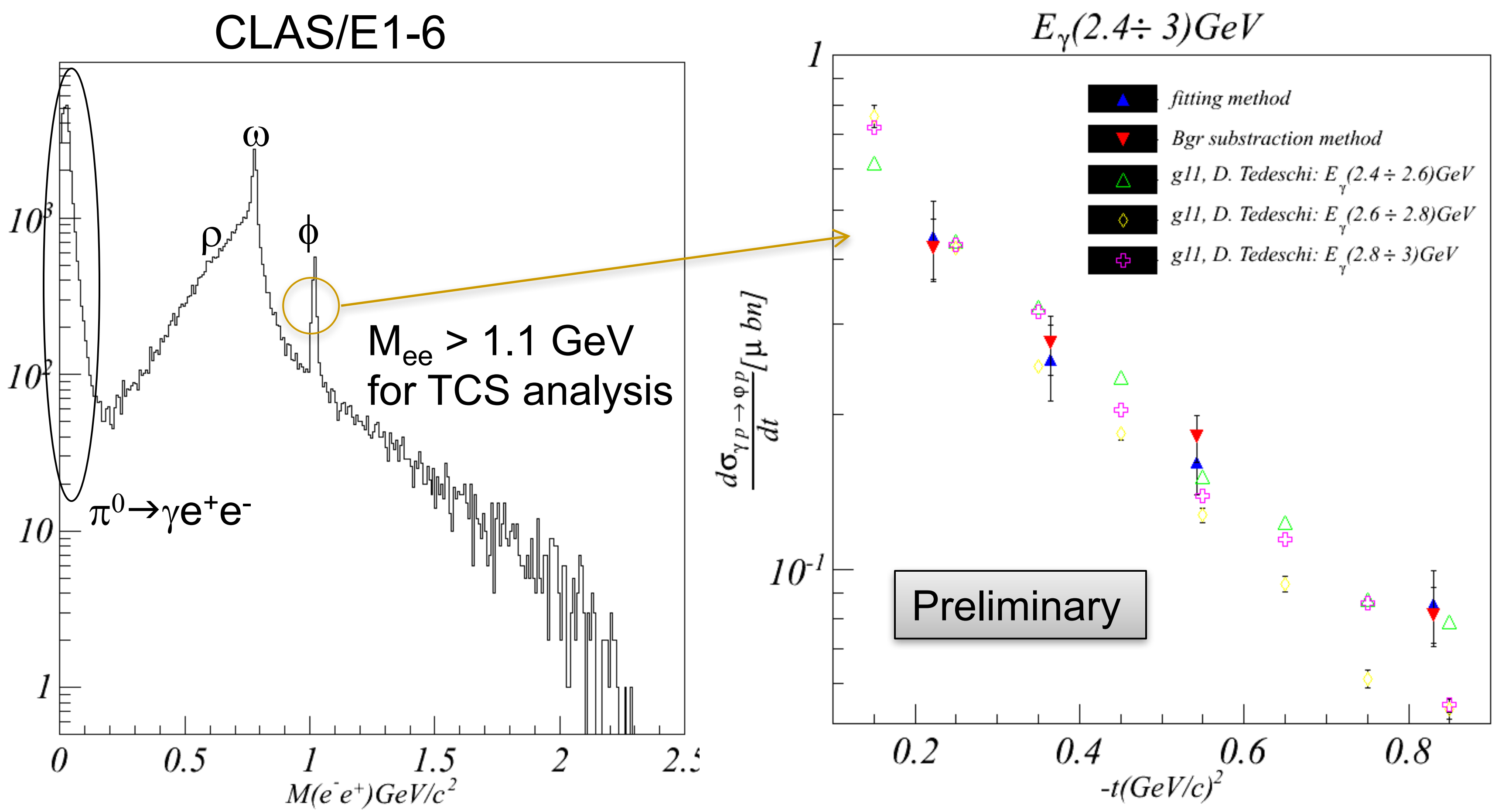
$$ep \rightarrow e^+e^- pX$$




X – is identified as an electron scattered at 0 degrees, $Q^2<0.01$ $(GeV/c)^2$ and $|M_X^2|<0.1$ $(GeV)^2$

