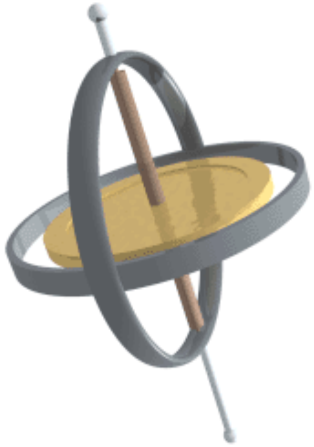

MESON 2021

16th International Workshop on Meson Physics

17th - 20th May 2021, online via ZOOM

Organized by Jagiellonian University Kraków, Forschungszentrum Jülich, INFN-LNF Frascati, Institute of Nuclear Physics PAS

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https://meson.if.uj.edu.pl

Outlook Talk

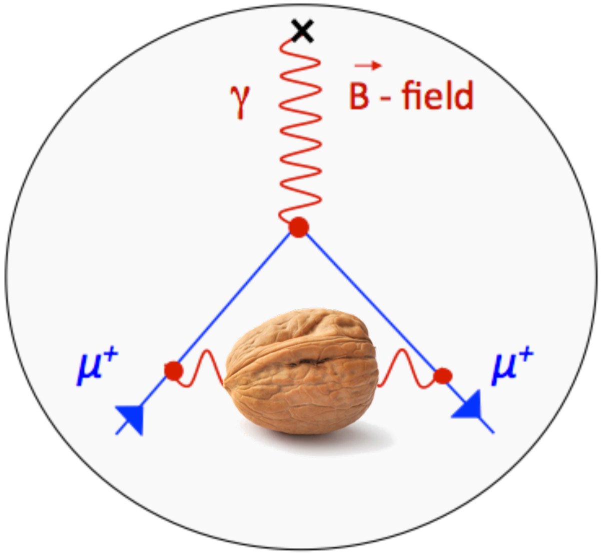
Status of the g-2 Problem

SFB 1044
THE LOW-ENERGY FRONTIER
OF THE STANDARD MODEL

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

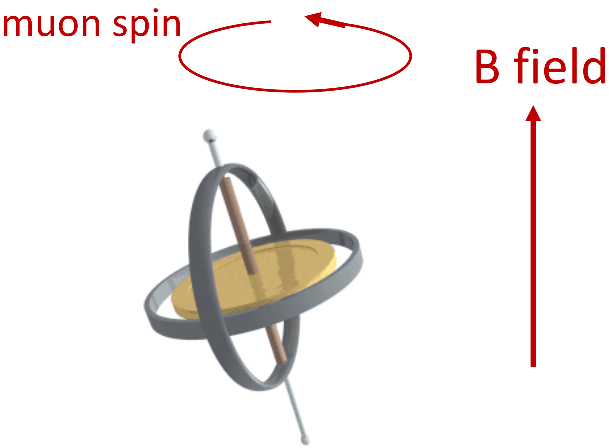
May 20, 2021
Achim Denig
Johannes Gutenberg University Mainz

$(g\text{-}2)_\mu$: *The SM in a Nutshell*



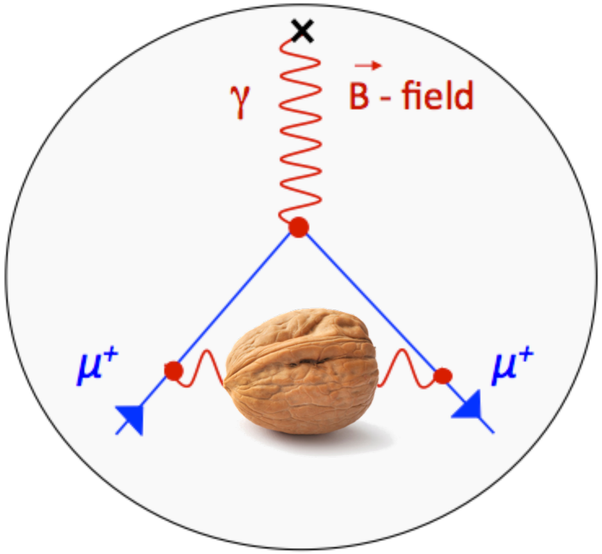
$$a_\mu^{SM} = (g_\mu - 2)/2 = a_\mu^{QED} + a_\mu^{weak} + a_\mu^{had}$$

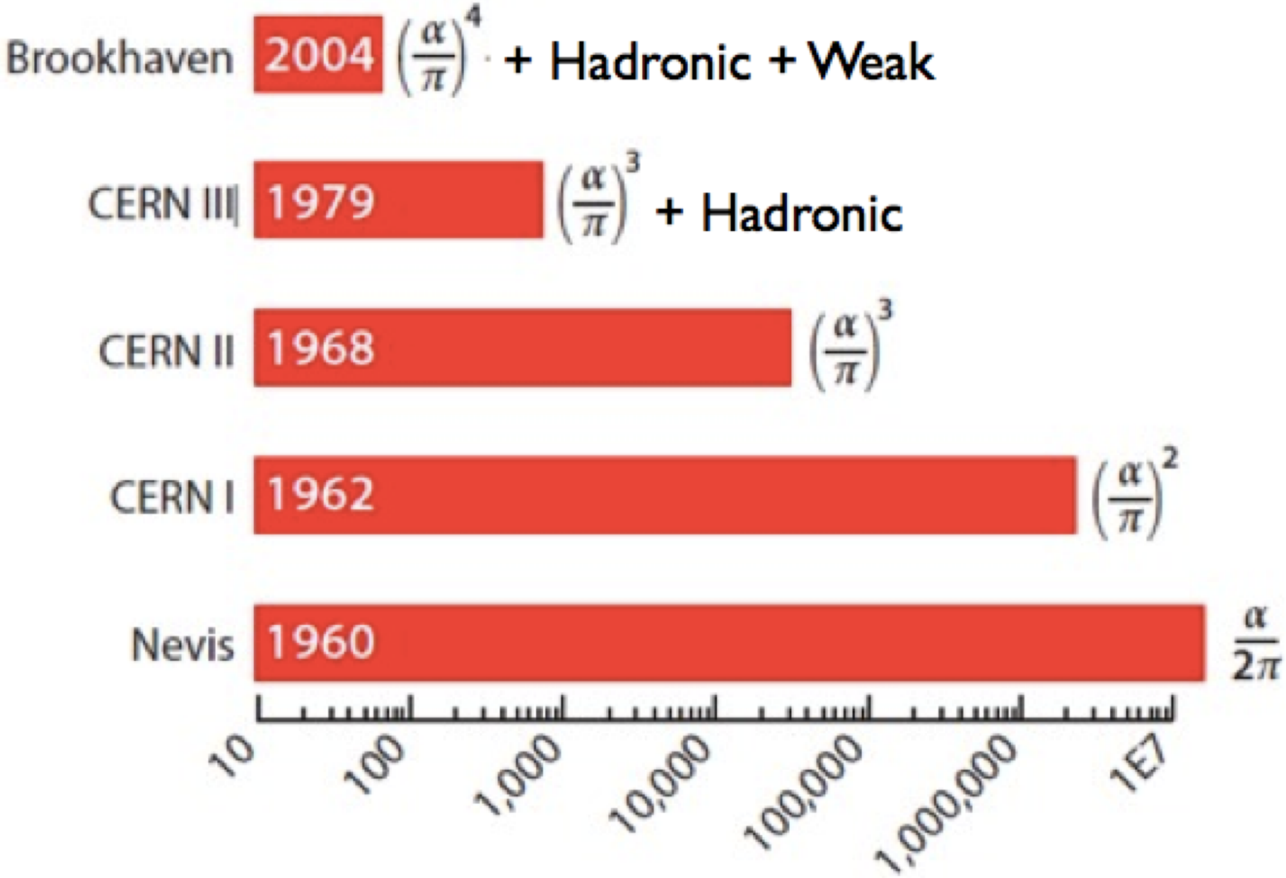
gyromagnetic factor of the muon



$(g\text{-}2)_\mu$: *The SM in a Nutshell*

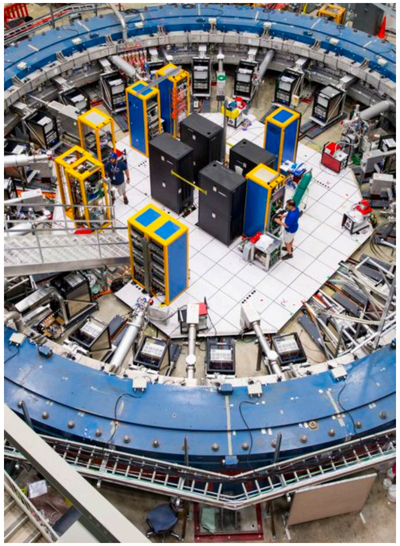
$$a_\mu^{SM} = (g_\mu - 2)/2 = a_\mu^{QED} + a_\mu^{weak} + a_\mu^{had}$$





Uncertainty of measurement in 10^{-11}

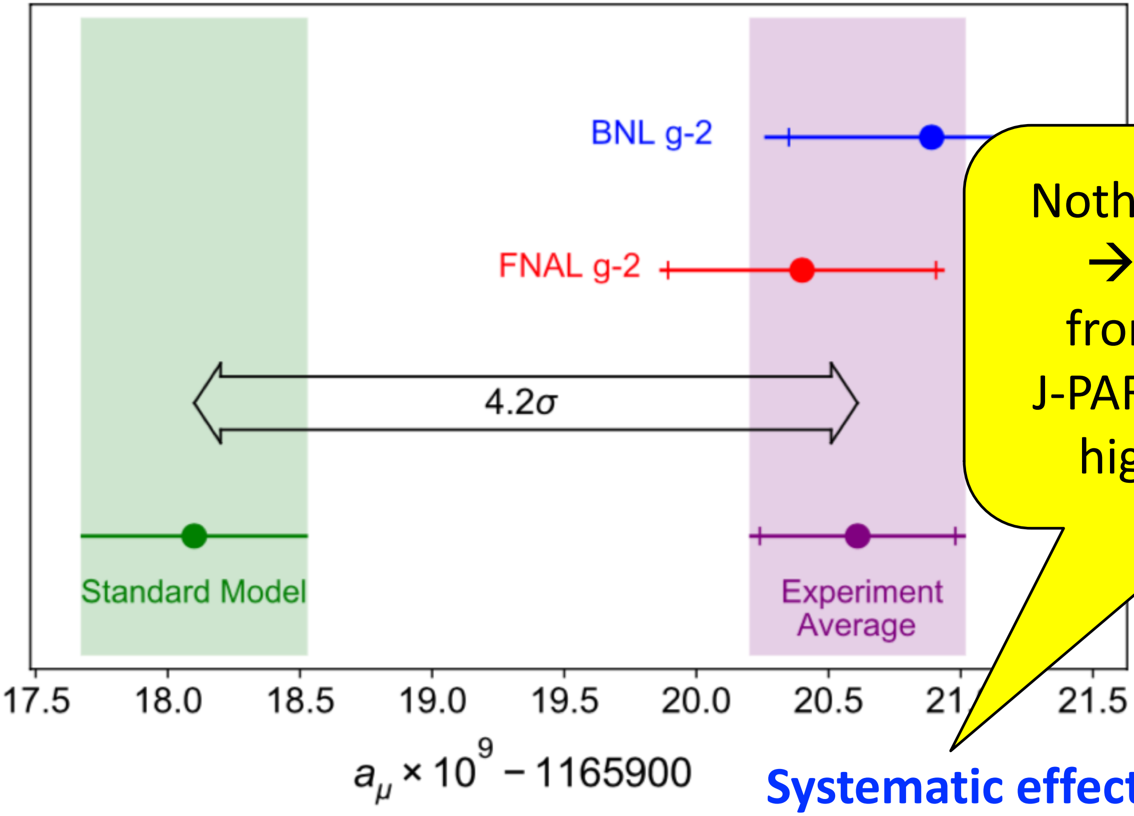
FNAL



CERN I

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 !

