Baryon resonance production at BESIII

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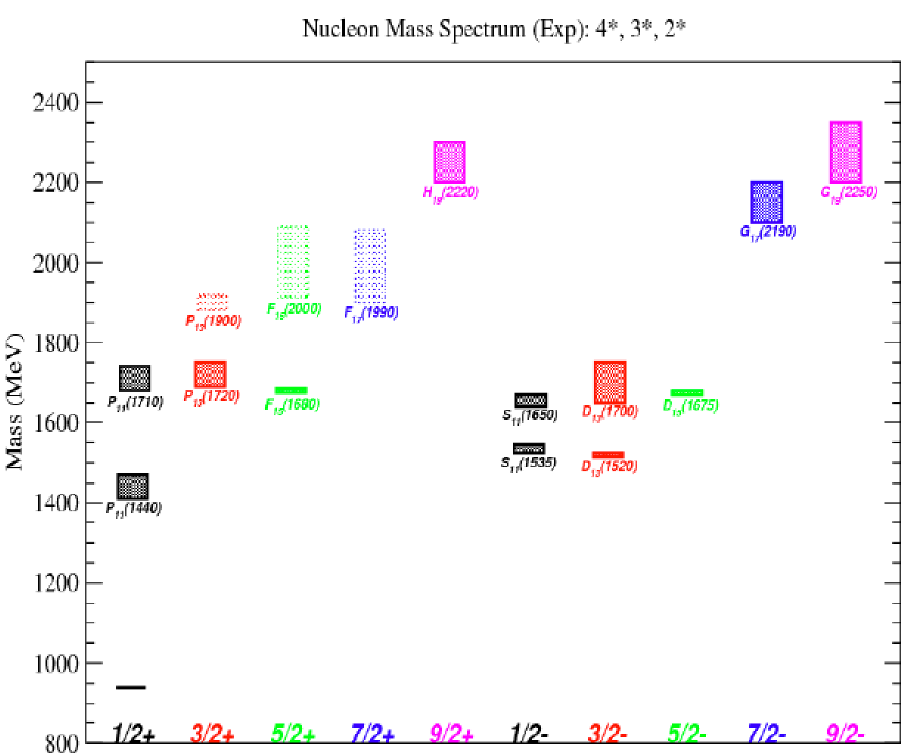
For the BESIII collaboration

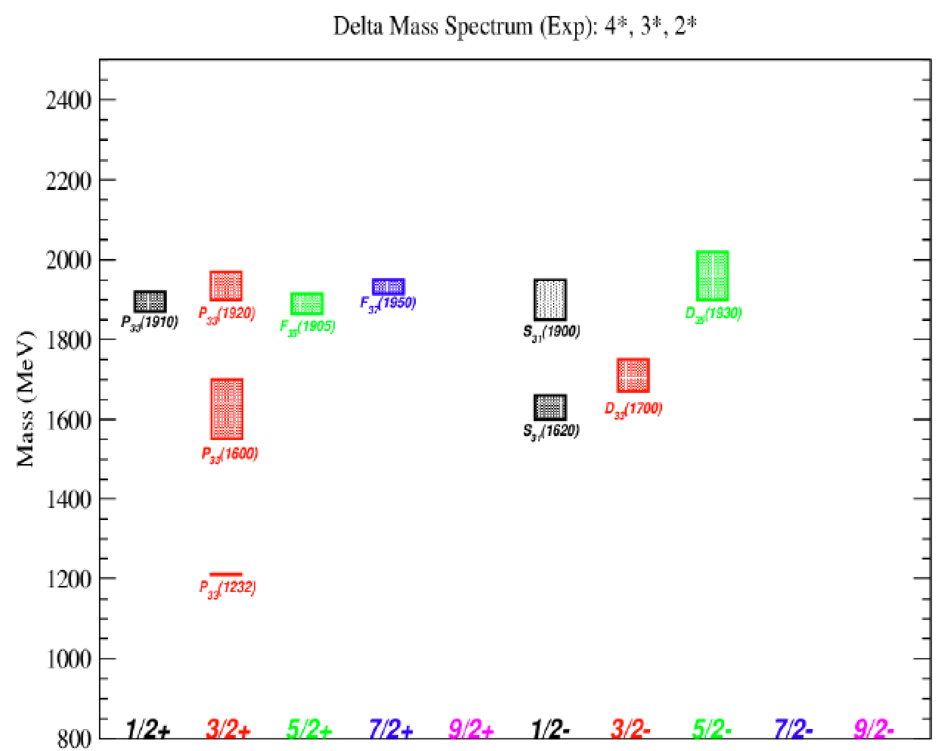
ATHOS3/PWA8 2015, GWU

Spectrum of Nucleon Resonances

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

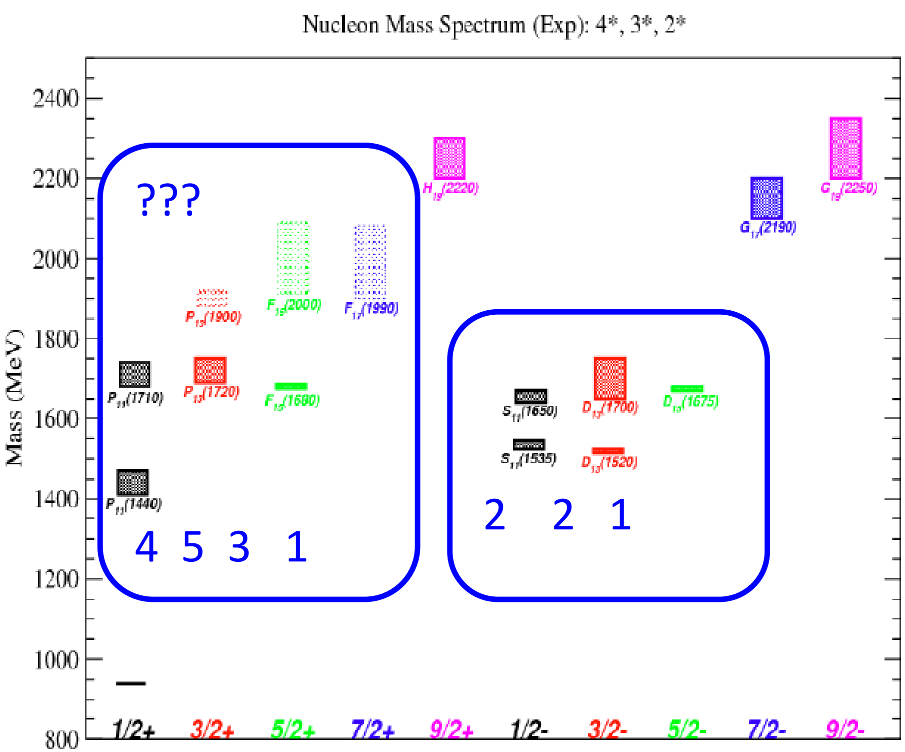
→ Particle Data Group
(Phys. Rev. D**86**, 010001 (2012))
→ Many open questions left

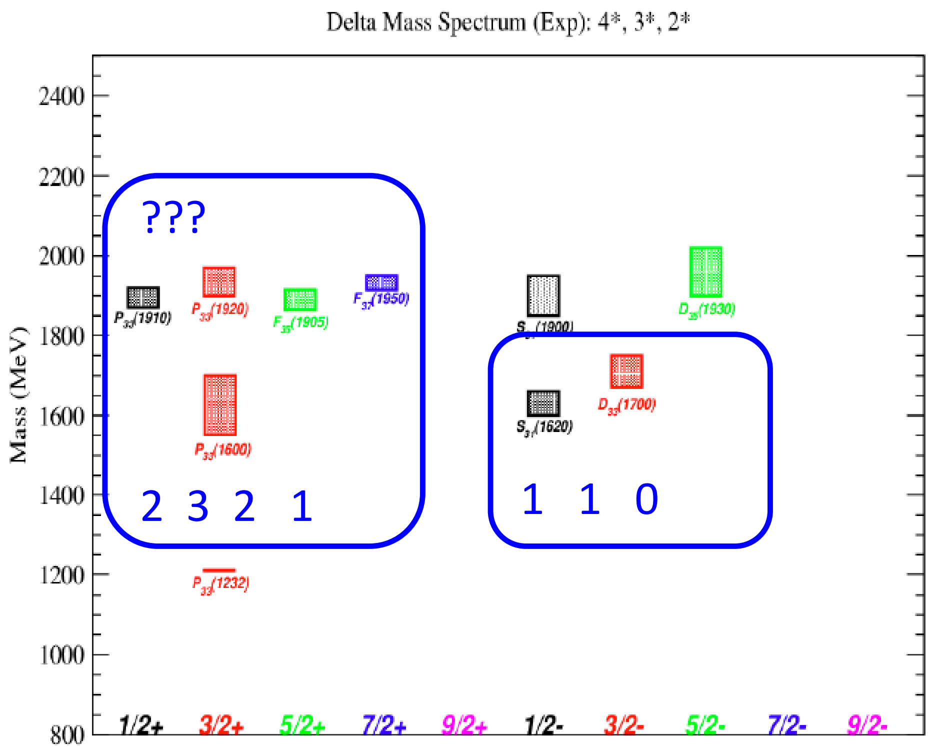




Where are the “missing” baryons?

