

# Testing $\chi_c$ properties at BELLE II

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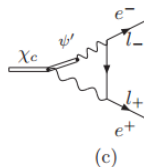
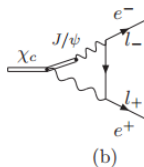
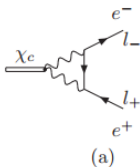
30<sup>th</sup> June 2017

# Outline

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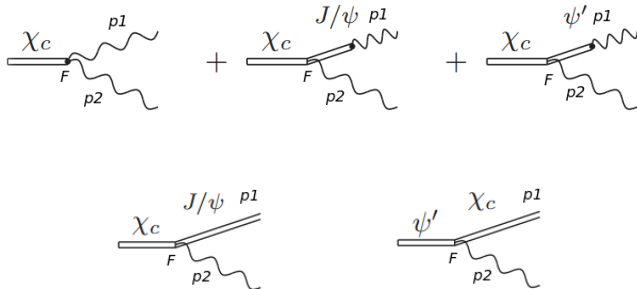
# Motivation

- The integrated luminosity in BELLE II experiment: 20-50  $\text{ab}^{-1}$ .
- The process  $e^+ e^- \rightarrow e^+ e^- (\chi_{ci} \rightarrow \gamma(J/\psi \rightarrow \mu^+ \mu^-))$ .
- The predictions of the width of  $\chi_{c1}$  and  $\chi_{c2}$  charmonia within recently published models:



	H. Czyz et al.	N. Kivel et al.	D. Yang et al.	A. Denig et al.
$\Gamma(\chi_{c1} \rightarrow e^+ e^-)[\text{eV}]$	0.43	0.09	0.367	0.1
$\Gamma(\chi_{c2} \rightarrow e^+ e^-)[\text{eV}]$	4.25	0.07	0.137	-

# The model



*H.Czyz, J.H.Kuhn, S.Tracz, Phys.Rev. D94 (2016) no.3, 034033  
 and talk by J. H. Kuhn at PhiPsi 2017*

# The model

- J=0

$$A_0 = \sqrt{\frac{1}{6}} c \frac{1}{M_{\chi_{c0}}} [l_1^0 (M_{\chi_{c0}}^2 + p_1 \cdot p_2) - 2l_2^0] \quad (1)$$

where  $l_1^0 = F_{\mu\nu}^1 F^{2\mu\nu}$ ,  $l_2^0 = p_1^\nu F_{\mu\nu}^1 F^{2\mu\alpha} p_{2\alpha}$

- J=1

$$A_1 = -\frac{i}{2} c [l_1^1 + l_2^1] \quad (2)$$

where  $l_1^1 = F_{\mu\nu}^1 \varepsilon^{\mu\nu\alpha\beta} F_{\alpha\gamma}^2 p^{2\gamma} \varepsilon_\beta$ ,  $l_2^1 = F_{\mu\nu}^2 \varepsilon^{\mu\nu\alpha\beta} F_{\alpha\gamma}^1 p^{1\gamma} \varepsilon_\beta$

- J=2

$$A_2 = -c\sqrt{2} M_{\chi_{c2}} l_2^2 \quad (3)$$

where  $l_2^2 = \varepsilon^{\mu\alpha} F_\mu^{1\beta} F_{\alpha\beta}^2$

$$F_{\mu\nu} = \varepsilon_\mu p_\nu - \varepsilon_\nu p_\mu$$

# The model

$$C = \frac{16\pi\alpha a}{\sqrt{m}} \frac{1}{((p_1 - p_2)^2/4 - m^2 + i\varepsilon)^2}$$

Form factors:

$$c_\gamma = \frac{4e^2}{\sqrt{m}} \left( a + \frac{fa_J}{M_{J/\psi}^2} + \frac{f' a_{\psi'}}{M_{\psi'}^2} \right) \frac{1}{(M_{\chi_{ci}}^2/2 + b_i^2/4 + b_i M_{\chi_{ci}}/2)^2} \quad (4)$$

$$c_{J/\psi} = \frac{4ea_J}{\sqrt{m}} \frac{1}{(M_{\chi_{ci}}^2/2 + b_i^2/4 + b_i M_{\chi_{ci}}/2 - M_{J/\psi}^2/2)^2} \quad (5)$$

$$c_{\psi'} = \frac{4ea_{\psi'}}{\sqrt{m}} \frac{1}{(M_{\chi_{ci}}^2/4 + m^2 - M_{\psi'}^2/2)^2} \quad (6)$$

where

$$a = \sqrt{\frac{1}{4\pi}} 3Q^2 \Phi'(0) \quad (Q = 2/3), \quad b_i = 2m_i - M_{\chi_{ci}},$$

$$f = \sqrt{\frac{3\Gamma_{J/\psi \rightarrow e^+e^-} M_{J/\psi}^3}{4\pi\alpha^2}}, \quad f' = \sqrt{\frac{3\Gamma_{\psi' \rightarrow e^+e^-} M_{\psi'}^3}{4\pi\alpha^2}}$$

