Physics at the EIC with real photons

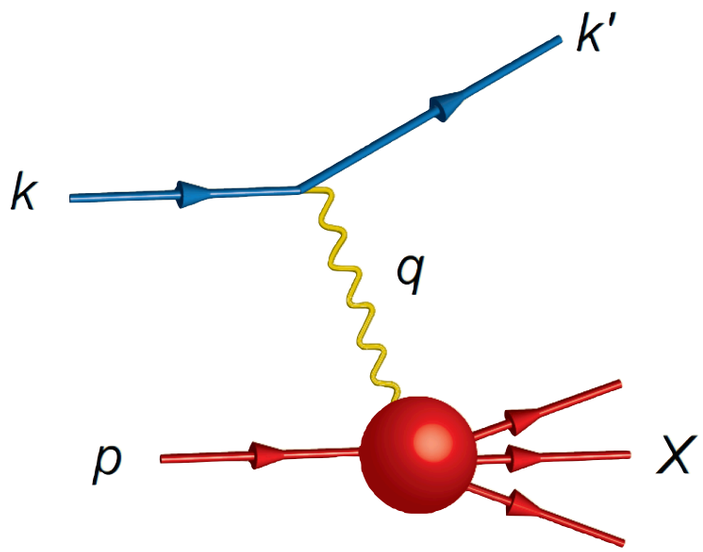
Justin Stevens

EIC Users Group Meeting: 1.9.16

U.S. DEPARTMENT OF ENERGY

Jefferson Lab

Photoproduction

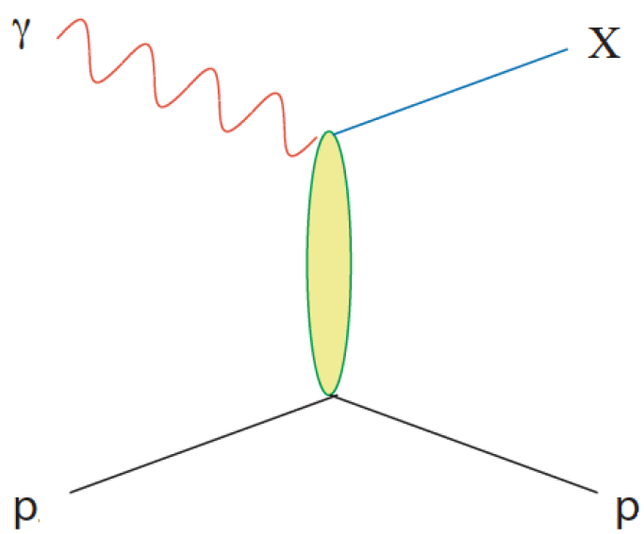


Quasi-real photons: $Q^2 < 1$ GeV^2
Real photons: $Q^2 = 0$

No hard scale in production

- What are some questions we can address with photoproduction?

Photoproduction



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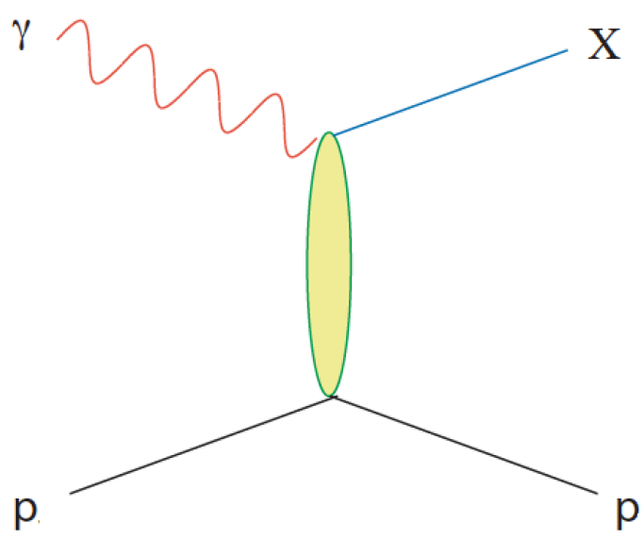


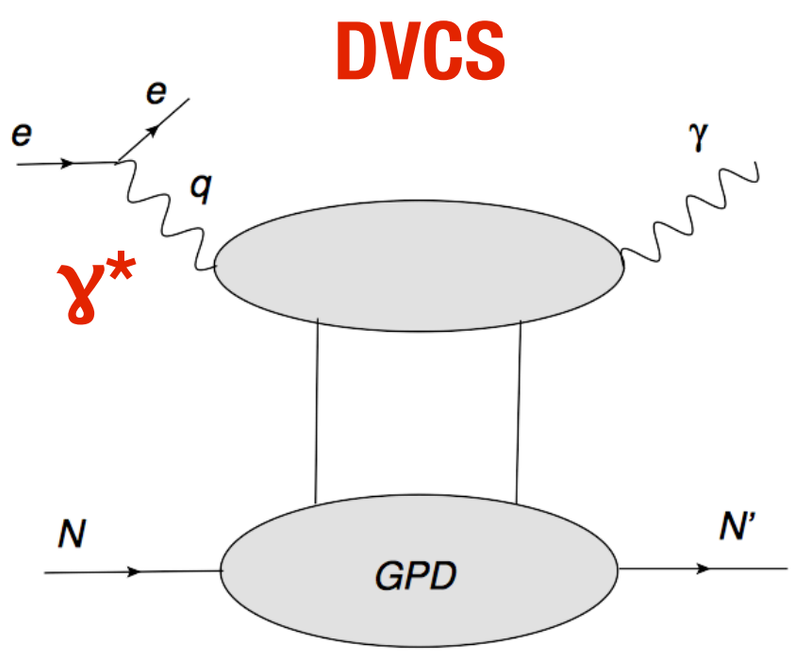
Quasi-real photons: $Q^2 < 1$ GeV^2
Real photons: $Q^2 = 0$

No hard scale in production

- What are some questions we can address with photoproduction?
  - **White paper physics (hard scale set by final state):**
    - Nucleon structure (GPDs): **Timelike Compton Scattering**
    - Gluon distributions in nucleons and nuclei: **Exclusive VM production**
  - **Partonic structure of the photon**
  - **Hadron spectroscopy: XYZ, pentaquarks, gluonic hybrids, etc.**
- What requirements might this place on the machine and detector designs?

White paper physics

See J. Wagner's talk



- Timelike Compton Scattering: perturbative hard scale set by outgoing di-lepton pair, rather than scattered electron

White paper physics

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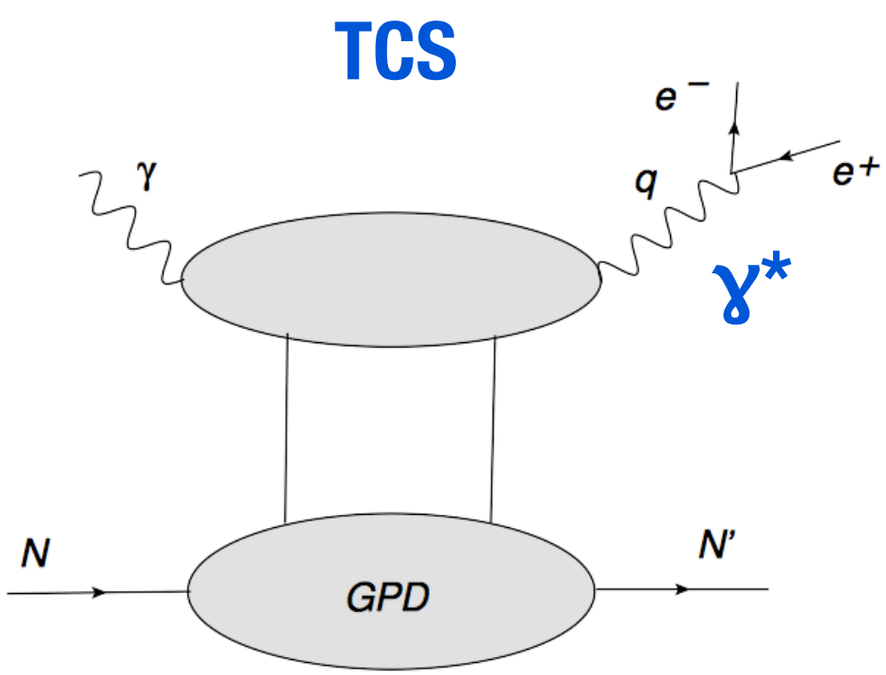

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White paper physics

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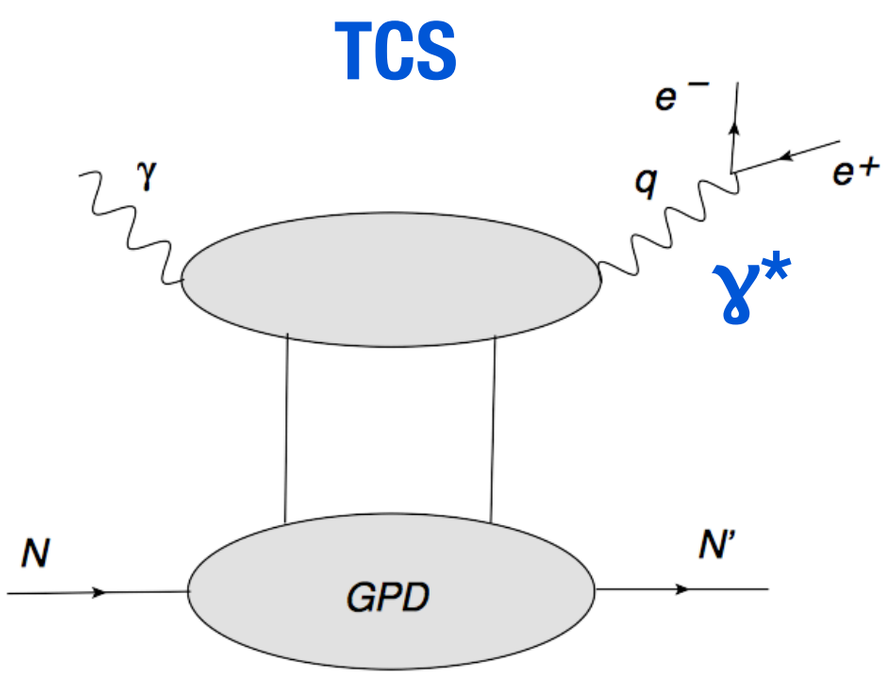
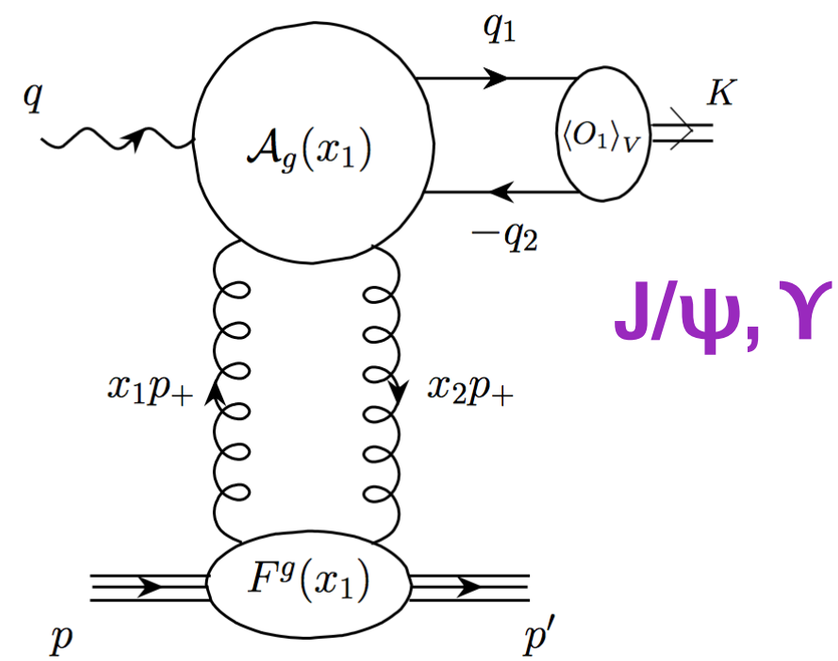




- **Timelike Compton Scattering**: perturbative hard scale set by outgoing di-lepton pair, rather than scattered electron
- **Heavy VM photoproduction:** gluon distribution in nucleons and nuclei beyond measurements at HERA, LHC, and RHIC
  - Ongoing UPC AA or pA at RHIC and LHC: eA is a cleaner probe
  - Polarized impact on GPD E: first look at RHIC with UPC

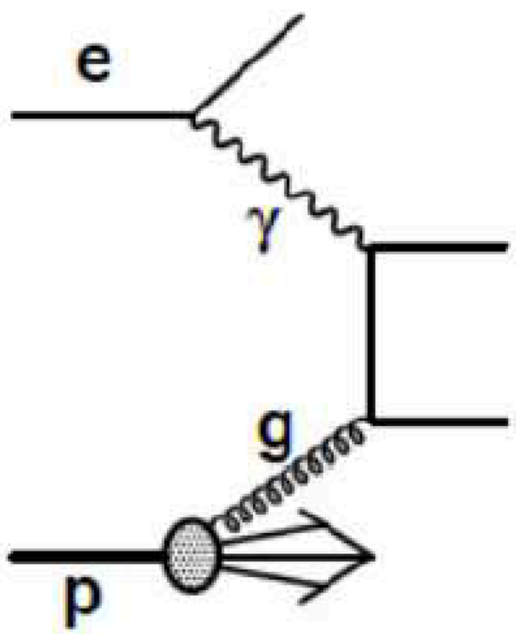
Partonic structure of photons

Discussed in INT Report [1108.1713]:

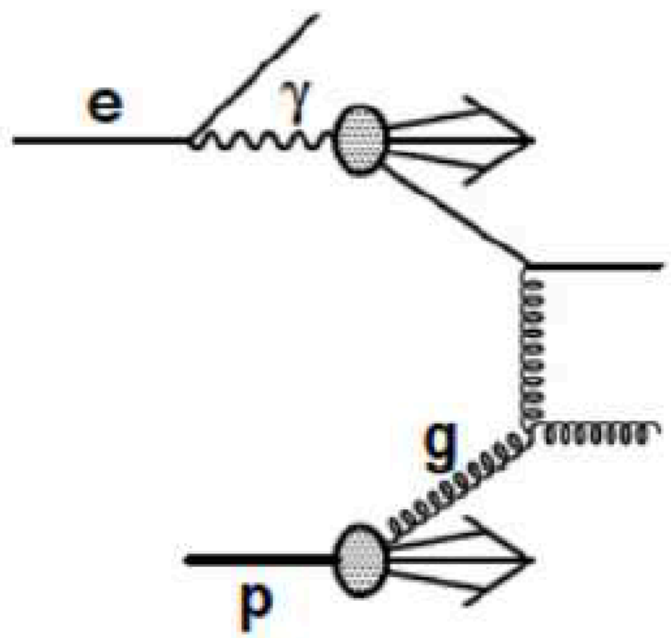
1.14 Photoproduction processes at an EIC

Hubert Spiesberger, Marco Stratmann

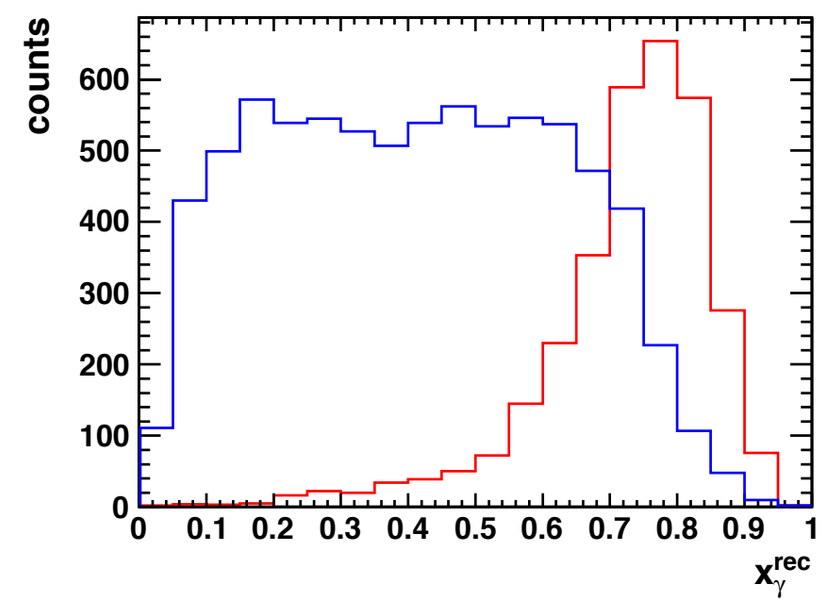
Direct



Resolved



Separable using di-jets at the EIC



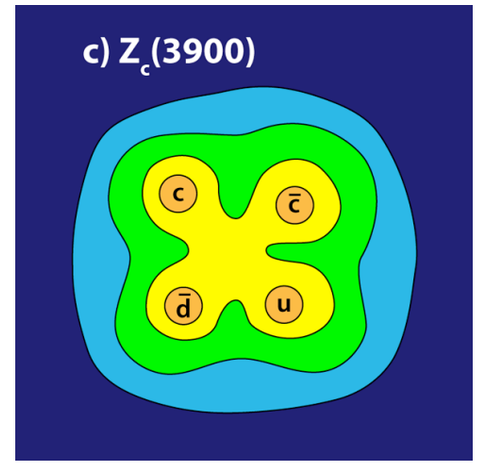
See X. Chu's talk yesterday

- Described in terms of photon PDFs, similar to the familiar proton PDFs
- Initial studies of unpolarized structure HERA
- Currently no data on polarized photon structure, valuable input to ILC γγ option

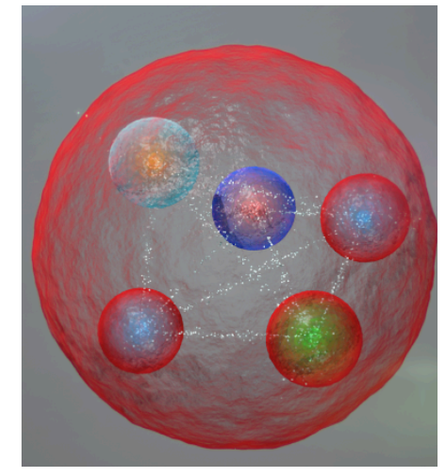
From J Qiu's: "Big questions/puzzles about QCD (ep + eA)"

- **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, ...**

Tetraquark



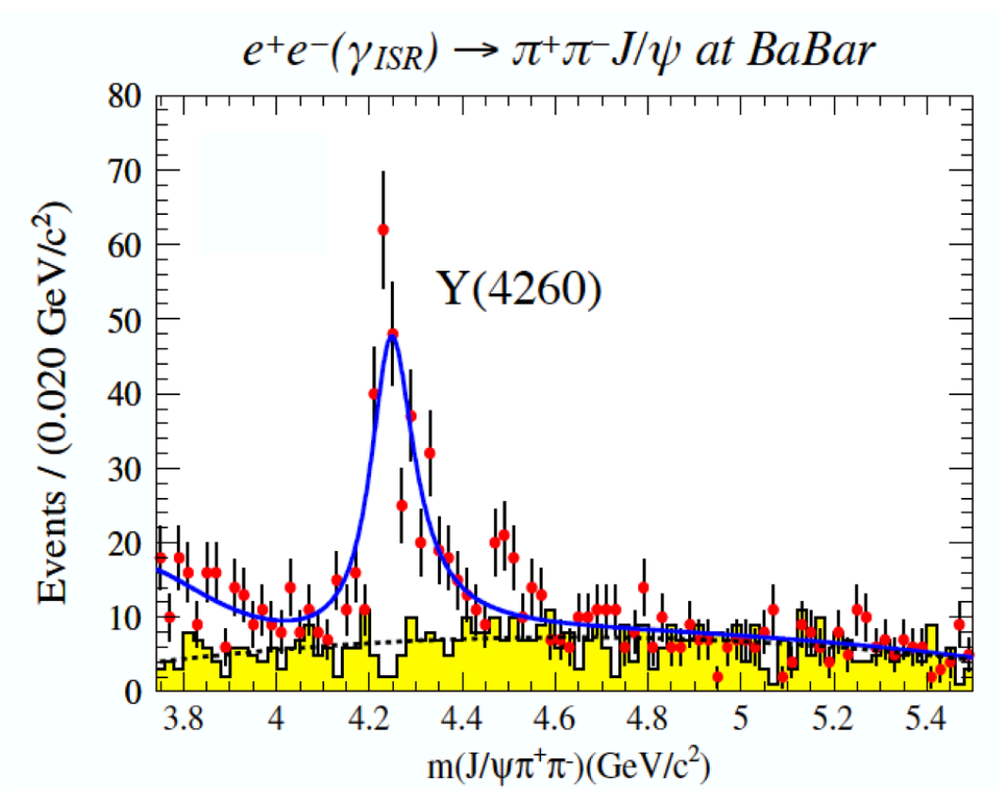
Pentaquark

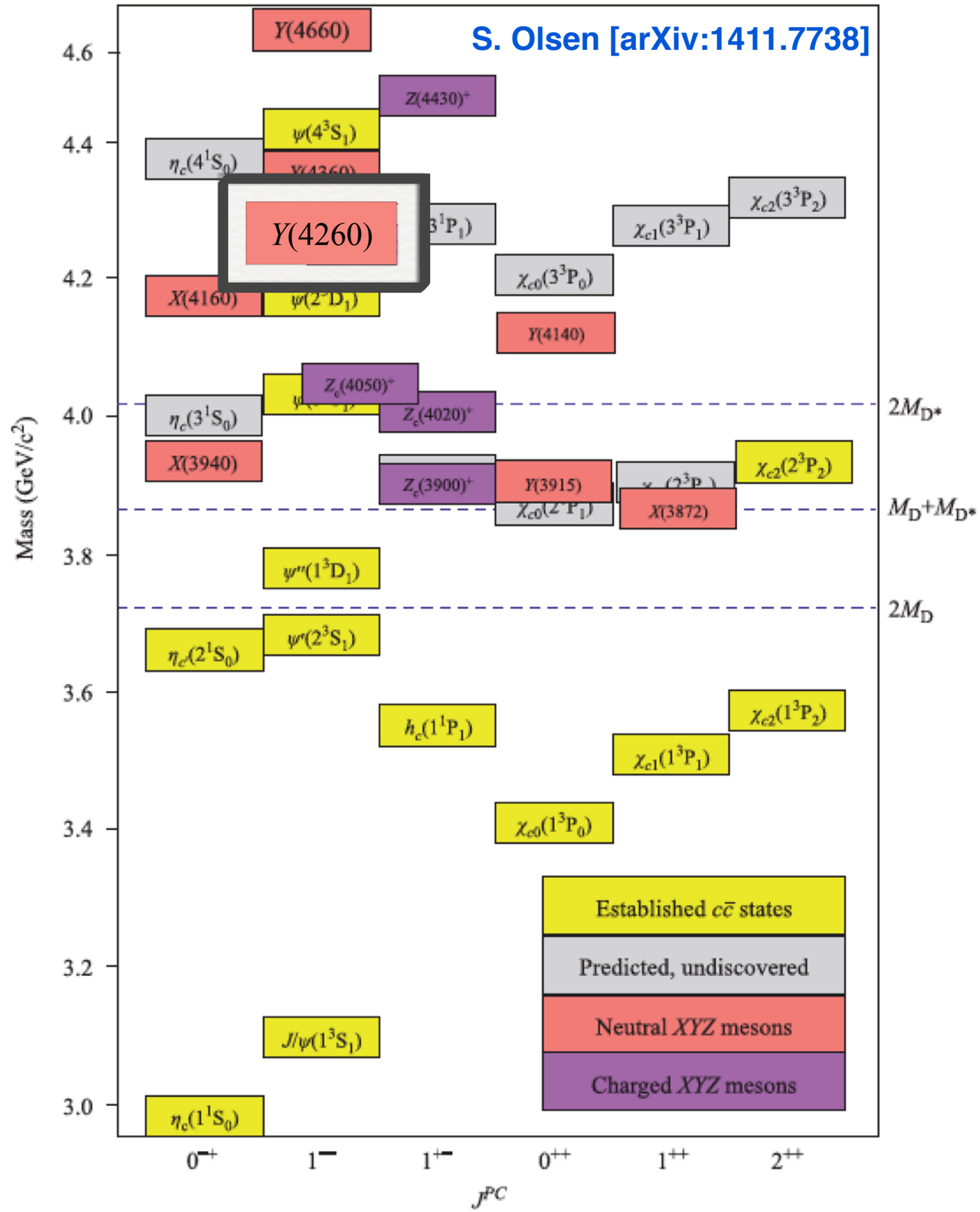


- Recent discovery of many new "exotic" states whose quark content contains both charm-anticharm and light quarks
- Where to look for them?
  - **e^+e^-**: CLEO, BESIII, BaBar, Belle II ($J^{PC} = 1^{--}$)
  - pp : LHCb, etc.
  - $p\bar{p}$: PANDA@GSI
- **Photoproduction:** GlueX, CLAS12, ... **EIC!**

