Light Hadron Spectroscopy

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Outline

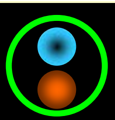
- Introduction
- Light hadron spectroscopy
  - Search for non-$q\bar{q}$ states
  - baryon spectroscopy
- Future prospects
- Summary

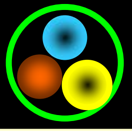
Apologize for only covering some of the topics and selected results (due to the limitation of my own knowledge and time …)

New forms of hadrons

- **Hadrons consist of 2 or 3 quarks：**

Naive Quark Model：

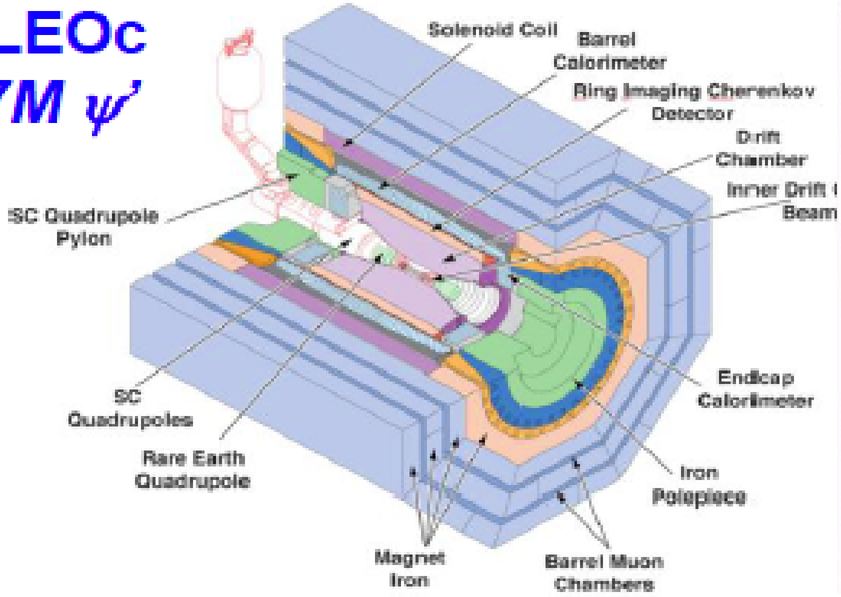
Meson（q $\bar{q}$） 

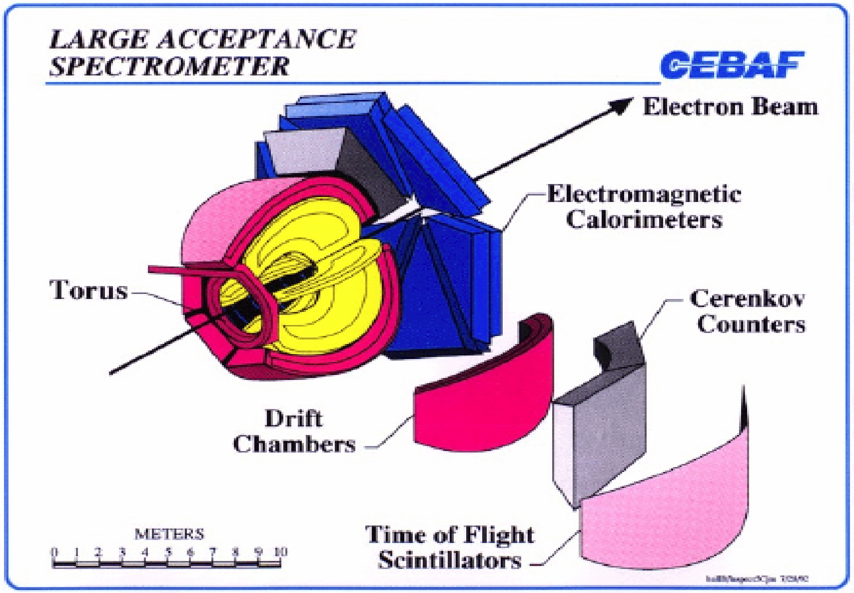
Baryon（q q q） 

- **QCD allows the new forms of hadrons:**
  - **Multi-quark states： Number of quarks >＝ 4**
  - **Hybrids： $q\bar{q}g$， qqqg …**
  - **Glueballs： gg， ggg …**

- **None of the non-$q\bar{q}$ or non-qqq states is established experimentally. Search for new hadrons and systematic study of the spectroscopy – a way of understanding the internal structure of hadrons.**

CLEOc
27M ψ'

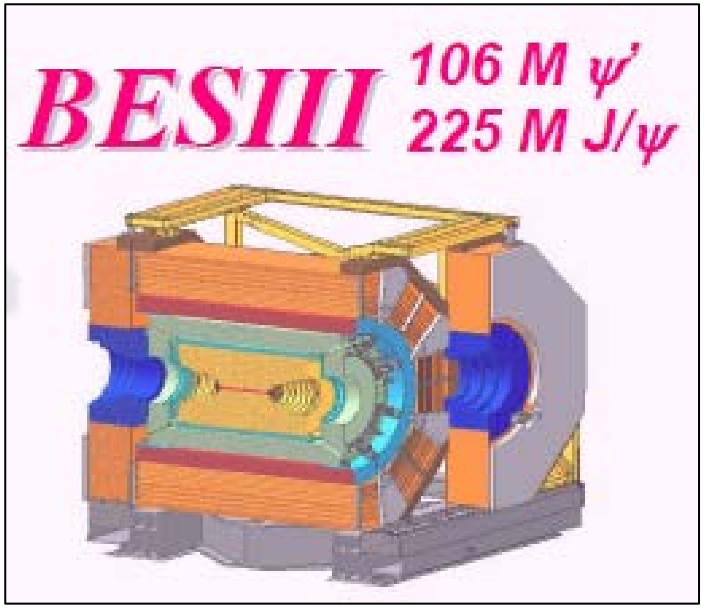




COMPASS

VES

E852



Exotic 1^{-+} states: VES (1993, 2005)

VES

PLB 313, 276 (1993)

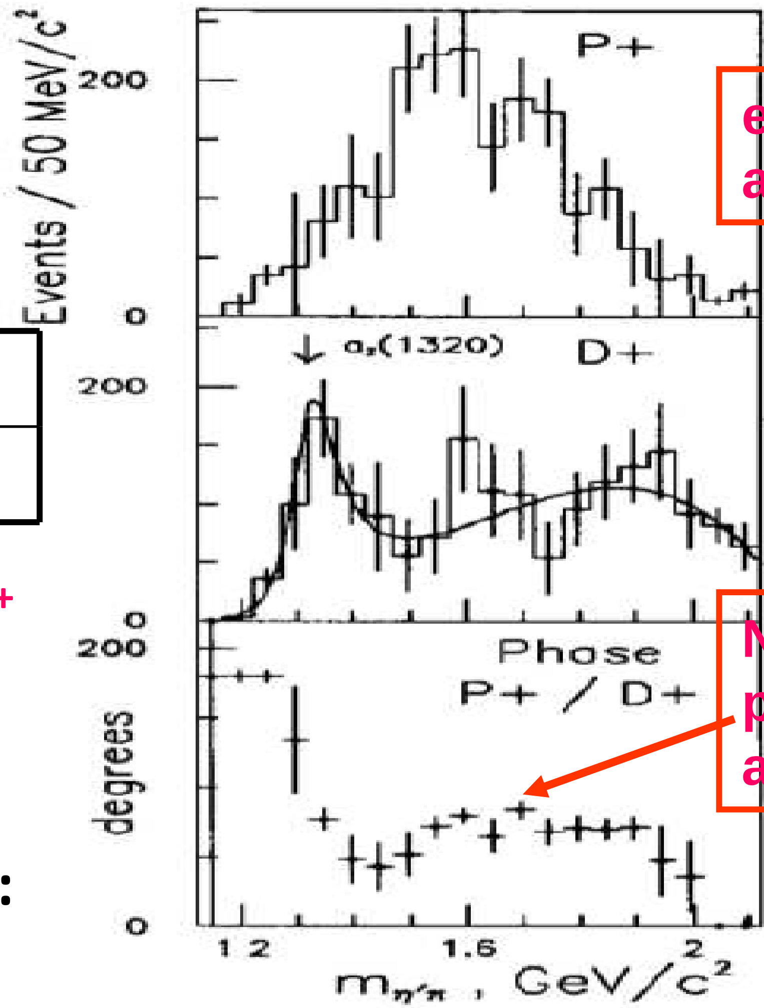
37 GeV $\pi^- N \to \eta' \pi^- N$

Possible J^{PC} for $\eta'\pi$ system:

L	*S*-wave	*P*-wave	…
J^{PC}	0^{++}	1^{-+}	…

A P-wave resonant – exotic 1^{-+}

- Strong P wave structure
- $a_2(1320)$ in D^+ wave
- Broad structure in D^+ wave: $a_2(1700)$+exotic $\pi_1(1600)$



exotic 1^{-+} at 1.6 GeV?

No relative phase jump at 1.6 GeV

A jump in P+-D+ relative phase at 2 GeV?

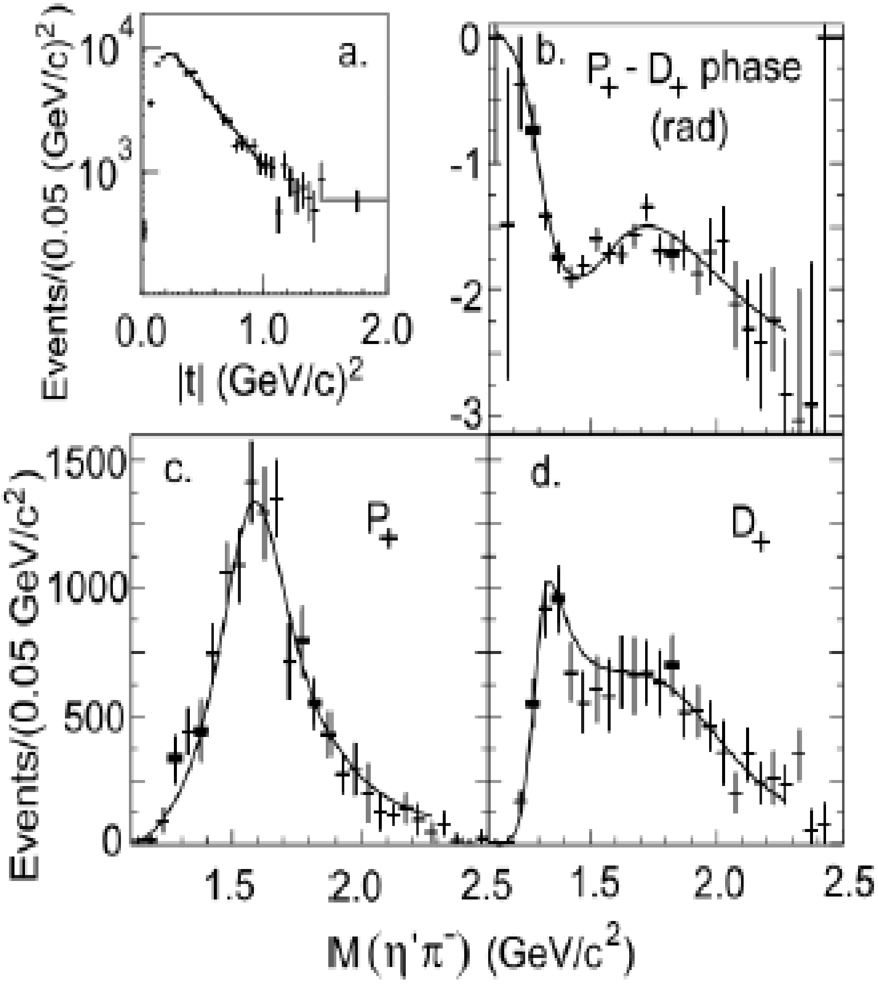
E852 18 GeV $\pi^- p \to \eta' \pi^- p$ (2001)

E852

PLB 563, 3997 (2001)

- **Strong P wave structure**
- **$a_2(1320)$ in D+ wave**
- **Broad structure in D+ wave:**

  $a_2(1700)$+exotic $\pi_1(1600)$
- **A G+ wave is added in the fit for $a_4(2040)$**

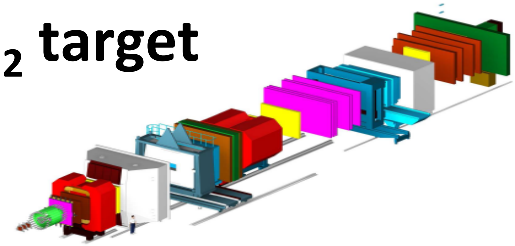


A jump in P+-D+ relative phase at 2 GeV?

