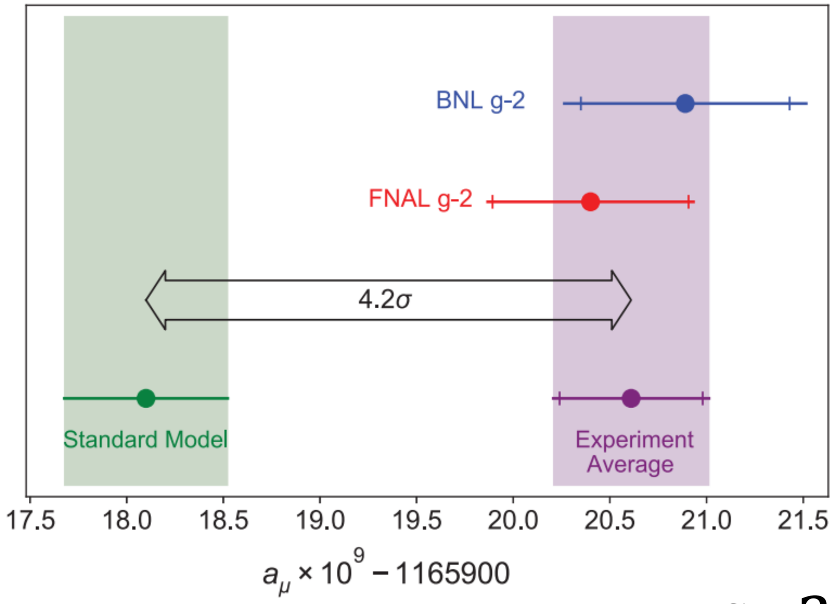
Status and plan on Hadron Vacuum Polarization (HVP) measurement at Belle II

Yuki Sue
Nagoya University
on behalf of the Belle II collaboration

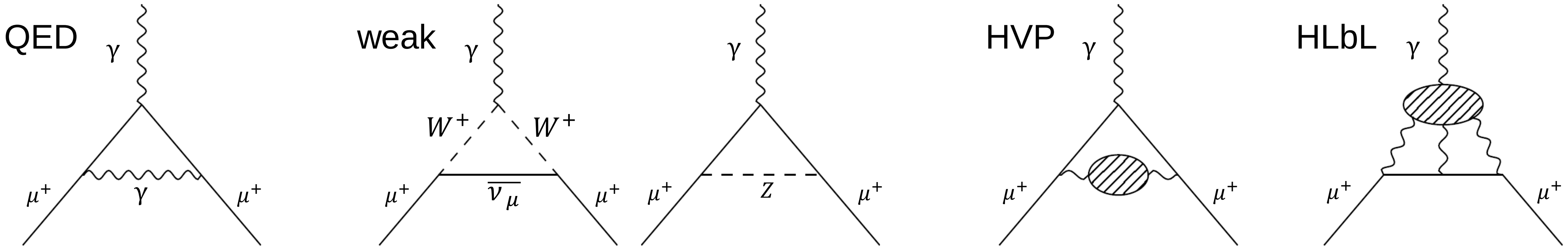
KEK Flavor Factories workshop (KEK-FF 2023), February 9th, 2023

Introduction for muon g-2



Contribution	Value $a_\mu \times 10^{11}$	Error $\delta a_\mu \times 10^{11}$
QED	116 584718.931	0.104
HVP LO (Leading-Order)	6931	40
HVP HO (Higher-Order)	-85.9	1.2
HLbL (Light-by-Light)	92	19
EW (Electroweak)	153.6	1
SM total (Dispersive)	**116591810**	**43**
Experiment (BNL+FNAL)	**116592061**	**41**
Experiment – SM	**251**	**59**

$$a_\mu^{\mathrm{SM}} = \frac{g-2}{2} = a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{weak}} + a_\mu^{\mathrm{HVP}} + a_\mu^{\mathrm{HLbL}}$$



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T. Aoyama *et al.*, Phys. Rept. 887 (2020).

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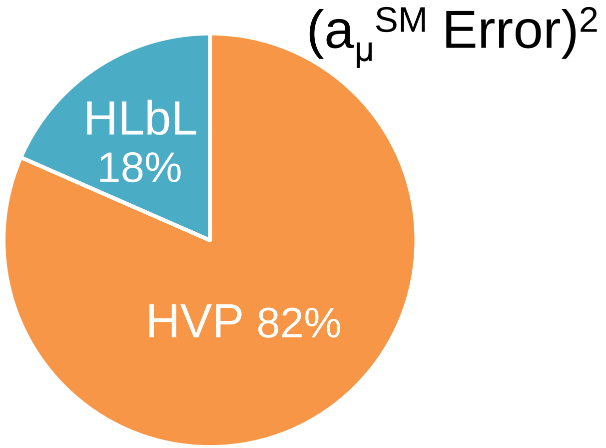

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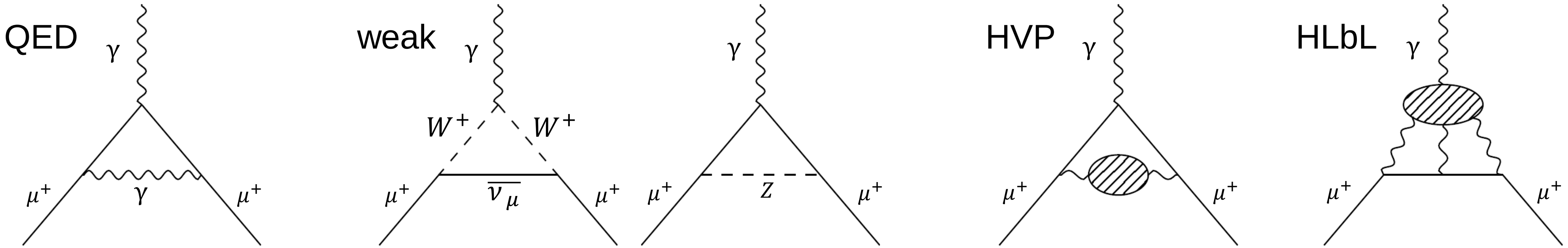

