ISR-Physics in the energy region 2-7 GeV

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Johannes Gutenberg-University Mainz

HIEPA, Hefei
January 14, 2015

Outline

1. Motivation: muon-anomaly a_μ
2. ISR-physics at flavor-factories
3. Impact of data from super-flavor factories
4. Summary

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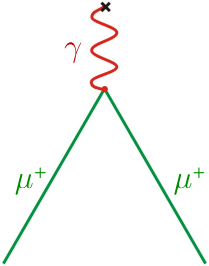
2. ISR-physics at flavor-factories → Hadronic cross sections; → Look for something new
3. Impact of data from super-flavor factories
4. Summary

The anomalous magnetic moment of the muon a_μ

gyromagnetic ratio: g

$$\vec{\mu} = g \frac{e\hbar}{2mc} \vec{S}$$

(1918) Dirac particles: $g = 2$



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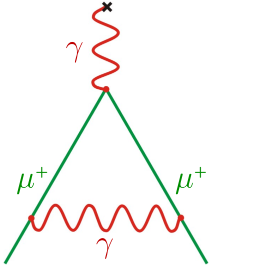
QED:



Schwinger: $a_\mu^{QED,LO} = \frac{\alpha}{2\pi}$

[Schwinger, PR **73**, 416 (1948)]

corresponds to an additional magnetic moment associated with the electron spin, of magnitude $\delta\mu/\mu = (\frac{1}{2}\pi)e^2/\hbar c = 0.001162$. It is indeed gratifying that recently acquired experimental data confirm this prediction. Measurements

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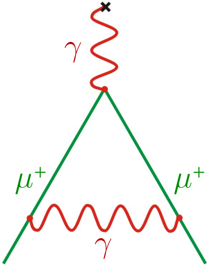

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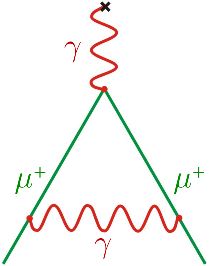
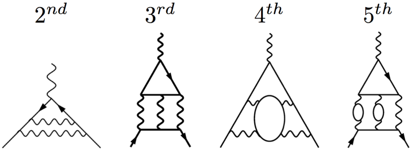
QED	11 658 471.895 ± 0.008
Schwinger	11 620 000

a_μ units in 10^{-10}

QED:



examples for higher order QED corrections:



[T.Kinoshita *et al.*, PR L **109**, 111808 (2012)]

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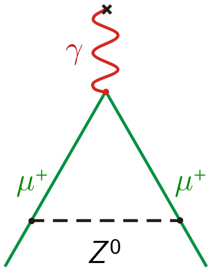
weak:



[A. Czarnecki *et al.*, PR D **67**, 073006 (2003)
Erratum-ibid. D**73**, 119901 (2006)]
[M. Knecht *et al.*, JHEP 0211, 003 (2002)]

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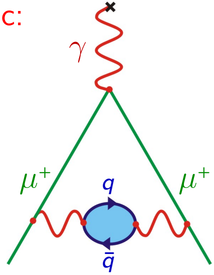
hadronic:



[M. Davier *et al.*, EPJ **C** 71, 1515 (2011)]

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had	693.0	±4.9
BNL–SM	28.7	±8.0

a_μ units in 10^{-10}

experiment:

Brookhaven National Laboratory (BNL)
[G.W. Bennett *et al.*, PR D **73**, 072003 (2006)]

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$a_\mu^{\text{SM}} - a_\mu^{\text{exp}}$:
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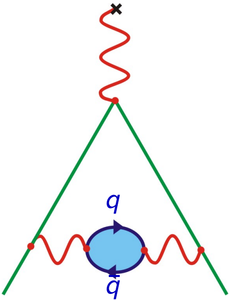
Theoretical prediction of $(g-2)_\mu$



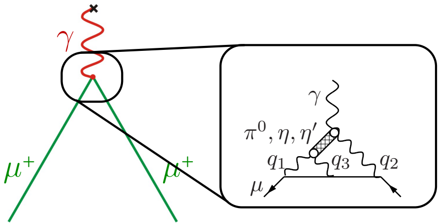
Hadronic contributions dominate the uncertainty!

