Status and prospect of R measurements at Belle II

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Nagoya University

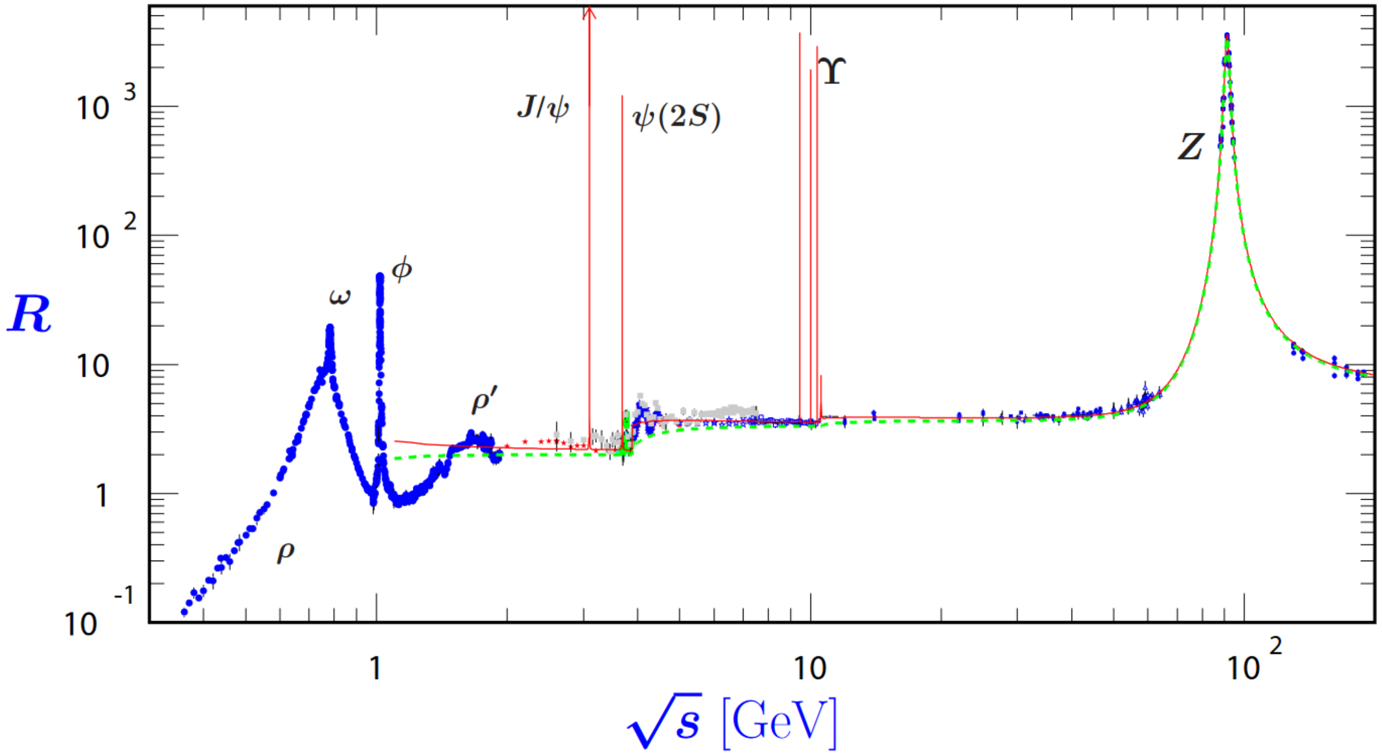
B1 Heavy Flavor and Dark Matter Joint Unit Symposium, March 29th, 2023

Hadronic cross section measurement

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

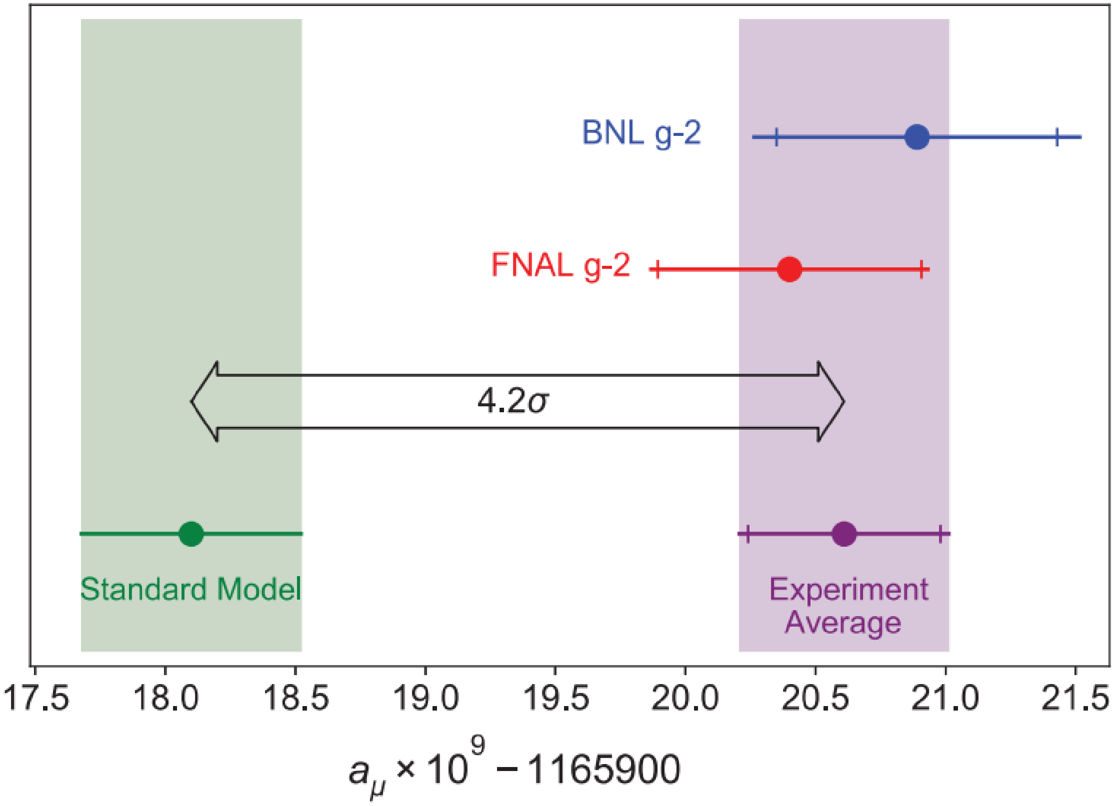
- The hadronic cross section data, R-ratio, is crucial inputs to the QCD physics.

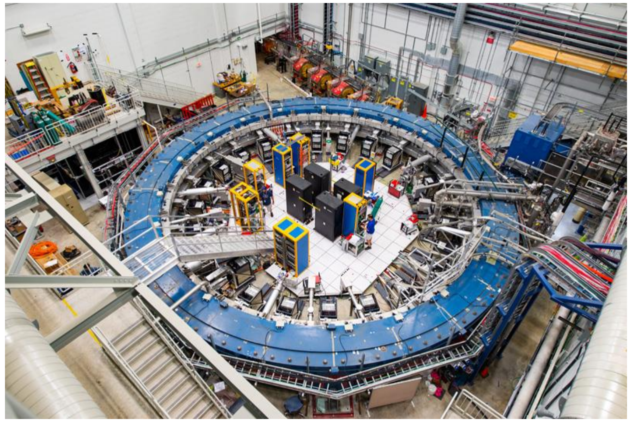
→ Tests of perturbative QCD, light vector mesons parameters, hadronic corrections to $\alpha(M_Z^2)$, muon g-2, …



Introduction for muon g-2

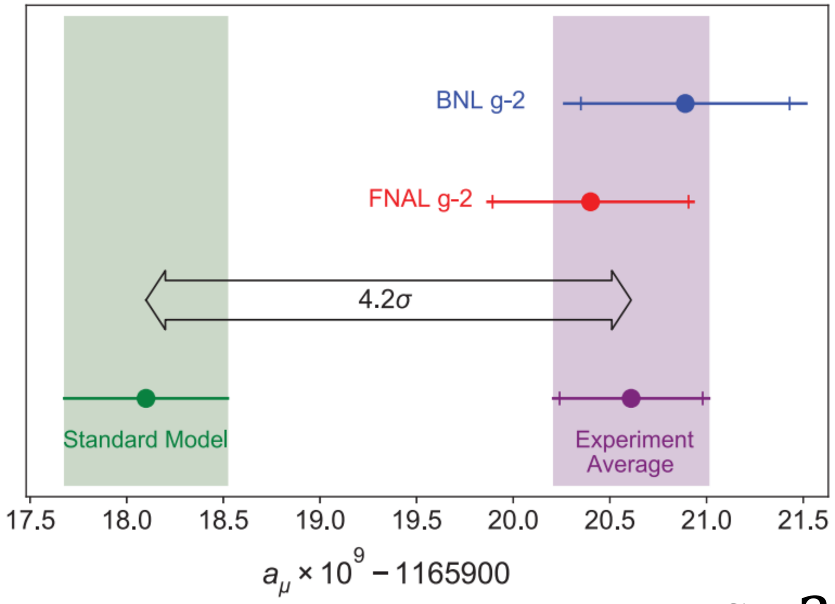
B. Abi *et al*,, PRL126, 141801 (2021).
T. Aoyama *et al.*, Phys. Rept. 887 (2020).





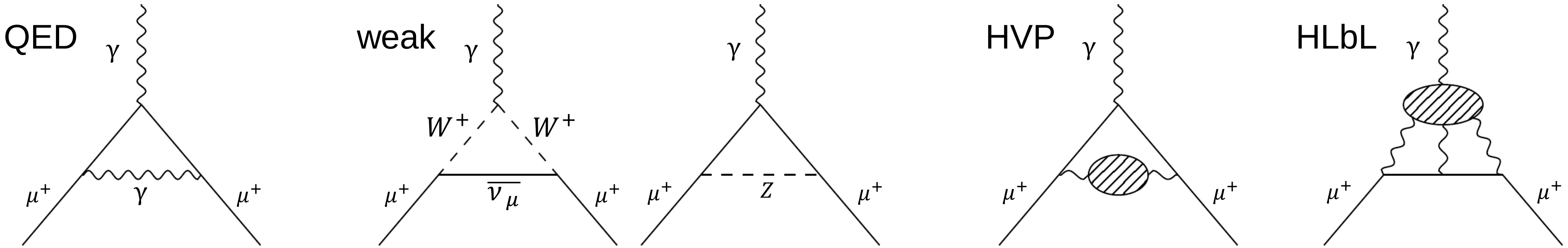
Muon anomalous magnetic moment $a_\mu = \frac{g_\mu - 2}{2}$

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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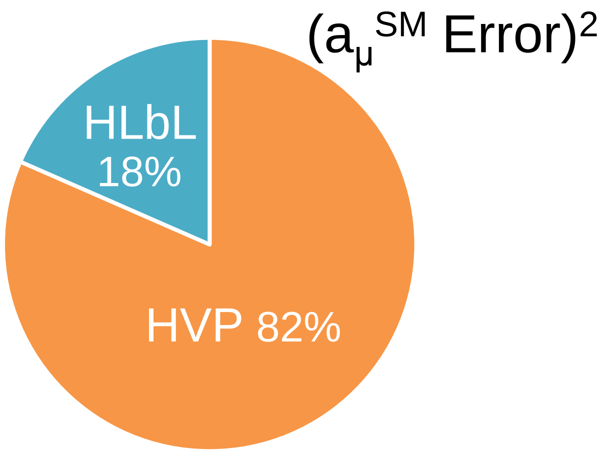

$(a_\mu^{\mathrm{SM}}\ \mathrm{Error})^2$

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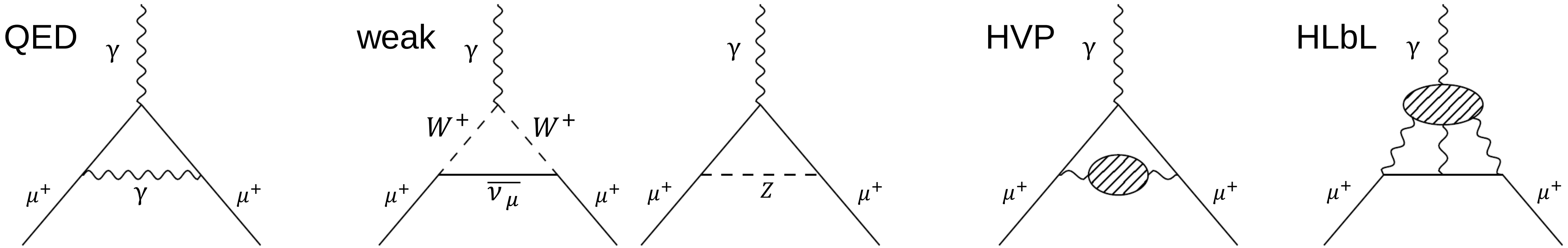

