Hadron Spectroscopy

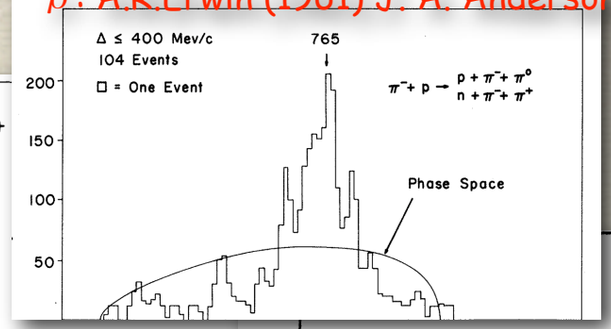
Adam Szczepaniak
Indiana University

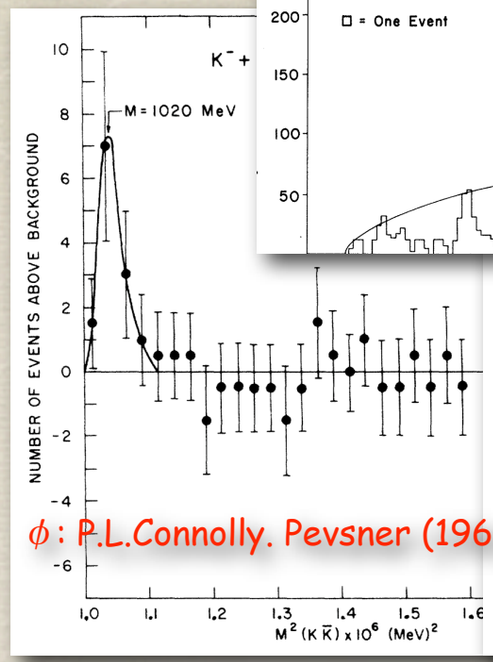
- Hadrons, QCD and the new states of matter

- Recent results: experiment, theory and phenomenology and connection between them
  Too many results: focus on "-onia"

- Challenges: Amplitude analysis

ρ : A.R.Erwin (1961) J. A. Anderson (1960)





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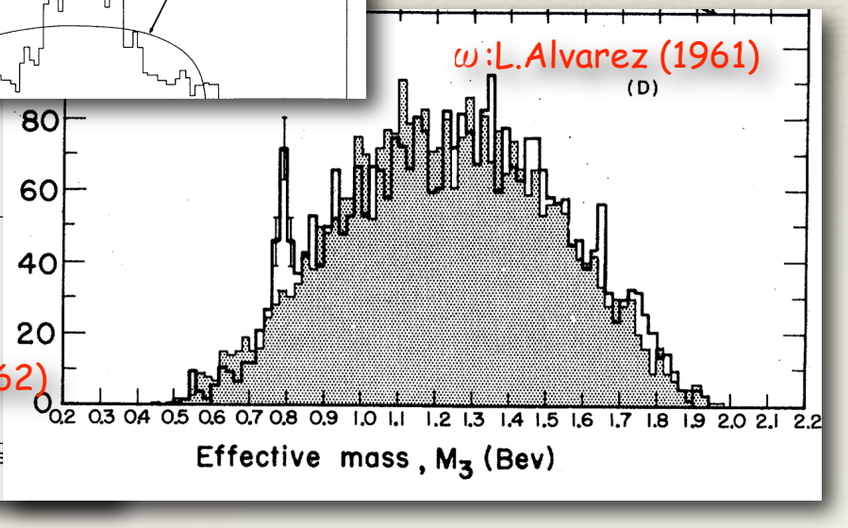

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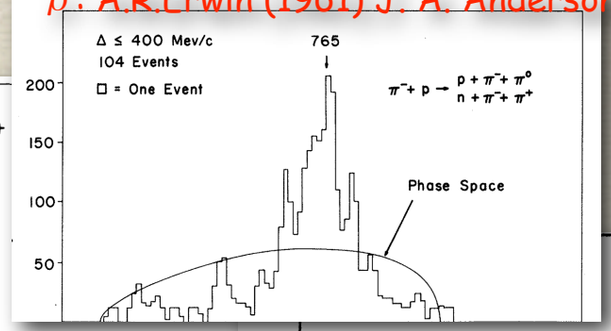

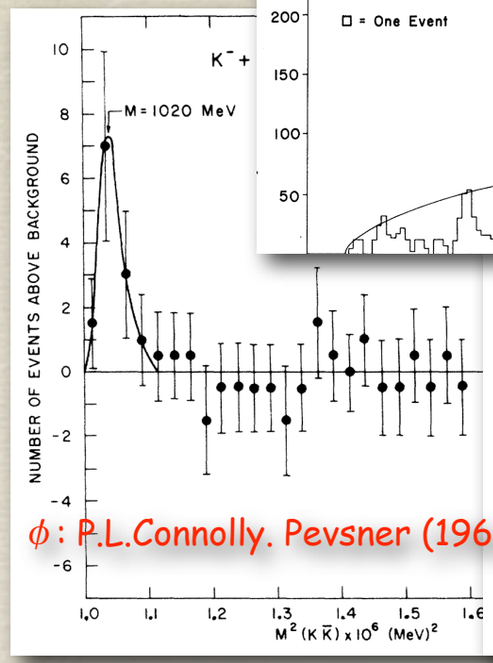

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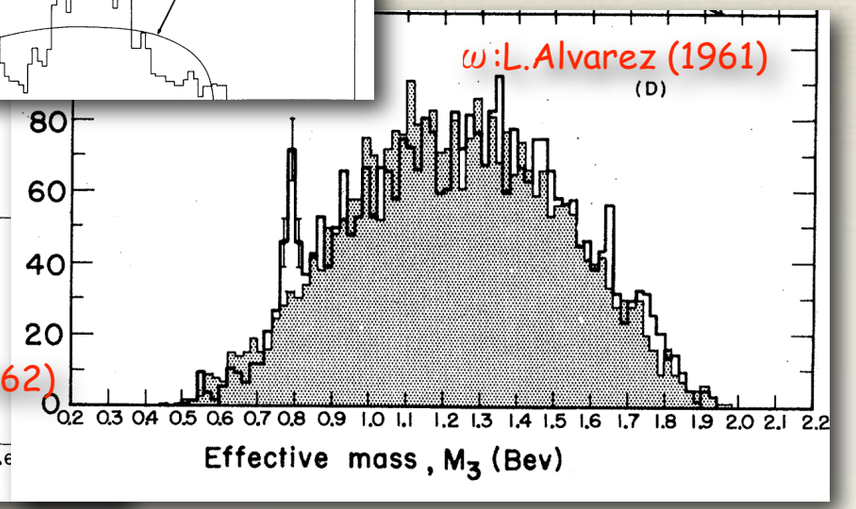
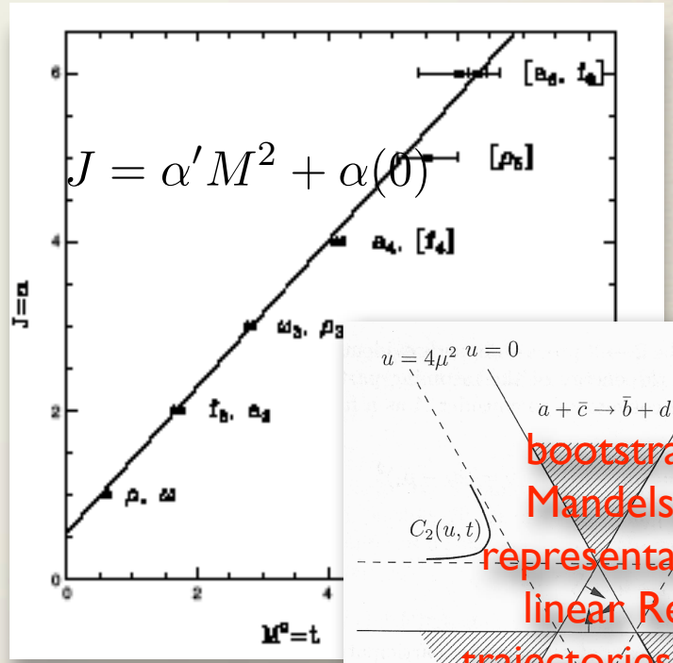


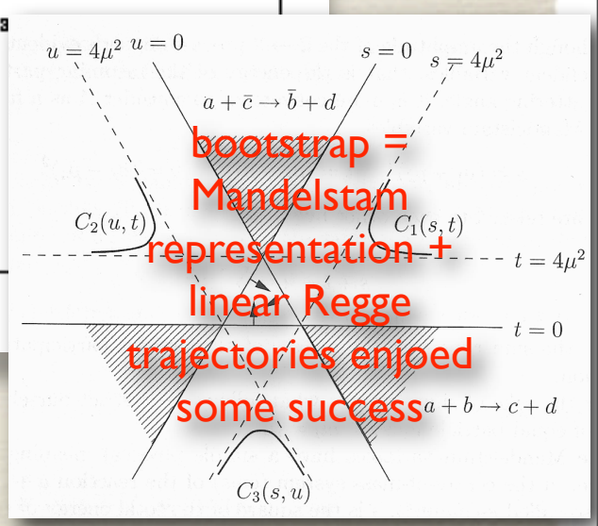
REVIEWS OF MODERN PHYSICS VOLUME 34, NUMBER 3 JULY, 1962

S-Matrix Theory of Strong Interactions without Elementary Particles*†

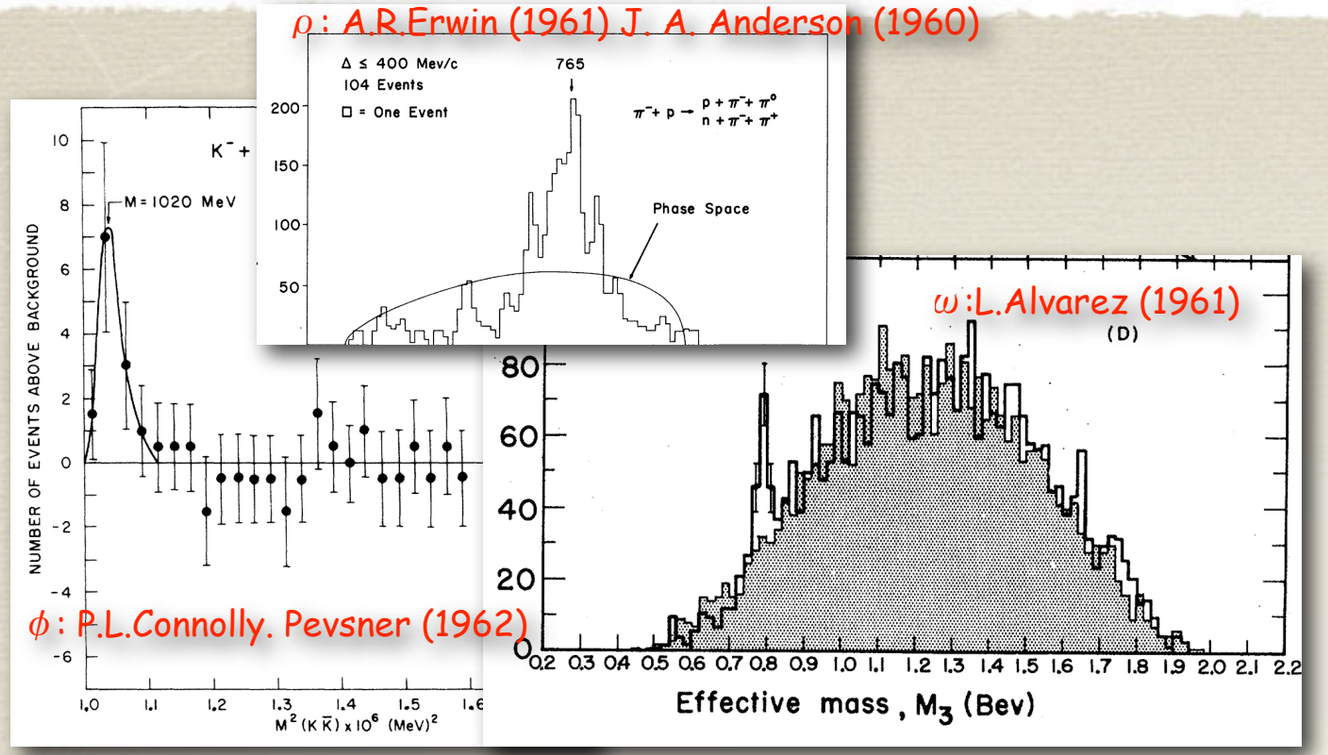
GEOFFREY F. CHEW
Department of Physics and Lawrence Radiation Laboratory, University of California, Berkeley, California

"The bootstrap manifesto"





bootstrap = Mandelstam representation + linear Regge trajectories enjoed some success



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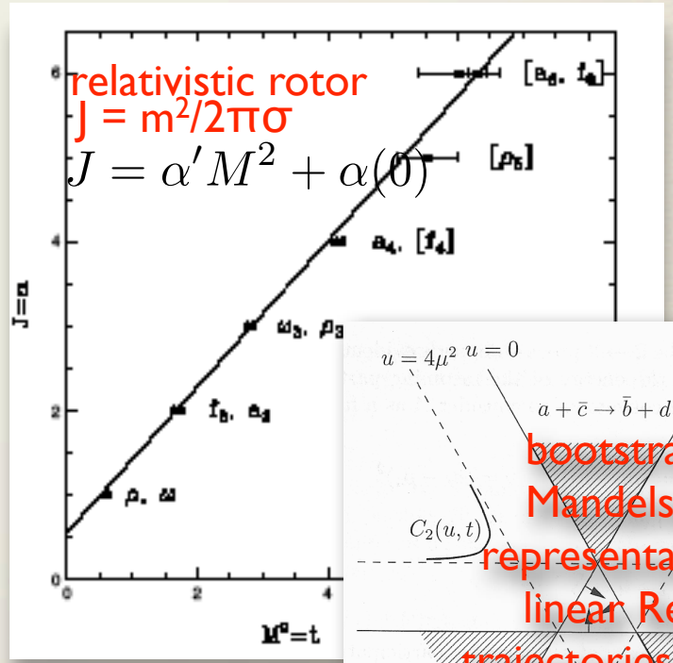

strong interactions
as a
string theory

$$A(s,t) = \frac{\Gamma(-\alpha(s))\Gamma(-\alpha(t))}{\Gamma(-\alpha(t) - \alpha(s))}$$

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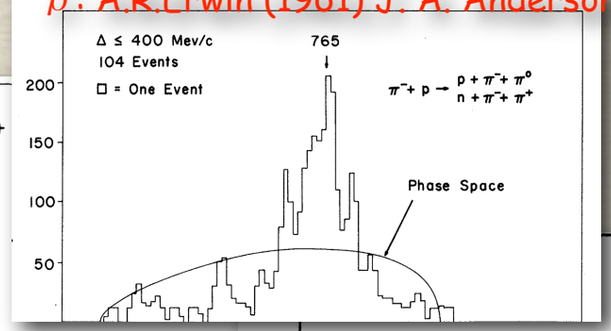

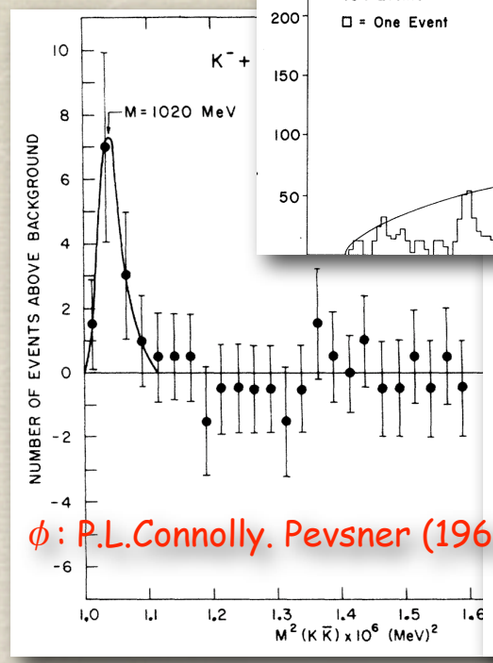

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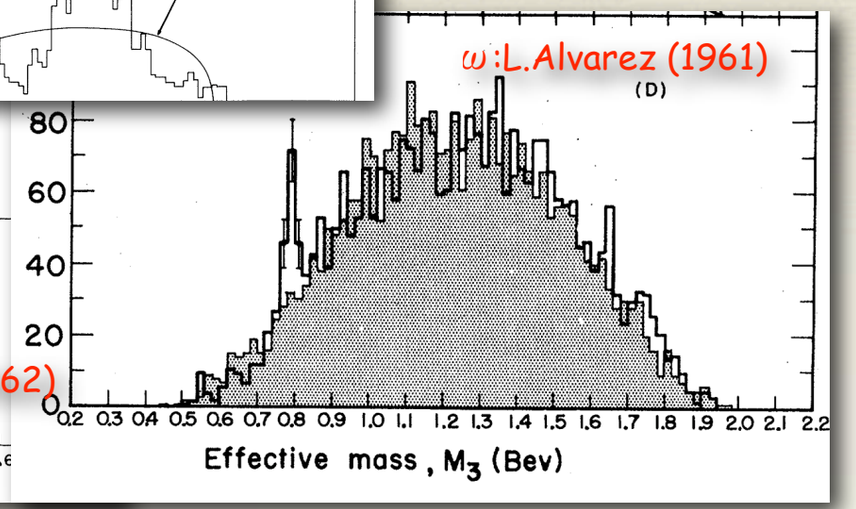

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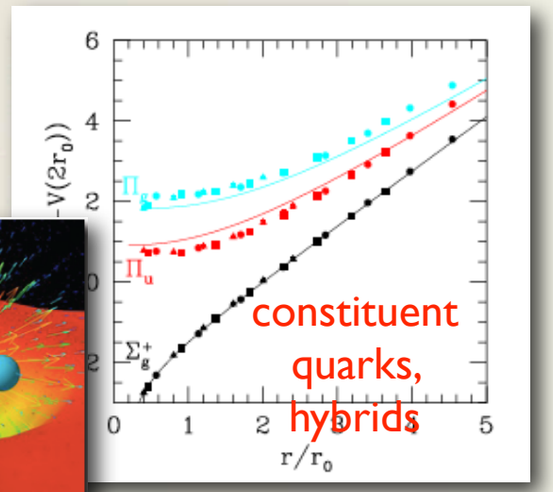
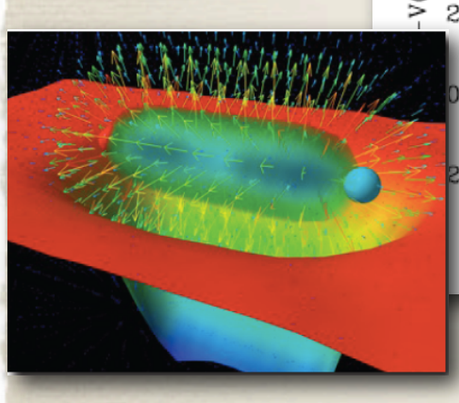


constituent quarks, hybrids

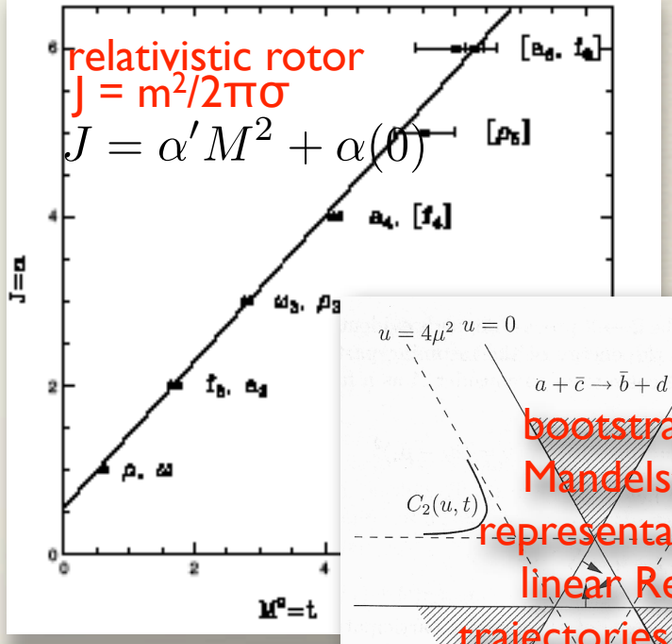


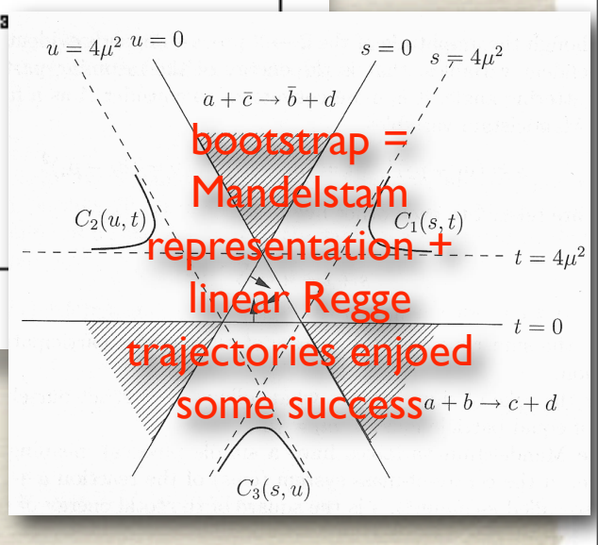
strong interactions as a string theory

Polyakov, Wilson: loop theory

AdS/CFT

relativistic rotor
$J = m^2/2\pi\sigma$
$J = \alpha' M^2 + \alpha(0)$





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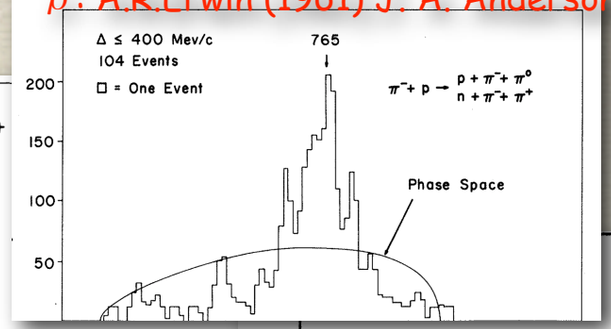

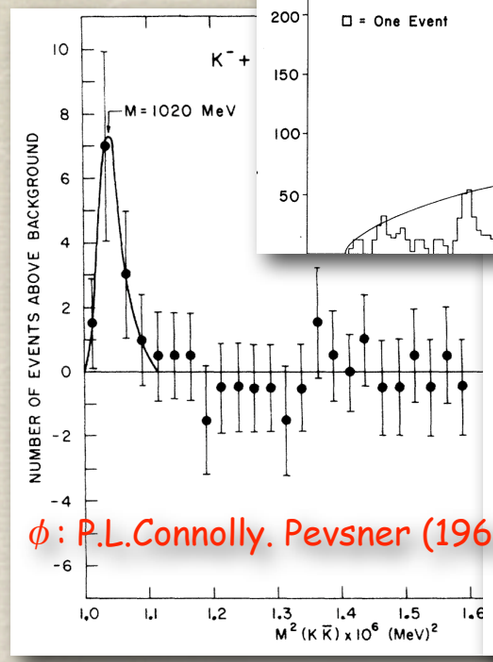

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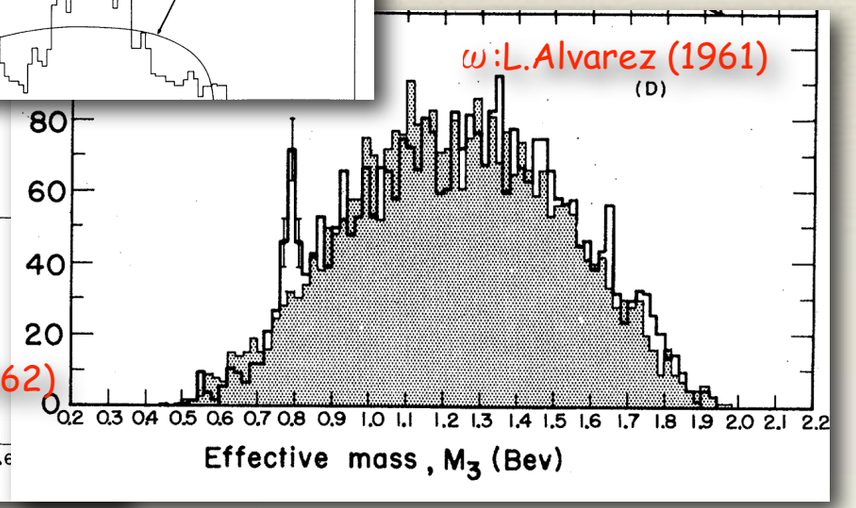

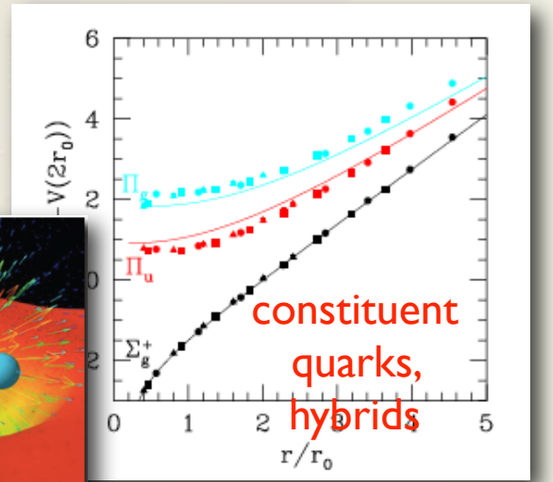

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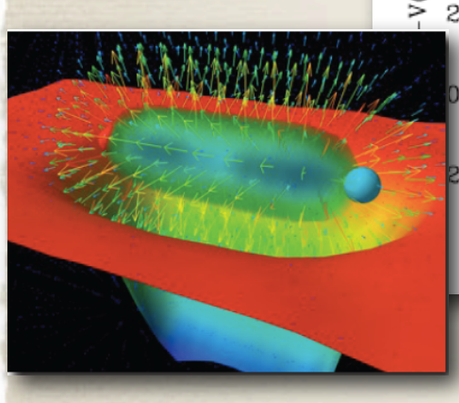

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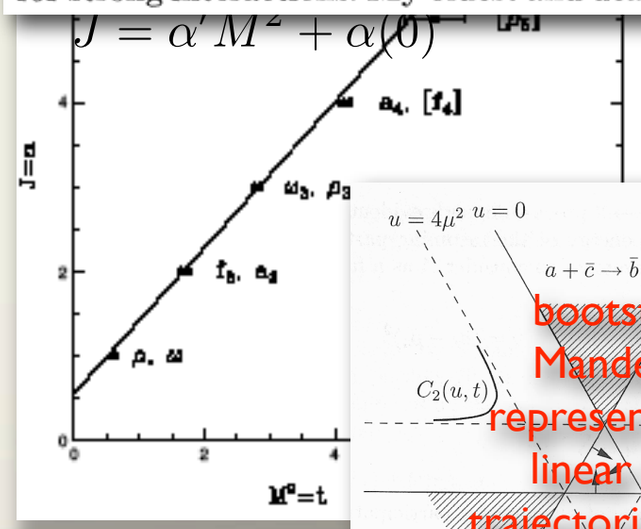
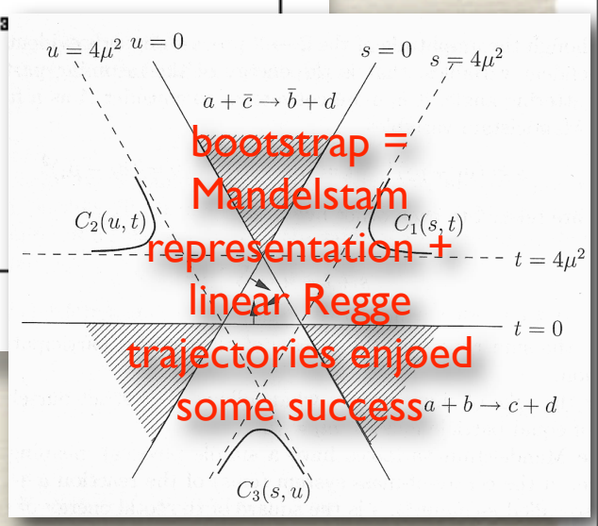
1. INTRODUCTION

IN this paper I present an indecently optimistic view of strong interaction theory. My belief is that a major breakthrough has occurred and that within a relatively short period we are going to achieve a depth of understanding of strong interactions that a few years ago I, at least, did not expect to see within my lifetime. I know that few of you will be convinced by the arguments given here, but I would be masking my feelings if I were to employ a conventionally cautious attitude in this talk. I am bursting with excitement, as are a number of other theorists in this game.

I present my view of the current situation entirely in terms of the analytically continued S matrix, because there is no other framework that I understand for strong interactions. My oldest and dearest friends





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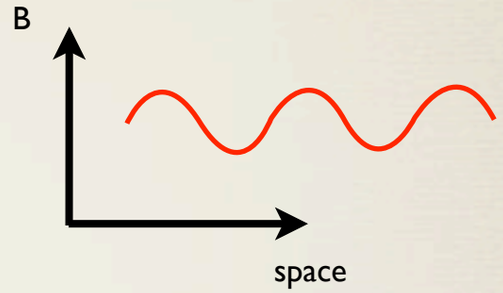
- QED (at the atomic scale)

weakly interacting photons +
non-relativistic charges

Vacuum fields : Coulomb potential
+ (de-coupled) harmonic oscillators

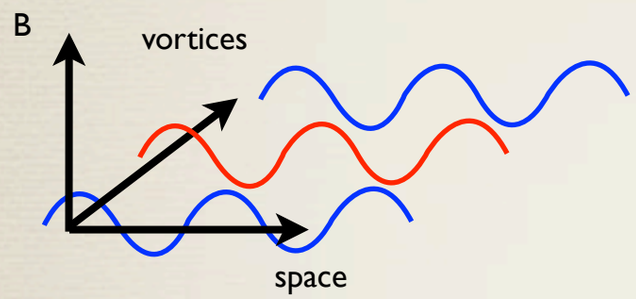


Conventional bound states (atoms):
radiation coupled
$|H\rangle = |e^+ p\rangle|\gamma\rangle$

- QCD (at the nuclear scale)

self-interacting gluons with strong coupling + relativistic (light) or non-relativistic (c,b) quarks

Vacuum fields : Confined Coulomb potential + (coupled) magnetic charges (monopoles,vortices)



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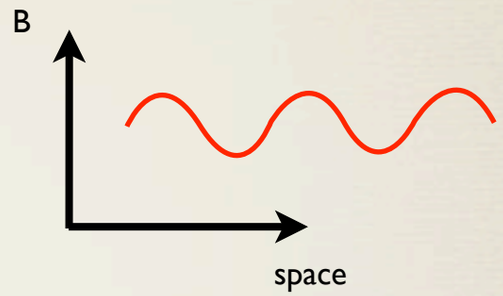
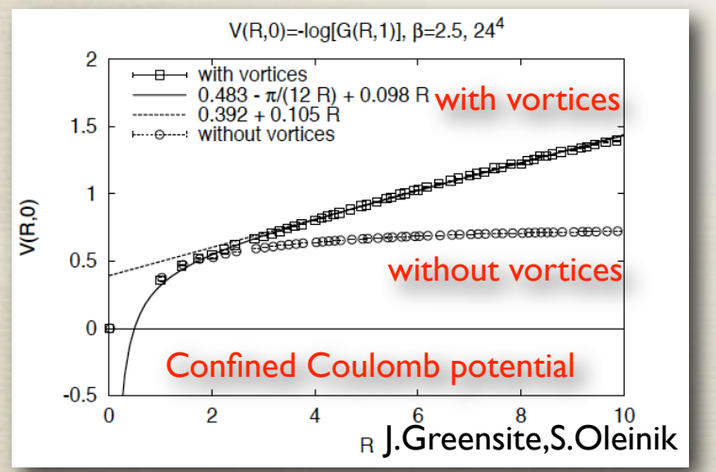


New states of matter (hadrons): radiation strongly coupled

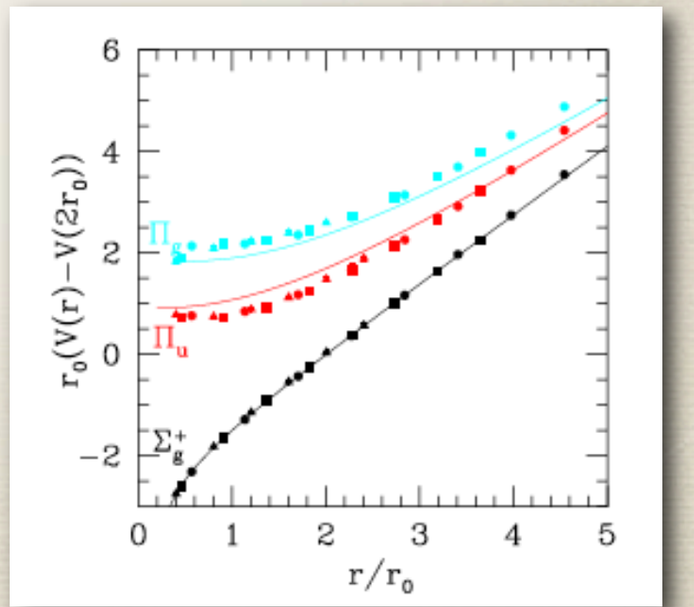
$|H\rangle = \Sigma_i |q_i\, g_i\rangle$



Heavy quarkonia: Confined Coulomb + excited glue (quark model template)

Conventional bound states (atoms): radiation coupled

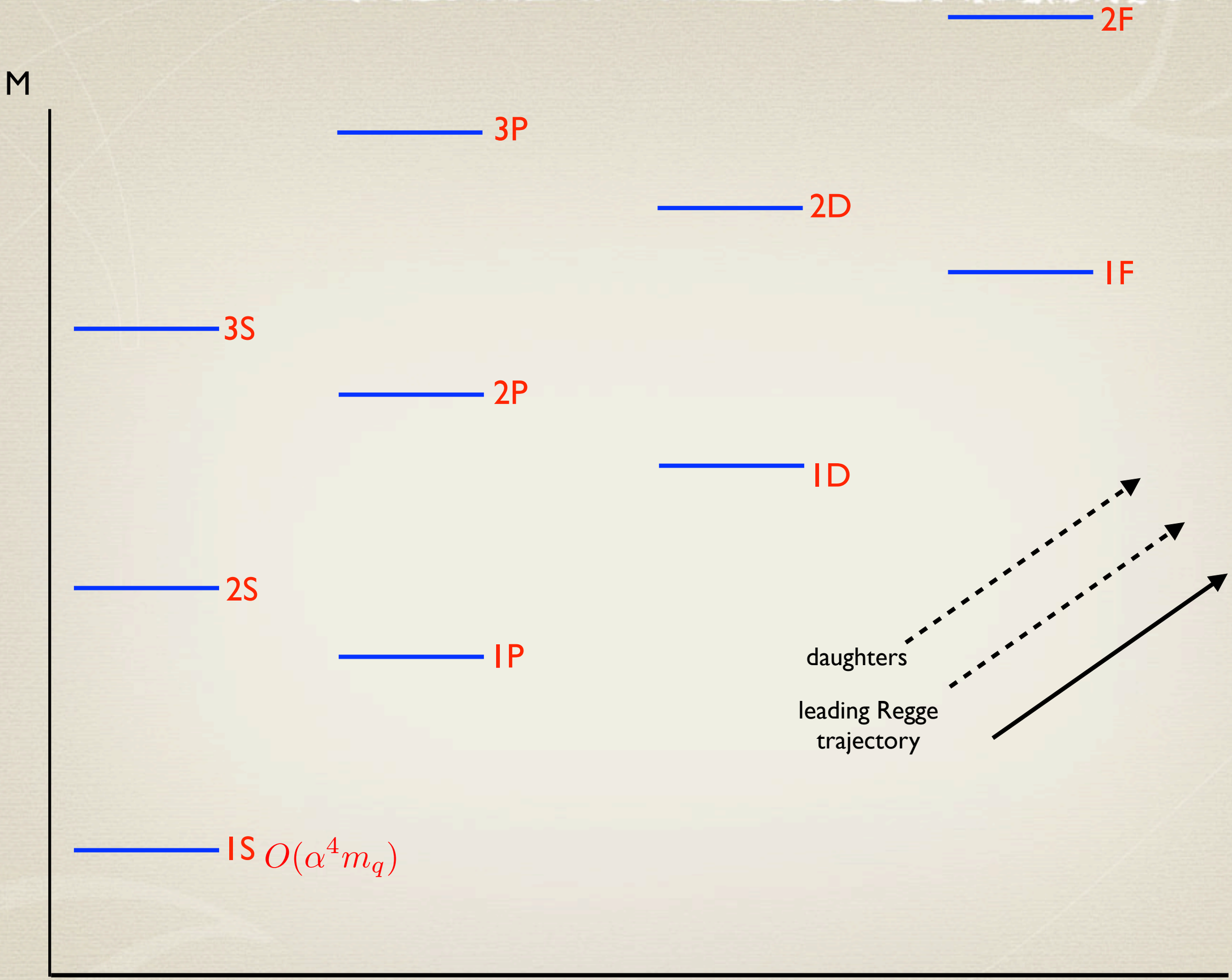
$|H\rangle = |e^+ p\rangle|\gamma\rangle$



Features of the Hadron Spectrum: Charmonium

- ☑ quark model template ⇢ ground state flux tube dominates
- ☑ hybrid candidate X(4260) ⇢ sign of excited glue
- ☑ molecular ($D\bar{D}^*$) candidate X(3872) ⇢ residual hadronic forces
- ☑ possible extra states M=3900 - 4200 ⇢ ?
- ☑ charged charmonia M=4000 - 4500 (aka tetraquarks) ⇢ ???

