

# Baryon-resonance spectroscopy in three-body reactions

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# Baryons

◇ Light-flavor quark system

q=u,d

Light baryons

\* poor evidence  
 \*\* fair  
 \*\*\* likely  
 \*\*\*\* well established

PDG (2020)

$p$	$1/2^+$	****	$\Delta(1232)$	$3/2^+$	****	$\Sigma^+$	$1/2^+$	****	$\Xi^0$	$1/2^+$	****	$\Xi_{cc}^{++}$	qcc	***
$n$	$1/2^+$	****	$\Delta(1600)$	$3/2^+$	****	$\Sigma^0$	$1/2^+$	****	$\Xi^-$	$1/2^+$	****	$\Lambda_b^0$	$1/2^+$	***
$N(1440)$	$1/2^+$	****	$\Delta(1620)$	$1/2^-$	****	$\Sigma^-$	$1/2^+$	****	$\Xi(1530)$	$3/2^+$	****	$\Lambda_b(5912)^0$	$1/2^-$	***
$N(1520)$	$3/2^-$	****	$\Delta(1700)$	$3/2^-$	****	$\Sigma(1385)$	$3/2^+$	****	$\Xi(1620)$	*	*	$\Lambda_b(5920)^0$	$3/2^-$	***
$N(1535)$	$1/2^-$	****	$\Delta(1750)$	$1/2^+$	*	$\Sigma(1580)$	$3/2^-$	*	$\Xi(1690)$	***	***	$\Lambda_b(6145)^0$	$3/2^+$	***
$N(1650)$	$1/2^-$	****	$\Delta(1900)$	$1/2^-$	***	$\Sigma(1620)$	$1/2^-$	*	$\Xi(1820)$	$3/2^-$	***	$\Lambda_b(6151)^0$	$3/2^+$	***
$N(1675)$	$5/2^-$	****	$\Delta(1905)$	$5/2^+$	****	$\Sigma(1660)$	$1/2^+$	***	$\Xi(1950)$	***	***	$\Lambda_b(6151)^0$	$3/2^+$	***
$N(1680)$	$5/2^+$	****	$\Delta(1910)$	$1/2^+$	****	$\Sigma(1670)$	$3/2^-$	****	$\Xi(2030)$	qss	$5/2^?$	$\Sigma_b$	$1/2^+$	***
$N(1700)$	$3/2^-$	***	$\Delta(1920)$	$3/2^+$	***	$\Sigma(1750)$	$1/2^-$	***	$\Xi(2120)$	*	*	$\Sigma_b^*$	$3/2^+$	***
$N(1710)$	$1/2^+$	****	$\Delta(1930)$	$5/2^-$	***	$\Sigma(1775)$	$5/2^-$	****	$\Xi(2250)$	**	**	$\Sigma_b(6097)^+$	***	***
$N(1720)$	$3/2^+$	****	$\Delta(1940)$	$3/2^-$	**	$\Sigma(1780)$	$3/2^+$	*	$\Xi(2370)$	**	**	$\Sigma_b(6097)^-$	***	***
$N(1860)$	$5/2^+$	**	$\Delta(1950)$	$7/2^+$	****	$\Sigma(1880)$	$1/2^+$	**	$\Xi(2500)$	*	*	$\Xi_b^0, \Xi_b^-$	$1/2^+$	***
$N(1875)$	$5/2^-$	***	$\Delta(2000)$	$5/2^+$	**	$\Sigma(1900)$	$1/2^-$	**	$\Omega^-$	$3/2^+$	****	$\Xi_b'$	$5/2^+$	***
$N(1880)$	$1/2^+$	***	$\Delta(2150)$	$1/2^-$	*	$\Sigma(1910)$	$3/2^-$	***	$\Omega(2012)^-$	$?^-$	***	$\Xi_b(5945)^0$	$3/2^+$	***
$N(1895)$	$1/2^-$	****	$\Delta(2200)$	$7/2^-$	***	$\Sigma(1915)$	$5/2^+$	****	$\Omega(2250)$	sss	***	$\Xi_b(5955)^-$	$3/2^+$	***
$N(1900)$	$3/2^+$	****	$\Delta(2300)$	$9/2^+$	**	$\Sigma(1940)$	$3/2^+$	*	$\Omega(2380)^-$	**	**	$\Xi_b(6227)$	***	***
$N(1990)$	$7/2^+$	**	$\Delta(2350)$	$5/2^-$	*	$\Sigma(2010)$	$3/2^-$	*	$\Omega(2470)^-$	**	**	$\Omega_b^-$	$1/2^+$	***
$N(2000)$	$5/2^+$	**	$\Delta(2390)$	$7/2^+$	*	$\Sigma(2030)$	$7/2^+$	****				$P_c(4312)^+$	*	*
$N(2040)$	$3/2^+$	*	$\Delta(2400)$	$9/2^-$	**	$\Sigma(2070)$	$5/2^+$	*				$P_c(4380)^+$	*	*
$N(2060)$	$5/2^-$	***	$\Delta(2420)$	$11/2^+$	****	$\Sigma(2080)$	$3/2^+$	*	$\Lambda_c^+$	$1/2^+$	****	$P_c(4440)^+$	*	*
$N(2100)$	$1/2^+$	***	$\Delta(2750)$	$13/2^-$	**	$\Sigma(2100)$	$7/2^-$	*	$\Lambda_c(2595)^+$	$1/2^-$	***	$P_c(4457)^+$	*	*
$N(2120)$	$3/2^-$	***	$\Delta(2950)$	$15/2^+$	**	$\Sigma(2160)$	$1/2^-$	*	$\Lambda_c(2625)^+$	$3/2^-$	***			
$N(2190)$	$7/2^-$	****				$\Sigma(2230)$	$3/2^+$	*	$\Lambda_c(2765)^+$	*	*			
$N(2220)$	$9/2^+$	****	$\Lambda$	$1/2^+$	****	$\Sigma(2250)$	***	***	$\Lambda_c(2850)^+$	$3/2^+$	***			
$N(2250)$	$9/2^-$	****	$\Lambda$	$1/2^-$	**	$\Sigma(2455)$	**	**	$\Lambda_c(2850)^+$	$5/2^+$	***			
$N(2300)$	$1/2^+$	**	$\Lambda(1405)$	$1/2^-$	****	$\Sigma(2620)$	**	**	$\Lambda_c(2940)^+$	$3/2^-$	***			
$N(2570)$	$5/2^-$	**	$\Lambda(1520)$	$3/2^-$	****	$\Sigma(3000)$	*	*	$\Sigma_c(2455)$	$1/2^+$	****			
$N(2600)$	$11/2^-$	***	$\Lambda(1600)$	$1/2^+$	****	$\Sigma(3170)$	*	*	$\Sigma_c(2520)$	$3/2^+$	***			
$N(2700)$	$13/2^+$	**	$\Lambda(1670)$	$1/2^-$	****				$\Sigma_c(2800)$	***	***			
			$\Lambda(1690)$	$3/2^-$	****				$\Xi_c^+$	$1/2^+$	***			
			$\Lambda(1710)$	$1/2^+$	*				$\Xi_c^0$	$1/2^+$	****			
			$\Lambda(1800)$	$1/2^-$	***				$\Xi_c^+$	$1/2^+$	***			
			$\Lambda(1810)$	$1/2^+$	***				$\Xi_c^0$	$1/2^+$	***			
			$\Lambda(1820)$	$5/2^+$	****				$\Xi_c(2645)$	$3/2^+$	***			
			$\Lambda(1830)$	$5/2^-$	****				$\Xi_c(2700)$	$1/2^-$	***			
			$\Lambda(1890)$	$3/2^+$	****				$\Xi_c(2815)$	$3/2^-$	***			
			$\Lambda(2000)$	$1/2^-$	*				$\Xi_c(2930)$	**	**			
			$\Lambda(2050)$	$3/2^-$	*				$\Xi_c(2970)$	***	***			
			$\Lambda(2070)$	$3/2^+$	*				$\Xi_c(3055)$	***	***			
			$\Lambda(2080)$	$5/2^-$	*				$\Xi_c(3080)$	***	***			
			$\Lambda(2085)$	$7/2^+$	**				$\Xi_c(3123)$	*	*			
			$\Lambda(2100)$	$7/2^-$	****									
			$\Lambda(2110)$	$5/2^+$	***				$\Omega_c^u$	$1/2^+$	***			
			$\Lambda(2325)$	$3/2^-$	*				$\Omega_c(2770)^0$	$3/2^+$	***			
			$\Lambda(2350)$	$9/2^+$	***				$\Omega_c(3000)^0$	***	***			
			$\Lambda(2585)$	**	**				$\Omega_c(3050)$	***	***			
									$\Omega_c(3065)^0$	***	***			
									$\Omega_c(3090)^0$	***	***			
									$\Omega_c(3120)^0$	***	***			

◇ Heavy + Light quark system

Bottom baryons

Pentaquark states (from 2020)

Charmed baryons

# Baryons

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PDG (2024)

p	1/2 <sup>+</sup>	****	Δ(1232)	3/2 <sup>+</sup>	****	Σ <sup>+</sup>	1/2 <sup>+</sup>	****	Λ <sub>c</sub> <sup>+</sup>	1/2 <sup>+</sup>	****	Λ <sub>b</sub> <sup>0</sup>	1/2 <sup>+</sup>	***
n	1/2 <sup>+</sup>	****	Δ(1600)	3/2 <sup>+</sup>	****	Σ <sup>0</sup>	1/2 <sup>+</sup>	****	Λ <sub>c</sub> (2595) <sup>+</sup>	1/2 <sup>-</sup>	***	Λ <sub>b</sub> (5912) <sup>0</sup>	1/2 <sup>-</sup>	***
N(1440)	1/2 <sup>+</sup>	****	Δ(1620)	1/2 <sup>-</sup>	****	Σ <sup>-</sup>	1/2 <sup>+</sup>	****	Λ <sub>c</sub> (2625) <sup>+</sup>	3/2 <sup>-</sup>	***	Λ <sub>b</sub> (5920) <sup>0</sup>	3/2 <sup>-</sup>	***
N(1520)	3/2 <sup>-</sup>	****	Δ(1700)	3/2 <sup>-</sup>	****	Σ(1385)	3/2 <sup>+</sup>	****	Λ <sub>c</sub> (2765) <sup>+</sup>	*		Λ <sub>b</sub> (6070) <sup>0</sup>	1/2 <sup>+</sup>	***
N(1535)	1/2 <sup>-</sup>	****	Δ(1750)	1/2 <sup>+</sup>	*	Σ(1580)	3/2 <sup>-</sup>	*	Λ <sub>c</sub> (2800) <sup>0</sup>	1/2 <sup>+</sup>	***	Λ <sub>b</sub> (6146) <sup>0</sup>	3/2 <sup>+</sup>	***
N(1650)	1/2 <sup>-</sup>	****	Δ(1900)	1/2 <sup>-</sup>	***	Σ(1620)	1/2 <sup>-</sup>	*	Λ <sub>c</sub> (2880) <sup>+</sup>	5/2 <sup>+</sup>	***	Λ <sub>b</sub> (6100) <sup>0</sup>	1/2 <sup>+</sup>	***
N(1675)	5/2 <sup>-</sup>	****	Δ(1905)	5/2 <sup>+</sup>	****	Σ(1660)	1/2 <sup>+</sup>	***	Λ <sub>c</sub> (2910) <sup>+</sup>	*		Σ <sub>b</sub>	1/2 <sup>+</sup>	***
N(1680)	5/2 <sup>+</sup>	****	Δ(1910)	1/2 <sup>+</sup>	****	Σ(1670)	3/2 <sup>-</sup>	****	Λ <sub>c</sub> (2940) <sup>+</sup>	3/2 <sup>-</sup>	***	Σ <sub>b</sub> <sup>*</sup>	3/2 <sup>+</sup>	***
N(1700)	3/2 <sup>-</sup>	***	Δ(1920)	3/2 <sup>+</sup>	***	Σ(1750)	1/2 <sup>-</sup>	***	Σ <sub>c</sub> (2455)	1/2 <sup>+</sup>	****	Σ <sub>b</sub> (6097) <sup>+</sup>		***
N(1710)	1/2 <sup>+</sup>	****	Δ(1930)	5/2 <sup>-</sup>	***	Σ(1775)	5/2 <sup>-</sup>	****	Σ <sub>c</sub> (2520)	3/2 <sup>+</sup>	***	Σ <sub>c</sub> (6097) <sup>-</sup>		***
N(1720)	3/2 <sup>+</sup>	****	Δ(1940)	3/2 <sup>-</sup>	**	Σ(1780)	3/2 <sup>+</sup>	*	Σ <sub>c</sub> (2800)		***	Ξ <sub>b</sub> <sup>-</sup>	1/2 <sup>+</sup>	***
N(1860)	3/2 <sup>+</sup>	**	Δ(1950)	5/2 <sup>+</sup>	****	Σ(1880)	1/2 <sup>+</sup>	**	Ξ <sub>c</sub> <sup>+</sup>	1/2 <sup>+</sup>	***	Ξ <sub>b</sub> <sup>0</sup>	1/2 <sup>+</sup>	***
N(1875)	3/2 <sup>-</sup>	***	Δ(2000)	5/2 <sup>+</sup>	**	Σ(1900)	1/2 <sup>-</sup>	**	Ξ <sub>c</sub> <sup>0</sup>	1/2 <sup>+</sup>	****	Ξ <sub>b</sub> (5935) <sup>-</sup>	1/2 <sup>+</sup>	***
N(1880)	1/2 <sup>+</sup>	***	Δ(2150)	1/2 <sup>-</sup>	*	Σ(1910)	3/2 <sup>-</sup>	****	Ξ <sub>c</sub> <sup>+</sup>	1/2 <sup>+</sup>	***	Ξ <sub>b</sub> (5912) <sup>0</sup>	3/2 <sup>+</sup>	***
N(1895)	1/2 <sup>-</sup>	****	Δ(2200)	7/2 <sup>-</sup>	***	Σ(1915)	5/2 <sup>+</sup>	****	Ξ <sub>c</sub> <sup>0</sup>	1/2 <sup>+</sup>	***	Ξ <sub>b</sub> (5935) <sup>0</sup>	3/2 <sup>+</sup>	***
N(1900)	3/2 <sup>+</sup>	****	Δ(2300)	9/2 <sup>+</sup>	**	Σ(1940)	3/2 <sup>+</sup>	*	Ξ <sub>c</sub> (2455)	3/2 <sup>+</sup>	***	Ξ <sub>b</sub> (6087) <sup>0</sup>	3/2 <sup>-</sup>	***
N(1990)	7/2 <sup>+</sup>	**	Δ(2350)	5/2 <sup>-</sup>	*	Σ(2010)	3/2 <sup>-</sup>	*	Ξ <sub>c</sub> (2790)	1/2 <sup>-</sup>	***	Ξ <sub>b</sub> (6095) <sup>0</sup>	3/2 <sup>-</sup>	***
N(2000)	5/2 <sup>+</sup>	**	Δ(2390)	7/2 <sup>+</sup>	*	Σ(2030)	7/2 <sup>+</sup>	****	Ξ <sub>c</sub> (2815)	3/2 <sup>-</sup>	***	Ξ <sub>b</sub> (6100) <sup>-</sup>	3/2 <sup>-</sup>	***
N(2040)	3/2 <sup>+</sup>	*	Δ(2400)	9/2 <sup>-</sup>	**	Σ(2070)	5/2 <sup>+</sup>	*	Ξ <sub>c</sub> (2882)	*		Ξ <sub>b</sub> (6227) <sup>-</sup>		***
N(2060)	5/2 <sup>-</sup>	***	Δ(2420)	11/2 <sup>+</sup>	****	Σ(2080)	3/2 <sup>+</sup>	*	Ξ <sub>c</sub> (2923)	**		Ξ <sub>b</sub> (6227) <sup>0</sup>		***
N(2100)	1/2 <sup>+</sup>	***	Δ(2750)	13/2 <sup>-</sup>	**	Σ(2100)	7/2 <sup>-</sup>	*	Ξ <sub>c</sub> (2930)	**		Ξ <sub>b</sub> (6327) <sup>0</sup>		***
N(2120)	3/2 <sup>-</sup>	***	Δ(2950)	15/2 <sup>+</sup>	**	Σ(2110)	1/2 <sup>-</sup>	*	Ξ <sub>c</sub> (2970)	1/2 <sup>+</sup>	***	Ξ <sub>b</sub> (6333) <sup>0</sup>		***
N(2190)	7/2 <sup>-</sup>	****				Σ(2230)	3/2 <sup>+</sup>	*	Ξ <sub>c</sub> (3055)		***	Ω <sub>b</sub> <sup>-</sup>	1/2 <sup>+</sup>	***
N(2220)	9/2 <sup>+</sup>	****	Λ	1/2 <sup>+</sup>	****	Σ(2250)	**		Ξ <sub>c</sub> (3080)		***	Ω <sub>b</sub> (6316) <sup>-</sup>		***
N(2250)	9/2 <sup>-</sup>	****	Λ(1380)	1/2 <sup>-</sup>	**	Σ(2455)	*		Ξ <sub>c</sub> (3123)	*		Ω <sub>b</sub> (6335) <sup>-</sup>		***
N(2300)	1/2 <sup>+</sup>	**	Λ(1405)	1/2 <sup>-</sup>	****	Σ(2620)	*		Ω <sub>c</sub> <sup>0</sup>	1/2 <sup>+</sup>	***	Ω <sub>b</sub> (6340) <sup>-</sup>		***
N(2570)	5/2 <sup>-</sup>	**	Λ(1520)	3/2 <sup>-</sup>	****	Σ(3000)	*		Ω <sub>c</sub> (2770) <sup>0</sup>	3/2 <sup>+</sup>	***	Ω <sub>b</sub> (6350) <sup>-</sup>		***
N(2600)	11/2 <sup>-</sup>	***	Λ(1600)	1/2 <sup>+</sup>	****	Σ(3170)	*		Ω <sub>c</sub> (3000) <sup>0</sup>		***	P <sub>cc</sub> (4312) <sup>+</sup>	*	
N(2700)	13/2 <sup>+</sup>	**	Λ(1670)	1/2 <sup>-</sup>	****				Ω <sub>c</sub> (3065) <sup>0</sup>		***	P <sub>cc</sub> (4380) <sup>+</sup>	*	
			Λ(1690)	3/2 <sup>-</sup>	****				Ω <sub>c</sub> (3090) <sup>0</sup>		***	P <sub>cc</sub> (4459) <sup>-</sup>	*	
			Λ(1710)	1/2 <sup>+</sup>	*	Ξ <sup>0</sup>	1/2 <sup>+</sup>	****	Ω <sub>c</sub> (3120) <sup>0</sup>		***	P <sub>ccs</sub> (4459) <sup>0</sup>	*	
			Λ(1800)	1/2 <sup>-</sup>	***	Ξ <sup>-</sup>	1/2 <sup>+</sup>	****	Ω <sub>c</sub> (3185) <sup>0</sup>		***			
			Λ(1810)	1/2 <sup>+</sup>	***	Ξ(1530)	3/2 <sup>+</sup>	****	Ω <sub>c</sub> (3227) <sup>0</sup>		***			
			Λ(1870)	1/2 <sup>+</sup>	****	Ξ(1620)	**							
			Λ(1830)	5/2 <sup>-</sup>	****	Ξ(1690)	***							
			Λ(1890)	3/2 <sup>+</sup>	****	Ξ(1820)	5/2 <sup>-</sup>	***						
			Λ(2000)	1/2 <sup>-</sup>	*	Ξ(1950)	***							
			Λ(2050)	3/2 <sup>-</sup>	*	Ξ(2030)	≥5/2?	***						
			Λ(2070)	3/2 <sup>+</sup>	*	Ξ(2120)	*							
			Λ(2080)	5/2 <sup>-</sup>	**	Ξ(2250)	**							
			Λ(2085)	7/2 <sup>+</sup>	**	Ξ(2370)	**							
			Λ(2100)	7/2 <sup>-</sup>	****	Ξ(2500)	*							
			Λ(2110)	5/2 <sup>+</sup>	***									
			Λ(2325)	3/2 <sup>-</sup>	*	Ω <sup>-</sup>	3/2 <sup>+</sup>	****						
			Λ(2350)	9/2 <sup>+</sup>	***	Ω(2010) <sup>-</sup>	***							
			Λ(2585)	*		Ω(2250) <sup>-</sup>	***							
						Ω(2380) <sup>-</sup>	**							
						Ω(2470) <sup>-</sup>	**							

# Baryons

◇ Light-flavor quark system

q=u,d

Light baryons →

□ Missing Resonance Puzzle:  
More baryon resonances are predicted by quark models than are observed in experiments.

PDG 2010	PDG 2012
	$N(1860, \frac{5}{2}^+)$ **
	$N(1875, \frac{3}{2}^-)$ ***
	$N(1895, \frac{1}{2}^-)$ **
$F_{15}(2000)$ **	$N(2000, \frac{5}{2}^+)$ **
$D_{13}(2080)$ **	$N(2060, \frac{5}{2}^-)$ **
$S_{11}(2090)$ *	$N(2120, \frac{3}{2}^-)$ **
$D_{15}(2200)$ **	

\* poor evidence  
\*\* fair  
\*\*\* likely  
\*\*\*\* well established

PDG (2024)

$\Lambda_c^+$	1/2 <sup>+</sup>	****
$\Lambda_c(2595)^+$	1/2 <sup>-</sup>	***
$\Lambda_c(2625)^+$	3/2 <sup>-</sup>	***
$\Lambda_c(2765)^+$	*	
$\Lambda_c(2845)^+$	1/2 <sup>+</sup>	***
$\Lambda_c(2880)^+$	5/2 <sup>+</sup>	***
$\Lambda_c(2910)^+$	*	
$\Lambda_c(2940)^+$	3/2 <sup>-</sup>	***
$\Sigma_c(2455)$	1/2 <sup>+</sup>	****
$\Sigma_c(2520)$	3/2 <sup>+</sup>	***
$\Sigma_c(2800)$		***
$\Xi_c^+$	1/2 <sup>+</sup>	***
$\Xi_c^0$	1/2 <sup>+</sup>	****
$\Xi_c^+$	1/2 <sup>+</sup>	***
$\Xi_c^0$	1/2 <sup>+</sup>	***
$\Xi_c(2455)$	3/2 <sup>+</sup>	***
$\Xi_c(2790)$	1/2 <sup>-</sup>	***
$\Xi_c(2815)$	3/2 <sup>-</sup>	***
$\Xi_c(2882)$	*	
$\Xi_c(2923)$	**	
$\Xi_c(2930)$	**	
$\Xi_c(2970)$	1/2 <sup>+</sup>	***
$\Xi_c(3055)$		***
$\Xi_c(3080)$		***
$\Xi_c(3123)$	*	
$\Omega_c^0$	1/2 <sup>+</sup>	***
$\Omega_c(2770)^0$	3/2 <sup>+</sup>	***
$\Omega_c(3000)^0$		***
$\Omega_c(3050)^0$		***
$\Omega_c(3065)^0$		***
$\Omega_c(3090)^0$		***
$\Omega_c(3120)^0$		***
$\Omega_c(3185)^0$		***
$\Omega_c(3327)^0$		***
$\Xi_{cc}^+$		*
$\Xi_{cc}^{++}$		***

$\Lambda_b^0$	1/2 <sup>+</sup>	***
$\Lambda_b(5912)^0$	1/2 <sup>-</sup>	***
$\Lambda_b(5920)^0$	3/2 <sup>-</sup>	***
$\Lambda_b(6070)^0$	1/2 <sup>+</sup>	***
$\Lambda_b(6146)^0$	3/2 <sup>+</sup>	***
$\Lambda_b(6180)^0$	1/2 <sup>+</sup>	***
$\Sigma_b$	1/2 <sup>+</sup>	***
$\Sigma_b^*$	3/2 <sup>+</sup>	***
$\Sigma_b(6097)^+$		***
$\Sigma_b(6097)^-$		***
$\Xi_b^-$	1/2 <sup>+</sup>	***
$\Xi_b^0$	1/2 <sup>+</sup>	***
$\Xi_b(5935)^-$	1/2 <sup>+</sup>	***
$\Xi_b(5935)^0$	3/2 <sup>+</sup>	***
$\Xi_b(5935)^+$	3/2 <sup>+</sup>	***
$\Xi_b(6087)^0$	3/2 <sup>-</sup>	***
$\Xi_b(6095)^0$	3/2 <sup>-</sup>	***
$\Xi_b(6100)^-$	3/2 <sup>-</sup>	***
$\Xi_b(6227)^-$		***
$\Xi_b(6227)^0$		***
$\Xi_b(6327)^0$		***
$\Xi_b(6333)^0$		***
$\Omega_b^-$	1/2 <sup>+</sup>	***
$\Omega_b(6316)^-$		***
$\Omega_b(6330)^-$		***
$\Omega_b(6340)^-$		***
$\Omega_b(6350)^-$		***
$P_{cc}(4312)^+$	*	
$P_{cc}(4380)^+$	*	
$P_{cc}(4440)^+$	*	
$P_{cc}(4459)^0$	*	

◇ Heavy + Light quark system

Bottom baryons

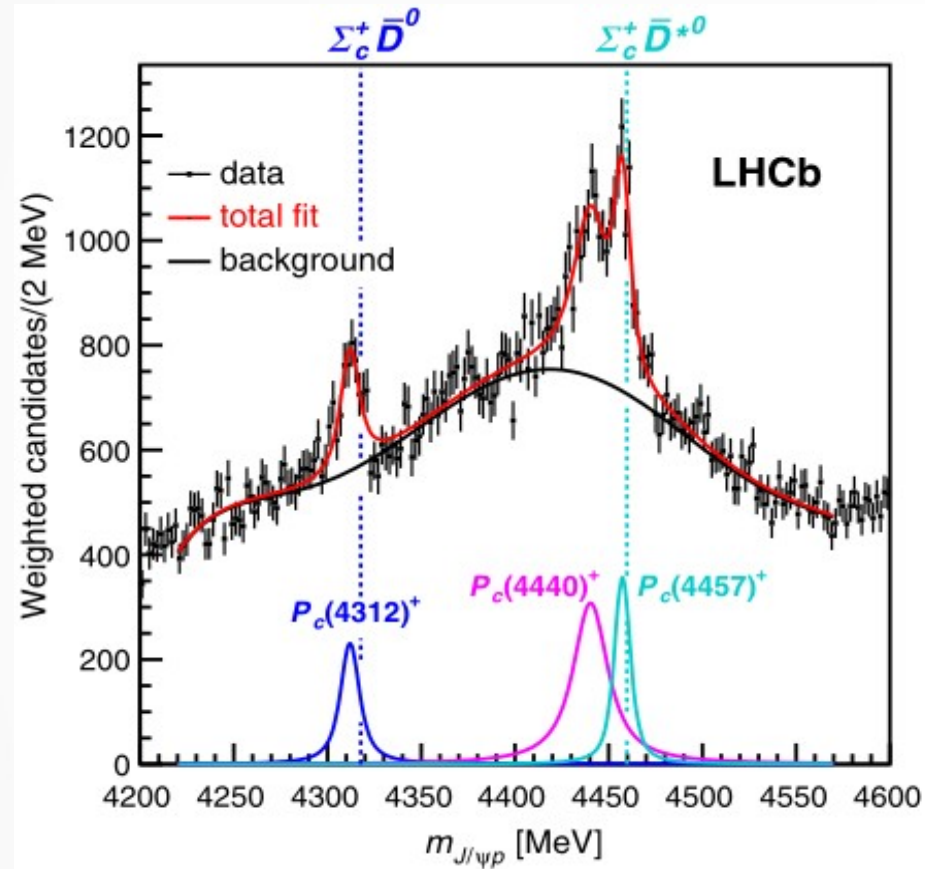
Pentaquark states

Charmed baryons

# 1. introduction

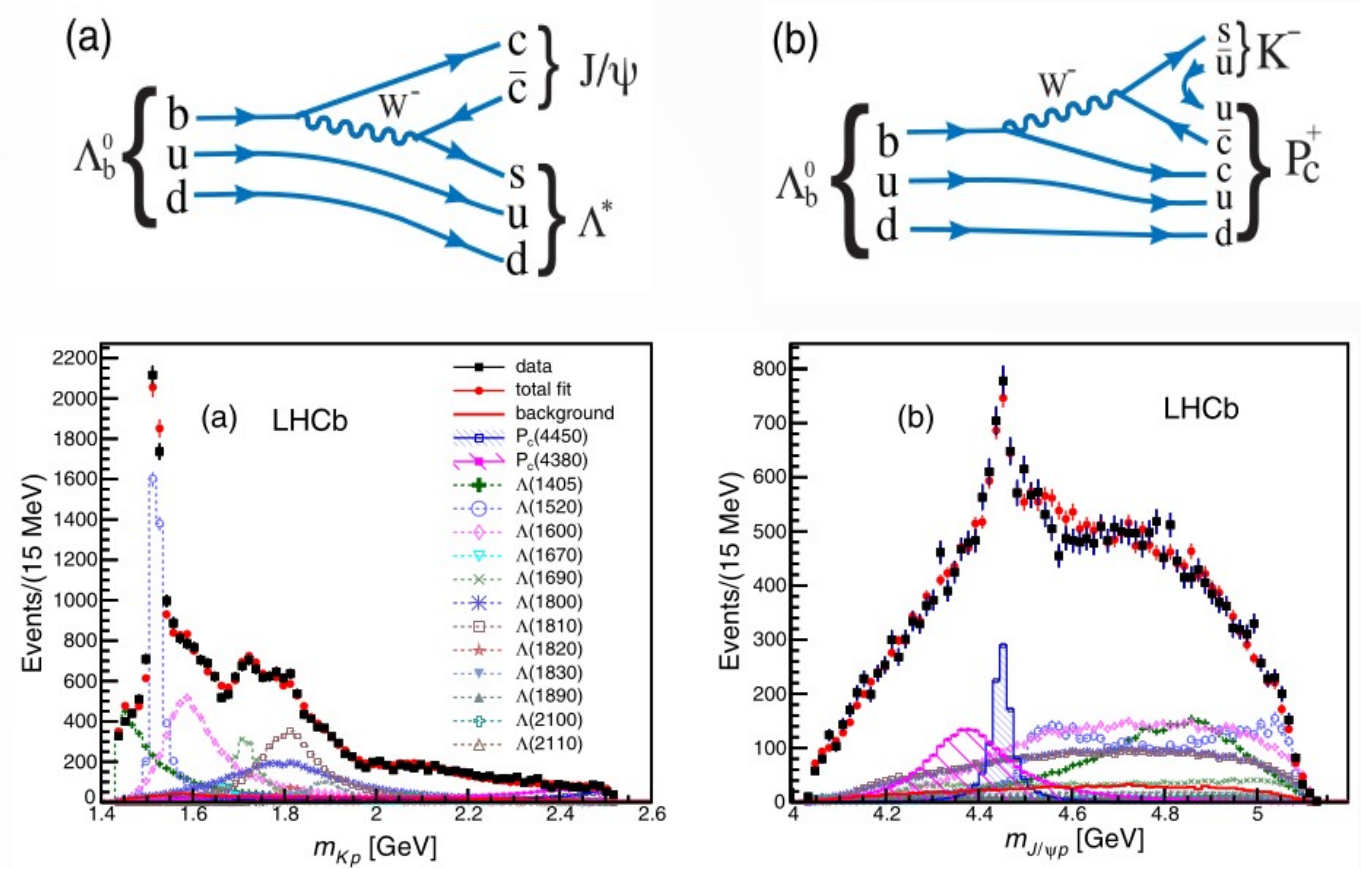
□ The heavy pentaquark states,  $P_c$  [ $uudc\bar{c}$ ], were observed in the weak decays “ $\Lambda_b^0 \rightarrow J/\psi p K^-$ ”.

