Spectrum of light baryons @ BESIII

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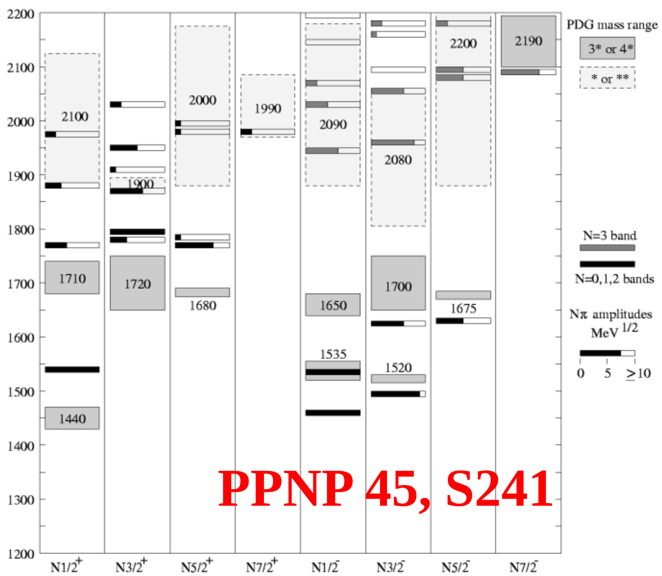
On behalf of BESIII Collaboration

第二届理论与实验联合研讨会：重子谱和衰变，兰州，2018.12.16

Outline

- **Introduction**
- **Light baryon spectrum @ BESIII**
  - ✓ **N* spectrum**
  - ✓ **Λ* spectrum**
  - ✓ **Σ* spectrum**
  - ✓ **Ξ* spectrum**
- **Baryon electromagnetic form factor (G_E & G_M)**
- **Summary**

Nucleon resonances spectrum



Particle	J^P	overall	Status as seen in									
			$N\gamma$	$N\pi$	$\Delta\pi$	$N\sigma$	$N\eta$	ΛK	ΣK	$N\rho$	$N\omega$	$N\eta'$
N	$1/2^+$	****										
$N(1440)$	$1/2^+$	****	****	****	****	***						
$N(1520)$	$3/2^-$	****	****	****	****	**	****					
$N(1535)$	$1/2^-$	****	****	****	***	*	****					
$N(1650)$	$1/2^-$	****	****	****	***	*	****	*				
$N(1675)$	$5/2^-$	****	****	****	****	***	*	*	*			
$N(1680)$	$5/2^+$	****	****	****	****	***	*	*	*			
$N(1700)$	$3/2^-$	***	**	***	***	*	*			*		
$N(1710)$	$1/2^+$	****	****	****	*		***	**	*	*	*	
$N(1720)$	$3/2^+$	****	****	****	***	*	*	****	*	*	*	
$N(1860)$	$5/2^+$	**	*	**		*	*					
$N(1875)$	$3/2^-$	***	**	**	*	**	*	*	*	*	*	
$N(1880)$	$1/2^+$	***	**	*	**	*	*	**	**		**	
$N(1895)$	$1/2^-$	****	****	*	*	*	****	**	**	*	*	****
$N(1900)$	$3/2^+$	****	****	**	**	*	*	**	**		*	**
$N(1990)$	$7/2^+$	**	**	**			*	*	*			
$N(2000)$	$5/2^+$	**	**	*	**	*	*				*	
$N(2040)$	$3/2^+$	*		*								
$N(2060)$	$5/2^-$	***	***	**	*	*	*	*	*	*	*	
$N(2100)$	$1/2^+$	***	**	***	**	**	*	*		*	*	**
$N(2120)$	$3/2^-$	***	***	**	**	**		**	*		*	*
$N(2190)$	$7/2^-$	****	****	****	****	**	*	**	*	*	*	
$N(2220)$	$9/2^+$	****	**	****			*	*	*			
$N(2250)$	$9/2^-$	****	**	****			*	*	*			
$N(2300)$	$1/2^+$	**		**								
$N(2570)$	$5/2^-$	**		**								
$N(2600)$	$11/2^-$	***		***								
$N(2700)$	$13/2^+$	**		**								

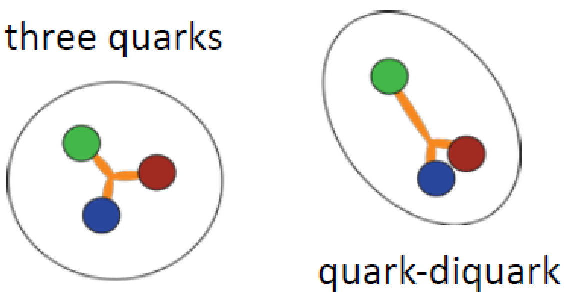
PDG18

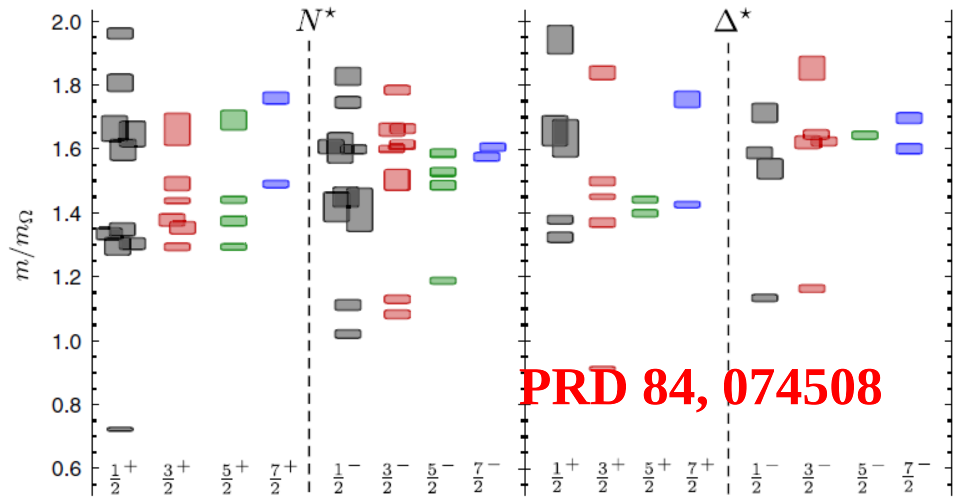
- **Up to 2.4GeV, there are about 45 N* states are predicted, but only 20 are established (four/three star) and 5 are tentative (one/two star).**

”Missing resonances” problem

- **Important goal: search for “missing resonances” not observed experimentally.**

- **Theoretically: reduce the number of degree of freedom.**

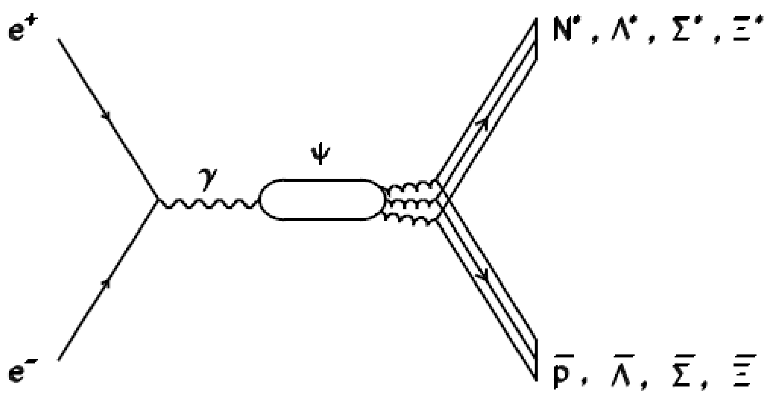




PRD 84, 074508

- **Experimentally: If the missing N*s have small coupling to πN and γN, they would not have been discovered by experiments Using photons or pions**

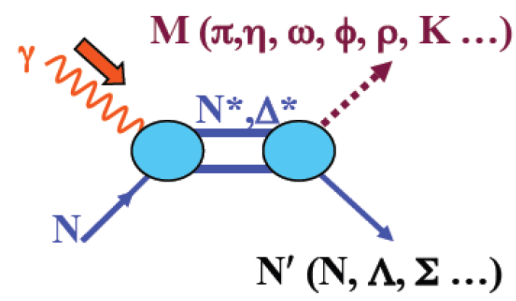
Baryon spectrum at BESIII



	Previous	BESIII	BESIII Goal
J/ψ	58M @ BES	1.2B	10B
$\psi(3686)$	28M @CLEO	0.5B	3B
$\psi(3770)$	$0.8fb^{-1}$@CLEO	$2.9fb^{-1}$	$20fb^{-1}$
χ_{CJ}	$\psi(3686) \rightarrow \gamma\, \chi_{CJ}$ @ (9-10) %		
$\eta_C(1S)$	$J/\psi \rightarrow \gamma\, \eta_C(1S)$ @ 1.7 %		

- **Pure isospin 1/2 filter: $\psi \rightarrow N\bar{N}\pi$ (or $N\bar{N}\pi\pi$)**
- **Missing N* with small couplings to πN and γN, but large coupling to gggN.**
- **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**
- **Not only N*, but also Λ*, Σ*, Ξ*.**
- **High statistics of charmonium at BESIII.**

JLab, ELSA, MAMI, ESRF, Spring-8, ….



N* spectrum

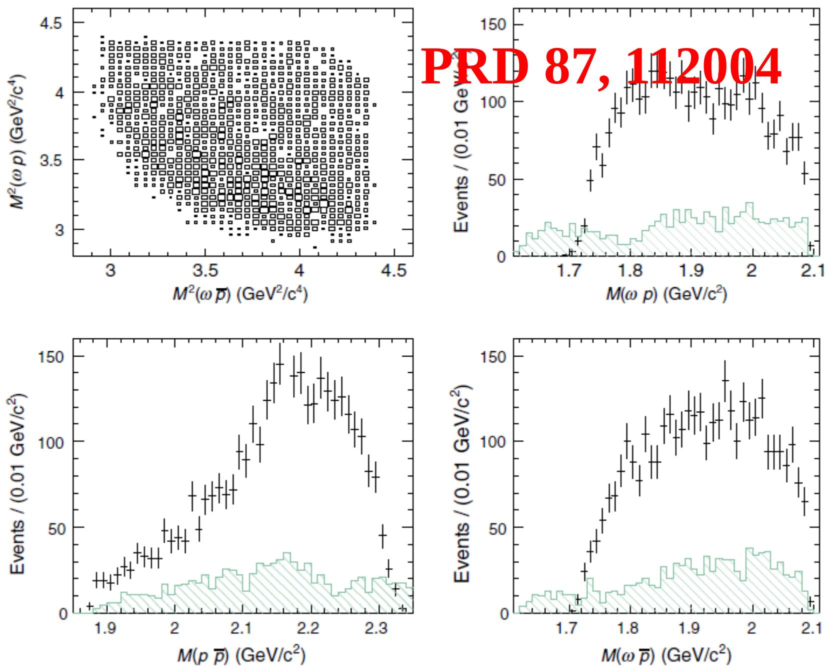
Particle	J^P	overall	Status as seen in									
			$N\gamma$	$N\pi$	$\Delta\pi$	$N\sigma$	$N\eta$	ΛK	ΣK	$N\rho$	$N\omega$	$N\eta\prime$
N	$1/2^+$	****										
$N(1440)$	$1/2^+$	****	****	****	****	***						
$N(1520)$	$3/2^-$	****	****	****	****	**	****					
$N(1535)$	$1/2^-$	****	****	****	***	*	****					
$N(1650)$	$1/2^-$	****	****	****	***	*	****	*				
$N(1675)$	$5/2^-$	****	****	****	****	***	*	*	*			
$N(1680)$	$5/2^+$	****	****	****	****	***	*	*	*			
$N(1700)$	$3/2^-$	***	**	***	***	*	*			*		
$N(1710)$	$1/2^+$	****	****	****	*		***	**	*	*	*	
$N(1720)$	$3/2^+$	****	****	****	***	*	*	****	*	*	*	
$N(1860)$	$5/2^+$	**	*	**		*	*					
$N(1875)$	$3/2^-$	***	**	**	*	**	*	*	*	*	*	
$N(1880)$	$1/2^+$	***	**	*	**	*	*	**	**		**	
$N(1895)$	$1/2^-$	****	****	*	*	*	****	**	**	*	*	****
$N(1900)$	$3/2^+$	****	****	**	**	*	*	**	**		*	**
$N(1990)$	$7/2^+$	**	**	**			*	*	*			
$N(2000)$	$5/2^+$	**	**	*	**	*	*				*	
$N(2040)$	$3/2^+$	*		*								
$N(2060)$	$5/2^-$	***	***	**	*	*	*	*	*	*	*	
$N(2100)$	$1/2^+$	***	**	***	**	**	*	*		*	*	**
$N(2120)$	$3/2^-$	***	***	**	**	**		**	*		*	*
$N(2190)$	$7/2^-$	****	****	****	****	**	*	**	*	*	*	
$N(2220)$	$9/2^+$	****	**	****			*	*	*			
$N(2250)$	$9/2^-$	****	**	****			*	*	*			
$N(2300)$	$1/2^+$	**		**								
$N(2570)$	$5/2^-$	**		**								
$N(2600)$	$11/2^-$	***		***								
$N(2700)$	$13/2^+$	**		**								