Christopher Hearty (BaBar)
(Hadron Spectroscopy, Friday)


M
2F
3P
2D
1F
3S
2P
1D
2S
1P
1S $O(\alpha^4 m_q)$
daughters
leading Regge trajectory

M

3P

2F

2D

1F

3S

2P

1D

2S

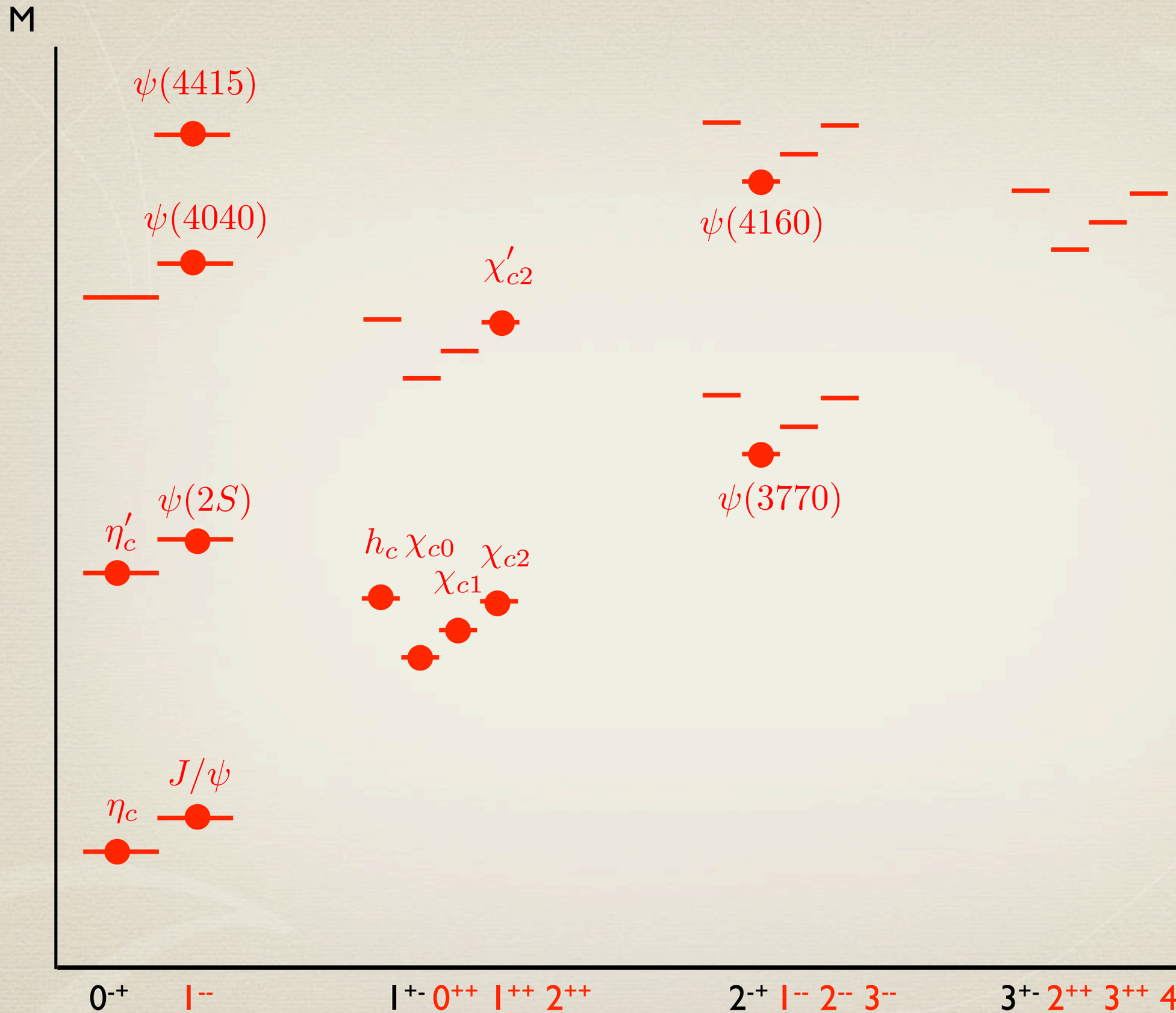
1P

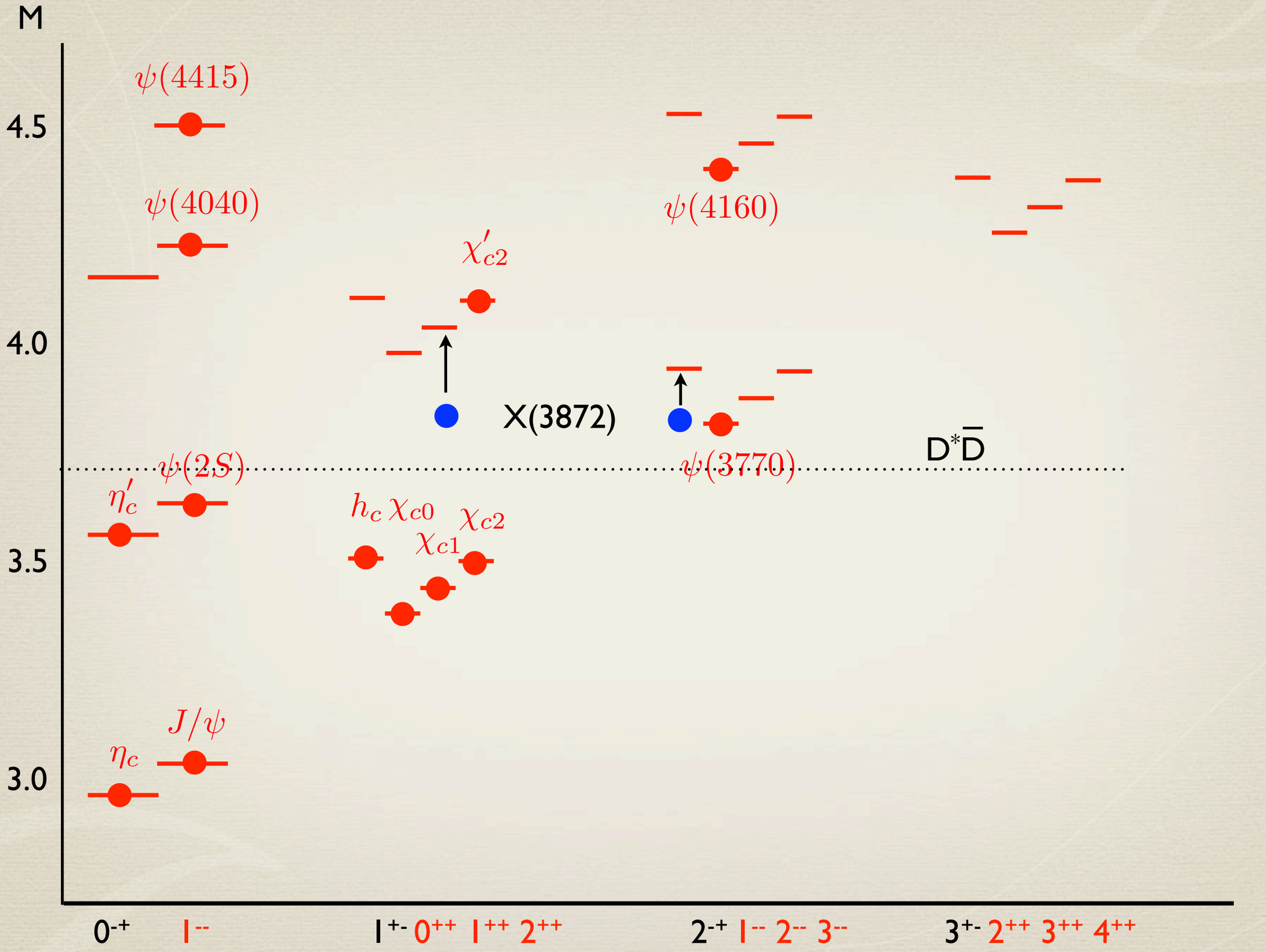
1S $O(\alpha^4 m_q)$

daughters

leading Regge trajectory

0^{-+} 1^{--} 1^{+-} 0^{++} 1^{++} 2^{++} 2^{-+} 1^{--} 2^{--} 3^{--} 3^{+-} 2^{++} 3^{++} 4^{++}


M
$\psi(4415)$
$\psi(4040)$
χ'_{c2}
$\psi(4160)$
$\psi(2S)$
η'_c
$h_c\,\chi_{c0}$
χ_{c2}
χ_{c1}
$\psi(3770)$
J/ψ
η_c
0^{-+}
1^{--}
1^{+-} 0^{++} 1^{++} 2^{++}
2^{-+} 1^{--} 2^{--} 3^{--}
3^{+-} 2^{++} 3^{++} 4^{++}


M
4.5
4.0
3.5
3.0
$\psi(4415)$
$\psi(4040)$
χ'_{c2}
$\psi(4160)$
X(3872)
$\psi(3770)$
D*D̄
$\psi(2S)$
η'_c
h_c χ_{c0}
χ_{c1}
χ_{c2}
J/ψ
η_c
0-+ 1-- 1+- 0++ 1++ 2++ 2-+ 1-- 2-- 3-- 3+- 2++ 3++ 4++

M

4.5

4.0

3.5

3.0

$\psi(4415)$

$\psi(4040)$

χ'_{c2}

X(4260)

$\psi(4160)$

X(3872)

$\psi(2S)$

$\psi(3770)$

$D^*\bar{D}$

η'_c

h_c χ_{c0} χ_{c2} χ_{c1}

J/ψ

η_c

0^{-+} 1^{--} 1^{+-} 0^{++} 1^{++} 2^{++} 2^{-+} 1^{--} 2^{--} 3^{--} 3^{+-} 2^{++} 3^{++} 4^{++}

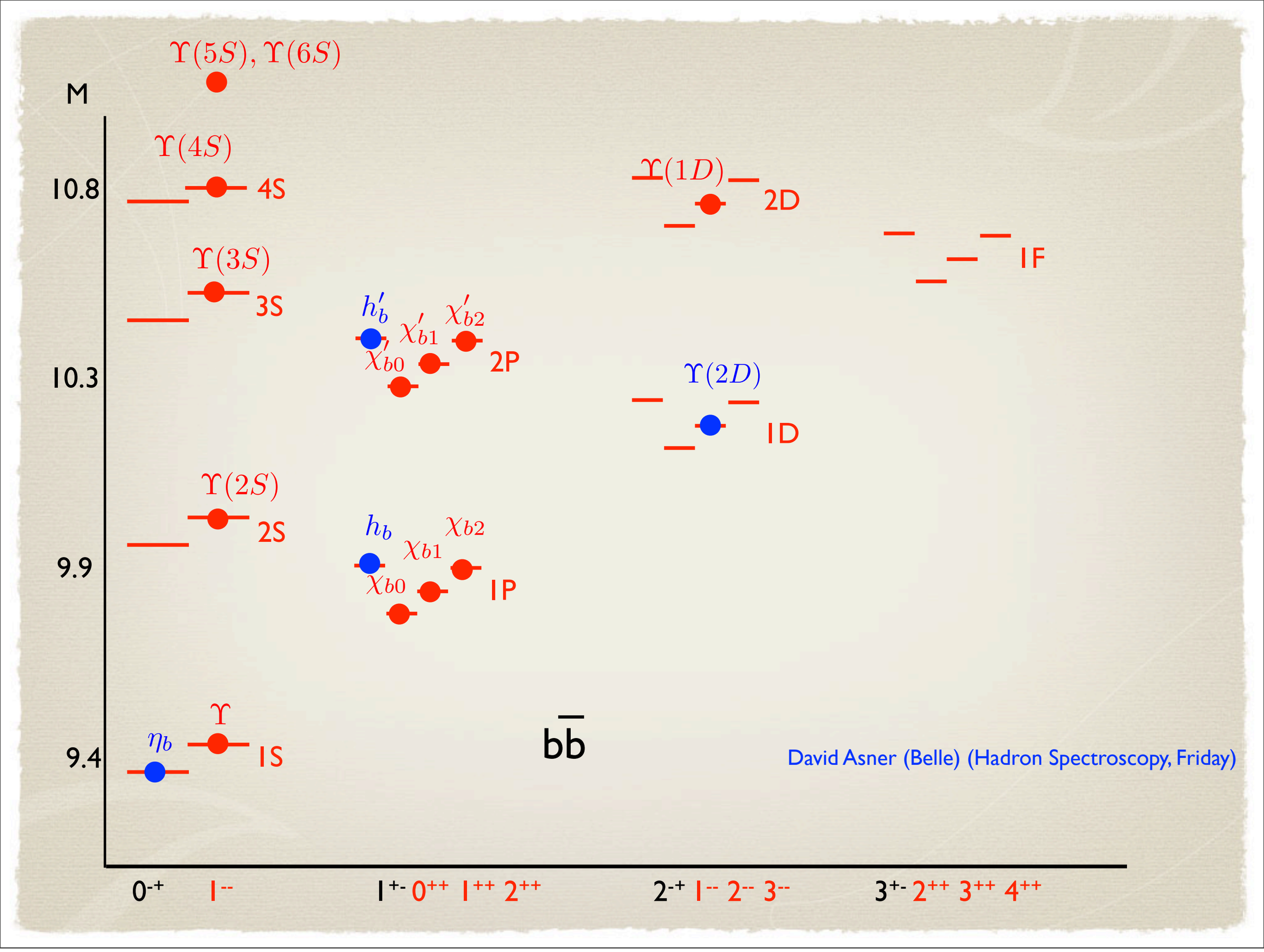
PDG'11

c c MESONS

$\eta_c(1S)$	$0^+(0^{-+})$	• $X(3915)$	$0^+(?^{?+})$	• $X(4350)$	$0^+(?^{?+})$
$J/\psi(1S)$	$0^-(1^{--})$	$\chi_{c2}(2P)$	$0^+(2^{++})$	• $X(4360)$	$?^?(1^{--})$
$\chi_{c0}(1P)$	$0^+(0^{++})$	• $X(3940)$	$?^?(?^{??})$	$\psi(4415)$	$0^-(1^{--})$
$\chi_{c1}(1P)$	$0^+(1^{++})$	$\psi(4040)$	$0^-(1^{--})$	• $X(4430)^\pm$	$?(?^?)$
$h_c(1P)$	$?^?(1^{+-})$	• $X(4050)^\pm$	$?(?^?)$	• $X(4660)$	$?^?(1^{--})$
$\chi_{c2}(1P)$	$0^+(2^{++})$	• $X(4140)$	$0^+(?^{?+})$		
$\eta_c(2S)$	$0^+(0^{-+})$	$\psi(4160)$	$0^-(1^{--})$		
$\psi(2S)$	$0^-(1^{--})$	• $X(4160)$	$?^?(?^{??})$		
$\psi(3770)$	$0^-(1^{--})$	• $X(4250)^\pm$	$?(?^?)$		
$X(3872)$	$0^?(?^{?+})$	$X(4260)$	$?^?(1^{--})$		

• — OMITTED FROM SUMMARY TABLE

X' :10 out, 2 in

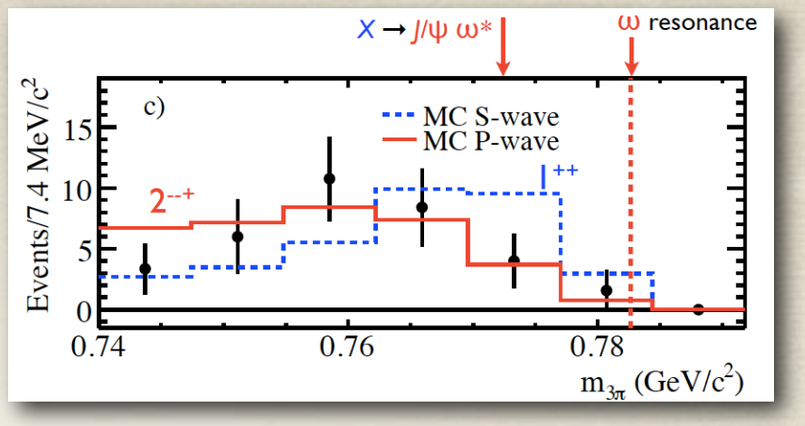


David Asner (Belle) (Hadron Spectroscopy, Friday)

- X(3872) discovered by Belle in $J/\psi\ \pi^+\pi^-$ (2003) confirmed by CDF other modes from Bell,BaBar

  mass between D^*D and $DD\pi$ thresholds O(MeV) width (1MeV)

  - if $J^{PC}=1^{++}$ then S-wave D^*D molecule (several fm)?
  - 2^{-+} (BaBar, 2010) QM ?



P.del Amo Sanchez et al., PRD82, 132002 (2010)

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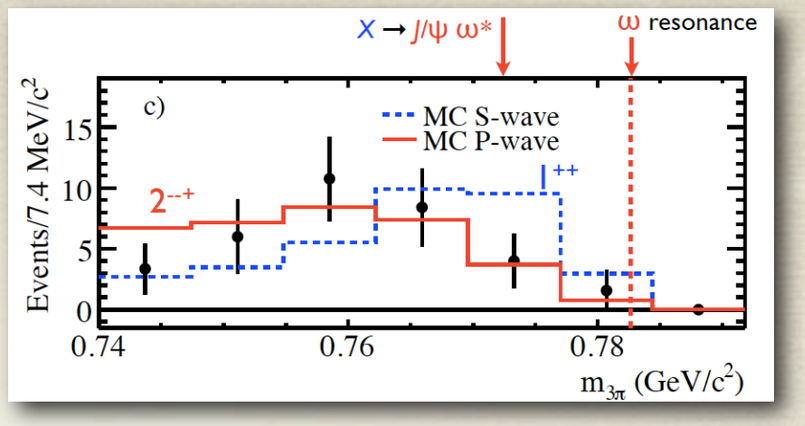
  - need radiative decays of X, 2P and 1D



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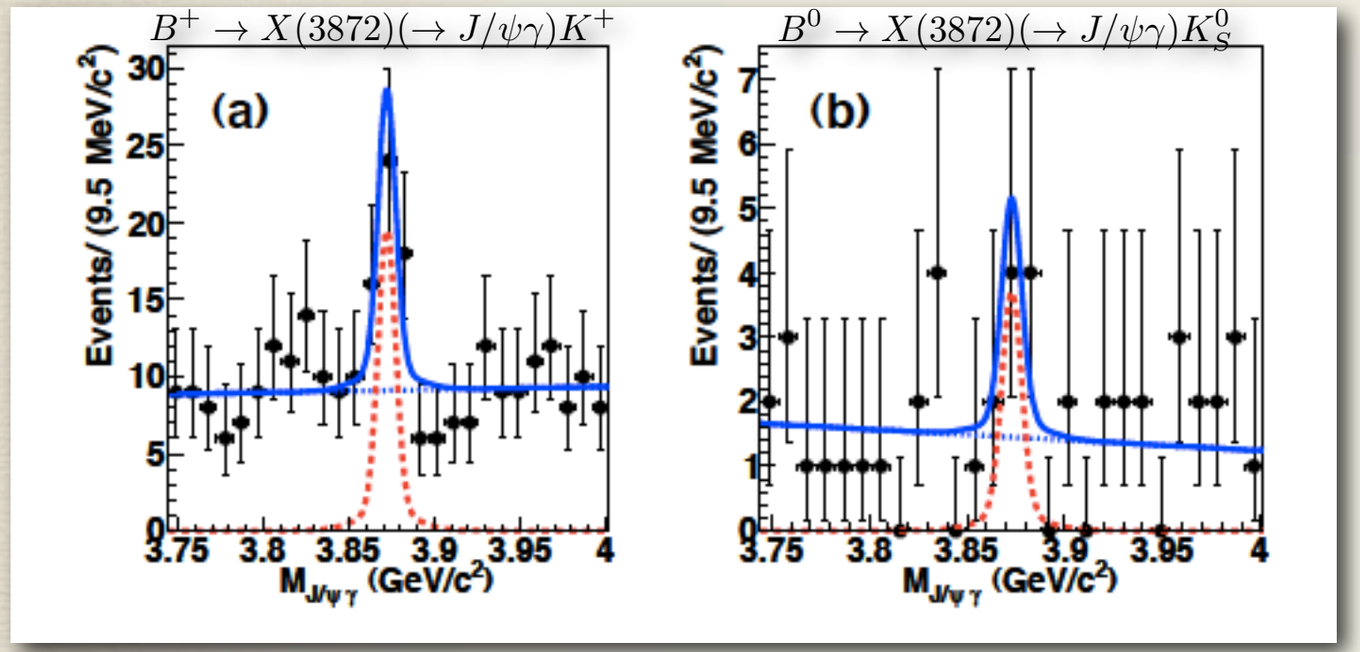
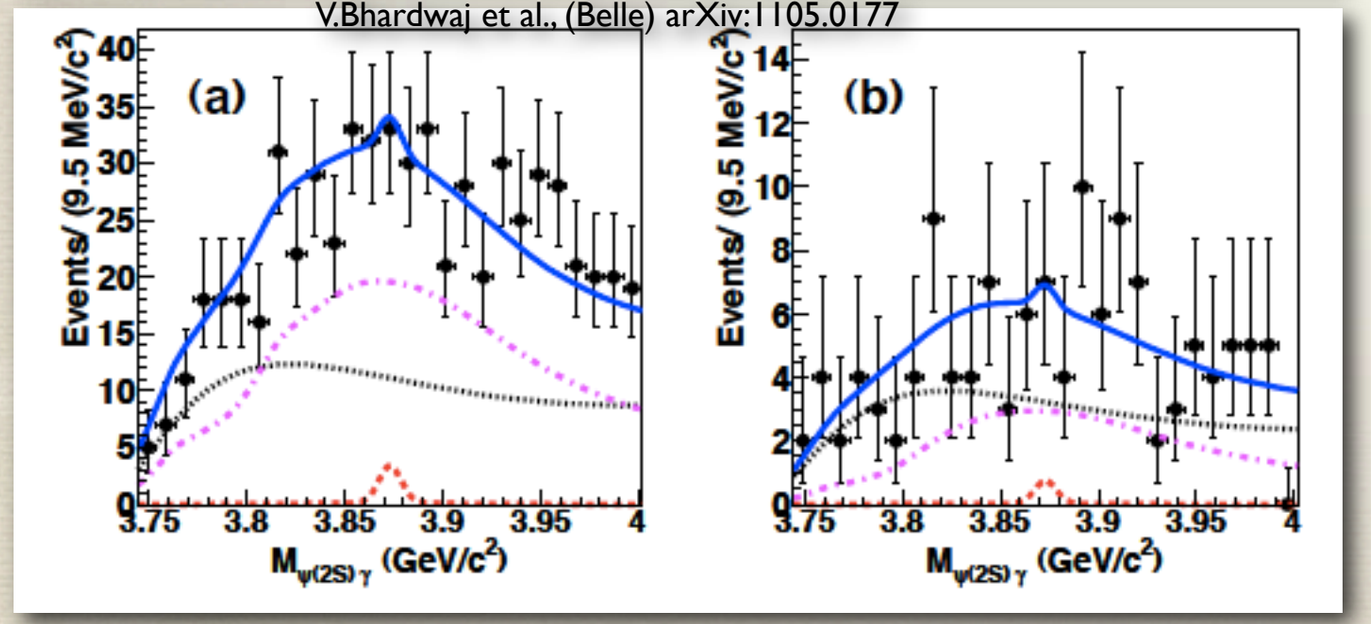
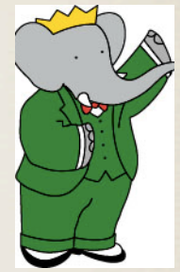


V.Bhardwaj et al., (Belle) arXiv:1105.0177



$$\mathcal{B}(B^+ \to K^+ X(3872)\mathcal{B}(X(3872) \to R\gamma), 10^{-6}$$



J/ψ	$1.78^{+0.48}_{-0.44} \pm 0.12$	$2.8 \pm 0.8 \pm 0.1$
ψ'	< 3.45	$9.5 \pm 2.7 \pm 0.6$

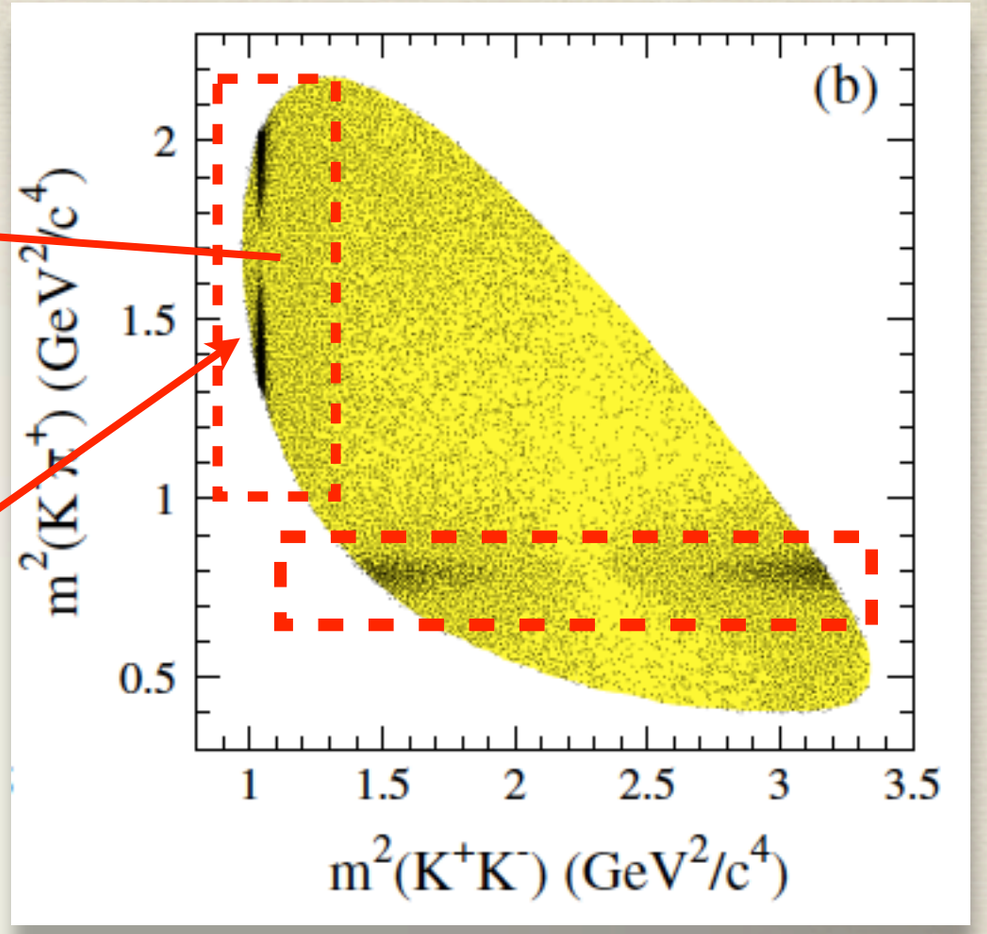
small cc component ?
The jury is still out

- if molecule then maybe closely related to the $f_0(980)$ in KK

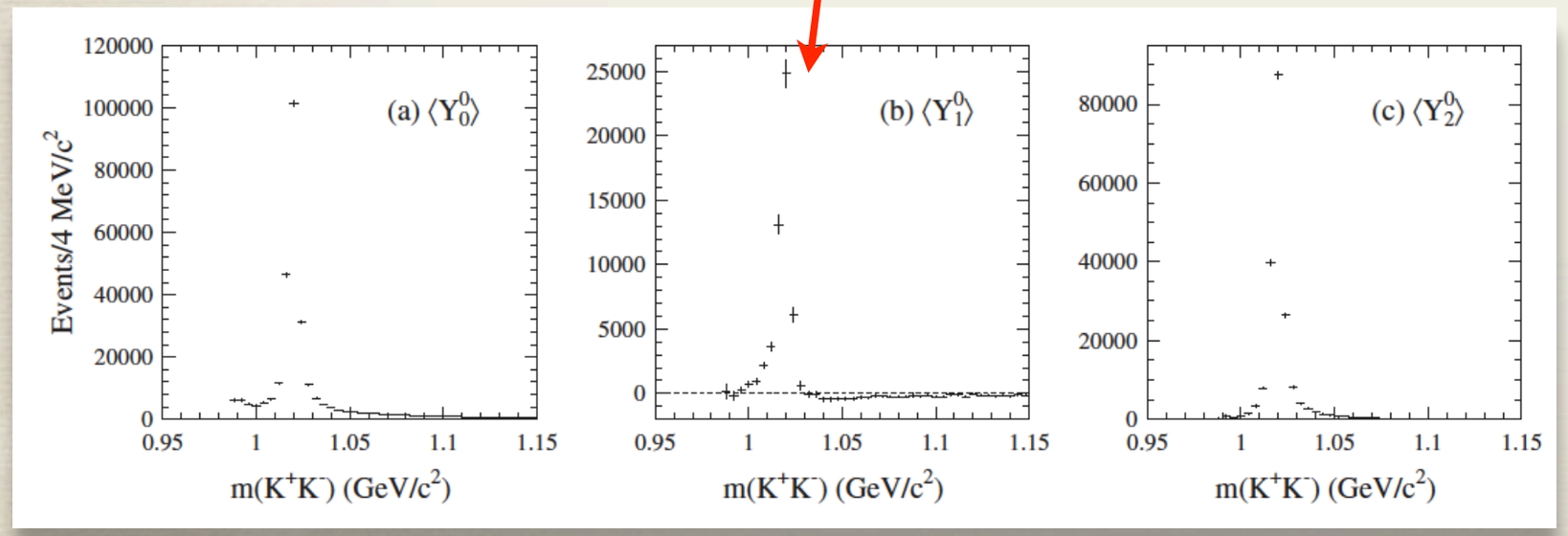
precision strong phases from weak D-decays

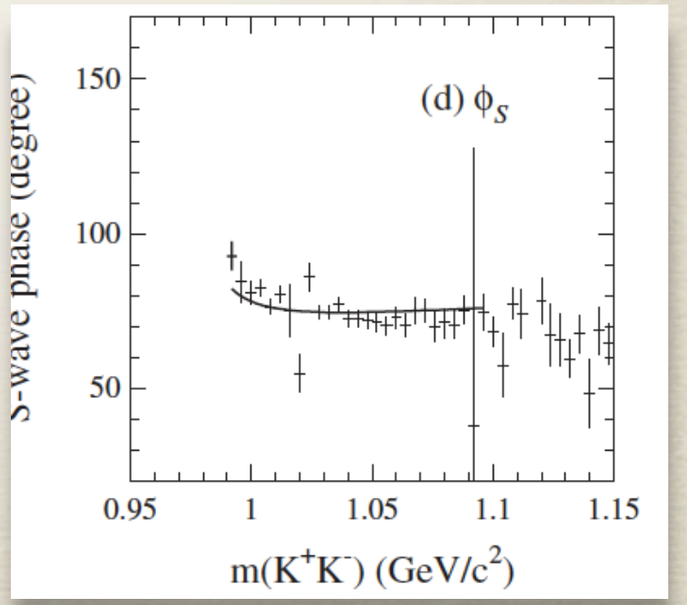
$D^+_s \to K^+K^-\pi^+$ (Babar 2011)

$$\sqrt{4\pi}\langle Y_0^0\rangle = |S|^2 + |P|^2$$
$$\sqrt{4\pi}\langle Y_2^0\rangle = \frac{2}{\sqrt{5}}|P|^2,$$
$$\sqrt{4\pi}\langle Y_1^0\rangle = 2|S||P|\cos\phi_{SP}$$



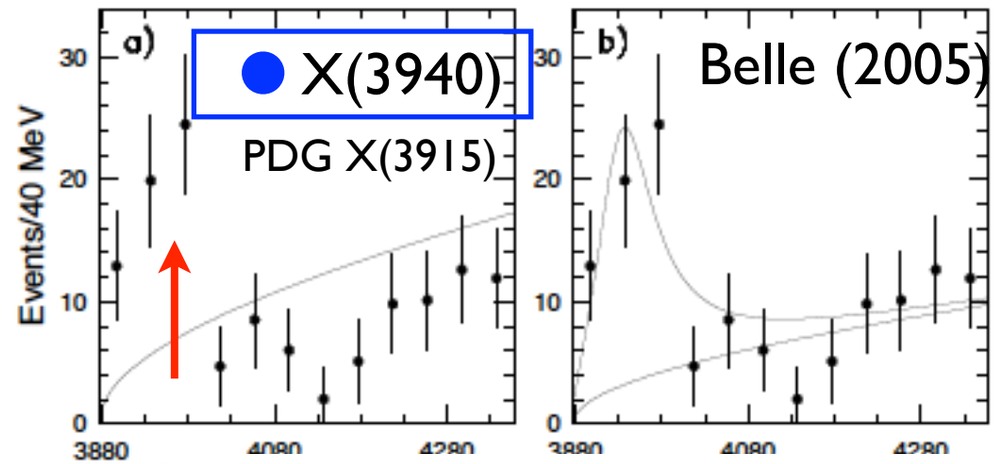
slightly "tilted" P-wave distribution due to S-wave interference



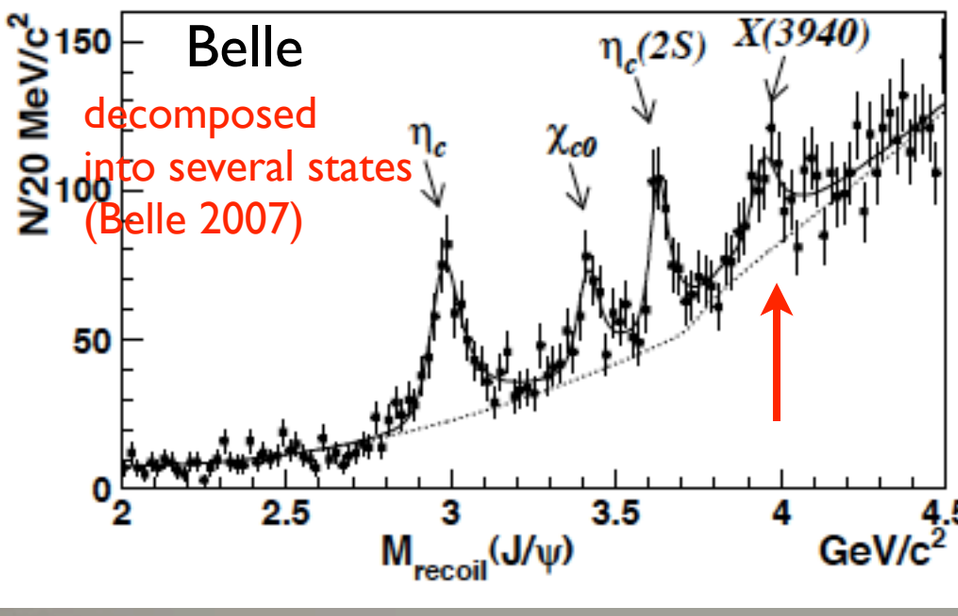


model independent determination of S-wave phase

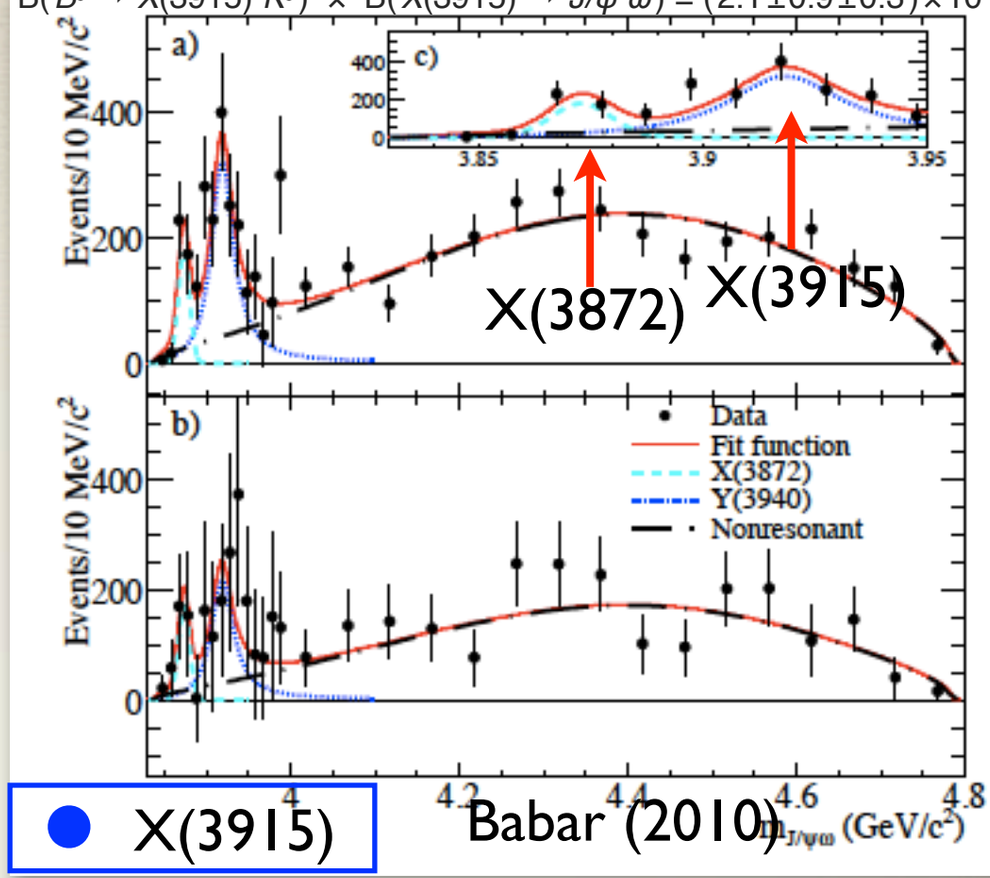
$B(B \to X(3915)\,K) \times B(X(3915) \to J/\psi\,\omega) = (7.1 \pm 1.3 \pm 3.1) \times 10^{-5}$.



M(J/ψω)



$B(B^{\pm} \to X(3915)\,K^{\pm}) \times B(X(3915) \to J/\psi\,\omega) = (3.0^{+0.7}_{-0.6}{}^{+0.5}_{-0.3}) \times 10^{-5}$,
$B(B^0 \to X(3915)\,K^0) \times B(X(3915) \to J/\psi\,\omega) = (2.1 \pm 0.9 \pm 0.3) \times 10^{-5}$.

