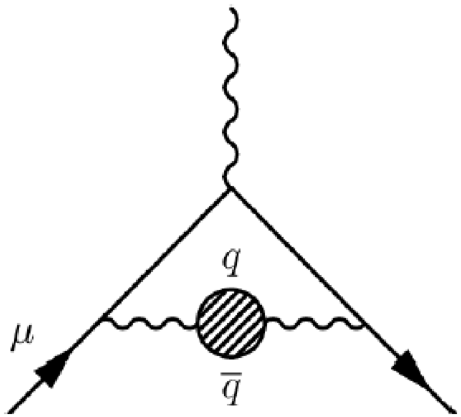
New BABAR studies of high-order radiation and the new landscape of data-driven hadronic vacuum polarization predictions of the muon g-2



HVP
Hadronic Vacuum Polarisation

BEACH 2024

XV International Conference on Beauty, Charm, Hyperons in Hadronic Interactions

Charleston, SC, USA

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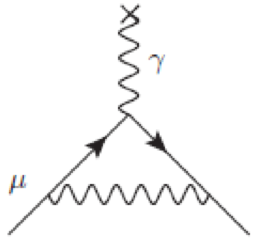
on behalf of the BABAR Collaboration

Outline

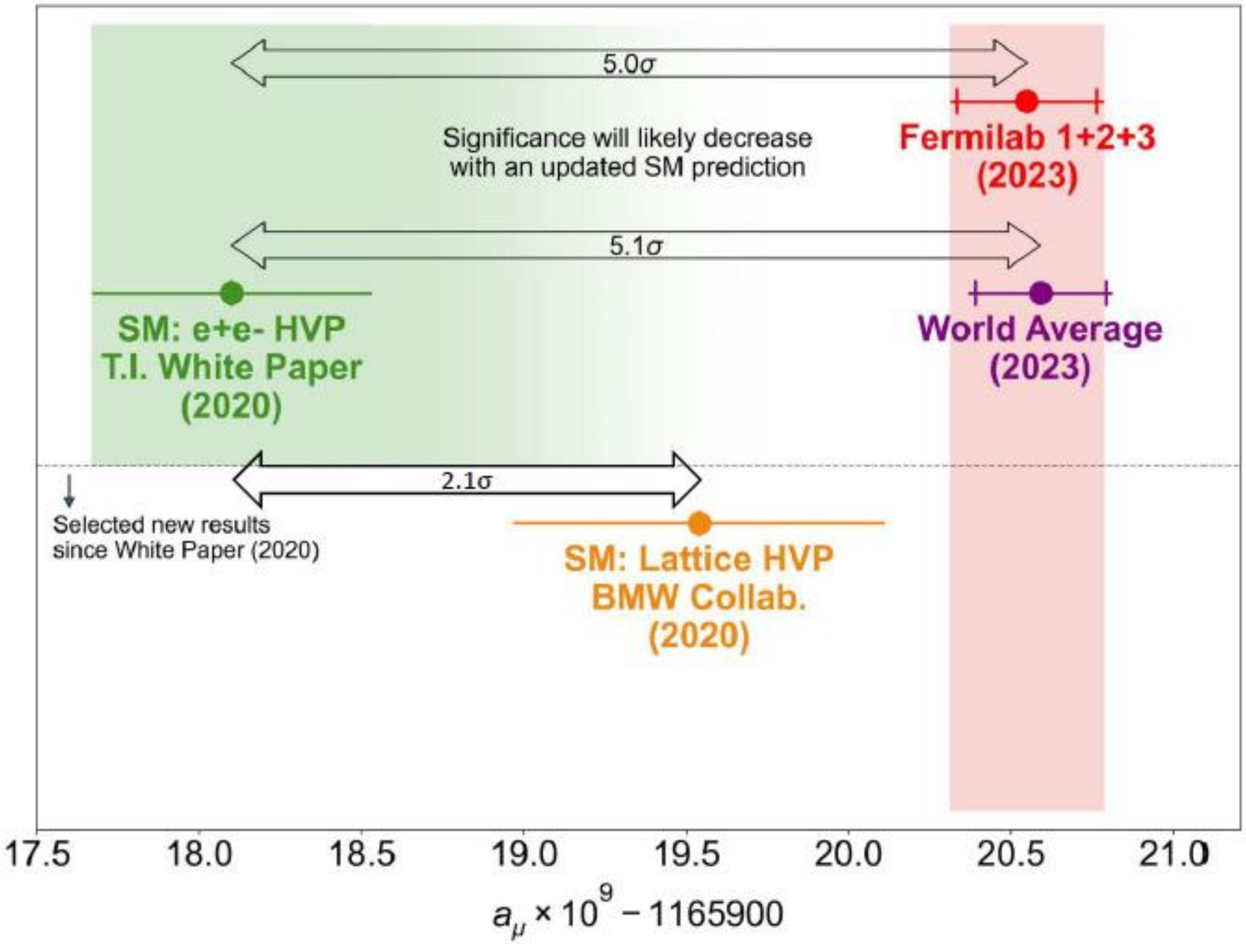
- Data-driven prediction for g-2
- Cross section measurements at BABAR
- Study of high-order radiation by BABAR
- New landscape of HVP prediction for g-2

Introduction to data-driven HVP evaluations for g-2

The g-2 puzzle



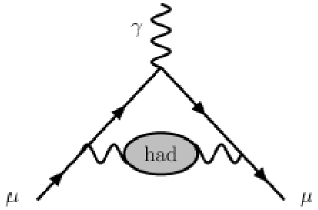
- Lepton anomalous magnetic moment:
  $$a_l = \frac{1}{2}(g-2)_l$$
- Precise test of the Standard Model
- Long-standing discrepancy between theory and experiment for the muon (g-2)



g-2 Calculation

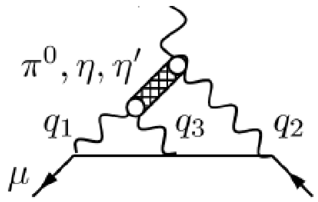
$$a_\mu = a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{EW}} + a_\mu^{\mathrm{hadronic}} + a_\mu^{\mathrm{NP?}}$$

Hadronic Vacuum Polarisation (VP)

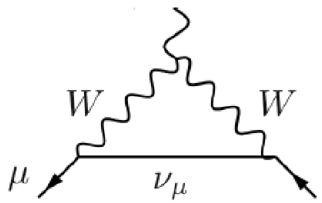


This talk

Hadronic light-by-light Scattering



Weak Interactions



QED	11 658 471.89	± 0.01
Leading hadronic vacuum polarization	693.1	± 4.0
Sub-leading hadronic vacuum polarization	-8.59	± 0.07
Hadronic light-by-light	9.2	± 1.7
Electroweak	15.36	± 0.10
Prediction	11 659 181.0	± 4.3