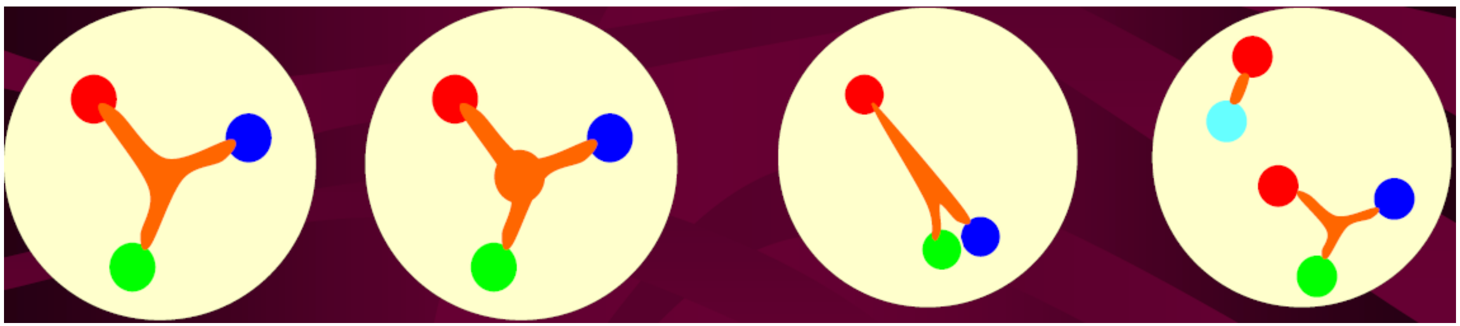
Quark models predict many more baryons than have been observed





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 …

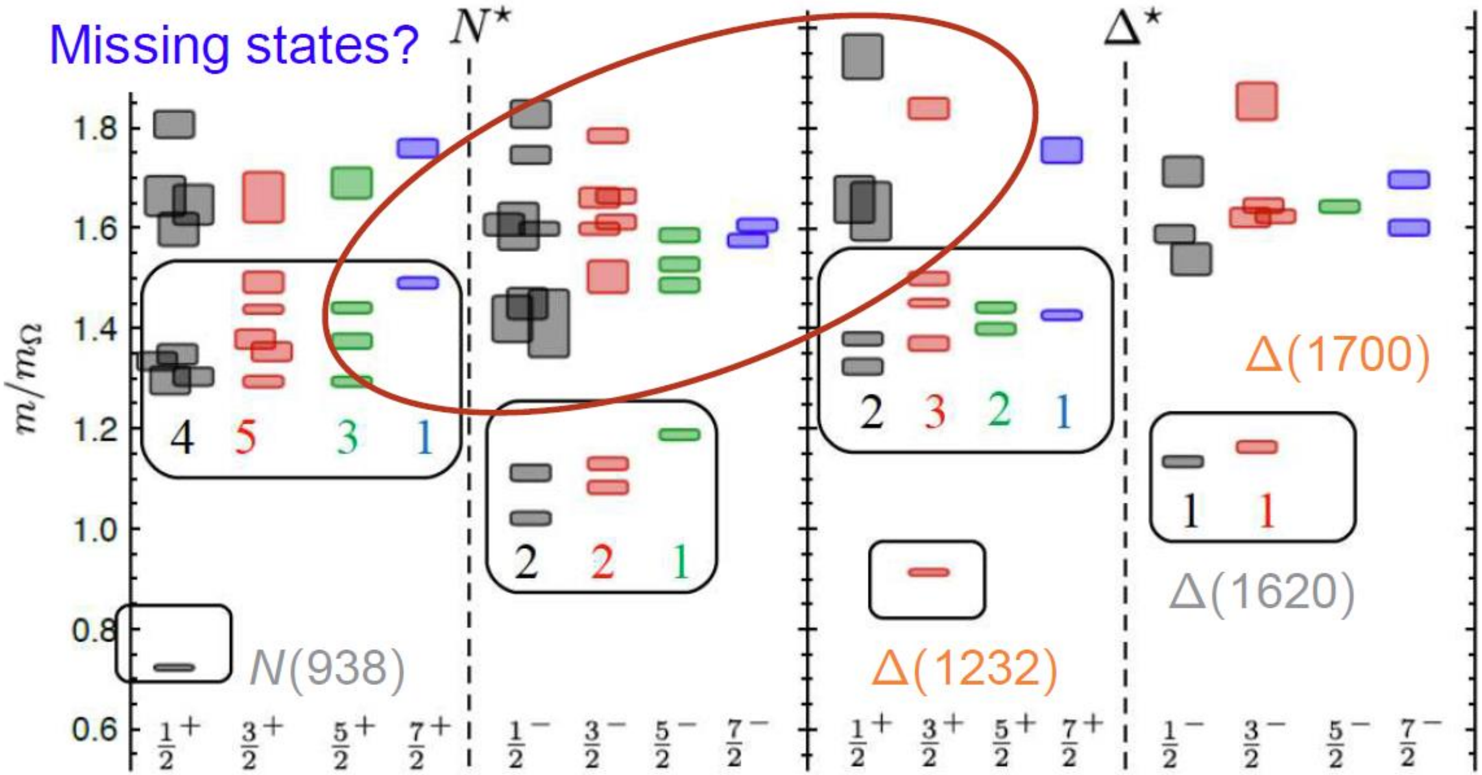
$N_{predictied}$: $N_4>N_2>N_1>N_3$, $N_{observed} << N_1$

- 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)