# Fits

$a[\text{GeV}^{5/2}]$	$m[\text{GeV}]$	$a_J[\text{GeV}^{5/2}]$	$a_J^0[\text{GeV}^{5/2}]$	$a_{\psi'}[\text{GeV}^{5/2}]$	$a_{\psi'}^0[\text{GeV}^{5/2}]$	$\chi^2$	model
0.0786	1.69	0.150	-	-0.070	-	0.165	[1]
0.0796	1.67	0.129	0.073	-0.078	0.122	0.943	[2]

Widths [GeV]	$\chi_{c0}$	$\chi_{c1}$	$\chi_{c2}$
$\Gamma(\chi \rightarrow \gamma\gamma)_{th}$	$2.24 \cdot 10^{-6}$	—	$5.46 \cdot 10^{-7}$
$\Gamma(\chi \rightarrow J/\psi\gamma)_{th}$	$1.34 \cdot 10^{-4}$	$2.82 \cdot 10^{-4}$	$3.74 \cdot 10^{-4}$
$\Gamma(\psi' \rightarrow \chi\gamma)_{th}$	$2.96 \cdot 10^{-5}$	$2.88 \cdot 10^{-5}$	$2.64 \cdot 10^{-5}$
$\Gamma(\chi \rightarrow \gamma\gamma)_{exp}$	$2.3(2) \cdot 10^{-6}$	—	$5.3(4) \cdot 10^{-7}$
$\Gamma(\chi \rightarrow J/\psi\gamma)_{exp}$	$1.3(1) \cdot 10^{-4}$	$2.8(2) \cdot 10^{-4}$	$3.7(3) \cdot 10^{-4}$
$\Gamma(\psi' \rightarrow \chi\gamma)_{exp}$	$2.96(11) \cdot 10^{-5}$	$2.8(1) \cdot 10^{-5}$	$2.7(1) \cdot 10^{-5}$

[1] H.Czyz, J.H.Kuhn, S.Tracz, *Phys.Rev. D94 (2016) no.3, 034033*

[2] H.Czyz, P.Kisza, *Phys.Lett. B771 (2017) 487-491*

## EKHARA MC generator

- version 1.0

$e^+e^- \rightarrow e^+e^-\pi^+\pi^-$  to simulate background for the pion form factor measurements

- version 2.0

$e^+e^- \rightarrow e^+e^-\pi^0$

- version 2.1

$e^+e^- \rightarrow e^+e^-\eta, \eta'$

- version 2.2

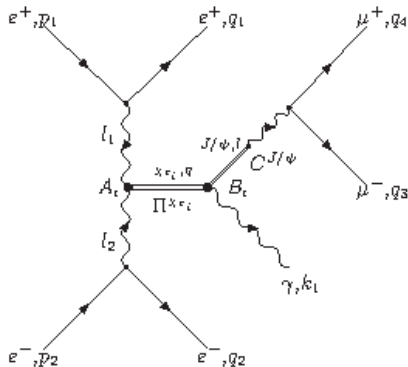
$e^+e^- \rightarrow e^+e^-\chi_{ci}$

and  $e^+e^- \rightarrow e^+e^-\chi_{ci}(\rightarrow \gamma\mathbf{J}/\psi(\rightarrow \mu^+\mu^-))$

<http://prac.us.edu.pl/~ekhara/>



# Feynman diagram



Event selection:

$$E_{e^+} = 4 \text{ GeV}$$

$$E_{e^-} = 7 \text{ GeV}$$

crossing angle = 83 mrad

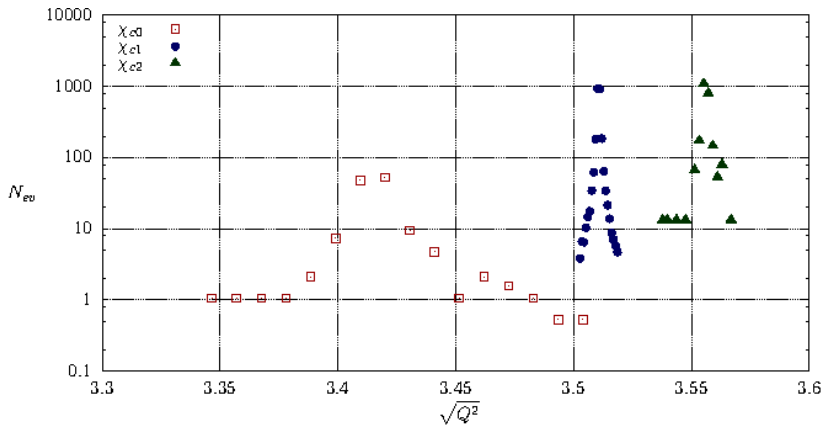
integrated luminosity =  $50 \text{ ab}^{-1}$

polar angles =  $17^\circ$ - $150^\circ$

invariant masses = invariant masses  $\pm 10\Gamma$

# Interferences

All the amplitudes drop rapidly, when the invariant mass is a bit off-resonance.



