HVP Overview: The Status from the KEK workshop

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(University of Illinois and Fermilab)

Second Plenary Workshop of the Muon g-2 Theory Initiative, Helmholtz-Institut Mainz, 18-22 June 2018

Outline

- Introduction and Overview
- Experimental inputs
- Dispersive HVP
- Lattice HVP
- MUonE

First Workshop of the Muon g-2 Theory Initiative

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

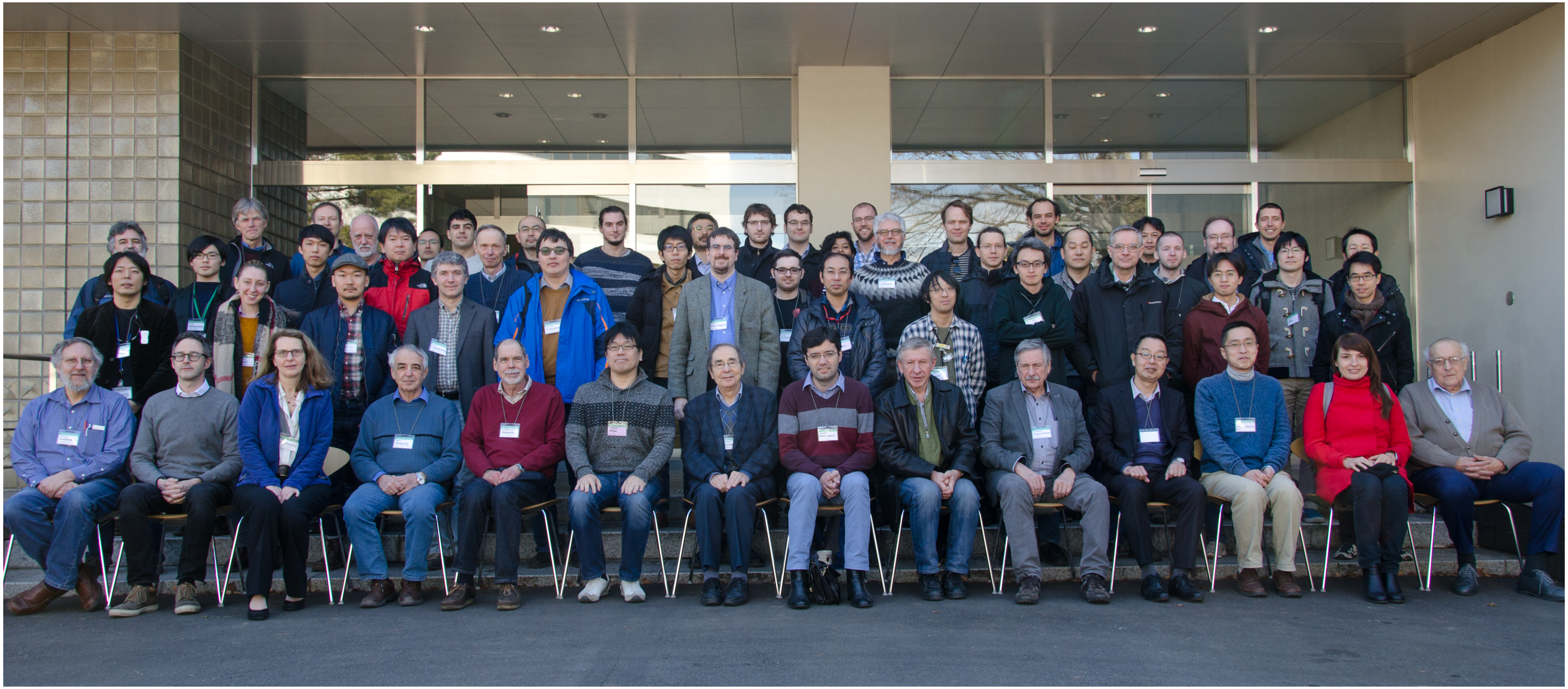
Search

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

Workshop on hadronic vacuum polarization contributions to muon g-2

February 12-14, 2018
KEK, Tsukuba, Japan

http://www-conf.kek.jp/muonHVPws/index.html



70 registered participants, 28 talks, 6 discussion sessions (330 minutes)

KEK workshop

28 talks + 6 discussion sessions

- joint session with KEK-PH meeting:
  P. Urquijo for Belle II (overview), S. Ganguly for Fermilab E989, T. Yamazaki for J-PARC E-34, H. Davoudiasl on BSM and g-2.
- Inputs from e+e- experiments:
  Y. Maeda for Belle II, M. Davier for BaBar, C. Redmer for BESIII, S. Serednyakov for SND, I. Logashenko for CMD-3, K. Todyshev for KEDR, S. Müller for KLOE, H. Czyż on MC generators
- dispersive HVP:
  F. Jegerlehner, B. Malaescu for DHMZ, A. Keshavarzi for KNT, M. Benayoun on HLS model, M. Hoferichter (disp. constraints on pion vector form factor)
- Lattice HVP:
  C. Lehner+A. Meyer+M. Bruno for RBC/UKQCD, G. von Hippel for Mainz, L. Lellouch +K.Miura for BMW, R. Van de Water for FNAL/MILC/HPQCD, E. Shintani for PACS
- misc theory and new ideas:
  M. Nio on QED corrections (8th and 10th order), J. Bijnens (analytic results), M. Passera on MUonE, M. Marinkovic on Lattice for MUonE.

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S. Eidelman (review+outlook), E. Solodov (Novosibirsk), M. Davier (tensions), S. Tracz + H. Czyż on radiative corrections and MC generators

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  updates from RBC/UKQCD, Mainz, FNAL/MILC/HPQCD, BMW, ETM + discussions on long distance effects, FV effects, QED+SIB, comparisons and cross checks

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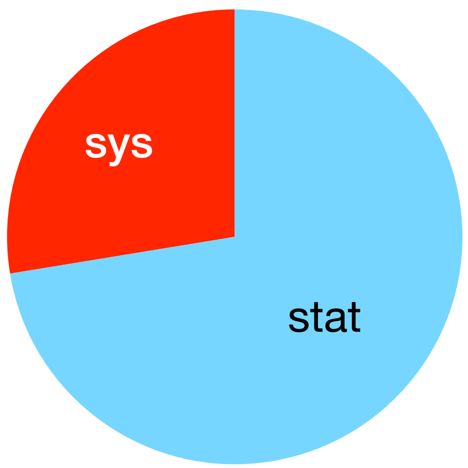
- misc theory and new ideas:

  analytical FV (A. Portelli), Hybrid approach (K. Schilcher), Mellin-Barnes (E. de Rafael), tau decays (M. Bruno), MUonE (C. Carloni, M. Marinkovic)

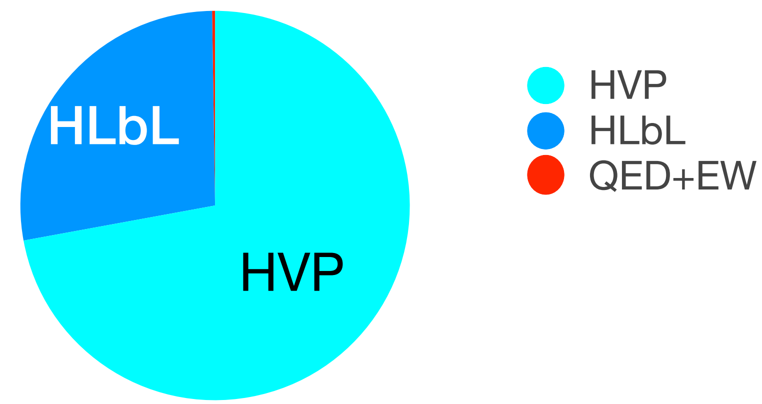
Introduction

Error budget comparison

BNL E821

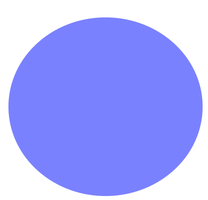


SM theory



coordinated effort

FNAL E989



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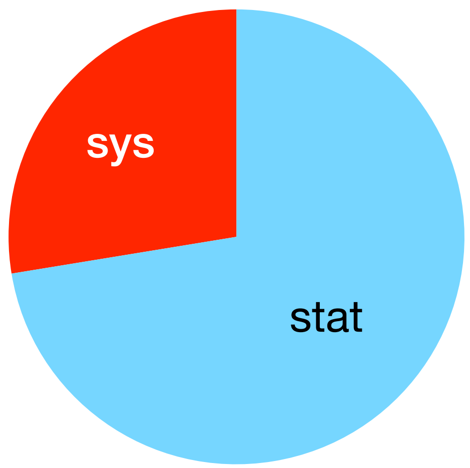

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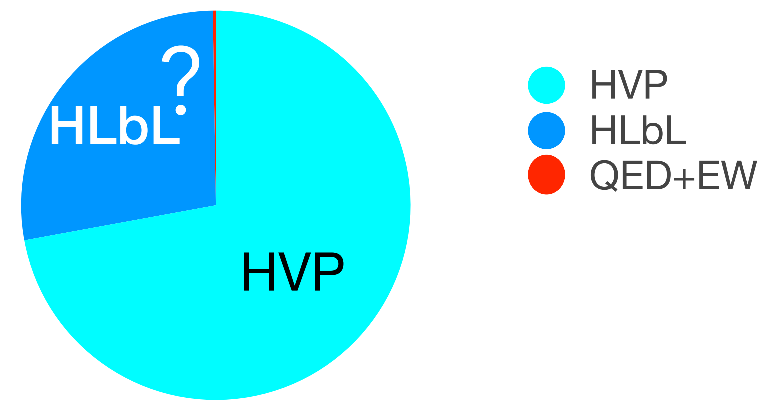

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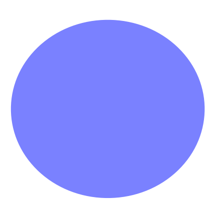
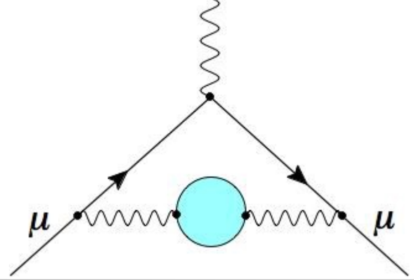
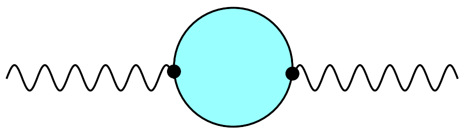




Hadronic vacuum polarization



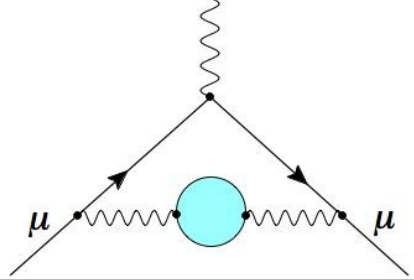
$$\hat{\Pi}(q^2) = \Pi(q^2) - \Pi(0)$$

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

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:

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



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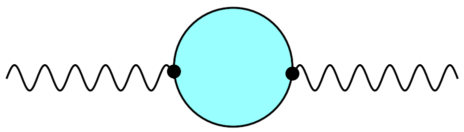

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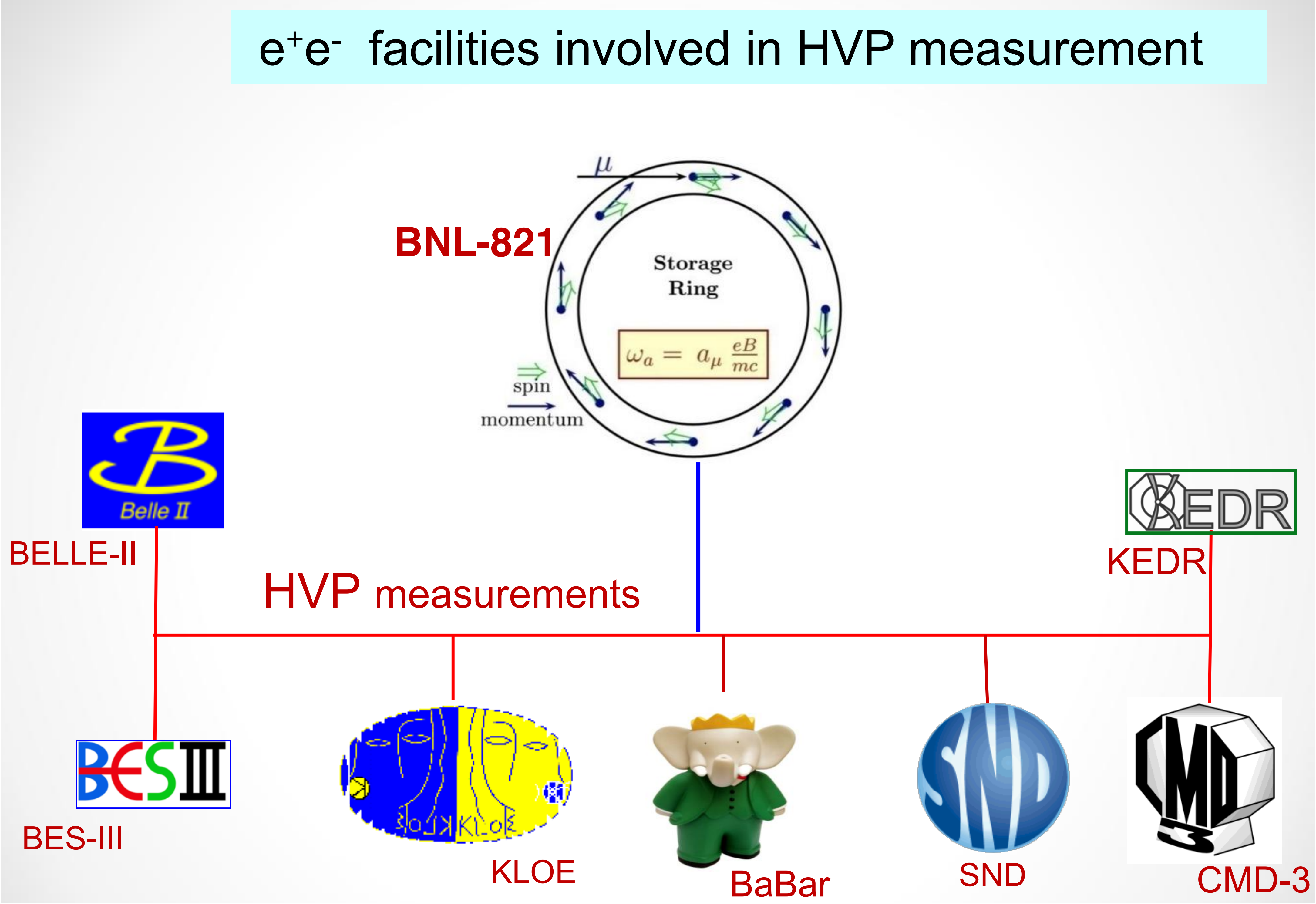
Dominant contributions from low energies

