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Study of the $\psi(2S)\pi^+\pi^-$ final state produced in e^+e^- collisions with Initial State Radiation (ISR).

Stefano Zambito[1]

On behalf of the BaBar Collaboration

[1]INFN Turin
(now at Brandeis University (US))

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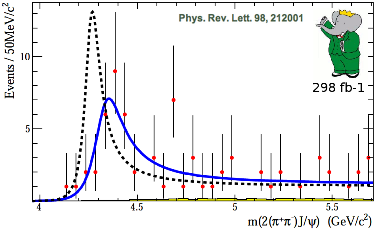
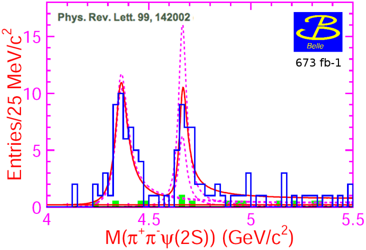
Analysis Motivations

After the discovery of the $Y(4260)$ in its decay into $\pi^+\pi^- J/\psi$ [Phys. Rev. Lett. 95, 142001], two more resonances found by *BABAR* and *Belle* in the study of ISR $\psi(2S)\pi^+\pi^-$:



BABAR results:

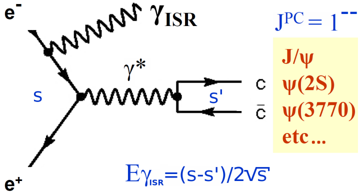
- $M = 4324 \pm 24 \; MeV/c^2$
- $\Gamma_{tot} = 172 \pm 33 \; MeV$



Belle results:

- $M_1 = 4361 \pm 9 \pm 9 \; MeV/c^2$
- $\Gamma_1^{tot} = 74 \pm 15 \pm 10 \; MeV$
- $M_2 = 4664 \pm 11 \pm 5 \; MeV/c^2$
- $\Gamma_1^{tot} = 48 \pm 15 \pm 3 \; MeV$

Analysis Strategy



We study the processes:

$e^+e^- \to \gamma_{ISR}\,\psi(2S)\pi^+\pi^-$

$\quad\quad \hookrightarrow \ell^+\ell^-$ (NEW!)

$\quad\quad \hookrightarrow J/\psi\,\pi^+\pi^-$

$\quad\quad\quad\quad \hookrightarrow \ell^+\ell^-$

We use 473.22 fb^{-1} of integrated luminosity collected by the *BABAR* detector at the $\Upsilon(4S)$ resonance, and additional 31.16 fb^{-1} at $\Upsilon(3S)$ and 15.90 fb^{-1} at $\Upsilon(2S)$: total of $\approx$ 520 fb^{-1}.

The analysis strategy:

- *ISR photon detection not necessary*
- *Require mass recoiling against final state compatible with zero* $\to \gamma_{ISR}$
- *Missing transverse momentum must be low*

Background Evaluation

$\psi(2S)\pi^+\pi^-$, $\psi(2S) \to \pi^+\pi^- J/\psi$ decay mode.

4 pions in the final state:

$\to$ high probability of an interchange

$\to$ expected large (dominant) **combinatorial background**.

4 *zero-charged* and 2 *doubly-charged* combinations of $\pi^\pm$ possible:

zero-charged		*doubly-charged*
$\pi_1^+\pi_1^-(\pi_2^+\pi_2^- J/\psi)$	$\pi_1^+\pi_2^-(\pi_2^+\pi_1^- J/\psi)$	$\pi_1^+\pi_2^+(\pi_1^-\pi_2^- J/\psi)$
$\pi_2^+\pi_1^-(\pi_1^+\pi_2^- J/\psi)$	$\pi_2^+\pi_2^-(\pi_1^+\pi_1^- J/\psi)$	$\pi_2^-\pi_1^-(\pi_2^+\pi_1^+ J/\psi)$

Background estimated with doubly-charged combinations in the same data.
Consistency check: we look also at $\psi(2S)$ sidebands.

$\psi(2S)\pi^+\pi^-$, $\psi(2S) \to \ell^+\ell^-$ decay mode.

We expect an important source of background from **radiative Bhabhas**, like $e^+e^- \to e^+e^-\gamma$ where the photon converts in the material.

