Pion Form Factor Measurement at BESIII

Martin Ripka on behalf of the BESIII colaboration

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Motivation: Why Form Factor Measurements at BESIII?

- Muon anomalous magnetic moment $a_\mu = (g_\mu - 2)/2$
- Experimental measurement at BNL:
  $a_\mu^{exp} = 11659208.9(5.4)(3.3) \times 10^{-10}$ [PRD 73 072003 (2006)]
- Theoretical calculation:
  $a_\mu^{theo} = 11659182.8(4.9) \times 10^{-10}$ [J. Phys. G 38, 085003 (2011)]
- Theory and experiment not in agreement:
  $a_\mu^{exp} - a_\mu^{theo} \approx (30 \pm 8) \times 10^{-10} \Rightarrow 3 - 4 \sigma$ deviation

Theoretical calculation of $a_\mu$

\[ a_\mu^{theo} = a_\mu^{QED} + a_\mu^{weak} + a_\mu^{QCD} \]

\[ a_\mu^{QED} = (11658471.8 \pm 0.0) \times 10^{-10} \quad [PRL 109, 111808 (2012)] \]

\[ a_\mu^{weak} = (15.36 \pm 0.1) \times 10^{-10} \quad [PRD 88, 053005 (2013)] \]

\[ a_\mu^{QCD} = a_\mu^{LbL} + a_\mu^{VP,LO} + a_\mu^{VP,HO} \]

\[ a_\mu^{VP,LO} = (694.9 \pm 4.2) \times 10^{-10} \quad [J. Phys. G 38, 085003 (2011)] \]

\[ a_\mu^{VP,HO} = (-98.4 \pm 0.7) \times 10^{-10} \quad [J. Phys. G 38, 085003 (2011)] \]

\[ a_\mu^{LbL} = (11.6 \pm 3.9) \times 10^{-10} \quad [Phys. Rept. 477, 1 (2009)] \]
The Vacuum Polarisation Contribution to $a_{\mu}^{\text{QCD}}$

- Loop can not be calculated for low momentum hadrons
- Optical theorem connects VP amplitude with hadronic cross sections:
  $$\sigma(s)_{e^+e^-\rightarrow \text{hadrons}} = \frac{4\pi\alpha}{s} \text{Im} \Pi_\gamma(s)$$

  \[
  \begin{align*}
  \gamma^* & \quad \text{had} & \quad \gamma^* \\
  \text{had} & \quad \text{had} \\
  \end{align*}
  \]

  photon self-energy function $\text{Im} \Pi_\gamma(s)$

  hadronic cross-section $\sigma_{\text{had}}(s)$

- $a_{\mu}^{\text{VP,LO}} = \frac{1}{4\pi^3} \int_0^\infty ds K(s)\sigma_{e^+e^-\rightarrow \text{hadrons}}(s)$

- Hadronic contributions to $a_{\mu}^{\text{QCD}}$:

Most important channels: $\pi^+\pi^-, KK, \pi^+\pi^-\pi^0, \pi^+\pi^-2\pi^0$

Largest contribution to uncertainty: $\pi^+\pi^-, \pi^+\pi^-2\pi^0, KK$
Babar and Kloe each claim sub-percent precision
Measurements do not agree with each other
Another high precision measurement needed $\Rightarrow$ BESIII
- $\tau$-charm factory
- Energy range: 2 - 4.6 GeV
- Design luminosity: $10^{33} \text{ cm}^{-2}\text{s}^{-1}$ (at 3.77 GeV)
- Linac + double storage ring
- Multilayer Drift Chamber (MDC)
- Time of Flight system (ToF)
- Electromagnetic Calorimeter (EMC)
- Super Conducting magnet 1 Tesla (SC)
- Resistive Plate Chamber (RPC) for muon detection
Need $\sigma_{had}(s)$ in the entire energy range where pQCD fails

Initial State Radiation (ISR) reduces the effective CMS-energy of the collision: $m_{had}^2 = E_{CMS}^2 - 2E_{CMS}E_{ISR}$

Non radiative cross-section can be obtained by

$$\frac{d\sigma_{(had+\gamma)}}{dm_{had}} = \frac{2m_{had}}{s} W(s, E_{ISR}, \theta_{ISR}) \sigma_{had}$$

Radiator-function $W(s, E_{ISR}, \theta_{ISR})$ gives the amplitude to emit an ISR photon
Emission of ISR photons is suppressed by $\alpha/\pi$.

