Precision Physics at High Intensities: Convener's Highlights

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CIPANP 2018, Palm Springs, CA,
28 May – 03 June 2018

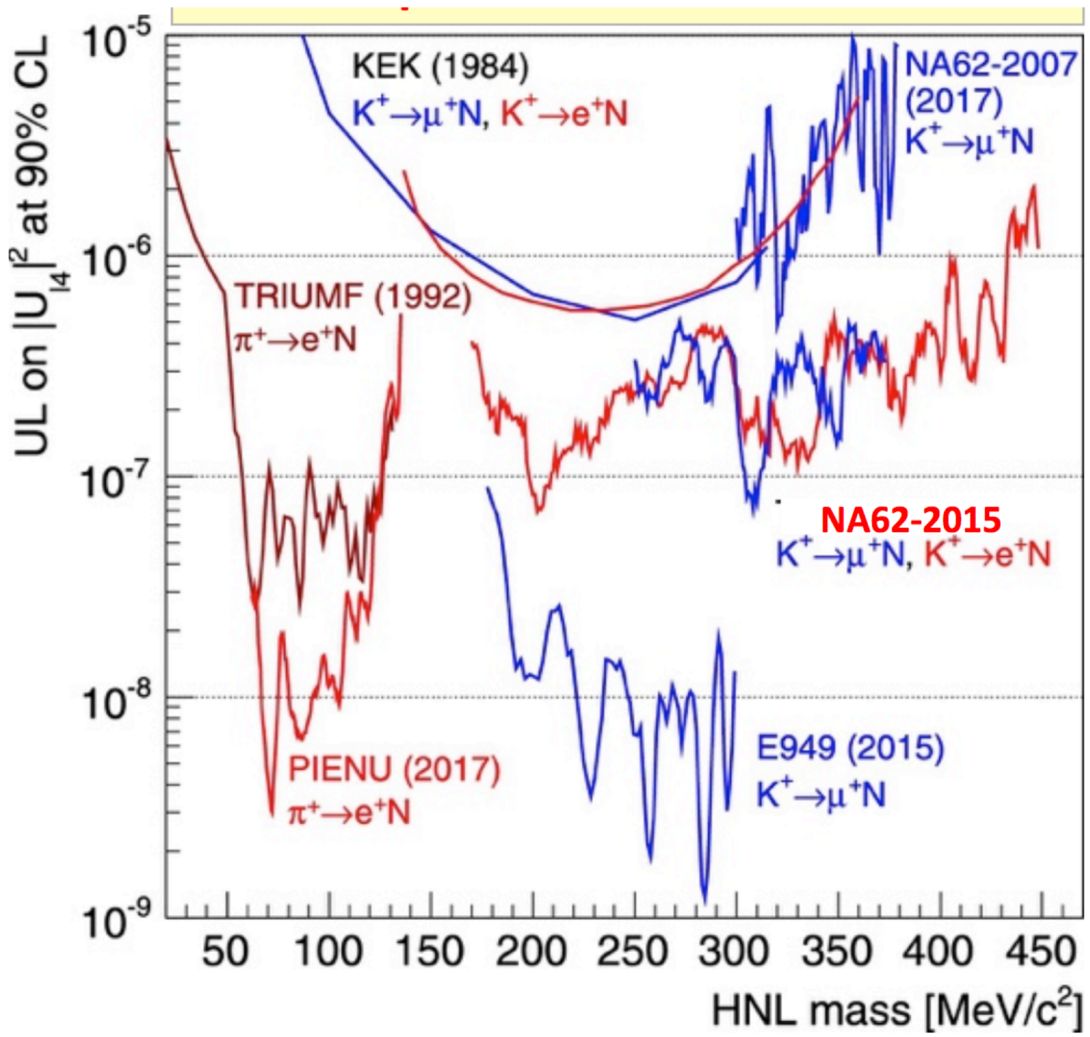
Precision Physics at High Intensities

- 40 talks in total : *http://dev-cipanp18.pantheon.berkeley.edu/sites/default/files/files/2PPHI.pdf*
- Topics included:
  - Rare Decays (*Joint session with Heavy Flavor CKM*)
  - Lepton Flavor Universality and Lepton Flavor Violation (*Joint session with Heavy Flavor CKM*)
  - Muon g-2
  - Dark Photons (*Joint session with Dark Matter*)
  - Symmetry tests (*Joint session with Tests of Symmetry & the Electroweak Interaction*)
  - Muons and electrons
  - Proton Radius (*joint session with QCD*)

Heavy Neutrinos

Biino Parallel 1, Mischke Parallel 2

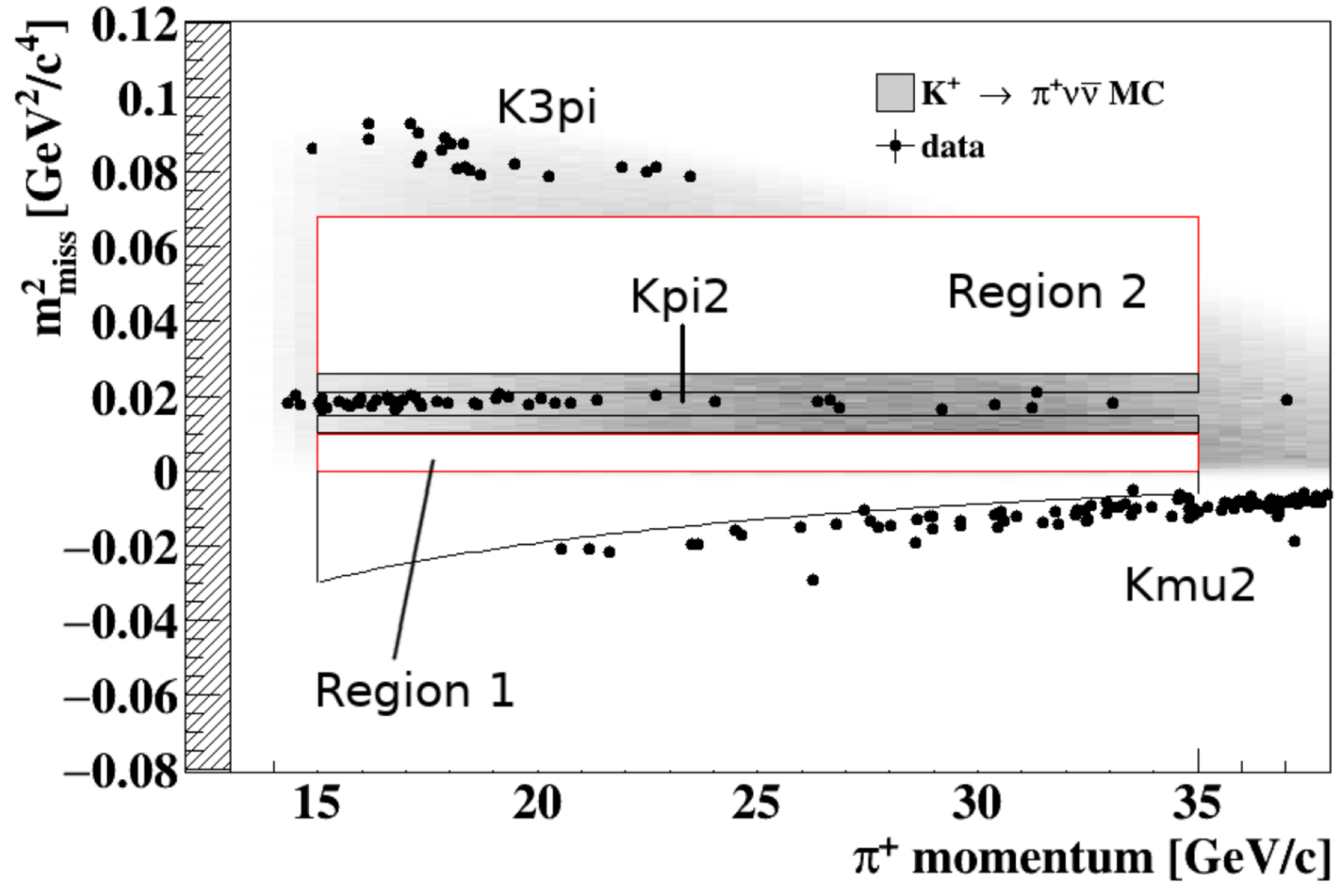
- Many SM extensions include additional massive neutrinos $\nu_{H.}$ They provide DM candidates, and introduce CPV phases that produce the Baryon Asymmetry.
- The PiENu experiment at TRIUMF sets limits on the coupling of ν_H to the electron by looking at stopped pions. : Phys.Rev. D97, 072012 (2018)
- The NA62 experiment at CERN looks for peaks in the M_{miss} of Kaon decays. Phys.Lett. B772, 712 (2017) & Phys.Lett. B778, 137 (2018)



$K^+ \to \pi^+ \nu \bar{\nu}$

Velghe Parallel 1

- Flavor Changing Neutral currents highly suppressed in SM ~10^{-10}
- Channel is featured in many BSM scenarios , ie SUSY, Z'models, LFV
- NA62 at CERN IDs and matched K+π and vetos on **μ**, γ.
- Signal (Region 2) and control (Region 1) regions blinded.
- Current results based on 4 weeks of data from 2016
- 20x more data expected by end of 2018



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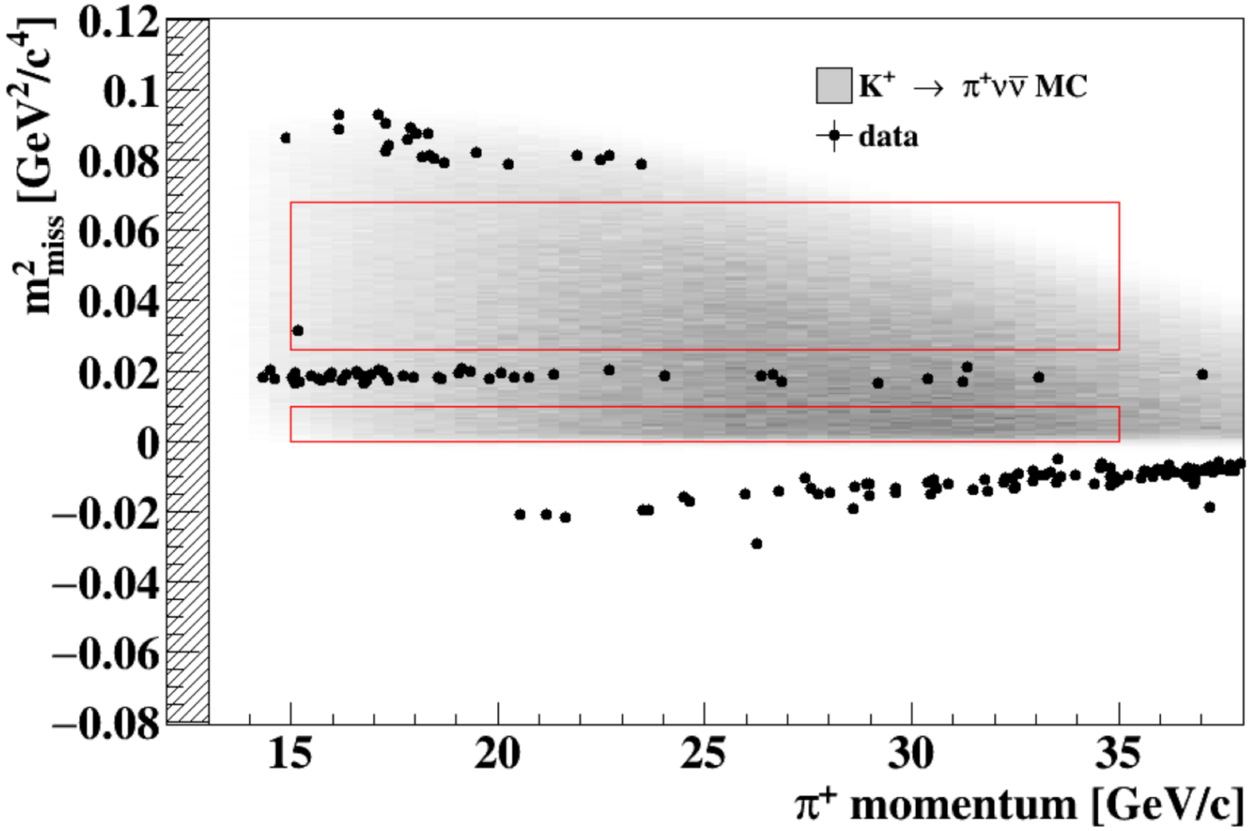


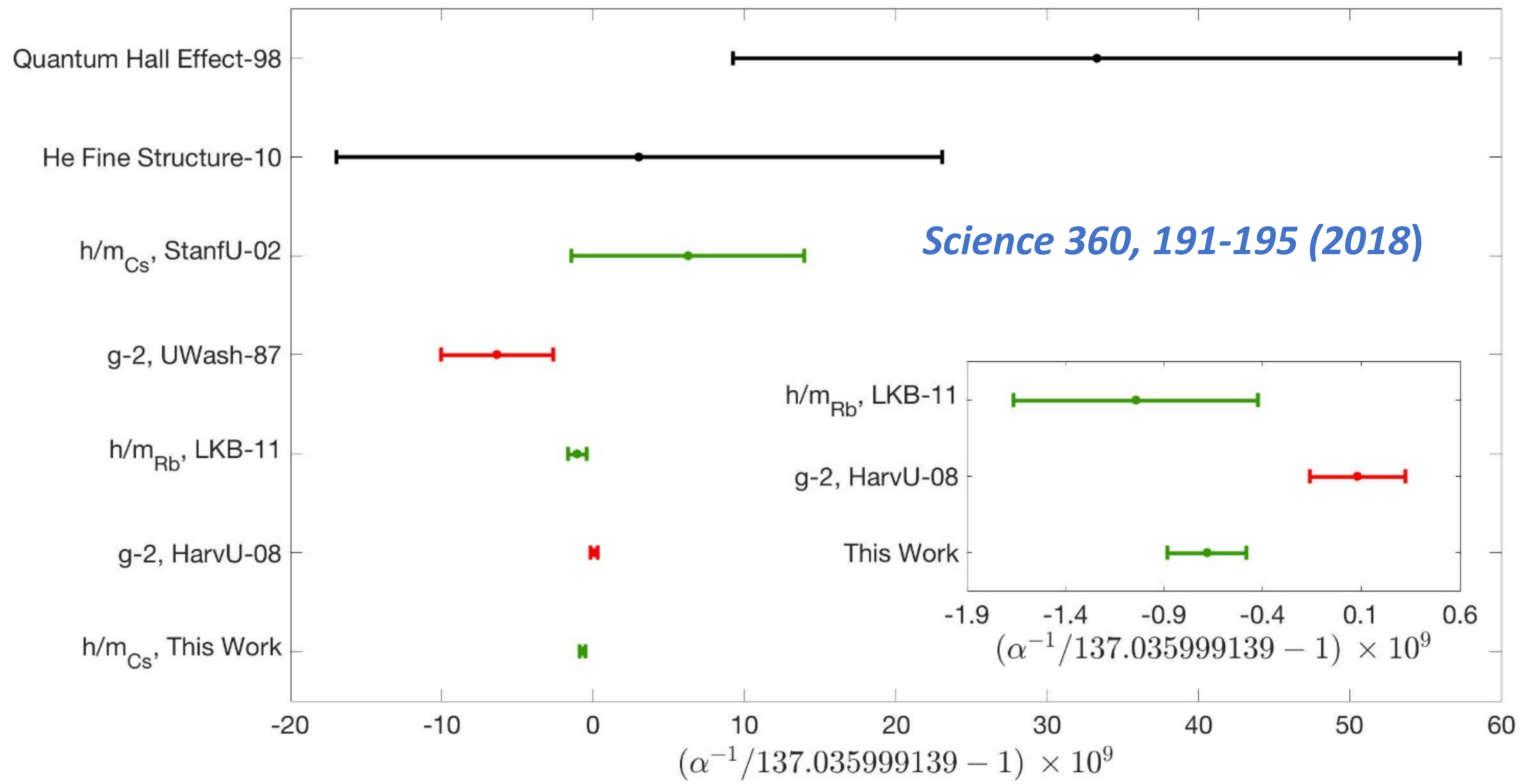
$$\mathcal{B}\left(K^+ \to \pi^+ \nu \bar{\nu}\right) < 14 \times 10^{-10}\ 95\%\ \text{C.L.}$$

Fine Structure Constant

$$\alpha = \frac{e^2}{4\pi\epsilon_0\hbar c}$$

Müller Parallel 6

- Defines the strength of interaction between electric charge and electromagnetic field.
- Müller group at U.C. Berkeley recorded most accurate measurement to date using recoil frequency of cesium-133 atoms in a matter wave interferometer.



