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Status of hadronic R Measurements (including ISR)

THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

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

Workshop on Flavour Conserving and Changing Processes (FCCP2019)
Anacapri, August 29, 2019

Outline

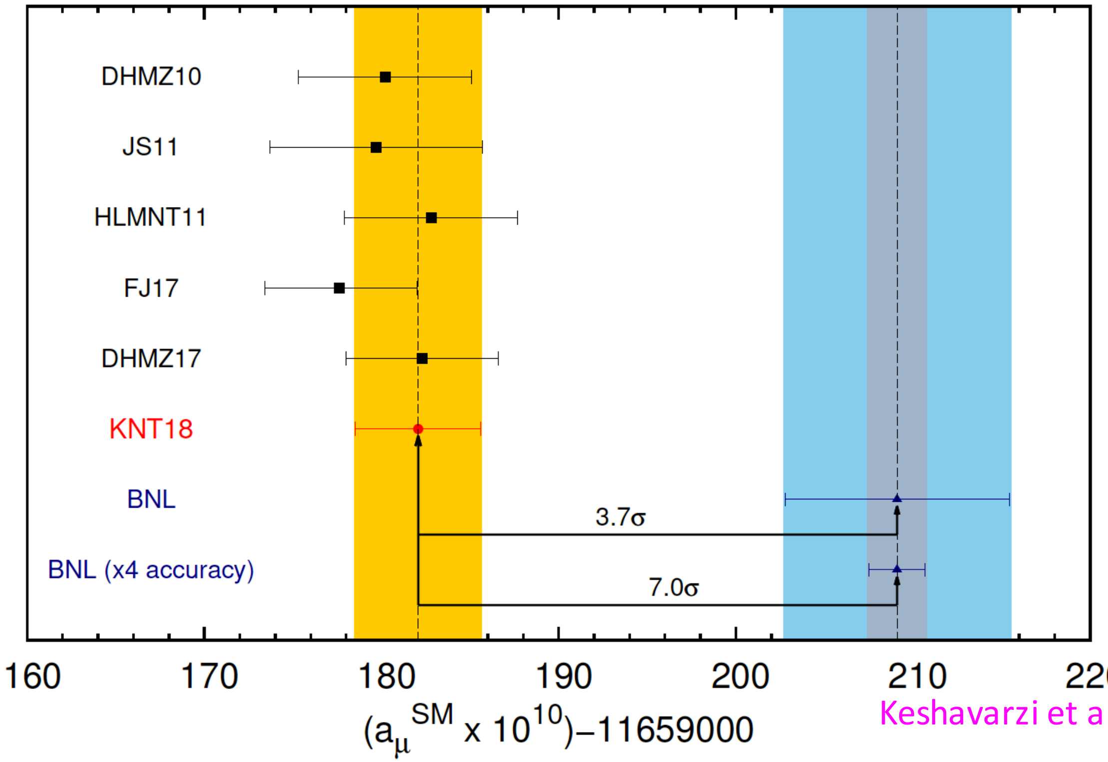
$$R = \frac{\sigma^{(0)}(e^+e^- \to \text{hadrons})}{\sigma^{(0)}(e^+e^- \to \mu^+\mu^-)}$$

- Motivation for R measurements: $(g-2)_\mu, \alpha_{em}(M_Z^2)$
- Two-Pion Channel
- Higher Multiplicity States and $K\overline{K}$
- Inclusive R Measurements
- Conclusions and Outlook

Muon Magnetic Moment: $(g\text{-}2)_\mu$

Muon Anomaly

$a_\mu = (g\text{-}2)_\mu / 2 = \alpha_{em} / 2\pi + \ldots = 0.001161\ldots.$



Keshavarzi et al. 2018

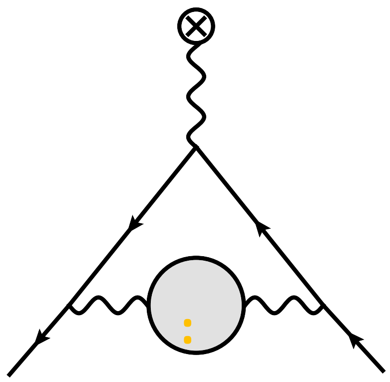
One of the most significant tests of the SM

$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = (27.05 \pm 7.28) \cdot 10^{-10}$ **(3.7σ) !!!**

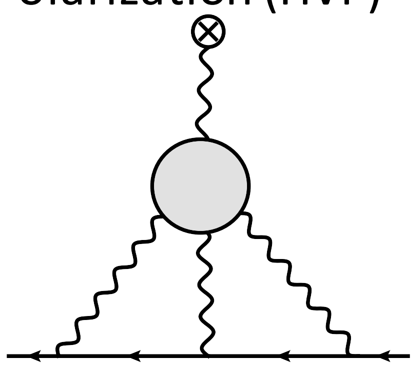
Error or New Physics ???

Muon Magnetic Moment: $(g\text{-}2)_\mu$

SM prediction limited by



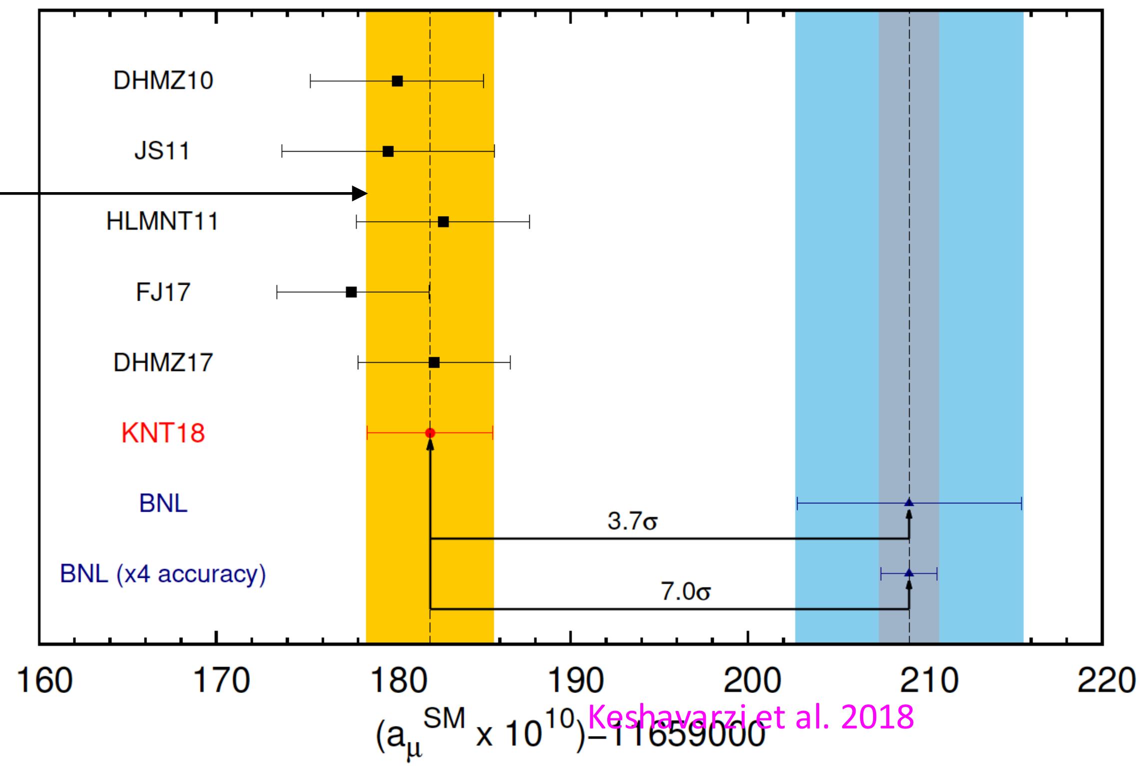
Hadronic vacuum Polarization (HVP)



Hadronic Light-by-Light scattering (HLbL)

Muon Anomaly

$$a_\mu = (g\text{-}2)_\mu / 2 = \alpha_{em} / 2\pi + \ldots = 0.001161\ldots$$



One of the most significant tests of the SM

$$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = (27.05 \pm 7.28) \cdot 10^{-10} \quad (3.7\sigma) \text{ !!!}$$

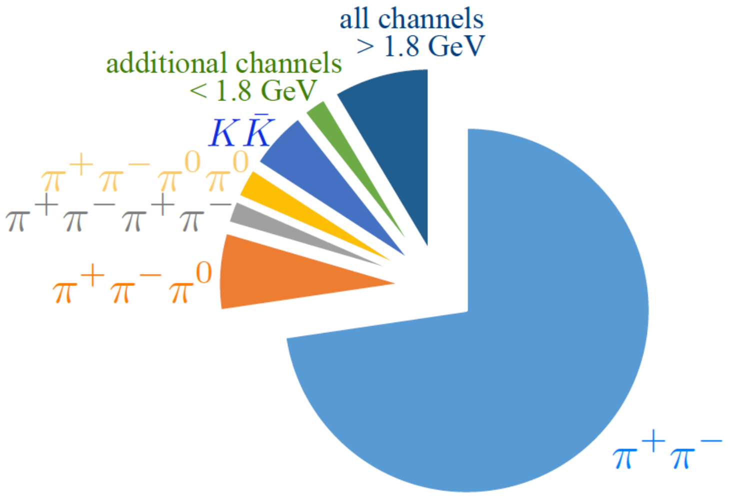
Error or New Physics ???

Hadronic Contribitutions to $(g\text{-}2)_\mu$ and $\alpha_{em}(M_Z^2)$

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

$$\sigma_{had} = \sigma(\, e^+e^- \rightarrow \; hadrons \,)$$

→ **HVP**: Hadronic Vacuum Polarization (692.3 ± **4.2**) · 10^{-10}



Most relevant channels at low energies

< -- > *exclusive* measurements

Hadronic Contribitutions to $(g\text{-}2)_\mu$ and $\alpha_{em}(M_Z^2)$

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

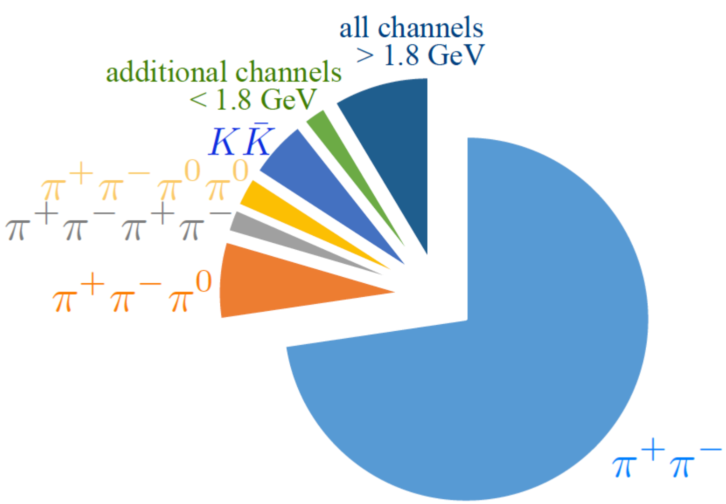
$$\sigma_{had} = \sigma(e^+e^- \to hadrons)$$