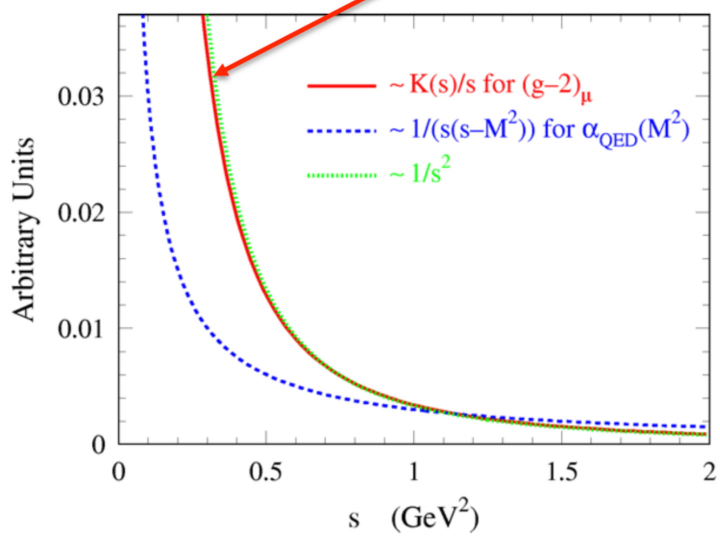
White Paper, Phys. Rep. 887 (2020)

units of 10^{-10}

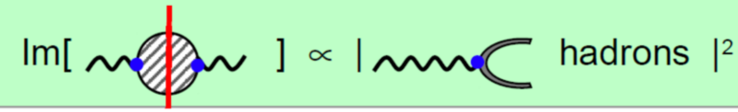
Dispersive approach

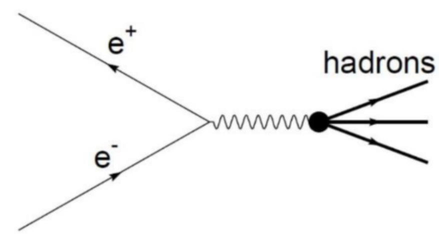
- Calculation of leading order hadronic vacuum polarization

$$a_\mu^{\text{had,LO}} = \frac{\alpha^2}{3\pi^2}\int_{4m_\pi^2}^{\infty} ds \, \frac{K(s)}{s} R(s)$$



$$12\pi \, \mathrm{Im}\Pi_\gamma(s) = \frac{\sigma^0 \, [e^+e^- \to \text{hadrons}\,(\gamma_{FSR})]}{\sigma_{pt}} \equiv R(s)$$



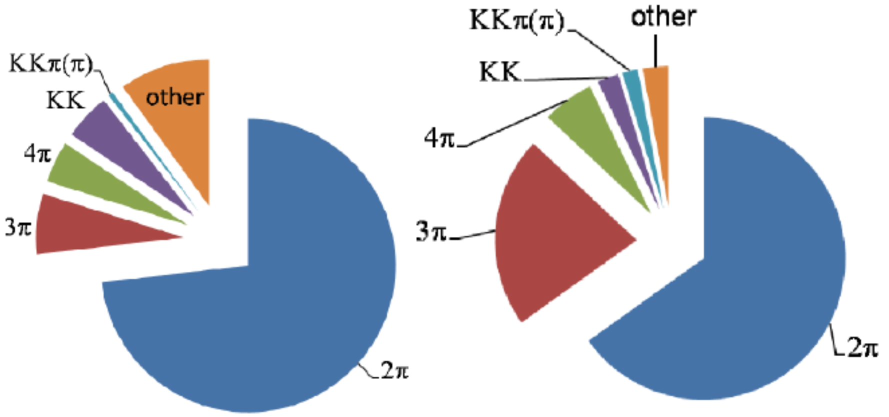


- Calculation needs experimental inputs: hadronic cross sections
- Low energy data contribute most

Hadronic cross sections and g-2

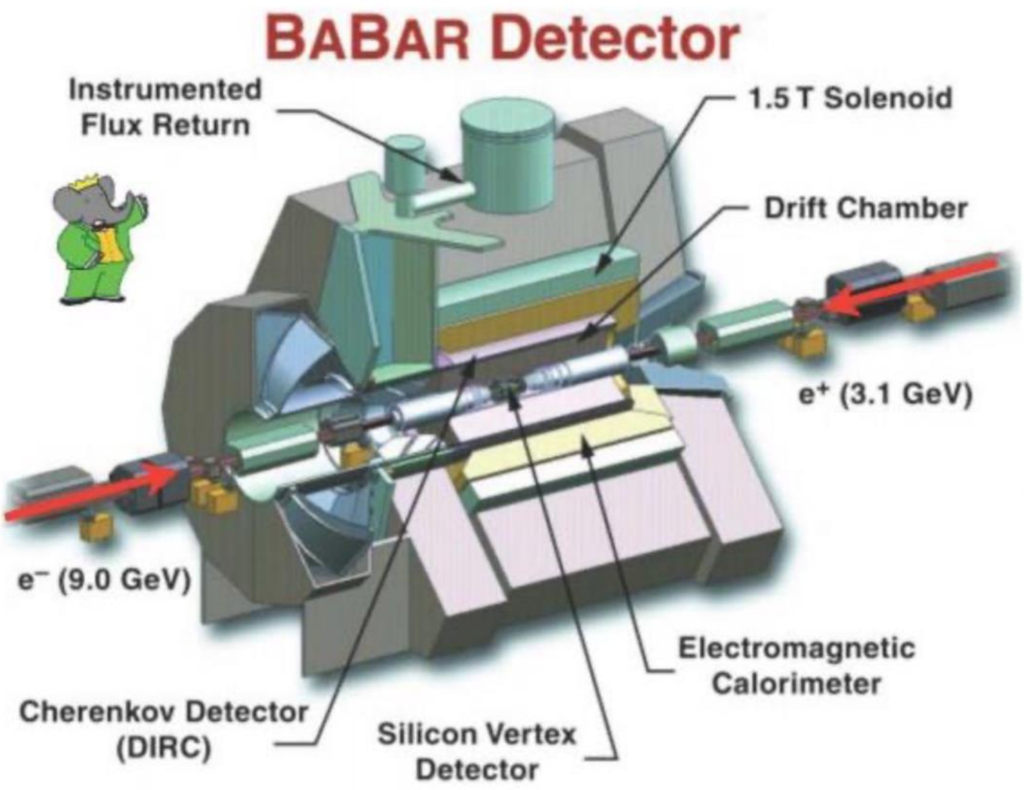
- At low energy total hadronic cross section determined from finite sum of exclusive modes
- $e^+ e^- \rightarrow \pi^+ \pi^- (\gamma)$ mode most important
  - Dominant contribution to the value (73%) of a_μ^{had} and to its uncertainty squared (70%)
  - Discrepancy between various measurements

