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$R_{\text{had}}, \gamma\gamma$ Form Factors and the Standard Model Prediction of the Muon Anomaly

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5th Intl. Symposium on Lepton Moments
The Hadronic Contribution to $(g-2)_\mu$

$(g-2)_\mu$ Standard Model Theory

- $R_{\text{had}}$ ratio, i.e. $\sigma_{\text{had}} = \sigma( e^+ e^- \to \text{Hadrons})$
- Meson transition form factors $|F(Q^2, Q'^2)|$

Hadronic Vacuum Polarization

Hadronic Light-by-Light Scattering

Perturbative Calculations (Theory)

Electroweak Contribution

$(g-2)_\mu$ Experiment

(g-2)$_\mu$ Interpretation

R$_{\text{had}}$, $\gamma\gamma$ form factors and the Muon Anomaly

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Outline

Hadronic Vacuum Polarization  \(\leftrightarrow\) \(R_{\text{had}}\)
- Overview hadronic cross section measurements
  Initial State Radiation: KLOE vs. BABAR
- BES III status and expectations

Hadronic Light-by-Light  \(\leftrightarrow\) \(F(Q_1^2,Q_2^2)\)
- Overview meson transition form factors
- BES III status and expectations

Conclusions & Outlook
$R_{\text{had}}$

Hadronic Cross Section

$\sigma_{\text{had}}$
Hadronic Cross Section Data (last 20 years)

- SLAC/Stanford BABAR \( \sqrt{s}=10.58 \text{ GeV} \)
- LNF/Frascati KLOE(-II) \( \sqrt{s}=1.02 \text{ GeV} \)
- IHEP/Beijing BESII, R scan >2 GeV
- Novosibirsk/CMD, SND \( R \text{ Scan} < 2.0 \text{ GeV} \)
- Novosibirsk/CMD, SND \( R \text{ Scan} < 2.0 \text{ GeV} \)
- KEK/Tsukuba BELLE-II \( \sqrt{s}=10.58 \text{ GeV} \)
- BESIII \( \sqrt{s}=3 ... 4 \text{ GeV} \)
  - also new R scan > 2 GeV

R Scan e+e- Radiative Return e+e-
Initial State Radiation (ISR) aka Radiative Return

- Pioneered by KLOE
- Needs no systematic variation of beam energy
- High statistics thanks to high integrated luminosities
- Precise knowledge of radiative corrections mandatory ($H_{rad}$)

PHOKHARA event generator Czyż, Kühn, et al.


Entire $E$ range $<E_{CM}$ accessible

$pQCD$
**Most relevant Channel**: \( e^+ e^- \rightarrow \pi^+ \pi^- \)

Systematic Uncertainties

- BABAR 0.5%
- KLOE 0.8%
- CMD2 0.8%*
- SND 1.5%*

* limited in addition by statistics

\( \rho \) resonance

\( \rho - \omega \) interference
Most relevant Channel: $e^+e^- \rightarrow \pi^+\pi^-$

- KLOE and BABAR dominate the world average
- Relatively large systematic differences, esp. above $\rho$ peak
- Knowledge of $a_\mu^{\text{had}}$ dramatically limited due to this difference

Note: KLOE05 superseded by KLOE08
**Status Hadronic Vacuum Polarization**

Future improvement of $a^\text{had}_\mu$?

1\textsuperscript{st} priority:
Clarify situation regarding $\pi^+\pi^-$
(KLOE vs. BABAR puzzle)

2\textsuperscript{nd} priority:
Measure $3\pi$, $4\pi$ channels

3\textsuperscript{rd} priority:
KK and higher multiplicities

Ongoing ISR analyses
BESIII, BEPC-II collider

$R^\text{had}_{\gamma\gamma}$ form factors and the Muon Anomaly
BEPC II Project

CM Energy $2.0 - 4.6$ GeV
Design Luminosity $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$
Achieved Luminosity 70%@ψ(3770)
Data Samples for ISR Physics

Integrated luminosities BESIII

ISR luminosity = Ldt x H_{rad}
**BES III Detector**

- **Main Drift Chamber (MDC)**
  - $\sigma(p)/p = 0.5\%$
  - $\sigma_{dE/dx} = 6.0\%$

- **Time-of-flight system (TOF)**
  - $\sigma(t) = 90\text{ps (barrel)}$
  - $\sigma(t) = 110\text{ps (endcap)}$

- **EMC**
  - 6240 CsI(Tl) crystals
  - $\sigma(E)/E = 2.5\%$
  - $\sigma_{Z,\Phi}(E) = 0.5 - 0.7\text{ cm}$

- **Muon Chambers**
  - 8 – 9 layers of RPC
  - $p > 400\text{ MeV/c}$
  - $\delta R\Phi = 1.4 \sim 1.7\text{ cm}$

- **Superconducting Magnet**
  - 1 T magnetic field

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R$_{\text{had},\gamma\gamma}$ form factors and the Muon Anomaly
Flagship ISR Analysis: $e^+e^- \rightarrow \pi^+\pi^-\gamma_{ISR}$

Event yield after acceptance cuts only

Features:
- $\psi(3770)$ data only (2.9 fb$^{-1}$)
- no dedicated background subtraction
- tagged ISR photon
- large statistics of $e^+e^- \rightarrow \pi\pi\gamma$ events
- background dominated by $e^+e^- \rightarrow \mu\mu\gamma$
- data – MC differences visible

