U boson search in $e^+e^- \rightarrow \mu^+\mu^-\gamma$ process at KLOE

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Outline

• Radiative Events at $e^+ e^-$ Colliders

• DAΦNE Complex and KLOE Detector

• $e^+ e^- \rightarrow \mu^+ \mu^- \gamma$ Data Analysis: based on KLOE Analysis fot the $\sigma_{\pi\gamma}$ measurement
  - Event Selection
  - Background Subtraction Procedure
  - Data/MC Comparison

• $\varepsilon^2$ Upper limit extraction in the region 600÷1000 MeV

• Future Perspectives and Conclusions
- $e^+/e^-$ excess in the cosmic ray flux and the absence of a similar effect in proton/anti-proton observations by PAMELA
- 511 KeV gamma ray signal form galactic center by INTEGRAL satellite
- total $e^+/e^-$ flux measured by ATIC, HESS, Fermi
- DAMA/LIBRA annual modulation signal

All these observations could be explained if one assume that a dark matter gauge boson, mediator of an unknown dark force with $m_U < 2m_p$, exists.
Radiative events at $e^+e^-$ Colliders

High luminosity $e^+e^-$ Colliders Experiments at GeV scale can be a direct probe of Dark Forces. At flavor factories a particular clean channel is the production of the U boson plus a photon with the consequent decay of the boson in a leptons pairs: $e^+e^-$→Uγ→l$^+l^-$γ, l= e,μ

The expected U boson signal should have the shape of a narrow Breit-Wigner peak in the invariant mass distribution of the leptons pair

Sensitivity to the kinetic mixing parameter in the range $\varepsilon \sim 10^{-3}$-$10^{-2}$ for a $M_U$ up to a few GeV

DAΦNE is a $e^+e^-$ Colliders with $\sqrt{s} = m_\phi = 1.0195$ GeV, at LNF Frascati. The DAΦNE Accelerator Complex consists of a linear accelerator, a damping ring, nearly 180 m of transfer lines, two storage rings that intersect at two points, a beam test area (BTF) and three synchrotron light lines.
The **KLOE detector** is made up of a large cylindrical drift chamber (DC), surrounded by a lead scintillating fiber electromagnetic calorimeter (EMC). A superconducting coil around the EMC provides a 0.52 T magnetic field.

**EMC**: measurement of **photon energies** and **impact point**, accurate measurement of the **time of arrival of particles**.

**DC**: **tracking** of the particles and **reaction vertex reconstruction**
Beam line

End-caps C-shaped to minimize dead zones:
98% coverage of full solid angle

\[ \sigma_E/E = 5.7\% / \sqrt{E(\text{GeV})} \]
\[ \sigma_T = 54 \text{ ps} / \sqrt{E(\text{GeV})} \pm 100 \text{ ps} \]

(Bunch length contribution subtracted from constant term)

excellent time resolution
All-stereo geometry, 4m diameter, 3m long fiber epoxy composite, **12,000 sense wires**
Filled with gas mixture: 90% He 10% C$^4$H$^{10}$

$\sigma_{xy} \sim 150\mu m$, $\sigma_z = 2 mm$

$\sigma_{p_\perp} / p_\perp$ better than 0.4%
for large angle tracks ($40^\circ \leq \theta \leq 140^\circ$)

**vertex resolution** = $\sim 3 mm$

Excellent momentum resolution
Measure of $|F_\pi|^2$ by the bin by bin ratio of pions over muons yields

$$|F_\pi(s')|^2 \approx \frac{4(1 + 2m_\mu^2/s') \beta_\mu}{\beta_\pi^3} \frac{d\sigma_{\pi\pi\gamma}}{ds'} d\sigma_{\mu\mu\gamma} ds'$$

$$(\sigma_{\mu\mu} / \sigma_{\pi\pi}^{Born})$$

High precision measure

KLOE12: $a_{\mu\pi}(0.35-0.95 \text{ GeV}^2) = (385.1 \pm 1.1_{\text{stat}} \pm 4.4_{\text{sys}} \pm 1.2_{\text{theo}}) \cdot 10^{-10}$

Results presented by G. Mandaglio @TAU2012
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KLOE12: $a_\mu^{\pi\pi}(0.35\text{-}0.95 \text{ GeV}^2) = (385.1 \pm 1.1\text{stat} \pm 4.4\text{sys} \pm 1.2\text{theo}) \cdot 10^{-10}$
$\text{e}^+\text{e}^-\rightarrow\mu^+\mu^-\gamma$ Data Analysis: SA Event Selection


- Undetected photon emitted at small angle ($\theta_\gamma < 15^\circ$, $\theta_\gamma > 165^\circ$)

- Two charged tracks with $50^\circ < \theta_\mu < 130^\circ$.

