Preliminary Update on the HVP Determination

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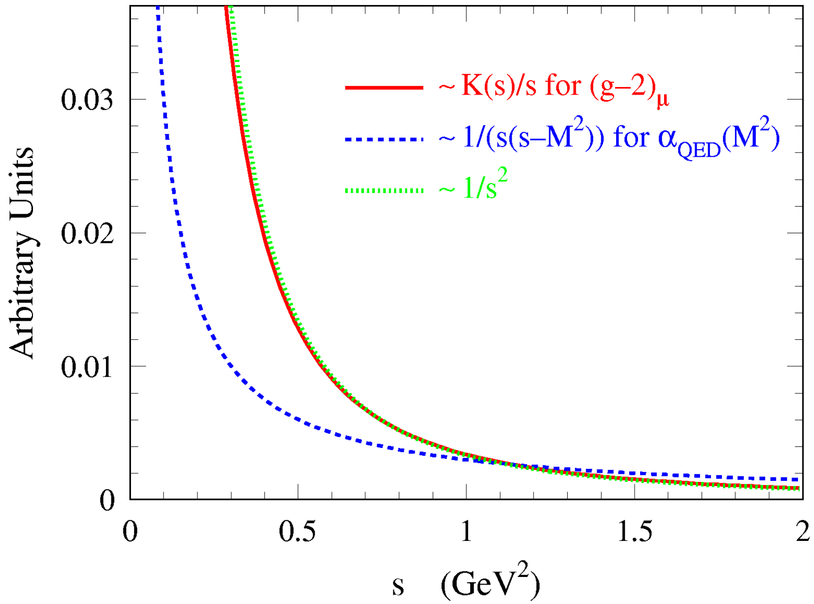
$$a_\mu^{\mathrm{Had,LO}} = \frac{1}{3}\left(\frac{\alpha}{\pi}\right)^2 \int_{m_\pi^2}^{\infty} ds \frac{K(s)}{s} R(s)$$



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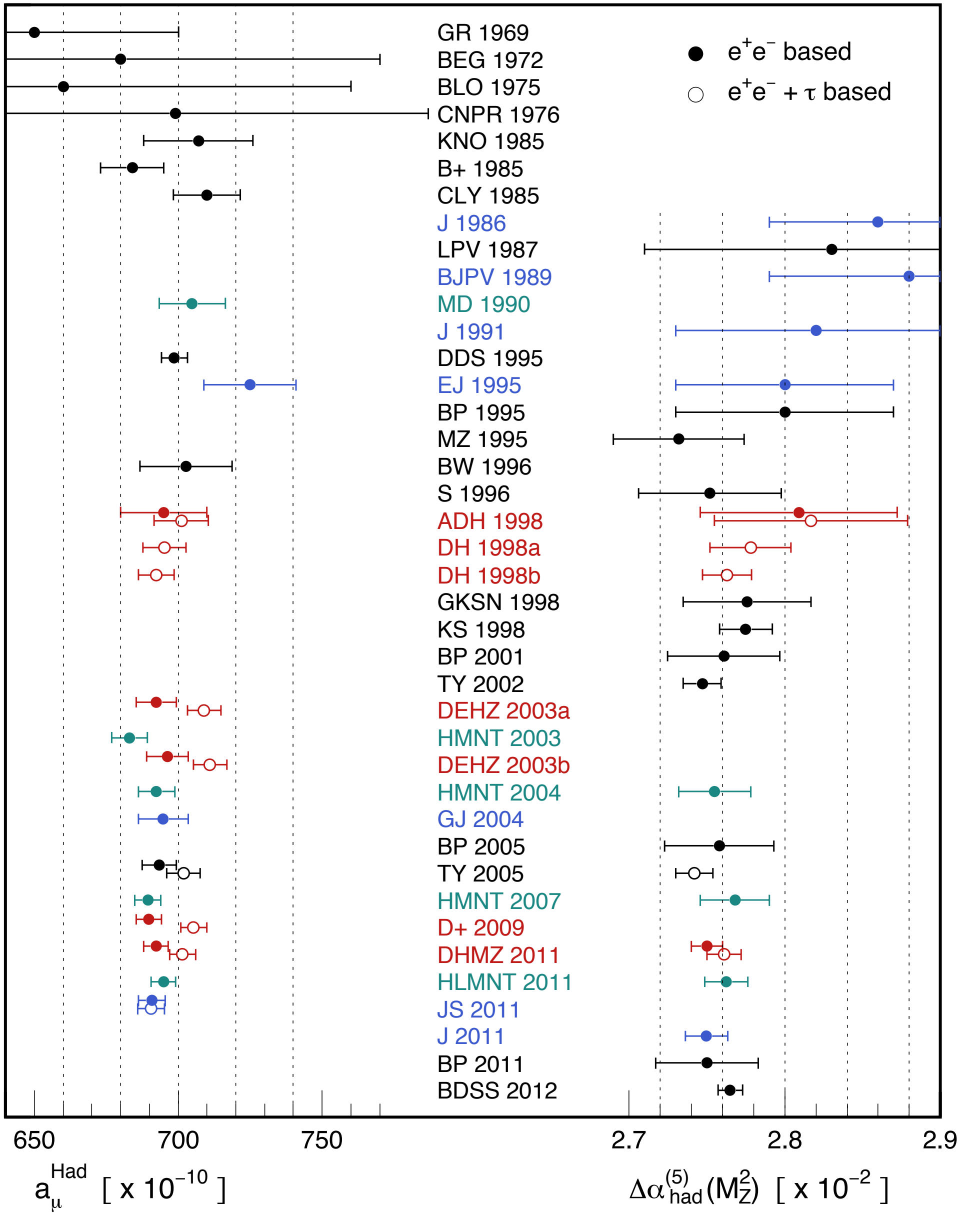
Overview



LO Hadronic Vacuum Polarization (HVP) being the most uncertain part for a_μ & $\Delta\alpha$ has been the focus over last 5 decades.

