Status of Belle II Measurements Related with HVP Contribution to Muon g-2

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June 29, 2021 – Muon g-2 theory initiative workshop, virtual meeting

Outline

- **Introduction for a_μ^{HVP}**
- **SuperKEKB and Belle II Detector**
- **Initial State Radiation Method**
- **Low-Energy Hadronic Channels**
  - $e^+e^- \to \gamma_{ISR}\pi^+\pi^-$
  - $e^+e^- \to \gamma_{ISR}\pi^+\pi^-\pi^0$
  - Other channels
- **Conclusions**

Introduction for a_μ^{HVP}

- **Muon anomalous magnetic moment a_μ:**

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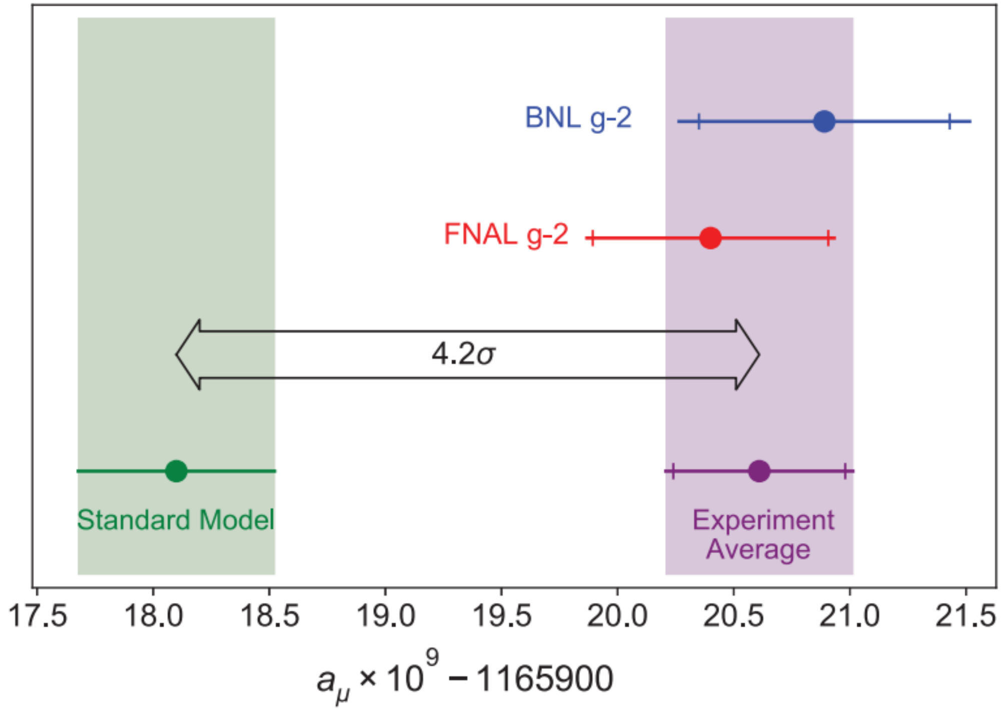
$$a_\mu = \frac{g_\mu - 2}{2}$$



- The latest result from Muon g-2 experiment at Fermilab, combined with BNL E821 result, exhibits a $\mathbf{4.2\ \sigma}$ tension with the standard model predicted a_μ^{SM}.

Standard Model (SM) prediction for a_μ:

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{HVP} + a_\mu^{HLbL}$$

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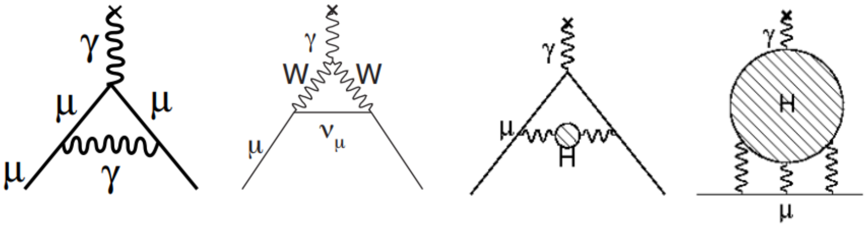

a_μ^{QED}: $116\,584\,718.931(104) \times 10^{-11}$

a_μ^{EW} : $153.6(1.0) \times 10^{-11}$

a_μ^{HVP}: $6845(40) \times 10^{-11}$ *data driven*

a_μ^{HLbL}: $92(19) \times 10^{-11}$ *data driven*

- **HVP** has the **largest uncertainty** to the prediction!

If the HVP uncertainty is decreased by 50%, then HLbL uncertainty is very important.

Contributions for a_μ^{HVP}

$$a_\mu^{HVP} = a_\mu^{HVP,\,LO} + a_\mu^{HVP,\,NLO} + a_\mu^{HVP,NNLO}$$

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$\boldsymbol{a_\mu^{HVP,\,LO}}$	$: 6931(40) \times 10^{-11}$	*data driven*
$a_\mu^{HVP,\,NLO}$	$: -98.3(7) \times 10^{-11}$	*data driven*
$a_\mu^{HVP,\,NNLO}$	$: 12.4(1) \times 10^{-11}$	*data driven*

- Contribution from **HVP LO** is dominant

$a_\mu^{LO\ HVP}$ and $\sigma(e^+e^- \to \text{hadrons})$:

- Dispersion relation:

$$a_\mu^{LO\ HVP} = \frac{\alpha^2}{3\pi^2}\int_{s_{th}}^{\infty} ds \frac{K(s)}{s} R(s)$$

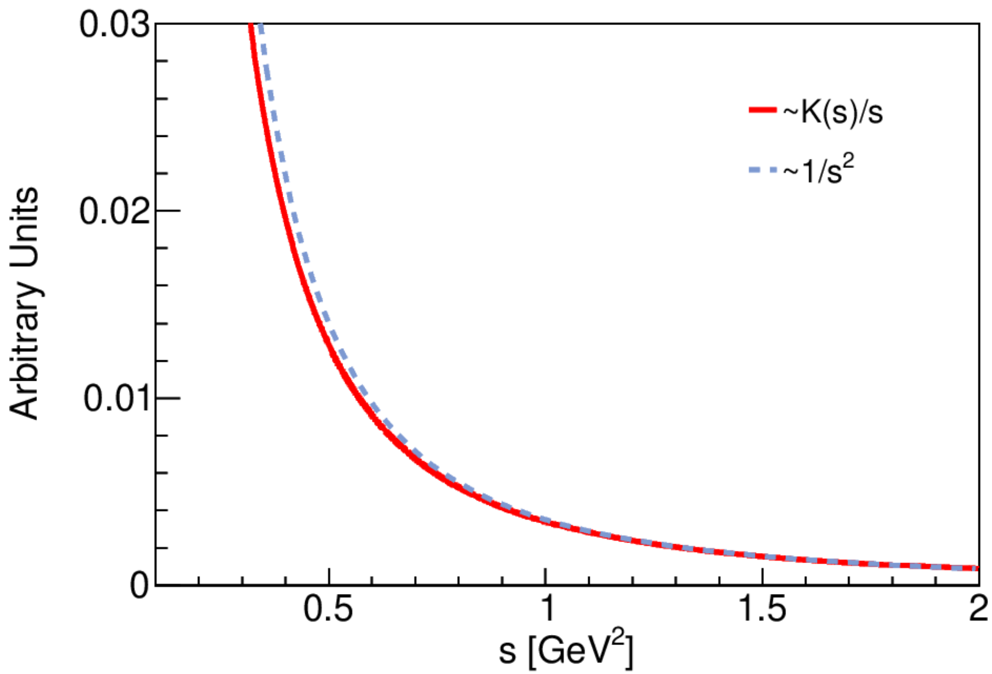
  - $R(s) = \sigma(e^+e^- \to \gamma^* \to hadrons)/\ \sigma(e^+e^- \to \mu^+\mu^-)$
  - QED kernel $K(s)$:

$$K(s) = \frac{x^2}{2}(2-x^2) + \frac{(1+x^2)(1+x)^2}{x^2}\left(log(1+x) - x + \frac{x^2}{2}\right) + \frac{1+x}{1-x}x^2 logx$$

$$x = \frac{1-\beta_\mu}{1+\beta_\mu}$$

$$\beta_\mu = \sqrt{1 - \frac{4m_\mu^2}{s}}$$

$K(s)/s$ Gives greater weight for **lower energies**



$a_\mu^{LO\ HVP}$ and $\sigma(e^+e^- \to \text{hadrons})$:

- Magnitudes of contributions from different channels

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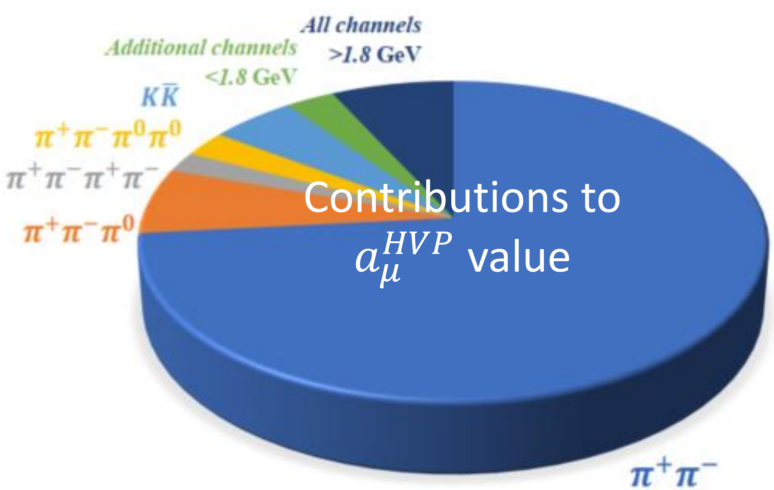
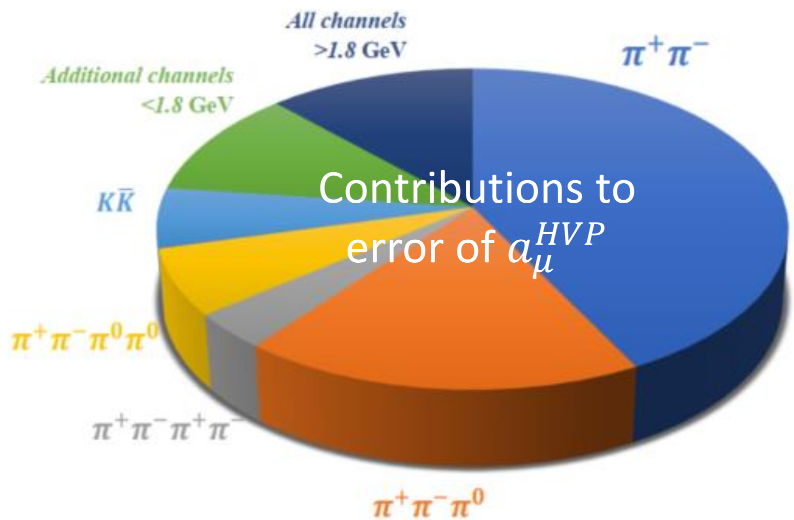