[PRL.122.222001 (2019), PRL.128.062001 (2022)]



State	$M$ [MeV]	$\Gamma$ [MeV]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.1}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+5.7}_{-1.9}$

[PRL.115.072001 (2015)]

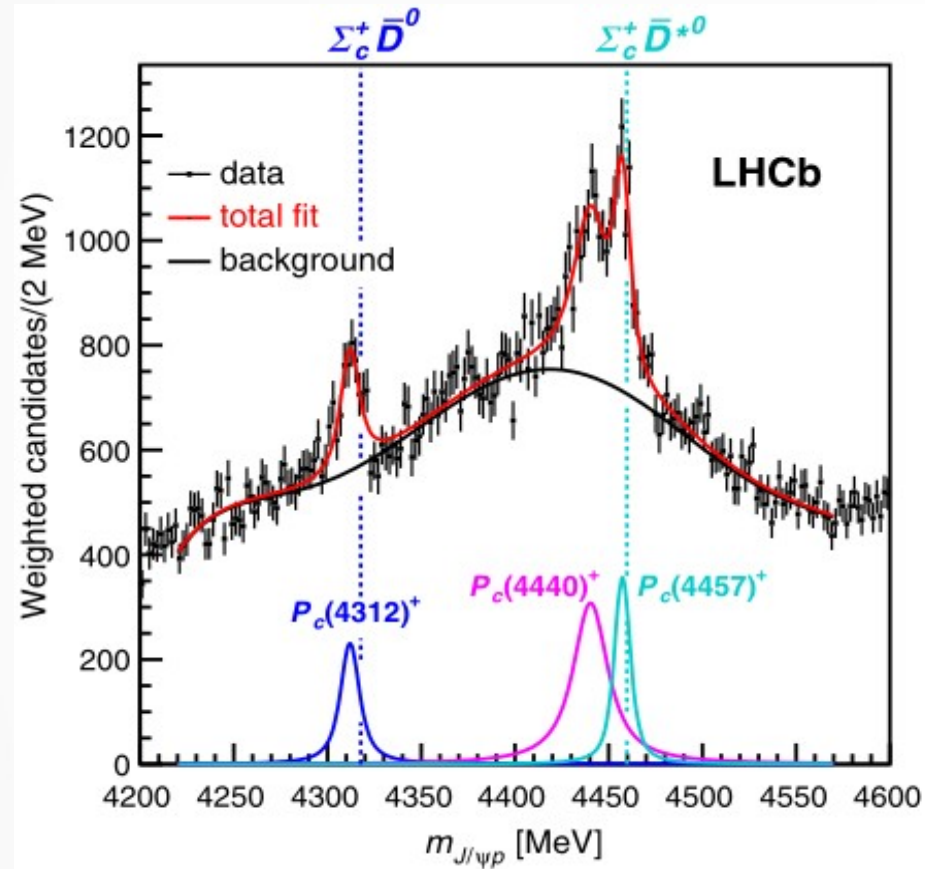


State	$M$ [MeV]	$\Gamma$ [MeV]
$P_c(4380)$	$4380 \pm 8 \pm 29$	$205 \pm 18 \pm 86$
$P_c(4450)$	$4449.8 \pm 1.7 \pm 2.5$	$39 \pm 5 \pm 19$

# 1. introduction

□ The heavy pentaquark states,  $P_c$  [ $uudc\bar{c}$ ], were observed in the weak decays “ $\Lambda_b^0 \rightarrow J/\psi p K^-$ ”.

[PRL.122.222001 (2019), PRL.128.062001 (2022)]



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$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+5.7}_{-1.9}$

□ Candidates of exotic structures?

Compact multiquarks

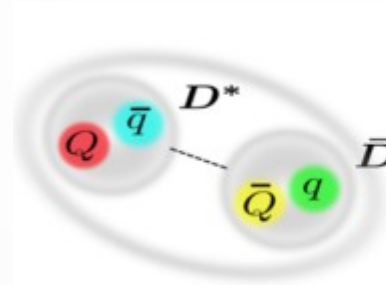


Tetraquark

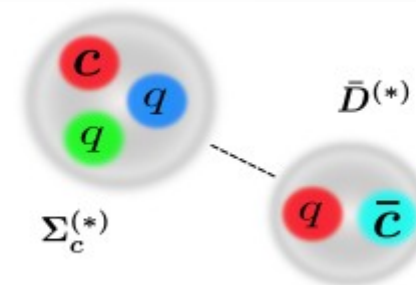


Pentaquark

Hadronic molecules

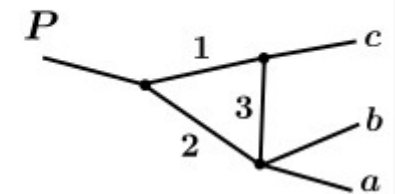


Meson-Meson



Baryon-Meson

Triangle Singularity

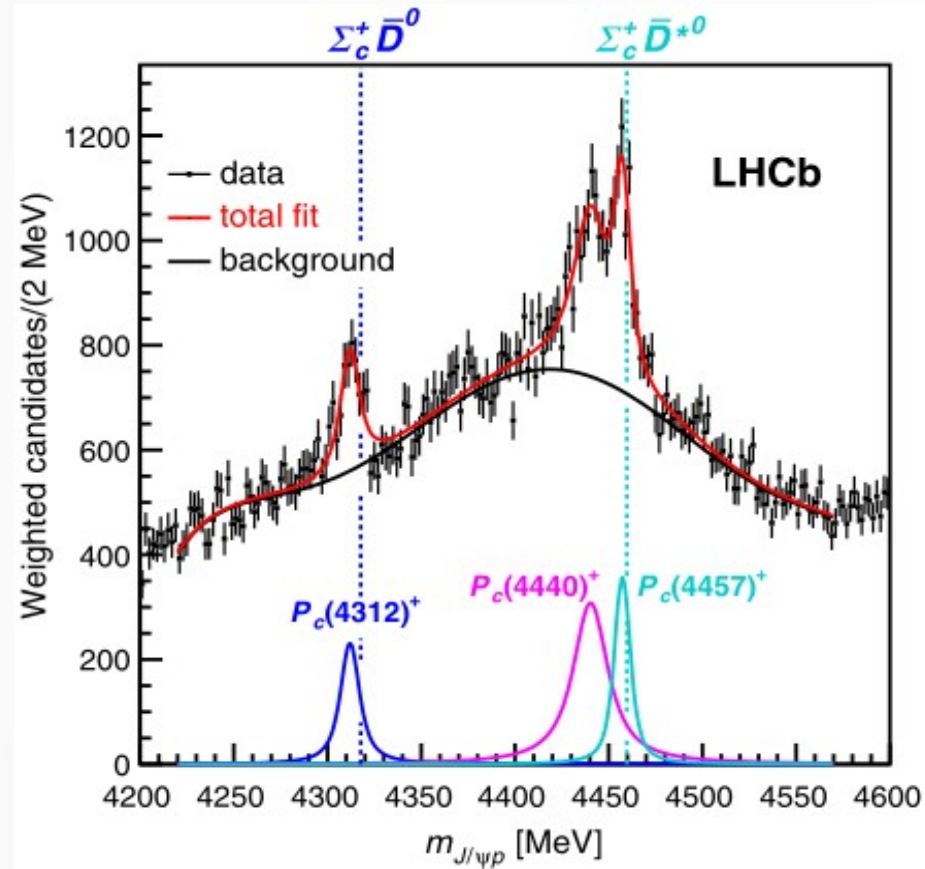


not Resonance

# 1. introduction

□ The heavy pentaquark states,  $P_c$  [ $uudc\bar{c}$ ], were observed in the weak decays “ $\Lambda_b^0 \rightarrow J/\psi p K^-$ ”.

[PRL.122.222001 (2019), PRL.128.062001 (2022)]



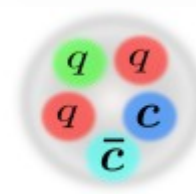
State	$M$ [MeV]	$\Gamma$ [MeV]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$
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$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+5.7}_{-1.9}$

□ Candidates of exotic structures?

Compact multiquarks

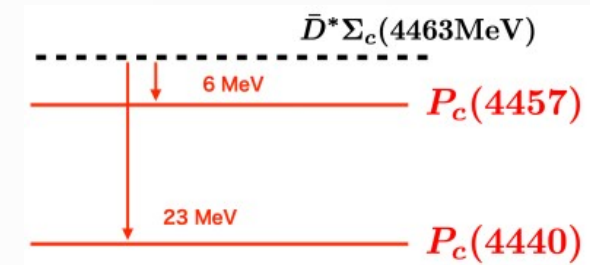


Tetraquark

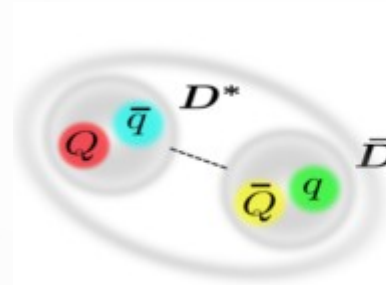


Pentaquark

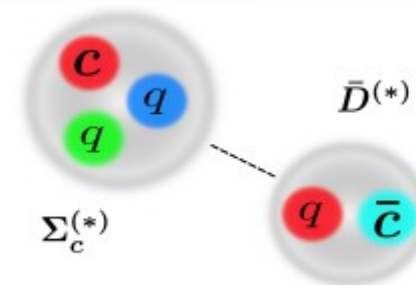
$P_c = D^{(*)} \Sigma_c$  molecules?



Hadronic molecules



Meson-Meson



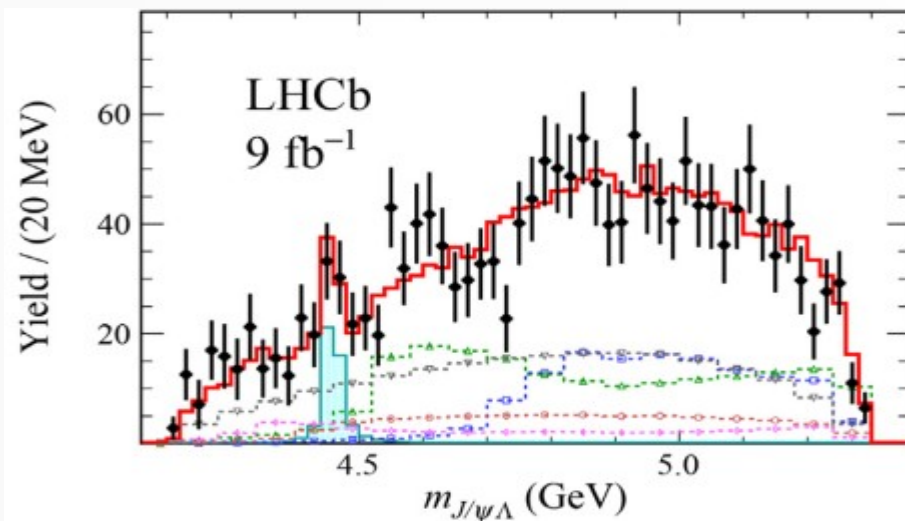
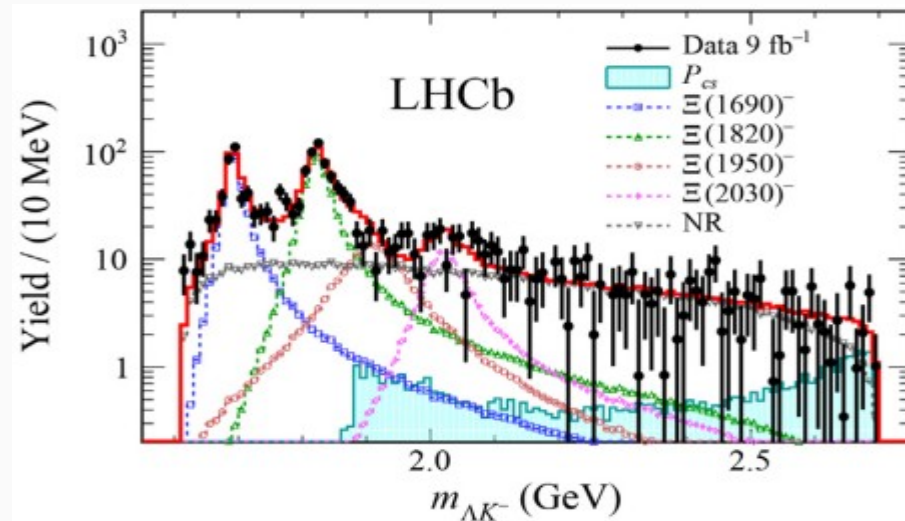
Baryon-Meson

# 1. introduction

□ The heavy pentaquark states,  $P_{cs}$  [ $udsc\bar{c}$ ], were observed in the weak decays.

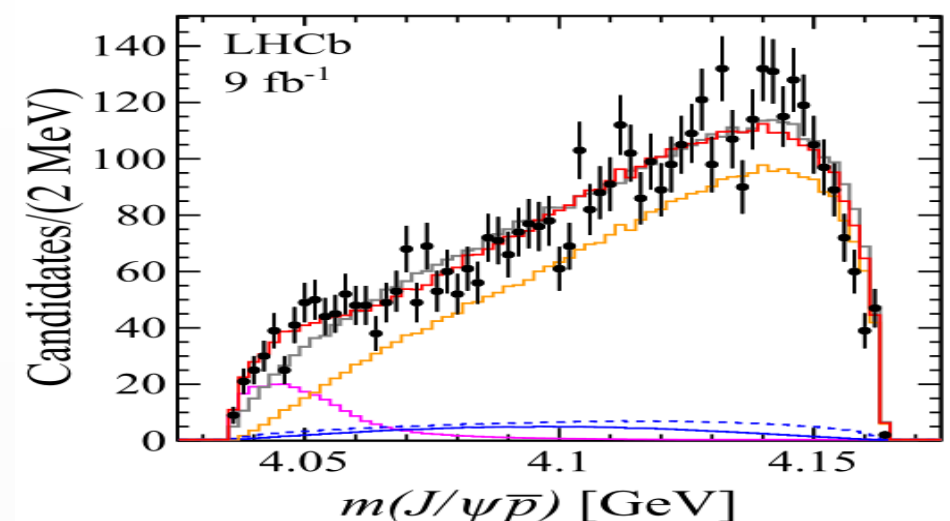
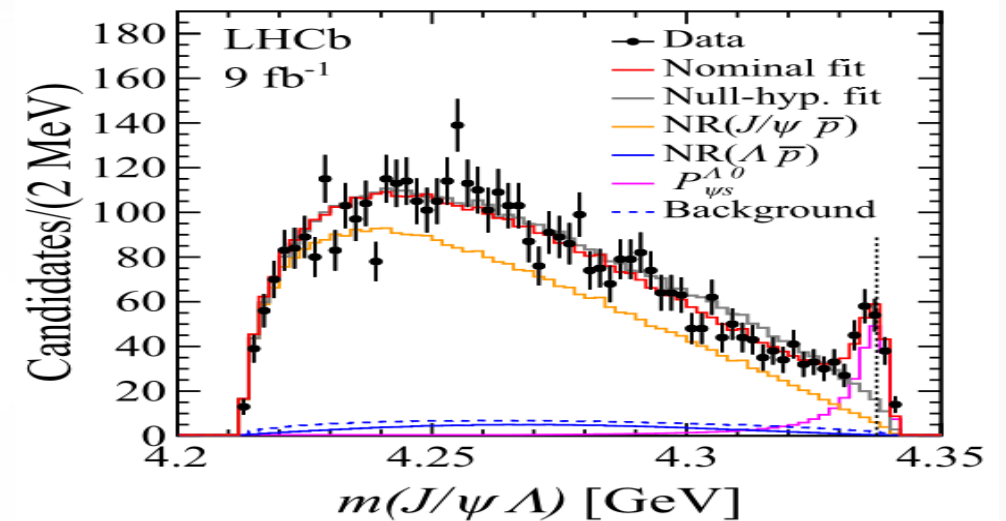
[Sci.Bull.66.1278 (2021)]

“ $\Lambda_b^0 \rightarrow J/\psi \Lambda K^-$ ”



[PRL.131.031901 (2023)]

“ $B^- \rightarrow J/\psi \Lambda \bar{p}$ ”







# Mesons

LIGHT UNFLAVORED (S = C = B = 0)		STRANGE (S = ±1, C = B = 0)		CHARMED, STRANGE continued I(J <sup>PC</sup> )		c $\bar{c}$ continued I(J <sup>PC</sup> )			
I <sup>G</sup> (J <sup>PC</sup> )	I <sup>G</sup> (J <sup>PC</sup> )	I(J <sup>PC</sup> )	I(J <sup>PC</sup> )						
• $\pi^\pm$	1 <sup>-</sup> (0 <sup>-</sup> )	• $\rho(1700)$	1 <sup>+</sup> (1 <sup>-</sup> -)	• $K^\pm$	1/2(0 <sup>-</sup> )	• $D_{s0}(2590)^+$	0(0 <sup>-</sup> )	• $\psi(4230)$	0 <sup>-</sup> (1 <sup>-</sup> -)
• $\pi^0$	1 <sup>-</sup> (0 <sup>-</sup> +)	• $a_2(1700)$	1 <sup>-</sup> (2 <sup>+</sup> +)	• $K^0$	1/2(0 <sup>-</sup> )	• $D_{s1}^*(2700)^\pm$	0(1 <sup>-</sup> )	• $\chi_{c1}(4274)$	0 <sup>+</sup> (1 <sup>+</sup> +)
• $\eta$	0 <sup>+</sup> (0 <sup>-</sup> +)	• $a_0(1710)$	1 <sup>-</sup> (0 <sup>+</sup> +)	• $K_S^0$	1/2(0 <sup>-</sup> )	• $D_{s1}^*(2860)^\pm$	0(1 <sup>-</sup> )	• $X(4350)$	0 <sup>+</sup> (? ? ?)
• $f_0(500)$	0 <sup>+</sup> (0 <sup>+</sup> +)	• $f_0(1710)$	0 <sup>+</sup> (0 <sup>+</sup> +)	• $K_L^0$	1/2(0 <sup>-</sup> )	• $D_{s3}^*(2860)^\pm$	0(3 <sup>-</sup> )	• $\psi(4360)$	0 <sup>-</sup> (1 <sup>-</sup> -)
• $\rho(770)$	1 <sup>+</sup> (1 <sup>-</sup> -)	• $X(1750)$	? <sup>-</sup> (1 <sup>-</sup> -)	• $K_0^*(700)$	1/2(0 <sup>+</sup> )	• $D_{sJ}(3040)^\pm$	0(? <sup>?</sup> )	• $\psi(4415)$	0 <sup>-</sup> (1 <sup>-</sup> -)
• $\omega(782)$	0 <sup>-</sup> (1 <sup>-</sup> -)	• $\eta(1760)$	0 <sup>+</sup> (0 <sup>-</sup> +)	• $K_0^*(892)$	1/2(1 <sup>-</sup> )	BOTTOM (B = ±1)		• $\chi_{c0}(4500)$	0 <sup>+</sup> (0 <sup>+</sup> +)
• $\eta'(958)$	0 <sup>+</sup> (0 <sup>-</sup> +)	• $f_0(1770)$	0 <sup>+</sup> (0 <sup>+</sup> +)	• $K_1(1270)$	1/2(1 <sup>+</sup> )	• $B^\pm$	1/2(0 <sup>-</sup> )	• $X(4630)$	0 <sup>+</sup> (? ? ?)
• $f_0(980)$	0 <sup>+</sup> (0 <sup>+</sup> +)	• $\pi(1800)$	1 <sup>-</sup> (0 <sup>-</sup> +)	• $K_1(1400)$	1/2(1 <sup>+</sup> )	• $B^0$	1/2(0 <sup>-</sup> )	• $\psi(4660)$	0 <sup>-</sup> (1 <sup>-</sup> -)
• $a_0(980)$	1 <sup>-</sup> (0 <sup>+</sup> +)	• $f_2(1810)$	0 <sup>+</sup> (2 <sup>+</sup> +)	• $K^*(1410)$	1/2(1 <sup>+</sup> )	• $B^\pm/B^0$ ADMIXTURE		• $\chi_{c1}(4685)$	0 <sup>+</sup> (1 <sup>+</sup> +)
• $\phi(1020)$	0 <sup>-</sup> (1 <sup>-</sup> -)	• $X(1835)$	0 <sup>+</sup> (0 <sup>-</sup> +)	• $K_0^*(1430)$	1/2(0 <sup>+</sup> )	• $B^\pm/B^0/B_S^0/b$ baryon ADMIXTURE		• $\chi_{c0}(4700)$	0 <sup>+</sup> (0 <sup>+</sup> +)
• $h_1(1170)$	0 <sup>-</sup> (1 <sup>+</sup> -)	• $\phi_3(1850)$	0 <sup>-</sup> (3 <sup>-</sup> -)	• $K_2^*(1430)$	1/2(2 <sup>+</sup> )	• $B^+$	1/2(1 <sup>-</sup> )	b $\bar{b}$	
• $b_1(1235)$	1 <sup>+</sup> (1 <sup>+</sup> -)	• $\eta_1(1855)$	0 <sup>+</sup> (1 <sup>-</sup> +)	• $K(1460)$	1/2(0 <sup>-</sup> )	• $B_1^*(5721)$	1/2(1 <sup>+</sup> )	• $\eta_b(1S)$	0 <sup>+</sup> (0 <sup>-</sup> +)
• $a_1(1260)$	1 <sup>-</sup> (1 <sup>+</sup> +)	• $\eta_2(1870)$	0 <sup>+</sup> (2 <sup>-</sup> +)	• $K_2(1580)$	1/2(2 <sup>-</sup> )	• $B_1^*(5732)$	?(? <sup>?</sup> )	• $T(1S)$	0 <sup>-</sup> (1 <sup>-</sup> -)
• $f_2(1270)$	0 <sup>+</sup> (2 <sup>+</sup> +)	• $\pi_2(1880)$	1 <sup>-</sup> (2 <sup>-</sup> +)	• $K(1630)$	1/2(? <sup>?</sup> )	• $B_2^*(5747)$	1/2(2 <sup>+</sup> )	• $\chi_{b0}(1P)$	0 <sup>+</sup> (0 <sup>+</sup> +)
• $f_1(1285)$	0 <sup>+</sup> (1 <sup>+</sup> +)	• $\rho(1900)$	1 <sup>+</sup> (1 <sup>-</sup> -)	• $K_1(1650)$	1/2(1 <sup>+</sup> )	• $B_2^*(5747)$	1/2(2 <sup>+</sup> )	• $\chi_{b1}(1P)$	0 <sup>+</sup> (1 <sup>+</sup> +)
• $\eta(1295)$	0 <sup>+</sup> (0 <sup>-</sup> +)	• $f_2(1910)$	0 <sup>+</sup> (2 <sup>+</sup> +)	• $K^*(1680)$	1/2(1 <sup>-</sup> )	• $B_J^*(5840)$	1/2(? <sup>?</sup> )	• $h_b(1P)$	0 <sup>-</sup> (1 <sup>+</sup> -)
• $\pi(1300)$	1 <sup>-</sup> (0 <sup>-</sup> +)	• $a_0(1950)$	1 <sup>-</sup> (0 <sup>+</sup> +)	• $K_2(1770)$	1/2(2 <sup>-</sup> )	• $B_J^*(5840)$	1/2(? <sup>?</sup> )	• $\chi_{b2}(1P)$	0 <sup>+</sup> (2 <sup>+</sup> +)
• $a_2(1320)$	1 <sup>-</sup> (2 <sup>+</sup> +)	• $f_2(1950)$	0 <sup>+</sup> (2 <sup>+</sup> +)	• $K_3^*(1780)$	1/2(3 <sup>-</sup> )	• $B_J(5970)$	1/2(? <sup>?</sup> )	• $\eta_b(2S)$	0 <sup>+</sup> (0 <sup>-</sup> +)
• $f_0(1370)$	0 <sup>+</sup> (0 <sup>+</sup> +)	• $a_4(1970)$	1 <sup>-</sup> (4 <sup>+</sup> +)	• $K_2(1820)$	1/2(2 <sup>-</sup> )	BOTTOM, STRANGE (B = ±1, S = ∓1)		• $T(2S)$	0 <sup>-</sup> (1 <sup>-</sup> -)
• $\pi_1(1400)$	1 <sup>-</sup> (1 <sup>-</sup> +)	• $\rho_3(1990)$	1 <sup>+</sup> (3 <sup>-</sup> -)	• $K(1830)$	1/2(0 <sup>-</sup> )	• $B_s^0$	0(0 <sup>-</sup> )	• $T_2(1D)$	0 <sup>-</sup> (2 <sup>-</sup> -)
• $\eta(1405)$	0 <sup>+</sup> (0 <sup>-</sup> +)	• $\pi_2(2005)$	1 <sup>-</sup> (2 <sup>-</sup> +)	• $K_0^*(1950)$	1/2(0 <sup>+</sup> )	• $B_s^+$	0(1 <sup>-</sup> )	• $\chi_{b0}(2P)$	0 <sup>+</sup> (0 <sup>+</sup> +)
• $h_1(1415)$	0 <sup>-</sup> (1 <sup>+</sup> -)	• $f_2(2010)$	0 <sup>+</sup> (2 <sup>+</sup> +)	• $K_2^*(1980)$	1/2(2 <sup>+</sup> )	• $B_s^*$	0(1 <sup>-</sup> )	• $\chi_{b1}(2P)$	0 <sup>+</sup> (1 <sup>+</sup> +)
• $f_1(1420)$	0 <sup>+</sup> (1 <sup>+</sup> +)	• $f_0(2020)$	0 <sup>+</sup> (0 <sup>+</sup> +)	• $K_4(2045)$	1/2(4 <sup>+</sup> )	• $B_{s1}(5830)^0$	0(1 <sup>+</sup> )	• $h_b(2P)$	0 <sup>-</sup> (1 <sup>+</sup> -)
• $\omega(1420)$	0 <sup>-</sup> (1 <sup>-</sup> -)	• $f_4(2050)$	0 <sup>+</sup> (4 <sup>+</sup> +)	• $K_2(2250)$	1/2(2 <sup>-</sup> )	• $B_{s2}^*(5840)^0$	0(2 <sup>+</sup> )	• $\chi_{b2}(2P)$	0 <sup>+</sup> (2 <sup>+</sup> +)
• $f_2(1430)$	0 <sup>+</sup> (2 <sup>+</sup> +)	• $\pi_2(2100)$	1 <sup>-</sup> (2 <sup>-</sup> +)	• $K_3(2320)$	1/2(3 <sup>+</sup> )	• $B_{sJ}^*(5850)$	?(? <sup>?</sup> )	• $T(3S)$	0 <sup>-</sup> (1 <sup>-</sup> -)
• $a_0(1450)$	1 <sup>-</sup> (0 <sup>+</sup> +)	• $f_0(2100)$	0 <sup>+</sup> (0 <sup>+</sup> +)	• $K_4^*(2380)$	1/2(5 <sup>-</sup> )	• $B_{sJ}(6063)^0$	0(? <sup>?</sup> )	• $\chi_{b1}(3P)$	0 <sup>+</sup> (1 <sup>+</sup> +)
• $\rho(1450)$	1 <sup>+</sup> (1 <sup>-</sup> -)	• $f_2(2150)$	0 <sup>+</sup> (2 <sup>+</sup> +)	• $K_4(2500)$	1/2(4 <sup>-</sup> )	• $B_{sJ}(6114)^0$	0(? <sup>?</sup> )	• $\chi_{b2}(3P)$	0 <sup>+</sup> (2 <sup>+</sup> +)
• $\eta(1475)$	0 <sup>+</sup> (0 <sup>-</sup> +)	• $\rho(2150)$	1 <sup>+</sup> (1 <sup>-</sup> -)	• $K(3100)$	? <sup>?</sup> (? ? ?)	BOTTOM, CHARMED (B = C = ±1)		• $T(4S)$	0 <sup>-</sup> (1 <sup>-</sup> -)
• $f_0(1500)$	0 <sup>+</sup> (0 <sup>+</sup> +)	• $\phi(2170)$	0 <sup>-</sup> (1 <sup>-</sup> -)	CHARMED (C = ±1)		• $B_c^+$	0(0 <sup>-</sup> )	• $T(10753)$	? <sup>?</sup> (1 <sup>-</sup> -)
• $f_1(1510)$	0 <sup>+</sup> (1 <sup>+</sup> +)	• $f_0(2200)$	0 <sup>+</sup> (0 <sup>+</sup> +)	• $D^\pm$	1/2(0 <sup>-</sup> )	• $B_c(2S)^\pm$	0(0 <sup>-</sup> )	• $T(10860)$	0 <sup>-</sup> (1 <sup>-</sup> -)
• $f_2'(1525)$	0 <sup>+</sup> (2 <sup>+</sup> +)	• $f_J(2220)$	0 <sup>+</sup> (2 <sup>+</sup> +)	• $D^0$	1/2(0 <sup>-</sup> )	c $\bar{c}$ I(J <sup>PC</sup> )		• $T(11020)$	0 <sup>-</sup> (1 <sup>-</sup> -)
• $f_2(1565)$	0 <sup>+</sup> (2 <sup>+</sup> +)	• $\omega(2220)$	0 <sup>-</sup> (1 <sup>-</sup> -)	• $D^*(2007)^0$	1/2(1 <sup>-</sup> )	• $\eta_c(1S)$	0 <sup>+</sup> (0 <sup>-</sup> +)	• $T_{cs0}^*(2870)^0$	? <sup>?</sup> (0 <sup>+</sup> )
• $\rho(1570)$	1 <sup>+</sup> (1 <sup>-</sup> -)	• $\eta(2225)$	0 <sup>+</sup> (0 <sup>-</sup> +)	• $D^*(2010)^\pm$	1/2(1 <sup>-</sup> )	• $J/\psi(1S)$	0 <sup>-</sup> (1 <sup>-</sup> -)	• $T_{cs1}^*(2900)^0$	? <sup>?</sup> (1 <sup>-</sup> )
• $h_1(1595)$	0 <sup>-</sup> (1 <sup>+</sup> -)	• $\rho_3(2250)$	1 <sup>+</sup> (3 <sup>-</sup> -)	• $D_0^*(2300)$	1/2(0 <sup>+</sup> )	• $\chi_{c0}(1P)$	0 <sup>+</sup> (0 <sup>+</sup> +)	• $T_{cs0}^*(2900)$	1(0 <sup>+</sup> )
• $\pi_1(1600)$	1 <sup>-</sup> (1 <sup>-</sup> +)	• $f_2(2300)$	0 <sup>+</sup> (2 <sup>+</sup> +)	• $D_1(2420)$	1/2(1 <sup>+</sup> )	• $\chi_{c1}(1P)$	0 <sup>+</sup> (1 <sup>+</sup> +)	• $T_{cc}(3875)^+$	? <sup>?</sup> (? ? ?)
• $a_1(1640)$	1 <sup>-</sup> (1 <sup>+</sup> +)	• $f_4(2300)$	0 <sup>+</sup> (4 <sup>+</sup> +)	• $D_1(2430)^0$	1/2(1 <sup>+</sup> )	• $h_c(1P)$	0 <sup>-</sup> (1 <sup>+</sup> -)	• $T_{ccl}(3900)$	1 <sup>+</sup> (1 <sup>+</sup> +)
• $f_2(1640)$	0 <sup>+</sup> (2 <sup>+</sup> +)	• $f_0(2330)$	0 <sup>+</sup> (0 <sup>+</sup> +)	• $D_2^*(2460)$	1/2(2 <sup>+</sup> )	• $\chi_{c2}(1P)$	0 <sup>+</sup> (2 <sup>+</sup> +)	• $T_{ccs1}(4000)$	1/2(1 <sup>+</sup> +)
• $\eta_2(1645)$	0 <sup>+</sup> (2 <sup>-</sup> +)	• $f_2(2340)$	0 <sup>+</sup> (2 <sup>+</sup> +)	• $D_0(2550)^0$	1/2(0 <sup>-</sup> )	• $\eta_c(2S)$	0 <sup>+</sup> (0 <sup>-</sup> +)	• $T_{cc}(4020)$	1 <sup>+</sup> (? ? ?)
• $\omega(1650)$	0 <sup>-</sup> (1 <sup>-</sup> -)	• $\rho_5(2350)$	1 <sup>+</sup> (5 <sup>-</sup> -)	• $D_1^*(2600)^0$	1/2(1 <sup>-</sup> )	• $\psi(2S)$	0 <sup>-</sup> (1 <sup>-</sup> -)	• $T_{cc}(4050)^+$	1 <sup>-</sup> (? ? ?)
• $\omega_3(1670)$	0 <sup>-</sup> (3 <sup>-</sup> -)	• $X(2370)$	? <sup>?</sup> (? ? ?)	• $D^*(2640)^\pm$	1/2(? <sup>?</sup> )	• $\psi(3770)$	0 <sup>-</sup> (1 <sup>-</sup> -)	• $T_{cc}(4055)^+$	1 <sup>+</sup> (? ? ?)
• $\pi_2(1670)$	1 <sup>-</sup> (2 <sup>-</sup> +)	• $f_0(2470)$	0 <sup>+</sup> (0 <sup>+</sup> +)	• $D_2(2740)^0$	1/2(2 <sup>-</sup> )	• $\psi_2(3823)$	0 <sup>-</sup> (2 <sup>-</sup> -)	• $T_{cc}(4100)^+$	1 <sup>-</sup> (? ? ?)
• $\phi(1680)$	0 <sup>-</sup> (1 <sup>-</sup> -)	• $f_6(2510)$	0 <sup>+</sup> (6 <sup>+</sup> +)	• $D_2^*(2750)$	1/2(3 <sup>-</sup> )	• $\psi_3(3842)$	0 <sup>-</sup> (3 <sup>-</sup> -)	• $T_{ccl}(4200)^+$	1 <sup>+</sup> (1 <sup>+</sup> +)
• $\rho_3(1690)$	1 <sup>+</sup> (3 <sup>-</sup> -)			• $D_1^*(2760)^0$	1/2(1 <sup>-</sup> )	• $\chi_{c0}(3860)$	0 <sup>+</sup> (0 <sup>+</sup> +)	• $T_{ccs1}(4220)^+$	1/2(1 <sup>+</sup> +)
				• $D(3000)^0$	1/2(? <sup>?</sup> )	• $\chi_{c1}(3872)$	0 <sup>+</sup> (1 <sup>+</sup> +)	• $T_{cc0}(4240)^+$	1 <sup>+</sup> (0 <sup>-</sup> -)
				CHARMED, STRANGE (C = ±1, S = ±1)		• $\chi_{c2}(3915)$	0 <sup>+</sup> (0 <sup>+</sup> +)	• $T_{cc}(4250)^+$	1 <sup>-</sup> (? ? ?)
				• $D_s^\pm$	0(0 <sup>-</sup> )	• $\chi_{c0}(3930)$	0 <sup>+</sup> (2 <sup>+</sup> +)	• $T_{cc}(4430)^+$	1 <sup>+</sup> (1 <sup>+</sup> +)
				• $D_s^{*\pm}$	0(1 <sup>-</sup> )	• $X(3940)$	? <sup>?</sup> (? ? ?)	• $T_{bs}(5568)^+$	1(? <sup>?</sup> )
				• $D_{s0}^*(2317)^\pm$	0(0 <sup>+</sup> )	• $\psi(4040)$	0 <sup>-</sup> (1 <sup>-</sup> -)	• $T_{cccc}(6900)^0$	0 <sup>+</sup> (? ? ?)
				• $D_{s1}^*(2460)^\pm$	0(1 <sup>+</sup> )	• $\chi_{c1}(4140)$	0 <sup>+</sup> (1 <sup>+</sup> +)	• $T_{bb1}(10610)$	1 <sup>+</sup> (1 <sup>+</sup> +)
				• $D_{s1}(2536)^\pm$	0(1 <sup>+</sup> )	• $\psi(4160)$	0 <sup>-</sup> (1 <sup>-</sup> -)	• $T_{bb1}(10650)^+$	1 <sup>+</sup> (1 <sup>+</sup> +)
				• $D_{s2}^*(2573)$	0(2 <sup>+</sup> )	• $X(4160)$	? <sup>?</sup> (? ? ?)	Further States	