$a_\mu^{had,LO-VP}$ $\qquad$ $a_\mu^{had,LO-VP}$ uncertainty squared

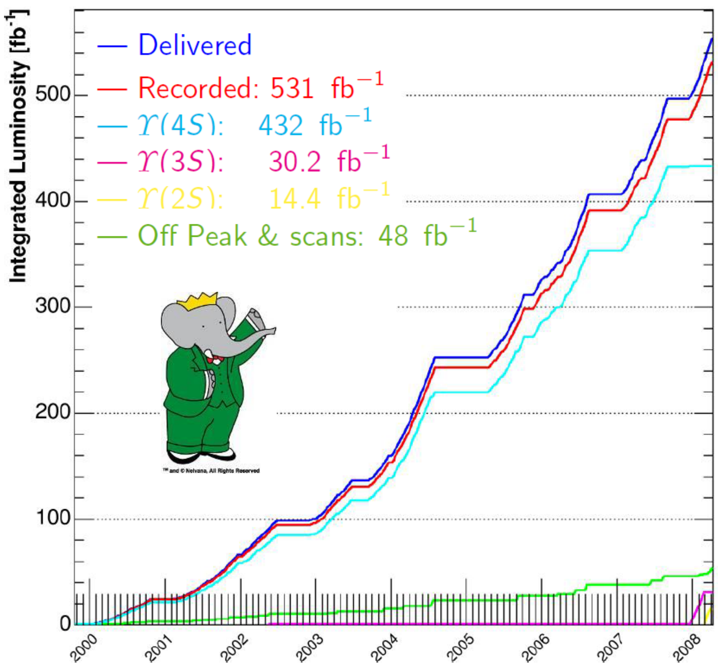


Hadronic cross section measurements in BABAR

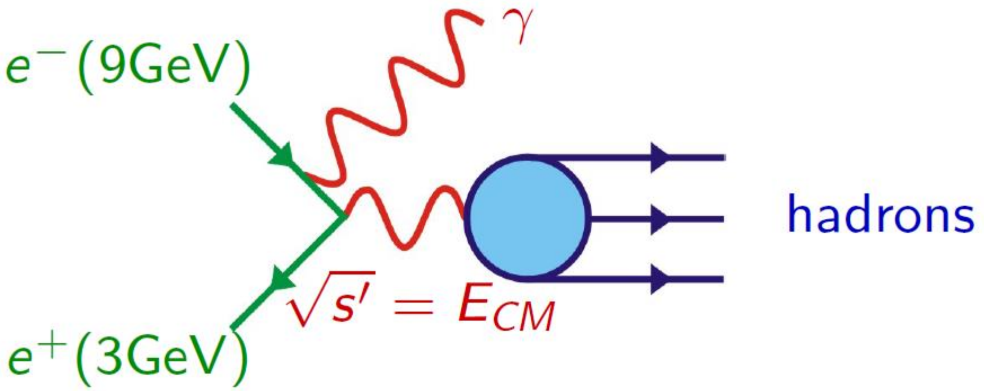
Detector and data sample

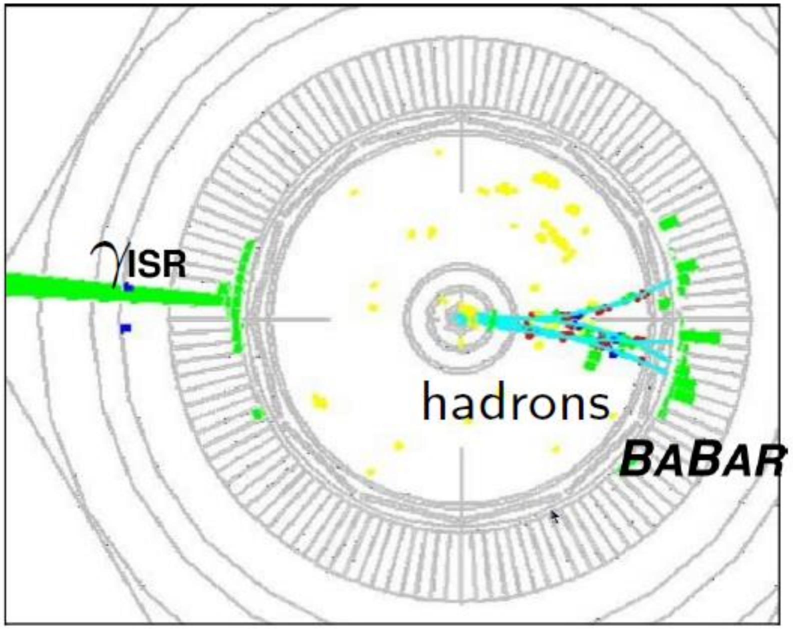


0.5 ab^{-1} over 10 years



ISR method

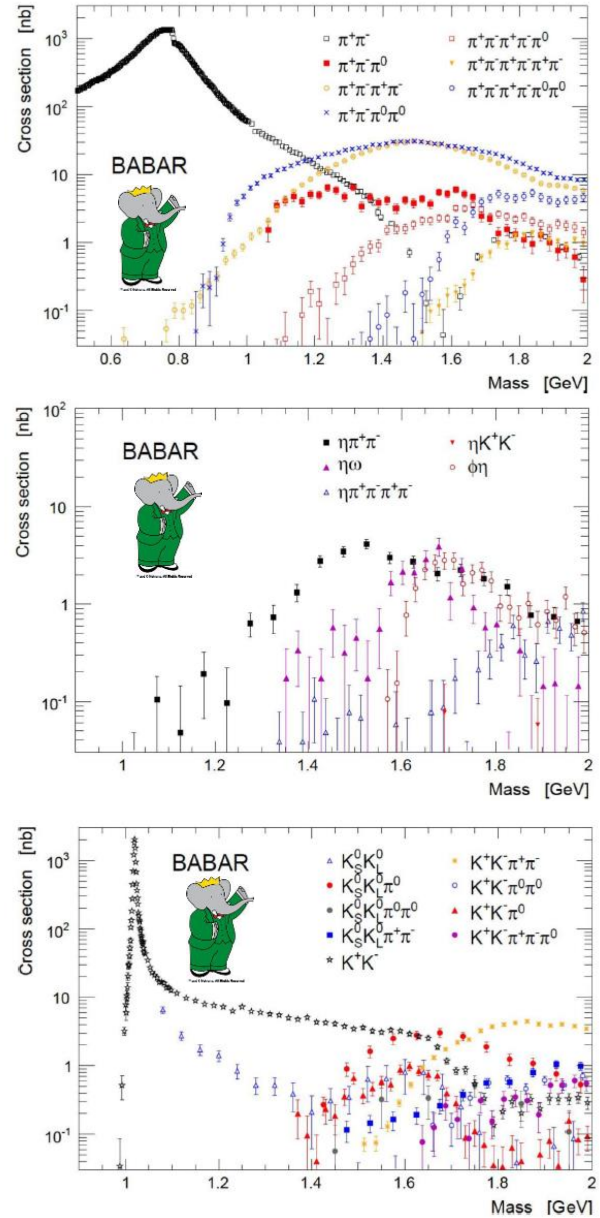




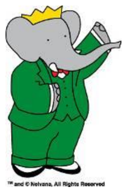
- Photon emitted from e^+ or e^- as Initial State Radiation (ISR).
  - allows to measure cross sections at low energy.
- Hadronic system boosted and back to back with photon.
  - Good detection even at threshold.
  - In detector acceptance: fully reconstructed.

Cross sections from BABAR

- Comprehensive program of hadronic cross section measurements in BABAR
- Many modes measured for the first time
- Contributions to a_μ from channels not directly measured but estimated from isospin symmetry
  - 0.87 ± 0.15 %   (DEHZ 2003)
  - 0.69 ± 0.07 %   (DHMZ 2010)
  - 0.09 ± 0.02 %   (DHMZ 2017)
  - 0.016 ± 0.016 %   (DHMZ 2019)



Additional radiation



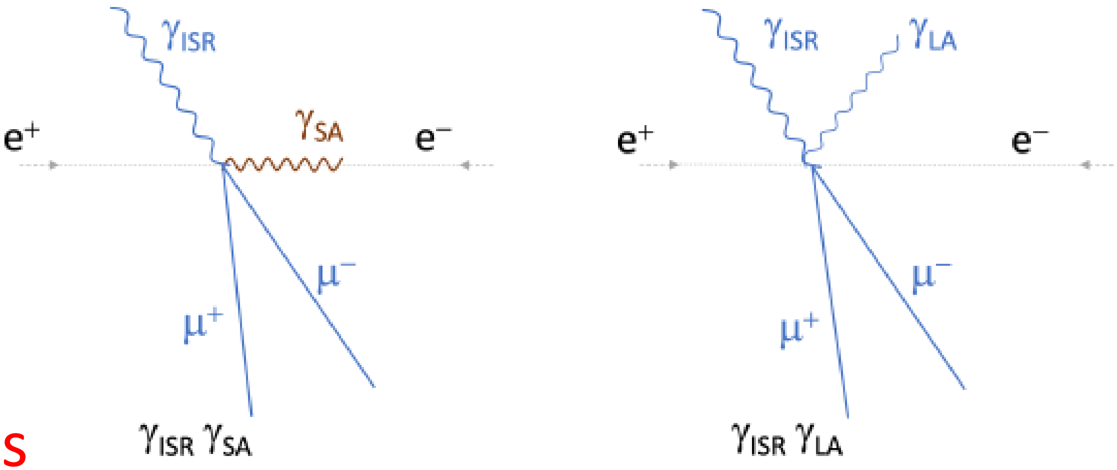
Measurement of additional radiation in the initial-state-radiation processes $e^+e^- \rightarrow \mu^+\mu^-\gamma$ and $e^+e^- \rightarrow \pi^+ \pi^-\gamma$ at BABAR, BABAR Collaboration, Phys. Rev. D 108, L111103 (2023)

