Opportunities in Hadron Spectroscopy at the EIC

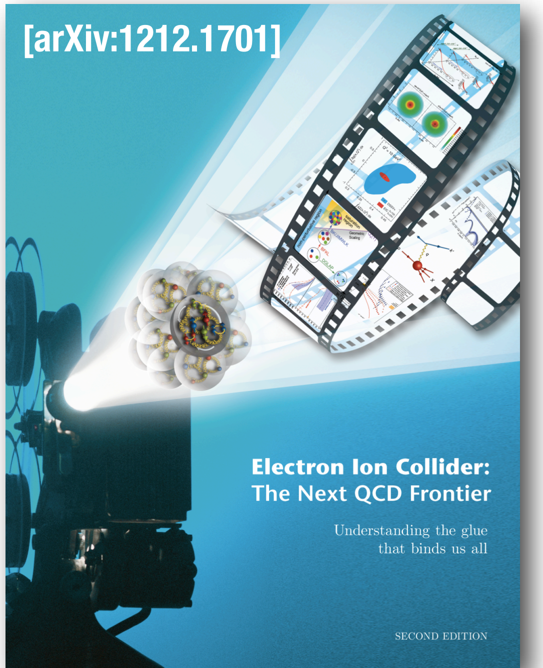
Justin Stevens

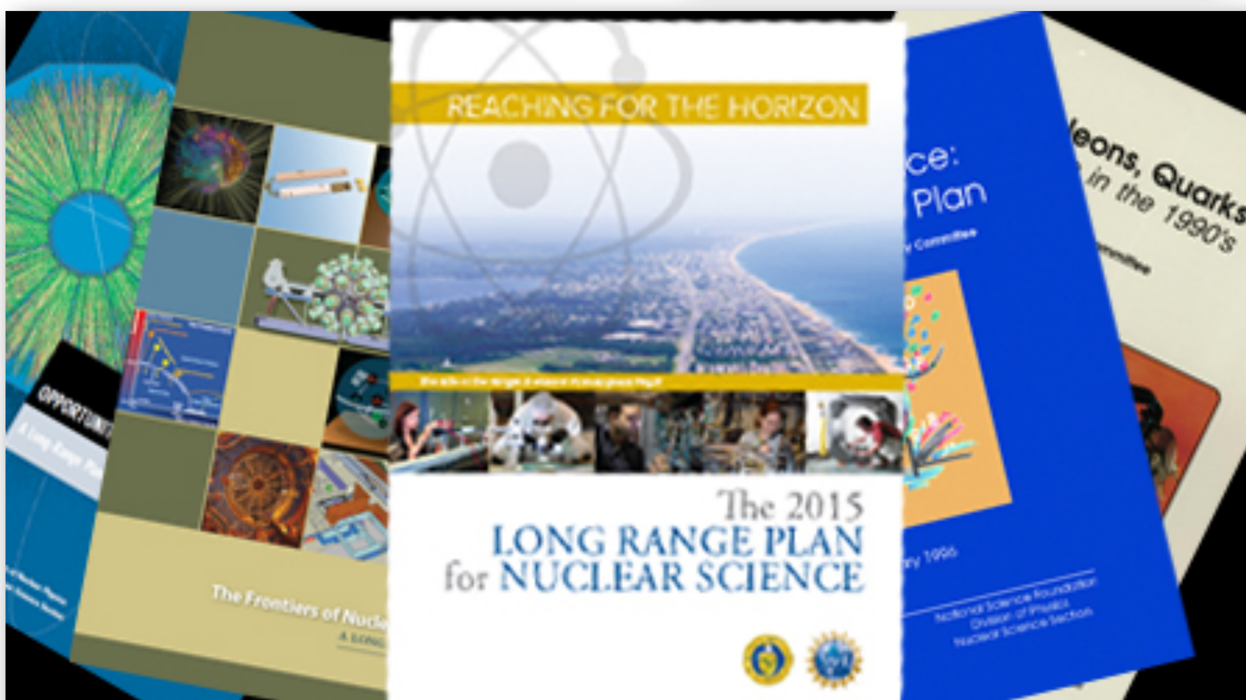
CLAS Collaboration Meeting: 2.24.16

U.S. DEPARTMENT OF ENERGY

Jefferson Lab

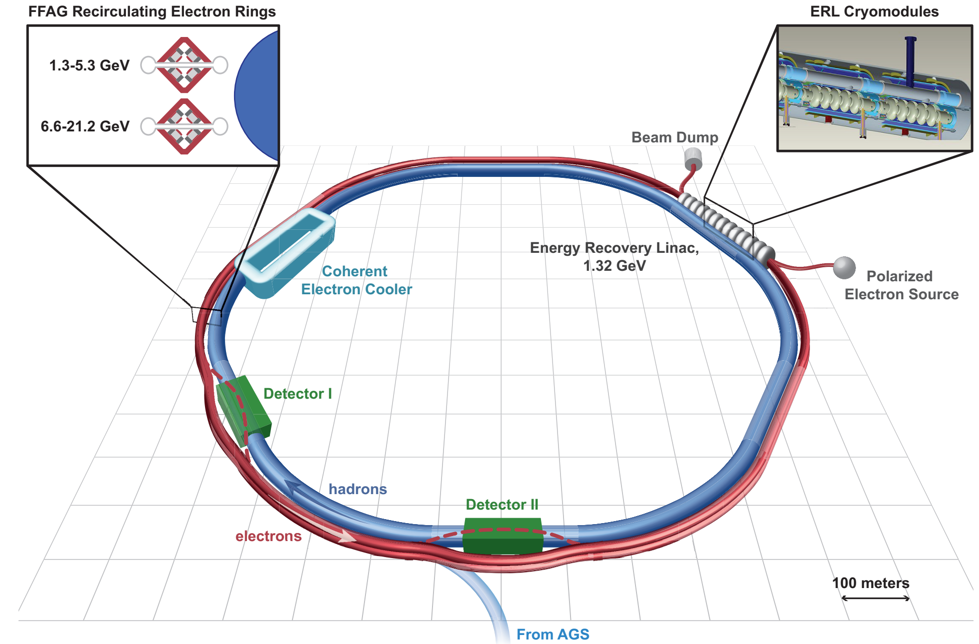
Electron Ion Collider





Recommendation III: "...EIC as the highest priority for new facility construction following the completion of FRIB."

eRHIC



[arXiv:1409.1633]

JLEIC

Big questions for "QCD in 2025" in ep/eA

- ❑ How quarks and gluons are confined inside the hadrons – 3D structure?
- ❑ How does the glue fill out hadron's inner space – 3D glue distribution?
- ❑ How hadrons are emerged from the color charge(s)?

From J. Qiu's talk at EIC Users Meeting

https://conferences.lbl.gov/event/56/

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- ❑ How does the glue fill out hadron's inner space – 3D glue distribution?
- ❑ How hadrons are emerged from the color charge(s)?
- ❑ **How to understand the family of hadrons?**
  - ✧ Can we see gluonic excitations in hadron spectrum?
  - ✧ Interpretations of GlueX data from JLab, precisions?
  - ✧ XYZ particles at future ep + eA, …

From J. Qiu's talk at EIC Users Meeting

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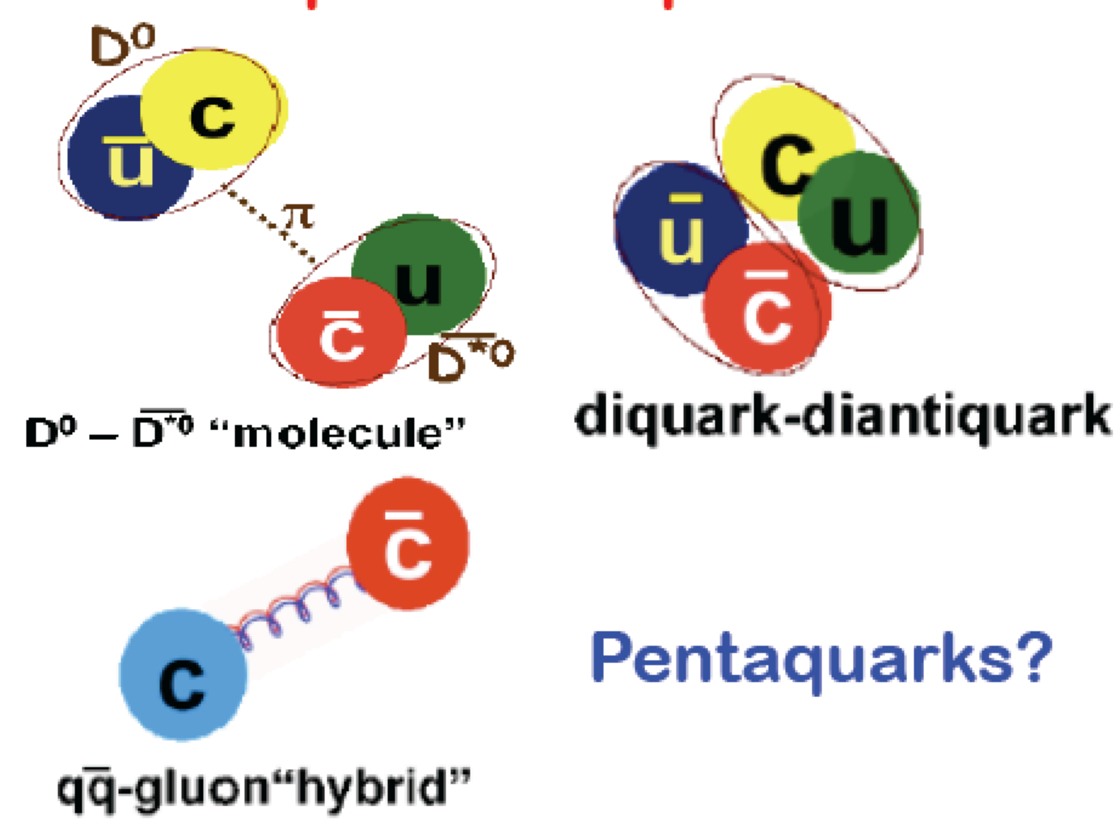
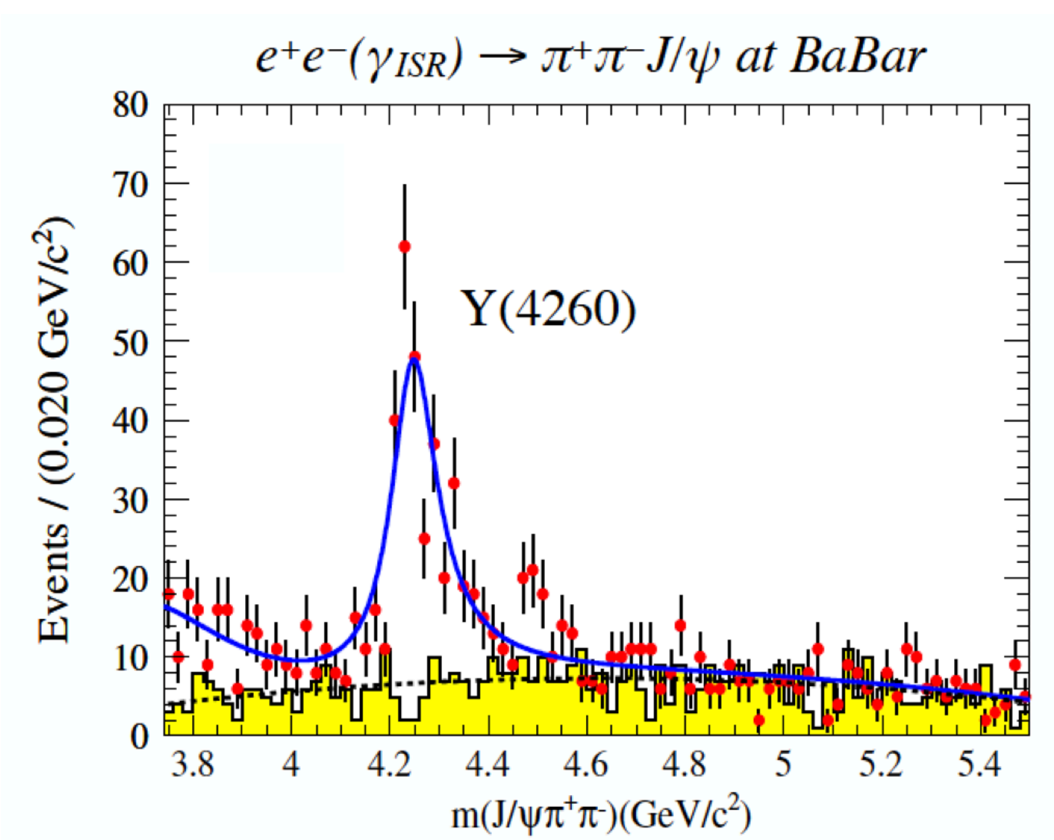
A new particle explosion?

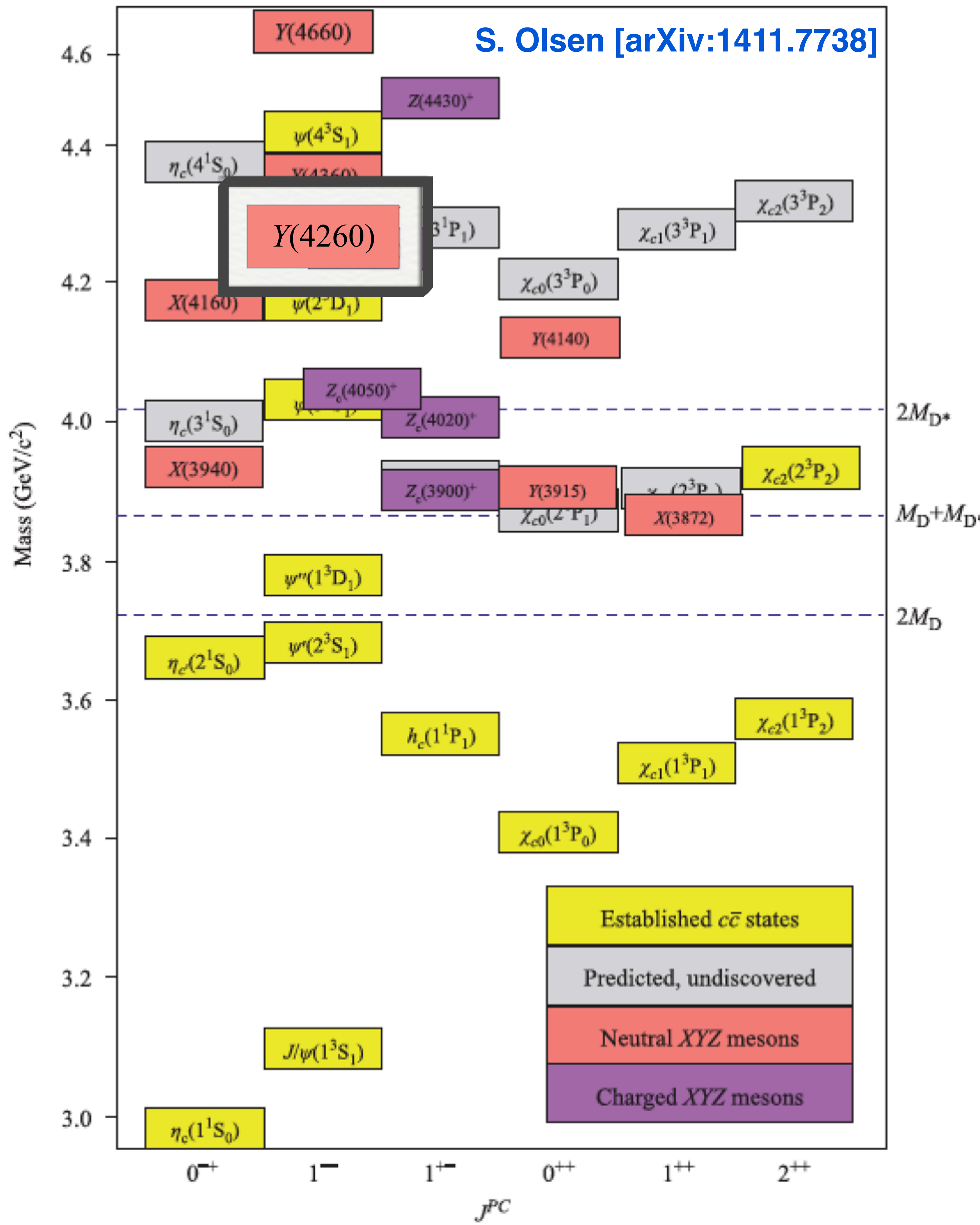


Pentaquarks?

XYZ states

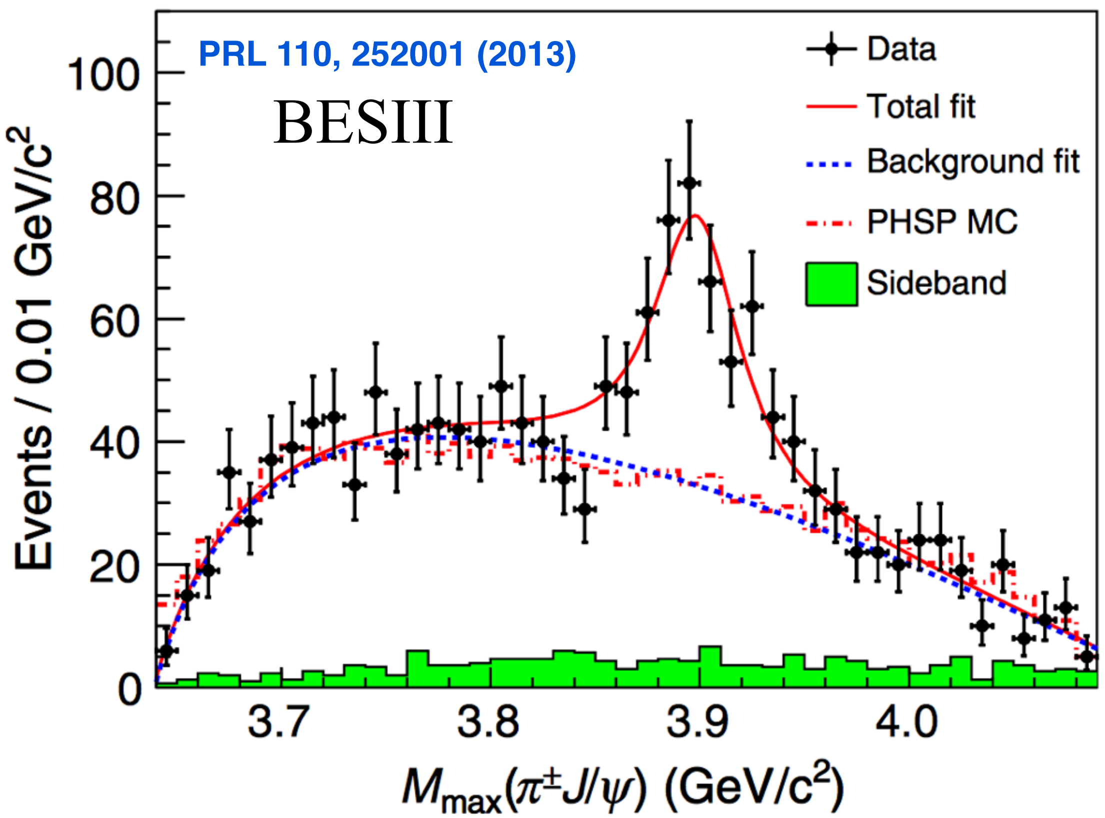
- Many new states observed in the last few years
- Not predicted by the standard charmonium models
- Many models for interpretation: resonant states, meson molecules, re-scattering effects, etc.



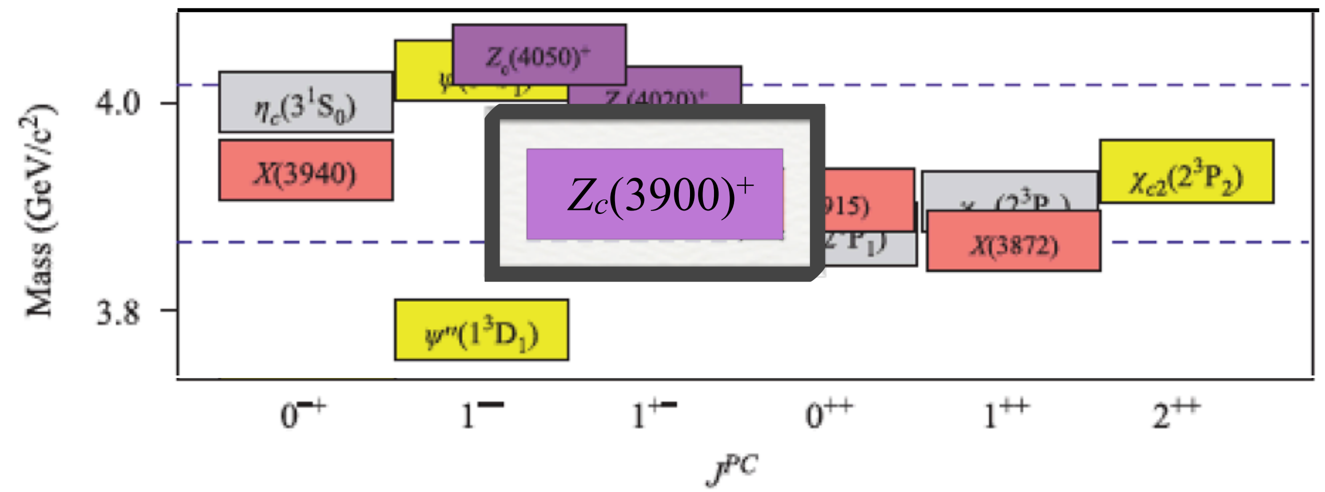


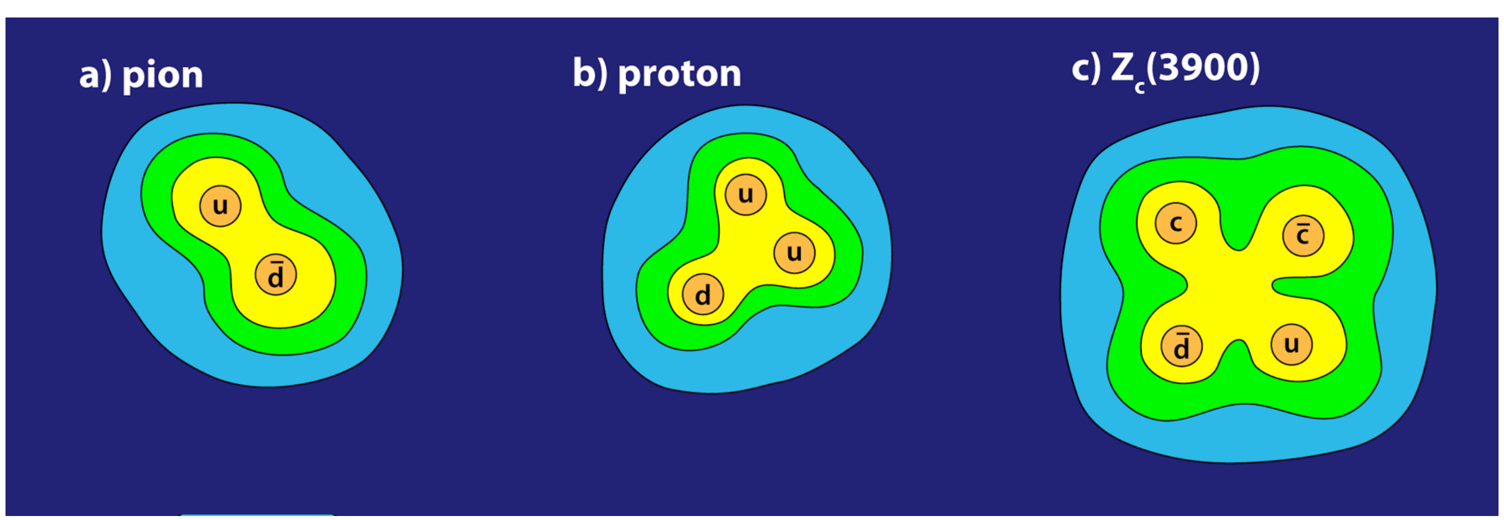
Charged charmonium states

$$e^+e^- \to \pi^+\pi^- J/\psi \ (4260 \text{ MeV})$$



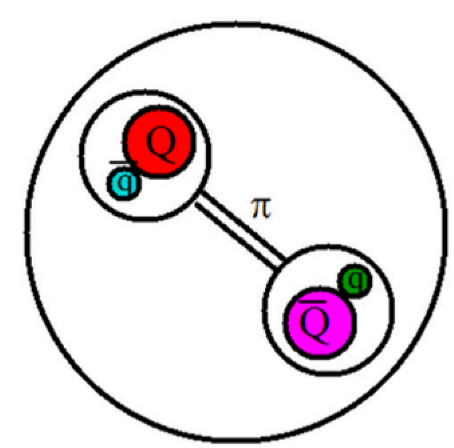
4-quark content ($c\bar{c}u\bar{d}$)





Physics Viewpoint 6, 69 (2013)

Meson Molecule?



