Recent Developments in Hadron Spectroscopy

– Introduction

– Naive Quark Model of Hadrons

– Extensions of the Model/Exotic States

– Determination of Hadronic Properties

– Experiments/Analysis Methods in Hadron Spectroscopy

– Overview on Exotic States
(see M. Amarian / K. Götzen / T. Nakano / M. Ostrick)

– Conclusions

Introduction (1)

Leptons	—	Hadrons
(e, μ, τ, ν_e, ν_μ, ν_τ)		(p, n, π, K, ···, f_2(1270, ···)
(only weak and e.-m. interactions)		(In addition: Strong interaction (QCD))
		Baryons (B=1) Mesons (B=0)
		Mass Region: 140 MeV(π) - 10 GeV (Υ)

Introduction (2)

Life times (Decays)

Proton (938) $:\tau = \infty$?

Neutron (940)	$:\tau = 885\text{s}$	(Weak Decay)	Ground States / Particles
$\pi^+(140)$	$:\tau = 2.6\text{x}10^{-8}\text{s}$	(")	
$K^+(494)$	$:\tau = 1.2\text{x}10^{-8}\text{s}$	(")	
$D^+(1869)$	$:\tau = 1.05\text{x}10^{-12}\text{s}$	(")	
$B^+(5279)$	$:\tau = 1.67\text{x}10^{-12}\text{s}$	(")	
$\pi^0(135)$	$:\tau = 8.4\text{x}10^{-17}\text{s}$	(e.– m. Decay)	

$f_2(1270)$	$:\tau = 3.5\text{x}10^{-24}\text{s} / \Gamma = 185\text{MeV}$	(Strong Decay)	Excited States / Resonances
⋮			
⋮			

Light Hadrons : Few Decay Modes (π^+)

Heavy Hadrons : > 100 Decay Modes (D^+)

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Meson Summary Table

See also the table of suggested $q\bar{q}$ quark-model assignments in the Quark Model section.

• Indicates particles that appear in the preceding Meson Summary Table. We do not regard the other entries as being established.

† Indicates that the value of J given is preferred, but needs confirmation.

LIGHT UNFLAVORED ($S = C = B = 0$)

	$I^G(J^{PC})$		$I^G(J^{PC})$
• $\pi^{\pm}$	$1^-(0^-)$	• $\phi(1680)$	$0^-(1^{--})$
• π^0	$1^-(0^{-+})$	• $\rho_3(1690)$	$1^+(3^{--})$
• η	$0^+(0^{-+})$	• $\rho(1700)$	$1^+(1^{--})$
• $f_0(600)$	$0^+(0^{++})$	$a_2(1700)$	$1^-(2^{++})$
• $\rho(770)$	$1^+(1^{--})$	• $f_0(1710)$	$0^+(0^{++})$
• $\omega(782)$	$0^-(1^{--})$	$\eta(1760)$	$0^+(0^{-+})$
• $\eta'(958)$	$0^+(0^{-+})$	• $\pi(1800)$	$1^-(0^{-+})$
• $f_0(980)$	$0^+(0^{++})$	$f_2(1810)$	$0^+(2^{++})$
• $a_0(980)$	$1^-(0^{++})$	• $\phi_3(1850)$	$0^-(3^{--})$
• $\phi(1020)$	$0^-(1^{--})$	$\eta_2(1870)$	$0^+(2^{-+})$
• $h_1(1170)$	$0^-(1^{+-})$	$\rho(1900)$	$1^+(1^{--})$
• $b_1(1235)$	$1^+(1^{+-})$	$f_2(1910)$	$0^+(2^{++})$
• $a_1(1260)$	$1^-(1^{++})$	$f_2(1950)$	$0^+(2^{++})$
• $f_2(1270)$	$0^+(2^{++})$	$\rho_3(1990)$	$1^+(3^{--})$
• $f_1(1285)$	$0^+(1^{++})$	$X(2000)$	$1^-(?^{?+})$
• $\eta(1295)$	$0^+(0^{-+})$	• $f_2(2010)$	$0^+(2^{++})$
• $\pi(1300)$	$1^-(0^{-+})$	$f_0(2020)$	$0^+(0^{++})$
• $a_2(1320)$	$1^-(2^{++})$	• $a_4(2040)$	$1^-(4^{++})$
• $f_0(1370)$	$0^+(0^{++})$	• $f_4(2050)$	$0^+(4^{++})$
$h_1(1380)$	$?^-(1^{+-})$	$\pi_2(2100)$	$1^-(2^{-+})$
$\pi_1(1400)$	$1^-(1^{-+})$	$f_0(2100)$	$0^+(0^{++})$
• $f_1(1420)$	$0^+(1^{++})$	$f_2(2150)$	$0^+(2^{++})$
• $\omega(1420)$	$0^-(1^{--})$	$\rho(2150)$	$1^+(1^{--})$
$f_2(1430)$	$0^+(2^{++})$	$f_0(2200)$	$0^+(0^{++})$
• $\eta(1440)$	$0^+(0^{-+})$	$f_J(2220)$	$0^+(2^{++}$ or $4^{++})$
• $a_0(1450)$	$1^-(0^{++})$		
• $\rho(1450)$	$1^+(1^{--})$	$\eta(2225)$	$0^+(0^{-+})$
• $f_0(1500)$	$0^+(0^{++})$	$\rho_3(2250)$	$1^+(3^{--})$
$f_1(1510)$	$0^+(1^{++})$	• $f_2(2300)$	$0^+(2^{++})$
• $f_2'(1525)$	$0^+(2^{++})$	$f_4(2300)$	$0^+(4^{++})$
$f_2(1565)$	$0^+(2^{++})$	$f_0(2330)$	$0^+(0^{++})$
$h_1(1595)$	$0^-(1^{+-})$	• $f_2(2340)$	$0^+(2^{++})$
$\pi_1(1600)$	$1^-(1^{-+})$	$\rho_5(2350)$	$1^+(5^{--})$
$X(1600)$	$2^+(2^{++})$	$a_6(2450)$	$1^-(6^{++})$
$a_1(1640)$	$1^+(1^{++})$	$f_6(2510)$	$0^+(6^{++})$
$f_2(1640)$	$0^+(2^{++})$		
$\eta_2(1645)$	$0^+(2^{-+})$		
• $\omega(1650)$	$0^-(1^{--})$		
• $\omega_3(1670)$	$0^-(3^{--})$		
• $\pi_2(1670)$	$1^-(2^{-+})$		

OTHER LIGHT UNFLAVORED ($S = C = B = 0$)

Further States

STRANGE ($S = \pm1, C = B = 0$)

	$I(J^P)$
• $K^{\pm}$	$1/2(0^-)$
• K^0	$1/2(0^-)$
• K^0_S	$1/2(0^-)$
• K^0_L	$1/2(0^-)$
• $K^*(892)$	$1/2(1^-)$
• $K_1(1270)$	$1/2(1^+)$
• $K_1(1400)$	$1/2(1^+)$
• $K^*(1410)$	$1/2(1^-)$
• $K^*_0(1430)$	$1/2(0^+)$
• $K^*_2(1430)$	$1/2(2^+)$
$K(1460)$	$1/2(0^-)$
$K_2(1580)$	$1/2(2^-)$
$K(1630)$	$1/2(?^?)$
$K_1(1650)$	$1/2(1^+)$
• $K^*(1680)$	$1/2(1^-)$
• $K_2(1770)$	$1/2(2^-)$
• $K^*_3(1780)$	$1/2(3^-)$
• $K_2(1820)$	$1/2(2^-)$
$K(1830)$	$1/2(0^-)$
$K^*_0(1950)$	$1/2(0^+)$
$K^*_2(1980)$	$1/2(2^+)$
• $K^*_4(2045)$	$1/2(4^+)$
$K_2(2250)$	$1/2(2^-)$
$K_3(2320)$	$1/2(3^+)$
$K^*_5(2380)$	$1/2(5^-)$
$K_4(2500)$	$1/2(4^-)$
$K(3100)$	$?^?(?^{??})$

CHARMED ($C = \pm1$)

	$I(J^P)$
• $D^{\pm}$	$1/2(0^-)$
• D^0	$1/2(0^-)$
• $D^*(2007)^0$	$1/2(1^-)$
• $D^*(2010)^{\pm}$	$1/2(1^-)$
• $D_1(2420)^0$	$1/2(1^+)$
$D_1(2420)^{\pm}$	$1/2(?^?)$
• $D^*_2(2460)^0$	$1/2(2^+)$
• $D^*_2(2460)^{\pm}$	$1/2(2^+)$
$D^*(2640)^{\pm}$	$1/2(?^?)$

CHARMED, STRANGE ($C = S = \pm1$)

	$I(J^P)$
• $D^{\pm}_s$	$0(0^-)$
• $D^{*\pm}_s$	$0(?^?)$
• $D_{s1}(2536)^{\pm}$	$0(1^+)$
• $D_{sJ}(2573)^{\pm}$	$0(?^?)$

BOTTOM ($B = \pm1$)

	$I(J^P)$
• $B^{\pm}$	$1/2(0^-)$
• B^0	$1/2(0^-)$
• $B^{\pm}/B^0$ ADMIXTURE	
• $B^{\pm}/B^0/B^0_s/b$-baryon ADMIXTURE	
V_{cb} and V_{ub} CKM Matrix Elements	
• B^*	$1/2(1^-)$
$B^*_J(5732)$	$?(?^?)$

BOTTOM, STRANGE ($B = \pm1, S = \mp1$)

	$I(J^P)$
• B^0_s	$0(0^-)$
B^*_s	$0(1^-)$
$B^*_{sJ}(5850)$	$?(?^?)$

BOTTOM, CHARMED ($B = C = \pm1$)

	$I(J^P)$
• $B^{\pm}_c$	$0(0^-)$

$c\bar{c}$

	$I^G(J^{PC})$
• $\eta_c(1S)$	$0^+(0^{-+})$
• $J/\psi(1S)$	$0^-(1^{--})$
• $\chi_{c0}(1P)$	$0^+(0^{++})$
• $\chi_{c1}(1P)$	$0^+(1^{++})$
$h_c(1P)$	$?^?(?^{??})$
• $\chi_{c2}(1P)$	$0^+(2^{++})$
$\eta_c(2S)$	$0^+(0^{-+})$
• $\psi(2S)$	$0^-(1^{--})$
• $\psi(3770)$	$0^-(1^{--})$
$\psi(3836)$	$0^-(2^{--})$
• $\psi(4040)$	$0^-(1^{--})$
• $\psi(4160)$	$0^-(1^{--})$
• $\psi(4415)$	$0^-(1^{--})$

$b\bar{b}$

	$I^G(J^{PC})$
$\eta_b(1S)$	$0^+(0^{-+})$
• $\Upsilon(1S)$	$0^-(1^{--})$
• $\chi_{b0}(1P)$	$0^+(0^{++})$
• $\chi_{b1}(1P)$	$0^+(1^{++})$
• $\chi_{b2}(1P)$	$0^+(2^{++})$
• $\Upsilon(2S)$	$0^-(1^{--})$
• $\chi_{b0}(2P)$	$0^+(0^{++})$
• $\chi_{b1}(2P)$	$0^+(1^{++})$
• $\chi_{b2}(2P)$	$0^+(2^{++})$
• $\Upsilon(3S)$	$0^-(1^{--})$
• $\Upsilon(4S)$	$0^-(1^{--})$
• $\Upsilon(10860)$	$0^-(1^{--})$
• $\Upsilon(11020)$	$0^-(1^{--})$

NON-$q\bar{q}$ CANDIDATES

NON-$q\bar{q}$ CANDIDATES

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Baryon Summary Table

This short table gives the name, the quantum numbers (where known), and the status of baryons in the Review. Only the baryons with 3- or 4-star status are included in the main Baryon Summary Table. Due to insufficient data or uncertain interpretation, the other entries in the short table are not established as baryons. The names with masses are of baryons that decay strongly. For N, Δ, and Ξ resonances, the partial wave is indicated by the symbol $L_{2I,2J}$, where L is the orbital angular momuntum (S, P, D, ...), I is the isospin, and J is the total angular momentum. For Λ and Σ resonances, the symbol is $L_{I,2J}$.

p	P_{11}	****	$\Delta(1232)$	P_{33}	****	Λ	P_{01}	****	Σ^+	P_{11}	****	Ξ^0, Ξ^-	P_{11}	****
n	P_{11}	****	$\Delta(1600)$	P_{33}	***	$\Lambda(1405)$	S_{01}	****	Σ^0	P_{11}	****	$\Xi(1530)$	P_{13}	****
$N(1440)$	P_{11}	****	$\Delta(1620)$	S_{31}	****	$\Lambda(1520)$	D_{03}	****	Σ^-	P_{11}	****	$\Xi(1620)$		*
$N(1520)$	D_{13}	****	$\Delta(1700)$	D_{33}	****	$\Lambda(1600)$	P_{01}	***	$\Sigma(1385)$	P_{13}	****	$\Xi(1690)$		***
$N(1535)$	S_{11}	****	$\Delta(1750)$	P_{31}	*	$\Lambda(1670)$	S_{01}	****	$\Sigma(1480)$		*	$\Xi(1820)$	D_{13}	***
$N(1650)$	S_{11}	****	$\Delta(1900)$	S_{31}	**	$\Lambda(1690)$	D_{03}	****	$\Sigma(1560)$		**	$\Xi(1950)$		***
$N(1675)$	D_{15}	****	$\Delta(1905)$	F_{35}	****	$\Lambda(1800)$	S_{01}	***	$\Sigma(1580)$	D_{13}	**	$\Xi(2030)$		***
$N(1680)$	F_{15}	****	$\Delta(1910)$	P_{31}	****	$\Lambda(1810)$	P_{01}	***	$\Sigma(1620)$	S_{11}	**	$\Xi(2120)$		*
$N(1700)$	D_{13}	***	$\Delta(1920)$	P_{33}	***	$\Lambda(1820)$	F_{05}	****	$\Sigma(1660)$	P_{11}	***	$\Xi(2250)$		**
$N(1710)$	P_{11}	***	$\Delta(1930)$	D_{35}	***	$\Lambda(1830)$	D_{05}	****	$\Sigma(1670)$	D_{13}	****	$\Xi(2370)$		**
$N(1720)$	P_{13}	****	$\Delta(1940)$	D_{33}	*	$\Lambda(1890)$	P_{03}	****	$\Sigma(1690)$		**	$\Xi(2500)$		*
$N(1900)$	P_{13}	**	$\Delta(1950)$	F_{37}	****	$\Lambda(2000)$		*	$\Sigma(1750)$	S_{11}	***			
$N(1990)$	F_{17}	**	$\Delta(2000)$	F_{35}	**	$\Lambda(2020)$	F_{07}	*	$\Sigma(1770)$	P_{11}	*	Ω^-		****
$N(2000)$	F_{15}	**	$\Delta(2150)$	S_{31}	*	$\Lambda(2100)$	G_{07}	****	$\Sigma(1775)$	D_{15}	****	$\Omega(2250)^-$		***
$N(2080)$	D_{13}	**	$\Delta(2200)$	G_{37}	*	$\Lambda(2110)$	F_{05}	***	$\Sigma(1840)$	P_{13}	*	$\Omega(2380)^-$		**
$N(2090)$	S_{11}	*	$\Delta(2300)$	H_{39}	**	$\Lambda(2325)$	D_{03}	*	$\Sigma(1880)$	P_{11}	**	$\Omega(2470)^-$		**
$N(2100)$	P_{11}	*	$\Delta(2350)$	D_{35}	*	$\Lambda(2350)$	H_{09}	***	$\Sigma(1915)$	F_{15}	****			
$N(2190)$	G_{17}	****	$\Delta(2390)$	F_{37}	*	$\Lambda(2585)$		**	$\Sigma(1940)$	D_{13}	***	Λ_c^+		****
$N(2200)$	D_{15}	**	$\Delta(2400)$	G_{39}	**				$\Sigma(2000)$	S_{11}	*	$\Lambda_c(2593)^+$		***
$N(2220)$	H_{19}	****	$\Delta(2420)$	$H_{3,11}$	****				$\Sigma(2030)$	F_{17}	****	$\Lambda_c(2625)^+$		***
$N(2250)$	G_{19}	****	$\Delta(2750)$	$I_{3,13}$	**				$\Sigma(2070)$	F_{15}	*	$\Lambda_c(2765)^+$		*
$N(2600)$	$I_{1,11}$	***	$\Delta(2950)$	$K_{3,15}$	**				$\Sigma(2080)$	P_{13}	**	$\Lambda_c(2880)^+$		**
$N(2700)$	$K_{1,13}$	**							$\Sigma(2100)$	G_{17}	*	$\Sigma_c(2455)$		****
									$\Sigma(2250)$		***	$\Sigma_c(2520)$		***
									$\Sigma(2455)$		**	Ξ_c^+, Ξ_c^0		***
									$\Sigma(2620)$		**	$\Xi_c'^+, \Xi_c'^0$		***
									$\Sigma(3000)$		*	$\Xi_c(2645)$		***
									$\Sigma(3170)$		*	$\Xi_c(2790)$		***
												$\Xi_c(2815)$		***
												Ω_c^0		***
												Λ_b^0		***
												Ξ_b^0, Ξ_b^-		*

**** Existence is certain, and properties are at least fairly well explored.

*** Existence ranges from very likely to certain, but further confirmation is desirable and/or quantum numbers, branching fractions, etc. are not well determined.

** Evidence of existence is only fair.

* Evidence of existence is poor.

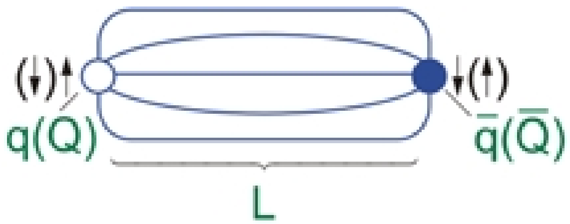
Naive Quark Model of Hadrons (1)

Quark-Species:

$$q = \underbrace{u(\approx 4\text{MeV}), d(\approx 8\text{MeV}), s(\approx 100\text{MeV})}_{\text{Light Quarks } (m<\Lambda_{QCD}\approx 200\text{MeV})} ; Q = \underbrace{c(\approx 1500\text{MeV}), b(\approx 4000\text{MeV}), (t(178000\text{MeV}))}_{\text{Heavy Quarks } (m>>\Lambda_{QCD})}$$

Mesons : $q\bar{q}$, $Q\bar{Q}$, $Q\bar{q}$

Two Quarks with similar masses ($q\bar{q}$, $Q\bar{Q}$)



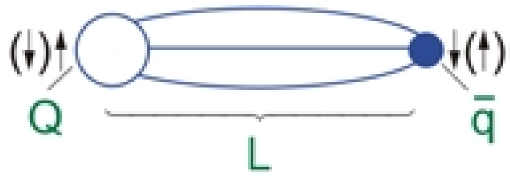
Good Quantum numbers: $L,\ S = S_1 + S_2,\ J = L + S$

Parity $P = (-1)^{L+1}$

Charge Parity $C = (-1)^{L+1}$

Analogy: Positronium (e^+e^-)

Heavy-Light Quark Systems ($q\bar{Q}$)



$Q =$ Nearly static Glue – Source

Good Quantum numbers: $L,\ j = L + S_q,\ J = S_Q + j$

Parity $P = (-1)^{L+1}$

Heavy Quark Symmetrie (HQS) in QCD:
Decoupling of S_Q for $m_Q \to \infty$

Analogy: H-Atom

Naive Quark Model of Hadrons (2)

Two Quarks with similar masses ($\bar{q}q$, $Q\bar{Q}$)	Heavy-Light Quark Systems ($q\bar{Q}$)

Ground States

$\uparrow\downarrow$ (S = 0); L = 0; $n_r = 0$

Example: $\pi^+ = u\bar{d}$ ($\uparrow\downarrow$); $J^{PC} = 0^{-(+)}$

$\uparrow\downarrow$ (J = 0); L = 0; $n_r = 0$

Example: $D^+ = c\bar{d}$ ($\uparrow$(j), $\downarrow$(S_Q)); $J^P = 0^-$

Resonances (Spin Flip States; L = 0)

$\uparrow\uparrow$ (S = 1); L = 0; $n_r = 0$

Example: $\rho^+ = u\bar{d}$ ($\uparrow\uparrow$); $J^{PC} = 1^{-(-)}$

$\uparrow\uparrow$ (J = 1); L = 0; $n_r = 0$

Example: $D^{*+} = c\bar{d}$ ($\uparrow\uparrow$); $J^P = 1^-$

Resonances (Orbital Excited States; L > 0)

L = 1 : One Singlett and three Triplett States

S = 0 : $J^{PC} = 1^{+-}$

S = 1 : $J^{PC} = 0^{++}, 1^{++}, 2^{++}$

Example: $b_1^+ = u\bar{d}$ ($\uparrow\downarrow$); $J^{PC} = 1^{+-}$

L = 1 : Two Doubletts

$j = {}^1/_2 : 0^+_{1/2}, 1^+_{1/2}$

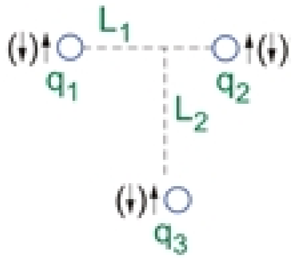
$j = {}^3/_2 : 1^+_{3/2}, 2^+_{3/2}$

Example: $D_2^{*+} = c\bar{d}$ ($\uparrow$(j),$\downarrow$ (S_Q)); $J^P = 2^+$

Naive Quark Model of Hadrons (3)

Baryons : qqq, Qqq, QQq, QQQ

Systems with similar Quark masses (qqq, QQQ)	Systems with one (two) Heavy Quarks (Qqq)



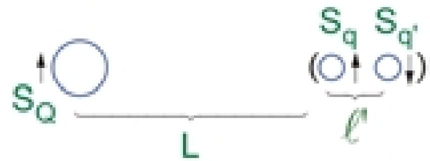
Good Quantum Numbers:

$L = L_1 + L_2 \quad = 0, 1, 2, \ldots$

$S = S_1 + S_2 + S_3 = {}^1/_2, {}^3/_2, \ldots$

$J = L + S \quad = {}^1/_2, {}^3/_2, {}^5/_2, \ldots$

$P = (-1)^{L_1} \cdot (-1)^{L_2}$



Good Quantum Numbers:

L

$j_{qq} = L + S_{qq} = L + S_q + S_{q'} + \ell'$

$J = S_Q + j_{qq}$

Ground States

↑↓↑ $(S = {}^1/_2)$; $L_1 = L_2 = L = 0$; $n_r = 0$

↳ $J^P = {}^1/_2{}^+$

Example : $p = uud$ (↑↑↓); $J^P = {}^1/_2{}^+$

$\Lambda = uds$ (↑↑↓); $J^P = {}^1/_2{}^+$

$\ell' = 0$; $S_{qq} = 0$; $L = 0$

↳ $J^P = {}^1/_2{}^+$

Example : $\Lambda_c^+ = udc$ (↑↑↓); $J^P = {}^1/_2{}^+$

Lowest Excited States

↑↑↑ $(S = {}^3/_2)$; $L_1 = L_2 = L = 0$; $n_r = 0$

Example: $\Delta^{++} = uuu$ (↑↑↑); $J^P = {}^3/_2{}^+$

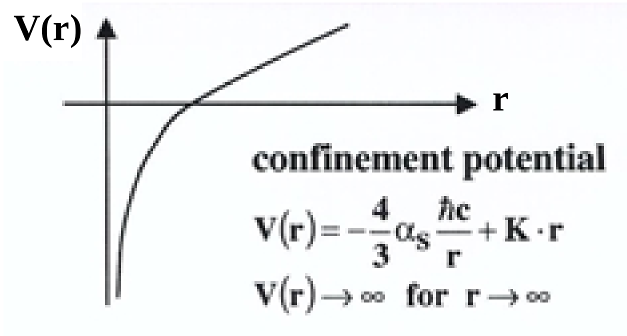
$\ell' = 0$, $S_{qq} = 0$; $L = 1$

Example: $\Lambda_c(2593)^+ = udc$ (↑↑↓); $J^P = {}^1/_2{}^-$

Naive Quark Model of Hadrons (4)

Quantitative Calculations:

SU(N)-Symmetry
QCD inspired models (Bag-Model, Potential Models, …) ↔ Constituent Quarks