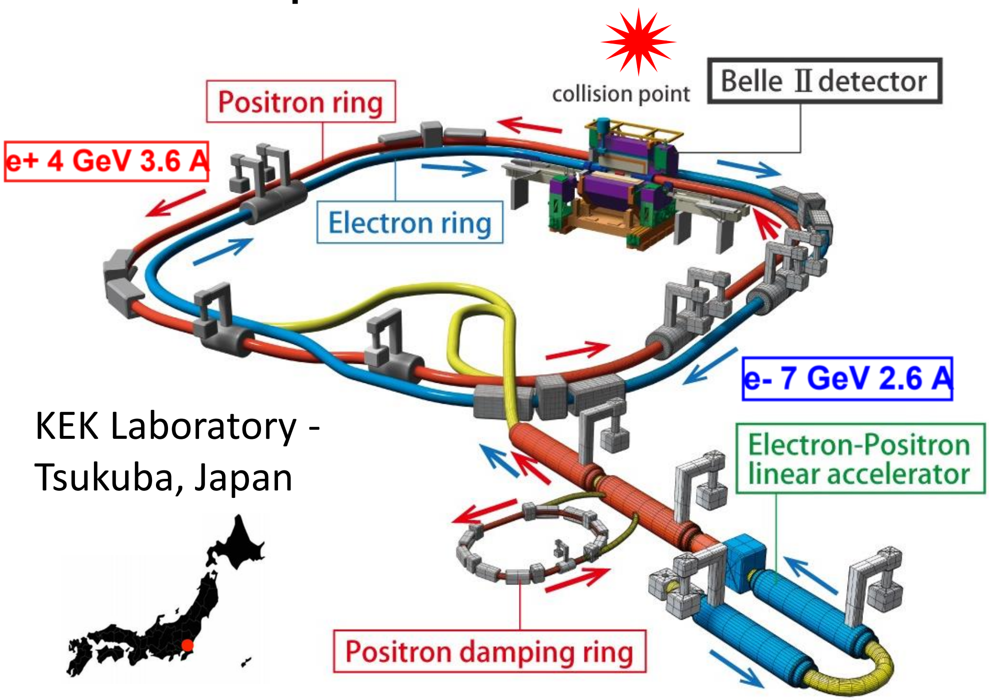


  - $e^+e^- \to \pi^+\pi^-$ channel has dominant contribution.
  - Besides, $e^+e^- \to \pi^+\pi^-\pi^0/\pi\pi\pi\pi/K\bar{K}$ channel also have large contribution.

- **Belle II** experiment could produce good measurements for these channels, with initial state radiation method!

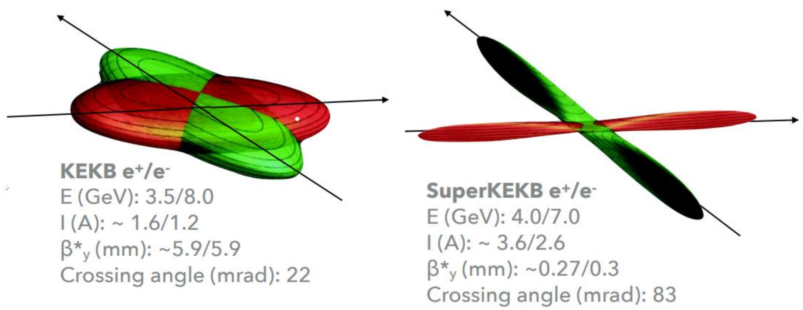
SuperKEKB and Belle II Detector

— SuperKEKB



KEK Laboratory - Tsukuba, Japan

- Nano beams technique
  beam size ↓ 20 times
  currents ↑ 1.5 times

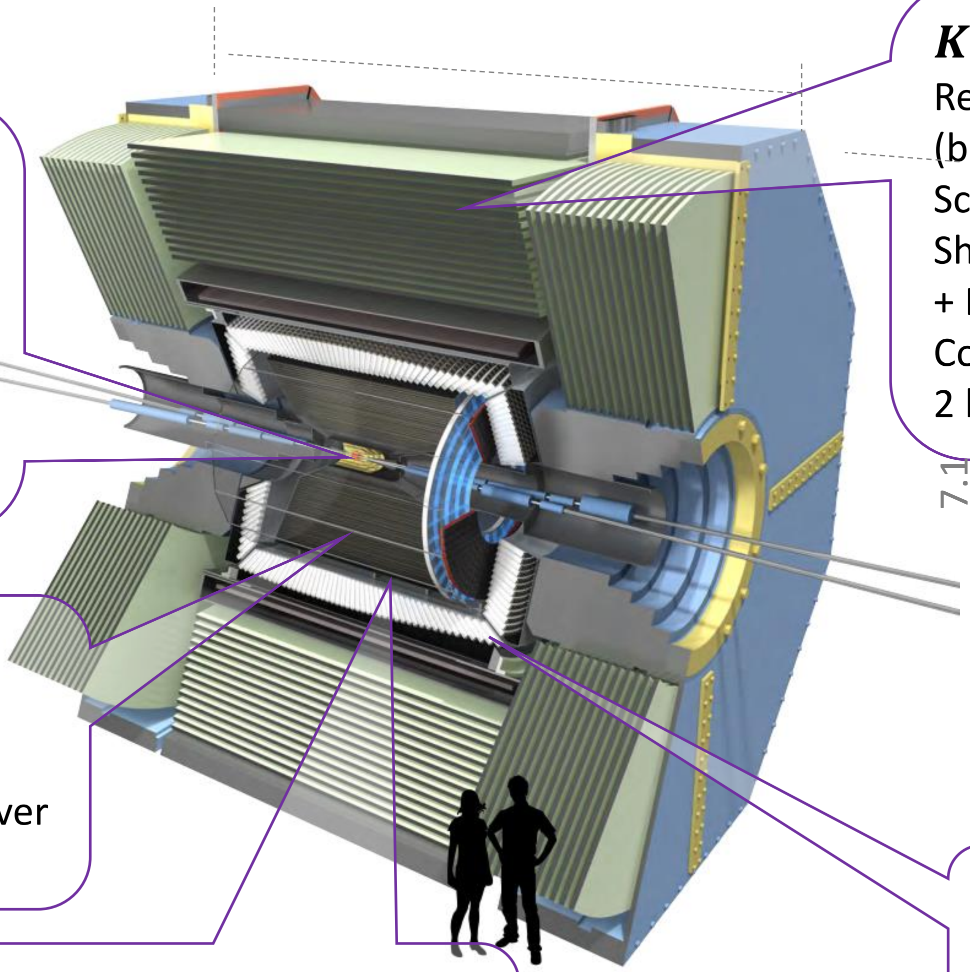


- $E_{CM} = 10.58\ \mathrm{GeV}\ (\Upsilon(4S))$
- Design peak luminosity
  $6.0 \times 10^{35}\ \mathrm{cm}^{-2}s^{-1}$

Recently achieved:
$3.0 \times 10^{34}\ \mathrm{cm}^{-2}s^{-1}$

SuperKEKB and Belle II Detector

— Belle II Detector



K_L & μ detector
Resistive Plate Chambers (barrel outer layers)
Scintillator + WaveLength Shifting Fibers + Multi-Pixel Photon Counter (end-caps , inner 2 barrel layers)