$\pi^+\pi^-$ channel: 73% of total $a_\mu^{\mathrm{HVP,LO}}$

Experimental Inputs

S. Serednyakov (for SND) @ HVP KEK workshop



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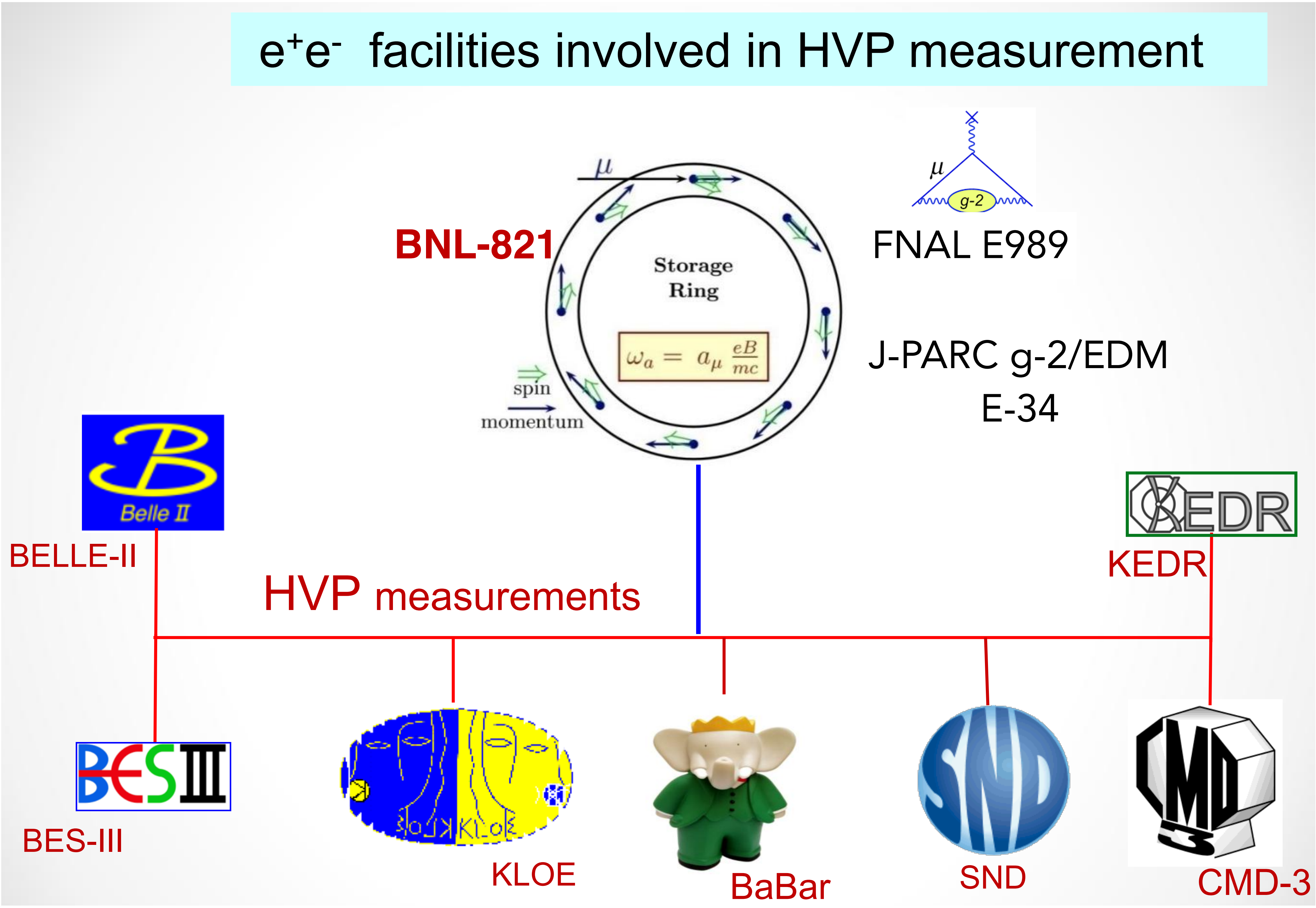

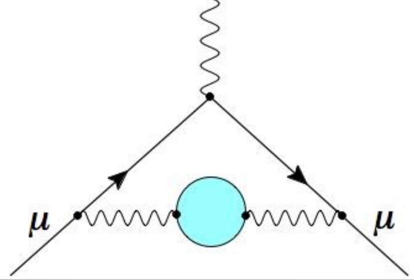

Hadronic vacuum polarization

- ✦ 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, KEDR, 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, Y,..)
  - Combine data from different experiments/measurements:
    understanding correlations, sources of sys. error, tensions…
  - include FS radiative corrections

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Experimental Inputs

Y. Maeda (for Belle II) @ HVP KEK workshop

- Belle II plans to analyze $\pi\pi$ channel using ISR data
- MC studies of trigger efficiency and backgrounds

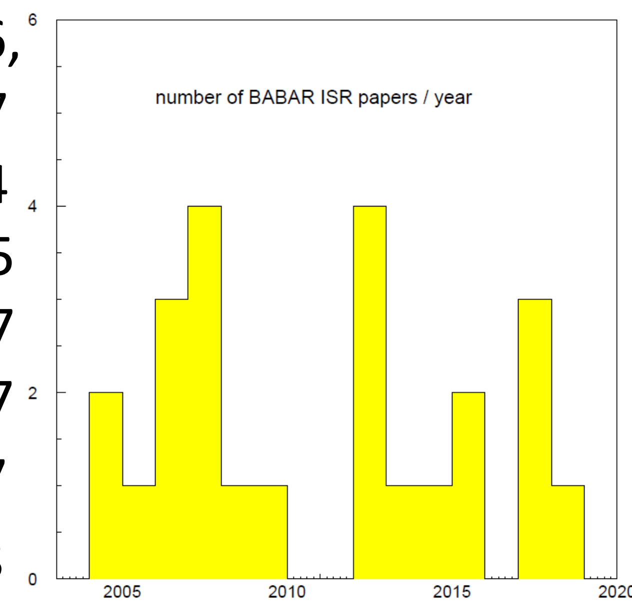
- Several simulation studies are performed for the ee→$\pi\pi\gamma$ mode, which shows
  - 100% L1 trigger efficiency for events with large angle ISR
  - BG level is found to be competitive to BaBar analysis with tentative event selection and PID
- further studies
  - selection optimization
  - effect of beam background

Experimental Inputs

M. Davier (for BaBar) @ HVP KEK workshop

almost complete set of exclusive hadronic e^+e^- annihilation channels up to 2 GeV

$\pi^+\pi^-$	PRL 2009; PRD 2012
$K^+ K^-$	PRD 2013
$\pi^+\pi^-\pi^0$	PRD 2004
$2(\pi^+\pi^-)$, $K^+K^-\pi^+\pi^-$, $K^+K^- 2\pi^0$, $2(K^+K^-)$	PRD 2007; PRD 2012; PRD 2012
$K^0_S K^{+-}\pi^{-+}$, $K^+K^-\pi^0$, $K^+K^-\eta$	PRD 2005; PRD 2008
$2(\pi^+\pi^-)\pi^0$, $2(\pi^+\pi^-)\eta$, $K^+K^-\pi^+\pi^-\pi^0$, $K^+K^-\pi^+\pi^-\eta$	PRD 2007
$3(\pi^+\pi^-)$, $2(\pi^+\pi^-\pi^0)$, $2(\pi^+\pi^-) K^+K^-$	PRD 2006
$\Phi\ f^0(980)$	PRD 2006; PRD 2007
$p\bar{p}$	PRD 2006,
$\Lambda\bar{\Lambda}$, $\Lambda\bar{\Sigma}^0$, $\Sigma^0\bar{\Sigma}^0$	PRD 2007
$K^0_S K^0_L$, $K^0_S K^0_L \pi^+\pi^-$, $K^0_S K^0_S \pi^+\pi^-$	PRD 2014
K^+K^- large Q^2	PRD 2015
$K^0_S K^{+-}\pi^{-+}\pi^0$, $K^0_S K^{+-}\pi^{-+}\eta$	PRD 2017
$K^0_S K^0_L \pi^0$, $K^0_S K^0_L \pi^0\pi^0$	PRD 2017
$\pi^+\pi^- 2\pi^0$	PRD 2017
$\eta\pi^+\pi^-$	PRD 2018
$J/\psi\ (\mu^+\mu^-)$	PRD 2004
$\pi^+\pi^-$, $\mu^+\mu^-$ LO ISR-FSR interference	PRD 2015



in progress: $\pi^+\pi^-$ new method + full data sample

not covered: $\pi^+\pi^- 3\pi^0$, $\pi^+\pi^- 4\pi^0$, $\pi^+\pi^-\pi^0$ below 1.05 GeV, ≥7 hadrons

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almost complete set of exclusive hadronic e^+e^- annihilation channels up to 2 GeV

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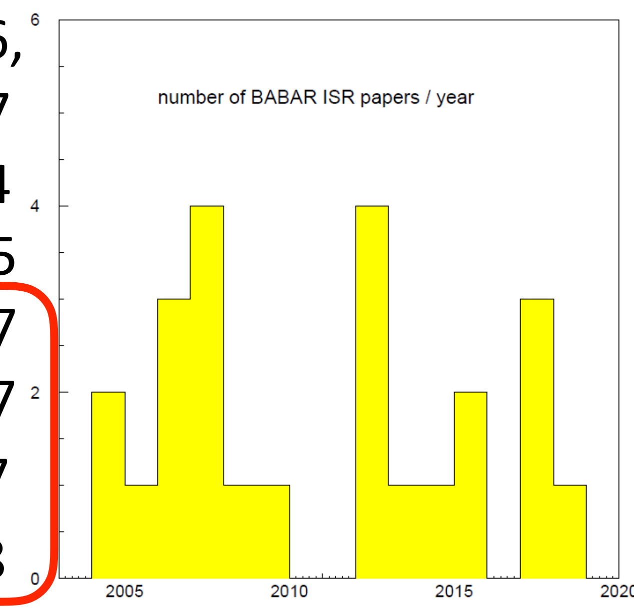


in progress: $\pi^+\pi^-$ new method + full data sample — by the end of 2018?

not covered: $\pi^+\pi^- 3\pi^0$, $\pi^+\pi^- 4\pi^0$, $\pi^+\pi^-\pi^0$ below 1.05 GeV, $\geq$7 hadrons

Experimental Inputs

C. Redmer (for BESIII) @ HVP KEK workshop

- Hadronic cross section measurements at BESIII
  - Scan, tagged and untagged ISR methods
  - Competitive accuracy
  - $\pi^+\pi^-$ result confirms $a_\mu^{\mathrm{theo,SM}} - a_\mu^{\mathrm{exp}} > 3\sigma$
  - 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

Experimental Inputs

S. Serednyakov (for SND) @ HVP KEK workshop

Conclusions

1. SND detector is taking data at the VEPP-2000 e^+e^- collider in the energy range 0.3-2.0 GeV. New data on e^+e^- cross section to hadrons are obtained :
   - ------ $e^+e^- \to \pi^+\pi^-\pi^0\eta$,
   - ------ $e^+e^- \to \omega\pi^0\eta$,
   - ------ $e^+e^- \to K^+K^-$,
   - ------ $e^+e^- \to \pi^0\gamma$
   - ------ $e^+e^- \to \eta K^+K^-$,
   - ------ $e^+e^- \to K_S K_L \pi^0$,
   - ------ $e^+e^- \to \eta\, \pi^+\pi^-$,

2. The $e^+e^- \to p\bar{p}+n\bar{n}$ step-like cross section does not lead to a step in the total cross section

3. The contribution of newly measured to the total hadronic cross section is estimated

Experimental Inputs

I. Logashenko (for CMD-3) @ HVP KEK workshop

At VEPP-2000 we do exclusive measurement of $\sigma(e^+e^- \to hadrons)$.

published
in progress

- 2 charged

$$e^+e^- \to \pi^+\pi^-, K^+K^-, K_S K_L, p\bar{p}$$

- 2 charged + γ's

$$e^+e^- \to \pi^+\pi^-\pi^0, \pi^+\pi^-\eta, K^+K^-\pi^0, K^+K^-\eta, K_S K_L \pi^0, \pi^+\pi^-\pi^0\eta,$$
$$\pi^+\pi^-\pi^0\pi^0, \pi^+\pi^-\pi^0\pi^0\pi^0, \pi^+\pi^-\pi^0\pi^0\pi^0\pi^0$$

- 4 charged

$$e^+e^- \to \pi^+\pi^-\pi^+\pi^-, K^+K^-\pi^+\pi^-, K_S K^*$$

- 4 charged + γ's

$$e^+e^- \to \pi^+\pi^-\pi^+\pi^-\pi^0, \pi^+\pi^-\eta, \pi^+\pi^-\omega, \pi^+\pi^-\pi^+\pi^-\pi^0\pi^0, K^+K^-\eta, K^+K^-\omega$$

- 6 charged

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

- γ's only

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

- other

$$e^+e^- \to n\bar{n}, \pi^0 e^+e^-, \eta e^+e^-$$

Experimental Inputs

I. Logashenko (for CMD-3) @ HVP KEK workshop

At VEPP-2000 we do exclusive measurement of $\sigma(e^+e^- \to hadrons)$.

published
in progress

- 2 charged

$$e^+e^- \to \pi^+\pi^-, K^+K^-, K_SK_L, p\bar{p}$$

- 2 charged + γ's

$$e^+e^- \to \pi^+\pi^-\pi^0, \pi^+\pi^-\eta, K^+K^-\pi^0, K^+K^-\eta, K_SK_L\pi^0, \pi^+\pi^-\pi^0\eta,$$
$$\pi^+\pi^-\pi^0\pi^0, \pi^+\pi^-\pi^0\pi^0\pi^0, \pi^+\pi^-\pi^0\pi^0\pi^0\pi^0$$

- In 2013-2016 the collider and the CMD-3 detector have been upgraded and the data taking was resumed in 2017 and about 65 1/pb were collected so far.
- Data analysis of exclusive modes of $e^+e^- \to hadrons$ is in progress. Many results have been published.

