Current Experiments

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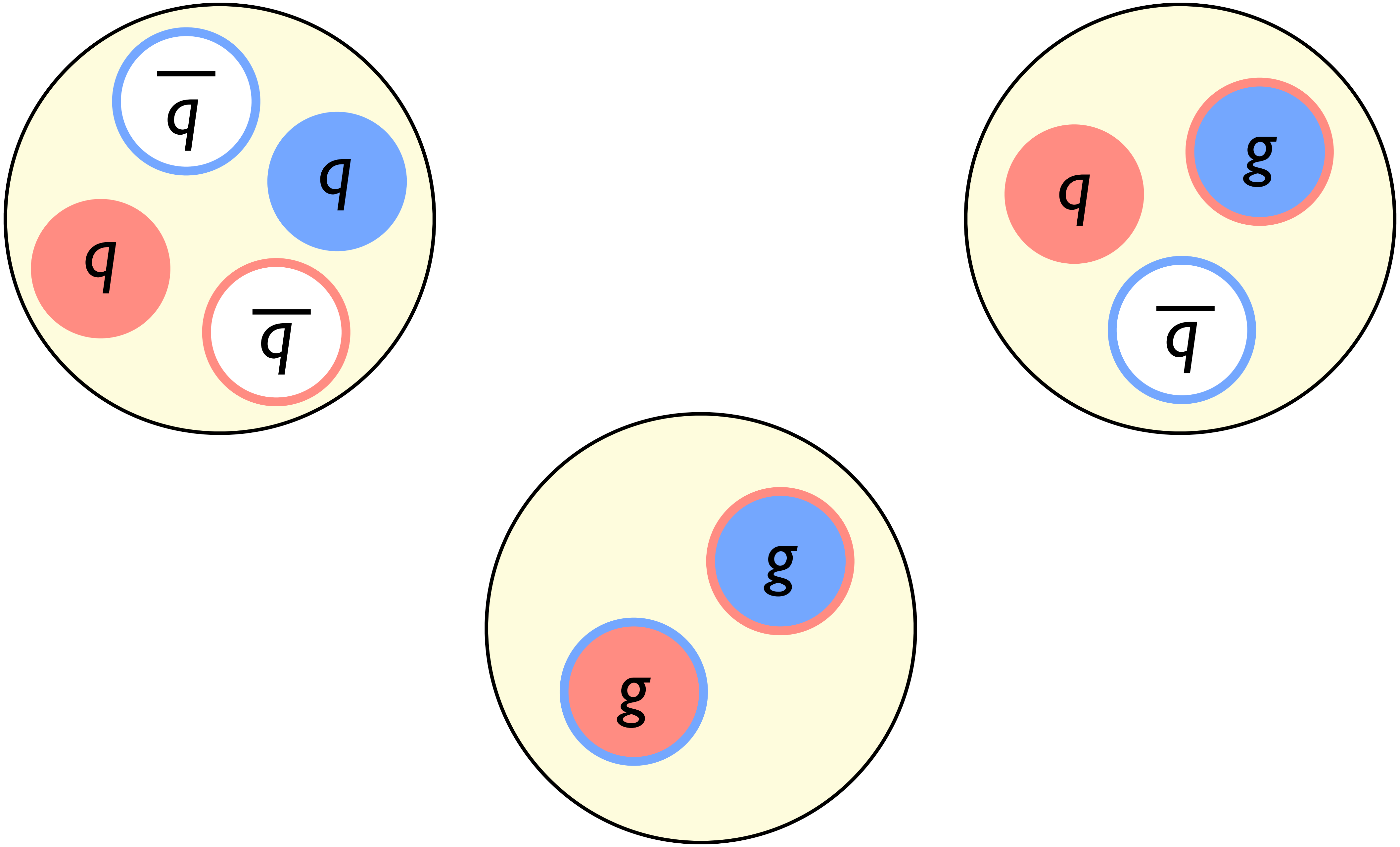
Indiana University

IU Summer ~~School~~ Workshop on Reaction Theory
June 8, 2015

Outline

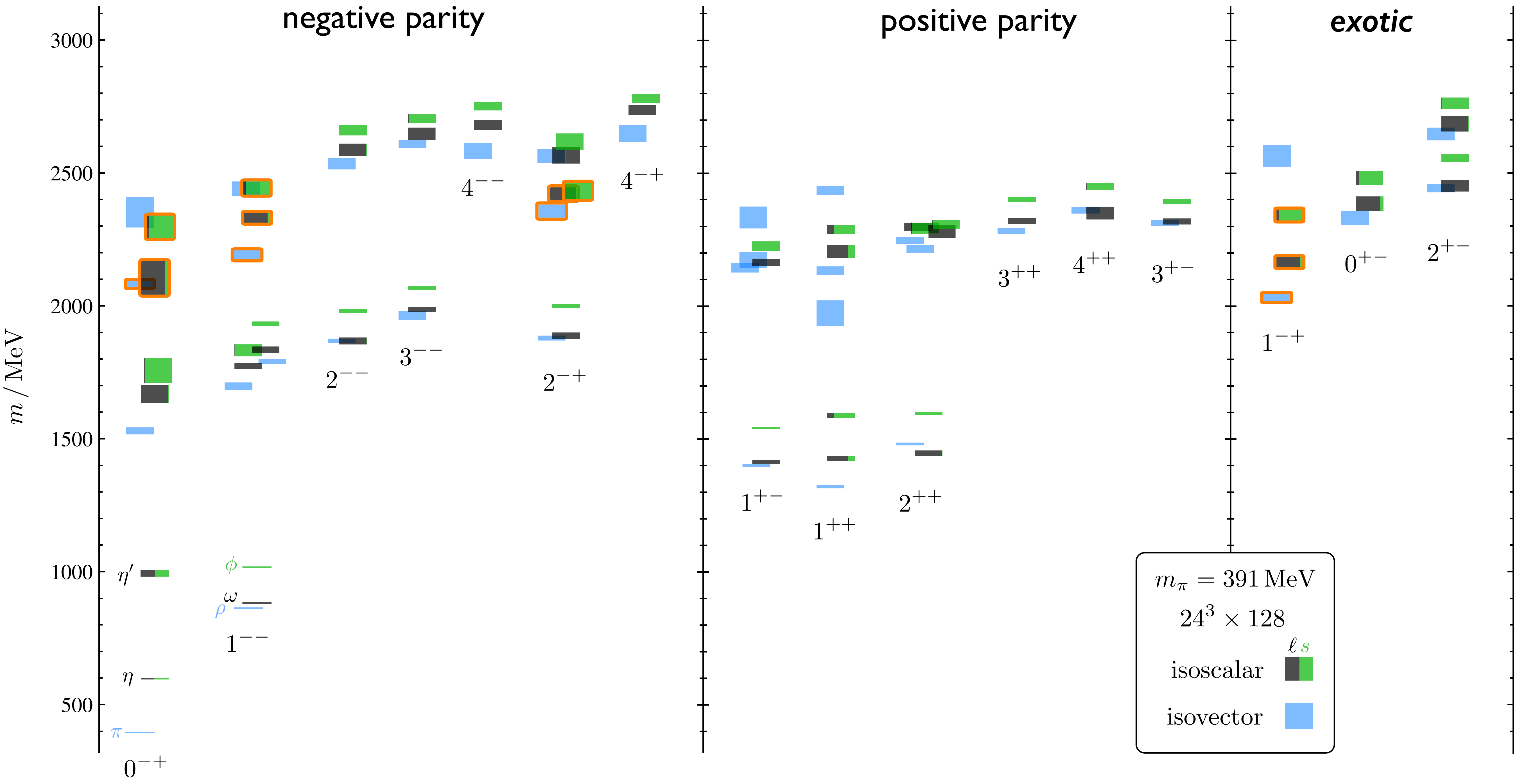
- Current challenges (with a spectroscopy bias)
- Some results that showcase current experiments

Reaction Products (?)



Meson Spectrum from Lattice QCD

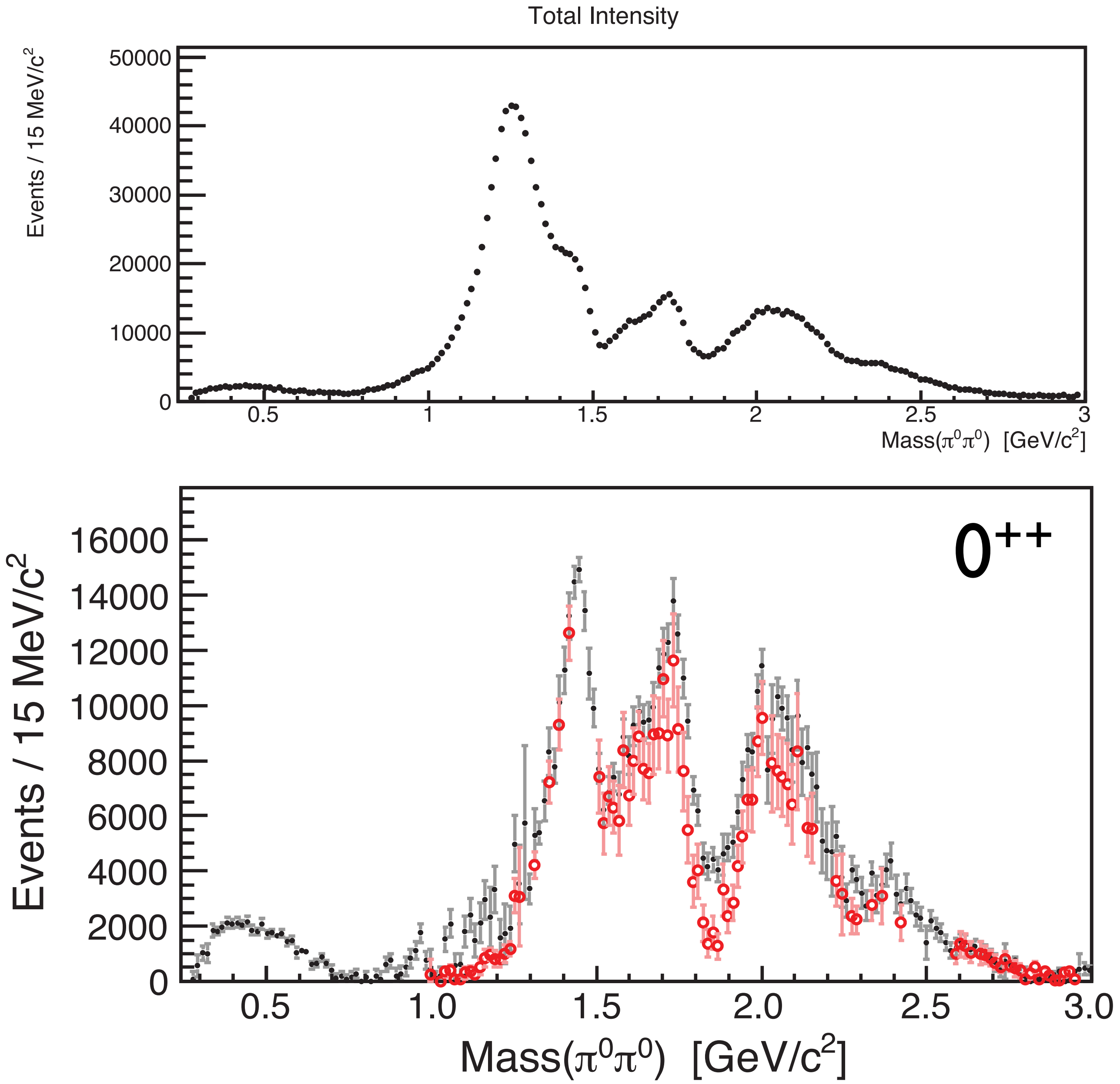
Dudek, Edwards, Guo, and Thomas, PRD 88, 094505 (2013)



DEPARTMENT OF PHYSICS
INDIANA UNIVERSITY
College of Arts and Sciences
Bloomington

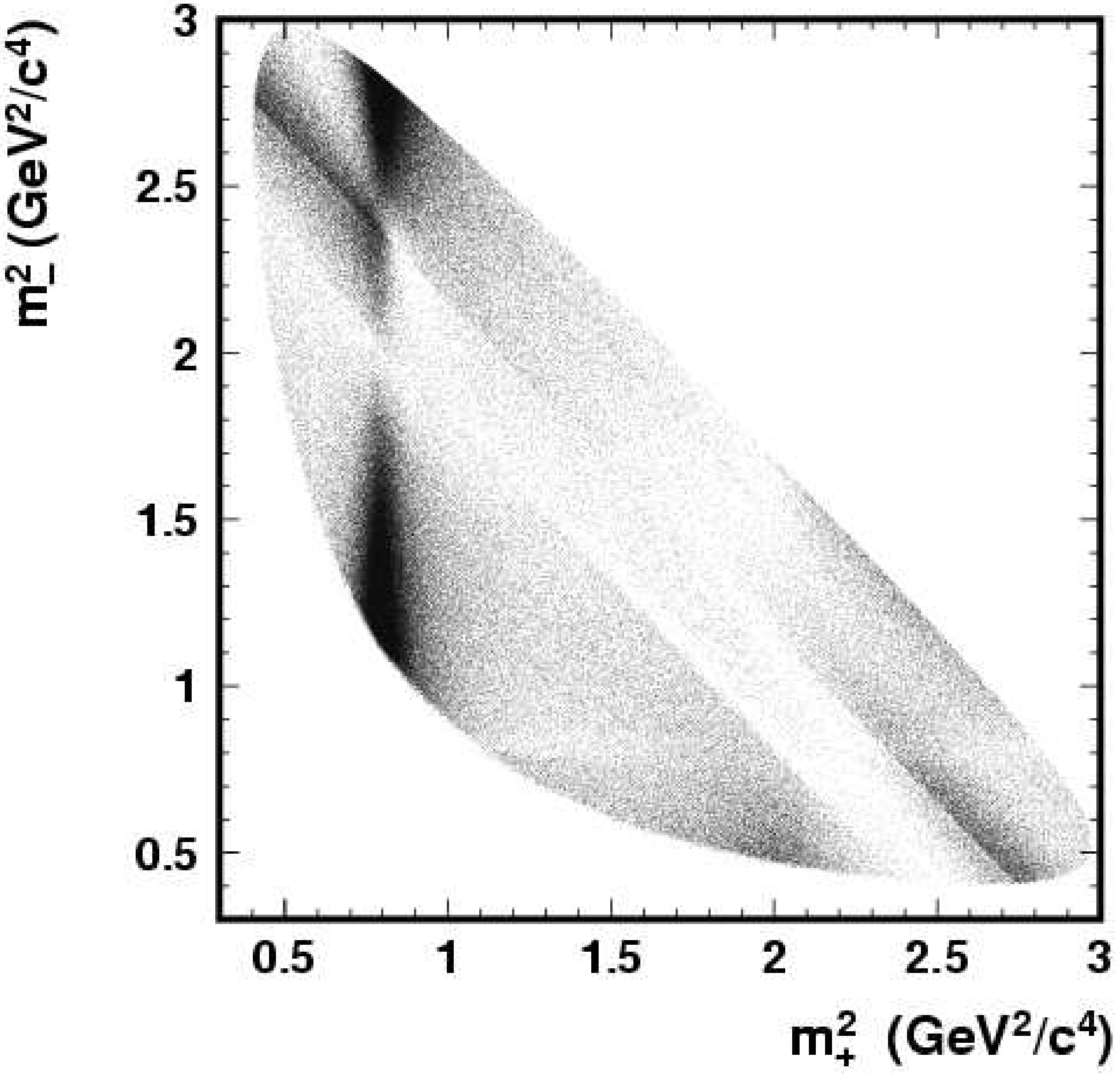
Precision Experiment

$J/\psi \to \gamma \pi^0 \pi^0$



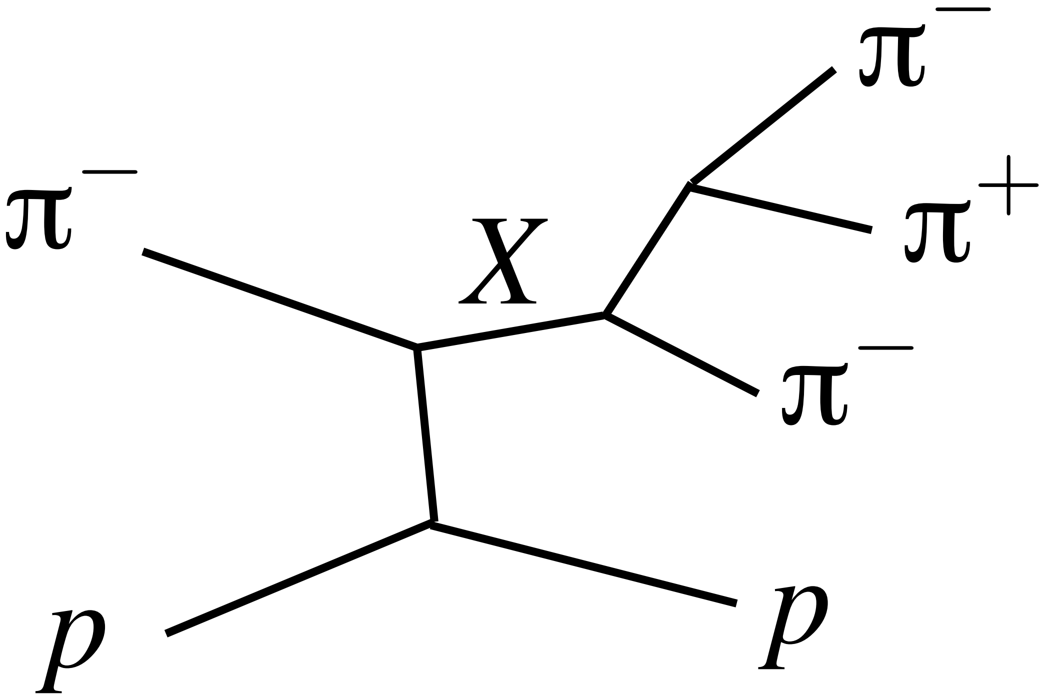
BESIII Collaboration, arXiv:1506.00546

$D \to K_S \pi^+ \pi^-$



Belle Collaboration, PRD 73, 112009 (2006)

Challenges of Precision Analysis



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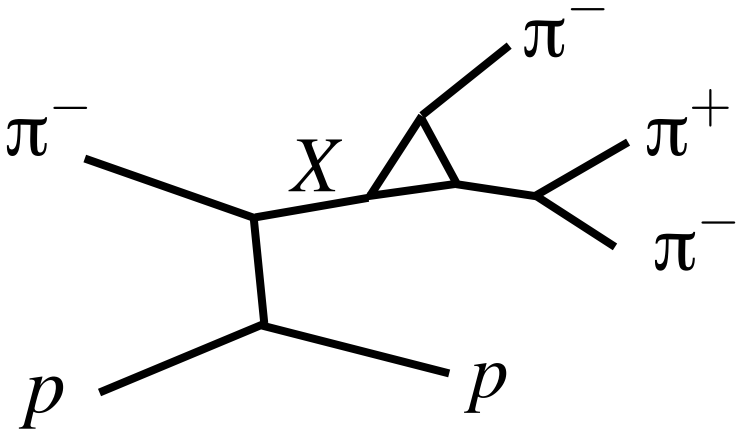
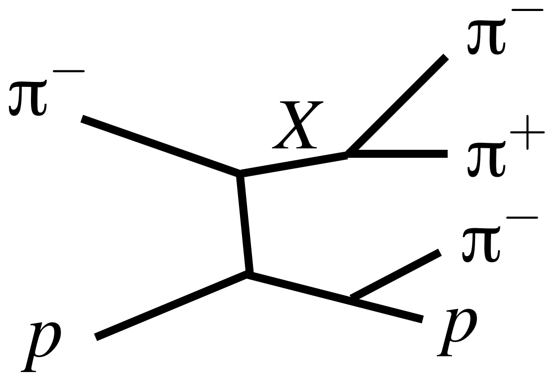
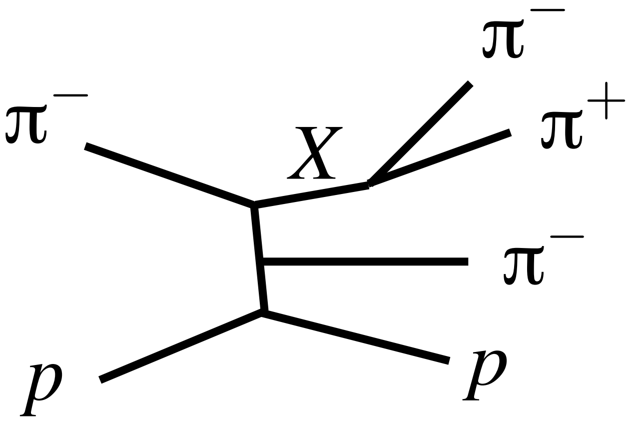






Theme

- advances in theory continue to sharpen and frame questions about QCD that can be addressed by experiment
- advances in experiment and technology have positioned us to address questions using data with unprecedented precision
- goal of this school: foster and share advances in phenomenology that help connect the two points above

A Selection of Recent Results

that showcase a variety of experiments and
emphasize the need for understanding reaction theory

