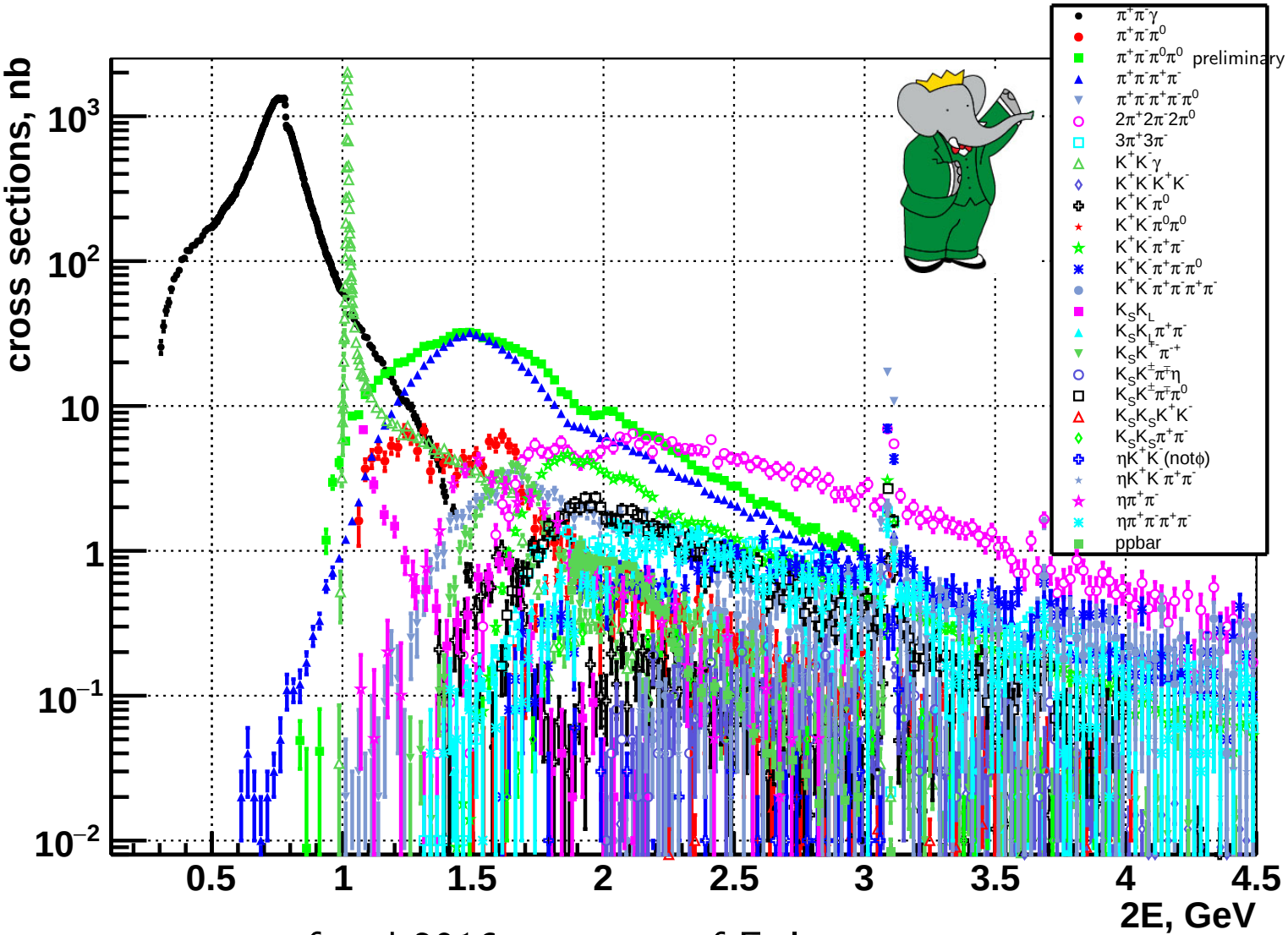
Review of ISR physics at *BABAR*

Konrad Griessinger
on behalf of the *BABAR* Collaboration

Institute for Nuclear Physics
Mainz University

Hadronic Physics with Lepton and Hadron Beams,
Jefferson Lab, September 2017

ISR hadronic cross sections at *BABAR*



as of end 2016, courtesy of F. Ignatov

The contributions to a_μ and its uncertainty

$$\begin{aligned} \vec{\mu} &= g_\mu \frac{e}{2m}\vec{s} \\ (g_\mu - 2)/2 &\equiv a_\mu = 0 \qquad \text{(Dirac equation)} \end{aligned}$$

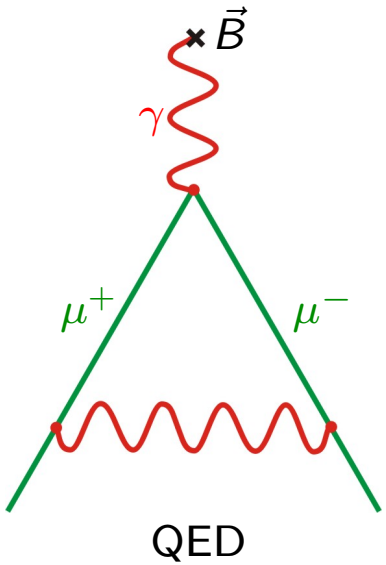
The contributions to a_μ and its uncertainty

$$\begin{aligned} \vec{\mu} &= g_\mu \frac{e}{2m}\vec{s} \\ (g_\mu - 2)/2 &=: a_\mu^{\text{SM}} = a_\mu^{\text{QED}} + a_\mu^{\text{weak}} + a_\mu^{\text{hadronic}} \end{aligned}$$

The contributions to a_μ and its uncertainty

$$\vec{\mu} = g_\mu \frac{e}{2m}\vec{s}$$

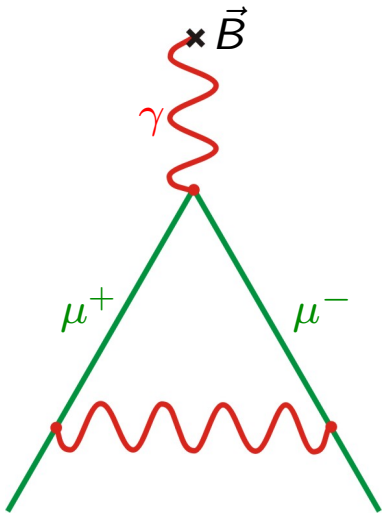
$$(g_\mu - 2)/2 =: a_\mu^{\text{SM}} = a_\mu^{\text{QED}} + a_\mu^{\text{weak}} + a_\mu^{\text{hadronic}}$$