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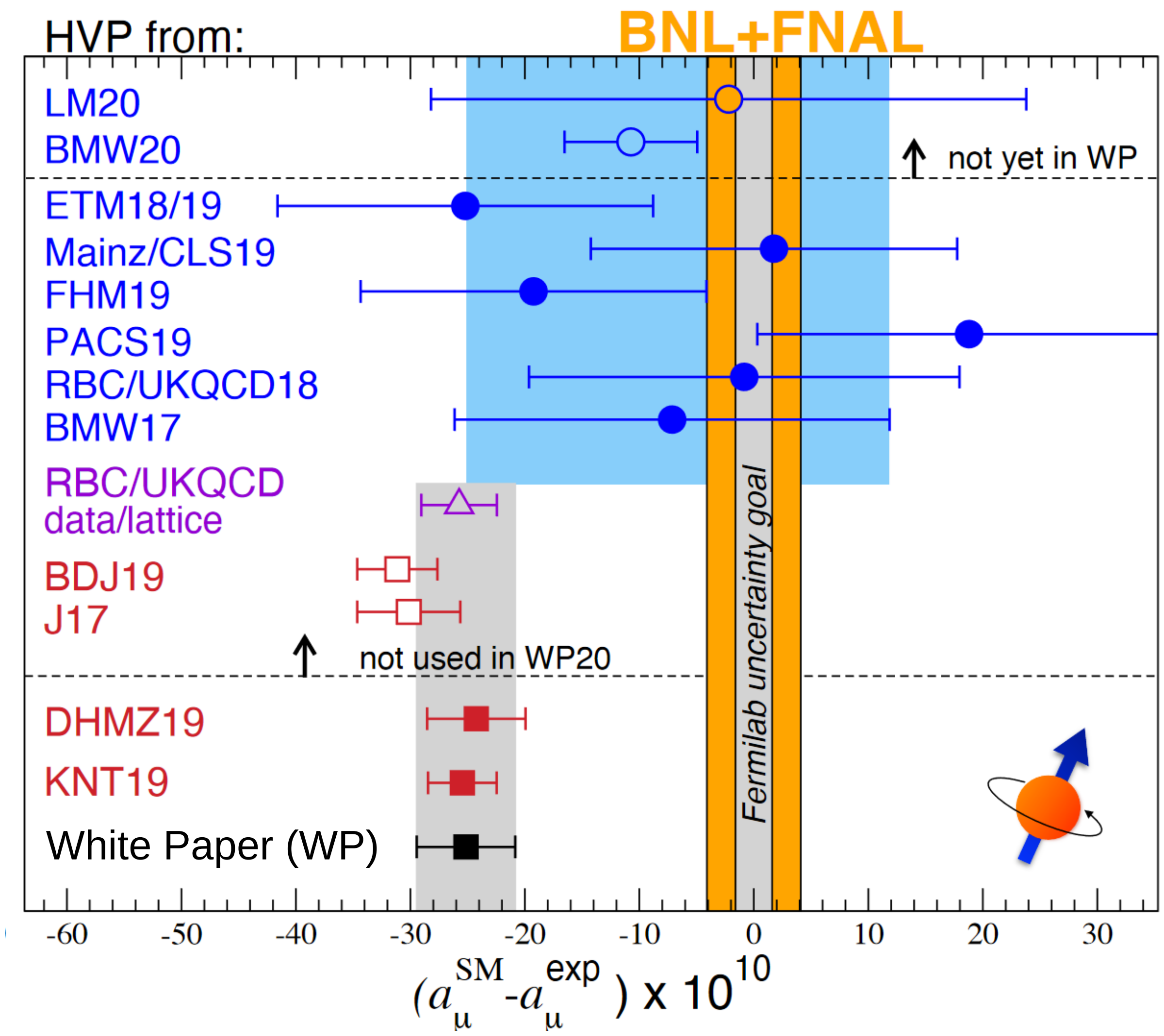
Hadron vacuum polarization (HVP) contribution

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



Lattice QCD

Data driven
(Dispersive)

MUonE experiment
(In future)

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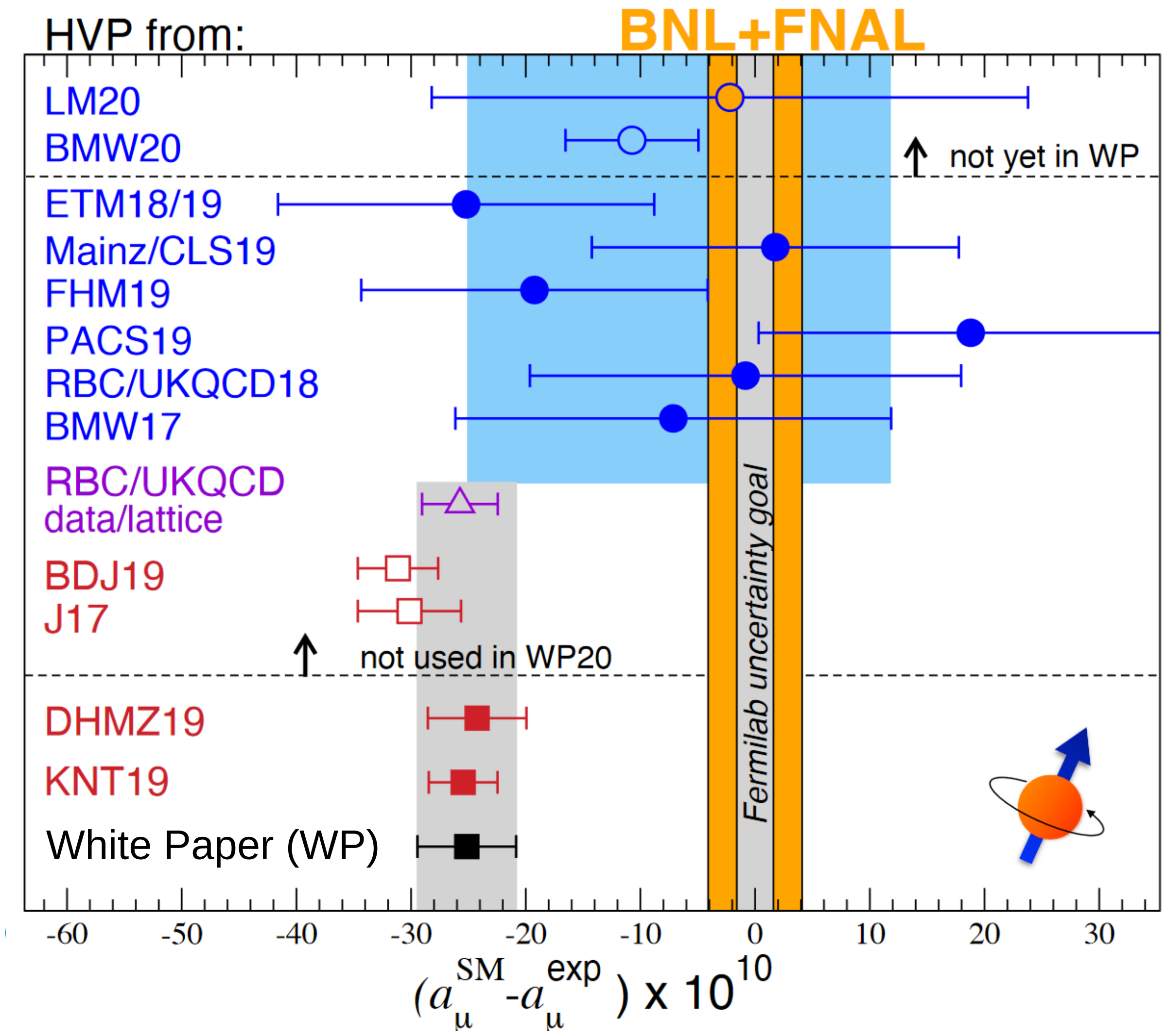
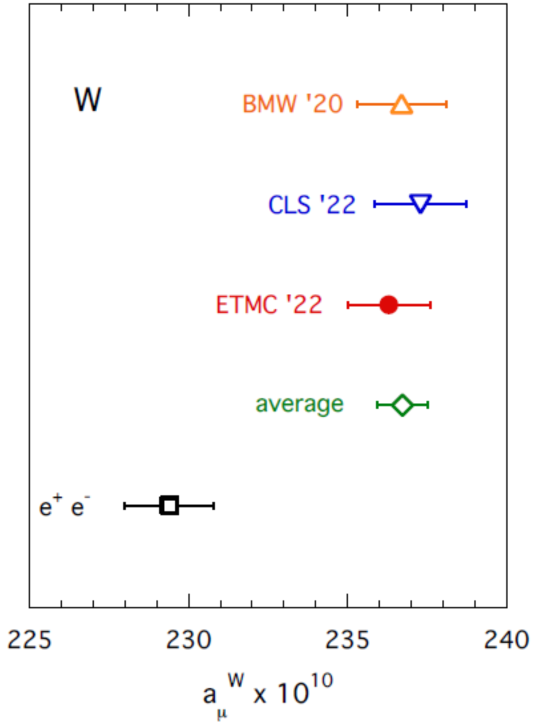