# Vector mesons in photoproduction of lepton pairs

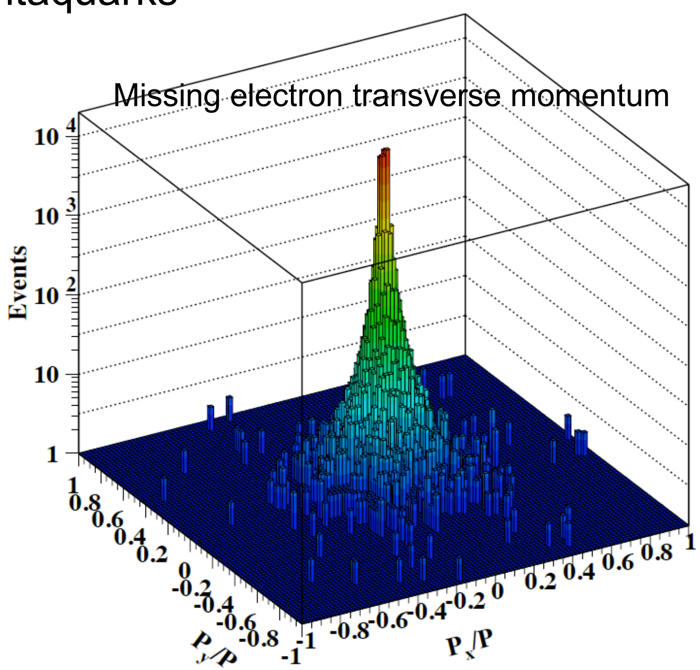


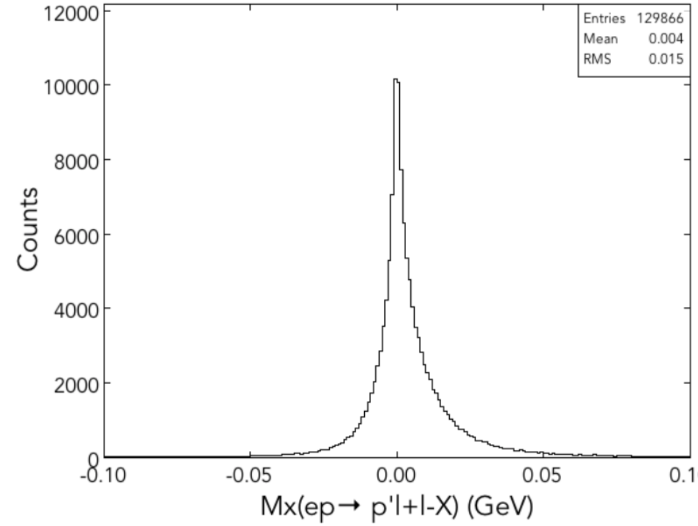

Data from CLAS e1-6 and e1f experiment, R. Paremuzyan

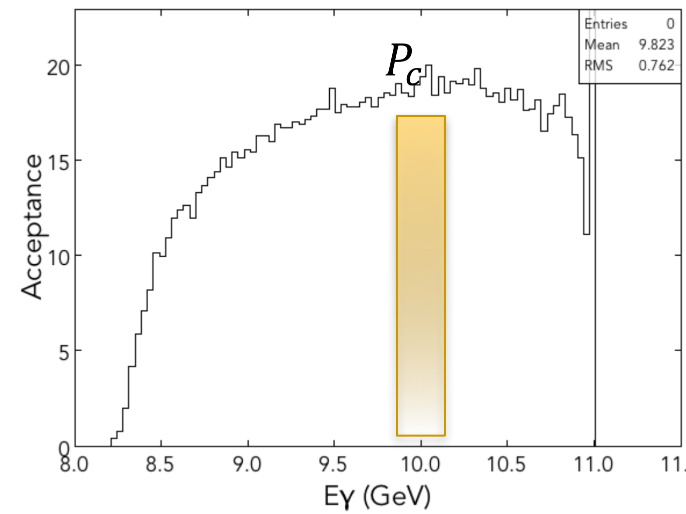
# CLAS12 performance – untagged potoproductionh

$$ep \rightarrow p' l^+ l^- (e'); l = e, \mu$$

- Recoil proton and decay leptons are detected
- Kinematcis of the scattered electron will be reconstructed in the missing momentum analysis - requires missing transvers momentum to be ~0
- Acceptance covers the mass range of charmed pentaquarks