including possibly non-q $\bar{q}$  states  
(charmonium-like / XYZ states)

Exotic states

• established

PDG (2024)

# Mesons

LIGHT UNFLAVORED (S = C = B = 0)		STRANGE (S = ±1, C = B = 0)		CHARMED, STRANGE continued I(J <sup>PC</sup> )		c $\bar{c}$ continued I(J <sup>PC</sup> )			
I <sup>G</sup> (J <sup>PC</sup> )	I <sup>G</sup> (J <sup>PC</sup> )	I(J <sup>PC</sup> )	I(J <sup>PC</sup> )						
• $\pi^\pm$	1 <sup>-</sup> (0 <sup>-</sup> )	• $\rho(1700)$	1 <sup>+</sup> (1 <sup>-</sup> -)	• $K^\pm$	1/2(0 <sup>-</sup> )	• $D_{s0}(2590)^+$	0(0 <sup>-</sup> )	• $\psi(4230)$	0 <sup>-</sup> (1 <sup>-</sup> -)
• $\pi^0$	1 <sup>-</sup> (0 <sup>-</sup> +)	• $a_2(1700)$	1 <sup>-</sup> (2 <sup>+</sup> +)	• $K^0$	1/2(0 <sup>-</sup> )	• $D_{s1}^*(2700)^\pm$	0(1 <sup>-</sup> )	• $\chi_{c1}(4274)$	0 <sup>+</sup> (1 <sup>+</sup> +)
• $\eta$	0 <sup>+</sup> (0 <sup>-</sup> +)	• $a_0(1710)$	1 <sup>-</sup> (0 <sup>+</sup> +)	• $K_S^0$	1/2(0 <sup>-</sup> )	• $D_{s1}^*(2860)^\pm$	0(1 <sup>-</sup> )	• $X(4350)$	0 <sup>+</sup> (? ? ?)
• $f_0(500)$	0 <sup>+</sup> (0 <sup>+</sup> +)	• $f_0(1710)$	0 <sup>+</sup> (0 <sup>+</sup> +)	• $K_L^0$	1/2(0 <sup>-</sup> )	• $D_{s3}^*(2860)^\pm$	0(3 <sup>-</sup> )	• $\psi(4360)$	0 <sup>-</sup> (1 <sup>-</sup> -)
• $\rho(770)$	1 <sup>+</sup> (1 <sup>-</sup> -)	• $X(1750)$	? <sup>-</sup> (1 <sup>-</sup> -)	• $K_0^*(700)$	1/2(0 <sup>+</sup> )	• $D_{sJ}(3040)^\pm$	0(? <sup>?</sup> )	• $\psi(4415)$	0 <sup>-</sup> (1 <sup>-</sup> -)
• $\omega(782)$	0 <sup>-</sup> (1 <sup>-</sup> -)	• $\eta(1760)$	0 <sup>+</sup> (0 <sup>-</sup> +)	• $K^*(892)$	1/2(1 <sup>-</sup> )	<b>BOTTOM</b> (B = ±1)		• $\chi_{c0}(4500)$	0 <sup>+</sup> (0 <sup>+</sup> +)
• $\eta'(958)$	0 <sup>+</sup> (0 <sup>-</sup> +)	• $f_0(1770)$	0 <sup>+</sup> (0 <sup>+</sup> +)	• $K_1(1270)$	1/2(1 <sup>+</sup> )	• $B^\pm$	1/2(0 <sup>-</sup> )	• $X(4630)$	0 <sup>+</sup> (? ? ?)
• $f_0(980)$	0 <sup>+</sup> (0 <sup>+</sup> +)	• $\pi(1800)$	1 <sup>-</sup> (0 <sup>-</sup> +)	• $K_1(1400)$	1/2(1 <sup>+</sup> )	• $B^0$	1/2(0 <sup>-</sup> )	• $\psi(4660)$	0 <sup>-</sup> (1 <sup>-</sup> -)
• $a_0(980)$	1 <sup>-</sup> (0 <sup>+</sup> +)	• $f_2(1810)$	0 <sup>+</sup> (2 <sup>+</sup> +)	• $K^*(1410)$	1/2(1 <sup>+</sup> )	• $B^\pm/B^0$ ADMIXTURE		• $\chi_{c1}(4685)$	0 <sup>+</sup> (1 <sup>+</sup> +)
• $\phi(1020)$	0 <sup>-</sup> (1 <sup>-</sup> -)	• $X(1835)$	0 <sup>+</sup> (0 <sup>-</sup> +)	• $K_0^*(1430)$	1/2(0 <sup>+</sup> )	• $B^\pm/B^0/B_S^0/b$ baryon ADMIXTURE		• $\chi_{c0}(4700)$	0 <sup>+</sup> (0 <sup>+</sup> +)
• $h_1(1170)$	0 <sup>-</sup> (1 <sup>+</sup> -)	• $\phi_3(1850)$	0 <sup>-</sup> (3 <sup>-</sup> -)	• $K_2^*(1430)$	1/2(2 <sup>+</sup> )	• $B^+$	1/2(1 <sup>-</sup> )	<b>b<math>\bar{b}</math></b>	
• $b_1(1235)$	1 <sup>+</sup> (1 <sup>+</sup> -)	• $\eta_1(1855)$	0 <sup>+</sup> (1 <sup>-</sup> +)	• $K(1460)$	1/2(0 <sup>-</sup> )	• $B_1(5721)$	1/2(1 <sup>+</sup> )	• $\eta_b(1S)$	0 <sup>+</sup> (0 <sup>-</sup> +)
• $a_1(1260)$	1 <sup>-</sup> (1 <sup>+</sup> +)	• $\eta_2(1870)$	0 <sup>+</sup> (2 <sup>-</sup> +)	• $K_2(1580)$	1/2(2 <sup>-</sup> )	• $B_1^*(5732)$	?(? <sup>?</sup> )	• $T(1S)$	0 <sup>-</sup> (1 <sup>-</sup> -)
• $f_2(1270)$	0 <sup>+</sup> (2 <sup>+</sup> +)	• $\pi_2(1880)$	1 <sup>-</sup> (2 <sup>-</sup> +)	• $K(1630)$	1/2(? <sup>?</sup> )	• $B_2^*(5747)$	1/2(2 <sup>+</sup> )	• $\chi_{b0}(1P)$	0 <sup>+</sup> (0 <sup>+</sup> +)
• $f_1(1285)$	0 <sup>+</sup> (1 <sup>+</sup> +)	• $\rho(1900)$	1 <sup>+</sup> (1 <sup>-</sup> -)	• $K_1(1650)$	1/2(1 <sup>+</sup> )	• $B_2^*(5747)$	1/2(2 <sup>+</sup> )	• $\chi_{b1}(1P)$	0 <sup>+</sup> (1 <sup>+</sup> +)
• $\eta(1295)$	0 <sup>+</sup> (0 <sup>-</sup> +)	• $f_2(1910)$	0 <sup>+</sup> (2 <sup>+</sup> +)	• $K^*(1680)$	1/2(1 <sup>-</sup> )	• $B_J^*(5840)$	1/2(? <sup>?</sup> )	• $h_b(1P)$	0 <sup>-</sup> (1 <sup>+</sup> -)
• $\pi(1300)$	1 <sup>-</sup> (0 <sup>-</sup> +)	• $a_0(1950)$	1 <sup>-</sup> (0 <sup>+</sup> +)	• $K_2(1770)$	1/2(2 <sup>-</sup> )	• $B_J^*(5840)$	1/2(? <sup>?</sup> )	• $\chi_{b2}(1P)$	0 <sup>+</sup> (2 <sup>+</sup> +)
• $a_2(1320)$	1 <sup>-</sup> (2 <sup>+</sup> +)	• $f_2(1950)$	0 <sup>+</sup> (2 <sup>+</sup> +)	• $K_3^*(1780)$	1/2(3 <sup>-</sup> )	• $B_J(5970)$	1/2(? <sup>?</sup> )	• $\eta_b(2S)$	0 <sup>+</sup> (0 <sup>-</sup> +)
• $f_0(1370)$	0 <sup>+</sup> (0 <sup>+</sup> +)	• $a_4(1970)$	1 <sup>-</sup> (4 <sup>+</sup> +)	• $K_2(1820)$	1/2(2 <sup>-</sup> )	<b>BOTTOM, STRANGE</b> (B = ±1, S = ∓1)		• $T(2S)$	0 <sup>-</sup> (1 <sup>-</sup> -)
• $\pi_1(1400)$	1 <sup>-</sup> (1 <sup>-</sup> +)	• $\rho_3(1990)$	1 <sup>+</sup> (3 <sup>-</sup> -)	• $K(1830)$	1/2(0 <sup>-</sup> )	• $B_s^0$	0(0 <sup>-</sup> )	• $T_2(1D)$	0 <sup>-</sup> (2 <sup>-</sup> -)
• $\eta(1405)$	0 <sup>+</sup> (0 <sup>-</sup> +)	• $\pi_2(2005)$	1 <sup>-</sup> (2 <sup>-</sup> +)	• $K_0^*(1950)$	1/2(0 <sup>+</sup> )	• $B_s^+$	0(1 <sup>-</sup> )	• $\chi_{b0}(2P)$	0 <sup>+</sup> (0 <sup>+</sup> +)
• $h_1(1415)$	0 <sup>-</sup> (1 <sup>+</sup> -)	• $f_2(2010)$	0 <sup>+</sup> (2 <sup>+</sup> +)	• $K_2^*(1980)$	1/2(2 <sup>+</sup> )	• $B_s^*$	0(1 <sup>-</sup> )	• $\chi_{b1}(2P)$	0 <sup>+</sup> (1 <sup>+</sup> +)
• $f_1(1420)$	0 <sup>+</sup> (1 <sup>+</sup> +)	• $f_0(2020)$	0 <sup>+</sup> (0 <sup>+</sup> +)	• $K_4(2045)$	1/2(4 <sup>+</sup> )	• $B_{s1}(5830)^0$	0(1 <sup>+</sup> )	• $h_b(2P)$	0 <sup>-</sup> (1 <sup>+</sup> -)
• $\omega(1420)$	0 <sup>-</sup> (1 <sup>-</sup> -)	• $f_4(2050)$	0 <sup>+</sup> (4 <sup>+</sup> +)	• $K_2(2250)$	1/2(2 <sup>-</sup> )	• $B_{s1}^*(5840)^0$	0(2 <sup>+</sup> )	• $\chi_{b2}(2P)$	0 <sup>+</sup> (2 <sup>+</sup> +)
• $f_2(1430)$	0 <sup>+</sup> (2 <sup>+</sup> +)	• $\pi_2(2100)$	1 <sup>-</sup> (2 <sup>-</sup> +)	• $K_3(2320)$	1/2(3 <sup>+</sup> )	• $B_{sJ}^*(5850)$	?(? <sup>?</sup> )	• $T(3S)$	0 <sup>-</sup> (1 <sup>-</sup> -)
• $a_0(1450)$	1 <sup>-</sup> (0 <sup>+</sup> +)	• $f_0(2100)$	0 <sup>+</sup> (0 <sup>+</sup> +)	• $K_4^*(2380)$	1/2(5 <sup>-</sup> )	• $B_{sJ}(6063)^0$	0(? <sup>?</sup> )	• $\chi_{b1}(3P)$	0 <sup>+</sup> (1 <sup>+</sup> +)
• $\rho(1450)$	1 <sup>+</sup> (1 <sup>-</sup> -)	• $f_2(2150)$	0 <sup>+</sup> (2 <sup>+</sup> +)	• $K_4(2500)$	1/2(4 <sup>-</sup> )	• $B_{sJ}(6114)^0$	0(? <sup>?</sup> )	• $\chi_{b2}(3P)$	0 <sup>+</sup> (2 <sup>+</sup> +)
• $\eta(1475)$	0 <sup>+</sup> (0 <sup>-</sup> +)	• $\rho(2150)$	1 <sup>+</sup> (1 <sup>-</sup> -)	• $K(3100)$	? <sup>?</sup> (? ? ?)	<b>BOTTOM, CHARMED</b> (B = C = ±1)		• $T(4S)$	0 <sup>-</sup> (1 <sup>-</sup> -)
• $f_0(1500)$	0 <sup>+</sup> (0 <sup>+</sup> +)	• $\phi(2170)$	0 <sup>-</sup> (1 <sup>-</sup> -)	<b>CHARMED</b> (C = ±1)		• $B_c^+$	0(0 <sup>-</sup> )	• $T(10753)$	? <sup>?</sup> (1 <sup>-</sup> -)
• $f_1(1510)$	0 <sup>+</sup> (1 <sup>+</sup> +)	• $f_0(2200)$	0 <sup>+</sup> (0 <sup>+</sup> +)	• $D^\pm$	1/2(0 <sup>-</sup> )	• $B_c(2S)^\pm$	0(0 <sup>-</sup> )	• $T(10860)$	0 <sup>-</sup> (1 <sup>-</sup> -)
• $f_2'(1525)$	0 <sup>+</sup> (2 <sup>+</sup> +)	• $f_J(2220)$	0 <sup>+</sup> (2 <sup>+</sup> +)	• $D^0$	1/2(0 <sup>-</sup> )	<b>c<math>\bar{c}</math></b> I(J <sup>PC</sup> )		• $T(11020)$	0 <sup>-</sup> (1 <sup>-</sup> -)
• $f_2(1565)$	0 <sup>+</sup> (2 <sup>+</sup> +)	• $\omega(2220)$	0 <sup>-</sup> (1 <sup>-</sup> -)	• $D^*(2007)^0$	1/2(1 <sup>-</sup> )	• $\eta_c(1S)$	0 <sup>+</sup> (0 <sup>-</sup> +)	• $T_{cs0}^+(2870)^0$	? <sup>?</sup> (0 <sup>+</sup> )
• $\rho(1570)$	1 <sup>+</sup> (1 <sup>-</sup> -)	• $\eta(2225)$	0 <sup>+</sup> (0 <sup>-</sup> +)	• $D^*(2010)^\pm$	1/2(1 <sup>-</sup> )	• $J/\psi(1S)$	0 <sup>-</sup> (1 <sup>-</sup> -)	• $T_{cs1}^+(2900)^0$	? <sup>?</sup> (1 <sup>-</sup> )
• $h_1(1595)$	0 <sup>-</sup> (1 <sup>+</sup> -)	• $\rho_3(2250)$	1 <sup>+</sup> (3 <sup>-</sup> -)	• $D_0^*(2300)$	1/2(0 <sup>+</sup> )	• $\chi_{c0}(1P)$	0 <sup>+</sup> (0 <sup>+</sup> +)	• $T_{cs0}^*(2900)$	1(0 <sup>+</sup> )
• $\pi_1(1600)$	1 <sup>-</sup> (1 <sup>-</sup> +)	• $f_2(2300)$	0 <sup>+</sup> (2 <sup>+</sup> +)	• $D_1(2420)$	1/2(1 <sup>+</sup> )	• $\chi_{c1}(1P)$	0 <sup>+</sup> (1 <sup>+</sup> +)	• $T_{cc}(3875)^+$	? <sup>?</sup> (? ? ?)
• $a_1(1640)$	1 <sup>-</sup> (1 <sup>+</sup> +)	• $f_4(2300)$	0 <sup>+</sup> (4 <sup>+</sup> +)	• $D_1(2430)^0$	1/2(1 <sup>+</sup> )	• $h_c(1P)$	0 <sup>-</sup> (1 <sup>+</sup> -)	• $T_{ccl}(3900)$	1 <sup>+</sup> (1 <sup>+</sup> +)
• $f_2(1640)$	0 <sup>+</sup> (2 <sup>+</sup> +)	• $f_0(2330)$	0 <sup>+</sup> (0 <sup>+</sup> +)	• $D_2^*(2460)$	1/2(2 <sup>+</sup> )	• $\chi_{c2}(1P)$	0 <sup>+</sup> (2 <sup>+</sup> +)	• $T_{ccs1}(4000)$	1/2(1 <sup>+</sup> +)
• $\eta_2(1645)$	0 <sup>+</sup> (2 <sup>-</sup> +)	• $f_2(2340)$	0 <sup>+</sup> (2 <sup>+</sup> +)	• $D_0(2550)^0$	1/2(0 <sup>-</sup> )	• $\eta_c(2S)$	0 <sup>+</sup> (0 <sup>-</sup> +)	• $T_{cc}(4020)$	1 <sup>+</sup> (? ? ?)
• $\omega(1650)$	0 <sup>-</sup> (1 <sup>-</sup> -)	• $\rho_5(2350)$	1 <sup>+</sup> (5 <sup>-</sup> -)	• $D_1^*(2600)^0$	1/2(1 <sup>-</sup> )	• $\psi(2S)$	0 <sup>-</sup> (1 <sup>-</sup> -)	• $T_{cc}(4050)^+$	1 <sup>-</sup> (? ? ?)
• $\omega_3(1670)$	0 <sup>-</sup> (3 <sup>-</sup> -)	• $X(2370)$	? <sup>?</sup> (? ? ?)	• $D^*(2640)^\pm$	1/2(? <sup>?</sup> )	• $\psi_2(3823)$	0 <sup>-</sup> (2 <sup>-</sup> -)	• $T_{cc}(4055)^+$	1 <sup>+</sup> (? ? ?)
• $\pi_2(1670)$	1 <sup>-</sup> (2 <sup>-</sup> +)	• $f_0(2470)$	0 <sup>+</sup> (0 <sup>+</sup> +)	• $D_2(2740)^0$	1/2(2 <sup>-</sup> )	• $\psi_3(3842)$	0 <sup>-</sup> (3 <sup>-</sup> -)	• $T_{cc}(4100)^+$	1 <sup>-</sup> (? ? ?)
• $\phi(1680)$	0 <sup>-</sup> (1 <sup>-</sup> -)	• $f_6(2510)$	0 <sup>+</sup> (6 <sup>+</sup> +)	• $D_3^*(2750)$	1/2(3 <sup>-</sup> )	• $\chi_{c0}(2S)$	0 <sup>+</sup> (0 <sup>-</sup> +)	• $T_{ccl}(4200)^+$	1 <sup>+</sup> (1 <sup>+</sup> +)
• $\rho_3(1690)$	1 <sup>+</sup> (3 <sup>-</sup> -)			• $D_1^*(2760)^0$	1/2(1 <sup>-</sup> )	• $\psi(3770)$	0 <sup>-</sup> (1 <sup>-</sup> -)	• $T_{ccs1}(4220)^+$	1/2(1 <sup>+</sup> +)
				• $D(3000)^0$	1/2(? <sup>?</sup> )	• $\psi_2(3823)$	0 <sup>-</sup> (2 <sup>-</sup> -)	• $T_{cc0}(4240)^+$	1 <sup>+</sup> (0 <sup>-</sup> -)
				<b>CHARMED, STRANGE</b> (C = ±1, S = ±1)		• $\chi_{c1}(3872)$	0 <sup>+</sup> (1 <sup>+</sup> +)	• $T_{cc}(4250)^+$	1 <sup>-</sup> (? ? ?)
				• $D_s^\pm$	0(0 <sup>-</sup> )	• $\chi_{c0}(3915)$	0 <sup>+</sup> (0 <sup>+</sup> +)	• $T_{cc}(4430)^+$	1 <sup>+</sup> (1 <sup>+</sup> +)
				• $D_s^{*\pm}$	0(1 <sup>-</sup> )	• $\chi_{c2}(3930)$	0 <sup>+</sup> (2 <sup>+</sup> +)	• $T_{bs}(5568)^+$	1(? <sup>?</sup> )
				• $D_{s0}^*(2317)^\pm$	0(0 <sup>+</sup> )	• $X(3940)$	? <sup>?</sup> (? ? ?)	• $T_{cccc}(6900)^0$	0 <sup>+</sup> (? ? ?)
				• $D_{s1}^*(2460)^\pm$	0(1 <sup>+</sup> )	• $\psi(4040)$	0 <sup>-</sup> (1 <sup>-</sup> -)	• $T_{bb1}(10610)$	1 <sup>+</sup> (1 <sup>+</sup> +)
				• $D_{s1}(2536)^\pm$	0(1 <sup>+</sup> )	• $\chi_{c1}(4140)$	0 <sup>+</sup> (1 <sup>+</sup> +)	• $T_{bb1}(10650)^+$	1 <sup>+</sup> (1 <sup>+</sup> +)
				• $D_{s2}^*(2573)$	0(2 <sup>+</sup> )	• $\psi(4160)$	0 <sup>-</sup> (1 <sup>-</sup> -)	• Further States	
						• $X(4160)$	? <sup>?</sup> (? ? ?)		

including possibly non-q $\bar{q}$  states  
(charmonium-like / XYZ states)

Exotic states

• established

PDG (2024)

# 1. introduction

## □ First findings on exotic mesons

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### Observation of a Narrow Charmoniumlike State in Exclusive $B^\pm \rightarrow K^\pm \pi^+ \pi^- J/\psi$ Decays

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(Belle Collaboration) 2967 citations

In summary, we have observed a strong signal for a state that decays to  $\pi^+ \pi^- J/\psi$  with

$$M = 3872.0 \pm 0.6(\text{stat}) \pm 0.5(\text{syst}) \text{ MeV},$$

$$\Gamma < 2.3 \text{ MeV} \quad (90\% \text{ C.L.}).$$

$$\chi_{c1}(3872) 0^+(1^{++})$$

$$Y(3940), Z(4430)$$



Meson



Tetraquark



과학상 물리·수학부문

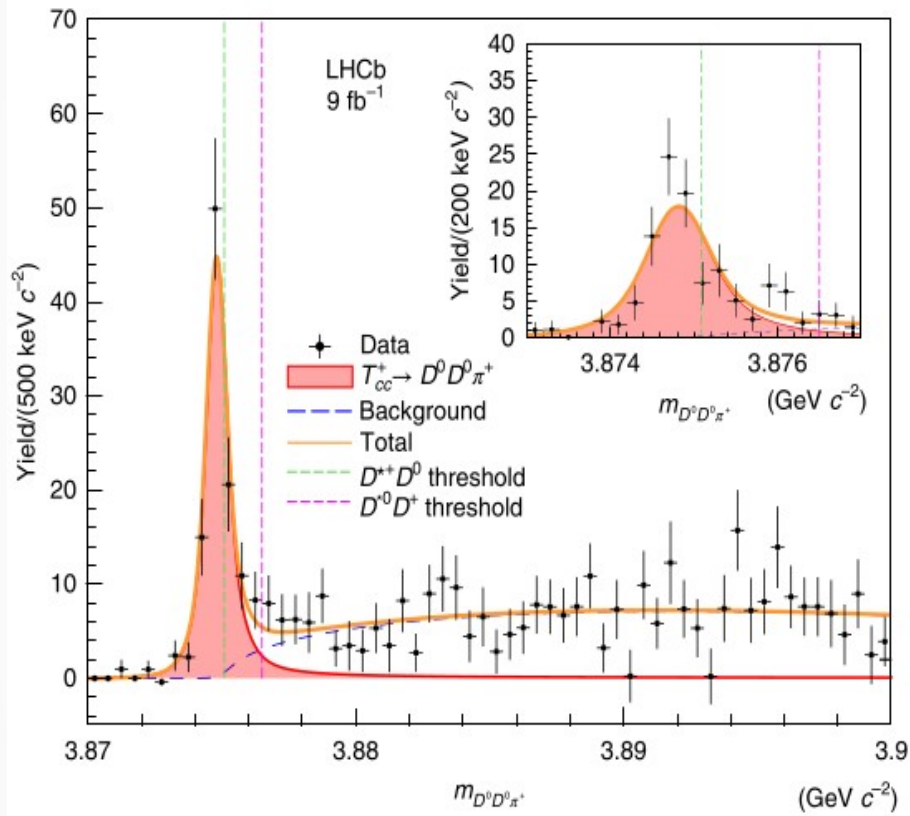
물리 및 수학, 관련 융합과학 분야에서 창의적이고 탁월한 연구 업적으로 해당 학문 분야의 발전에 기여한 인사에게 주어지는 상입니다.