C. Alexandrou *et al.*, arXiv:2206.15084 [hep-lat] (2022)

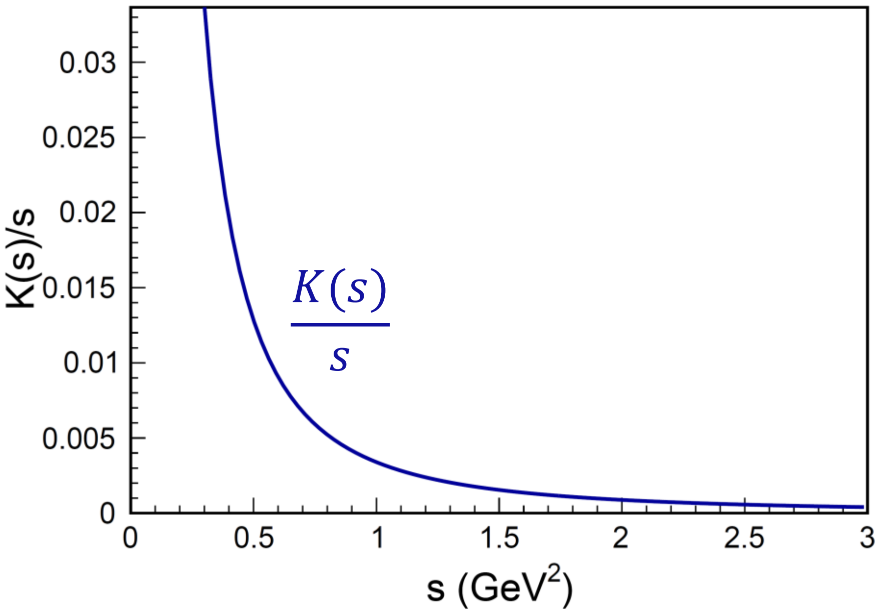


Data-driven method and R measurement

Leading order HVP contribution using dispersion relation

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

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



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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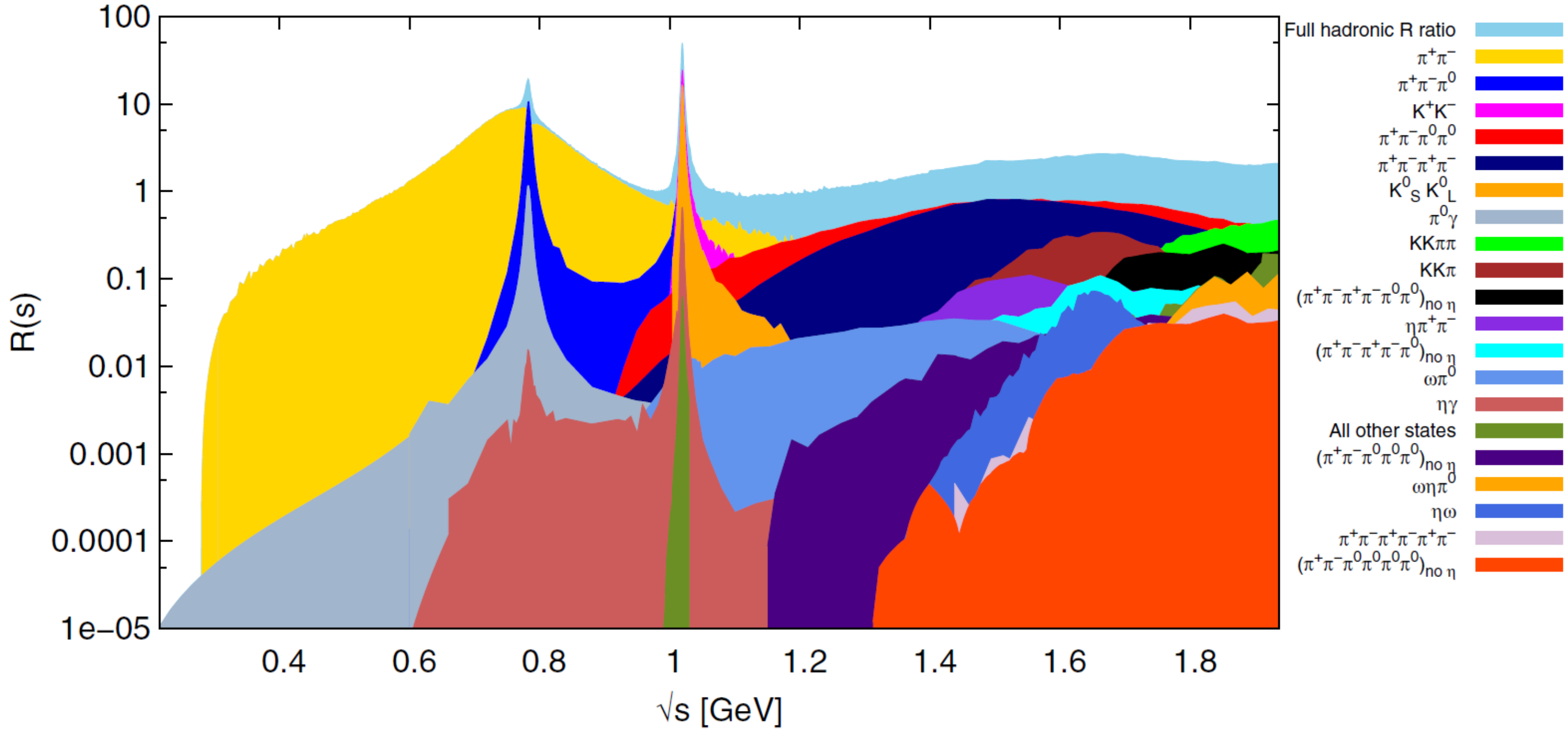

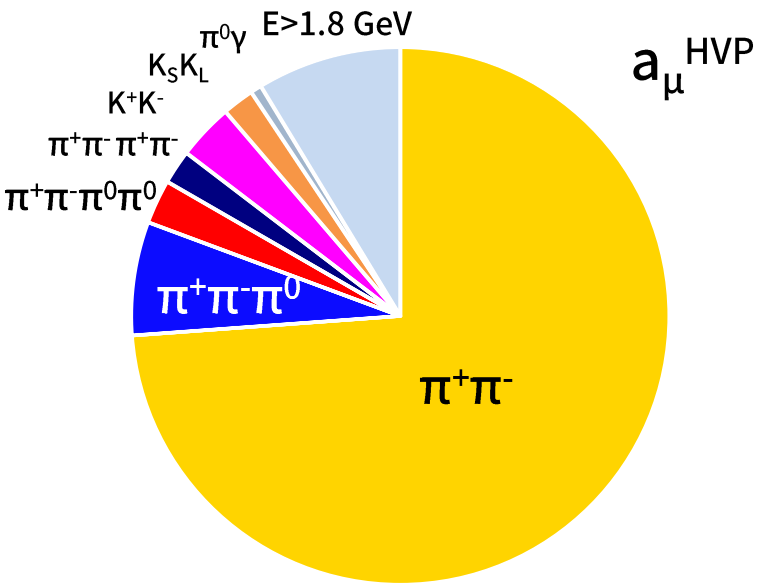

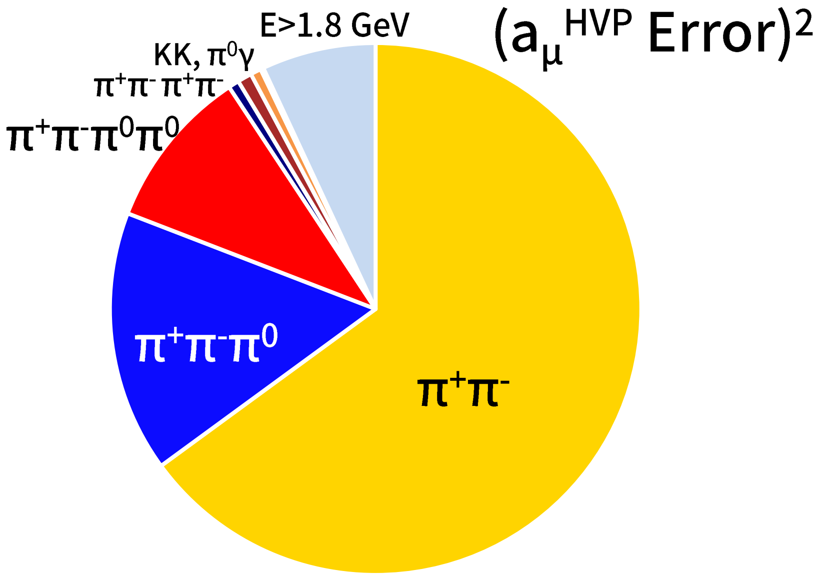

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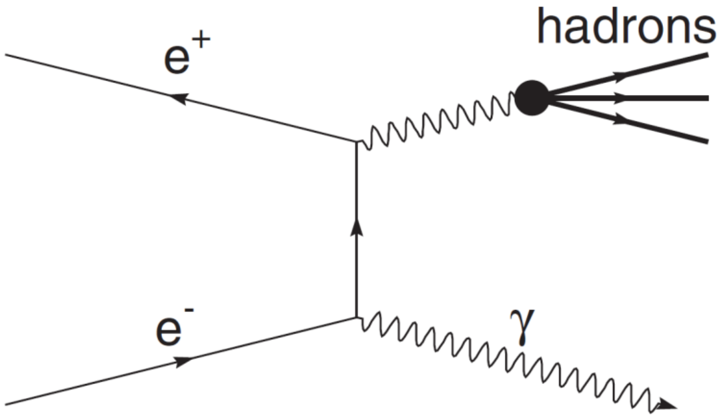
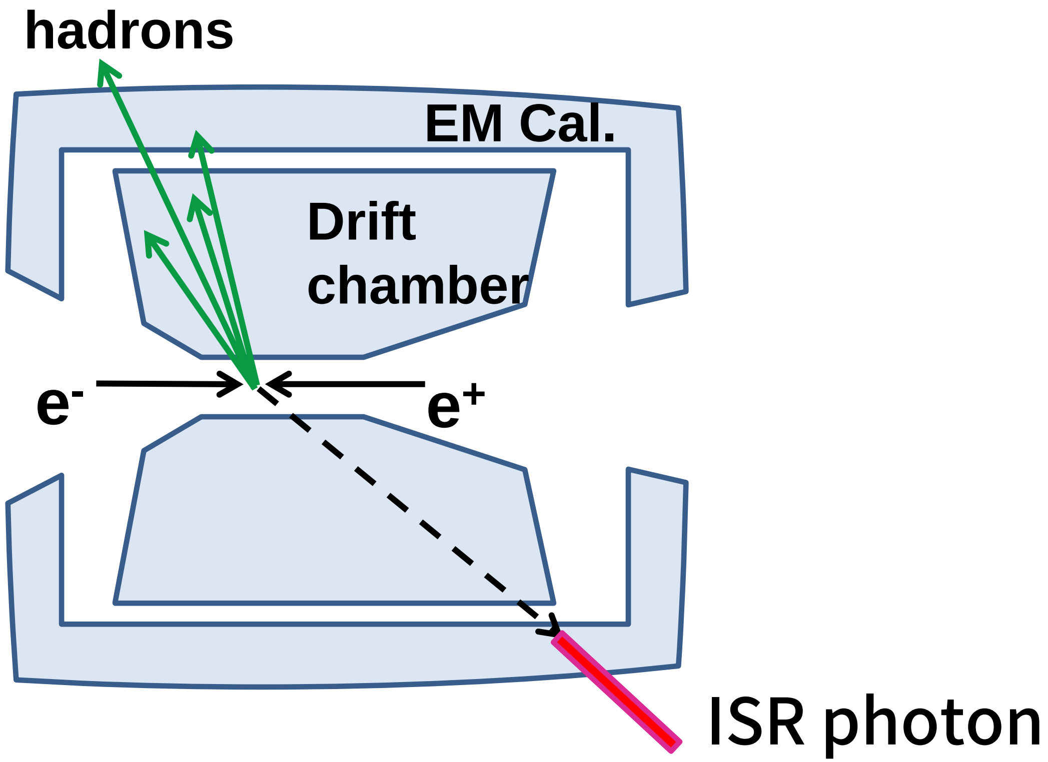
Radiative return method