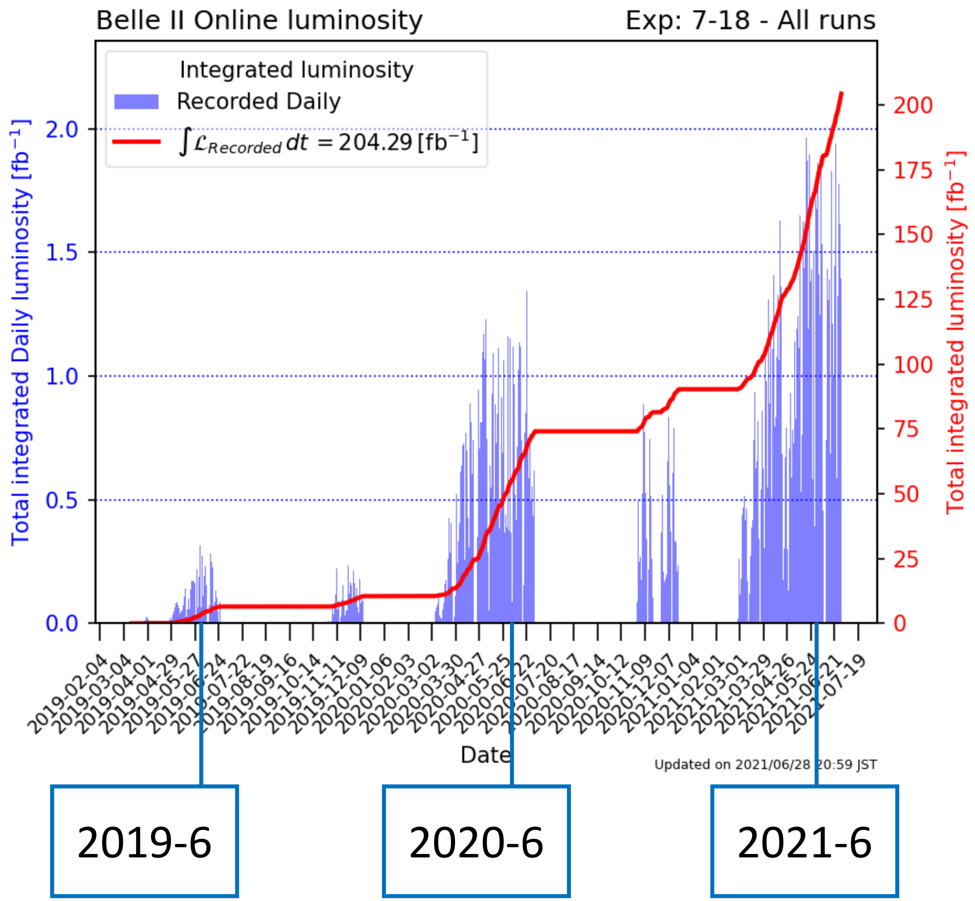
Vertex Detector
PXD: 2 layers DEPFET pixels detector
SVD: 4 layers double side Si strips detector (DSSD)

Central Drift Chamber
He(50%): C_2H_6(50%), small cell size, long lever arm, fast electronics

EM Calorimeter
CsI(Tl), **waveform sampling** (barrel)

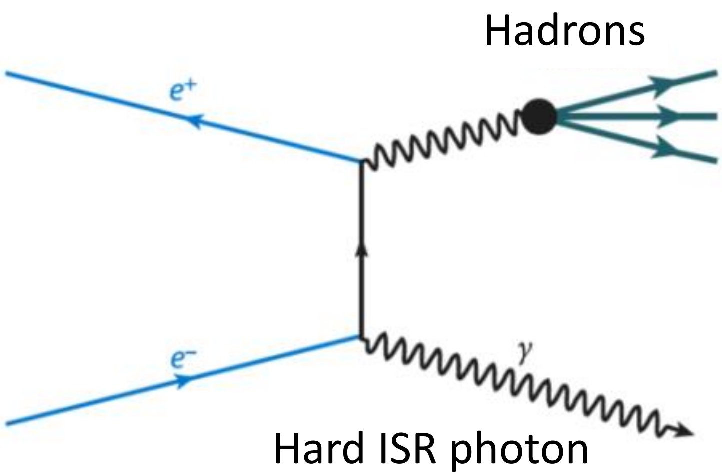
Particle Identification
Time-of-Propagation counter (barrel)
Proximity focusing Aerogel RICH (fwd)

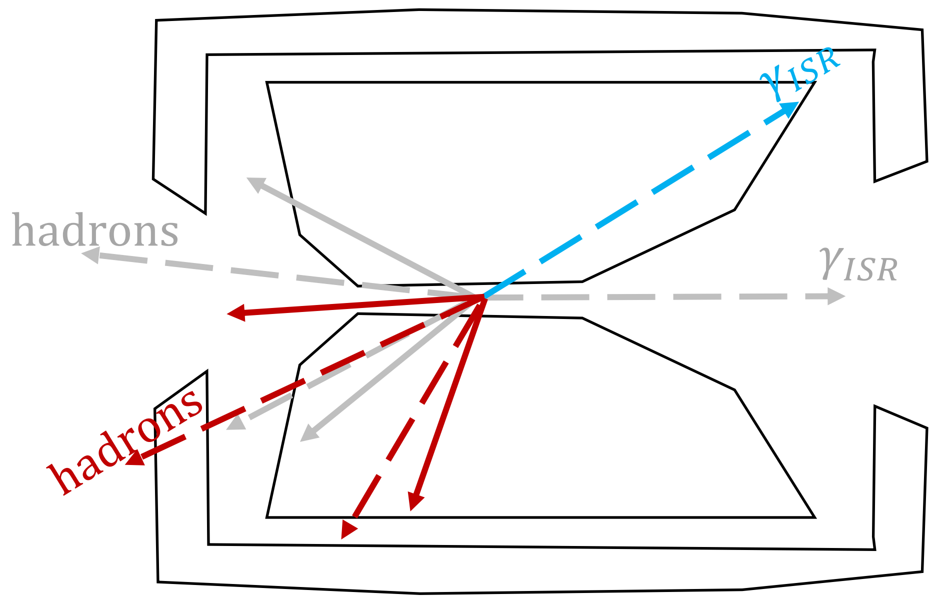
SuperKEKB and Belle II Detector



- Target dataset : 50 ab^{-1} (50×Belle)
- Integrated luminosity for **pilot run** (phase 2, 2018) $\approx 0.5\ \mathrm{fb}^{-1}$
- Integrated luminosity for **physics run** (phase 3, 2019-now) $\approx 204.29\ \mathrm{fb}^{-1}$, collecting $1{\sim}1.5\ \mathrm{fb}^{-1}$ per day

Initial State Radiation Method





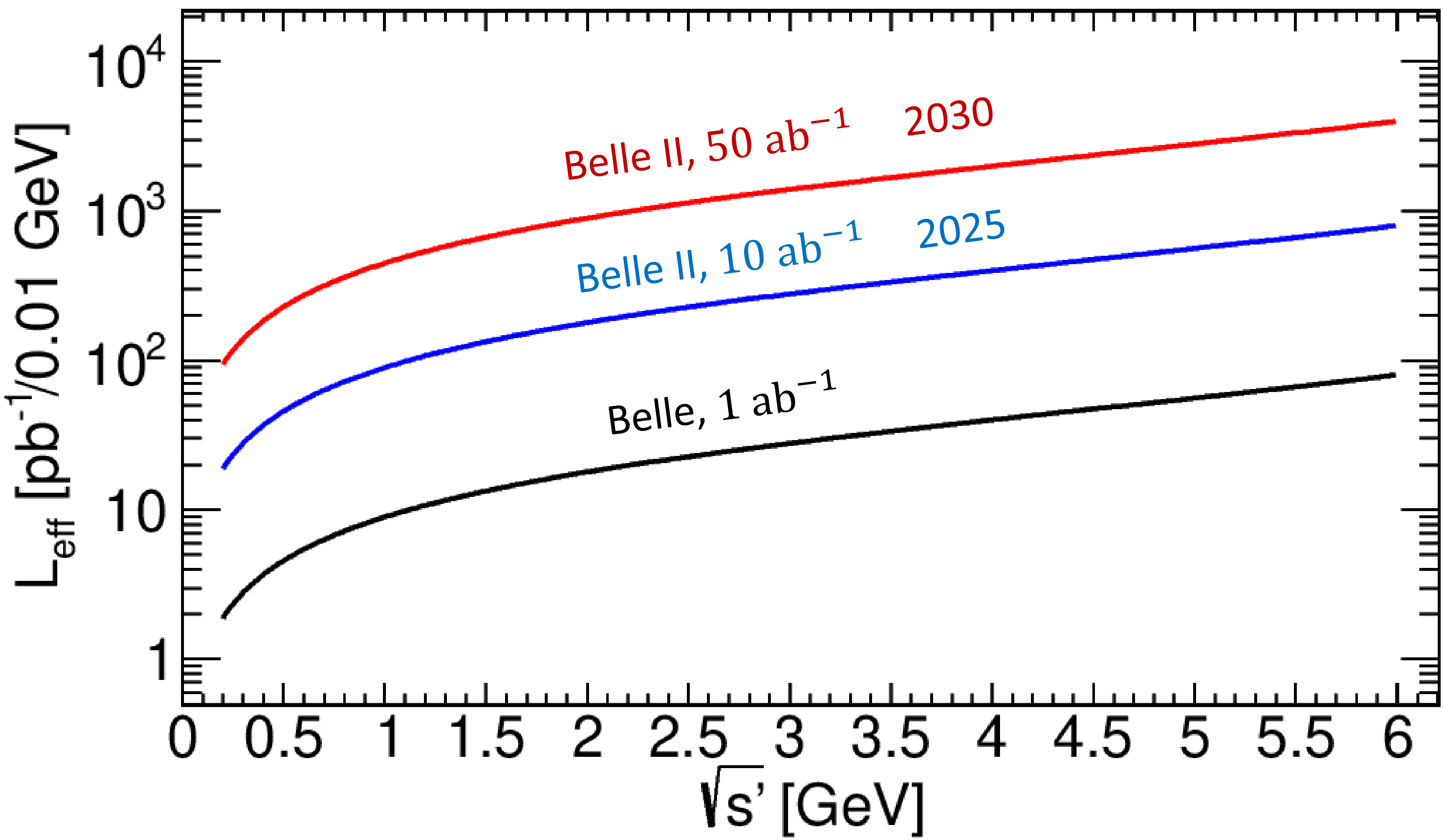
- **Initial State Radiation Method :** $e^+e^- \rightarrow \gamma_{ISR}$ hadrons
- **Advantages:** Continuous cross section measurement over a broad energy range down to threshold
- **Difficulties:** Energy leakage of the very high energy ISR photon, acceptance, trigger (Bhabha veto issue), background simulation … …

Effective luminosity:

$$L_{eff}(s') = L_{integrated}(s) \times W(s,x)$$

Photon emission probability

$$s' = s(1-x)$$



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  - Other channels
- Conclusions