- hadronic Light-by-Light
- hadronic Vacuum Polarization

Dominating hadronic contributions (1): $a_\mu^{\text{had,LbL}}$

total hadronic contribution: $a_\mu^{\text{had}} = (693.0 \pm 4.9) \cdot 10^{-10}$

Light-by-Light (LbL): $a_\mu^{\text{had,LbL}} = (10.5 \pm 2.6) \cdot 10^{-10}$



- pseudoscalar meson exchange contribution important (π^0, η, η')
- photon-meson transition form factors (TFF) need to be measured

[J. Prades *et al.*, arXiv:0901.0306 (2009)]

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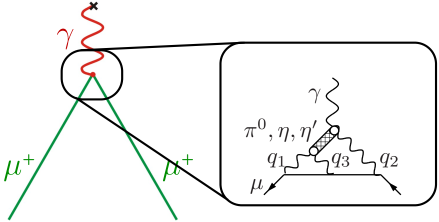

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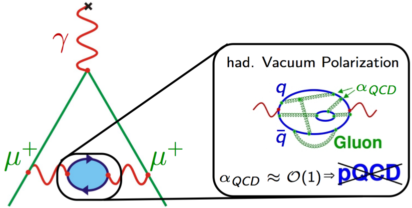
Two photon physics by Simon Eydelman, today, 16:15

Dominating hadronic contributions (2): $a_\mu^{\text{had,VP}}$

total hadronic contribution: $a_\mu^{\text{had}} = (693.0 \pm 4.9) \cdot 10^{-10}$

Hadronic Vacuum Polarization (VP): $a_\mu^{\text{had,VP}} = (692.3 \pm 4.2) \cdot 10^{-10}$

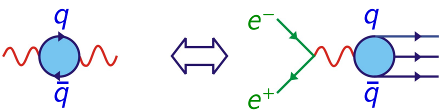


- largest hadronic contribution to a_μ
- largest absolute uncertainty of a_μ
- running of $\alpha_s \Rightarrow$ pQCD not applicable

[M. Davier *et al.*, EPJ **C** 71, 1515 (2011)]

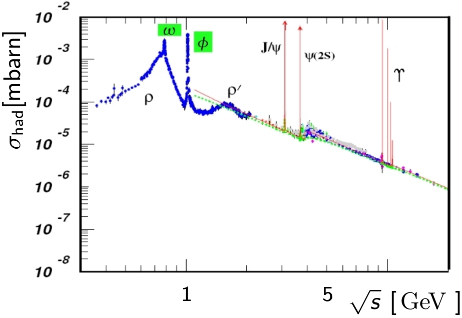
Dominating hadronic contributions (2): $a_\mu^{\text{had},VP}$

Optical theorem



Dispersion integral

$$a_{\mu,LO}^{\text{had}} = \frac{1}{4\pi^3} \int_{m_{\pi^0}^2}^{\infty} ds\, K(s)\, \sigma_{\text{had}}(s)$$



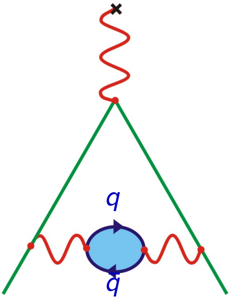
$$\sigma_{\text{had}}(s) \sim 1/s \quad \& \quad K(s) \sim 1/s$$
$$\Downarrow$$
$$\sim 1/s^2$$

Low energy contributions important!

Needed:

hadronic cross section σ_{had}

Experimental input for a_μ^{Theory}



Hadronic contributions dominate the uncertainty!

- hadronic Light-by-Light
- hadronic Vacuum Polarization

$\Rightarrow$ Need experimental input!

Experimental input for a_μ^{had}

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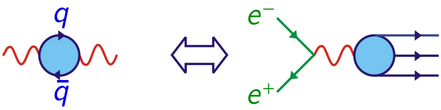
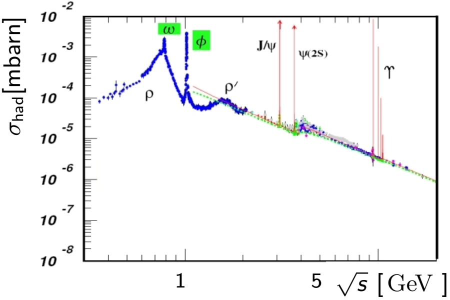


Energy scan

- CMD & SND, VEPP-2M & VEPP-2000, Novosibirsk
- BES-I & II, BEPC, Beijing



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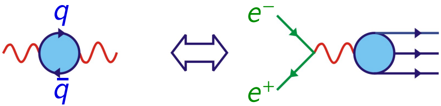
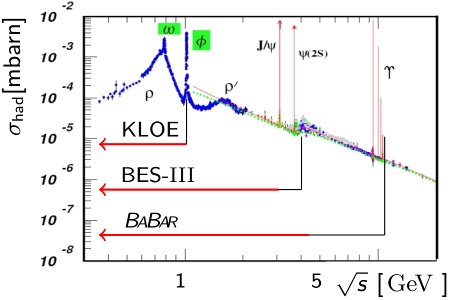
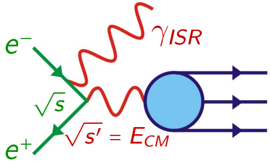


