Hadron Spectroscopy at GlueX and Beyond (5)

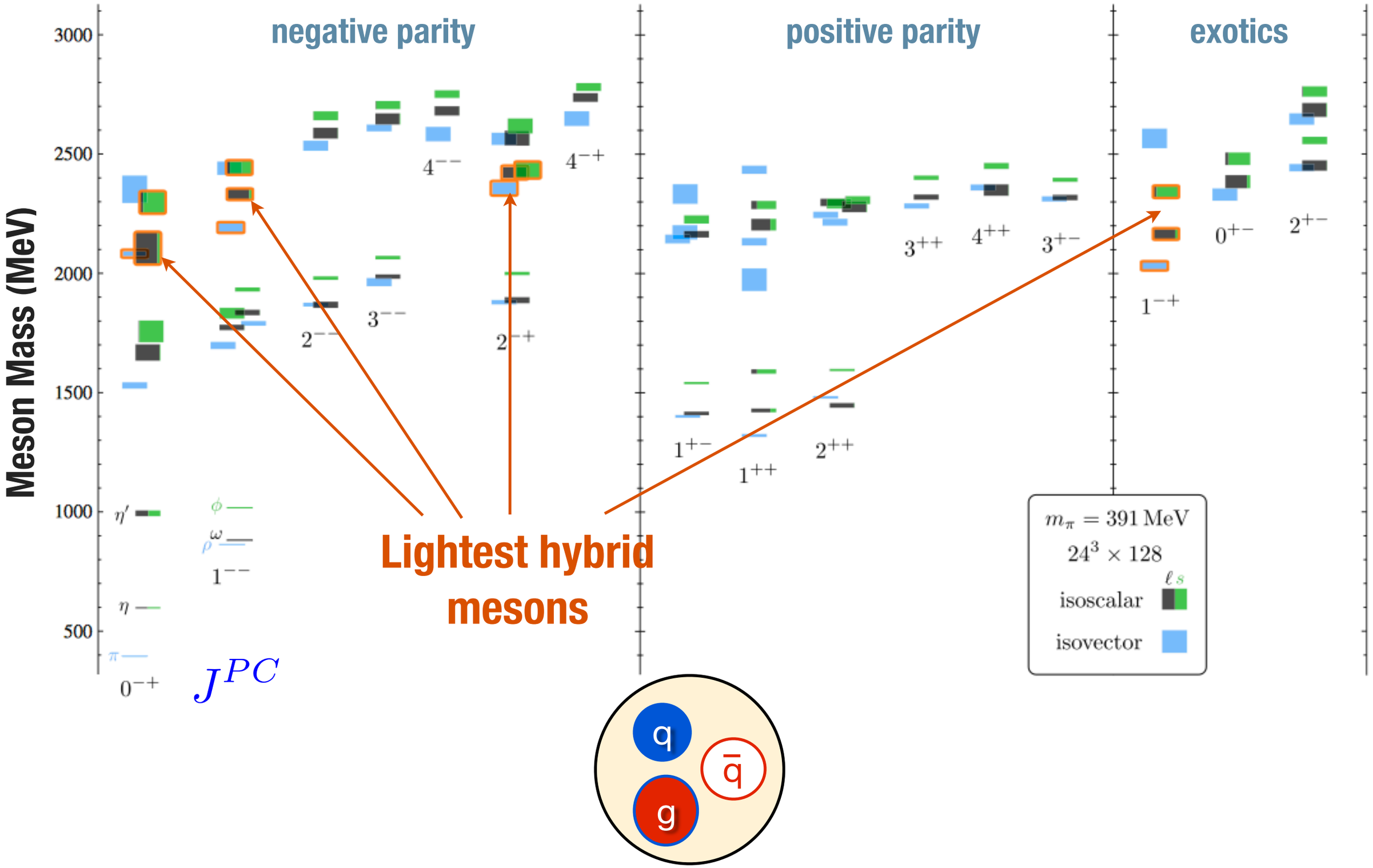
Justin Stevens

WILLIAM & MARY
CHARTERED 1693

Lattice QCD: Mesons

hadspec
hadron spectrum collaboration

PRD 88 (2013) 094505



Lattice QCD: Baryons

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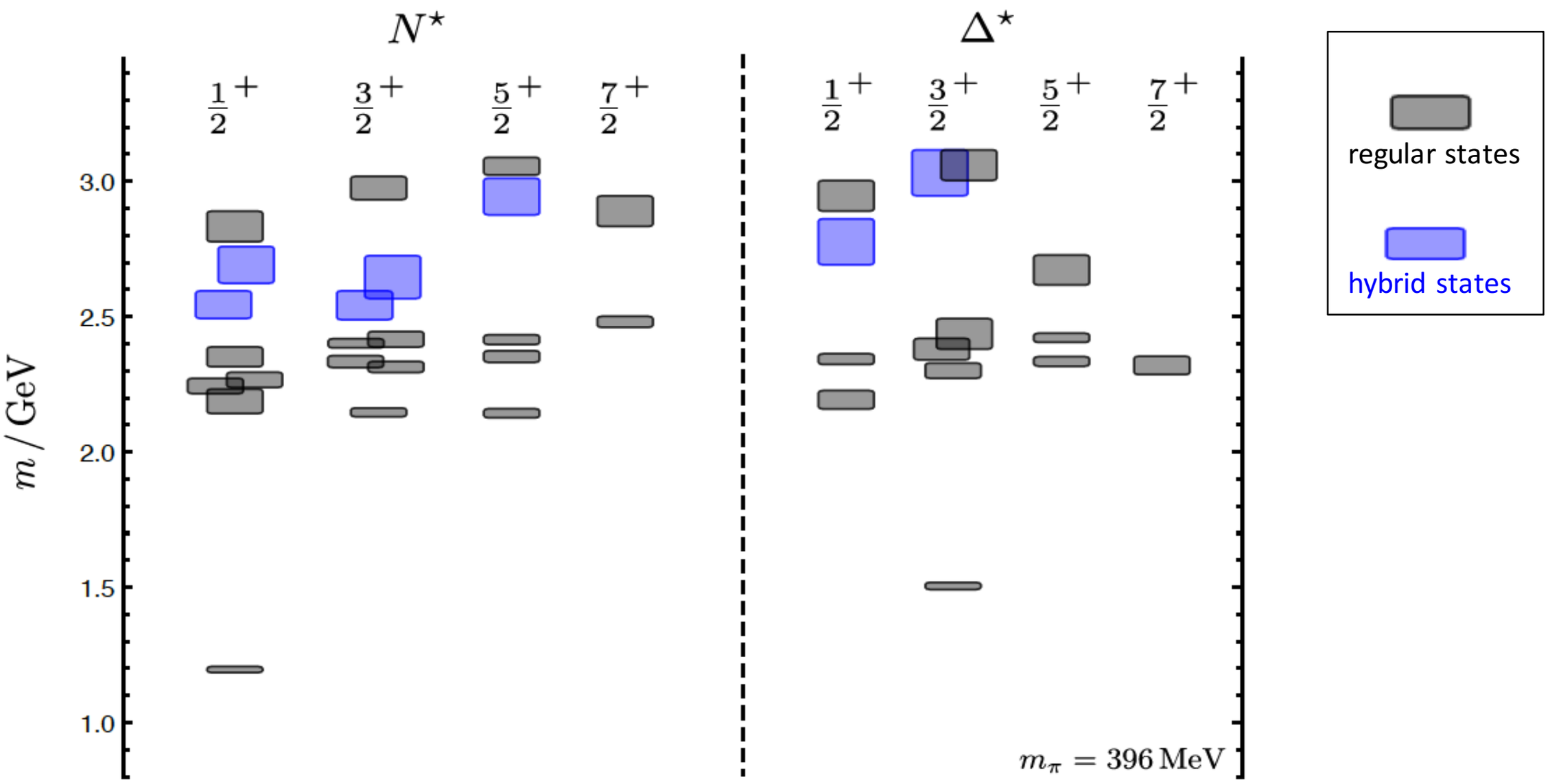
PRD 85 (2012) 054016



- No exotic quantum numbers unlike meson sector
- Expect additional states in the spectrum for hybrids **(later)**

Lattice QCD: Putting it all together

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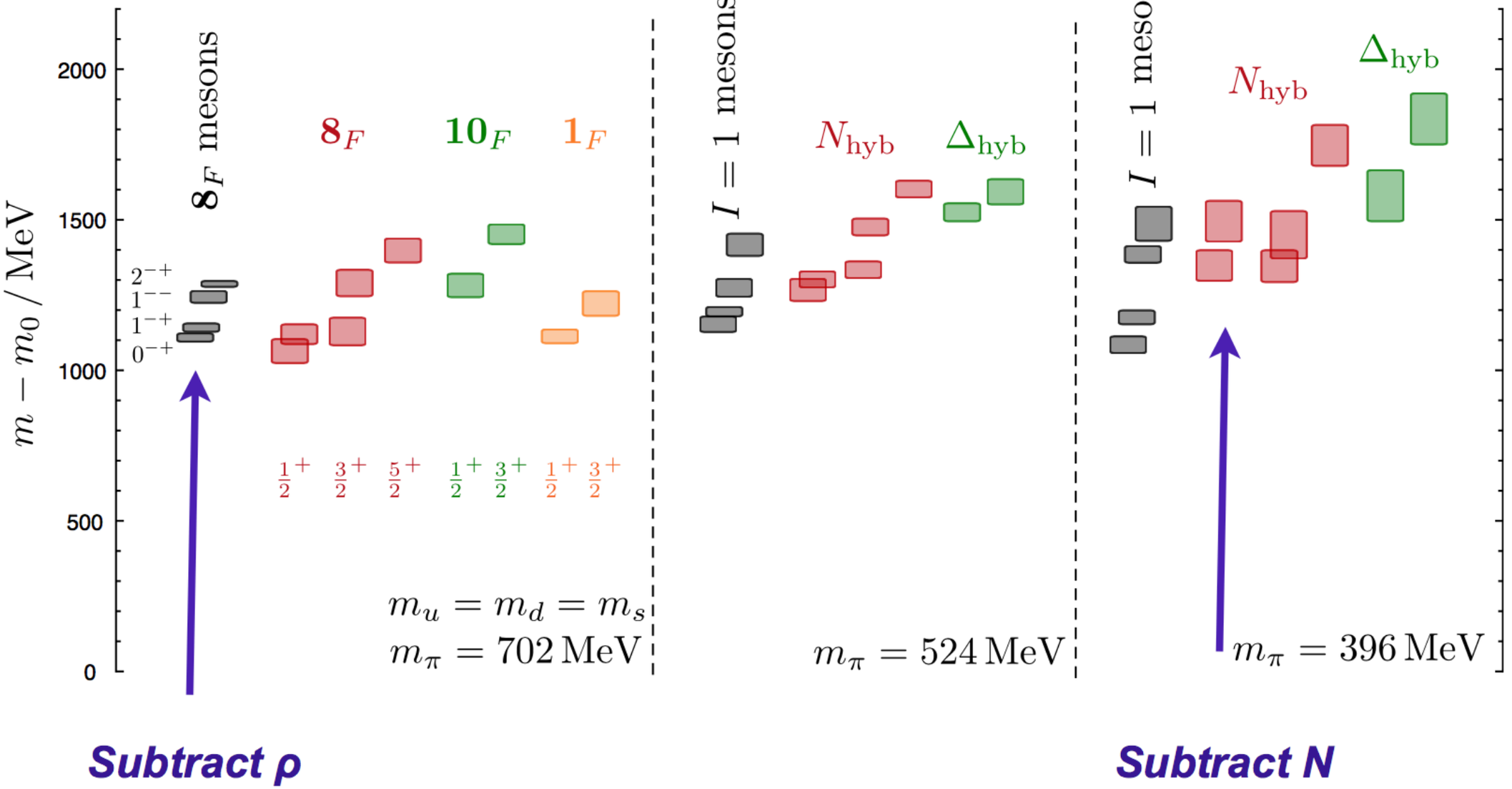
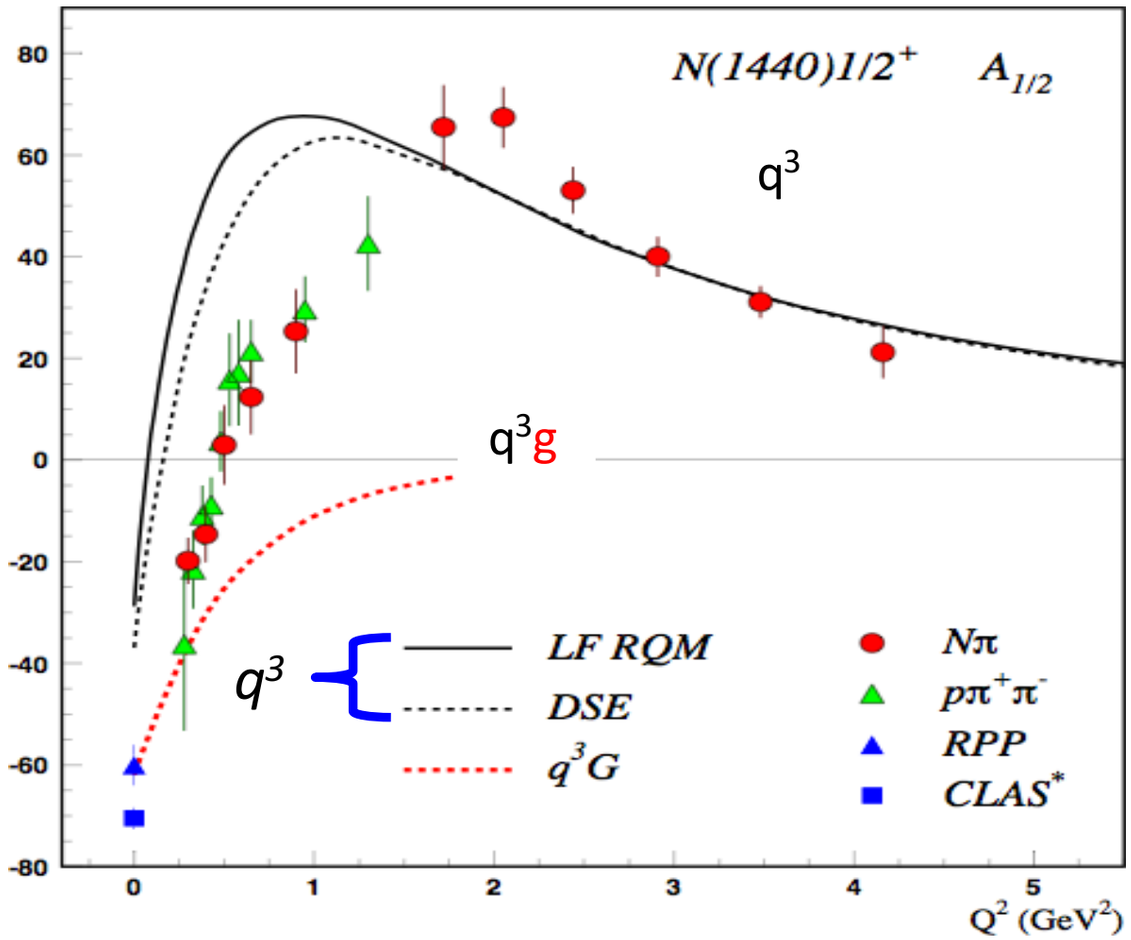
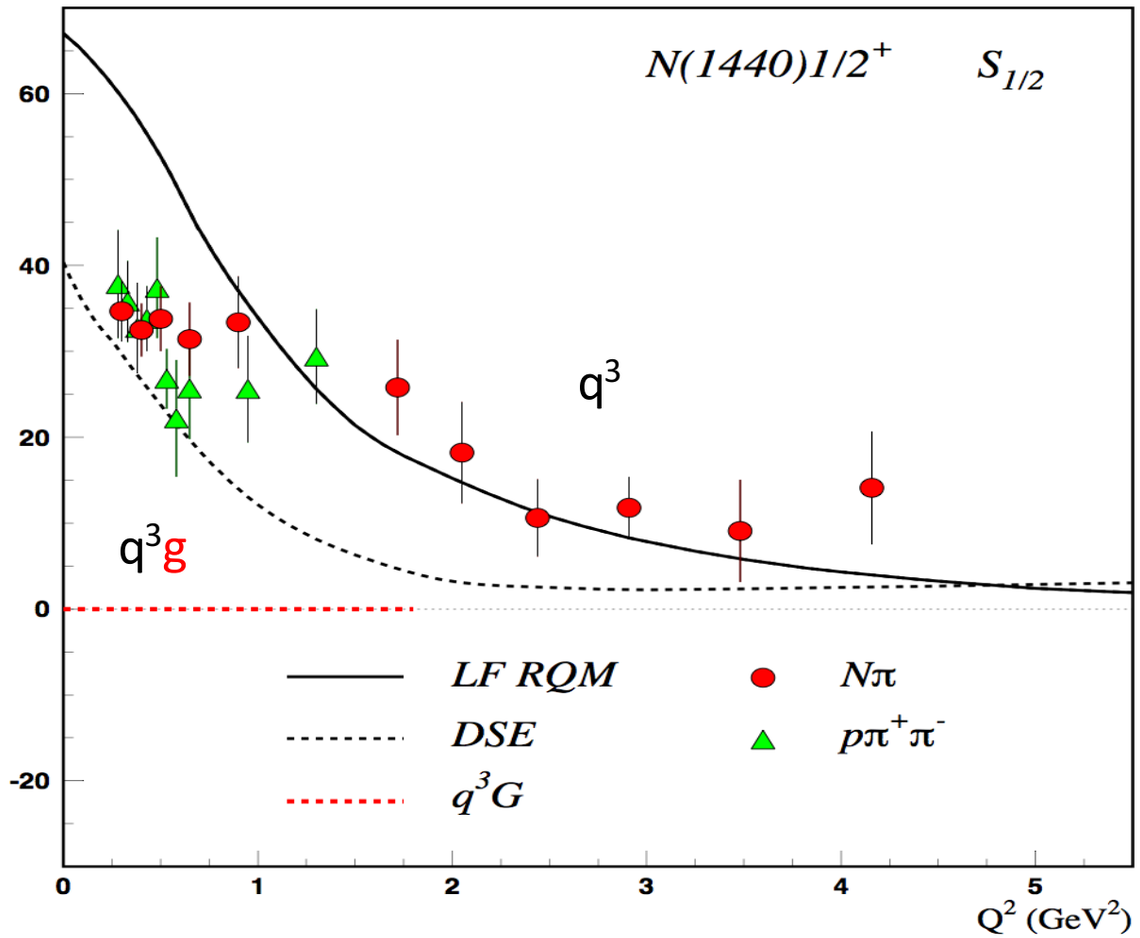


Subtract ρ ***Subtract N***

- Common mechanism both meson and baryon hybrids: **gluonic field** with $J^{PC}=1^{+-}$ and M=1-1.5 GeV

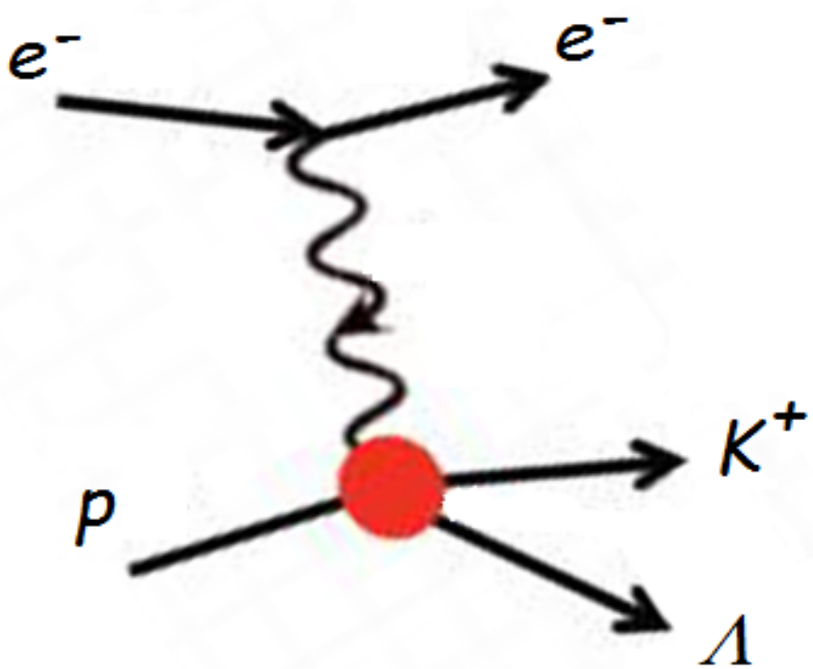
Hybrid Baryons:

