Experimental Input to the Hadronic Corrections of the muon g-2

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SFB 1044 THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

Cluster of Excellence PRISMA+

DFG Deutsche Forschungsgemeinschaft

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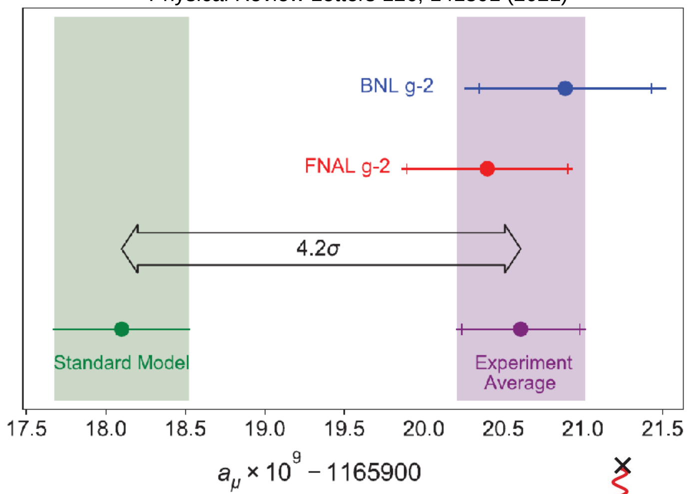
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

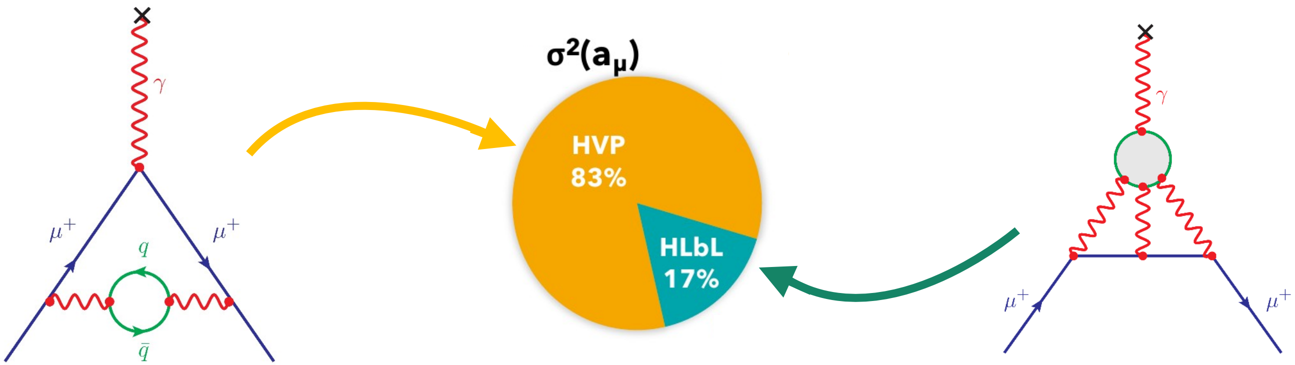
Anomalous Magnetic Moment of the Muon

Physical Review Letters 126, 141801 (2021)

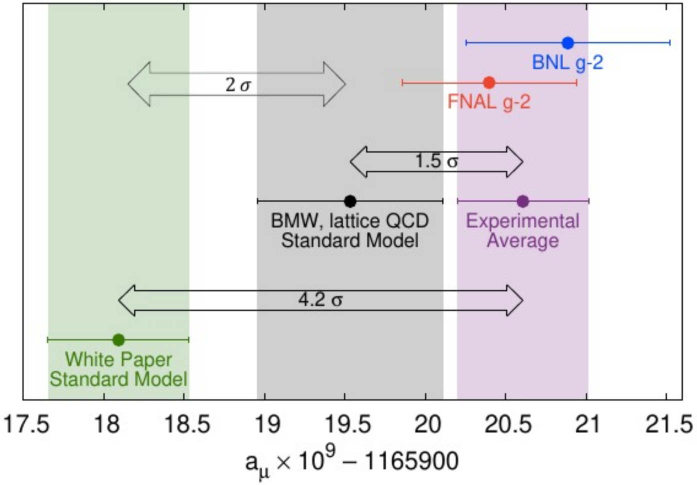


Muon anomaly $a_\mu = \frac{g_\mu - 2}{2}$

- Less than 0.5 ppm accuracy in experiment and theory
  - Exp: 116 592 061(41) × 10^{-11} (Physical Review Letters 126, 141801 (2021))
  - SM: 116 591 810(43) × 10^{-11} (Physics Reports 887 (2020) 1–16)
- Discrepancy between SM prediction and experiment
- Hadronic contributions dominate uncertainty of a_μ^{SM}

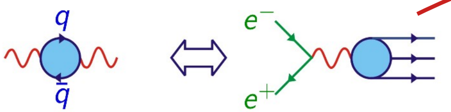


Hadronic Vacuum Polarizaton



Standard Model prediction (WP) data-driven

- Dispersive evaluation



$$a_\mu^{\text{HVP}} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{2m_\pi}^{\infty} \mathrm{d}s \frac{R(s)K(s)}{s^2}$$

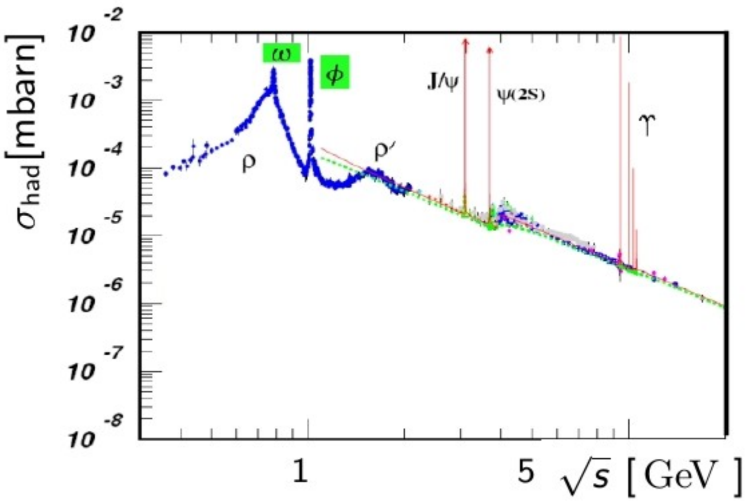
- Systematic improvement of prediction with improved measurements

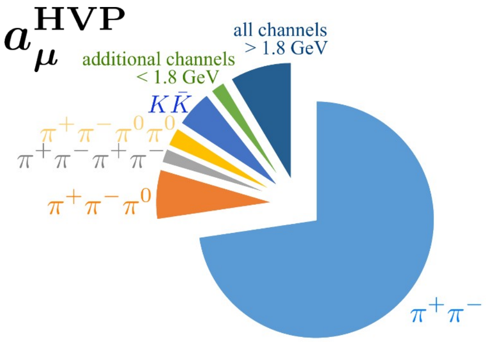
- Tension with FNAL result at 4.2σ
- Tension with Lattice QCD at ~ 2σ
- Better understanding strictly needed!