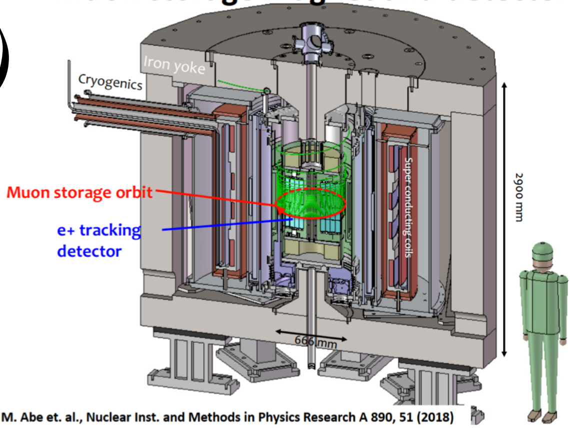
Systematic effect in
BNL/FNAL method ?

?

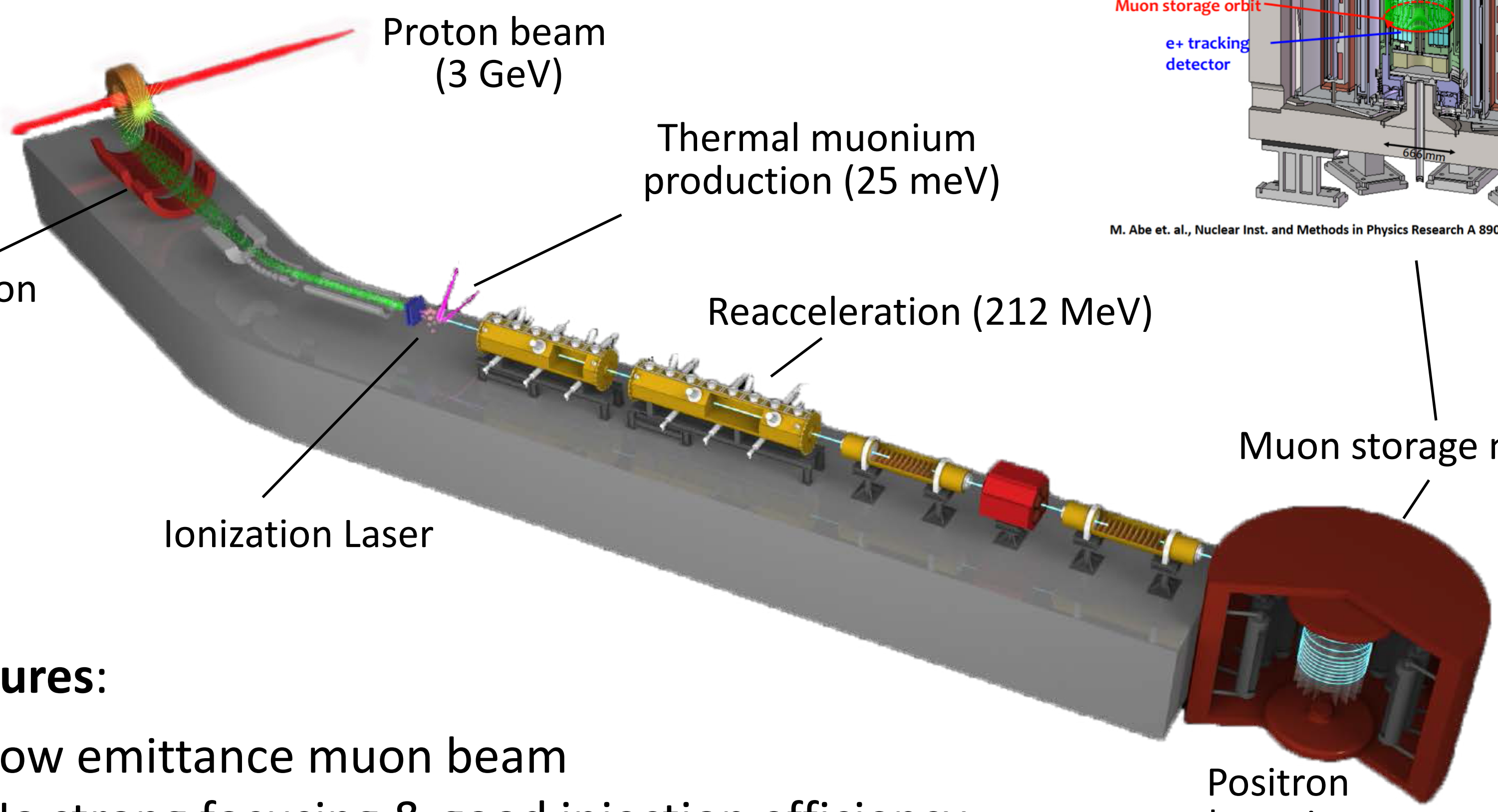
Meson2021
Dinko Pocanic

J-PARC g-2 Experiment (2024+)

Muon storage magnet and detector



M. Abe et. al., Nuclear Inst. and Methods in Physics Research A 890, 51 (2018)



Proton beam (3 GeV)

Thermal muonium production (25 meV)

Surface Muon (4 MeV)

Reacceleration (212 MeV)

Muon storage magnet

Ionization Laser

Positron detection

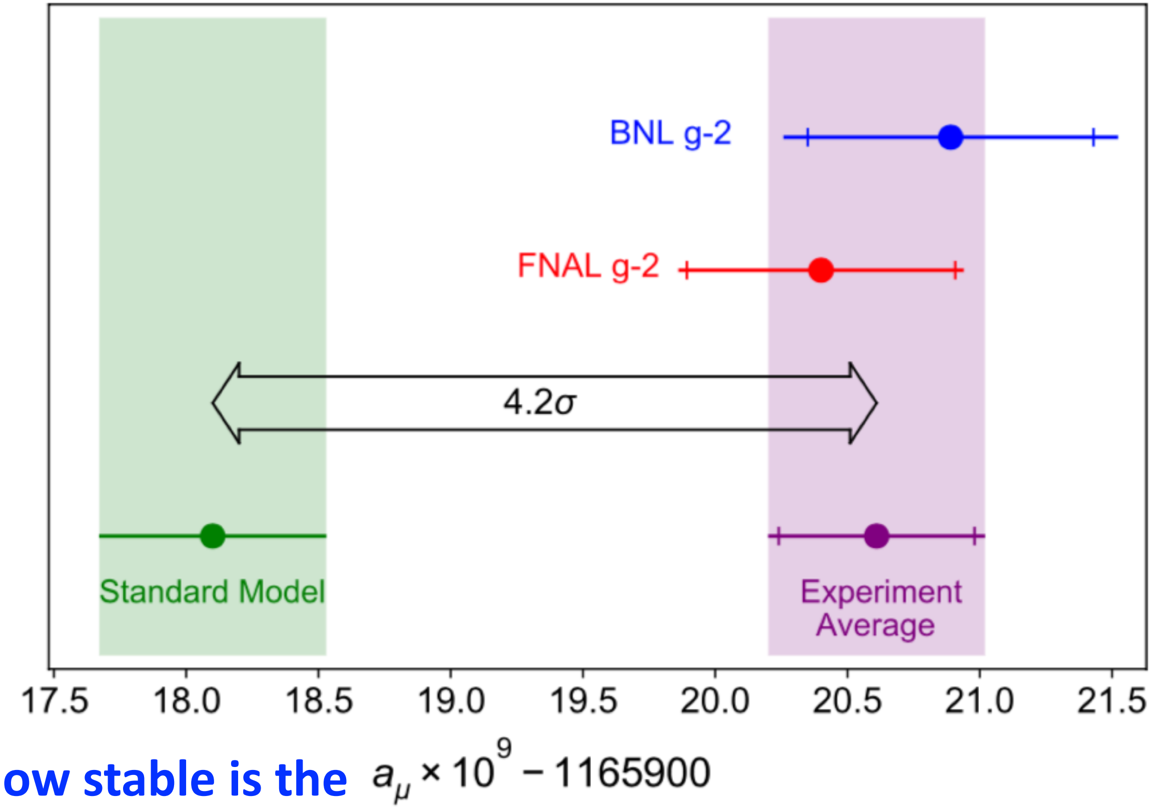
Features:

- Low emittance muon beam
- No strong focusing & good injection efficiency
- Compact storage ring
- Tracking detectors with large acceptance

→ Completely different from BNL/FNAL method

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

Strong indication for physics beyond the SM ?!



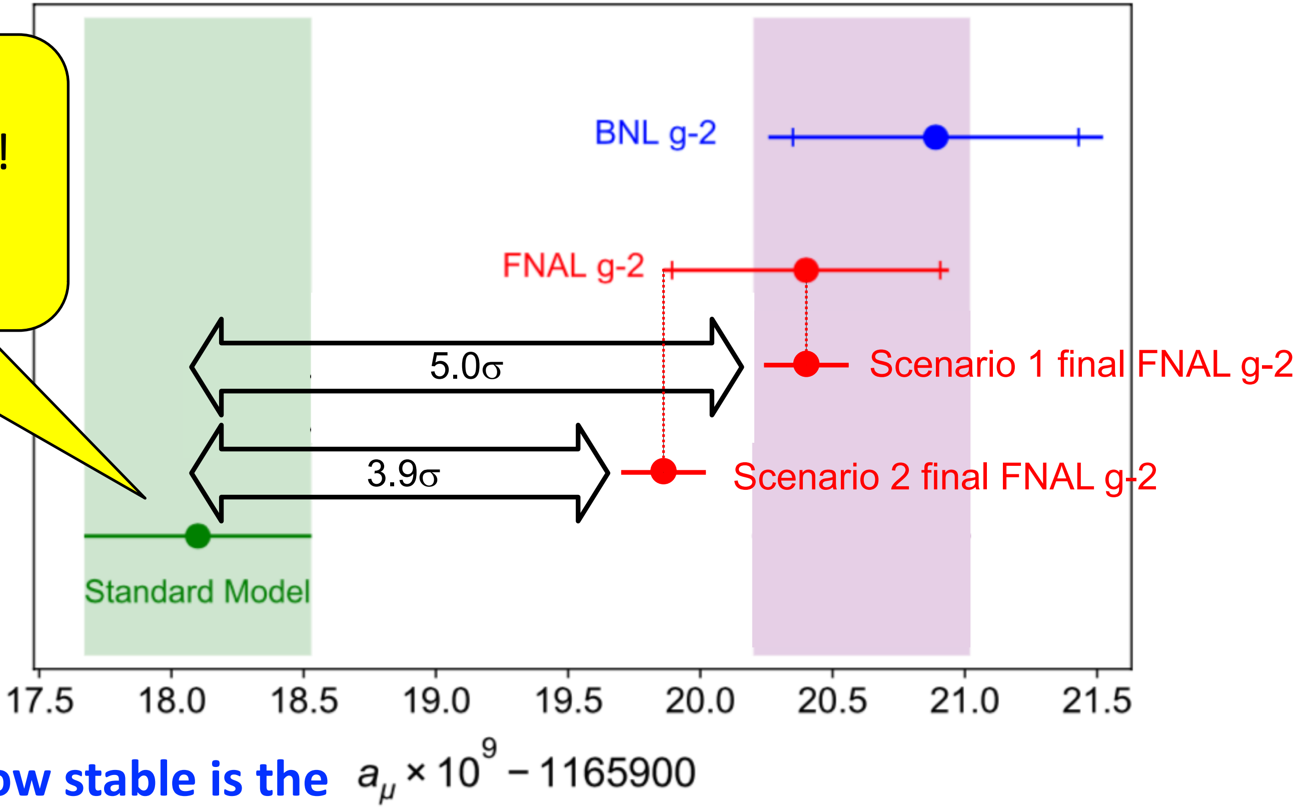
How stable is the SM prediction ?

