Light hadron multi-quark states in charmonium decays

Mihajlo Kornicer

University of Hawaii

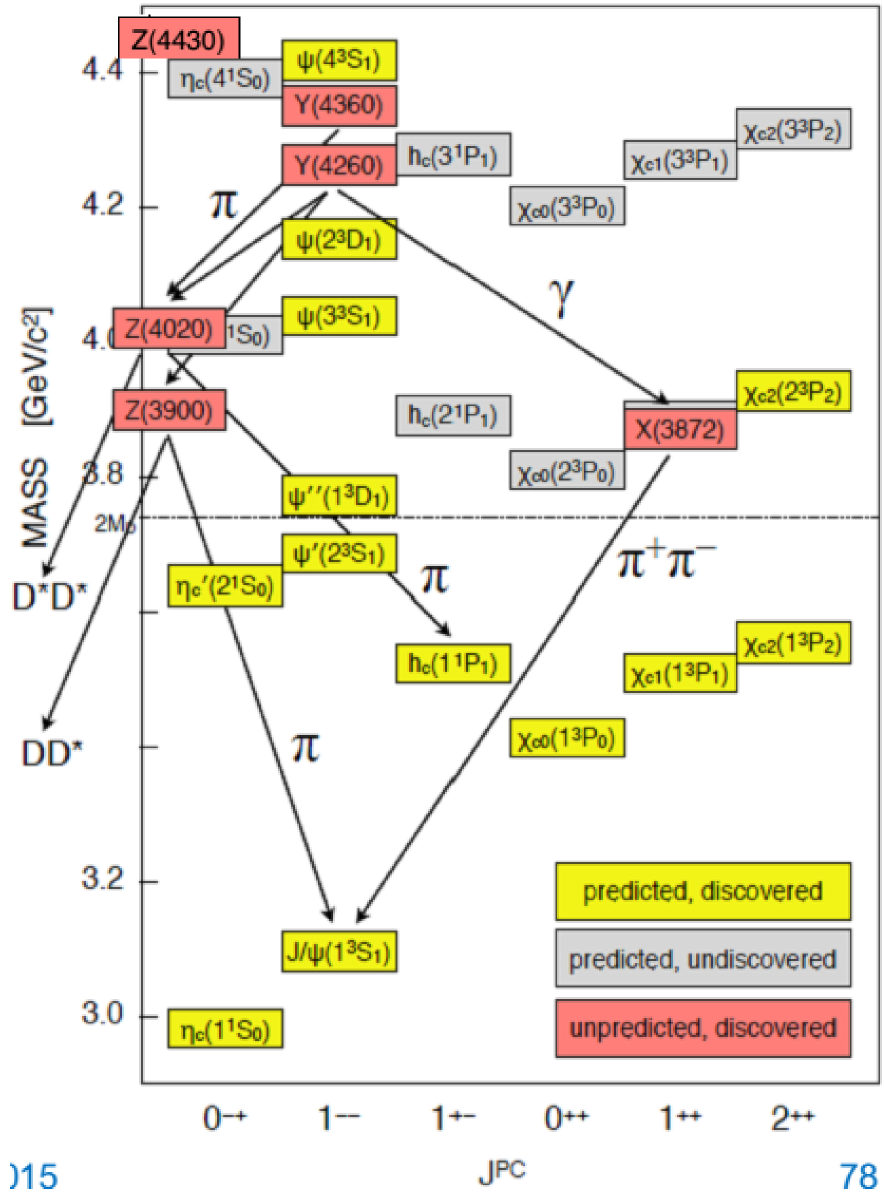
INT – Modern Exotic Hadrons 2015

Outline

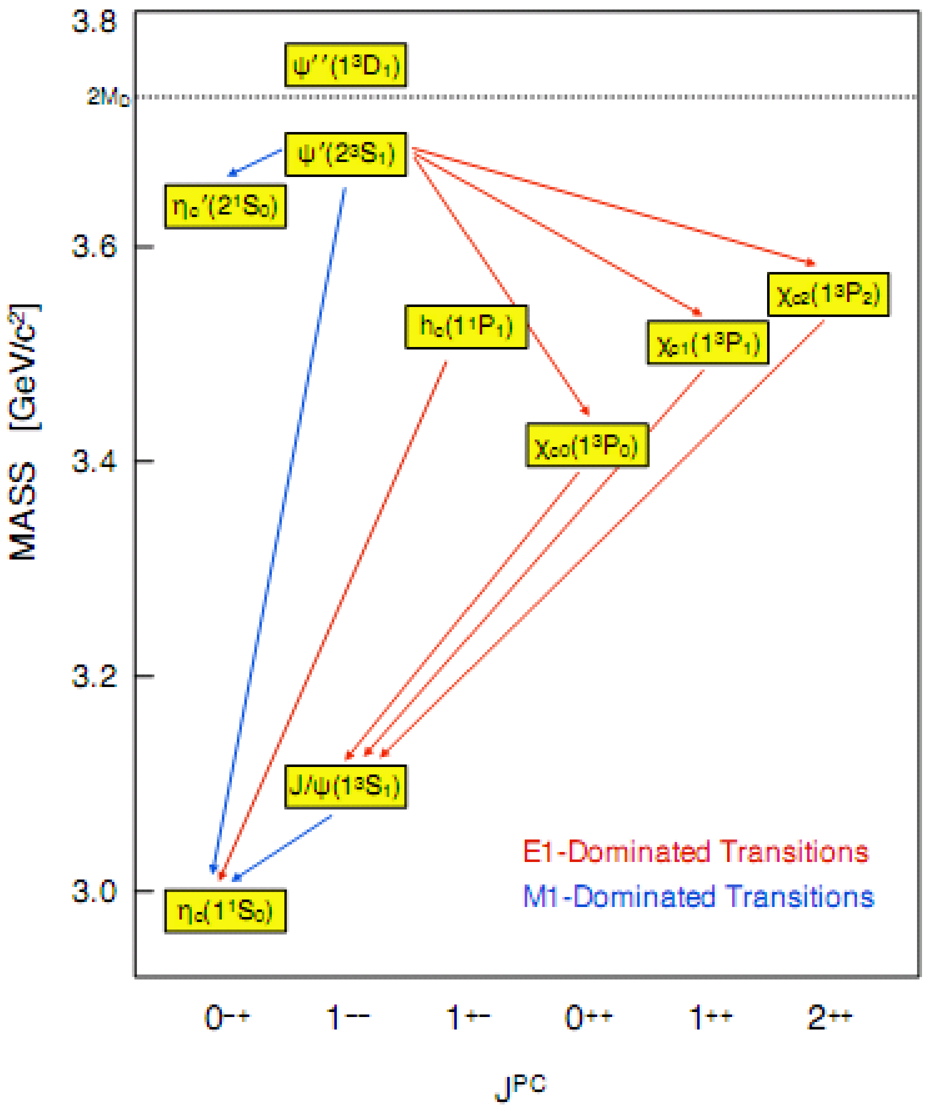
1) Motivation and overview
2) Light hadron $0^-0^-0^-$ system from charmonium
3) What can we learn form $a_0(980)$ and $\pi\pi$ line-shapes?
4) Relevance to modern exotics?

Charmonium spectrum

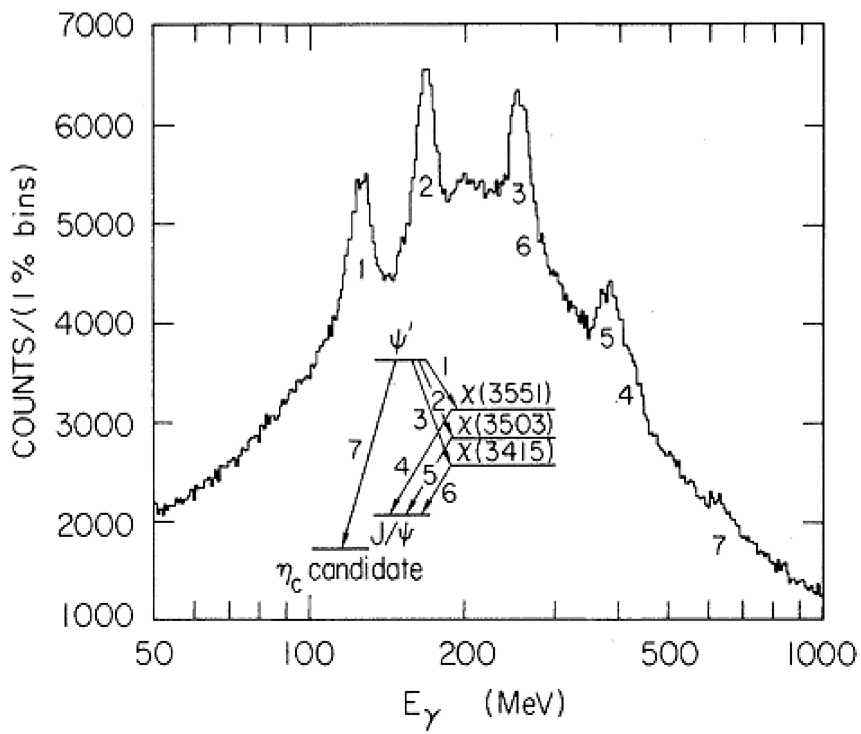
& some transitions:



Charmonium: radiative transitions

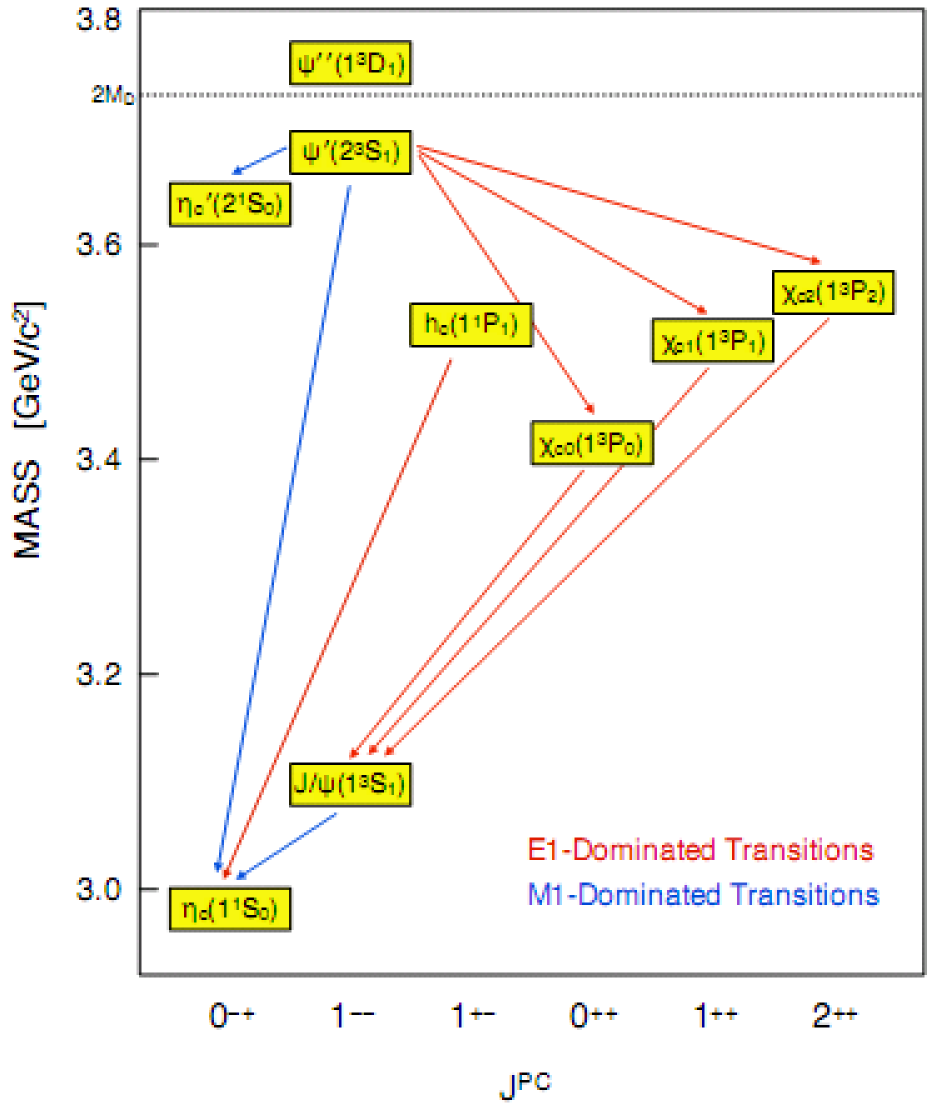


PRL 45, 1150 (1980)



Charmonium lab:

radiative transitions



Current statistics based on PDG rates and

~0.5B ψ(2S) & 1.3B J/ψ :

- χ_{cJ} – 40M (each)
- η_c – 25M (all 'feeding')
- also h_c – 0.4M

Compare with CLEO:

- χ_{cJ} – 2.6M

$J^{PC} \rightarrow 0^-0^-0^-$ (hhh = $\eta\pi\pi$)

Consider isobar model, two-body processes:

- I=0: $\chi_{cJ} \rightarrow R_J + \eta(L)$; $R_J \rightarrow \pi\pi$
- I=1: $\chi_{cJ} \rightarrow R_J + \pi(L)$; $R_J \rightarrow \eta\pi$

χ_{c1} (1++)

J^{PC}	L	Final state
0^{++}	P	$f_0\eta$; $a_0\pi$
1^{-+}	**S**, D	$\pi_1\pi$
2^{++}	P, F	$f_2\eta$; $a_2\pi$

Only S-wave is exotic!

χ_{c2} (2++)

J^{PC}	L	Final state
0^{-+}	D	NA
1^{-+}	D	$\pi_1\pi$
2^{++}	P, F	$f_2\eta$; $a_2\pi$

Exotic has one combination!

$J^{PC} \to 0^-0^-0^-$ (hhh = $\eta\pi\pi$)

Consider isobar model, two-body processes:

- $I=0$: $\eta_c \to R_J + \eta(L)$; $R_J \to \pi\pi$
- $I=1$: $\eta_c \to R_J + \pi(L)$; $R_J \to \eta\pi$

One exotic configuration!

All this holds if $\eta \to \eta'$

$\eta_c (0^{-+})$

J^{PC}	L	Final state
0^{++}	S	$f_0\eta$; $a_0\pi$
1^{-+}	P	$\pi_1\pi$
2^{++}	S, D	$f_2\eta$; $a_2\pi$

Replace $\pi\pi$ with KK and other interesting possibilities emerge.