- other

$$e^+e^- \to n\bar{n}, \pi^0e^+e^-, \eta e^+e^-$$

Experimental Inputs

K. Todyshev (for KEDR)
@ HVP KEK workshop

- J/ψ results:

$$\Gamma_{ee}(J/\psi) = 5.550 \pm 0.056 \pm 0.089\,\text{keV}$$
$$\Gamma_{ee}(J/\psi) \times \mathcal{B}_{\text{hadrons}}(J/\psi) = 4.884 \pm 0.048 \pm 0.078\,\text{keV}$$
$$\Gamma_{ee}(J/\psi) \times \mathcal{B}_{\text{ee}}(J/\psi) = 0.3331 \pm 0.0066 \pm 0.0040\,\text{keV}$$

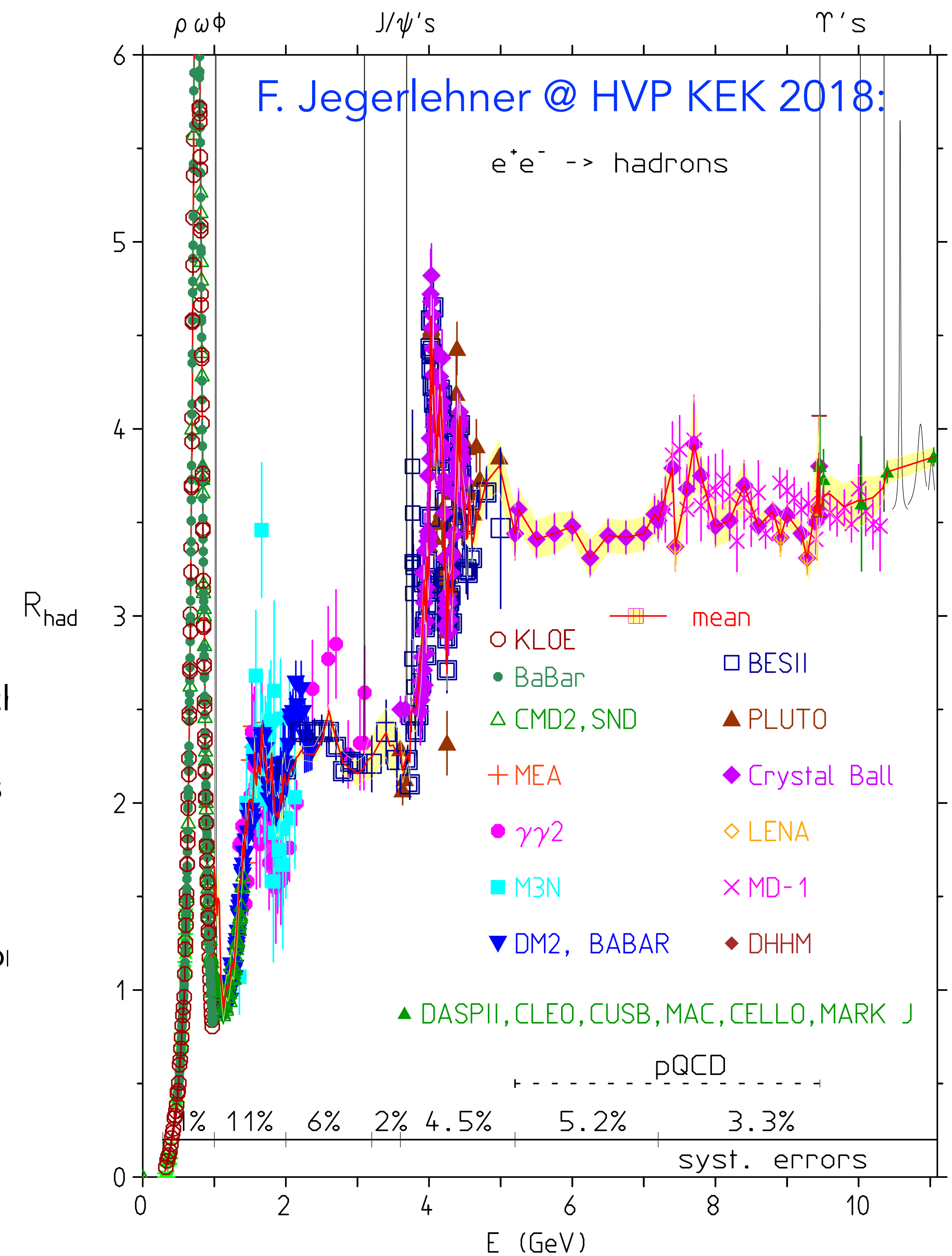
- $\psi(2S)$ results:

$$\Gamma_{ee} = 2.282 \pm 0.015 \pm 0.042\ \text{keV}$$
$$\Gamma_{ee} \times \Gamma_{\mu\mu}/\Gamma = 19.3 \pm 0.3 \pm 0.5\ \text{eV}$$

- We have determined the values of R at thirteen points of the center-of-mass energy between 1.84 and 3.05 GeV. The achieved accuracy is about or better than 3.9% at most of energy points witl a systematic uncertainty less than 2.4%.
- We measured the values of R at seven points of the center-of-mass energy between 3.12 and 3.72 GeV. The total achieved accuracy is about or better than 3.3% at most of energy points with a systematic uncertainty of about 2.1%.
- R measurement in the energy range 3.077 – 3.72 GeV after detectoı repair and upgrade: analysis in progress.

- We plan to measure R value in the energy range 5-7 GeV

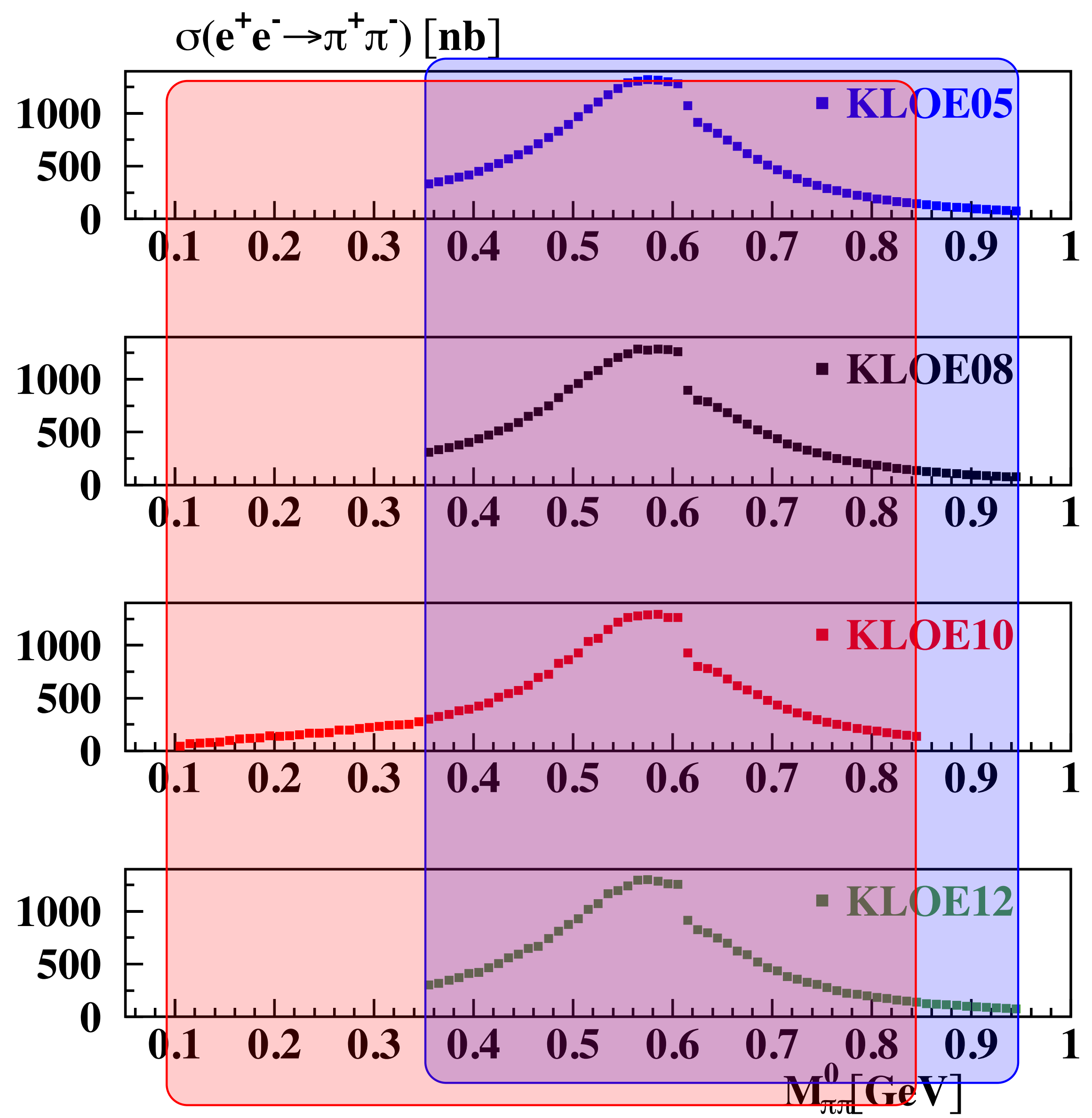
F. Jegerlehner @ HVP KEK 2018:



Experimental Inputs

S. Müller (for KLOE) @ HVP KEK workshop

The KLOE data sets



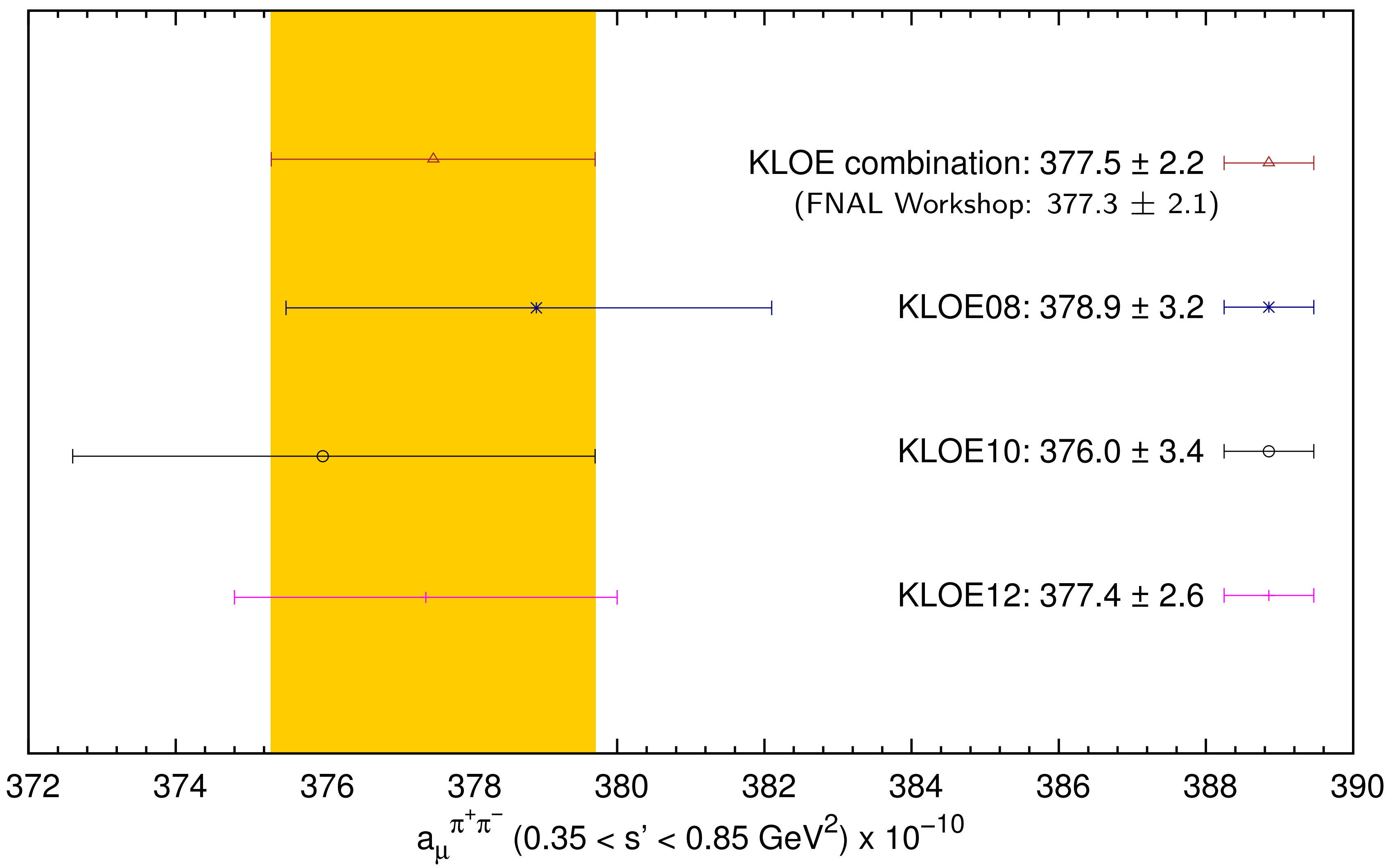
combined covariance matrices constructed for these data