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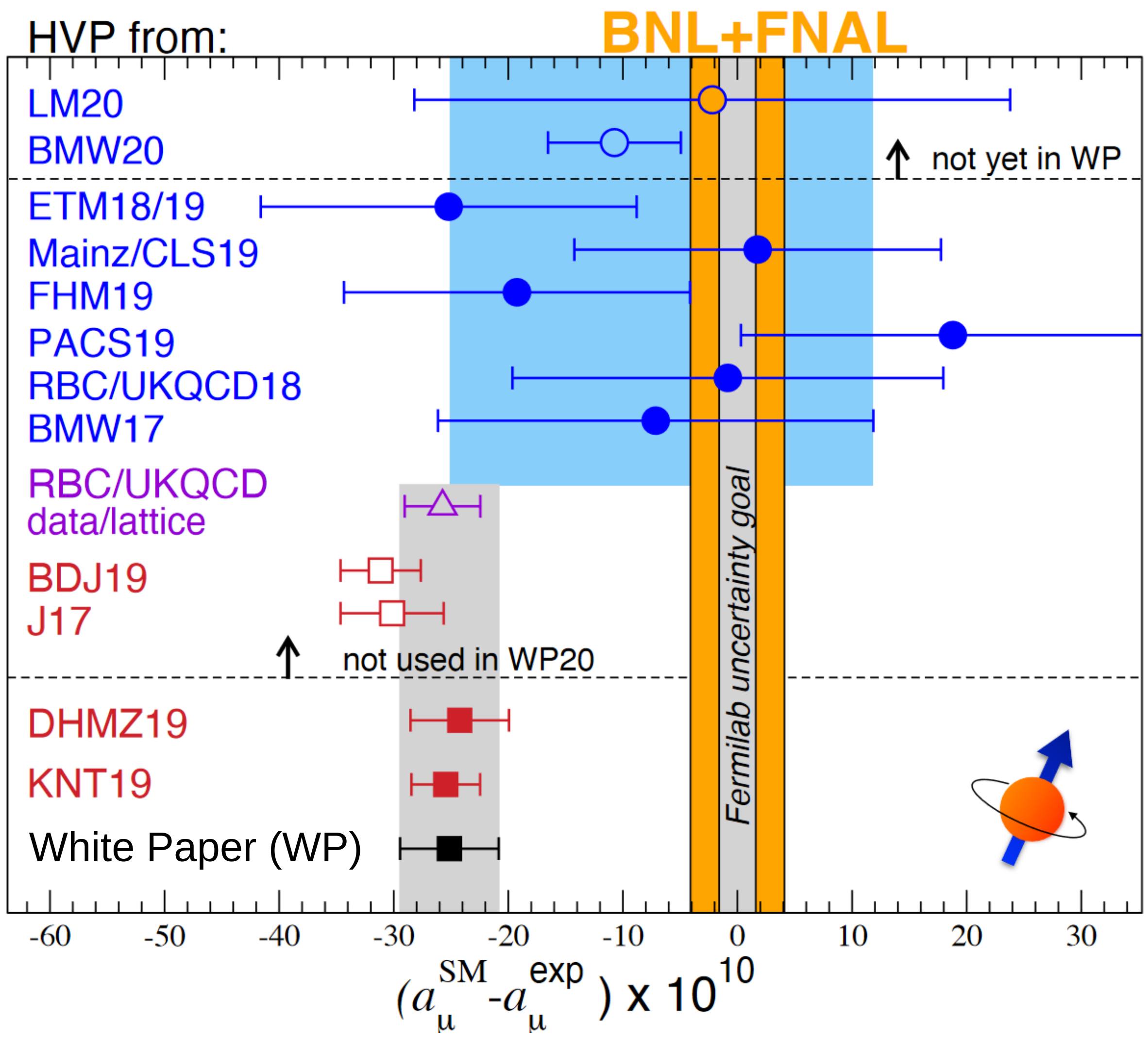
HVP contribution

G. Colangelo *et al.*, arXiv:2203.15810 [hep-ex] (2022)

Lattice QCD

Data driven (Dispersive)

MUonE experiment (In future)



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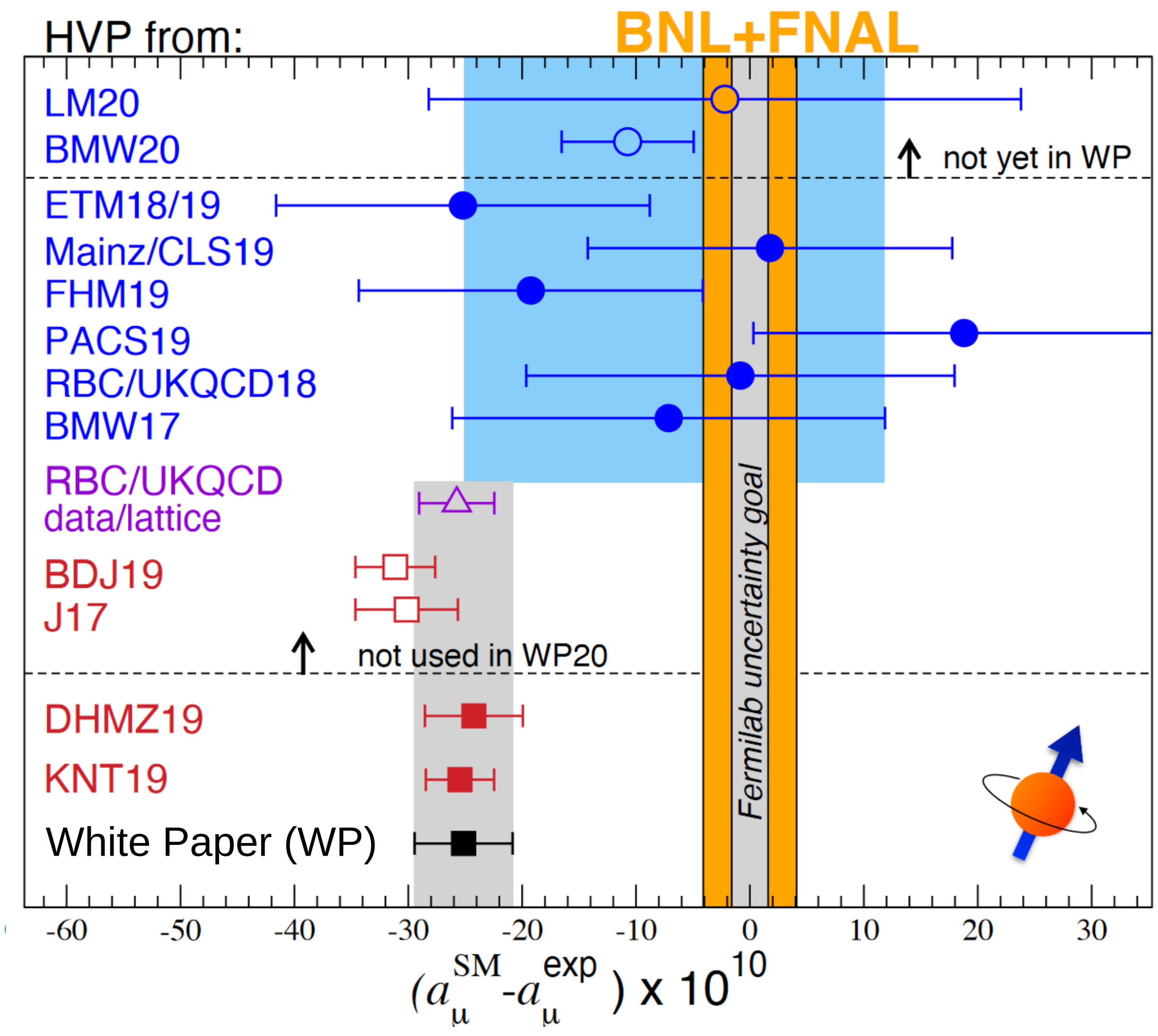
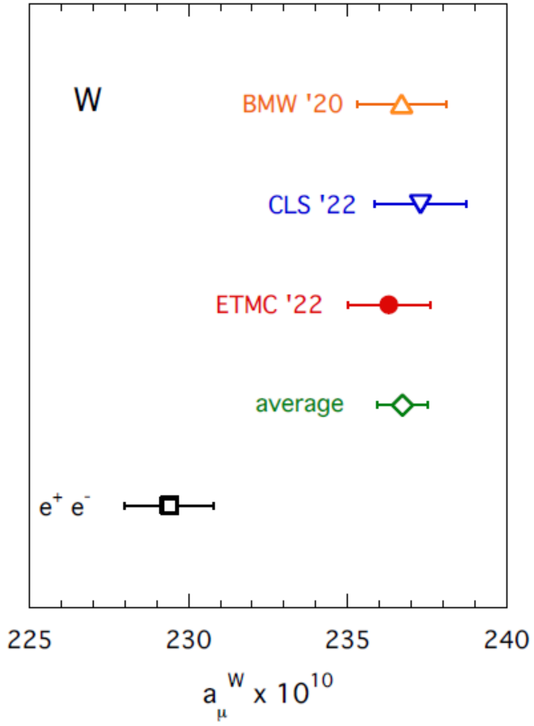