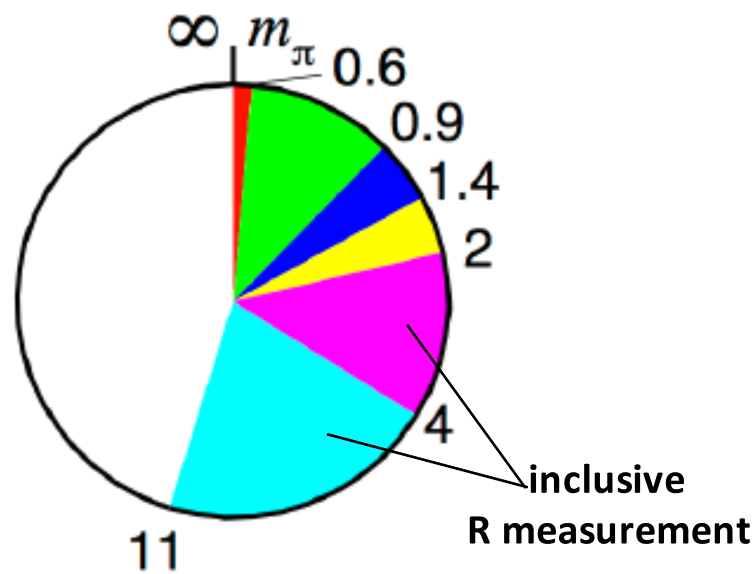
→ **HVP**: Hadronic Vacuum Polarization (692.3 ± **4.2**) · 10^{-10}

$$\Delta\alpha^{(5)}_{\text{had}}(M_Z^2) = -\frac{\alpha \cdot M_Z^2}{3\pi} \int ds\, \frac{R(s)}{s(s - M_Z^2)}$$

hadronic R ratio → **hadronic VP**

$\Delta\alpha$ = (276.11 ± **1.1**) · 10^{-4}

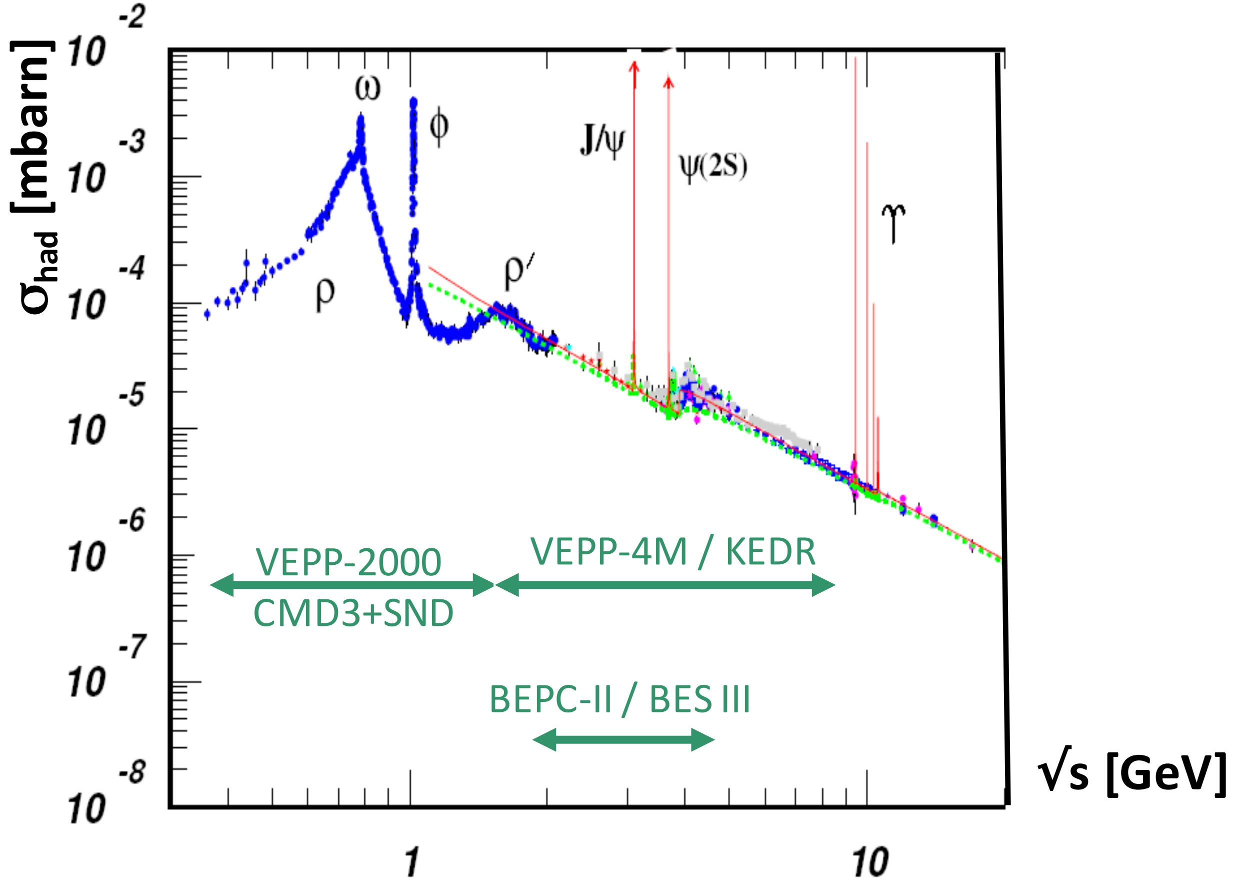




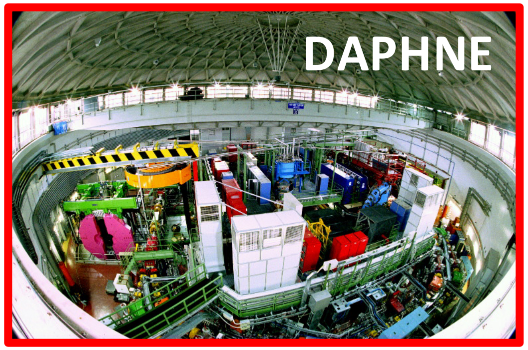
Most relevant channels at low energies
< -- > *exclusive* measurements

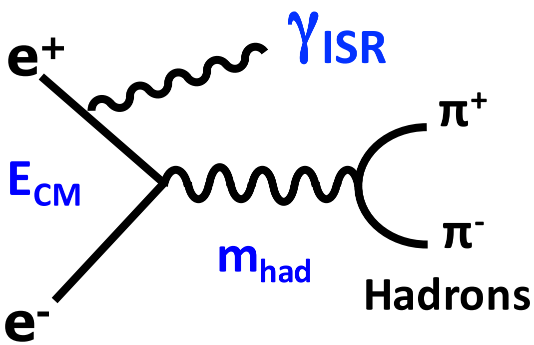
Most relevant energy range > few GeV
< -- > *inclusive* R measurements !

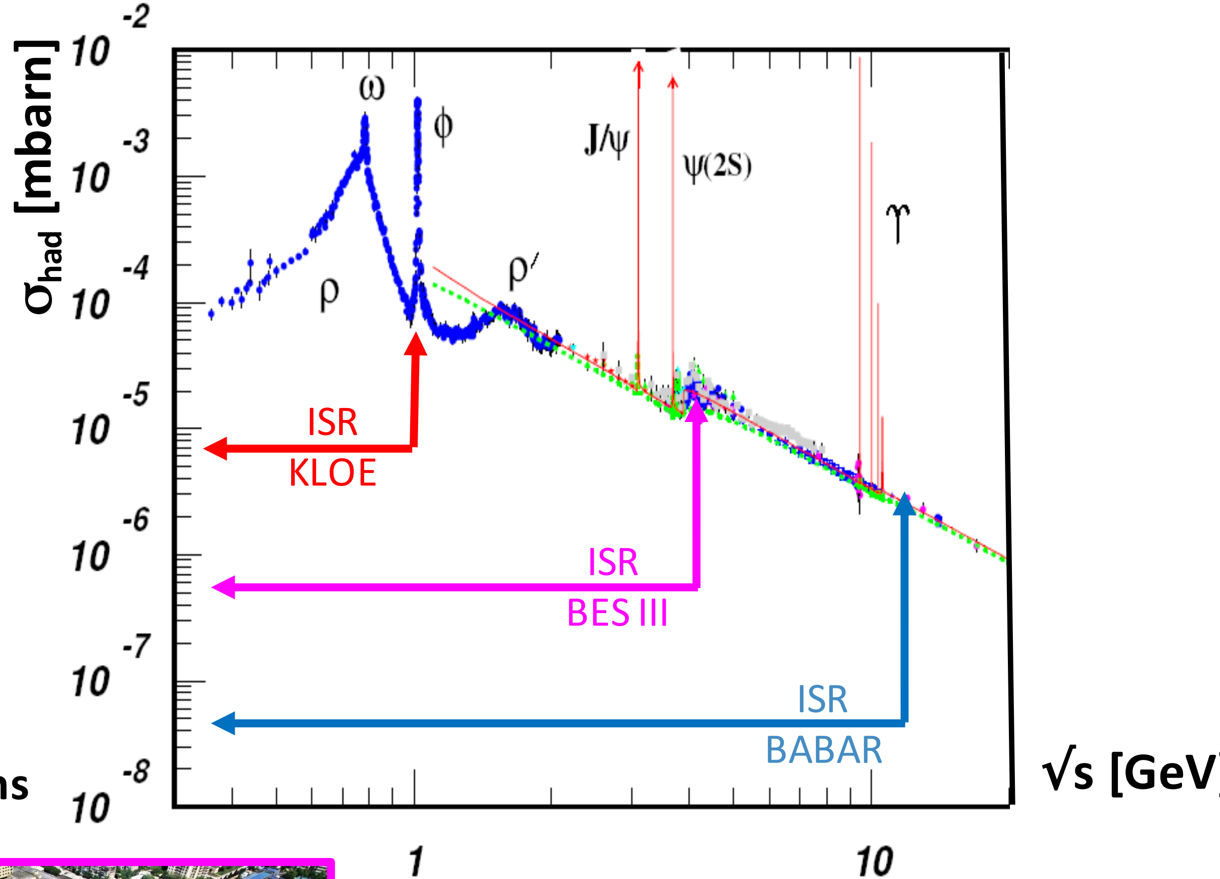
Initial State Radiation (ISR) vs. Energy Scan

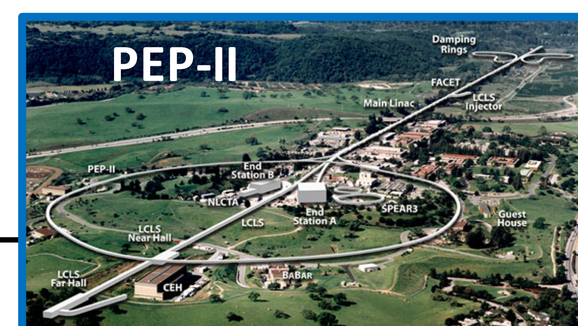


Initial State Radiation (ISR) vs. Energy Scan





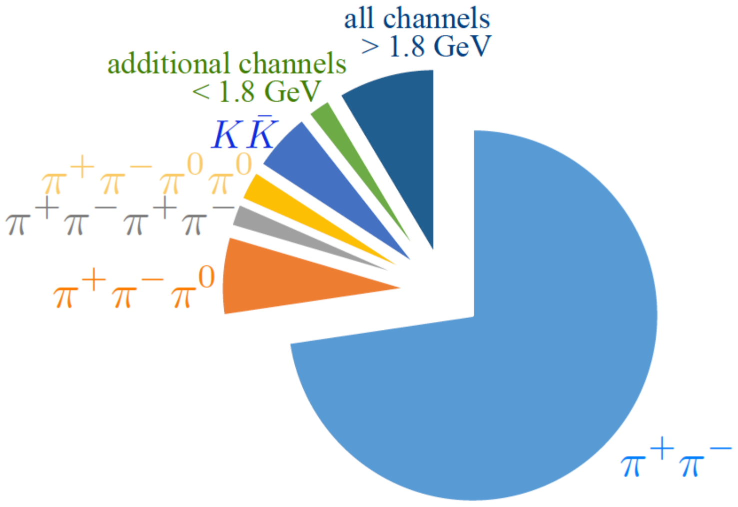




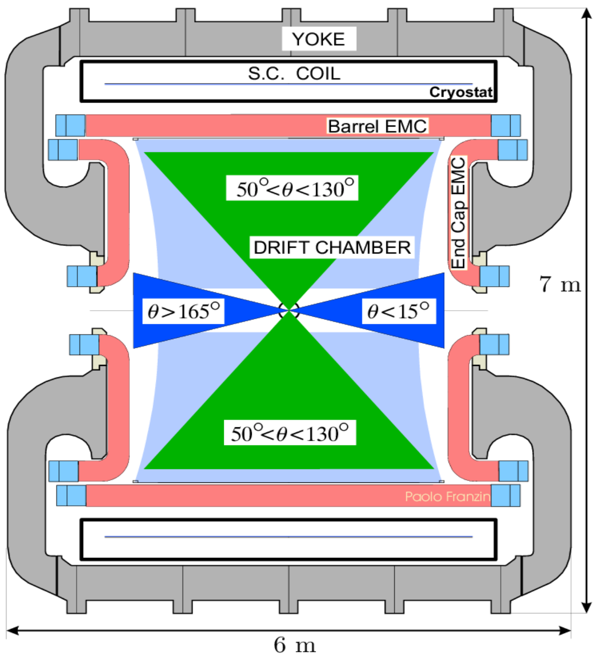
The Two-Pion Channel

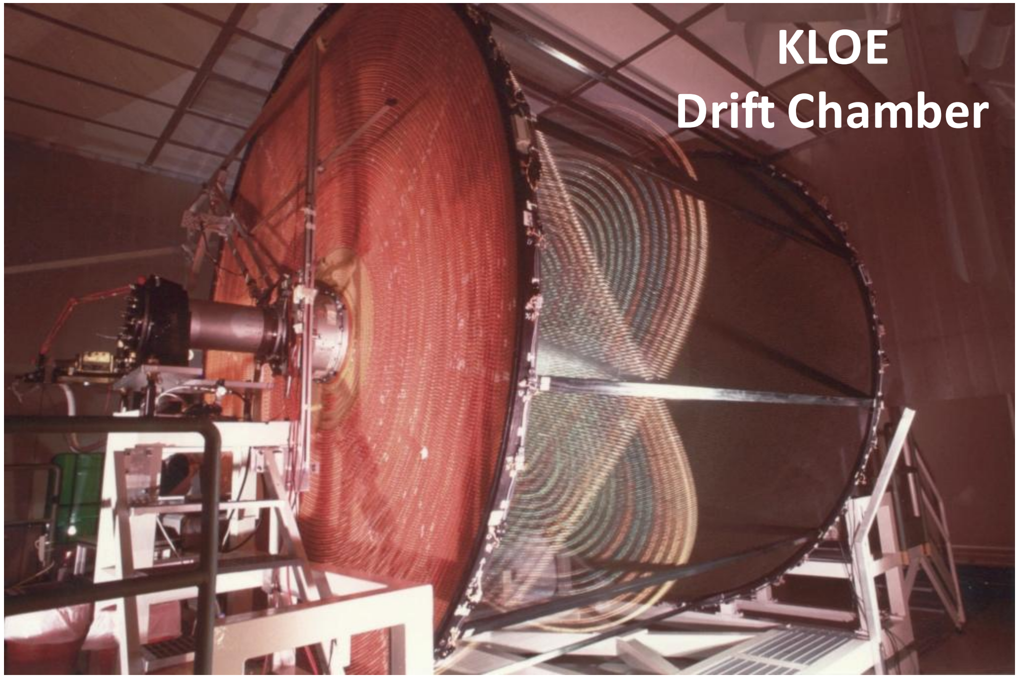
e+e- → π+π-

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



ISR@KLOE: $e^+e^- \rightarrow \pi^+\pi^-\gamma_{ISR}$





Publication	Mode	Normalization	Int. Luminosity*
Phys.Lett. B606 (2005) 12	untagged	Radiator	141 pb^{-1}
Phys.Lett. B670 (2009) 285	untagged	Radiator	240 pb^{-1}
Phys.Lett. B700 (2011) 102	tagged	Radiator	232 pb^{-1}
Phys.Lett. B720 (2013) 336	untagged	$\mu^+\mu^-\gamma$	240 pb^{-1}