- 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

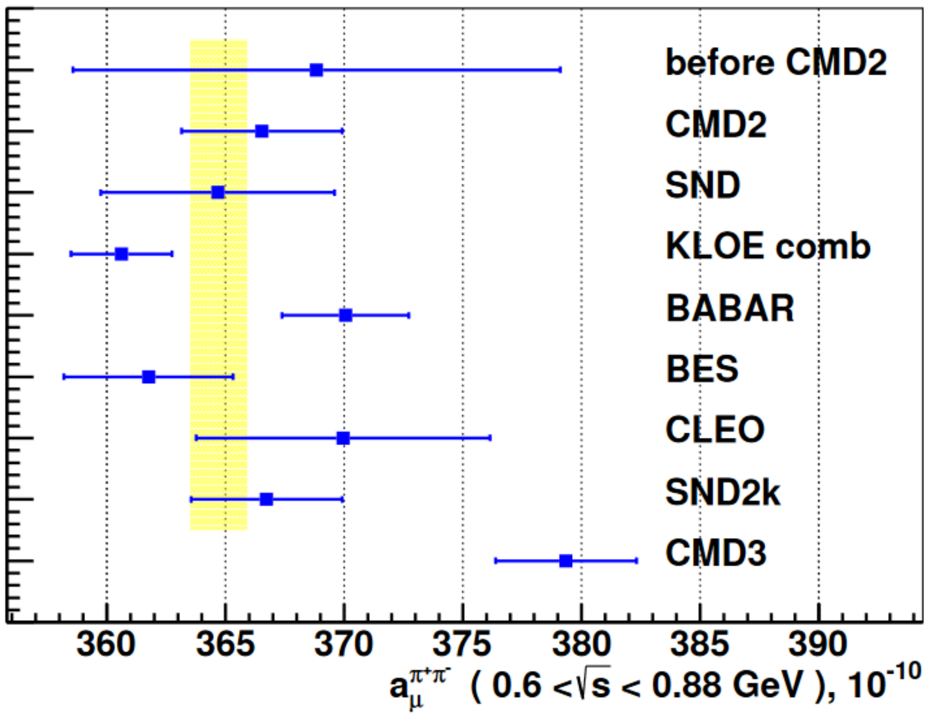


Present experimental status : $e^+e^- \to \pi^+\pi^-$

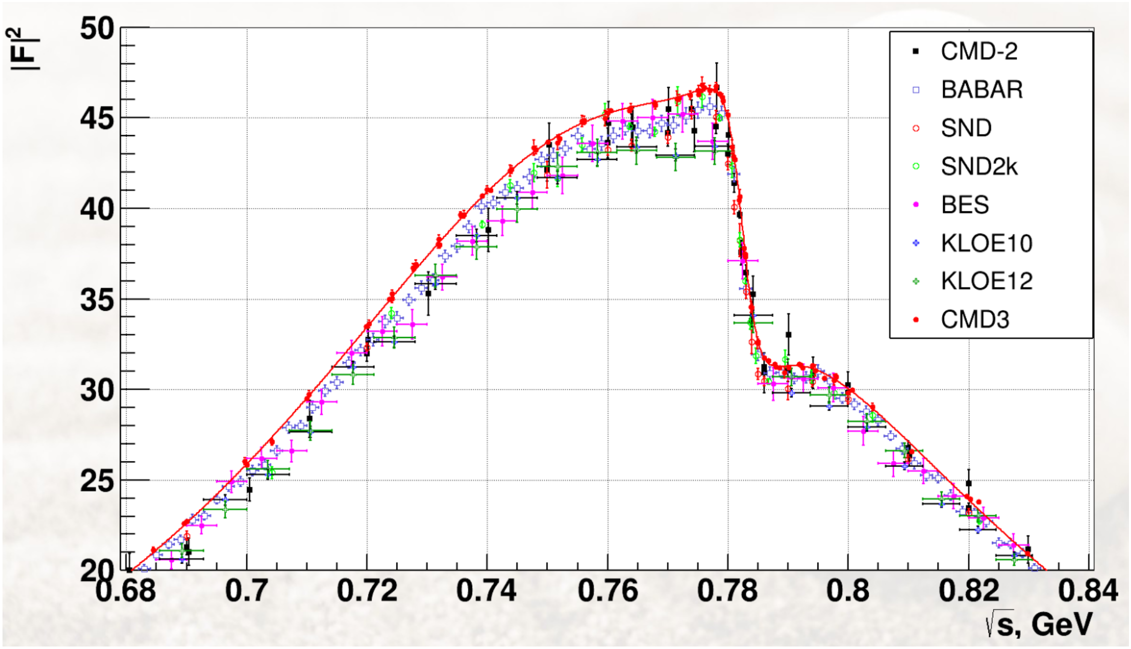
- $e^+e^- \to \pi^+\pi^-$ channel is the largest contribution and uncertainty.
- Already measured by several experiments with $\lesssim 1\%$ precision.
- Small discrepancy among measurements.

→ Follow-up tests in Belle II would be important.

a_μ at ρ resonance



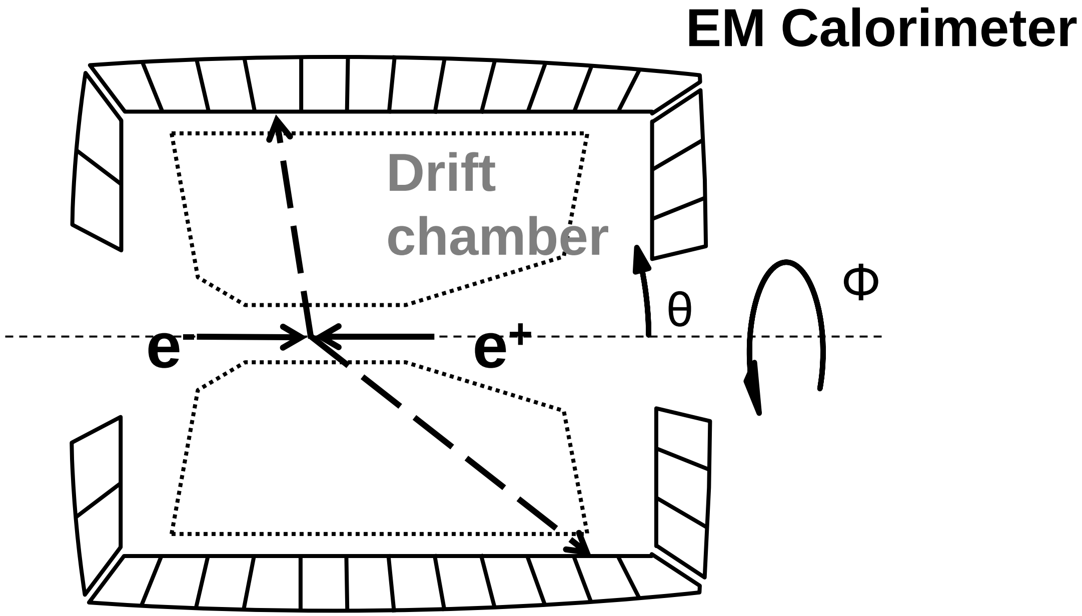
Form factor at ρ resonance



CMD-3 collaboration, arXiv:2302.08834 [hep-ex] (2023).
KEK IPNS seminar https://kds.kek.jp/event/45889/

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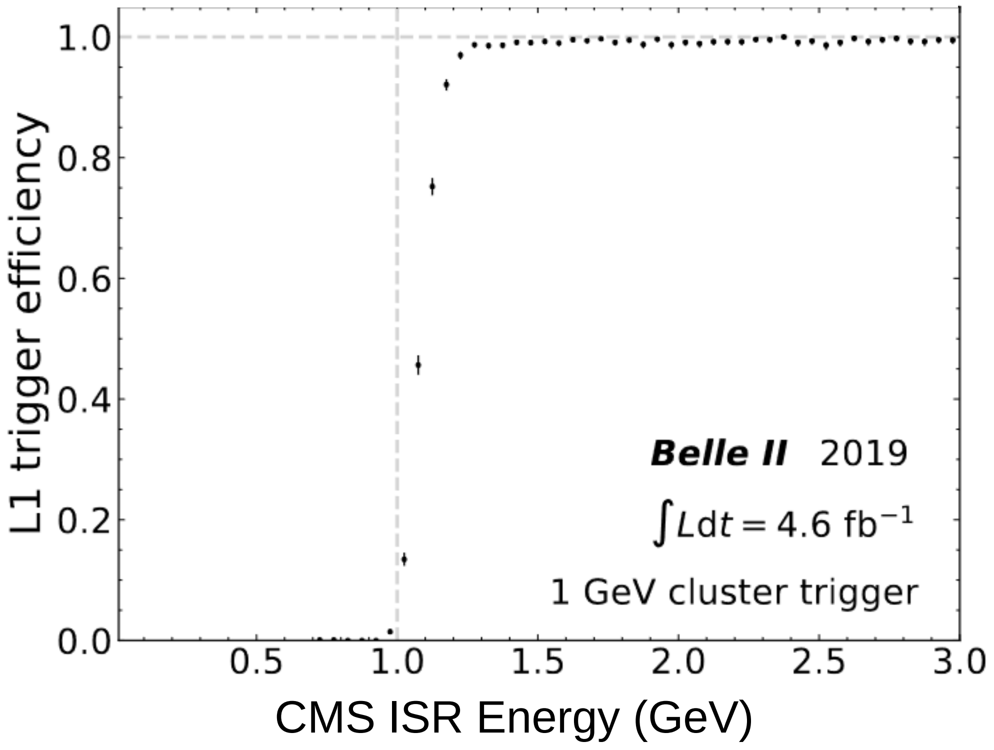
- The trigger efficiency of EM Calorimeter triggers for energetic ISR can be measured by making the orthogonal tracking trigger a reference.
  - Efficiency for energetic ISR > 99%
  - Event loss due to 3D bhabha veto is suppressed in μμγ.
- The high trigger efficiency for energetic ISR is beneficial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

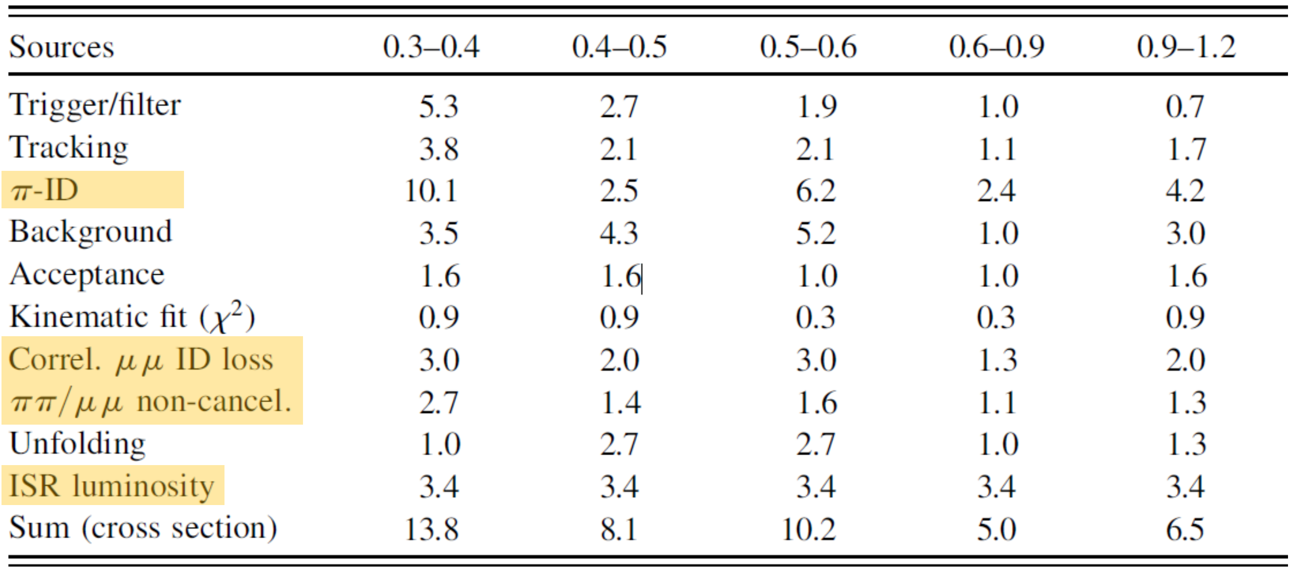
Belle II trigger efficiency for μμγ (data)



$e^+e^-\rightarrow\pi^+\pi^-$: 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→ππ uncertainty (10^{-3}) at BaBar

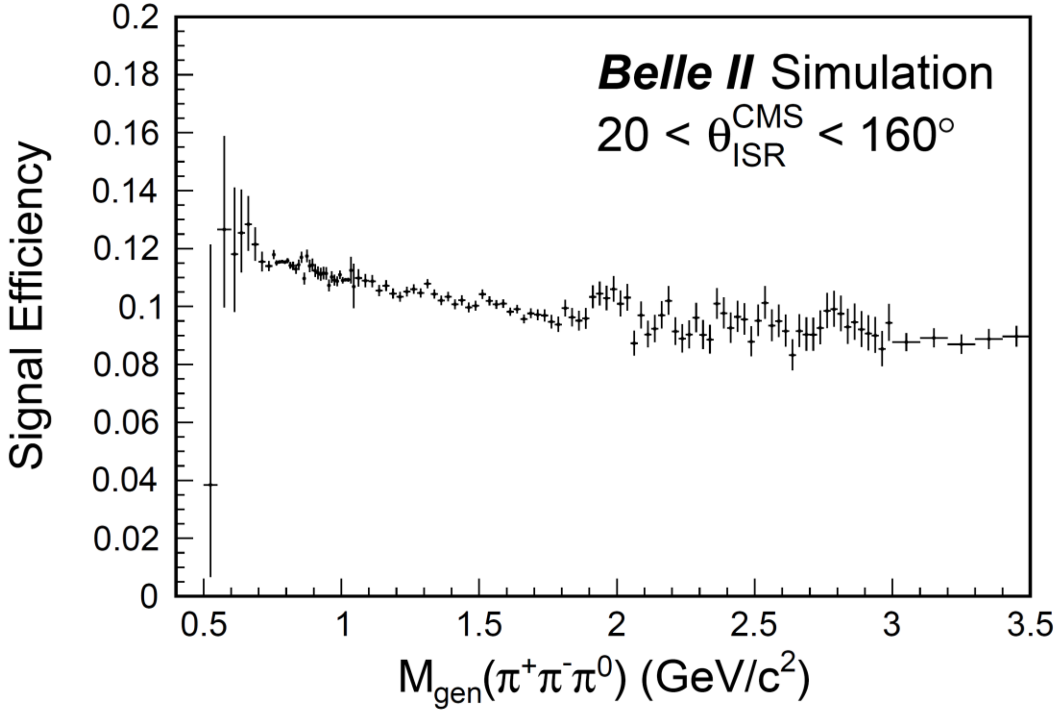


Sources	0.3–0.4	0.4–0.5	0.5–0.6	0.6–0.9	0.9–1.2
Trigger/filter	5.3	2.7	1.9	1.0	0.7
Tracking	3.8	2.1	2.1	1.1	1.7
π-ID	10.1	2.5	6.2	2.4	4.2
Background	3.5	4.3	5.2	1.0	3.0
Acceptance	1.6	1.6	1.0	1.0	1.6
Kinematic fit (χ^2)	0.9	0.9	0.3	0.3	0.9
Correl. $\mu\mu$ ID loss	3.0	2.0	3.0	1.3	2.0
$\pi\pi/\mu\mu$ 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