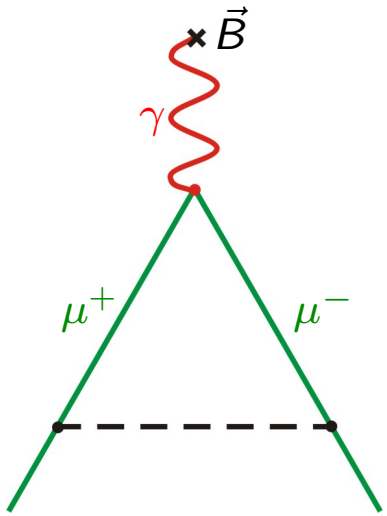
The contributions to a_μ and its uncertainty

$$\vec{\mu} = g_\mu \frac{e}{2m}\vec{s}$$

$$(g_\mu - 2)/2 =: a_\mu^{\text{SM}} = a_\mu^{\text{QED}} + a_\mu^{\text{weak}} + a_\mu^{\text{hadronic}}$$



QED

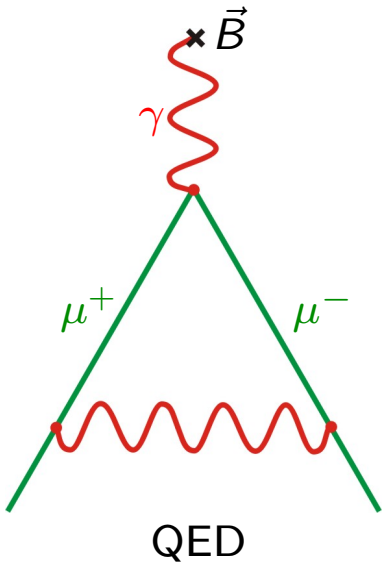


weak

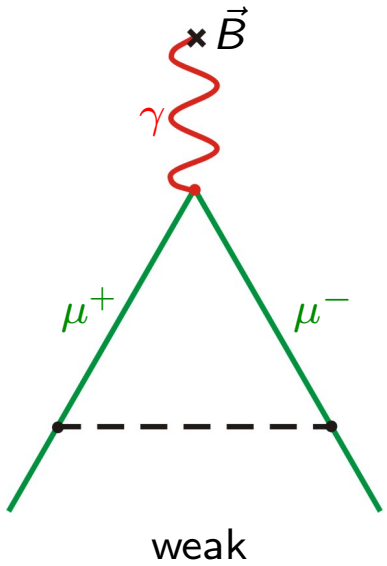
The contributions to a_μ and its uncertainty

$$\vec{\mu} = g_\mu \frac{e}{2m}\vec{s}$$

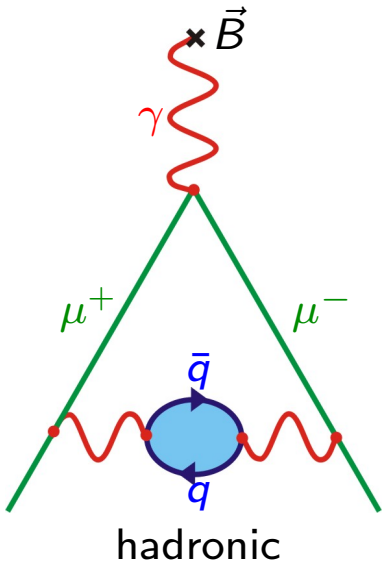
$$(g_\mu - 2)/2 =: a_\mu^{\text{SM}} = a_\mu^{\text{QED}} + a_\mu^{\text{weak}} + a_\mu^{\text{hadronic}}$$



QED



weak



hadronic

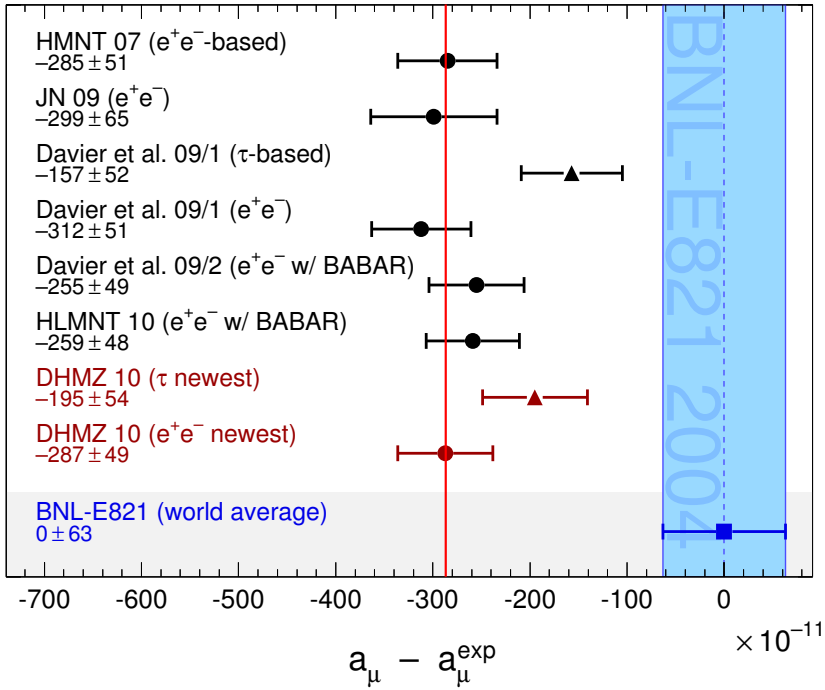
The contributions to a_μ and its uncertainty

$$\vec{\mu} = g_\mu \frac{e}{2m}\vec{s}$$

$$(g_\mu - 2)/2 =: a_\mu^{\text{SM}} = a_\mu^{\text{QED}} + a_\mu^{\text{weak}} + a_\mu^{\text{hadronic}}$$

	Contribution $[\cdot 10^{-10}]$	Uncertainty $[\cdot 10^{-10}]$
QED [1]	11 658 471.8951	0.0080
weak [8]	15.36	0.1
hadronic VP [5, 11]	683.7	4.3
hadronic LbL [10, 4]	11.9	4.1
theory total	11 659 182.8	6.0
Experiment E821 [14]	11 659 208.9	6.3
Experiment-Theory	26.1	8.7

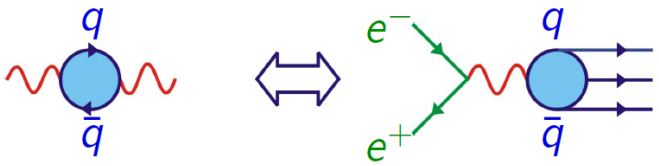
Discrepancy between SM prediction and direct measurement from Eur.Phys.J., C71:1515, 2011 [5].



