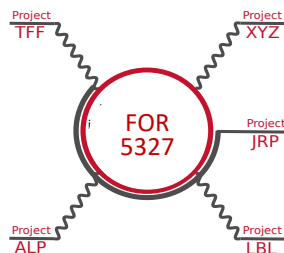


**International School
of Nuclear Physics, 44th Course
Erice, September 18-24, 2023**



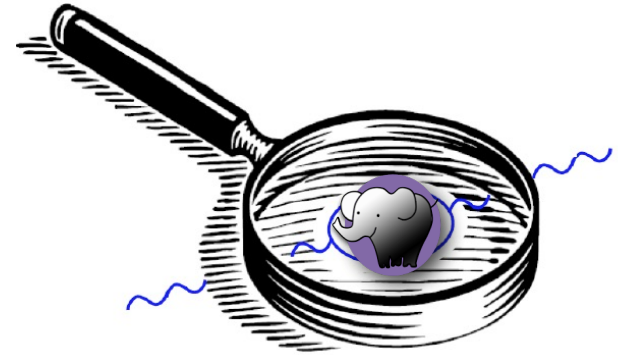
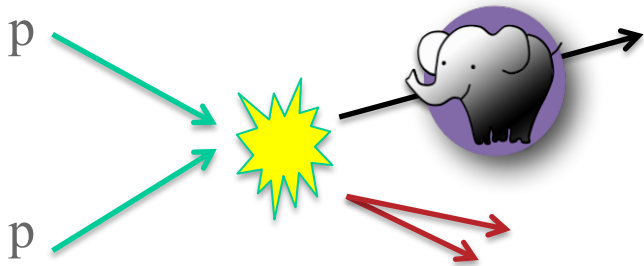
Meson form factors and their impact on the muon $g-2$



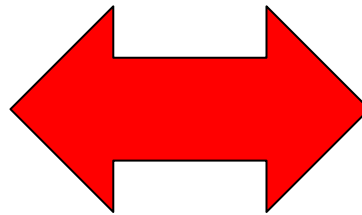
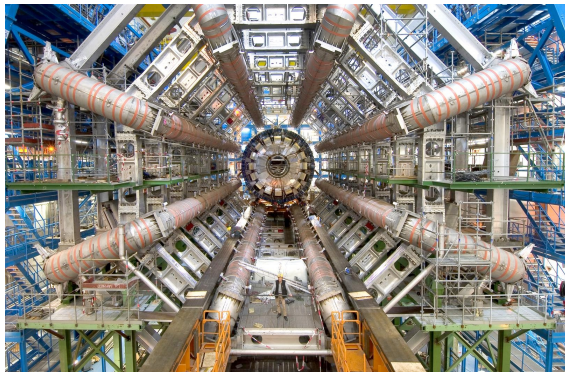
Cluster of Excellence
PRISMA⁺
Precision Physics,
Fundamental Interactions
and Structure of Matter

***Achim Denig
JGU Mainz***

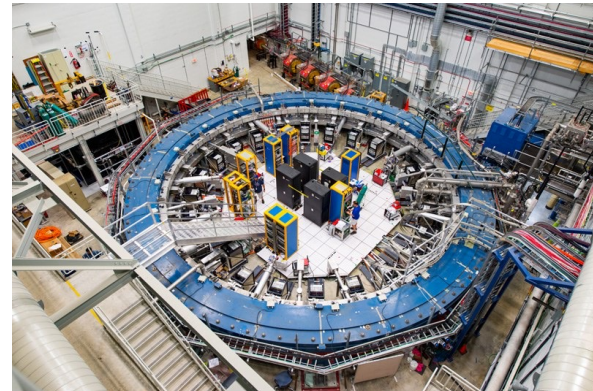
The Search for Physics beyond the Standard Model



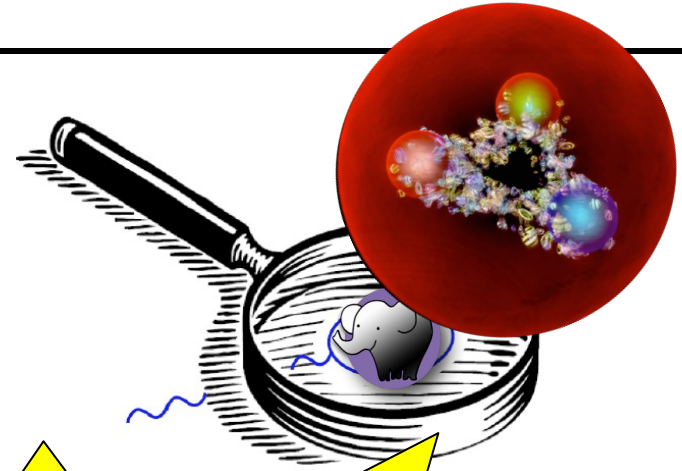
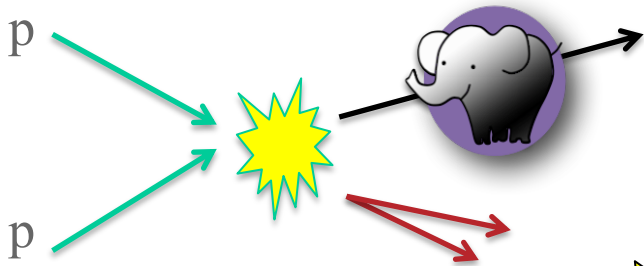
*High Energy Frontier
(e.g. LHC/CERN)*



*Precision Frontier
($g-2$, Flavour Ph., ...)*

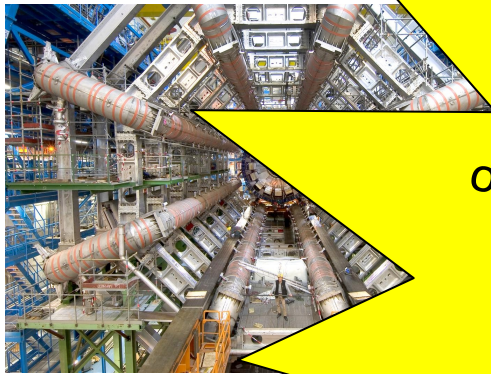


The Search for Physics beyond the Standard Model



High Energy Frontier
(e.g. LHC (CERN))

Precision Frontier
(our Ph... ..)



Improved understanding of
Hadron Physics
of utmost importance for BSM searches via
precision physics

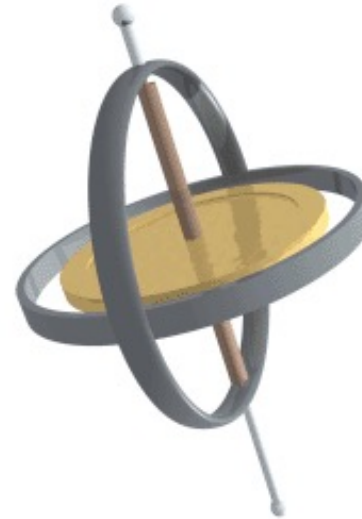
Muon Magnetic Moment: $(g-2)_\mu$

Confront a high-precision SM prediction with a high-precision measurement

Definition: $\vec{\mu} = \mu_B \cdot g \cdot \vec{S}$

Dirac: $g = 2$

QFT: $a_\mu = (g - 2)/2 \approx \alpha/\pi$



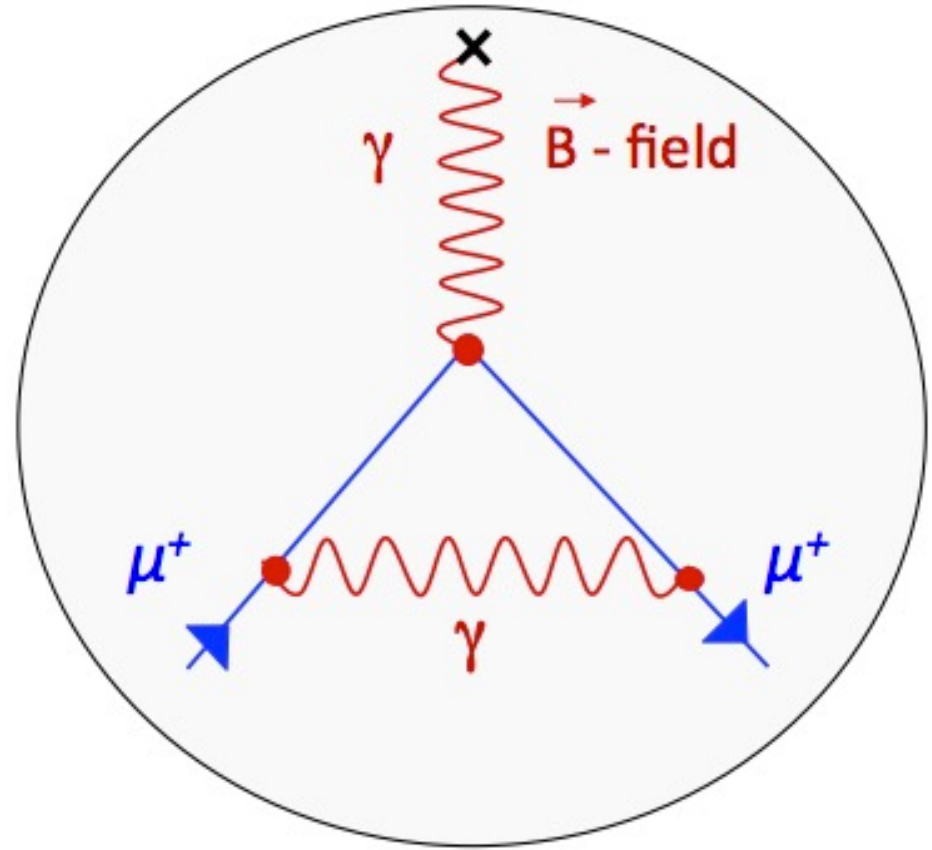
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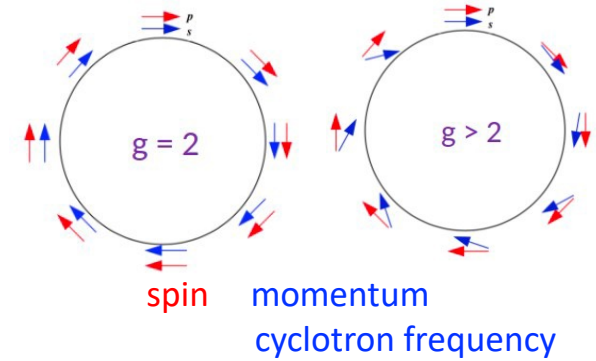
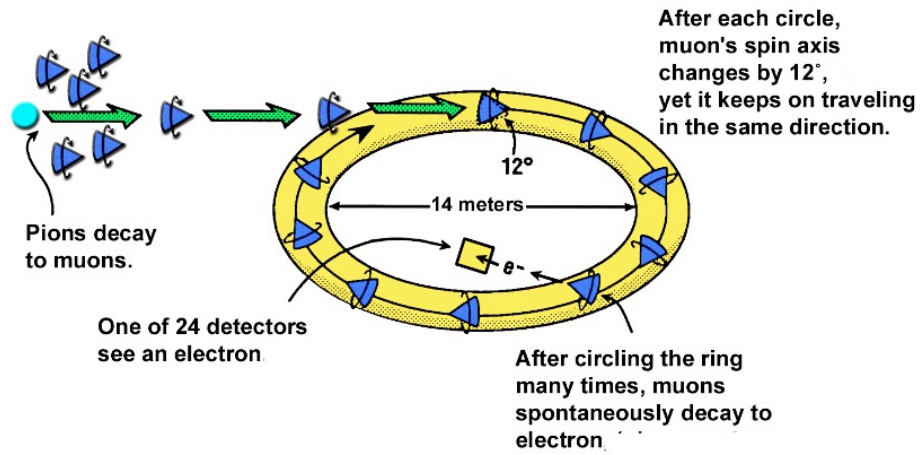
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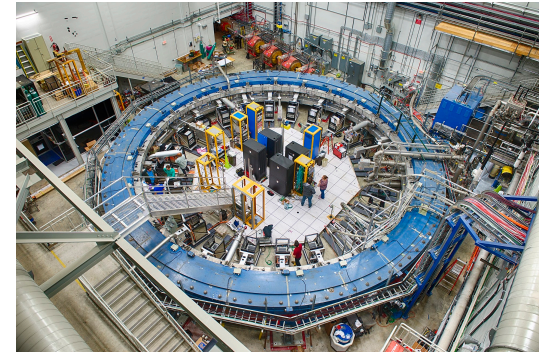
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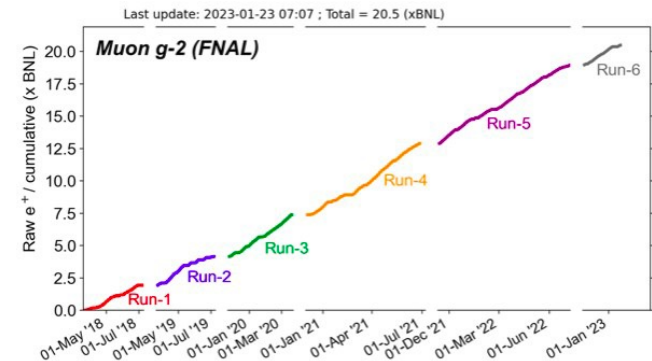
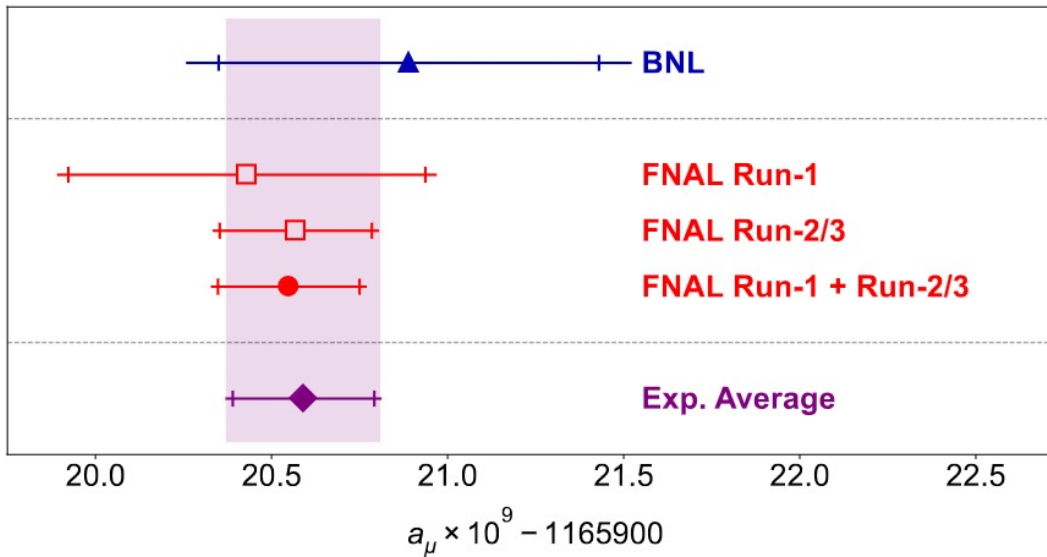
$$\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c = -a_\mu \frac{q\vec{B}}{m}$$