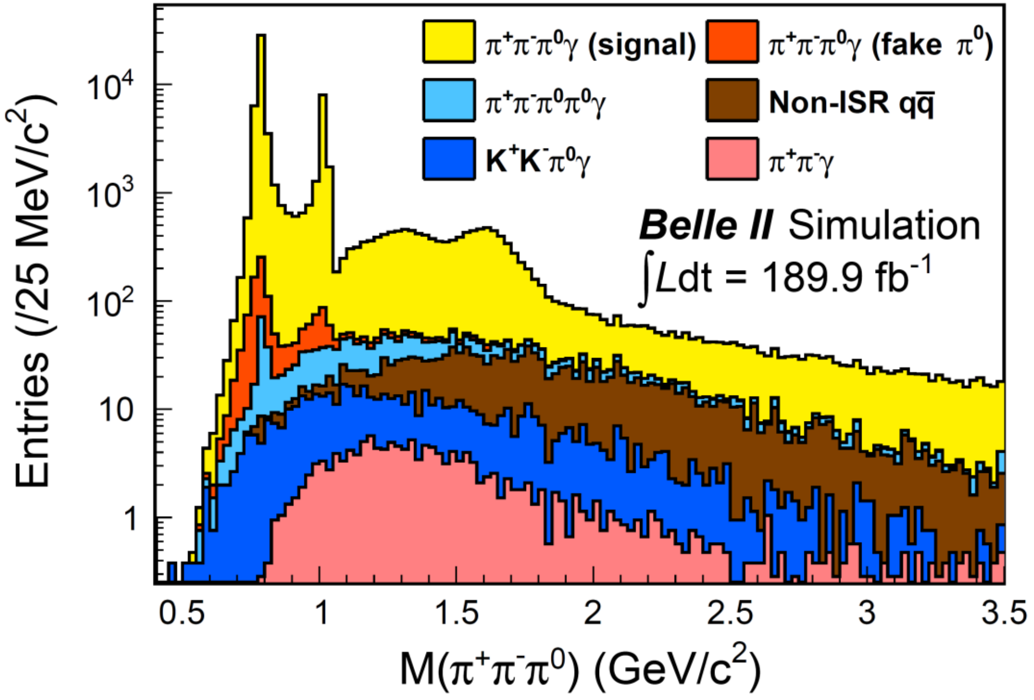
$e^+e^-\to\pi^+\pi^-\pi^0$ at Belle II

- $e^+e^-\to\pi^+\pi^-\pi^0$ 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



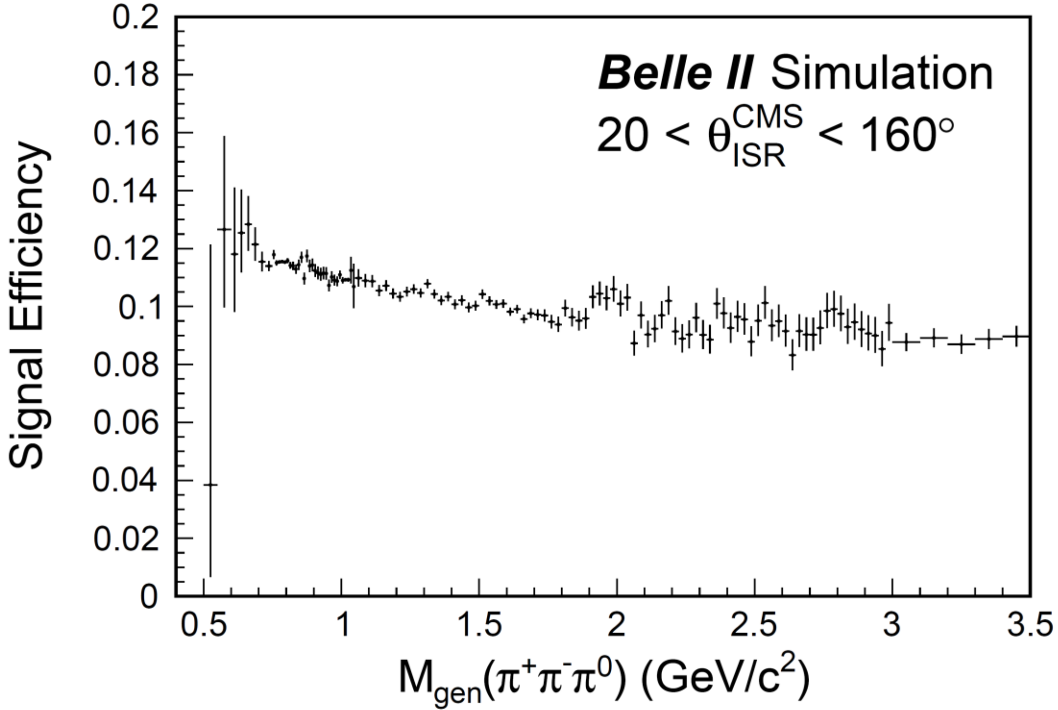
M(3π) distribution after selection (MC)



$e^+e^-\rightarrow\pi^+\pi^-\pi^0$ 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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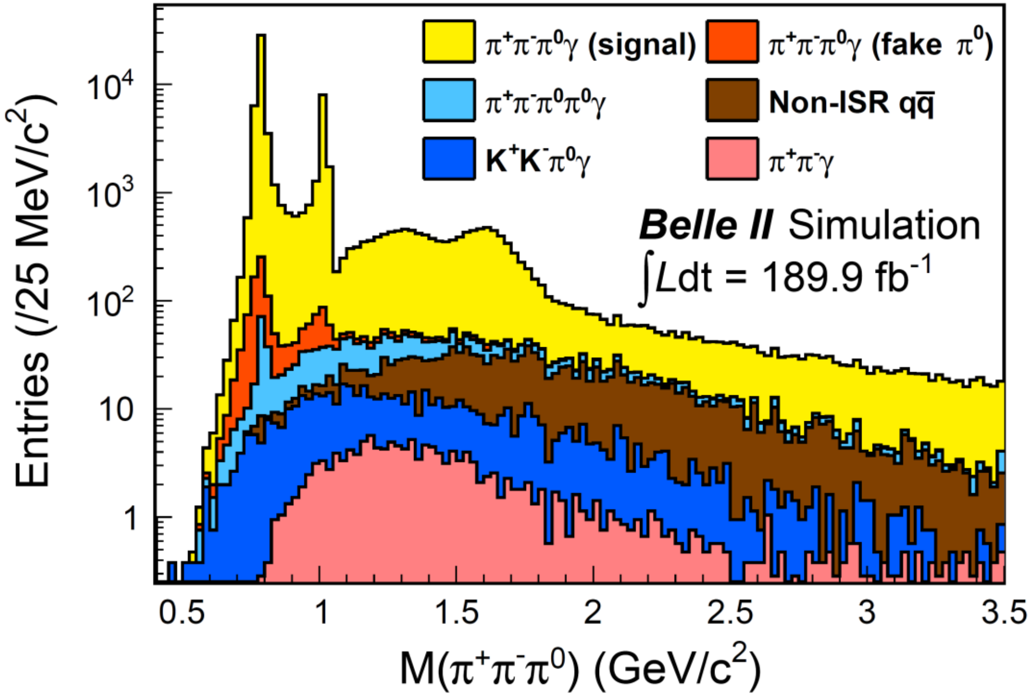
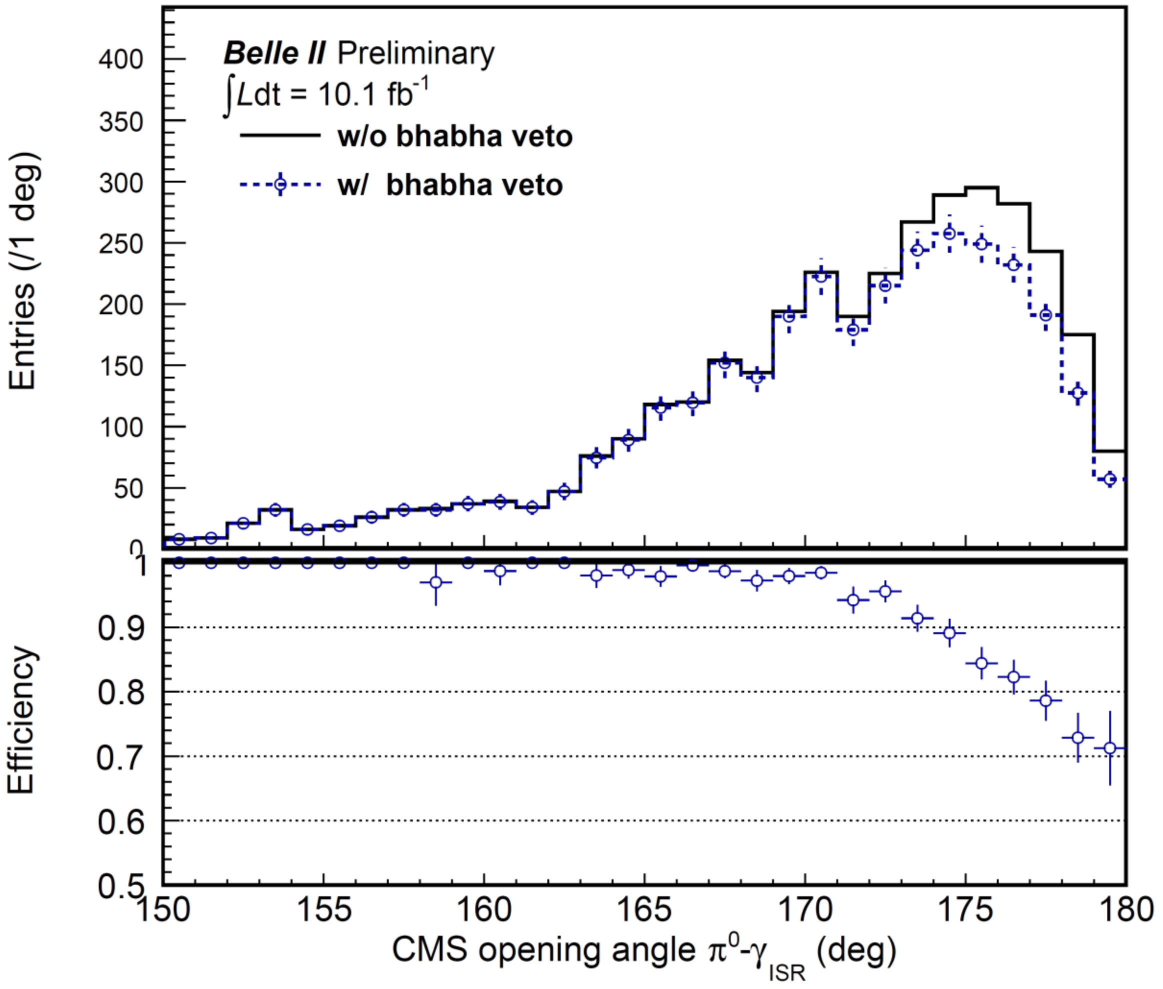