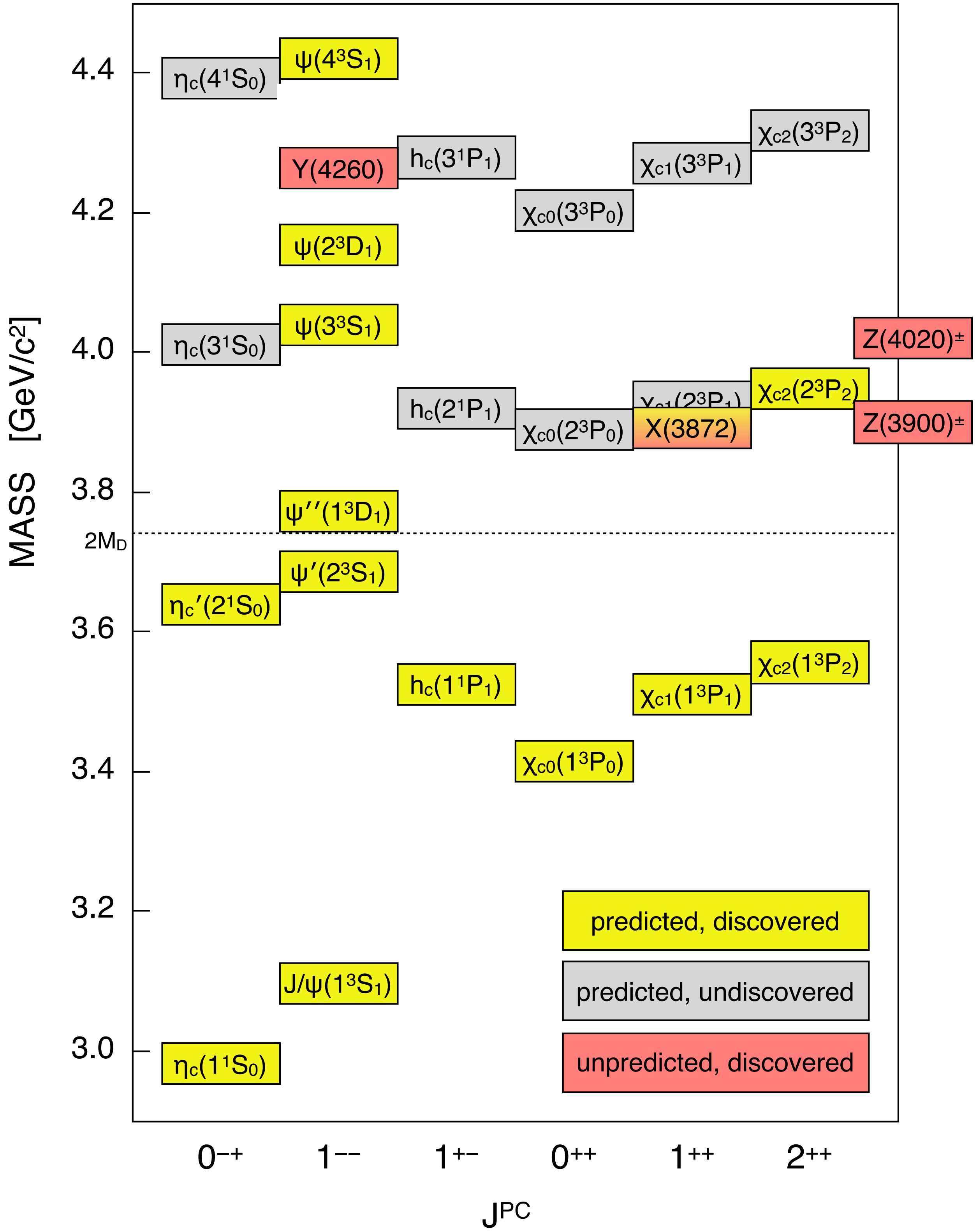
$e^+e^- \rightarrow$ hadrons

BaBar at PEP-II SLAC (Menlo Park, CA)
Belle at KEK (Tsukuba, Japan)
BESIII at BEPCII (Beijing, China)

Charmonium Landscape

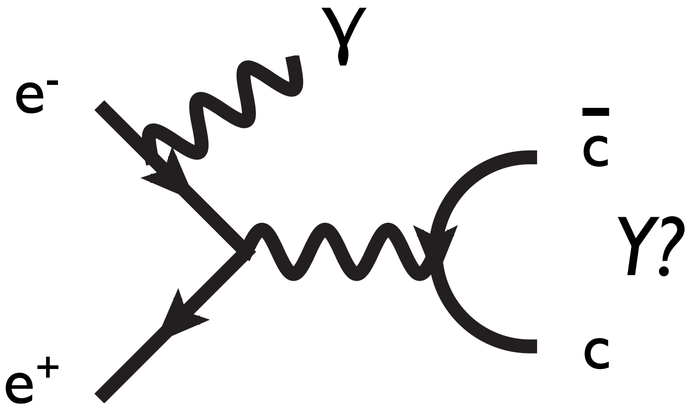
- Key players:
  - Y(4260): ???
  - J/ψ: S_q=1 L=0, J^{PC} = 1^{--}
  - h_c: S_q=0 L=1, J^{PC} = 1^{+-}
- Key transitions:
  - $Y \to \pi\pi J/\psi$
  - $Y \to \pi\pi h_c$
- Study of *Y*(4260) led to discovery of charged *Z*(3900)$^\pm$ and *Z*(4020)$^\pm$ structures

Quark Model Prediction:
Barnes *et al.*, PRD 72, 054026 (2005)
(approximate — not all XYZ candidates shown!)

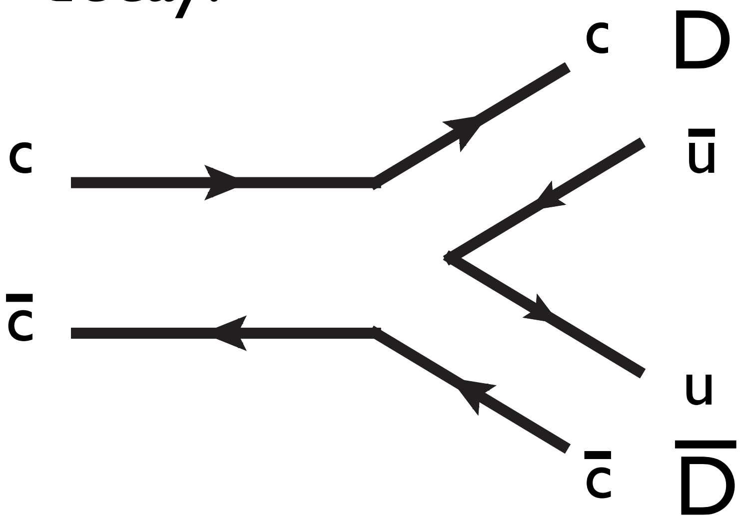


The Y(4260)

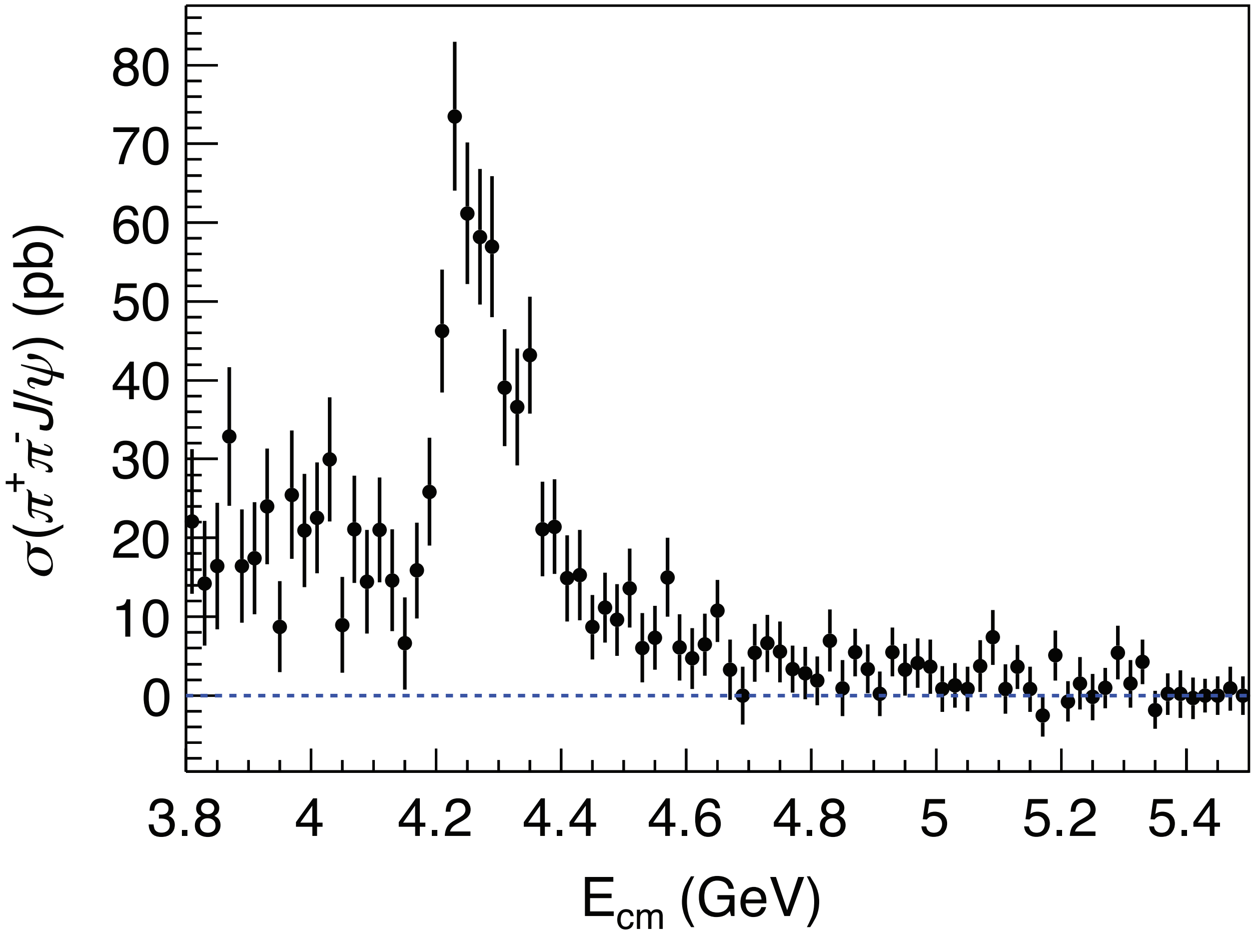
- 1^{--} state produced in e^+e^-



- mass greater than 2M(*D*) so we expect OZI favored decay:



Belle Collaboration, PRL 110, 252002 (2013)



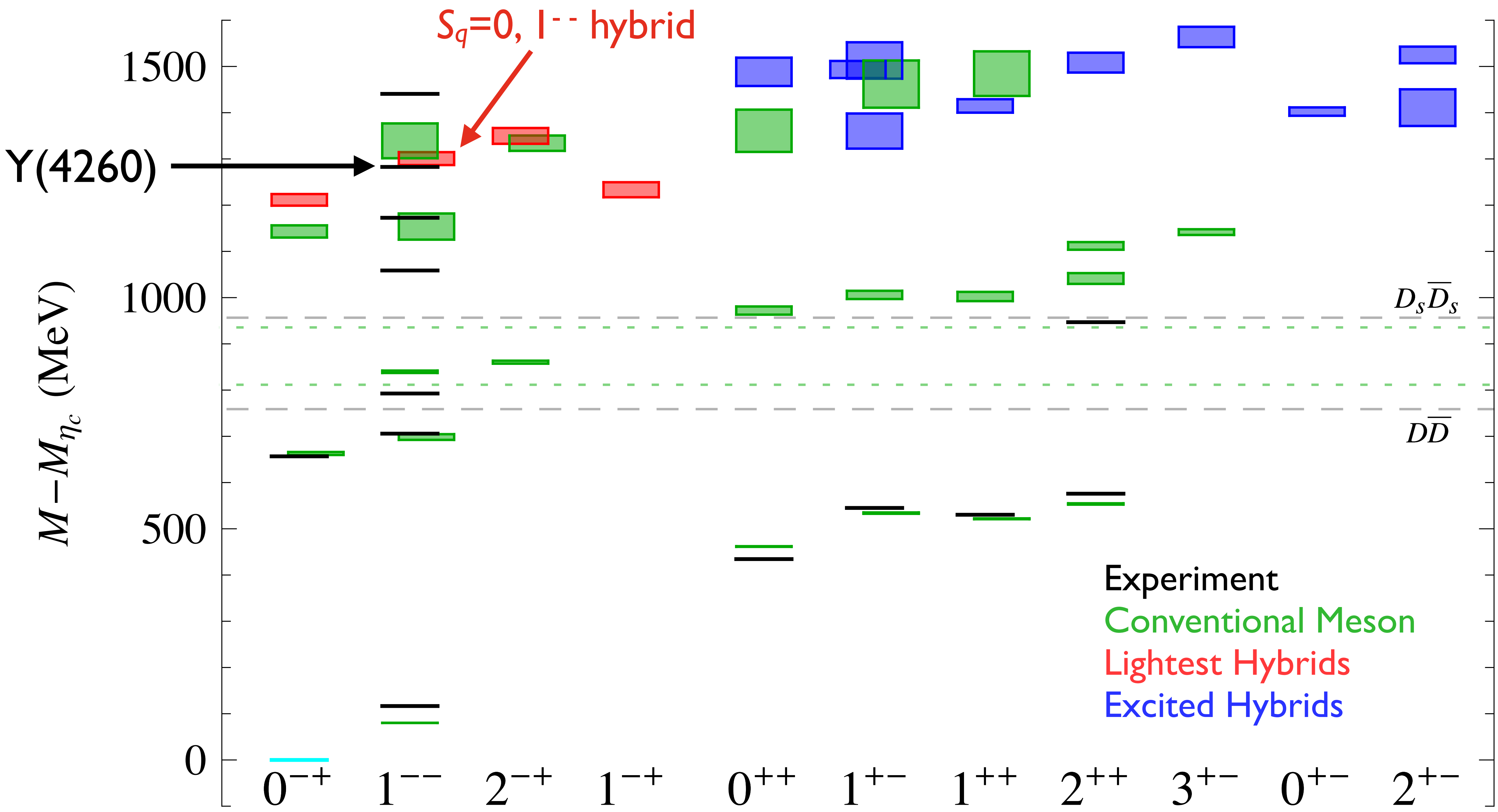
CLEO Collaboration, PRD 80, 072001 (2009)

$$\frac{\mathcal{B}(Y(4260) \to D\bar{D})}{\mathcal{B}(Y(4260) \to \pi\pi J/\psi)} < 4$$

compare with ≈500 for ψ(3770)

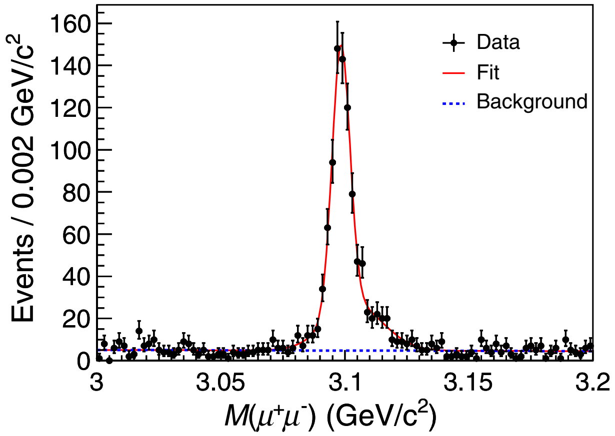
Charmonium from Lattice QCD

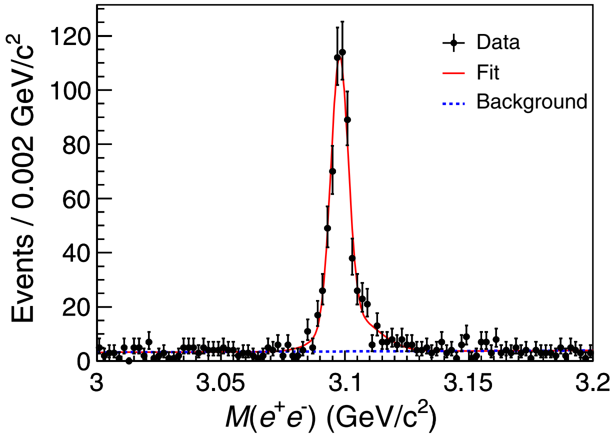
L. Liu *et al.* [Hadron Spectrum Collab.], JHEP07 126 (2012)



$e^+e^- \rightarrow \pi^+\pi^- J/\psi$ at E_{cm} = 4260 MeV

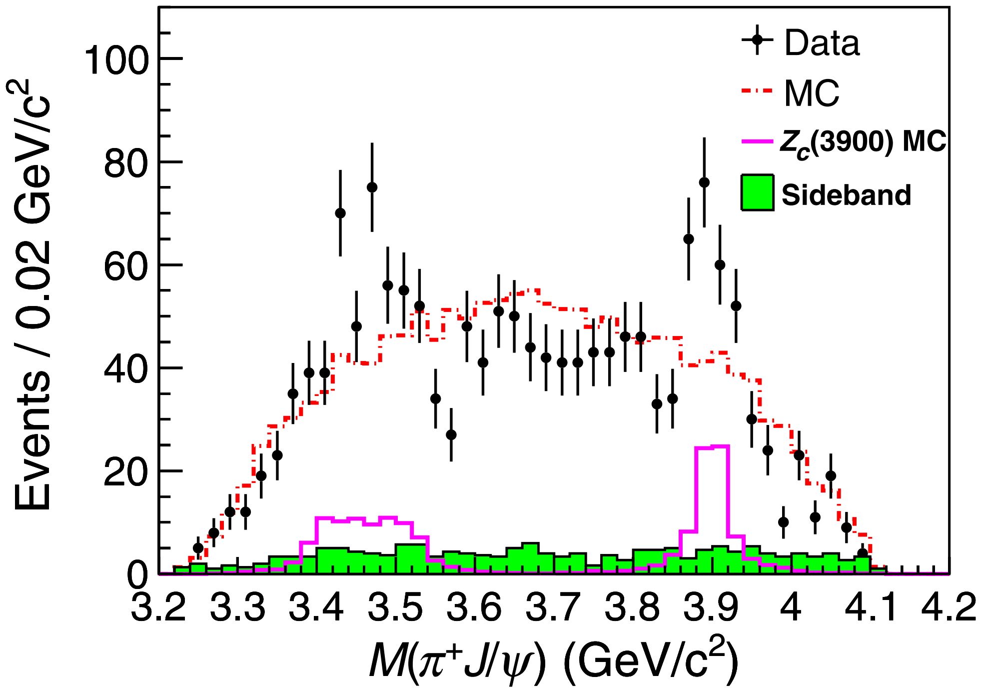
- J/ψ is cleanly identified in dilepton decay modes

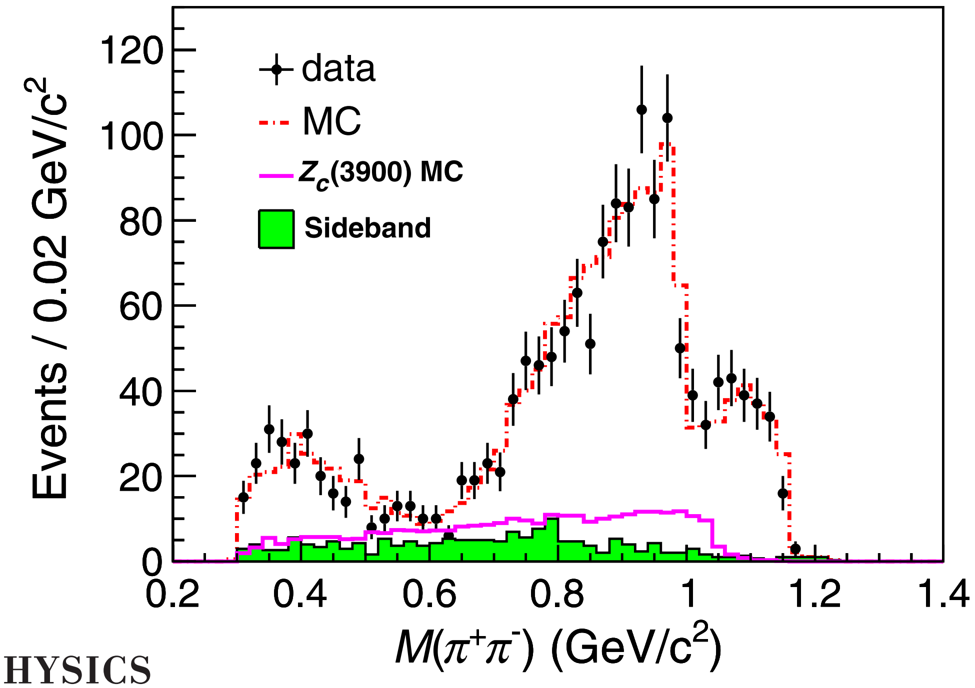


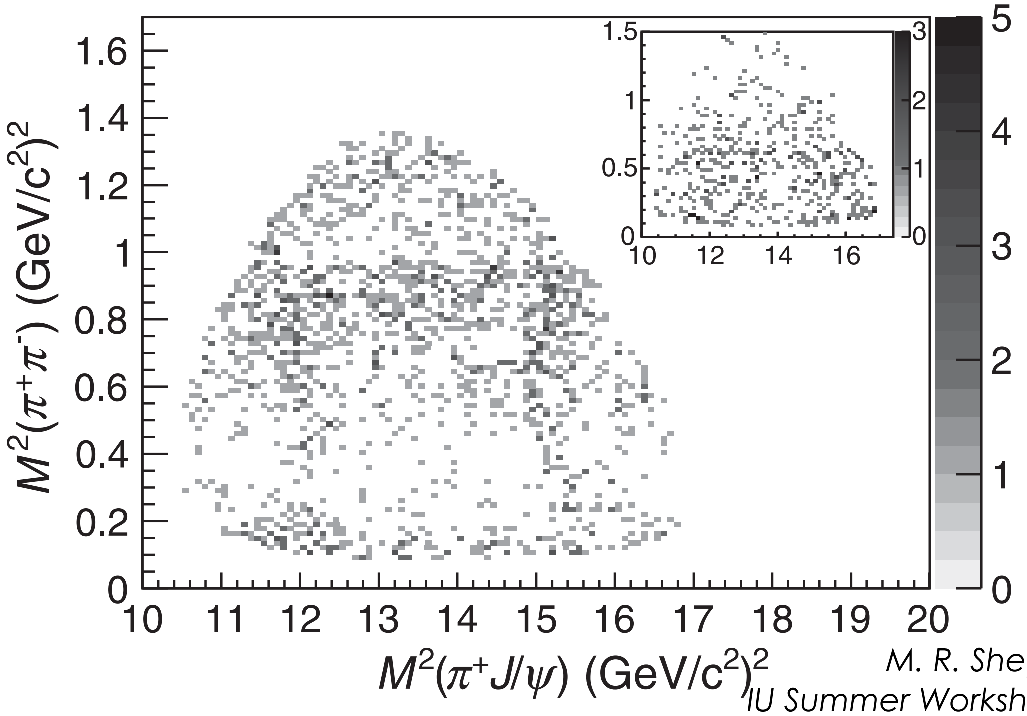


- Structure in π^+J/ψ mass that does not arise from $\pi^+\pi^-$ interactions

BESIII Collaboration, PRL 110, 252001 (2013)