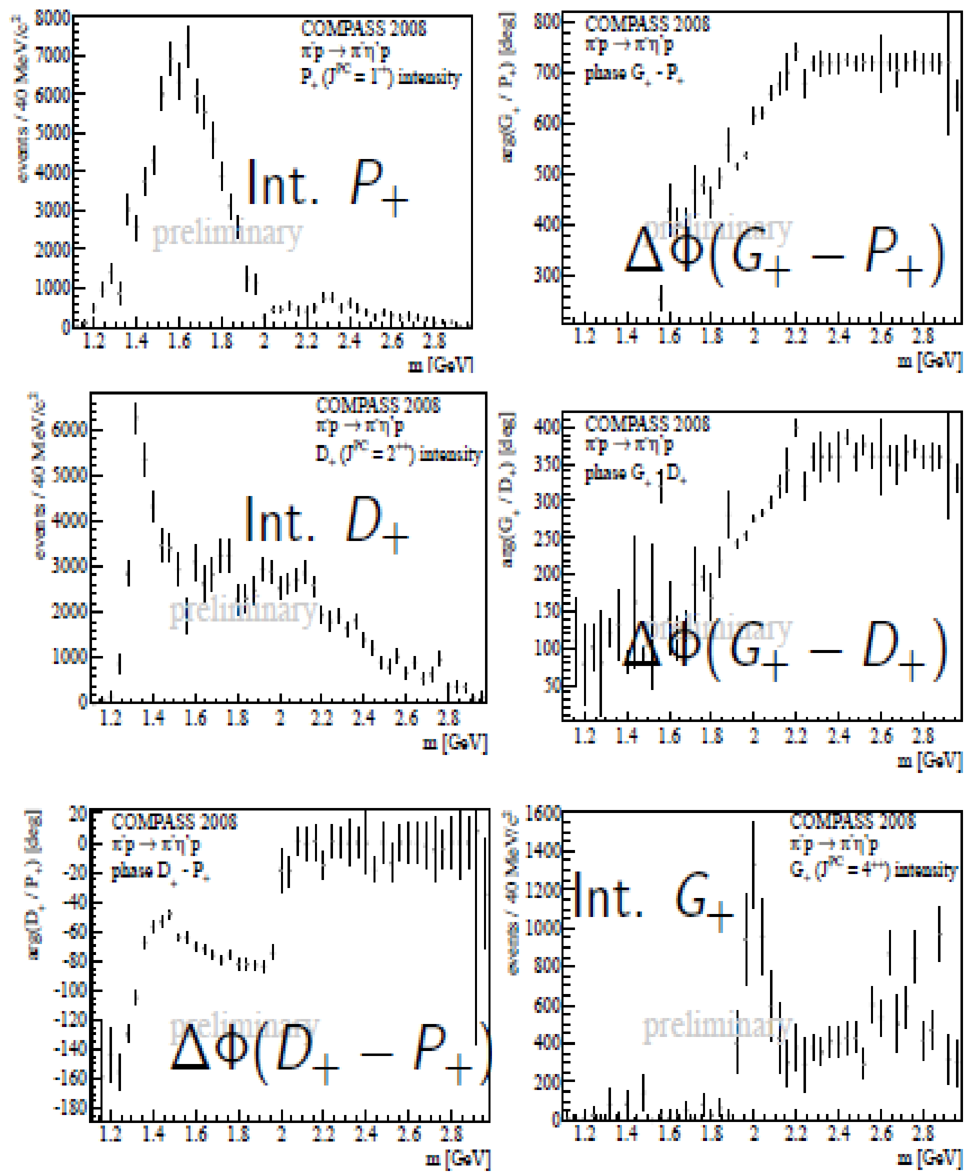
COMPASS 190 GeV $\pi^- p \to \eta' \pi^- p$ (2008 data)

T. Schlueter
Hadron2011

- **Fixed target exp. at CERN SPS accelerator**
- **Liquid H_2 target**



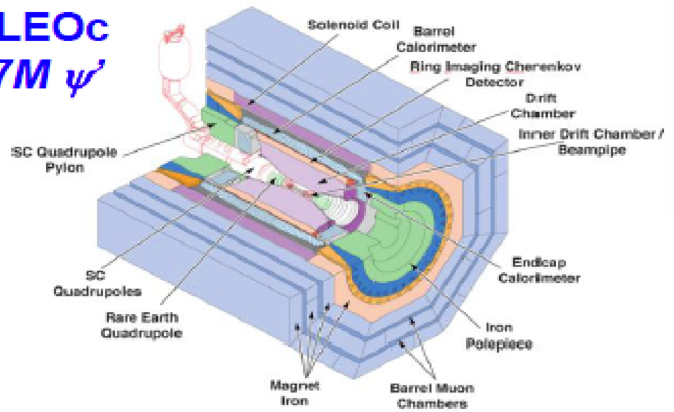
- **Strong P-wave**
- **Evidence for $a_4(2040)$**
- **Resonant P-wave cannot be confirmed.**

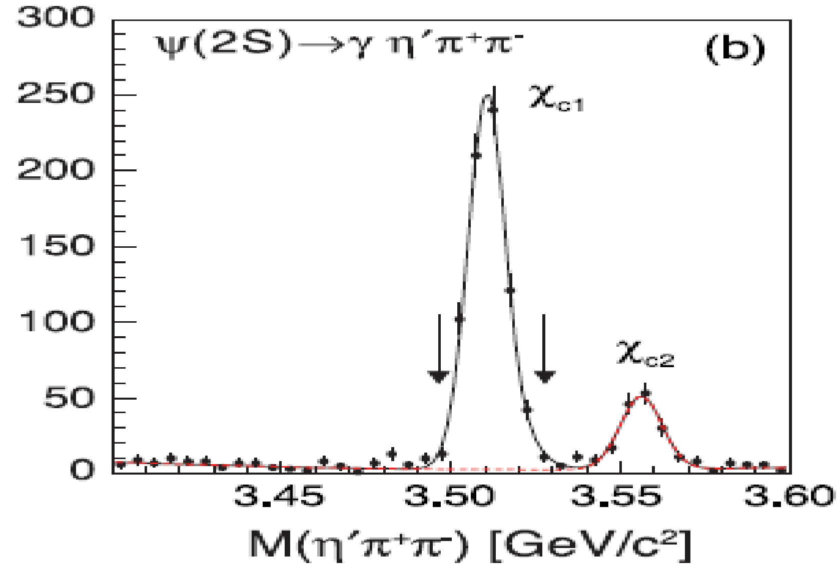


Evidence for $\pi_1(1600)$ in $\chi_{c1} \to \eta' \pi^+ \pi^-$ at CLEO-c

arXiv: 1109.5843

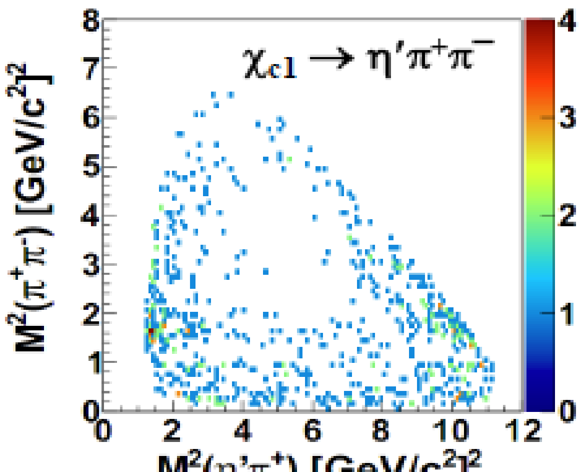
CLEOc
27M ψ'

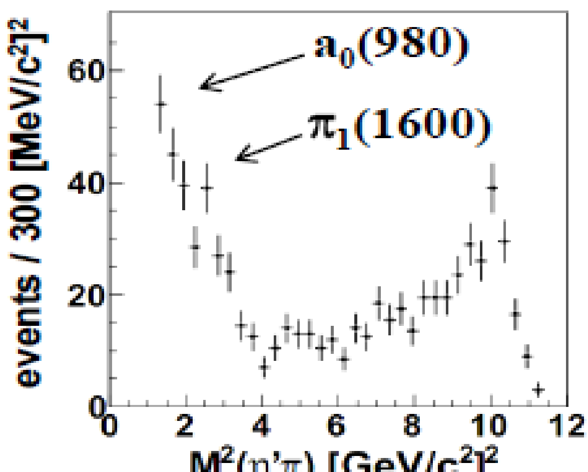


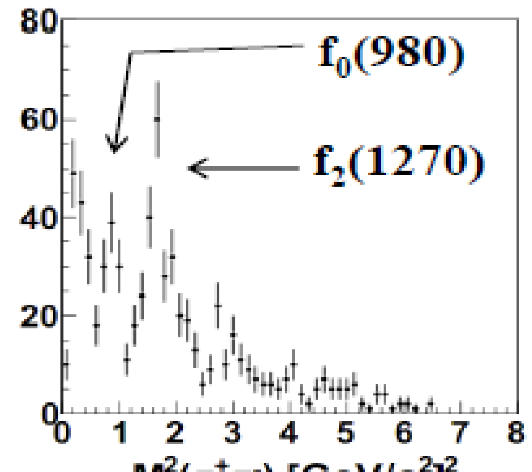


χ_{c1} produced in $\psi(2S) \to \gamma\chi_{c1}$

Signal purity: 94.6% (1.3%)





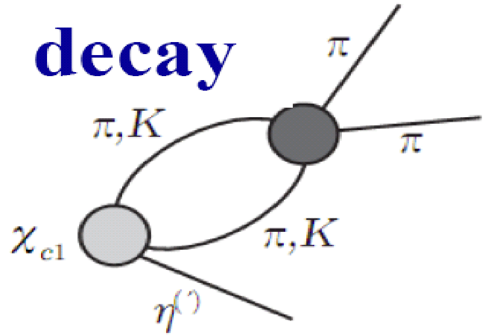


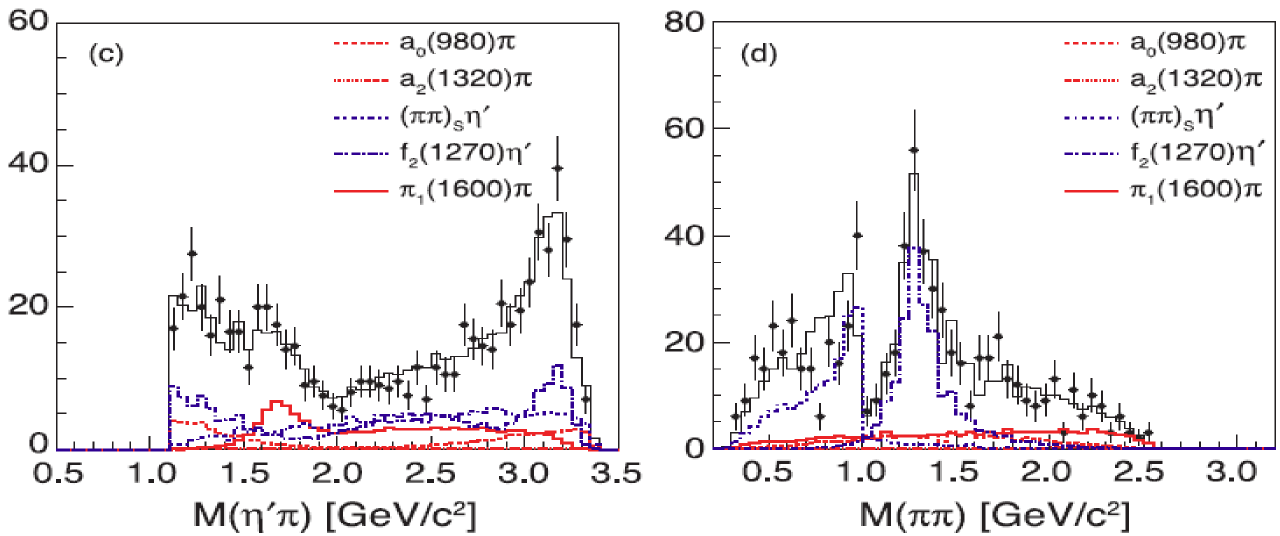
A full amplitude analysis with isobar model :

BW for most of resonances

Flatte: $a_0(980)$

$\pi\pi$-S wave : KK, $\pi\pi$ scattering





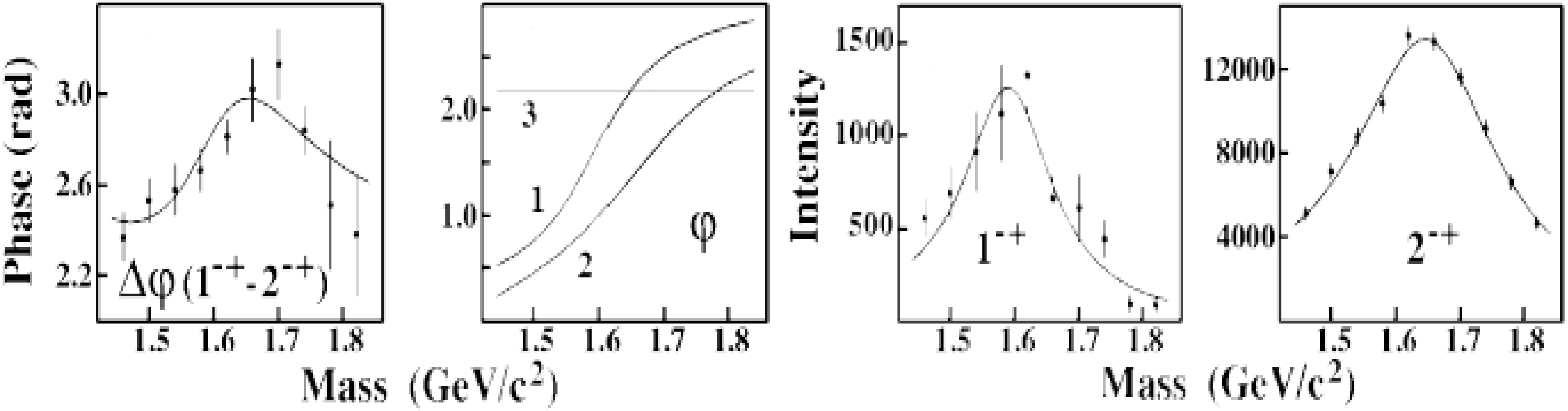
Assuming BW shape for 1^{-+} :

M=1670±30±20 MeV/c^2 , Γ =240 ±50 ±60 MeV

Significance > 4.0 σ (different models)

E852 : $\pi^- p \rightarrow \pi^+\pi^-\pi^- p$

PRD 65, 072001 (2001)



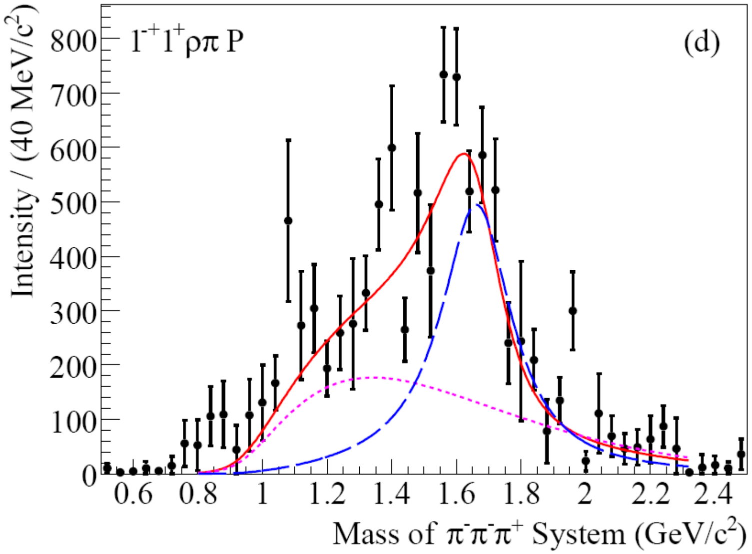
$$1^{-+}\ \pi_1(1600) \rightarrow \rho(770)\pi$$