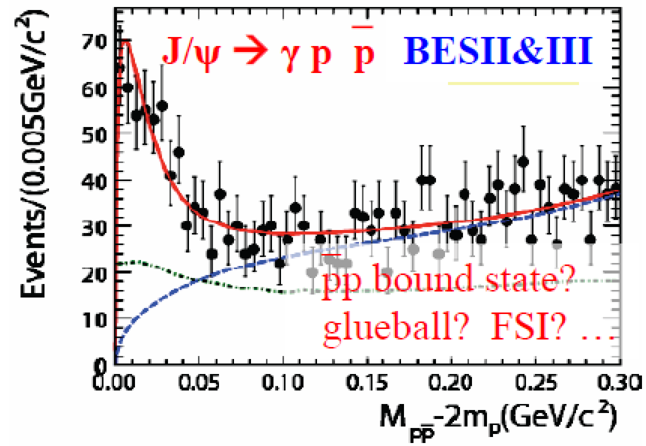
PDG18

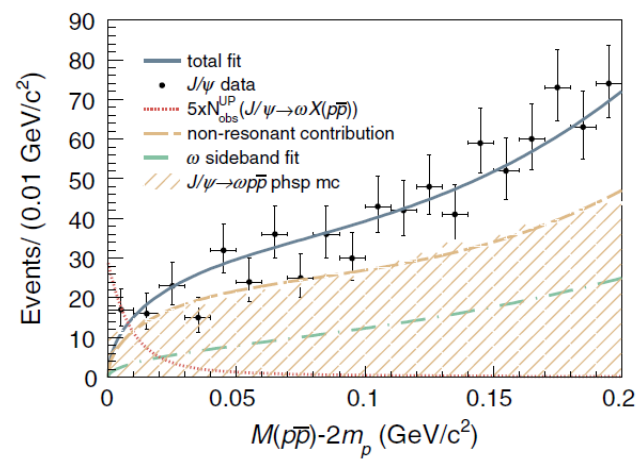
- $J/\psi \rightarrow p\bar{p}\phi$
- $J/\psi \rightarrow p\bar{p}\omega$
- $J/\psi \rightarrow p\bar{p}\, a_0(980)$
- $\psi(3686) \rightarrow p\bar{p}\pi^0$
- $\psi(3686) \rightarrow p\bar{p}\eta$
- $e^+e^- \rightarrow p\bar{p}\pi^0$ around 3.773 GeV
- $e^+e^- \rightarrow p\bar{p}\pi^0$ @ [4.008, 4.600]GeV
- $\psi(3686) \rightarrow \bar{p}K^+\Sigma^0$ + c.c.
- $\chi_{cJ} \rightarrow p\bar{n}\pi^-$ + c.c
- $\chi_{cJ} \rightarrow p\bar{n}\pi^-\pi^0$ + c.c

$J/\psi \to p\bar{p}\omega$

PRD 87, 112004

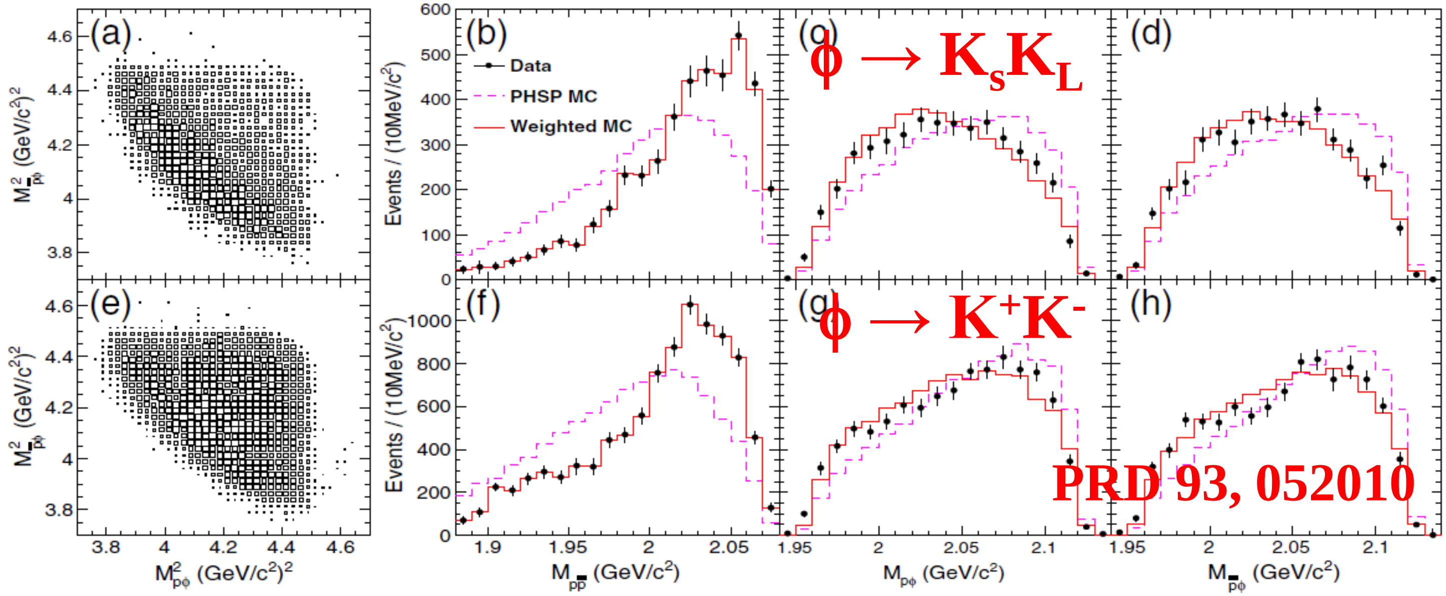


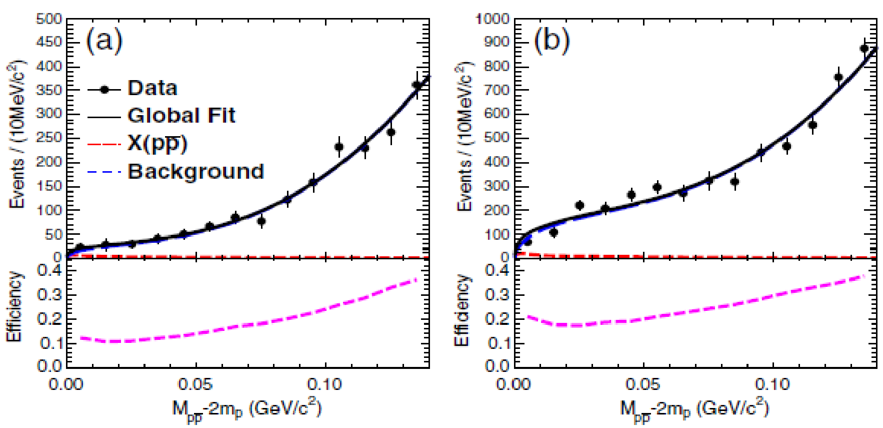




- **There are no obvious structures, but distributions are different from phase space MC.**
- **No obvious $p\bar{p}$ threshold**
- **Disfavior pure FSI interpretation**

$J/\psi \to p\bar{p}\phi$





- **We have neither observed a significant structure in $p\phi$ and $\bar{p}\phi$ mass spectra nor found evidence of an enhancement in $p\bar{p}$ mass spectrum near its threshold**

J/ψ → p$\bar{p}$$a_0$(980)

- **PRC69, 015201: J/ψ → N$\bar{N}$MM**

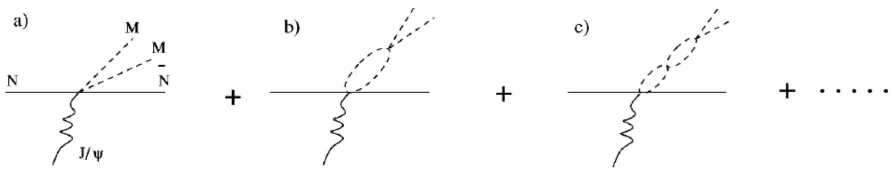
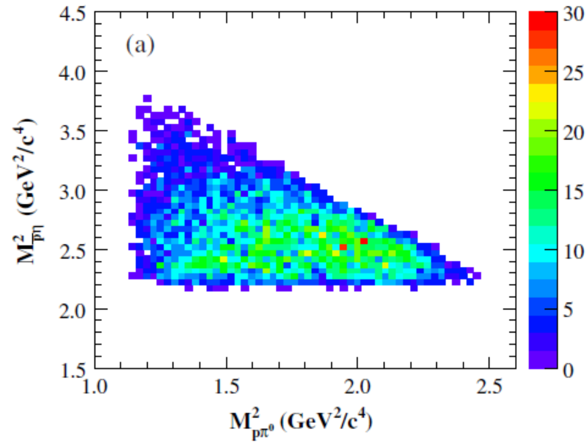
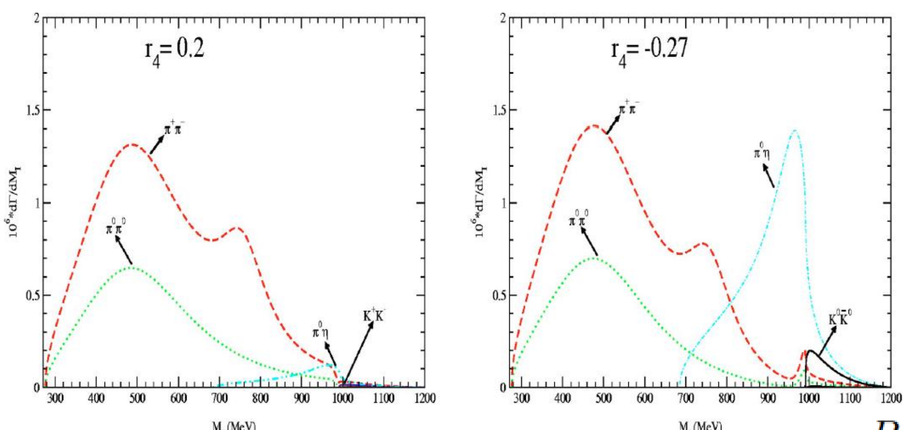
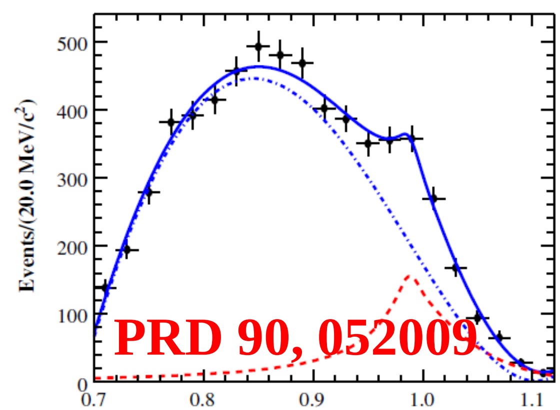


FIG. 1. Diagrams for $J/\psi \to N\bar{N}MM$ decays including the meson meson final state interaction.



- **Ambiguities from fitting to J/ψ → p$\bar{p}$MM**



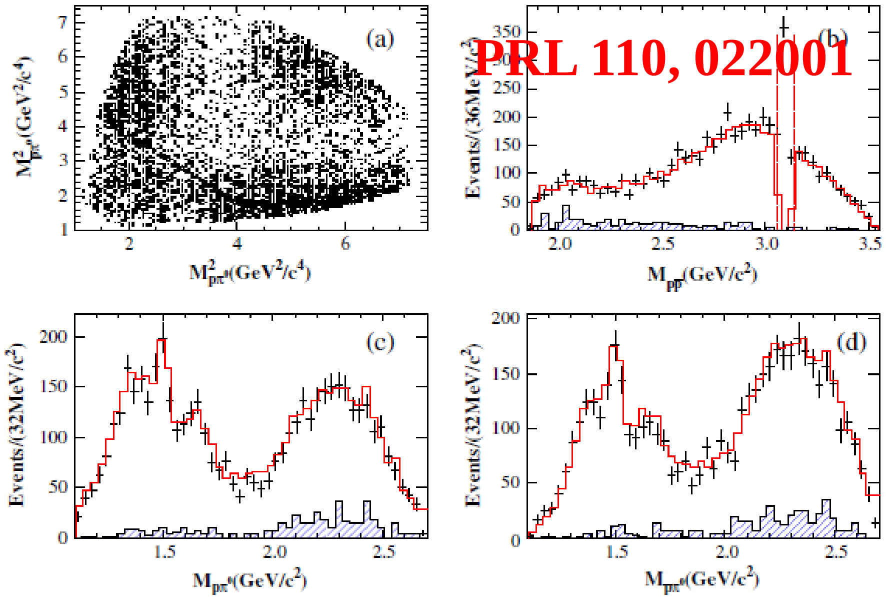


$$Br(J/\psi \to p\bar{p}a_0(980) \to p\bar{p}\pi^0\eta) = (6.8 \pm 1.2 \pm 1.3) \times 10^{-5}$$

- **Comparing to J/ψ → p$\bar{p}$ππ in PDG, r4=0.2 is preferable.**

$\psi(3686) \to p\bar{p}\pi^0$

PRL 110, 022001



Resonance	M(MeV/c^2)	Γ(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)	$\mathbf{2300^{+40+109}_{-30-0}}$	$\mathbf{340^{+30+110}_{-30-58}}$	**120.7**	**4**	$\mathbf{15.0\sigma}$
N(2570)	$\mathbf{2570^{+19+34}_{-10-10}}$	$\mathbf{250^{+14+69}_{-24-21}}$	**78.9**	**6**	$\mathbf{11.7\sigma}$

$$\psi(3686) \to X\pi^0 \to p\bar{p}\pi^0$$

$$\psi(3686) \to p\bar{N}^* + c.c \to p\bar{p}\pi^0$$

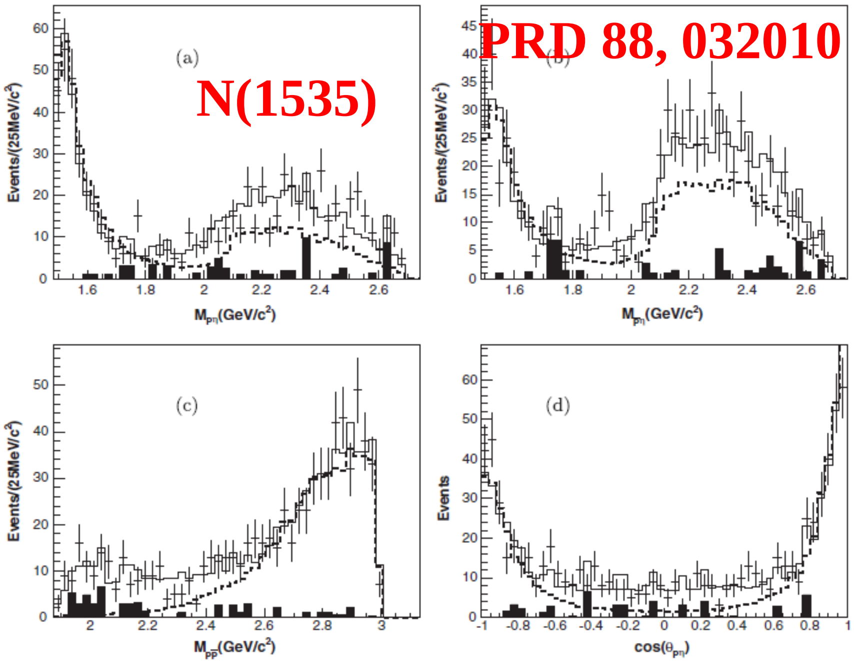
- **Isospin conservation: Δ suppressed.**
- **Two new excited states N(2300) ($1/2^+$) and N(2570) ($5/2^-$) are observed.**
- **The $p\bar{p}$ threshold enhancement most likely is due to interference of N*s.**
- **No clear evidence for N(1885) and N(2065).**