기존의 입자와는 성질이 전혀 다른 새로운 유형의 X, Y, Z 입자를 세계 최초로 발견했다.

# 1. introduction

□ The doubly charmed tetraquark,  $T_{cc}^+$  [ $cc\bar{u}\bar{d}$ ], were observed in the “ $D^0 D^0 K^+$ ” mass spectrum.

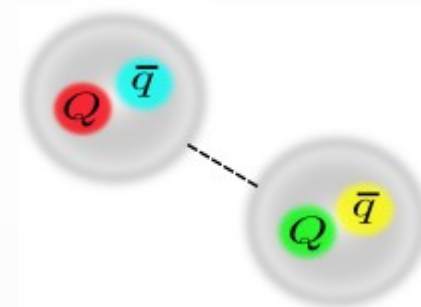
[NaturePhys.18.751 (2022)]



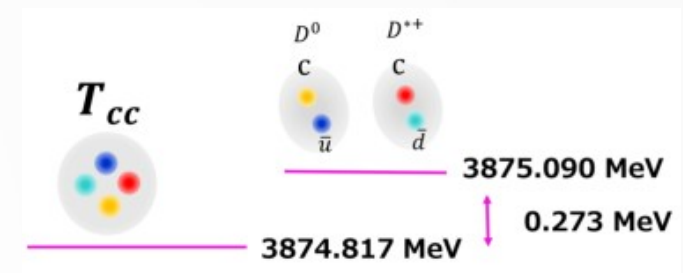
Compact Tetraquark ( $cc\bar{q}\bar{q}$ )



Hadronic molecules ( $DD^*$ )



□ Found just below  $DD^*$  threshold



□ Breit-Wigner parameterization

$$\delta m_{\text{BW}} = -273 \pm 61 \pm 5^{+11}_{-14} \text{ keV } c^{-2}$$

$$\Gamma_{\text{BW}} = 410 \pm 165 \pm 43^{+18}_{-38} \text{ keV}$$

□  $J^P = 1^+$  and  $I = 0$  is favored.

- Existence and properties (mass, width, decay mode, ...) of most  $N^*$  and  $\Delta^*$  resonances were derived from partial wave analyses (PWA) of  $\gamma N$  and  $\pi N$  elastic scattering data.

<b>SAID</b>	model independent single channel PWA [ $\pi N \rightarrow (\pi N, \eta N)$ , $\gamma N \rightarrow (\pi N, \eta N)$ ] <a href="http://gwdac.phys.gwu.edu/">http://gwdac.phys.gwu.edu/</a>
<b>BnGa</b>	multichannel partial wave analysis [ $\pi N$ , $\eta N$ , $\pi\pi N$ , $K\Lambda$ , $K\Sigma$ , $\gamma N$ ] <a href="http://pwa.hiskp.uni-bonn.de/">http://pwa.hiskp.uni-bonn.de/</a>
<b>MAID</b>	unitary isobar model, single channel [ $\gamma N \rightarrow \pi N$ , $\eta N$ , $K\Lambda$ , $K\Sigma$ ] <a href="http://www.kph.uni-mainz.de/MAID/">http://www.kph.uni-mainz.de/MAID/</a>
<b>Jülich</b>	dynamical model with coupled channel [ $\pi N$ , $\eta N$ , $\pi\pi N$ , $K\Lambda$ , $K\Sigma$ , ..., $\gamma N$ ]
<b>Gießen</b>	coupled channel unitary Lagrangian model [ $\pi N$ , $\eta N$ , $\pi\pi N$ , $K\Lambda$ , $K\Sigma$ , $\gamma N$ ]
<b>ANL-Osaka</b>	dynamical model with coupled channel [ $\pi N$ , $\eta N$ , $\pi\pi N$ , $K\Lambda$ , $K\Sigma$ , ..., $\gamma N$ ]

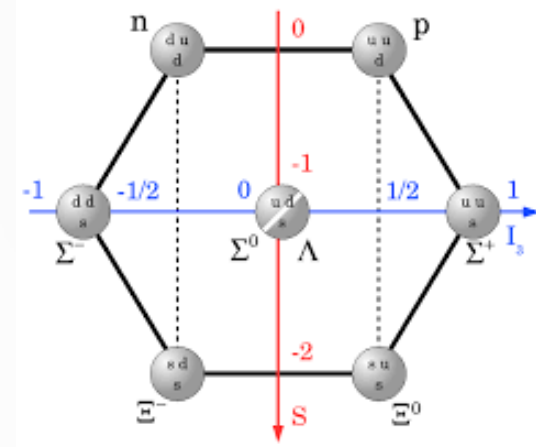
- Those of  $\Lambda^*$  and  $\Sigma^*$  resonances were derived from  $\bar{K}N$  elastic scattering data.

- Single channel analysis is also important.

# 1. introduction

How to produce **multistrangeness baryons** in hadron physics?

- ❑ **Multistrangeness baryons** are of importance in our understanding of strong interactions. However, the information of them is very limited currently.
  - ❑ SU(3) flavor symmetry allows as many  $S = -2$  baryons, i.e.  $\Xi$ , but only 11  $\Xi$  baryons are observed, whereas there are  $\sim 25$   $\Lambda^*$  or  $\Sigma^*$  resonances ( $S = -1$ ).
  - ❑ This is mainly because multistrangeness hadron production have small cross section rates relatively.
  - ❑ (a)  $p\bar{p}$  interaction ( $p\bar{p} \rightarrow \Xi^{(*)} \bar{\Xi}^{(*)}, \Omega^{(*)} \bar{\Omega}^{(*)}$ ) at GSI-FAIR
  - ❑ (b) photoproduction ( $\gamma p \rightarrow K K \Xi^{(*)}, K K K \Omega^{(*)}$ ) at JLab
  - ❑ (c) K induced reaction ( $K^- p \rightarrow K^{(*)} \Xi^{(*)}$ ) at J-PARC
    - > [KimSH, et al, PRC.107.065202 (2023)]
- > May provide substantial contributions to the spectroscopy of cascade baryons.



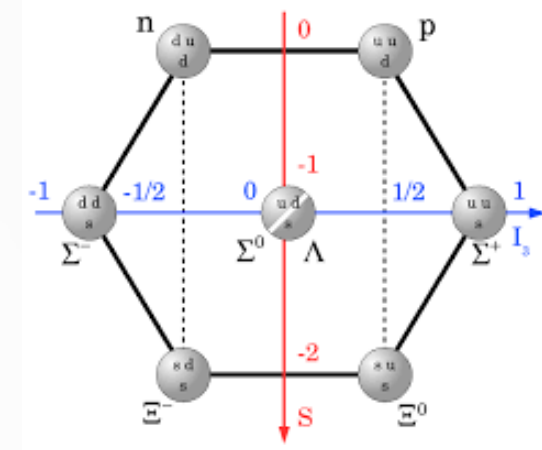
Particle	$J^P$	Overall status
$\Xi(1318)$	1/2+	****
$\Xi(1530)$	3/2+	****
$\Xi(1620)$		*
$\Xi(1690)$		***
$\Xi(1820)$	3/2-	***
$\Xi(1950)$		***
$\Xi(2030)$		***
$\Xi(2120)$		*
$\Xi(2250)$		**
$\Xi(2370)$		**
$\Xi(2500)$		*

# 1. introduction

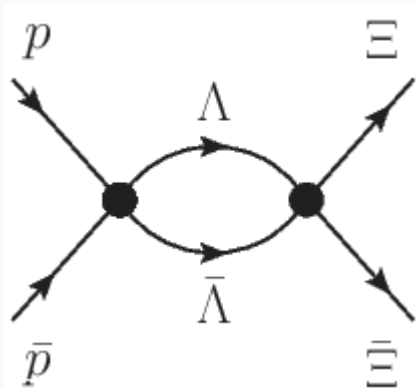
How to produce **multistrangeness baryons** in hadron physics?

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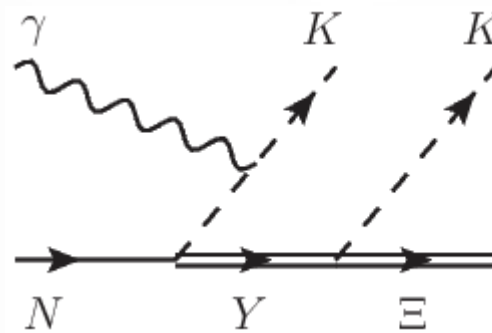


(a)  $p\bar{p}$  interaction ( $p\bar{p} \rightarrow \Xi\bar{\Xi}$ )  
at GSI-FAIR



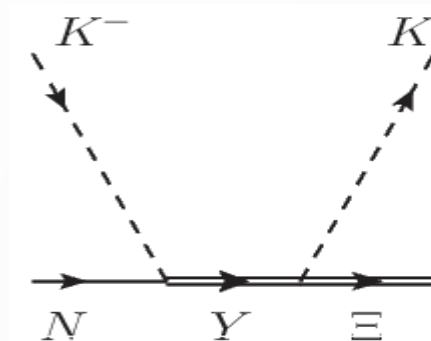
$\sim 10$  nb (theory)

(b) photoproduction ( $\gamma p \rightarrow K K \Xi$ )  
at Jefferson Lab



$\sim 10$  nb

(c) K induced reaction ( $K^- p \rightarrow K \Xi$ )  
at J-PARC



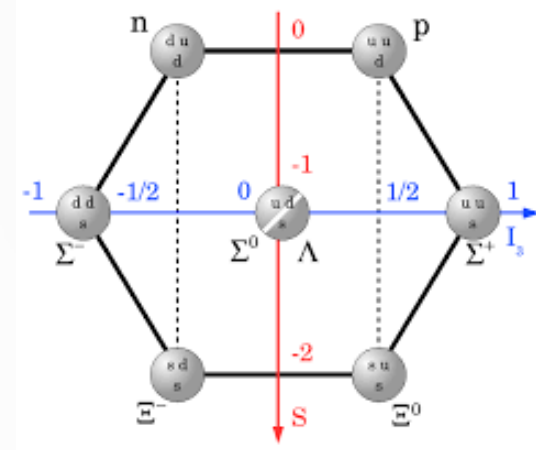
$\sim 10^2$   $\mu$ b

- > (a,b) The production mechanism is a two-step process.
- > (c)  $\Xi$  baryons are produced directly when we use only K beams.

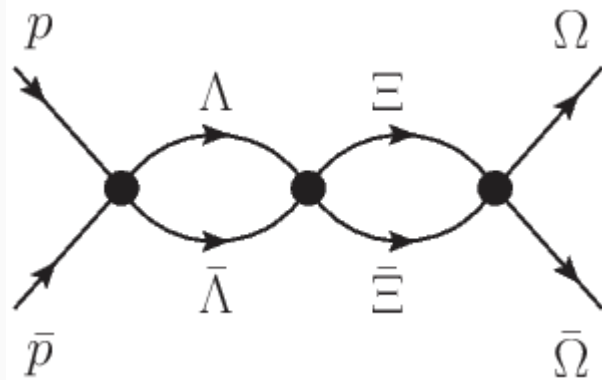
# 1. introduction

How to produce **multistrangeness baryons** in hadron physics?

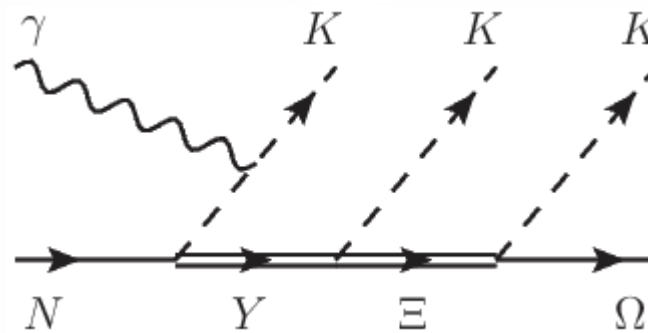
- **Multistrangeness baryons** are of importance in our understanding of strong interactions. However, the information of them is very limited currently.
- SU(3) flavor symmetry allows as many  $S = -2$  baryons, i.e.  $\Xi$ , but only 11  $\Xi$  baryons are observed, whereas there are  $\sim 25$   $\Lambda^*$  or  $\Sigma^*$  resonances ( $S = -1$ ).



(a)  $p\bar{p}$  interaction ( $p\bar{p} \rightarrow \Omega\bar{\Omega}$ ) at GSI-FAIR

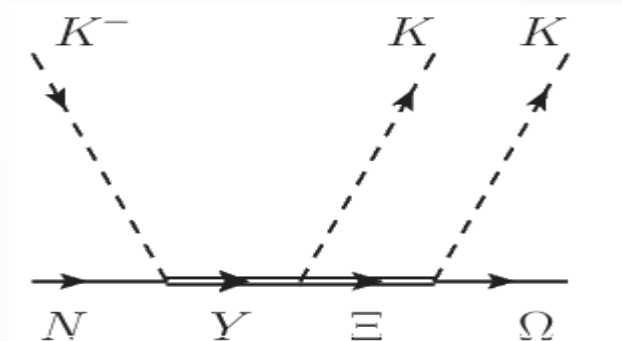


(b) photoproduction ( $\gamma p \rightarrow K K K \Omega$ ) at Jefferson Lab



$\sim 1$  pb (theory)

(c) K induced reaction ( $K^- p \rightarrow K K \Omega$ ) at J-PARC



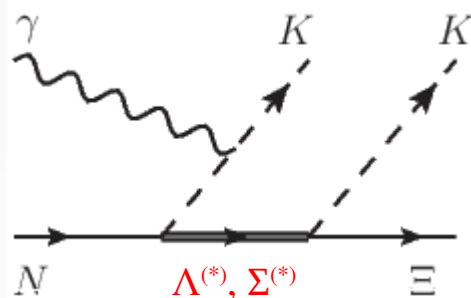
$\sim 1$   $\mu$ b

> For  $\Omega$  baryon production, the mechanisms become more complicated.

## 2. theoretical framework

□ In this work, we study the reaction  $\gamma N \rightarrow K K \Xi^*$  in a hadron exchange model.

$\gamma N \rightarrow K K \Xi$



□ Several  $Y^*(\Lambda^*, \Sigma^*)$  states should be included since multiple “ $Y^* \rightarrow K \Xi$ ” decay channels exist.

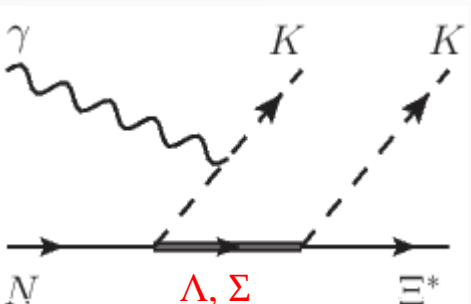
[Liu, PRC.69.045204 (2004)]

[Nakayama, PRC.74.035205 (2006)]

[Man, PRC.83.055201 (2011)]

$\Lambda$ state ( $J^P$ )	$\mathcal{B}(\Lambda^* \rightarrow K \Xi)$ [%]	$\Sigma$ state ( $J^P$ )	$\mathcal{B}(\Sigma^* \rightarrow K \Xi)$ [%]
$\Lambda(1820)5/2^+$	—	$\Sigma(1880)1/2^+$	—
$\Lambda(1830)5/2^-$	—	$\Sigma(1900)1/2^-$	$3 \pm 2$
$\Lambda(1890)3/2^+$	$\sim 1$ [41]	$\Sigma(1910)3/2^-$	—
$\Lambda(2000)1/2^-$	—	$\Sigma(1915)5/2^+$	—
$\Lambda(2050)3/2^-$	—	$\Sigma(1940)3/2^+$	—
$\Lambda(2070)3/2^+$	$7 \pm 3$	$\Sigma(2010)3/2^-$	$3 \pm 2$
$\Lambda(2080)5/2^-$	$4 \pm 1$	$\Sigma(2030)7/2^+$	$< 2$
$\Lambda(2085)7/2^+$	—	$\Sigma(2070)5/2^+$	—
$\Lambda(2100)7/2^-$	$< 3$	$\Sigma(2080)3/2^+$	—
$\Lambda(2110)5/2^+$	—	$\Sigma(2100)7/2^-$	—
$\Lambda(2325)3/2^-$	—	$\Sigma(2110)1/2^-$	—
$\Lambda(2350)9/2^+$	—	$\Sigma(2230)3/2^+$	$2 \pm 1$
$\Lambda(2585) \ ?^?$	—	$\Sigma(2250) \ ?^?$	—
		$\Sigma(2455) \ ?^?$	—
		$\Sigma(2620) \ ?^?$	—

$\gamma N \rightarrow K K \Xi^*$



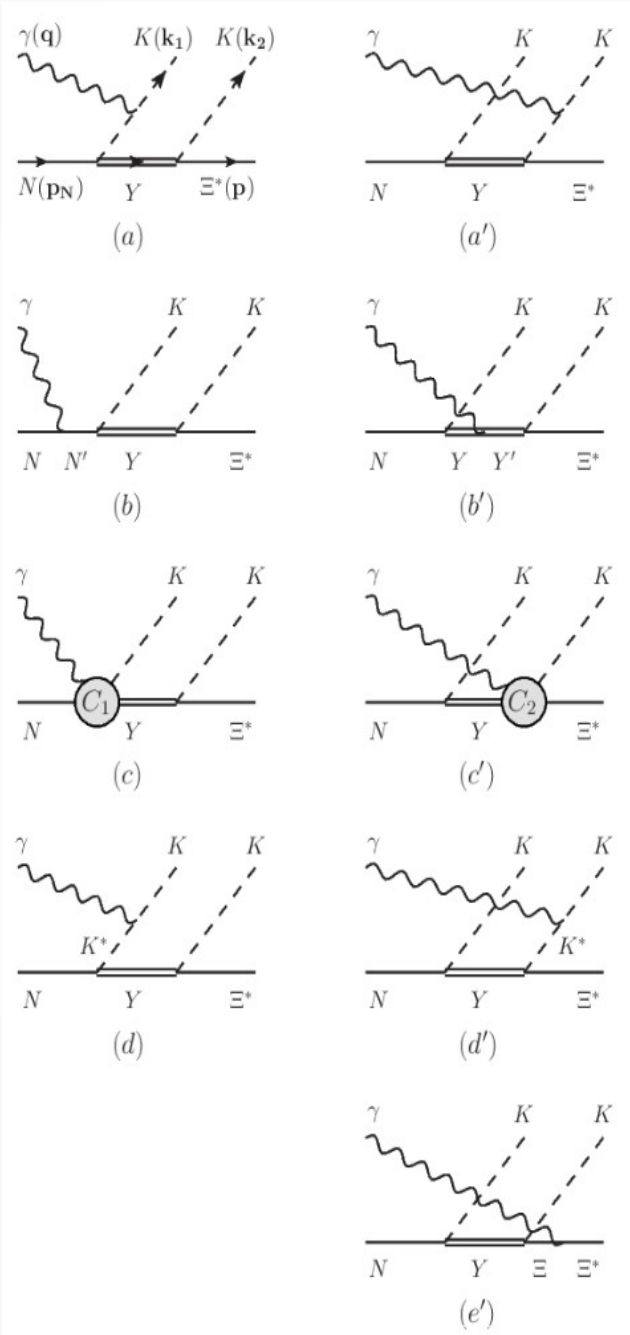
□ We consider only the ground state,  $Y(\Lambda, \Sigma)$ , due to the lack of information on “ $Y^* \rightarrow K \Xi^*$ ”.

□ Only one decay channel is listed in the PDG.

$\Sigma(2250) \rightarrow K \Xi^*$  [ $B = 18\%$ ]

□ The calculations can be further simplified than  $\gamma N \rightarrow K K \Xi$ .

## 2. theoretical framework

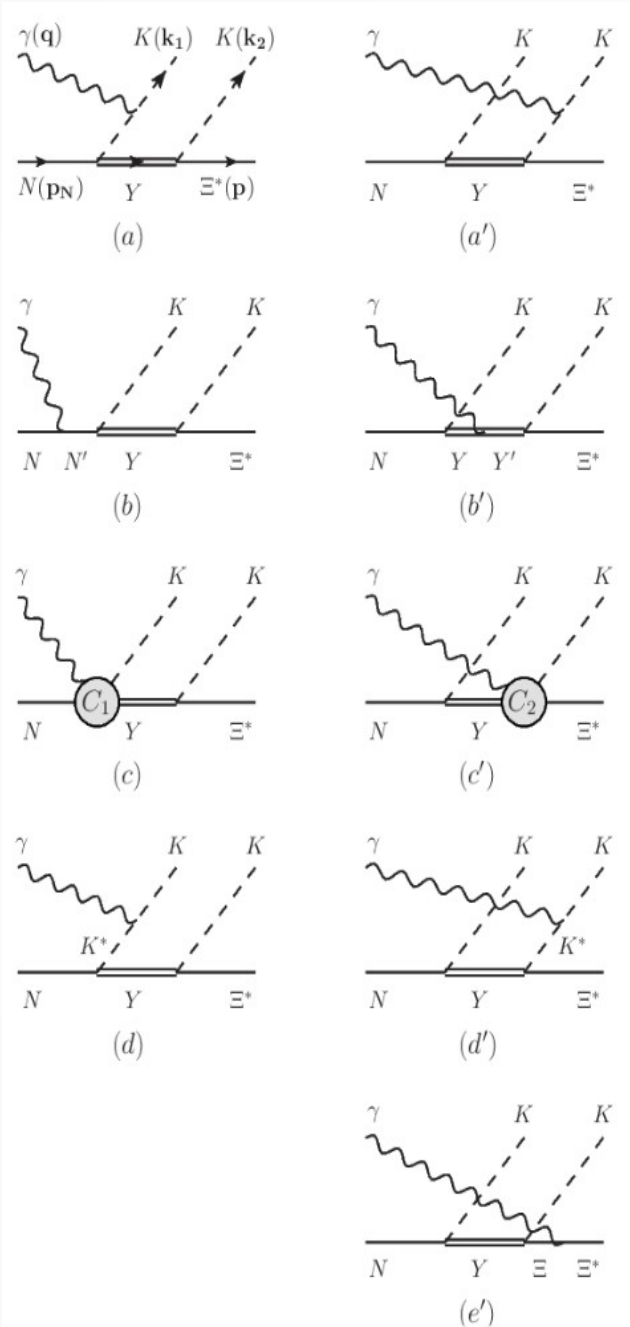


$$\gamma(\mathbf{q}) + N(\mathbf{p}_N) \rightarrow K(\mathbf{k}_1) + K(\mathbf{k}_2) + B(\mathbf{p})$$

$$\Xi^*(1530, 3/2^+)$$

$\mathbf{p}_N = -\mathbf{q},$	
$\mathbf{k}_1 = \mathbf{k},$	(c.m.)
$\mathbf{k}_2 = -(\mathbf{k} + \mathbf{p})$	

## 2. theoretical framework



$$\gamma(\mathbf{q}) + N(\mathbf{p}_N) \rightarrow K(\mathbf{k}_1) + K(\mathbf{k}_2) + B(\mathbf{p})$$

$$\Xi^*(1530, 3/2^+)$$

$$\begin{aligned} \mathbf{p}_N &= -\mathbf{q}, \\ \mathbf{k}_1 &= \mathbf{k}, \quad (\text{c.m.}) \\ \mathbf{k}_2 &= -(\mathbf{k} + \mathbf{p}) \end{aligned}$$

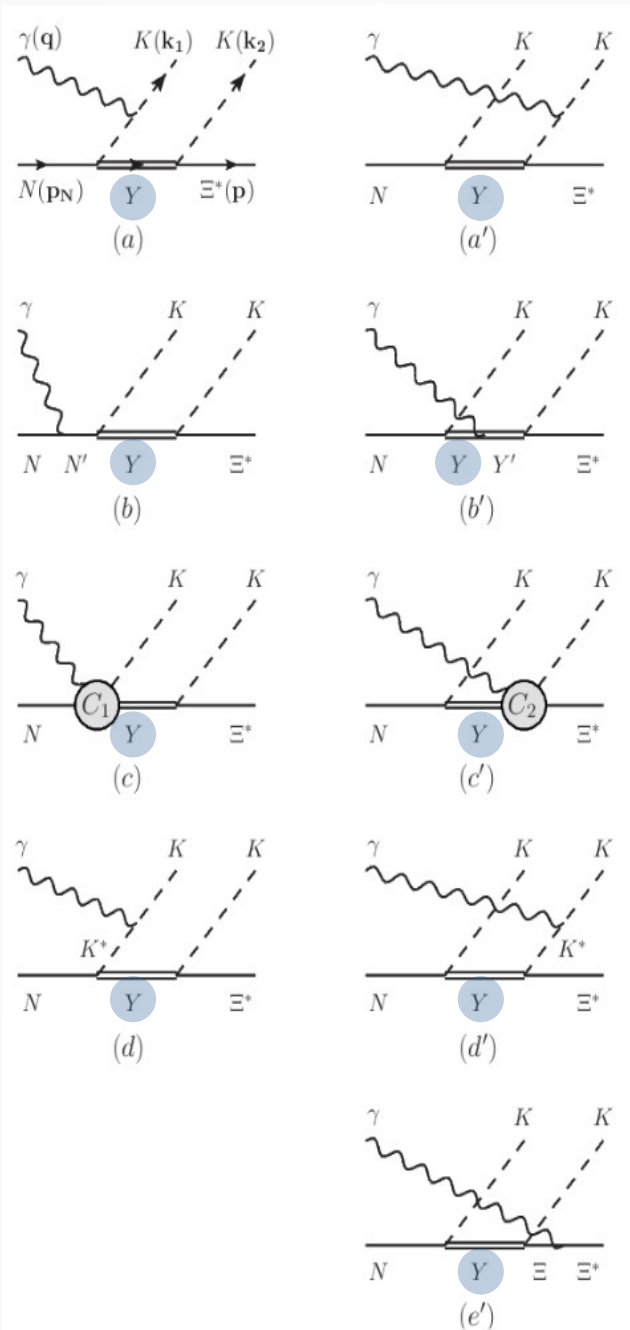
### Cross Sections

$$\begin{aligned} \sigma &= \frac{(2\pi)^4}{1 + q/E_N(q)} \int d\mathbf{p} \int d\mathbf{k} \delta(W - E_K(\mathbf{k}) - E_K(|\mathbf{k} + \mathbf{p}|) - E_B(\mathbf{p})) \\ &\times \frac{1}{4} \sum_{\lambda, m_{s_N}, m_{s_B}} |\langle \mathbf{p} m_{s_B}, \mathbf{k}_1, \mathbf{k}_2 | T(W) | \mathbf{q} \lambda, \mathbf{p}_N m_{s_N} \rangle|^2 \end{aligned}$$

$$\begin{aligned} \frac{d\sigma}{d\Omega_p} &= \frac{(4\pi)^2}{|\mathbf{q}|^2} \rho_{\gamma N}(\mathbf{q}, W) \int p^2 dp \int d\Omega_k \rho_f(\mathbf{k}, \mathbf{p}, W) \\ &\times \frac{1}{4} \sum_{\lambda, m_{s_N}, m_{s_B}} |\langle \mathbf{p} m_{s_B}, \mathbf{k}_1, \mathbf{k}_2 | T(W) | \mathbf{q} \lambda, \mathbf{p}_N m_{s_N} \rangle|^2 \end{aligned}$$

$$\begin{aligned} &\frac{1}{(2\pi)^{9/2}} \frac{1}{\sqrt{2E_K(\mathbf{k})}} \frac{1}{\sqrt{2E_K(\mathbf{k} + \mathbf{p})}} \sqrt{\frac{M_B}{E_B(\mathbf{p})}} \\ &\times \langle m_{s_B} | I(\mathbf{p}, \mathbf{k}_1, \mathbf{k}_2; \mathbf{q}, \mathbf{p}_N) | \lambda m_{s_N} \rangle \frac{1}{\sqrt{2|\mathbf{q}|}} \sqrt{\frac{M_N}{E_N(\mathbf{p}_N)}} \end{aligned}$$