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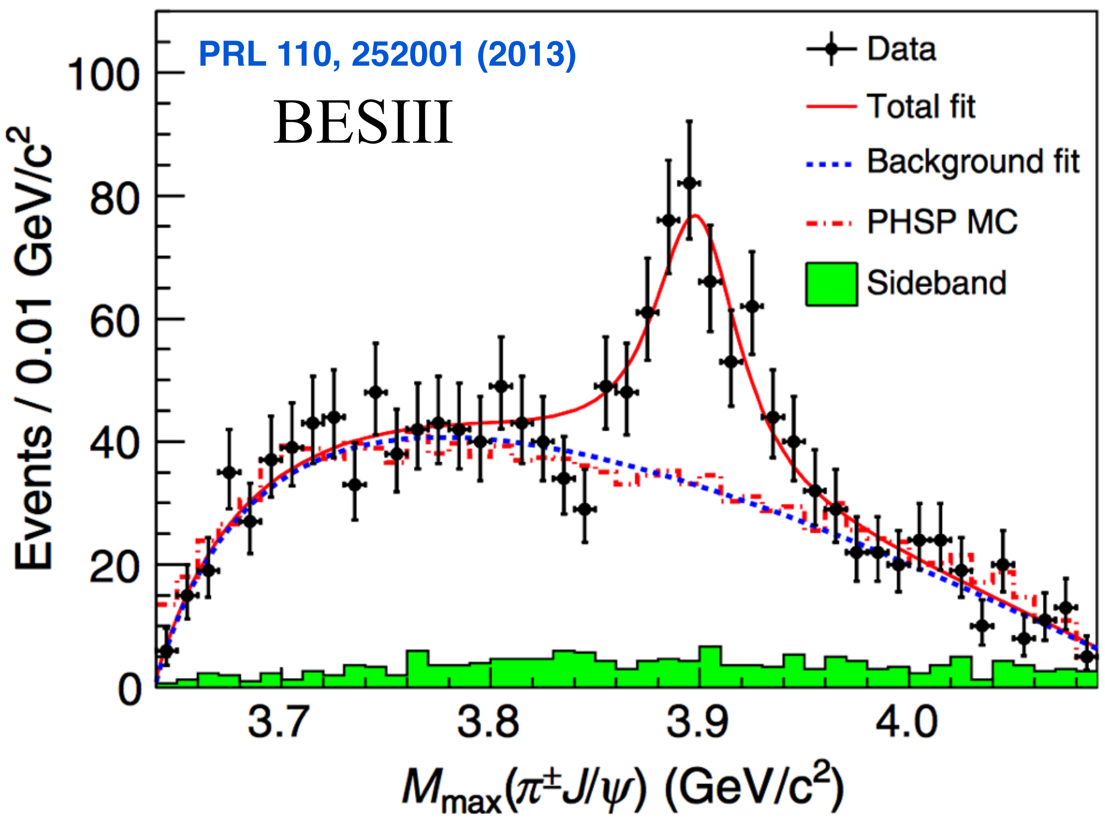

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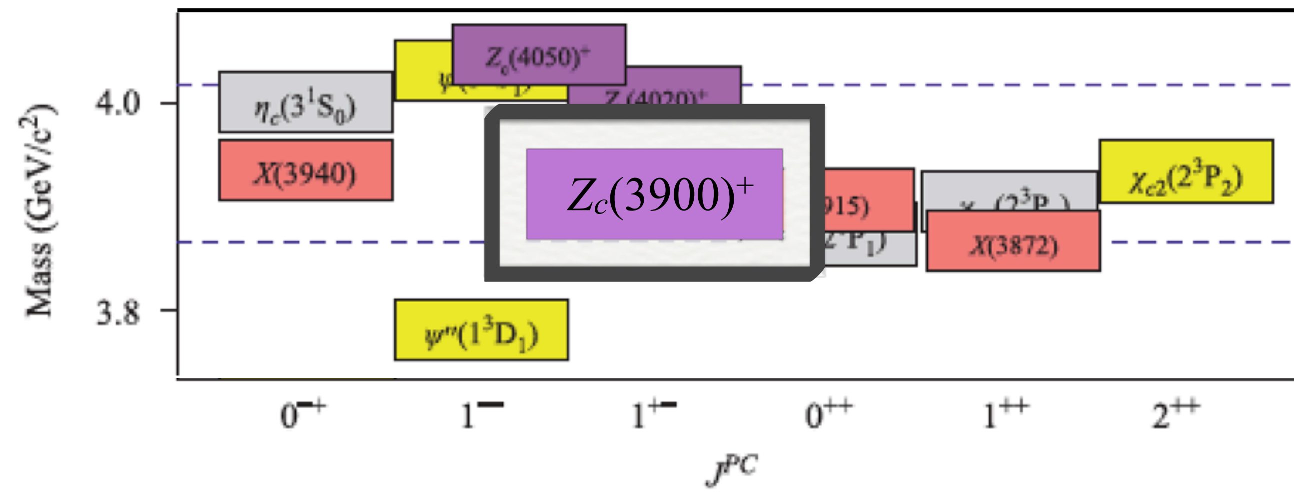
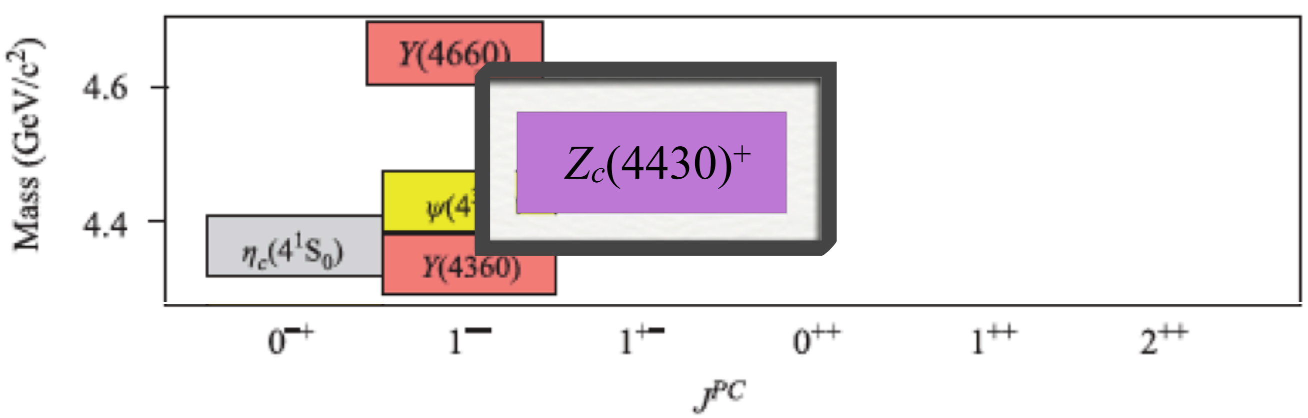
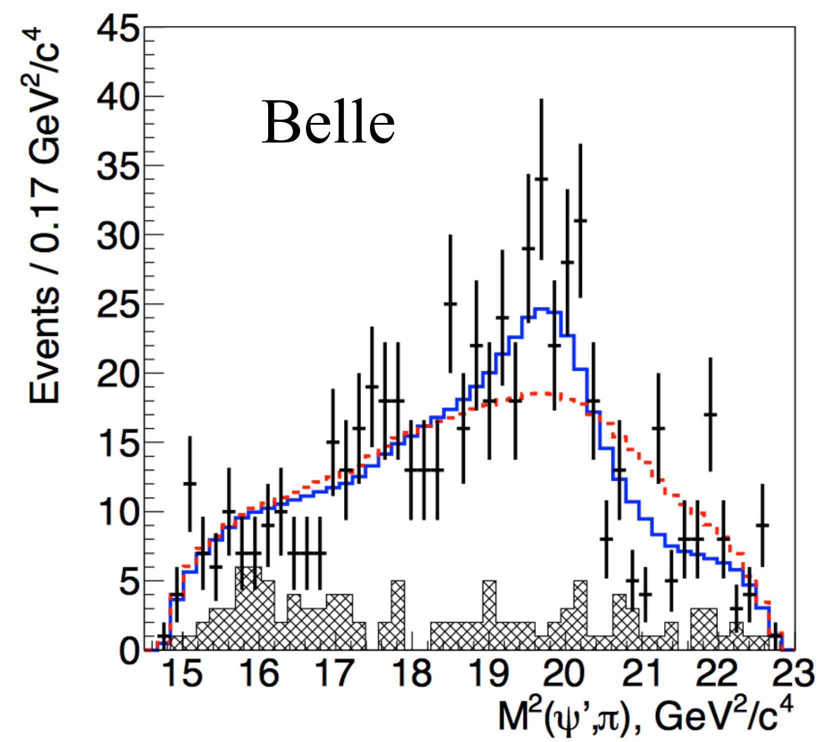




$B \to K(\pi\psi')$



PRD 88, 074026 (2013)

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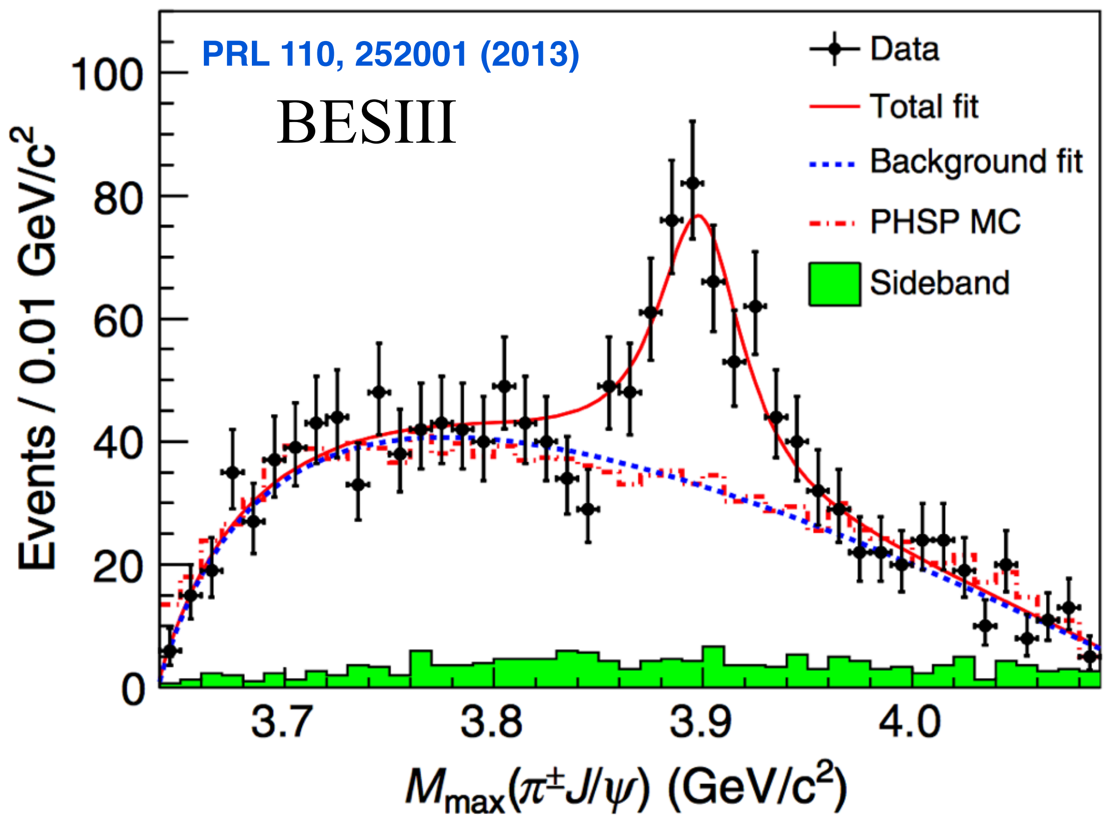

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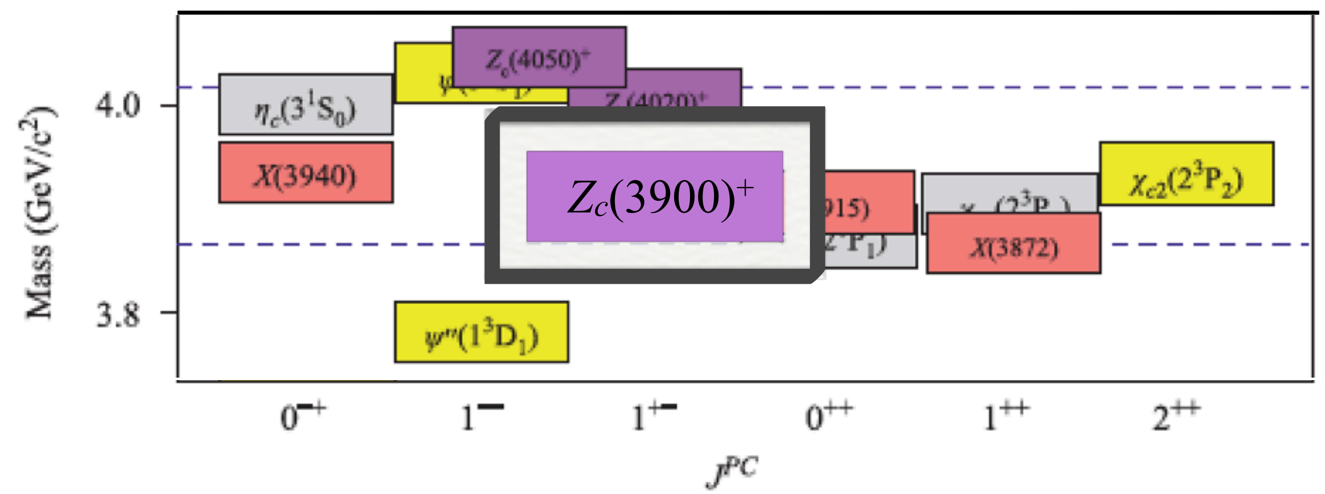

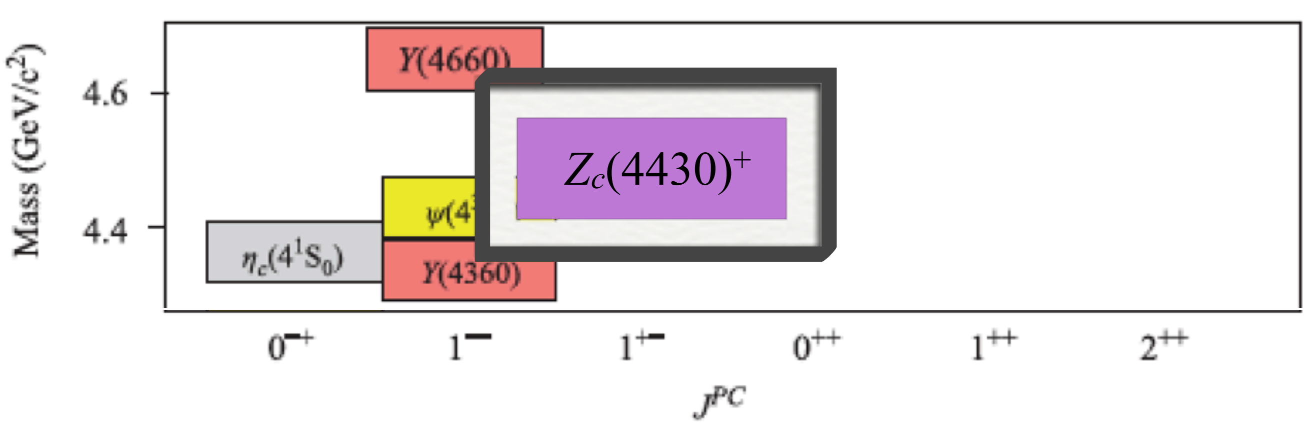

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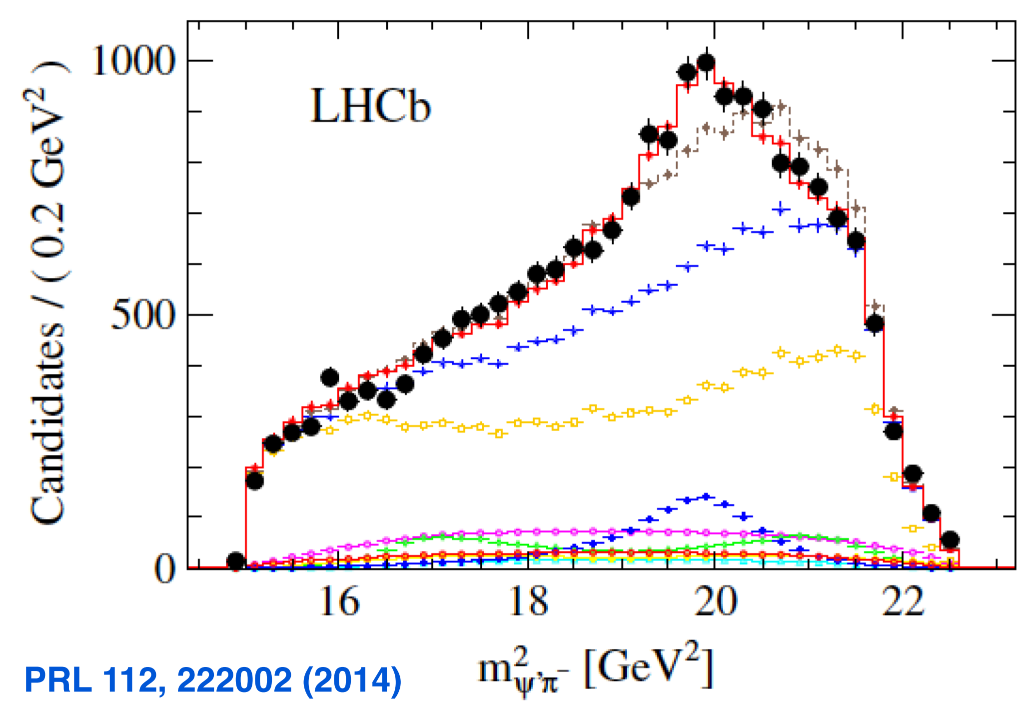

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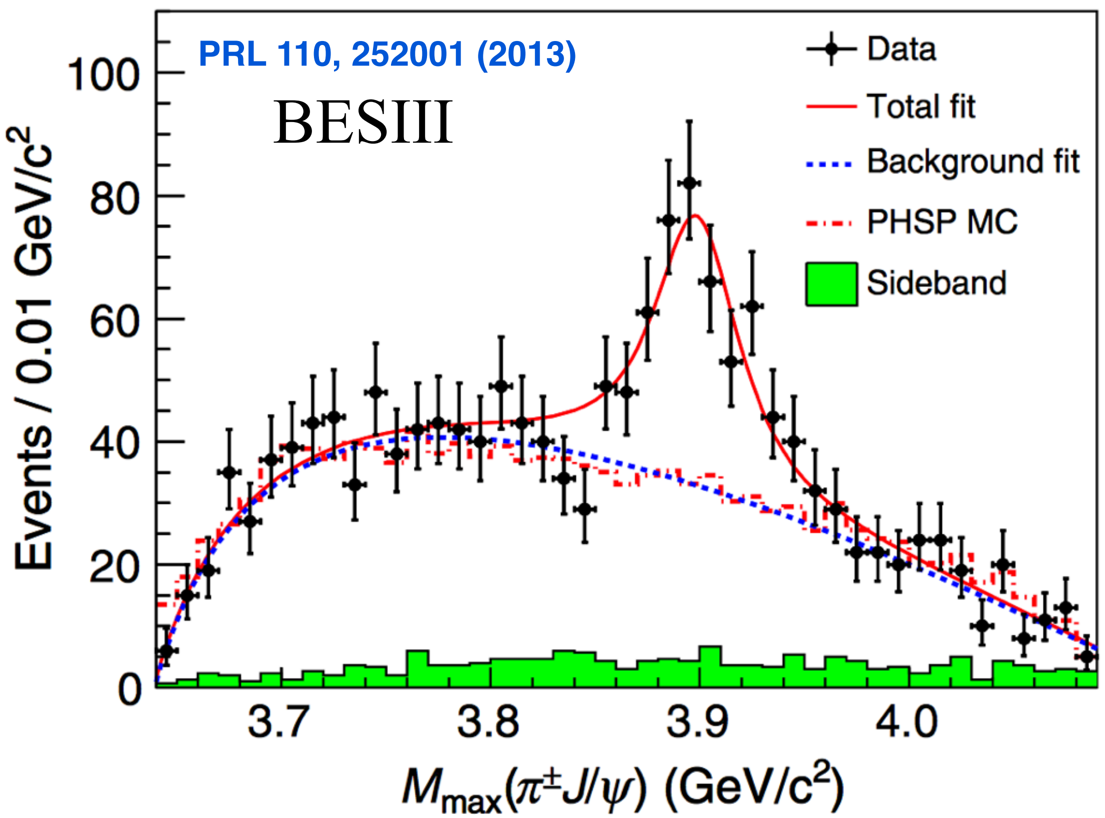

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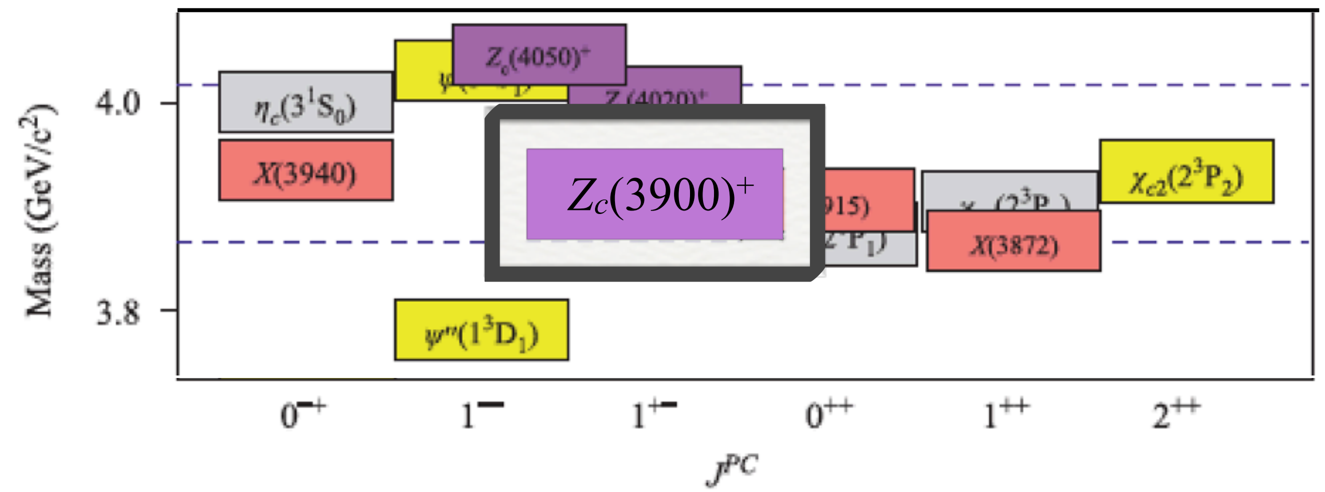