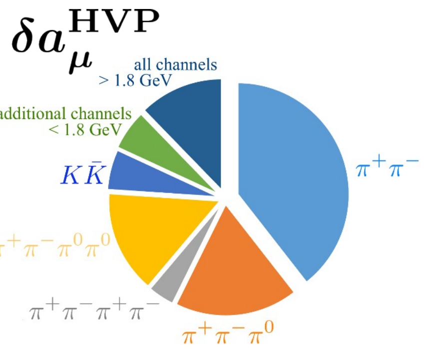
Hadronic Vacuum Polarizaton

$$a_\mu^{hVP,LO} = \frac{1}{4\pi^3} \int_{4m_\pi^2}^{\infty} K(s)\sigma(e^+e^- \to \mathrm{hadr})\mathrm{d}s$$

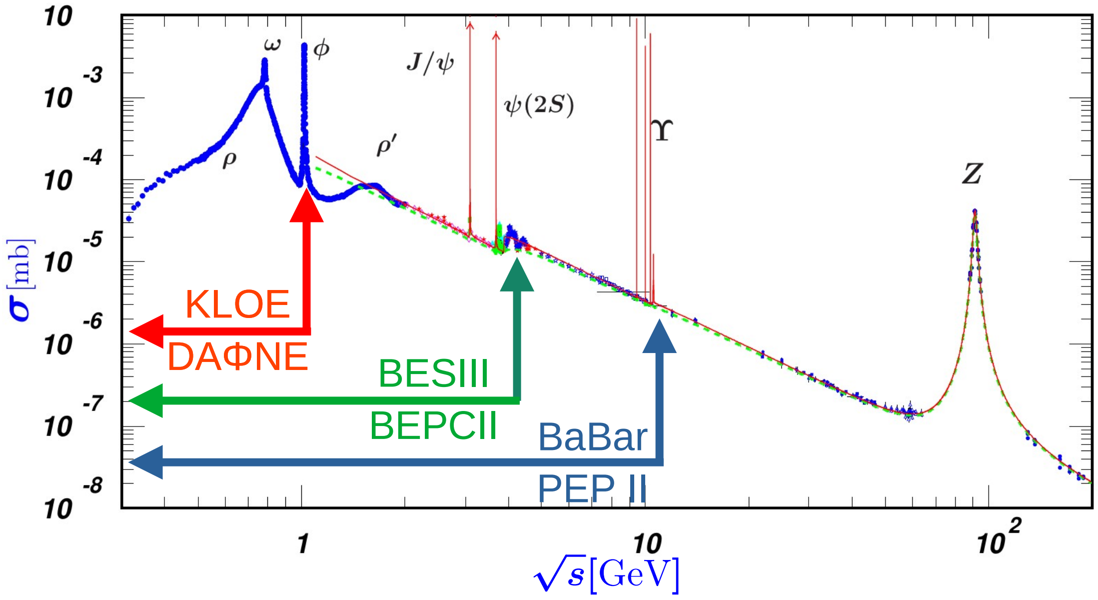
Low energy contributions dominate ! $\begin{cases} K(s) \sim \dfrac{1}{s} \\ \sigma(e^+e^- \to \mathrm{hadr}) \sim \dfrac{1}{s} \end{cases}$







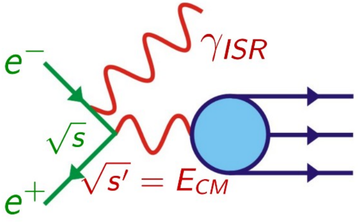
Energy Scan and Initial State Radiation



Energy Scan

- Measurement at single $\sqrt{s}$
- SND and CMD experiments (Novosibirsk)

Initial State Radiation (ISR)