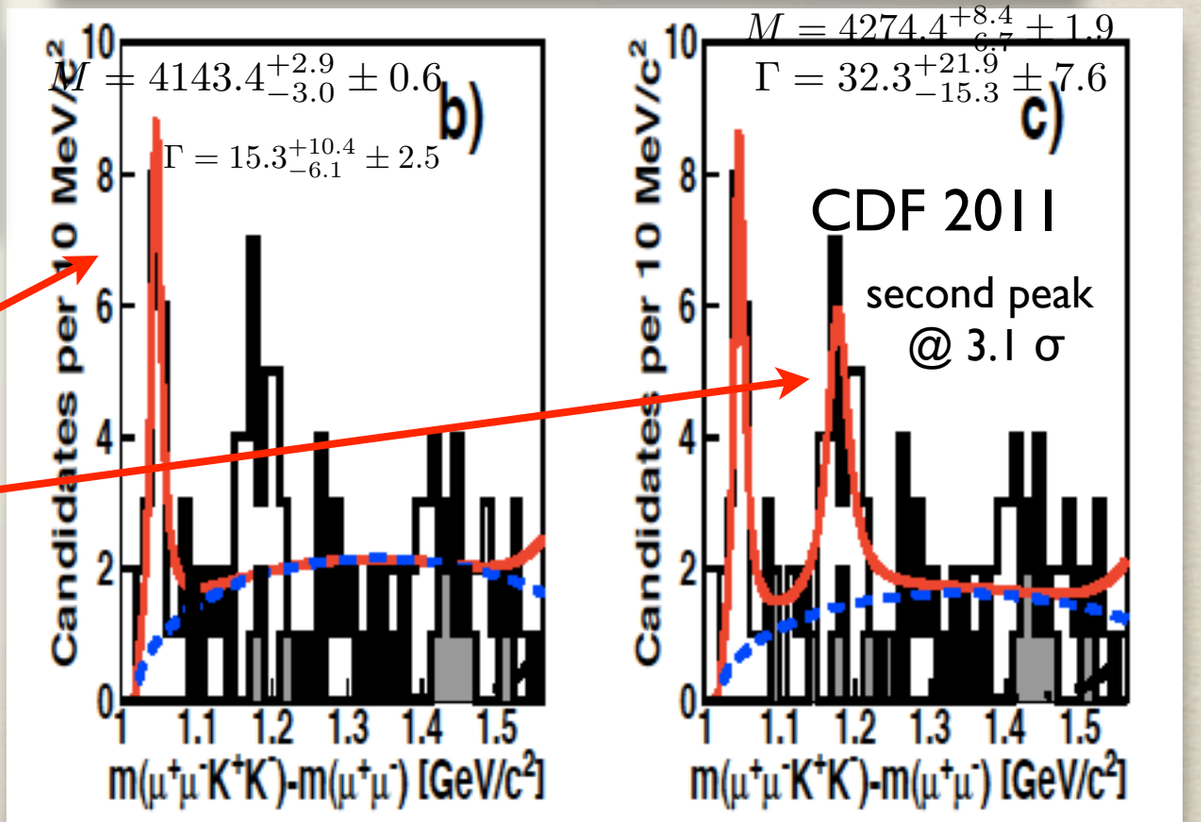


$c\bar{c}s\bar{s}$ candidate

Y(4140)

M=3900 - 4200
range

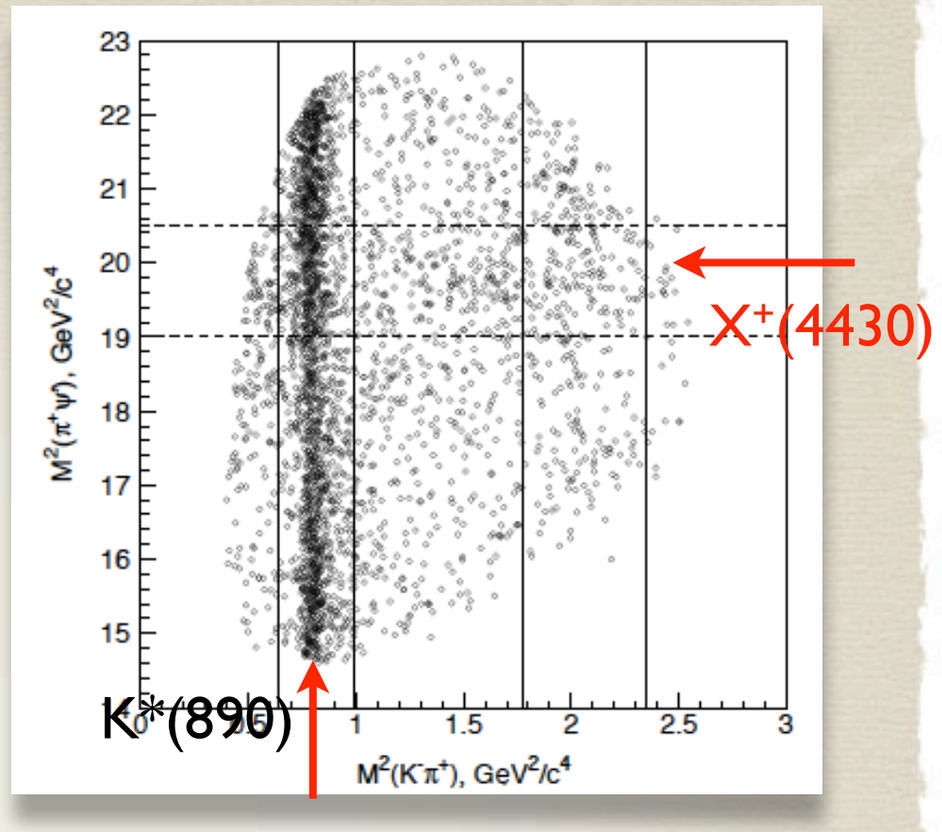
not seen in Belle
(and possible Y(4275)



$$\mathcal{B}(B^+ \to Y(4140)K^+)/\mathcal{B}(B^+ \to J/\psi\phi K^+) = 0.149 \pm 0.039 \pm 0.024$$

- $X^{\pm}$ (4430) Belle (2009) $\bar{B}^0 \to K^-(\psi'\pi^+), B^+ \to K^0_s(\psi'\pi^+)$

  not seen in BaBar (also in $J/\psi\,\pi^-$)



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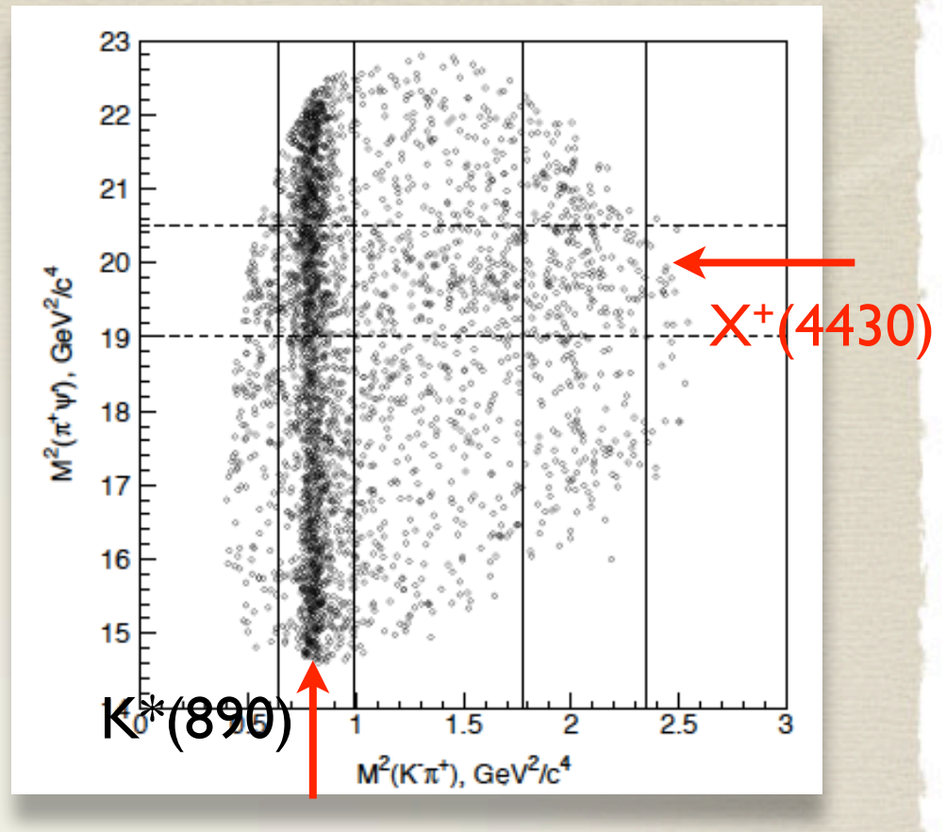

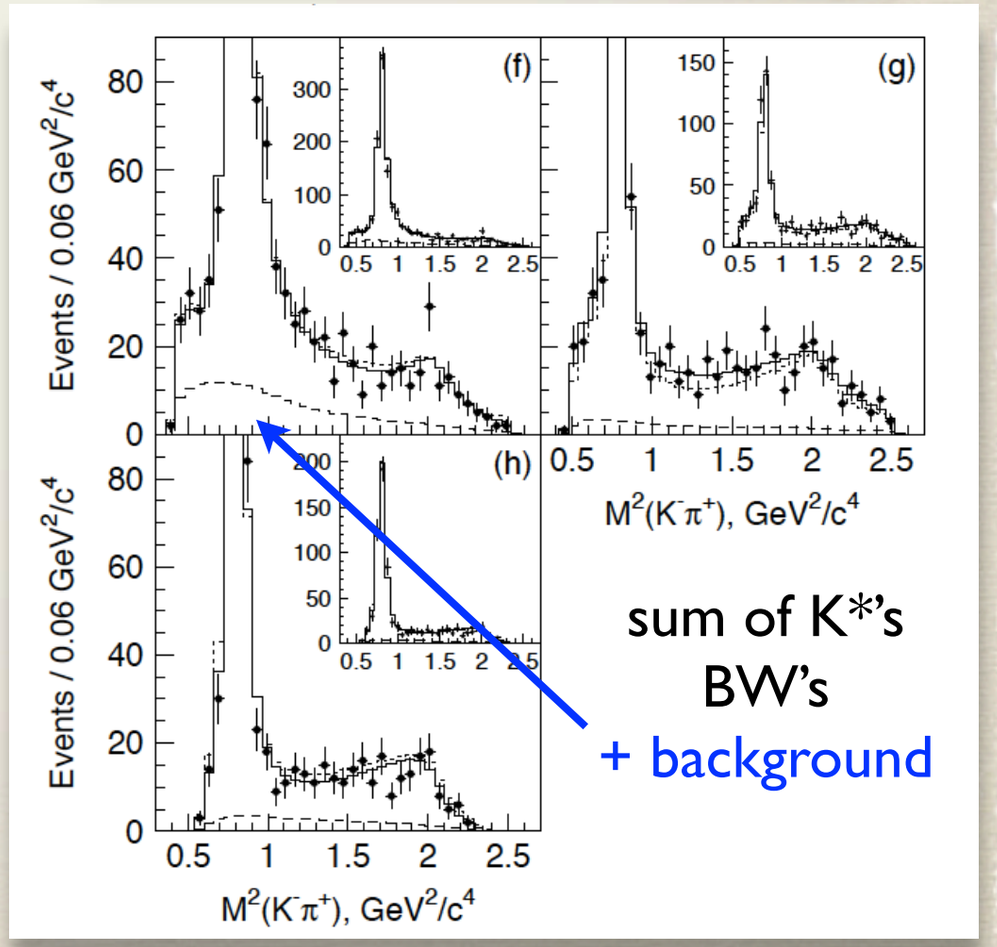

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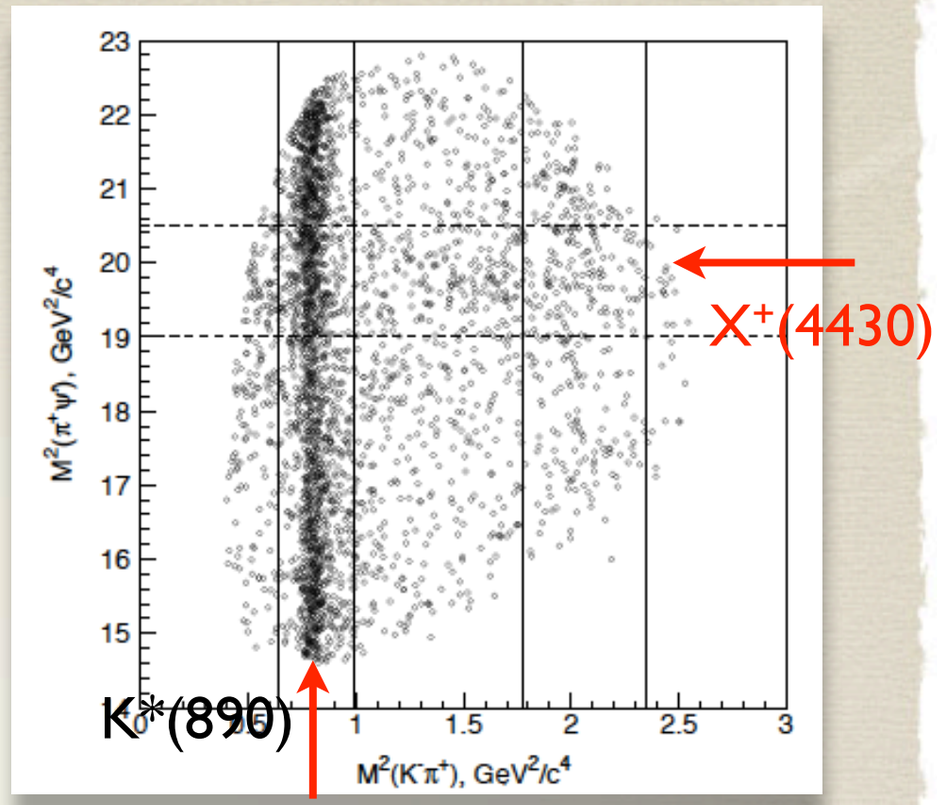

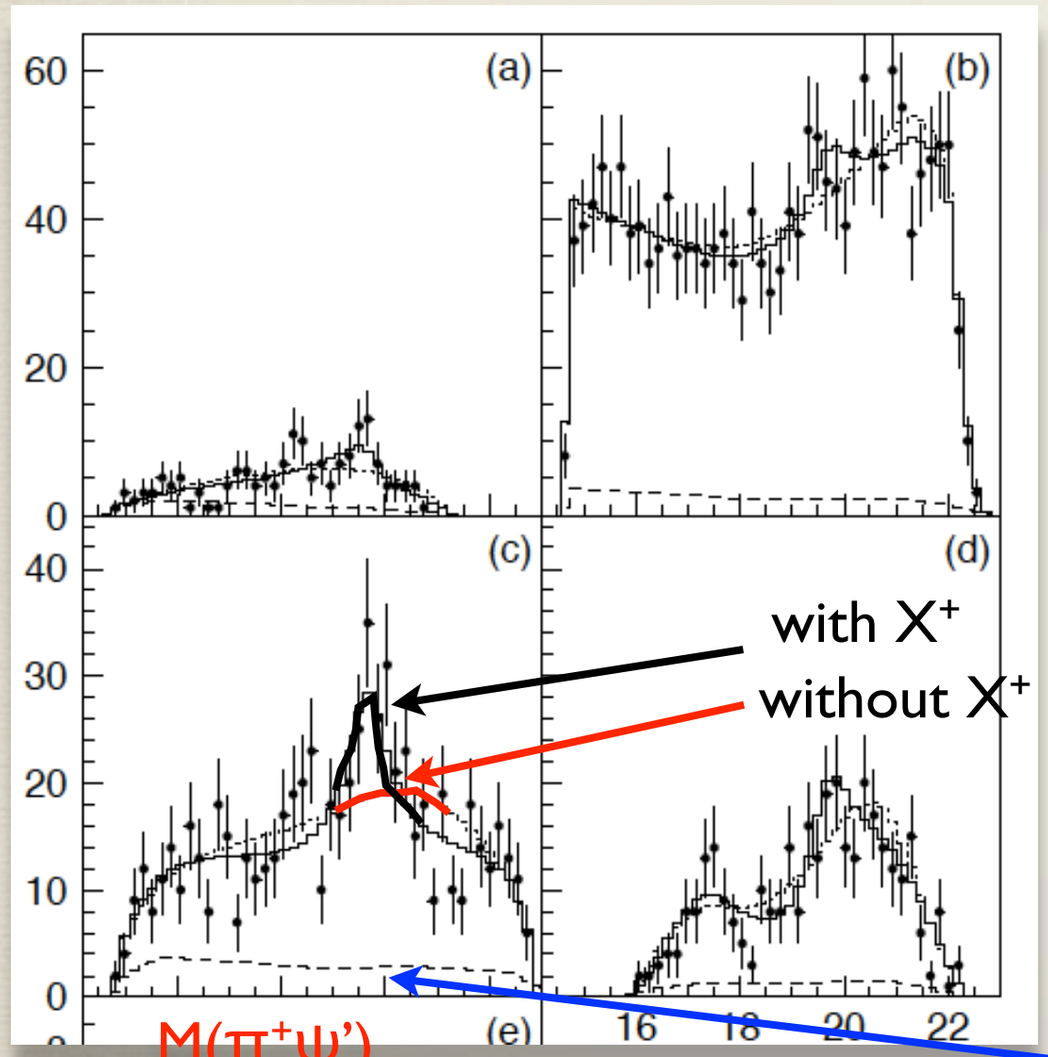

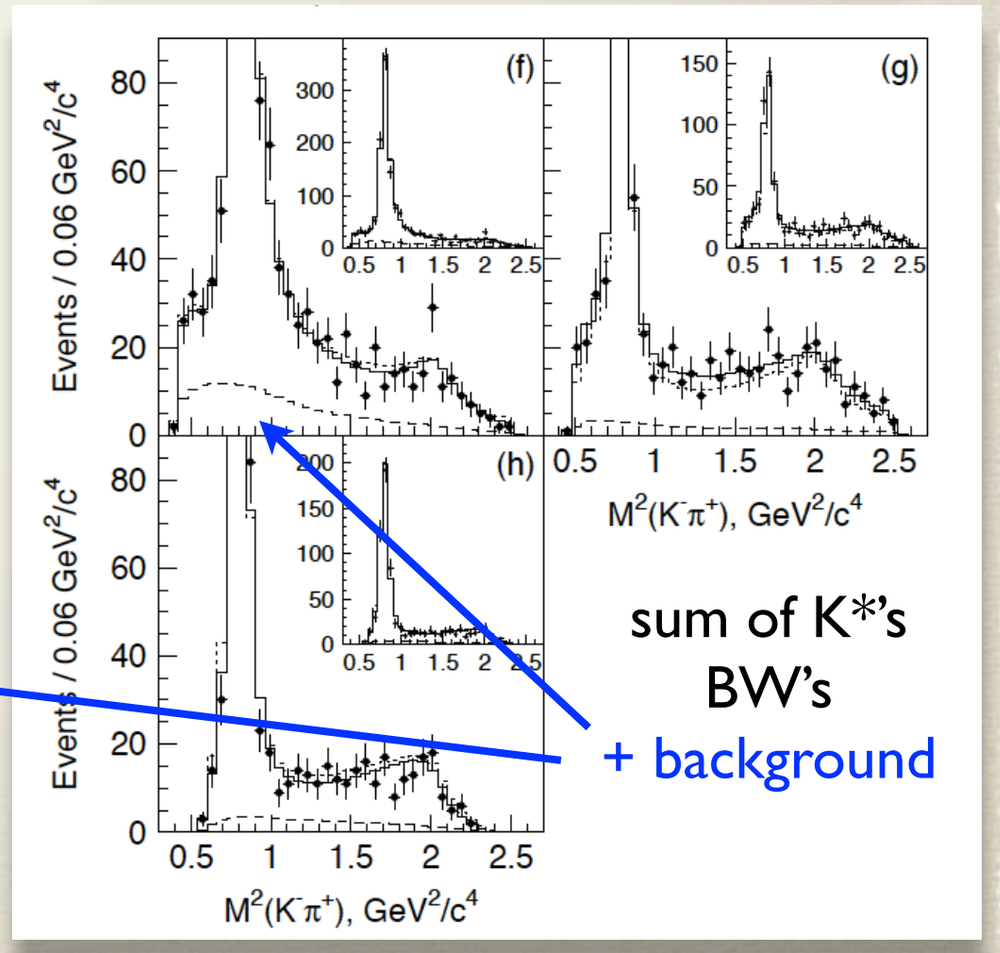

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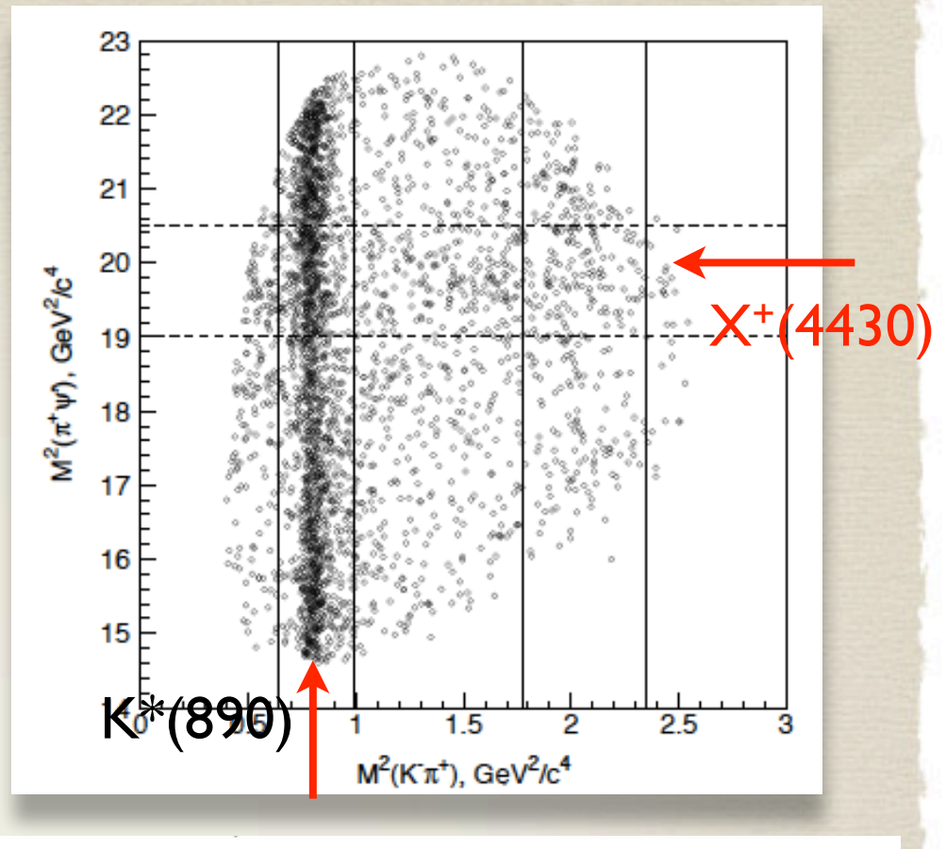
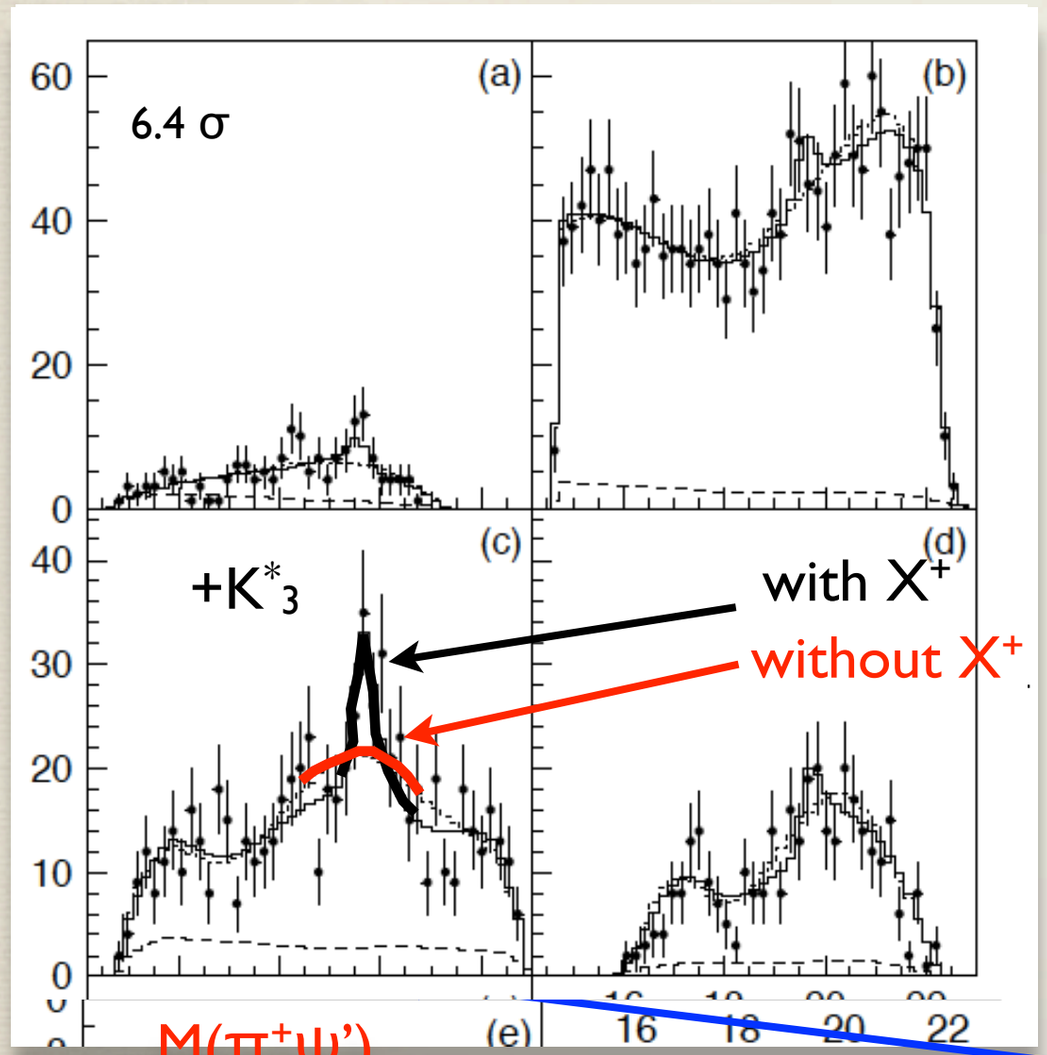
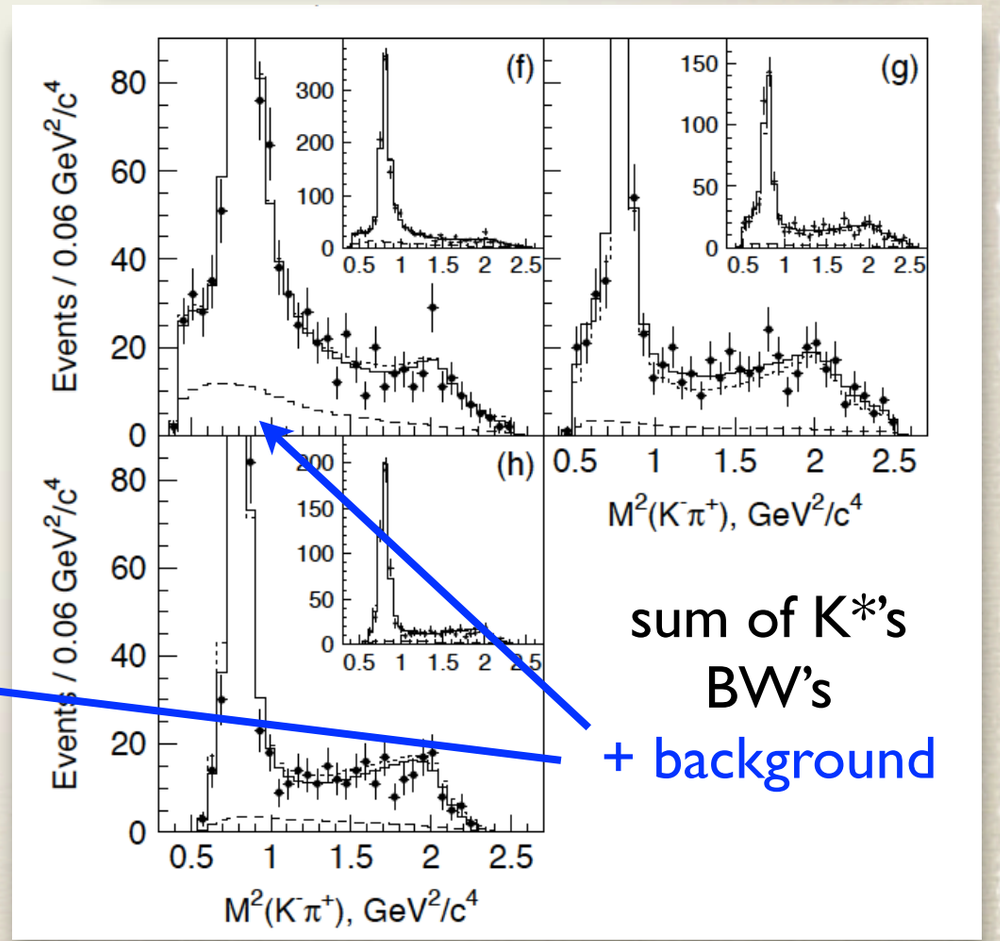
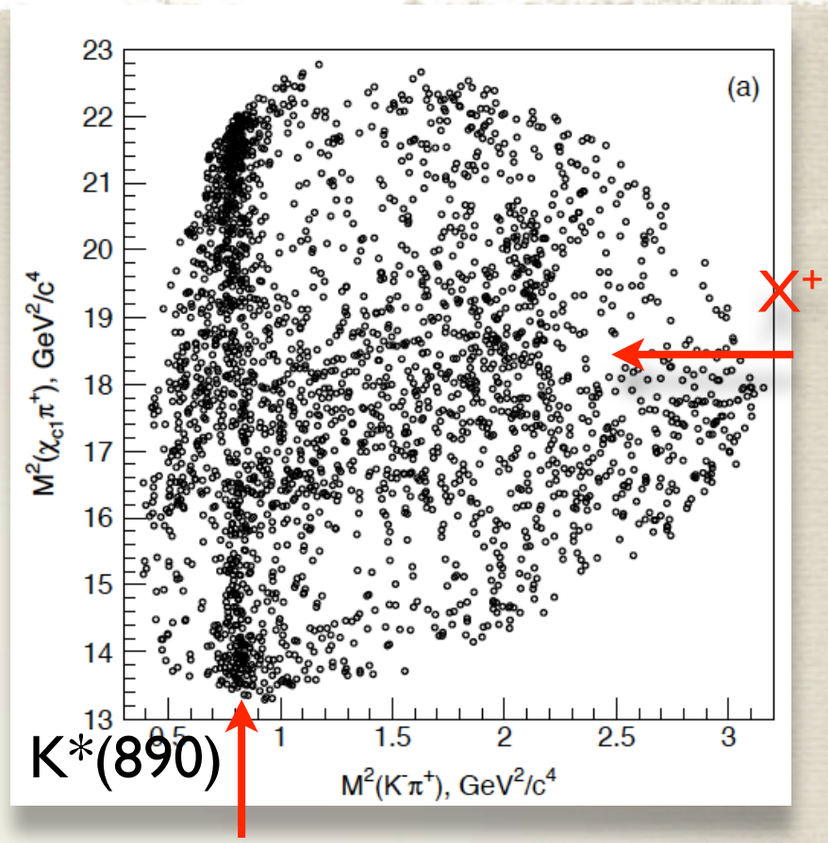






- X^+ (4050,4250) Belle (2009) $\overline{B}^0 \rightarrow K^-(\chi_{c1}\pi^+)$



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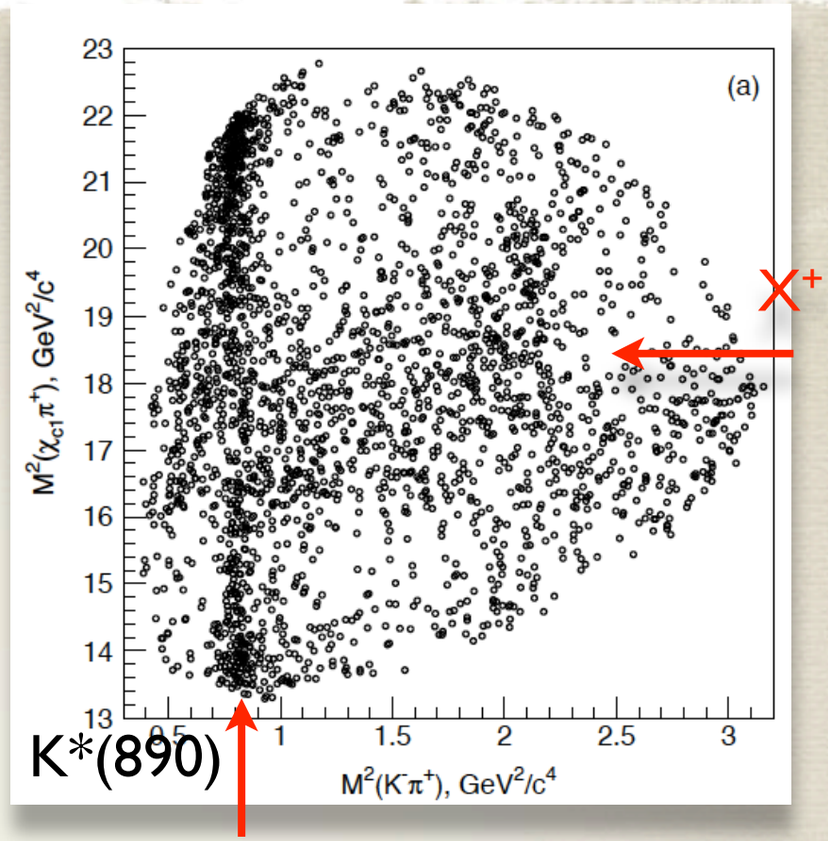

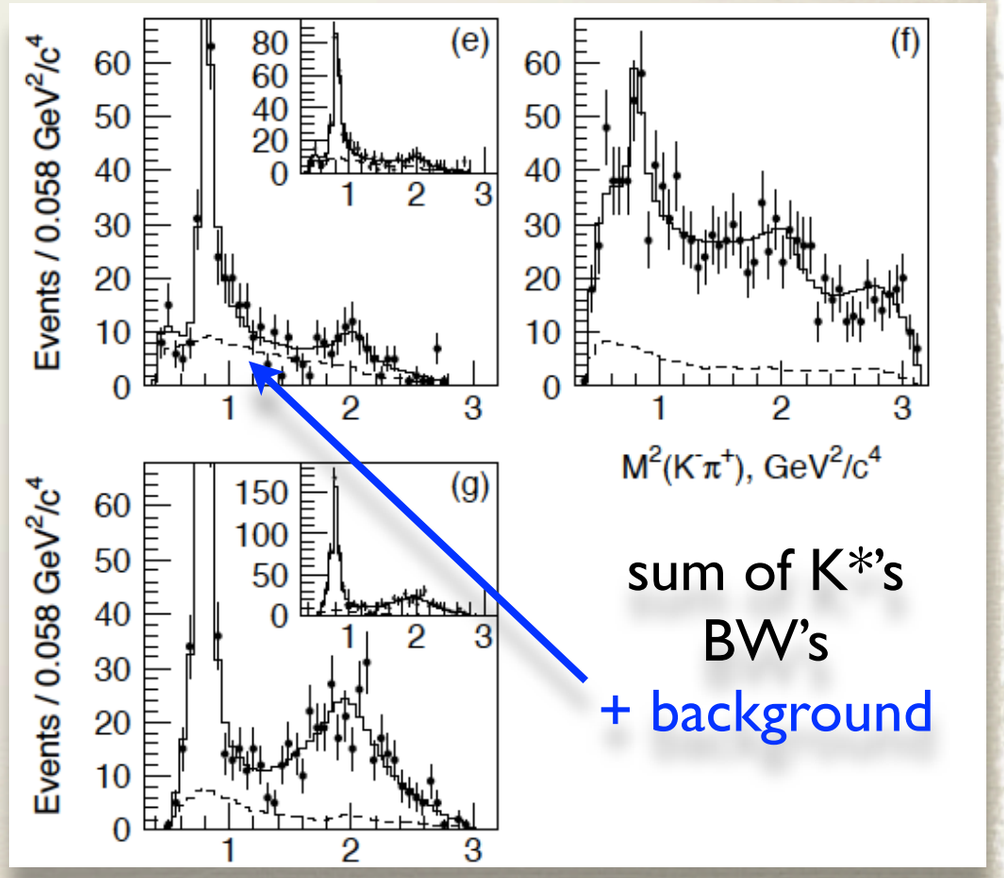

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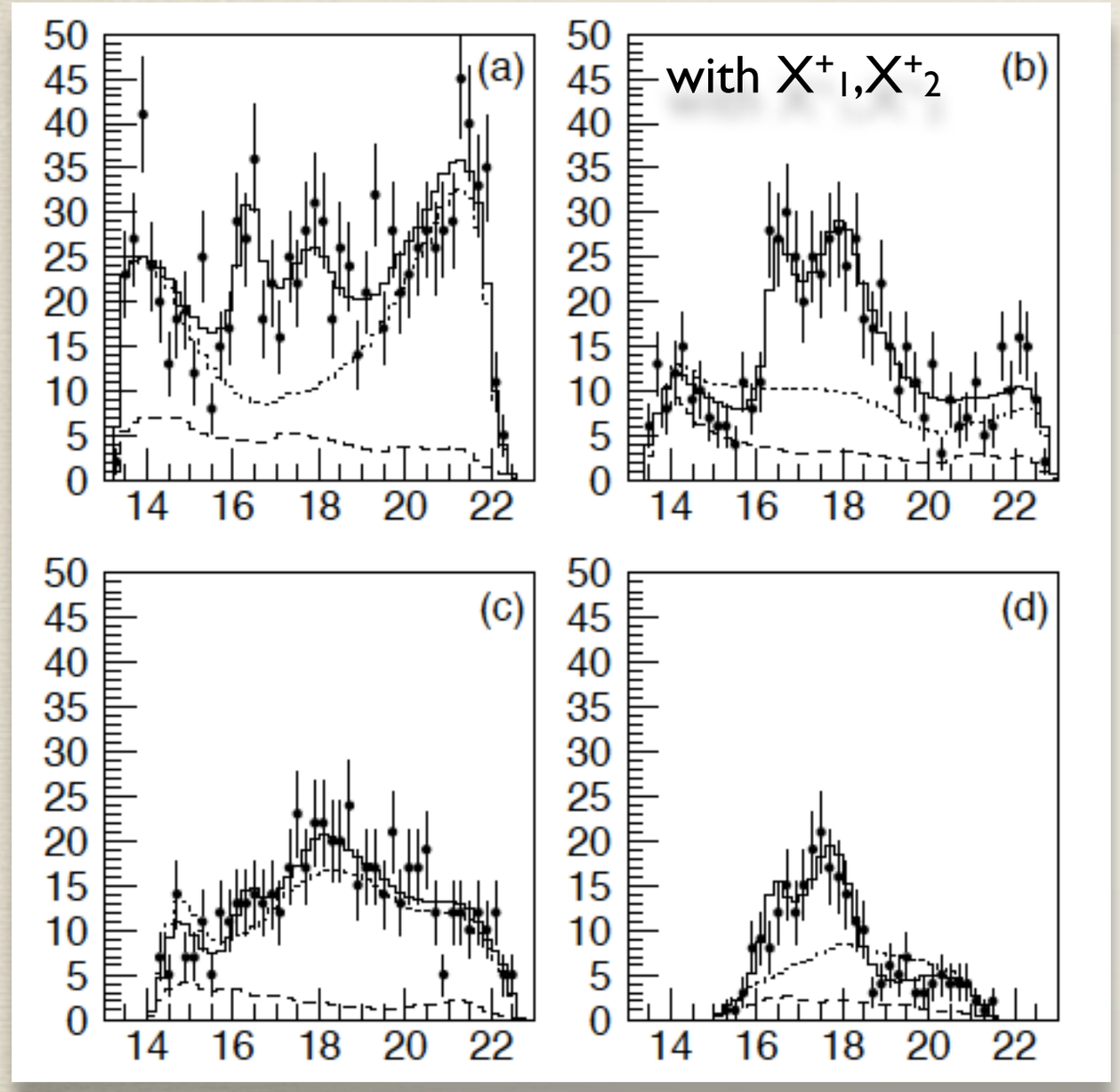
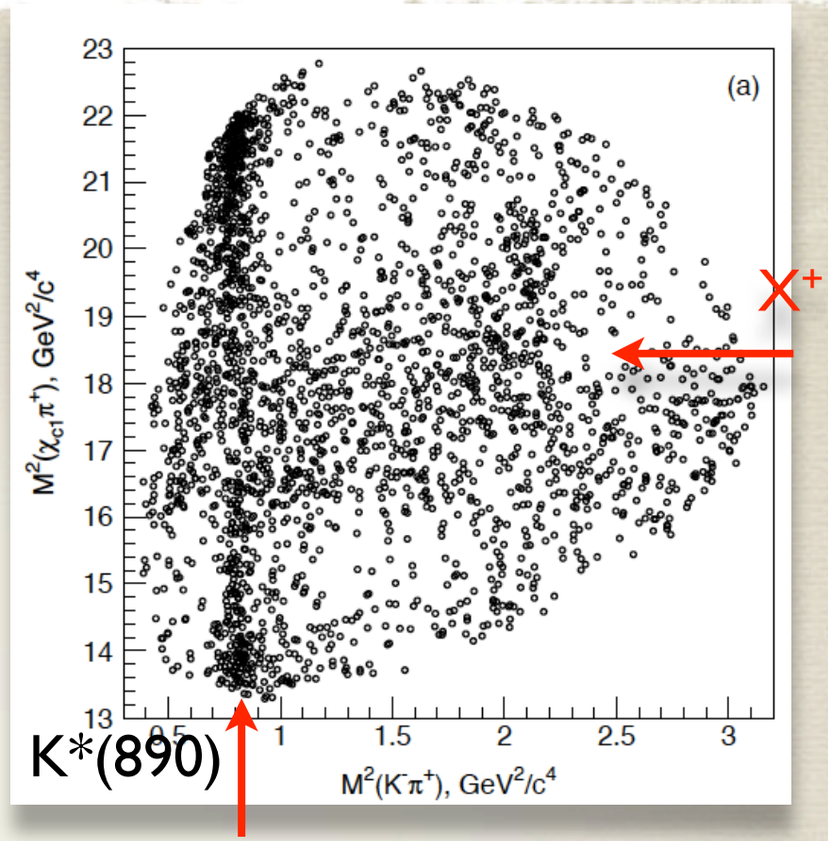
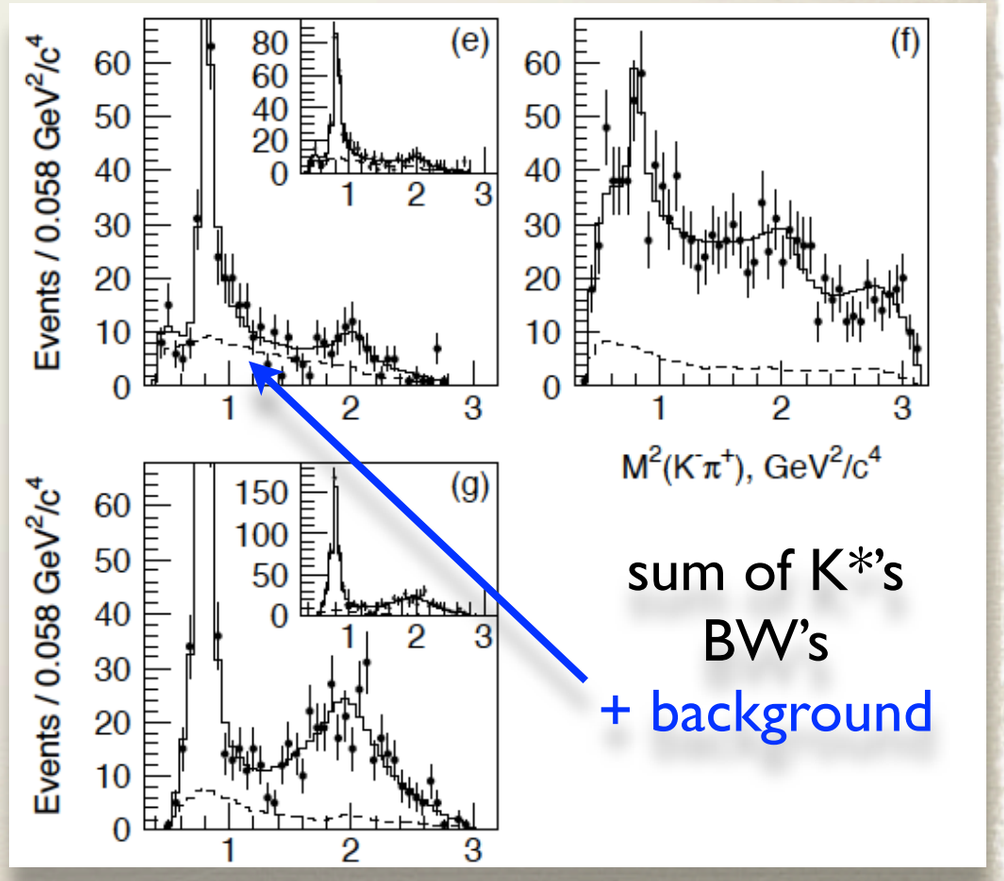