$e^+e^-\to\pi^+\pi^-\pi^0$: Efficiency correction

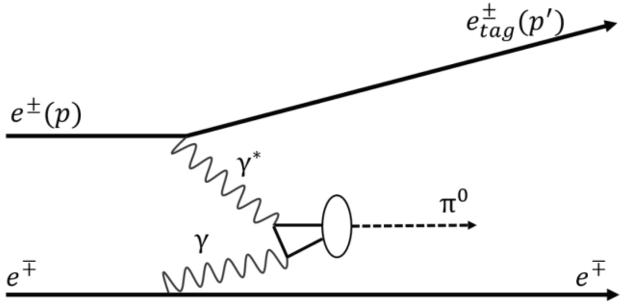
- Photon, tracking and trigger efficiency are confirmed.
- The additional data-driven corrections being evaluated: π^0 efficiency, correlated tracking inefficiency, and background rejection criteria.
- Study for trigger bhabha veto :
  - For ee->$\pi^+\pi^-\pi^0$ high energy π^0->γγ emitted back-to-back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

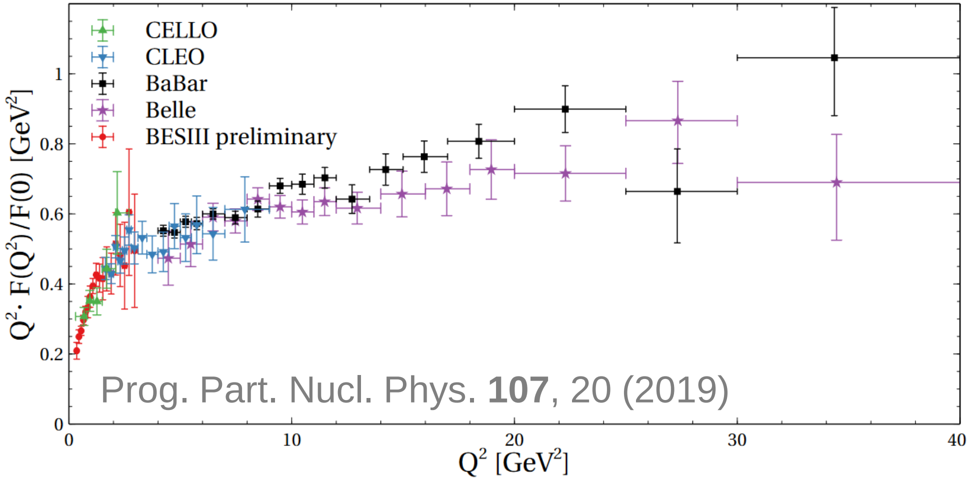


Other channels

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.





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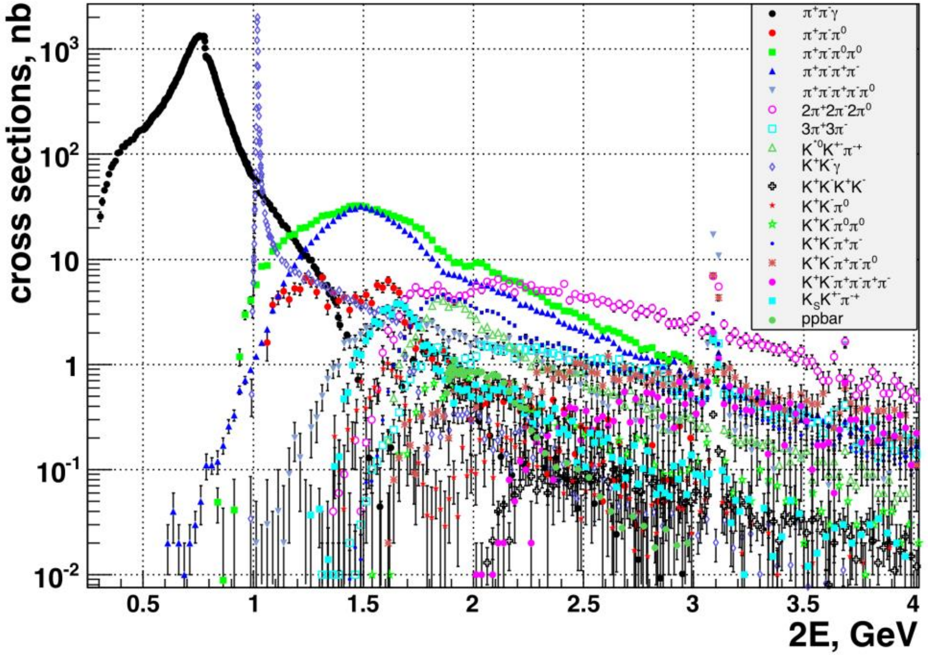
Further final states can be explored.

- >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.

Backup

MUonE

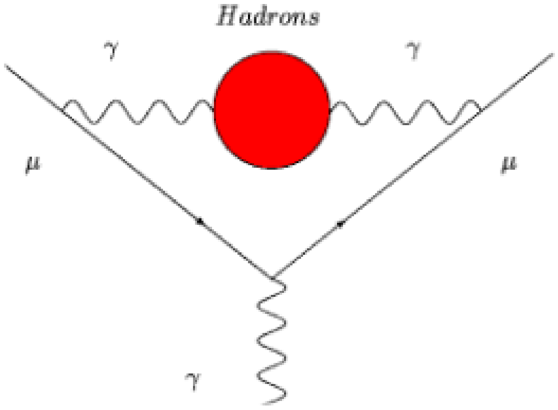
Time-like formula

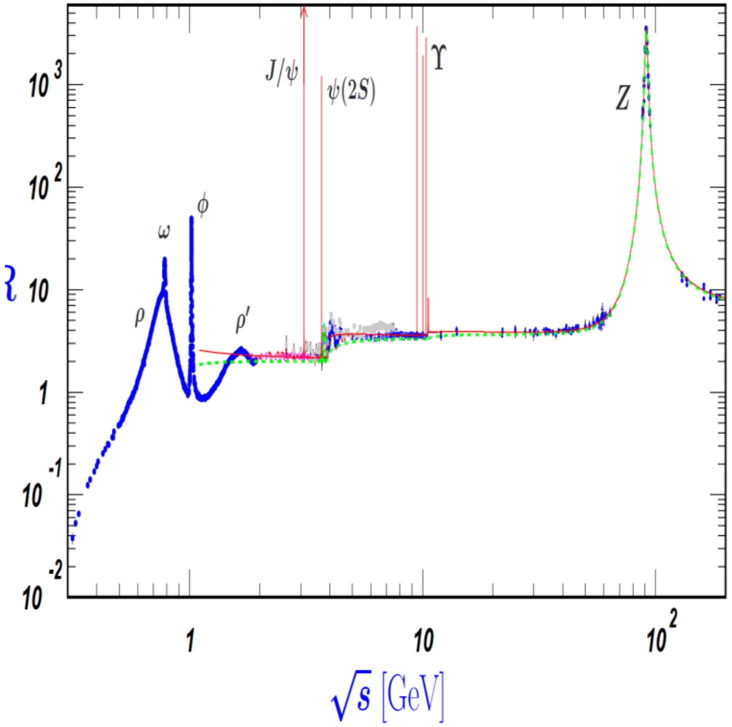
$$a_\mu^{\mathrm{HVP,LO}} = \frac{\alpha^2}{3\pi^2}\int_{m_\pi^2}^{\infty} \frac{K(s)}{s}\, R(s)ds$$

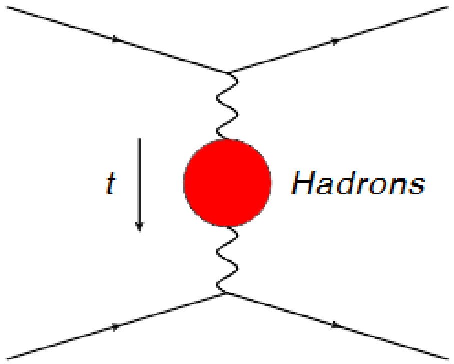
Space-like formula

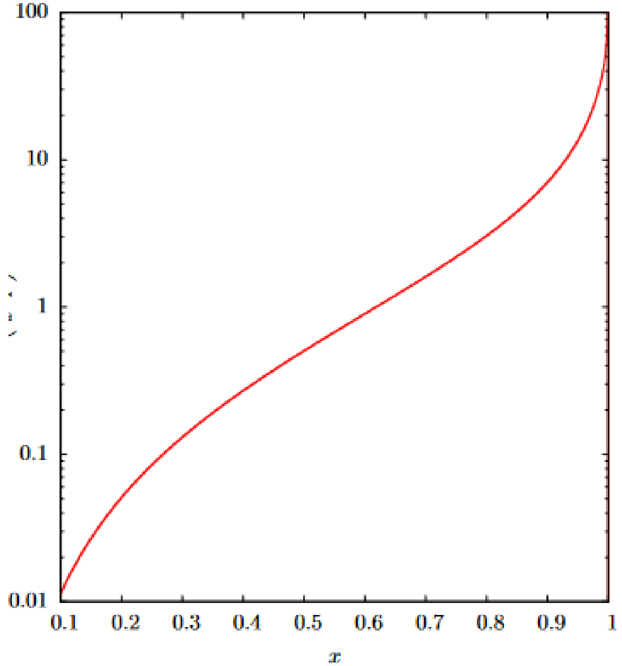
$$a_\mu^{\mathrm{HVP,LO}} = \frac{\alpha}{\pi}\int_0^1 dx(1-x)\Delta\alpha_{\mathrm{had}}\,[t(x)]$$

$$t(x) = \frac{x^2 m_\mu^2}{x-1}$$









HVP lattice QCD : Window method

- The window method divides this Euclidean time integral interval by a window function.
- Conversely, it can also be calculated from the R-ratio.

$$a_\mu^{\mathrm{HVP}} = \sum_{t=0}^{\infty} w_t C(t)$$

Lattice QCD+QED correlator $$C(t) = \frac{1}{3}\sum_{i,\vec{x}} \langle V_i(\vec{x},t) V_i(\vec{0},0)\rangle$$

R-ratio correlator $$C(t) = \frac{1}{12\pi^2}\int_0^\infty d(\sqrt{s}) R(s) s e^{-\sqrt{s}t}$$

$$a_\mu = a_\mu^{\mathrm{SD}} + a_\mu^{\mathrm{W}} + a_\mu^{\mathrm{LD}}$$

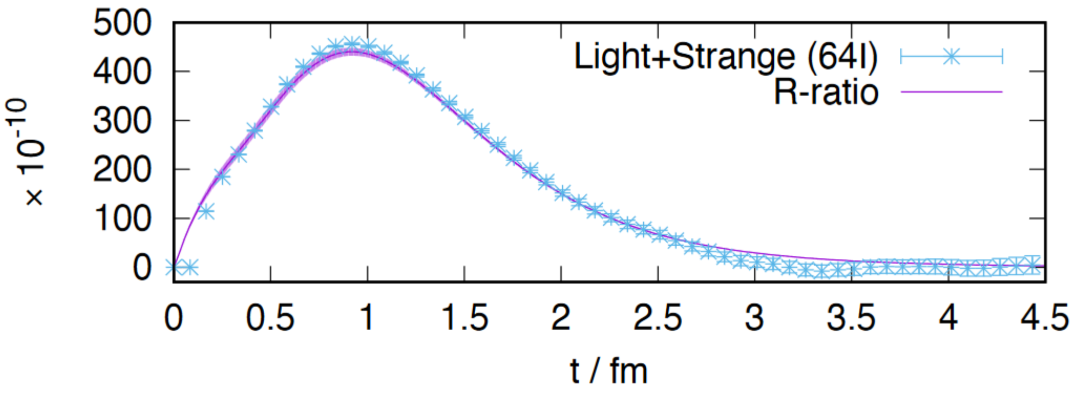
$$a_\mu^{\mathrm{SD}} = \sum_t C(t) w_t [1 - \Theta(t, t_0, \Delta)]\,,$$

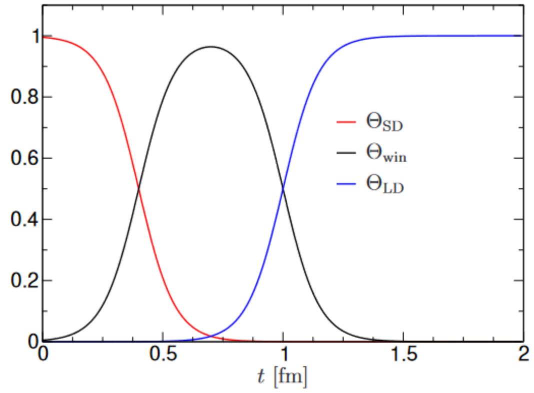
$$a_\mu^{\mathrm{W}} = \sum_t C(t) w_t [\Theta(t, t_0, \Delta) - \Theta(t, t_1, \Delta)]\,,$$

