Tensions in e+e- data for the muon g-2

Michel Davier (LAL – Orsay)

- the dominant $\pi^+\pi^-(\gamma)$ channel
- the $K^+K^-(\gamma)$ channel
- the inclusive region
-

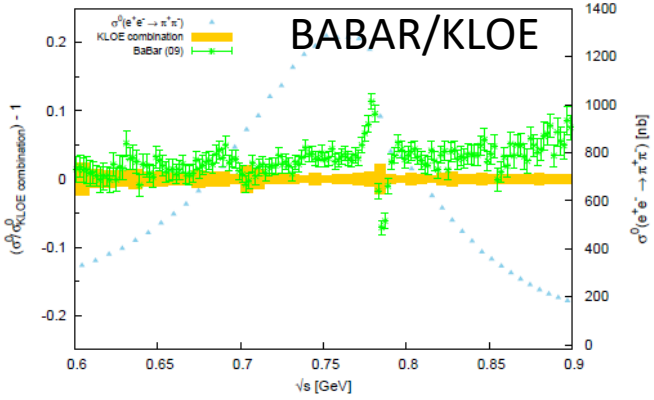
g-2 Theory Initiative
Mainz, 18-22 June 2018

Introductory remarks

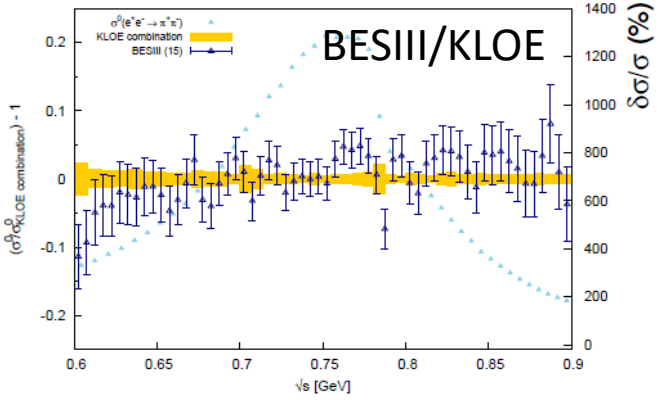
- Two steps: (1) acquire good data (2) combination of all data
- HVP dispersive approach depends directly on quality of data
- Statistics
- Systematic uncertainties: crucial aspect (needs information from experiment on different sources, their mass dependence, their correlations between channels and between different experiments)
- Focus here on areas where there are tensions which require better understanding and necessitate proper treatment
- We need reliable prediction: better to be on the conservative side

The BABAR/KLOE discrepancy for $\pi\pi\gamma(\gamma)$

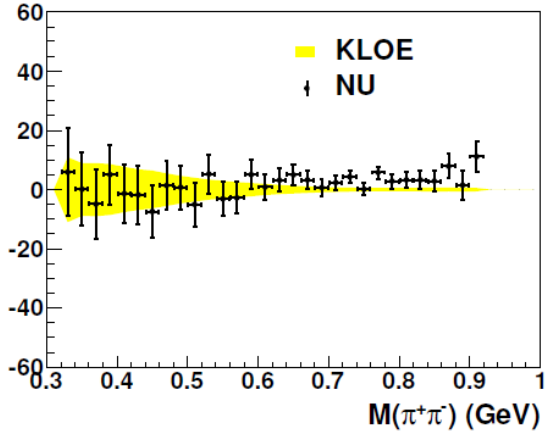
- BABAR and KLOE measurements most precise to date, but in poor agreement
- Others are in between, but not precise enough to decide
- New KLOE-KT combination of their 3 measurements: systematic uncertainties squeezed
  $\Rightarrow$ discrepancy worse

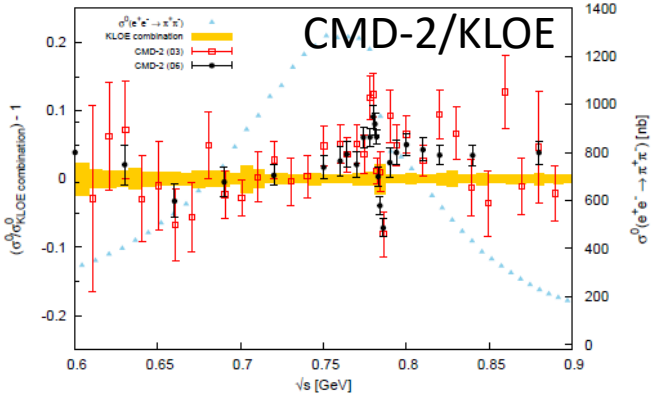


(b) KLOE combination vs. BaBar

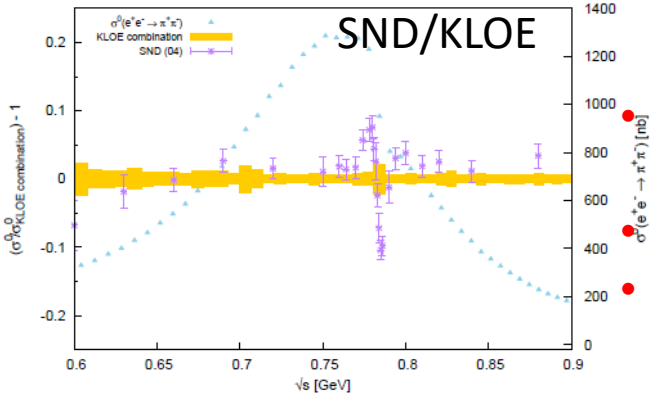


(c) KLOE combination vs. BESIII





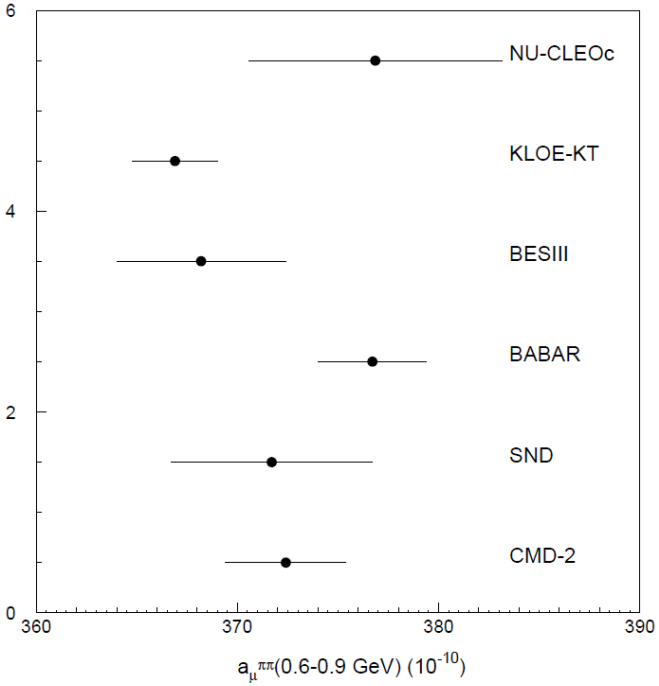
(d) KLOE combination vs. CMD-2



(e) KLOE combination vs. SND

- Direct comparison of cross sections
- Slope / KLOE in all expts
- ρ-ω interference deviation not accounted for

The BABAR/KLOE discrepancy for $\pi\pi\gamma(\gamma)$



- BABAR and KLOE measurements most precise to date, but in poor agreement
- Others are in between, but not precise enough to decide

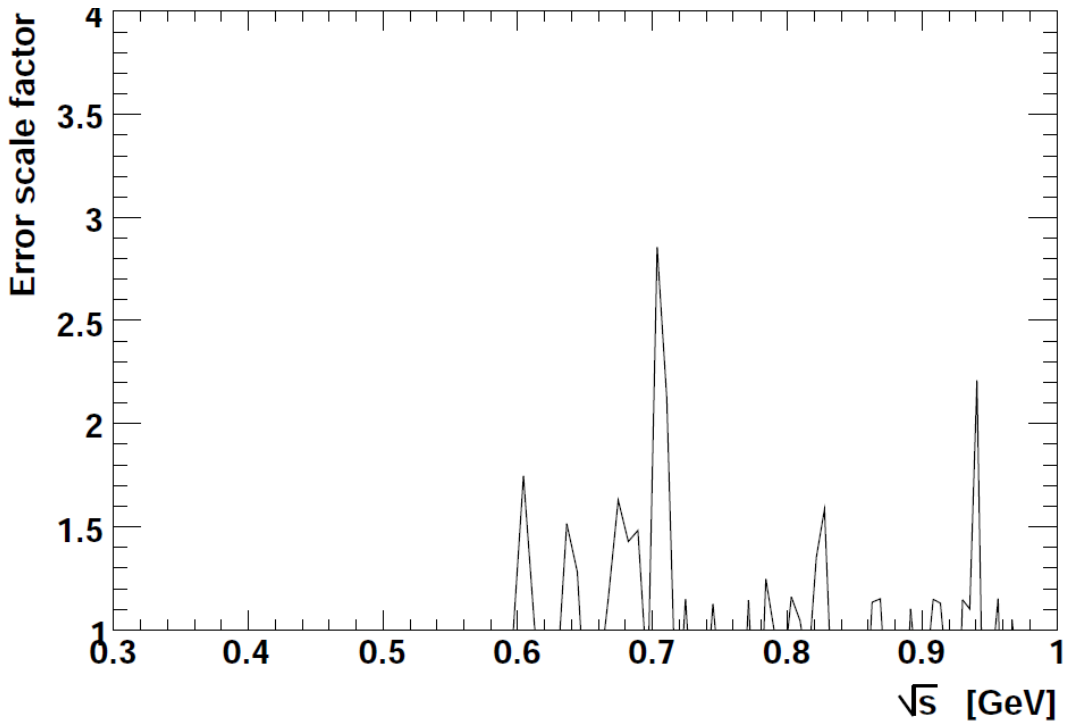
- No progress achieved in understanding the reason(s) of the discrepancy
- consequence: accuracy of combined results degraded