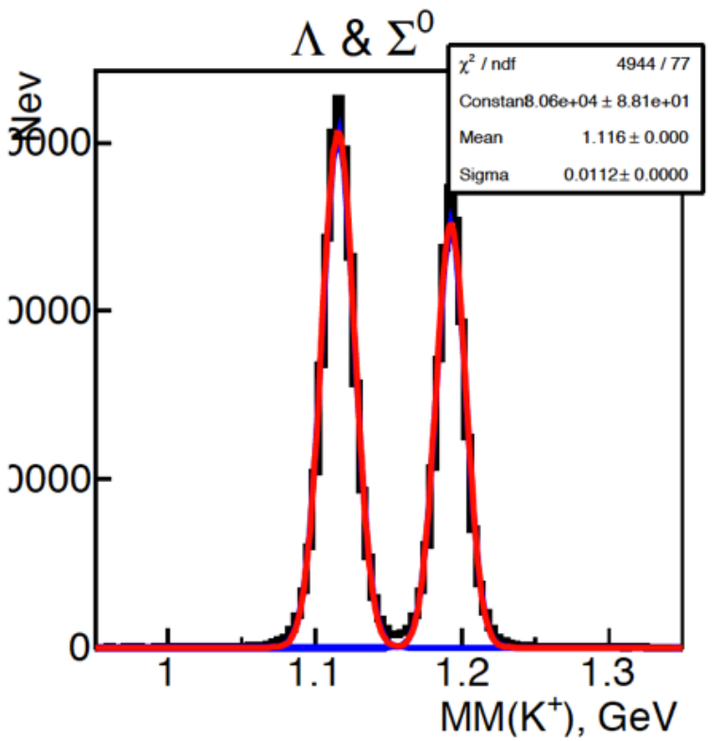


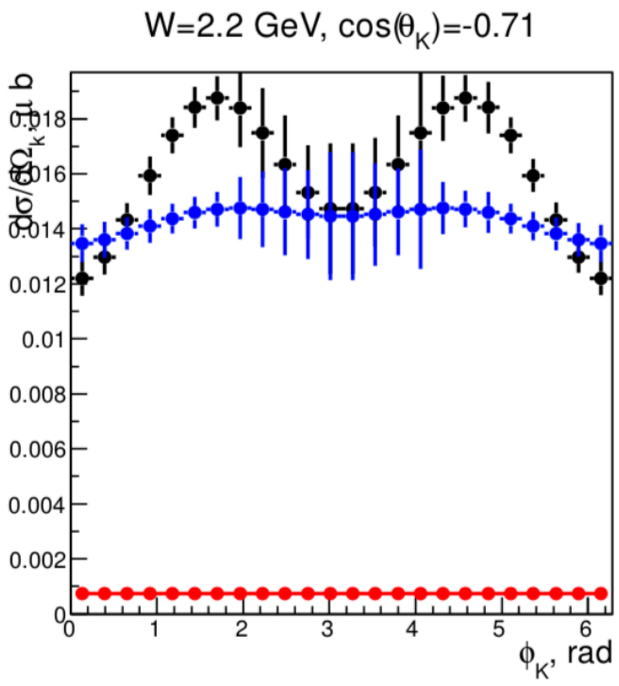


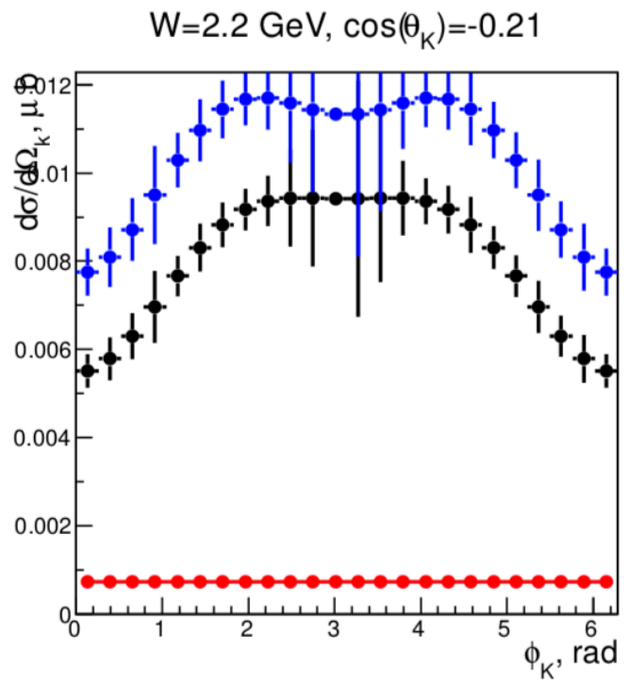
- Models predict different Q^2 dependence for amplitudes
- N(1440) not a hybrid based on CLAS 6 GeV data, extend to more N* states with CLAS12

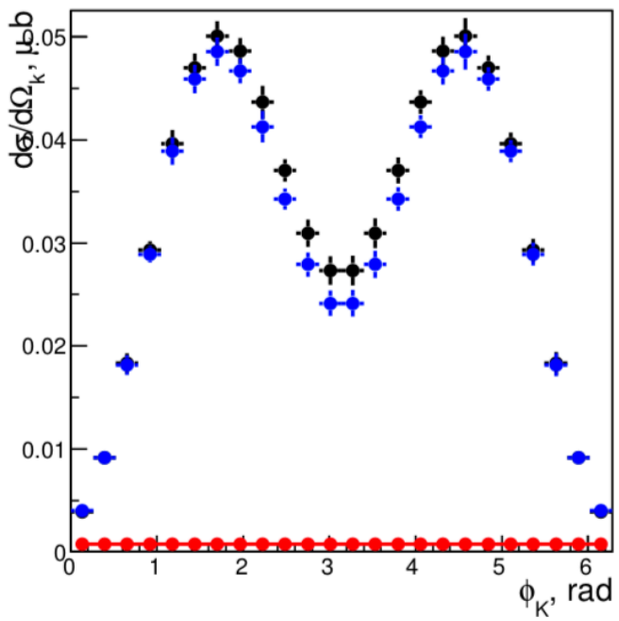
Hybrid Baryons: CLAS12

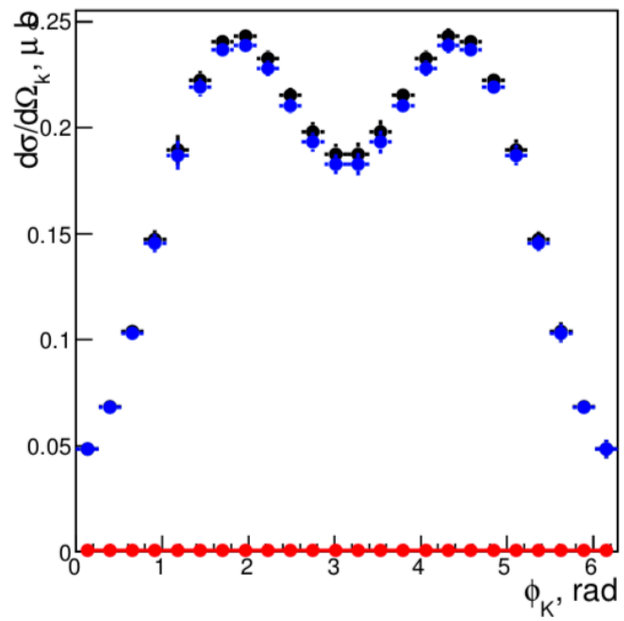










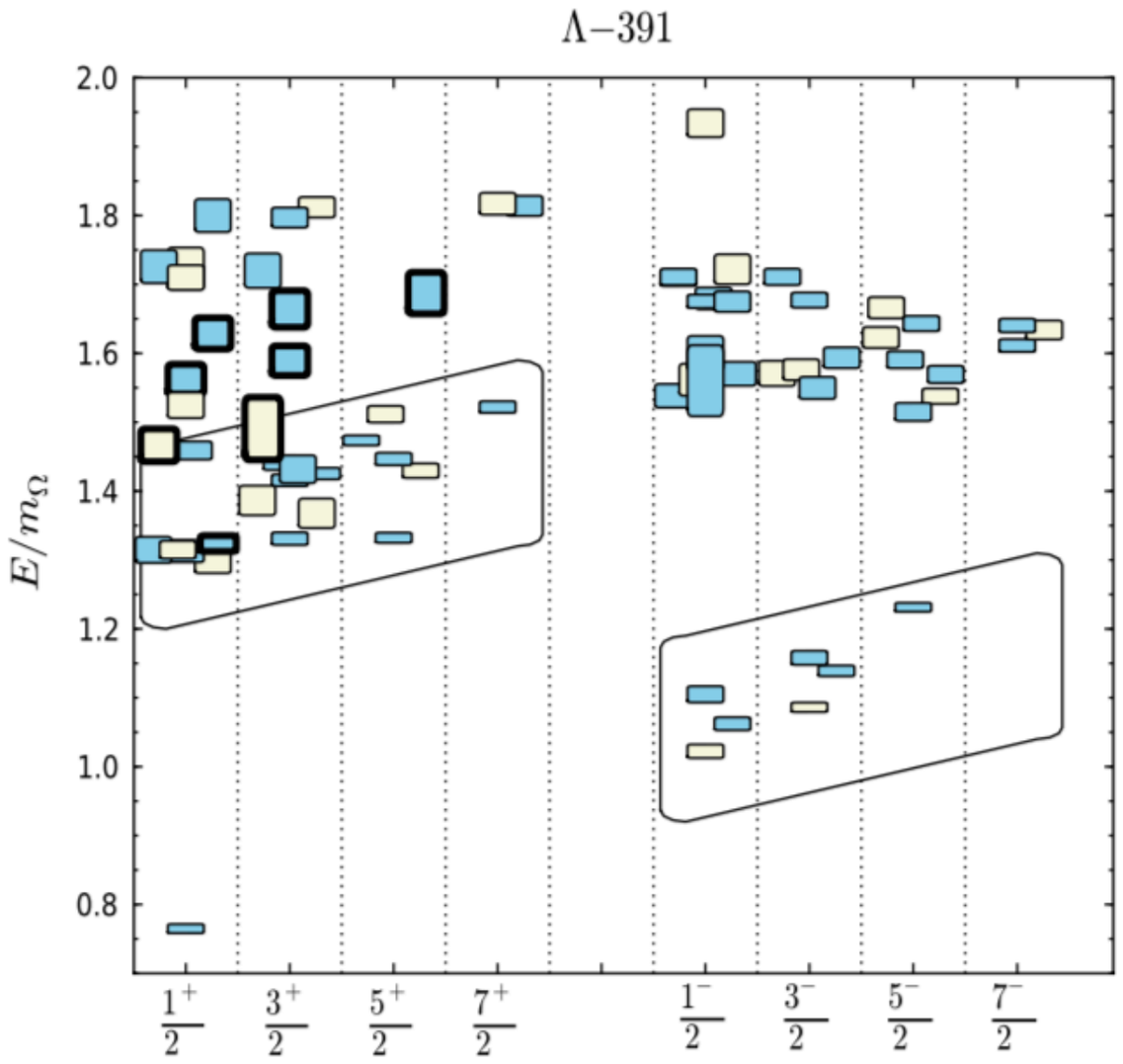


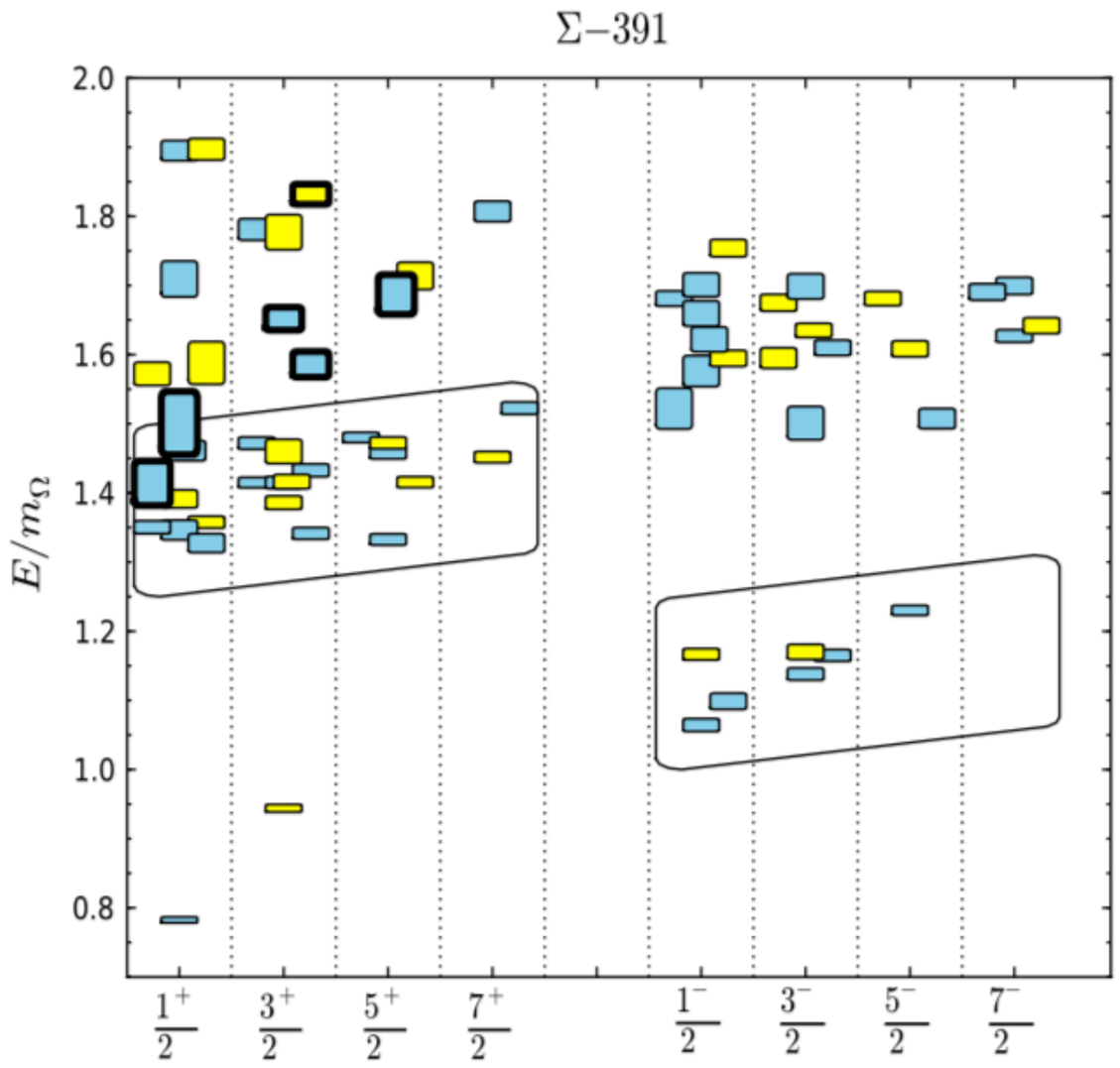
PAC Proposal: PR12-16-010

Lattice QCD: hyperons

hadspec
hadron spectrum collaboration

PRD 87 (2013) 054506





- Many “missing” states predicted (quark model and LQCD) but not observed or “need confirmation” (PDG)

Lattice QCD: hyperons

hadspec
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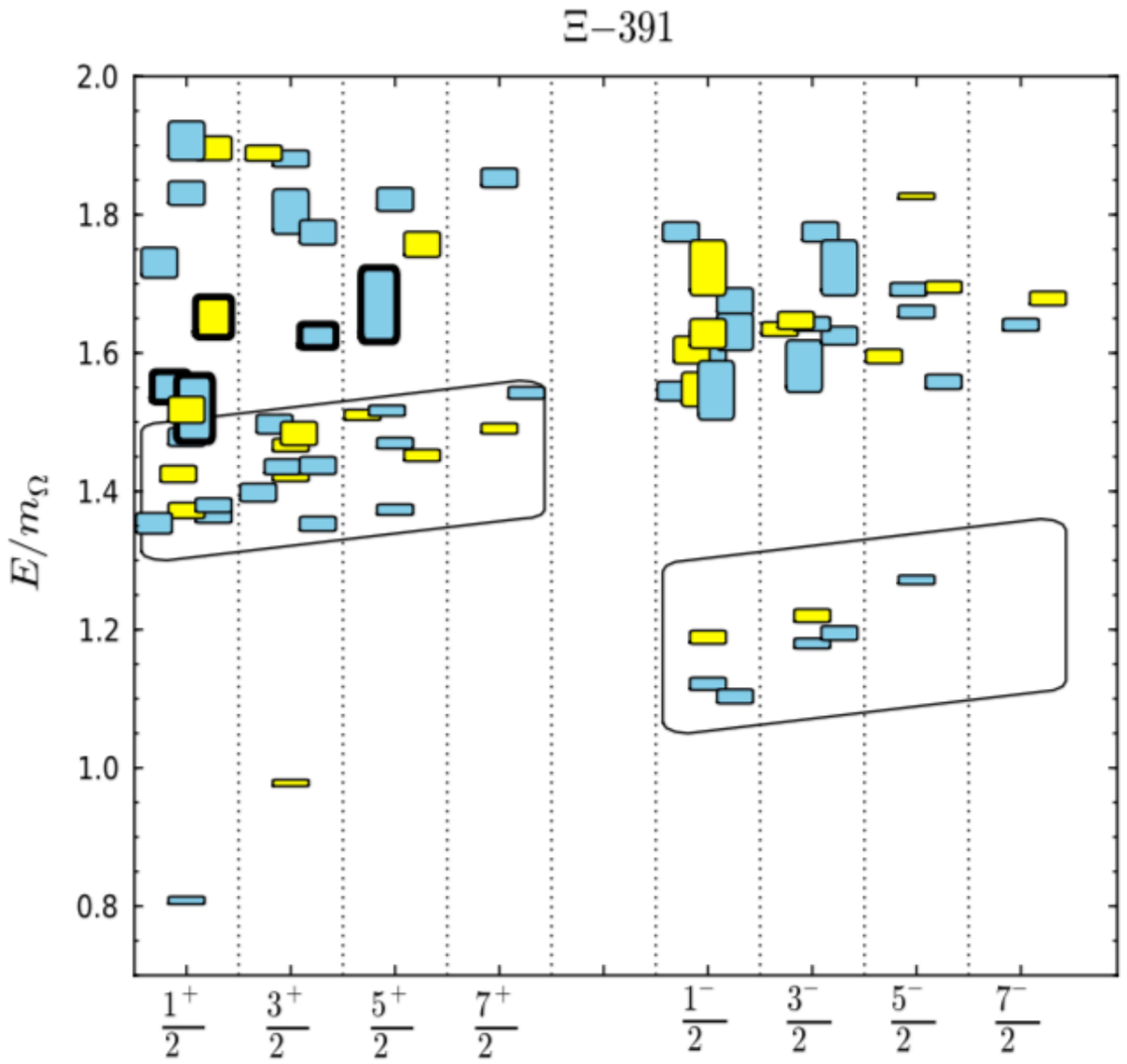
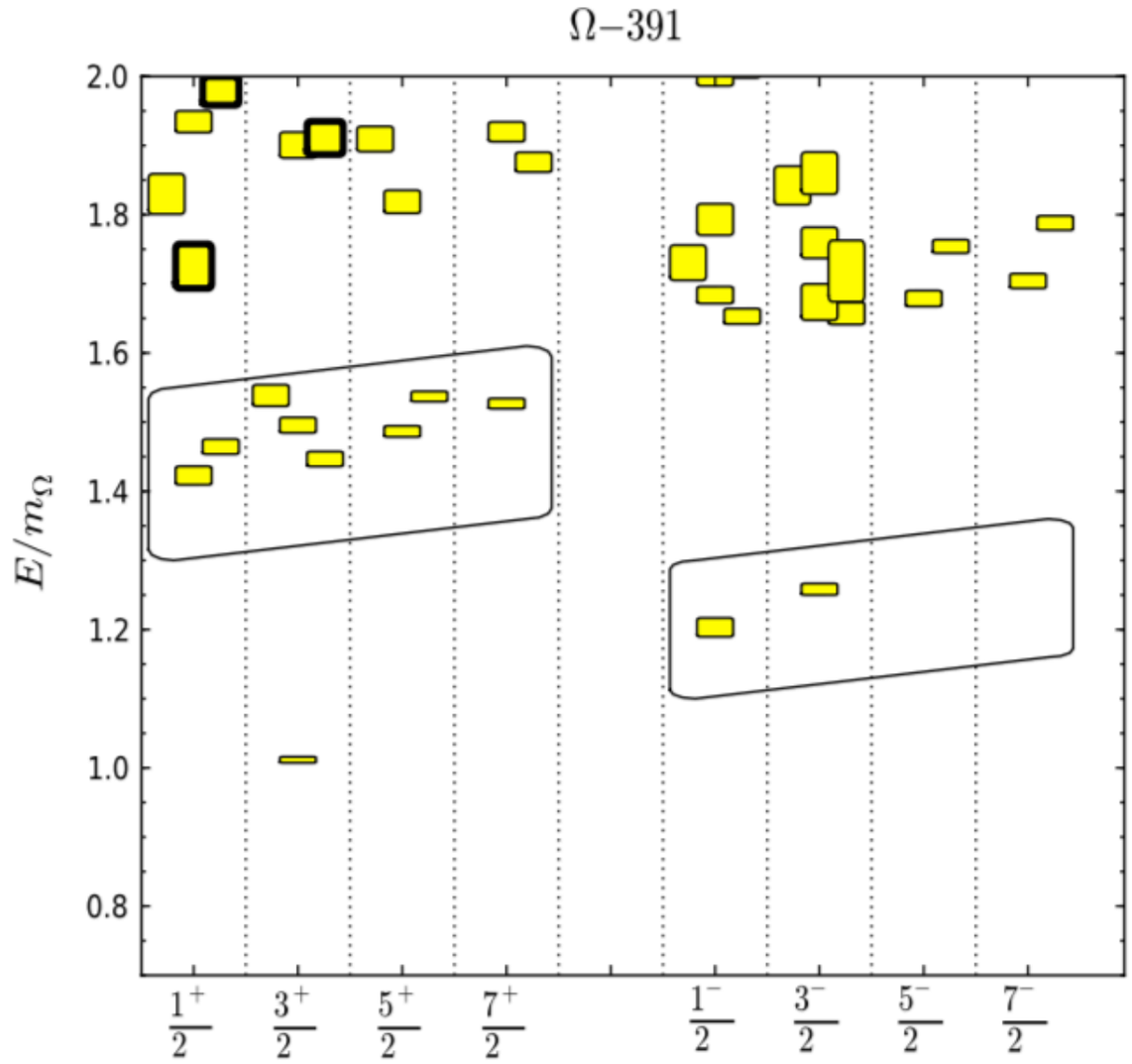
PRD 87 (2013) 054506