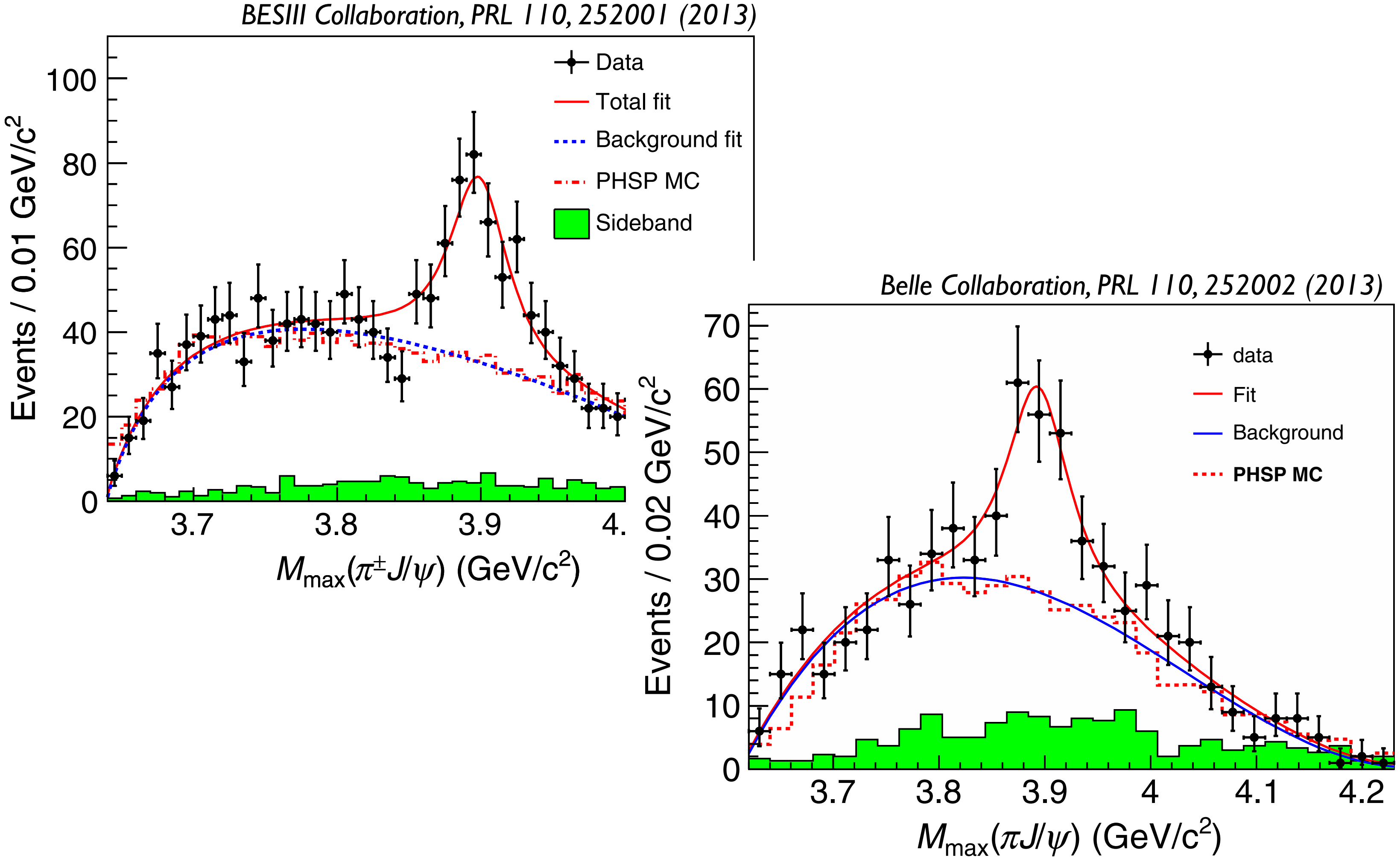




$Z(3900)^\pm \to \pi^\pm J/\psi$

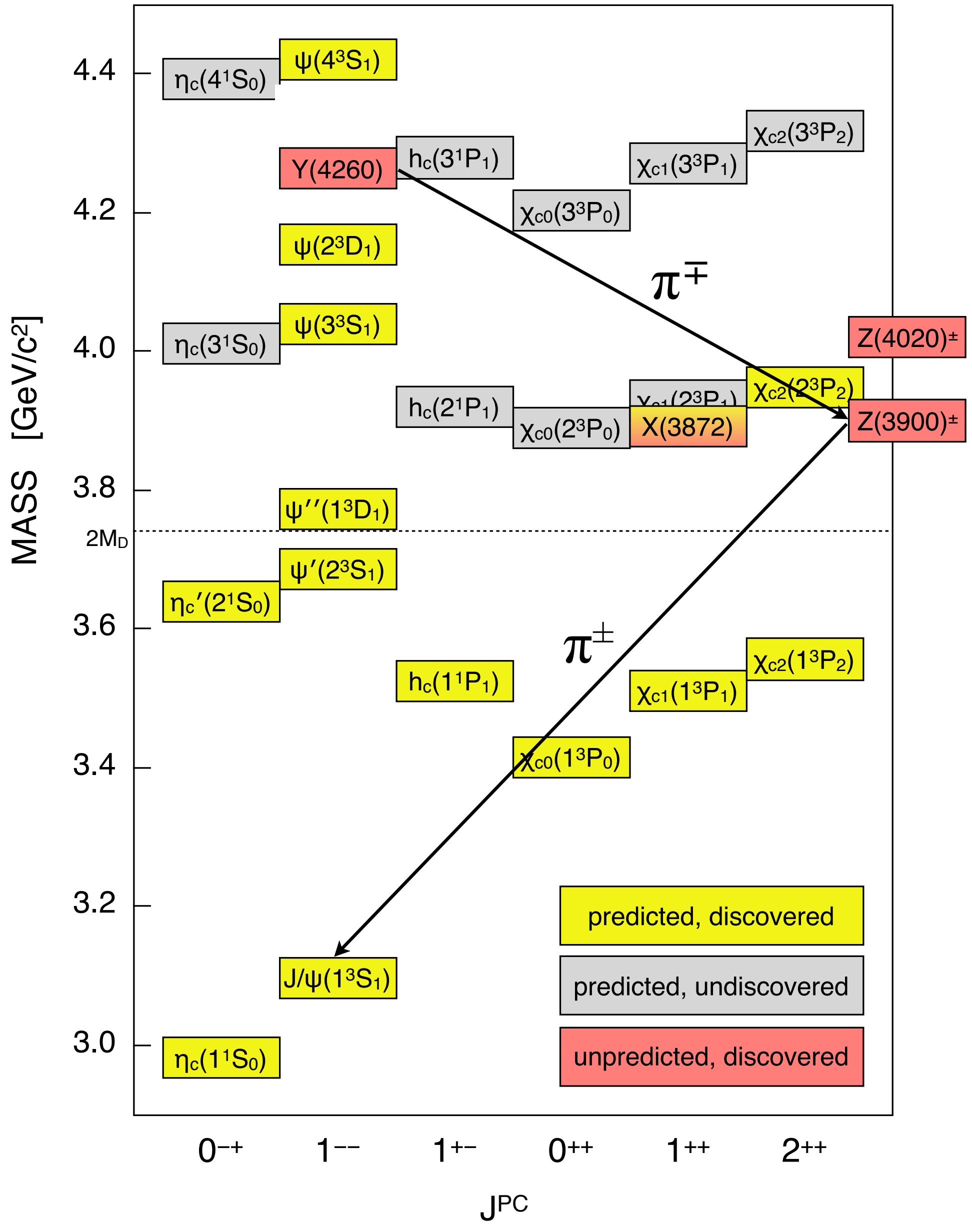
BESIII Collaboration, PRL 110, 252001 (2013)

Belle Collaboration, PRL 110, 252002 (2013)



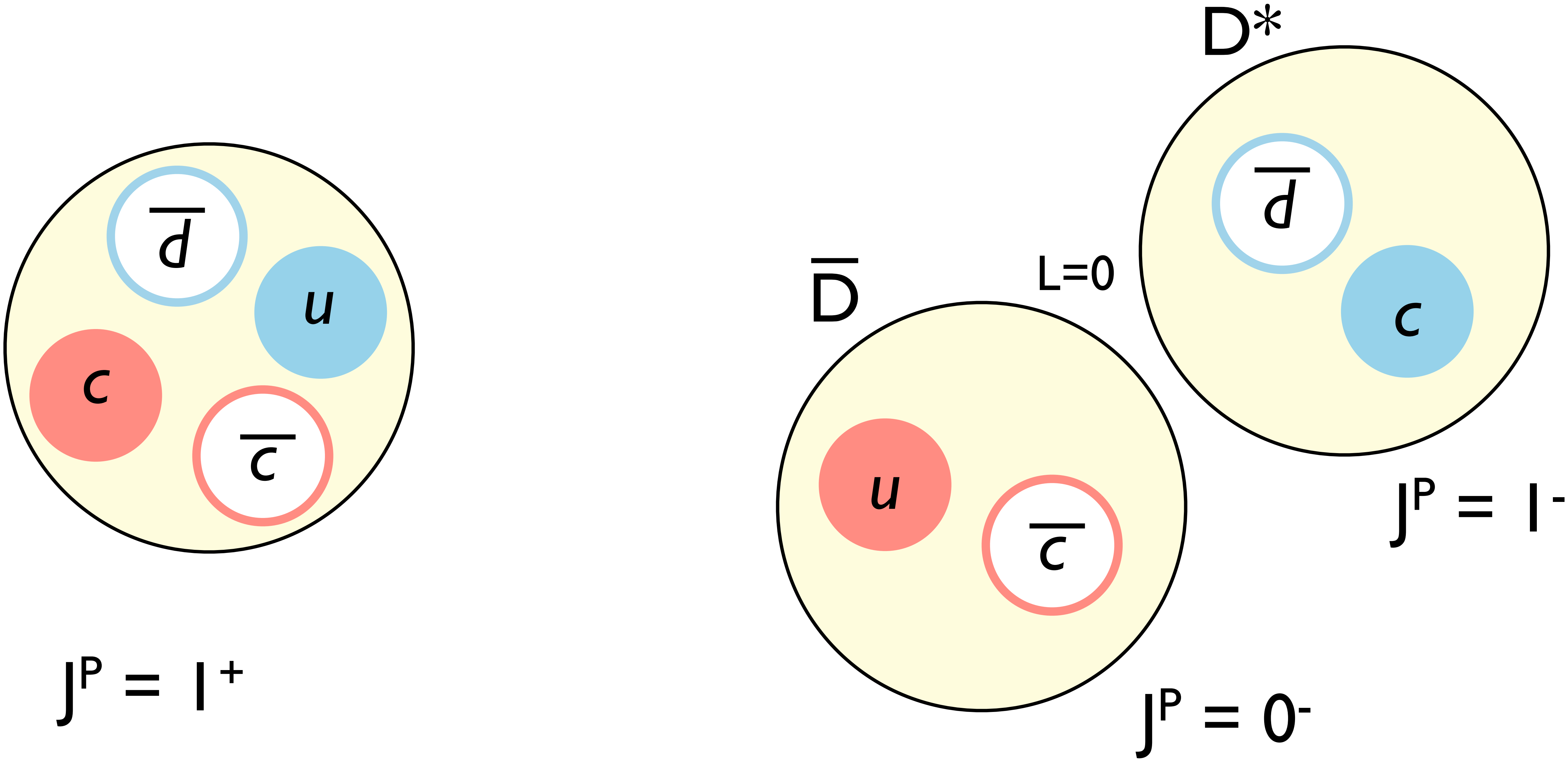
Study:

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



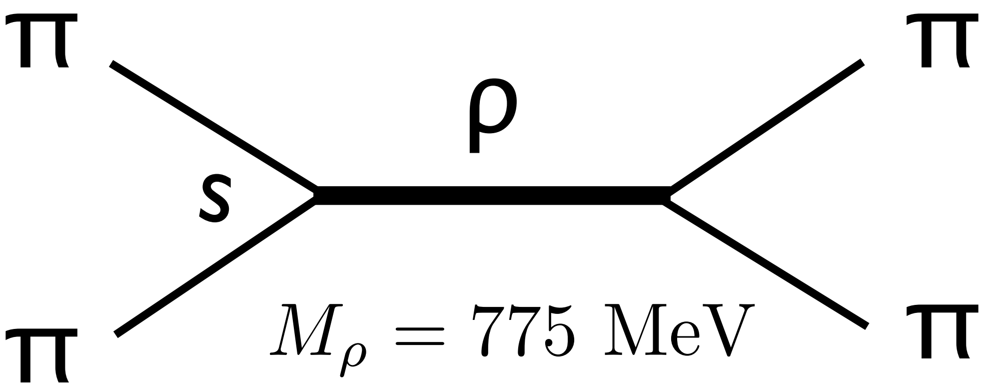
- Narrow (≈50 MeV) and *charged*
- Not conventional charmonium: tetraquark?
- Evidence of neutral partner
  [*T. Xiao et al., PLB 727, 366 (2013)*]

What is Z(3900)?



How is it connected to Y(4260)?

What is a Resonance?

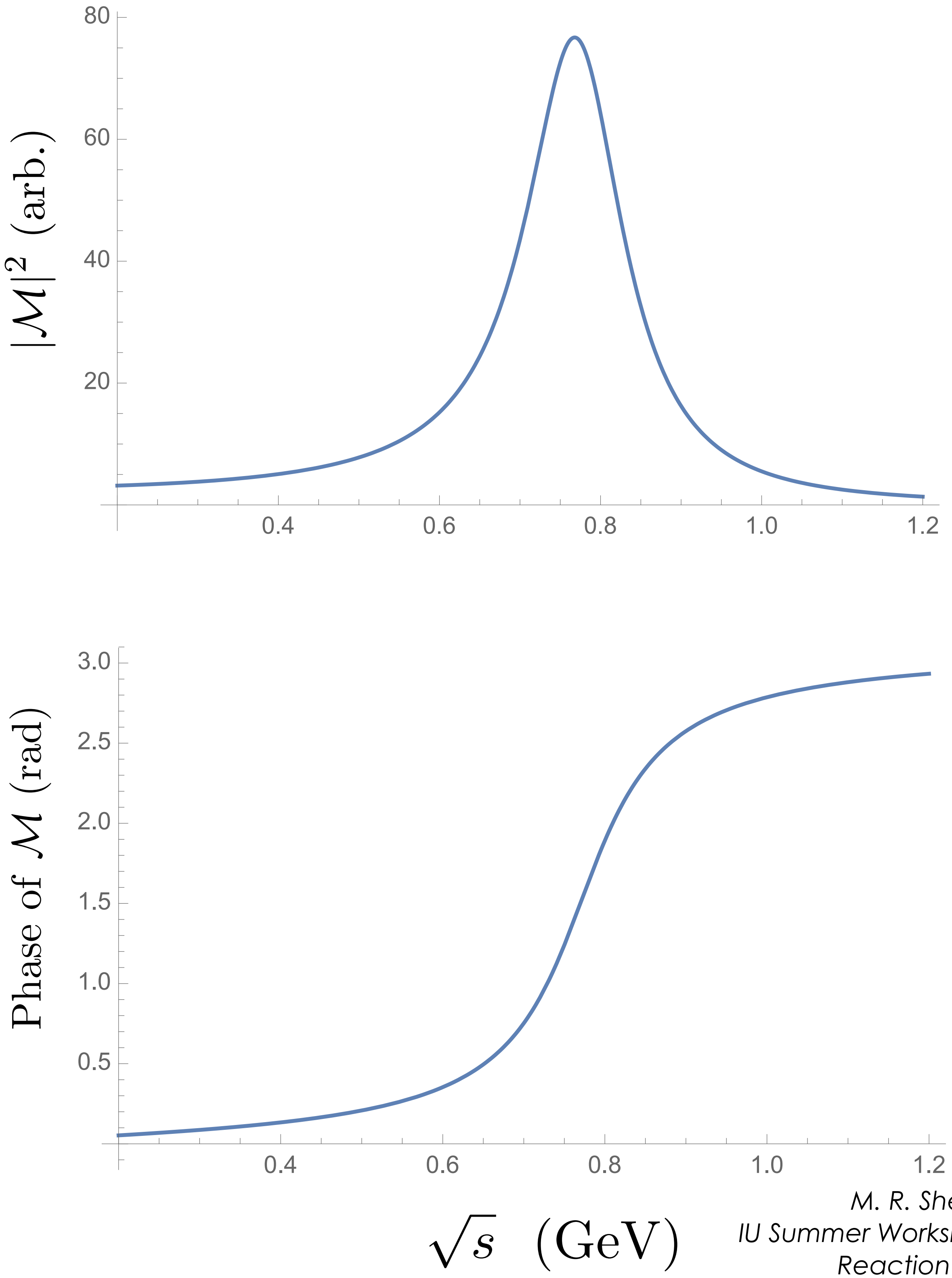


$$M_\rho = 775\ \mathrm{MeV}$$
$$\Gamma_\rho = 148\ \mathrm{MeV}$$

$$\mathcal{M} \propto \frac{1}{M^2 - s - i\sqrt{s}\Gamma}$$

$$\text{pole}: \quad \sqrt{s} = M - i\Gamma/2$$

Expt.: s = [M(ππ)]^2 (real)



Notes from the Editors: Highlights of the Year

Published December 30, 2013 | Physics **6**, 139 (2013) | DOI: 10.1103/Physics.6.139

***Physics* looks back at the standout stories of 2013.**

As 2013 draws to a close, we look back on the research covered in *Physics* that really made waves in and beyond the physics community. In thinking about which stories to highlight, we considered a combination of factors: popularity on the website, a clear element of surprise or discovery, or signs that the work could lead to better technology. On behalf of the *Physics* staff, we wish everyone an excellent New Year.

– Matteo Rini and Jessica Thomas

Images from popular *Physics* stories in 2013.

Four-Quark Matter

Quarks come in twos and threes—or so nearly every experiment has told us. This summer, the BESIII Collaboration in China and the Belle Collaboration in Japan reported they had sorted through the debris of high-energy electron-positron collisions and seen a mysterious particle that appeared to contain four quarks. Though other explanations for the nature of the particle, dubbed $Z_c(3900)$, are possible, the "tetraquark" interpretation may be gaining traction: BESIII has since seen a series of other particles that appear to contain four quarks.

Strangers from Beyond our Solar System

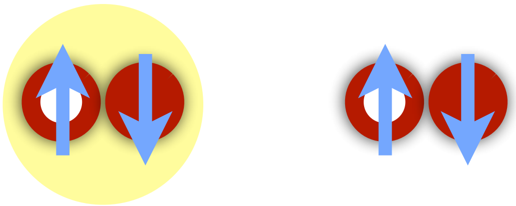
Detector experiments hunting for rare events can go years and never see anything out of the ordinary. So it was cause for excitement when IceCube, a giant neutrino telescope at the South Pole, reported the detection of two neutrinos with energies of around 1000 tera-electron-volts (TeV), roughly a billion times more energetic than those arriving from the Sun. Scientists at IceCube have since further analyzed their data and reported 26 more neutrinos with energies above 30 TeV. Researchers will need to

Y(4260) hybrid test?