LQCD

Explanation of most of the states
Decay Probabilities
Magnetic moments
Masses

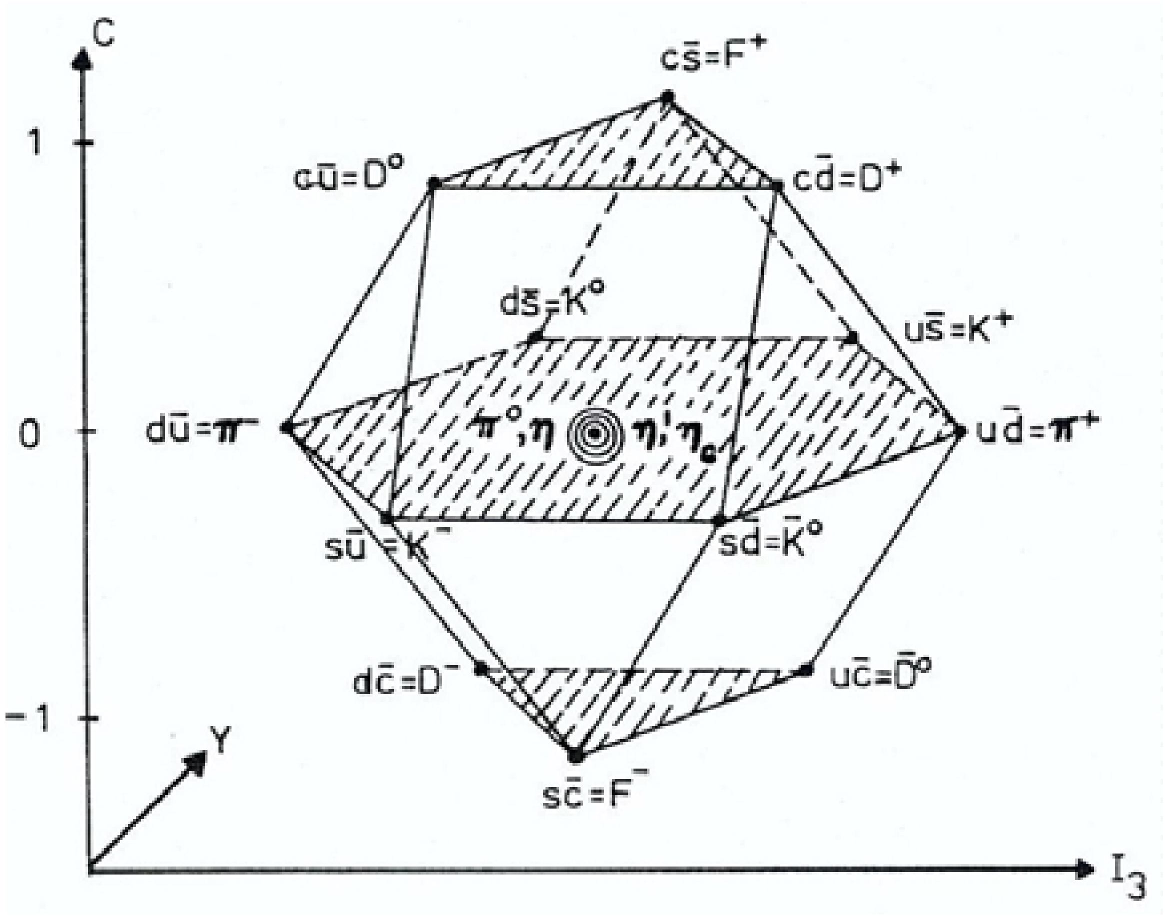
(Magnetic moments and Masses: Ratios)

Naive Quark Model of Hadrons (5)

Basic Flavor-Symmetry : SU(2) (Isospin)/SU(3)/SU(4)

SU(3) : $3 \times \bar{3} = 8+1$

SU(4) : $4 \times \bar{4} = 15 + 1$



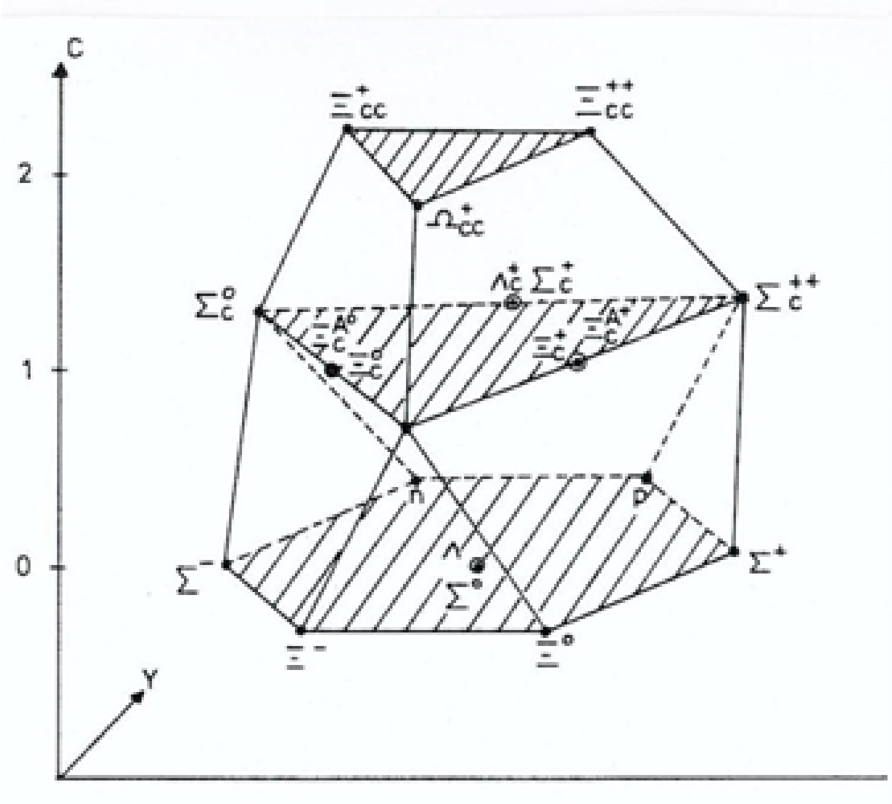
Naive Quark Model of Hadrons (6)

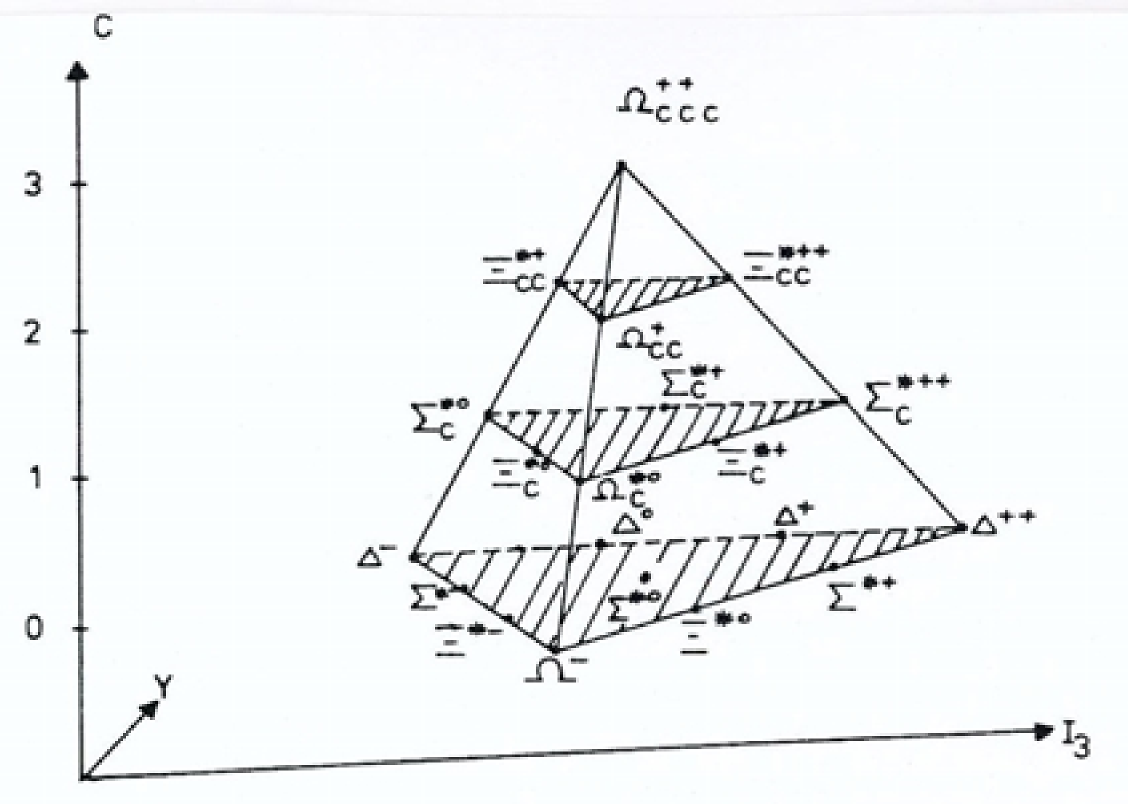
Baryons :   qqq, Qqq, QQq, QQQ

SU(3) / SU(4) - Flavor-Symmetry → Baryon-Multipletts

SU(3) : $3x3x3 = 10_S + 8_M + 8_M + 1_A$

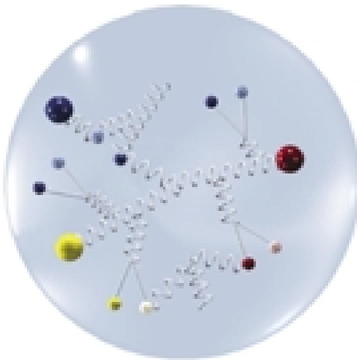
SU(4) : $4x4x4 = 20_S + 20_M + 20_M + 4_A$





Extension of the Model/Exotic States (1)

Problems with the naive Quark Model



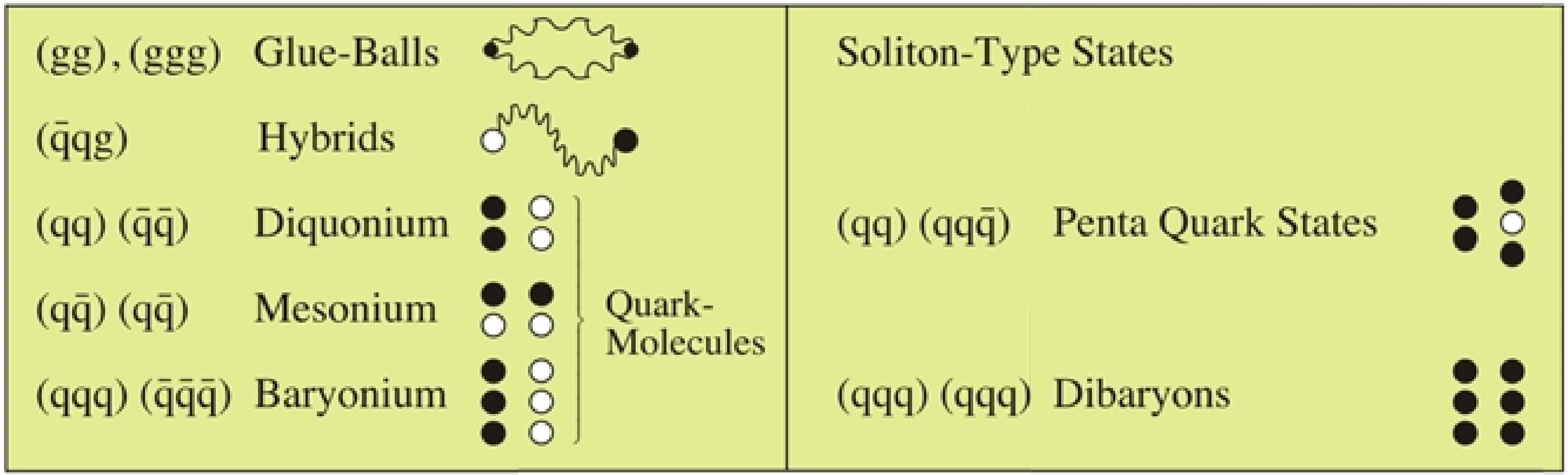
– DIS-Experiments:

– Mass of the Hadrons much heavier than expected:

Example (Proton): $M \approx 3 \times 5\text{MeV}$, $M_{exp.} = 938\text{MeV}$ } Large dynamical mass generation process

– Many of the new discoveries don't fit into the picture (see later)

– QCD allows many more states than described by the naive model (Exotic States)



Extension of the Model/Exotic States (2)

Three categories of Exotic States

	Mesons	Baryons
1.	e.g.: I / |S| / |C| / |B| > 1	e.g.: I > 3/2, S > 0, C < 0, B > 0
2.	$J^{PC} = 0^{+-}, 0^{--}, 1^{-+}, 2^{+-}, \cdots$ (Exot. Q.-N.)	—
3.	Surplus in Multipletts; Masses, Total- (Partial-) widths at variance with naive Quark Model predictions.	

Often characteristic for exotics: **Long lifetimes (Γ small)**

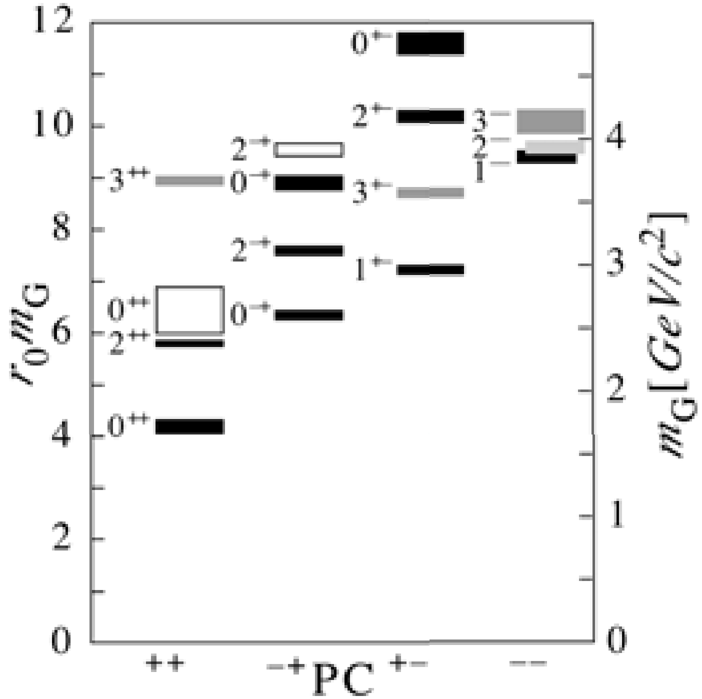
Reality: Mixing of states with same quantum numbers:

$$\left.\begin{aligned} \text{Meson} &= a_1 q\bar{q} + a_2 q\bar{q}q\bar{q} + a_3 q\bar{q}g + \dots \\ \text{Baryon} &= \underbrace{b_1 qqq}_{\text{Naive Quark Model}} + \underbrace{b_2 qqqq\bar{q}}_{\text{Multi-Quark-States}} + \underbrace{b_3 qqqg}_{\text{Hybrid States}} + \dots \end{aligned}\right\} \text{Fock space expansion}$$

Extension of the Model/Exotic States (3)

Best, but very tedious solution: Solve the QCD-Lagrangian (Lattice)

Good example: Glue-Ball-Spectrum



In parallel: Model calculations

BAG Model	→	Properties of $q\bar{q}$, qqq-states, but also:
Flux Tube Model		Hybrid state predictions
Quark-Molecule Models		Spectrum of molecular states
Chiral models		Prediction of Parity-Doubletts, ...

Production of Hadrons

Electromagnetic Probes

Low Energies: $\gamma\,(2\text{ GeV})\ p \rightarrow \Theta^{+} + K_s^0$ (ELSA/Bonn)

$\hookrightarrow nK^{+} \quad \hookrightarrow \pi^{+}\pi^{-}$

High Energies: $e^{-}(9.0\text{ GeV})\ e^{+}\,(3.1\text{ GeV}) \rightarrow D_{sJ}^{*}(2317) + X$ (BaBar/Stanford)

$\hookrightarrow D_s\pi^0$

$\hookrightarrow \phi\pi$

$\hookrightarrow K^{+}K^{-}$

Total process calculable, small cross section

Hadronic Probes

Low Energies: $\bar{p}\,(200\text{MeV})\,p \rightarrow G + \pi^0$ (LEAR/CERN)

$\hookrightarrow \pi^0\pi^0$

High Energies: $\pi^{-}(500\text{GeV})\,p \rightarrow D^{\pm} + X$ (E791/Fermilab)

$\hookrightarrow K^{-}\pi^{+}\pi^{\pm}$

Large cross sections $\rightarrow$ High sensitivity for rare states

Determination of Hadronic Properties (1)

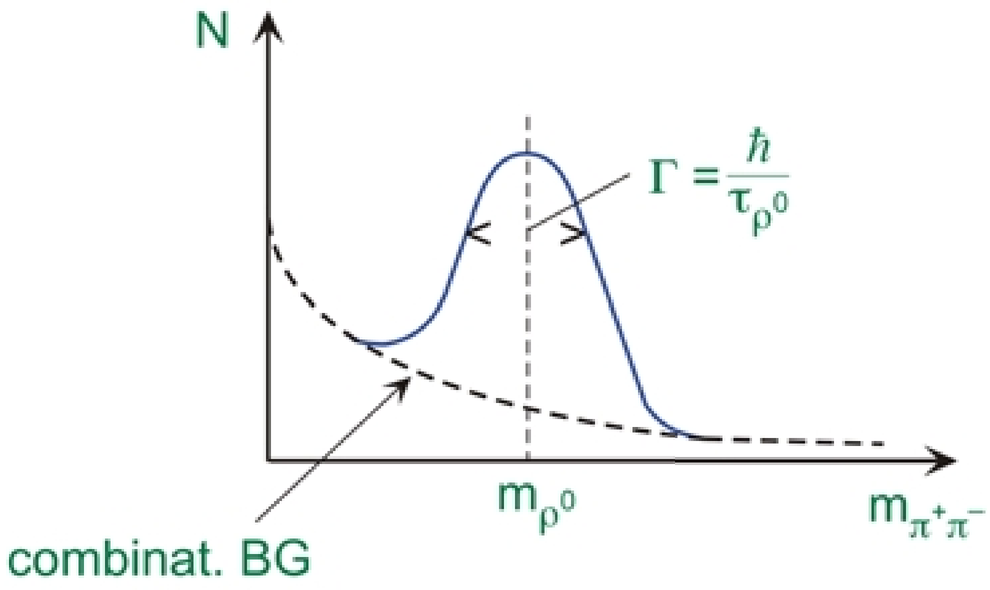
Mass/Life Time:

<u>Long living particles</u> (Protons, Pions, ⋯):
Deflection and TOF in combined electr./magn. fields

<u>Short living particles/Resonances</u> ($f_2(1270)$, Δ^{++}, ⋯):
Invariant Mass Spectra of decay products

$$\text{Examples}: \quad \rho^0 \to \pi^+\pi^- (2 \quad \text{Particle} \;\; \text{Decay})$$

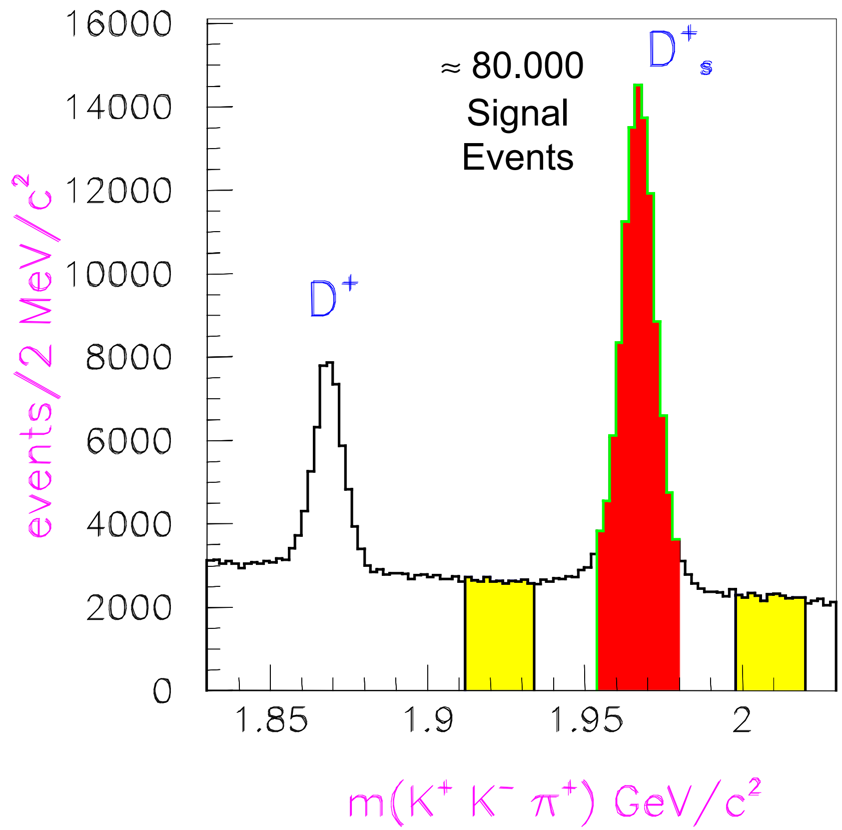
$$m_{\pi^+\pi^-} = \left\{ \left(E_{\pi^+} + E_{\pi^-}\right)^2 - \left(\vec{P}_{\pi^+} + \vec{P}_{\pi^-}\right)^2 \right\}^{1/2} (\text{Invariant} \quad 2-\text{Body}-\text{Mass})$$



Determination of Hadronic Properties (2)

$D \rightarrow K\overline{K}\pi$ (3 particles)

$$m_{K\overline{K}\pi} = \left\{ (E_K + E_{\overline{K}} + E_\pi)^2 - (\vec{p}_K + \vec{p}_{\overline{K}} + \vec{p}_\pi)^2 \right\}^{1/2}$$ (Invariant 3 – Body – Mass)



Determination of Hadronic Properties (3)

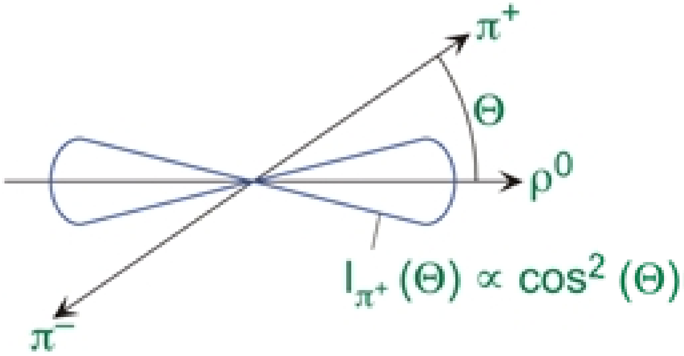
Spin$^{\text{Parity}}$ (J^P):

Long living particles (Proton, Neutron, Λ, Antiproton, ⋯):

Deflection in inhomogeneous B-field, Rotation in homogeneous B-field, Exot. Atoms

Resonances:

Angular distribution of decay particles



Example: $D^0 \to \rho^0\pi^0$ ($0^{-+} \to 1^{--} + 0^{-+}$)

$\hookrightarrow \pi^+ \pi^-$

$\pi^0(\rho^0)$ are emitted isotropically

But: Preferred direction of π^+ (π^-) in respect to ρ^0-direction

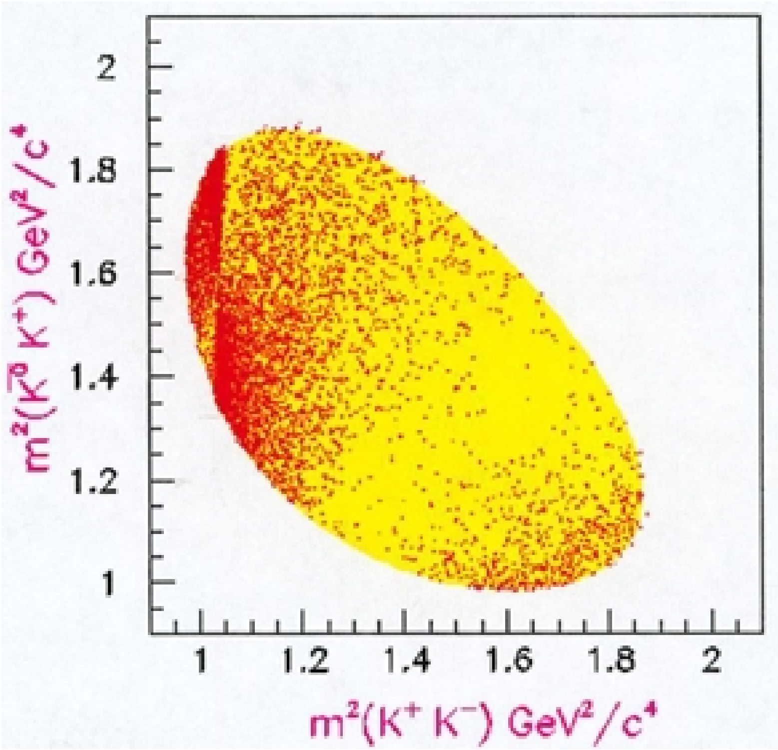
Reason: ρ^0 is polarized

$I_{\pi^+}(\Theta) \propto \cos^2(\Theta)$, Characteristic for J=1 intermediate state (ρ^0)

Determination of Hadronic Properties (4)

Special diagram for 3-body-states : Dalitz Plot

$$\text{Example}: D^0 \to \overline{K}^0 K^+ K^-$$



Interference between

$$\phi \to K^+ K^- : A_\phi$$

$$\text{and} \quad \text{(skalar)} \quad \text{background}: A_S$$

$$|A|^2 = |A_S + A_\phi|^2 = |A_S + \cos\vartheta \cdot \underbrace{\sin\varphi \;\; e^{i\varphi}}_{\dfrac{\Gamma/2}{\left(\sqrt{M_{K^+K^-}} - M_\phi\right) - i\Gamma/2}}|^2 \quad \text{near resonance}$$