Exotic candidates: 1^{-+}

Rev:C. A. Meyer and E. S. Swanson: hep-ph/1502.07276

π_1(1400) reported in decays to $\eta\pi$ final state, by GAMS, VES, KEK, C. Barrel, E852

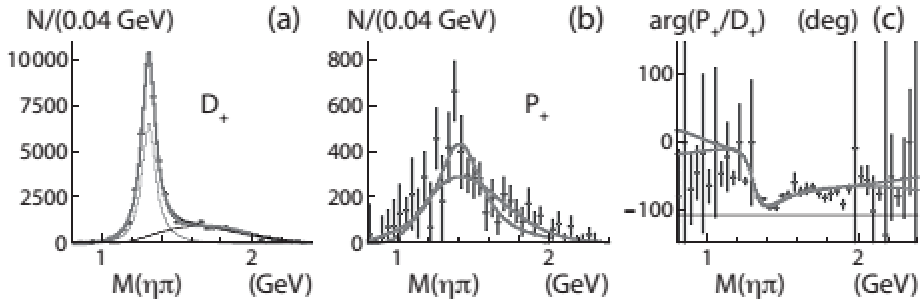


Figure 12: The results of a partial-wave analysis of the $\eta\pi^-$ final state from VES. (a) shows the intensity in the 2^{++} partial wave, (b) shows the intensity in the 1^{-+} partial wave and (c) shows the relative phase between the waves. (Figure reproduced from reference [126].)

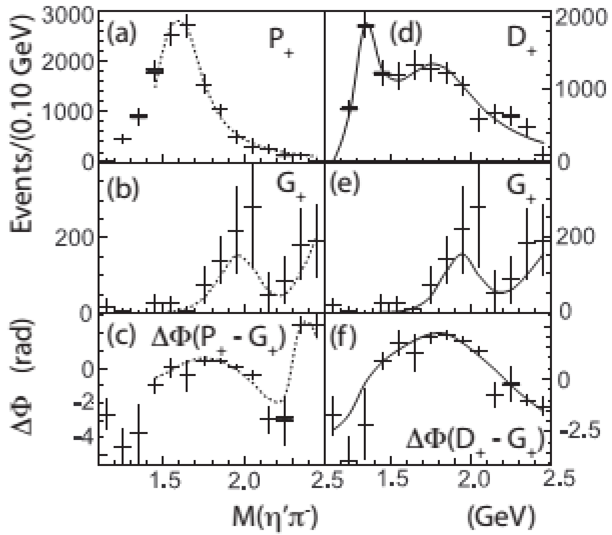
VES: Phys. Atom. Nucl. 68, 359 (2005)

$\rho\pi$ mode questionable, seen by OBELIX

Exotic candidates: 1^{-+}

Rev:C. A. Meyer and E. S. Swanson: hep-ph/1502.07276

π_1**(1600)** most promising candidate so far, seen in $f_1\pi$, $\eta'\pi$, $b_1\pi$; by VES, E852, COMPASS, CLEO-c



E852: PRL 86, 3977 (2001)

- not seen in $\eta\pi$ final state

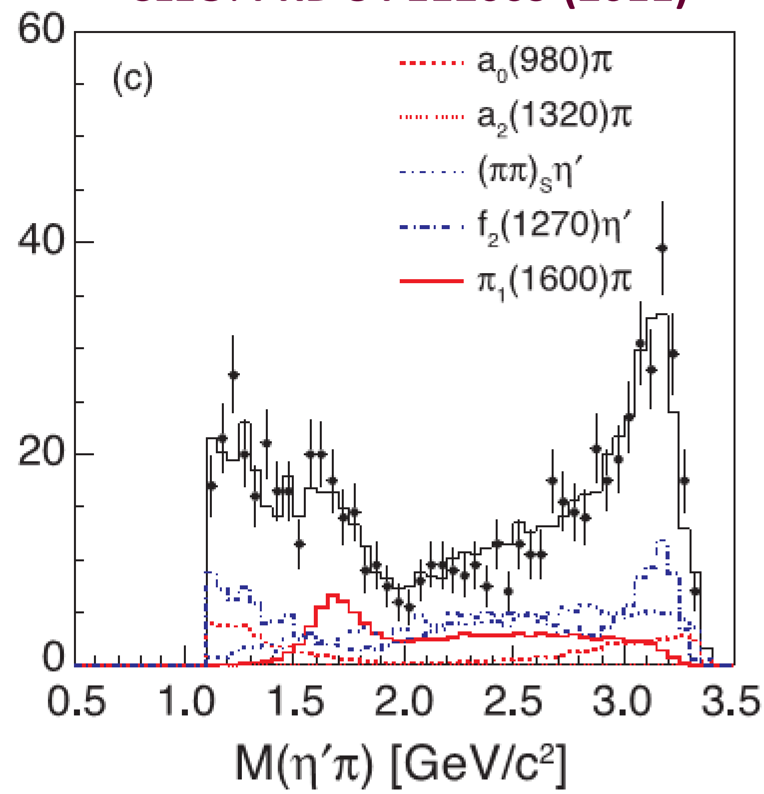
Exotic candidates: 1^{-+}

Rev:C. A. Meyer and E. S. Swanson: hep-ph/1502.07276

π_1**(2015)** least promising so far, reported by E582 in $f_1\pi$; $b_1\pi$

$\chi_{c1} \rightarrow \eta\pi\pi$
suitable environment
to look for exotics
$J^{PC} = 1^{-+}$
plus …

CLEO: PRD 84 112009 (2011)



Multi-quark states

Concentrate on $a_0(980)$ facts:

- Discovered four decades ago, its nature still not resolved, consensus: it has a large **KK-loop** contribution

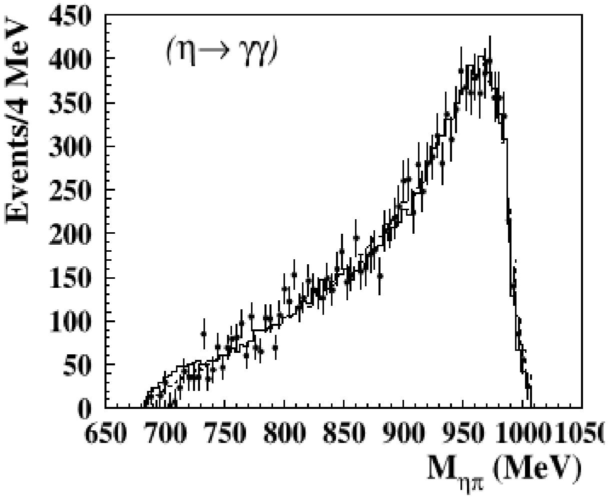
- Couples to: $\gamma\gamma$, $\eta\pi$, KK, and $\eta'\pi$, mixing with $f_0(980) \to \pi\pi$

- $\mathbf{a_0(980)} \to \eta'\pi$ observed only recently by CLEO-c coupling $g^2_{\eta'\pi}$ consistent with zero, based on ~2.5K events

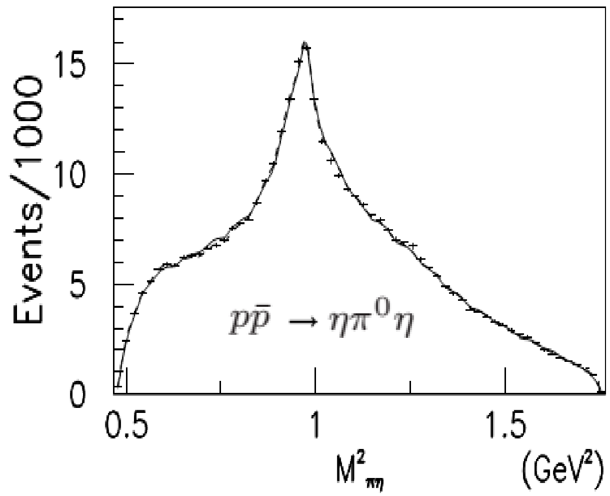
- $\mathbf{a_0(980)} \to \eta\pi$: large variations in coupling value, reported by different experiments: $0.15 \pm 0.02 < \mathbf{g^2_{\eta\pi}\ [GeV/c]^2} < 0.36 \pm 0.04$

$a_0(980)$ line-shape

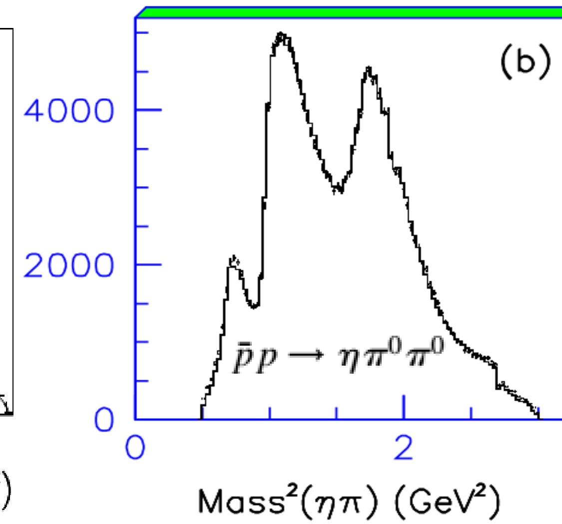
KLOE: PLB 681 5 (2009)



IJMP A 24 2481 (2009)

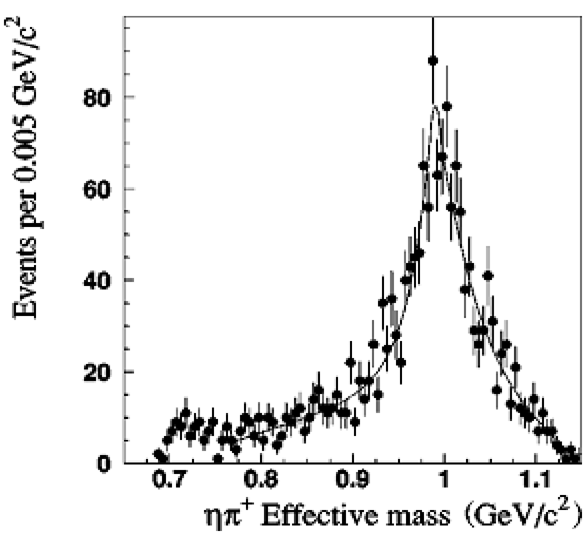


PRD 78 74023 (2008)

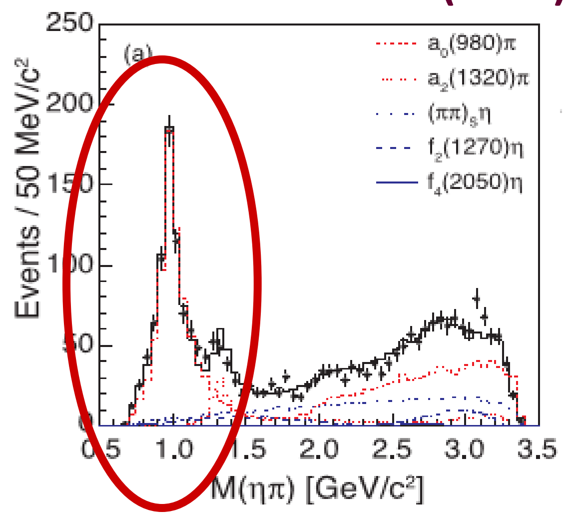


Crystal Barrel data

E852: PRD 59 12001 (1998)



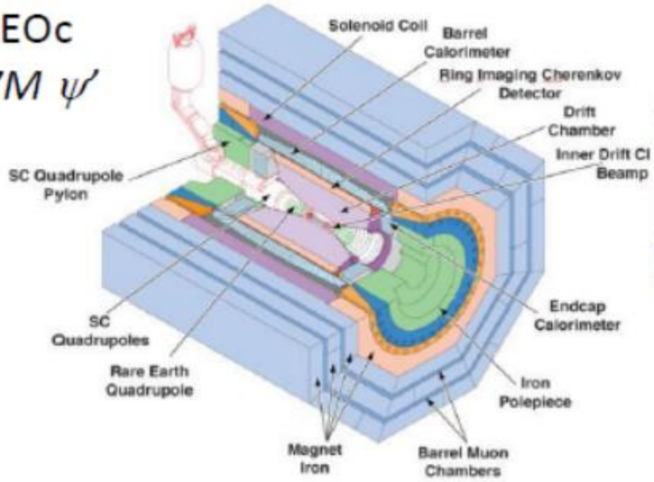
CLEO: PRD 84 112009 (2011)



	$g^2_{\eta\pi}$ [GeV]	$g^2_{KK}/g^2_{\eta\pi}$
KLOE	0.15 ± 0.02	1.16±0.06
C.Barrel	0.16 ± 0.02	1.05±0.10
E852	0.24±0.015	0.91±0.10
CLEO	0.36 ± 0.04	0.87±0.15

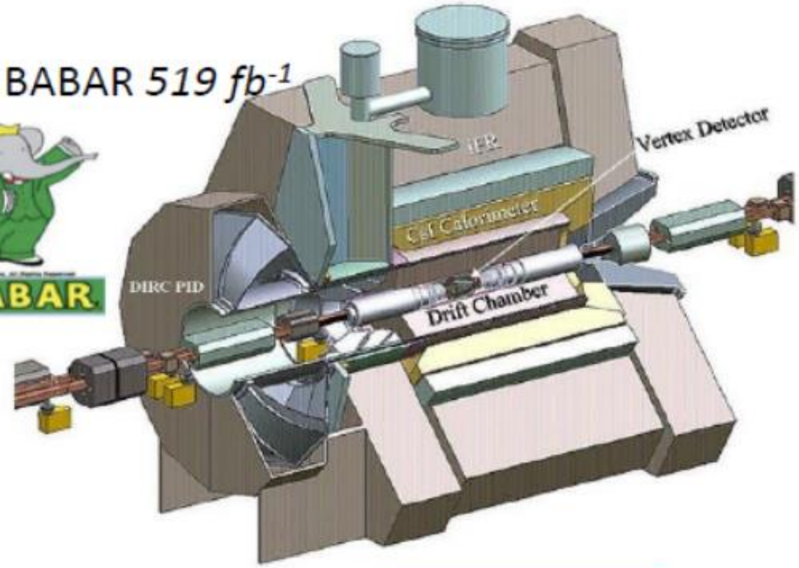
Experiments

CLEOc
27M ψ'