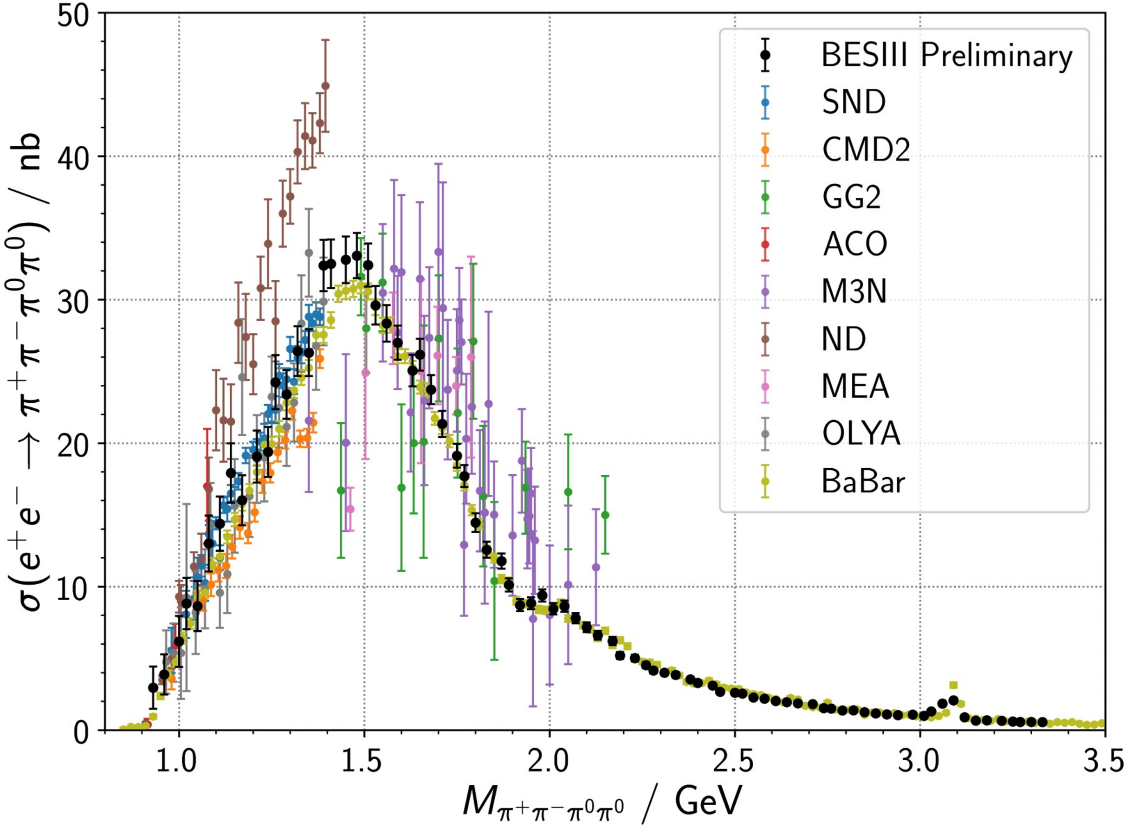
$$\sqrt{s'} = \sqrt{s - 2\sqrt{s}E_\gamma}$$

- Reduced effective $\sqrt{s}$
- Emission suppressed by $\frac{\alpha}{\pi}$
- Radiator function relates to non-radiative process

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

- (un)tagging of γ_{ISR} for different kinematics
  - Hadrons boosted to opposite hemisphere

Benefit of ISR Measurements



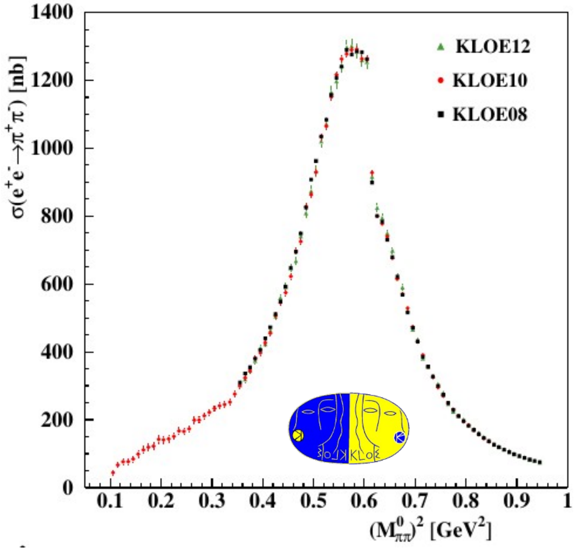
Pros:

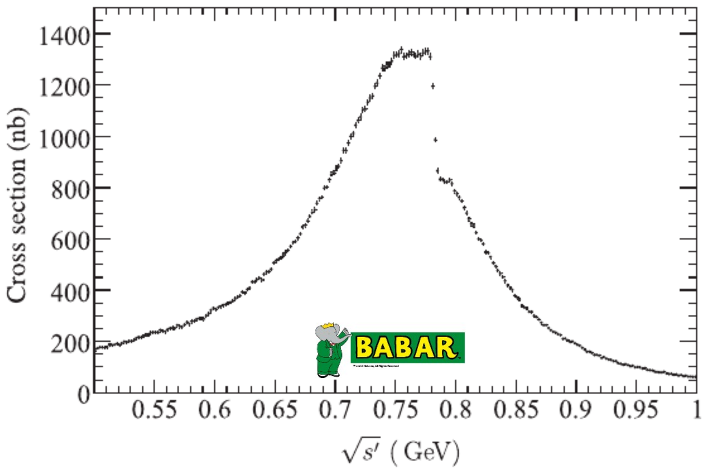
- "Scan" from fixed energy
- Consistent data taking conditions
- Access to threshold region
- Normalization fixed over full range

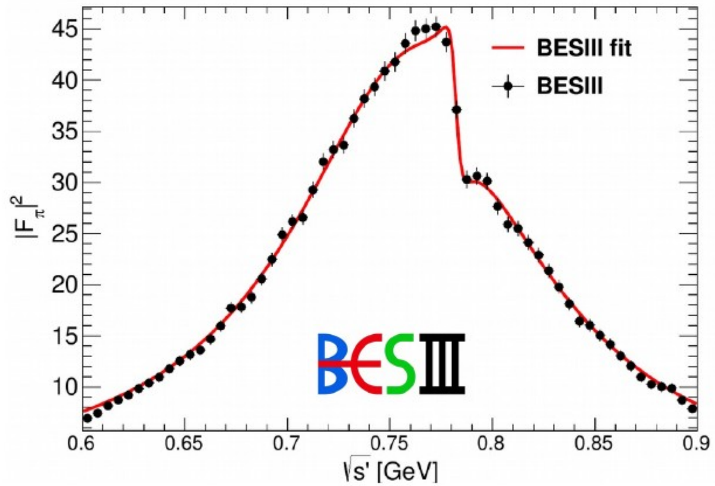
Cons:

- Limited energy resolution
- Uncertainty of radiator function
- FSR contribution

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







KLOE

- Three measurements
- Tagged and untagged ISR
- Track mass
- Different data / normalization procedure
- $\delta a_\mu / a_\mu = 0.6\%$