$\psi(3686) \to p\bar{p}\eta$

$Br[\psi(3686) \to p\bar{p}\eta] = (6.4 \pm 0.2 \pm 0.6) \times 10^{-5}$

$Br[\psi(3686) \to N(1535)\bar{p} + c.c.] = (5.2 \pm 0.3^{+3.2}_{-1.2}) \times 10^{-5}$

$\frac{Br[\psi(3686) \to p\bar{p}\eta]}{Br[J/\psi \to p\bar{p}\eta]} = (3.2 \pm 0.4)\%$

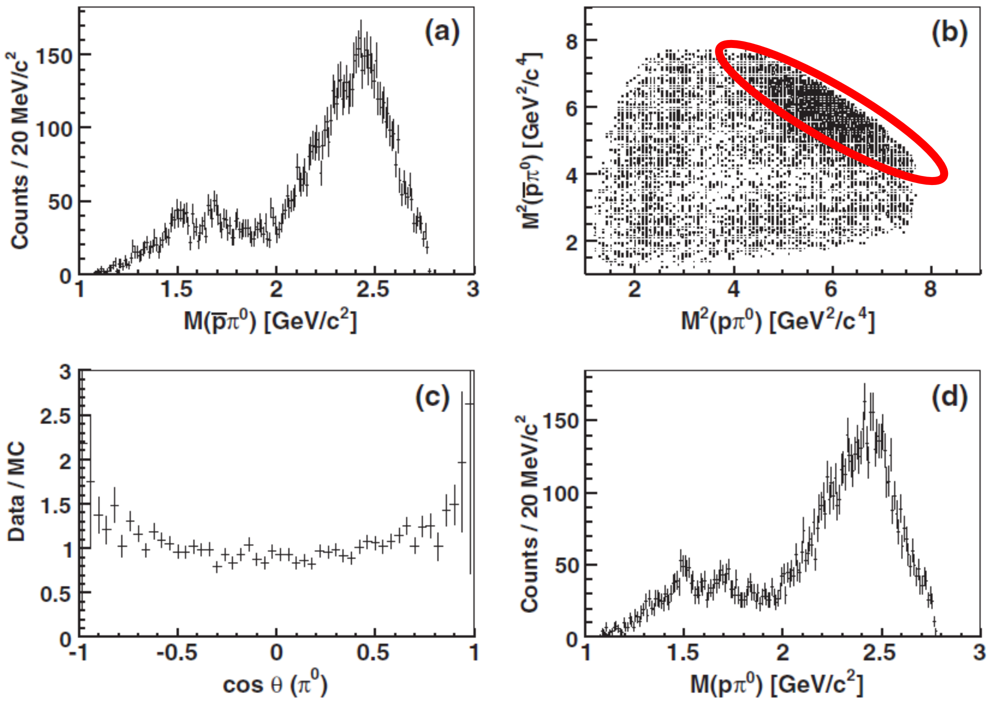


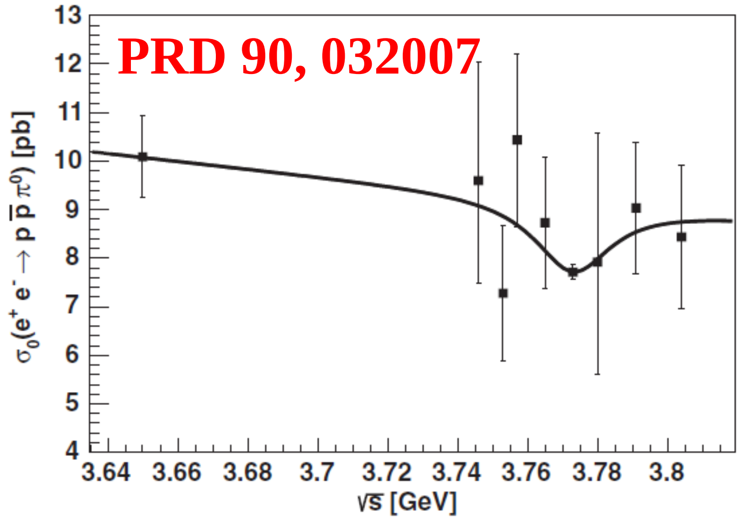
Explained by interference between N(1535) and phase space

- **PWA: N(1535) and PHSP are dominant**
  - ✓ N(1535) @ PWA: M=1524±5^{+10}_{-4}MeV; Γ =130^{+27+57}_{-24-10}MeV
  - ✓ N(1535) @ PDG: M=1525 to 1545 MeV; Γ = 125 to 175 MeV
- **No evidence for a $p\bar{p}$ resonance**
- **12% rule: violated in $p\bar{p}\eta$ mode.**

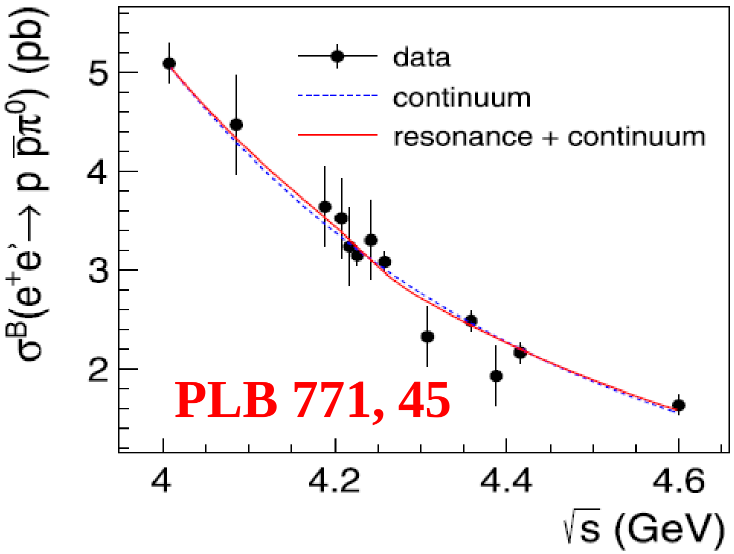
$e^+e^- \to p\bar{p}\pi^0$ @ 3.773 GeV

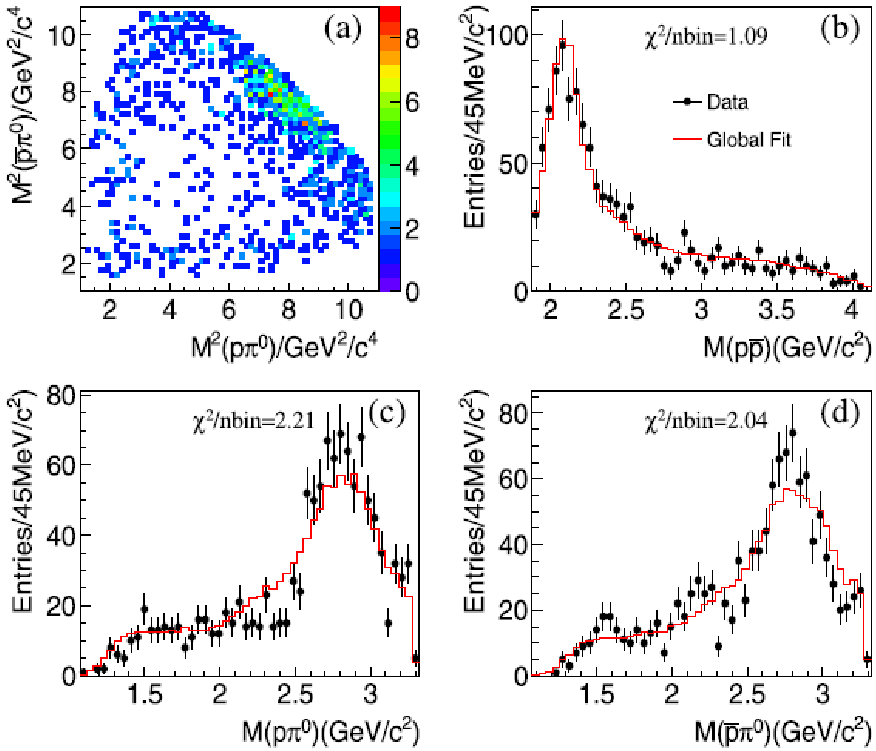
- $\psi(3770) \to$ non-$D\bar{D}$: BESII: (14.7±3.2)%; theory prediction < 5%
  - ✓ Search for non-$D\bar{D}$ decay modes: useful to understand puzzle
- $\psi(3770) \to N\bar{N}$ + hadrons provides a chance to study N*
  - ✓ @3.773GeV: $\psi(3770)$ strong decays or $\gamma^* \to N\bar{N}$ + hadrons





$e^+e^- \to p\bar{p}\pi^0$ @ [4.008, 4.600]GeV



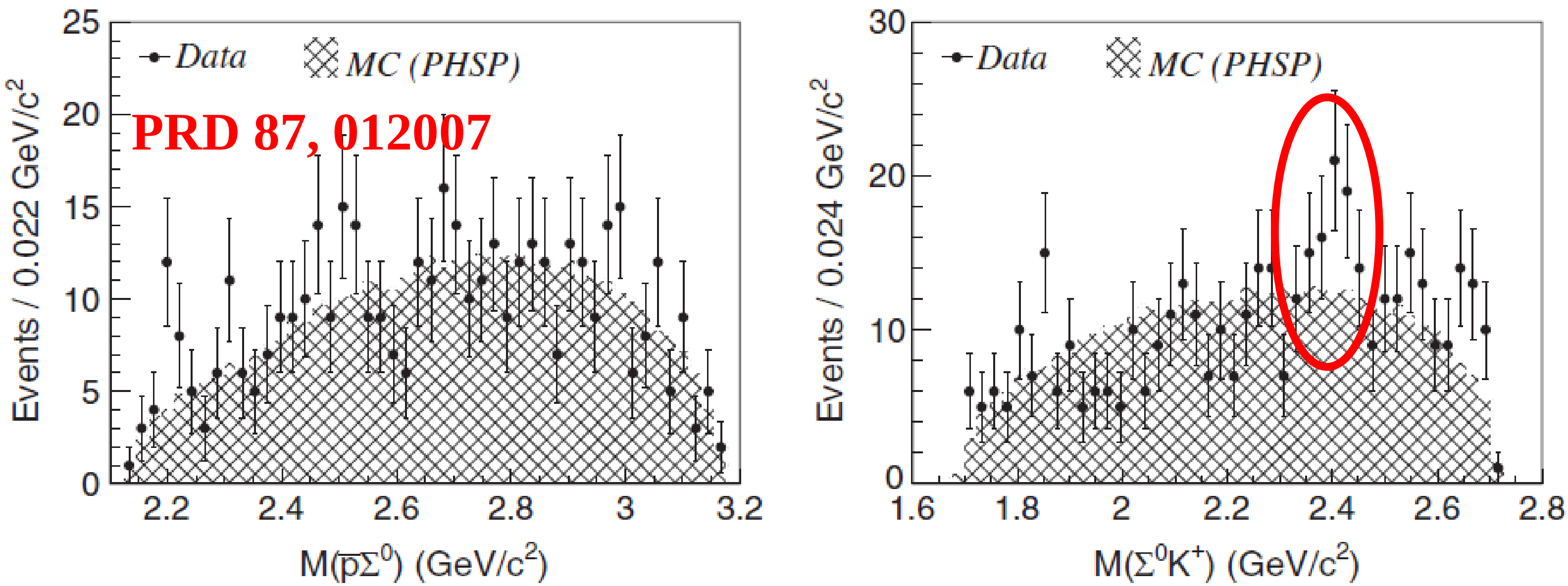


- **PWA for MC production**
  - ✓ $e^+e^- \to p\bar{N}^* + c.c$
  - ✓ $e^+e^- \to p\bar{\Delta}^* + c.c$
  - ✓ $e^+e^- \to \rho^*(\omega^*)\pi^0$

1203 event @ 4.258GeV

- **[4.189, 4.600] GeV: N(1440), ρ(2150) and ρ_3(1990)**
- **[4.008, 4.085] GeV: N(1520), N(2570), ρ(2150) and ρ_3(1990)**

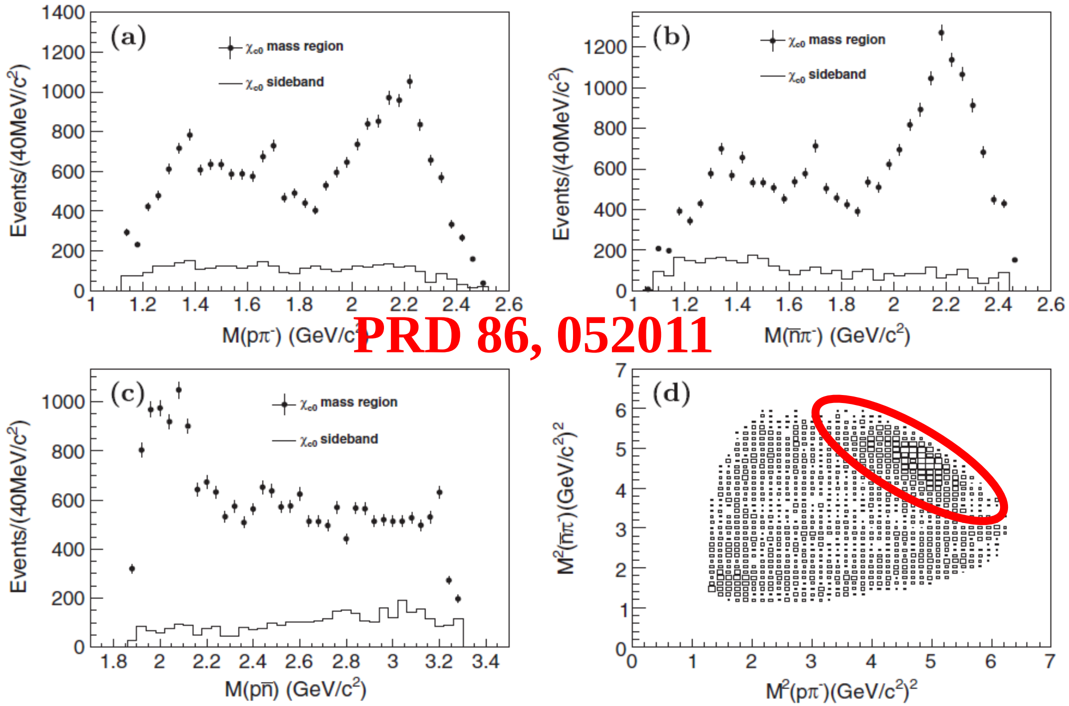
$\psi(3686) \to \bar{p}K^+\Sigma^0 + c.c.$