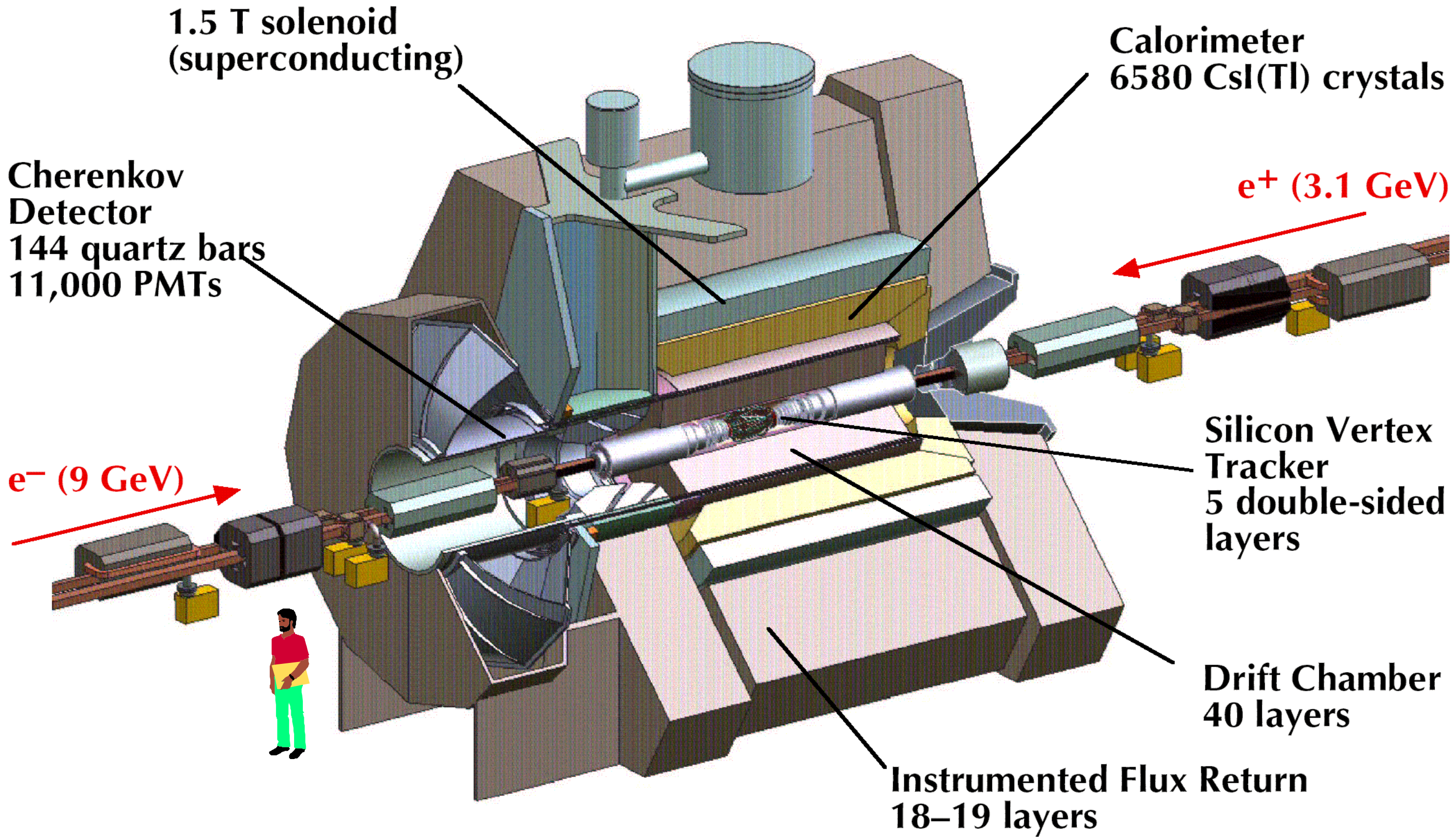
$$\varphi(M_{K^+K^-}) = \text{scattering phase; } 90° \quad \text{at} \quad m_{K^+K^-} = 1020\,\text{MeV}(\phi)$$

In addition:

$$a_0^+(980) \to \overline{K}^0 K^+$$

Experiments/Analysis Methods in Hadron Spectroscopy (1)

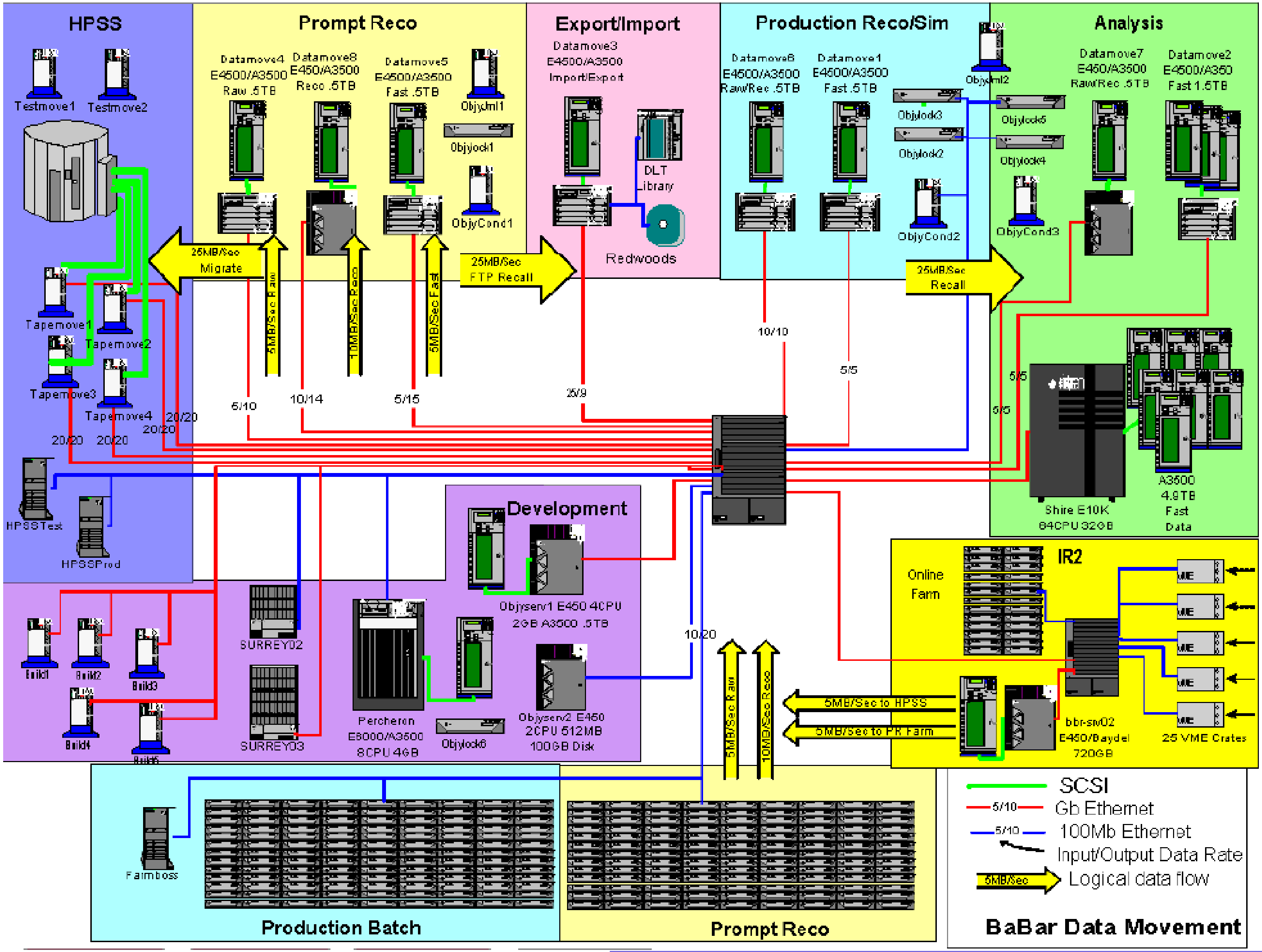
Example: BaBar-Detector/SLAC/Stanford

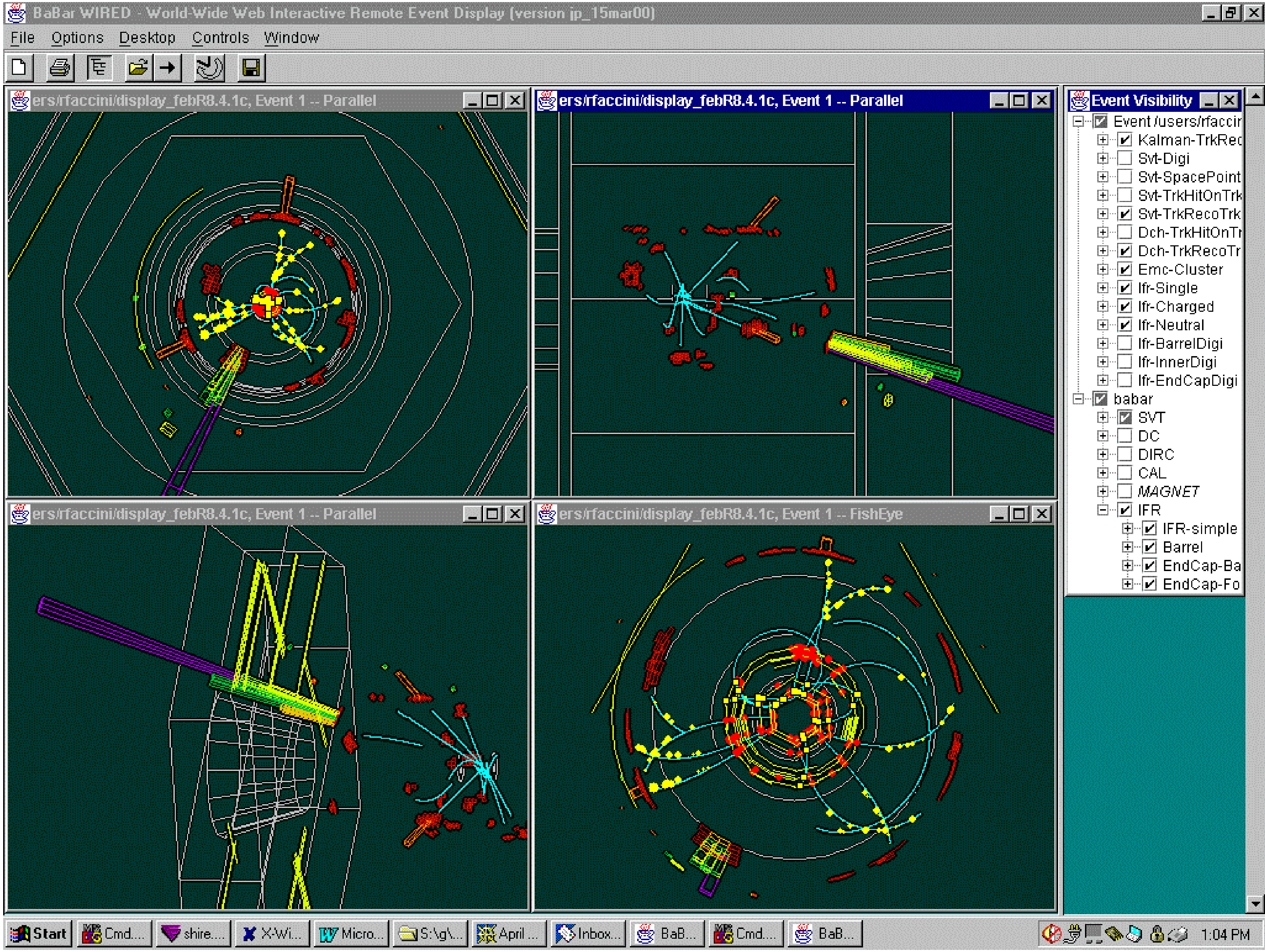


On-line-Computer - Farm: Reconstruction

10^6 channels $\Rightarrow$ Momenta, Energies, Directions
Particle masses, Secondary Vertices

$\Rightarrow$ On average 20 4-vectors per event


HPSS
Testmove1
Testmove2
Tapemove1
Tapemove2
Tapemove3
Tapemove4
HPSSTest
HPSSProd
Prompt Reco
Datamove4 E4500/A3500 Raw .5TB
Datamove8 E450/A3500 Reco .5TB
Datamove5 E4500/A3500 Fast .5TB
Objyjml1
Objylock1
ObjyCond1
25MB/Sec Migrate
5MB/Sec Raw
10MB/Sec Reco
5MB/Sec Fast
Export/Import
Datamove3 E4500/A3500 Import/Export
DLT Library
Redwoods
25MB/Sec FTP Recall
Production Reco/Sim
Datamove6 E4500/A3500 Raw/Rec .5TB
Datamove1 E4500/A3500 Fast .5TB
Objylock3
Objylock2
ObjyCond2
25MB/Sec Recall
Analysis
Objyjml2
Objylock5
Objylock4
ObjyCond3
Datamove7 E450/A3500 Raw/Rec .5TB
Datamove2 E4500/A350 Fast 1.5TB
Shire E10K 64CPU 32GB
A3500 4.9TB Fast Data
5/10
10/14
5/15
25/9
10/10
5/5
20/20
10/20
Development
Objyserv1 E450 4CPU 2GB A3500 .5TB
Objyserv2 E450 2CPU 512MB 100GB Disk
Objylock6
Percheron E6000/A3500 8CPU 4GB
SURREY02
SURREY03
Build1
Build2
Build3
Build4
Build5
IR2
Online Farm
bbr-srv02 E450/Baydel 720GB
25 VME Crates
5MB/Sec to HPSS
5MB/Sec to PR Farm
5MB/Sec Raw
10MB/Sec Reco
Farmboss
Production Batch
Prompt Reco
SCSI
Gb Ethernet
100Mb Ethernet
Input/Output Data Rate
Logical data flow
BaBar Data Movement


BaBar WIRED - World-Wide Web Interactive Remote Event Display (version jp_15mar00)
File Options Desktop Controls Window
ers/rfaccini/display_febR8.4.1c, Event 1 -- Parallel
ers/rfaccini/display_febR8.4.1c, Event 1 -- Parallel
ers/rfaccini/display_febR8.4.1c, Event 1 -- Parallel
ers/rfaccini/display_febR8.4.1c, Event 1 -- FishEye
Event Visibility
Event /users/rfaccir
Kalman-TrkRec
Svt-Digi
Svt-SpacePoint
Svt-TrkHitOnTrk
Svt-TrkRecoTrk
Dch-TrkHitOnTr
Dch-TrkRecoTr
Emc-Cluster
Ifr-Single
Ifr-Charged
Ifr-Neutral
Ifr-BarrelDigi
Ifr-InnerDigi
Ifr-EndCapDigi
babar
SVT
DC
DIRC
CAL
MAGNET
IFR
IFR-simple
Barrel
EndCap-Ba
EndCap-Fo
Start
Cmd...
shire....
X-Wi...
Micro...
S:\g\...
April ...
Inbox...
BaB...
Cmd...
BaB...
1:04 PM

Experiments/Analysis Methods in Hadron Spectroscopy (2)

Analysis of Data (10^9 hadronic events ; 1 Peta Byte)

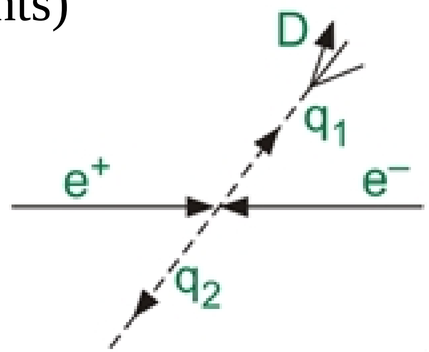
Example: $e^+(3.1\,\text{GeV})\ e^-(9\,\text{GeV}) \to D_s^\pm + X$

$\hookrightarrow \phi\pi^\pm$

$\hookrightarrow K^+K^-$

Cuts:

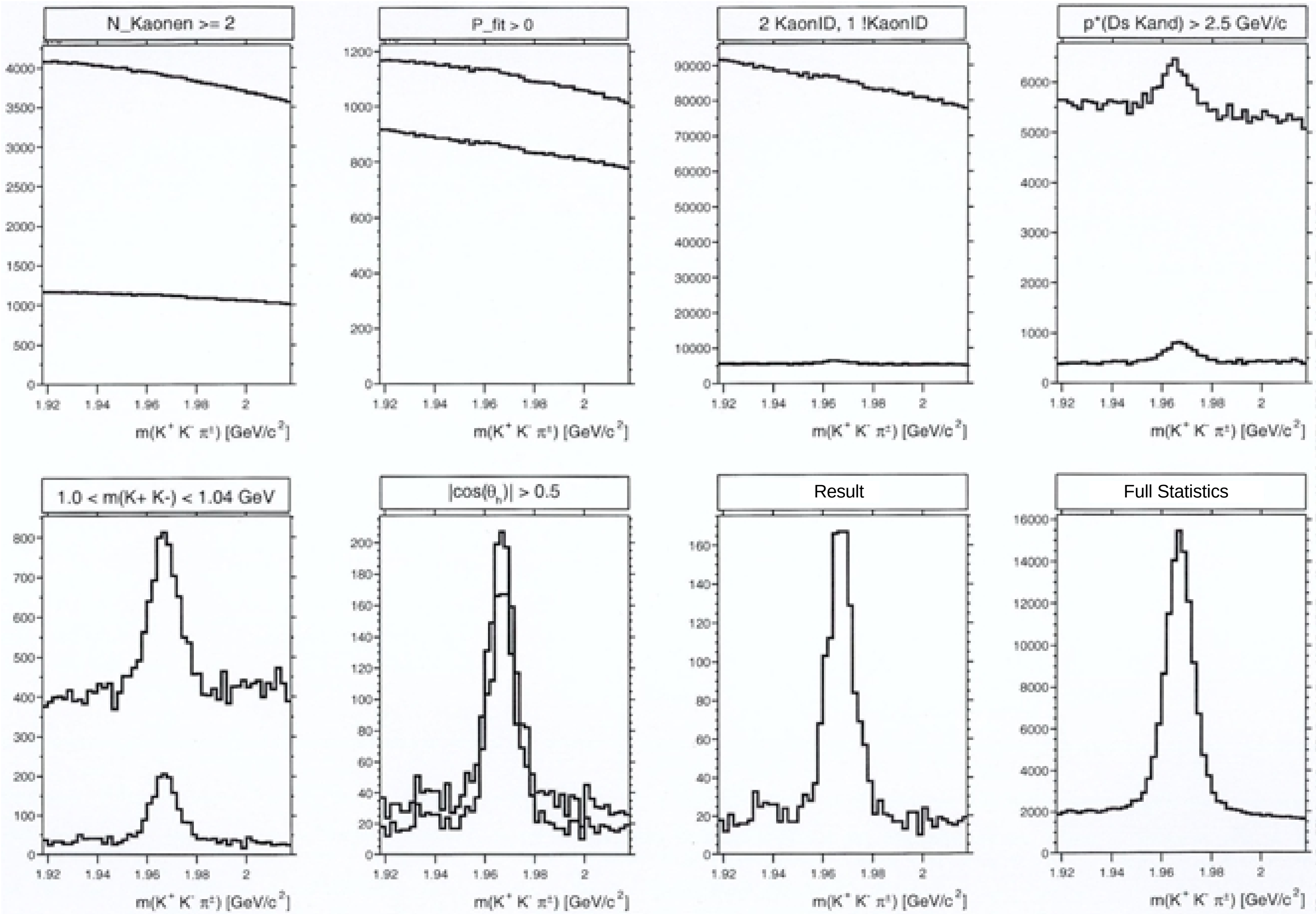
– At least two charged Kaons in event
– 3 tracks with different charges (Q=±1) with common vertex
– 2 tracks must belong to Kaons of different charge,
  3. track must not be a Kaon
– Momentum of ($\bar{K}K\pi$)-system in e^+e^--CMS must be > 2.5 GeV/c
  (Select jet-like (non $\bar{B}B$) events)



– K^+, K^- must originate from ϕ-decay
– $|\cos\theta_{K^+(K^-)}| > 0.5$ (Helicity Cut; J = 1-system (ϕ) emitts ($K^+(K^-)$) preferably along/against flight direction)

Optimization of all cut parameters via neural net- and evolutionary algorithm-techniques

Experiments Analysis Methods in Hadron Spectroscopy (3)



Overview on Exotic States (1)

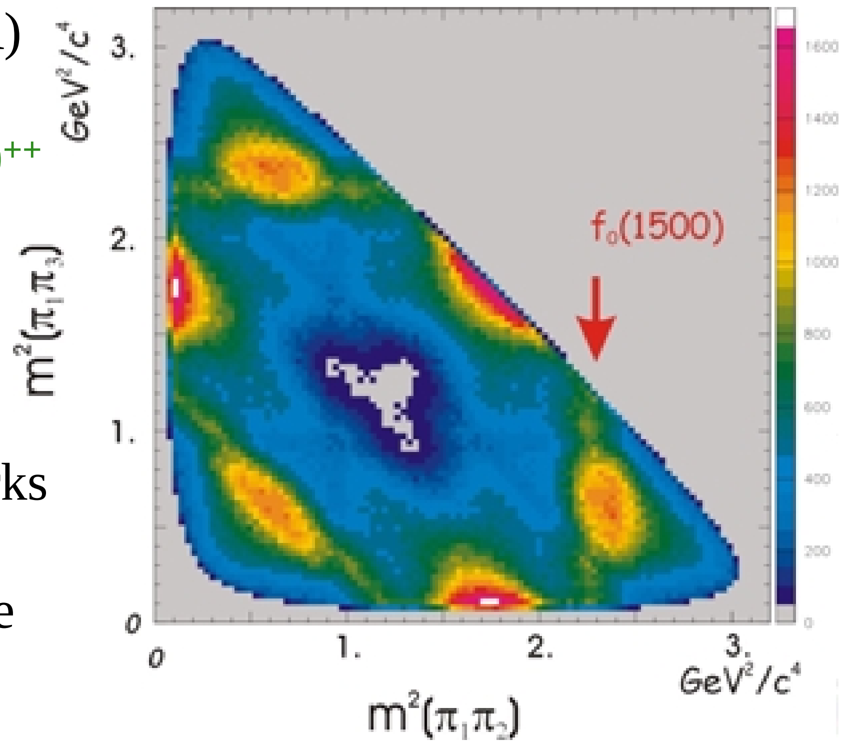
Glue-Ball Candidate

$f_0(1500)$ (Best candidat for the Glueball-ground state)

Production : $p\bar{p} \rightarrow$ **$f_0(1500)$**π^0 (Crystal Barrel/LEAR)

Decays : $f_0(1500) \rightarrow 2\pi, 4\pi, \eta\eta, \eta\eta', K\bar{K}$

$M = (1505 \pm 9)$ MeV ; $\Gamma = (111 \pm 12)$ MeV ; $J^{PC} = 0^{++}$



Exotic?

- Surplus state in 0^{++}-Nonett
- Relatively narow width
- Decays in particles, which contain u, d and s-Quarks
- Mass and Quantum numbers in good agreement with mit Lattice QCD-prediction for the **Glueball-ground state**

Overview on Exotic States (2)

Meson-like states with exotic quantum number combination

$\pi_1(1400)$ / $\pi_1(1600)$

Production/Decays :

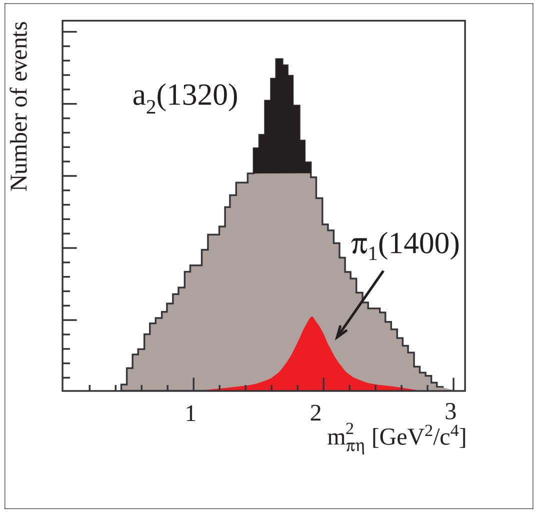
$\pi^- p \rightarrow \pi_1(1400)p$ (E835/BNL) and $\bar{p}n \rightarrow \pi_1(1400)\pi^0$ (Crystal Barrel/LEAR)
$\hookrightarrow \eta\pi^-$ $\hookrightarrow \eta\pi^-$

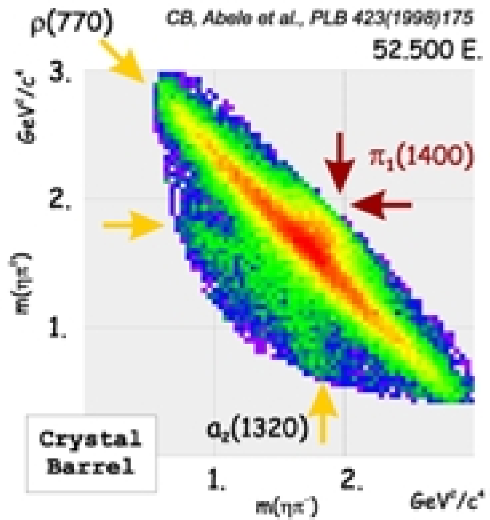
$\pi^- p \rightarrow \pi_1(1600)p$ (E835 BNL) and $\bar{p}p \rightarrow \pi_1(1600)\pi^+$ (Crystal Barrel/LEAR)
$\hookrightarrow \pi^-\eta$ $\hookrightarrow \pi^-\eta$

$M \approx 1400, 1600$ MeV ; $\Gamma \approx 300$ MeV ; $J^{PC} = \mathbf{1^{-+}}$ (Exotic Q.-N., At variance with naive Quark-model)

Exotic?
Exotic J^{PC}-combination

Hybrids?
Multi-Quark-states?