Data samples

- Analysis on the full BABAR dataset: 468 fb^{-1}
  - 424 fb^{-1} on Υ(4S) peak, 44 fb^{-1} off peak
- MC signal samples: $e^+e^- \rightarrow \mu\mu\gamma(\gamma)$, $\pi\pi\gamma(\gamma)$
  - Phokhara9.1: full NLO ISR (10 x data stat)
    - Including large angle ISR and ISR-FSR interference
  - AfkQED: NLO + NNLO ISR (1/2 x data stat)
    - Collinear approximation for ISR γ
- MC background samples
  - Phokhara9.1/AfkQED : K K γ / $\pi^+ \pi^- \pi^0$ γ, $\pi^+ \pi^- 2\pi^0$ γ, …
  - JETSET: $q\,\bar{q}$
  - KK2f: $\tau^+ \tau^-$

'NLO' fits

- Two tracks
  - Opposite charge
- ISR photon
  - Largest $E_\gamma^* > 4$ GeV
  - $0.35<\theta<2.4$ rad

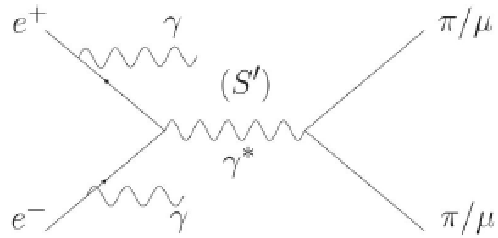


- Two 'NLO' kinematic fits
  - Small angle (SA): γ fitted assuming collinear approximation
  - Large angle (LA): γ detected, $0.35<\theta<2.4$ rad
- Three categories
  - NLO SA sample: $E_{\gamma SA}^* > 200$ MeV, $\chi^2_{SA} < \chi^2_{LA}$
  - NLO LA sample: $E_{\gamma LA} > 200$ MeV, $\chi^2_{LA} < \chi^2_{SA}$
  - LO sample: other events with no γ above threshold

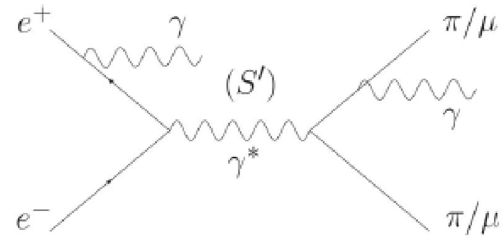
‘NLO’ LA fit results

- LA ISR and FSR separation
  - Using minimum angle between additional photon and tracks
  - Separation at 20 deg.

