Measurement of cross section of light hadron production in $e^+e^-$ collisions in the Belle II experiment

Y. Maeda (KMI, Nagoya Univ.) for the Belle II collaboration

16th Nov, 2018

2018 WPI-next mini-workshop “Hints for New Physics in Heavy Flavors”
muon g-2 and the $ee \rightarrow \pi\pi\pi$ process

- muon g-2 SM value

$$a_{\mu}^{\text{SM}} = a_{\mu}^{\text{QED}} + a_{\mu}^{\text{EW}} + a_{\mu}^{\text{Had,LO}} + a_{\mu}^{\text{Had,HO}} + a_{\mu}^{\text{Had,LbL}}$$

- $>3\sigma$ deviation from experiments
- SM uncertainty is dominated by hadronic effects

future projection

SM calculation

error$^2$ budget

from arXiv:1311.2198

exp't

hadronic light-by-light

lowest order hadronic

hadronic

PRD97, 114025 (2018)
muon g-2 and the $ee \rightarrow \pi\pi$ process

- leading order hadronic effect
  - hadronic loop
  - involves low energy QCD calculation is difficult
  - but, $ee \rightarrow \text{(hadrons)}$
    cross section data can be used
- $ee \rightarrow \pi\pi$ gives the largest contribution

\[
Im \left( \begin{array}{c}
\cdots \\
\mu
\end{array} \right) = \begin{array}{c}
\text{dispersion relation} \\
\text{& optical theorem}
\end{array}
\]

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

\[
R_\text{had}(s) = \sigma(e^+e^- \rightarrow \text{hadrons}) \left/ \frac{4\pi \alpha(s)^2}{3s} \right.
\]
**ee → ππ** gives the largest contribution
measurement methods

- **direct scan**: 
  - change collision energy and measure # of events 
  - e.g. CMD3 and SND in Novosibirsk, and also those measurements at LHC, CERN 

- **fine scan is possible for sharp resonances**
- **different conditions among different energy**
- **difficulty in handling low-momentum particles**

- **radiative return method**: 
  - collision energy is fixed 
  - require energetic $\gamma$ (Initial State Radiation, ISR) 
  - effectively low energy collision 
  - measure mass spectrum of final state hadrons 
  - e.g. BaBar, BES III, KLOE

\[ \sqrt{s} = M_{\gamma(45)} \Rightarrow \sqrt{s'} = M_{\text{had}} \]
measurement methods

- large statistics
- uncertainty due to correction of iso-spin breaking effect
- tau hadronic decay with CVC:
  - Conserved Vector Current hypothesis
  - \( \pi \pi \) mass spectrum in \( \tau \rightarrow \pi \pi \nu_\tau \)
  - e.g. LEP exp’ts, CLEO, Belle
- radiative return method:
  - collision energy is fixed
  - require energetic \( \gamma \) (Initial State Radiation, ISR)
  - effectively low energy collision
  - measure mass spectrum of final state hadrons
  - e.g. BaBar, BES III, KLOE
measurement methods

- **direct scan**:  
  - change collision energy  
  - low statistics due to ISR requirement ($O(\alpha)$)  
  - but is compensated high luminosity machines  
  - can scan cross section for wide energy range in the same experimental condition

- **e.g.** LEP exp’ts, CLEO, Belle

- **radiative return method**:
  - collision energy is fixed
  - require energetic $\gamma$ (Initial State Radiation, ISR)
    - effectively low energy collision
  - measure mass spectrum of final state hadrons
  - e.g. BaBar, BES III, KLOE
status of $\pi\pi$ cross section measurement

- Already measured precisely ($\lesssim$1%) by several experiments
- small discrepancy (a few %) among measurements
- must be confirmed by Belle II
- target: 0.5% precision (similar or better than Babar)
advantages in Belle II

