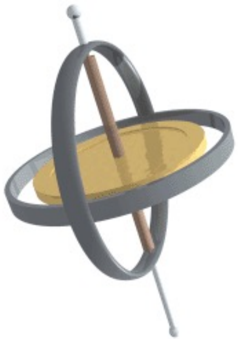
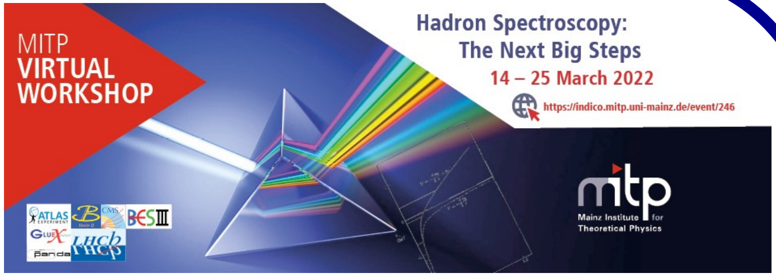




Measuring the hadronic corrections to the anomalous magnetic moment of the muon

SFB 1044
THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

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

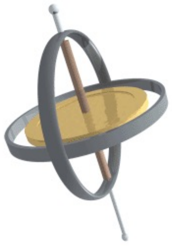
JG|U

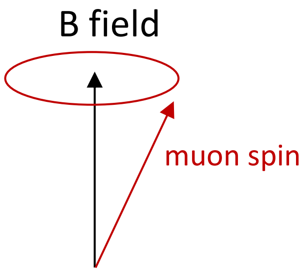
March 18, 2022
Achim Denig
Johannes Gutenberg University Mainz

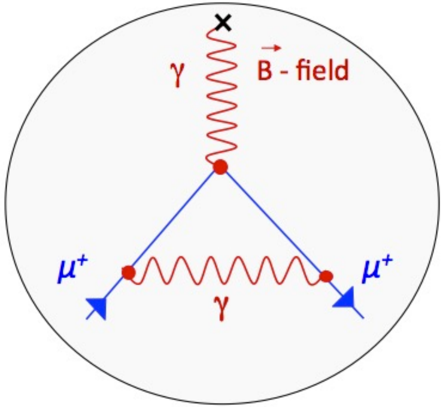
Standard Model Contribution to (g-2)$_\mu$

$$a_\mu^{SM} = (g_\mu - 2)/2 = a_\mu^{QED} + a_\mu^{weak} + a_\mu^{had}$$

gyromagnetic factor of the muon

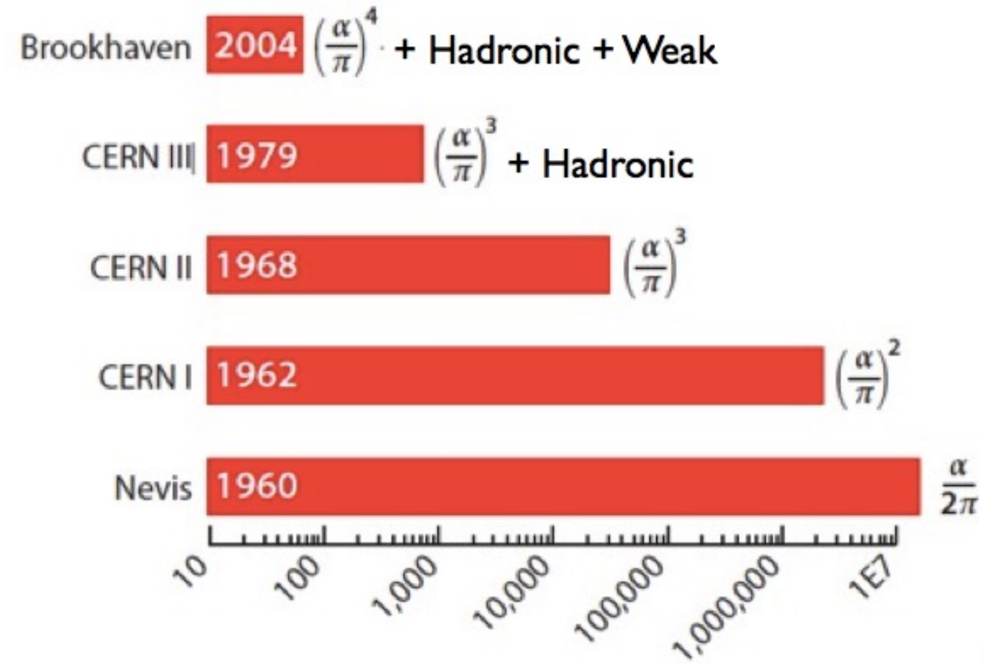




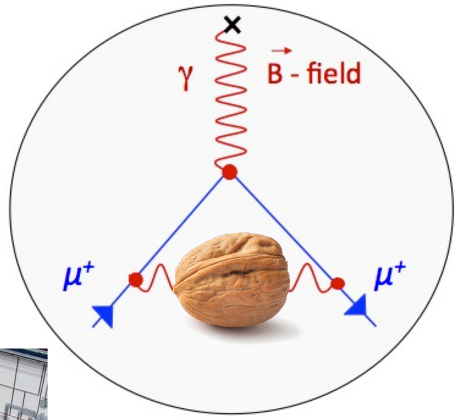


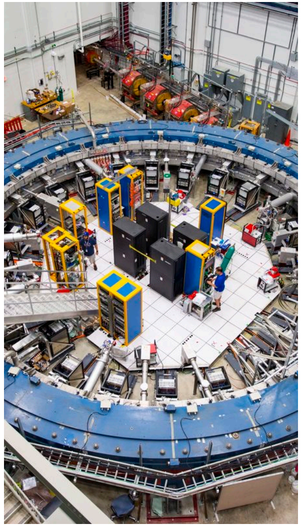
Standard Model Contribution to $(g\text{-}2)_\mu$

$$a_\mu^{SM} = (g_\mu - 2)/2 = a_\mu^{QED} + a_\mu^{weak} + a_\mu^{had}$$



Uncertainty of measurement in 10^{-11}



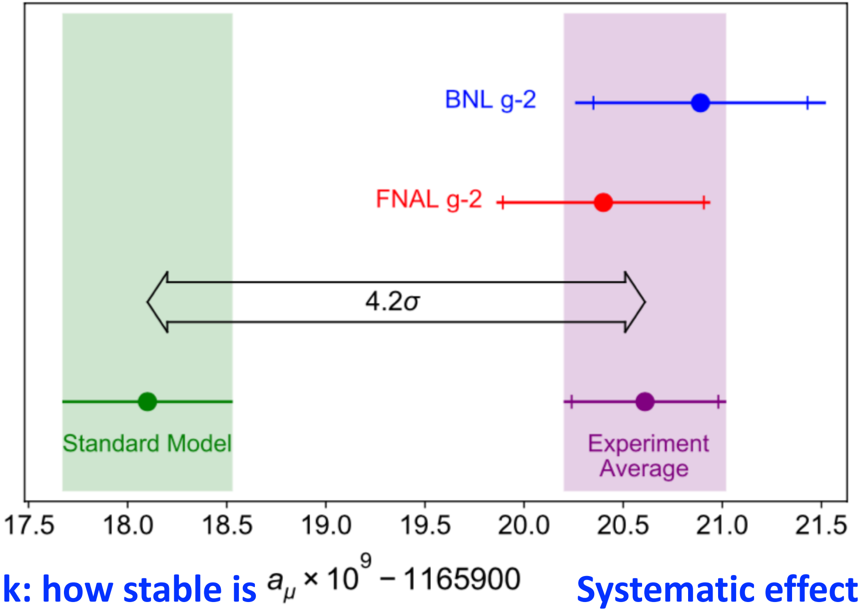


FNAL (2021++)
Goal: improve BNL accuracy by a factor of 4

CERN I (1962)

First Result from new direct $(g\text{-}2)_\mu$ Measurement FNAL

Strong indication for physics beyond the SM ?!



Nothing found so far,
→ confirmation from independent J-PARC measurement highly desirable !

This talk: how stable is the SM prediction ?

Systematic effect in BNL/FNAL method ?