$M(\pi^+\chi_{c1})$





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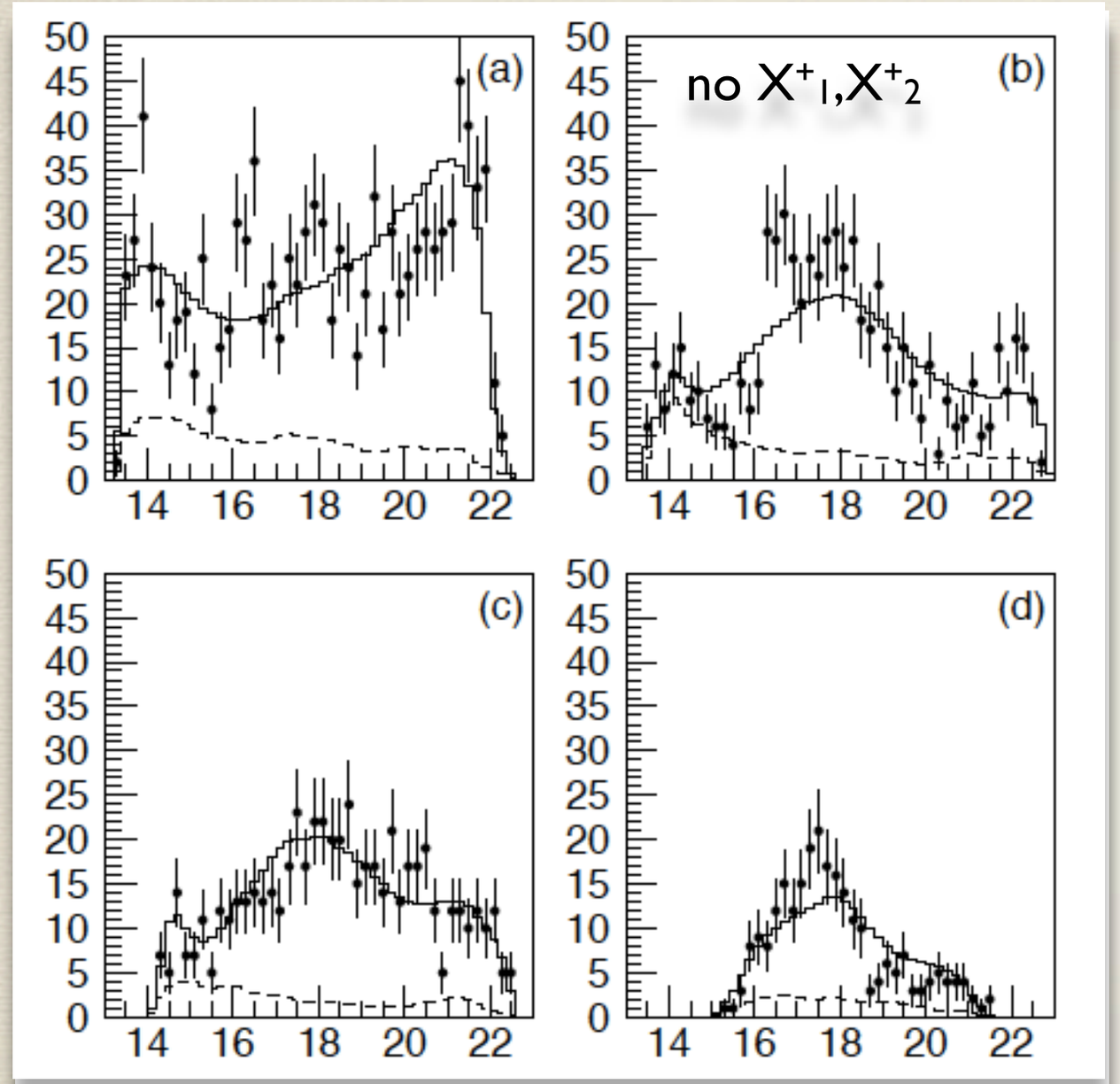

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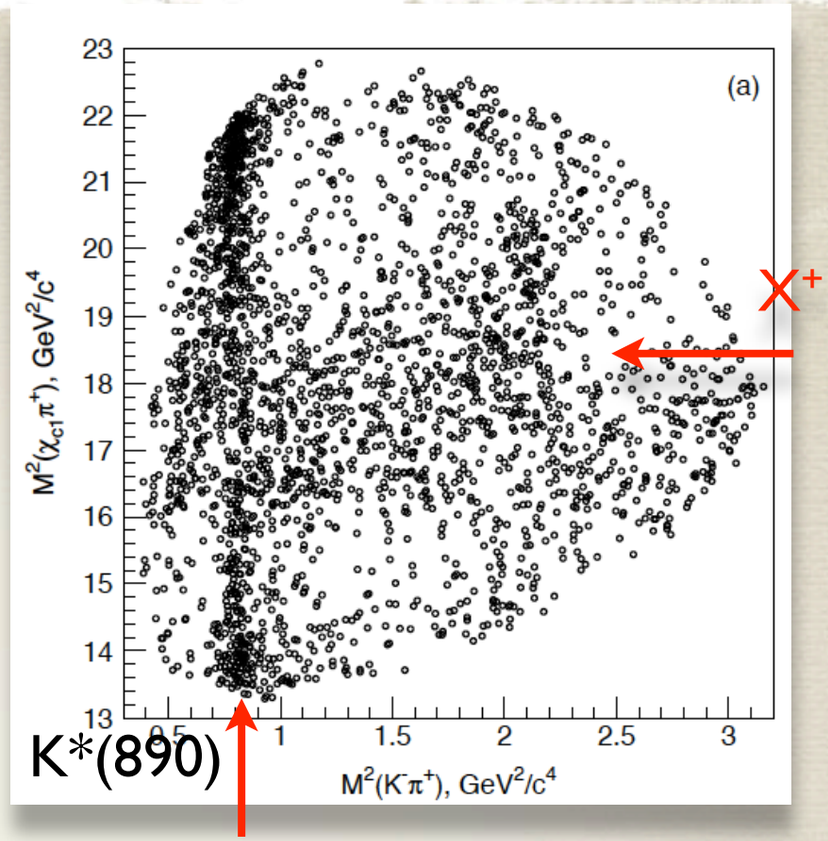

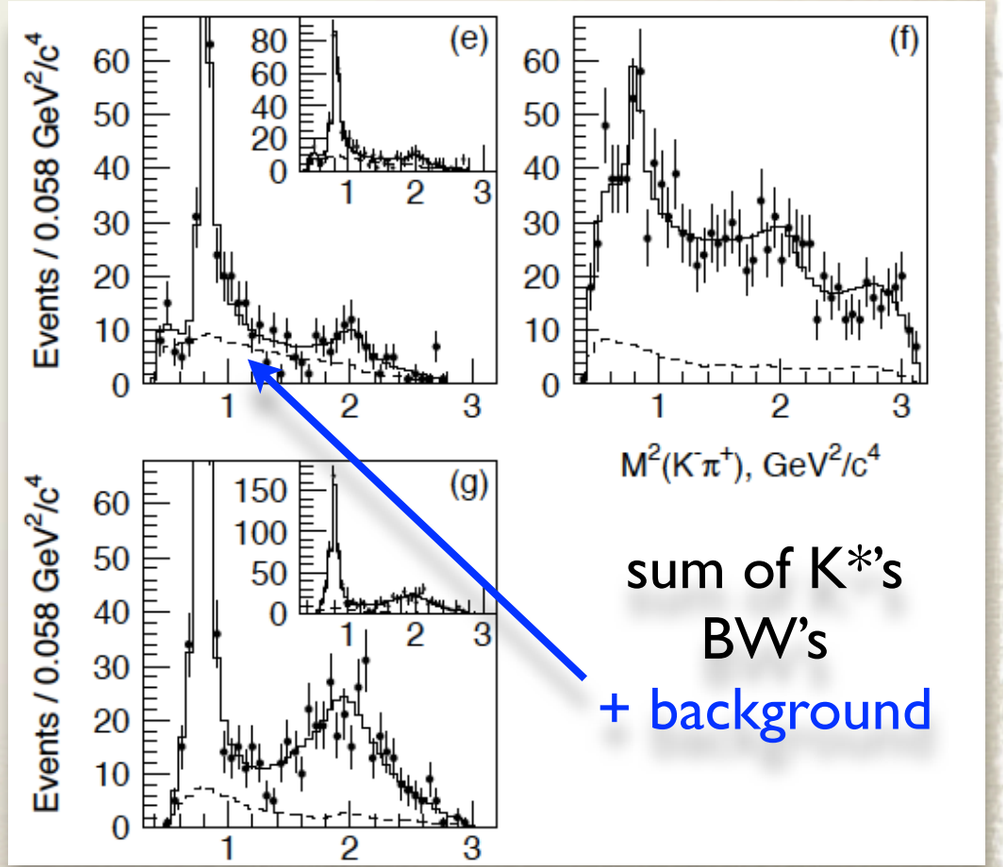

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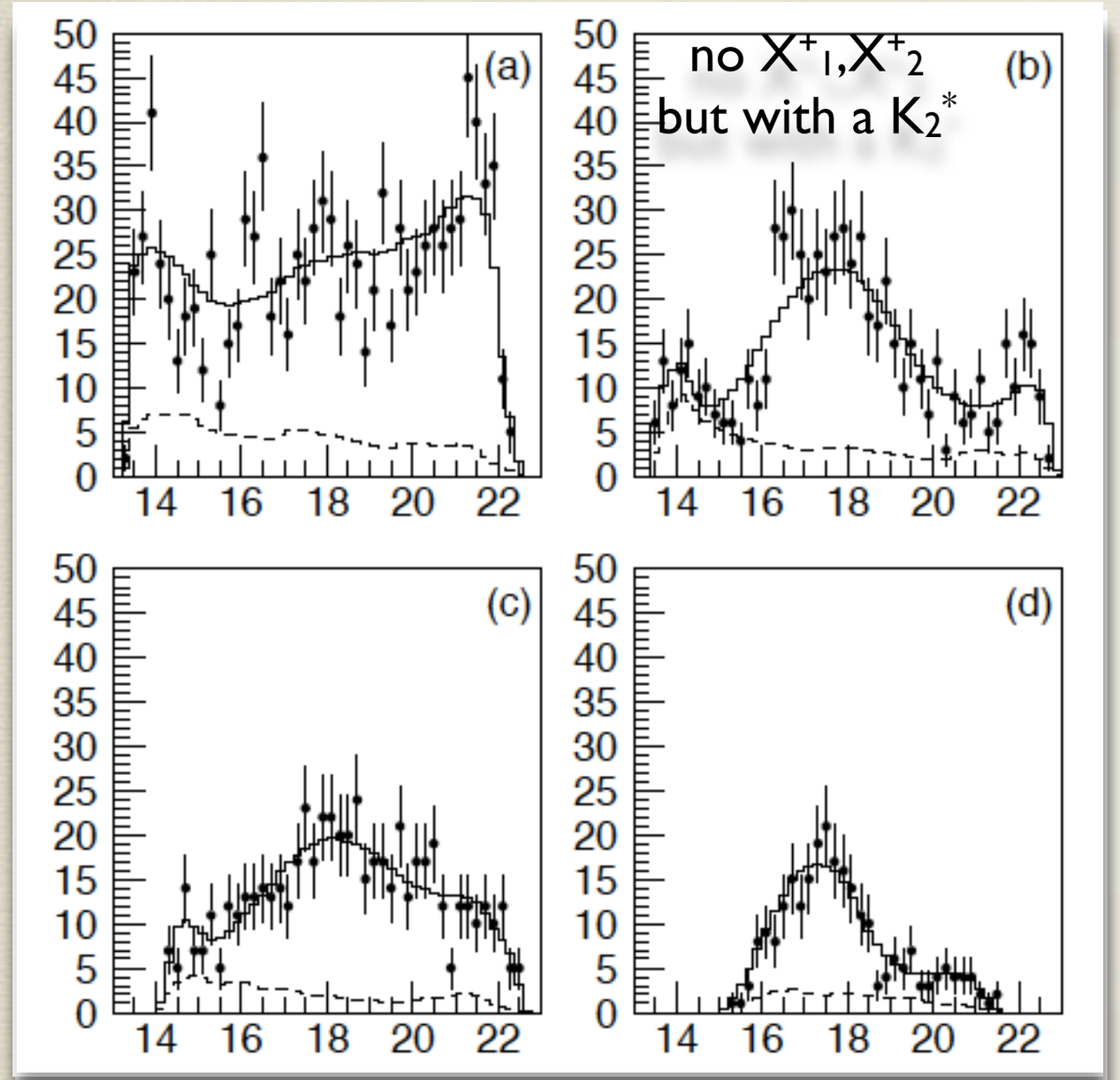

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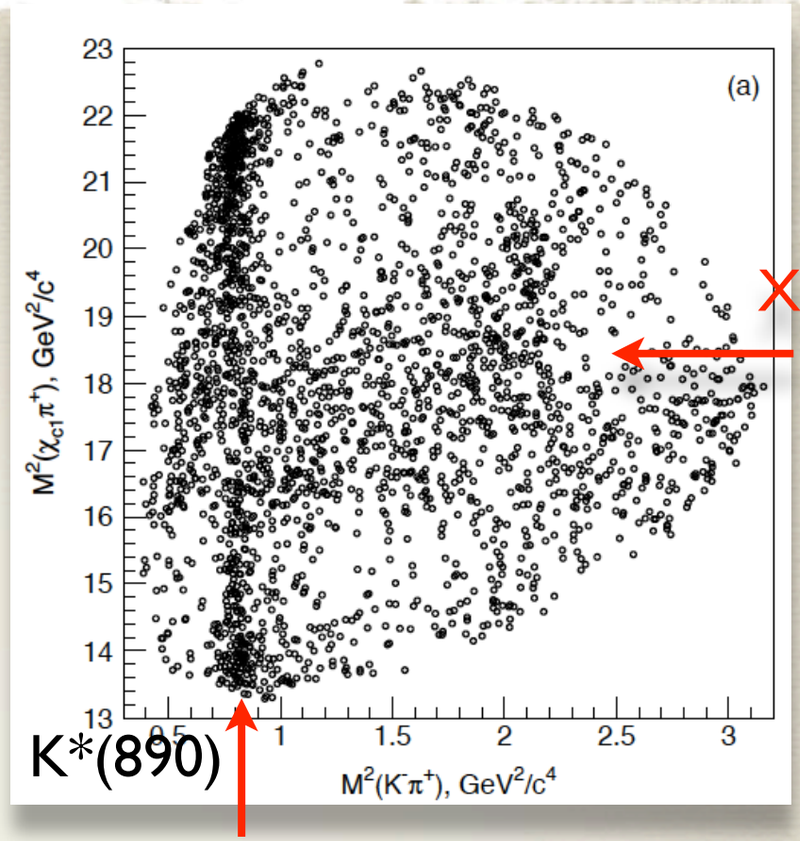
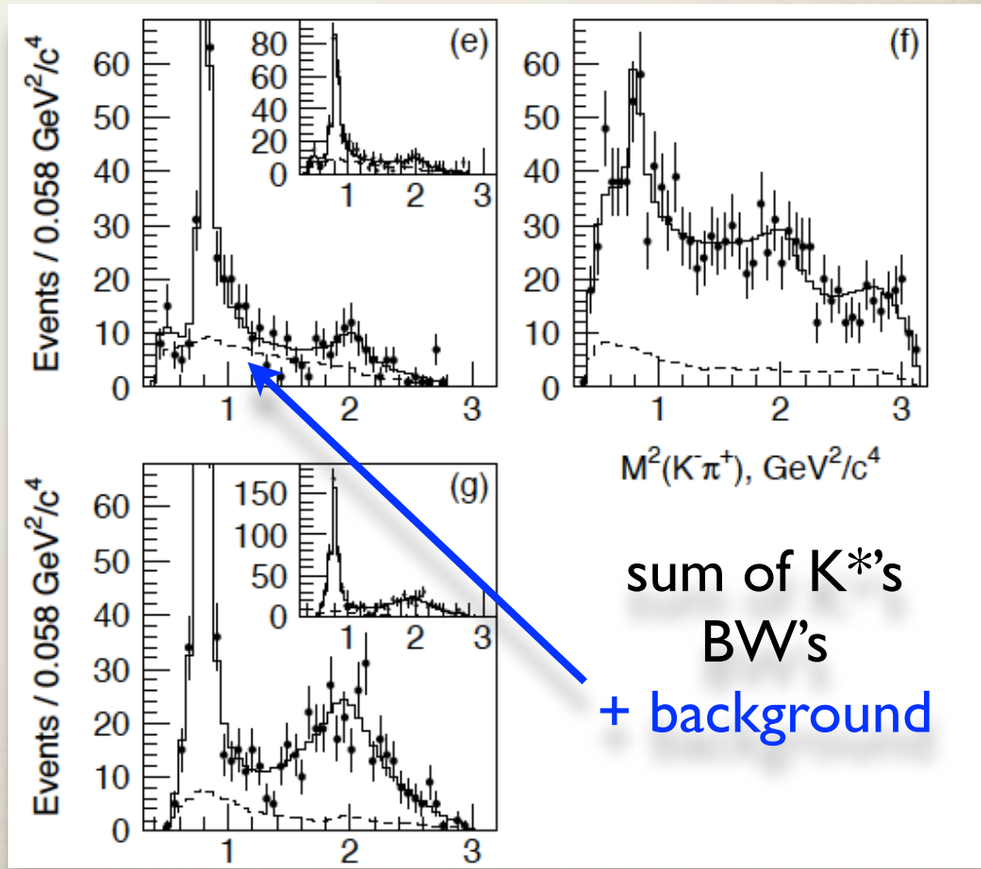
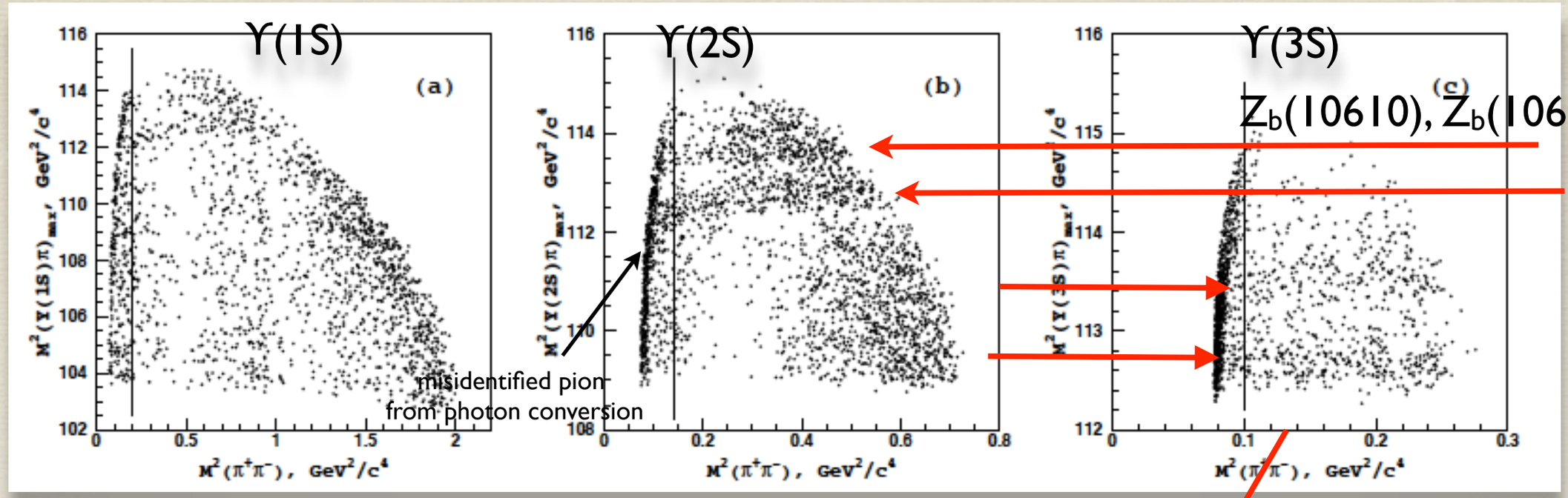


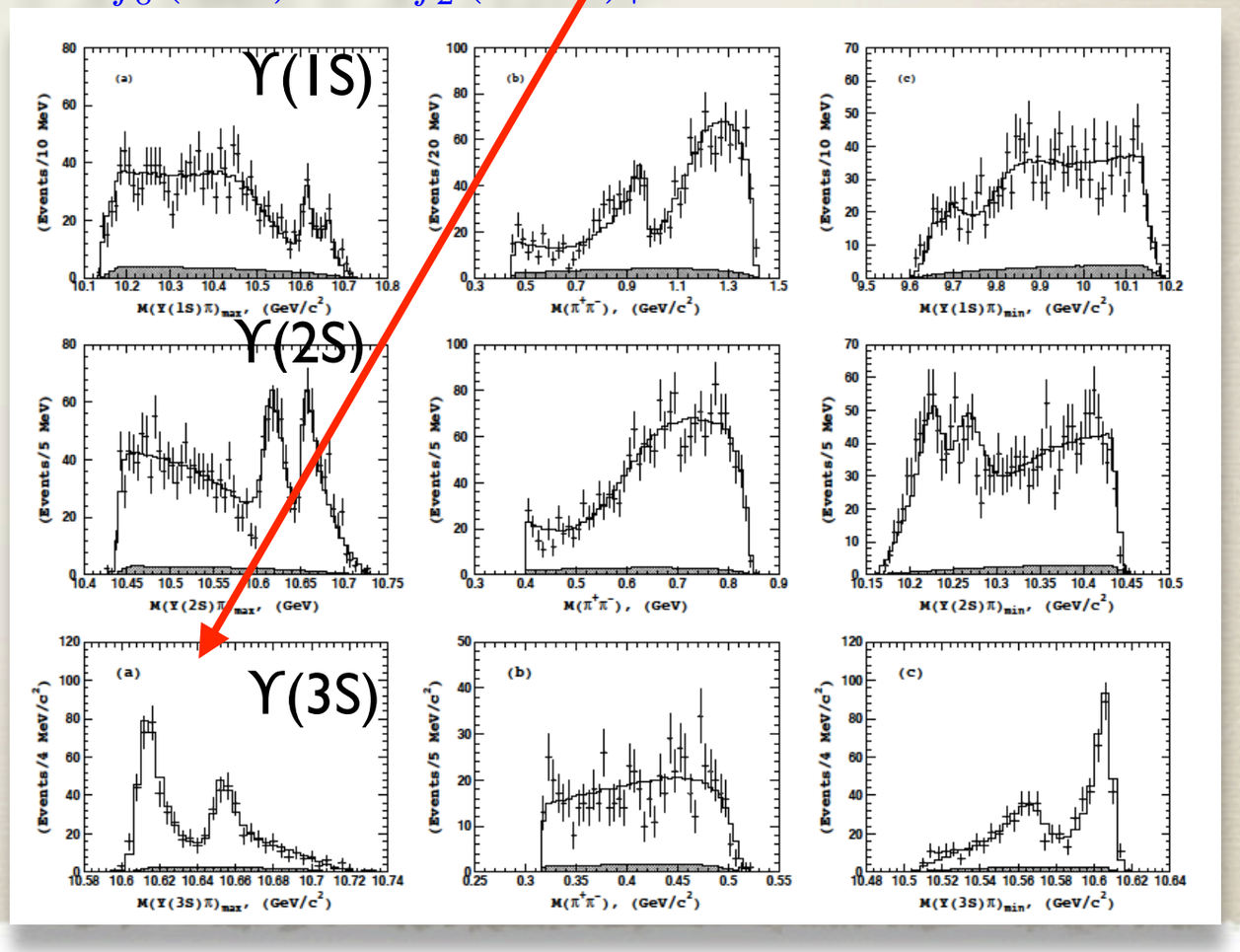


- $Z_b(10610)$, $Z_b(10650)$ Belle (2011)



$$A(s_1, s_2) = |BW_Z(s_1) + BW_Z(s_2) + A_{NR} + A_{f_0}(980) + A_{f_2}(1275)|^2$$

Charged resonances in Dalitz plot analysis of $\Upsilon(5S)$ decays to $(\Upsilon(1S), \Upsilon(2S), \Upsilon(3S), h_b, h_b')\ \pi^+\pi^-$,

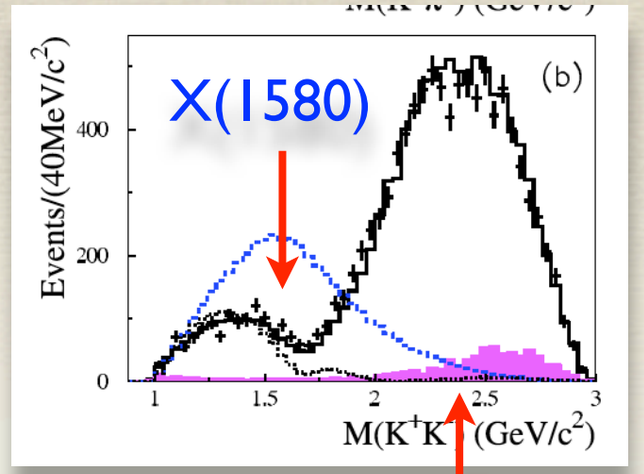


Physical (coherent) backgrounds
are important

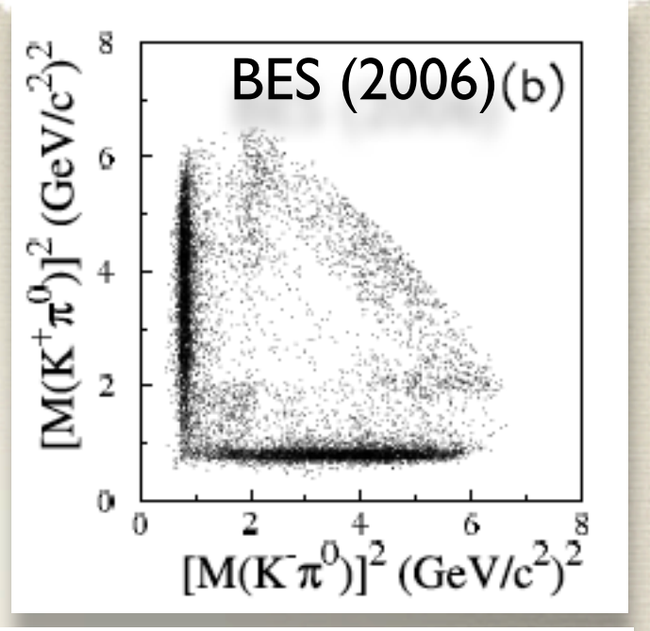
Role of hadronic backgrounds

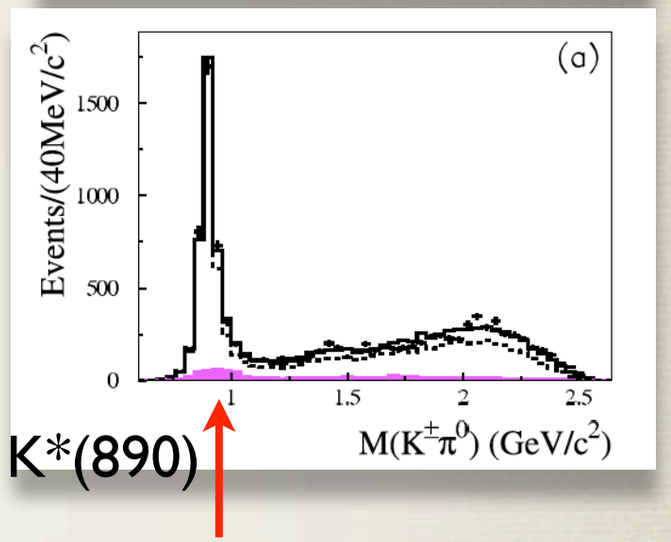
BESII proposed a new J=I=1, (ρ-like) _ broad resonance strongly coupled to KK

$J/\psi \rightarrow K^+K^-\pi^0$



K*(890) reflection





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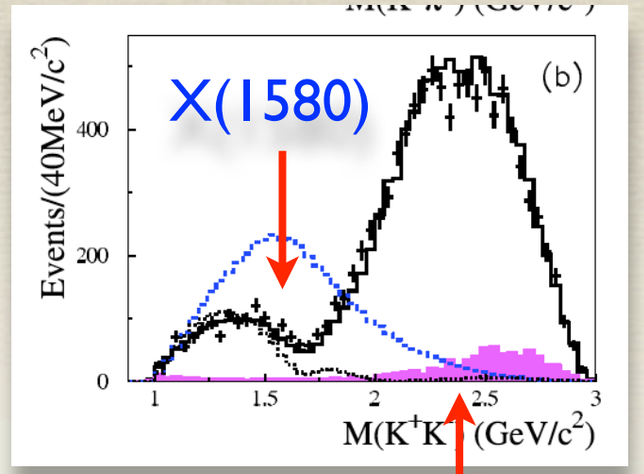

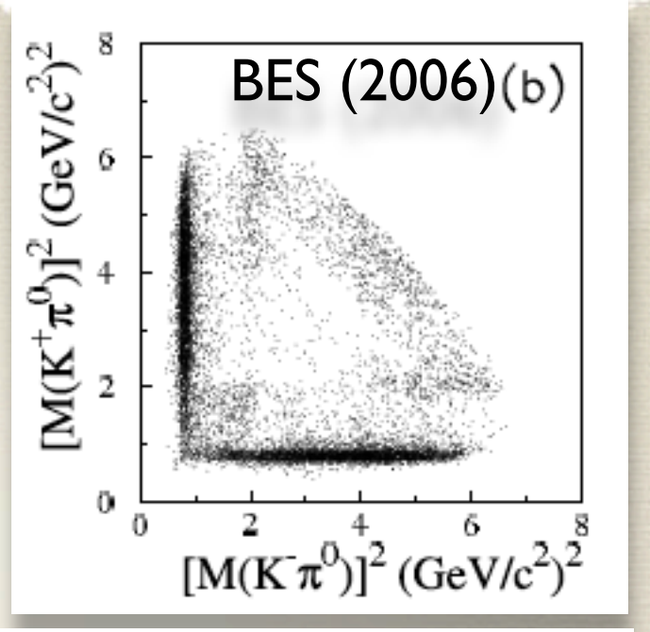

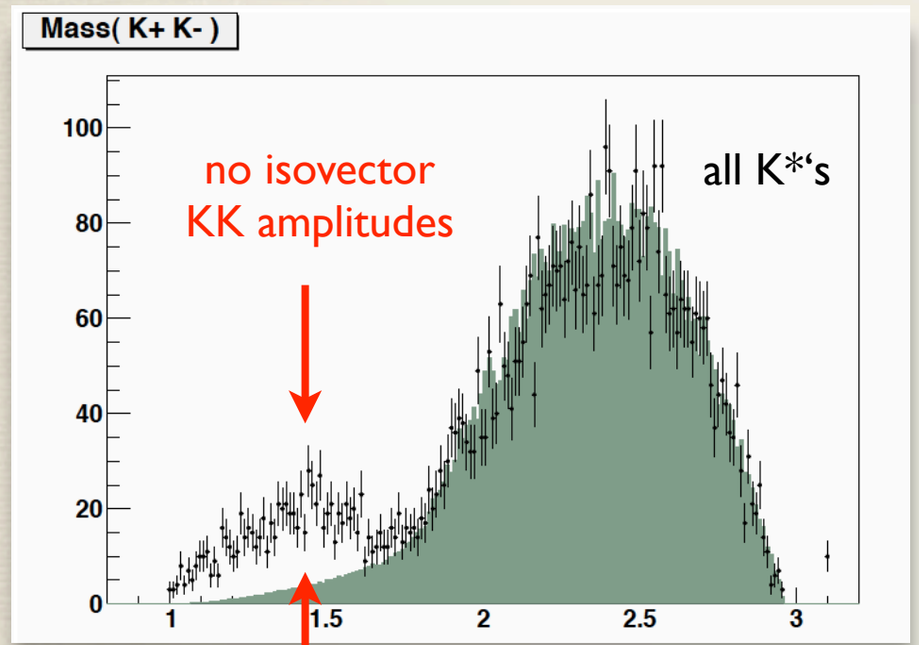

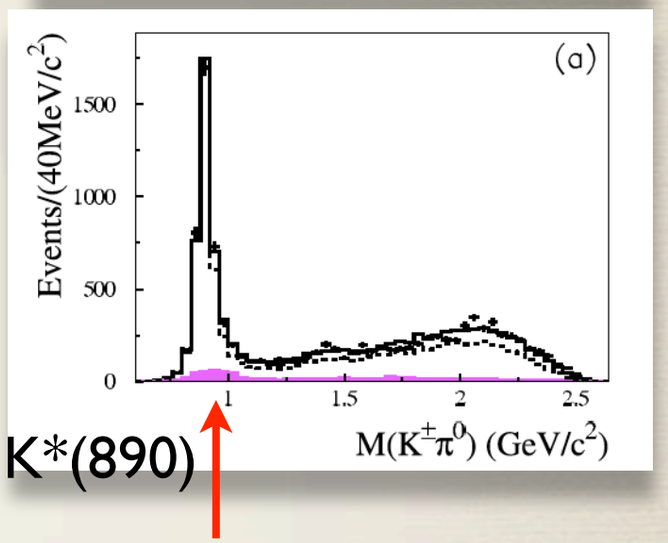

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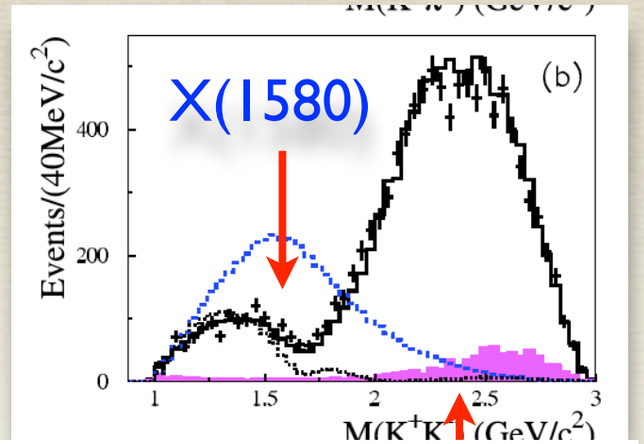
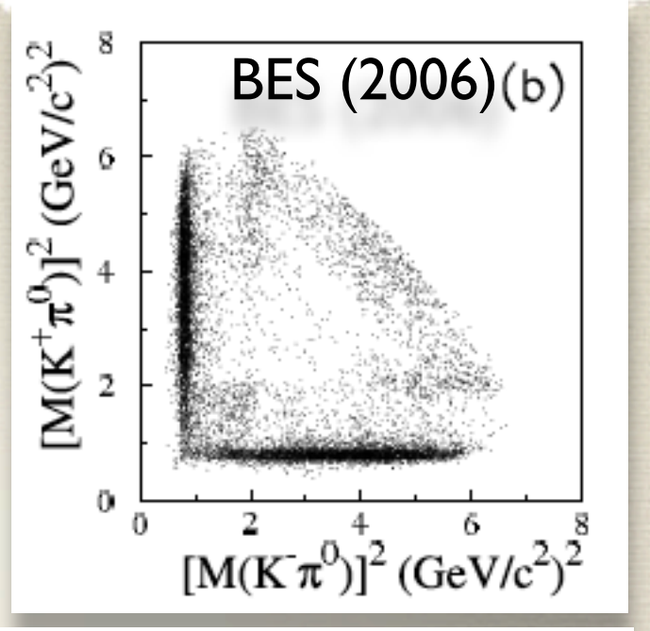
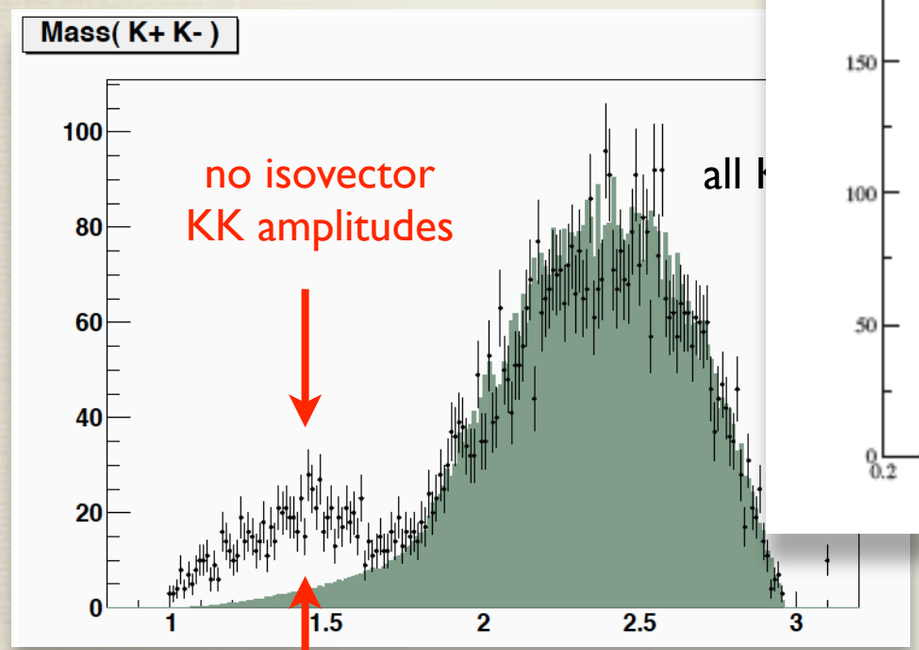
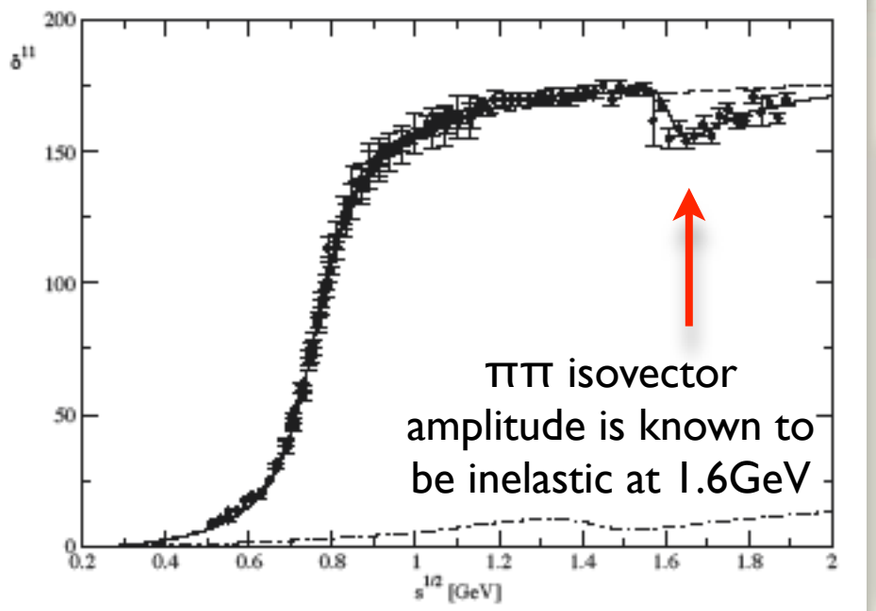