The precision is steadily improving thanks to

- more precise/complete e^+e^- annihilation (& tau) data
- state of the art techniques for data interpolation, combination and error correlation treatment

Davier, Hoecker, Malaescu, Zhang, for "**Standard Theory Essays in the 60th Anniversary of CERN**", **published recently by World Scientific**

Overview

Project at Orsay initiated by Alemany, Davier, Hoecker in 1998
joined by Zhang since 2003 and Malaescu since 2009
with contributions from a few others, e.g. Eidelman, Yuan

Relative (%)	$\delta a_\mu^{had, LO}$	$\Delta\alpha^{(5)}_{had}$
1998 [ADH]	2.1 [e^+e^-] 1.3 [$e^+e^- \oplus$tau]	2.2 [e^+e^-] 2.2 [$e^+e^- \oplus$tau]
2003 [DEHZ]	1.0 [e^+e^-] 0.8 [tau]	
2009 [DHMZ+]	0.59-0.76 [e^+e^-] 0.64 [tau]	
2011 [DHMZ]	0.61 [e^+e^-] 0.67 [tau]	0.36 [e^+e^-] 0.40 [tau]
2017 [DHMZ]	0.49 [e^+e^-]	0.34 [e^+e^-]

- Uncertainty on a_μ reduced by 20% wrt 2011, and a factor of >4 over 20 years
- Tau less precise now and involves isospin breaking corrections

Combination Procedure (HVPTools)

- ❒ The integration of data points belonging to different experiments, with different within-experiment and inter-experiment correlated systematic errors, and with different data densities requires a careful treatment

- ❒ DHMZ approach (HVPTools since 2009):
  - ➤ Quadratic interpolation of the data points/bins for each experiment
  - ➤ Local weighted average between interpolations performed in infinitesimal bins (1 MeV)
  - ➤ Full covariance matrices: correlations between data points of an experiment (systematic errors), between experiments and channels (VP, luminosity, …)
  - ➤ Consistent error propagation using pseudo experiments (toys)
  - ➤ Possible bias tested in 2π channel using a GS model: negligible for quadratic interpolation, but not for linear model (trapezoidal rule)

Main New Inputs for the Update

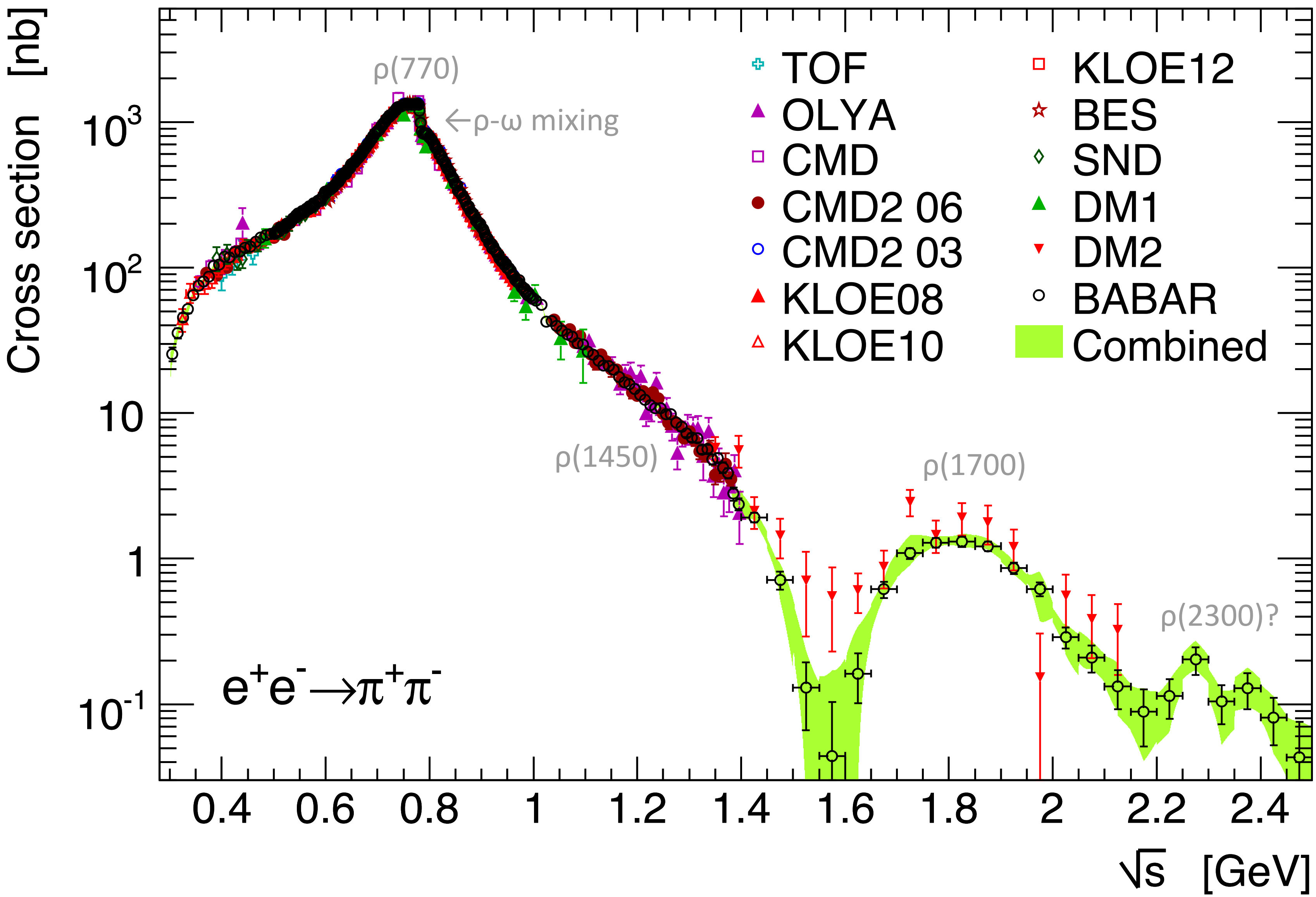
39 exclusive channels (vs. 22 for 2011)

Previous evaluation used estimation from isospin symmetry for quite a few unmeasured channels, ~(0.69 ± 0.07)% of $a_\mu^{had,LO}$

