Analysis of $e^+e^- \to J/\psi\eta\eta$

Charmonium Group Meeting 12/19/2018

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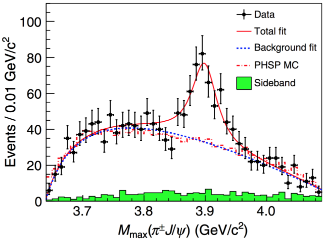
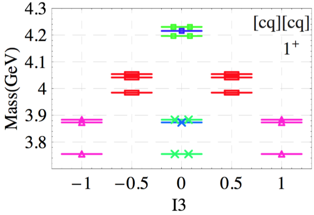
Motivation

PRL 110, 252001 (2013)



- Obeservation of $Z_c(3900) \rightarrow \pi J/\psi$
- Isospin triplet

N.Drenska et al., Riv. Nuovo Cim. 033 (2010) 633



- Complete multiplets to be observed?
- e.g. $J^P = 0^+, 1^+, 2^+ \ldots$ spin state partners
- Further charmonia channels needed

Overview

- Analysis of $e^+e^- \to J/\psi\,\eta\,\eta$ at $\sqrt{s} = 4.23$, 4.26, 4.36, 4.42 and 4.60 GeV
- Determine X-section $e^+e^- \to J/\psi\,\eta\,\eta$
- Search for isospin partner of $Z_c(3900)$ in $J/\psi\,\eta$
- Using BOSS 6.6.5.p01

Track Selection

Photon Selection

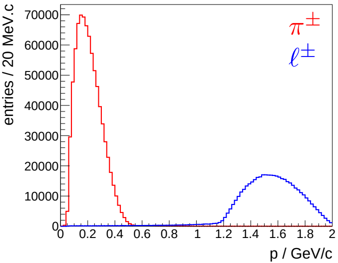
- $E \geq 50\,\text{MeV}$ if $0.86 < |\cos\theta| < 0.92$ (endcaps)
- $E \geq 25\,\text{MeV}$ if $|\cos\theta| < 0.8$ (barrel)
- EMC timing cut: $0 \leq T \leq 14$ (in units of 50 ns)
- $\measuredangle\left(\gamma, X_{charged}\right) > 20^\circ$
- $4 \leq n(\gamma) \leq 60$

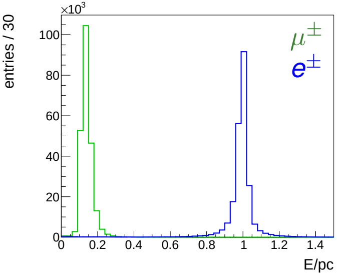
Charged Track Selection

- $|z_0| < 10.0\,\text{cm}$
- $|r_{xy}| < 1.0\,\text{cm}$
- $|\cos\theta| < 0.93$
- Total charge $= 0$

Particle Identification

- Leptons: $p \geq 1\,\text{GeV}/\,c$, Pions: $p < 1\,\text{GeV}/\,c$
- $e^{\pm}$: both tracks with $E/(pc) > 0.7$
- $\mu^{\pm}$: both tracks with $E/(pc) < 0.3$
  at least one track with $N_{layers} > 6$
- $\pi^{\pm}$: use dE/dx and TOF ($\mathcal{P} > 0.001$)





Event Selection - π^0/η Candidate Selections

- $\pi^0 \to \gamma\gamma$:
  - $0.08\,\mathrm{GeV}/c^2 \leq m_{\gamma\gamma} \leq 0.14\,\mathrm{GeV}/c^2$
  - 1C fit (m_{π^0}) with cut on $\chi^2_{1C} \leq 2500$
- $\eta \to \gamma\gamma$: $\mathcal{B} = 39.41\,\%$
  - $0.40\,\mathrm{GeV}/c^2 \leq m_{\gamma\gamma} \leq 0.70\,\mathrm{GeV}/c^2$
  - 1C fit (m_η) with cut on $\chi^2_{1C} \leq 2500$
- $\eta \to \pi^+\pi^-\pi^0$: $\mathcal{B} = 22.92\,\%$
  - $0.40\,\mathrm{GeV}/c^2 \leq m_{3\pi} \leq 0.70\,\mathrm{GeV}/c^2$
  - Vertex fit for $\pi^+\pi^-$
  - 2C fit (m_η, m_{π^0}) with cut on $\chi^2_{2C} \leq 2500$
- $n(\eta) \geq 2$
- $\eta \to 3\pi^0$ omitted due to very low efficiency and high background