- Lattice QCD predicts the hybrid 1^{--} state to have spin $S = 0$

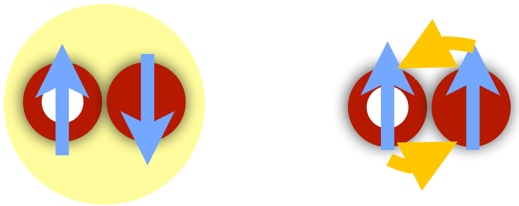
Using LQCD Dudek *et al.* predict [PRD 79, 094504 (2009)]

$$Y_{\rm hybrid} \to \gamma\eta_c$$



rate is comparable
or larger than

$$Y_{\rm hybrid} \to \gamma\chi_{c0}$$



Potential "hybrid test" for *Y*(4260), but no experimental sensitivity…yet

Two decays that we can attempt to compare instead:

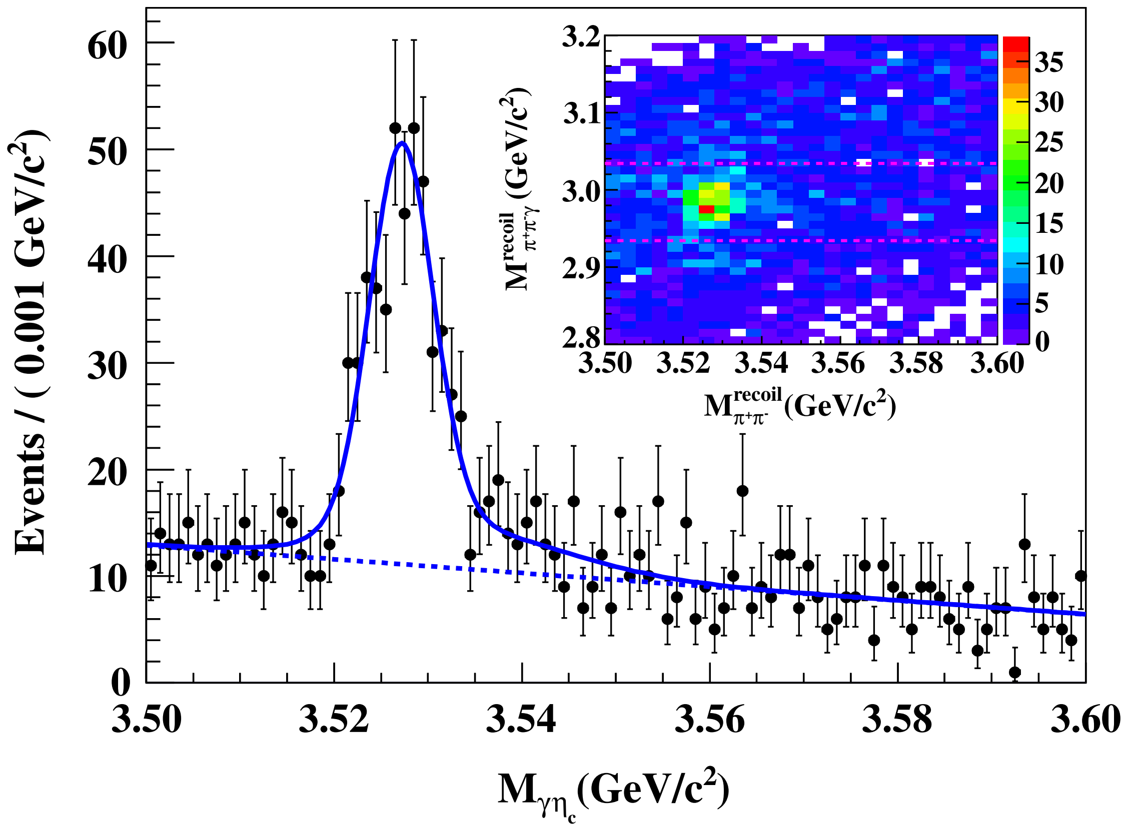
$$Y(4260) \to \pi\pi h_c$$

??

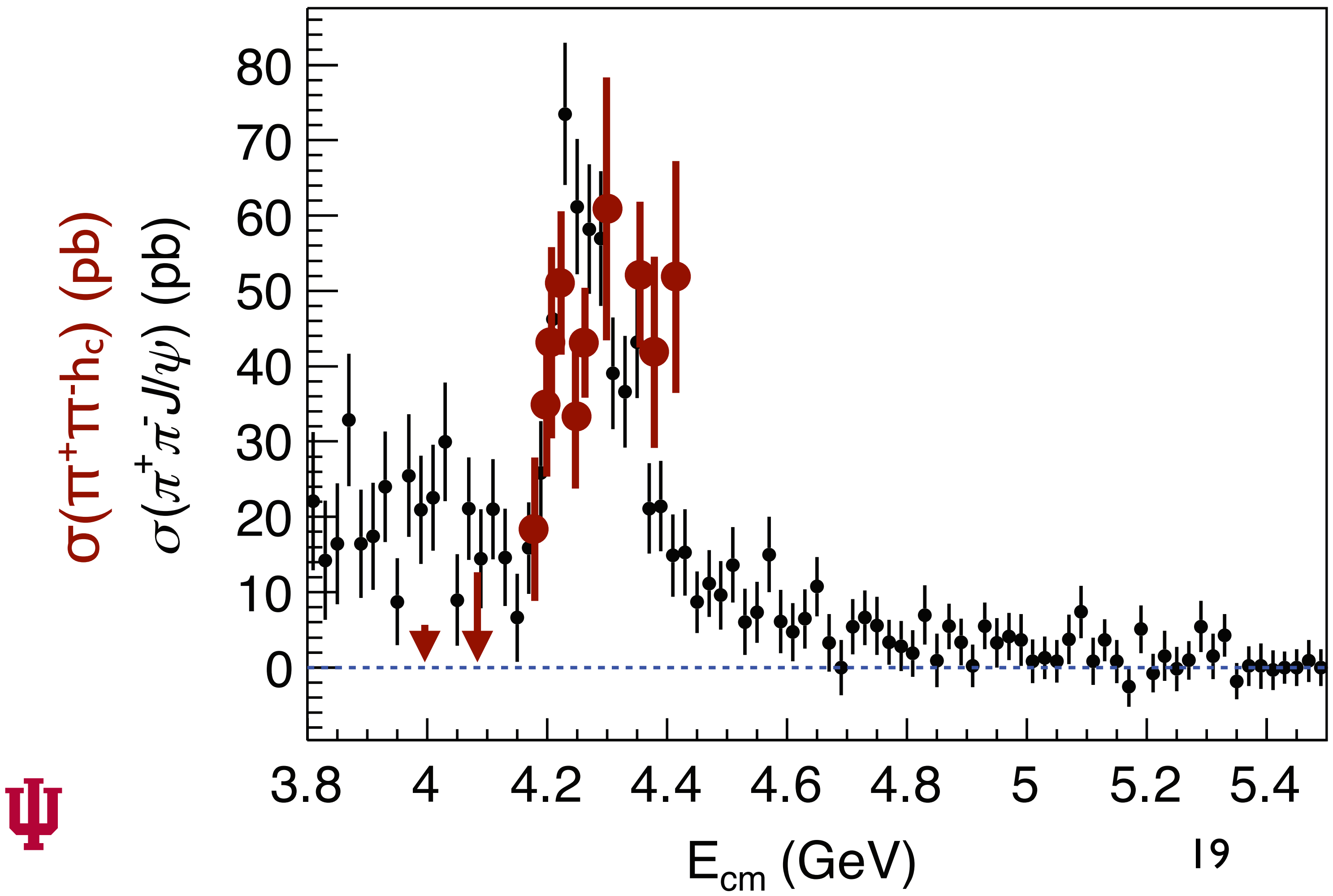
$$Y(4260) \to \pi\pi J/\psi$$

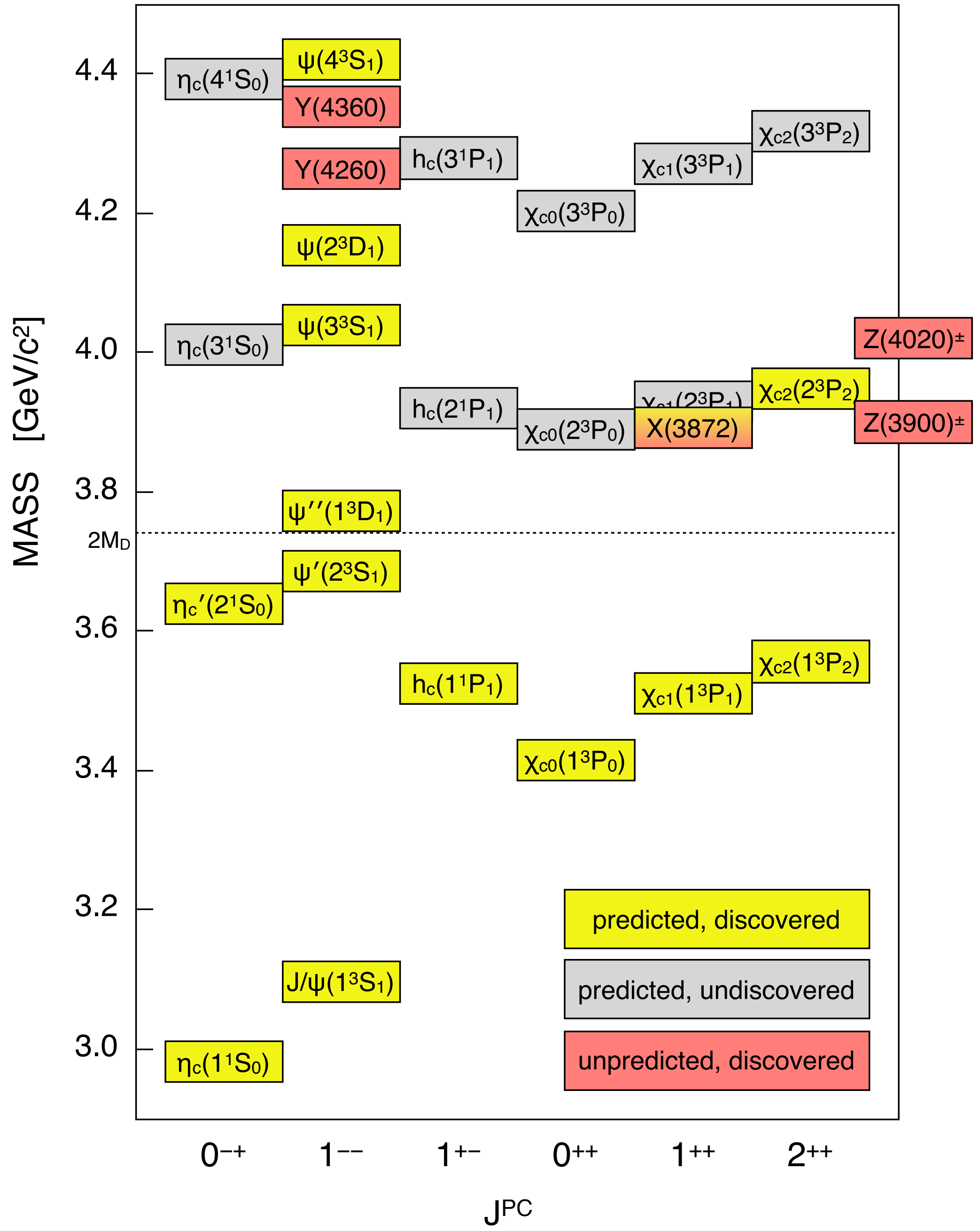
??

$e^+e^- \rightarrow \pi^+\pi^- h_c$

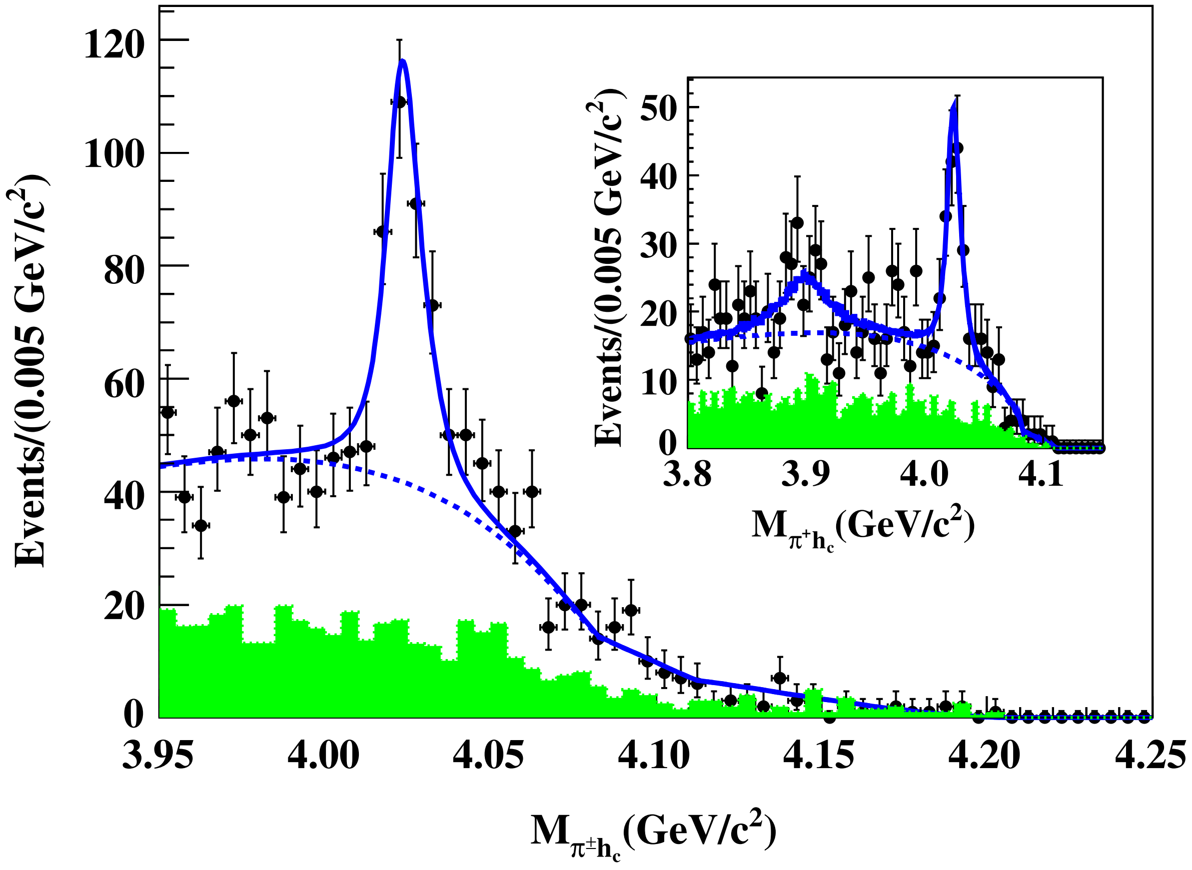


BESIII Collaboration, PRL 111, 242001 (2013)



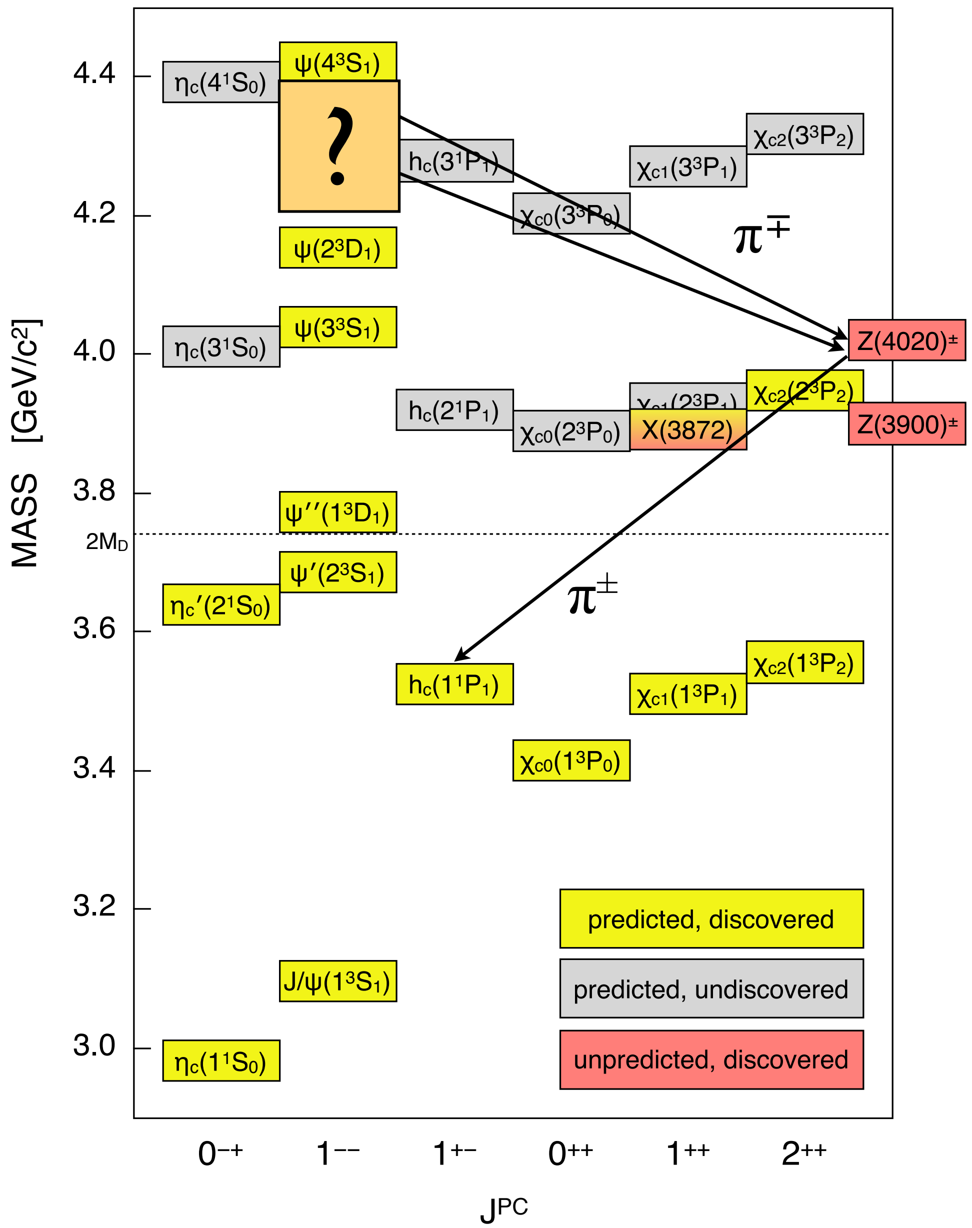


$Z(4020)^{\pm} \rightarrow \pi^{\pm} h_c$



BESIII Collaboration, PRL 111, 242001 (2013)

Study:
$e^+e^- \rightarrow \pi^+\pi^- h_c$

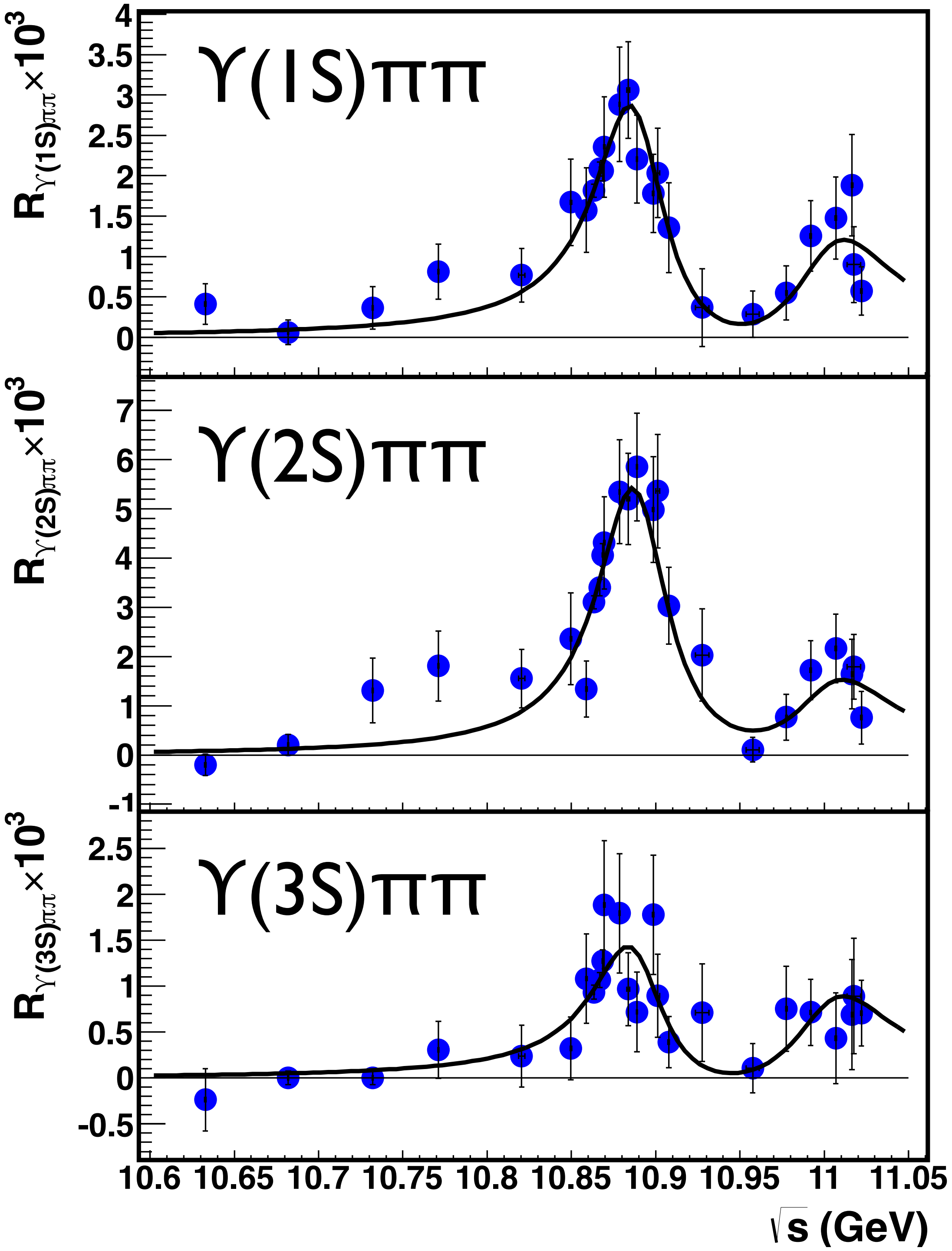


- No *Y*(4260)-like peaking structure in $\pi^+\pi^- h_c$ cross section, which is comparable to peak in $\sigma(\pi^+\pi^- J/\psi)$
- Very narrow charged $\pi^{\pm}h_c$ structure near *DD** threshold
- Not conventional charmonium

What about *b* quarks?