*full KLOE statistics 2,500 pb^{-1}

NEW

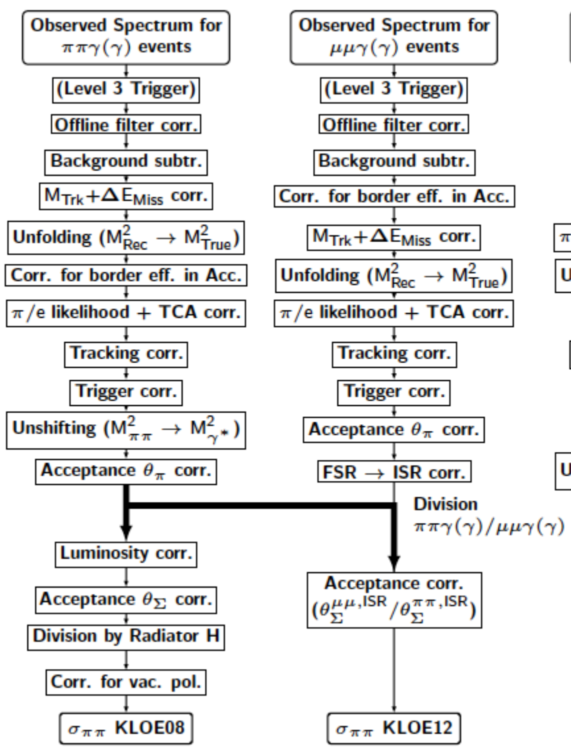
Combination of KLOE Results

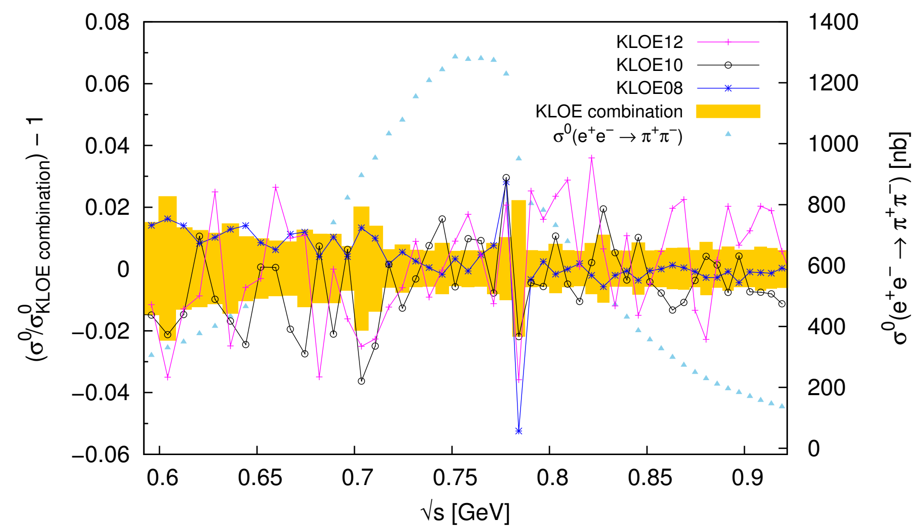
KLOE-2, JHEP1803 (2018)

Goal: Combination of three KLOE analyses

Requires systematic treatment of statistical and systematic uncertainties in 195x195 covariance matrix → final result obtained by itiratively minimizing a χ^2 function

Analysis flow for 3 analyses

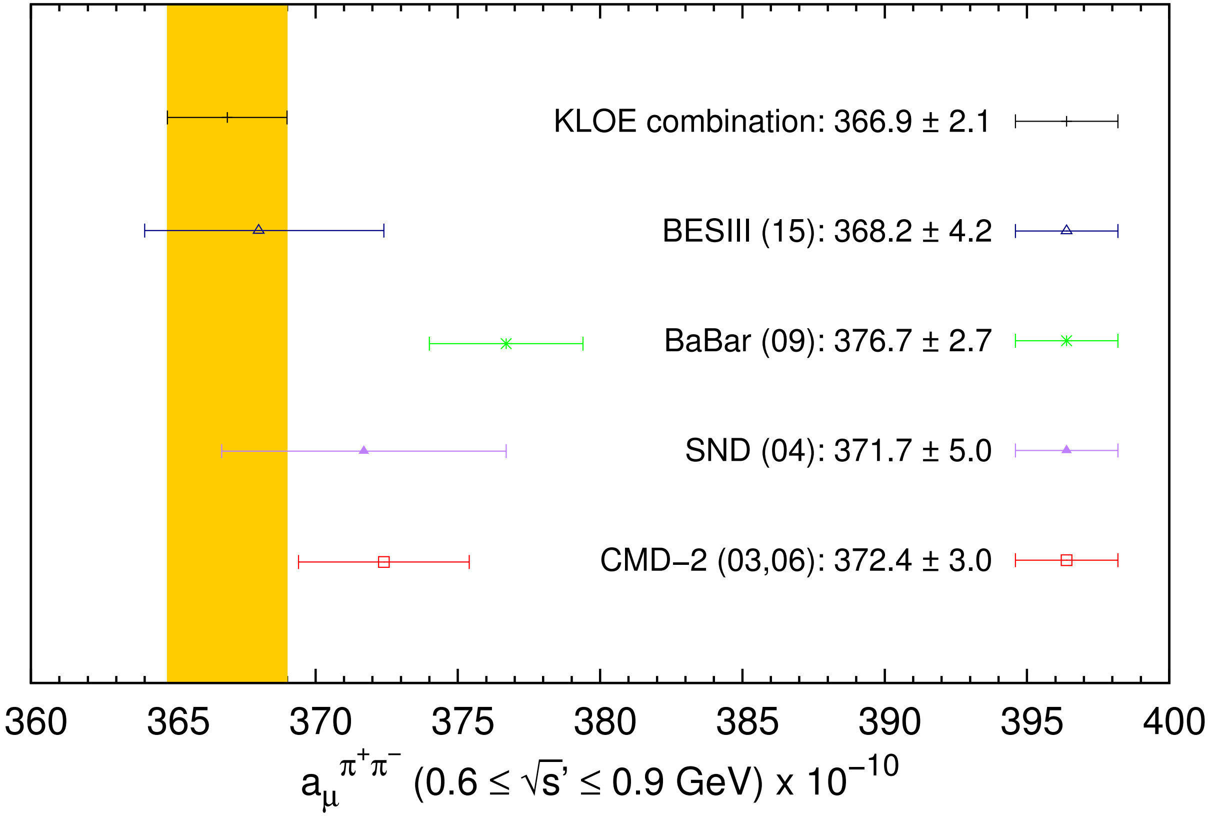




systematic. uncertainty combination ~0.5 % around rho peak*

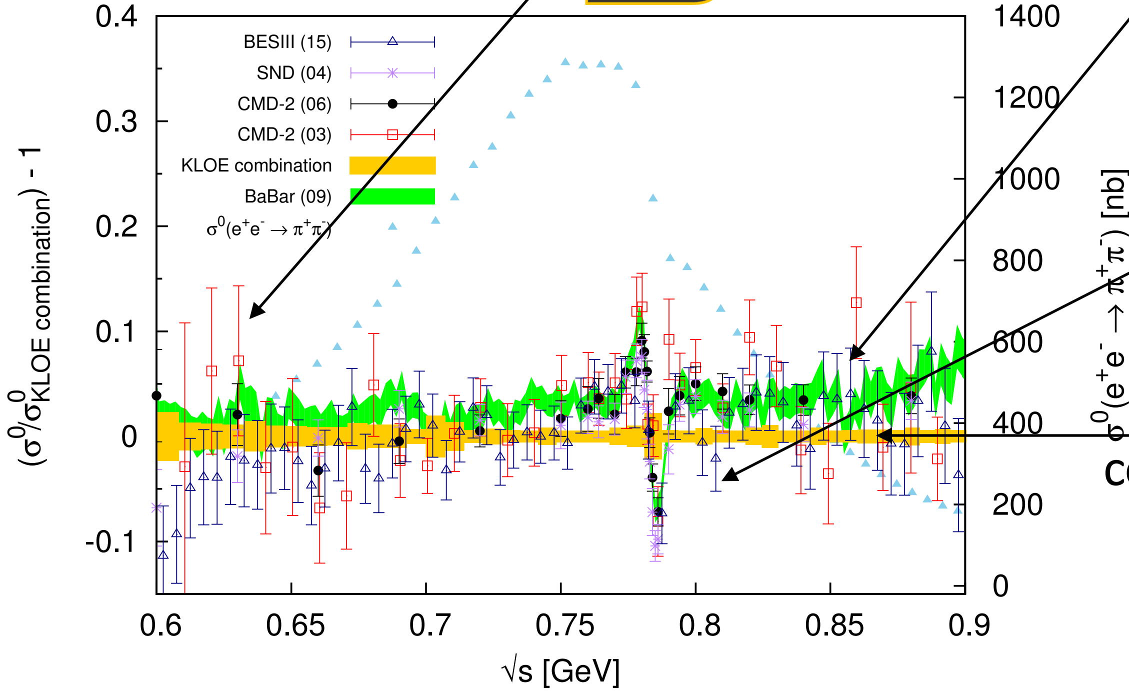
* not used in arxiv:1908.00921 (Davier et al.)