Overview on Exotic States (3)

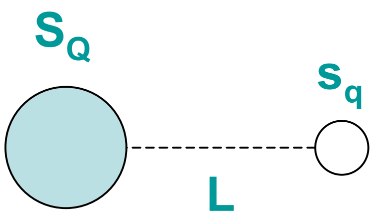
States with Open Charm

$D^+ = c\bar{d}$; $D^0 = c\bar{u}$ (+Antiparticles)

Ground states : $I(J^P) = {}^1/_2(0^-)$

$D_S^+ = c\bar{s}$ (+Antiparticle)

Groundstate = $I(J^P) = 0(0^-)$

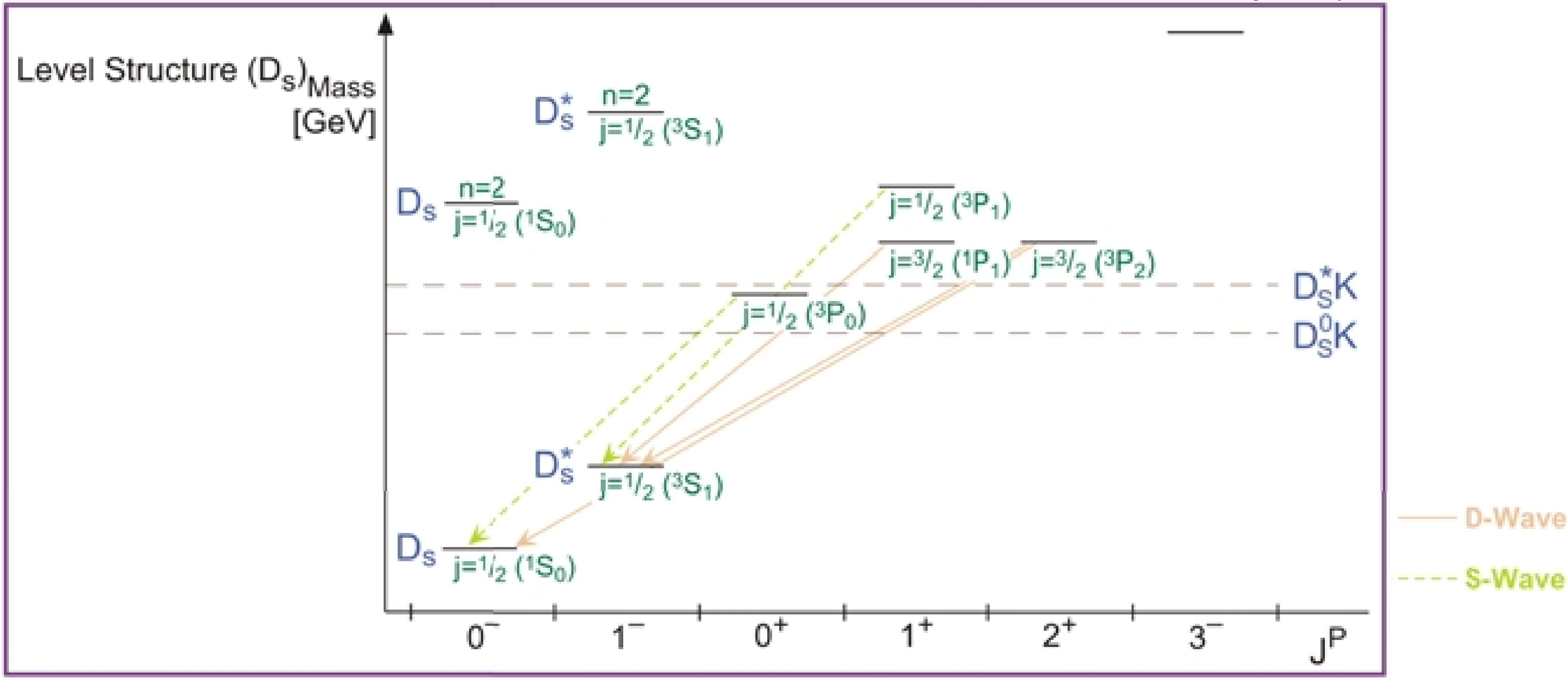


$j = L + s_q$ (Good q.-n. for $m_c \rightarrow \infty$)

$J = j + S_Q$

$P = (-1)^{L+1}$

Symbol: $n^{2S+1}L_J$, n^jL_J, J^P ($S = S_Q + s_q$)

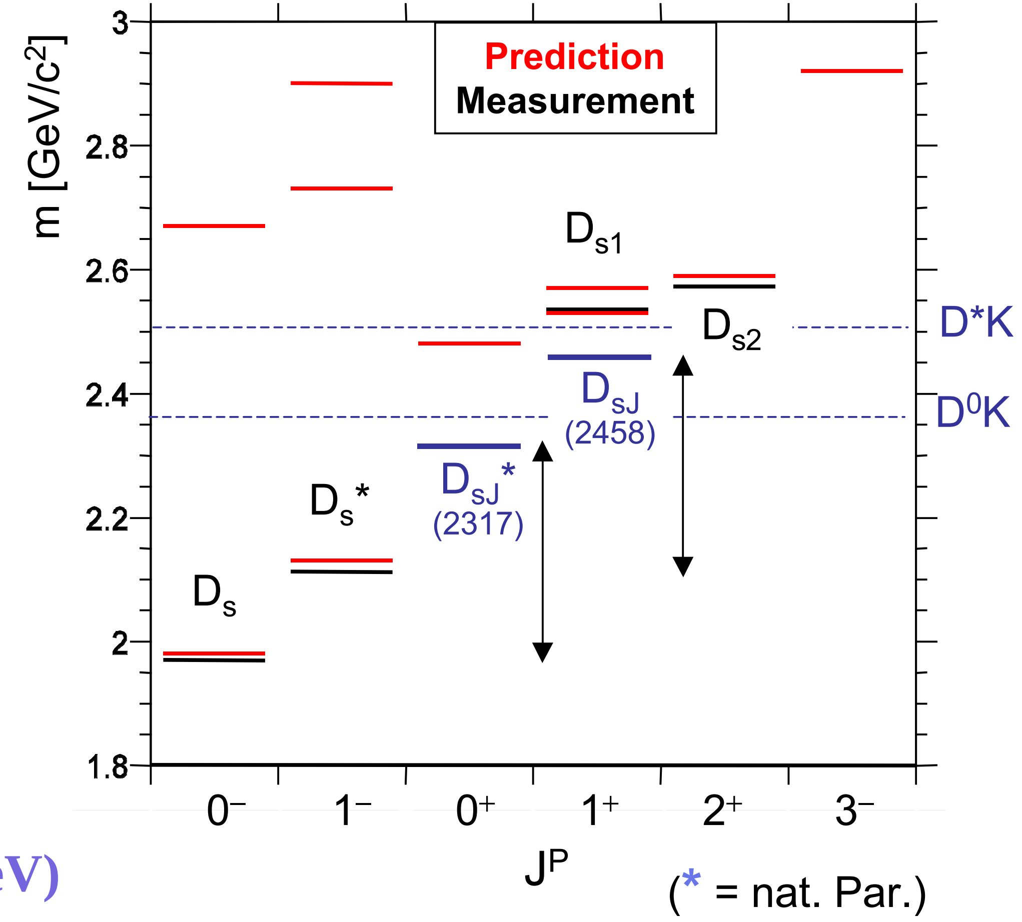


Overview on Exotic States (4)

$D^*_{sJ}(2317)$, $D_{sJ}(2458)$

- Quark-Potential-Models in the D_s Sector (e. g. Godfrey, Isgur & Kokoski)
- Already known states: D_s, $D_s^*(2112)$, $D_{s1}(2536)$, $D_{s2}(2573)$
- Recently disvovered new states (BABAR, BELLE, CLEO, …) **m=2317 MeV and m=2458 MeV**
- Masses much lower than predicted values
- States below DK- and D*K-thresholds, respectively, and **very narrow ! (Γ < 9 MeV)**

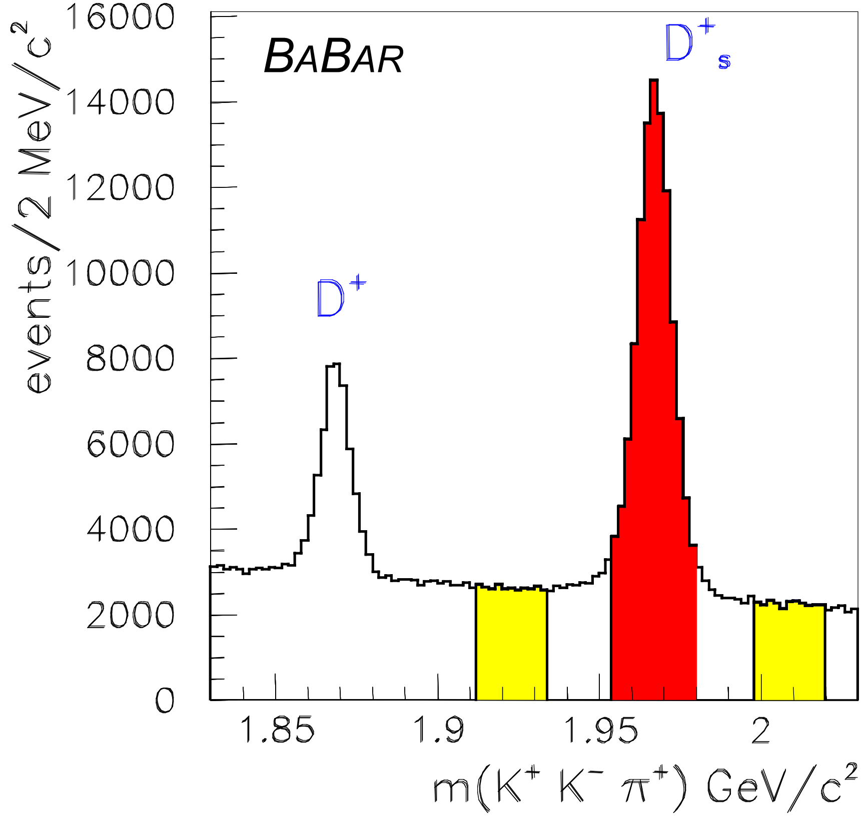
$D_s^\pm$: Energy Scheme



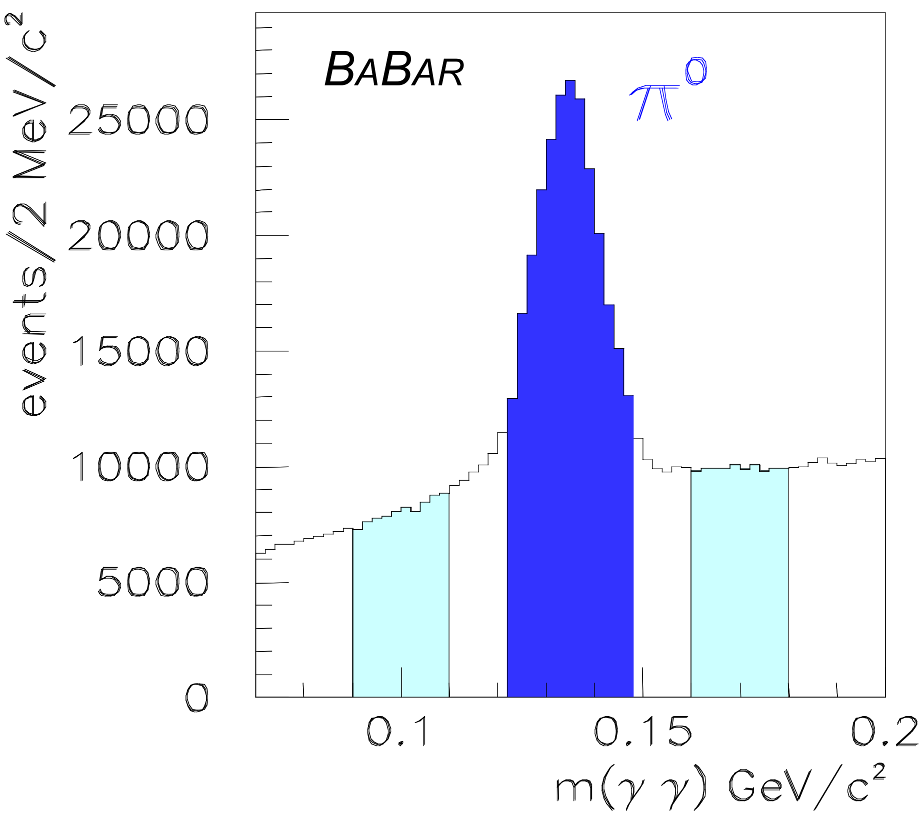
Overview on Exotic States (5)

$D^*_{sJ}(2317)^\pm \to D_s^\pm \pi^0$ (BaBar)

$D_s^\pm \to K^+ K^- \pi^\pm$
- $\phi \to K^+ K^-$
- $K^{*0} \to K^\pm \pi^\mp$



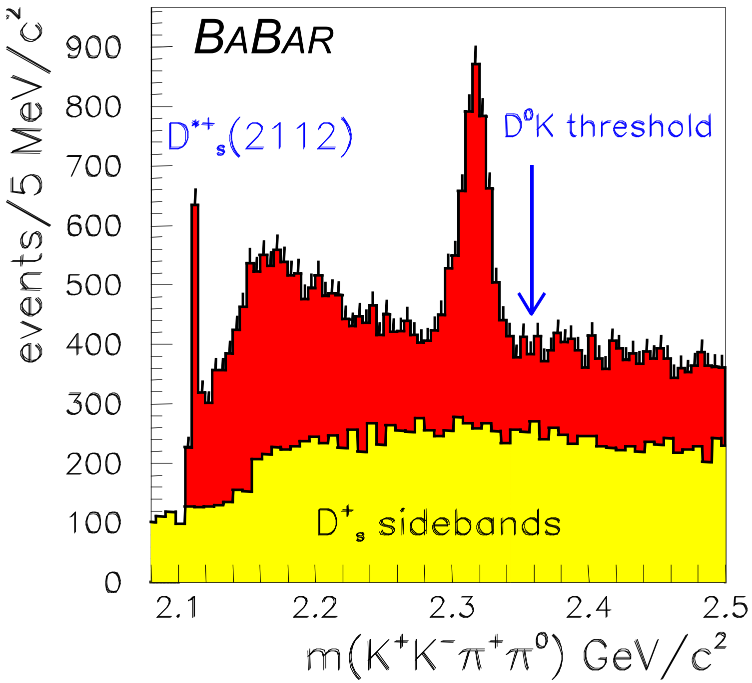
$\pi^0 \to \gamma\gamma$

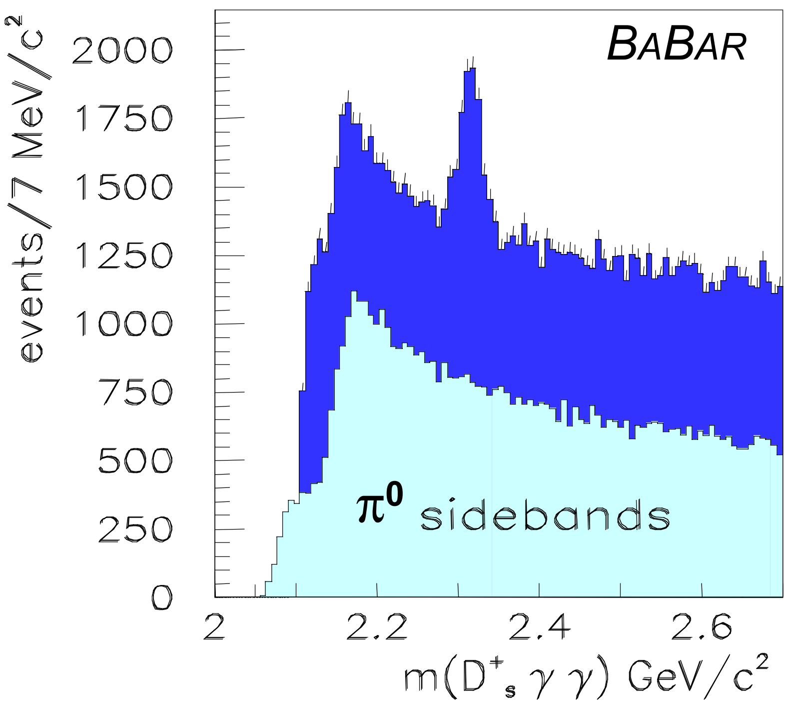


Overview on Exotic States (6)

$D_{sJ}^{*}(2317)^{\pm} \to D_s^{\pm}\pi^0$ (BABAR)

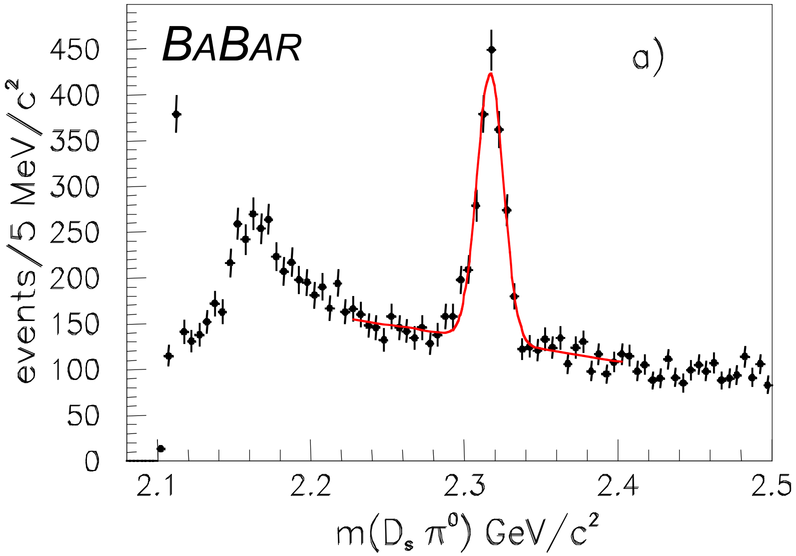
- Combine $D_s^{\pm}$ candidate with π^0 candidate
- narrow signal at **m ≈ 2.32 GeV/c²** (≈ 2200 events)
- no signal in sidebands ($D_s^{\pm}$, π^0)
  - ⇒ signal associated with $D_s^{\pm}$ and π^0
- known state $D_s^{*\pm}$ (2112) $\to D_s^{\pm}\pi^0$ also visible





Overview on Exotic States (7)

$D^{*}_{sJ}(2317)^{\pm}$: Mass/Width

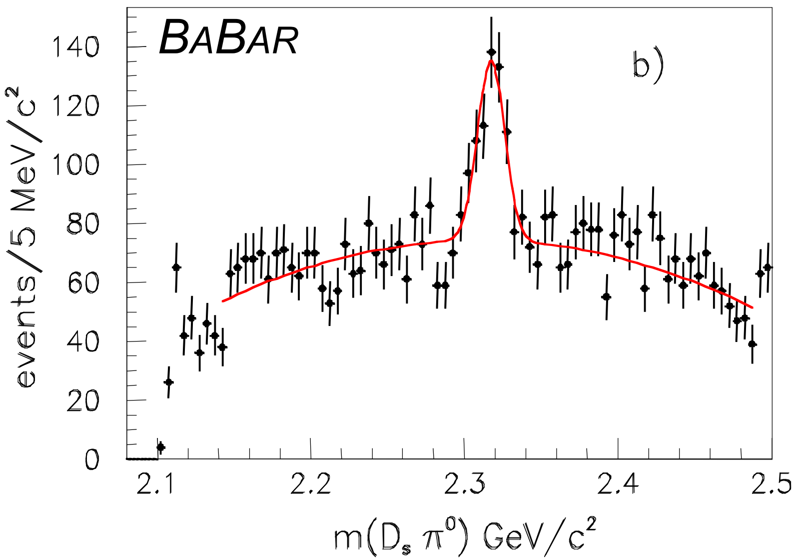


$D^{*}_{sJ}(2317)^{+} \rightarrow D_s^{+}\,\pi^0$
$D_s^{+} \rightarrow K^{+}K^{-}\pi^{+}$

$M = 2316.8 \pm 0.4$ MeV/c^2
$\sigma = 8.6 \pm 0.5$ MeV/c^2

Resolution from MC:

$\sigma = 8.9 \pm 0.2$ MeV/c^2



$D^{*}_{sJ}(2317)^{+} \rightarrow D_s^{+}\,\pi^0$
$D_s^{+} \rightarrow K^{+}K^{-}\pi^{+}\,\pi^0$

$M = 2317.6 \pm 1.3$ MeV/c^2
$\sigma = 8.8 \pm 1.1$ MeV/c^2

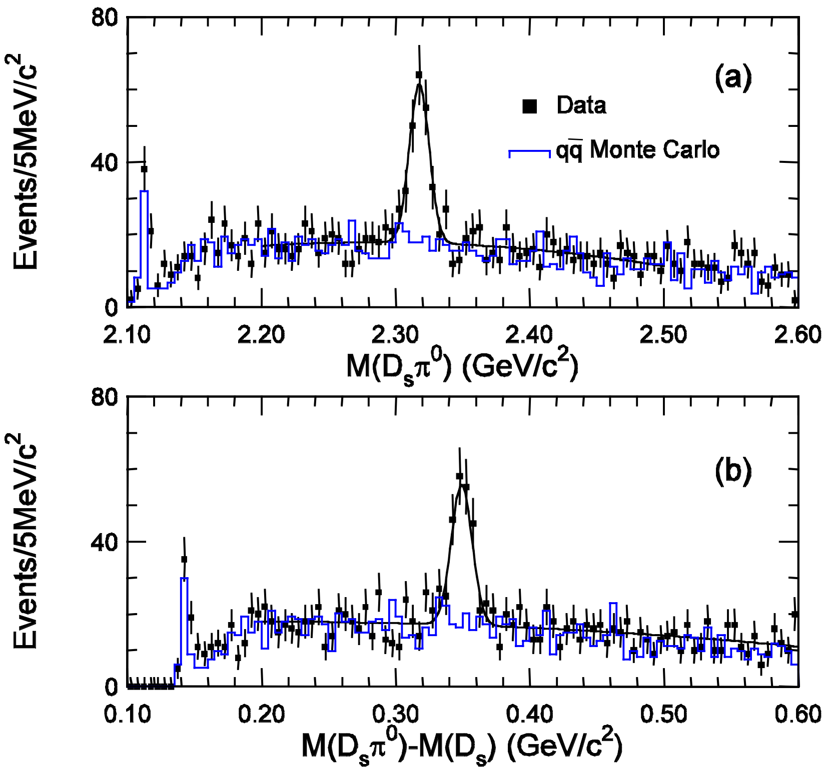
Overview on Exotic States (8)

$D^*_{sJ}(2317)^{\pm}$: CLEO / BELLE

CLEO

$m = 2318.5 \pm 1.2$ MeV/c^2

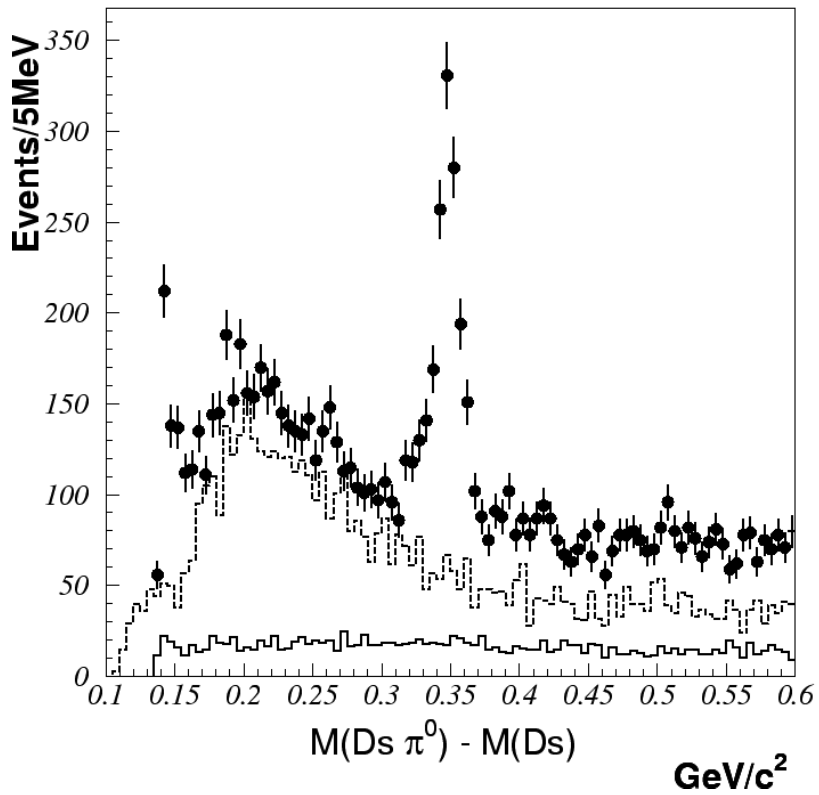
$\sigma = 8.0 \pm 1.2$ MeV/c^2



BELLE

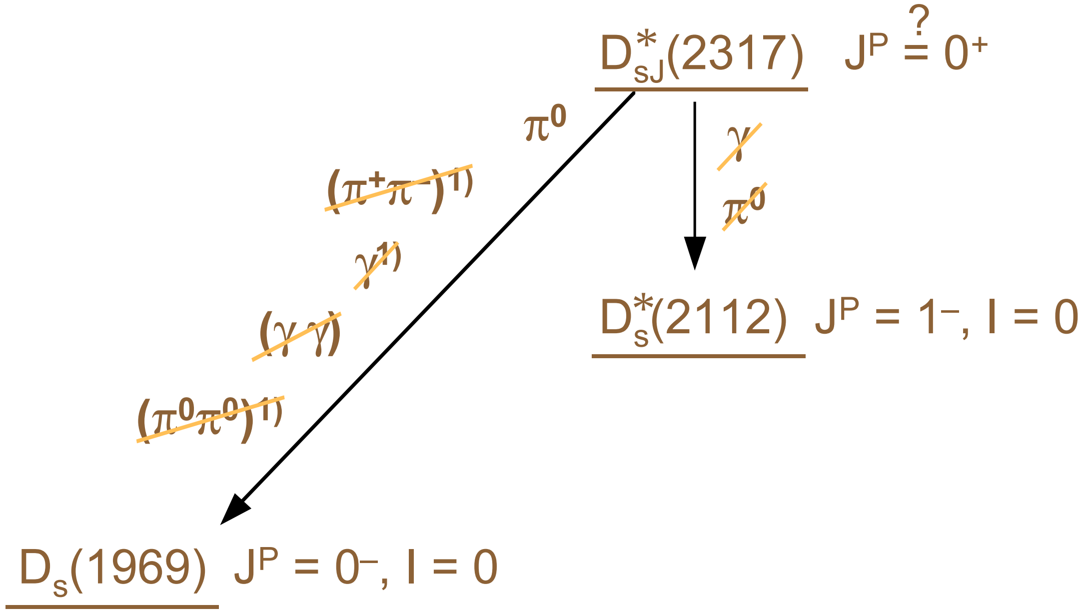
$m = 2317.2 \pm 0.5$ MeV/c^2

$\sigma = 7.4 \pm 0.4$ MeV/c^2



Overview on Exotic States (9)

$D_{sJ}^{*}(2317)^{\pm}$: Decay Scheme



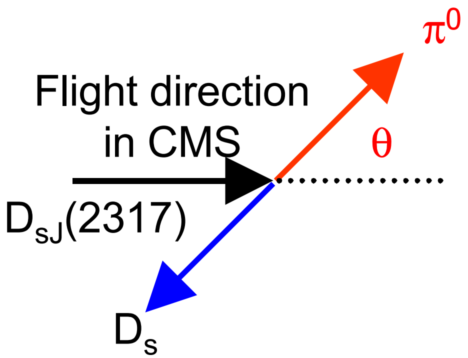
1) Forbidden for $0 \rightarrow 0$

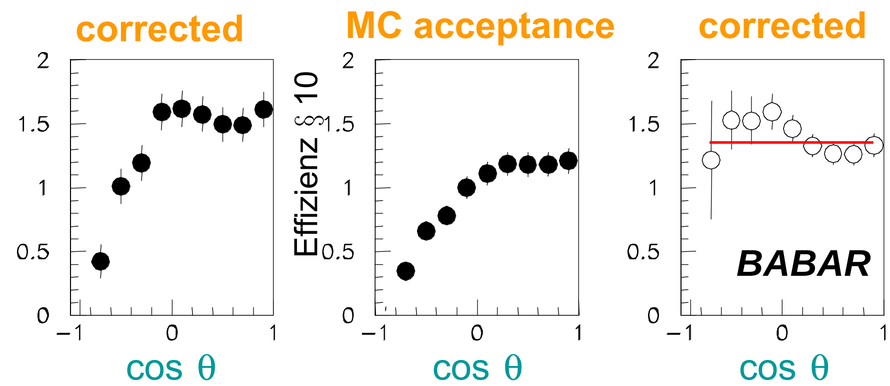
Overview on Exotic States (10)

$D_{sJ}^{*}(2317)^{\pm}$: Quantum Numbers

I = ? : Not seen in $D_s^{\pm}\pi^{\pm}$ and $D_s^{\pm}\pi^{\pm}$ (CDF) $\Rightarrow$ I (D_{sJ}^{*}(2317)) = 0 $\rightarrow$ Transition is isospin violating

J^P = ?





