Belle II Prospects for HVP Measurements

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• HVP measurements at Belle II
• Status of SuperKEKB/Belle II
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References:
• Talks by Yosuke Maeda at
  • Workshop on HVP contributions to muon g-2, KEK, Feb. 12-14, 2018
  • Mini-workshop “Hints for New Physics in Heavy Flavors”, Nagoya, Nov.15-17, 2019
(g-2)\(\mu\) status and SM prediction

- The world average (dominated by the BNL-E821 measurements):
  \[
  a_{\mu}^{\text{exp}} = 11659209.1(5.4)(3.3) \times 10^{-10}
  \]

- The SM prediction:
  \[
  a_{\mu}^{\text{SM}} = a_{\mu}^{\text{QED}} + a_{\mu}^{\text{EW}} + a_{\mu}^{\text{Had,LO}} + a_{\mu}^{\text{Had,HO}} + a_{\mu}^{\text{Had,LbL}}
  \]

  >3\(\sigma\) deviation from experiments

  SM uncertainty is dominated by hadronic contributions

Error\(^2\) budget (e.g. in KNT18)
(g-2)_{\mu} and \sigma(e^+e^- \rightarrow \text{hadrons})

- The leading order hadronic effect (a_{\mu,\text{Had,LO}}) involves low-energy QCD, and calculation is difficult.

- Dispersion relation and optical theorem relate a_{\mu,\text{Had,LO}} to the cross section \sigma (e^+e^- \rightarrow \text{hadrons}), which can be experimentally measured.

\[ a_{\mu,\text{had;LO}}^{\text{LO}} = \left( \frac{\alpha m_{\mu}}{3\pi} \right)^2 \int_{m_\pi^2}^{\infty} \frac{ds}{s^2} K(s) R(s), \]

where \[ R \equiv \frac{\sigma_{\text{tot}}(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)} \]

- The energy region below 0.9 GeV dominates, predominantly due to the \(\pi^+\pi^-\) channel.

- These data are important also for determination of \(\alpha_{\text{QED}}(M_Z)\).
Measurement Methods

Belle II strategy is to use the Initial State Radiation (ISR) method.

- Tag ISR photon
- Can scan wide energy range
- With the same experimental condition
- Lower statistics due to $O(\alpha)$ suppression
  - Can be compensated by high luminosity
- The method has been demonstrated by BaBar, BES, KLOE.

Direct scan method
e.g.: Novosibirsk
Present Experimental Status ($\pi^+\pi^-$)

- The $\pi^+\pi^-$ channel has the most significant contribution to $a_\mu^{\text{Had, LO}}$, dominating both its mean value and uncertainty.
- Already measured precisely ($\lesssim 1\%$), by several experiments.
- Small discrepancy (a few %) among measurements.
  - New ISR data from KLOE and BES III have improved the estimate in the $\rho$ region.
  - Tension exists between BaBar and others.
- Must be confirmed by Belle II
  - w/ target precision of $\rightarrow 0.5\%$

Comparison of each experimental data and the fit in the $\rho$ region
Advantages in Belle II

• High luminosity provides large statistics not only for signals themselves, but also for control samples need to estimate systematic uncertainties.

• The measurement is programmed from the beginning of the experiment, therefore, well-designed & optimized triggers can be used.

• Belle suffered from large efficiency loss because the measurement was not considered for the trigger design.

• Larger detector coverage (less asymmetry w.r.t BaBar)

• Lessons from previous experiments, as well as improved generators, can be utilized.

- e.g. systematic errors in the BaBar measurements.

- Relatively large error in PID.

With large data sample, PID error may be removed if $\pi\pi\gamma$ and $\mu\mu\gamma$ can be separated using angular distribution difference.  

\[ \text{arXiv:1808.10567} \]

\[ \text{PRD 86, 032013 (2012)} \]

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Expected Background and Efficiency

- With particle ID cuts applied, the background is dominated by other ISR modes ($\pi^+\pi^-\pi^0$, $K^+K^-$, ...),
- $O(\%)$ level, similarly to BaBar
- High background at low mass; $\pi^+\pi^-\pi^0$ with low energy $\pi^0$ (can be reduced by e.g. kinematical fit, ...)

- Efficiency = 49% for $50^\circ < \theta_{\text{ISR}} < 110^\circ$
- Expect > 1M events with 500fb$^{-1}$
- Early Belle II run will provide results with competitive errors to previous experiments

With larger data sample, errors can shrink to $\sim 1\% \rightarrow \sim 0.5\%$
T Spectral Functions

- HVP can be estimated also by T hadronic spectral functions and CVC, together with isospin breaking corrections.
- Earlier results showed discrepancy between e+e- and T based evaluations, but more recent studies with $\gamma$-$\rho$ mixing and Hidden Local Symmetry (HLS) show that two are rather compatible.