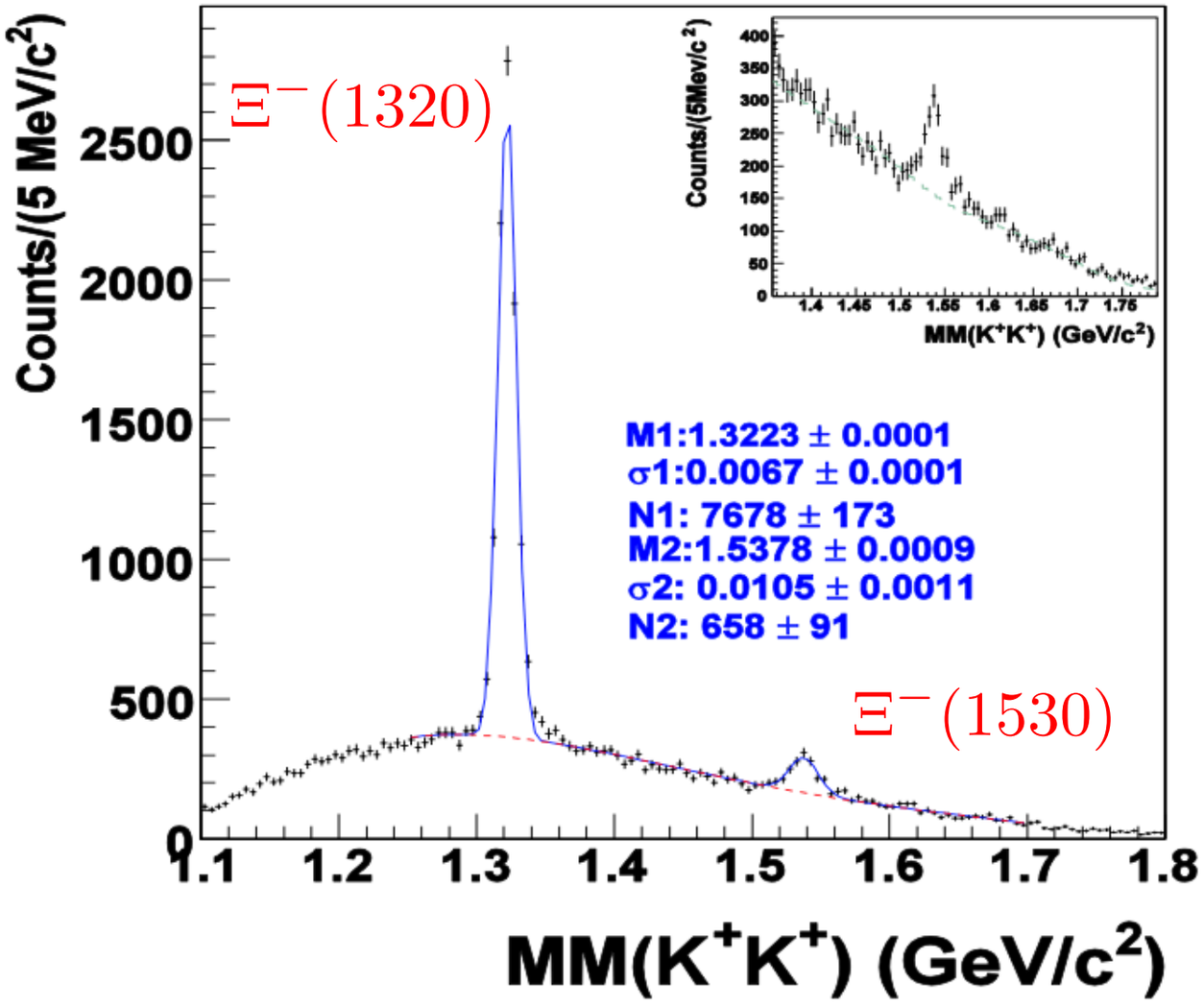


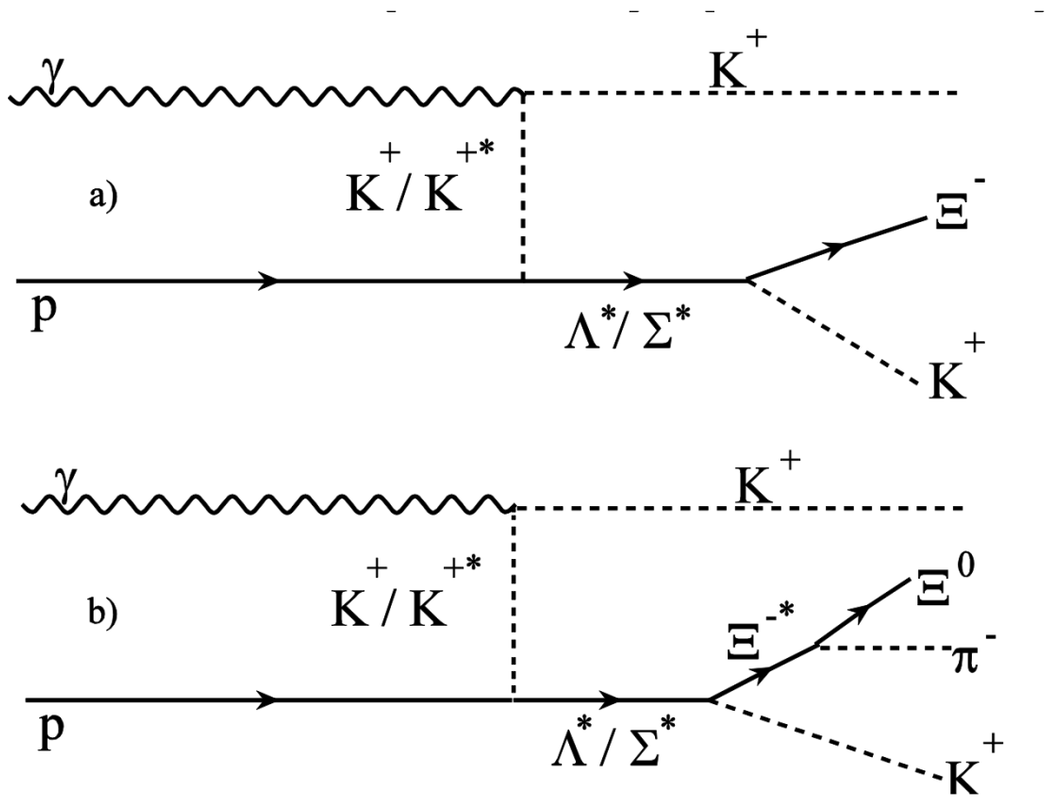


- Many “missing” states predicted (quark model and LQCD) but not observed or “need confirmation” (PDG)

Hyperon Spectroscopy: $\Xi^-(dss)$

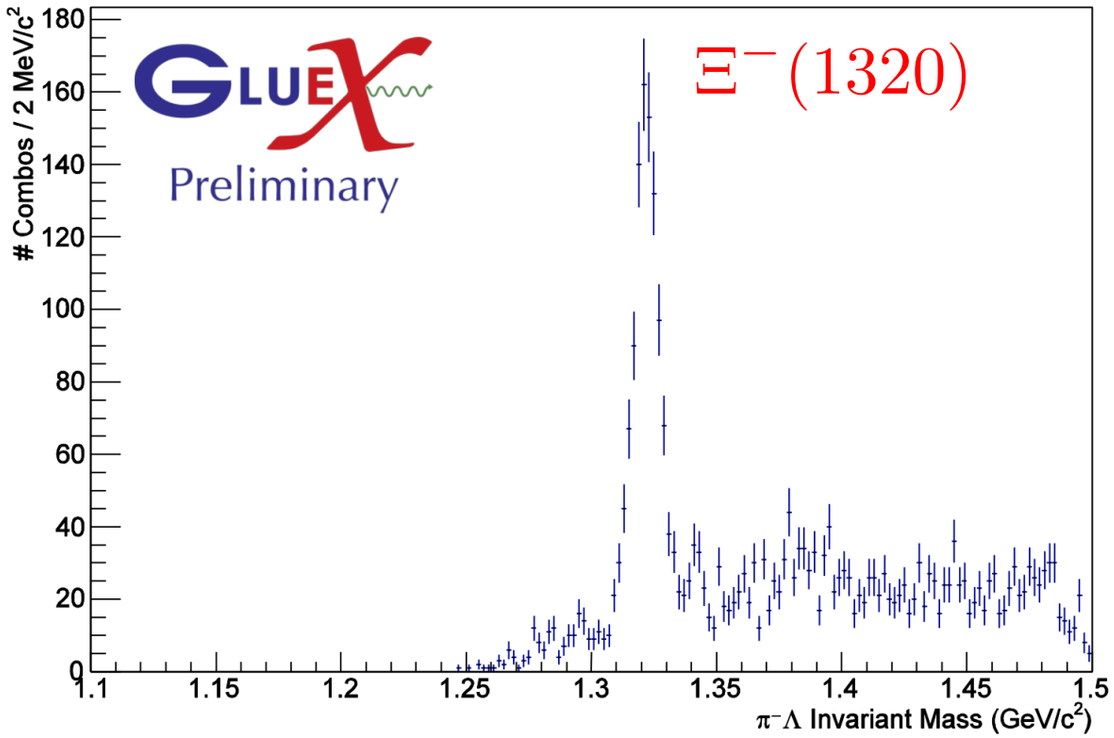
6 GeV



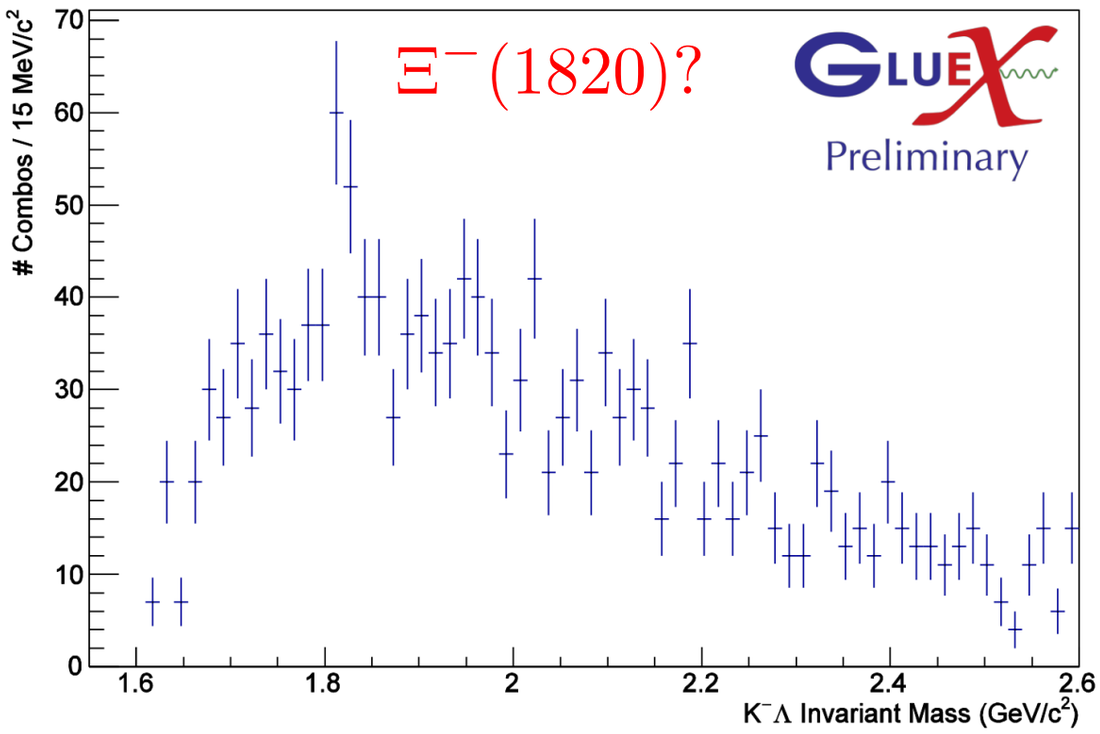


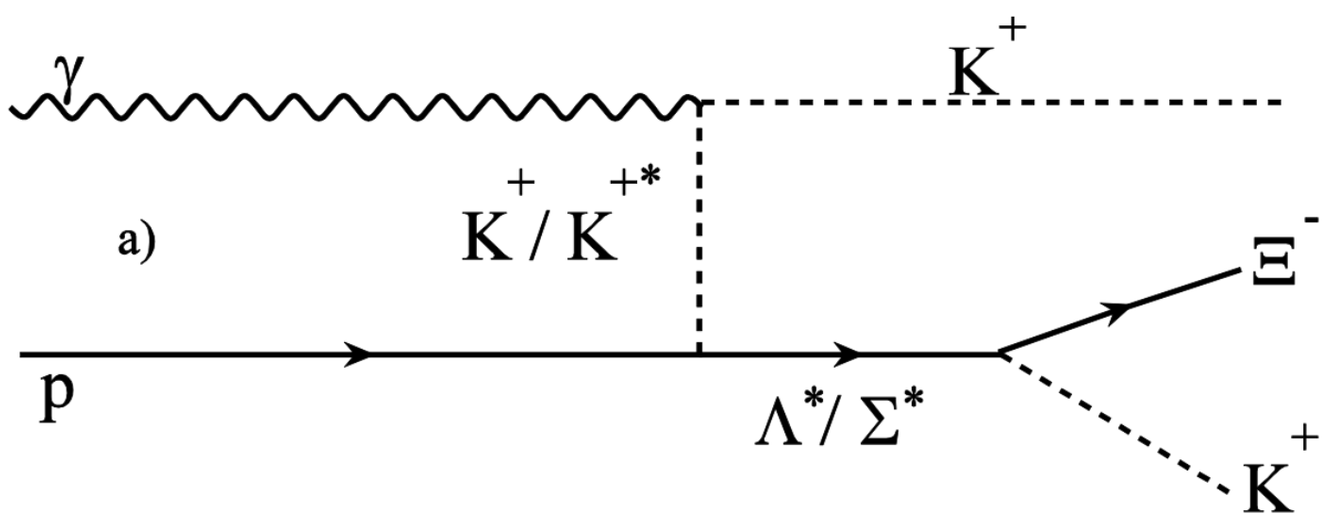
Hyperon Spectroscopy: $\Xi^-(dss)$

$\gamma p \to K^+ K^+ \Lambda \pi^-$

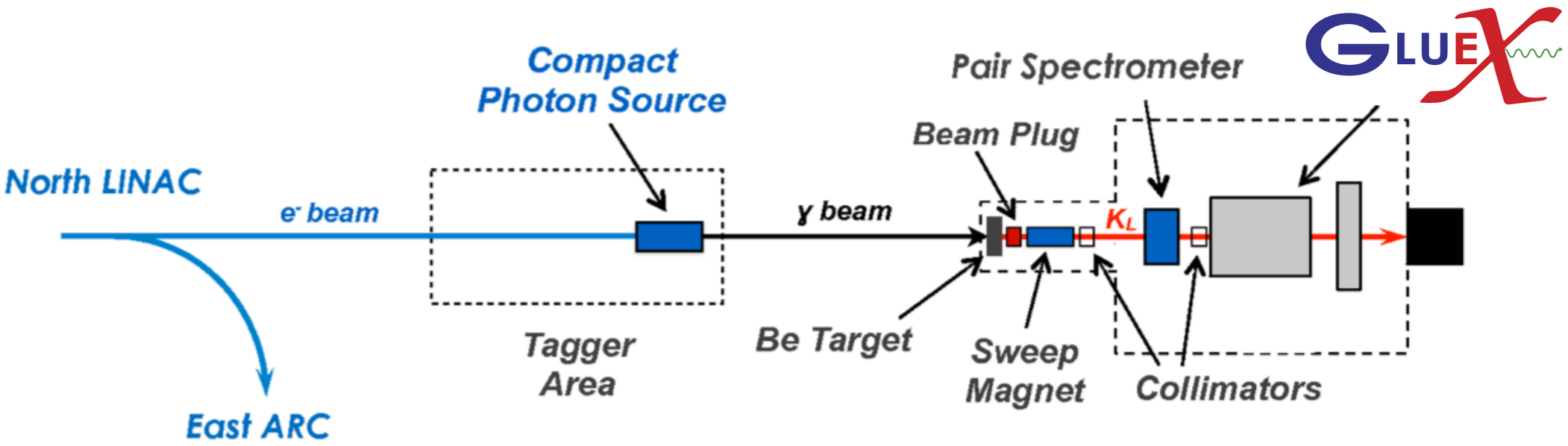


$\gamma p \to K^+ K^+ \Lambda K^-$





Hyperon spectroscopy

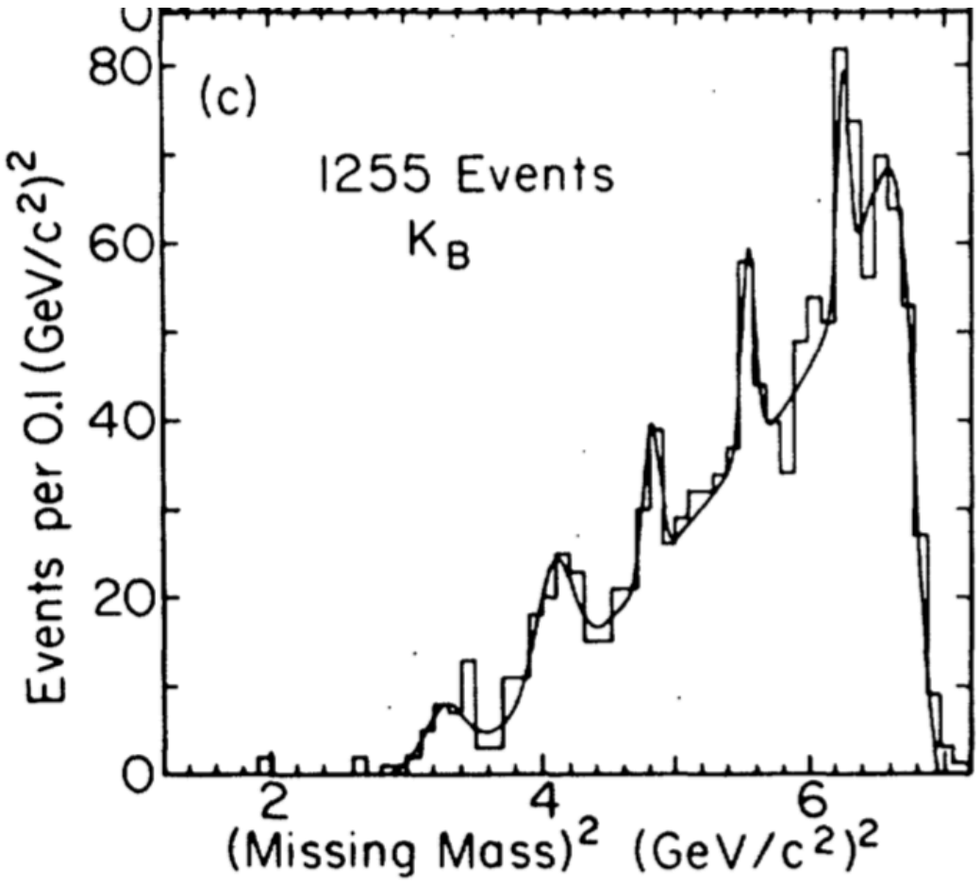


- K_{Long} Facility (**KLF**): **PAC proposal**
  - Create secondary beam of neutral K_L and use GlueX to study the K_Lp and K_Ln interactions
  - Strange quark in initial state provides enhanced source of hyperon production