Fermilab $(g-2)_\mu$ Experiment

- FNAL Run 1 in agreement with BNL measurement
- 08/23: FNAL Run 2 + 3 in agreement with Run 1
- FNAL Run 1-6, further reduction of uncertainty by a factor of 2 !



arxiv:2308.06230



$$a_\mu^{exp} = (11\,659\,205.9 \pm 2.2) \cdot 10^{-10}$$

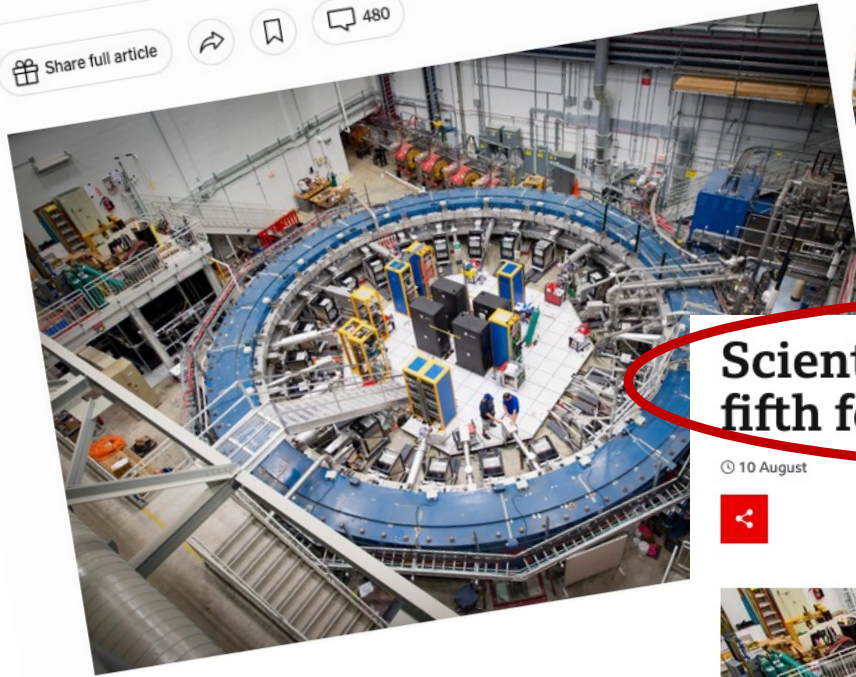
statistics dominated error

Physicists Move One Step Closer to a Theoretical Showdown

The deviance of a tiny particle called the muon might prove that one of the most well-tested theories in physics is incomplete.

Share full article

480



SEARCHES FOR NEW PHYSICS | NEWS

New Muon g-2 result bolsters earlier measurement

10 August 2023



Scientists at Fermilab close in on fifth force of nature

© 10 August



Standard Model Prediction of $(g-2)_\mu$

EW contributions: A **triumph** of perturbative QFT and computing

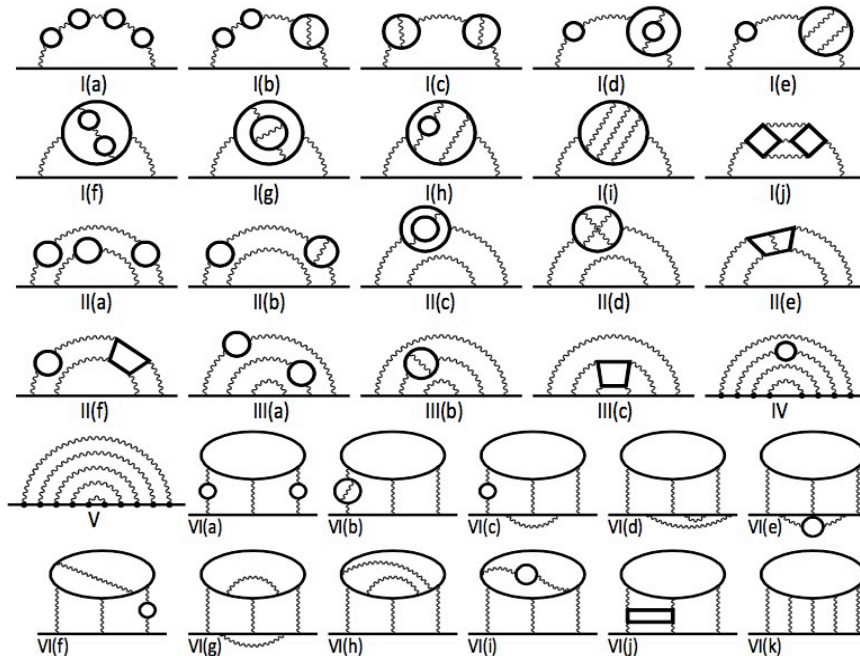
$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{weak} + a_\mu^{had}$$

Kinoshita et al. '12
 $(11\,658\,471.808 \pm 0.015) \cdot 10^{-10}$

Czarnecki et al.
 $(15.4 \pm 0.2) \cdot 10^{-10}$

*Absolute contribution dominated by QED
 Uncertainty dominated by hadronic contribution*

10th
 12672
 diagrams



Standard Model Prediction of $(g-2)_\mu$

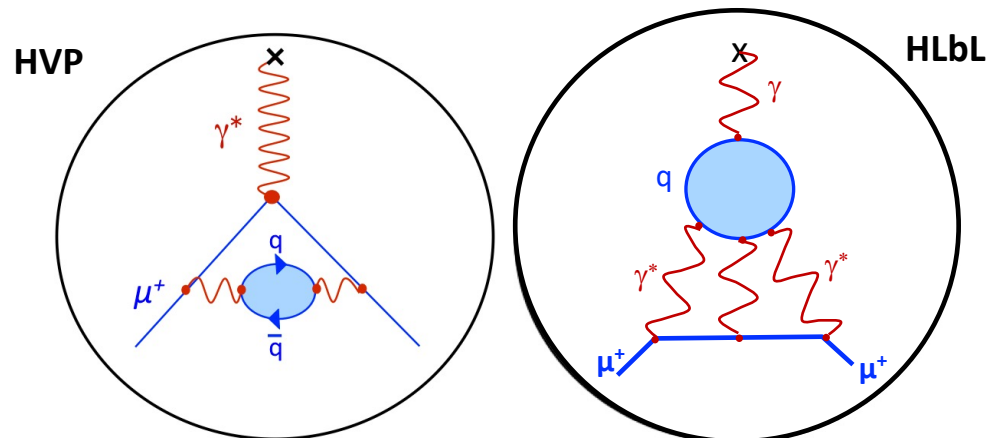
Hadronic contribution **non-perturbative, the limiting contribution**

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{weak} + a_\mu^{had}$$

→ **HVP**: Hadronic Vacuum Polarization ($\cong 687 \dots 694 \pm 2.4 \dots 4.1$) $\cdot 10^{-10}$

	BDJ19	DHMZ19	FJ17	KNT19
$a_\mu^{HVP,LO} \times 10^{10}$	687.1(3.0)	694.0(4.0)	688.1(4.1)	692.8(2.4)

→ **HLbL**: Hadronic Light-by-Light (10.5 ± 2.6) $\cdot 10^{-10}$ Glasgow „consensus“ value



NLO $(-9.8 \pm 0.1) \cdot 10^{-10}$;
NNLO $(1.2 \pm 0.01) \cdot 10^{-10}$

B. Kubis
D.G.M. Porras

$(g-2)_\mu$ Theory Initiative (since 2017)

Goal:

theory consensus value of muon g-2 SM prediction (most relevant hadronic contributions!)

196 pages, 103 figures

- Working groups on HVP, HLbL, LatticeQCD, ...
- Six collaboration meetings and various workshops on subtopics
- Scrutiny of various theoretical evaluations

2006.04822 [hep-ph] 8 Jun 2020

FERMILAB-PUB-20-207-T
INT-PUB-20-025
KEK Preprint 2020-5
MTHY-20-028

CERN-TH.2020.073
BFGM-MEUSK-20-74
LMI-ASC-18/20
LTH-12/24
LIT-TH-20-20
MANTHEP/2020/03
PFI-PH-20-06
IWBK-2020-14
ZU-TH-18/20

The anomalous magnetic moment of the muon in the Standard Model

T. Aoyama^{1,2,3}, M. Asmussen⁴, M. Benayoun⁵, J. Bijnens⁶, T. Blum^{7,8}, M. Bruno⁹, I. Caprini¹⁰, C. M. Carlson¹¹, M. Czakon^{12,13}, G. Colangelo¹⁴, F. Cucchiesi^{15,16}, H. Czyz¹⁷, I. Danilkin¹⁸, M. Davier¹⁹, C. T. H. Davies²⁰, M. Della Morte²¹, S. I. Eidelman^{22,23}, A. X. El-Khadra^{24,25}, A. Gérardin²⁶, D. Giusti^{27,28}, M. Götzmann²⁹, S. Golligorsky³⁰, V. Golitsyn³¹, F. Hagelstein³², M. Hayakawa³³, G. Henderson³⁴, D. W. Herrero-Scoones³⁵, A. Hocker³⁶, M. Hofmeier^{37,38}, B.-L. Hoid³⁹, R. J. Hudspeth^{40,41}, F. Ignotov⁴², T. Irzchack⁴³, F. Jegerlehner⁴⁴, L. Jin⁴⁵, A. Keshavarzi⁴⁶, T. Kinoshita^{47,48}, R. Kubie⁴⁹, A. Kupchik⁵⁰, A. Kupke^{42,43}, I. Laach⁵¹, S. C. Lehar^{26,52}, L. Leifels⁵³, I. Lysghoul⁵⁴, B. Malaescu⁵⁵, K. Maltman^{56,57}, M. M. Martinovic^{58,59}, P. Masjuan⁶⁰, A. S. Meyer⁶¹, H. B. Meyer^{62,63}, T. Mibe⁶⁴, K. Miura^{65,66}, S. E. Müller^{67,68}, M. Nio^{69,70}, D. Nomura^{71,72}, A. Nyffeler^{73,74}, V. Pascalutsa⁷⁵, M. Passera⁷⁶, E. Perez del Rio⁷⁷, S. Peris^{78,79}, A. Portillo⁸⁰, M. Procura⁸¹, C. F. Redmer⁸², S. J. Roberts⁸³, P. Sánchez-Puertas⁸⁴, S. Seidelmann⁸⁵, B. Shwartz⁸⁶, S. Simola⁸⁷, D. Stockinger⁸⁸, H. Stückings-Klein⁸⁹, P. Stoffer⁹⁰, T. Tait⁹¹, R. Van de Waas⁹², M. Vanderhaeghe^{93,94}, G. Venanzoni⁹⁵, G. von Hippel⁹⁶, H. Wang^{12,17}, Z. Zhang⁹⁷.

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Bern 2023



FNAL 2017



Mainz 2018



Seattle 2019



Edinburgh 2022

KEK (virtual) 2021



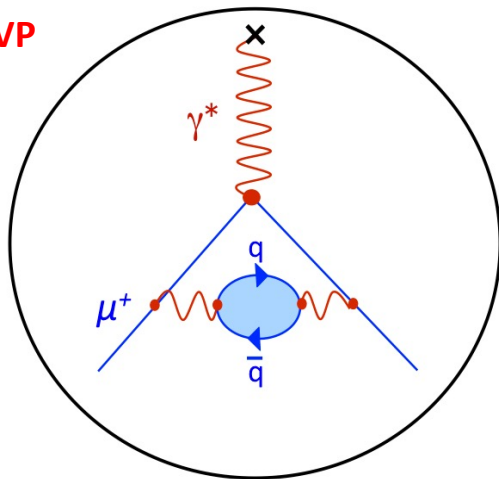
ETTORE MAJORANA FOUNDATION AND
CENTRE FOR SCIENTIFIC CULTURE

TO PAY A PERMANENT TRIBUTE TO ARCHIMEDES AND GALILEO GALILEI, FOUNDERS OF MODERN SCIENCE
AND TO ENRICO FERMI, THE "ITALIAN NAVIGATOR", FATHER OF THE WEAK FORCES



Hadronic Vacuum Polarization (HVP)

HVP



Estimate of (g-2) Theory Initiative
based on dispersive approach
(including higher orders):