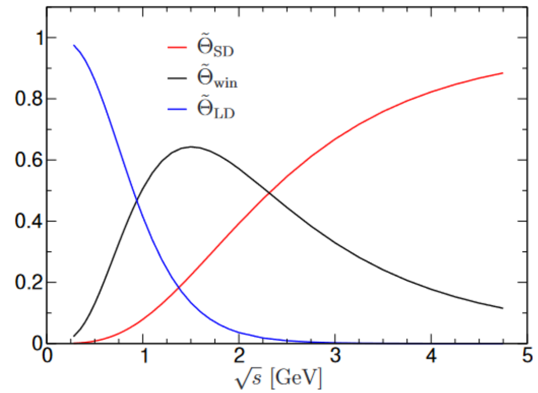
$$a_\mu^{\mathrm{LD}} = \sum_t C(t) w_t \Theta(t, t_1, \Delta)\,,$$

$$\Theta(t, t', \Delta) = [1 + \tanh[(t - t')/\Delta]]/2\,.$$

$w_t C(t)$







HVP lattice QCD : Window method

- The major systematic error sources differ for each Euclidean time domain.
- The main error sources, short distance (SD) and long distance (LD), can be eliminated.
- Detailed comparisons can be made by extracting only the accurate part of the values: a_μ^{win}.

$$a_\mu^{\mathrm{HVP}} = \sum_{t=0}^{\infty} w_t C(t)$$

Lattice QCD+QED correlator
$$C(t) = \frac{1}{3} \sum_{i,\vec{x}} \langle V_i(\vec{x},t) V_i(\vec{0},0) \rangle$$

R-ratio correlator
$$C(t) = \frac{1}{12\pi^2} \int_0^\infty d(\sqrt{s}) R(s) s e^{-\sqrt{s}t}$$

$$a_\mu = a_\mu^{\mathrm{SD}} + a_\mu^{\mathrm{W}} + a_\mu^{\mathrm{LD}}$$

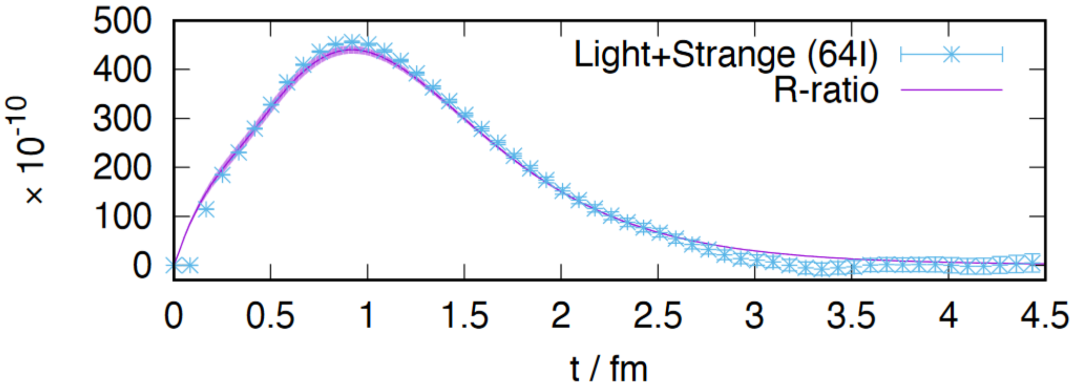
$$a_\mu^{\mathrm{SD}} = \sum_t C(t) w_t [1 - \Theta(t, t_0, \Delta)] \,,$$

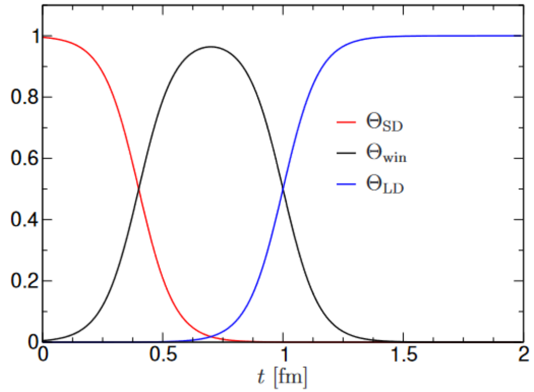
$$a_\mu^{\mathrm{W}} = \sum_t C(t) w_t [\Theta(t, t_0, \Delta) - \Theta(t, t_1, \Delta)] \,,$$

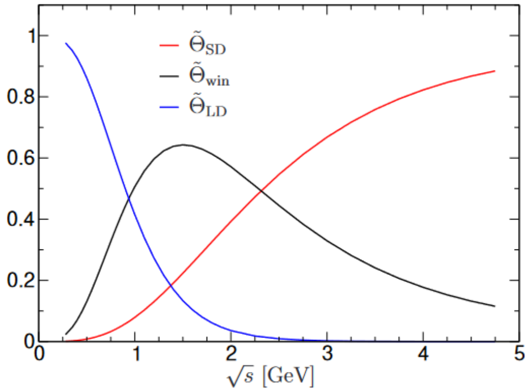
$$a_\mu^{\mathrm{LD}} = \sum_t C(t) w_t \Theta(t, t_1, \Delta) \,,$$

$$\Theta(t, t', \Delta) = [1 + \tanh[(t - t')/\Delta]]/2 \,.$$

$w_t C(t)$



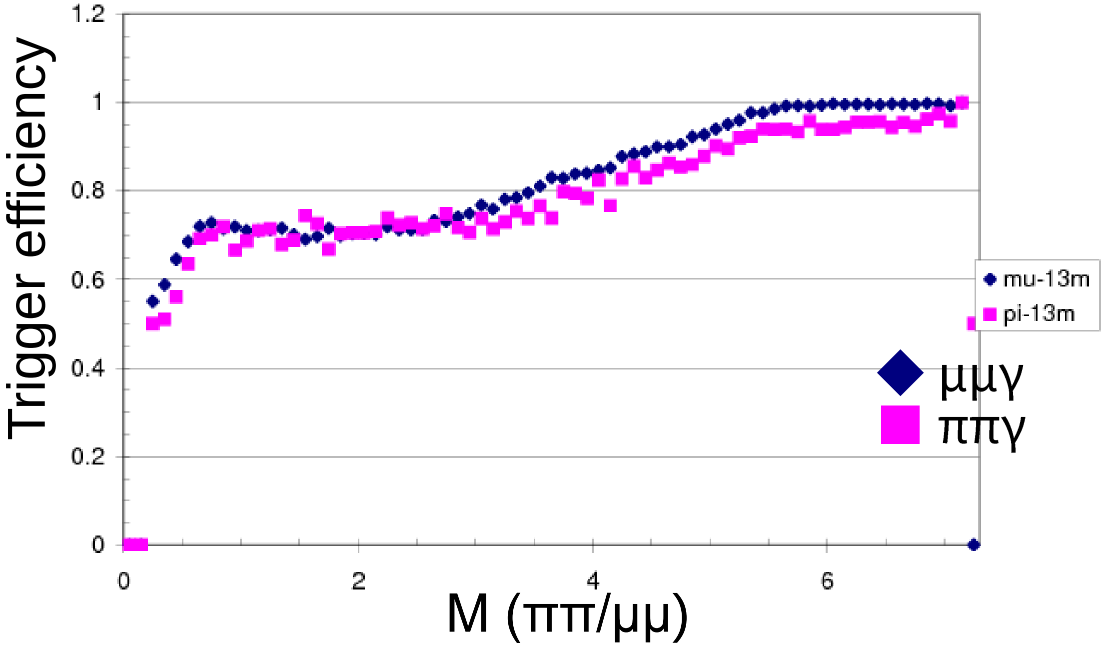




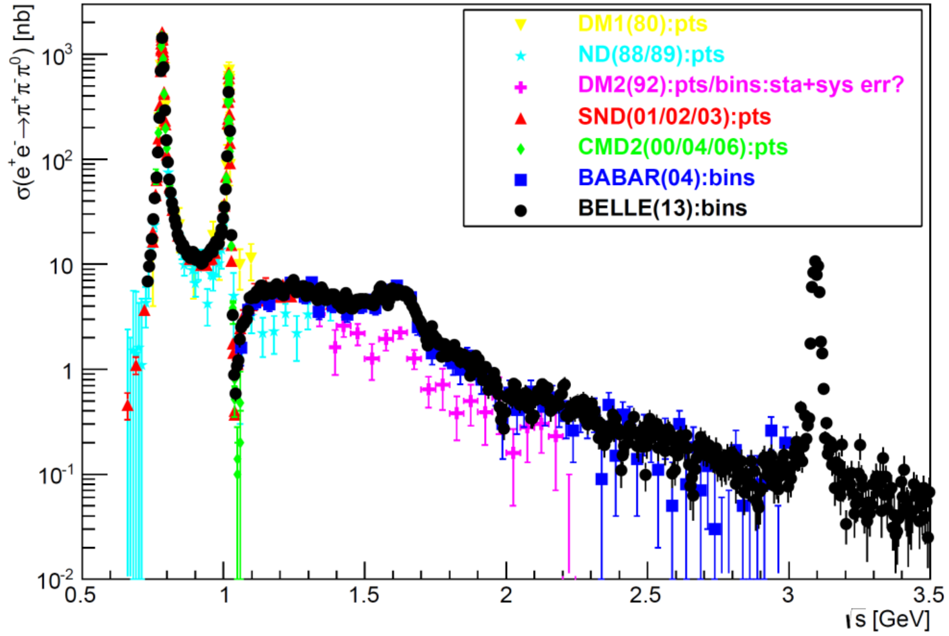
Light hadron cross section measurement at BELLE

- The measurement for $\sigma(e^+e^-\rightarrow\pi^+\pi^-\pi^0)$ was attempted, but could not be published.
  - Systematic uncertainty goal was 5%.
  - Large uncertainty of level-1 trigger efficiency prevents publication, and the preliminary result is recorded in a PhD thesis.
- A study for ee->ππ was also conducted but the triggering efficiency was critical for systematic.
- Other ee->hadron cross section has also not been measured at BELLE.

BELLE trigger efficiency for ππγ/μμγ (MC)



$e^+e^-\rightarrow\pi^+\pi^-\pi^0$ [J. Crnkovic, PhD thesis, Illinois U. (2013)]



Belle II Detector

Particle Identification

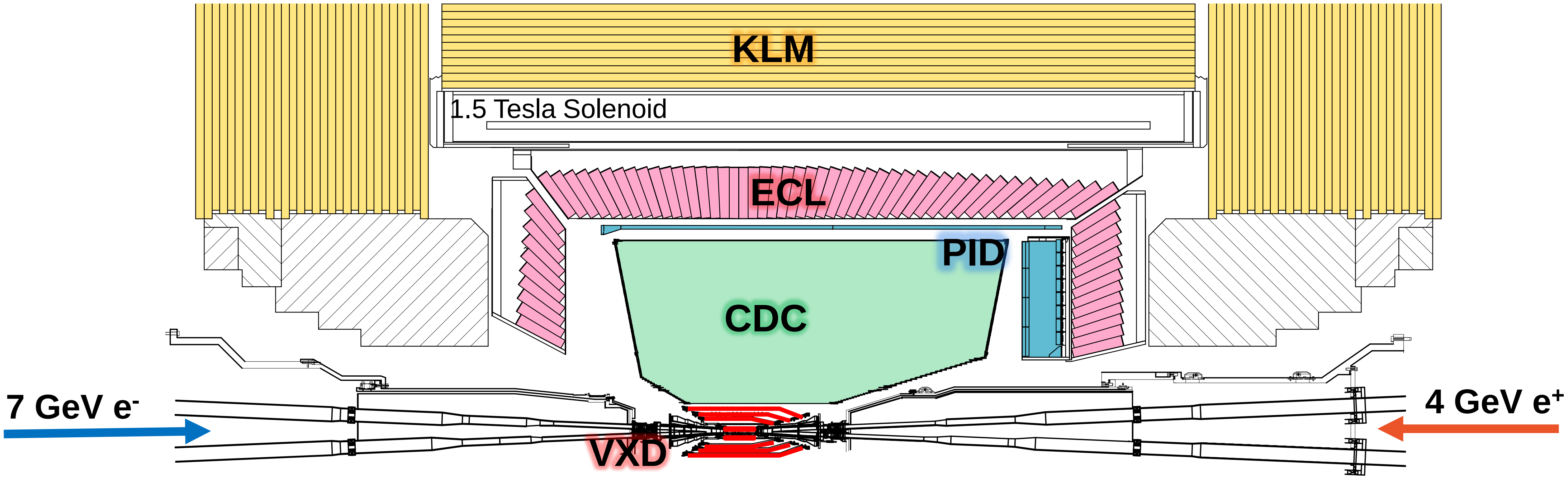
- Aerogel RICH in the forward endcap
- Time-of-Propagation counter in the barrel
- **K/π ID : K efficiency 90% at 1.8% π fake**