Just a fluctuation?

3σ effect, thus reduction of uncertainties necessary!

Connection between a_μ and $\sigma_{\rm had}$

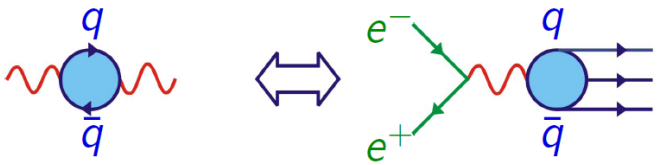


$$a_\mu^{\rm had} = \frac{1}{4\pi^3}\int_{m_\pi^2}^{\infty}\frac{\sqrt{1-\frac{4m_e^2}{s}}}{1+\frac{2m_e^2}{s}}K_\mu(s)\cdot\sigma_{e^+e^-\to{\rm had}}(s)\,{\rm d}s$$

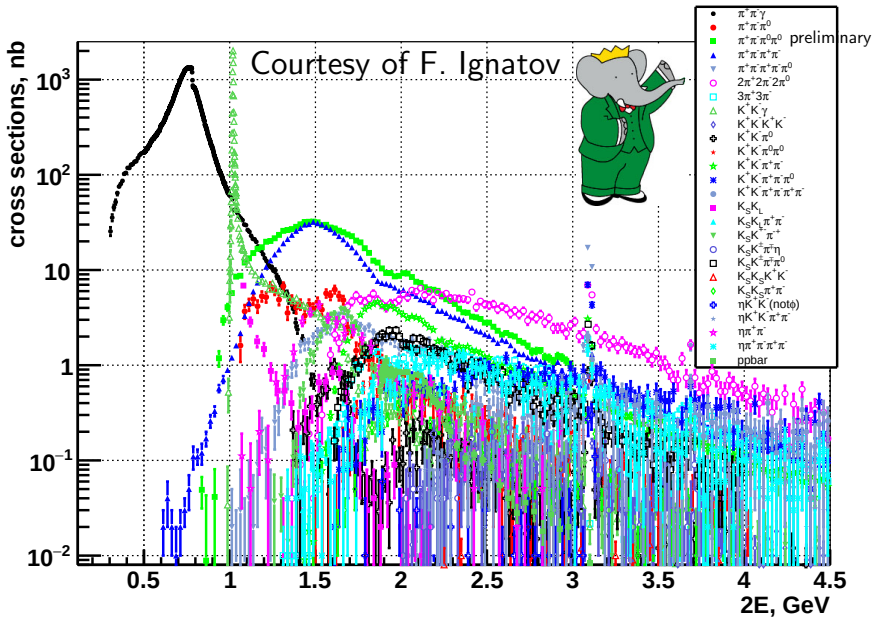
Kernel function

cross section

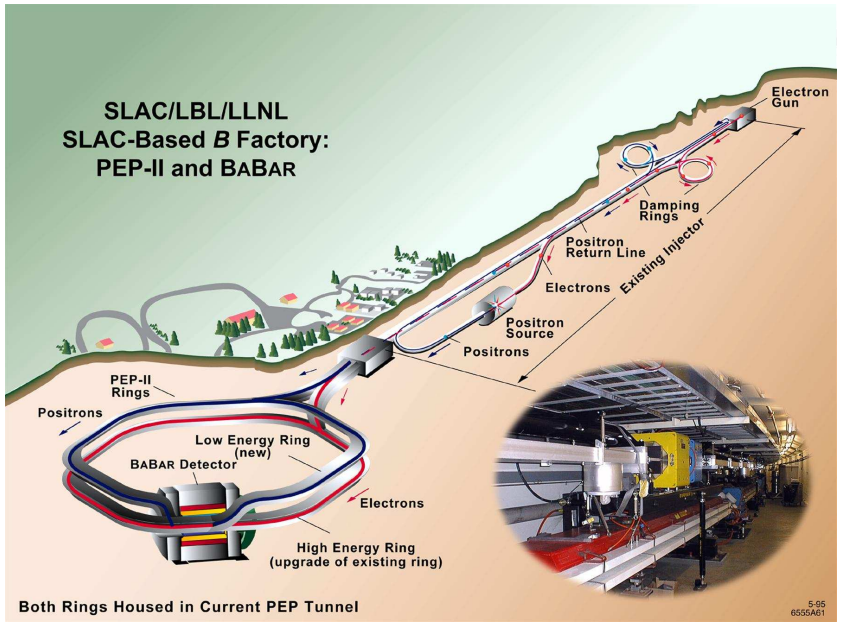
Connection between a_μ and $\sigma_{\rm had}$



$$a_\mu^{\rm had} = \frac{1}{4\pi^3}\int_{m_\pi^2}^{\infty}\frac{\sqrt{1-\frac{4m_e^2}{s}}}{1+\frac{2m_e^2}{s}}K_\mu(s)\cdot\sigma_{e^+e^-\to{\rm had}}(s){\rm d}s$$