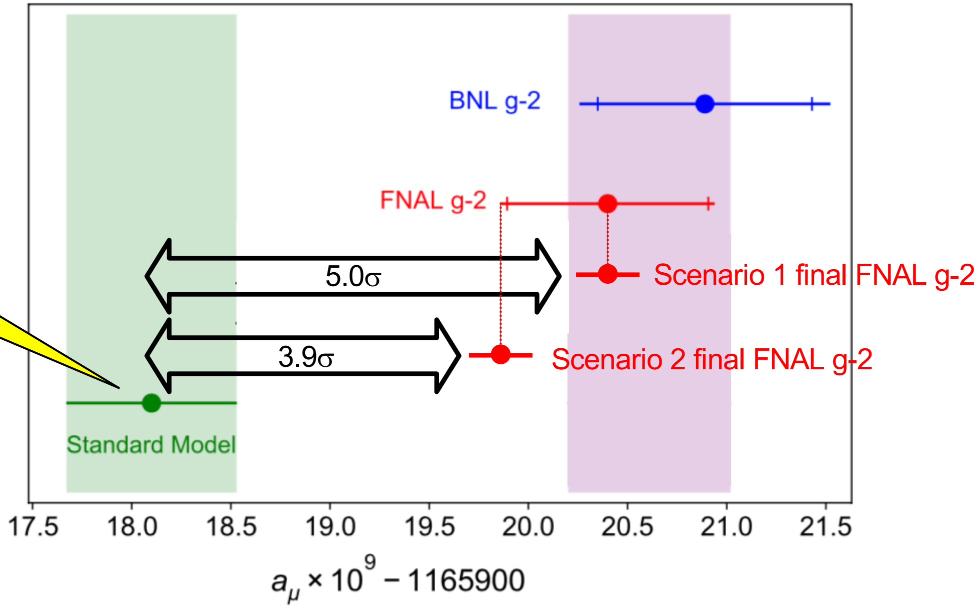
?

?

New direct $(g\text{-}2)_\mu$ Measurement FNAL

Speculations: possible final outcome of FNAL experiment

Reduction of SM prediction needed for final interpretation
→ **Impact from Hadron Physics !**



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

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{weak} + a_\mu^{had} = (\,11\,659\,181.0 \pm 4.3\,) \cdot 10^{-10}$$

Czarnecki et al.

$(\,15.4 \pm \mathbf{0.2}\,) \cdot 10^{-10}$

Kinoshita et al. '12

$(\,11\,658\,471.808 \pm \mathbf{0.015}\,) \cdot 10^{-10}$

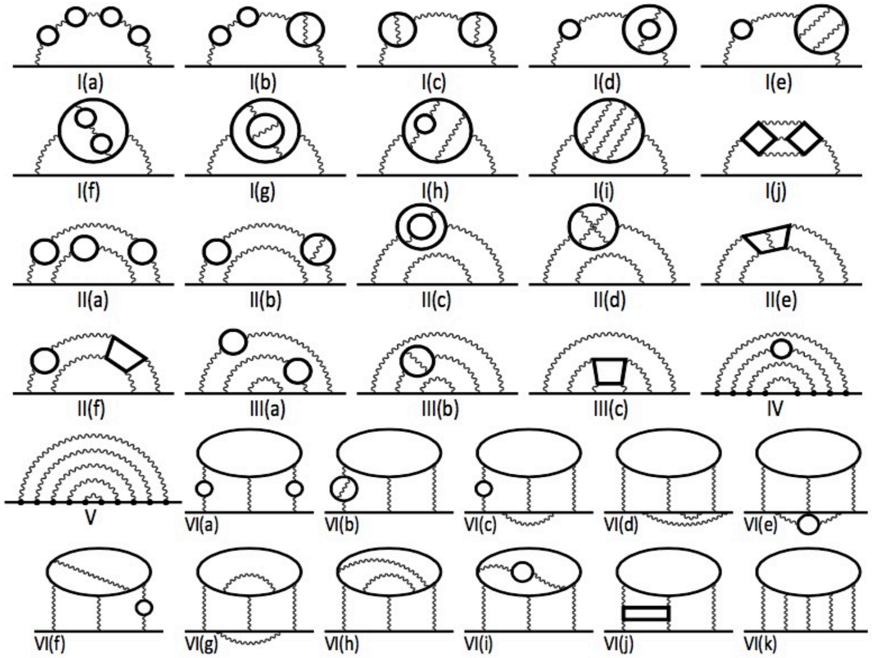
Absolute contribution dominated by QED

Uncertainty dominated by hadronic contribution

10th

12672

diagrams



2019: Standard Model Prediction of $(g\text{-}2)_\mu$

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

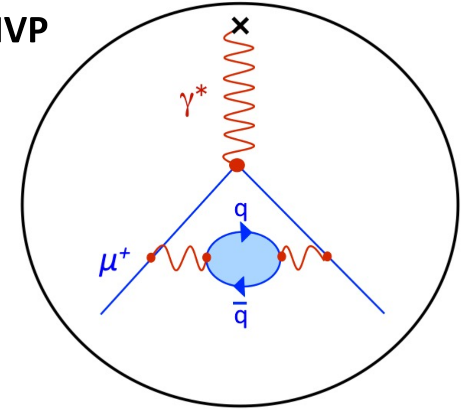
$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{weak} + a_\mu^{had}$$

→ **HVP**: Hadronic Vacuum Polarization (≅ **687 ... 694** ± **2.4 ... 4.1**) · 10^{-10}

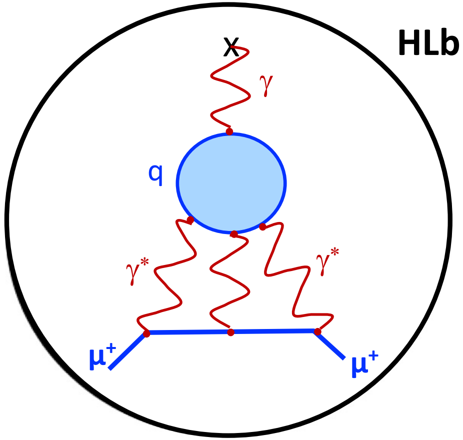
	BDJ19	DHMZ19	FJ17	KNT19
$a_\mu^{\mathrm{HVP,\,LO}} \times 10^{10}$	687.1(3.0)	694.0(4.0)	688.1(4.1)	692.8(2.4)

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

HVP



HLbL



NLO (-9.8 ± **0.1**) · 10^{-10} ;
NNLO (1.2 ± **0.01**) · 10^{-10}

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


FERMILAB-PUB-20-207-T
INT-PUB-20-021
KEK Preprint 2020-5
MITP/20-028

CERN-TH-2020-075
IFT-UAM/CSIC-20-74
LMU-ASC 18/20
LTH 1234
LU TP 20-20
MAN/HEP/2020/003
PSI-PR-20-06
UWThPh 2020-14
ZU-TH 18/20

arXiv:2006.04822 [hep-ph] 8 Jun 2020

The anomalous magnetic moment of the muon in the Standard Model

T. Aoyama[1,2,3], N. Asmussen[4], M. Benayoun[5], J. Bijnens[6], T. Blum[7,8], M. Bruno[9], I. Caprini[10], C. M. Carloni Calame[11], M. Cè[9,12,13], G. Colangelo[14], F. Curciarello[15,16], H. Czyż[17], I. Danilkin[12], M. Davier[18], C. T. H. Davies[19], M. Della Morte[20], S. I. Eidelman[21,22], A. X. El-Khadra[23,24], A. Gérardin[25], D. Giusti[26,27], M. Golterman[28], Steven Gottlieb[29], V. Gülpers[30], F. Hagelstein[14], M. Hayakawa[31,2], G. Herdoíza[32], D. W. Hertzog[33], A. Hoecker[34], M. Hoferichter[14,35], B.-L. Hoid[36], R. J. Hudspith[12,13], F. Ignatov[21], T. Izubuchi[37,8], F. Jegerlehner[38], L. Jin[7,8], A. Keshavarzi[39], T. Kinoshita[40,41], B. Kubis[36], A. Kupich[21], A. Kupść[42,43], L. Laub[14], C. Lehner[26,37], L. Lellouch[25], I. Logashenko[21], B. Malaescu[5], K. Maltman[44,45], M. K. Marinković[46,47], P. Masjuan[48,49], A. S. Meyer[37], H. B. Meyer[12,13], T. Mibe[1], K. Miura[12,13,3], S. E. Müller[50], M. Nio[2,51], D. Nomura[52,53], A. Nyffeler[12], V. Pascalutsa[12], M. Passera[54], E. Perez del Rio[55], S. Peris[48,49], A. Portelli[30], M. Procura[56], C. F. Redmer[12], B. L. Roberts[57], P. Sánchez-Puertas[49], S. Serednyakov[21], B. Shwartz[21], S. Simula[27], D. Stöckinger[58], H. Stöckinger-Kim[58], P. Stoffer[59], T. Teubner[60], R. Van de Water[24], M. Vanderhaeghen[12,13], G. Venanzoni[61], G. von Hippel[12], H. Wittig[12,13], Z. Zhang[18], M. N. Achasov[21], A. Bashir[62], N. Cardoso[47], B. Chakraborty[63], E.-H. Chao[12], J. Charles[25], A. Crivellin[64,65], O. Deineka[12], A. Denig[12,13], C. DeTar[66], C. A. Dominguez[67], A. E. Dorokhov[68], V. P. Druzhinin[21], G. Eichmann[69,47], M. Fael[70], C. S. Fischer[71], E. Gámiz[72], Z. Gelzer[23], J. R. Green[9], S. Guellati-Khelifa[73], D. Hatton[19], N. Hermansson-Truedsson[14], S. Holz[36], B. Hörz[74], M. Knecht[25], J. Koponen[1], A. S. Kronfeld[24], J. Laiho[75], S. Leupold[42], P. B. Mackenzie[24], W. J. Marciano[37], C. McNeile[76], D. Mohler[12,13], J. Monnard[14], E. T. Neil[77], A. V. Nesterenko[68], K. Ottnad[12], V. Pauk[12], A. E. Radzhabov[78], E. de Rafael[25], K. Raya[79], A. Risch[12], A. Rodríguez-Sánchez[6], P. Roig[80], T. San José[12,13], E. P. Solodov[21], R. Sugar[81], K. Yu. Todyshev[21], A. Vainshtein[82], A. Vaquero Avilés-Casco[66], E. Weil[71], J. Wilhelm[12], R. Williams[71], A. S. Zhevlakov[78]