C. Alexandrou *et al.*, arXiv:2206.15084 [hep-lat] (2022)

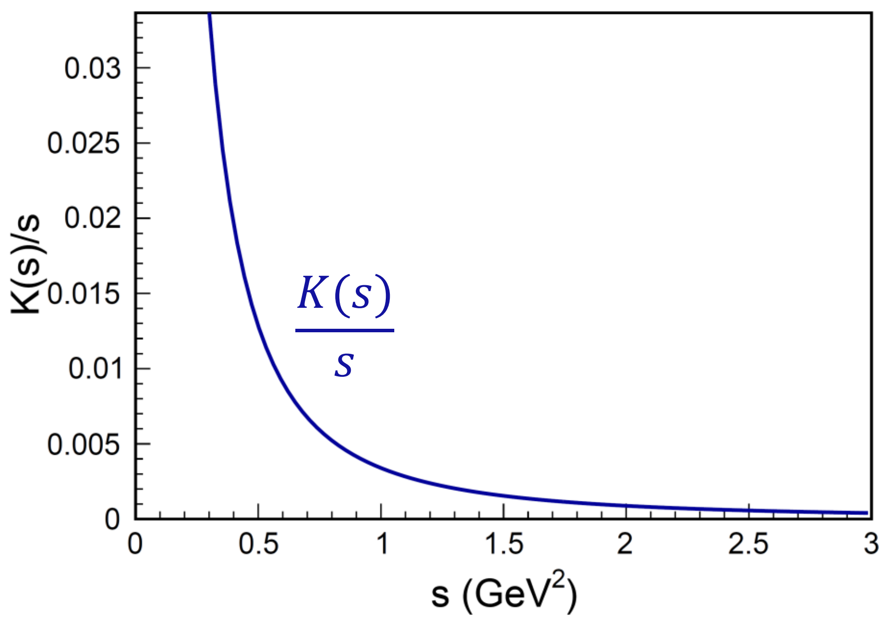


Data-driven method and R-ratio measurement

Leading order HVP contribution using dispersion relation

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

$$R(s) = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$



Kernel function

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

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

A. Keshavarzi, D. Nomura, and T. Teubner, Phys. Rev. D101, 014029 (2020).

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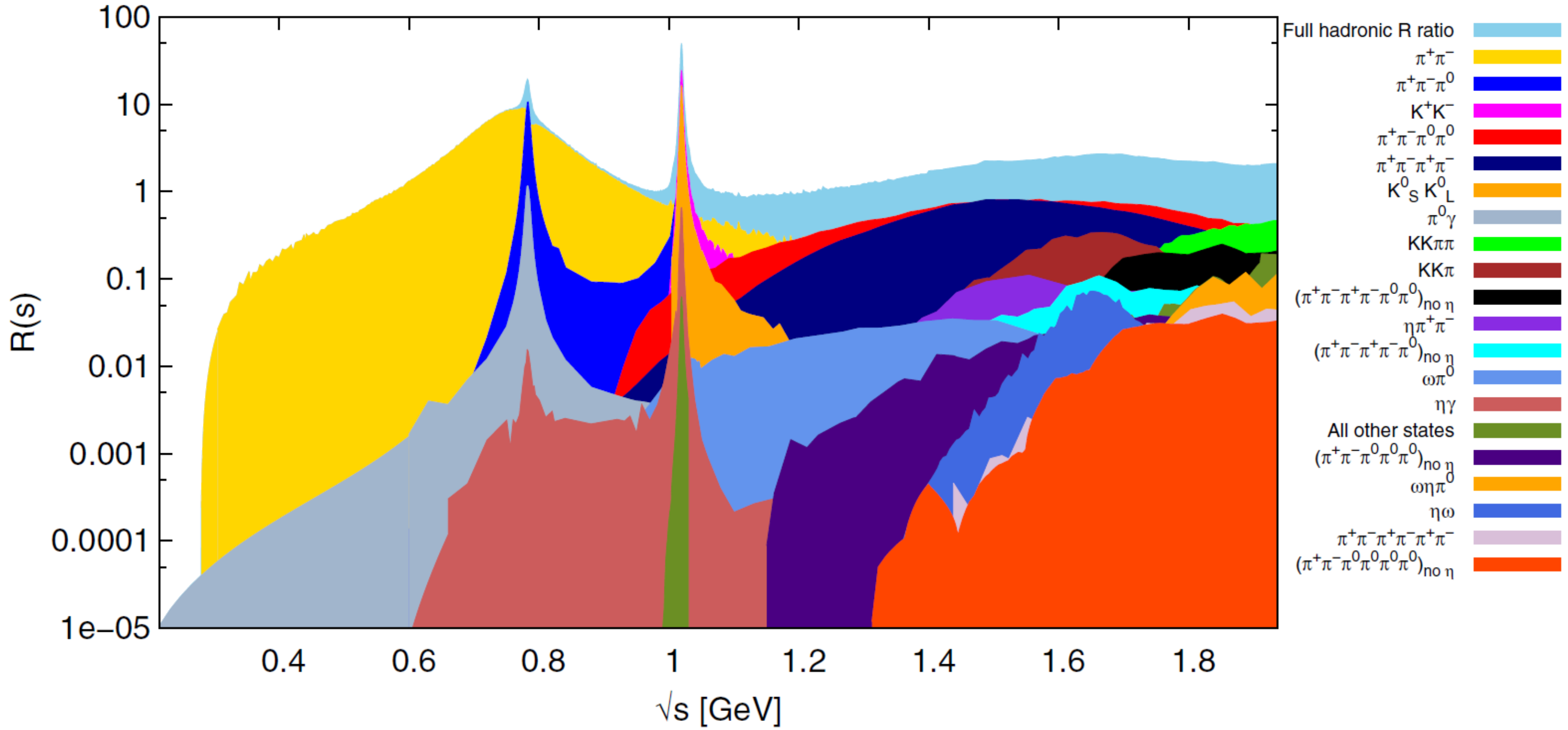