- High statistics signal

- Significant reduction of $\Phi$ resonant and FSR radiative processes backgrounds.

Kinematics: $\vec{p}_\gamma = \vec{p}_{\text{miss}} = - (\vec{p}_1 + \vec{p}_2)$
\[ e^+ e^- \rightarrow \mu^+ \mu^- \gamma \] Data Analysis: Event Selection

Background contributes coming from:
\[ e^+ e^- \rightarrow e^+ e^- \gamma(\gamma) \]
\[ e^+ e^- \rightarrow \pi^+ \pi^- \gamma(\gamma) \]
\[ \varphi \rightarrow \pi^+ \pi^- \pi^0 \]

Removed using kinematical cuts in the \( M_{\text{TRK}} - M_{\pi\pi}^2 \) plane.

\( M_{\text{TRK}} \) defined by 4-momentum conservation assuming 2 charged particles of the same mass and 1 \( \gamma \) in the final state.

\[
(\sqrt{s} - \sqrt{|p_+|^2 + M_{\text{TRK}}^2} - \sqrt{|p_-|^2 + M_{\text{TRK}}^2})^2 - (p_+ + p_-)^2 = 0
\]

cut on variable \( M_{\text{TRK}} \) to reduce \( \pi\pi\gamma \) tail contamination in the \( \mu\mu\gamma \) region, by requiring:

\( M_{\text{TRK}} < 115 \text{ MeV} \) for muons
\( M_{\text{TRK}} > 130 \text{ MeV} \) for pions

The systematic uncertainty on the muons cross section is about 1%

Data corrected by Trig, Track and PID efficiencies.
Three main background components:

- $e^+ e^- \gamma(\gamma)$
- $\pi^+ \pi^- \gamma(\gamma)$
- $\pi^+ \pi^- \pi^0$

- Backgrounds contributions obtained for 32 $M_{\mu\mu}^2$ slices of 0.02GeV$^2$ between 0.32 and 0.96 GeV$^2$

- $e^+ e^- \gamma$, $\pi^+ \pi^- \gamma$ and $3\pi$ distribution taken by MC

- tuning of $\pi^+ \pi^- \pi^0$ $M_{\text{TRK}}$ tail correction applied.
Background Subtraction

Two steps:

- eeγ weights
- ππγ, 3π weights

The resulting ratio Background spectrum, was fitted and transformed by function of GeV^2 to GeV and then subtracted to data.
Cut on $\sigma_{MTRK}$

continuous function cut on the quality of fitted tracks parametrized by the error of $M_{Trk}$
Effect of the cut:
- significant reduction of $\pi\pi\gamma$ contamination in the $M_{\mu\mu}$ region.
- improvement of $\pi/\mu$ separation
Crosscheck of the goodness of the cut: Quality Factor $R_{\pi/\mu}$.

$R_{\pi/\mu} < 1$ means the cut is efficient

$$R_{\pi/\mu} = \frac{r_{\pi/\mu} \text{ (after cut)}}{r_{\pi/\mu} \text{ (before cut)}}$$

$$r_{\pi/\mu} = \frac{N_{\pi\pi\gamma}}{N_{\mu\mu\gamma}}$$

Reduction of the $\pi\pi\gamma$ fractional background in the $\mu\mu\gamma$ $M_{\text{TRK}}$ region of a factor $>2$

Efficiency of the cut $\sim 70\%$
Data/MC Comparison

\[
\frac{d\sigma_{\mu\mu\gamma}^{\text{obs}}}{dM_{\mu\mu}} = \frac{\Delta N^{\text{obs}} - \Delta N^{\text{bckg}}}{\epsilon_{\text{sel}} \int L \, dt} \frac{1}{\sqrt{s}}
\]

- \mu\mu\gamma absolute cross section obtained by subtracting residual backgrounds and dividing it for efficiencies (track and trig) and luminosity, \( \sigma_{\text{MTRK}} \) cut included.

- comparison of the computed cross section with the NLO QED prediction of PHOKHARA.