- large statistics
  - signal events themselves
  - control samples for estimation of systematic uncertainty
- well-designed triggers
  - Neither Belle and BaBar had optimized trigger for this measurement
  - Belle suffered from large efficiency loss due to trigger
- larger detector coverage
- better generator
- lessons from the BaBar measurement
  - All are giving comparable uncertainty, but PID-related ones are relatively large

Sources
Trigger/filter
Tracking
$\pi$-ID
Background
Acceptance
Kinematic fit ($\chi^2$)
Correl. $\mu\mu$ ID loss
$\pi\pi/\mu\mu$ non-cancel.
Unfolding
ISNR luminosity
Sum (cross section)
First look at the Belle II data

- Belle II phase2 operation
  - commissioning of the accelerator with collisions
  - end of March – middle of July
  - the first collision at 26th April
- Full data of 472 pb\(^{-1}\) was used
- Goal of the analysis
  - to observe \(\rho\) meson peak in the mass spectrum
  - yield comparison with MC simulation
  - study of trigger efficiency
analysis procedure

- select events with
  - one energetic photon ($E^{CMS}>3$ GeV)
  - two charged tracks ($p>1$ GeV/c)

- selection criteria
  - photon points to central part of the barrel region ($50^\circ<\theta_{ISR}<110^\circ$)
  - $E/p<0.8$
    - remove Radiative Bhabha ($ee\rightarrow ee\gamma$) contribution
  - $10<\mathcal{M}(\pi\pi\gamma)<11$ GeV/c$^2$
    - no other extra particles
analysis procedure

- select events with
  - one energetic photon \(E^{CMS}>3\) GeV
  - two charged tracks \((p>1\) GeV/c)

- selection criteria
  - photon points to central part of the barrel region \((50^\circ<\theta_{ISR}<110^\circ)\)
  - \(E/p<0.8\)
    - remove Radiative Bhabha \((ee\rightarrow ee\gamma)\) contribution
  - \(10<M(\pi\pi\gamma)<11\) GeV/c\(^2\)
    - no other extra particles
analysis procedure

- select events with
  - one energetic photon ($E_{CMS}^\gamma > 3$ GeV)
  - two charged tracks ($p > 1$ GeV/c)

- selection criteria
  - photon points to central part of the barrel region $50^\circ < \theta_{ISR} < 110^\circ$
  - $E/p < 0.8$
    - remove Radiative Bhabha ($ee \rightarrow ee\gamma$) contribution
  - $10 < M(\pi\pi\gamma) < 11$ GeV/c$^2$
    - no other extra particles
ππ mass spectrum

- ρ meson peak is clearly observed!
  - Belle II first “rediscovery” of $\rho^0 \rightarrow \pi^+\pi^-$

- no PID cuts except for the $E/\rho$ cut
  - contribution from $\mu\mu\gamma$ / $KK\gamma$
    - peak at low mass due to $\phi \rightarrow K^+K^-$
    - high mass (>1 GeV/$c^2$) is dominated by $\mu\mu\gamma$

- reasonable data/MC agreement
  - data/MC = $1.065\pm0.037$ _stat._ (0.5-1 GeV/$c^2$)
    - MC trigger efficiency is assumed to be 100%

\[\int L \, dt = 472 \text{ pb}^{-1}\]

Phase2 data

$e^+e^- \rightarrow \pi^+\pi^-\gamma$
- MC $\pi\pi\gamma$
- MC $\mu\mu\gamma$
- MC $KK\gamma$
- data

$M(\pi\pi)$ [GeV/$c^2$]
results for other modes

- the $ee \rightarrow \pi\pi\pi\gamma$ process is also studied with phase2 data
  - 2nd biggest contribution to $a_\mu^{\text{had};\text{LO}}$
- $\omega, \phi$ peaks are successfully observed “rediscovery”
- reasonable data/MC agreement

**Diagram:**

- Contribution of each mode to $a_\mu^{\text{had};\text{LO}}$ ($\sqrt{s}<1.8$ GeV)
- $\pi\pi\pi$ mass distribution