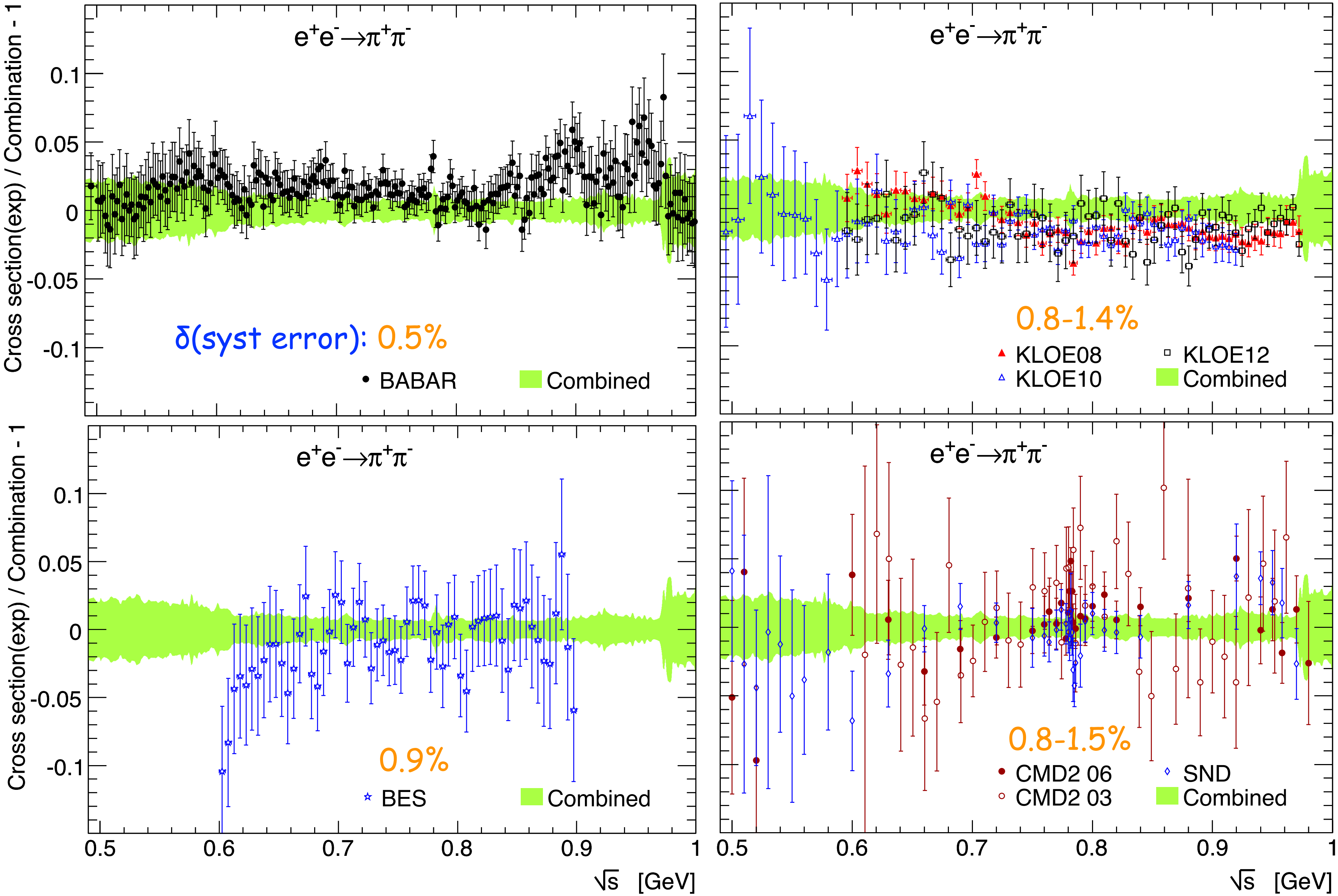
$\pi^+\pi^-$:	KLOE-2012, BES-2015
$\pi^+\pi^-2\pi^0$:	Babar-2016
$2\pi^+2\pi^-$:	Babar-2012, CMD3-2017
K_SK_L:	Babar-2014, CMD3-2016
K^+K^-:	SND-2016
$K_SK^\pm\pi^\mp$, $K^+K^-\pi^0$, $K_SK_L\pi^0$:	Babar-2011
$K^+K^-\pi^+\pi^-$, $K^+K^-2\pi^0$:	Babar-2011
$K_SK_L2\pi$, $2K_S2\pi$:	Babar-2014
$K_SK_L2\pi^0$, $K_SK^\pm\pi^\mp\pi^0$:	Babar 2017
$2K2\pi$:	Babar-2012 (update), CMD3-2016
$2K2\pi^0$:	Babar-2012 (update)
$2K_L2\pi$:	estimated by CP symmetry