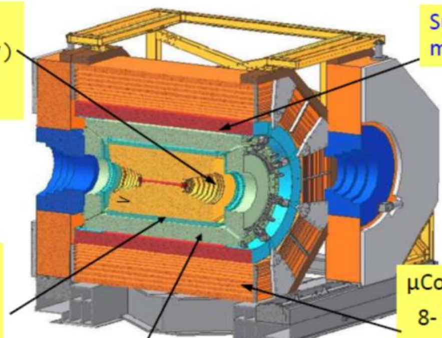
$m_\pi = 400$ MeV

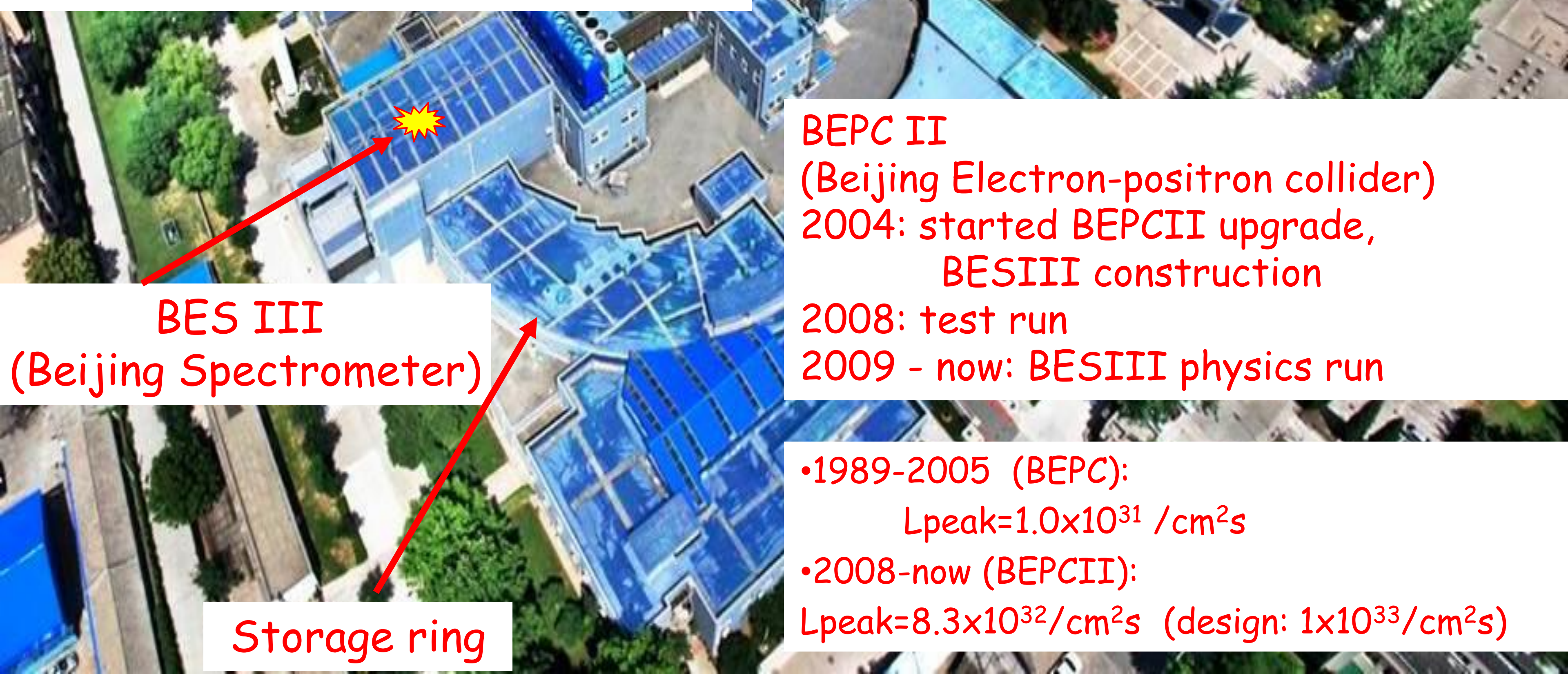
Exhibits broad features expected of $SU(6) \otimes O(3)$ symmetry

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

NIM A614, 345 (2010)

The BESIII Detector





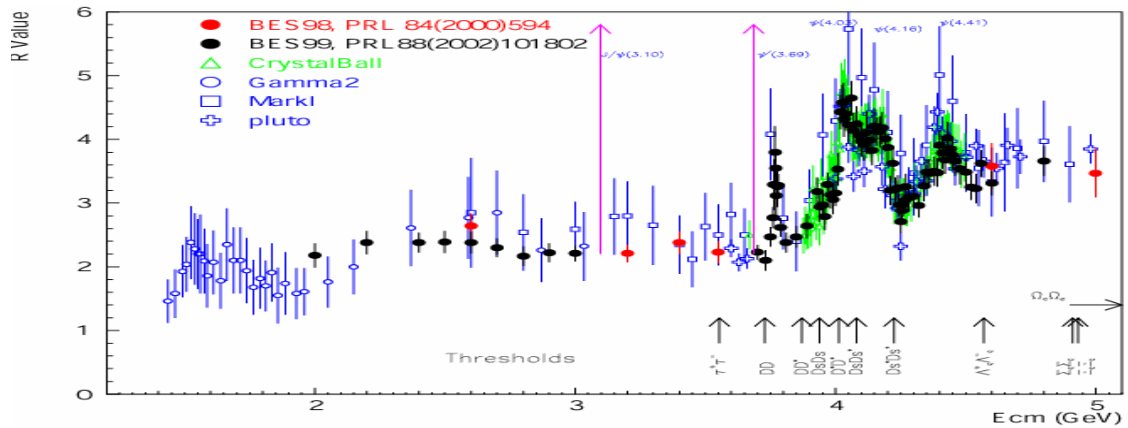
beam energy: 1.0 – 2.3 GeV

BEPC II
(Beijing Electron-positron collider)
2004: started BEPCII upgrade,
BESIII construction
2008: test run
2009 - now: BESIII physics run

- 1989-2005 (BEPC):
  Lpeak=1.0×10^{31} /cm^{2}s
- 2008-now (BEPCII):
  Lpeak=8.3×10^{32}/cm^{2}s (design: 1×10^{33}/cm^{2}s)

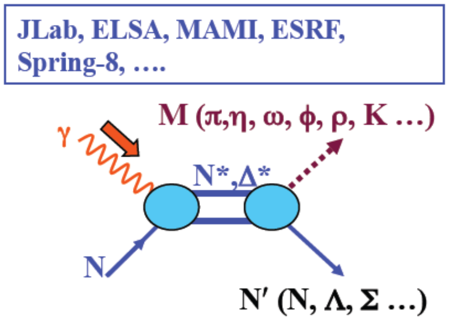
Features of the BEPC Energy Region

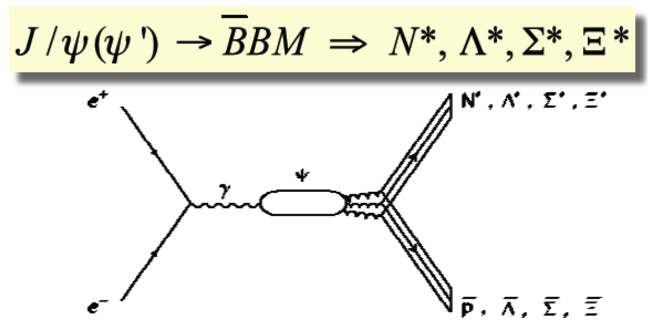
- Rich of **resonances:** charmonia and charmed mesons
- **Threshold** characteristics (pairs of τ, D, D_s, …)
- **Transition between** perturbative and non-perturbative QCD
- Energy location of the **glueonic excitations and multi-quark states**



Energy & Physics	L or N	Physics Topics
J/ψ	$1.3*10^9$	Light hadron spectroscopy
ψ'	$0.6*10^9$	Charmonium transitions; Light hadron spectroscopy
$\psi(3770)$	2.9 fb^{-1}	D decays
$\psi(4040)$	0.5 fb^{-1}	Charmonium spectroscopy
3554 MeV, τ threshold	0.024 fb^{-1}	τ mass measurement
4230 MeV - 4260 MeV, Y(4260)	1.9 fb^{-1}	Charmonium spectroscopy
4360 MeV, Y(4360)	0.5 fb^{-1}	Charmonium spectroscopy
4100 MeV – 4400 MeV	0.5 fb^{-1}	Coarse scan, Charmonium spectroscopy
3850 MeV – 4590 MeV	0.8 fb^{-1}	Fine scan, R measurement, Charmonium spectroscopy
4600 MeV	0.5 fb^{-1}	Charmonium spectroscopy
4420 MeV, $\psi(4415)$	1.0 fb^{-1}	Charmonium spectroscopy

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





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

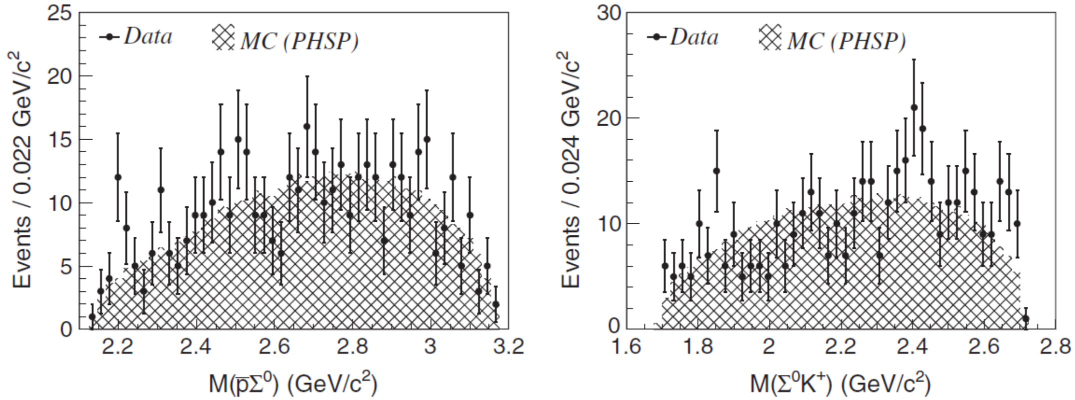
Recent results @ BESIII

- Measurements of $\psi' \to \bar{p}K^{+}\Sigma^{0}$ and $\chi_{cJ} \to \bar{p}K^{+}\Lambda$
- Measurements of $\psi' \to (\gamma)K^{-}\Lambda\bar{\Xi}^{+} + c.c.$
- Observation of $\psi' \to \Lambda\bar{\Sigma}^{\pm}\pi^{\mp} + c.c.$
- Observation of $\mathrm{J}/\psi \to a_0(980)p\bar{p}$
- PWA of $\psi' \to \pi^{0}p\bar{p}$
- PWA of $\psi' \to \eta p\bar{p}$