Low-Energy Hadronic Channels

— $e^+e^- \to \gamma_{ISR}\pi^+\pi^-$

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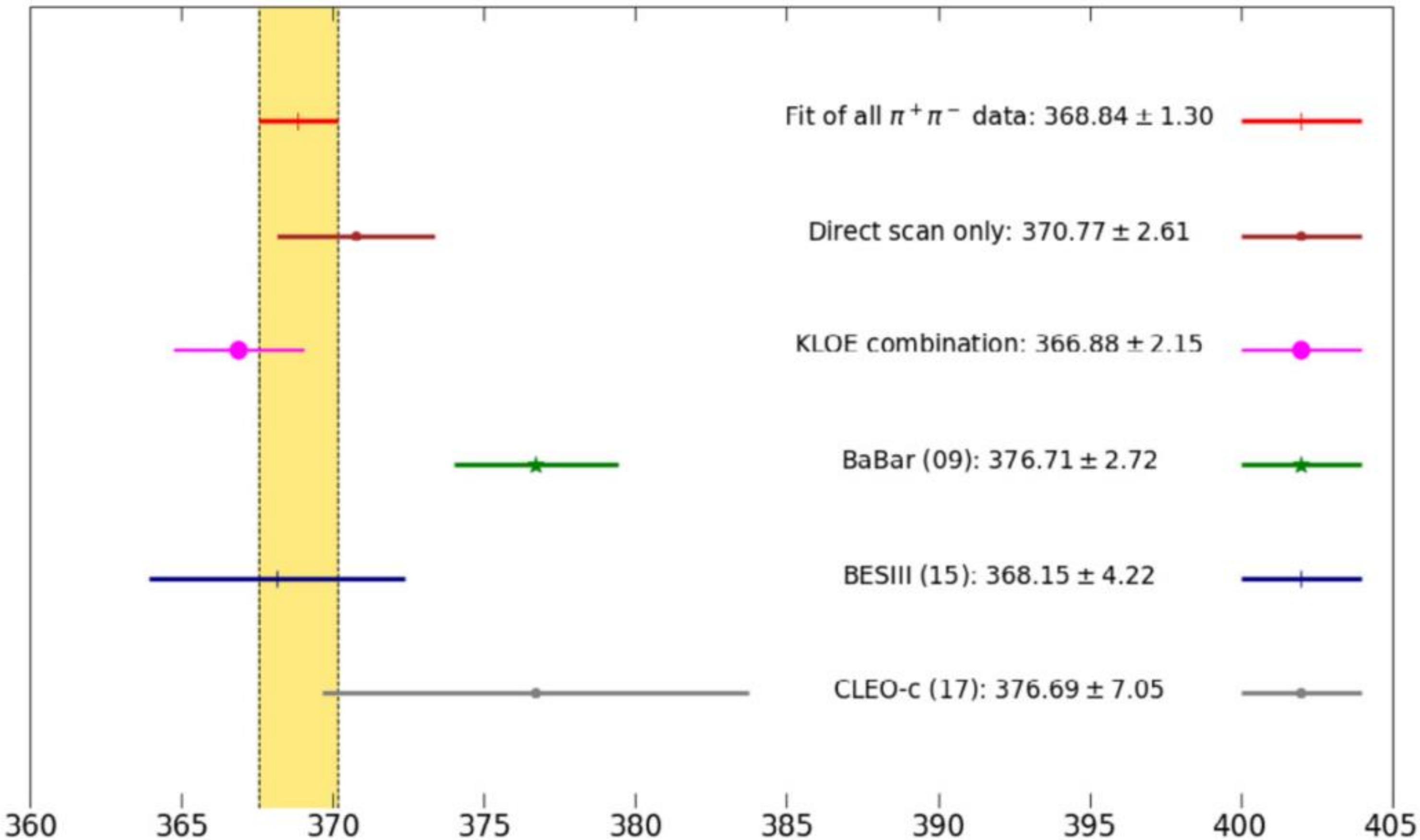
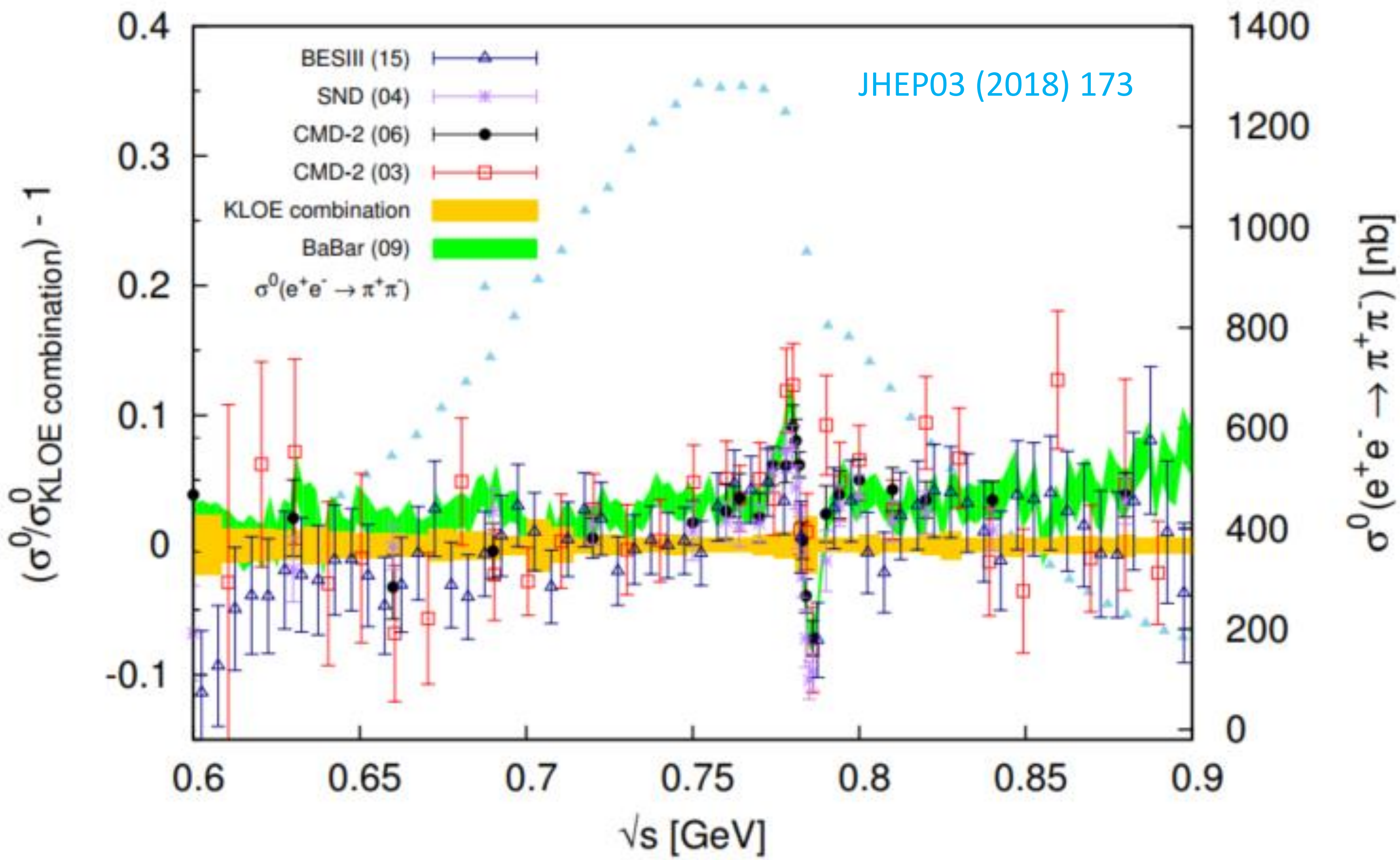


$$\boxed{a_\mu^{\pi^+\pi^-}\,(0.6 \le \sqrt{s} \le 0.9\ \text{GeV}) \times 10^{10}}$$

- Already measured precisely ($\sim 1\%$) by several experiments

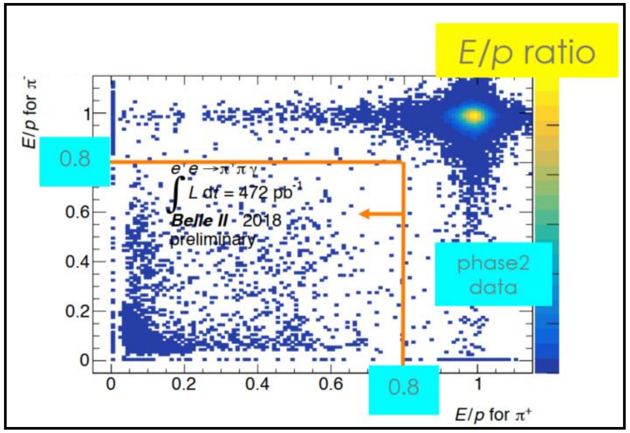


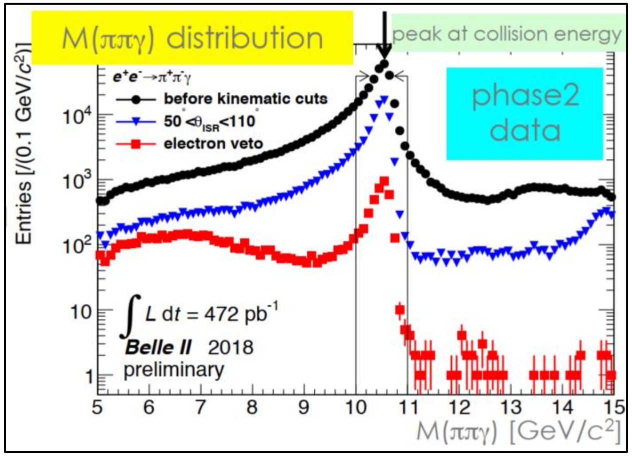
- The discrepancy between BaBar and KLOE on $\sigma(e^+e^- \to \pi^+\pi^-)$ has dominant contribution to HVP uncertainty
  - Uncertainty of a_μ^{HVP} : $\sim 40 \times 10^{-11}$ Phys. Rept. 887 (2020) 1
  - Uncertainty accounting for the tension between BaBar and KLOE : $\sim 28 \times 10^{-11}$
- Belle II's contribution would be important !