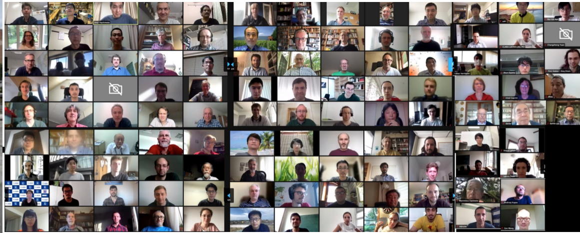
196 pages, 103 figures

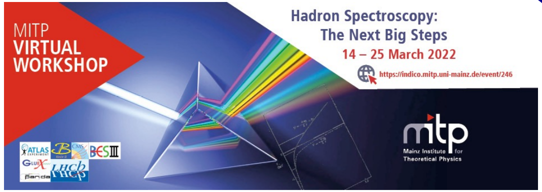
Goal:

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

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

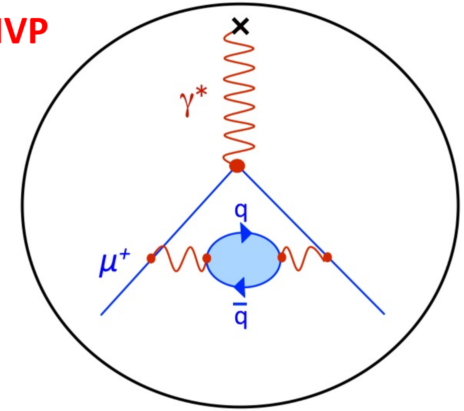
KEK (virtual) 2021





Hadronic Vacuum Polarization (HVP)

HVP



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

(**693.1** ± **4.0**) · 10^{-10}

was (≅ 687 ... 694 ± 2.4 ... 4.1) · 10^{-10}

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

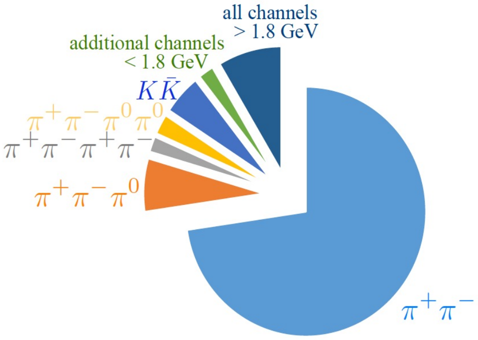
Optical theorem (unitarity) and analyticity:

Data-driven approach: *K(s):* known kernel function
s: energy²

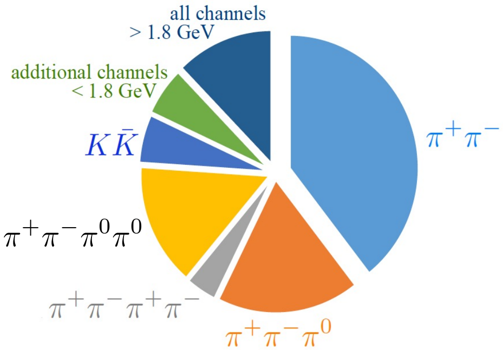
$$a_\mu^{HVP} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} ds\, K(s)\, \boldsymbol{\sigma_{\mathrm{had}}(s)}$$

$$\boldsymbol{\sigma_{had}(s) = \sigma_{\mathrm{tot}}(e^+e^- \to \mathrm{Hadrons})}$$

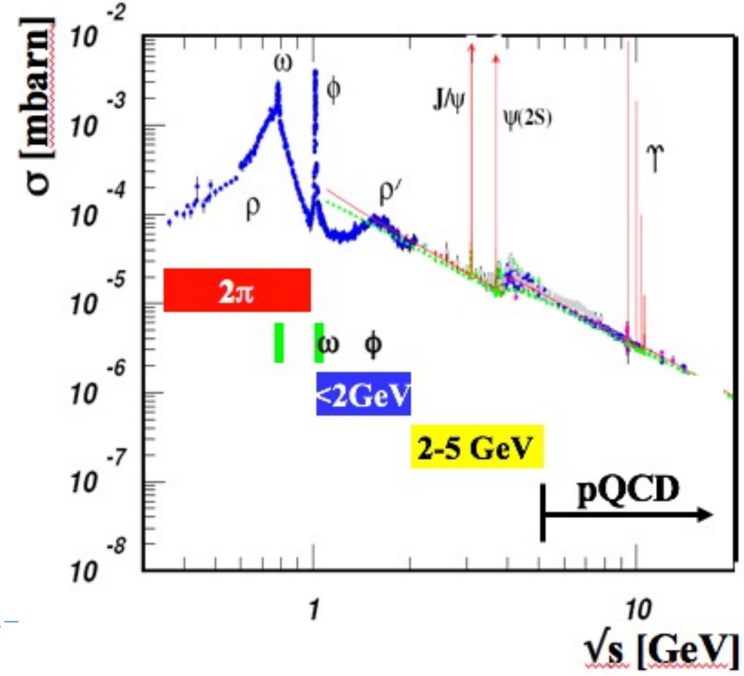
low energy contributions especially important!



Contributions to HVP integral

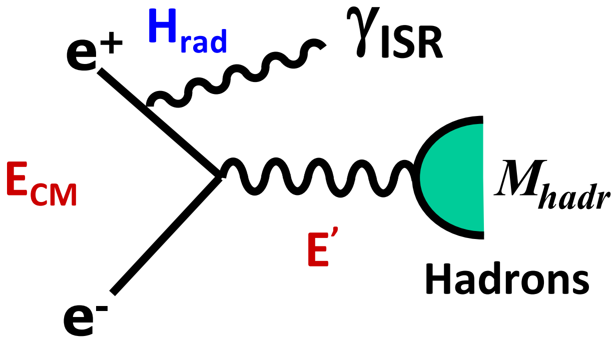


Contributions to HVP error



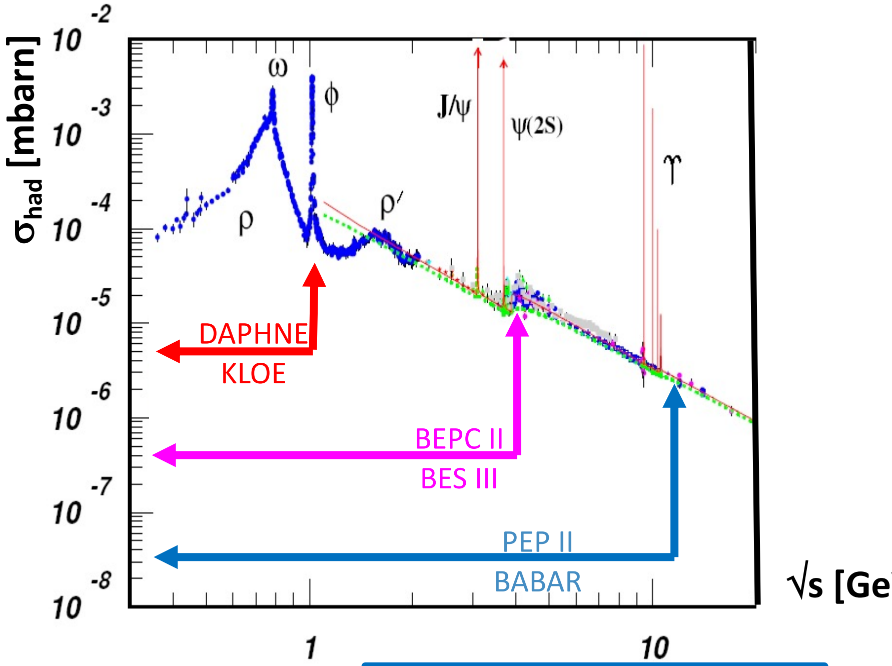
Initial State Radiation (ISR)

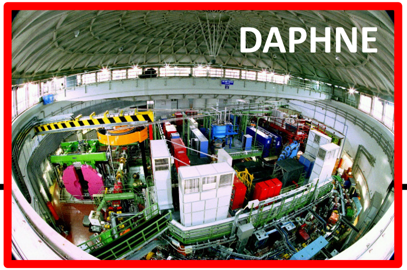
Initial State Radiation aka Radiative Return

