Effects of Z_b states in $\Upsilon(3S, 4S)$ dipion transitions

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Based on:

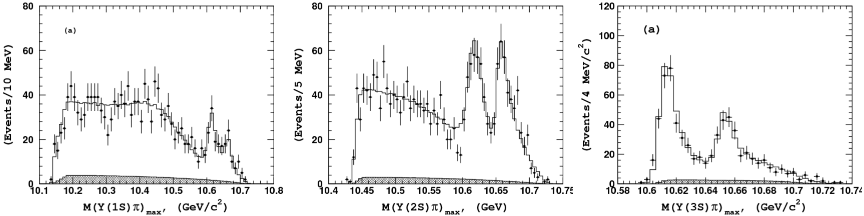
Y.-H. Chen, J. T. Daub, FKG, B. Kubis, U.-G. Meißner, B.-S. Zou, PRD93(2016)034030;

Y.-H. Chen, M. Cleven, J. T. Daub, FKG, C. Hanhart, B. Kubis, U.-G. Meißner, B.-S. Zou, PRD95(2017)034022

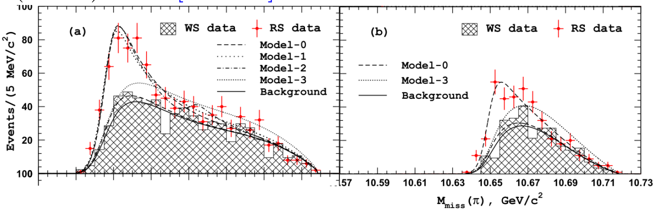
Z_b states

- $Z_b(10610)$ and $Z_b(10650)$: Belle, arXiv:1105.4583; PRL108(2012)122001

  observed in $\Upsilon(10860) \to \pi^{\mp}[\pi^{\pm}\Upsilon(1S, 2S, 3S)/h_b(1P, 2P)]$

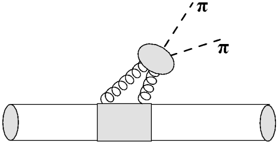


also in $\Upsilon(10860) \to \pi^{\mp}[B^{(*)}\bar{B}^{*}]^{\pm}$ Belle, arXiv:1209.6450; PRL116(2016)212001



Pre-history of Z_b (I)

- Dipion transitions between heavy quarkonia: often QCD multipole expansion + soft pion theorems Gottfried (1978);...



- this gives a smooth $\pi\pi$ invariant mass distribution with a single peak at high pion momenta: $\psi' \to J/\psi\pi\pi$ (BES (2000)) and $\Upsilon' \to \Upsilon\pi\pi$ (CLEO (1998))

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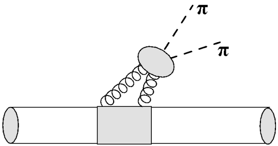

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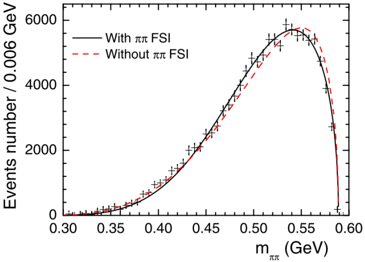
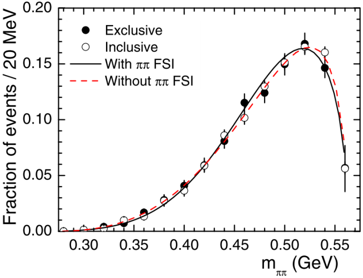
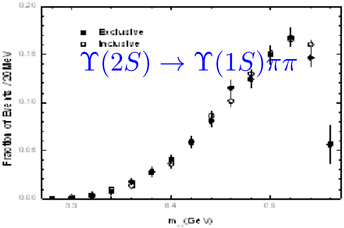
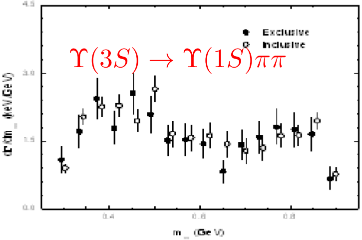




Pre-history of Z_b (II)

- Double-bump structure for $\Upsilon(3S) \to \Upsilon(1S)\pi\pi$ (discovered by CUSB, 1982)





- Lots of models

  Lipkin, Tuan (1988); Belanger, DeGrand, Moxhay (1989); Uehara (2003); Voloshin (2006); ...