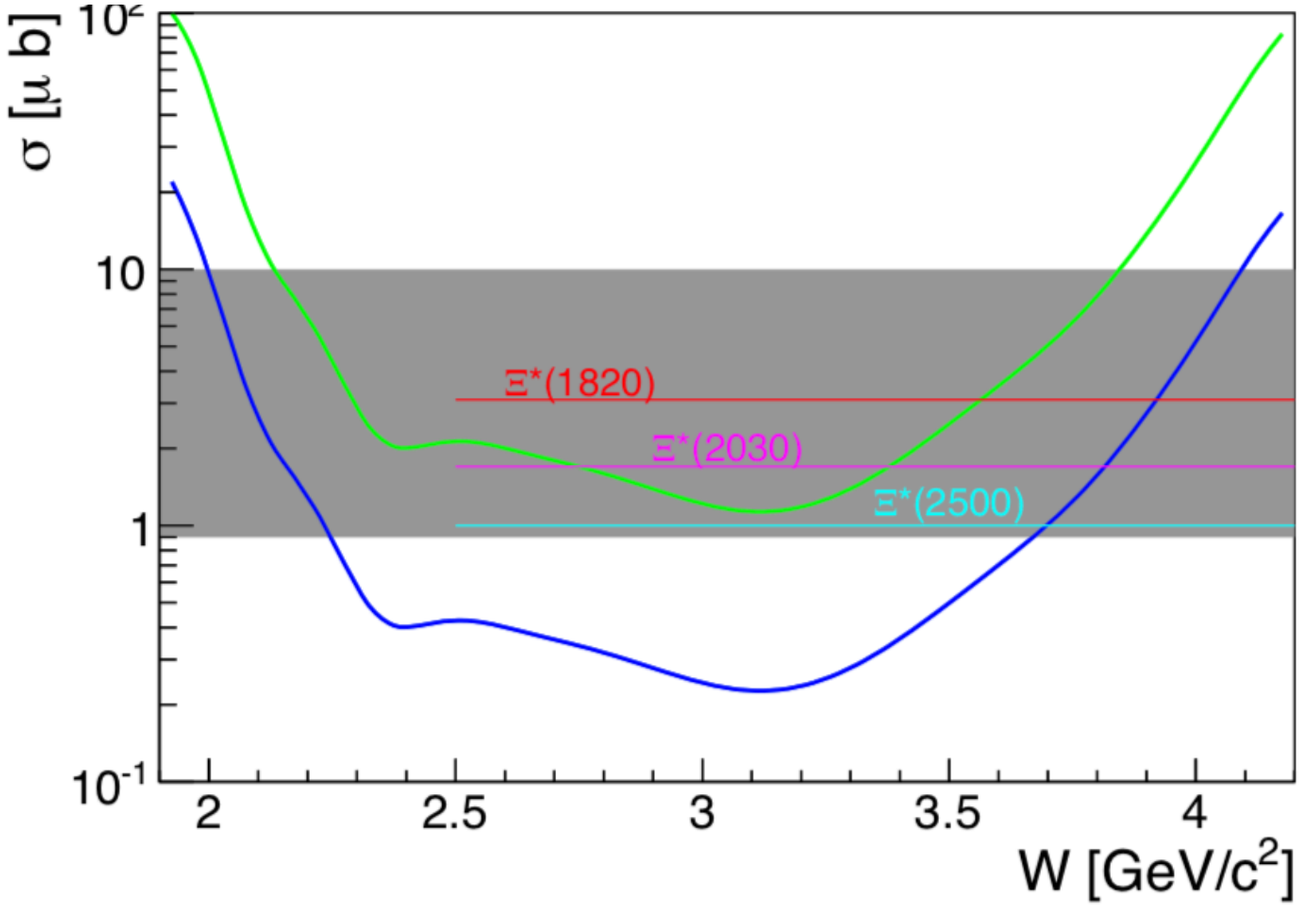
Hyperon spectroscopy

Previous evidence for Ξ* in

$$K^- p \to K^+ X$$

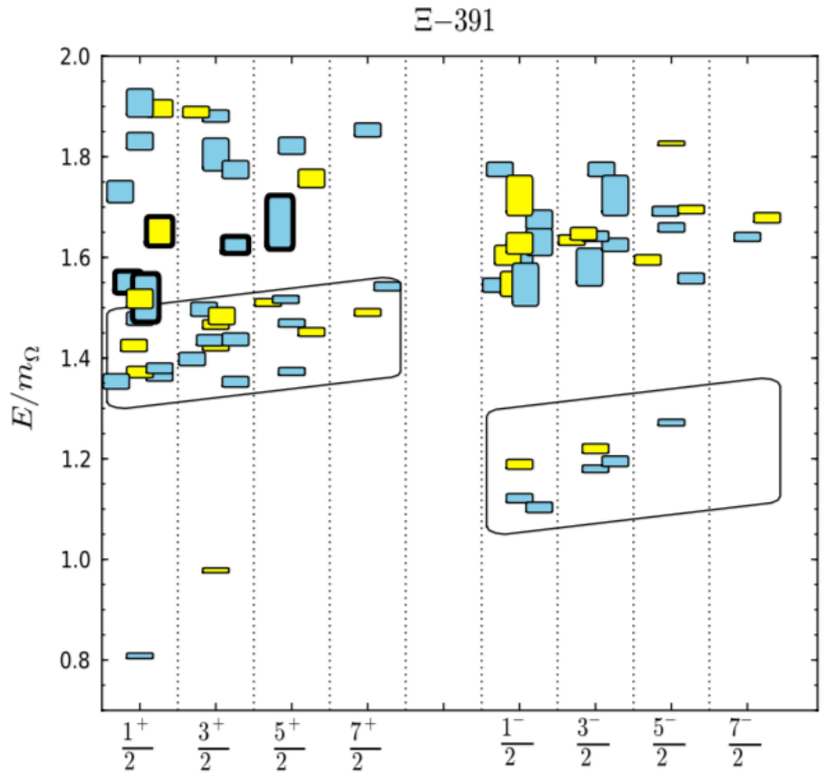


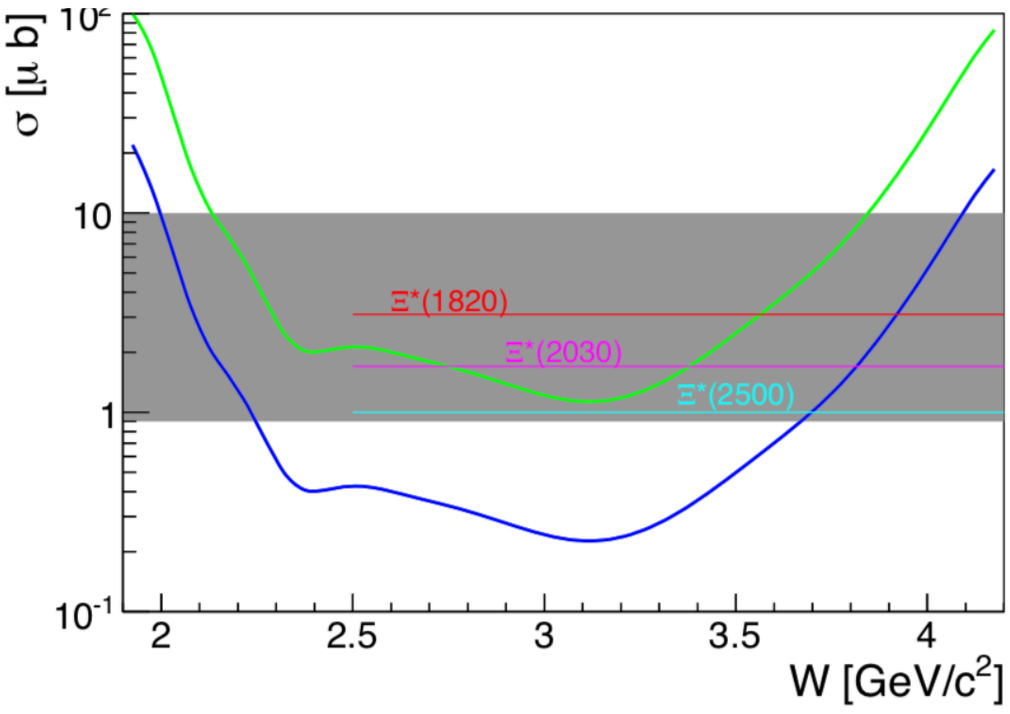
Projected sensitivity for KLF for beamtime of 20 days or 100 days



Summary: baryon spectroscopy

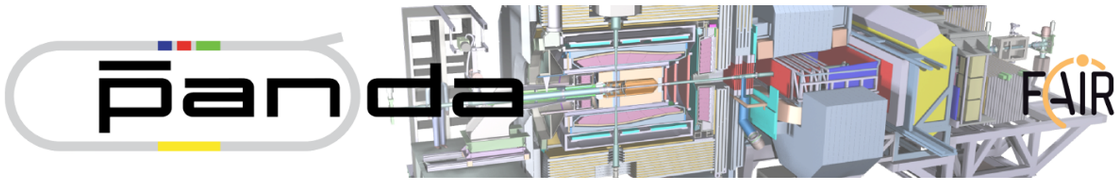
- Common mass scale for hybrid mesons and baryons, but no exotic quantum numbers for baryons
- Many excited hyperon states not yet observed, proposed program at JLab
- Interested in connections to recently observed states in the heavy quark sector

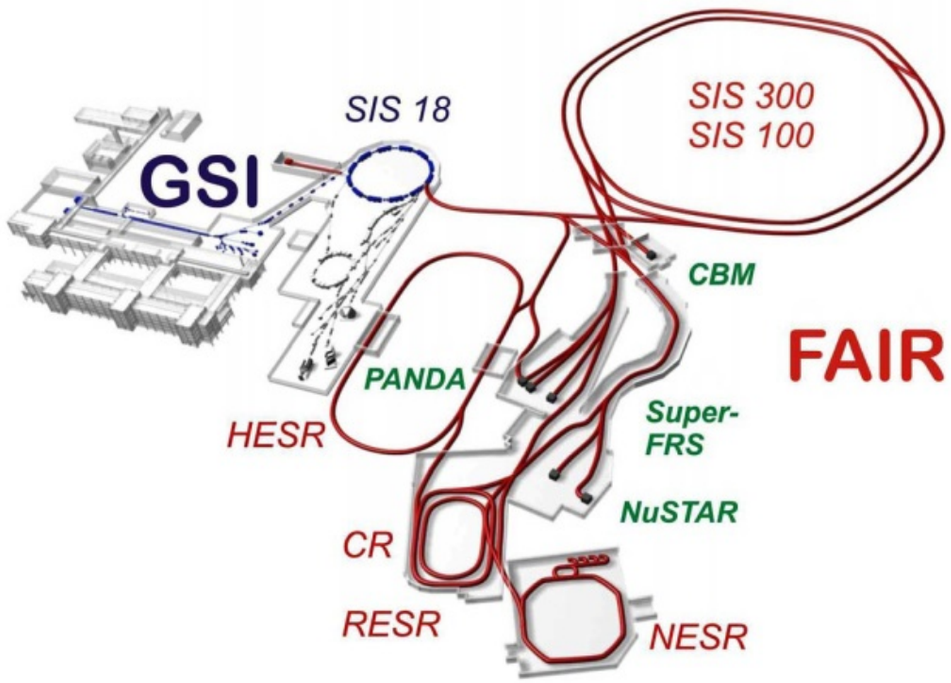




Future directions in spectroscopy

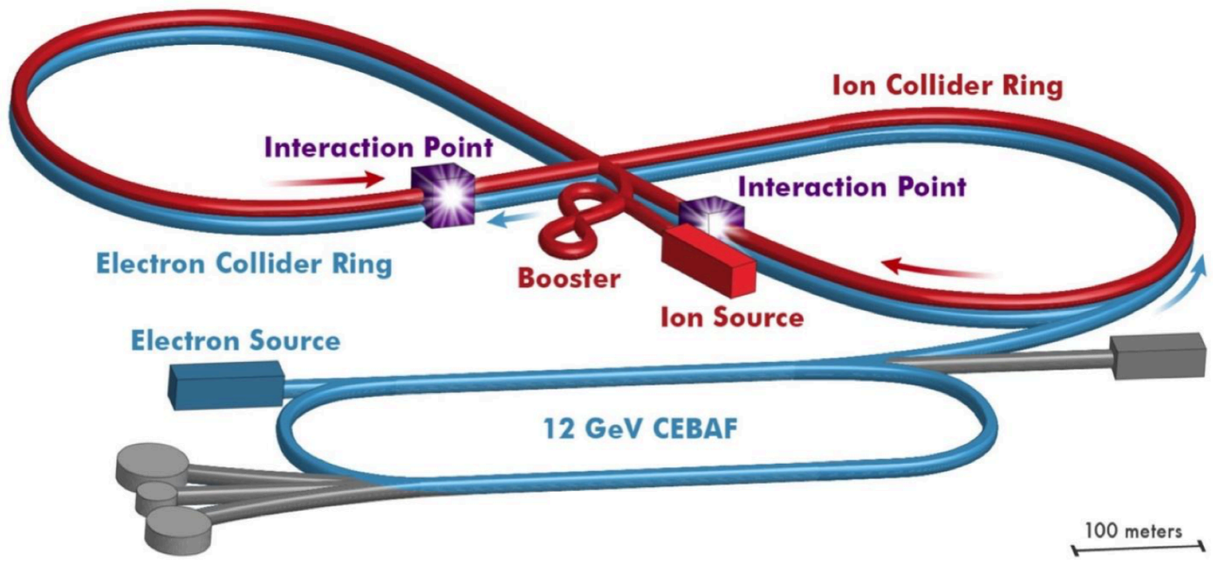
- Conclusion to the XYZ story?
- Explore new production mechanisms?





GSI: Darmstadt, Germany

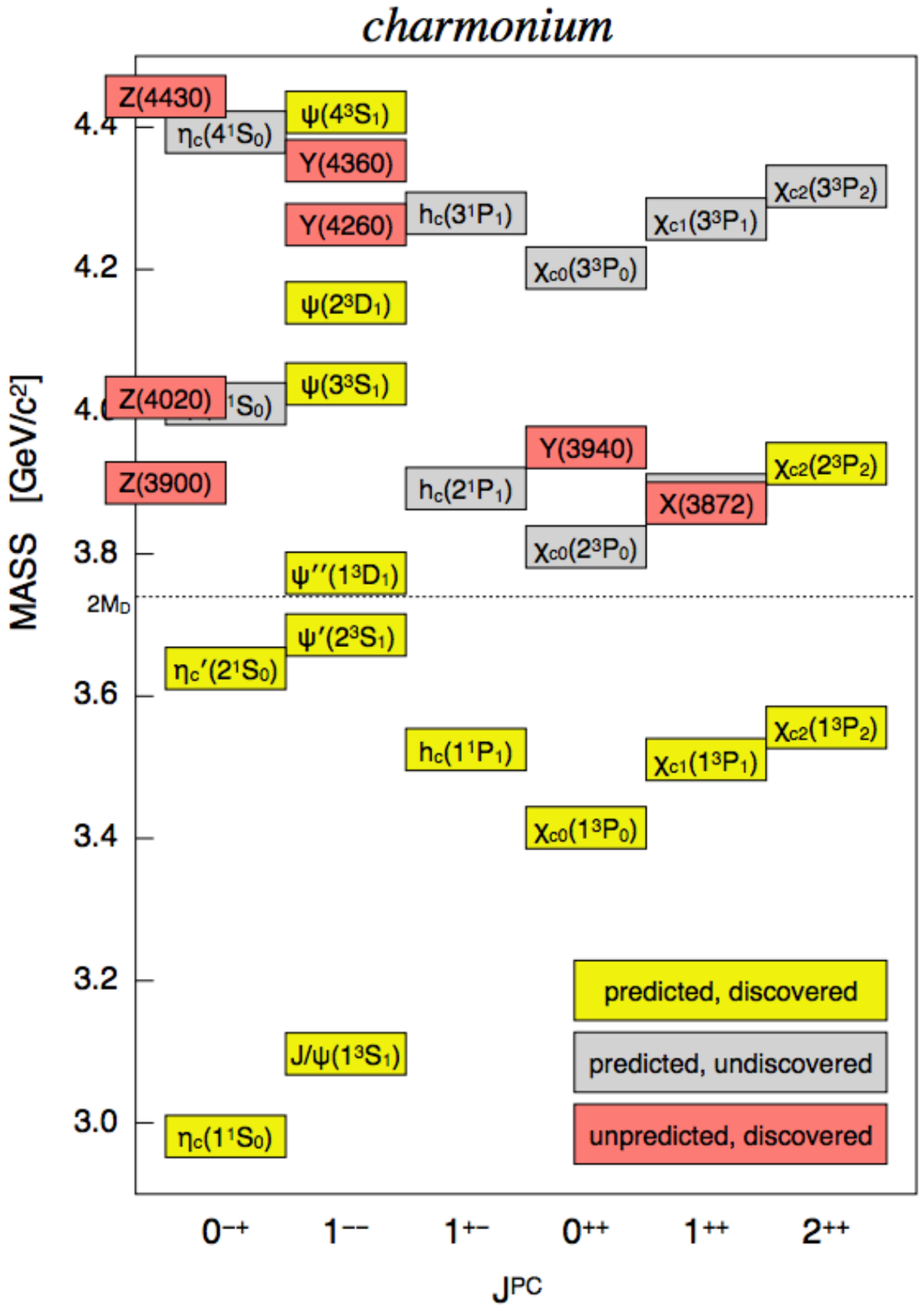
Electron Ion Collider



JLab or BNL

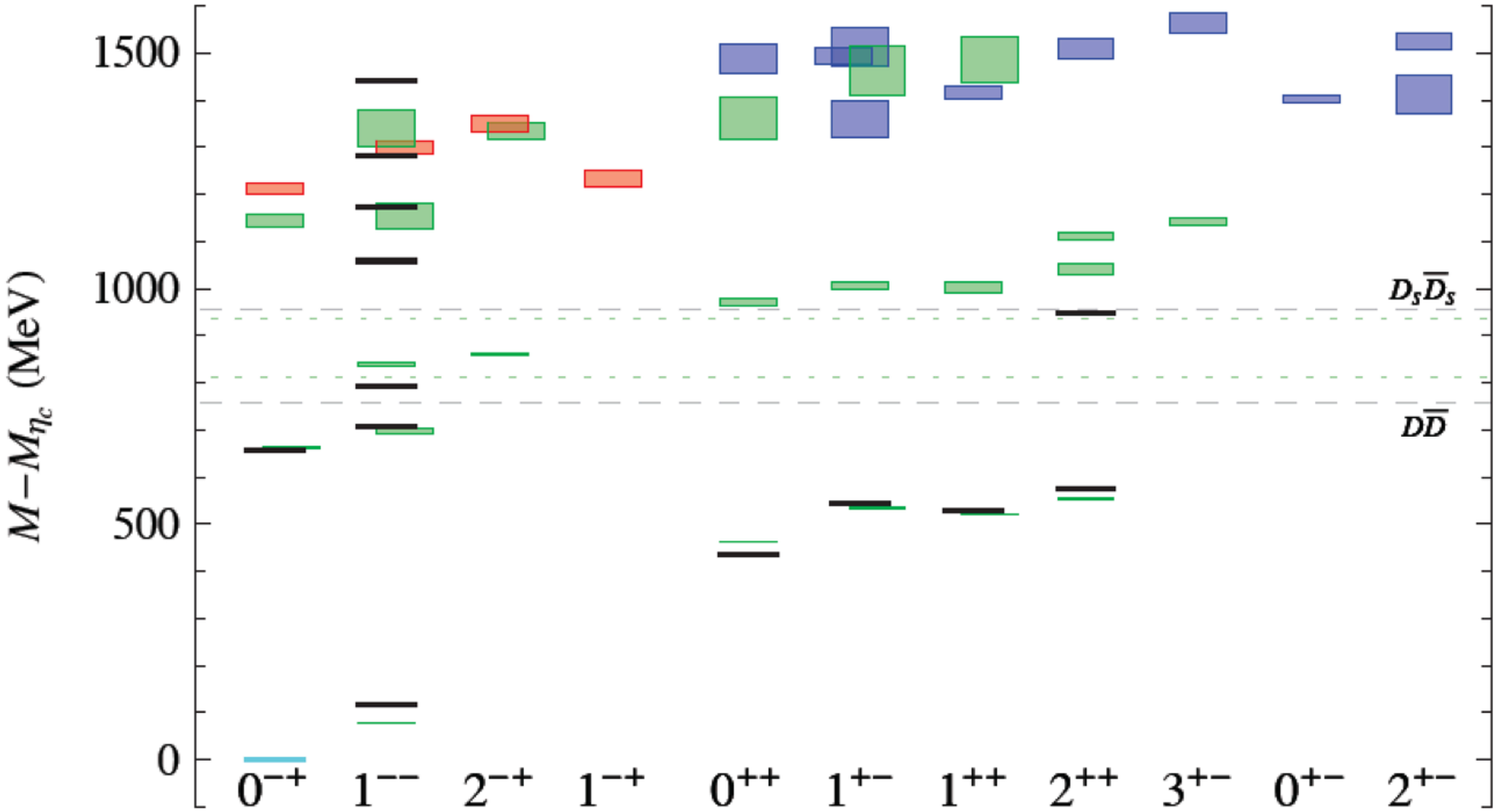
Reminder: heavy quark summary

- Explosion of new heavy quark XYZ states
- No signs of slowing: more data from LHCb, BESIII, Belle II, and PANDA
- Models describing tightly bound resonances, molecules, rescattering…
- New decay modes and production mechanism shed new light

