Status and Prospects for the Measurement of the Pion Vector Form Factor

Riccardo Aliberti, JGU Mainz

MESON 2026

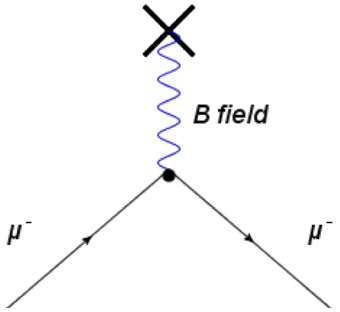
Krakow 30.06.2026

The Muon Anomaly

A **charged particle with spin** carries a **magnetic moment** $\vec{\mu}$

$$\vec{\mu} = g_\mu \frac{e}{2m_\mu} \vec{S}$$

From Dirac equation: $\left|\vec{S}\right| = {}^1/_2 \rightarrow \boldsymbol{g_\mu = 2}$



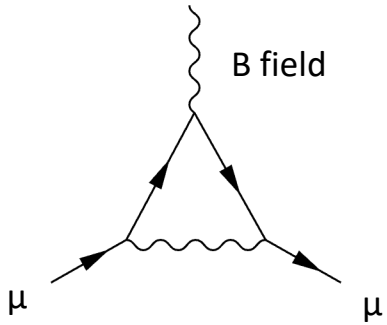
$$a_\mu = \frac{|g_\mu - 2|}{2}$$

The Anomaly

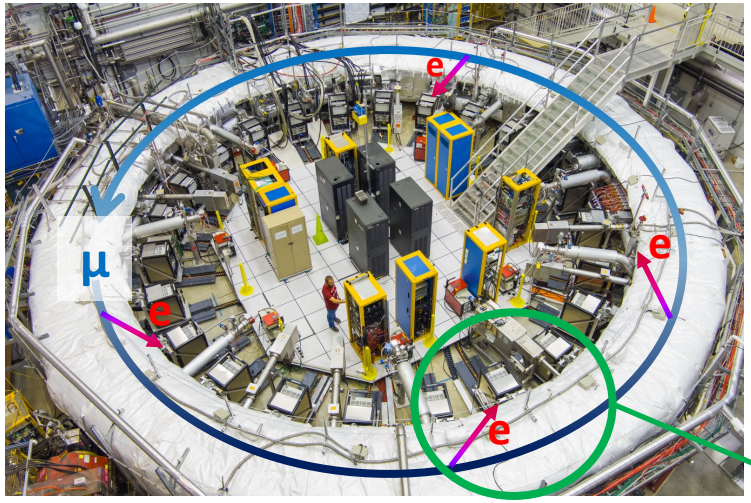
Going **beyond tree level**, contribution from loop

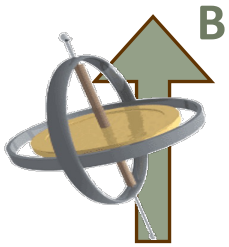
$$a_\mu = \frac{\alpha}{2\pi}$$

Schwinger term

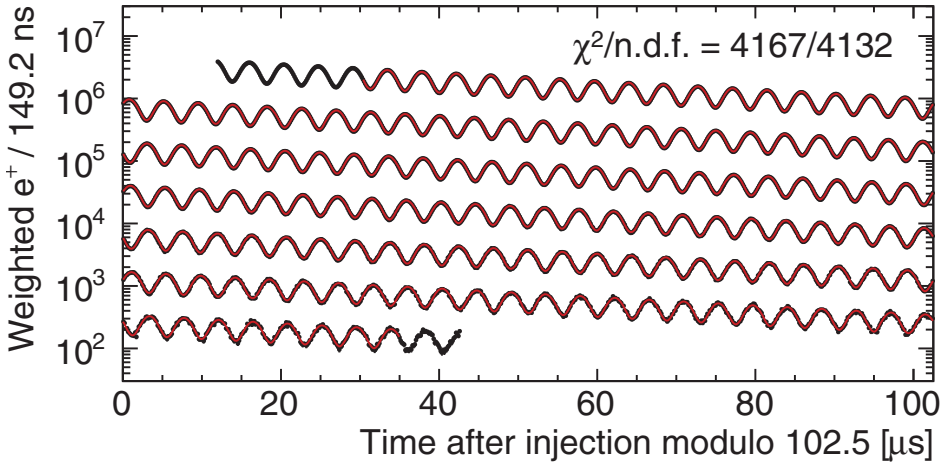


Theory and Experiment





$$\omega_a \simeq a_\mu \frac{e}{m_\mu} \left| \vec{B} \right|$$



Measure spin precession frequency:

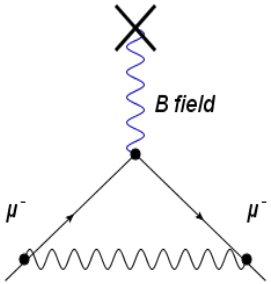
- Frequency determined by $\mathbf{a_\mu}$
- Measured at BNL and FNAL
- Precision: 0.19 ppm

$$a_\mu^{exp} = 116\,592\,059\,(22) \times 10^{-11}$$

(*Phys.Rev.D* 110 (2024) 3, 032009)

The SM Prediction

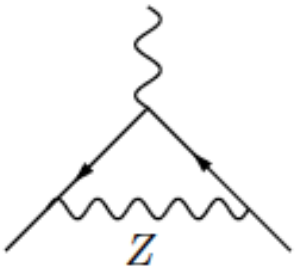
QED 99.993%



$$\frac{\alpha}{2\pi} + \cdots$$

+

EW 0.0002%

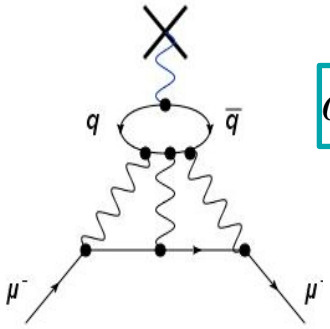


$$a_\mu^{QED+EW} = 116\,584\,873 \times 10^{-11}$$

(Phys.Rept. 1143 (2025) 1-158)

QCD 0.006%

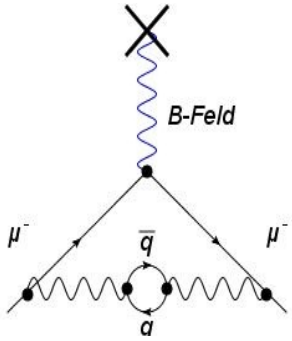
HLbL



$$a_\mu^{HLbL} = 115(10) \times 10^{-11}$$

(Phys.Rept. 1143 (2025) 1-158)

HVP



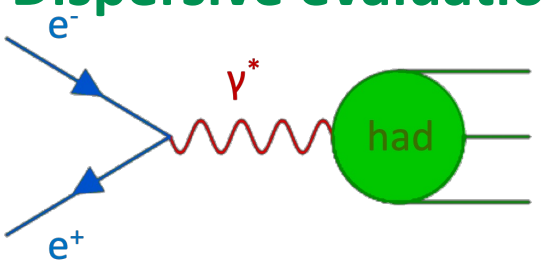
???