Angular distribution consistent with being unform $\rightarrow$ $J^P = 0^+$ or isotropic polarization

↳In conjunction with unobserved transitions:

$J^P = 0^+$ highly probable

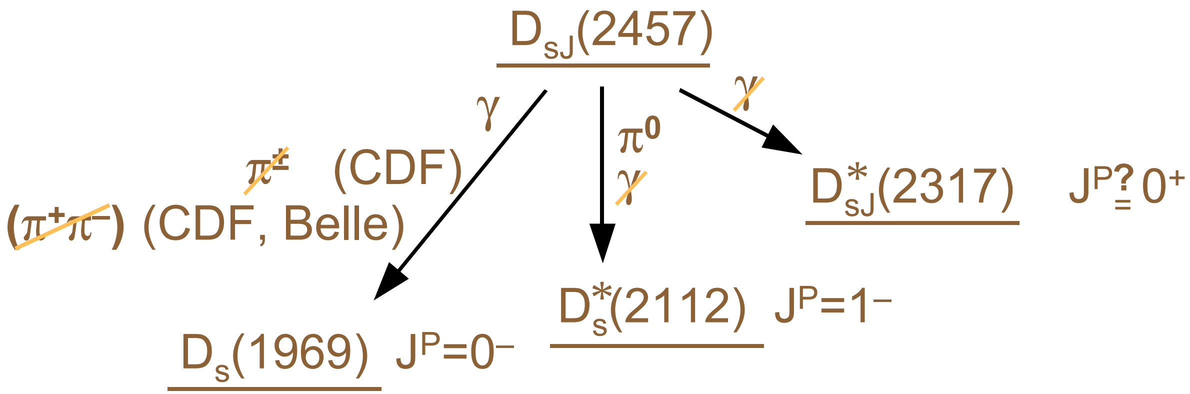
Overview on Exotic States (11)

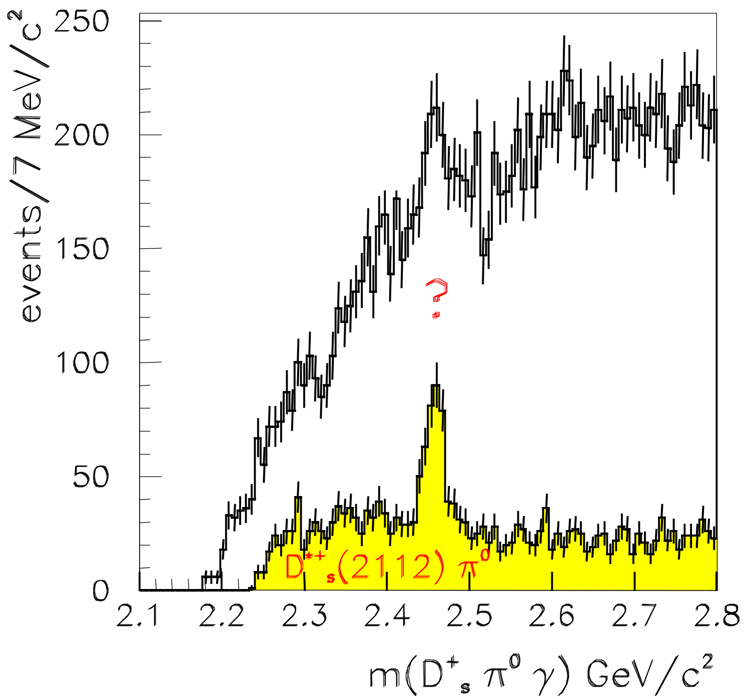
$D_{sJ}(2458)^{\pm}$: Belle, BABAR, CLEO, ...

$$BR\left(D_{sJ}(2457)\begin{array}{l}\to D_s\gamma \\ \to D_s^*\pi^0\end{array}\right) = 0.38 \pm 0.11$$

$M = (2458.0 \pm 1.4)\ MeV/c^2$
$\Gamma = (8.5 \pm 1.0)\ MeV/c^2$

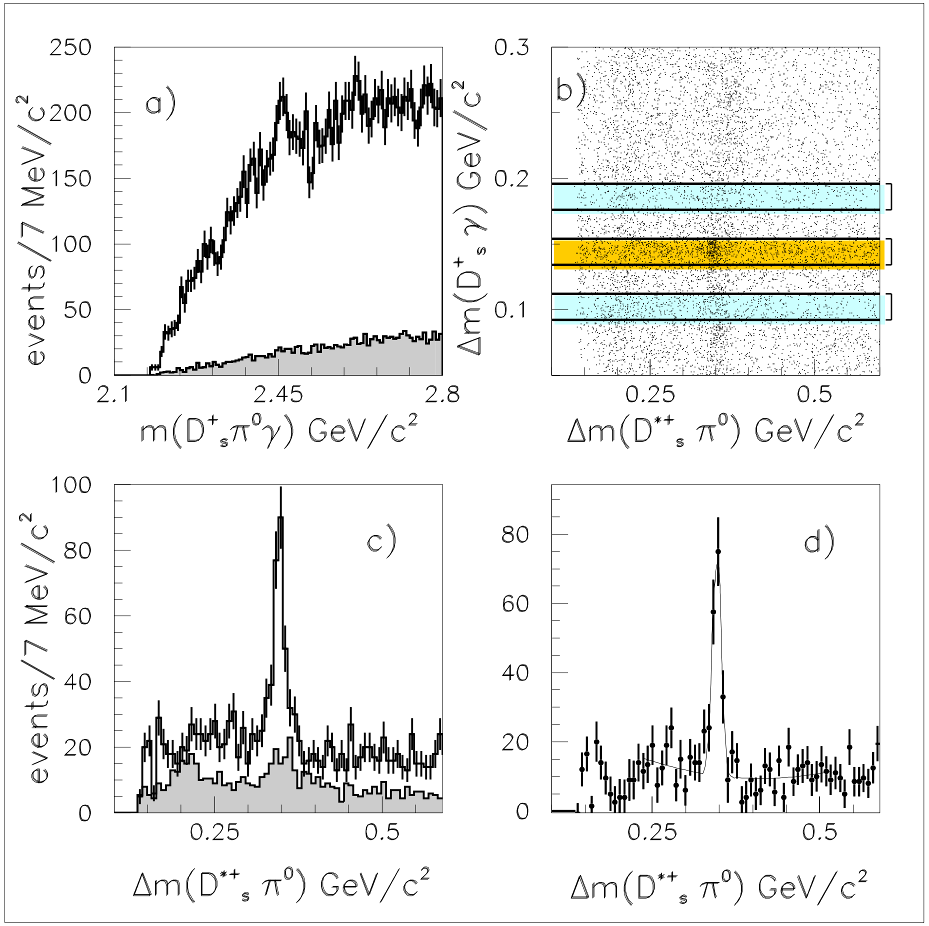
Decay Scheme:





Overview on Exotic States (12)

$D_{sJ}(2458)^{\pm}$: Mass/Width



- $m = (2458.0 \pm 1.4)$ MeV/c²
- $\sigma_{Gauss} = (8.5 \pm 1.0)$ MeV/c²

$$\Delta m(D_s\,\gamma) = m(D_s\gamma) - m(D_s)$$
$$\Delta m(D_s^*\pi^0) = m(D_s\gamma\,\pi^0) - m(D_s\gamma)$$

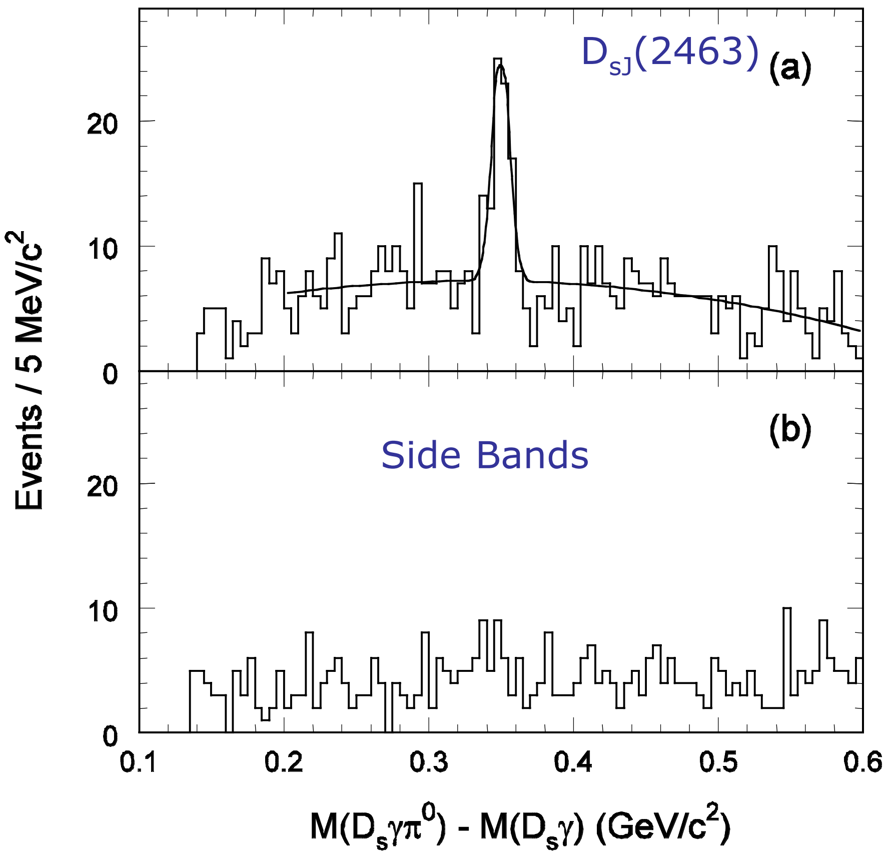
Overview on Exotic States (13)

$D_{sJ}(2458)^{\pm}$: CLEO/BELLE

CLEO

m = 2463.6 ± 2.1 MeV/c^2

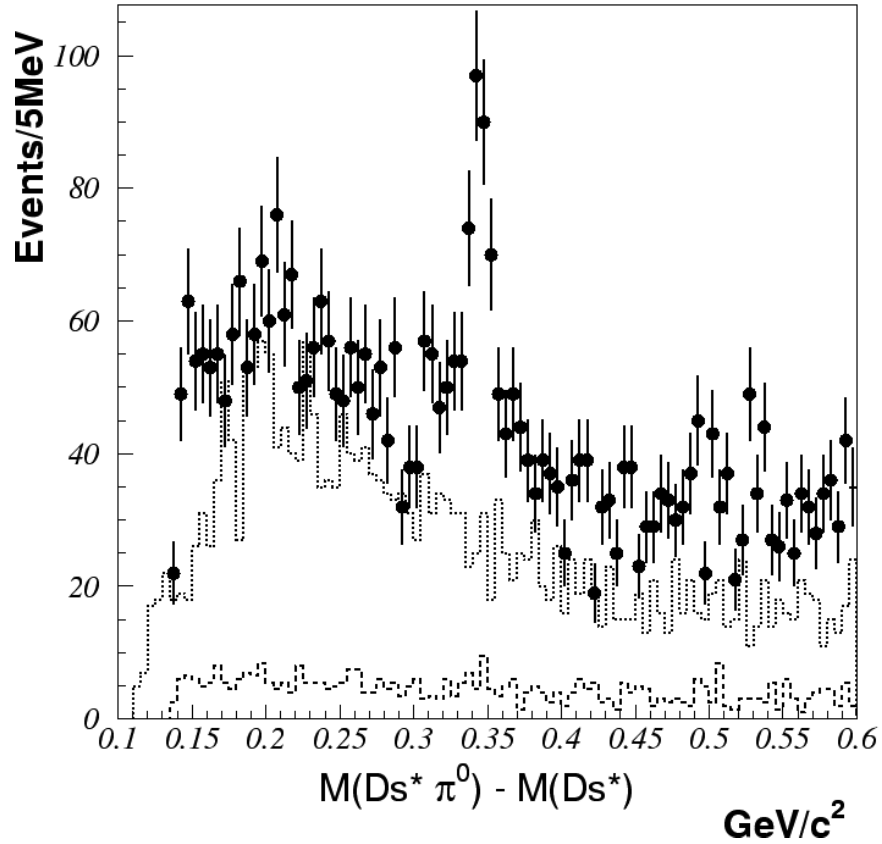
σ = 6.1 ± 1.1 MeV/c^2



BELLE

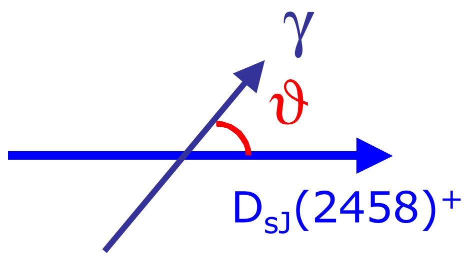
m = 2456.5 ± 1.3 MeV/c^2

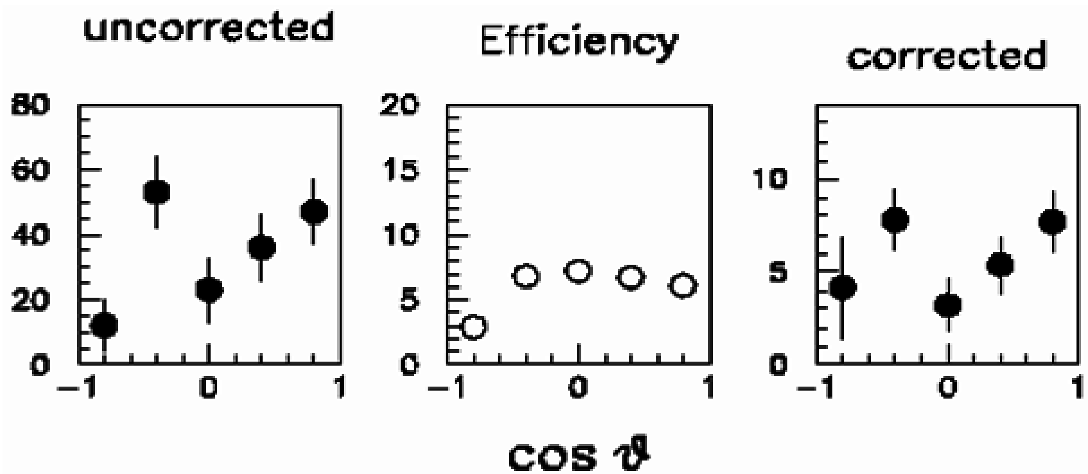
σ = 5.8 ± 1.3 MeV/c^2

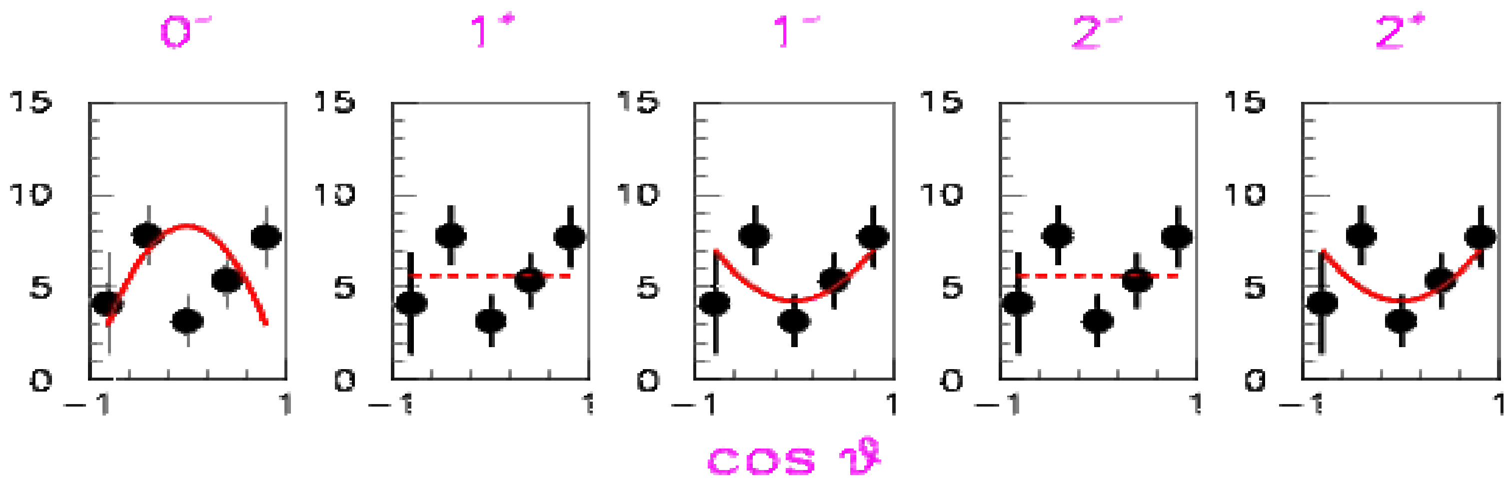


Overview on Exotic States (14)

$D_{sJ}(2458)^{\pm}$: Spin/Parity



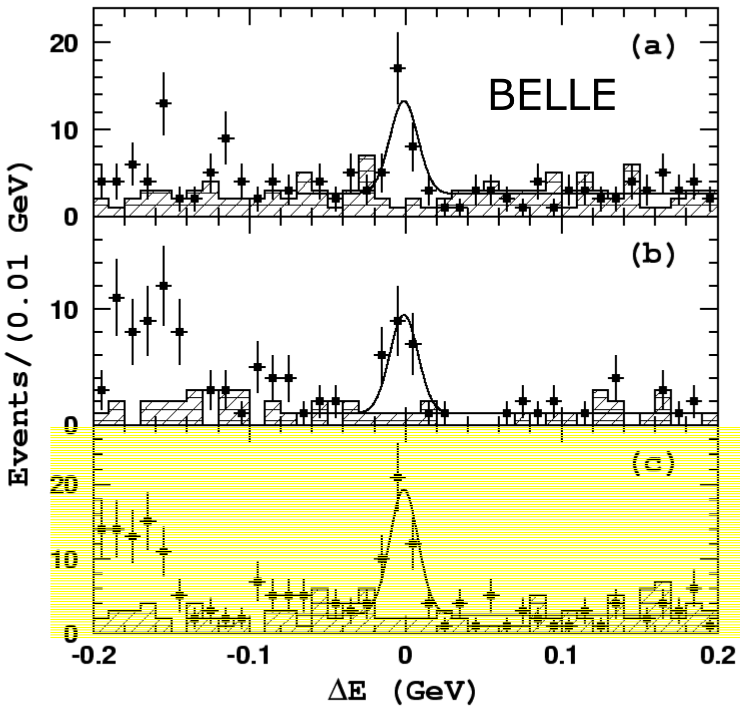




D_{sJ}-Polarization unknown ⇒ **No discrimination between $J^P = 1^+, 2^-, 3^+$**

Overview on Exotic States (15)

D_{sJ} -Production in B-Decays (BELLE):



$B \to D\, D_{sJ}(2317)$

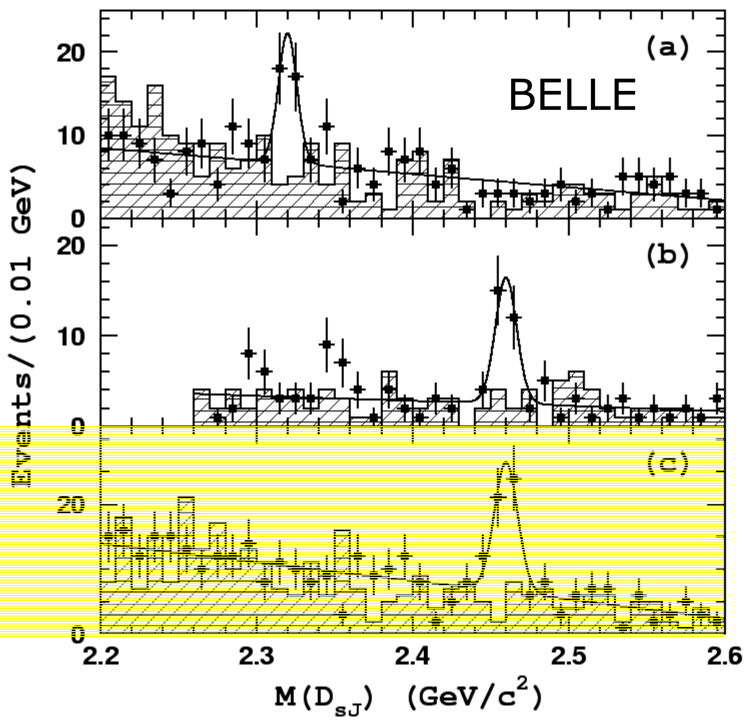
$D_{sJ}(2317) \to D_s\, \pi^0$

$B \to D\, D_{sJ}(2457)$

$D_{sJ}(2457) \to D_s^* \pi^0$

$B \to D\, D_{sJ}(2457)$

$D_{sJ}(2457) \to D_s\, \gamma$



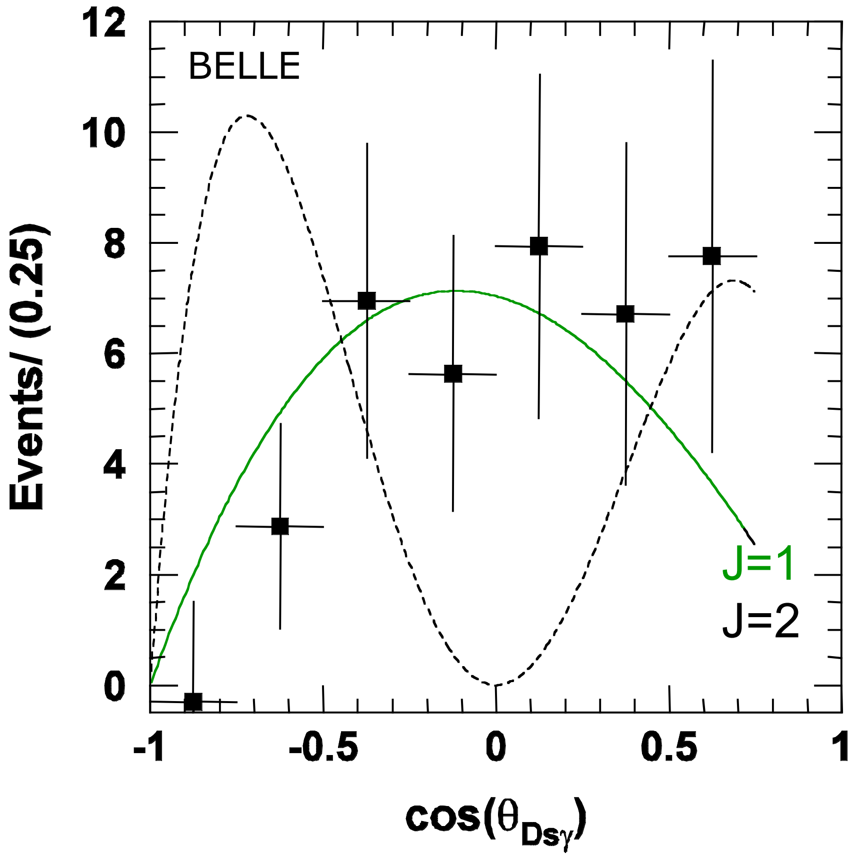
$BF(B \to DD_{sJ}^*(2317)) \times BF(D_{sJ}^*(2317) \to D_s\pi^0) = (8.5 \pm 2.0 \pm 2.6) \times 10^{-4}$

$BF(B \to DD_{sJ}(2458)) \times BF(D_{sJ}(2458) \to D_s^*\pi^0 = (17.8 \pm 4.2 \pm 5.3) \times 10^{-4}$

$BF(B \to DD_{sJ}(2458)) \times BF(D_{sJ}(2458) \to D_s\gamma) = (6.7 \pm 1.3 \pm 2.0) \times 10^{-4}$

Overview on Exotic States (16)

Angular Distribution of $D_{sJ}(2457) \to D_s\gamma$



Consistent with

$J^P = 1^+$ Hypothesis;

0^+, 2^+ excluded

Overview on Exotic States (17)