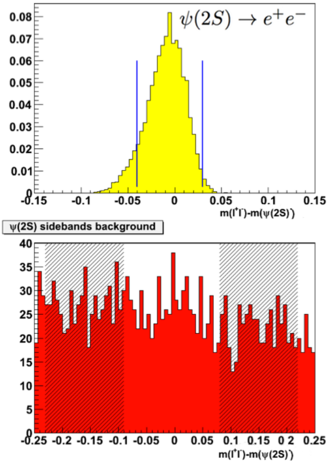
Background estimated using $\psi(2S)$ sidebands.

Background Evaluation: $\psi(2S)$ Sidebands

Signal MC Truth Matched

Background Events

Cut Position



Selection Criteria, $\psi(2S) \to \pi^+\pi^- J/\psi$

	Final Selection:	$J/\psi \to e^+e^-$	$J/\psi \to \mu^+\mu^-$
Mass Window	$m(\pi^+\pi^- J/\psi) - m(\psi(2S))$	$[-10, +10]$ MeV/c^2	$[-10, +10]$ MeV/c^2
	$m(\ell^+\ell^-) - m(J/\psi)$	$[-60, +45]$ MeV/c^2	$[-45, +45]$ MeV/c^2
ISR Selection	Δp^*	$[-100, +70]$ MeV/c	$[-100, +70]$ MeV/c
	pt^*_{miss}	≤ 2.0 GeV/c	≤ 2.0 GeV/c
	$nTRK$	$nTRK = 6$	$nTRK = 6$
Other Cuts	$m(\pi^+\pi^-$ from $\psi(2S))$	≥ 350 MeV/c^2	≥ 350 MeV/c^2
	$N(\eta + \pi^0)$	$N(\eta + \pi^0) = 0$	$N(\eta + \pi^0) = 0$
	pions tracks quality	BaBar standard PID	
	leptons tracks quality	Bremsstrahlung recovery + PID	BaBar standard PID
	vertex-fit	$Prob(vtx - fit) > 10^{-3}$	$Prob(vtx - fit) > 10^{-3}$

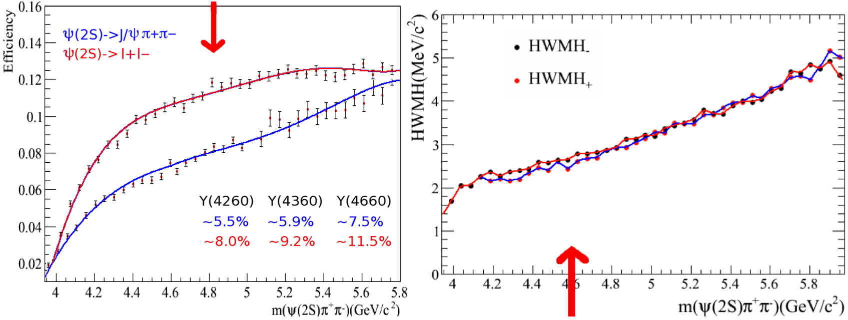
Selection criteria are optimized on the significancy $N_S/\sqrt{N_S + N_B}$

Selection Criteria, $\psi(2S) \to \ell^+\ell^-$

	Final Selection:	$\psi(2S) \to e^+e^-$	$\psi(2S) \to \mu^+\mu^-$
Mass Window	$m(\ell^+\ell^-) - m(\psi(2S))$	$[-40, +30]$ MeV/c^2	$[-30, +30]$ MeV/c^2
ISR Selection	Δp^*	$[-70, +60]$ MeV/c	$[-70, +60]$ MeV/c
ISR Selection	$nTRK$	$nTRK = 4$	$nTRK = 4$
ISR Selection	pt^*_{miss}	≤ 1.7 GeV/c	≤ 1.7 GeV/c
Decay Topology	$cos\theta_l$	$[-0.70, +0.70]$	$[-0.70, +0.70]$
Decay Topology	$cosP$	$[-0.86, +0.86]$	$[-0.86, +0.86]$
	pions tracks quality	BaBar standard PID	BaBar standard PID
	leptons tracks quality	Bremsstrahlung recovery + PID	BaBar standard PID
	vertex-fit	$Prob(vtx - fit) > 10^{-3}$	$Prob(vtx - fit) > 10^{-3}$
	$m(e^+e^- \leftrightarrow \pi^+\pi^-)$	≥ 100 MeV/c^2	-
	Reconstructed ISR photon or $\lvert cos\theta^*_{2\pi\psi(2S)}\rvert > 0.95$		