BABAR *519 fb^{-1}*

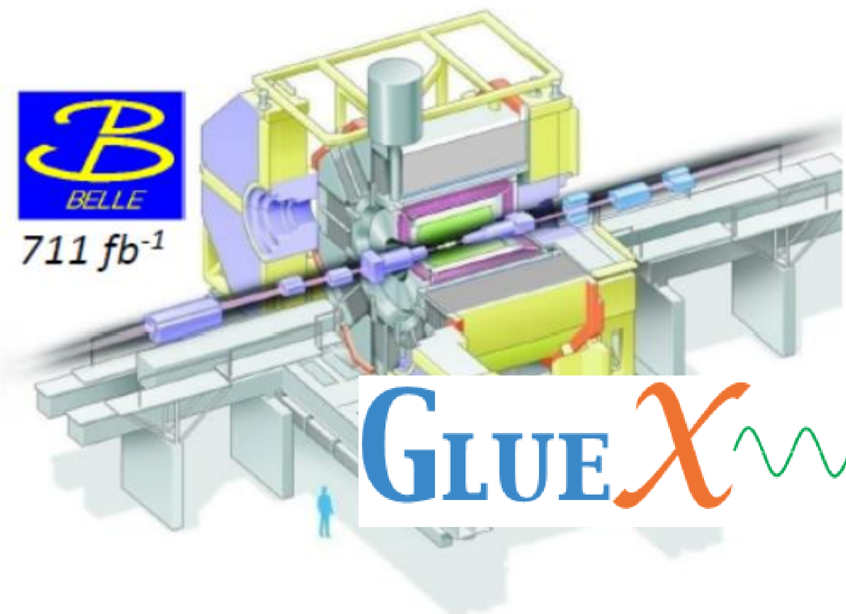
BABAR



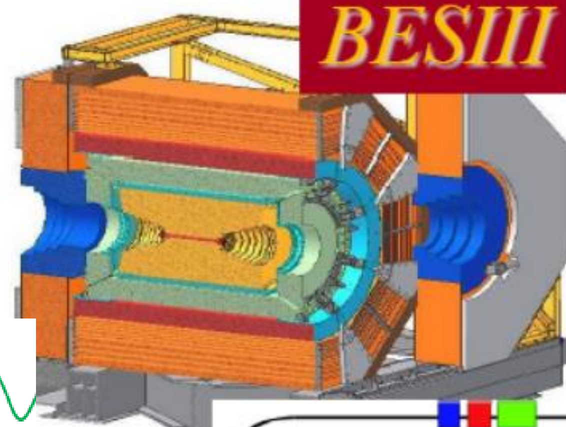
CDF II

DØ

BELLE
711 fb^{-1}



BESIII



LHCb

GlueX

p̄anda

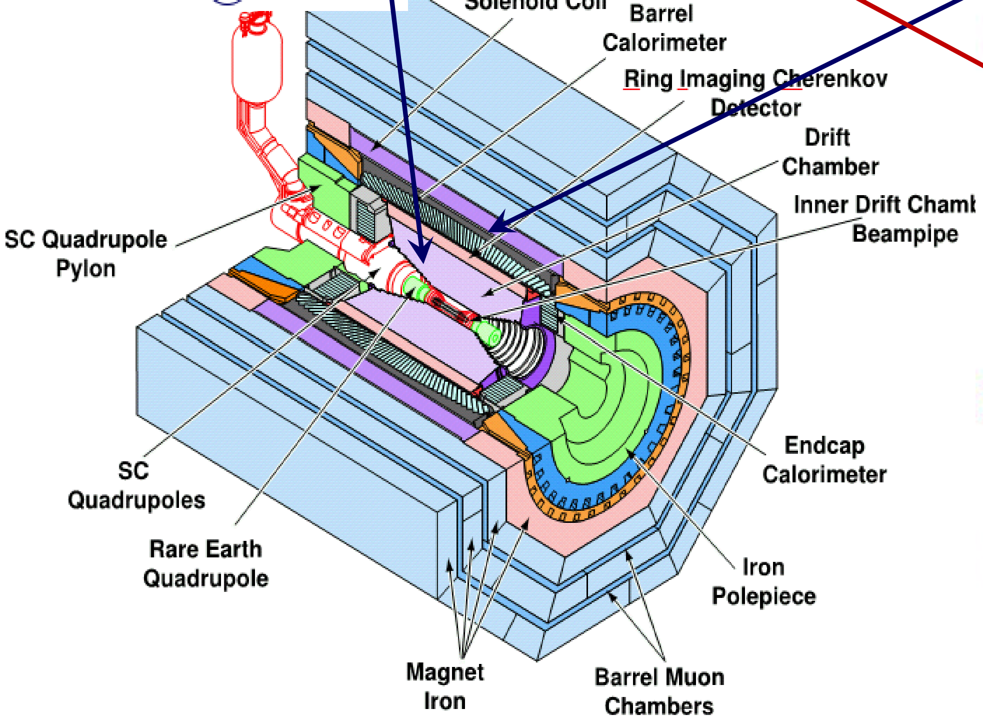
Experiments: ~ 94% of 4π

Excellent tracking & shower reconstruction!

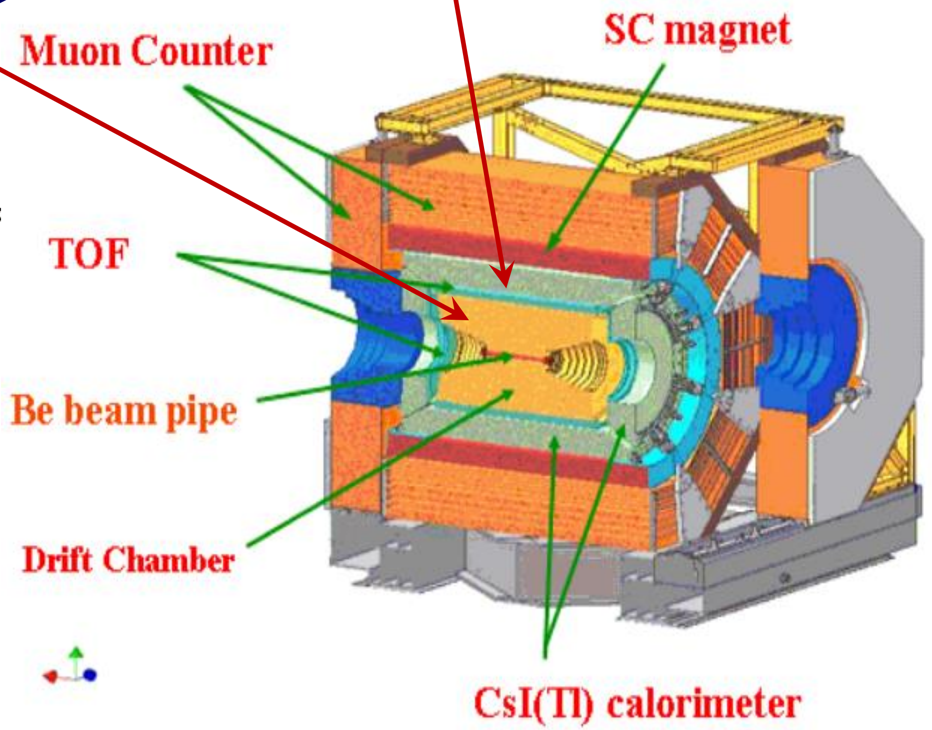
$\delta p/p$ = **0.6** (**0.5**)% @ 1 GeV/c

$\delta E/E$ = **2.2** (**2.5**)% @ 1 GeV

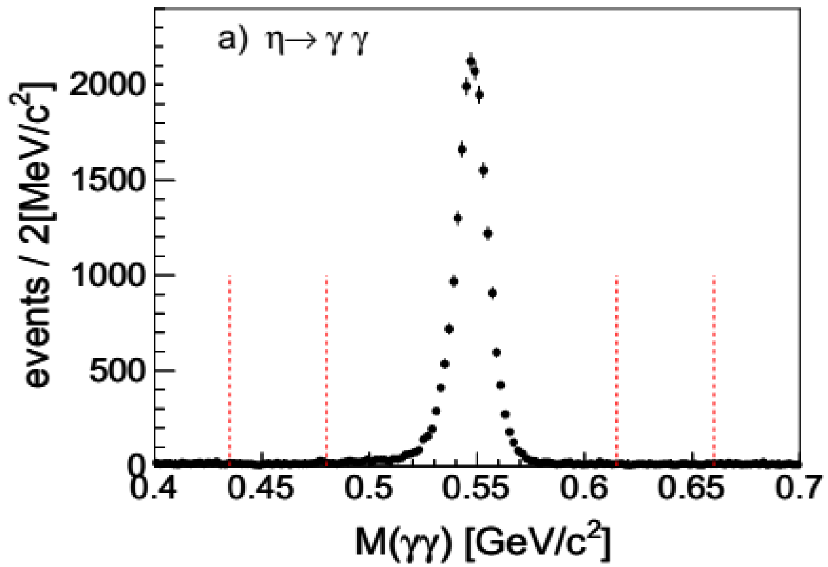
CLEO-c @ CESR



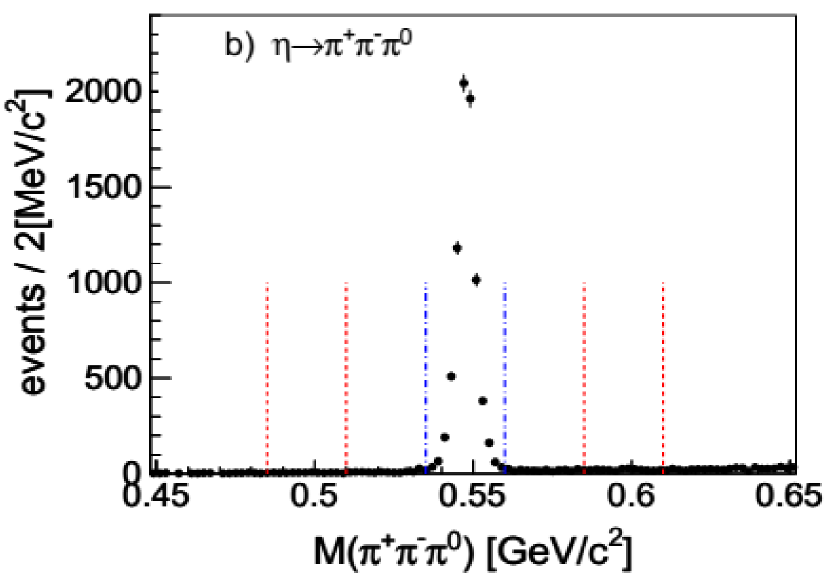
BESIII

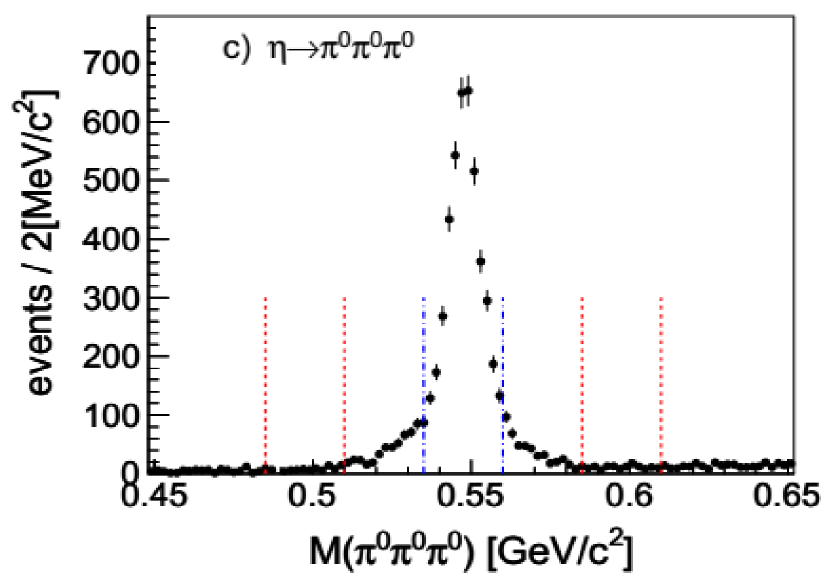


$\psi(2S) \to \gamma\chi_{c1}$; $\chi_{c1} \to \eta\pi^+\pi^-$



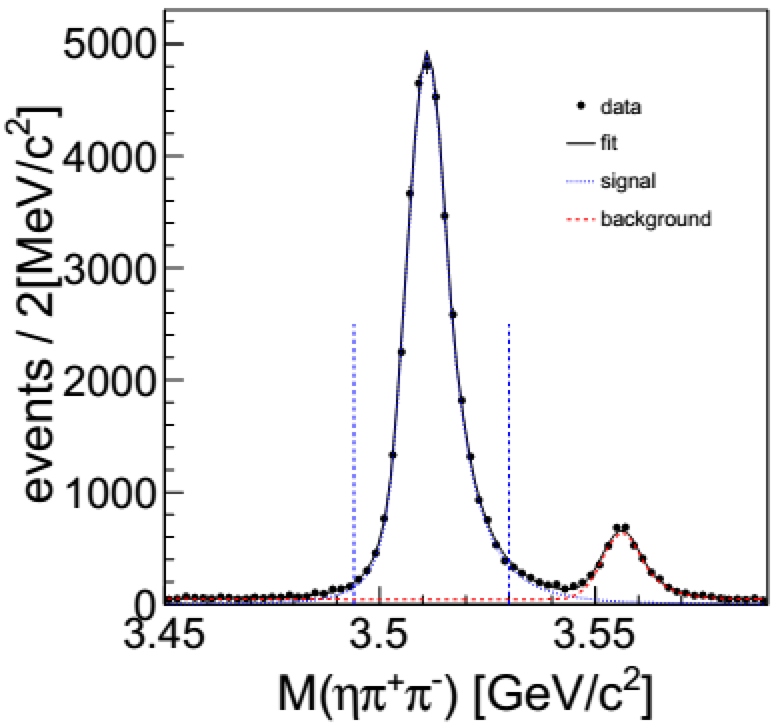
Decay	$\mathcal{B}$ [%] [3]	Topology
$\eta \to \gamma\gamma$	39.41±0.20	$3\gamma 1(\pi^+\pi^-)$
$\eta \to \pi^+\pi^-\pi^0$	22.92±0.28	$3\gamma 2(\pi^+\pi^-)$
$\eta \to \pi^0\pi^0\pi^0$	32.68±0.23	$7\gamma 1(\pi^+\pi^-)$
total	95.01±0.71	