- Same story, heavier characters
  - $Y(4260) \rightarrow \Upsilon$ or $\Upsilon(10860)$
  - $J/\psi \rightarrow \Upsilon$
  - $h_c \rightarrow h_b$
- at 10890 MeV: peak in ππ transitions to ϒ(nS) states
- Study πϒ and πh_b structure in transitions

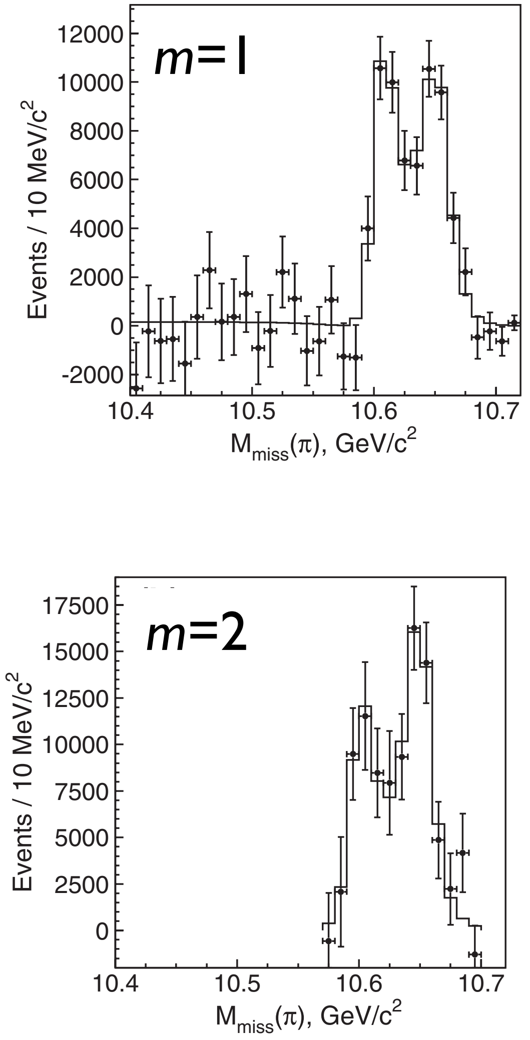
Belle Collaboration, arXiv:1501.01137



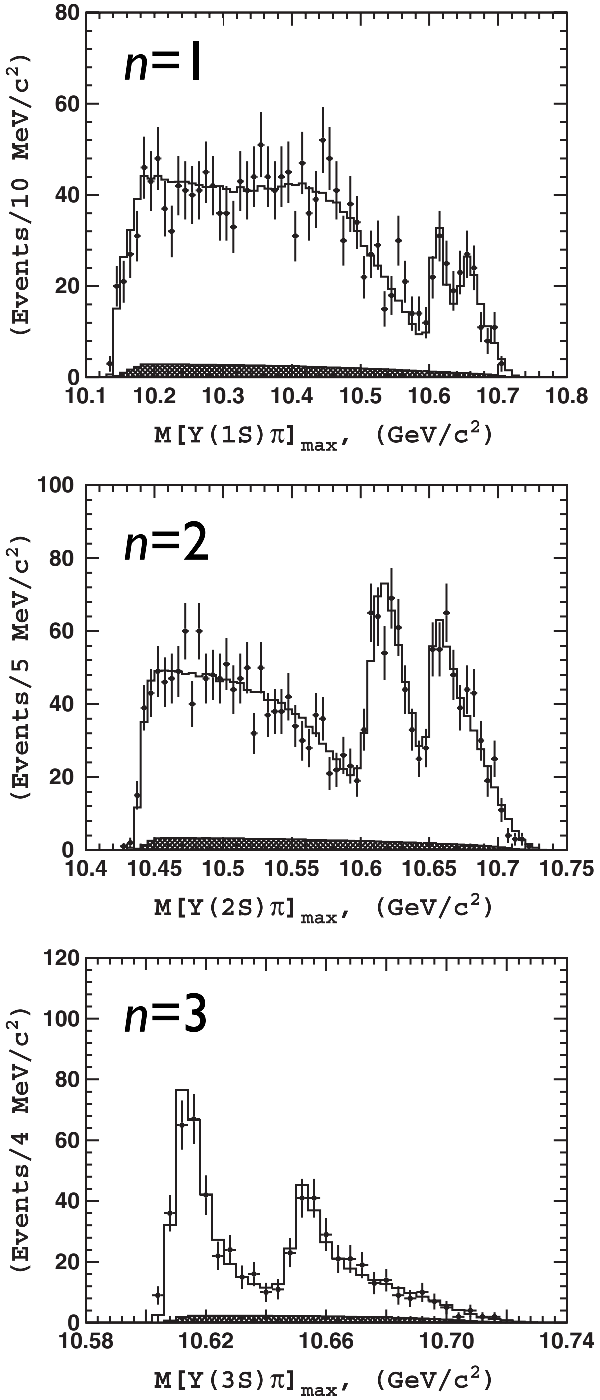
Observation of $Z_b(10610)^\pm$ and $Z_b(10650)^\pm$

- Belle observes two charged states in the bottomonium spectrum
  - couple to $\pi^\pm h_b$ and $\pi^\pm \Upsilon$
- consistent masses and widths *in five different decay modes*
- masses at or just above BB^* and B^*B^* thresholds
- decays to $B^{(*)}\overline{B}^*$: *[Belle Collaboration arXiv:1209.6450]*

$\pi^\pm h_b(mP)$



$\pi^\pm \Upsilon(nS)$



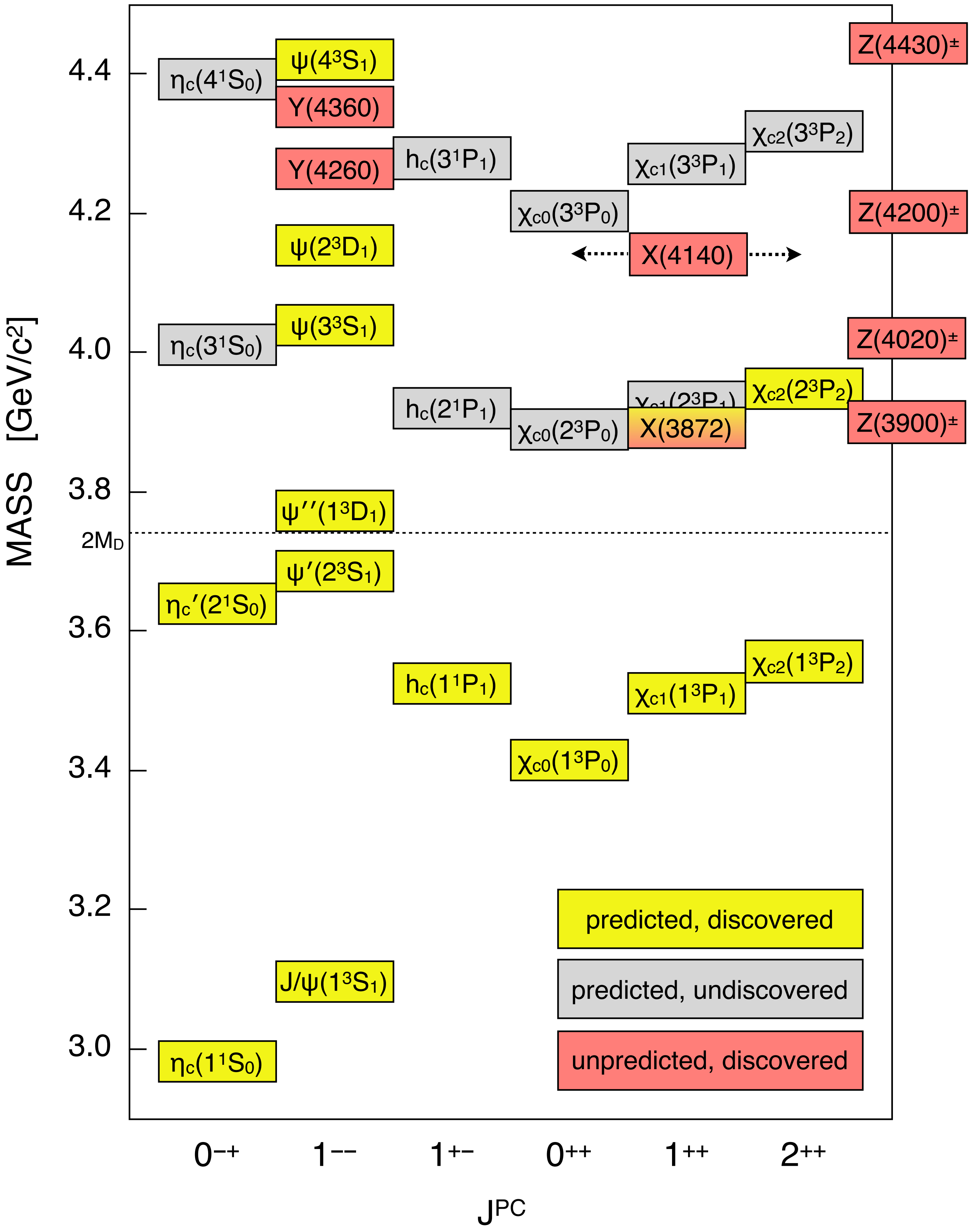
Belle Collaboration, PRL 108, 122001 (2012)

Decays of B Mesons

LHCb at the LHC
BaBar at PEP-II SLAC (Menlo Park, CA)
Belle at KEK (Tsukuba, Japan)

Charmonium in *B* Decay

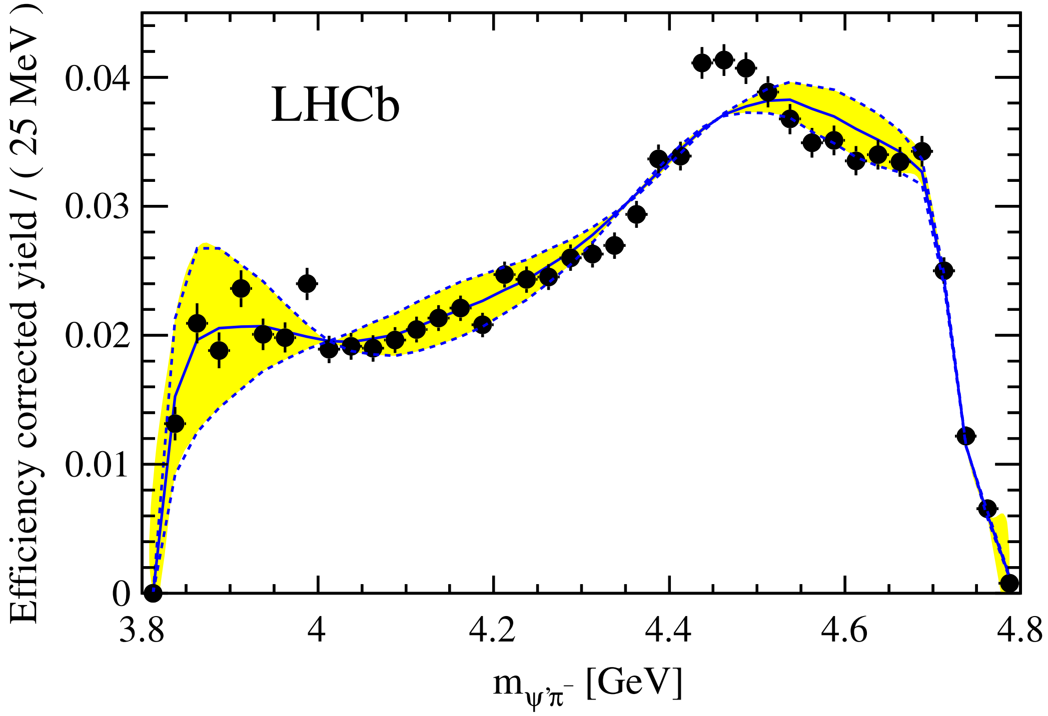
- Hadronic decays of the *B* meson (M(*B*) = 5.27 GeV) can be used to study the charmonium spectrum
  - useful tool at hadron colliders
- Recent hot topics:
  - charged states: *Z*(4430) and *Z*(4200) in $\pi^\pm\psi(')$
  - narrow neutral state: *X*(4140) in $\Phi J/\psi$

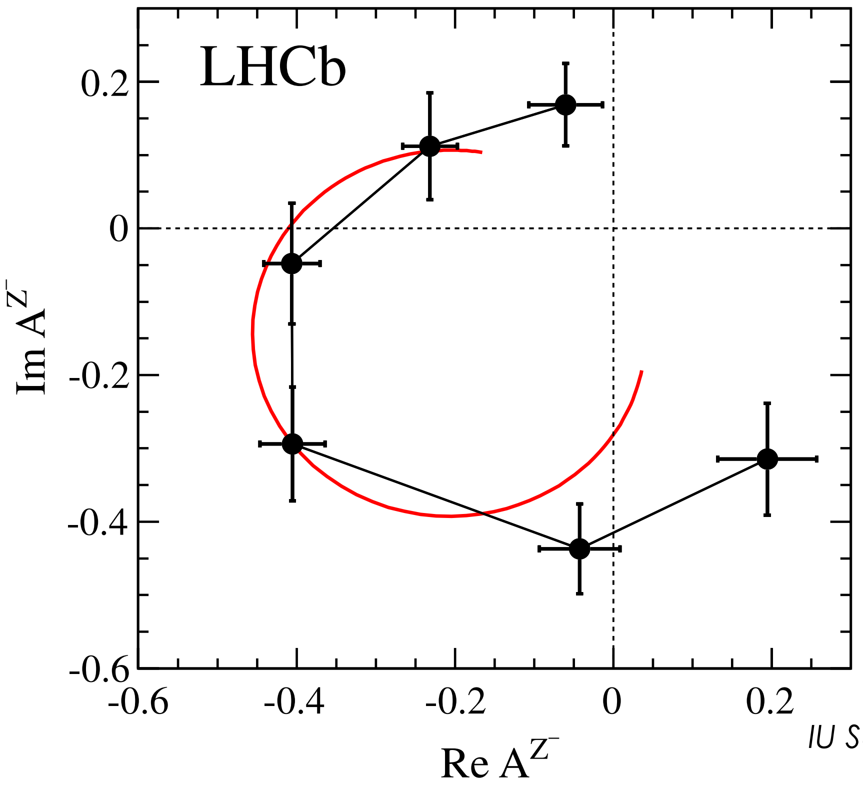


$Z(4430)^{\pm} \rightarrow \psi'\pi^{\pm}$

- Examine $\psi'\pi^{\pm}$ produced in $B \rightarrow \psi' K\pi^{\pm}$
  - need to understand Kπ structure
- *Z*(4430) reported initially by Belle [PRL 100, 142001 (2008)], but not confirmed by BaBar [PRD 79, 112001 (2009)]
- *Z*(4430) recently confirmed with 10x more data at LHCb
- established $J^P = 1^+$
  - not S-wave $D^*(2007)D_1(2420)$ or $D^*(2007)D_2{}^*(2460)$
- Broad structure: $\Gamma_{tot} \approx 200$ MeV
- LHCb: second structure around 4200 at 6σ; resonant nature inclusive

LHCb Collaboration, PRL 112, 222002 (2014)

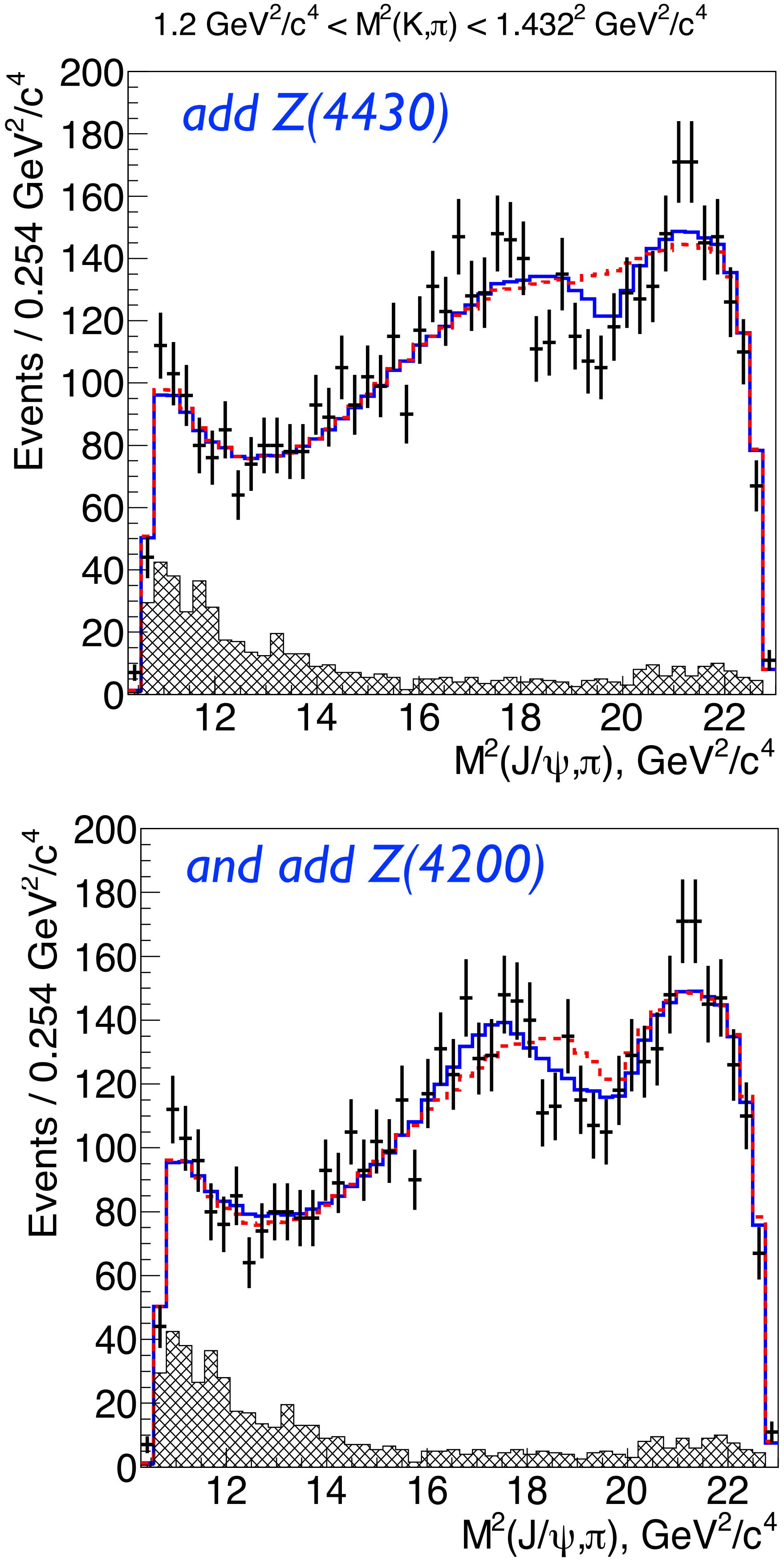




$B \to K\pi^{\pm}J/\psi$

- Belle reports evidence for $Z(4430) \to \pi^{\pm}J/\psi$
    - about 10x smaller than $Z(4430) \to \pi^{\pm}\psi'$
- Belle: $Z(4200)^{\pm} \to \pi^{\pm}J/\psi$ at 6.2σ
    - broad: $\Gamma_{tot} \approx 400$ MeV
    - $J^P = 1^+$ favored
    - compatible with "structure" in LHCb analysis of $\pi^{\pm}\psi'$
- No evidence for the $Z(3900)$ that is correlated with $Y(4260)$ decay
    - production mechanism dependence?
    - $Z(3900)$ is fundamentally different from $Z(4200)$ and $Z(4430)$?