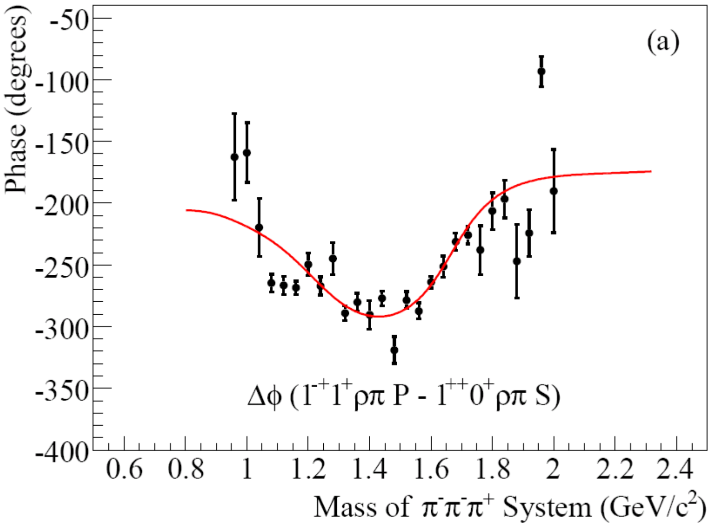
$$M = 1593 \pm 8^{+29}_{-47}\ \text{MeV}/c^2,$$

$$\Gamma = 168 \pm 20^{+150}_{-12}\ \text{MeV}/c^2.$$

COMPASS(2004 data): $\pi^- Pb \to \pi^+\pi^-\pi^- Pb$

PRL 104 (2010) 241803



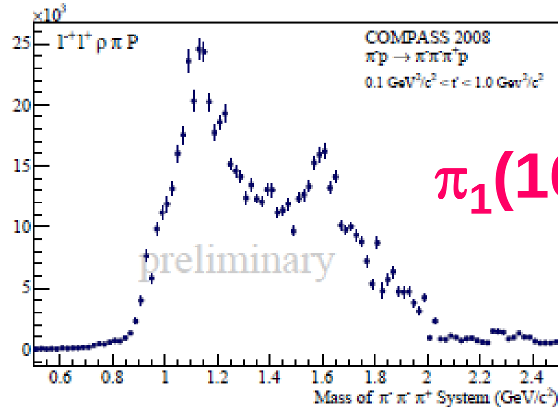


- **A 1^{-+} $\rho\pi$ P-wave $\pi_1(1600)$ is evident,**
- **Fit $\pi_1(1600)$ with a BW + BG yields:**

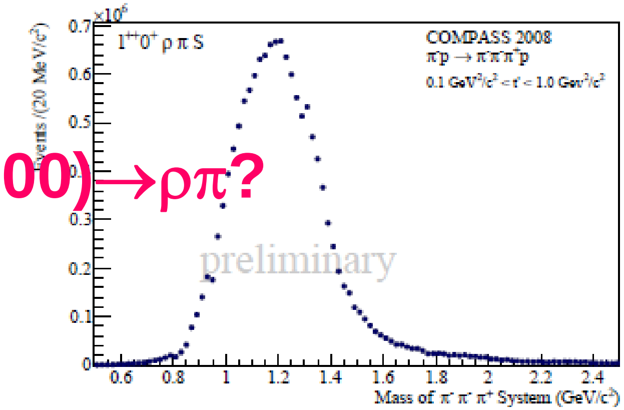
$$M = (1.660 \pm 0.010^{+0.000}_{-0.064})\ \mathrm{GeV/c^2}$$

$$\Gamma = (0.269 \pm 0.021^{+0.042}_{-0.064})\ \mathrm{GeV/c^2}$$

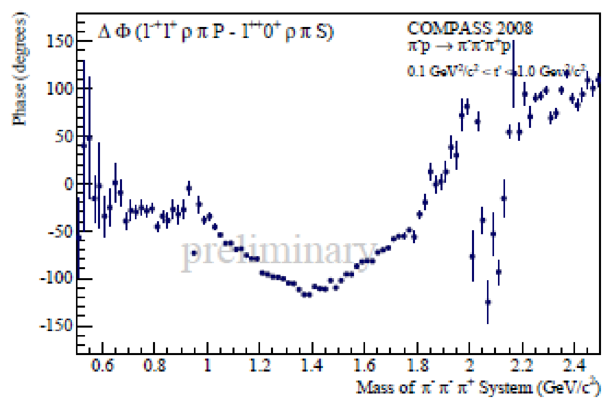
COMPASS $\pi^- p \rightarrow \pi^-\pi^+\pi^- p$
190GeV π^- beam on LH_2 (2008 data)



π1(1600)→ρπ?



H. Faas
Hadron2011

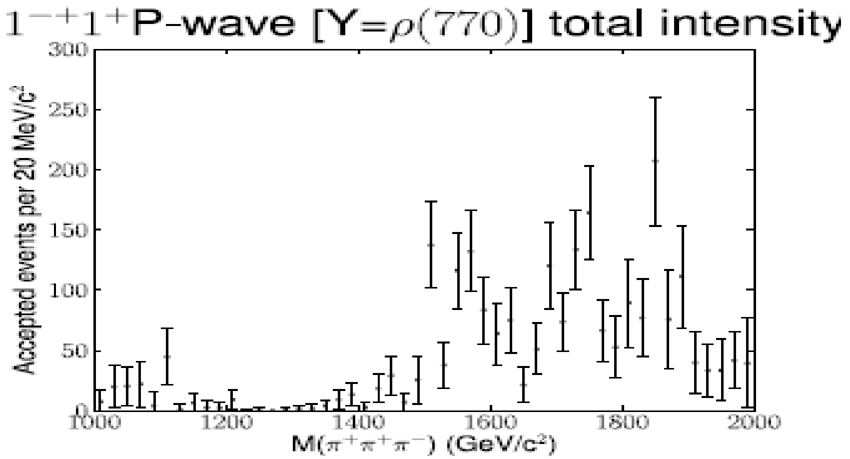


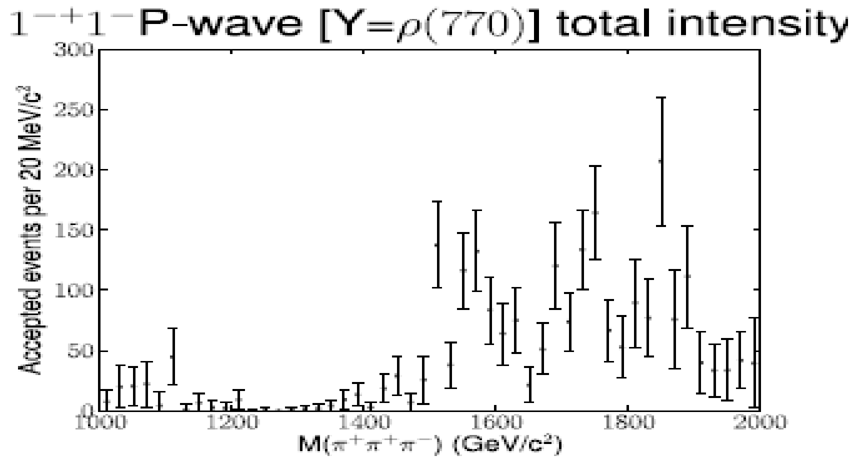
- **Observe $\pi_1(1600) \rightarrow \rho\pi$?**
- **Further study, consistency check in neutral mode**

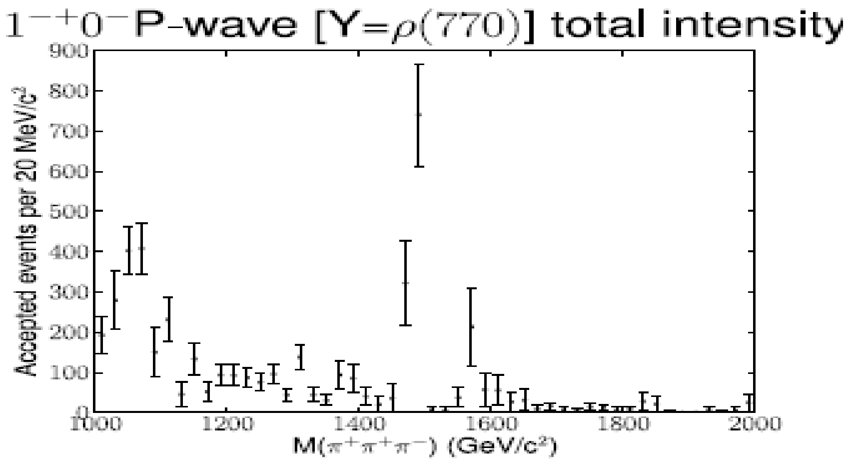
1^{-+} search in $\gamma p \to \pi^+\pi^+\pi^- n$ with CLAS at JLAB