Pion Form Factor: Current Situation



Pion Form Factor: Current Situation

large statistical uncertainties



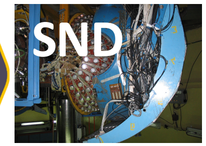
significant deviation

closer to KLOE

KLOE combination

Pion Form Factor: Current Situation

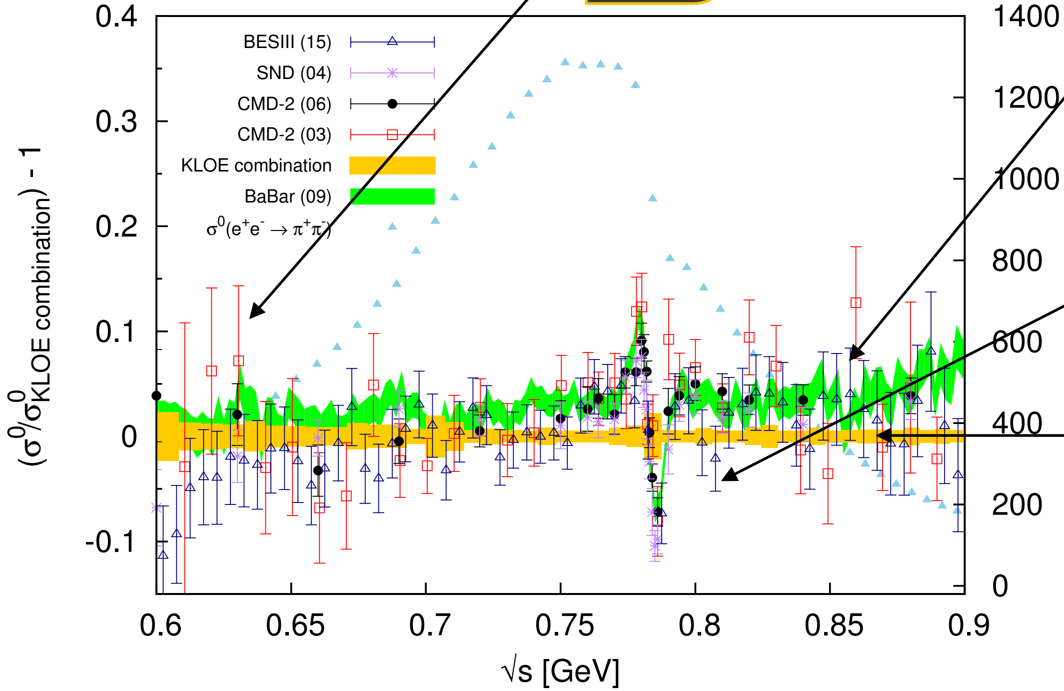
large statistical uncertainties



BaBar significant deviation

BESIII closer to KLOE

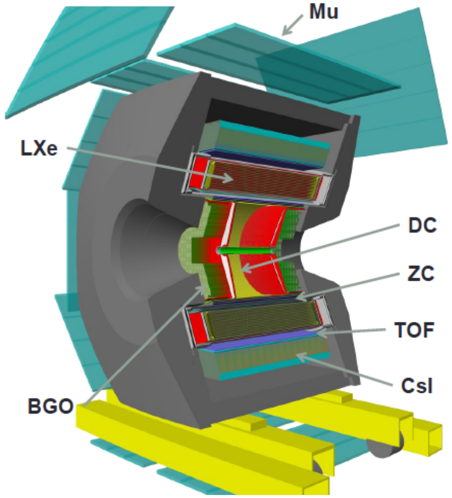
KLOE combination



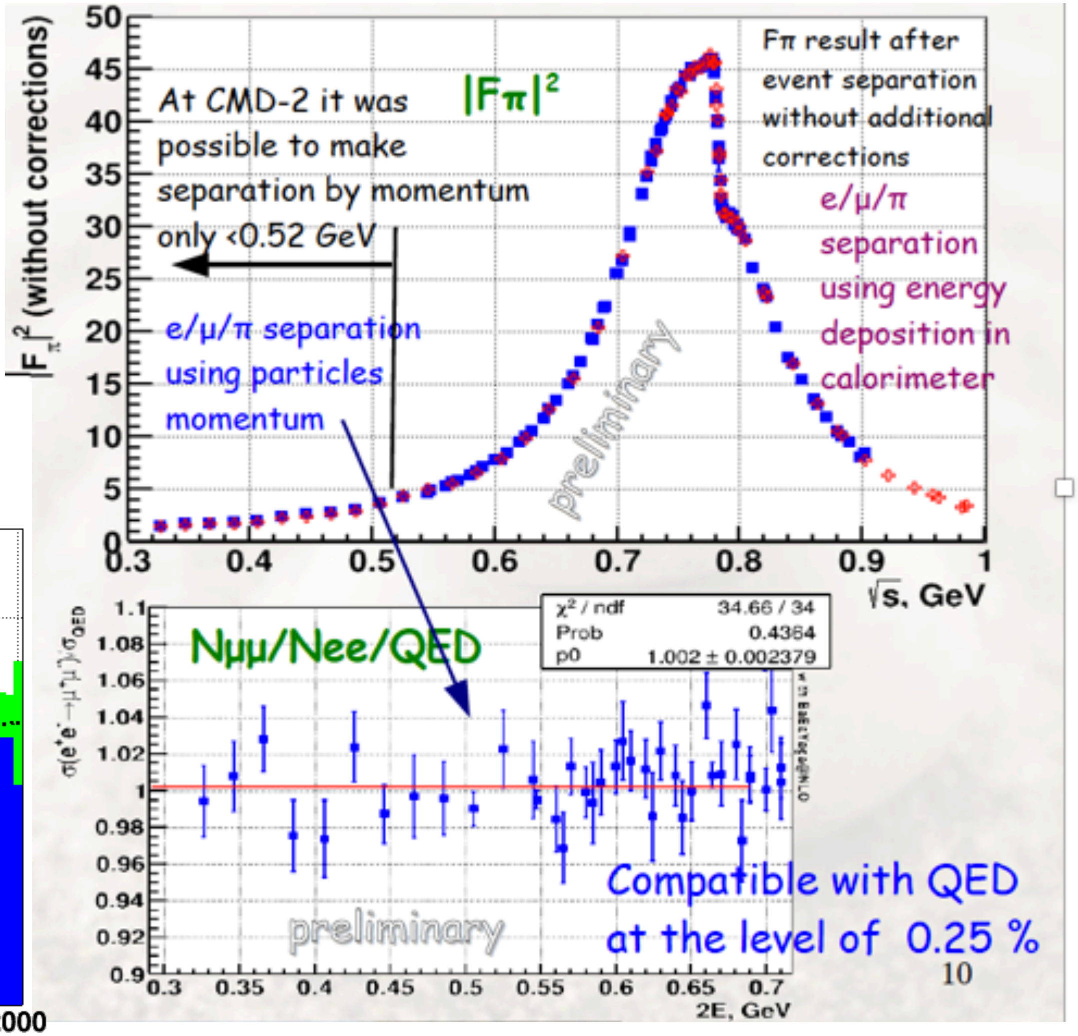
Future:
- New BABAR ISR analysis of full data set
- New BESIII ISR analyses of newer data sets
- BELLE-II will be able to perform ISR analyses
- Energy Scan: CMD-3 / SND at VEPP-2000

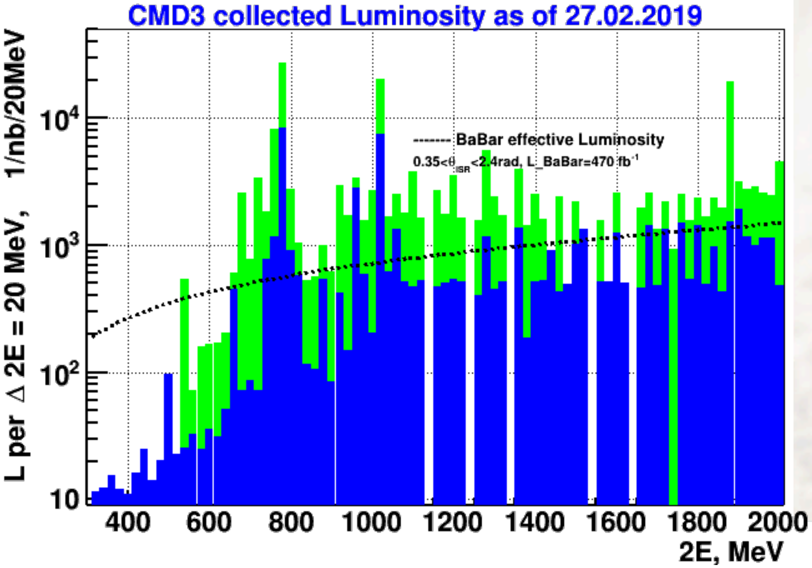
Goal:
< 0.5% accuracy

F_π @ CMD3: Eagerly waiting for ....



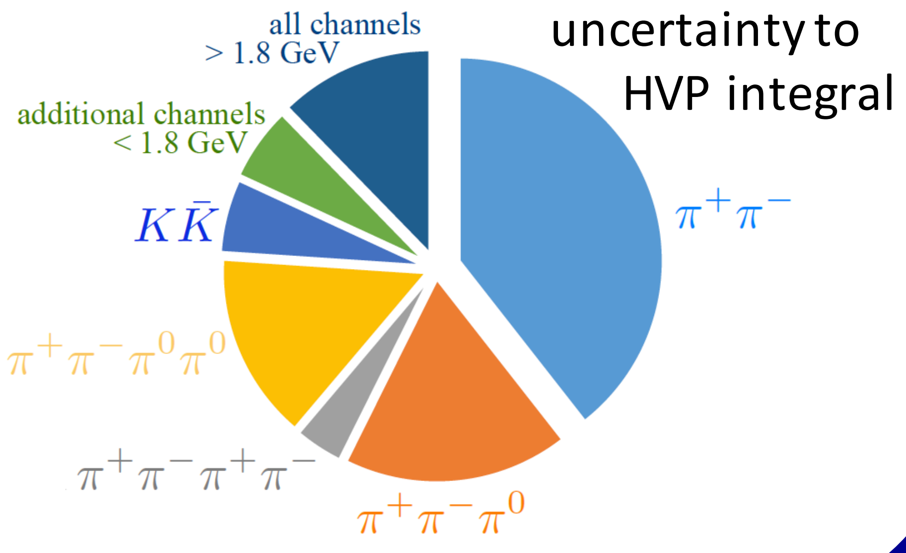
Fedor Ignatov @ Phipsi19



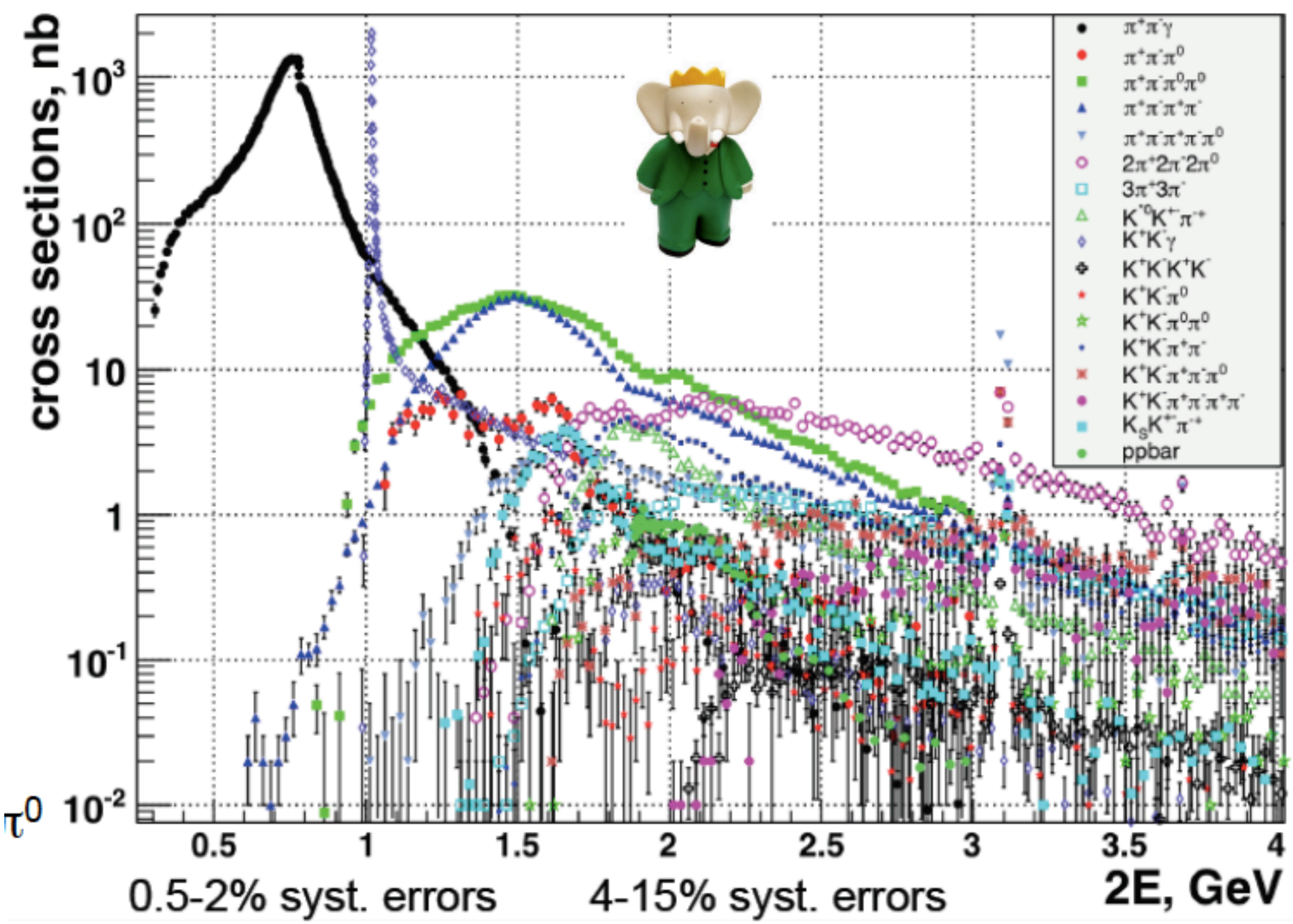


Higher Multiplicity States and $K\bar{K}$

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



Legacy of  BABAR ISR Data



Precision:

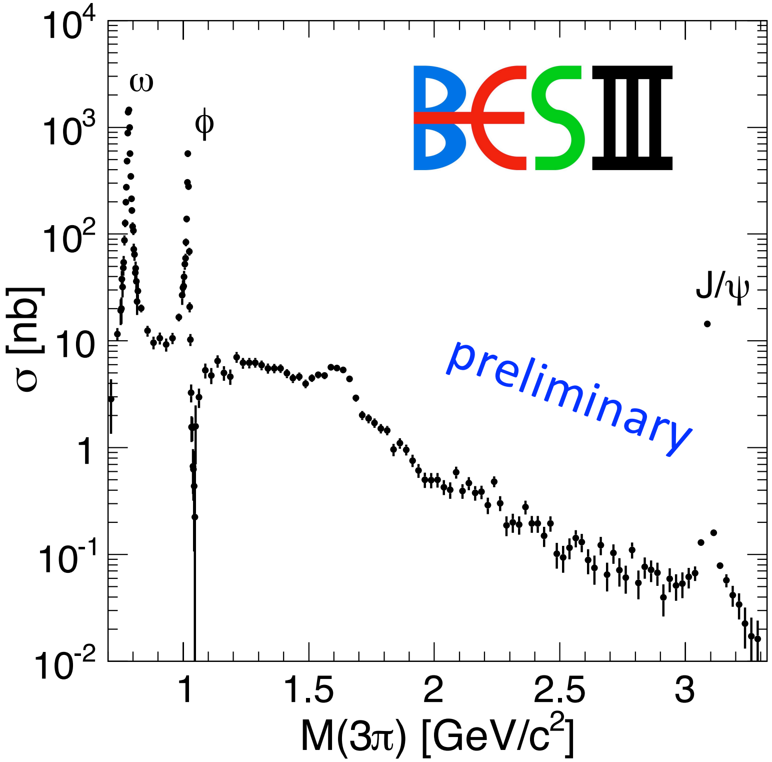
2π: < 1%

3π: ~10%

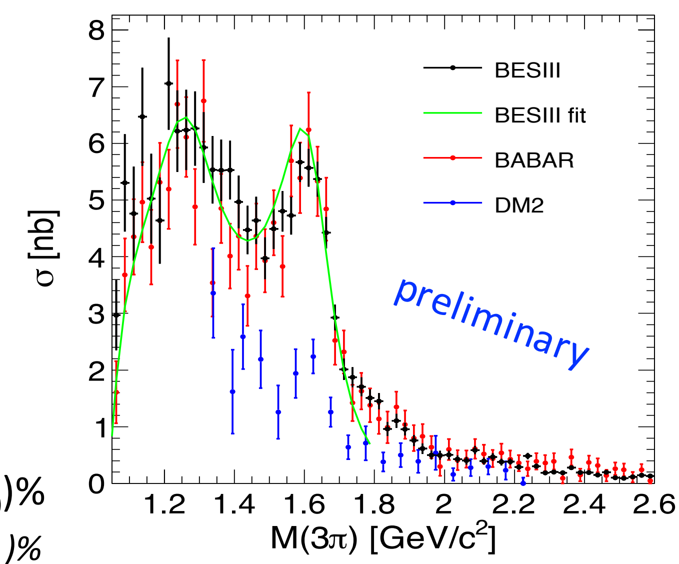
4π: ~ 3%

≥ 5π: 10% and higher

BES III: $e^+e^- \rightarrow 3\pi$ Measurement (ISR)



- Existing precision data from CMD-2, SND (< 1.4 GeV), and BABAR (>1.05 GeV)
- BESIII: tagged **and** untagged ISR measurement
- Spectrum dominated by narrow **ω, ϕ, J/ψ resonances**
- World's highest statistics above 1.4 GeV/c^2
  Systematic error: ~2% on ω and ϕ peaks

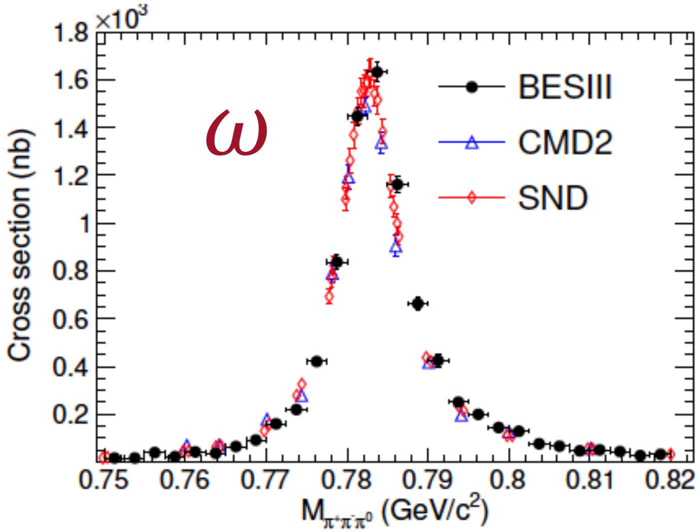


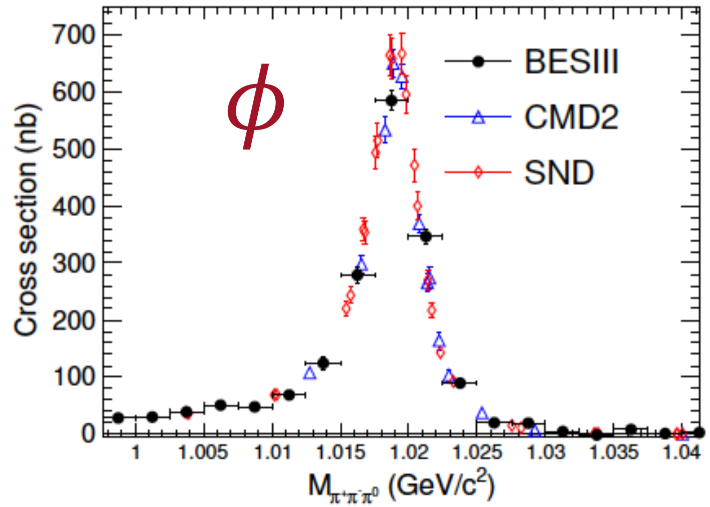
- BESIII **confirms ω(1420), ω(1650)** resonances
- World's best **J/ψ branching ratio**
  $BR(J/\psi \rightarrow 3\pi) = (\, 2.179 \pm 0.024 \pm 0.023 \pm 0.045_{\Gamma ee(J/\psi)})\%$

PDG: (2.10 ± 0.08)%

PRELIMINARY

BES III: $e^+e^- \to 3\pi$ Measurement (ISR)



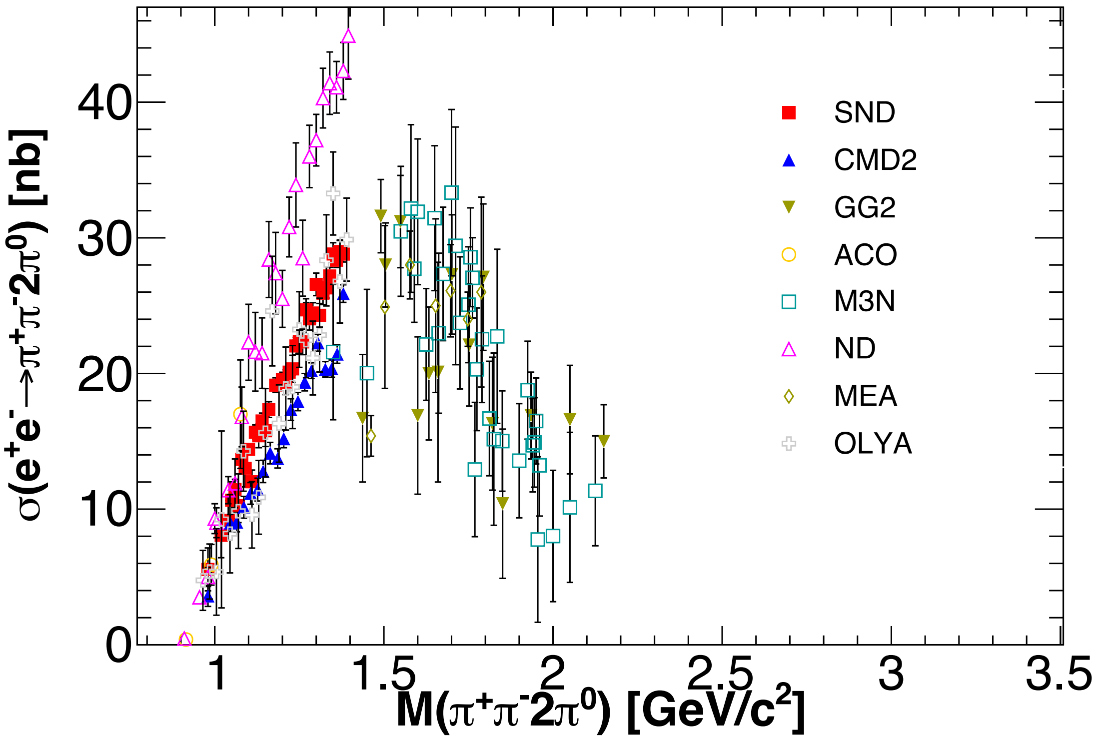


Parameters	PDG [6]	BABAR	Fitted results
χ^2/NDF	-	$146/148$	$443/390$
m_ω (MeV/c^2)	782.65 ± 0.12	782.45 ± 0.24	$783.20 \pm 0.07 \pm 0.24$
m_ϕ (MeV/c^2)	1019.46 ± 0.02	1018.86 ± 0.20	$1020.00 \pm 0.06 \pm 0.41$
$m_{\omega(1420)}$ (MeV/c^2)	$1400 \sim 1450$	$1350 \pm 20 \pm 20$	$1388 \pm 39 \pm 55$
$m_{\omega(1650)}$ (MeV/c^2)	1670 ± 30	$1660 \pm 10 \pm 2$	$1699 \pm 9 \pm 7$

PRELIMINARY

NEW

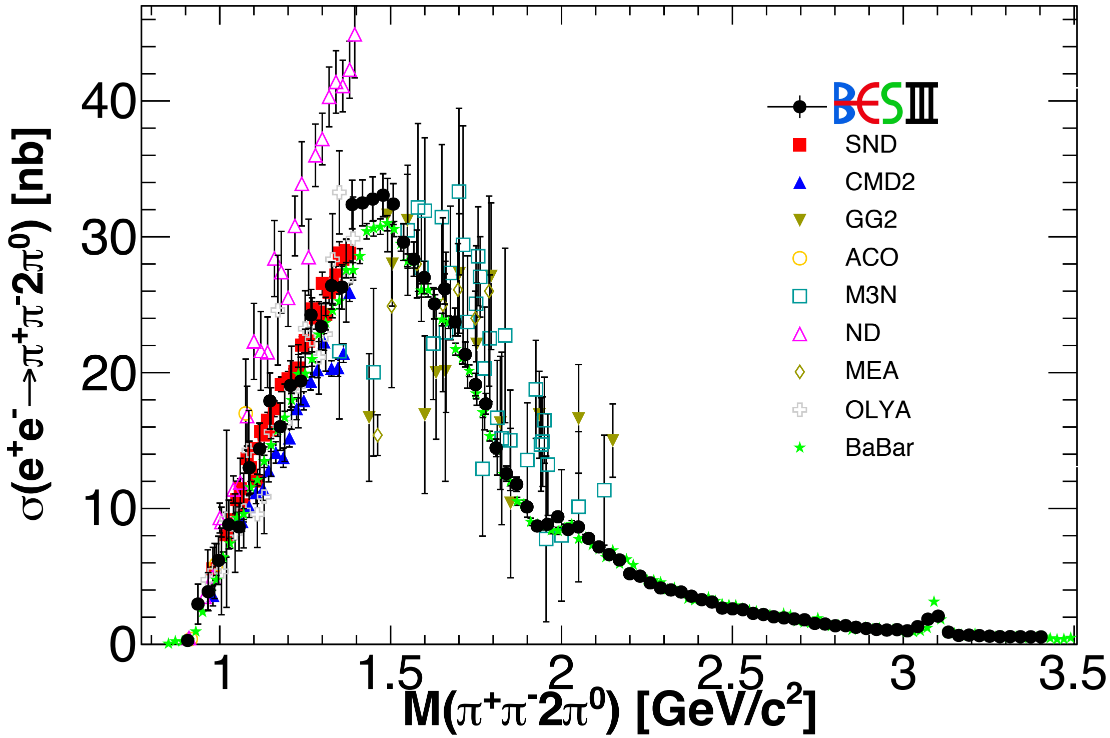
BABAR/BES III: $e^+e^- \rightarrow \pi^+\pi^-2\pi^0\gamma_{ISR}$



	$a_\mu^{\pi^+\pi^-2\pi^0,\mathrm{LO}}/10^{-10}$
Before	$16.76 \pm 1.31 \pm 0.20_{\mathrm{rad}}$