- Voloshin proposed an isovector $b\bar{b}q\bar{q}$ in 1982

Possible four-quark isovector resonance in the family of Υ particles

M. B. Voloshin
Institute of Theoretical and Experimental Physics

(Submitted 15 November 1982)
Pis'ma Zh. Eksp. Teor. Fiz. **37**, No. 1, 58–60 (5 January 1983)

It is suggested, on the basis of data on the pion spectrum in the decay $\Upsilon'' \to \Upsilon\pi^+\pi^-$, that there is an isovector resonance with a mass near the Υ'' mass.

Pre-history of Z_b (III)

- Revisited by Anisovich et al. PRD51(1995)378(R)

RAPID COMMUNICATIONS

PHYSICAL REVIEW D VOLUME 51, NUMBER 9 1 MAY 1995

$\Upsilon(3S)\to\Upsilon(1S)\pi\pi$ decay: Is the $\pi\pi$ spectrum puzzle an indication of a $b\bar{b}q\bar{q}$ resonance?

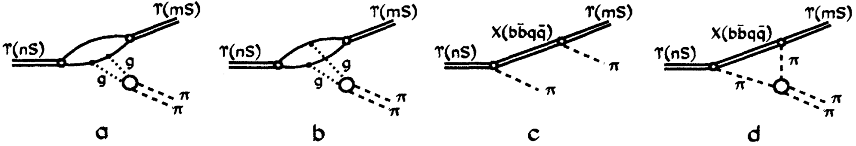
V. V. Anisovich,[1,2] D. V. Bugg,[1] A. V. Sarantsev,[1,2] and B. S. Zou[1]

[1]*Queen Mary and Westfield College, London E1 4NS, United Kingdom*

[2]*Petersburg Nuclear Physics Institute, Gatchina, 188350, Russia*

(Received 22 August 1994; revised manuscript received 2 February 1995)

- mechanism: an isovector $b\bar{b}q\bar{q}$ with $J^P = 1^+$



suggested its mass: $\in [10.4, 10.8]$ GeV $\Leftarrow$ no band in the Dalitz plot

Necessity of reanalyzing $\Upsilon(3S) \to \Upsilon(1S)\pi\pi$

- Belle fitted data using Breit–Wigner Belle, PRL108(2012)122001

$$Z_b(10610): \quad M = (10607.2 \pm 2.0)\text{ MeV} \qquad \Gamma = (18.4 \pm 2.4)\text{ MeV}$$

$$Z_b(10650): \quad M = (10652.2 \pm 1.5)\text{ MeV} \qquad \Gamma = (11.5 \pm 2.2)\text{ MeV}$$

- Branching fractions Belle, arXiv:1209.6450 $\Rightarrow$ coupling constants??

TABLE V: List of branching fractions for the $Z_b^+(10610)$ and $Z_b^+(10650)$ decays.

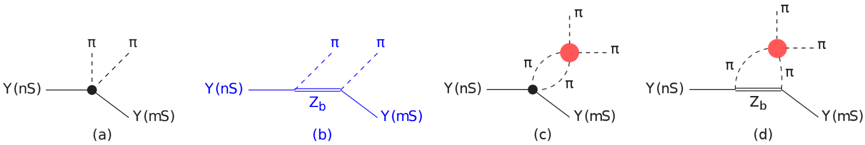
Channel	Fraction, %	
	$Z_b(10610)$	$Z_b(10650)$
$\Upsilon(1S)\pi^+$	0.32 ± 0.09	0.24 ± 0.07
$\Upsilon(2S)\pi^+$	4.38 ± 1.21	2.40 ± 0.63
$\Upsilon(3S)\pi^+$	2.15 ± 0.56	1.64 ± 0.40
$h_b(1P)\pi^+$	2.81 ± 1.10	7.43 ± 2.70
$h_b(2P)\pi^+$	4.34 ± 2.07	14.8 ± 6.22
$B^+\bar{B}^{*0} + \bar{B}^0 B^{*+}$	86.0 ± 3.6	–
$B^{*+}\bar{B}^{*0}$	–	73.4 ± 7.0