- however imperative to improve accuracy of prediction (forthcoming g-2 results at FNAL, J-PARC)

- Other efforts at VEPP-2000 underway (CMD-3, SND)

- new independent BABAR analysis in progress:
  full data sample, no PID used for $\mu\mu/\pi\pi$ separation (largest systematics of previous results), statistics x8

Direct comparison of the 3 KLOE measurements



→ Local χ^2 /ndof test of the local compatibility between KLOE 08 & 10 & 12, taking into account the correlations: some tensions observed

→ Does not probe general trends of the difference between the measurements (e.g. slopes in the ratio)

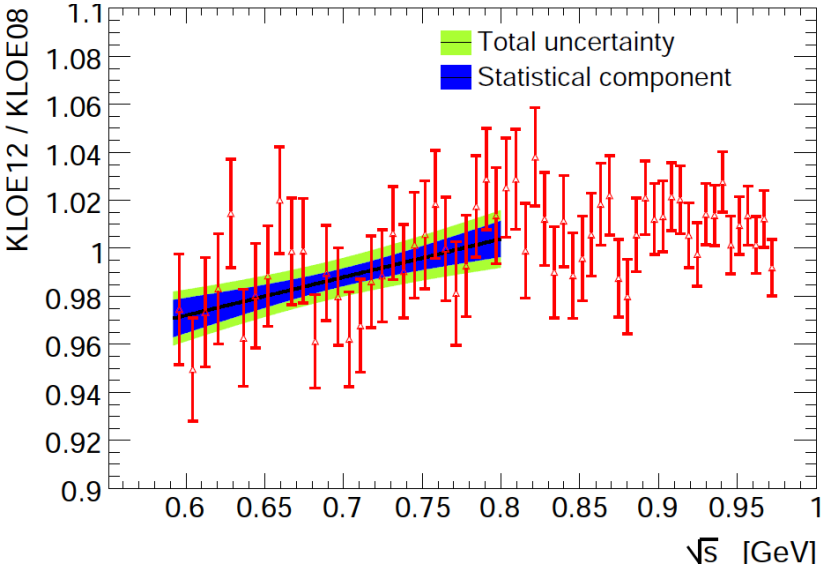
→ Compute ratio between pairs of KLOE measurements

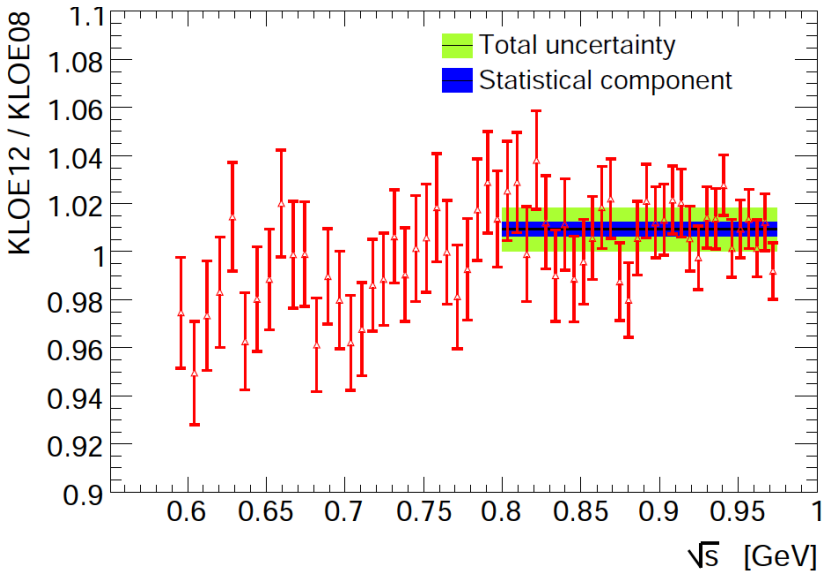
→ Full propagation of uncertainties and correlations using pseudo-experiments (agreement with analytical linear uncertainty propagation)

Direct comparison of the 3 KLOE measurements

→ Fitting the ratio taking into account correlations

→ Full propagation of uncertainties and correlations – 3 methods yielding consistent results: ±1σ shifts of each uncertainty, pseudo-experiments and fit uncertainties from Minuit



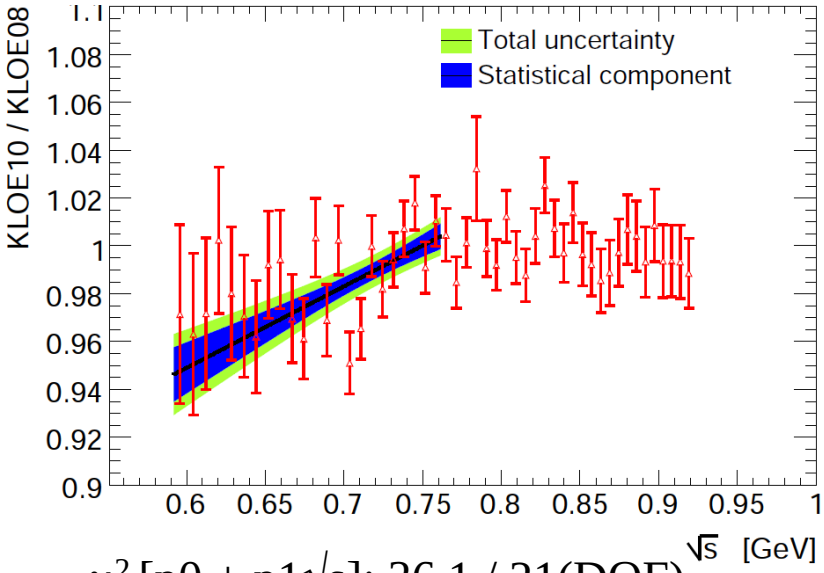


χ^2 [p0 + p1√s]: 20.7 / 27(DOF)
p-value= 0.80
p0 : 0.876 ± 0.056
p1 : 0.159 ± 0.081

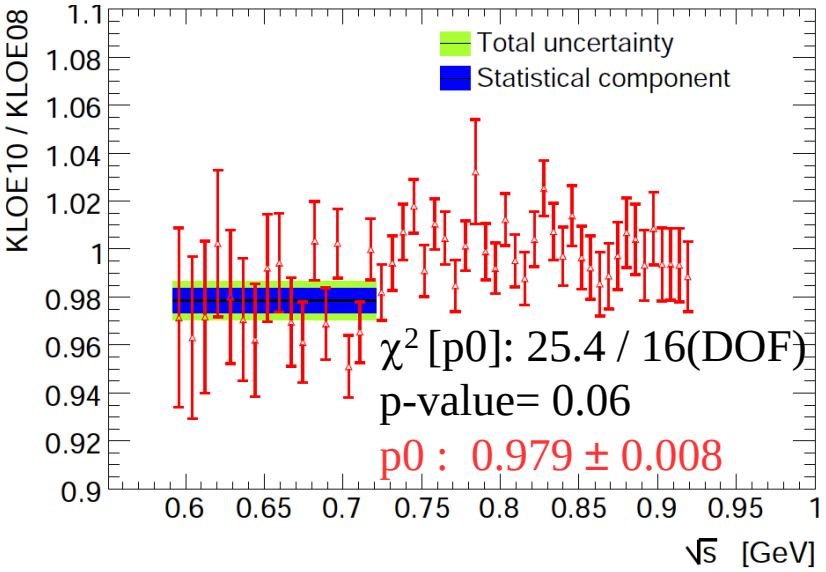
χ^2 [p0]: 38.4 / 30(DOF)
p-value= 0.14
p0 : 1.009 ± 0.009

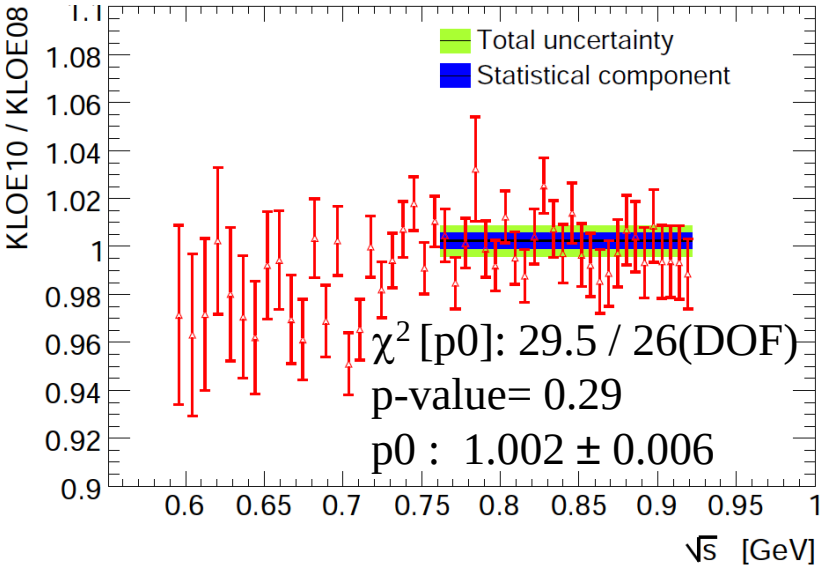
→ Significant shift and slope (~2σ) at low √s, no significant shift at high √s

Direct comparison of the 3 KLOE measurements



χ^2 [p0 + p1√s]: 36.1 / 21(DOF)
p-value= 0.02
p0 : 0.745 ± 0.085
p1 : 0.341 ± 0.117





→ Significant shift and slope (~2.5-3σ) at low √s, no significant shift at high √s