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$R_{had, \gamma\gamma}$ form factors and the Muon Anomaly
$e^+e^- \rightarrow \pi^+\pi^-\gamma_{ISR}$: $\pi - \mu$ Separation

TMVA method (Neural Network):
- trained using $\mu\gamma$ and $\pi\pi\pi\gamma$ MC events
- information based on track level
- efficiency matrix ($p,\Theta$) for data, MC
- correct for data - MC differences
- cross checked for different TMVA methods

Kolmogorov-Smirnov test: signal (background) probability = 0.735 (0.455)

Event yield $\pi\pi\gamma$ after $\pi$-$\mu$ separation
Event yield \( \mu \mu \gamma \) after \( \pi - \mu \) separation and all efficiency corrections

**Features:**
- background from \( \pi \pi \gamma \) very small
- PHOKHARA accuracy <0.5%
- luminosity measurement based on Bhabha ev., 1.0% accuracy

\[ \Delta(\text{MC/QED-data}) = (0.51 \pm 0.28)\% \]

\( R_{\text{had}, \gamma \gamma} \) form factors and the Muon Anomaly
**Result (still blind):** $\sigma(e^+e^- \rightarrow \pi^+\pi^-)$

**2 normalization methods:**

1) normalization to $L_{\text{int}}$ (obtained from Bhabha events)

$$\sigma_{\text{bare}}(e^+e^- \rightarrow \pi^+\pi^-) = \frac{N_{\pi\pi\gamma}/\epsilon_{\text{exp}}}{L_{\text{int}} \cdot H_{\text{rad}} \cdot \delta_{\text{vac}} \cdot (1 + \delta_{\text{FSR}})}$$

2) normalization to $\mu\mu\gamma$ events, i.e. $R$ ratio ($\pi\pi\gamma/\mu\mu\gamma$)

$\rightarrow L_{\text{int}}, H_{\text{rad}}, \delta_{\text{vac}}$ cancel in ratio!

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![Plot](image)

- using the luminosity
- using the $R$ ratio

**luminosity / $R$ ratio**

$$= (0.35 \pm 1.68)\%$$

limited by low $\mu\mu\gamma$ statistics
Meson Transition Form Factors

$F(Q_1^2, Q_2^2)$
**Meson Transition Form Factors \( P \rightarrow \gamma^* \gamma(\gamma) \)**

**Time-like transition form factors:**

- Dalitz decays
  - \( 0 < q^2 < M_P^2 \)

- Annihilation process
  - \( q^2 = s > M_P^2 \)

**Space–like transition form factors:**

- Two-photon production of mesons in \( e^+e^- \)
**Space-Like FFs** $\gamma \gamma^* \rightarrow P$

**Selection criteria**
- 1 electron (positron) detected
- 1 positron (electron) along beam axis
- Meson fully reconstructed
→ cut on angle of missing momentum

**Momentum transfer**
- tagged: $Q^2 = -q_1^2 = -(p - p')^2$
  → Highly virtual photon
- untagged: $q^2 = -q_2^2 \sim 0$ GeV$^2$
  → Quasi-real photon

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EKRARA event generator
Czyż, Ivashyn
Existing Data on SL Transition Form Factors

Features:

- recent high-$Q^2$ data from BABAR and BELLE $Q^2 > 4 \text{ GeV}^2$
- above 1.5 GeV$^2$ data from CLEO
- below 1.5 GeV$^2$ data from CELLO, very poor accuracy

→ low $Q^2$ range not covered

most relevant for HLbL contribution to $(g-2)_\mu$

→ most relevant channels: $\pi^0, \eta, \eta', \pi\pi$

Initial BESIII publication $< 3.1 \text{ GeV}^2$
BES III Analysis: $e^+e^- \rightarrow e^+e^- \pi^0$

Event Selection:
- exactly one lepton candidate
- at least two, max four photons
- Helicity angle $\cos \Theta_H > 0.8$
- Kinematic cuts to reject ISR background
  $\rightarrow$ cut on angle of missing momentum

Strategy:
- Count $\pi^0$ yield in bins of $Q^2$
- $d\sigma/dQ^2$
- Form factor $F(Q^2)$
**BES III Analysis:** $e^+e^- \rightarrow e^+e^-\pi^0$

- **Full Simulation**
  - $L_{\text{int}}$: 2.92 fb$^{-1}$
  - Single Tag with both, $e^\pm$
  - Extract TFF for $0.3 \leq Q^2[\text{GeV}^2] \leq 3.1$

→ Unprecedented $Q^2 < 1.5$ GeV$^2$
Input for $(g-2)_\mu$

only MC shown red error bars correspond to BESIII statistics
Conclusions & Outlook
Conclusions and Outlook

• Exciting results to be expected from BESIII
  → Precision R measurements relevant for HVP contribution to \((g-2)_\mu\)
  → Space-like transition form factors of meson(s)

• Competing experiments ongoing in Frascati, Novosibirsk, soon BELLE-II (?)

What accuracy can be achieved for \(a^\text{had}_\mu\)?

Reduction of factor 2 of uncertainty in reach
New \((g-2)_\mu\) ring arrived at FNAL, also JPARC measurement Factor 4 improvement!

**Let's speculate 😊**

assume new exptl. measurement will be 1 sigma lower than today's value

assume we observe New Physics in \((g-2)_\mu\)

→ without change in theoretical uncertainty: \(\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = 4.3 \text{ sigma}\)

→ reduction of theoretical uncertainty of factor 2: \(\Delta a_\mu = 7.7 \text{ sigma}\)