Energy scan

- CMD & SND@VEPP-2M & VEPP-2000 in Novosibirsk
- BES-III@BEPC-II in Beijing



Initial State Radiation



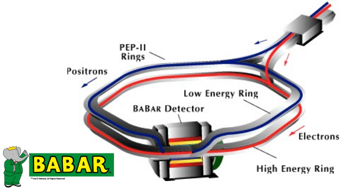
- KLOE@DAϕNE in Frascati
- *BABAR*@PEP-II in Stanford
- BES-III@BEPC-II in Beijing

KLOE and *B*-factories (*BABAR* and Belle) – A success story

main purpose: *B*-physics → *CP* violation

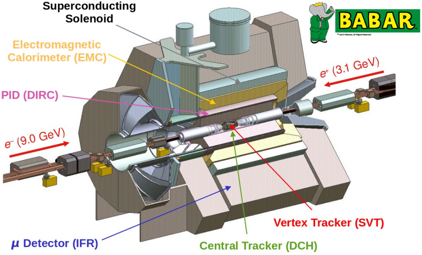
PEP-II@SLAC and KEKB@Tsukuba

- asymmetric e^+e^--colliders
- $\sqrt{s} = 10.58\,\mathrm{GeV} \Rightarrow \Upsilon(4S)$
  $\Rightarrow$ above $B\bar{B}$-threshold

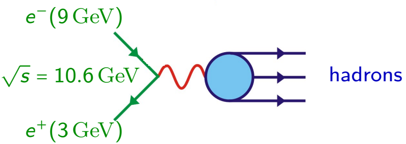


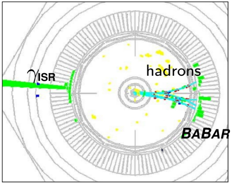
BABAR- and Belle-detector

- multi purpose detectors
- *BABAR* from 1999 – 2008:
  $\mathcal{L}_{int} \approx 0.5\,\mathrm{ab}^{-1} \approx 4.7 \cdot 10^8 \;\; B\bar{B}$
- Belle from 1999 – 2010:
  $\mathcal{L}_{int} \approx 1\,\mathrm{ab}^{-1} \approx 7.7 \cdot 10^8 \;\; B\bar{B}$



Initial State Radiation (ISR) events at *BABAR*





ISR selection

- Detected high energy photon: $E_\gamma > 3\,\mathrm{GeV}$
  → defines E_{CM} & provides strong background rejection
- Event topology: γ_{ISR} back-to-back to hadrons
  → high acceptance
- Kinematic fit including γ_{ISR}
  → very good energy resolution ($4 - 15\,\mathrm{MeV}$)
- Continuous measurement from threshold to ~$4.5\,\mathrm{GeV}$
  → provides common, consistent systematic uncertainties

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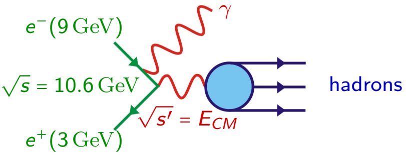

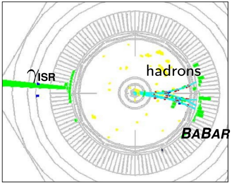

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ISR analyses at flavor factories

published by KLOE

$e^+e^- \to \pi^+\pi^-$ PL B 606, (2005), 12, PL B 670, (2009), 285, PL B 700, (2011) 102-110, PL B 720, (2013) 336-343

published by *BABAR*

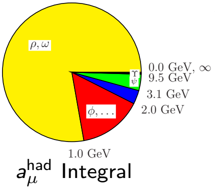
$e^+e^- \to \pi^+\pi^-$	PR D 86 (2012) 032013, PR L 103 (2009) 231801
$e^+e^- \to K^+K^-$	PR D 88, (2013) 032013
$e^+e^- \to \phi f_0(980)$	PR D 74 (2006) 091103, PR D 76 (2007) 012008
$e^+e^- \to \pi^+\pi^-\pi^0$	PR D 70 (2004) 072004
$e^+e^- \to K^+K^-\eta, K^+K^-\pi^0, K_S^0K^\pm\pi^\mp$	PR D 77 (2008) 092002, PR D 71 (2005) 052001
$e^+e^- \to 2(\pi^+\pi^-)$	PR D 85 (2012) 112009, PR D 76 (2007) 012008
$e^+e^- \to K^+K^-\pi^0\pi^0, K^+K^-\pi^+\pi^-, 2(K^+K^-)$	PR D 86 (2012) 012008, PR D 76 (2007) 012008
$e^+e^- \to K_S^0K_L^0, K_S^0K_L^0\pi^+\pi^-, K_S^0K_S^0\pi^+\pi^-, K_S^0K_S^0K^+K^-$	PR D 89 (2014) 092002
$e^+e^- \to 2(\pi^+\pi^-)\pi^0, 2(\pi^+\pi^-)\eta, K^+K^-\pi^+\pi^-\pi^0, K^+K^-\pi^+\pi^-\eta$	PR D 76 (2007) 092005
$e^+e^- \to 3(\pi^+\pi^-), 2(\pi^+\pi^-\pi^0), 2(\pi^+\pi^-)K^+K^-$	PR D 73 (2006) 052003

