Direct production of states with positive charge conjugation in e^+e^- annihilation

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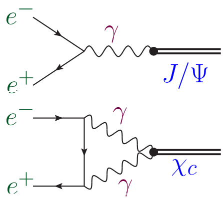
The Principle



$J^{PC} = 1^{--}$
(quantum numbers of photon)

$J^{PC} = \cancel{0^{++}}, 1^{++}, 2^{++}$ Spin!
(quantum numbers of 2 photons)

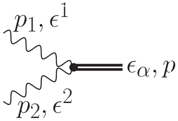
production rates:

$$J/\Psi \sim |e^2 Q_c R(0)|^2$$
$$\chi_c \sim |e^4 Q_c^2 R'(0)|^2$$

$$\Rightarrow \frac{\Gamma(\chi_{1,2} \to e^+e^-)}{\Gamma(J/\Psi \to e^+e^-)} \sim e^4 Q_c^2 \left| \frac{\Phi'_\chi(0)}{\Phi_\Psi(0)} \right|^2$$
$$\approx (4\pi\alpha)^2 \left(\frac{2}{3}\right)^2 0.1^2$$

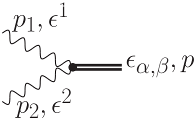
$\chi_J =$ nonrelativistic bound state $= {}^3P_J$
expect $\Gamma(\chi_J \to e^+e^-) \sim (0.05 - 0.5)$ eV

The Structure



Spin $J = 1$, polarization ϵ_α,
momentum $p = p_1 + p_2$

$$A_1^{\alpha\beta}(p_1, p_2, \epsilon)\epsilon^1_\alpha\epsilon^2_\beta = ic\{p_1^2(\epsilon, \epsilon^1, \epsilon^2, p_2) + p_2^2(\epsilon, \epsilon^2, \epsilon^1, p_1) + \epsilon^1 p_1(\epsilon, \epsilon^2, p_1, p_2) + \epsilon^2 p_2(\epsilon, \epsilon^1, p_2, p_1)\}$$



Spin $J = 2$, polarization $\epsilon^{\alpha\beta}$,
momentum $p = p_1 + p_2$

$$A_2^{\alpha\beta}(p_1, p_2, \epsilon)\epsilon^1_\alpha\epsilon^2_\beta = \sqrt{2}cM_{\chi_{c_2}}\{(p_1p_2)\epsilon^1_\mu\epsilon^2_\nu + p_{1\mu}p_{2\nu}(\epsilon^1\epsilon^2) - p_{1\mu}\epsilon^2_\nu(\epsilon^1 p_2)) - p_{2\mu}\epsilon^1_\nu(\epsilon^2 p_1))\}\epsilon^{\mu\nu}$$

The Structure

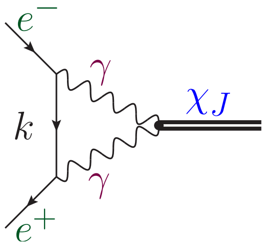
where, in quarkonium model

$$c = \frac{16\pi\alpha}{\sqrt{m}}\sqrt{\frac{1}{4\pi}}3Q_c^2\Phi'(0)\frac{1}{((p_1-p_2)^2/4-m^2+i\epsilon)^2}$$

with

- $m = m_{charm}$
- $Q_c = 2/3$
- $\phi'(0) =$ derivative of wave function at origin
- $\epsilon^{\mu}_{1,2} =$ polarization vectors of photon
- $\epsilon^{\mu} =$ polarization vector of χ_1
- $\epsilon^{\mu\nu} =$ polarization tensor of χ_2

The structure



$$A(e^+e^- \to\ ^3P_J) = ie\int \frac{\mathrm{d}p_1}{(2\pi)^4}\overline{v}(l_+)\frac{\gamma_\nu \not{h}\gamma_\mu}{h^2 p_1^2 p_2^2}u(l_-)A_J^{\mu\nu}(p_1, p_2, \epsilon)$$

with $h = l_- - p_1$

Model results

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- $A(e^+e^- \to {}^3P_0) = 0$ (helicity)
- $A(e^+e^- \to {}^3P_1) = g_1 \overline{v} \gamma_5 \not{\epsilon} u$
- $A(e^+e^- \to {}^3P_2) = g_2 \overline{v} \gamma_\mu u \epsilon_{\mu\nu} (l_+^\nu - l_-^\nu)/M_{\chi_2}$

leading term: short distance approximation

- $g_1 = -\frac{\alpha^2 \sqrt{2}}{M_{\chi_1}^{5/2}} 32 \frac{3}{\sqrt{4\pi}} Q_c^2 \Phi'(0) \log \frac{2b_1}{M_{\chi_1}}$
- $g_2 = \frac{\alpha^2}{M_{\chi_2}^{5/2}} 64 \frac{3}{\sqrt{4\pi}} Q_c^2 \Phi'(0) \left[\log \frac{2b_2}{M_{\chi_2}} + \frac{1}{3}(i\pi + \log 2 - 1) \right]$

with $b_i = 2m - M_{\chi_i}$ = "binding energy"

- $\Gamma({}^3P_1 \to -> e^+e^-) = \frac{1}{3} \frac{|g_1|^2}{4\pi} M_{\chi_1}$
- $\Gamma({}^3P_2 \to -> e^+e^-) = \frac{1}{5} \frac{|g_2|^2}{8\pi} M_{\chi_2}$