NLO BABAR measurement μμγ(γ), ππγ(γ),KKγ(γ)

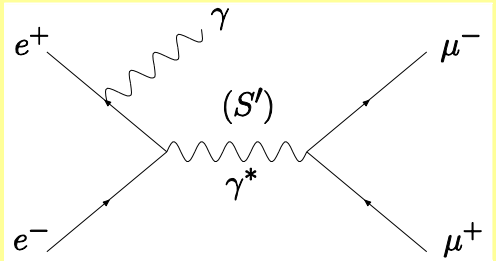
$e^+e^- \to \mu^+\mu^-\gamma\,(\gamma)$ and $\pi^+\pi^-\gamma\,(\gamma)$, $K^+K^-\,\gamma(\gamma)$ measured simultaneously
Kinematic fits with additional small-angle ISR or detected (ISR or FSR) photon

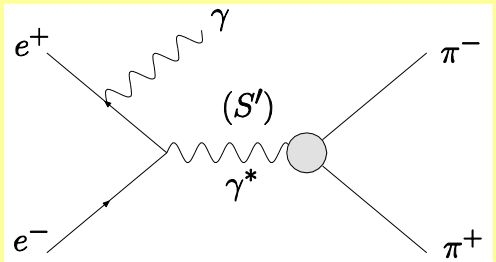
ee and ISR lumi drops out

only expt so far measuring NLO photons

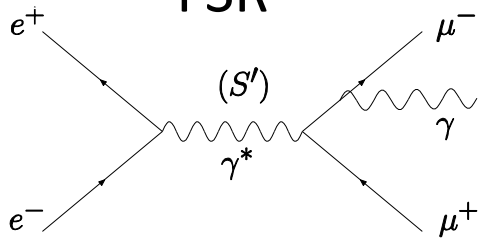
ππ/μμ/KK separated by particle ID

ISR



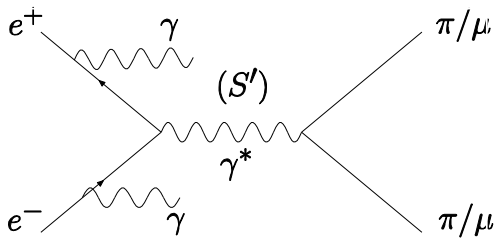


FSR

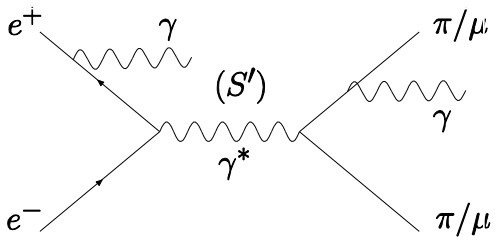


LO FSR negligible for ππ at s~$(10.6\ \text{GeV})^2$, but checked by measuring ISR-FSR interference (charge asymmetry, PRD 2014)
Is it the case for expts at lower s?

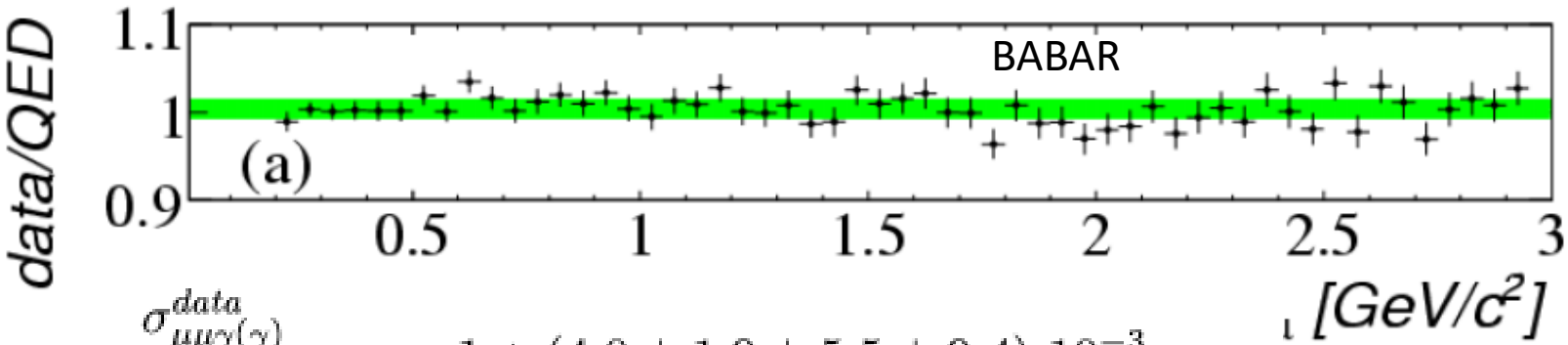
ISR + add. ISR



ISR + add. FSR



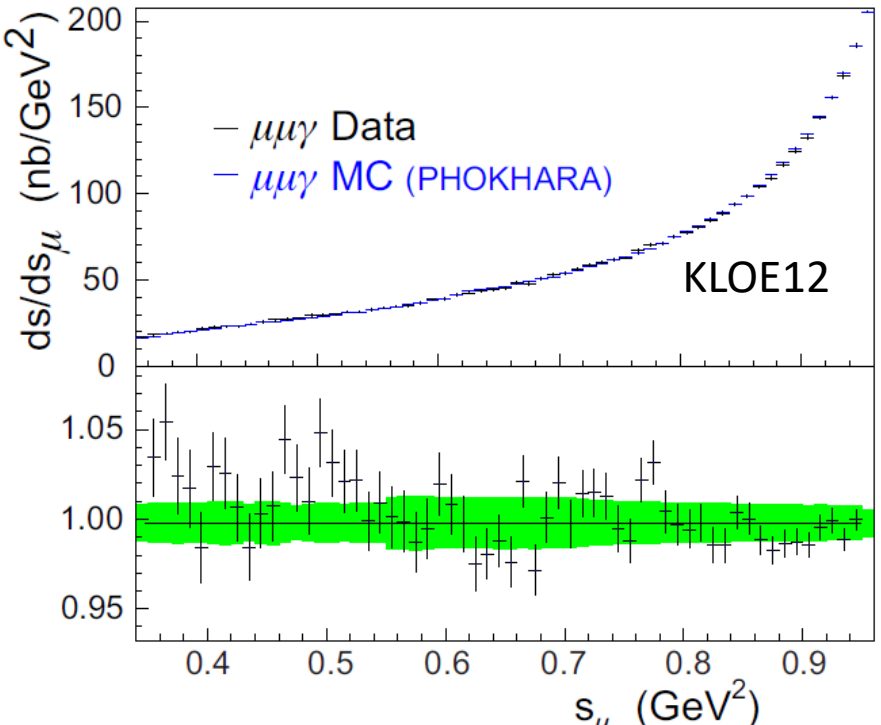
QED Test with $\mu\mu\gamma$ sample



$$\frac{\sigma^{data}_{\mu\mu\gamma(\gamma)}}{\sigma^{NLO\ QED}_{\mu\mu\gamma(\gamma)}} = 1 + (4.0 \pm 1.9 \pm 5.5 \pm 9.4)\ 10^{-3}$$