**Figure 6:** This shows distribution of $M(\pi^+\pi^-\pi^0)$ for $ee \rightarrow \pi^+\pi^-\pi^0\gamma$ events with the full phase2 data. Further detail is described in BELLE2-NOTE-PH-2018-030.

\[
\int L \, dt = 472 \text{ pb}^{-1}
\]

*Belle II 2018 preliminary*
trigger efficiency for $\pi\pi\gamma$

- high trigger efficiency is necessary for precision measurement
- Belle II trigger for $ee \rightarrow \pi\pi\gamma$
  - total calorimeter energy $> 1$ GeV
  - Bhabha veto
    - loss of this veto must be small
- large loss by Bhabha veto in Belle
  - precision measurement was difficult
- all Bhabha events were collected in phase2
  - Efficiency loss can be easily evaluated by counting the number of events with Bhabha trig.
efficiency loss by Bhabha veto

- two kinds of Bhabha veto logic
  - “Belle-type” Bhabha veto
  - “new” Bhabha veto

- results of loss evaluation
  - “Belle-type” : \((6.4\pm1.3_{\text{stat}})\%\)
  - “new” logic : 2 events / 360 events \((0.6\pm0.4_{\text{stat}})\%\)

\(\Rightarrow\) the “new” Bhabha veto logic is feasible for future runs
expected performance by MC sim.

- apply PID cuts
- BG contribution
  - dominant BG: other ISR modes ($\pi^+\pi^0$, $K^+K^-$,..)
  - O(%) level BG; same level with BaBar
  - high BG at low mass: $\pi\pi\pi^0$ with low-E $\pi^0$
  - can be reduced (kinematic fit...)
- efficiency
  - 49% for $50<\theta_{\text{ISR}}<110^\circ$
  - expect $>1$M events with 500 fb$^{-1}$
  - can have results with early Belle II data!!

[Belle II MC (w/o beam BG)]

[BG ratio to total]

[Points: BaBar result]
summary

- $e\bar{e} \rightarrow \pi\pi$ cross section measurement in Belle II with ISR method is critical to reduce uncertainty of theoretical value for muon $g-2$
- In Phase2 data, $\rho$ meson peak was clearly observed and good data-MC agreement was confirmed.
- Peaks for $\omega$, $\phi \rightarrow \pi^+\pi^-\pi^0$ are also observed.
- Although Belle suffered from large efficiency loss due to Bhabha veto in the trigger level, such loss is evaluated to be small ($\lesssim 1\%$) with a new Bhabha veto logic in phase2 data.
- The first $O(100) \text{ fb}^{-1}$ data will give enough signal events, which will be expected in a few years.
backup slides
muon g-2

- “g-factor” of μ (also e) is slightly larger than 2 due to QED effect
  - \( \alpha_\mu = (g-2)/2 \)
  - ~3σ discrepancy btw theo. and exp.
    - both have ~0.5 ppm precision
- strong interaction and weak interaction also contribute
  - strong : ~60 ppm
  - weak : ~1.3 ppm
**ee→ππ measurement at Belle II**

- radiative return method: detect **ee→ππγ** events
  - require energetic γ (Initial State Radiation, ISR)
  - effectively low energy collision
- hadron inv. mass distribution
  - corrections (BG, eff., unfolding...)
  - cross section for each √s

- simultaneous measurement of **ππγ** (signal) and **μμγ** (normalization)
- cancellation of various errors
hadronic contribution

- lowest order
  - ~60 ppm contribution
- related to hadron production cross section from $e^+e^-$
  - dominating theor. uncertainty
- higher order
  - smaller uncertainty
- light-by-light
  - (not discussed here)
Fermion pair production in $e^+e^-$ collisions

- Cross section is well understood
  \[ \sigma(e^+e^- \rightarrow \mu^+\mu^-) = \frac{4\pi\alpha^2}{3s} \sqrt{1 - \frac{4M_{\mu}^2}{s}(1 + 2\frac{M_{\mu}^2}{s})} \]