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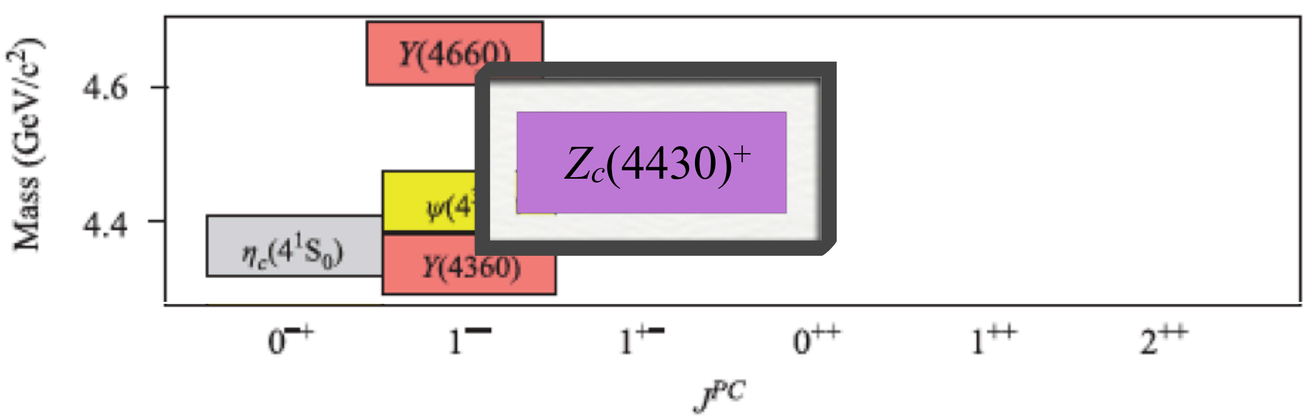
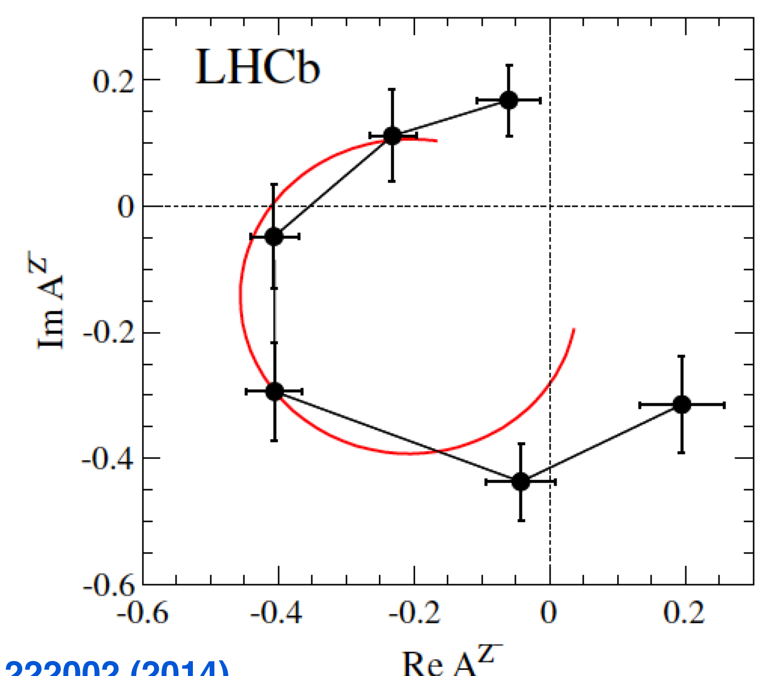


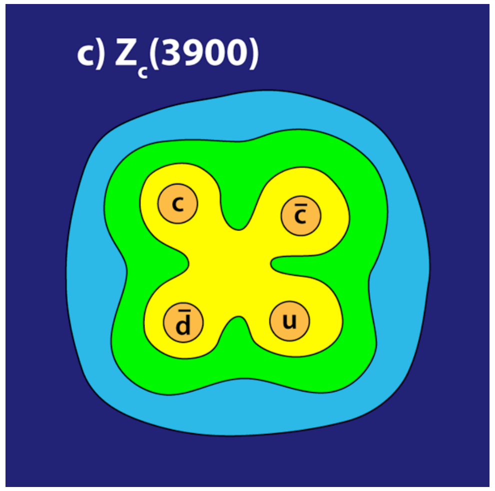


PRL 112, 222002 (2014)

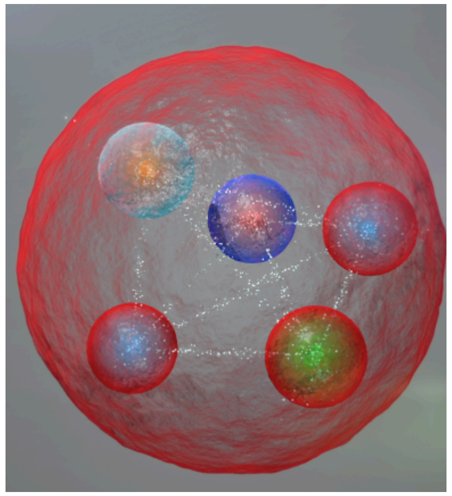
Exotic states

- **Why are they exotic?**
  - Some decay to ψ (ie. contain $c\bar{c}$) and are charge which requires 4+ quarks (tetra- and penta- quarks)
  - Predictions for others with exotic quantum numbers eg. hybrid mesons with excited gluonic field in wavefunction
- **Where to look for them?**
  - **e⁺e⁻**: CLEO, BESIII, BaBar, Belle II ($J^{PC} = 1^{--}$)
  - pp: LHCb, etc.
  - $p\bar{p}$: PANDA@GSI (glue rich environment, associated meson production for exotic J^{PC})
  - **Photoproduction:** GlueX, CLAS12, ... **EIC**!
    - Produce any J^{PC} and some models predict hybrid meson production comparable to conventional mesons

Tetraquark?

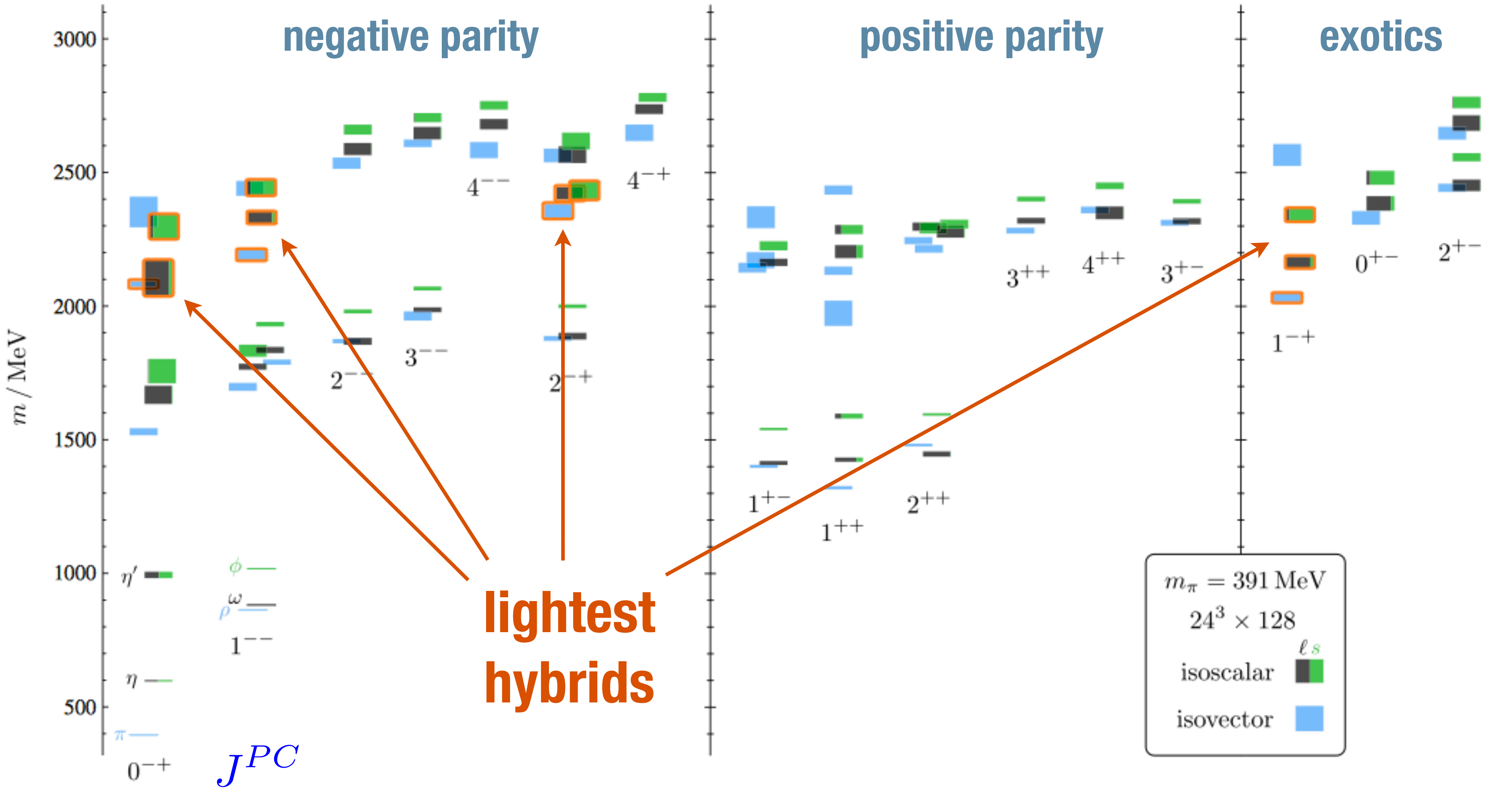


Pentaquark?



Light quark hybrids

Dudek et al. PRD 88 (2013) 094505



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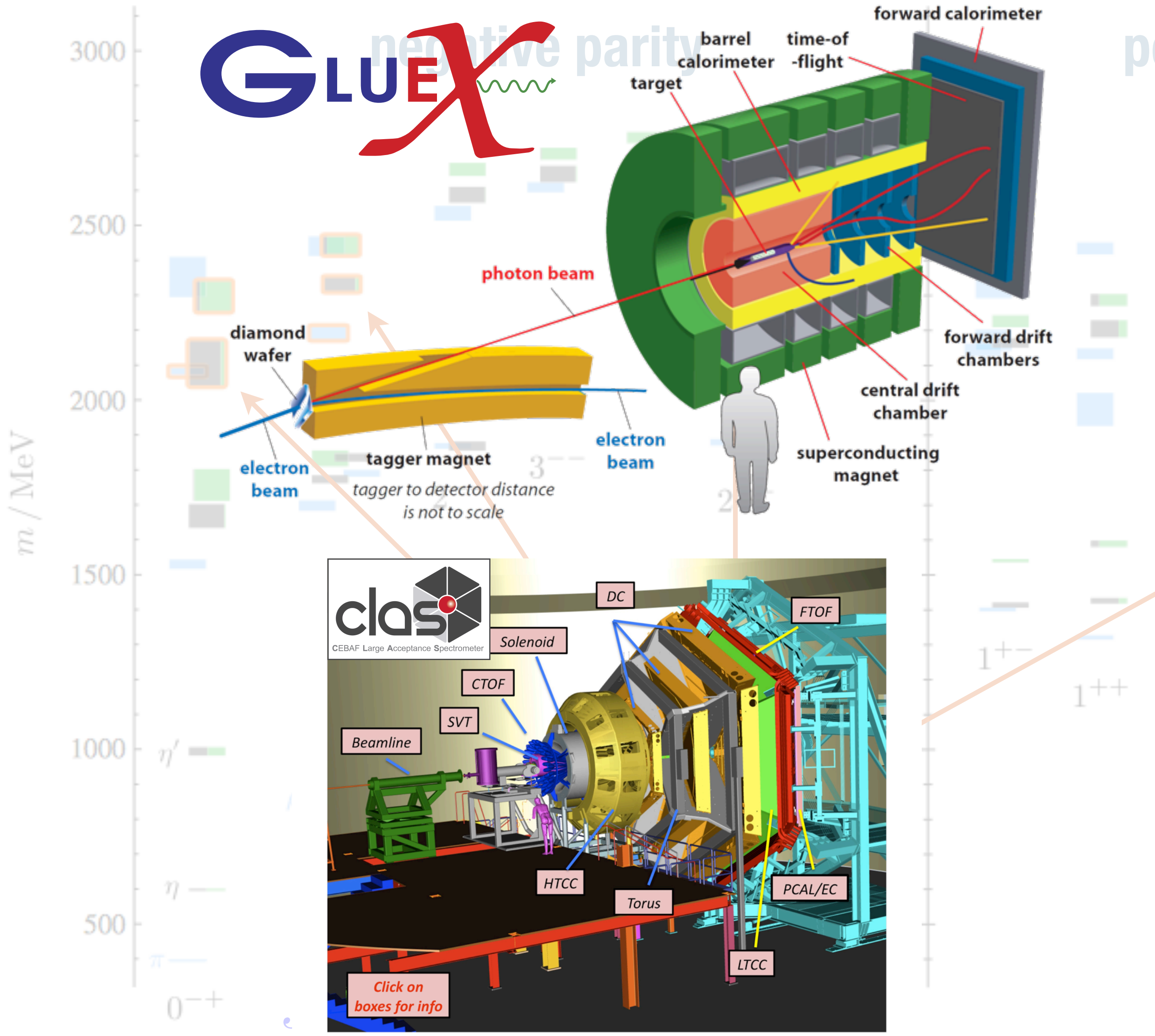
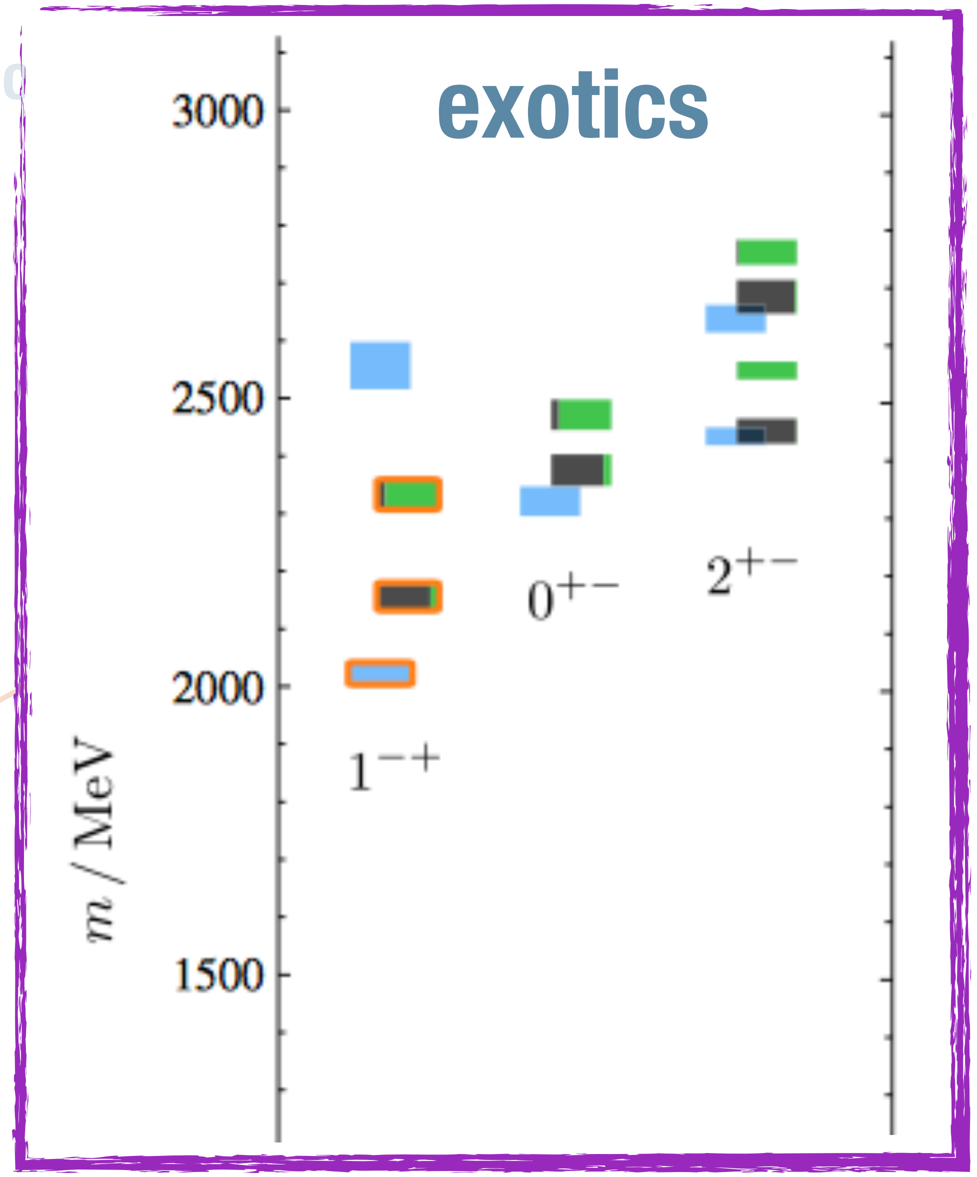
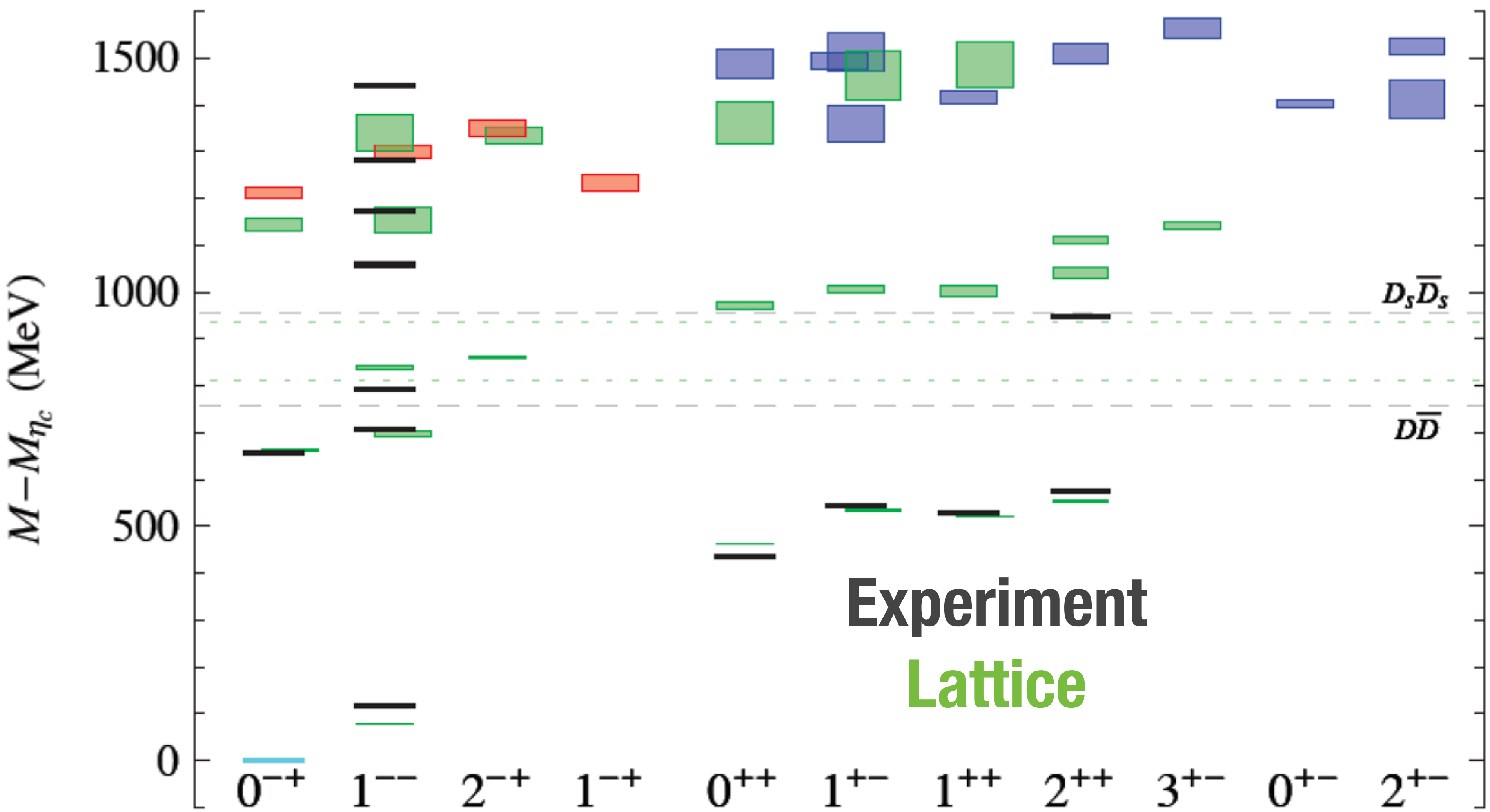




- The goal of the JLab 12 spectroscopy program is to search for and ultimately map out the spectrum of light quark hybrid mesons
- What about hybrid mesons containing charm?

Charmed hybrids

Hadron Spectrum Collaboration: JHEP 1207 (2012) 126



Charmed hybrids

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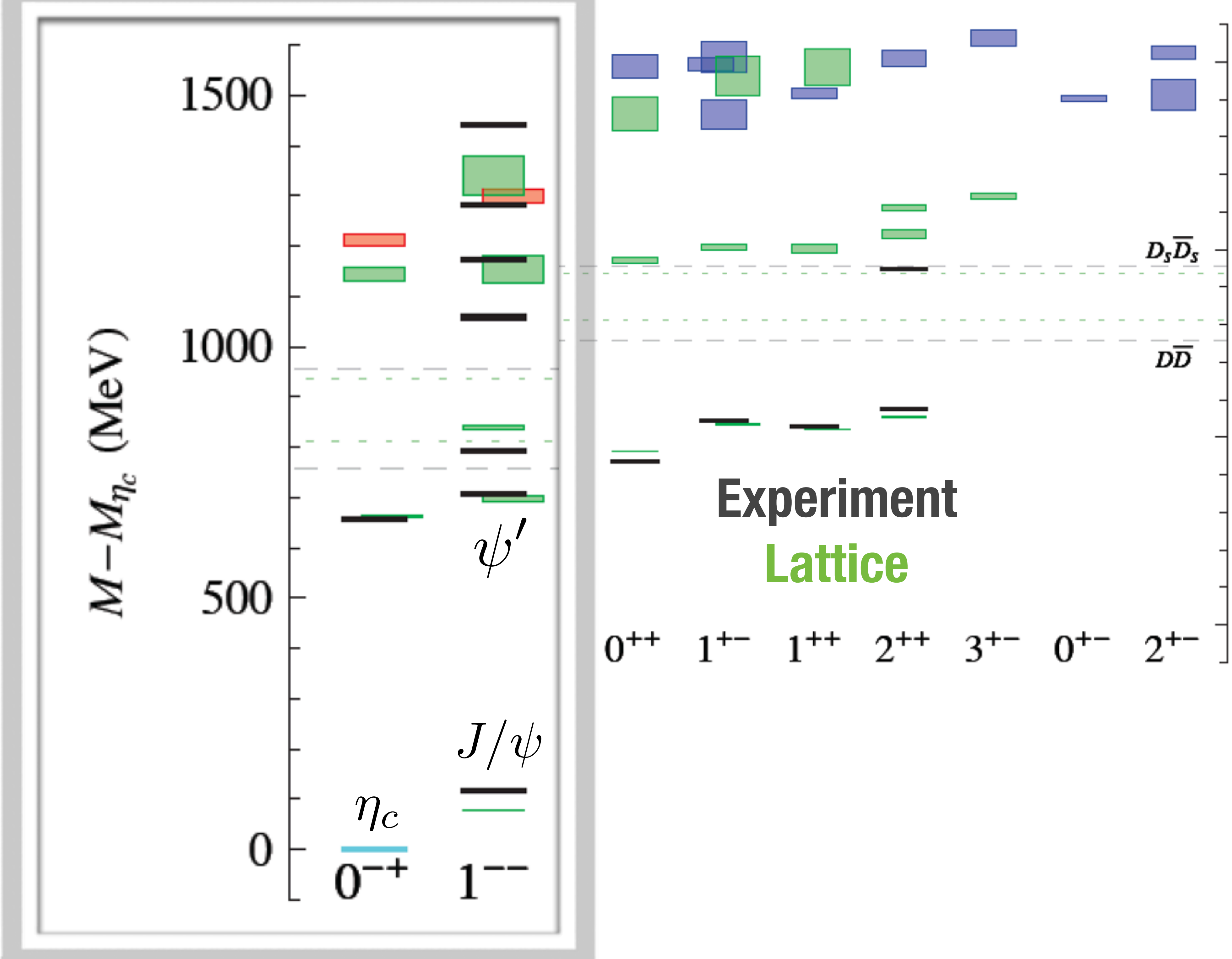