NEW

BABAR/BES III: $e^+e^- \to \pi^+\pi^-2\pi^0\gamma_{ISR}$



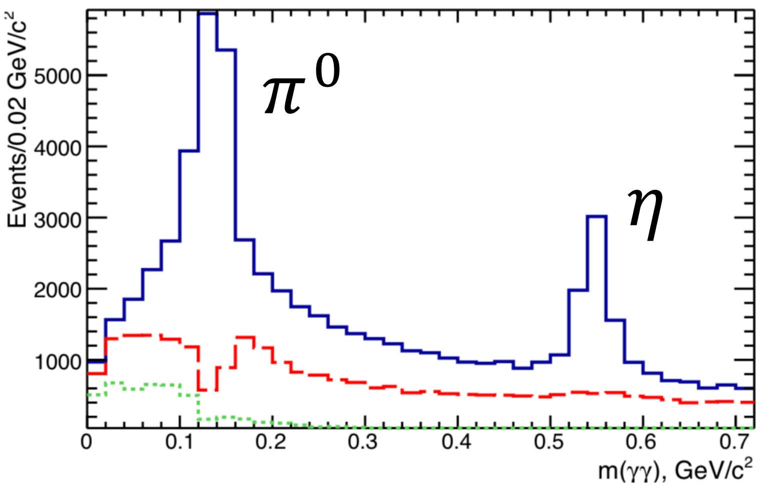
		$a_\mu^{\pi^+\pi^-2\pi^0,\text{LO}}/10^{-10}$	
NPP Proc. 294 (2018) 158	BESIII (preliminary)	$18.63 \pm 0.27 \pm 0.57$	~3pb^{-1}, ~3% syst.
PRD 96, 092009 (2017)	BABAR	$17.9 \pm 0.1 \pm 0.6$	~450 pb^{-1}, ~3% syst.
	Before	$16.76 \pm 1.31 \pm 0.20_{\text{rad}}$	

NEW

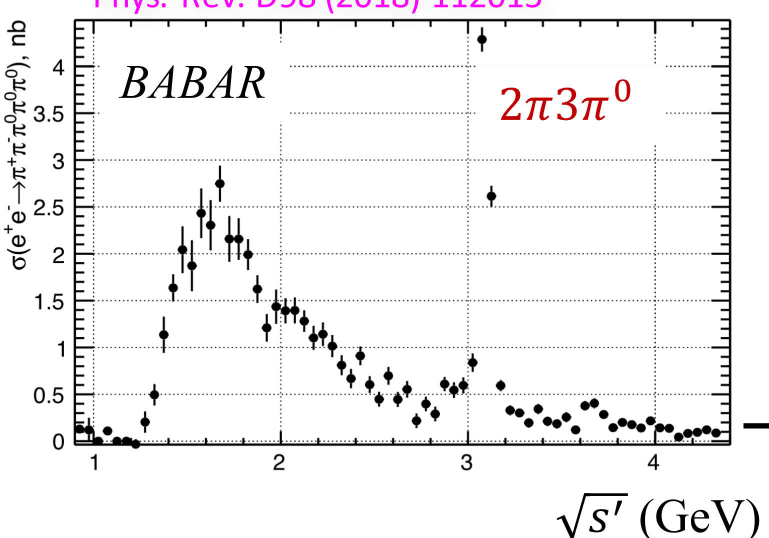
BABAR: $e^+e^- \rightarrow \pi^+\pi^-3\pi^0 / \pi^+\pi^-2\pi^0\eta$

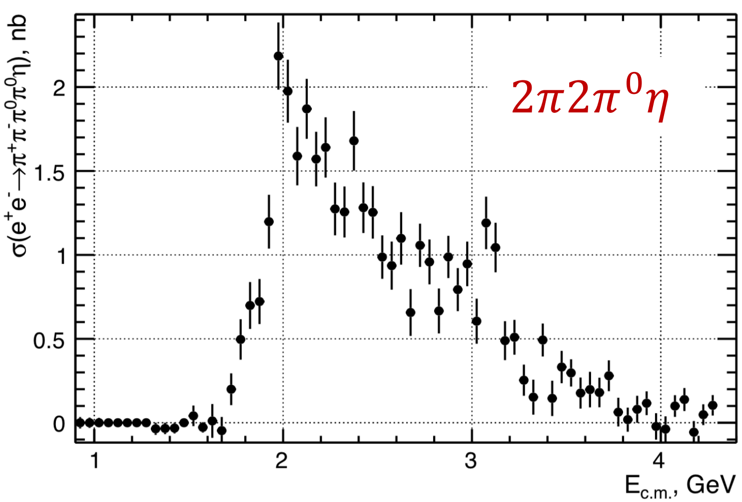
- Combined analysis of both channels
- Kinematic fit:
  - Constrain 2 of the π^0 candidates to π^0 mass
  - $m_{\gamma\gamma}$ of 3rd used for η or π^0 signal extraction
  - Constrain entire event to e^+e^- 4-momentum
- First precision measurements of both channels
- Detailed studies of internal structures and of J/ψ branching ratios

Invariant-mass $m_{\gamma\gamma}$ of 3rd photon pair shows clear π^0 and η peaks



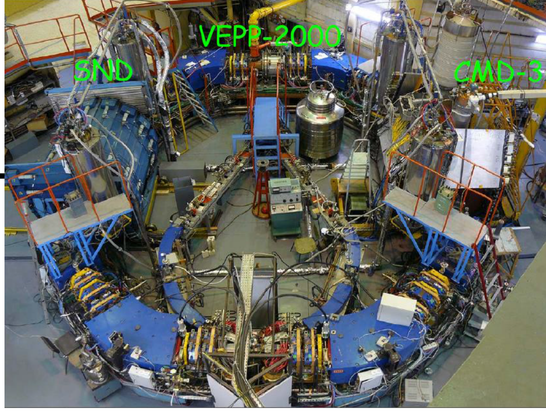
Phys. Rev. D98 (2018) 112015





(provided also for intermediate resonances)

Results from VEPP-2000



Energy range is 0.32-2.0 GeV
unique optics –“round beams”
Design luminosity is L=$10^{32}/cm^2s$@s=2GeV
Experiments with detectors CMD-3 and SND

1. $e^+e^- \to \pi^0\pi^0\gamma$, Phys.Rev.D, (2013)
2. $e^+e^- \to nn$, Phys.Rev.D,(2014)
3. $e^+e^- \to NN+6\pi$, JETP Lett.,(2014)
4. $e^+e^- \to \eta\gamma$, Phys.Rev.D,(2014)
5. $e^+e^- \to \eta'$, Phys.Lett.B,(2015)
6. $e^+e^- \to \eta\pi^+\pi^-$, Phys.Rev.D,(2015)
7. $e^+e^- \to \pi^+\pi^-\pi^0$, JETP,(2015)
8. $e^+e^- \to \eta$ JETP Lett.,(2015)
9. $e^+e^- \to \omega\eta\pi^0$, Phys.Rev.D,(2016)
10. $e^+e^- \to \omega\eta$, Phys.Rev.D,(2016)
11. $e^+e^- \to \pi^0\gamma$, Phys.Rev.D,(2016)
12. $e^+e^- \to \pi^0\pi^0\gamma$, Phys.Rev.D, (2016)
13. $e^+e^- \to K^+K^-$ Phys. Rev. D, (2016)

✔Published (or submitted):

$e+e- \to pp$,	Phys.Lett. B759 (2016) 634-640
$e^+e^- \to \eta'$	Phys.Lett. B740 (2015) 273-277
$2(\pi^+\pi^-)$, $3(\pi^+\pi^-)$,	Phys.Lett. B768 (2017) 345-350 Phys.Lett. B723 (2013) 82-89
$\omega\eta$, $\eta\pi^+\pi^-\pi^0$,	Phys.Lett. B773 (2017) 150-158
$3(\pi^+\pi^-)\pi^0$,	arXiv:1902.06449, submitted to PLB
K^+K^-, K_SK_L,	Phys.Lett. B760 (2016) 314-319 Phys.Lett. B779 (2018) 64-71
$K^+K^-\pi^+\pi^-$	Phys.Lett. B756 (2016) 153-160

NEW

CMD-3: $e^+e^- \to K_S K_L$

- Measurement 1.004 – 1.070 GeV
- 1.8% systematic uncertainty (BABAR 2.9%)
- Reconstruction of $K_S \to \pi^+\pi^-$
- Fit to cross section:

$$\sigma_{e^+e^-\to K_S^0 K_L^0}(s) = \frac{8\pi\alpha}{3s^{5/2}} p^3_{K^0} \left| \frac{g_{\rho\gamma} g_{\rho KK}}{D_\rho(s)} + \frac{g_{\omega\gamma} g_{\omega KK}}{D_\omega(s)} + \frac{g_{\phi\gamma} g_{\phi KK}}{D_\phi(s)} + A_{\rho',\omega',\phi'} \right|^2,$$

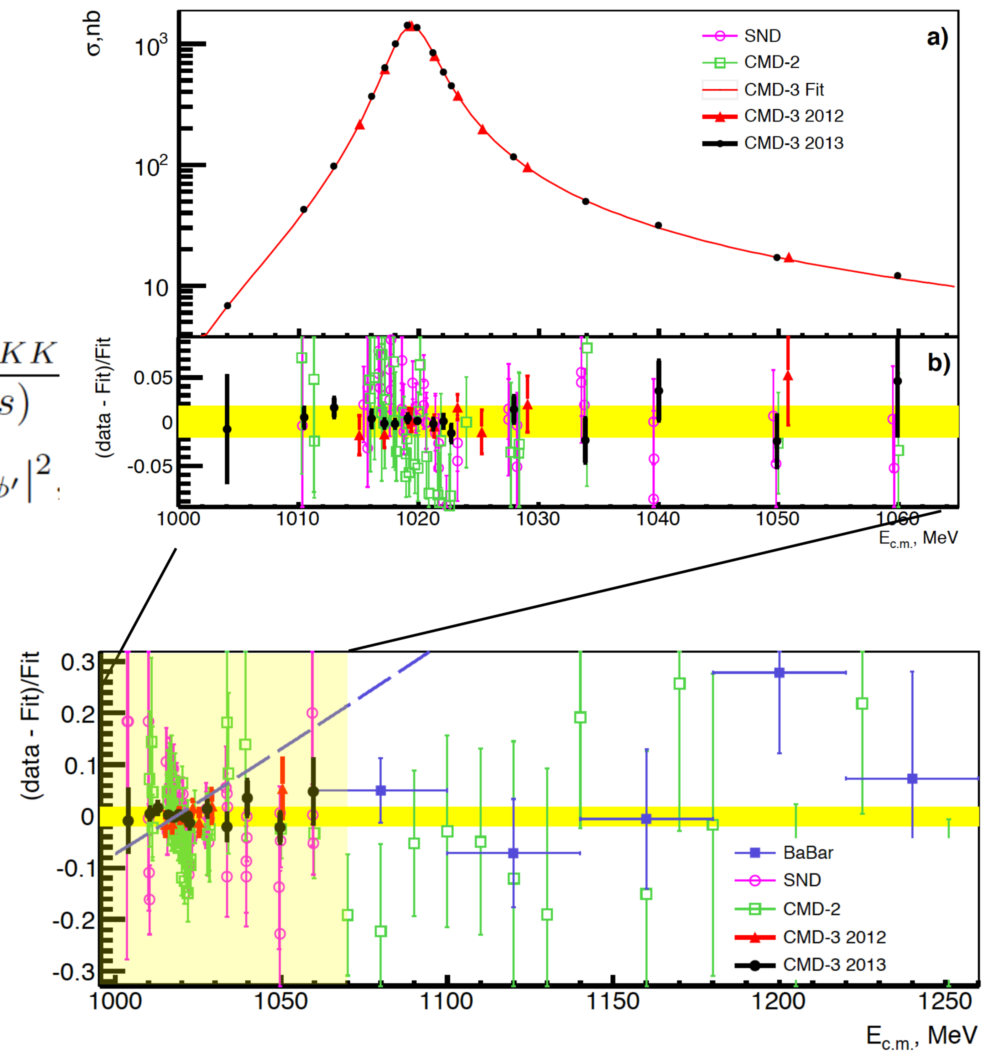
$$|g_{V\gamma}| = \sqrt{\frac{3m_V^3 \Gamma_{Vee}}{4\pi\alpha}}; \quad |g_{VKK}| = \sqrt{\frac{6\pi m_V^2 \Gamma_V B_{VKK}}{p^3_{K^0}(m_V)}};$$

$$D_V(s) = m_V^2 - s - i\sqrt{s}\Gamma_V(s)$$

$$\Gamma_V(s) = \Gamma_V \sum_{V\to f} B_{V\to f} \frac{P_{V\to f}(s)}{P_{V\to f}(m_V^2)}$$