Experimental Inputs

S. Müller (for KLOE) @ HVP KEK workshop

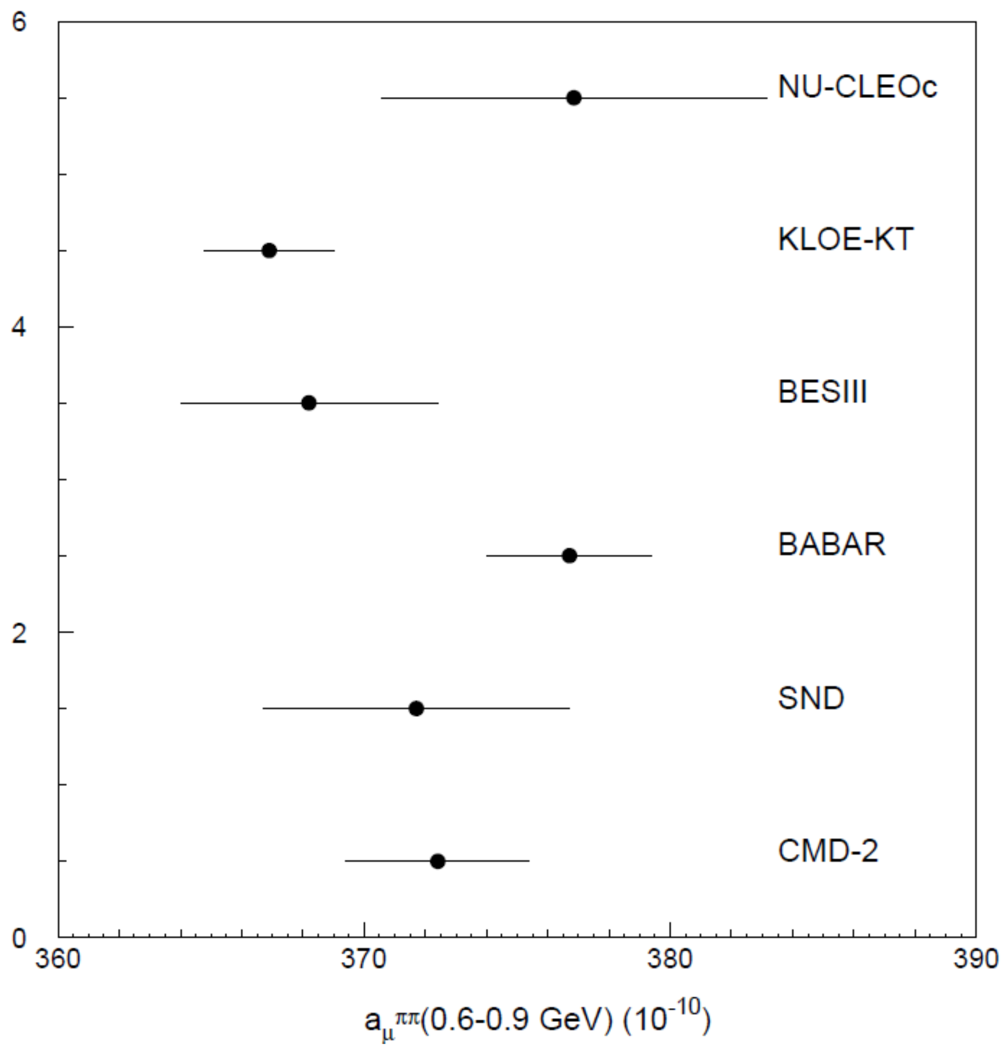
Combination of KLOE data sets

Estimates of $\Delta a_\mu^{\pi\pi}$ in the range $0.35 \leq s' \leq 0.85$ GeV^2 for the different KLOE analyses and the prel. combination:

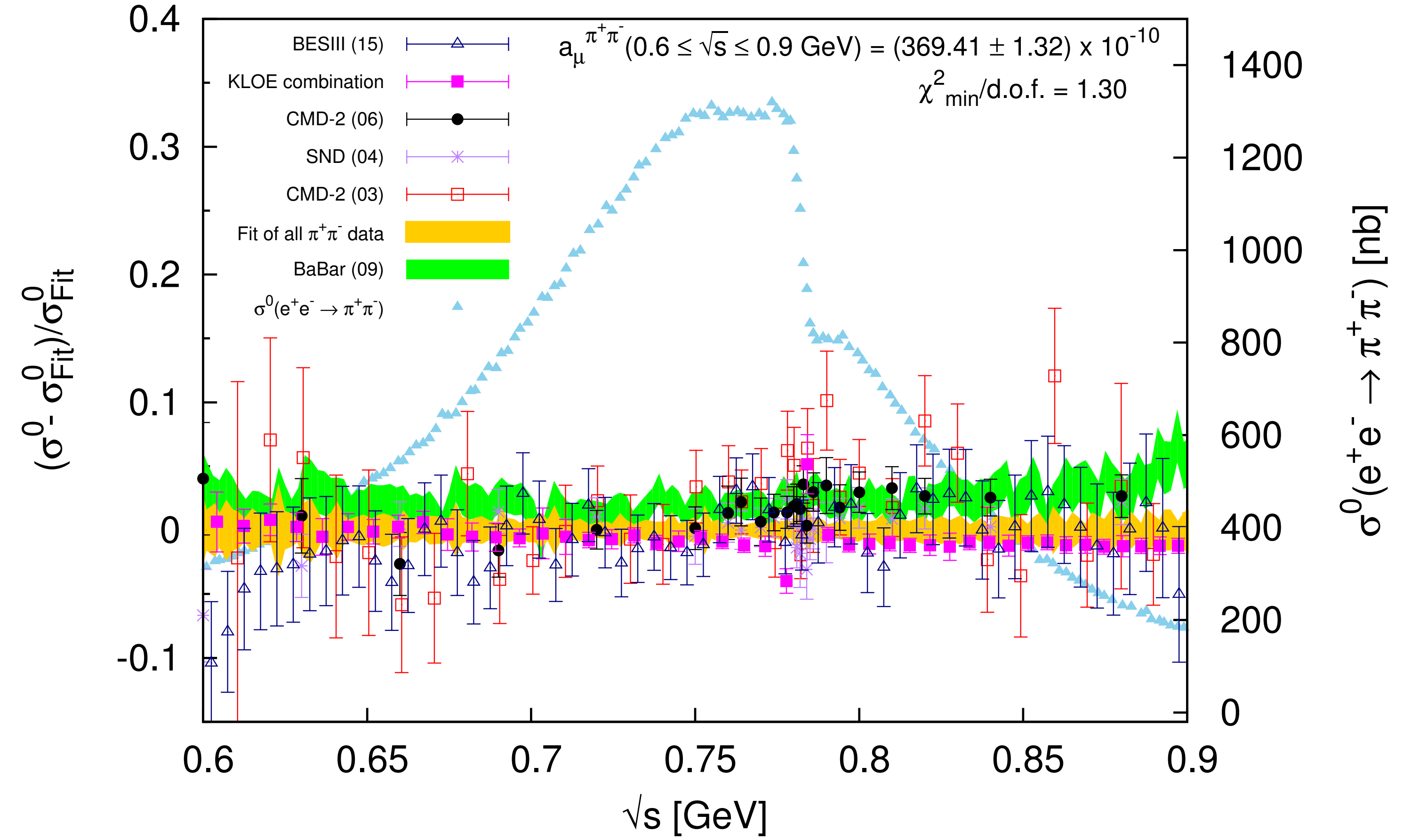


Experimental Inputs

M. Davier @ HVP KEK 2018



A. Keshavarzi @ HVP KEK 2018



Tension in $\pi\pi$ channel between different data sets

Experimental Inputs

H. Czyż @ HVP KEK 2018 workshop

$\Rightarrow$ PHOKHARA and EKHARA in brief

$\Rightarrow$ Recent developments in PHOKHARA and EKHARA

- $\Rightarrow$ χ_{c_i} production: PHOKHARA and EKHARA
- $\Rightarrow$ Models: $\mathcal{L}_{\gamma\gamma P}$, $\mathcal{L}_{\gamma V}$,$\mathcal{L}_{V\gamma P}$, $\mathcal{L}_{VVP}$
- $\Rightarrow$ PHOKHARA: $e^+e^- \to P\gamma(\gamma)$
- $\Rightarrow$ EKHARA: $e^+e^- \to e^+e^-P$
- $\Rightarrow$ $a_\mu(P)$

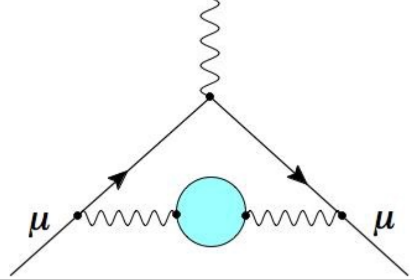
$\Rightarrow$ Radiative corrections in EKHARA

$\Rightarrow$ Radiative corrections in PHOKHARA

➠update on NLO corrections by Szymon Tracz

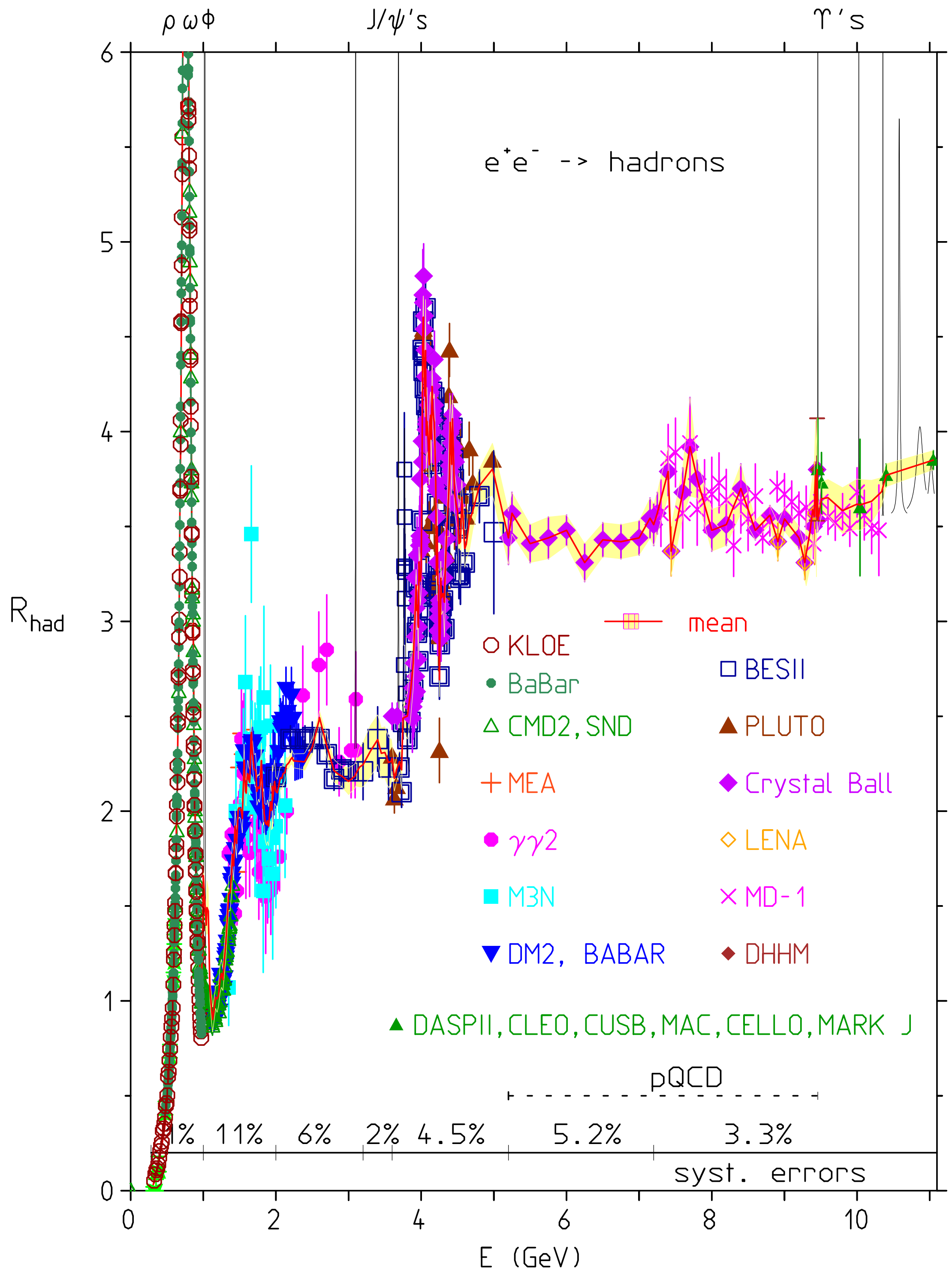
Outline

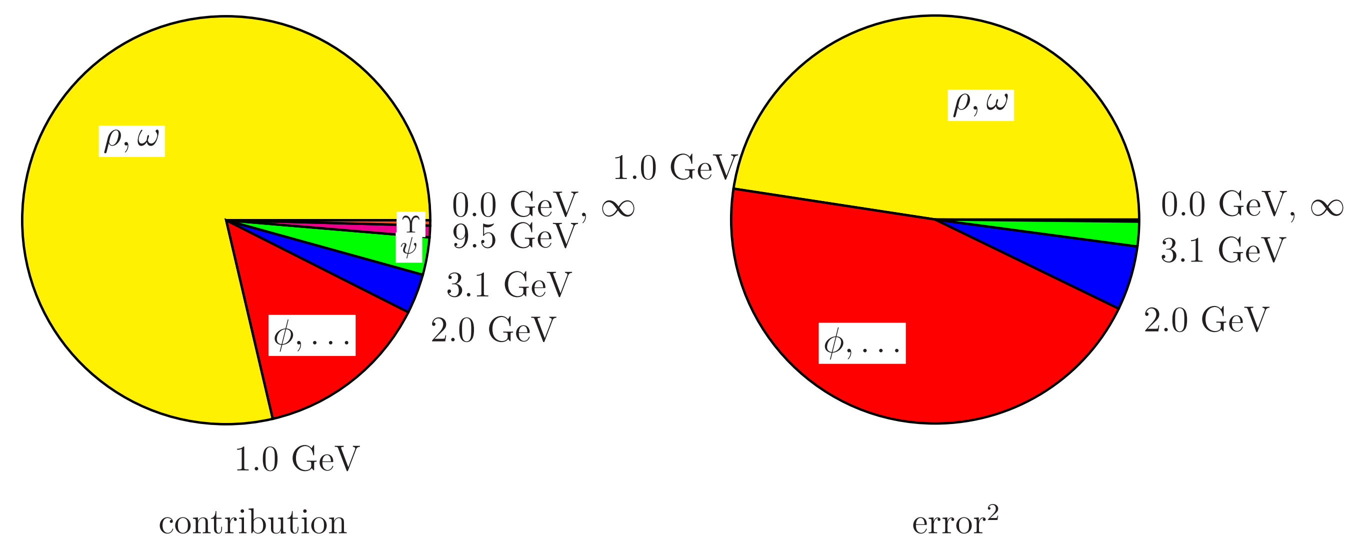
- Introduction and Overview
- Experimental inputs
- Dispersive HVP
- Lattice HVP
- MUonE