BaBar

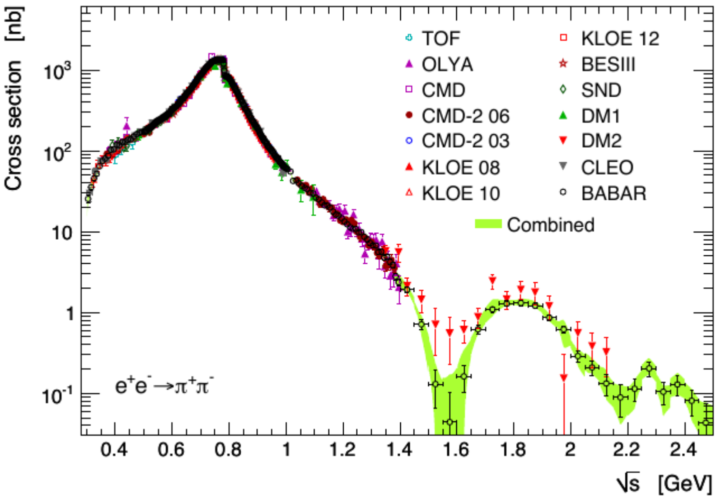
- Single measurement
- Tagged ISR
- Kinematic fit + PID
- Normalization to muon yield
- $\delta a_\mu / a_\mu = 0.7\%$

BESIII

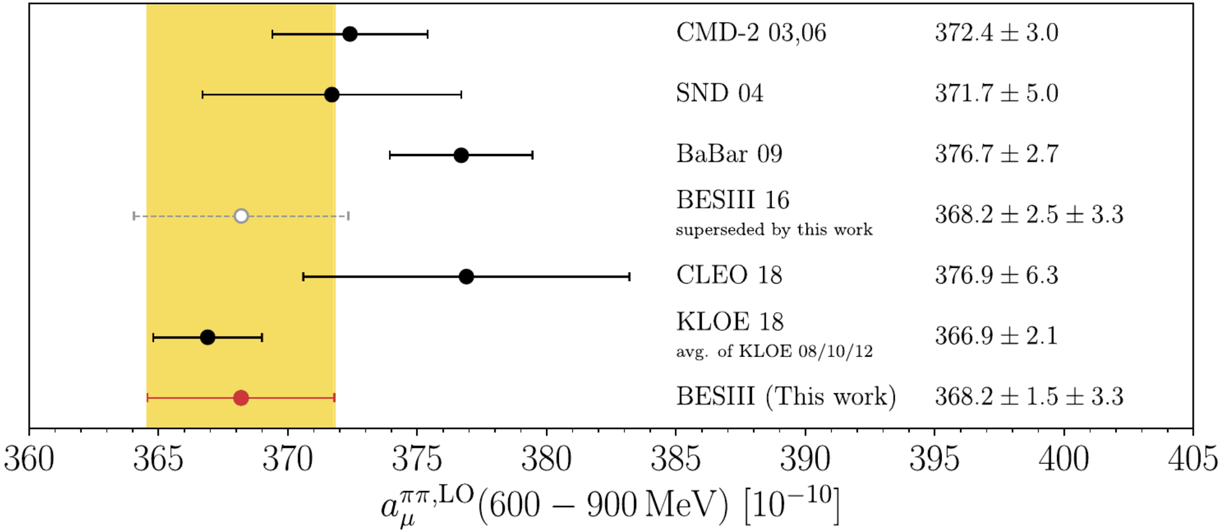
- Single measurement
- Tagged ISR
- Kinematic fit + PID
- Normalization to luminosity
- $\delta a_\mu / a_\mu = 0.9\%$

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

Eur.Phys.J. C80 (2020) 241



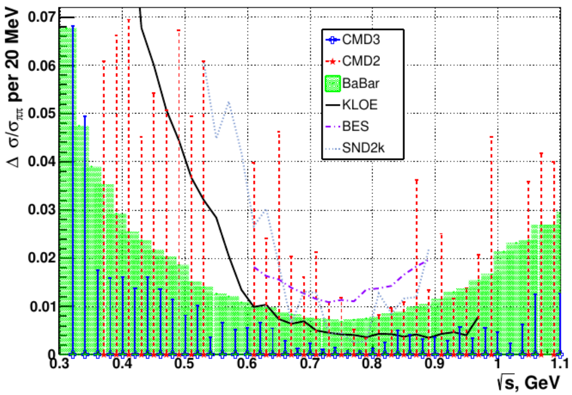
Phy.Lett. B812 (2021) 135982



- Largest contribution to HVP
- ISR measurements with sub-percent accuracy
  - Different analysis strategies
- Long-standing KLOE-BaBar discrepancy

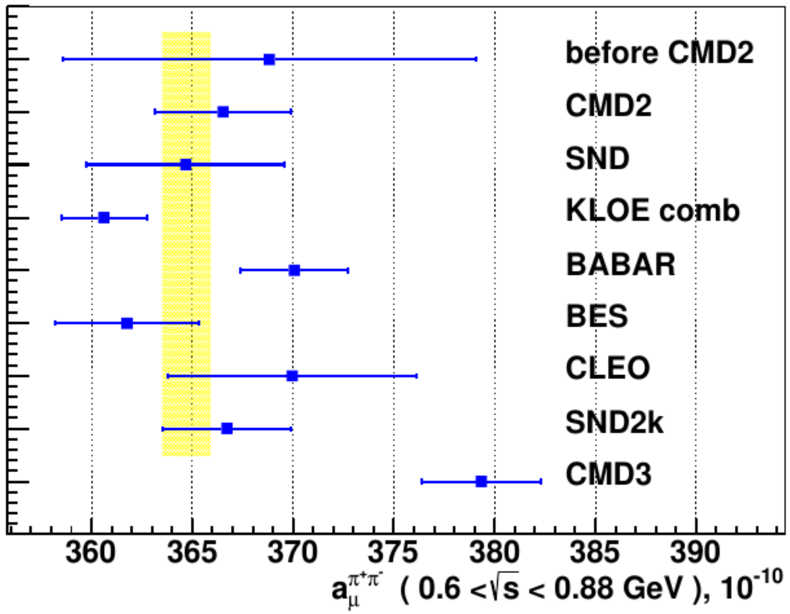
The CMD-3 Shock of February 2023

- Energy scan at VEPP2000 $(\sqrt{s} \leq 2\,\mathrm{GeV})$
- Competitive statistics $(3.4 \times 10^7\,\pi^+\pi^-, 4.4 \times 10^7\,e^+e^-)$