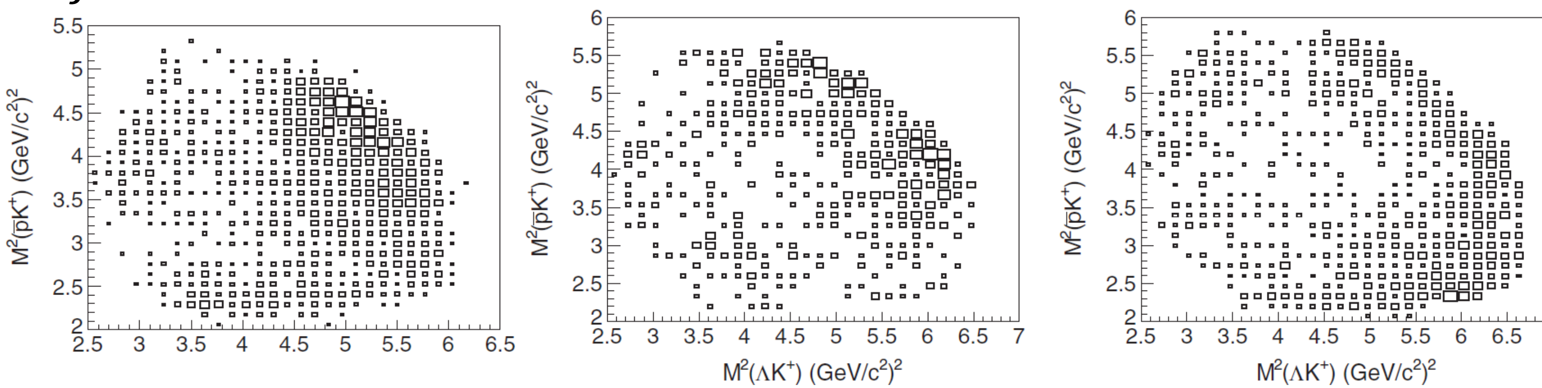
*These analyses based on 108*10^6 ψ' decays and 225*10^6 J/ψ decays.*

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

BESIII Phys.Rev. D87, 012007 (2013)



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

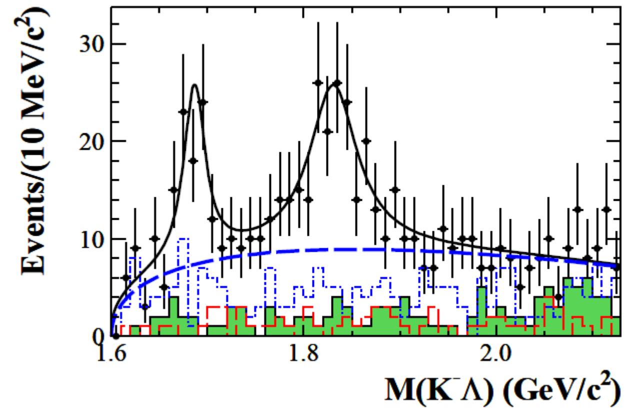


χ_{c0} χ_{c1} χ_{c2}

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		$(10.2 \pm 1.9) \times 10^{-4}$	$(3.2 \pm 1.0) \times 10^{-4}$	$(9.1 \pm 1.8) \times 10^{-4}$

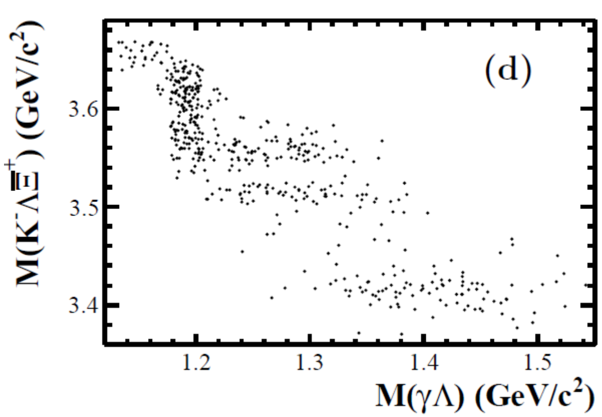
BESIII arxiv:1504.02025

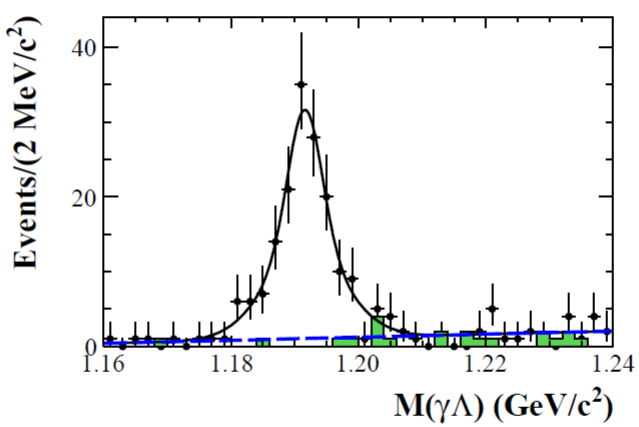
$\Xi^-(1690)$ *and* $\Xi^-(1820)$ *are* observed in $\psi' \to K^-\Lambda\bar{\Xi}^+ + c.c.$
Resonance parameters consist with PDG

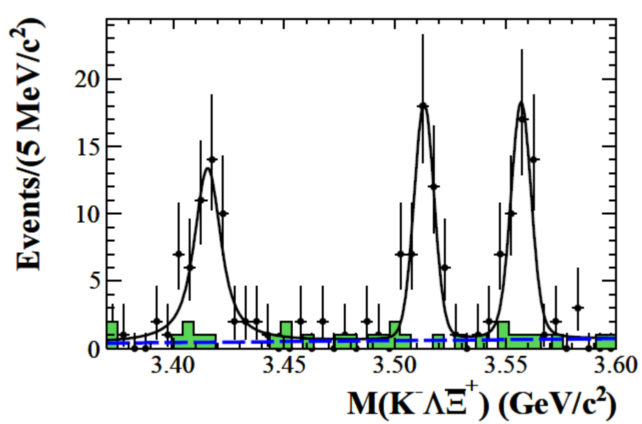


Decay	Branching fraction
$\psi(3686) \to K^-\Lambda\bar{\Xi}^+$	$(3.86 \pm 0.27 \pm 0.32) \times 10^{-5}$
$\psi(3686) \to \Xi(1690)^-\bar{\Xi}^+,\ \Xi(1690)^- \to K^-\Lambda$	$(5.21 \pm 1.48 \pm 0.57) \times 10^{-6}$
$\psi(3686) \to \Xi(1820)^-\bar{\Xi}^+,\ \Xi(1820)^- \to K^-\Lambda$	$(12.03 \pm 2.94 \pm 1.22) \times 10^{-6}$
$\psi(3686) \to K^-\Sigma^0\bar{\Xi}^+$	$(3.67 \pm 0.33 \pm 0.28) \times 10^{-5}$
$\psi(3686) \to \gamma\chi_{c0},\ \chi_{c0} \to K^-\Lambda\bar{\Xi}^+$	$(1.90 \pm 0.30 \pm 0.16) \times 10^{-5}$
$\psi(3686) \to \gamma\chi_{c1},\ \chi_{c1} \to K^-\Lambda\bar{\Xi}^+$	$(1.32 \pm 0.20 \pm 0.12) \times 10^{-5}$
$\psi(3686) \to \gamma\chi_{c2},\ \chi_{c2} \to K^-\Lambda\bar{\Xi}^+$	$(1.68 \pm 0.26 \pm 0.15) \times 10^{-5}$
$\chi_{c0} \to K^-\Lambda\bar{\Xi}^+$	$(1.96 \pm 0.31 \pm 0.16) \times 10^{-4}$
$\chi_{c1} \to K^-\Lambda\bar{\Xi}^+$	$(1.43 \pm 0.22 \pm 0.12) \times 10^{-4}$
$\chi_{c2} \to K^-\Lambda\bar{\Xi}^+$	$(1.93 \pm 0.30 \pm 0.15) \times 10^{-4}$