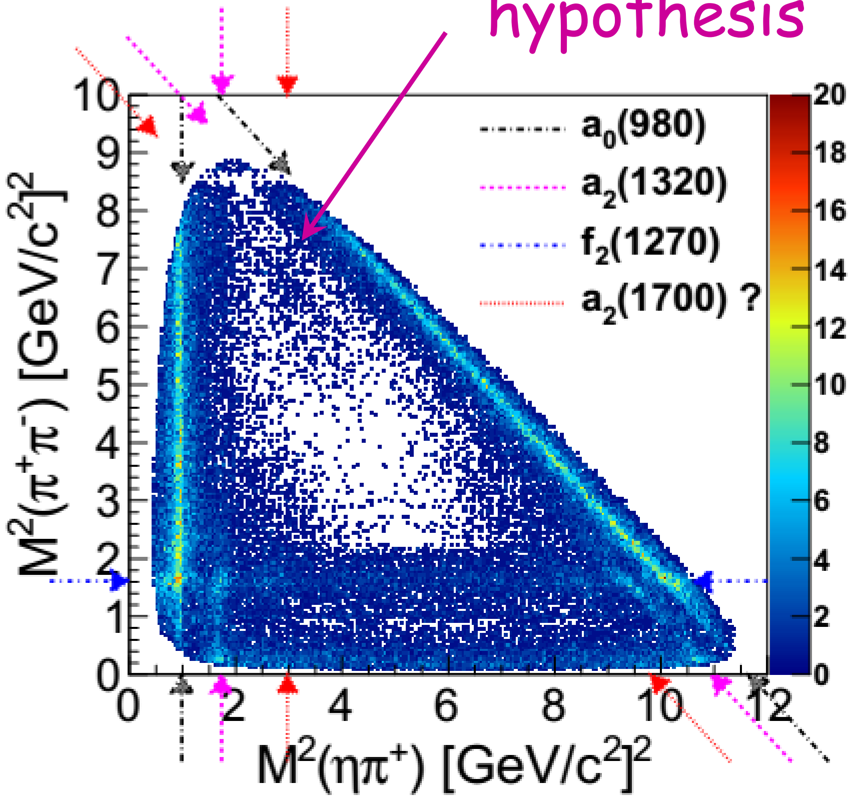


$\psi(2S) \rightarrow \gamma\chi_{c1}$; $\chi_{c1} \rightarrow \eta\pi^+\pi^-$

combine all η modes



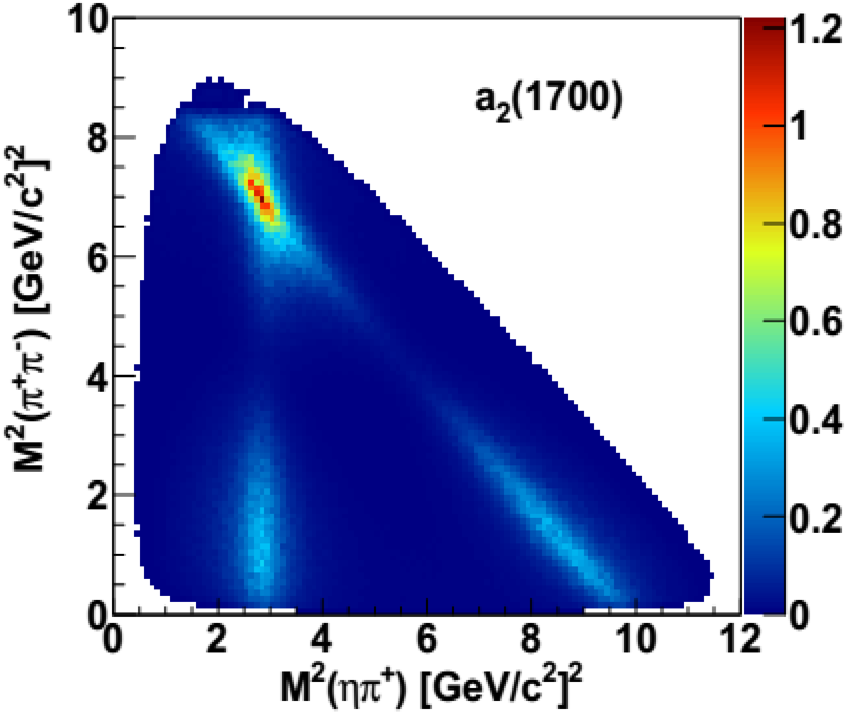
a₂(1700) hypothesis

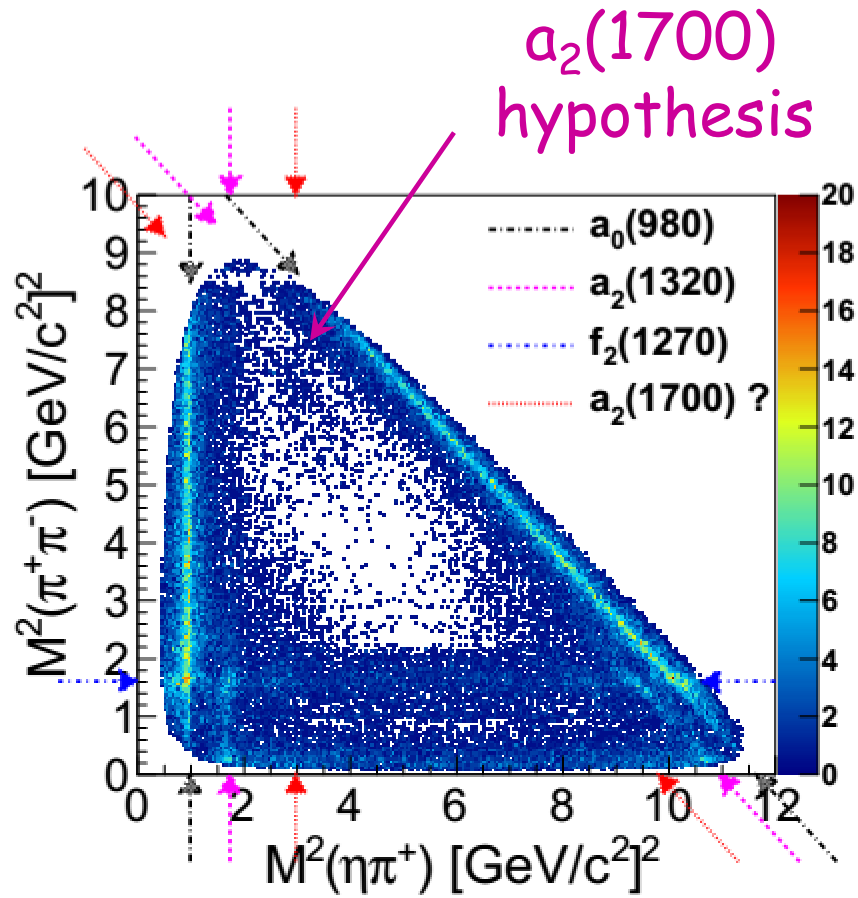


$N(\chi_{c1}) \sim 35K$

$98.3 \pm 0.5\%$ purity

$\psi(2S) \rightarrow \gamma\chi_{c1}$; $\chi_{c1} \rightarrow \eta\pi^+\pi^-$





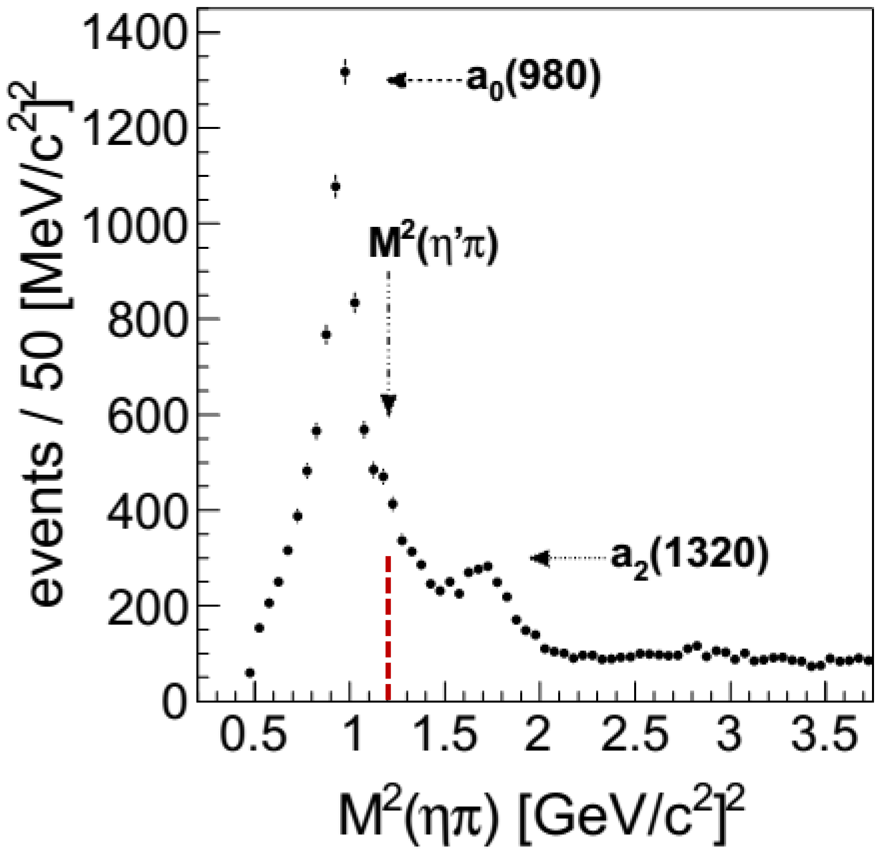
Recent **a_2(1700)** reporting:

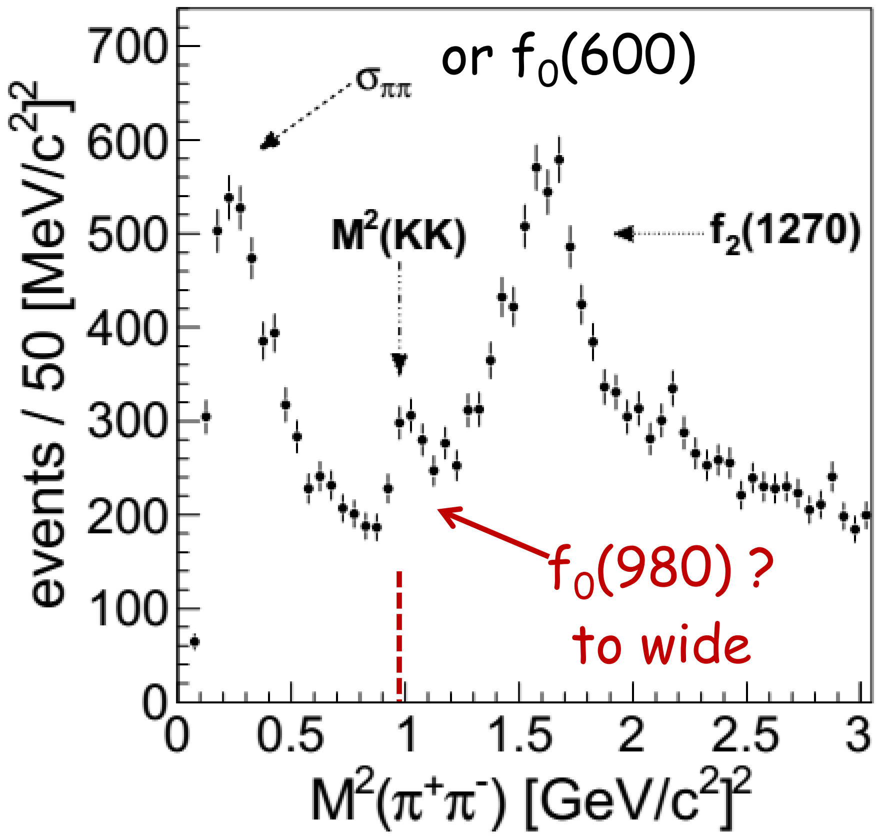
Belle: $\gamma\gamma \rightarrow K^+K^-$; Eur.Phys.J. C32, 323 (2003)

C.Barrel: $pp \rightarrow 3\pi^0$, $2\pi^0\eta$, $\pi^0\eta\eta$; Eur.Phys.J. C23, 29 (2002)

Two-body structures

Threshold effects in both projections!





- make sure these are not reflections

Helicity formalism

Adopted from PRD84 112009 (2011)

$$A^{\alpha}_{M_\psi,\lambda_\gamma}(\mathbf{x}) = \sum_{\lambda_\chi=\pm1,0} C(M_\psi,\lambda_\gamma,\lambda_\chi) \sum_{M'_\chi=\pm1,0} D^{1*}_{M'_\chi,-\lambda_\chi}(\phi_\gamma,\theta_\gamma,0) \times \sum_{M'_L,M'_J} \langle 1M'_\chi|LM'_L,JM'_J\rangle Y_L^{M'_L*}(\theta'_I,\phi'_I) Y_J^{M'_J*}(\theta'_h,\phi'_h)^* p^L q^J T_\alpha(s)$$

Likelihood minimization

$$\mathcal{L} = \frac{e^{-\mu}\mu^N}{N!}\prod_{i=1}^{N}\frac{\eta(x)I(x)}{\int\eta(x)I(x)}$$

Intensity

$$I(\mathbf{x}) = \sum_{M_\psi,\lambda_\gamma}\left|\sum_\alpha V^{\alpha}_{M_\psi,\lambda_\gamma}A^{\alpha}_{M_\psi,\lambda_\gamma}(\mathbf{x})\right|^2$$

Line-shapes: **T_α(s) = BW**, all structures except:

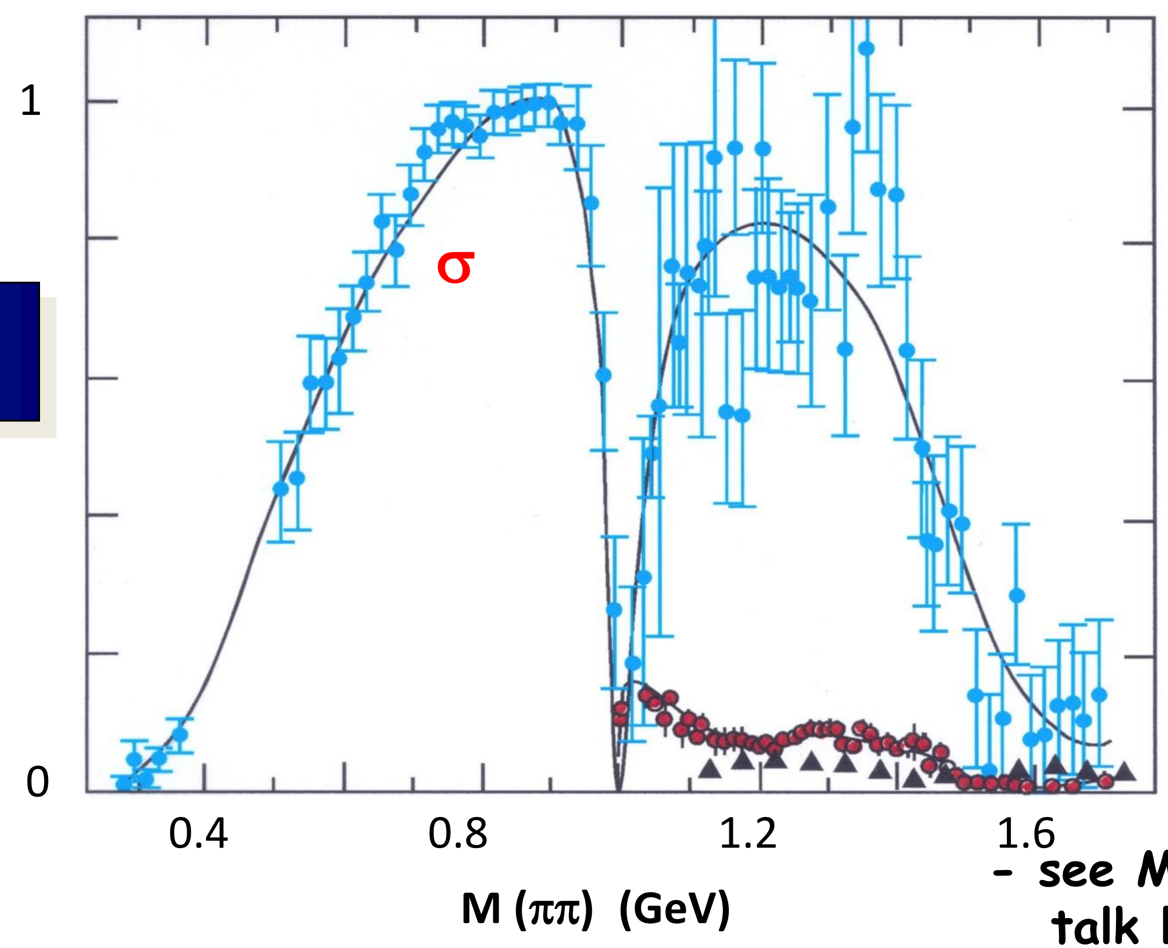
ππ **S-wave** & **a_0(980)**

ππ S-wave

Starting with:

ππ ⟶ ππ

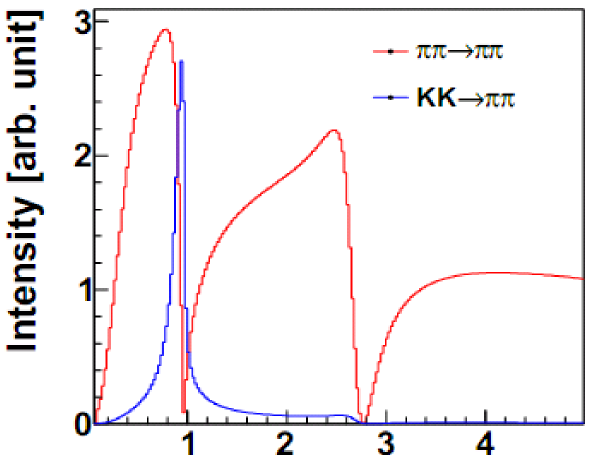
I = J = 0

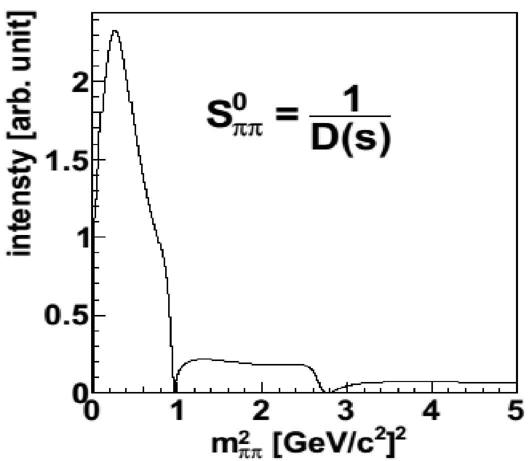


- see M. Pennington talk last Thursday

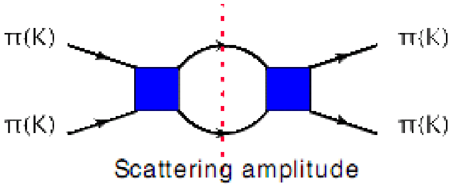
ππ S-wave

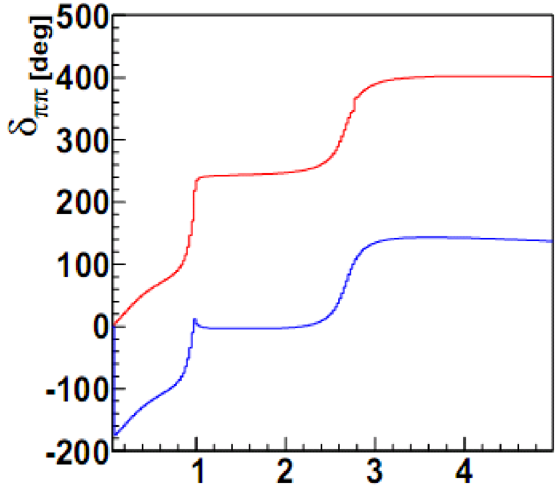
Starting with:





Eur.Phys.J.C9,141 (1999)
PRD50,3145 (1994)

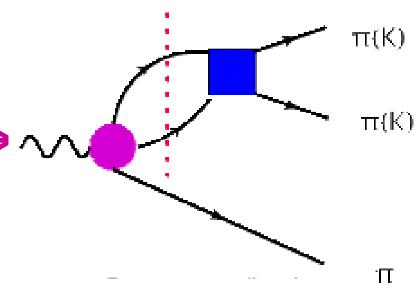




A. Szczepaniak:

transform ππ→ππ component:

use 1/D(s) as a basis to account for differences in decay vs. scattering processes:



PRD84 112009 (2011)

$\pi\pi$ S-wave

*PRD84 112009 (2011)

1. S_{KK} : for $KK \to \pi\pi$
2. $S_{\pi\pi}$: for $\pi\pi \to \pi\pi$, **expanded using $S^0 = D^{-1}(s)$**

* use additional terms in expansion and two conformal transformations $z_{th}(s,s_{th})$:

$$z_{KK}(s) = \frac{\sqrt{s+s_0} - \sqrt{4m_K^2 - s}}{\sqrt{s+s_0} + \sqrt{4m_K^2 - s}}$$

$$z_{s\prime}(s) = \frac{\sqrt{s+s_0} - \sqrt{s\prime - s}}{\sqrt{s+s_0} + \sqrt{s\prime - s}}$$

$$S(s)_{\pi\pi} = c_0 S^0(s) + \sum_{i=1} c_i [z_{KK}(s)]^i S^0(s) + \sum_{i=1} c_i' [z_{s'}'(s)]^i S^0(s)$$

optimize c_i and s'

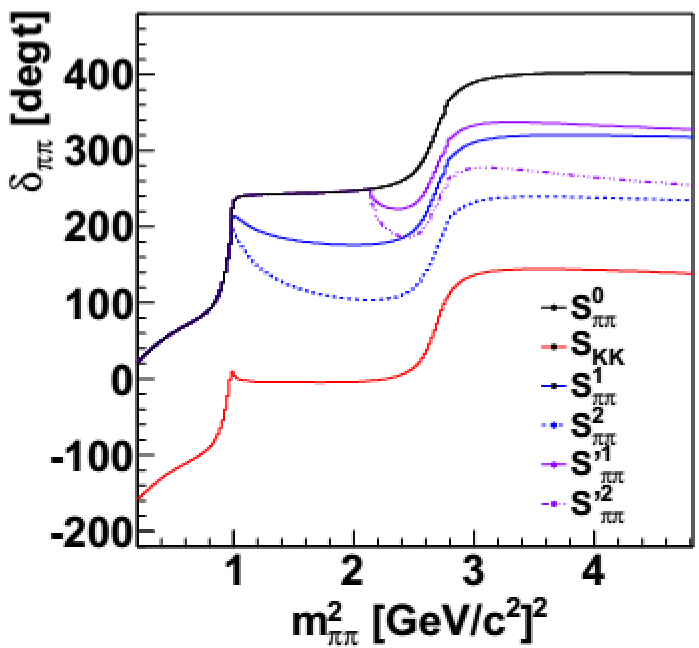
ππ S-wave

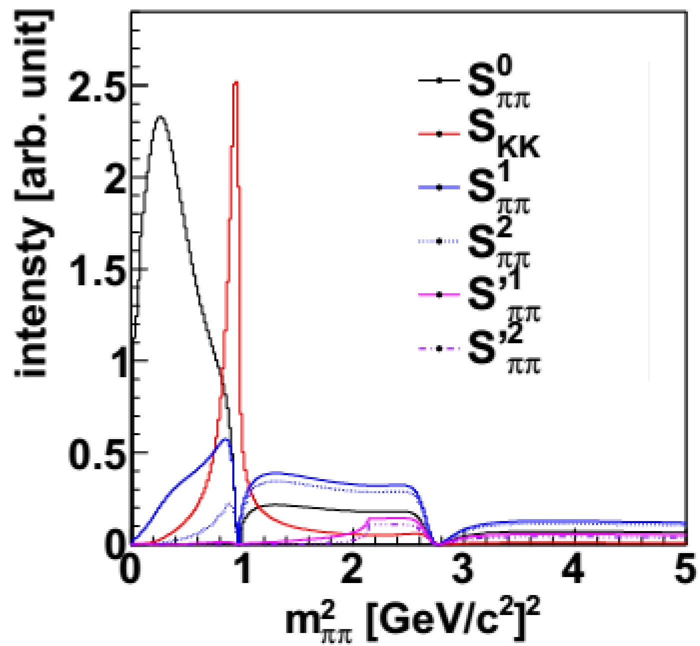
1. S_{KK} : for KK→ππ
2. $S_{\pi\pi}$: for ππ→ππ

$$z_{KK}(s) = \frac{\sqrt{s+s_0} - \sqrt{4m_K^2 - s}}{\sqrt{s+s_0} + \sqrt{4m_K^2 - s}}$$

$$z_{s\prime}(s) = \frac{\sqrt{s+s_0} - \sqrt{s\prime - s}}{\sqrt{s+s_0} + \sqrt{s\prime - s}}$$

$$S(s)_{\pi\pi} = c_0 S^0(s) + \sum_{i=1} c_i [z_{KK}(s)]^i S^0(s) + \sum_{i=1} c_i' [z_{s'}'(s)]^i S^0(s)$$





$a_0(980)$ Flatte formulae

$$D_{\mathrm{a}_0(980)\pi}(s) = m_0^2 - s - i\sum_c g_c^2 \rho_c$$

- ρ_c = phase space for given channel
- $g^2{}_c$ = coupling to given channel
- consider: $\eta\pi$, KK, $\eta'\pi$ channels

$a_0(980)$ dispersion integrals vs Flatte formulae

- similar denominator: $$D_\alpha(s) = m_0^2 - s - \sum_{ch} \Pi_{ch}(s)$$
- same imaginary part: $$Im\Pi_{ch}(s) = g_{\eta\pi}^2 \rho_{\eta\pi} + g_{KK}^2 \rho_{KK} + g_{\eta'\pi}^2 \rho_{\eta'\pi}$$
- Different analytical continuation: $$Re\Pi_{ch}(s) = \frac{1}{\pi} P \int_{s_{th}}^{\inf} \frac{Im\Pi_{ch}(s')ds'}{(s'-s)}$$

❖ False singularity no issue? $$|\vec{p_1}| = |\vec{p_2}| = \frac{[(M^2-(m_1+m_2)^2)(M^2-(m_1-m_2)^2)]^{1/2}}{2M},$$

$s < (m_1 - m_2)^2$ case, i.e. $s < (m_{\eta'} - m_\pi)^2$

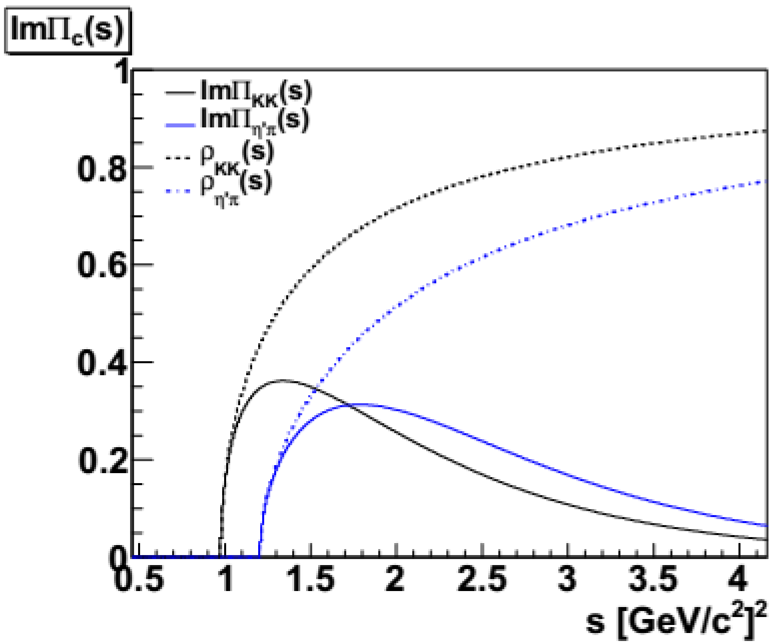
treated by $\rho = \sqrt{1-(m_{\eta'}+m_\pi)^2/m}$ if Flatte is used!

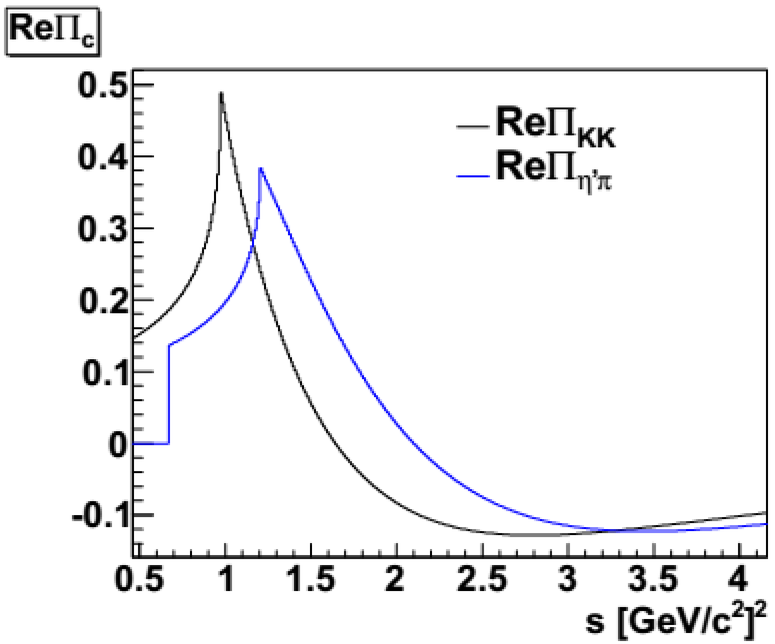
❖ E.P.J. A16, 229 (2003)

D.Bug: PRD 78 74023 (2008)

$a_0(980)$ dispersion integrals

$$D_\alpha(s) = m_0^2 - s - \left[\sum_{ch} Re\Pi_{ch}(s) - Re\Pi_{ch}(m_0^2)\right] - i\sum_{ch} Im\Pi_{ch}$$





Form factor to remove divergence: $F_{ch}(s) = e^{-\alpha q_{ch}^2(s)}$

$a_0(980)$ couplings

$$D_\alpha(s) = m_0^2 - s - \left[\sum_{ch} Re\Pi_{ch}(s) - Re\Pi_{ch}(m_0^2)\right] - i\sum_{ch} Im\Pi_{ch}$$

$$g_{\eta\pi}^2\rho_{\eta\pi} + g_{KK}^2\rho_{KK} + g_{\eta'\pi}^2\rho_{\eta'\pi}$$

