Recent results of baryon spectroscopy at BESIII

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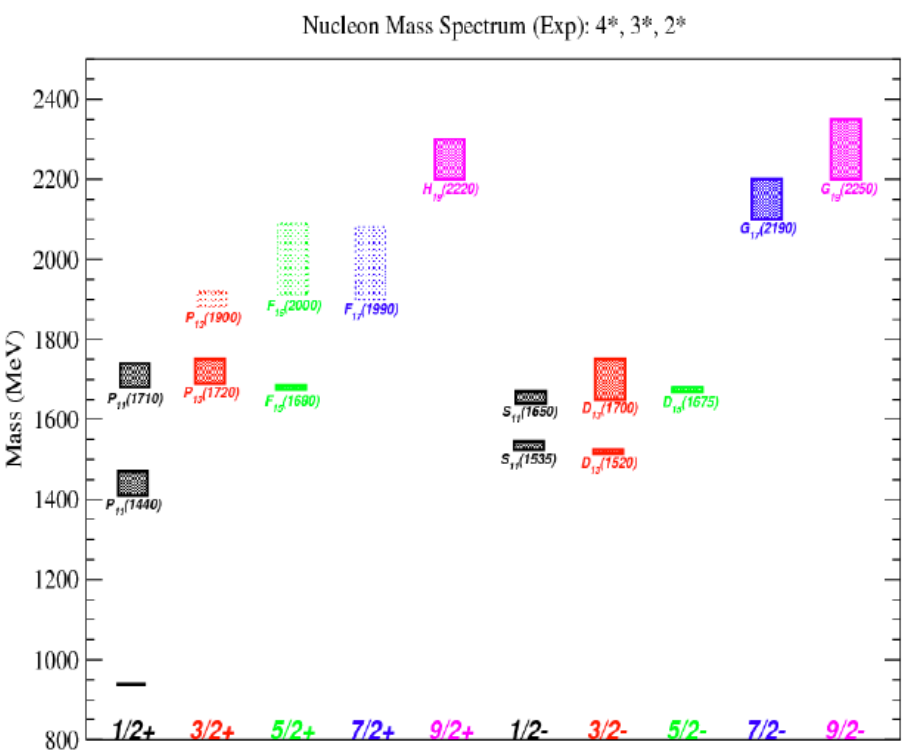
For BESIII collaboration

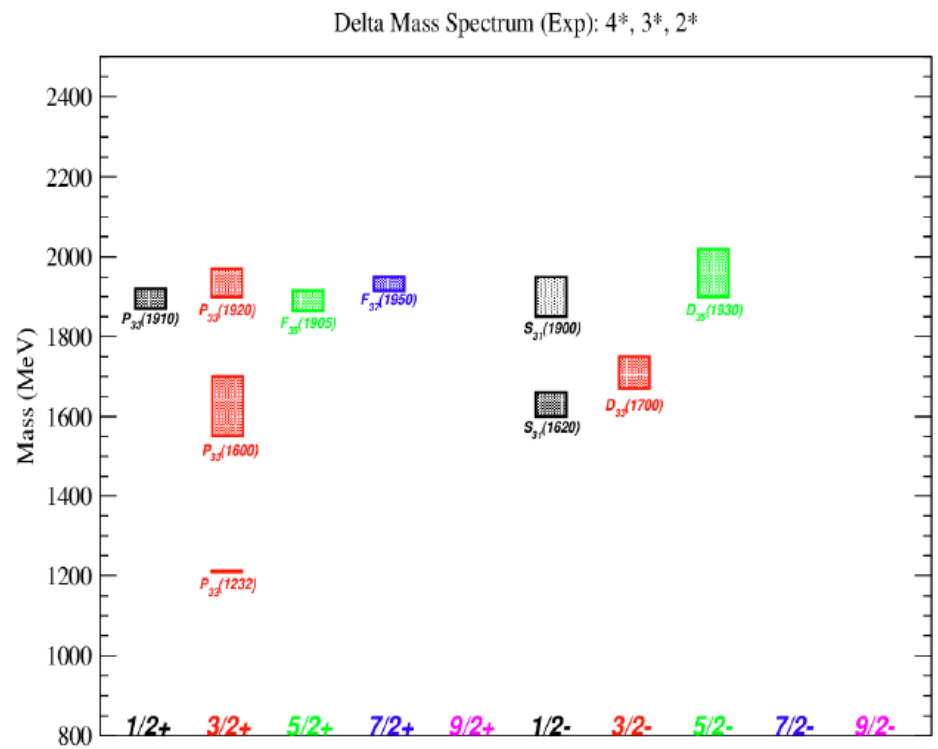
Hadron 2013, Nara, Japan

Spectrum of Nucleon Resonances

	****	***	**	*
N Spectrum	10	5	7	3
Δ Spectrum	7	3	7	5

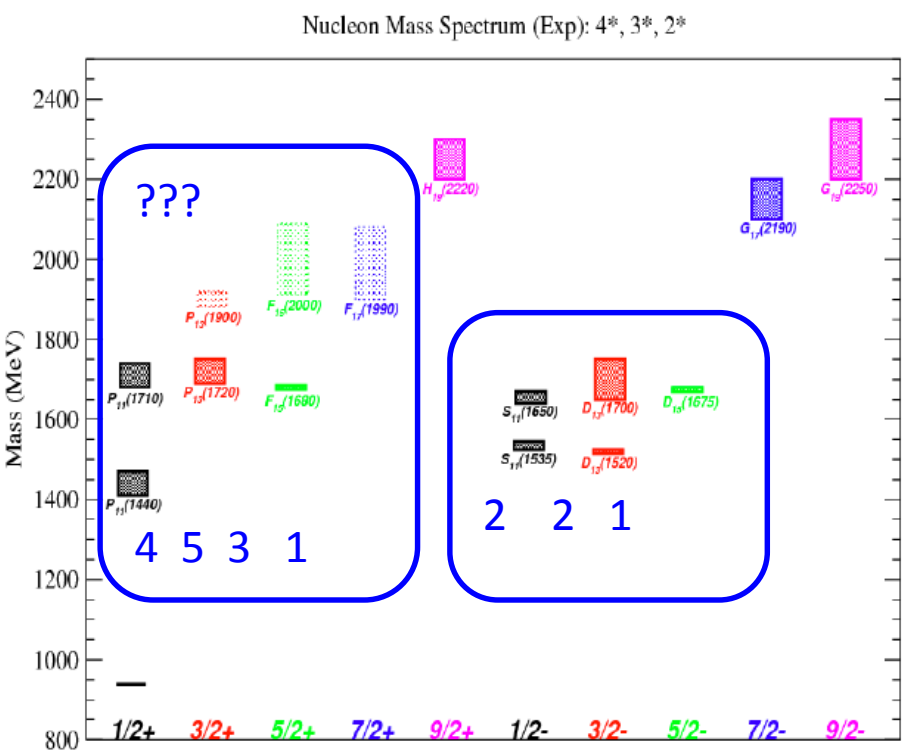
→ Particle Data Group
(Phys. Rev. D**86**, 010001 (2012))
→little known
(many open questions left)