XYZ states

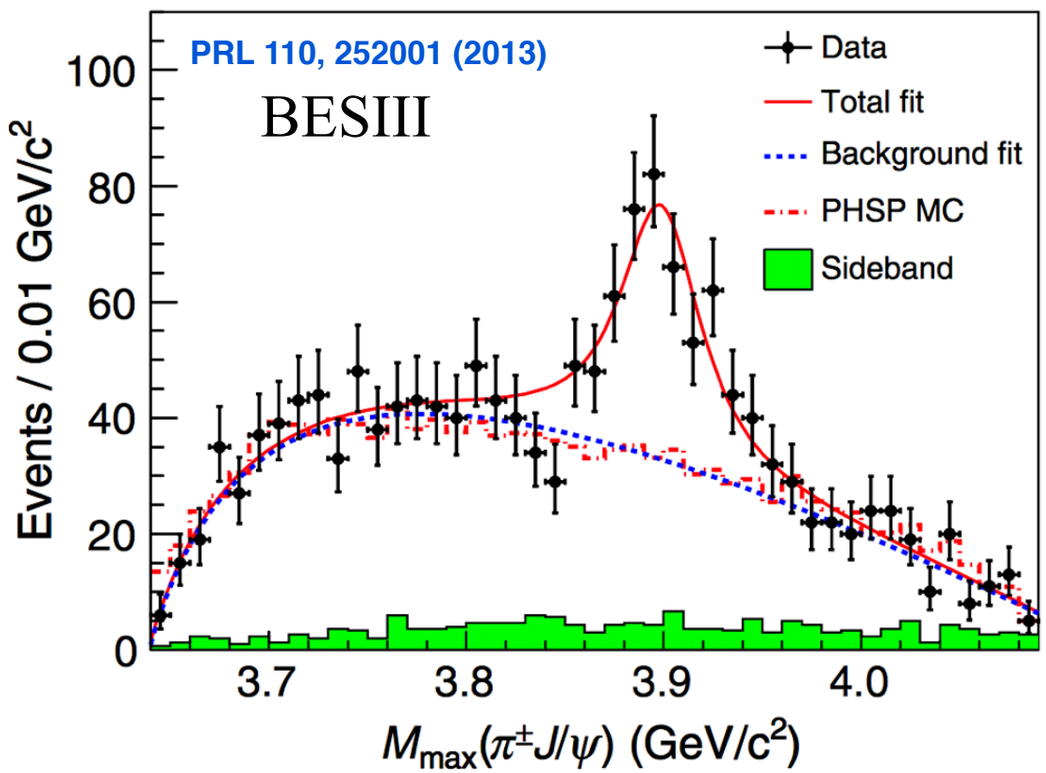
- Many new states observed in the last few years
- Not predicted by the standard charmonium models
- Many models for interpretation: resonant states, meson molecules, re-scattering effects, etc.



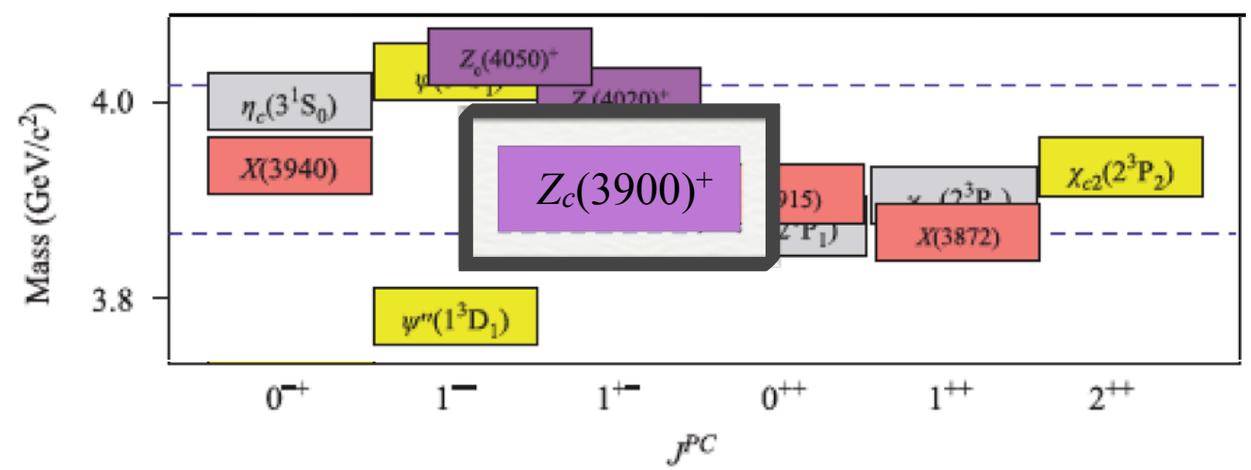


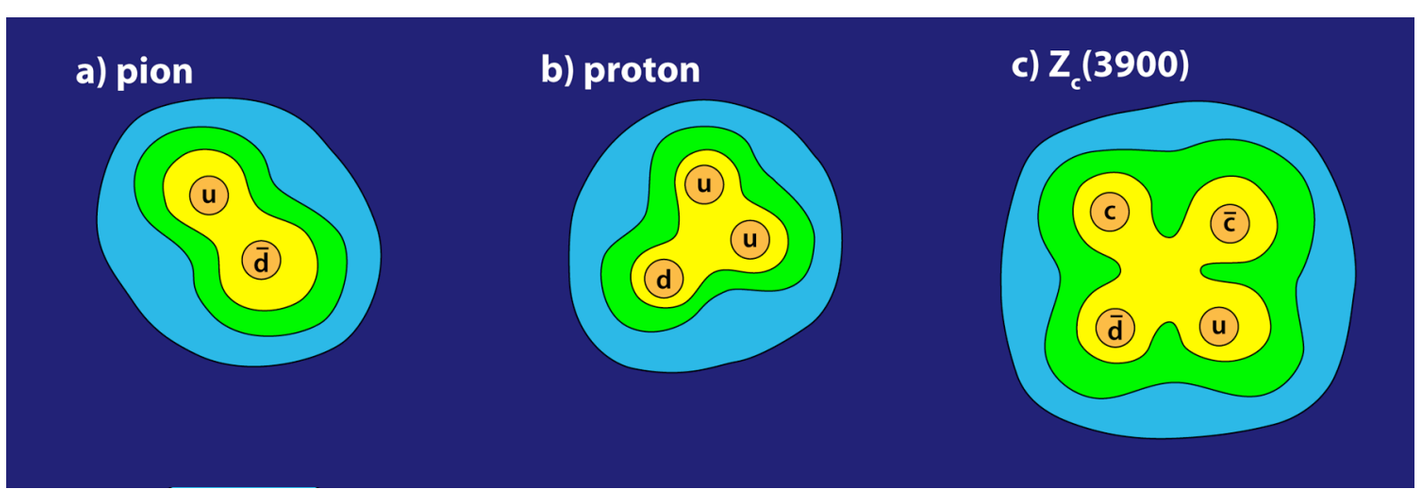
Charged charmonium states

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



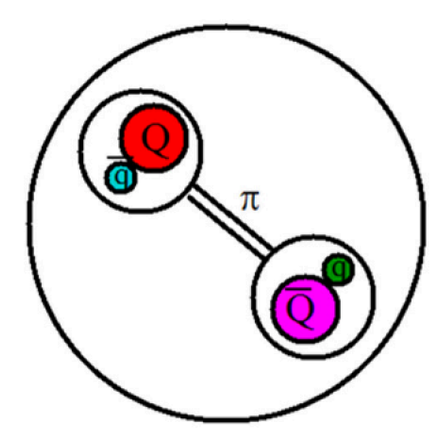
4-quark content ($c\bar{c}u\bar{d}$)



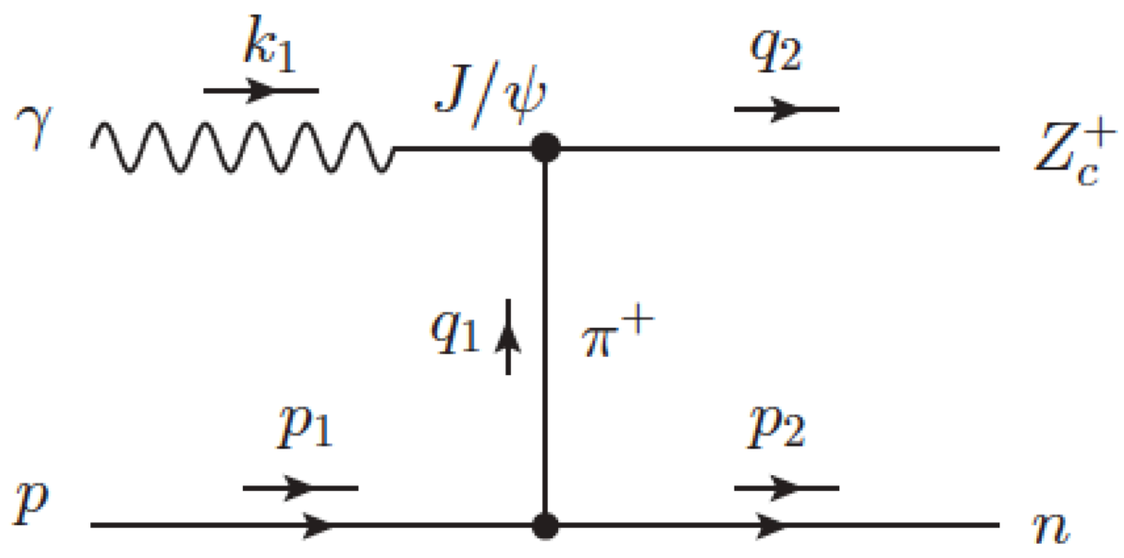


Physics Viewpoint 6, 69 (2013)

Meson Molecule?



XYZ states in photoproduction



PRD 88 (2013) 114009

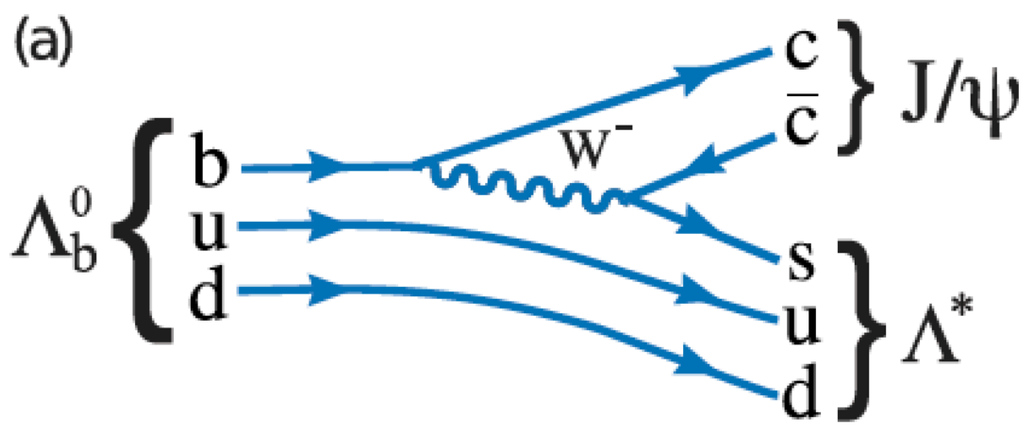
$$\mathcal{L}_{V\gamma} = -\frac{eM_V^2}{f_V} V_\mu A^\mu$$

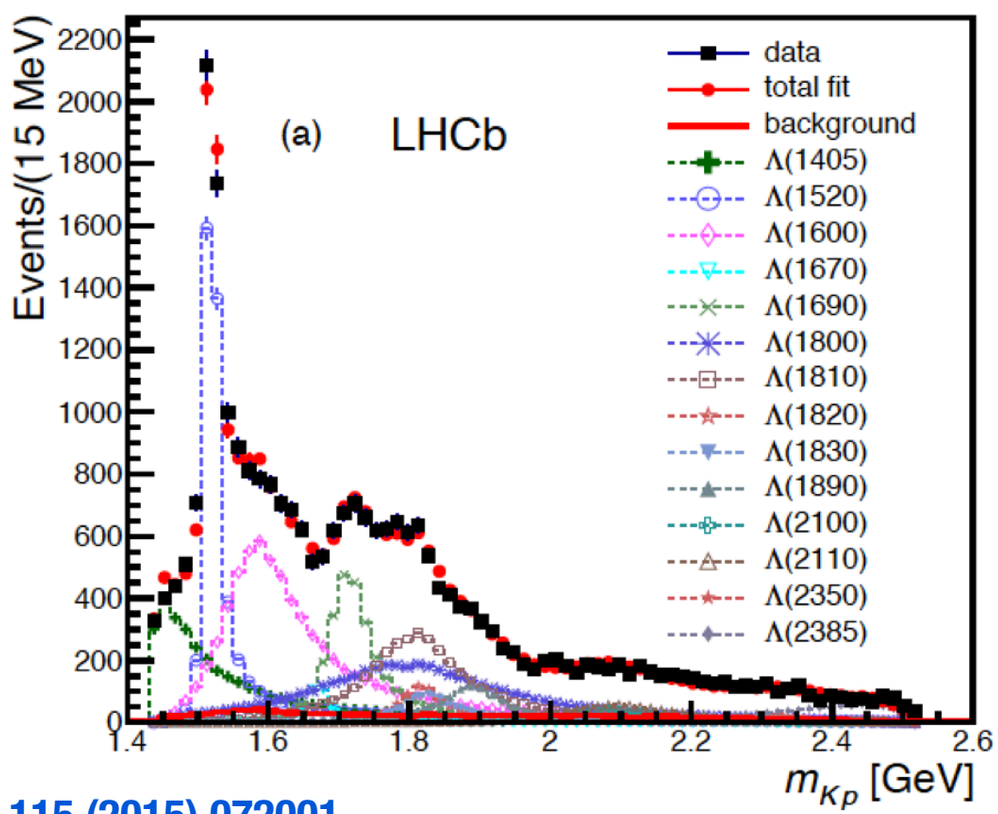
$$\mathcal{L}_{Z\psi\pi} = \frac{g_{Z\psi\pi}}{M_Z}\left(\partial^\mu\psi^\nu\partial_\mu\pi Z_\nu - \partial^\mu\psi^\nu\partial_\nu\pi Z_\mu\right)$$

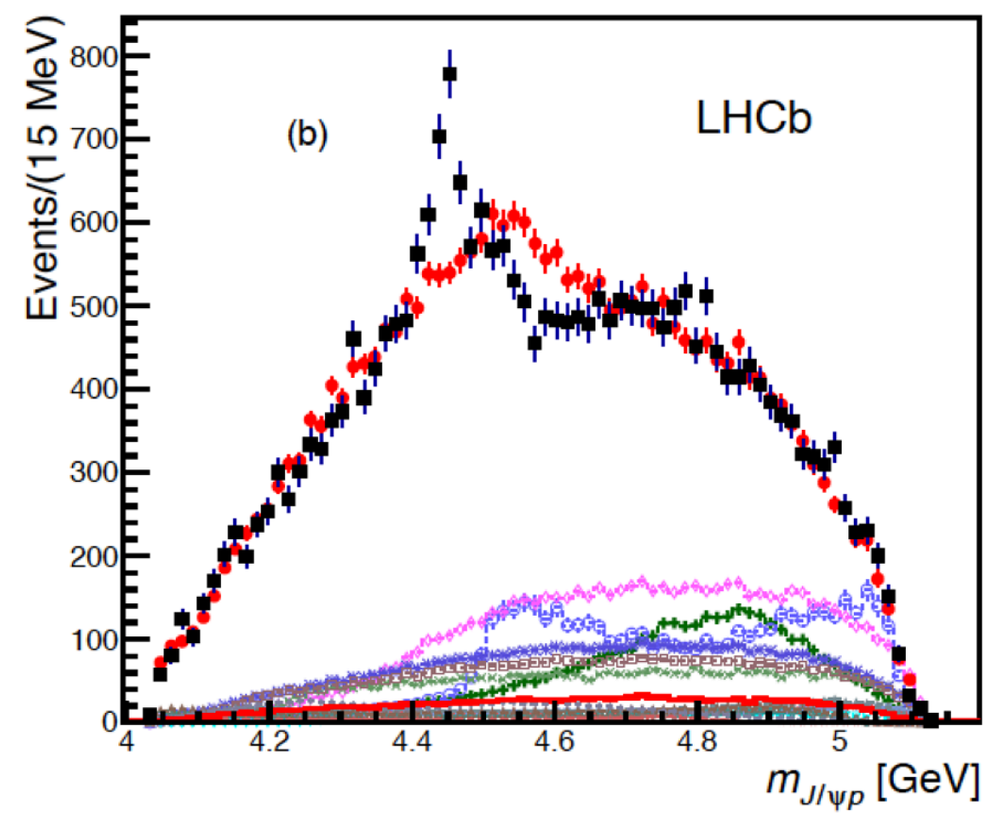
$$\mathcal{L}_{\pi NN} = -\frac{g_{\pi NN}}{2m_N}\bar{N}\gamma_5\gamma_\mu(\vec{\tau}\cdot\partial^\mu\vec{\pi})N$$