Channel	$\psi' \to \bar{p}K^+\Sigma^0 + c.c.$
$\mathcal{B}$(BESIII)	$(1.67 \pm 0.13 \pm 0.12) \times 10^{-5}$
PDG	

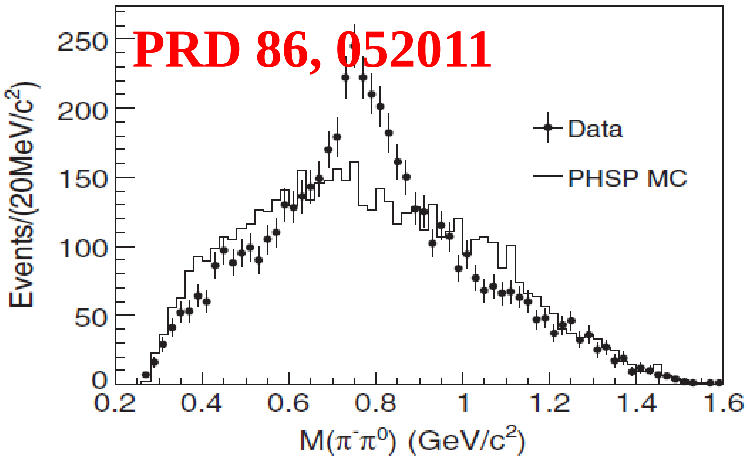
- **A hint for structure N* around 2.4GeV.**

$\chi_{cJ} \to p\bar{n}\pi^- + c.c$



- A large enhancement around $p\bar{n}$ threshold
- Structure around 1.4 & 1.7GeV for $p\pi^-$ and $\bar{n}\pi^-$ invariant mass spectrum, peak around 2.0GeV due to high mass N* or reflection of $p\bar{n}$ threshold enhancement.

$\chi_{cJ} \to p\bar{n}\pi^-\pi^0$ + c.c



- **No obvious N* state**
- **Similar to that of phase space, except for ρ signal**
- **A chance for $\chi_{cJ} \to p\bar{n}\rho$**

	$\chi_{cJ} \to p\bar{n}\pi^-\pi^0$			$\chi_{cJ} \to \bar{p}n\pi^+\pi^0$		
	χ_{c0}	χ_{c1}	χ_{c2}	χ_{c0}	χ_{c1}	χ_{c2}
N_{sig}	2480 ± 85	1082 ± 52	2128 ± 62	2757 ± 94	1261 ± 60	2352 ± 69
ε_{cJ} (%)	10.4 ± 0.1	10.4 ± 0.2	9.8 ± 0.1	12.2 ± 0.1	12.3 ± 0.2	11.2 ± 0.1
$\mathcal{B}$ (10^{-3})	2.36 ± 0.08	1.08 ± 0.05	2.38 ± 0.07	2.23 ± 0.08	1.06 ± 0.05	2.30 ± 0.07

Λ^* spectrum

			Status as seen in —			
Particle	J^P	Overall status	$N\overline{K}$	$\Lambda\pi$	$\Sigma\pi$	Other channels
$\Lambda(1116)$	1/2+	****		F		$N\pi$(weakly)
$\Lambda(1405)$	1/2−	****	****	o	****	
$\Lambda(1520)$	3/2−	****	****	r	****	$\Lambda\pi\pi, \Lambda\gamma$
$\Lambda(1600)$	1/2+	***	***	b	**	
$\Lambda(1670)$	1/2−	****	****	i	****	$\Lambda\eta$
$\Lambda(1690)$	3/2−	****	****	d	****	$\Lambda\pi\pi, \Sigma\pi\pi$
$\Lambda(1800)$	1/2−	***	***	d	**	$N\overline{K}^*, \Sigma(1385)\pi$
$\Lambda(1810)$	1/2+	***	***	e	**	$N\overline{K}^*$
$\Lambda(1820)$	5/2+	****	****	n	****	$\Sigma(1385)\pi$
$\Lambda(1830)$	5/2−	****	***	F	****	$\Sigma(1385)\pi$
$\Lambda(1890)$	3/2+	****	****	o	**	$N\overline{K}^*, \Sigma(1385)\pi$
$\Lambda(2000)$		*		r	*	$\Lambda\omega, N\overline{K}^*$
$\Lambda(2020)$	7/2+	*	*	b	*	
$\Lambda(2100)$	7/2−	****	****	i	***	$\Lambda\omega, N\overline{K}^*$
$\Lambda(2110)$	5/2+	***	**	d	*	$\Lambda\omega, N\overline{K}^*$
$\Lambda(2325)$	3/2−	*	*	d		$\Lambda\omega$
$\Lambda(2350)$		***	***	e	*	
$\Lambda(2585)$		**	**	n		

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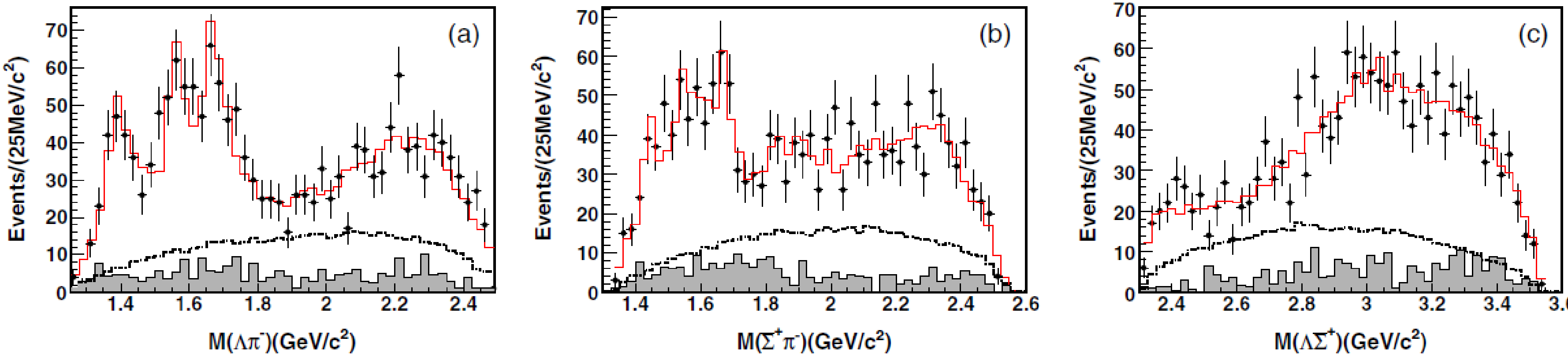
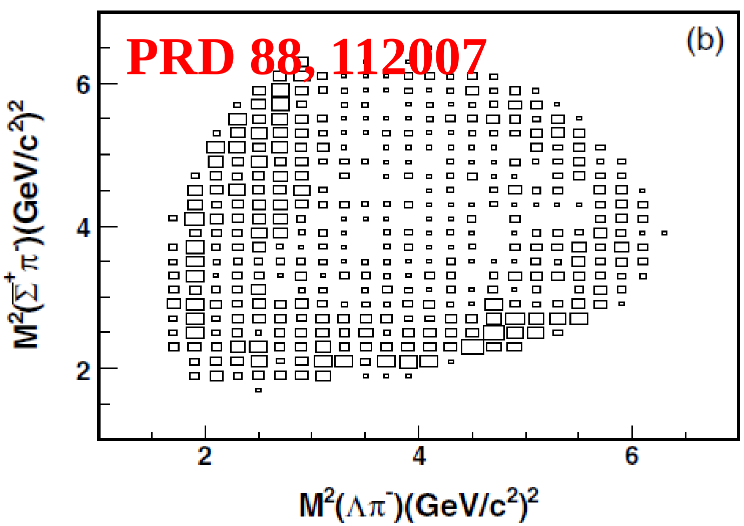
- **$\psi(3686) \rightarrow \Lambda\bar{\Sigma}^+\pi^-$ + c.c.**
- **$\chi_{cJ} \rightarrow p\bar{p}K^+K^-$**
- **$\chi_{cJ} \rightarrow \bar{p}K^+\Lambda$ + c.c.**
- **$e^+e^- \rightarrow pK_s\bar{n}K^-$ @ [3.773, 4.600]GeV**

$\psi(3686) \to \Lambda\bar{\Sigma}^{+}\pi^{-} + c.c.$





PRD 88, 112007

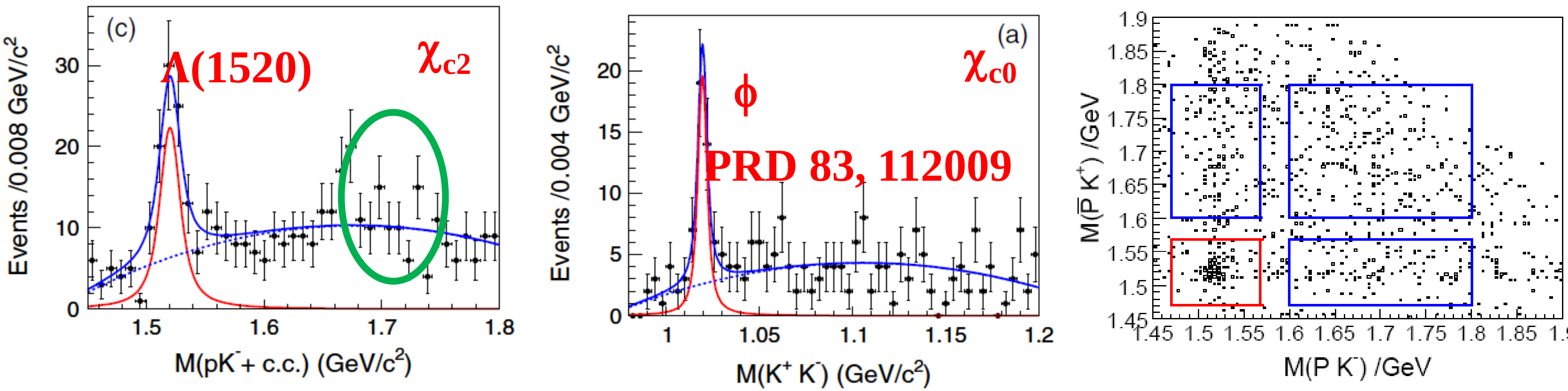
- **Excited strange baryons between 1.5GeV and 1.7GeV are observed.**

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

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

$$Q_{\Lambda\bar{\Sigma}^{-}\pi^{+}} = \frac{\mathcal{B}(\psi(3686) \to \Lambda\bar{\Sigma}^{-}\pi^{+})}{\mathcal{B}(J/\psi \to \Lambda\bar{\Sigma}^{-}\pi^{+})} = (9.3 \pm 1.2)\%,$$

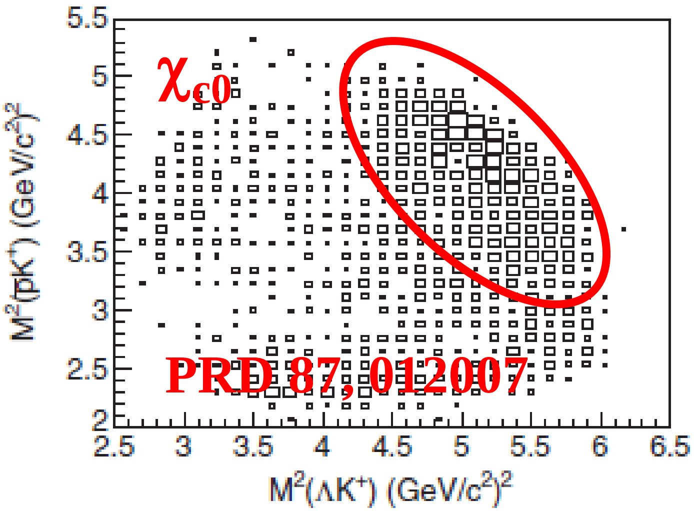
$\chi_{cJ} \to p\bar{p}K^{+}K^{-}$

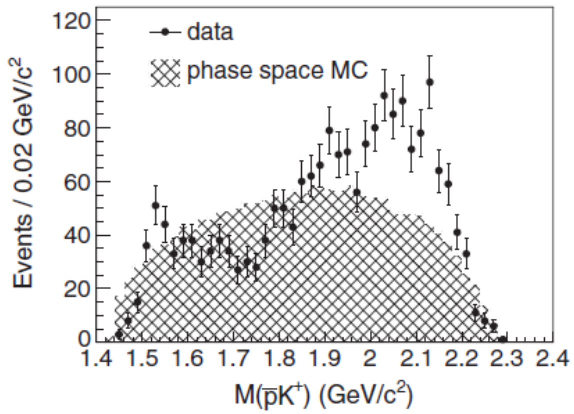


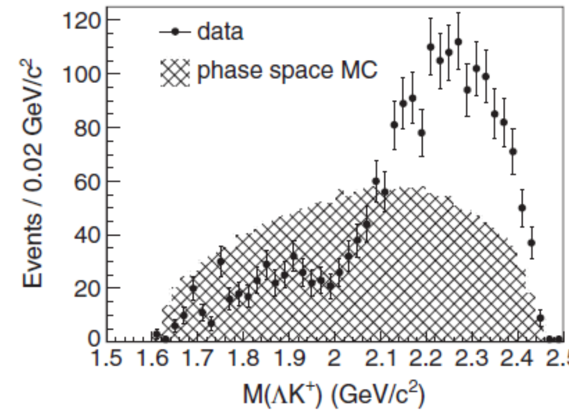
- Clear Λ(1520), a hint for Λ* around 1.67GeV
- $\chi_{cJ} \to p\bar{p}\phi$: $p\phi$ or $p\bar{p}$ invariant mass ?
- $\chi_{cJ} \to \Lambda(1520)\,\bar{\Lambda}(1520)$: test of Colour Octet Model