?

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

Strong indication for physics beyond the SM ?!

Reduction of SM prediction needed!
→ **Impact from Meson Physics !**



How stable is the SM prediction ?

?

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

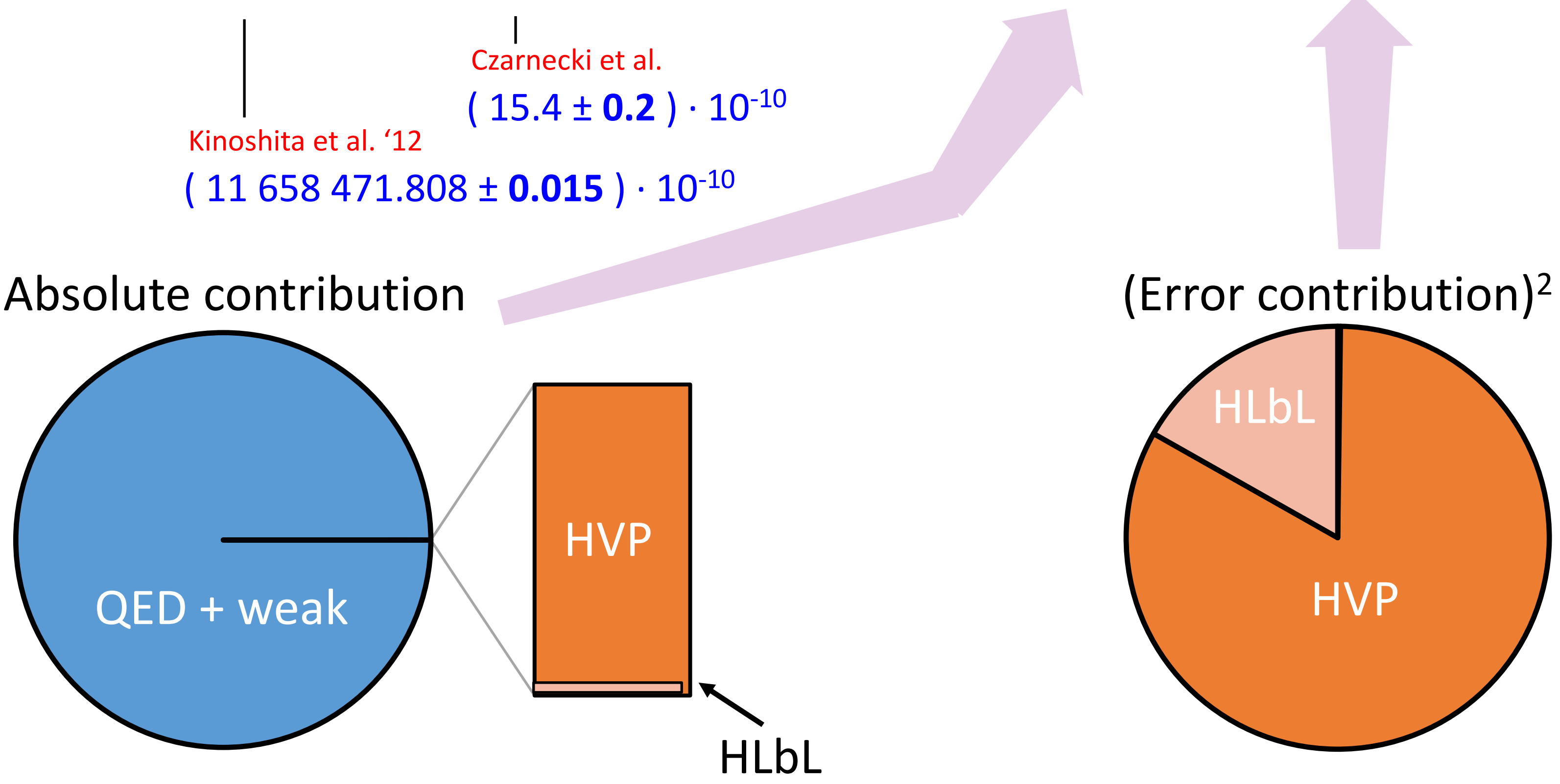
$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{weak} + a_\mu^{had} = (\,11\,659\,181.0 \pm 4.3\,)\cdot 10^{-10}$$

Czarnecki et al.

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

Kinoshita et al. ‘12

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



The absolute value of the SM prediction to muon (g-2) is dominated by QED !
The error to the SM prediction to muon (g-2) is dominated by the hadronic contribution, where both HVP and HLbL are of relevance !

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

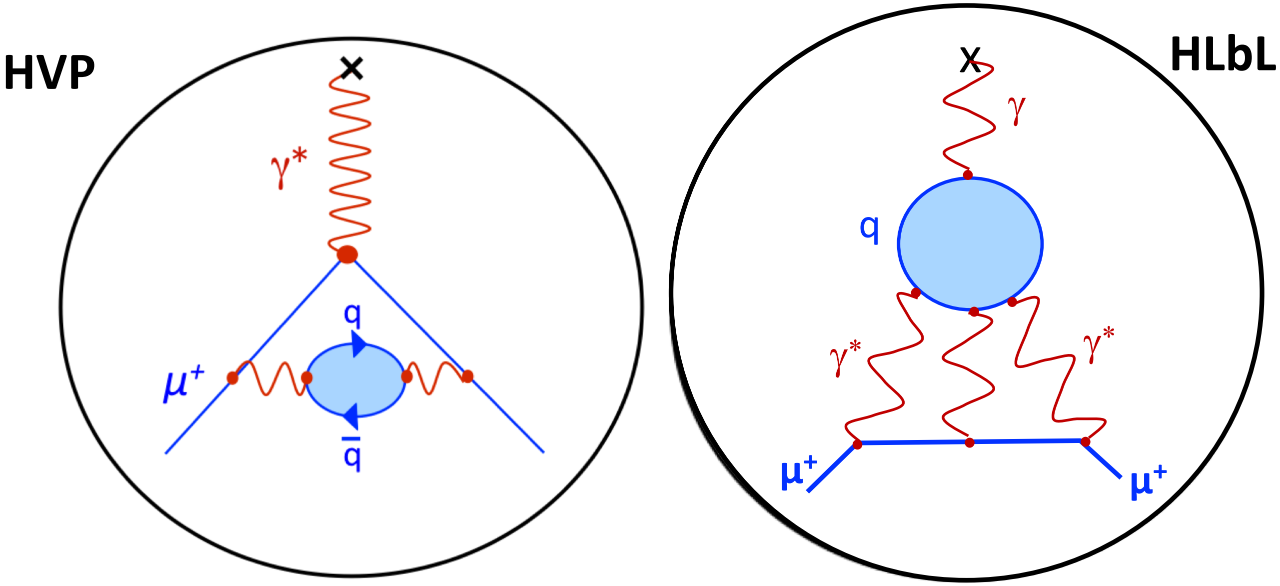
Hadronic contribution **non-perturbative,** the **limiting** contribution

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

→ **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



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

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

196 pages, 103 figures

[hep-ph] 8 Jun 2020

2006.04822

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

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]

[1] Institute of Particle and Nuclear Studies, High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801, Japan
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[8] RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, NY 11973, USA
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[13] Helmholtz Institute Mainz, 55099 Mainz, Germany and GSI Helmholtzzentrum für Schwerionenforschung, 64291 Darmstadt, Germany
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[15] Dipartimento di Fisica e Astronomia "Ettore Majorana," Università di Catania, Italy
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[18] IJCLab, Université Paris-Saclay and CNRS/IN2P3, 91405 Orsay, France
[19] SUPA, School of Physics and Astronomy, University of Glasgow, Glasgow G12 8QQ, United Kingdom
[20] IMADA and CP3-Origins, University of Southern Denmark, Odense, Denmark
[21] Budker Institute of Nuclear Physics, 11 Lavrentyev St., and Novosibirsk State University, 2 Pirogova St., Novosibirsk 630090, Russia
[22] Lebedev Physical Institute, 53 Leninskiy Pr., Moscow 119333, Russia

Goal:
theory consensus value of
muon g-2 SM prediction

- Working groups on HVP, HLbL, LatticeQCD, ...
- Three collaboration meetings
and various workshops on subtopics
- Scrutiny of various theoretical evaluations
- One consensus value both for HVP and for HLbL

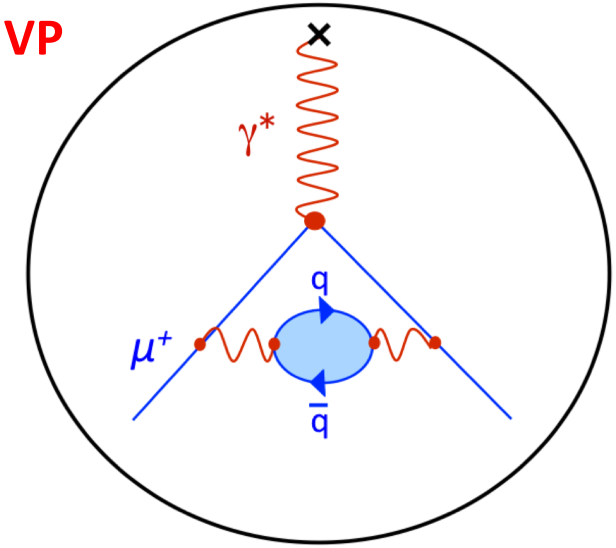
FNAL 2017

Mainz 2018

Seattle 2019

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}

see also Meson2021
Bastian Kubis
Pere Masjuan

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

Optical theorem (unitarity) and analyticity:

Data-driven approach:

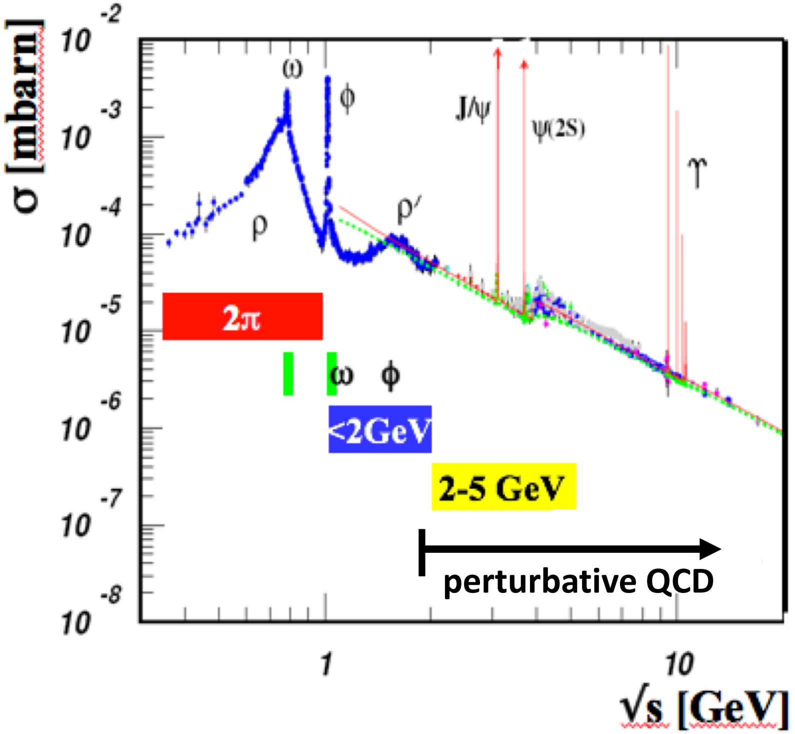
K(s): known kernel function

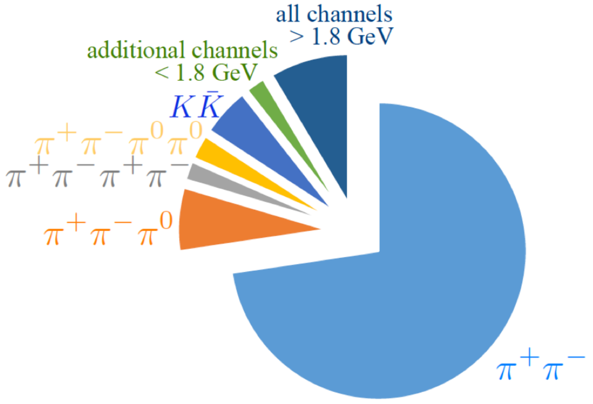
s: energy^2

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

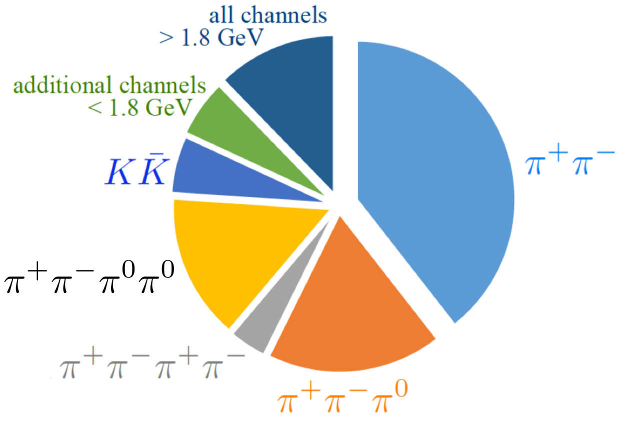
$$\boldsymbol{\sigma_{had}(s) = \sigma_{\mathbf{tot}}(e^+e^- \to \mathbf{Hadrons})}$$

low energy contributions
especially important!





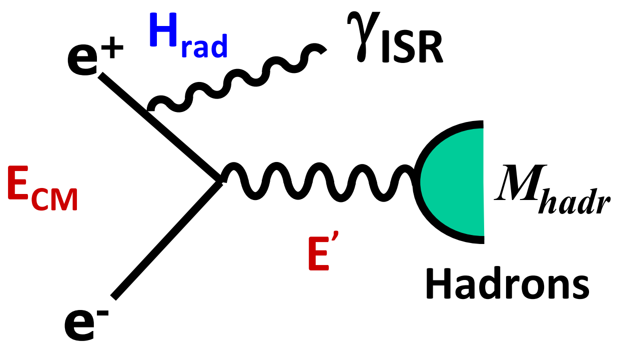
Contributions to HVP integral



Contributions to HVP error

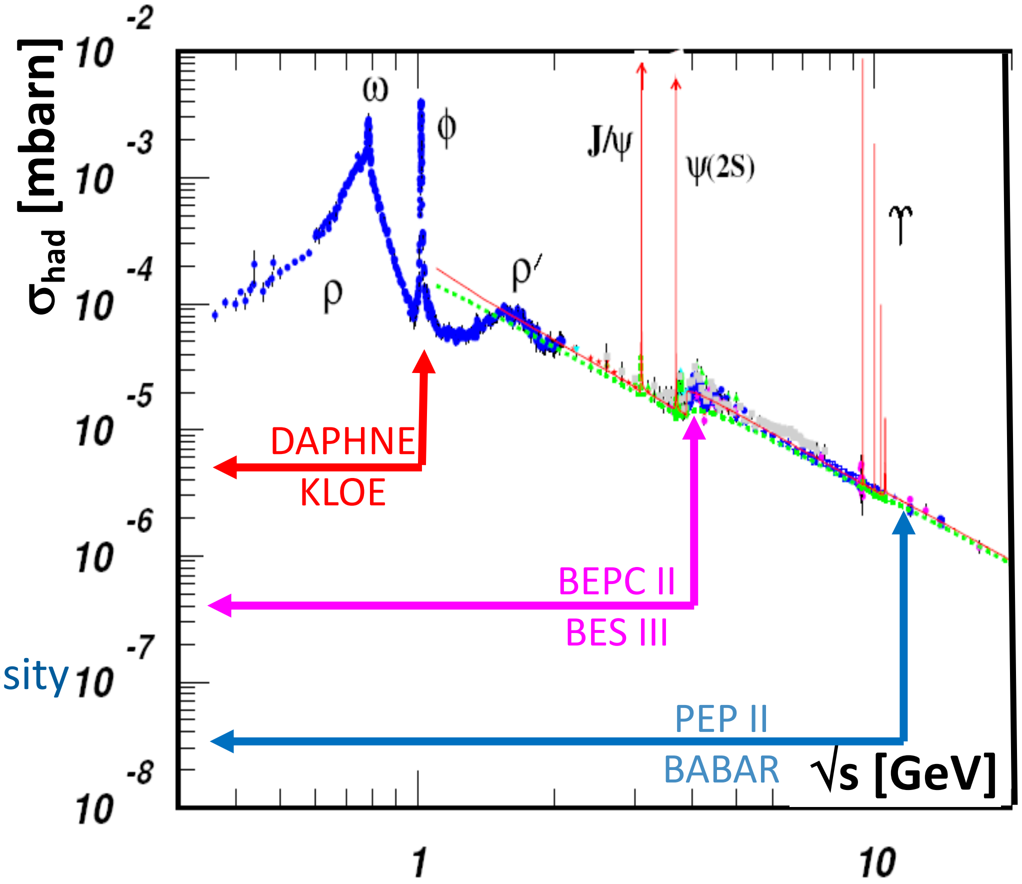
Initial State Radiation (ISR)

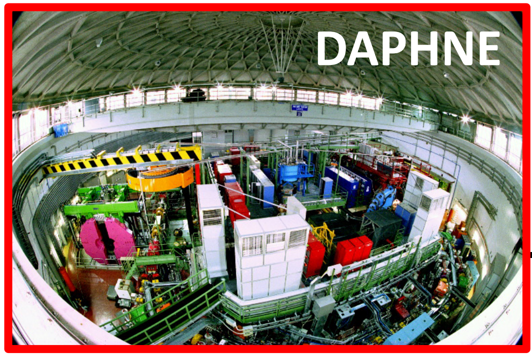
Initial State Radiation (ISR)
aka Radiative Return

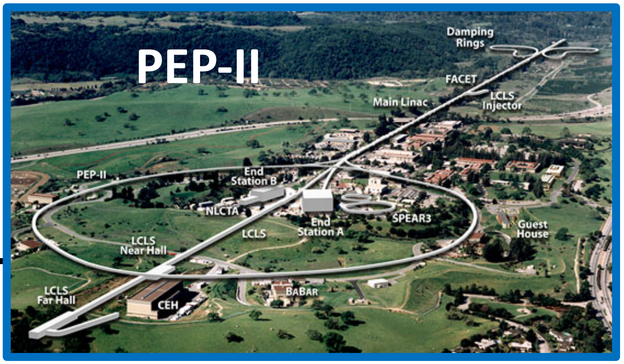


- No systematic variation of E_{beam}
- High statistics thanks to high luminosity
- Precise knowledge of radiative corrections mandatory (H_{rad})