High integrated luminosity needed for precision measurements.

Untagged analysis possible above $\approx 1$ GeV.
Event Selection and Particle Identification (PID)

- Kinematic Fit for $\pi^+\pi^-\gamma_{ISR}$ final state
- Standard BESIII PID system for electron rejection
- Artificial Neuronal Network for muon-pion separation

**Before ANN**

**After ANN**
## Systematic Uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photon efficiency correction</td>
<td>0.2</td>
</tr>
<tr>
<td>Pion tracking efficiency correction</td>
<td>0.3</td>
</tr>
<tr>
<td>Pion ANN efficiency correction</td>
<td>0.2</td>
</tr>
<tr>
<td>Pion e-PID efficiency correction</td>
<td>0.2</td>
</tr>
<tr>
<td>ANN</td>
<td>negl.</td>
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<tr>
<td>Angular acceptance</td>
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<tr>
<td>Background subtraction</td>
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</tr>
<tr>
<td>Unfolding</td>
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</tr>
<tr>
<td>FSR correction $\delta_{\text{FSR}}$</td>
<td>0.2</td>
</tr>
<tr>
<td>Vacuum polarisation correction $\delta_{\text{vac}}$</td>
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</tr>
<tr>
<td>Radiator function</td>
<td>0.5</td>
</tr>
<tr>
<td>Luminosity $\mathcal{L}$</td>
<td>0.5</td>
</tr>
<tr>
<td><strong>Sum</strong></td>
<td><strong>0.9</strong></td>
</tr>
</tbody>
</table>
\[ \sigma^{\text{bare}}(\sqrt{s'}) = \frac{1}{2\sqrt{s'}} W(s,x) \epsilon(\sqrt{s'}) \mathcal{L}_{\text{vac}} \delta_{\text{FSR}} \frac{dN}{d\sqrt{s'}} \]

- \( \rho - \omega \) interference clearly visible
### Form Factor (Gounaris-Sakurai Parametrisation)

![Graph showing the form factor](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>BESIII Value</th>
<th>PDG 2014</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_\rho$ [MeV/c²]</td>
<td>$776.0 \pm 0.4$</td>
<td>$775.26 \pm 0.25$</td>
</tr>
<tr>
<td>$\Gamma_\rho$ [MeV]</td>
<td>$151.7 \pm 0.7$</td>
<td>$147.8 \pm 0.9$</td>
</tr>
<tr>
<td>$m_\omega$ [MeV/c²]</td>
<td>$782.2 \pm 0.6$</td>
<td>$782.65 \pm 0.12$</td>
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<tr>
<td>$\Gamma_\omega$ [MeV]</td>
<td>fixed to PDG</td>
<td>$8.49 \pm 0.08$</td>
</tr>
<tr>
<td>$</td>
<td>c_\rho</td>
<td>[10^{-3}]$</td>
</tr>
<tr>
<td>$</td>
<td>\phi_\omega</td>
<td>[\text{rad}]$</td>
</tr>
</tbody>
</table>
Comparison to Other $\pi^+\pi^-$ Measurements

- New BESIII measurement agrees with KLOE and BaBar
- Small shift wrt. BaBar above $\rho$-$\omega$ interference
Final Result: Contribution to $a_{\mu}^{VP,LO}$

- Precision competitive with previous measurements
- BESIII measurement between BaBar and KLOE
- $a_{\mu}^{\pi\pi,LO}(600 - 900 \text{ MeV}) = (370.0 \pm 2.5_{\text{stat}} \pm 3.3_{\text{sys}}) \cdot 10^{-10}$
- Confirms deviation of $3.4\sigma$ between experiment and theory
- arXiv:1507.08188 and submitted to PLB
- Extend tagged $\pi^+\pi^-$ ISR study to threshold region
- Use Untagged ISR technique for $\pi^+\pi^-$ cross section at higher energies
- Analyse $\pi^+\pi^-$ form factor from R-scan data
  (130 points, $\mathcal{L} \approx 1.3\text{fb}^{-1}$)

- Ongoing investigation of $\pi^+\pi^-\pi^0$ and $\pi^+\pi^-\pi^0\pi^0$

Thank You