ISR γ efficiency 3.4 syst.
trigger/tracking/PID 4.0

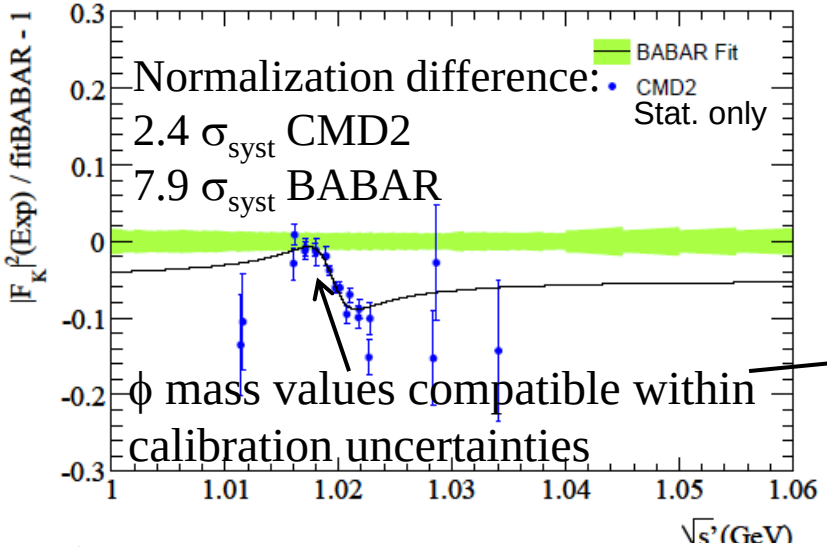
BaBar ee luminosity

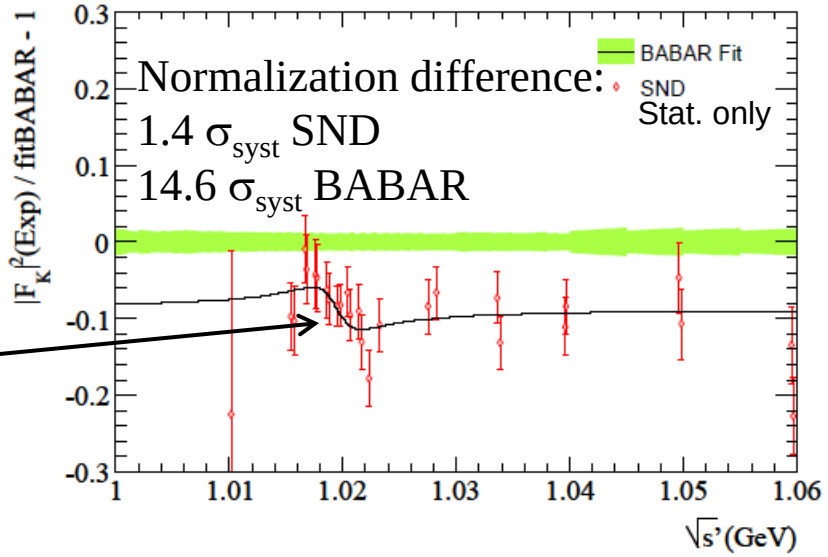


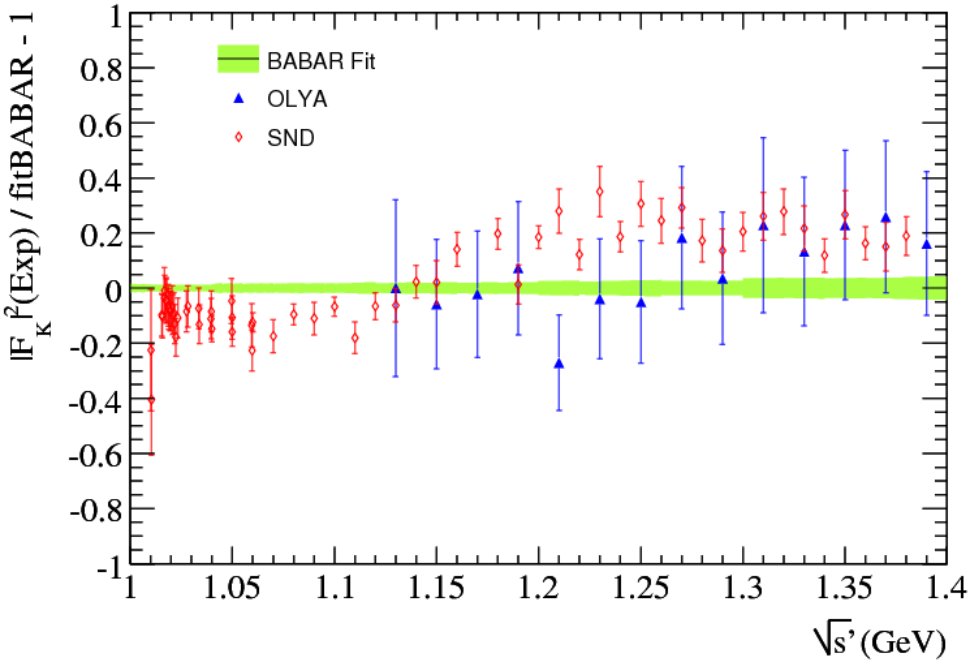
KLOE12 $0.9981 \pm 0.0015\_stat \pm syst?$

slope?

K^+K^- : Comparison BABAR/previous CMD-2/SND





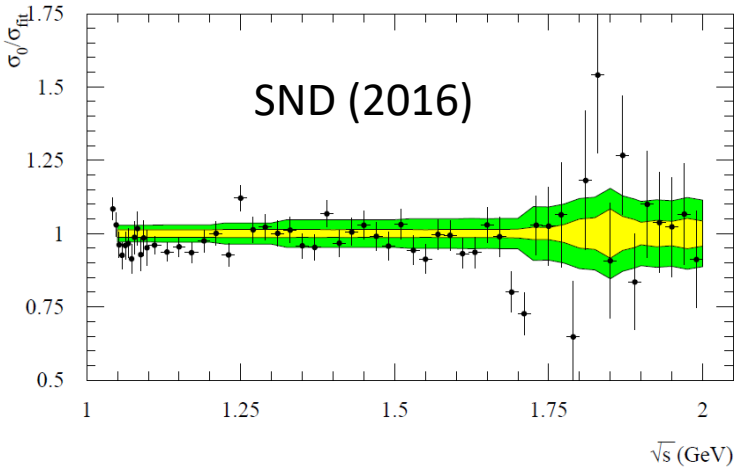


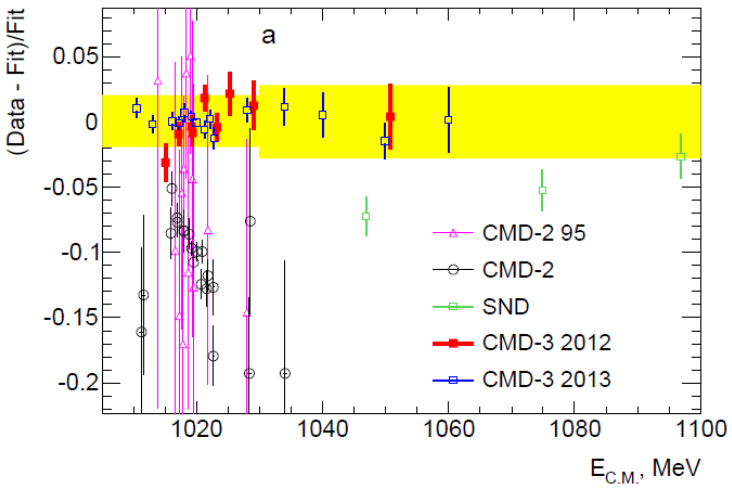
New developments:

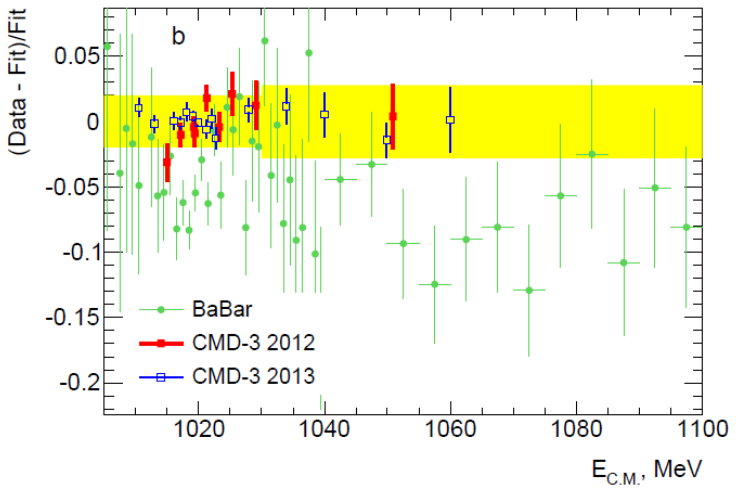
- recent SND measurement at VEPP-2000 disagrees with older SND VEPP-2M results in 1.15-1.4 GeV and agrees with BABAR
- results from CMD-3 (2016) on the $\Phi(1020)$ strongly disagree with older published CMD-2 data

K^+K^- : Comparison to recent VEPP-2000 results

- 2016: recent SND measurement at VEPP-2000 above the $\Phi(1020)$ disagrees (20%) with older SND VEPP-2M results in 1.15-1.4 GeV and now agrees with BABAR
- 2017: results from CMD-3 on the $\Phi(1020)$ strongly disagree with older published CMD-2 data





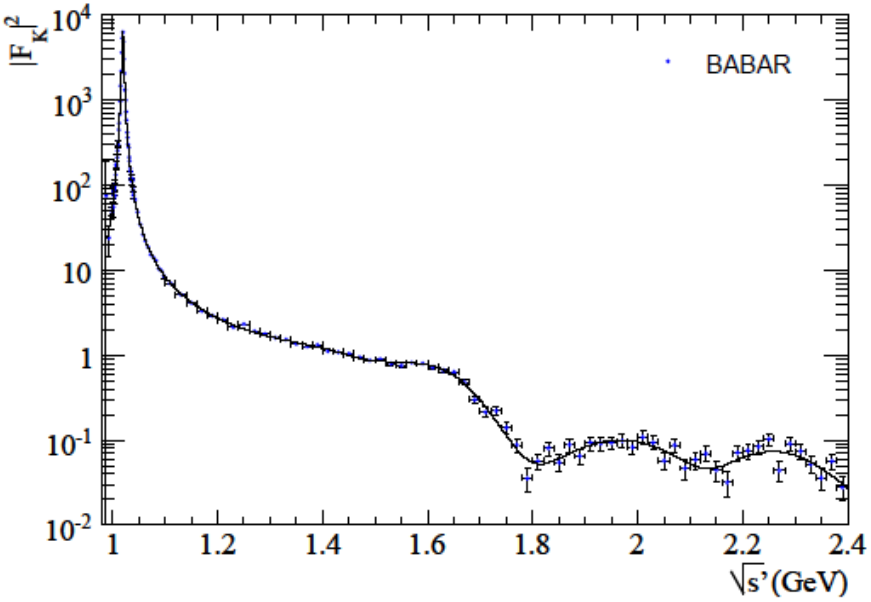


The $\phi(1020)$ parameters

BABAR: m_ϕ, Γ_ϕ, and ϕ cross section obtained from a VDM fit of the form factor

$m_\phi = (1019.51 \pm 0.02 \pm 0.05)$ MeV
$\Gamma_\phi = (4.29 \pm 0.04 \pm 0.07)$ MeV

good agreement with PDG:
$m_\phi = 1019.455 \pm 0.020$ MeV
$\Gamma_\phi = 4.26 \pm 0.04$ MeV



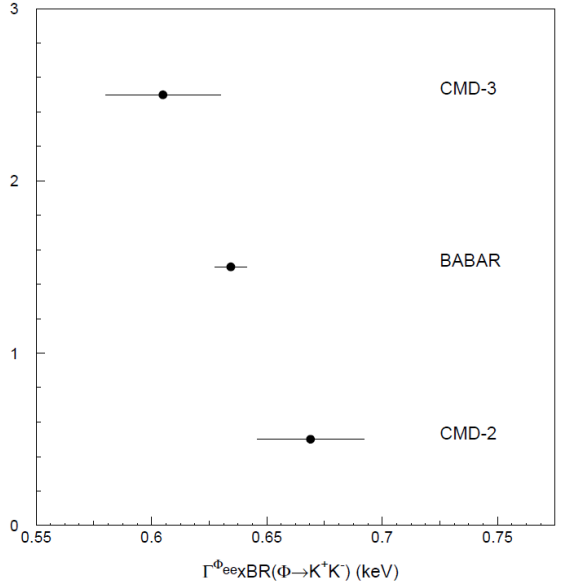
integrating ϕ peak $\Rightarrow \Gamma^{\phi}_{ee} \times B(\phi \to K^+K^-)$