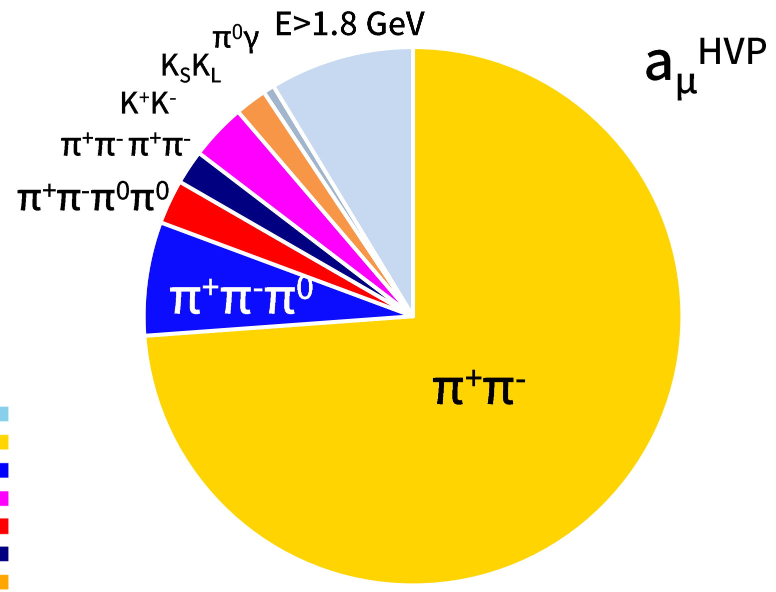

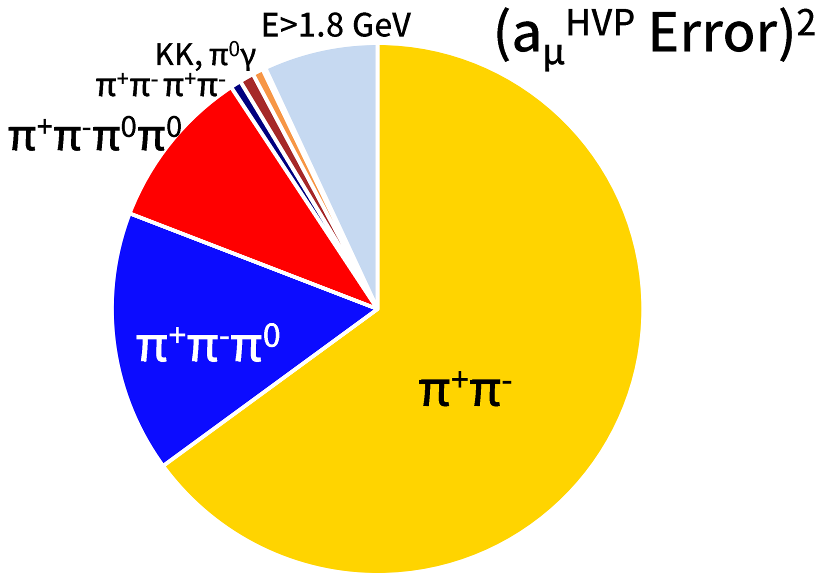

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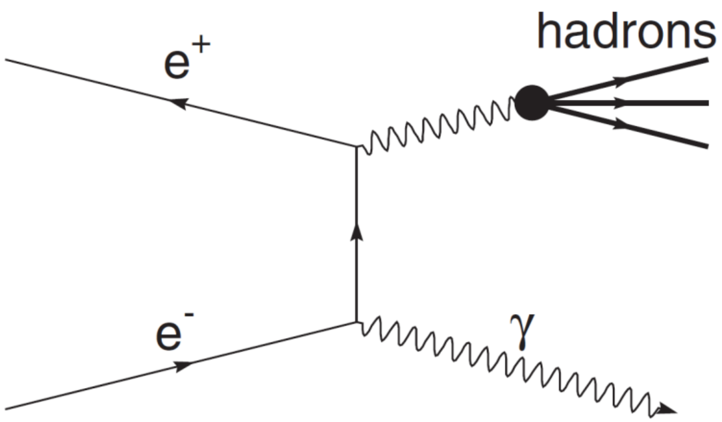
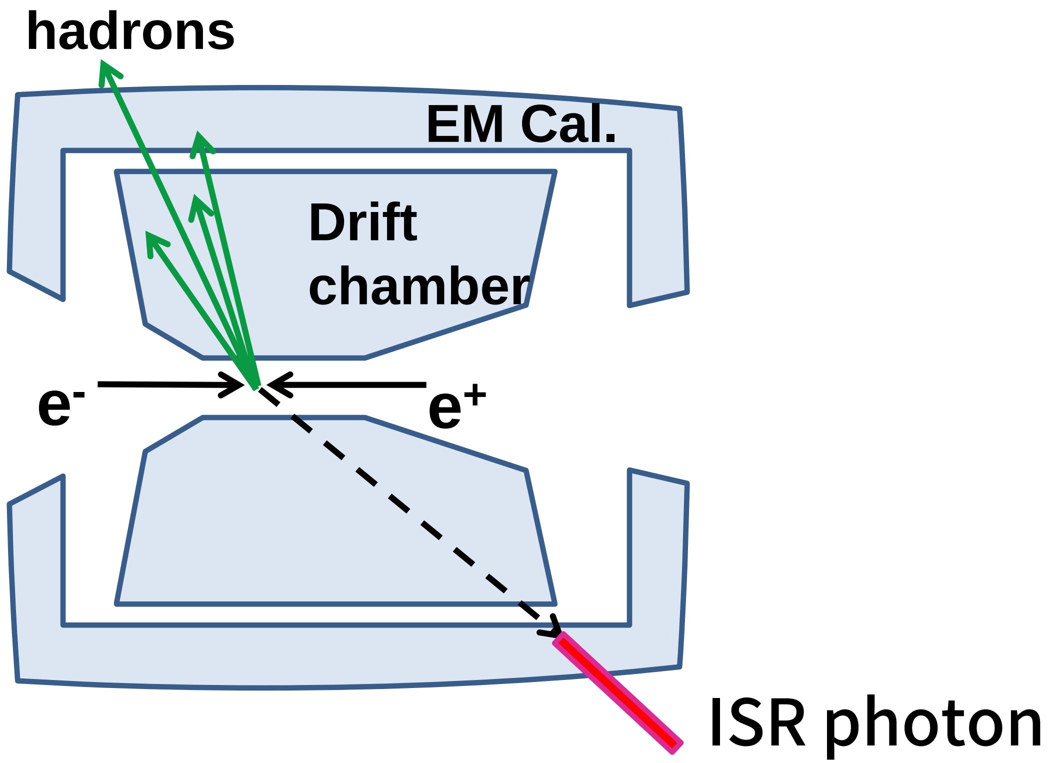
Radiative return method

- Radiative return : BaBar, KLOE, BESIII (↔ Direct scan : e.g. Novosibirsk)
  - Scan the energy of hadronic system at fixed energy using ISR.
  - Access to the entire hadronic mass range with single dataset
  - Boosted final hadrons