Efficiency and Resolution Studies

Efficiency Studies Results:

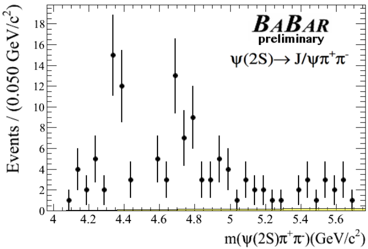


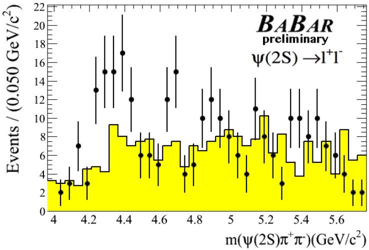
Resolution Studies Results:

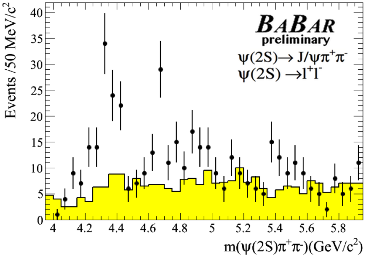
- the **mass resolution** goes from 2 to 5 MeV/c^2 in the range [4,6] GeV/c^2.
- the **mass shift** introduced by the reconstruction procedure is **very small**, $\sim 0.5\ \mathrm{MeV}/c^2$, and will be accounted as a systematic error.

Results after Unblinding

$\psi(2S)\pi^+\pi^-$ Invariant Mass Distribution (I)

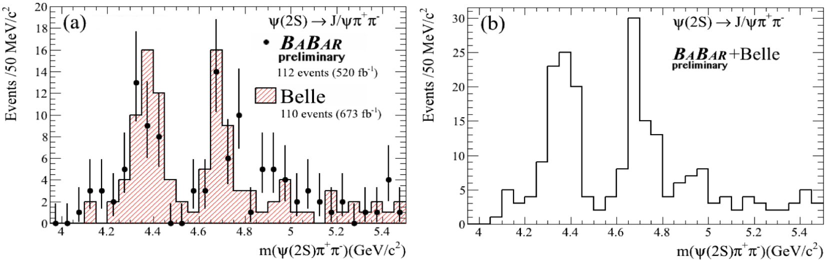






$\psi(2S)\pi^+\pi^-$ Invariant Mass Distribution (II)

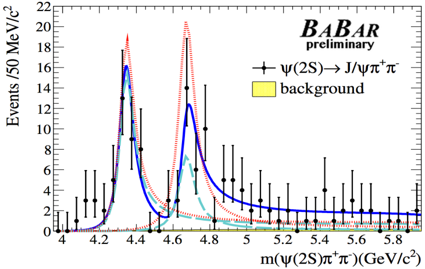
BaBar vs. Belle: Results Comparison

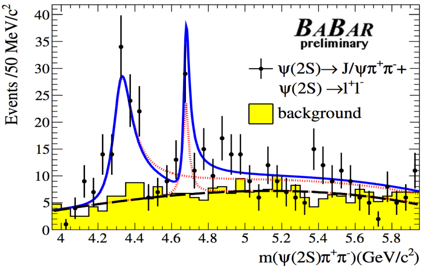


- Comparison of "raw data" (not rescaled) in the hadronic channel.
- Consistent resolution $\rightarrow$ a comparison makes sense!
- After combining datasets ($\approx 1.2\ ab^{-1}$), hints of some additional activity around 4.9 GeV/c^2 become evident...

Fit to $\psi(2S)\pi^+\pi^-$ Mass Spectrum

We perform an **Unbinned Maximum Likelihood fit** to the $\pi^+\pi^-\psi(2S)$ invariant mass spectrum. We hypotize **two distinct resonances** $\rightarrow$ **interference term**.