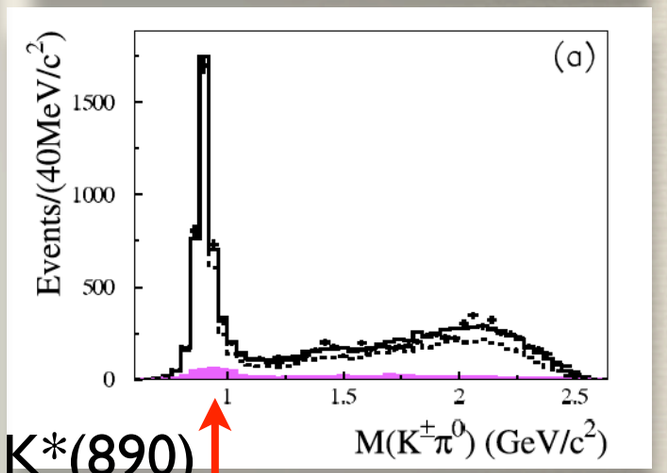




missing strength
at "X" location



unitarity demands other
channel most likely
$\pi\pi \rightarrow K\bar{K}$



K*(890)

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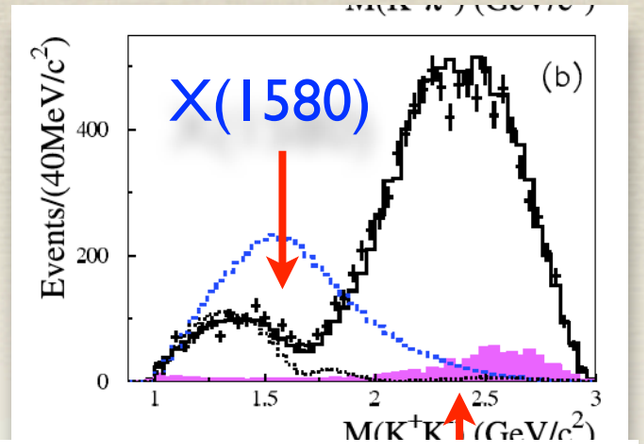

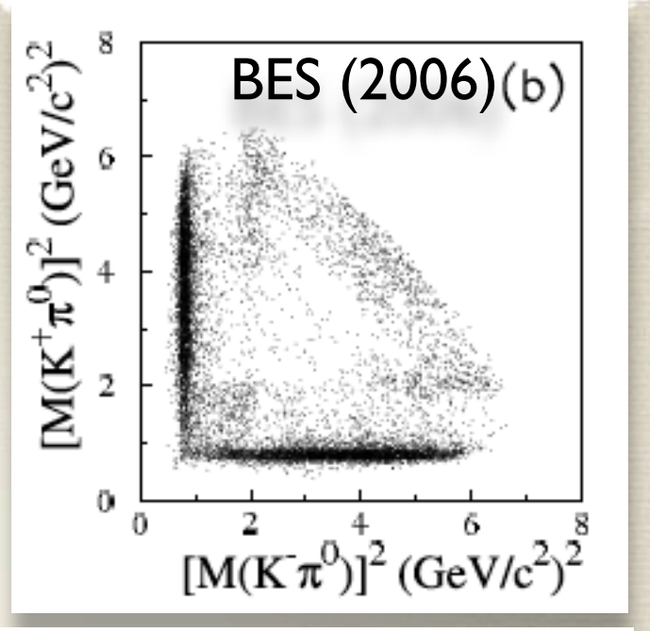

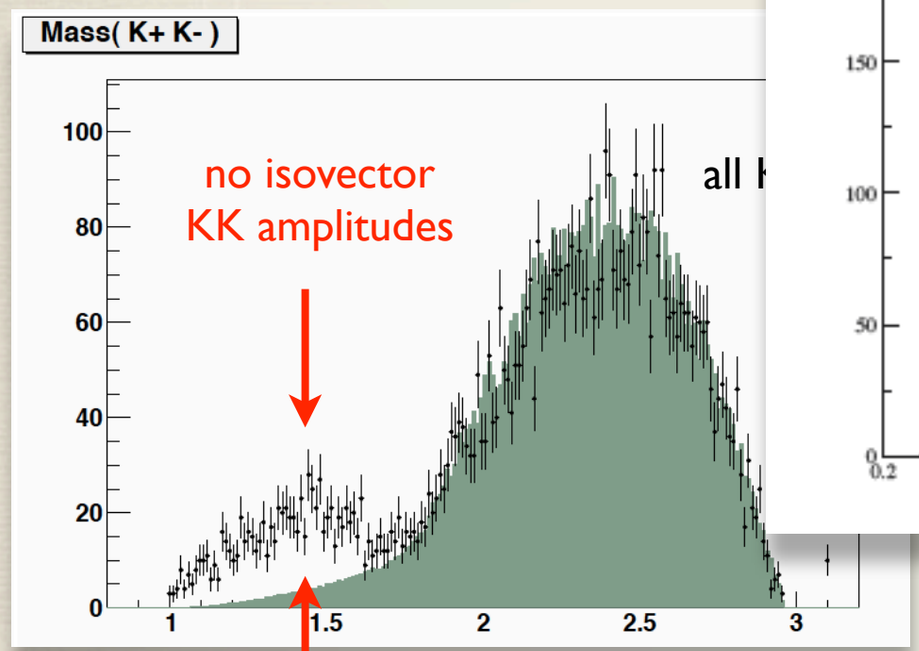

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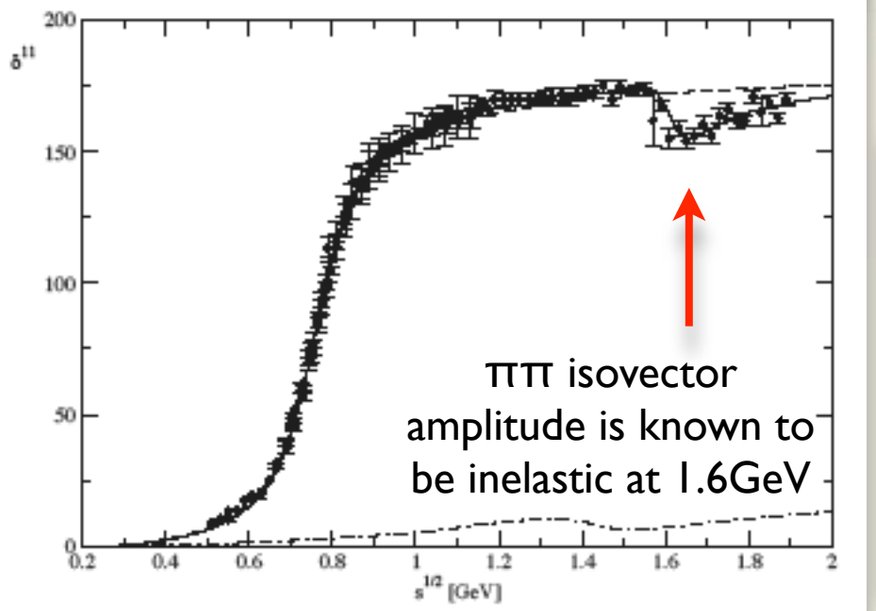
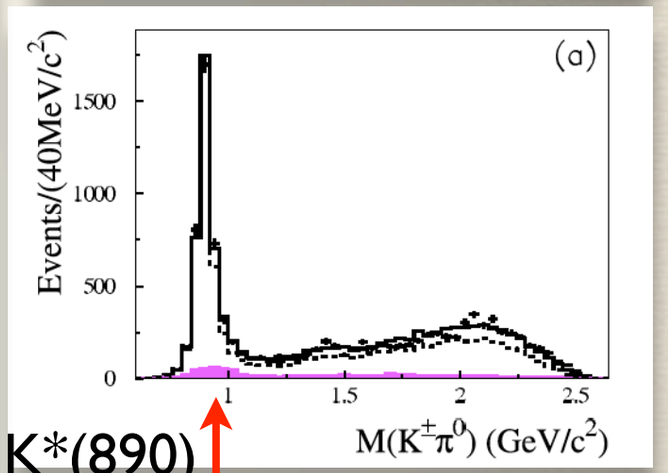
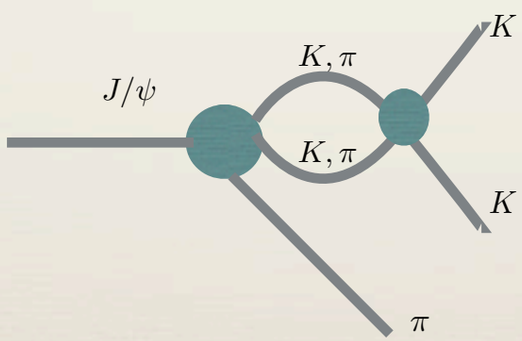
at "X" location





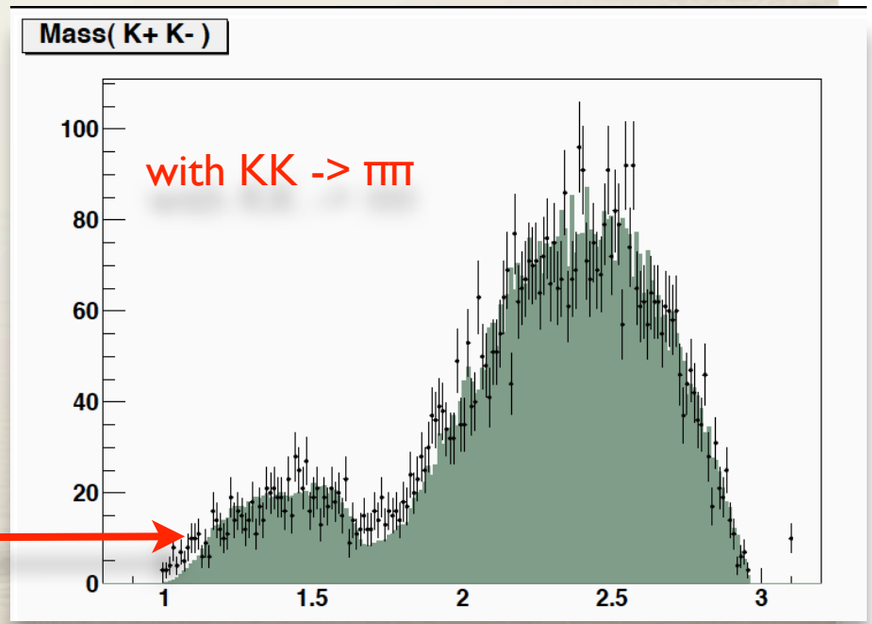
K*(890)

unitarity demands other
channel most likely
$\pi\pi \rightarrow K\bar{K}$



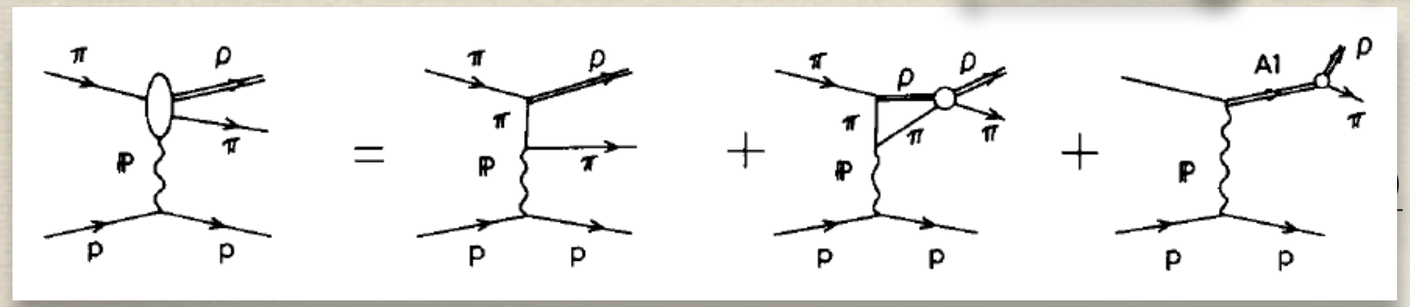
the virtual ππ channel in $J/\psi \rightarrow (\pi\pi)\pi \rightarrow KK\pi$
may explain the "X"

P.Guo et al. (IU 2011)



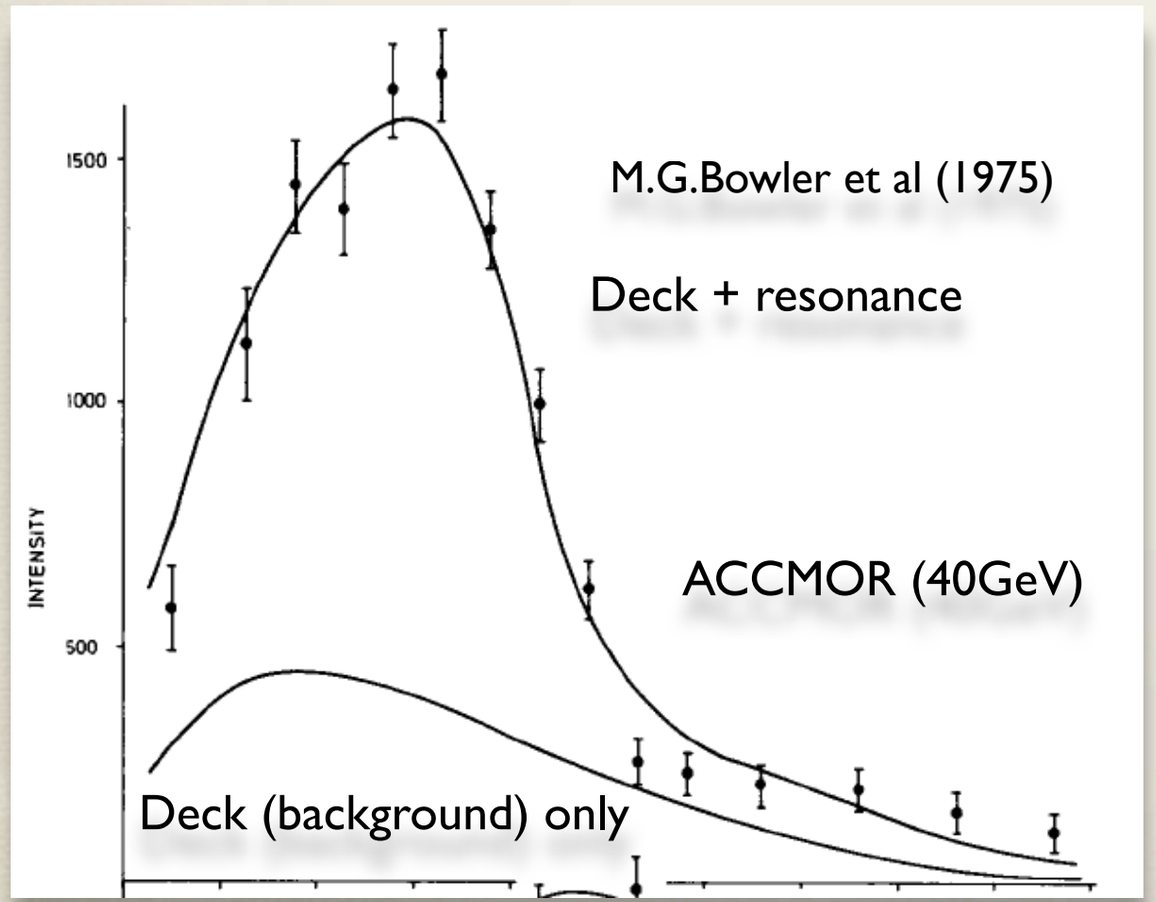
$\pi^- p \to \pi^+ \pi^- \pi^- p$

Resonance production:
Compact source



Deck background:
extended source

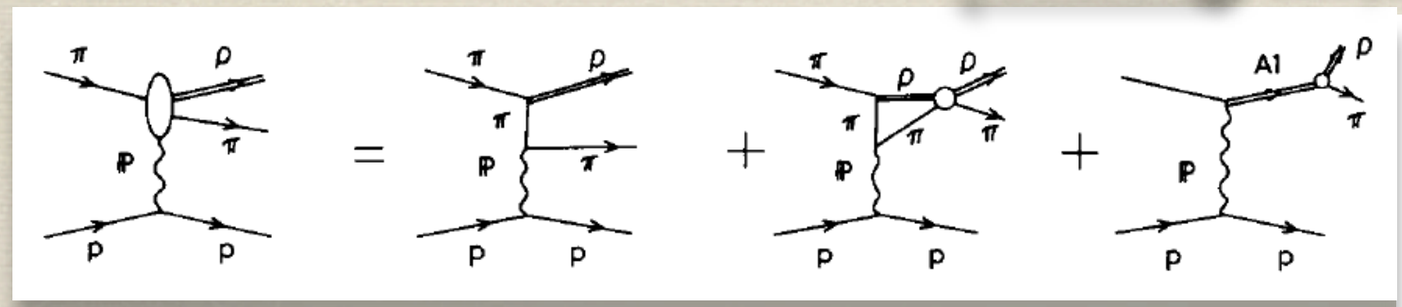
Difference in phase motion
seen in mass dependence



Mass 3π

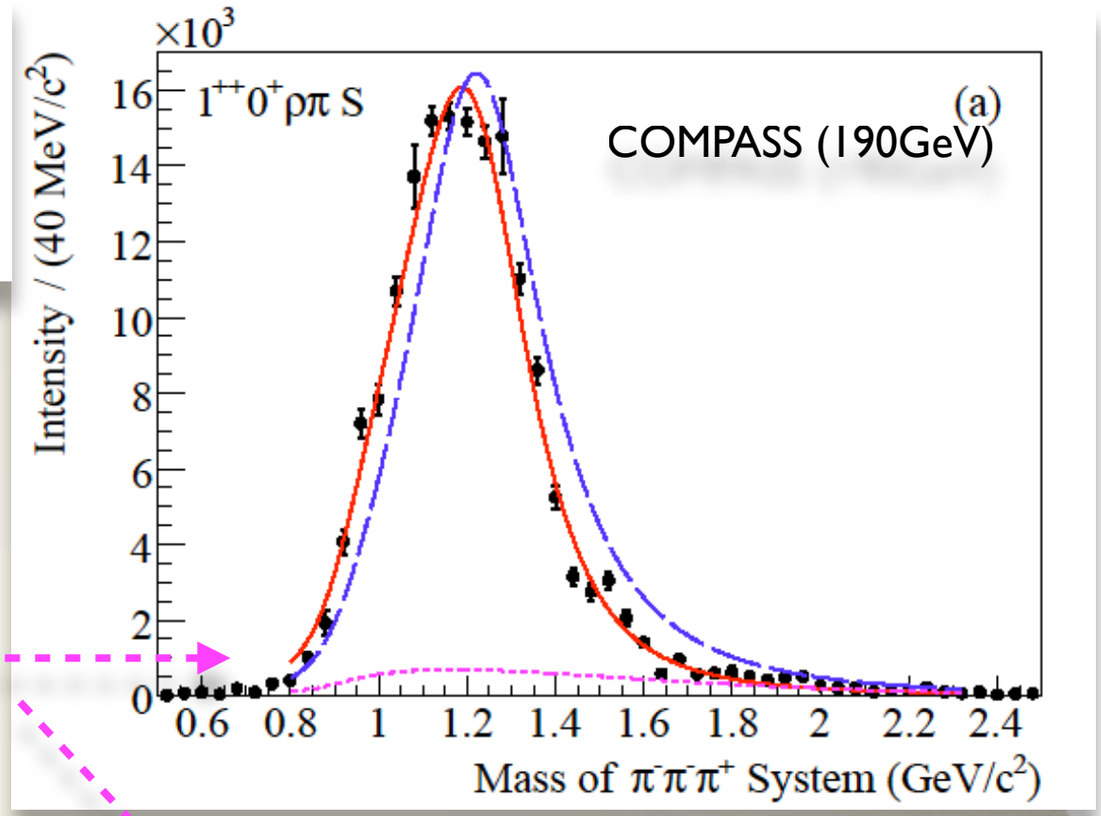
$\pi^- p \to \pi^+ \pi^- \pi^- p$

Resonance production:
Compact source

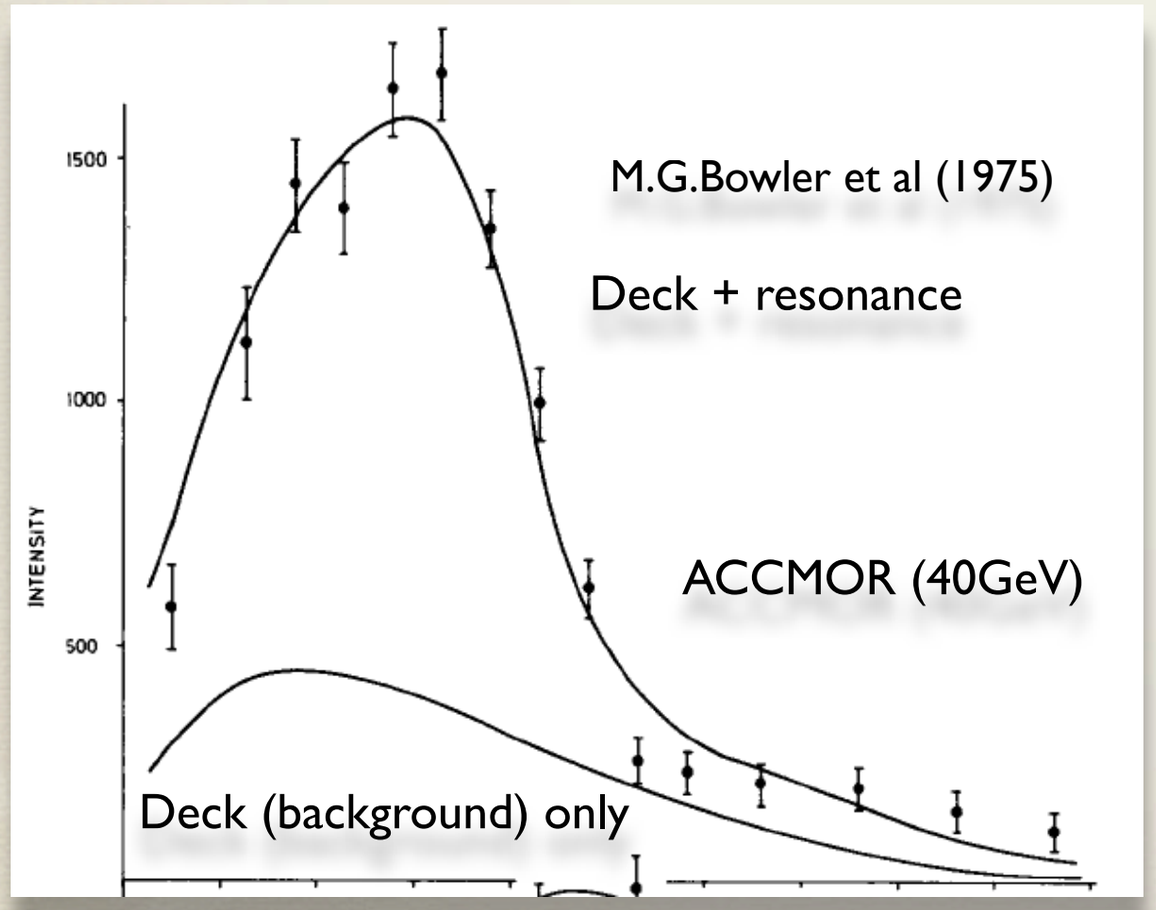


Deck background:
extended source

Difference in phase motion
seen in mass dependence



intensity comparable to background



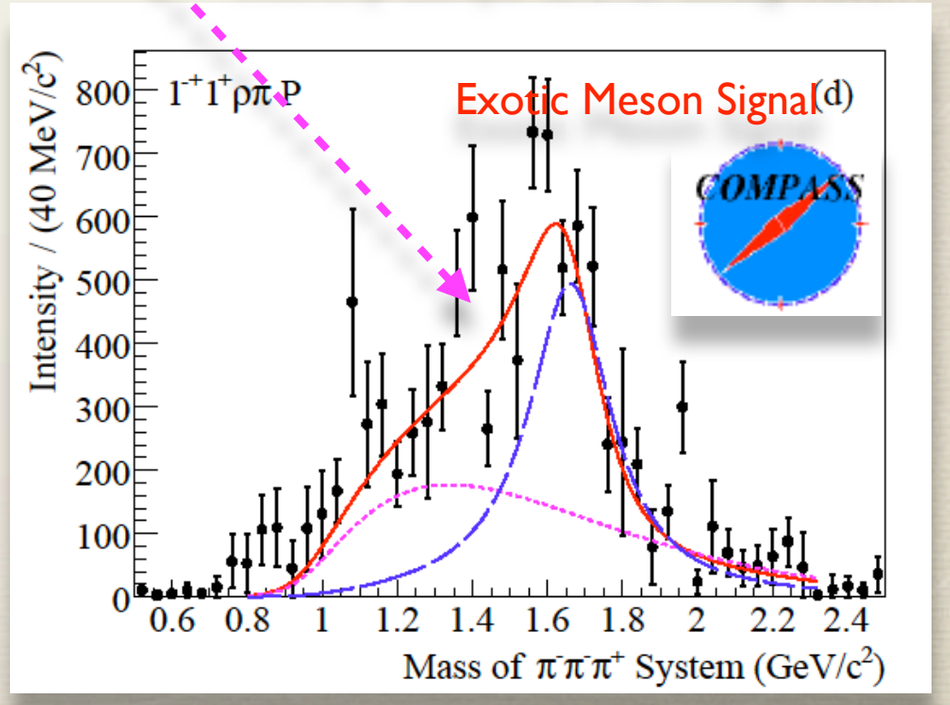
M.G.Bowler et al (1975)

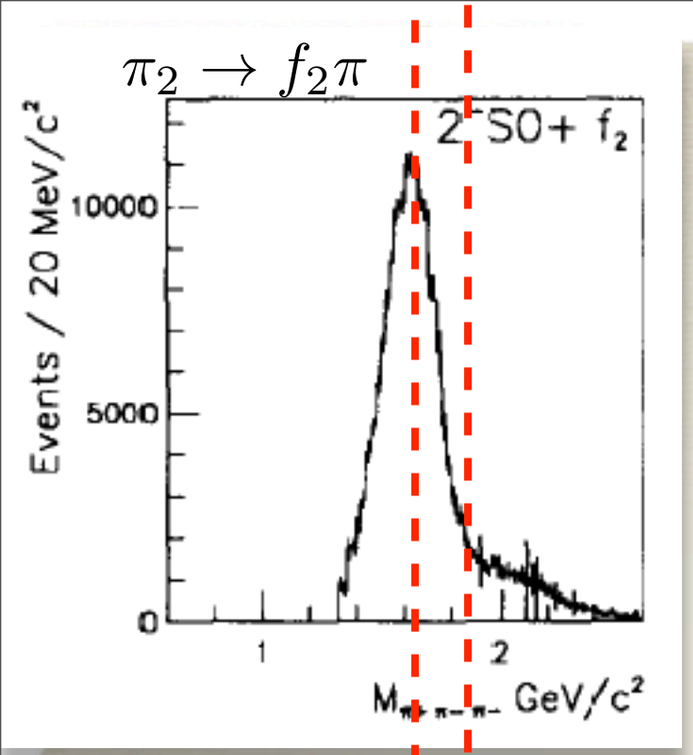
Deck + resonance

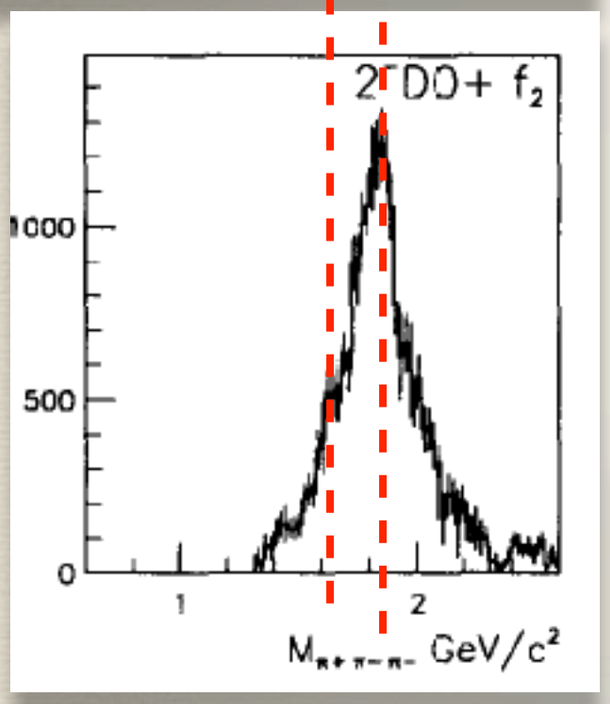
ACCMOR (40GeV)

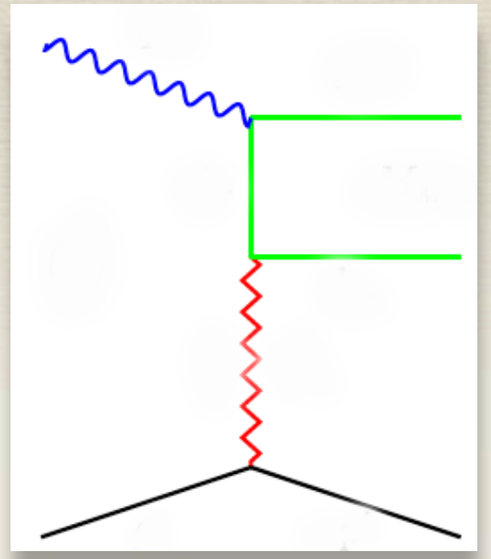
Deck (background) only

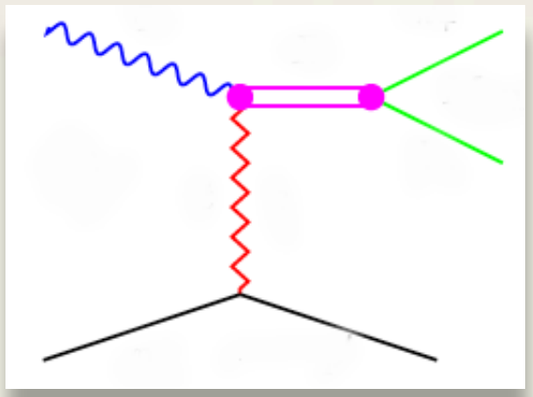
Mass 3π





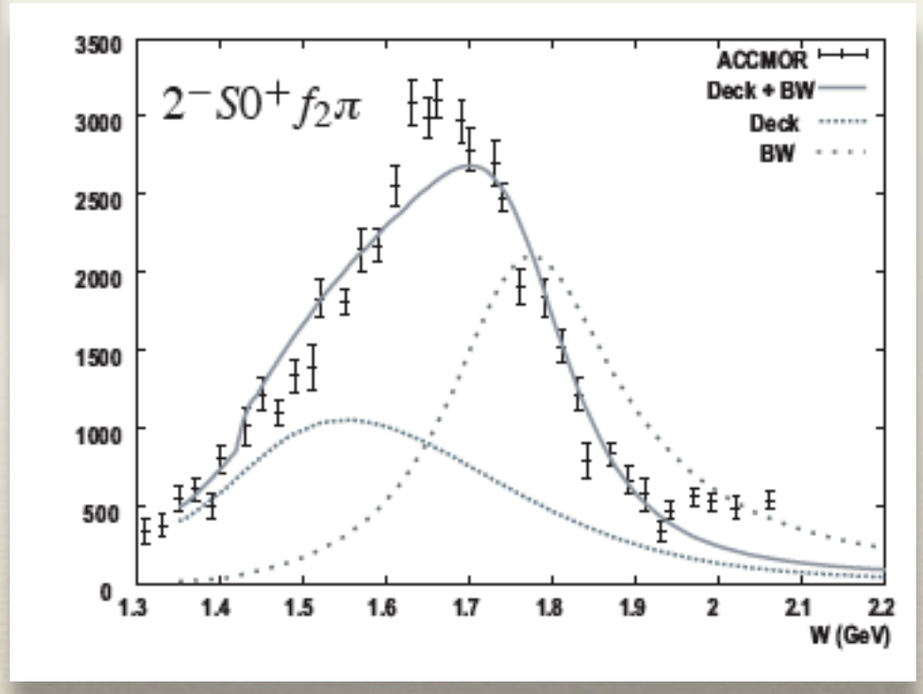


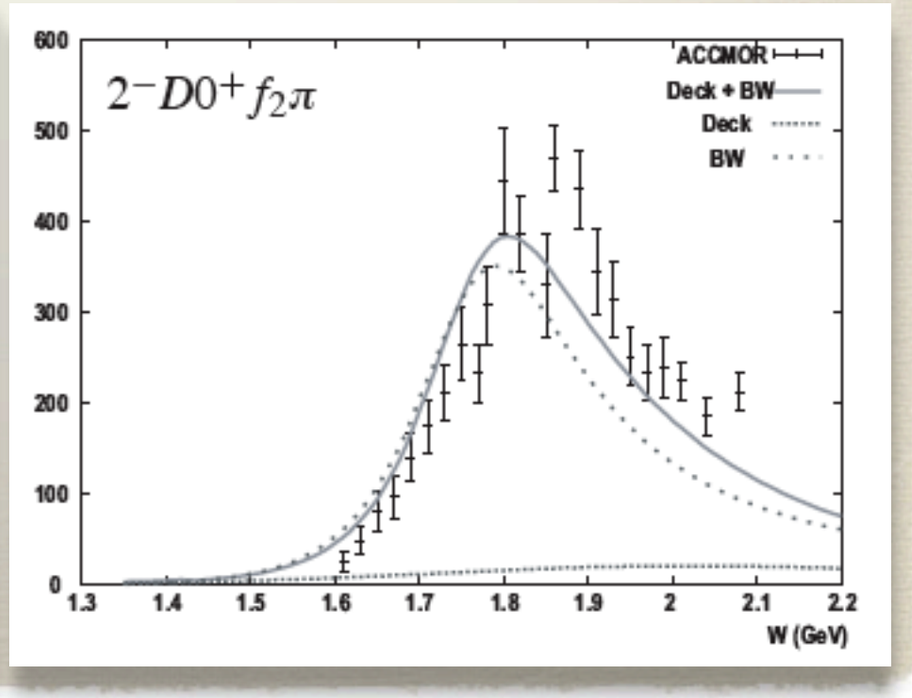




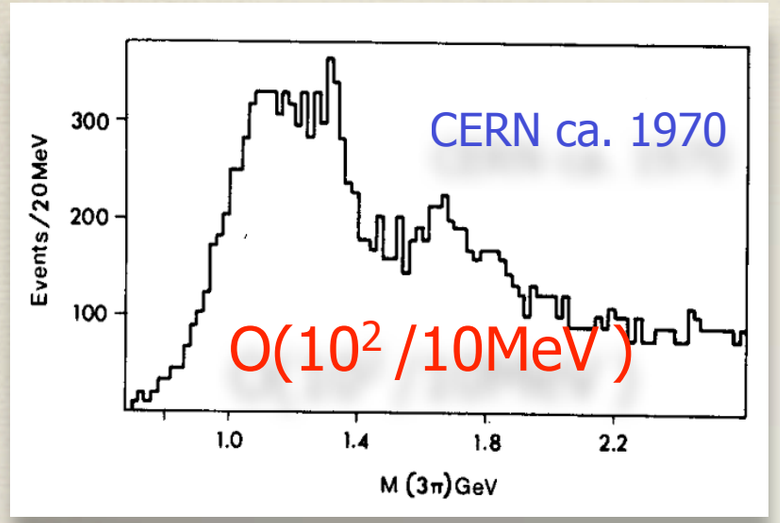
PDG: 2 entires for $\pi_2(1670)$

VALUE (MeV)			EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1672.4± 3.2 OUR AVERAGE				Error includes scale factor of 1.4. See the ideogram below.				
1749	±10	±100	145k	LU	05	E852		18 $\pi^- p \to \omega\pi^-\pi^0 p$
1676	± 3	± 8		[1] CHUNG	02	E852		18.3 $\pi^- p \to \pi^+\pi^-\pi^- p$
1685	±10	± 30		[2] BARBERIS	01			450 $p p \to p_f 3\pi^0 p_s$
1687	± 9	± 15		AMELIN	99	VES		37 $\pi^- A \to \omega\pi^-\pi^0 A^*$
1669	± 4			BARBERIS	98B			450 $p p \to p_f \rho\pi p_s$
1670	± 4			BARBERIS	98B			450 $p p \to p_f f_2(1270)\pi p_s$
1730	±20			[3] AMELIN	95B	VES		36 $\pi^- A \to \pi^+\pi^-\pi^- A$
1690	±14			[4] BERDNIKOV	94	VES		37 $\pi^- A \to K^+K^-\pi^- A$
1710	±30		700	ANTIPOV	87	SIGM	–	50 π^- Cu $\to \mu^+\mu^-\pi^-$ Cu
1676	± 6			[4] EVANGELISTA	81	OMEG	–	12 $\pi^- p \to 3\pi p$
1657	±14			[4,5] DAUM	80D	SPEC	–	63–94 $\pi p \to 3\pi X$
1662	±10		2000	[4] BALTAY	77	HBC	+	15 $\pi^+ p \to p 3\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •								
1742	±31	± 49		ANTREASYAN	90	CBAL		$e^+e^- \to e^+e^-\pi^0\pi^0\pi^0$
1624	±21			[1] BELLINI	85	SPEC		40 $\pi^- A \to \pi^-\pi^+\pi^- A$
1622	±35			[6] BELLINI	85	SPEC		40 $\pi^- A \to \pi^-\pi^+\pi^- A$
1693	±28			[7] BELLINI	85	SPEC		40 $\pi^- A \to \pi^-\pi^+\pi^- A$
1710	±20			[8] DAUM	81B	SPEC	–	63,94 $\pi^- p$
1666	±10			[4] ASCOLI	73	HBC	–	5–25 $\pi^- p \to p\pi_2$