- 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

Pentaquarks: LHCb

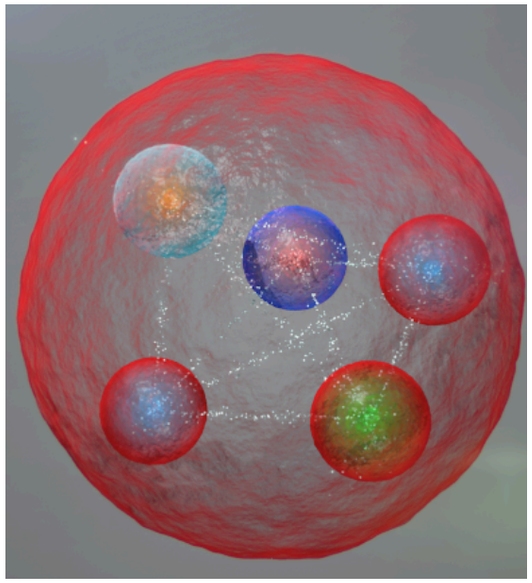


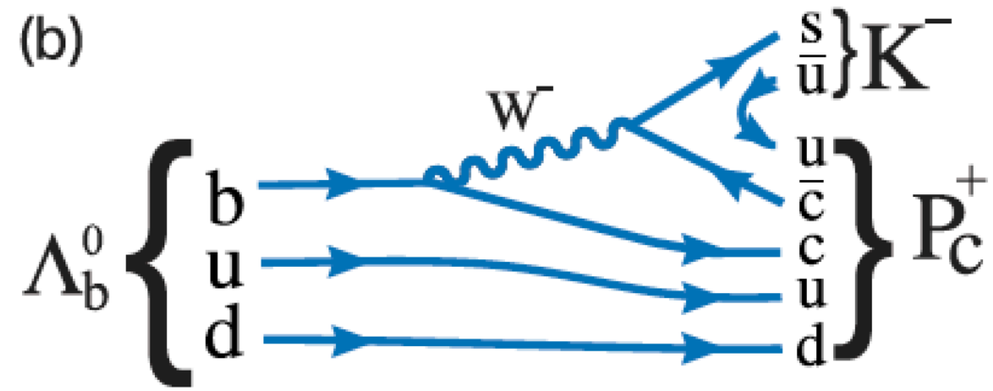


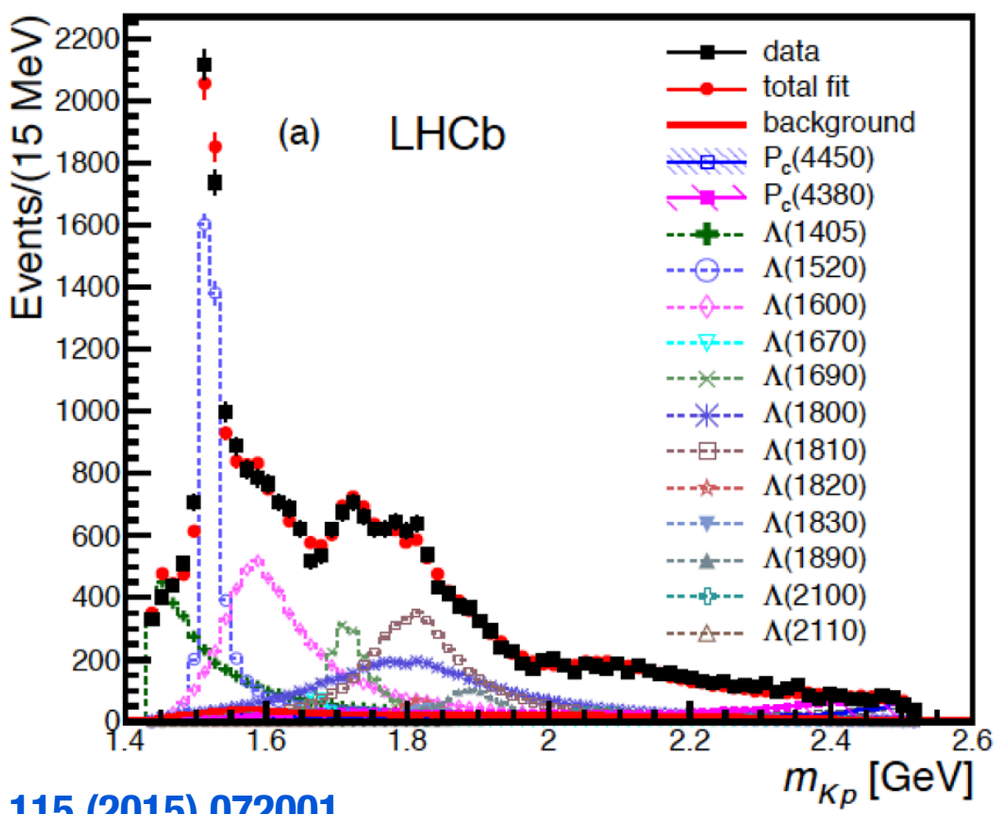


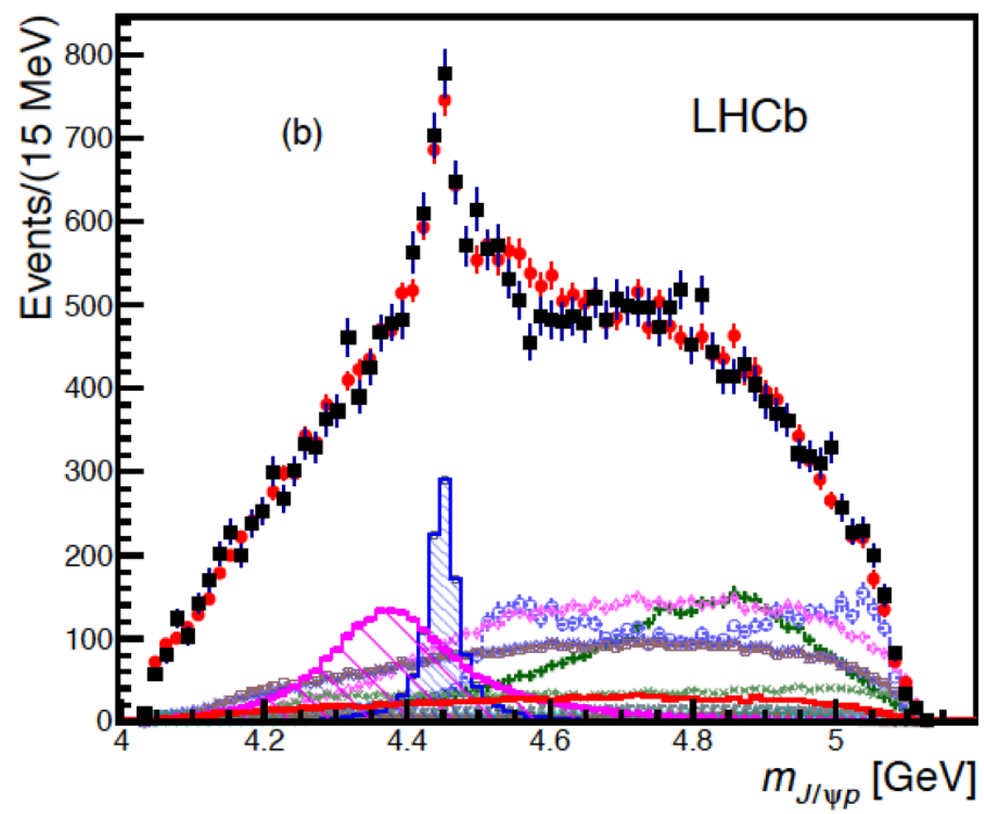
PRL 115 (2015) 072001

Pentaquarks: LHCb





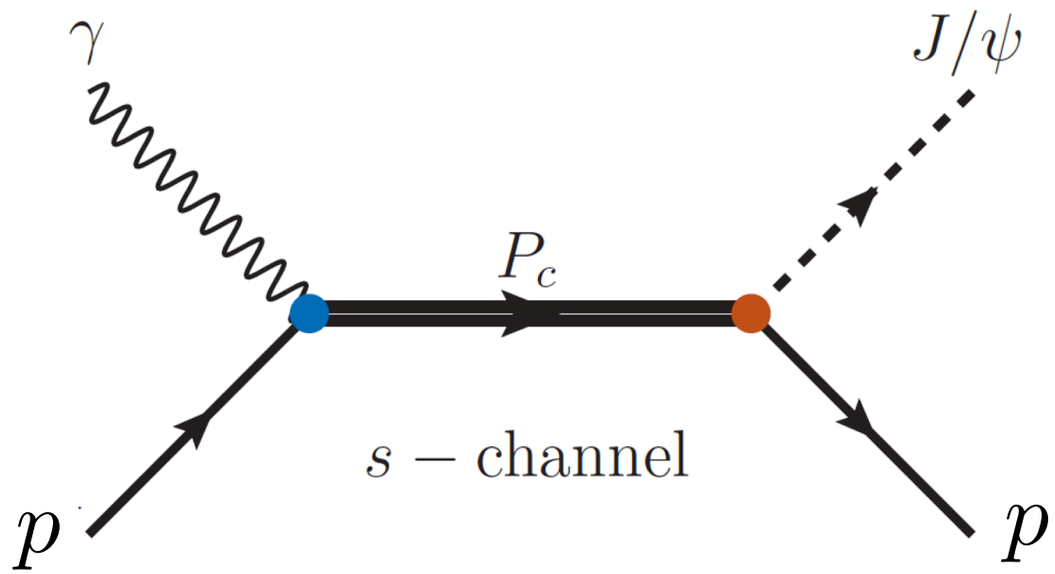




PRL 115 (2015) 072001

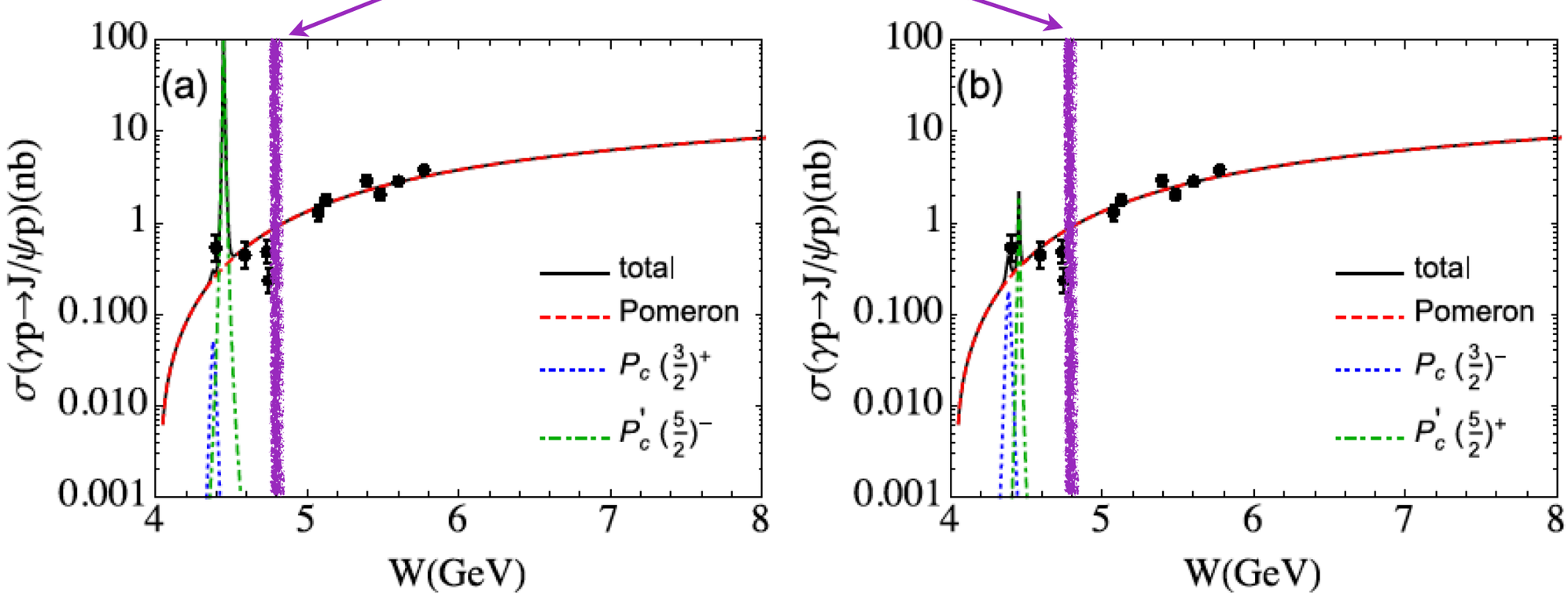
Pentaquark Photoproduction

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



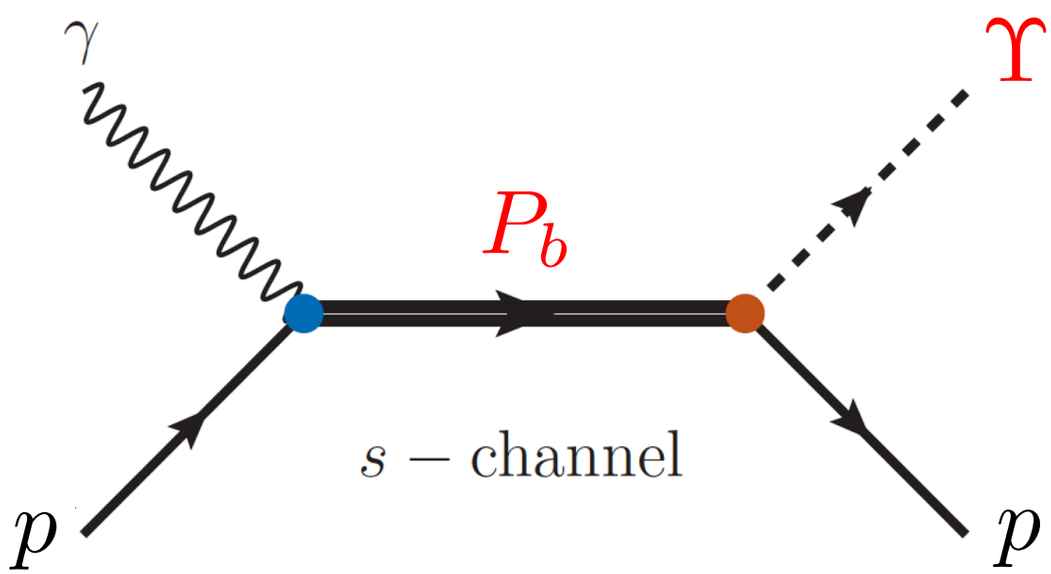
arXiv:1508.00339
arXiv:1508.00888
arXiv:1508.01496

JLab 12 GeV Max



Pentaquark Photoproduction

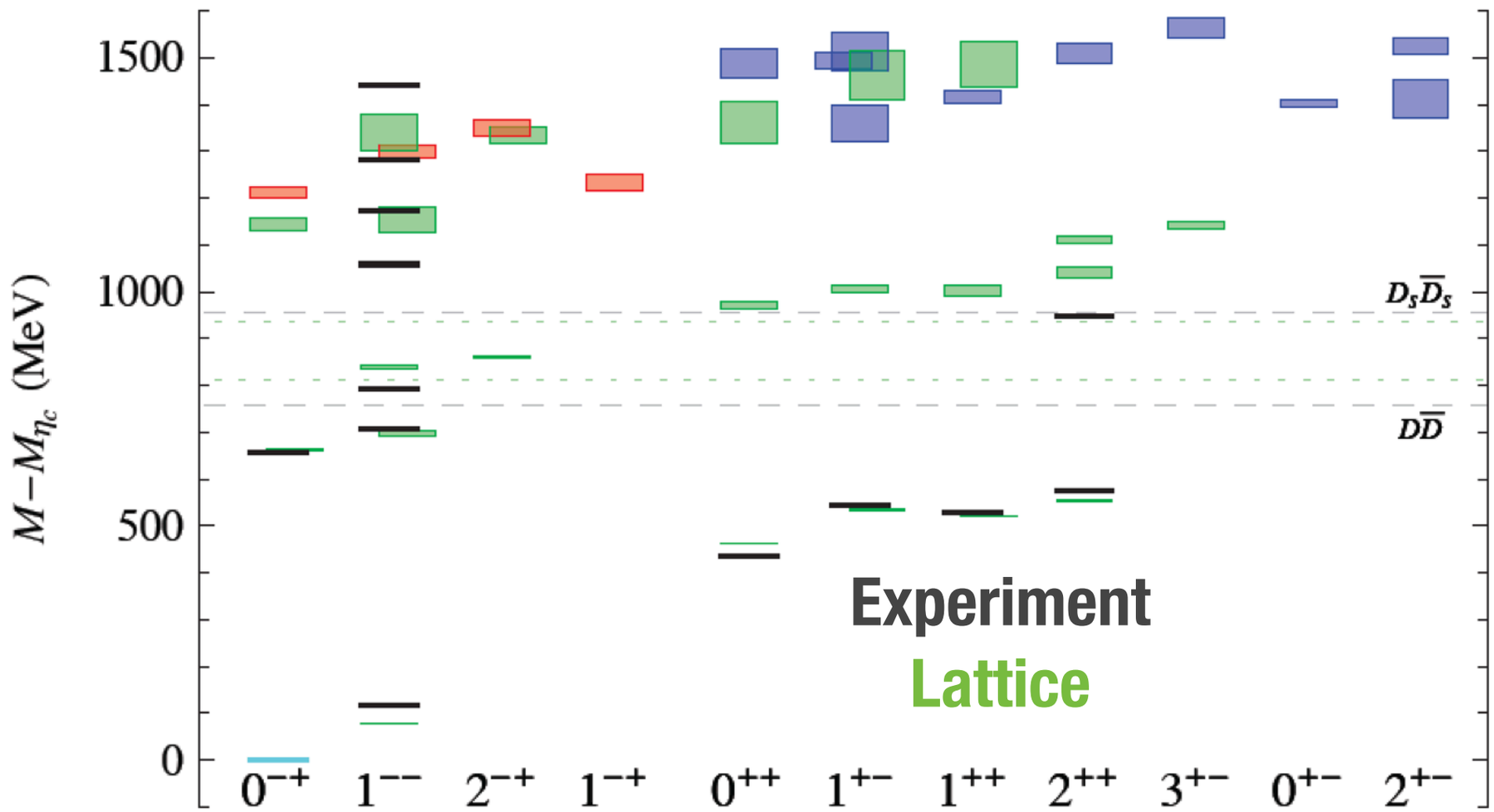
- What about a bottomonium pentaquark? **arXiv:1508.01496**



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

Hybrid mesons

Hadron Spectrum Collaboration: JHEP 1207 (2012) 126



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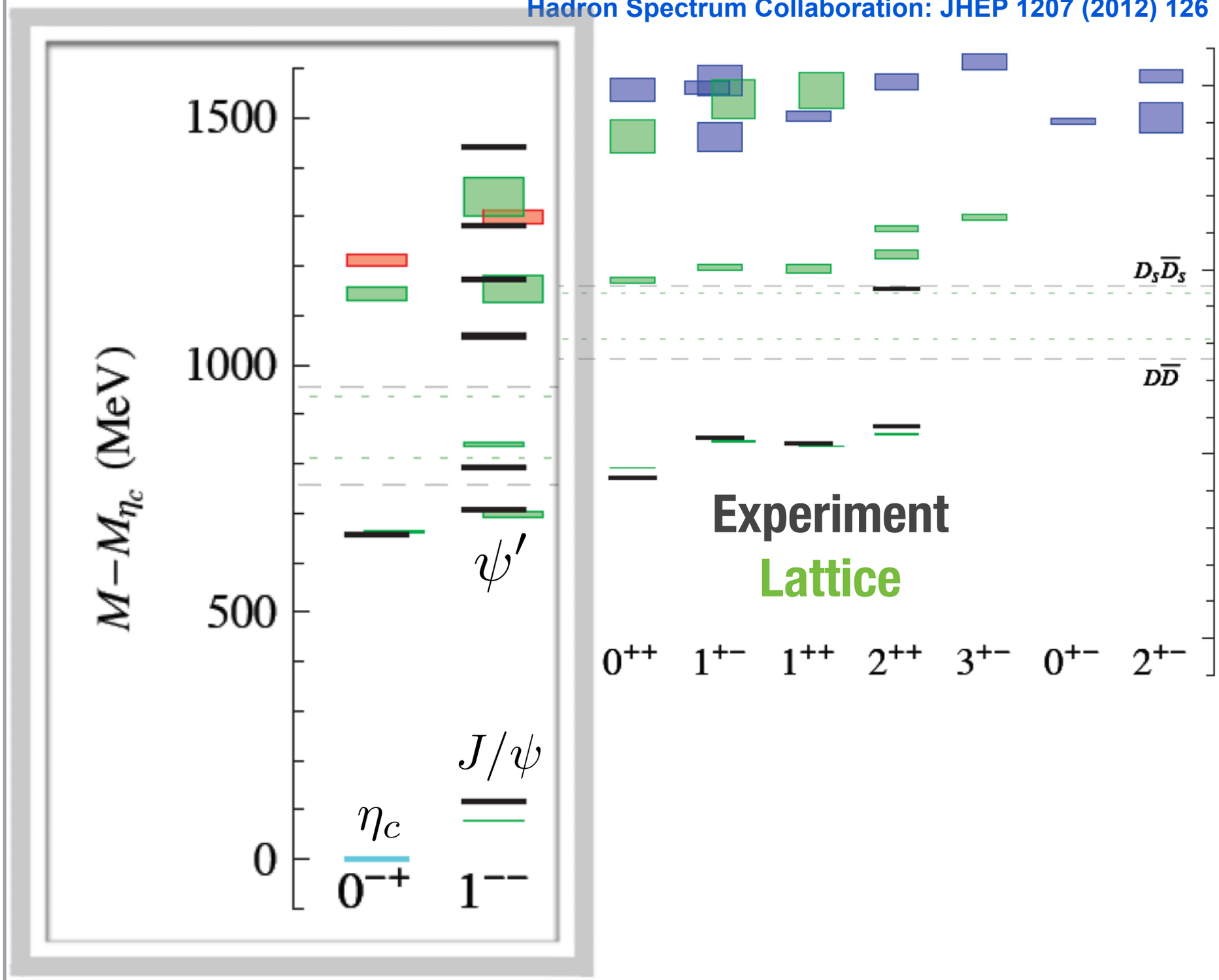