Candidate Selection

- Combine $\ell^+\ell^-\eta\eta$
- Vertex fit for $\ell^+\ell^-$ [$2(\pi^+\pi^-)$]
- 7C kinematic fit (initial P, $m_{J/\psi}$, $2 \times m_\eta$)
- Best candidate with smallest χ^2_{7C}

Naming:

(1) $\eta \rightarrow \gamma\gamma$

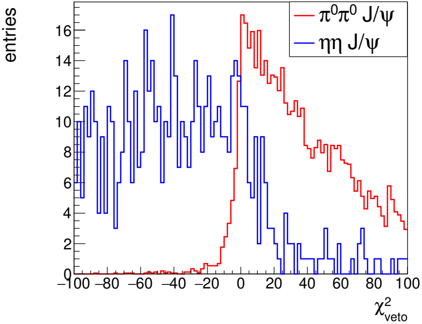
(4) $\eta \rightarrow \pi^+\pi^-\pi^0$

$\pi^0\pi^0$-Veto

- Largest background from $e^+e^- \rightarrow \pi^0\pi^0 J/\psi$
- Define $\pi^0\pi^0$-Veto:

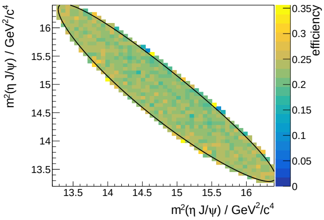
$$\chi^2_{veto} = \chi^2_{1C}(\eta_1) + \chi^2_{1C}(\eta_2) - \chi^2_{1C}(\pi^0_1) - \chi^2_{1C}(\pi^0_2)$$

- If $\chi^2_{veto} \geq 0$ event is rejected
- Only applied for mode (11)

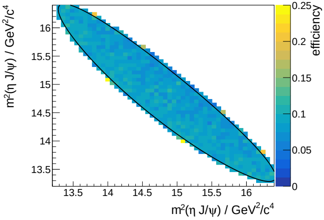


Efficiency

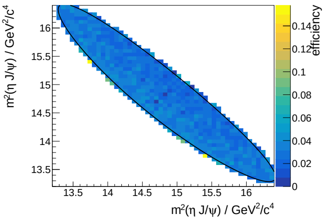
$\sqrt{s} = 4.6\,\text{GeV}$ (11)



$\sqrt{s} = 4.6\,\text{GeV}$ (14)



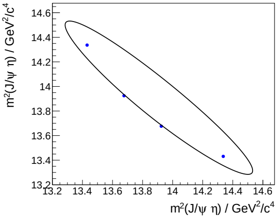
$\sqrt{s} = 4.6\,\text{GeV}$ (44)



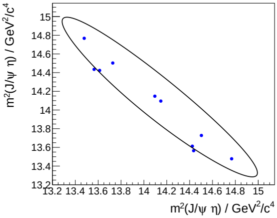
channel	ϵ
(11)	0.24
(14)	0.09
(44)	0.03

Dalitz Plots

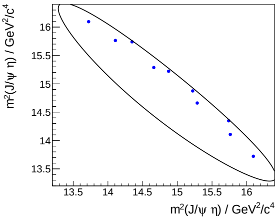
data @4.36 GeV



data @4.42 GeV



data @4.60 GeV



- Dalitz plots symmetrized
- Only very few events in data
- No events for $\sqrt{s} =$ 4.23 and 4.26 GeV

Reduced Luminosity

- Include systematic uncertainties from $\mathcal{L}$ and $\mathcal{B}$
- Both have influence on upper limit, but *no* influence on reconstruction efficiency