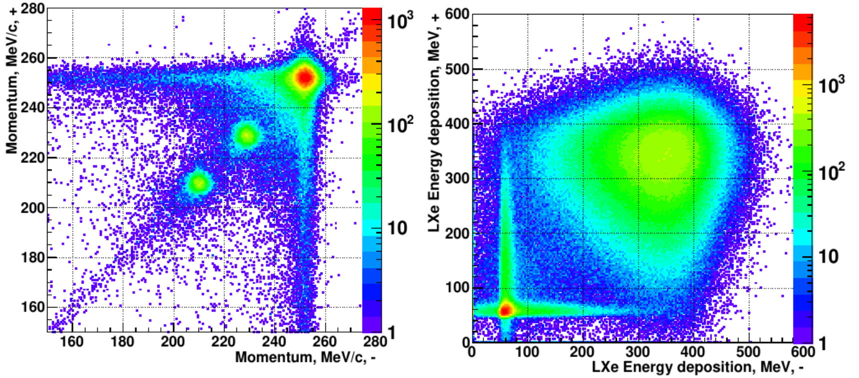
- 0.8% accuracy
- **Significant tension with previous measurements**

arXiv:2302.08834



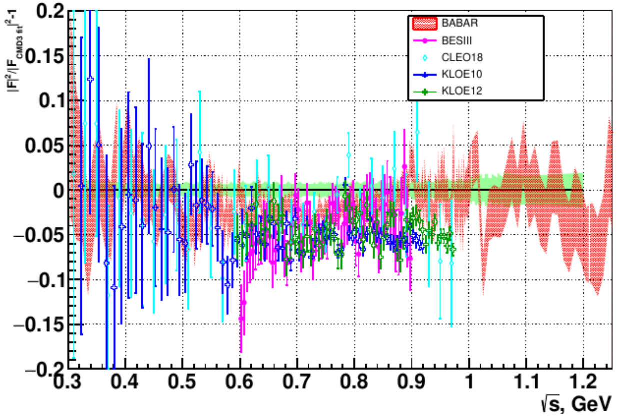
CMD-3 Analysis

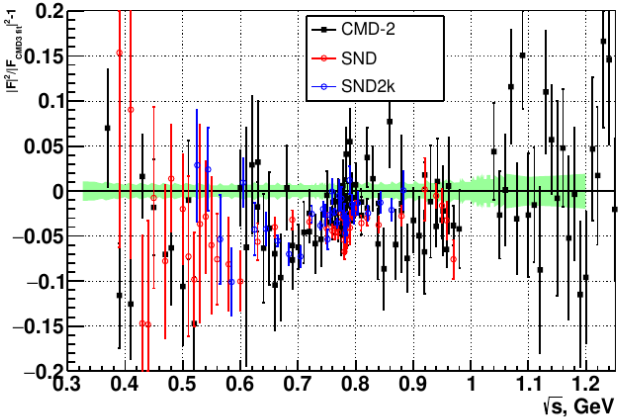
- Select back-to-back tracks
- PID by fit to momentum and energy deposit distributions
- Normalize to Bhabha scattering events
- Improved theory input
- Various cross checks



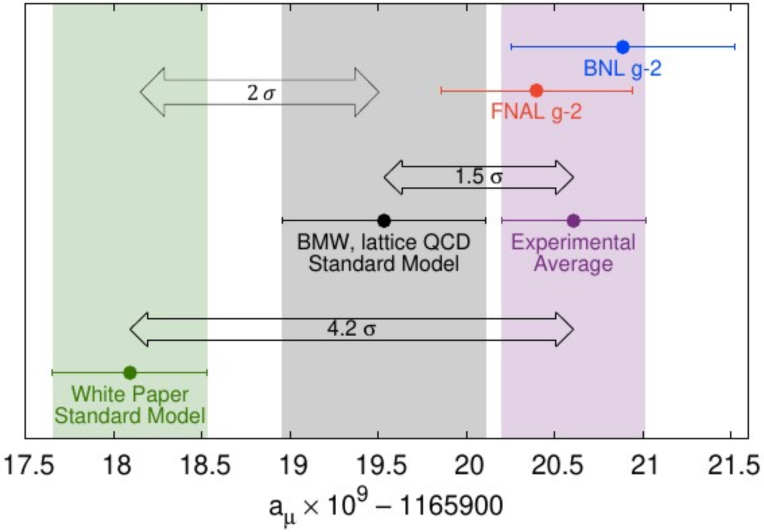
arXiv:2302.08834

- Common disagreement around ρ(770)
- Origin of discrepancy with SND/CMD-2 still unclear





Perspectives



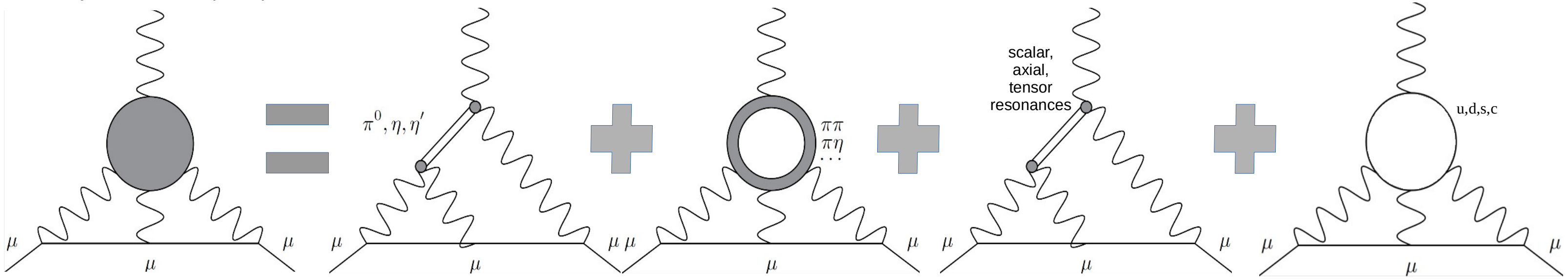
- CMD-3 result could settle lattice/dispersive tension
- **Confirmation is needed!**
  - Source of difference CMD-2 vs CMD-3 ?
  - Origin of disagreement of previous measurements?

