

# Simulation of Two-photon physics at Belle II

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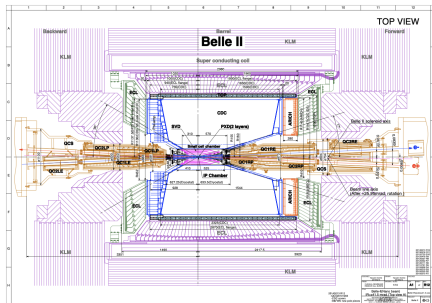
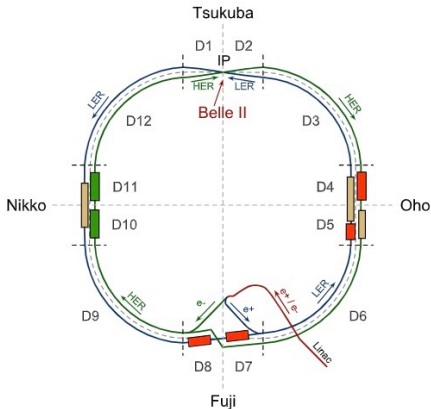
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- Two-photon processes are a powerful probe of  $C$ -even resonances and light-hadron spectroscopy, and provide precision tests of QCD. However, ISR events constitute a major and irreducible background.
- Although kinematic selections based on transverse momentum, photon energy  $E_\gamma$ , and recoil mass squared  $M_{\text{recoil}}^2$  can suppress ISR, a sizable residual background remains.
- In two-photon events, the scattered  $e^+$  and  $e^-$  are typically emitted at very small angles and escape through the beam pipe. Reconstructing these leptons would provide a clean and efficient two-photon tag.

# Introduction

- At Belle II, the focusing magnets bend the beams to keep them on orbit. In two-photon events, the scattered  $e^+e^-$  are low in energy and are deflected by the magnetic field, causing them to hit the beam-pipe wall.
- These beam-pipe hits provide a practical signature for tagging two-photon events.



# Motivation: $\gamma\gamma \rightarrow \gamma\psi(2S)$

- **P-wave triplet near 3.9 GeV:**

- $\chi_{c0}(2P)$  candidate:  $X(3915)$  or  $X^*(3860)$
- $\chi_{c2}(2P)$  candidate:  $Z(3930)$
- $X(3872)$  as  $\chi_{c1}(2P)$

- $\gamma\gamma \rightarrow \gamma\psi(2S)$  selects  $J^{PC} = 0^{++}$  and  $2^{++}$  states via  $E1$  transitions

- Predicted partial widths:  $\Gamma(\chi_{c0} \rightarrow \gamma\psi(2S)) \approx 135$  keV,  
 $\Gamma(\chi_{c2} \rightarrow \gamma\psi(2S)) \approx 207$  keV

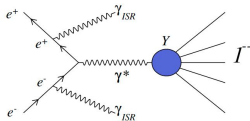
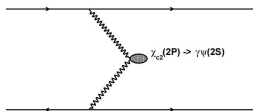
- **Key physics drivers:**

- Resolve  $\chi_{c2}(2P)$ - $\chi_{c0}(2P)$  hyperfine splitting ( $\sim 12$  MeV observed vs.  $\sim 60$  MeV predicted)
- Search for  $2^{++}$  partner of  $X(3872)$ , motivated by Belle's  $\gamma\gamma$  evidence for  $X(3872)$

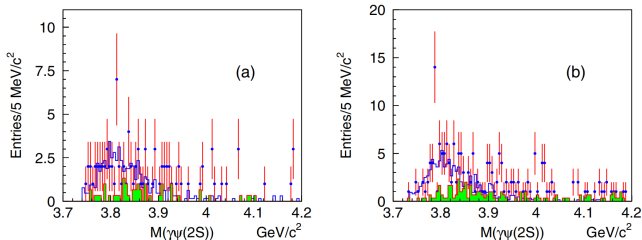
**Thus,  $\gamma\gamma \rightarrow \gamma\psi(2S)$  is a key channel to search for missing  $\chi_{cJ}(2P)$  states and probe XYZ structure.**