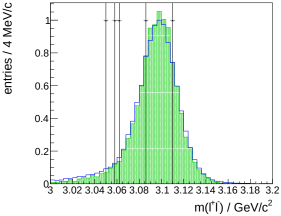
⇒ Define "Reduced Luminosity" as:

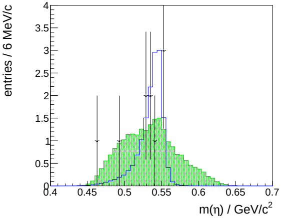
$$\mathcal{L}_{red} = \mathcal{L} \sum \mathcal{B}_{ij} \, \epsilon_{ij}$$

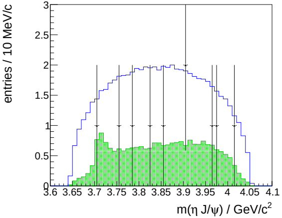
$\sqrt{s}$	4.23 GeV	4.26 GeV	4.36 GeV	4.42 GeV	4.60 GeV
$\mathcal{L}/\text{pb}^{-1}$	1086.20	825.68	541.38	1074.40	563.45
ϵ_{11}	0.264	0.250	0.236	0.232	0.227
$\mathcal{B}_{11}$			0.01853		
ϵ_{14}	0.095	0.091	0.086	0.084	0.085
$\mathcal{B}_{14}$			0.01065		
ϵ_{44}	0.029	0.028	0.029	0.028	0.030
$\mathcal{B}_{44}$			0.00612		
$\mathcal{L}_{red}/\text{pb}^{-1}$	6.324	4.766	2.960	5.517	2.983

Background Study

Analyzed inclusive MC samples + additional $e^+e^- \rightarrow hadrons$ channels







- $\sqrt{s} = 4.6\,\text{GeV}$
- data
- signal mc
- background (abitrary scaled)

Background Channels

Cross sections σ_{obs}/pb of dominanting background channels:

$\sqrt{s}$	4.23 GeV	4.26 GeV	4.36 GeV
$\eta\psi(2S)$	—	< 4.66	< 3.06
$\omega\chi_{c1}$	—	—	< 0.88
$\omega\chi_{c2}$	—	—	< 15.86
$\pi^0\pi^0 J/\psi$	41.64 ± 1.53	32.88 ± 1.51	12.65 ± 1.01
$\pi^0\pi^0\psi(2S)$	13.46 ± 2.37	13.11 ± 2.87	35.65 ± 4.58
$\pi^0\psi(2S)$	?	?	?

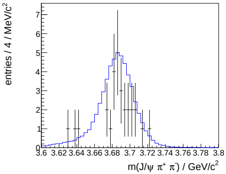
$\sqrt{s}$	4.42 GeV	4.60 GeV
$\eta\psi(2S)$	$1.29^{+0.57}_{-0.46}$	< 1.10
$\omega\chi_{c1}$	< 3.80	11.73 ± 2.59
$\omega\chi_{c2}$	26.13 ± 4.00	< 9.48
$\pi^0\pi^0 J/\psi$	4.85 ± 1.47	1.63 ± 0.07
$\pi^0\pi^0\psi(2S)$	19.49 ± 2.00	4.09 ± 1.39
$\pi^0\psi(2S)$	?	?

Study of Background Channel $\pi^0\,\psi(2S)$

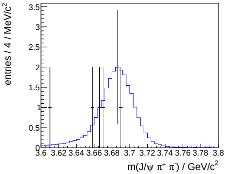
- Explicitly reconstruct $e^+e^- \to \pi^0\,\psi(2S) \to (\gamma\gamma)\,(\pi^+\pi^- J/\psi)$ to determine upper limit for background estimation
- Might be suppresed depending on production mechanism ($G = +1$)
- Same selection criteria for tracks, photons, π^0 as for $e^+e^- \to \eta\eta J/\psi$
- 7C-Kinematic fit (initial P, $m_{J/\psi}$, m_{π^0}, $m_{\psi(2S)}$)
- Best candidate with smallest χ^2_{7C}