ongoing: $e^+e^- \to \pi^+\pi^-\pi^0\pi^0, \pi^+\pi^-\pi^0\pi^0\pi^0, K_S^0K^\pm\pi^\mp\pi^0/\eta$

ongoing analyses @BESIII: $e^+e^- \to \pi^+\pi^-, \pi^+\pi^-\pi^0, \pi^+\pi^-\pi^0\pi^0$
ongoing analyses @Belle: $e^+e^- \to \pi^+\pi^-\pi^0$

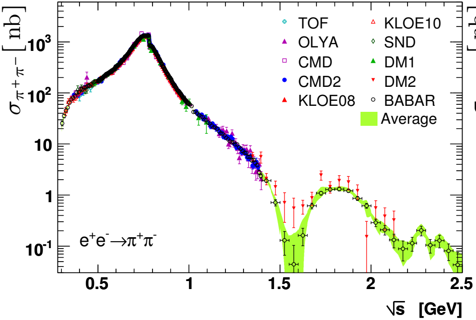
Contributions of exclusive final states to $g_\mu - 2$

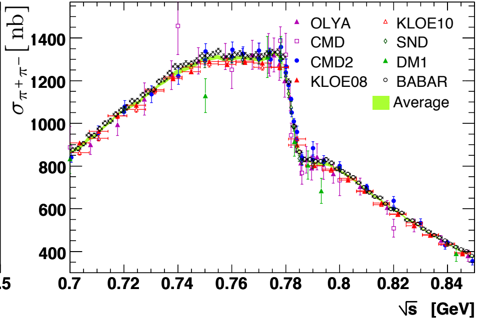
Contributions of different energy regions to the dispersion integral



→ $E < 1\,\mathrm{GeV}$ region dominates
→ $\pi^+\pi^-$ channel needed!

$\pi^+\pi^-$ cross section



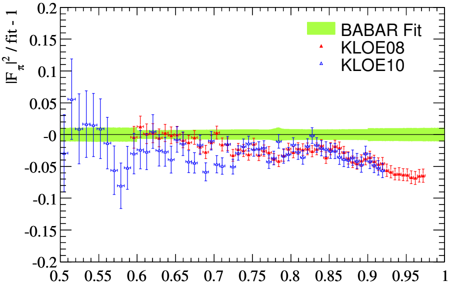


- ρ peak
- $\rho - \omega$ interference
- Dip at 1.6 GeV: excited ρ states
- Dip at 2.2 GeV
- Contribution to a_μ^{had}: 75%!

Systematic Uncertainties

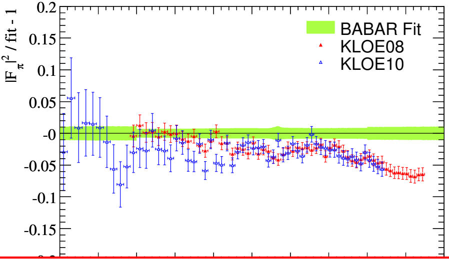
BABAR:	0.5%
CMD2:	0.8%
SND:	1.5%
KLOE:	0.8%

$\pi^+\pi^-$ cross section



- KLOE and *BABAR* dominate the world average
- Uncertainty of both measurements smaller than 1%
- Systematic difference, especially above ρ peak
- Difference → relatively large uncertainty for a_μ^{had}

$\pi^+\pi^-$ cross section



Need to solve this discrepancy!

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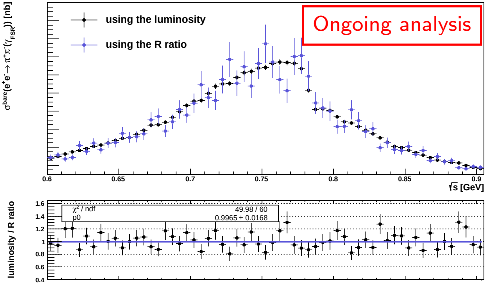
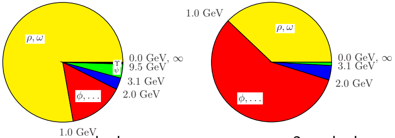
$\pi^+\pi^-$ cross section at BESIII



- Target uncertainty: 1%
- Different systematic effects
  $\to$ important insights into $\pi^+\pi^-$ discrepancy