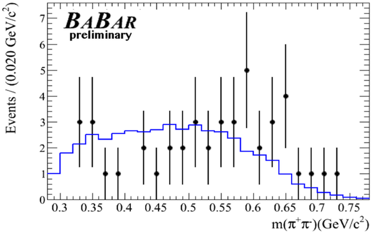


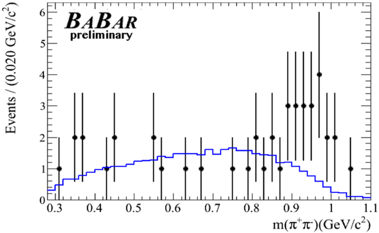
Mass Y(4360)(MeV/c^2)	$4340 \pm 16 \pm 9$	
Width Y(4360)(MeV)	$94 \pm 32 \pm 13$	
$\mathcal{B} \times \Gamma_{ee}(Y(4360))$(eV)	$6.0 \pm 1.0 \pm 0.5$	$7.2 \pm 1.0 \pm 0.6$
Mass Y(4660)(MeV/c^2)	$4669 \pm 21 \pm 3$	
Width Y(4660)(MeV)	$104 \pm 48 \pm 10$	
$\mathcal{B} \times \Gamma_{ee}(Y(4660))$(eV)	$2.7 \pm 1.3 \pm 0.5$	$7.5 \pm 1.7 \pm 0.7$
$\phi(^\circ)$	$12 \pm 27 \pm 4$	$-78 \pm 12 \pm 3$

Mass Y(4360)(MeV/c^2)	$4318^{+15}_{-19} \pm 3$
Width Y(4360)(MeV)	$123 \pm 20 \pm 13$
$\mathcal{B} \times \Gamma_{ee}(Y(4360))$(eV)	$7.4 \pm 0.9 \pm 0.7$
Mass Y(4660)(MeV/c^2)	$4667^{+6}_{-7} \pm 2$
Width Y(4660)(MeV)	36^{+32}_{-14}
$\mathcal{B} \times \Gamma_{ee}(Y(4660))$(eV)	$1.4 \pm 0.5 \pm 0.2$
$\phi(^\circ)$	$+25 \pm 21 \pm 2$

$\pi^+\pi^-$ Invariant Mass Distribution, $\psi(2S) \to \pi^+\pi^- J/\psi$

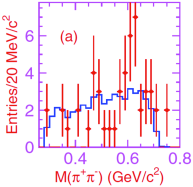
Observed distributions differ from the phase space expectation and tend to peak at high masses, underlying the presence of a **dynamical effect**.



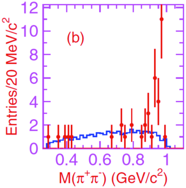


$4.0\ GeV/c^2 < m_{\psi(2S)\pi^+\pi^-} < 4.5\ GeV/c^2$

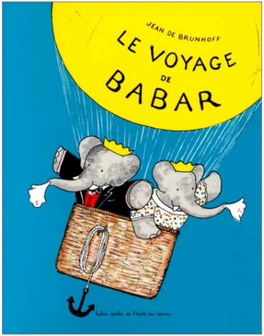
$4.5\ GeV/c^2 < m_{\psi(2S)\pi^+\pi^-} < 4.9\ GeV/c^2$



BELLE RESULT



Conclusions & Future Plans



Results... In a nutshell

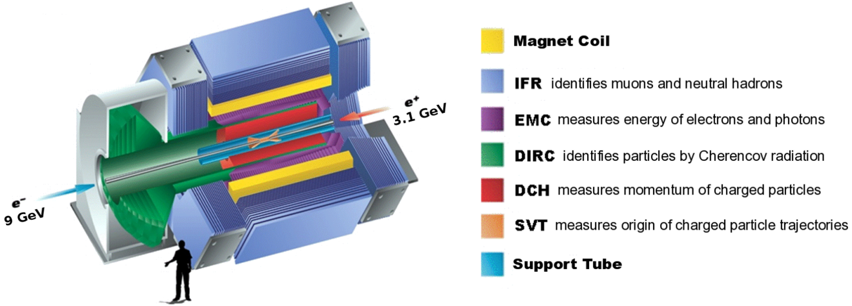
- Two different stuctures observed, and hints of some activity around 4.9 GeV/c^2...
- A fit to the $\psi(2S)\pi^+\pi^-$ spectrum yields the measurement of the two resonances' relevant properties (mass, width, ...).
- The paper's review procedure from the BaBar collaboration is almost at the end... Publication!!! :-)

Looking forward to SuperB and Belle II!