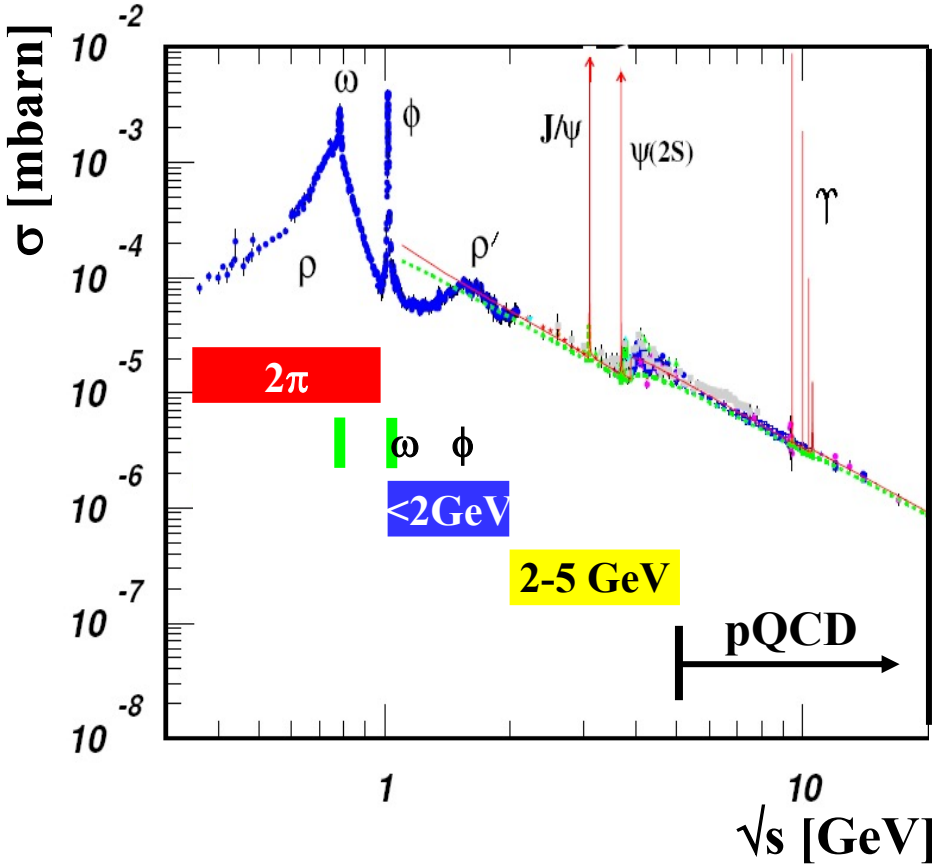
$$(693.1 \pm 4.0) \cdot 10^{-10}$$

was ($\cong 687 \dots 694 \pm 2.4 \dots 4.1$) $\cdot 10^{-10}$

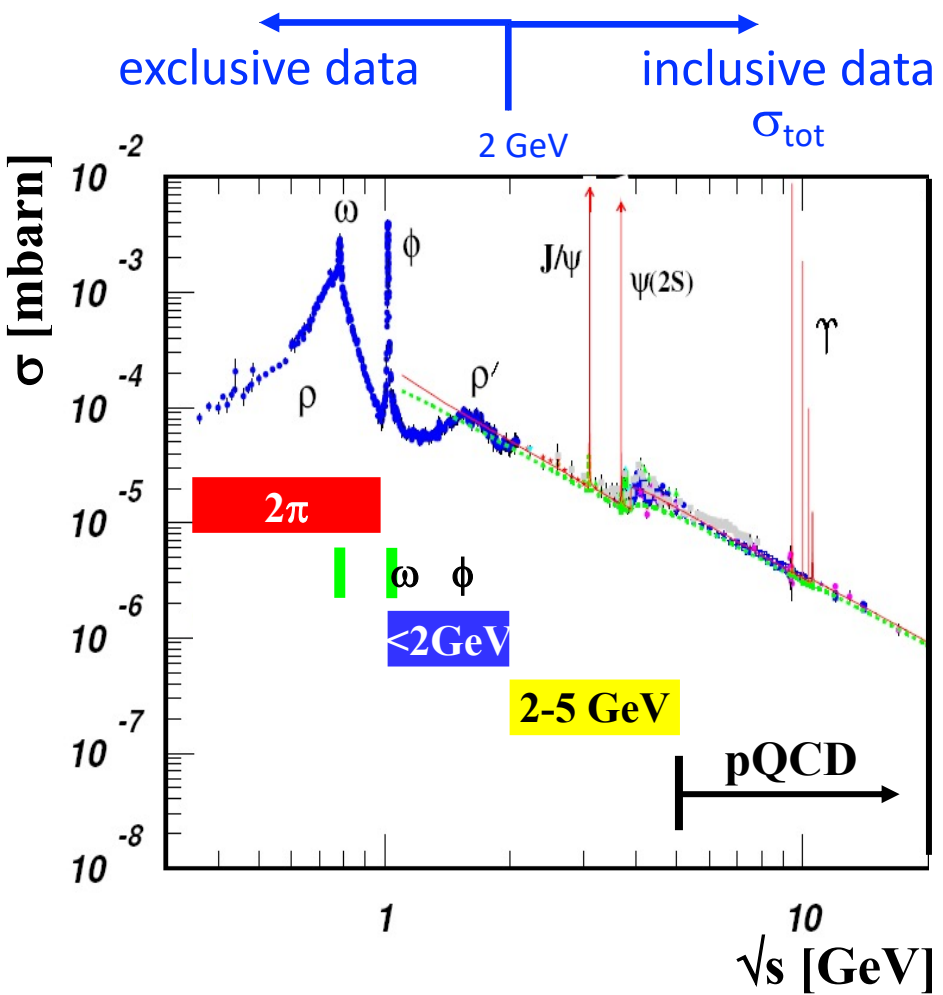
Hadronic Vacuum Polarization Contrib. to $(g-2)_\mu$

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

Intrinsic $\sim 1/s^2$
low energy contributions
 especially important!

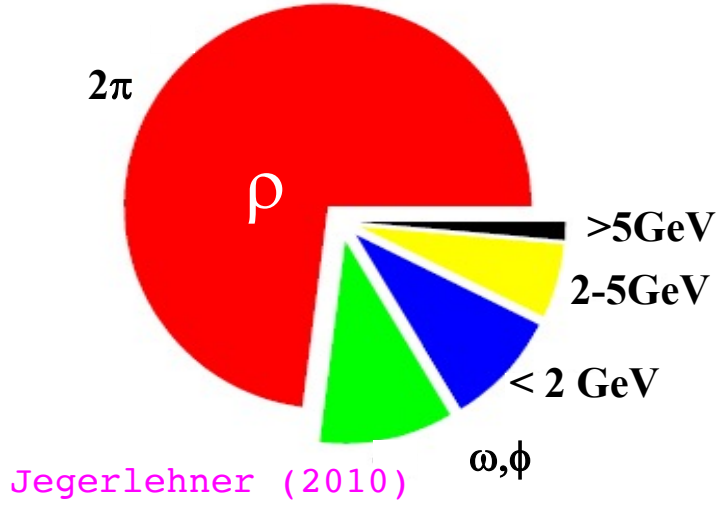


Hadronic Vacuum Polarization Contrib. to $(g-2)_\mu$



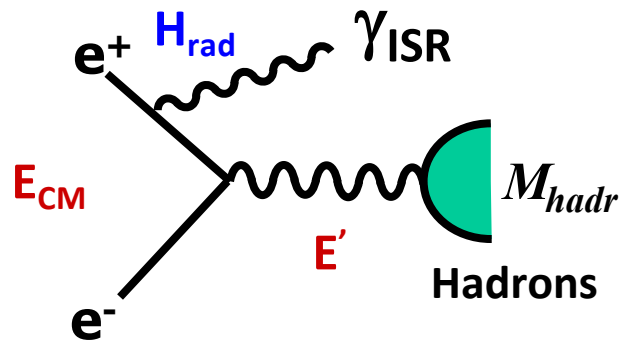
$$a_\mu^{HVP} = \frac{1}{4\pi^3} \int_{4m_\pi^2}^{\infty} ds K(s) \sigma_{\text{had}}(s)$$

Intrinsic $\sim 1/s^2$
low energy contributions
especially important!



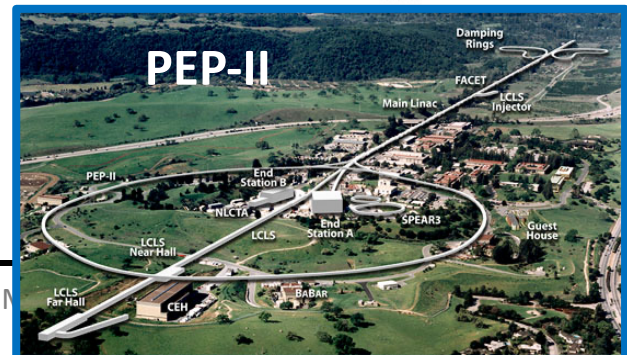
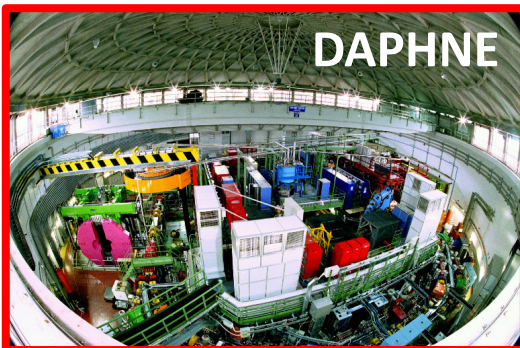
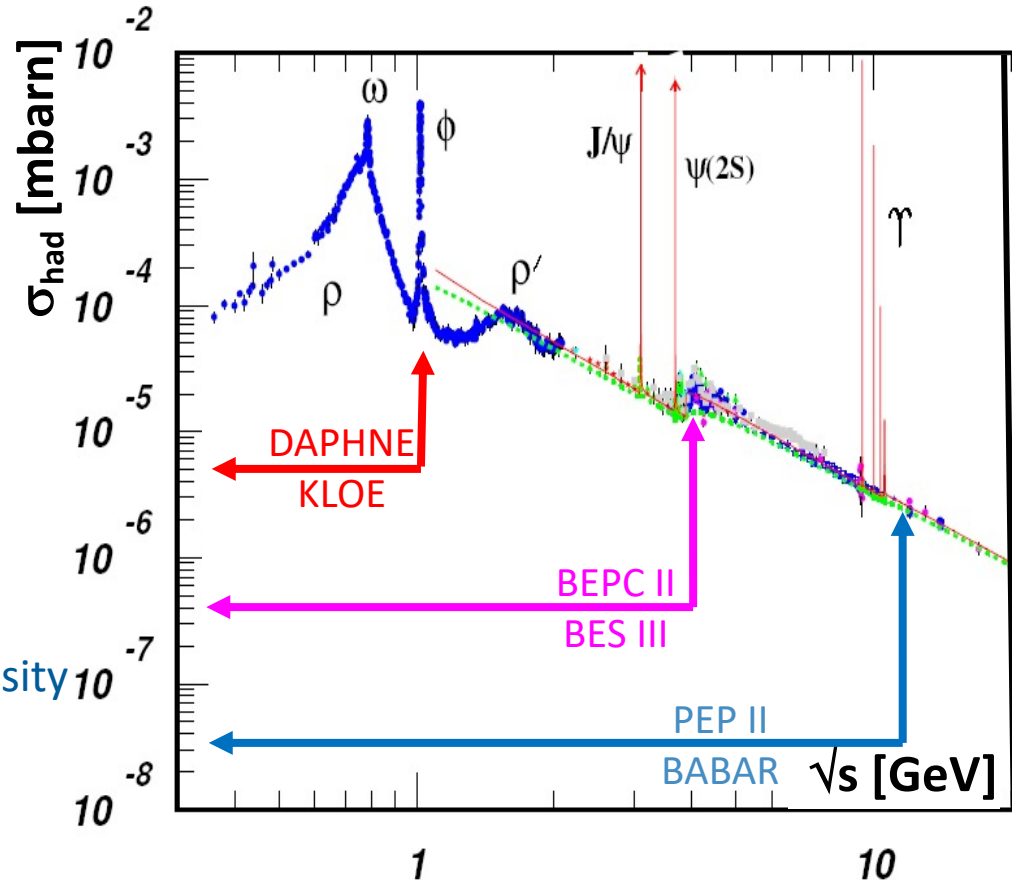
Initial State Radiation (ISR)

Initial State Radiation (ISR) aka Radiative Return

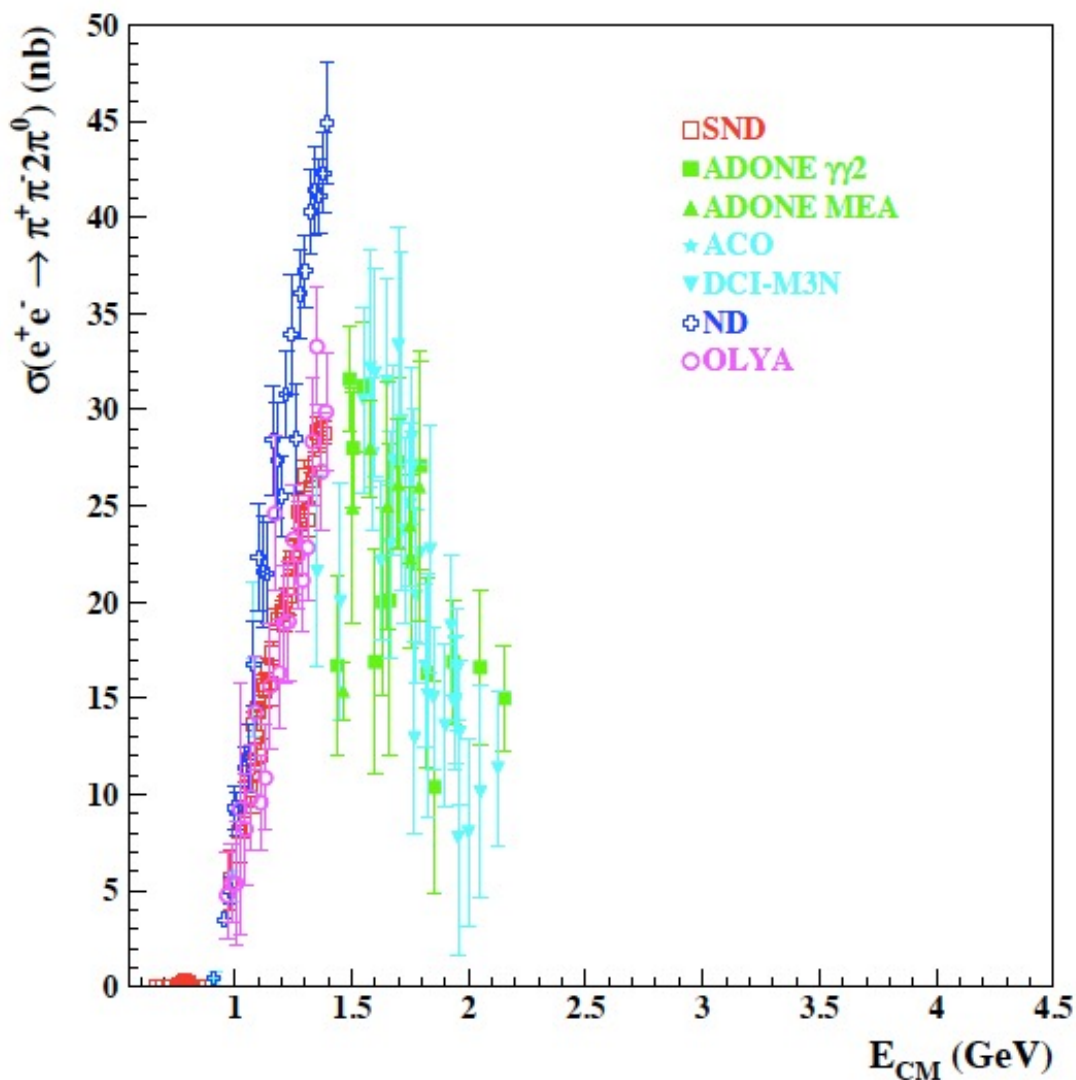


- No systematic variation of E_{beam}
- High statistics thanks to high luminosity
- Precise knowledge of radiative corrections mandatory (H_{rad})