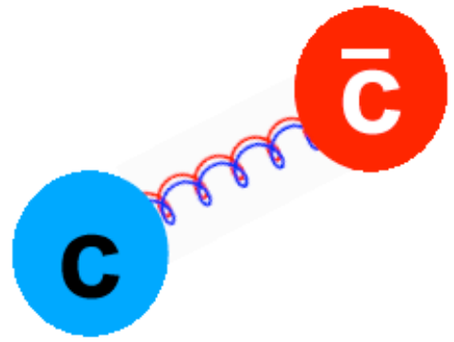


Charmonium hybrids

Hadron Spectrum Collaboration: JHEP 1207 (2012) 126



$c\bar{c}g$ Hybrid



Constituent Gluon:

Mass ~ 1-1.5 GeV

$J^{PC} = 1^{+-}$

- 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)

Charmonium hybrids

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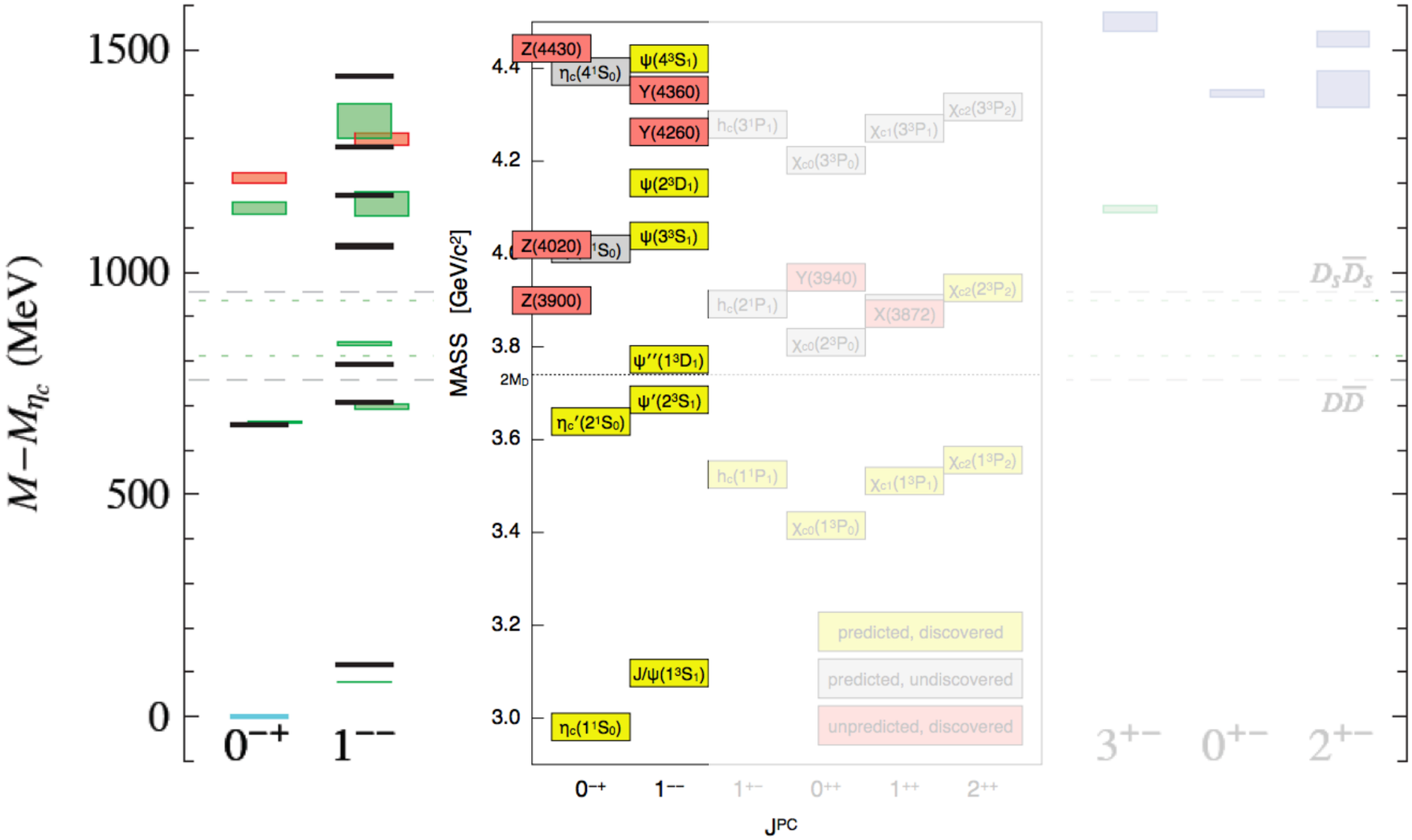

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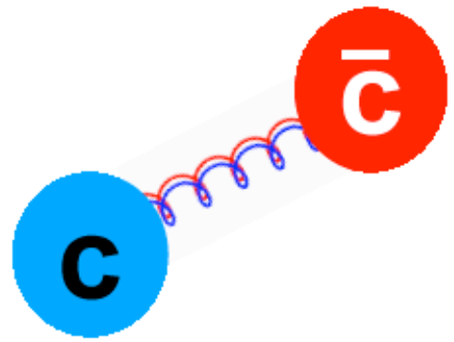

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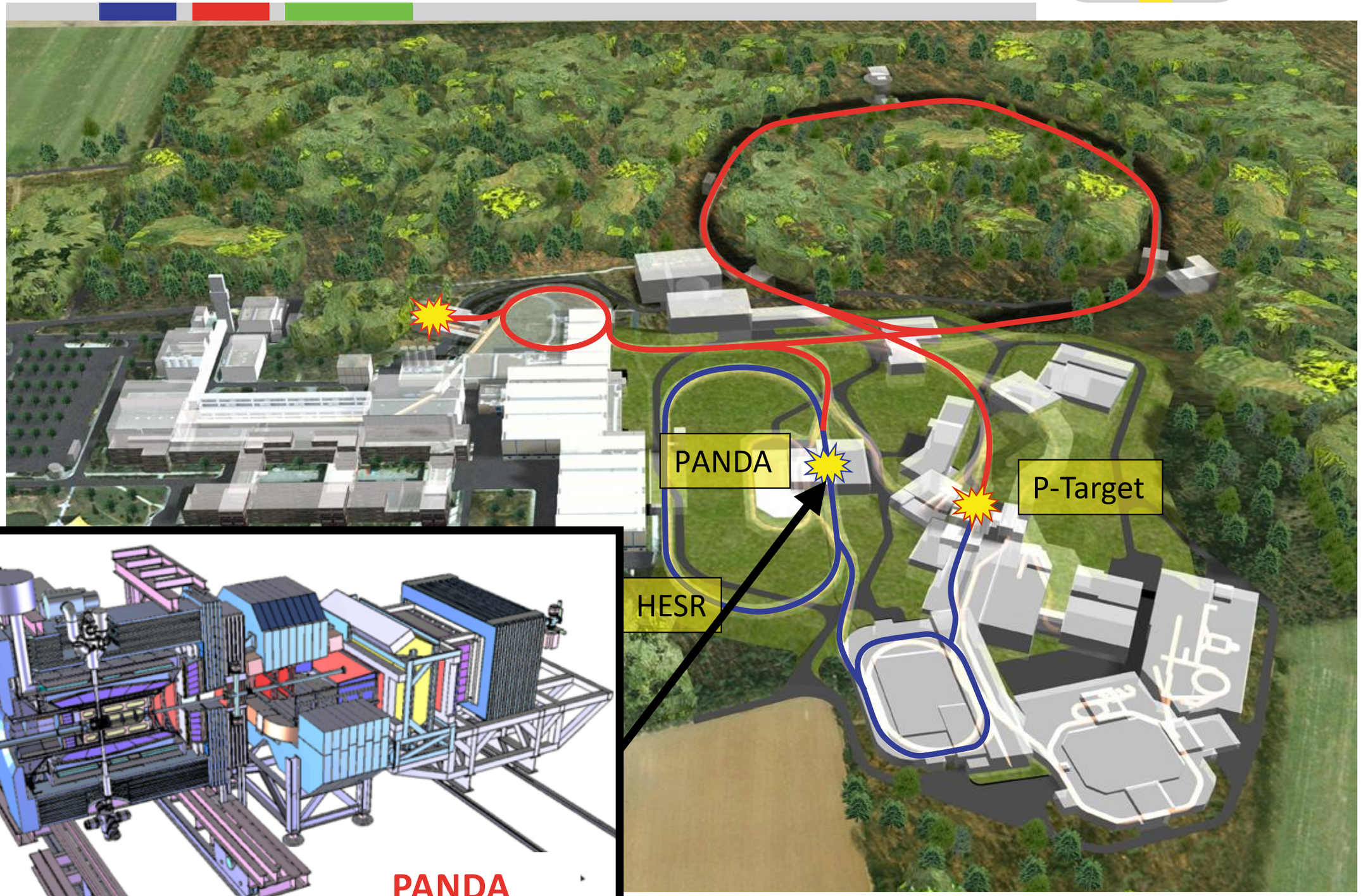
PANDA: $\bar{p}$ storage ring

Expect 1st beam in ~2023



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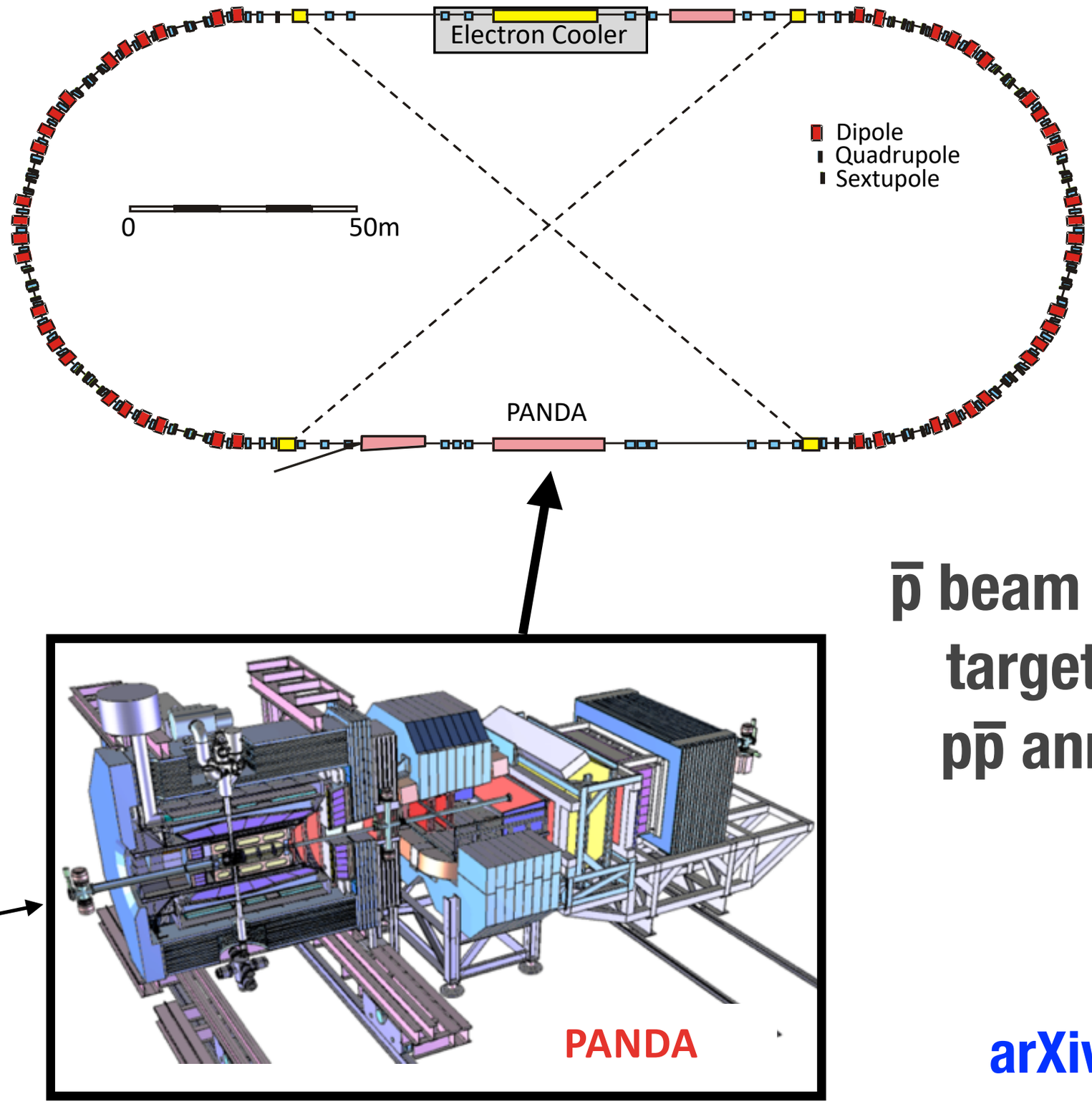
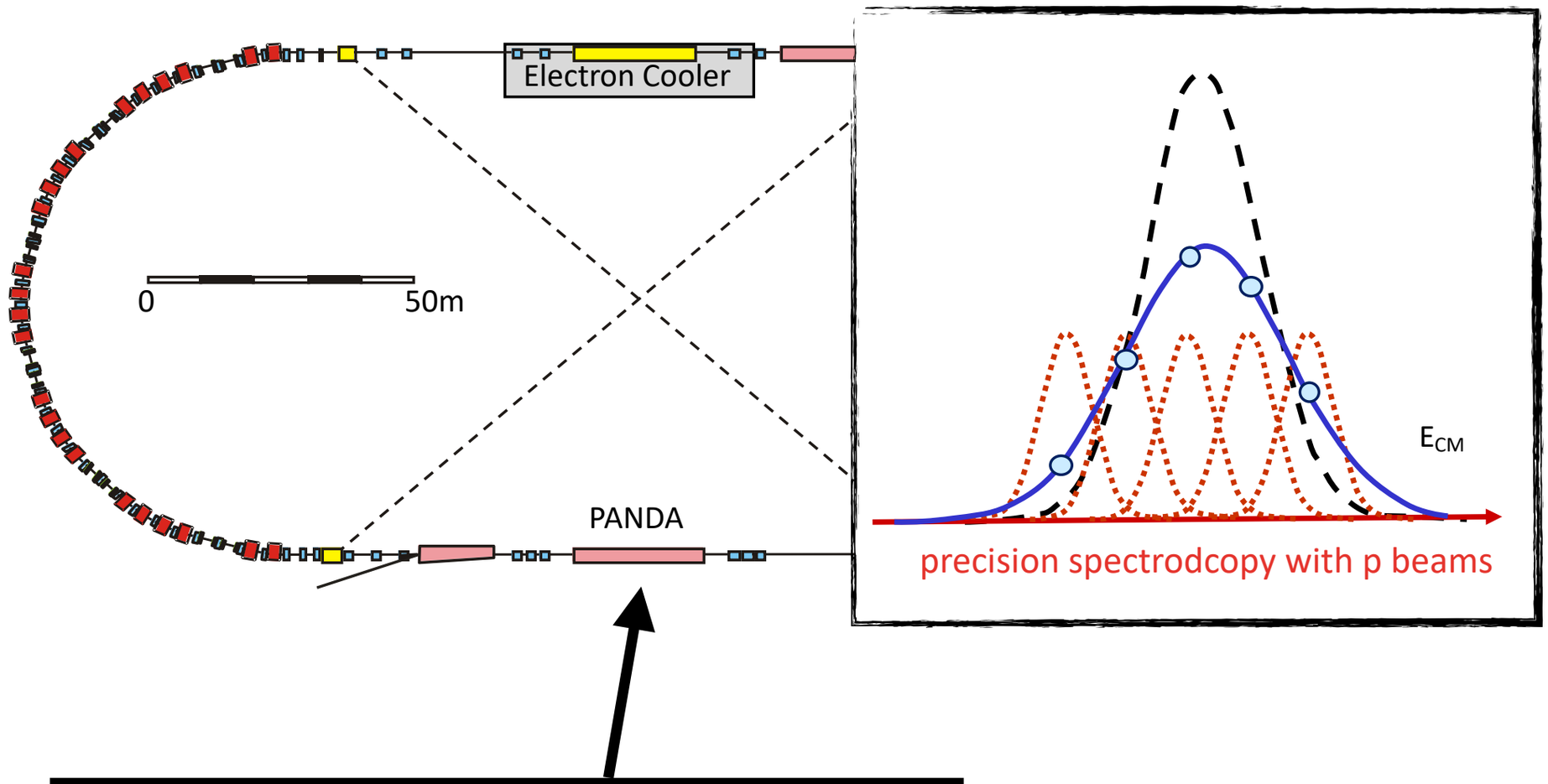