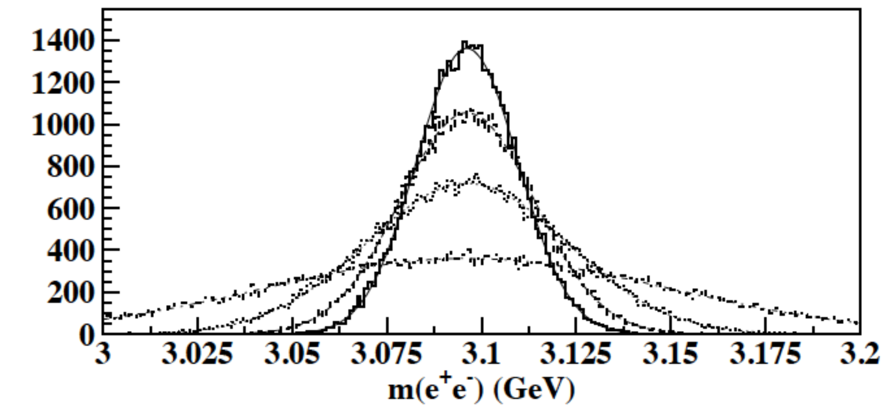


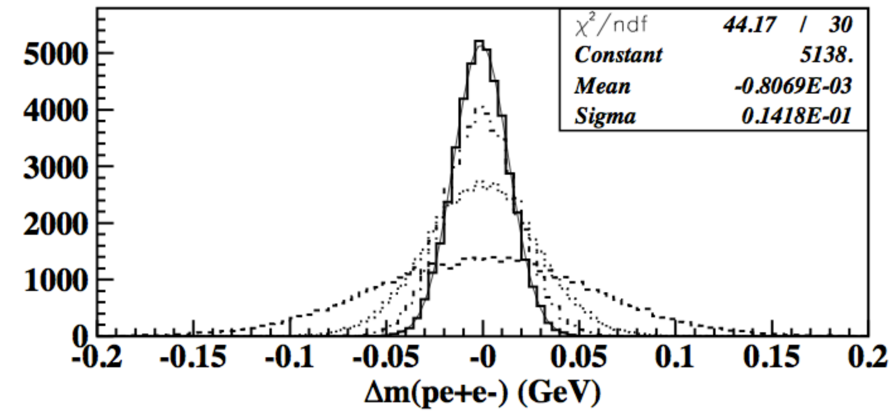



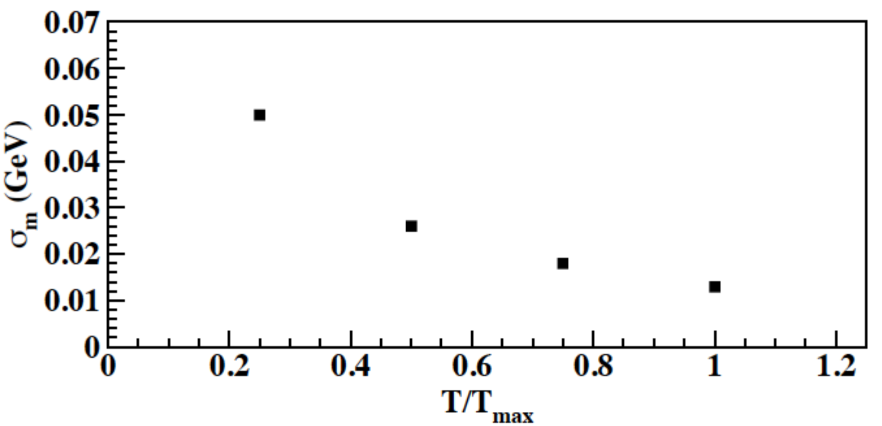



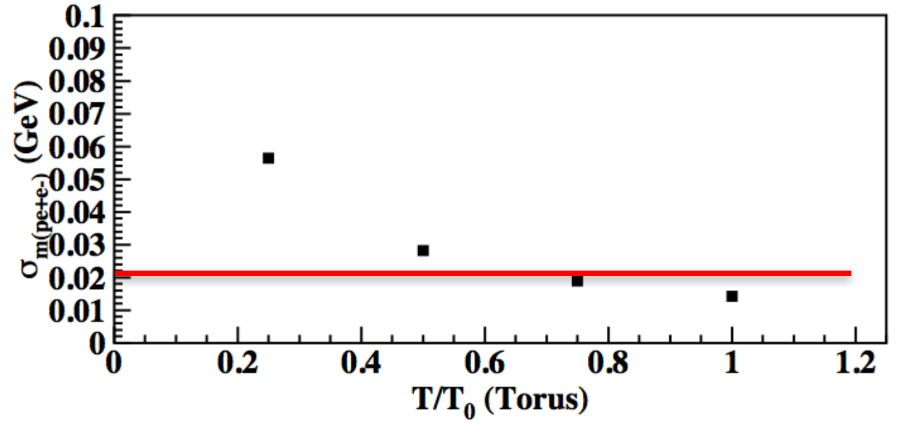
# Mass resolutions

- J/$\psi$ will be identified in the lepton pair invariant mass analysis
- Charmed pentaquarks, $P_c(4380)$ and $P_c(4450)$, will be identified in the invariant mass of $p'l^+l^-; l = e, \mu$



# CLAS12 performance – tagged photoproduction

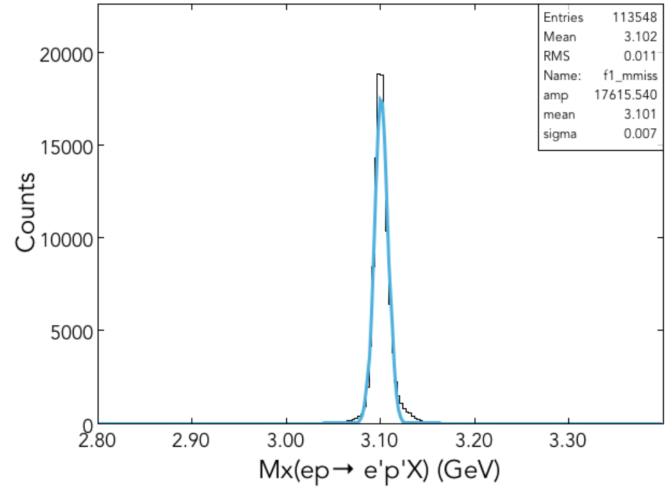
- About x10 lower photon flux, but …
- Multiple final states to measure J/$\psi$ photoproduction
- Excellent mass resolutions:
  - J/$\psi$ as sharp peak either in the invariant mass of decay leptons or in the electron-proton missing mass
  - Pentaquarks will be reconstructed in the missing mass analysis of the scattered electron (W-distribution)