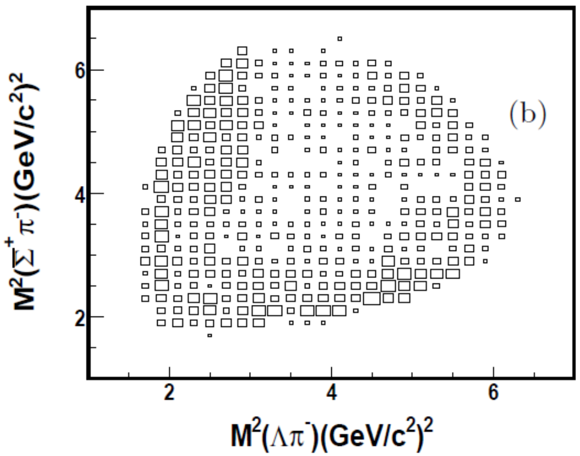
In the study of $\psi' \to \gamma K^-\Lambda\bar{\Xi}^+ + c.c.$, *the branching fraction of* $\psi' \to K^-\Sigma^0\bar{\Xi}^+ + c.c.$ and $\chi_{cJ} \to K^-\Lambda\bar{\Xi}^+ + c.c.$ *are measured*





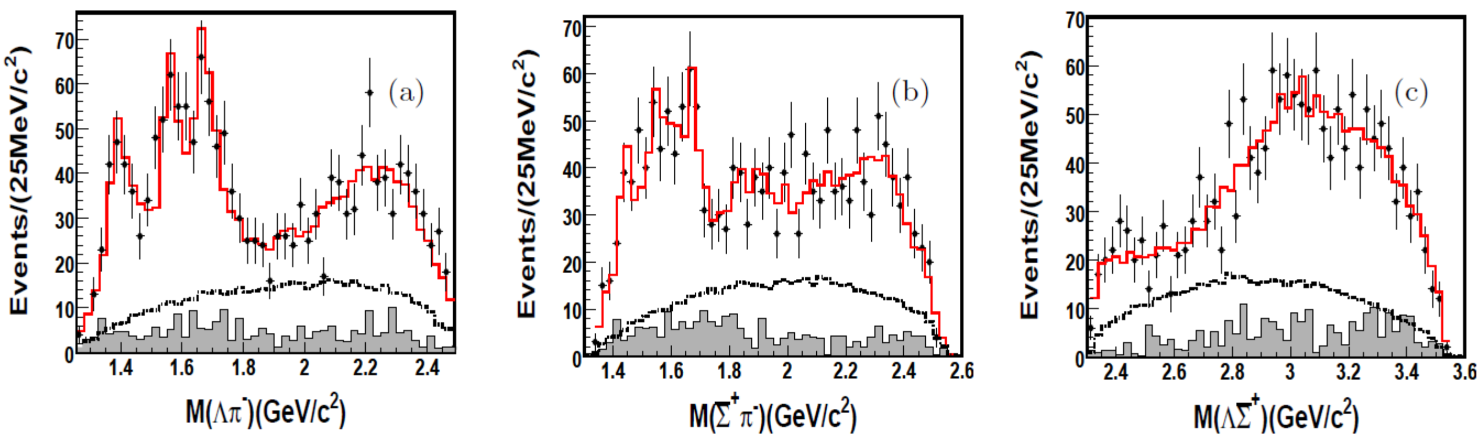


Observation of $\psi' \to \Lambda\bar{\Sigma}^{\pm}\pi^{\mp} + c.c.$



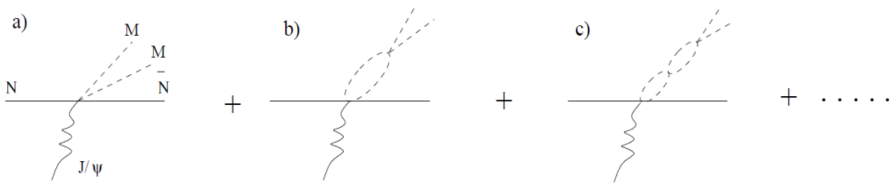
BESIII Phys.Rev. D88, 112007 (2013)

$$\mathcal{B}(\psi(3686) \to \Lambda\bar{\Sigma}^+\pi^- + c.c.) = (1.40 \pm 0.03 \pm 0.13) \times 10^{-4},$$
$$\mathcal{B}(\psi(3686) \to \Lambda\bar{\Sigma}^-\pi^+ + c.c.) = (1.54 \pm 0.04 \pm 0.13) \times 10^{-4},$$

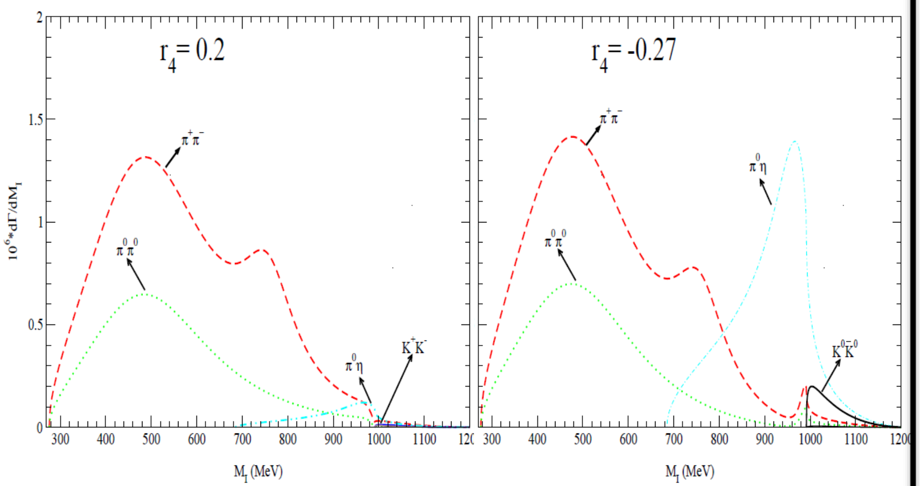


Observation of $J/\psi \to a_0(980)p\bar{p}$

A chiral unitary approach including FSI [Phys.Rev. C68 015201]

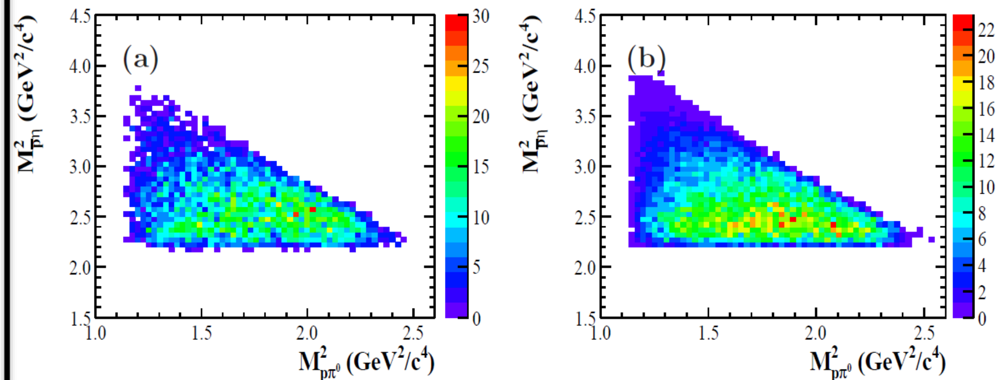


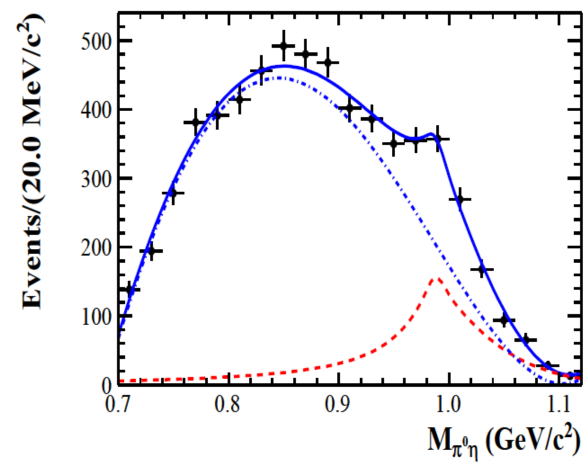
Ambiguities from fitting to $J/\psi \to p\bar{p}\pi^+\pi^-$



** r_4 is one of the coefficients in the parameterization of meson-meson amplitudes in [Phys.Rev. C68 015201].*

BESIII Phys.Rev. D90, 052009 (2014)