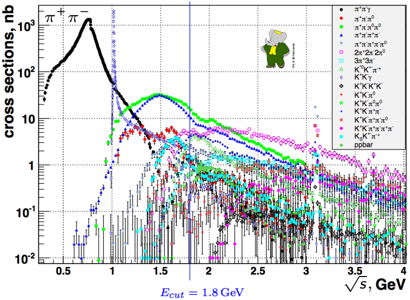
Contributions of exclusive final states

Contributions of different energy regions to the dispersion integral



Integral a_μ^{had} Uncertainty^2 $\delta a_\mu^{\mathrm{had}}$

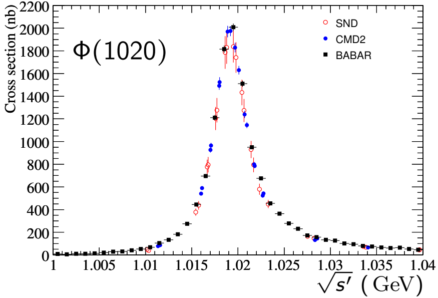
$\Rightarrow$ Precise measurements $1\,\mathrm{GeV} < E < 2\,\mathrm{GeV}$ needed!

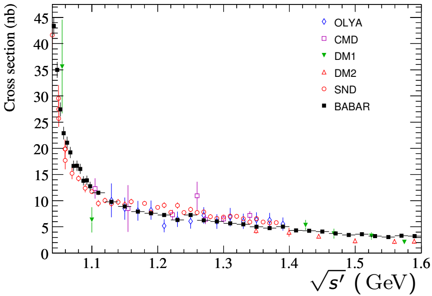


$\Rightarrow$ Other channels important!

- K^+K^-
- $K_S^0 K_L^0$
- $\pi^+\pi^-\pi^+\pi^-$
- $\pi^+\pi^-\pi^0$
- $\pi^+\pi^-\pi^0\pi^0$

Cross section $\sigma(e^+e^- \to K^+K^-)$





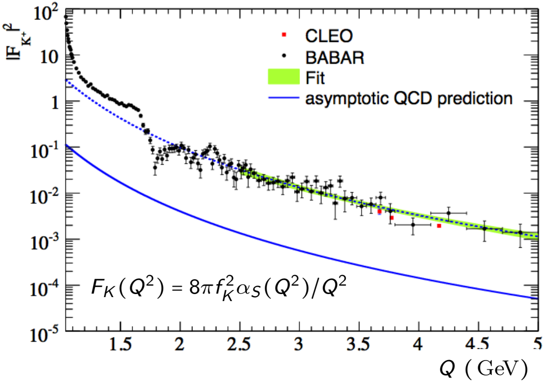
- uncertainties near ϕ peak:
  BABAR: 0.8%
  CMD2: 2.2%
- extracted m_ϕ agree within calibration uncertainties
- normalization difference:
  $\approx$ 1 s.d. to SND
  $\approx$ 2 s.d. to CMD2

$\Rightarrow$ some tension between the results

Charged kaon form factor at large Q^2

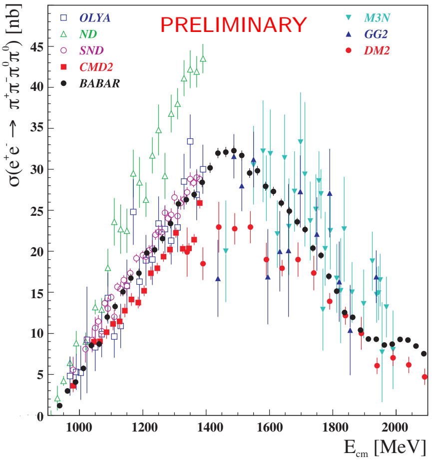
Predictions based on QCD in asymptotic regime (Chernyak, Brodsky-Lepage, Farrar-Jackson)

- Power law: $F_K \propto \alpha_S(Q^2)Q^{-n}$ with $n = 2$
  $\rightarrow$in good agreement with the data (2.5-5 GeV $n = 2.10 \pm 0.23$)
- HOWEVER: data on $|F_K|^2$ factor ≈ 20 above prediction!
- No trend in data up to 25 GeV^2 for approaching the asymp. QCD prediction

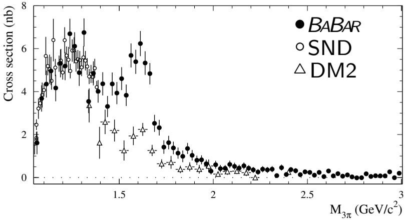


Higher multiplicities: $e^+e^- \to \pi^+\pi^-\pi^0(\pi^0)$

$\pi^+\pi^-\pi^0\pi^0$



$\pi^+\pi^-\pi^0$



a_μ units in 10^{-10}

Channel	$a_\mu^{had,LO}$	σ_{stat}	σ_{syst}
$\pi^+\pi^-$	507.80	1.22	2.56
$\pi^+\pi^-\pi^0$	46.00	0.42	1.42
$\pi^+\pi^-\pi^0\pi^0$	18.01	0.14	1.24
Total	692.3	1.4	3.9

[EPJ C66, 1 (2011).]