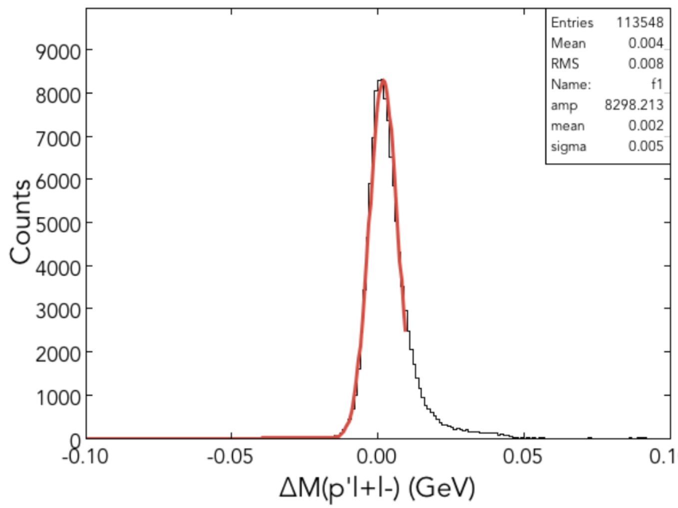
$$ep \to e'p'l^{+(-)}(l^{-(+)}); l = e, \mu$$

Detection efficiency ~28%

$$ep \to e'l^{+}l^{-}(p'); l = e, \mu$$

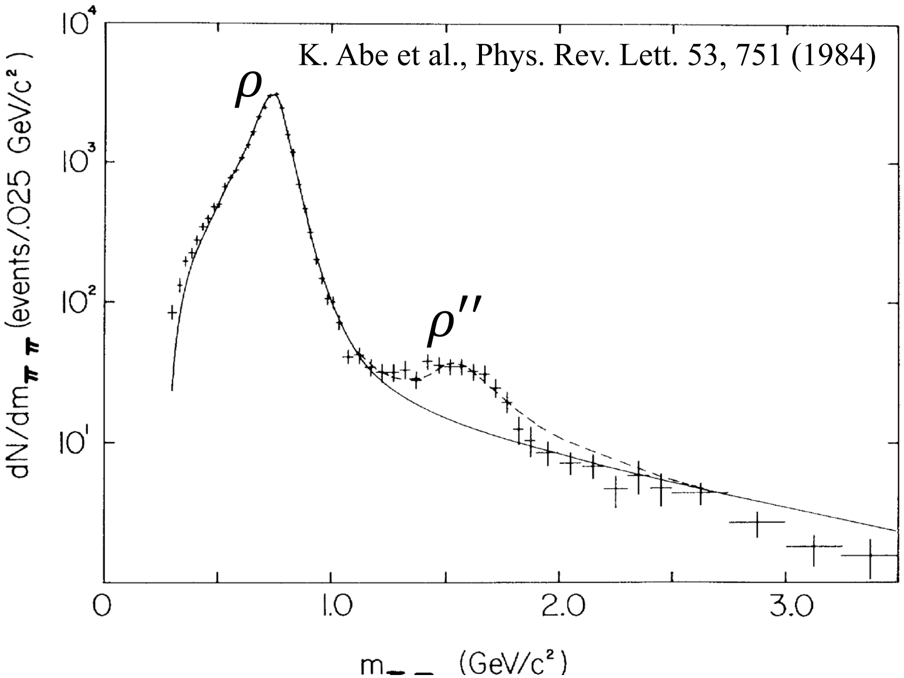
Detection efficiency ~18%

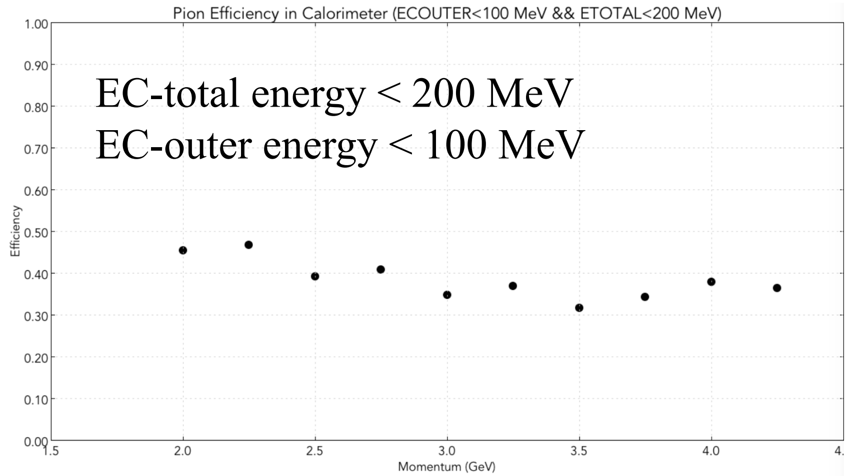


# Muon final state

- The main background to muon final state is from $\gamma p \rightarrow p'\pi^+\pi^-$
- In our energy rage $\sigma_{tot}^{\pi\pi} \approx 15\ \mu b$
- The fraction of pion pairs with $M_{\pi\pi}$ > 3 GeV is $< 2 \cdot 10^{-4}$
- The effective cross section for pion pair photoproduction in the region of $J/\psi$ is expected to be < 5 nb
- Charged pion detection efficiency with MIP signature is $\lesssim$0.4, pion pair suppression factor ~6
- The rate of pion pairs with the invariant mass > 3 GeV is the same order as $J/\psi$ production