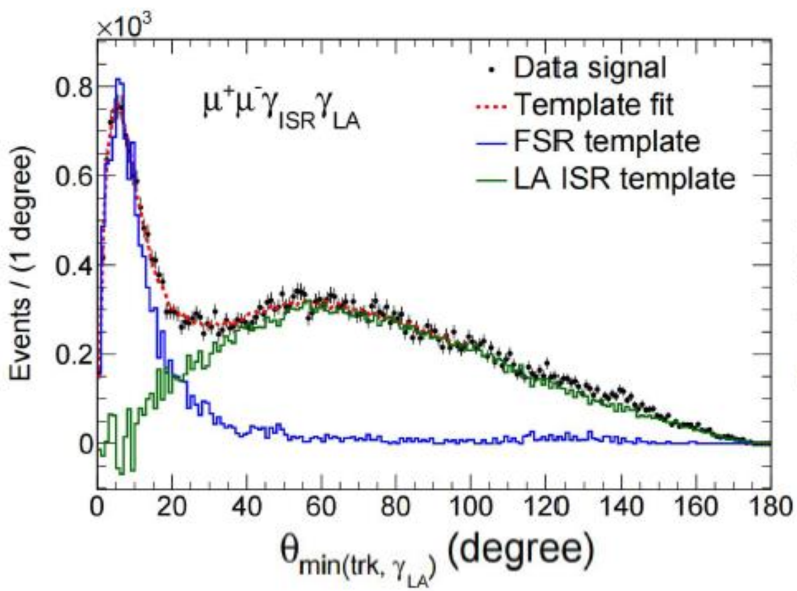
Next-to-leading-order **(NLO) ISR**

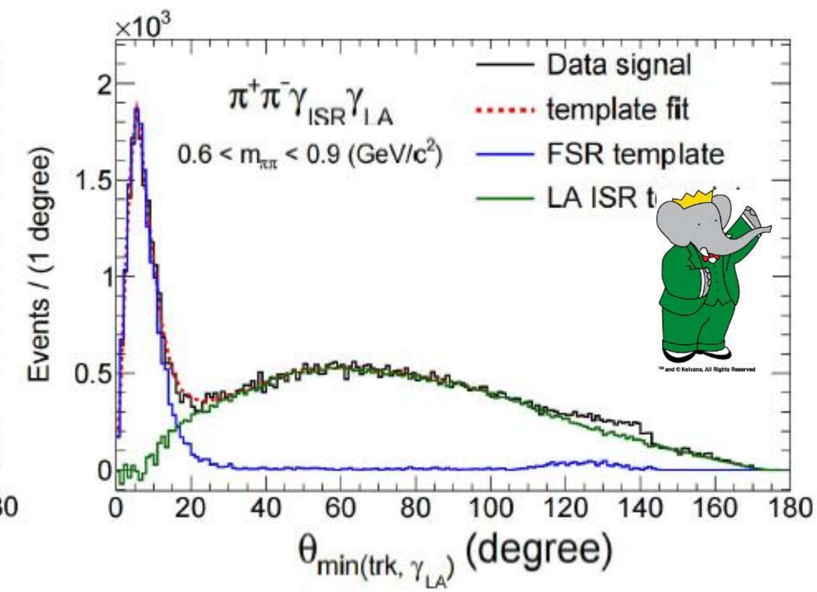


Next-to-leading-order **(NLO) FSR**

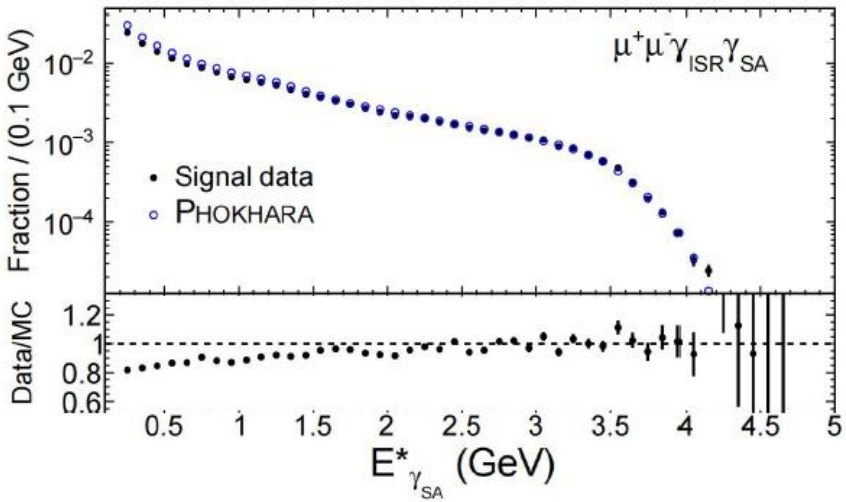


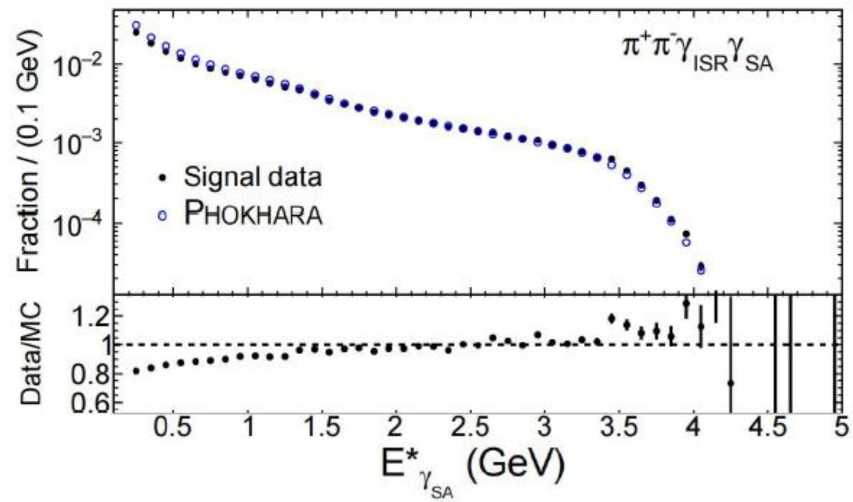
- Good agreement with MC



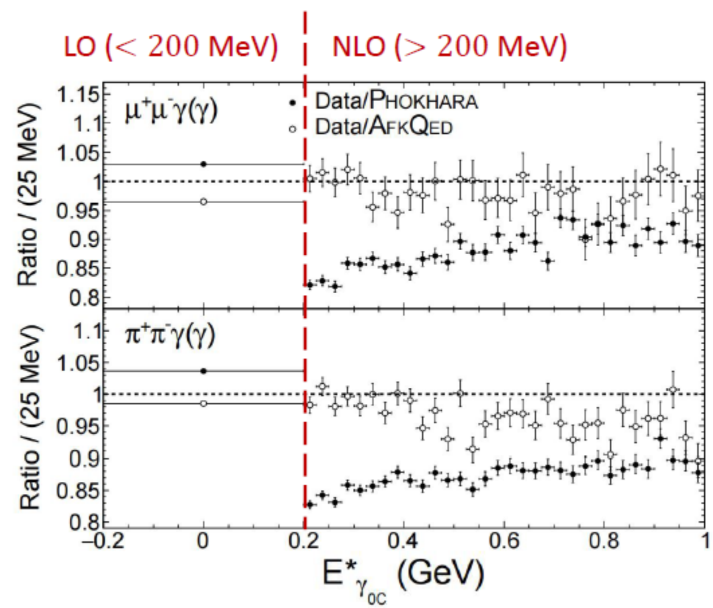


'NLO' SA fit results





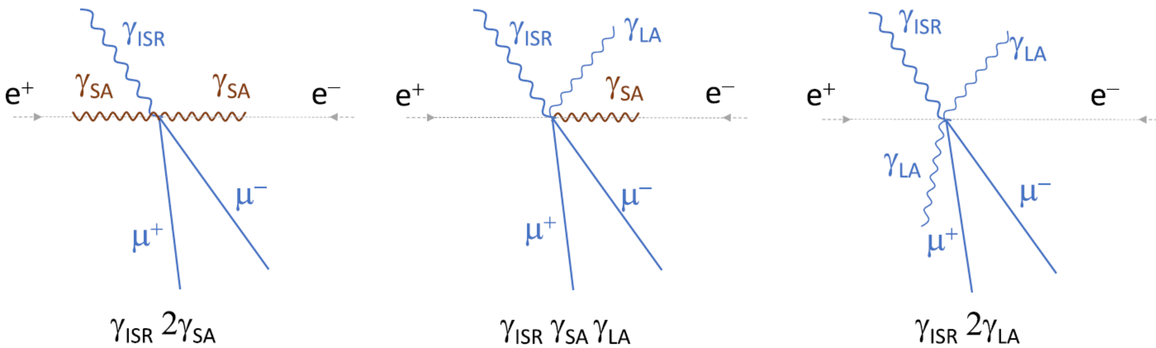
- Excess of SA events in Phokhara
  - Especially at lower energies
  - Even with zero-constraint (0C) (no collinear assumption)



- AfkQED consistent with data

'NNLO' fits

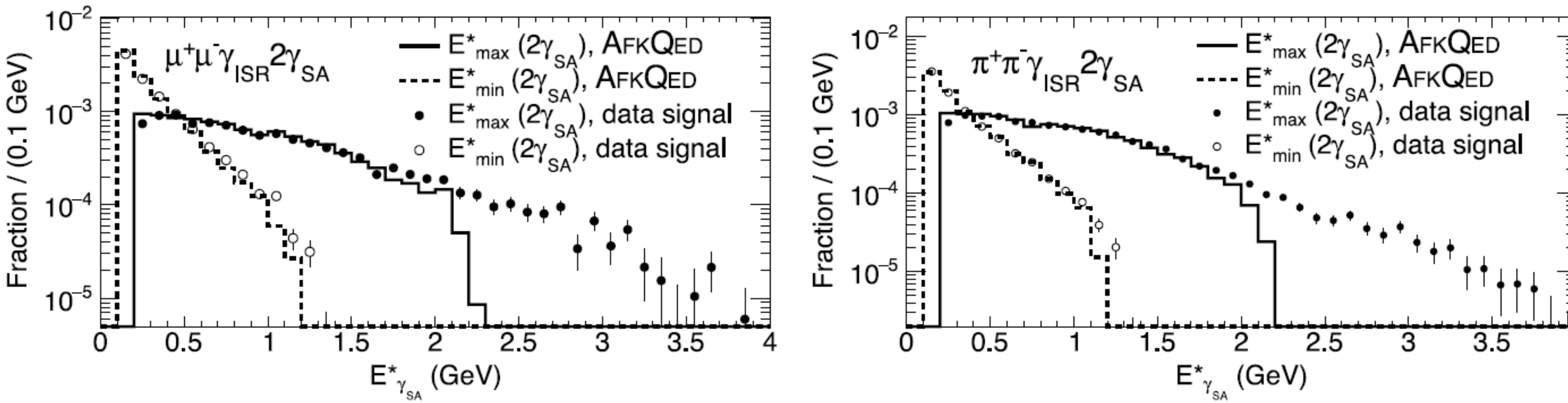
- Three 'NNLO' fits
  - 2SA, SA+LA, 2 LA
  - Events assigned to a category if χ^2 smaller than any other category
- Significant NNLO signal observed
  - With a fraction of about 3.5%
  - 2SA category dominant



Category	$\mu\mu$ $m_{\pi\pi} < 1.4\,\mathrm{GeV}/c^2$	$\pi\pi$ $0.6 < m_{\pi\pi} < 0.9\,\mathrm{GeV}/c^2$
LO	0.7716(4)(14)	0.7839(5)(12)
NLO SA-ISR	0.1469(3)(36)	0.1401(2)(16)
NLO LA-ISR	0.0340(2)(9)	0.0338(2)(9)
NLO ISR	0.1809(4)(35)	0.1739(3)(20)
NLO FSR	0.0137(2)(7)	0.0100(1)(16)
NNLO ISR [a]	0.0309(2)(38)	0.0310(2)(39)
NNLO FSR [b]	0.00275(6)(9)	0.00194(12)(50)
NNLO 2LA [c]	0.00103(3)(1)	0.00066(4)(4)