Craig Bookwalter
Hadron2011

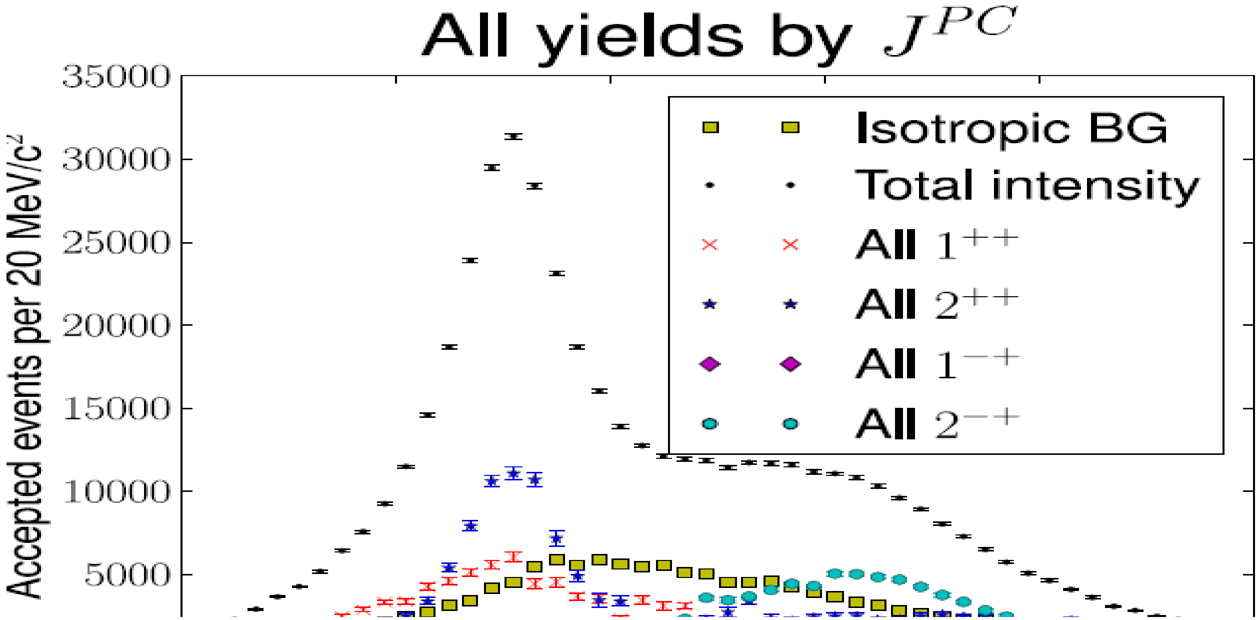
g12 Run: (2008), PWA performed





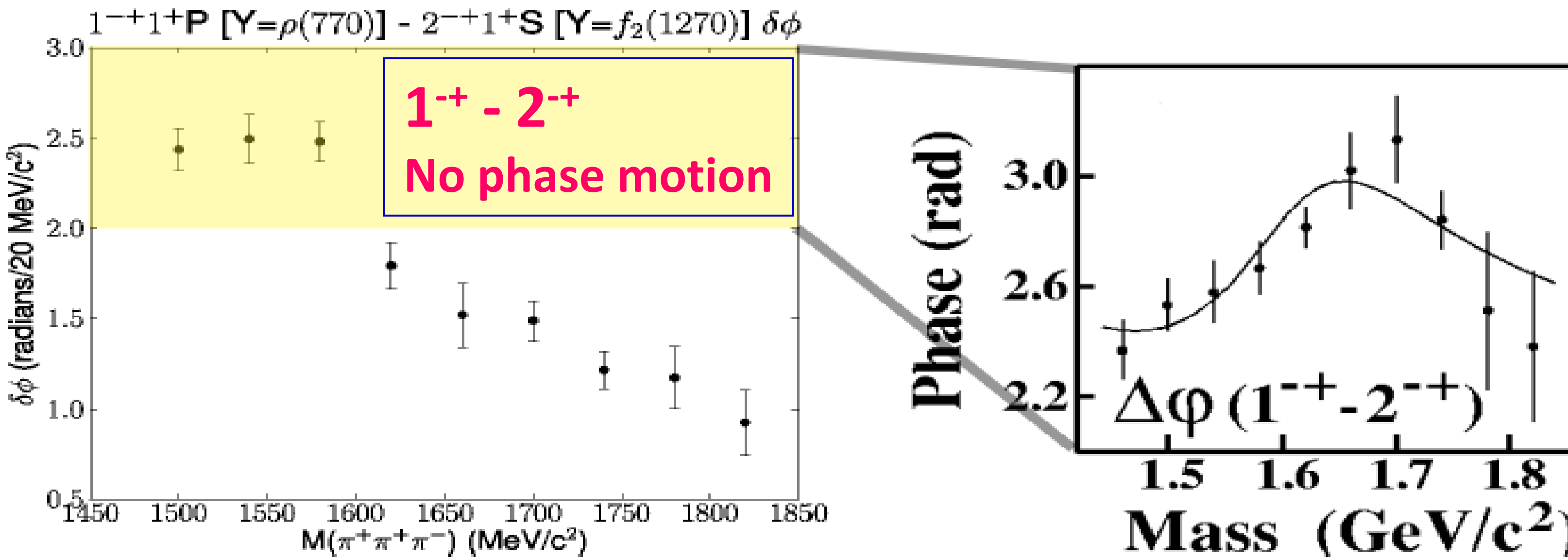


- accounts for up to 2% of total intensity



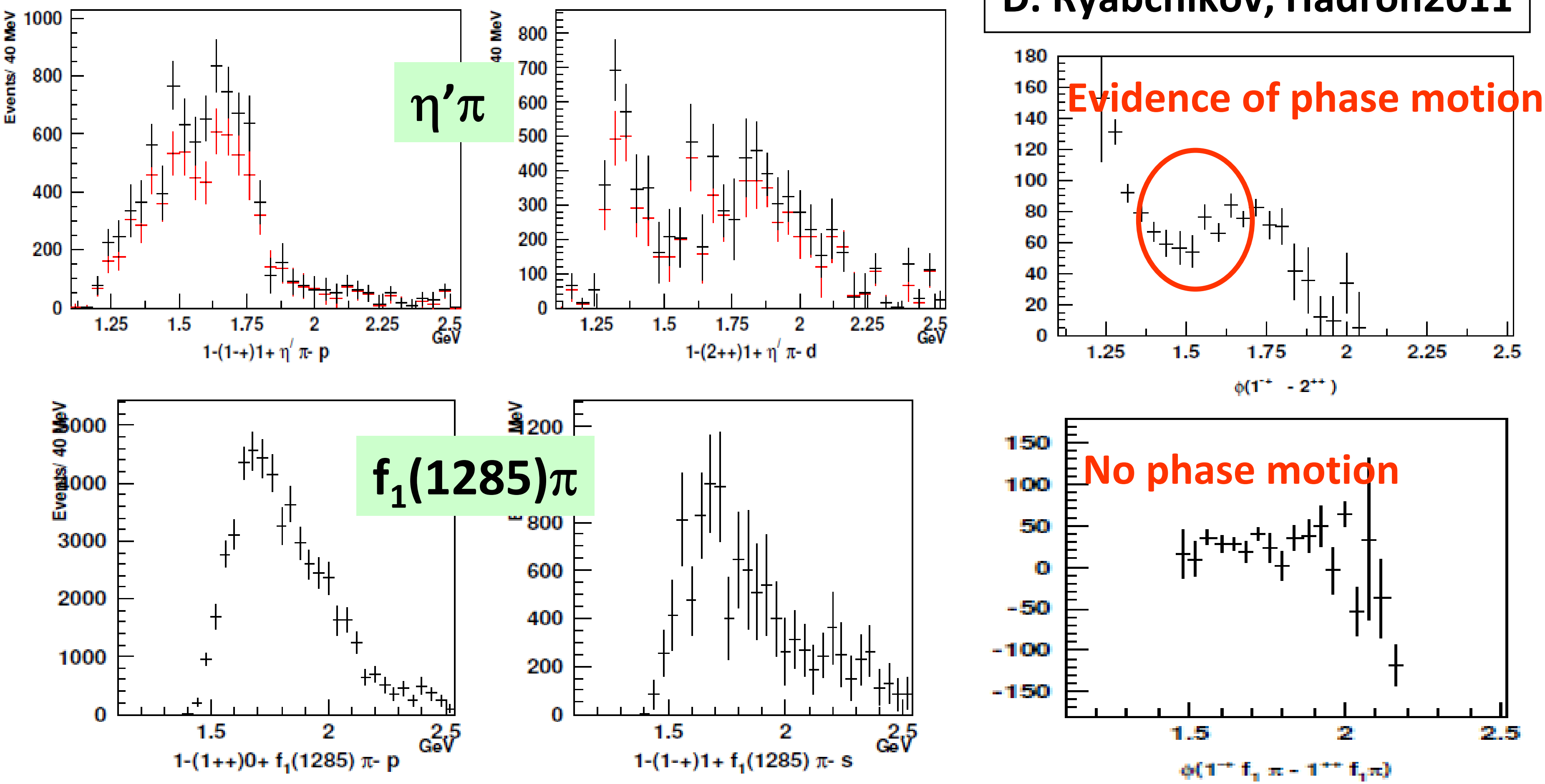
No evidence for a 1^{-+} resonance!

CLAS g12 BNL-E852



1^{-+} search in $\pi^- Be \rightarrow \eta\pi^+\pi^-\pi^-$ Be at VES

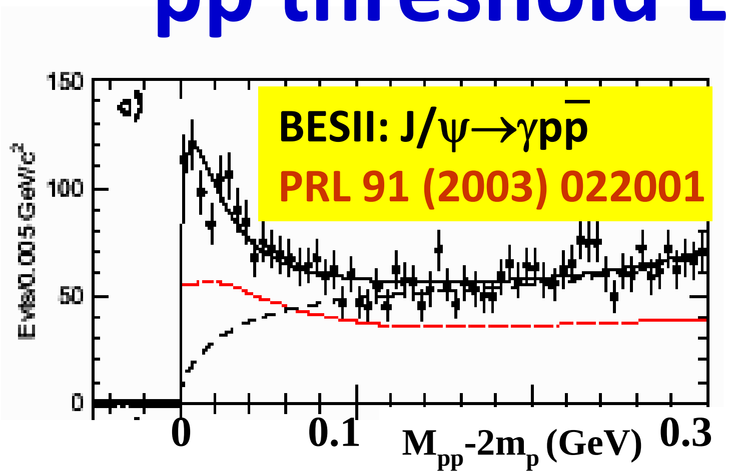
D. Ryabchikov, Hadron2011



$\eta' \pi^-$ has $a_2(1320)$ + exotic wave,

Resonant: M=1.640 ±0.020 GeV, Γ=0.400 ±0.050 GeV

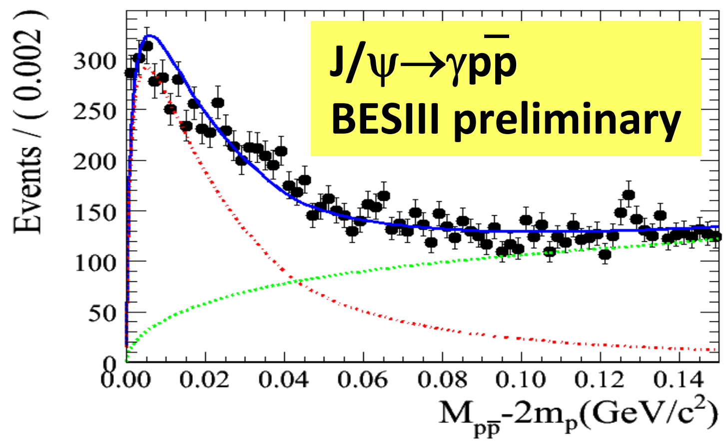
$p\bar{p}$ threshold Enhancement at BESIII

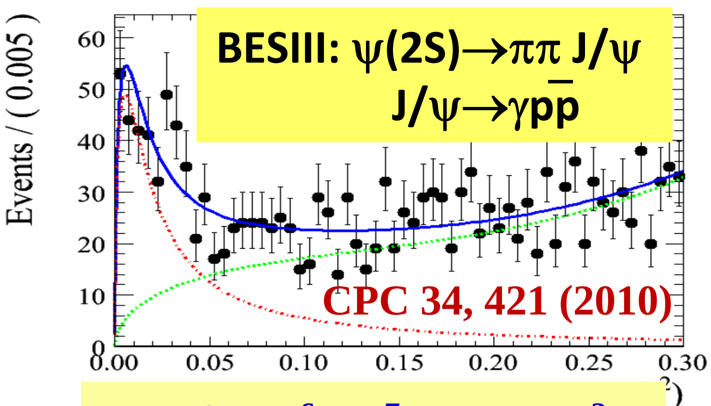


$M=1859\ ^{+3}_{-10}\ ^{+5}_{-25}$ MeV/c²

$\Gamma < 30$ MeV/c² (90% CL)

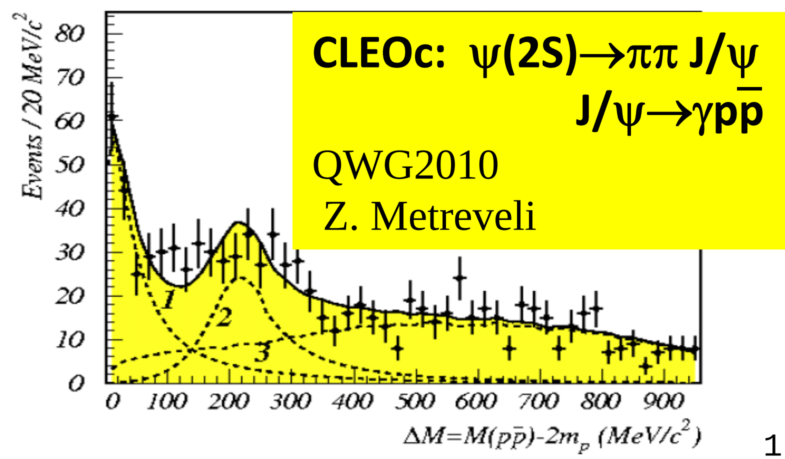
- **Observed at BESII in 2003**
- **Confirmed by CLEOc and BESIII**
- **Agree with BESII results**





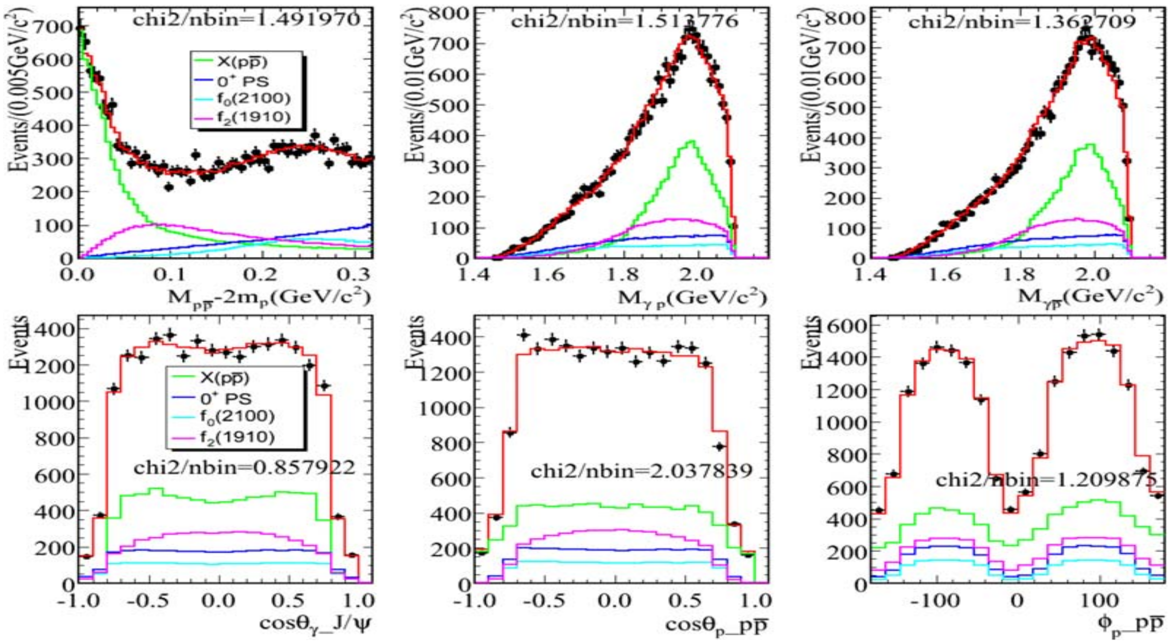
$M=1861\ ^{+6}_{-13}\ ^{+7}_{-26}$ MeV/c²

$\Gamma < 38$ MeV/c² (90% CL)



PWA of $J/\psi \rightarrow \gamma p\bar{p}$

$f_0(2100)$ and $f_2(1910)$ fixed to PDG.
Significance of $X(p\bar{p})$ >>30σ



- The fit with a BW and S-wave FSI(I=0) factor can well describe ppb mass threshold structure.
- It is much better than that without FSI effect, and Δ2lnL=51 ⇒ 7.1σ.

Nature of $X(p\bar{p})$?

$$J^{pc} = 0^{-+}$$

$$M = 1832 \pm 5(\text{stat})^{+19}_{-17}(\text{syst}) \pm 19(\text{mod})\ \text{MeV/c}^2$$

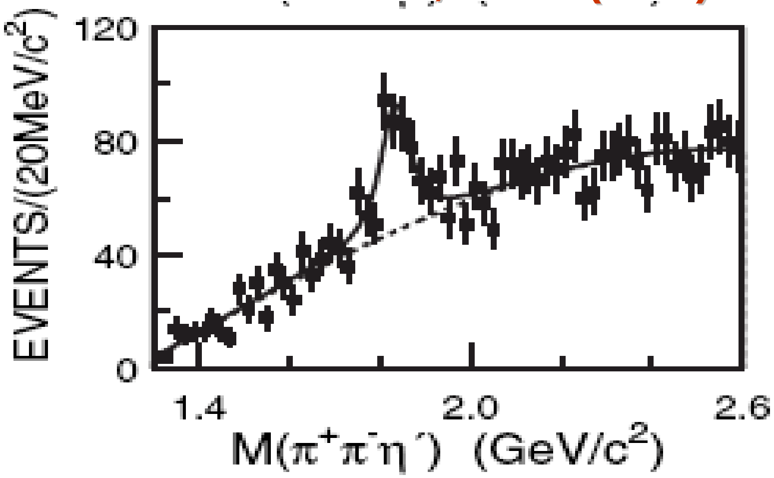
$$\Gamma = 13 \pm 20(\text{stat})^{+11}_{-33}(\text{syst}) \pm 4(\text{mod})\text{MeV/c}^2 \text{ or } \Gamma < 48\text{MeV/c}^2\ @90\%\,C.L.$$

$$B(J/\psi \rightarrow \gamma X(p\bar{p}))B(X(p\bar{p}) \rightarrow p\bar{p}) = (9.0 \pm 0.7(\text{stat})^{+1.5}_{-5.1}(\text{syst}) \pm 2.3(\text{mod})) \times 10^{-5}$$

X(1835) in $J/\psi \rightarrow \gamma\pi^+\pi^-\eta'(\eta'\rightarrow\gamma\rho/\eta\pi\pi)$ at BESIII

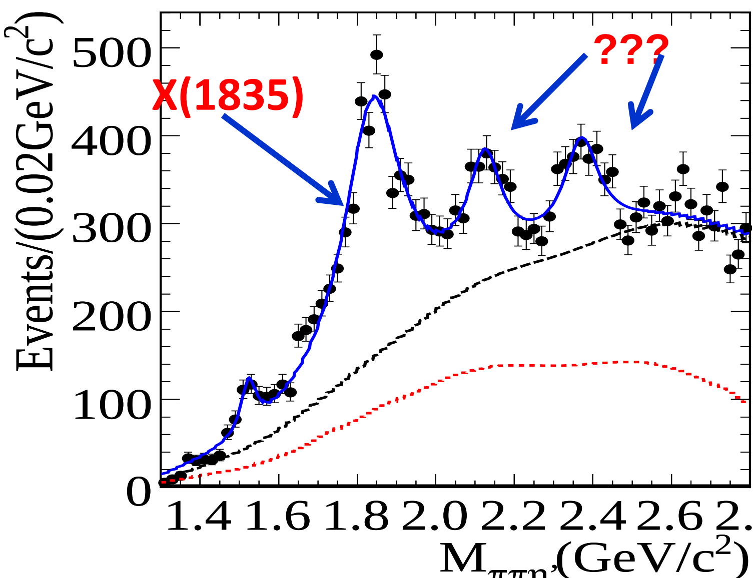
PRL., 106 (2011) 072002

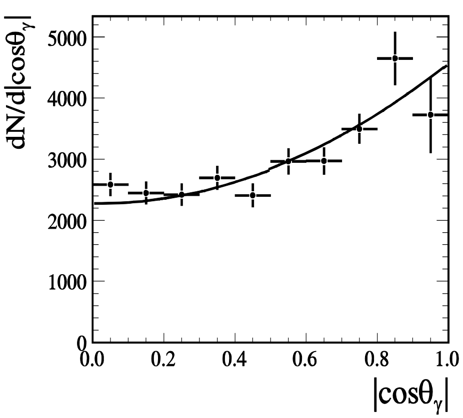
BESII PRL 95,262001(2005)



- BESII observed X(1835)
- BESIII confirmed X(1835)
- Observed two new resonances.