## 2. theoretical framework



$$\langle m_{s_B} | I(\mathbf{p}, \mathbf{k}_1, \mathbf{k}_2; \mathbf{q}, \mathbf{p}_N) | \lambda m_{s_N} \rangle = \sum_{m_{s_Y}} \mathcal{M}_2(p_Y; k', p') \frac{2M_Y}{p_Y^2 - M_Y^2} \mathcal{M}_1(k, p; p_Y)$$

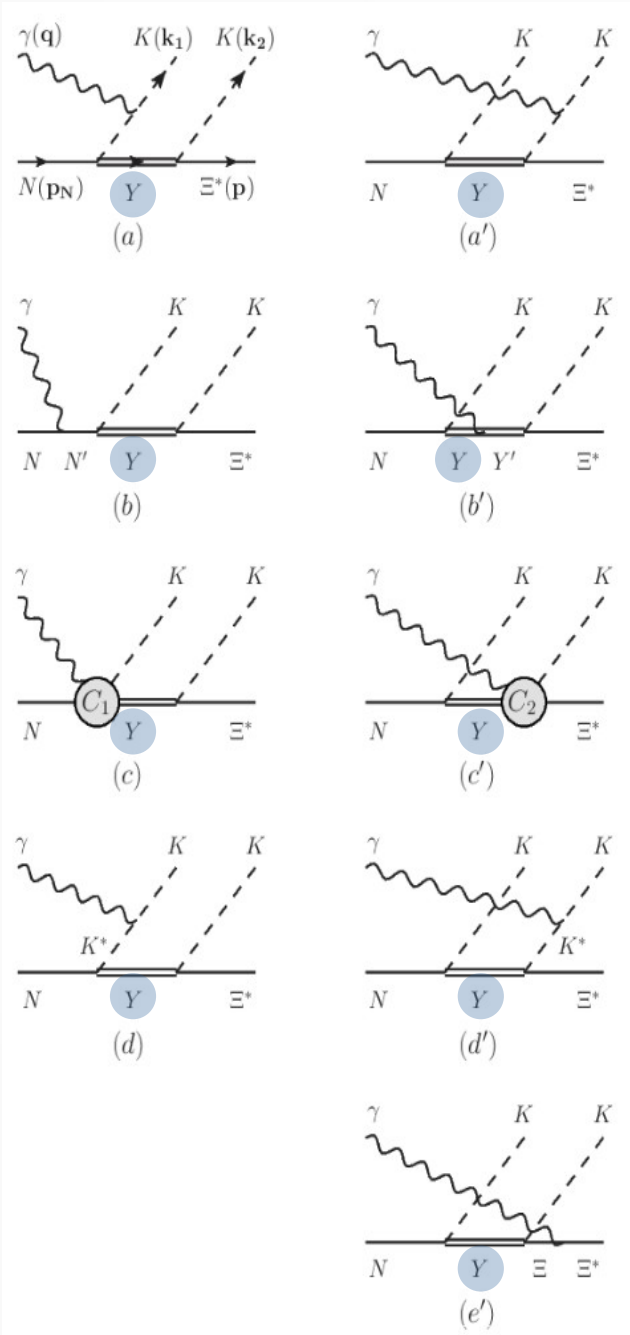
### Baryon Propagator

$$\sum u(\mathbf{p}) \bar{u}(\mathbf{p}) = \not{p} + M \quad \bar{u}(\mathbf{p})_{m'_s} u(\mathbf{p})_{m_s} = 2M \delta_{m_s, m'_s} \quad (\text{Peskin})$$

$$\sum u(\mathbf{p}) \bar{u}(\mathbf{p}) = \frac{\not{p} + M}{2M} \quad \bar{u}(\mathbf{p})_{m'_s} u(\mathbf{p})_{m_s} = \delta_{m_s, m'_s} \quad (\text{Ours})$$

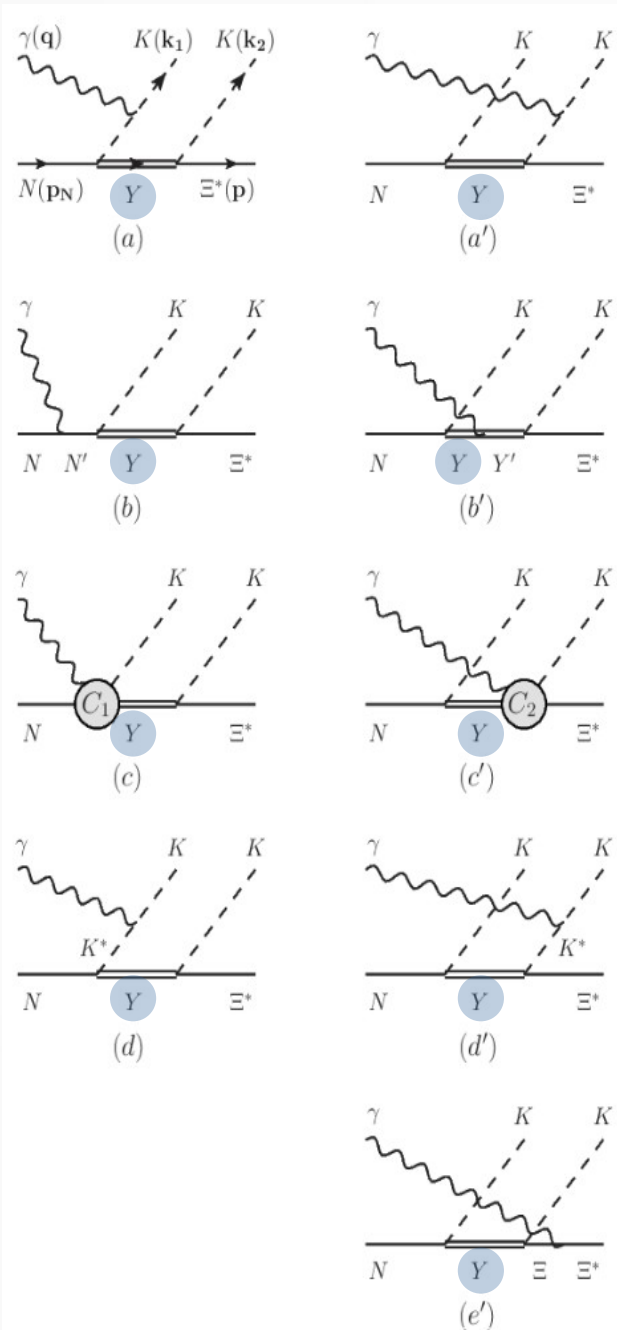
$$\frac{1}{\not{p} - M} = \frac{\not{p} + M}{p^2 - M^2} = \frac{2M \sum u \bar{u}}{p^2 - M^2} \quad (\text{Ours})$$

## 2. theoretical framework



$$\langle m_{s_B} | I(\mathbf{p}, \mathbf{k}_1, \mathbf{k}_2; \mathbf{q}, \mathbf{p}_N) | \lambda m_{s_N} \rangle = \sum_{m_{s_Y}} \mathcal{M}_2(p_Y; k', p') \frac{2M_Y}{p_Y^2 - M_Y^2} \mathcal{M}_1(k, p; p_Y)$$

## 2. theoretical framework



$$\langle m_{s_B} | I(\mathbf{p}, \mathbf{k}_1, \mathbf{k}_2; \mathbf{q}, \mathbf{p}_N) | \lambda m_{s_N} \rangle = \sum_{m_{s_Y}} \mathcal{M}_2(p_Y; k', p') \frac{2M_Y}{p_Y^2 - M_Y^2} \mathcal{M}_1(k, p; p_Y)$$

### Effective Lagrangians

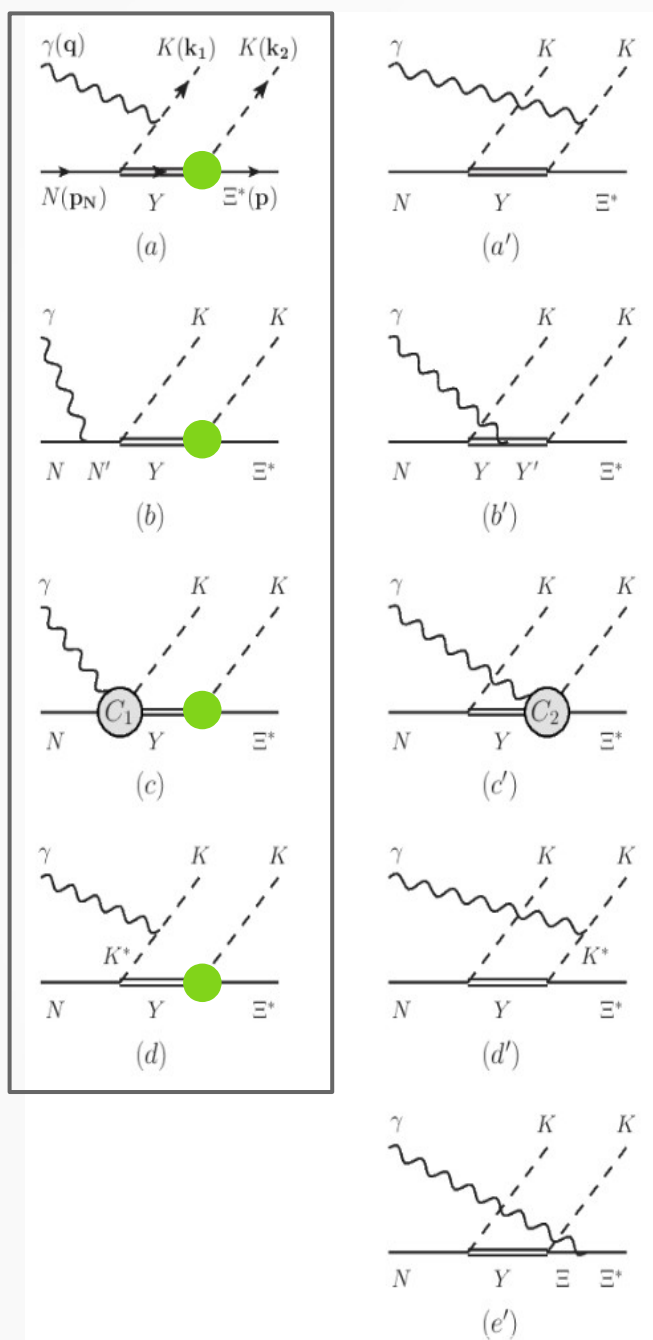
□ EM vertex

$$\begin{aligned} \mathcal{L}_{\gamma KK} &= -ie[K^\dagger(\partial_\mu K) - (\partial_\mu K^\dagger)K]A^\mu, \\ \mathcal{L}_{\gamma KK^*} &= \frac{eg_{\gamma KK^*}^c}{M_K} \epsilon^{\mu\nu\alpha\beta} \partial_\mu A_\nu (\partial_\alpha K_\beta^{*-} K^+ + \partial_\alpha K_\beta^{*+} K^-) \\ &\quad + \frac{eg_{\gamma KK^*}^0}{M_K} \epsilon^{\mu\nu\alpha\beta} \partial_\mu A_\nu (\partial_\alpha \bar{K}_\beta^{*0} K^0 + \partial_\alpha K_\beta^{*0} \bar{K}^0), \\ \mathcal{L}_{\gamma NN} &= -e\bar{N} \left[ \gamma^\mu A_\mu - \frac{\kappa_N}{2M_N} \sigma^{\mu\nu} \partial_\nu A_\mu \right] N, \\ \mathcal{L}_{\gamma YY} &= \frac{e\kappa_Y}{2M_N} \bar{Y} \sigma^{\mu\nu} \partial_\nu A_\mu Y, \\ \mathcal{L}_{\gamma \Xi \Xi^*} &= \frac{ieg_{\gamma \Xi \Xi^*}}{2M_N} \bar{\Xi}_\mu^* \gamma_\nu \gamma_5 \Xi F^{\mu\nu} + \text{H.c.}, \end{aligned}$$

□ strong vertex

$$\begin{aligned} \mathcal{L}_{KNY} &= -ig_{KNY} \bar{K} \bar{Y} \gamma_5 N + \text{H.c.}, \\ \mathcal{L}_{KY\Xi^*} &= \frac{g_{KY\Xi^*}}{M_K} \bar{\Xi}_\mu^* Y \partial^\mu \bar{K} + \text{H.c.}, \\ \mathcal{L}_{K^*Y\Xi^*} &= \frac{ig_{K^*Y\Xi^*}}{2M_N} \bar{\Xi}_\mu^* \gamma_\nu \gamma_5 Y \bar{K}^{*\mu\nu} + \text{H.c.}, \end{aligned}$$

## 2. theoretical framework



$$\langle m_{s_B} | I(\mathbf{p}, \mathbf{k}_1, \mathbf{k}_2; \mathbf{q}, \mathbf{p}_N) | \lambda m_{s_N} \rangle = \sum_{m_{s_Y}} \mathcal{M}_2(p_Y; k', p') \frac{2M_Y}{p_Y^2 - M_Y^2} \mathcal{M}_1(k, p; p_Y)$$

### Invariant Amplitudes

$$I_a = \mathcal{M}_{Y \rightarrow K_2 \Xi^*} \frac{2M_Y}{\text{Prop}_1} \mathcal{M}_{\gamma N \rightarrow K_1 Y}^{t(K)}$$

$$I_b = \mathcal{M}_{Y \rightarrow K_2 \Xi^*} \frac{2M_Y}{\text{Prop}_1} \mathcal{M}_{\gamma N \rightarrow K_1 Y}^{s(N')}$$

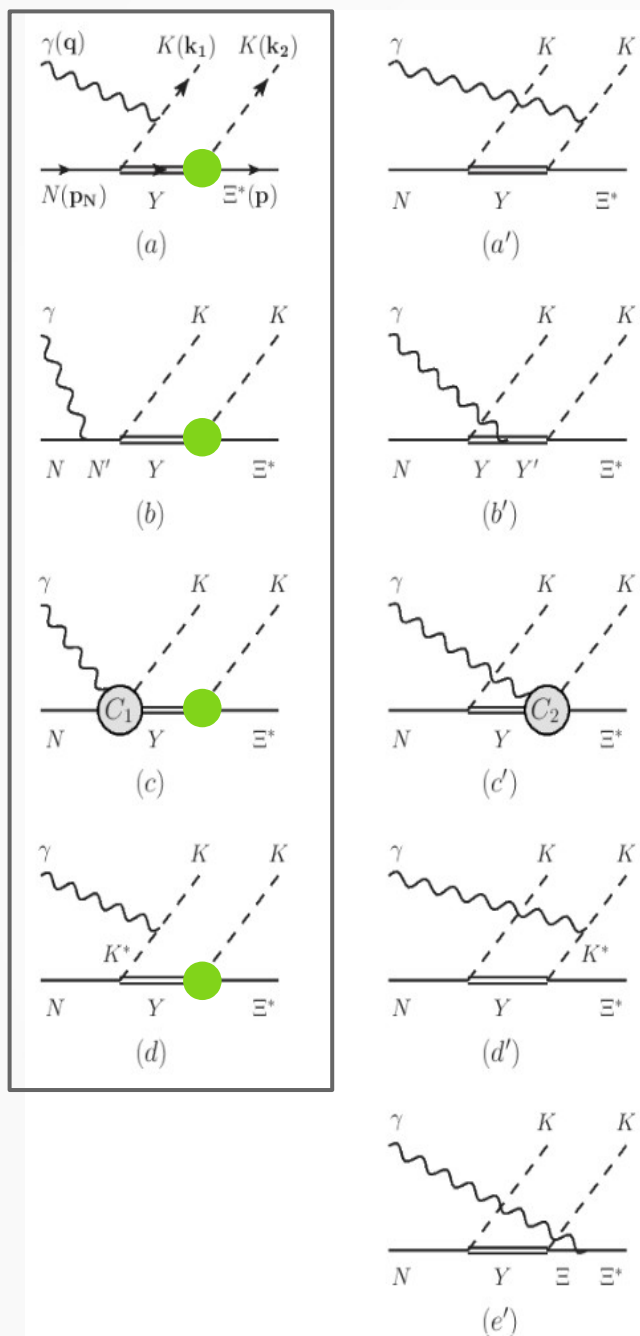
$$I_c = \mathcal{M}_{Y \rightarrow K_2 \Xi^*} \frac{2M_Y}{\text{Prop}_1} \mathcal{M}_{\gamma N \rightarrow K_1 Y}^C$$

$$I_d = \mathcal{M}_{Y \rightarrow K_2 \Xi^*} \frac{2M_Y}{\text{Prop}_1} \mathcal{M}_{\gamma N \rightarrow K_1 Y}^{t(K^*)}$$

$$\text{Prop}_1 = (k_2 + p)^2 - M_Y^2$$

$$\mathcal{M}_{Y \rightarrow K_2 \Xi^*} = -i \frac{g_{KY\Xi^*}}{M_K} (k_2 \cdot \bar{U}_{\Xi^*}) u_Y$$

## 2. theoretical framework



$$\langle m_{s_B} | I(\mathbf{p}, \mathbf{k}_1, \mathbf{k}_2; \mathbf{q}, \mathbf{p}_N) | \lambda m_{s_N} \rangle = \sum_{m_{s_Y}} \mathcal{M}_2(p_Y; k', p') \frac{2M_Y}{p_Y^2 - M_Y^2} \mathcal{M}_1(k, p; p_Y)$$

### Invariant Amplitudes

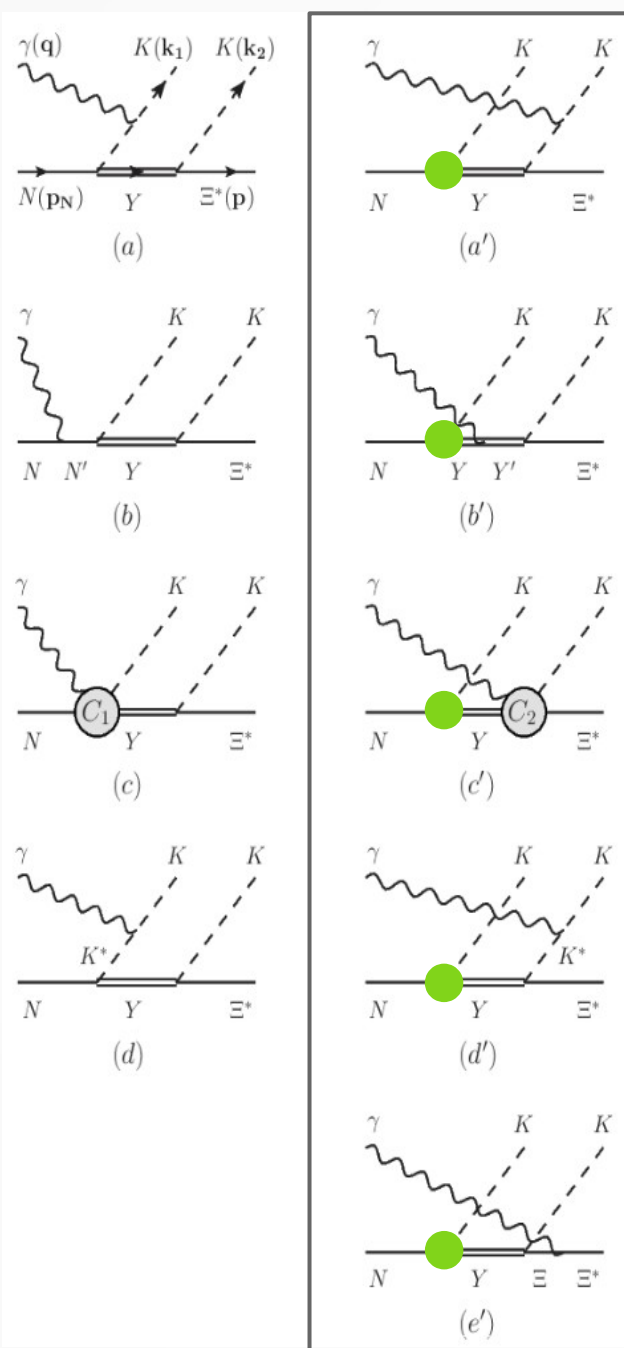
$$\begin{aligned} I_a &= \mathcal{M}_{Y \rightarrow K_2 \Xi^*} \frac{2M_Y}{\text{Prop}_1} \mathcal{M}_{\gamma N \rightarrow K_1 Y}^{t(K)} \\ I_b &= \mathcal{M}_{Y \rightarrow K_2 \Xi^*} \frac{2M_Y}{\text{Prop}_1} \mathcal{M}_{\gamma N \rightarrow K_1 Y}^{s(N')} \\ I_c &= \mathcal{M}_{Y \rightarrow K_2 \Xi^*} \frac{2M_Y}{\text{Prop}_1} \mathcal{M}_{\gamma N \rightarrow K_1 Y}^C \\ I_d &= \mathcal{M}_{Y \rightarrow K_2 \Xi^*} \frac{2M_Y}{\text{Prop}_1} \mathcal{M}_{\gamma N \rightarrow K_1 Y}^{t(K^*)} \end{aligned}$$

$$\text{Prop}_1 = (k_2 + p)^2 - M_Y^2$$

$$\mathcal{M}_{Y \rightarrow K_2 \Xi^*} = -i \frac{g_{KY\Xi^*}}{M_K} (k_2 \cdot \bar{U}_{\Xi^*}) u_Y$$

$$\begin{aligned} \mathcal{M}_{\gamma N \rightarrow K_1 Y}^{t(K)} &= \frac{2ieg_{KNY}}{(k_1 - q)^2 - M_K^2} (k_1 \cdot \epsilon) (\bar{u}_Y \gamma_5 u_N), \\ \mathcal{M}_{\gamma N \rightarrow K_1 Y}^{s(N')} &= \frac{ieg_{KNY}}{(q + p_N)^2 - M_{N'}^2} \bar{u}_Y \gamma_5 \\ &\quad \times (\not{q} + \not{p}_N + M_N) \left[ \gamma^\mu + \frac{i\kappa_N}{2M_N} q_\nu \sigma^{\mu\nu} \right] \epsilon_\mu u_N, \\ \mathcal{M}_{\gamma N \rightarrow K_1 Y}^C &= ie \frac{g_{KNY}}{2M_N} \bar{u}_Y \gamma^\mu \epsilon_\mu \gamma_5 u_N, \\ \mathcal{M}_{\gamma N \rightarrow K_1 Y}^{t(K^*)} &= \frac{-eg_{\gamma KK^*} g_{K^* NY}}{(k_1 - q)^2 - M_{K^*}^2} \frac{1}{M_K} \epsilon^{\mu\nu\alpha\beta} \bar{u}_Y \\ &\quad \times \left[ \gamma_\mu - \frac{ik_{K^* NY}}{2M_N} (k_1 - q)^\lambda \sigma_{\mu\lambda} \right] u_N q_\nu k_{1\alpha} \epsilon_\beta, \end{aligned}$$

## 2. theoretical framework



$$\langle m_{s_B} | I(\mathbf{p}, \mathbf{k}_1, \mathbf{k}_2; \mathbf{q}, \mathbf{p}_N) | \lambda m_{s_N} \rangle = \sum_{m_{s_Y}} \mathcal{M}_2(p_Y; k', p') \frac{2M_Y}{p_Y^2 - M_Y^2} \mathcal{M}_1(k, p; p_Y)$$

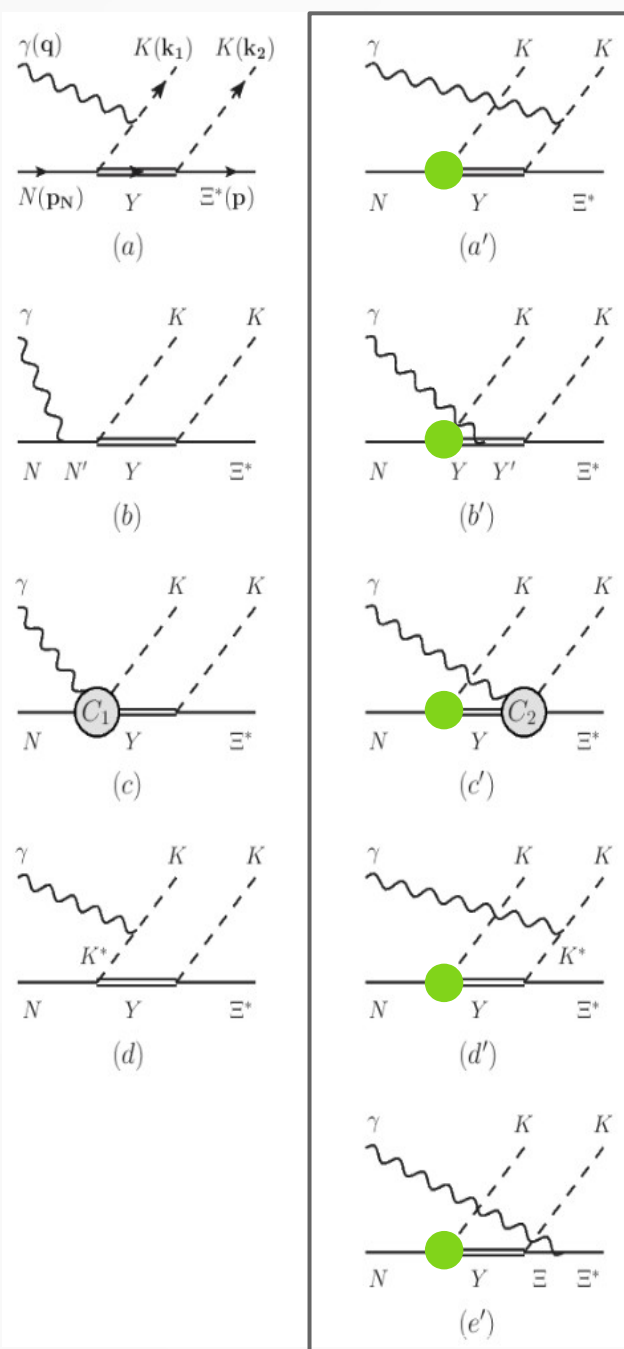
### Invariant Amplitudes

$$\begin{aligned}
 I_{a'} &= \mathcal{M}_{\gamma Y \rightarrow K_2 \Xi^*}^{t(K)} \frac{2M_Y}{\text{Prop}_2} \mathcal{M}_{N \rightarrow K_1 Y} \\
 I_{b'} &= \mathcal{M}_{\gamma Y \rightarrow K_2 \Xi^*}^{s(Y')} \frac{2M_Y}{\text{Prop}_2} \mathcal{M}_{N \rightarrow K_1 Y} \\
 I_{c'} &= \mathcal{M}_{\gamma Y \rightarrow K_2 \Xi^*}^C \frac{2M_Y}{\text{Prop}_2} \mathcal{M}_{N \rightarrow K_1 Y} \\
 I_{d'} &= \mathcal{M}_{\gamma Y \rightarrow K_2 \Xi^*}^{t(K^*)} \frac{2M_Y}{\text{Prop}_2} \mathcal{M}_{N \rightarrow K_1 Y} \\
 I_{e'} &= \mathcal{M}_{\gamma Y \rightarrow K_2 \Xi^*}^{u(\Xi)} \frac{2M_Y}{\text{Prop}_2} \mathcal{M}_{N \rightarrow K_1 Y}
 \end{aligned}$$

$$\text{Prop}_2 = (p_N - k_1)^2 - M_Y^2$$

$$\mathcal{M}_{N \rightarrow K_1 Y} = ig_{KNY} \bar{u}_Y \gamma_5 u_N$$

## 2. theoretical framework



$$\langle m_{s_B} | I(\mathbf{p}, \mathbf{k}_1, \mathbf{k}_2; \mathbf{q}, \mathbf{p}_N) | \lambda m_{s_N} \rangle = \sum_{m_{s_Y}} \mathcal{M}_2(p_Y; k', p') \frac{2M_Y}{p_Y^2 - M_Y^2} \mathcal{M}_1(k, p; p_Y)$$