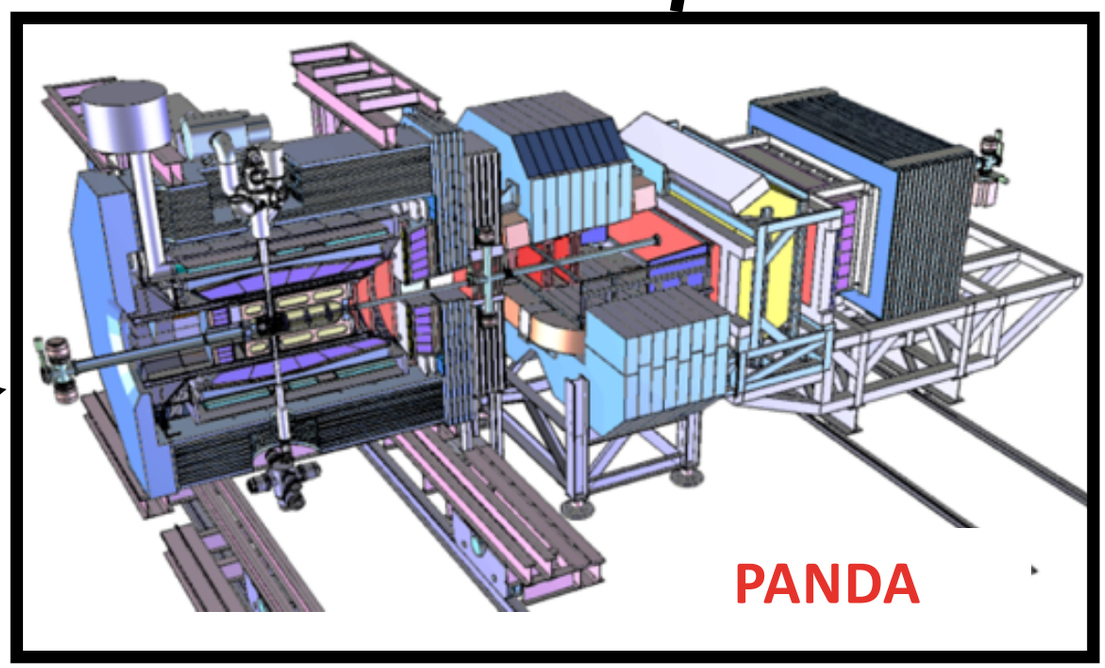
$\bar{p}$ beam and proton target to study $p\bar{p}$ annihilation

arXiv:0903.3905

PANDA: $\bar{p}$ storage ring

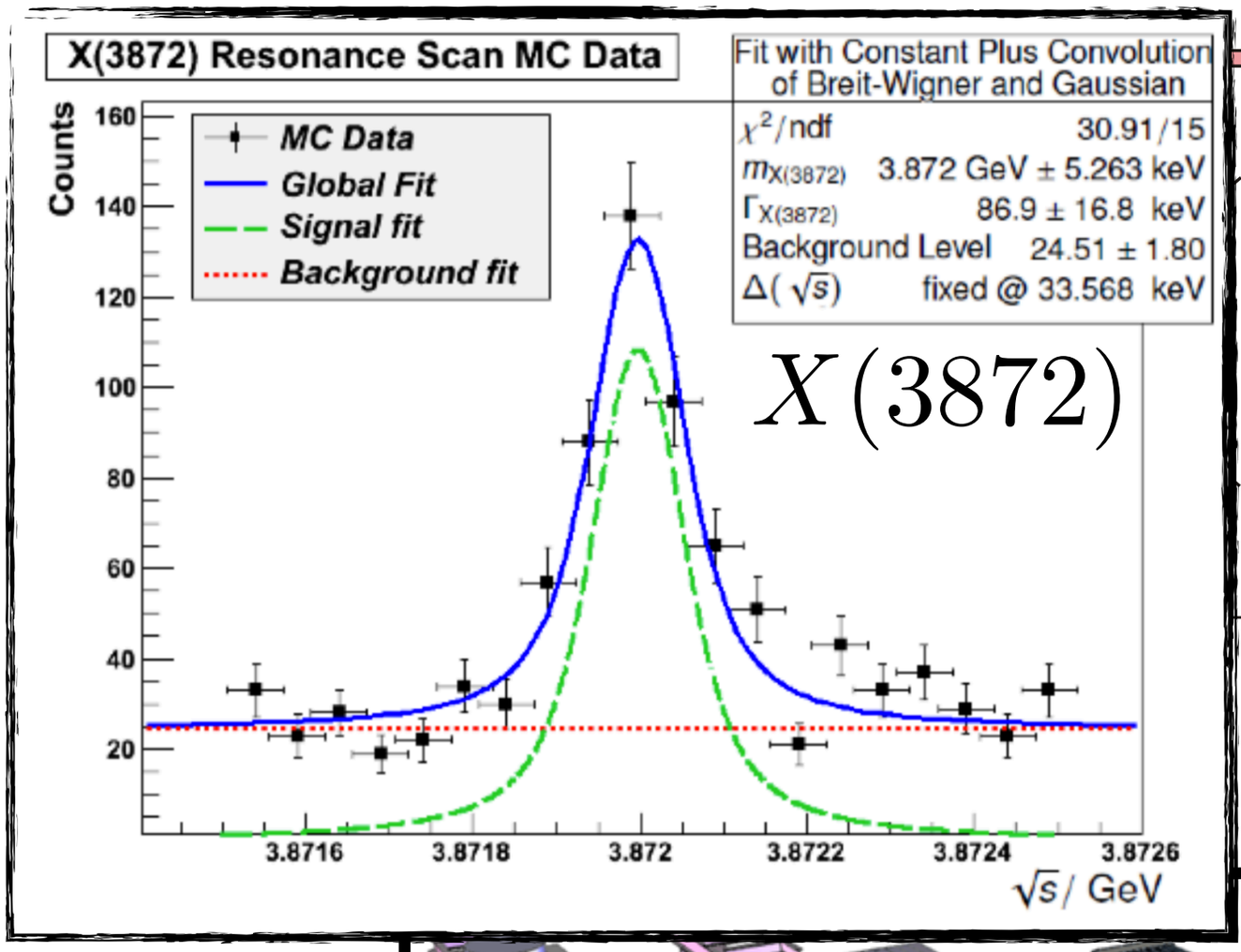


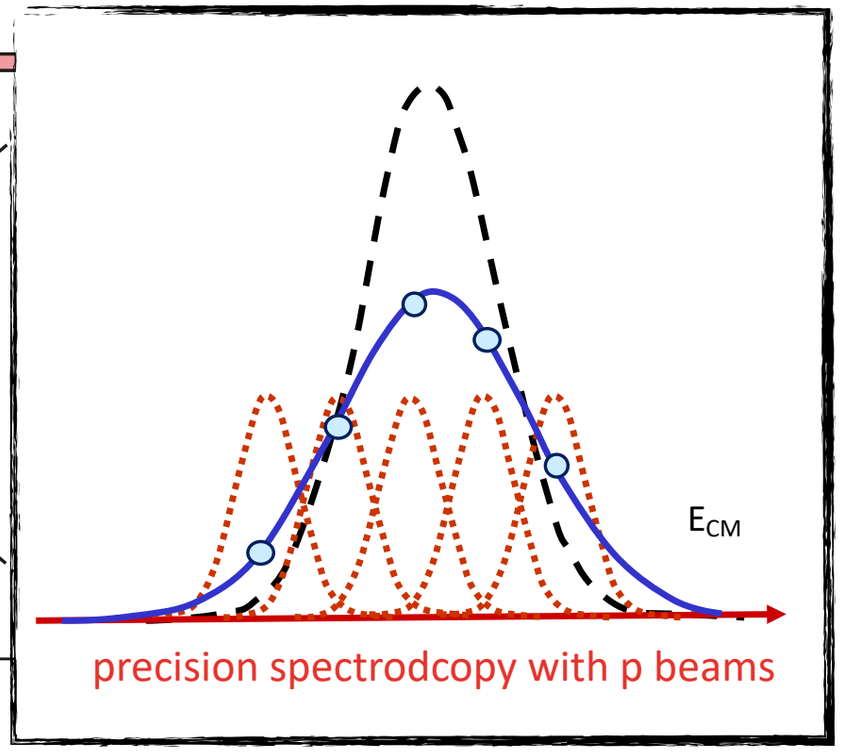
$\bar{p}$ beam

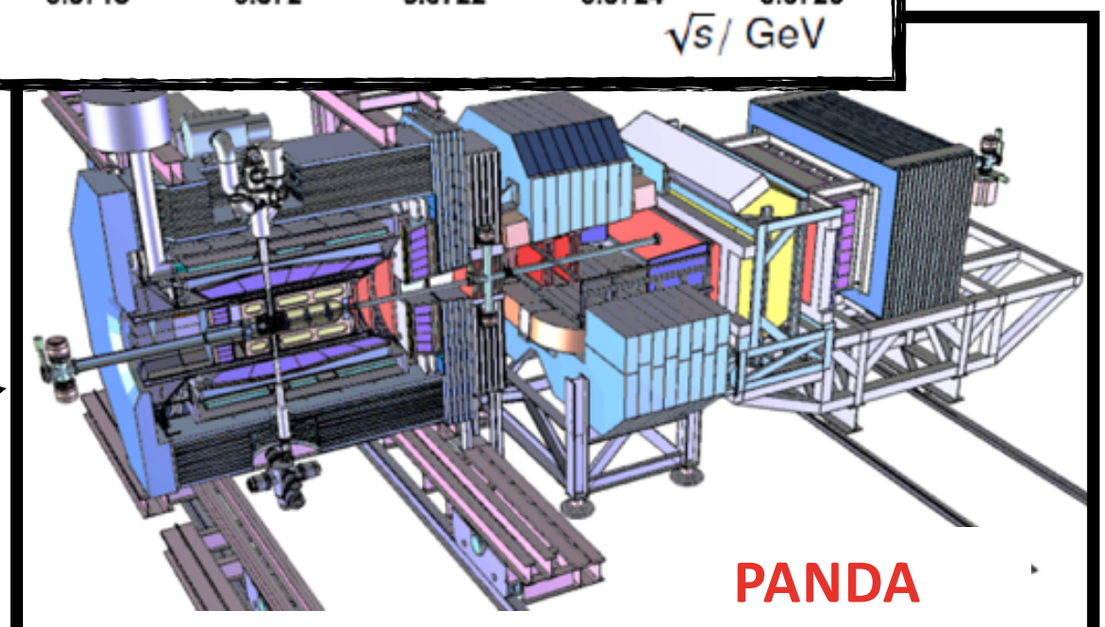


arXiv:0903.3905

PANDA: $\bar{p}$ storage ring







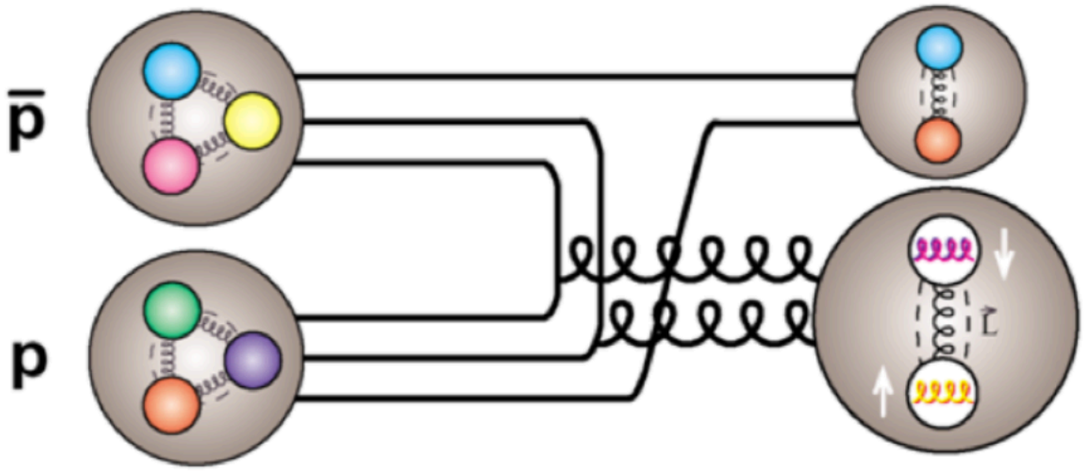
$\bar{p}$ beam

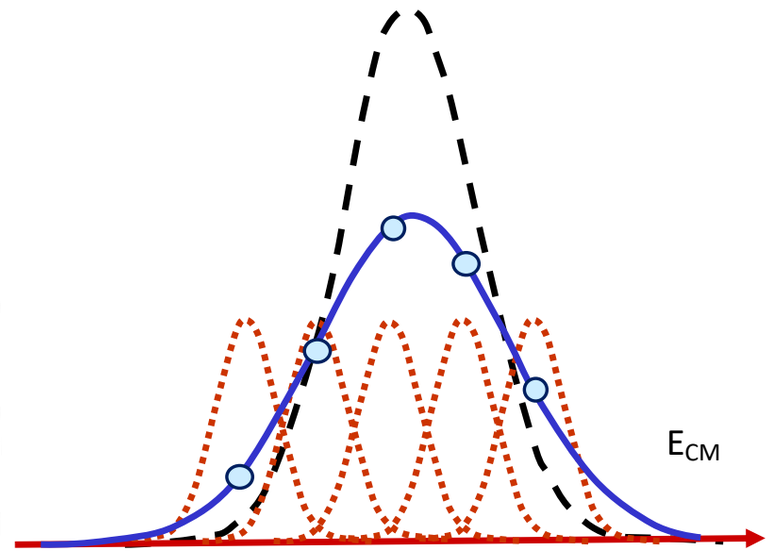
PANDA is expected to be an XYZ factory!

arXiv:0903.3905

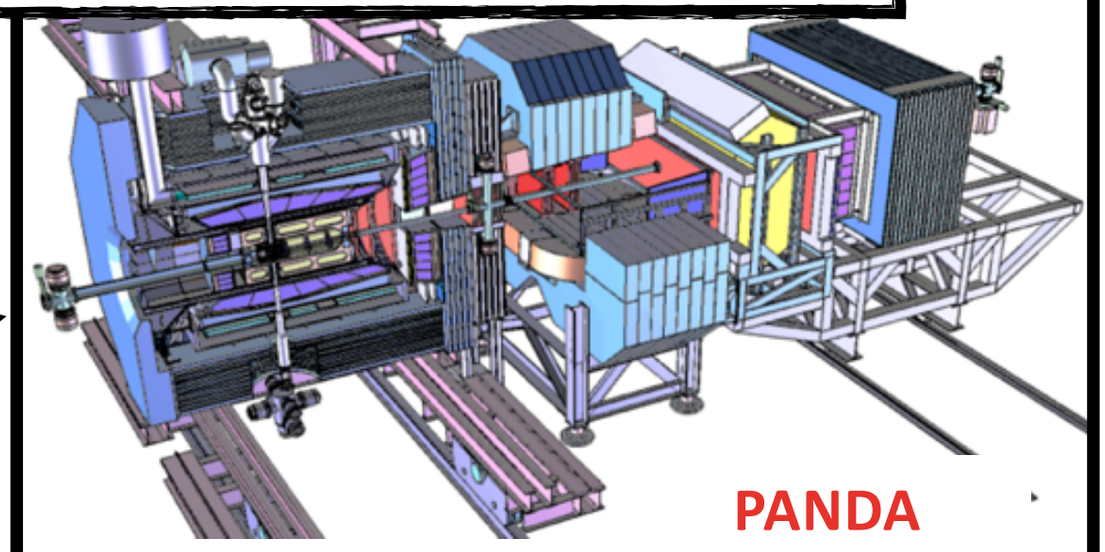
PANDA: $\bar{p}$ storage ring

Glue rich environment to study charmonium hybrids





precision spectrodcopy with p beams



$\bar{p}$ beam

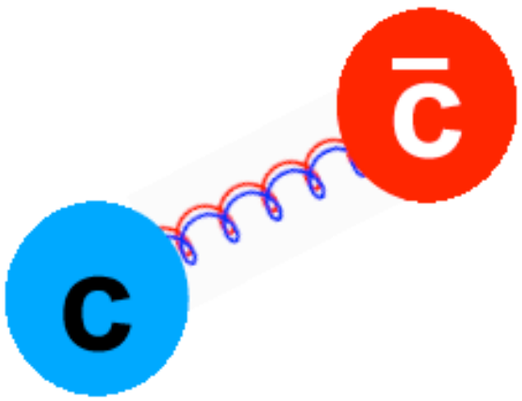
Physics program also includes hyperon spectroscopy, nucleon structure, etc.

arXiv:0903.3905

Hybrid photoproduction

- 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



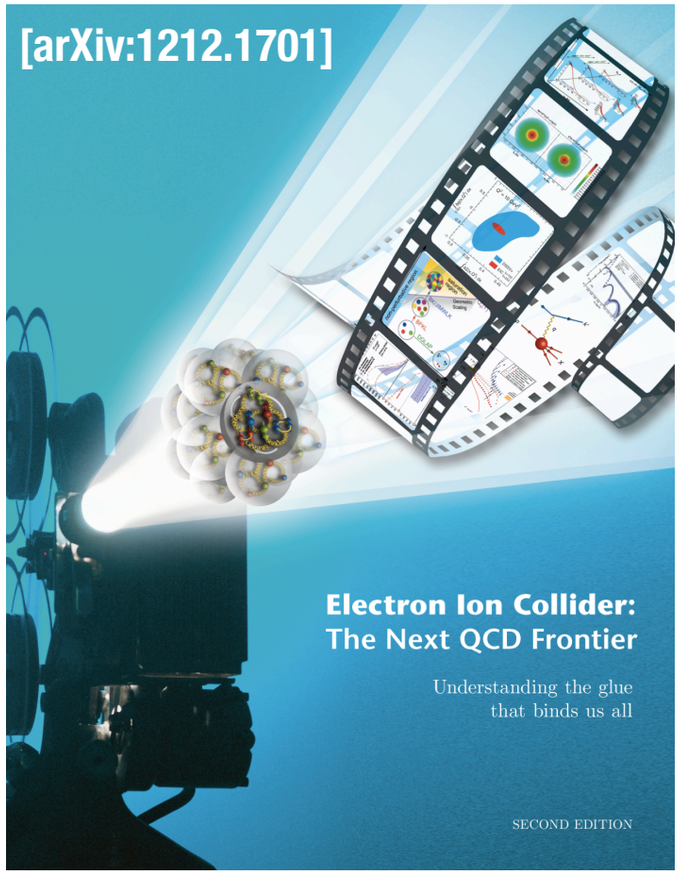
transition	Γ_{lattice} (keV)	Γ_{expt} (keV)
$\chi_{c0} \to J/\psi\gamma$	199(6)	131(14)
$\psi' \to \chi_{c0}\gamma$	26(11)	30(2)
$\psi'' \to \chi_{c0}\gamma$	265(66)	199(26)
$c\bar{c}g(1^{--}) \to \chi_{c0}\gamma$	< 20	
$J/\psi \to \eta_c\gamma$	2.51(8)	1.85(29)
$\psi' \to \eta_c\gamma$	0.4(8)	0.95 –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

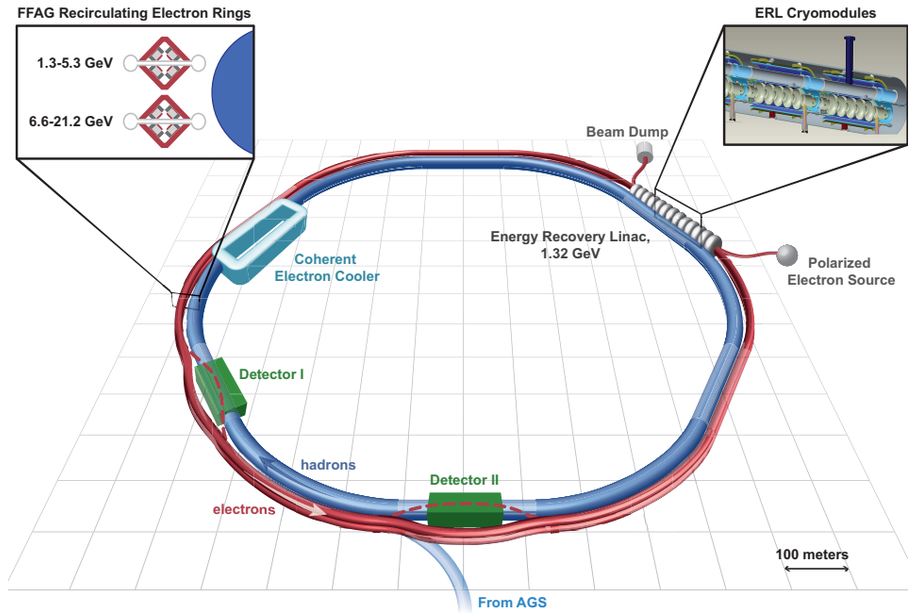
PRD 79 (2009) 094504 and Review article 1502.07276

Electron Ion Collider



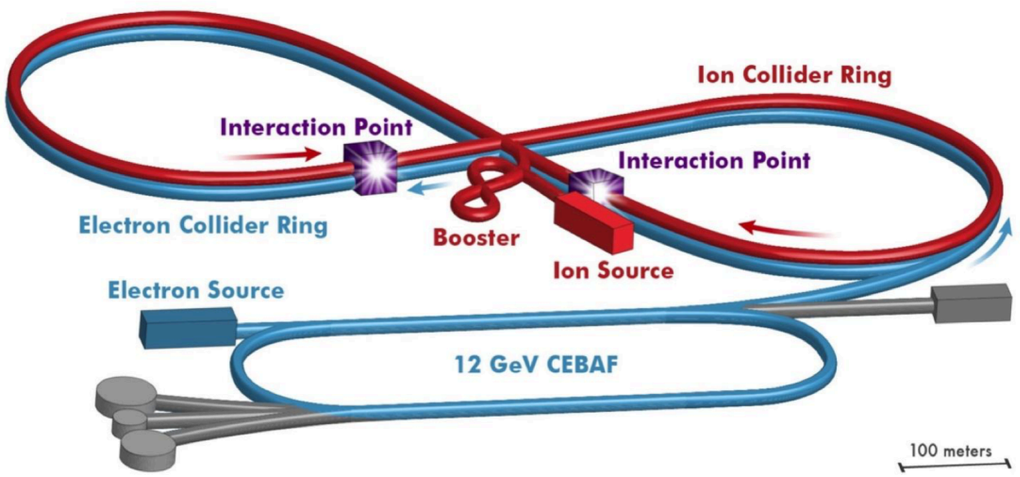
- Versatile high luminosity, polarized e+p and e+A collider to explore:
  - Nucleon spin and 3D structure
  - High gluon density and saturation
- New opportunity in hadron spectroscopy?