The SM Prediction: HVP

$$a_\mu^{\mathrm{HVP}} = \frac{1}{4\pi^3} \int_{4m_\pi^2}^{\infty} K(s)\, \sigma_{e^+e^-\to \mathrm{had}}\, ds$$

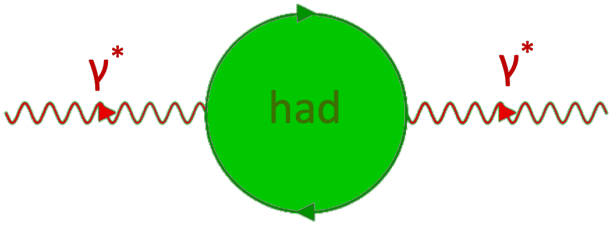
Optical Theorem

Dispersive evaluation



$$a_\mu^{HVP,\ e^+e^-} = 6845(40) \times 10^{-11}$$

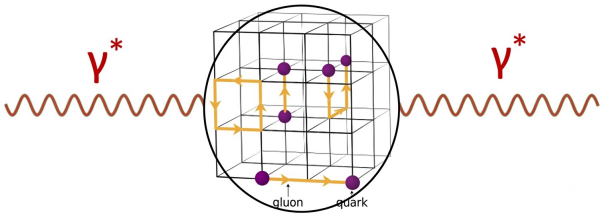
(Phys.Rept. 887 (2020) 1-166)



$$a_\mu^{HVP,\ \mathrm{LQCD}} = 7045(61) \times 10^{-11}$$

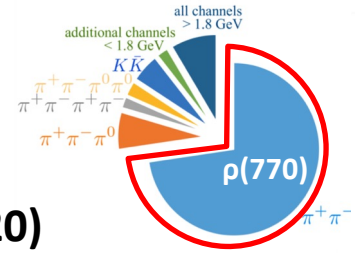
(Phys.Rept. 1143 (2025) 1-158)

Discretization



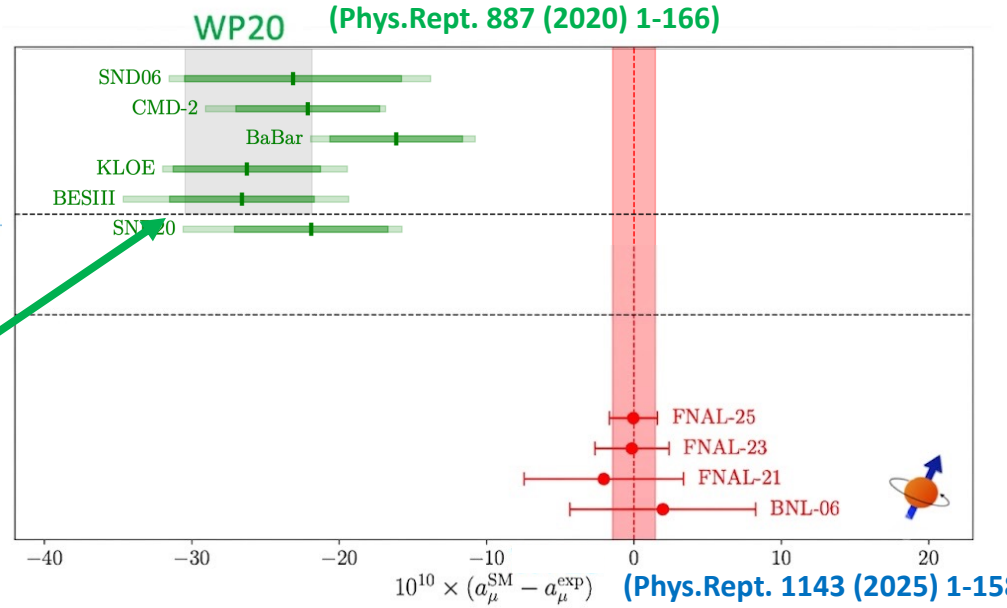
Lattice QCD

The HVP Puzzle



White Paper 2020 (WP20)

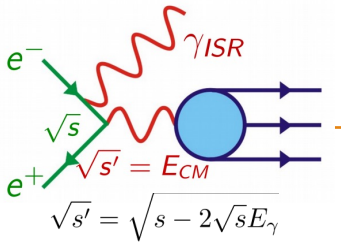
- Tension between data sets
- Underestimation of systematics?
- **Combination with inflated uncertainty**
- **No precise Lattice QCD calculation**



The HVP Puzzle

KLOE

Initial-State-Radiation technique (ISR)



$$\frac{d\sigma_{ISR}(\sqrt{s'})}{d\sqrt{s'}} = \frac{2\sqrt{s'}}{s} W(s, E_\gamma, \theta_\gamma)\, \sigma(\sqrt{s'})$$

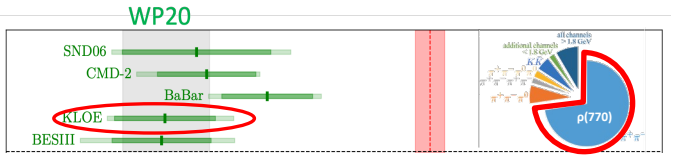
Uncertainty: 0.6% (on a_μ)

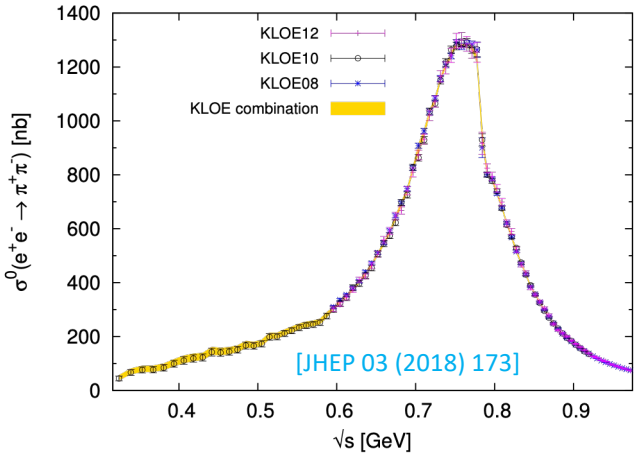
Result is a combination of 3 measurements: [JHEP 03 (2018) 173]

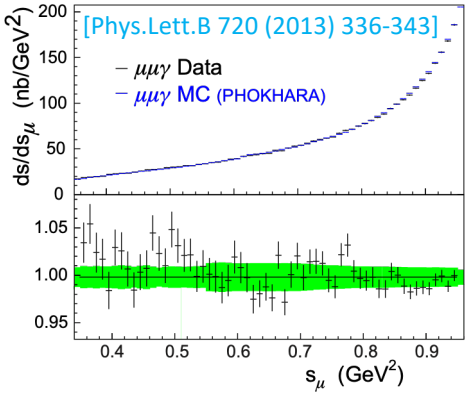
- **Untagged analysis** of 240 pb^{-1} **@ m_Φ (KLOE08)** [Phys.Lett.B 670 (2009)]
- **Tagged analysis** of 250 pb^{-1} **@ 1 GeV (KLOE10)** [Phys.Lett.B 700 (2011)]
- KLOE08 with **normalization to $e^+e^- \to \mu^+\mu^-$ (KLOE12)** [Phys.Lett.B 720 (2013)]