PHOKHARA event generator

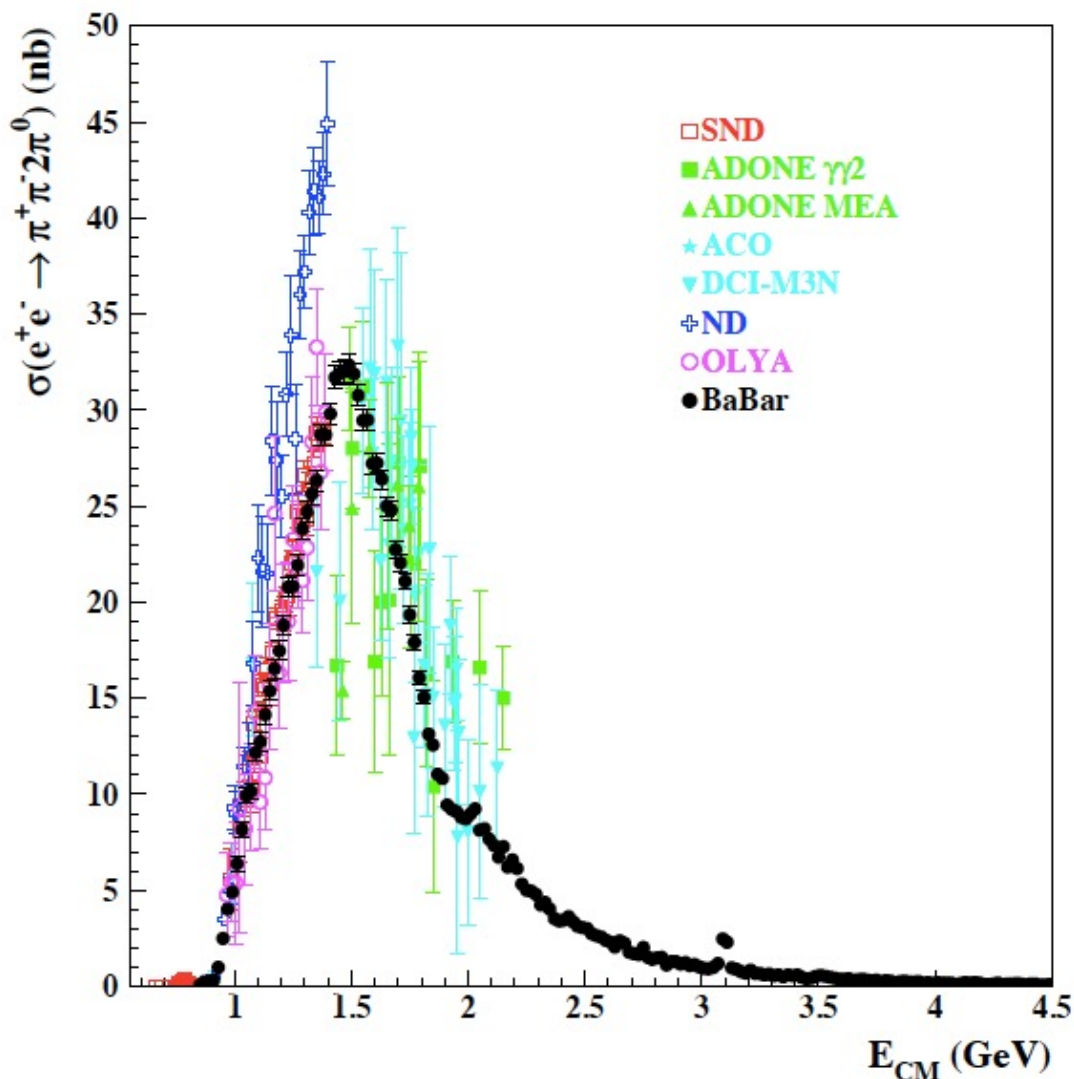


BABAR: $e^+e^- \rightarrow \pi^+\pi^-2\pi^0\gamma_{ISR}$



- Tagged ISR analysis (2017)
Phys. Rev. D96 (2017) 092009
- Huge improvement over existing data sets suffering from normalization issues
- Confirmed by BES III analysis (preliminary)

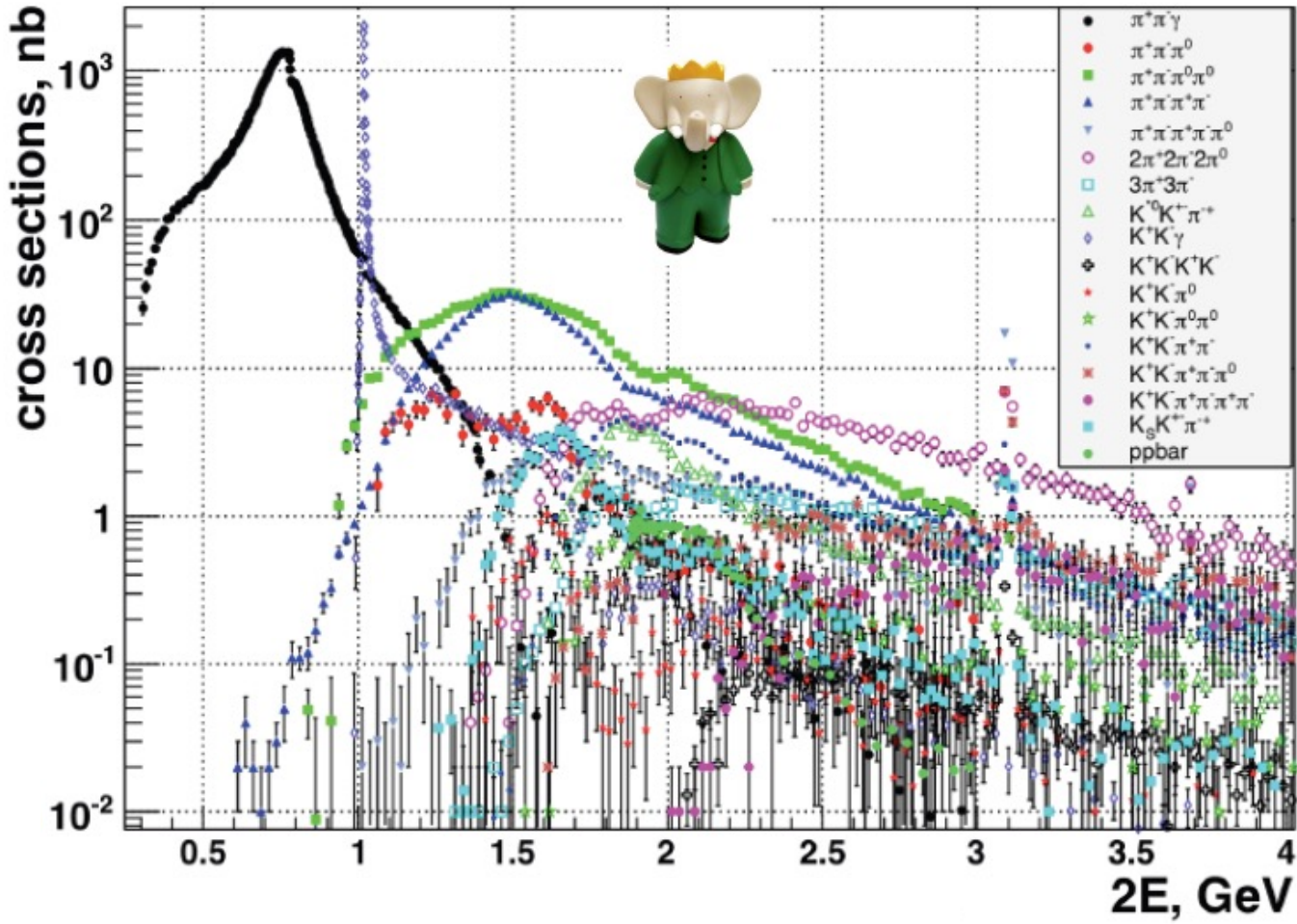
BABAR: $e^+e^- \rightarrow \pi^+\pi^-2\pi^0\gamma_{ISR}$



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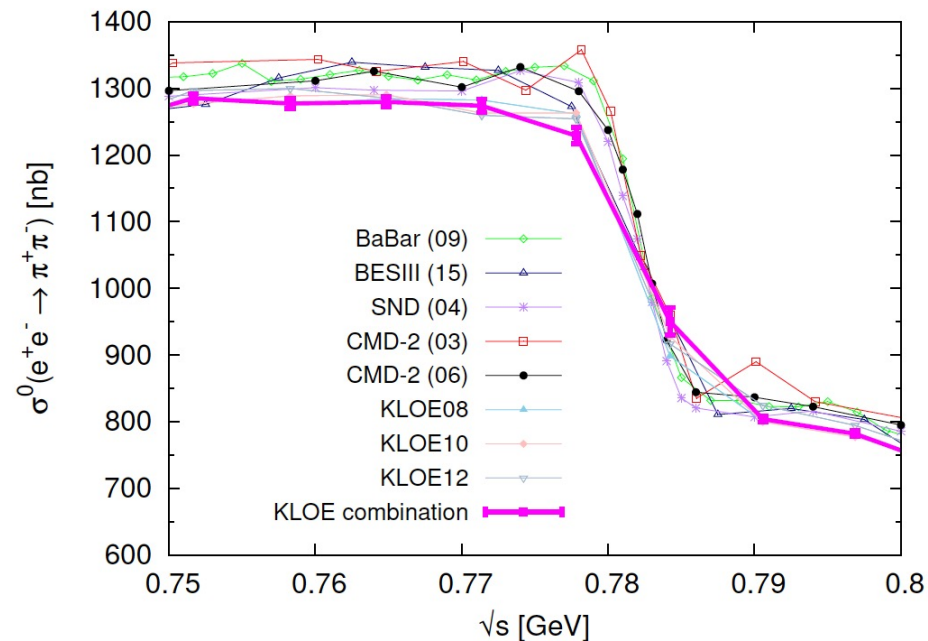
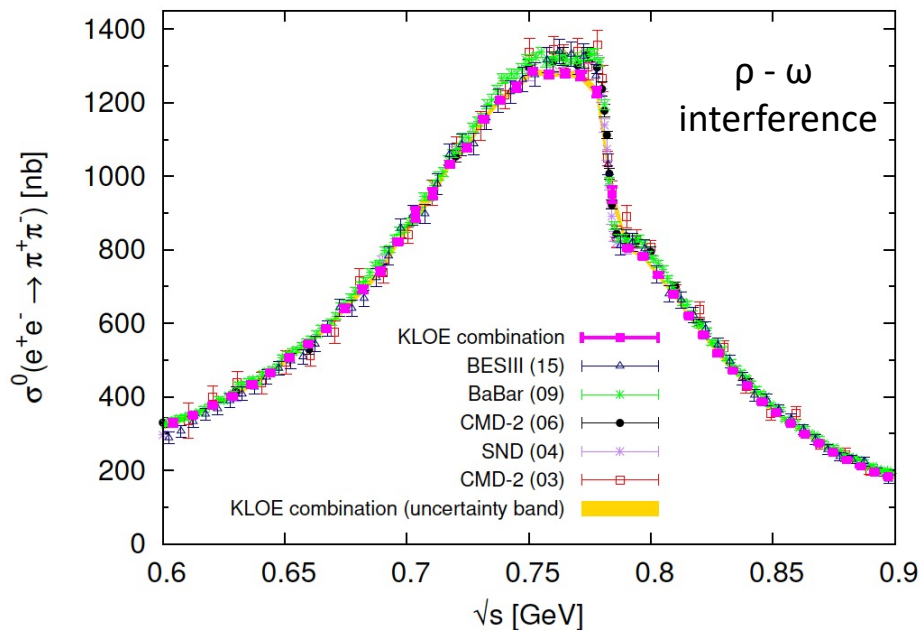
BABAR ISR Results



Precision:

- 2π: < 1%
- 3π: ~10%
- 4π: ~ 3%
- ≥ 5π: 10% and higher

Most relevant Channel: $e^+e^- \rightarrow \pi^+\pi^-$

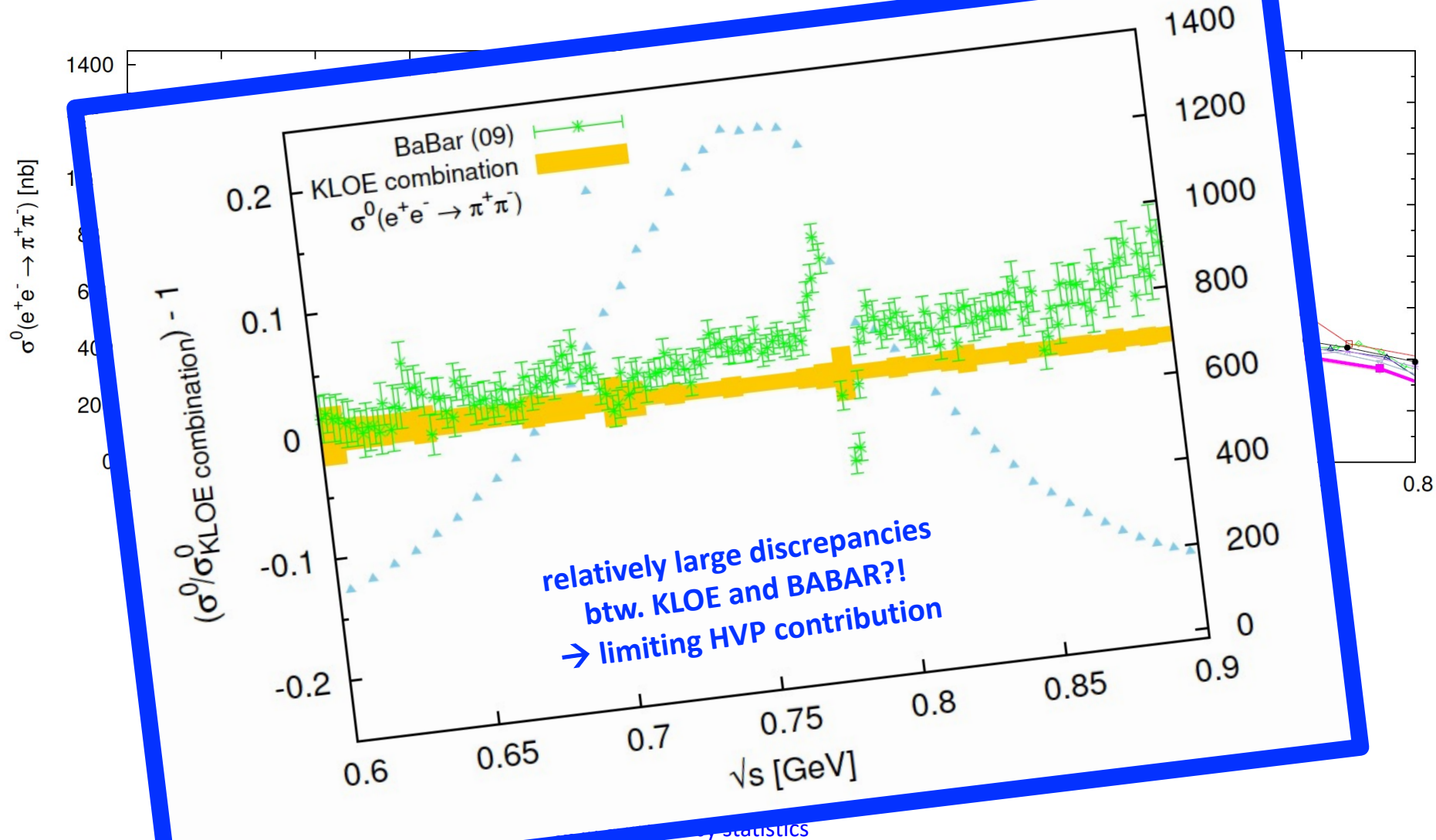


Systematic Uncertainties on $\rho(770)$ peak

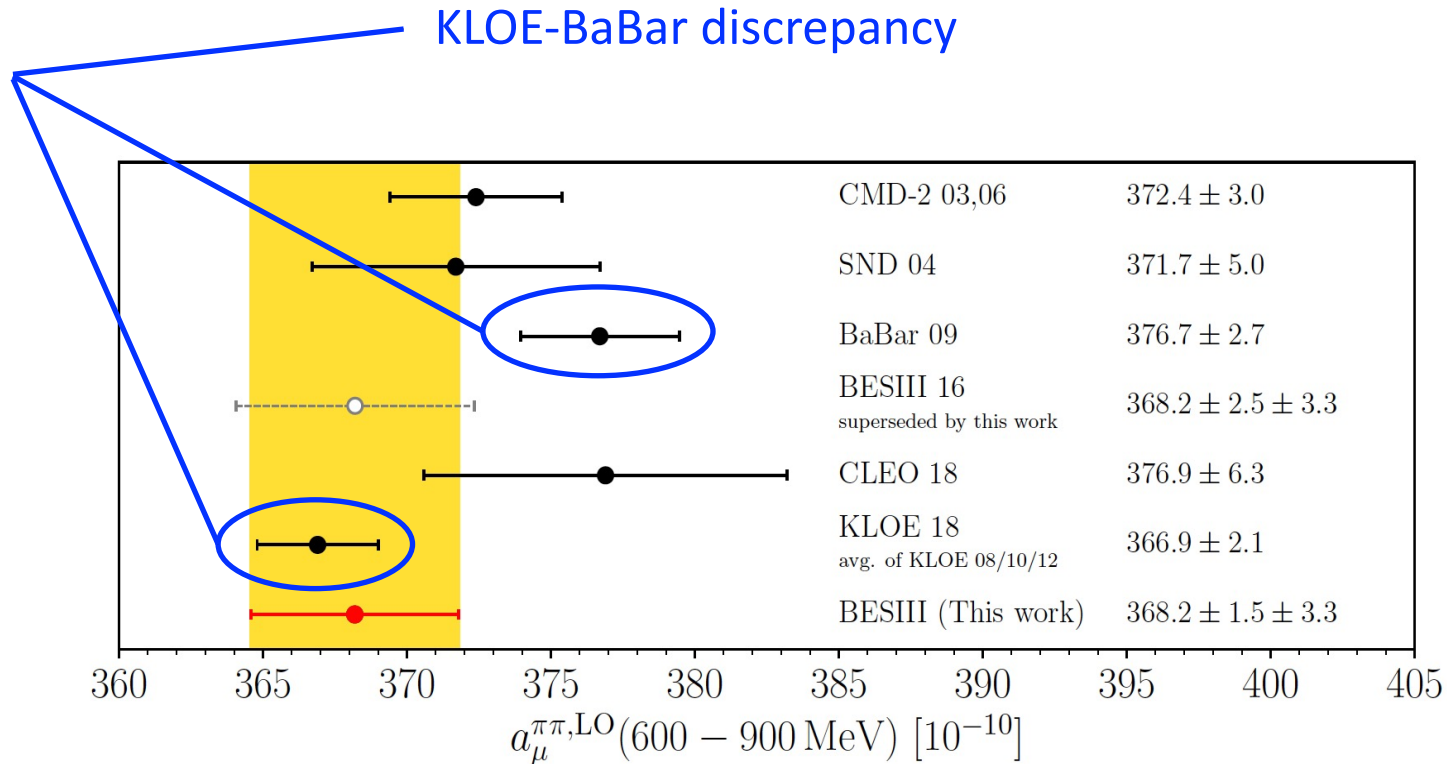
- ISR BABAR 0.5%
- ISR KLOE 0.6% (average of 3 analyses)
- ISR BESIII 0.9%
- Energy Scan CMD2 0.8%*

* limited in addition by statistics

Most relevant Channel: $e^+e^- \rightarrow \pi^+\pi^-$



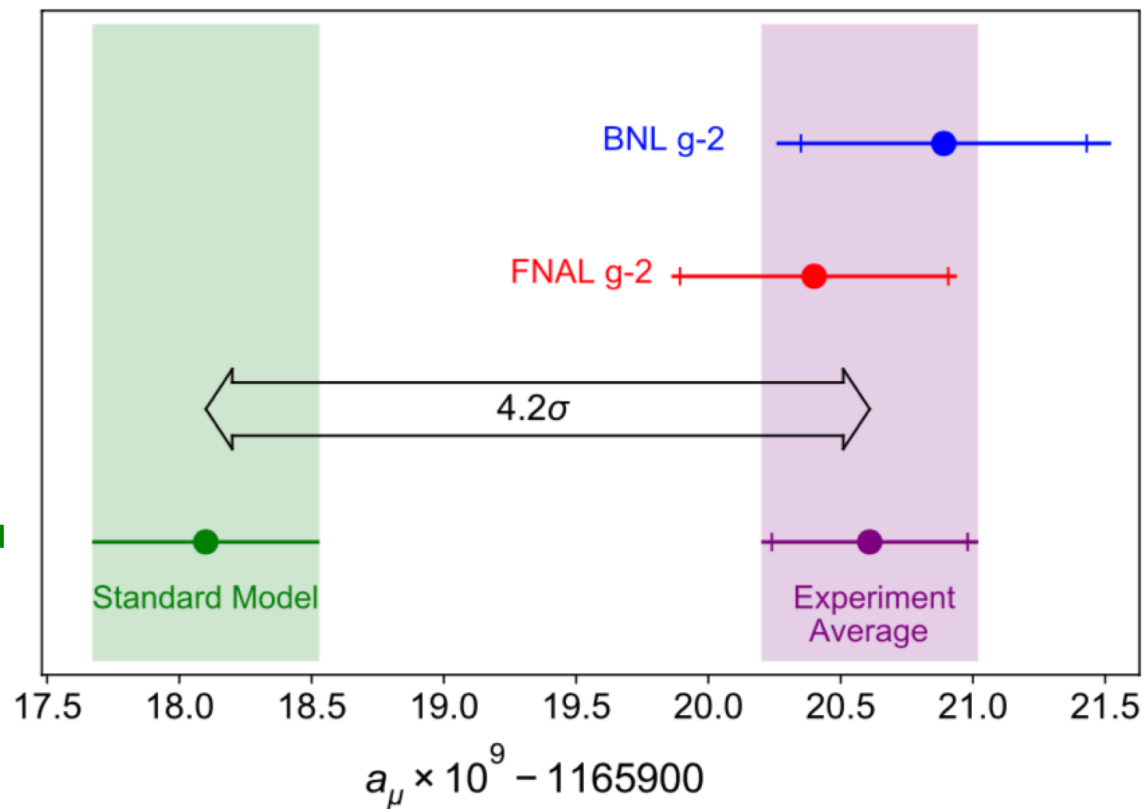
Knowledge of the 2π Contribution



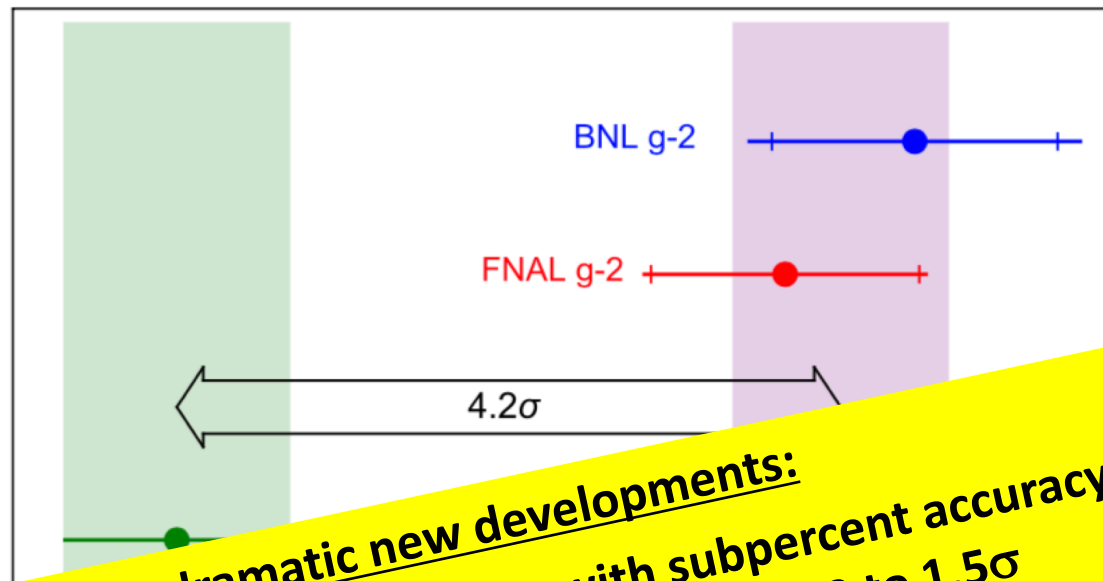
**Situation 2021: Knowledge of 2π contribution to HVP largely limits accuracy of SM prediction to the muon $g-2$
 → New data needed to clarify situation**

Situation 2021: Muon Magnetic Moment: $(g-2)_\mu$

$$a_\mu^{SM} = a_\mu^{\text{QED}} + a_\mu^{\text{weak}} + a_\mu^{\text{had}}$$



Situation 2021: Muon Magnetic Moment: $(g-2)_\mu$



$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{weak} + a_\mu^{had}$$

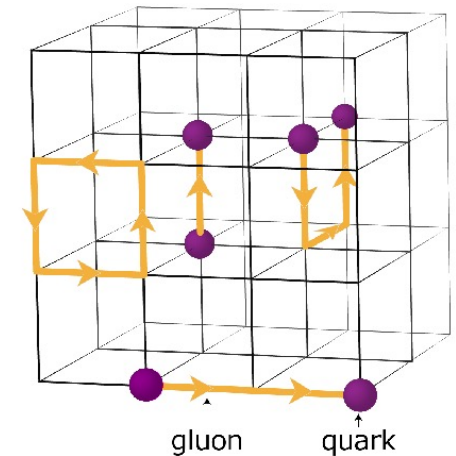
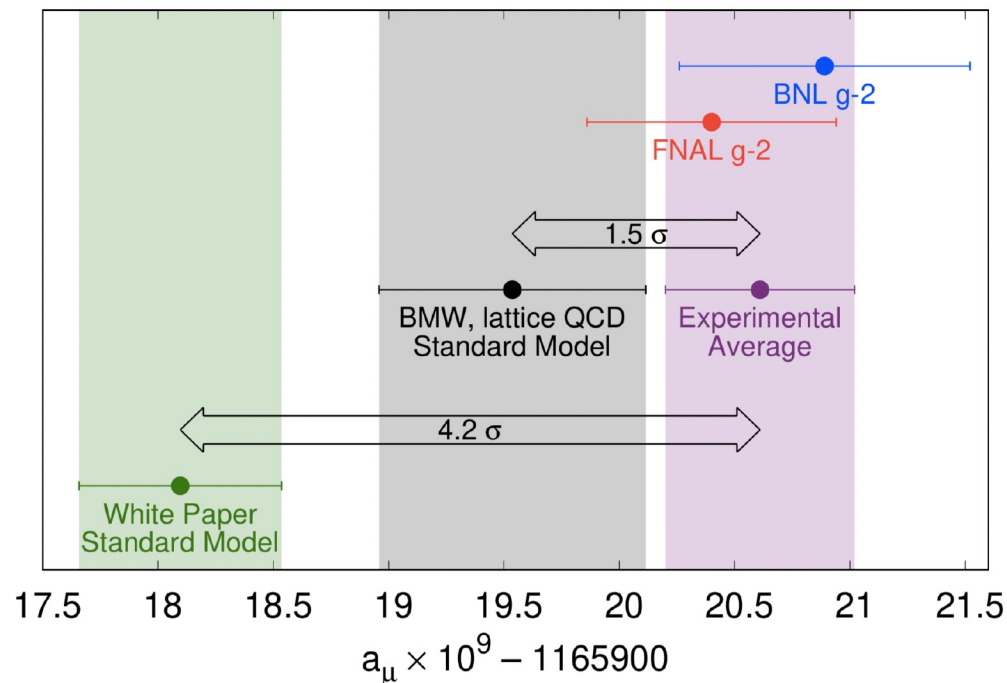
Since release of whitepaper (2020), dramatic new developments:

- 2021 Lattice QCD calculation of HVP by BMW collab. with subpercent accuracy
→ reduces discrepancy between SM prediction and FNAL g-2 to 1.5 σ
- 2022 Lattice QCD window fever
- 2023 CMD-3 measurement of pion FF: $e^+e^- \rightarrow \pi^+\pi^-$