Belle Collaboration, arXiv:1408.6457 (2014)



Comments/Questions

- e^+e^- → hadrons
  - Similar physics in both bottom and charm systems
  - Experimentally significant narrow peaks in the mass spectrum
    - resonances?

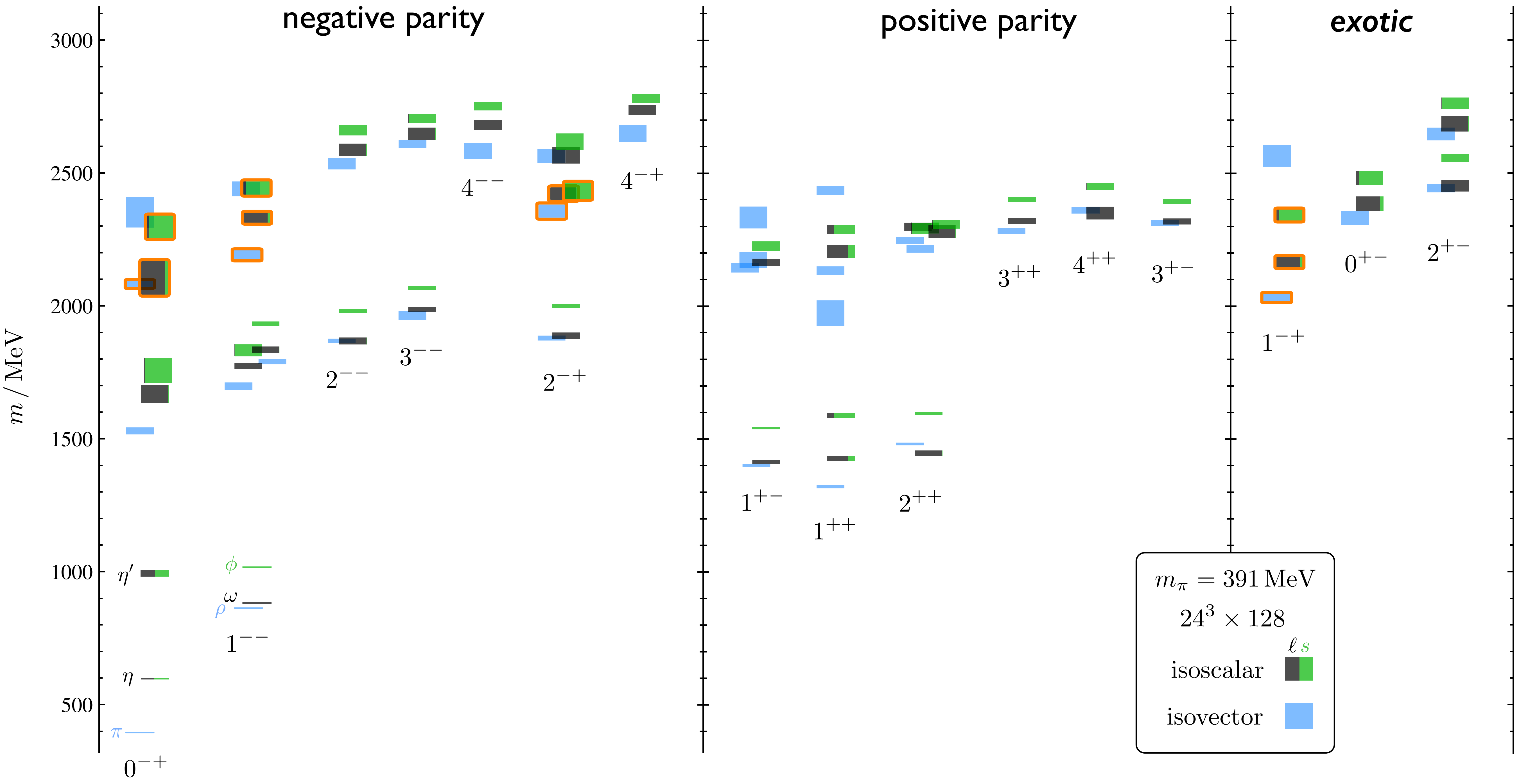
- Decays of B Mesons
  - Additional charged states observed in B decay
    - significantly broader
    - one appears to have phase motion of a resonance

π Beam Data

COMPASS at CERN

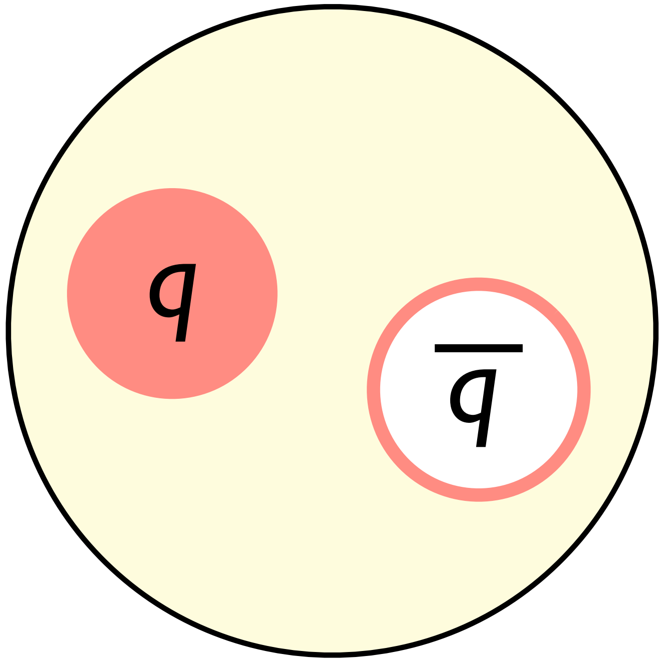
Meson Spectrum from Lattice QCD

Dudek, Edwards, Guo, and Thomas, PRD 88, 094505 (2013)



Hybrid Mesons

color singlet
quark anti-quark

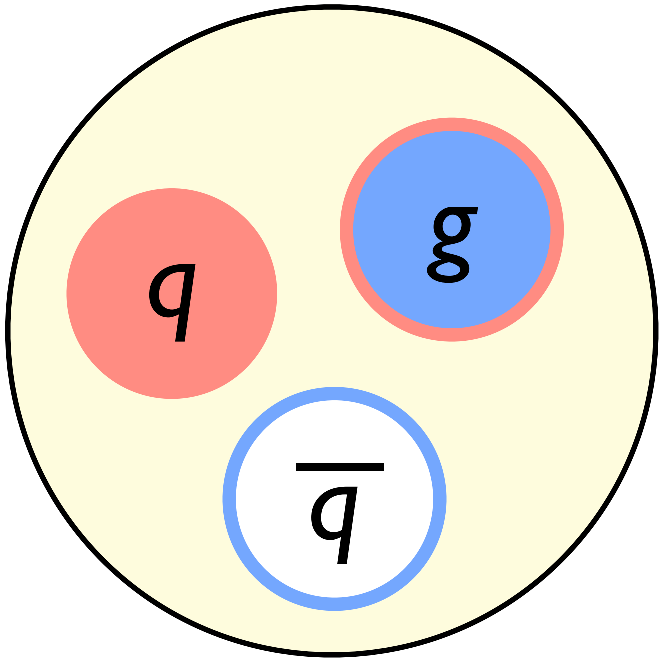


$J = L + S \quad P = (-1)^{L+1} \quad C = (-1)^{L+S}$

Allowed J^{PC}: $0^{-+}, 0^{++}, 1^{--}, 1^{+-}, 2^{++}, \ldots$
Forbidden J^{PC}: $0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, \ldots$

“constituent gluon”
$(J^{PC})_g = 1^{+-}$
mass ≈ 1.0-1.5 GeV

color-octet
$q\bar{q}$ pair



Lightest Hybrids

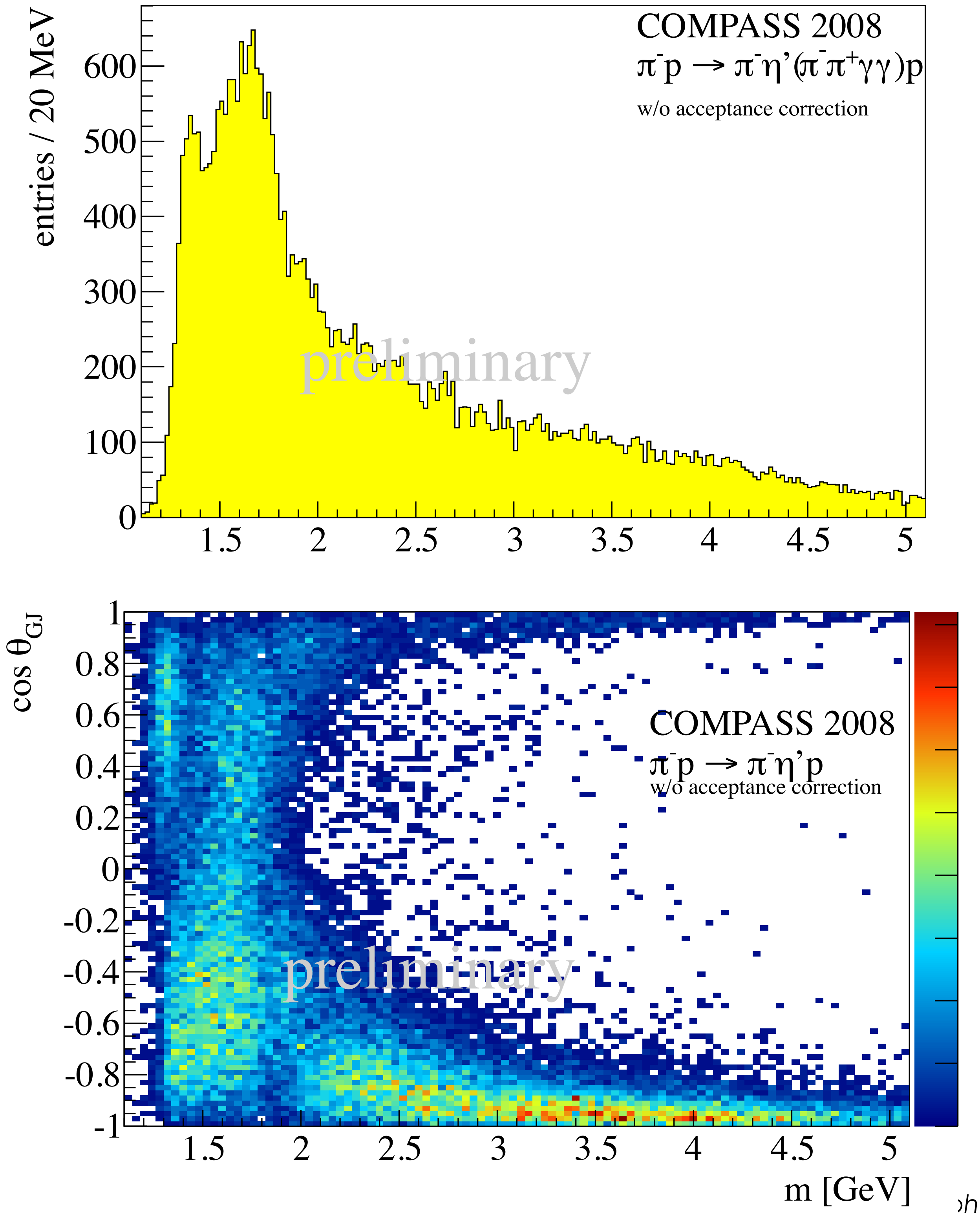
	$S_{q\bar{q}} = 1$	$S_{q\bar{q}} = 0$
J^{PC}:	$0^{-+}, 1^{-+}, 2^{-+}$	1^{--}

“exotic hybrid”

$\pi^- p \rightarrow \eta' \pi^- p$

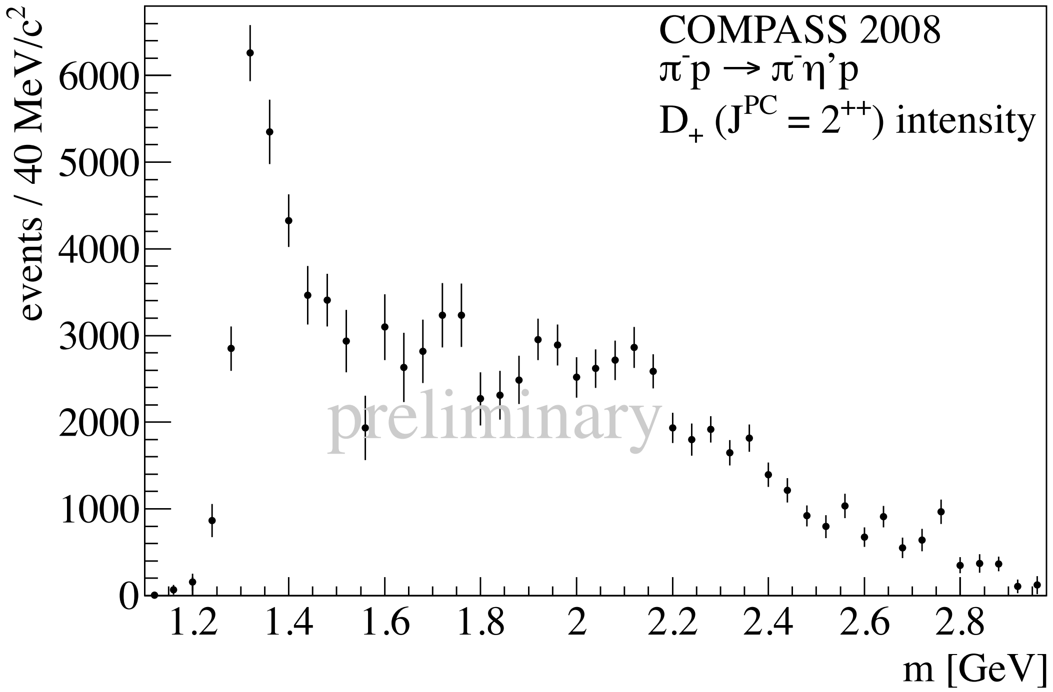
- Data collected from COMPASS using a 190 GeV pion beam
- $\eta' \pi^-$ in a P-wave: L=1
    - parity: -
    - G: -
    - isospin: 1
    - J^{PC} of neutral isovector is 1^{-+} (exotic!)