Excellent Data/MC agreement
Exclusion Plot for Number of Events

-Observed spectrum and MC prediction by Phokara as input of Tlimit procedure (data and predicted background respectively)

-each spectra divided in slices of 0.002 GeV (our binning factor)

-each $M_U$ sub-sample used to compute, by Tlimit Root Class (CLS technique), the exclusion plot of number of events
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![Graph showing MC normalized to observed spectrum with systematic error on background ~2%](image)
Exclusion Plot for Number of Events

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U.L. on signal events @ 90% CL
\( \varepsilon^2 = \frac{N_{\text{CLS}}}{(\varepsilon_{\text{eff}} \cdot L) \cdot H} \cdot I \)

\( N_{\text{CLS}} \) = number of signal entries of the ROOT hypothesis

\( \varepsilon_{\text{eff}} \) = acceptance

\( \theta_{\gamma} < 180^\circ \), \( \theta_{\mu} < 180^\circ \)

+ eff. corrections

\( H = \frac{d \sigma_{\mu\mu \gamma}}{d \sqrt{s_{\mu}}} \)

\( \sigma_{\mu \mu \gamma} = \sigma(e^+ e^- \rightarrow \mu^+ \mu^-, s) \)

\( I = \int \sigma_{\mu \mu}^U ds_i \)

\( s = M_U^2 \)

\( s_i = \text{bin} \)

\( \sigma_{\mu \mu}^U = \sigma(e^+ e^- \rightarrow \mu^+ \mu^-, s) \)
Upper limit extraction in the region $600\div1000$ MeV

$\varepsilon^2 = \frac{N_{CLS}/(\varepsilon_{eff} \cdot L)}{H \cdot I}$

$N_{CLS} =$ #entries of signal hypothesis of ROOT Tlimit procedure

$\varepsilon_{eff} =$ acceptance

$(0^\circ < \theta_\gamma < 180^\circ, 0^\circ < \theta_\mu < 180^\circ) +$ eff. corrections

$H = \frac{d\sigma_{\mu\mu}}{d\sqrt{s_\mu}} / \sigma (e^+ e^- \rightarrow \mu^+ \mu^-, s)$

$L = 239.29 \text{ pb}^{-1}$

$I = \int_i \sigma_{U}^{\mu\mu} \text{ ds}_i \ s = M_U^2 \ s_i = \text{ bin}

\sigma_{U}^{\mu\mu} = \sigma (e^+ e^- \rightarrow U \rightarrow \mu^+ \mu^-, s)$
Upper limit extraction in the region 600–1000 MeV

U. L. between $2.6 \cdot 10^{-6}$ and $3.5 \cdot 10^{-7}$ in the energy range 600-1000 MeV


Future Perspectives: muon acceptance extension
Also $\theta_\gamma$ acceptance extension investigated with no effects on the muon invariant mass distribution.
The result presented is based on ~240 pb$^{-1}$ with the photon at small angle.

By using the full KLOE statistics (2.5 fb$^{-1}$), the current sensitivity can be improved by a factor of ~3.

In addition we can perform the analysis down to the threshold region by using a data sample off-peak (1GeV) to suppress the $\Phi \to \pi^+ \pi^- \pi^0$ background.
Conclusions

• We used 239.29 pb\(^{-1}\) of 2002 KLOE data to search for light vector boson in the \(e^+e^-\rightarrow\mu^+\mu^-\gamma\) channel.

• No evidence was found and an U.L. has been extracted on the kinetic mixing parameter \(\varepsilon^2\) in the energy range between 600 and 1000 MeV.

• By changing muons acceptance selection and performing the analysis at full statistics and off-peak, we will have the possibility to explore the muons lower invariant mass region.

• Work is in progress to finalize this analysis and submit the result for publication
Thank you!
SPARE SLIDES
Motivations of KLOE collaboration to exclude BaBar UL

-The BaBar Collaboration never performed a direct search of the U boson. The exclusion plot is just an estimate from the search of a light, narrow scalar particle in $\Upsilon$ decays: $\Upsilon(3S) \rightarrow \gamma A_0$

-The analysis is close to the search of $e^+e^- \rightarrow \gamma U$, but obviously acceptance and selection efficiency are different for scalar and vector particles.

- The $\mu^+\mu^-$ background shape from continuum production has been obtained from data taken at $\Upsilon(4S)$, with the assumption that the $A_0$ is produced in decays and not in QED continuum processes. This is true for the $A_0$, but not for the vector U boson.