- Z_b states couple to both $\Upsilon(1S)\pi$ and $\Upsilon(3S)\pi$, should contribute to $\Upsilon(3S) \to \Upsilon(1S)\pi\pi$

New analysis of $\Upsilon(3S) \to \Upsilon(1S)\pi\pi$

Y.-H. Chen, J. T. Daub, FKG, B. Kubis, U.-G. Meißner, B.-S. Zou, PRD93(2016)034030

- Mechanism



- Method:
  - ☞ $\pi\pi$ FSI from dispersion relation: unitarity, analyticity and crossing symmetry
  - ☞ left-hand cut from t-channel Z_b exchange

    $\Rightarrow$ parameter: $C_{nm} \equiv C_{Z\Upsilon(nS)\pi} C_{Z\Upsilon(mS)\pi}$
  - ☞ chiral Lagrangian $\Rightarrow$ contact term [diag. (a)]

    $\Rightarrow$ subtraction terms in the subtracted dispersion relation

    two parameters: $c_1,\ c_2$

Best fit with couplings constrained by Belle branching fractions

- if we fix the $Z_b \Upsilon \pi$ couplings from the branching fractions reported by Belle in arXiv:1209.6450 [hep-ex]

$$\Gamma(Z_b \to \Upsilon\pi) = \Gamma_{\rm tot}(Z_b) \times {\rm Br}(Z_b \to \Upsilon\pi)$$

then we get $\quad C^{\rm naive}_{31,Z_b(10610)} = (0.014 \pm 0.004)\ {\rm GeV}^2$

- w/o Z_b or w/ Z_b using $C^{\rm naive}_{31,Z_b(10610)}$ for $C_{31} = C_{Z\Upsilon(3S)\pi} C_{Z\Upsilon(1S)\pi}$

Bad description! what is wrong?

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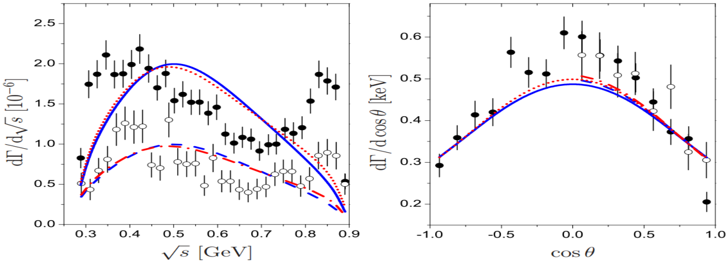


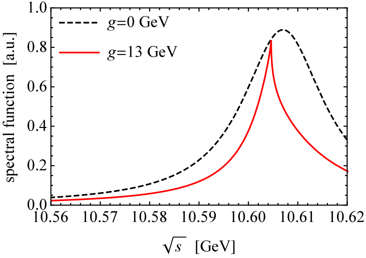
Bad description! what is wrong?

Fletté (I)

- Belle used BW parameterization in fit/extraction of branching fractions
- $Z_b^{(\prime)}$ located at the $B^{(*)}\bar{B}^*$ threshold $\Rightarrow$ use Flatté parameterization

$$\frac{1}{\left|s - m_{Z_b}^2 + i m_{Z_b}\left[\Gamma_1 + \Gamma_{B\bar{B}^*}(s)\right]\right|^2}$$

here $\Gamma_{B\bar{B}^*}(s) = \frac{g^2}{8\pi m_{Z_b}^2}\left[k\,\theta(\sqrt{s} - m_B - m_{B^*}) + i\,\kappa\,\theta(-\sqrt{s} + m_B + m_{B^*})\right]$



using $m_{Z_b} = 10.607$ GeV and $\Gamma_1 = 20$ MeV

- Γ_1 should be larger than the nominal peak width

Fletté (II)

TABLE V: List of branching fractions for the $Z_b^+(10610)$ and $Z_b^+(10650)$ decays.