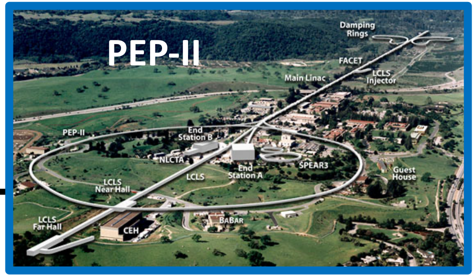


- No systematic variation of E_{beam}
- High statistics thanks to high luminosity
- Precise knowledge of radiative corrections mandatory (H_{rad})

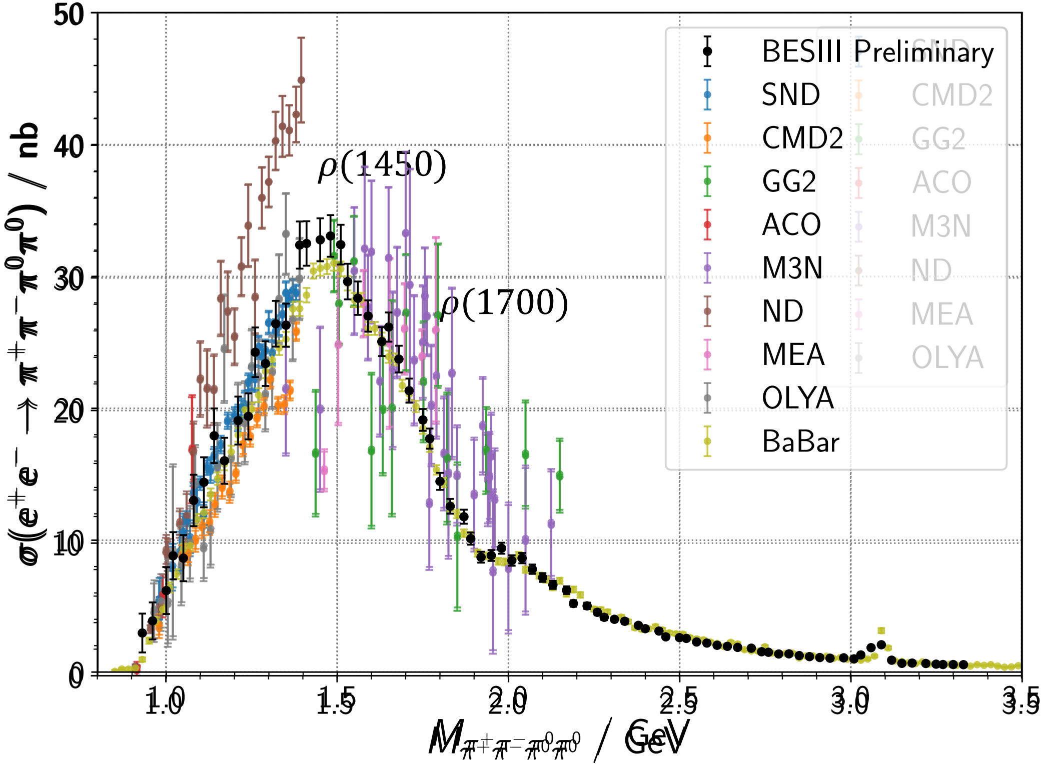
PHOKHARA event generator







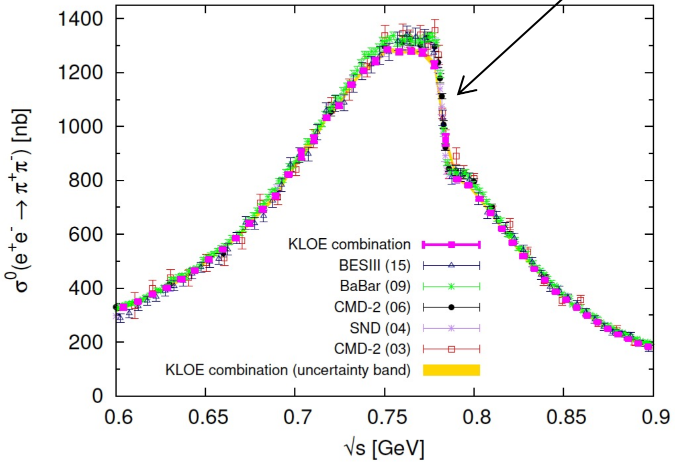
ISR (BABAR & BESIII): $e^+e^- \to \pi^+\pi^-\pi^0\pi^0$

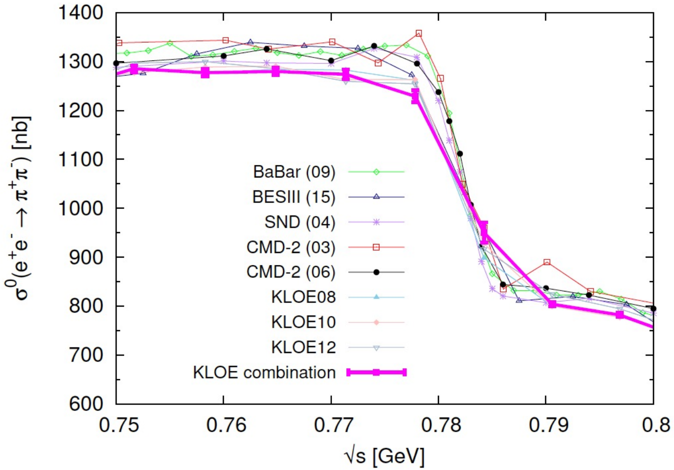


Most relevant Channel: $e^+e^- \rightarrow \pi^+\pi^-$

KLOE-2, JHEP1803 (2018)