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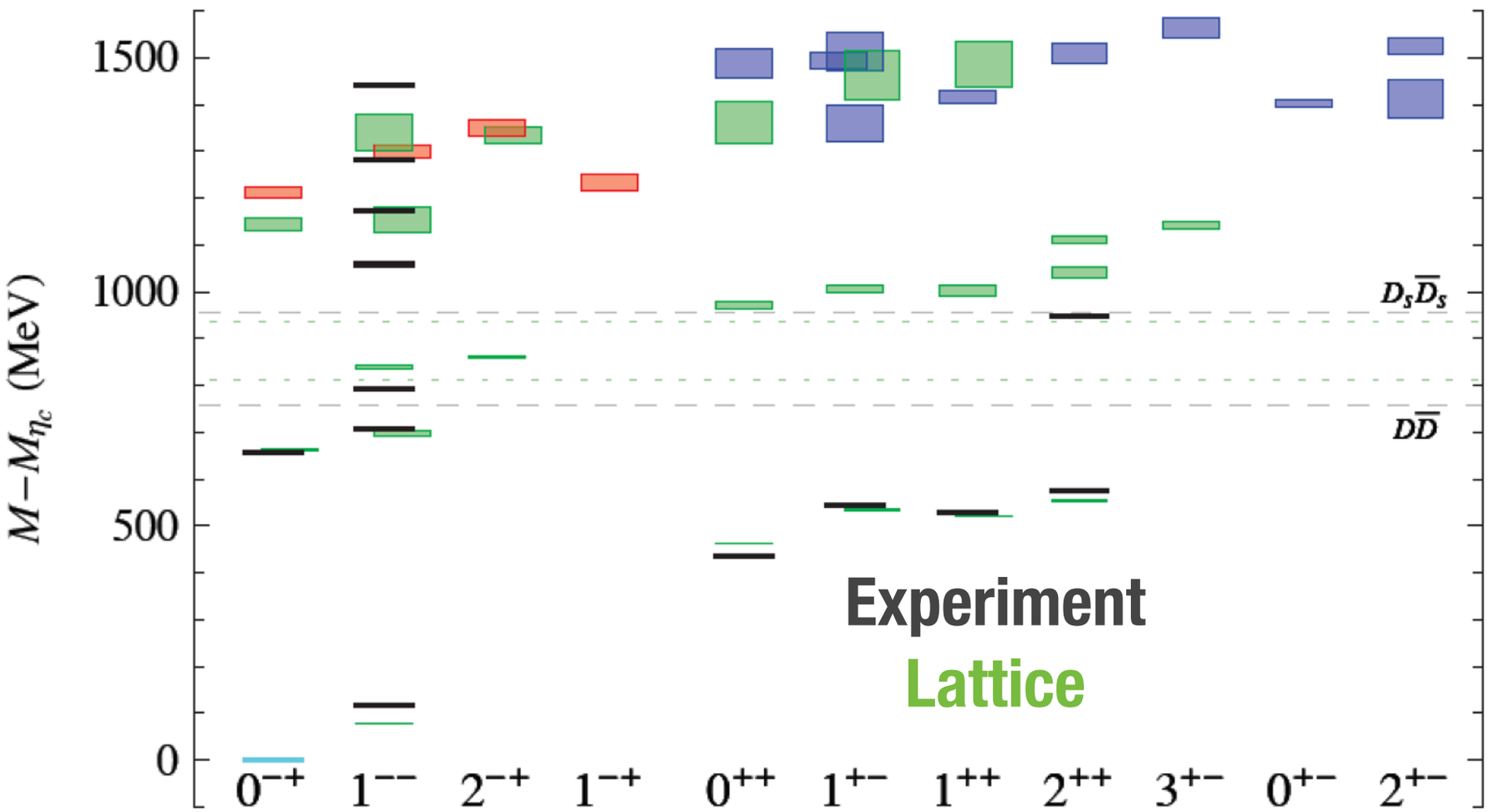
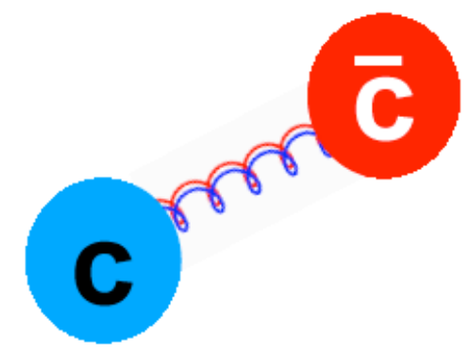


$c\bar{c}g$ Hybrid

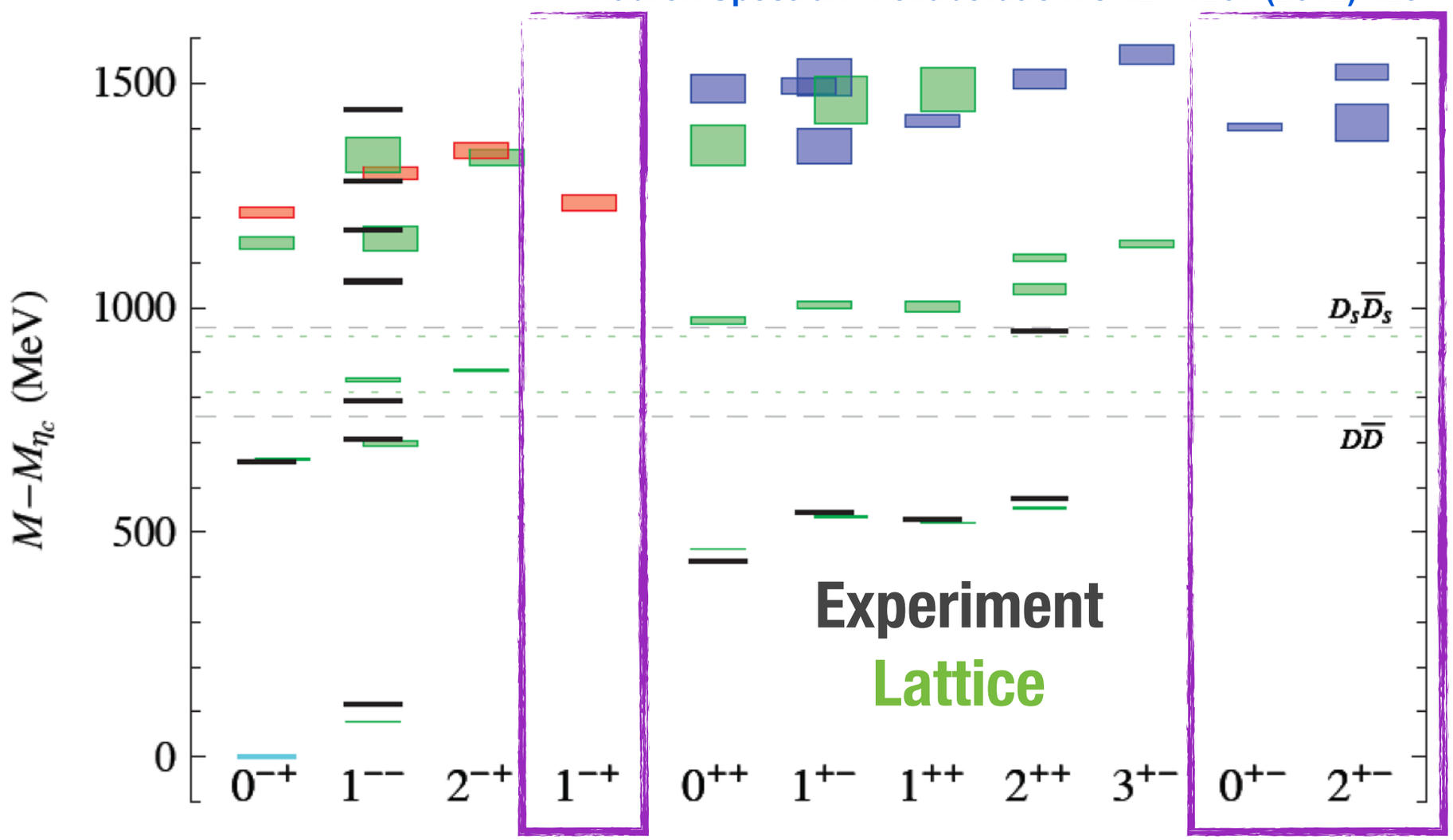


Lightest Hybrids

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

Hybrid mesons

Hadron Spectrum Collaboration: JHEP 1207 (2012) 126



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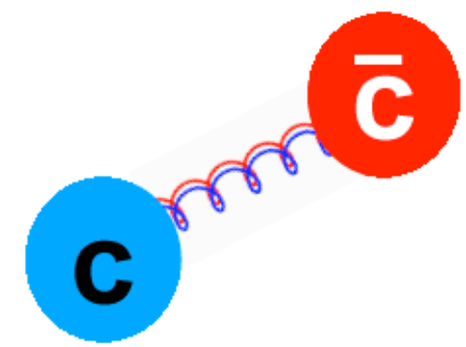
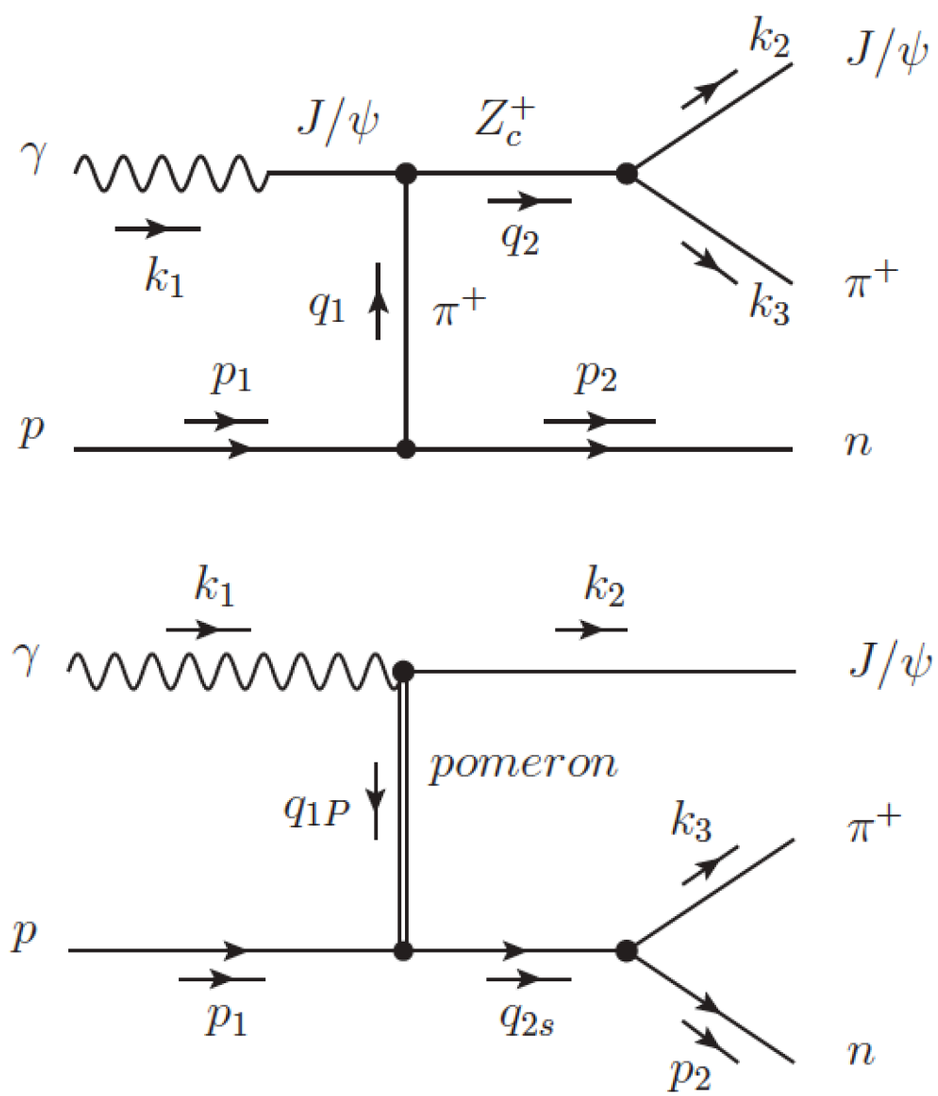


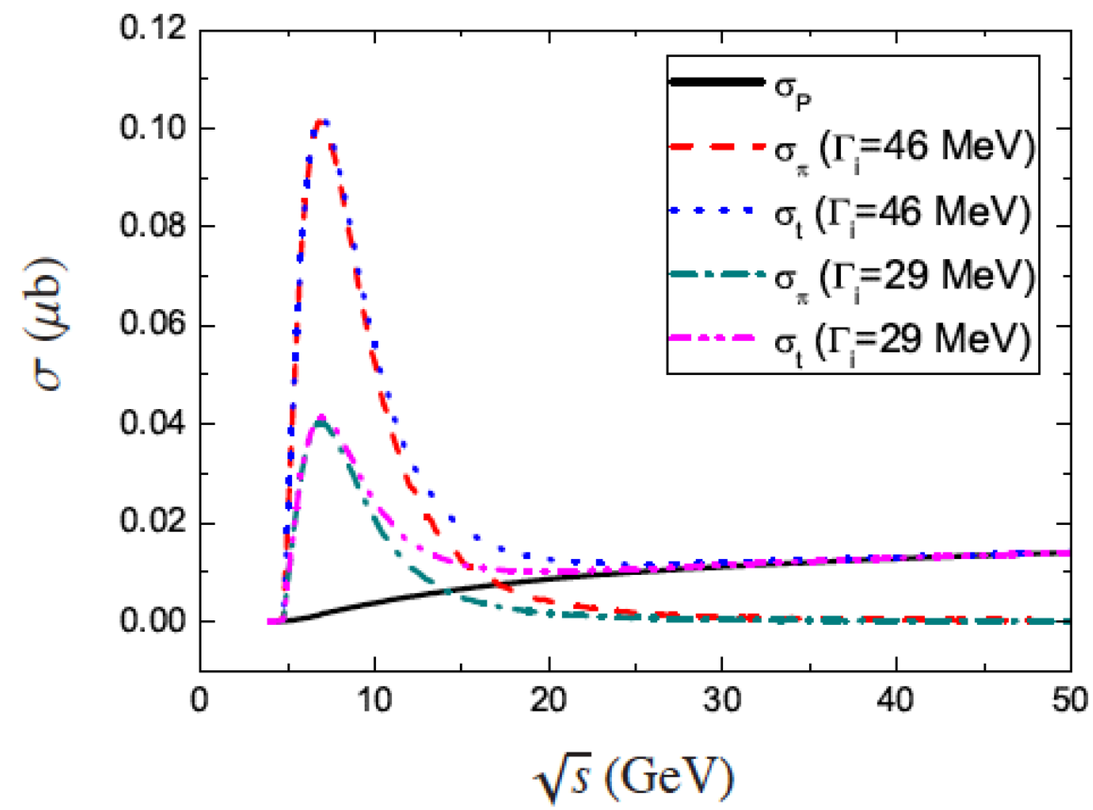
Lightest Hybrids

- 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)

Example: $Z_c^+(3900)$



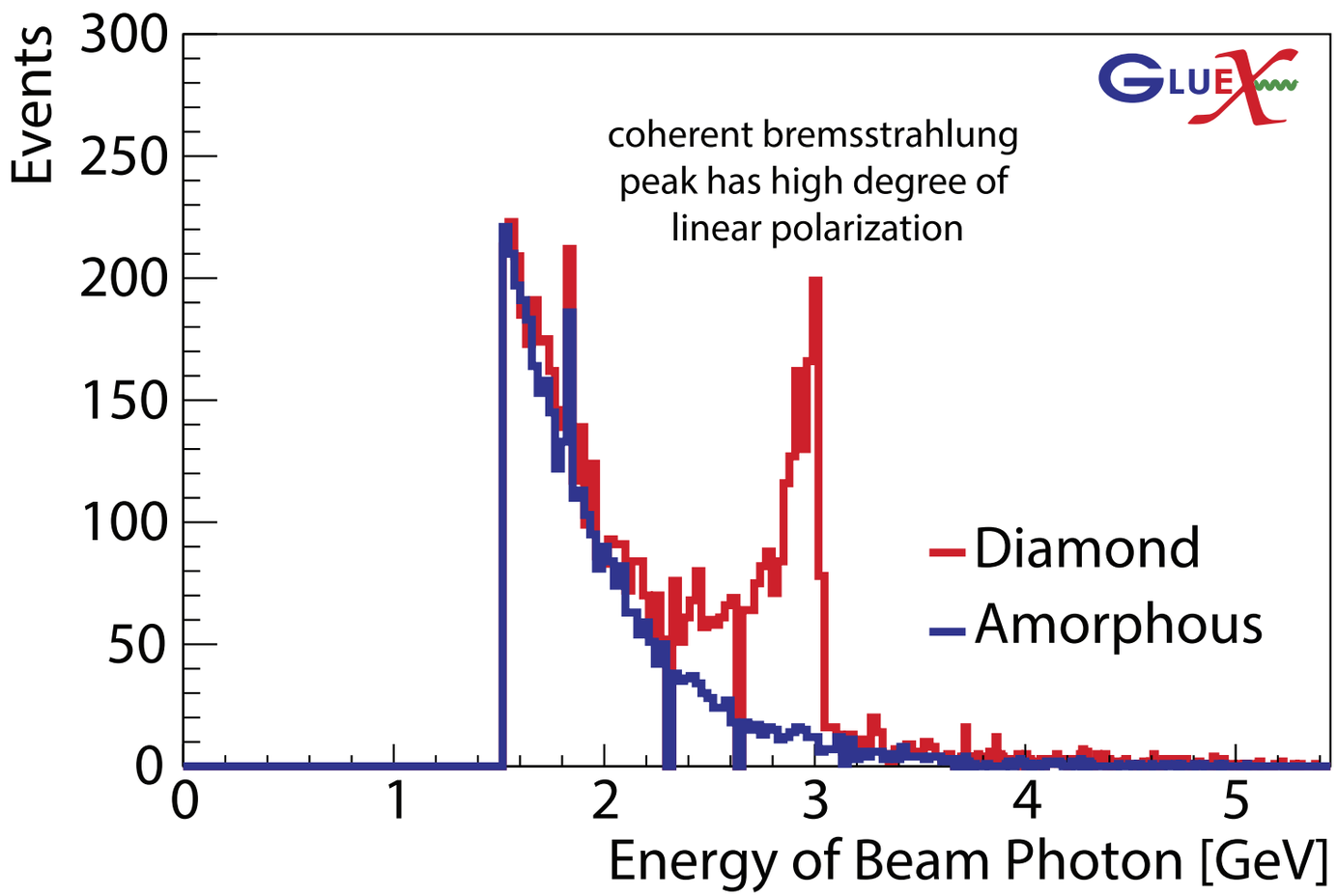
PRD 88 (2013) 114009



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

Photoproduction at the EIC

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



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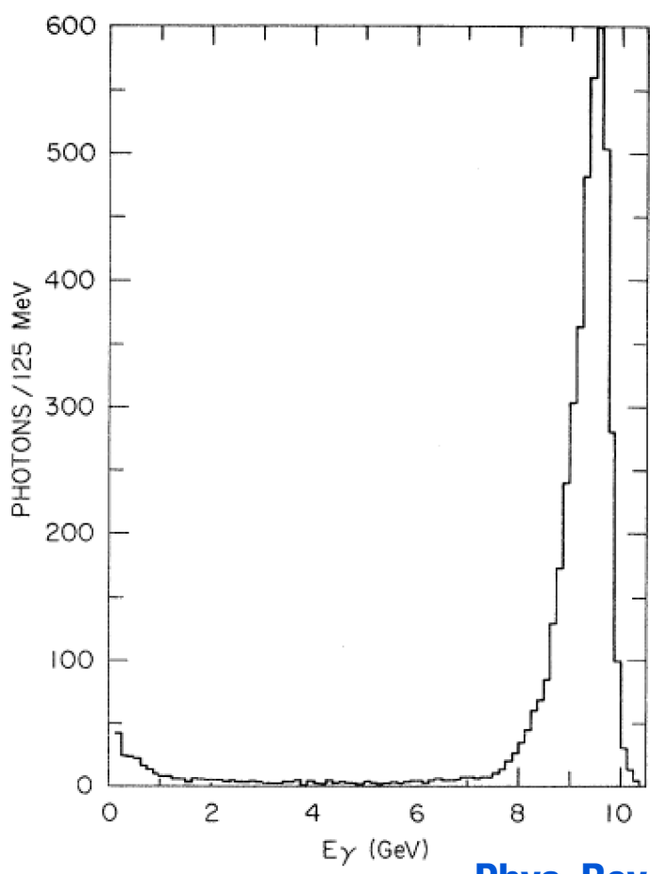
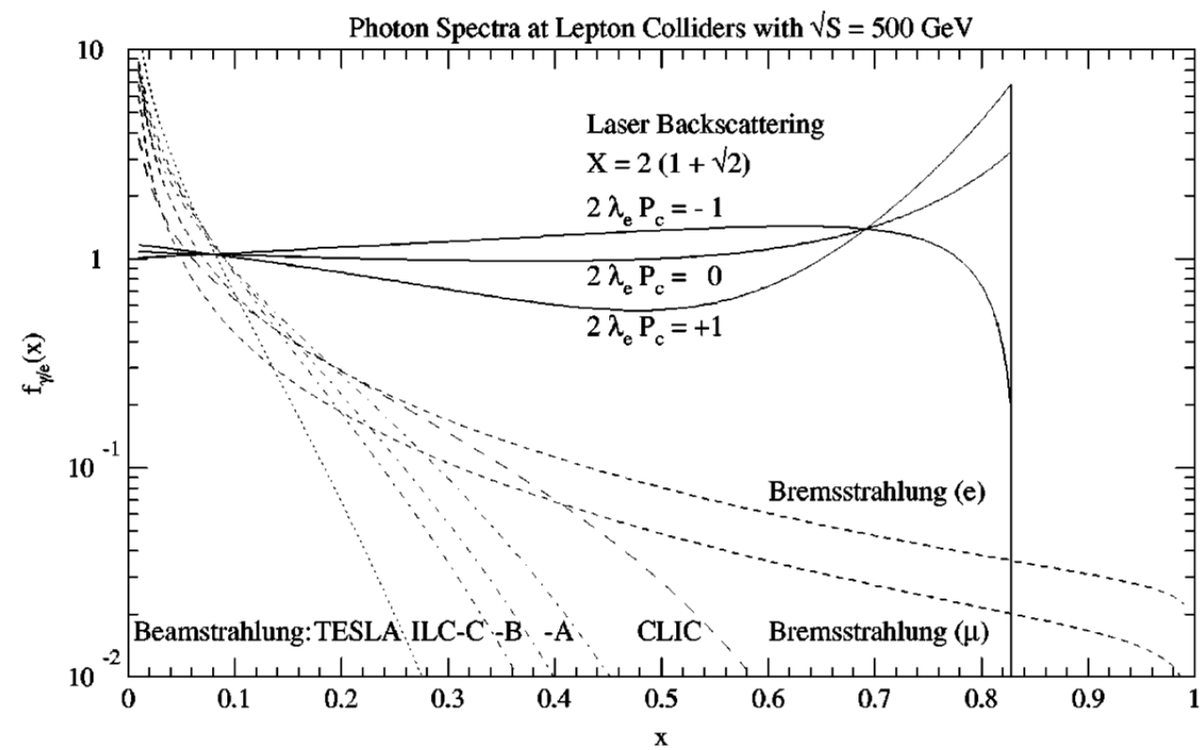
SLAC (1973)