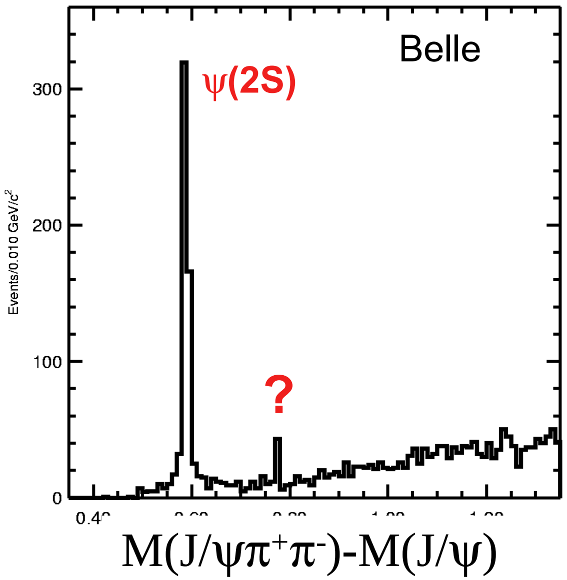
Explanations for $D^*_{sJ}(2317)/\,D_{sJ}(2457)$:

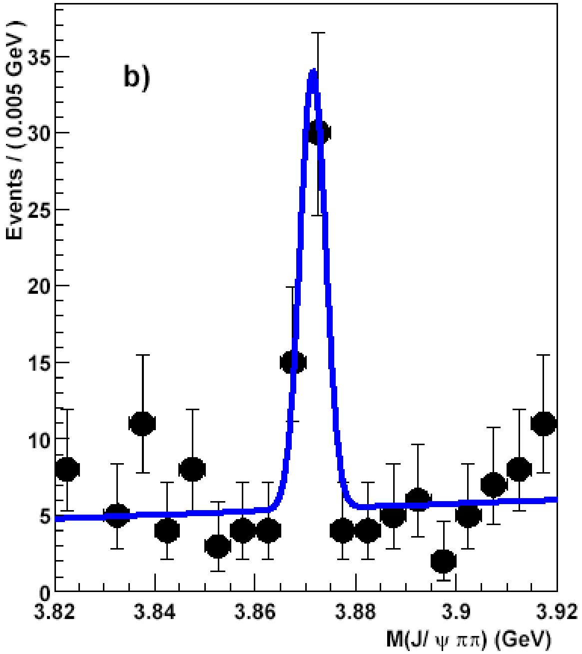
- $0^+/1^+$ $c\bar{s}$-states ?
  Very problematic to achieve a consistent fit for all $c\bar{s}$-states
  Also very difficult to reproduce in LQCD-calculations
- DK-Molecules
- Charmed Cousins of the light scalar nonet
- Charmed Four Quark States
- Chiral Multiplets of Heavy-Light Mesons

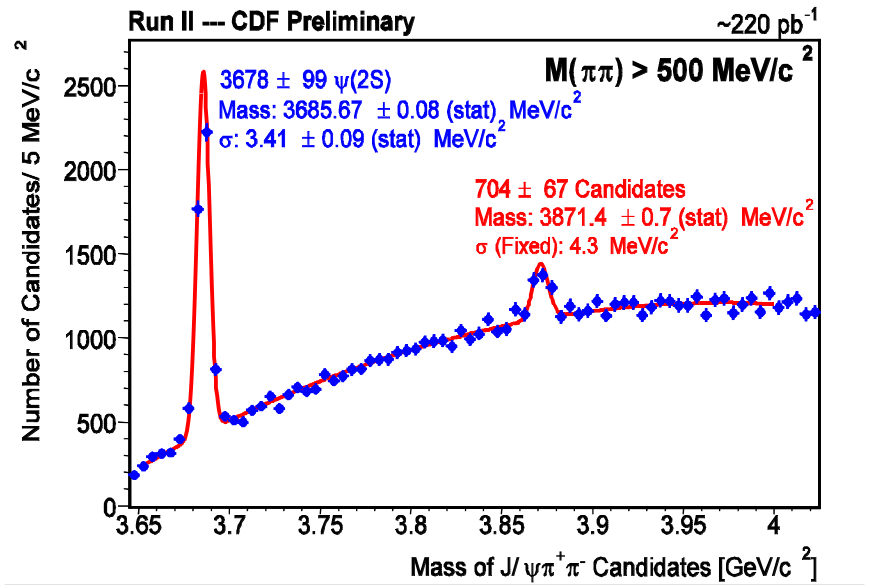
Overview on Exotic States (18)

Charmonium-like State : X(3872) $\rightarrow J/\psi\, \pi^+\pi^-$

BELLE finds new, very narrow state in the decay
$B^\pm \rightarrow K^\pm\, (J/\psi\pi^+\pi^-)$, $J/\psi \rightarrow \mu^+\mu^-$ and e^+e^-
Confirmed by CDF







CDF, preliminary, Bauer, QWG 2003

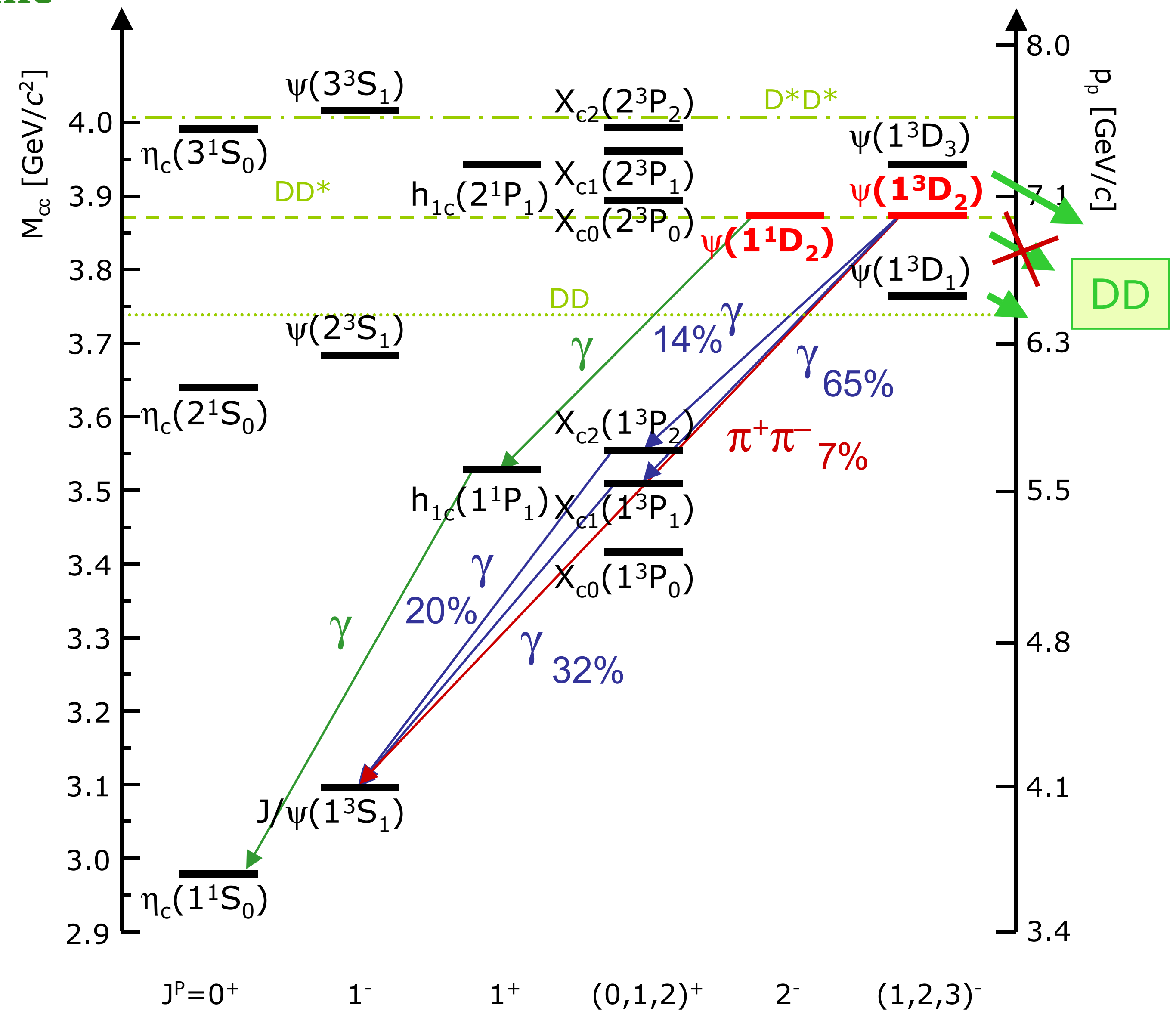
$M = 3872.0 \pm 0.6 \pm 0.5$ MeV
$\Gamma < 2.3$ MeV (90 % C.L.) !!

$M = 3871.4 \pm 0.7 \pm 0.4$ MeV

Overview on Exotic States (19)

Charmonium Level Scheme

X(3872)



Overview on Exotic States (20)

X(3872) : Interpretations

- **$\psi(1^3D_2)$** D-state(L=2) has negative Parity; J=2 forbids decay to $D\bar{D}$
  State narrow, if below $D\bar{D}^*$-threshold
  But: Models predict large partial decay width for $\pi^+\pi^- J/\psi$-decay
  Models can't explain the observed ^3D-pattern

- **$\psi(1^1D_2)$** decays dominantly to h_{1c} ; decay to $\pi^+\pi^- J/\psi$ is suppressed

- **$D^0\bar{D}^{*0}$ Molecule?**

Overview on Exotic States (21)

Rediscovery

$\eta_c(2S) = \eta_c' \rightarrow K_S^0 K^+ \pi^-$ from B-decays (Belle)

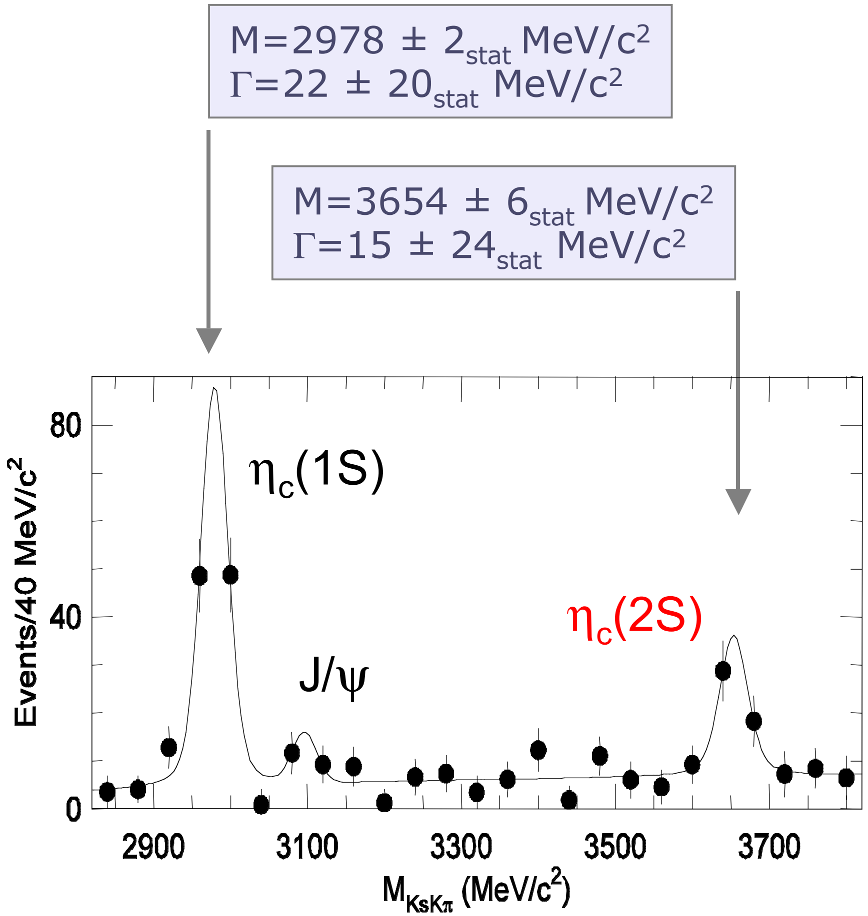
m(η_c(2S)) important for determination of $c\bar{c}$-Hyperfine interaction

Production: $B \rightarrow K\,\eta_c(2S)$

Decay: $\eta_c(2S) \rightarrow K_S^0 K^+ \pi^-$

M(η_c(2S)) = 3654 ± 6 ± 8 MeV/c^2
Γ(η_c(2S)) < 55 MeV/c^2

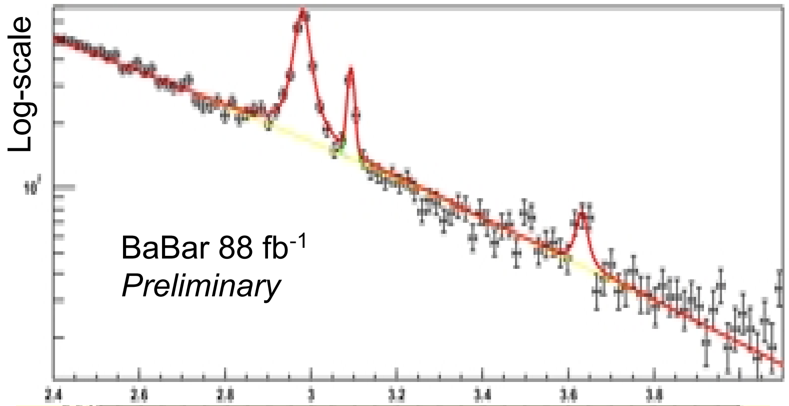
Discrepancy with respect to Crystal Ball measurement (m = 3594 ± 5 MeV/c^2)

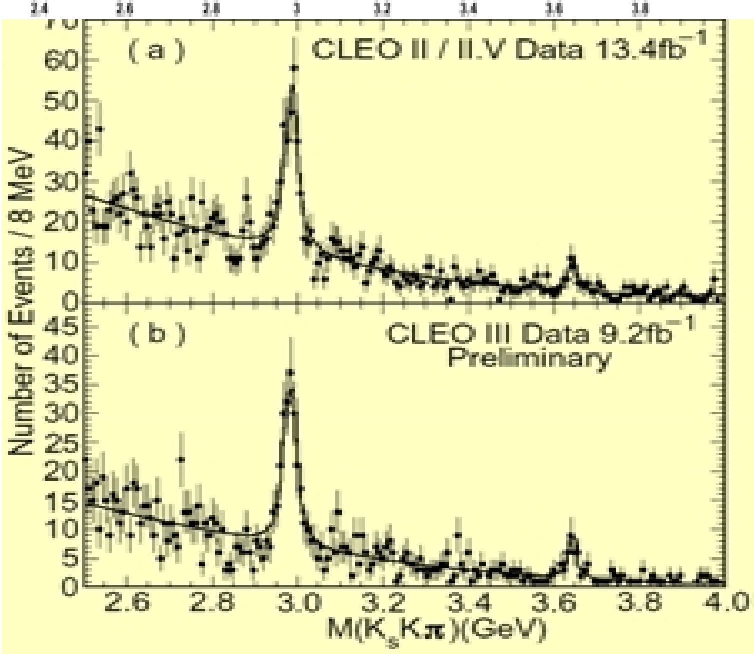


Overview on Exotic States (22)

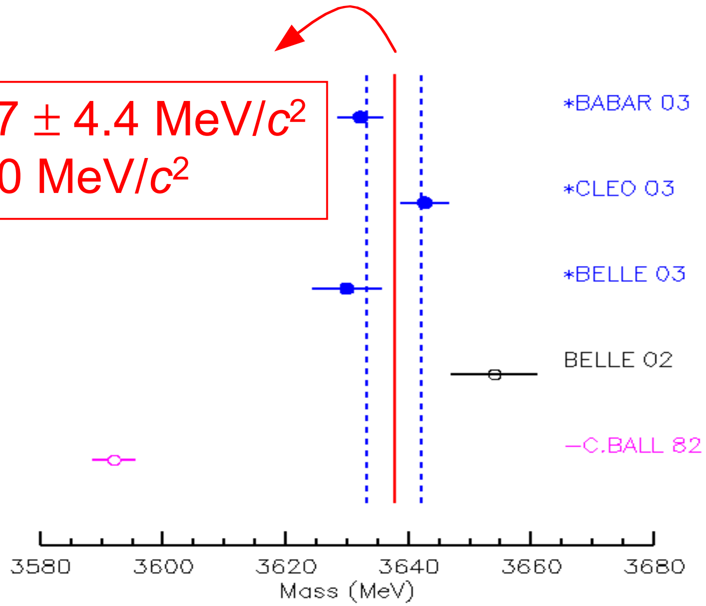
$\gamma\gamma \rightarrow \eta_c(2S)$

$\hookrightarrow K\bar{K}\pi$: BABAR/CLEO





$M(\eta'_c) = 3637.7 \pm 4.4$ MeV/c^2
$\Gamma(\eta'_c) = 19 \pm 10$ MeV/c^2

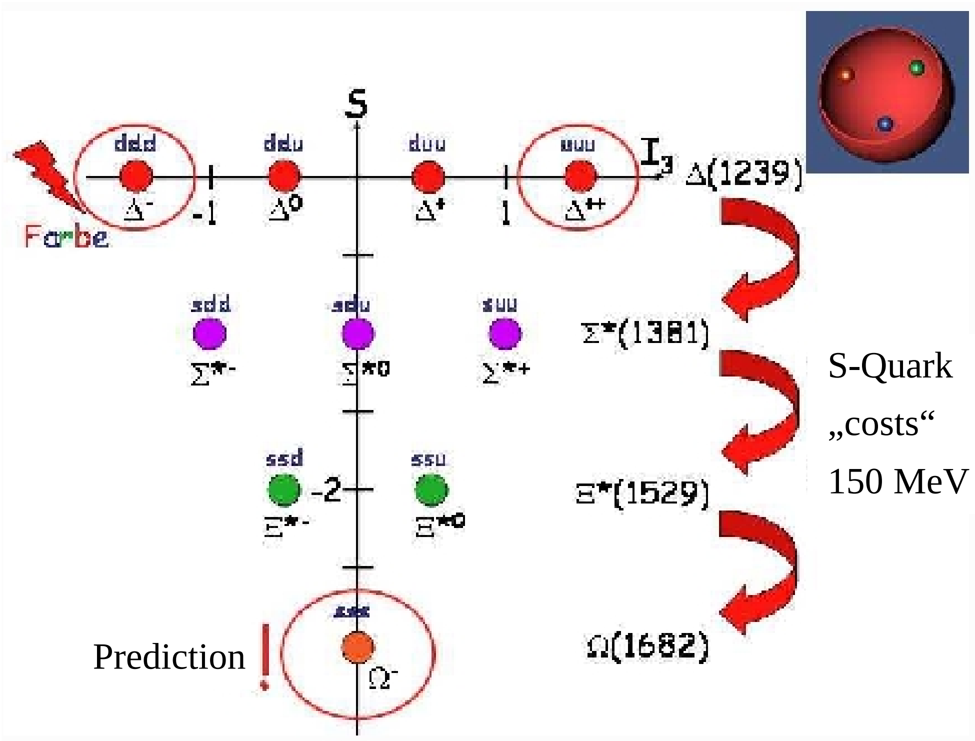


Overview on Exotic States (23)

Exotic Baryons/Penta-Quarks

Non Exotic Baryons : Three Quark Model

$3 \oplus 3 \oplus 3 = 1_A + 8_M + 8_M + 10_S$



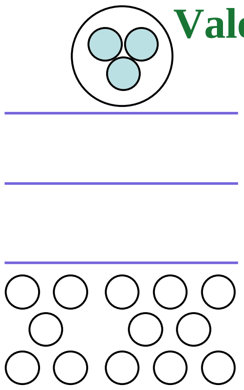
Decuplet of 3q baryons

Only states with zero or negative Strangeness possible

Positive Parity States only possible for L > 0

Overview on Exotic States (24)

Particularly Interesting Baryon-Model: Instanton-induced interactions/Soliton-Model
(For light quarks only)



Valence Quarks

m_q

0

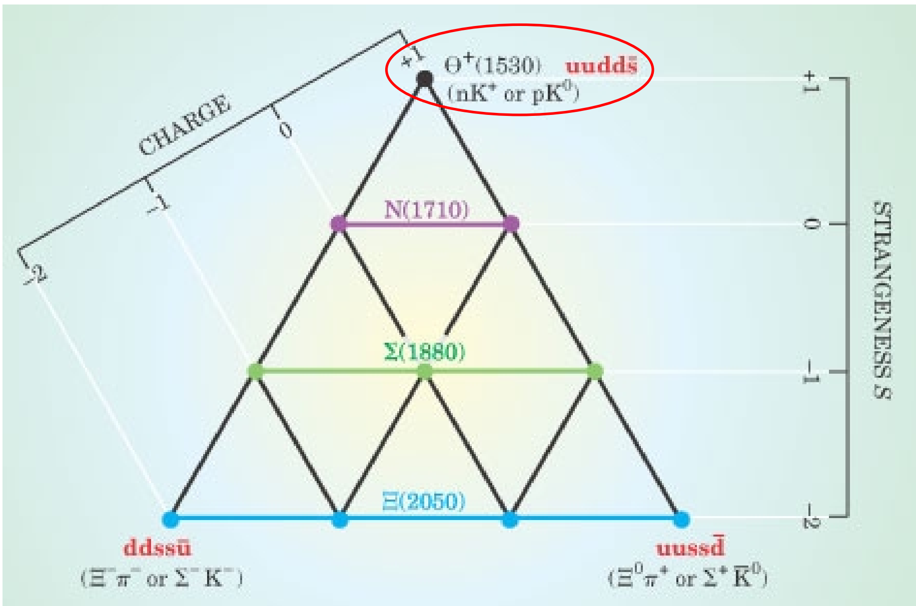
$-m_q$

Sea Quarks (QCD-Vacuum)

Quarks interact via changes of the QCD vacuum
Quarks and Sea Quarks are dynamically coupled
Constituent Quarks acquire their mass by spontaneous symmetry breaking

↳ Exotic quark configurations should exist
Lowest lying Baryonmultipletts: 8, 10 and $\overline{10}$!

$\overline{10}$-Decuplett:



Exotic states:

uudds̄ (Θ^+)
ddssū (Ξ^{--})
uussd̄ (Ξ^+)

Diakonov, Petrov, Polyakov (1997):

$M(\Theta^+) = 1530\ \text{MeV}/c^2$
$\Gamma(\Theta^+) < 15\ \text{MeV}/c^2$

Overview on Exotic States (25)

Experimental Evidences for Θ^+:

Exclusive Reactions

$\gamma p(d, C)$	:	SPRING-8/CLAS/SAPHIR
pp	:	TOF–COSY

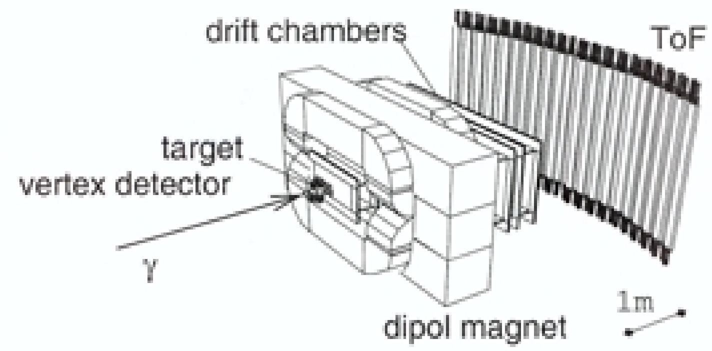
(Semi)-Inclusive Reactions

$K^+Xe \rightarrow K_s^0 pX$	ITEP
$\nu A \rightarrow pK_s^0 X$	CERN/Fermilab
$e(\mu)A \rightarrow pK_s^0 X$	HERMES/ZEUS/COMPASS

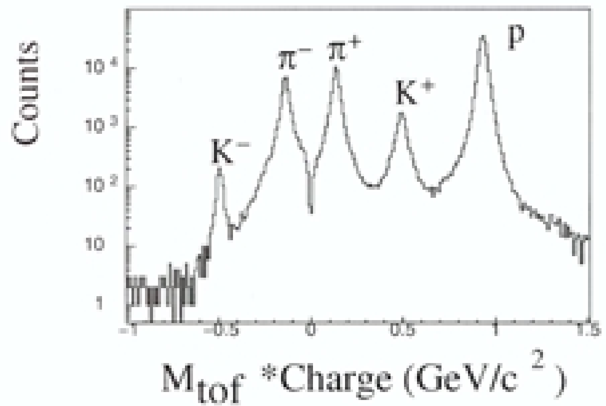
Overview on Exotic States (26)

LEPS-Coll.@SPRING8

- Spring–8: synchotron radiation facility
- photon beam 1.5 – 2.4 GeV



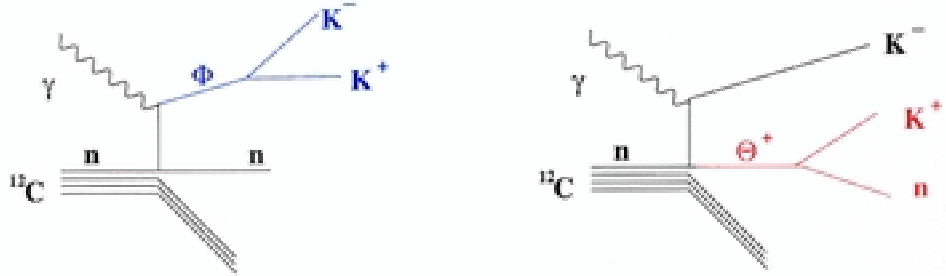
- charged particle tracking in magnetic field
  → momentum
- time of flight (ToF) measurement
  → particle identification: $M_{tof} = p \cdot \sqrt{(t/s)^2 - 1}$



Overview on Exotic States (27)