# The dominant background: $e^+e^- \rightarrow \gamma_{ISR}\psi(2S)$

## The Feynman diagrams:



## Previous Belle measurement:



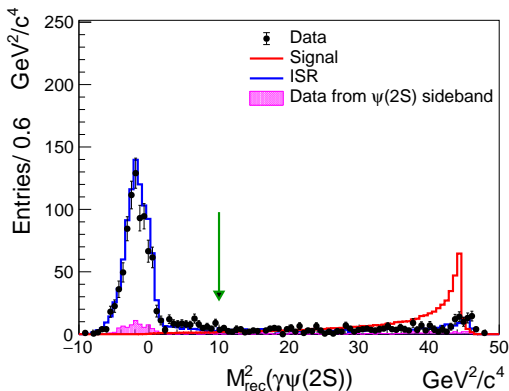
**Figure:** The invariant mass distributions of  $\gamma\psi(2S)$  from (a)  $e^+e^-$  mode and (b)  $\mu^+\mu^-$  mode. Dots: data; shaded histograms: sideband bkg; blank histograms: scaled ISR MC.

# ISR Background Rejection with $M_{\text{recoil}}^2$

- A conventional variable to suppress ISR background uses the recoil mass squared of the  $\gamma\psi(2S)$  system:

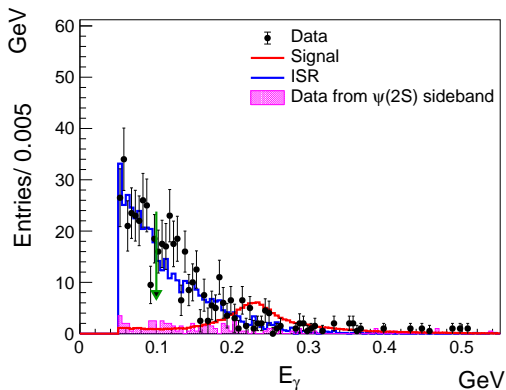
$$M_{\text{recoil}}^2(\gamma\psi(2S)) = (P_{e^+} + P_{e^-} - P_{\gamma} - P_{\psi(2S)})^2,$$

where  $P_{e^+}$ ,  $P_{e^-}$ ,  $P_{\gamma}$ , and  $P_{\psi(2S)}$  are the four-momenta of the positron, electron, photon, and  $\psi(2S)$ .



# ISR Background Rejection with $E_\gamma$

- In the two-body final state  $\gamma\psi(2S)$ , the photon energy  $E_\gamma$  in the laboratory frame depends on the invariant energy  $\sqrt{s}$  of the  $\gamma\gamma$  system in its c.m.s.;  $E_\gamma$  is expected to be  $\approx 224$  MeV in the  $Z(3930)$  decays.
- In an ISR event, a reconstructed photon is often a fake or the true low-energy ISR photon  $\gamma_{\text{ISR}}$ , so  $E_\gamma$  tends to be small.

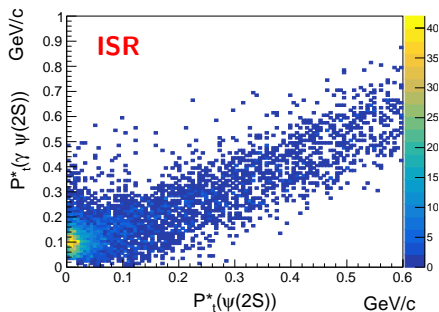
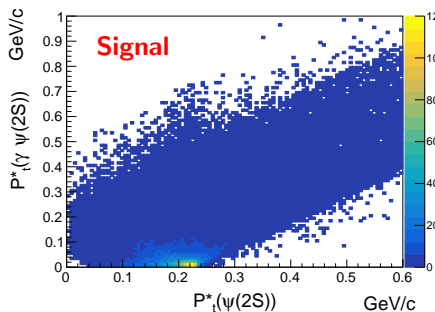