+ many others (small cross section) channels

The Dominant 2π Channel

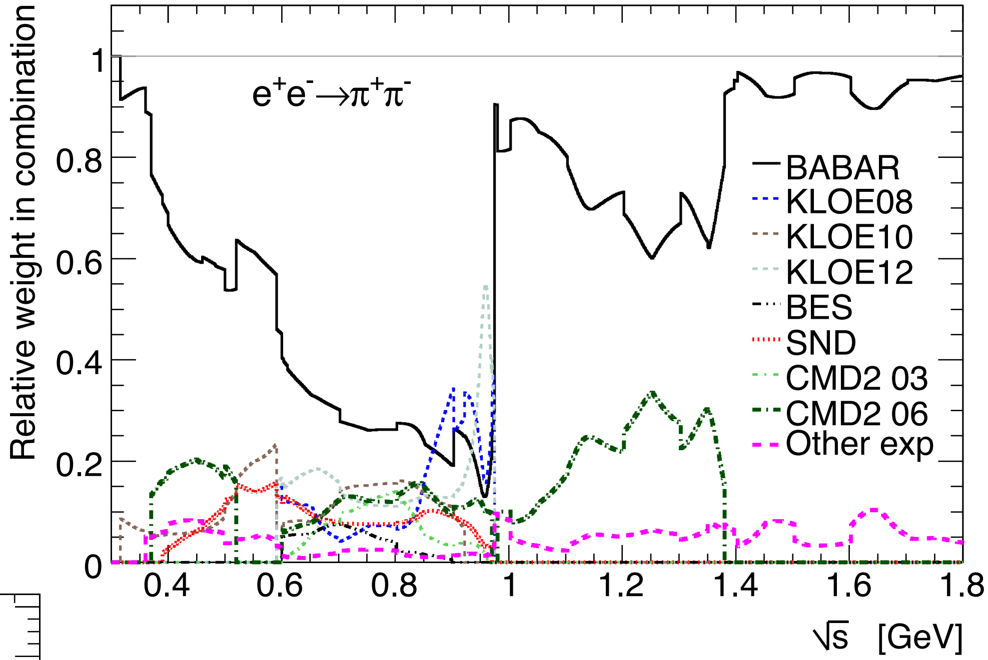


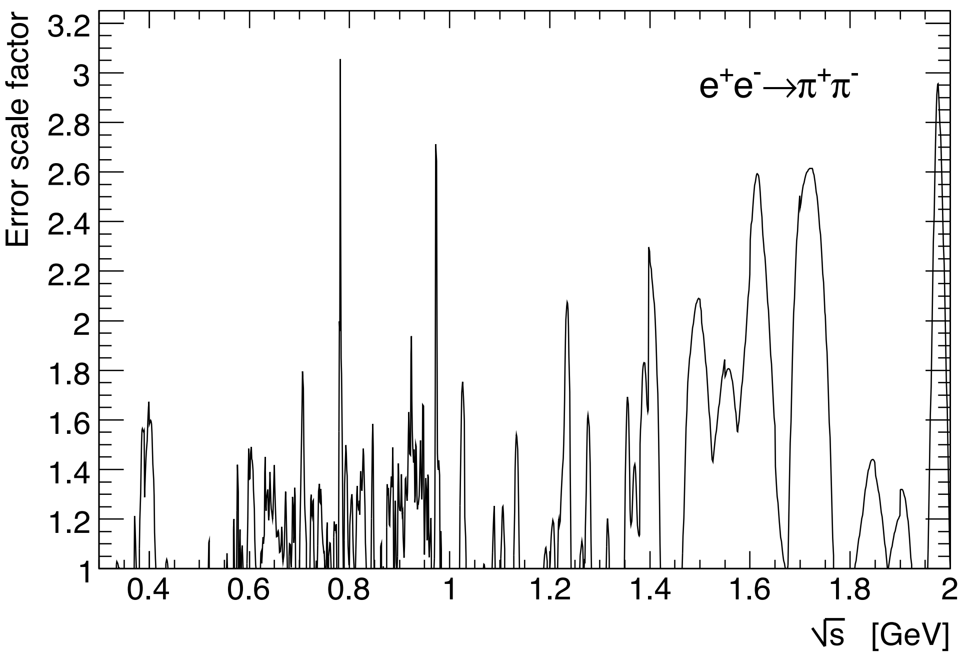
Closer Comparison of Different Measurements



Relative Weights & Inconsistency

Dominated by Babar except [~0.85, 0.97] GeV where KLOE has larger weight





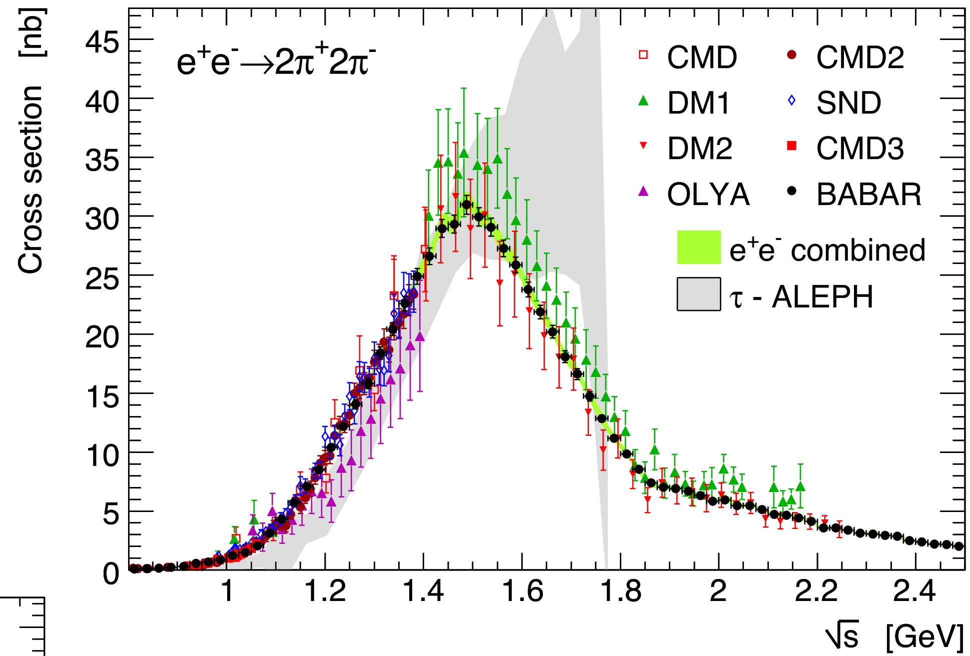
Inconsistency between measurements reflected by large scale factor defined by

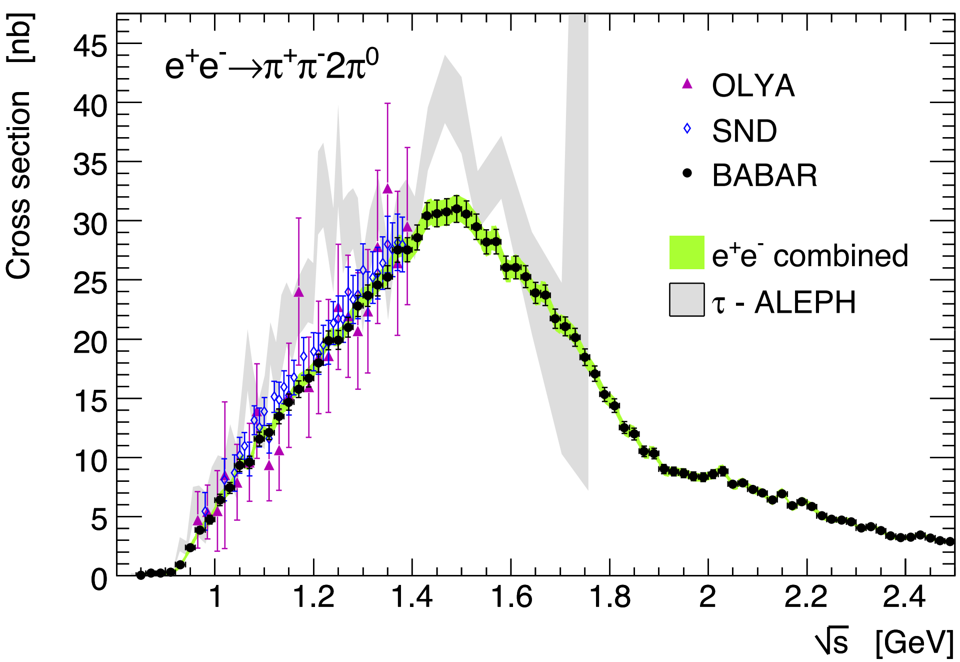
$$\sqrt{\chi^2_{\rm local}/n_{\rm dof}}$$

a la PDG approach (~15% increase on δa_μ^{had})