Science 360, 191-195 (2018)

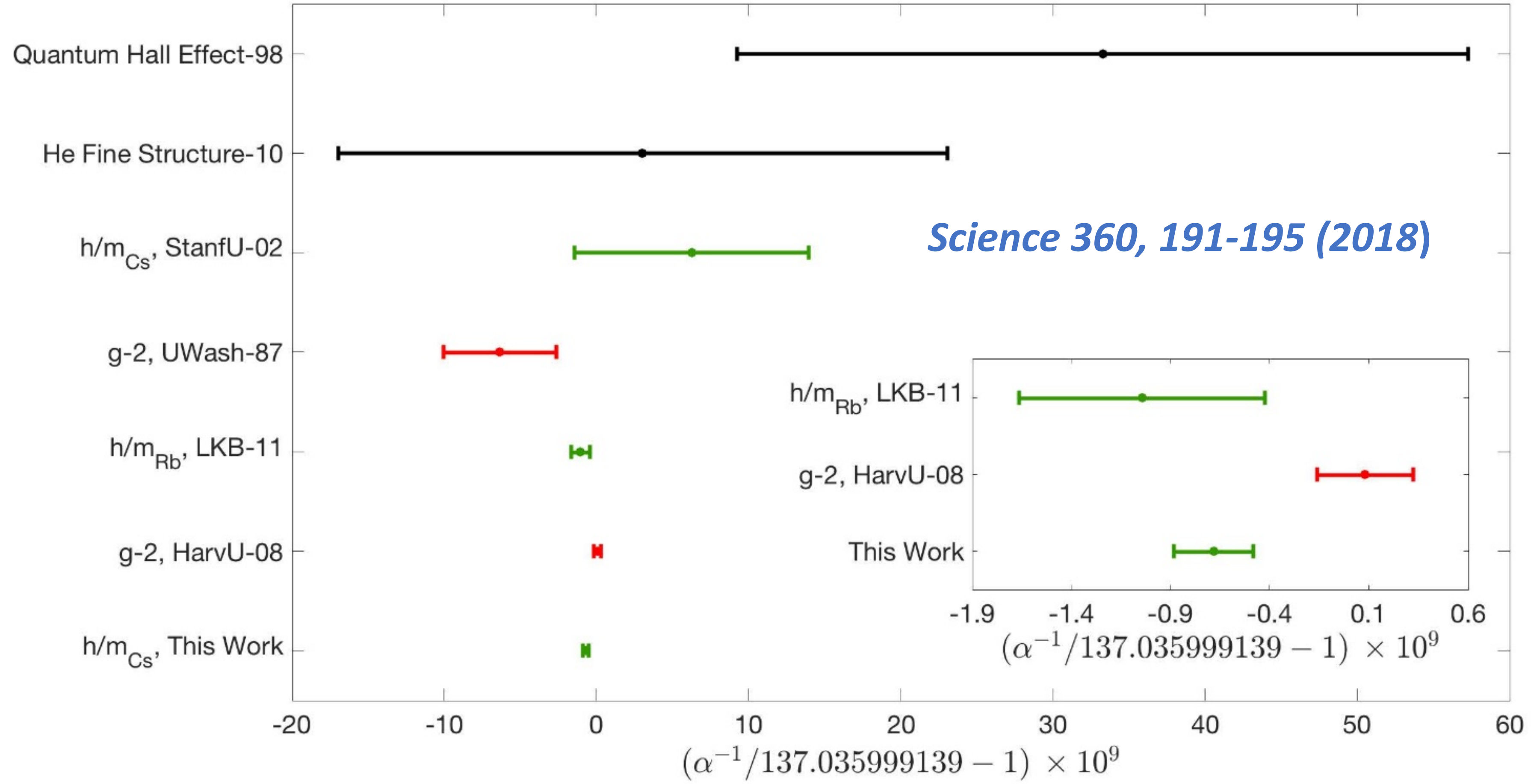
$\alpha = 1/137.035999046(27)$ at 2.0 x 10^{-10} accuracy.

Fine Structure Constant

$$\alpha = \frac{e^2}{4\pi\epsilon_0\hbar c}$$

Müller Parallel 6

- Measurements of anomalous magnetic moment of the electron a_μ = g-2/2 allows extraction of α
- Previous highest precision measurement by Gabrielse group at Harvard (Phys.Rev.Lett. 100 120801).
- 2.5σ tension rules out dark photons as cause for muon g-2 deviation



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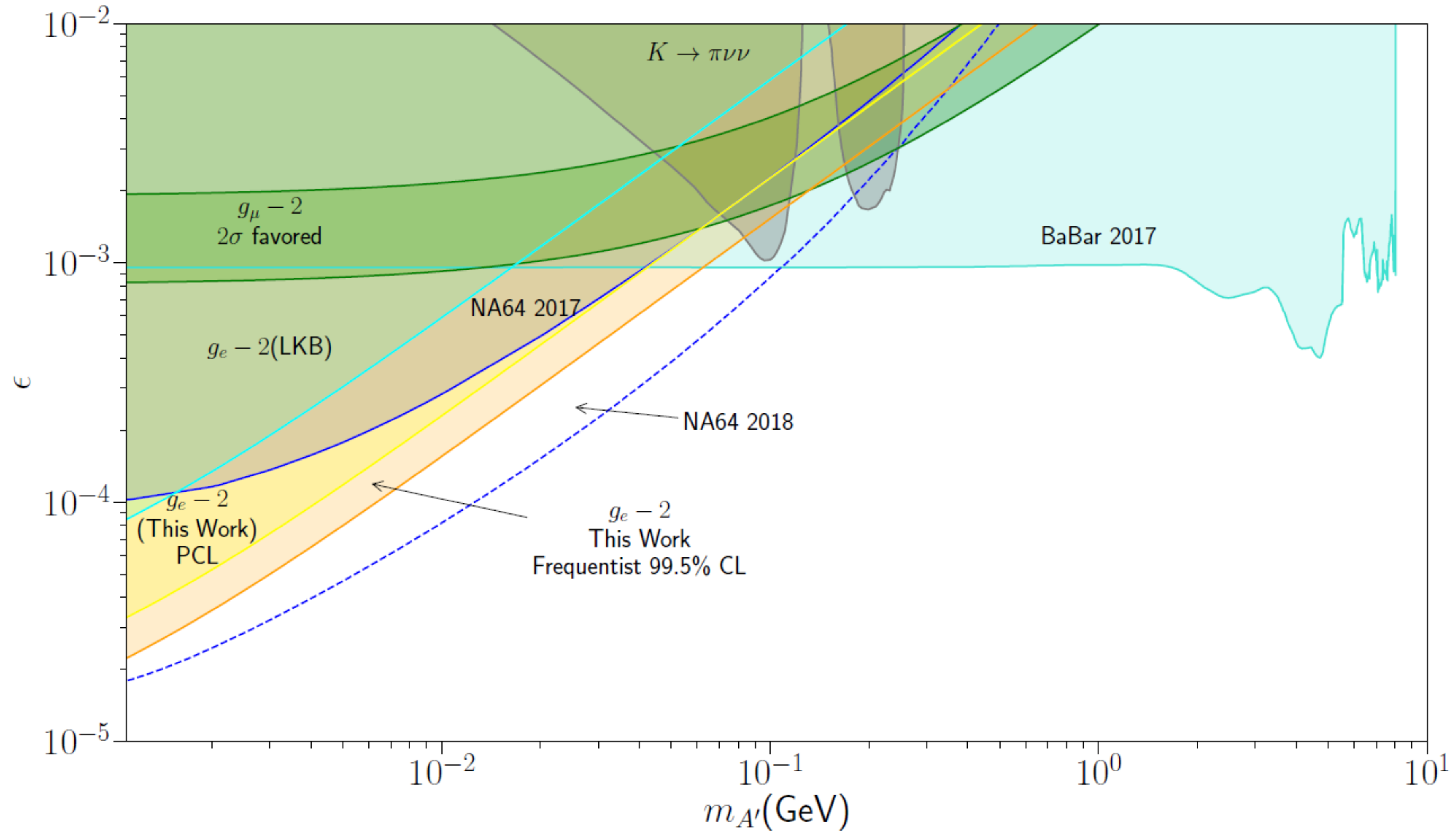
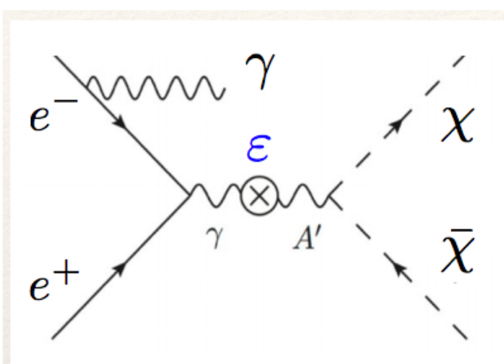
- Axial Vector Dark Sector candidates are still viable.



Dark Photon

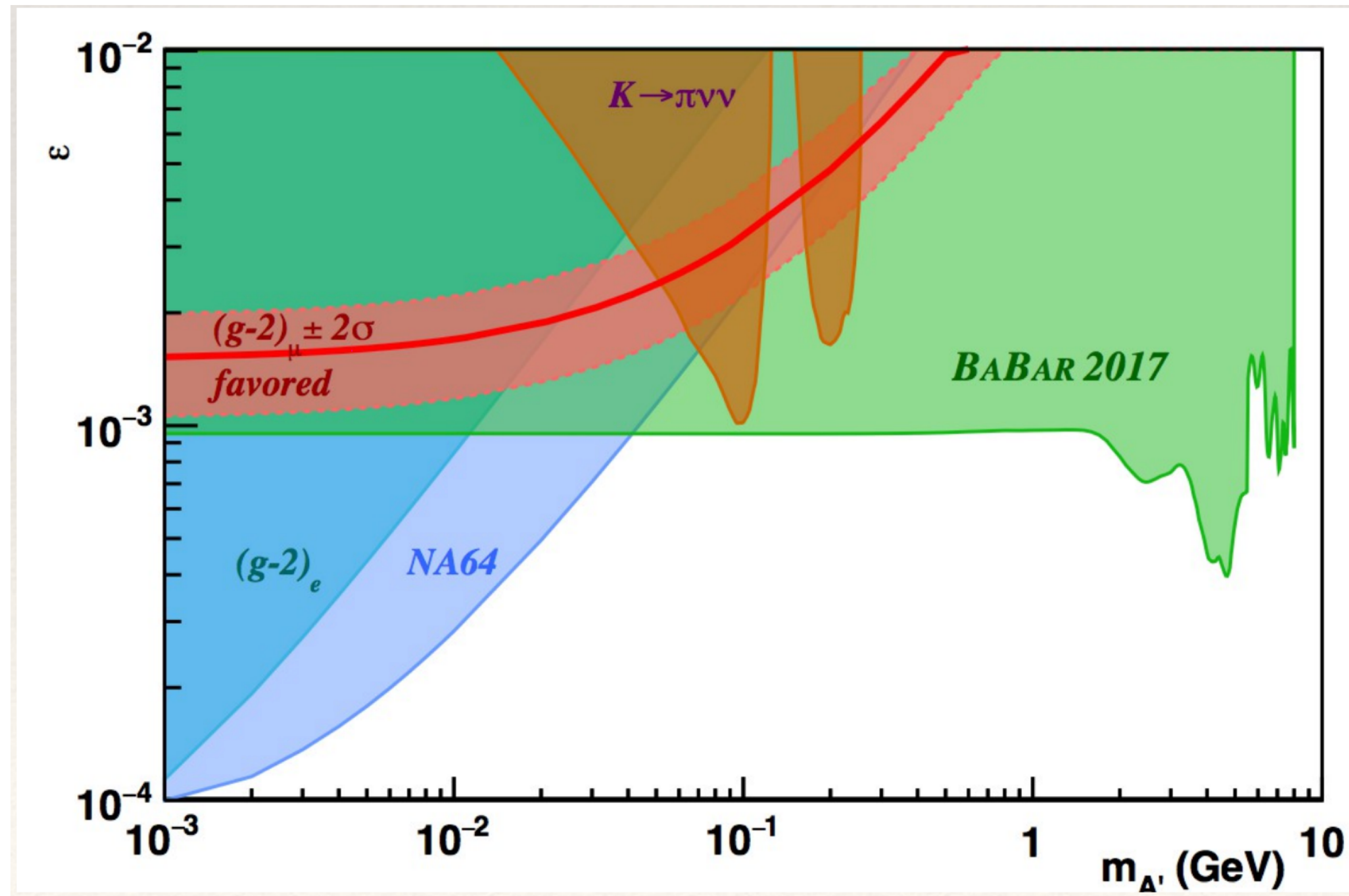
Shuve Parallel 4

- Previous search $A' \to \ell^+\ell^-$ PRL 113 20, 201801 (2014)
- New search $A' \to \gamma + \chi$.