Good **agreement** of $\sigma(e^+e^- \to \mu^+\mu^-)$ **to QED** predictions

Event generator: **Phokhara**

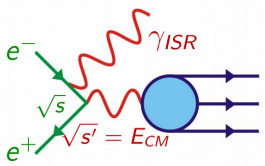


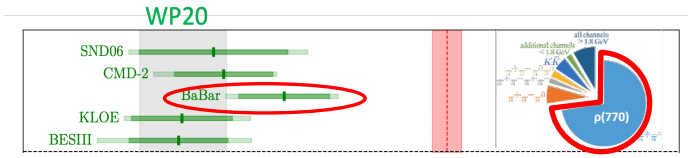




The HVP Puzzle

BaBar





Initial-State-Radiation technique (**ISR**)

Tagged analysis (ISR photon at large angle)

232 fb^{-1} @ $\Upsilon(4S)$

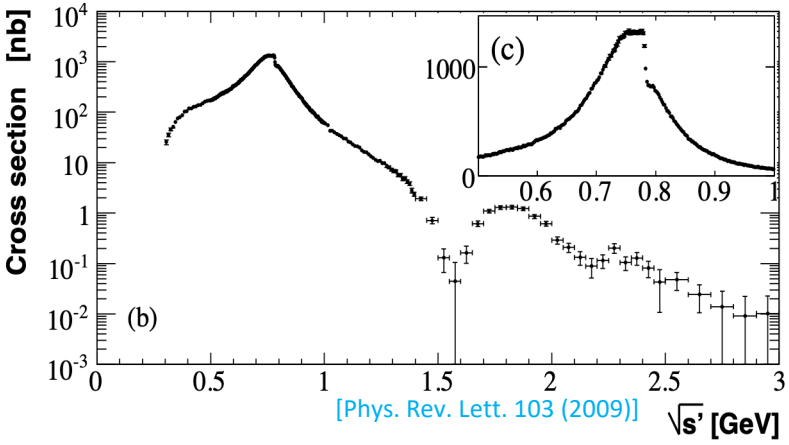
Normalization to $e^+e^- \rightarrow \mu^+\mu^-$

Uncertainty: 0.7% (on a_μ)

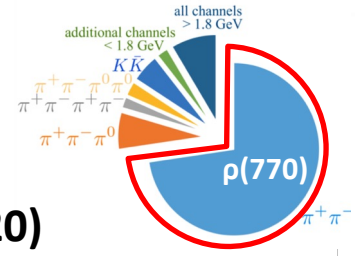
Analysis built to **accept $\mu\mu\gamma(\gamma)$, $\pi\pi\gamma(\gamma)$** events

Good **agreement** of $\sigma(e^+e^- \rightarrow \mu^+\mu^-)$ **to QED** predictions

Event generator: **AfkQED + corrections from Phokhara**



The HVP Puzzle



White Paper 2020 (WP20)

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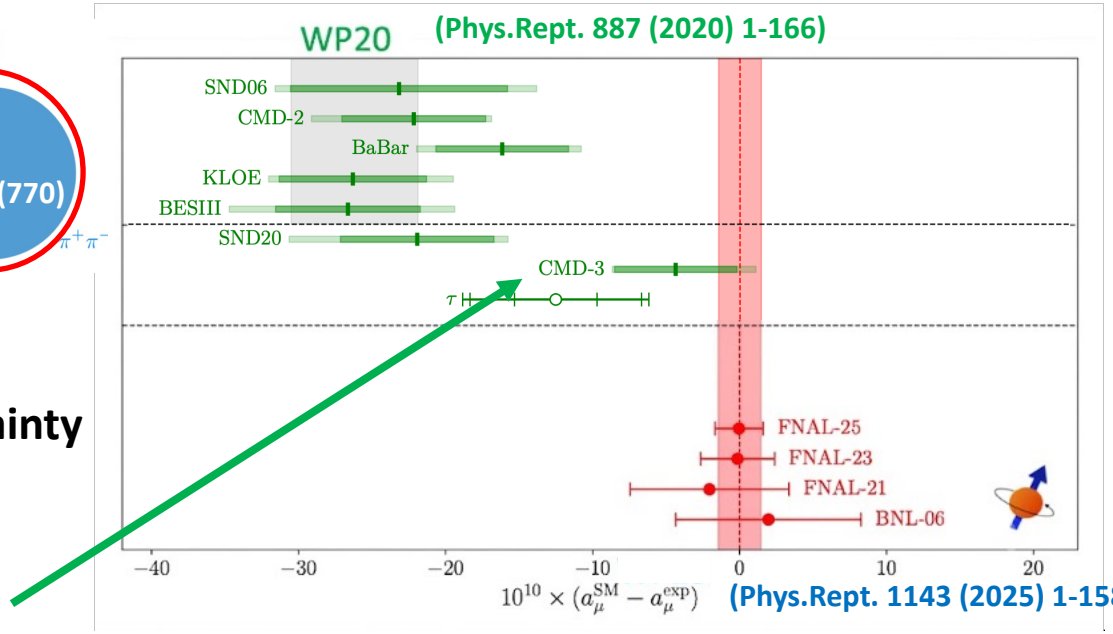


CMD-3 Pion FF (2023)

- New result published after WP2020
- Result in strong disagreement to previous measurements
- **Good agreement with experimental result**

CMD-3 Analysis Strategy

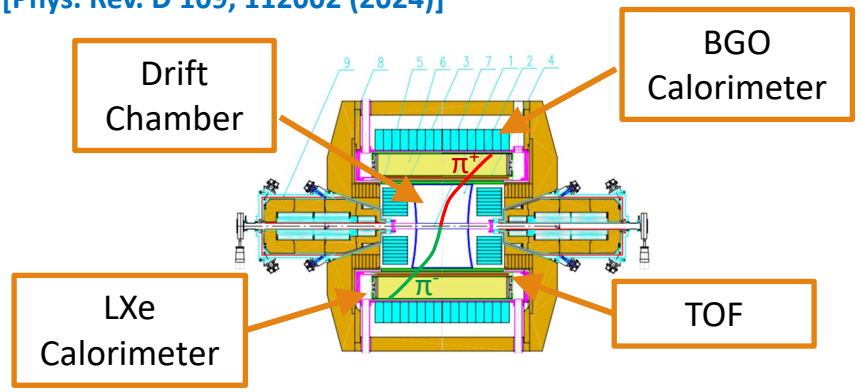
Data collected at VEPP-2000 collider

- CM : 0.3 < √s < 1.2 GeV
- Three data sets (2013,18,20)
- Different data taking conditions

Simple selection conditions

- Back-to-back topology
- Timing

[Phys. Rev. D 109, 112002 (2024)]