Improvement: binding energy corrections

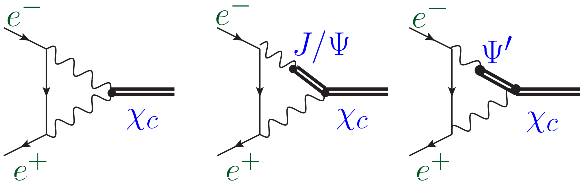
$\Rightarrow$ terms of order $\left(M_{\chi_i}^2 - 4m^2\right)/M_{\chi_i}^2$

	$\Gamma(\chi_1 \to e^+e^-)$	$\Gamma(\chi_2 \to e^+e^-)$
	$b = +0.5$ GeV	
leading term	0.0226 eV	0.0243 eV
full result	0.0317 eV	0.0159 eV
	$b = -0.5$ GeV	
leading term	0.164 eV	0.0512 eV
full result	0.141 eV	0.0731 eV

significant impact!

Improvement: Short and Long distance corrections

include correct coupling of χ_J to $J/\Psi\ \gamma$, χ_J to $\Psi'\ \gamma$, and χ_2 to $\gamma\gamma$, as derived from the corresponding decay rates



	QED	$\gamma\gamma$	$J/\Psi\gamma$	$\Psi'\gamma$	QED + Z^0
$\Gamma(\chi_1 \to e^+e^-)$[eV]	0.43	0.10	0.01	0.09	0.41
$\Gamma(\chi_2 \to e^+e^-)$[eV]	4.25	0.04	1.41	0.45	-

Experimental Perspectives
1.) Hadronic final state

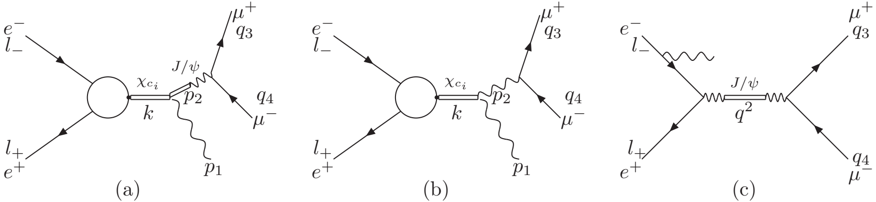
$$R_{\mathrm{peak}} = \frac{\Gamma_{ee}}{\Delta} \frac{9}{4\alpha^2} \sqrt{2\Pi} \frac{\Gamma_{\mathrm{had}}}{\Gamma_{\mathrm{tot}}} N_Z$$

- $\Delta =$ machine energy resolution $\approx$ 4 MeV
- $N_Z \approx 0.7$
- $\Gamma_{\mathrm{had}}/\Gamma_{\mathrm{tot}} \approx 0.66$
- $\Gamma_{ee} =$ 0.1 eV - 0.5 eV

$$\Rightarrow R_{\mathrm{peak}} = 2 \cdot 10^{-3} - 1 \cdot 10^{-2}$$

2.) Leptonic final state

$e^+e^- \to \chi_J \to \gamma\, J/\Psi\ (\to \mu^+\mu^-)$ and $e^+e^- \to \gamma\, J/\Psi\ (\to \mu^+\mu^-)$



nontrivial phase relation between signal and background

Experiment

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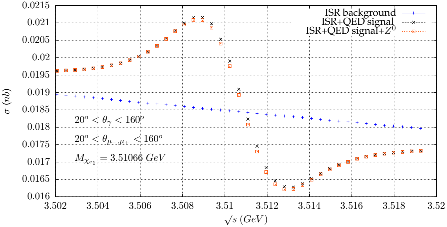
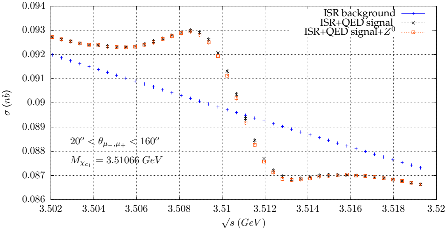
angular cuts on photon and leptons
$(20^\circ < \theta_\gamma < 160^\circ; 20^\circ < \theta_{\mu^+\mu^-} < 160^\circ)$



χ_1

cuts on μ-pairs and photons

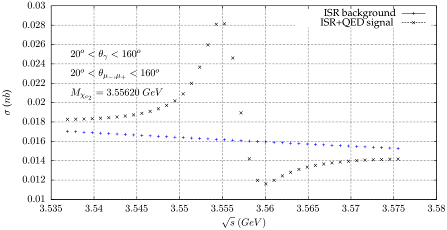


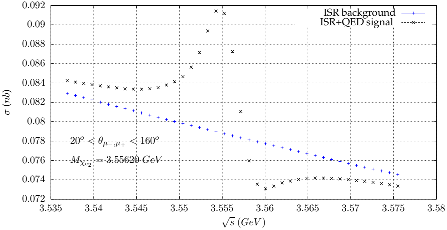
χ_1

cuts on photons only

(most optimistic choice for couplings; important effect of phase)

Experiment





χ_2

cuts on μ-pairs and photons

χ_2

cuts on photons only

Summary

- resonant production of χ_1 and χ_2 in e^+e^- annihilation is possible
- hadronic final states and leptonic final states are accesible in principle
- precise numerical predictions are strongly model dependent