- No significant deviation from background hypothesis

PRL 118 13, 131804 (2017)

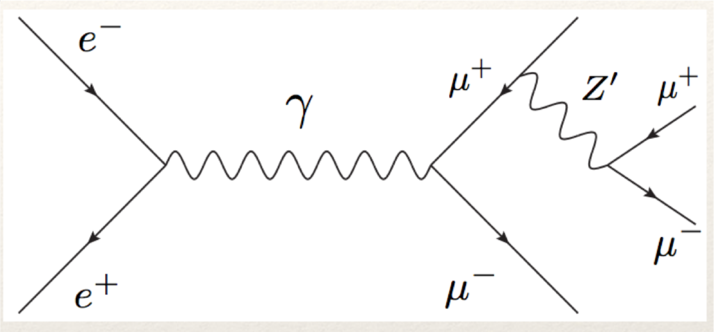


Excludes the entire g-2 anomaly

Dark Photon

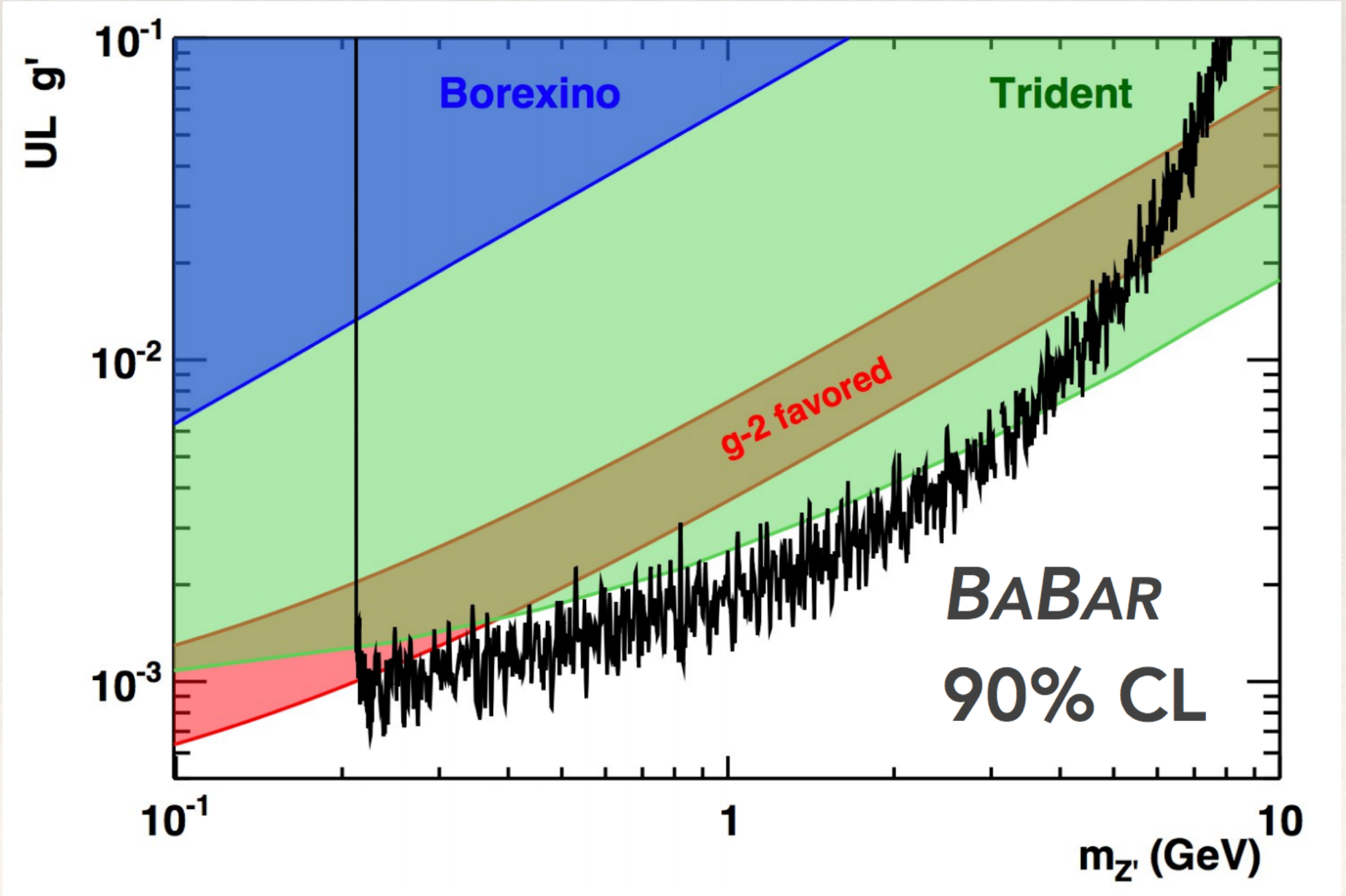
Shuve Parallel 4

- Dark force could couple predominately to heavy leptons
- Search for Z' final state radiation



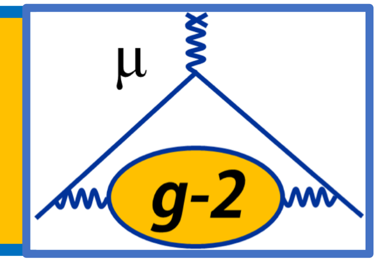
- First direct limits on muonic Z'
- ***Significant constraints on muon g–2 motivated parameters.***

PRD 94 1,011102 (2016)



Limits (90% C.L.) on Z' coupling

Muon anomalous magnetic dipole moment

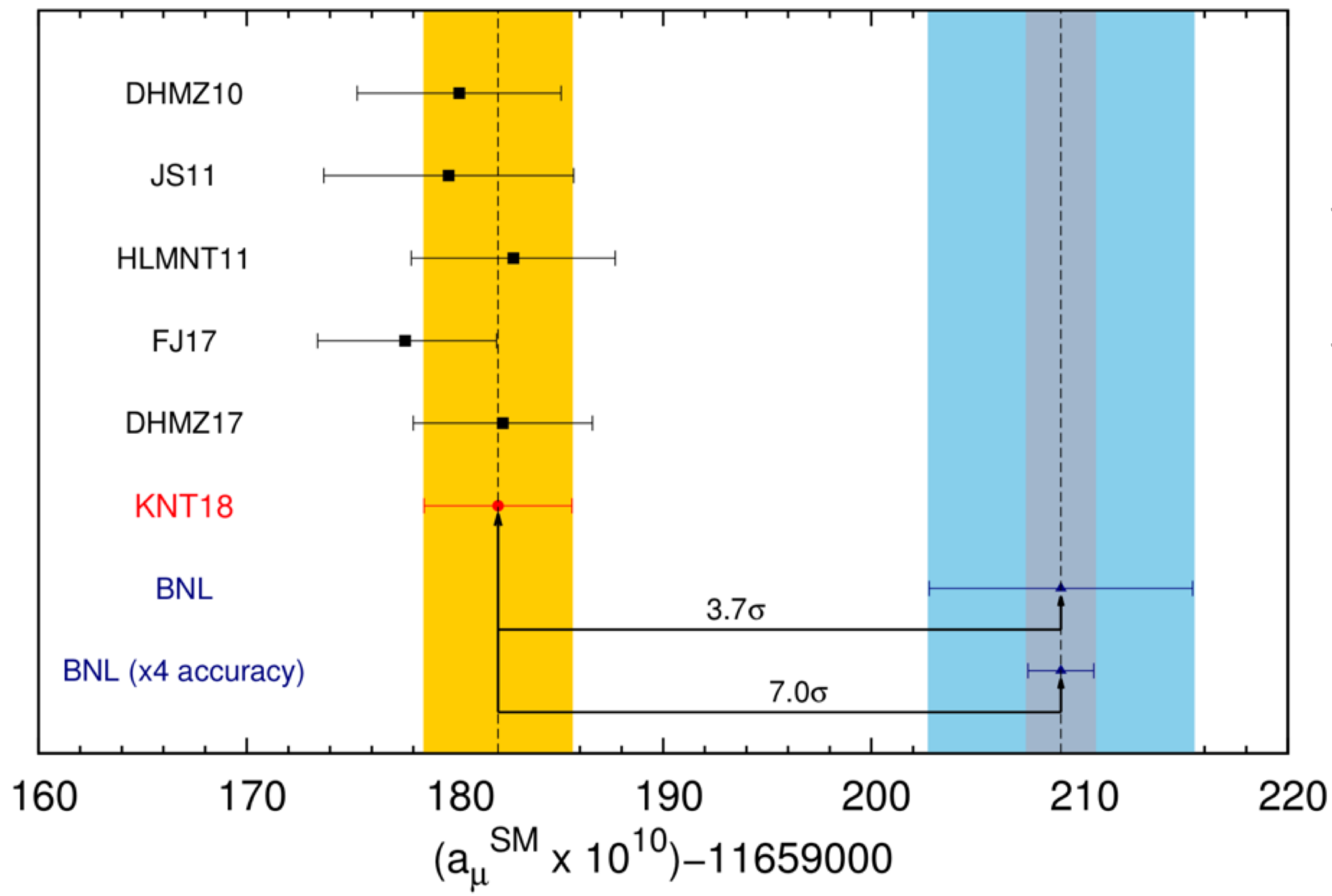


Hong Parallel 3, Price Parallel 6

The g-factor relates the magnetic moment to angular momentum. Dirac predicted g=2 for a point-like fermion.

$$\vec{\mu} = g\frac{Qe}{2m}\vec{S} \qquad a_\mu = \frac{g-2}{2}$$

Deviations from 2 arise from virtual loops that encapsulate all possible interactions with an external field. These interactions may include contributions from BSM particles and/or forces..



Keshavarzi, Nomura, Teubner arXiv: 1902.02995

Muon anomalous magnetic dipole moment

Hong Parallel 3, Price Parallel 6

The new g-2 experiment at FNAL (E989) aims to reduce the total error on the previous BNL measurement by a factor of x4!

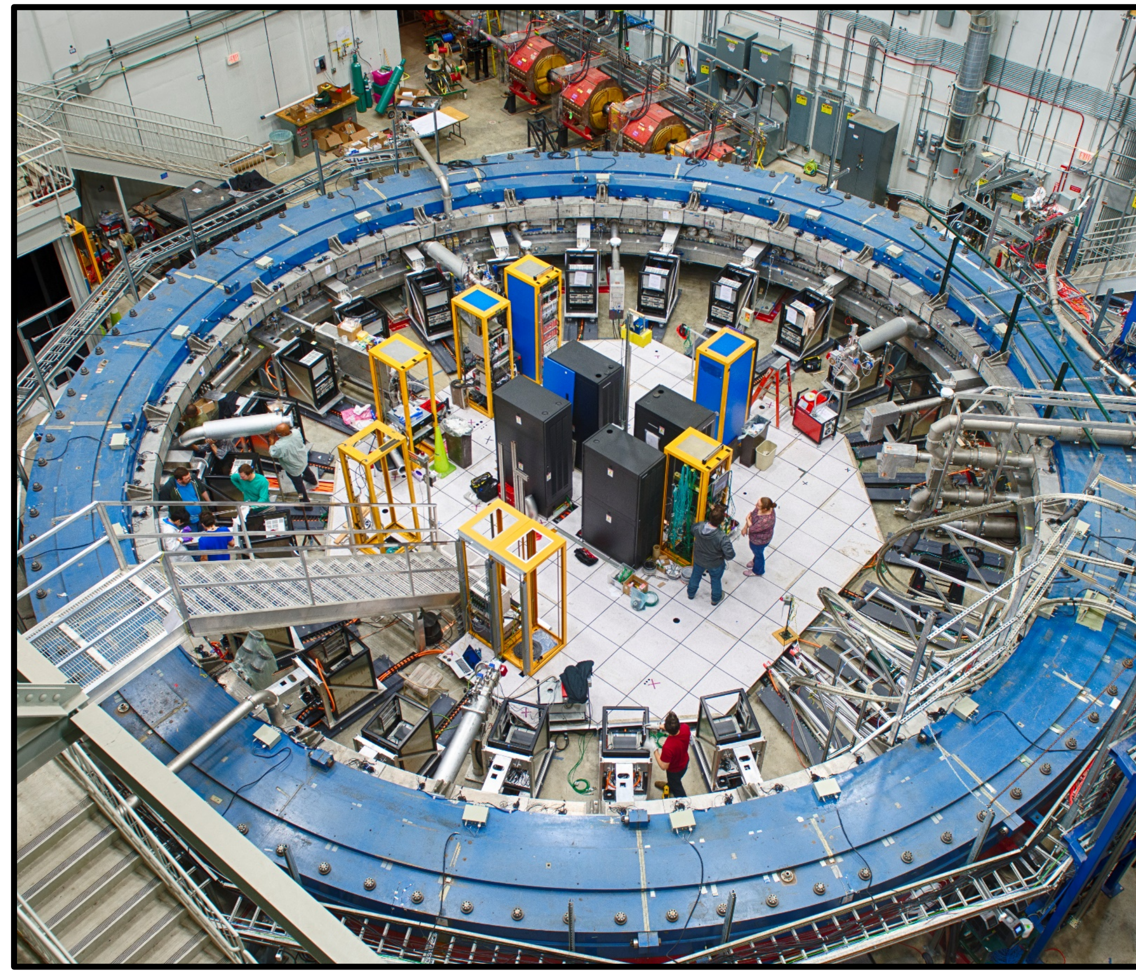
$70_{sys,precess} + 70_{sys,field} + 100_{stat} =$ 140 ppb total

The experiment completed a successful engineering run in the spring of 2017.

E989 is in the midst of their first physics run. Blinding was implemented mid-March with plans to collect a BNL sized dataset by early July shutoff.

Physics rusn in 2019 and 2020 are necessary to collect x20 more events than BNL.

Timeline is right for final results to be presented at CIPANP 2021!