ρ - ω interference





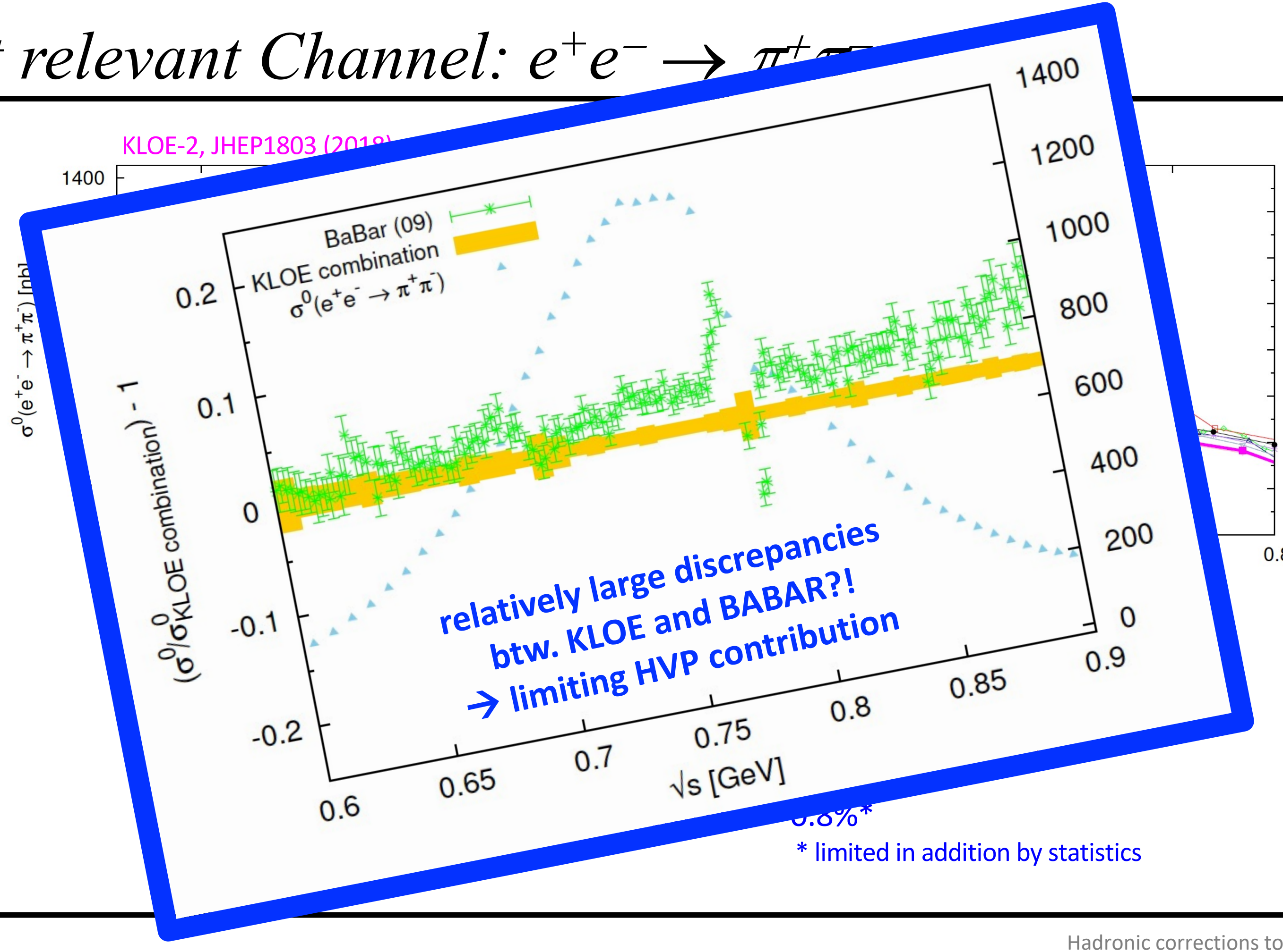
Systematic Uncertainties on ρ(770) peak

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

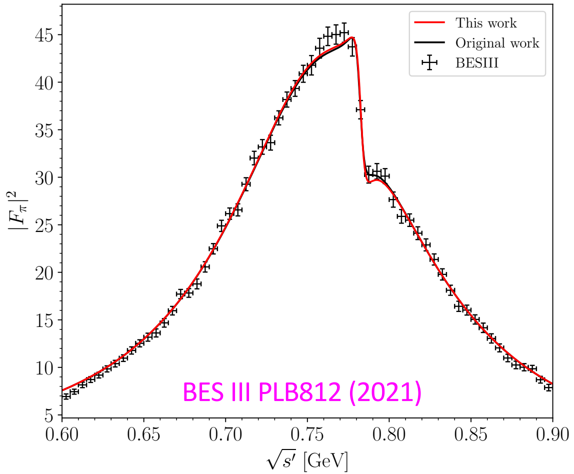
KLOE-2, JHEP1803 (2018)



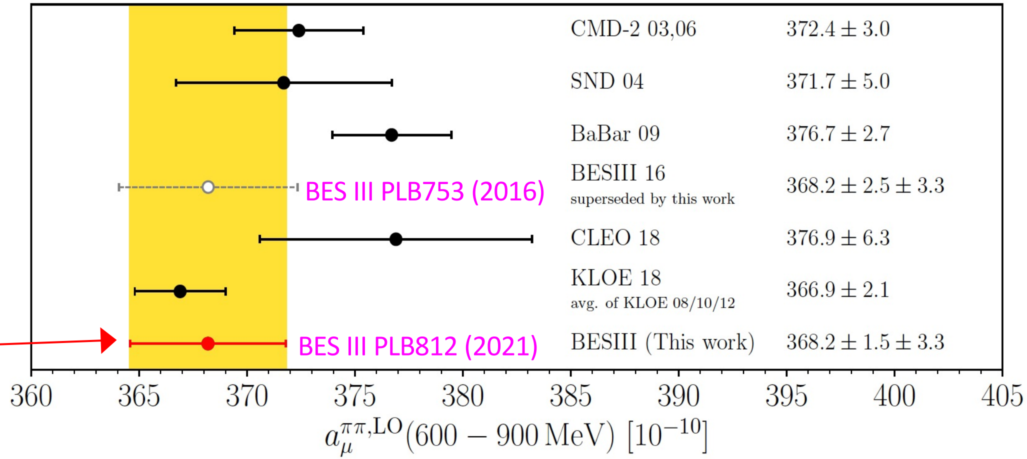
0.8%*

* limited in addition by statistics

BESIII Analysis $e^+e^- \to \pi^+\pi^-\gamma_{ISR}$



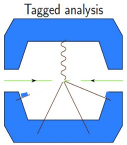
Source	BESIII 2016 2.9/fb (Update)
Photon efficiency	0.2
Pion tracking efficiency	0.3
Pion ANN efficiency	0.2
Pion e-PID efficiency	0.2
Angular acceptance	0.1
Background subtraction	0.1
Unfolding procedure	0.2
Luminosity $\mathcal{L}$	0.5
FSR correction	0.2
Vacuum polarization	0.2
Radiator function	0.5
Sum Systematics	**0.9**
Statistical error	**0.4**



BESIII Analysis $e^+e^- \rightarrow \pi^+\pi^-\gamma_{ISR}$

Source	BESIII 2016 2.9/fb (Update)	LA Analysis Normalization to $\mu^+\mu^-\gamma$ events
Photon efficiency	0.2	-
Pion tracking efficiency	0.3	0.2
Pion ANN efficiency	0.2	0.3
Pion e-PID efficiency	0.2	0.1
Angular acceptance	0.1	0.1
Background subtraction	0.1	0.1
Unfolding procedure	0.2	0.2
Luminosity $\mathcal{L}$	0.5	-
FSR correction	0.2	0.2
Vacuum polarization	0.2	-
Radiator function	0.5	-
Sum Systematics	**0.9**	**0.5**
Statistical error	**0.4**	**0.3**

- BESIII aims for new two-pion analysis with precision goal of 0.5% (tagged analysis)



- 20/fb of data at 3.77 GeV available soon
- Normalization to $\mu^+\mu^-\gamma$ events
- Improved pion-muon separation

$$R = \frac{N_{\pi^+\pi^-}}{N_{\mu^+\mu^-}} \cdot \frac{\varepsilon_{\mu^+\mu^-} \cdot \left(1 + \delta^{\mathrm{FSR}}_{\mu^+\mu^-}\right)}{\varepsilon_{\pi^+\pi^-} \cdot \left(1 + \delta^{\mathrm{FSR}}_{\pi^+\pi^-}\right)}$$

BESIII Analysis $e^+e^- \to \pi^+\pi^-\gamma_{ISR}$

Source	BESIII 2016 2.9/fb (Update)	LA Analysis Normalization to $\mu^+\mu^-\gamma$ events
Photon efficiency	0.2	-
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Background subtraction	0.1	0.1
Unfolding procedure	0.2	0.2
Luminosity $\mathcal{L}$	0.5	-
FSR correction	0.2	0.2
Vacuum polarization	0.2	-
Radiator function	0.5	-
Sum Systematics	**0.9**	**0.5**
Statistical error	**0.4**	**0.3**

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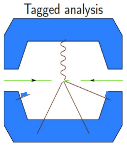

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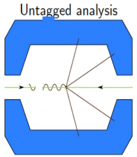
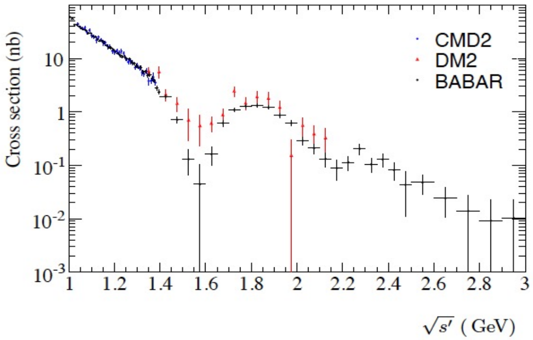
- BESIII aims for an improved measurement of the mass range above 1 GeV (untagged analysis)





BES III PRL (2022)

New Inclusive R Measurement at BESIII

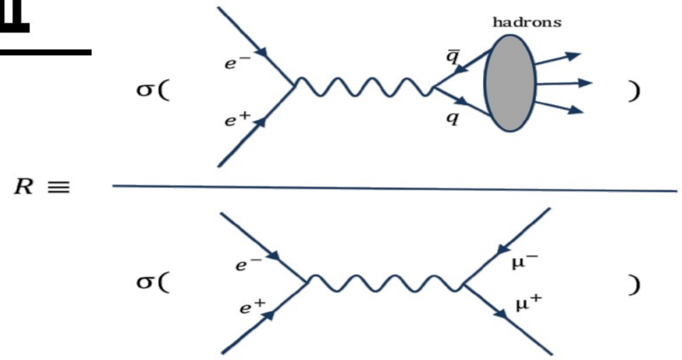
Relevant for hadronic corrections to $(g-2)_\mu$ and $\alpha_{em}(M_Z^2)$

$$R_{\rm had}(s) = \frac{1}{\sigma_{\mu^+\mu^-}} \cdot \frac{N_{\rm had} - N_{\rm bkg}}{\mathcal{L} \cdot \varepsilon_{\rm had} \cdot (1+\delta)}$$

background

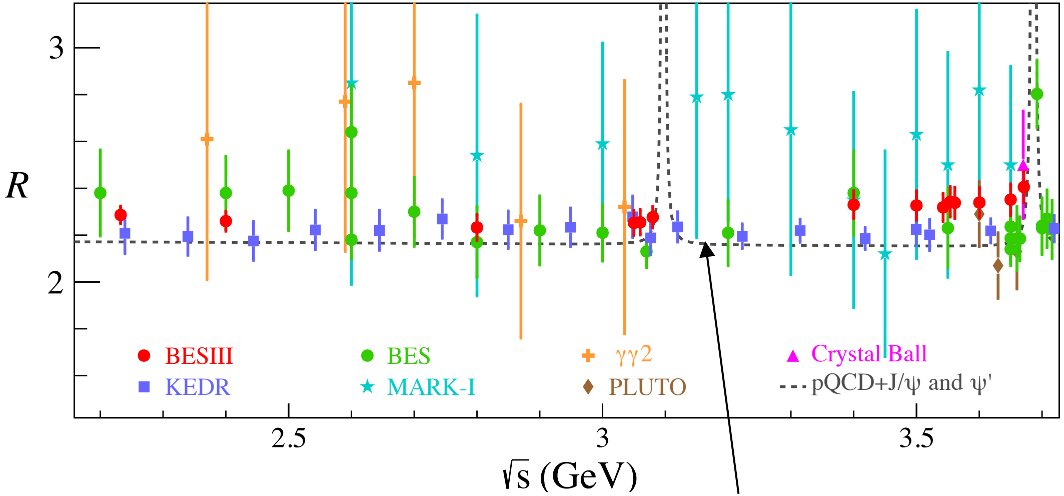
luminosity

rad. corrections



Efficiency of hadronic event selection:

- based on hadronic MC generators
- uncertainty (2.3%) limiting total error (<3%)
- Two independent MC codes:
  - LUARLW (theoretical model with model parameters tuned to expt. Distributions)
  - Hybrid (combination of PHOKHARA, measured spectra, LUARLW)



Result found to be above prediction of pQCD!