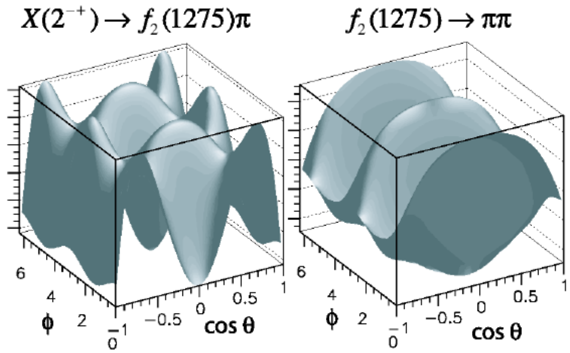




$$Br(J/\psi \to p\bar{p}a_0(980) \to p\bar{p}\pi^0\eta) = (6.8 \pm 1.2 \pm 1.3) \times 10^{-5}$$

Comparing to Br($J/\psi \to p\bar{p}\pi^+\pi^-$) in PDG, r_4=0.2 is preferable

Partial wave analysis at BESIII



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-based 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

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

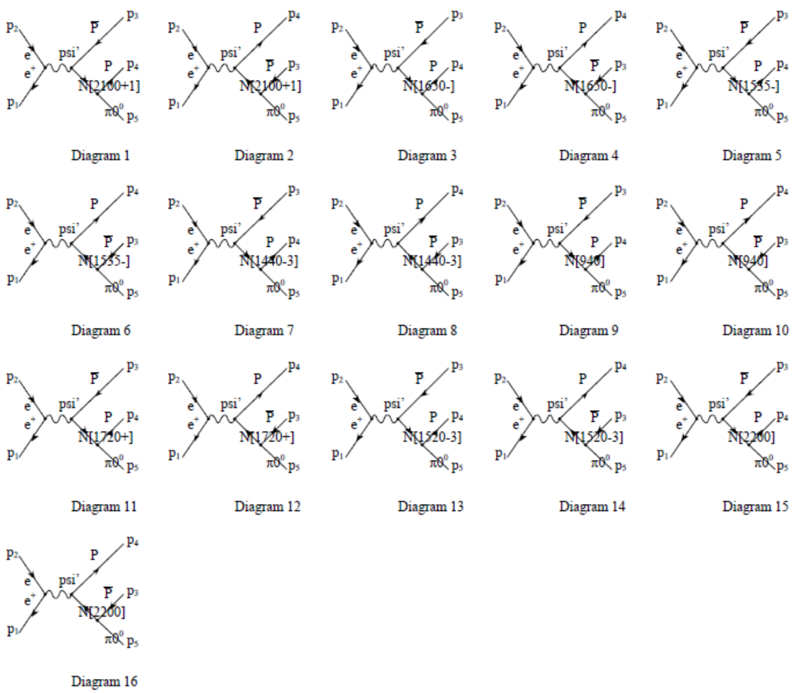
Tools: PWA

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

FDC-PWA: automatic generation of the complicated partial wave amplitudes for baryon spectroscopy

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

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



Using an effective Lagrangian approach and covariant tensors, FDC-PWA construct amplitudes with spin wave functions, propagators and effective couplings.

For example, for $J/\psi \to \bar{N}N^*(\frac{3}{2}^+) \to \bar{N}(\kappa_1, s_1)\times N(\kappa_2, s_2)\pi(\kappa_3)$, the amplitude can be constructed as

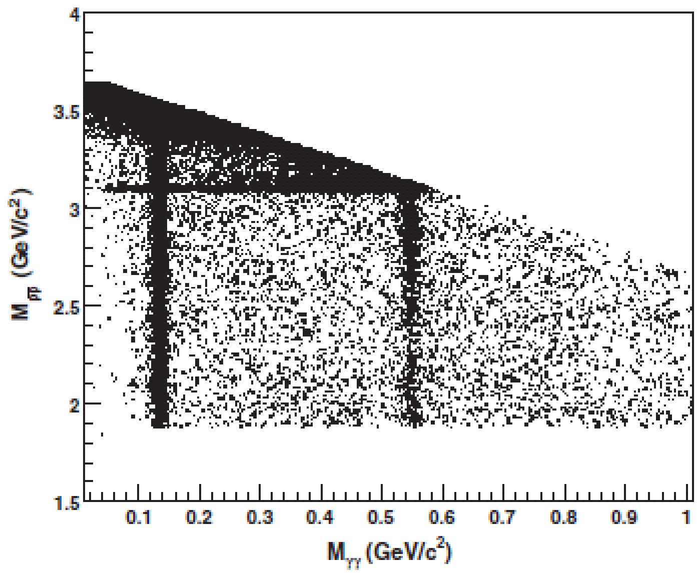
$$A_{(3/2)^+} = \bar{u}(\kappa_2, s_2)\kappa_{2\mu}P^{\mu\nu}_{3/2}(c_1 g_{\nu\lambda} + c_2\kappa_{1\nu}\gamma_\lambda + c_3\kappa_{1\nu}\kappa_{1\lambda})\gamma_5 v(\kappa_1, s_1)\psi^\lambda, \quad (4)$$

where $u(\kappa_2, s_2)$ and $v(\kappa_1, s_1)$ are $\frac{1}{2}$-spinor wave functions for N and $\bar{N}$, respectively; ψ^λ is the spin-1 wave function, i.e., the polarization vector for J/ψ. The c_1, c_2, and c_3 terms correspond to three possible couplings for the $J/\psi \to \bar{N}N^*(\frac{3}{2}^+)$ vertex. They can be taken as constant parameters or as smoothly varying vertex form factors. The spin $\frac{3}{2}^+$ propagator $P^{\mu\nu}_{3/2+}$ for $N^*(\frac{3}{2}^+)$ is

$$P^{\mu\nu}_{3/2+} = \frac{\gamma\cdot p + M_{N^*}}{M^2_{N^*} - p^2 + iM_{N^*}\Gamma_{N^*}}\left[g^{\mu\nu} - \frac{1}{3}\gamma^\mu\gamma^\nu - \frac{2p^\mu p^\nu}{3M^2_{N^*}} + \frac{p^\mu\gamma^\nu - p^\nu\gamma^\mu}{3M_{N^*}}\right], \quad (5)$$

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

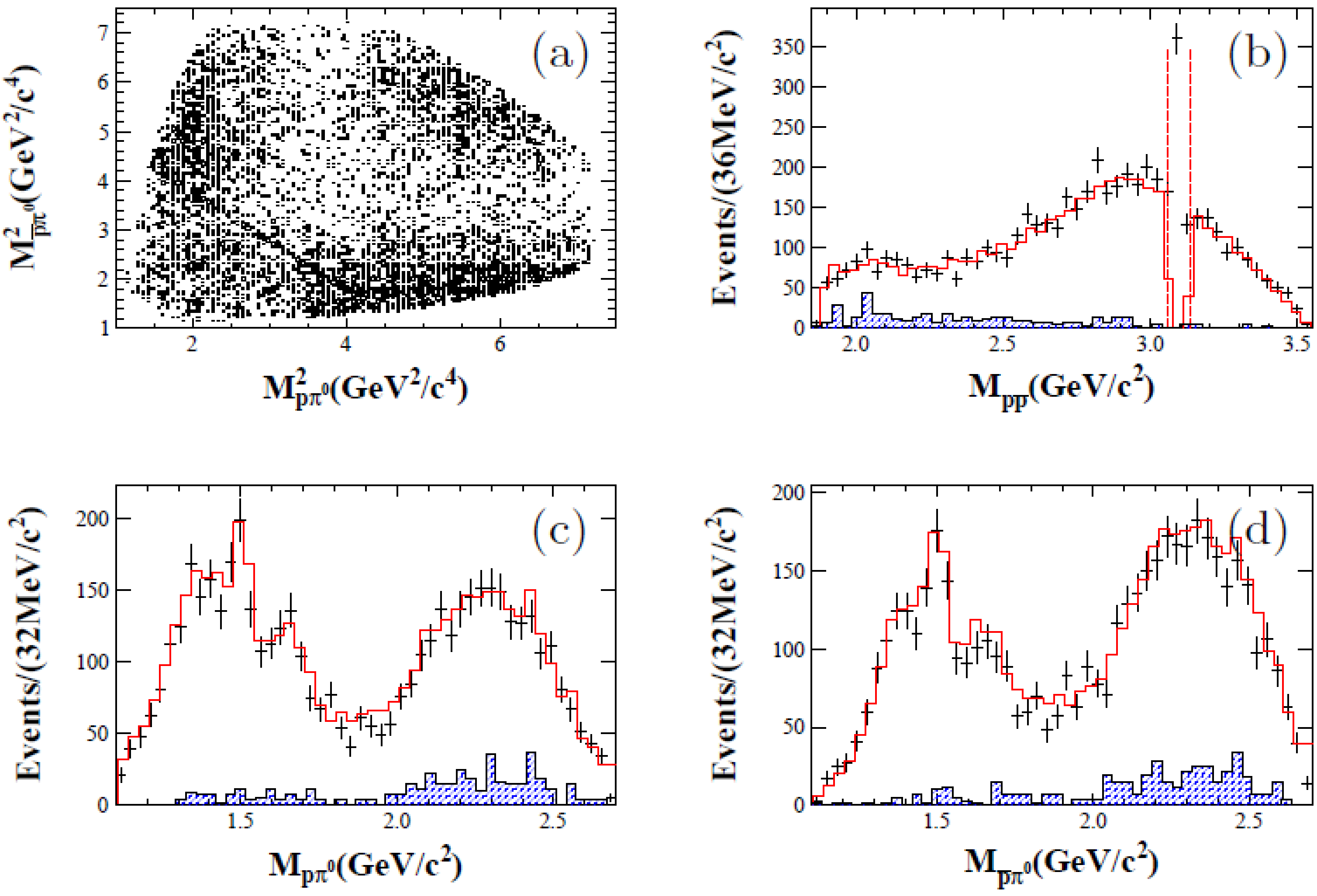
Scatter plots of $p\bar{p}$ invariant mass versus $\gamma\gamma$ invariant mass