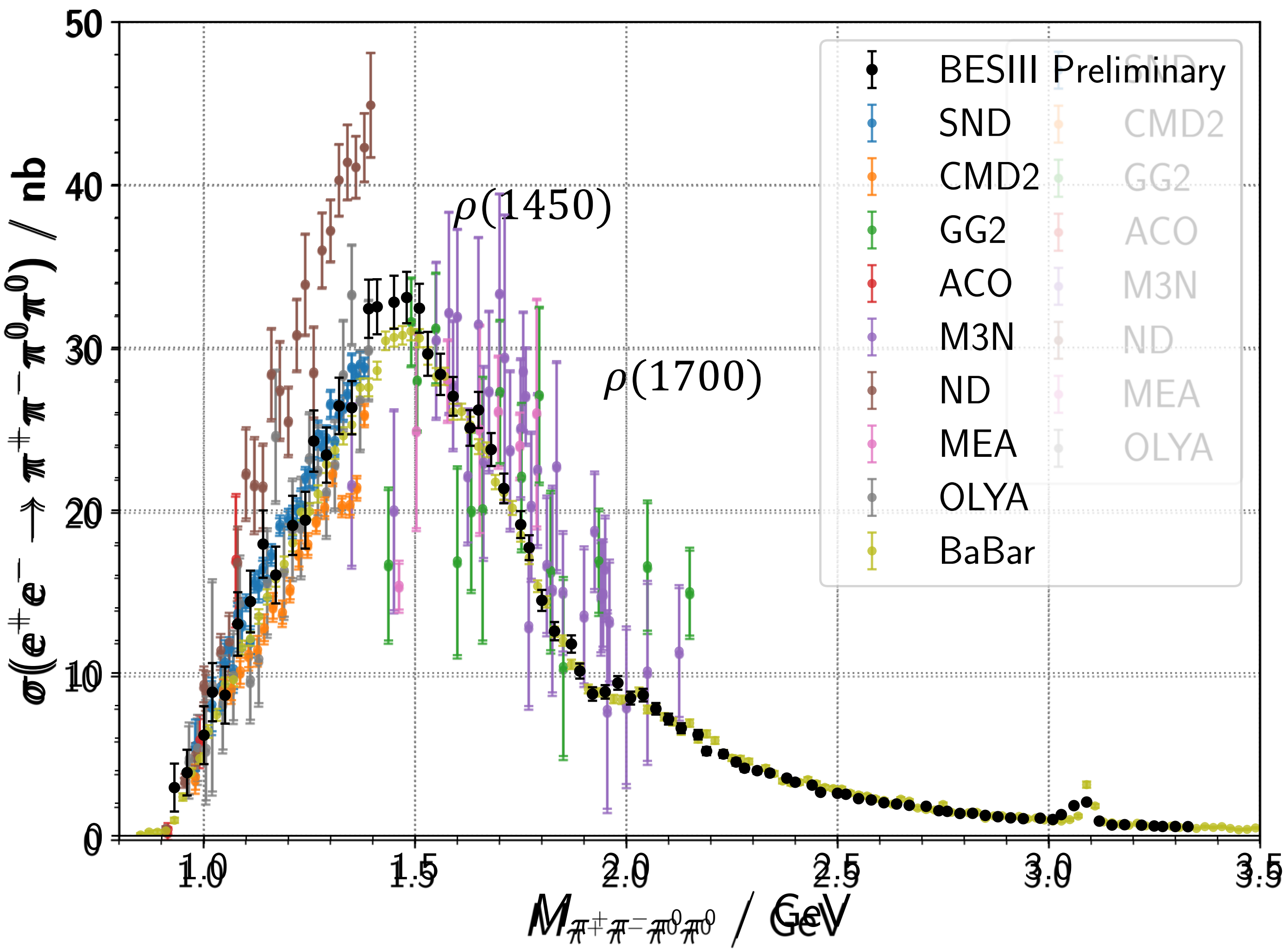
`PHOKHARA event generator`







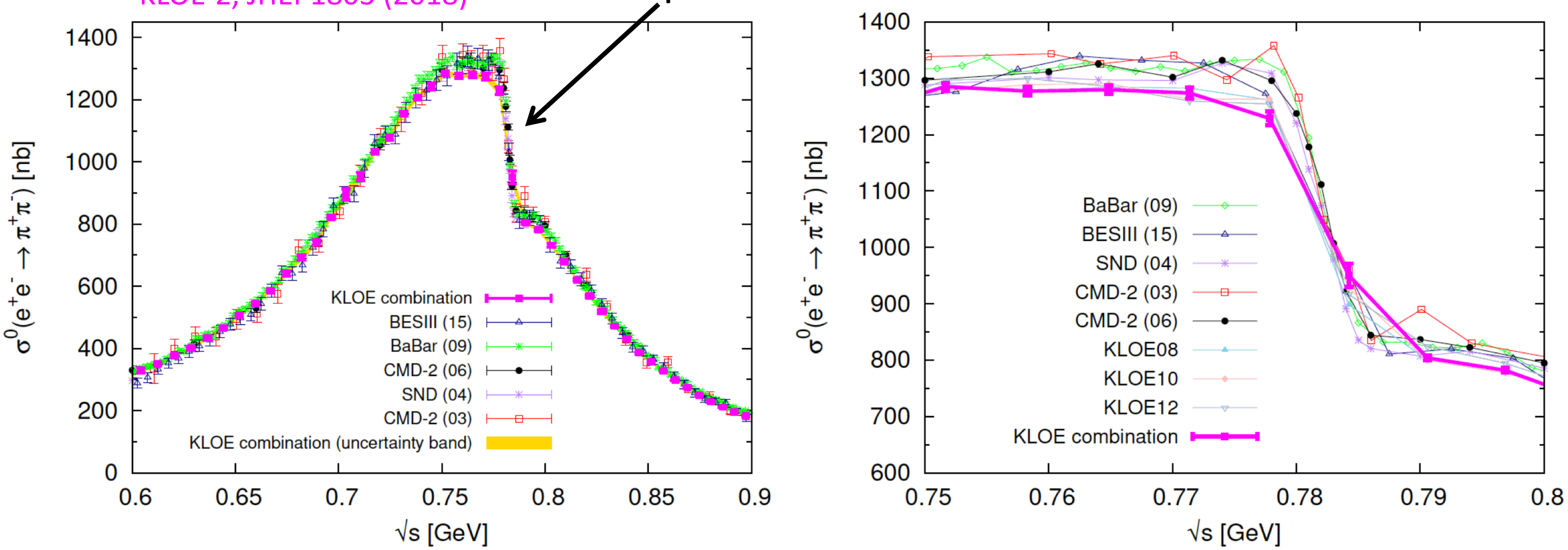
ISR (BABAR&BESIII): $e^+e^- \to \pi^+\pi^-\pi^0\pi^0$



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

KLOE-2, JHEP1803 (2018)

ρ - ω interference



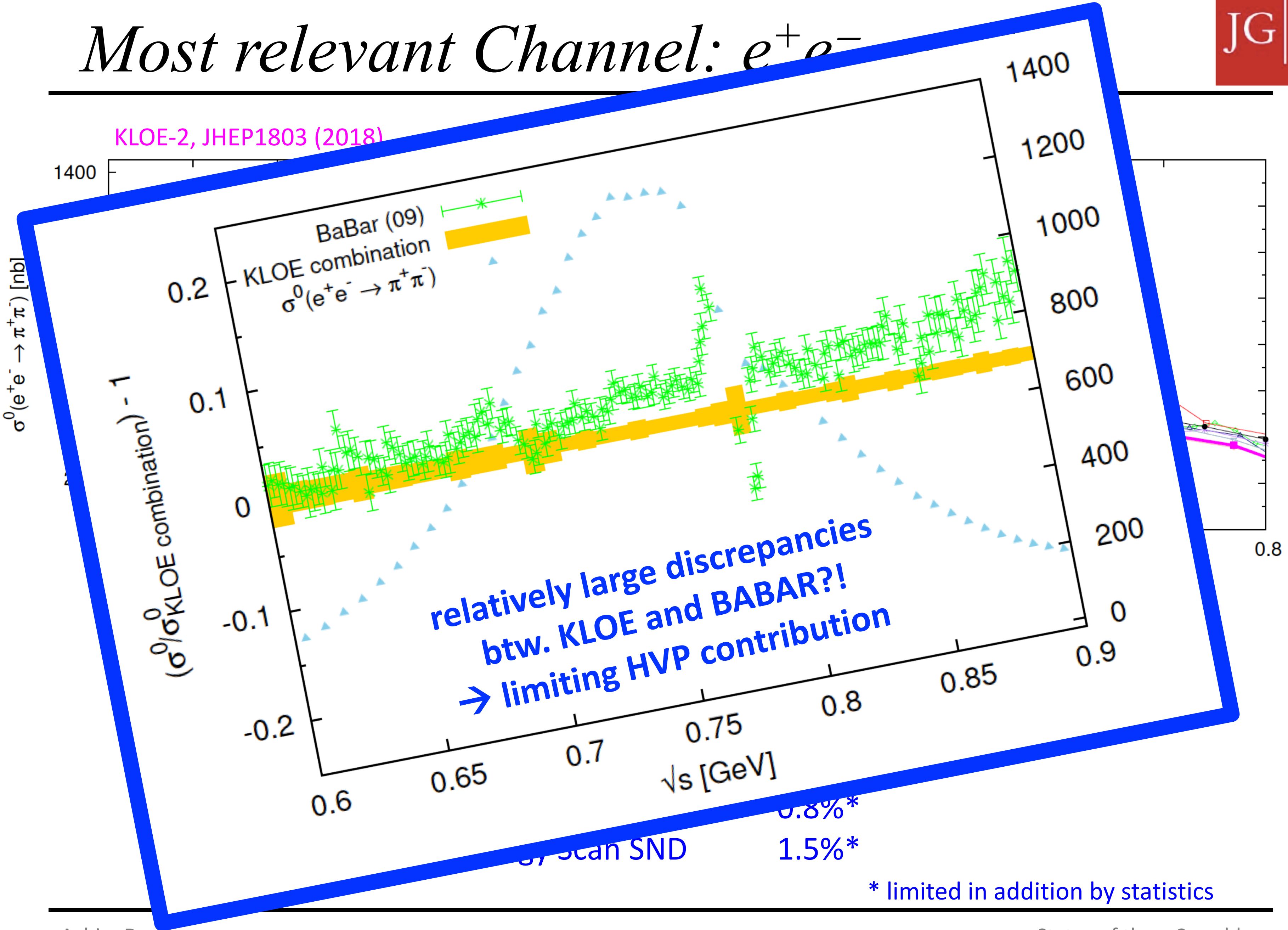
Systematic Uncertainties on ρ(770) peak

- ISR BABAR 0.5%
- ISR KLOE 0.6% (average of 3 analyses)
- ISR BESIII 0.9%
- Energy Scan CMD2 0.8%*
- Energy Scan SND 1.5%*

* limited in addition by statistics

Most relevant Channel: e^+e^-

KLOE-2, JHEP1803 (2018)



relatively large discrepancies btw. KLOE and BABAR?!
→ limiting HVP contribution

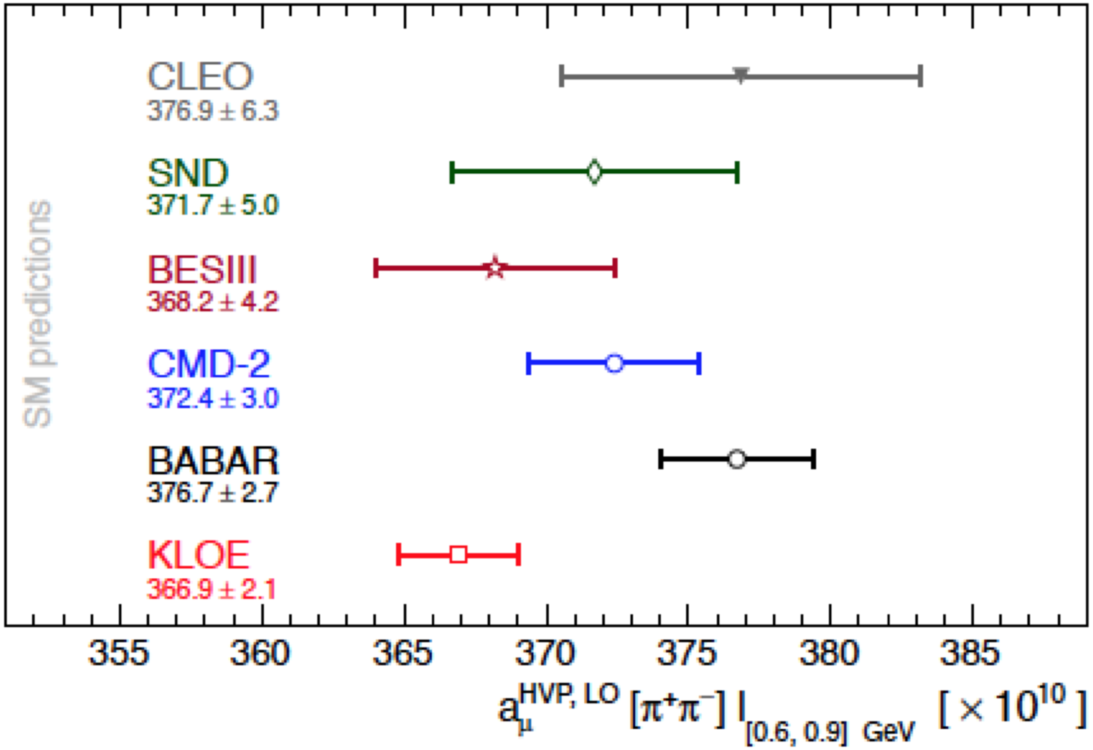
0.8%*

scan SND 1.5%*

* limited in addition by statistics

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

2π contribution to HVP contribution to g-2 (600 – 900 MeV)



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
- High statistics energy scans from VEPP-2000/Novosibirsk (CMD-3, SND):
  Expect similar accuaracy