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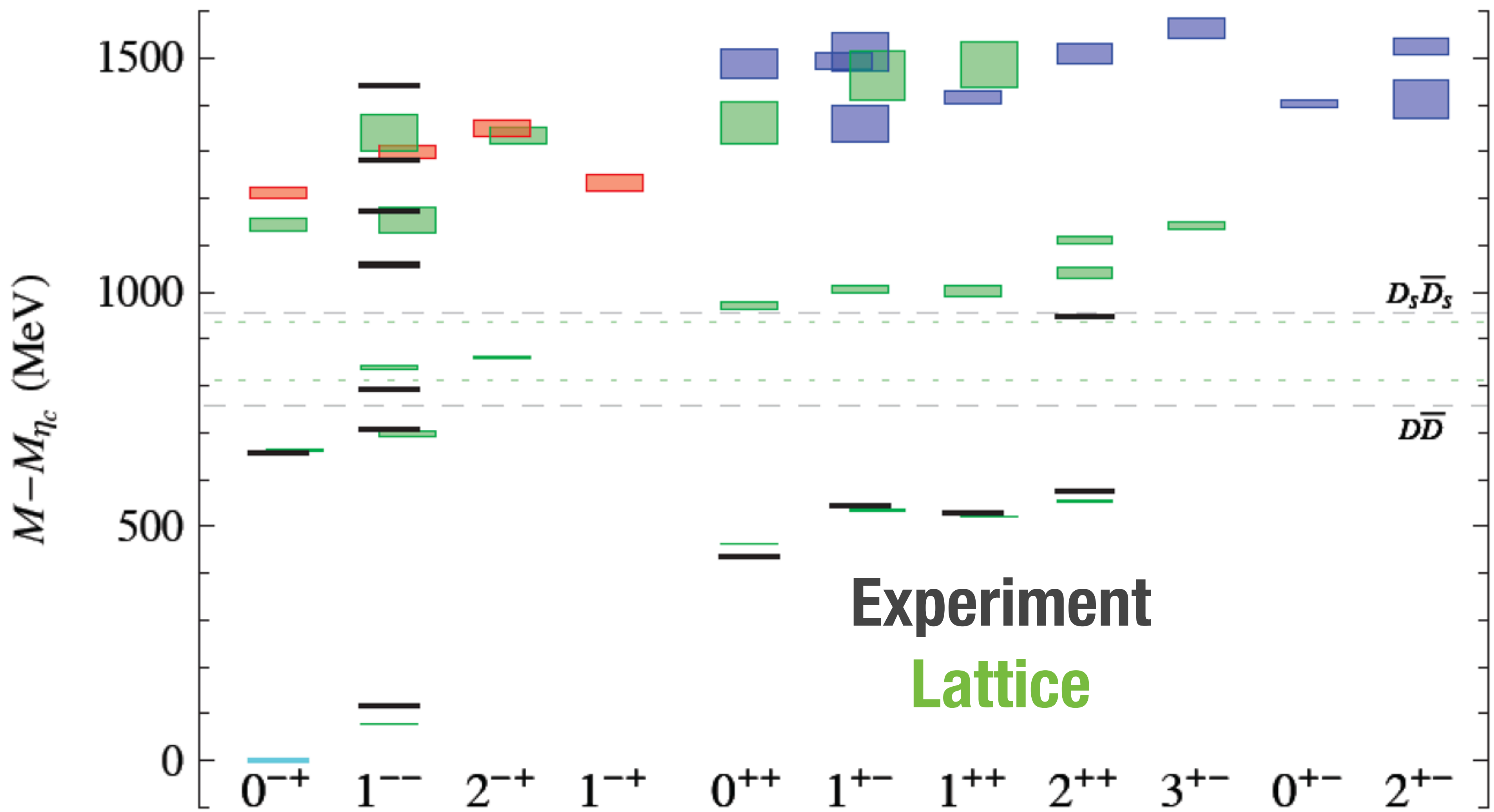

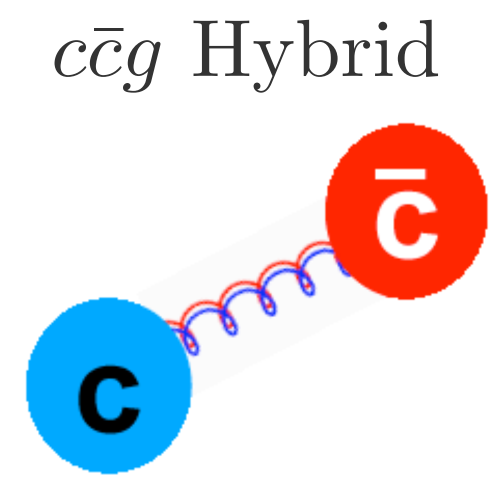

Lightest
Hybrids

- Lattice QCD predicts hybrid states charmonium states with gluonic contribution to their wavefunction

Charmed hybrids

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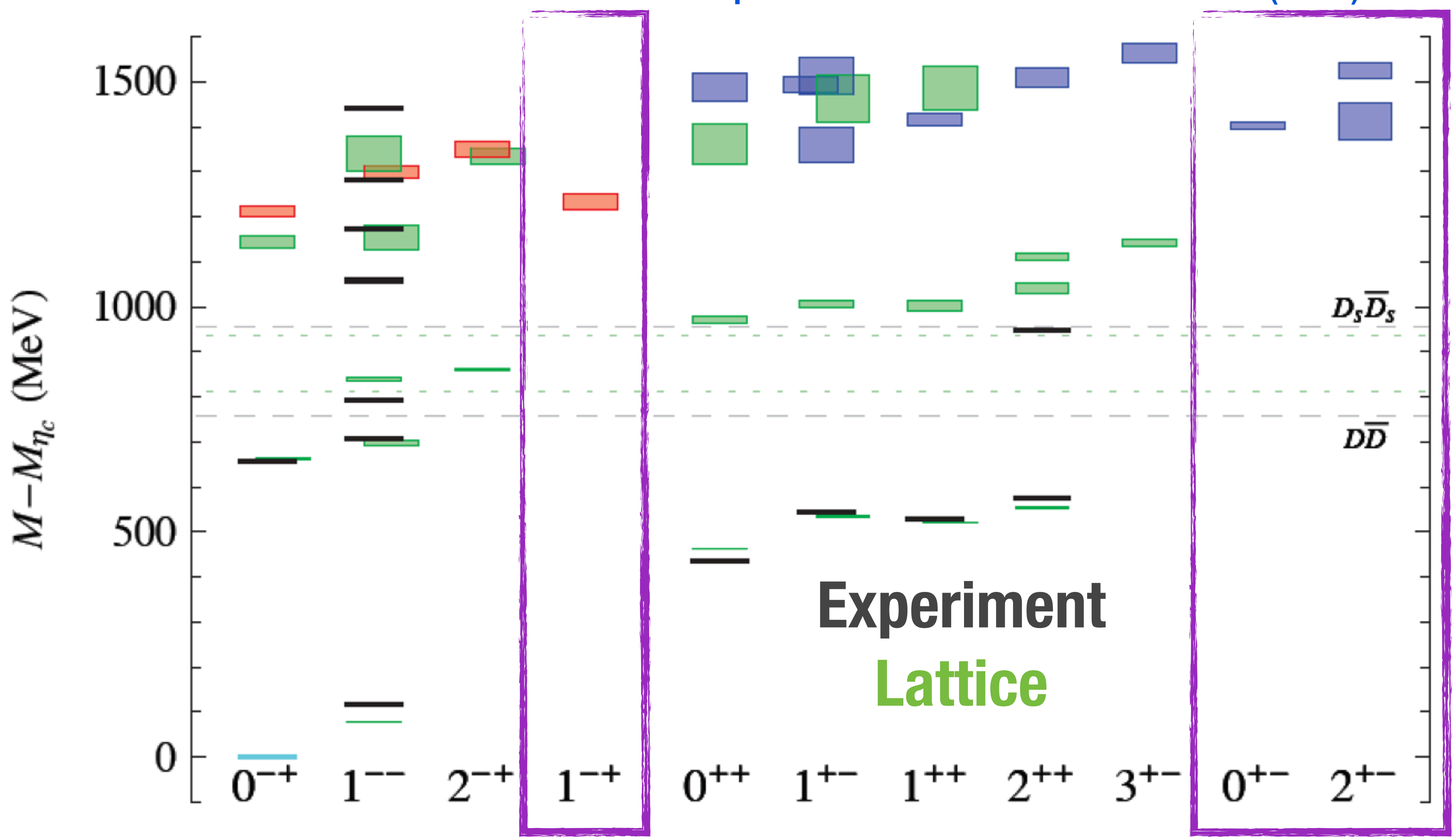
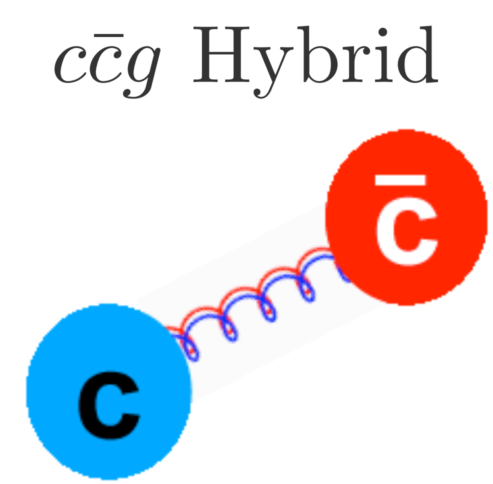
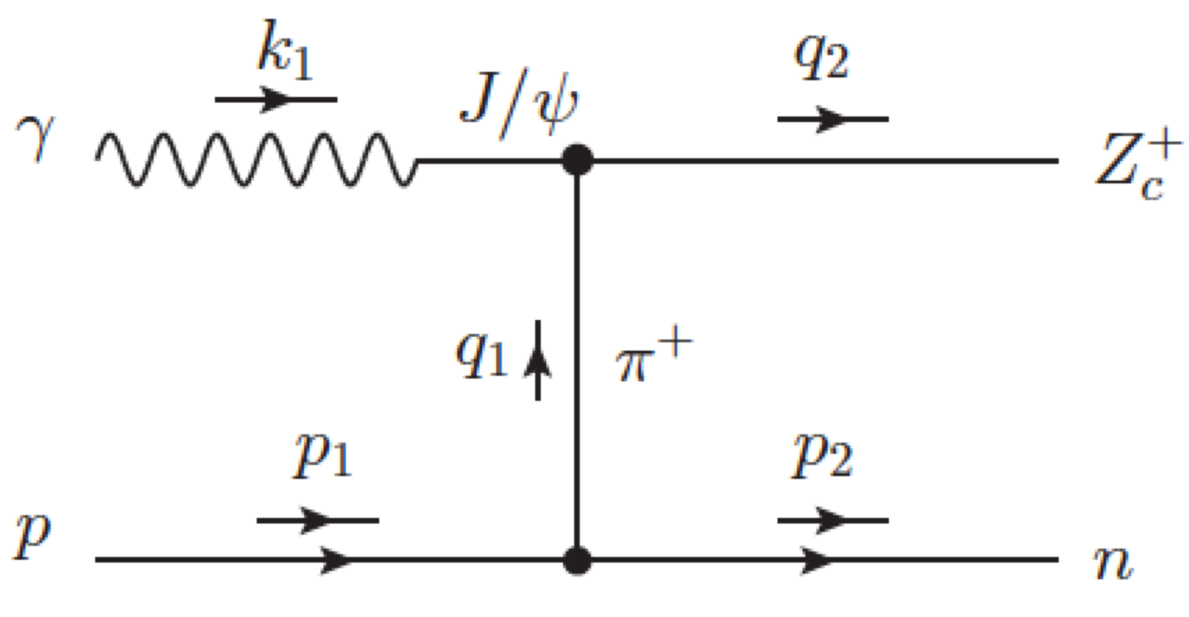




Lightest
Hybrids

- Lattice QCD predicts hybrid states charmonium states with gluonic contribution to their wavefunction including **exotic J^{PC} = 1^{-+}, 0^{+-}, 2^{+-}**
- Exotic J^{PC} not accessible in e^+e^-, but could be studied through other mechanisms like **photoproduction** or $p\bar{p}$ annihilation (eg. PANDA@GSI)

XYZ states in photoproduction



PRD 88 (2013) 114009

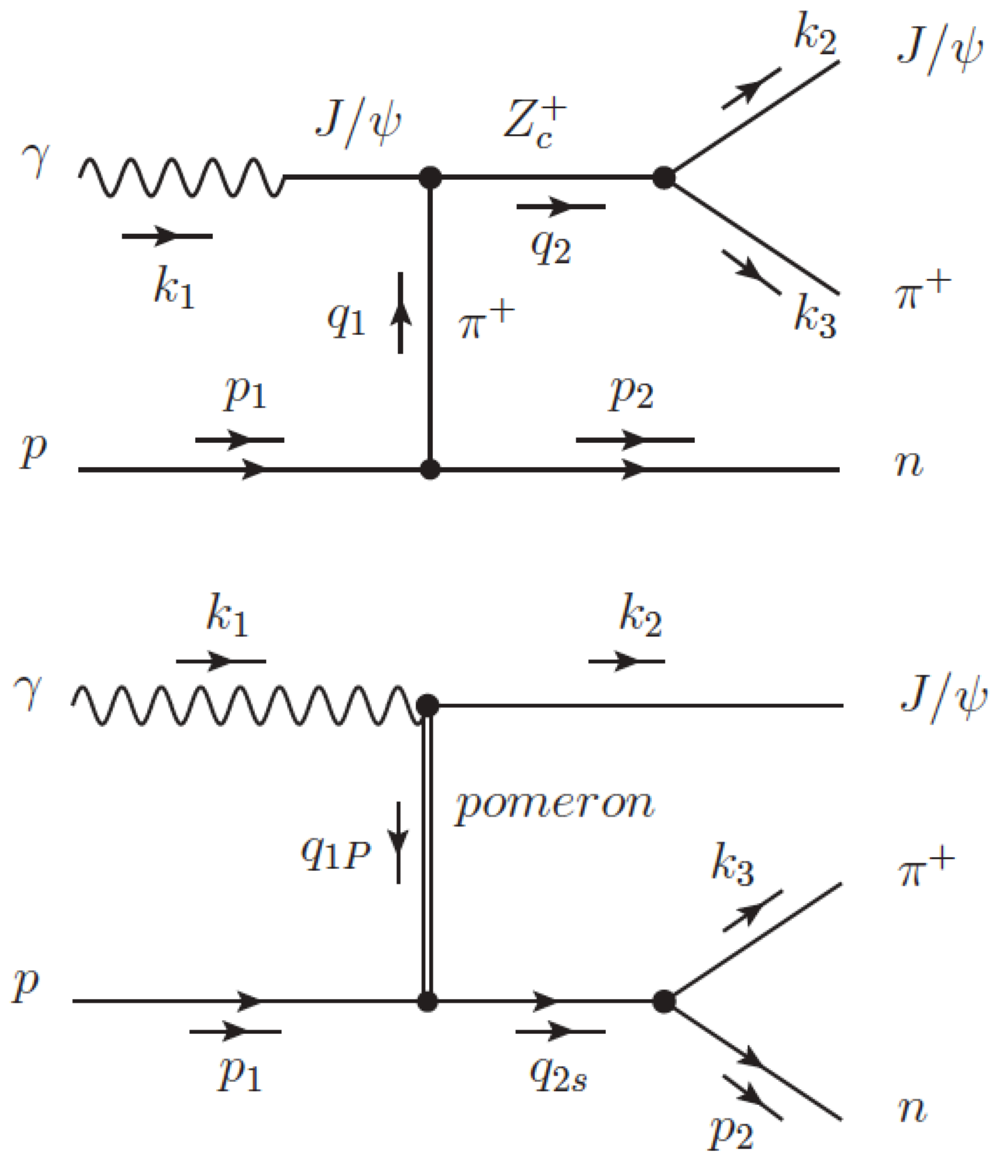
$$\mathcal{L}_{V\gamma} = -\frac{eM_V^2}{f_V} V_\mu A^\mu$$

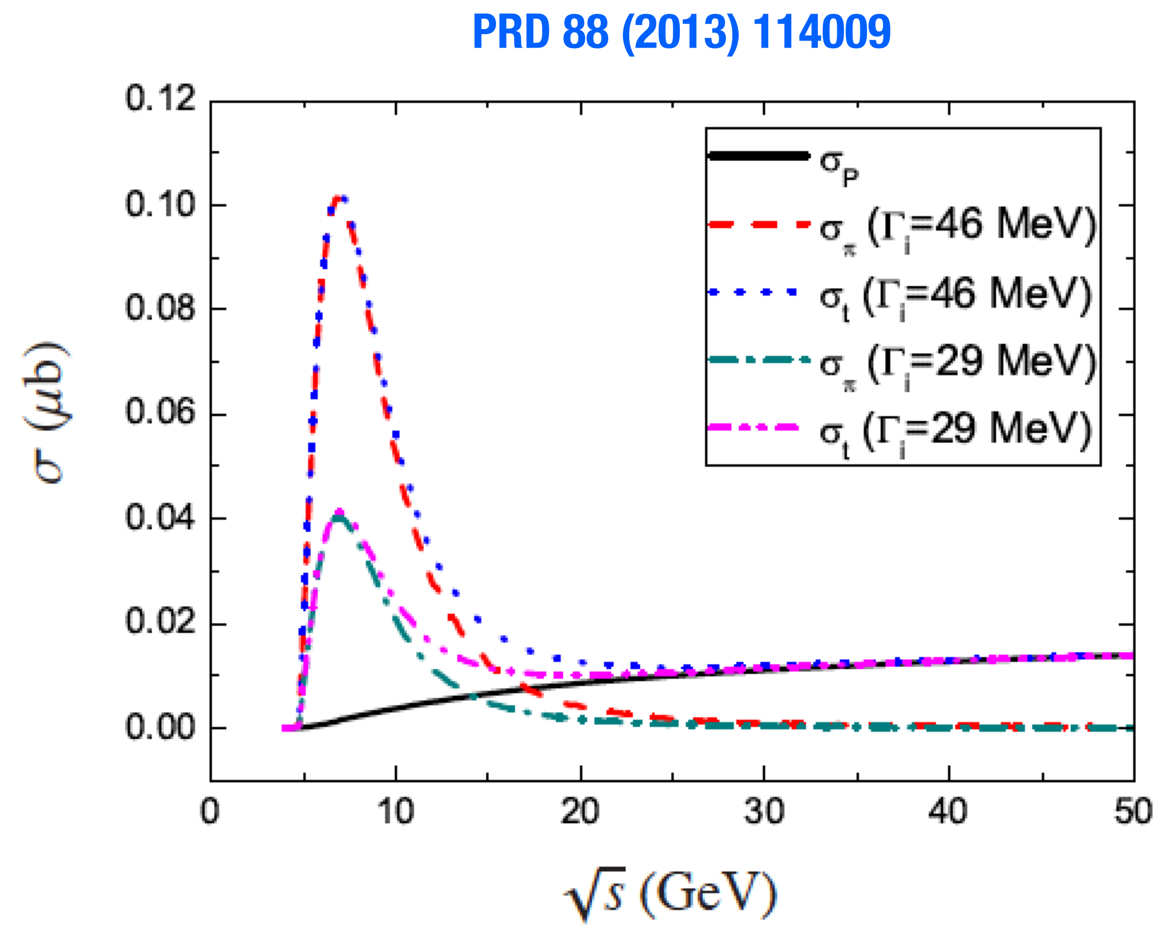
$$\mathcal{L}_{Z\psi\pi} = \frac{g_{Z\psi\pi}}{M_Z}\left(\partial^\mu \psi^\nu \partial_\mu \pi Z_\nu - \partial^\mu \psi^\nu \partial_\nu \pi Z_\mu\right)$$

$$\mathcal{L}_{\pi NN} = -\frac{g_{\pi NN}}{2m_N}\bar{N}\gamma_5\gamma_\mu(\vec{\tau}\cdot\partial^\mu\vec{\pi})N$$

- Several proposals to study XYZ states in photoproduction
  - $\gamma p \to Z_c^+(3900)n, Z_c^+ \to J/\psi\pi^+$ PRD 88 (2013) 114009
  - $\gamma p \to Z_c^+(4430)n, Z_c^+ \to \psi'\pi^+$ PRD 77 (2008) 094005, PRC 83 (2011) 065203
  - $\gamma p \to Z_c^+(4200)n, Z_c^+ \to J/\psi\pi^+$ arXiv:1503:02125 (incl. Regge trajectories in model)
  - $\gamma p \to Y(3940)p, Y(3940) \to J/\psi\omega$ PRD 80 (2009) 114007
- Use an Effective Lagrangian approach with Vector Meson Dominance

Example: $Z_c^+(3900)$

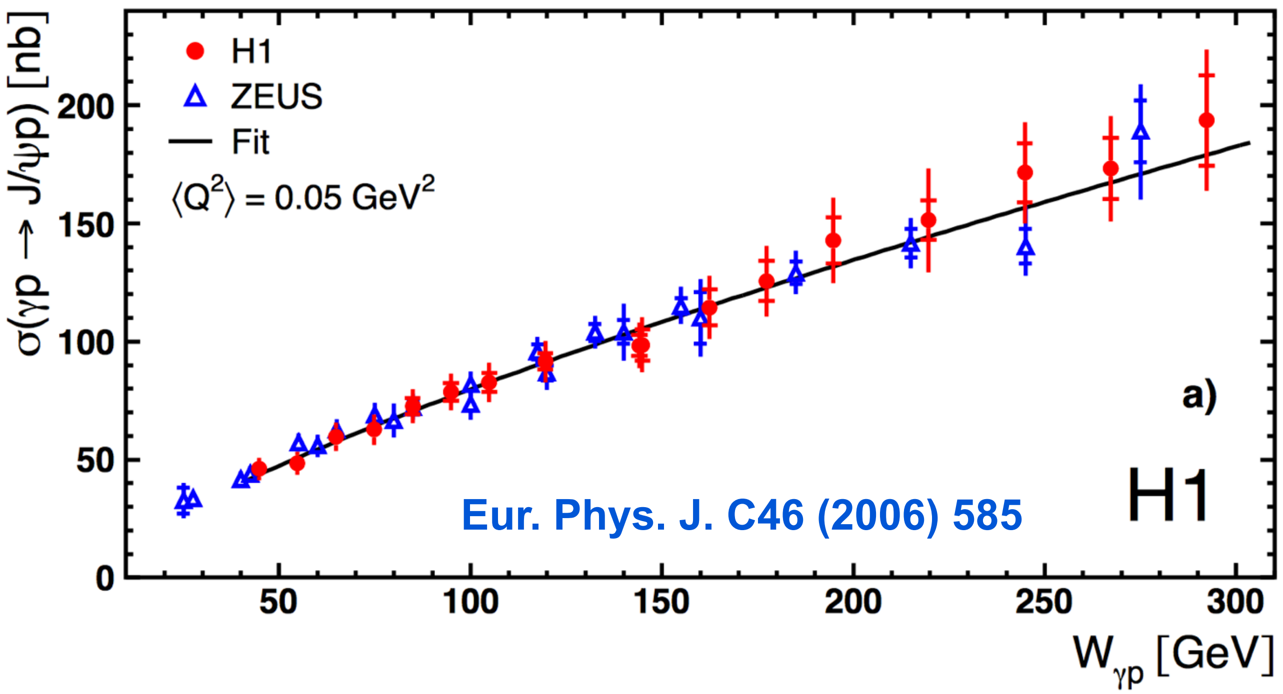




- Model prediction that photoproduction is enhanced at threshold
  - Unknown $Z_c \rightarrow J/\psi\ \pi$ decay width drives total cross section
  - Pomeron background at higher COM energies

Previous experiments

- Photoproduciton at HERA in e+p
  - Quasi-real photons at low-Q^2
  - Same idea as MesonEx@CLAS12



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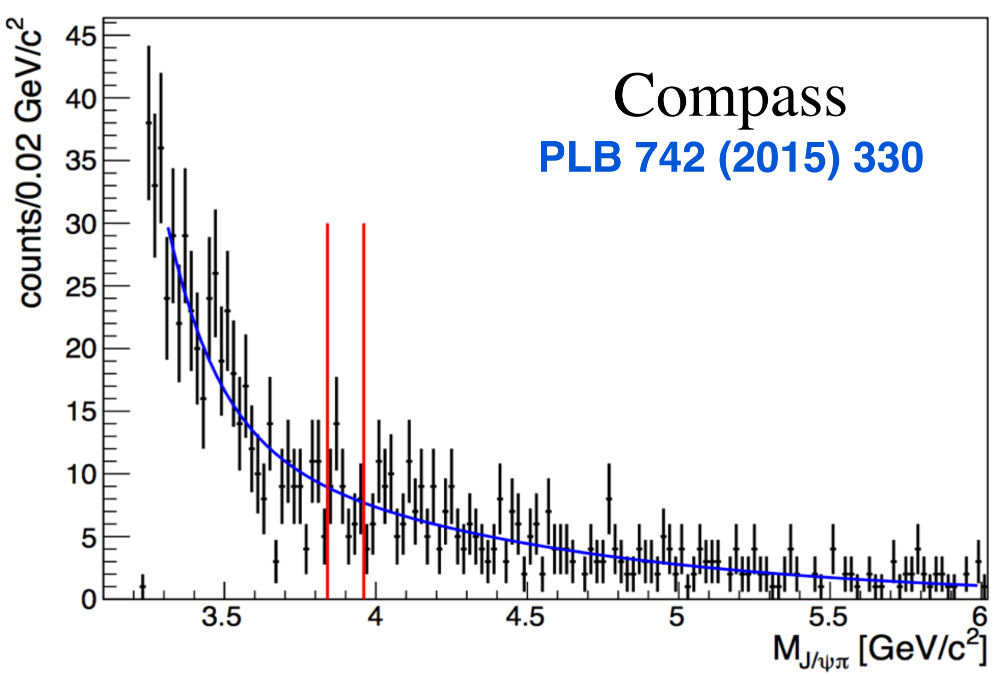
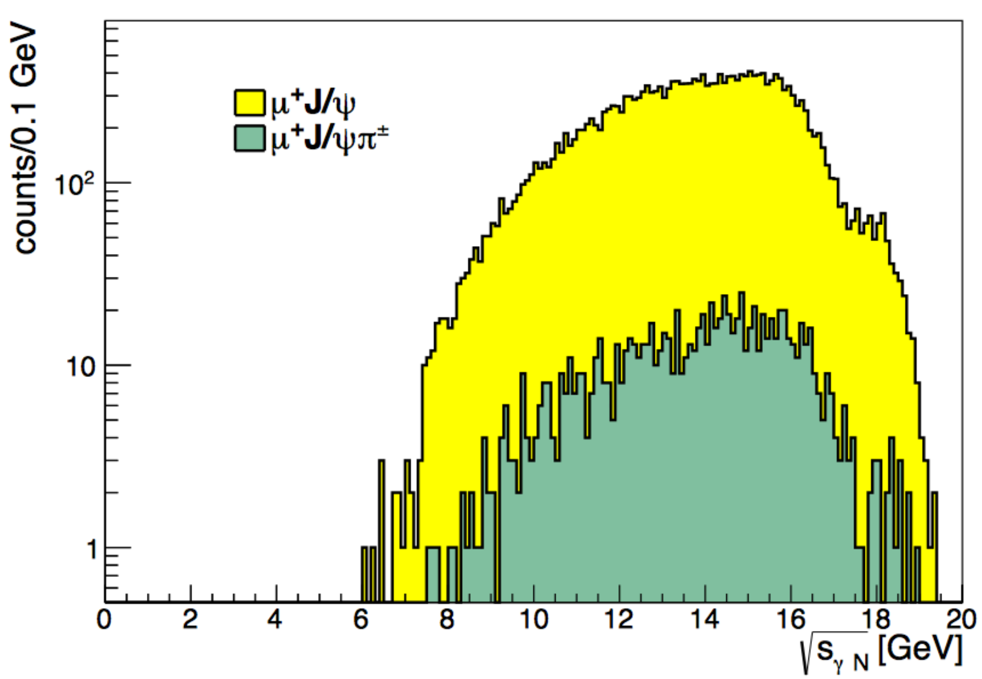
- Recent result from Compass in μ+p to search for $Z_c(3900)$
  - Already some constraints on $Z_c \to J/\psi\, \pi$ decay width?
- What could the EIC do in e+p?