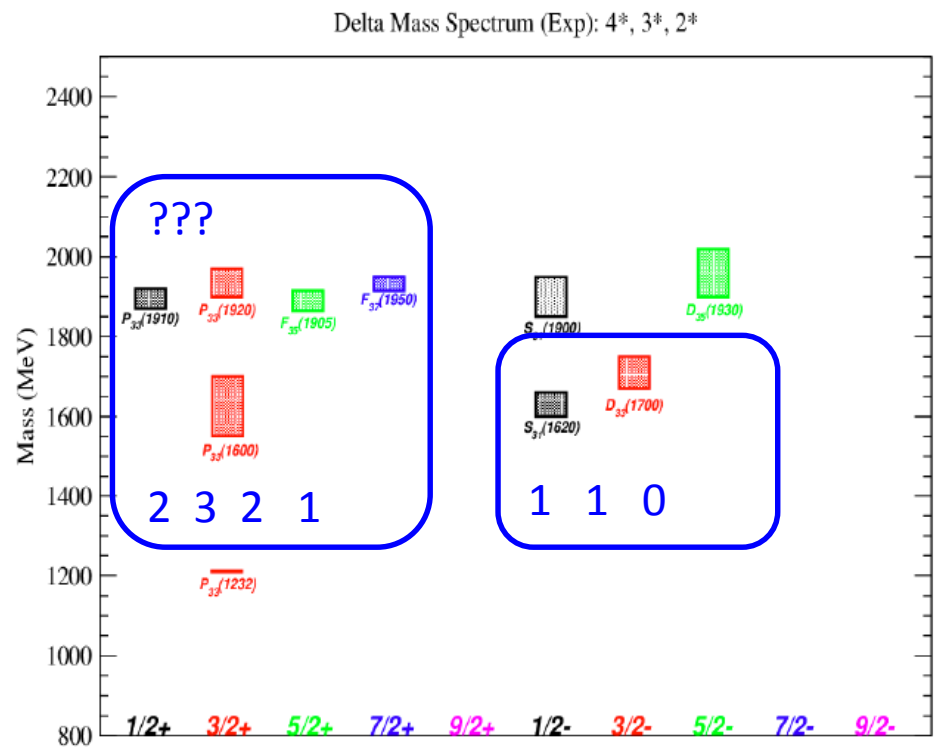




Where are the "missing" baryons

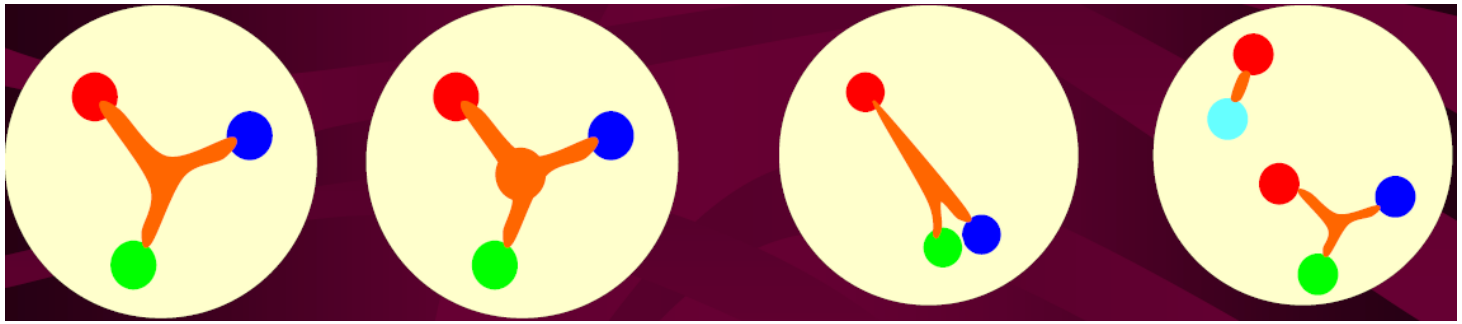
Quark models predict many more baryons than have been observed





Where are the "missing" baryons

- Are the states missing in the predicted spectrum because our models do not capture the correct degrees of freedom?



...

1, 3 quarks | 2, quarks and flux tubes | 3, quark-diquark | 4, multi quarks

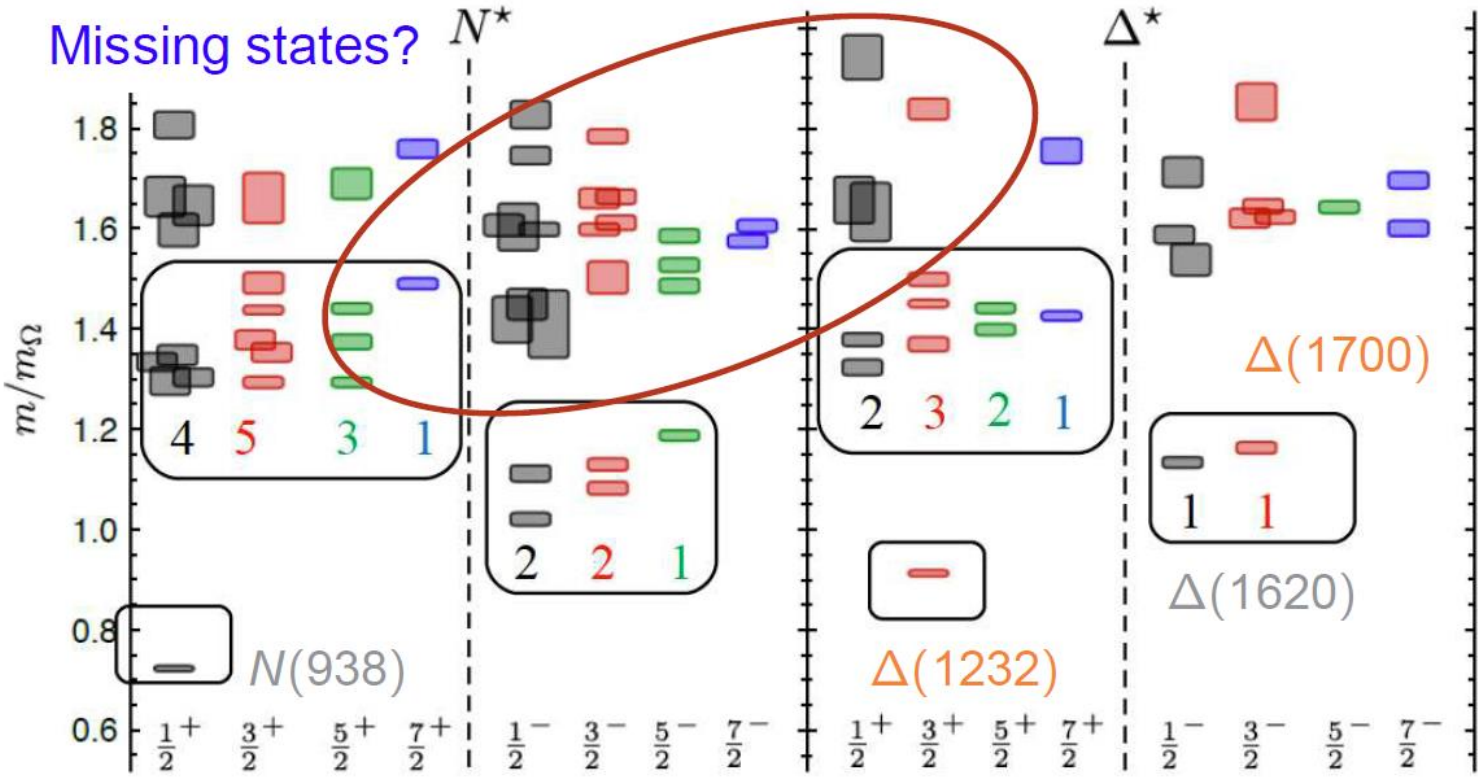
$N_{predictied}$: $N_4 > N_2 > N_1 > N_3$, $N_{observed} << N_1$

- Or have the resonances simply escaped detection?

Nearly all existing data result from πN experiments

Excited state baryon spectroscopy from lattice QCD

R. Edwards *et al.*, PR D84 074508 (2011)



$m_\pi = 400$ MeV

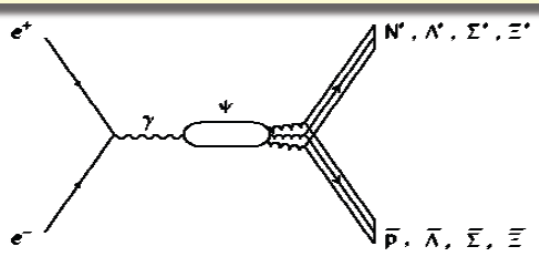
Exhibits broad features expected of $SU(6) \otimes O(3)$ symmetry

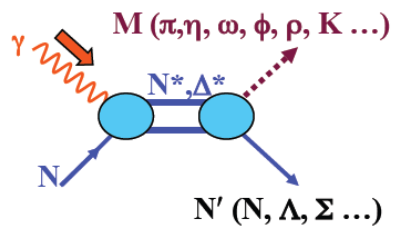
➜ Counting of levels consistent with non-rel. quark model, no parity doubling

Charmonium decays can give novel insights into baryons and give complementary information to other experiments

$J/\psi(\psi') \to \bar{B}BM \Rightarrow N^*, \Lambda^*, \Sigma^*, \Xi^*$

JLab, ELSA, MAMI, ESRF, Spring-8, ….