New measurements ongoing:

- SND to evaluate full VEPP2000 data set
- BaBar to evaluate full data set with reduced systematic on PID
- New BESIII data being taken (×7), different strategies, normalization to muon yield
- KLOE-2 data available
- Belle II

Hadronic Light-by-Light Scattering

de Rafael, Phys.Lett. B322 (1994) 239



- Pseudoscalar exchange and meson loops dominate
- Data driven estimates for individual contributions
  - Require transition form factors and partial waves as input
- More experimental input on scalar, tensor, and axial contributions needed!

Phys.Rept. 887 (2020) 1

Contribution	$\times 10^{-11}$
Pseudoscalars	93.8 ± 4.0
π & K Loops/Boxes + *s*-wave rescattering	-24.4 ± 3
Tensors and Scalars	-1 ± 3
Axials	6 ± 6
u,d,s Loops / short distance	18 ± 11

Experimental access to TFFs

<u>Time-like</u>

- Meson Dalitz decays

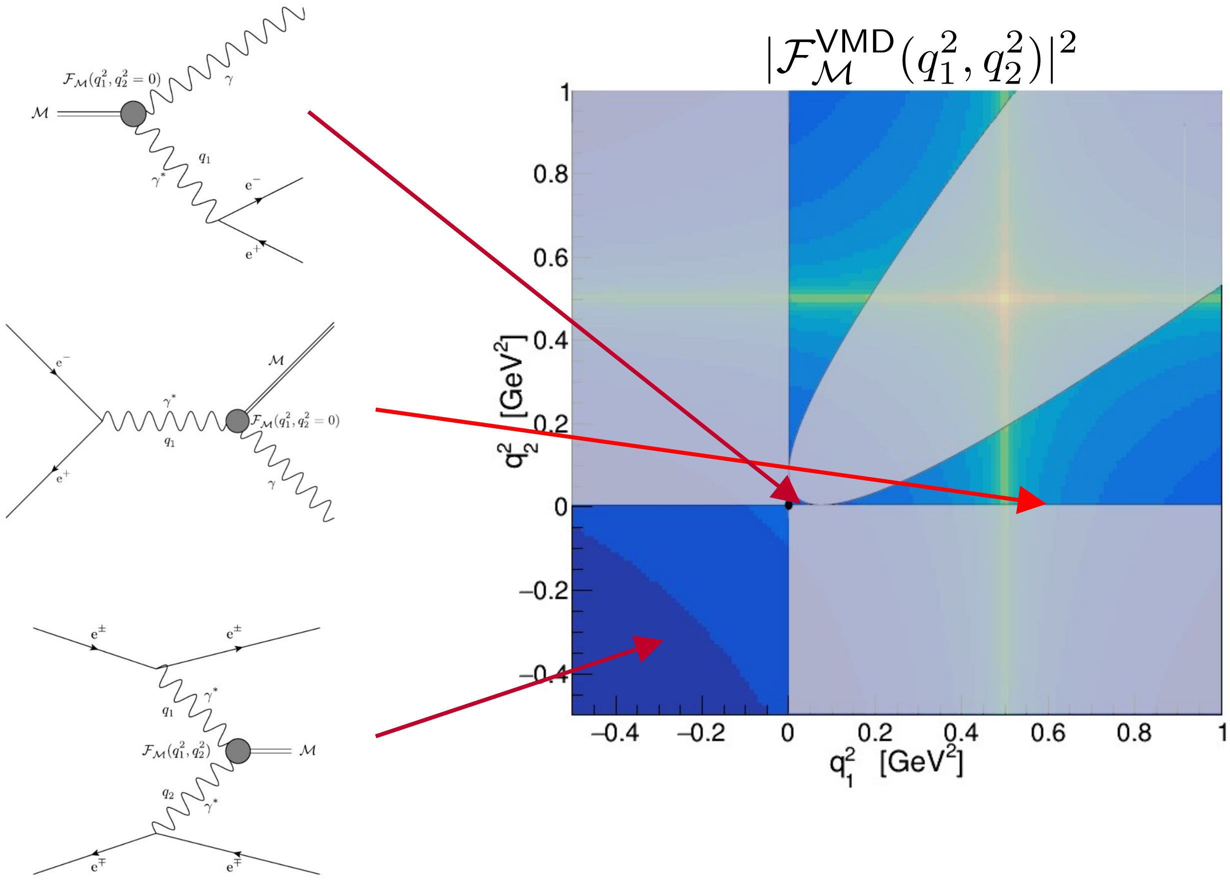
  $$m_{ll}^2 < q^2 < m_P^2$$

- Radiative production

  $$q^2 = s; \quad q^2 > m_P^2$$