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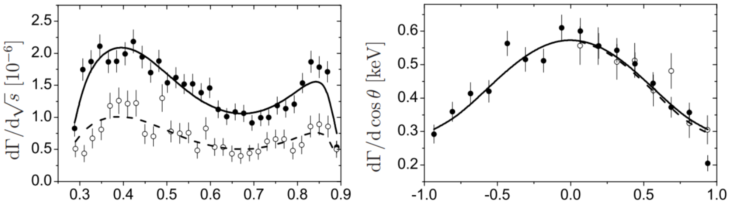
- For $Z_b(10610)$, Br$(Z_b \to \text{non-}B\bar{B}^*) \simeq 14\%$
  $\Rightarrow \Gamma_{\text{tot}} \times \text{Br}(\text{non-}B\bar{B}^*) \sim 3$ MeV
- It should, however, be larger than the nominal peak width ($\sim$20 MeV).
  We thus expect

$$\left|C_{31,Z_b(10610)}\right| = \mathcal{O}\left(0.1\ \text{GeV}^2\right)$$

recall: $C^{\text{naive}}_{31,Z_b(10610)} = (0.014 \pm 0.004)\ \text{GeV}^2$

Best fit with free couplings

- best fit keeping the coupling C_{31} a free parameter

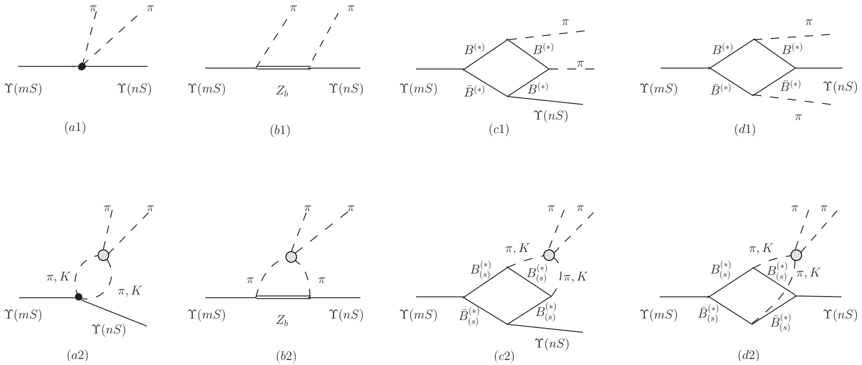


	$\Upsilon(3S) \to \Upsilon(1S)\pi\pi$	$\Upsilon(2S) \to \Upsilon(1S)\pi\pi$	$\Upsilon(3S) \to \Upsilon(2S)\pi^0\pi^0$
c_1	-0.025 ± 0.001	0.09 ± 0.05	-0.6 ± 0.1
c_2	0.026 ± 0.001	0.04 ± 0.08	0.2 ± 0.3
$C_{nm,1}$ [GeV^2]	0.145 ± 0.006	1.3 ± 1.4	3.7 ± 2.6
$\frac{\chi^2}{\mathrm{d.o.f}}$	$\frac{108.18}{87-3} = 1.29$	$\frac{101.68}{40-3} = 2.75$	$\frac{12.18}{11-3} = 1.52$

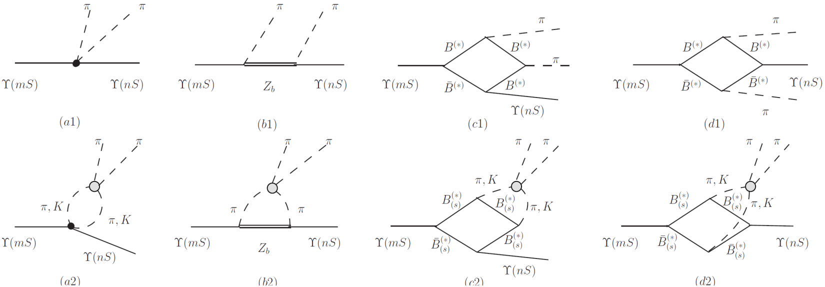
much larger than $C^{\mathrm{naive}}_{31,Z_b(10610)} = (0.014 \pm 0.004)\ \mathrm{GeV}^2$, but $= \mathcal{O}\left(0.1\ \mathrm{GeV}^2\right)$!