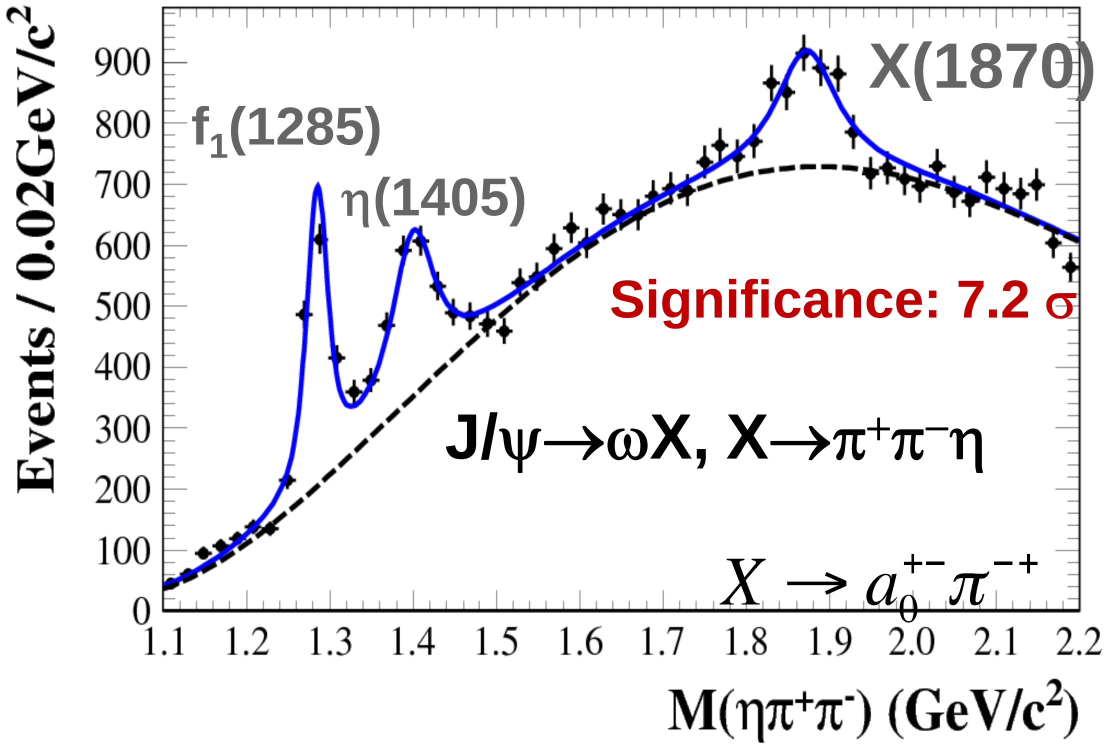
Resonance	M(MeV/c^2)	Γ(MeV/c^2)	Stat.Sig.
X(1835)	$1836.5\pm3.0^{+5.6}_{-2.1}$	$190.1\pm9.0^{+38}_{-36}$	>20σ
X(2120)	$2122.4\pm6.7^{+4.7}_{-2.7}$	$83\pm16^{+31}_{-11}$	7.2σ
X(2370)	$2376.3\pm8.7^{+3.2}_{-4.3}$	$83\pm17^{+44}_{-6}$	6.4σ





- X(1835) consistent with 0-+. Others not excluded.
- η' excited state? Glueball state? Same as ppbar enhancement?

Observed X(1870) in $J/\psi \to \omega\eta\pi^+\pi^-$ at BESIII



$f_1(1285)$, $\eta(1405)$ and X(1870) decay primary through $a_0(980)\pi^{\pm}$.

New particle?

$\eta_2(1870)$?

X(1835)?

Resonance	Mass (MeV/c^2)	Width (MeV/c^2)	$\mathcal{B}$ (10^{-4})
$f_1(1285)$	$1285.1 \pm 1.0^{+1.6}_{-0.3}$	$22.0 \pm 3.1^{+2.0}_{-1.5}$	$1.25 \pm 0.10^{+0.19}_{-0.20}$
$\eta(1405)$	$1399.8 \pm 2.2^{+2.8}_{-0.1}$	$52.8 \pm 7.6^{+0.1}_{-7.6}$	$1.89 \pm 0.21^{+0.21}_{-0.23}$
$X(1870)$	$1877.3 \pm 6.3^{+3.4}_{-7.4}$	$57 \pm 12^{+19}_{-4}$	$1.50 \pm 0.26^{+0.72}_{-0.36}$

arXiv: 1107.1806

Accepted by PRL

Excited baryons

- **The understanding of the internal quark-gluon structure of baryons is one of the most important tasks in both particle and nuclear physics.**
- **The systematic study of various baryon spectroscopy will provide us with critical insights into the nature of QCD in the confinement domain.**
- **Jefferson Lab, ELSA, GRAAL, SPRING8, COSY… and BES for the excited baryon states.**
- **The available experimental information is still poor, especially for the excited baryon states with two strange quarks, e.g., Ξ^*. Theories predict more than 30 such kinds of baryons, however only two are experimentally well settled. Totally only about 10% excited baryons are observed.**

N* Resonances (uud, udd)

Particle	$L_{2I \cdot 2J}$	Overall status	Status as seen in — $N\pi$	$N\eta$	ΛK	ΣK	$\Delta\pi$	$N\rho$	$N\gamma$
$N(939)$	P_{11}	****							
$N(1440)$	P_{11}	****	****	*			***	*	***
$N(1520)$	D_{13}	****	****	***			****	****	****
$N(1535)$	S_{11}	****	****	****			*	**	***
$N(1650)$	S_{11}	****	****	*	***	**	***	**	***

PDG2011

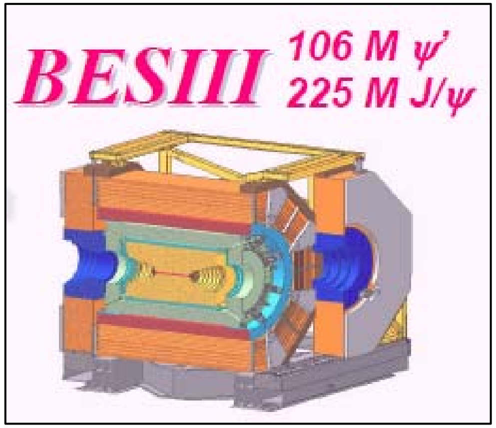
Theory predicts much more baryons than what observed → missing baryons

Particle	$L_{2I \cdot 2J}$	Overall status	$N\pi$	$N\eta$	ΛK	ΣK	$\Delta\pi$	$N\rho$	$N\gamma$
$N(1990)$	F_{17}	**	**	*	*	*			*
$N(2000)$	F_{15}	**	**	*	*	*	*	**	
$N(2080)$	D_{13}	**	**	*	*				*
$N(2090)$	S_{11}	*	*						
$N(2100)$	P_{11}	*	*	*					
$N(2190)$	G_{17}	****	****	*	*	*		*	*
$N(2200)$	D_{15}	**	**	*	*				
$N(2220)$	H_{19}	****	****	*					

(**) not well-established

	****	***	**	*
N Spectrum	11	3	6	2
Δ Spectrum	7	3	6	6

Baryon spectroscopy study: many experiments



Only selected results are reported here.

A narrow structure in the excitation function of ηn at ELSA

I. Jaegle et al., arXiv:1107.2046

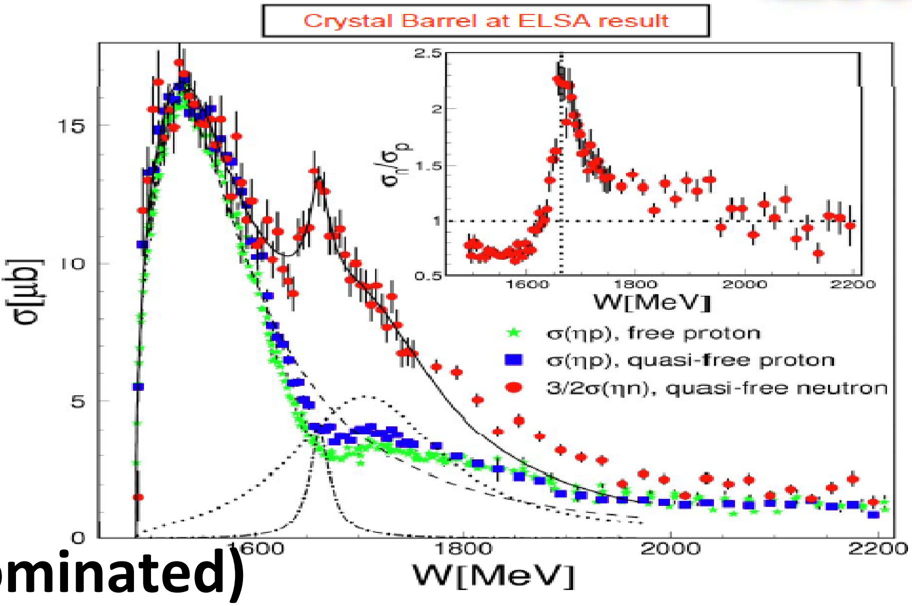
$$\gamma + d \rightarrow n + p + \eta$$

A very narrow structure

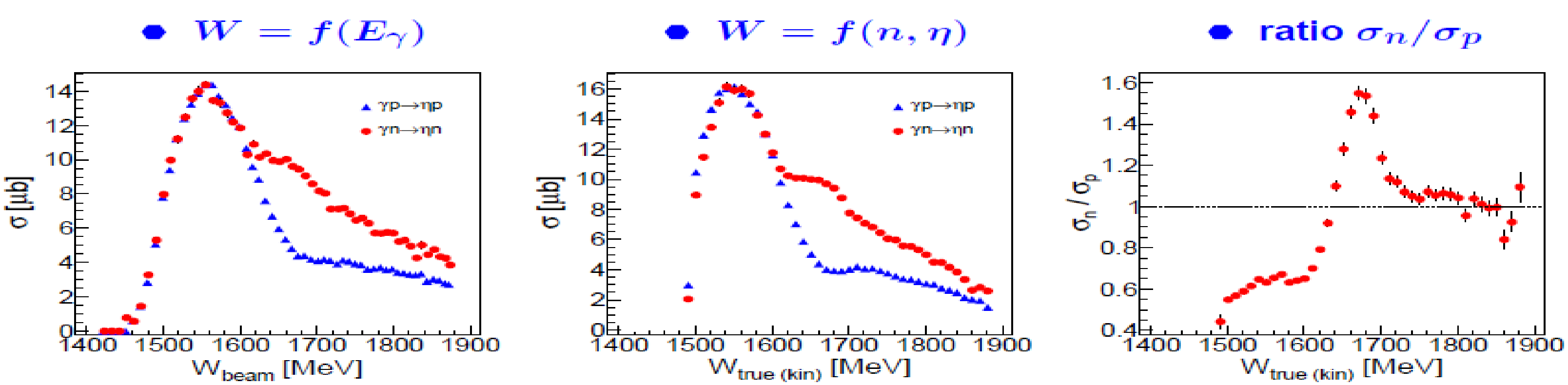
In ηn final state.

$M \approx 1670$ MeV

$\Gamma \approx 25 \pm 10$ MeV (resolution dominated)



Similar narrow structure in ηn final state at MAMI



Evidence from other experiments

- GRAAL: $W \approx$ 1680 MeV, $\Gamma <$ 30 MeV
- Tohoku-LNS: $W \approx$ 1670 MeV, $\Gamma <$ 40 MeV
- ELSA: $W \approx$ 1665 MeV, $\Gamma <$ 40 MeV
- MAMI-C: $W \approx$ 1675 MeV, $\Gamma <$ 50 MeV
- MAMI-C, ^{3}He: $W \approx$ 1650 MeV, $\Gamma <$ 50 MeV

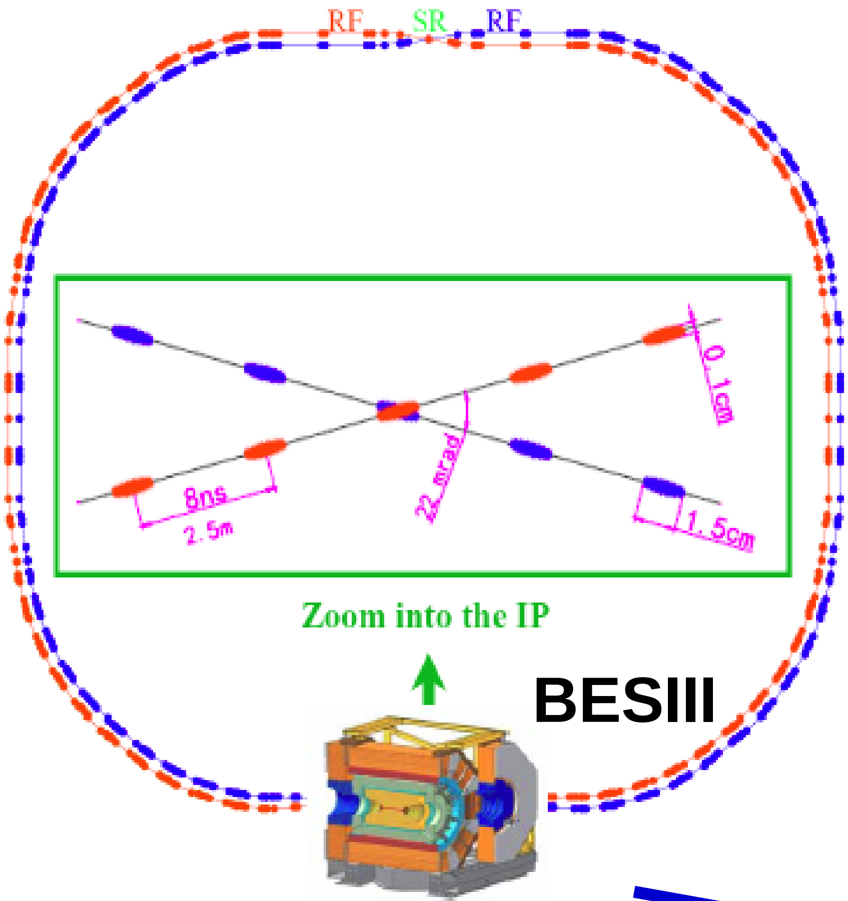
- Quantum numbers of the structure?
- Nature of the structure?