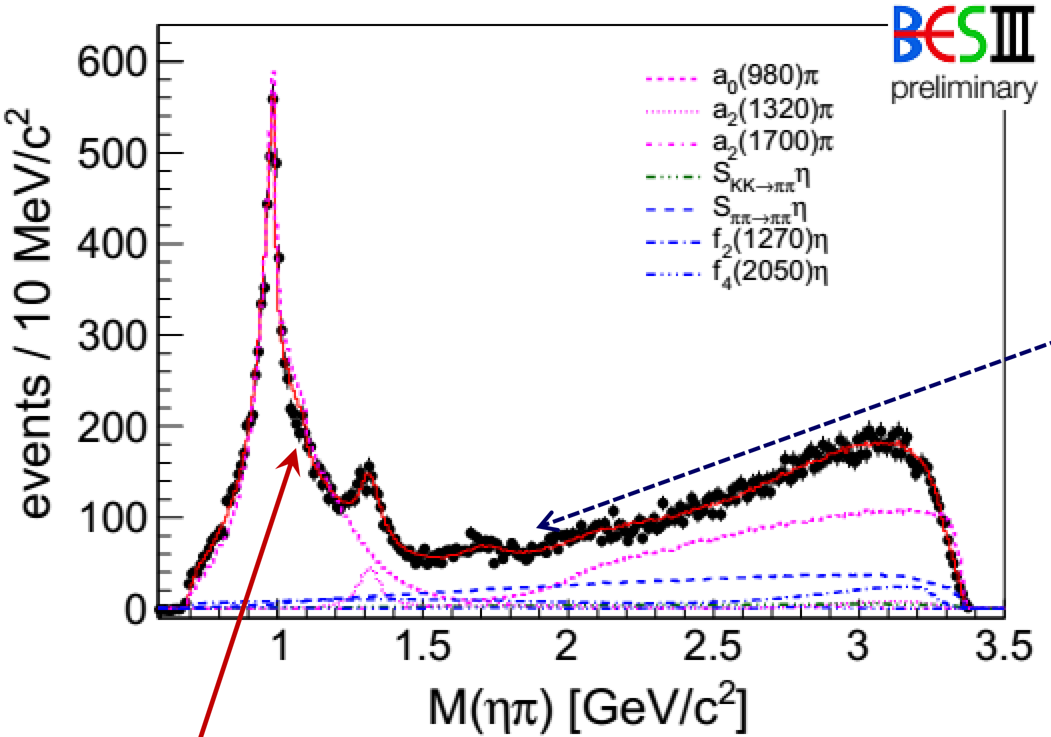
Expectation from SU(3) depends on angle $\phi = 54.7^0 - \Theta_{PS}$ related to pseudo-scalar mixing angle Θ_{PS}.

$$\phi = (41.3 \pm 1.2)^0$$

$$g_{KK}^2/g_{\eta\pi}^2 = 1/(2\cos^2\phi) = 0.886 \pm 0.034,$$

$$g_{\eta'\pi}^2/g_{\eta\pi}^2 = \tan^2\phi = 0.772 \pm 0.068,$$

Bundle all together: ηπ



Featuring for the first time:

$a_2(1700)$ > 17σ

vs: a_0, π_1, a_4

mass & width ~ PDG

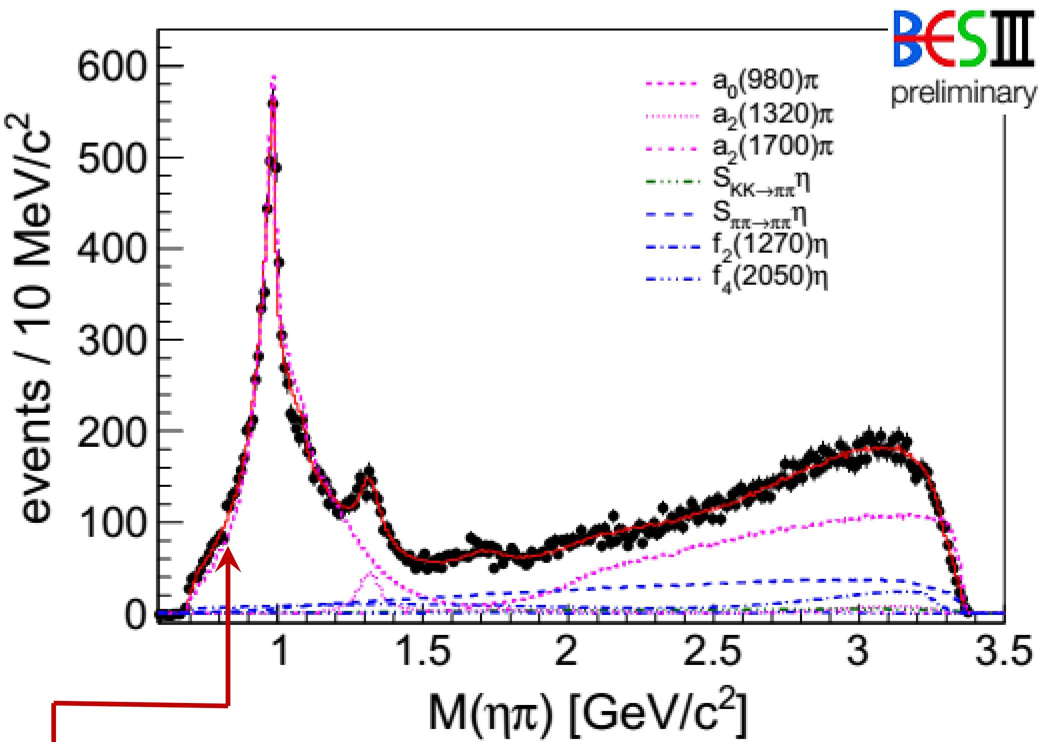
also for the first-time:

$a_0(980)$: $g_{\eta'\pi} \neq 0$

η'π threshold

Amplitude	$\mathcal{F}$ [%]	$N\sigma$
$a_0(980)\pi$	$72.47 \pm 0.59 \pm 2.33$	$> 100\sigma$
$a_2(1320)\pi$	$3.84 \pm 0.18 \pm 0.74$	32σ
$a_2(1700)\pi$	$1.04 \pm 0.10 \pm 0.29$	20σ
$S_{kk}\eta$	$2.42 \pm 0.18 \pm 0.36$	22σ
$S_{pp}\eta$	$16.12 \pm 0.47 \pm 0.79$	$> 100\sigma$
$f_2(1270)\eta$	$7.78 \pm 0.26 \pm 1.142$	$> 100\sigma$
$f_4(2050)\eta$	$0.56 \pm 0.11 \pm 0.18$	6.8σ

$a_0(980)$ parameters



❖ PRD84 112009 (2011)

➢ PRD 78 74023 (2008)

Comparing:

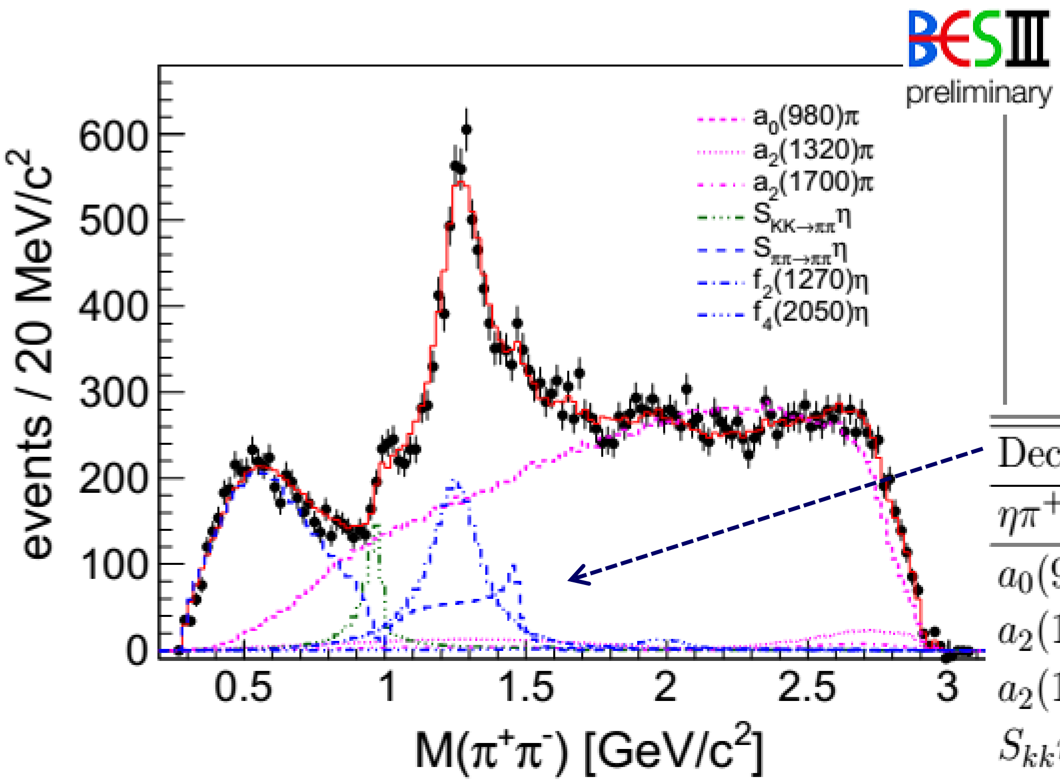
$g^2_{\eta'\pi} \sim 0.5\, g^2_{\eta\pi}$

$g^2_{\eta'\pi} = 0$: $\sim 9\sigma$

Data	m_0 [GeV/c^2]	$g^2_{\eta\pi}$ [GeV/c^2]	$g^2_{KK}/g^2_{\eta\pi}$	$g^2_{\eta'\pi}/g^2_{\eta\pi}$
CLEO-c [2]	998 ± 16	0.36 ± 0.04	0.872 ± 0.148	0.00 ± 0.17
C.Bari ❖ [4]	987 ± 4	0.164 ± 0.011	1.05 ± 0.09	**0.772**
BESIII ➢	995.5±2.4±6.5	0.368±0.003±0.013	0.931±0.028±0.090	0.489±0.046±0.103
Fix R^2_{31}	0.990±0.001	0.341±0.004	0.892±0.022	**0.0**

note: we see η'π effect, can we see η' – π false singularity in data?

ππ distribution



Note: **dip at KK** threshold reproduced well☺

kink could be better☹

Featuring for the first time:

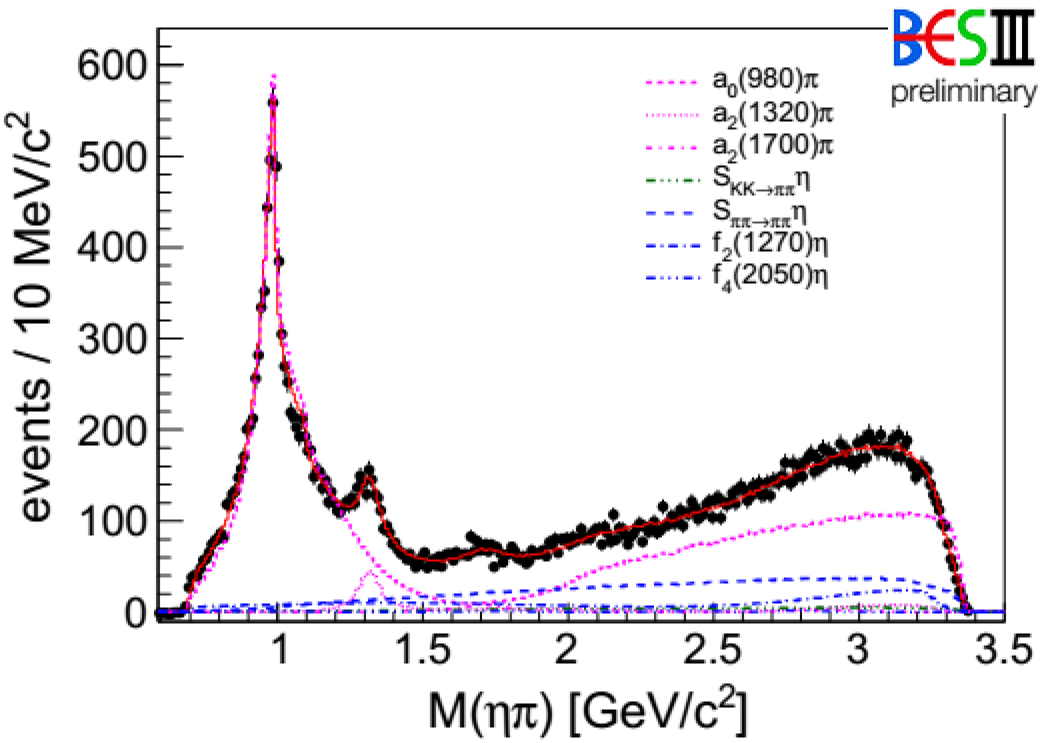
$$S'^{i}(s) = z^{i}_{s'(th)} S^{0}_{\pi\pi}$$

$\sqrt{s'_{th}} \sim 1500\ MeV/c^2$

Decay mode	$\mathcal{B}(\chi_{c1} \to \eta\pi^+\pi^-) \times 10^{-3}$
$\eta\pi^+\pi^-$	$4.819 \pm 0.031 \pm 0.088 \pm 0.210$
$a_0(980)^{\pm}\pi^{\mp}$	$3.506 \pm 0.034 \pm 0.182 \pm 0.153$
$a_2(1320)^{\pm}\pi^{\mp}$	$0.185 \pm 0.009 \pm 0.038 \pm 0.008$
$a_2(1700)^{\pm}\pi^{\mp}$	$0.048 \pm 0.005 \pm 0.014 \pm 0.002$
$S_{kk}\eta$	$0.123 \pm 0.007 \pm 0.018 \pm 0.005$
$S_{pp}\eta$	$0.791 \pm 0.019 \pm 0.037 \pm 0.035$
$\pi^+\pi^-_S\eta$	$0.859 \pm 0.021 \pm 0.031 \pm 0.037$
$(f_2(1270) \to \pi^+\pi^-)\eta$	$0.371 \pm 0.012 \pm 0.054 \pm 0.016$
$(f_4(2050) \to \pi^+\pi^-)\eta$	$0.027 \pm 0.004 \pm 0.009 \pm 0.001$

$$S(s)_{\pi\pi} = c_0 S^0_{\pi\pi} + c_1 z_{KK} S^0_{\pi\pi} + c'_1 z_{s'} S^0_{\pi\pi} + c'_2 z^2_{s'} S^0_{\pi\pi}$$

Exotic ηπ candidates ?