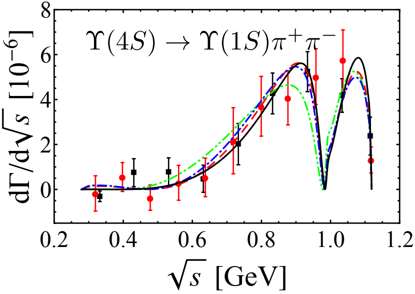
Transitions from $\Upsilon(4S)$ (I)

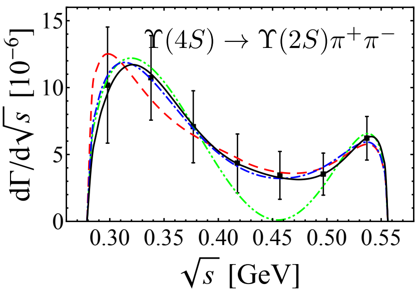
- Features of the $\Upsilon(4S)$ transitions:
  - ☞ $\Upsilon(4S)$ is above the $B\bar{B}$ threshold
    $\Rightarrow$ branch cut from the $B\bar{B}$ threshold needs to be considered in dispersion relation
  - ☞ $M_{\Upsilon(4S)} - M_{\Upsilon(1S)} = 1.12$ GeV, $K\bar{K}$ channel needs to be considered in FSI
- Much more complicated:



Transitions from $\Upsilon(4S)$ (II)



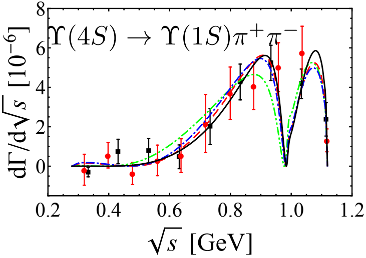


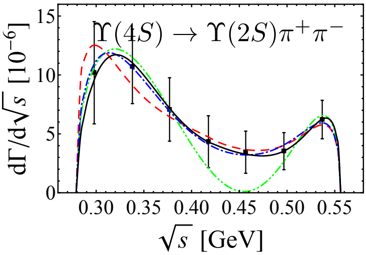


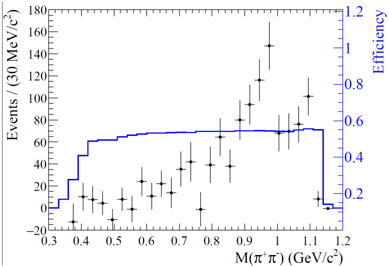
green: (a1+a2) ; red: (a1+a2+b1+b2); blue: (a1+a2+c1+c2+d1+d2); black: full

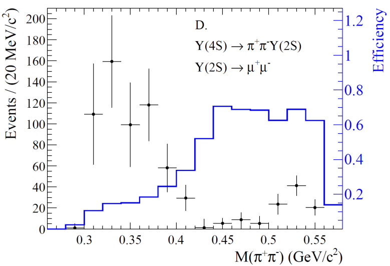
Confronting with the new Belle data in arXiv:1707.04973

- Dipion invariant mass distributions

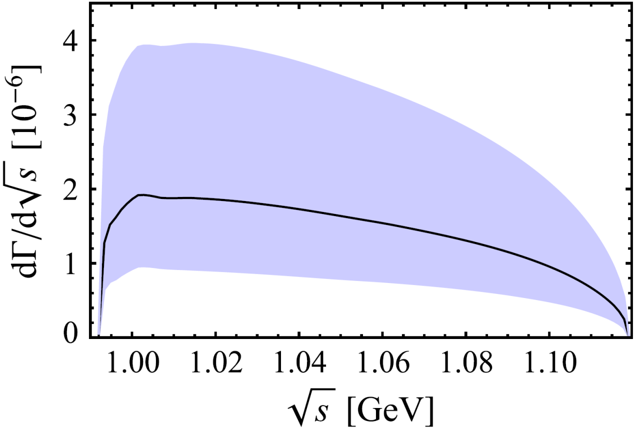








- Double-peak structure at ∼1 GeV: FKG et al., PLB568(2007)27



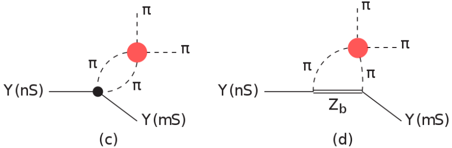
- There should be a rapid rise close to the $K\bar{K}$ threshold due to the presence of $f_0(980)$.