Phys. Rev. D 8, 1277

Concept for ILC



Rev. Mod. Phys. 74, 1221

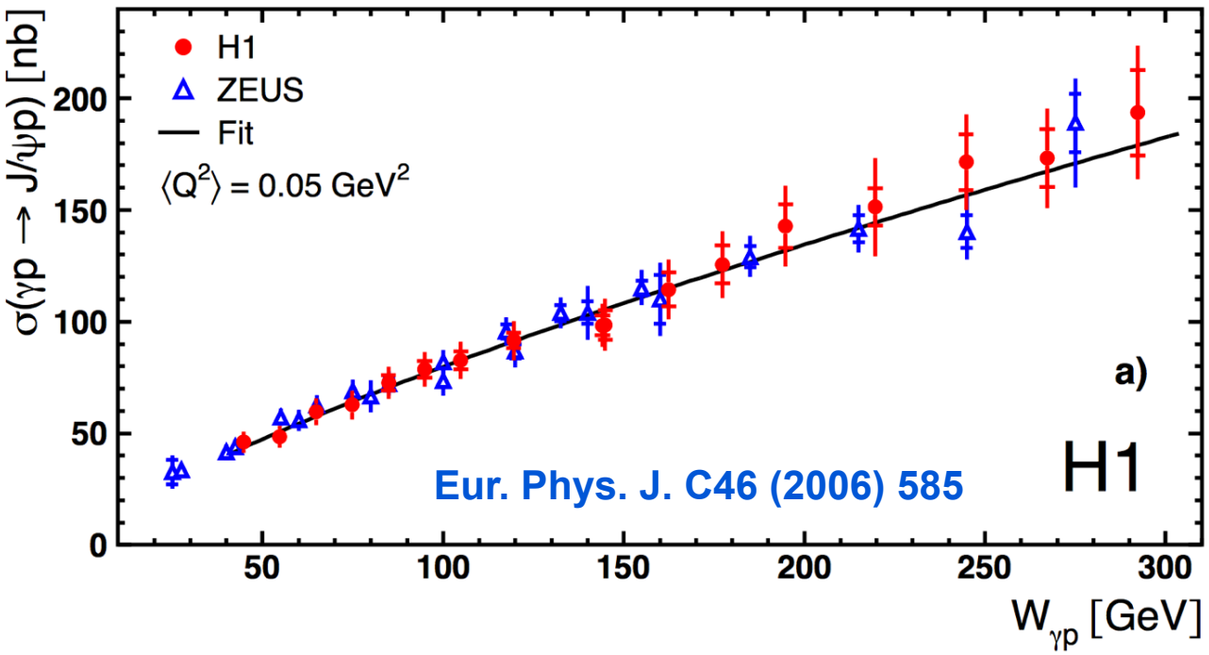
Photoproduction at the EIC

- **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)

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

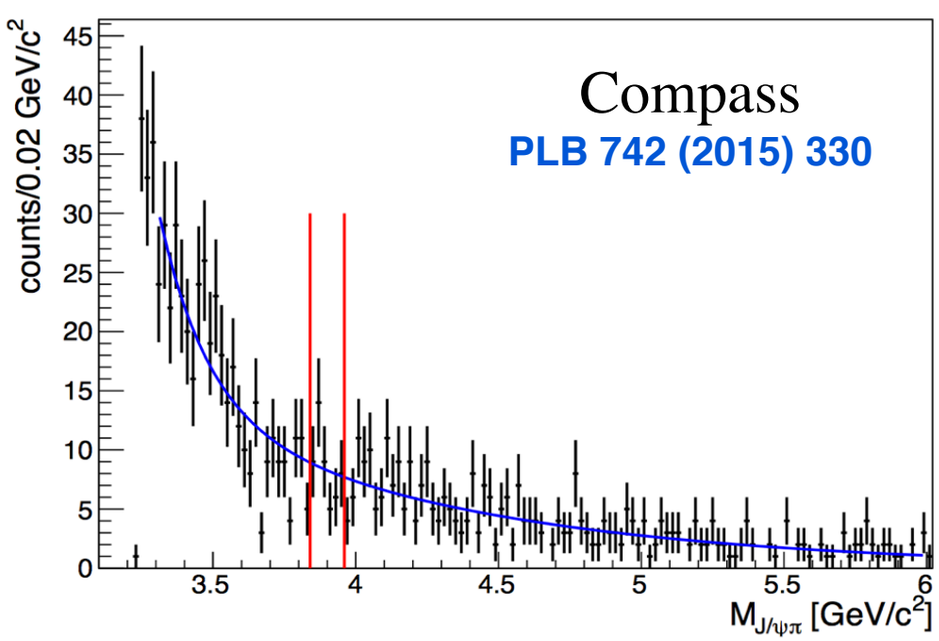
Previous experiments

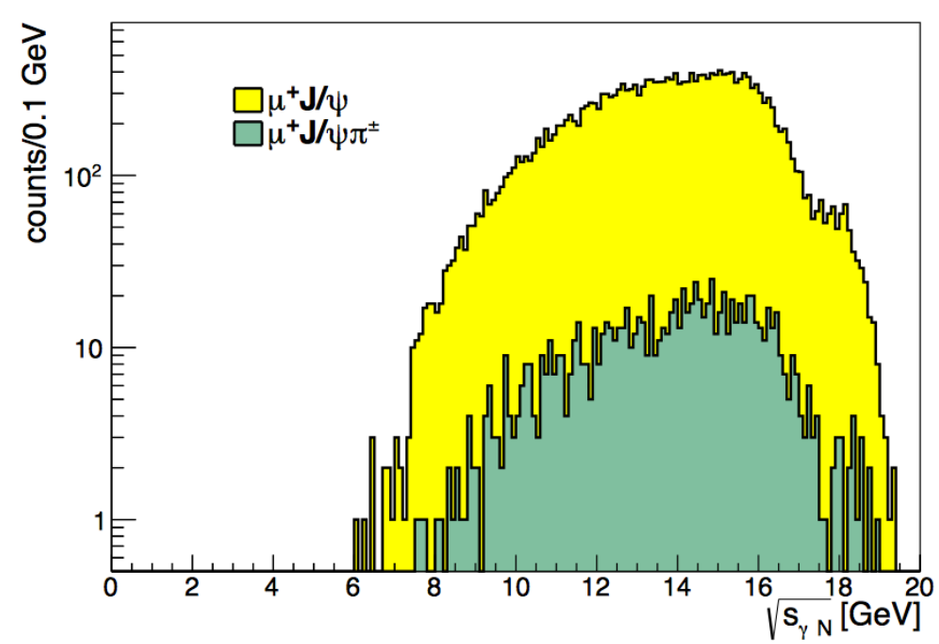
- Photoproduciton at HERA in e+p
  - Quasi-real photons at low-Q^2



Previous experiments

- Photoproduciton at HERA in e+p
  - Quasi-real photons at low-Q^2
- Recent result from Compass in μ+p to search for $Z_c(3900)$
  - Most $\sqrt{s_{\gamma p}}$ far above threshold
  - Already some constraints on $Z_c \rightarrow J/\psi\ \pi$ decay width?
- What could the EIC do in e+p?





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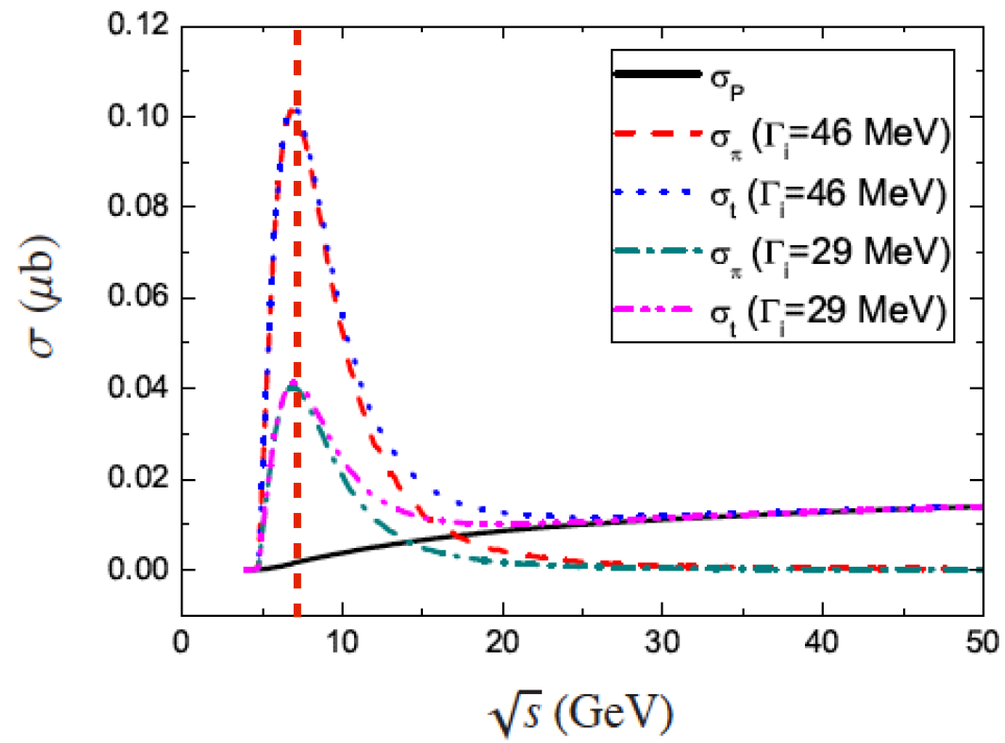
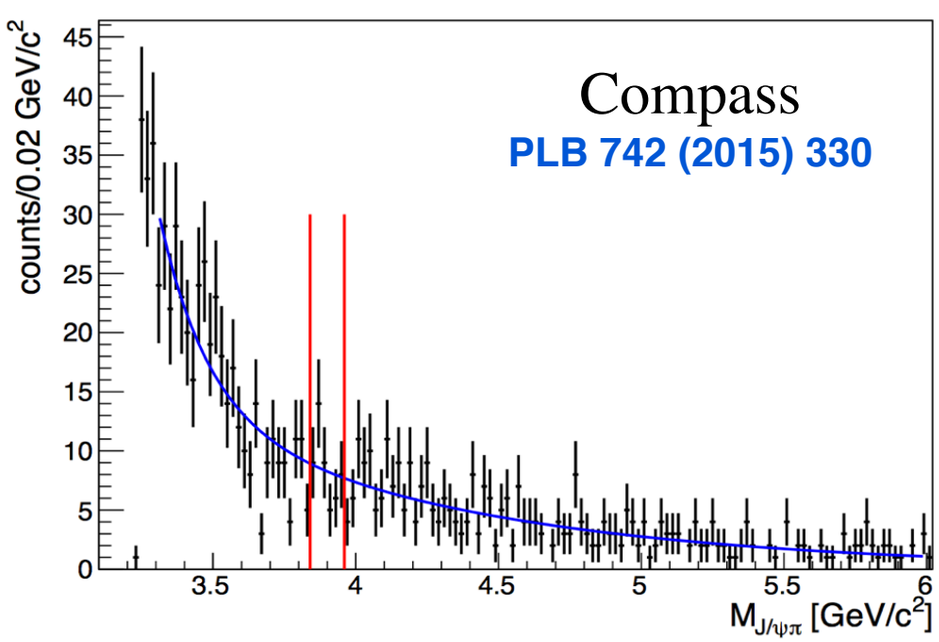
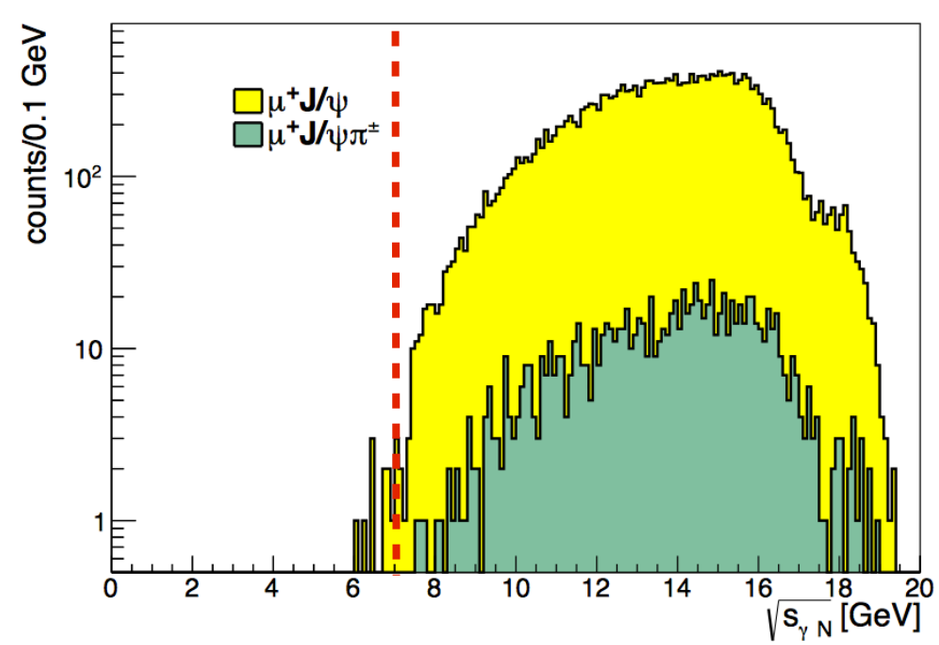
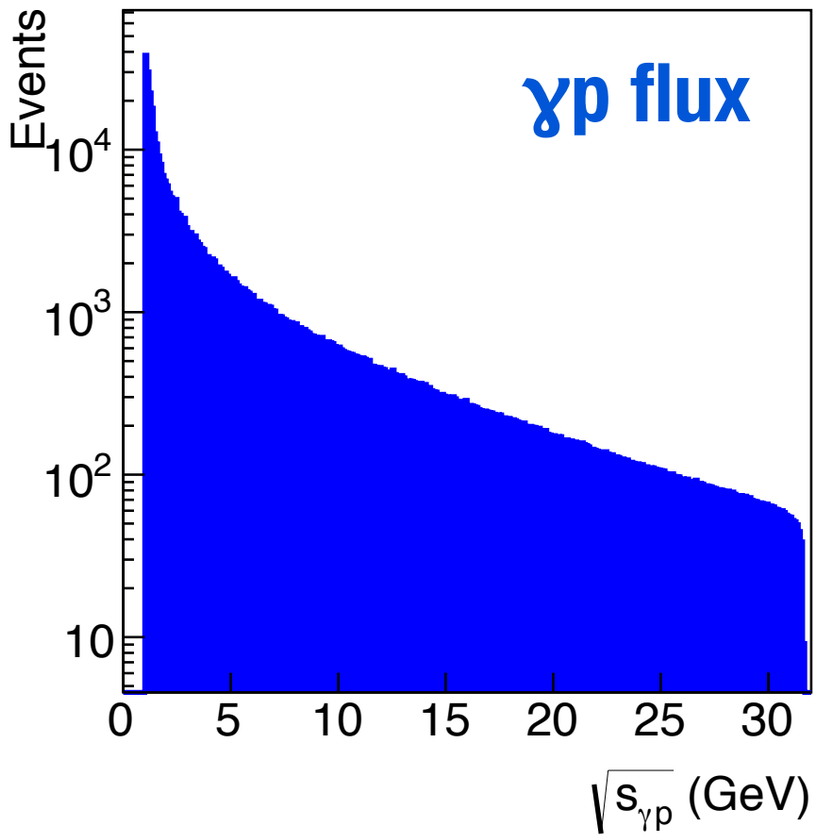
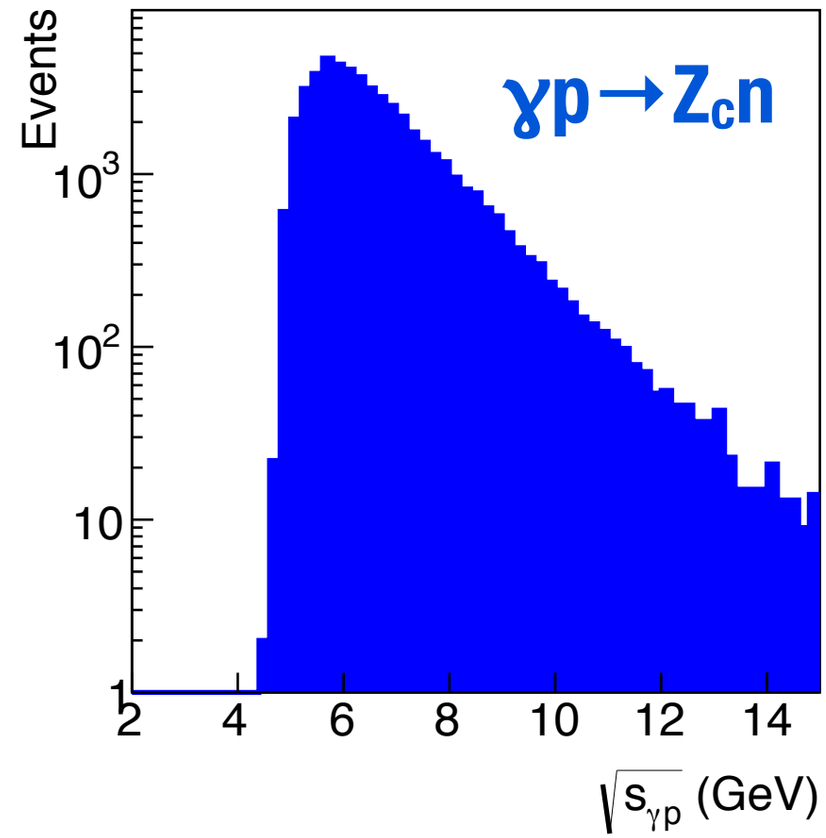






$Z_c^+(3900)$ at the EIC

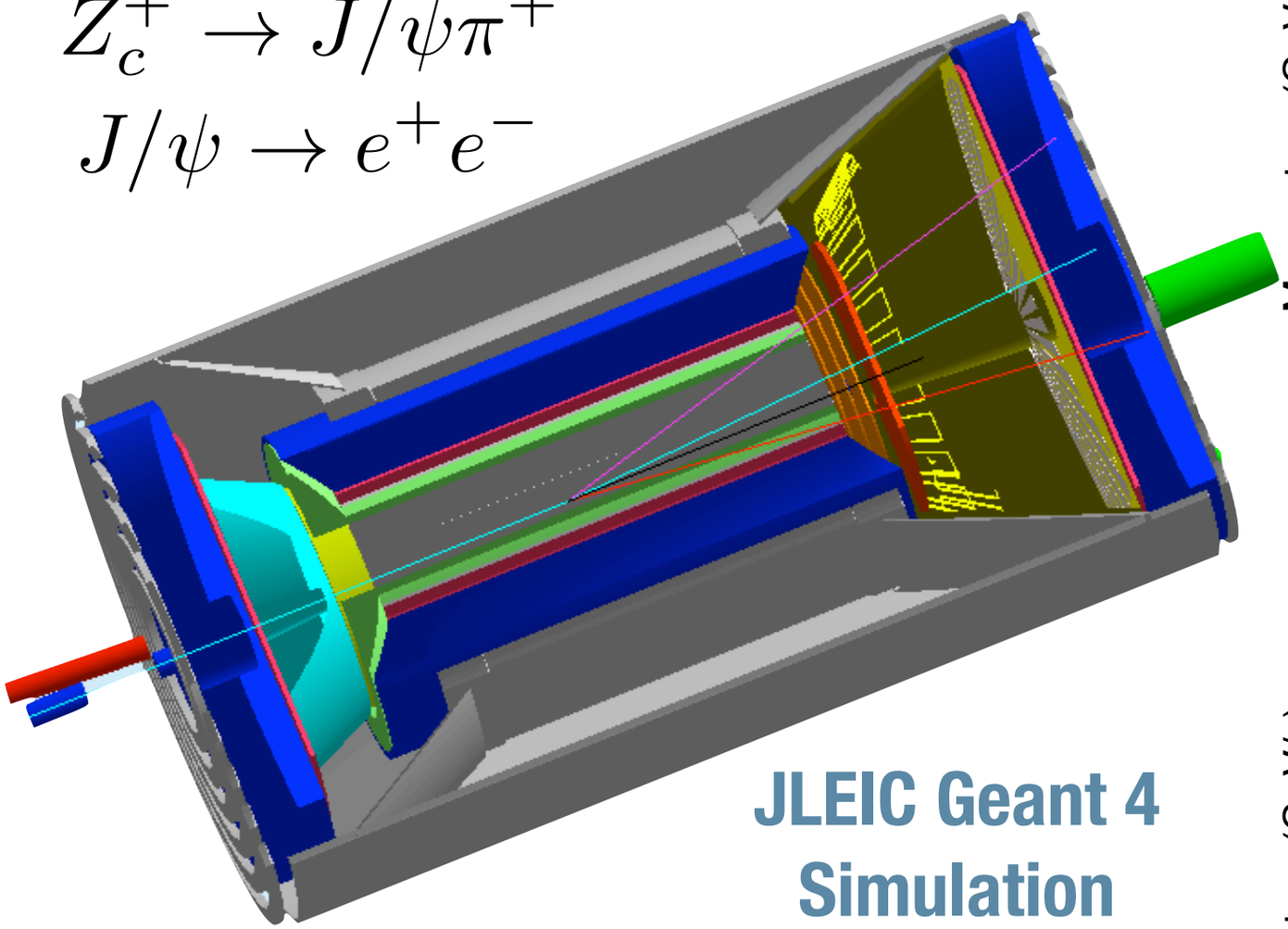




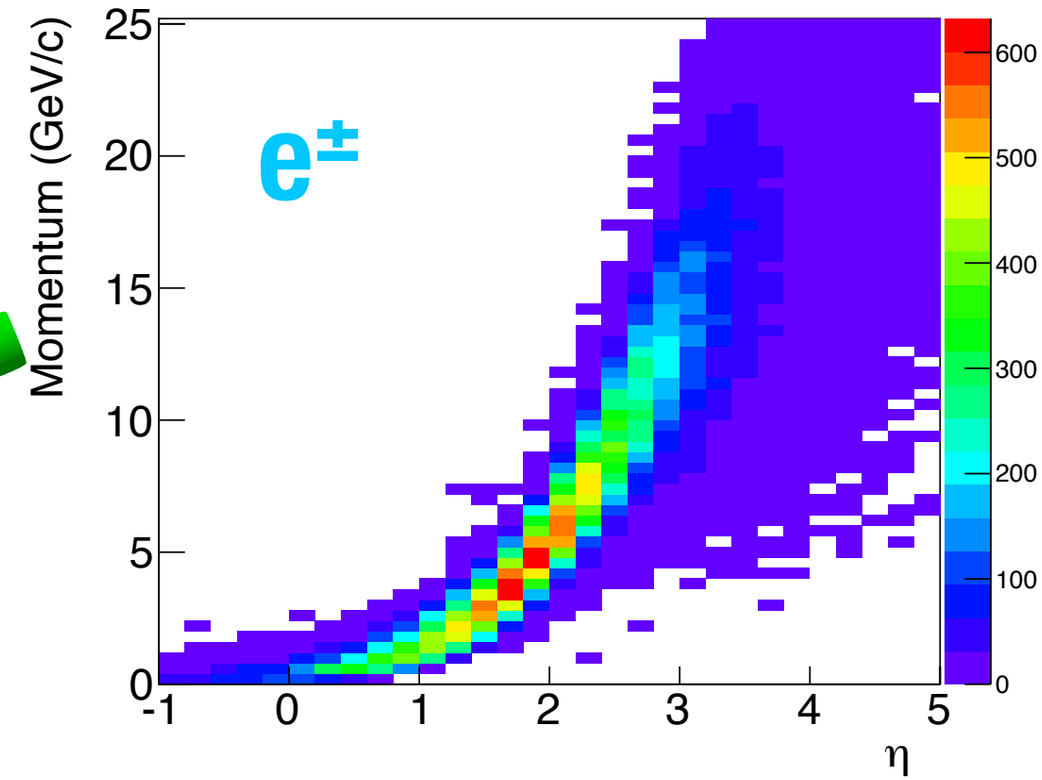
- Assume modest energy electron and proton beams: **E_p = 50 GeV** and **E_e = 5 GeV**
- Z_c and subsequent decays are boosted in proton direction
- Low-Q^2 electron and neutron very close to beamline