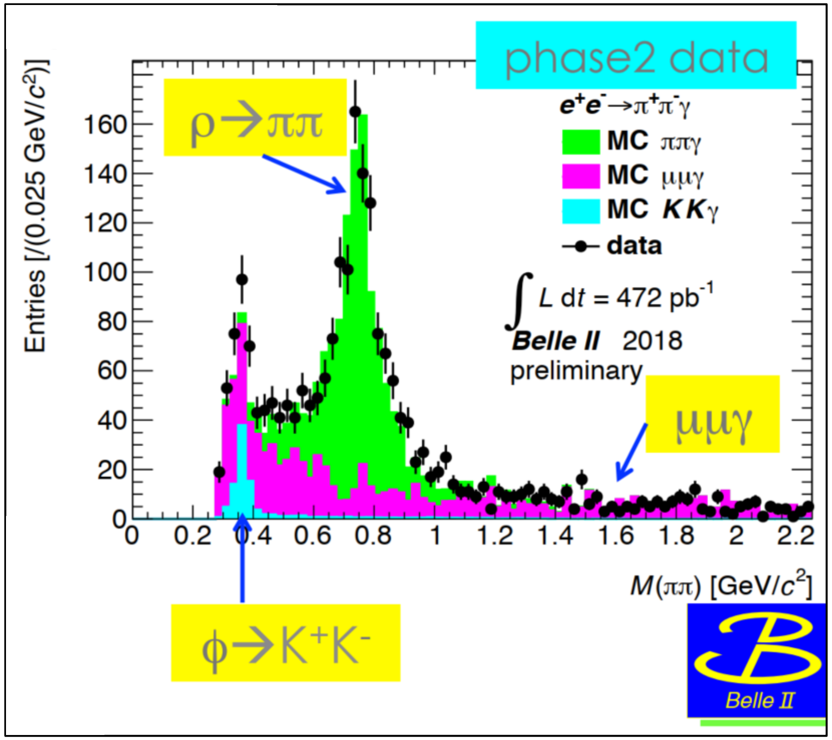
Low-Energy Hadronic Channels

— $e^+e^- \to \gamma_{ISR}\pi^+\pi^-$: Status at Belle II

- Rediscovery of $\rho \to \pi^+\pi^-$ in with Belle II phase 2 data (2018)
  - Tag the hard ISR photon ($E^{CMS} > 3$ GeV)
  - Remove radiative Bhabha events ($e^+e^- \to \gamma e^+e^-$) with $E/p < 0.8$
  - $10 < M(\gamma\pi\pi) < 11$ GeV$/c^2$ → no other extra particles







- Reasonable data/MC agreement :
  data/MC (0.5-1 GeV$/c^2$) $= 1.065 \pm 0.037_{stat.}$

Trigger check with Belle II phase 2 data (2018)

- High trigger efficiency is necessary for precision measurement
- Belle suffered from large trigger efficiency loss and the trigger systematic uncertainty. The major problem came from the Bhabha veto in Belle … …
- A trigger bit designed for $e^+e^- \to \gamma_{ISR}\pi^+\pi^-$ channel, in Belle II
  - Total calorimeter energy > 1 GeV
  - The event is not a Bhabha event (Bhabha veto)

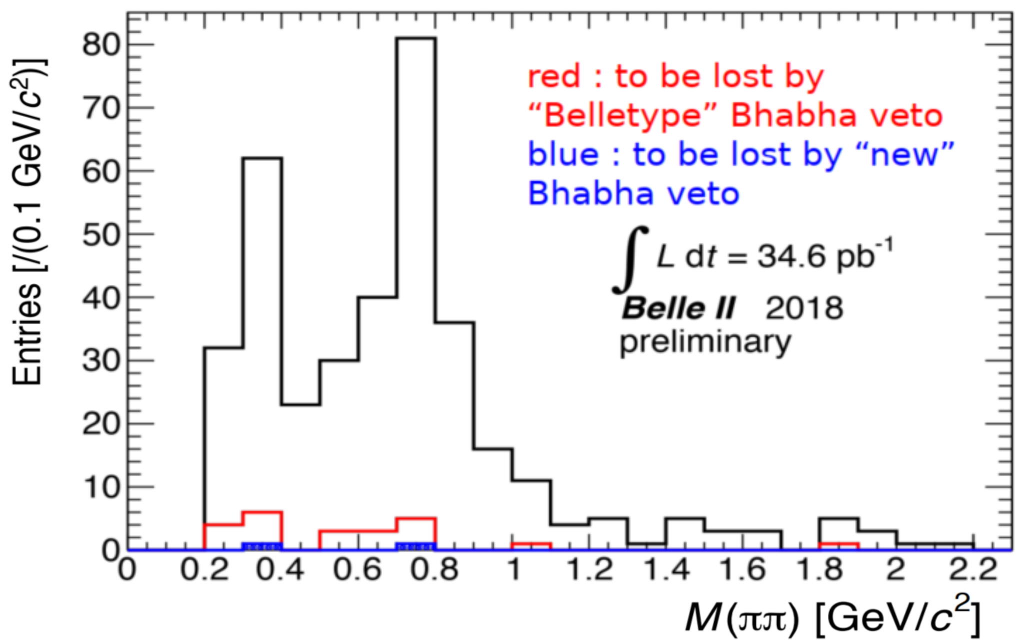
- All Bhabha events were collected in phase 2
  - Able to compare **"Belle-type"** and **"new"** Bhabha veto's effect on data
  - Results of loss evaluation

    "Belle-type":

    $(6.4 \pm 1.3_{stat})\%$

    "new":