Summary

- Z_b: distinguished candidates for exotic hadrons
- important effects of virtual Z_b in $\Upsilon(3S)$ decays
- Z_b data should be reanalyzed to get the correct partial widths
  $\Rightarrow$ more conclusive understanding of the long-standing issue of
  $\Upsilon(3S) \to \Upsilon(1S)\pi\pi$ transitions
- there should a clear structure at around 1 GeV in $m_{\pi\pi}$ distribution in
  $\Upsilon(4S) \to \Upsilon(1S)\pi\pi$ transitions, confirmed by the latest Belle data
- analysis needs to be updated . . .

Thank you !

FSI including Z_b



$$\mathrm{Im}\, M_l(s) = \left[M_l(s) + \hat{M}_l(s)\right] \theta\left(s - s_{\rm th}\right) \sin\delta_l^0(s) e^{-i\delta_l^0(s)}$$

- $M_l(s)$: FSI in the s-channel
- $\hat{M}_l(s)$: inhomogeneity, from t-channel Z_b exchange
- Omnès problem with inhomogeneity — Anisovich, Leutwyler, PLB375(1996)335

  Omnès function:

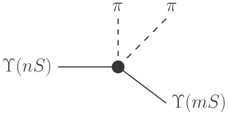
  $$\Omega_l(s) = \exp\left[\frac{s}{\pi}\int_{s_{\rm th}}^{\infty} dz \frac{\delta_l(z)}{z(z-s)}\right] \;\Rightarrow\; \Omega_l(s+i\epsilon) = \Omega_l(s-i\epsilon)\exp[2i\delta_l(s)]$$

$$\mathrm{disc}\left[\frac{M_l(s)}{\Omega_l(s)}\right] = \frac{\sin\delta_l(s)\,\hat{M}_l(s)}{|\Omega_l(s)|}$$

Solution: $$M_l(s) = \Omega_l(s)\left\{P_l^{n-1}(s) + \frac{s^n}{\pi}\int_{4M_\pi^2}^{\infty} dz \frac{\hat{M}_l(z)\sin\delta_l(z)}{|\Omega_l(z)|z^n(z-s)}\right\}$$

Chiral Lagrangians with HQSS

- Treating Υ and Z_b nonrelativistically.
  S-wave $Q\bar{Q}$ spin multiplet in notation of bispinor superfield: $J = \vec{\Upsilon} \cdot \vec{\sigma} + \eta_b$
  spin symmetry transformation: $J \to SJS^{-1}$; $[S, \sigma^i] \neq 0$



$$\mathcal{L}_{\Upsilon\Upsilon'\pi\pi} = \frac{c_1}{2} \left\langle J^\dagger J' \right\rangle \mathrm{Tr}(u_\mu u^\mu) + \frac{c_2}{2} \left\langle J^\dagger J' \right\rangle \mathrm{Tr}(u_\mu u_\nu) v^\mu v^\nu + \mathrm{h.c.}$$

u_μ : axial current;

here, $\langle , \rangle$: trace in spinor space; Tr: in light flavor space;

☞ matching the dispersive representation w/o FSI to the contact terms gives the subtraction polynomials ⇒ two parameters: c_1, c_2

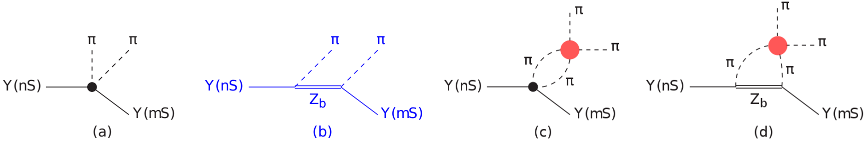
- $Z_b \Upsilon \pi$ coupling in S-wave :

$$\mathcal{L}_{Z_b\Upsilon\pi} = C_Z \Upsilon^i \mathrm{Tr}\left(Z^{i\dagger} u_\mu\right) v^\mu + \mathrm{h.c.}$$