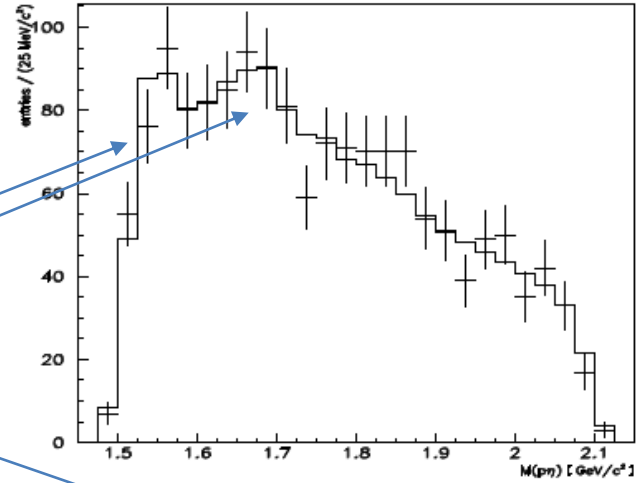


- ✓ Pure isospin 1/2 filter: $\psi \to N\bar{N}\pi$, $\psi \to N\bar{N}\pi\pi$
- ✓ Missing N* with small couplings to πN & γN , but large coupling to gggN : $\psi \to N\bar{N}\pi/\eta/\eta'/\omega/\phi$, $\bar{p}\Sigma\pi$, $\bar{p}\Lambda K$ …
- ✓ Interference between N* and N*bar bands in $\psi \to N\bar{N}\pi$ Dalitz plots may help to distinguish some ambiguities in PWA of πN
- ✓ Not only N*, but also Λ^*, Σ^*, Ξ^*
- ✓ High statistics of charmonium @ BES III

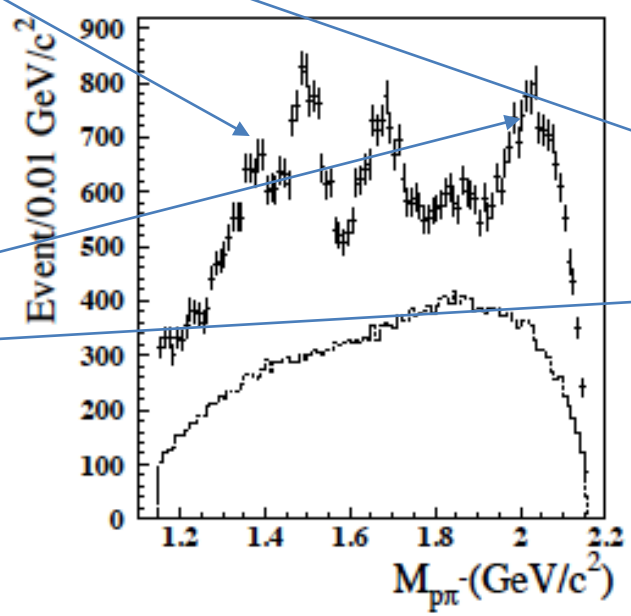
	Previous Data	BESIII now	Goal
J/ψ	BESII 58 M	1.2 B (20x BESII)	10 B
ψ (3686)	CLEO: 28M	0.5 B (20x CLEO)	3 B
ψ (3770)	CLEO: 0.8/fb	2.9/fb (3.5x CLEO)	20/fb
Above open charm threshold	CLEO: 0.6/fb@4160	0.4/fb @4040, 2/fb@4260, 0.5/fb @4360, Data for lineshape	5-10/fb
R scan & τ	BESII	R @2.23,2.4,2.8,3.4, 25/pb tau	

$N(1440)\,1/2^+$	****
$N(1520)\,3/2^-$	****
$N(1535)\,1/2^-$	****
$N(1650)\,1/2^-$	****
$N(1675)\,5/2^-$	****
$N(1680)\,5/2^+$	****
$N(1685)\,?^?$	*
$N(1700)\,3/2^-$	***
$N(1710)\,1/2^+$	***
$N(1720)\,3/2^+$	****
$N(1860)\,5/2^+$	**
$N(1875)\,3/2^-$	***
$N(1880)\,1/2^+$	**
$N(1895)\,1/2^-$	**
$N(1900)\,3/2^+$	***
$N(1990)\,7/2^+$	**
$N(2000)\,5/2^+$	**
$N(2040)\,3/2^+$	*
$N(2060)\,5/2^-$	**
$N(2100)\,1/2^+$	*
$N(2120)\,3/2^-$	**
$N(2190)\,7/2^-$	****
$N(2220)\,9/2^+$	****
$N(2250)\,9/2^-$	****
$N(2300)\,1/2^+$	**
$N(2570)\,5/2^-$	**
$N(2600)\,11/2^-$	***
$N(2700)\,13/2^+$	**

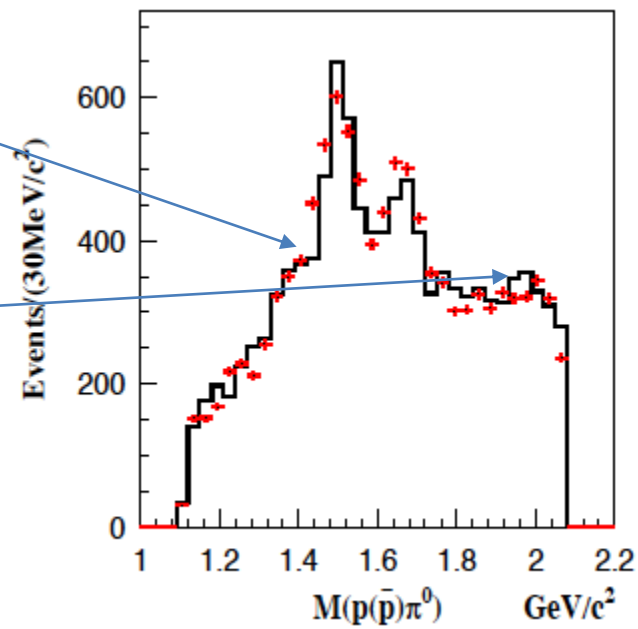
$N(\sim$ 3000 Region)Partial-Wave Analyses



$J/\psi \to \eta\bar{p}p$ @ BES1



$J/\psi \to \pi^+\bar{p}n$ @BES2



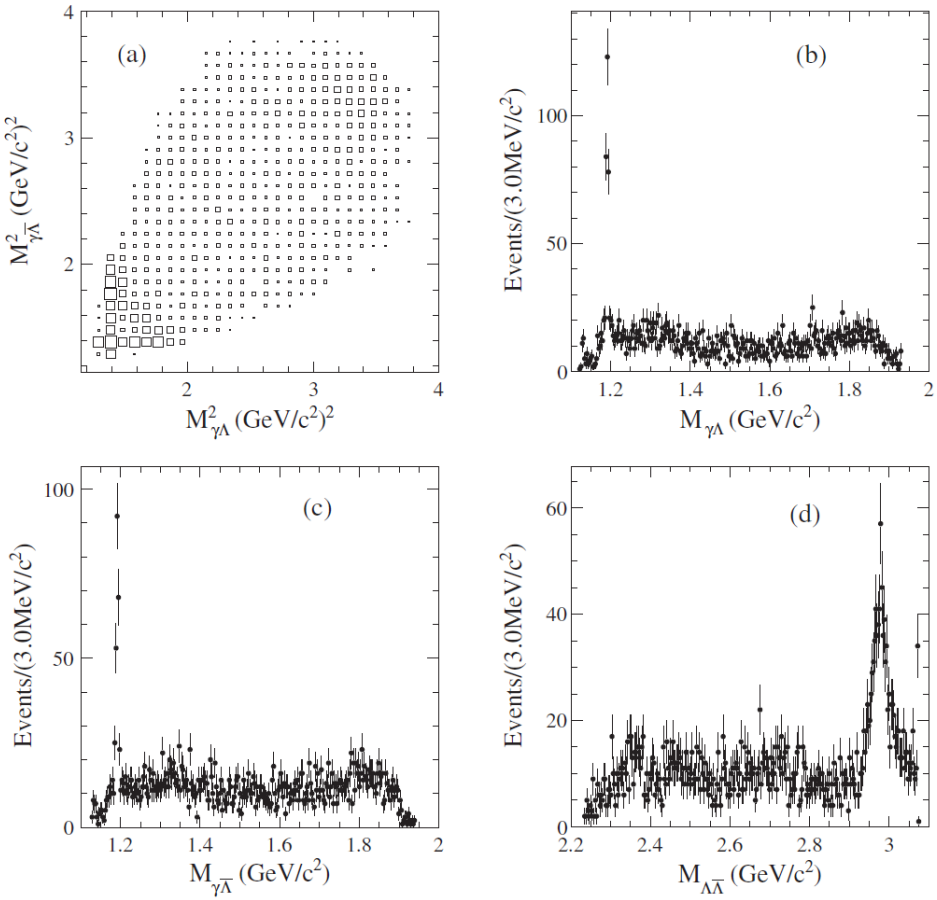
$J/\psi \to \pi^0\bar{p}p$ @BES2

Recent results @ BES3

- Observation of the isospin violating decay $J/\psi \to \Lambda\bar{\Sigma}^0 + c.c.$
- Measurements of $\chi_{cJ} \to p\bar{n}\pi^- \; and \; p\bar{n}\pi^-\pi^0$
- Measurements of $\psi' \to \bar{p}K\Sigma^0$ and $\chi_{cJ} \to \bar{p}K\Lambda$
- PWA of $\psi' \to \pi^0 p\bar{p}$
- PWA of $\psi' \to \eta p\bar{p}$

Using 2009 data sets

Observation of the isospin violating decay $J/\psi \to \Lambda\bar{\Sigma}^0 + c.c.$