# ISR Background Rejection with $p_T^*$

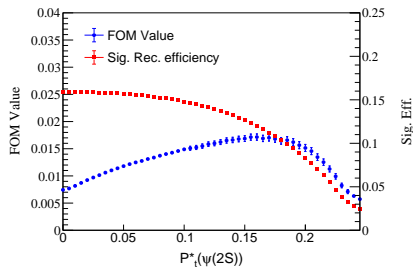
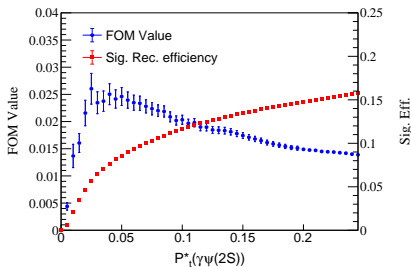
- **Key difference:**

- Signal ( $\gamma\gamma \rightarrow \psi(2S)$  via resonance):  $p_T^*(\gamma\psi(2S)) < p_T^*(\psi(2S))$ .
- ISR background:  $p_T^*(\gamma\psi(2S)) > p_T^*(\psi(2S))$ .

**Physical reason:** Two-photon collisions naturally yield small total  $p_T^*$ , while a  $\psi(2S)$  from a resonance decay can carry larger  $p_T^*$ . In ISR events, the radiated photon boosts the  $\gamma\psi(2S)$  system, producing large  $p_T^*(\gamma\psi(2S))$  and a relatively soft  $\psi(2S)$ .



# ISR Background Rejection: Selection Optimization

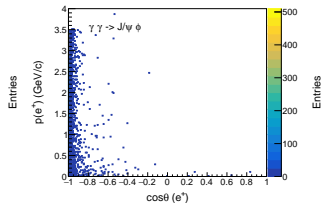
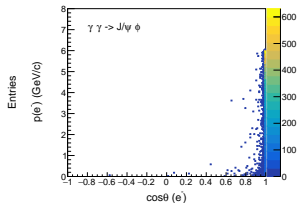
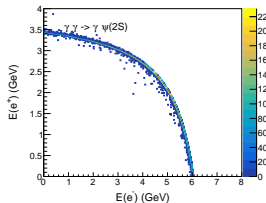
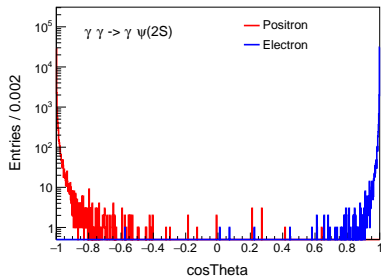
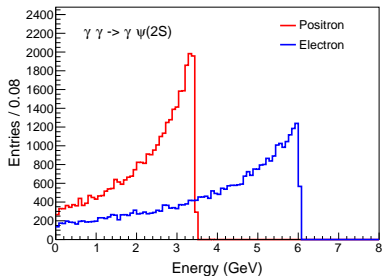


The tight selections discussed above lead to a loss of signal efficiency.

Selection	$\epsilon_{\text{sig}(3930)} [\%]$	$\epsilon_{\text{ISR}} [\%]$
$M_{\text{recoil}}^2(\gamma\psi(2S)) > 10 \text{ (GeV}/c^2)^2$	96.77	18.84
$E_\gamma > 100 \text{ MeV}$	93.36	47.13
$p_t^*(\psi(2S)) > 0.03 \text{ GeV}/c$	99.37	66.12
$p_t^*(\gamma\psi(2S)) < 0.2 \text{ GeV}/c$	64.54	36.90
Overall	57.94	2.17