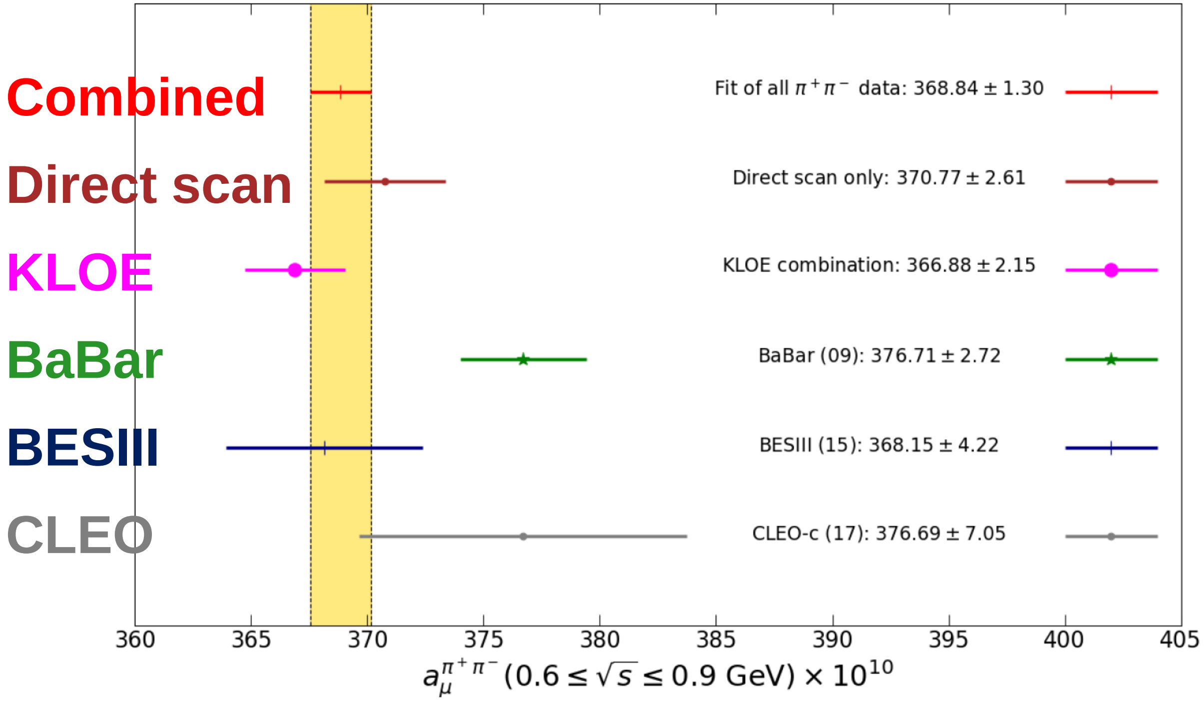


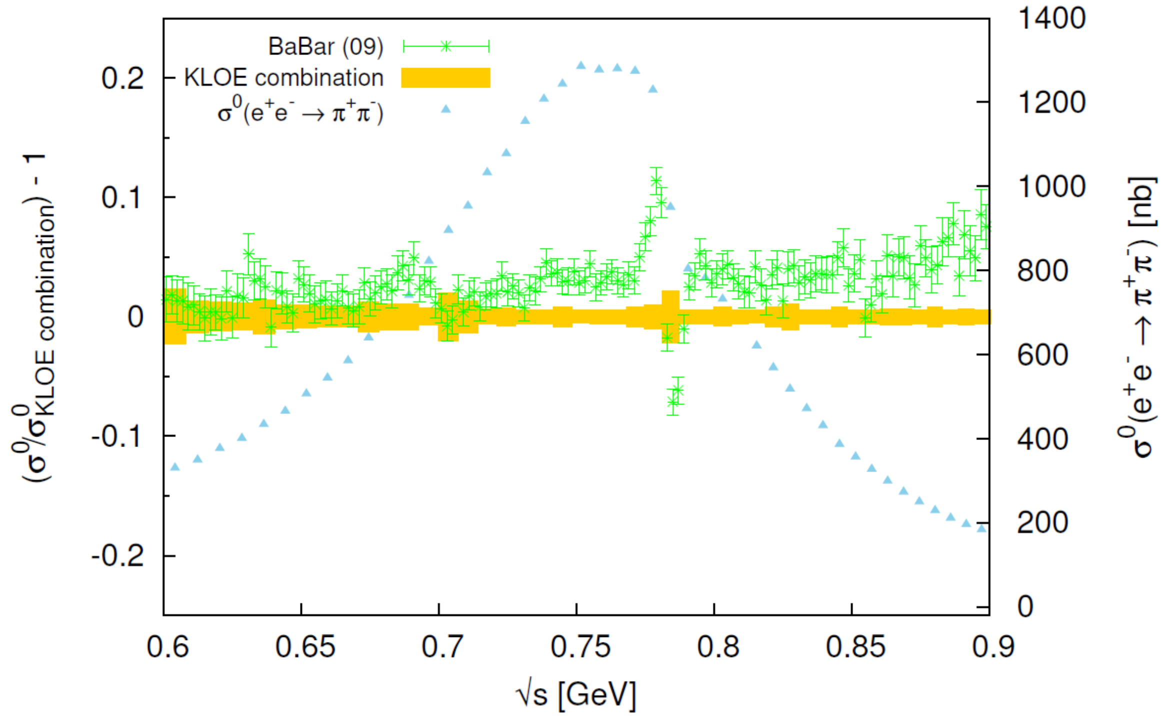
Energetic ISR photon



Present experimental status : $e^+e^-\to\pi^+\pi^-$

- $e^+e^-\to\pi^+\pi^-$ channel is the largest contribution and uncertainty.
- Already measured by several experiments with $\lesssim$ 1% precision.
- Small discrepancy among measurements.





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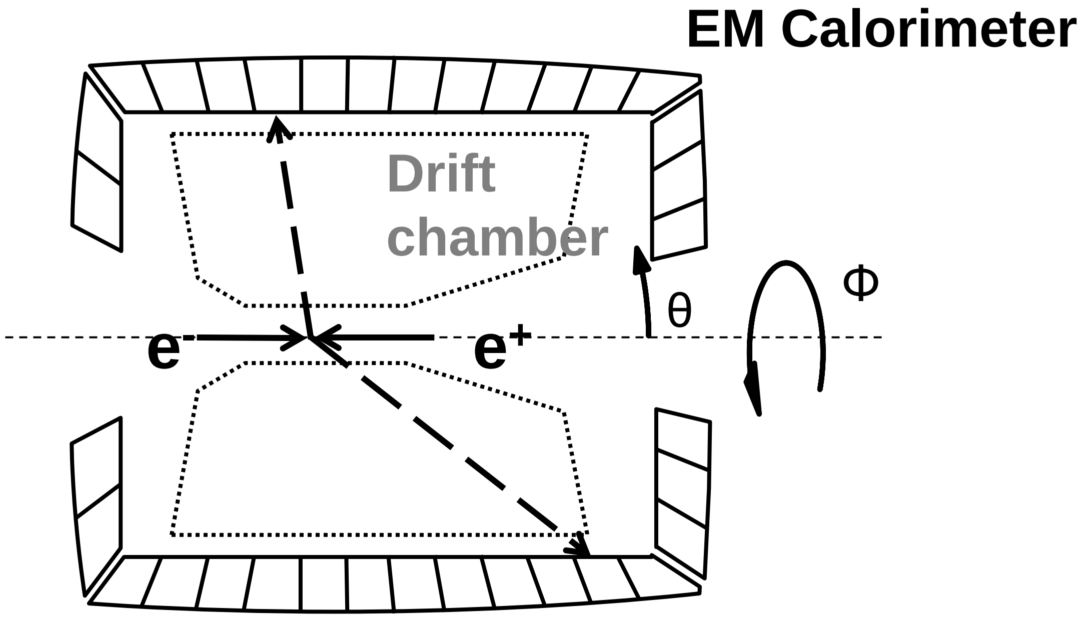
A. Anastasi et al. (KLOE-2), JHEP 03, 173 (2018).

Trigger challenge at Belle II

- Light hadron cross section measurement at BELLE was suffered from the trigger efficiency.
  - The measurement for $\sigma(e^+e^- \rightarrow \pi^+\pi^-\pi^0)$ was attempted, but could not be published.
    [J. Crnkovic, PhD thesis, Illinois U. (2013)]
- Bhabha veto has been upgraded to avoid the inefficiency and uncertainty.
  - BELLE bhabha veto was based on only θ angle.
  - Belle II 3D bhabha veto uses θ and Φ angle.
- The trigger efficiency of EM Calorimeter triggers for energetic ISR can be measured by making the orthogonal tracking trigger a reference.



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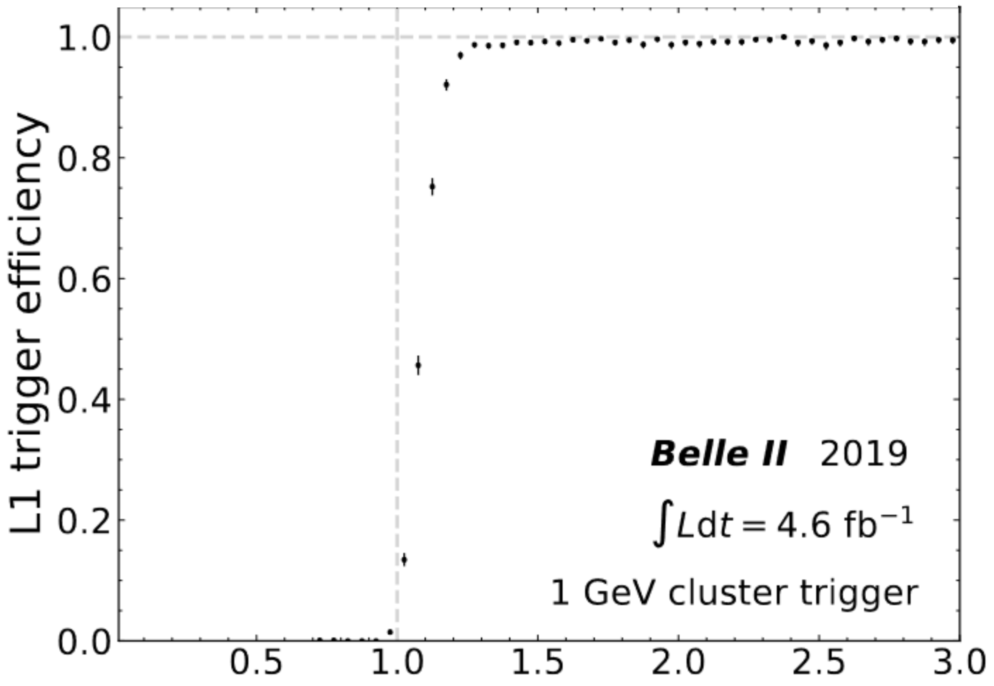
  - BELLE bhabha veto was based on only θ angle.
  - Belle II 3D bhabha veto uses θ and Φ angle.
- The trigger efficiency of EM Calorimeter triggers for energetic ISR can be measured by making the orthogonal tracking trigger a reference.
  - Efficiency for energetic ISR > 99%
  - Event loss due to 3D bhabha veto is suppressed in μμγ.
- The high trigger efficiency for energetic ISR is beneficial for most light hadron cross section measurements in the radiative return method.