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

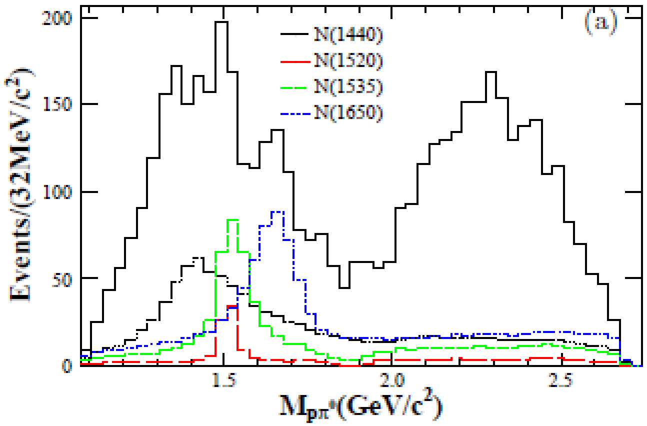
PWA of $\psi' \to \pi^0 p\bar{p}$

BESIII Phys.Rev.Lett. 110 (2013) 022001



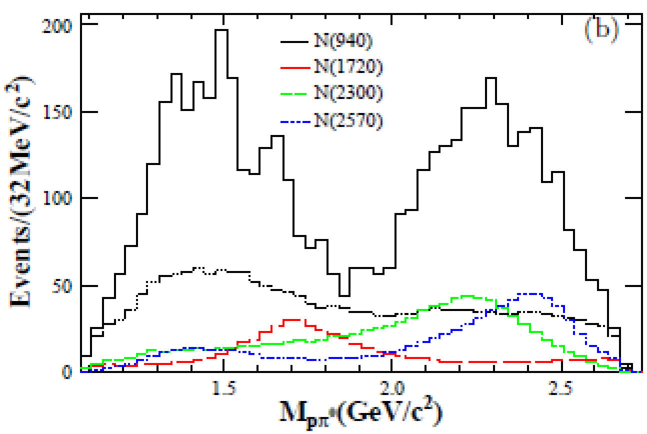
PWA of $\psi' \to \pi^0 p\bar{p}$

BESIII, Phys.Rev.Lett. 110 (2013) 022001



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

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



The energy dependent width BW for

$$\Gamma_{N(1440)} \to \Gamma_{N(1440)}(0.7\frac{B_1(q_{\pi N})\rho_{\pi N}(s)}{B_1(q_{\pi N}^{N*})\rho_{\pi N}(M_{N*}^2)} + 0.3\frac{B_1(q_{\pi\Delta})\rho_{\pi\Delta}(s)}{B_1(q_{\pi\Delta}^{N*})\rho_{\pi\Delta}(M_{N*}^2)})$$

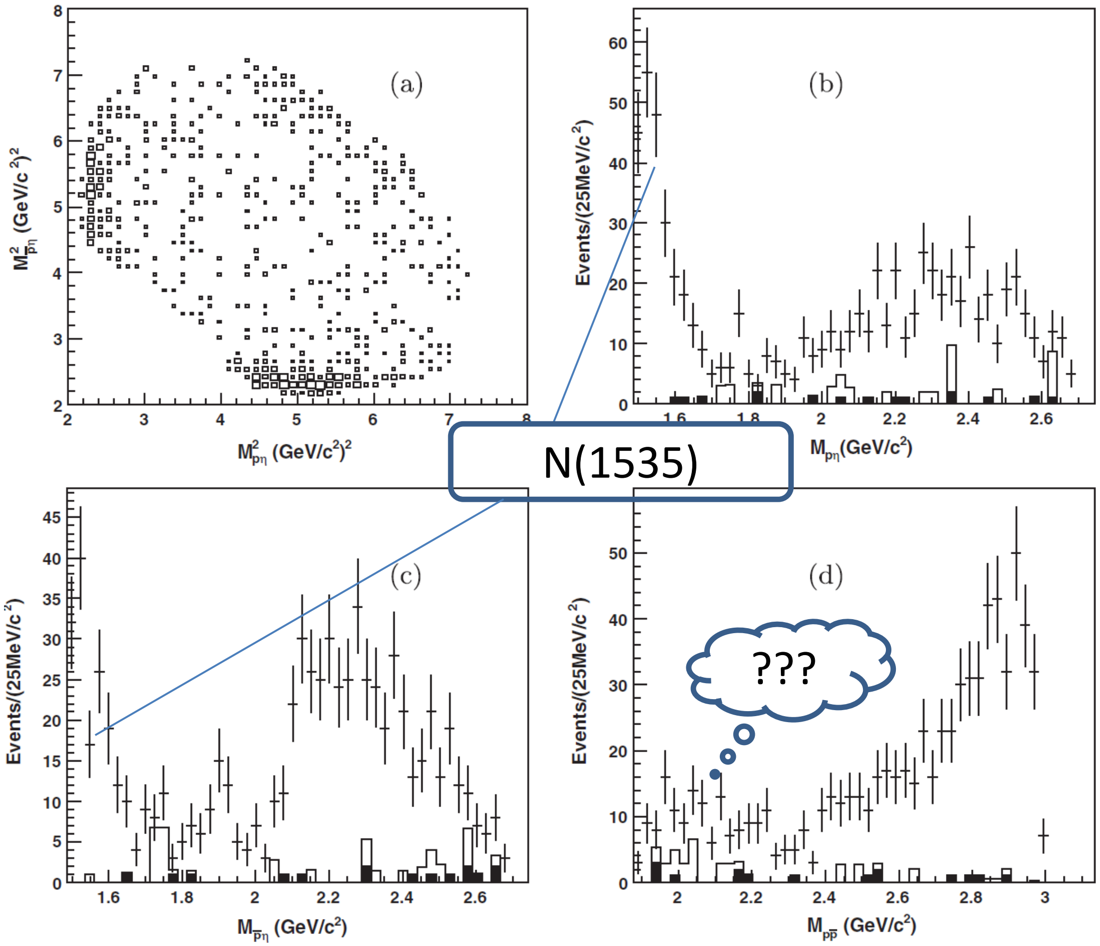
$$\Gamma_{N(1520)} \to \Gamma_{N(1520)}\frac{B_2(q_{\pi N})\rho_{\pi N}(s)}{B_2(q_{\pi N}^{N*})\rho_{\pi N}(M_{N*}^2)}$$

$$\Gamma_{N(1535)} \to \Gamma_{N(1535)}(0.5\frac{\rho_{\pi N}(s)}{\rho_{\pi N}(M_{N*}^2)} + 0.5\frac{\rho_{\eta N}(s)}{\rho_{\eta N}(M_{N*}^2)})$$