PR D 86, 032008 (2012)

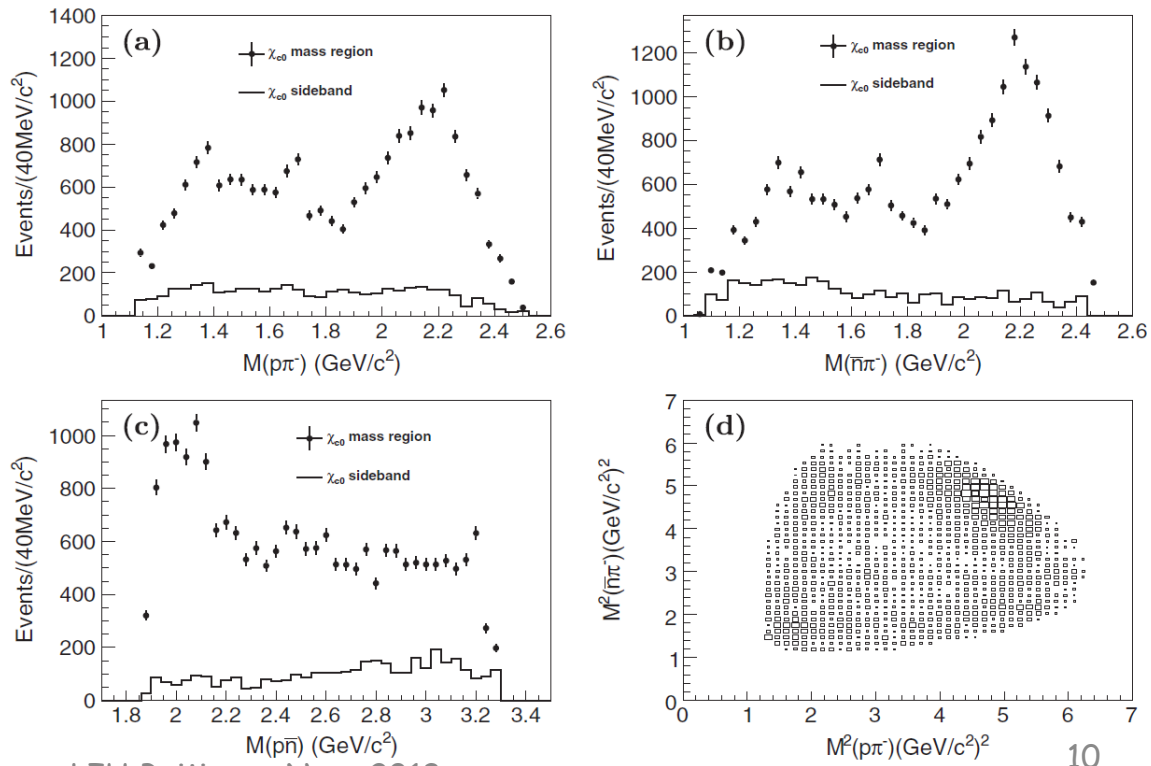
J/ψ decay mode	BESIII	PDG
$\bar{\Lambda}\Sigma^0$	$1.46 \pm 0.11 \pm 0.12$	<7.5
$\Lambda\bar{\Sigma}^0$	$1.37 \pm 0.12 \pm 0.11$	<7.5
$\gamma\eta_c(\eta_c \to \Lambda\bar{\Lambda})$	$1.98 \pm 0.21 \pm 0.32$	$\cdots$
$\Lambda\bar{\Lambda}(1520)$ + c.c.$(\bar{\Lambda}(1520) \to \gamma\bar{\Lambda})$	<0.41	$\cdots$

$\chi_{cJ} \to p\bar{n}\pi^- \; and \; p\bar{n}\pi^-\pi^0$

PR D 86, 052011 (2012)

	χ_{c0}	χ_{c1}	χ_{c2}
$\mathcal{B}(\chi_{cJ} \to p\bar{n}\pi^-)$ (10^{-3})	$1.30 \pm 0.03 \pm 0.12$	$0.40 \pm 0.02 \pm 0.05$	$0.91 \pm 0.02 \pm 0.10$
$\mathcal{B}(\chi_{cJ} \to \bar{p}n\pi^+)$ (10^{-3})	$1.38 \pm 0.03 \pm 0.12$	$0.41 \pm 0.02 \pm 0.04$	$0.98 \pm 0.02 \pm 0.09$
$\mathcal{B}(\chi_{cJ} \to p\bar{n}\pi^-\pi^0)$ (10^{-3})	$2.36 \pm 0.08 \pm 0.20$	$1.08 \pm 0.05 \pm 0.12$	$2.38 \pm 0.07 \pm 0.20$
$\mathcal{B}(\chi_{cJ} \to \bar{p}n\pi^+\pi^0)$ (10^{-3})	$2.23 \pm 0.08 \pm 0.18$	$1.06 \pm 0.05 \pm 0.11$	$2.30 \pm 0.07 \pm 0.20$
$\mathcal{B}(\chi_{cJ} \to p\bar{n}\pi^-)$ (10^{-3}) (PDG [1])	1.14 ± 0.31	$\cdots$	1.10 ± 0.40

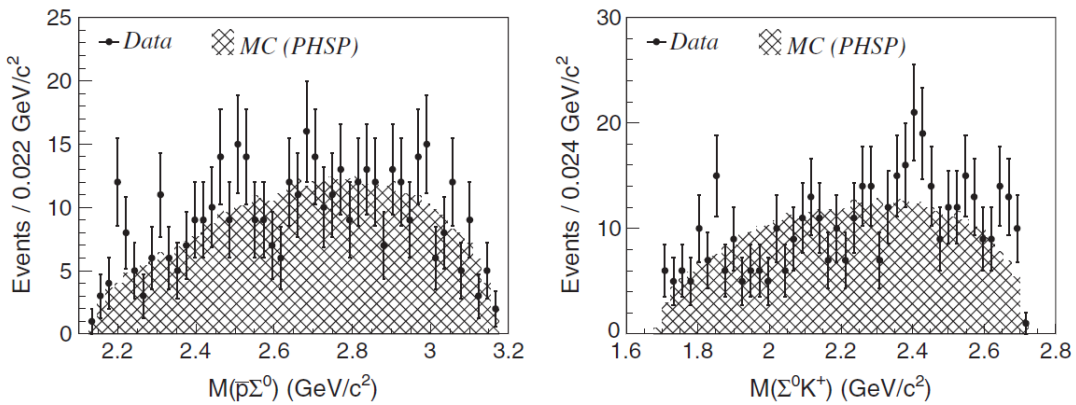
Substructures of $\chi_{c0} \to p\bar{n}\pi^-$



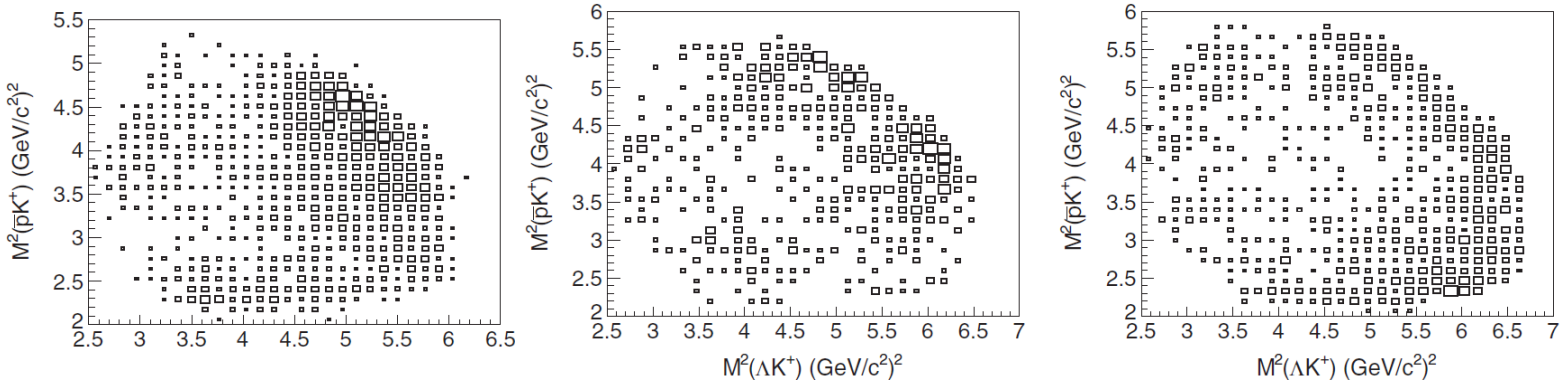
similar threshold enhancements: a $p\bar{p}$ threshold enhancement in B meson decays, ψ' decays, and in the shape of the timelike electromagnetic form factor of the proton measured at BABAR.