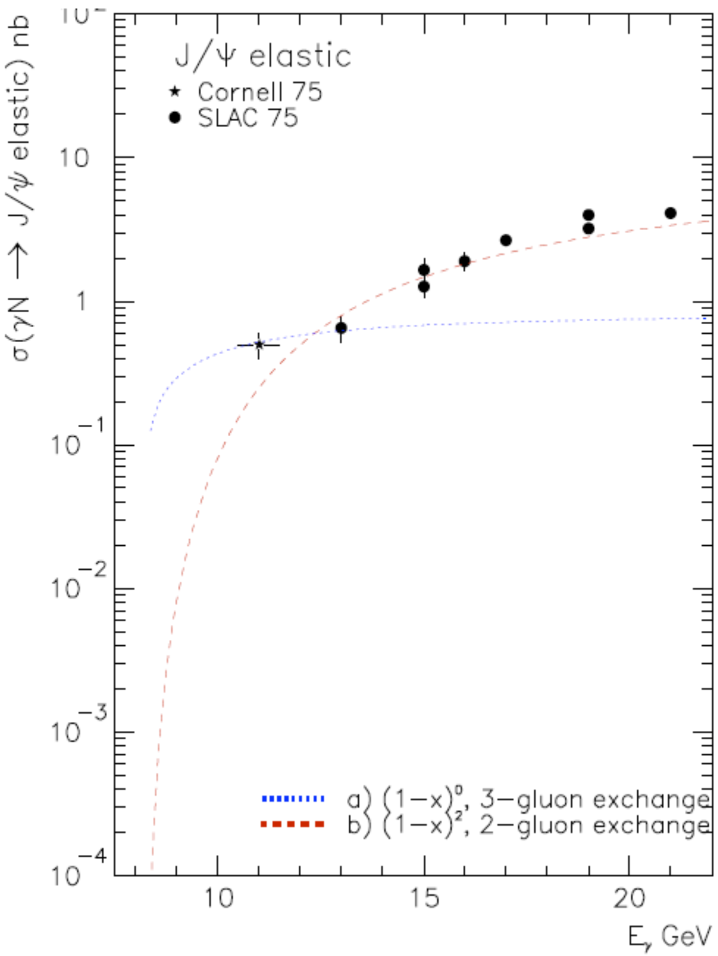
# $J/\psi$ Triggers

- The final states that will have an electron or a positron in CLAS12 FD will be a subset of events recorded using the CLAS12 standard electron trigger
- For final states with muons
  - two charged particles detected in CLAS12 FD with 0.3 − 3 GeV electron cluster in the FT
  - three charged particles in CLAS12 FD

| Trigger # | Final state | Trigger setting | Expected trigger rate |
|---|---|---|---|
| 1 | $e'p'\mu^{\pm}$ | Cluster in FT $\otimes$ 2-charged tracks in CLAS12 FD | 4 kHz |
| 2 | $p'\mu^{+}\mu^{-}$ | 3-charged tracks in CLAS12 FD | 2.5 kHz |
| 3 | $e'p'e^{\pm}$<br>$(e')e^{+}e^{-}$<br>$p'e^{+}e^{-}$ | CLAS12 electron trigger | 2 kHz |
| 4 | $e'p'l^{+}l^{-}$ | MesonX trigger[a] | 2.8 kHz |

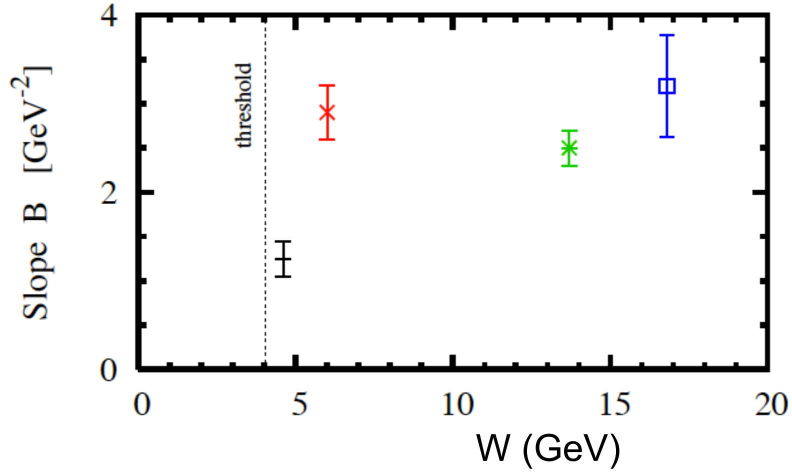
[a] subset of trigger #1

# Cross section estimate




S.J. Brodsky, E. Chudakov, P. Hoyer, and J-M. Laget, Phys.Lett. B498, 23-28 (2001)

$$\frac{d\sigma}{dt} = \mathcal{N}_{2g} v \frac{(1-x)^2}{R^2 \mathcal{M}^2} F_{2g}^2(t)(s-m_p^2)^2$$