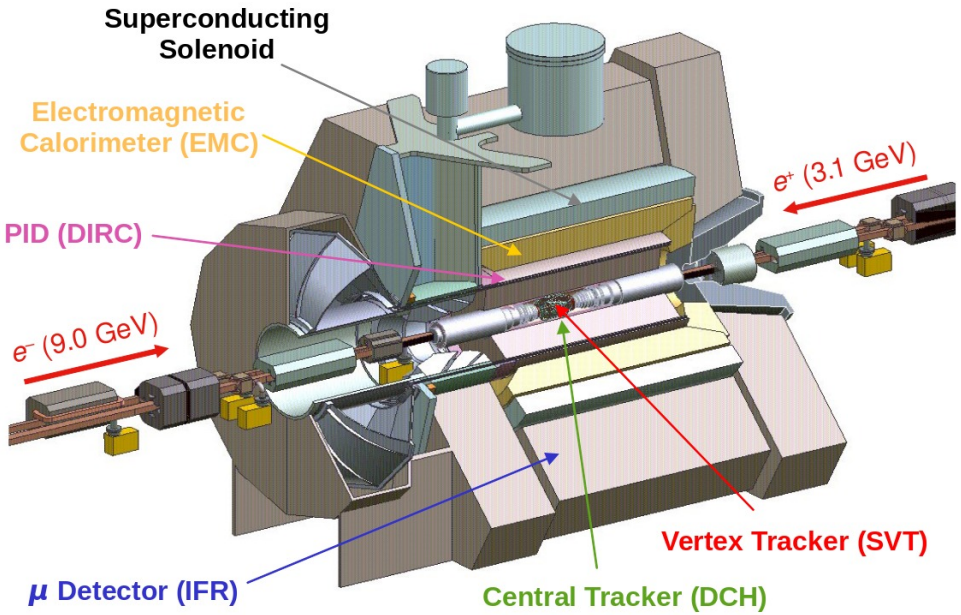
The *BABAR* Experiment



Experimental specifications

Energy: $\sqrt{s} \approx 10.58\,\text{GeV}$ $(E_{e^-} \approx 9.0\,\text{GeV}, E_{e^+} \approx 3.1\,\text{GeV})$,
Luminosity: $\mathcal{L} \approx 500\,\text{fb}^{-1}$ (mostly $\Upsilon(4S)$)

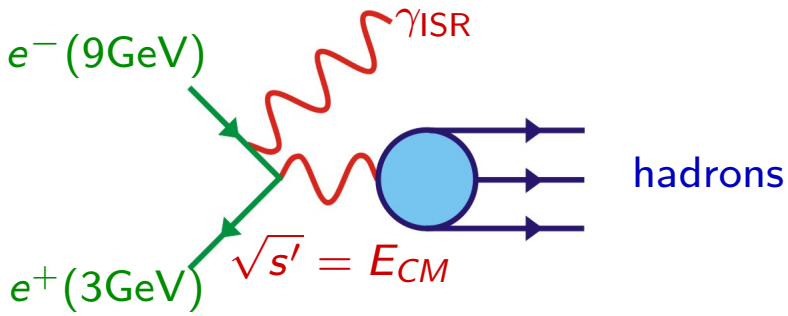
The *BABAR* Experiment

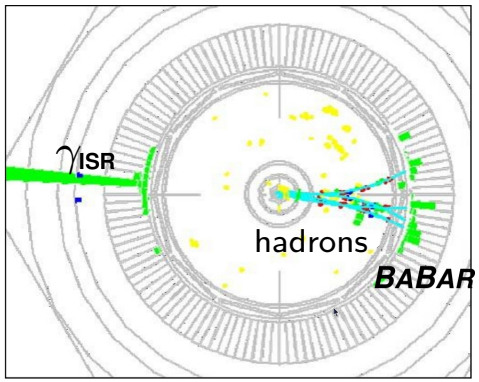


Experimental specifications

Energy: $\sqrt{s} \approx 10.58\,\text{GeV}$ $(E_{e^-} \approx 9.0\,\text{GeV}, E_{e^+} \approx 3.1\,\text{GeV})$,
Luminosity: $\mathcal{L} \approx 500\,\text{fb}^{-1}$ (mostly $\Upsilon(4S)$)

Initial State Radiation (ISR) events at *BABAR*





ISR selection

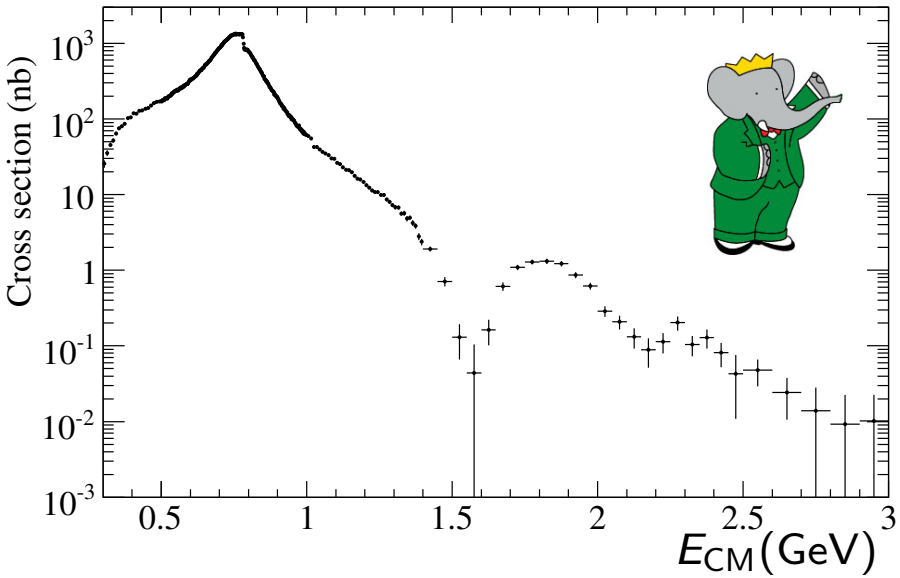
- Detected high energy photon: $E_\gamma > 3$GeV
  $\rightarrow$ defines E_{CM} & provides strong background rejection
- Event topology: γ_{ISR} back-to-back to hadrons
  $\rightarrow$ high acceptance
- Kinematic fit including γ_{ISR}
  $\rightarrow$ very good energy resolution (4 – 15MeV)
- Continuous measurement from threshold to $\sim$5GeV
  $\rightarrow$ provides common, consistent systematic uncertainties

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

Phys. Rev. D86 (2012) 032013 [13]