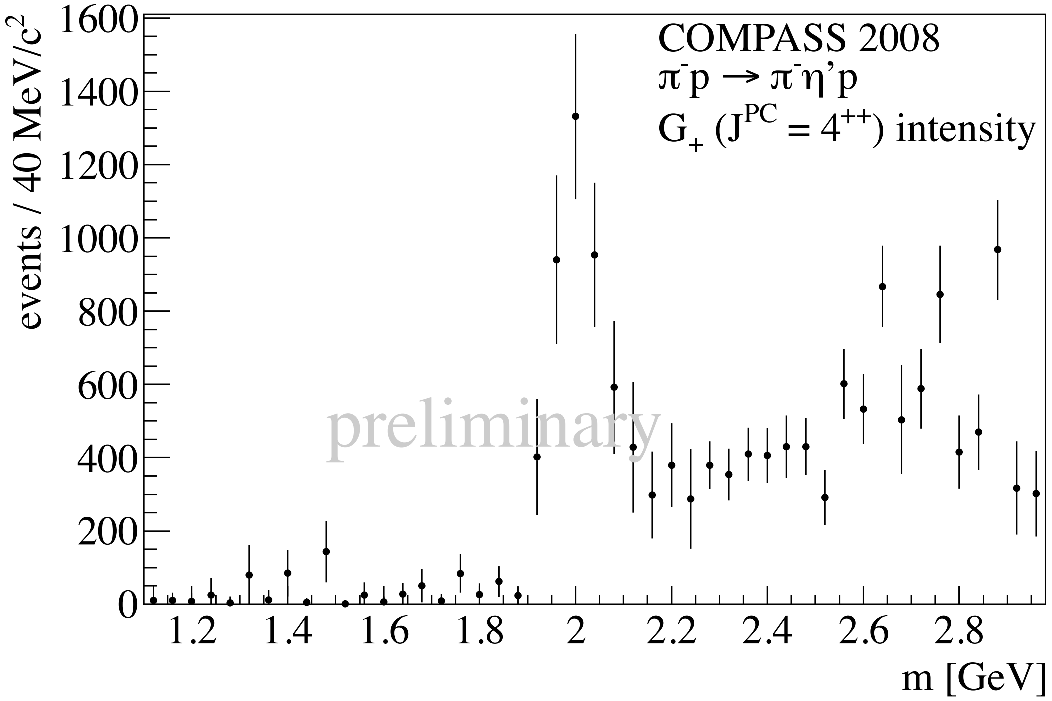
arXiv: 1108.6191

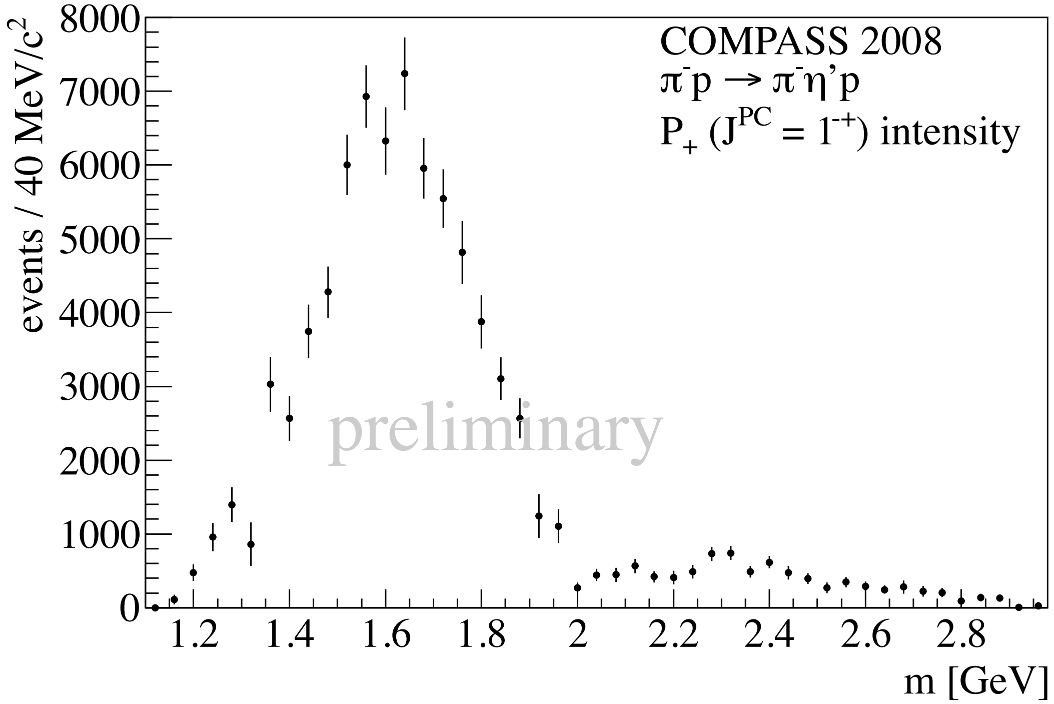


$\pi^- p \to \eta' \pi^- p$

arXiv: 1108.6191

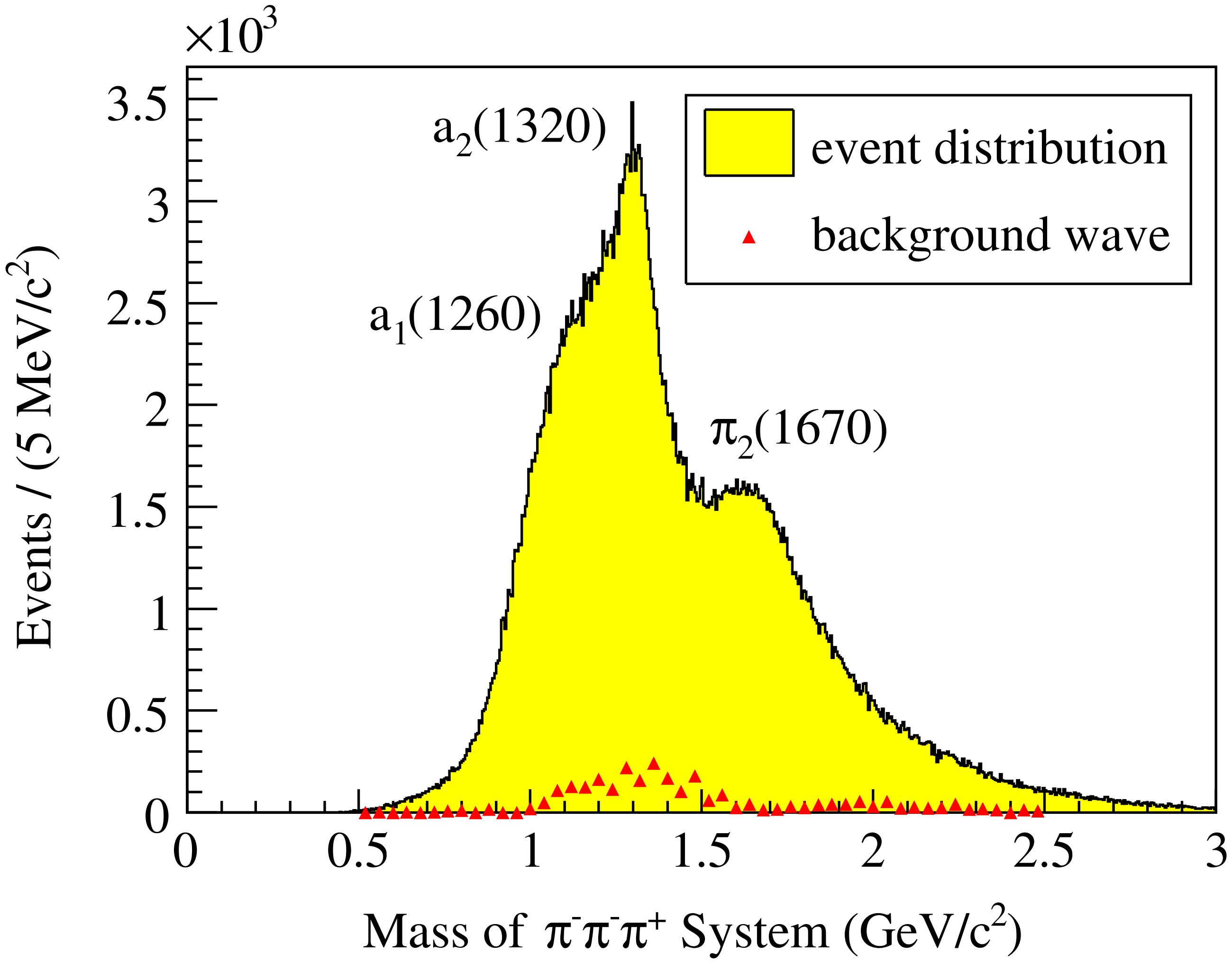






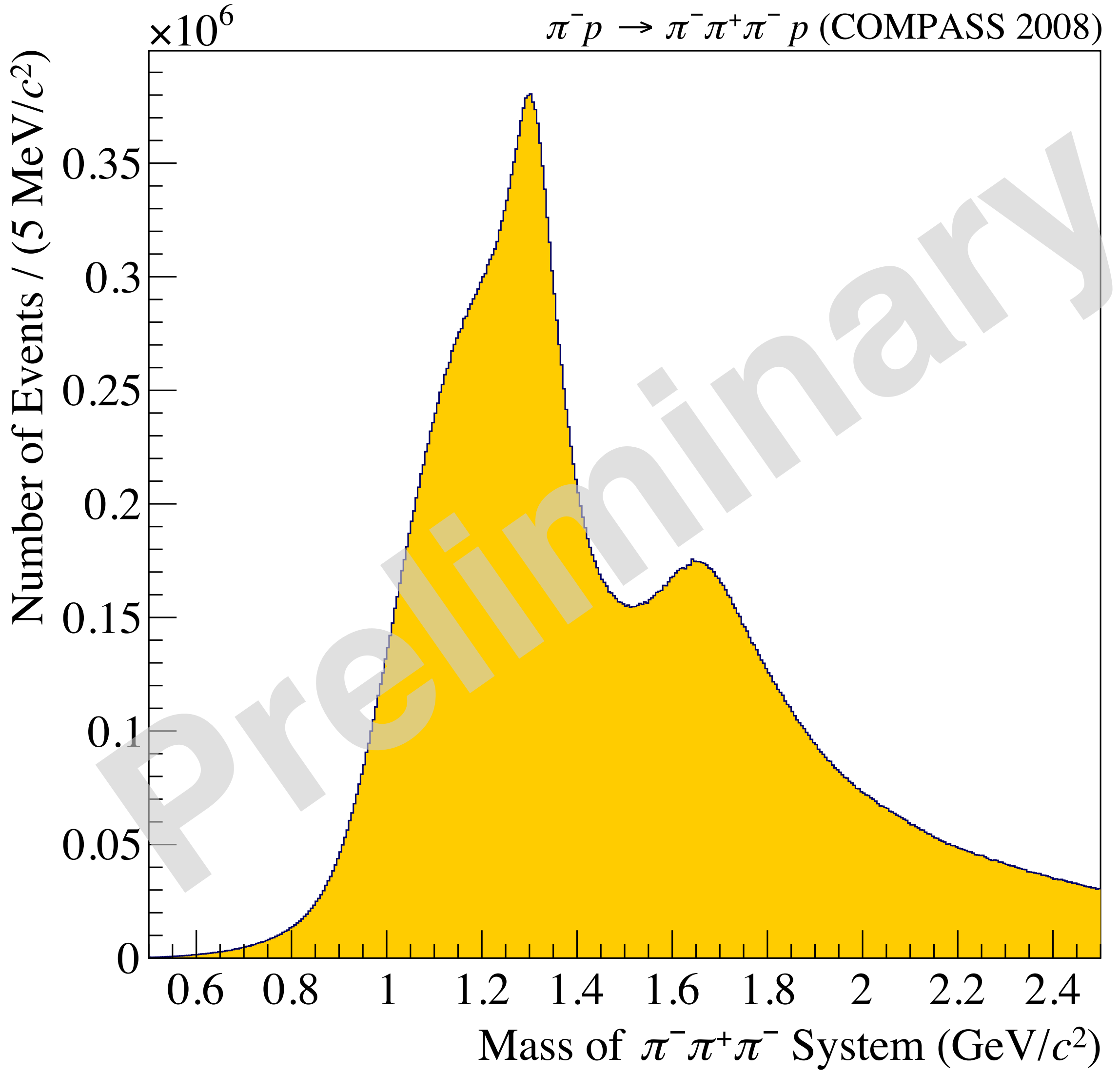
π beam data from COMPASS

$\pi^-\pi^-\pi^+$ from 190 GeV π on Pb



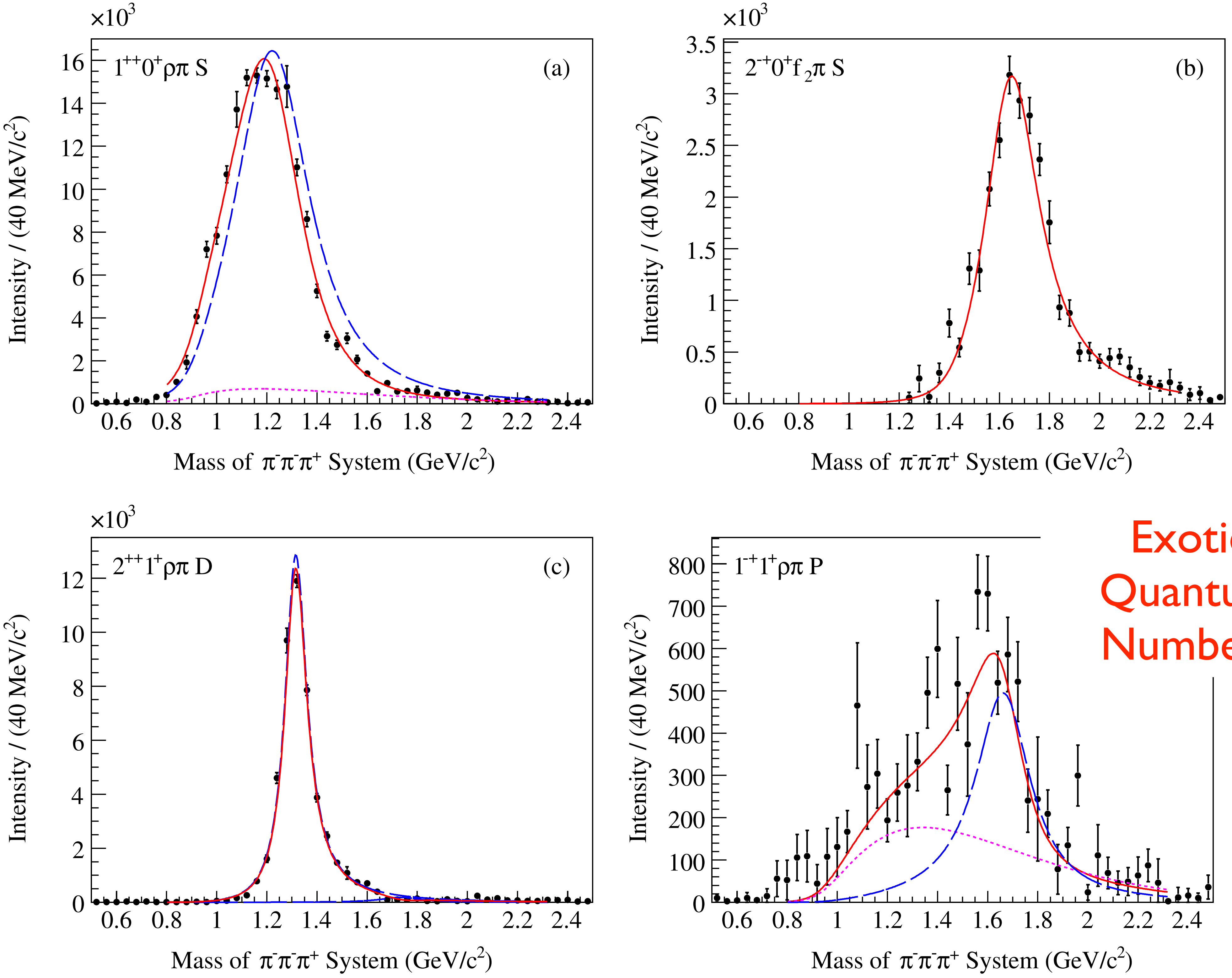
COMPASS Collab., PRL 104, 241803 (2010)

$\pi^-\pi^-\pi^+$ from 190 GeV π on p



F. Krinner, POS (Bormio 2014), 031

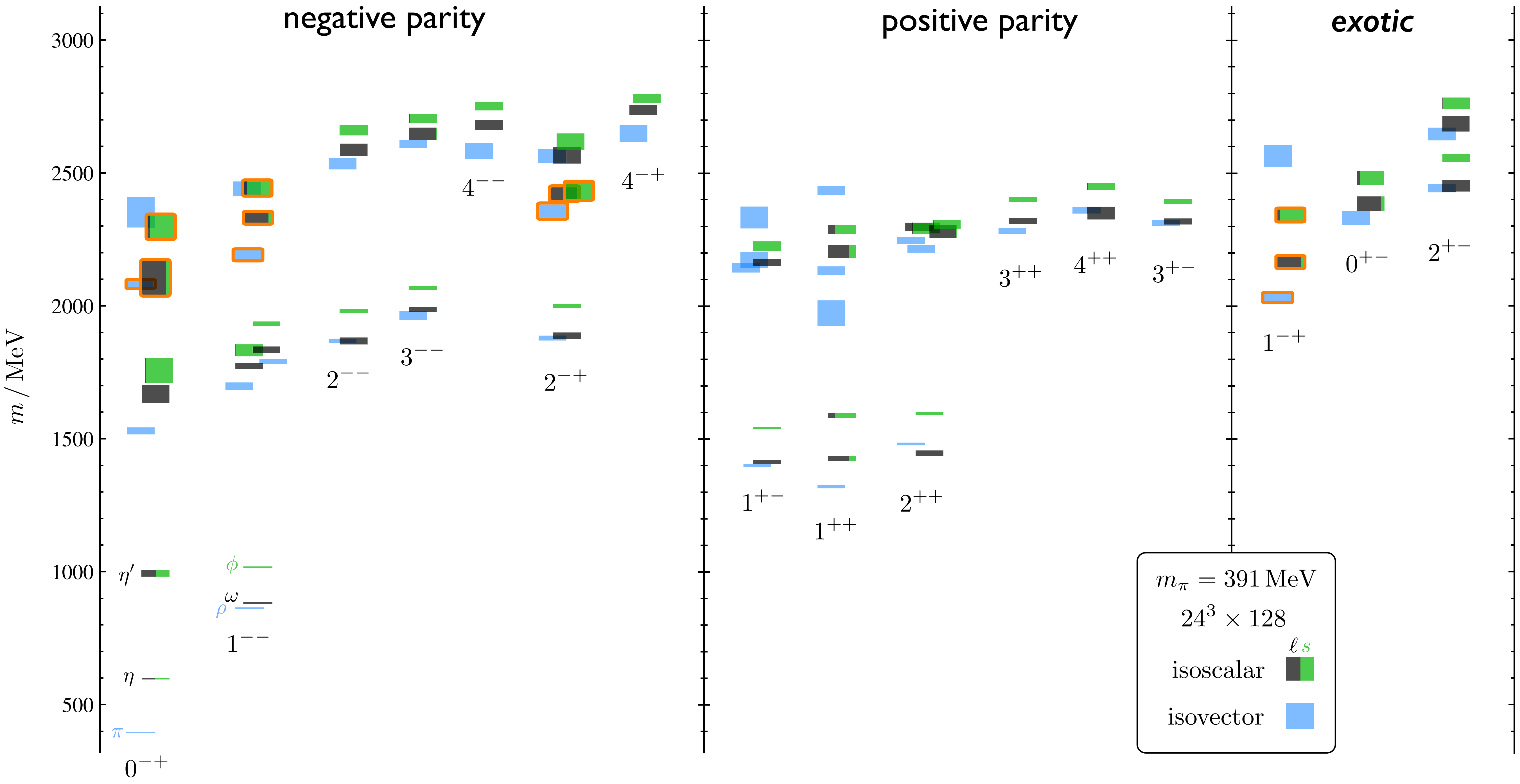
The biggest is not the most important



Exotic Quantum Numbers

Meson Spectrum from Lattice QCD

Dudek, Edwards, Guo, and Thomas, PRD 88, 094505 (2013)



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College of Arts and Sciences
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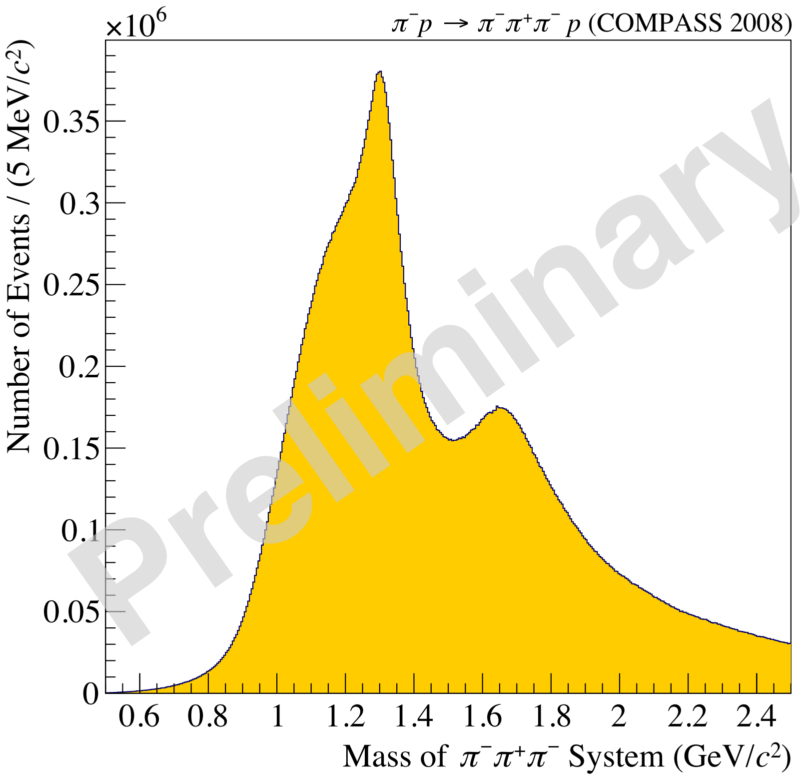
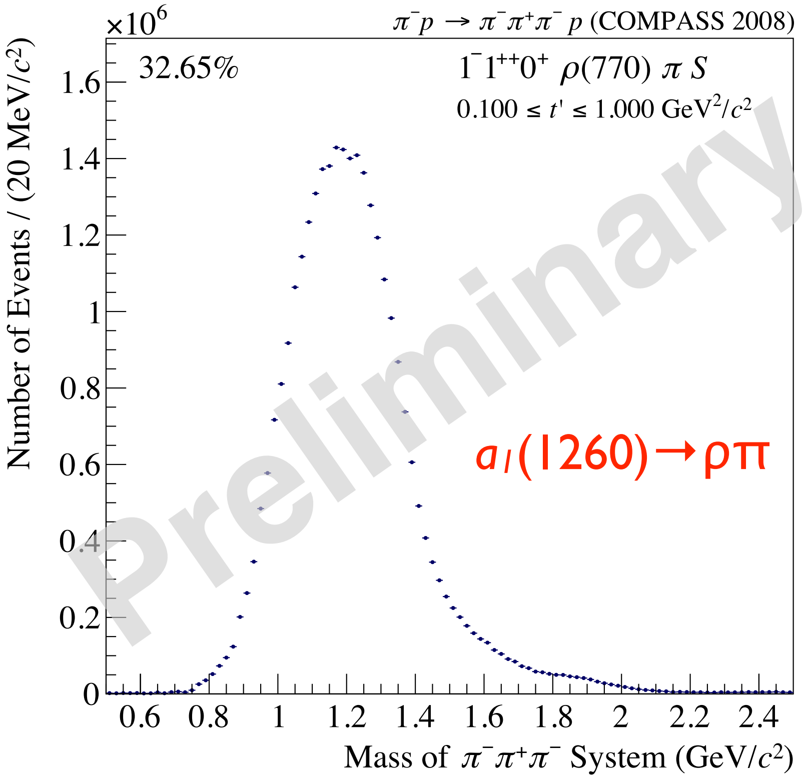
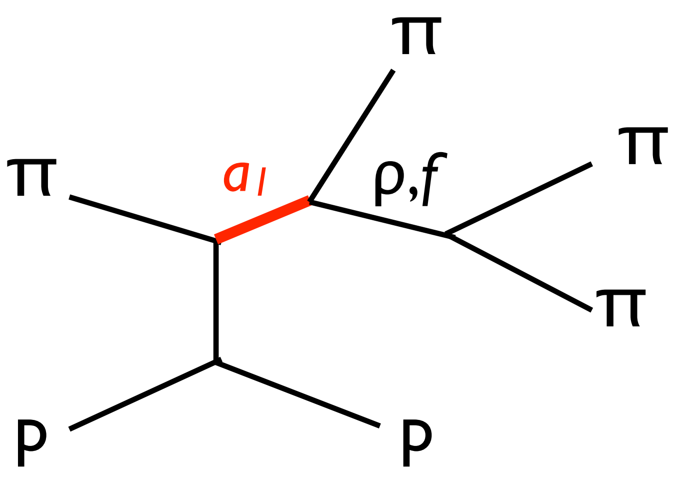
Two sides of the same coin?