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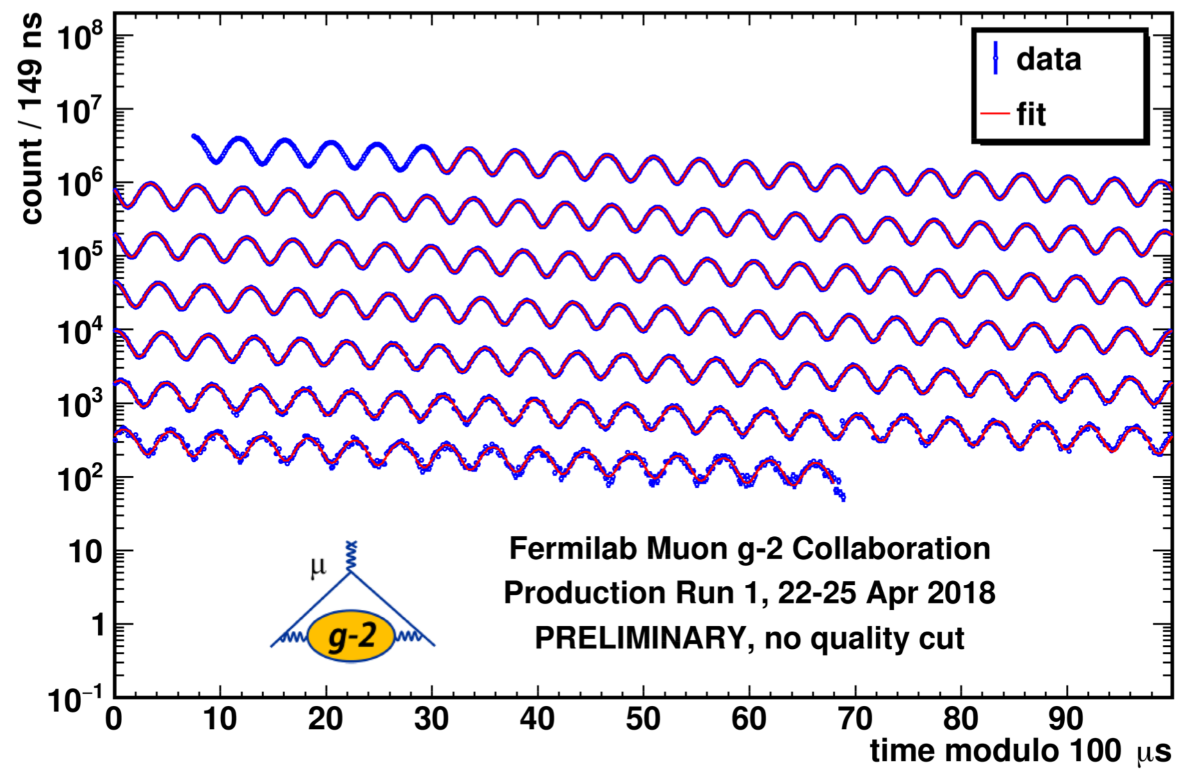
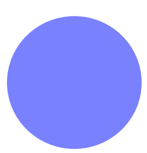


"Wiggle plot" from ~1 billion positrons

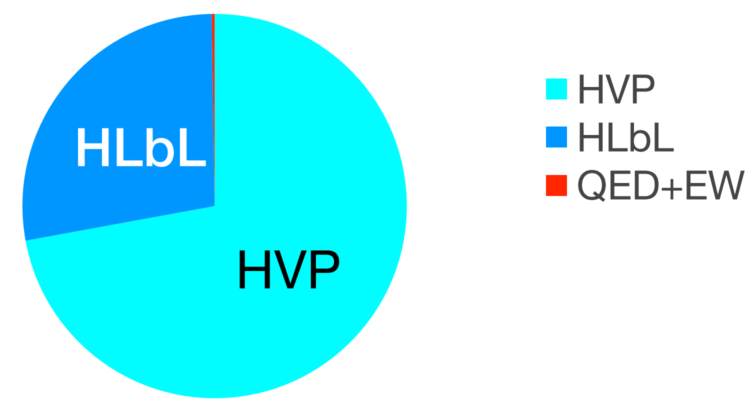
Muon g-2 error comparison: exp vs theory

BNL E821

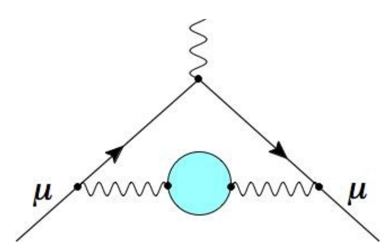
FNAL E989



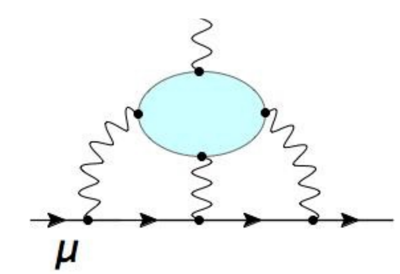
SM theory



Need to reduce and better control the errors on the hadronic corrections:



Hadronic Vacuum Polarization



Hadronic Light-by-Light

Muon g-2 error comparison: exp vs theory

BNL E821

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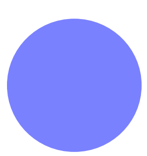

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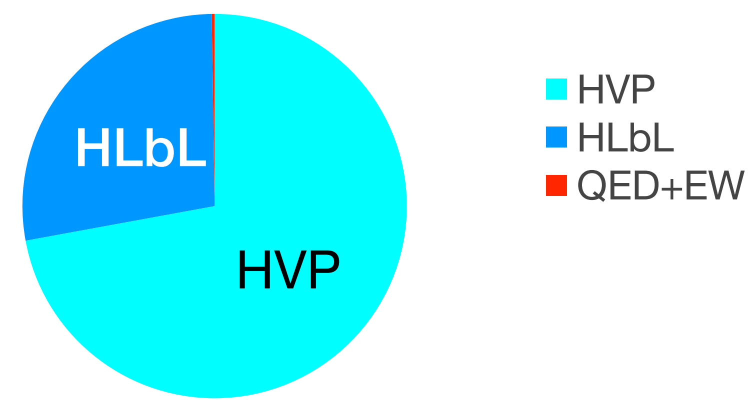
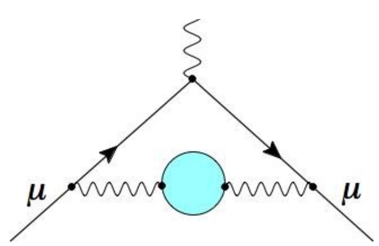
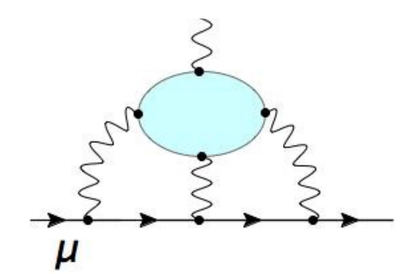


coordinated effort:
Muon g-2 Theory Initiative





Hadronic Vacuum Polarization

Hadronic Light-by-Light

Muon g-2 Theory Initiative

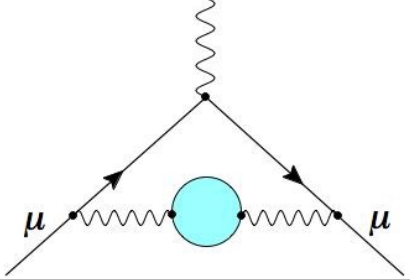
- Maximize the impact of the Fermilab and J-PARC experiments
  ➟ quantify and reduce the uncertainties on the hadronic corrections
- summarize the theory status and assess reliability of uncertainty estimates
- organize workshops to bring the different communities together
  First plenary workshop: held near Fermilab, June 2017
  HVP workshop @ KEK: 12-14 February 2018
  HLbL workshop @ U Connecticut: 12-14 March 2018
  Second plenary workshop: Mainz, 18-22 June 2018
- two working groups, one for HVP and one for HLbL:
  invite community participation: 53 in HVP WG, 33 in HLbL WG
- write the first report before the Fermilab experiment announces its first result with ``Brookhaven level'' statistics
  target date for first report: December 2018

Muon g-2 Theory Initiative

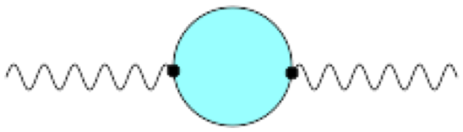
First Workshop of the Muon g-2 Theory Initiative

3-6 June 2017 *Q Center*
US/Central timezone

66 participants, 40 talks, 15 discussion sessions (525 minutes)



Hadronic vacuum polarization



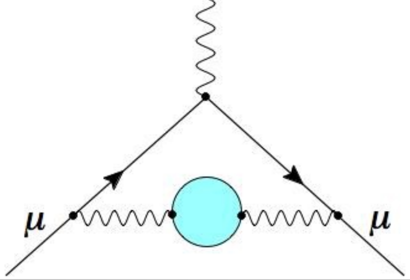
$$\hat{\Pi}(q^2) = \Pi(q^2) - \Pi(0)$$

$$\Pi_{\mu\nu} = \int d^4x e^{iqx} \langle j_\mu(x) j_\nu(0) \rangle = (q_\mu q_\nu - q^2 g_{\mu\nu}) \Pi(q^2)$$

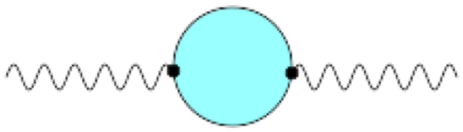
Leading order HVP correction: $a_\mu^{\mathrm{HVP,LO}} = \left(\frac{\alpha}{\pi}\right)^2 \int dq^2 \omega(q^2)\, \hat{\Pi}(q^2)$

- Use optical theorem and dispersion relation to rewrite the integral in terms of the hadronic *e+e-* cross section:

$$a_\mu^{\mathrm{HVP,LO}} = \frac{m_\mu^2}{12\pi^3} \int ds \frac{\hat{K}(s)}{s} \sigma_{\mathrm{exp}}(s)$$



Hadronic vacuum polarization



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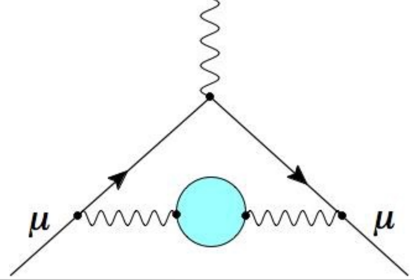
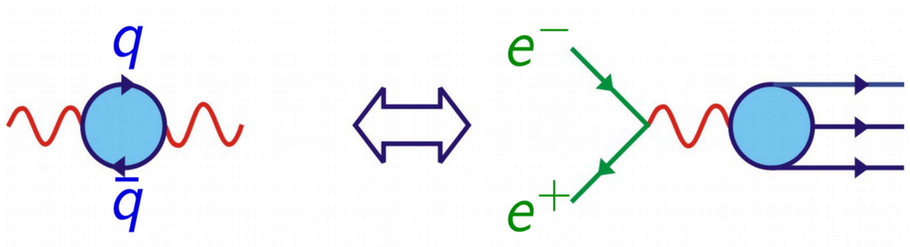
Dominant contributions from low energies
$\pi^+\pi^-$ channel: 73% of total $a_\mu^{\text{HVP,LO}}$



Hadronic vacuum polarization

C. Redmer for BESIII (PPHI, P3):

Related to hadronic cross sections by optical theorem



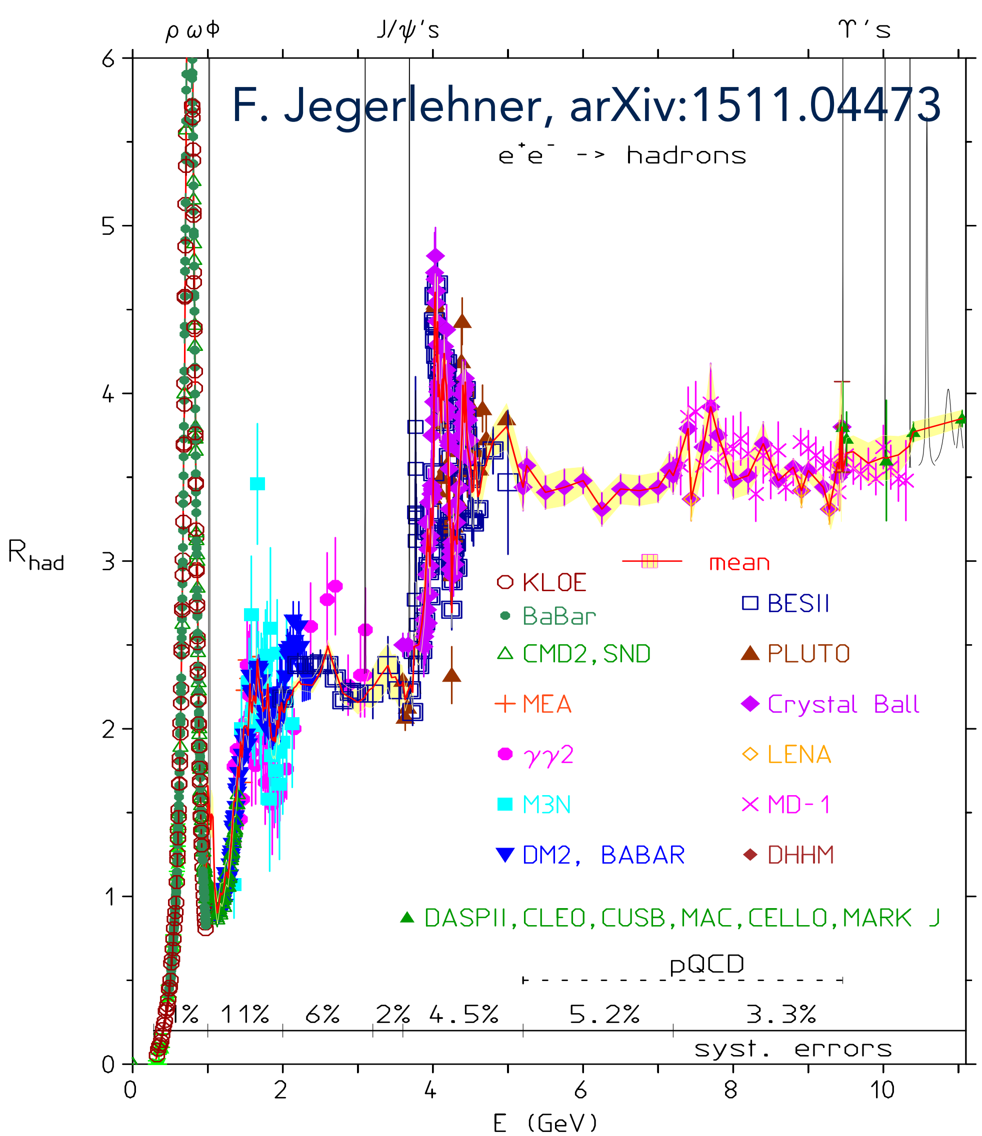
Dispersion integral :

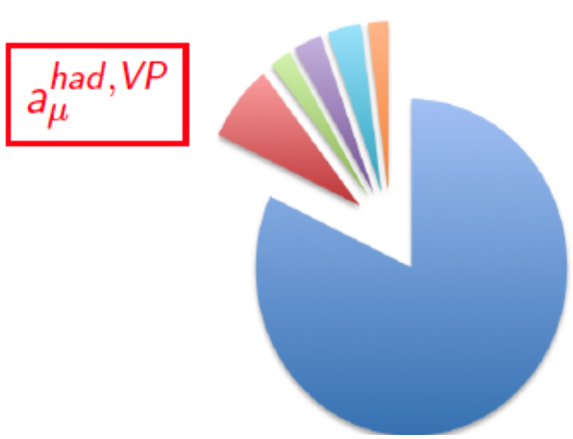
$$a_\mu^{hVP,LO} = \frac{1}{4\pi^3} \int_{4m_\pi^2}^{\infty} K(s)\sigma(e^+e^- \to \text{hadr})ds$$

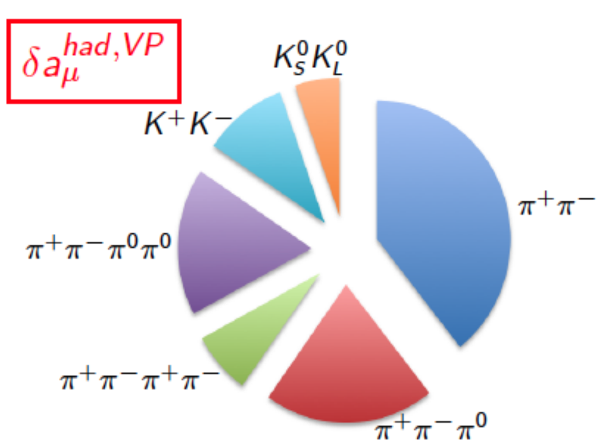
$$K(s) \sim \frac{1}{s}$$

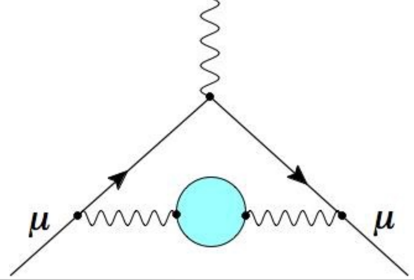
$$\sigma(e^+e^- \to \text{hadr}) \sim \frac{1}{s}$$

Low energy contributions dominate !