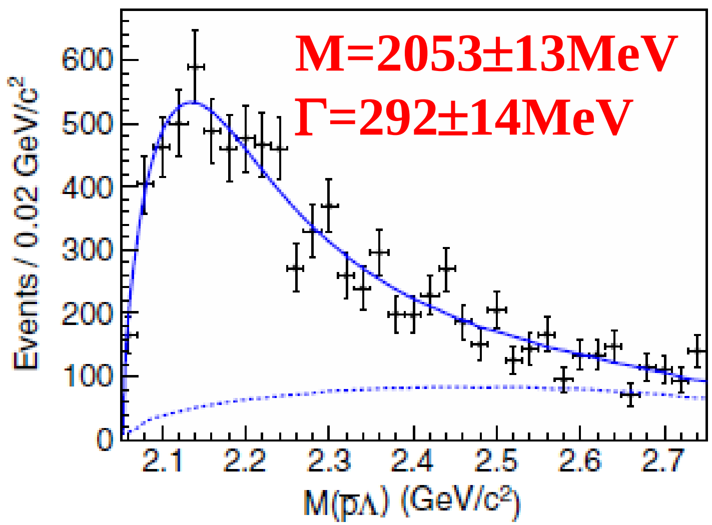
	χ_{c0}	χ_{c1}	χ_{c2}
$\mathcal{B}(\chi_{cJ} \to p\bar{p}K^{+}K^{-})$ (10^{-4})	$1.24 \pm 0.20 \pm 0.18$	$1.35 \pm 0.15 \pm 0.19$	$2.08 \pm 0.19 \pm 0.30$
$\mathcal{B}(\chi_{cJ} \to \bar{p}K^{+}\Lambda(1520) + \text{c.c.})$ (10^{-4})	$3.00 \pm 0.58 \pm 0.50$	$1.81 \pm 0.38 \pm 0.28$	$3.06 \pm 0.50 \pm 0.54$
$\mathcal{B}(\chi_{cJ} \to \Lambda(1520)\bar{\Lambda}(1520))$ (10^{-4})	$3.18 \pm 1.11 \pm 0.53$	<1.00	$5.05 \pm 1.29 \pm 0.93$
$\mathcal{B}(\chi_{cJ} \to p\bar{p}\phi)$ (10^{-5})	$6.12 \pm 1.18 \pm 0.86$	<1.82	$3.04 \pm 0.85 \pm 0.43$

$\chi_{cJ} \rightarrow \bar{p}K^{+}\Lambda$ + c.c.



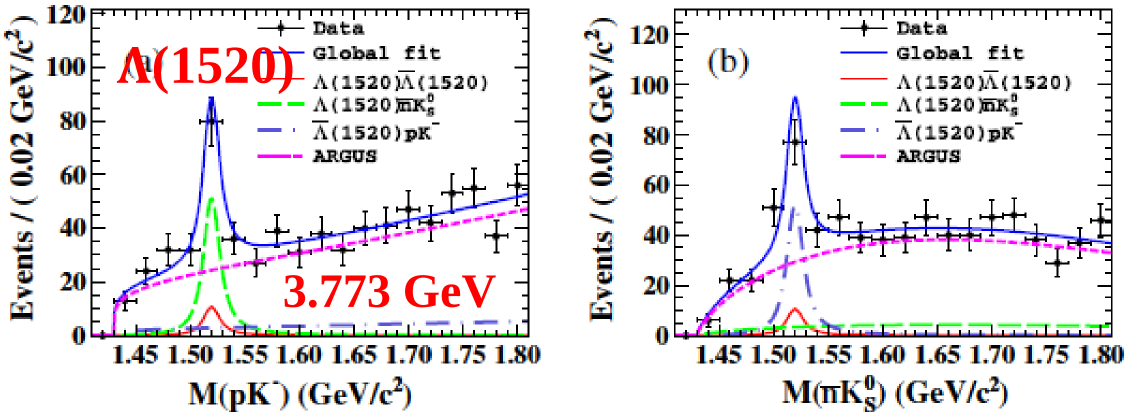


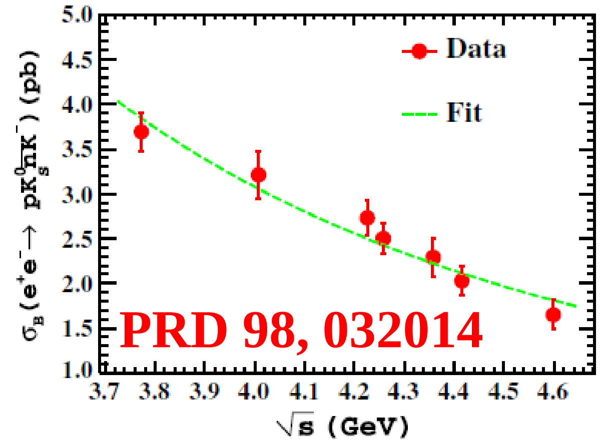


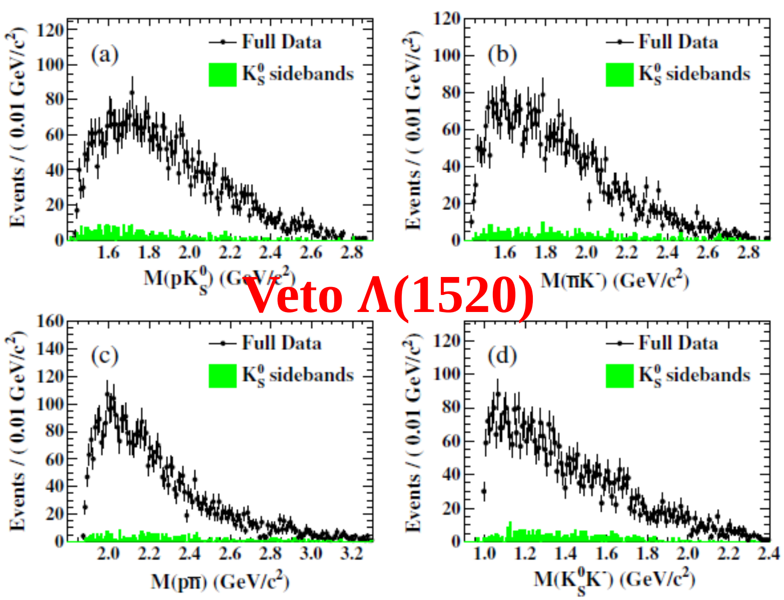


- **Possible reasons**
  - ✓ **Quasi bound di-baryon state**
  - ✓ **Final state interactions**
  - ✓ **Interference of high mass N* and Λ* states**

$e^+e^- \to pK_s\bar{n}K^-$ @ [3.773, 4.600]GeV







Mode	$\sqrt{s}$ (GeV)	$\mathcal{L}$ (pb^{-1})	ϵ (%)	$\frac{1}{\lvert 1-\Pi \rvert^2}$	$1+\delta$	$N_{\rm sig}$	S (σ)	σ_B (pb)
$\Lambda(1520)\bar{n}K^0_S$	3.773	2931.8	23.87	1.057	0.878	122 ± 21	8.3	$1.21 \pm 0.21 \pm 0.09$
	4.008	482.0	24.64	1.044	0.927	24.7 ± 9.0	3.5	$1.38 \pm 0.50 \pm 0.10$
	4.226	1047.3	25.34	1.056	0.933	20.5 ± 9.4	3.1	$0.50 \pm 0.23 \pm 0.04$
	4.258	825.7	25.44	1.054	0.936	21.0 ± 7.8	3.3	$0.65 \pm 0.24 \pm 0.04$
	4.358	539.8	25.76	1.051	0.954	8.3 ± 5.9	3.0	$0.38 \pm 0.27 \pm 0.03$
	4.416	1028.9	25.95	1.053	0.962	25.5 ± 8.7	4.0	$0.61 \pm 0.21 \pm 0.04$
	4.600	566.9	26.53	1.055	0.970	10.3 ± 6.1	4.0	$0.43 \pm 0.25 \pm 0.03$
$\Lambda(1520)\bar{p}K^+$	3.773	2931.8	27.22	1.057	0.879	250 ± 27	11.9	$4.33 \pm 0.47 \pm 0.28$
	4.008	482.0	27.33	1.044	0.931	40 ± 11	4.3	$4.01 \pm 1.10 \pm 0.27$
	4.226	1047.3	27.45	1.056	0.935	60 ± 14	5.6	$2.72 \pm 0.63 \pm 0.18$
	4.258	825.7	27.46	1.054	0.936	24.9 ± 8.7	3.9	$1.43 \pm 0.50 \pm 0.10$
	4.358	539.8	27.51	1.051	0.951	16.1 ± 8.1	3.1	$1.39 \pm 0.70 \pm 0.10$
	4.416	1028.9	27.54	1.053	0.957	46 ± 12	4.5	$2.07 \pm 0.54 \pm 0.14$
	4.600	566.9	27.63	1.055	0.974	6.4 ± 6.8	3.0	$0.51 \pm 0.54 \pm 0.04$
$\Lambda(1520)\bar{\Lambda}(1520)$	3.773	2931.8	27.65	1.057	0.882	$< 24(13.9 \pm 7.5)$	2.1	< 1.9
	4.008	482.0	28.77	1.044	0.928	$< 5.5(0.0 \pm 3.5)$	0.1	< 2.4
	4.226	1047.3	29.81	1.056	0.932	$< 7.5(1.6 \pm 3.8)$	0.5	< 1.4
	4.258	825.7	29.95	1.054	0.939	$< 7.7(2.4 \pm 2.0)$	1.6	< 1.8
	4.358	539.8	30.42	1.051	0.954	$< 2.8(0.0 \pm 0.8)$	0.3	< 1.0
	4.416	1028.9	30.71	1.053	0.956	$< 5.3(0.3 \pm 2.9)$	0.1	< 1.0
	4.600	566.9	31.55	1.055	0.970	$< 2.4(0.0 \pm 0.8)$	0.1	< 0.8

Σ* spectrum

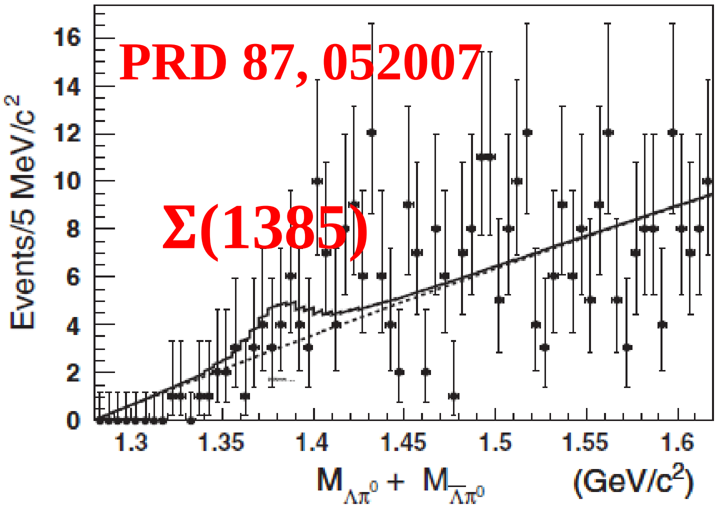
Particle	J^P	Overall status	Status as seen in —			
			$N\overline{K}$	$\Lambda\pi$	$\Sigma\pi$	Other channels
Σ(1193)	1/2+	****				$N\pi$(weakly)
Σ(1385)	3/2+	****		****	****	
Σ(1480)		*	*	*	*	
Σ(1560)		**		**	**	
Σ(1580)	3/2−	*	*	*		
Σ(1620)	1/2−	**	**	*	*	
Σ(1660)	1/2+	***	***	*	**	
Σ(1670)	3/2−	****	****	****	****	several others
Σ(1690)		**	*	**	*	$\Lambda\pi\pi$
Σ(1750)	1/2−	***	***	**	*	$\Sigma\eta$
Σ(1770)	1/2+	*				
Σ(1775)	5/2−	****	****	****	***	several others
Σ(1840)	3/2+	*	*	**	*	
Σ(1880)	1/2+	**	**	**		$N\overline{K}^*$
Σ(1915)	5/2+	****	***	****	***	$\Sigma(1385)\pi$
Σ(1940)	3/2−	***	*	***	**	quasi-2-body
Σ(2000)	1/2−	*		*		$N\overline{K}^*$, $\Lambda(1520)\pi$
Σ(2030)	7/2+	****	****	****	**	several others
Σ(2070)	5/2+	*	*		*	
Σ(2080)	3/2+	**		**		
Σ(2100)	7/2−	*		*	*	
Σ(2250)		***	***	*	*	
Σ(2455)		**	*			
Σ(2620)		**	*			
Σ(3000)		*	*	*		
Σ(3170)		*				multi-body

PDG18

- **J/ψ and ψ(3686) → $\Lambda\bar{\Lambda}\pi^0$ and $\Lambda\bar{\Lambda}\eta$**
- **χ_{cJ} → $\Lambda\bar{\Lambda}\pi^+\pi^-$**

J/ψ and ψ(3686) → $\Lambda\bar{\Lambda}\pi^0$ and $\Lambda\bar{\Lambda}\eta$

- Large uncertainty in literature
- Systematic measurement
  - ✓ $\Lambda\bar{\Lambda}\pi^0$: isospin breaking
  - ✓ $\Lambda\bar{\Lambda}\eta$: conserve isospin
- Test on 12% rule