Electromagnetic Calorimeter (ECL)

- CsI(Tl) crystals + Waveform sampling
- **Electron ID eff. 90% at <0.1% fake**
- **Energy resolution 1.6-4%**
- **94% of solid angle coverage**

K-long and Muon Detector (KLM)

- Alternating iron and detector plates
- Scintillator / Resistive Plate Chamber
- **Muon ID efficiency 90% at 2% fake**



Vertex Detector (VXD)

- Inner 2 layer : Pixel
- Outer 4 layer : Double side strip
- vertex resolution 20-30 μm

Central Drift Chamber (CDC)

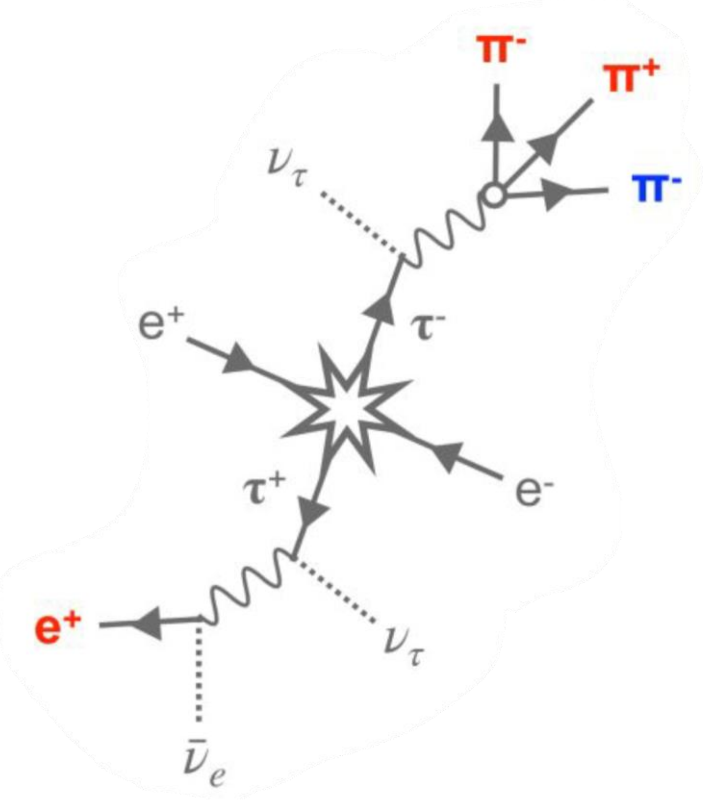
- **91% of solid angle coverage**
- **p_T resolution ~ 0.4%/p_T**
- dE/dx resolution 5% (low-p PID)

Trigger and DAQ

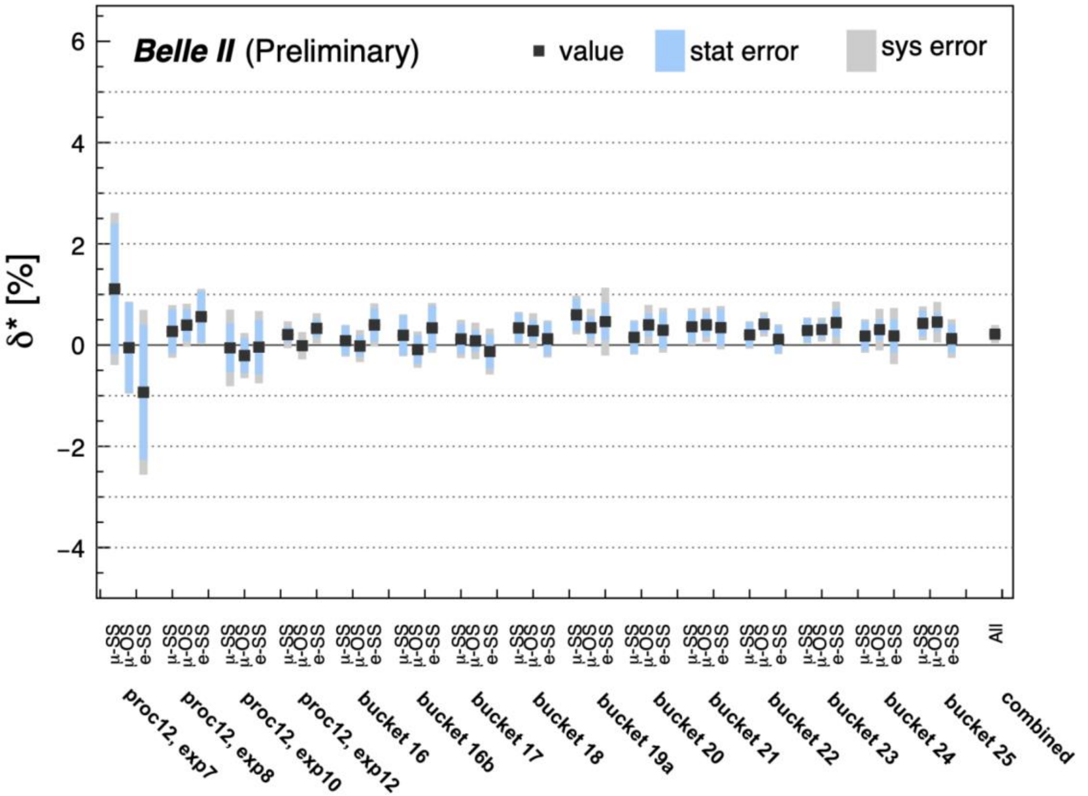
- L1 Trigger rate 30 kHz (design)
- **New trigger line for low-multiplicity events**
- Constant improvements of trigger algorithm

Performance : Tracking Efficiency

- Tracking efficiency is measured by tag-and-probe method on ee→ττ→1×3 prong.
  - 3 good quality tracks for tag
  - Look for 4th track for probe
- Uncertainty for tracking efficiency is 0.30% per track.

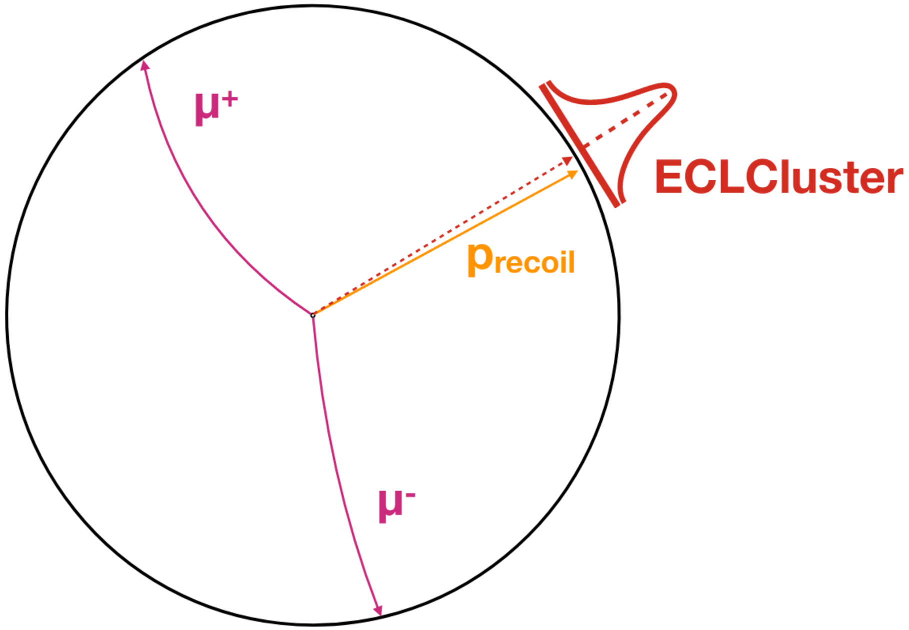


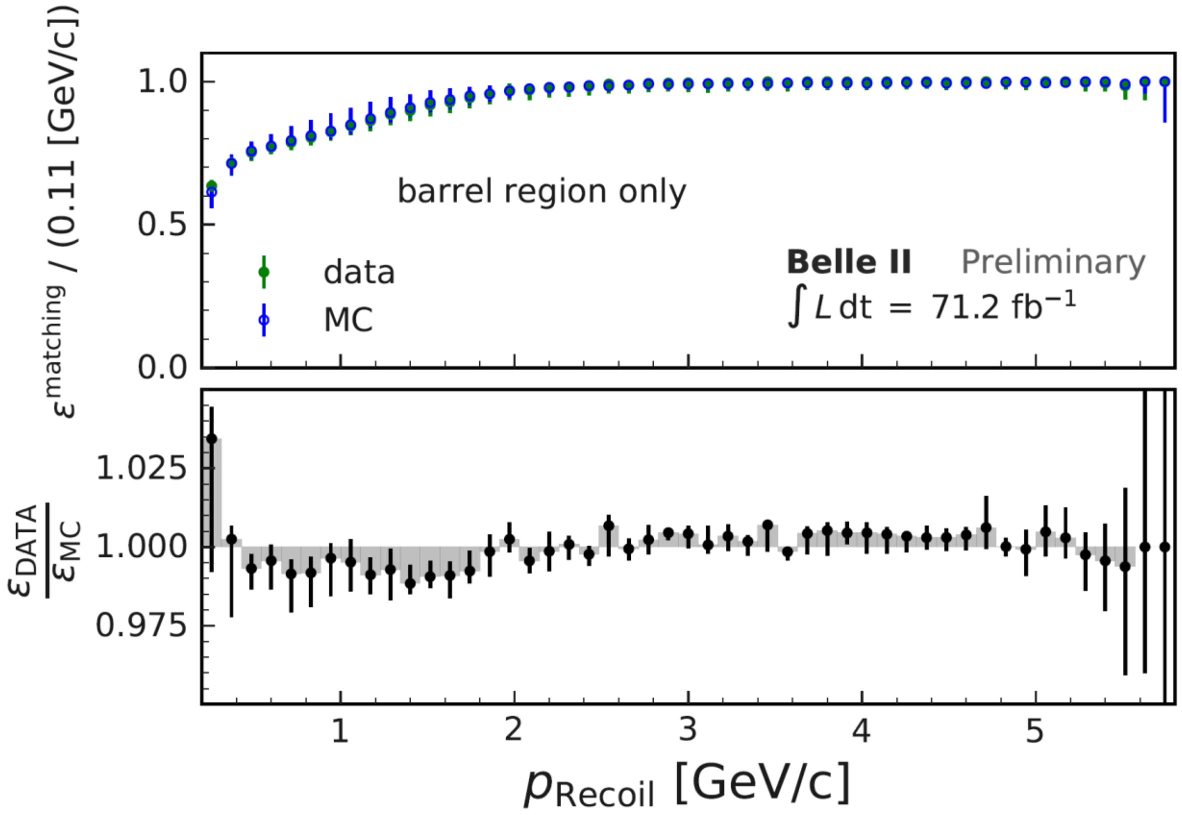
Data/MC discrepancy of tracking efficiency



Performance : Photon Detection Efficiency

- Photon detection efficiency is measured using ee→μμγ events.
  - Detection efficiency is estimated by taking match between a ECL cluster and the missing momentum of dimuon system.
- Data/MC agreement is good. Uncertainty for photon detection efficiency is 0.30%.





$e^+e^-\rightarrow\pi^+\pi^-$: Analysis strategy

- Loose selection :two tracks + one hard photon
- Kinematic fitting for Signal/Background separation
  - One fit assuming FSR and one assuming ISR
- PID selaration ππ/μμ/KK
- Efficiency corrections

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