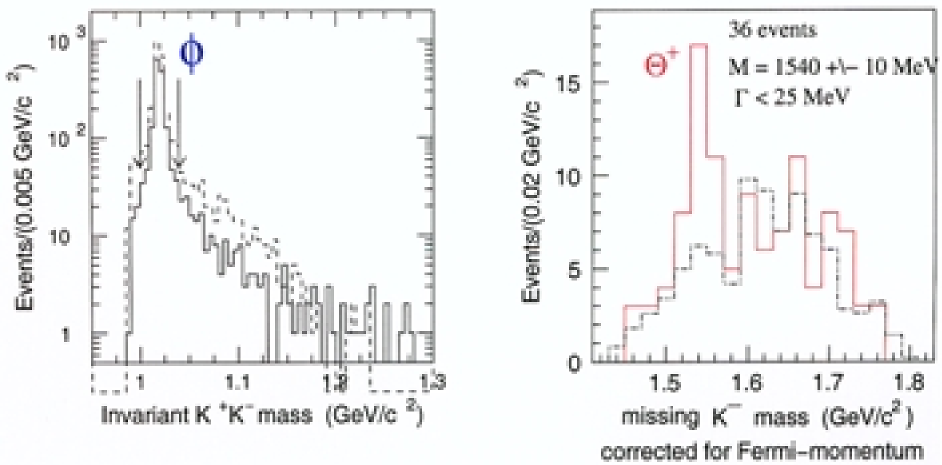
LEPS-Coll.@SPRING8

$$\gamma n \;\rightarrow\; K^+ K^- n$$



distribution of "invariant" and "missing"–masses

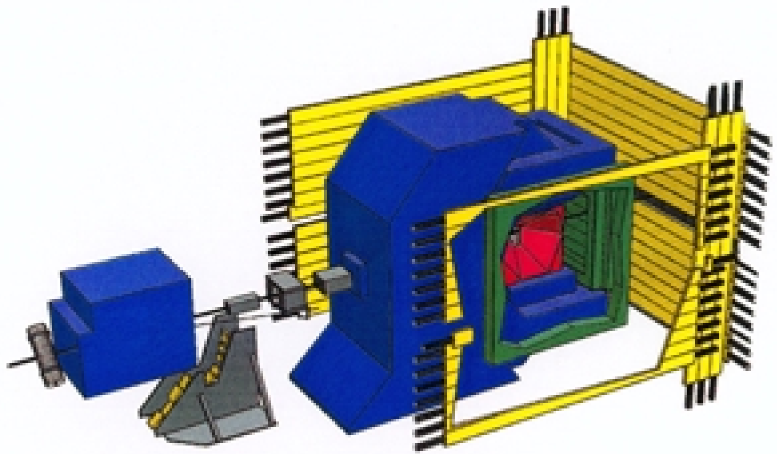
$$M^K_{miss} := \sqrt{(p_{initial} - p_{K^-})^2}$$



Overview on Exotic States (28)

SAPHIR Spectrometer/ELSA

hep–ex/0307083



magnetic dipol field E_γ^{max} =2.6 GeV

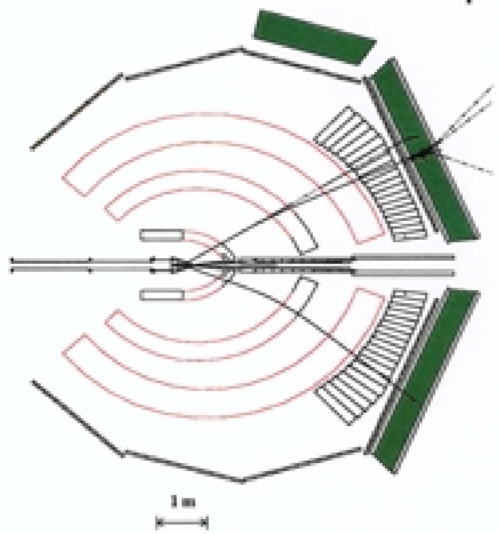
drift chambers N_γ $=10^6$ /s

time–of–flight counter

CLAS Spectrometer/ CEBAF

Jefferson–Lab/Newport News

hep–ex/0307018



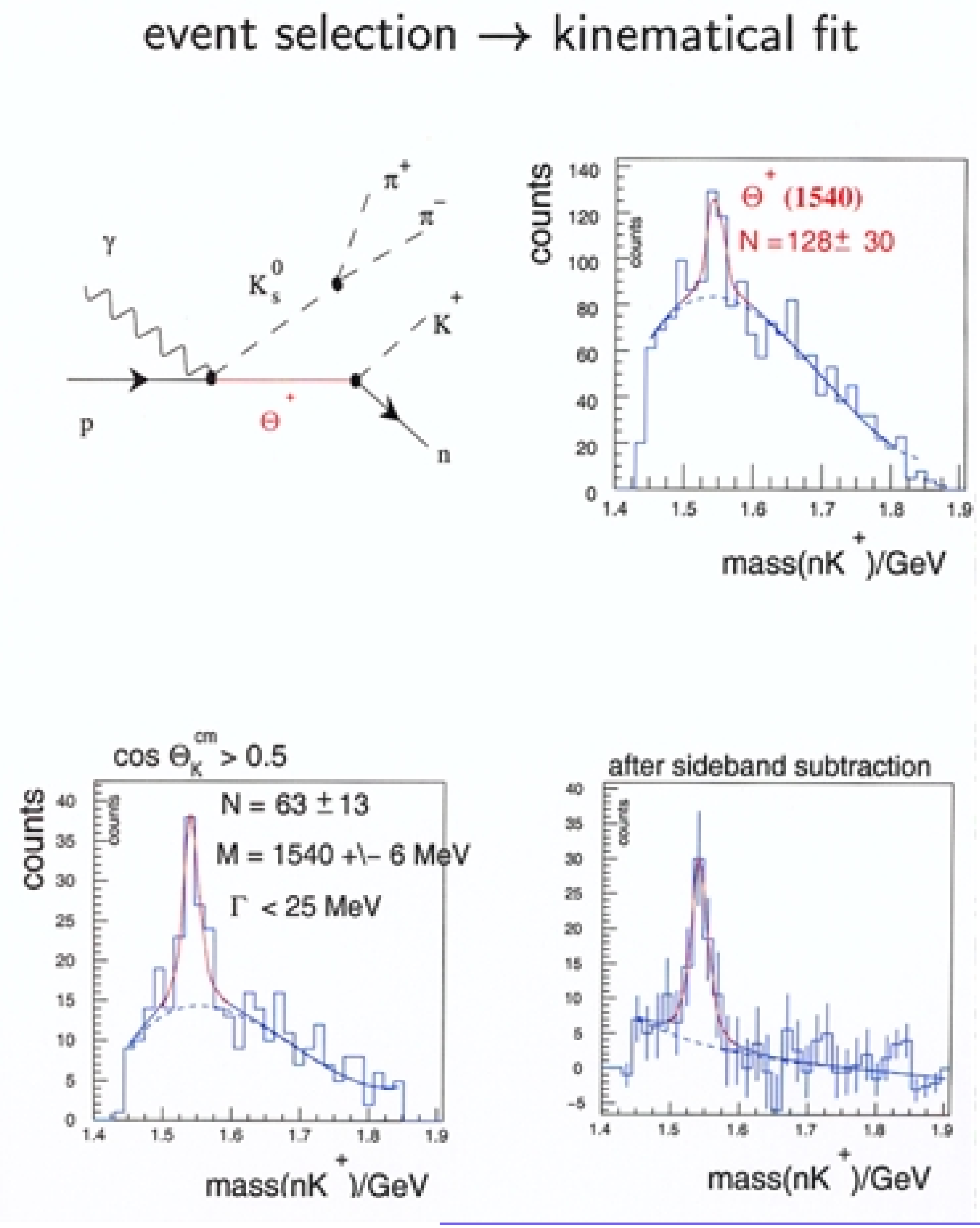
toroidal magnetic field E_γ^{max} =6 GeV

drift chambers N_γ $=10^7$/s

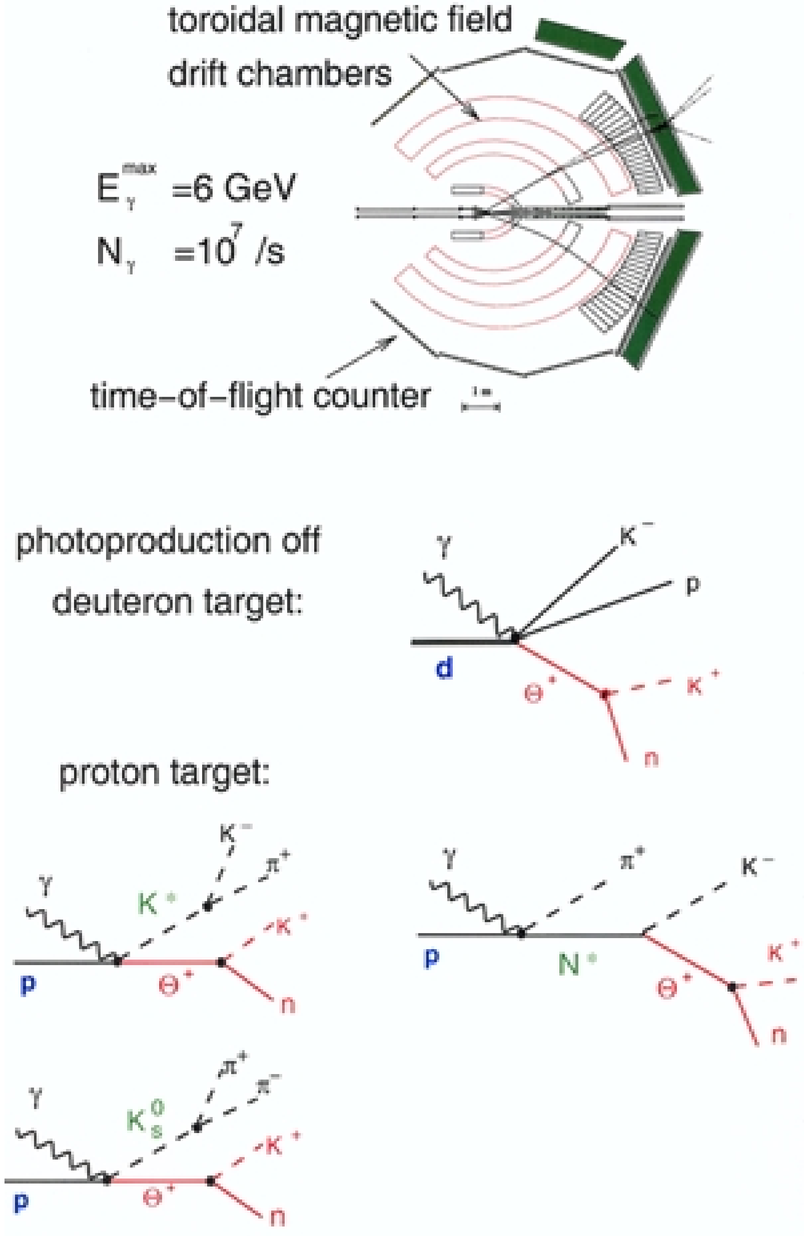
time–of–flight counter

Overview on Exotic States (29)

SAPHIR

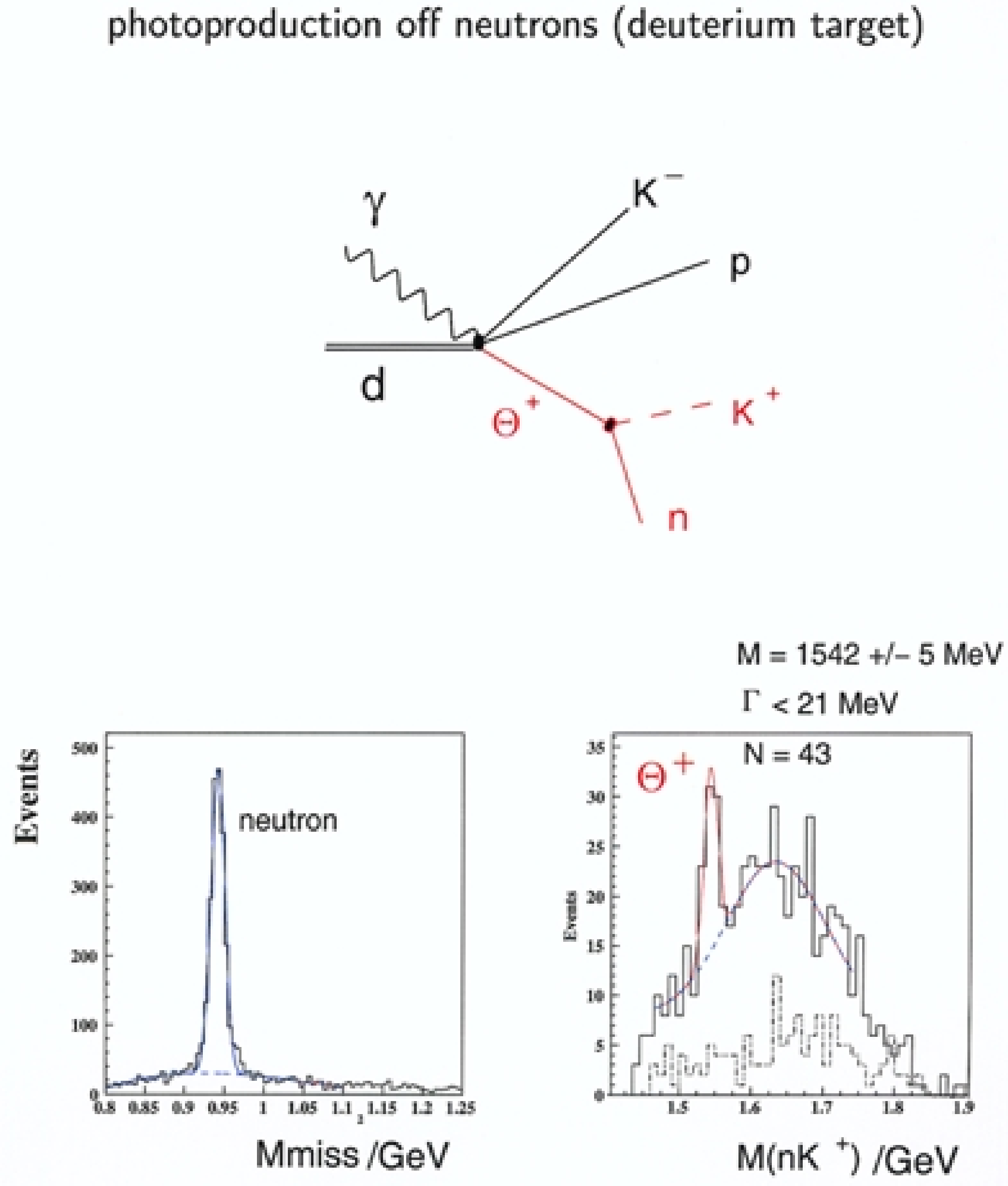


CLAS


toroidal magnetic field
drift chambers
E_γ^{max} =6 GeV
N_γ =10^7 /s
time-of-flight counter
photoproduction off
deuteron target:
γ
K^-
p
d
Θ^+
K^+
n
proton target:
γ
K^-
π^+
K^*
K^+
p
Θ^+
n
γ
π^+
K^-
p
N^*
K^+
Θ^+
n
γ
π^+
π^-
K_s^0
K^+
p
Θ^+
n

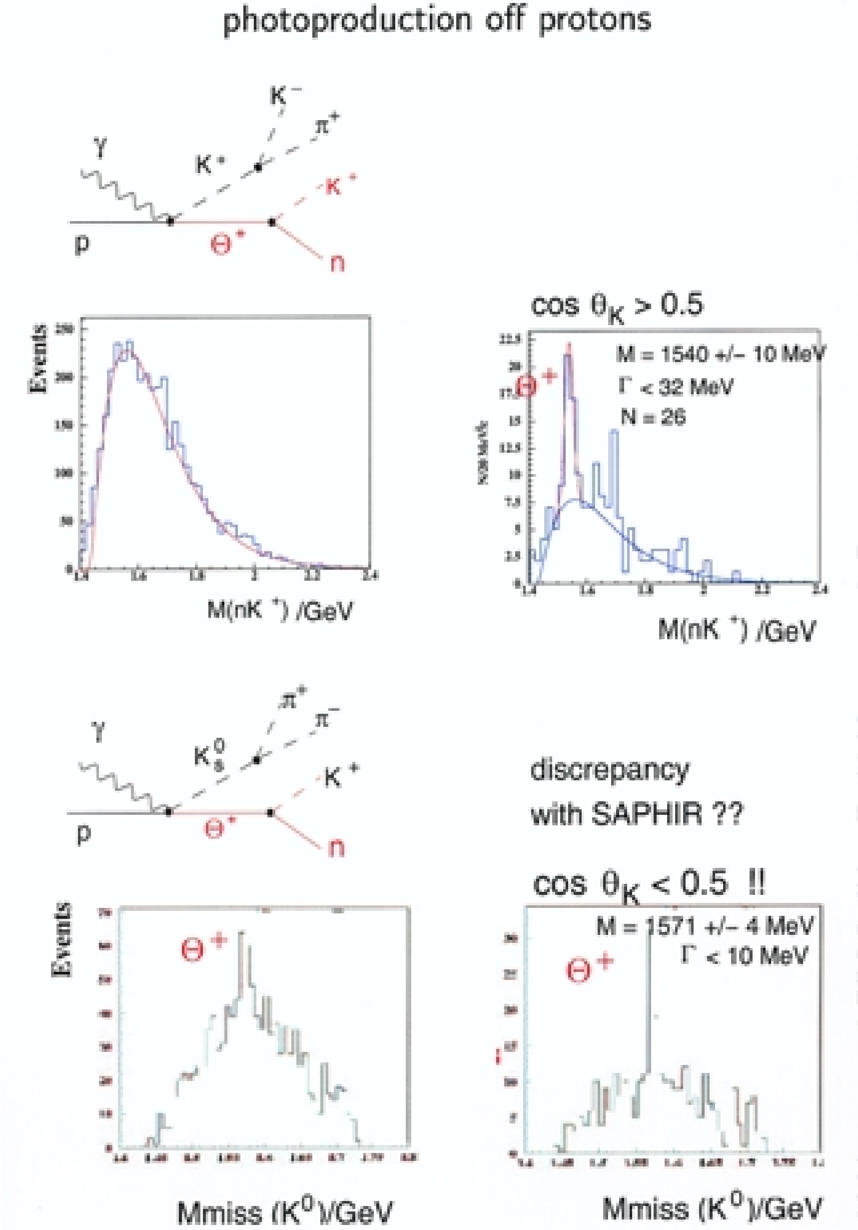
Overview on Exotic States (31)

CLAS



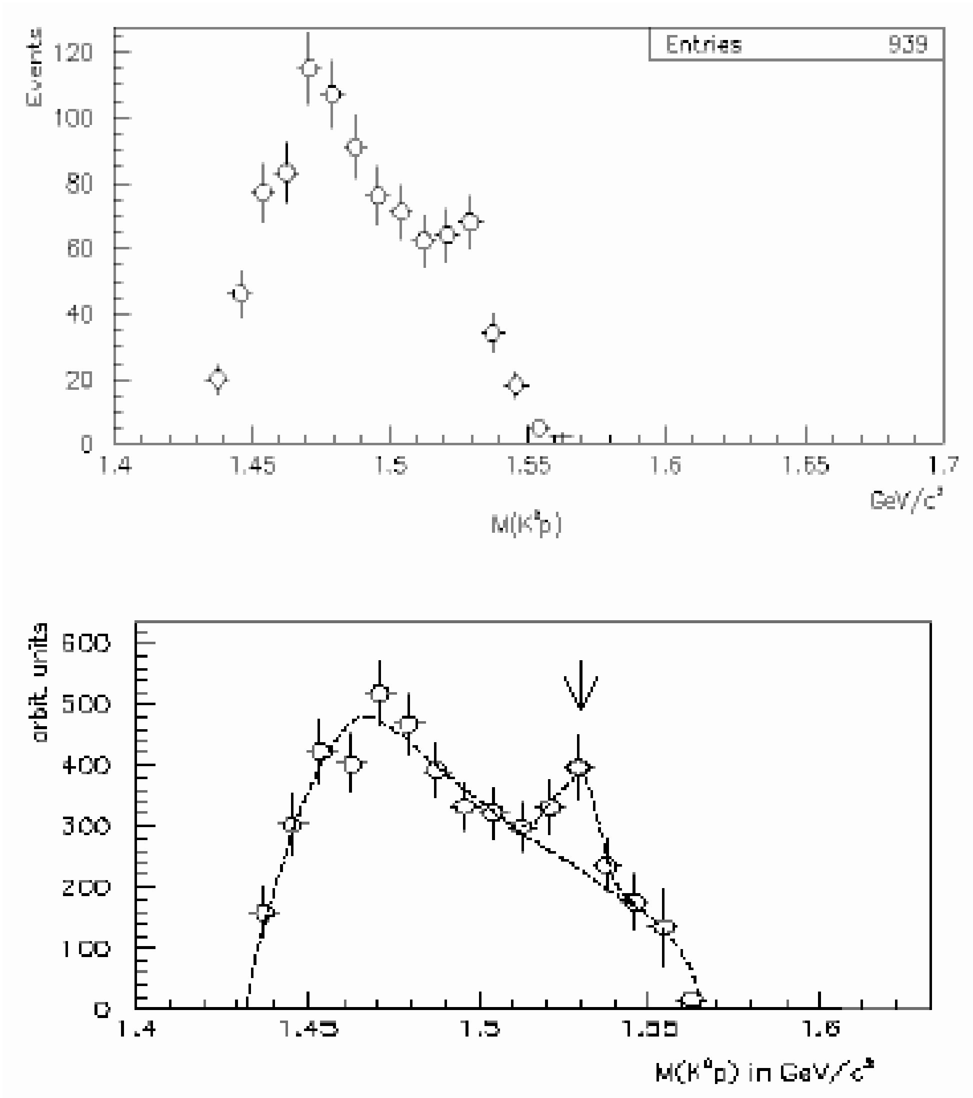
Overview on Exotic States (32)

CLAS



Overview on Exotic States (33)

COSY-TOF $pp \rightarrow \Theta^{+}\Sigma^{+} \rightarrow K^{0}p\Sigma^{+}$ hep-ex/0403011



$M = 1530 \pm 5$ MeV

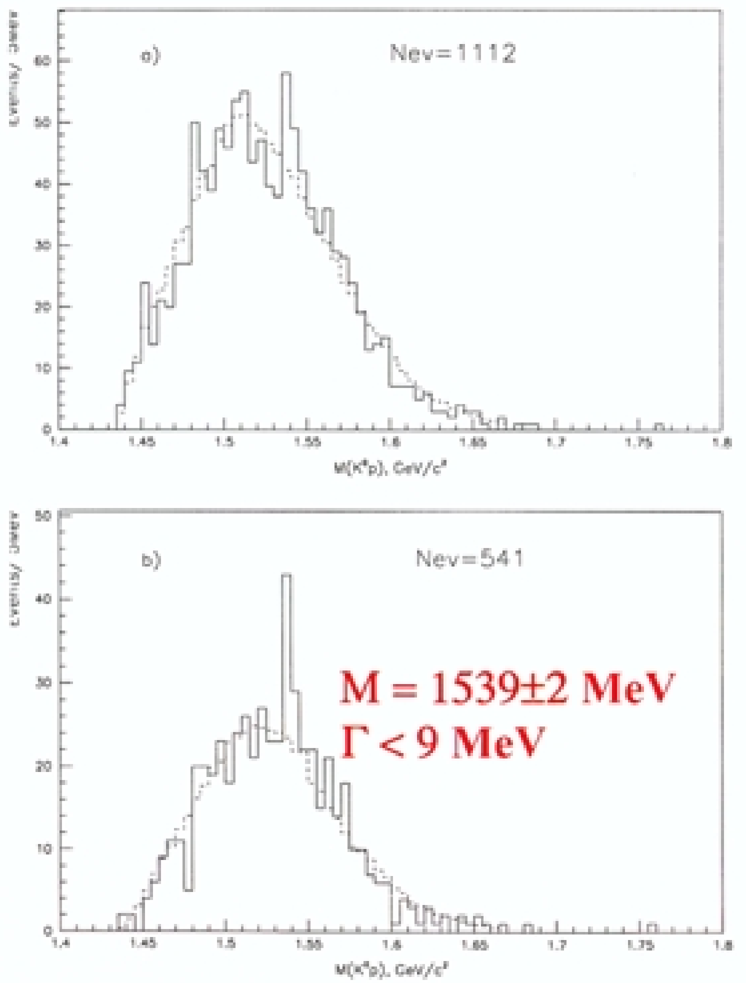
$\Gamma < 18$ MeV

$\sigma = 0.4 \pm 0.1 \pm 0.1\ \mu b$

Overview on Exotic States (34)

DIANA/ITEP

$K^+ Xe \rightarrow K^0 p X$
$(K^+ n \rightarrow K^0 p)$



hep-ex/0304040

- **P_{K+} < 530 MeV/c**
- **Require θ_K<100deg. & θ_p<100 deg.**
- **Remove cos ϕ_{pK} <0 ← back-to-back**

$K^+ n \rightarrow \Theta^+$ ⟷ $\Theta^+ \rightarrow K^+ n$

$\Gamma = 0.9 \pm 0.3$ MeV

Cahn and Trilling hep-ph/0311245

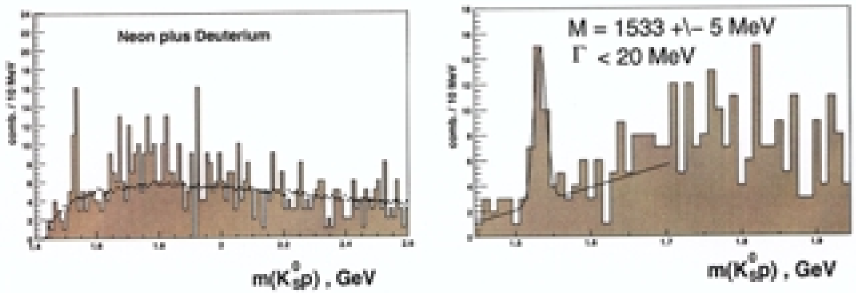
consistent with KN phase shift analysis by Arndt et. al.