BABAR: $(0.6344 \pm 0.0059_{exp} \pm 0.0033_{fit} \pm 0.0015_{cal})$ keV (1.1%)

CMD-2: $(0.605 \pm 0.021 \pm 0.013)$ keV (4.1%)]

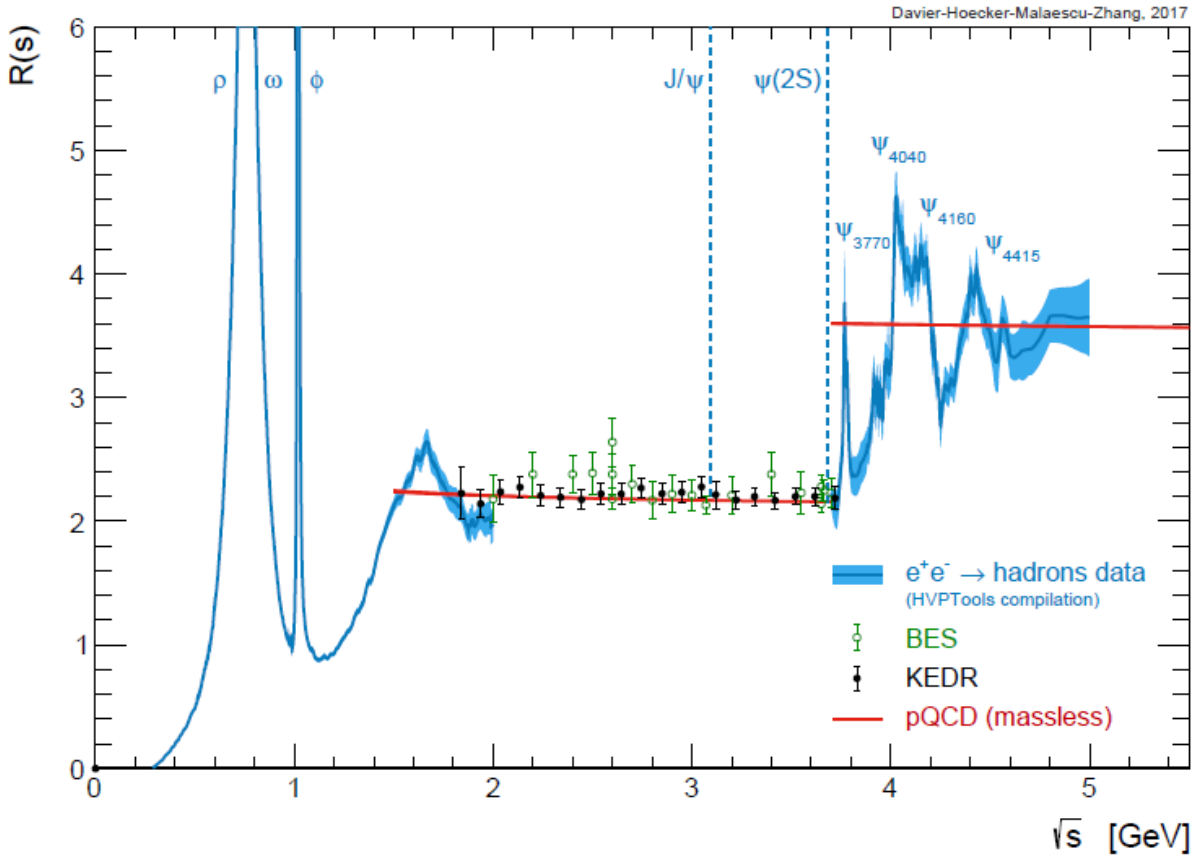
CMD-3: $(0.669 \pm 0.001 \pm 0.022 \pm 0.005)$ keV (3.4%)]

- K detection at threshold delicate for scan experiments
- Clear advantage of ISR (K strongly boosted)



Combined R determination (DHMZ)

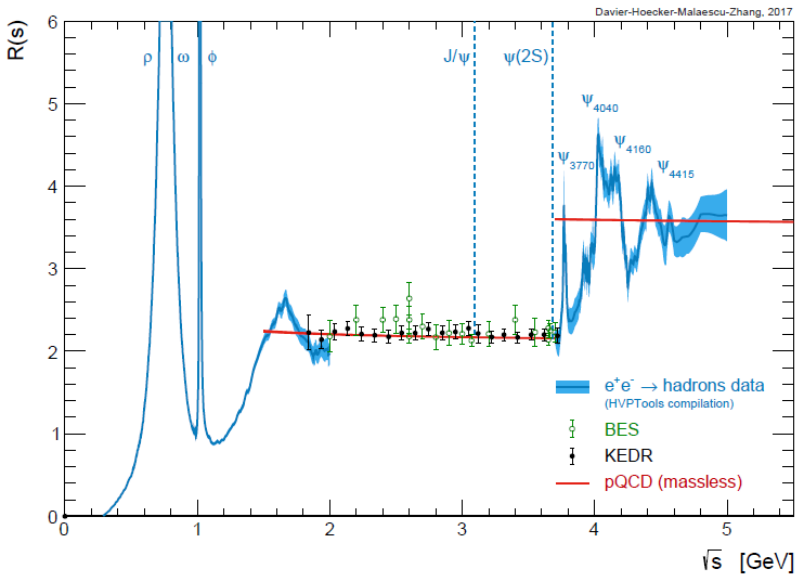
- R obtained by summing up all exclusive cross sections up to 2 GeV
- All significant channels covered up to 1.8 GeV (BABAR dominated)
- Could miss opening of new channels above 1.8 GeV (ex. new results on $3\pi^+3\pi^-\pi^0$)
- Matches well with inclusive measurements, especially most precise KEDR result



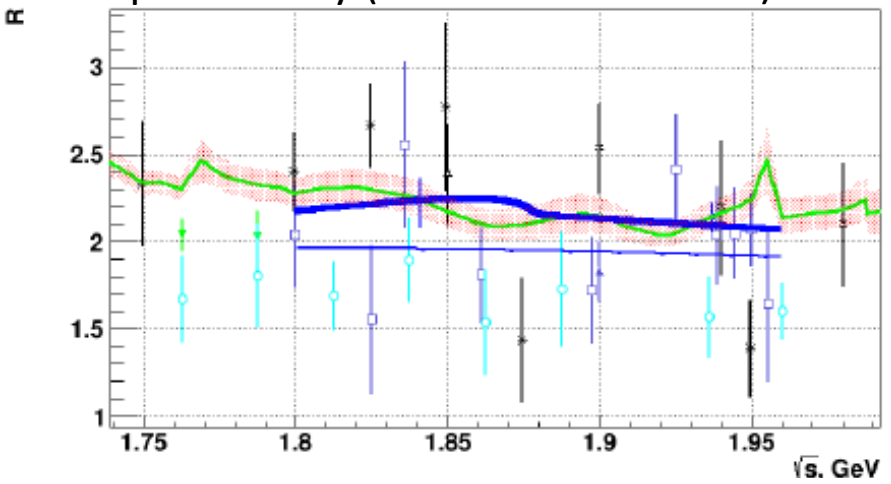
Combined R determinations

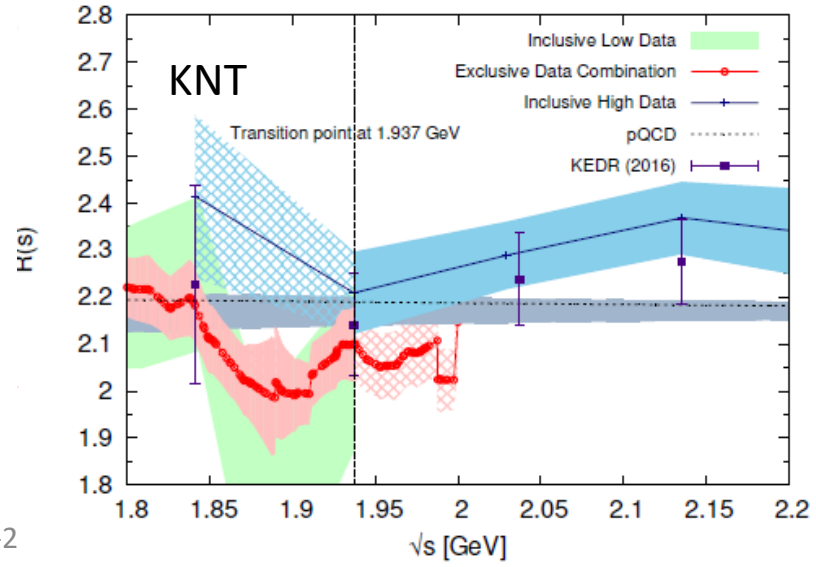
- Compare DHMZ, KNT, preliminary Novosibirsk
- Differences in values and errors? Effect of missing channels?