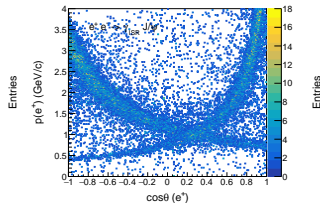
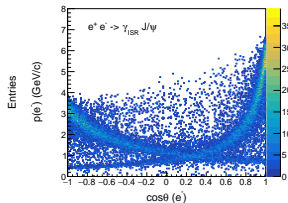
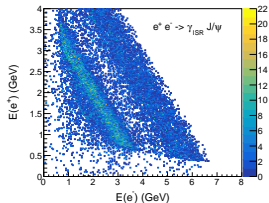
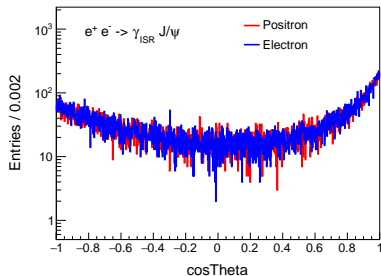
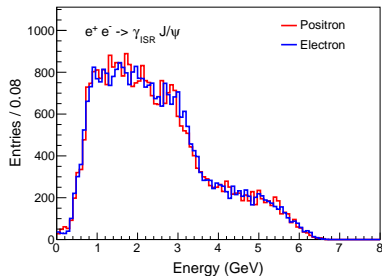
# Simulation: $\gamma\gamma \rightarrow \gamma\psi(2S)$

TREPS generator simulation for the process  $\gamma\gamma \rightarrow \gamma\psi(2S)$ .



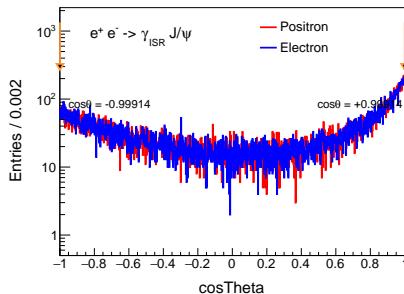
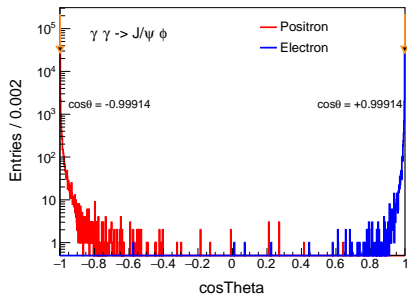
# Simulation: $e^+e^- \rightarrow \gamma_{\text{ISR}} J/\psi$

PHOKHARA generator simulation for the process  $e^+e^- \rightarrow \gamma_{\text{ISR}} J/\psi$ .



# ISR Background Rejection with e-Tagging

If we could tag  $e^+e^-$  that escape the beam pipe.



Selection	$\epsilon_{\text{sig}(3930)} [\%]$	$\epsilon_{\text{ISR}} [\%]$
beam pipe acceptance	$55.04 \pm 0.53$	$0.30 \pm 0.03$

Note: “beam pipe acceptance” means at least one of  $e^+$  or  $e^-$  escapes the beam pipe, i.e.  $|\cos\theta| > 0.99914$ .

# Significance Improvement with e-Tagging

- Using the Belle observation of  $Z(3930)$  at  $3.1\sigma$ , we project the expected Belle II sensitivity by scaling the signal and background yields.
- The expected significance increases from 0.89 to 3.14 with conventional ISR cuts, and further to 5.72 with e-tagging.
- Relative to the traditional ISR rejection, e-tagging improves the significance by about 82%.

## Selection efficiencies

Method	Eff <sub>sig</sub> [%]	Eff <sub>ISR</sub> [%]
Traditional	57.97	2.17
e-tagging	55.04	0.30

## Projected significance

0.89 → 3.14

baseline → ISR cuts

0.89 → **5.72**

baseline → e-tagging

# Motivation: $\gamma\gamma \rightarrow \omega J/\psi$

- $X(3915)$  discovered in  $\gamma\gamma \rightarrow \omega J/\psi$  (Belle 2010, BaBar 2012):  $M = 3915 \text{ MeV}/c^2$ ,  $\Gamma = 17 \text{ MeV}$ . Nature still unresolved after 15 years.
- **Spin-parity tension:**
  - BaBar angular analysis strongly favours  $J^P = 0^\pm$  over  $2^+$ .
  - Combined  $\gamma\gamma \rightarrow \omega J/\psi + D\bar{D}$  analysis prefers  $J^{PC} = 2^{++}$ , hinting at a tensor state; possibly the same as  $X(3930)$ .
- Hints of structures above 4 GeV in  $\omega J/\psi$  invariant mass – limited by previous statistics.