Belle II trigger efficiency for μμγ (data)



CMS ISR Energy (GeV)

$e^+e^-\to\pi^+\pi^-$: Status at Belle II

- Target precision : 0.5% of $a_\mu(2\pi)$
- Trying to follow BaBar methods as a base line.
- Systematics uncertainty dominant analysis
  - BaBar : 232 /fb [Phys. Rev. D 86 (2012), 032013]
  - We can use large statistics to control systematic uncertainties.
- Implementation of kinematic fitting tools
  - Useful for reducing background and correction for tracking efficiency.
  - Implementation of basic fitter has been completed.
- Sanity check on signal generator and background MC using < 2 fb^{-1} data .
- Design of data-driven efficiency corrections for tracking, trigger and π/μ/K ID is ongoing.

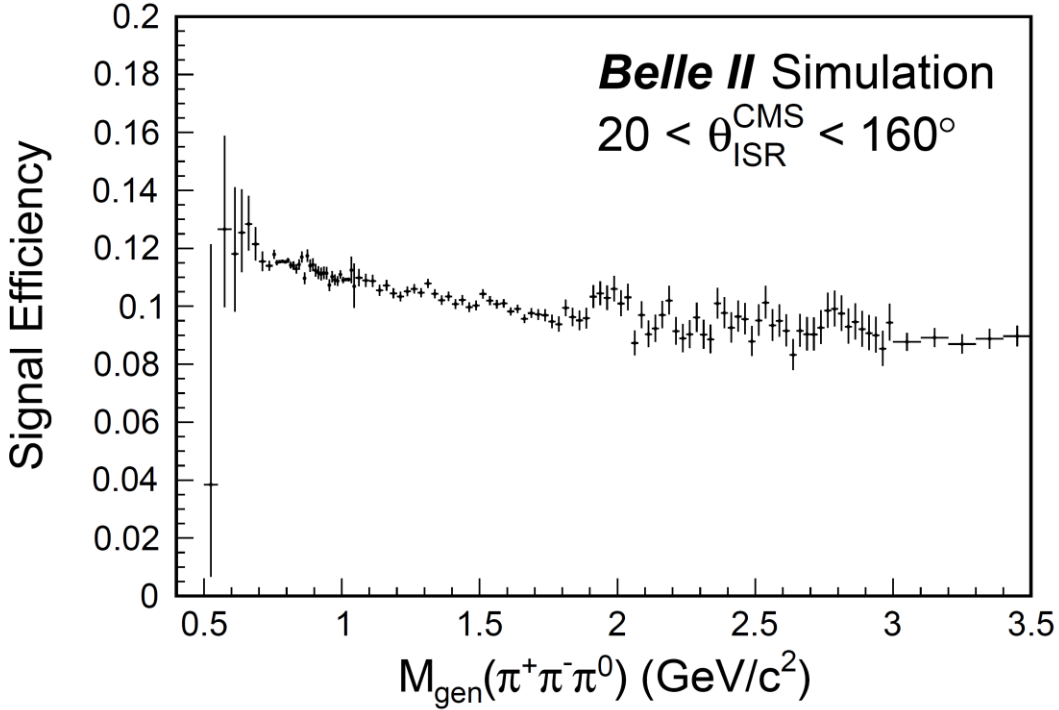
$ee\to\pi\pi$ uncertainty (10^{-3}) at BaBar

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

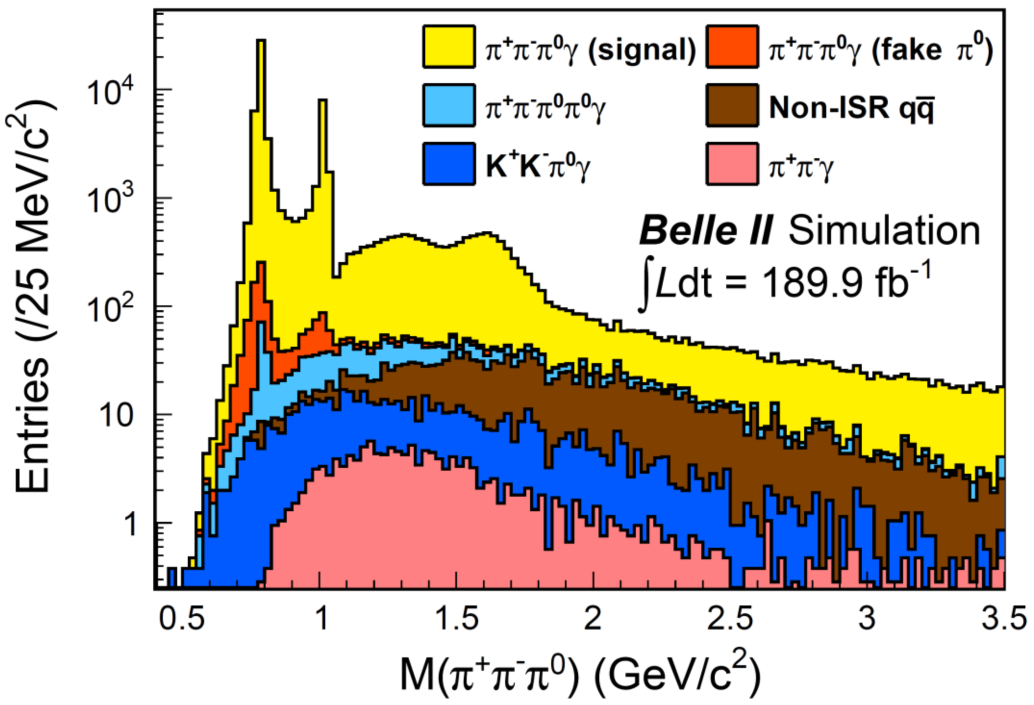
$e^+e^-\rightarrow\pi^+\pi^-\pi^0$ at Belle II

- $e^+e^-\rightarrow\pi^+\pi^-\pi^0$ channel is the 2nd largest contribution to HVP term.
- Aim ~2% precision measurement using 190 fb^{-1} data
- Most analysis methods are fixed and are in final confirmation with 10% data