Resulting cross section

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



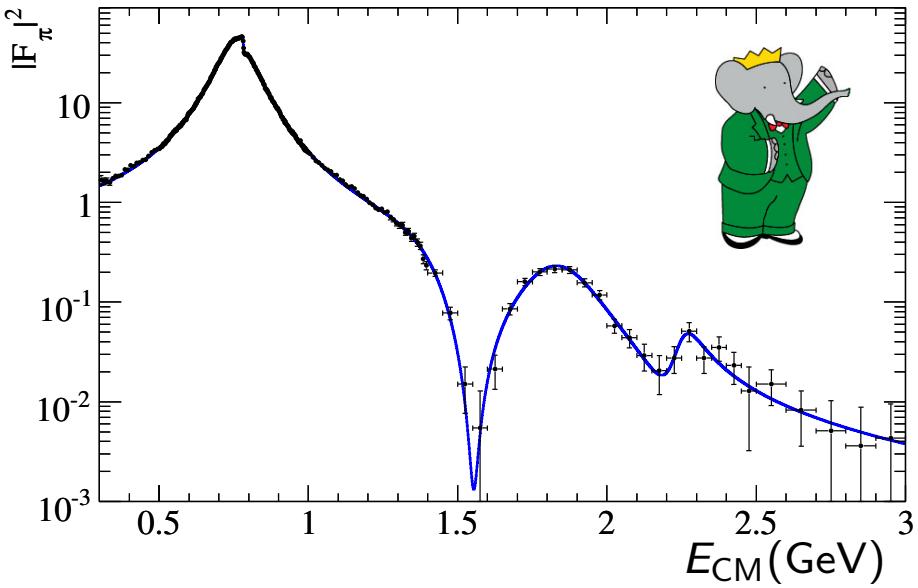
E_{CM}(GeV)	Syst. unc.
0.3 – 0.6	0.8 – 1.4%
0.6 – 0.9	0.50%
0.9 – 1.2	0.65%
1.2 – 3.0	1.4 – 5.3%

- dominant background $\mu^+\mu^-(\gamma)$
- CS calculated relative to $\mu^+\mu^-\gamma$
- half of *BABAR* dataset used, new analysis in progress

Contribution to $g_\mu - 2$

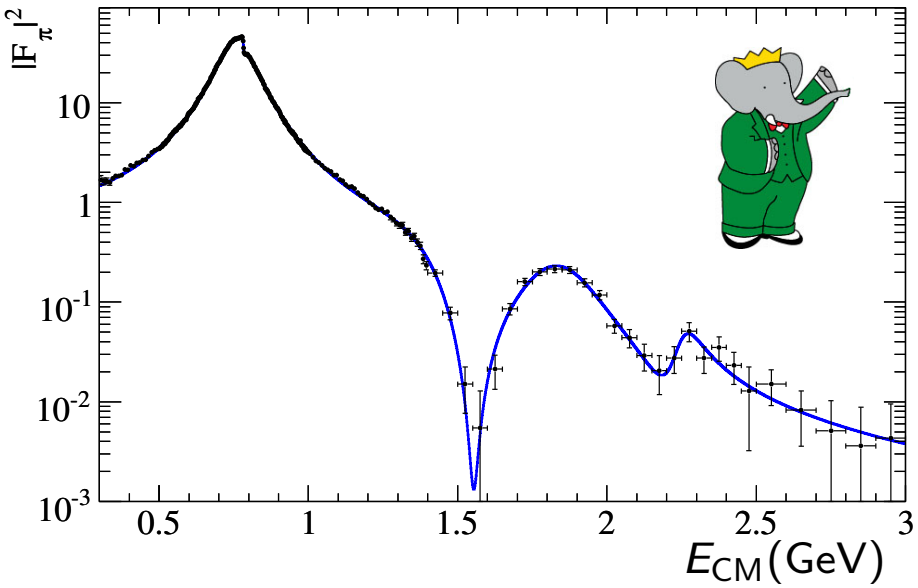
$$a_\mu(\sqrt{s} < 1.8\,\text{GeV}) = (514.09 \pm 2.22_{\text{stat}} \pm 3.11_{\text{syst}}) \times 10^{-10}$$

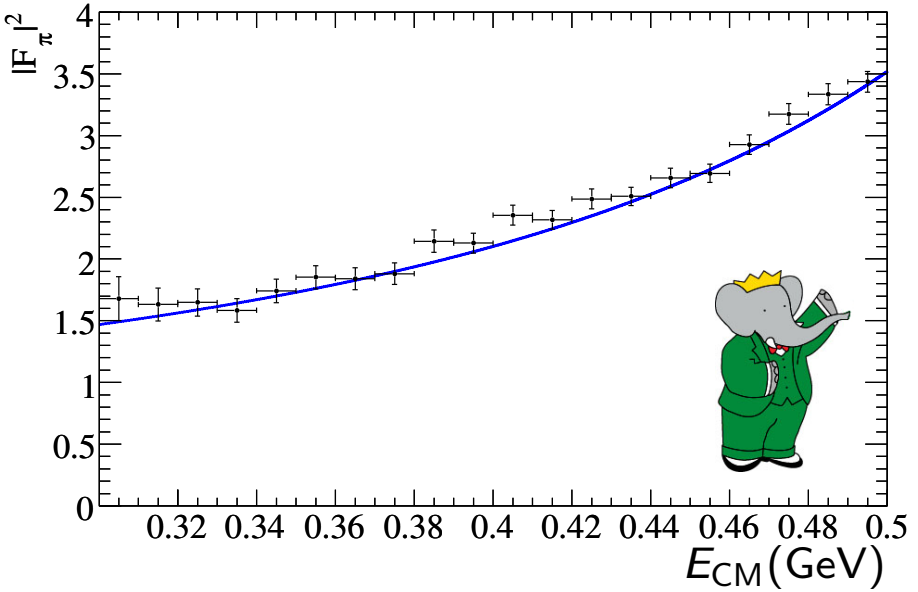
Pion form factor



- Fitted with Gounaris-Sakurai parameterization [9]
- motivated by VMD
- allows comparison to other data