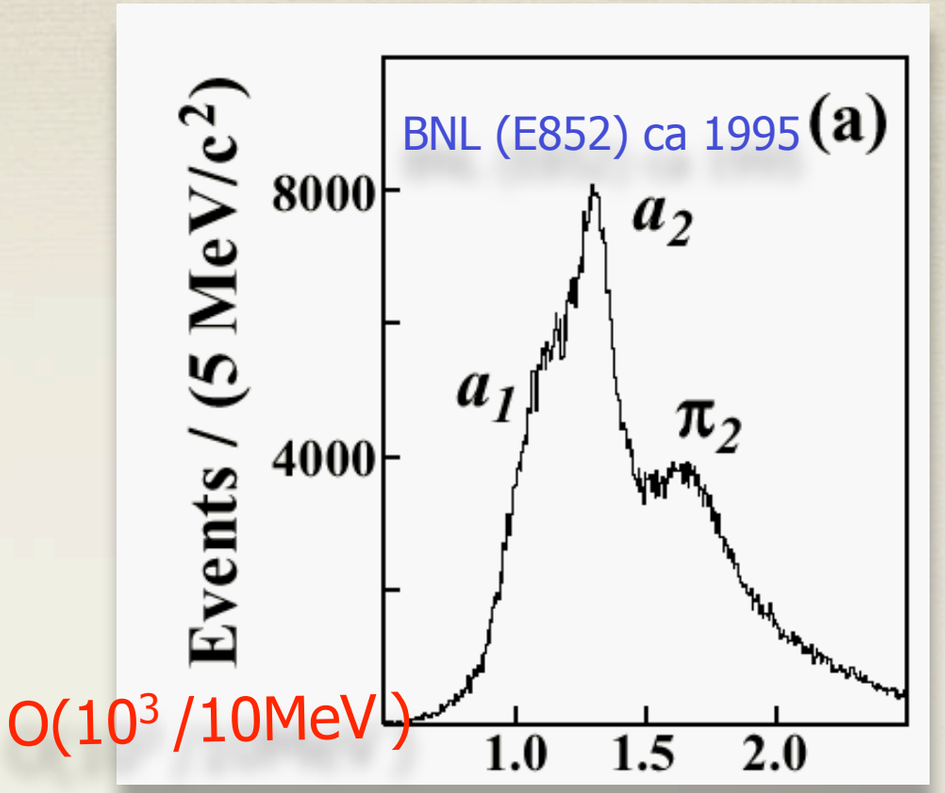




evolution in statistics $\pi^- p \rightarrow \pi^-\pi^+\pi^- p$

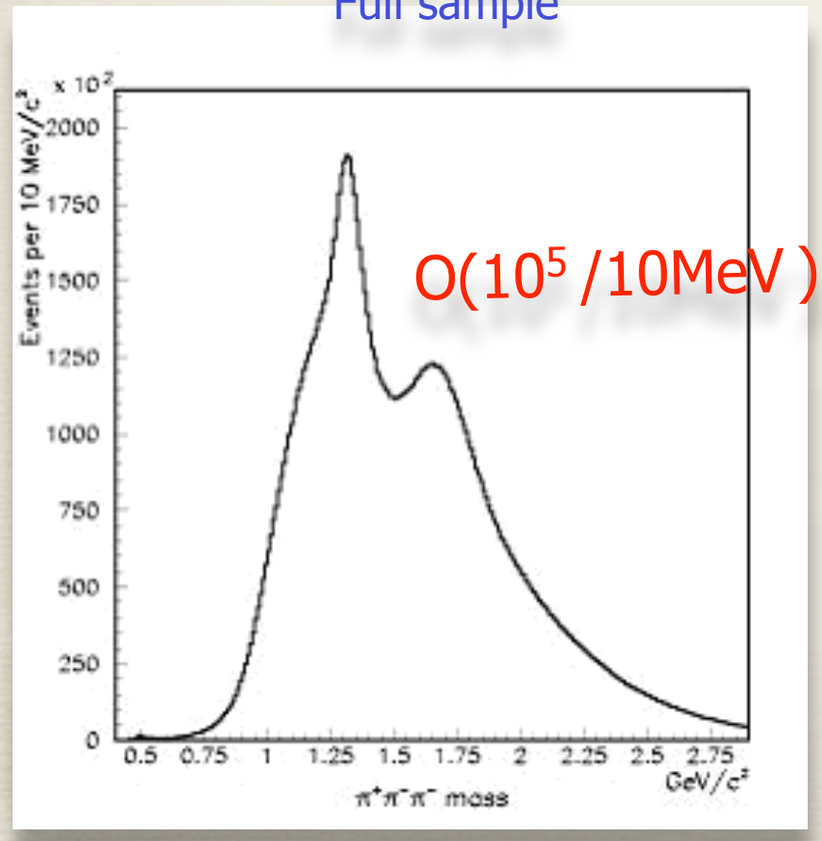


O(10^2 /10MeV)

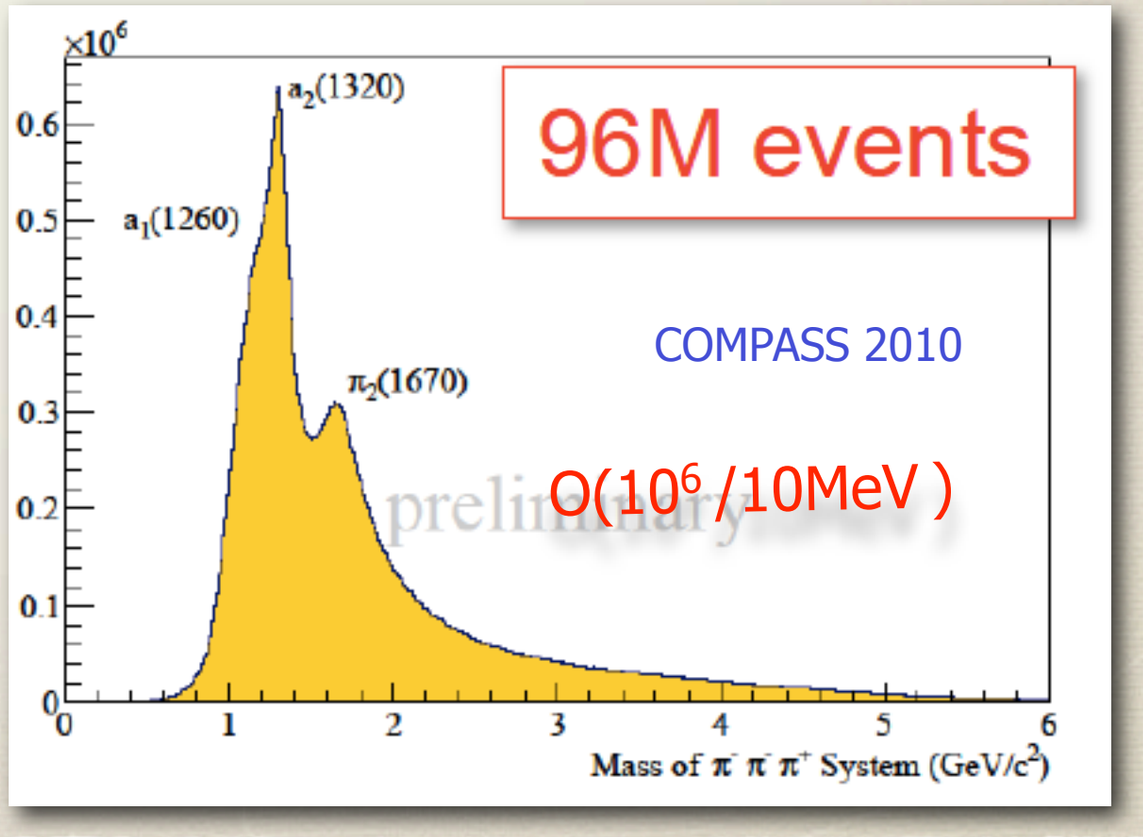


O(10^3 /10MeV)

E852 2003
Full sample

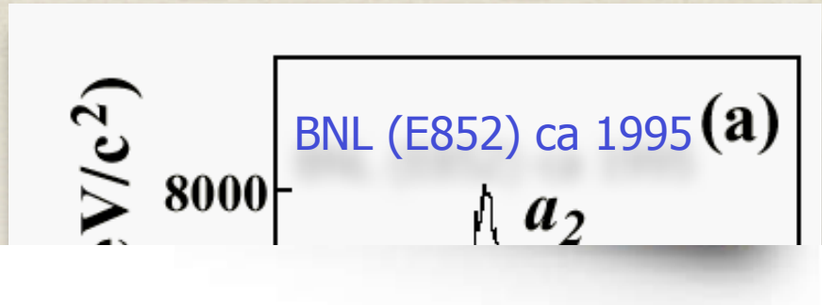


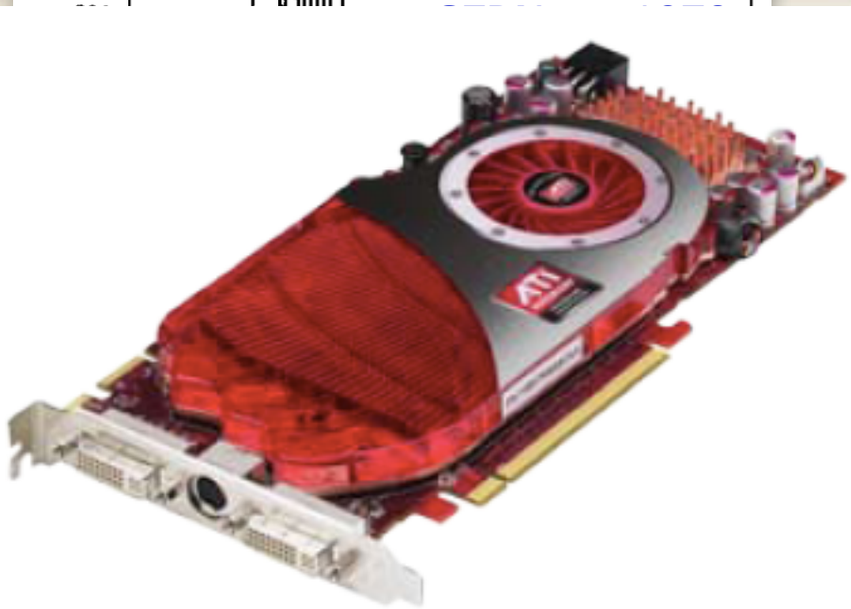
O(10^5 /10MeV)



O(10^6 /10MeV)

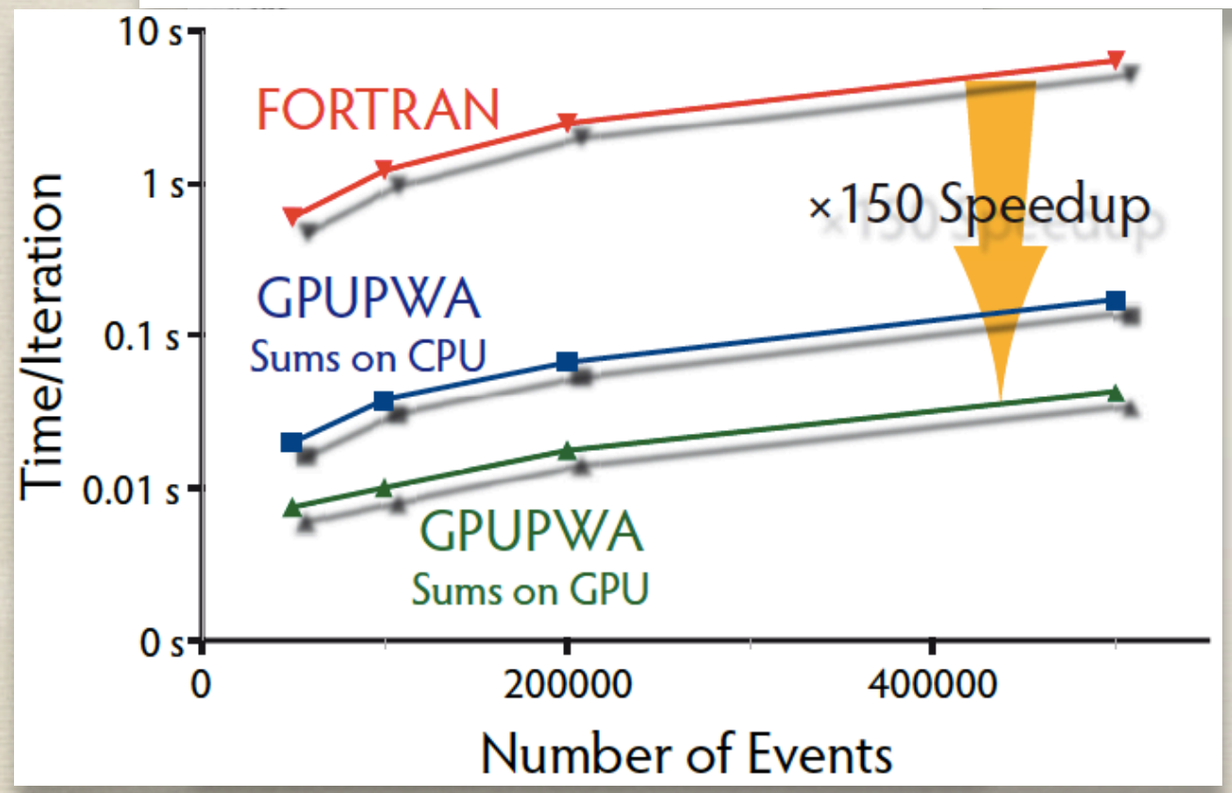
evolution in statistics $\pi^- p \rightarrow \pi^-\pi^+\pi^- p$

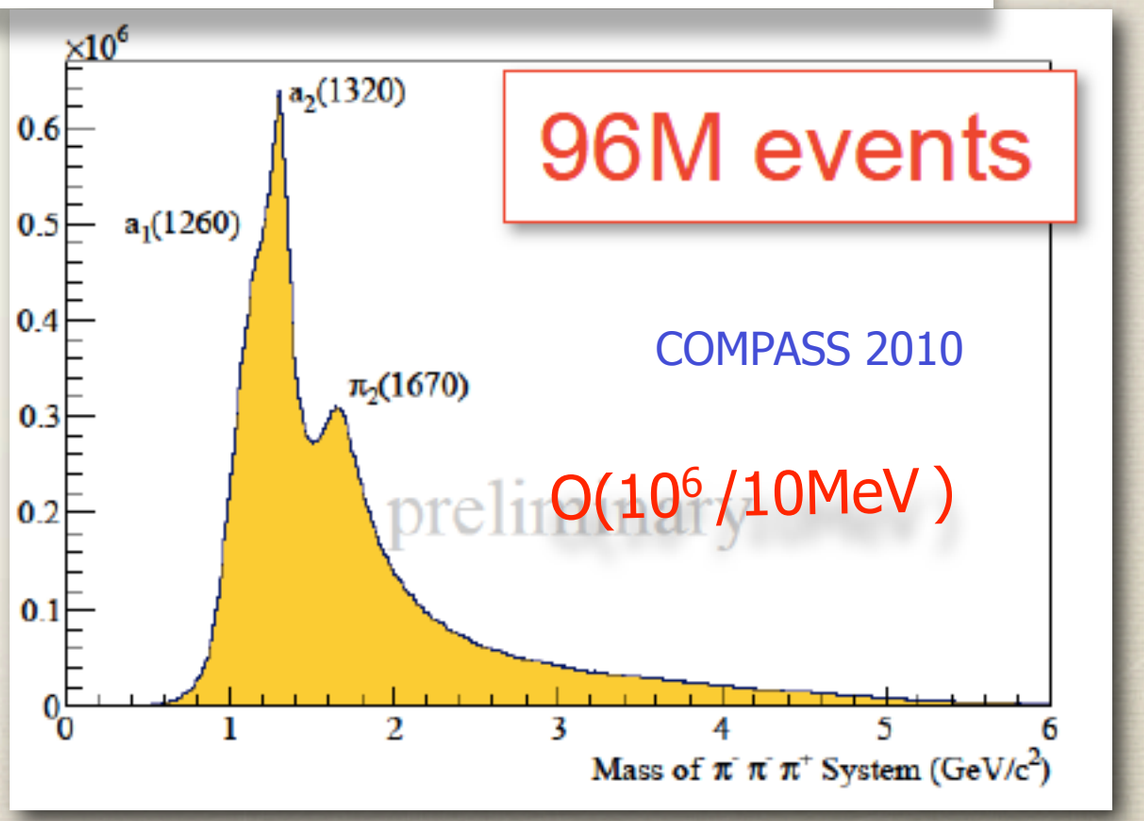




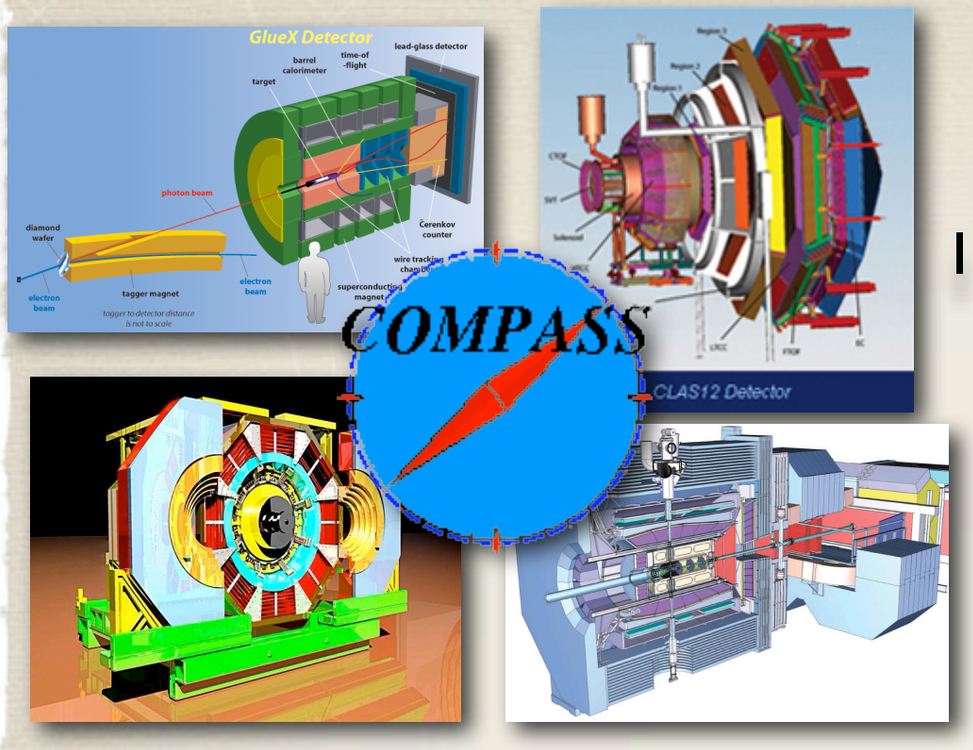
Graphics Processor

- Almost infinite floating-point power
- Fast communication with CPU
- Short latency

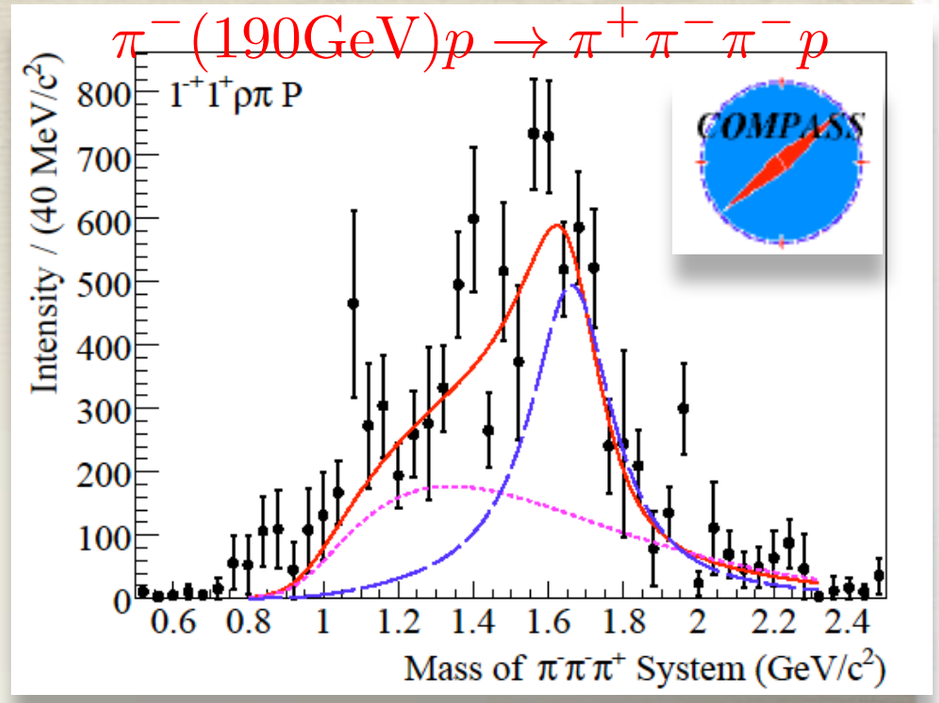




Amplitude Analysis: Major challenge

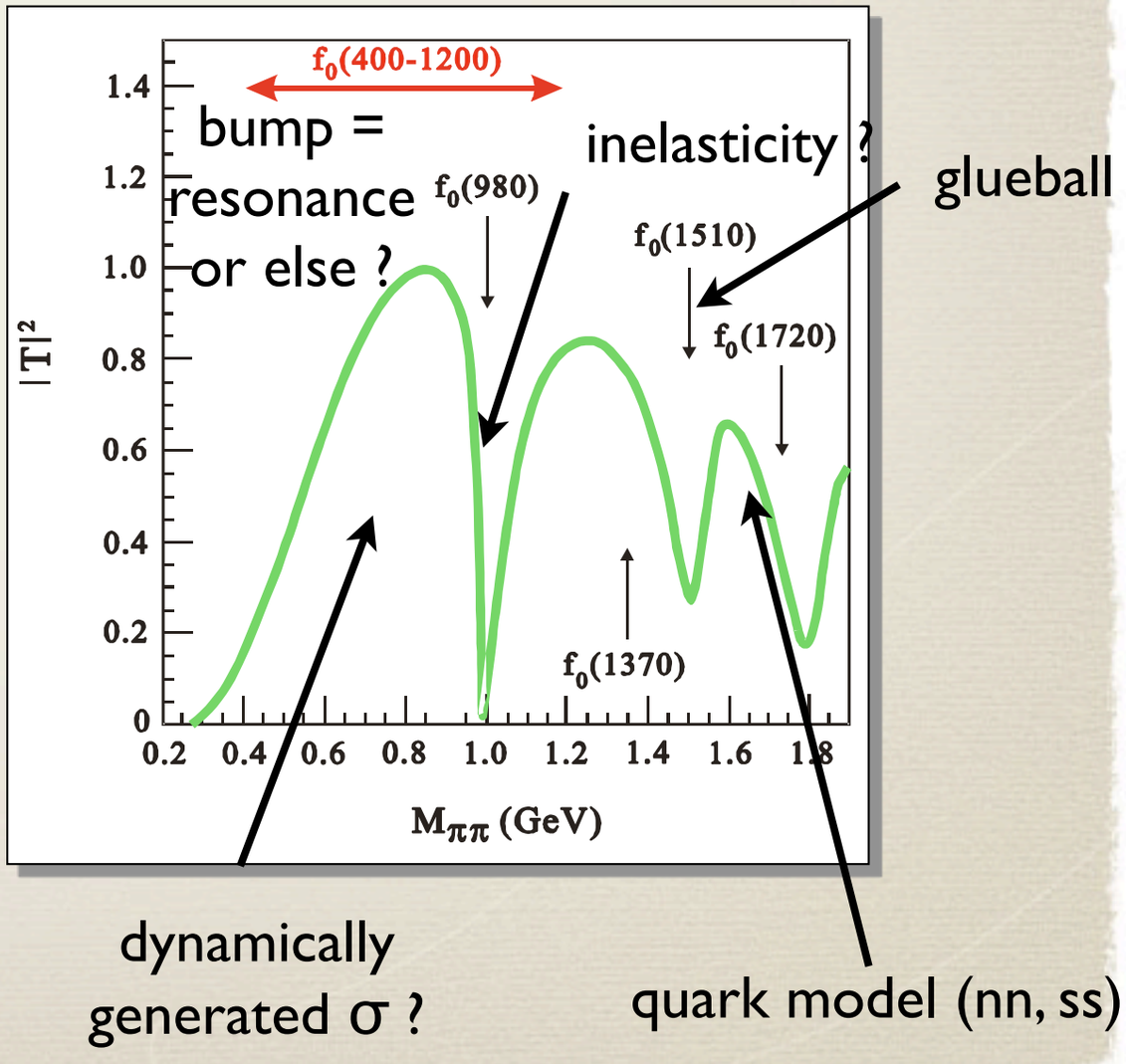


I Amplitude extraction is model dependent



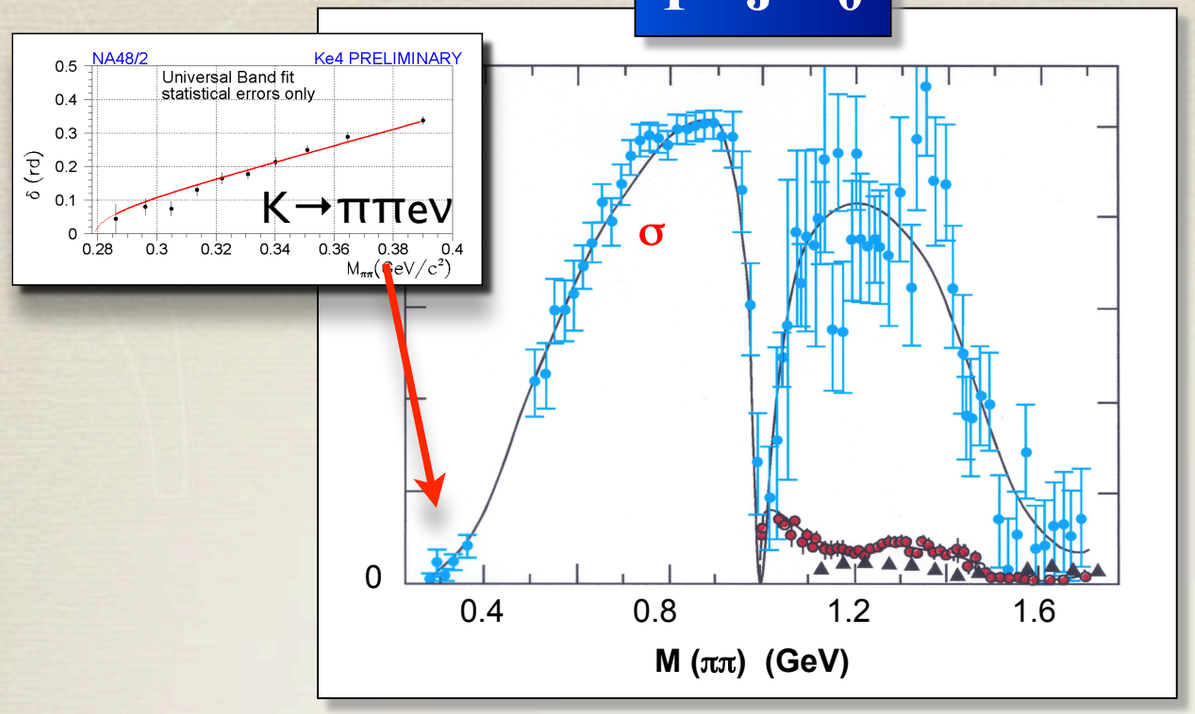
2. Analytical continuation to complex energy plane is needed to extract resonance parameters

3. Finally connection between S-matrix poles and QCD: lattice, models needs to be made



1. precision data

I = J = 0



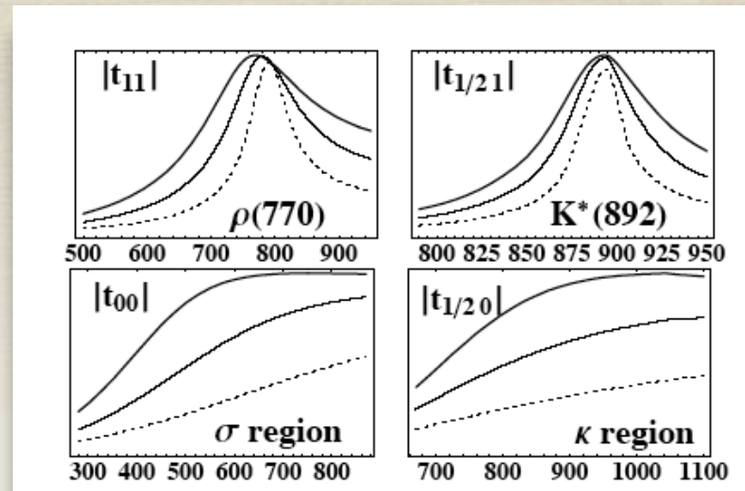
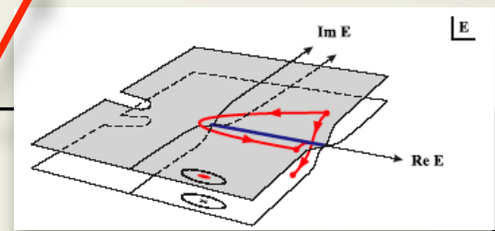


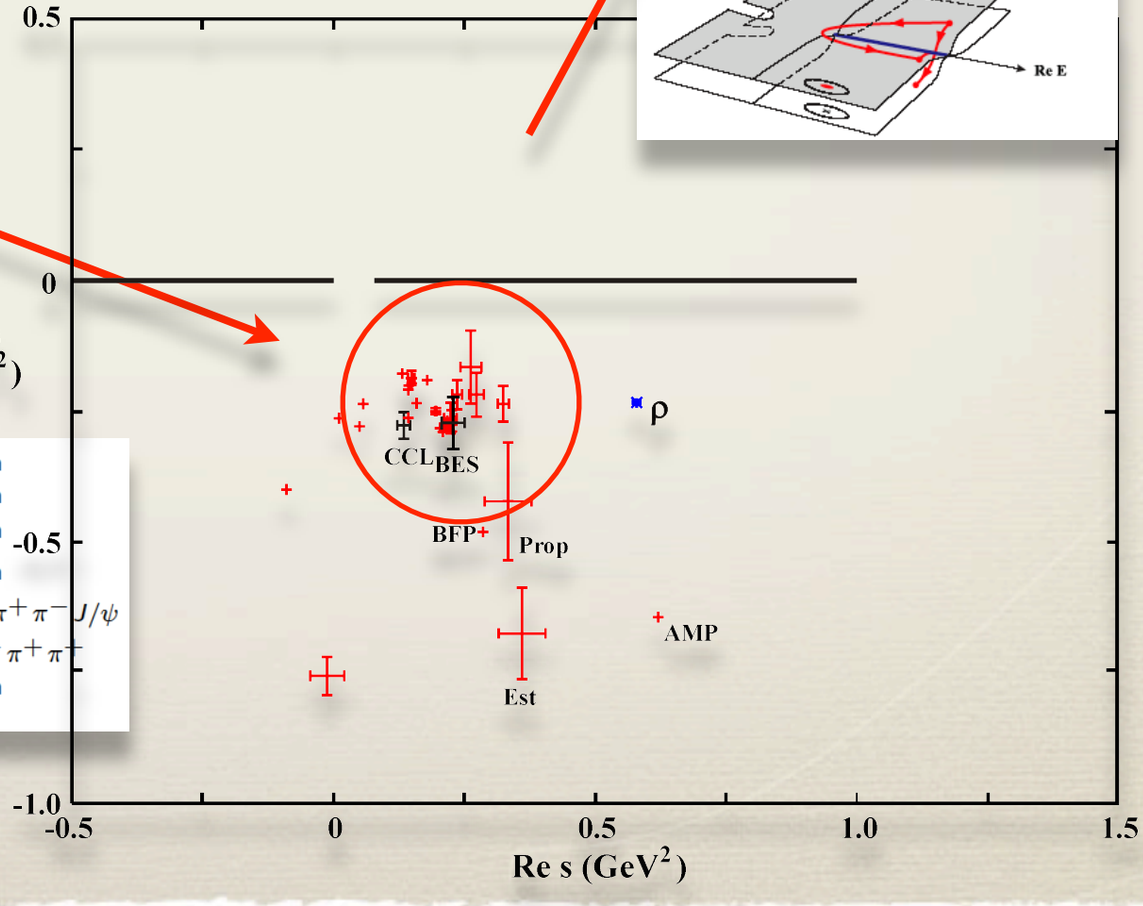
FIG. 1: Modulus of amplitudes in different meson-meson channels for $N_c = 3$ (thick line) $N_c = 5$ (thin continuous line) and $N_c = 10$ (thin dotted line), scaled at $\mu = 770$ MeV.