The other N* use constant width BW

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

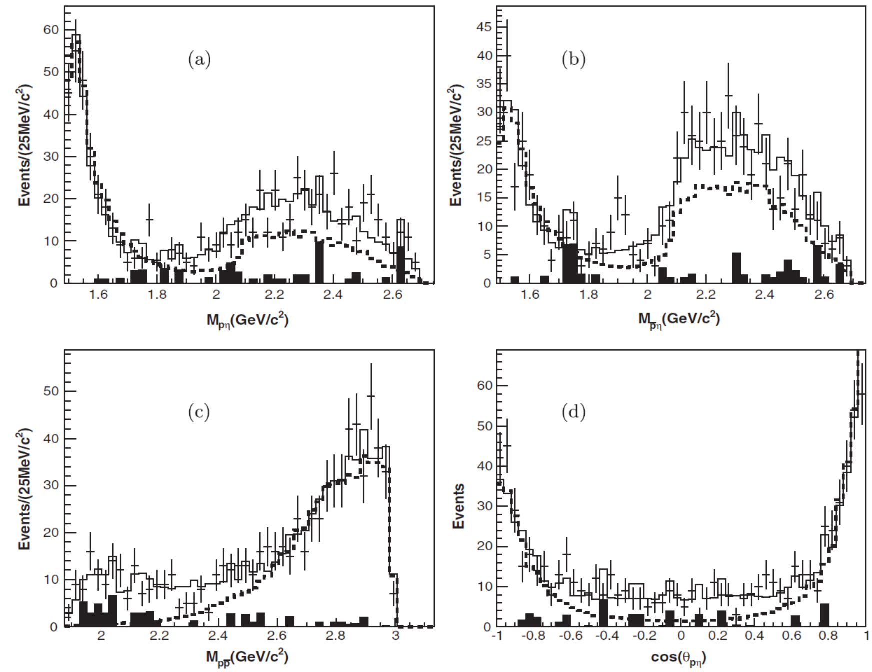
BESIII Phys.Rev. D88, 032010 (2013)



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

BESIII PRD 88, 032010 (2013)

- N(1535) and PHSP(1/2-) are dominant
- No evidence for a $p\bar{p}$ 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:

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

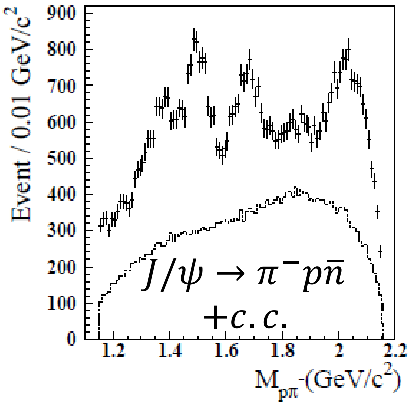
* For N(1535)

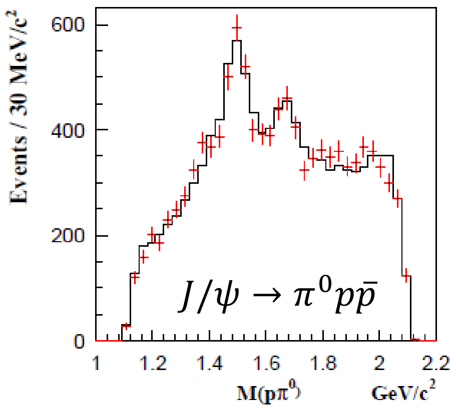
$$\mathrm{BW}(s) = \frac{1}{M_{N^*}^2 - s - iM_{N^*}\Gamma_{N^*}(s)}$$

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

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

Summary of N*'s @ BES





Modified from
Rept.Prog.Phys. 76 (2013) 076301
by V. Crede and W. Roberts

N*	PDG Rating (2014)	J/ψ			ψ'	
		$\pi^0 p\bar{p}$	$\pi^- p\bar{n} + c.c.$	$\eta p\bar{p}$	$\pi^0 p\bar{p}$	$\eta p\bar{p}$
N(1440)1/2+	****	BES2	BES2	BES1	BES3	
N(1520)3/2-	****	BES2			BES3	BES3
N(1535)1/2-	****	BES2		BES1	BES3	
N(1650)1/2-	****	BES2		BES1	BES3	
N(1710)1/2+	***	BES2				
N(1720)3/2+	****				BES3	
N(2040)3/2+	*	BES2	BES2			
N(2300)1/2+	**				BES3	
N(2570)5/2-	**				BES3	

Recent development of PWA tools for baryon spectroscopy at BESIII

- FDC-PWA has been used to generate the complicated amplitudes for baryon spectroscopy [Fortran codes].
- PWA is time-consuming for high statistics data sets.
- Porting amplitudes (lots of codes) to GPU (OpenCL/ CUDA) is a burden.
- We built a test-bed with Intel Xeon Phi:
  - **Offload large computations to many-cores co-processor**
    - **Matrix element for each event**
  - **Speed up with Vector and Thread Parallelism**
    - **Events are independent**
  - **Easy to port**
    - **x86 based**

Summary and outlook

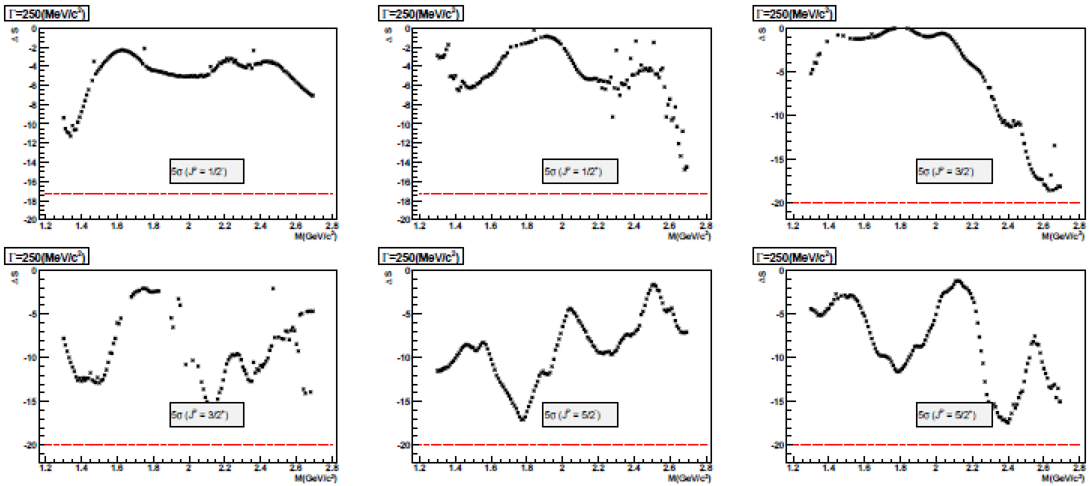
- **The decays of charmonium have proven to be a good laboratory in recent years for studying not only excited nucleon states, but also excited hyperons**
- ✓ **BESIII collected $0.6\times10^9\ \psi'$ and $1.3\times10^9\ J/\psi$ (and a lot of χ_c, η_c)**

- **BESIII also provides new opportunities for Λc studies**
- ✓ **0.5fb^{-1} @4600:**

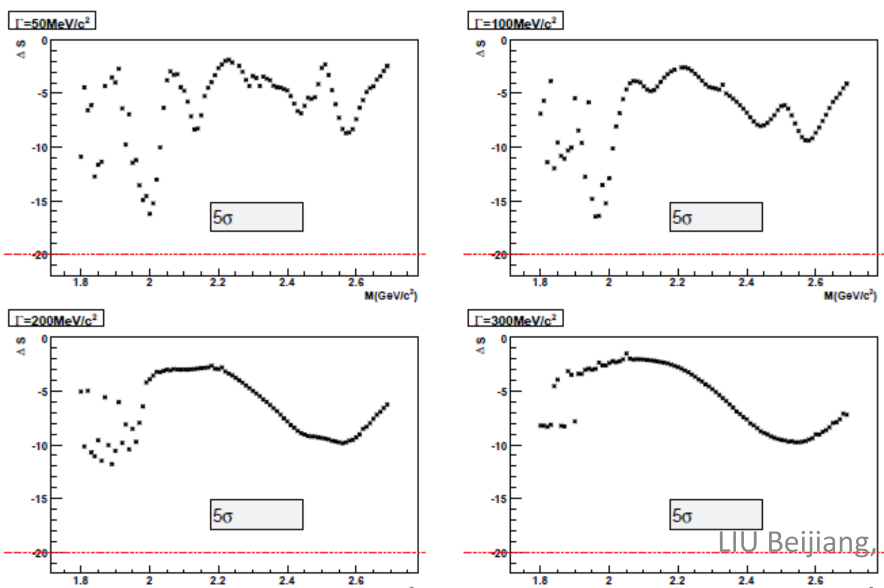
Thank you for your attention

Backups: check for extra resonance in PWA of $\psi' \to \pi^0 p\bar{p}$

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
check for extra resonance in PWA of $\psi' \to \eta p\bar{p}$

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