Hadronic vacuum polarization

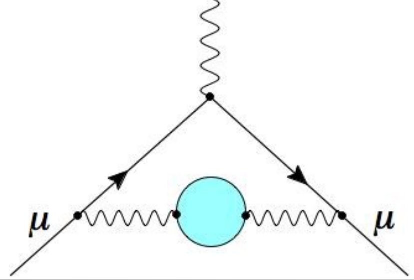
F. Jegerlehner @ HVP KEK 2018:





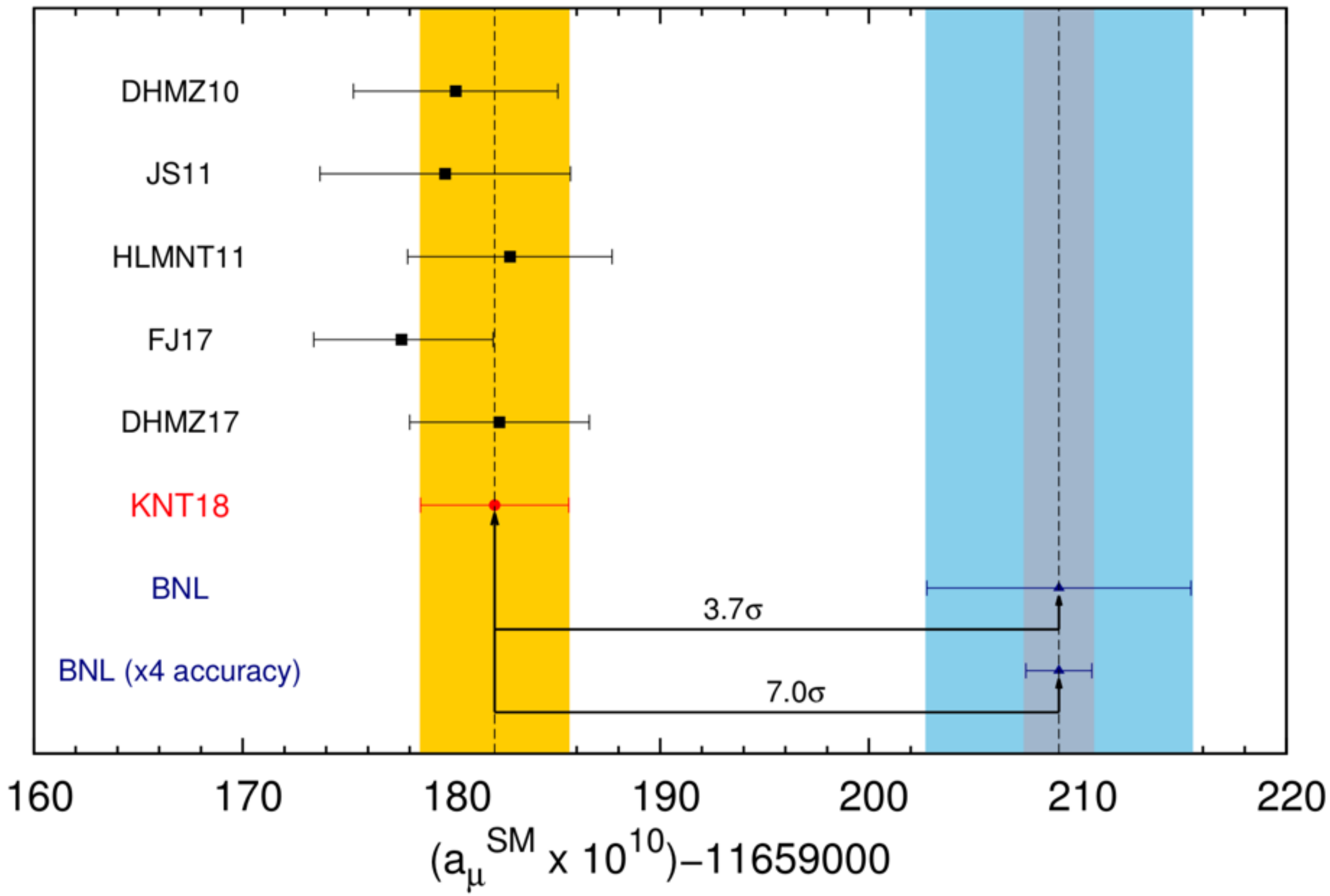
$$a_\mu^{\mathrm{had}(1)} = (686.99 \pm 4.21)[687.19 \pm 3.48]\ 10^{-10}$$

e^+e^-–data based [incl. τ]

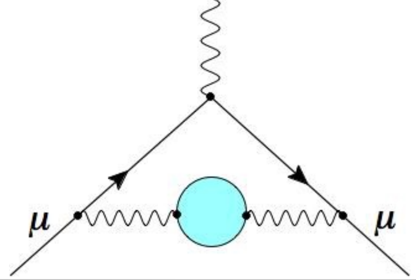


Hadronic vacuum polarization

A. Keshawarzi @ HVP KEK 2018 (arXiv:1802.02995):



M. Benayoun @ HVP KEK 2018: BHLS218: 4.5 σ



Hadronic vacuum polarization

M. Hoferichter @ HVP KEK 2018:

Dispersive constraints on the pion vector form factor

- Overview of constraints from **analyticity** and **unitarity**
- Role of **radiative corrections**
  - define $F_\pi^V(s)$ in QCD (**without VP**)
  - with $\pi\pi$ channel described dispersively, no issues with ρ–γ mixing
  - radiative corrections to ω **pole parameters** at the level of PDG uncertainties
- Some preliminary fit results
- Outlook
  - Error analysis: both experimental uncertainties and systematics of dispersive fit
  - Combination of data sets in global fit
  - Space-like data, ω parameters
  - Goal: **independent way to assess HVP uncertainty in $\pi\pi$ channel**, accounting for global constraints from analyticity and unitarity

Outline

- Introduction and Overview
- Experimental inputs
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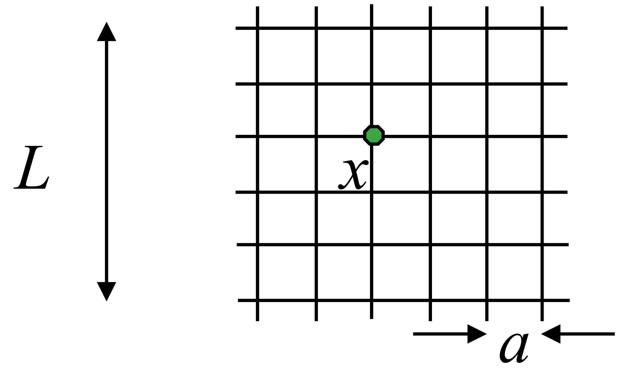
- Lattice HVP
- MUonE

Lattice QCD Introduction

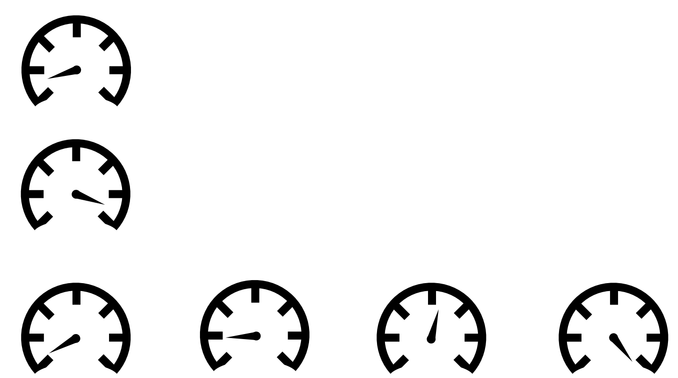
$$\mathcal{L}_{\mathrm{QCD}} = \sum_f \bar{\psi}_f (\not{D} + m_f)\psi_f + \frac{1}{4}\mathrm{tr} F_{\mu\nu}F^{\mu\nu}$$



- ✦ discrete Euclidean space-time (spacing a)
  derivatives ➙ difference operators, etc…
- ✦ finite spatial volume (L)
- ✦ finite time extent (T)

adjustable parameters

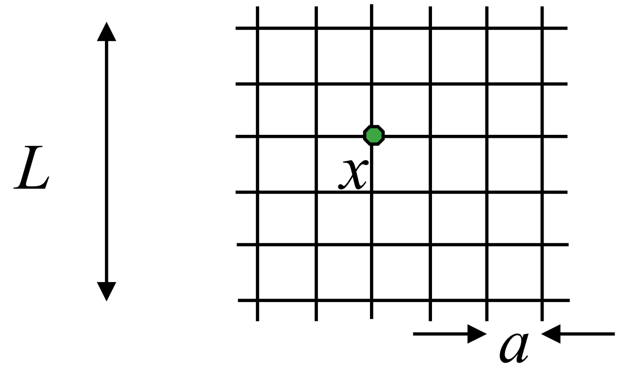
- ❖ lattice spacing: $a \to 0$
- ❖ finite volume, time: $L \to \infty,\ T > L$
- ❖ quark masses (m_f): $M_{H,\mathrm{lat}} = M_{H,\mathrm{exp}}$
  tune using hadron masses $m_f \to m_{f,\mathrm{phys}}$
  extrapolations/interpolations



m_{ud} m_s m_c m_b

Lattice QCD Introduction

$$\mathcal{L}_{\rm QCD} = \sum_f \bar\psi_f (\not{D} + m_f)\psi_f + \frac{1}{4}{\rm tr}F_{\mu\nu}F^{\mu\nu}$$



✦ discrete Euclidean space-time (spacing a)
derivatives ➙ difference operators, etc…

✦ finite spatial volume (L)

✦ finite time extent (T)

Integrals are evaluated numerically using monte carlo methods.

adjustable parameters

❖ lattice spacing: $a \to 0$

❖ finite volume, time: $L \to \infty,\ T > L$

❖ quark masses (m_f): $M_{H,\rm lat} = M_{H,\rm exp}$

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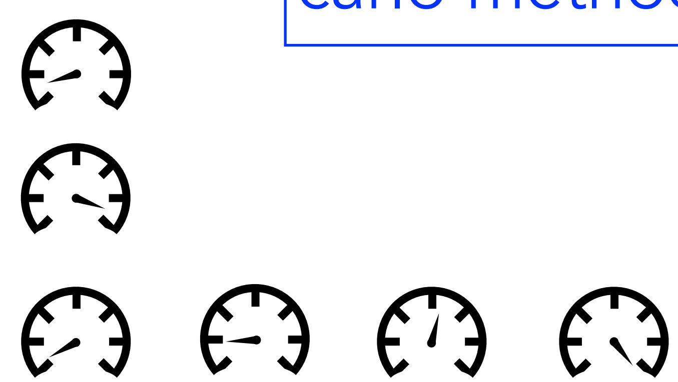
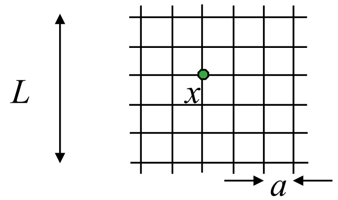


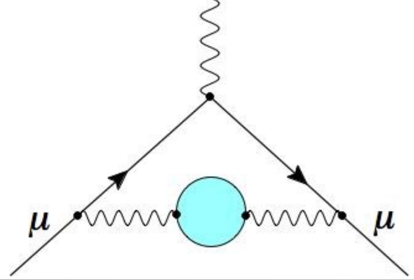
m_{ud} m_s m_c m_b



Lattice QCD Introduction

The State of the Art

- ☆ Lattice QCD calculations of simple quantities (with at most one stable meson in initial/final state) that **quantitatively account for all systematic effects** (discretization, finite volume, renormalization,…) , in some cases with
  - sub percent precision.
  - total errors that are commensurate (or smaller) than corresponding experimental uncertainties.
- ☆ Scope of LQCD calculations is increasing due to continual development of new methods:
  - nucleons and other baryons
  - nonleptonic decays ($K \to \pi\pi$, …)
  - resonances, scattering, long-distance effects, …
  - QED effects
  - radiative decay rates …



Hadronic vacuum polarization

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

- Calculate $a_\mu^{\rm HVP}$ 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 $C(t) = \frac{1}{3}\sum_{i,x}\langle j_i(x,t) j_i(0,0)\rangle$

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

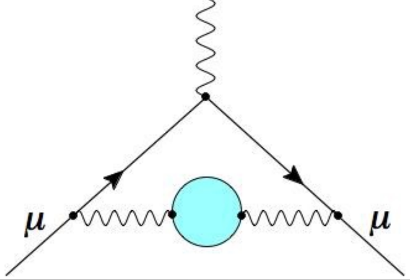
(Bernecker & Meyer, EPJ 12)

  - ✦ Time-moments: (Chakraborty et al, PRD 14)

Taylor expand $\hat{\Pi}(q^2) = \sum_k q^{2k} \Pi_k$

and compute Taylor coefficients from time moments:

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



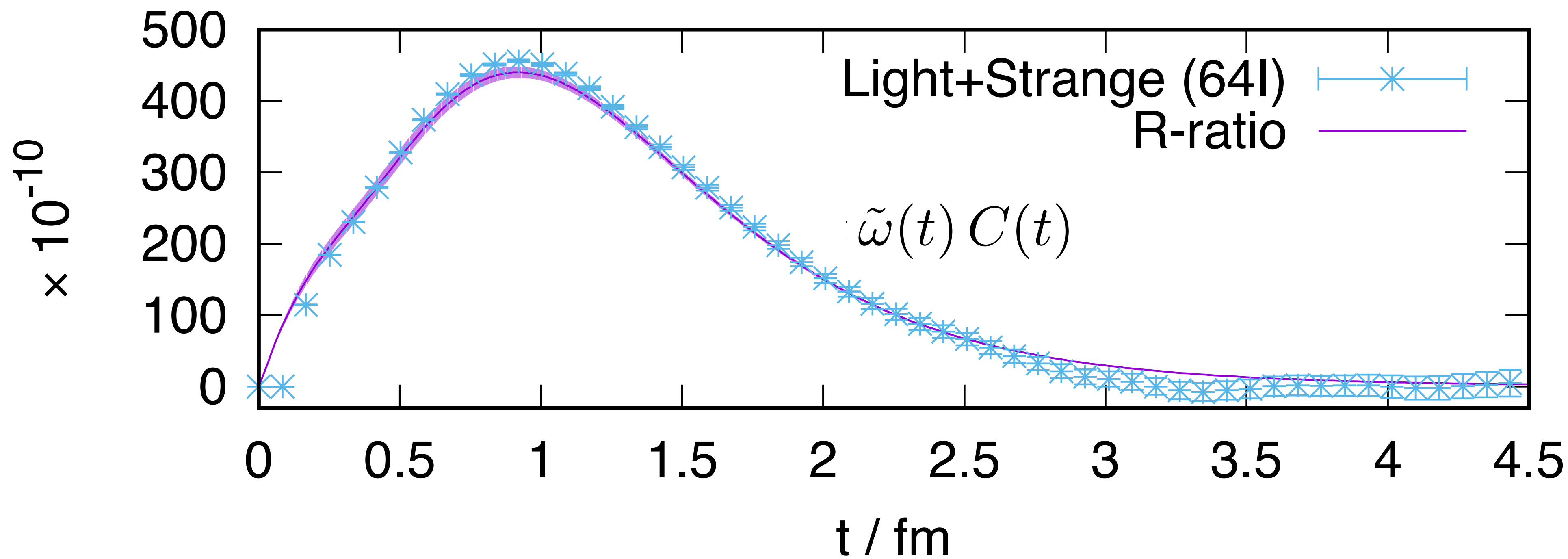
Hadronic vacuum polarization

$$C(t) = \frac{1}{3}\sum_{i,x}\langle j_i(x,t)j_i(0,0)\rangle$$

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

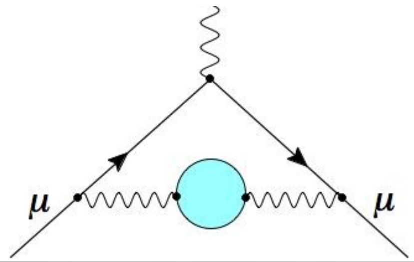
(Bernecker & Meyer, EPJ 12)