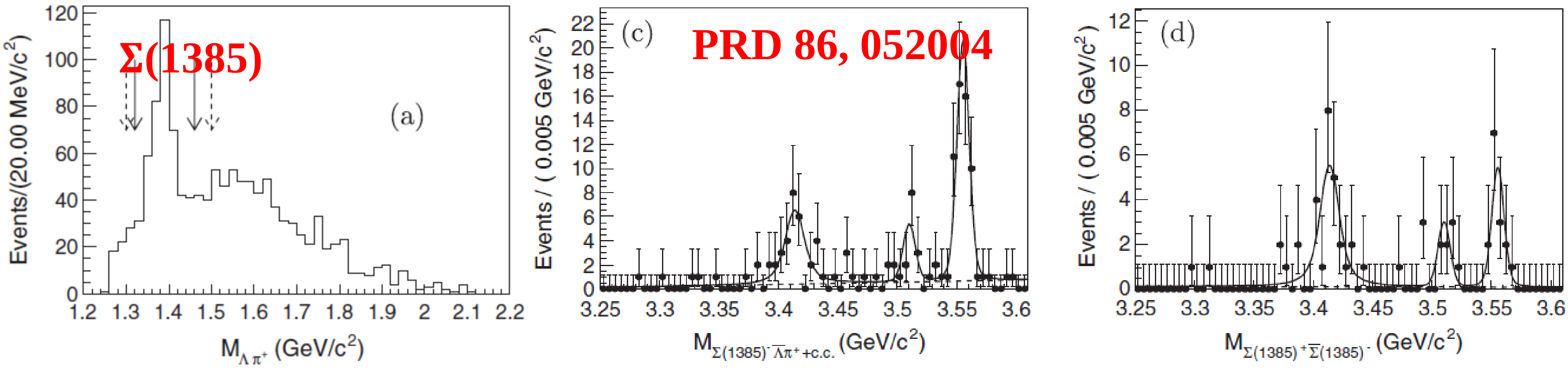
$$Q_h = \frac{\mathcal{B}(\psi' \to \Lambda\bar{\Lambda}\pi^0)}{\mathcal{B}(J/\psi \to \Lambda\bar{\Lambda}\pi^0)} < 10.0\%$$

$$Q_h = \frac{\mathcal{B}(\psi' \to \Lambda\bar{\Lambda}\eta)}{\mathcal{B}(J/\psi \to \Lambda\bar{\Lambda}\eta)} = (15.7 \pm 2.9)\%.$$

TABLE III. A comparison of the branching fractions of this work with the results of previous experiments (10^{-5}). The first error is statistical and the second one indicates the systematical uncertainty.

Experiments	$\mathcal{B}(J/\psi \to \Lambda\bar{\Lambda}\pi^0)$	$\mathcal{B}(J/\psi \to \Lambda\bar{\Lambda}\eta)$	$\mathcal{B}(\psi' \to \Lambda\bar{\Lambda}\pi^0)$	$\mathcal{B}(\psi' \to \Lambda\bar{\Lambda}\eta)$
This experiment	$3.78 \pm 0.27 \pm 0.30$	$15.7 \pm 0.80 \pm 1.54$	<0.29	$2.48 \pm 0.34 \pm 0.19$
BESII [3]	<6.4	$26.2 \pm 6.0 \pm 4.4$	<4.9	<12
BESI [2]	$23.0 \pm 7.0 \pm 8.0$			
DM2 [1]	$22.0 \pm 5.0 \pm 5.0$			

$\chi_{cJ} \to \Lambda\bar{\Lambda}\pi^+\pi^-$



- **Clear Σ(1385), a bump around 1.5-1.6 GeV**
- **$\chi_{cJ} \to \Sigma(1385)\,\bar{\Sigma}(1385)$: test of Colour Octet Model**

χ_{cJ} decay mode	χ_{c0}			χ_{c1}			χ_{c2}		
	$\mathcal{B}$	UL	S	$\mathcal{B}$	UL	S	$\mathcal{B}$	UL	S
$\Lambda\bar{\Lambda}\pi^+\pi^-$(w/o$\Sigma(1385)$)	$28.6 \pm 12.6 \pm 2.7$	<54	2.2	$26.2 \pm 5.5 \pm 3.3$		4.8	$71.8 \pm 14.5 \pm 8.2$		6.4
$\Sigma(1385)^+\bar{\Lambda}\pi^- + c.c.$	$34.8 \pm 13.2 \pm 3.4$	<55	2.2		<14	0.3	$23.6 \pm 11.8 \pm 2.7$	<42	1.7
$\Sigma(1385)^-\bar{\Lambda}\pi^+ + c.c.$	$24.6 \pm 12.7 \pm 2.4$	<50	1.6		<14	0.0	$37.8 \pm 11.8 \pm 4.4$	<61	2.6
$\Sigma(1385)^+\bar{\Sigma}(1385)^-$	$16.4 \pm 5.7 \pm 1.6$		3.1	$4.4 \pm 2.5 \pm 0.6$	<10	1.9	$7.9 \pm 4.0 \pm 0.9$	<17	2.0
$\Sigma(1385)^-\bar{\Sigma}(1385)^+$	$23.5 \pm 6.2 \pm 2.3$		4.3		<5.7	0.9		<8.5	0.0
$\Lambda\bar{\Lambda}\pi^+\pi^-$ (total)	$119.0 \pm 6.4 \pm 11.4$		>10	$31.1 \pm 3.4 \pm 3.9$		>10	$137.0 \pm 7.6 \pm 15.7$		>10

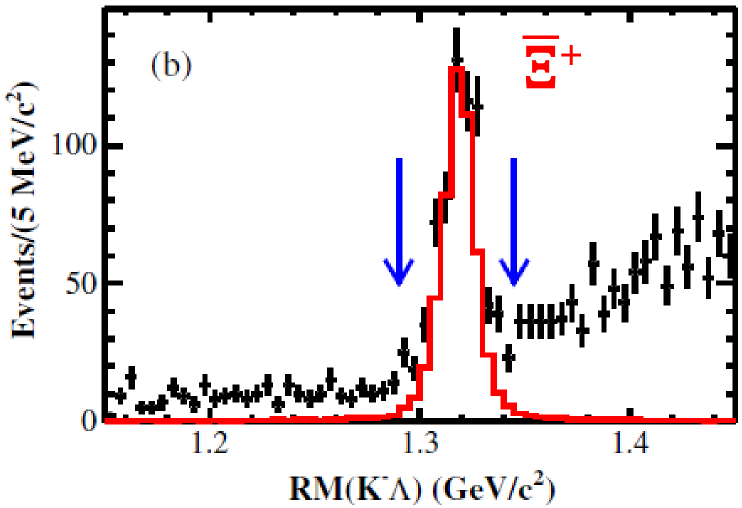
Ξ^* spectrum

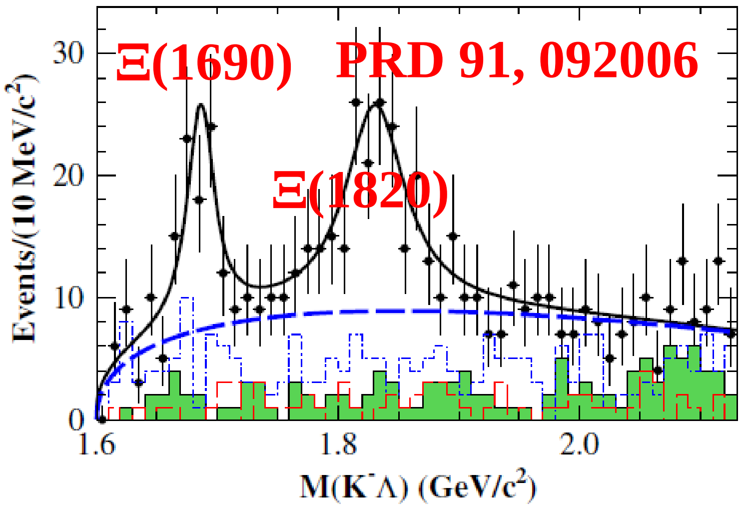
Particle	J^P	Overall status	Status as seen in — $\Xi\pi$	ΛK	ΣK	$\Xi(1530)\pi$	Other channels
$\Xi(1318)$	1/2+	****					Decays weakly
$\Xi(1530)$	3/2+	****	****				
$\Xi(1620)$		*	*				
$\Xi(1690)$		***		***	**		
$\Xi(1820)$	3/2−	***	**	***	**	**	
$\Xi(1950)$		***	**	**		*	
$\Xi(2030)$		***		**	***		
$\Xi(2120)$		*		*			
$\Xi(2250)$		**					3-body decays
$\Xi(2370)$		**					3-body decays
$\Xi(2500)$		*		*	*		3-body decays

PDG18

- **$\psi(3686)$ and $\chi_{cJ} \to K^- \Lambda \bar{\Xi}^+$ + c.c.**

$\psi(3686) \rightarrow K^{-}\Lambda\overline{\Xi}^{+}$ + c.c.

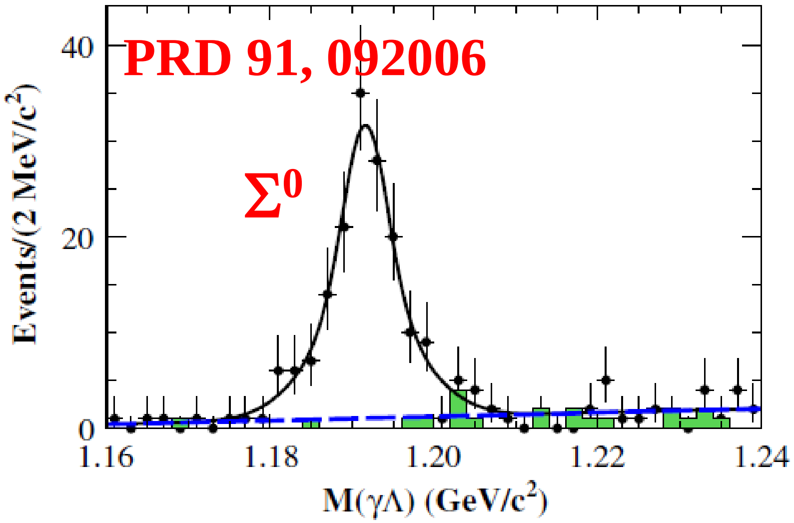


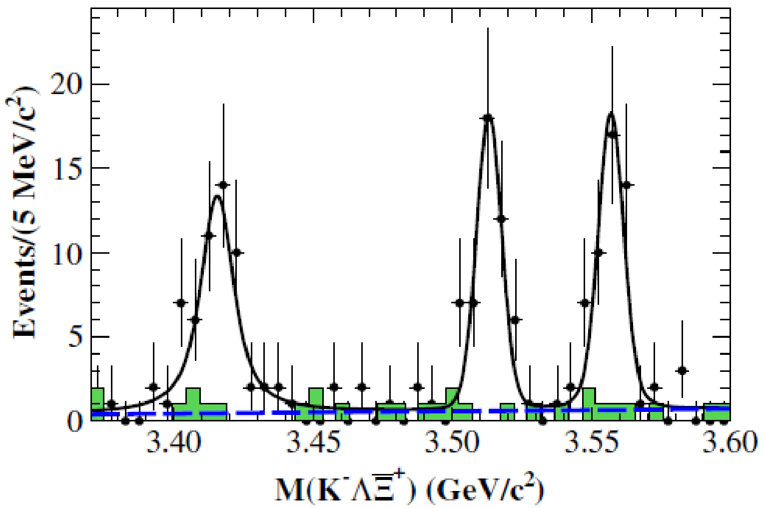


- Use $\Lambda \rightarrow p\,\pi^{-}$ and $\overline{\Xi}^{+} \rightarrow \overline{\Lambda}\,\pi^{+}$
- The resonance parameters of Ξ(1690) and Ξ(1820) are consistent with PDG.

	$\Xi(1690)^{-}$	$\Xi(1820)^{-}$
M(MeV/c^2)	$1687.7 \pm 3.8 \pm 1.0$	$1826.7 \pm 5.5 \pm 1.6$
Γ(MeV)	$27.1 \pm 10.0 \pm 2.7$	$54.4 \pm 15.7 \pm 4.2$
Event yields	74.4 ± 21.2	136.2 ± 33.4
Significance(σ)	4.9	6.2
Efficiency(%)	32.8	26.1
$\mathcal{B}(10^{-6})$	$5.21 \pm 1.48 \pm 0.57$	$12.03 \pm 2.94 \pm 1.22$
$M_{\rm PDG}$(MeV/c^2)	1690 ± 10	1823 ± 5
$\Gamma_{\rm PDG}$(MeV)	< 30	24^{+15}_{-10}

$\psi(3686) \to \gamma K^{-} \Lambda \bar{\Xi}^{+}$ + c.c.