2022: Lattice-QCD calculation of HVP

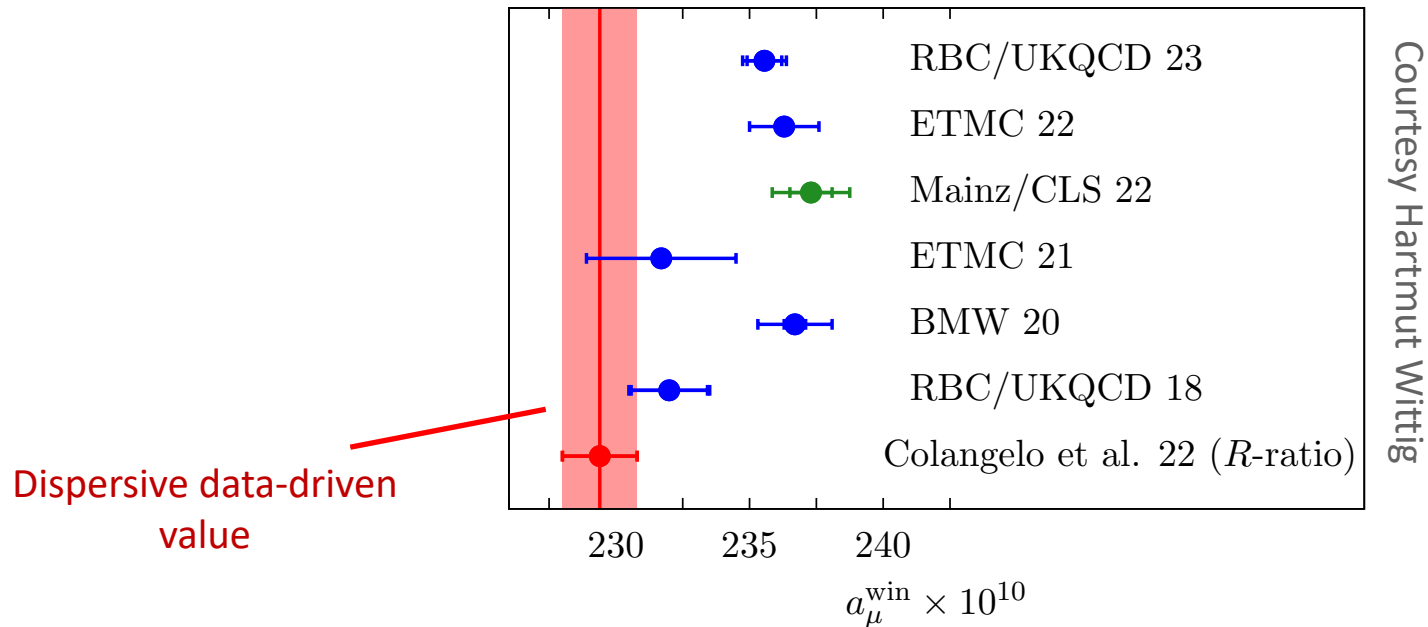
First time ab-initio precision calculation of HVP contribution by means of Lattice QCD (BMW 2021)

Similar accuracy as dispersive data-based calculation



2022: Lattice-QCD Window Fever

Lattice QCD calculations (spacelike!) with largest systematic effects at small and long distances → **intermediate window** (~1/3 of total HVP contribution)!

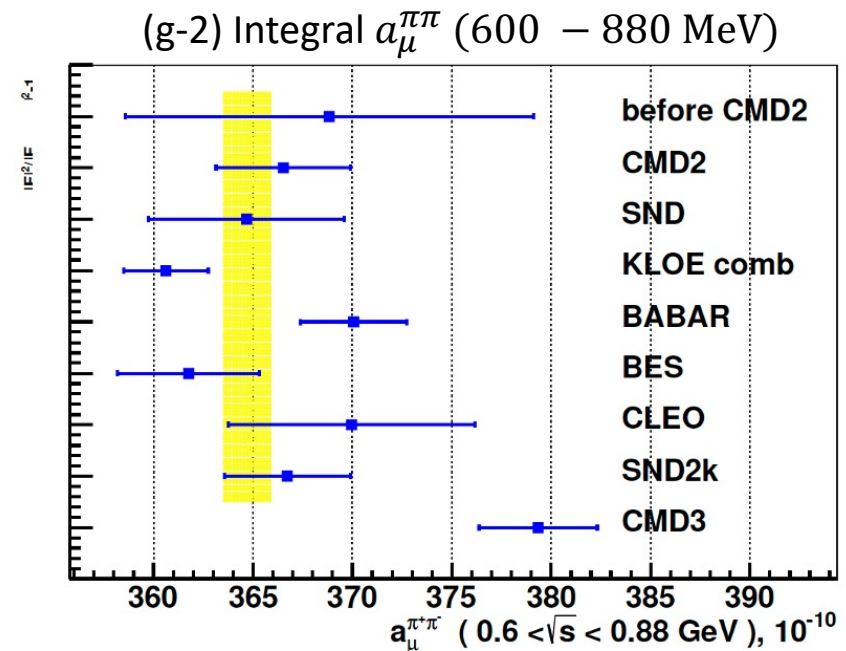
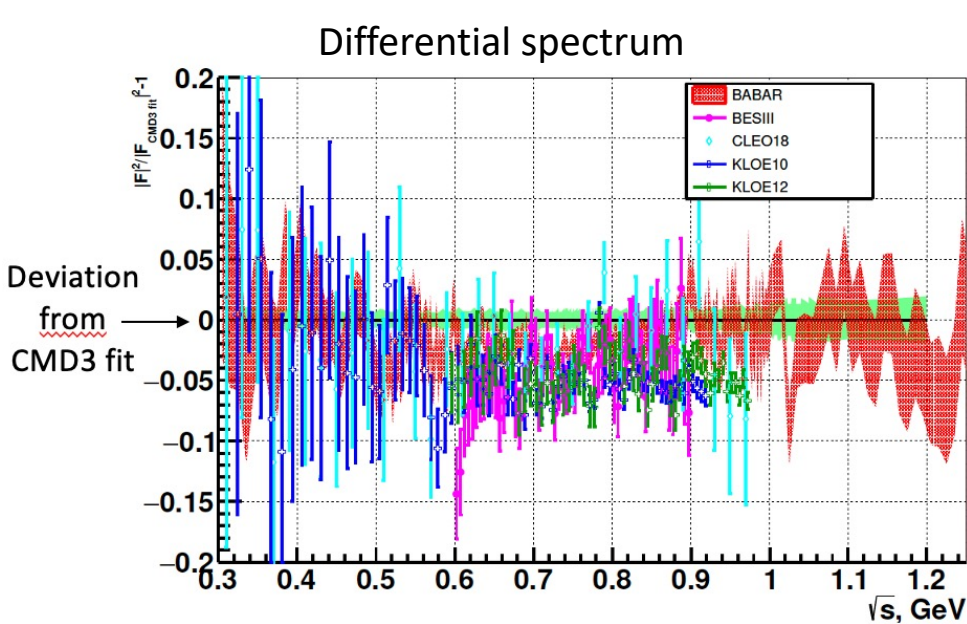


Excellent agreement among all Lattice QCD calculations and disagreement with data-driven approach confirmed !
However, effect is quite (too?) large in intermediate window?!

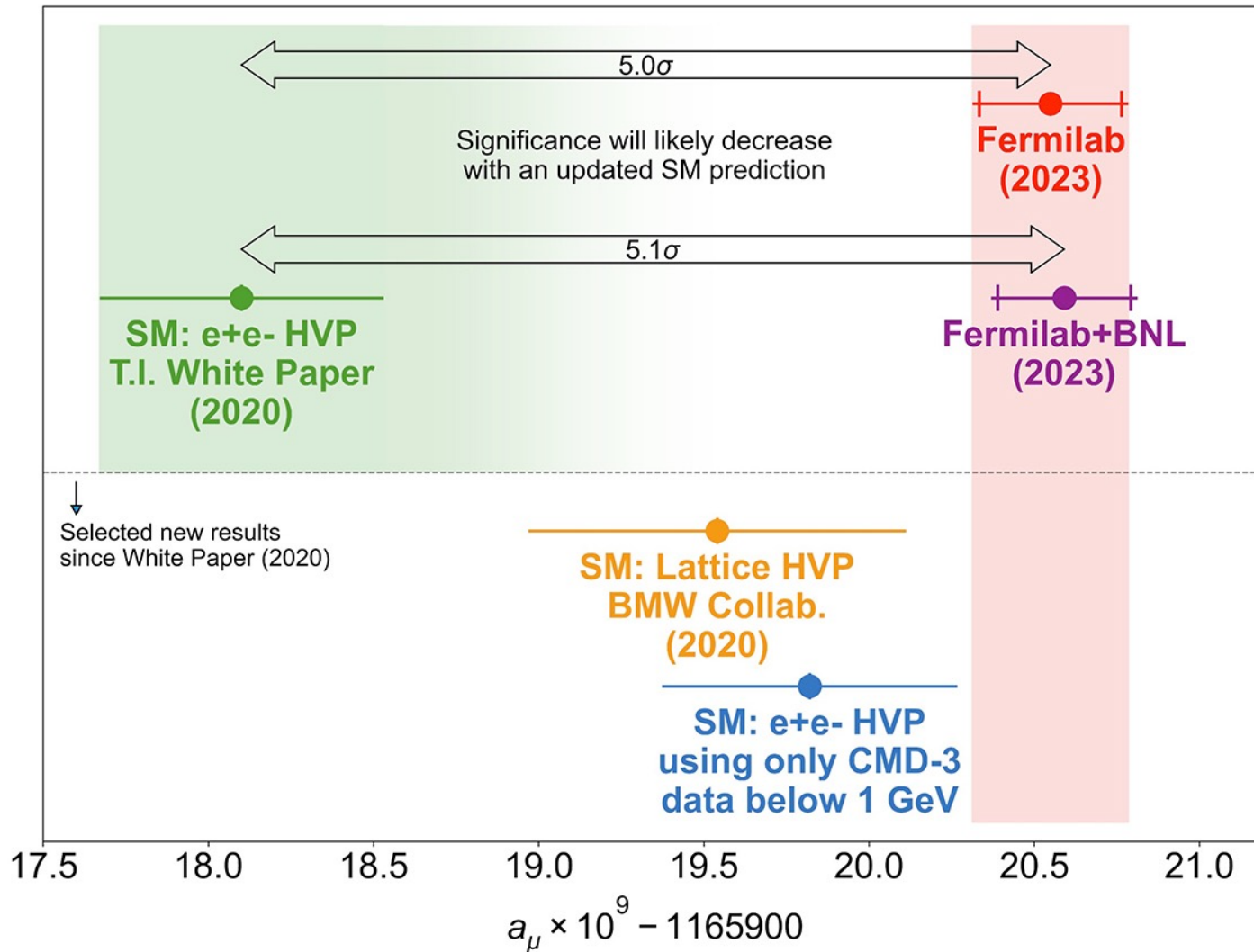
2023 Shock: CMD-3@Novosibirsk $e^+e^- \rightarrow \pi^+\pi^-$

arxiv:2302.08834

- New result from CMD-3 collaboration @ VEPP-2000 collider in Novosibirsk
 - Energy scan method, no ISR!
 - Energy range from threshold up to 1.2 GeV
 - Highest statistics data sample up to now, systematic uncertainty 0.7% on ρ peak
- Significant deviation from previous ISR and energy scan experiments ! Why?



Situation 2023: Muon Magnetic Moment: $(g-2)_\mu$



Situation 2023: Muon Magnetic Moment: $(g-2)_\mu$

Situation HVP 2023



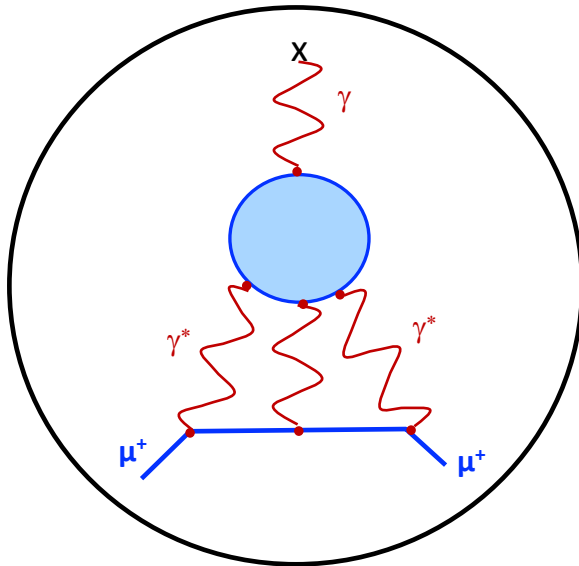


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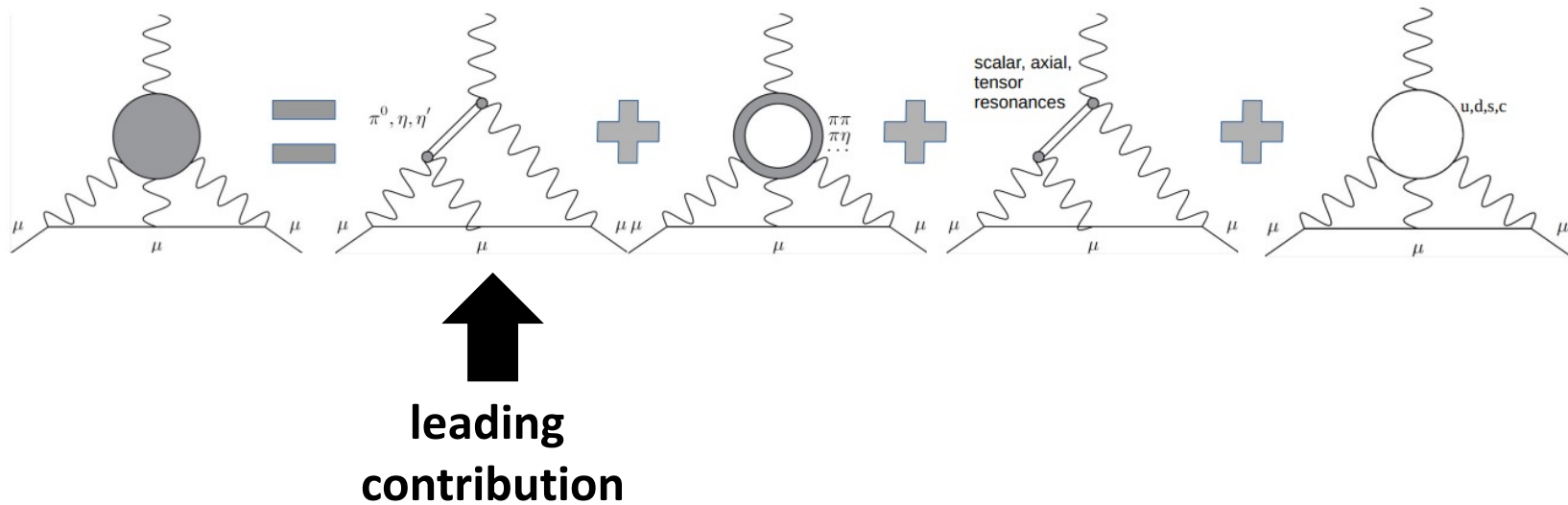
Hadronic Light-by-Light Contribution (HLbL)