Signal Efficiency



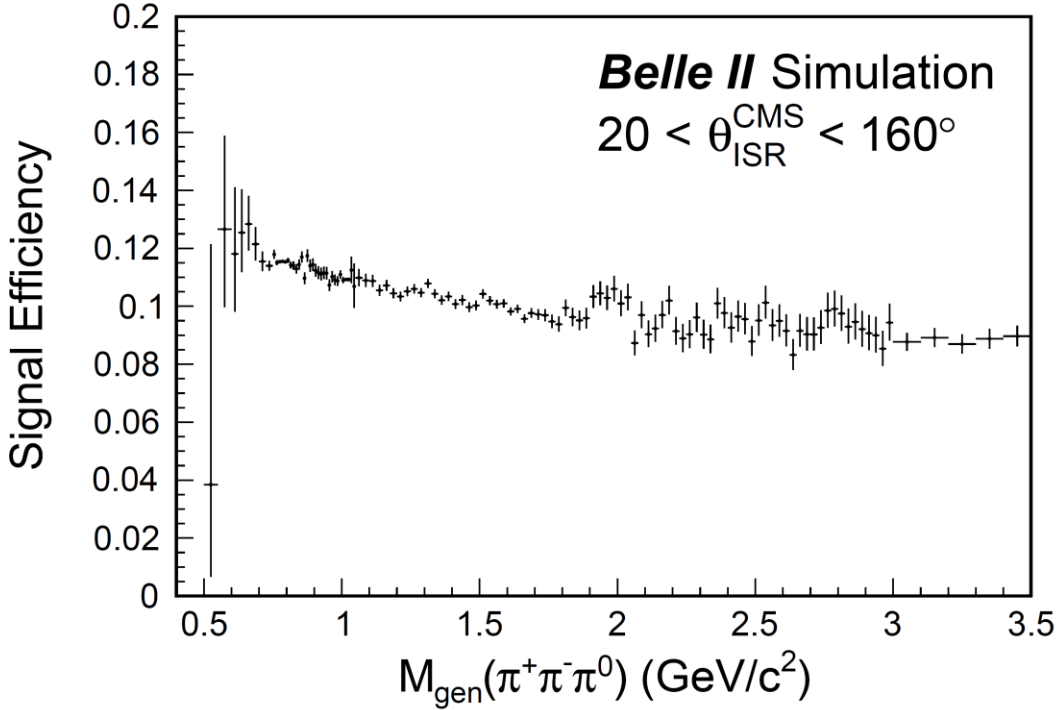
M(3π) distribution after selection (MC)



$e^+e^- \to \pi^+\pi^-\pi^0$ at Belle II

- Selection : two charged tracks + three photon
  - Use kinematic fit χ^2 probability to select events consistent with signal topology
  - Prioritising the reduction of systematic errors.
- Signal efficiency of ~10% is expected.
- Main remaining background : π^0 combinatorial, $\pi^+\pi^-\pi^0\pi^0\gamma$, non-ISR qqbar
- MC study using 10 times more than data.

Signal Efficiency



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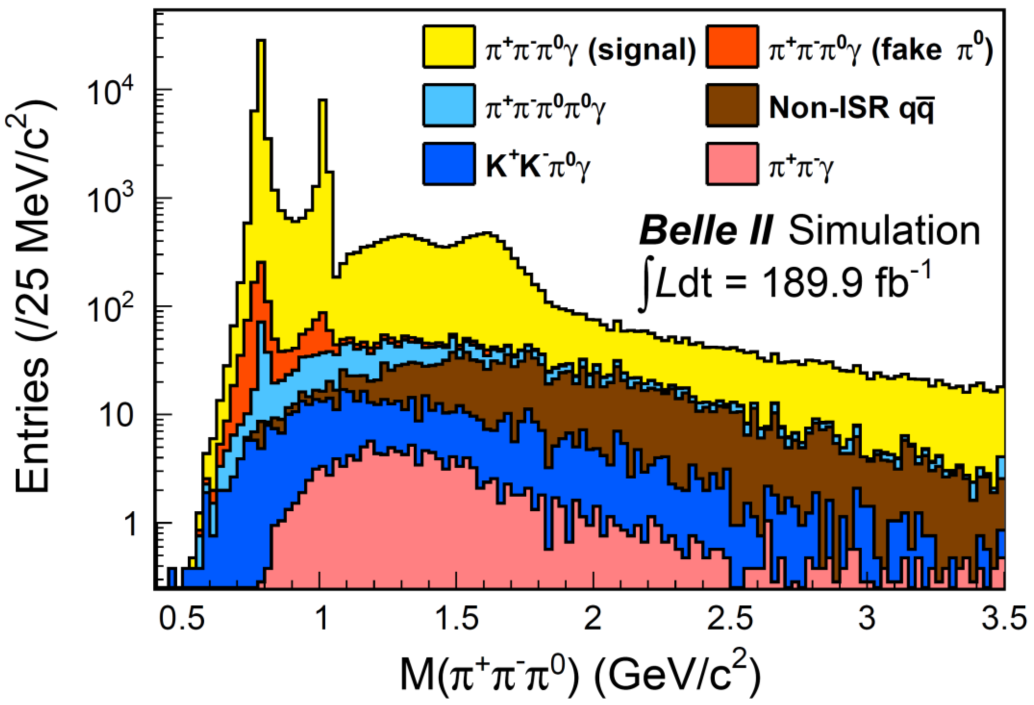
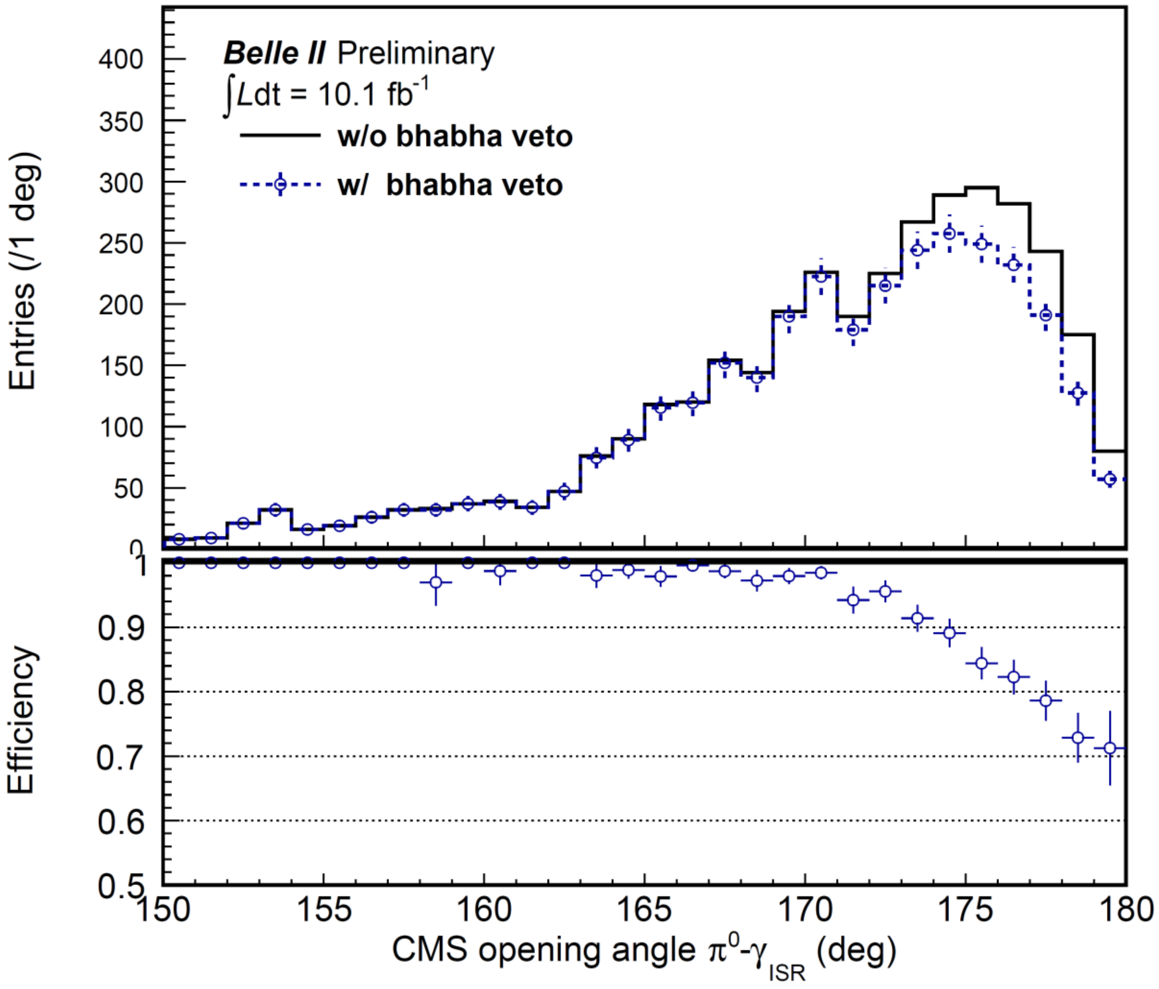