C. Lehner @ HVP KEK 2018 (for RBC/UKQCD):



Errors on the lattice data increase rapidly with Euclidean time:

- sensitive to long-distance and finite volume corrections
  use EFT methods
- control statistical noise at long distances through
  fits, including $\pi\pi$ correlation functions, …



Hadronic vacuum polarization

G. von Hippel @ HVP KEK (for Mainz):

The time-momentum representation – large-time correlator

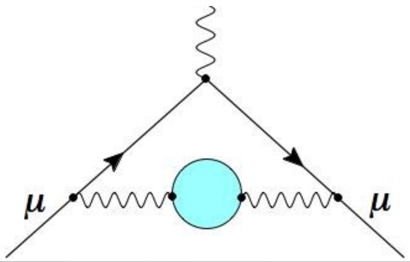
Large-time modelling of the vector correlator:

- Extract naive ground-state mass from fit to a smeared correlator, model $G(t)$ as single exponential at large t;
- Use the large-time approximation

$$G_{\infty}^{\rho\rho}(t) = \frac{1}{48\pi^2}\int_0^{\infty} \mathrm{d}\omega\,\omega^2 \left(1 - \frac{4m_\pi^2}{\omega^2}\right)^{\frac{3}{2}} |F_\pi(\omega)|^2 \mathrm{e}^{-\omega t}$$

extracting F_π using the Lüscher method → B. Hörz, F. Erben (PhD)

In both cases finite-volume effects can be studied by comparing infinite-volume $G_{\infty}^{\rho\rho}$ with finite-volume $G_L^{\rho\rho}$ reconstructed by summing finite-volume matrix elements using Lüscher method in reverse.



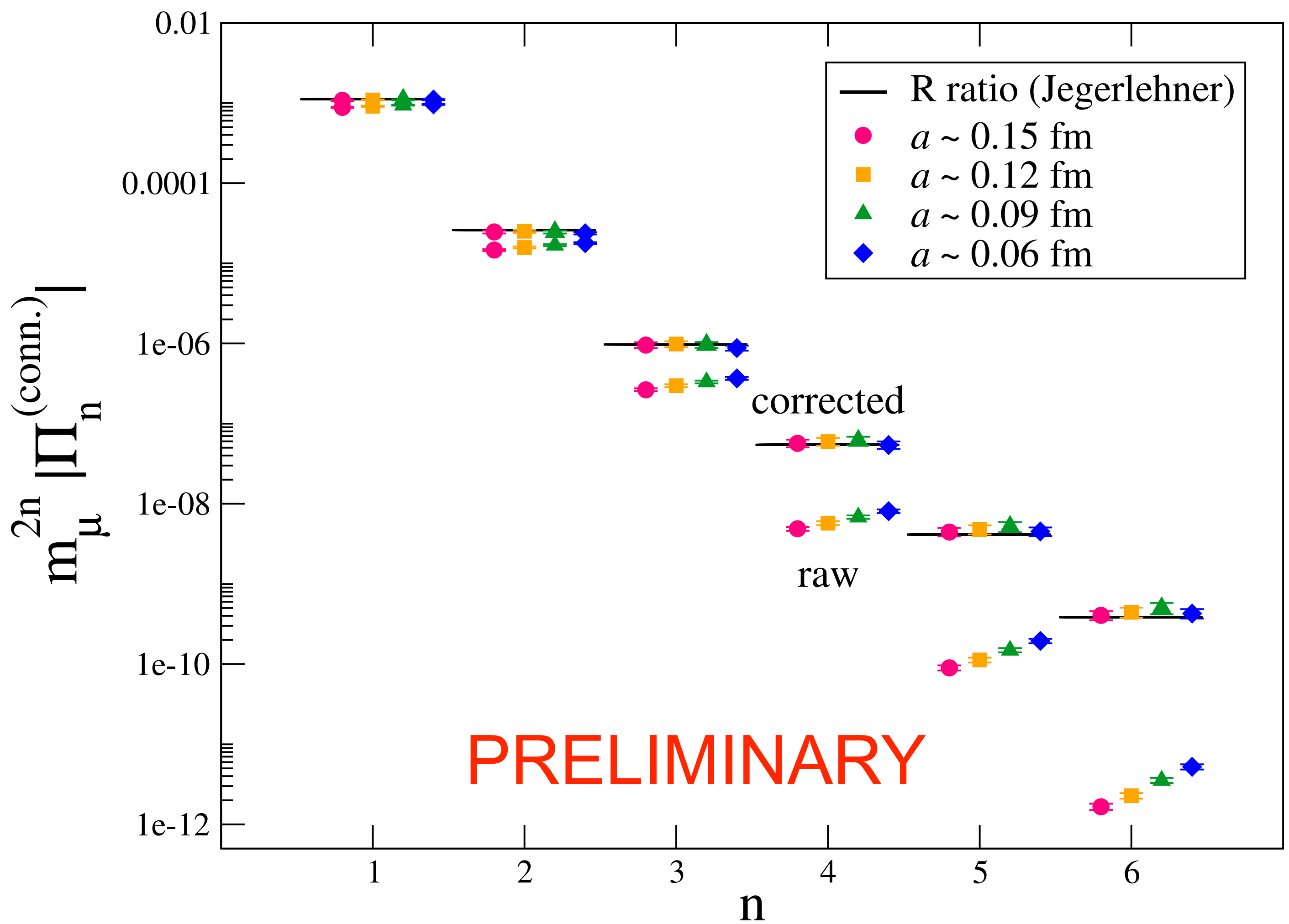
Hadronic vacuum polarization

- ✦ 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
- ✦ Compare intermediate quantities (Taylor coefficients,…) with R-ratio data.

Compare Taylor coefficients to R-ratio data

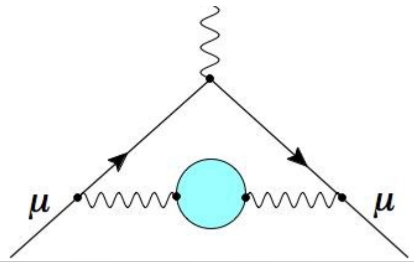
R. Van de Water @ HVP KEK 2018 (for FNAL/MILC/HPQCD):

Compare Taylor coefficients before and after (finite volume, discretization,..) corrections with R-ratio data:



- Corrections are calculated in EFT.
- First comparison performed by RVdW on HPQCD initial's data set **after** HPQCD paper was posted.

Lowest moments make the largest contributions to a_μ.



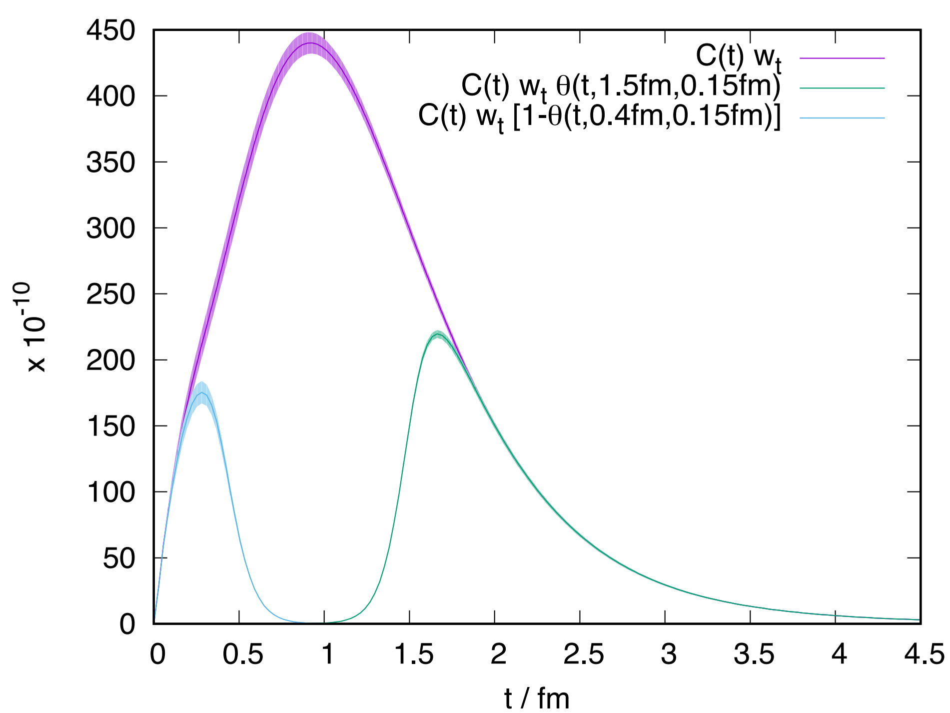
Hadronic vacuum polarization

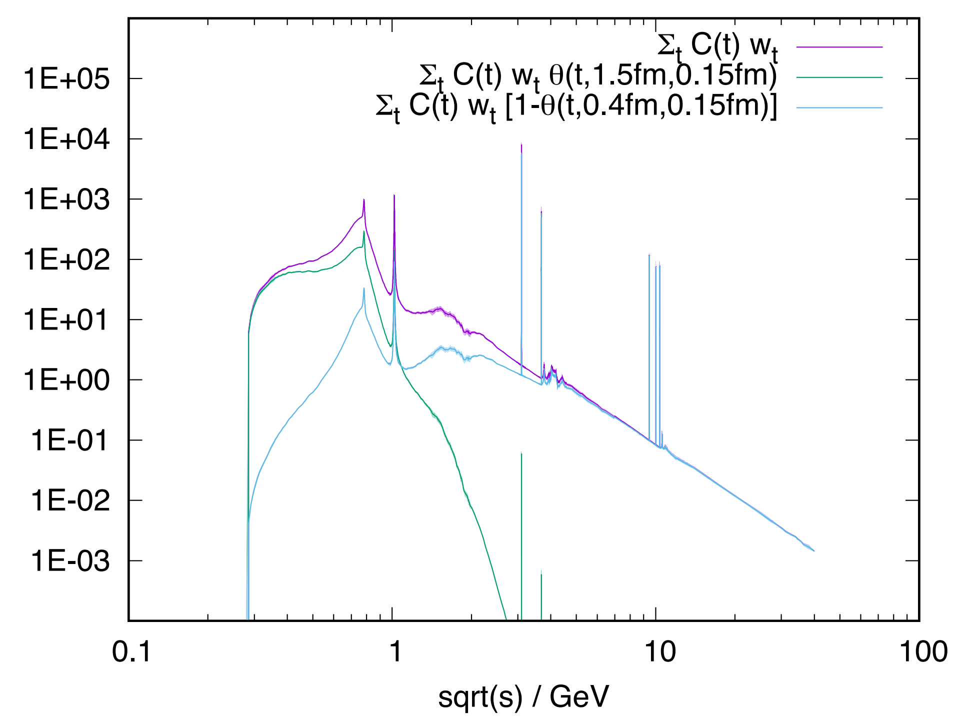
Hybrid method: combine LQCD with R-ratio data

C. Lehner @ HVP KEK 2018 (from T. Blum et al, arXiv:1801.07224)

Direct LQCD calculations of HVP are still less precise than dispersive methods. But comparisons between R-ratio and lattice data are already useful.