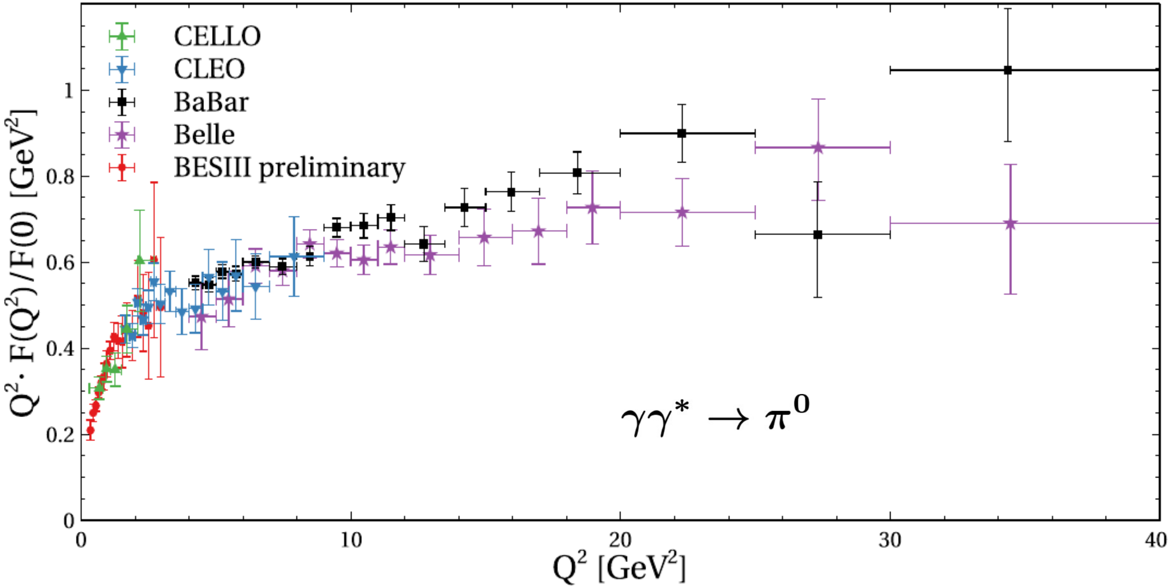
<u>Space-like</u>

- Two-photon collisions



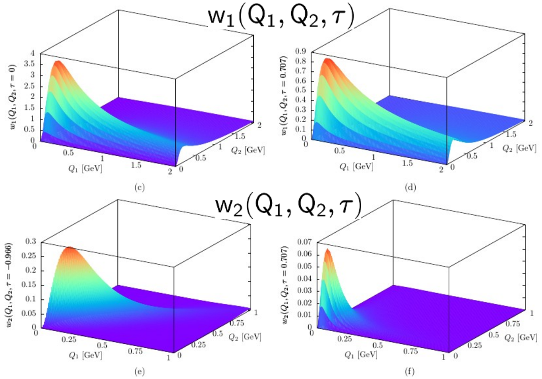
Light Pseudoscalar Meson TFFs

Prog.Part.Nucl.Phys. 107 (2020) 20



- Single-tagged measurements
- Data mostly from B-factories
  - Only at large momentum transfers
  - BaBar – Belle puzzle
- Relevant momentum region: $Q_i^2 \leq 1\,\mathrm{GeV}^2$

Model independent weighting functions



Phys.Rev.D94,053006, 2016

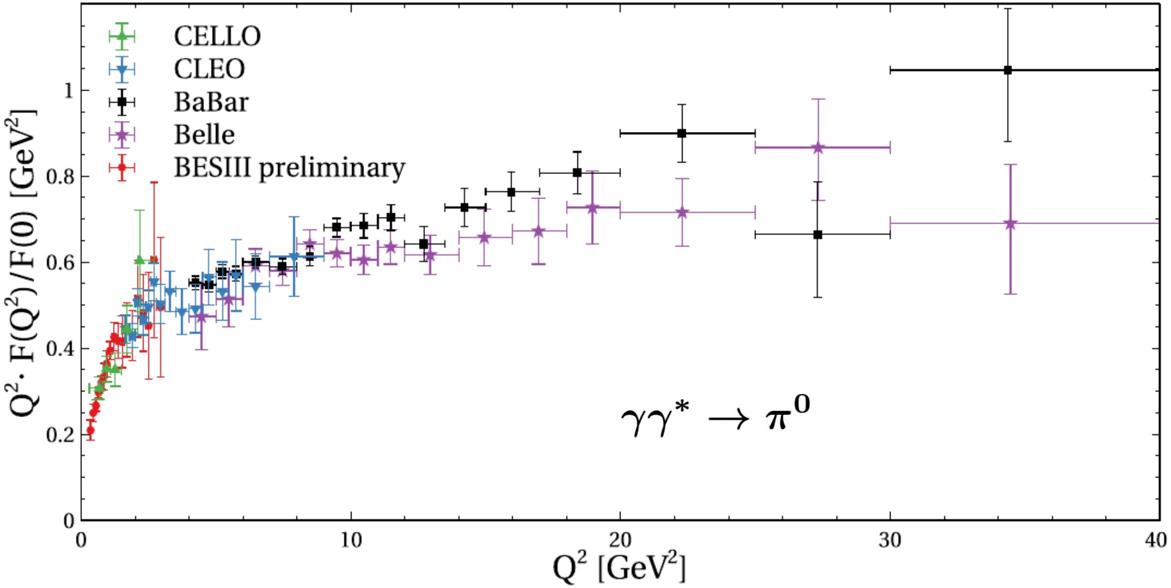
From 3D integral representation of PS contribution

$$a_\mu^{HLbL;\pi^0(1)} = \int_0^\infty dQ_1 \int_0^\infty dQ_2 \int_{-1}^1 d\tau\, w_1(Q_1,Q_2,\tau)\mathcal{F}_{\pi^0\gamma^*\gamma^*}(-Q_1^2, -(Q_1+Q_2)^2)\mathcal{F}_{\pi^0\gamma^*\gamma^*}(-Q_2^2, 0)$$

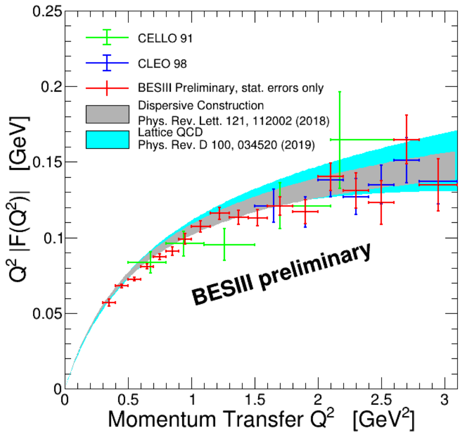
$$a_\mu^{HLbL;\pi^0(2)} = \int_0^\infty dQ_1 \int_0^\infty dQ_2 \int_{-1}^1 d\tau\, w_2(Q_1,Q_2,\tau)\mathcal{F}_{\pi^0\gamma^*\gamma^*}(-Q_1^2, -Q_2^2)\mathcal{F}_{\pi^0\gamma^*\gamma^*}(-(Q_1+Q_2)^2, 0)$$