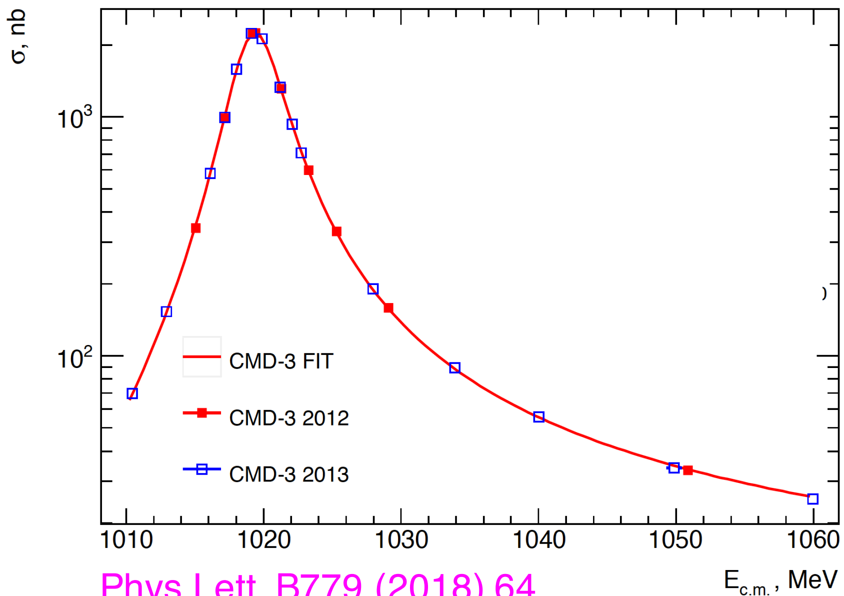
- Overall good agreement

Phys.Lett. B760 (2016) 314



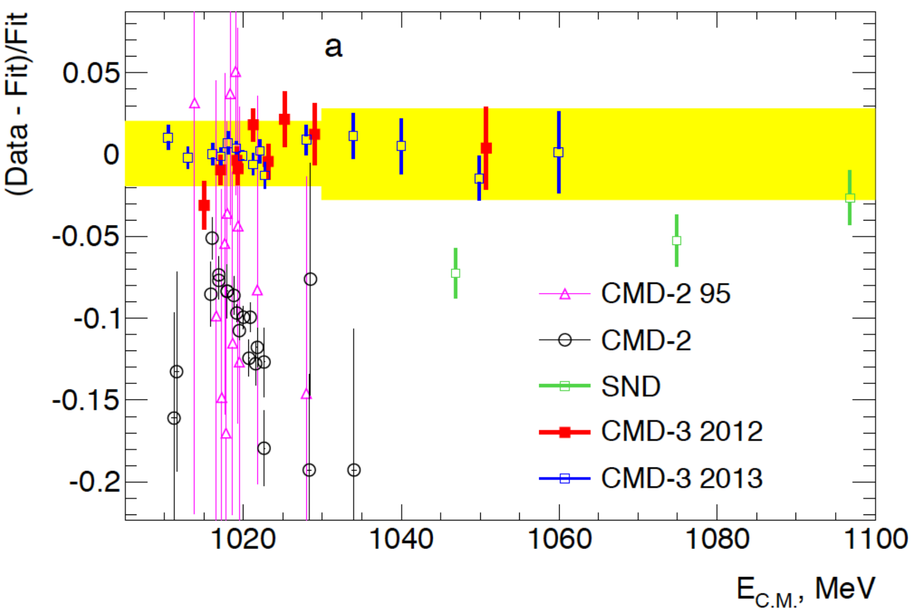
NEW

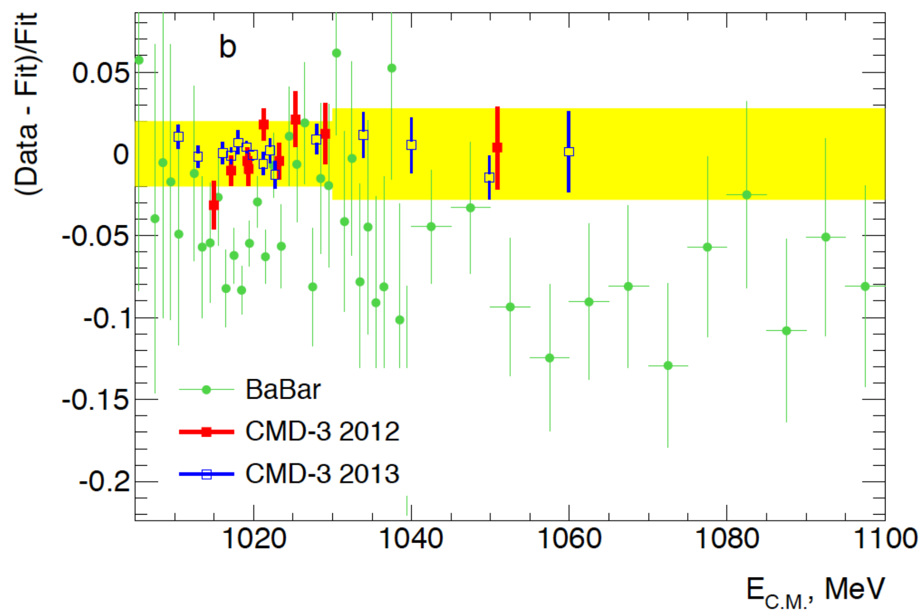
CMD-3: $e^+e^- \to K^+K^-$



Phys.Lett. B779 (2018) 64

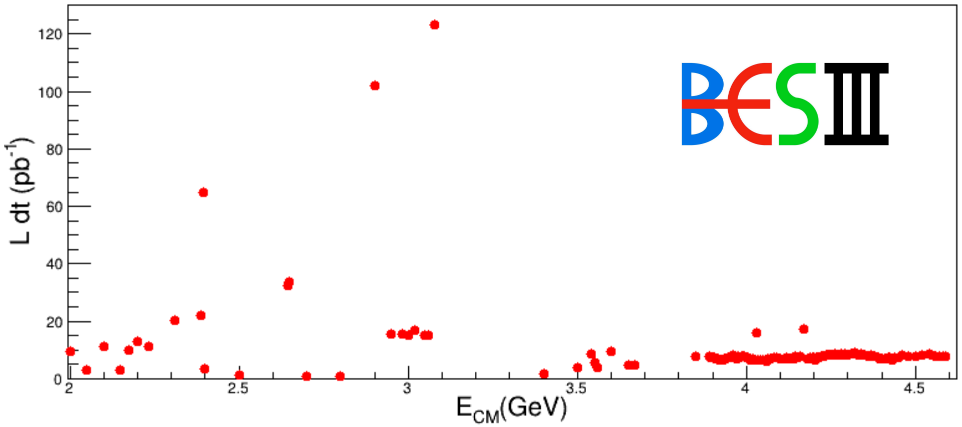
- Measurement 1.010 – 1.060 GeV
- 2.0% systematic uncertainty (BABAR 0.72 – 1.41 % in that range)
- Similar fit to cross section as for $K_S K_L$ Parameters:
- New CMD-3 data above CMD-2 / BABAR ???





NEW

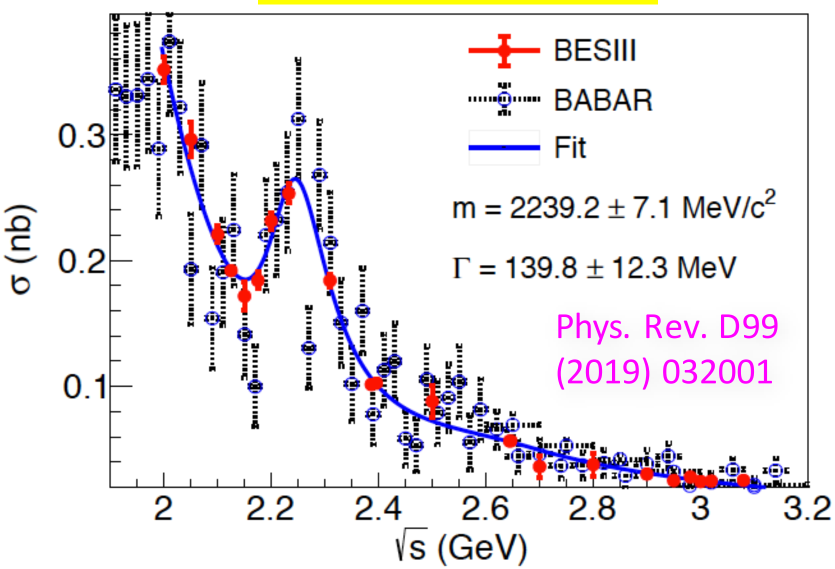
BES III: Energy Scan 2.0 – 4.6 GeV



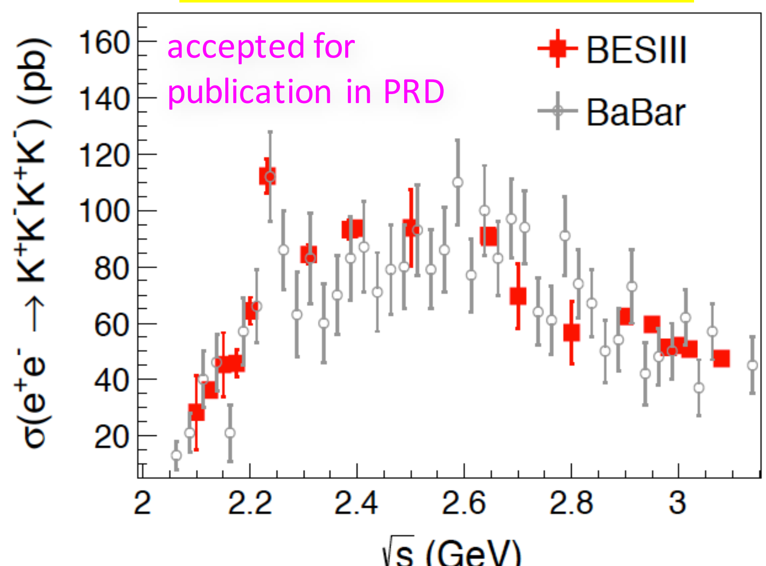
R Scan 2.0 – 4.6 GeV

- > 10 000 events per scan point
- below J/ψ highest statistics
- very fine binning in XYZ region
- improved statistics wrt BABAR

$e^+e^- \to K^+K^-$

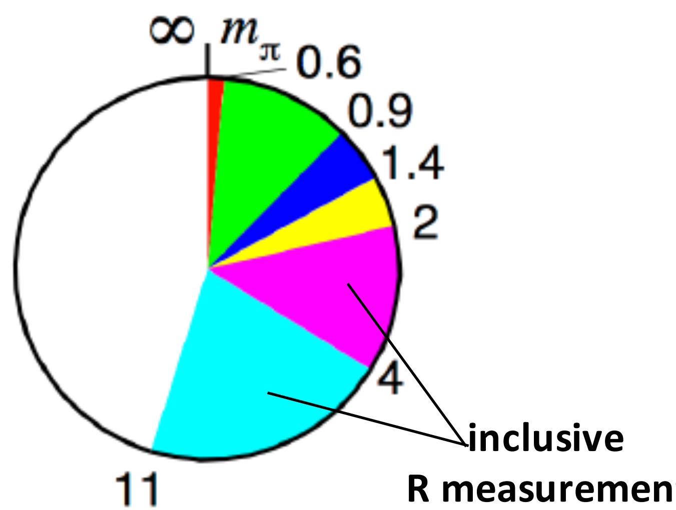


$e^+e^- \to K^+K^-K^+K^-$



Inclusive R_{had} Measurements

$$\Delta\alpha^{(5)}_{\mathrm{had}}(M_Z^2) = -\frac{\alpha \cdot M_Z^2}{3\pi}\int ds\, \frac{R(s)}{s(s-M_Z^2)}$$

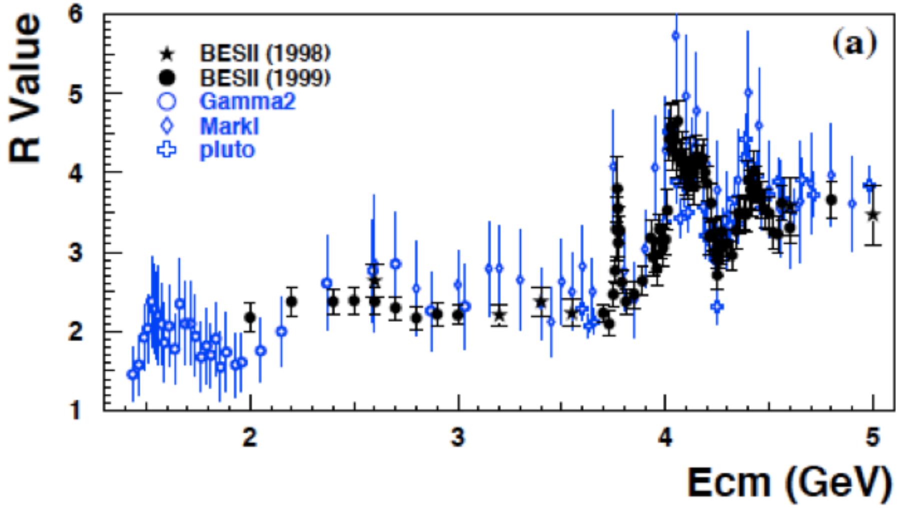


R_{incl} at BES III: Work in Progress

Improve upon BES/BESII measurement with 6% systetic error

$R_{incl} = \sigma_{had}/\sigma_{\mu\mu}$ ratio with targeted 3% systematic accuracy

