Search for a dark photon using initial state radiation at BESIII

Benedikt Kloss
for the BESIII Collaboration

Institute of Nuclear Physics – Mainz University

Twelfth Conference on the Intersections of Particle and Nuclear Physics
May 2015, Vail, Colorado
A new U(1) gauge boson $\gamma'$ ("dark photon") might be the connection between the standard model and a dark sector:
**Goal of the analysis**

Existing exclusion limits on the dark photon ($\gamma'$) mass and mixing parameter ($\varepsilon$):

Dark photon coupling strength to SM matter: $\alpha'$

Mixing parameter: $\varepsilon^2 = \frac{\alpha'}{\alpha}$

**GOAL:** make a contribution at
The BESIII experiment
BESIII Collaboration

Europe (13)
- Germany: Univ. of Bochum, Univ. of Giessen, GSI
- Germany: Univ. of Johannes Gutenberg, Helmholtz Ins. In Mainz
- Russia: JINR Dubna; BINF Novosibirsk
- Italy: Univ. of Torino, Univ. of Ferrara, Frascati Lab
- Netherlands: KVI/Univ. of Groningen
- Sweden: Uppsala Univ.
- Turkey: Turkey Accelerator Center

Korea (1)
- Seoul Nat. Univ.

Japan (1)
- Tokyo Univ.

Pakistan (2)
- Univ. of Punjab
- COMSAT CIIT

China (31)
- IHEP, CCAST, GUCAS, Shandong Univ., Univ. of Sci. and Tech. of China
- Zhejiang Univ., Huangshan Coll.
- Huazhong Normal Univ., Wuhan Univ.
- Zhengzhou Univ., Henan Normal Univ.
- Peking Univ., Tsinghua Univ., Zhongshan Univ., Nankai Univ.
- Shanxi Univ., Sichuan Univ., Univ. of South China
- Hunan Univ., Liaoning Univ.
- Nanjing Univ., Nanjing Normal Univ.
- Guangxi Normal Univ., Guangxi Univ.
- Suzhou Univ., Hangzhou Normal Univ.
- Lanzhou Univ., Henan Sci. and Tech. Univ.
- Beihang Univ., Beijing Petrol Chemical Univ.

US (5)
- Univ. of Hawaii
- Carnegie Mellon Univ.
- Univ. of Minnesota
- Univ. of Rochester
- Univ. of Indiana

~400 members
53 institutions from 11 countries
BEPCII Collider:

- located in Beijing, China
- symmetric $e^+e^-$ collider
- $2 \text{ GeV} < E_{\text{CMS}} < 4.6 \text{ GeV}$
- data taken at $\sqrt{s} = 3.77 \text{ GeV} : 2.9 \text{ fb}^{-1}$
BESIII Detector

- 1T superconducting solenoid magnet
- Muon Chamber
- Time-Of-Flight System
- Main Drift Chamber
- CsI Crystal Calorimeter
- ELECTRO MAGNETIC CALORIMETER
- RPC: 9 layers
- SC Solenoid
- Barrel ToF
- Endcap ToF
- SC Quadrupole

(Graphic produced by Matthias Ulrich, Gießen)
Initial State Radiation
Initial state radiation

- photon emitted in the initial state
- CMS energy lowered by the energy of the emitted photon
  \[ \Rightarrow \text{measurements at different energies possible} \]

\[ E_{\text{cms}} = 3.77 \text{ GeV} \]
Initial State Radiation

Two different analysis types:
- tagged: photon is detected in the Electromagnetic Calorimeter
- untagged: photon leaves the detector (most probable case)
**Initial State Radiation**

**Two different analysis types:**
- tagged: photon is detected in the Electromagnetic Calorimeter
- untagged: photon leaves the detector (most probable case)
**Analysis idea**

**Idea:** Search for the ISR processes

\[ e^+ e^- \rightarrow \gamma_{ISR} \gamma' \rightarrow \gamma_{ISR} \mu^+ \mu^- \]

and

\[ e^+ e^- \rightarrow \gamma_{ISR} \gamma' \rightarrow \gamma_{ISR} e^+ e^- \]

Use **untagged** ISR events and 2.9 fb\(^{-1}\) data, taken at 3.77 GeV.