  - $86.85\text{ nb} / (s [\text{GeV}^2/c^4])$

- Quark production is also well described at large $\sqrt{s}$
  - Charge/flavor/color

- For small $\sqrt{s} (<2\text{ GeV})$, experimental data is necessary
  - Low energy QCD

\[ R = \frac{\sigma(\text{ee} \rightarrow \text{hadrons})}{\sigma(\text{ee} \rightarrow \mu\mu)} \]

\[ R = 3\Sigma e_q^2 \]

\[ \sqrt{s} = 2\text{ GeV} \]
detection eff. study

- reduction of systematic errors is crucial
  → need to understand each efficiency within 0.5%

- important to keep high efficiency
  - geometrical acceptance
  - trigger efficiency
  - reconstruction efficiency
  - cut efficiency
    - momentum threshold
    - PID cut
    - ...
  - background / unfolding / normalization...

Sources
- Trigger/filter
- Tracking
- π-ID
- Background
- Acceptance
- Kinematic fit ($\chi^2$)
- Correl. $\mu\mu$ ID loss
- ππ/μμ non-cancel.
- Unfolding
- ISR luminosity
- Sum (cross section)
acceptance study

- Efficiency is flat for large angle ISR $\gamma$ by limiting ISR $\gamma \theta$ angle, acceptance can be kept high.
  - Lose some events, but can be easily compensated by Belle II high stat.
- 10-20% loss due to momentum cut ($p > 1$ GeV/$c$)
  - For good muon-ID

![Graph showing acceptance study results](image-url)
efficiency for each selection

- reconstruction efficiency
  - ~10% loss, due to γ conversion / π interaction
  - “good track” selection (fit quality, distance from the interaction point, …)

- efficiency of event selection cuts (tentative)
  - $10 < E^*_{\pi\pi\gamma} < 11$ GeV, $P^*_{\pi\pi\gamma} < 0.5$ GeV/c
  - no other extra particles (add. ISR, …)

- PID cut

- total eff.: 49%
  (to all MC generated events)
  - $50^\circ < \theta_{\text{ISR}} < 110^\circ$
  - statistics: >1 M events / 500 fb$^{-1}$

- efficiency to all MC events
- good tracks selection after reconstruction
- applying all the cuts

Belle II MC (w/o BG)
**ISR $\gamma$ energy in lab frame**

- $\sqrt{s} = 10.583$ GeV
- $M_{\text{had}} = 0.3$ GeV/c$^2$ ($E_{\gamma}^{\text{CM}} = 5.289$ GeV)
- $M_{\text{had}} = 0.75$ GeV/c$^2$ ($E_{\gamma}^{\text{CM}} = 5.278$ GeV)
- $M_{\text{had}} = 2.2$ GeV/c$^2$ ($E_{\gamma}^{\text{CM}} = 5.177$ GeV)

**Belle II condition**

$(\beta\gamma = 0.28)$

- $E_{\text{lab}} \gtrsim 4$ GeV
- $(E^* = 5.18$ GeV) for $M_{\text{had}} = 2.2$ GeV/c$^2$
trigger simulation

- 100% efficiency for good events with ISR $\gamma$ pointing the barrel region
  - Bhabha veto is considered
  - some loss ($O(\%)$) for endcap, as designed
    (but these events are not used as discussed later)
- photon trigger is working effectively as expected

sum of all the trigger line (except 2, 11 & 12, to be prescaled)

3 or more clusters (at least one >300 MeV)
E* > 2 GeV (photon trigger)

red: $\pi\pi$, blue: $\mu\mu$
closed: $\gamma$ in barrel
open: $\gamma$ in endcap

Belle II MC

2 3D tracks
to be prescaled
**PID algorithm**

- assign unique PID for each track
- require both tracks to be identified as the particle of interest
- study items
  - $\mu\mu \leftrightarrow \pi\pi$ cross feed
  - correlated efficiency loss

\[
\text{likelihood ratio (LR)} = \frac{L_x}{L_x + L_\pi}
\]