Measurement of polarization observables in progress

Future prospects on light hadron spectroscopy

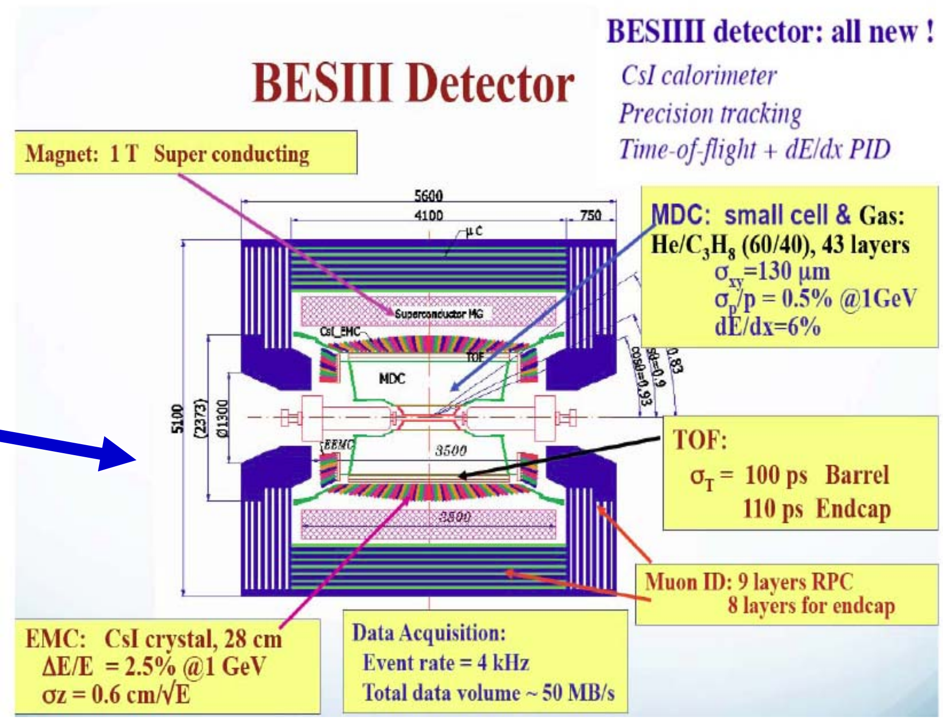
- **BESIII/BEPCII: BESIII high statistics data**
- **12 GeV upgrade program at JLAB**
- **PANDA at FAIR**
- **Future super τ-charm factory**
- **……**

BEPCII/BESIII



Data collected since 2009

- 225 M J/ψ
- 106 M ψ'
- 2.9 fb^{-1} $\psi(3770)$
- 0.5 fb^{-1} @4010 MeV



Beam: 1.0 – 2.3 GeV
Designed L: 1×10^{33} $cm^{-2}s^{-1}$
Achieved: 0.65×10^{33} $cm^{-2}s^{-1}$

BESIII Data Samples

	Previous	BESIII (2009-2014)	BESIII target
J/ψ	BESII: 58M	2009：225M 2012：1 B	10B
ψ'	CLEO: 28 M	2009：106M 2012：0.7-1.0 B	3 B
$\psi(3770)$	CLEO：0.8 /fb	2010：0.9/fb 2011：2/fb	20 /fb
$\psi(4040)$, $\psi(4160)$,… & scan	CLEO: 0.6 /fb	2011: 0.5/fb 2013：5/fb	
R scan & Tau	BESII	2014	

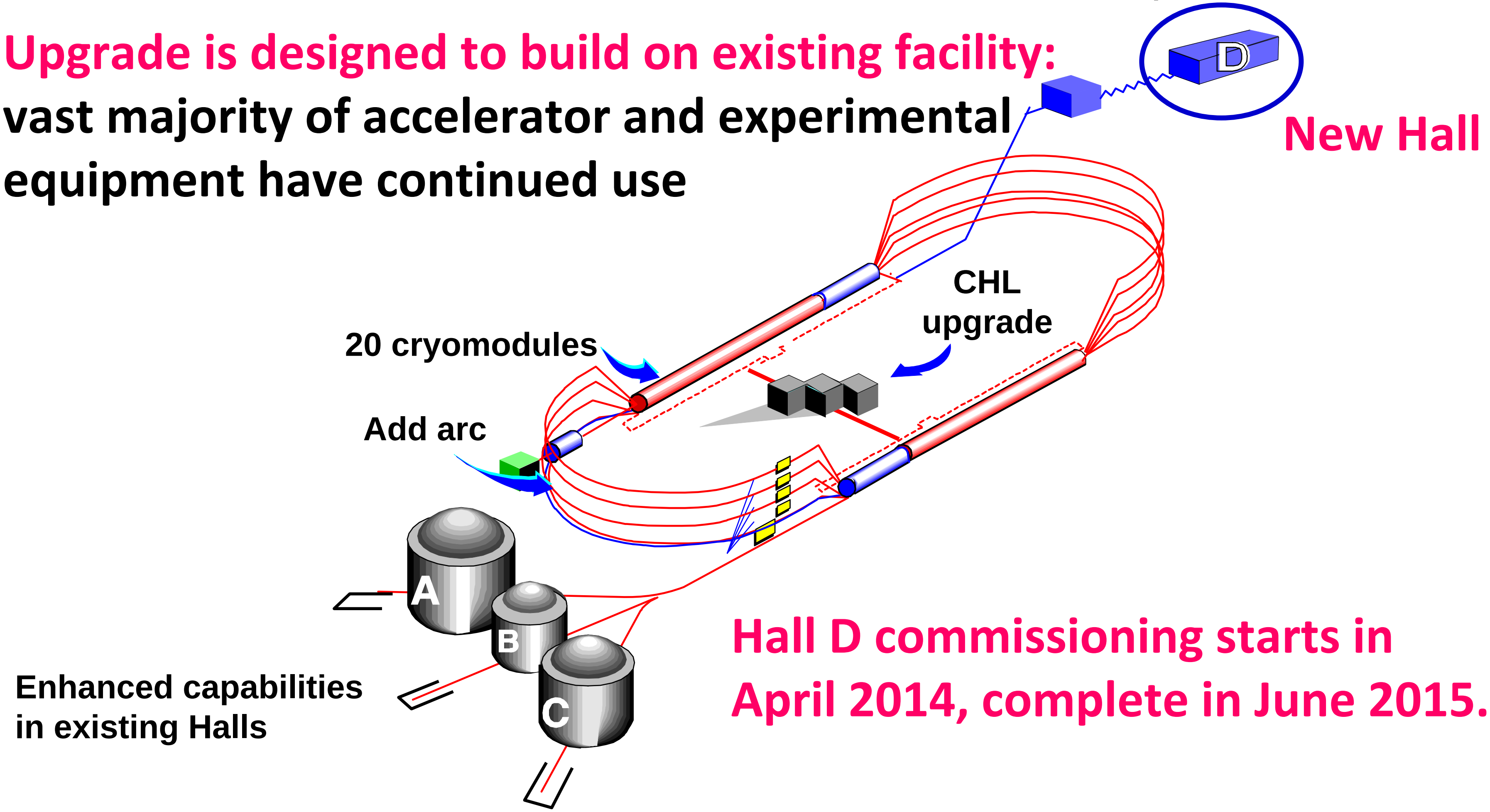
BESIII huge data sample for light hadron spectroscopy

12 GeV Upgrade Project at JLab

R. D. McKeown, Weihai 2011

Upgrade is designed to build on existing facility:

vast majority of accelerator and experimental equipment have continued use



Hall D commissioning starts in April 2014, complete in June 2015.

GlueX: The Hadron spectra as probes of QCD.

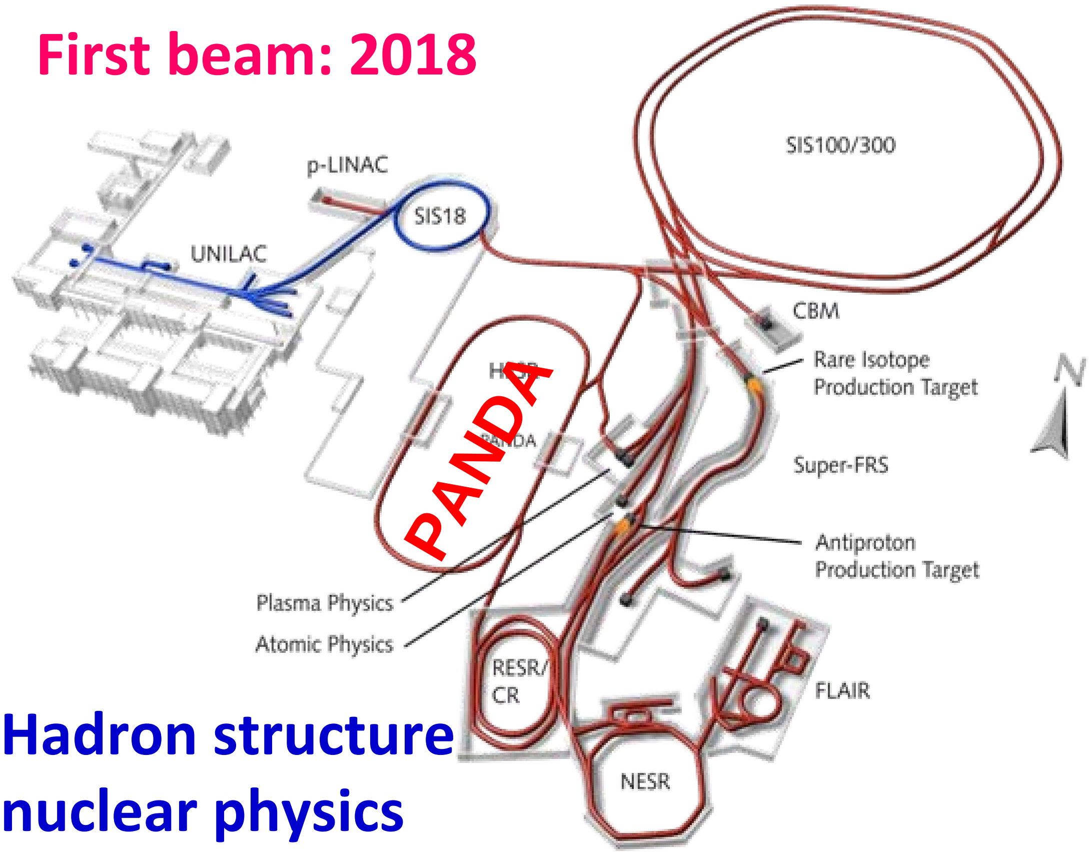
Heavy baryon and meson spectroscopy.

PANDA at FAIR

L. Schmitt, Hadron 2011

Ground break: 2012

First beam: 2018



Hadron structure
nuclear physics

Primary beams

- U up to 35 AGeV
- Protons up to 30 GeV/c

Secondary beams

- Broad range of rare isotopes
- – p: 0-15 GeV/c

Storage and cooler rings

- Radioactive beams
- e^-- A (or p - A) collider
- Antiprotons

Hadorn spectroscopy:

- Search for new hadrons
- Systematic study of the spectroscopy (also XYZ...)
- Masses, widths & quantum numbers J^{PC} of resonances

Production of states of all quantum numbers

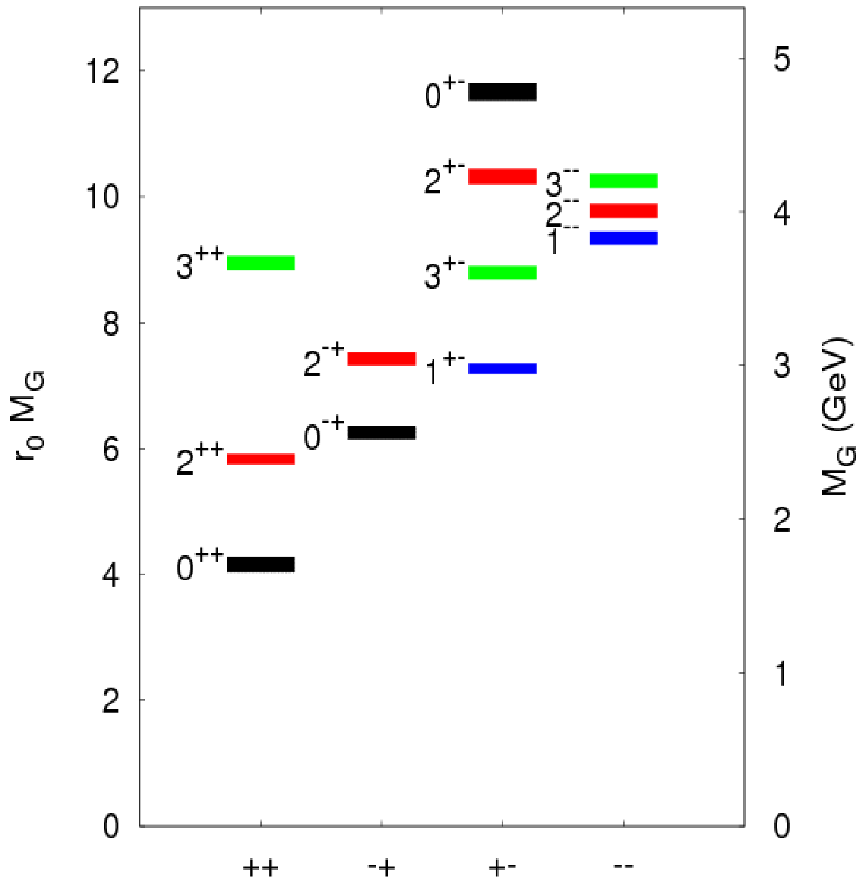
Summary

- Hadron spectroscopy is a powerful tool for the understanding of the structure of the hadrons and QCD.
- More and more observed resonances in the light hadron mass range – over populated! We have more and more information, but we are more and more puzzled.
- After many years efforts, it is still in a mess. None of the new hadrons is established (model dependent, analysis dependent, …)
- COMPASS, BESIII, JLAB, PANDA at FAIR, Super-TC….. are and will be the principal players for the study of light hadron spectroscopy. Stay tuned!
- Higher statistics data from new generation of sophistic detector might be the key for disentangle the current "mess" situation. Joint effort from both theorists and experimentalist is crucial.