Phys. Rev. C68, 042201(R)

Overview on Exotic States (35)

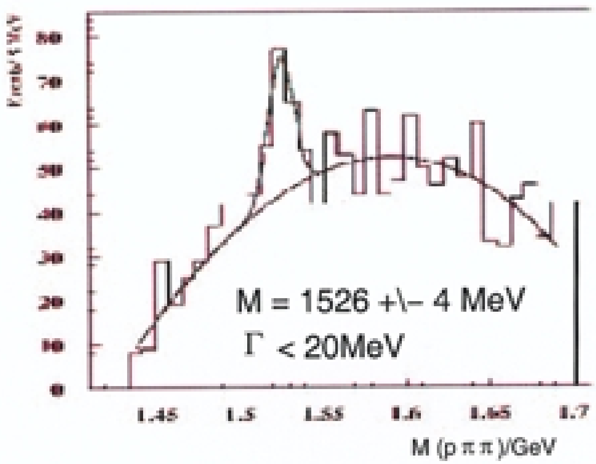
- CERN (WA21,WA25,WA59)
  FNAL(E180, E632)

$$\nu_\mu(\overline{\nu_\mu}) \;\rightarrow\; \mu^-(\mu^+)\, pK^0_S\, X$$



- DESY (HERMES)

$$eD \;\rightarrow\; pK^0_S\, X$$



Overview on Exotic States (36)

Summary of positive results

Experiment	Θ^+ Mass (MeV)	Γ (MeV)
LEPS/SPring-8	: $1540 \pm 10 \pm 5$	: 25
DIANA	: $1539 \pm 2 \pm$ few	: 9
CLAS(d)	: $1542 \pm 2 \pm 5$	: 21
SAPHIR	: $1540 \pm 4 \pm 2$	: 25
ITEP(ν)	: 1533 ± 5	: 20
CLAS(p)	: $1555 \pm 1 \pm 10$	: 26 ± 7
HERMES	: $1528 \pm 2.6 \pm 2.1$	: $19 \pm 5 \pm 2$
ITEP(p)	: $1526 \pm 3 \pm 3$	: 24
ZEUS	: 1527 ± 3	: 10 ± 2

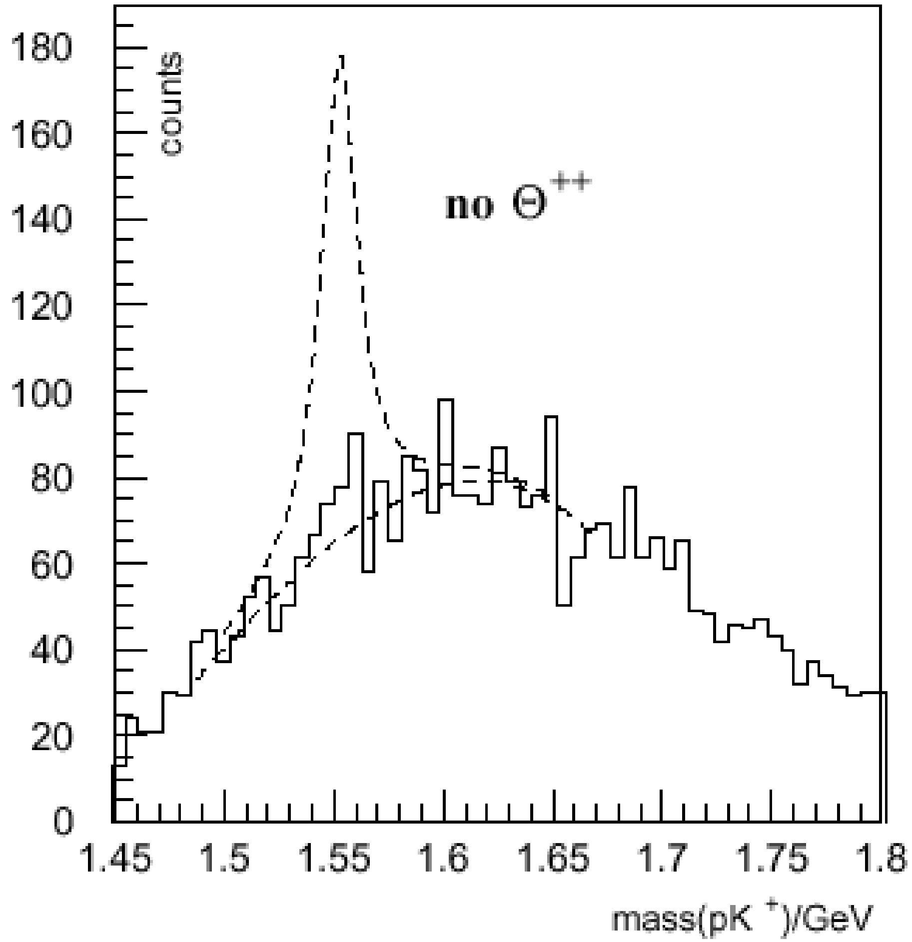
Quantum Numbers : I = 0 ; J^P = ?

Overview on Exotic States (37)

SAPHIR : Isospin of Θ^+

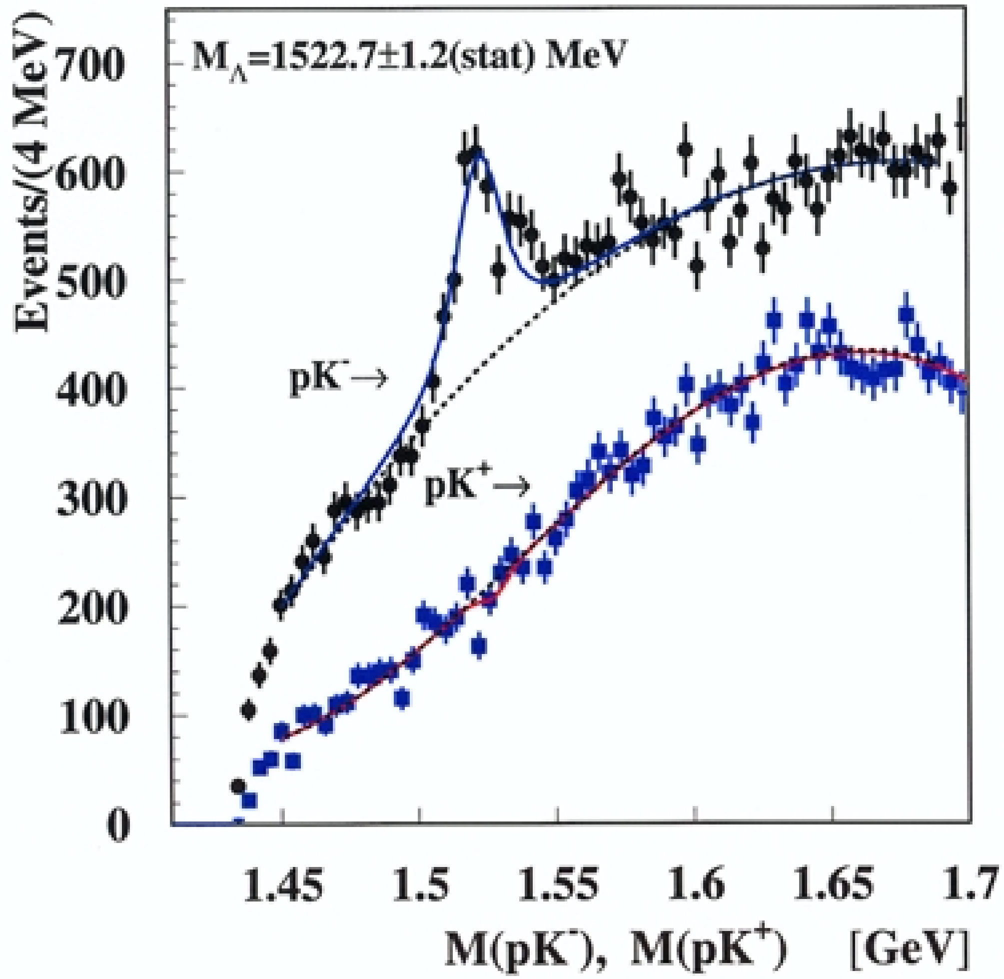
search for:

$$\gamma p \rightarrow \Theta^{++} K^-$$
$$\rightarrow p K^+ K^-$$



Overview on Exotic States (38)

The Θ^+ Isospin from Hermes (prelim.)



- Clear signal for $\Lambda(1520)$
- Gell-Mann-Nishijima relation
- Gell-Mann-Nishidjim Y=B+S
  $Q = I_3 + Y/2$, where Y=B+
- if no Θ^{++} then:
- $\rightarrow \Theta^+$ is an isosinglet

Overview on Exotic States (39)

Questions to be answered

- To be or not to be?
- What is the true mass?
  - Ranges from 1526 MeV to 1555 MeV.
- How narrow is the width?
  - Only upper limits were given.
  - Hard to explain if $\Gamma<1$ MeV.
- What is the Spin and Parity? How to measure?
  - $1/2^-$ (Lattice, Quark Model) or $1/2^+$ (Di-quark, Chiral soliton)
- Is there $J^+=3/2^+$ partner? Still narrow?
- Other members of the anti-decuplet?

Overview on Exotic States (40)

Theory prediction

D. Diakonov *et al.* (chiral quark soliton)	: $1/2^+$, I=0
Naive quark model	: $1/2^-$
S. Capstick *et al.* (isotensor formulation)	: $1/2^-$, $3/2^-$, $5/2^-$, I=2
Fl. Stancu, D.O. Riska (qq with π int.)	: $1/2^+$
A. Hosaka (chiral potential)	: $1/2^+$ (strong π)
M. Karliner *et al.* (qq-qqq)	: $1/2^+$, I=0
R. L. Jaffe *et al.* (qq-qq-q : 10 + 8)	: 1/2+, I=0
J. Sugiyama *et al.* (QCD sum rule)	: $1/2^-$, I=0
F. Csikor *et al.* (Lattice QCD)	: $1/2^+$ -> $1/2^-$, I=0
S. Sasaki (Lattice QCD)	: $1/2^-$, I=0

Mass, width, Spin, Parity, Production mechanism, Partners…

Overview on Exotic States (41)

Theoretical predictions for Multi-Quark-States

Strange Sector:

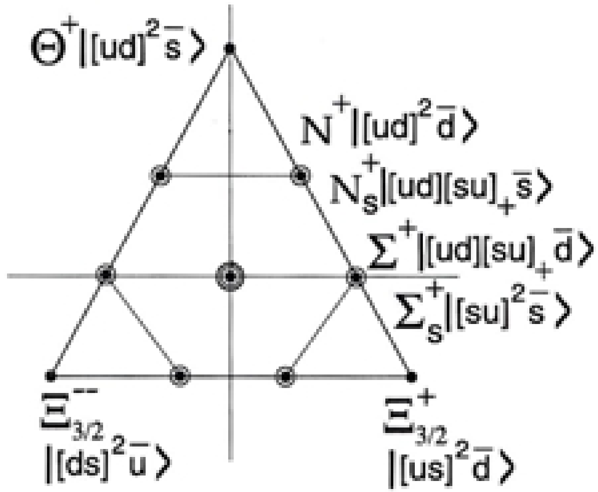
– Uncorrelated Bag Models (R. Jaffe, D. Strottman, 1979)

Many states predicted

$^1/_2{}^-$-states (ground states) < 1500 MeV (No exp. evidence)

– Correlated Bag Models (R. Jaffe/F. Wilczek; M. Karliner/H. Lipkin; 2003)

$(qq)(qq)\,\bar{s}$-state : $\bar{3} \oplus \bar{3} \oplus \bar{3} = (3 + \bar{6}) \oplus \bar{3} = 1 + 8 + \underbrace{8 + \overline{10}}_{\text{Degenerate}}$



Fewer states predicted

Exotic states $\Theta^+ = [ud]^2\bar{s}$, $\Xi^{--} = [ds]^2\bar{u}$, $\Xi^+ = [us]^2\bar{d}$

$N^+ = [ud]^2\bar{d}$ = Roper-Resonance (N(1440) ?

Mass splittings, Widths ≈ in accordance with (preliminary) data

$J^P = {}^1/_2{}^+$ plausible

Overview on Exotic States (42)

– Skyrme Model (M. Praszalowicz, 1987)

Lightest 5q-state ≈ 1530 MeV; Widths: No statements

– χQSM (Chiral Quark Soliton Model) (D. Diakonov, V. Petrov, M. Polyakov, 1997)

χQSM predicts existance of an anti-decuplet

$\Theta^+ = uudd\bar{s}$, $J^P = {}^1/_2{}^+$

$M(\Theta^+) = 1530$ MeV (Assuming N(1710) is $duud\bar{d}(\overline{10})$); $\Gamma < 15$ MeV

– LQCD (Sasaki, F. Csikor et al., 2003)

Sasaki:

$M(uudd\bar{s}) =$ 1.76 GeV ($J^P = {}^1/_2{}^-$)
2.62 GeV ($J^P = {}^1/_2{}^+$)

Csikor et al.:

M(uudds) : Consistent with 1540 GeV ($J^P = {}^1/_2{}^-$)
> 1540 GeV ($J^P = {}^1/_2{}^+$)

Charme/Bottom-Sector:

– Correlated Bag Models (R. Jaffe/F. Wilczek; M. Karliner/H. Lipkin)

$\Theta_c^0 = [ud]^2\bar{c}$: $M(\Theta_c^0) \approx 2710 - 2985$ MeV

$\Theta_b^+ = [ud]^2\bar{b}$: $M(\Theta_b^0) \approx 6050 - 6398$ MeV

– LQCD

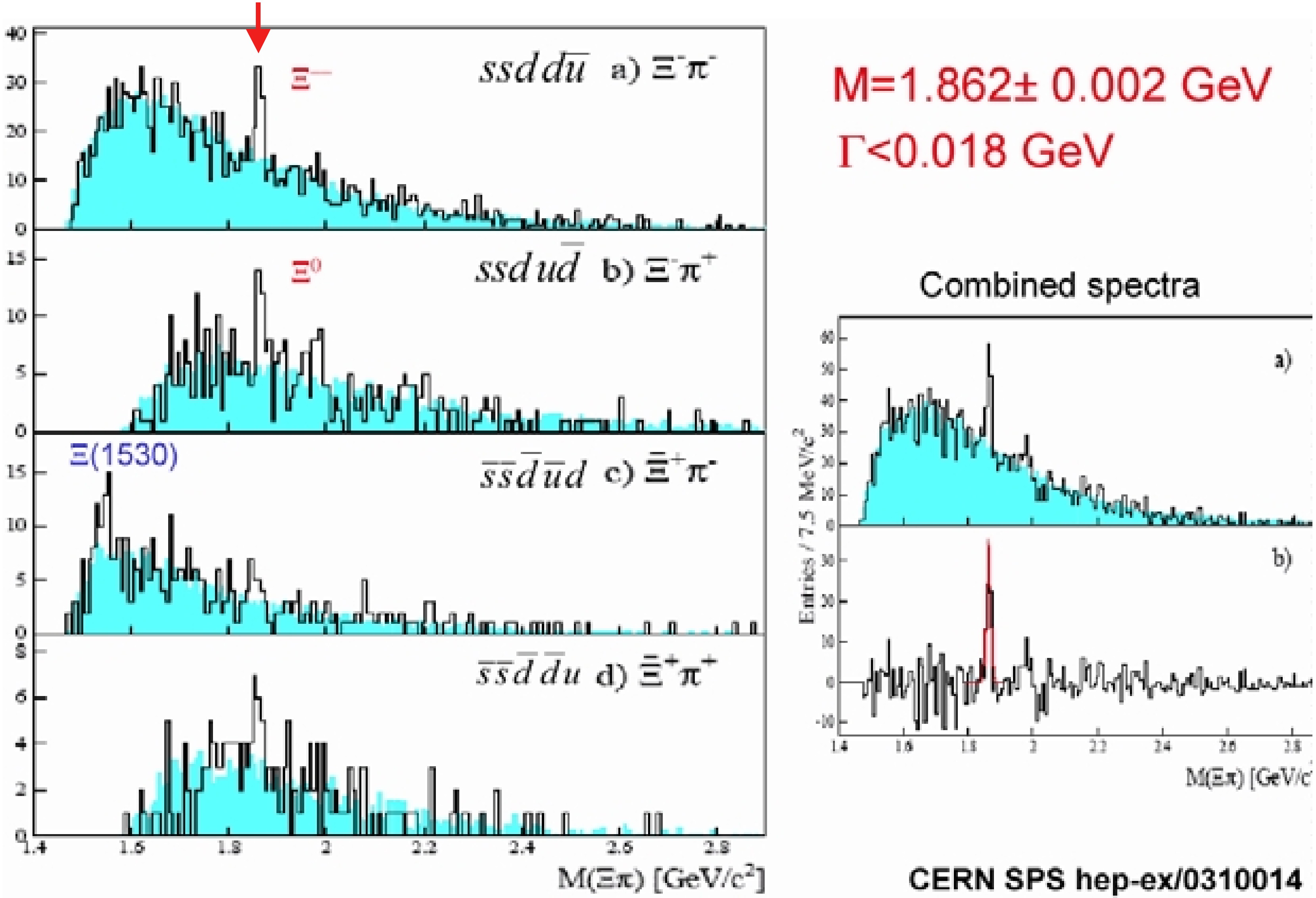
$M(uudd\bar{c}) \approx$ 3.45 GeV ($J^P = {}^1/_2{}^-$)
(> M(DN))

Overview on Exotic States (43)

- *R.L.Jaffe*: “Physicist do not understand how quarks fit together into the particles that make up 99% of the familiar matter in the universe. Looking at these exotic states is one of the ways we can learn the subtleties of the structure of matter”
- *F.Wilczek*: “The discovery of a “pentaquark” exotic opens a new chapter in hadronic physics”
- *J.Ellis*:”Whatever the explanation of this exotic turns out to be, it is very exciting. It looks like the beginning of a whole new hadron spectroscopy. That would become a key testing ground for quark and skyrmion views of baryon structure”

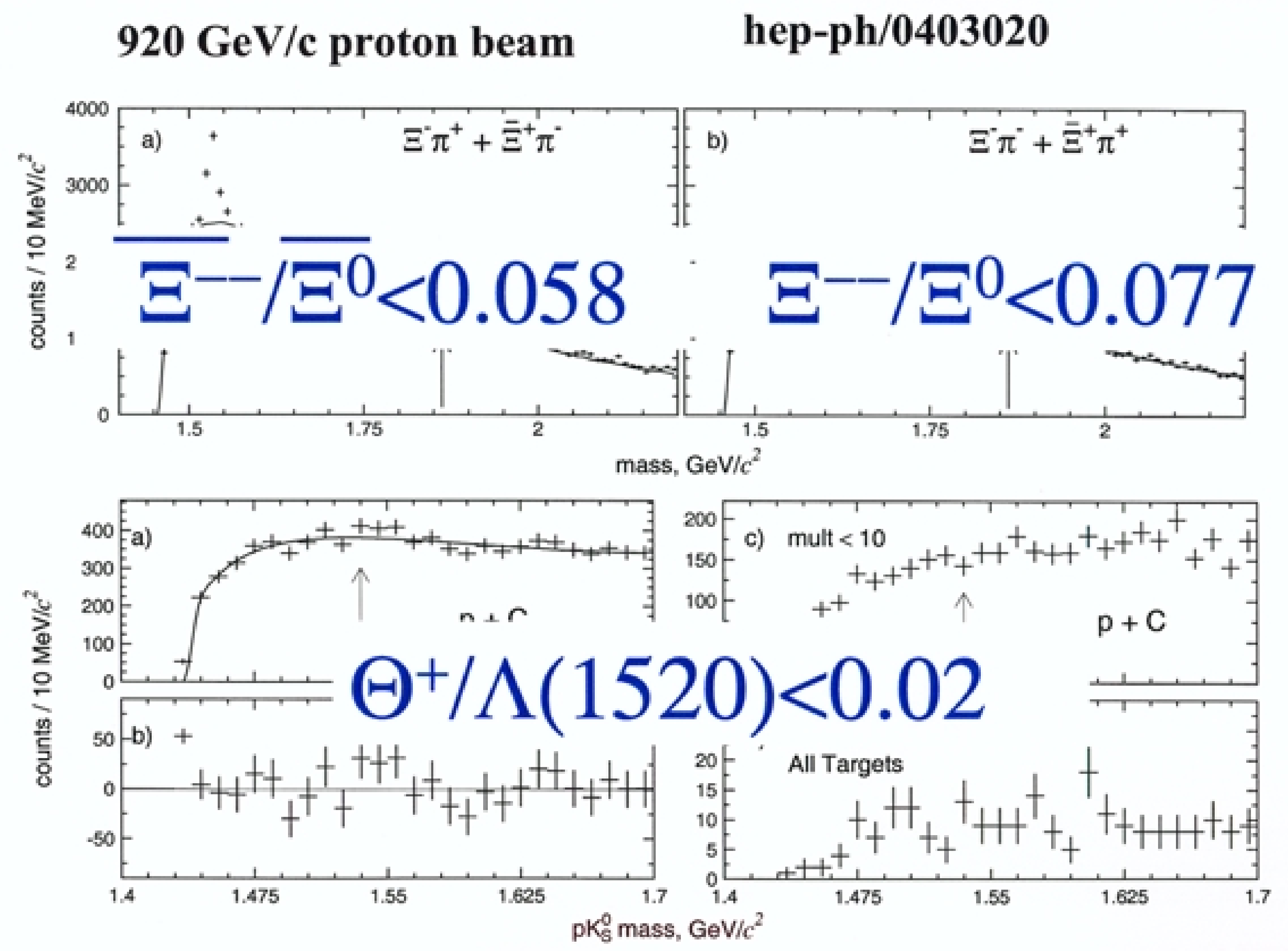
Overview on Exotic States (44)

Further Exotics: Ξ^{--} (NA49/CERN)



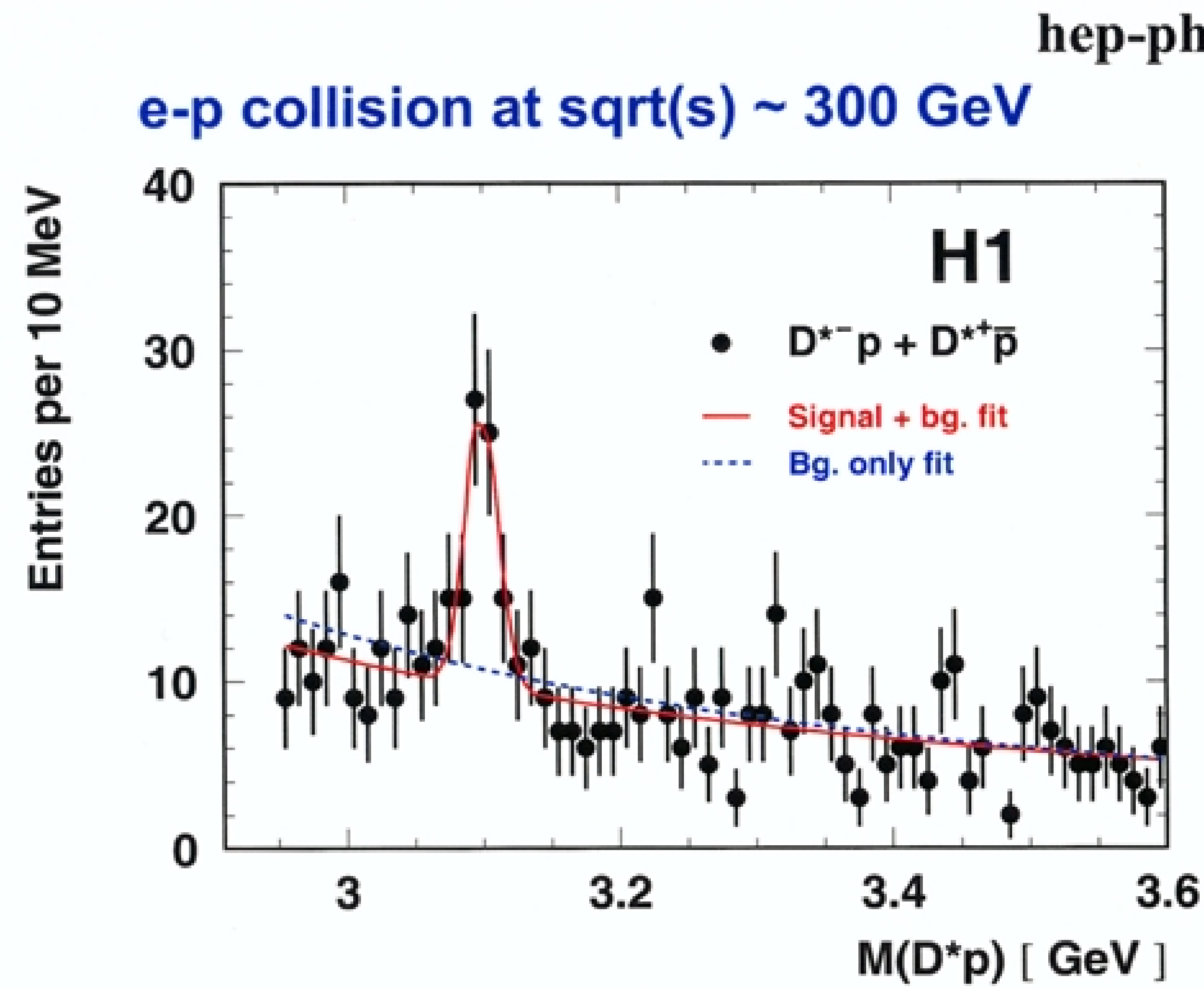
Overview on Exotic States (45)

Negative results from HERA-B



Overview on Exotic States (46)

Further Exotics: Θ_c^0 (H1/DESY)



$M = 3099 \pm 3 \pm 5$ MeV
$\sigma = 12 \pm 3$ MeV

630 MeV above DN threshold.

Too narrow width?

Conclusions

– Recently many new and surprising discoveries in Hadron Physics

– Extension of Hadron Spectrocopy in the Charm/Bottom-sector very valuable

– There is evidence for mesonic/hadronic states, whose properties are hard (or not) to explain in the usual quark-picture

– Possibly, the ideas regarding the structure of hadrons must be revised

– Further interesting results are expected in the future (Medium and High Energy Laboratories)