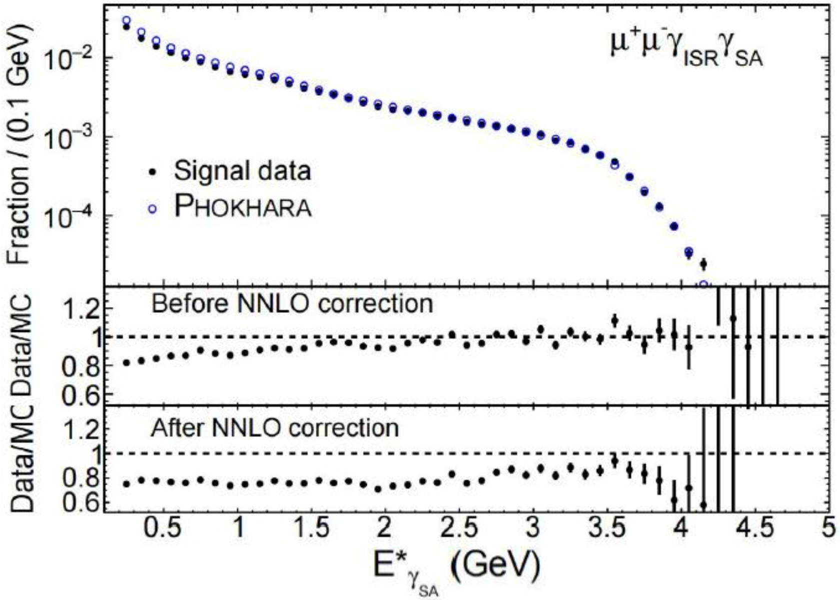
[a] NNLO ISR = 2SA-ISR or SA-ISR + LA-ISR
[b] NNLO FSR = SA-ISR + LA-FSR
[c] NNLO 2LA = 2LA-ISR, LA-ISR + LA-FSR or 2LA-FSR

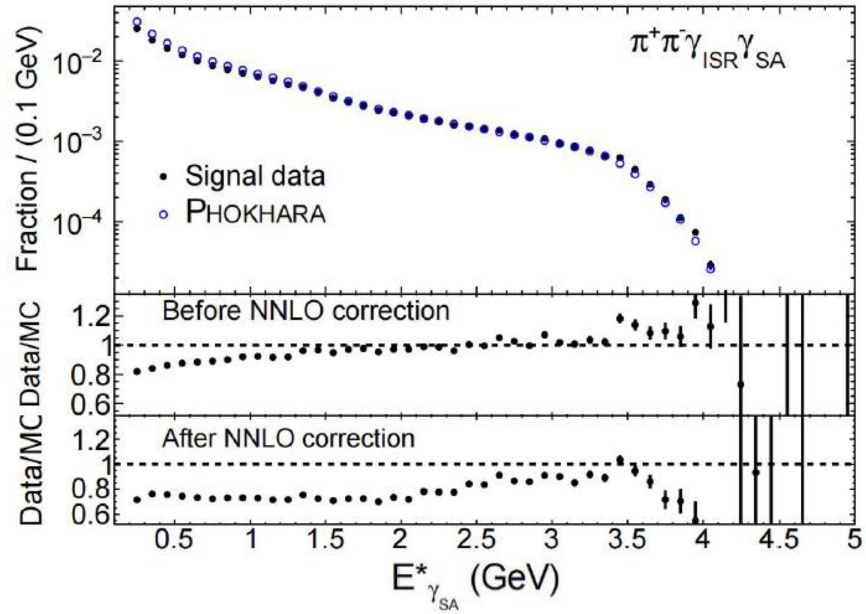
'NNLO' 2 SA fit results



- Higher E^*_γ > 200 Mev, lower E^*_γ > 100 MeV
- Good agreement in E^*_γ shape with AfkQED up to 2.3 GeV

NNLO correction to ‘NLO’ SA results





- Correct for migration between categories
  - NNLO 2 SA from same beam not distinguishable from NLO SA
- Better agreement in shape but still excess of 25% in Phokhara

Consequences

- How does this affect current $e^+e^- \to \pi^+\pi^-(\gamma)$ cross sections measurements?

- BABAR analysis essentially unaffected
  - Performed with loose selection
  - Using ππ/μμ ratio
  - Efficiencies obtained with data
  - The effect of Phokhara excess on acceptance is (0.03±0.01)% well below the quoted systematic uncertainty of 0.5%

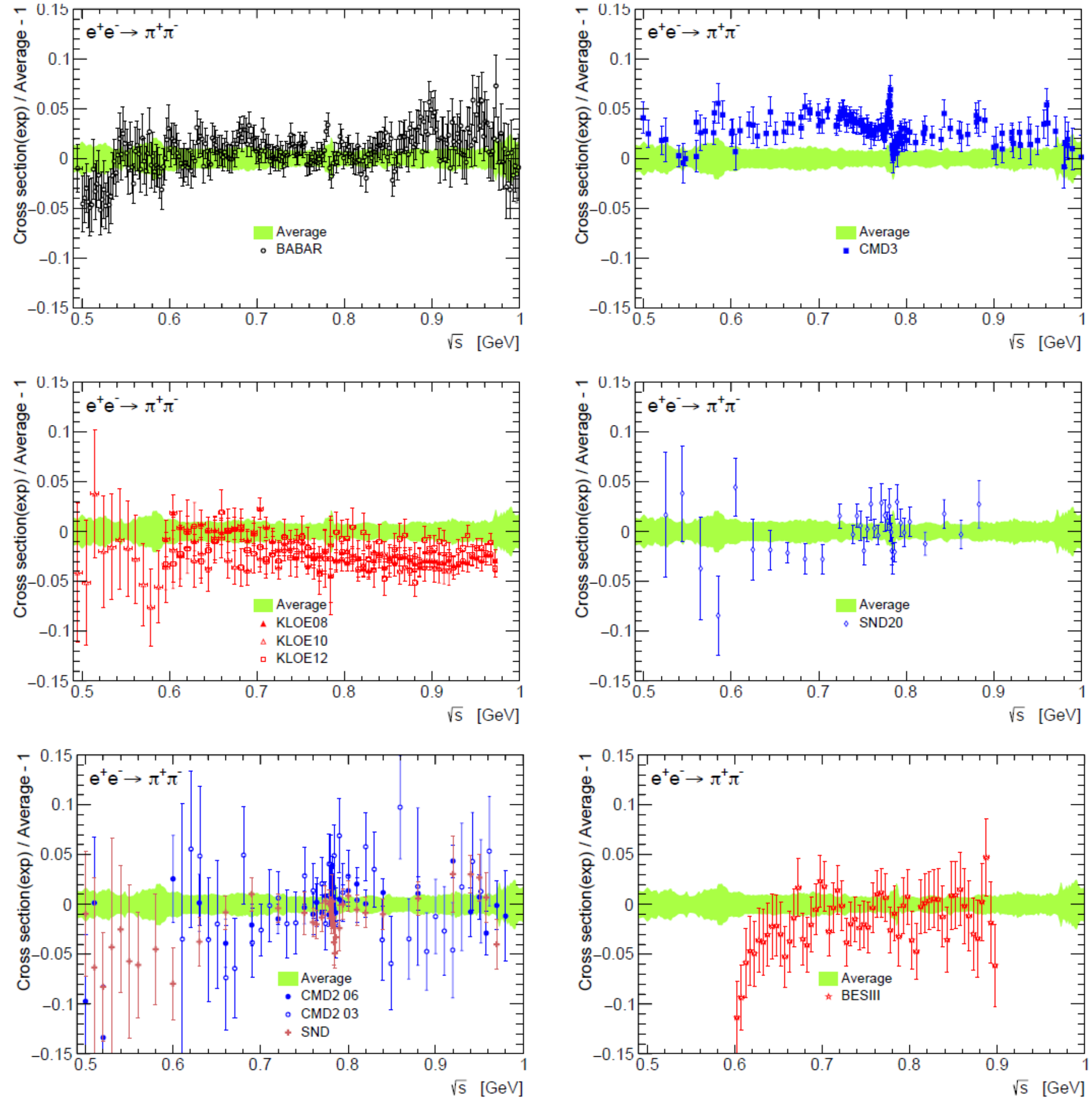
- Other ISR results relying on Phokhara might be affected
  - Larger systematics?