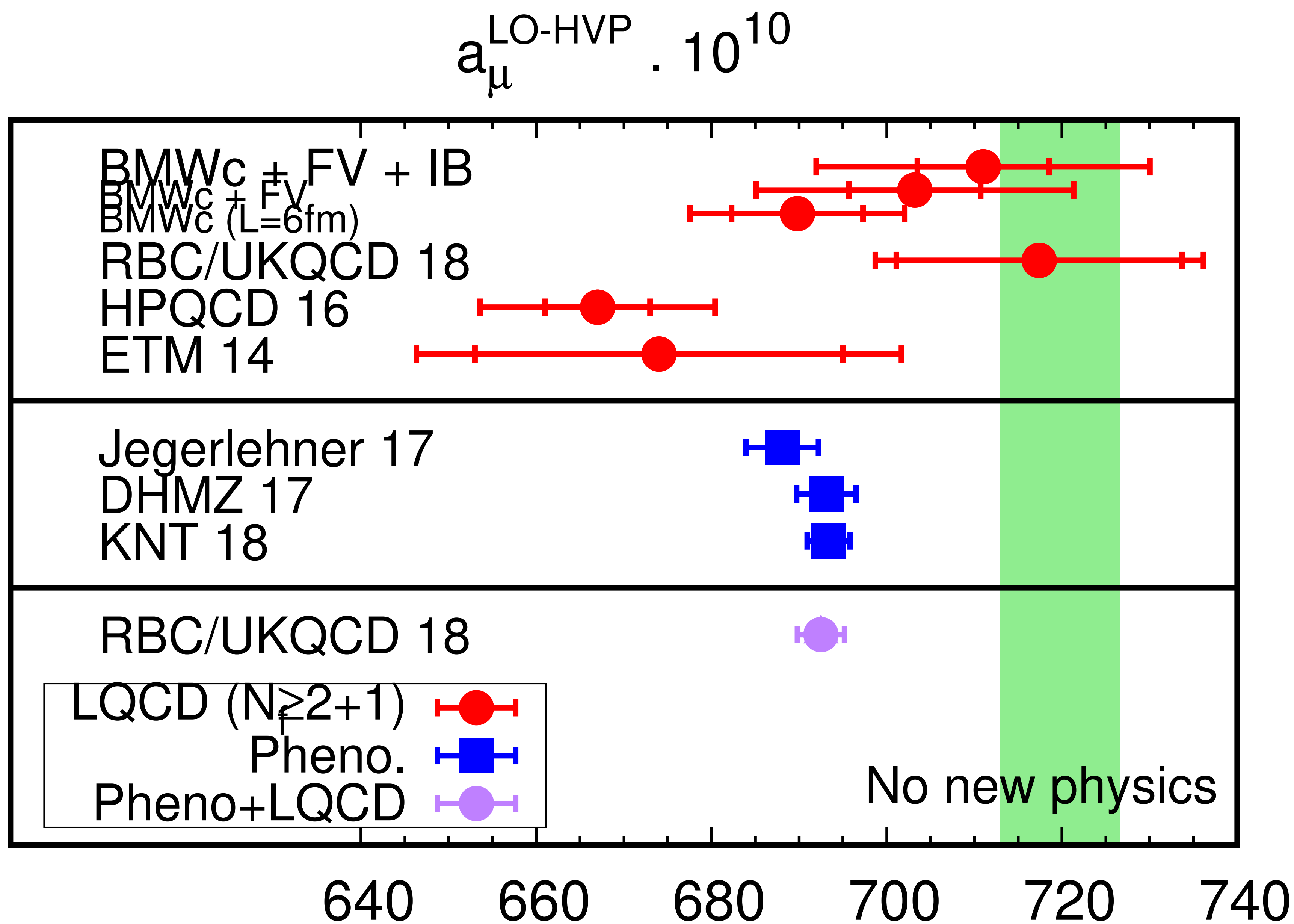
- Convert R-ratio data to Euclidean correlation function (via the dispersive integral).
- Compare lattice/R-ratio data (after adding all the corrections and extrapolating to continuum, infinite volume).
- Use R-ratio data where LQCD errors are large and vice versa.





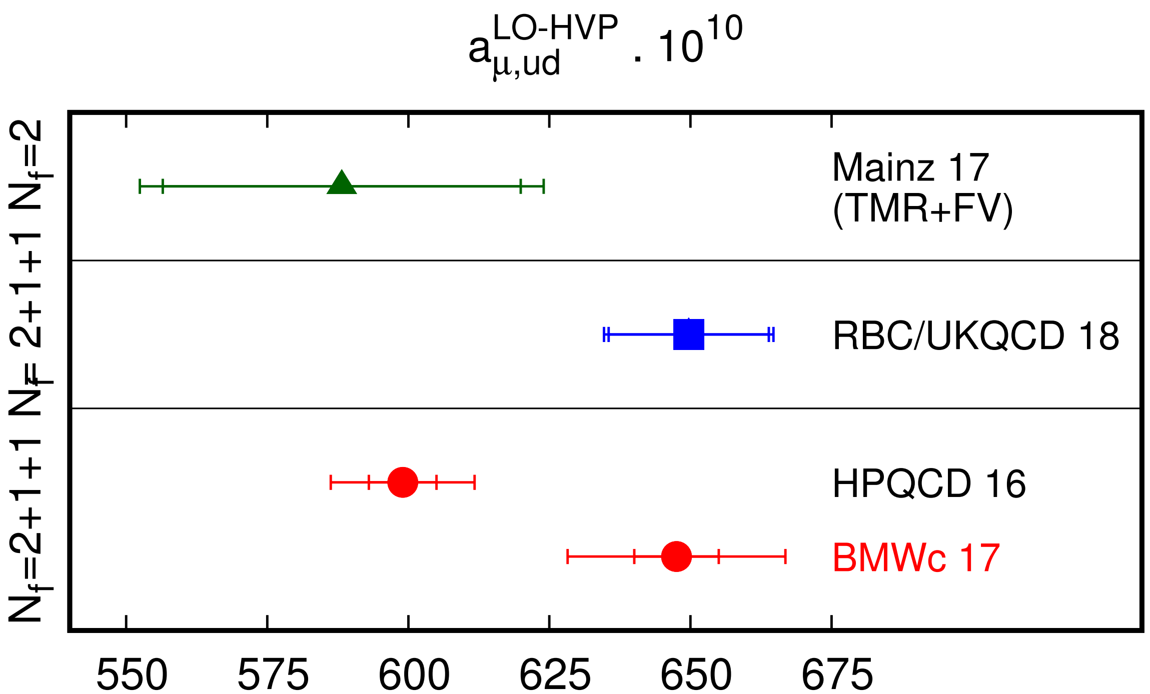
Summary of recent HVP results

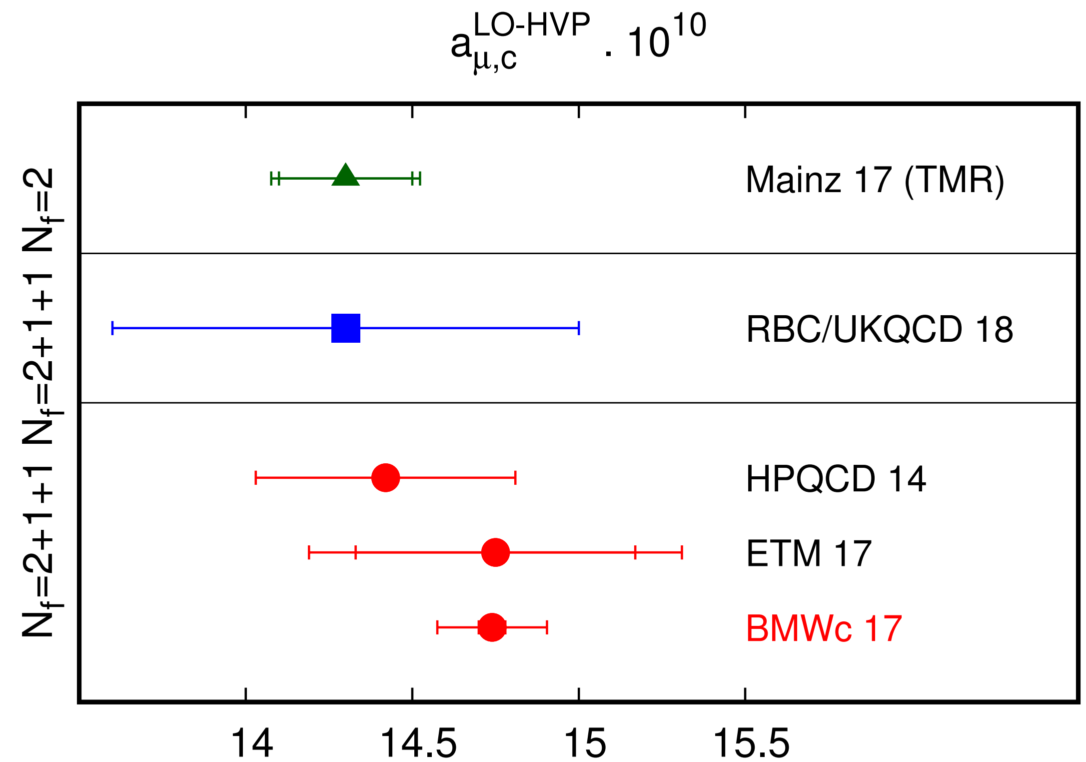
L. Lellouch @ HVP KEK 2018 (for BMW collaboration)

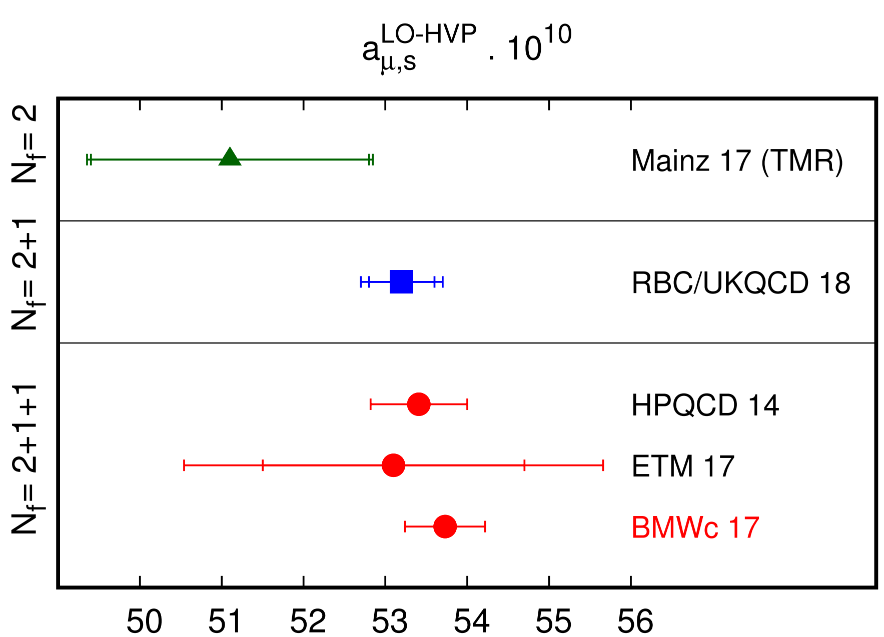


Detailed comparison of lattice HVP results

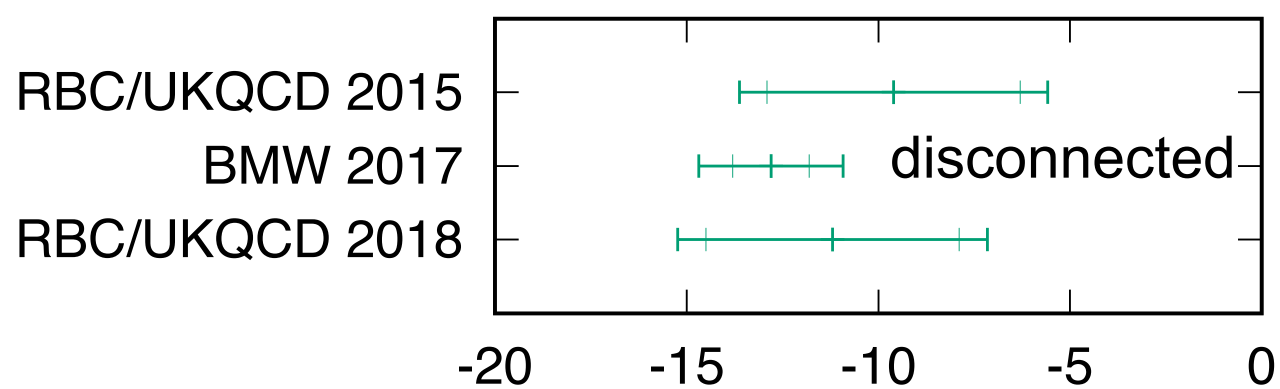
L. Lellouch @ HVP KEK 2018 (for BMW collaboration)







C. Lehner @ HVP KEK 2018 (for RBC/UKQCD)



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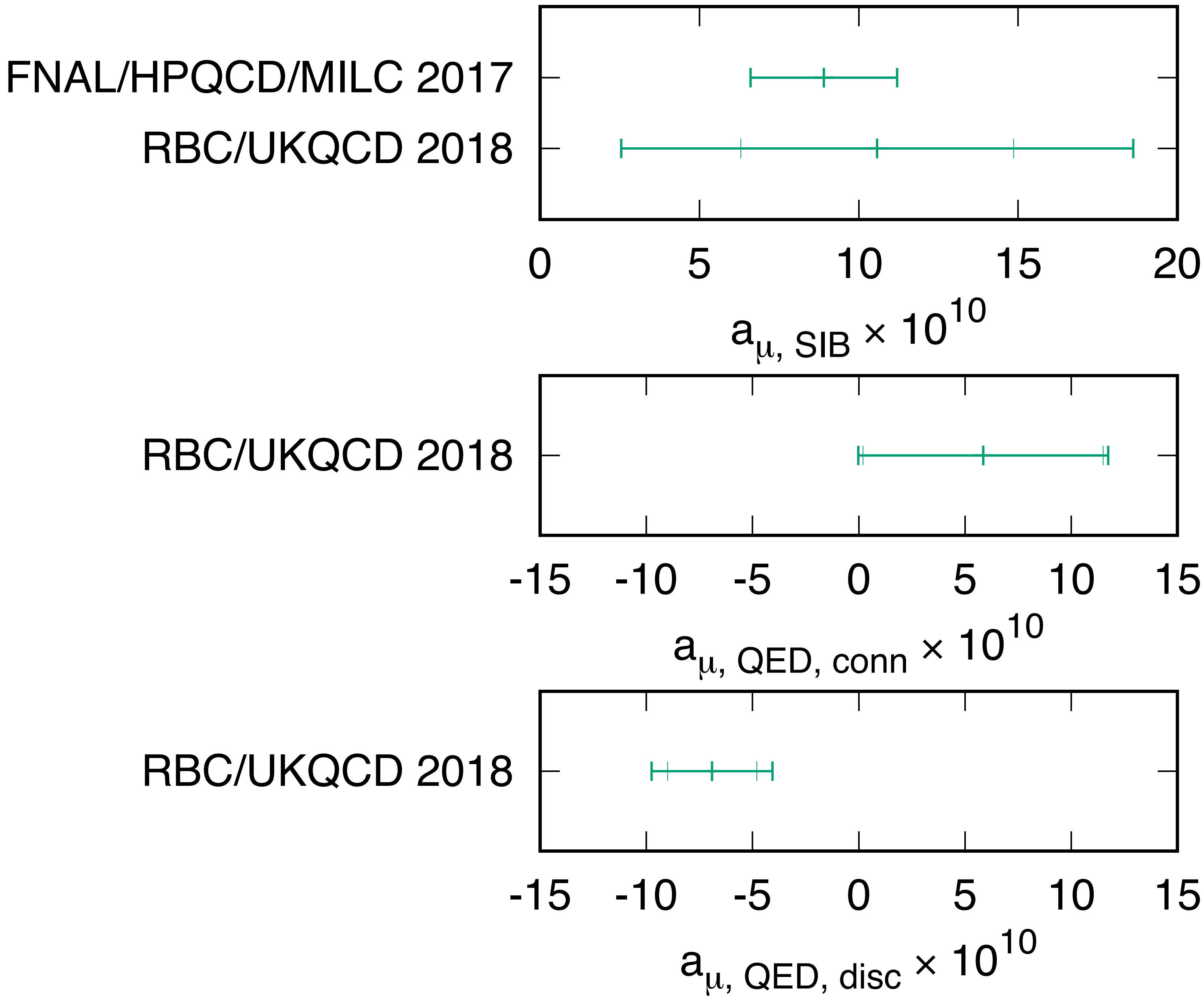