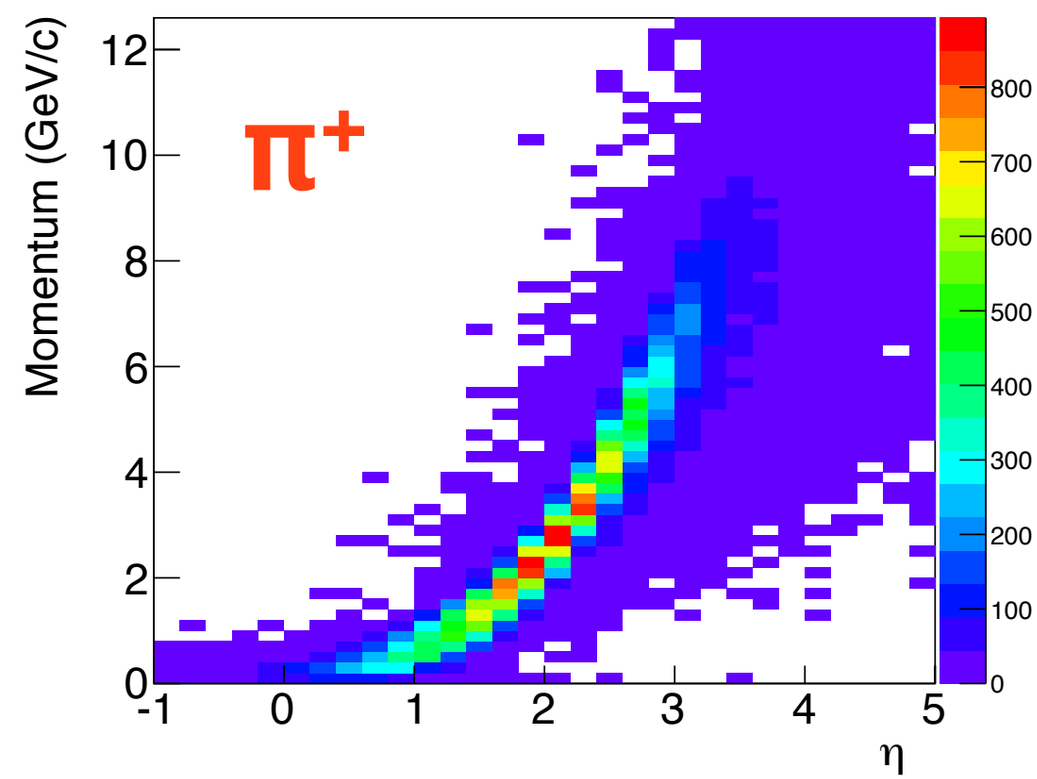
$Z_c^+(3900)$ at the EIC

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



JLEIC Geant 4 Simulation

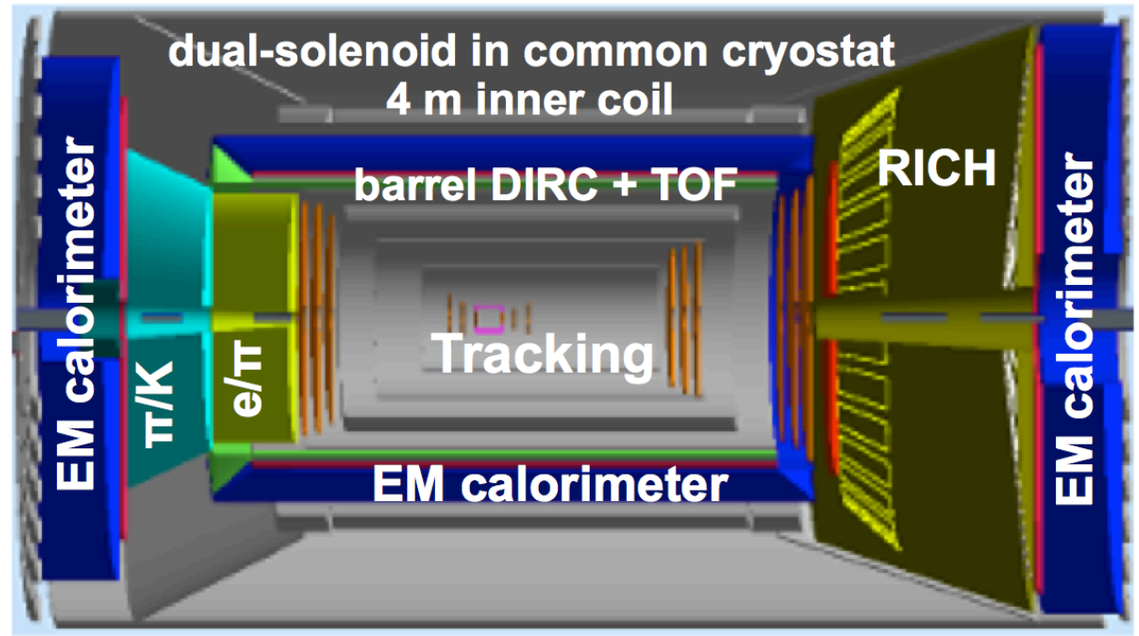


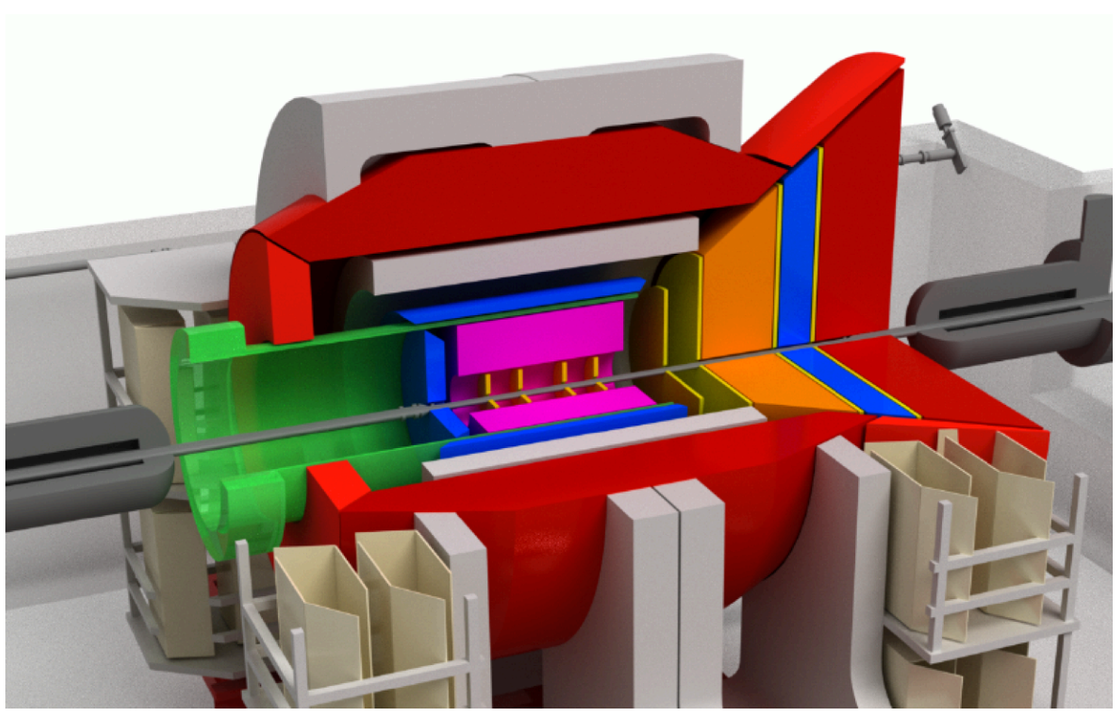


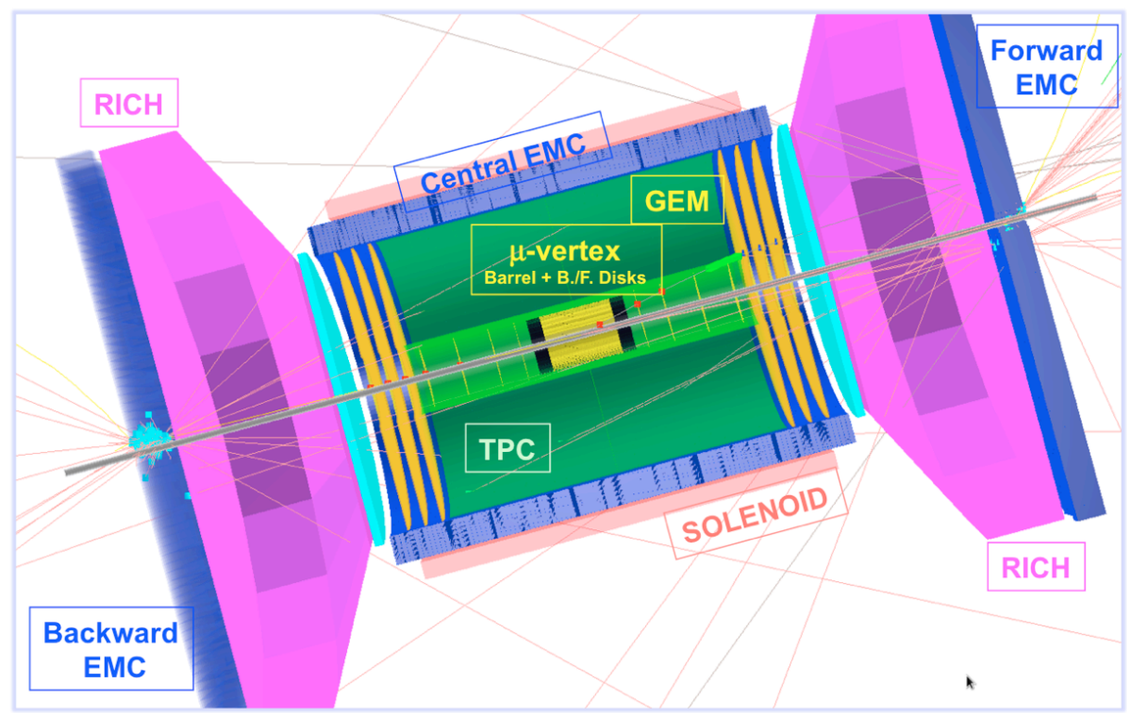
- Decay $e^\pm$ and π^+ boosted in proton beam direction
- Need excellent hadron and $e^\pm$ PID and momentum resolution

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 μ ID for J/ψ?
- Beamline detectors ensure exclusivity: low-Q^2 tagger, ZDCs, Roman Pots







Summary and Outlook

- Photoproduction provides some interesting new avenues to pursue the physics program laid out in the white paper and beyond
- New “exotic” states in heavy quarkonium are challenging our understanding of the hadron spectrum and QCD in general

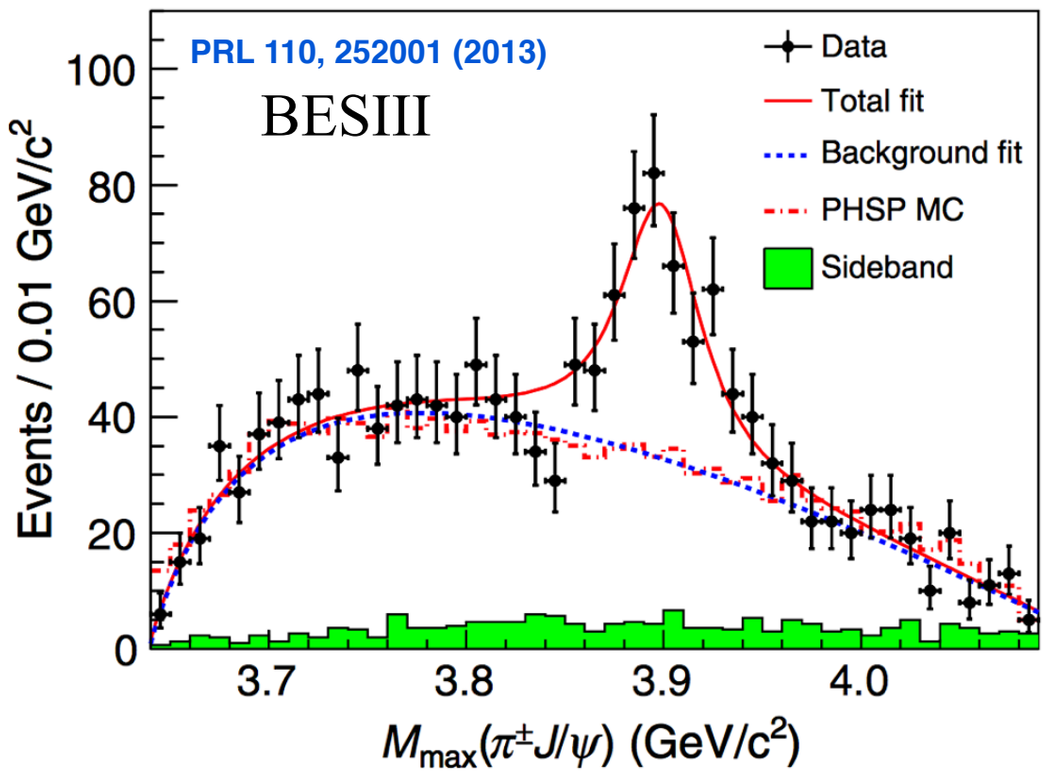
Summary and Outlook

- Photoproduction provides some interesting new avenues to pursue the physics program laid out in the white paper and beyond
- New “exotic” states in heavy quarkonium are challenging our understanding of the hadron spectrum and QCD in general
- **Thoughts on “QCD in 2025”:**
  - Expect advances in light quark spectroscopy + hybrid mesons from JLab 12 GeV (GlueX and CLAS12)
  - Plenty more data from BESIII, Belle II, LHC, PANDA, etc.
  - What will the hadron landscape look like 10 years from now?
  - Natural connection between ongoing Nuclear and High Energy programs to attract interested people

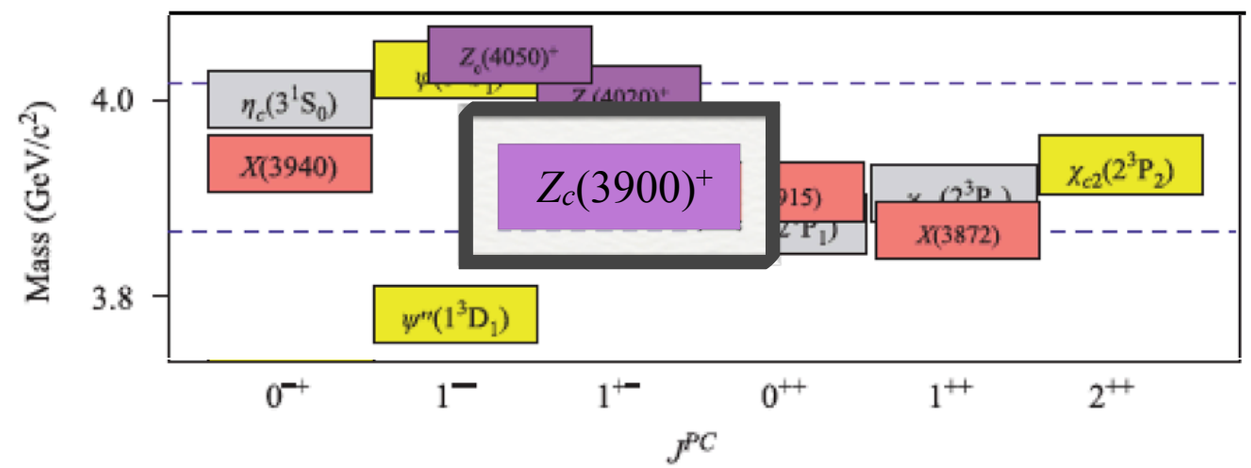
Backup

Charged charmonium states

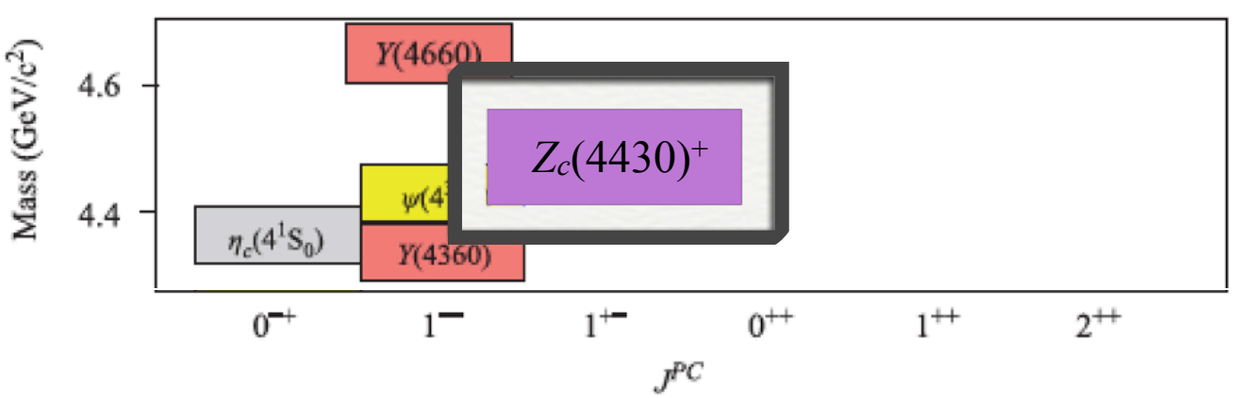
$e^+e^- \to \pi^+\pi^- J/\psi$ (4260 MeV)

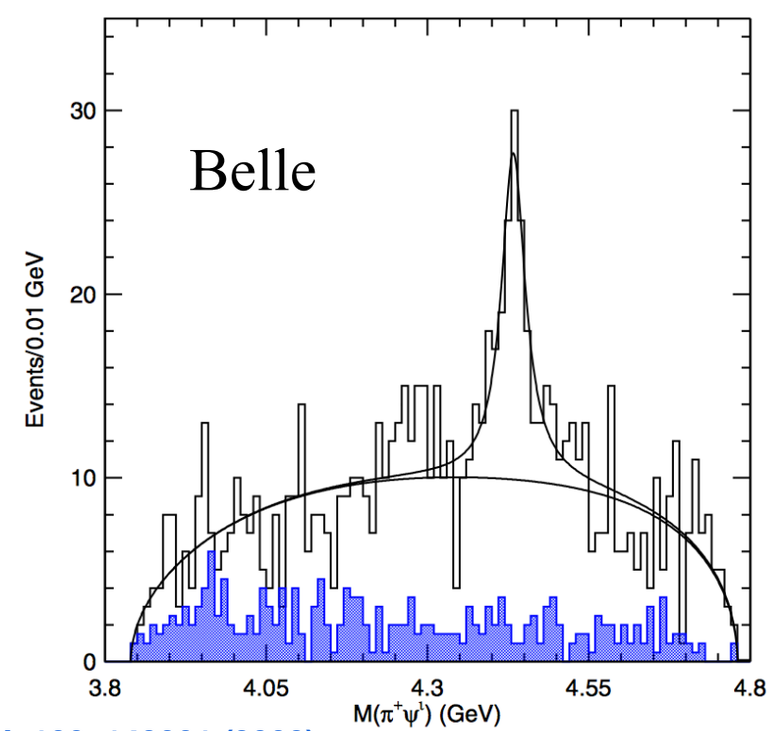


4-quark content ($c\bar{c}u\bar{d}$)



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





PRL 100, 142001 (2008)