$\psi' \to \bar{p}K\Sigma^0, \Sigma^0 \to \gamma\Lambda$

PR D 87, 012007 (2013)



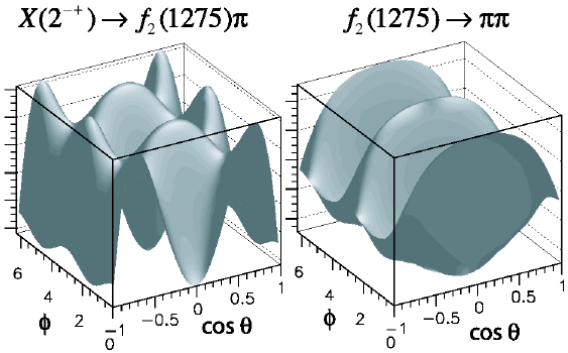
$\psi' \to \gamma\chi_{cJ}, \chi_{cJ} \to \bar{p}K\Lambda$



χ_{c0} χ_{c1} χ_{c2}

Channel	$\psi' \to \bar{p}K^+\Sigma^0$ + c.c.	$\chi_{c0} \to \bar{p}K^+\Lambda$ + c.c.	$\chi_{c1} \to \bar{p}K^+\Lambda$ + c.c.	$\chi_{c2} \to \bar{p}K^+\Lambda$ + c.c.
$\mathcal{B}$(BESIII)	$(1.67 \pm 0.13 \pm 0.12) \times 10^{-5}$	$(13.2 \pm 0.3 \pm 1.0) \times 10^{-4}$	$(4.5 \pm 0.2 \pm 0.4) \times 10^{-4}$	$(8.4 \pm 0.3 \pm 0.6) \times 10^{-4}$
PDG		$(10.2 \pm 1.9) \times 10^{-4}$	$(3.2 \pm 1.0) \times 10^{-4}$	$(9.1 \pm 1.8) \times 10^{-4}$

Partial wave analysis



Tasks:

- **Map out the resonances**
- **Systematic determination of resonance properties:**
  spin-parity,
  resonance parameters,
  production properties,
  decay properties, …
  - resonances tend to be broad and plentiful, leading to intricate interference patterns, or buried under a background in the same and in other waves.

Event-wise ML fit to all observables simultaneously

dynamic angular

$$\omega(\xi) \equiv \frac{d\sigma}{d\Phi} = \left| \sum_i c_i R_i B(p,q) Z(L) \right|^2$$

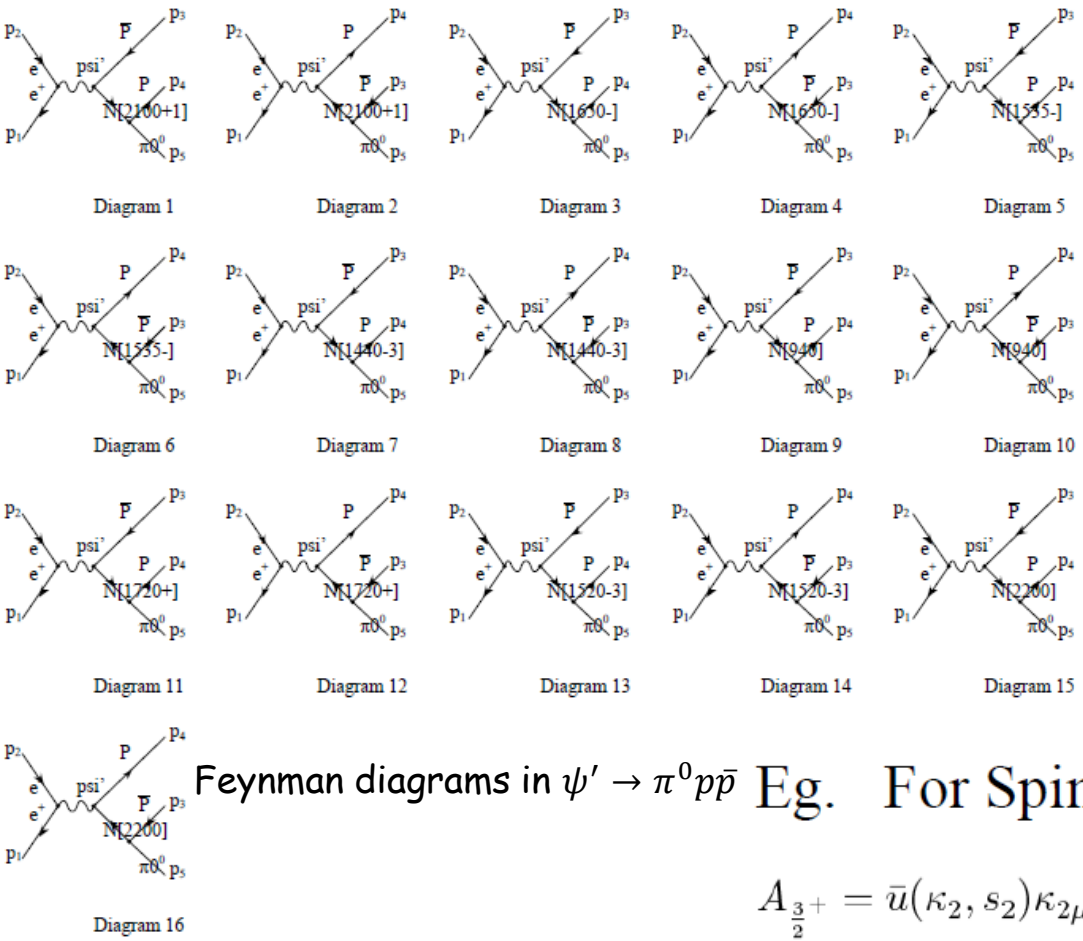
Event-wise efficiency correction

$$P(\xi) = \frac{\omega(\xi)\epsilon(\xi)}{\int \omega(\xi)\epsilon(\xi)}$$

Tools: PWA

- ✓ **Decompose to partial wave amplitudes**
- ✓ **Make full use of data**
- ✓ **Handle the interference**
- ✓ **Extract resonance properties with high sensitivity and accuracy**

Feynman Diagram Calculation toolkit : automatic generate partial wave amplitudes



Feynman diagrams in $\psi' \to \pi^0 p\bar{p}$

The amplitude constructed using the effective Lagrangian approach with the Rarita-Schwinger formalism can be written out by Feynman rules for tree diagrams (the spin wave functions for particles, the propagators, and the effective vertex couplings).

Eg. For Spin = 3/2

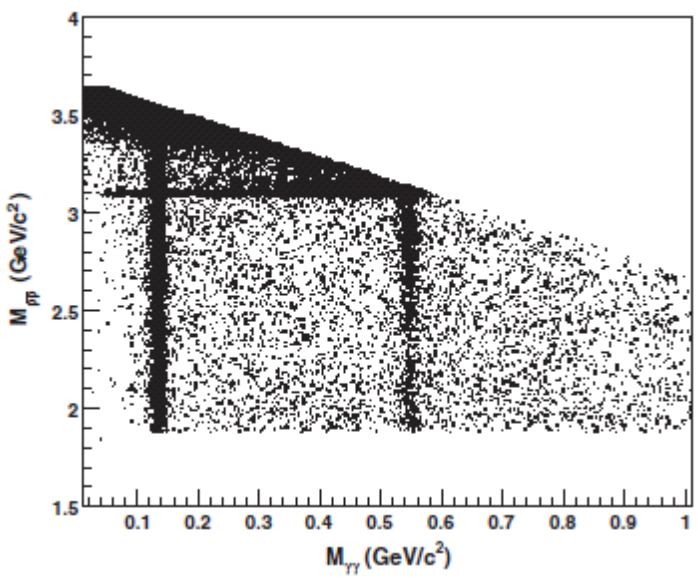
$$A_{\frac{3}{2}^+} = \bar{u}(\kappa_2, s_2)\kappa_{2\mu} P^{\mu\nu}_{3/2}(c_1 g_{\nu\lambda} + c_2\kappa_{1\nu}\gamma_\lambda + c_3\kappa_{1\nu}\kappa_{1\lambda})\gamma_5 v(\kappa_1, s_1)\psi^\lambda$$

$$P^{\mu\nu}_{3/2+} = \frac{\gamma\cdot p + M_{N^*}}{M^2_{N^*} - p^2 + iM_{N^*}\Gamma_{N^*}}[g^{\mu\nu} - \frac{1}{3}\gamma^\mu\gamma^\nu - \frac{2p^\mu p^\nu}{3M^2_{N^*}} + \frac{p^\mu\gamma^\nu - p^\nu\gamma^\mu}{3M_{N^*}}]$$