Conclusions & Outlook HVP

- HVP error (and therefore SM prediction of muon g-2) largely limited by KLOE– BABAR discrepancy of the pion FF measurement
- Existing BESIII and SND measurements (0.9%, 0.8% error) not yet precise enough to rule out either KLOE or BABAR
- New ISR measurements expected from BABAR, BESIII, BELLE-II: Try to push systematic uncertainties down to 0.5% or better
- New energy scans from VEPP-2000/Novosibirsk (CMD-3, SND): expect similar accuaracy
- Better accuaracy from higher multiplicity states and R_{incl} (KEDR, BESIII)

Conclusions & Outlook HVP

- HVP error (and therefore SM prediction of muon g-2) largely limited by KLOE– BABAR discrepancy of the pion FF measurement
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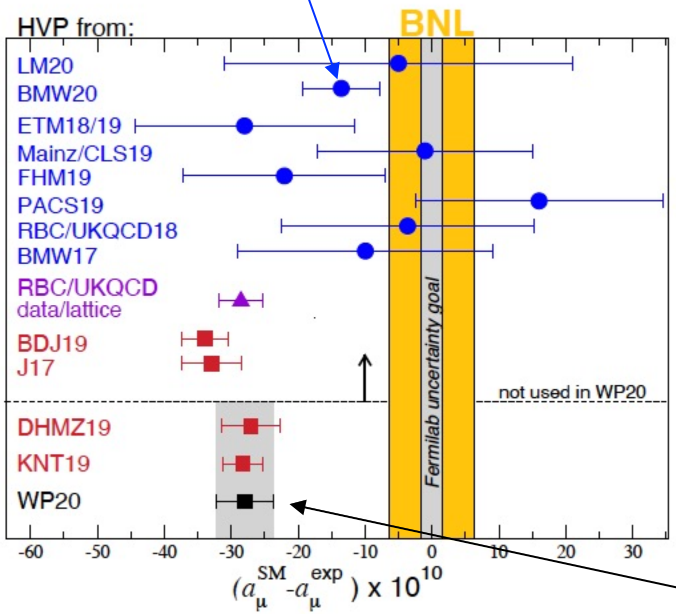
- Better accuaracy from higher multiplicity states and R_{incl} (KEDR, BESIII)

→ Assuming agreement among new BABAR, BESIII, BELLE-II, CMD-3, KLOE and individual accuracies on the 0.5% level (or eventually better)

REDUCTION OF UNCERTAINTY OF HVP BY FACTOR OF 2 IN REACH !

Yet another puzzle? Lattice QCD calculation of HVP

First LatticeQCD result (BMW) with sub-percent precision
→ needs clarification by other Lattice groups



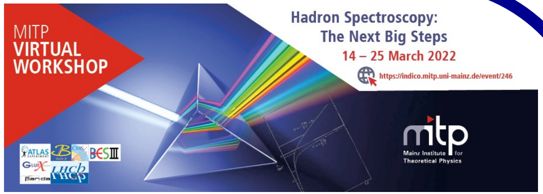
Ab-initio lattice QCD(+QED) calculations are maturing

Difficult problem: scales from $2m_\pi$ to several GeV enter; cross-checks needed at high precision

Hybrid window method restricts scales that enter from lattice/dispersive data

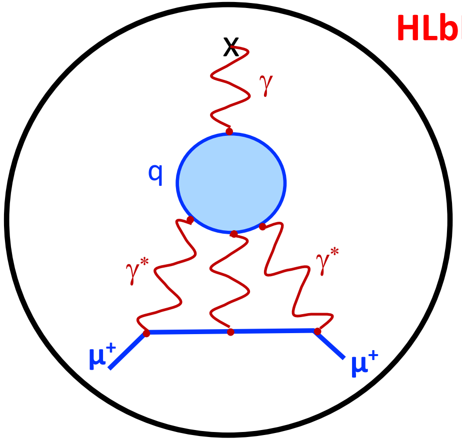
Dispersive, $e^+e^- \to$ hadrons (20+ years of experiments)

HVP value from
g-2 Theory Initiative



Hadronic Light-by-Light Contribution (HLbL)

HLbL



Estimate of (g-2) Theory Initiative:

$(\ \mathbf{9.2 \pm 1.8} \ ) \cdot 10^{-10}$

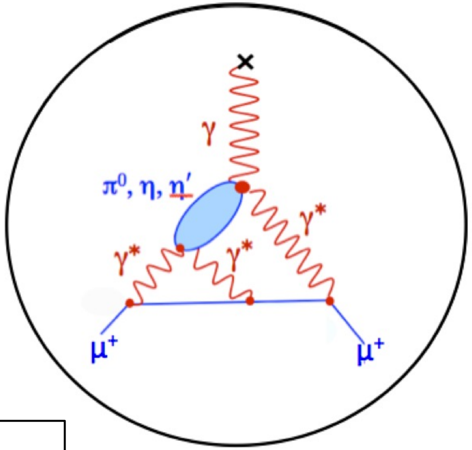
was $(10.5 \pm \mathbf{2.6}) \cdot 10^{-10}$

Hadronic Light-by-Light (HLbL)

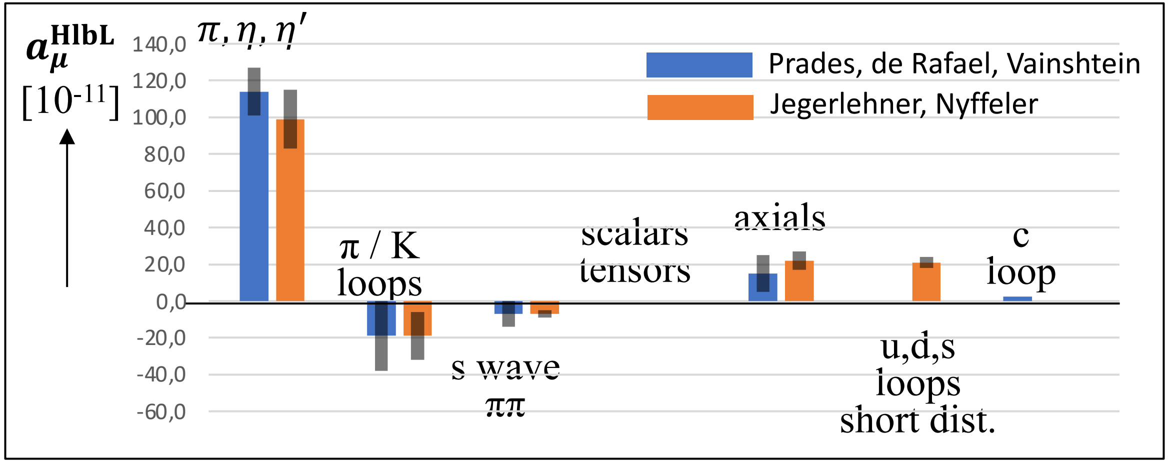
Glasgow consensus value: (10.5 ± **2.6**) · 10^{-10}
Prades, de Rafael, Vainshtein '09

model-dependent !

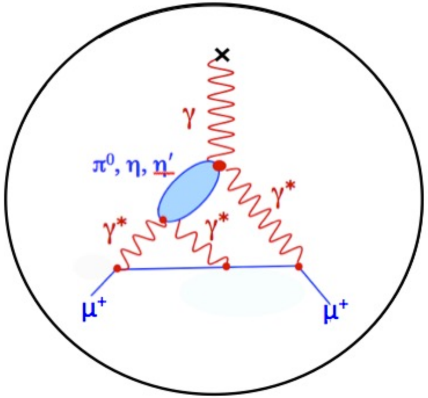
(11.6 ± **3.9**) · 10^{-10}
Jegerlehner, Nyffler '09



Decomposition in terms of individual contributions:



Data-Driven Approaches (e.g. Pion-Pole)



Dispersion Relations being developed
using experimental measurements
of meson transition form factors!