Thank You

谢谢

Glueball spectrum – Lattice QCD



Y. Chen et al., PRD 73 (2006) 014516

- LQCD predicts the lowest glueball state is 0^{++}. The mass is around 1.5 GeV – 1.7 GeV.
- LQCD predicts the next lightest glueball is 2^{++}. The mass is around 2.4 GeV.
- The mix of glueball with ordinary $q\bar{q}$ meson makes the situation more difficult.

Hybrid states – Lattice QCD

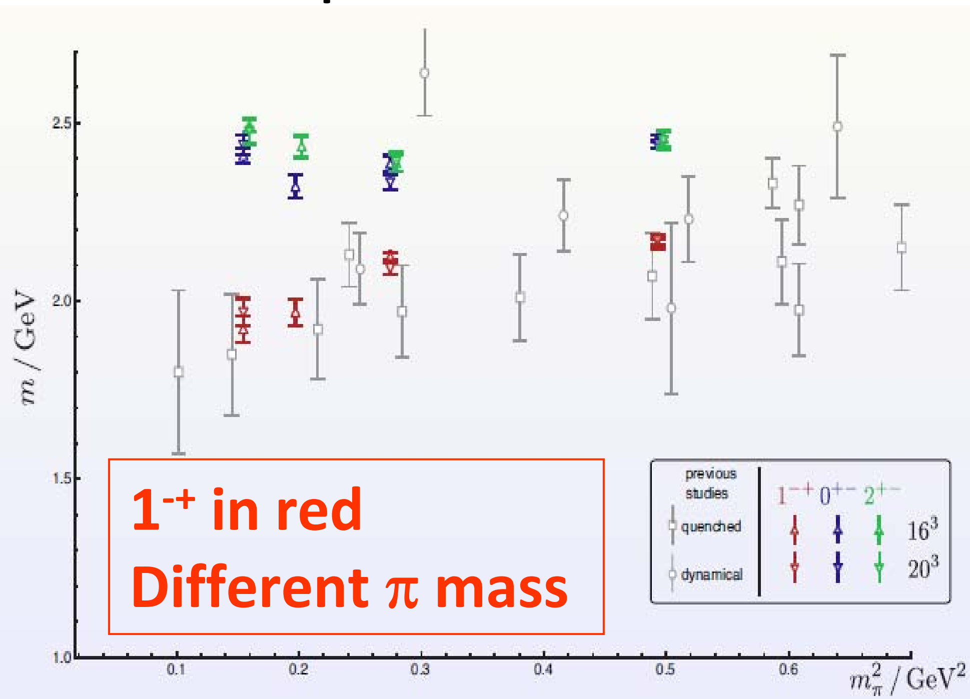
Sinead Ryan, Hadron2011

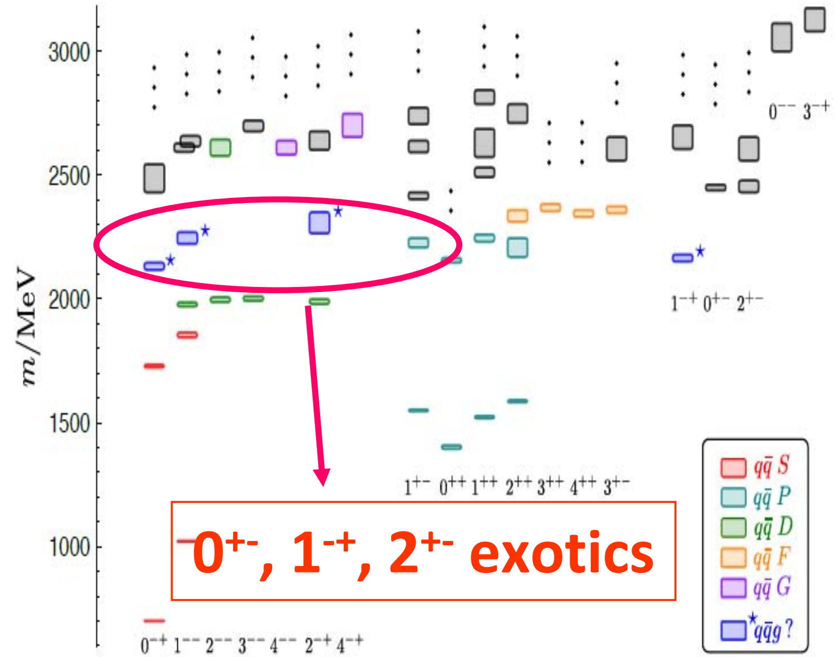
Hadron Spectrum Collaboration

J. J. Dudek, arXiv: 1106.5515

π mass: 700 MeV

Box size: statistical uncertainty

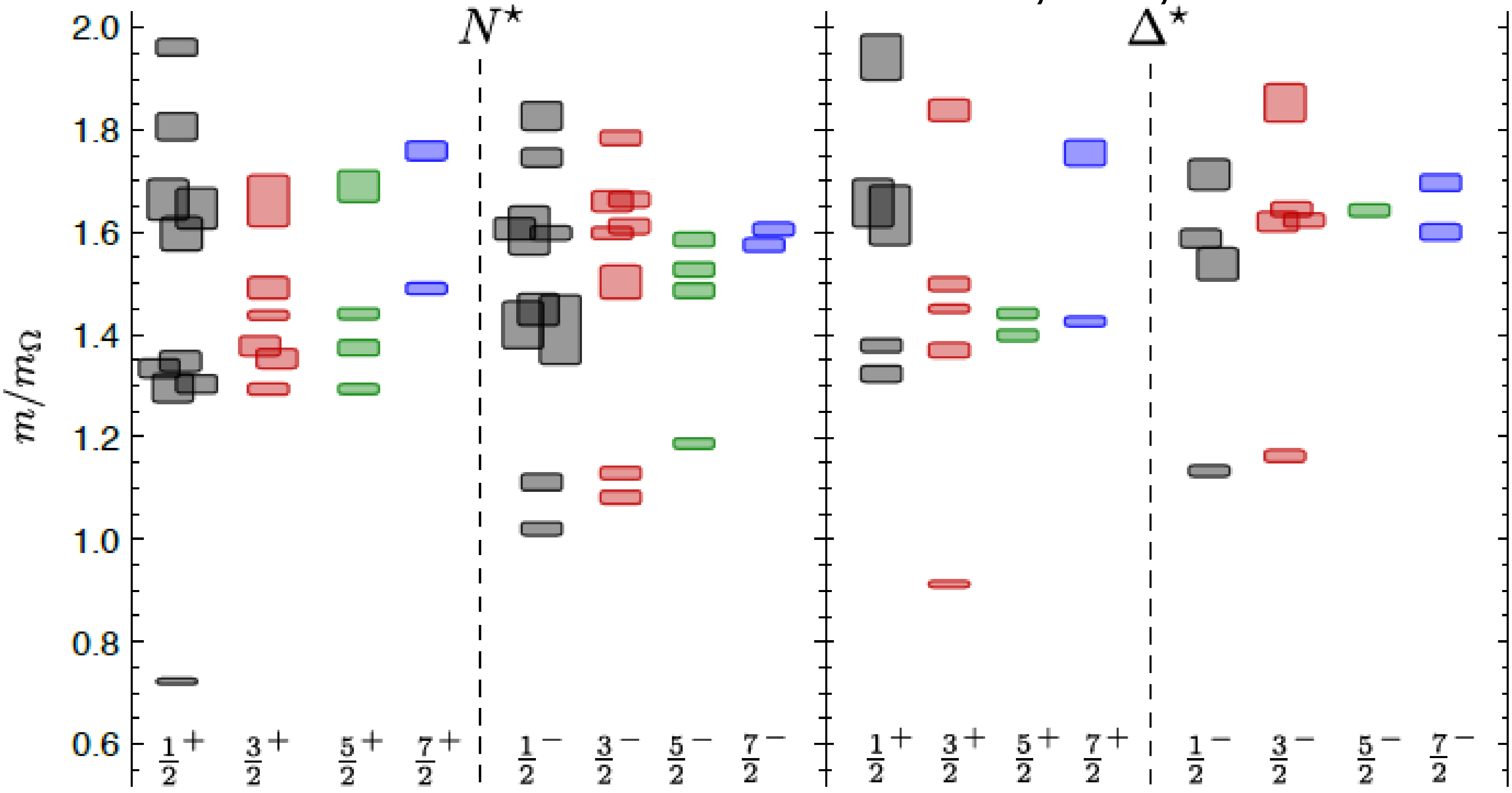




- **The hybrid states with the exotic quantum numbers would be evidence for non-$q\bar{q}$ degrees of freedom.**
- **LQCD predicts: $M_{1^{-+}} > 2.1$ GeV**
  Flux-tube model predicts: $M_{1^{-+}} \sim 1.9$ GeV