J.Pelaez

3."microscopic" study: N_C dependence



2. dispersion relation + chiral constraints give precise determination of the σ resonance



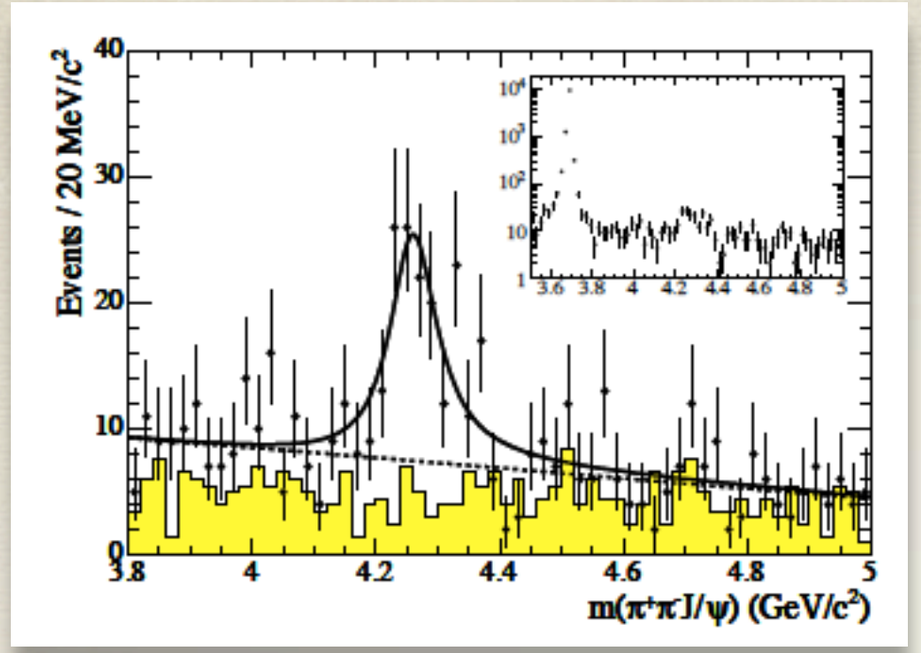
$(452 \pm 13) - i(259 \pm 16)$	1 MENNESSIER	10	RVUE	Compilation
$(448 \pm 43) - i(266 \pm 43)$	2 MENNESSIER	10	RVUE	Compilation
$(455 \pm 6^{+31}_{-13}) - i(556 \pm 12^{+68}_{-86})$	3 CAPRINI	08	RVUE	Compilation
$(463 \pm 6^{+31}_{-17}) - i(518 \pm 12^{+66}_{-68})$	4 CAPRINI	08	RVUE	Compilation
$(552^{+84}_{-106}) - i(232^{+81}_{-72})$	5 ABLIKIM	07A	BES2	$\psi(2S) \to \pi^+\pi^- J/\psi$
$(466 \pm 18) - i(223 \pm 28)$	6 BONVICINI	07	CLEO	$D^+ \to \pi^-\pi^+\pi^+$
$(472 \pm 30) - i(271 \pm 30)$	7 BUGG	07A	RVUE	Compilation
$(484 \pm 17) - i(255 \pm 10)$	GARCIA-MAR..	07	RVUE	$Ke4$

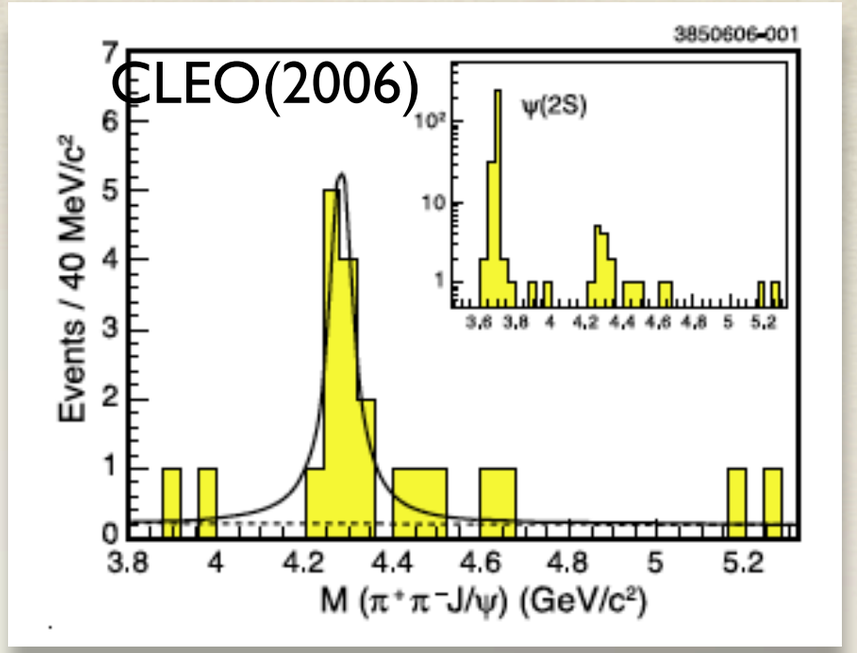
Amir Fariborz (Hadron Spectroscopy, Friday)

Hunting for the hybrid meson

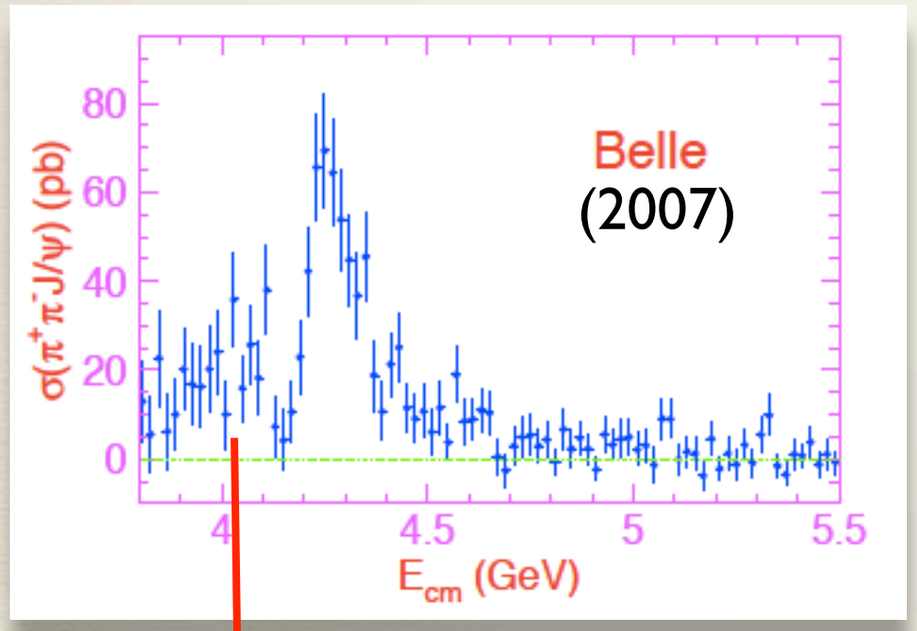
- Y(4260) discovered by BaBar in J/ψ $\pi^+\pi^-$ (2005) confirmed by CLEO,Belle other modes from BaBar

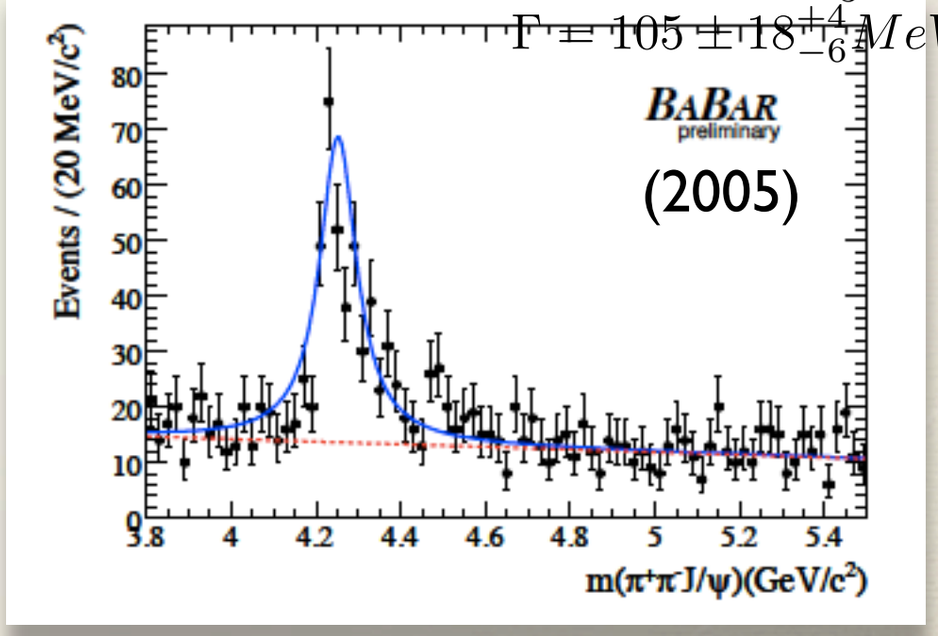
  $J^{PC}=1^{--}$ (from e^+e^-) width O(100MeV)





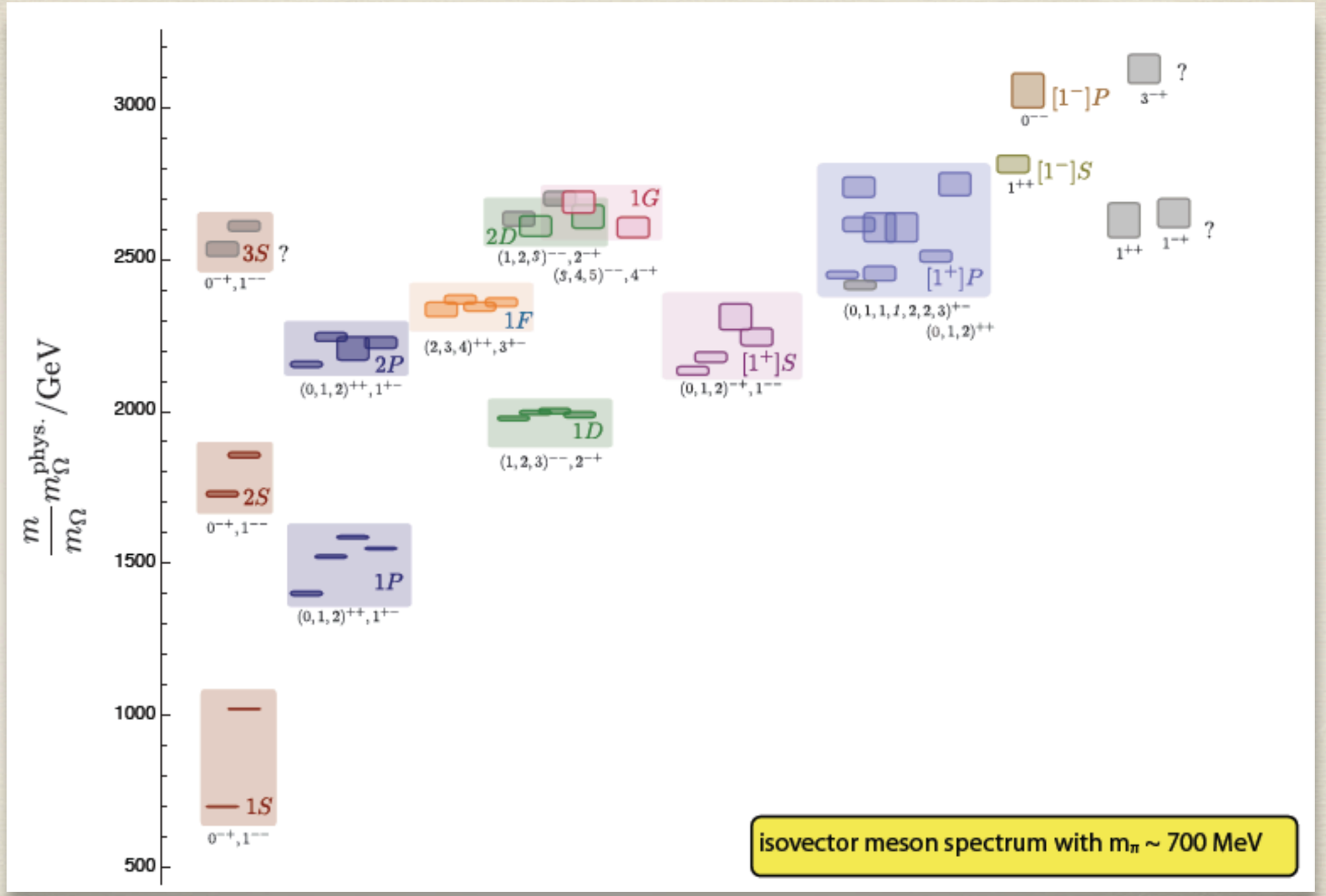
$$M = 4252 \pm 6^{+2}_{-3} MeV$$
$$\Gamma = 105 \pm 18^{+4}_{-6} MeV$$





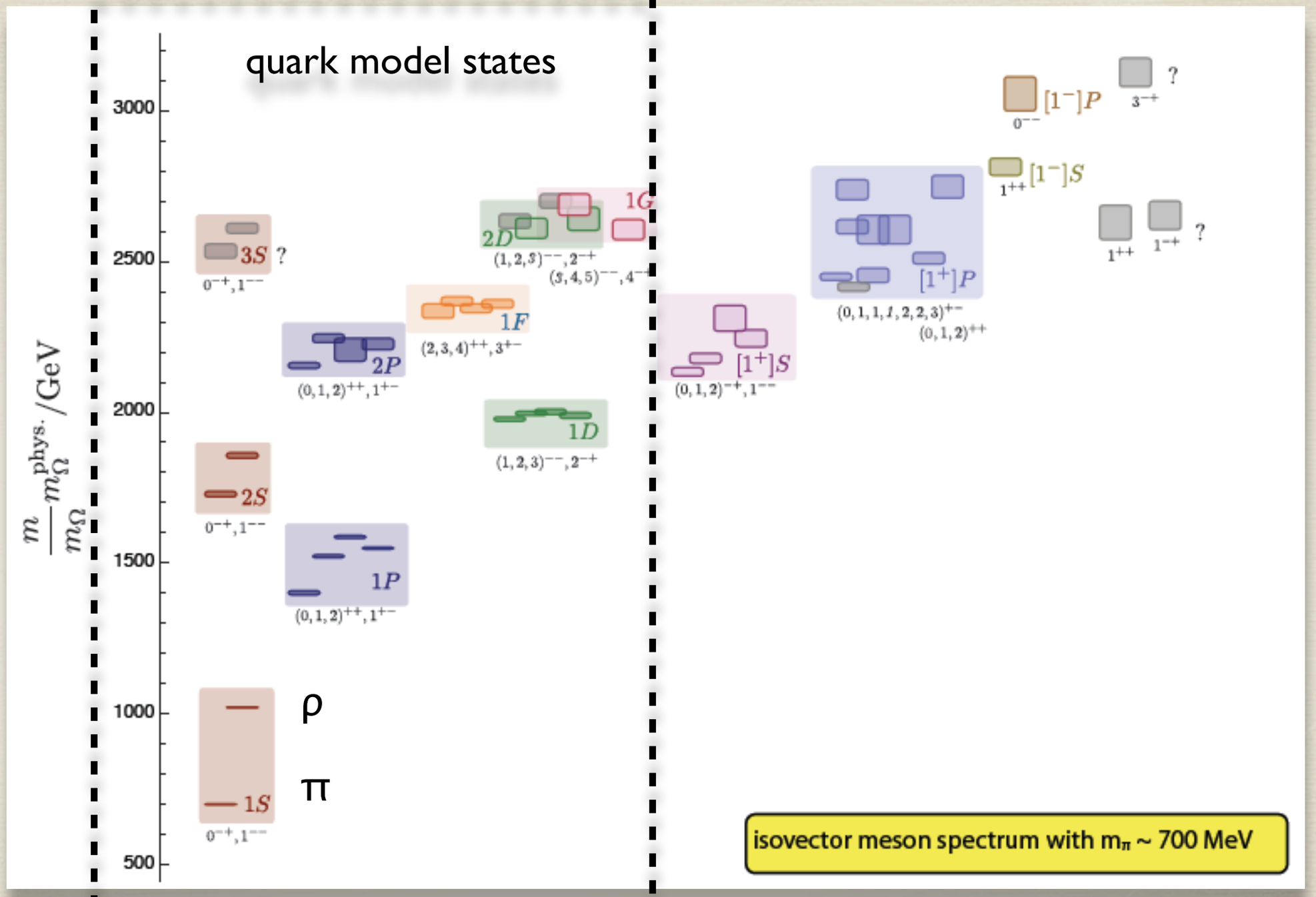
- possible Y(4050) not confirmed in BaBar
- Theory favor: Hybrid

- new multiplets from lattice



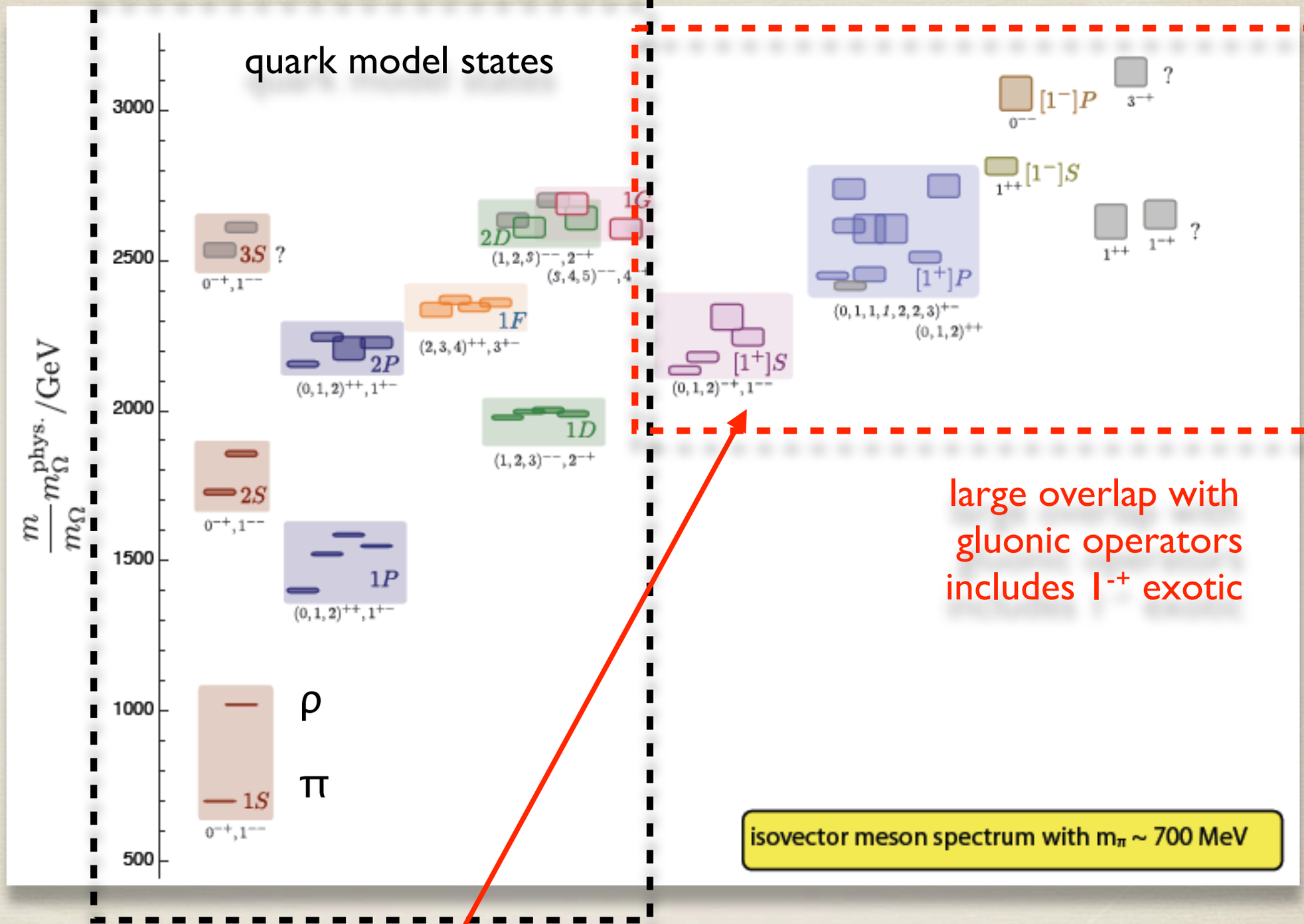
J.Dudek et al. JLab

- new multiplets from lattice



J.Dudek et al. JLab

- new multiplets from lattice



same pattern in $\bar{s}s$, $\bar{c}c$

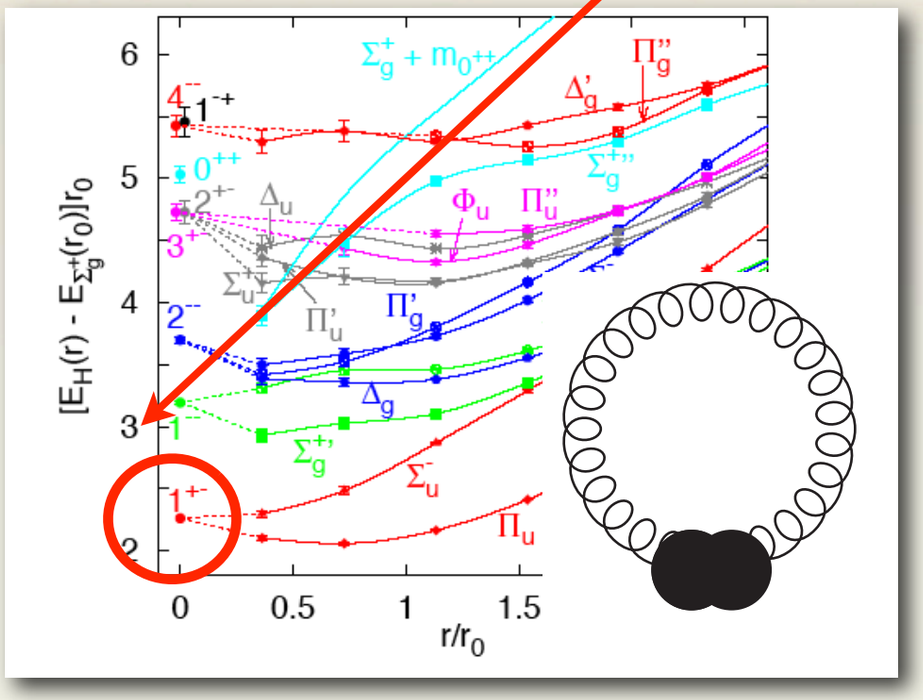
hybrid interpretation of the Y(4260)

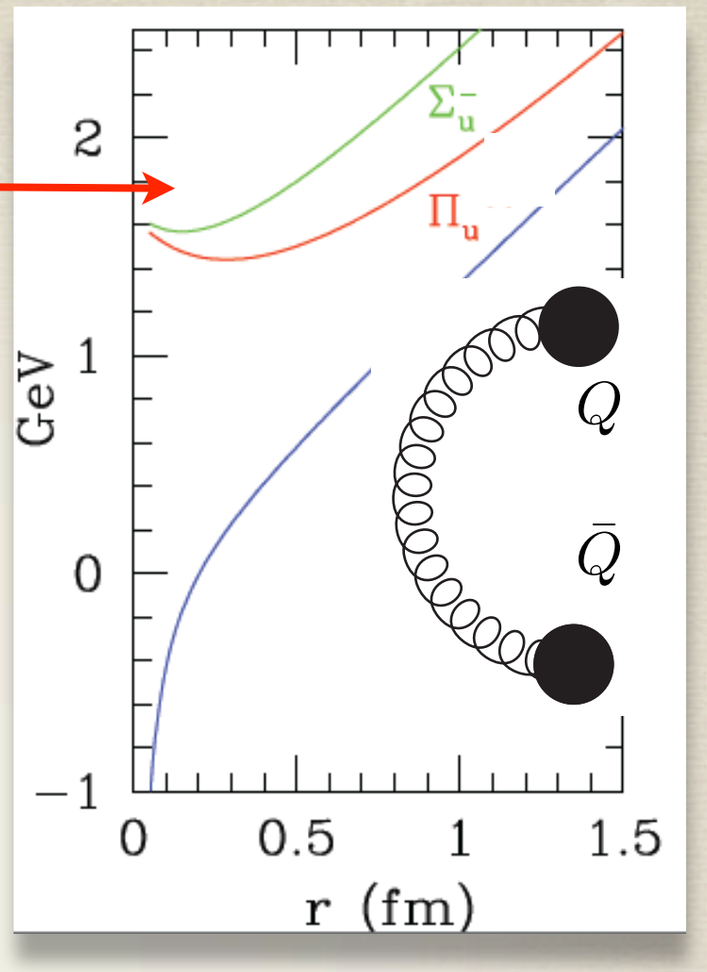
J.Dudek et al. JLab

* lowest quasi-gluon eigenstate in presence of static source has $J^{PC}=1^{+-}$ quantum numbers

(one unit of orbital angular momentum)

$P_g=1^+$



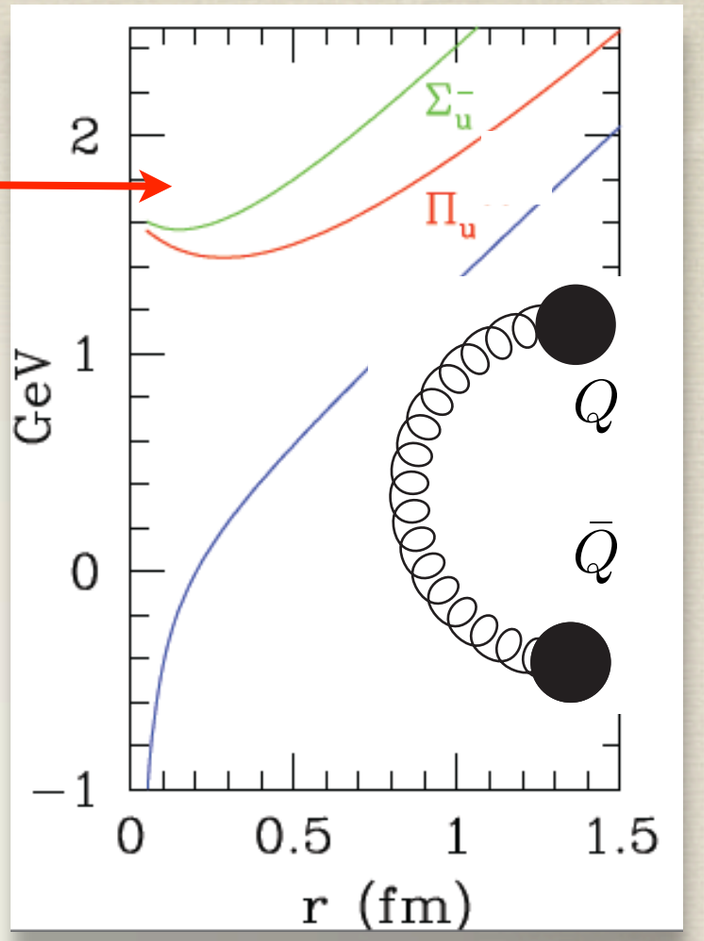


C.Morningstar et al,
G.Ball.

* lowest quasi-gluon eigenstate in presence of static source has $J^{PC}=1^{+-}$ quantum numbers

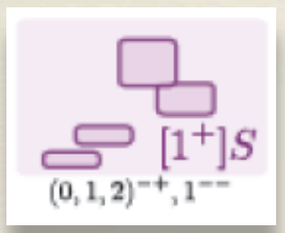
(one unit of orbital angular momentum)

$P_g=1^+$



C.Morningstar et al,
G.Ball.

* hybrid "="



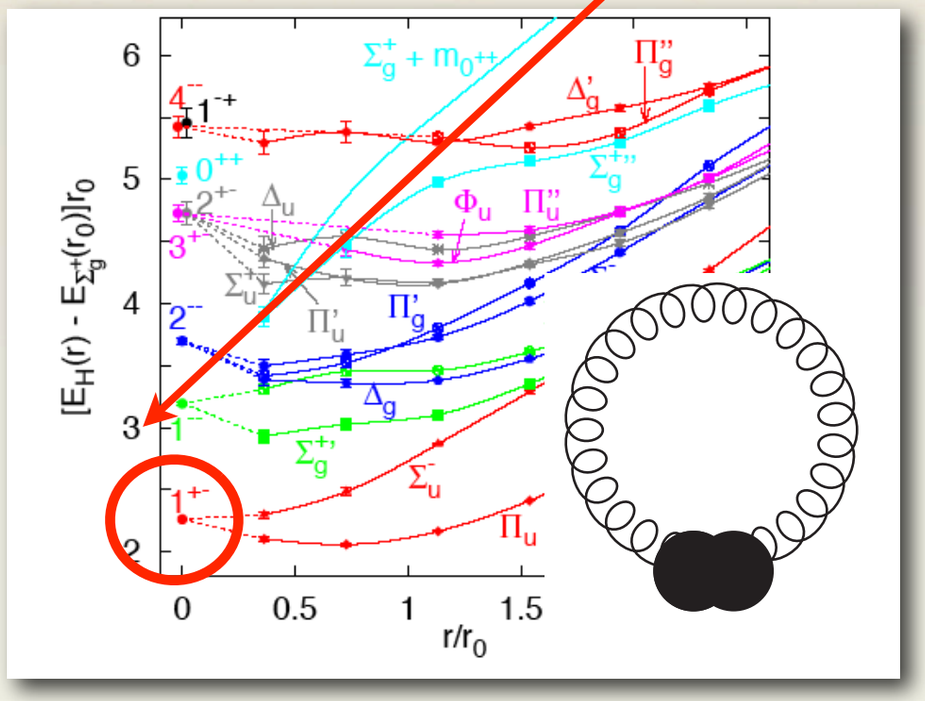
J^{PC} glue

J^{PC} $Q\bar{Q}$ 1^{--}

$$1^{+-} \times 0^{-+}_{S_{Q\bar{Q}}} = \boxed{1^{--}}$$

$$1^{+-} \times 1^{--}_{S_{Q\bar{Q}}=1} =$$

$$\boxed{0^{-+}, 1^{-+}, 2^{-+}}$$

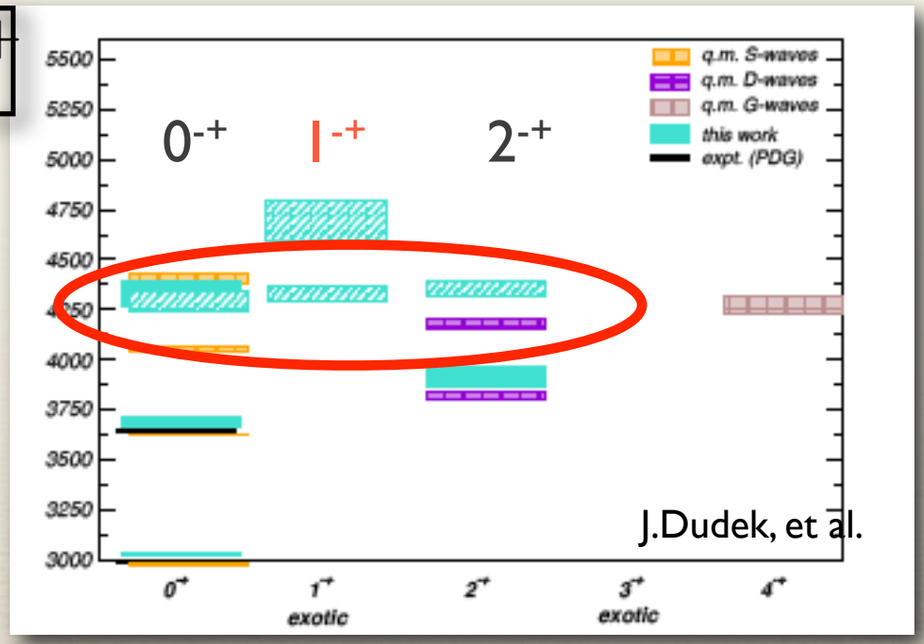


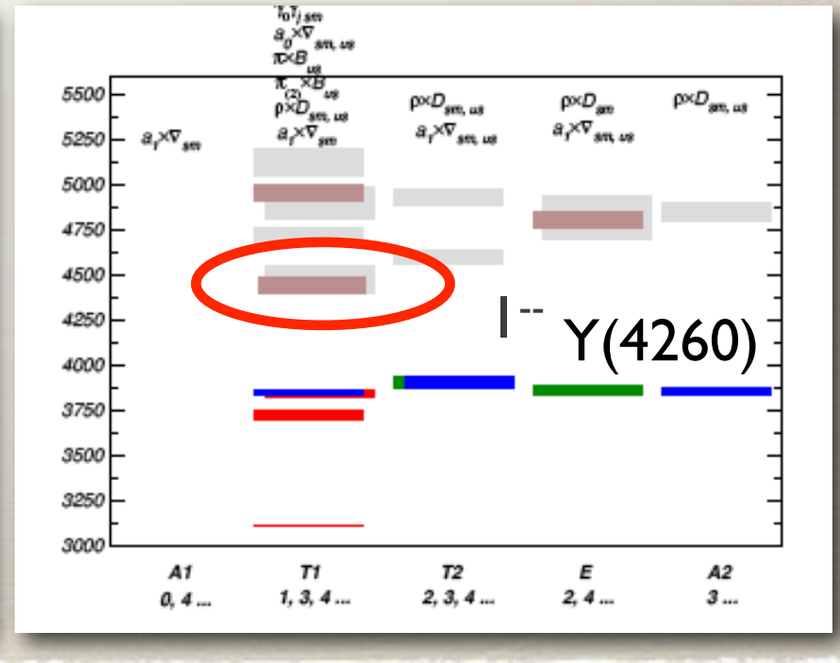
From (variational)
QCD in the Coulomb gauge

P.Guo, et al.

also from other models

J.Dudek, et al.

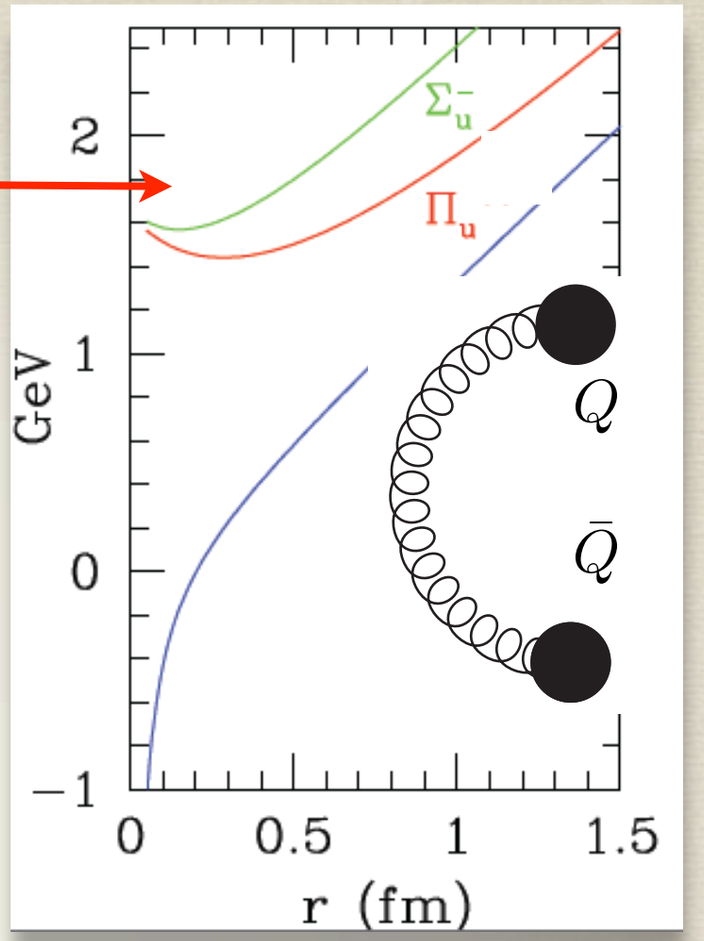




* lowest quasi-gluon eigenstate in presence of static source has $J^{PC}=1^{+-}$ quantum numbers

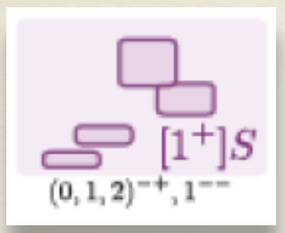
(one unit of orbital angular momentum)

$P_g=1^+$



C.Morningstar et al,
G.Ball.

* hybrid "="



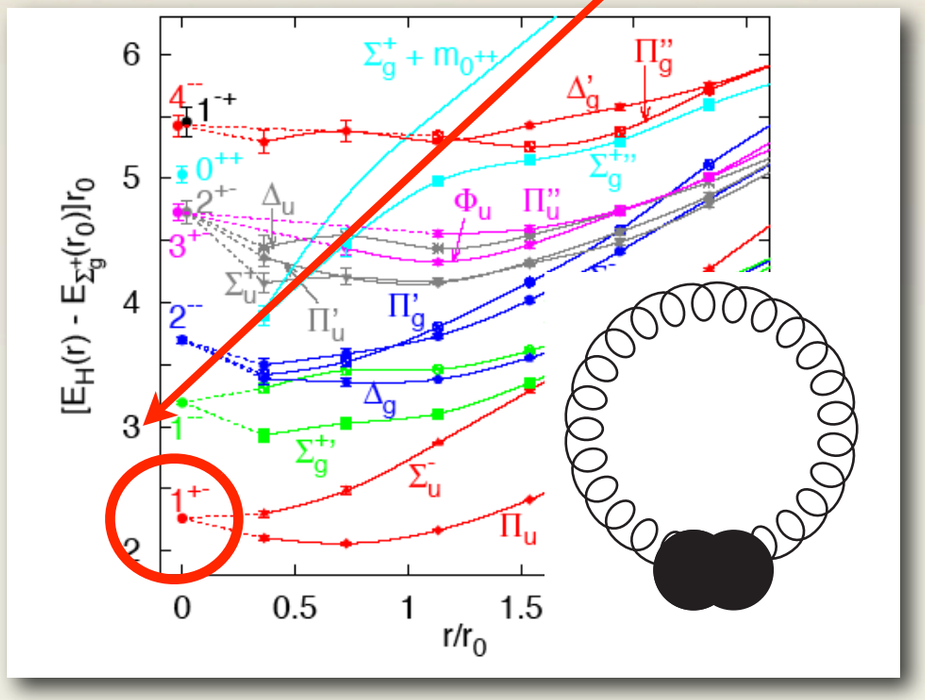
J^{PC} glue

J^{PC} $Q\bar{Q}$ 1^{--}

$$1^{+-} \times 0^{-+}_{S_{Q\bar{Q}}} = \boxed{1^{--}}$$

$$1^{+-} \times 1^{--}_{S_{Q\bar{Q}}=1} =$$

$$\boxed{0^{-+}, 1^{-+}, 2^{-+}}$$



$s\bar{s}$ analogue ? Y(2175)

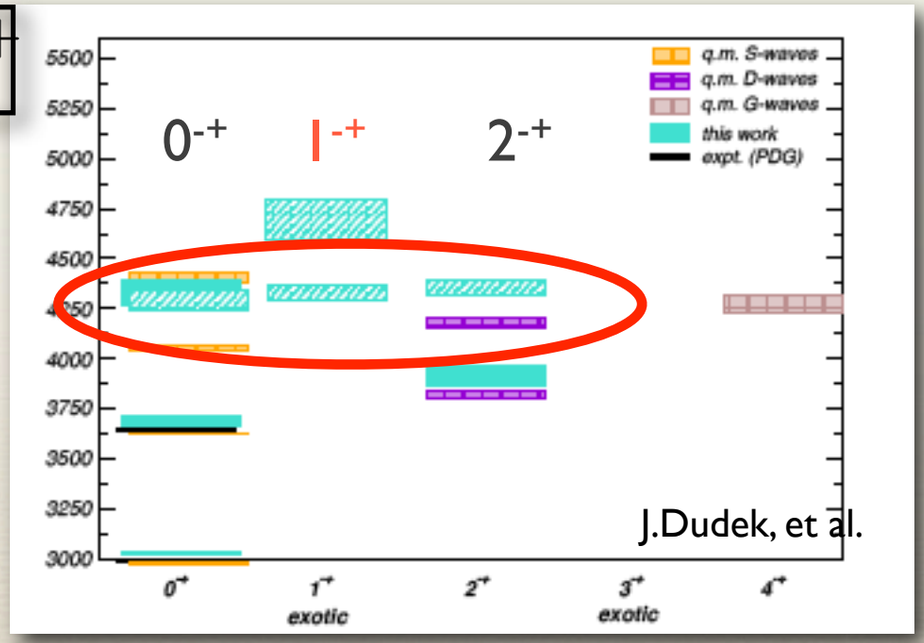
David Muller (BaBar)
(Hadron Spectroscopy, Friday)

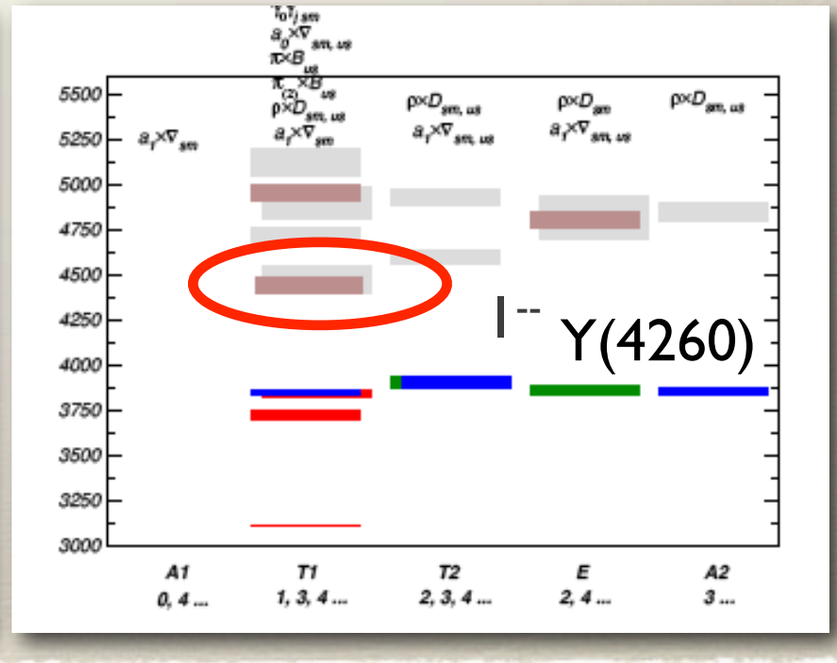
From (variational)
QCD in the Coulomb gauge

P.Guo, et al.

also from other models

J.Dudek, et al.