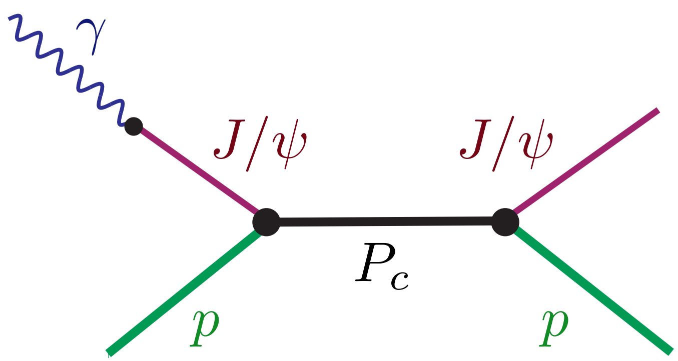

$$\frac{d\sigma}{dt} \propto e^{Bt}; \quad B = 1.2\,GeV^{-2}$$

and

$$\frac{d\sigma}{dt} \propto \frac{1}{Q^4}$$

# Pentaquark photo-production

- The production of pentaquarks proceeds as an s-channel resonance
- VDM can be used to relate initial and final states

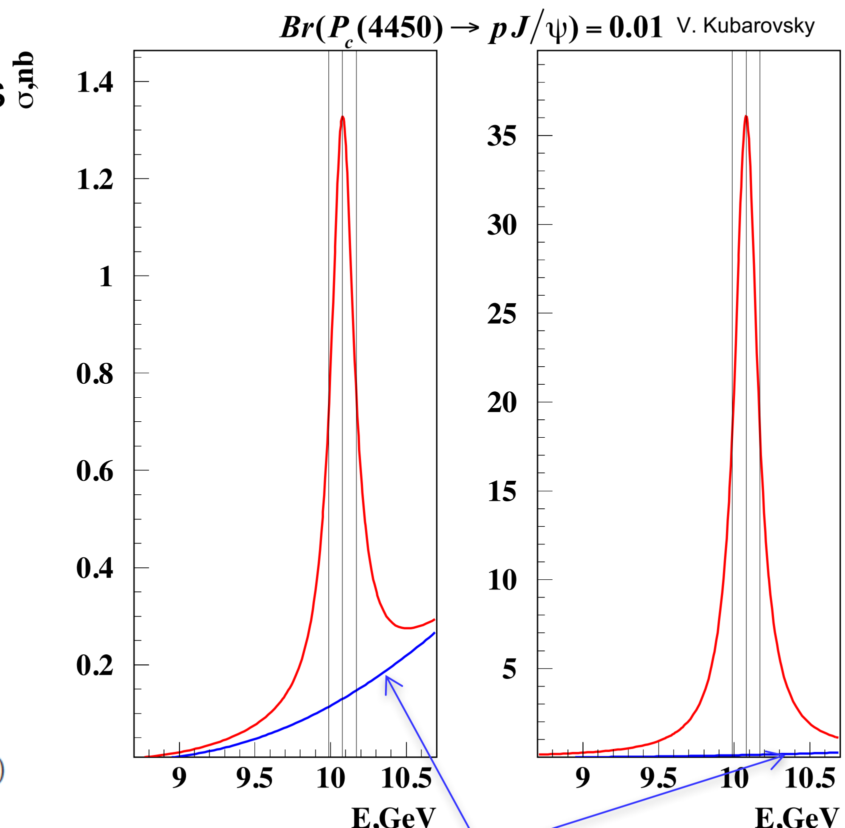



$$\sigma(W)| = \frac{2J+1}{4}\frac{4\pi}{k^2}\frac{\Gamma^2/4}{(W-M_c)^2+\Gamma^2/4} Br(P_c \to \gamma + p)\, Br(P_c \to J/\psi + p)$$

$$\Gamma(P_c \to \gamma + p) = \frac{3\Gamma_{ee}(J/\psi)}{\alpha\, M(J/\psi)} \sum_L f_L \left(\frac{k}{p}\right)^{2L+1} \Gamma_L(P_c \to J/\psi + p)$$

$$1.5 \times 10^{-30}\,\mathrm{cm}^2 < \frac{\sigma_{max}[\gamma + p \to P_c(4380) \to J/\psi + p]}{Br^2[P_c(4380) \to J/\psi + p]} < 47 \times 10^{-30}\,\mathrm{cm}^2$$

$$1.2 \times 10^{-29}\,\mathrm{cm}^2 < \frac{\sigma_{max}[\gamma + p \to P_c(4450) \to J/\psi + p]}{Br^2[P_c(4450) \to J/\psi + p]} < 36 \times 10^{-29}\,\mathrm{cm}^2$$