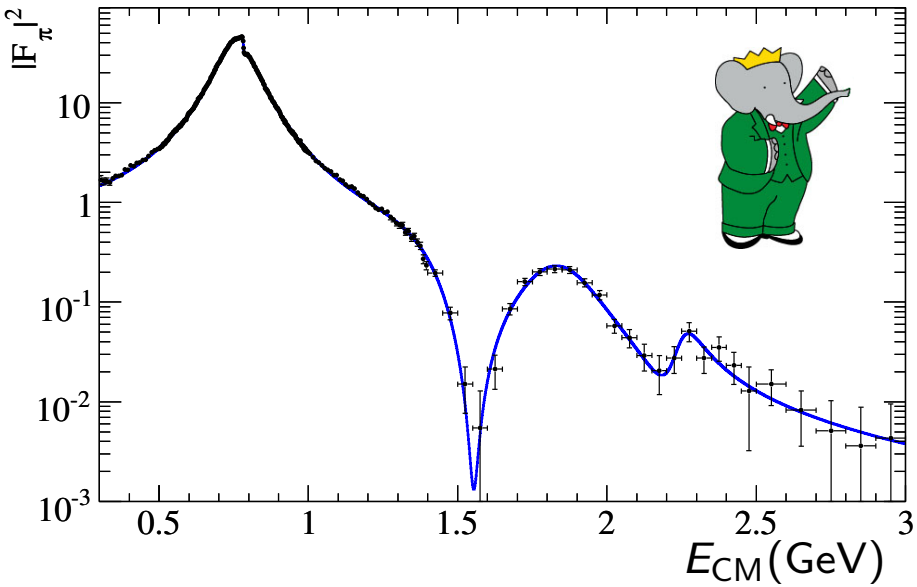
Pion form factor



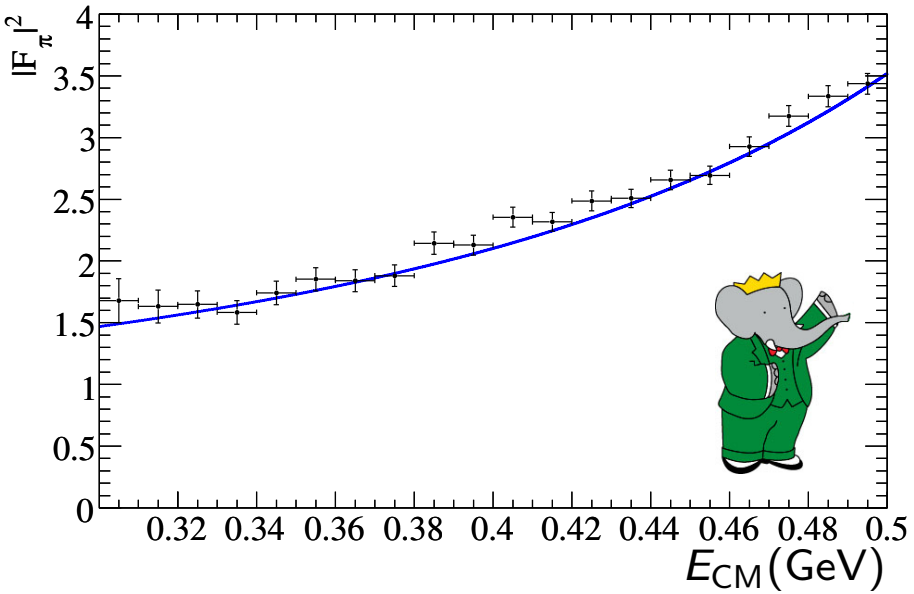


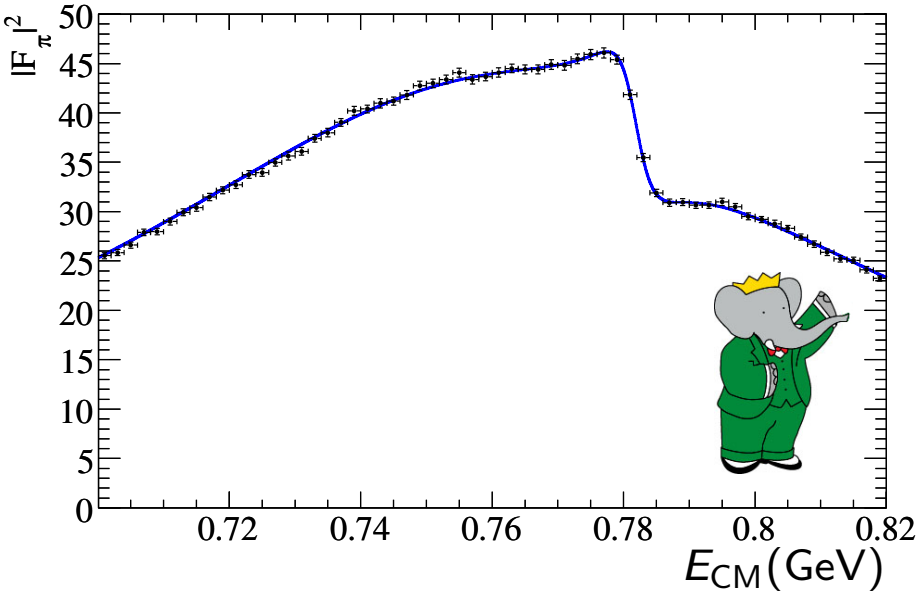
- Fitted with Gounaris-Sakurai parameterization [9]
- motivated by VMD
- allows comparison to other data

Pion form factor



- Fitted with Gounaris-Sakurai parameterization [9]
- motivated by VMD
- allows comparison to other data



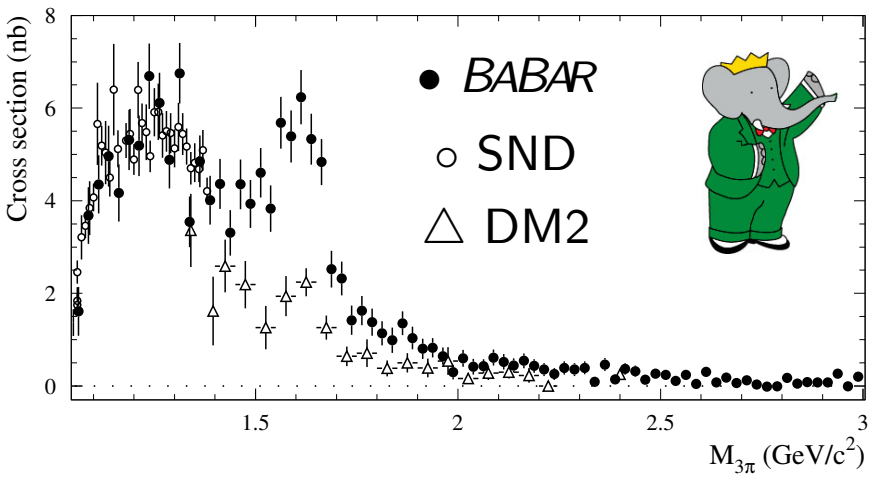


$e^+e^- \to \pi^+\pi^-\pi^0$

Phys. Rev. D70 (2004) 072004 [2]