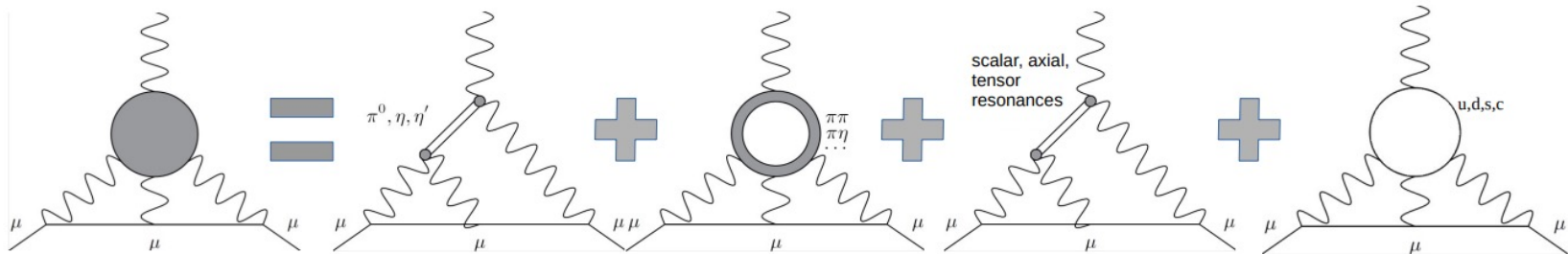
**Estimate of (g-2) Theory Initiative:
(9.2 ± 1.8) · 10⁻¹⁰**

was (10.5 ± 2.6) · 10⁻¹⁰

HLbL and Impact of BESIII Data



HLbL and Impact of BESIII Data

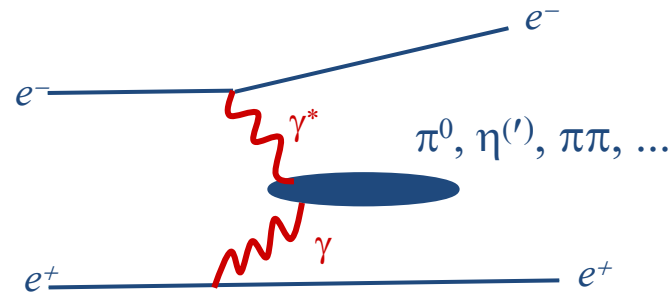


leading
contribution

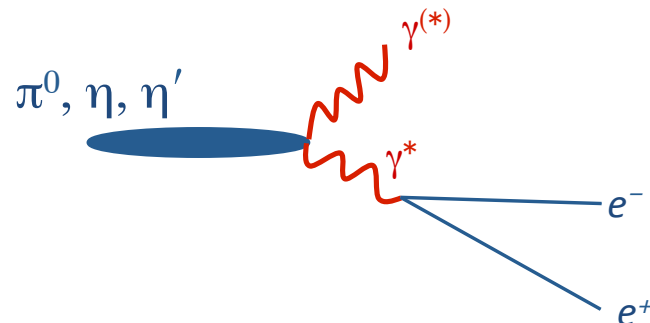
NEW

Data-driven approach!

Exp. Input:
Transition
Form Factors $F(Q^2)$
below $\sim 2 \text{ GeV}^2$



BESIII
 e^+e^- collider
 $\sqrt{s} 2 \dots 5 \text{ GeV}$



Hadronic Light-by-Light $(g-2)_\mu$

Leading contributions are pole contribution from π^0, η, η'

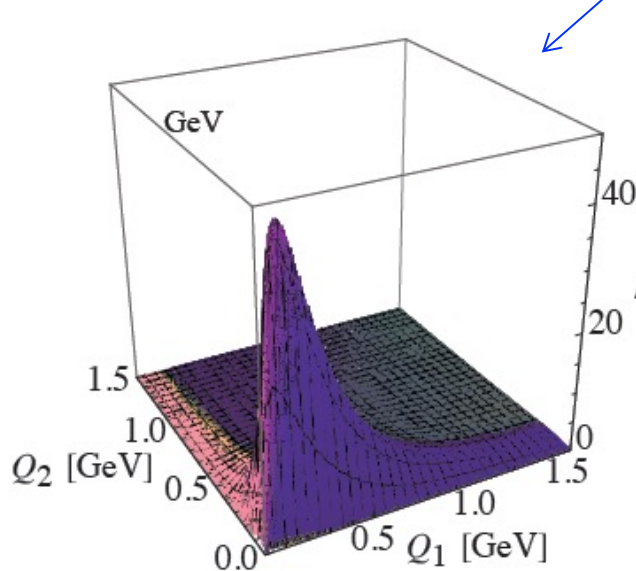
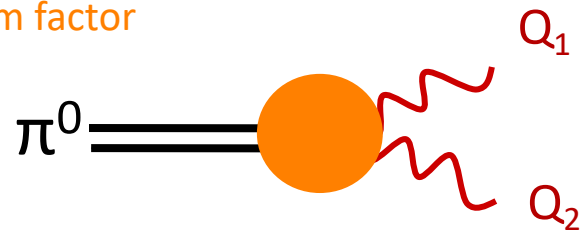
$$a_\mu^{\text{HLbL}; \pi^0(1)} = \int_0^\infty dQ_1 \int_0^\infty dQ_2 \int_{-1}^1 d\tau w_1(Q_1, Q_2, \tau) \mathcal{F}_{\pi^0 \gamma^* \gamma^*}(-Q_1^2, -(Q_1 + Q_2)^2) \mathcal{F}_{\pi^0 \gamma^* \gamma^*}(-Q_2^2, 0)$$

3D integral representation

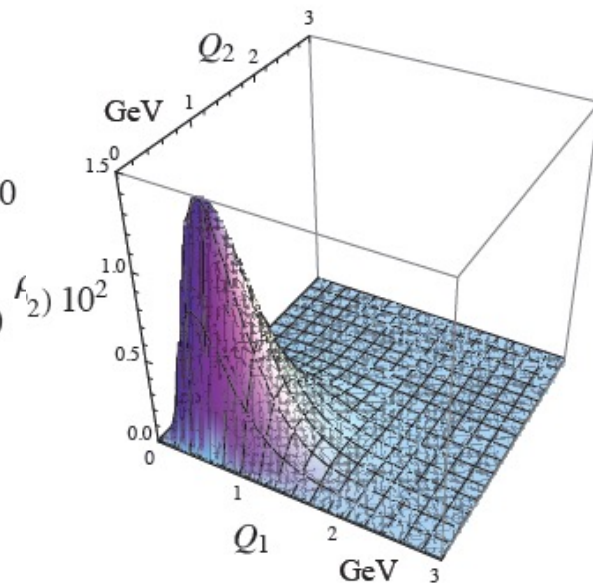
[Nyffeler 2016]

weighting
function

transition
form factor



Pseudoscalar Mesons



Axial Vector Mesons

→ Need doubly virtual form factors of π^0, η, η' at low Q^2

Two-Photon Physics Programme at BESIII

Selection criteria

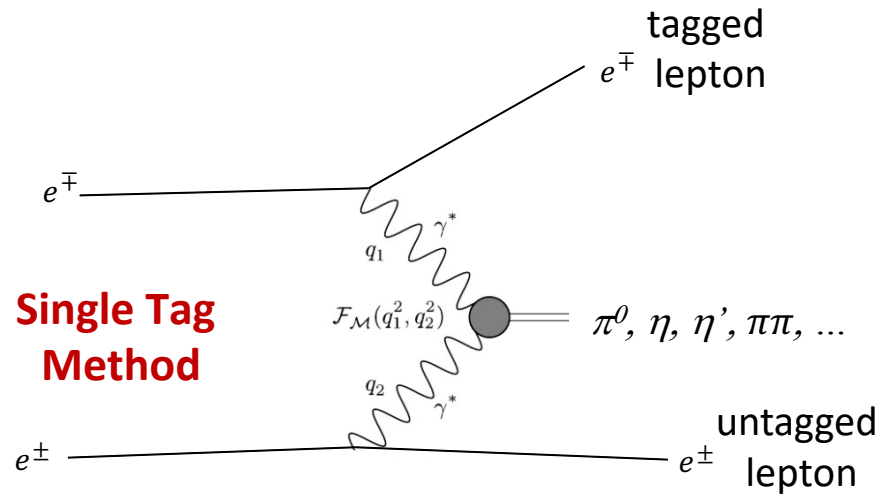
- 1 electron (positron) detected
- 1 positron (electron) along beam axis
- Meson fully reconstructed
- **cut on angle of missing momentum**

Momentum transfer

- tagged: $Q^2 = -q_1^2 = -(p - p')^2$
→ Highly virtual photon
- untagged: $q^2 = -q_2^2 \sim 0 \text{ GeV}^2$
→ Quasi-real photon

EKHARA event generator

$$Q^2 = 4 \cdot E \cdot E' \cdot \sin^2(\theta/2)$$



Two-Photon Physics Programme at BESIII

Selection criteria

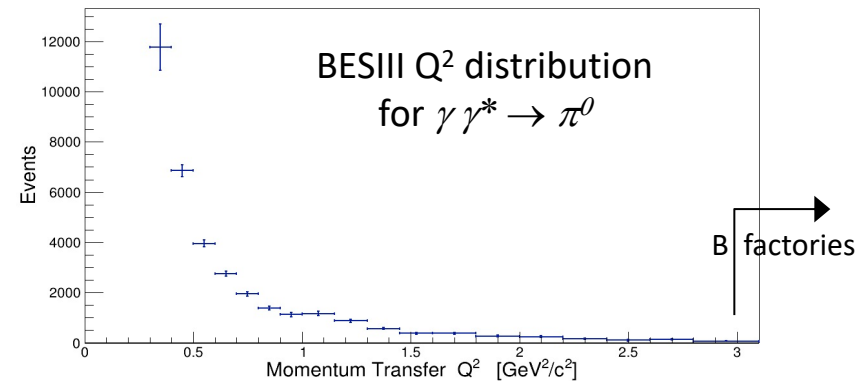
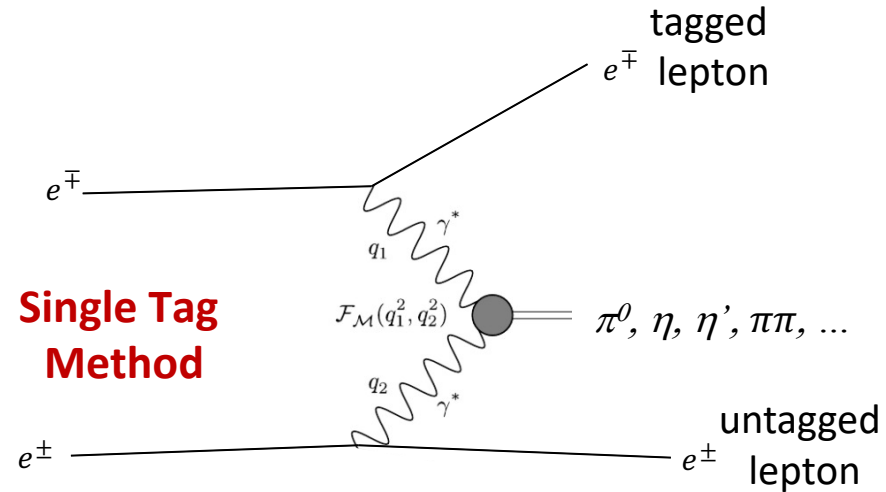
- 1 electron (positron) detected
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Momentum transfer

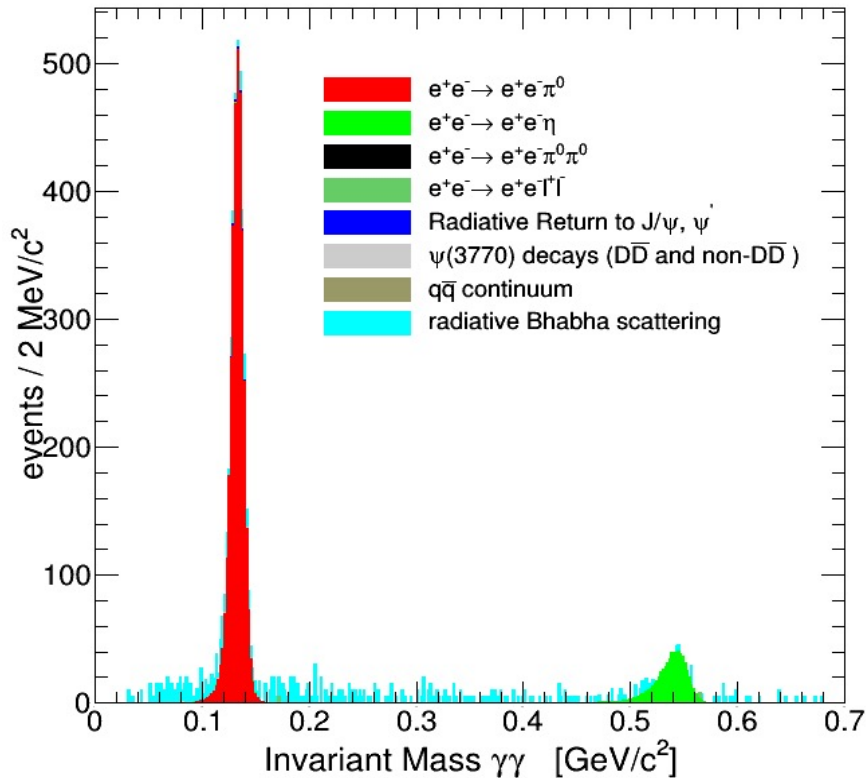
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EKHARA event generator

$$Q^2 = 4 \cdot E \cdot E' \cdot \sin^2(\theta/2)$$



BES III Analysis: $e^+e^- \rightarrow e^+e^- \pi^0$



Event Selection:

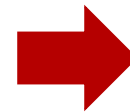
- exactly one lepton candidate
 - at least two, max four photons
 - Helicity angle $\cos \Theta_H > 0.8$
 - Kinematic cuts to reject ISR background
- **cut on angle of missing momentum**

Strategy:

Count
 π^0 yield in
bins of Q^2

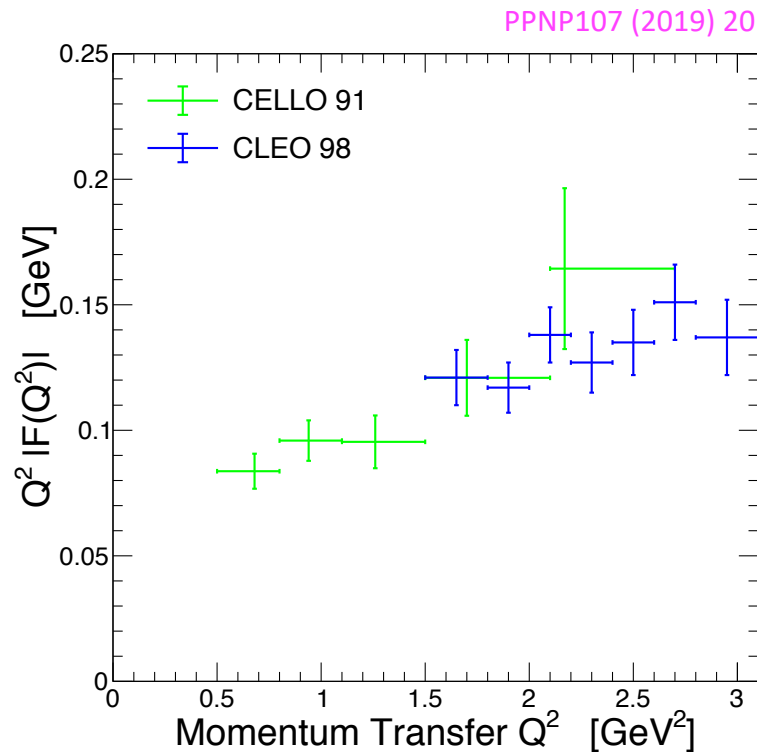


$d\sigma/dQ^2$



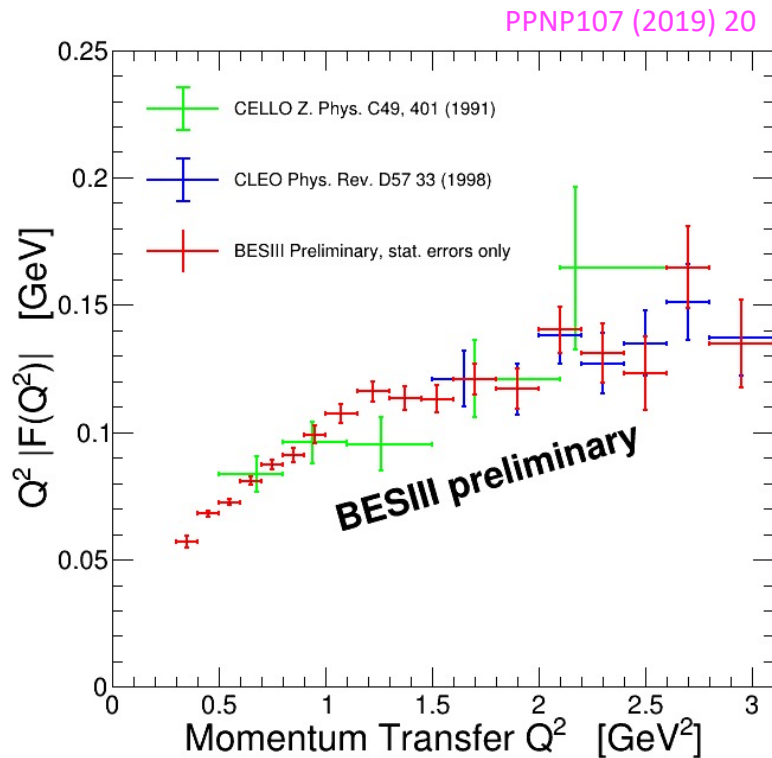
Form factor
 $F(Q^2)$

BES III Analysis: $\gamma \gamma^* \rightarrow \pi^0$



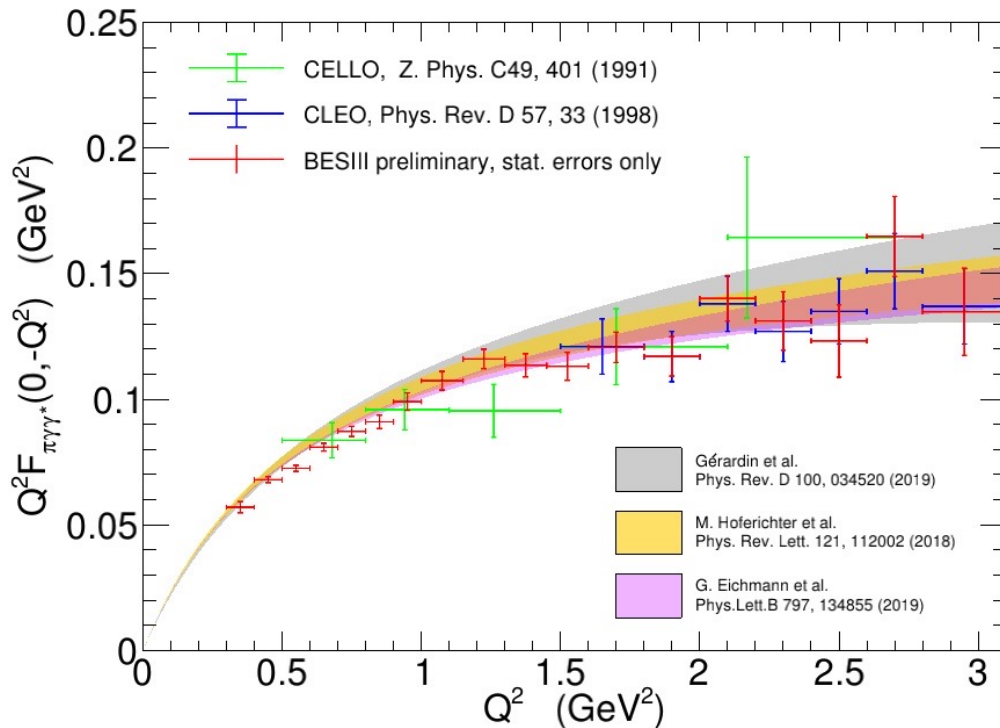
- $\sqrt{s}_{\text{BESIII}} = 3.77$ GeV, $L = 2.9/\text{fb}$
- Unprecedented accuracy of BESIII
- Relevant Q^2 range for HLbL
- ➔ **Very good agreement with recent dispersive analysis and of Lattice QCD calculation**
- Q^2 range below 0.3 GeV 2 accessible at BESIII with data from lower c.m. energy

BES III Analysis: $\gamma\gamma^* \rightarrow \pi^0$



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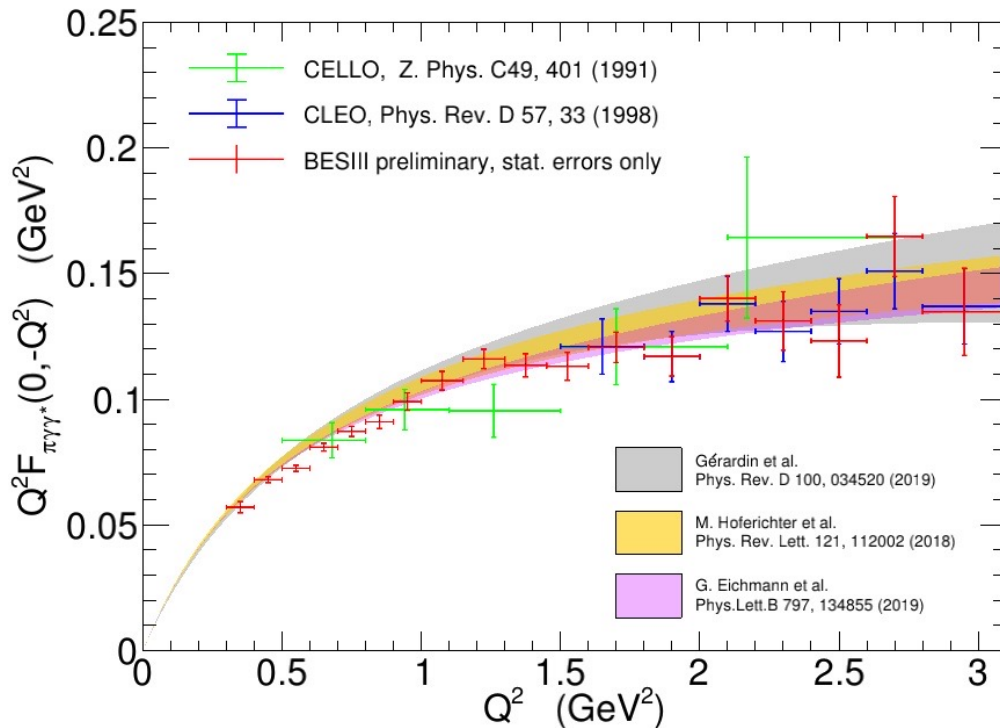
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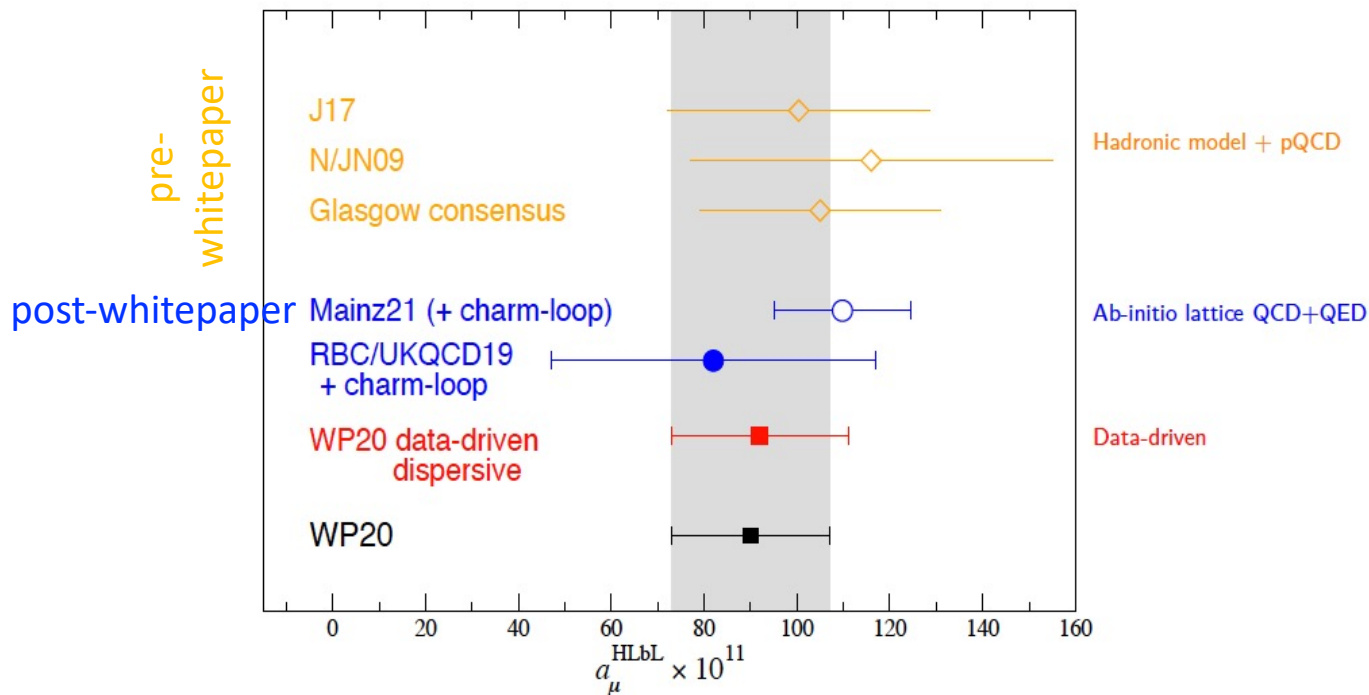
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**Very good agreement with recent
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Lattice QCD calculation**

Q^2 range below 0.3 GeV^2 accessible
at BESIII with data from lower
c.m. energy

**similar results for η and η' TFFs;
first measurement ever $\pi\pi$;
many other channels**

Hadronic Light-by-Light (HLbL)



- Differently from the HVP contribution, in the case of HLbL excellent agreement between the data-driven estimate and Lattice QCD
- With upcoming new form factor data ample room for improvement
- Community goal: relative uncertainty <10%

Hadronic Light-by-Light (HLbL)

Situation HLbL 2023



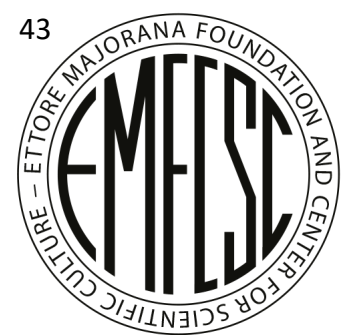


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Conclusions



Conclusions

- Interpretation of FNAL **muon g-2** experiment calls for a **detailed understanding of hadronic effects**:
 - Hadronic Vacuum Polarization (HVP) contribution
 - Hadronic Light-by-Light (HLbL) contribution
- Following the standard approach to determine HVP contribution via dispersion relation shows a **discrepancy of 5.1σ between (g-2) SM theory and experiment**:

New Physics ?

Too early to say - Two new g-2 puzzles:

- Lattice QCD calculation (BMW) of HVP suggests significantly **lower discrepancy**
- Recent CMD-3 result for timelike pion form factor also suggest **lower discrepancy** → reason for deviation to all previous experiments unknown → **Quest for new measurements of form factors !**

Thank you !

**g-2 is not an experiment
[not a number] –
It is a way of life ...**

John Adams, former Director General CERN