Prediction of 2-gluon exchange model for J/ψ elastic photoproduction

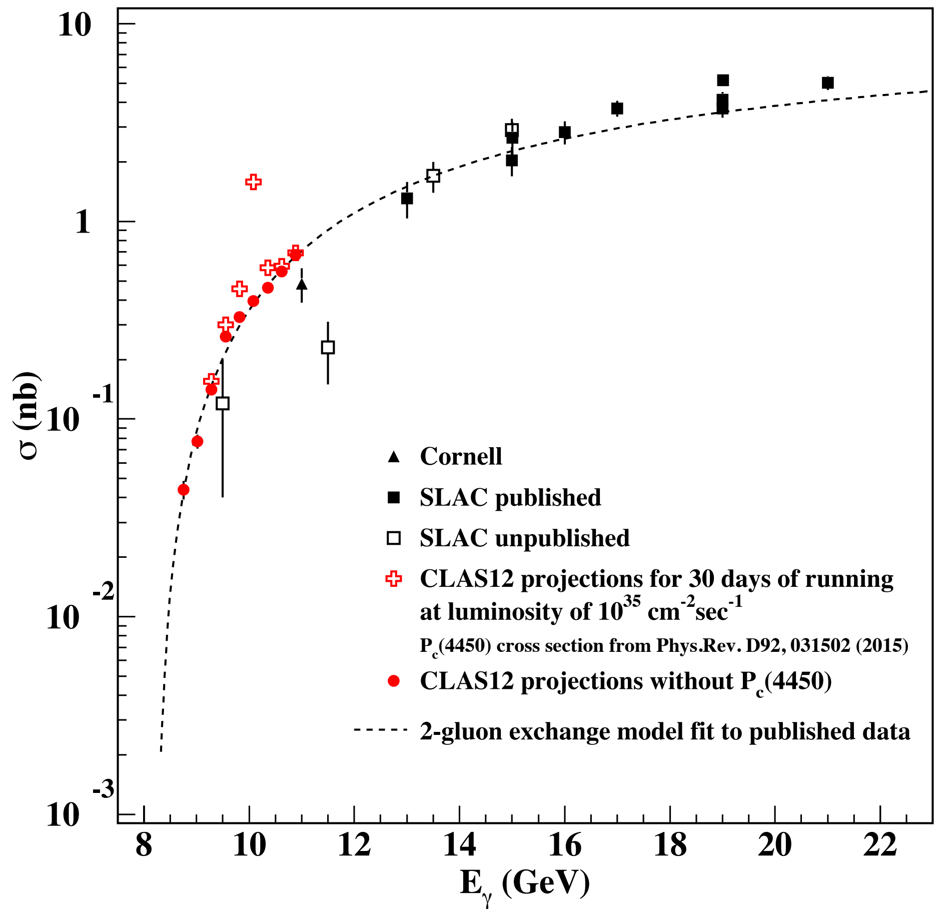
Q. Wang, X. H. Liu and Q. Zhao, arXiv:1508:00339.
V. Kubarovsky and M.B. Voloshin, arXiv:1508.00888.
M. Karliner and J.L. Rosner, arXiv:1508.01496.

# CLAS12 expected results

- From the two gluon exchange prediction for cross section, we expect total of 45 $J/\psi$ detected per day in the whole energy rage
- Expected total number of charmed pentaquarks 98 per day