Outline

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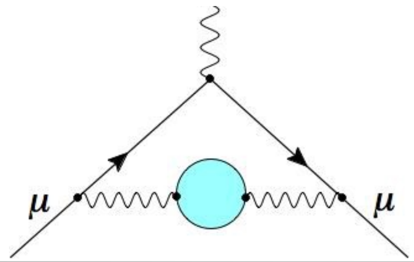
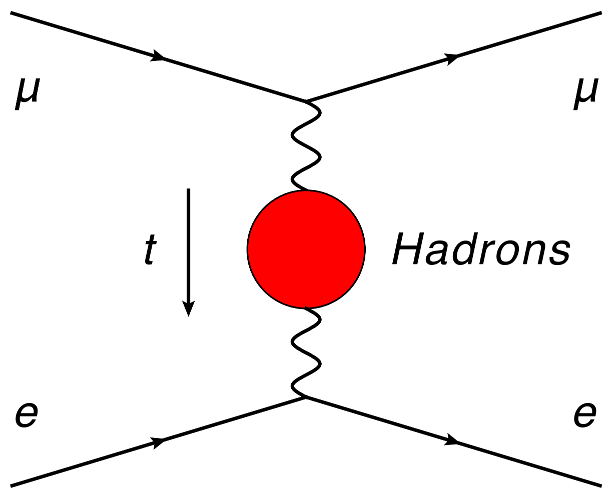
- MUonE



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)



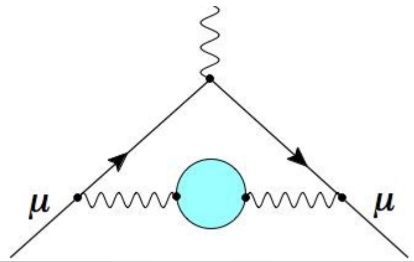
$$a_\mu^{\mathrm{HLO}} = \frac{\alpha}{\pi} \int_0^1 dx\,(1-x)\,\Delta\alpha_{\mathrm{had}}[t(x)]$$

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

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

MUonE

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



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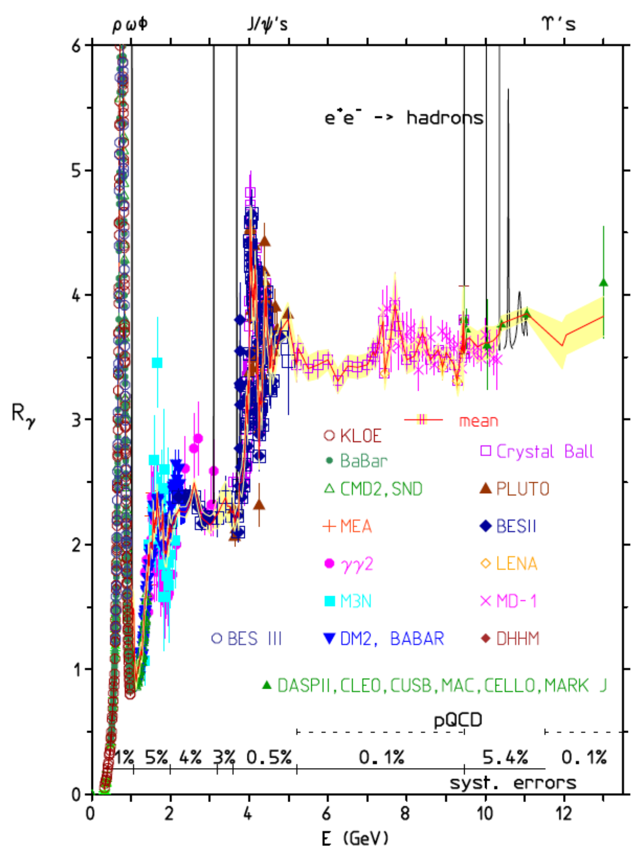
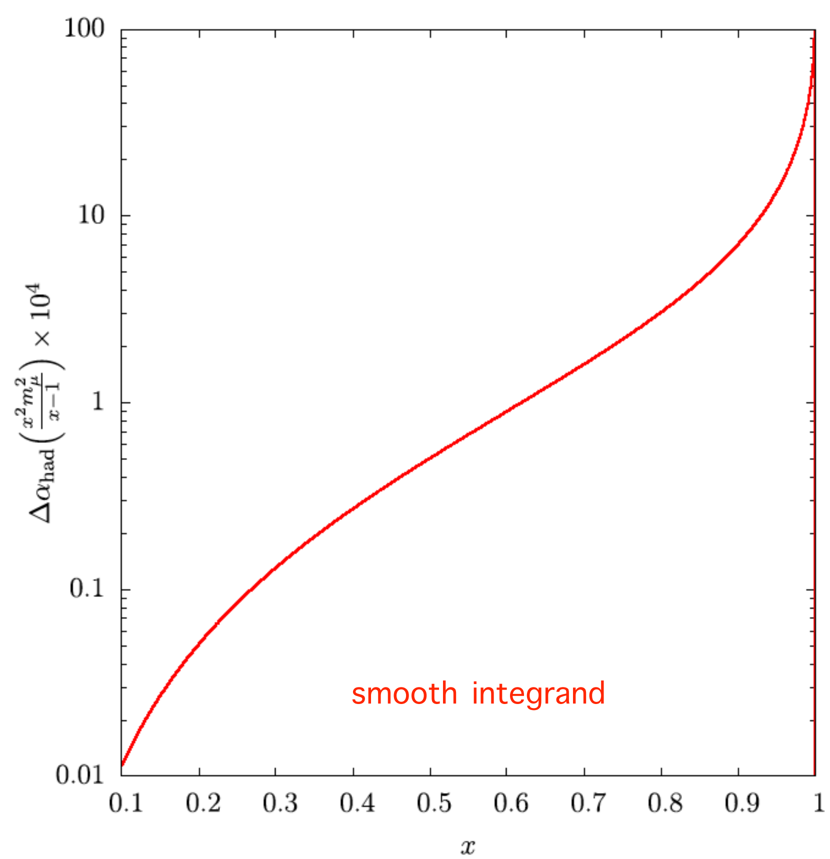
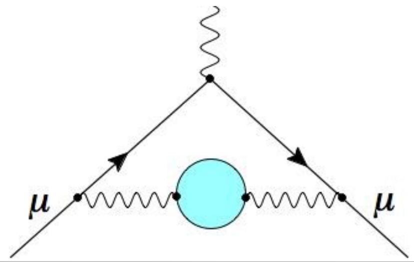
Time-like → **Space-like**





- requires NNLO QED calculation, …
- complement region not accessible to experiment with LQCD calculation (M. Marinkovic @ HVP KEK 2018)



Hadronic vacuum polarization

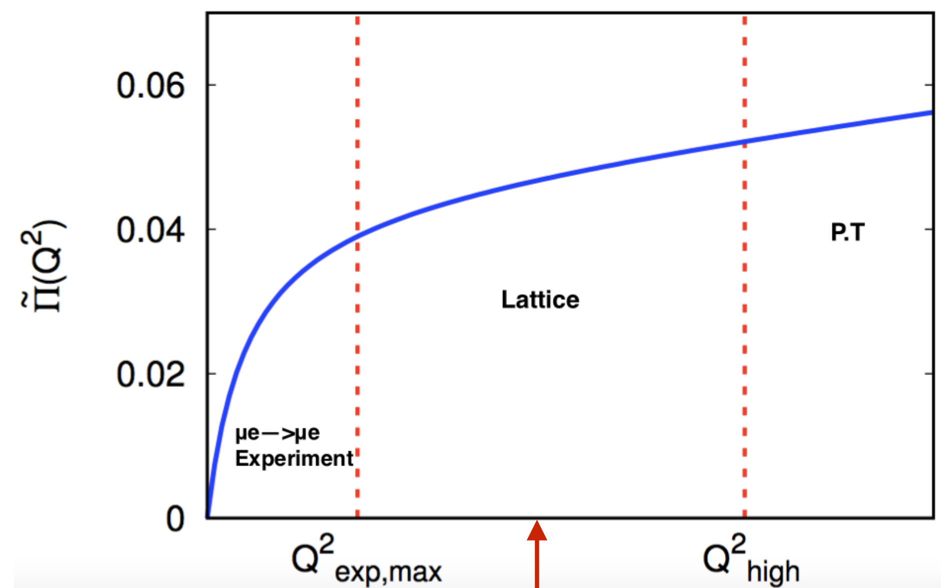
μ-e elastic scattering to measure $a_\mu^{\rm HVP}$

Hybrid method

Phys. Rev. D 90, 074508 (2014), [Golterman,Maltman,Peris]

M. Marinkovic @ HVP KEK 2018:

- complement region not accessible to experiment with LQCD calculation



- **Low momentum region**
  - ➡ **Experiment (NLO, NNLO, radiative corrections …)**

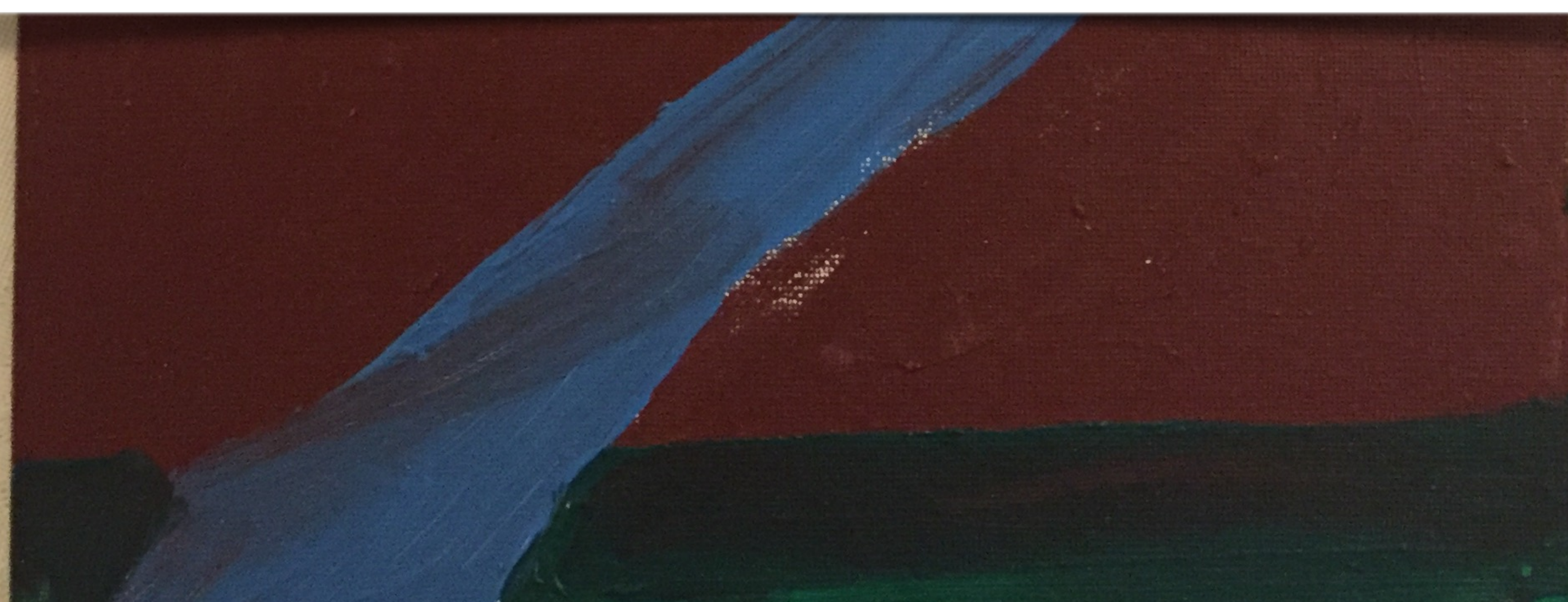
- **Vary low and high Q^2 cut**

- ➡ **continuum limit: a—> 0**
- ➡ **infinite volume limit: V—> ∞**
- ➡ **physical quark masses**
- ➡ **isospin breaking corrections ($m_u \neq m_d$ and $\alpha_{em} \neq 0$)**

strategy proposed for the hybrid determination of the total HVP (u+d+s+c+b)

Summary and Outlook

- ⭐ Experimental inputs:
  new recent results by BaBar, KLOE, BESIII, SND, CMD-3, KEDR, and more expected soon
- ⭐ dispersive HVP determinations
  improved precision, but suffer from tension between experimental inputs for $\pi\pi$ channel
- ⭐ LQCD calculations
  many groups, new methods, a lot of activity
  need to understand tensions between LQCD results: compare intermediate quantities (Taylor coefficients)
- ⭐ room for new ideas



Amala Willenbrock

HVP sessions @ Mainz workshop

- Inputs from e+e- experiments:
  S. Eidelman (review+outlook), E. Solodov (Novosibirsk), M. Davier (tensions), S. Tracz + H. Czyż on radiative corrections and MC generators
- dispersive HVP:
  B. Malaescu for DHMZ, A. Keshavarzi for KNT, M. Benayoun on HLS model, M. Hoferichter (disp. constraints on pion vector form factor), Malaescu + Teubner on error propagation
- Lattice HVP:
  C. Lehner (RBC/UKQCD), H. Meyer (Mainz), R. Van de Water (FNAL/MILC/HPQCD), K. Miura (BMW), S. Simula (ETM)
  + discussions on:
  long distance effects (von Hippel), FV effects (Giusti), QED+SIB (Gülpers), comparisons and cross checks (Lellouch)
- misc theory and new ideas:
  analytical FV (A. Portelli), Hybrid approach (K. Schilcher), Mellin-Barnes (E. de Rafael), tau decays (M. Bruno), MUonE (C. Carloni, M. Marinkovic)

Thank you!

Farah Willenbrock

Appendix

Introduction

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	

The difference is large: ~ 2 × (EW contribution)

Introduction

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