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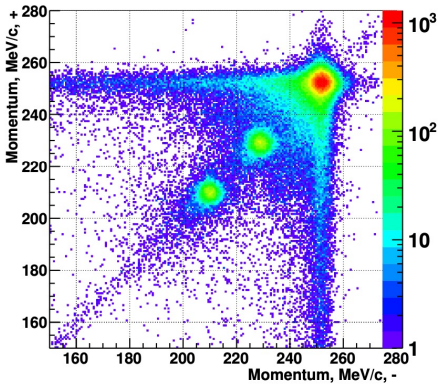
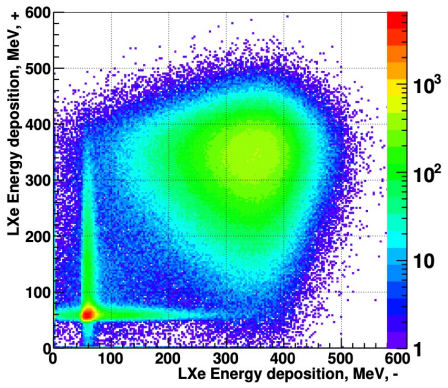
Three methods for signal extraction:

- Momentum
- Energy deposit in LXe calorimeter
- Angular distribution

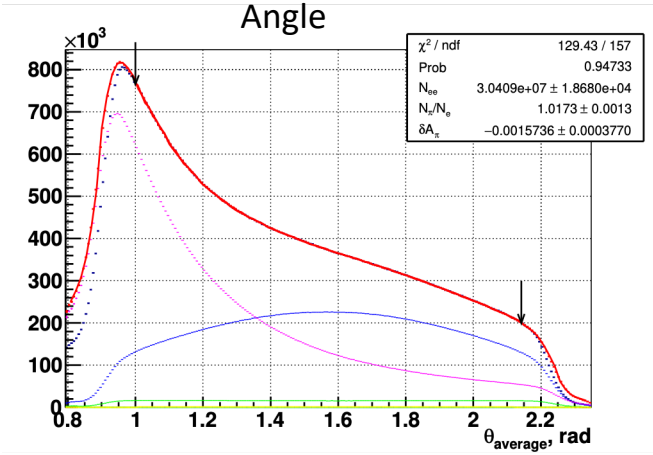
Momentum



Energy



Angle



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- Energy deposit in LXe calorimeter
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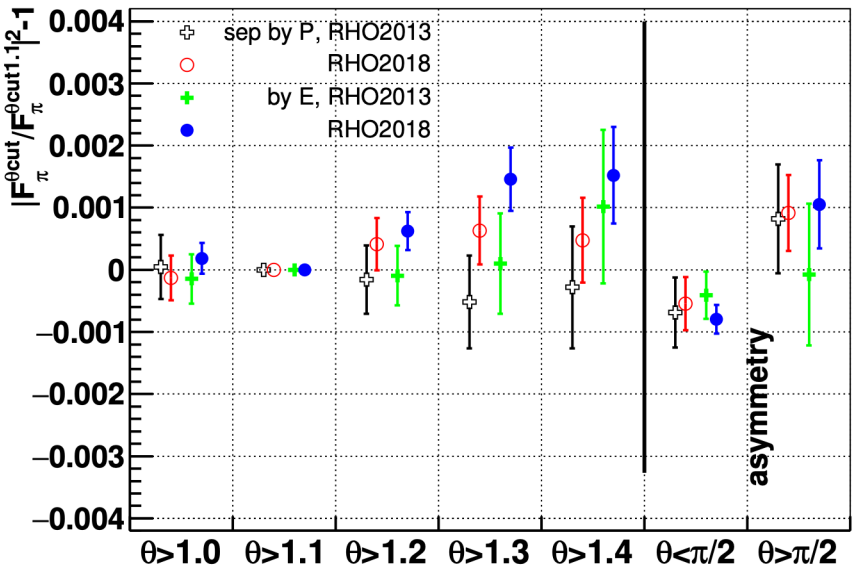
Careful check of systematic effects

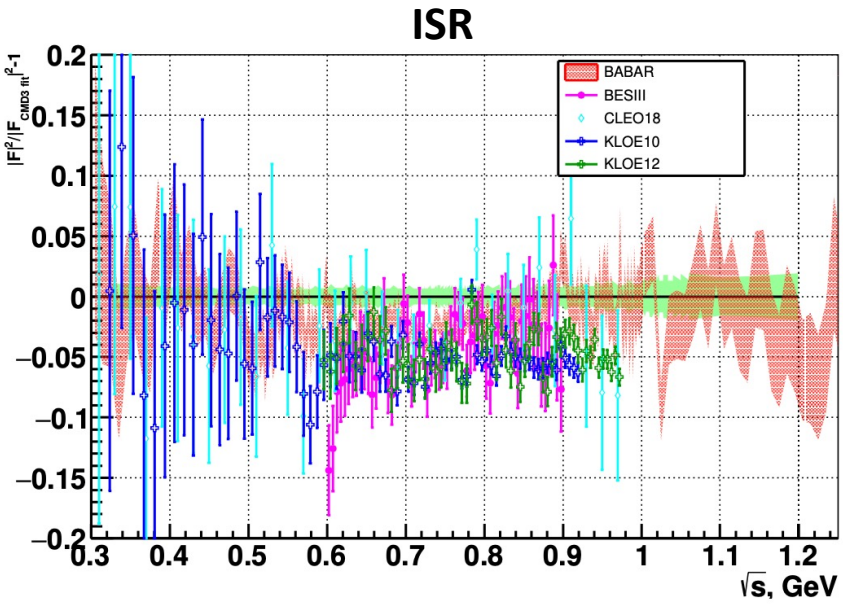
- Acceptance, radiative corrections, …

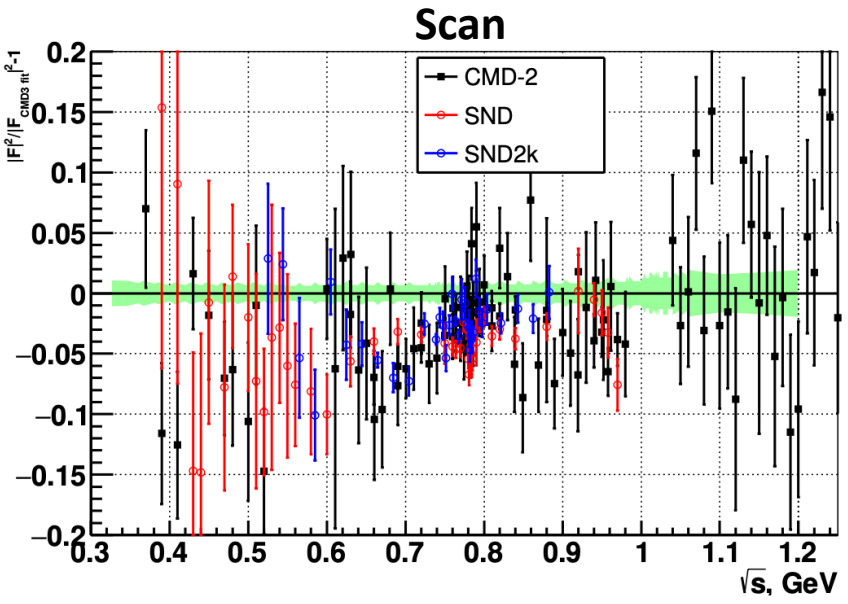
[Phys. Rev. D 109, 112002 (2024)]