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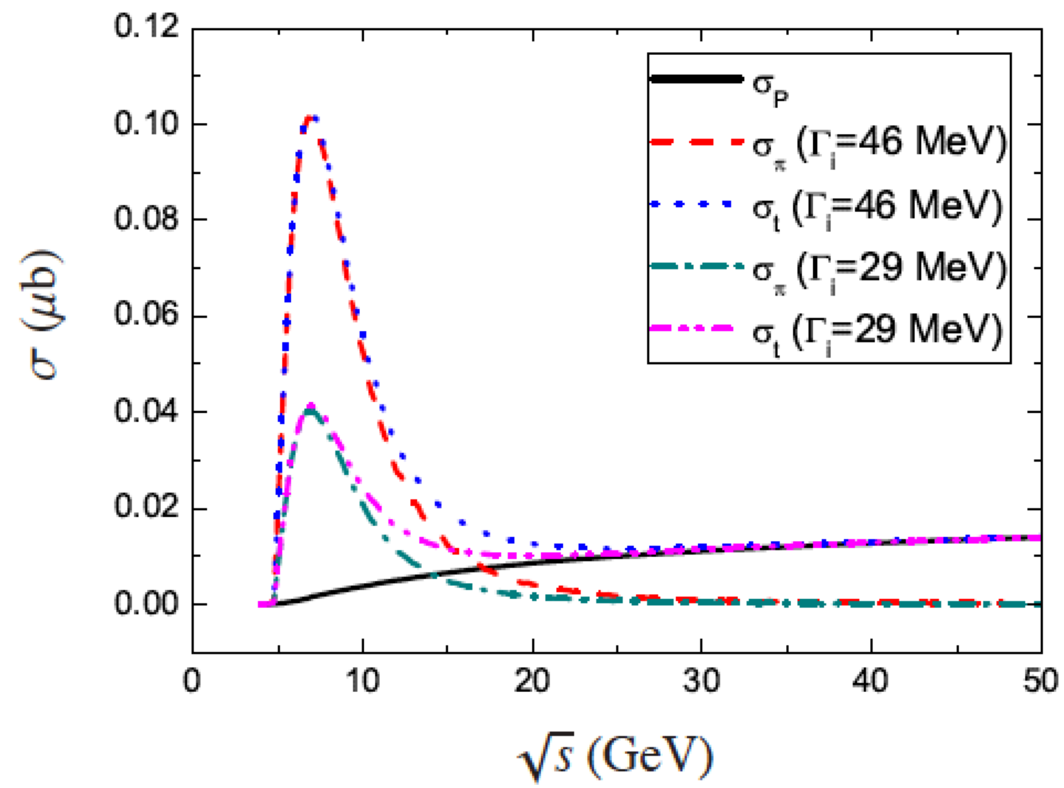
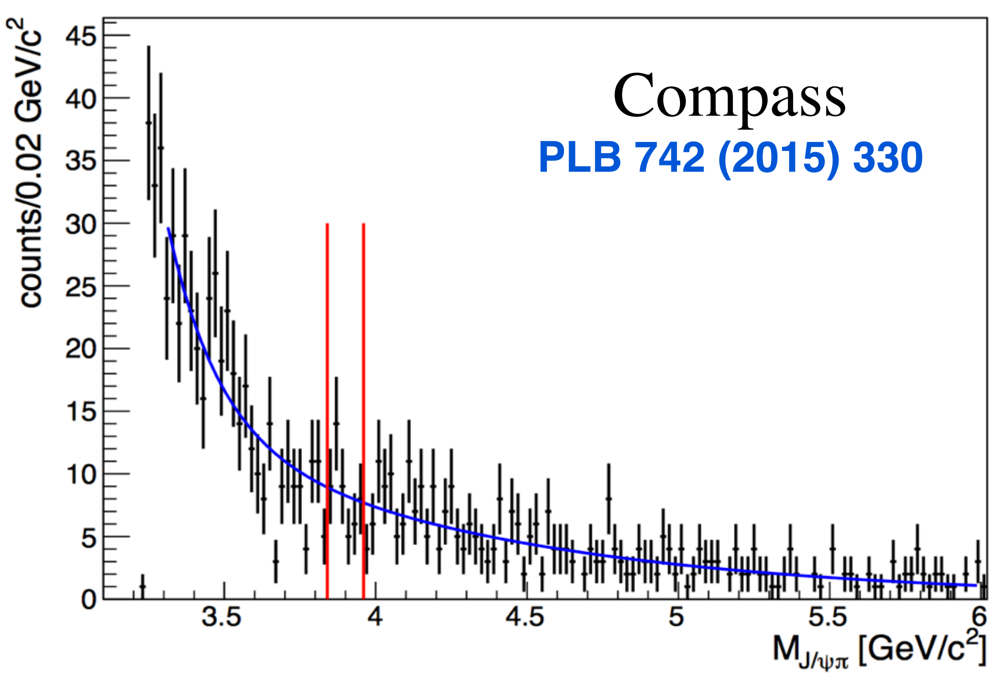
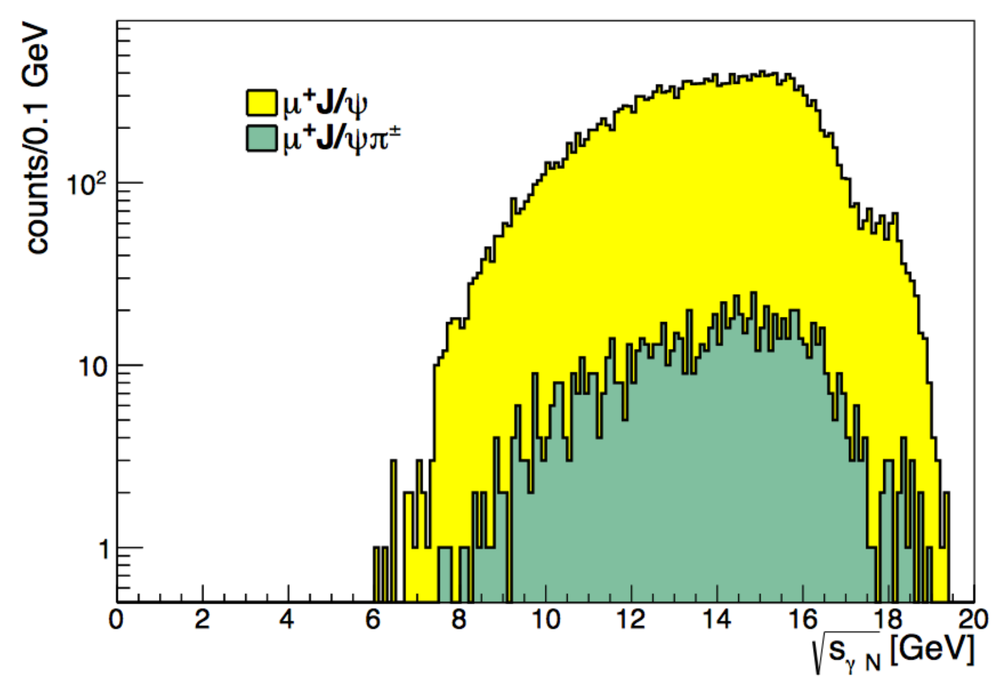
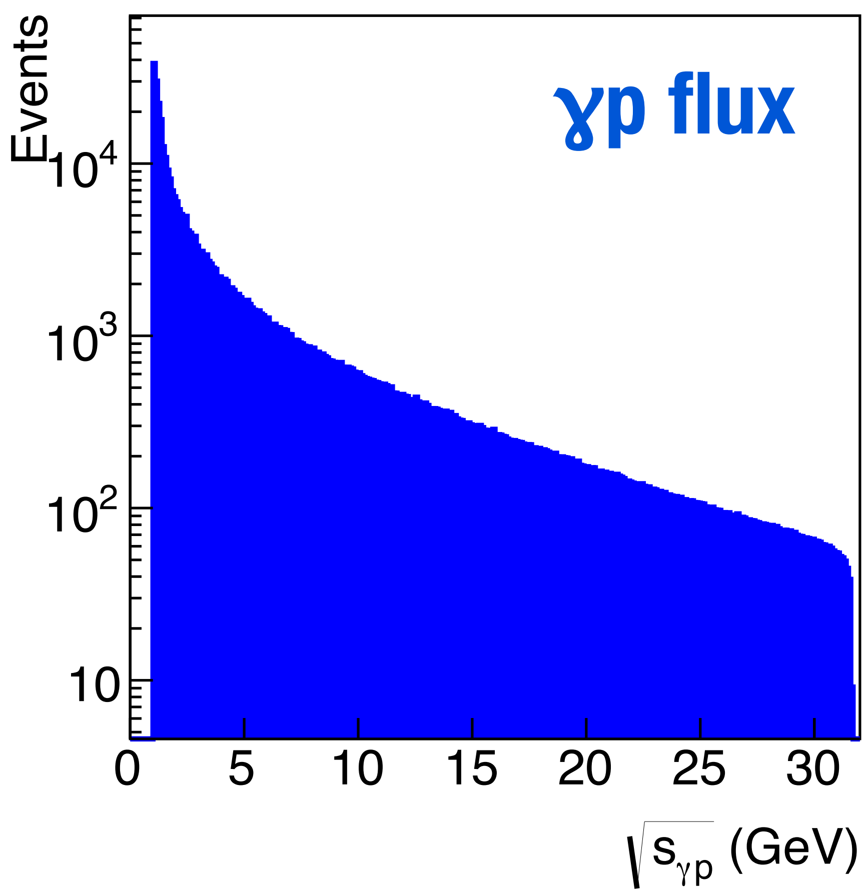
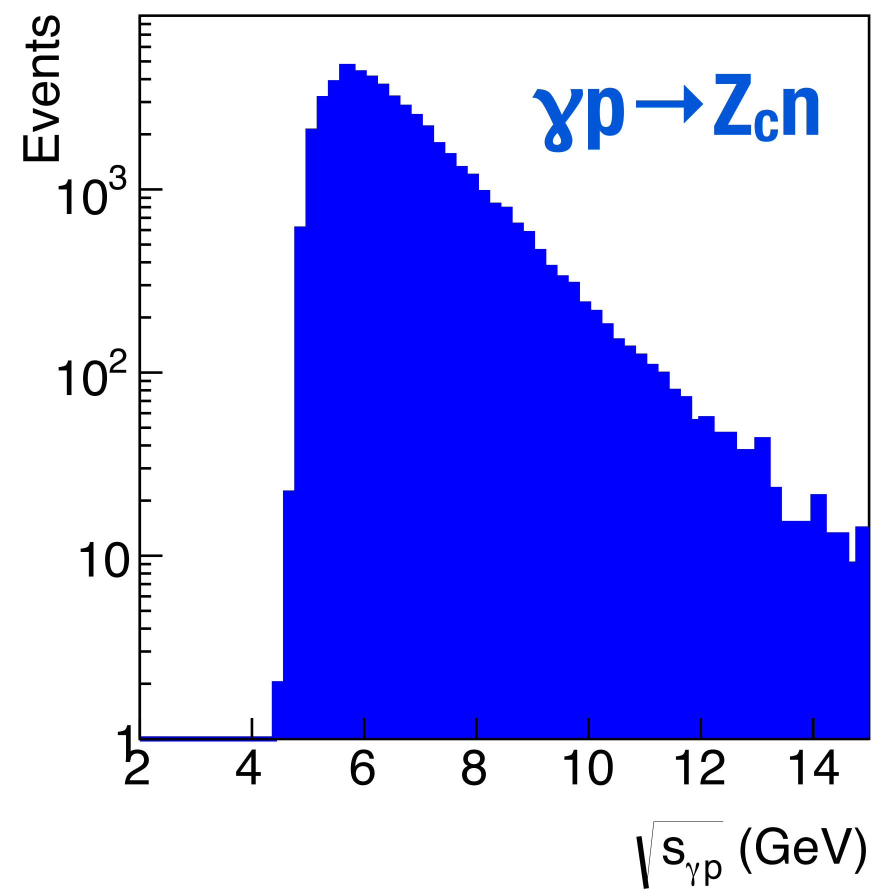






$Z_c^+(3900)$ at the EIC

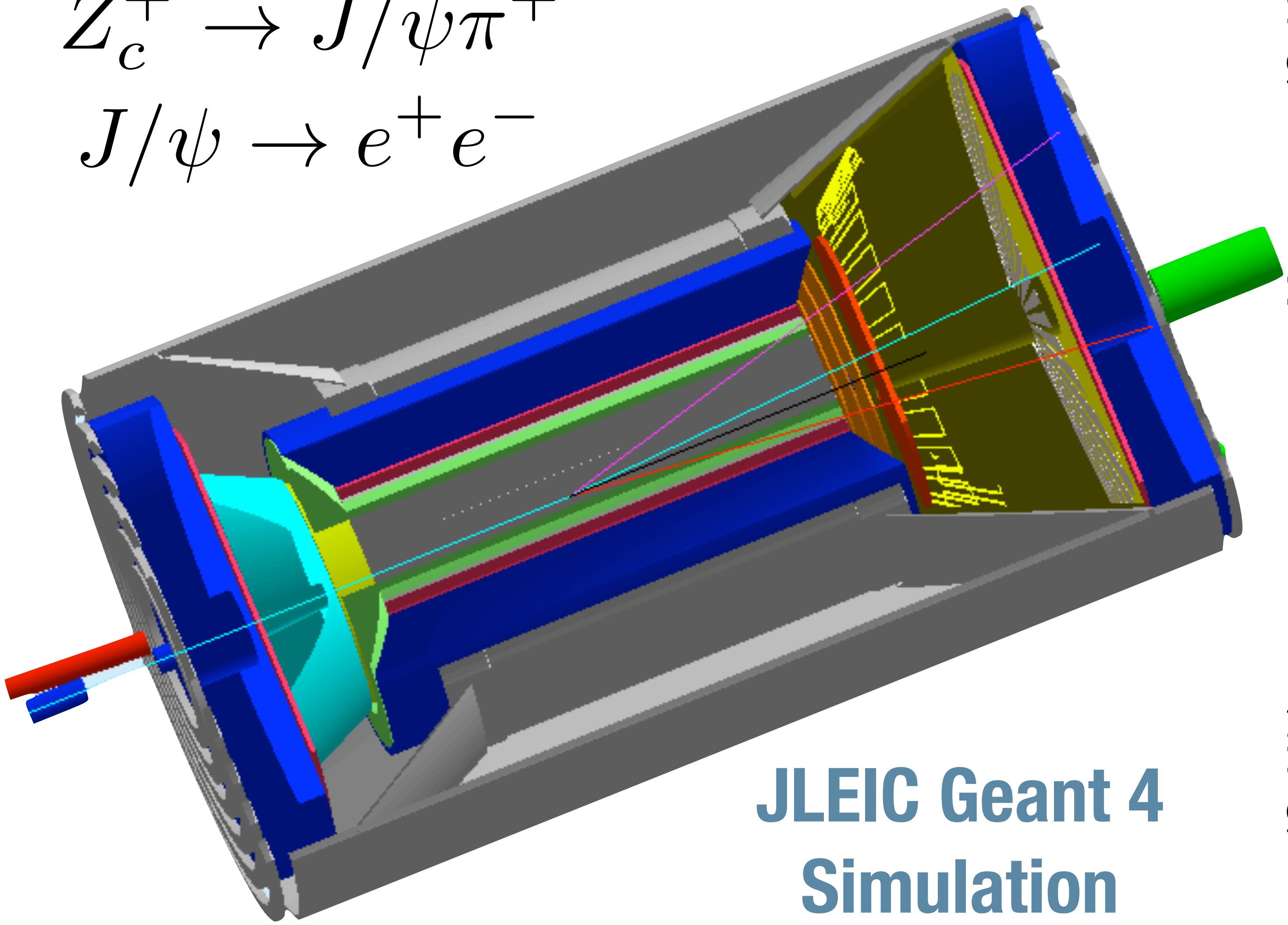




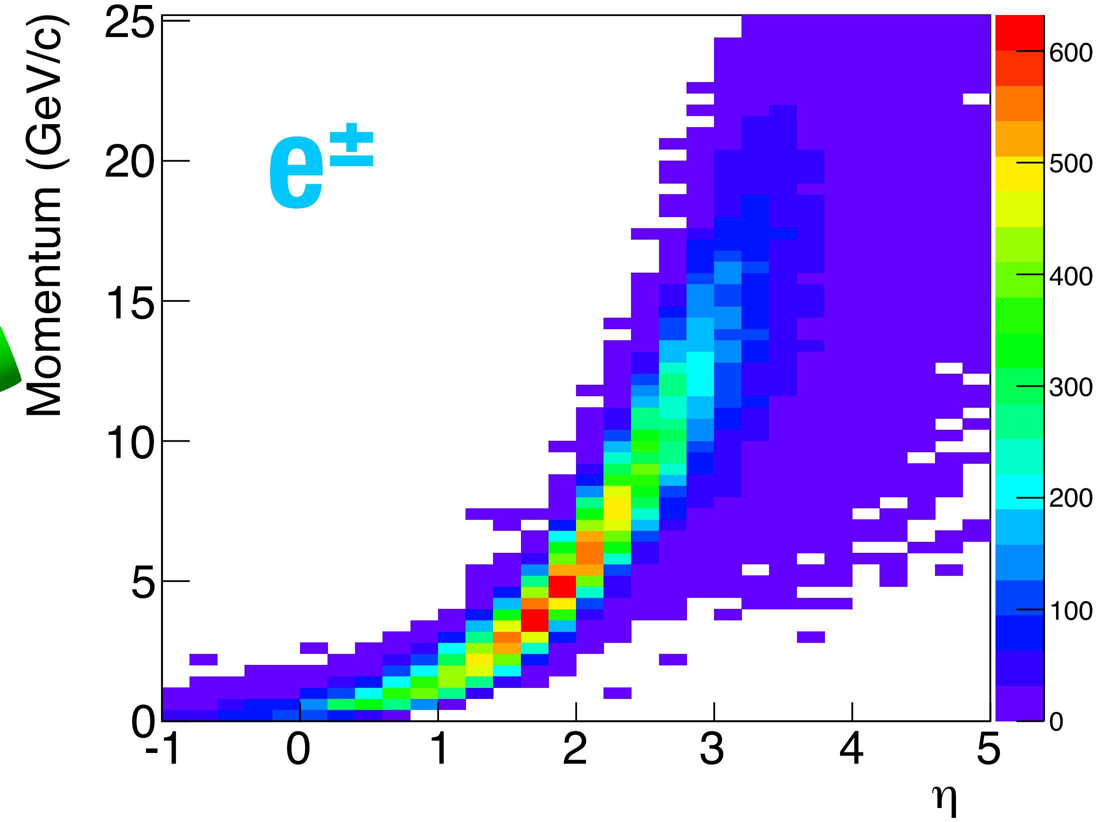
- Assume modest energy electron and proton beams: **E_p = 50 GeV** and **E_e = 5 GeV**
- Z_c and subsequent decays are boosted in proton direction
- Low-Q^2 electron and neutron very close to beamline