Four Pions Channels

Error reduction: a factor of 1.7 (2017 vs 2011)
Discrepancy with less precise tau data



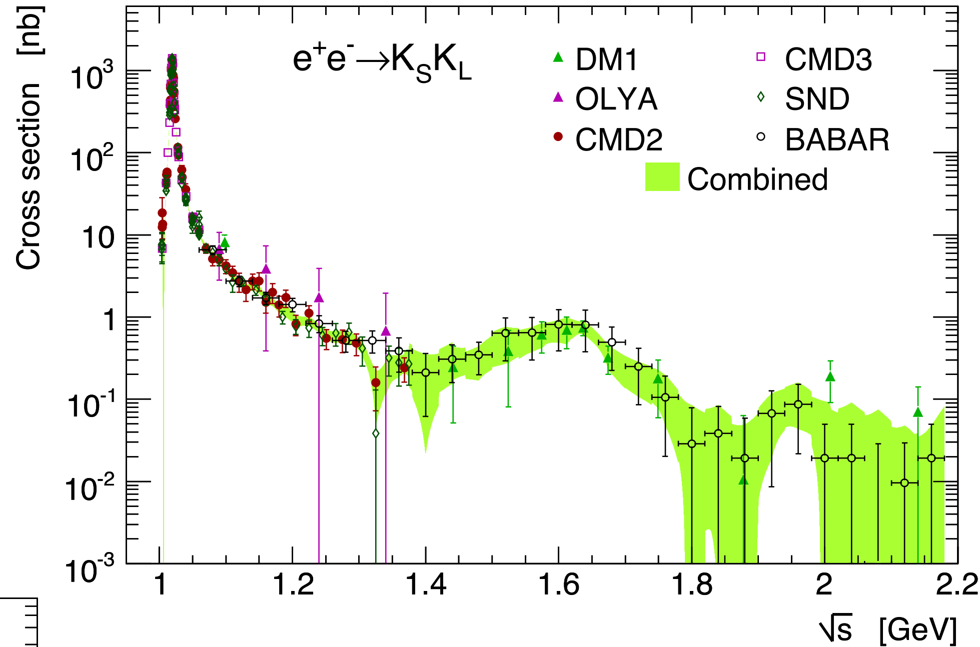


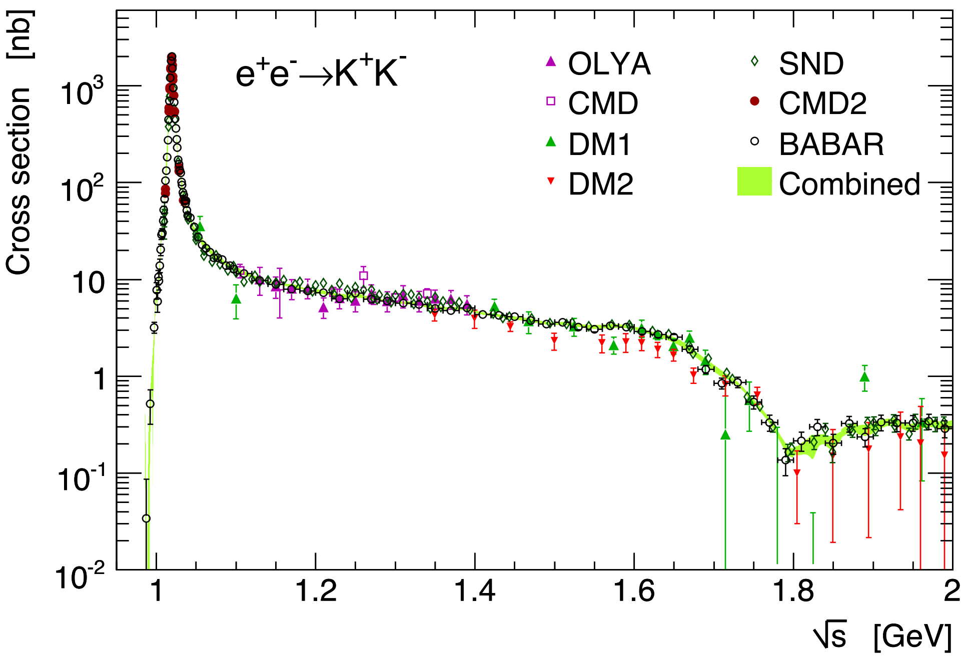
Babar: 3.1% below 2.7GeV (was ~10% with prel results)

Overall:
Error reduction: a factor 2.3 (2017 vs. 2011)

KKbar Channels

Error reduction: a factor of 1.6 (2017 vs 2011)