$x = e, \mu, K$

![Diagram showing PID algorithm with electron, muon, and pion identification with likelihood ratios](image)
muon/pion separation

- mis-identified muons tend to be recognized as pions \( \Rightarrow \mu\)-id ineff. = fake \( \pi \)
- avoiding KLM module gaps, where \( \mu\)-id efficiency is poor
  - visible in \( p_T-\phi \) plane
  - set veto regions (for barrel/endcap, positive/negative \( \mu \))
  - require at least one track to be outside of the veto regions
$\mu\mu$ BG in $\pi\pi$ analysis

- reduction by a factor of 5 by introduction of KLM module gap veto
- 9% additional efficiency loss
- the same level with BaBar
correlated loss of PID eff.

- additional efficiency loss can exist due to two tracks close to each other
- compare two efficiencies
  - $\mu$-id for both tracks (including correlated loss)
  - product of $\mu$-id efficiency, which was taken from single $\mu$ MC (do not include correlated loss)
- significant correlated efficiency loss was not seen
BaBar trigger/filter eff. correction
BaBar tracking eff. correction
## L1 trigger menu

<table>
<thead>
<tr>
<th>Bit</th>
<th>Phase 2 description</th>
<th>Prescale Phase 2</th>
<th>Changes for 2020</th>
<th>Prescale 2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>3 or more 3D tracks</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>2 3D tracks, ≥1 within 25 cm, not a trkBhabha</td>
<td></td>
<td>2 3D tracks, ≥1 within 10 cm, not a trkBhabha</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>2 3D tracks, not a trkBhabha</td>
<td>20</td>
<td></td>
<td>20</td>
</tr>
<tr>
<td>3</td>
<td>2 3D tracks, trkBhabha</td>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>1 track, &lt;25cm, clust same hemi, no 2 GeV clust</td>
<td></td>
<td>1 track, &lt;10cm, clust same hemi, no 2 GeV clust</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>1 track, &lt;25cm, clust opp hemi, no 2 GeV clust</td>
<td></td>
<td>1 track, &lt;10cm, clust opp hemi, no 2 GeV clust</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>≥3 clusters inc. ≥1 300 MeV, not an eclBhabha</td>
<td></td>
<td>≥3 clusters inc. ≥2 300 MeV, not an eclBhabha</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>2 GeV E^* in [4,14], not a trkBhabha</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>2 GeV E^* in [4,14], trkBhabha</td>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>9</td>
<td>2 GeV E^* in 2,3,15,16, not eclBhabha</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>2 GeV E^* in 2,3,15 or 16, eclBhabha</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>2 GeV E^* in 1 or 17, not eclBhabha</td>
<td>10</td>
<td></td>
<td>20</td>
</tr>
<tr>
<td>12</td>
<td>2 GeV E^* in 1 or 17, eclBhabha</td>
<td>10</td>
<td></td>
<td>20</td>
</tr>
<tr>
<td>13</td>
<td>exactly 1 E^*&gt;1 GeV and 1 E&gt;300 MeV, in [4,15]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>exactly 1 E^*&gt;1 GeV and 1 E&gt;300 MeV, in 2,3 or 16</td>
<td></td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>15</td>
<td>clusters back-to-back in phi, both &gt;250 MeV, no 2 GeV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>clusters back-to-back in phi, 1 &lt;250 MeV, no 2 GeV</td>
<td></td>
<td>clust back-to-back in phi, &lt;250 MeV, no 2 GeV, no trk&gt;25cm</td>
<td>3</td>
</tr>
<tr>
<td>17</td>
<td>clusters back-to-back in 3D, no 2 GeV</td>
<td></td>
<td></td>
<td>5</td>
</tr>
</tbody>
</table>
light hadron production