**e.g.: $\tau \rightarrow \pi\pi\pi^0$ form factor by Belle, compared to CLEO and ALEPH**

$B(\tau^- \rightarrow \pi^- \pi^0 \nu_\tau) = (25.24 \pm 0.01 \pm 0.39)\%$

$a^\pi_\mu = (523.5 \pm 1.5(\text{exp}) \pm 2.6(\text{Br}) \pm 2.5(\text{isospin})) \times 10^{-10}$ \quad $\sqrt{s} = 2m_\pi - 1.8 \text{ GeV}/c^2$
SuperKEKB Accelerator

- Low emittance (“nano-beam”) scheme employed (originally proposed by P. Raimondi)

### Machine parameters

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<td>$L$(cm$^{-2}$s$^{-1}$)</td>
<td>$80 \times 10^{34}$</td>
<td>$2.1 \times 10^{34}$</td>
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Belle II Detector

- Deal with higher background ($\times 10-20$), radiation damage, higher occupancy, higher event rates (L1 trigger $0.5 \rightarrow 30$ kHz)
- Improved performance and hermeticity

- KL and muon detector:
  - Resistive Plate Counter (barrel outer layers)
  - Scintillator + WLSF + MPPC (end-caps, inner 2 barrel layers)

- EM Calorimeter:
  - CsI(Tl), waveform sampling electronics

- Vertex Detector
  - 2 layers Si pixel (DEPFET) + 4 layers Si double sided strip DSSD

- Central Drift Chamber
  - He(50%):C$_2$H$_6$(50%), Small cells, long lever arm, fast electronics

- Particle Identification
  - Time-of-Propagation counter (barrel)
  - Prox. focusing Aerogel RICH (fwd)
• Belle II has now grown to ~ 1000 researchers from 112 institutions in 26 countries.

• Large international collaboration hosted by KEK, Japan
SuperKEKB/Belle II Plan

Phase 1 (w/o QCS/Belle II)
- Accelerator basic tuning with single beams
- Feb-June, 2016

Phase 2 (w/ QCS/Belle II but w/o VX)
- Verification of nano-beam scheme
- Understand beam background
- Physics run (April 27 - June 17, 2018)

Phase 3 (w/ full detector)
- Physics run (March 27 - July 1, 2019)
- 5ab⁻¹ by ~2022
- 50ab⁻¹ by ~2027
SuperKEKB/Belle II Phase 3

- SuperKEKB operation started March
- $e^+e^-$ collision started on March 25.
  - Physics run from March 27 to July
- Accumulated $\sim 6.49$ fb$^{-1}$.
  - 0.83 fb$^{-1}$ recorded below the $\Upsilon(4S)$
- $L_{peak} \sim 5 \times 10^{33}$ cm$^{-2}$s$^{-1}$ in physics runs with $\beta_y^* = 3$mm optics.
- $L_{peak} \sim 1.2 \times 10^{34}$ cm$^{-2}$s$^{-1}$ was recorded with $\beta_y^* = 2$mm optics and 820/830 mA (LER/HER).
- Belle II was OFF due to high background.
Belle II Performance
Snapshots

- Signals involving photons
  \[ e^+ e^- \rightarrow \mu^+ \mu^- \gamma \]

- Signals involving charged tracks
  \[ \eta \rightarrow \gamma \gamma \]

- Signals involving charged tracks
  \[ J/\psi \rightarrow e^+ e^- \]

- Signals involving charged tracks
  \[ J/\psi \rightarrow \mu^+ \mu^- \]
First Belle II Physics Plots

Rediscovery of B mesons

Evidence for $B^0 \rightarrow D \cdot K^+$

Observation of $B \rightarrow K^* \gamma$

B-B mixing w/ $B \rightarrow D^{*+} l^{-} \nu$
$\rightarrow D^0 \pi^+ l^{-} \nu$

Charm lifetime

$\Upsilon(2S), \Upsilon(3S)$ via ISR
Search for Dark Sector  
(Belle II First Physics)

- A novel result on the dark sector ($Z' \rightarrow$ nothing) recoiling against di-muons or an electron-muon pair.
- Both possibilities are poorly constrained at low $Z'$ mass and in the first case, could explain the muon g-2 anomaly.