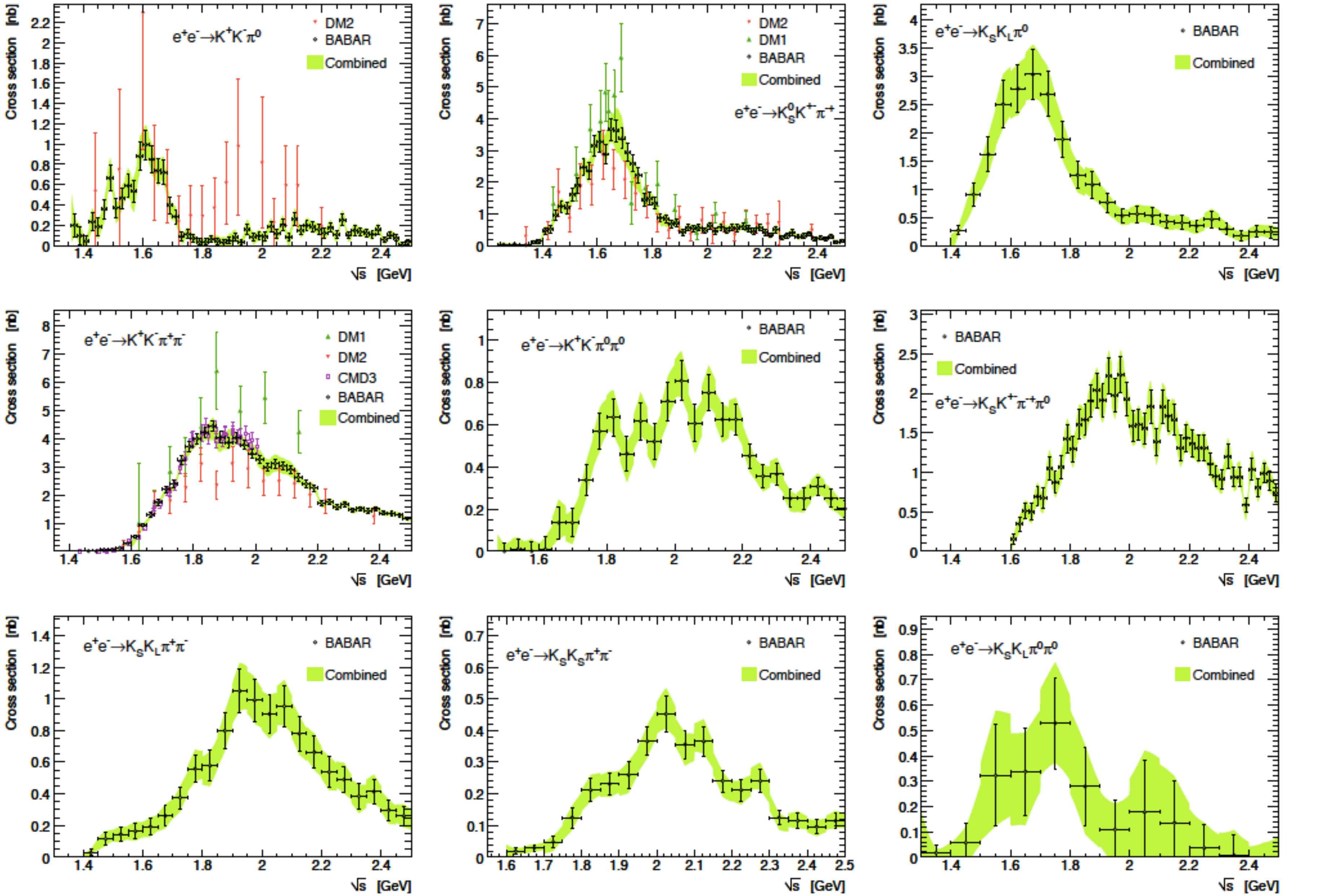


Concern:

Babar has δ(syst)~0.7% but σ(φ→K+K-) > CMD2 (SND) by 5.1% (9.6%)

Preliminary CMD3 data show discrepancies the other way around ~5% (Babar), ~11% (CMD2)

KKbar+π's Channels (Very Recent Babar Results)



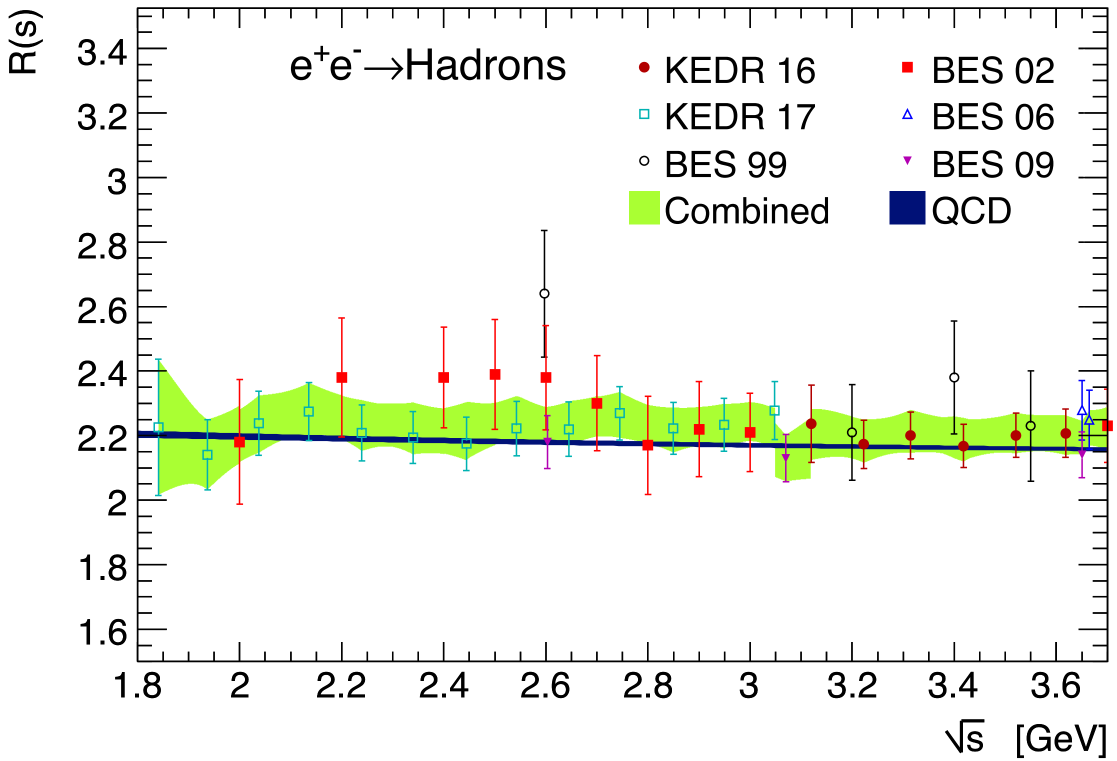
Improvement of 2017 Update over 2011 Version

Exclusive data integrated up to 1.8 GeV and in charm region [3.7 - 5] GeV
pQCD otherwise

Channel	a_μ^{had} [10^{-10}] 2017	a_μ^{had} [10^{-10}] 2011	$\delta a_\mu^{had, LO}$ reduction
$\pi^+\pi^-$	507.14 ± 1.13 ± 2.20 ± 0.75	507.80 ± 1.22 ± 2.50 ± 0.56	-9%
$2\pi^+2\pi^-$	13.68 ± 0.03 ± 0.27 ± 0.14	13.35 ± 0.10 ± 0.43 ± 0.29	-42%
$\pi^+\pi^-2\pi^0$	18.03 ± 0.06 ± 0.48 ± 0.26	18.01 ± 0.14 ± 1.17 ± 0.40	-56%
K^+K^-	22.81 ± 0.24 ± 0.28 ± 0.17	21.63 ± 0.27 ± 0.58 ± 0.36	-46%
K_SK_L	12.82 ± 0.06 ± 0.18 ± 0.15	12.96 ± 0.18 ± 0.25 ± 0.24	-38%
$KK^{bar}\pi$	2.45 ± 0.06 ± 0.12 ± 0.07	Est:2.39 ± 0.07 ± 0.12 ± 0.08	-6%
$KK^{bar}2\pi$	0.85 ± 0.02 ± 0.05 ± 0.01	Est:1.35 ± 0.09 ± 0.38 ± 0.03	-86%
R_{QCD}	33.45 ± 0.28 ± 0.59_{dual}	33.45 ± 0.28	
missing (%)	0.10 ± 0.03	0.69 ± 0.07	
Sum	693.1±1.2±2.6±1.7±0.1±0.7	692.3±1.4±3.1±2.4±0.2±0.3	-19%