Full amplitude including FSI

Y.-H. Chen, J. T. Daub, FKG, B. Kubis, U.-G. Meißner, B.-S. Zou, PRD93(2016)034030

- Finally,



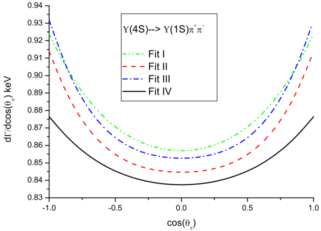
- Full decay amplitude including both S-wave and D-wave $\pi\pi$ FSI

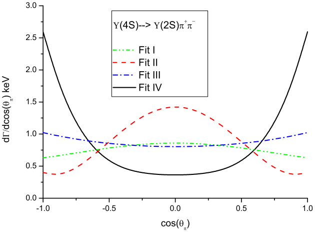
$$\mathcal{M}^{\text{full}}(s,\cos\theta) = \epsilon_{\Upsilon(nS)} \cdot \epsilon_{\Upsilon(mS)} \sum_{l=0,2} \left[M_l(s) + \hat{M}_l(s) \right] P_l(\cos\theta),$$

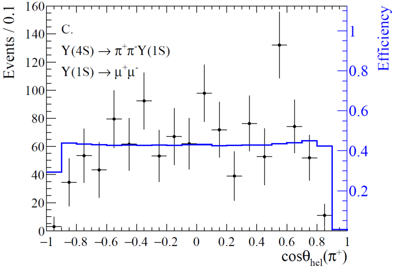
$$M_l(s) = \Omega_l^0(s) \left\{ P_l^{n-1}(s) + \frac{s^n}{\pi} \int_{4M_\pi^2}^{\infty} \frac{\mathrm{d}x}{x^n} \frac{\hat{M}_l(x) \sin\delta_l^0(x)}{|\Omega_l^0(x)|(x-s)} \right\}$$

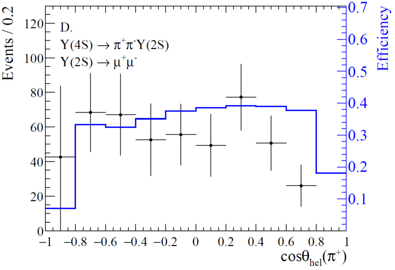
with Omnès function: $\Omega_l^I(s) = \exp\left\{ \frac{s}{\pi} \int_{4M_\pi^2}^{\infty} \frac{\mathrm{d}x}{x} \frac{\delta_l^I(x)}{x-s} \right\}$

- Helicity angular distributions

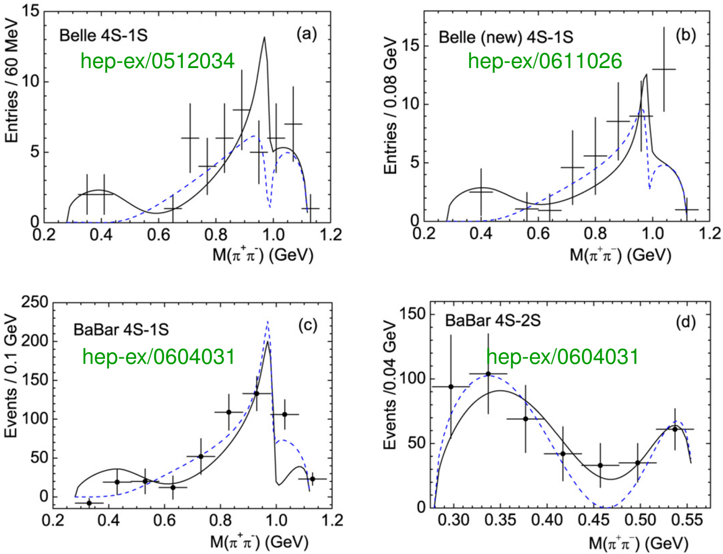








A bit more history



FKG, P.-N. Shen, H.-C. Chiang, R.-G. Ping, PLB568(2007)27