`Meson2021: Alexander Obrazovsky`

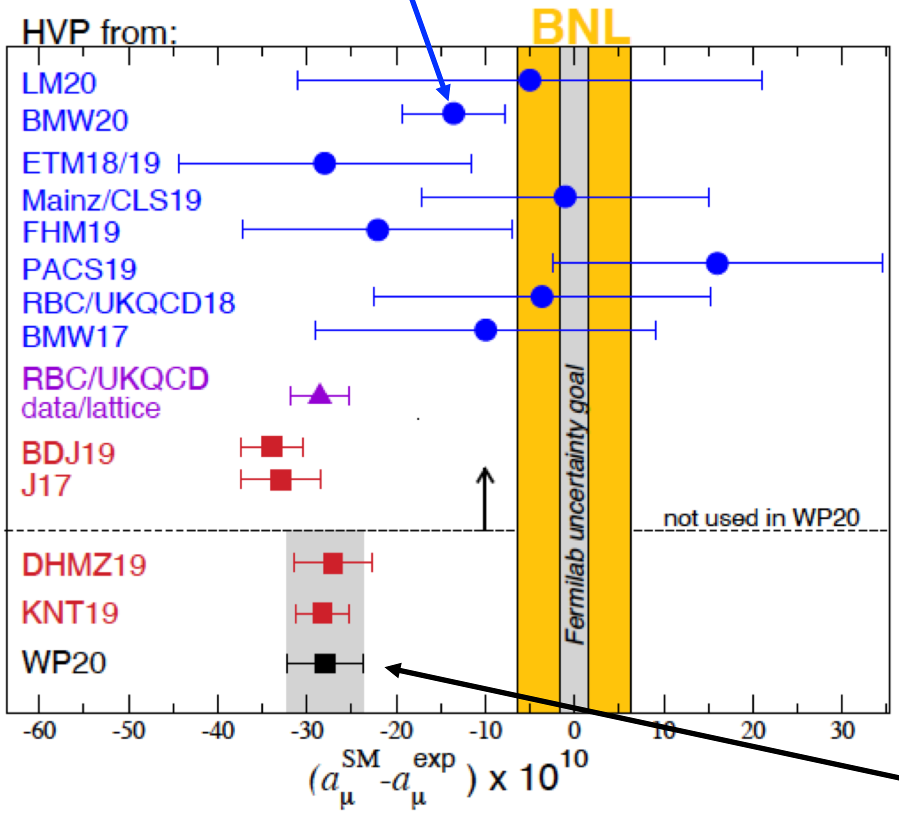
- Better accuaracy from higher multiplicity states and R_{incl} (KEDR, BESIII)

→ 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 !

Conclusions & Outlook 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

HVP and Electroweak Precision Physics

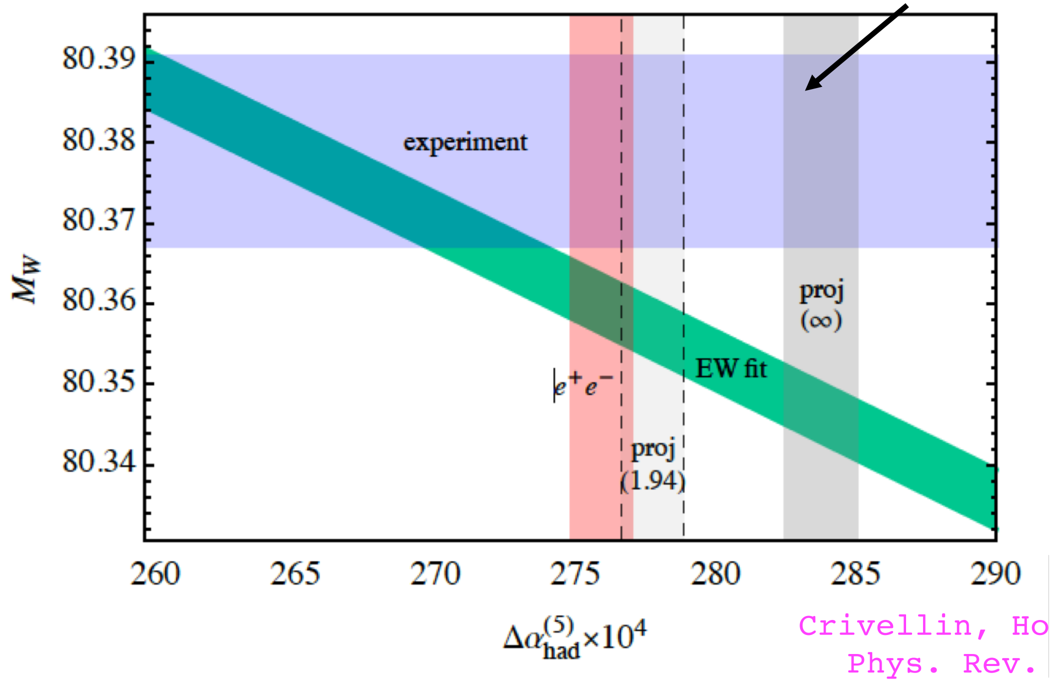
Artificially increasing e^+e^- cross sections (over full energy range) to mach a_μ^{exp}

→ Impact on running of fine structure constant $\Delta\alpha_{\text{had}}(M_Z^2)$

→ increasing deviation btw. EW fit and EW measurements (e.g. M_H, M_W, ...) ?!

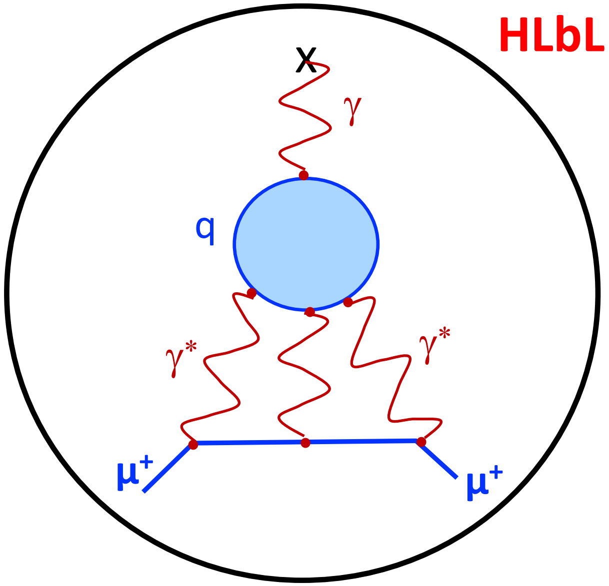
existing e+e- data

modified e+e- data to fix g-2 problem



Crivellin, Hoferichter, Manzari, Montull
Phys. Rev. Lett. 125, 091801 (2020)

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}

see also Meson2021
Bastian Kubis
Emilie Passemar

Hadronic Light-by-Light (HLbL)

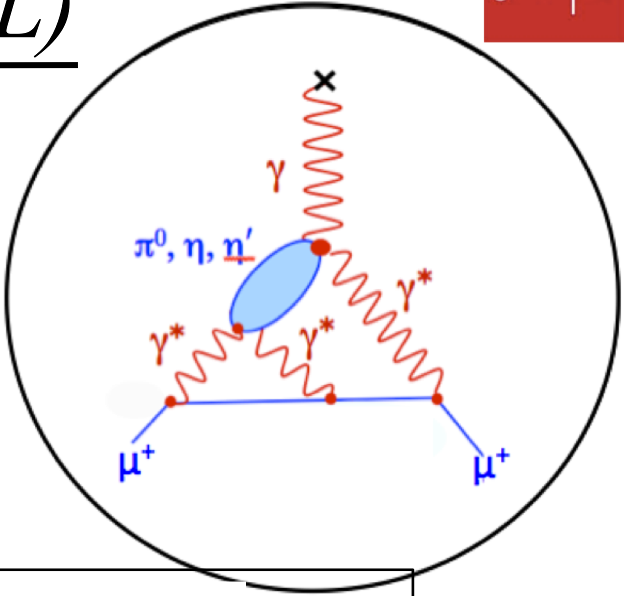
Glasgow consensus value: (10.5 ± **2.6**) · 10^{-10}

Prades, de Rafael, Vainshtein ‘09

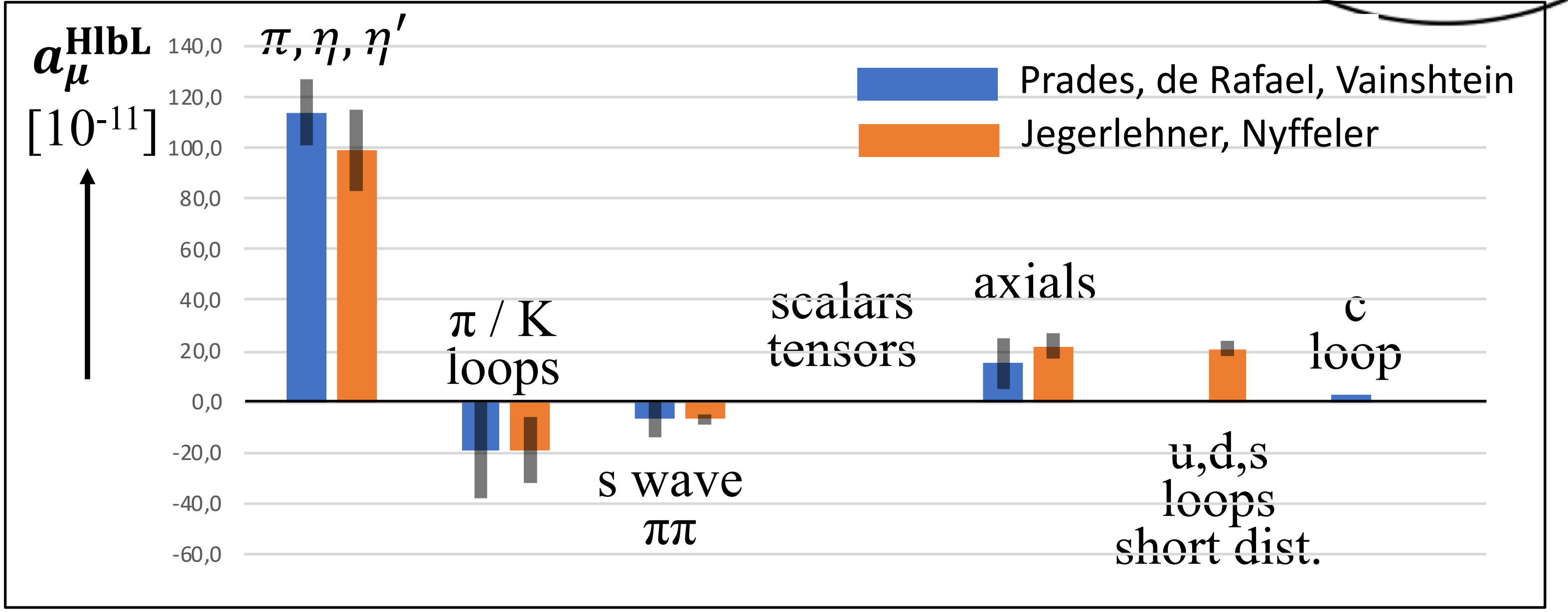
model-dependent !