stat, sys, cor, ψ, QCD

Contribution in the Region 1.8 - 3.7 GeV

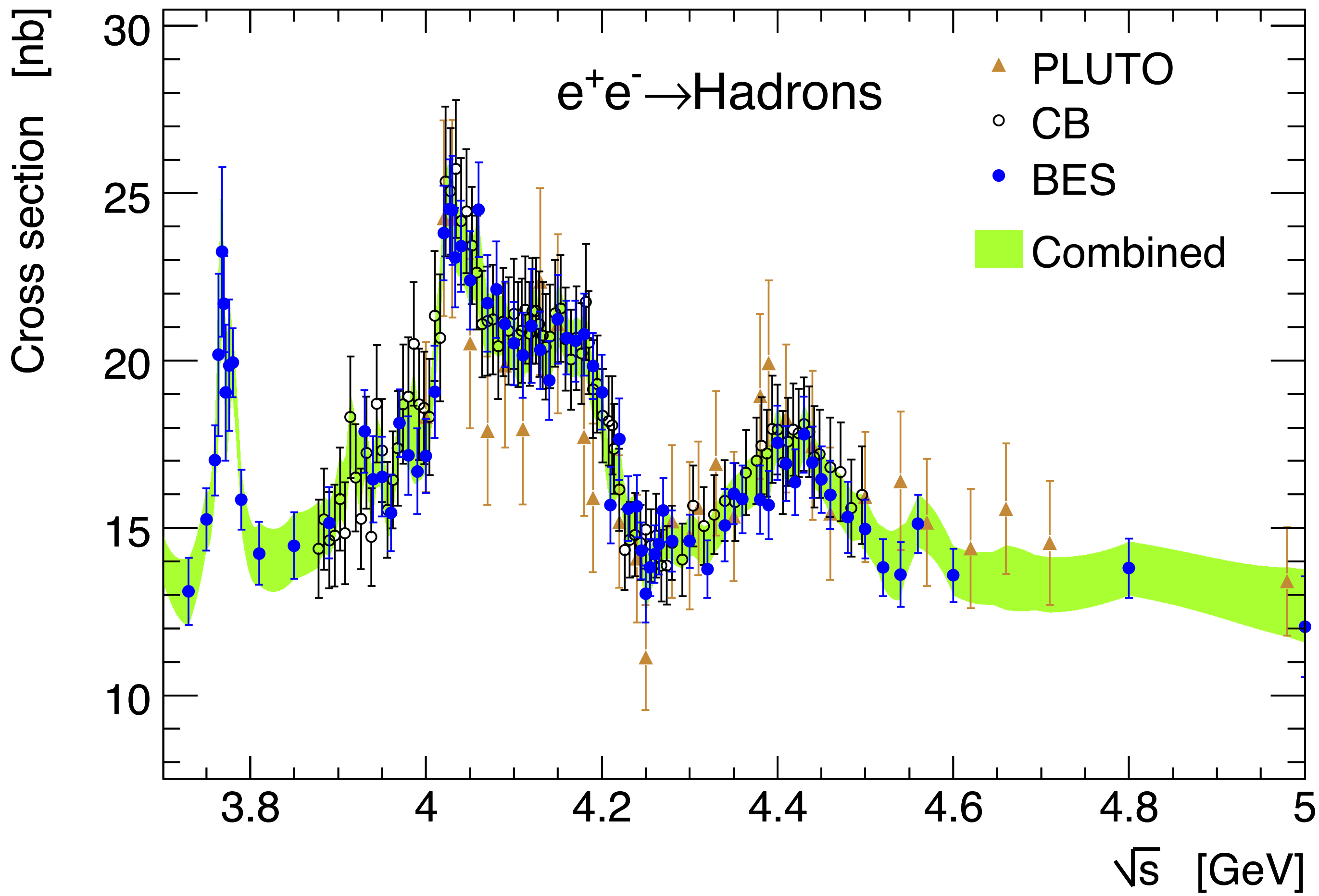


Energy range [GeV]	1.8 - 2.0	2.0 - 3.7
Data	7.71 ± 0.32	25.82 ± 0.61
pQCD	8.30 ± 0.09	25.15 ± 0.19
Difference	0.59 → dual	agree < 1σ