Resulting cross section

$$e^+e^- \to \pi^+\pi^-\pi^0$$



- dominant bkg $\pi^+\pi^-\pi^0\pi^0$
- disagreement with DM2 around $1.6\,\mathrm{GeV}/c^2$
- energy range $1.05 < E_{\mathrm{CM}} < 3\,\mathrm{GeV}$

Systematic uncertainties:

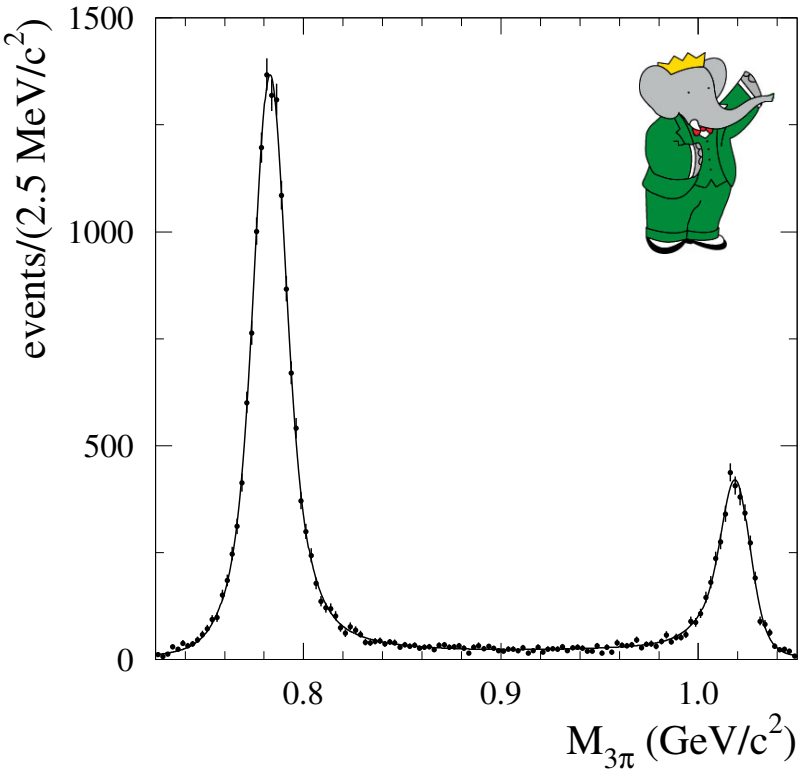
$\sim 5 - 10\%$

Contribution to $g_\mu - 2$ (comp. [6])

$a_\mu(\sqrt{s} < 1.8\,\mathrm{GeV}) =$
$(46.20 \pm 0.40_{\mathrm{stat}} \pm 1.40_{\mathrm{syst}}) \times 10^{-10}$

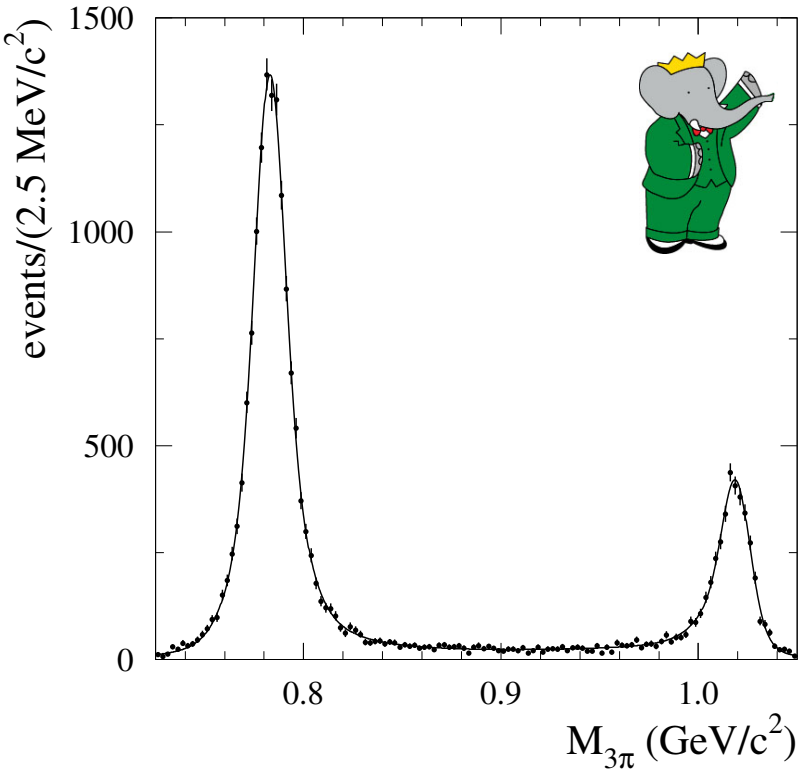
Intermediate resonances: ω, $\phi \to \pi^+\pi^-\pi^0$