(11.6 ± **3.9**) · 10^{-10}

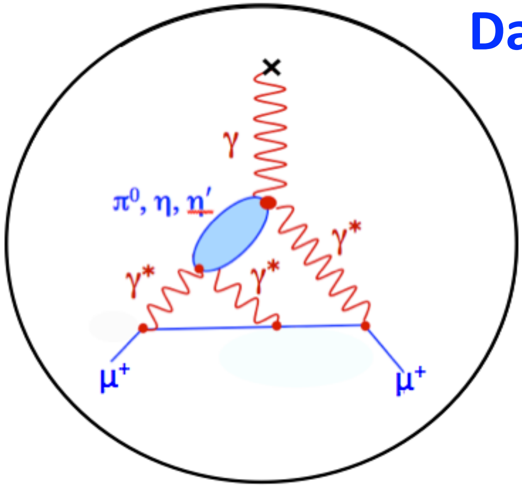
Jegerlehner, Nyffler '09



Decomposition in terms of individual contributions:



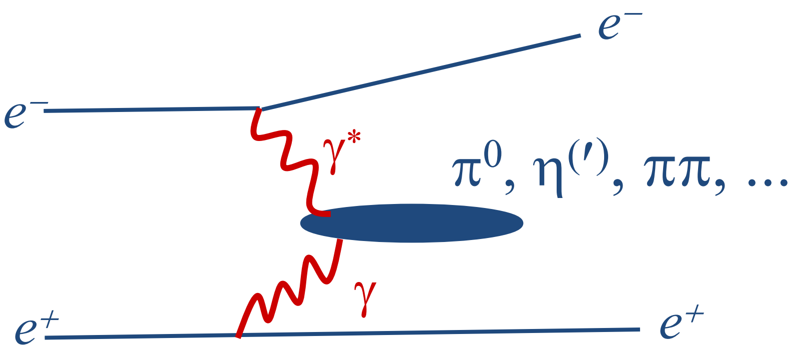
Data-Driven Approaches (e.g. Pion-Pole)

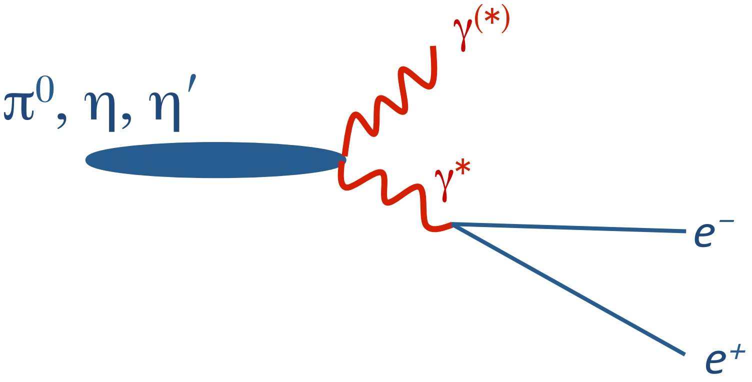


Data-driven approach!

⇔

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



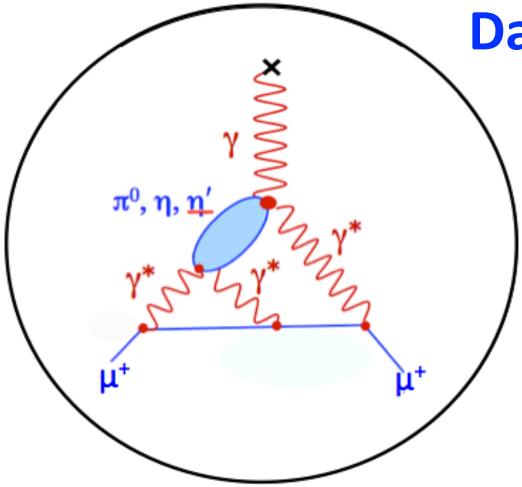


NEW

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

Colangelo et al '14; Pauk, Vanderhaeghen '14

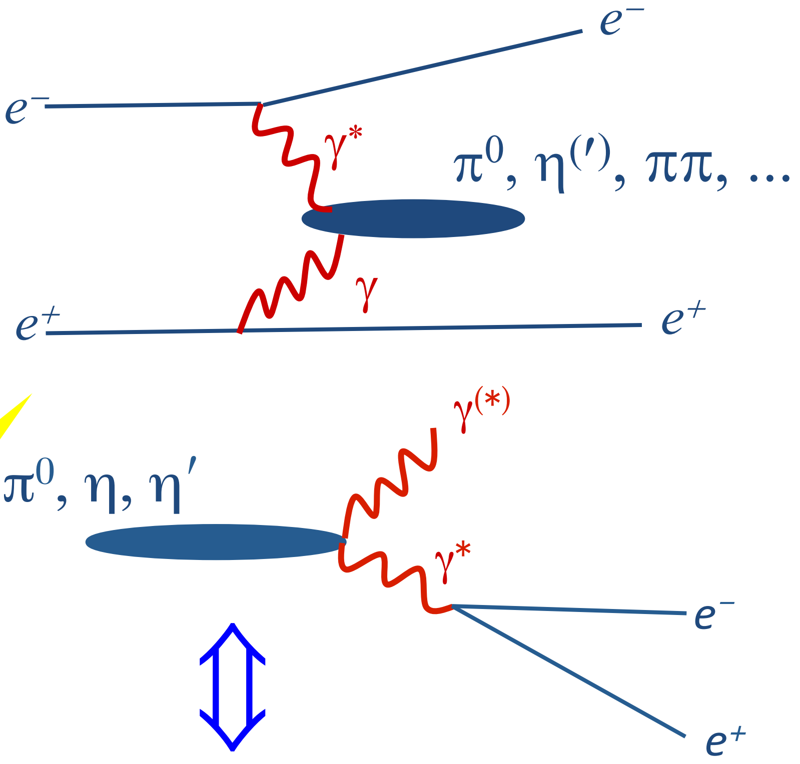
Data-Driven Approaches (e.g. Pion-Pole)



Data-driven approach!

⇔

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



NEW

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

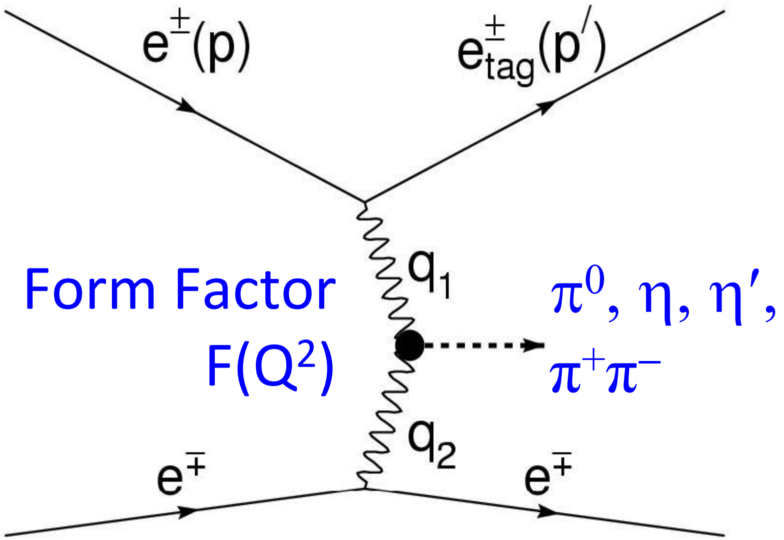
Spacelike FFs $\gamma\gamma^* \to P$

Single Tag Method

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: $q^2 = -q_2^2 \sim 0\ \mathrm{GeV}^2$

  → Quasi-real photon

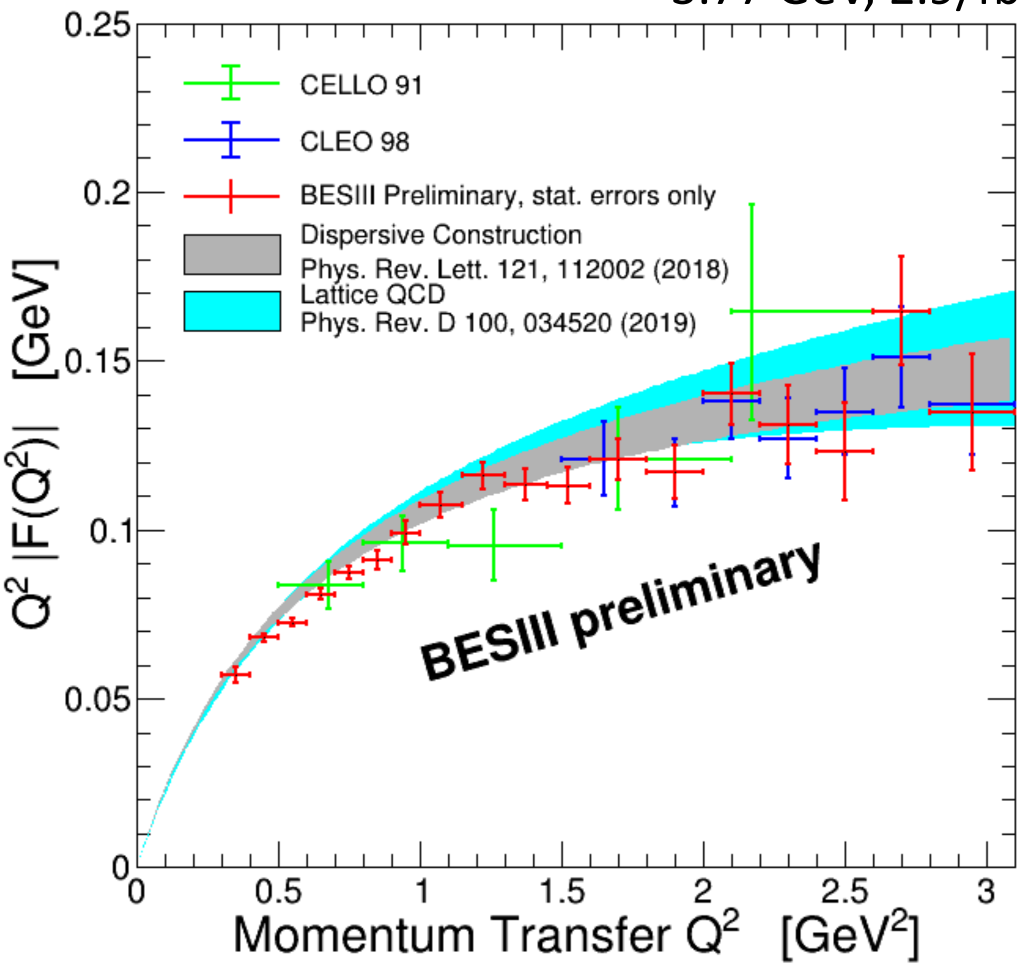
$$Q^2 = 4 \cdot E \cdot E' \cdot sin^2(\theta/2)$$