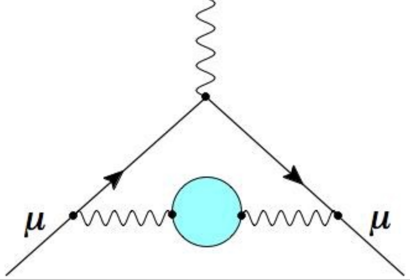






Hadronic vacuum polarization

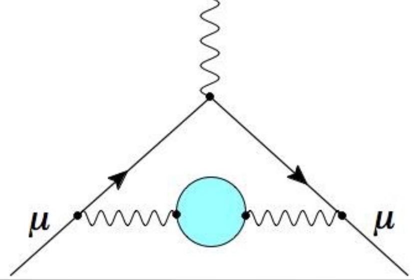
- ✦ Target: ~0.2% total error
- ✦ Dispersion relation + experimental data for $e^+e^- \to \mathrm{hadrons}$ (and τ data)
  - current uncertainty ~0.4-0.5%
  - can be improved with more precise experimental data
  - new experimental measurements expected/ongoing at BaBar, BES-III, Belle-II, CMD-3, SND, KLOE,….
- ✦ Challenges:
  - below ~2 GeV: sum ~30 exclusive channels: 2π, 3π, 4π, 5π, 6π, 2K, 2Kπ, 2K2π, ηπ,…. (use isospin relations for missing channels)
  - above ~1.8 GeV:
    inclusive, pQCD (away from flavor thresholds)
    + narrow resonances (J/ψ, Υ,..)
  - Combine data from different experiments/measurements: understanding correlations, sources of sys. error, tensions…
  - include FS radiative corrections



Hadronic vacuum polarization

W. Gary for BaBar (PPHI/TSEI, P6):

- Recent exclusive hadronic cross section measurements
  - $e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0$ PRD 96 (2017) 092009
  - $e^+e^- \rightarrow \pi^+\pi^-\eta$ PRD 97 (2018) 052007
  - $e^+e^- \rightarrow K_SK_L\pi^0,\ K_SK_L\eta,\ K_SK_L\pi^0\pi^0$ PRD 95 (2017) 052001
  - $e^+e^- \rightarrow K_SK^+\pi^-\pi^0,\ K_SK^+\pi^-\eta$ PRD 95 (2017) 092005

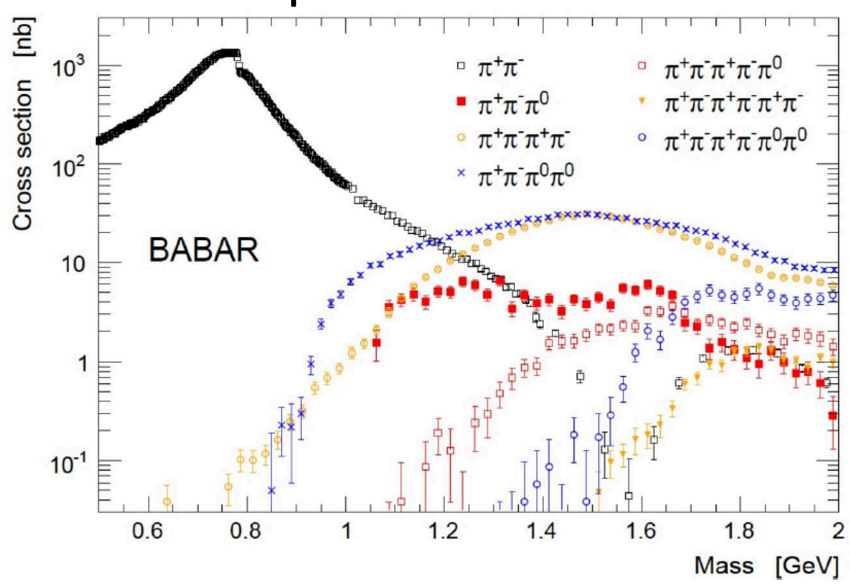


Hadronic vacuum polarization

W. Gary for BaBar (PPHI/TSEI, P6):

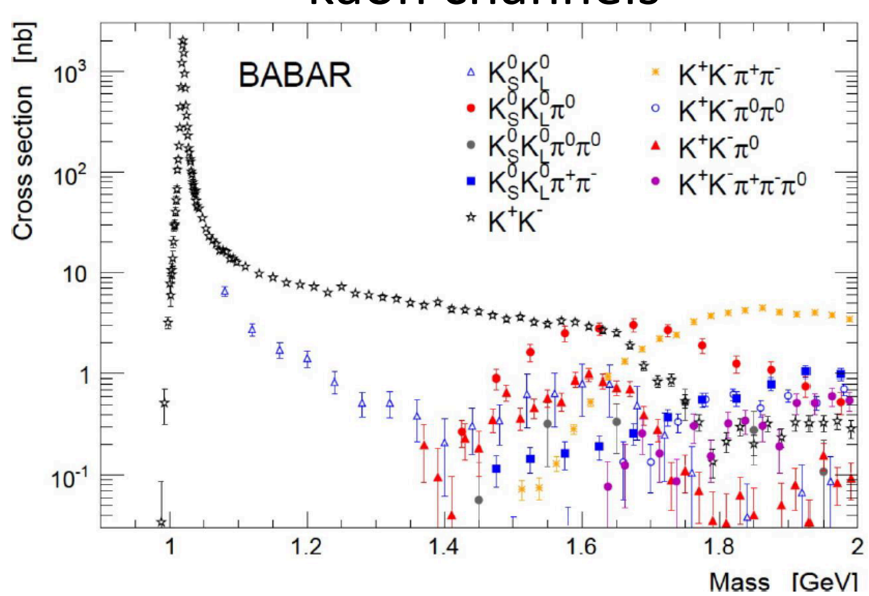
Summary of BABAR ISR results

pion channels

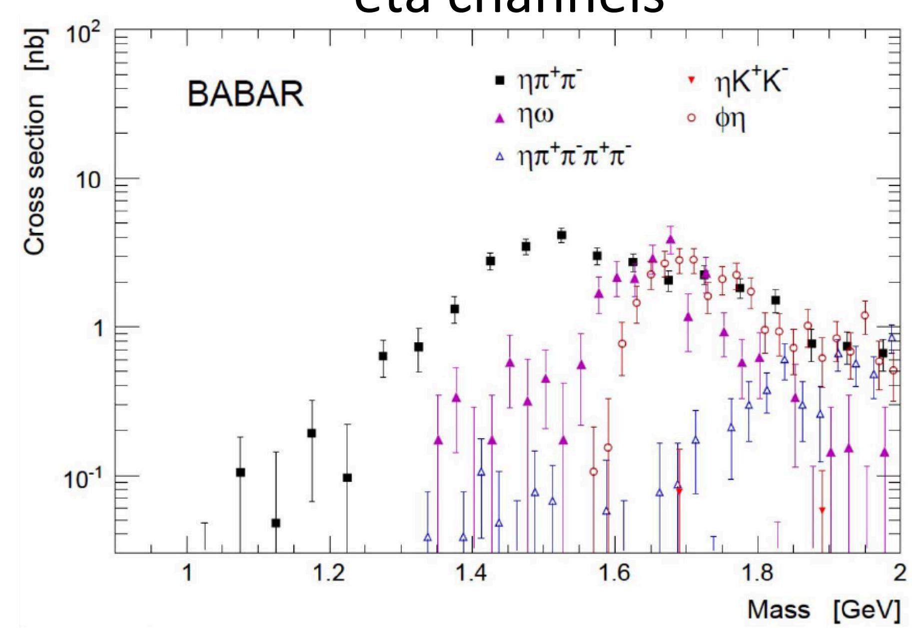


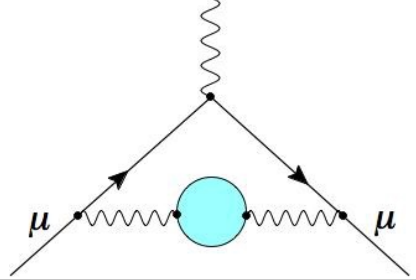
- Plots don't yet contain all the latest results
- Discrepancy of up to 3% between BABAR and KLOE in the all-important $\pi^+\pi^-$ channel
- New BABAR analysis on $\pi^+\pi^-$ with reduced systematics and 8 times more data expected around the end of 2018

kaon channels



eta channels

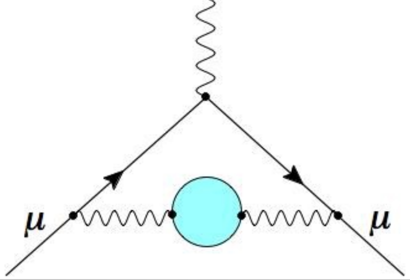




Hadronic vacuum polarization

W. Gary for BaBar (PPHI/TSEI, P6):

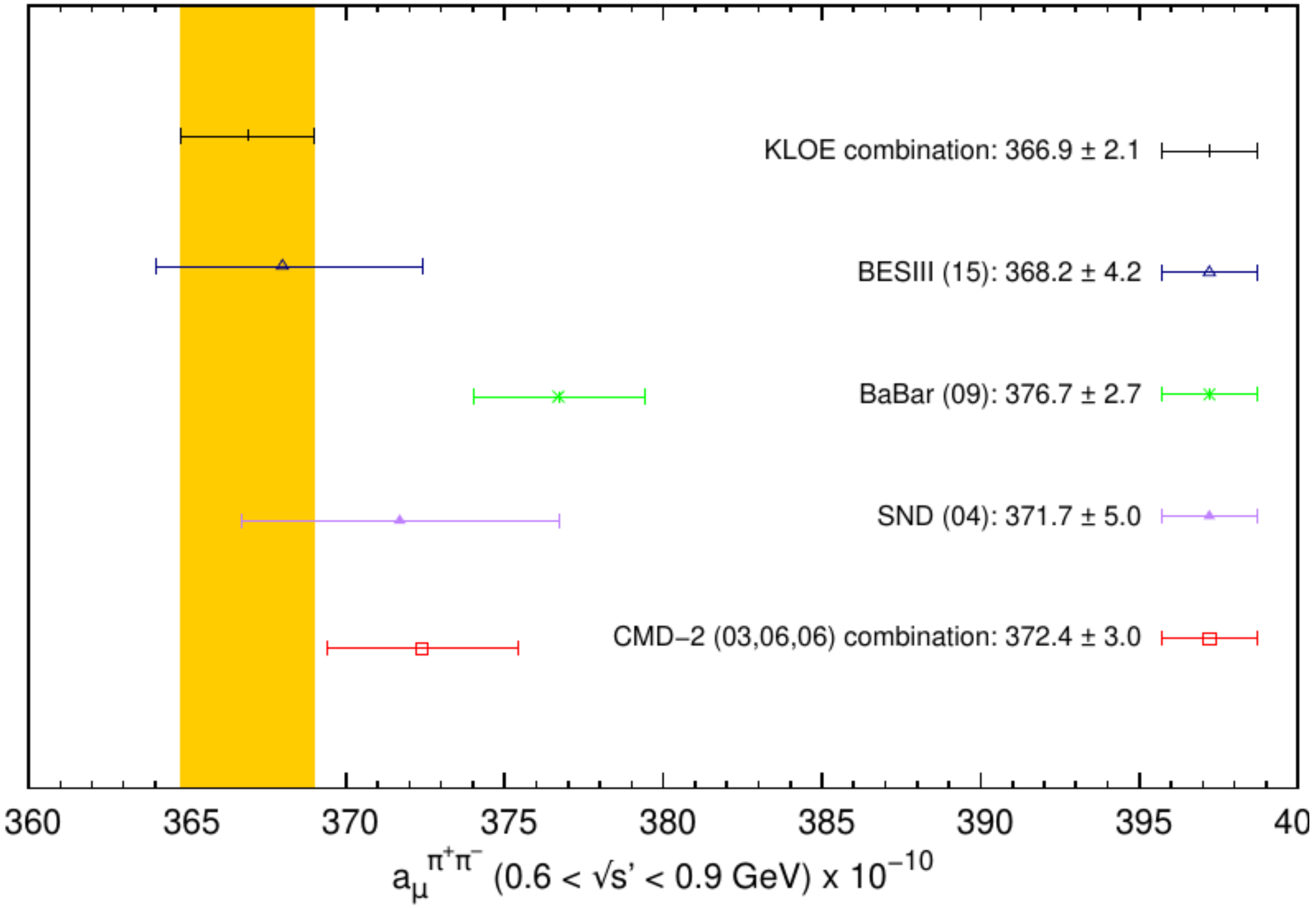
- New BABAR results reduce the uncertainty in $a_\mu^{had,LO}$
  - $e^+e^- \longrightarrow \pi^+\pi^-\pi^0\pi^0$ from around 7% to around 3%
  - $e^+e^- \longrightarrow KK\pi\pi$ from around 30% to around 6%
- Future progress in $a_\mu^{had,LO}$ will come from reduced systematic uncertainties in $e^+e^- \rightarrow \pi^+\pi^-$ (BABAR and CMD3) and perhaps eventually lattice QCD