Light Pseudoscalar Meson TFFs

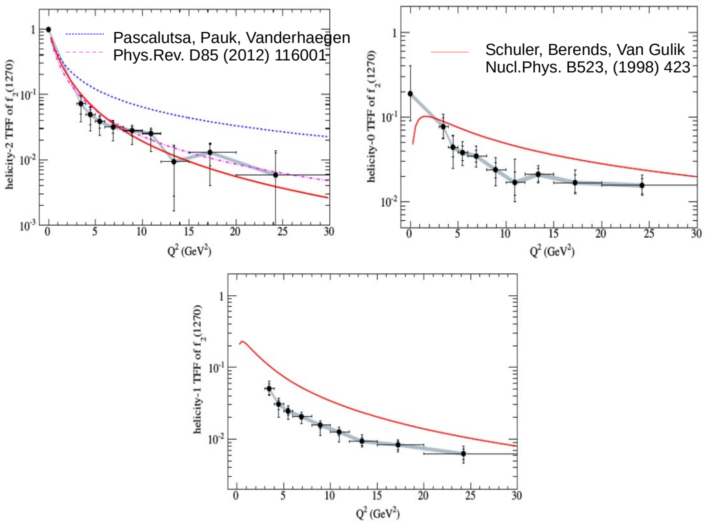
Prog.Part.Nucl.Phys. 107 (2020) 20



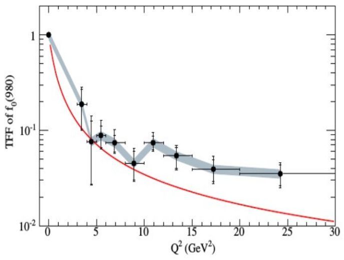
- Data mostly from B-factories
  - Only at large momentum transfers
  - BaBar – Belle puzzle
- Relevant momentum region: $Q_i^2 \leq 1\,\mathrm{GeV}^2$
- Important input from BESIII
  - Supports dispersive construction and lattice calculation of π^0 TFF



Two-pion Contribution

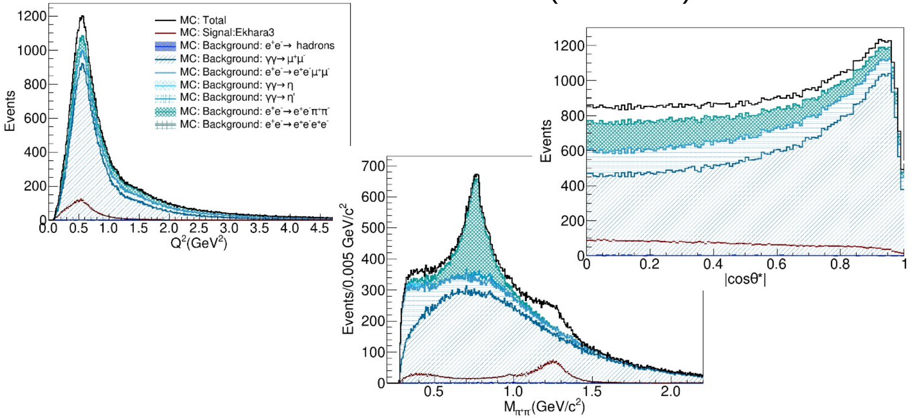


Belle, Phys.Rev.D93 (2016) 032003



- Only data from Belle published on $\pi^0\pi^0$
  - At large momentum transfers > 3 GeV²
  - TFFs of contributing resonances determined
- Input from BESIII in preparation
  - $\pi^0\pi^0$ and $\pi^+\pi^-$
  - Low momentum transfers, small invariant masses, full coverage of helicity angle

Full simulation at BESIII (4.23 GeV)



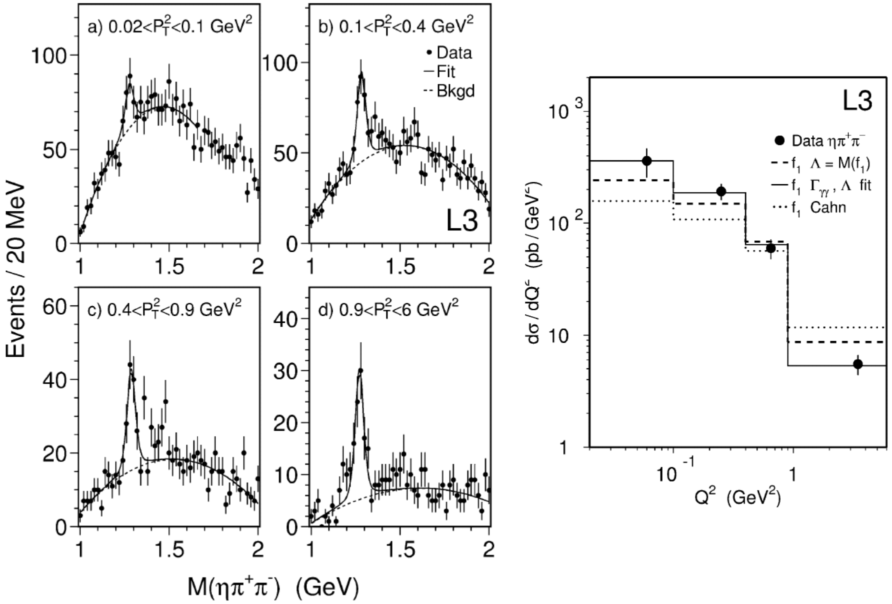
Axial Vector Mesons

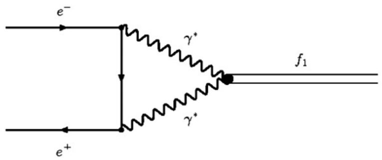
- Virtual photons required by Landau-Yang theorem
- Latest measurement by L3
  - $f_1(1285) \to \pi^+\pi^-\eta$
  - Q² dependence inferred from p_T
  - Only lepton-based cross section available
    - Fits with different models
- Ongoing work at BaBar and BESIII
  - Measure Q² dependence
  - Separate helicity contributions
- Alternative approach at SND: “two-photon annihilation”

$$\sigma(e^+e^- \to f_1(1285)) = 45^{+33}_{-24}\,\mathrm{pb}$$

Phys.Lett. B800 (2020) 135074

Phys.Lett. B526 (2002) 269





Summary

Experimental inputs crucial to handle hadronic corrections of $(g-2)_\mu$

- Hadronic Vacuum Polarization
  - Dispersive approach to systematically improve prediction with data
  - Tension: dispersive – lattice
  - Tension: KLOE-BaBar, CMD-3
  - New measurements needed to settle puzzles

- Hadronic Light-by-Light
  - Transition form factors and partial waves at arbitrary momentum transfers as input
  - Singly-virtual data on light pseudoscalar form BaBar, Belle, BESIII
  - Important input on axial mesons available soon
  - Doubly-virtual measurements needed