CMD-3: Result and Comparisons

[Phys. Rev. D 109, 112002 (2024)]





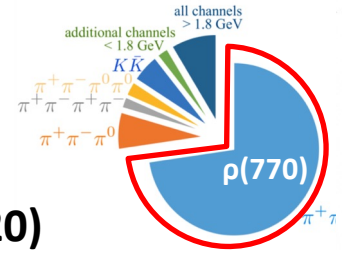
Measurement accuracy of about 0.8%, close to KLOE and BaBar (0.6-0.7%)

Common (and flat) disagreement around ρ(770)

Consistency at larger and smaller energies

Source of CMD 2 vs 3 disagreement still unclear

The HVP Puzzle



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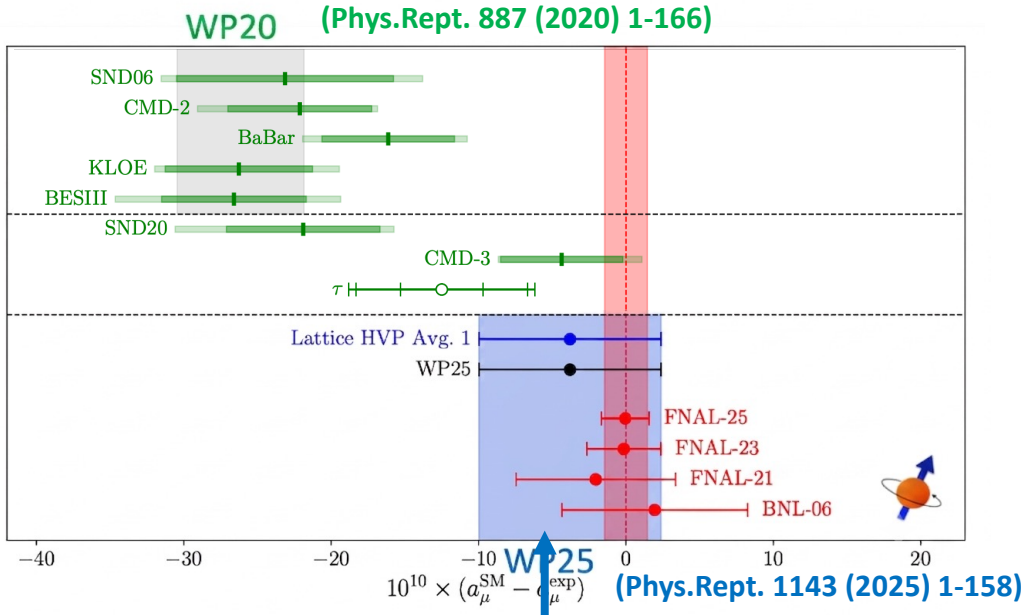

CMD-3 Pion FF (2023)

- New result published after WP2020
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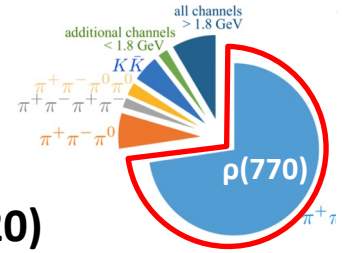
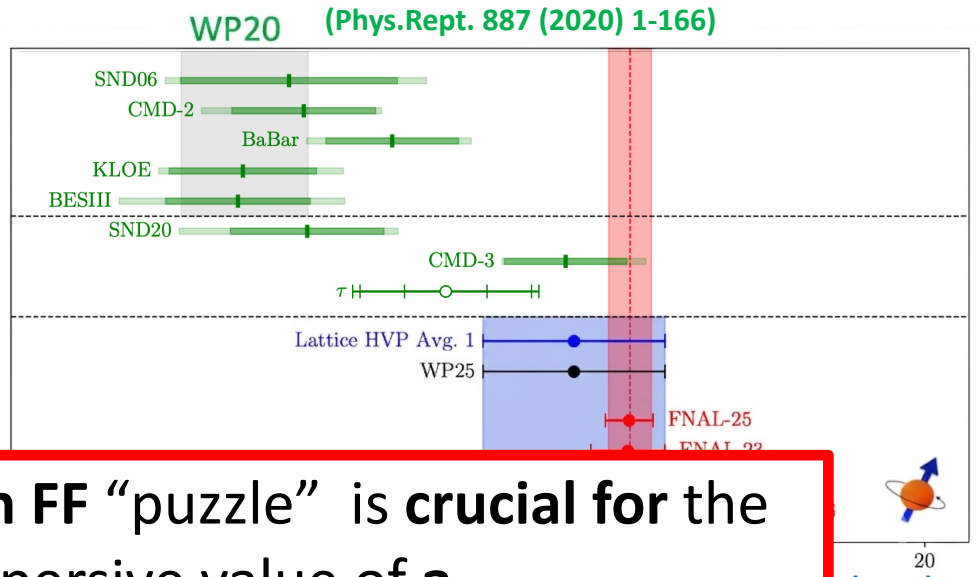
- **Good agreement with lattice and experimental result**

White Paper 2025 (WP25)

- Pion FF data sets are incompatible
- A combination is not possible
- **Only combination of Lattice QCD results**

The HVP Puzzle





White Paper 2020 (WP20)

- Tension between data sets
- Underestimation of systematics?
- **Combination with inflated uncertainty**
- **No precise Latt**

Resolving the pion FF "puzzle" is **crucial for** the evaluation of a dispersive value of $\mathbf{a_\mu}$

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How to clarify the picture?

Several activities worldwide on-going to understand:

- **Improvement** of **event generators** (RadioMonteCarLow 2)
- New scan measurement: SND
- **New** ISR **measurements:** BaBar, BESIII, KLOE and Belle II

Joint effort to investigate the discrepancies from **both experiment and theory** perspective

Radiative Corrections

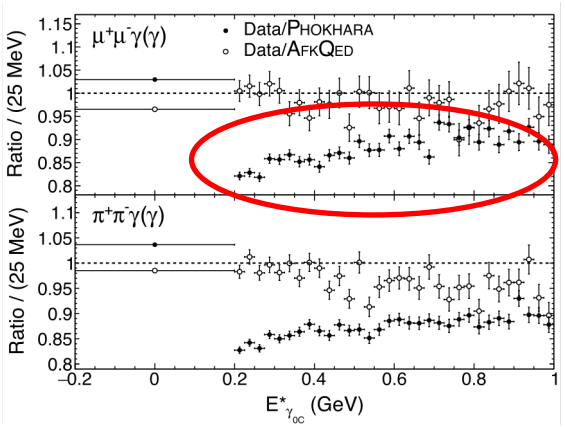
Investigation of events with 2 radiated photons by BaBar

- Phokhara is found to overestimate the contribution!
- Impact on various ISR analyses?
- Need dedicated studies, but which generators to use?