Colangelo et al '14; Pauk, Vanderhaeghen '14

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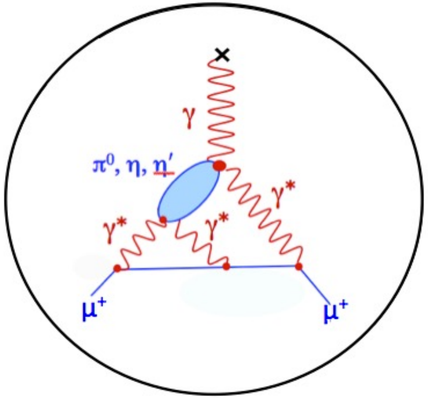
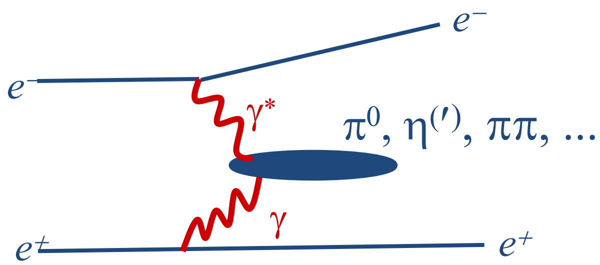
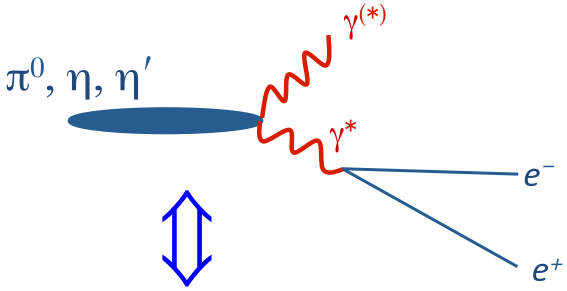


Data-driven approach!

⇔

Exp. Input !
Transition
Form Factors $F(Q^2)$
below ~ 2 GeV^2





Dispersion Relations being developed using experimental measurements of meson transition form factors!

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Problem: double-virtual TFFs needed, for which no measurements exist yet!

Way out: use theory calculations for double-virtual TFFs:
- Lattice QCD calculation
- Dispersive analysis

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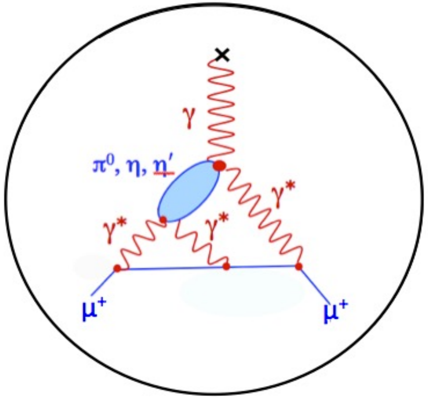

Data-driven approach!

$\Leftrightarrow$

Exp. Input !
Transition
Form Factors $F(Q^2)$
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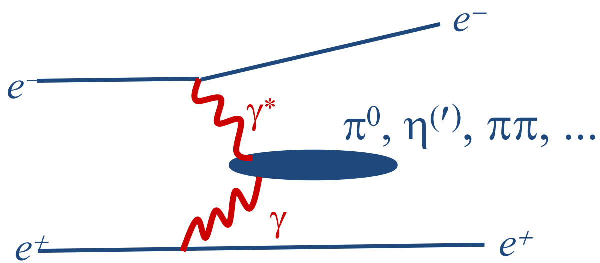
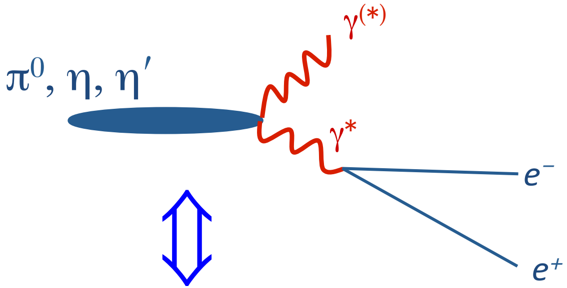




$\Updownarrow$

Experimental challenges:

<u>Now</u>: measure single-virtual TFF and compare with theory assumption!

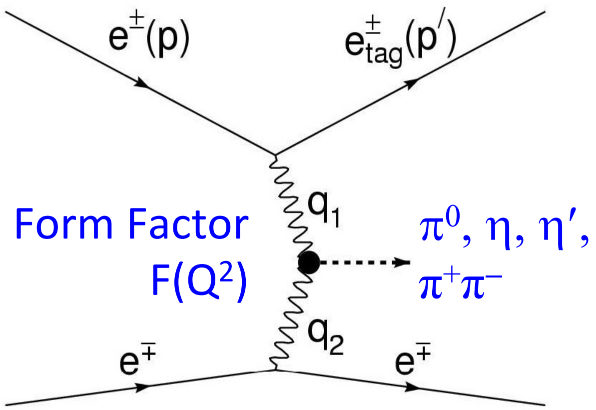
<u>Future</u>: provide measurements of double-virtual TFFs

Problem: double-virtual TFFs needed, for which no measurements exist yet!

Way out: use theory calculations for double-virtual TFFs:
- Lattice QCD calculation
- Dispersive analysis

Spacelike FFs $\gamma\gamma^* \to P$

Single Tag Method



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

EKHARA event generator
Czyż, Ivashyn

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: $q^2 = -q_2^2 \sim 0\ GeV^2$
  → Quasi-real photon

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

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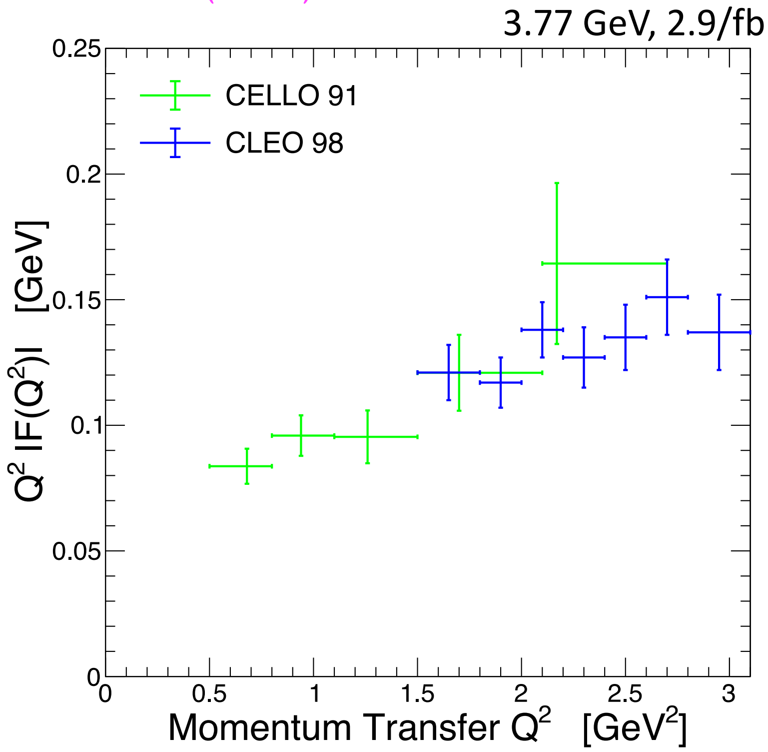

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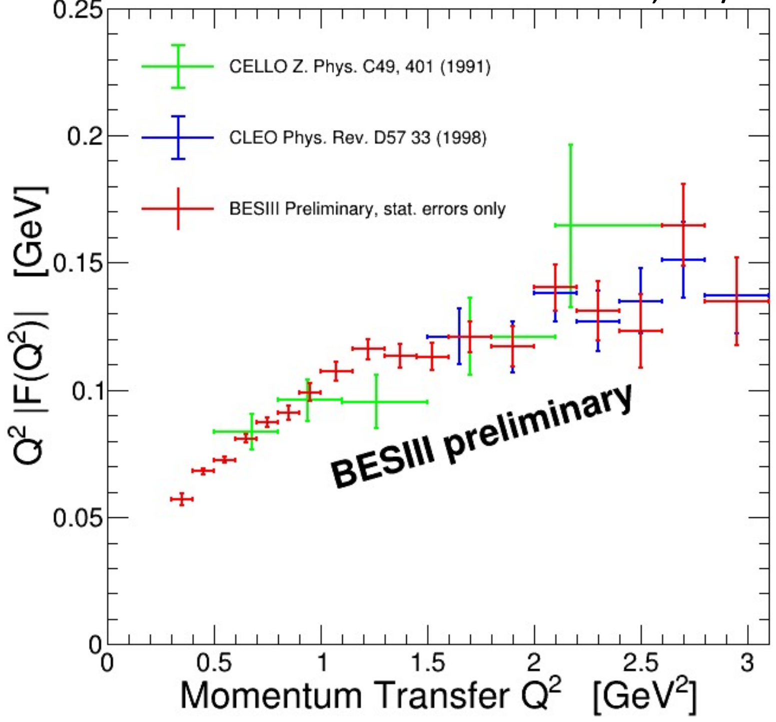
PPNP107(2019)20