Compared to -

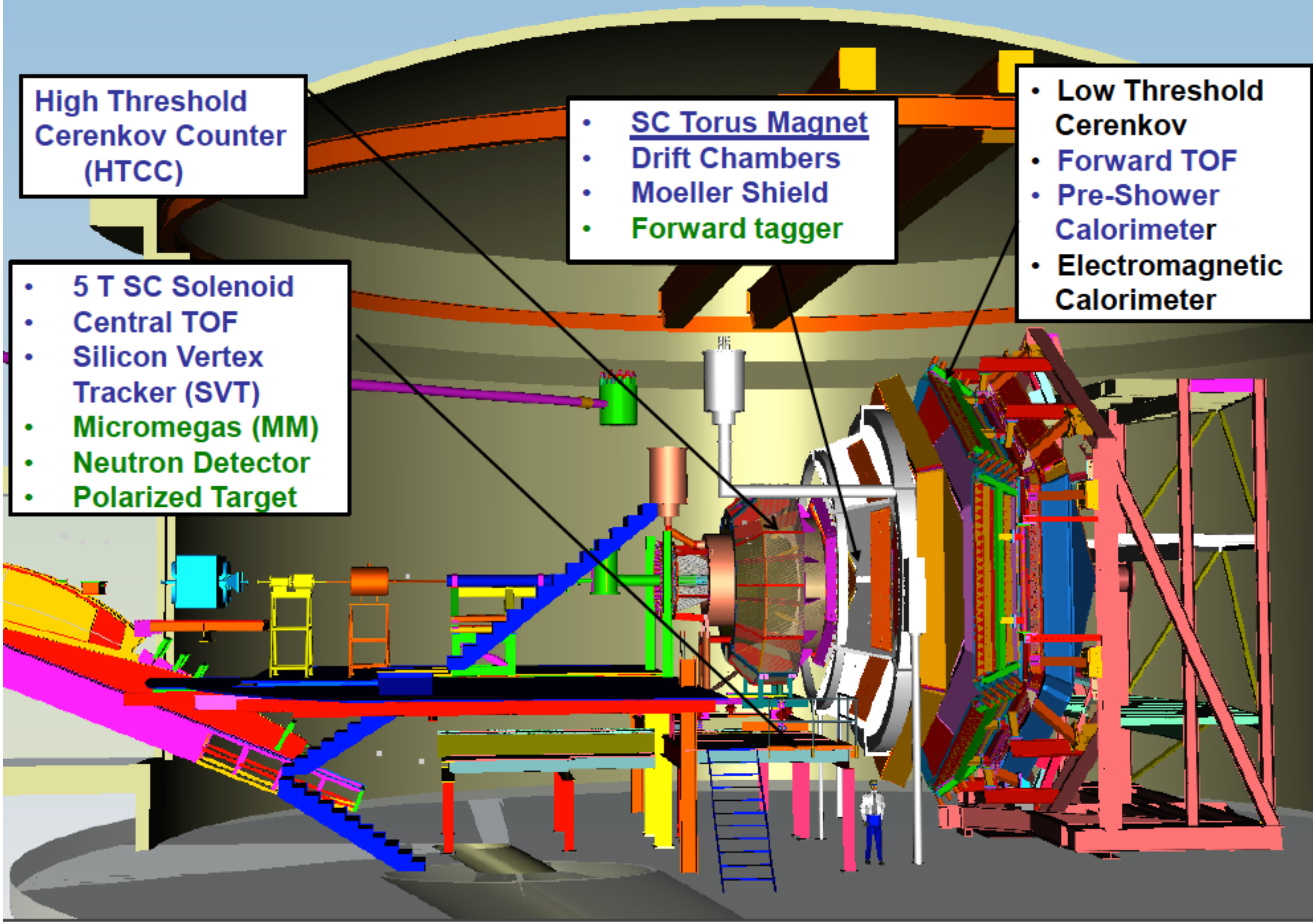
- The Hall-C E12-16-007 with the same cross section formalism will detect 70 pentaquarks per day
- The Hall-A experiment E12-12-006 with future SoLID detector expects ~42 $J/\psi$ per day
- With current luminosity Hall-D Gluex experiments expects 5-10 $J/\psi$ per day



# Summary

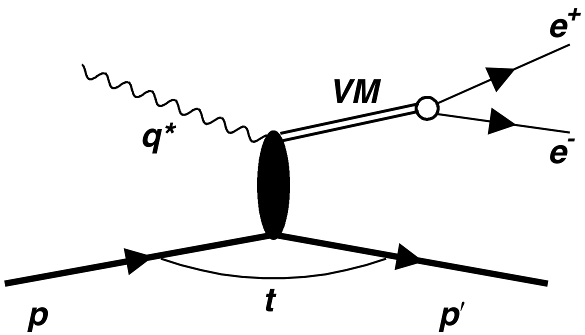
- The energy reach of upgraded JLAB machine crosses the threshold of charmonioum production on the nucleon
- Together with new experimental facilities this provides an opportunity for detailed study of production of ground state charmoniom, $J/\psi$
- Particular interest is the uncharted near threshold region, where different mechanisms for the production have been proposed. In this region, $J/\psi$ production probes gluonic form-factors of the nucleon
- These data sets can be used to search and study LHCb hidden charm pentaquark states in the $pJ/\psi$ decay mode, $P_c(4380)$ and $P_c(4450)$
- Three experiments (in Halls A, B and C) for $J/\psi$ photoproduction have already been approved
- First data from the Hall-D Gluex experiment has been already presented
- A new proposal for CLAS12 has been submitted to PAC45 that will extend previous measurement to multiple final states and will study chartmed pentaquarks
- Future plans include $J/\psi$ production on deuterium and heavier nuclear targets

# CLAS12 in Hall B



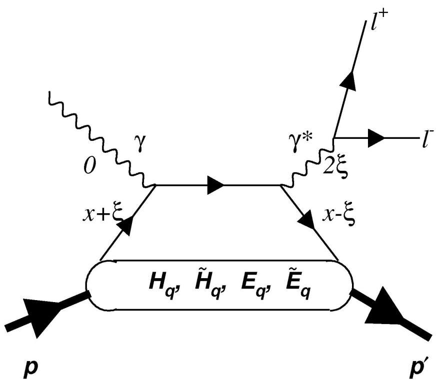
# $e^+e^-$ with CLAS12 – E12-12-001

## Vector Meson Production




$$VM = \rho^0; \omega; \phi; J/\psi$$

## Time-like Compton Scattering




## Bethe-Heitler Process