Charged charmonium states

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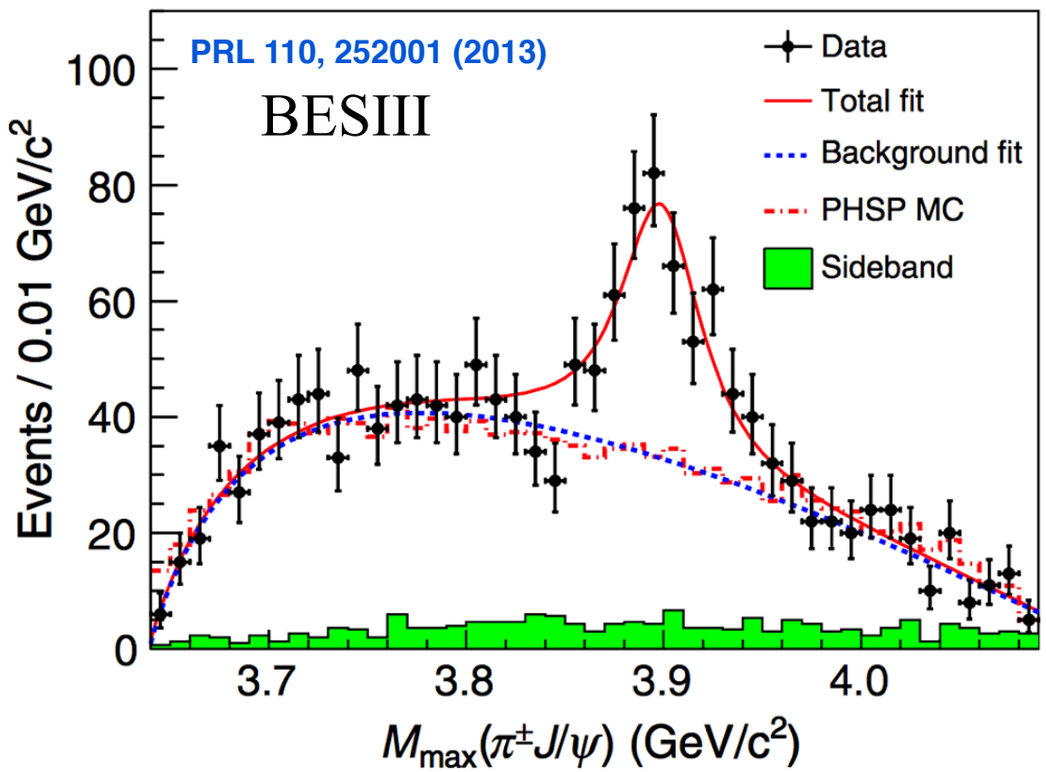

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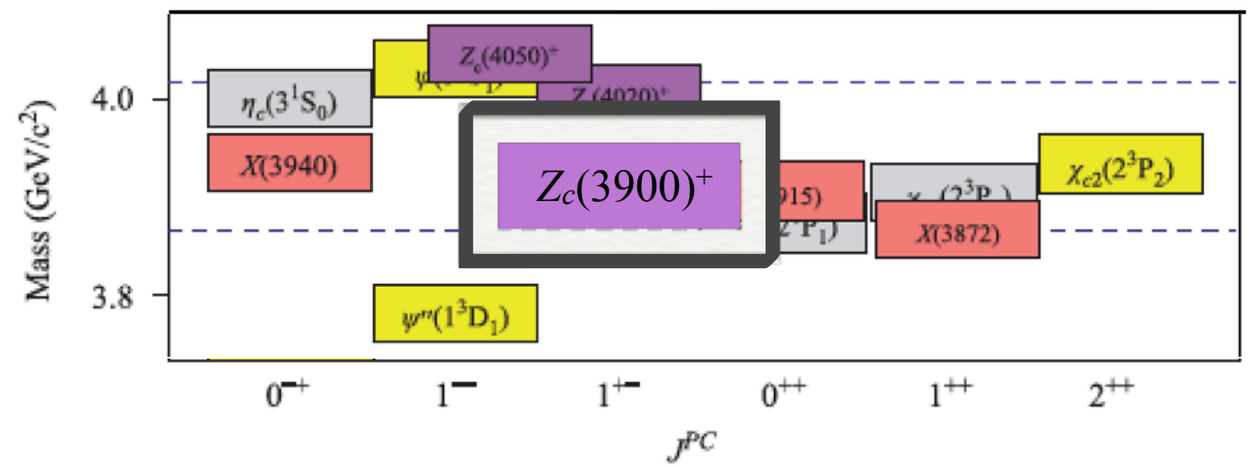

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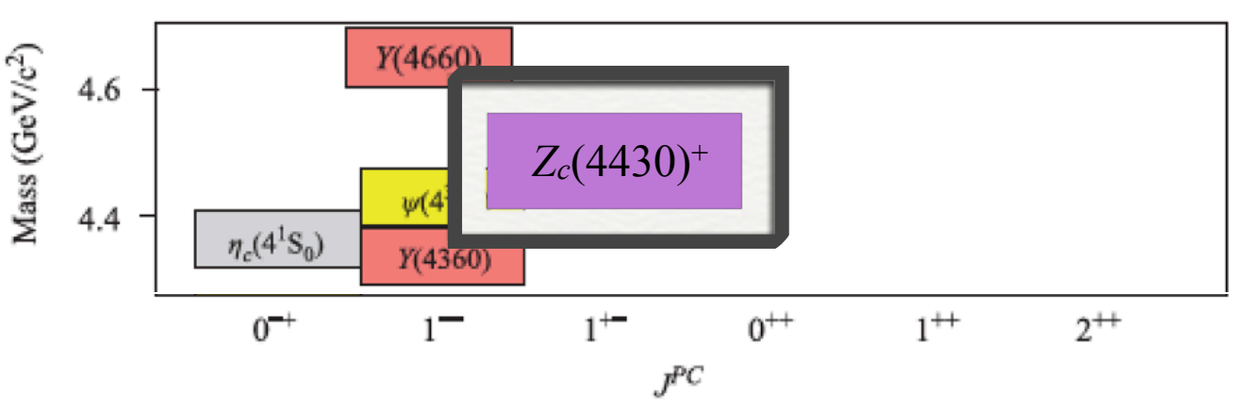
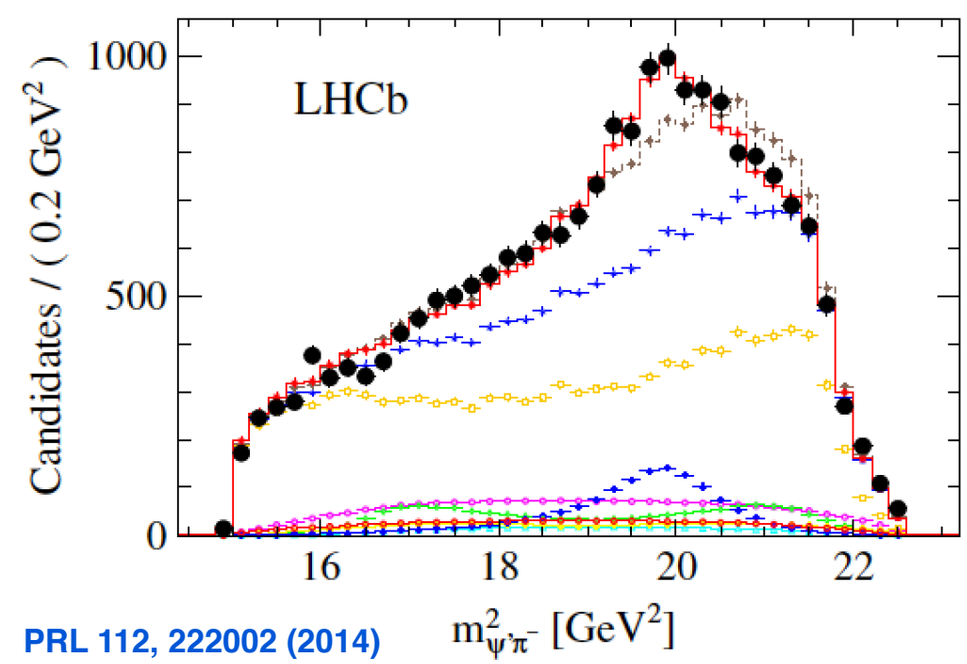
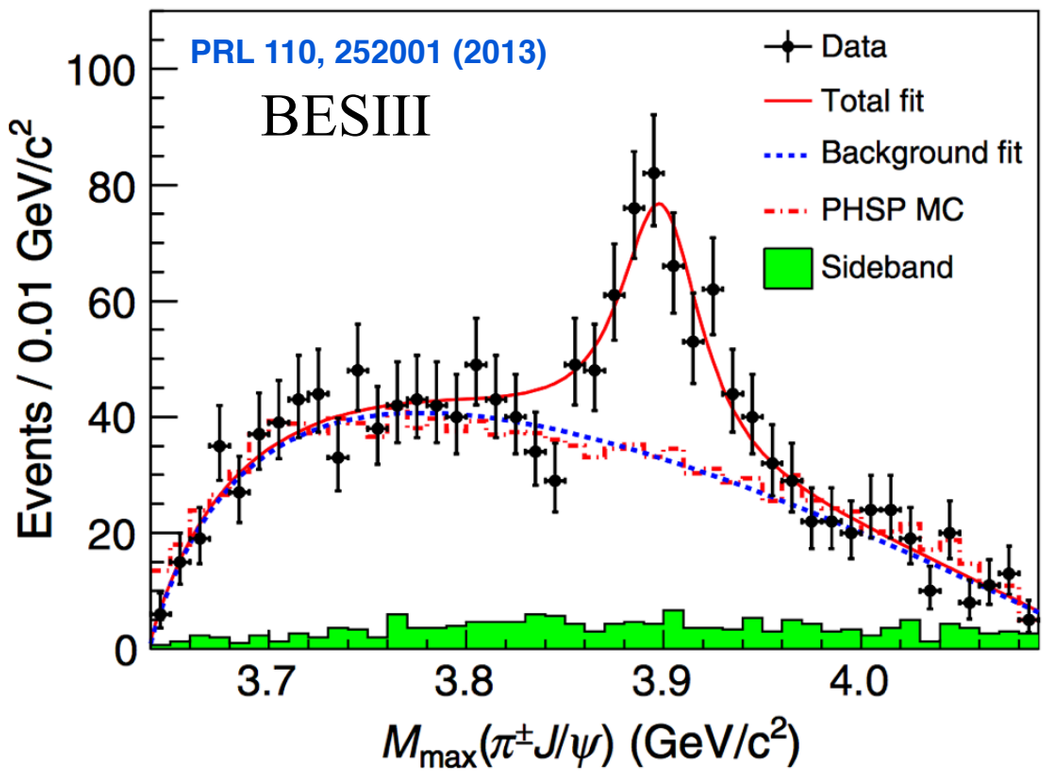




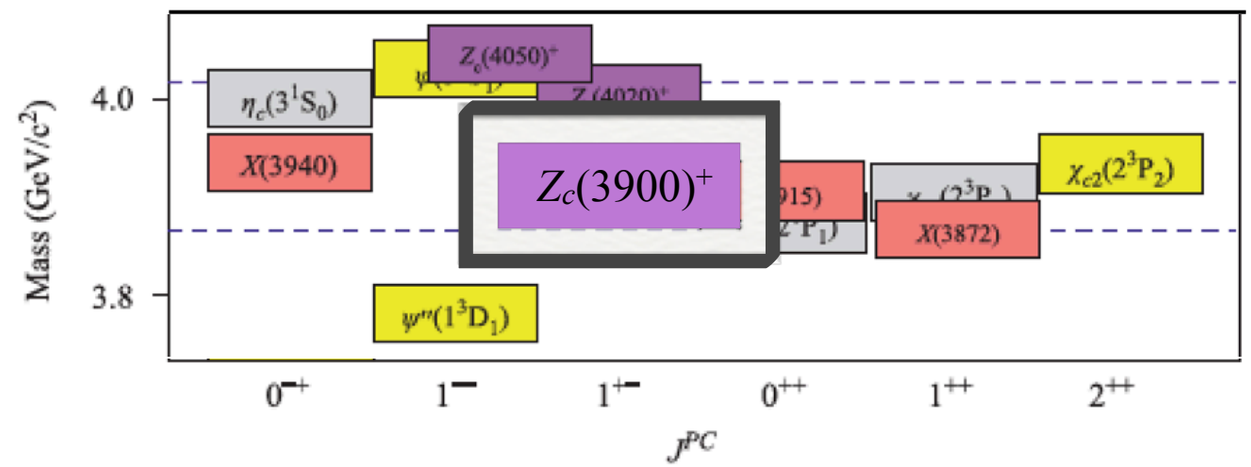
PRL 112, 222002 (2014)

Charged charmonium states

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



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



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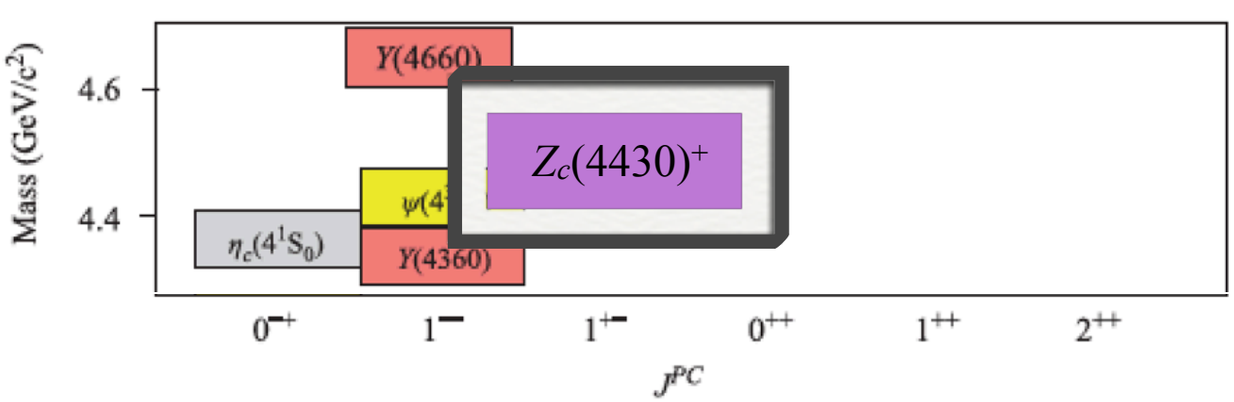
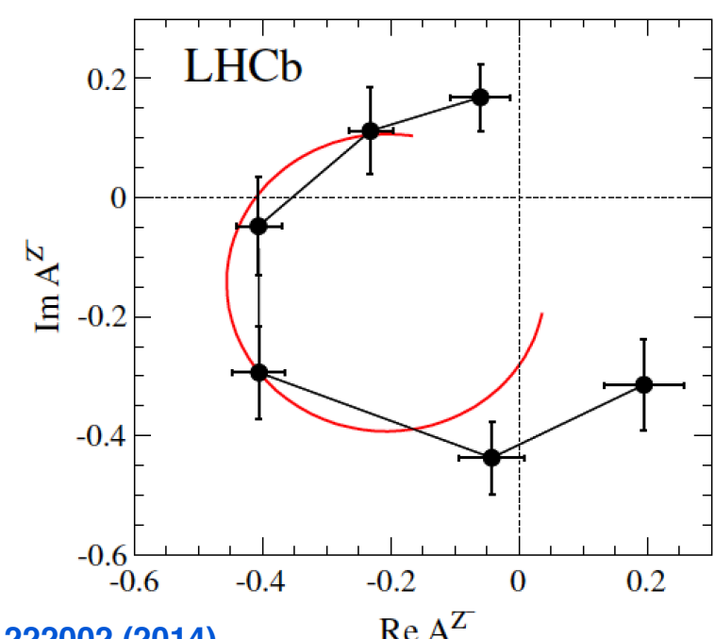
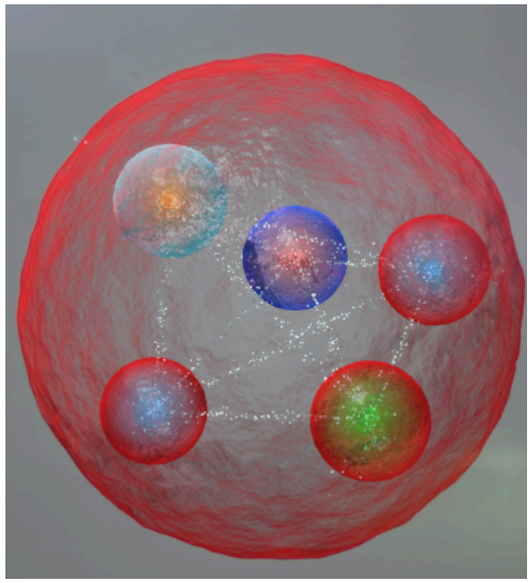
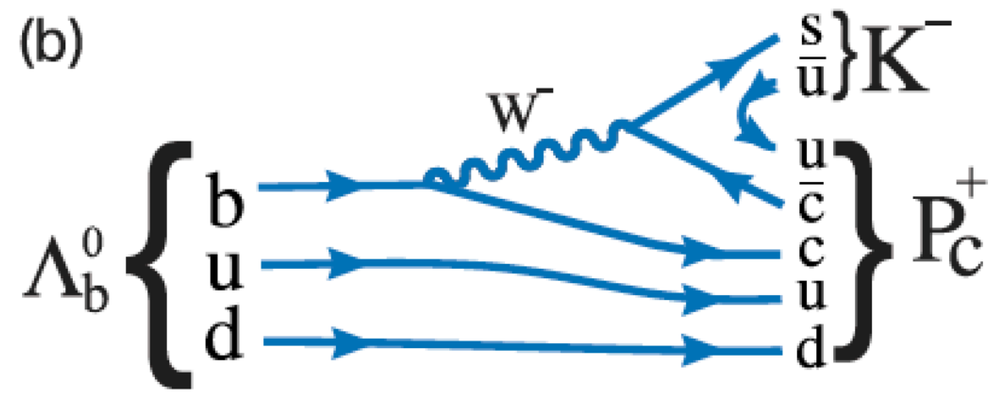


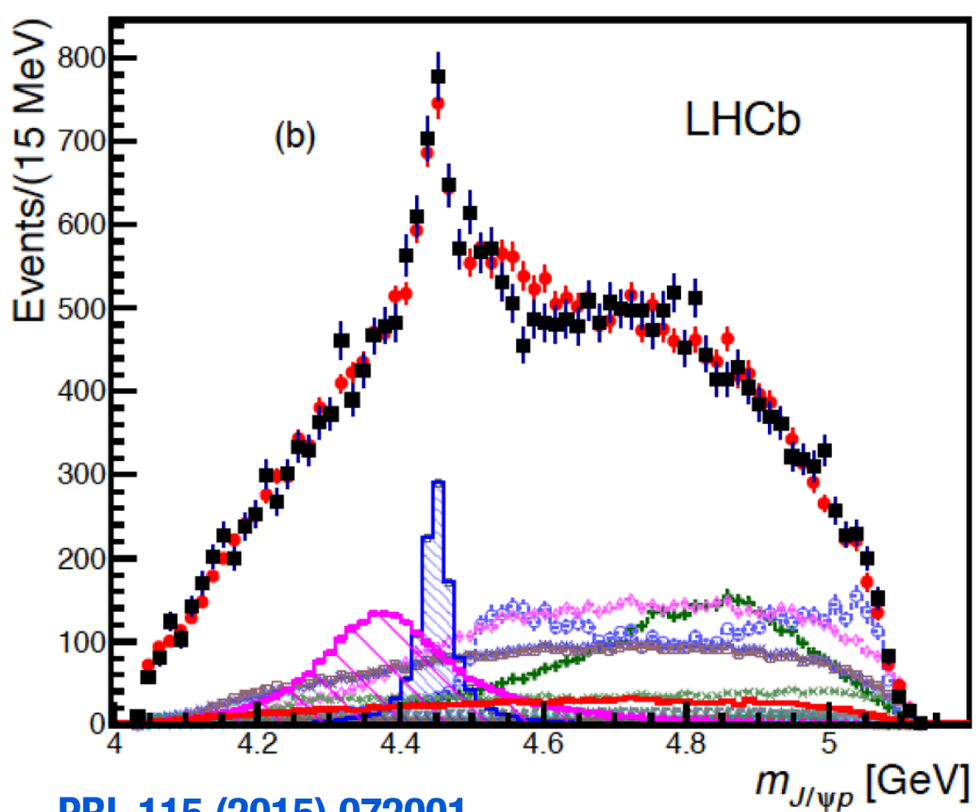


PRL 112, 222002 (2014)