### Invariant Amplitudes

$$\begin{aligned} I_{a'} &= \mathcal{M}_{\gamma Y \rightarrow K_2 \Xi^*}^{t(K)} \frac{2M_Y}{\text{Prop}_2} \mathcal{M}_{N \rightarrow K_1 Y} \\ I_{b'} &= \mathcal{M}_{\gamma Y \rightarrow K_2 \Xi^*}^{s(Y')} \frac{2M_Y}{\text{Prop}_2} \mathcal{M}_{N \rightarrow K_1 Y} \\ I_{c'} &= \mathcal{M}_{\gamma Y \rightarrow K_2 \Xi^*}^C \frac{2M_Y}{\text{Prop}_2} \mathcal{M}_{N \rightarrow K_1 Y} \\ I_{d'} &= \mathcal{M}_{\gamma Y \rightarrow K_2 \Xi^*}^{t(K^*)} \frac{2M_Y}{\text{Prop}_2} \mathcal{M}_{N \rightarrow K_1 Y} \\ I_{e'} &= \mathcal{M}_{\gamma Y \rightarrow K_2 \Xi^*}^{u(\Xi)} \frac{2M_Y}{\text{Prop}_2} \mathcal{M}_{N \rightarrow K_1 Y} \end{aligned}$$

$$\text{Prop}_2 = (p_N - k_1)^2 - M_Y^2$$

$$\mathcal{M}_{N \rightarrow K_1 Y} = ig_{KNY} \bar{u}_Y \gamma_5 u_N$$

$$\begin{aligned} \mathcal{M}_{\gamma Y \rightarrow K_2 \Xi^*}^{t(K)} &= \frac{-2ie}{(k_2 - q)^2 - M_K^2} \frac{g_{KY\Xi^*}}{M_K} (k_2 \cdot \epsilon) \\ &\quad \times [(k_2 - q) \cdot \bar{U}_{\Xi^*}] u_Y, \\ \mathcal{M}_{\gamma Y \rightarrow K_2 \Xi^*}^{s(Y')} &= \frac{-ie}{(k_2 + p)^2 - M_{Y'}^2} \frac{g_{KY\Xi^*}}{M_K} (k_2 \cdot \bar{U}_{\Xi^*}) \\ &\quad \times (k_2 + \not{p} + M_Y) \left[ \gamma^\mu + \frac{i\kappa_Y}{2M_N} q_\nu \sigma^{\mu\nu} \right] \epsilon_\mu u_Y, \\ \mathcal{M}_{\gamma Y \rightarrow K_2 \Xi^*}^C &= ie \frac{g_{KY\Xi^*}}{M_K} (\epsilon \cdot \bar{U}_{\Xi^*}) u_Y, \\ \mathcal{M}_{\gamma Y \rightarrow K_2 \Xi^*}^{t(K^*)} &= \frac{-eg_{\gamma KK^*}}{(k_2 - q)^2 - M_{K^*}^2} \frac{1}{M_K} \frac{g_{K^*Y\Xi^*}}{2M_N} \epsilon^{\mu\nu\alpha\beta} \\ &\quad \times \left[ (p - q) \cdot \bar{U}_{\Xi^*} \gamma_\mu \gamma_5 u_Y \right. \\ &\quad \left. - \bar{U}_{\Xi^*} \cdot \mu (\not{p} - \not{q}) \gamma_5 u_Y \right] q_\nu p_\alpha \epsilon_\beta, \\ \mathcal{M}_{\gamma Y \rightarrow K_2 \Xi^*}^{u(\Xi)} &= \frac{-ieg_{\gamma \Xi \Xi^*} g_{KY\Xi}}{(p - k_1)^2 - M_\Xi^2} \frac{1}{2M_N} \bar{U}_{\Xi^*}^\mu \gamma^\nu \\ &\quad \times \gamma_5 (q_\mu \epsilon_\nu - q_\nu \epsilon_\mu) (\not{p} - \not{q} + M_\Xi) \gamma_5 u_Y, \end{aligned}$$

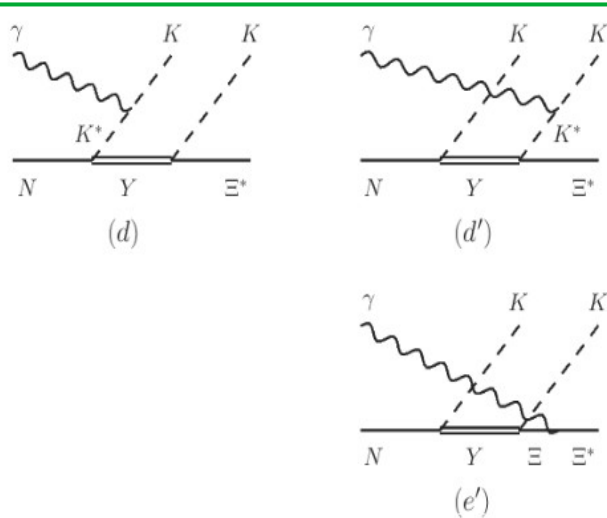
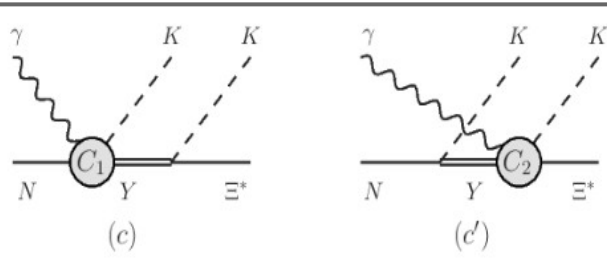
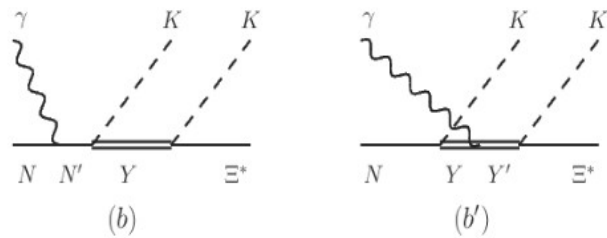
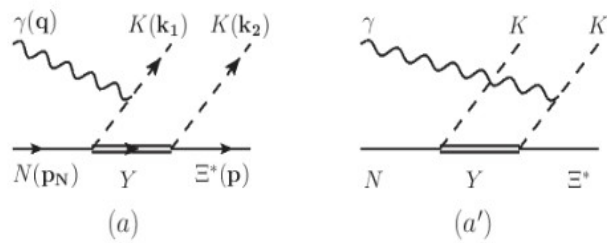
## 2. theoretical framework

$$(I) \gamma p \rightarrow K^+ K^+ \Xi^{*-}, \quad (II) \gamma p \rightarrow K^+ K^0 \Xi^{*0}$$

### Gauge Invariant; Contact terms

Extension from one-meson to two-meson photoproduction

[Haberzettl, PRC.56.2041 (1997), 58.R40 (1998), Nakayama, PRC.74.035205 (2006)]



→ self gauge invariant

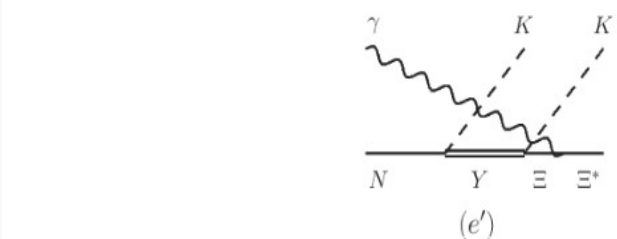
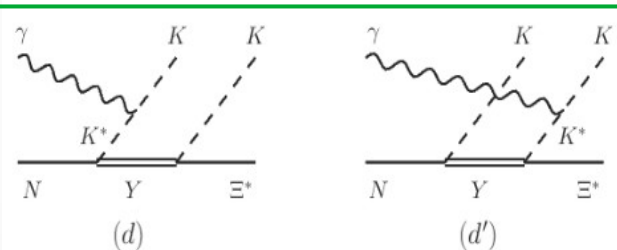
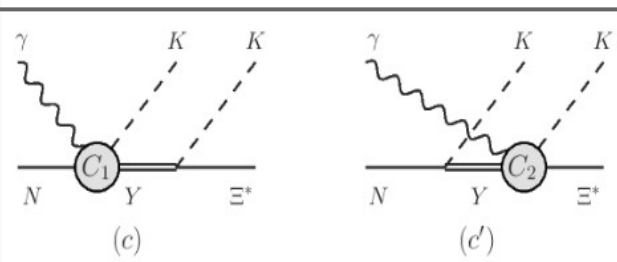
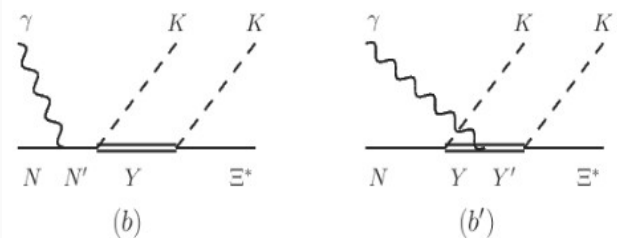
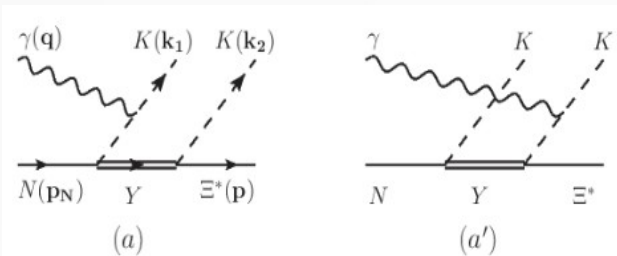
## 2. theoretical framework

$$(I) \gamma p \rightarrow K^+ K^+ \Xi^{*-}, \quad (II) \gamma p \rightarrow K^+ K^0 \Xi^{*0}$$

### Gauge Invariant; Contact terms

Extension from one-meson to two-meson photoproduction

[Haberzettl, PRC.56.2041 (1997), 58.R40 (1998), Nakayama, PRC.74.035205 (2006)]



$$C_1^\mu = \frac{\Gamma_{c1}^\mu (e_i \tilde{R}_{s1} - e_B \tilde{R}_1)}{\gamma \text{KNY}} + \frac{\Gamma_1 \tilde{C}_1^\mu}{\text{KNY}}$$

$$C_2^\mu = \frac{\Gamma_{c2}^\mu (e_B \tilde{R}_2 - e_f \tilde{R}_{u2})}{\gamma \text{KY}\Xi^*} + \frac{\Gamma_2 \tilde{C}_2^\mu}{\text{KY}\Xi^*}$$

$$\begin{aligned} \tilde{C}_1^\mu = & -e_1 \frac{(2k_1 - q)^\mu}{t_1 - k_1^2} (\tilde{R}_{t1} - \hat{F}_1) \\ & -e_i \frac{(2p_N + q)^\mu}{s_1 - p_N^2} (\tilde{R}_{s1} - \hat{F}_1) \\ & -e_B \frac{(2p_N - 2k_1 + q)^\mu}{u_1 - s_2} (\tilde{R}_1 - \hat{F}_1) \end{aligned}$$

$$\begin{aligned} \tilde{C}_2^\mu = & -e_2 \frac{(2k_2 - q)^\mu}{t_2 - k_2^2} (\tilde{R}_{t2} - \hat{F}_2) \\ & -e_f \frac{(2p + q)^\mu}{u_2 - p^2} (\tilde{R}_{u2} - \hat{F}_2) \\ & -e_B \frac{(2p - 2k_2 + q)^\mu}{s_2 - u_1} (\tilde{R}_2 - \hat{F}_2) \end{aligned}$$

$$\hat{F}_1 = \hat{R}_1 + \frac{1}{\hat{R}_1^2} (\delta_1 \tilde{R}_{t1} - \hat{R}_1) (\delta_i \tilde{R}_{s1} - \hat{R}_1) (\delta_B \tilde{R}_1 - \hat{R}_1)$$

$$\hat{F}_2 = \hat{R}_2 + \frac{1}{\hat{R}_2^2} (\delta_2 \tilde{R}_{t2} - \hat{R}_2) (\delta_f \tilde{R}_{u2} - \hat{R}_2) (\delta_B \tilde{R}_2 - \hat{R}_2)$$

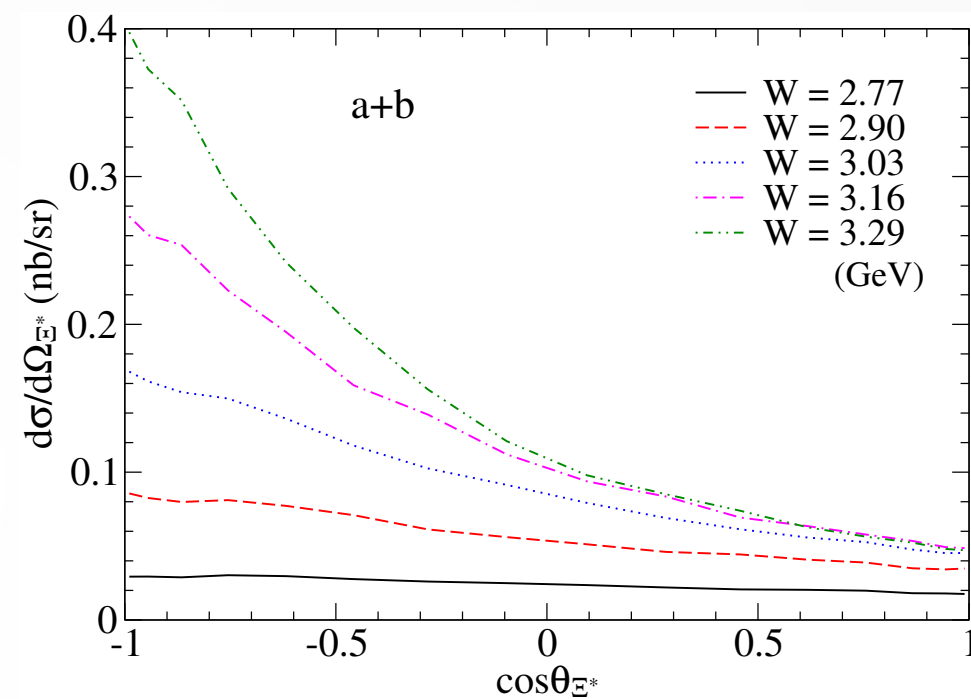
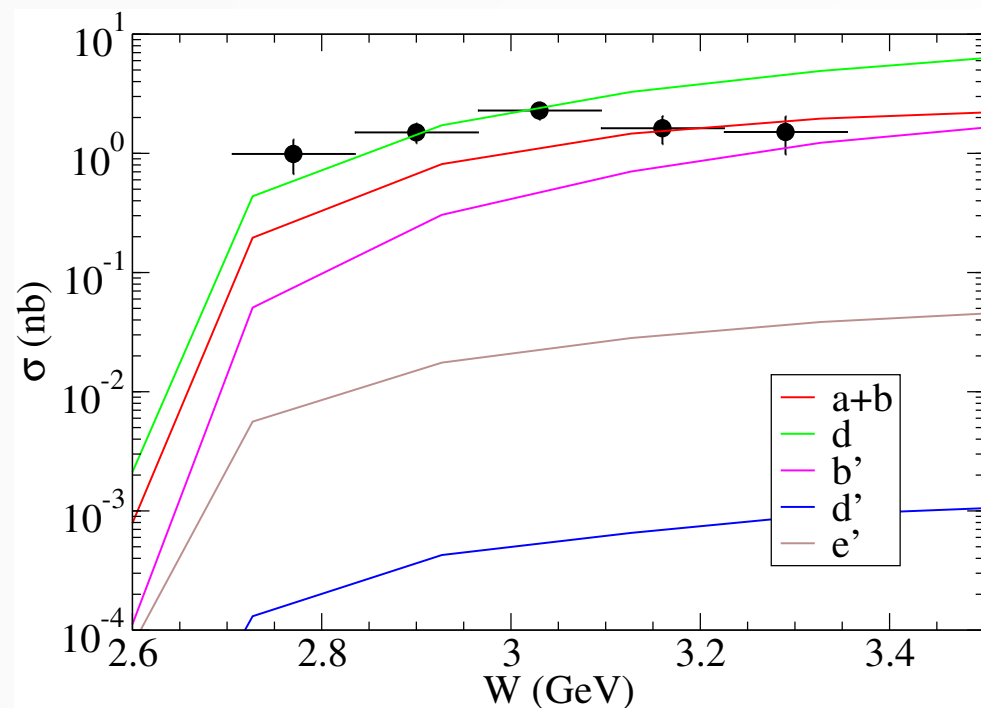
$$F(p'^2, p^2, q^2) = f_B(p'^2) f_B(p^2) f_M(q^2),$$

$$f_B(p^2) = \left( \frac{n \Lambda_B^4}{n \Lambda_B^4 + (p^2 - m_B^2)^2} \right)^n$$

$$e_B = e_f + e_2 = e_i - e_1$$

→ self gauge invariant

### 3. numerical results

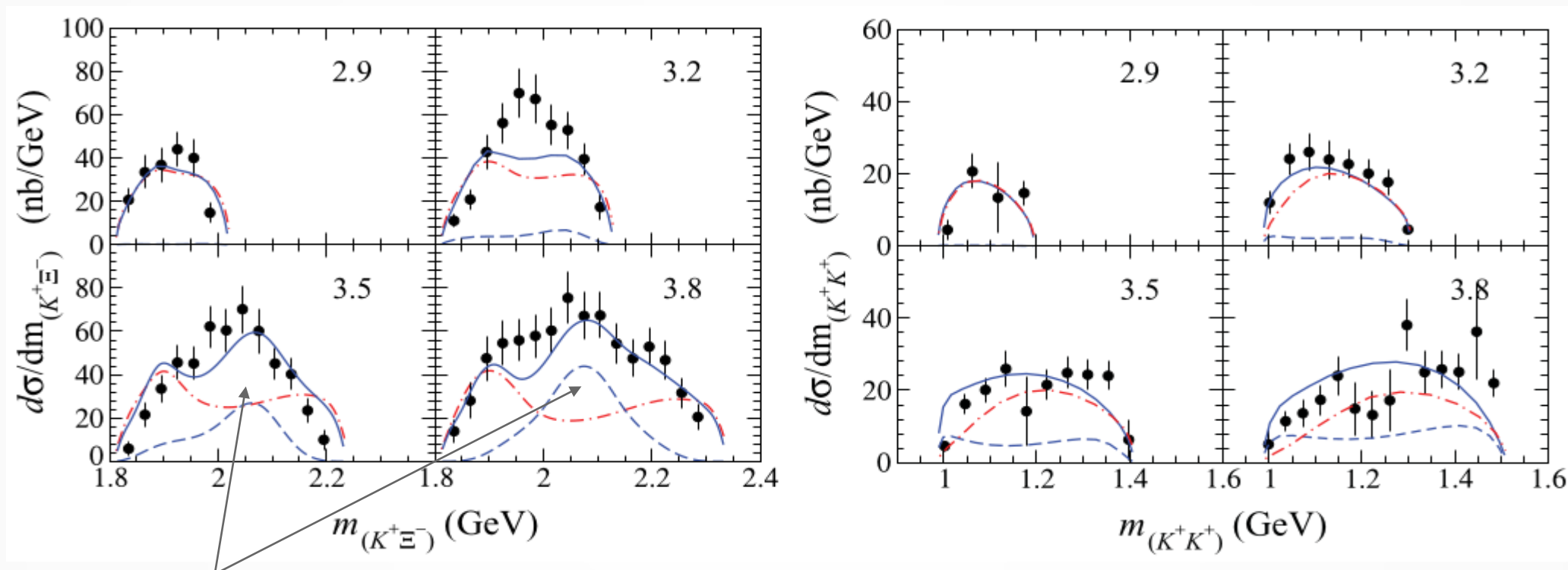


[CLAS, PRC.98.062201 (2018)]

Preliminary Result

- The processes (a – d) are more dominant than those of (a' – e').
- The results of invariant-mass distributions and Dalitz plots will come soon.

### 3. numerical results



□ The local structure is due to  $\Sigma^*(2030, 7/2^+)$ .

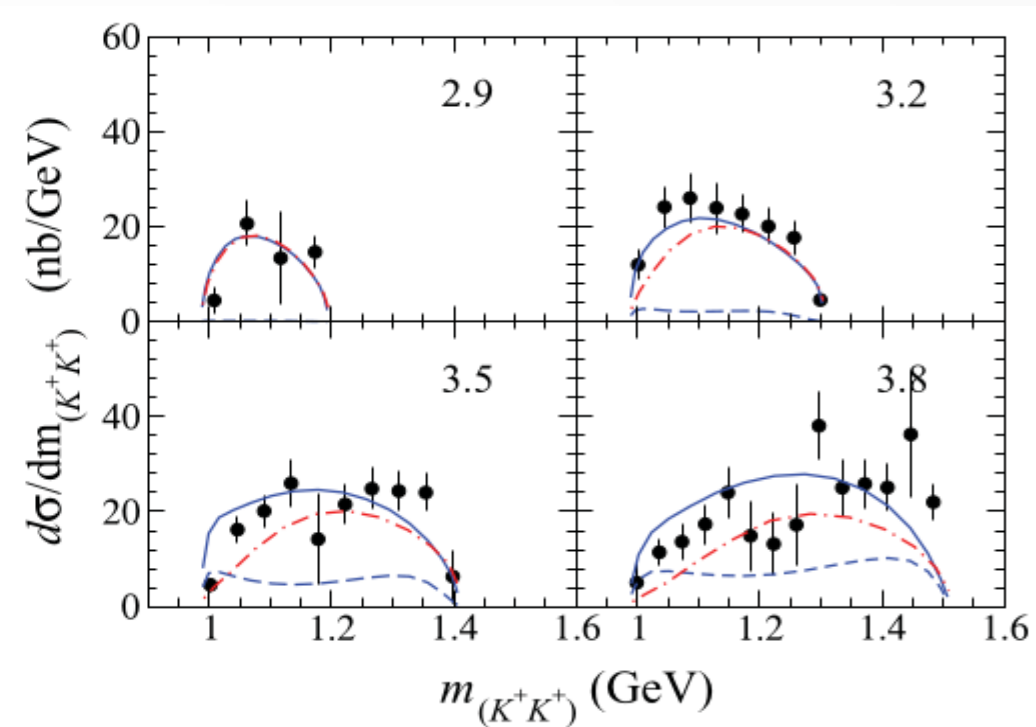
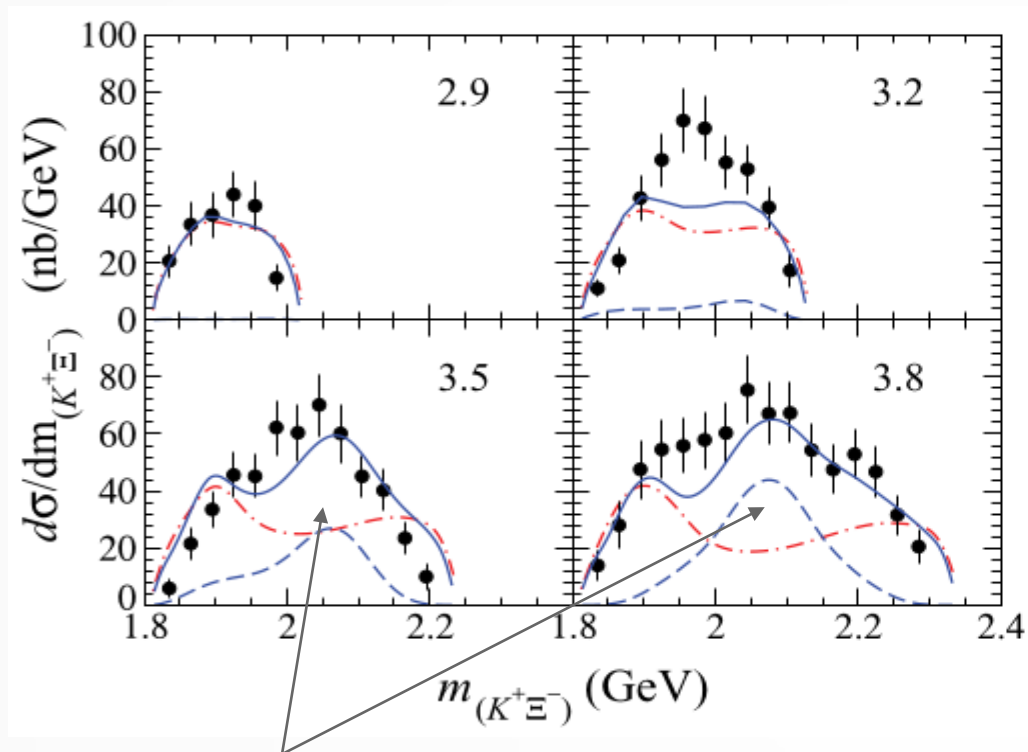
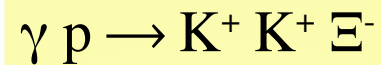
□ The absence of any structure is due to the absence of  $S=+2$  exotic meson production.

Only spin-(1/2, 3/2)  $\Lambda^*$  and  $\Sigma^*$  resonances are included. [Nakayama, PRC.74.035205 (2006)]

[CLAS, PRC.98.062201(R) (2018)]

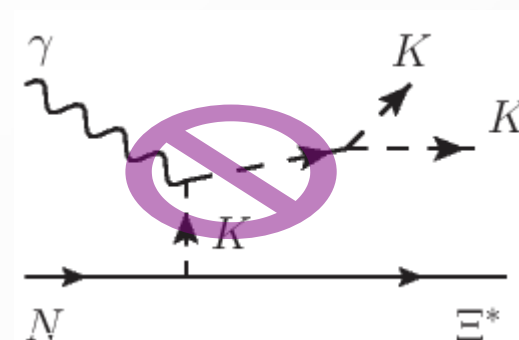
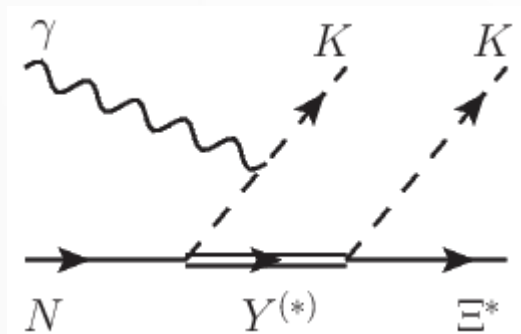
Spin-(5/2, 7/2)  $\Lambda^*$  and  $\Sigma^*$  resonances are additionally included. [Man, PRC.83.055201 (2011)]

### 3. numerical results

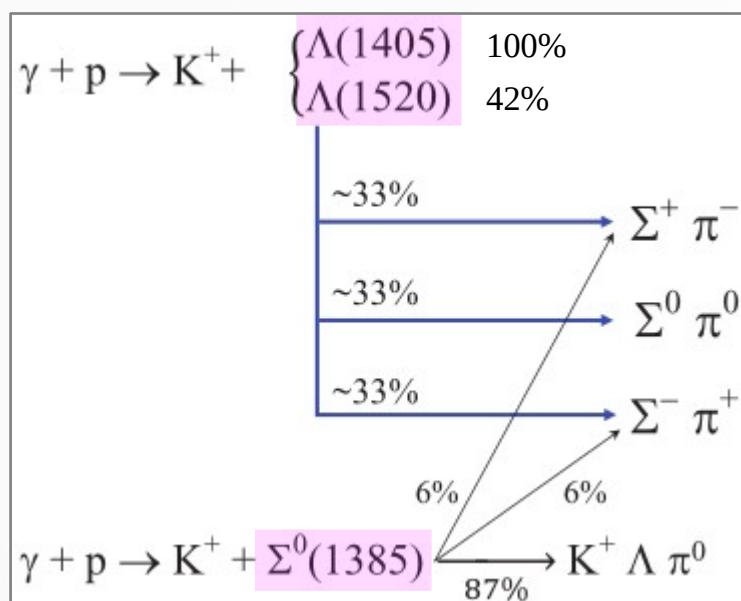
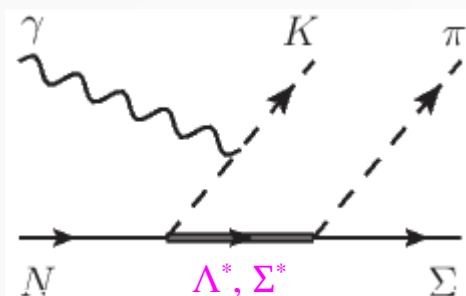


□ The local structure is due to  $\Sigma^*(2030, 7/2^+)$ .

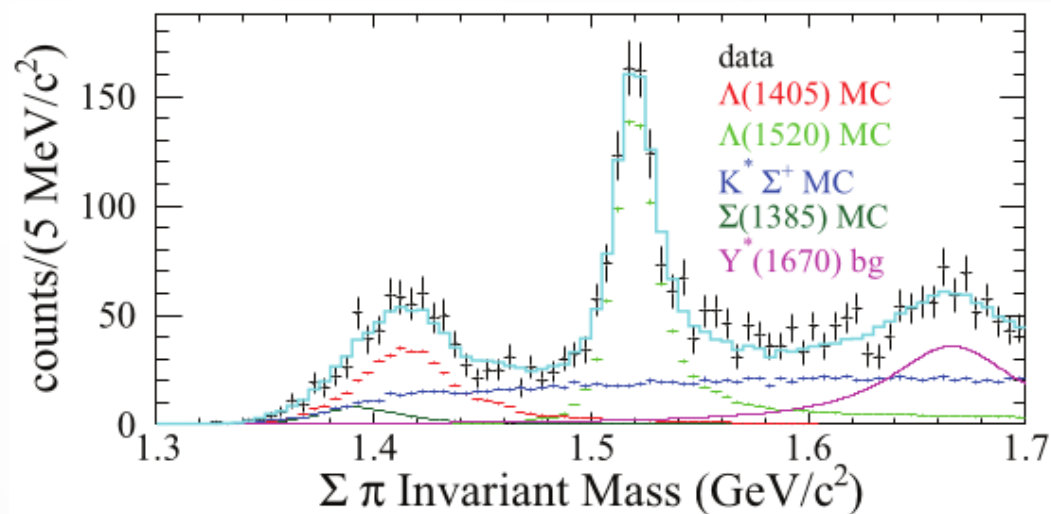
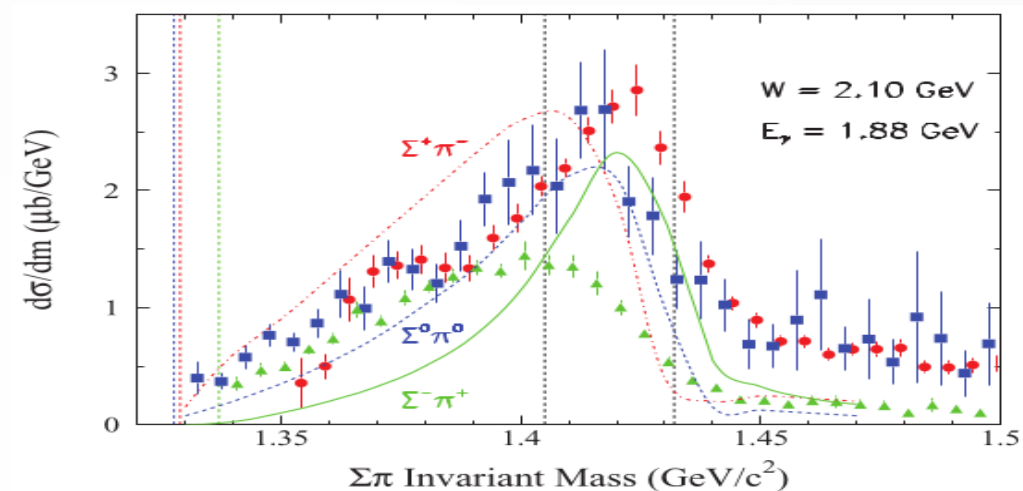
□ The absence of any structure is due to the absence of  $S=+2$  exotic meson production.