$e^+e^- \to \pi^+\pi^-\pi^0$: Efficiency correction

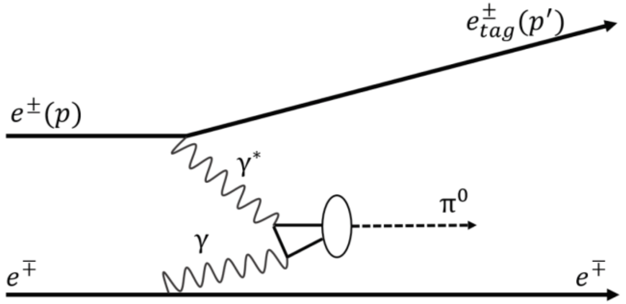
- Photon, tracking and trigger efficiency are confirmed.
- The additional data-driven corrections being evaluated: π^0 efficiency, correlated tracking inefficiency, and background rejection criteria.
- Study for trigger bhabha veto :
  - For ee->$\pi^+\pi^-\pi^0$ high energy π^0->γγ emitted back-to-back to ISR induces 10-15% loss.
  - Almost half of the data affected
    - 100 /fb : without Bhabha veto
    - 90 /fb : with Bhabha veto

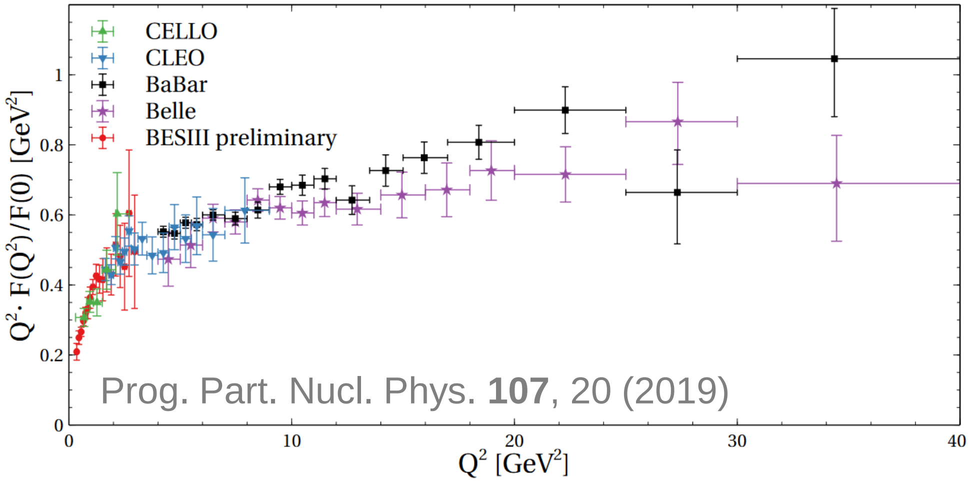


Other channels

Ongoing channels :

- $\gamma\gamma^* \to \pi^0$ (Not HVP but Hadron Light-by-Light contribution)
  - Preliminary check using 12 /fb data is done.
  - Further analysis is underway for results using larger dataset.

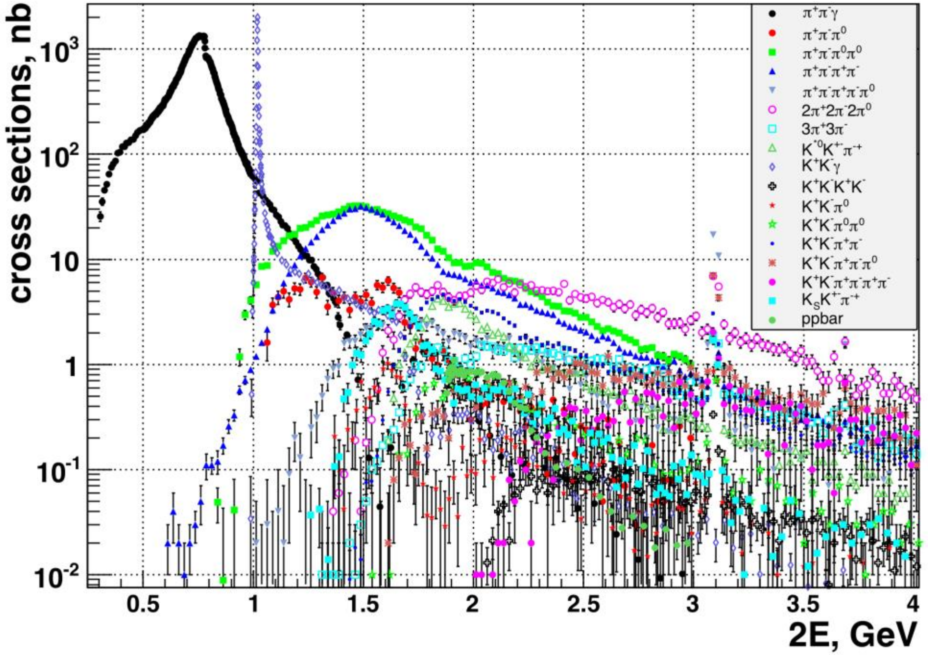




Further final states can be explored.

- >20 exclusive channels were studied in the BABAR.
  - $\pi^+\pi^-$, $\pi^+\pi^-\pi^0$, $\pi^+\pi^-\pi^0\pi^0$, $\pi^+\pi^-\pi^+\pi^-$, $2\pi^+2\pi^-2\pi^0$, $3\pi^+3\pi^-$, $K^+K^-\pi^0$, $K^0K^\pm\pi^\mp$, K^+K^-, $K^+K^-K^+K^-$, $K^+K^-\pi^0\pi^0$, pp…
- Trigger upgrade allows us to measure other final states.

Measured cross sections at BaBar



Conclusion

- The light hadron cross section is important in the data-driven method for calculating the HVP contribution of muon g-2.
- The trigger upgrade provides us very good efficiency for the cross section measurement.
- Analysis relating to muon g-2 are active and in progress.
  - $\pi^+\pi^-$
    - Aim high precision measurement of 0.5%.
    - A methodology based on the BABAR is being established.
    - Focusing on data/MC sanity checks using tiny data of less than 2/fb.
  - $\pi^+\pi^-\pi^0$
    - Aim to release result with ~2% precision using 190/fb data.
    - Most analysis methods are fixed and are in final confirmation with 10% of the data.
  - $\gamma\gamma^* \rightarrow \pi^0$
    - Preliminary check using 12 /fb data is done.
    - Further analysis is underway for results using larger dataset.
- Further channel analysis can be expected in the future.