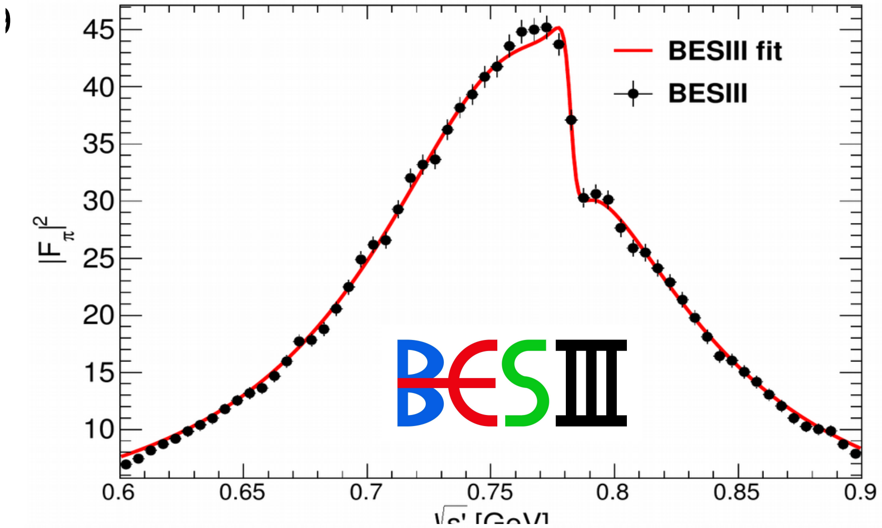


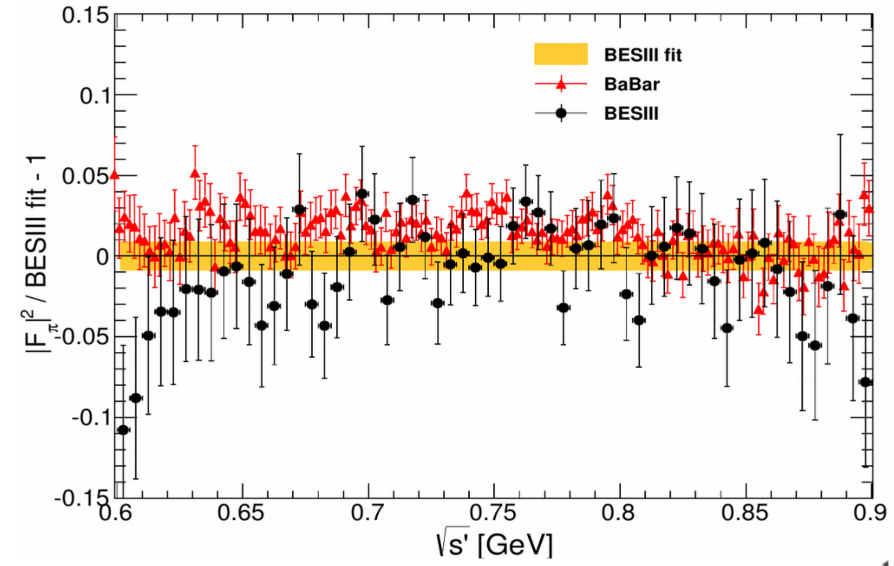
Hadronic vacuum polarization

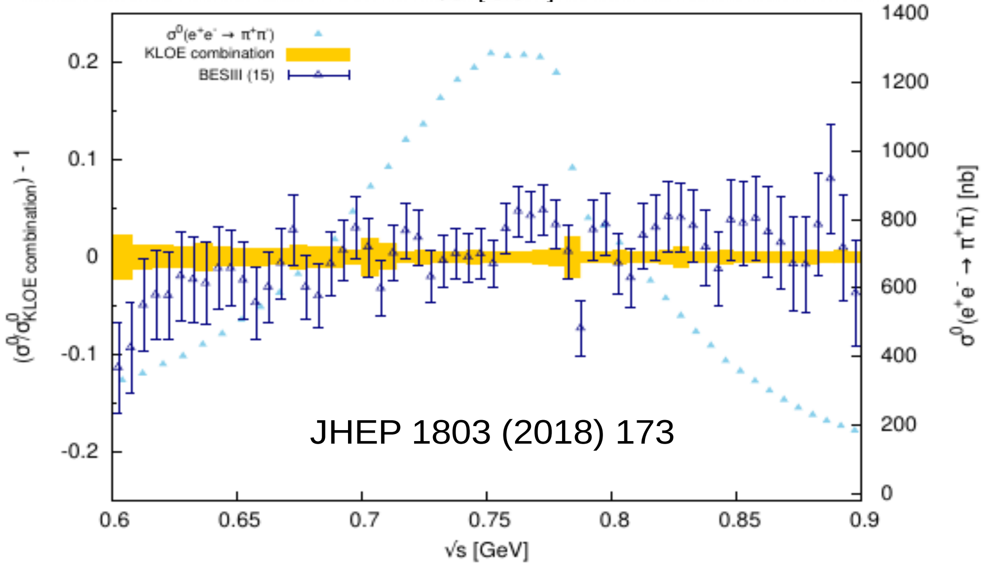
C. Redmer for BES III (PPHI, P3)

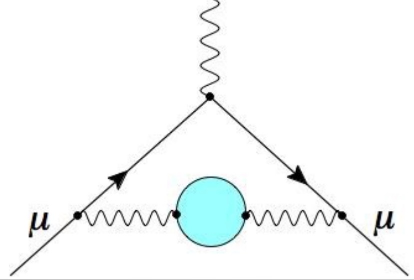
- evaluation for $0.6 \leq m_{\pi\pi} \leq 0.9$
  - 70% of total 2π contribution
  - 50% of a_μ^{hVP} contribution











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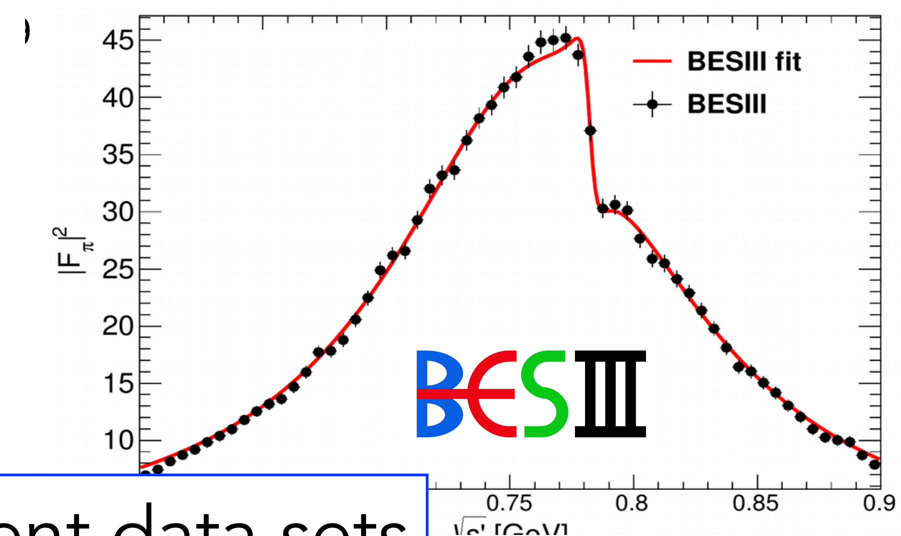
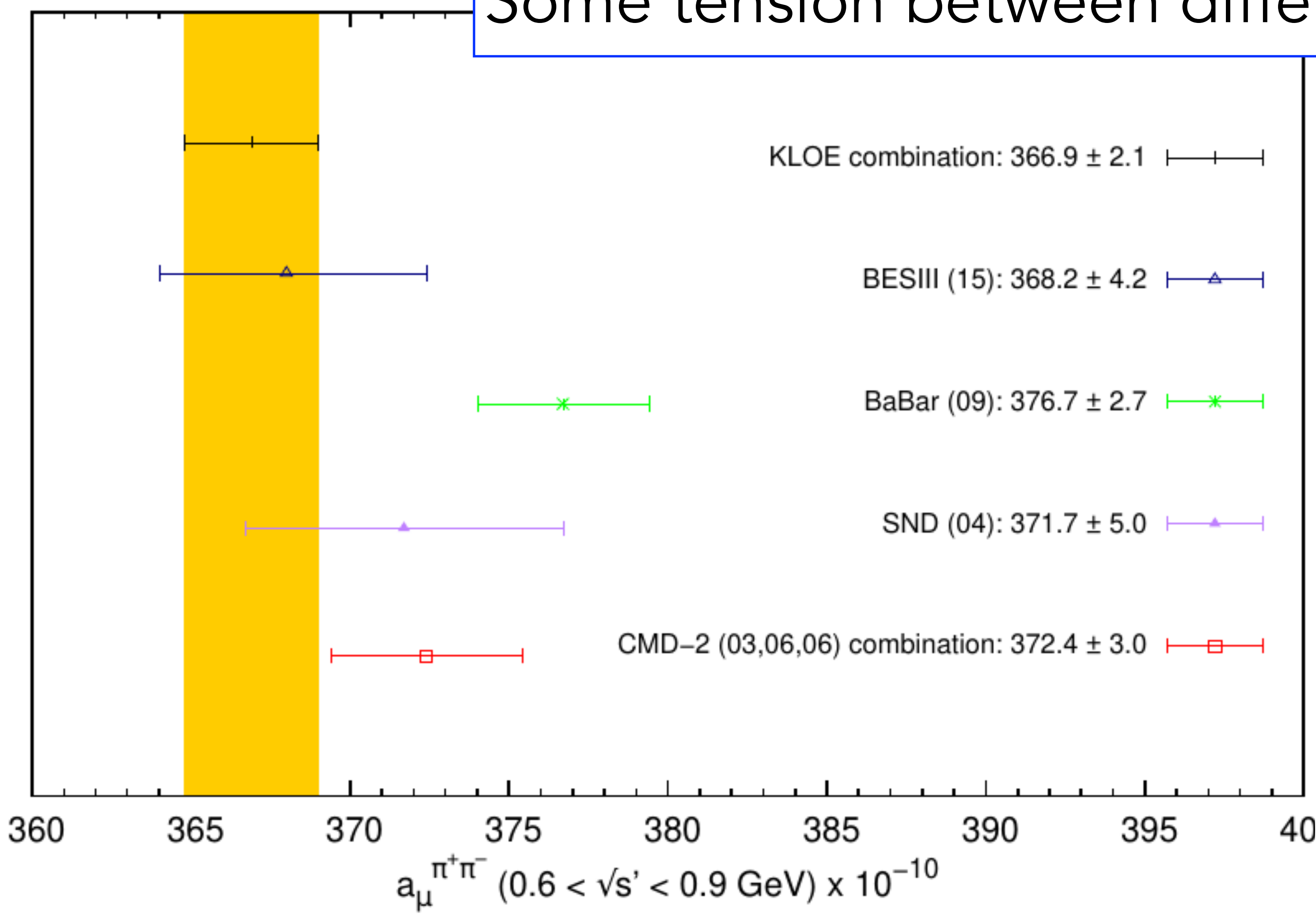
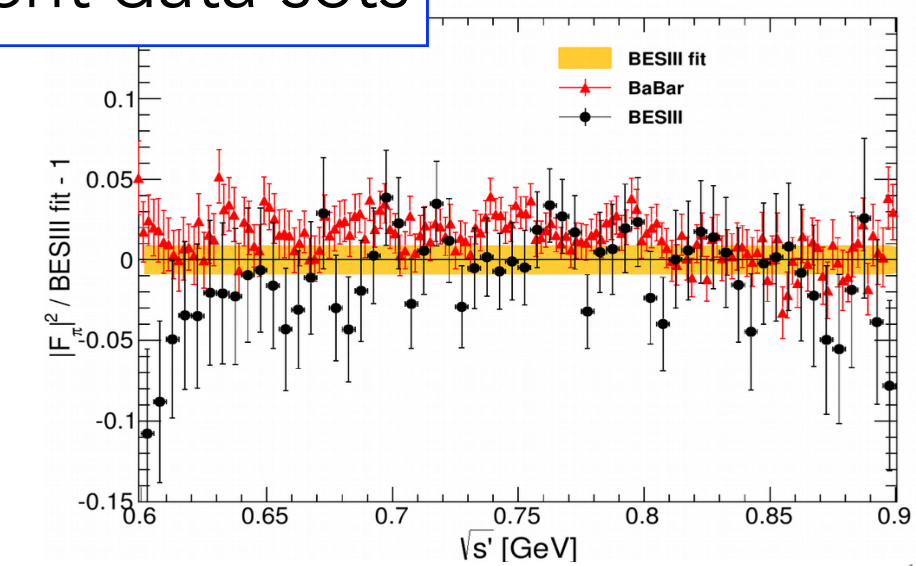
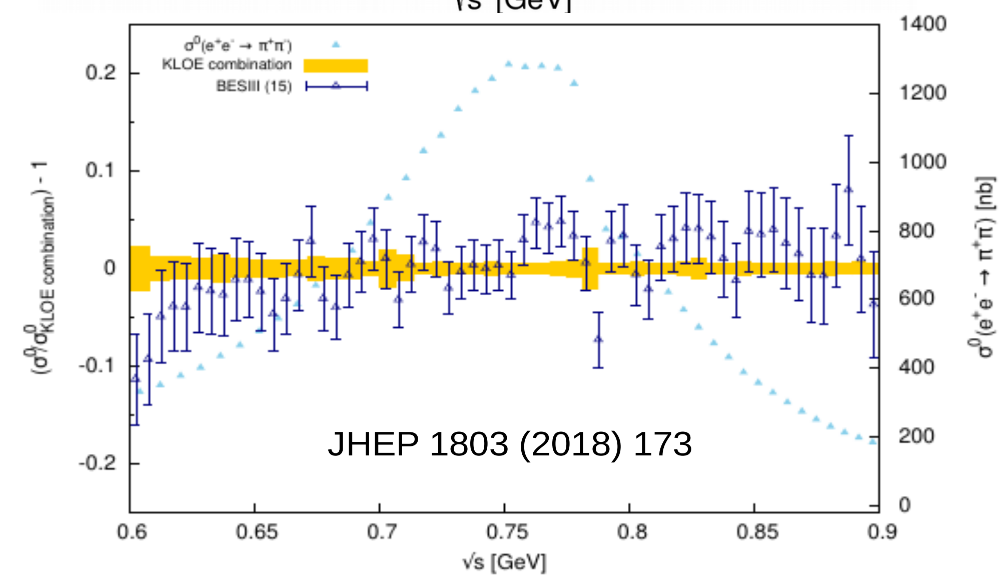
- evaluation for $0.6 \leq m_{\pi\pi} \leq 0.9$
  - 70% of total 2π contribution
  - 50% of a_μ^{hVP} contribution

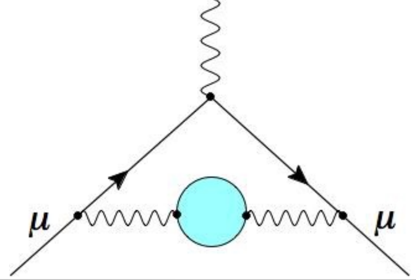


Some tension between different data sets





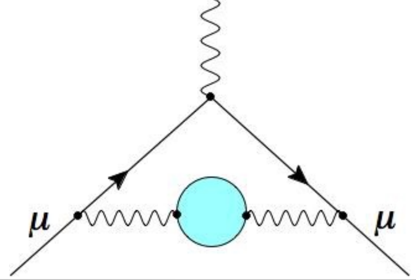




Hadronic vacuum polarization

C. Redmer for BES III (PPHI, P3)

- Hadronic cross section measurements at BESIII
  - Scan, tagged and untagged ISR methods
  - Competitive accuracy
  - $\pi^+\pi^-$result confirms $a_\mu^{\text{theo,SM}} - a_\mu^{\text{exp}} > 3\sigma$
  - Preliminary results on $e^+e^- \to \pi^+\pi^-\pi^0$, $e^+e^- \to \pi^+\pi^-\pi^0\pi^0$and $e^+e^- \to \pi^+\pi^-3\pi^0$
  - Measurement of R value ongoing, 3% accuracy targeted
  - Pion form factor to be evaluated in additional mass regions from ISR and scan data
  - Additional exclusive final states in preparation



Hadronic vacuum polarization

Leading order HVP correction: $$a_\mu^{\text{HVP,LO}} = \left(\frac{\alpha}{\pi}\right)^2 \int dq^2 \omega(q^2)\, \hat{\Pi}(q^2)$$

- Calculate a_μ^{HVP} in Lattice QCD:
  - Calculate $\hat{\Pi}(q^2)$ and evaluate the integral (Blum,PRL 03, Lautrup et al, 71)
  - Time-momentum representation: reorder the integrations and compute $C(t) = \frac{1}{3}\sum_{i,x}\langle j_i(x,t) j_i(0,0)\rangle$