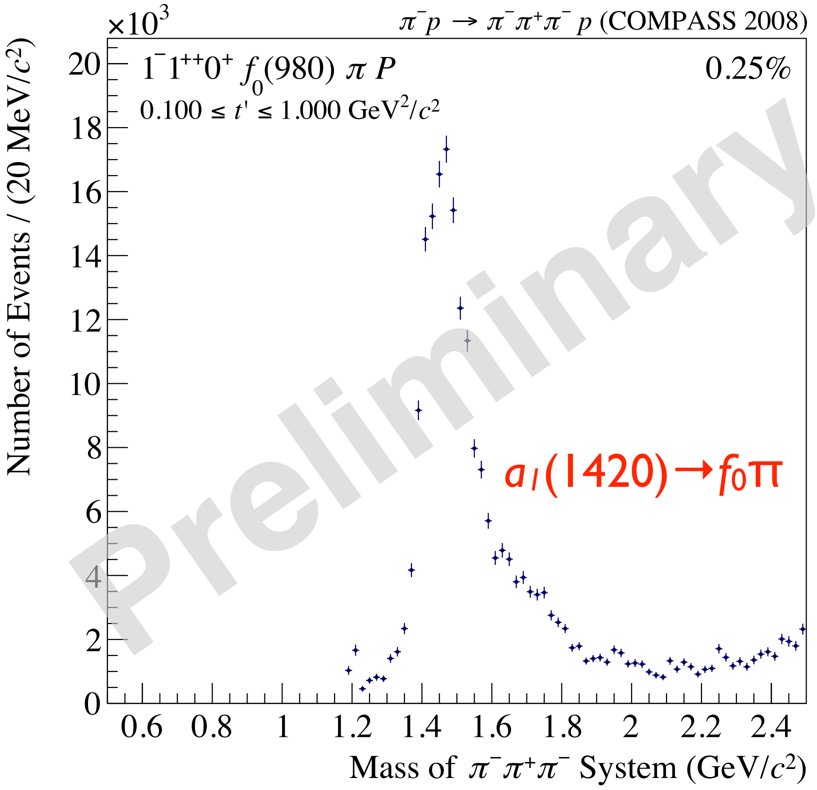




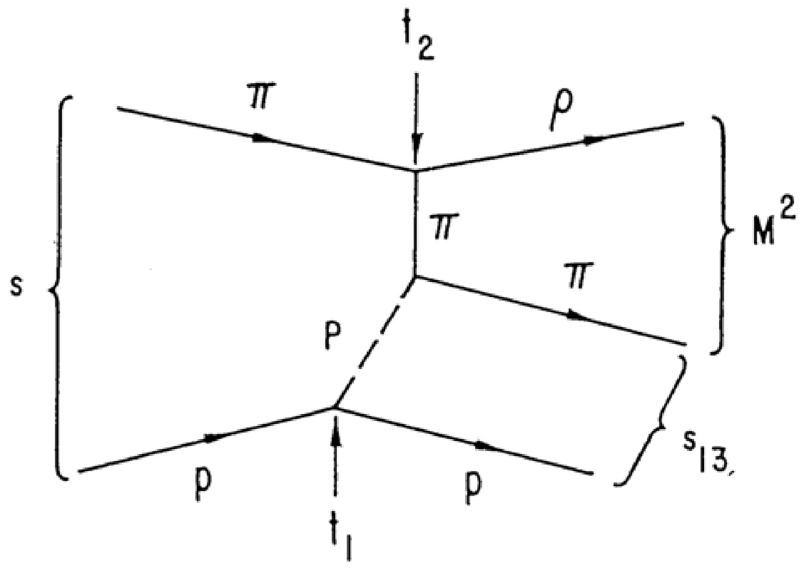


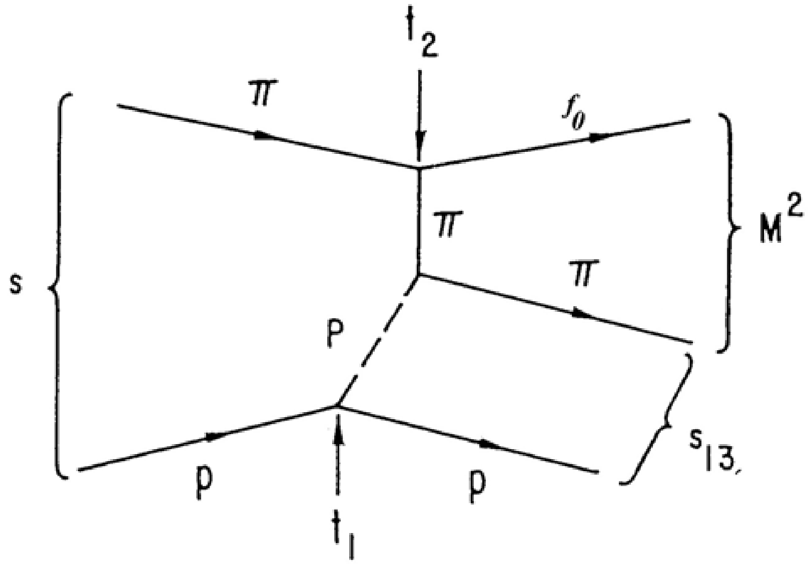
F. Krinner, POS (Bormio 2014), 031

See also: *COMPASS Collab., arXiv:1501.05732*



Basdevant and Berger, PRL 114, 192001 (2015)





Comments

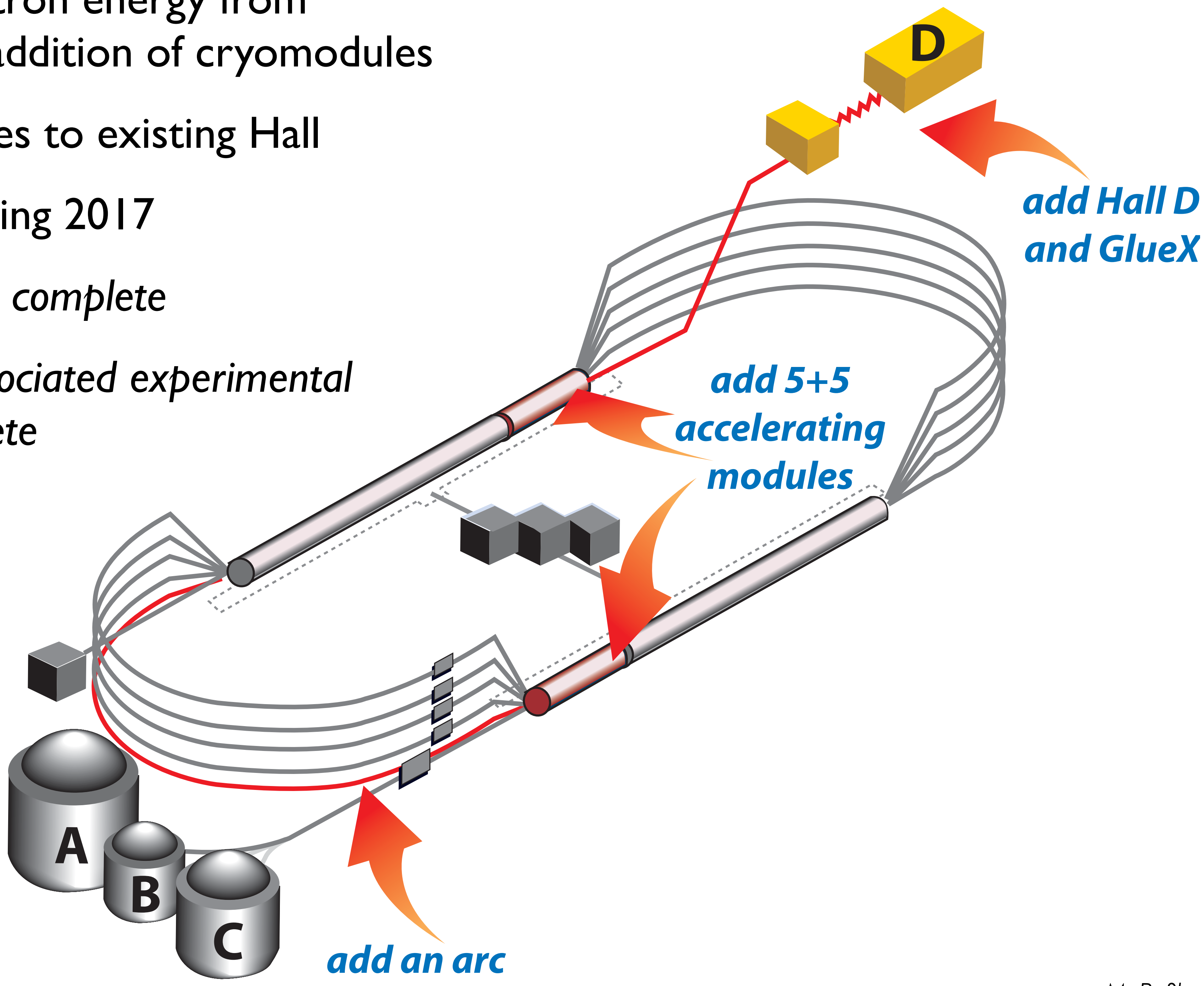
- Excellent data in hand with amazing statistical precision
- Modeling of the reaction in analysis seems to be the dominant systematic error when interpreting data
    - The ability to make major discoveries depends on the ability to quantify and limit this systematic uncertainty

Current and Future Opportunities

	hadron probes		electromagnetic probes	
	completed/analysis	ongoing/future	ongoing/future	completed/analysis
colliding beam	CDF II DØ	ATLAS CMS LHCb	BESIII Belle II	BaBar BELLE
fixed target	COMPASS	panda	GlueX CLAS12	clas CEBAF Large Acceptance Spectrometer

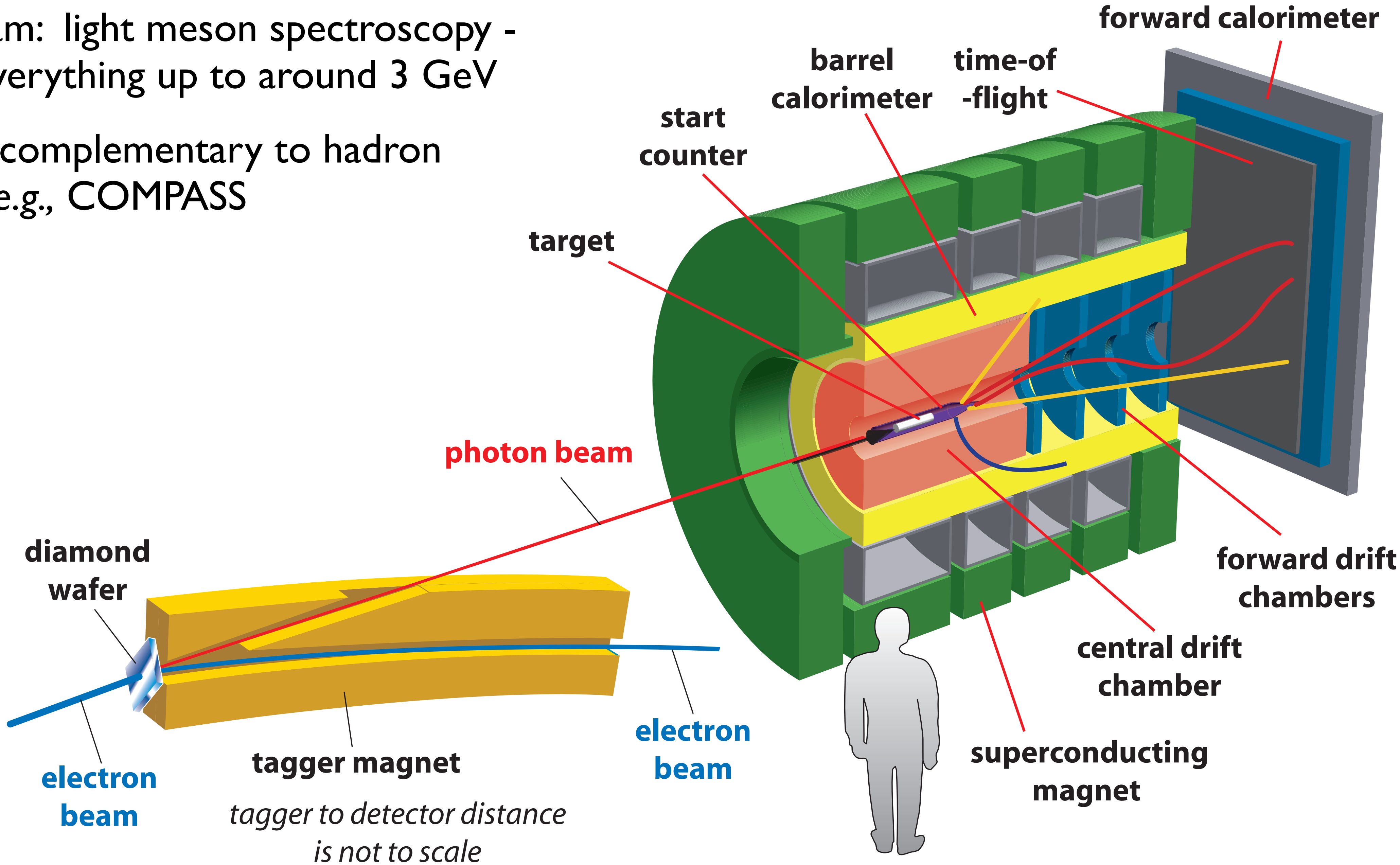
12 GeV Upgrade to JLab

- Upgrade maximum electron energy from 6 GeV to 12 GeV with addition of cryomodules
- New Hall D and upgrades to existing Hall
- Project completion: Spring 2017
  - *Accelerator upgrade is complete*
  - *Hall D facility and associated experimental equipment are complete*



GlueX in Hall D

- high intensity, linearly-polarized photoproduction experiment: 9 GeV photons
  - core program: light meson spectroscopy - access to everything up to around 3 GeV
  - unique and complementary to hadron beam data, *e.g.*, COMPASS

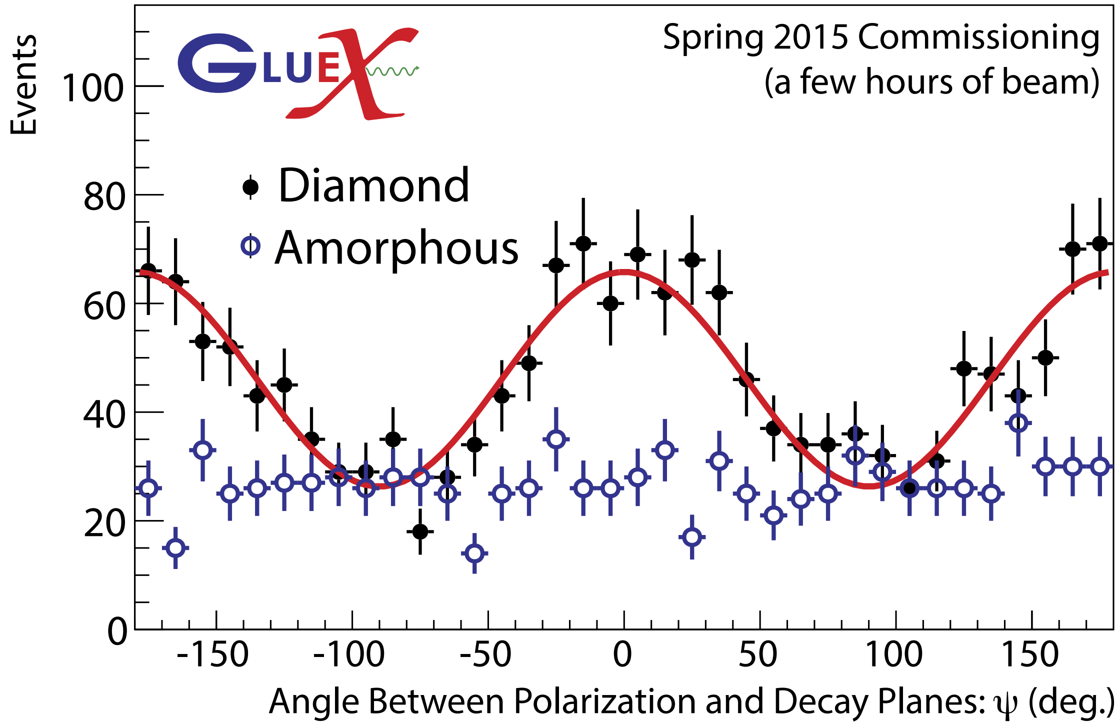


tagger to detector distance is not to scale

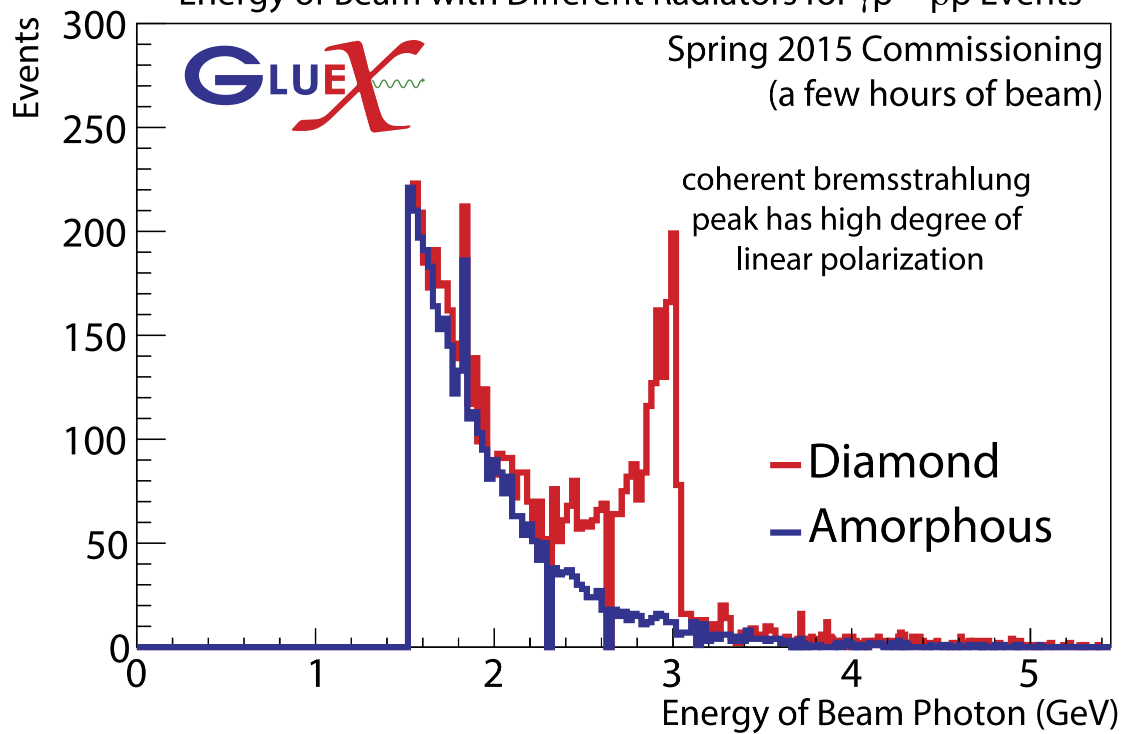
GlueX Detector with
Prof. Curtis Meyer
GlueX Spokesperson
October 2014

Hall D/GlueX Polarized Photon Beam

data collected on May 2, 2015

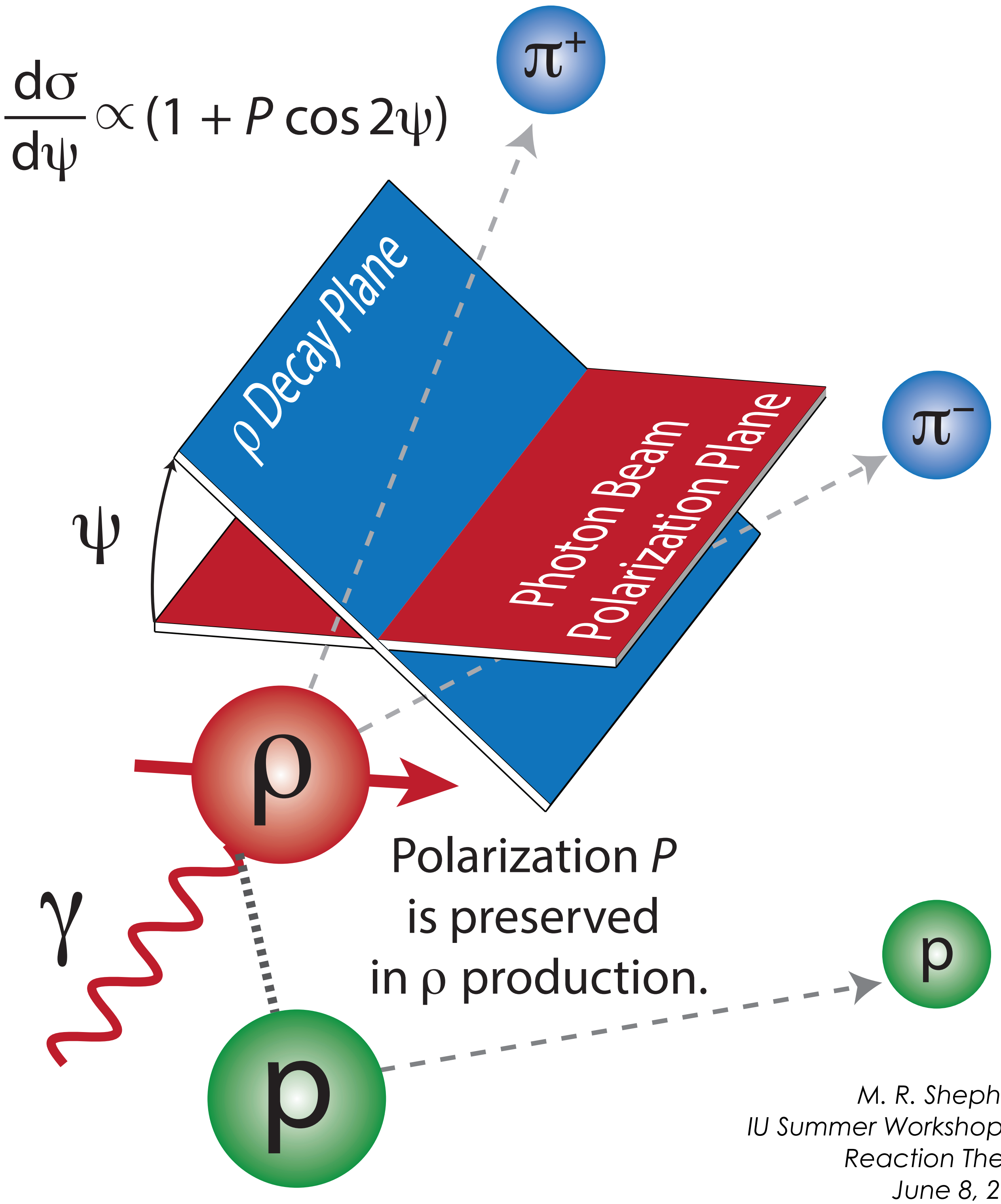


Energy of Beam with Different Radiators for γp→ρp Events



$$\gamma p \rightarrow \rho^0 p \rightarrow \pi^+ \pi^- p$$

$$\frac{d\sigma}{d\psi} \propto (1 + P\cos 2\psi)$$



Polarization *P*
is preserved
in ρ production.

Conclusions

- Exciting developments in experimental studies of spectroscopy in the last ten years
  - understanding underlying reaction dynamics is critical
  - data will keep coming: new experiments studying different reactions are starting now
- Advances in technology and sociology
  - statistically precise data for many related reactions
  - high-performance analysis machinery
  - new (old) ideas about theory and experiment collaboration
- Ability to draw firm conclusions from the data depends on having a good understanding of underlying reaction dynamics