DHMZ



preliminary (Genia Solodov here)





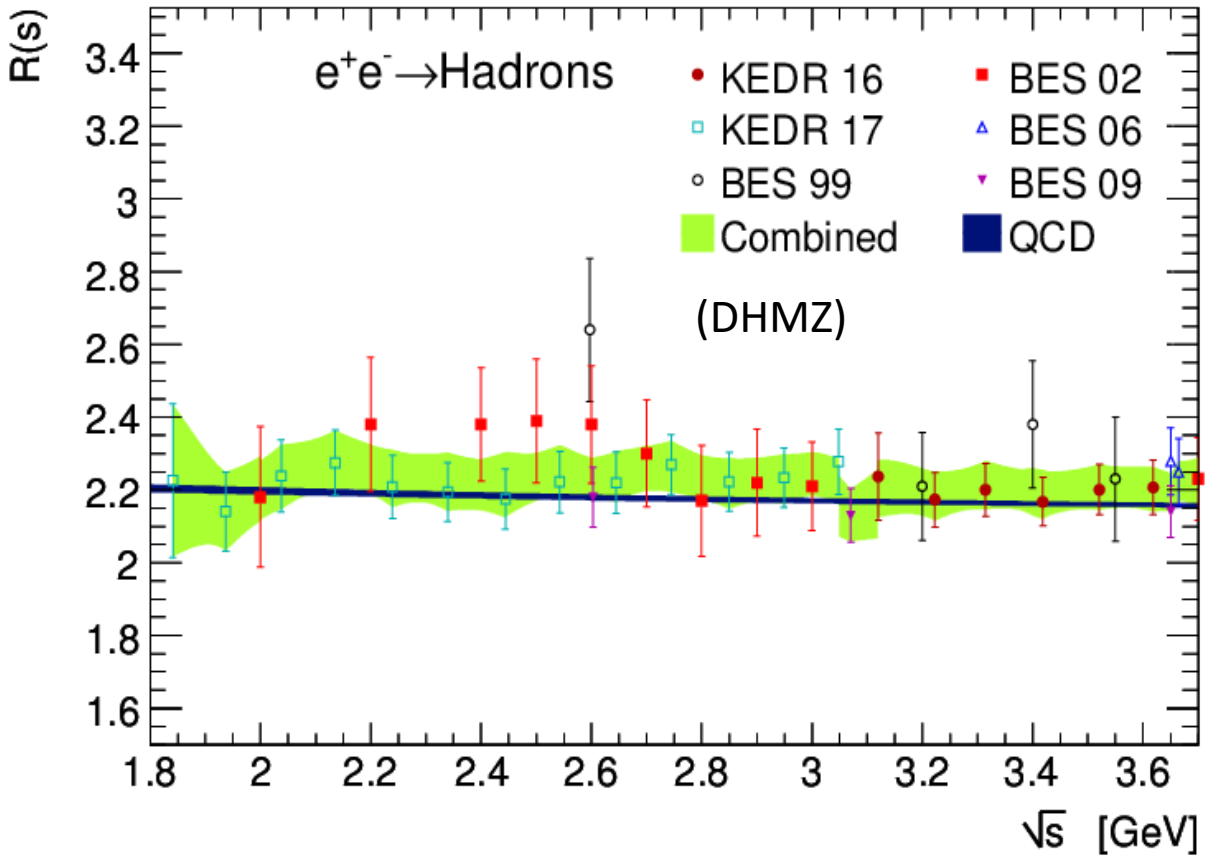
Inclusive measurements 1.8 – 3.7 GeV region

Progress in R data

BES → BESII → BESIII
trend downward

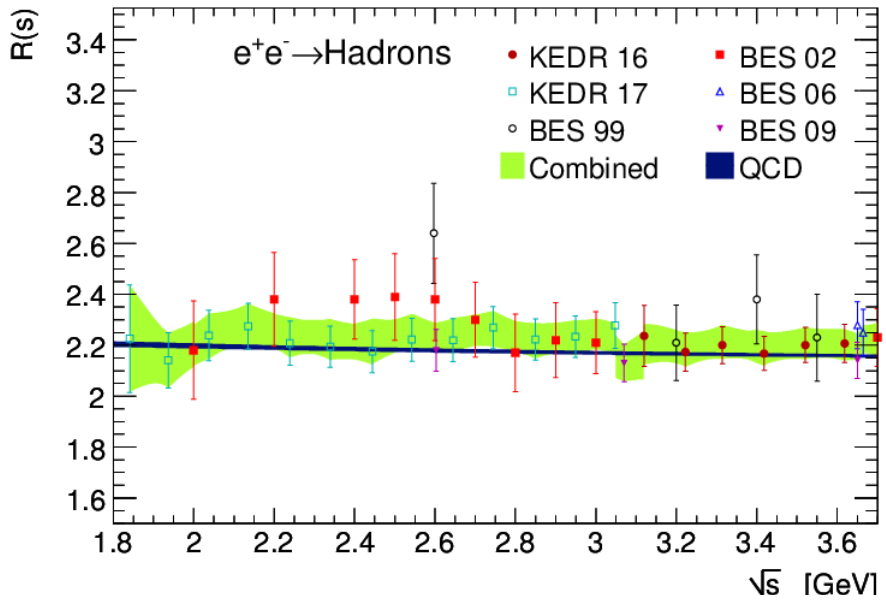
More precision from KDR
agreement with pQCD

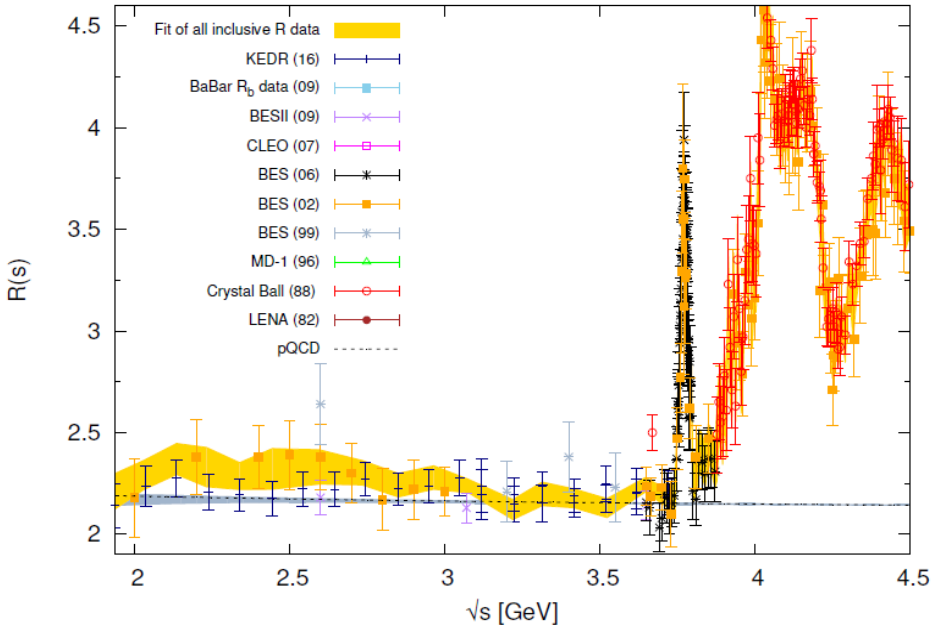
Large data sample collected
at BESIII, analysis in progress



→ evaluation with pQCD (at 4 loops + $O(\alpha_s^2)$ quark mass corrections)
→ uncertainties: α_s, truncation of perturbative series, CIPT/FOPT, m_q
→ 1.8-2.0 GeV: 7.71 ± 0.37 (data excl.); 8.30 ± 0.09 (QCD) $[10^{-10}]$
→ 2.0-3.7 GeV: 25.82 ± 0.61 (data incl.); 25.15 ± 0.19 (QCD); agreement within 1σ
⇒ DHMZ: use pQCD and add systematic uncertainty 0.59 (data-QCD 1.8-2)

Inclusive measurements 1.8 – 3.7 GeV region





Difference in DHMZ/KNT data combination.

Same data, few experiments

Why? Apparently, different weights given to experiments in the combination

Conclusions

- BABAR/KLOE $\pi\pi$ discrepancy unsolved
- KLOE-KT combination minimizing uncertainty enhances the tension
- Other existing results consistent with either BABAR or KLOE. More precision needed.
- Fortunately, new precise measurements in progress $\rightarrow$ end 2018

  CMD-3, SND (preliminary results shown here), BABAR
- Hopefully the overall situation for $\pi\pi$ will be better understood

- Large discrepancies in K+K-: CMD-2/CMD-3, BABAR in between

- Trend of inclusive data above 1.8 GeV toward pQCD. More precision needed and more scrutiny concerning opening channels

Backup slides

Combining the 3 KLOE measurements - $a_\mu^{\pi\pi}$ contribution

KLOE08 a_μ[0.6 ; 0.9] : 368.3 ± 3.2 [10^{-10}]
KLOE10 a_μ[0.6 ; 0.9] : 365.6 ± 3.3
KLOE12 a_μ[0.6 ; 0.9] : 366.8 ± 2.5
→Correlation matrix:

	08	10	12
08	1	0.70	0.35
10	0.70	1	0.19
12	0.35	0.19	1

→Amount of independent information provided by each measurement

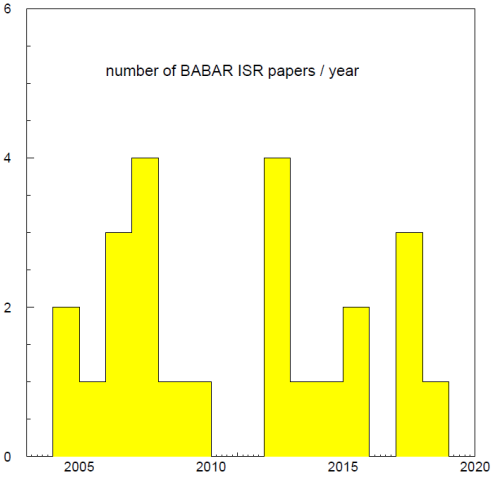
→KLOE-08-10-12(DHMZ) - a_μ[0.6 ; 0.9] : 366.5 ± 2.8 (Without χ^2 rescaling: ± 2.2)
→Conservative treatment of uncertainties and correlations (not perfectly known) in weight determination

→KLOE-08-10-12(KLOE-KT) - a_μ[0.6 ; 0.9]GeV : 366.9 ± 2.2
→Assuming perfect knowledge of the correlations to minimize average uncertainty
→Impact of the scaling factor?