eRHIC

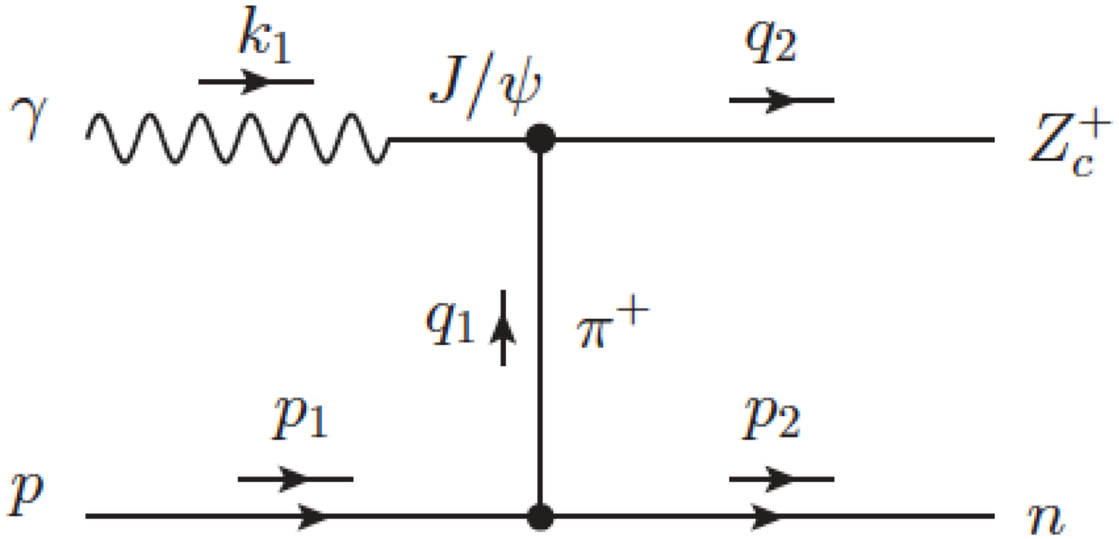


[arXiv:1409.1633]

JLEIC



XYZ states in photoproduction



PRD 88 (2013) 114009

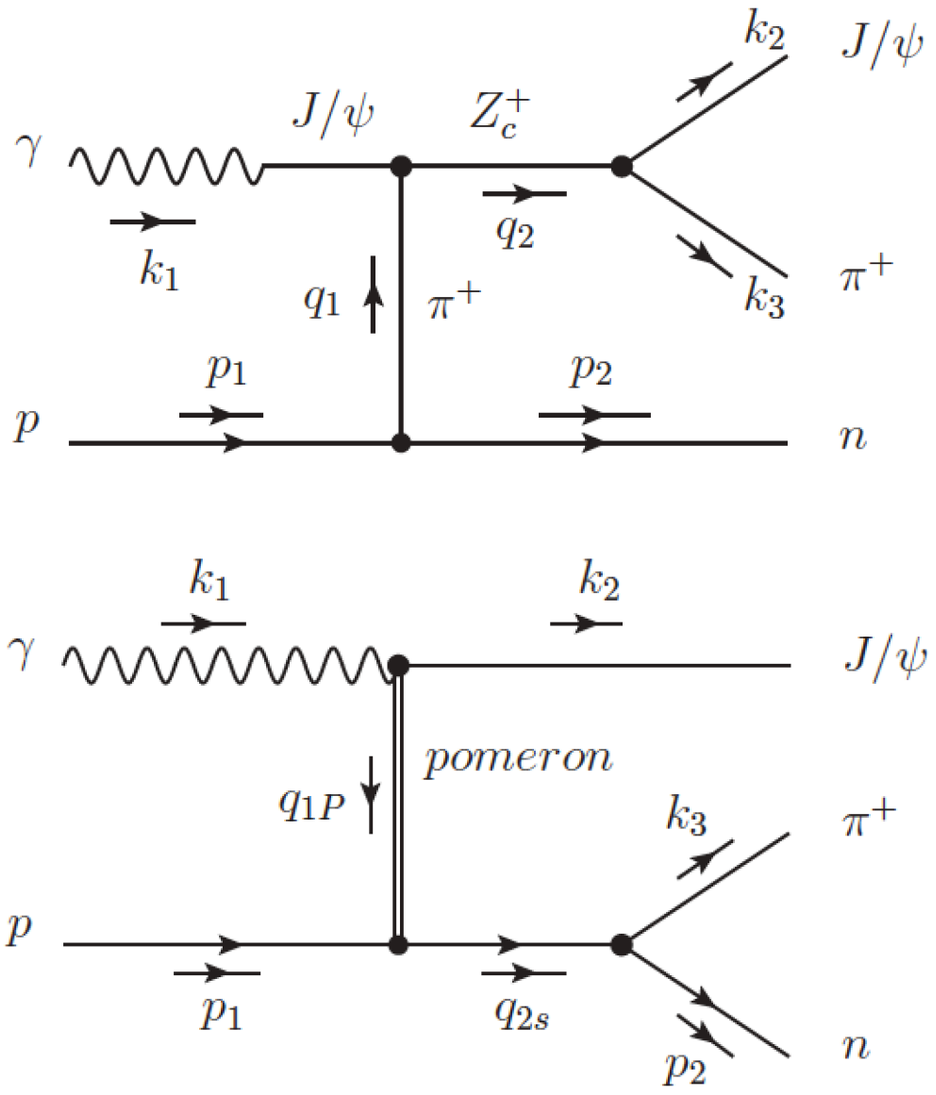
$$\mathcal{L}_{V\gamma} = -\frac{eM_V^2}{f_V} V_\mu A^\mu$$

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

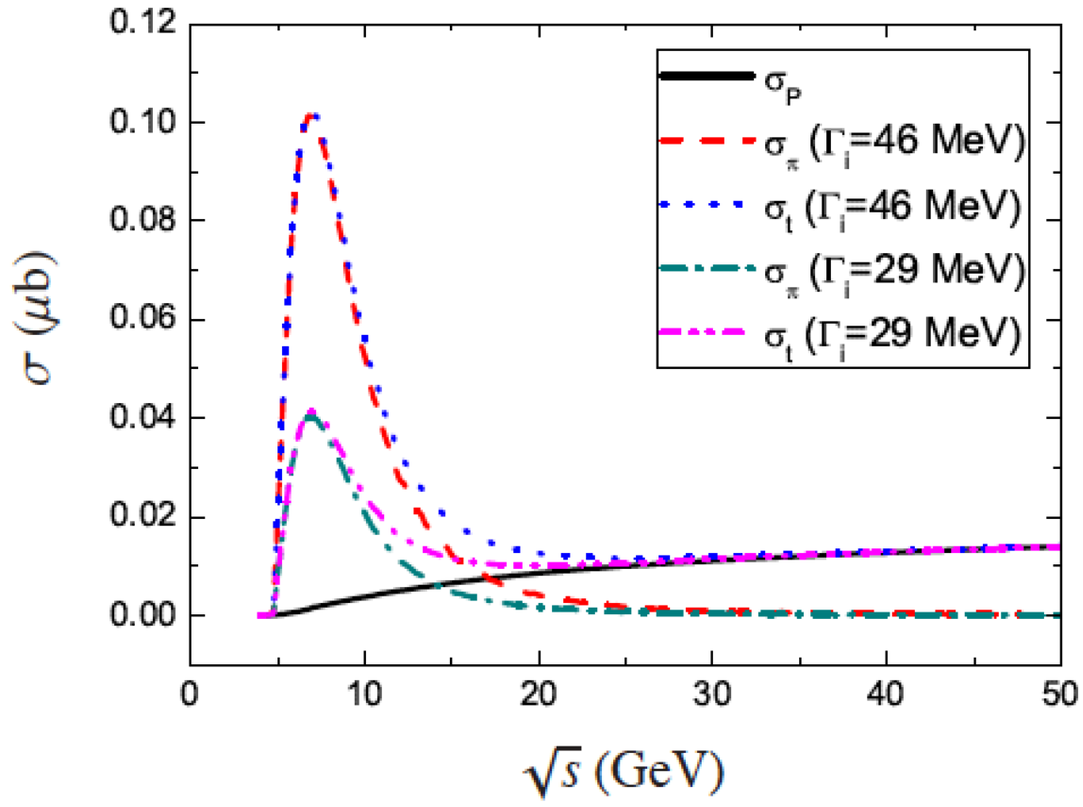
$$\mathcal{L}_{\pi NN} = -\frac{g_{\pi NN}}{2m_N}\bar{N}\gamma_5\gamma_\mu(\vec{\tau}\cdot\partial^\mu\vec{\pi})N$$

- 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: $Z_c^+(3900)$



PRD 88 (2013) 114009



- 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

Weizsäcker-Williams Approximation

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

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

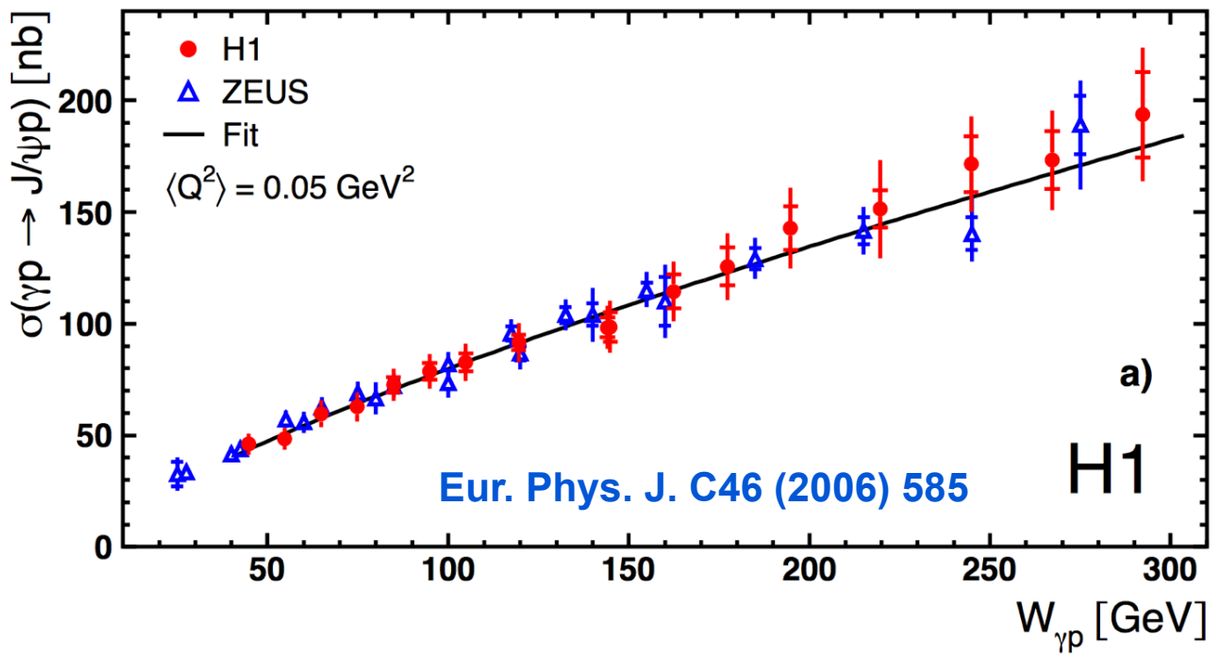
$$f_\gamma^{(e)}(y) = \frac{\alpha_{\rm em}}{2\pi}\left[2m_e^2 y\left(\frac{1}{q^2_{max}} - \frac{1}{q^2_{min}}\right) + \frac{1+(1-y)^2}{y}\log\frac{q^2_{min}}{q^2_{max}}\right]$$

- 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

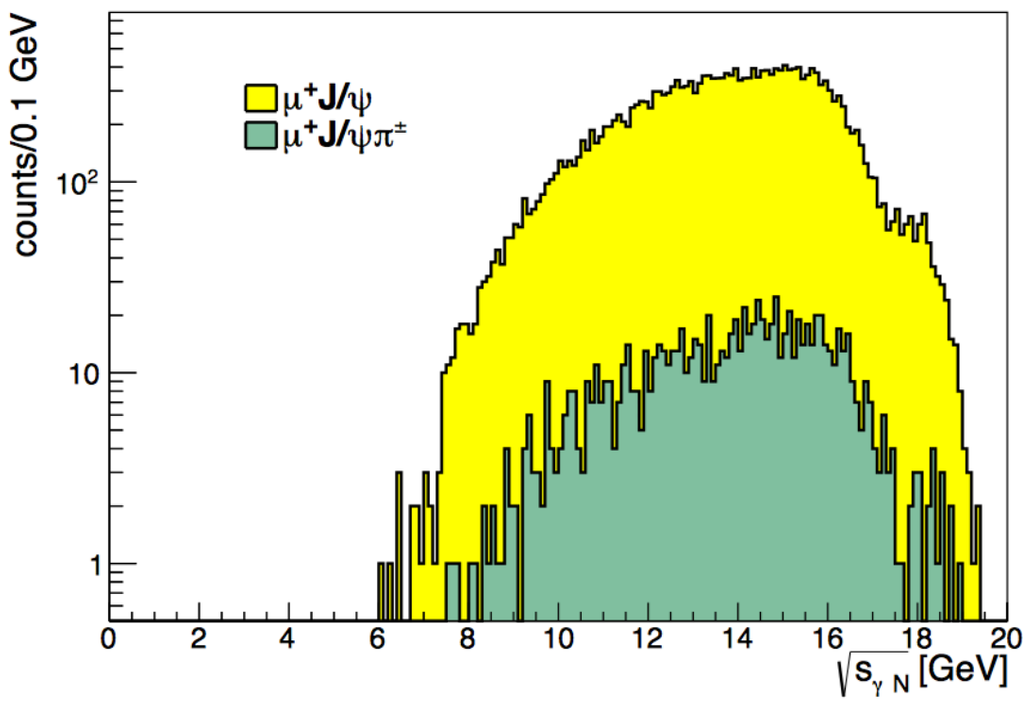
Frixione et. al. PLB 319 (1993) 339

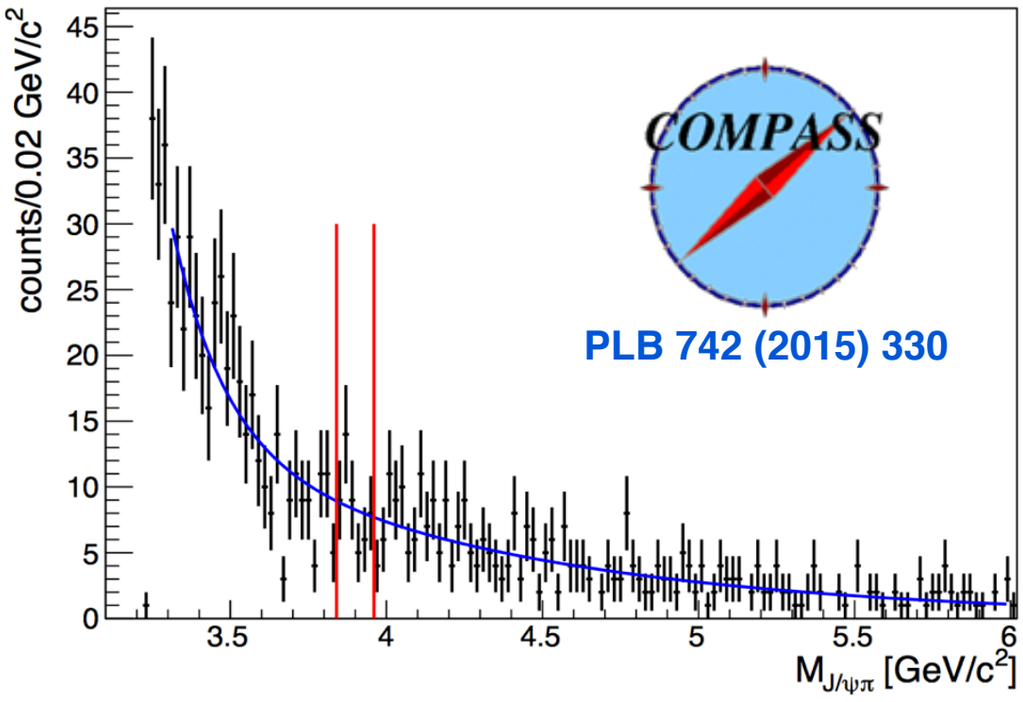
Previous experiments

- 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 $Z_c \to J/\psi\,\pi$ decay width

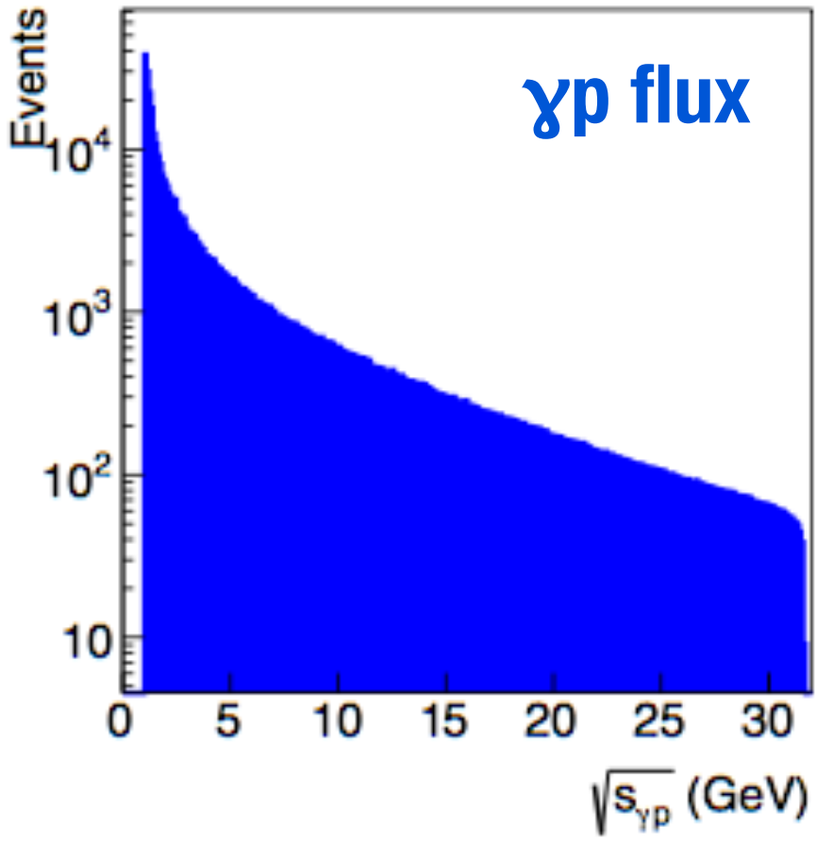


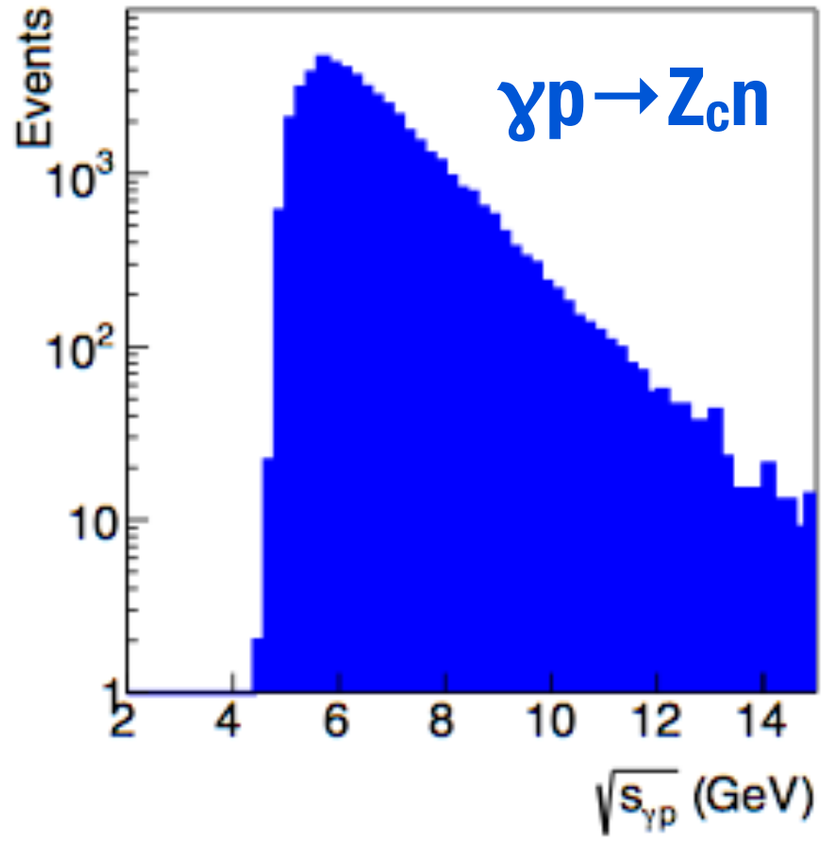
- What could the EIC do in e+p?