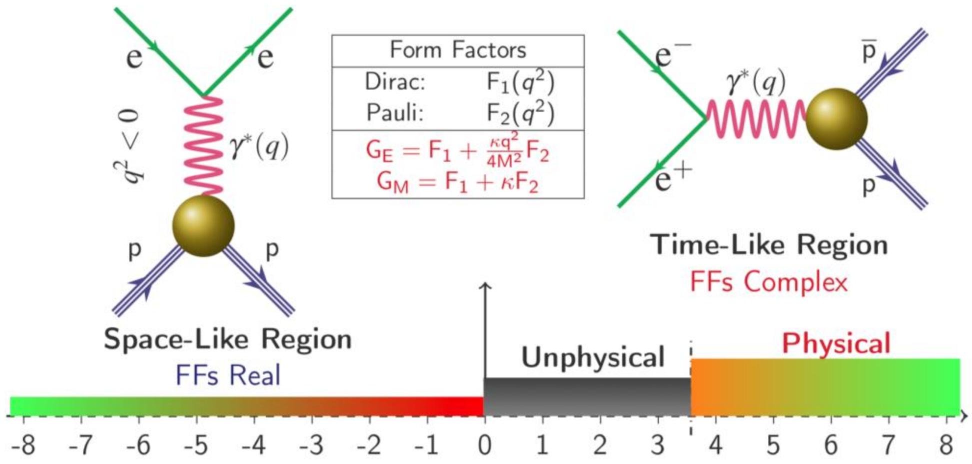


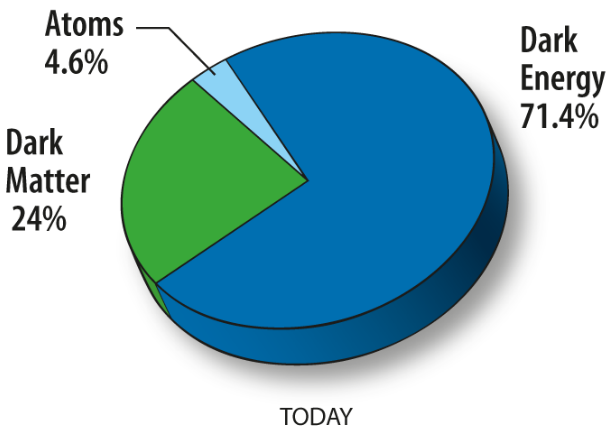


- **Use $\Lambda \to p\,\pi^-$ and $\bar{\Xi}^+ \to \bar{\Lambda}\,\pi^+$**
- **Clear Σ^0 and χ_{cJ} states with low background**

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

Form factor of nucleon





- **Hadron vertex are described by Dirac FF (F_1) & Pauli FF (F_2)**

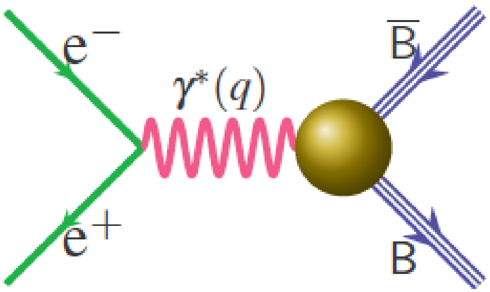
$$\Gamma_\mu(p', p) = \gamma_\mu F_1(q^2) + \frac{i\sigma_{\mu\nu}q^\nu}{2m_p} F_2(q^2)$$

- **Sachs FFs: electric G_E and magnetic G_M**

$$G_E(q^2) = F_1(q^2) + \tau\kappa_p F_2(q^2) \qquad \tau = \frac{q^2}{4m_p^2}, \quad \kappa_p = \frac{g_p - 2}{2} = \mu_p - 1$$
$$G_M(q^2) = F_1(q^2) + \kappa_p F_2(q^2)$$

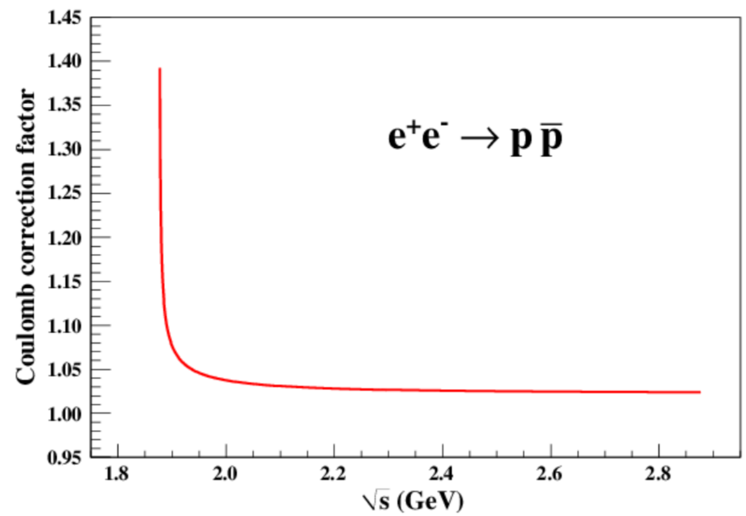
- **G_E & G_M : spatial distribution of charge and magnetization, charge density distribution**

$e^+e^- \rightarrow B\bar{B}$



- **In one-photon exchange approximation**
  - ✓ $\frac{d\sigma}{dcos\theta_B} = \frac{\pi\alpha^2\beta C}{2s^2}[|G_M|^2(1 + cos^2\theta_B) + \frac{1}{\tau}|G_M|^2 sin^2\theta_B]$
  - ✓ **Baryon velocity** $\beta = (1 - 4m_B^2/s)^{0.5}$

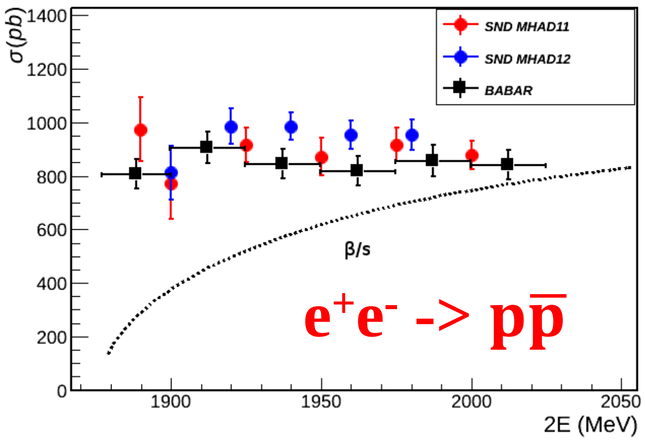
- **Coulomb factor C**
  - ✓ **for s-wave only**
  - ✓ **C=1 @ neutral**
  - ✓ $C=\frac{\pi\alpha}{\beta}\frac{1}{1-e^{-\pi\alpha/\beta}}$ **@ charged**

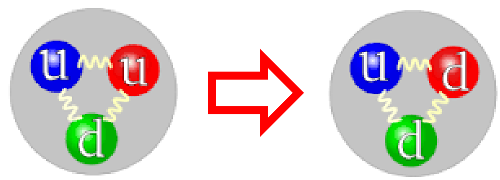


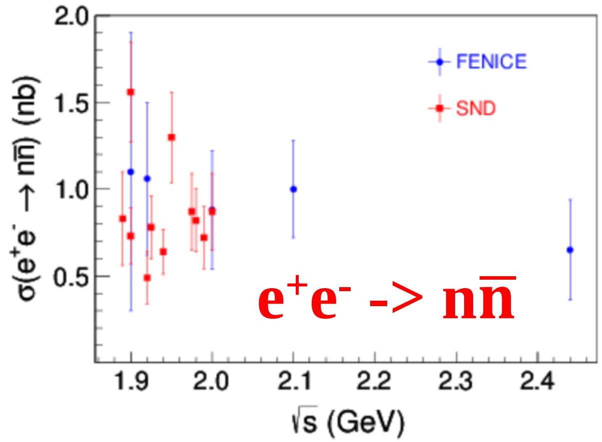
- **Cross section at threshold**
  - ✓ **Neutral baryon:** $\sigma = 0$
  - ✓ **Charged baryon:** $\sigma \neq 0$

- **Effective FF define as** $|G(s)| = \sqrt{\frac{|G_M|^2+1/2\tau|G_E|^2}{1+1/2\tau}}$**, proportional to** $\sqrt{\sigma_{Born}}$

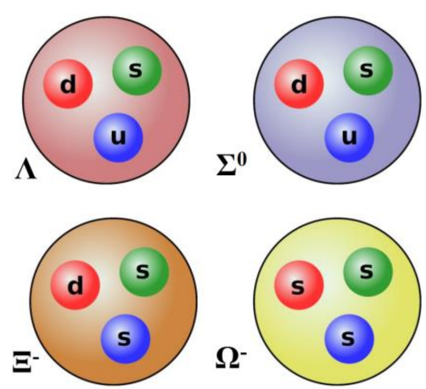
Baryon pair production

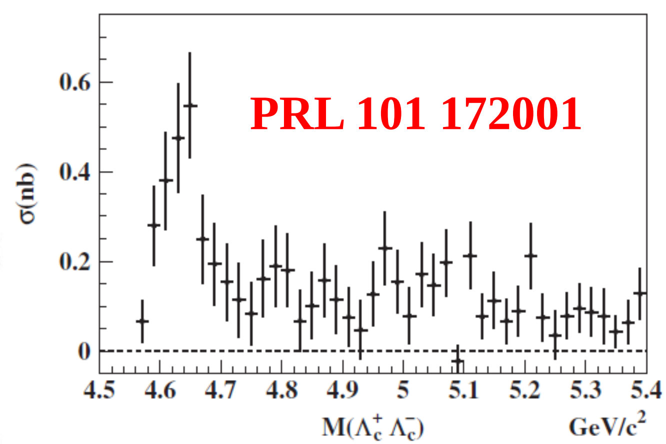




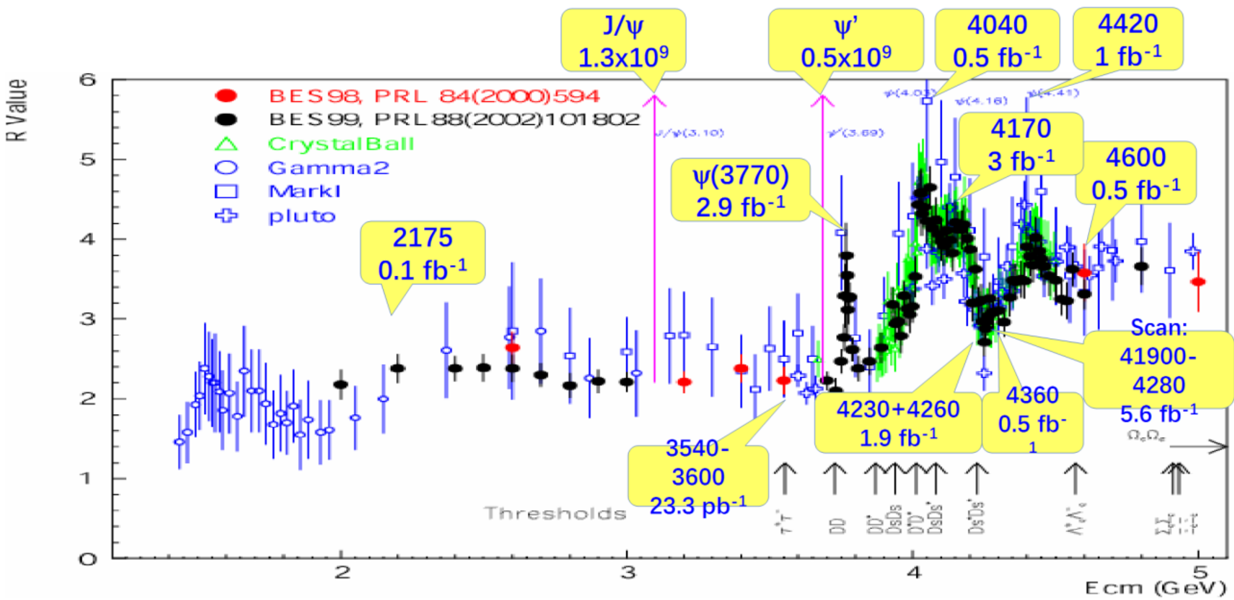


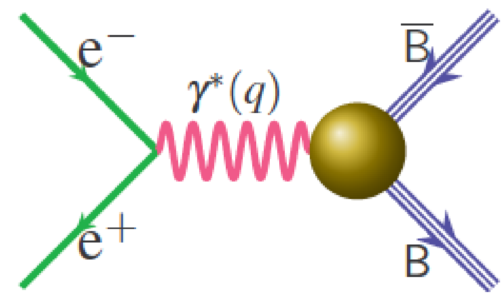
- Cross section at threshold
  - ✓ Charged: $\sigma \neq 0$
  - ✓ Neutral: $\sigma = 0$
- G_E & G_M form factor
- Search for resonance