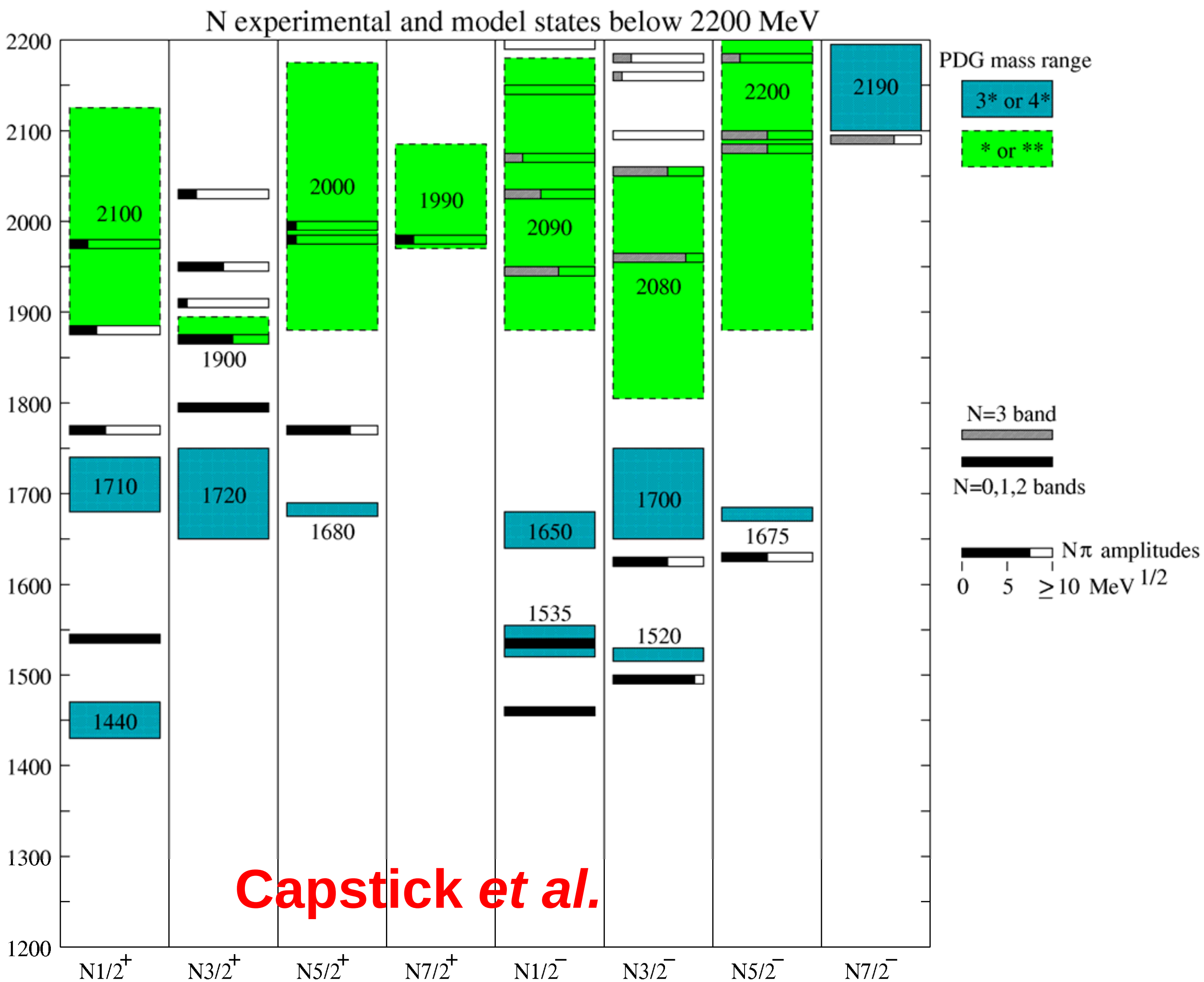
Excited baryons – Lattice QCD

R. G. Edwards, et al., arXiv: 1104.5152

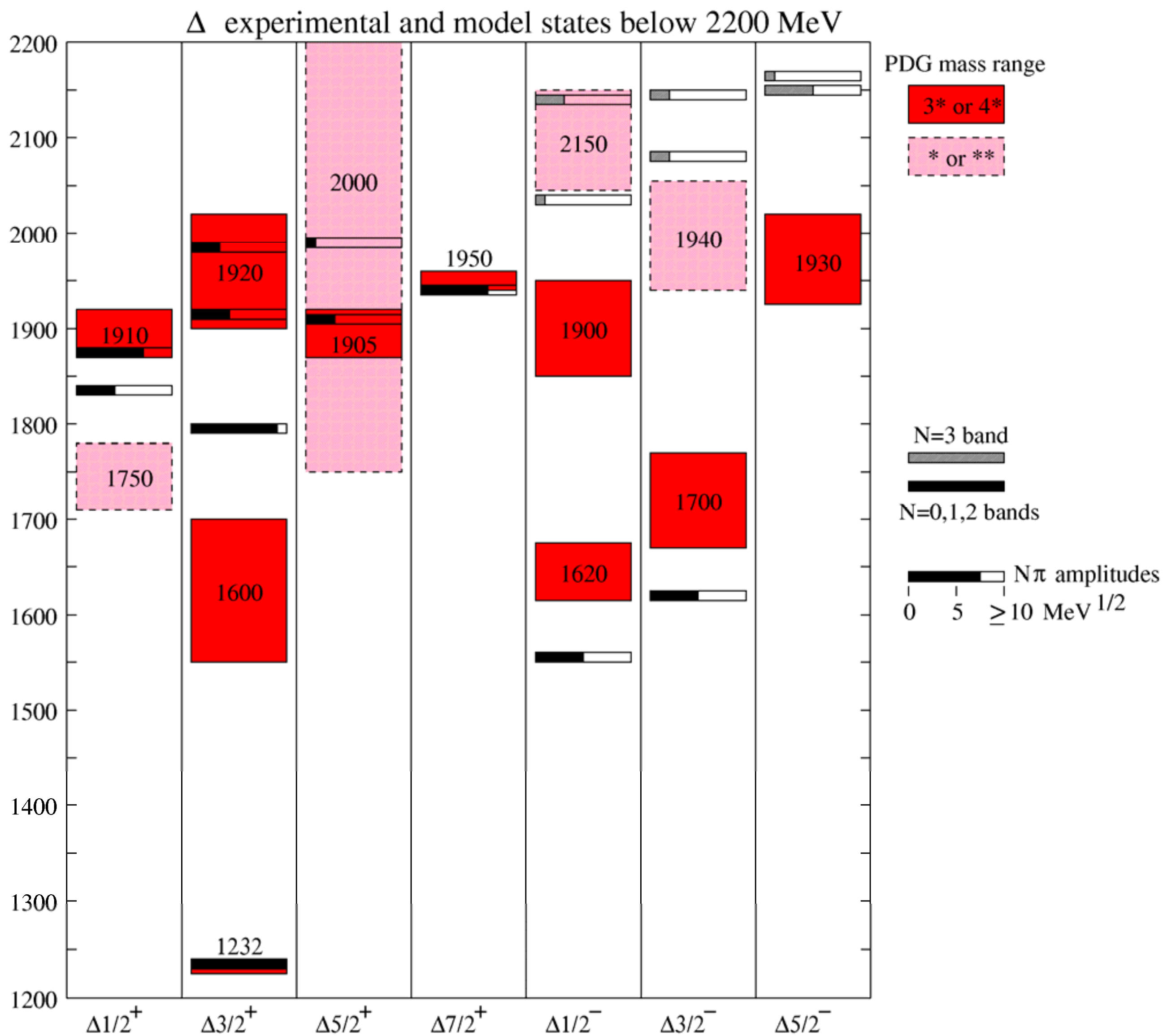


Pion mass of 396 MeV

Nucleon model states (πN couplings)

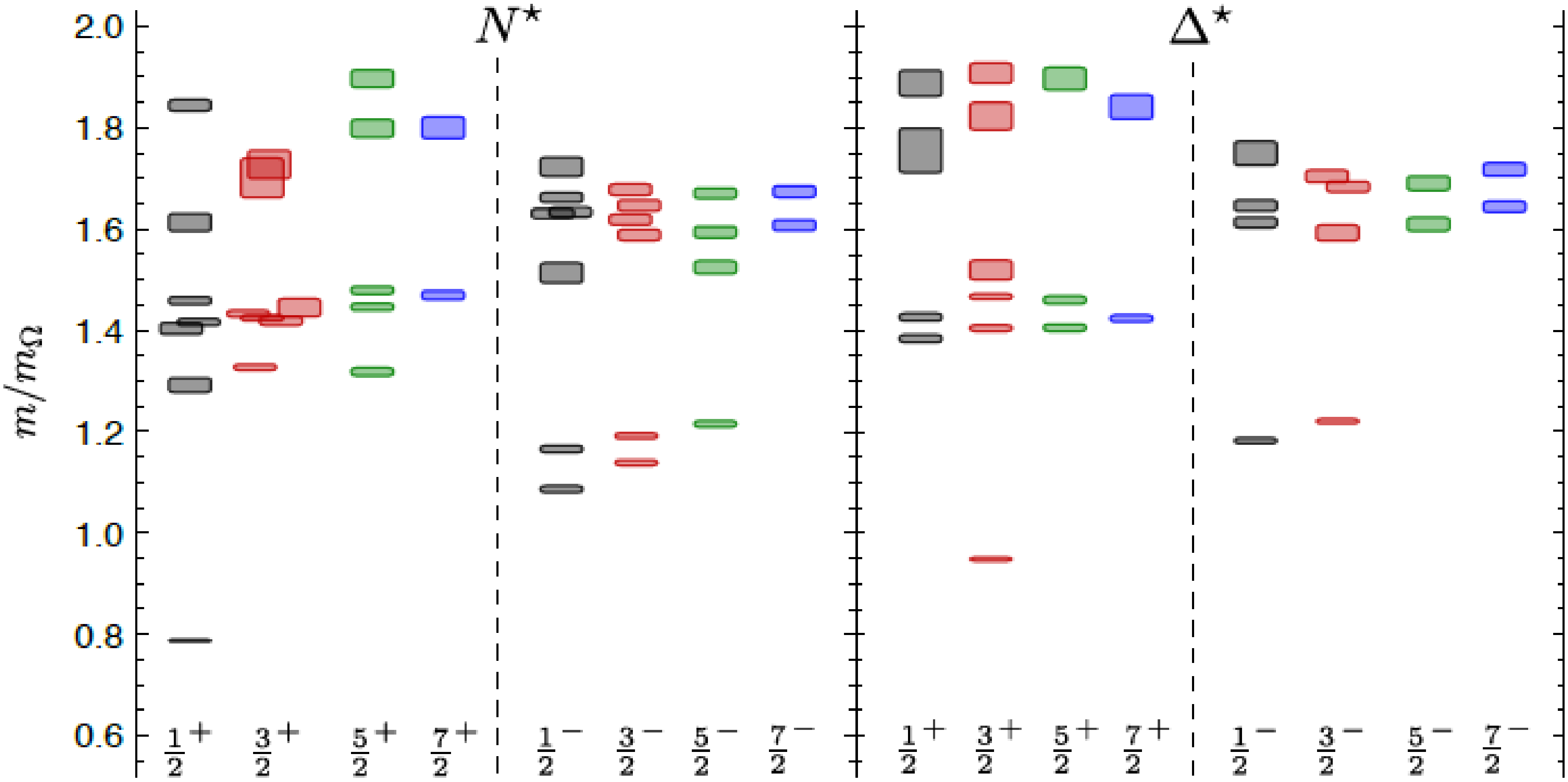


Δ model states (πN couplings)



Excited baryons – Lattice QCD

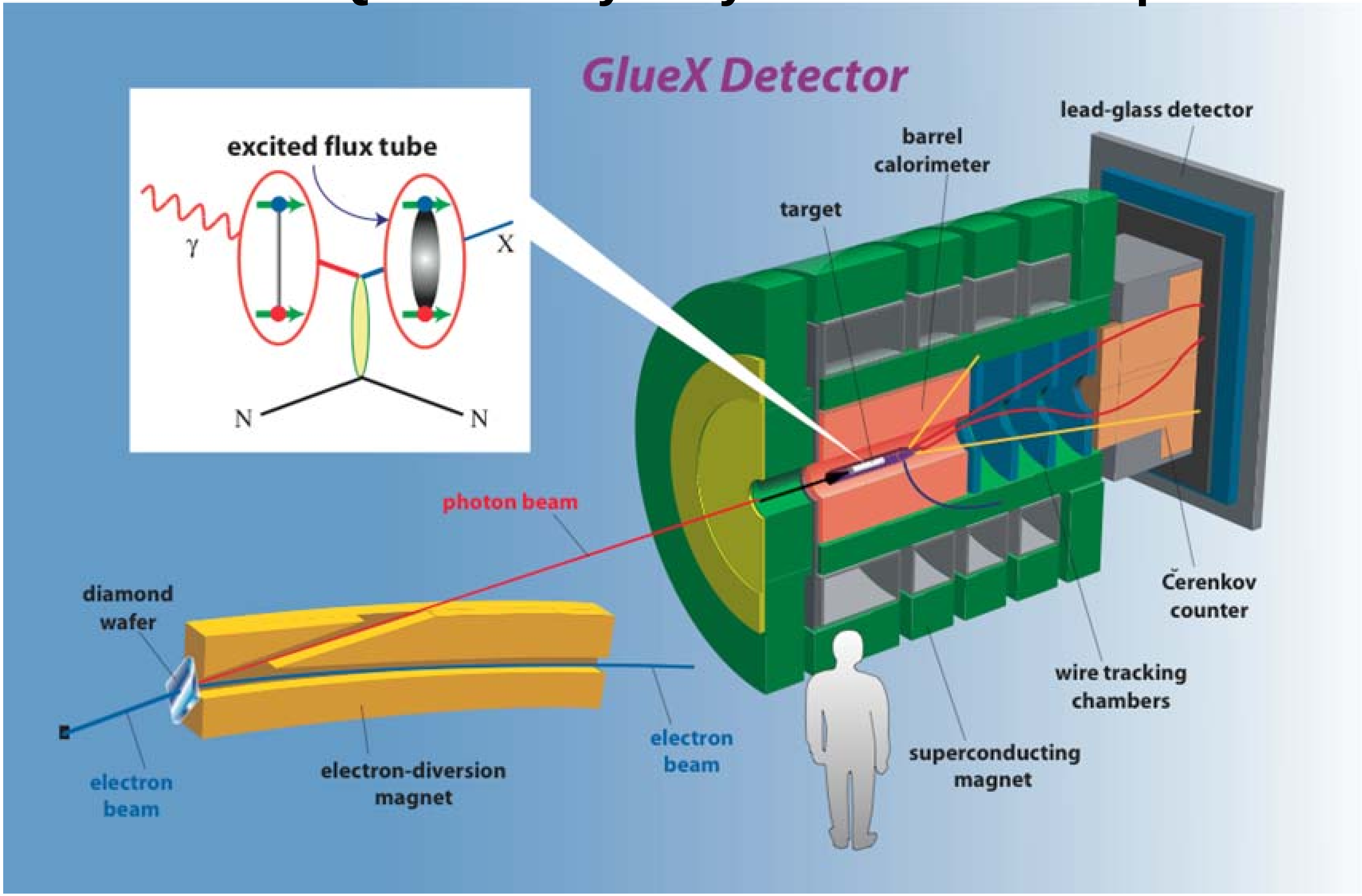
R. G. Edwards, et al., arXiv: 1104.5152



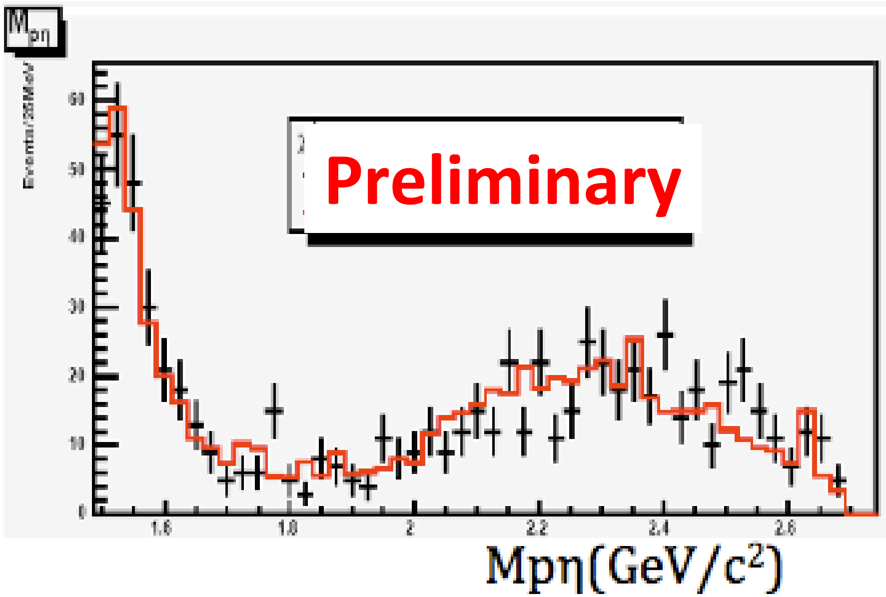
Pion mass of 524 MeV

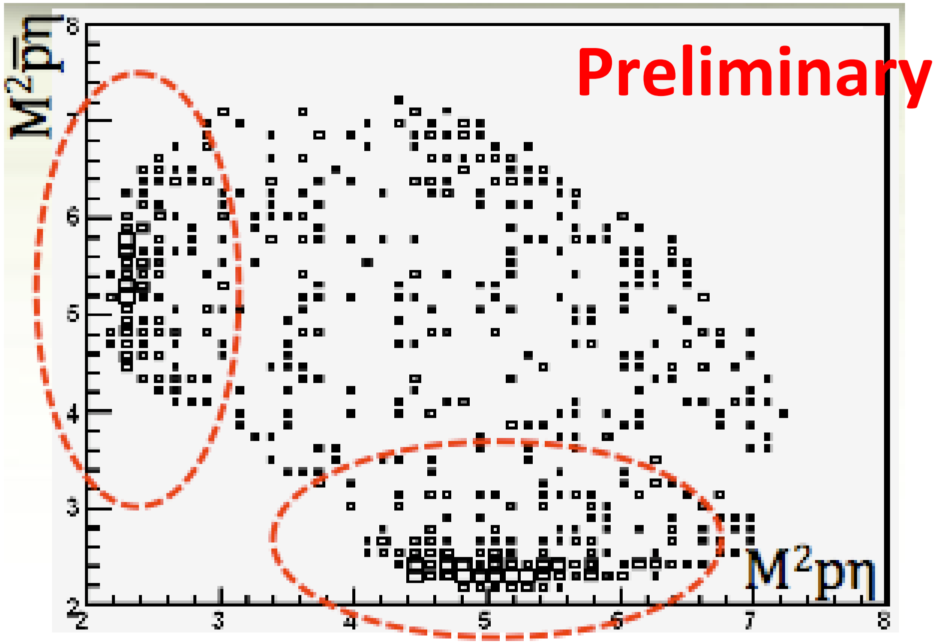
Hall D

GlueX: The Hadron spectra as probes of QCD. Heavy baryon and meson spectroscopy



$N^*(1535)$ from $\psi' \rightarrow p\bar{p}\eta$ at BESIII





BESIII preliminary

$$M = 1.524^{+0.005+0.016}_{-0.005-0.004}\ \mathrm{GeV/c^2}$$

$$\Gamma = 0.130^{+0.027+0.028}_{-0.027-0.014}\ \mathrm{GeV/c^2}$$

$$B(\psi' \rightarrow \eta p\bar{p}) = (6.6 \pm 0.2 \pm 0.6) \times 10^{-5}$$

PDG :

$$1.525 - 1.545\ \mathrm{GeV/c^2}$$

$$0.125 - 0.175\ \mathrm{GeV/c^2}$$

$$(6.0 \pm 1.2) \times 10^{-5}$$