The BaBar ISR program

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

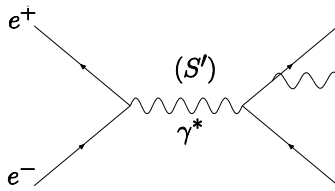
$\pi^+\pi^-$	PRL 2009; PRD 2012
K^+K^-	PRD 2013
$\pi^+\pi^-\pi^0$	PRD 2004
$2(\pi^+\pi^-)$, $K^+K^-\pi^+\pi^-$, $K^+K^-2\pi^0$, $2(K^+K^-)$	PRD 2007; PRD 2012; PRD 2012
$K^0_S K^{+-}\pi^{-+}$, $K^+K^-\pi^0$, $K^+K^-\eta$	PRD 2005; PRD 2008
$2(\pi^+\pi^-)\pi^0$, $2(\pi^+\pi^-)\eta$, $K^+K^-\pi^+\pi^-\pi^0$, $K^+K^-\pi^+\pi^-\eta$	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/ψ ($\mu^+\mu^-$)	PRD 2004
$\pi^+\pi^-$, $\mu^+\mu^-$ LO ISR-FSR interference	PRD 2015



- in progress: $\pi^+\pi^-$ new method + full data sample ; $\pi^+\pi^- 3\pi^0$
- not covered: $\pi^+\pi^- 4\pi^0$, $\pi^+\pi^-\pi^0$ below 1.05 GeV, ≥7 hadrons

LO FSR in $e^+e^- \to \mu^+\mu^-\gamma(\gamma)$ and $\pi^+\pi^-\gamma(\gamma)$

- Should be subtracted
- Theoretical prediction/estimation
  QED for ee→μμγ: reliable
  model dependent estimation for ee→ππγ: very small, big uncertainty
- **Measurement through charge asymmetry**

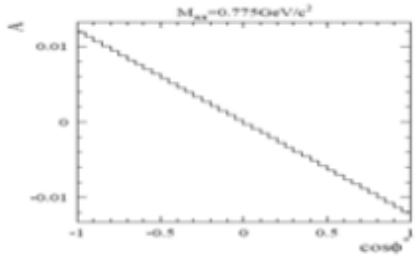


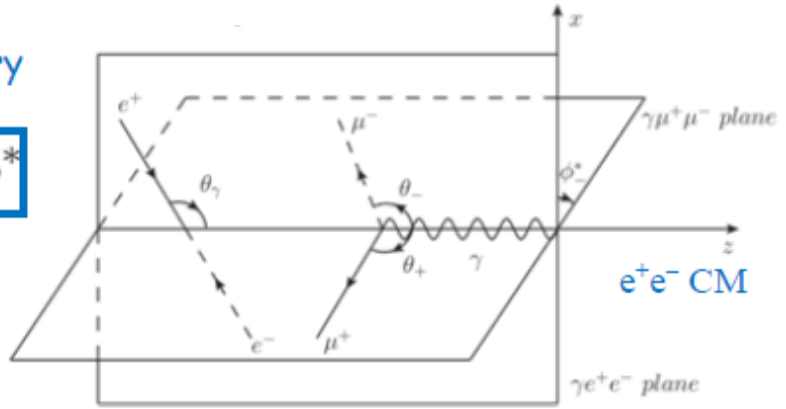
Charge asymmetry:

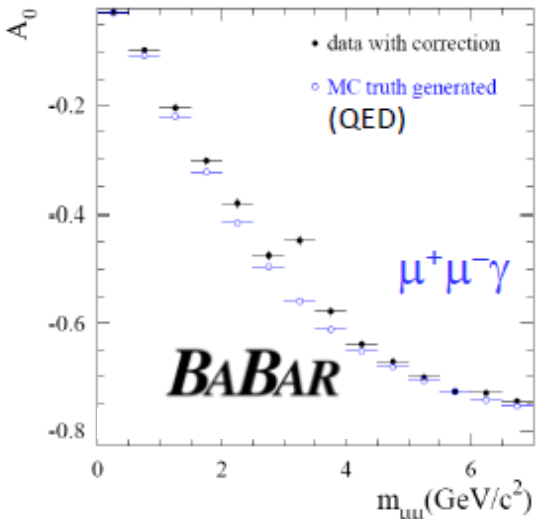
$$A = \frac{|\mathcal{M}|^2 - |\mathcal{M}_{x^+\leftrightarrow x^-}|^2}{|\mathcal{M}|^2 + |\mathcal{M}_{x^+\leftrightarrow x^-}|^2} = \frac{2\mathcal{R}e(\mathcal{M}_{\rm ISR}\mathcal{M}^*_{\rm FSR})}{|\mathcal{M}_{\rm ISR}|^2 + |\mathcal{M}_{\rm FSR}|^2}$$

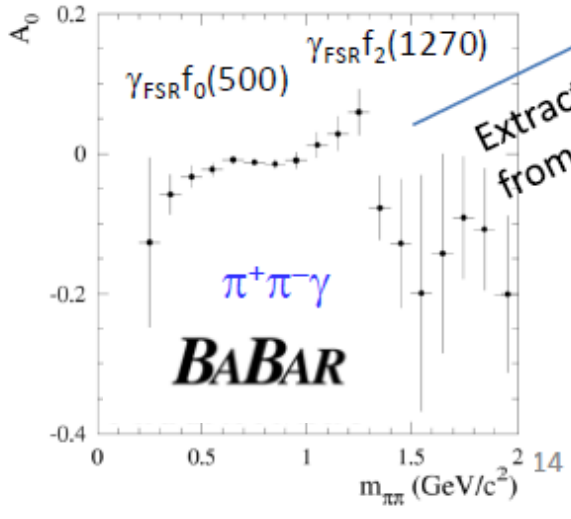
Simple charge asymmetry pattern found:

$$A(\phi^*) = A_0 \cos\phi^*$$

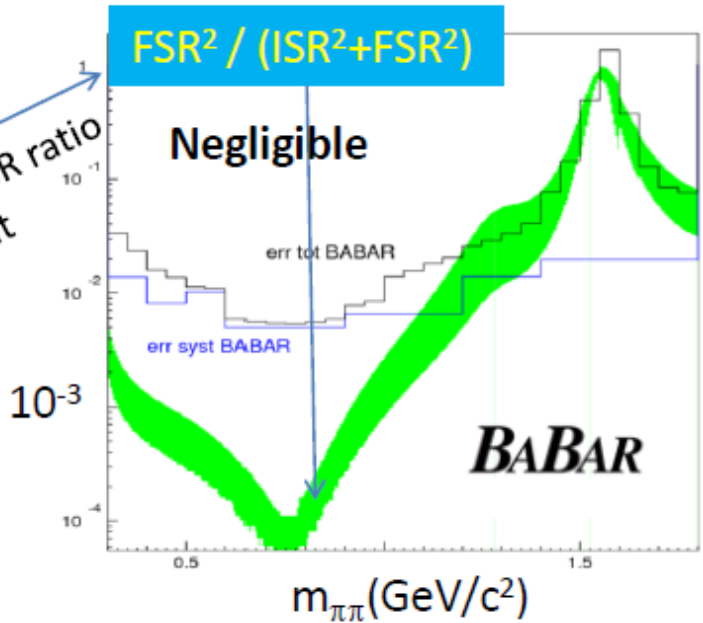




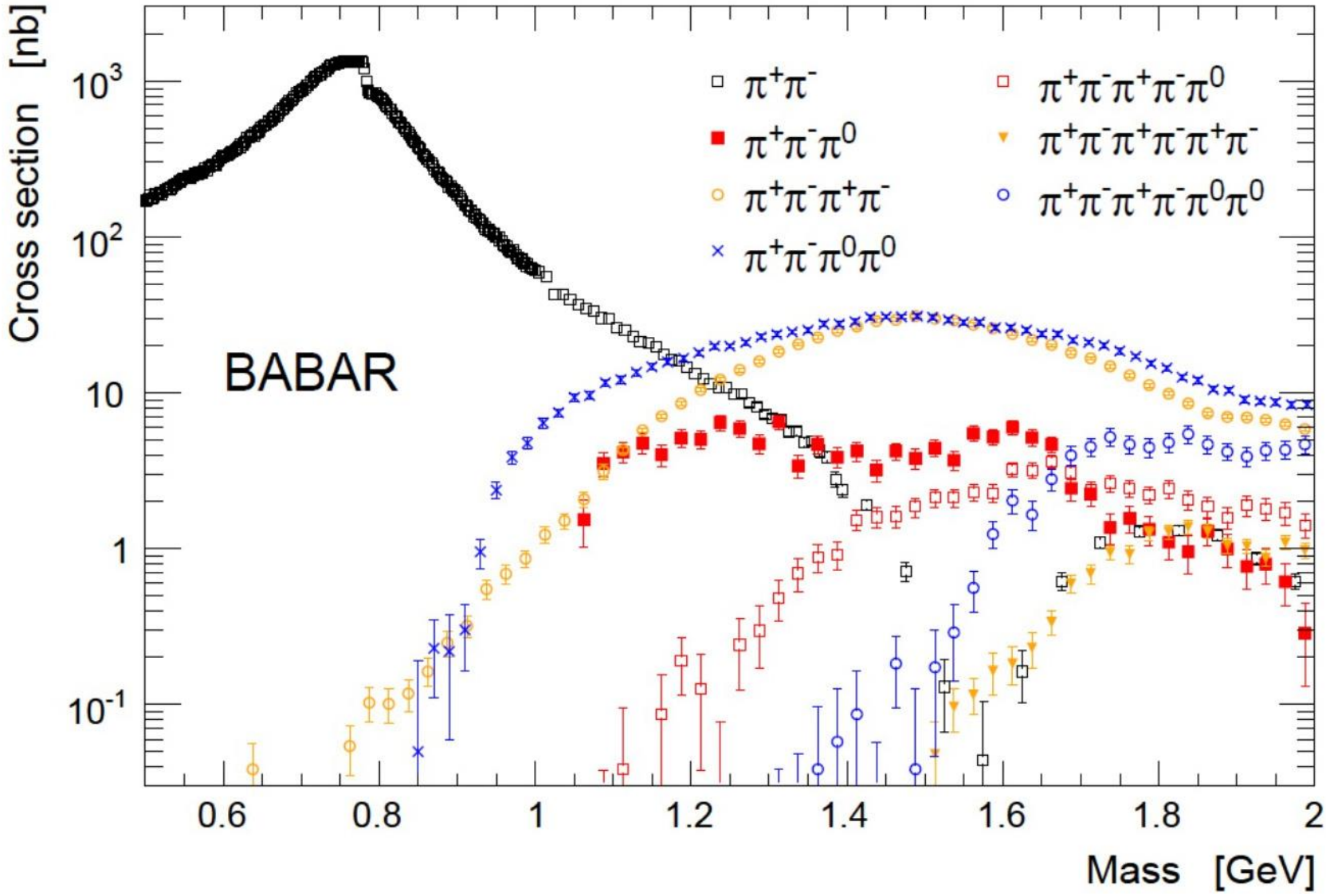




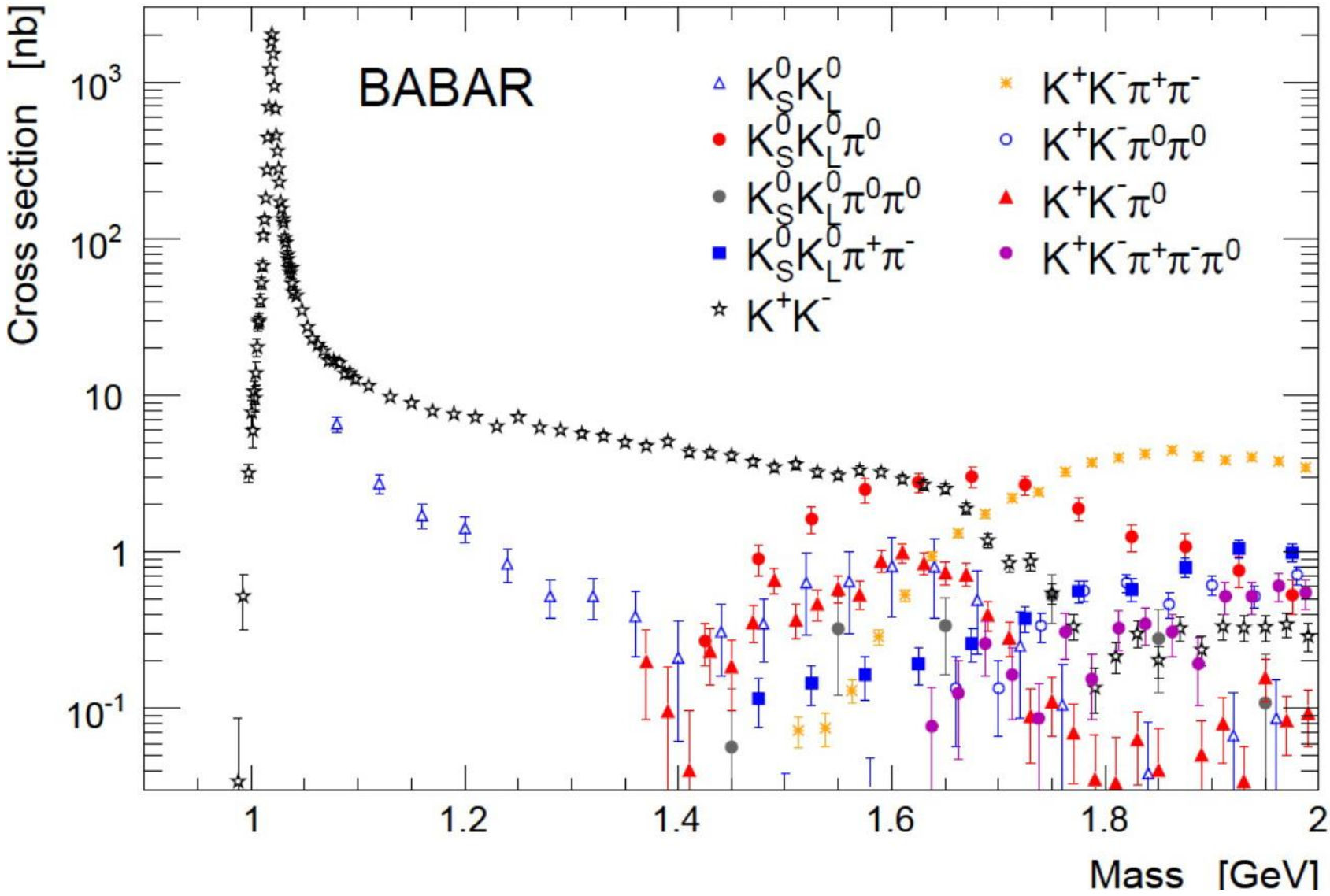
Extract FSR ratio from a fit



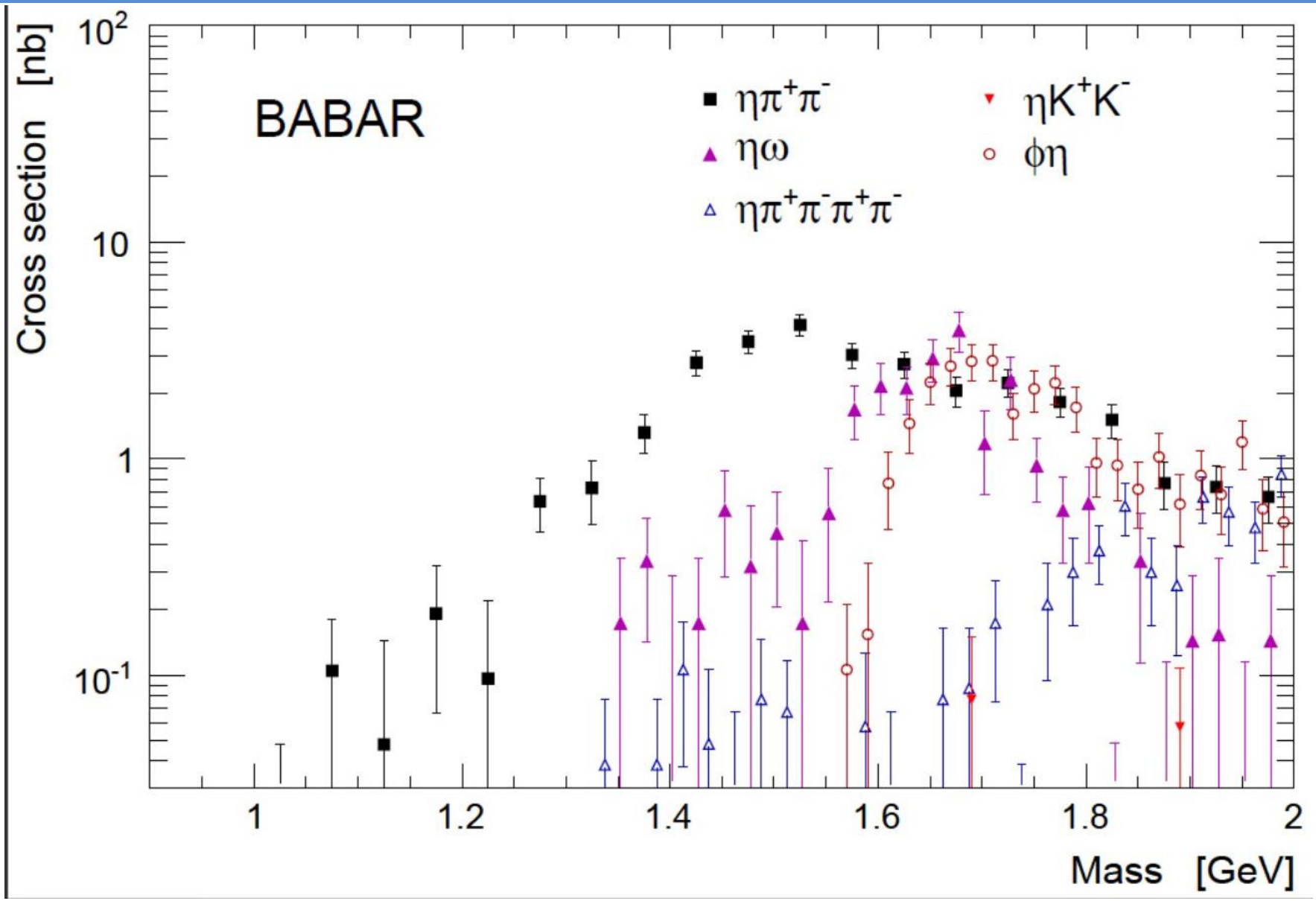
BABAR: multi-pion channels



BABAR: channels with K pair



BABAR: channels with η



Combined R determination (DHMZ)

- R obtained by summing up all exclusive cross sections up to 2 GeV
- All significant channels covered up to 1.8 GeV (BABAR dominated)
- Could miss opening of new channels above 1.8 GeV
- Matches well with inclusive measurements, especially most precise KEDR result