Upper limits in the region 1.4 -2.0 GeV

Mass:

$\pi_1(1400)$: 1354 ± 25;
$\pi_1(1600)$: 1662 ± 10
$\pi_1(2010)$: 2015 ± 20

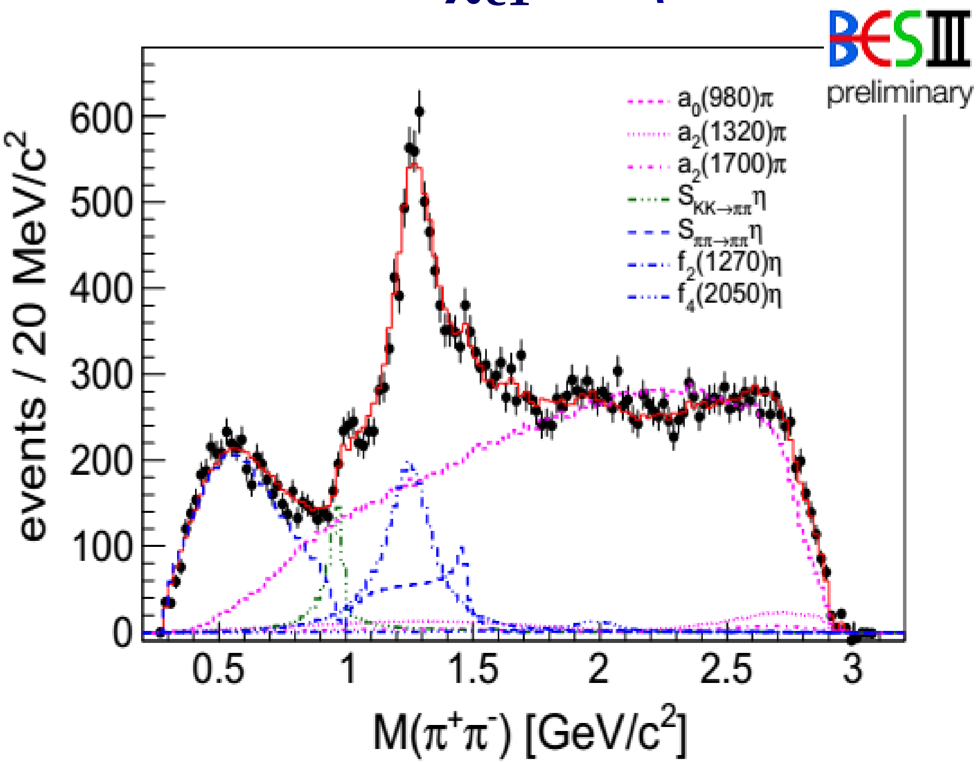
Decay mode	$\mathcal{B}(\chi_{c1} \to \eta\pi^+\pi^-) \times 10^{-3}$	
$\eta\pi^+\pi^-$	$4.819 \pm 0.031 \pm 0.088 \pm 0.210$	
		U.L. [90% c.l.]
$\pi_1(1400)^{\pm}\pi^{\mp}$	0.028 ± 0.010	< 0.048
$\pi_1(1600)^{\pm}\pi^{\mp}$	0.005 ± 0.005	< 0.016
$\pi_1(2015)^{\pm}\pi^{\mp}$	0.003 ± 0.002	< 0.008

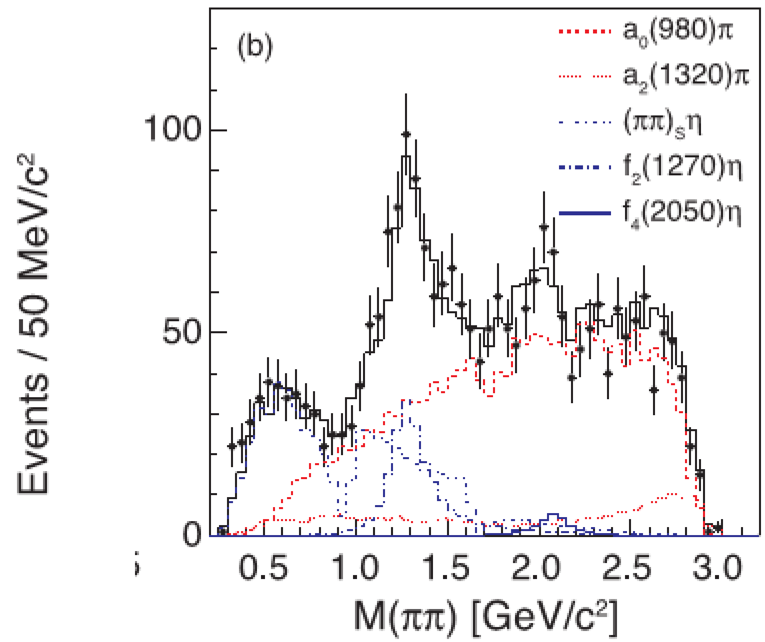
Compare ππ: CLEO vs BESIII

PRD84 112009 (2011)

$\chi_{c1} \rightarrow \eta\pi\pi$

CLEO-c





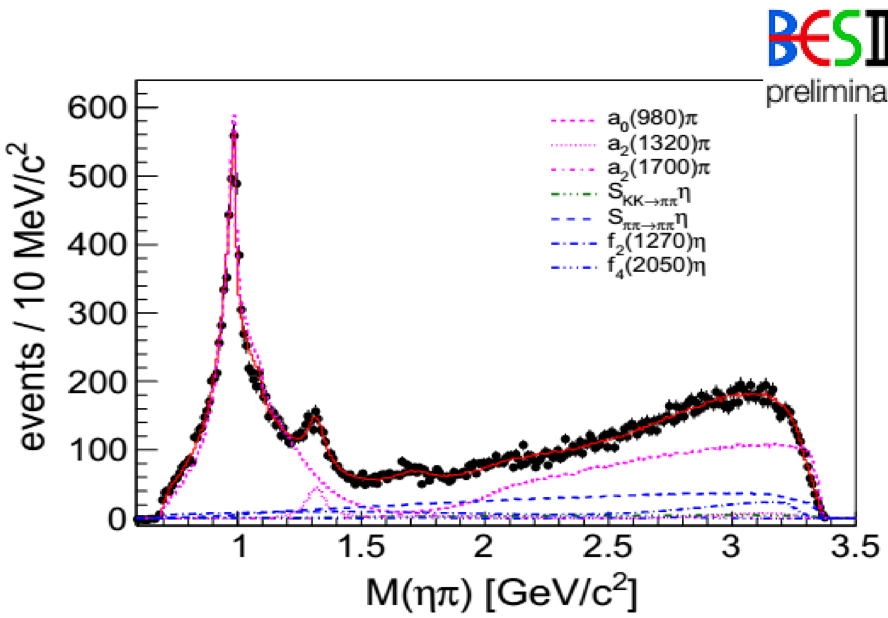
Similar distributions at BESIII and CLEO:
based on this, we can expect to see similar features in $\eta'\pi\pi$ data at BESIII!

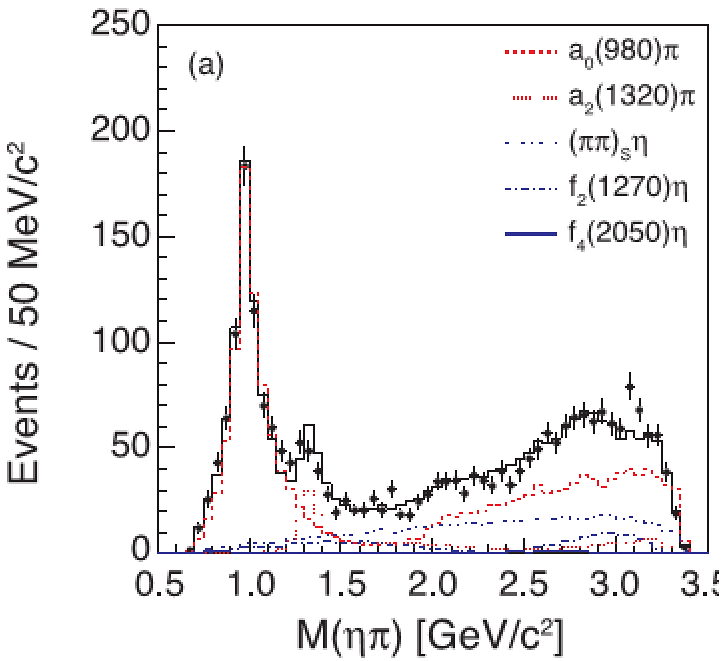
Compare ηπ: CLEO vs BES

PRD84 112009 (2011)

$\chi_{c1} \rightarrow \eta\pi\pi$

CLEO-c





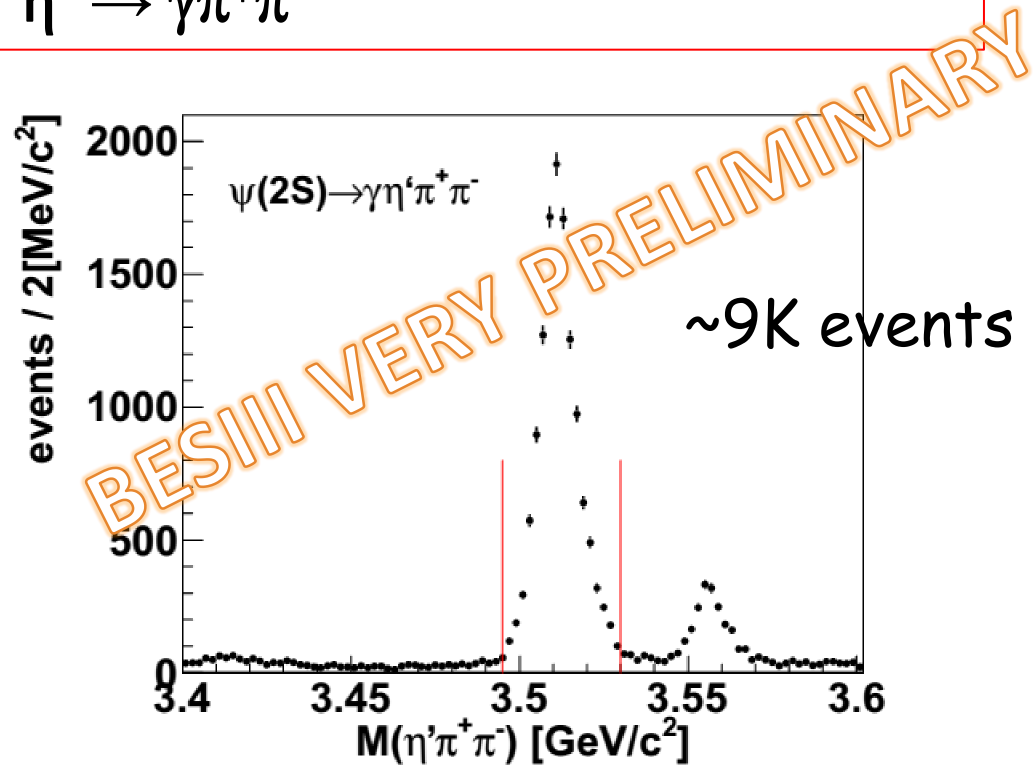
Similar distributions at BESIII and CLEO:
based on this, we can expect to see similar features in η′ππ data at BESIII!

Exotic $\eta'\pi$ candidates ?

$\chi_{c1} \rightarrow \eta'\pi^-\pi^+$: preliminary results

Six decay modes, 85% η' decays:

- $\eta' \rightarrow \eta\pi^+\pi^-$; $\eta \rightarrow \gamma\gamma + \pi^+\pi^-\pi^0 + \pi^0\pi^0\pi^0$
- $\eta' \rightarrow \eta\pi^0\pi^0$; $\eta \rightarrow \gamma\gamma + \pi^+\pi^-\pi^0$
- $\eta' \rightarrow \gamma\pi^+\pi^-$

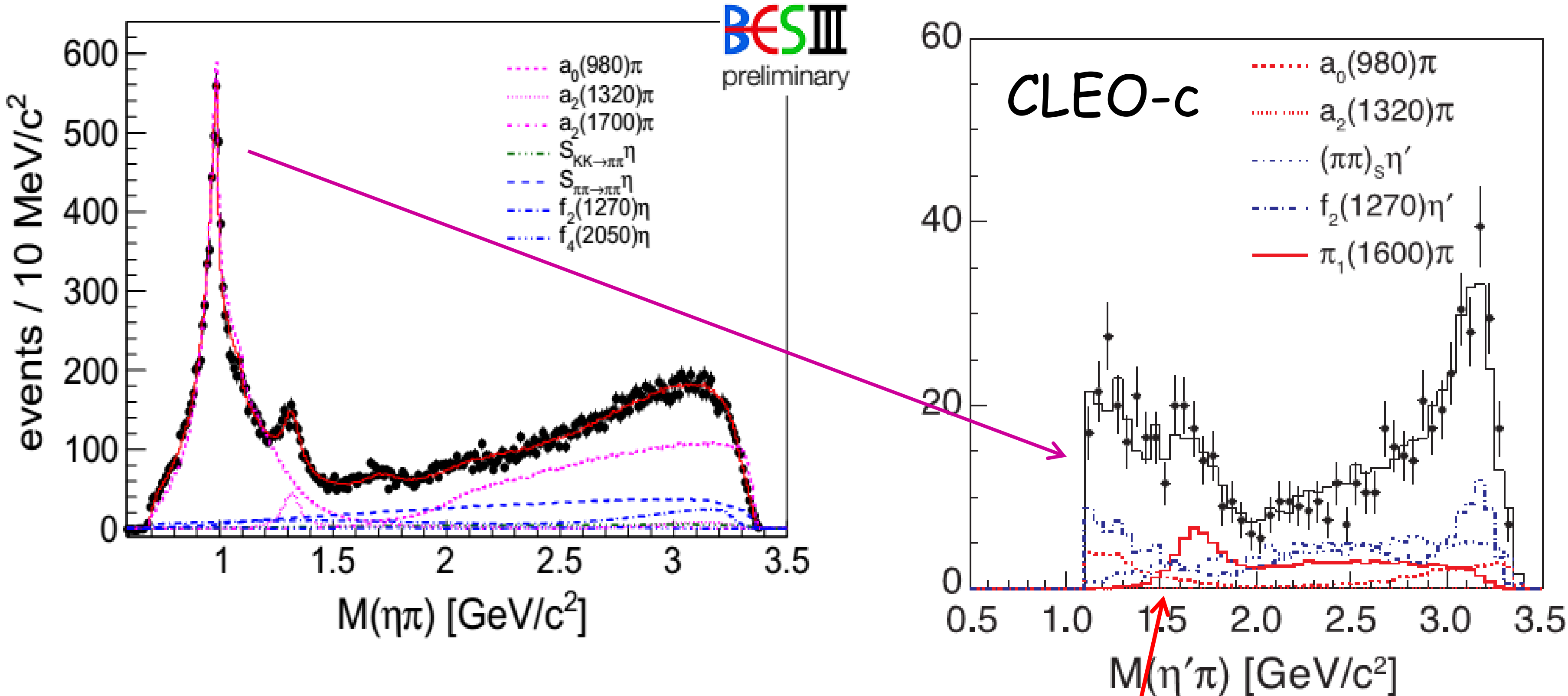


~9K events

Exotic $\eta'\pi$ candidates ?

PRD84 112009 (2011)

$\chi_{c1} \rightarrow \eta\pi\pi$ $\chi_{c1} \rightarrow \eta'\pi\pi$



a_0(980) projected into $\eta'\pi$:
Expect to see it at BESIII

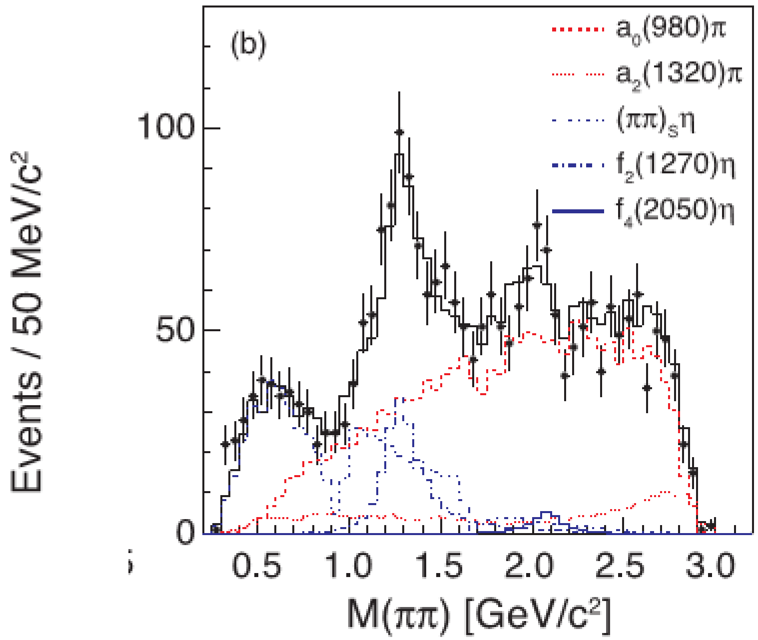
Will exotic wave dominate ~1.6-1.7 GeV at BESIII?