New landscape of data-driven HVP predictions for g-2

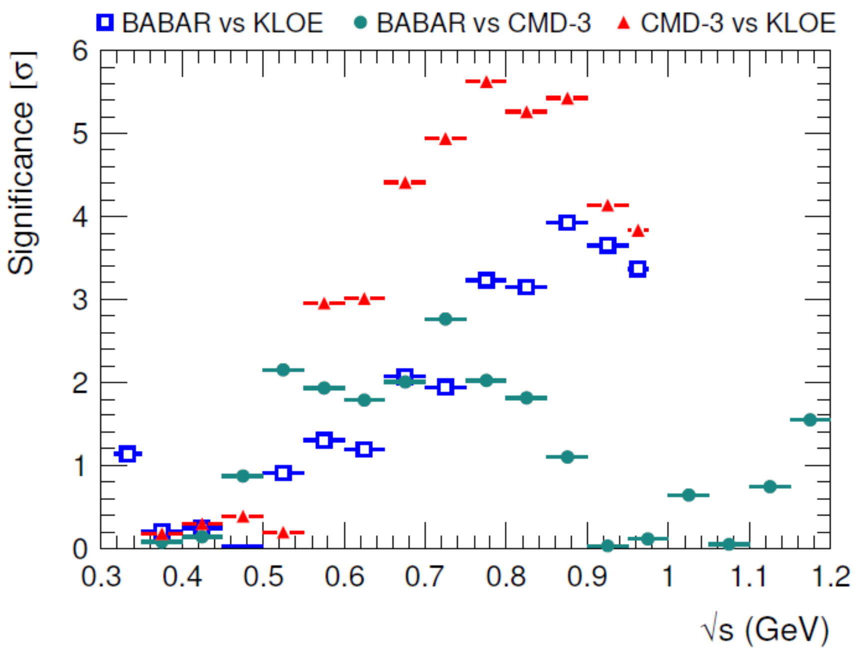
Tensions in $e^+e^- \to \pi^+ \pi^- (\gamma)$ measurements: the new landscape of data-driven hadronic vacuum polarization predictions for the muon g-2,
M. Davier, A. Hoecker, A.M. Lutz, B. Malaescu, and Z. Zhang,
arXiv:2312.02053 (2023)

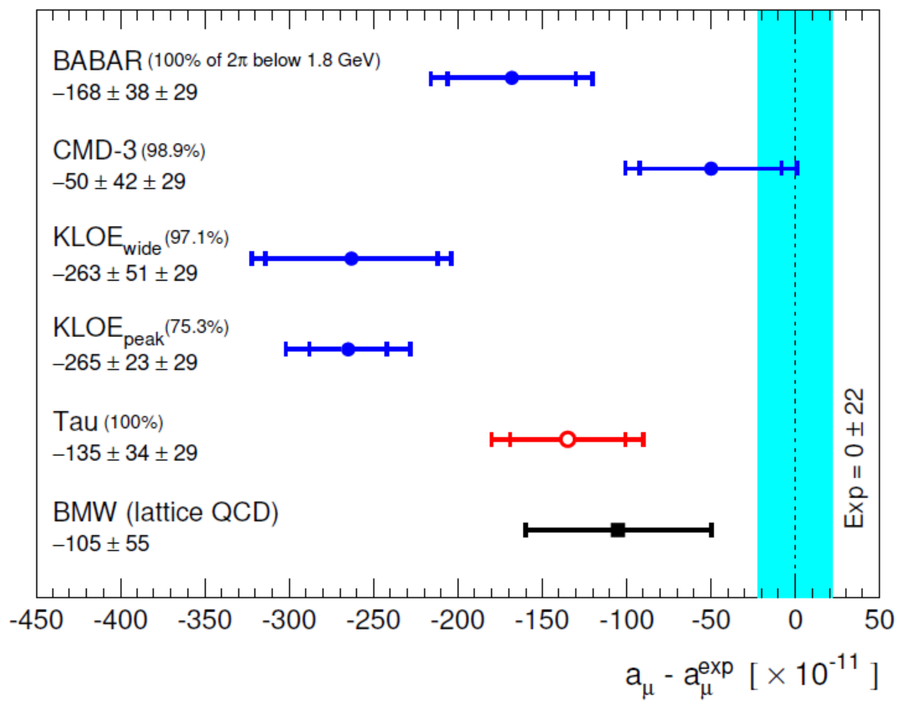
$e^+ e^- \to \pi^+\pi^-$ cross sections

- Dominant channel for g-2 prediction (value and uncertainty)
- Long-standing tension between KLOE and BABAR
- Recent CMD3 results



Tensions in $e^+ e^- \rightarrow \pi \pi$ cross sections and impact on g-2 prediction





Significance of differences between BABAR, KLOE and CMD3

- BABAR + CMD3 + τ
  - 2.5 σ below experiment
  - compatible with BMW

Upcoming $e^+ e^- \rightarrow \pi^+\pi^-$ analyses

- New results expected in the near future from many experiments: SND, CMD3, KLOE, BESSIII, BABAR and Belle II

- In BABAR, new analysis will
  - Increase data sample: 232 fb^{-1} → 468 fb^{-1}
  - Replace PID requirement (and associated momentum cut) with new technique based on angular distributions
    - Larger statistics : effective gain by a factor 7
    - Smaller systematics

Summary

- Recent progress on g-2 in all directions
  - Direct measurement
  - Lattice calculation
  - Data-driven prediction
    - Cross section measurements
    - Study of high-order radiation
    - Study of impact of $\pi^+\pi^-$ inputs
- May lead to a reduced discrepancy between experiment and theory for the muon g-2
- Expect new measurements by next year