Thanks for Your Attention!

Backup Slides

BABAR Detector Layout



SVT: 5 double side layers. 97% efficiency, 15μm z-hit resolution (inner layers, $\perp$ tracks).
SVT+DCH (momentum resolution): $\sigma(p_T)/p_T = 0.13\% \times p_T + 0.45\%$.
DIRC: 144 quartz bars, provides $K - \pi$ separation $\rightarrow 4.2(2.5)\sigma$ @ 2.4(4.0) GeV/c.
EMC: 6580 $CsI(Tl)$ crystals. Energy resolution: $\sigma_E/E = 2.3\% \times E^{-1/4} + 1.91\%$.

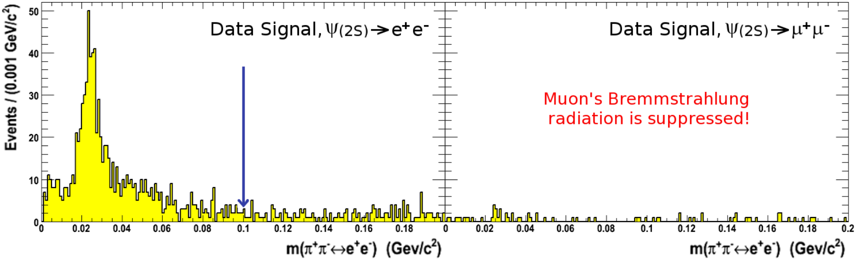
$\psi(2S) \to \ell^+\ell^-$ Issues: Electron Pair Contamination

Let's consider an $e^+e^- \to \gamma\ell^+\ell^-$ event where:

- *$\ell^+\ell^-$ pair's mass is compatible with $\psi(2S)$;*
- *the photon converts into an electron pair (e.g. by interacting with detector material);*
- *this new pair is misidentified as pions.*

$\Longrightarrow$ Get a fake $\psi(2S)\pi^+\pi^-$ candidate!!!

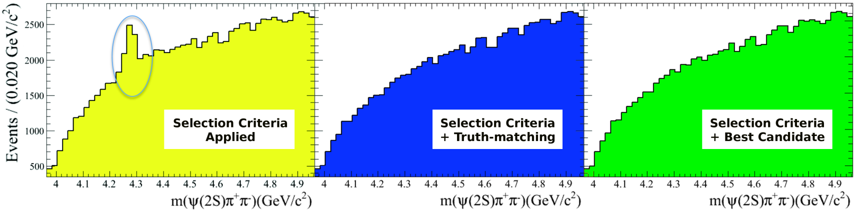
To remove this background we compute the $\pi^+\pi^-$ invariant mass assigning to the pions the electron mass: we discard events below 100 MeV/c^2 .



$\psi(2S) \to \pi^+\pi^- J/\psi$ Issues: Multiple Candidates

Multiple candidates in the same event are possible with 4 pions in the final state:
$\to$ the best candidate is selected based on its $\psi(2S)$ mass value.

MC studies: $m(\pi^+\pi^-\psi(2S))$ reconstructed from a sample generated with flat mass distribution (for efficiencies and resolution studies).



The **fake** peak around 4.28 GeV/c^2 (yellow histogram): wrong candidates where two pions are swapped.

It disappears:

- requiring **truth-matching** (blue histogram);
- selecting **only the best candidate** for each event (green).

Cross-section Measurement

$e^+e^- \to \pi^+\pi^-\psi(2S)$ exclusive process in ISR events, from threshold to 6 GeV

For each $\pi^+\pi^-\psi(2S)$ mass bin, the cross section is calculated according to:

$$\sigma_i = \frac{n_i^{obs} - n_i^{bkg}}{\epsilon_i \mathcal{L}_i \mathcal{B}(\psi(2S) \to \text{final state})},$$

$\mathcal{L}_i \to i$-th bin integrated luminosity
$\epsilon_i \to i$-th bin total efficiency