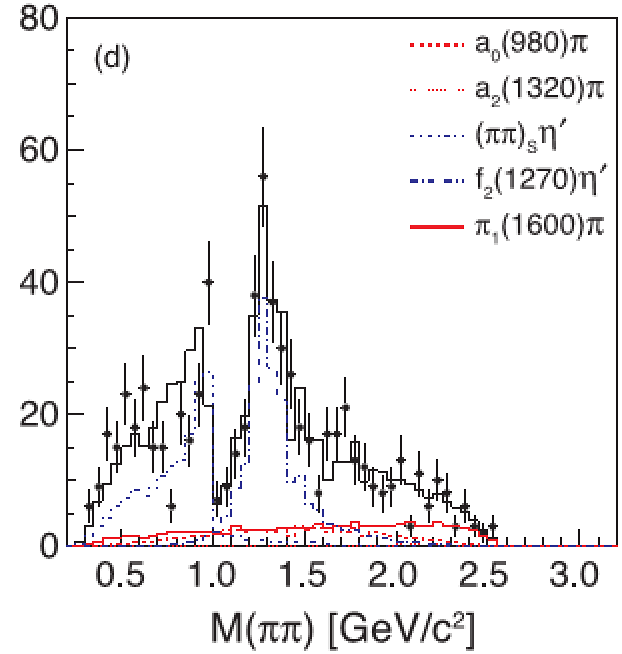
Compare ππ

PRD84 112009 (2011)

CLEO-c

$\chi_{c1} \rightarrow \eta\pi\pi$ $\chi_{c1} \rightarrow \eta'\pi\pi$



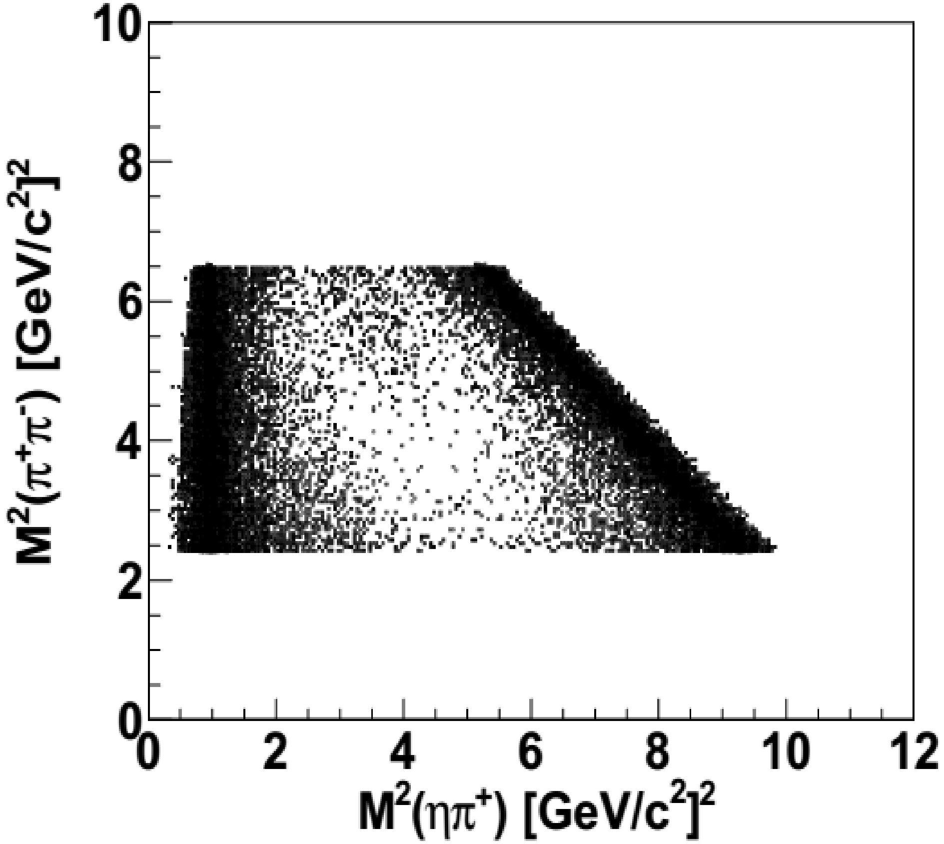


Differences: can we learn more (about f_0/a_0) with more data?

What's next

One strategy: suppress ππ

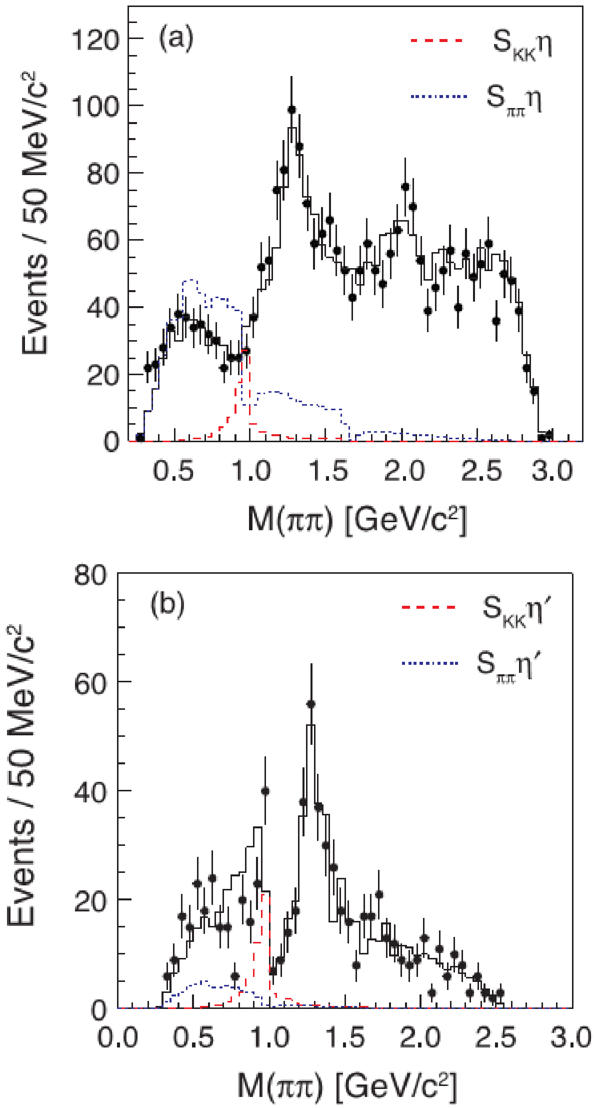
Explore threshold effect(s) without ππ resonances: by suppressing both low-mass and high-mass ππ, reduce the effect of heavier ηπ states:

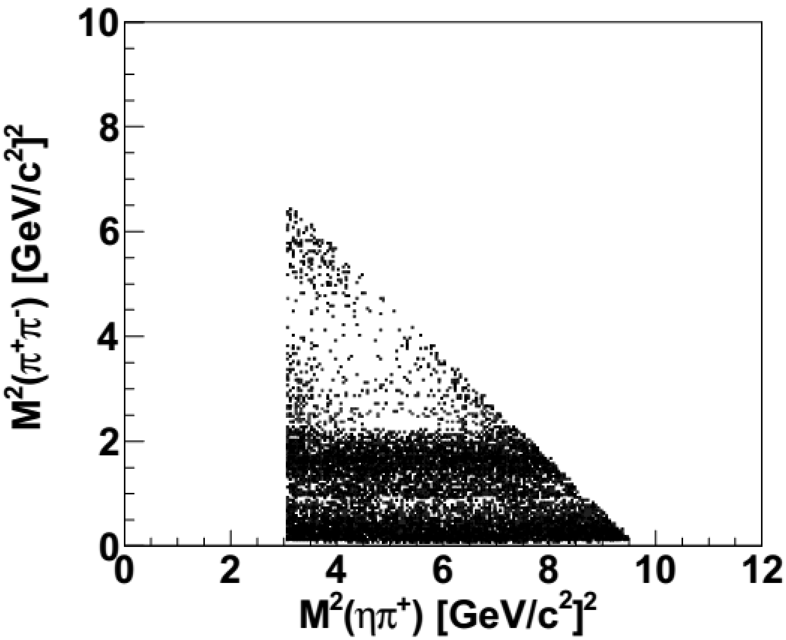


Another strategy: suppress $\eta\pi$

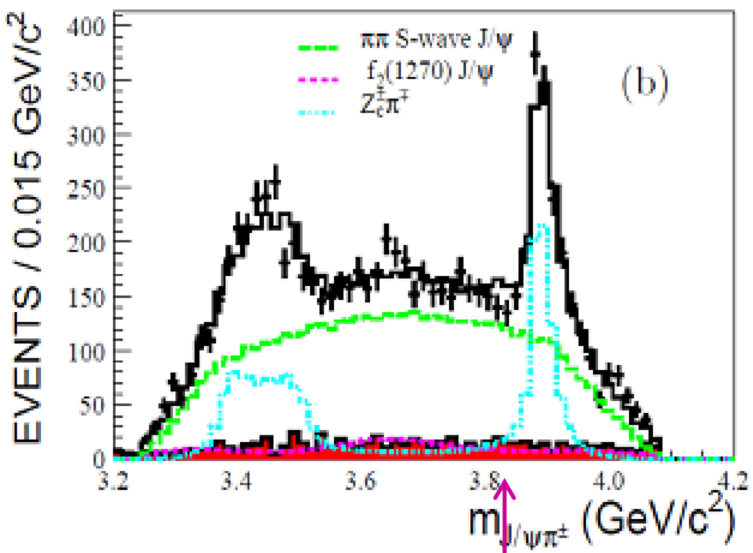
- Analyze $\pi\pi$ distribution in the region without $\eta\pi$ resonances:
- Explore differences: $\eta\pi\pi$ vs $\eta'\pi\pi$.
- Is it possible to train $\pi\pi$ amplitudes recoiling against known flavor states (η, η') ?

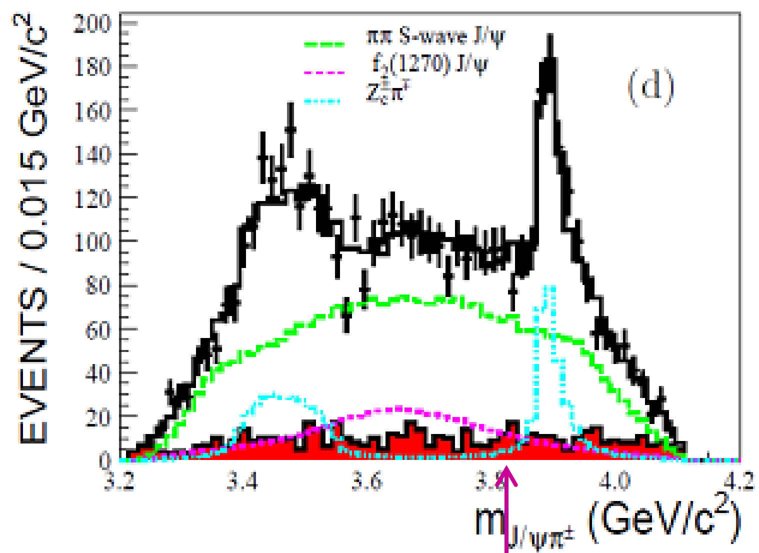
PRD84 112009 (2011)





one example, continue to look for a third channel elsewhere:

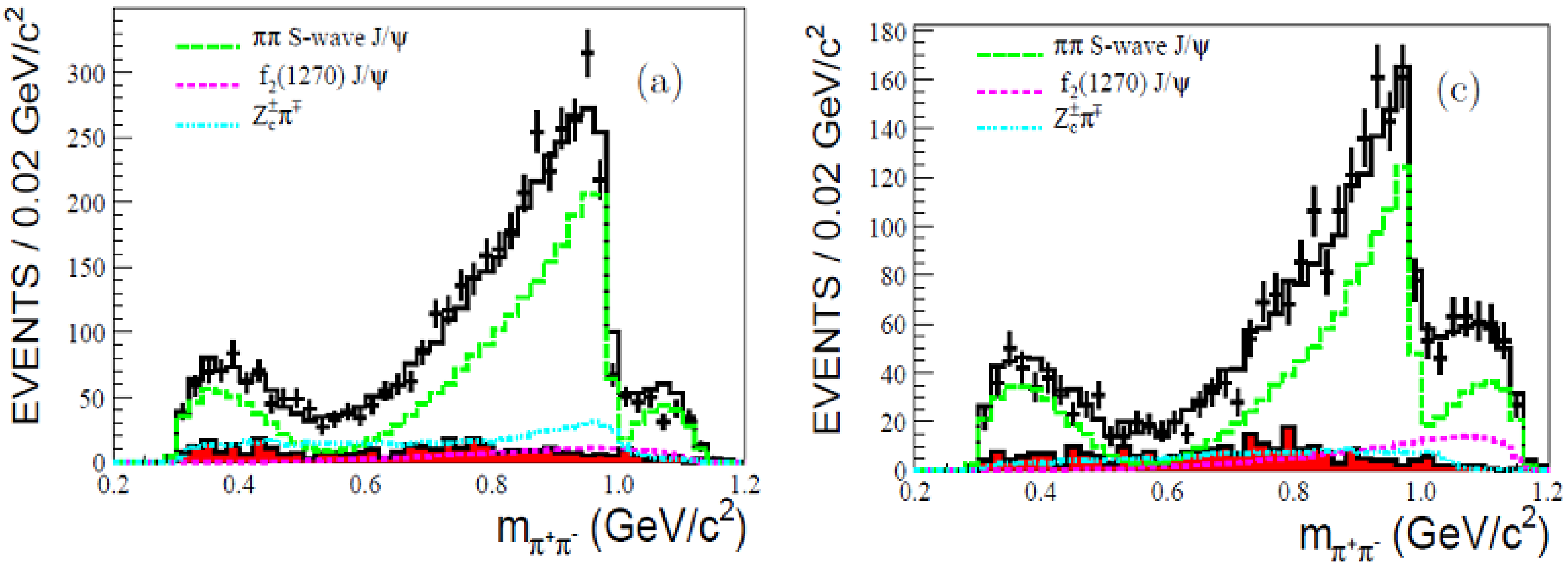




ψ(2S)+π = 3.83 GeV

Use ππ in XYZ region?

4.23 GeV vs 4.26 GeV



- differences in ππ spectra as a function of energy?
- can we use ππ as a filter to learn about Y(4260)?

Summary

- Entering precision phase in charmonium decays
- Use it to improve on our knowledge about light muti-quark states: f_0, a_0
- Extend it into XYZ region?
- Look for light exotics as well!