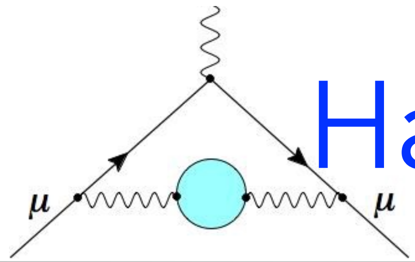
$$a_\mu^{\text{HVP}} = \left(\frac{\alpha}{\pi}\right)^2 \int dt\, \tilde{\omega}(t)\, C(t)$$

(Bernecker & Meyer, EPJ 12)

  - Time-moments: Taylor expand $\hat{\Pi}(q^2) = \sum_k q^{2k}\Pi_k$ (Chakraborty et al, PRD 14)

    and compute Taylor coefficients from time moments:

$$C_{2n} = a\sum_t t^{2n} C(t)$$

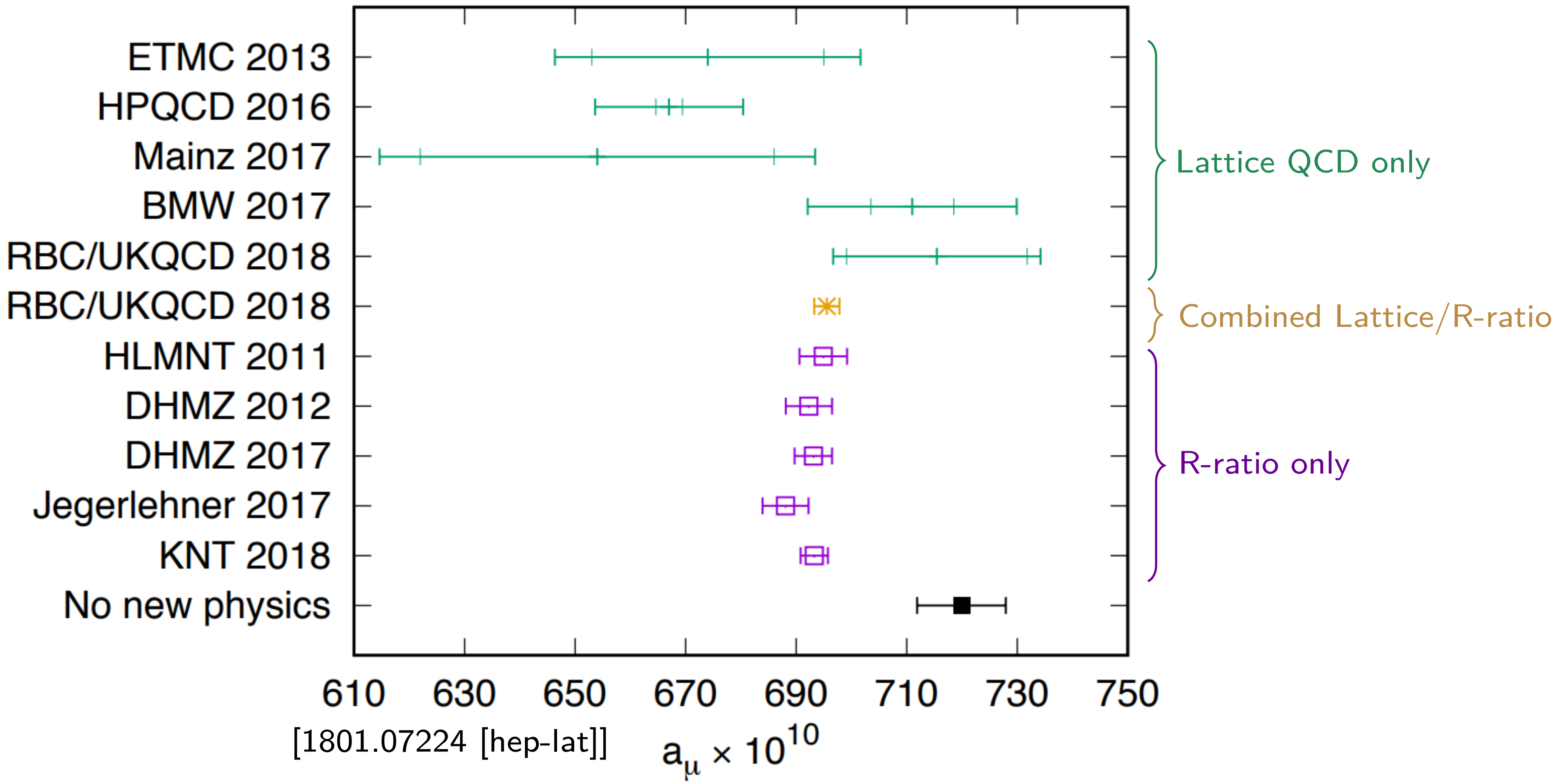


Hadronic vacuum polarization

- ✦ Target: ~0.2% total error
- ✦ Complete lattice QCD results by several groups.
  A complete LQCD result …
  - is based on physical mass ensembles
  - includes disconnected contributions
  - includes QED and strong isospin breaking corrections ($m_u \neq m_d$)
  - includes finite volume corrections, continuum extrapolation
- ✦ current uncertainties at ~2% level
  - Statistical errors grow at large Euclidean times
  - noise reduction methods
  - include two-pion channels into analysis

Summary of recent HVP results

A. Meyer for RBC/UKQCD (PPHI, P3)



[1801.07224 [hep-lat]]

Summary of recent HVP results

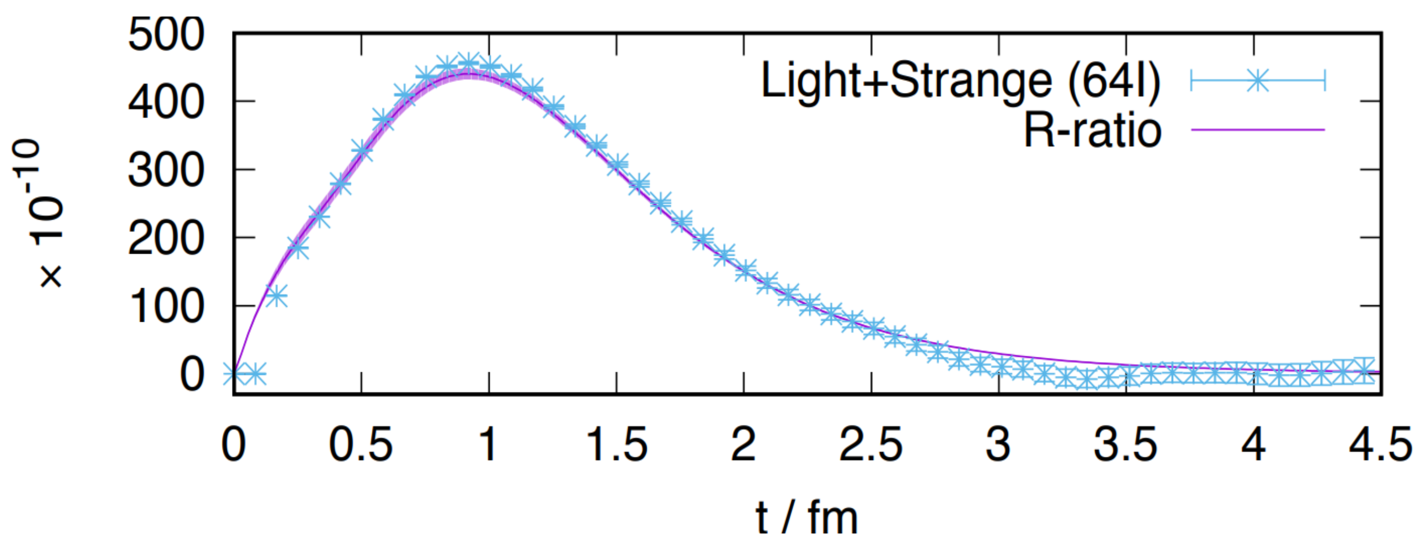
A. Meyer for RBC/UKQCD (PPHI, P3)

Lattice calculations are less precise than R-ratio at present

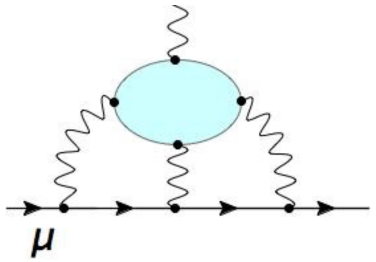
Lattice QCD/R-ratio are precise in complementary regions
$\Longrightarrow$ Combined Lattice/R-ratio for most precise estimate of HVP

Can improve lattice-only estimate of HVP by controlling statistical noise in long-distance correlation function

Goal for 2018/19 is reduce total uncertainty in lattice only calculations to ~1% level



A lot of activity, ongoing work by RBC/UKQCD, FNAL/MILC/HPQCD, ETM, Mainz, …



Hadronic Light-by-light

Hadronic light-by-light:

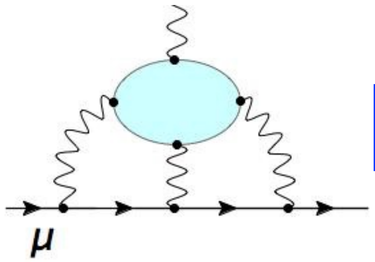
- Target: $\lesssim$ 10% fully quantified uncertainty
- current estimate “Glasgow consensus” based on models of QCD:
  ➠ theory error not quantified and not improvable

Dispersive approach:

- significantly more complicated than for HVP
  (talk by M. Vanderhaegen, PPHI P3)
- Data driven: need exp. data inputs, or LQCD inputs
- New idea: Schwinger sum rules (using analyticity, unitarity)
  (talk by V. Pascalutsa, PPHI P3)

Direct lattice QCD calculations:

- QCD + QED_L (finite volume)
  (Jin et al, arXiv:1610.04603, 2016 PRL; arXiv:1705.01067)
- QCD + QED (infinite volume & continuum)
  (Asmussen @Lattice 2017; Green et al, arXiv:PRL 2015; T. Blum et al, arXiv:1705.01067, 2017 PRD)
- dominant contribution from pion pole (transition form factors)
  (Gerardin et al, arXiv:1607.08174, 2016 PRD; Lattice 2017)



Hadronic Light-by-light: lattice QCD

Breakthrough (RBC/UKQCD):

First LQCD calculation of connected and leading disconnected contribution with good statistical significance (T. Blum et al, arXiv:1610.04603, 2017 PRL).

$$a_\mu^{\mathrm{HLbL}} = (5.35 \pm 1.35) \times 10^{-10}$$

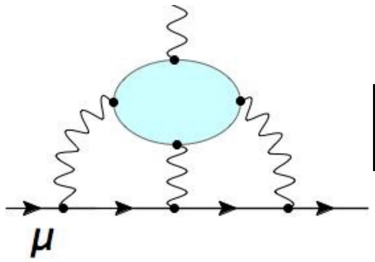
- a = 0.11 fm, L = 5.5 fm, physical pion mass, statistical error only.
- uses QCD + QED_L (finite volume)
- systematic error analysis (finite volume, continuum limit, …) in progress.

Mainz group:

- LbL forward scattering amplitude (Gerardin @ HLbL UConn 2018)
- pion transition form factor (Gerardin et al, arXiv:1607.08174, 2016 PRD; Lattice 2017)
  ➠ pion pole contribution: $$a_\mu^{\mathrm{HLbL},\pi-\mathrm{pole}} = 6.50(83) \cdot 10^{-10}$$

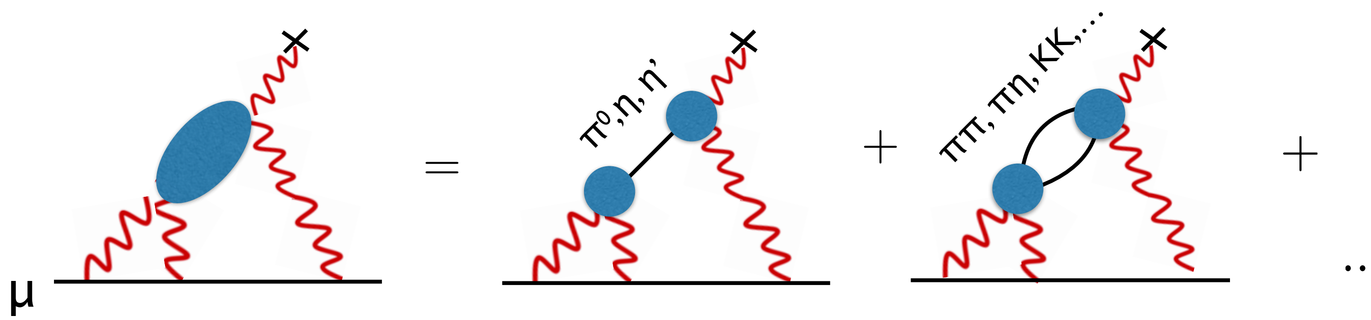
QCD + QED (infinite volume):

- RBC/UKQCD: in progress (can reuse QCD part from QCD+QED_L calculation)
- Mainz group: in progress (Asmussen @ Lattice 2017, HLbL UConn 2018)



Hadronic Light-by-light: disp. methods

M. Vanderhaegen (PPHI, P3):



- Pion pole contribution:
  Proof of principle calculation (Pauk, Vanderhaegen, 2014)

  Hoferichter et al (arXiv:1805.01471): $a_\mu^{\mathrm{HLbL},\pi-\mathrm{pole}} = 62.6(30) \cdot 10^{-11}$

Improvements: include multi-meson channels in a data-driven / dispersive approach

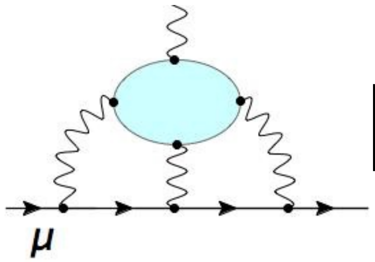
Coupled-channel dispersive treatment of $f_0(980)$ and $a_0(980)$ is **crucial**

$f_2(1270)$ described dispersively through Omnes function

$a_2(1320)$ described as a Breit Wigner resonance

$\pi^0\eta$: Danilkin, Deineka, Vdh (2017)

$\pi\pi$: Danilkin, Vdh (in progress)



Hadronic Light-by-light: disp. methods

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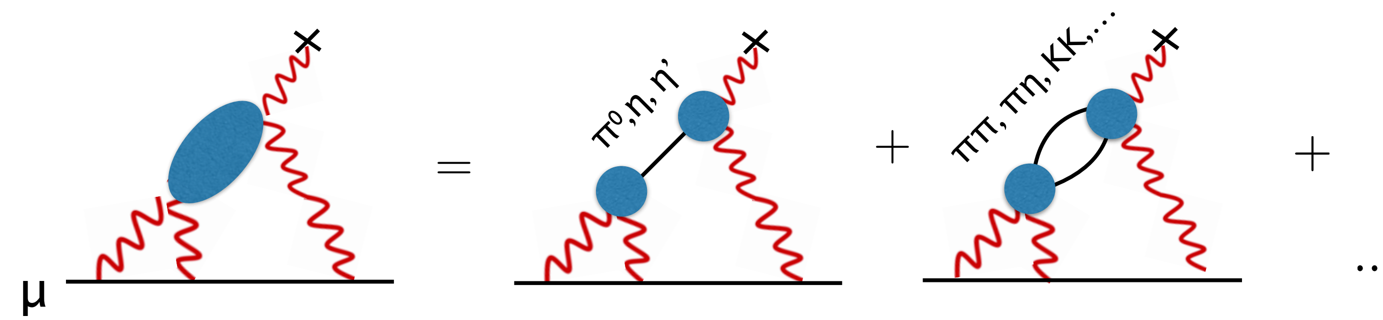