Study of Background Channel $\pi^0 \, \psi(2S)$

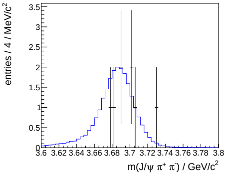
data @4.23 GeV



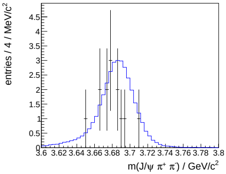
data @4.26 GeV



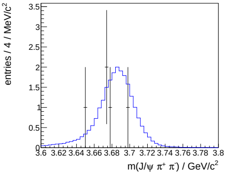
data @4.36 GeV



data @4.42 GeV



data @4.60 GeV



data
$\pi^0\psi(2S)$ MC

Upper Limit for Background Channel $\pi^0\,\psi(2S)$

- Assume all reconstructed events are signal ($n_{bkg} = 0$)

$\Rightarrow$ Upper limit might be overestimated (worst case for my signal)

- Systematic uncertainties from $\mathcal{L}$, $\mathcal{B}$ and tracking/photons
- Use cut and count method by W. Rolke et.al.
- Assume poissonian background and gaussian efficiency

$\sqrt{s}$	4.23 GeV	4.26 GeV	4.36 GeV	4.42 GeV	4.60 GeV
n_{data}	28	7	8	13	5
ϵ	0.228	0.230	0.243	0.245	0.256
$\mathcal{L}_{red}/\text{pb}^{-1}$	10.07	7.72	5.35	10.70	5.86
$\sigma_{sys}/\text{pb}^{-1}$	0.496	0.355	0.256	0.512	0.273
$\sigma_{obs}(90\,\%)/\text{pb}$	3.78	1.60	2.56	1.87	1.65

Estimated Background

- Determine expected background from Monte Carlo
- Number of expected events for $\tau\mathcal{L}$

$\Rightarrow$ Reduce statistical uncertainty

$\sqrt{s}$	4.23 GeV	4.26 GeV	4.36 GeV	4.42 GeV	4.60 GeV
$\eta\psi(2S)$	—	41.99	137.17	183.37	290.50
$\omega\chi_{c1}$	—	—	26.21	290.63	1391.22
$\omega\chi_{c2}$	—	—	331.52	1289.20	625.68
$\pi^0\pi^0 J/\psi$	17.02	71.09	287.55	338.48	258.22
$\pi^0\pi^0\psi(2S)$	0.15	5.21	151.38	279.29	111.66
$\pi^0\psi(2S)$	0.03	0.58	48.16	167.88	370.07
τ	**180.97**	**288.55**	**1146.16**	**1583.49**	**3878.69**
$\sum$	**17.20**	**118.87**	**981.98**	**2548.85**	**3047.34**

Systematic Uncertainties

- Add correction factors to "reduced Luminosity":

$$\mathcal{L}_{red} = \mathcal{L} \sum \mathcal{B}\, \epsilon\, \alpha_{trk}^{n}\, \alpha_{\gamma}^{m}\, \alpha_{veto}$$

- Recalulate $\mathcal{L}_{red}$ 1000 times and vary parameter within its errors
  Use standard deviation as systematic uncertainty

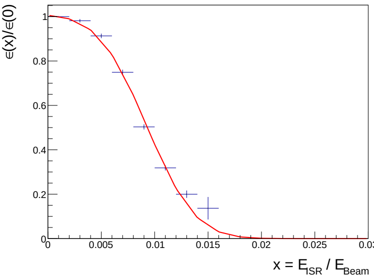
Source	4.23 GeV	4.26 GeV	4.36 GeV	4.42 GeV	4.60 GeV
$\mathcal{L}$	1 %	1 %	1 %	1 %	1 %
Tracking/Photons	0.238	0.174	0.108	0.203	0.108
$\mathcal{B}$	0.058	0.045	0.028	0.051	0.027
$\pi^0\pi^0$-Veto	0.003	0.016	0.005	0.008	0.002
KinFit	0.030	0.025	0.015	0.030	0.016
PID	0.024	0.081	0.050	0.096	0.050
σ_{sys}	0.279	0.204	0.127	0.239	0.127