$Z_c^+(3900)$ at an EIC

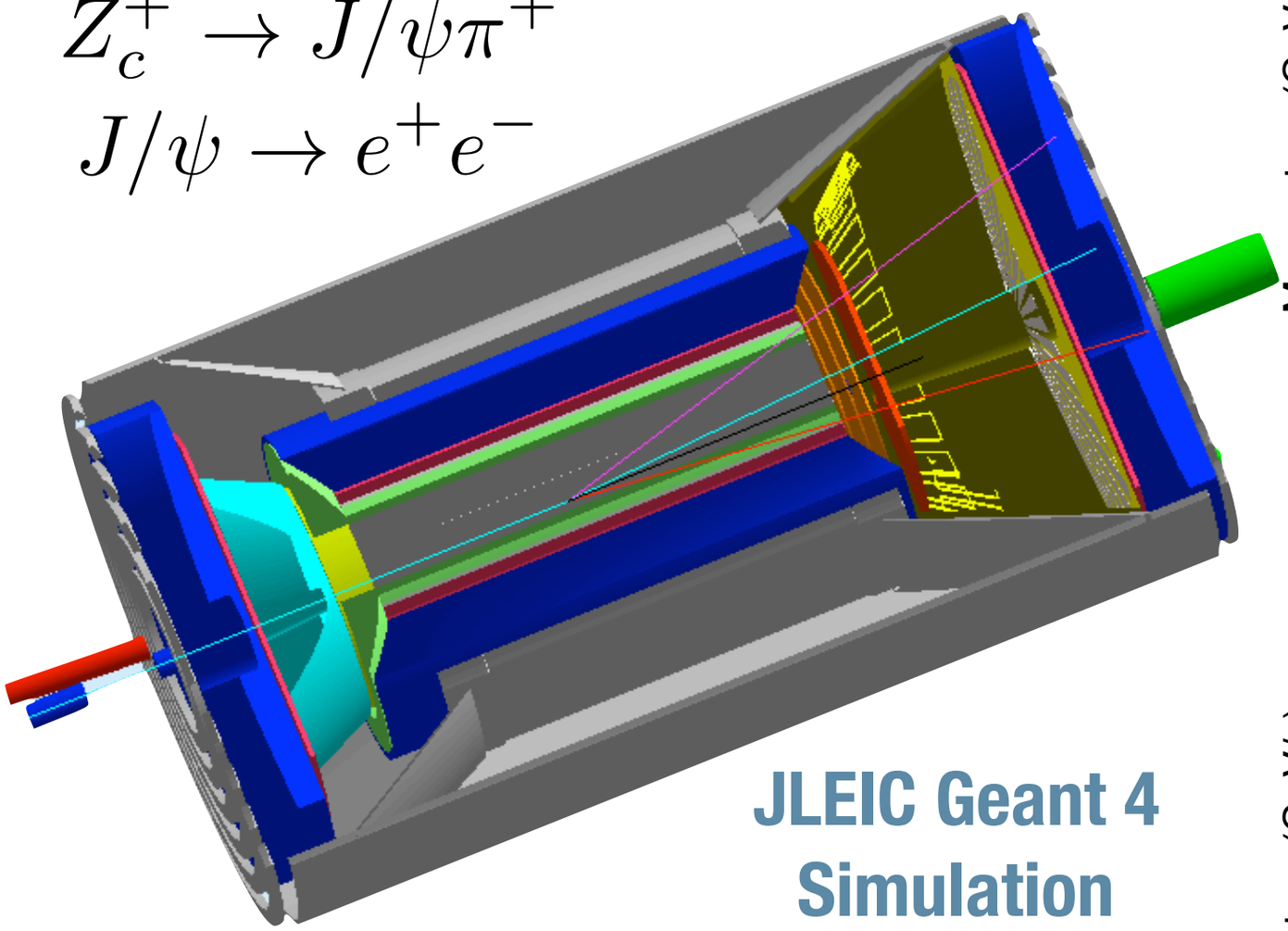




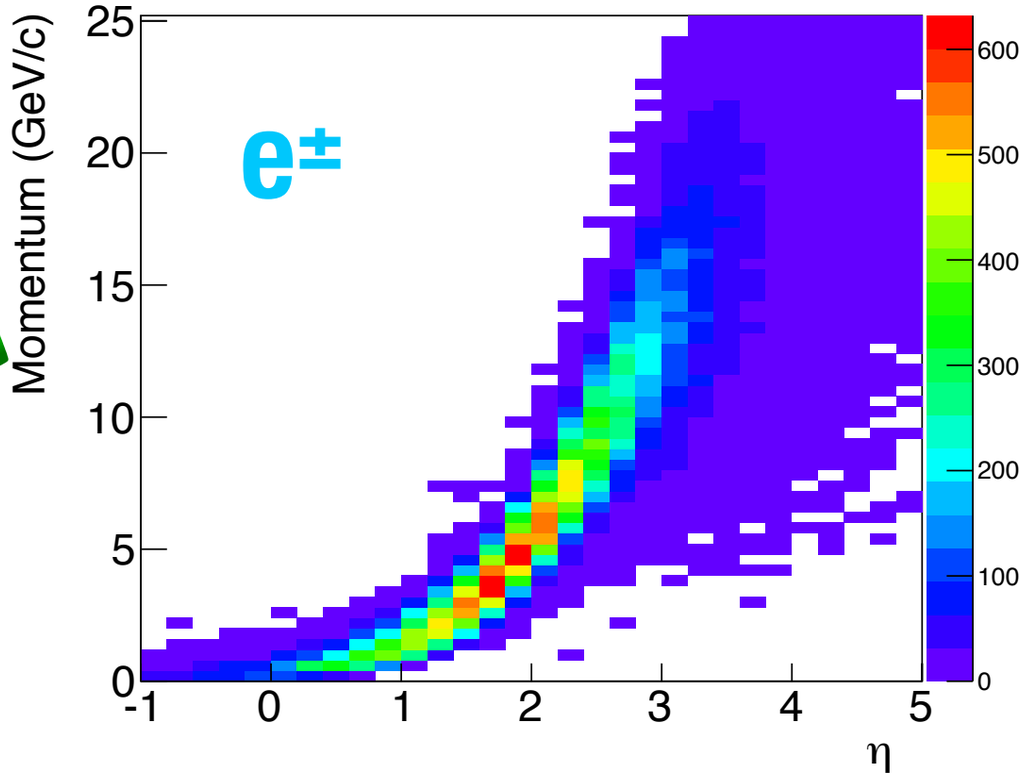
- Assume modest energy electron and proton beams: **E_p = 50 GeV** and **E_e = 5 GeV**
- Z_c and subsequent decays are boosted in proton direction
- Low-Q^2 electron and neutron very close to beamline

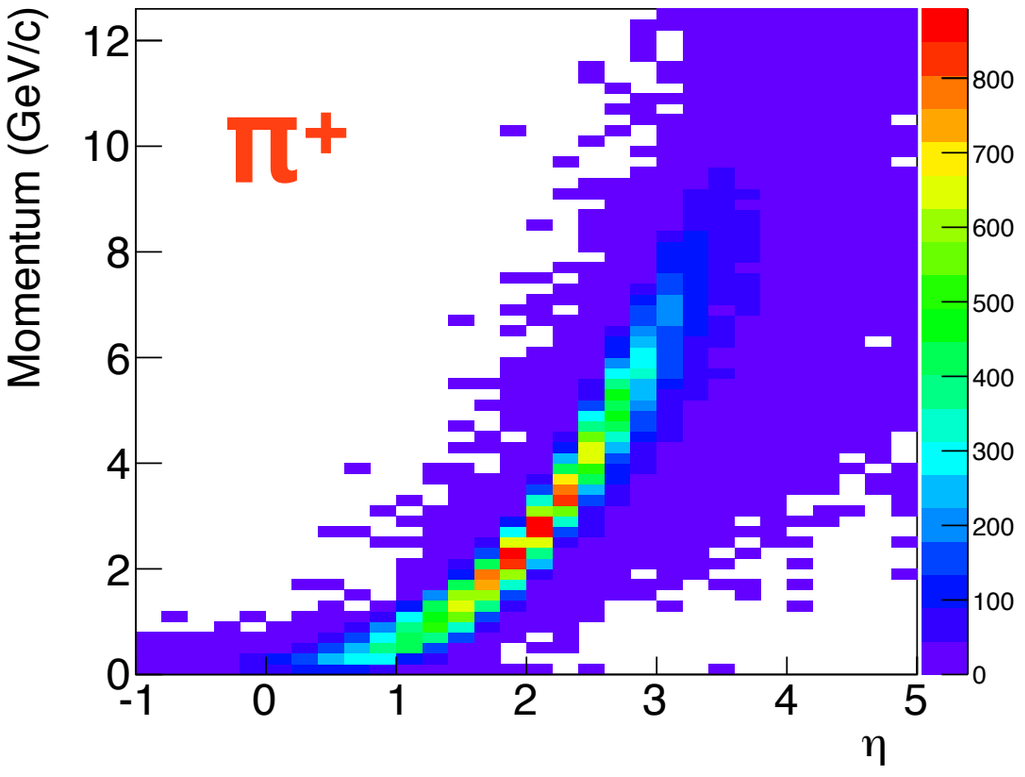
$Z_c^+(3900)$ at an EIC

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



JLEIC Geant 4 Simulation

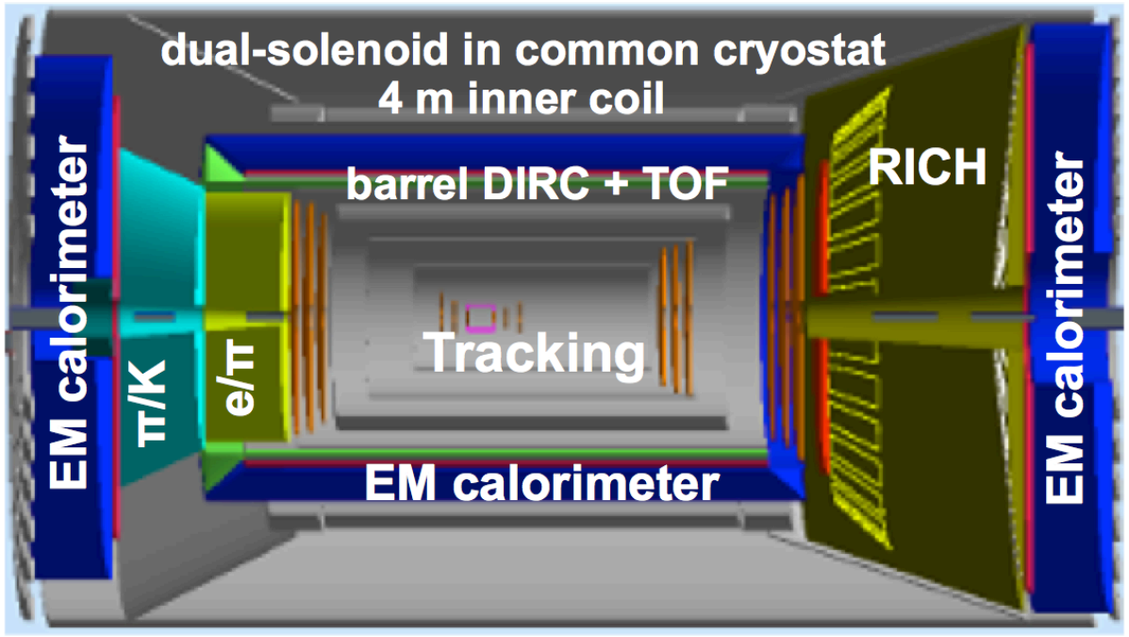


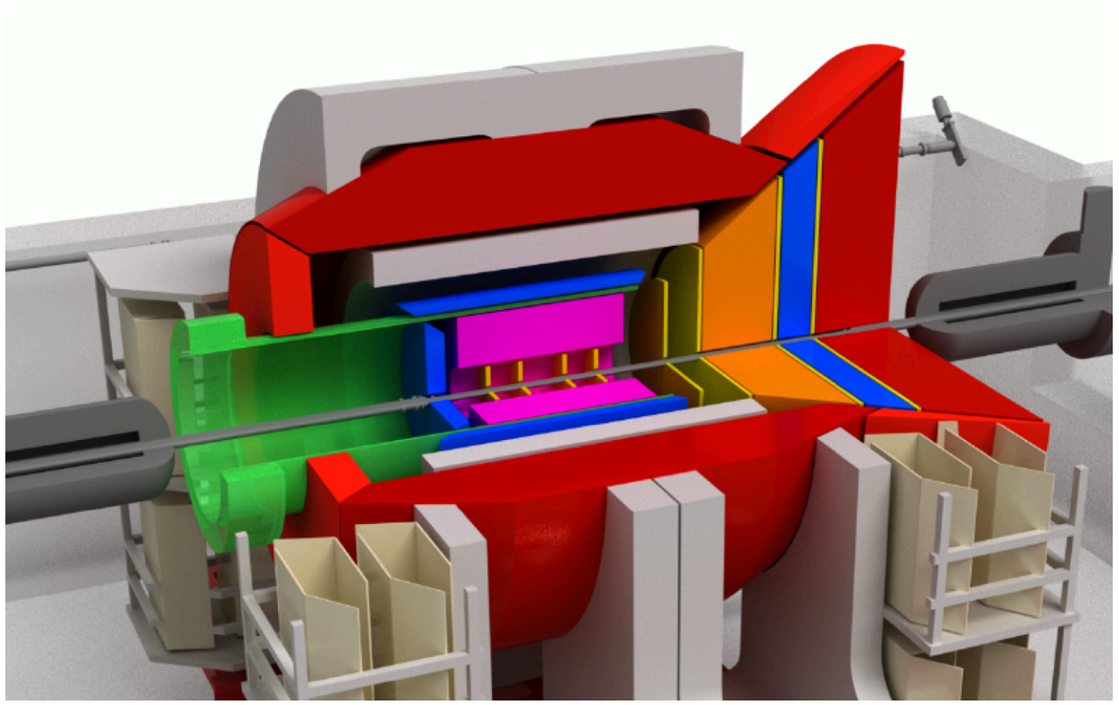


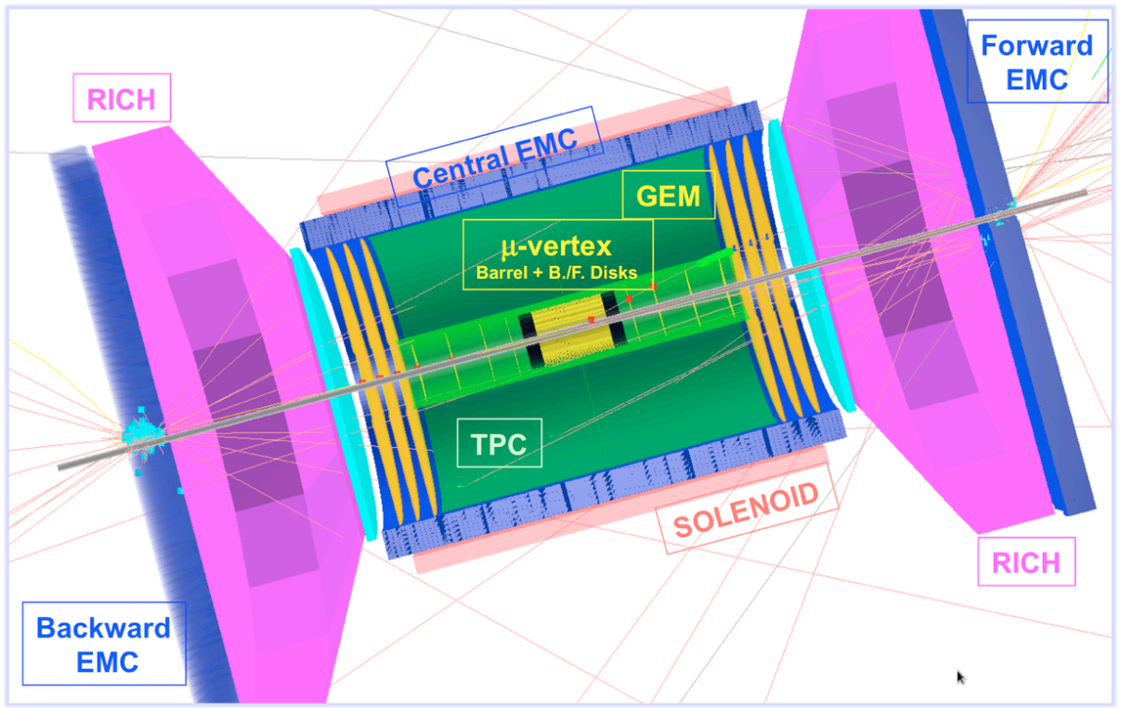
- Decay $e^{\pm}$ and π^+ boosted in proton beam direction
- Need excellent hadron and $e^{\pm}$ PID and momentum resolution

EIC detector designs

- Requirements for ideal EIC detector similar to spectroscopy needs!
  - Tracking: $|\eta| < 4$
  - Calorimetry: $|\eta| < 5$
  - Hadron and electron PID: $|\eta| < 3$
- Consider μ ID for J/ψ?







Spectroscopy: **a bright future!**

	Heavy quarks		Light quarks	
Electromagnetic probes	e^+e^-			γp
	BABAR	BESIII	CLAS12	clas CEBAF Large Acceptance Spectrometer
	BELLE	Belle II	GLUEX	
Hadronic probes	$\bar{p}p$	pp	$\bar{p}p$	πp
	DØ	CMS, ATLAS	PANDA	COMPASS
	CDF II	LHCb		

EIC?

Further Reading

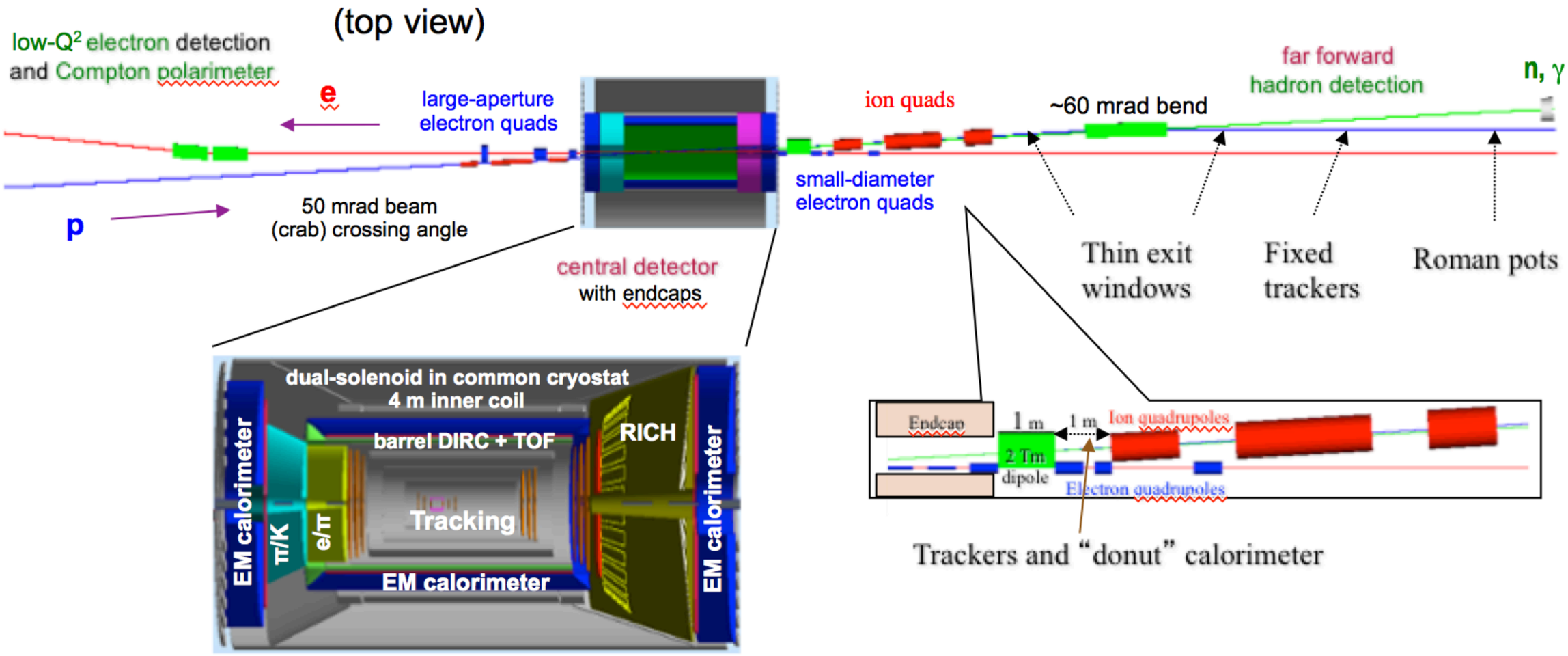
- **Heavy-Quark QCD Exotica**
  Richard F. Lebed, Ryan E. Mitchell, Eric S. Swanson, Progress in Particle and Nuclear Physics 93, 143–194 (2017)

- **Non-Standard Heavy Mesons and Baryons, an Experimental Review**
  Stephen Lars Olsen, Tomasz Skwarnicki, Daria Zieminska *[arXiv:1708.04012]*

- **Hybrid mesons**
  Curtis A. Meyer and Eric S Swanson, Progress in Particle and Nuclear Physics 82, 21-58 (2015)

Backup

EIC integrated IR design



- Detectors near the beamline are an integral part of the EIC physics program: e- polarimetry, proton and light ion tagging, etc.
  - Low-Q^2 electron detection integrated in IR design
  - Zero degree calorimeters for photons and neutrons downstream