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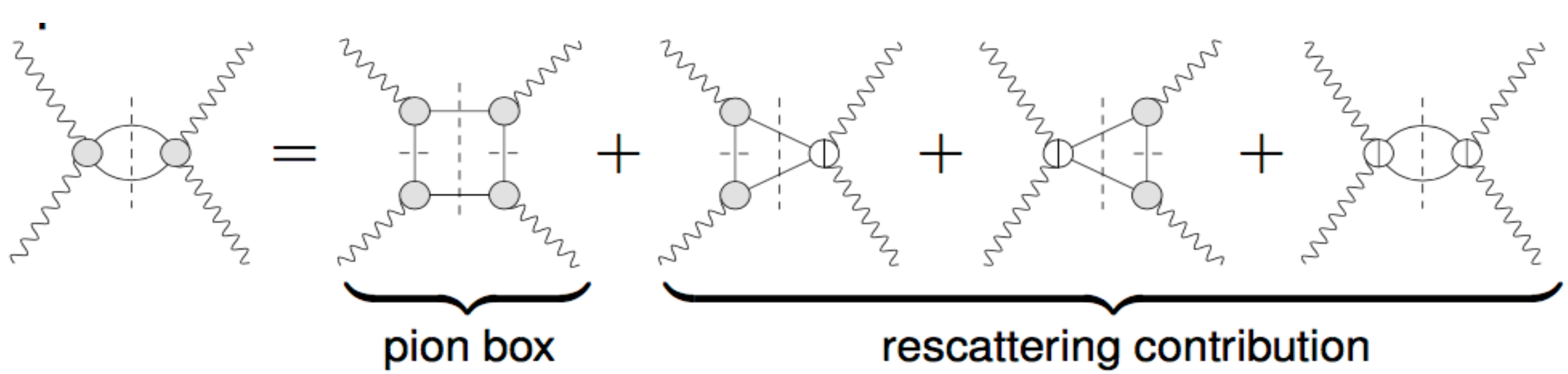
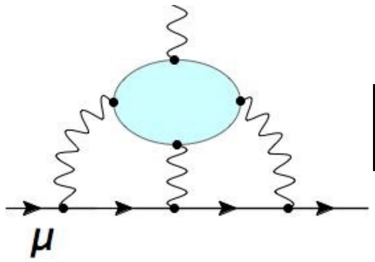
Improvements: include multi-meson channels in a data-driven / dispersive approach

pioneering dispersive analyses for ππ loop contribution to a_μ

Colangelo, Hoferichter, Procura, Stoffer (2014,2015, 2017)



$a_\mu^{\pi\text{-box}} = (-1.59 \pm 0.02) \times 10^{-10}$ $a_\mu^{\text{s-wave } \pi\pi} = (-0.8 \pm 0.1) \times 10^{-10}$



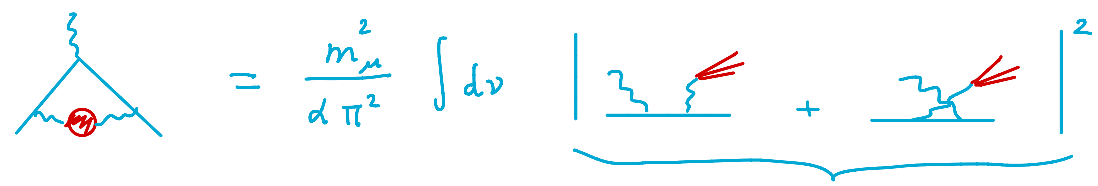
Hadronic Light-by-light: disp. methods

V. Pascalutsa (PPHI, P3):

(Hagelstein, Pascalutsa (2018 PRL))

1. Schwinger sum rule — dispersive formula applying equally to HVP and HLbL

2. Reproduces $\alpha/2\pi$ and HVP formula:



$$a_\mu^{HVP} = \frac{m_\mu^2}{\alpha\,\pi^2}\int d\nu \int dM_X^2\; \sigma_{LT}(\gamma\mu \to \gamma_X^*\mu)\;\Gamma(\gamma_X^* \to \text{hadrons})$$

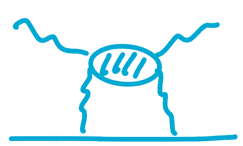
3. Splits contributions into hadron production and e.m. (LbL) channels

$\gamma\mu \to \mu + \text{hadrons}$

measurable

spin structure functions

$\gamma\mu \to \gamma\mu$



LQCD ?

$\gamma\mu \to \gamma\gamma\mu$

direct LbL scattering (ATLAS)

4. Partial calculation of pi0 contribution is a factor of 2 larger than the conventional model calculations.

to be continued…

Summary

- ⭐ New limits on heavy neutrinos, dark photons
- ⭐ New precise measurement of fine structure
- ⭐ Fermilab g-2 experiment is on track to present muon g-2 measurement at the 140 ppb level by CIPANP 2021
- ⭐ Efforts to improve SM theory predictions are on track
  - ➢ New measurements by BaBar, KLOE, BESIII, …
  - ➢ Rapid progress in lattice QCD calculations (HVP + HLbL)
  - ➢ Development of dispersive methods for HLbL, new ideas
- ⭐ Picture will be very different at CIPANP 2021

Appendix

SM theory error budget for muon g-2

SM contribution	10^{11} × (value ± error)		Refs and notes
QED (5 loops)	116584718.951	± 0.080	[Ayoma et al, 2012, Laporta'17]
EW (2 loops)	153.6	± 1.0	[Gnendiger et al, 2013]
HVP (LO)	6923	± 42	[DHMZ'11, see also HLMNT'11,JS'11,...]
HVP (NLO)	-98.4	± 1.0	[Hagiwara et al, 2011]
HVP (NNLO)	12.4	± 0.1	[Kurz et al, 2014]
HLbL	105	± 26	[Prades et al, 2014]``Glasgow consensus"
HLbL (NLO)	3	± 2	[Colangelo et al, 2014]
Total	116591803	± 49	[Davier et al, 2011]
Experiment	116592089	± 63	[Bennet at al, 2006]
Diff (Exp. - SM):	286	± 80	

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EW (2 loops)	153.6	± 1.0	[Gnendiger et al, 2013]
HVP (LO)	6923	± 42	→ ± (25-34) [KNT18, DHMZ'17]
HVP (NLO)	-98.4	± 1.0	[Hagiwara et al, 2011]
HVP (NNLO)	12.4	± 0.1	[Kurz et al, 2014]
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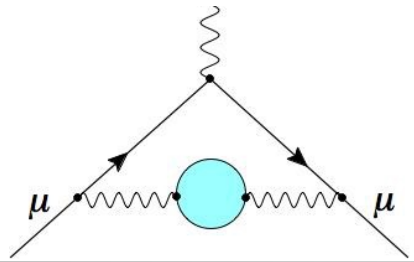
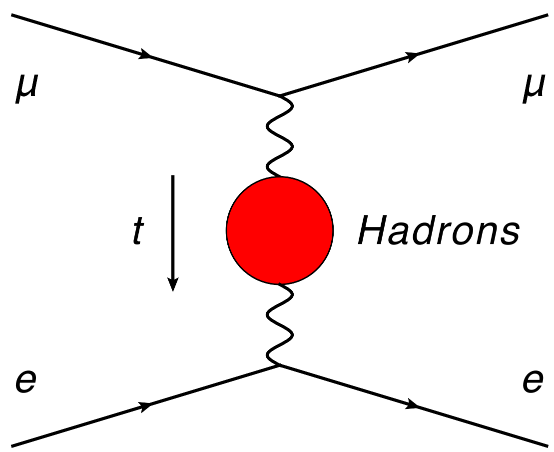
The difference is large: ~ 2 × (EW contribution



Hadronic vacuum polarization

μ-e elastic scattering to measure

M. Passera @ HVP KEK 2018 (A. Abbiendi et al, arXiv:1609.08987, EPJC 2017)

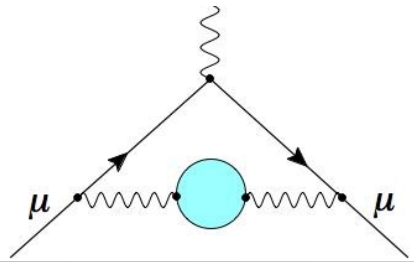


$$a_\mu^{\rm HLO} = \frac{\alpha}{\pi}\int_0^1 dx\,(1-x)\,\Delta\alpha_{\rm had}[t(x)]$$

$$t(x) = \frac{x^2 m_\mu^2}{x-1} < 0$$

$\Delta\alpha_{had}(t)$ is the hadronic contribution to the running of α in the space-like region. It can be extracted from scattering data!

- use CERN M2 muon beam (150 GeV)
- test detector prototype in August 2018
- LOI planned for 2018-2019
- Physics beyond colliders program @ CERN

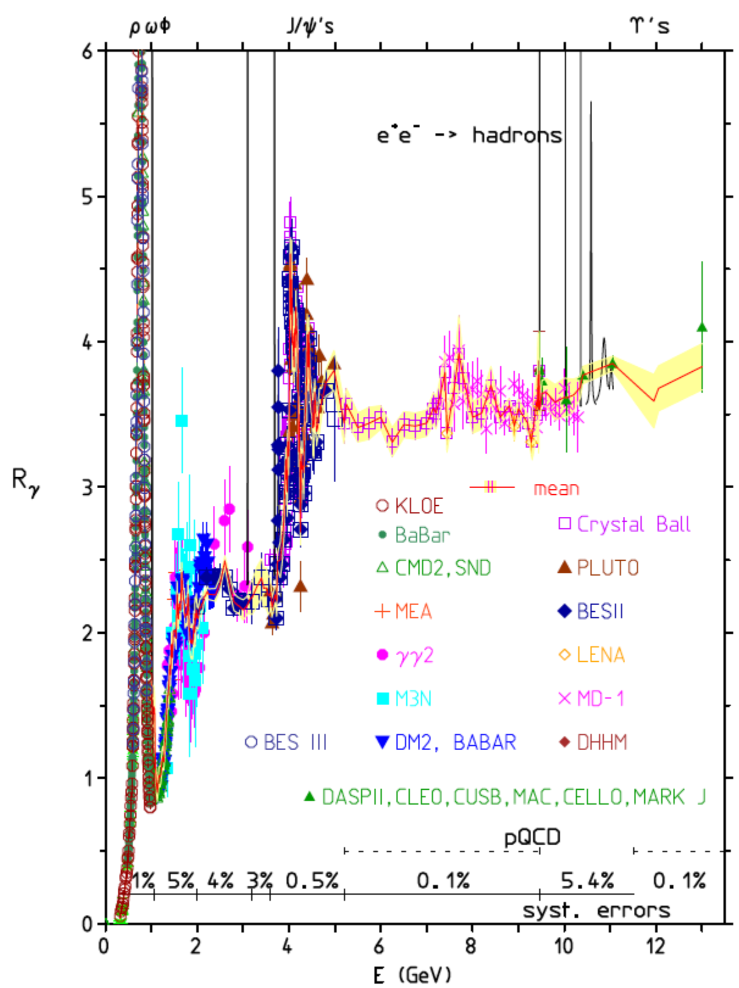


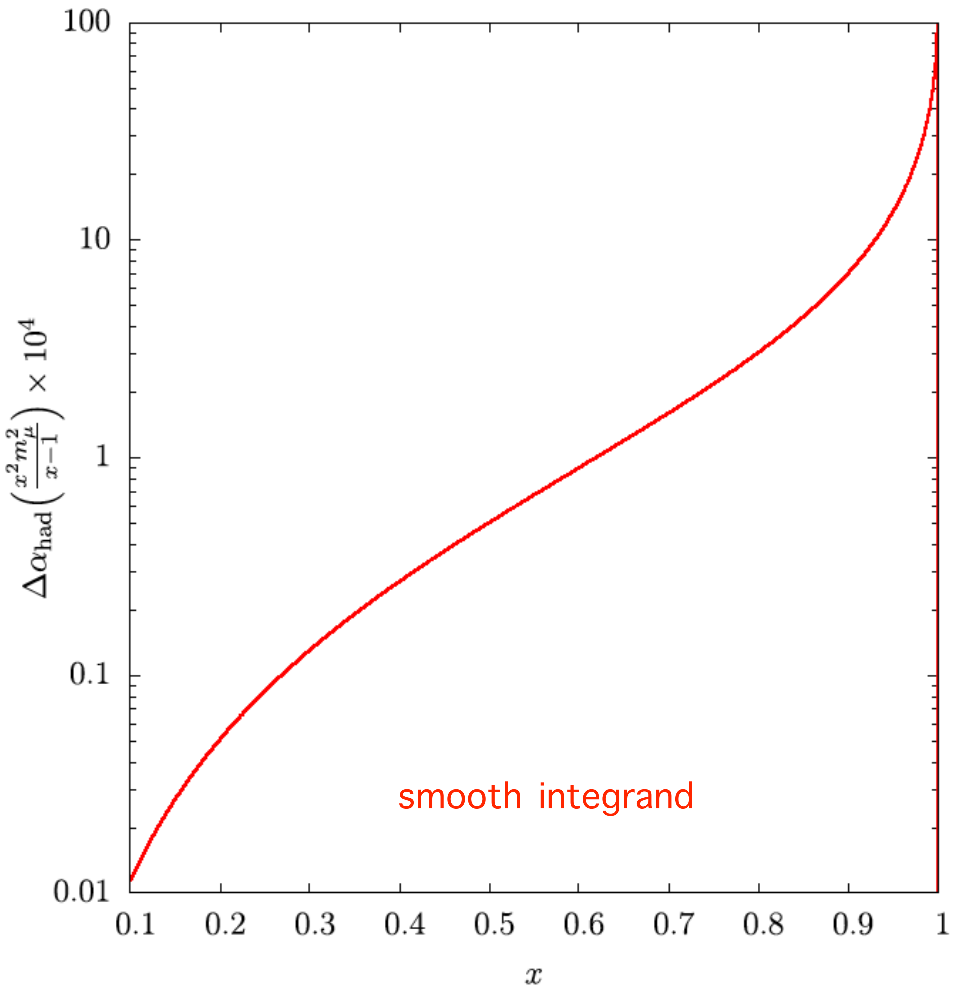
Hadronic vacuum polarization

μ-e elastic scattering to measure a_μ^{HVP}

M. Passera @ HVP KEK 2018 (A. Abbiendi et al, arXiv:1609.08987, EPJC 2017)

Time-like → **Space-like**





- complement region not accessible to experiment with LQCD calculation
- requires NNLO QED calculation, …