![Graph](chart.png)
**Idea:** Search for the ISR processes

\[ e^+ e^- \rightarrow \gamma_{ISR} \gamma' \rightarrow \gamma_{ISR} \mu^+ \mu^- \]

and

\[ e^+ e^- \rightarrow \gamma_{ISR} \gamma' \rightarrow \gamma_{ISR} e^+ e^- \]

**Irreducible background:**

\[ e^+ e^- \rightarrow \gamma_{ISR} \gamma^* \rightarrow \gamma_{ISR} \mu^+ \mu^- \]

\[ e^+ e^- \rightarrow \gamma_{ISR} \gamma^* \rightarrow \gamma_{ISR} e^+ e^- \]

QED process, same signature in detector!

Dark photon signal would appear as **peak** on the QED background.  
⇒ **Peak search!**
Analysis
Event selection: \( e^+ e^- \rightarrow \mu^+ \mu^- \gamma_{ISR} \) and \( e^+ e^- \rightarrow \mu^+ \mu^- \gamma_{ISR} \)

| Distance to Interaction Point | \( R_{xy} < 1.0 \text{ cm} \)  
|------------------------------| \( R_z < 10.0 \text{ cm} \)  |
| Acceptance of Charged Tracks | \( 0.4 \text{ rad} < \theta < \pi - 0.4 \text{ rad} \)  |
| To Suppress Background       | PID to select \( \mu \) or e  |
| # Charged Tracks             | = 2                          |
| Total Charge                 | = 0                          |
| # Photons                    | = 0 (untagged analysis)      |
| Missing Photon Angle         | \( < 0.1 \text{ rad} \) or \( > \pi - 0.1 \text{ rad} \)  |
| 1C Kinematic Fit             | \( \chi^2_{1C} < 20 \)      |
**Data-MC comparison: \( \mu^+\mu^- \) case**

MC simulated with PHOKHARA


Data-MC efficiency corrections applied on MC.

See talk on Wednesday:

“Measurement of the \( \pi^+\pi^- \) cross section at BESIII”
(PPHI, 16:40)
**Data-MC comparison: e^+e^- case**

MC simulated with BABAYAGA 3.5

*MC not corrected for data-MC differences.*

*MC simulated with BABAYAGA 3.5*

Fit to data

To get rid of the MC prediction:

Fit of the *continuous* mass spectrum in data with a polynomial and look for a peak in data:

\[ p(x) = a_0 + a_1 x + a_2 x^2 + a_3 x^3 + a_4 x^4 \]

Spare the region around J/\(\psi\).
Fit to data

To get rid of the MC prediction:

Fit of the continuous mass spectrum in data with a polynomial and look for a peak in data:

\[ p(x) = a_0 + a_1 x + a_2 x^2 + a_3 x^3 + a_4 x^4 \]

Spare the region around \( J/\psi \).

No peaking structure found. ⇒ Set exclusion limit.

\[ \sigma \text{ significance in } \gamma - \mu + \mu \]

\[ \sigma \text{ significance in } e - e \]

\[ \chi^2 / \text{ndf} = 196 / 145 \]

\[ a_0 = 1.638 \times 10^2 \pm 1.288 \times 10^5 \]

\[ a_1 = -3.663 \times 10^1 \pm 9.571 \times 10^4 \]

\[ a_2 = 3.155 \times 10^1 \pm 4.362 \times 10^4 \]

\[ a_3 = -1.16 \times 10^1 \pm 1.83 \times 10^4 \]

\[ a_4 = 1.687 \times 10^1 \pm 5.177 \times 10^4 \]
Analysis strategy for the dark photon search

event selection

compare with MC prediction

fit the invariant mass distribution in data

search for a peaking structure

calculate the exclusion limit between 1.5 GeV/c^2 and 3.4 GeV/c^2

check whether huge background is left

get rid of any data-MC comparison in the final result

none is found

below 1.5 GeV/c^2: pion background is dominant

above 3.4 GeV/c^2: too close to production threshold
90% confidence level (CL) calculated with the algorithm by Rolke et al. (TRolke)


**Exclusion limit**

Combined statistics, including systematics

**data - fit**

**CL = 90%**
Exclusion limit

We want to calculate it in bins of the mixing parameter \( \varepsilon \):

\[
\frac{d\sigma(e^+ e^- \rightarrow \gamma^* \gamma_{\text{ISR}} \rightarrow l^+ l^- \gamma_{\text{ISR}})}{d\sigma(e^+ e^- \rightarrow \gamma^* \gamma_{\text{ISR}} \rightarrow l^+ l^- \gamma_{\text{ISR}})} = \frac{3\pi}{2N_f l^+ l^-} \cdot \frac{\varepsilon^2}{\alpha} \cdot \frac{m_{\gamma'}}{\delta_m}
\]