$\pi^- p \to \eta \pi^- p$

$M = 1370 \pm 16^{+50}_{-30}\ \mathrm{MeV}/c^2$

$\Gamma = 385 \pm 40^{+65}_{-105}\ \mathrm{MeV}/c^2$

search for
$n\bar{n}$ hybrid $\pi_1(1600)$

$\pi^- p \to \eta \pi^0 n$

No consistent B-W interpretation
possible but a weak ηπ interaction
exists and can reproduce the exotic wave

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No consistent B-W interpretation possible but a weak $\eta\pi$ interaction exists and can reproduce the exotic wave

$\pi^- p \to \eta'\pi^- p$

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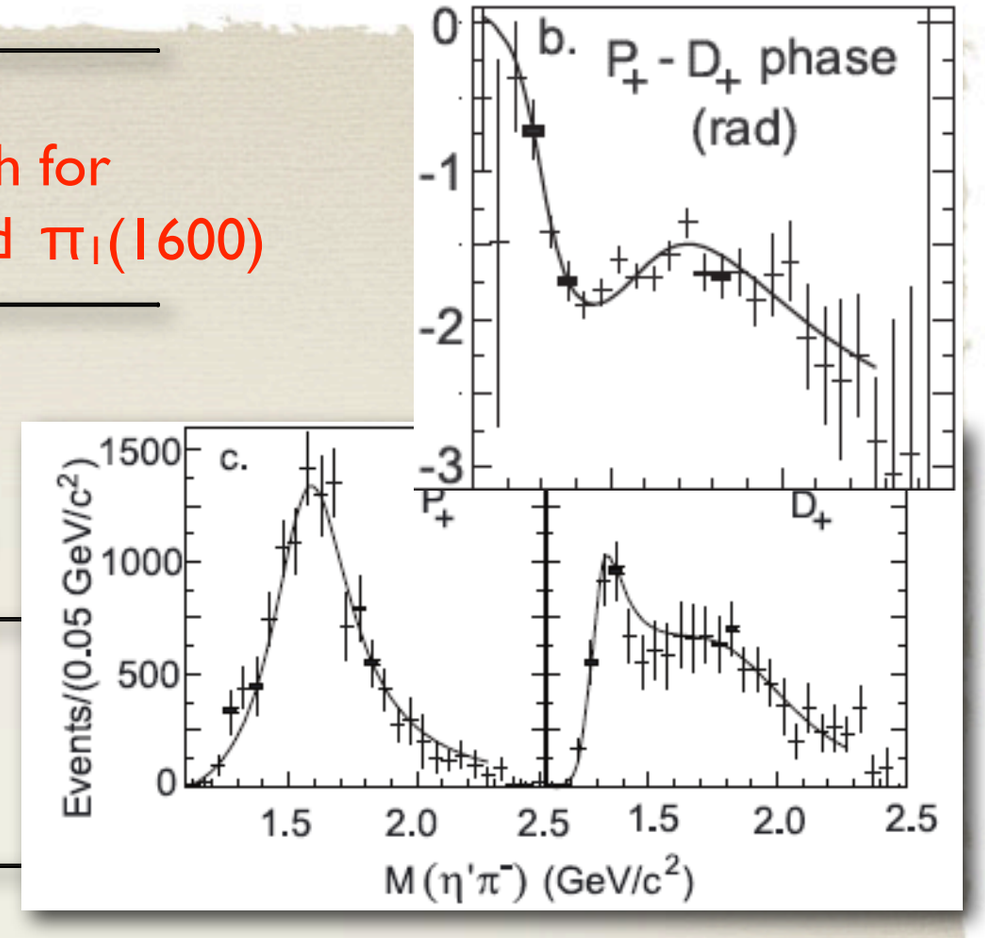
$\Gamma = 340 \pm 40^{+50}_{-50}$ MeV / c^2



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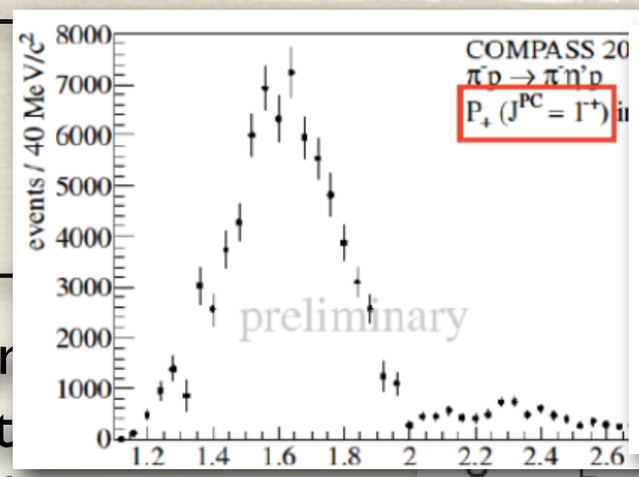

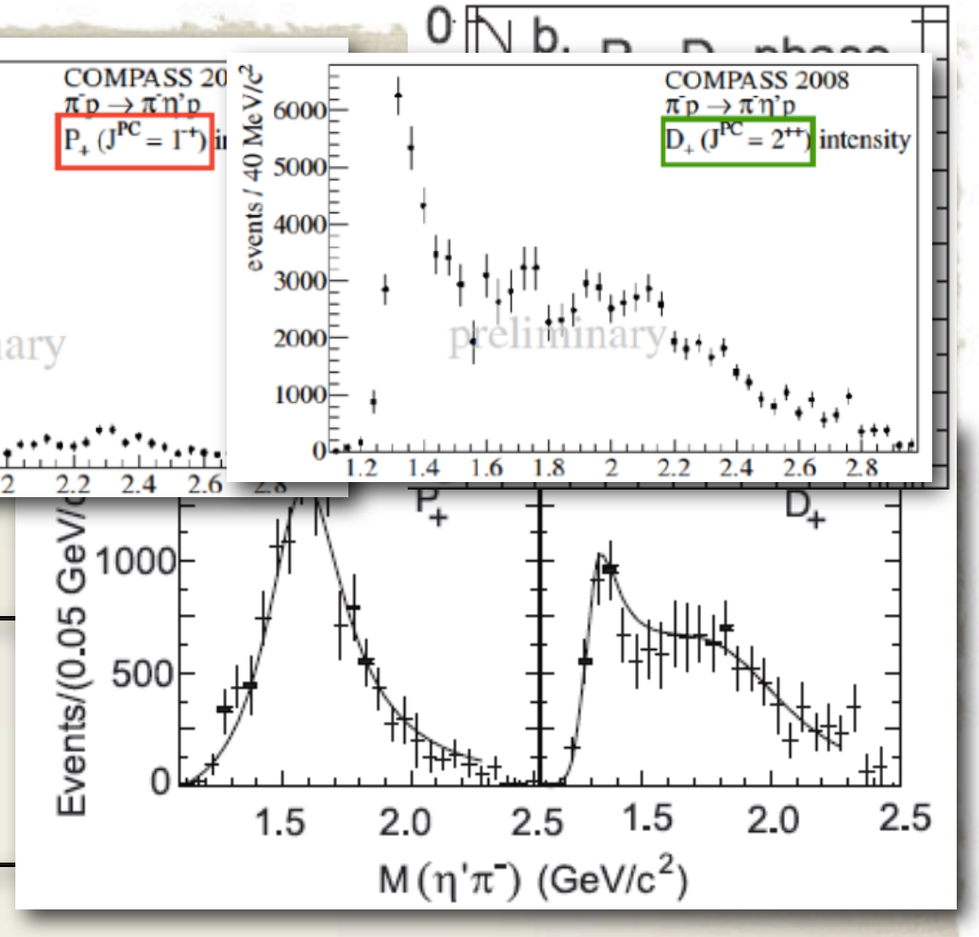

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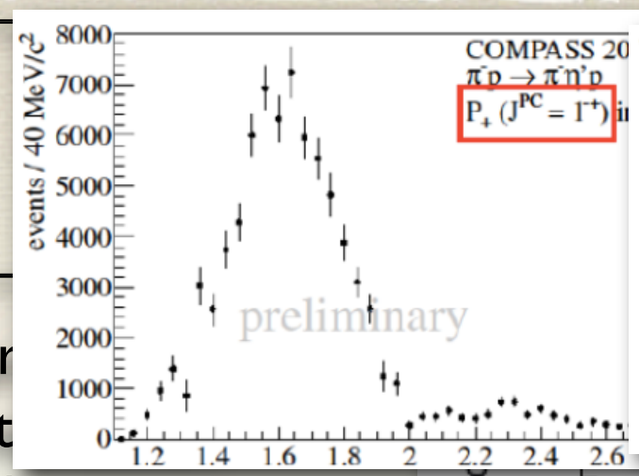

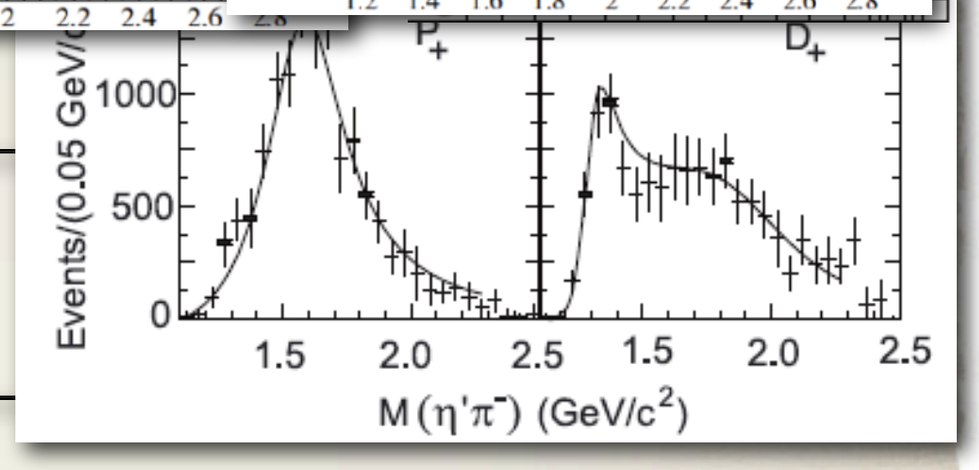

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$\pi^- p \to \rho^0 \pi^- p$

$M = 1593 \pm 8^{+29}_{-47}$ MeV / c^2

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BNL (E852) yes/no
COMPASS yes

E852 result

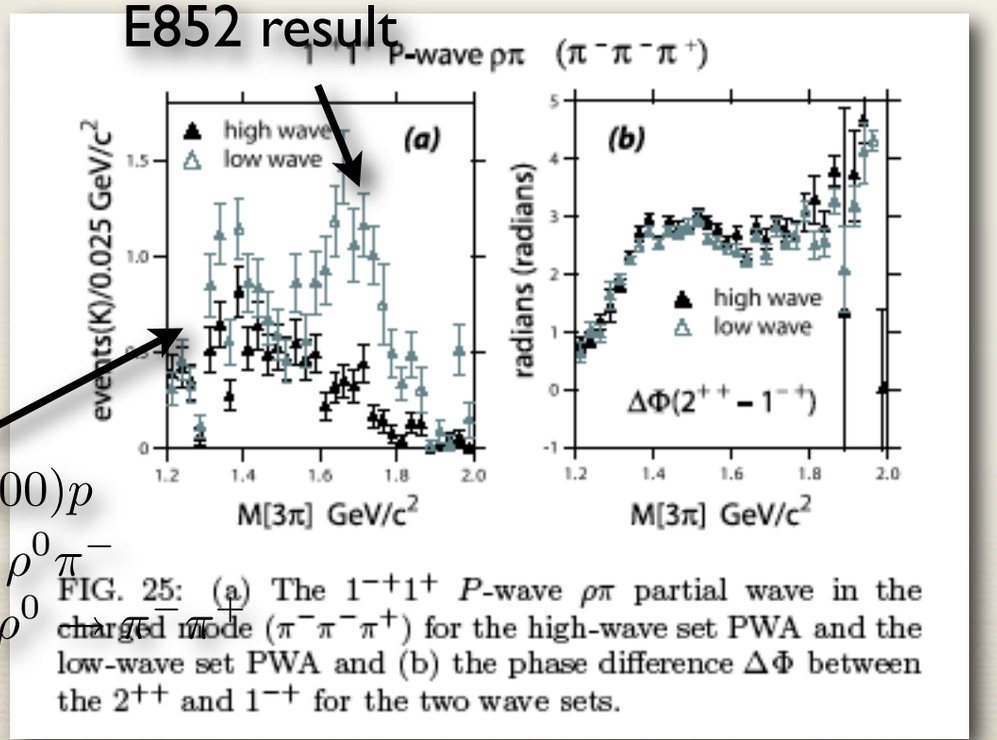

FIG. 25: (a) The $1^{-+}1^+$ P-wave $\rho\pi$ partial wave in the charged mode ($\pi^-\pi^-\pi^+$) for the high-wave set PWA and the low-wave set PWA and (b) the phase difference $\Delta\Phi$ between the 2^{++} and 1^{-+} for the two wave sets.

$\pi^- p \to \pi_2^-(1600) p$

$\pi_2^- \to \rho^0 \pi^-$

$\rho^0 \to \pi^- \pi^+$

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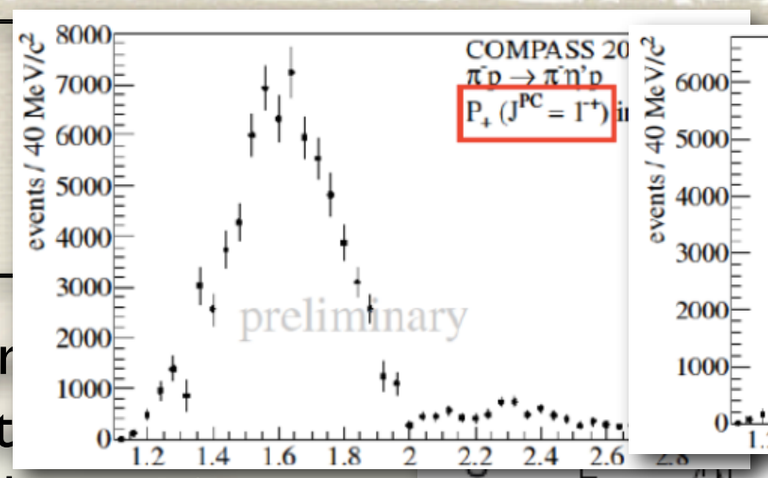

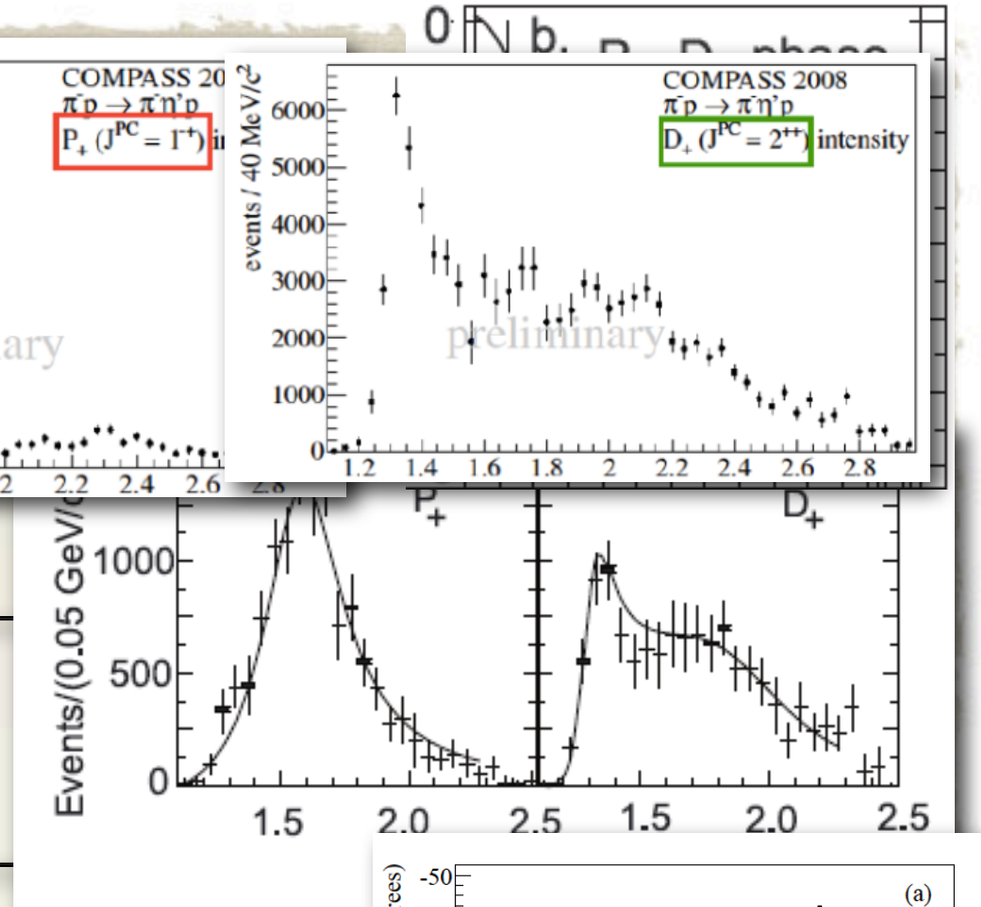

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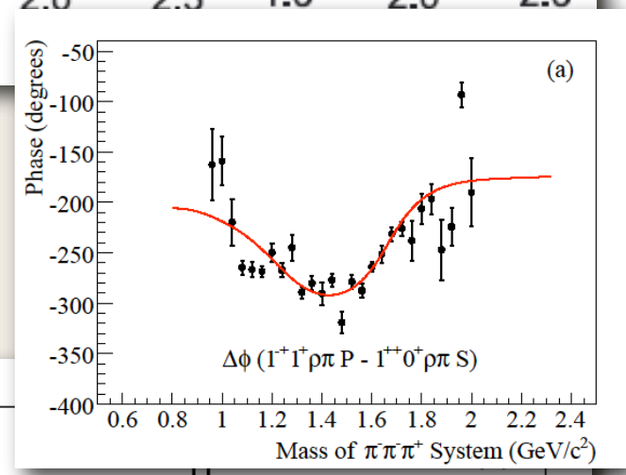
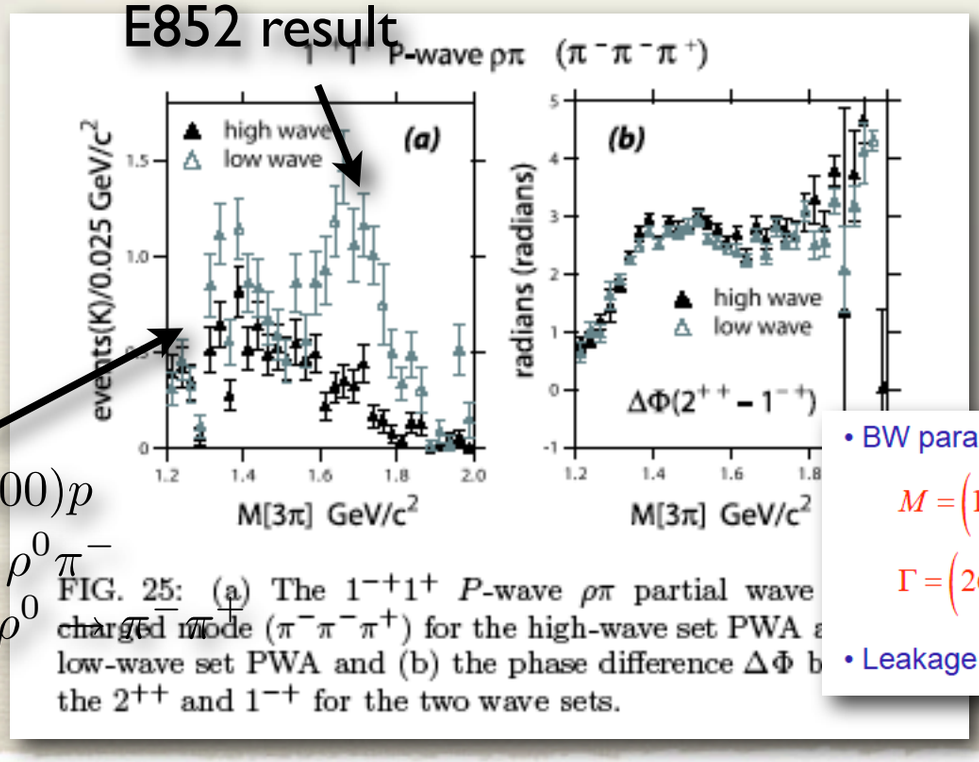


E852 result



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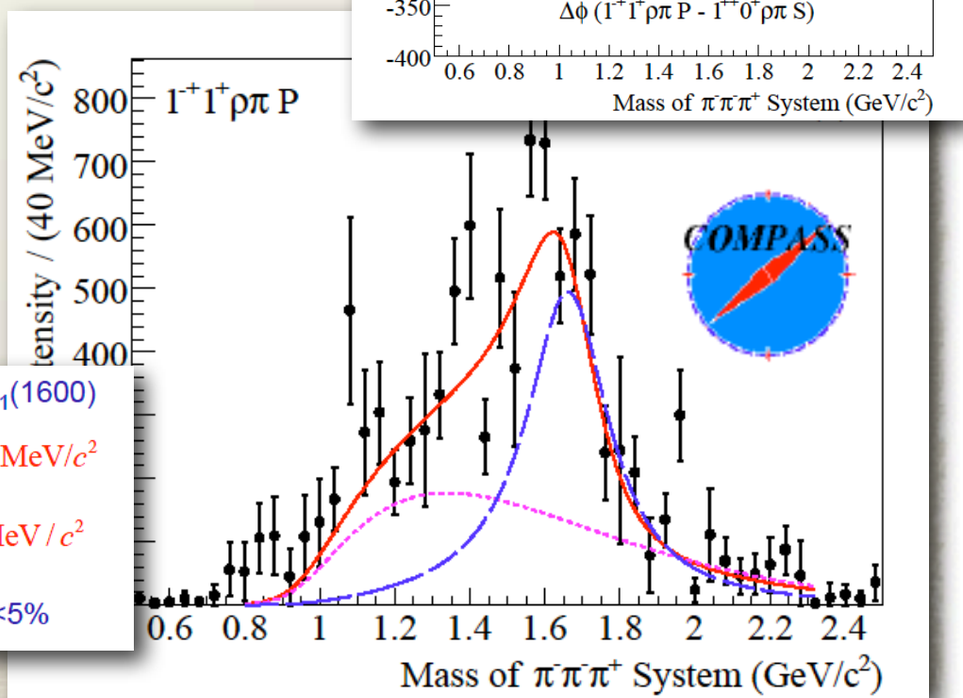
- BW parameters for $\pi_1(1600)$

$M = \left(1660 \pm 10^{+0}_{-64}\right)$ MeV/c^2

$\Gamma = \left(269 \pm 21^{+42}_{-64}\right)$ MeV / c^2

- Leakage negligible: <5%



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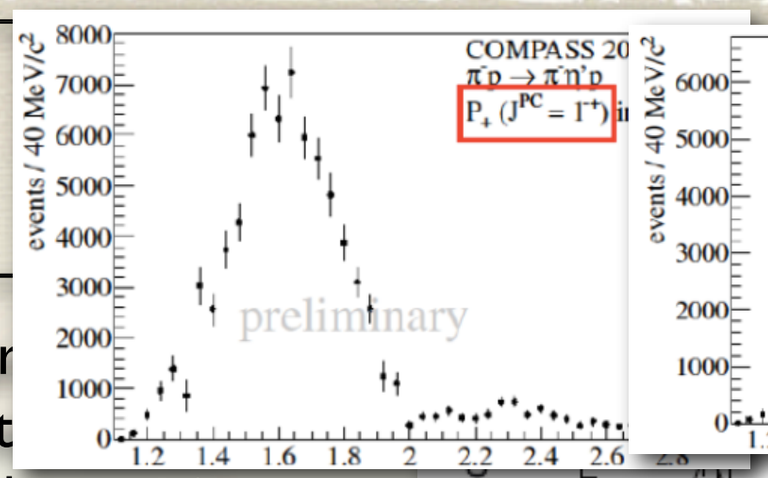

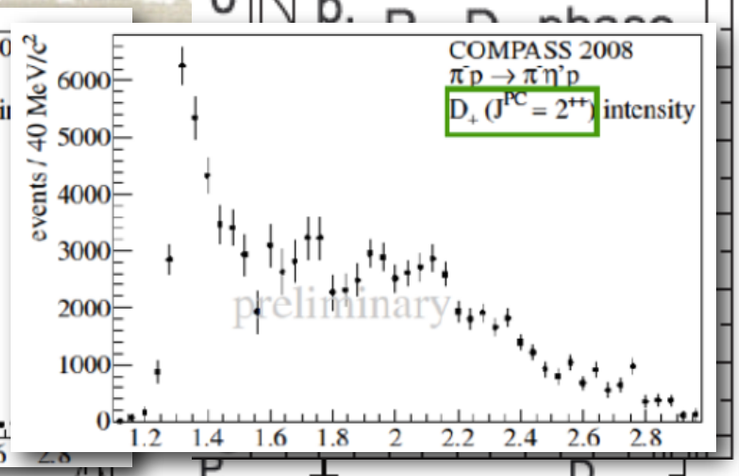

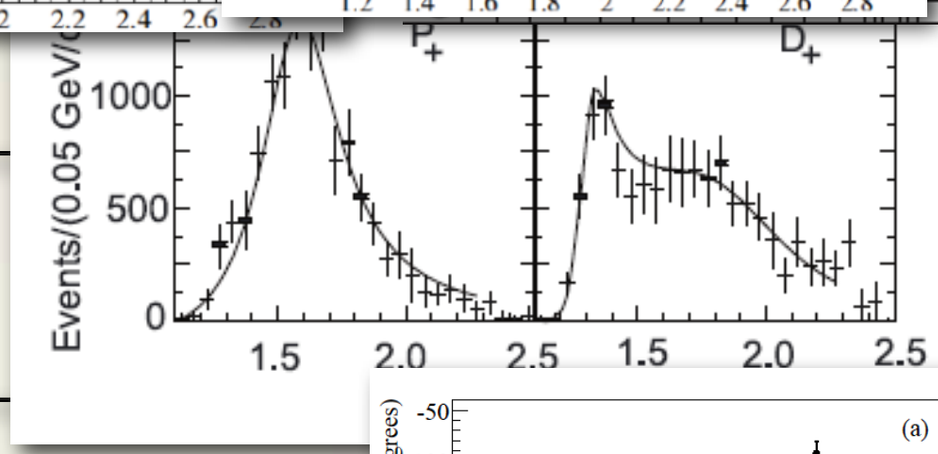

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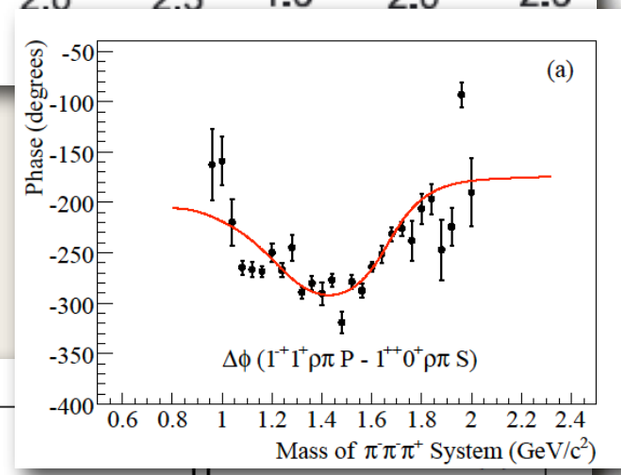
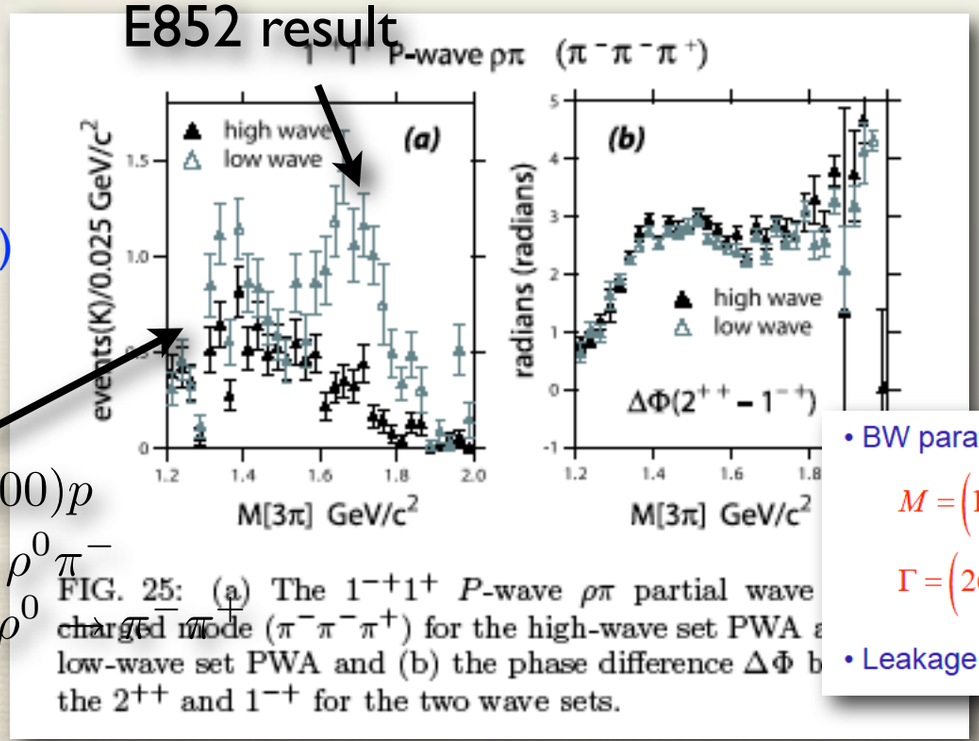


E852 result

Dennis Weygand
(Jlab)
(Hadron
Spectroscopy, Friday)



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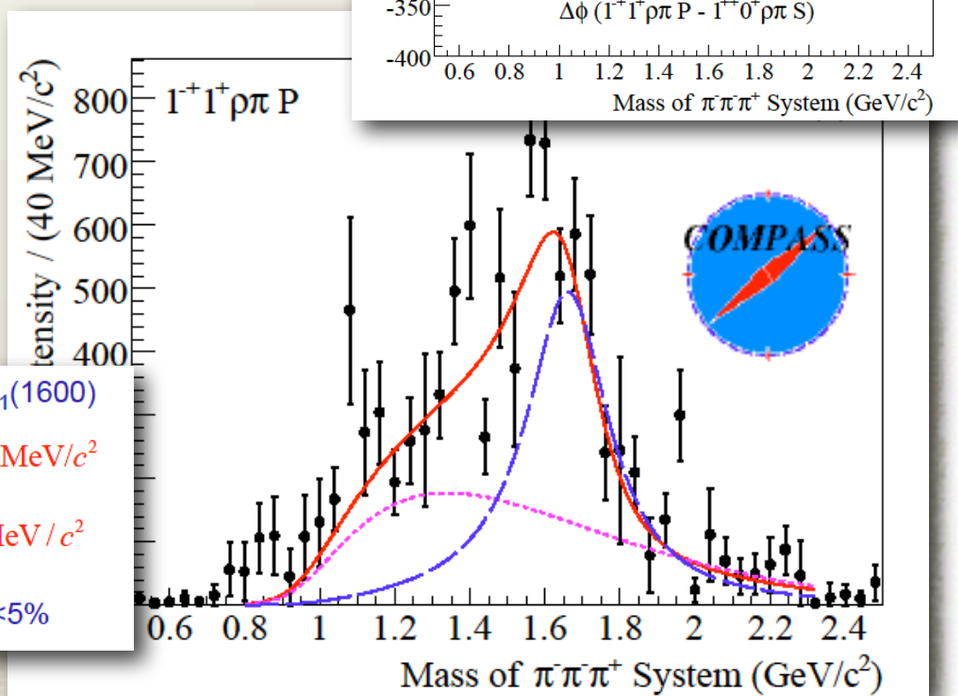
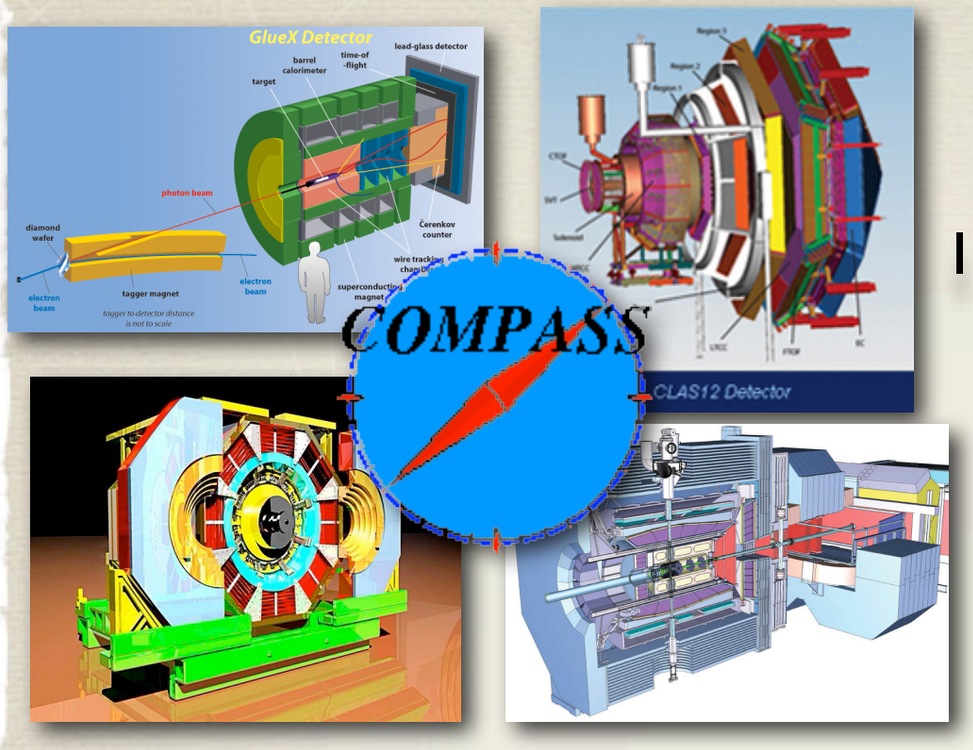
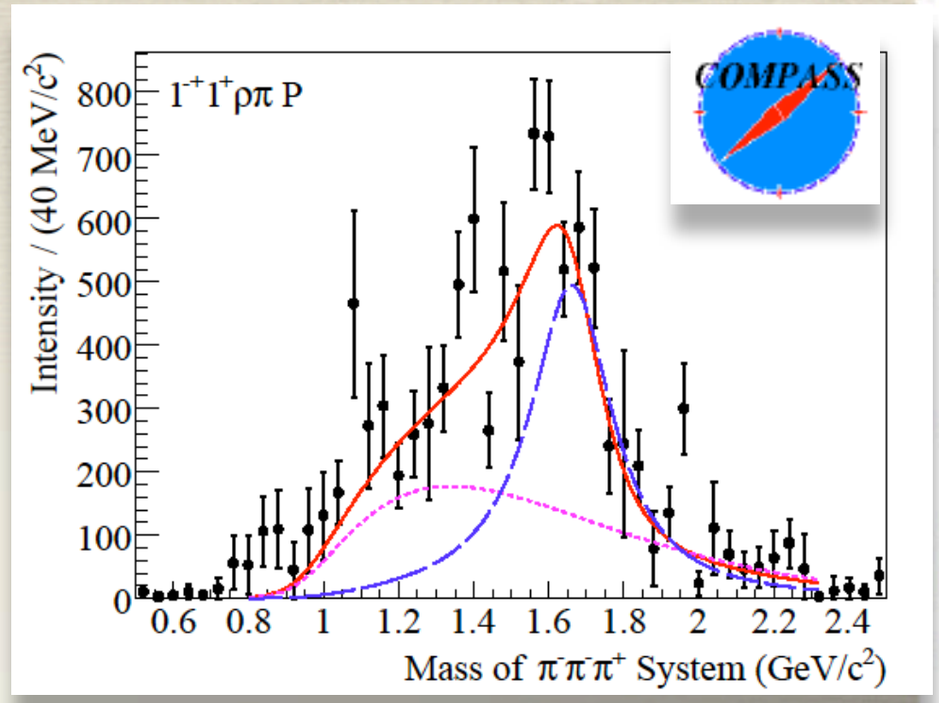


From Hadrons to QCD constituents

Major challenges

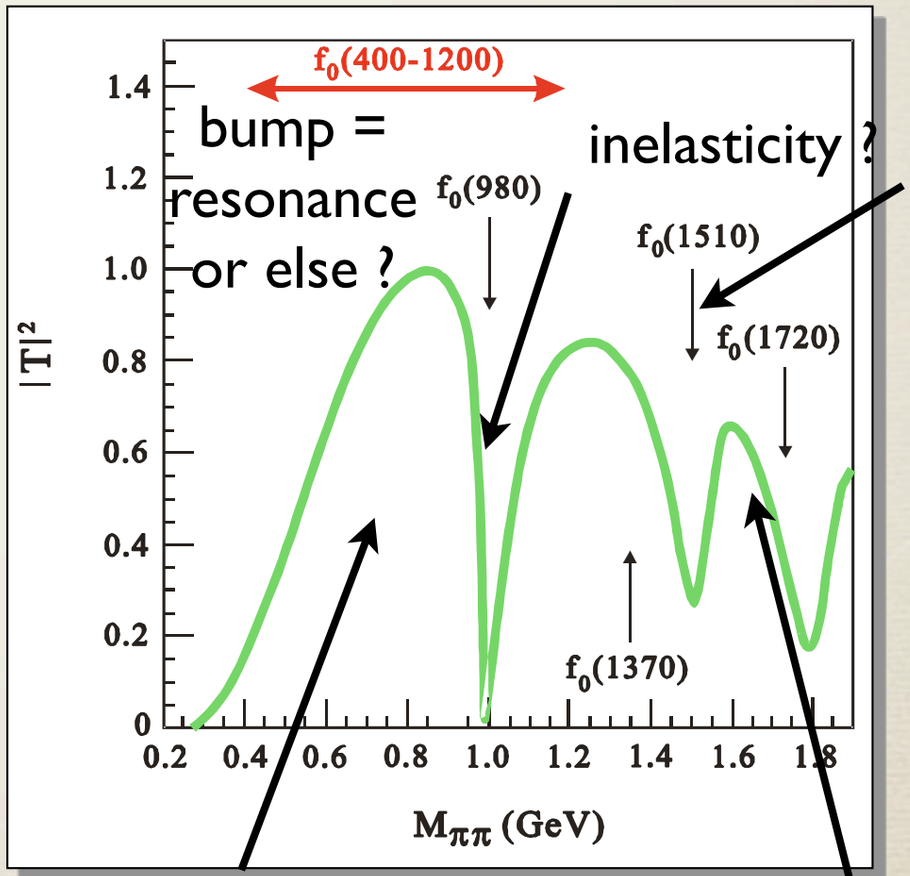


1 Amplitude extraction is model dependent



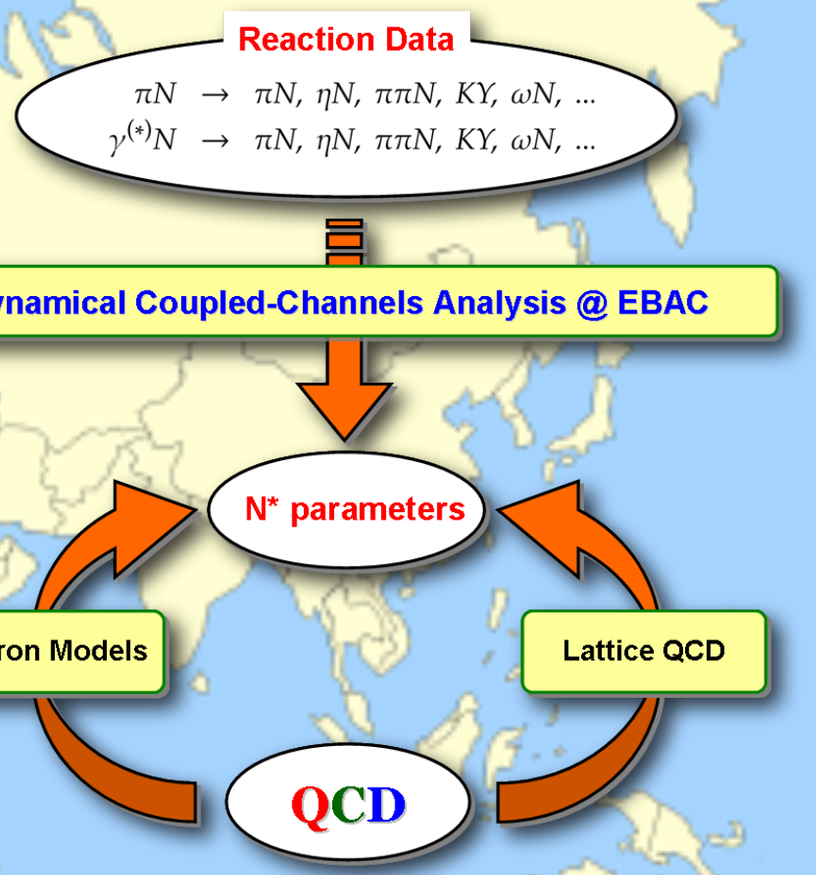
2. Analytical continuation to complex energy plane is needed to extract resonance parameters

3. Finally connection between S-matrix poles and QCD: lattice, models needs to be made



New initiatives for development of hadron spectroscopy efforts

Excited Baryon Analysis Center/JLab (EBAC)
Julich,Mainz,Giessen



Les NABIS

Extracting CP phases from Dalitz plot & CP studies (US/Germany)

Workshops/summer schools on hadronic physics and amplitude analysis
INT, ECT*, JLab

PWA-days @ JLab