FDC Project by J.X Wang, Nucl.Instrum.Meth. A534 (2004) 241

$\psi' \to \pi^0 p\bar{p}, \eta p\bar{p}$

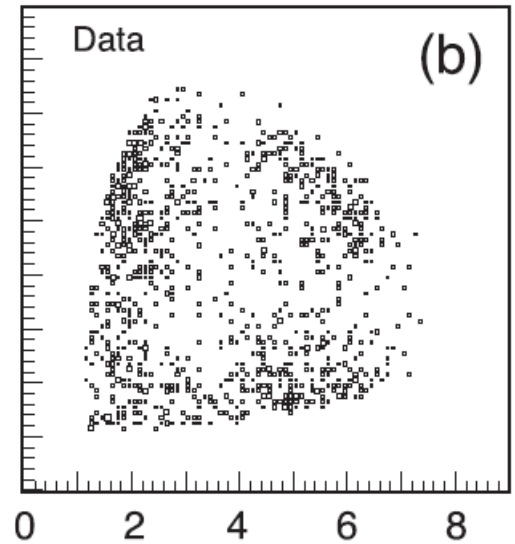
Scatter plots of $p\bar{p}$ invariant mass versus $\gamma\gamma$ invariant mass



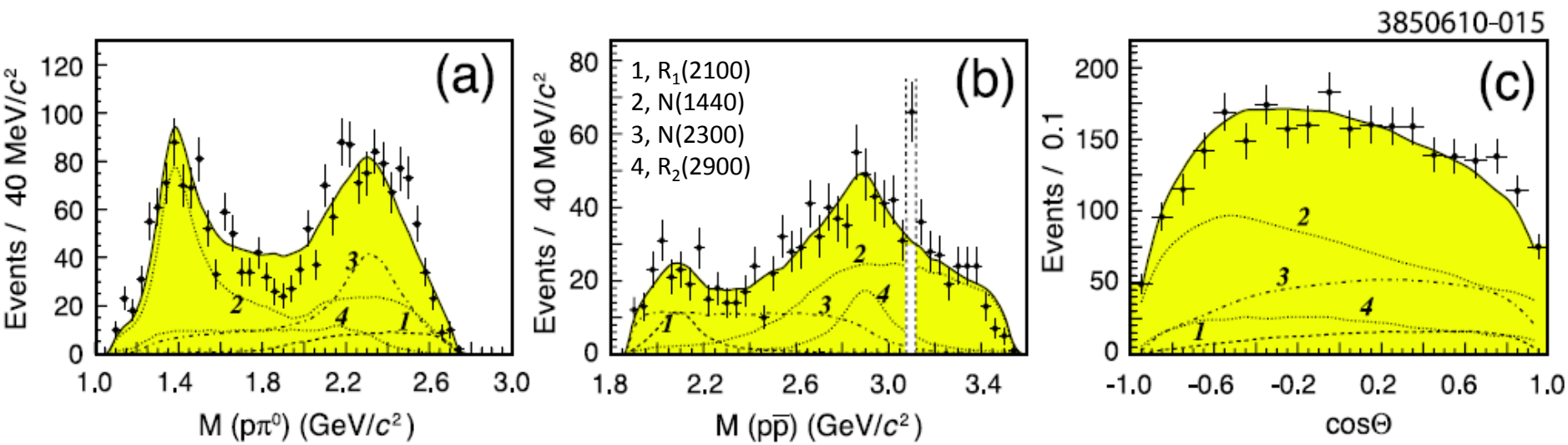
Two vertical bands: $\psi' \to \pi^0 p\bar{p}\,, \eta p\bar{p}$
Horizontal band: : $\psi' \to X + J/\psi\,, J/\psi \to p\bar{p}$

$\psi' \to \pi^0 p\bar{p}$

CLEO-c: PRD 82 092002 (2010)