These demonstrate how well Belle II controls low multiplicity events.
First Look at the Belle II Data

• Data collected during the Phase 2 physics run: 472 pb$^{-1}$

• Goal of the analyses:
  • To observe $\rho$ meson peak in the mass spectrum
  • Comparison to a MC simulation
  • Study of trigger efficiency

Example of an event display for a $\rho$ meson candidate
Analysis Procedure

• Select events with
  • One energetic photon \((E_{\text{CMS}} > 3\text{GeV})\)
  • Two charged tracks \((p_{\text{CMS}} > 1\text{GeV/c})\)

• Selection criteria
  • Photon in the central part of the barrel region \((50^\circ < \theta_{\text{ISR}} < 110^\circ)\)
  • \(E/p < 0.8\) to remove radiative Bhabha \((e^+e^- \rightarrow e^+e^- \gamma)\) contribution
  • \(10 < M(\pi\pi\gamma) < 11\text{ GeV/c}^2\) and no other extra particles

Y. Maeda, mini-workshop “Hints for New Physics in Heavy Flavors”, Nagoya, Nov.15-17, 2019,
also for plots in the following 3 slides
The $\rho$ meson peak is clearly observed.

No PID is used except for $E/\rho \rightarrow$ contribution from $\mu\mu\gamma$ and $KK\gamma$

Reasonable Data/MC agreement

- $\text{Data/MC} = 1.065 \pm 0.037_{\text{stat}} \ (0.5<E<1.0 \text{ GeV}/c^2)$
- 100% trigger efficiency is assumed in MC
Results for other modes

- The $e^+e^- \rightarrow \pi^+\pi^-\gamma$ process is also studied.
- 2nd largest contribution to HVP.
- The $\omega$ and $\varphi$ peaks are clearly observed.
- Reasonable agreement between data and MC.
Trigger Efficiency

- High trigger efficiency is necessary for precision measurements.
- Belle II trigger for $e^+e^- \rightarrow \pi\pi\gamma$.
  - Total calorimeter energy $> 1$ GeV
  - Bhabha veto ($\leftarrow$ loss due to this veto must be small)
    - “Belle-type Bhabha”: based on only $\theta$ angle
    - “3D Bhabha”: based on both $\theta$ and $\varphi$

- All Bhabha events were collected in Phase 2, and efficiency loss can be easily evaluated by counting #events w/ Bhabha trig.
  - Belle type: $(6.4 \pm 1.3$ stat)$%$
  - 3D Bhabha: $(0.6 \pm 0.4$ stat)$%$
    - 2 events lost / 360 events

The New Bhabha veto logic works!
Summary

- Precision measurement of $\sigma(\text{ee} \rightarrow \text{hadron})$ in Belle II with the ISR method will provide estimate of HVP effects, which is critical inputs to reduce uncertainty in the SM prediction $(g-2)_\mu$.

- The SuperKEKB/Belle II project has just started its data taking runs, and accumulated $O(\text{fb}^{-1})$ data by now.

- The first look at early Belle II data has shown:
  - Clear peak of the $\rho$ meson ($\pi^+\pi^-\pi^0$ mode).
  - Also $\omega$ and $\phi$ peaks ($\pi^+\pi^-\pi^0$ mode).
  - Reasonable agreement between data and MC.
  - Small efficiency loss due to Bhabha veto; $\leq 1\%$ w/ new 3D Bhabha veto logic.

- $O(100)\text{fb}^{-1}$ data expected within 1 year will provide the first result for HVP.

- Also possible to perform
  - $\tau$ spectral function measurement
  - Two-photon processes ($e^+e^- \rightarrow \gamma\gamma e^+e^-$ w/ double-tag) to constrain $a_\mu^{\text{HAD, LbL}}$

Stay Tuned!
Backup Slides
Two-photon Physics for $a_\mu^{\text{HAD, LbL}}$

- $\gamma\gamma$ physics allows one to constrain important input quantities needed for a data-driven analysis of $a_\mu^{\text{HAD, LbL}}$, with dispersion theory.

- Expansion in terms of the mass of intermediate states are dominated by pseudo scalar poles, $\pi^0$, $\eta$, $\eta'$, followed by two-meson states, $\pi\pi$, $KK$, and higher contributions.

- Two-photon processes, $e^+e^- \to \gamma\gamma e^+e^-$, can be studied at Belle II, both with single-tag and double-tag.

- Double-tag data are useful for HLbL.
  - Q2 of two virtual photons
  - Exclusive reconstruction of final-state hadrons
  - No data so far for $W<5\text{GeV}$.
  - Careful Bhabha-veto trigger design.

Fig. 200: $e^-e^- \to e^-e^-\pi^0$ and $e^+e^- \to e^+e^-\pi\pi$ in space-like (top) and time-like (bottom) kinematics.