# Cross sections in the narrow width approximation

Properties for a given particle:

$$\chi_{c0}: M = 3414.75 \pm 0.31 \text{ MeV}, \Gamma = 10.05 \pm 0.08 \text{ MeV}$$

$$\chi_{c1}: M = 3510.66 \pm 0.07 \text{ MeV}, \Gamma = 0.86 \pm 0.05 \text{ MeV}$$

$$\chi_{c2}: M = 3556.20 \pm 0.09 \text{ MeV}, \Gamma = 1.98 \pm 0.11 \text{ MeV}$$

$$J/\psi: M = 3096.900 \pm 0.006 \text{ MeV}, \Gamma = 92.9 \pm 2.8 \text{ MeV}$$

$e^+e^- \rightarrow e^+e^- (\chi_{c0} \rightarrow \gamma(J/\psi \rightarrow \mu^+\mu^-))$	Cross sections [nb]
NWA	$2.1346(23) \cdot 10^{-6}$
EKHARA	$2.2722(4) \cdot 10^{-6}$
$e^+e^- \rightarrow e^+e^- (\chi_{c1} \rightarrow \gamma(J/\psi \rightarrow \mu^+\mu^-))$	Cross sections [nb]
NWA	$1.7484(31) \cdot 10^{-6}$
EKHARA	$1.9289(4) \cdot 10^{-6}$
$e^+e^- \rightarrow e^+e^- (\chi_{c2} \rightarrow \gamma(J/\psi \rightarrow \mu^+\mu^-))$	Cross sections [nb]
NWA	$3.2802(27) \cdot 10^{-5}$
EKHARA	$3.2957(3) \cdot 10^{-5}$

## Expected number of events for $\chi_{ci}$ production

$e^+e^- \rightarrow e^+e^- \chi_{c0}$	Number of events (luminosity = $50ab^{-1}$ )
no cuts	140M
single tag	6.7M
double tag	249k

$e^+e^- \rightarrow e^+e^- \chi_{c1}$	Number of events (luminosity = $50ab^{-1}$ )
no cuts	4.3M
single tag	1.4M
double tag	174k

$e^+e^- \rightarrow e^+e^- \chi_{c2}$	Number of events (luminosity = $50ab^{-1}$ )
no cuts	143M
single tag	7.2M
double tag	295k

## Expected number of events for production

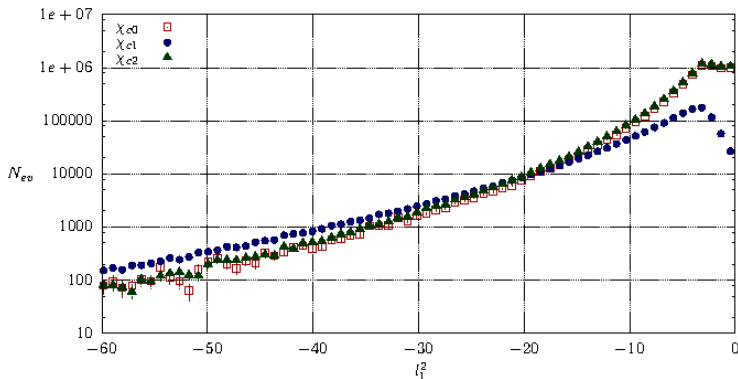


Figure : The distributions of expected number of events for  $\chi_{ci}$  production (the observed positron in the angular range  $17^\circ - 150^\circ$ )

## Expected number of events for decay

$e^+e^- \rightarrow e^+e^- (\chi_{c0} \rightarrow \gamma(J/\psi \rightarrow \mu^+\mu^-))$	Number of events (luminosity = $50ab^{-1}$ )
no cuts	114k
single tag	3.1k (2.7k)*
double tag	136
$e^+e^- \rightarrow e^+e^- (\chi_{c1} \rightarrow \gamma(J/\psi \rightarrow \mu^+\mu^-))$	Number of events (luminosity = $50ab^{-1}$ )
no cuts	96k
single tag	22k (18k)*
double tag	2.5k
$e^+e^- \rightarrow e^+e^- (\chi_{c2} \rightarrow \gamma(J/\psi \rightarrow \mu^+\mu^-))$	Number of events (luminosity = $50ab^{-1}$ )
no cuts	1.6M
single tag	44k (39k)*
double tag	2.5k