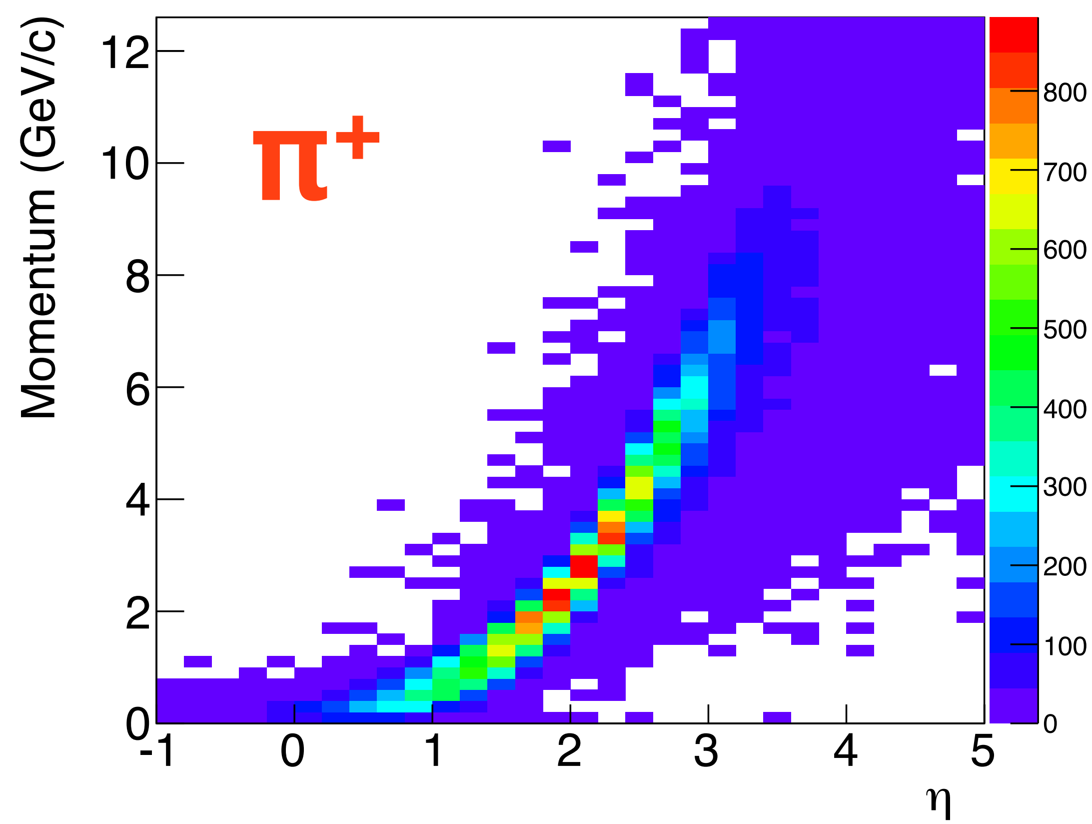
$Z_c^+(3900)$ at the EIC

$$Z_c^+ \to J/\psi\pi^+$$
$$J/\psi \to e^+e^-$$



JLEIC Geant 4 Simulation

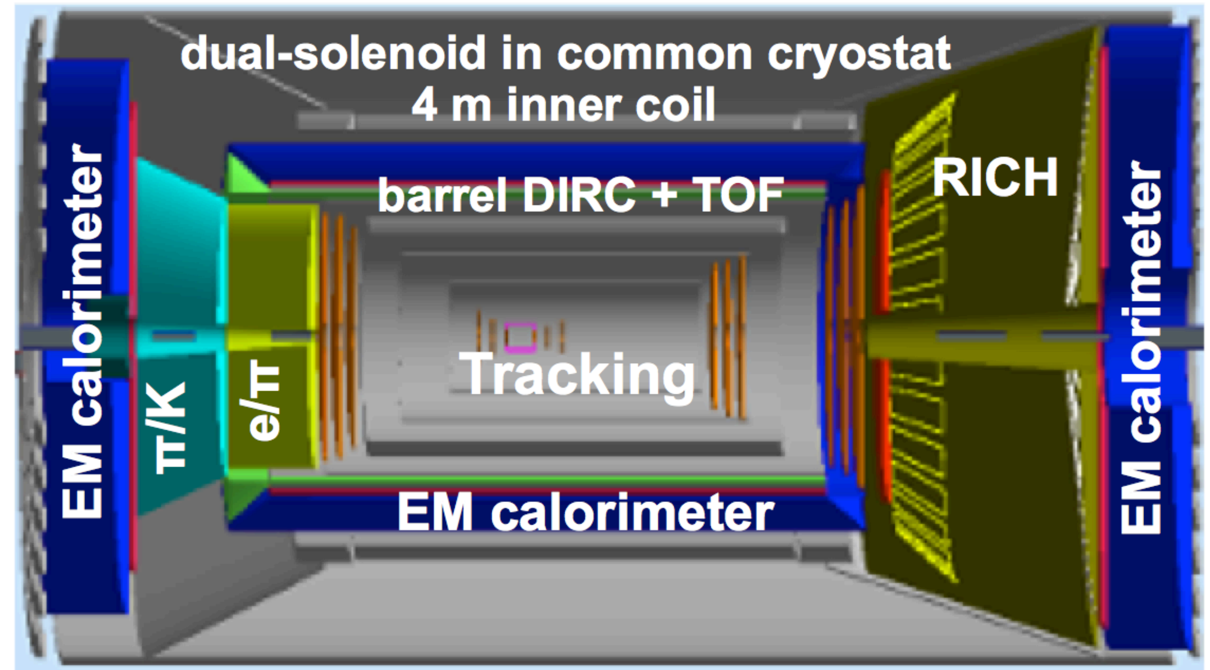


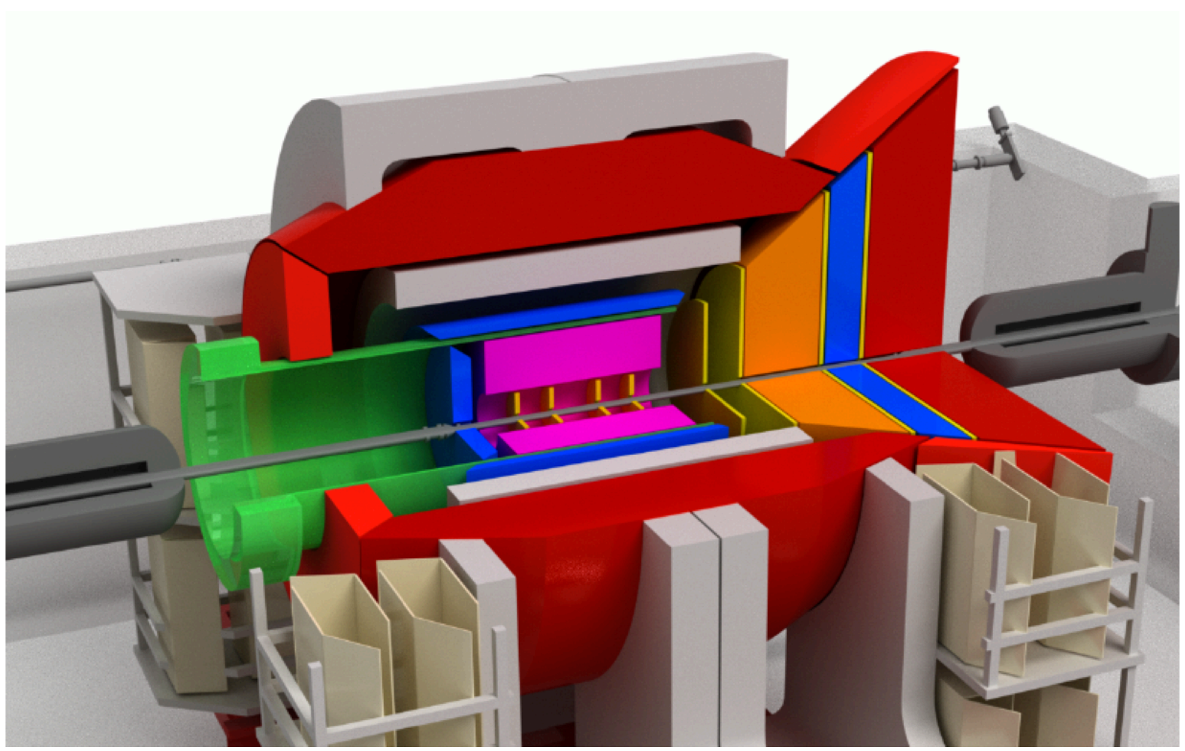


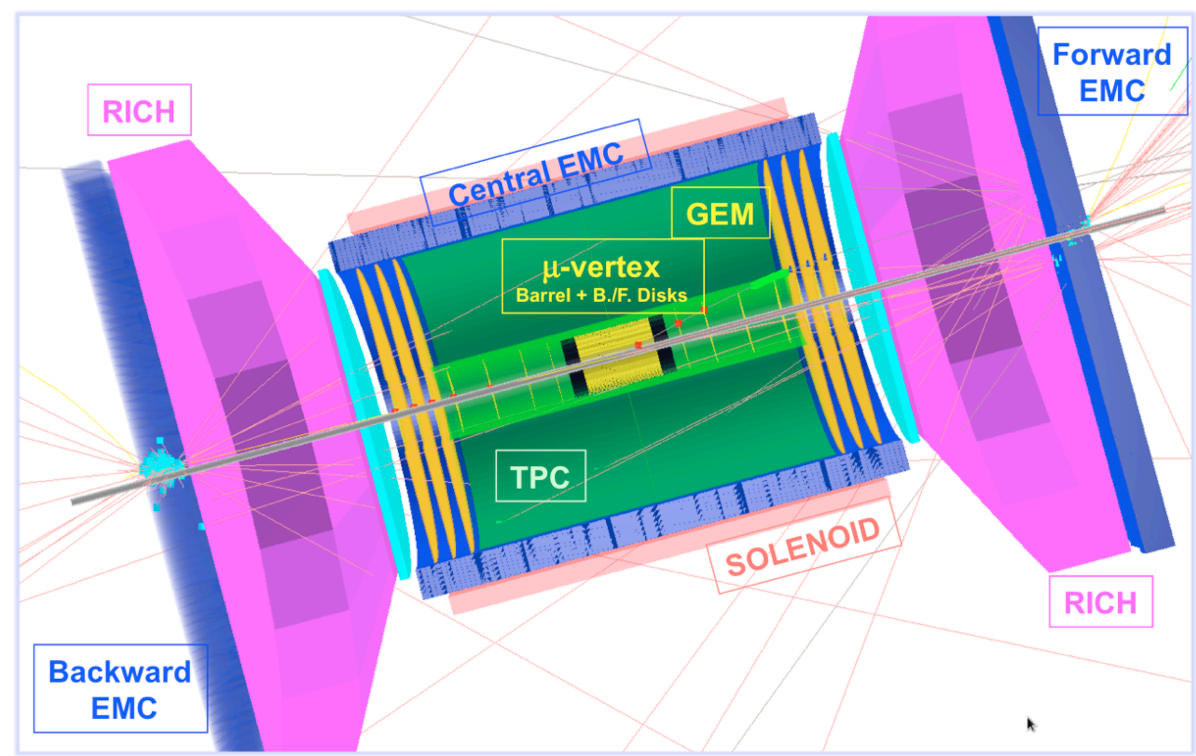
- Decay e± and π⁺ boosted in proton beam direction
- Need excellent hadron and e± PID and momentum resolution

EIC detector designs

- Requirements for EIC detector similar to hadron spectroscopy needs!
  - Vertex detector to explore open charm decays: eg. $Z_c \rightarrow D^*D$
  - Consider e and μ ID for J/ψ?
- Beamline detectors ensure exclusivity: low-Q^2 tagger, ZDCs, Roman Pots



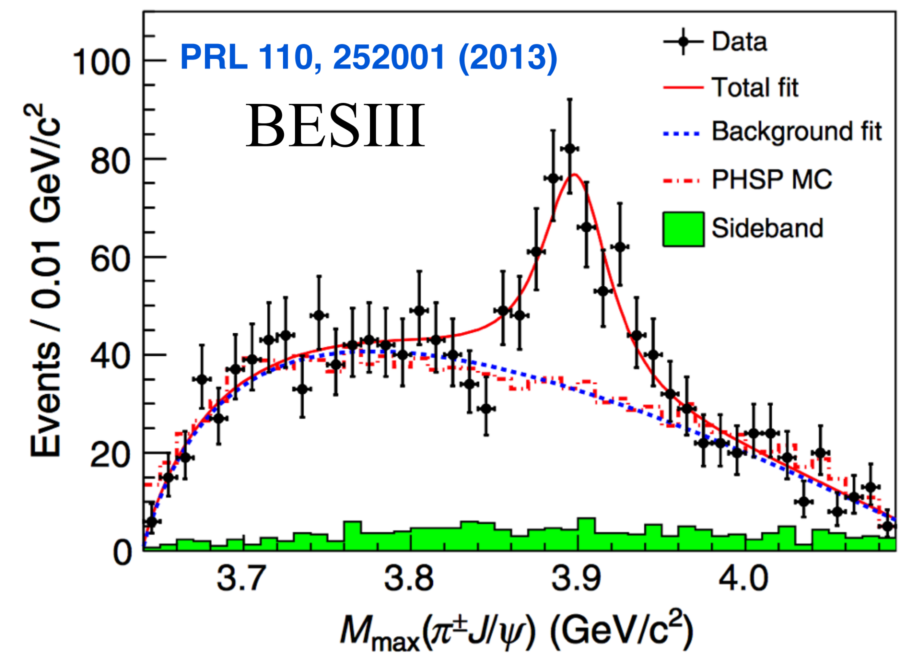


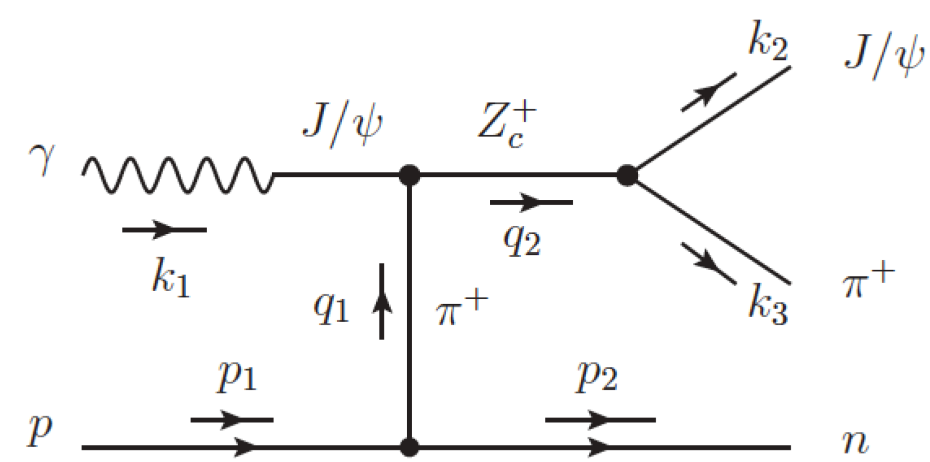


Summary and Outlook

- New "XYZ" states in heavy quarkonium are challenging our understanding of the meson spectrum
- It's possible to probe the XYZ states and possibly heavy quark hybrid mesons in photoproduction at an EIC
- Natural connection between light and heavy quark sectors with GlueX/CLAS12 and EIC hadron spectroscopy
- Future studies will be focused on "fast" simulation studies and to provide more detailed feedback on the detector requirements
- Plenty of room for people to make contributions, and develop this aspect of the EIC program

$$e^+e^- \to \pi^+\pi^- J/\psi \ (4260 \text{ MeV})$$

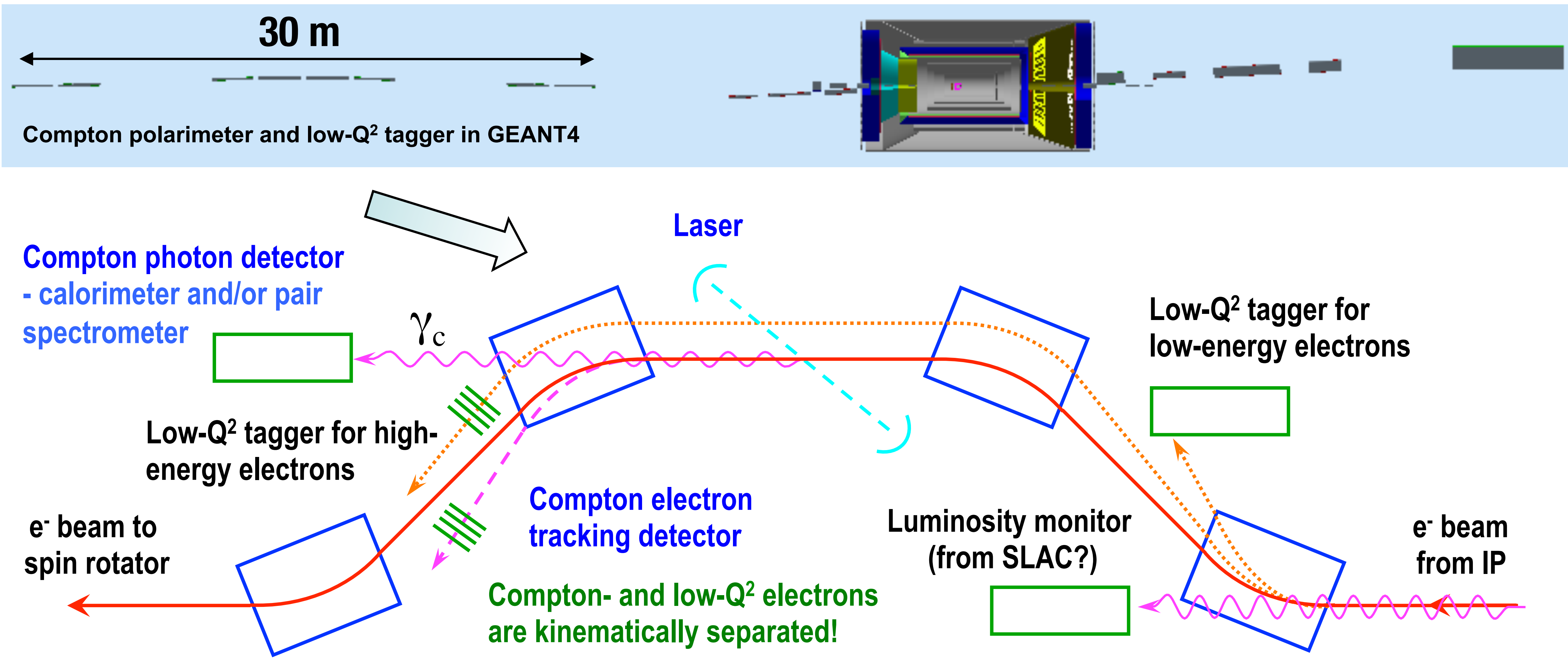




EIC User's Group: http://www.eicug.org/web/

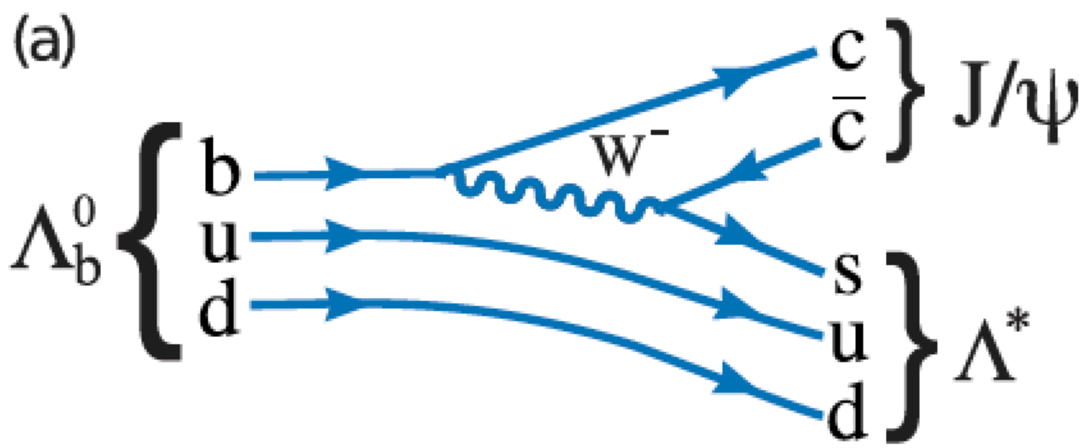
Backup

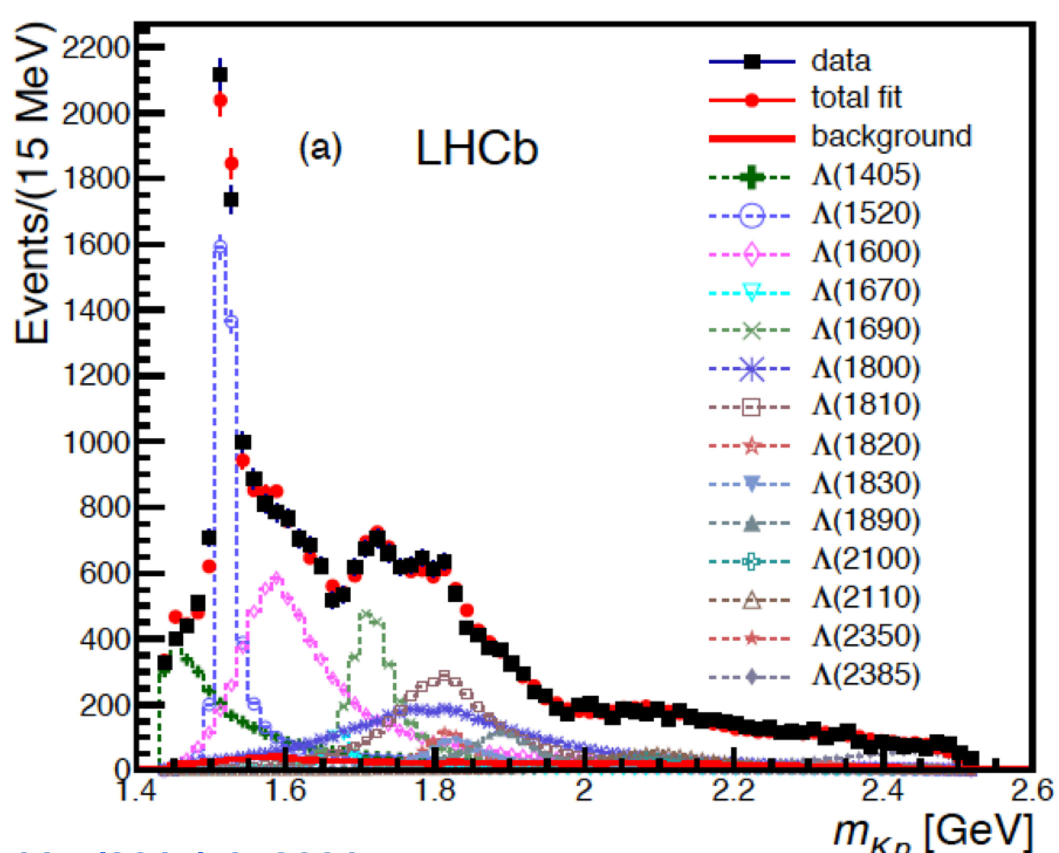
Low Q^2 electron tagger

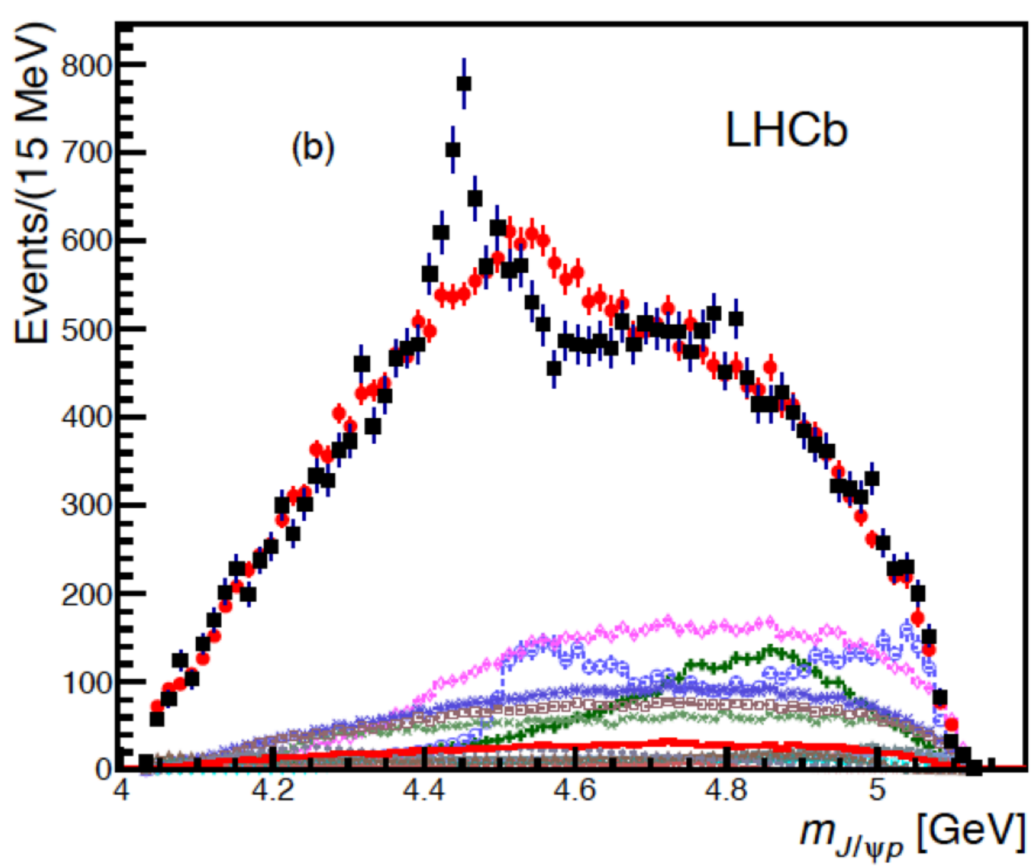


- Electron beam polarimetry essential to EIC physics program
- In same chicane used for Compton polarimeter, include taggers for quasi-real photons