- Hadron production cross section is an important input for hadronic contribution $a_{\mu}^{\text{had}}$ of $\mu g$-2

$$a_{\mu}^{(4)}(\text{vap, had}) = \left( \frac{\alpha m_{\mu}}{3\pi} \right)^2 \left( \int_{m_{\pi}^2}^{E_{\text{cut}}^2} ds \frac{R_{\text{had}}^\text{data}(s) \hat{K}(s)}{s^2} + \int_{E_{\text{cut}}^2}^{\infty} ds \frac{R_{\text{had}}^\text{PQCD}(s) \hat{K}(s)}{s^2} \right)$$

contribution to $a_{\mu}^{\text{had}}$ ($\sqrt{s} < 1.8 \text{ GeV}$)

- $\pi\pi$ mode gives dominant contribution ($\sqrt{s} < 1.8 \text{ GeV}$)

Figure 9: Estimated uncertainties \( a_\mu \) in units of \( 10^{11} \) according to Refs. [20, 21] and (last column) prospects for improved precision in the \( e^+e^- \) hadronic cross-section measurements. The final row projects the uncertainty on the difference with the Standard Model, \( a_\mu \). The figure gives the comparison between \( a_\mu^{SM} \) and \( a_\mu^{EXP} \). DHMZ is Ref. [20], HLMNT is Ref. [21]; "SMXX" is the same central value with a reduced error as expected by the improvement on the hadronic cross section measurement (see text); "BNL-E821 04 ave." is the current experimental value of \( a_\mu \); "New (g-2) exp." is the same central value with a fourfold improved precision as planned by the future (g-2) experiments at Fermilab and J-PARC.

References


efficiency

Belle II MC
(as a function of ISR $\theta$ angle)

$\pi\pi\gamma$ in detector acceptance, $p>1$ GeV/c

reconstruction

event selection (PID, $\pi\pi\gamma$ energy)

BaBar result
(as a function of $M_{\pi\pi}$)

BaBar $\mu\mu$ efficiency :
(3) $p>1$ GeV/c

3→4 IFR active area

4→5 DIRC active area

5→6 $\mu\mu$-id, $\chi^2$, other cuts
**R measurement**

- **scan method**
  - ☑ large statistics
  - ☹ limited energy range
  - ☠ point-to-point errors
  - being performed in Novosibirsk
- **Initial State Radiation (ISR) method** (colliders with fixed energy)
  - tag ISR photon (E>3 GeV)
  - ☑ can scan wide energy range
  - ☑ same exp’t’al condition
  - ☠ lower statistics due to ISR O(α) 
    - ☑ can be compensated by high luminosity
  - performed by BaBar / BES / KLOE

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

- muon ID inefficiency → fake π
- derived from module gaps of the K_L-μ detector (KLM)
  - also very forward region (θ<25°), not covered by KLM
- Avoiding this region helps to reduce μμ→ππ bkg
KLM-gap veto cut

- veto regions in track $p_T$-$\phi$ plane ($\phi$ is measured with respect to gap angle $\phi_0$)
- defined for each of particle charge and $\theta$ direction (endcap or barrel)
- require at least one track to be outside this veto region

when track $\phi=90^\circ$

$$\phi^* = \cos^{-1} \frac{cBR}{2p_T}$$

$\mu$ events identified as $\pi$ ($\mu^+$)

Belle II MC (single $\mu$)

$R = 2.5$ m

$R = 2.0$ m

barrel

$(40<\theta<130)$
PID performance – $\mu\mu$ mode

- $\mu\mu/\pi\pi$ modes can be background for each other
- MC stat. : ~5 fb$^{-1}$ equiv.
- $\mu\mu$-ID eff.
  - ~80%
  - loss by veto cut: 5%
- $\pi\pi \rightarrow \mu\mu$ bkg. ratio
  - ~0.4%
  - ($M_{\mu\mu} < 1$ GeV/c$^2$)
PID performance – ππ mode