\* for  $-1 \text{ GeV}^2 < l_2^2 < 0 \text{ GeV}^2$

## Expected number of events for decay

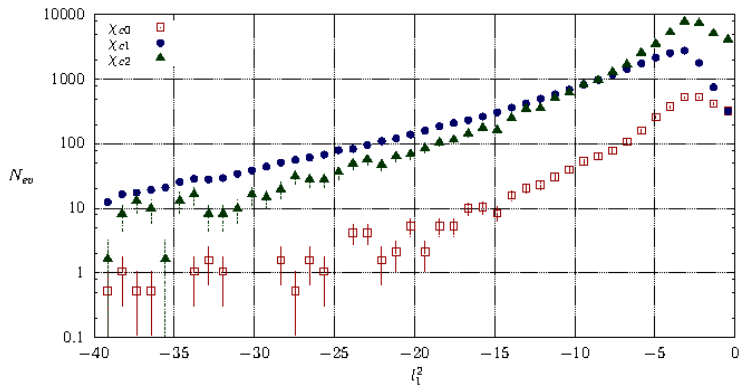
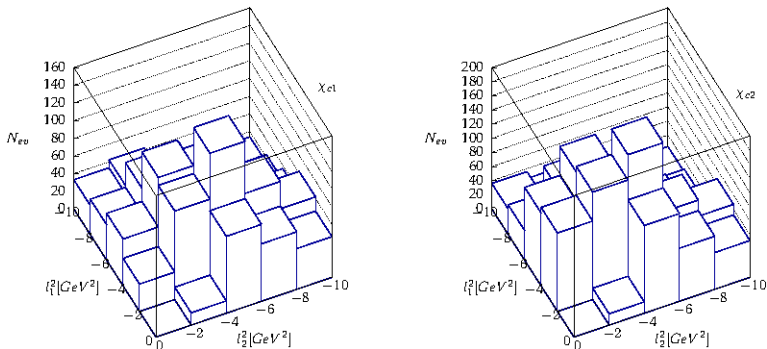


Figure : The distributions of expected number of events for  $\chi_{ci}$  production with subsequent decay to  $J/\psi(\rightarrow \mu^+ \mu^-) - \gamma$

## Expected number of events for decay



**Figure :** The distributions of expected number of events for  $\chi_{c1}$  and for  $\chi_{c2}$  production with subsequent decay to  $J/\psi \rightarrow (\mu^+ \mu^-) - \gamma$  when both electron and positron are tagged



## QED background with cuts

The events selections:

polar angles	$17^\circ - 150^\circ$
$l^2(\mu^+\mu^- \text{ inv. mass})$	3.09650 - 3.09730
$q^2(\mu^+\mu^-\gamma \text{ inv. mass})$ for $\chi_{c0}$	3.37000 - 3.50000
$q^2(\mu^+\mu^-\gamma \text{ inv. mass})$ for $\chi_{c1}$	3.50191 - 3.51941
$q^2(\mu^+\mu^-\gamma \text{ inv. mass})$ for $\chi_{c2}$	3.54750 - 3.56500

contain 99% of the signal events.

## Helac-Phegas results for the background

LAB ( $17^\circ - 150^\circ$ )	cross section [nb]		
	$\chi_{c0}$	$\chi_{c1}$	$\chi_{c2}$
<b>1 TAG</b>			
Signal	$0.59 \cdot 10^{-7}$	$4.18 \cdot 10^{-7}$	$8.09 \cdot 10^{-7}$
Background	<b><math>0.66 \cdot 10^{-7}</math></b>	$0.0064 \cdot 10^{-7}$	$0.057 \cdot 10^{-7}$
<b>2 TAGS</b>			
Signal	$0.25 \cdot 10^{-8}$	$4.87 \cdot 10^{-8}$	$4.57 \cdot 10^{-8}$
Background	<b><math>0.54 \cdot 10^{-8}</math></b>	$0.0033 \cdot 10^{-8}$	$0.080 \cdot 10^{-8}$

*A. Cafarella, C. G. Papadopoulos, M. Worek, Comput. Phys. Commun. 180 (2009) 1941–1955*

## Summary

- If the model we used is correct it will be possible to study:  $\chi_{ci} - \gamma^* - \gamma^*$  form factors at BELLE II.
- The planned BELLE II experiments will be good test of the models giving predictions for the  $\chi_{c1}$  and  $\chi_{c2}$  electronic widths.

Thank you for your attention =]