The RadioMonteCarLow 2 Working Group

- Review of available generators and radiative corrections

[Phys. Rev. D 108, L111103 (2023)]



SciPost Phys. Comm. Rep. 9 (2025)

Radiative corrections and Monte Carlo tools for low-energy hadronic cross sections in e^+e^- collisions

Riccardo Aliberti[1], Paolo Beltrame[2], Ettore Budassi[3,4], Carlo M. Carloni Calame[4], Gilberto Colangelo[5], Lorenzo Cotrozzi[2], Achim Denig[1], Anna Driutti[6,7], Tim Engel[8], Lois Flower[2,9], Andrea Gurgone[3,6,7], Martin Hoferichter[5], Fedor Ignatov[2], Sophie Kollatzsch[10,11], Bastian Kubis[12], Andrzej Kupść[13,14⋆], Fabian Lange[10,11], Alberto Lusiani[7,15], Stefan E. Müller[16], Jérémy Paltrinieri[2], Pau Petit Rosàs[2], Fulvio Piccinini[4], Alan Price[17], Lorenzo Punzi[7,15], Marco Rocco[10,18], Olga Shekhovtsova[19,20], Andrzej Siódmok[17], Adrian Signer[10,11⋆], Giovanni Stagnitto[21], Peter Stoffer[10,11], Thomas Teubner[2], William J. Torres Bobadilla[2], Francesco P. Ucci[3,4], Yannick Ulrich[2,5⋆] and Graziano Venanzoni[2,7⋆]
(RadioMonteCarLow 2 working group)

Radiative Corrections

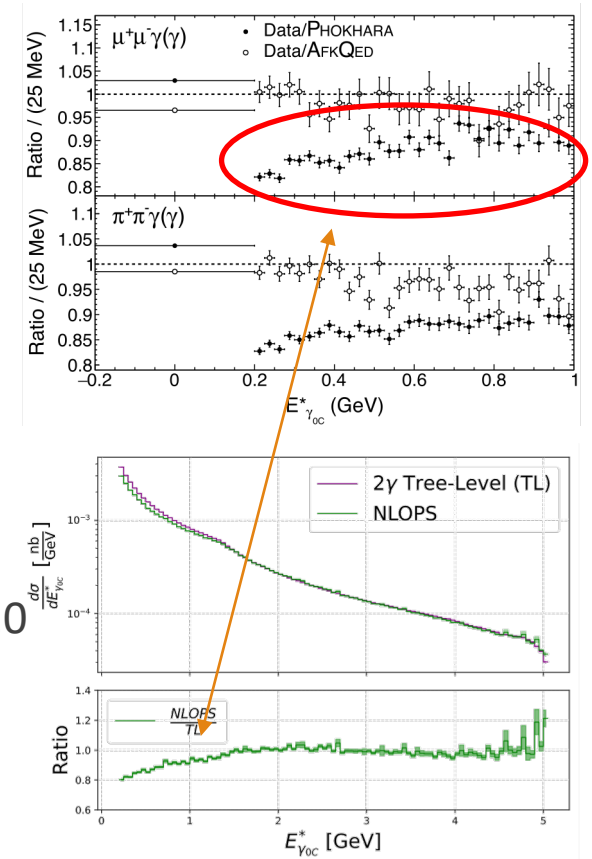
Investigation of events with 2 radiated photons by BaBar

- Phokhara is found to overestimate the contribution!
- Impact on various ISR analyses?
- Need dedicated studies, but which generators to use?

The RadioMonteCarLow 2 Working Group

- Review of available generators and radiative corrections
- Improve codes with new theoretical inputs
  - **First beyond NLO generator for ISR**: BaBayaga@NLO v2.0 [JHEP 05 (2026) 221]
  - Pion structure beyond scalar QED [arXiv:2603.28621, arXiv:2603.13171]
  - $e^+e^- \to \mu^+\mu^-\gamma$ @ NNLO (work on going) [Phokhara-Liverpool, McMule]

[Phys. Rev. D 108, L111103 (2023)]



[F. Piccinini @ muon (g-2) T.I. Meeting (2025)]

News from SND

Preliminary result presented at PhiPsi 2026

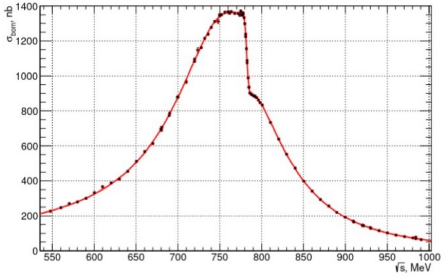
Experiment on **VEPP-2000 collider** (as CMD-3)

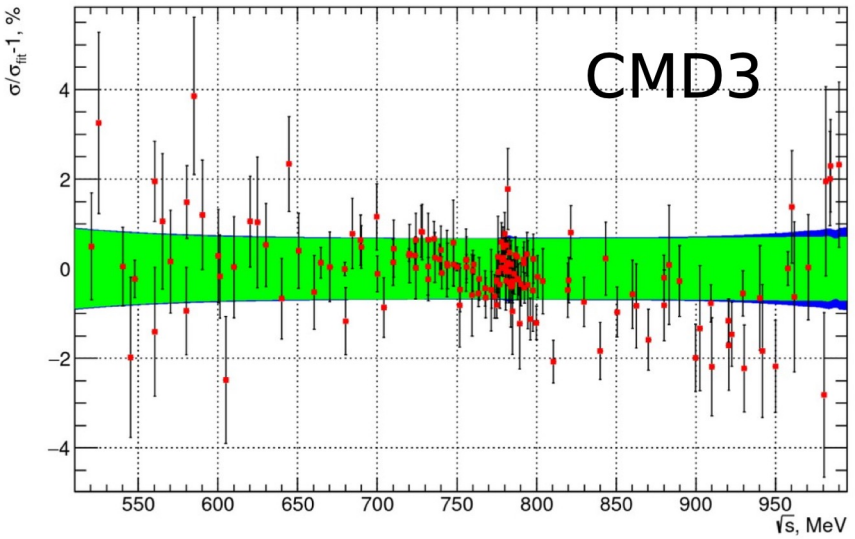
Selection based on:

- back-to-back topology
- PID with BDT

Uncertainty: ~0.7%

In agreement with CMD-3





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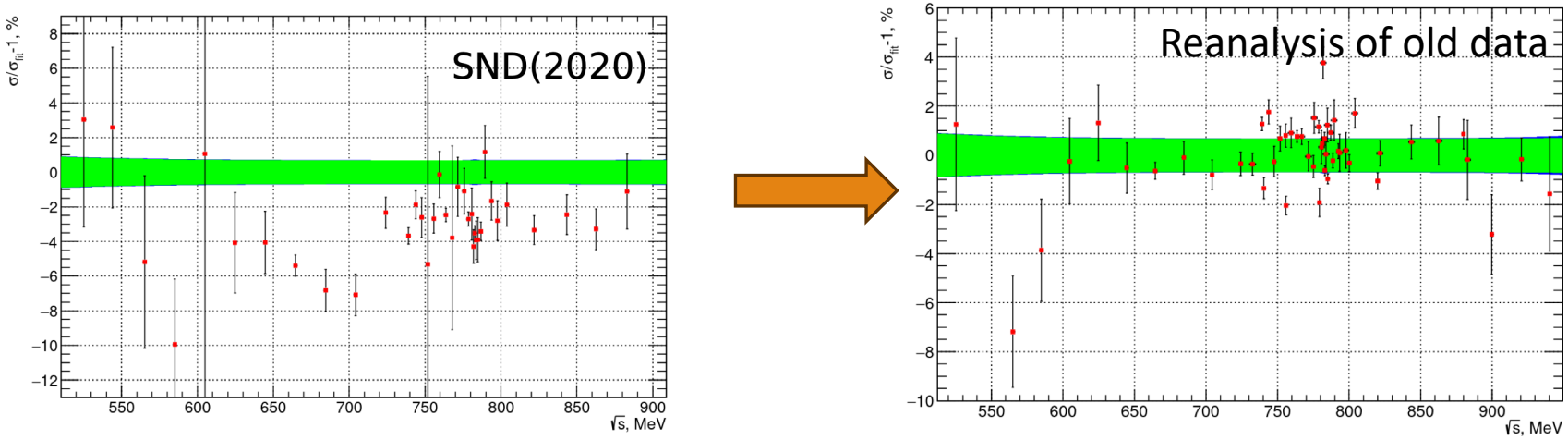

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Hints of unaccounted tracking inefficiency in old analysis

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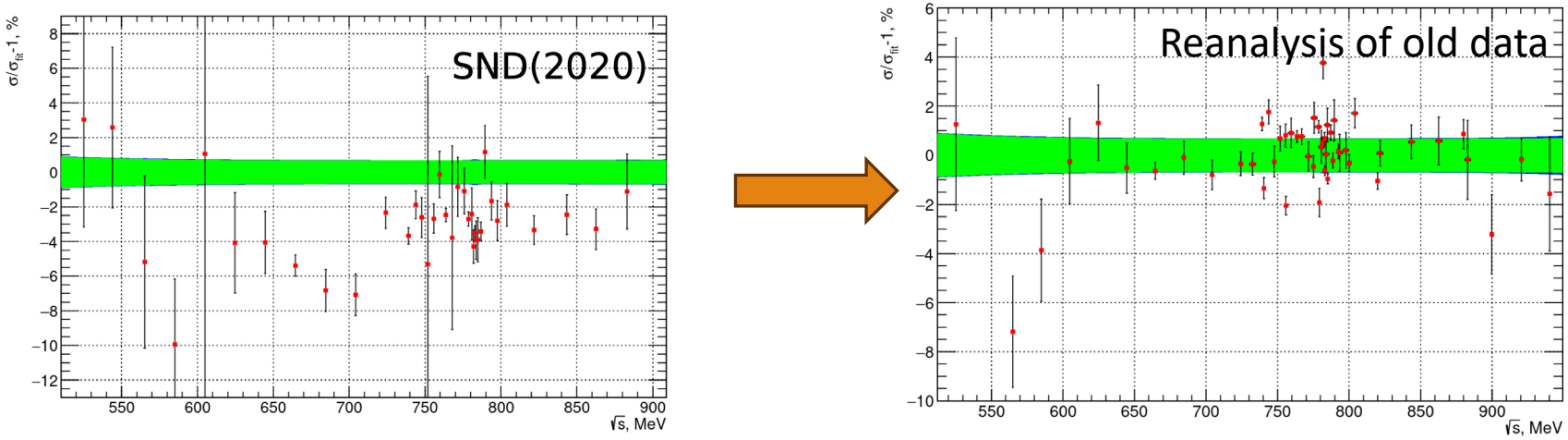


In agreement with CMD-3

Hints of unaccounted tracking inefficiency in old analysis

If confirmed, first validation of CMD-3 result with explanation!

New BaBar Measurement

Preliminary results presented at Lepton Photon 2025 [arXiv:2601.16587]

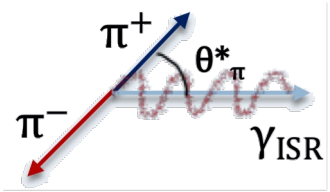
Full BaBar data set: 460 fb^{-1}@ Υ(4S)

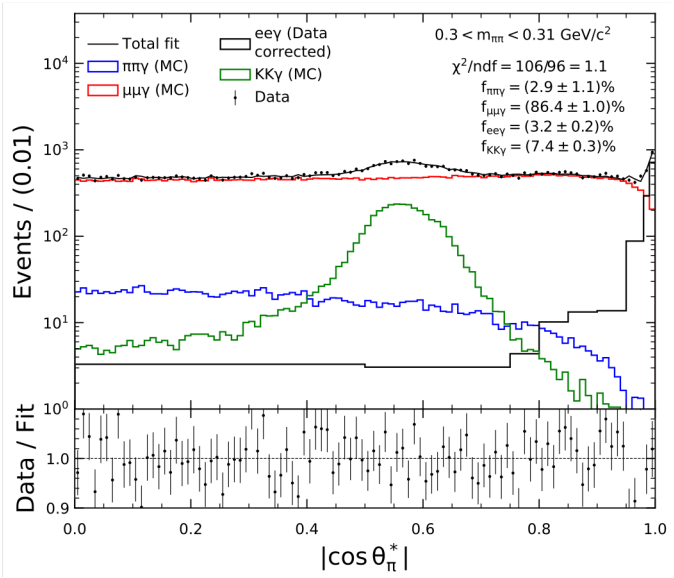
Normalization to $e^+e^- \rightarrow \mu^+\mu^-$

New technique for muon – pion separation

- Fit to helicity angle distribution
- Exploit different spins (μ = 1/2, π = 0)
- Simultaneous measurement of **μμγ(γ)** and **ππγ(γ)**