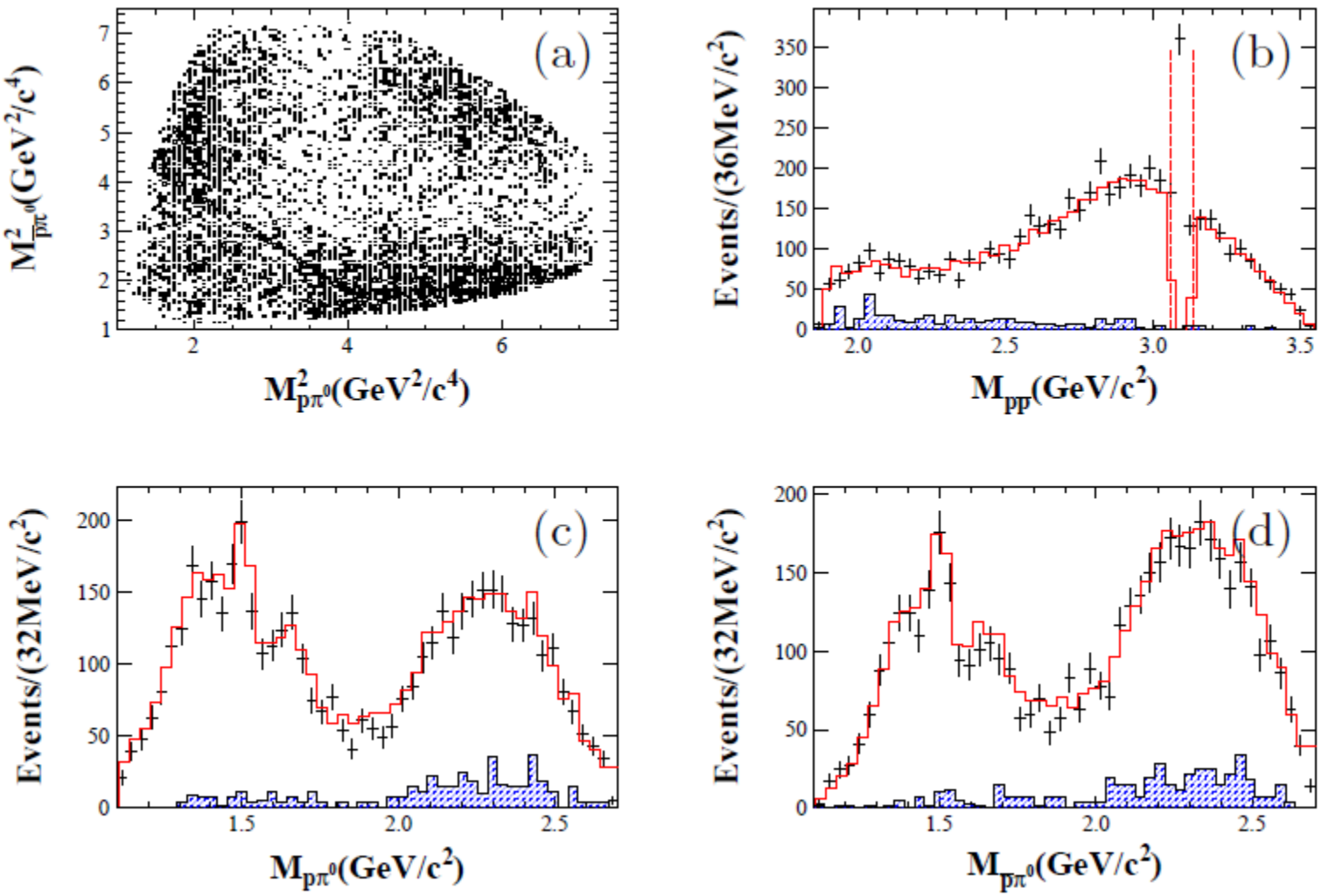


Interference is NOT considered



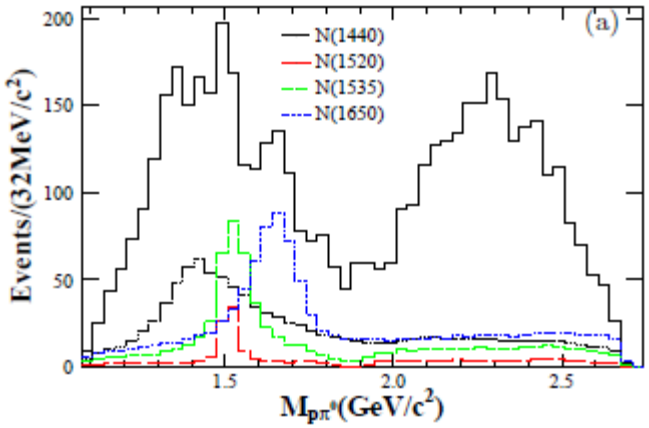
PWA of $\psi' \to \pi^0 p\bar{p}$

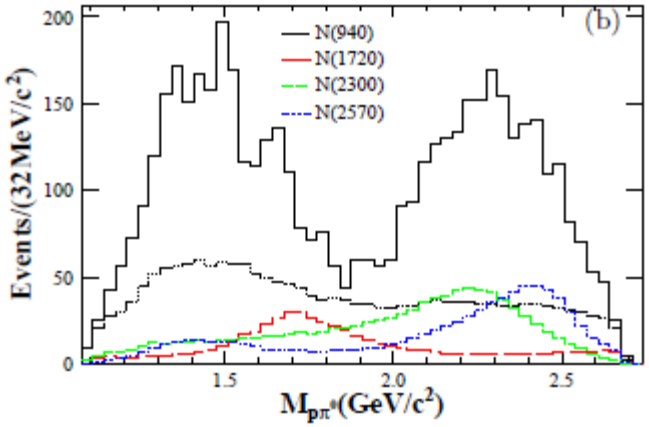
Phys.Rev.Lett. 110 (2013) 022001



PWA of $\psi' \to \pi^0 p\bar{p}$

Phys.Rev.Lett. 110 (2013) 022001



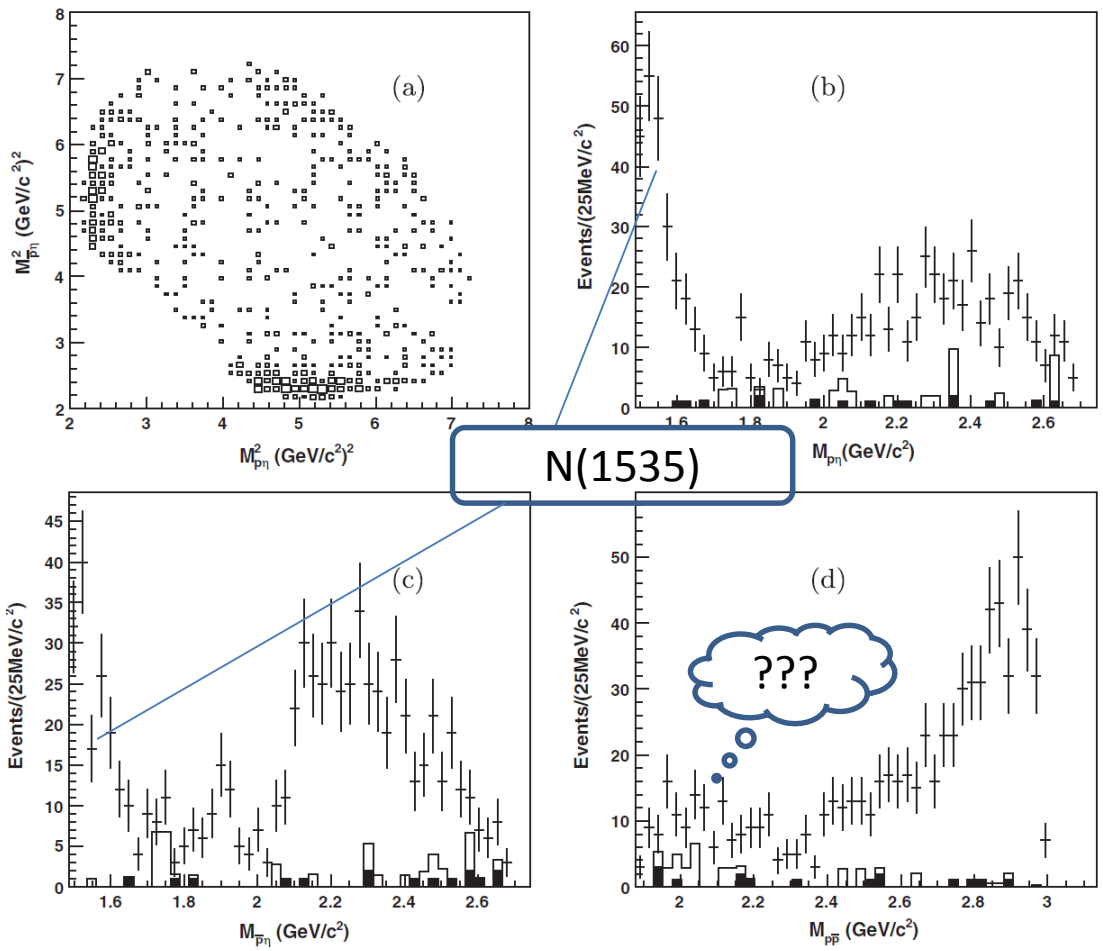


Resonance	$M(\mathrm{MeV}/c^2)$	$\Gamma(\mathrm{MeV}/c^2)$	ΔS	ΔN_{dof}	Sig.
$N(1440)$	1390^{+11+21}_{-21-30}	$340^{+46+70}_{-40-156}$	72.5	4	11.5σ
$N(1520)$	1510^{+3+11}_{-7-9}	115^{+20+0}_{-15-40}	19.8	6	5.0σ
$N(1535)$	1535^{+9+15}_{-8-22}	120^{+20+0}_{-20-42}	49.4	4	9.3σ
$N(1650)$	1650^{+5+11}_{-5-30}	150^{+21+14}_{-22-50}	82.1	4	12.2σ
$N(1720)$	1700^{+30+32}_{-28-35}	$450^{+109+149}_{-94-44}$	55.6	6	9.6σ
$N(2300)$	$2300^{+40+109}_{-30-0}$	$340^{+30+110}_{-30-58}$	120.7	4	15.0σ
$N(2570)$	2570^{+19+34}_{-10-10}	250^{+14+69}_{-24-21}	78.9	6	11.7σ

2 New N* are found
(1/2+, 5/2-)

PWA of $\psi' \to \eta p \bar{p}$

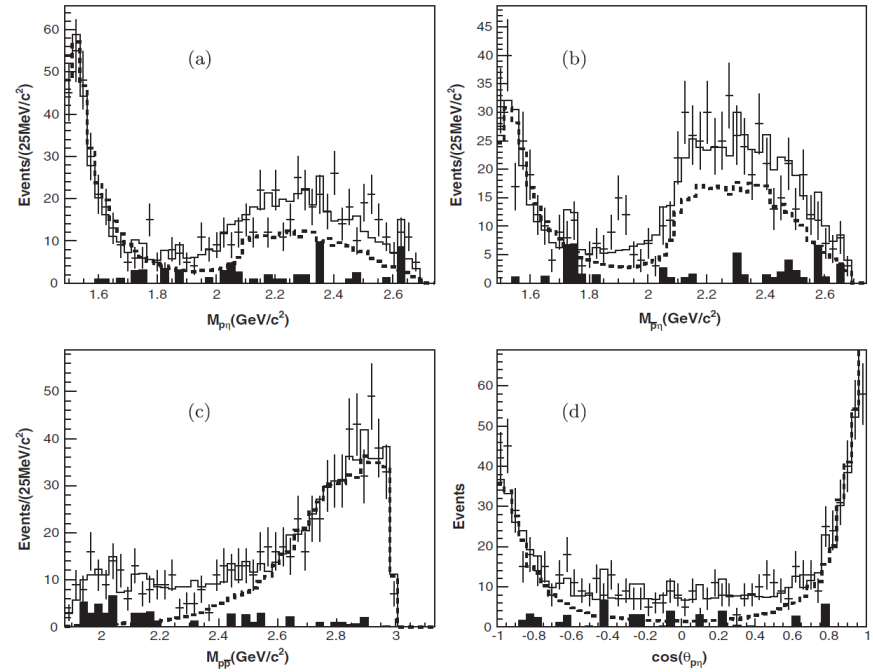
PR D 88, 032010 (2013)



PWA of $\psi' \to \eta p \bar{p}$

PR D 88, 032010 (2013)

- N(1535) and PHSP(1/2-) are dominant
- No evidence for a ppbar resonance



Mass and width of N(1535)

- $M = 1524 \pm 5^{+10}_{-4}$ MeV/c^2
- $\Gamma = 130^{+27+57}_{-24-10}$ MeV/c^2

PDG value:

- $M = 1525$ to 1545 MeV/c^2
- $\Gamma = 125$ to 175 MeV/c^2

Branching fraction:

- $B(\psi' \to N(1535)\bar{p}) \times B(N(1535) \to p\eta) + c.c. = (5.2 \pm 0.3^{+3.2}_{-1.2} \times 10^{-5})$

* For N(1535)

$$\mathrm{BW}(s) = \frac{1}{M_{N^*}^2 - s - iM_{N^*}\Gamma_{N^*}(s)}$$

$$\Gamma_{N^*}(s) = \Gamma^0_{N^*}\left(0.5\frac{\rho_{N\pi}(s)}{\rho_{N\pi}(M^2_{N^*})} + 0.5\frac{\rho_{N\eta}(s)}{\rho_{N\eta}(M^2_{N^*})}\right)$$

$$\rho_{NX}(s) = \frac{2q_{NX}(s)}{\sqrt{s}} = \frac{\sqrt{(s-(M_N+M_X)^2)(s-(M_N-M_X)^2)}}{s}$$