(statistical error <<1%)



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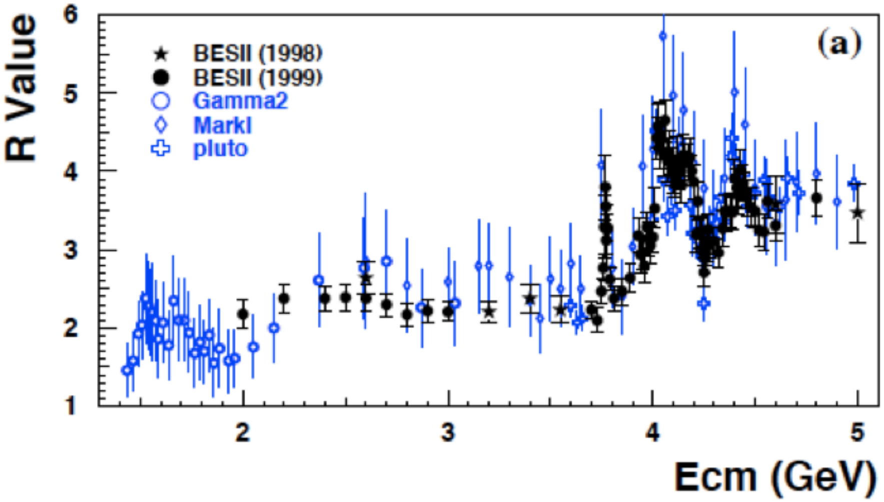


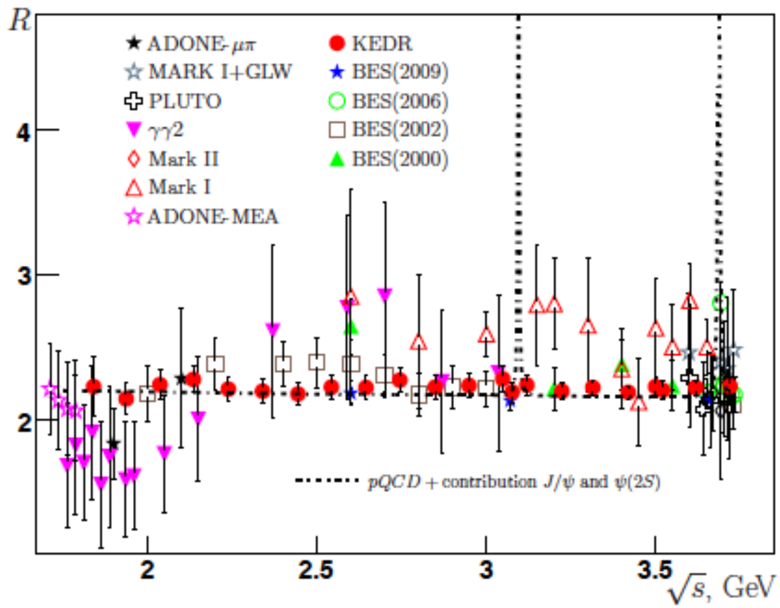
Status of R measurement (below open charm threshold):

- Event selection ✔
- Measurement of integrated luminosity with <1% accuracy ✔
- Radiative corrections with <1.5% accuracy ✔
- Subtraction of QED background ✔
- Tuning of *hadronic MC generator* (Lund model) for efficiency determination

NEW

R_{incl} at KEDR / Novosibirsk

S. Eidelman
@ g-2 workshop
Mainz, 06/2018



1.84-3.05 GeV $R = 2.225 \pm 0.020 \pm 0.047$ ($R_{\rm pQCD} = 2.18 \pm 0.02$)

V.V. Anashin et al., Phys. Lett. B770 (2017) 174

3.05-3.72 GeV $R_{\rm uds} = 2.204 \pm 0.013 \pm 0.030$ ($R_{\rm pQCD} = 2.16 \pm 0.01$)

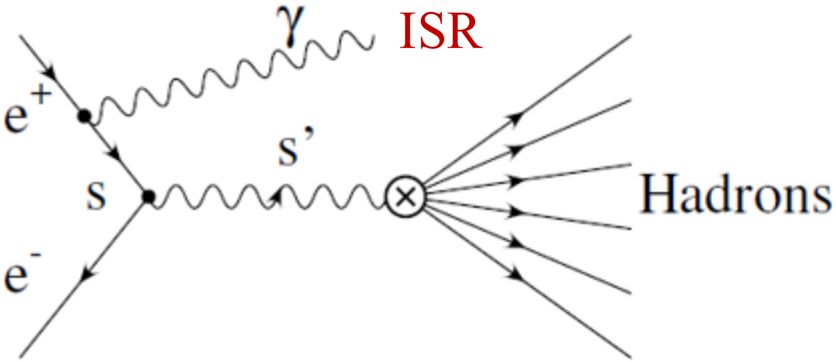
V.V. Anashin et al., Phys. Lett. B753 (2016) 533; arXiv:1805.06235

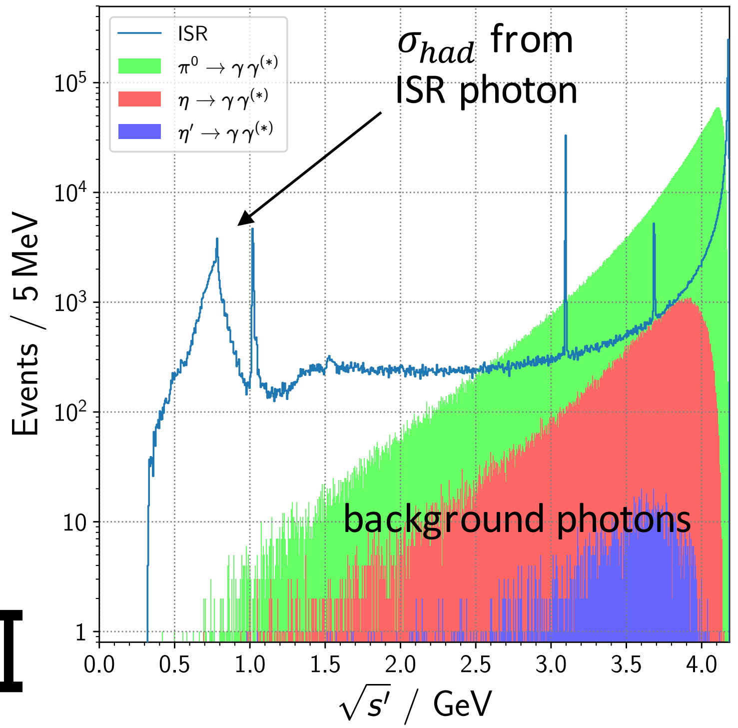
Total (syst. error) 3.9% (2.4%) at low, 2.6% (1.9%) at high $\sqrt{s}$

R measurement from 5 to 7 GeV in progress

R_{incl} Measurement via ISR ?

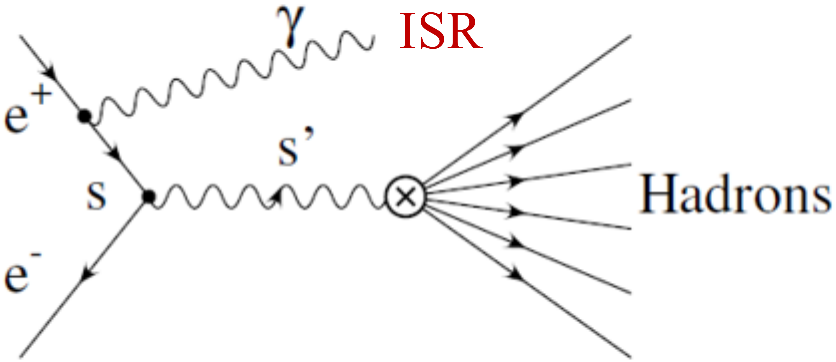
$$s' = m_{\text{had}}^2 = s - 2\sqrt{s}\,E_\gamma$$

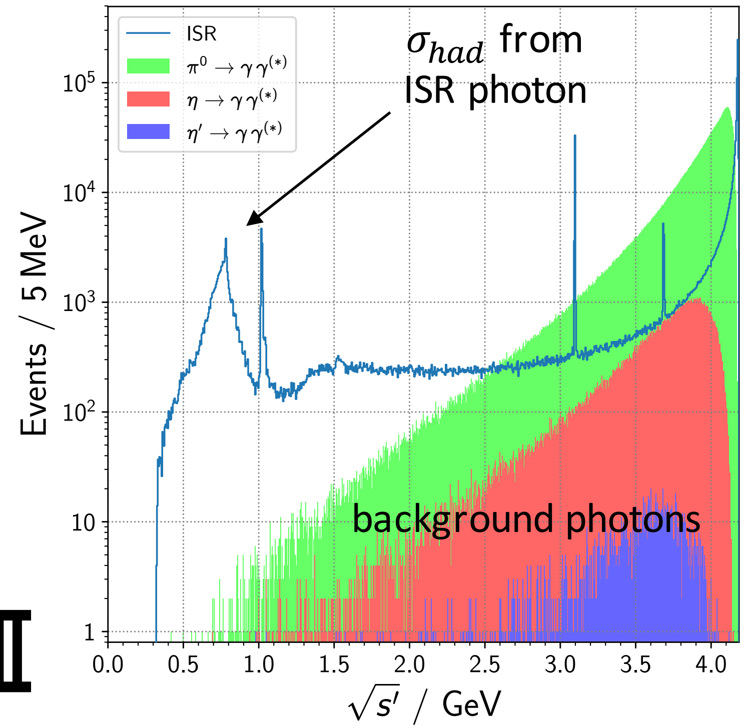


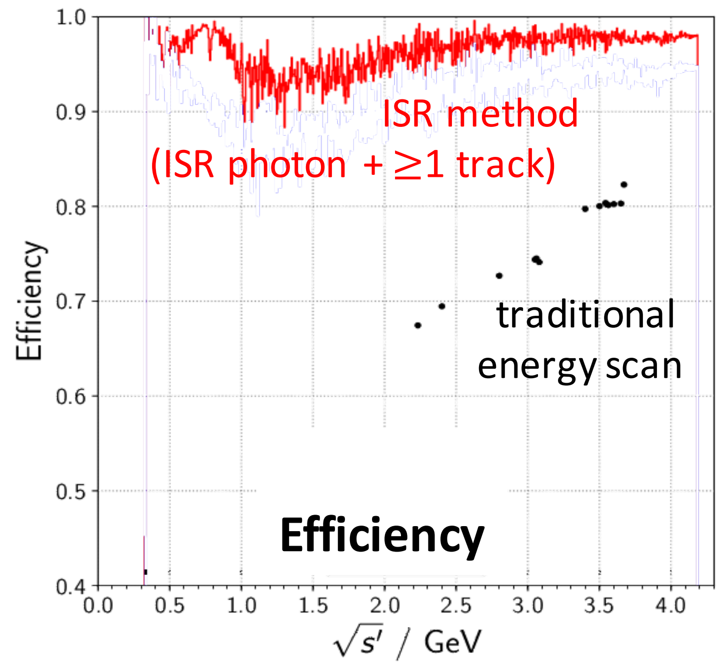


R_{incl} *Measurement via ISR ?*

$$s' = m_{\text{had}}^2 = s - 2\sqrt{s}\,E_\gamma$$







Advantage:

Much higher signal efficiency compared to scan

→ Less dependent on MC event generator

Challenges:

- Subtraction of QED background
- Unfolding of ISR photon spectrum
- Reliability of gamma gamma vetos
- ....

Achim Denig

Conclusions

and

Outlook

Conclusions

- Steady progress in R_{had} measurements
  → ISR and energy scan methods !
- In 2013 whitepaper arxiv:1311.2198 (*Blum et al.*) reduction of HVP uncertainty down to $\pm 2.6 \cdot 10^{-10}$ formulated as a goal → mission accomplished?
- However, accuracy of HVP contribution to $(g\text{-}2)_\mu$ limited by 2pi channel
  → overcoming KLOE-BABAR-BESIII puzzle is a major challenge
  Once this issue will be solved → full interpretation of FNAL g-2 measurement
- Improved value of $\alpha_{em}(M_Z^2)$ highly desirable in view of precision EW measurements at LHC, Mainz, JLAB, ... → needs improved value of R_{had}
  → Do we have all systematics under control for hadronic event generators?

THINKING BEYOND THE BOX

- MUonE at CERN
- R_{had} measurements via ISR
- ....