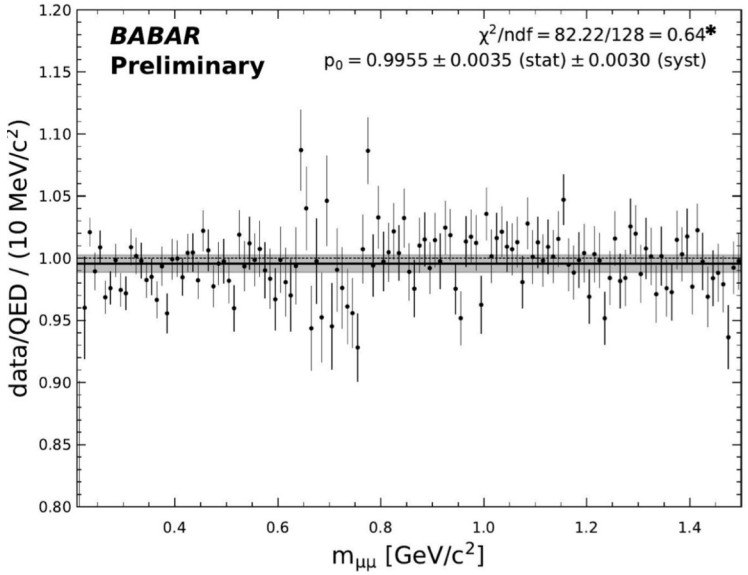
Blind Analysis





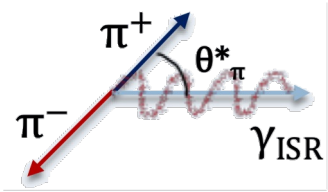
New BaBar Measurement

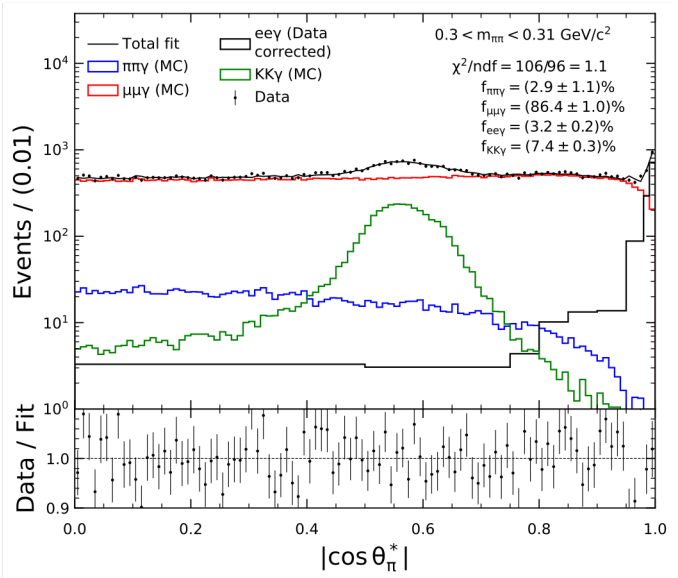
Preliminary results presented at Lepton Photon 2025 [arXiv:2601.16587]



QED test accuracy: 0.5%

Blind Analysis





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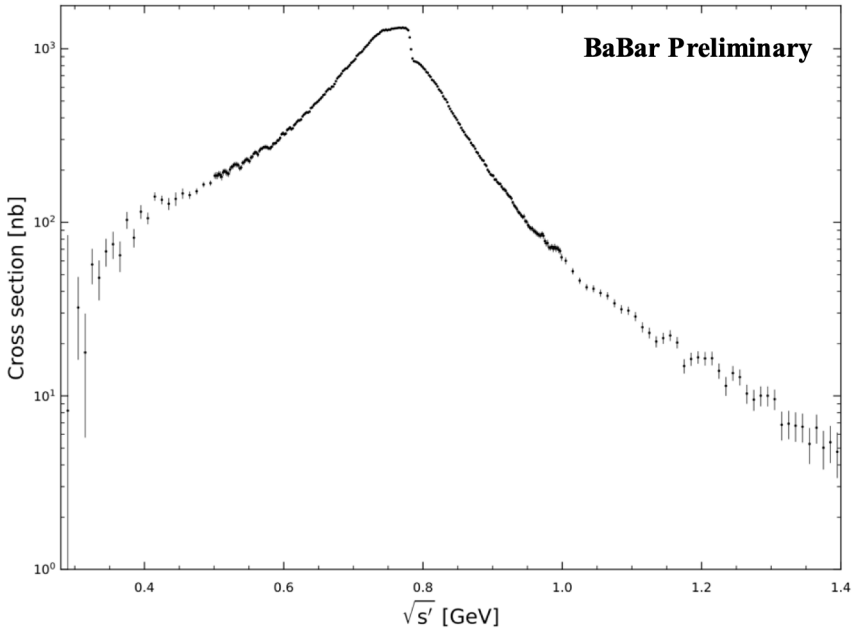

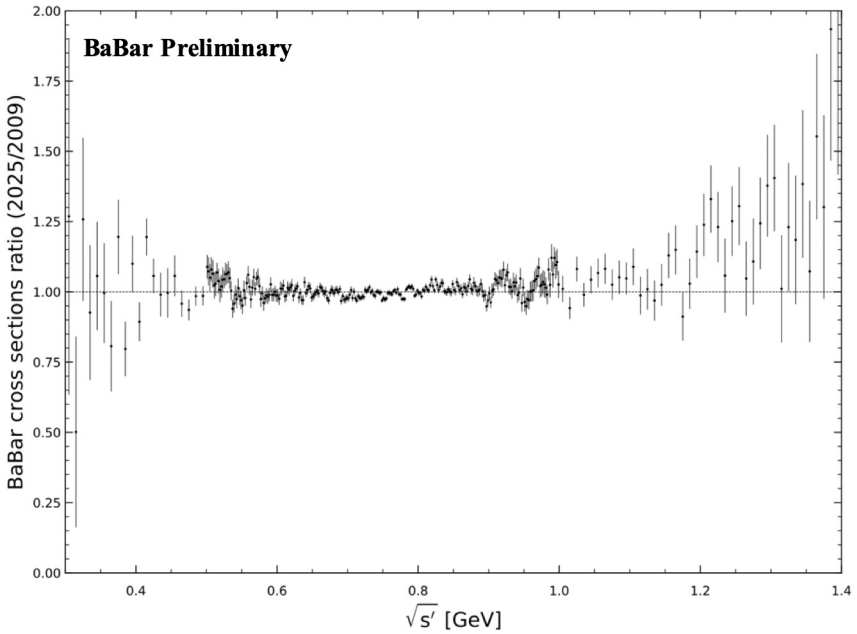

Pion FF in agreement with published result!

$a_\mu^{\pi\pi}(0.5\text{ -}1.4\text{ GeV}) = 4562(28)$ vs $4556(33)$ $(\times 10^{-11})$

What comes next?

- BESIII: [Phys.Rept. 1143 (2025) 1-158]
  - New measurements on-going
  - Aiming to achieve a final accuracy of *O*(0.5%)
  - First results, with O(0.7%) accuracy, expected soon
- Belle II: [Q. Liu@Muon g-2 TI meeting 2025]
  - Analysis of 427 fb^{-1} on-going
  - BaBar 2009 approach
  - Aim to *O*(0.5%) accuracy
- KLOE(-nxt): [L. Punzi@PhiPsi 2026]
  - Analysis of full KLOE data set (2 fb^{-1} vs 0.25 fb^{-1})
  - Aimed accuracy 0.4%, of which 0.2% from theory

All blind analyses

Conclusion

- Muon g-2 is (still) one of the most promising channels to test the SM
- Extremely successful experimental measurement at 0.19 ppm
- Now waiting for SM prediction to match the accuracy!
- Main limitation from hadronic contribution (HVP): Pion FF
- Huge effort on-going to understand the origin of the tensions
  - Theory: RadioMonteCarLow 2 initiative
  - New measurements: SND, BaBar, BESIII, Belle II, KLOE

Preparing for the next step in accuracy!