Exclusion limit

determined exclusion limit

mixing parameter

dark photon mass

number of decay modes of dark photon containing phase space (contains R ratio, see next slide)

fine structure constant

mass resolution, determined with MC

\[
\frac{d\sigma(e^+ e^- \rightarrow \gamma \gamma_{ISR} \rightarrow l^+ l^- \gamma_{ISR})}{d\sigma(e^+ e^- \rightarrow \gamma^* \gamma_{ISR} \rightarrow l^+ l^- \gamma_{ISR})} = \frac{3\pi}{2N_f l^1 l^-} \cdot \frac{e^2}{\alpha} \cdot \frac{m_{\gamma'}}{\delta_m}
\]
Number of decay modes $N_f$

\[
N_f^{l^+l^-} = \frac{\Gamma_{tot}}{\Gamma(\gamma' \rightarrow l^+l^-)}
\]

\[
\Gamma_{tot} = \Gamma(\gamma' \rightarrow e^+e^-) + \Gamma(\gamma' \rightarrow \mu^+\mu^-) \cdot (1 + R(\sqrt{s}))
\]

\[
\Gamma(\gamma' \rightarrow l^+l^-) = \frac{\alpha \varepsilon^2}{3m_{\gamma'}^2} \sqrt{m_{\gamma'}^2 - 4m_l^2} (m_{\gamma'}^2 + 2m_l^2)
\]

\[R = \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}\]

taken from PDG 2014

\[\sqrt{s} \text{ [GeV]}\]

\[R\]

Systematic uncertainty

Systematic uncertainty is estimated and implemented bin-by-bin (possible with TRolke algorithm\(^1\))

Completely dominated by the uncertainty of the R ratio (everywhere above 5%)

\[\text{uncertainty of the R ratio}\]

\[\text{taken from PDG 2014}\]

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>background subtraction</td>
<td>&lt; 0.5%</td>
</tr>
<tr>
<td>fitting error</td>
<td>&lt; 1%</td>
</tr>
<tr>
<td>mass resolution</td>
<td>&lt; 1%</td>
</tr>
<tr>
<td>R ratio</td>
<td>&gt; 5%</td>
</tr>
<tr>
<td>sum</td>
<td>&gt; 5%</td>
</tr>
</tbody>
</table>

\(^1\) see https://root.cern.ch/root/html/tutorials/math/Rolke.C.html
Now we are able to calculate the BESIII limit.
Result
Summary

• Goal of the analysis is to search a dark photon signal using $\mu^+\mu^-\gamma_{ISR}$ and $e^+e^-\gamma_{ISR}$ events

• no evidence has been found between 1.5 and 3.4 GeV/c$^2$

• an exclusion limit with 90% confidence has been calculated with the TRolke algorithm in bins of the mass and mixing parameter of the dark photon

• values down to $\varepsilon < 7 \times 10^{-3}$ can be excluded

• best exclusion limit in this mass range

Thank you for your attention!
Backup
Particle identification

\[ e^+ e^- \rightarrow \mu^+ \mu^- \gamma_{\text{ISR}} \]

\[ D\text{LL}(\mu,e) = 2 \cdot \log \left( \frac{p(\mu)}{p(e)} \right) > 0 \]

\[ e^+ e^- \rightarrow e^+ e^- \gamma_{\text{ISR}} \]

\[ E / p > 0.8 \]

<table>
<thead>
<tr>
<th>particle</th>
<th>suppression due to ( E/p &gt; 0.8 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>muons</td>
<td>99.95 %</td>
</tr>
<tr>
<td>pions</td>
<td>98.01 %</td>
</tr>
<tr>
<td>electrons</td>
<td>9.83 %</td>
</tr>
</tbody>
</table>
Result

combined exclusion limit

\[ N_f^{\text{combined}} = \frac{\Gamma_{\text{tot}}}{\Gamma(\gamma' \rightarrow e^+e^-) + \Gamma(\gamma' \rightarrow \mu^+\mu^-)} \]