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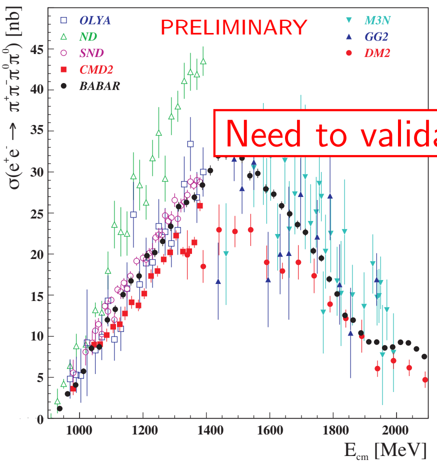
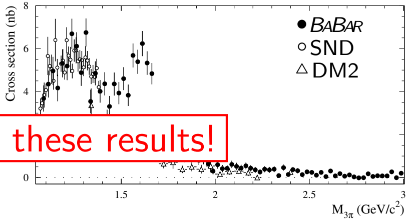


$\pi^+\pi^-\pi^0$



Need to validate these results!

a_μ units in 10^{-10}

Channel	$a_\mu^{had,LO}$	σ_{stat}	σ_{syst}
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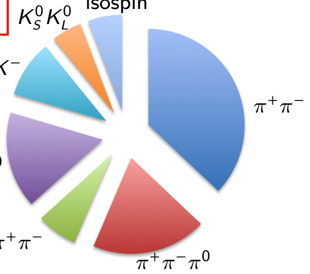
[EPJ C66, 1 (2011).]

Impact on $g_\mu - 2$: had. VP

$a_\mu^{\mathrm{VP,LO}} = (692.3 \pm 4.2) \cdot 10^{-10}$

$a_\mu^{had,VP}$

$\delta a_\mu^{had,VP}$



[data from Davier, EPJ **C** 71, 1515 (2011)]

channels estimated with isospin rels

largest contributions: $K\bar{K}\pi$ and $K\bar{K}\pi\pi$

$K_S^0 K_L^0$

BABAR not evaluated, yet

K^+K^-

BABAR reduces $\delta a_\mu^{had}(K^+K^-)$ by factor 2.7

$\pi^+\pi^-\pi^+\pi^-$

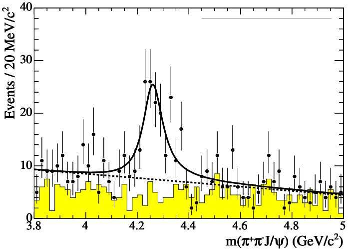
BABAR reduces $\delta a_\mu^{had}(\pi^+\pi^-\pi^+\pi^-)$ by 40%

$\pi^+\pi^-, \pi^+\pi^-\pi^0, \pi^+\pi^-\pi^0\pi^0$

wait for *BABAR*, BESIII, and CMD3 results

Spectroscopy via ISR: Y(4260), Y(2175), ...

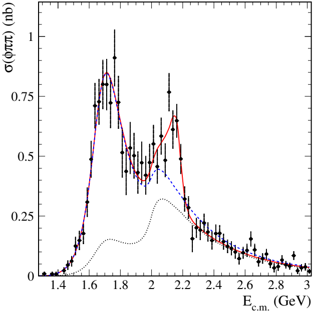
Y(4260) in $e^+e^- \to J/\psi\,\pi^+\pi^-$



- First observation by *BABAR* in 2005
- Confirmed by Belle, BESIII, ...

XYZ@*B*-factories by Roman Mizuk

Y(2175) in $e^+e^- \to \phi\pi\pi$

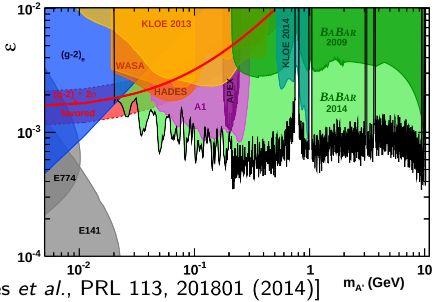


- Not a radial excitation:
  - width too small
  - should also decay in σ as $\phi(1680)$
- Strangeness partner of Y(4260)?