- ππ-ID cut efficiency
  - 69%
  - loss by veto cut: 8.8%
- μμ→ππ background
  - 0.15% (<1 GeV/c^2)
  - factor 5 reduction due to the veto cut
  - same level as BaBar
- required statistic
  - 5.3k evts / 5 fb^{-1} → >100 fb^{-1}
  - possible in early stage of Belle II run
  - (BaBar : 232 fb^{-1} PRD86 032013)
radiator function

- probability to emit ISR $\gamma$ to produce a particle system $(X)$ with mass of $m$

$$
\frac{d\sigma_{vis}(s, m)}{dm} = \frac{2m}{s} \varepsilon(s, m) W(s, x) \sigma_0(m)
$$

cross section for $e^+e^- \rightarrow X$ at $m$

$$
W_0(0, x) = \frac{\alpha}{\pi x} \left( \ln \frac{s}{m_e^2} - 1 \right) (2 - 2x + x^2)
$$

$$
m = 2E_0 \sqrt{1 - x}
$$

$$
E_0 = \sqrt{s}/2
$$

$$
x = 2E_{CM}^\gamma/\sqrt{s}
$$

ISR $\gamma$ to forward and backward directions is dominant

$\rightarrow$ only $\sim 10\%$ of ISR $\gamma$ can be detected
ISR luminosity

- $2m/s$ : to change $x$ to $m$

\[ \frac{d\sigma_{\text{vis}}(s, m)}{dm} = \frac{2m}{s} \varepsilon(s, m)W(s, x)\sigma_0(m) \]

- can be compared with direct scan exp'ts

KLOE: 0.24 fb$^{-1}$
BaBar: 500 fb$^{-1}$
SND at VEPP-2M (direct scan)

\[ m = 2E_0\sqrt{1 - x} \]

ISR luminosity 1 fb$^{-1}$
contribution of HVP


“charge screening”

closer to each other

(= high energy scale)

→ less screening

→ stronger interaction
without veto cuts ($\pi\pi$)

- $\pi\pi$ efficiency $\sim 75$
- $\mu\mu \rightarrow \pi\pi$ bkg. ratio $\sim 0.85$
- comparison with BaBar ana.
  (PRD86 032013)

$\mu\mu$ background ratio

Belle II MC

red points : BaBar analysis
slightly worse in this analysis

black & red : $\pi\pi$ sim. (signal)
red : $\pi$-ID for both tracks

Belle II MC

blue : $\mu\mu$ sim (bkg)
dashed/solid : before/after $\pi$-ID

$\rho$ peak

$\mu\mu$ background ratio

Belle II MC

red points : BaBar analysis
slightly worse in this analysis
cut optimization

<table>
<thead>
<tr>
<th></th>
<th>μμ efficiency</th>
<th>ππ→μμ BG</th>
<th>ππ efficiency</th>
<th>μμ→ππ BG</th>
</tr>
</thead>
<tbody>
<tr>
<td>no veto cut</td>
<td>85.2%</td>
<td>0.39%</td>
<td>75.3%</td>
<td>0.83%</td>
</tr>
<tr>
<td>loose cut</td>
<td>80.9%</td>
<td>0.39%</td>
<td>68.7%</td>
<td>0.15%</td>
</tr>
<tr>
<td>tight cut</td>
<td>58.2%</td>
<td>0.40%</td>
<td>46.2%</td>
<td>0.10%</td>
</tr>
</tbody>
</table>

M<1 GeV/c^2

- tight cut (require both tracks to be outside the veto regions) loses efficiency, while background reduction is not so large
trigger efficiency for $\pi\pi\gamma$

- high trigger efficiency is necessary for precision measurement
- Belle II trigger for $ee \rightarrow \pi\pi\gamma$
  - total calorimeter energy $> 1$ GeV
  - Bhabha veto, loss of this veto must be small
- large loss by Bhabha veto in Belle $\rightarrow$ precision measurement was difficult
- Bhabha veto logic in Belle II
  - 2D Bhabha veto: rely only on $\theta$ information
  - 3D Bhabha veto: include $\phi$ information
trigger efficiency study