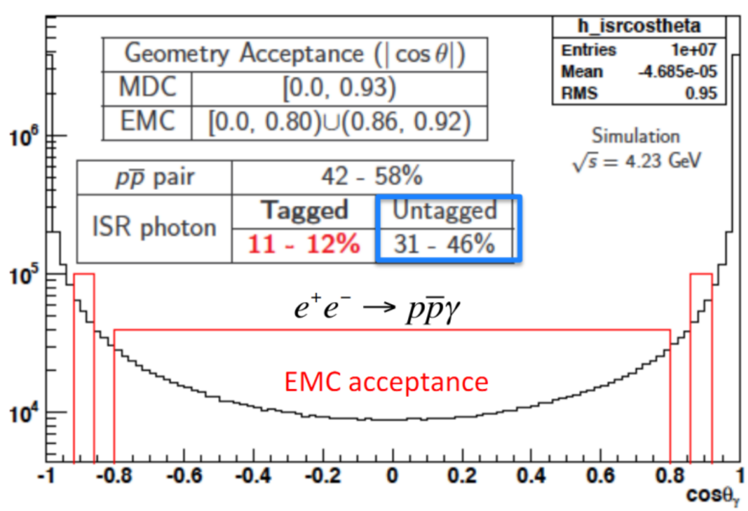


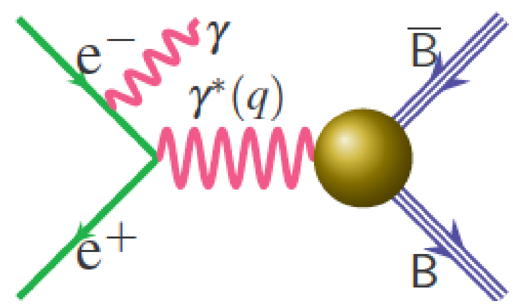
Baryon form factor @ BESIII





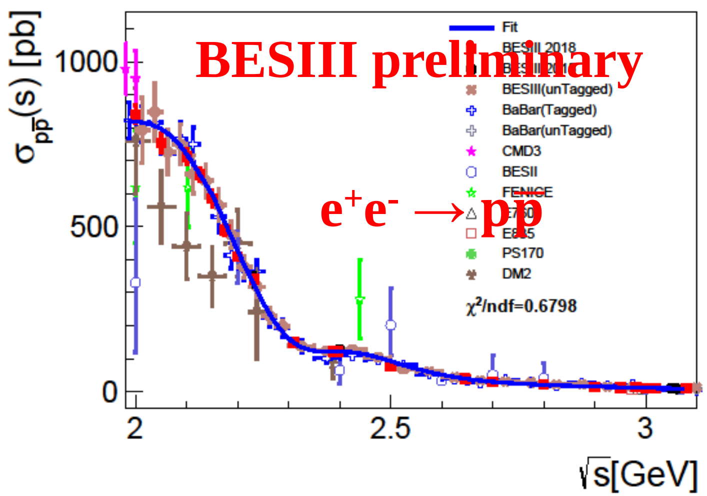
Energy scan method

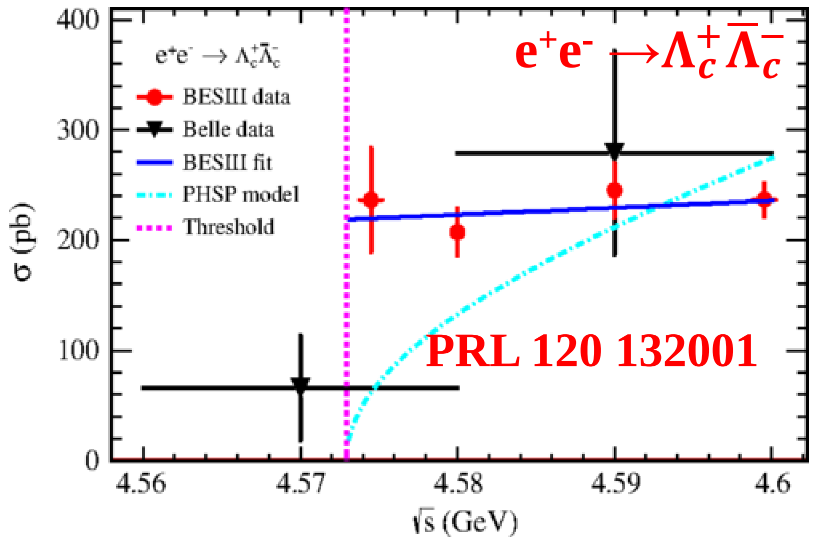


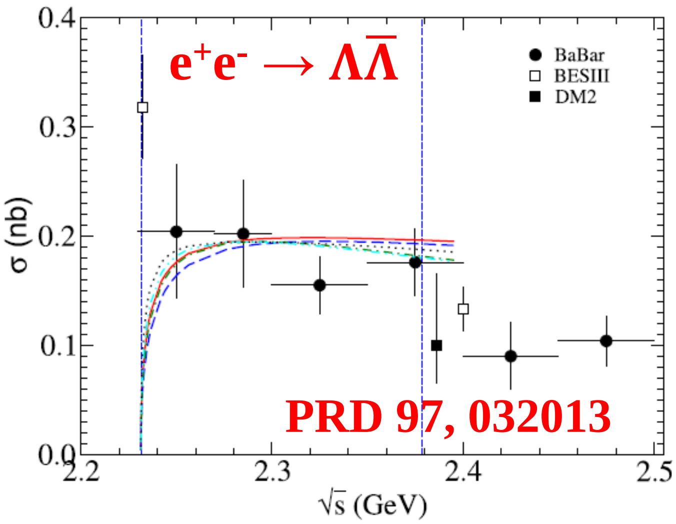


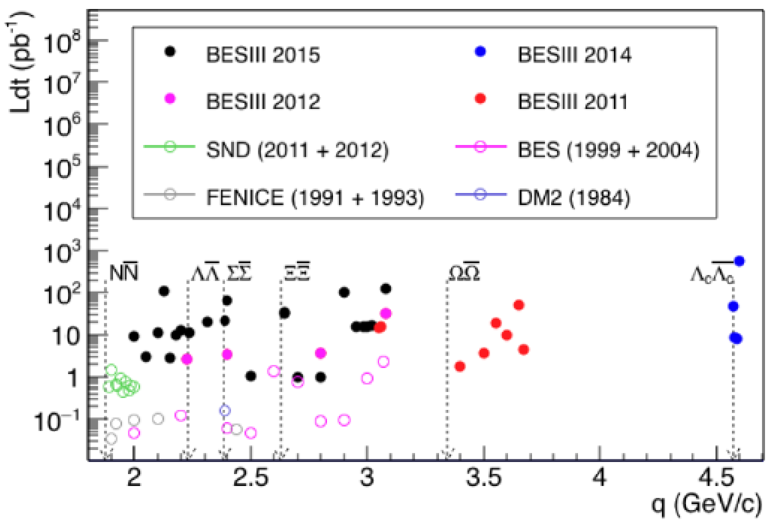
Initial state radiation (ISR) method

Threshold enhancement

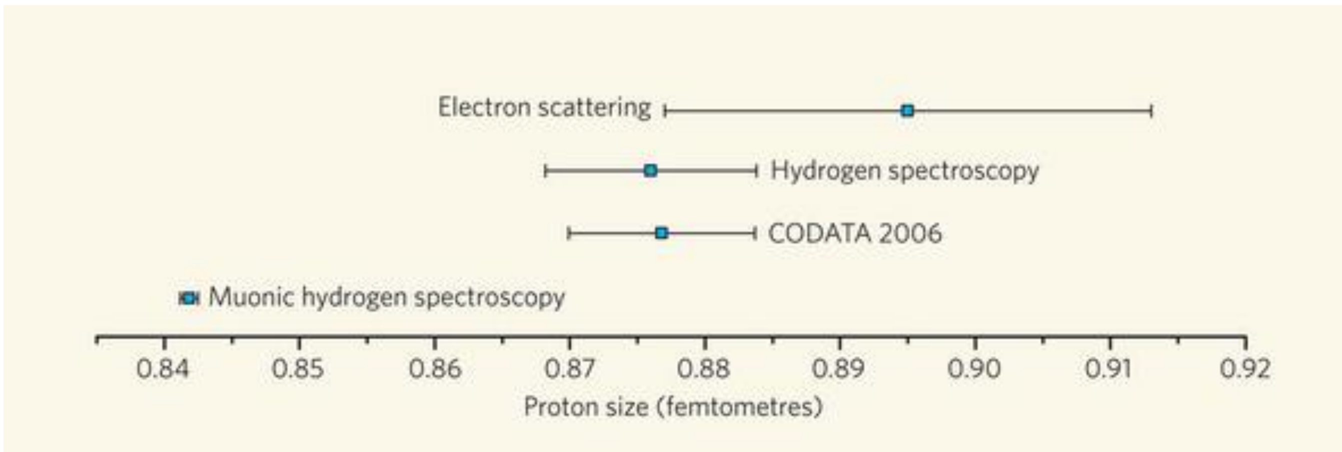


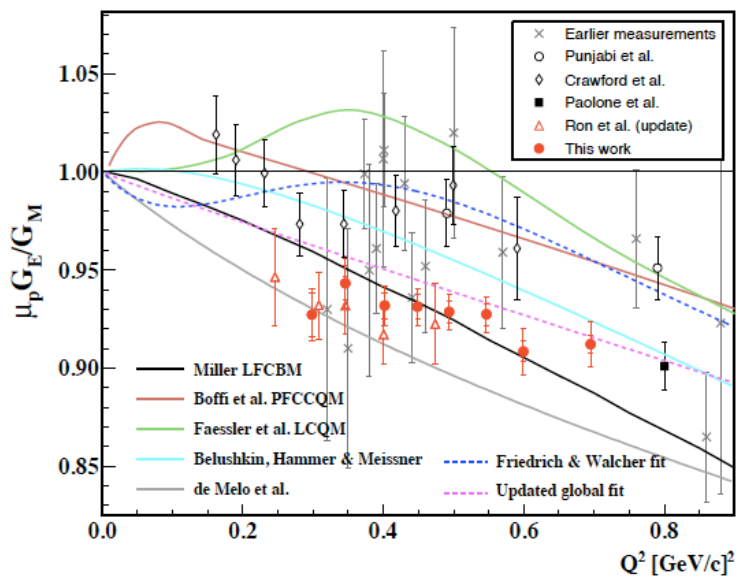


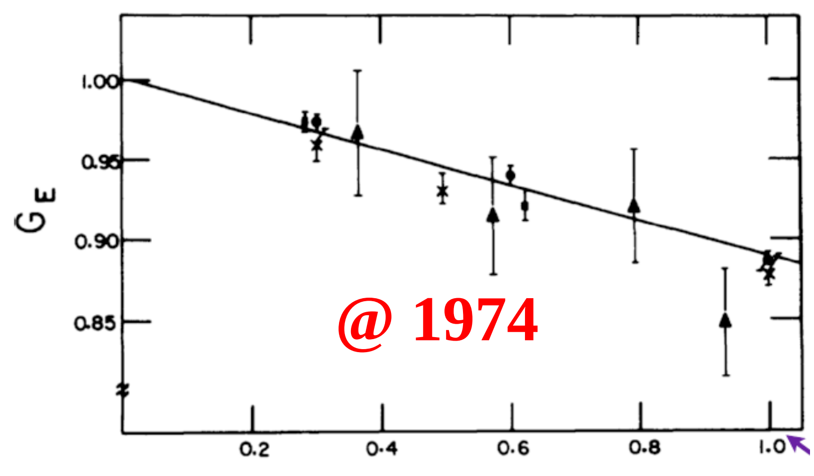




Size of proton



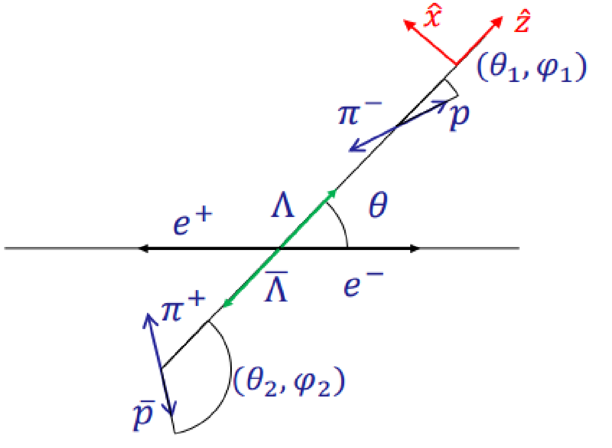




$$-6\frac{dG_{E,M}}{dQ^2}\bigg|_{Q^2=0} = \langle r^2_{E,M}\rangle \equiv r^2_{E,M}$$

Relative phase between G_E and G_M

- **Complex G_E and G_M**
  - ✓ $G_E = |G_E|e^{i\Phi_E}$, $G_M = |G_M|e^{i\Phi_M}$
  - ✓ **Relative phase:** $\Delta\Phi = \Phi_E\text{-}\Phi_M$
- **A non-zero phase has polarization effect on the baryons** $P_y \propto \sin\Delta\Phi$
- **The angular distribution of daughter baryon from hyperon weak decay is:**
  - ✓ $\frac{d\sigma}{d\Omega} \propto 1 + \alpha_\Lambda P_y \cdot \hat{q}$
  - ✓ α_Λ: **asymmetry parameter**
  - ✓ $\hat{q}$: **unit vector along the daughter baryon in hyperon rest frame**

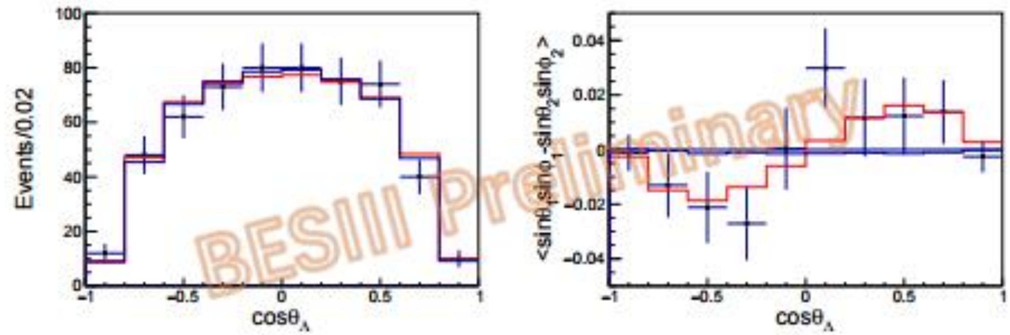


Relative phase between G_E and G_M

- **Helicity amplitude (PLB 772, 16)**

$$\begin{aligned}\mathscr{W}(\xi) =& \mathscr{T}_0(\xi)+\eta\,\mathscr{T}_5(\xi)\\ &-\alpha_\Lambda^2\left(\mathscr{T}_1(\xi)+\sqrt{1-\eta^2}\cos(\Delta\Phi)\mathscr{T}_2(\xi)+\eta\,\mathscr{T}_6(\xi)\right)\\ &+\alpha_\Lambda\sqrt{1-\eta^2}\sin(\Delta\Phi)\left(\mathscr{T}_3(\xi)-\mathscr{T}_4(\xi)\right).\end{aligned}$$

$$\begin{aligned}\mathscr{T}_0(\xi) &= 1\\ \mathscr{T}_1(\xi) &= \sin^2\theta\sin\theta_1\sin\theta_2\cos\phi_1\cos\phi_2+\cos^2\theta\cos\theta_1\cos\theta_2\\ \mathscr{T}_2(\xi) &= \sin\theta\cos\theta\,(\sin\theta_1\cos\theta_2\cos\phi_1+\cos\theta_1\sin\theta_2\cos\phi_2)\\ \mathscr{T}_3(\xi) &= \sin\theta\cos\theta\sin\theta_1\sin\phi_1\\ \mathscr{T}_4(\xi) &= \sin\theta\cos\theta\sin\theta_2\sin\phi_2\\ \mathscr{T}_5(\xi) &= \cos^2\theta\\ \mathscr{T}_6(\xi) &= \cos\theta_1\cos\theta_2-\sin^2\theta\sin\theta_1\sin\theta_2\sin\phi_1\sin\phi_2.\end{aligned}$$



$$\left|\frac{G_E}{G_M}\right| = 0.94 \pm 0.16(stat.) \pm 0.03(sys.) \pm 0.02(\alpha_\Lambda)$$

$$\Delta\Phi = 42^\circ \pm 16^\circ(stat.) \pm 8^\circ(sys.) \pm 6^\circ(\alpha_\Lambda)$$

Summary

- The charmonium provide a good platform for studying not only excited nucleon states, but also excited hyperons.
- With largest charmonium samples in the world, a new chance for N*, Λ*, Σ*, Ξ*.
- Baryon form factor G_E and G_M, threshold enhancement ?

	Previous	BESIII	BESIII Goal
J/ψ	58M @ BES	1.2B	10B
$\psi(3686)$	28M @CLEO	0.5B	3B
$\psi(3770)$	$0.8fb^{-1}$@CLEO	$2.9fb^{-1}$	$20fb^{-1}$
χ_{CJ}	$\psi(3686) \rightarrow \gamma\, \chi_{CJ}$ @ (9-10) %		
$\eta_C(1S)$	$J/\psi \rightarrow \gamma\, \eta_C(1S)$ @ 1.7 %		

Baryon form factor @ BESIII