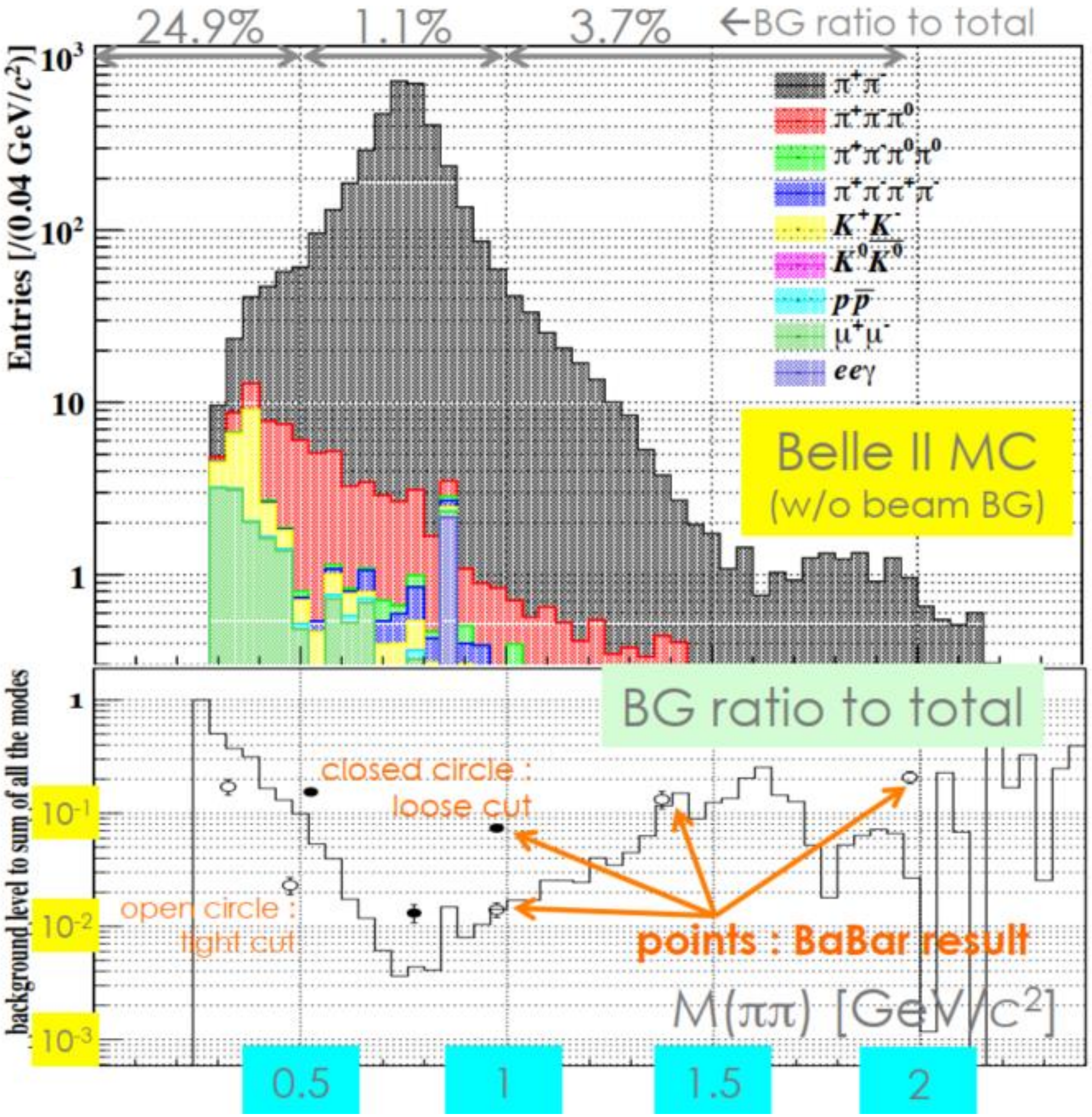
    $(0.6 \pm 0.4_{stat})\%$



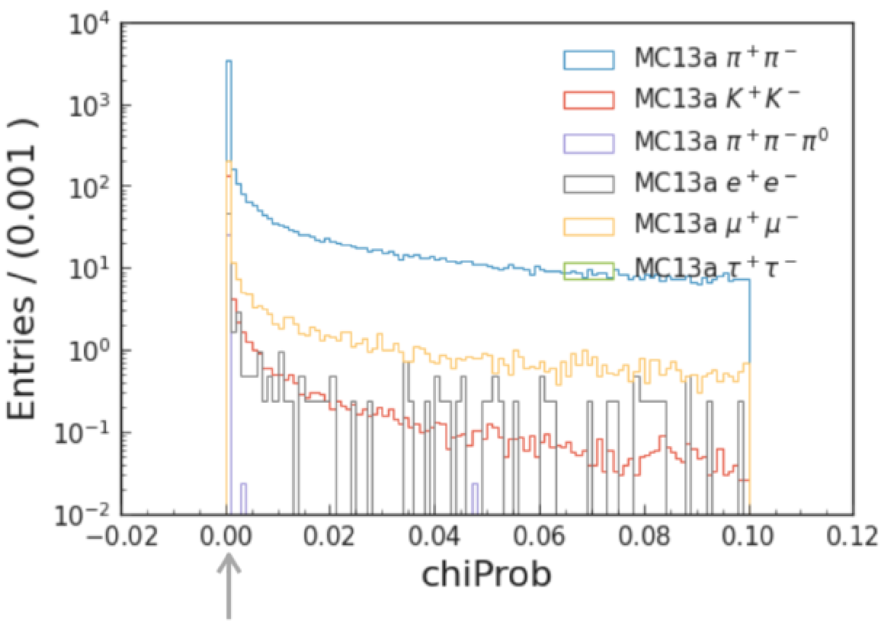
The new Bhabha veto is working fine!

Performance study with Belle II MC (2018)

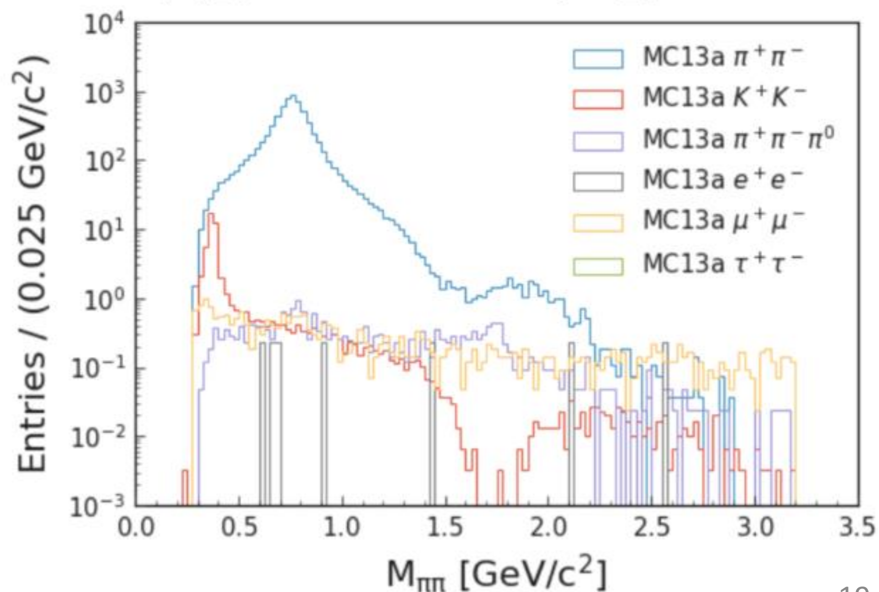
- PID cut is applied
- Background contribution
  - dominant BG: other ISR modes ($\gamma_{ISR}\pi^+\pi^-\pi^0$, $\gamma_{ISR}K^+K^-$, … …)
  - $O(\%)$ level BG: same level with BaBar
  - High BG at low mass: $\gamma_{ISR}\pi^+\pi^-\pi^0$ with low-E π^0 ← can be reduced with kinematic fit etc.
- Efficiency
  - 49% for $50° < \theta_{ISR} < 100°$
  - Expect $>$ **1M** events with **500 fb^{-1}**



- On going analysis with Belle II phase 3 data (2019-2021)
  - Target: $a_\mu^{\pi^+\pi^-}$ precision $\sim\mathbf{0.5\%}$
  - Currently trying to follow BaBar's method to build a base line
    Phys. Rev. D 86, 032013
  - Loose skim selection
    - 2 tracks + 1 hard photon
  - Double kinematic fit for S/B separation
    - Analysis must be inclusive over FSR and double ISR
    - One fit assuming FSR and one assuming ISR
    - Reject if both fits are bad
    - Related analysis tool is under study
  - Use PID to separate $\mu\mu/KK/\pi\pi$



pip_pionID > 0.01 and pim_pionID > 0.01



On going analysis with belle II phase 3 data (2019-2021)

$$\epsilon^{data} = \epsilon^{MC} \left(\frac{\epsilon^{data}}{\epsilon^{MC}}\right)_{trigger} \left(\frac{\epsilon^{data}}{\epsilon^{MC}}\right)_{PID} \left(\frac{\epsilon^{data}}{\epsilon^{MC}}\right)_{tracking} \left(\frac{\epsilon^{data}}{\epsilon^{MC}}\right)_{\chi^2}$$

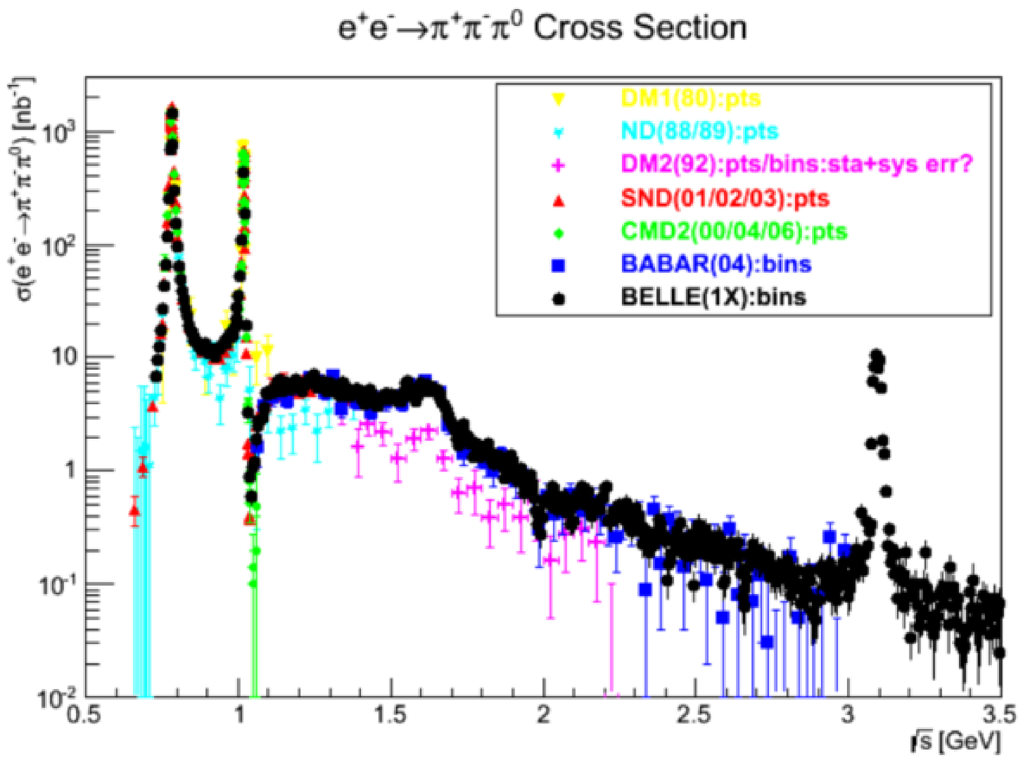
- MC efficiency
  - Good MC → small corrections → small systematic
  - Use PHOKAHARA 10.0 (October 2020)

- Correction factors
  - Trigger: evaluated with orthogonal triggers on data
  - PID: tag-and-probe on data
  - Tracking, chi2: TBD

- Data and MC correction study would benefit from the high statistics at Belle II