pQCD evaluated from 4 loops + $O(\alpha_s^2)$ quark mass corrections

Uncertainties: α_s, truncation, FOPT/CIPT, m_q

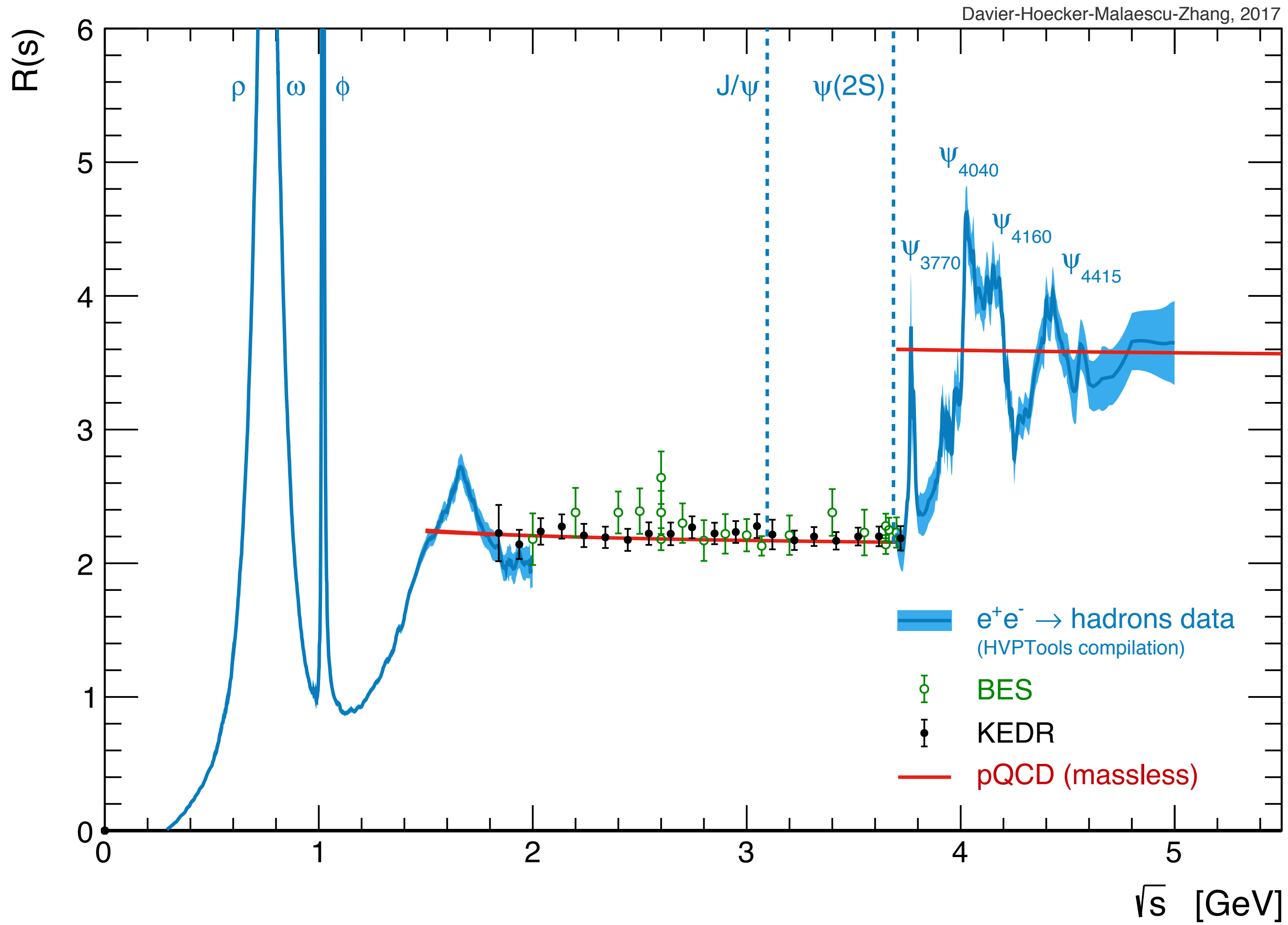
Contribution from the Charm Resonance Region



$7.29 \pm 0.05 \pm 0.30 \pm 0.00 \Rightarrow 1.05\%$ of $a_\mu^{had,\,LO}$

stat sys cor

$R_{ee}(s) \rightarrow$ Hadrons



Performed a non-trivial test:

$a_\mu^{had,\,LO}$ from R_{ee} agrees with that from sum of exclusive channels

Status of a_μ

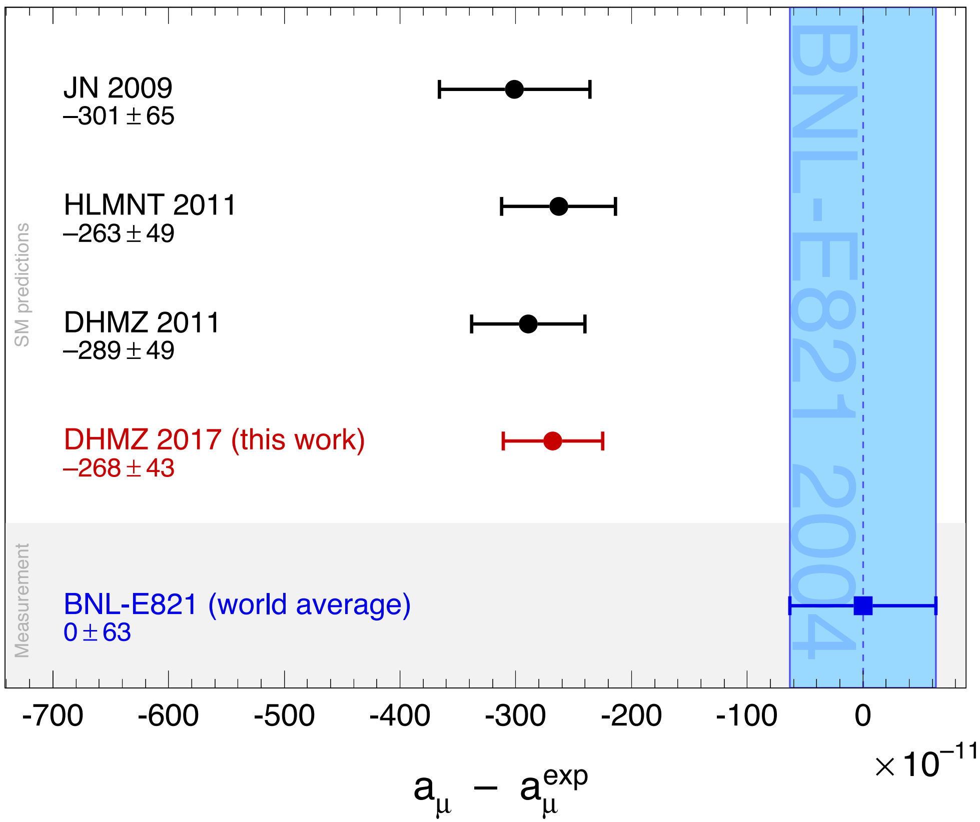
Include other contributions in unit of 10^{-10}:

QCD NLO: -9.87 ± 0.07; NNLO: 1.24 ± 0.01; LBL: 10.5 ± 2.6

EW: 15.36 ± 0.10

QED: 11 658 471.895 ± 0.008

$\Rightarrow a_\mu$ = 11 659 182.3 ± 3.4 ± 2.6 ± 0.2 (4.3_{tot})



In comparison with the direct measurement:

11 659 209.1 ± 5.4 ± 3.3 (6.3_{tot})

$\Rightarrow$ 26.8 ± 7.6 (3.5σ)

Summary & Perspectives

- $a_\mu^{had, LO}$ reaches 0.5% relative precision
  - A factor of ~2 improvement over last ~13 years
  - The precision is partially limited by the inconsistency between different measurements
- Need more precise and consistent data sets
  - Babar & CMD3 aim for 0.3% syst for $\pi^+\pi^-$
  - Important to improve $\pi^+\pi^-\pi^0$ and K^+K^- in [1-2] GeV mass range
- Uncertainty on LBL will be a next candidate to improve
  - Lattice QCD?
- Good perspective from direct measurements
  - Fermilab & JPARC aim for an improvement by a factor ~4