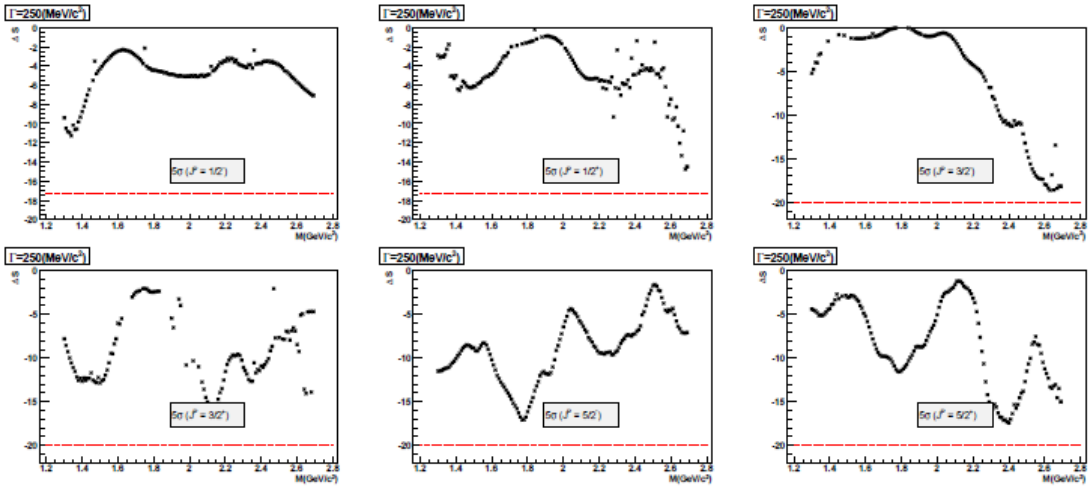
Summary and outlook

- PWA is a key tool in hadron spectroscopy
- Charmonium decays: a nice lab for N*, Σ^*, Δ^*, Λ^*, Ξ^*
- 0.5×10^8 ψ' and 1.2×10^9 J/ψ (and a lot of χ_c, η_c) @ BES3
- Many discoveries are expected.

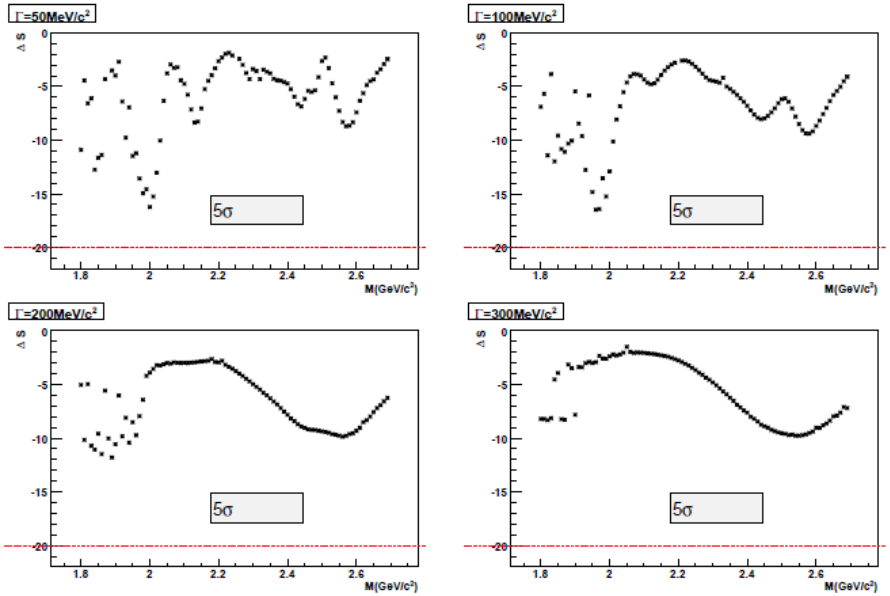
Thanks for your attention

backups

check of extra N^*



check of extra $1^-p\bar{p}$ resonance

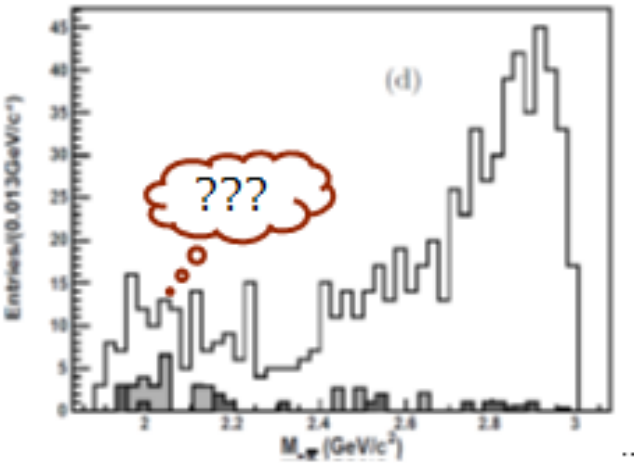


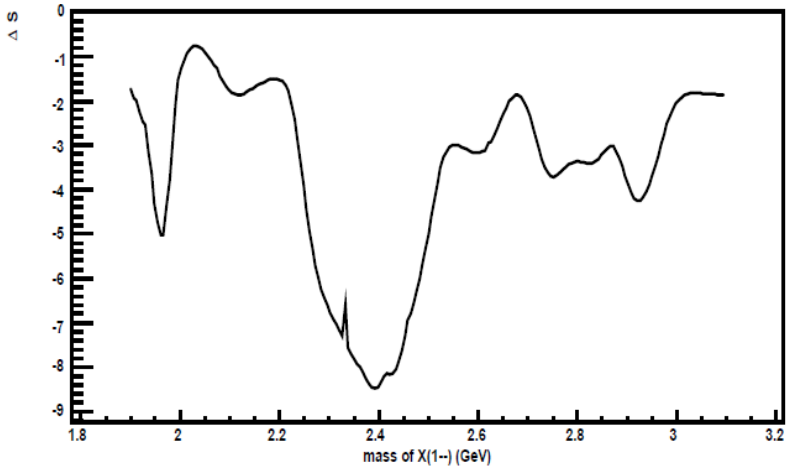
Insignificant N^*

Resonance	Mass(MeV)	Width(MeV)	J^P	C.L.
N(1675)	1675	145	$5/2^-$	2.3σ
N(1680)	1680	130	$5/2^+$	3.1σ
N(1700)	1700	100	$3/2^-$	1.0σ
N(1710)	1710	100	$1/2^+$	3.6σ
N(1885)	1885	160	$3/2^-$	1.0σ
N(1900)	1900	498	$3/2^+$	0.1σ
N(2000)	2000	300	$5/2^+$	2.4σ
N(2065)	2065	150	$3/2^+$	3.2σ
N(2080)	2080	270	$3/2^-$	0.9σ
N(2090)	2090	300	$1/2^-$	1.3σ
PHSP	10	10	$1/2^+$	0.1σ

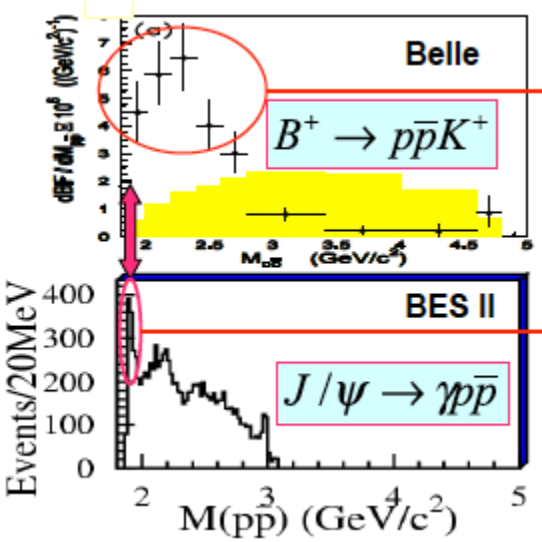
backups

N(1535) S11	**>>5σ**
PHSP S11	**>>5σ**
N(1440) P11	0.8σ
N(1520) D13	3.7σ
N(1650) S11	<0.1σ
N(1700) D13	1.7σ
N(1710) P11	2.0σ
N(1720) P13	2.5σ
N(1900) P13	3.1σ
N(2080) D13	0.6σ





backups



The structure in B decays is much wider and is **not really at threshold**. It can be explained by fragmentation mechanism.

Threshold enhancement in J/ψ decays is obviously much more narrow and just at threshold, and it cannot be explained by fragmentation mechanism.