Low-Energy Hadronic Channels

— $e^+e^- \to \gamma_{ISR}\pi^+\pi^-\pi^0$: Status at Belle

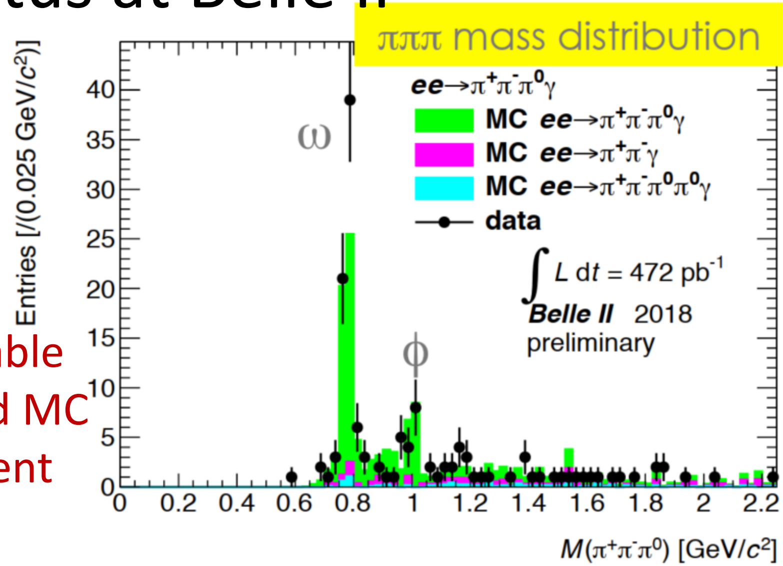


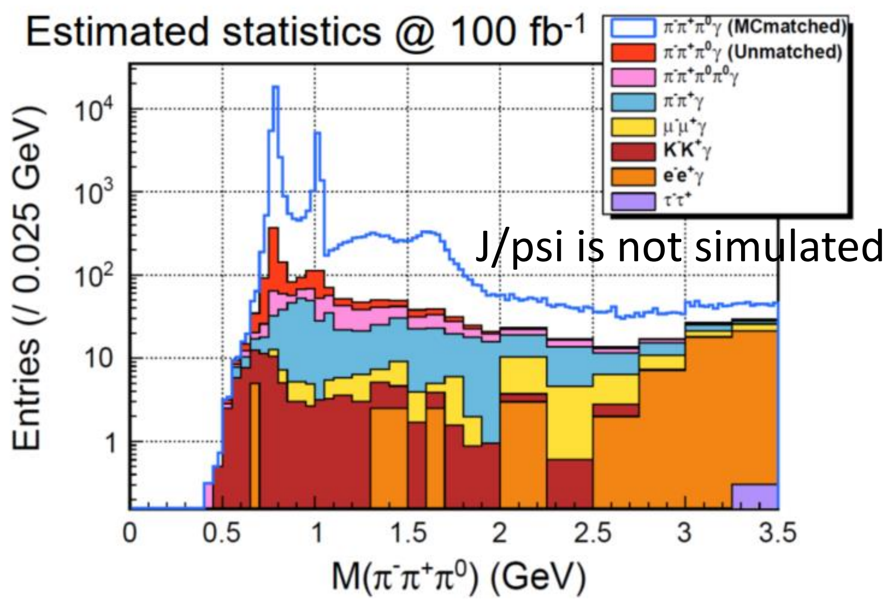
- Belle tried to measure with $526.6\ \mathrm{fb}^{-1}$ luminosity
- Aimed to achieve 5% precision
- Unpublished due to uncertainty of L1 trigger efficiency, recorded in a Ph.D thesis

Low-Energy Hadronic Channels — $e^+e^- \to \gamma_{ISR}\pi^+\pi^-\pi^0$: Status at Belle II

- Rediscovery of $\omega/\phi \to \pi^+\pi^-\pi^0$ peaks with Belle II phase 2 data (2018), event selection is similar to $e^+e^- \to \gamma_{ISR}\pi^+\pi^-$
- Trigger should be fine, according to trigger study in $e^+e^- \to \gamma_{ISR}\pi^+\pi^-$ channel. Further trigger efficiency study is also ongoing.
- Selection criteria, PID systematic uncertainty, background MC study are ongoing.

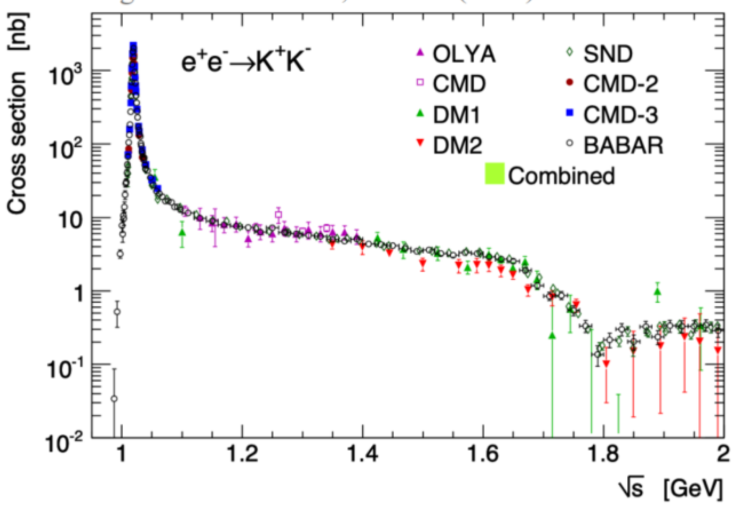
Reasonable data and MC agreement

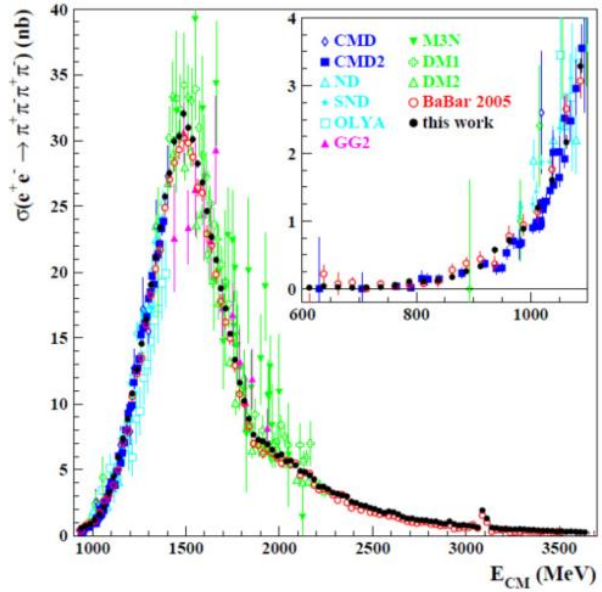


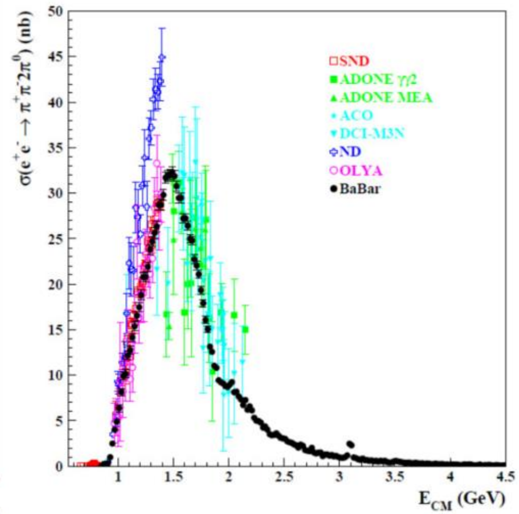


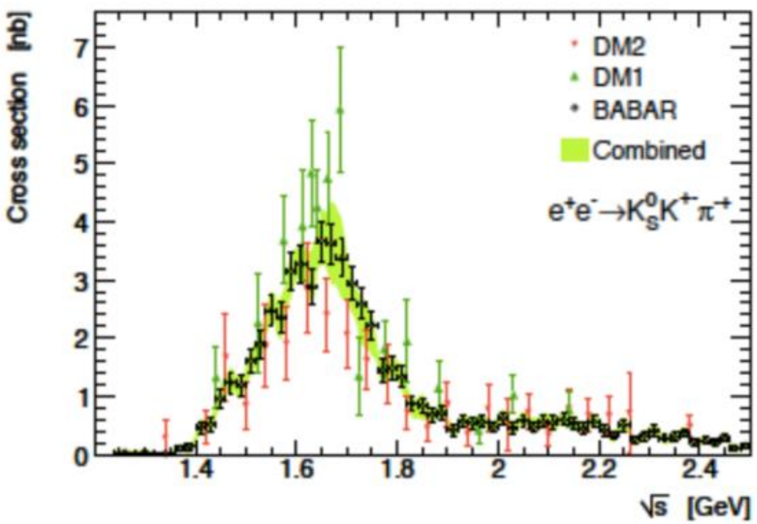
Other Channels

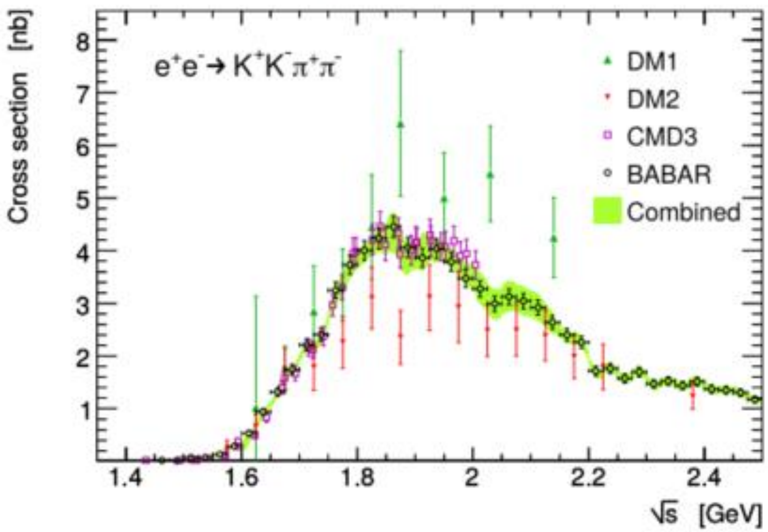
Figures from DHMZ, EPJC80 (2020) 241







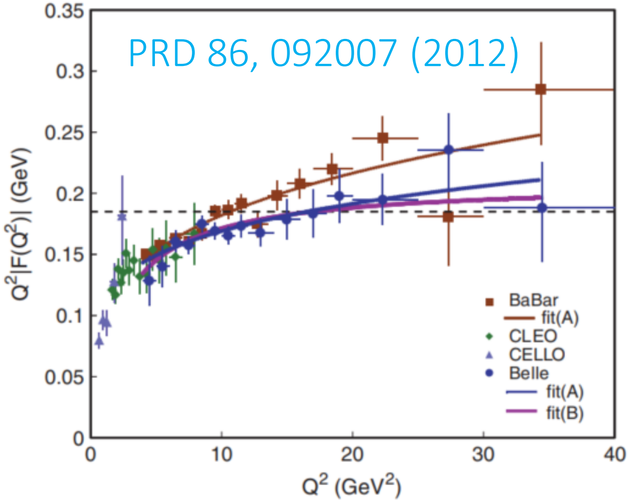




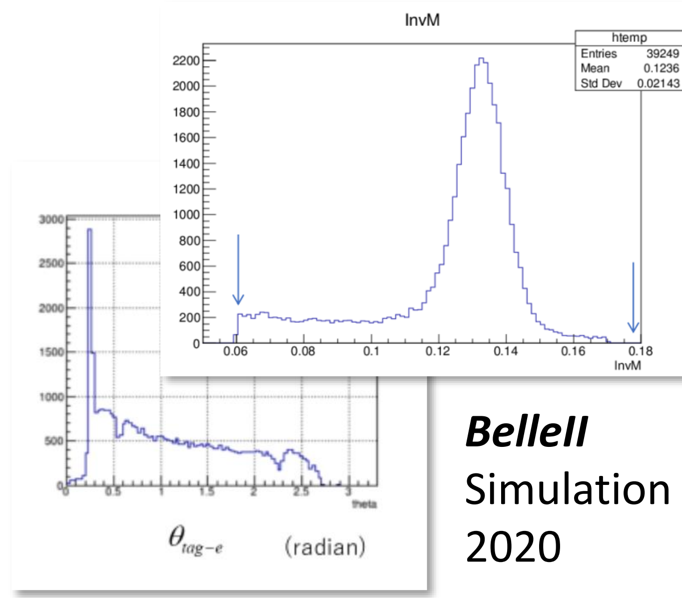
- More than 30 exclusive channels were studied in previous experiments, and would also be studied at Belle II. Preparation works are on going.