## 4. applications

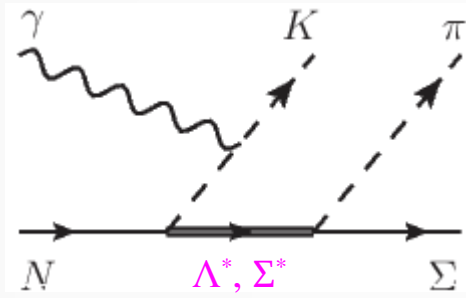


## $\gamma N \rightarrow K \pi \Sigma$ (Invariant Mass Distributions)

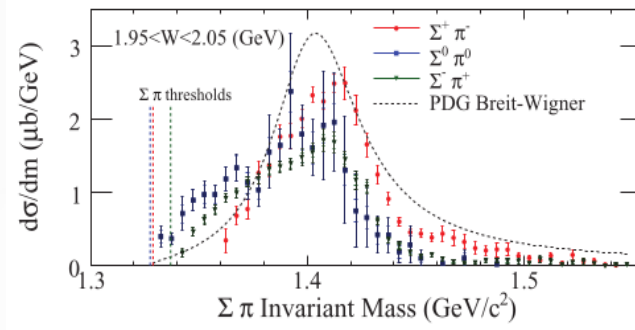


[Nacher, PLB.455.55 (1999)  
CLAS, PRC.87.035206 (2013)]

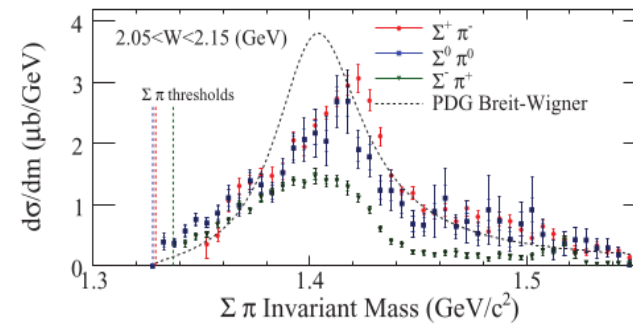
# 4. applications



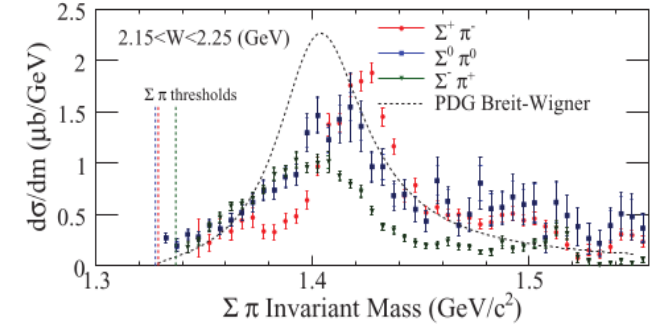
## $\gamma N \rightarrow K \pi \Sigma$ (Invariant Mass Distributions)



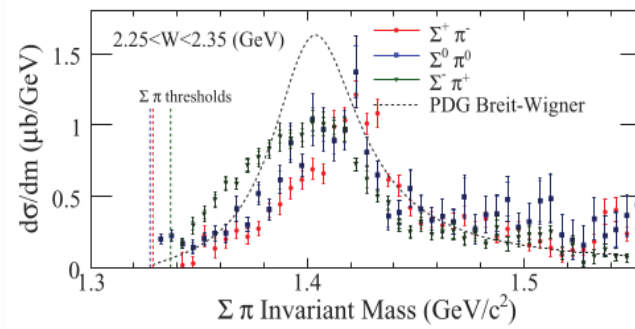
(a)



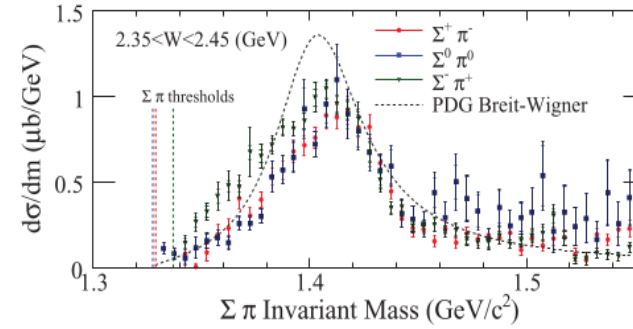
(b)



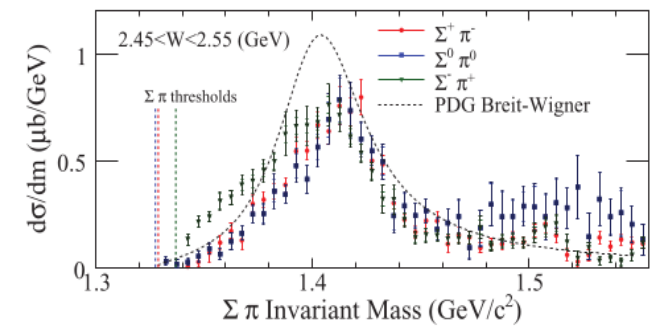
(c)



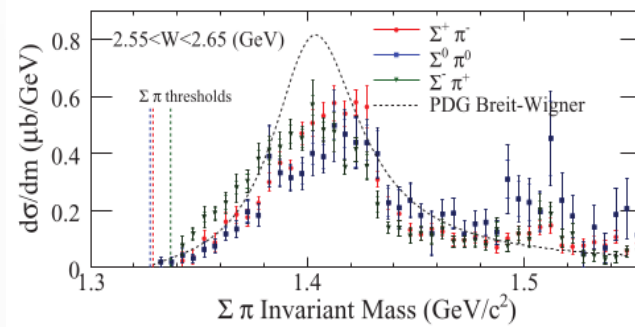
(d)



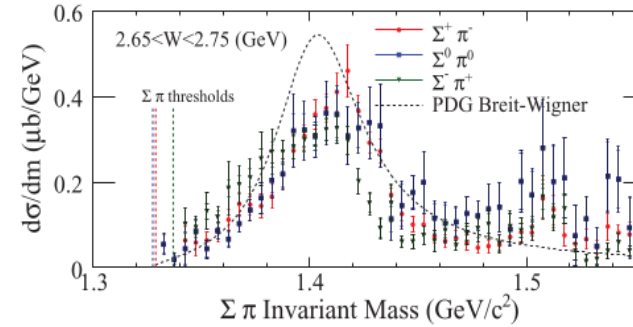
(e)



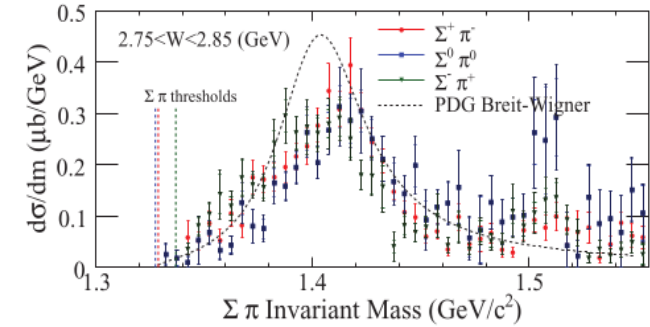
(f)



(g)

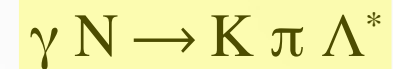
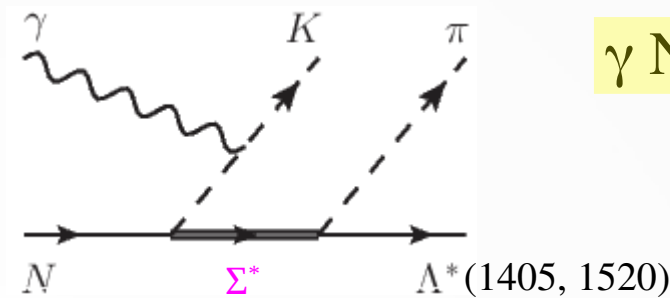
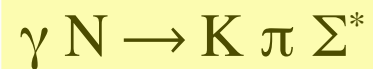
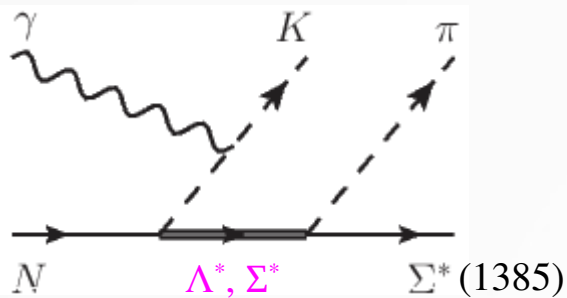


(h)



(i)

## 4. applications



$\pi \Sigma^*(1385)$     $\pi \Sigma$     $\pi \Lambda$  [%]

$\Lambda(1600, 1/2^+ \text{ ****})$	$\rightarrow$	9	35	
$\Lambda(1670, 1/2^- \text{ ****})$	$\rightarrow$	6	40	
$\Lambda(1710, 1/2^+ \text{ *})$	$\rightarrow$	20	21	
$\Lambda(1800, 1/2^- \text{ ***})$	$\rightarrow$	9	27	
$\Lambda(1810, 1/2^+ \text{ ***})$	$\rightarrow$	40	16	
$\Lambda(1820, 5/2^+ \text{ ****})$	$\rightarrow$	7.5	11	
$\Lambda(1830, 5/2^- \text{ ****})$	$\rightarrow$	> 15	55	
$\Sigma(1775, 5/2^- \text{ ****})$	$\rightarrow$	10	3.5	17

$\pi \Lambda^*(1405)$     $\pi \Sigma$     $\pi \Lambda$  [%]

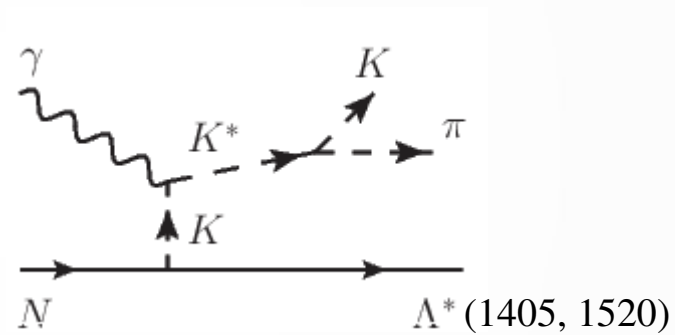
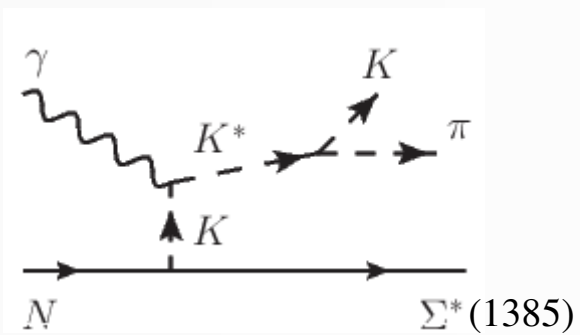
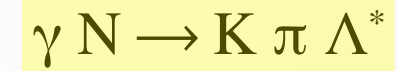
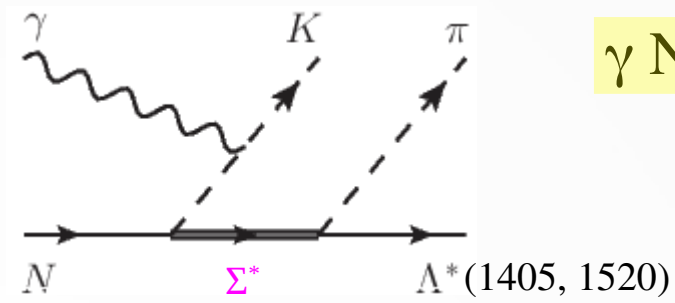
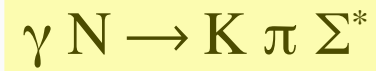
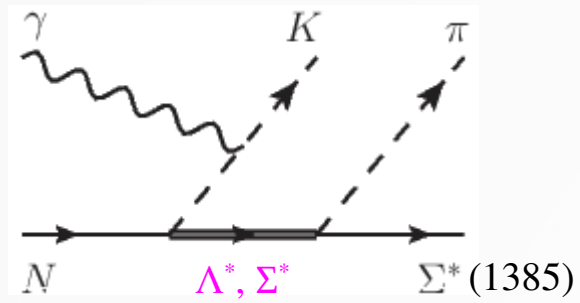
$\Sigma(1660, 1/2^+ \text{ ****})$	$\rightarrow$	4	37	35
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$\pi \Lambda^*(1520)$  [%]

$\Sigma(1620, 1/2^- \text{ *})$	$\rightarrow$	10	17	9
$\Sigma(1750, 1/2^- \text{ ***})$	$\rightarrow$	2	16	14
$\Sigma(1775, 5/2^- \text{ ****})$	$\rightarrow$	20	3.5	17
$\Sigma(1880, 1/2^+ \text{ **})$	$\rightarrow$	2		

- These reactions provide a valuable opportunity to study higher  $\Lambda^*$  and  $\Sigma^*$  resonances by measuring cross sections, invariant-mass distributions, and Dalitz plots, etc.

## 4. applications



□ These diagrams should essentially be included as part of the background contribution.

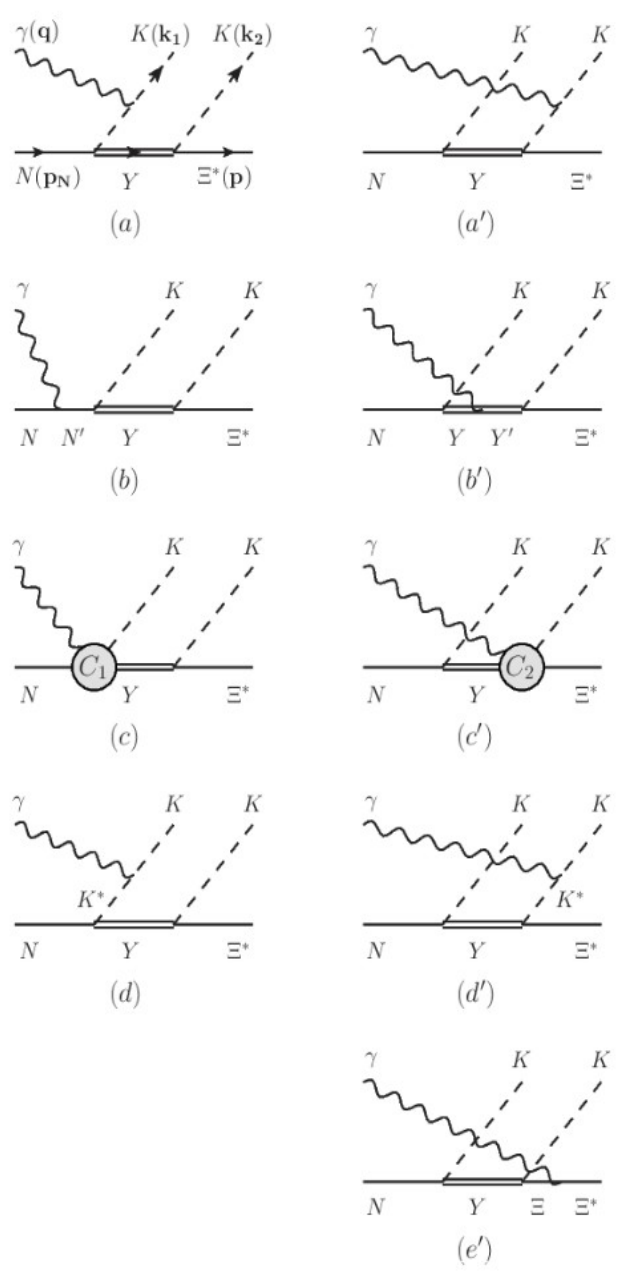
□ We can directly apply our current theoretical formalism to these reactions.

# 4. applications

$$\gamma N \rightarrow K K \Xi^*$$

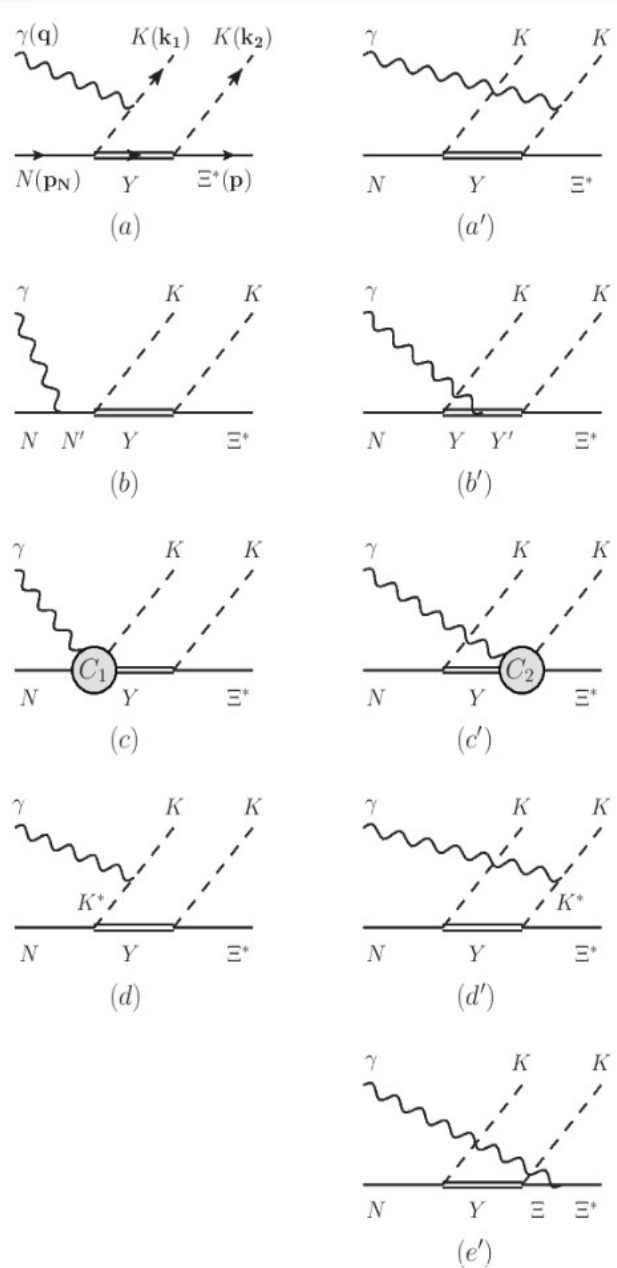


$$\pi N \rightarrow K K \Xi^*$$



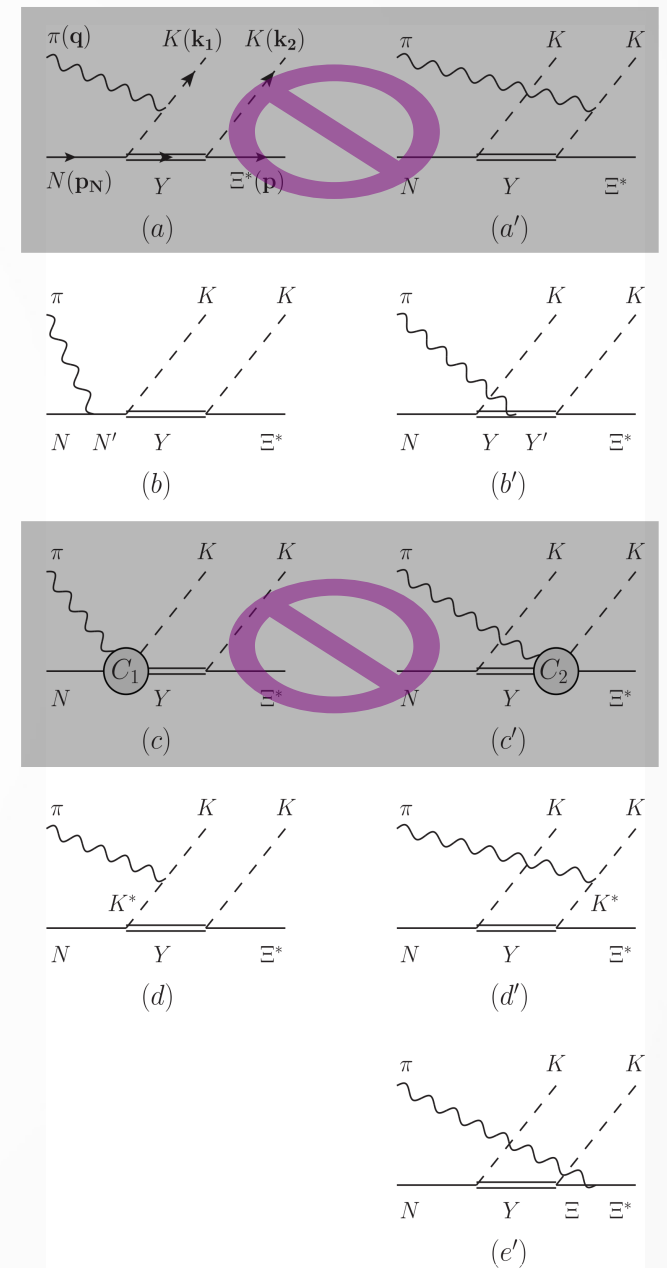
# 4. applications

$$\gamma N \rightarrow K K \Xi^*$$



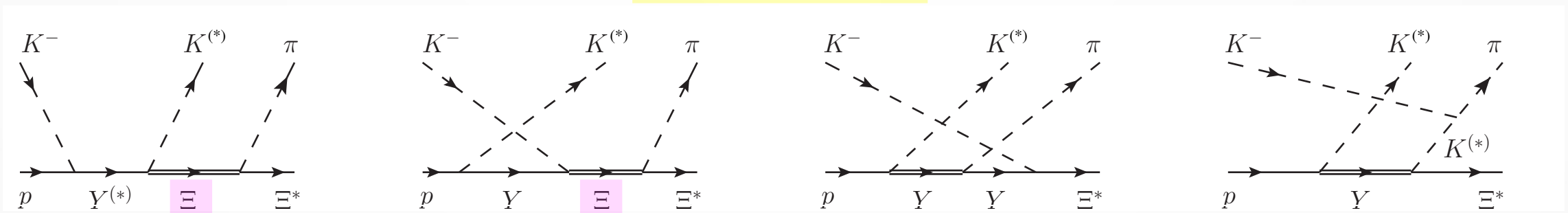
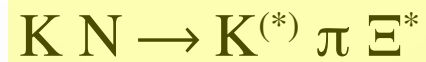
The number of possible Feynman diagrams is much reduced.

$$\pi N \rightarrow K K \Xi^*$$



## 4. applications

Particle	$J^P$	Overall status	Status as seen in —				
			$\Xi\pi$	$\Lambda K$	$\Sigma K$	$\Xi(1530)\pi$	
$\Xi(1318)$	$1/2^+$	****					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

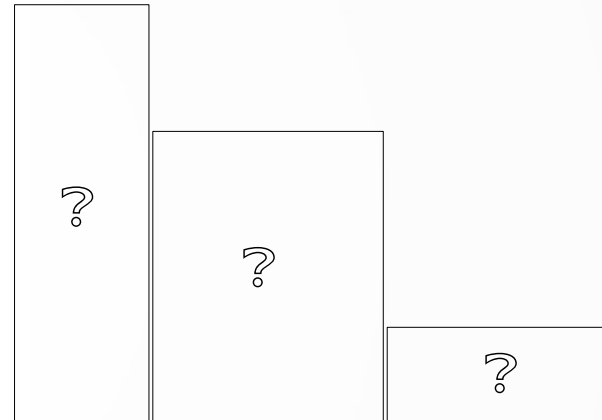
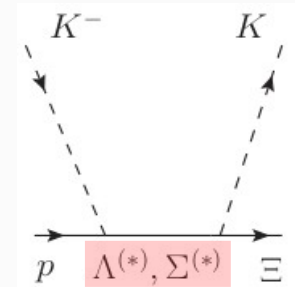


□ These reactions provide a valuable opportunity to study higher  $\Xi^*$  resonances.

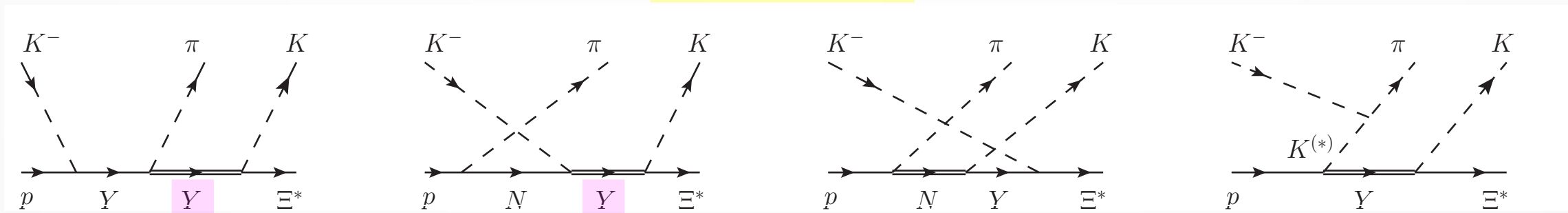
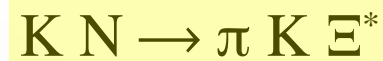
# 4. applications

Particle	$J^P$	Overall status	Status as seen in —		
			$N\bar{K}$	$\Sigma\pi$	Other channels
$\Lambda(1116)$	$1/2^+$	****			$N\pi$ (weak decay)
$\Lambda(1380)$	$1/2^-$	**	**	**	
$\Lambda(1405)$	$1/2^-$	****	****	****	
$\Lambda(1520)$	$3/2^-$	****	****	****	$\Lambda\pi\pi, \Lambda\gamma, \Sigma\pi\pi$
$\Lambda(1600)$	$1/2^+$	****	***	****	$\Lambda\pi\pi, \Sigma(1385)\pi$
$\Lambda(1670)$	$1/2^-$	****	****	****	$\Lambda\eta$
$\Lambda(1690)$	$3/2^-$	****	****	***	$\Lambda\pi\pi, \Sigma(1385)\pi$
$\Lambda(1710)$	$1/2^+$	*	*	*	
$\Lambda(1800)$	$1/2^-$	***	***	**	$\Lambda\pi\pi, N\bar{K}^*$
$\Lambda(1810)$	$1/2^+$	***	**	**	$N\bar{K}^*$
$\Lambda(1820)$	$5/2^+$	****	****	****	$\Sigma(1385)\pi$
$\Lambda(1830)$	$5/2^-$	****	****	****	$\Sigma(1385)\pi$
$\Lambda(1890)$	$3/2^+$	****	****	**	$\Sigma(1385)\pi, N\bar{K}^*$
$\Lambda(2000)$	$1/2^-$	*	*	*	
$\Lambda(2050)$	$3/2^-$	*	*	*	
$\Lambda(2070)$	$3/2^+$	*	*	*	
$\Lambda(2080)$	$5/2^-$	*	*	*	
$\Lambda(2085)$	$7/2^+$	**	**	*	
$\Lambda(2100)$	$7/2^-$	****	****	**	$N\bar{K}^*$
$\Lambda(2110)$	$5/2^+$	***	**	**	$N\bar{K}^*$
$\Lambda(2325)$	$3/2^-$	*	*	*	
$\Lambda(2350)$	$9/2^+$	***	***	*	
$\Lambda(2585)$		*	*	*	

$\Xi K$     $\Xi(1530) K$     $\Xi K(892)$



$\Xi K$   
 $\Xi(1530) K$   
 $\Xi K(892)$

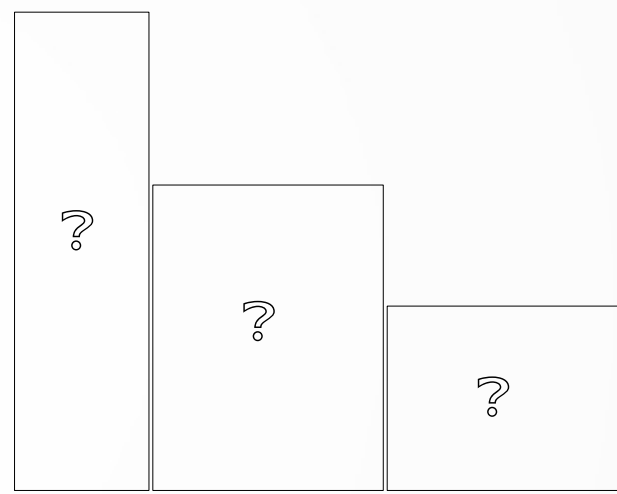
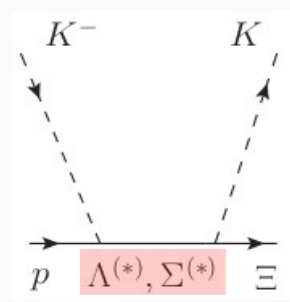


□ These reactions provide a valuable opportunity to study higher  $\Lambda^*$  and  $\Sigma^*$  resonances.