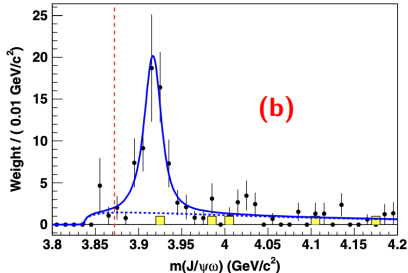
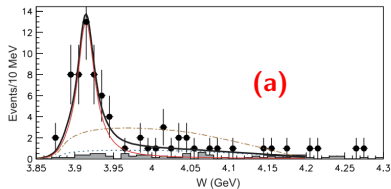
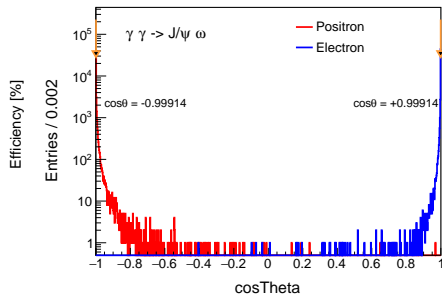
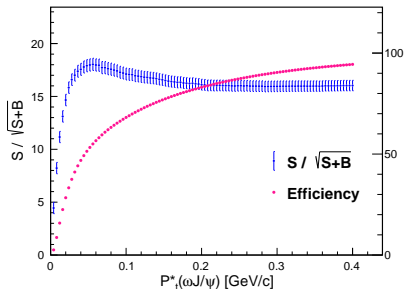


Figure: Belle (a) and BaBar (b) invariant mass distributions of  $\omega J/\psi$

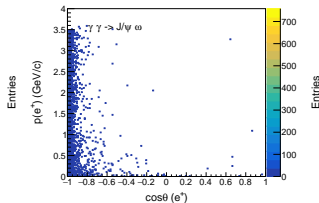
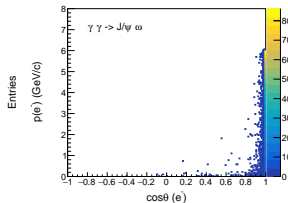
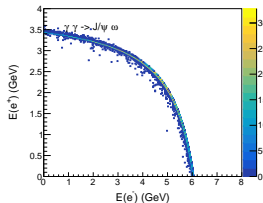
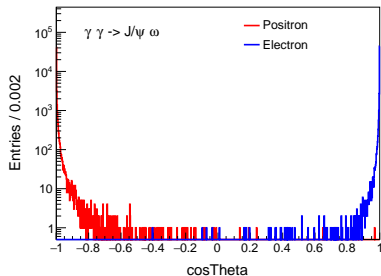
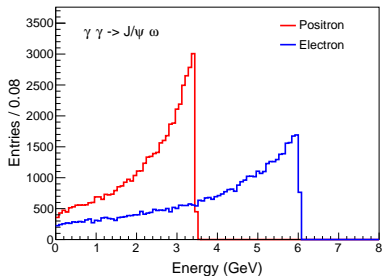
# ISR Background Rejection



The  $\cos\theta$  of scattered  $e^+e^-$  provides a strong discriminator against ISR events, compared to  $p_t^*(\omega J/\psi)$ .

# Simulation: $\gamma\gamma \rightarrow J/\psi\omega$ at Belle II

TREPS generator simulation for the process  $\gamma\gamma \rightarrow J/\psi\omega$  in Belle II.



# Summary

- ISR is the dominant background in two-photon processes, and standard kinematic cuts ( $M_{\text{recoil}}^2$ ,  $E_\gamma$ ,  $p_T^*$ ) do not fully suppress it.
- In  $\gamma\gamma$  events, the scattered  $e^+e^-$  are typically emitted at very small angles and intercepted by the beam pipe, providing a distinctive experimental signature.
- By tagging these beam-pipe hits, the expected significance for  $Z(3930) \rightarrow \gamma\psi(2S)$  improves from 3.14 to 5.72, corresponding to an 82% gain over conventional cuts.
- The same strategy can be extended to other two-photon processes, such as  $\gamma\gamma \rightarrow \omega J/\psi$ .

Thanks for your attention!