a_μ^{HLbL} and Z' at Belle II

π^0 transition form factor

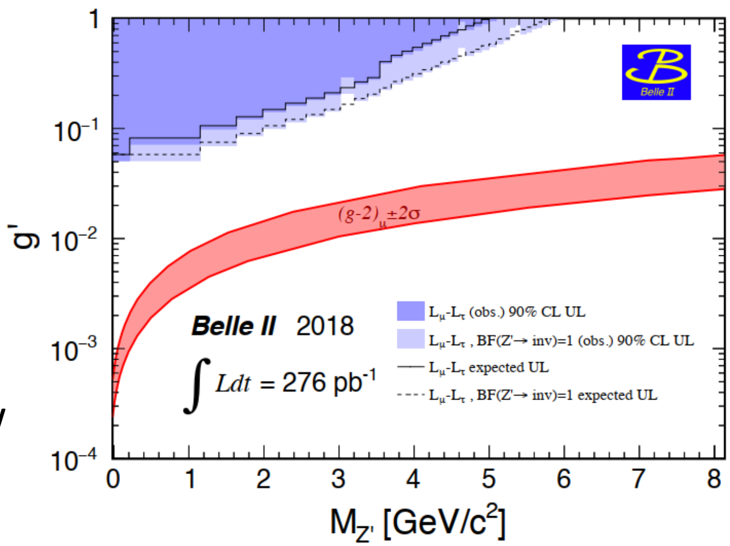


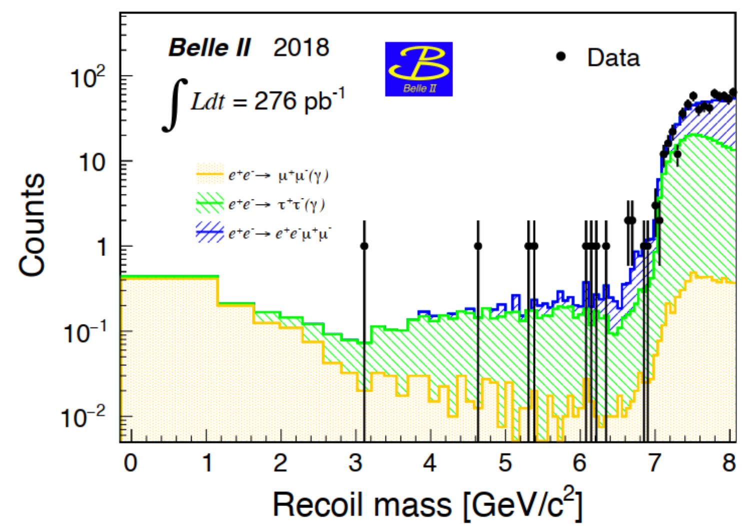
- Belle measured with 759 fb^{-1}
- Large stat. error in $Q^2 > 15\ \mathrm{GeV}^2$ region
- Ongoing analysis at Belle II



BelleII Simulation 2020

- It is possible to explain g-2 anomalies with Z'
- Already a Z' publication from Belle II
- Study with new data is ongoing





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Conclusions

- With increasing accuracy of experimental g-2 value, the improvement on accuracy of standard model prediction is important.
- Measurement of $e^+e^- \to \pi^+\pi^-$ cross section in Belle II with ISR method is critical to reduce uncertainty of theoretical prediction value for muon g-2, especially the large uncertainty caused by the BaBar and KLOE discrepancy.
- Belle II aims to reach $\sim\mathbf{0.5\%}$ precision for $a_\mu^{\pi^+\pi^-}$.
- According to rediscovery studies on the phase 2 data, $e^+e^- \to \gamma_{ISR}\pi^+\pi^-$ and $e^+e^- \to \gamma_{ISR}\pi^+\pi^-\pi^0$ channel have reasonable data/MC agreement, and the new trigger is much better than Belle's trigger.
- With phase 3 data, analyses on $e^+e^- \to \gamma_{ISR}\pi^+\pi^-$, $e^+e^- \to \gamma_{ISR}\pi^+\pi^-\pi^0$ and other channels are on going, and are expected to have decent statistics.
- In addition, Belle II is also expected to have important contribution to a_μ^{HLbL} and Z'.

Thank you!

Back Up

PRECISE MEASUREMENT OF THE ... PHYSICAL REVIEW D **86,** 032013 (2012)

TABLE V. Systematic uncertainties (in 10^{-3}) on the cross section for $e^+e^- \to \pi\pi(\gamma_{FSR})$ from the determination of the various efficiencies in different $\pi\pi$ mass ranges (in GeV/c^2). The statistical part of the efficiency measurements is included in the total statistical error in each mass bin. The last line gives the total systematic uncertainty on the $\pi\pi$ cross section, including the systematic error on the ISR luminosity from muons.

Sources	0.3–0.4	0.4–0.5	0.5–0.6	0.6–0.9	0.9–1.2	1.2–1.4	1.4–2.0	2.0–3.0
Trigger/filter	5.3	2.7	1.9	1.0	0.7	0.6	0.4	0.4
Tracking	3.8	2.1	2.1	1.1	1.7	3.1	3.1	3.1
π-ID	10.1	2.5	6.2	2.4	4.2	10.1	10.1	10.1
Background	3.5	4.3	5.2	1.0	3.0	7.0	12.0	50.0
Acceptance	1.6	1.6	1.0	1.0	1.6	1.6	1.6	1.6
Kinematic fit (χ^2)	0.9	0.9	0.3	0.3	0.9	0.9	0.9	0.9
Correl. $\mu\mu$ ID loss	3.0	2.0	3.0	1.3	2.0	3.0	10.0	10.0
$\pi\pi/\mu\mu$ non-cancel.	2.7	1.4	1.6	1.1	1.3	2.7	5.1	5.1
Unfolding	1.0	2.7	2.7	1.0	1.3	1.0	1.0	1.0
ISR luminosity	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4
Sum (cross section)	13.8	8.1	10.2	5.0	6.5	13.9	19.8	52.4

Table 5
Selected exclusive-mode contributions to $a_\mu^{\text{HVP, LO}}$ from DHMZ19 and KNT19, for the energy range $\leq 1.8\,\text{GeV}$, in units of 10^{-10}. Where three (or more) uncertainties are given for DHMZ19, the first is statistical, the second channel-specific systematic, and the third common systematic, which is correlated with at least one other channel. For the $\pi^+\pi^-$ channel, the uncertainty accounting for the tension between BABAR and KLOE (amounting to $\boxed{2.76 \times 10^{-10}}$) is included in the channel-specific systematic.

	DHMZ19	KNT19	Difference
$\pi^+\pi^-$	507.85(0.83)$\boxed{(3.23)}$(0.55)	504.23(1.90)	3.62
$\pi^+\pi^-\pi^0$	46.21(0.40)(1.10)(0.86)	46.63(94)	−0.42
$\pi^+\pi^-\pi^+\pi^-$	13.68(0.03)(0.27)(0.14)	13.99(19)	−0.31
$\pi^+\pi^-\pi^0\pi^0$	18.03(0.06)(0.48)(0.26)	18.15(74)	−0.12
K^+K^-	23.08(0.20)(0.33)(0.21)	23.00(22)	0.08
K_SK_L	12.82(0.06)(0.18)(0.15)	13.04(19)	−0.22
$\pi^0\gamma$	4.41(0.06)(0.04)(0.07)	4.58(10)	−0.17
Sum of the above	626.08(0.95)$\boxed{(3.48)}$(1.47)	623.62(2.27)	2.46
[1.8, 3.7] GeV (without $c\bar{c}$)	33.45(71)	34.45(56)	−1.00
J/ψ, $\psi(2S)$	7.76(12)	7.84(19)	−0.08
$[3.7, \infty)$ GeV	17.15(31)	16.95(19)	0.20
Total $a_\mu^{\text{HVP, LO}}$	694.0(1.0)$\boxed{(3.5)}$(1.6)$(0.1)_\psi(0.7)_{\text{DV+QCD}}$	692.8(2.4)	1.2

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Introduction for a_μ and a_μ^{HVP}

- **Magnetic moment for charged lepton:**
  - Definition:

$$\vec{\mu}_l = g_l\left(\frac{q_l}{2m_l}\right)$$

charge

mass

Landé splitting factor

  - With basic quantum mechanics, $g_e = 2$
    - 1928, predicted by Dirac
  - With first order correction from QED, $g_e = 2 + \alpha/\pi$
    - 1948, predicted by J. Schwinger
    - 1948, confirmed by Kusch & Foley, with Rabi's atomic beam magnetic resonance technique
  - The anomalous magnetic moment a_l:

$$a_l = \frac{g_l - 2}{2}$$