Pentaquarks: LHCb

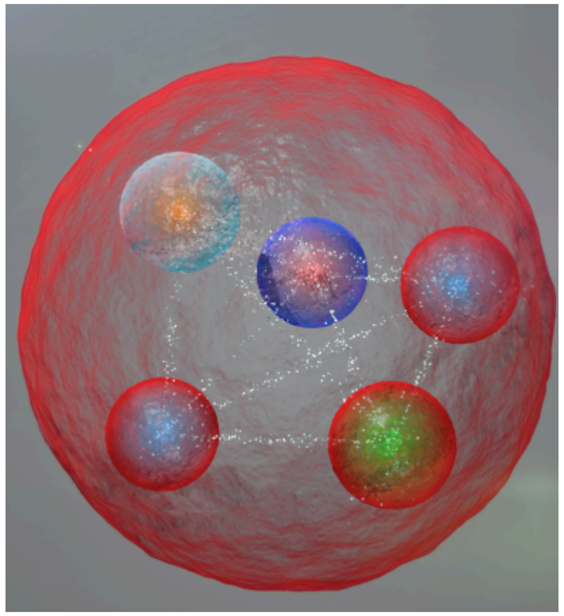


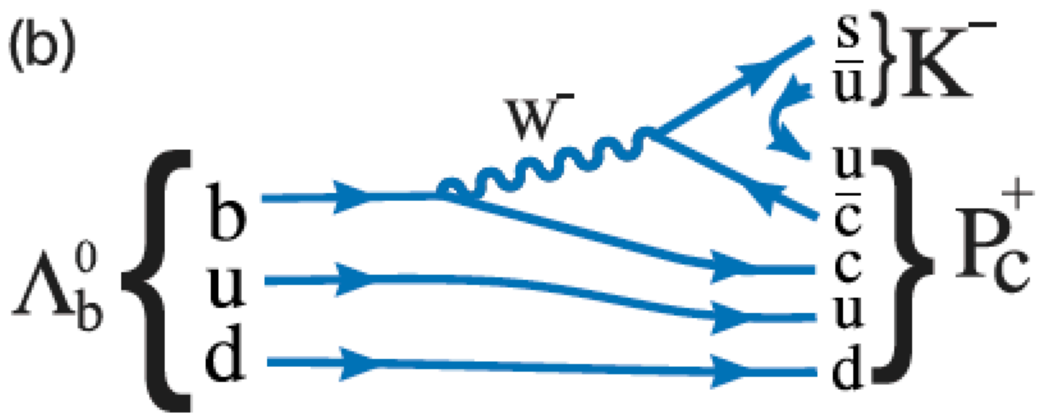


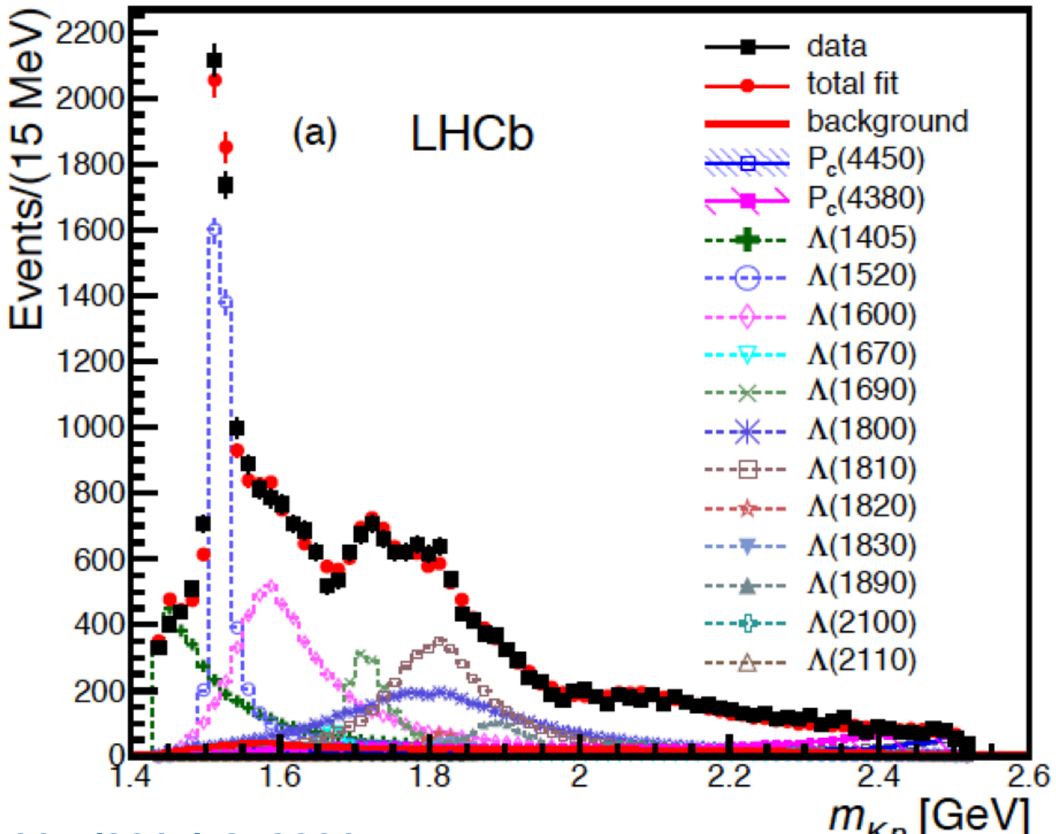


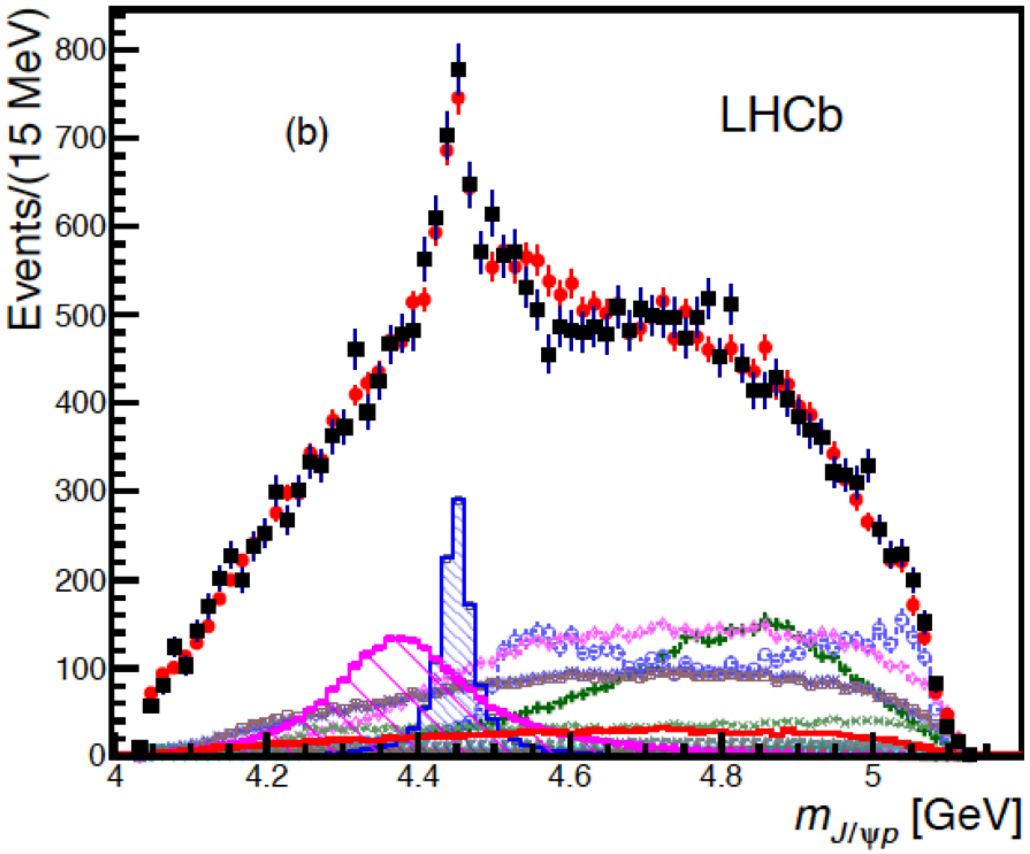
PRL 115 (2015) 072001

Pentaquarks: LHCb



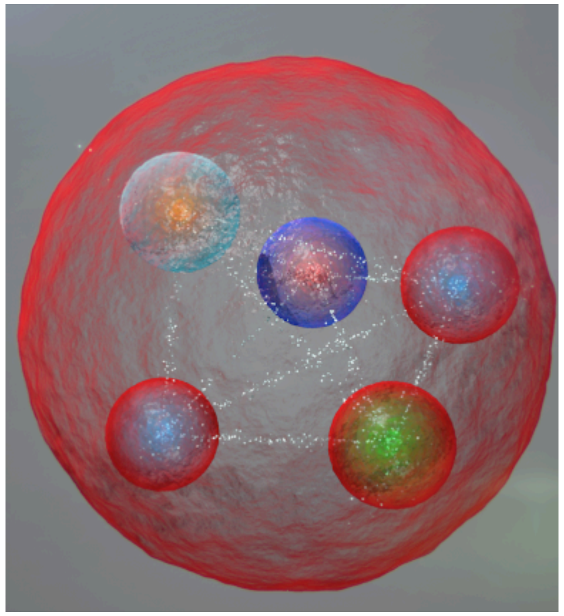


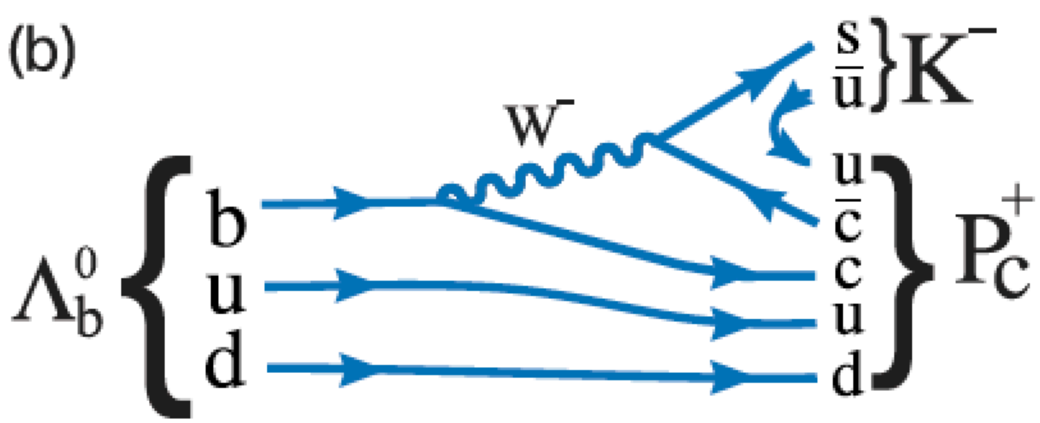


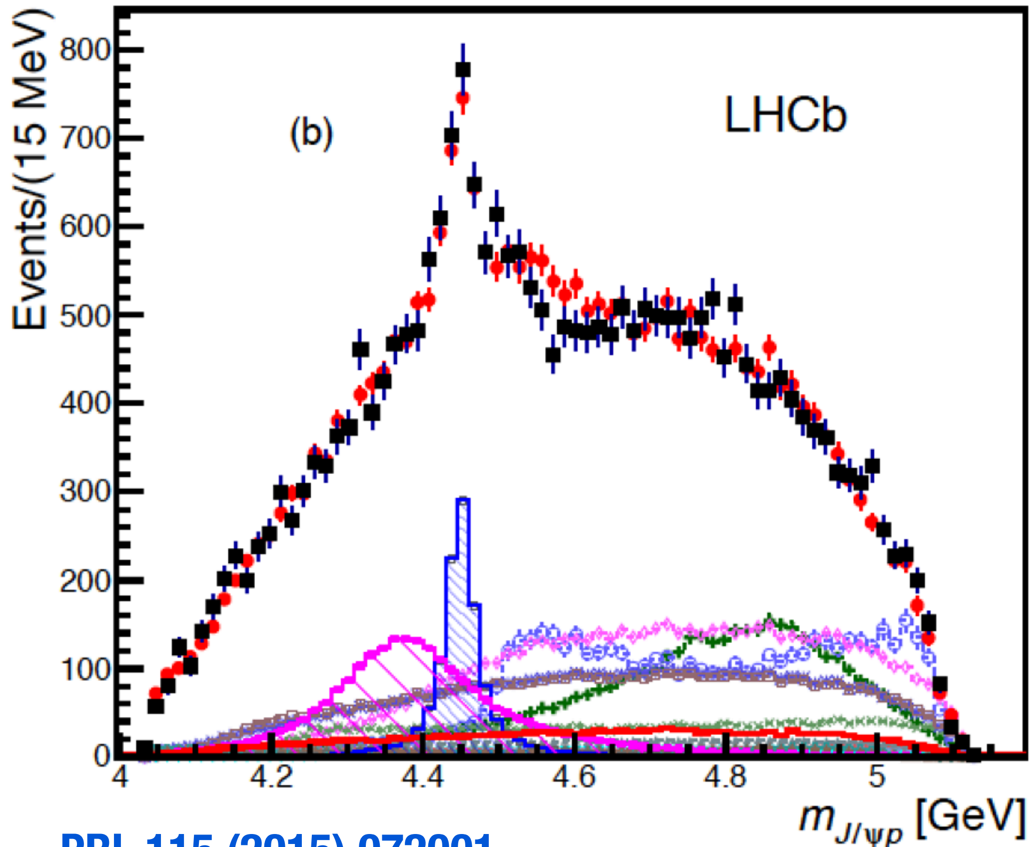


PRL 115 (2015) 072001

Pentaquarks: LHCb







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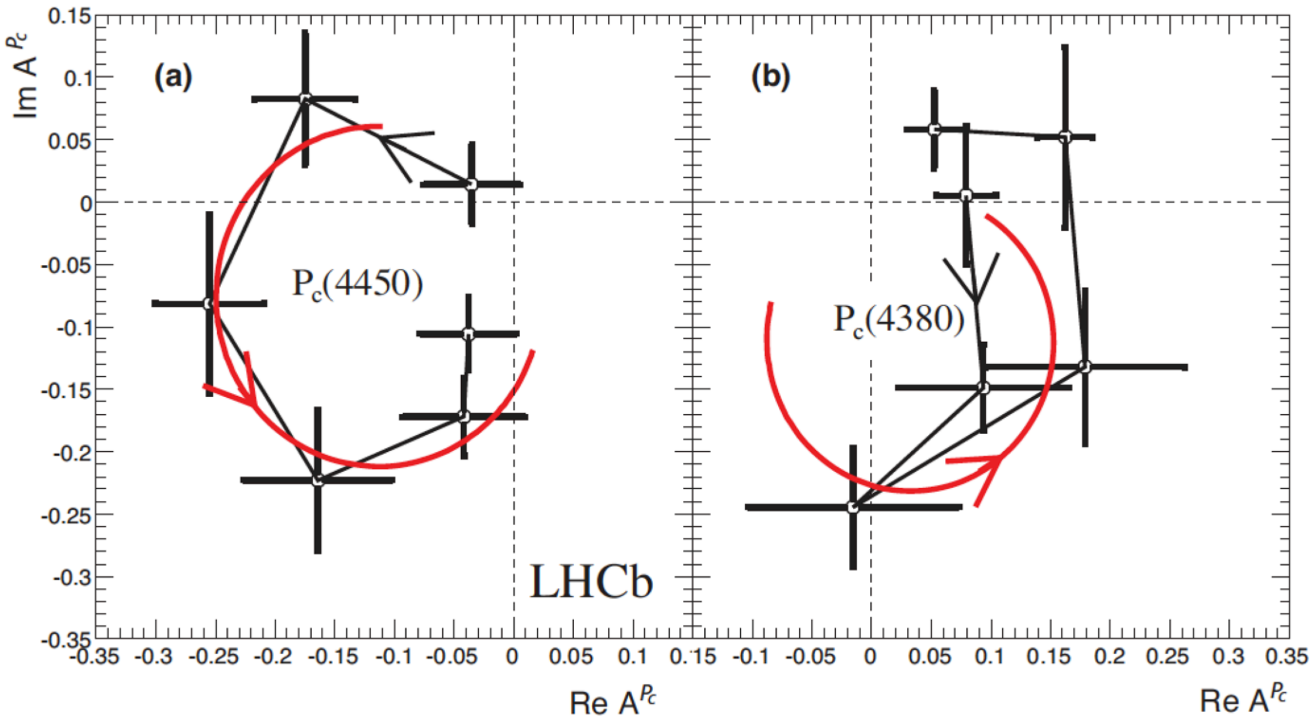
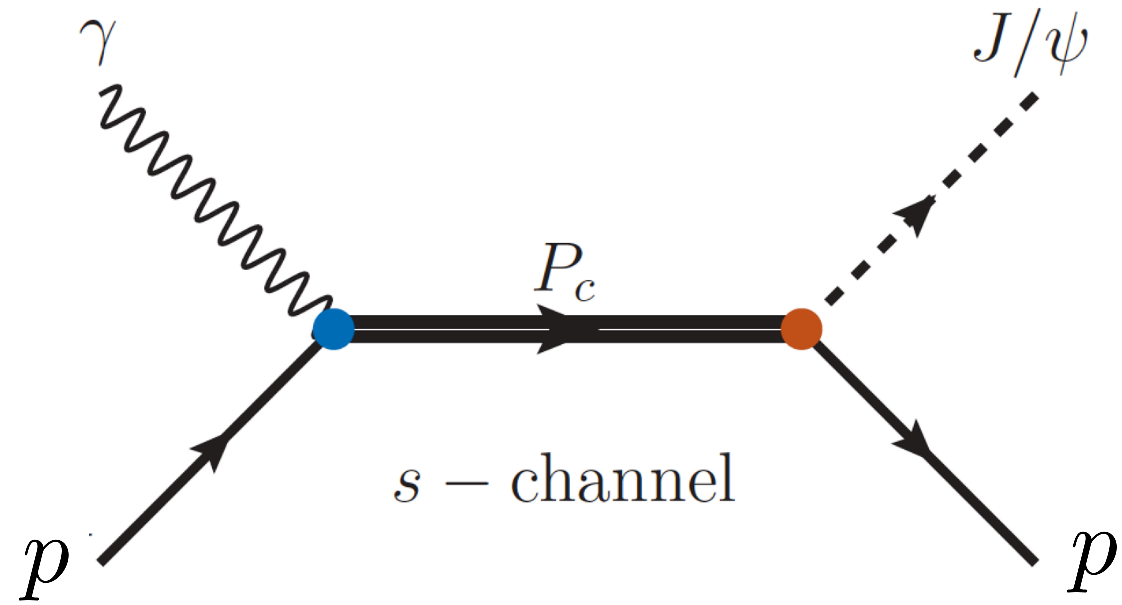


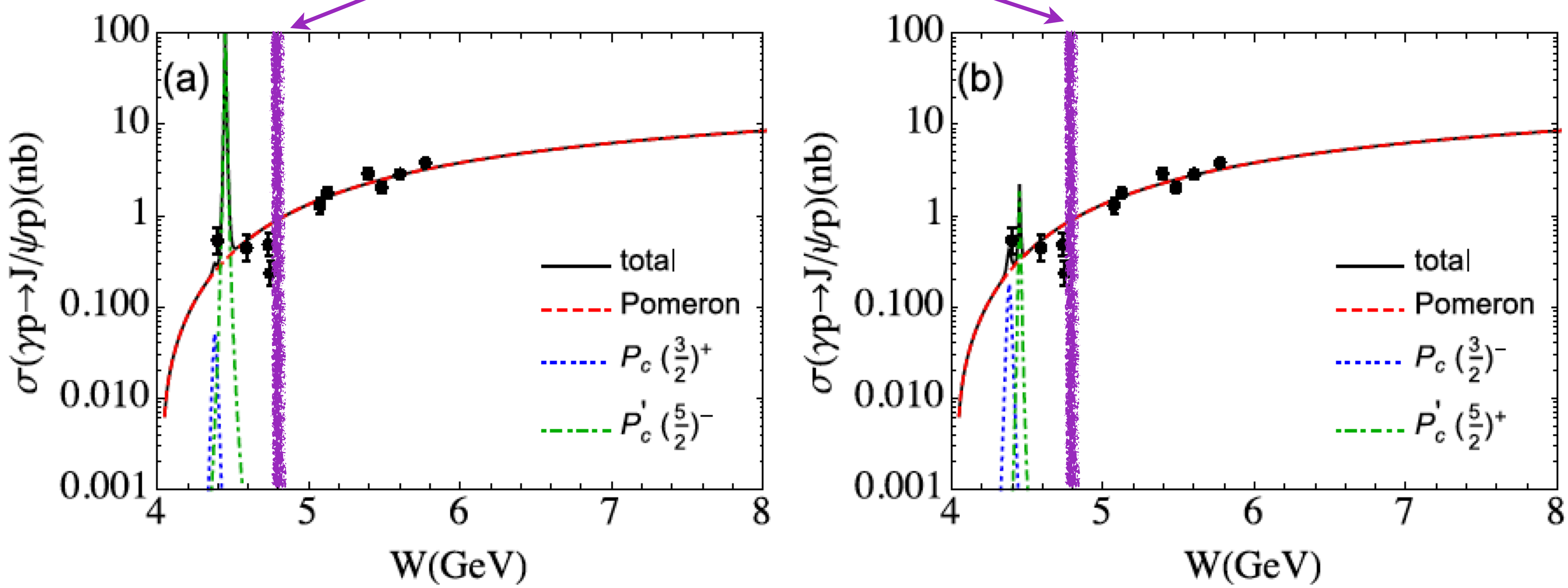
Pentaquark Photoproduction

Photoproduction of hidden charm pentaquark states $P_c^+(4380)$ and $P_c^+(4450)$



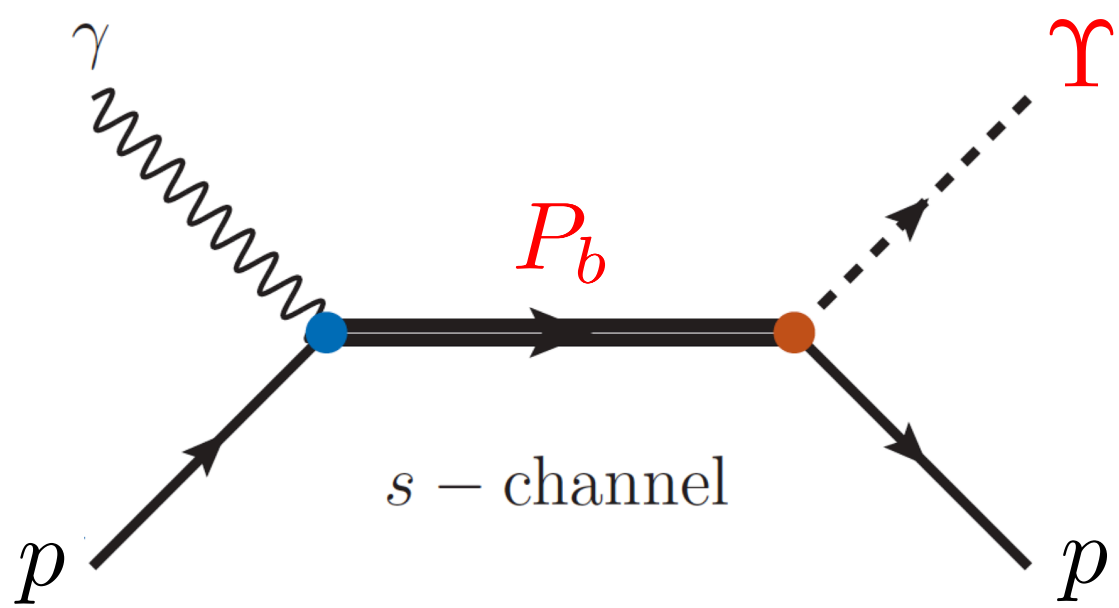
arXiv:1508.00339
arXiv:1508.00888
arXiv:1508.01496

JLab 12 GeV Max



Pentaquark Photoproduction

- What about a bottomonium pentaquark? arXiv:1508.01496

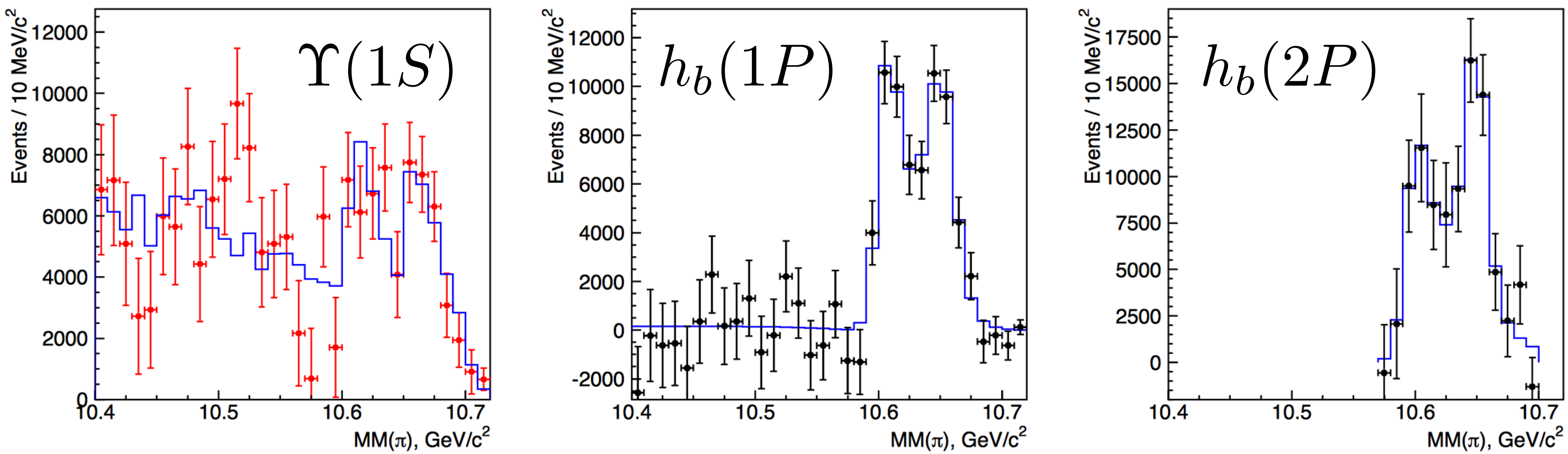


- Mass (~11 GeV) not accessible at JLab fixed target
- Unclear what other facilities could search for this

Other charged bottomonium states

Z_b(10610) and Z_b(10650)

Belle [1105.4583]

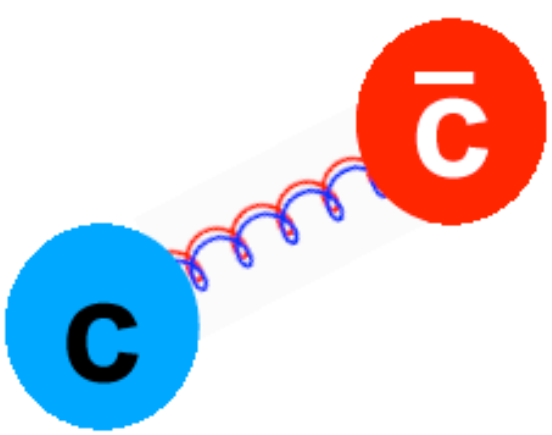


- Similar bottomonium-like spectrum in charged Z_b states observed at Belle near $B^*\bar{B}$ threshold
- Variable energies available at an EIC could probe these higher mass states in photoproduction as well

Hybrid photoproduction

- Expectations from the flux tube model is that hybrids should be photoproduced at a similar rate to conventional mesons
- Lattice QCD calculations of charmonium radiative decays
  - Conventional $c\bar{c}$ mesons in reasonable agreement with experiment
  - Sizable radiative transitions predicted for hybrid charmonium

$c\bar{c}g$ Hybrid



Y(4260)?