The Dark Photon: $a_\mu^{SM} - a_\mu^{exp} \stackrel{?}{=} a_\mu^{NP}$

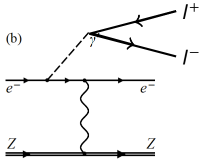
- New massive U(1) vector boson γ'
- Motivated by astrophysical observations
- $M_{\gamma'} \approx \mathcal{O}(1\,\mathrm{GeV}/c^2)$
- $\alpha' = \epsilon^2\alpha$
- Influence on $(g-2)_\mu$

[Arkani-Hamed *et al.*, PRD 79, 015014 (2009)]

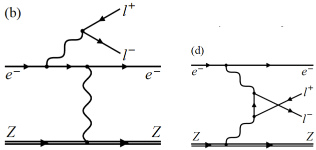


[Lees *et al.*, PRL 113, 201801 (2014)]

γ'-signal at fixed-target exp.



QED background



[Bjorken *et al.*, PRD 80, 075018 (2009)]

ISR physics in the next decade

Super-τ-charm factory and super-KEKB

Super-KEKB

- e^+e^--collider
- Center-of-Mass energy $\sqrt{s} = m(\Upsilon(4S))$
- Luminosity: $8 \cdot 10^{35} s^{-1}\,\mathrm{cm}^{-2}$
- Integrated luminosity: $50\,\mathrm{ab}^{-1}$

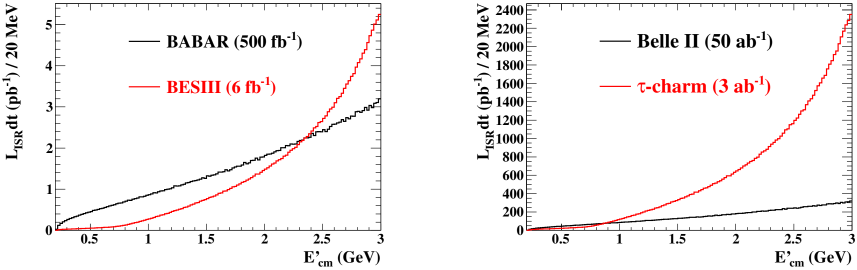
Super-τ-charm factory

- e^+e^--collider
- Center-of-Mass energy $\sqrt{s} = 2 - 7\,\mathrm{GeV}$
- Luminosity: $1 \cdot 10^{35} s^{-1}\,\mathrm{cm}^{-2}$
- Integrated luminosity: $6\,\mathrm{ab}^{-1}$

ISR-statistics: super-τ-charm factory vs. super-KEKB

$e^+e^- \to \pi^+\pi^-\gamma_{ISR}$:

- Phokhara event generator (standalone version)
- Luminosity * Radiator Function (PHOKHARA standalone)
- Acceptance of π: $21 - 159°$
- Super-τ-charm assumption: use half of integrated $\mathcal{L}$
  $\Rightarrow 1.5\,\text{ab}^{-1}$@Y(4260) and $1.5\,\text{ab}^{-1}$@Ψ''



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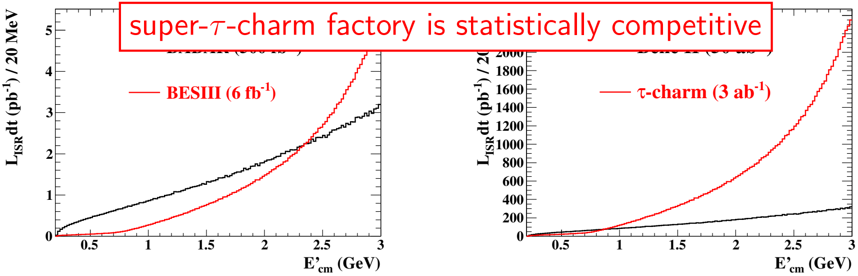
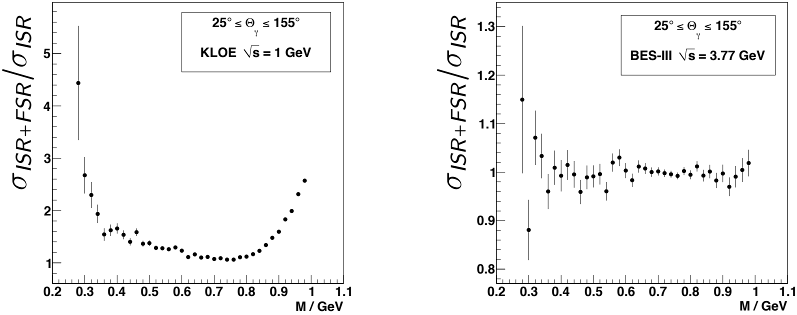
super-τ-charm factory is statistically competitive



super-τ-charm factory vs. KLOE@Daϕne

Final State Radiation (FSR)