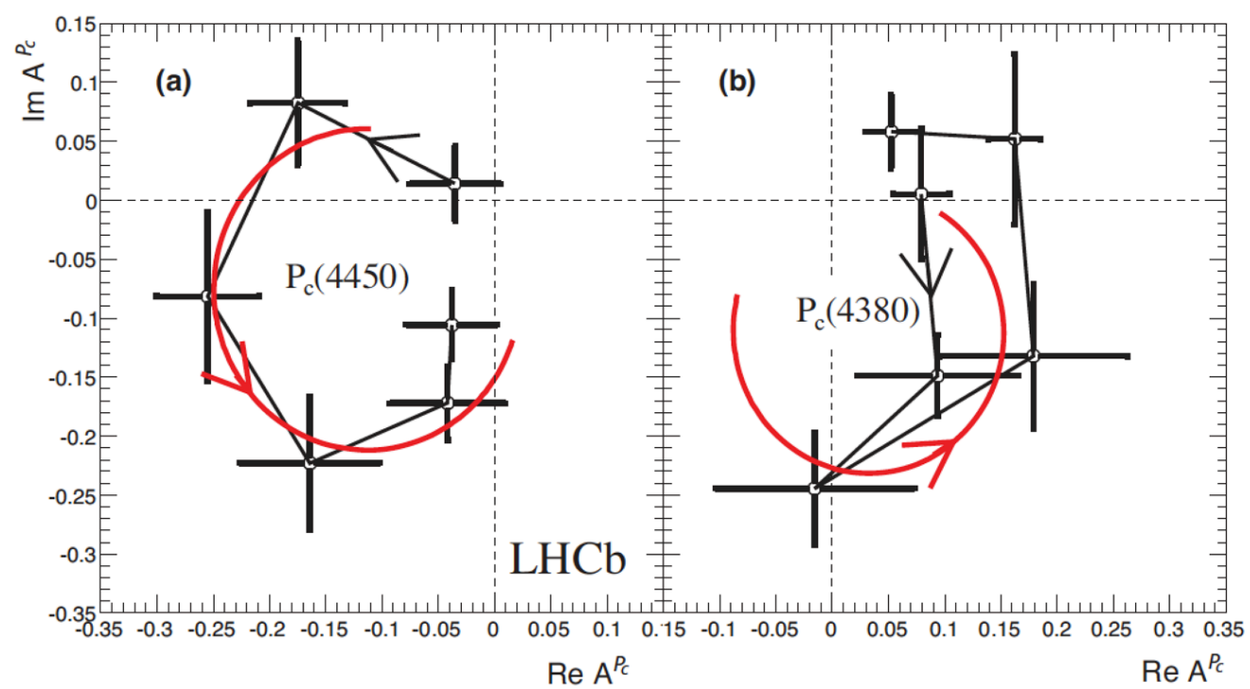
Pentaquarks: LHCb







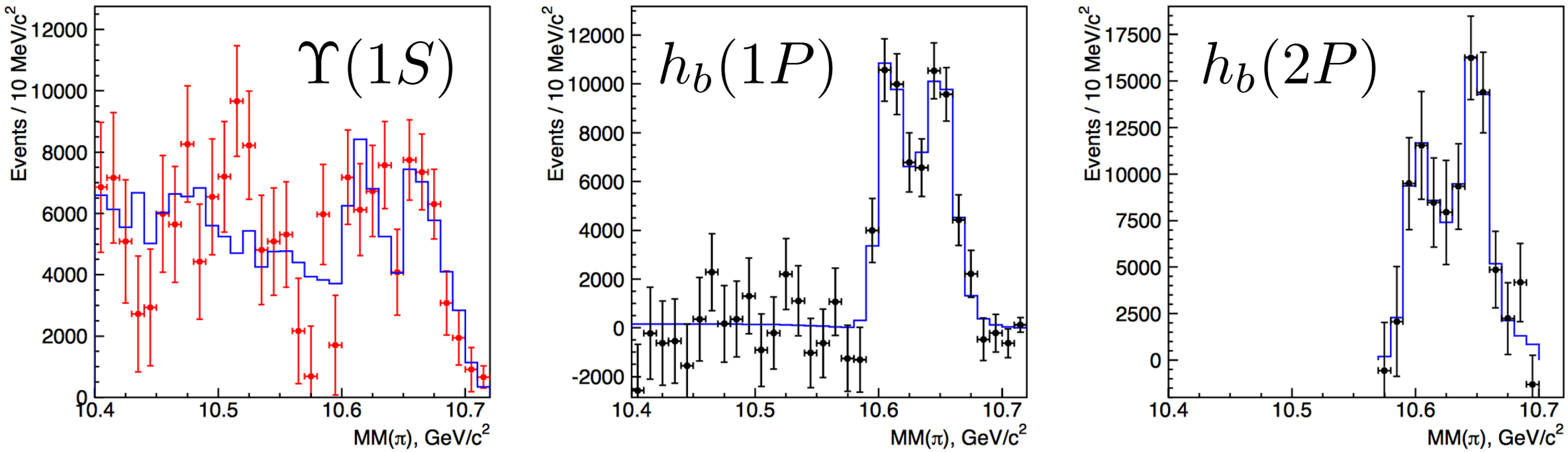
PRL 115 (2015) 072001



Other charged bottomonium states

$Z_b(10610)$ and $Z_b(10650)$

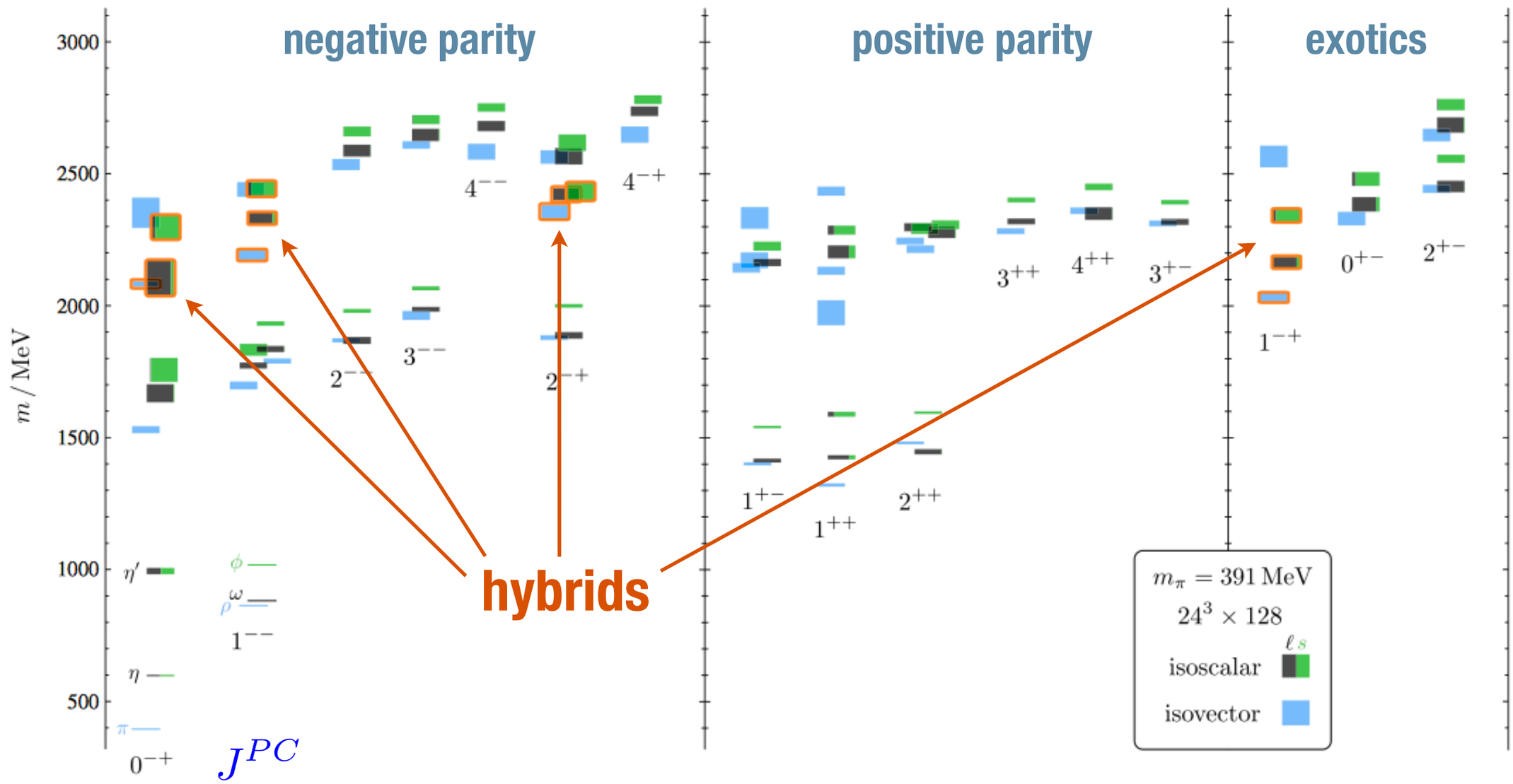
Belle [1105.4583]



- 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

Light quark hybrids

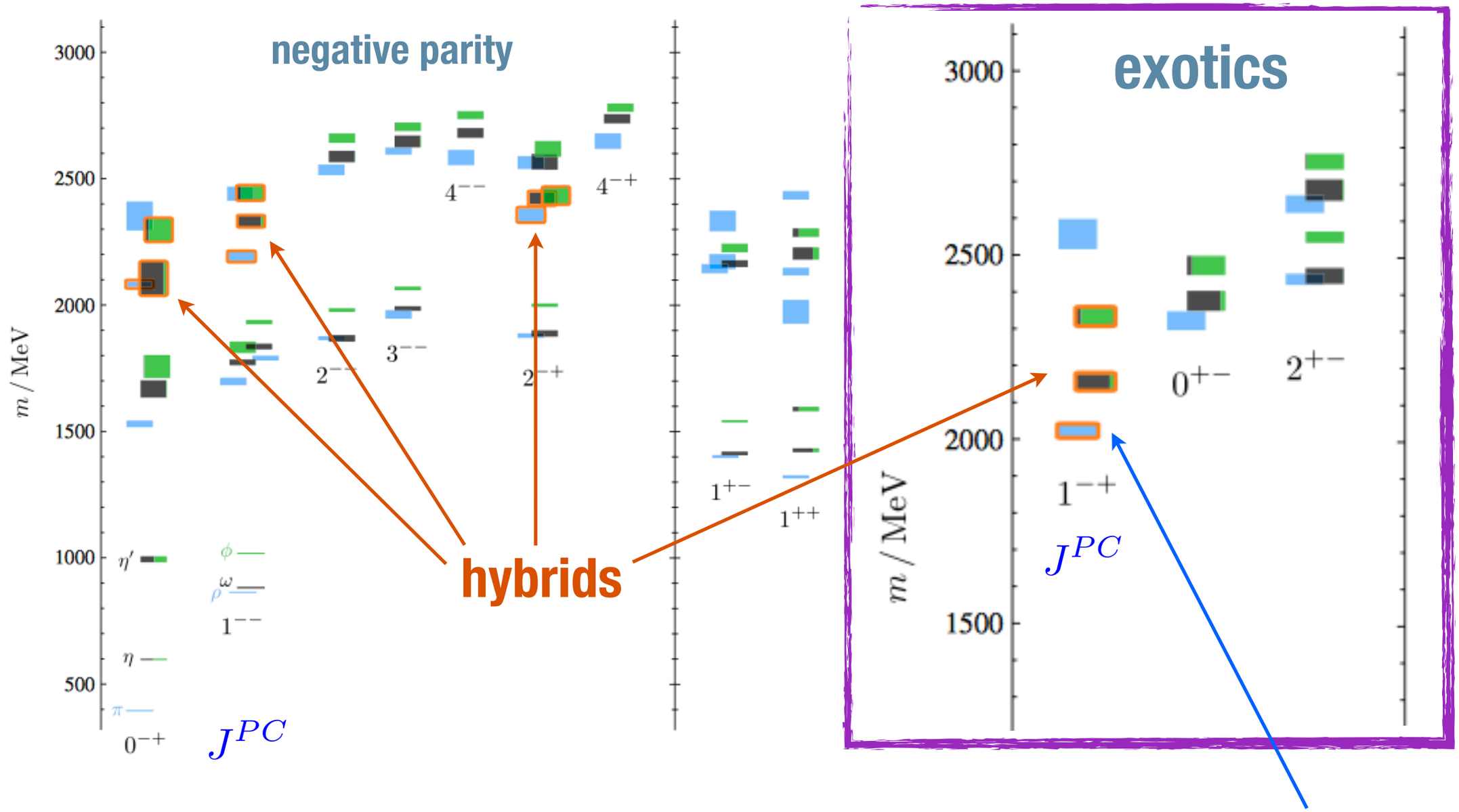
Dudek et al. PRD 88 (2013) 094505



- Most experimental searches for hybrids limited to the **π_1 state**
- The goal of the JLab 12 spectroscopy program is to search for and ultimately map out the spectrum of light quark hybrid mesons

Light quark hybrids

Dudek et al. PRD 88 (2013) 094505

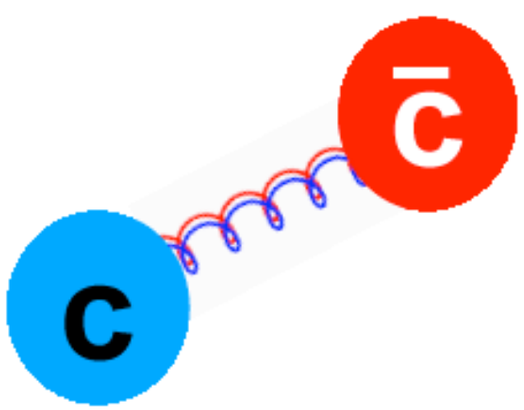


- Most experimental searches for hybrids limited to the **π_1 state**
- The goal of the JLab 12 spectroscopy program is to search for and ultimately map out the spectrum of light quark hybrid mesons

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



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)	

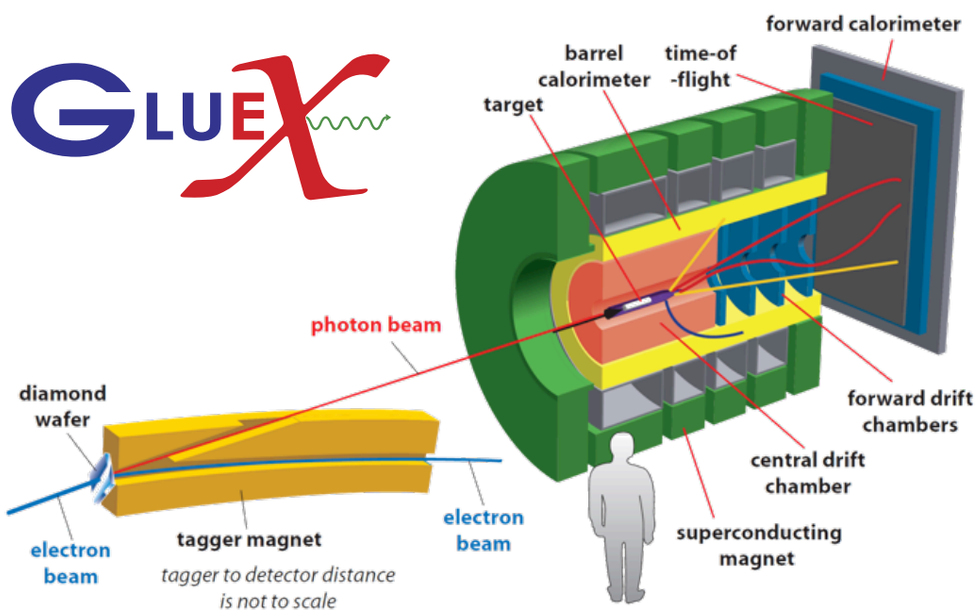
Y(4260)?

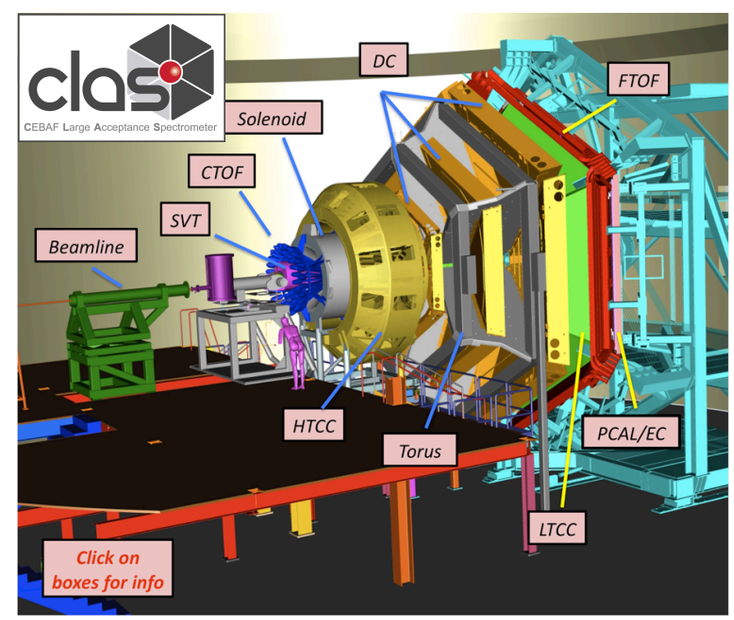
Exotic Hybrid

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

Weizsäcker-Williams Approximation

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

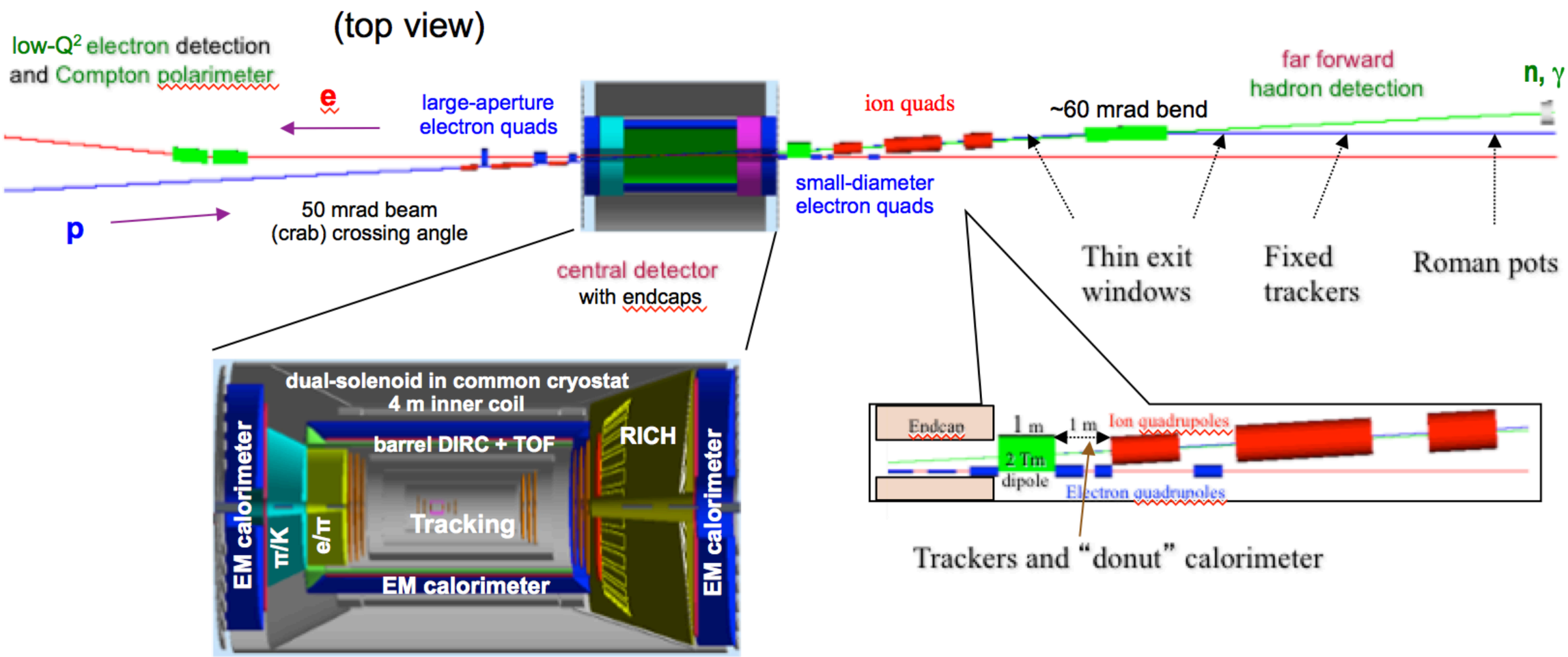
$$d\sigma_{ep} = \sigma_{\gamma p}(q,k) f_\gamma^{(e)}(y) dy$$

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

- 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

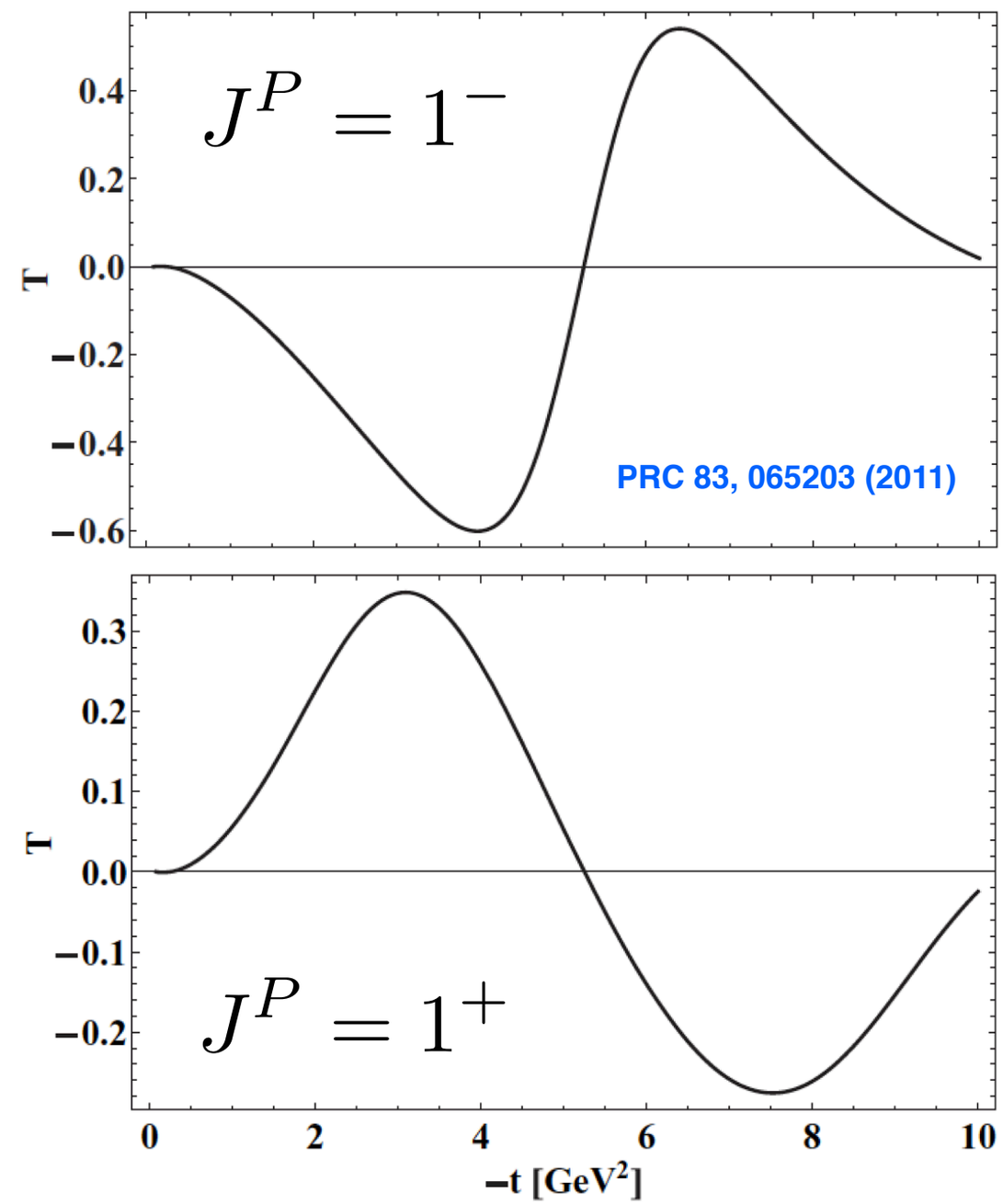
Frixione et. al. PLB 319 (1993) 339

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

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

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