- All the Bhabha events were recorded in phase2 data due to low luminosity
  - no loss of events by Bhabha veto
  - can evaluate expected loss directly

\[
\text{loss} = \frac{\text{# of events triggered by Bhabha trigger}}{\text{# of all events}}
\]

- standard calorimeter trigger (total $E > 1$ GeV & & !2D-Bhabha)
- OR
- 2D-Bhabha trigger
event loss by Bhabha veto

- 2D Bhabha
  - \((12.3\pm0.8_{\text{stat}})\% \ (M(\pi\pi)<2 \text{ GeV/c}^2)\)
  - significantly large

- 3D Bhabha
  - available only for the last short period
  - loosen \(\gamma\) angle cut to increase statistics \([50^\circ,110^\circ]\) \(\rightarrow [17^\circ,128^\circ]\)
  - 2 events / 360 events \((0.6\pm0.4_{\text{stat}})\%\)
  - much smaller loss
    - \(\rightarrow\) can use the 3D Bhabha veto logic instead of the Belle-type Bhabha veto

---

**2D Bhabha veto**

**3D Bhabha veto**
current situation of $e g-2$

- **Measurement**
  - (Harvard U)
  - $a_e^{exp} = 1 159 652 180.73 (28) \times 10^{-12} \pm 0.24 \text{ ppb}$

- **Theory**
  - $a_e^{(theory)} = 1 159 652 181.78 (6)(4)(2)(77) \times 10^{-12}$ [0.67 ppb]
  - QED mass-dependent term: $2.7478(2) \times 10^{-12}$
  - had $a_e^{(had.v.p.)} = 1.866(10)_{\text{exp}}^{(5)_{\text{rad}}} \times 10^{-12}$
    - $a_e^{(\text{NLOhad.v.p.)}} = -0.2234(12)_{\text{exp}}^{(7)_{\text{rad}}} \times 10^{-12}$
    - $a_e^{(had.l-l)} = 0.035(10) \times 10^{-12}$
  - weak $a_e^{(weak)} = 0.0297 (5) \times 10^{-12}$
current situation of $\mu g-2$

- **measurement**: (BNL E821)
- **theory**
  - QED
  - hadron
  - weak

$$a^\text{exp}_\mu = 1165920.89 (63) \times 10^{-11} \pm 0.54 \text{ ppm}$$

<table>
<thead>
<tr>
<th>order</th>
<th>$a^\text{QED}_\mu$ with $\alpha^{-1}(\text{Rb})$</th>
<th>$a^\text{QED}_\mu$ with $\alpha^{-1}(\text{a}_e)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>116 140 973.318 (77)</td>
<td>116 140 973.213 (30)</td>
</tr>
<tr>
<td>4</td>
<td>413 217.6291 (90)</td>
<td>413 217.6284 (89)</td>
</tr>
<tr>
<td>6</td>
<td>30 141.902 48 (41)</td>
<td>30 141.902 39 (40)</td>
</tr>
<tr>
<td>8</td>
<td>381.008 (19)</td>
<td>381.008 (19)</td>
</tr>
<tr>
<td>10</td>
<td>5.0938 (70)</td>
<td>5.0938 (70)</td>
</tr>
<tr>
<td>$a^\mu(\text{QED}) \times 10^{11}$</td>
<td>116 584 718.951 (80)</td>
<td>116 584 718.846 (37)</td>
</tr>
</tbody>
</table>

$$a^\text{QED}_\mu = 116 584 718.951 \ (0.009)(0.019)(0.007)(0.077) \times 10^{-11}$$

$$a^\text{had;LO}_\mu = (6923 \pm 42) \times 10^{-11}$$

$$a^\text{had;NLO}_\mu = (-98.4 \pm 0.6_{\exp} \pm 0.4_{\text{rad}}) \times 10^{-11}$$

$$a^\text{HLbL}_\mu = (105 \pm 26) \times 10^{-11}$$

$$a^\text{EW}_\mu = (153.6 \pm 1.0) \times 10^{-11}$$