- KLOE runs on $\phi(1020)$ resonance
- Contamination of FSR background in charmonium region negligible
- FSR description is model dependent



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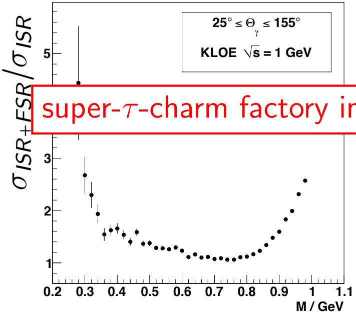
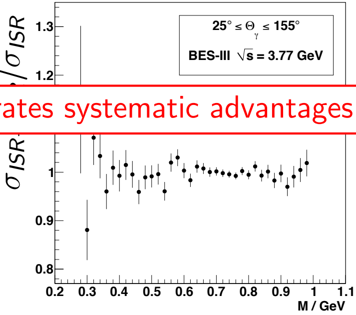




super-τ-charm factory incorporates systematic advantages

Summary

ISR-physics programme has a large impact on today's physics

Important improvement for a_μ

- Direct a_μ measurement will improve uncertainty by a factor of 4
- Theory improvement requires experimental input
  $\Rightarrow$ Higher precision in hadronic cross section measurements needed

Scan for the unknown

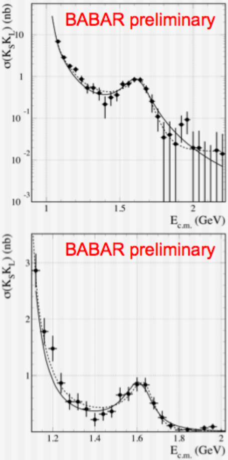
- New resonances have been found: Y(4260), Y(2175)
- Dark Photon

Further data of super flavor factories needed

backup slides

$\phi(1680) \to K_S^0 K_L^0$

Is it ϕ(1680) ?



$$\sigma(s) = \frac{P(s)}{s^{5/2}} \left| \frac{A_{\phi(1020)}}{\sqrt{P(m_\phi)}} + \frac{A_X}{\sqrt{P(m_X)}} \cdot e^{i\varphi} + A_{bkg} \right|^2$$

$$P(s) = \left((s/2)^2 - m_{K^0}^2 \right)^{3/2}$$

$$A(s) = \frac{\Gamma(m^2) \cdot m^3 \sqrt{\sigma_0 \cdot m}}{s - m^2 + i\sqrt{s}\Gamma(s)}$$

$$\Gamma(s) = \Gamma \cdot \sum_f B_f \cdot \frac{P_f(s)}{P_f(m_f^2)}$$

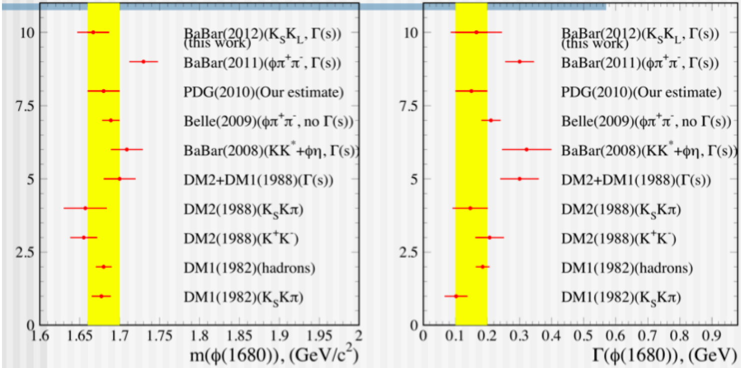
$$A_{\phi(1020)} = A_\phi + A_\omega - A_\rho, \qquad f = K^* K, \phi\eta, \phi\pi\pi, K_S K_L$$

σ_0 = 0.46 ± 0.10 ± 0.04 nb
m = 1674 ± 12 ± 6 MeV/c^2
Γ_0 = 165 ± 38 ± 70 MeV
φ = 3.01 ± 0.38 – fixed to π
σ_{bkg} = 0.36 ± 0.18 nb
$\Gamma_{ee} \cdot B_{KSKL}$ = 14.3 ± 2.4 ± 1.5 ± 6.0 eV

Simultaneous K_SK_L and K^+K^- (and $\pi\pi$) fit is needed to separate I=0,1 states and ω(1420, 1650), ρ(1450,1700) contribution ..

$\phi(1680)$ observations in other channels

What we know about ϕ(1680)



Energy dependence significantly increase width.

BaBar has measured ϕ(1680) parameters in major decay modes:

ϕ(1680) ➔ $K_SK\pi$, $KK\pi^0$ (K*K), ϕη, ϕππ, K_SK_L (preliminary) - still no info in PDG