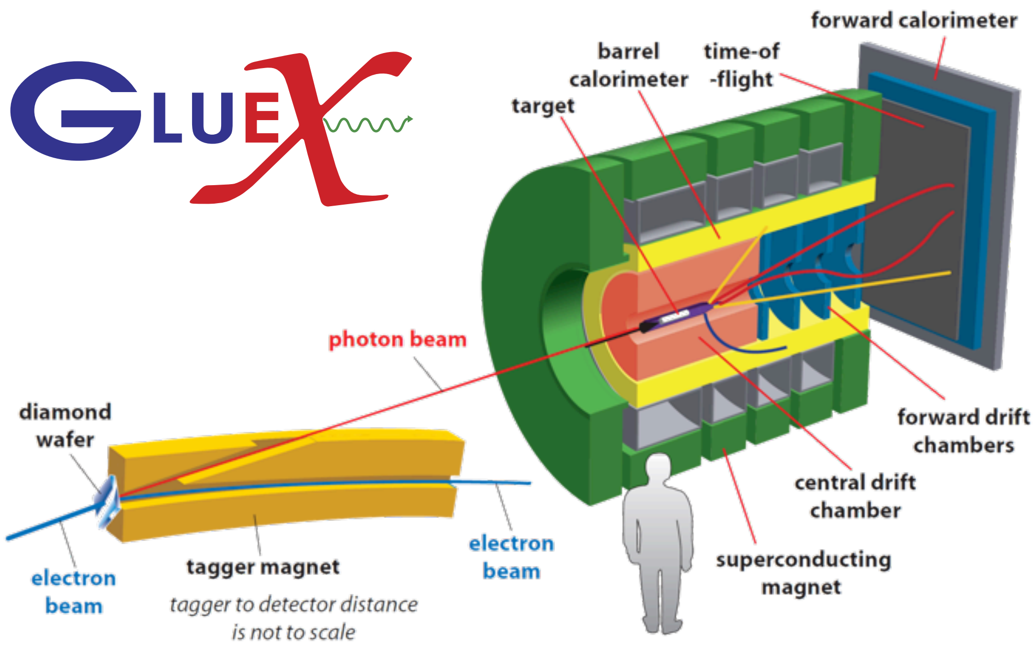
Exotic Hybrid

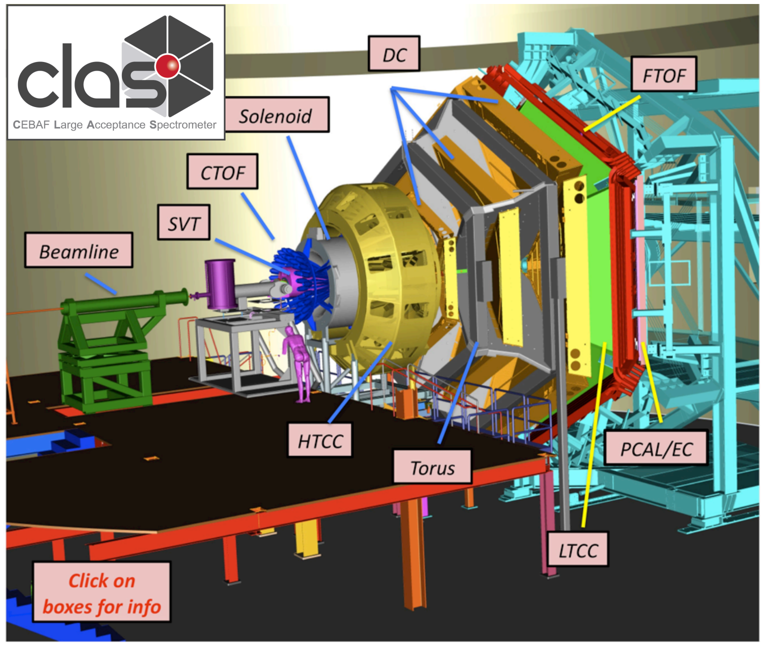
transition	Γ_{lattice} (keV)	Γ_{expt} (keV)
$\chi_{c0} \to J/\psi\gamma$	199(6)	131(14)
$\psi' \to \chi_{c0}\gamma$	26(11)	30(2)
$\psi'' \to \chi_{c0}\gamma$	265(66)	199(26)
$c\bar{c}g(1^{--}) \to \chi_{c0}\gamma$	< 20	
$J/\psi \to \eta_c\gamma$	2.51(8)	1.85(29)
$\psi' \to \eta_c\gamma$	0.4(8)	0.95 – 1.37
$\psi'' \to \eta_c\gamma$	10(11)	
$c\bar{c}g(1^{--}) \to \eta_c\gamma$	42(18)	
$c\bar{c}g(1^{-+}) \to J/\psi\gamma$	115(16)	

PRD 79 (2009) 094504 and Review article 1502.07276

Why photoproduction?

- New production mechanism for charged charmonium provides new insight into the nature of charged charmonia (Z_c)
- Spin-1 photon beam may provide enhanced production of “hybrid” mesons with a gluonic excitation component of their wavefunction
- JLab 12 GeV upgrade to map the spectrum of light and strange quark hybrid mesons at GlueX and CLAS12 (max $\sqrt{s_{\gamma p}}$ = 4.8 GeV)

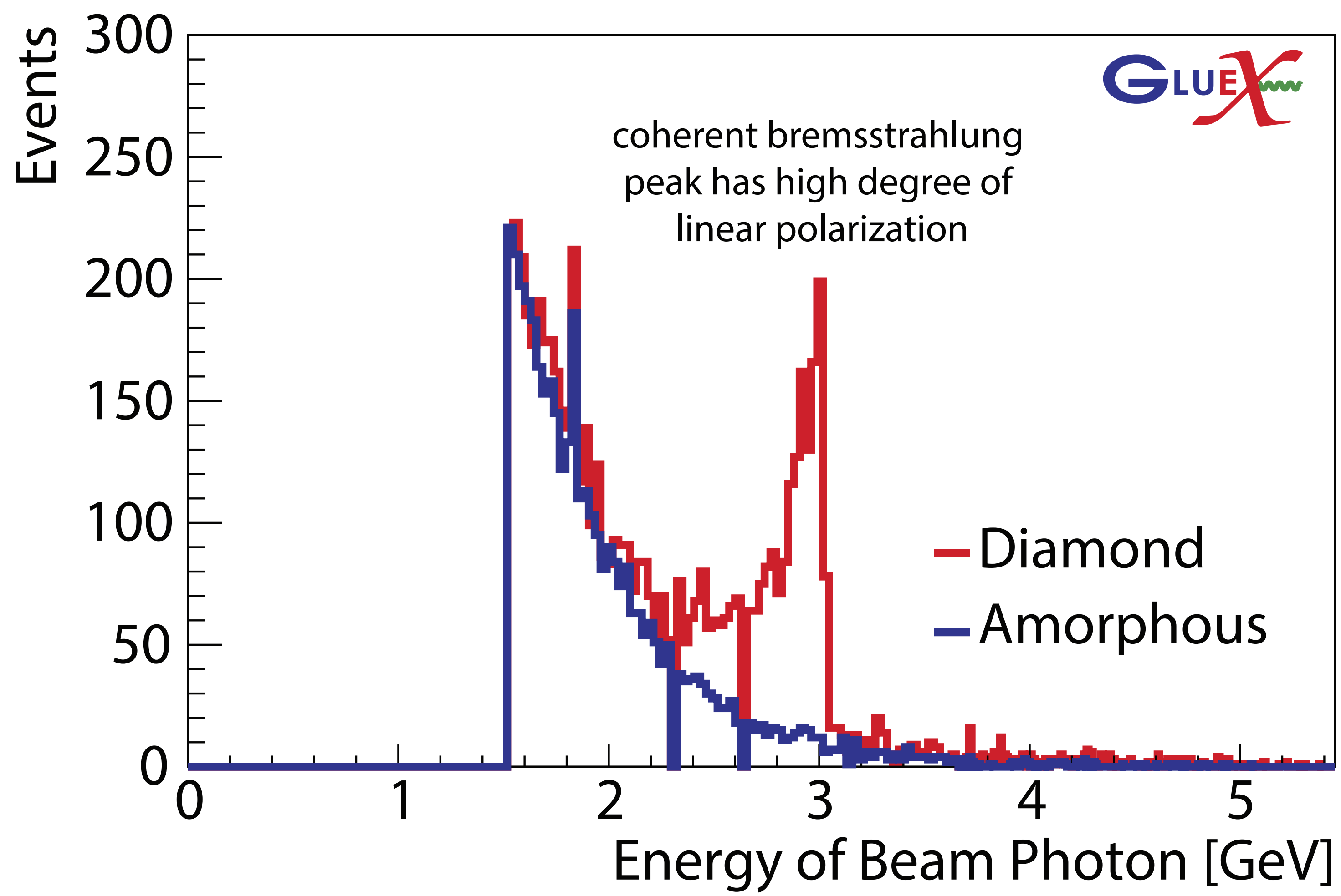




Photoproduction at an EIC could provide unique connections between JLab 12 GeV and Heavy Quark spectroscopy

Photoproduction at the EIC

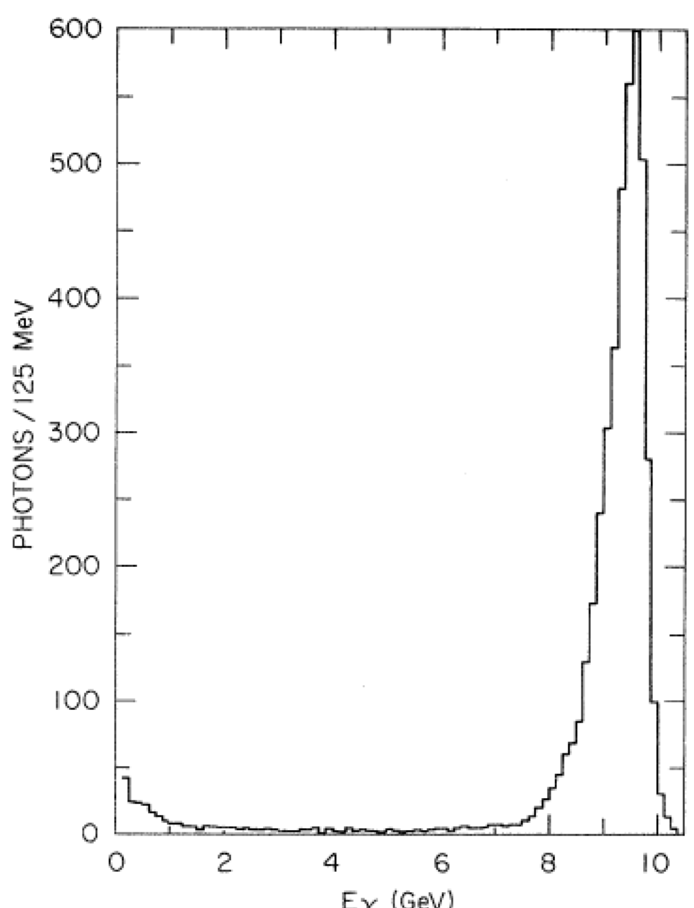
- **Real photon beams:**
  - Coherent bremsstrahlung (GlueX/Hall D @ JLab, Mainz, etc.)
  - Compton Backscattering (SLAC, ILC, etc.)



Photoproduction at the EIC

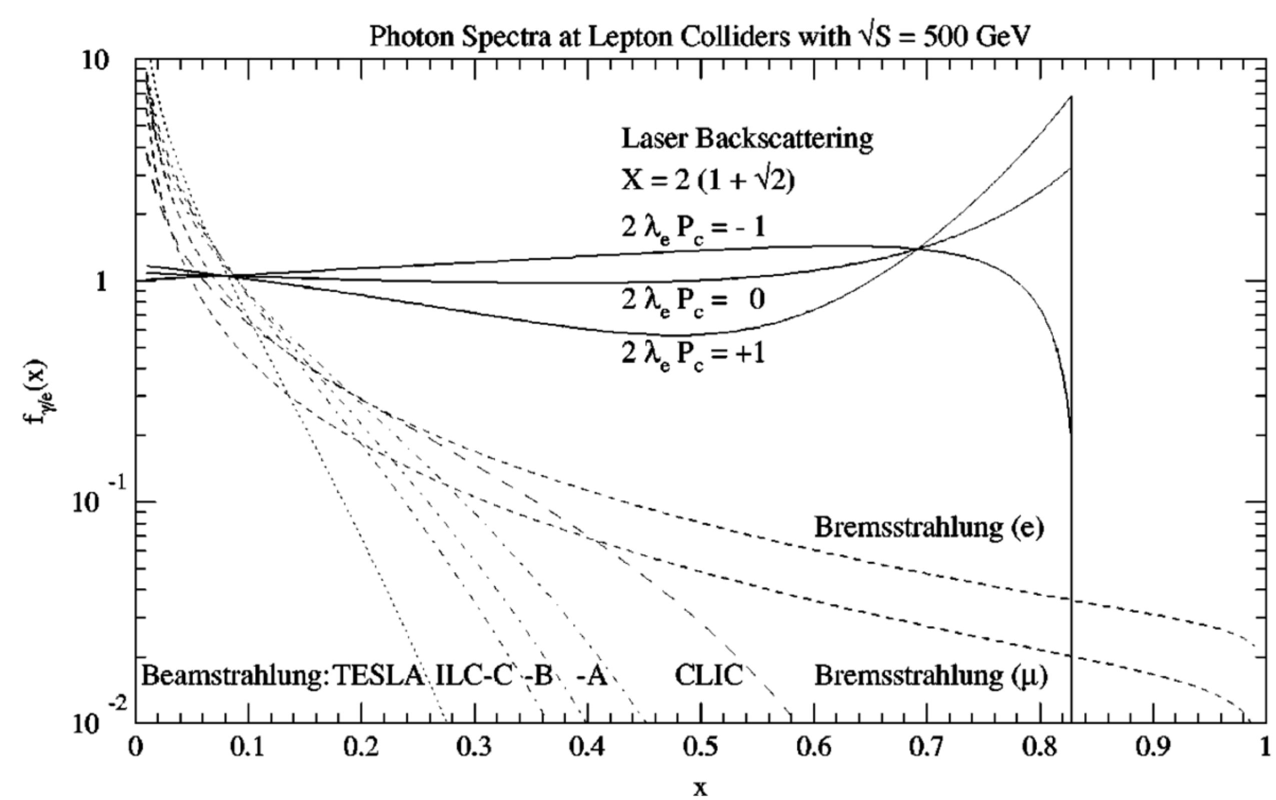
- **Real photon beams:**
  - Coherent bremsstrahlung (GlueX/Hall D @ JLab, Mainz, etc.)
  - Compton Backscattering (SLAC, ILC, etc.)

SLAC (1973)



Phys. Rev. D 8, 1277

Concept for ILC



Rev. Mod. Phys. 74, 1221

Photoproduction at the EIC

- **Real photon beams:**
  - Coherent bremsstrahlung (GlueX/Hall D @ JLab, Mainz)
  - Compton Backscattering (SLAC, ILC)
- **Quasi-real photons:**
  - Broad band photon beam induced from bremsstrahlung induced by EM field of proton/ion bunch (think UPCs for eA/ep)

$$f_\gamma^{(e)}(y) = \frac{\alpha_{\rm em}}{2\pi}\left[2m_e^2 y\left(\frac{1}{q^2_{max}} - \frac{1}{q^2_{min}}\right) + \frac{1+(1-y)^2}{y}\log\frac{q^2_{min}}{q^2_{max}}\right]$$

Weizsäcker-Williams Approximation

- Incoming electron beam considered to be the source of a broad-band photon beam with a photon flux: f_γ

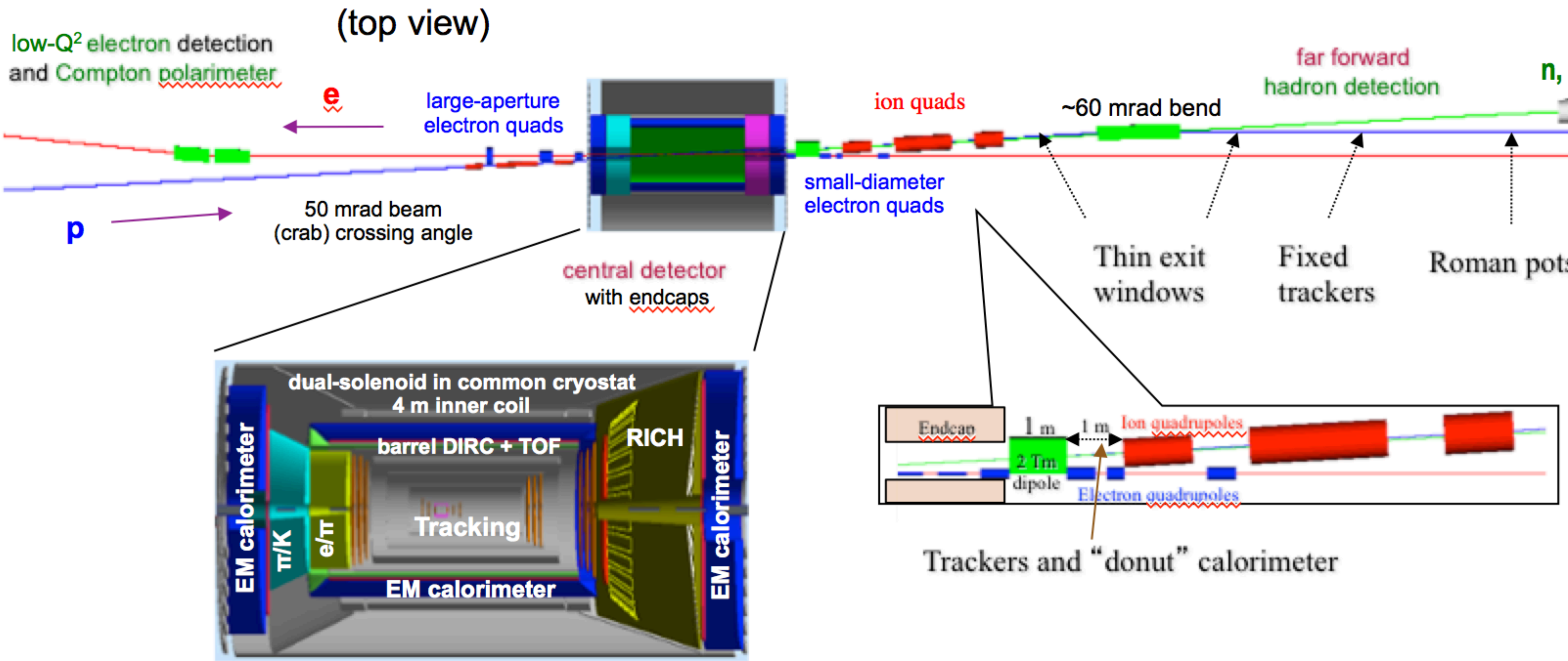
$$d\sigma_{ep} = \sigma_{\gamma p}(q,k) f_\gamma^{(e)}(y) dy$$

$$f_\gamma^{(e)}(y) = \frac{\alpha_{\rm em}}{2\pi}\left[2m_e^2 y\left(\frac{1}{q^2_{max}} - \frac{1}{q^2_{min}}\right) + \frac{1+(1-y)^2}{y}\log\frac{q^2_{min}}{q^2_{max}}\right]$$

- Select $Q^2 < 0.01$ for “quasi-real” photons
- Convolute predicted cross section ($\sigma_{\gamma p}$) dependence on $\sqrt{s_{\gamma p}}$ with photon flux for e+p collision kinematics
- Good agreement with previous measurements

Frixione et. al. PLB 319 (1993) 339

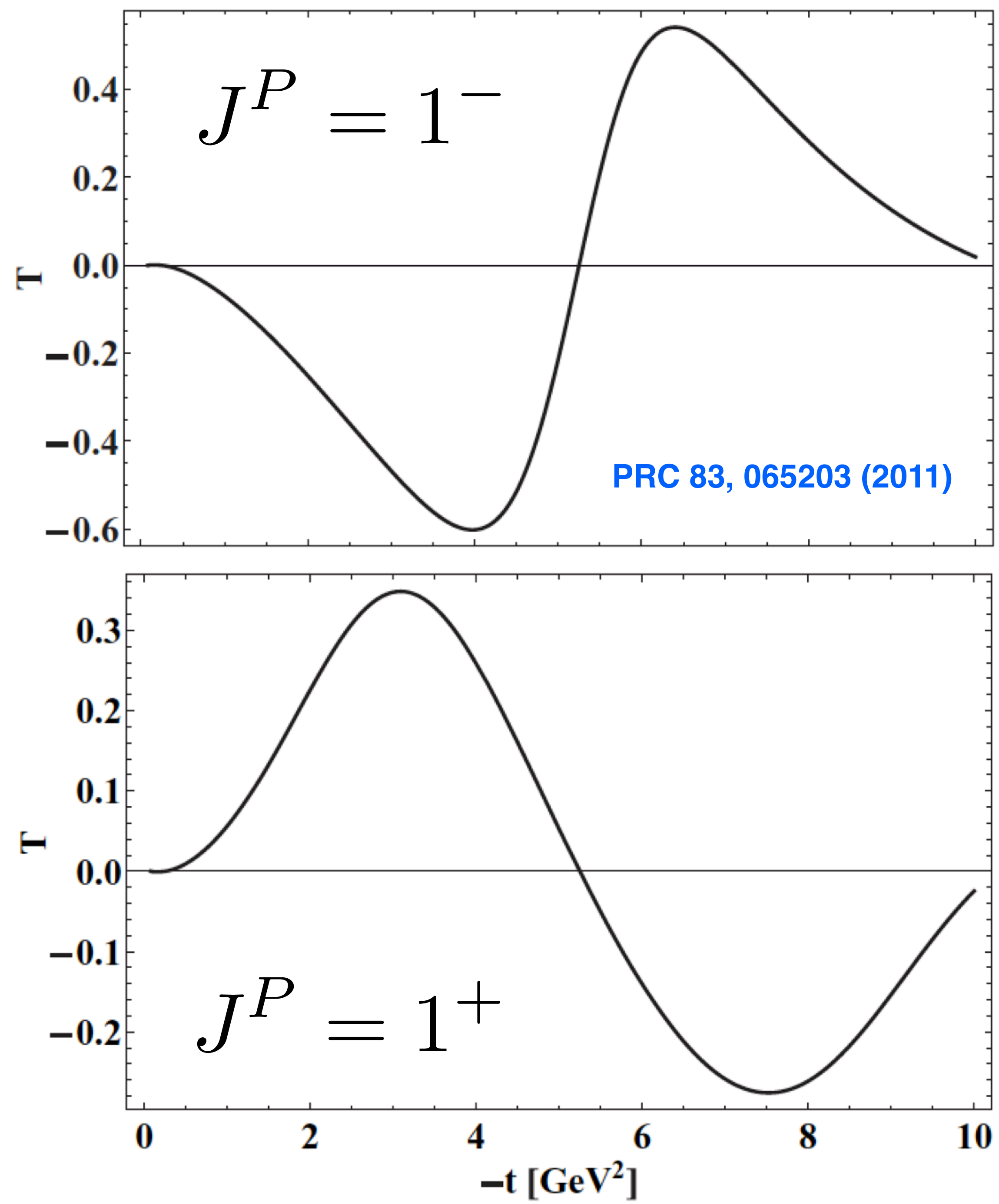
EIC integrated IR design



- Detectors near the beamline are an integral part of the EIC physics program, and are critical for exclusive reactions in spectroscopy
  - Low-Q^2 electron detection for photon tagging
  - Zero degree calorimeters for neutron detection

Polarization in spectroscopy

$$\gamma p \to Z_c^+(4430)n$$



- Highly polarized beams already in baseline EIC
- Additional observables to determine J^P, etc.