3.77 GeV, 2.9/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

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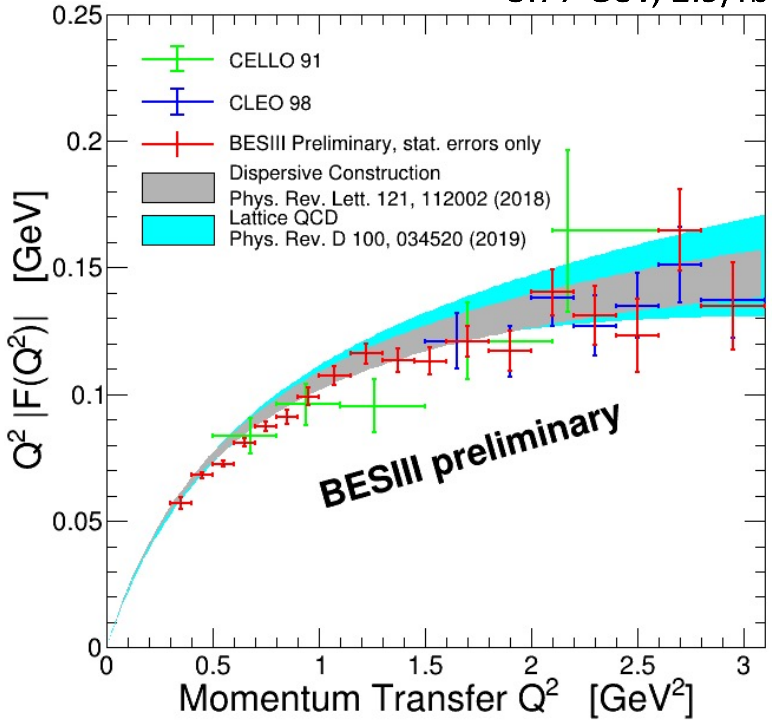

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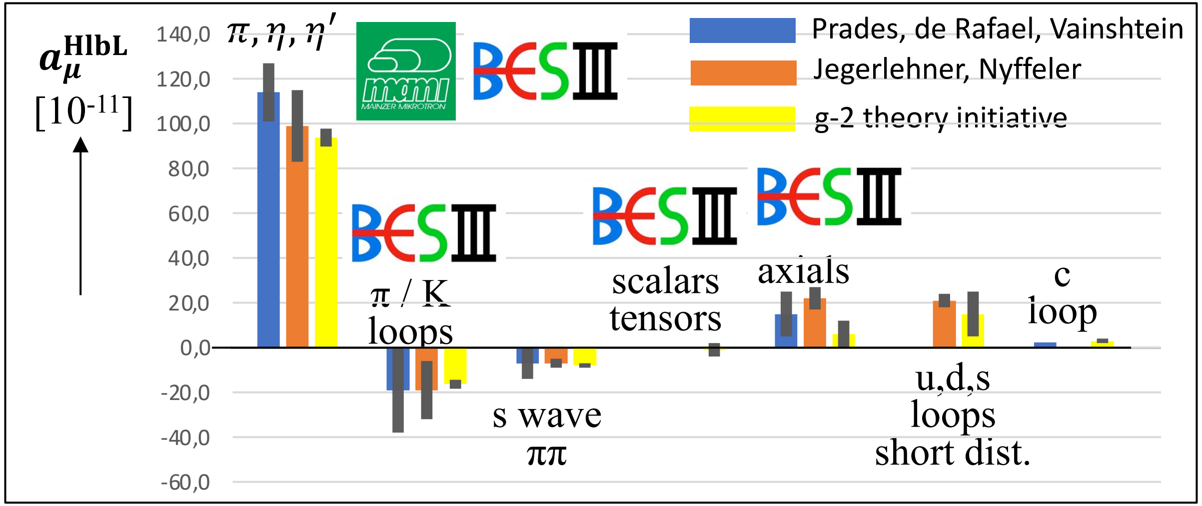
Conclusion & Outlook HLbL

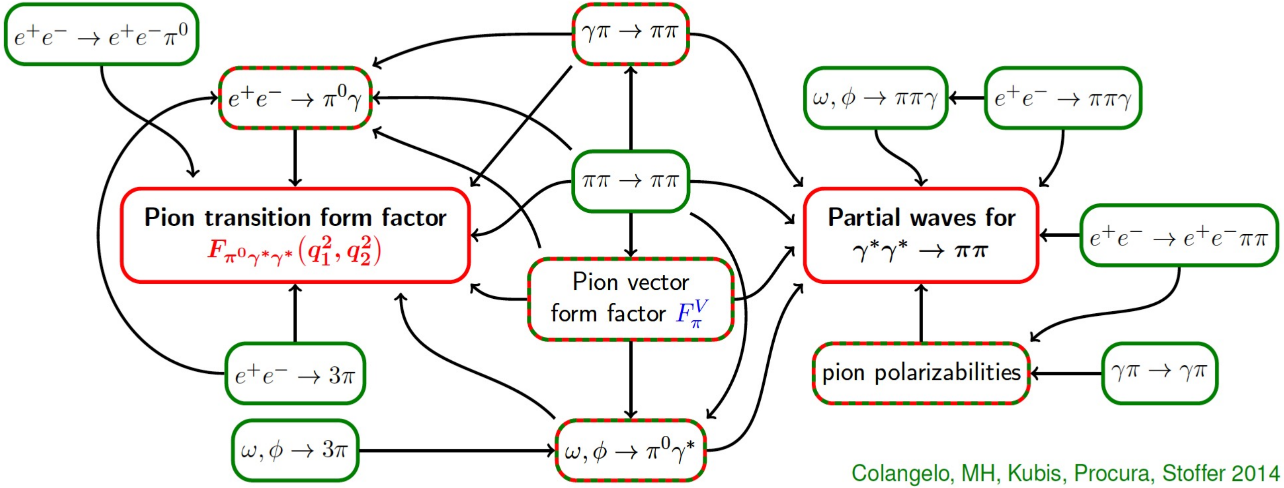
- Theory initiative was able to **significantly reduce the HLbL error** (data-driven approach) and also inclusion of first **Lattice QCD results**



- Dedicated programme at **BESIII** (in gamma-gamma interactions) as well at **A2/MAMI** (Dalitz decays of mesons) to **provide TFF measurements**

Conclusion & Outlook HLbL

- Usage of theoretical tools to relate meson decays & reactions

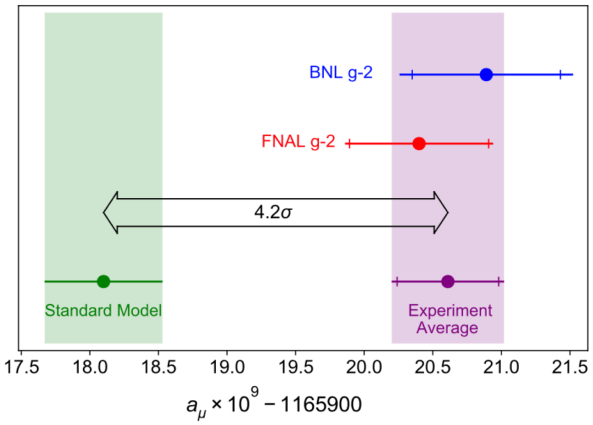


Colangelo, MH, Kubis, Procura, Stoffer 2014

- Dedicated program at various facilities in the world (Europe, US, Asia)

BESIII BABAR KLOE Belle II A2 SND CMD NA60 NA62 Jefferson Lab HADES

REDUCTION OF UNCERTAINTY OF HLbL BY FACTOR 1.5 IN REACH !



Conclusions:
Yes, we have good reasons to be excited!

Conclusions

- 20 year old BNL measurement of g-2 confirmed by FNAL
  4.2σ discrepancy to SM, J-PARC project upcoming!

- Final interpretation of FNAL result needs a continued program in hadron physics

- **HVP**: By combining new BESIII data on pion FF with KLOE and future data from BELLE II, CMD-3, and re-analysis of BABAR
  → reduction of uncertainty by a factor of 2 in a global effort!

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  → further reduction of uncertainty in reach (assume factor 1.5)

Conclusions

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Assumption: central value of SM stable and uncertainty will improve to $\pm 2.3 \cdot 10^{-10}$!

Scenario: New experimental value stays constant, factor 4 exptl. improvement

→ $\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = (25.1 \pm 2.7) \cdot 10^{-10}$ (9.4σ) !!!