# 4. applications

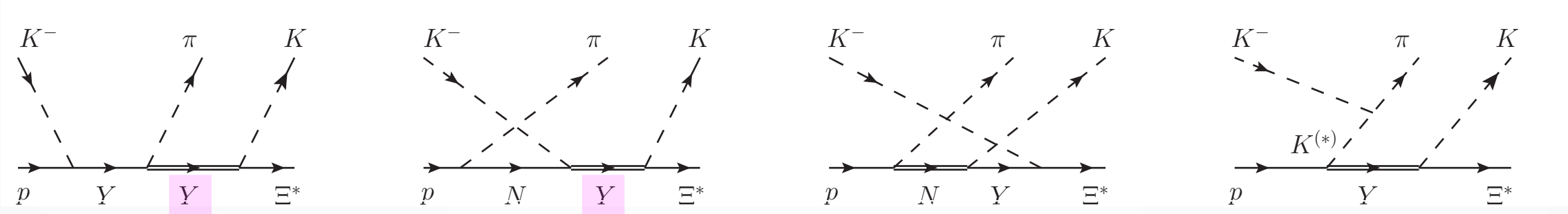
Particle	$J^P$	Overall status	Status as seen in —		
			$N\bar{K}$	$\Lambda\pi$	$\Sigma\pi$
$\Sigma(1193)$	$1/2^+$	****			
$\Sigma(1385)$	$3/2^+$	****		****	****
$\Sigma(1580)$	$3/2^-$	*	*	*	*
$\Sigma(1620)$	$1/2^-$	*	*	*	*
$\Sigma(1660)$	$1/2^+$	***	***	***	***
$\Sigma(1670)$	$3/2^-$	****	****	****	****
$\Sigma(1750)$	$1/2^-$	***	***	**	***
$\Sigma(1775)$	$5/2^-$	****	****	****	**
$\Sigma(1780)$	$3/2^+$	*	*	*	*
$\Sigma(1880)$	$1/2^+$	**	**	*	*
$\Sigma(1900)$	$1/2^-$	**	**	*	**
$\Sigma(1910)$	$3/2^-$	***	*	*	**
$\Sigma(1915)$	$5/2^+$	****	***	***	***
$\Sigma(1940)$	$3/2^+$	*	*		*
$\Sigma(2010)$	$3/2^-$	*	*	*	
$\Sigma(2030)$	$7/2^+$	****	****	****	**
$\Sigma(2070)$	$5/2^+$	*	*		*
$\Sigma(2080)$	$3/2^+$	*		*	
$\Sigma(2100)$	$7/2^-$	*	*	*	*
$\Sigma(2110)$	$1/2^-$	*	*	*	*
$\Sigma(2230)$	$3/2^+$	*	*	*	*
$\Sigma(2250)$		**	**	*	*
$\Sigma(2455)$		*	*		
$\Sigma(2620)$		*	*		
$\Sigma(3000)$		*	*	*	
$\Sigma(3170)$		*			

$\Xi K$     $\Xi(1530) K$     $\Xi K(892)$



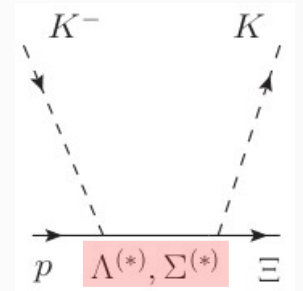
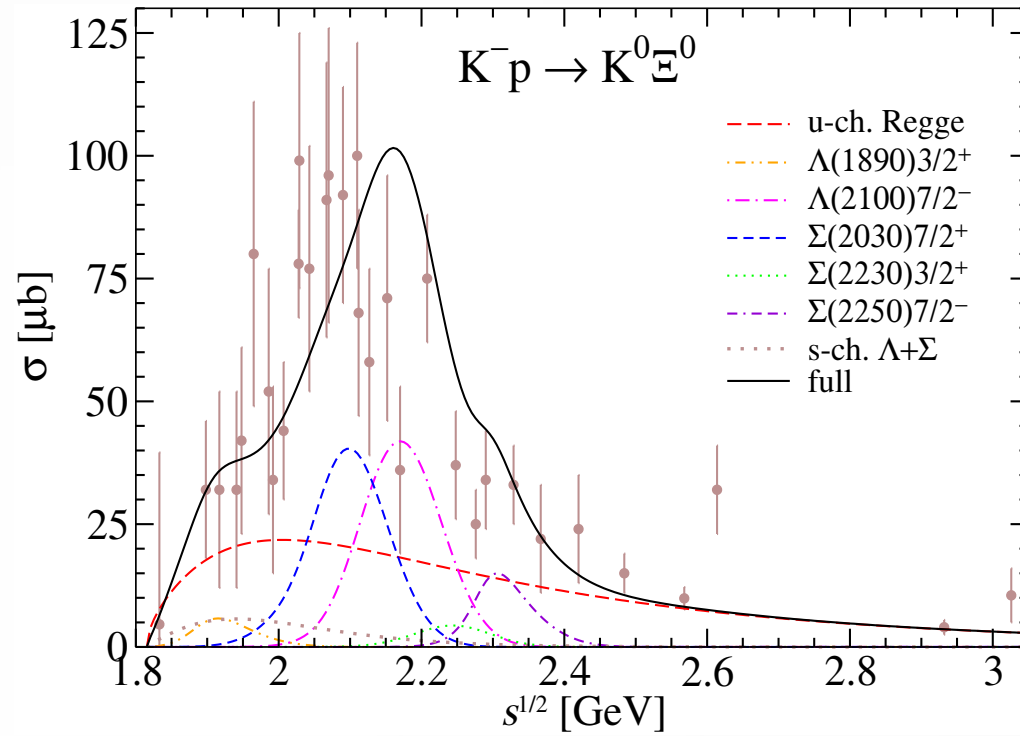
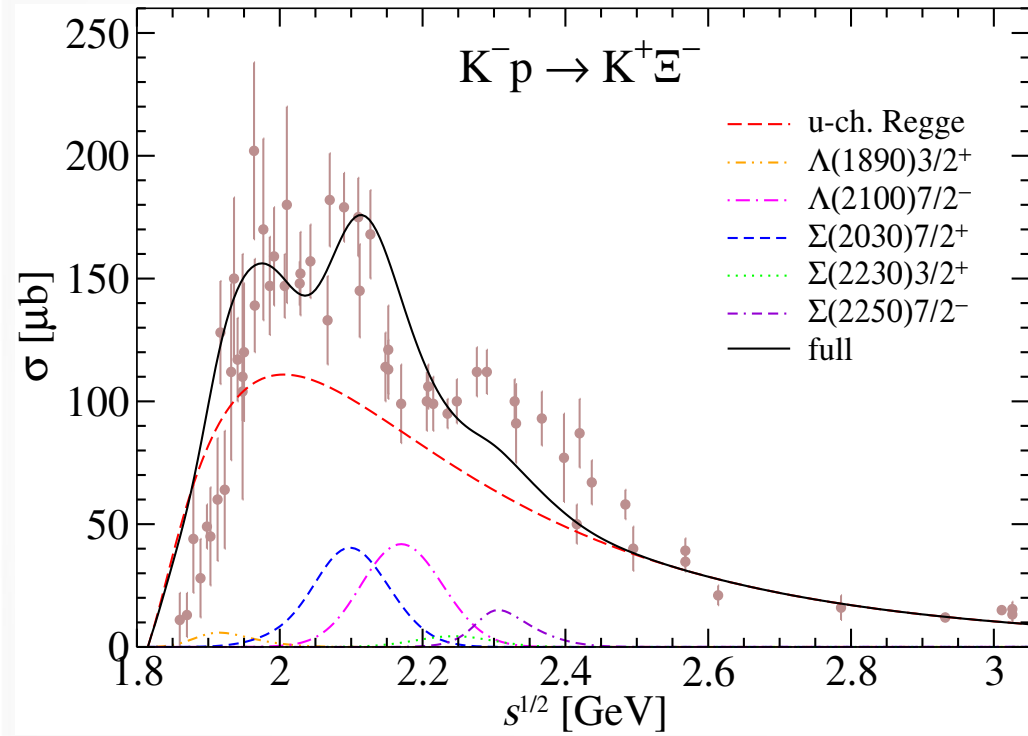
$\Xi K$   
 $\Xi(1530) K$   
 $\Xi K(892)$

$K N \rightarrow \pi K \Xi^*$



□ These reactions provide a valuable opportunity to study higher  $\Lambda^*$  and  $\Sigma^*$  resonances.

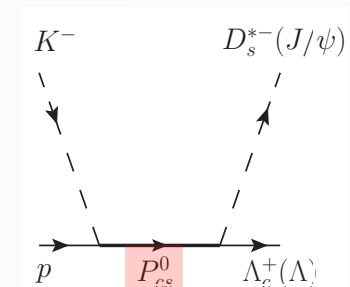
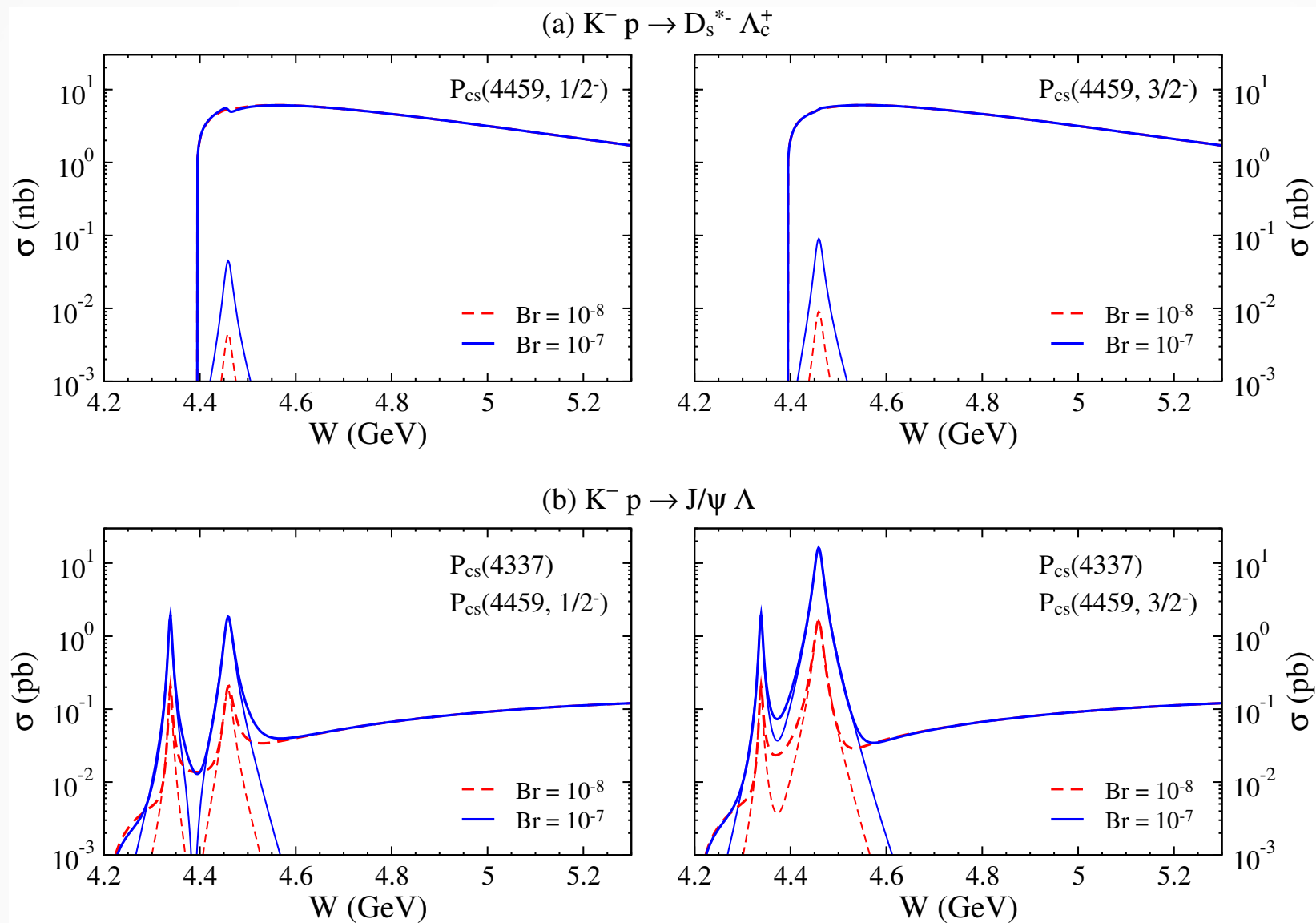
## 4. applications



[KimSH et al, PRC.107.065202 (2023)]

□ Higher  $\Lambda^*$  and  $\Sigma^*$  resonances can be identified through bump structures.

# 4. applications



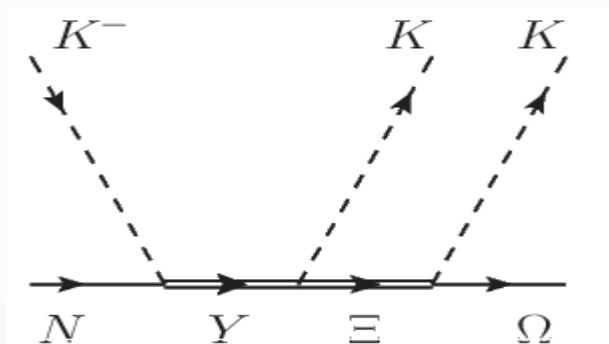
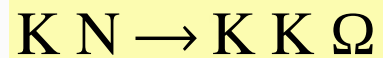
[KimSH, 2602.01768 (2026)]

□ The pentaquark states can be identified through bump structures.

Proposal for the J-PARC 30-GeV Proton Synchrotron (2021)

## Spectroscopy of Omega Baryons

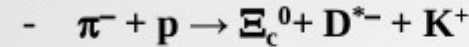
K. Aoki<sup>a</sup>, Y. Hidaka<sup>b,c,d</sup>, A. Hosaka<sup>e,f,g</sup>, N. Ishii<sup>e</sup>, T. Ishikawa<sup>h</sup>, Y. Komatsu<sup>a</sup>,  
 M. Naruki<sup>i,f</sup>, H. Noumi<sup>e,a</sup>, H. Ohnishi<sup>h</sup>, K. Ozawa<sup>a</sup>, Y. Morino<sup>a</sup>, F. Sakuma<sup>j</sup>,  
 T. Sekihara<sup>k</sup>, S.-I. Shim<sup>l</sup>, K. Shirotori<sup>e\*</sup>, H. Takahashi<sup>a</sup>, S. Takeuchi<sup>m,g</sup>, and  
 M. Takizawa<sup>n,b,j</sup>



- **Charmed baryons**



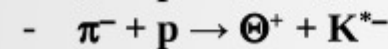
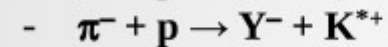
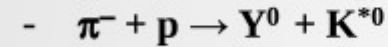
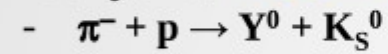
- **$\Xi_c$  baryons**



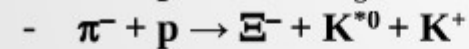
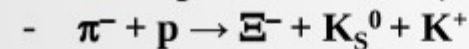
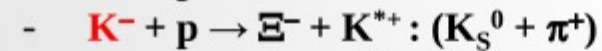
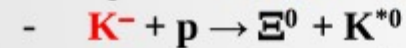
**Byproducts**

*Event selection as you like !*

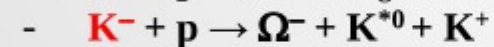
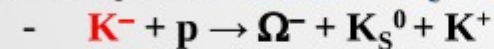
- **Y baryons: Yield =  $Y_c \times 10^4$**



- **$\Xi$  baryons: Yield =  $Y_c \times 10^3$**

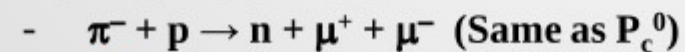


- **$\Omega$  baryons: Yield =  $Y_c \times 10^2$**



- **\* Hyperon beams as well**

- **Drell-Yan channels**

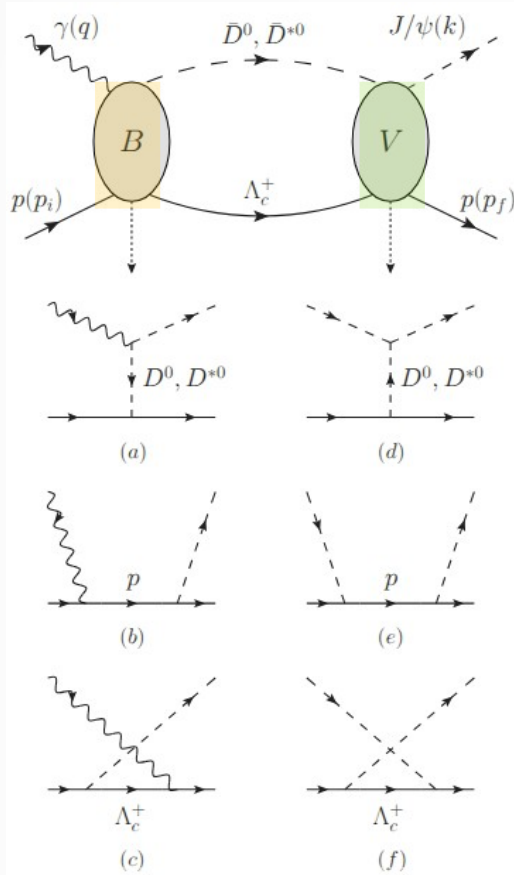


Slide by K. Shirotori

# 4. applications

## Rescattering effect ( $\gamma p \rightarrow \varphi p$ )

S. Sakinah, SHKim, HMChoi, 2604.14814 (2026)



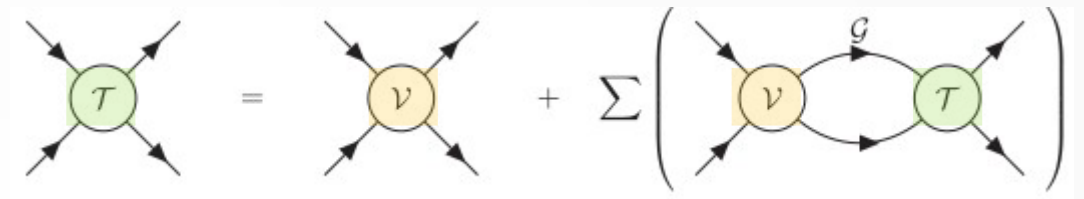
$$T_{\text{loop}}(q, k) = \int d^3\mathbf{q}' B_{\gamma p \rightarrow MB}(q, q') \frac{1}{2E_M(\mathbf{q}')} \frac{M_B}{E_B(\mathbf{q}')} \times G_{MN}(\mathbf{q}') V_{MB \rightarrow J/\psi p}(q', k).$$

$$G_{MN} = \frac{1}{E - H_0 + i\epsilon} = P \frac{1}{E - H_0} - i\pi\delta(E - H_0)$$

□ We consider both parts numerically.

## Final state interaction ( $\gamma p \rightarrow \varphi p$ )

S. Clymton, SHKim, HChKim, in preparation (2026)



□ An off-shell coupled-channel formalism is essential.

$$V = \begin{pmatrix} V_{J/\psi N \rightarrow J/\psi N} & V_{\bar{D}\Lambda_c \rightarrow J/\psi N} & V_{\bar{D}^*\Lambda_c \rightarrow J/\psi N} & V_{\bar{D}\Sigma_c \rightarrow J/\psi N} & V_{\bar{D}\Sigma_c^* \rightarrow J/\psi N} & V_{\bar{D}^*\Sigma_c \rightarrow J/\psi N} & V_{\bar{D}^*\Sigma_c^* \rightarrow J/\psi N} \\ V_{J/\psi N \rightarrow \bar{D}\Lambda_c} & V_{\bar{D}\Lambda_c \rightarrow \bar{D}\Lambda_c} & V_{\bar{D}^*\Lambda_c \rightarrow \bar{D}\Lambda_c} & V_{\bar{D}\Sigma_c \rightarrow \bar{D}\Lambda_c} & V_{\bar{D}\Sigma_c^* \rightarrow \bar{D}\Lambda_c} & V_{\bar{D}^*\Sigma_c \rightarrow \bar{D}\Lambda_c} & V_{\bar{D}^*\Sigma_c^* \rightarrow \bar{D}\Lambda_c} \\ V_{J/\psi N \rightarrow \bar{D}^*\Lambda_c} & V_{\bar{D}\Lambda_c \rightarrow \bar{D}^*\Lambda_c} & V_{\bar{D}^*\Lambda_c \rightarrow \bar{D}^*\Lambda_c} & V_{\bar{D}\Sigma_c \rightarrow \bar{D}^*\Lambda_c} & V_{\bar{D}\Sigma_c^* \rightarrow \bar{D}^*\Lambda_c} & V_{\bar{D}^*\Sigma_c \rightarrow \bar{D}^*\Lambda_c} & V_{\bar{D}^*\Sigma_c^* \rightarrow \bar{D}^*\Lambda_c} \\ V_{J/\psi N \rightarrow \bar{D}\Sigma_c} & V_{\bar{D}\Lambda_c \rightarrow \bar{D}\Sigma_c} & V_{\bar{D}^*\Lambda_c \rightarrow \bar{D}\Sigma_c} & V_{\bar{D}\Sigma_c \rightarrow \bar{D}\Sigma_c} & V_{\bar{D}\Sigma_c^* \rightarrow \bar{D}\Sigma_c} & V_{\bar{D}^*\Sigma_c \rightarrow \bar{D}\Sigma_c} & V_{\bar{D}^*\Sigma_c^* \rightarrow \bar{D}\Sigma_c} \\ V_{J/\psi N \rightarrow \bar{D}\Sigma_c^*} & V_{\bar{D}\Lambda_c \rightarrow \bar{D}\Sigma_c^*} & V_{\bar{D}^*\Lambda_c \rightarrow \bar{D}\Sigma_c^*} & V_{\bar{D}\Sigma_c \rightarrow \bar{D}\Sigma_c^*} & V_{\bar{D}\Sigma_c^* \rightarrow \bar{D}\Sigma_c^*} & V_{\bar{D}^*\Sigma_c \rightarrow \bar{D}\Sigma_c^*} & V_{\bar{D}^*\Sigma_c^* \rightarrow \bar{D}\Sigma_c^*} \\ V_{J/\psi N \rightarrow \bar{D}^*\Sigma_c} & V_{\bar{D}\Lambda_c \rightarrow \bar{D}^*\Sigma_c} & V_{\bar{D}^*\Lambda_c \rightarrow \bar{D}^*\Sigma_c} & V_{\bar{D}\Sigma_c \rightarrow \bar{D}^*\Sigma_c} & V_{\bar{D}\Sigma_c^* \rightarrow \bar{D}^*\Sigma_c} & V_{\bar{D}^*\Sigma_c \rightarrow \bar{D}^*\Sigma_c} & V_{\bar{D}^*\Sigma_c^* \rightarrow \bar{D}^*\Sigma_c} \\ V_{J/\psi N \rightarrow \bar{D}^*\Sigma_c^*} & V_{\bar{D}\Lambda_c \rightarrow \bar{D}^*\Sigma_c^*} & V_{\bar{D}^*\Lambda_c \rightarrow \bar{D}^*\Sigma_c^*} & V_{\bar{D}\Sigma_c \rightarrow \bar{D}^*\Sigma_c^*} & V_{\bar{D}\Sigma_c^* \rightarrow \bar{D}^*\Sigma_c^*} & V_{\bar{D}^*\Sigma_c \rightarrow \bar{D}^*\Sigma_c^*} & V_{\bar{D}^*\Sigma_c^* \rightarrow \bar{D}^*\Sigma_c^*} \end{pmatrix}$$

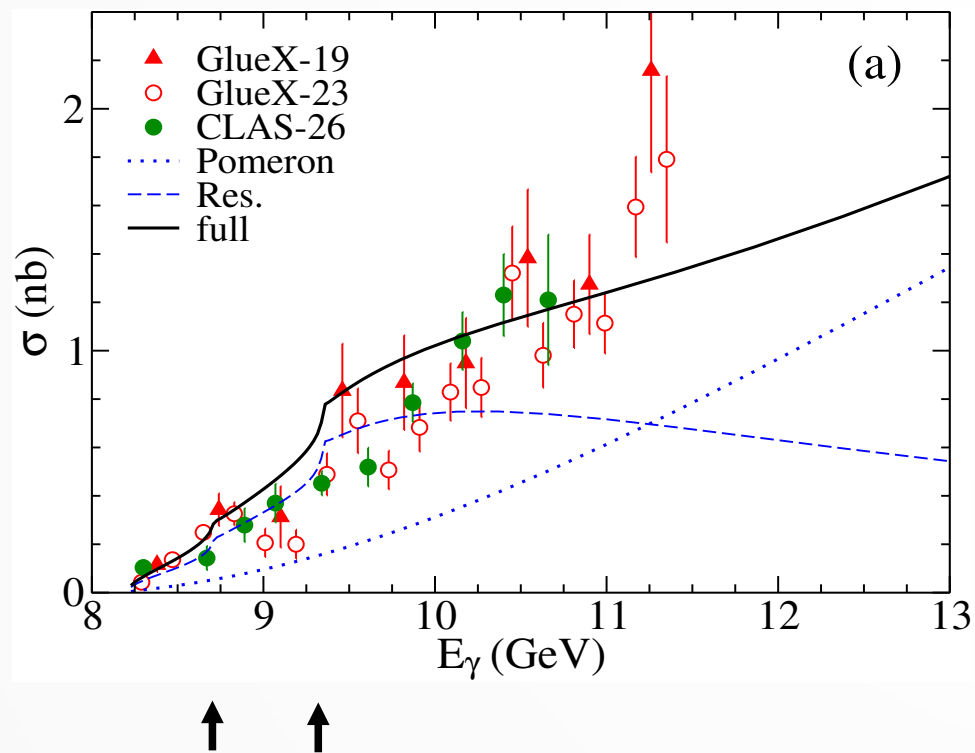
□  $T$  matrix is derived the Haftel-Tabakin method for matrix inversion:  $T = (1 - V\tilde{G})^{-1}V$

$$\mathcal{T}_{fi}(\mathbf{p}', \mathbf{p}) = \mathcal{V}_{fi}(\mathbf{p}', \mathbf{p}) + \frac{1}{(2\pi)^3} \sum_k \int \frac{d^3q}{2E_{k1}(\mathbf{q})E_{k2}(\mathbf{q})} \times \mathcal{V}_{fk}(\mathbf{p}', \mathbf{q}) \frac{E_k(\mathbf{q})}{s - E_k^2(\mathbf{q}) + i\epsilon} \mathcal{T}_{ki}(\mathbf{q}, \mathbf{p}),$$

## 4. applications

### Rescattering effect ( $\gamma p \rightarrow \varphi p$ )

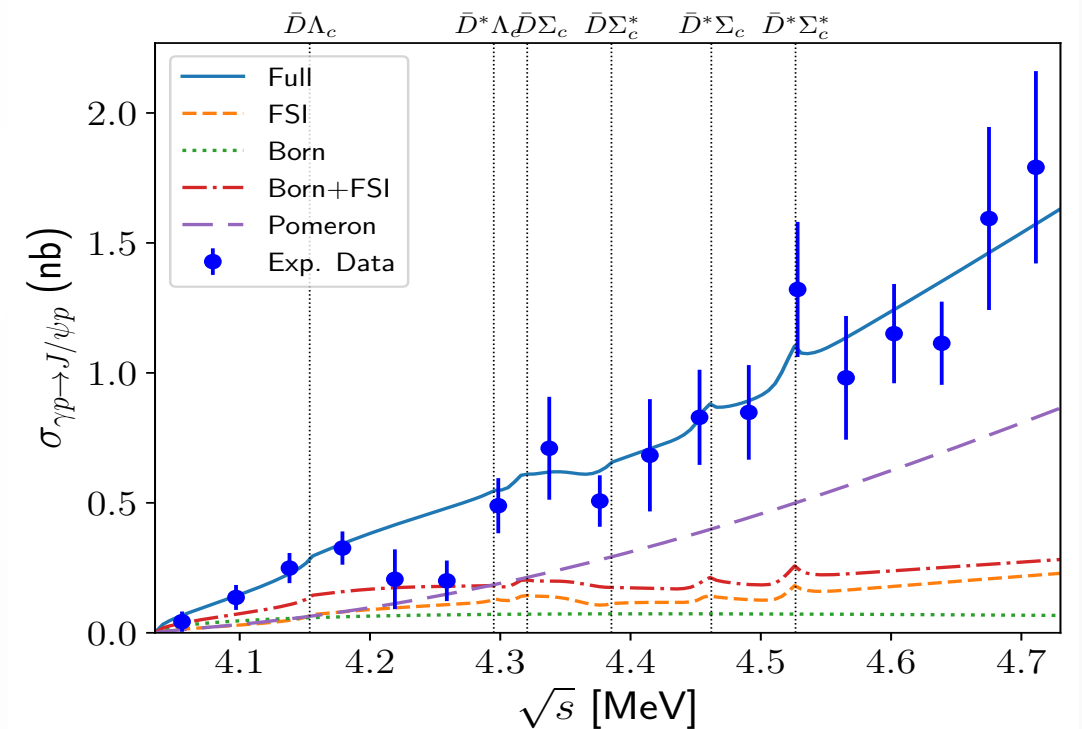
S. Sakinah, SHKim, HMChoi, 2604.14814 (2026)



- Two pronounced cusp structures are located at the  $\bar{D}\Lambda_c$  and  $\bar{D}^*\Lambda_c$  thresholds.

### Final state interaction ( $\gamma p \rightarrow \varphi p$ )

S. Clymton, SHKim, HChKim, in preparation (2026)



- Different cusp structures are generated automatically.

- We studied the  $\gamma p \rightarrow K^+ K^+ \Xi^{*-}$  reaction in a hadron exchange model.  
Nine Feynman diagrams are rigorously taken into account in a gauge invariant manner.
- The **total cross section** is calculated and is fitted to the JLAB/CLAS data.  
The results of **invariant-mass distributions** and **Dalitz plots** will come soon.
- We can apply our formalism to other 3-body reaction channels:  
 $\gamma N \rightarrow K \pi \Sigma^*$  (JLab),  $K N \rightarrow \pi K \Xi^*$ ,  $K K \Omega$  (J-PARC), etc.
- A comprehensive understanding of multistrangeness baryons requires a detailed investigation of three-body reaction mechanisms.

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Thank you very much for your attention