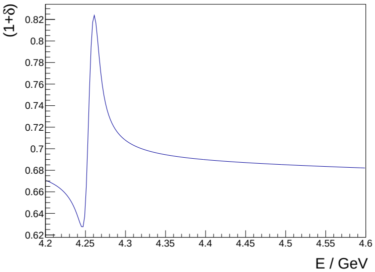
ISR Correction

- Using method presented by Ryan at Summer CM 2016
- Number of observed events ($x = E_{ISR}/E_{Beam}$):

$$N = \mathcal{L}\sigma(0)\epsilon(0) \underbrace{\int \frac{\sigma(x)}{\sigma(0)} \frac{\epsilon(x)}{\epsilon(0)} W(x)\mathrm{d}x}_{(1+\delta)}$$

- Use smallest $(1+\delta)$ from Breit-Wigner with $\Gamma = 10\,\mathrm{MeV}$





Results

- Use cut and count method by W. Rolke et.al.
- Assume poissonian background and gaussian efficiency
- Background determined from MC studies

$$\text{For } \sigma_{obs}: \quad \mathcal{L}_{red} = \mathcal{L} \sum \mathcal{B}_{ij}\, \epsilon_{ij}$$

$$\text{For } \sigma_{born}: \quad \mathcal{L}_{red} = \mathcal{L}\, (1+\delta)\, \frac{1}{|1-\Pi|^2} \sum \mathcal{B}_{ij}\, \epsilon_{ij}$$

$\sqrt{s}$	4.23 GeV	4.26 GeV	4.36 GeV	4.42 GeV	4.60 GeV
n_{data}	0	0	2	5	5
n_{bkg}/τ	0.095	0.412	0.857	1.610	0.786
$\mathcal{L}_{red}/\text{pb}^{-1}$	6.324	4.767	2.960	5.517	2.983
$\sigma_{sys}/\text{pb}^{-1}$	0.279	0.204	0.127	0.239	0.127
$(1+\delta)$	0.636	0.636	0.636	0.636	0.636
$\|1-\Pi\|^{-2}$	1.056	1.054	1.051	1.053	1.055
$\boldsymbol{\sigma_{obs}}$**(90 %)/pb**	**0.826**	**0.332**	**1.506**	**1.459**	**2.976**
$\boldsymbol{\sigma_{born}}$**(90 %)/pb**	**1.231**	**0.495**	**2.254**	**2.180**	**4.437**

Summary and Outlook

- Determined upper limit for $e^+e^- \to \eta\eta J/\psi$

$\sqrt{s}$	4.23 GeV	4.26 GeV	4.36 GeV	4.42 GeV	4.60 GeV
$\sigma_{obs}(90\,\%)/\mathrm{pb}$	0.826	0.332	1.506	1.459	2.976
$\sigma_{born}(90\,\%)/\mathrm{pb}$	1.231	0.495	2.254	2.180	4.437

- Statistics for Z_c search too low
- Preparing memo

BACKUP

Multiple Candidates per Event

Table: Fraction of events with multiple candidates

$\sqrt{s}$	4.23 GeV	4.26 GeV	4.36 GeV	4.42 GeV	4.60 GeV
Signal MC (11)	0.034	0.046	0.055	0.053	0.055
Signal MC (14)	0.036	0.039	0.044	0.049	0.057
Signal MC (44)	0.520	0.543	0.473	0.411	0.289

Table: Average Number of Candidates per Event

$\sqrt{s}$	4.23 GeV	4.26 GeV	4.36 GeV	4.42 GeV	4.60 GeV
Signal MC (11)	1.03	1.05	1.06	1.05	1.06
Signal MC (14)	1.04	1.04	1.05	1.05	1.06
Signal MC (44)	1.85	1.93	1.78	1.68	1.44

Table: Correctness for events with more than one candidate

$\sqrt{s}$	4.23 GeV	4.26 GeV	4.36 GeV	4.42 GeV	4.60 GeV
Signal MC (11)	0.938	0.952	0.952	0.957	0.954
Signal MC (14)	0.998	0.992	0.980	0.965	0.956
Signal MC (44)	0.863	0.806	0.827	0.821	0.823