EKHARA event generator
Czyż, Ivashyn

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

PPNP107(2019)20

3.77 GeV, 2.9/fb



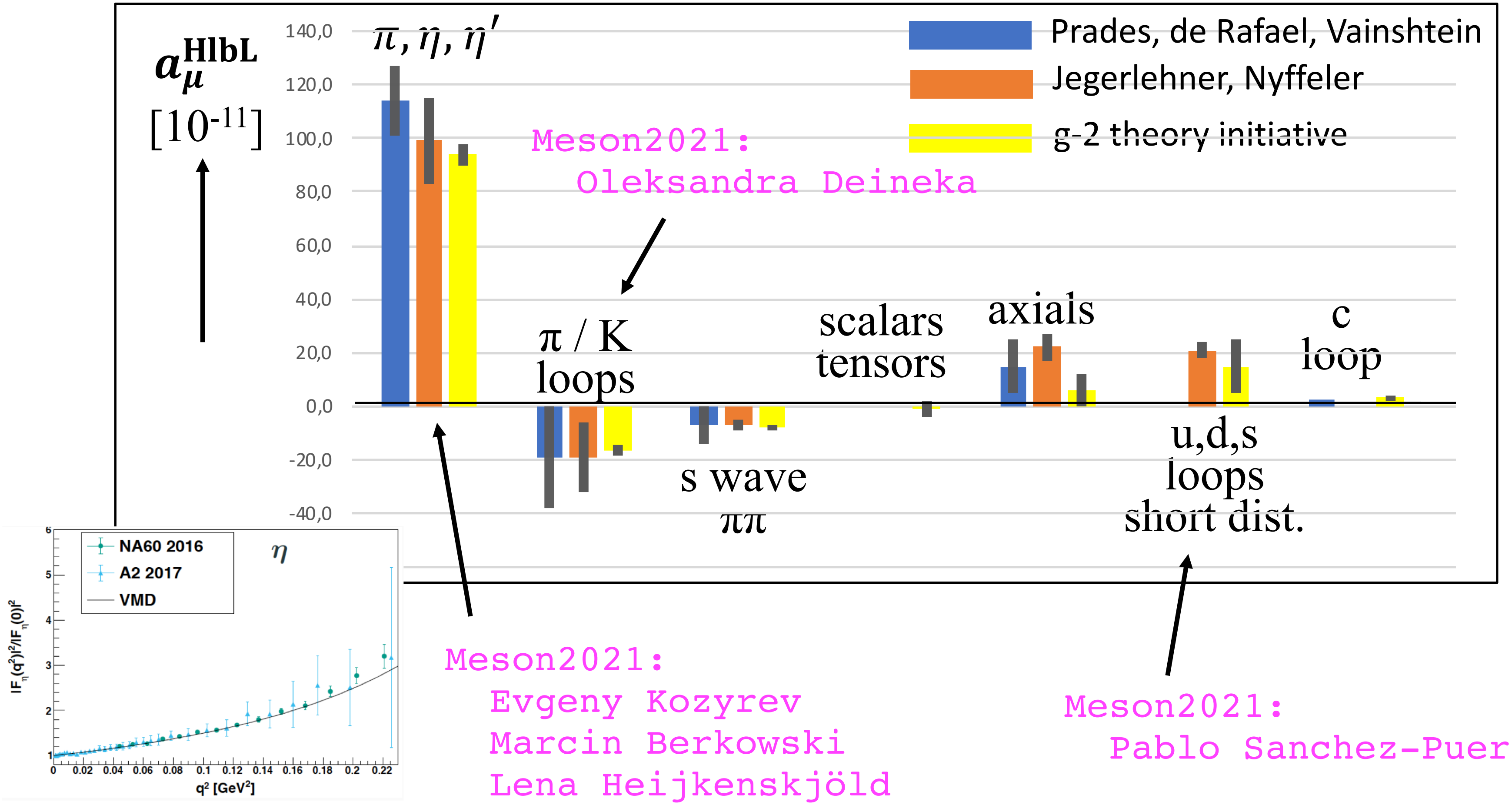
Unprecedented accuracy of BESIII
Relevant Q^2 range for HLbL
Very good agreement with recent dispersive analysis and of Lattice QCD calculation

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

Meson2021: Bastian Kubis

Conclusion & Outlook HLbL

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



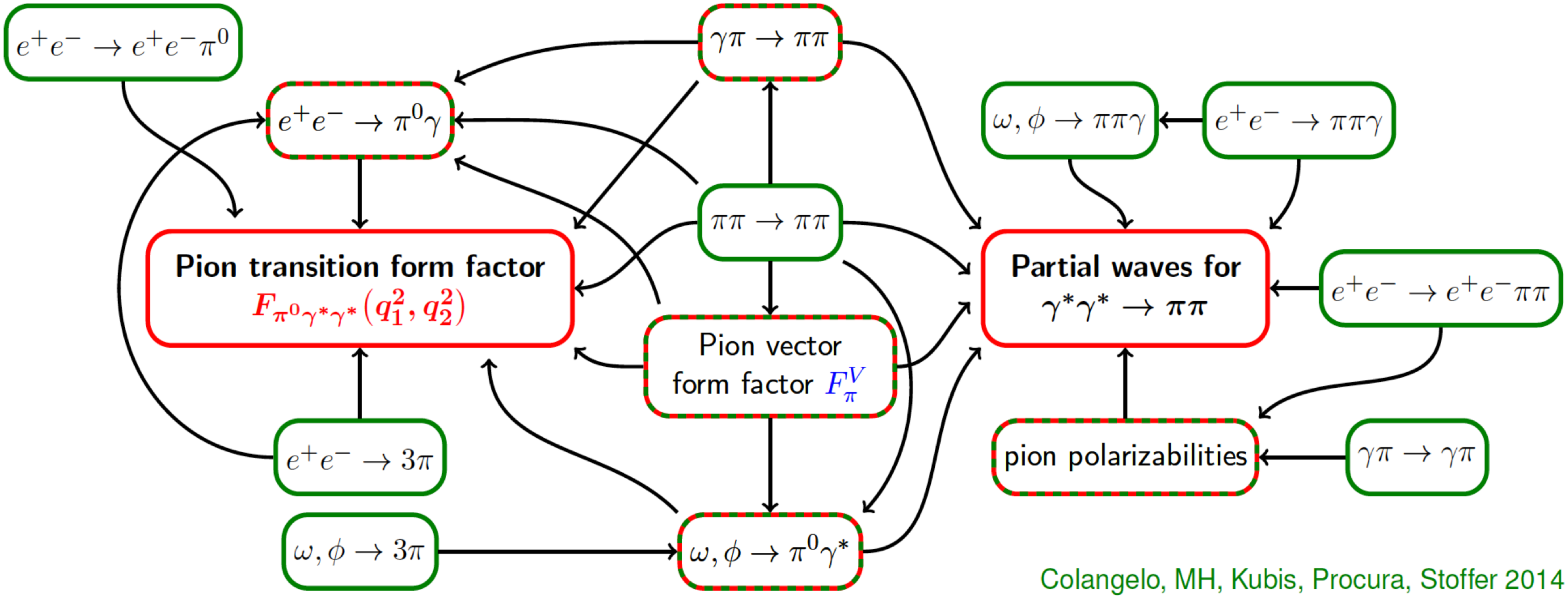
Meson2021:
Oleksandra Deineka

Meson2021:
Evgeny Kozyrev
Marcin Berkowski
Lena Heijkenskjöld

Meson2021:
Pablo Sanchez-Puertas

Conclusion & Outlook HLbL

- Usage of theoretical tools to relate meson decays & reactions



$e^+e^- \to e^+e^-\pi^0$

$\gamma\pi \to \pi\pi$

$e^+e^- \to \pi^0\gamma$

$\omega, \phi \to \pi\pi\gamma$

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

$\pi\pi \to \pi\pi$

Pion transition form factor $F_{\pi^0\gamma^*\gamma^*}(q_1^2, q_2^2)$

Partial waves for $\gamma^*\gamma^* \to \pi\pi$

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

Pion vector form factor F_π^V

$e^+e^- \to 3\pi$

pion polarizabilities

$\gamma\pi \to \gamma\pi$

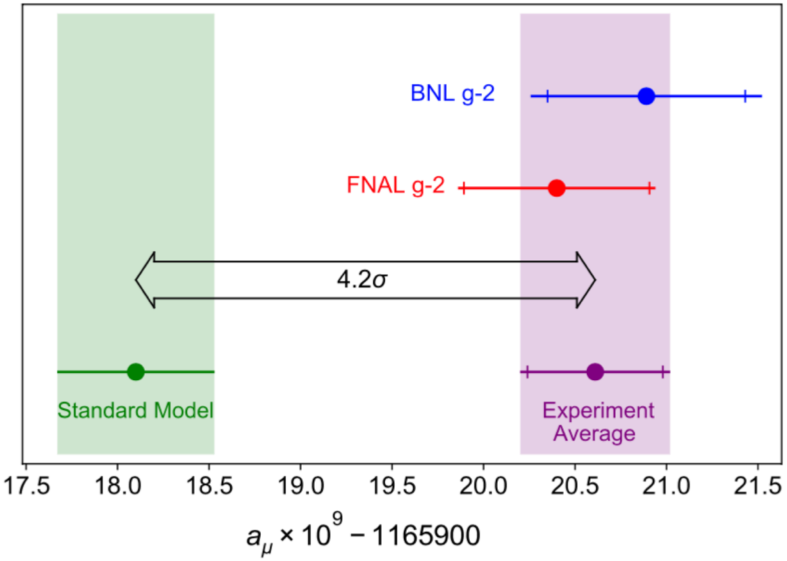
$\omega, \phi \to 3\pi$

$\omega, \phi \to \pi^0\gamma^*$

Colangelo, MH, Kubis, Procura, Stoffer 2014

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

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!

- **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!

- **HLbL**: new generation of transition FF measurements ongoing at various places,
  → further reduction of uncertainty in reach (assume factor 1.5)

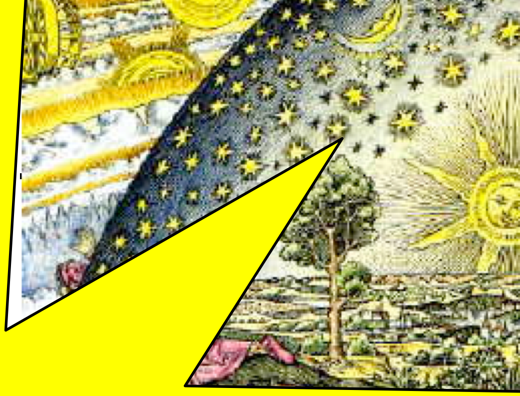
Assumption: central value of SM stable and uncertainty will improve to $\pm 2.3 \cdot 10^{-10}$!

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) !!!

- FF measurements for HVP and HLbL allow for searches for dark photons/ALPS

Meson2021: Attila Krasznahorkay



Conclusions

- 20 year old BNL … nt of
  4.2σ discrepancy
- fro…
  → red…
- **HLbL**: new … places,

A… 10^{-10}!

Scenar… l. improvemen…

10… !!!

- FF measur… allow… searches for dark photons/ALPS

Meson2021: Attila Krasznahorkay

Final interpretation of the muon g-2 crucially depends on Meson Physics research

MESON 2021

16th International Workshop on Meson Physics

17th - 20th May 2021, online via ZOOM

Thank you !

NEW DATE
AUG. 29 TO SEPT. 03, 2021
MAINZ, ERBACHER HOF

INTERNATIONAL PHYSICS SCHOOL

MUON DIPOLE MOMENTS
AND HADRONIC EFFECTS

https://indico.mitp.uni-mainz.de/e/g-2_school

TOPICS AND SPEAKERS

- **Muon Magnetic Moment Experiment** Graziano Venanzoni (INFN Pisa, Italy)
- **Muon Magnetic Moment Theory** Daisuke Nomura (KEK, Japan)
- **Hadronic Light-by-Light Phenomenology** Bastian Kubis (Bonn, Germany)
- **Data Input to Hadronic Vacuum Polarization** Erika de Lucia (Frascati, Italy)
- **Data Input to Hadronic Light-by-Light** Christoph Redmer (Mainz, Germany)
- **Particle Detectors** Wolfgang Kühn (Gießen, Germany)
- **Lattice QCD Theory** Marina Marinkovic (Dublin, Ireland), t.b.c.
- **New Physics Contributions to g-2** Svjetlana Fajfer (Ljubljana, Slovenia)
- **Atomic Physics Precision Experiments** Klaus Blaum (MPI Heidelberg, Germany)
- **Exercise Session** Lena Heijkenskjöld (JGU Mainz, Germany)

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