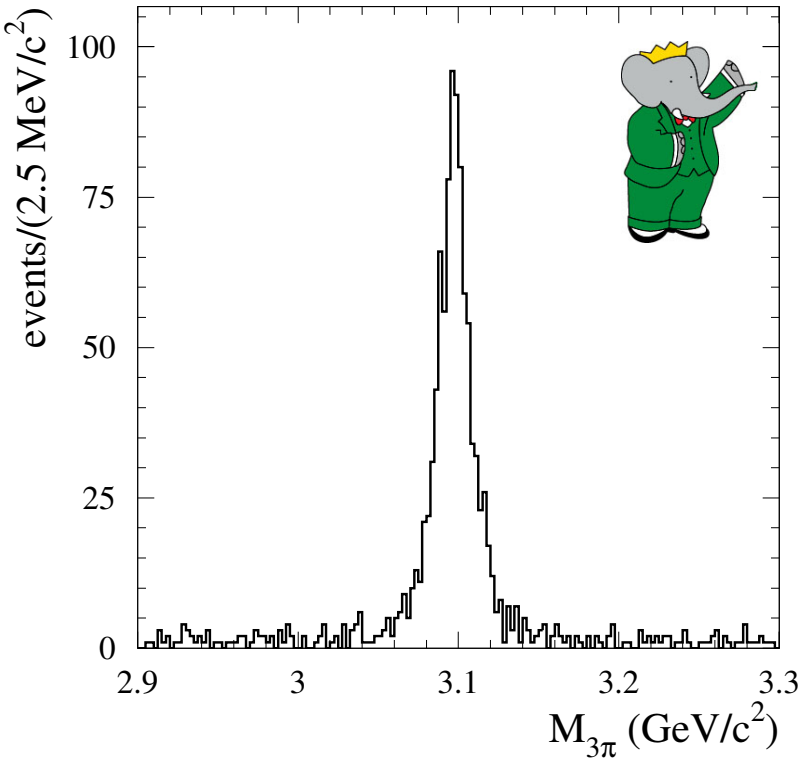
$$e^+e^- \to \pi^+\pi^-\pi^0$$



Intermediate resonances: ω, ϕ, and $J/\psi \to \pi^+\pi^-\pi^0$

$$e^+e^- \to \pi^+\pi^-\pi^0$$





J/ψ branching fraction

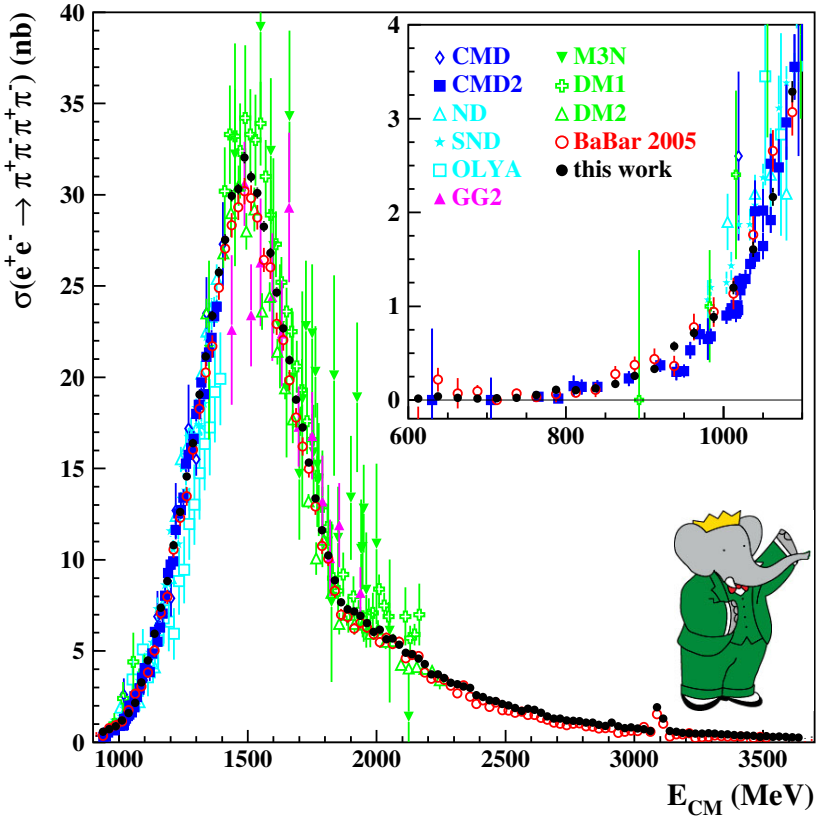
$$\mathcal{B}(J/\psi \to 3\pi) = (2.18 \pm 0.19)\,\%$$

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

Phys. Rev. D85 (2012) 112009 [12]

Resulting cross section

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



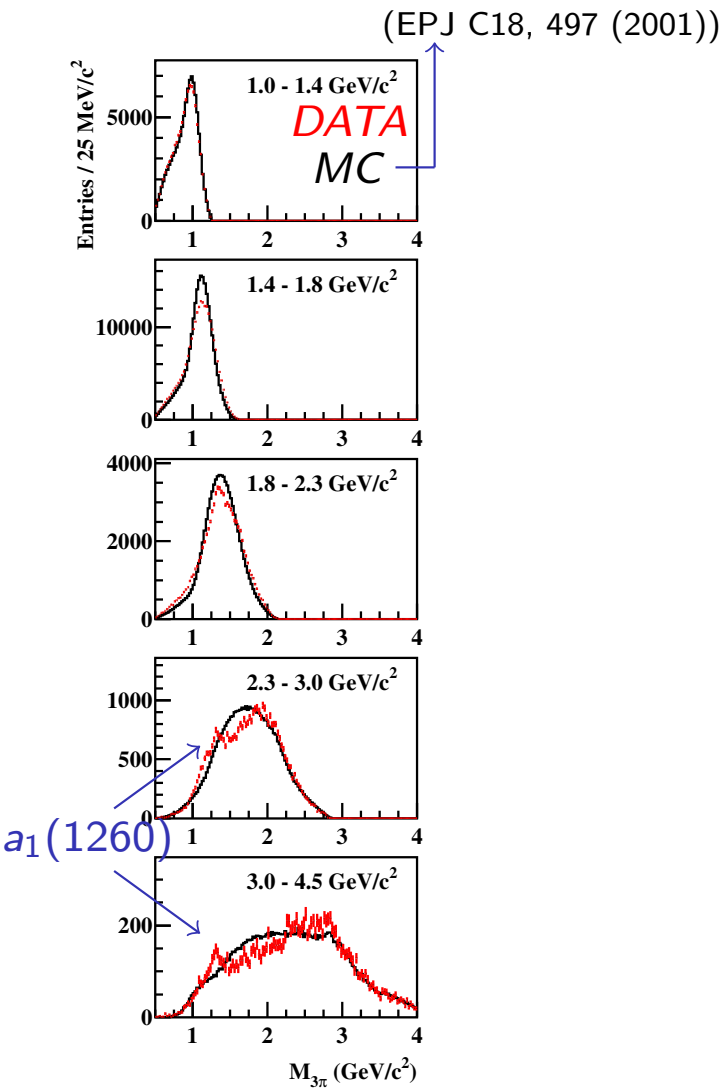
$E_{\rm CM}$(GeV)	Syst. unc.
0.6 – 1.1	11%
1.1 – 2.8	2.4%
> 2.8	4%

- dominant bkgs $K^+K^-\pi^+\pi^-$ and $K^0_S K^\pm\pi^\mp$
- full data set
- Photon detection and tracking systematics improved

Contribution to $g_\mu - 2$

$a_\mu(\sqrt{s} < 1.8\,\text{GeV}) =$
$(13.64 \pm 0.03_{\rm stat} \pm 0.36_{\rm syst}) \times 10^{-10}$

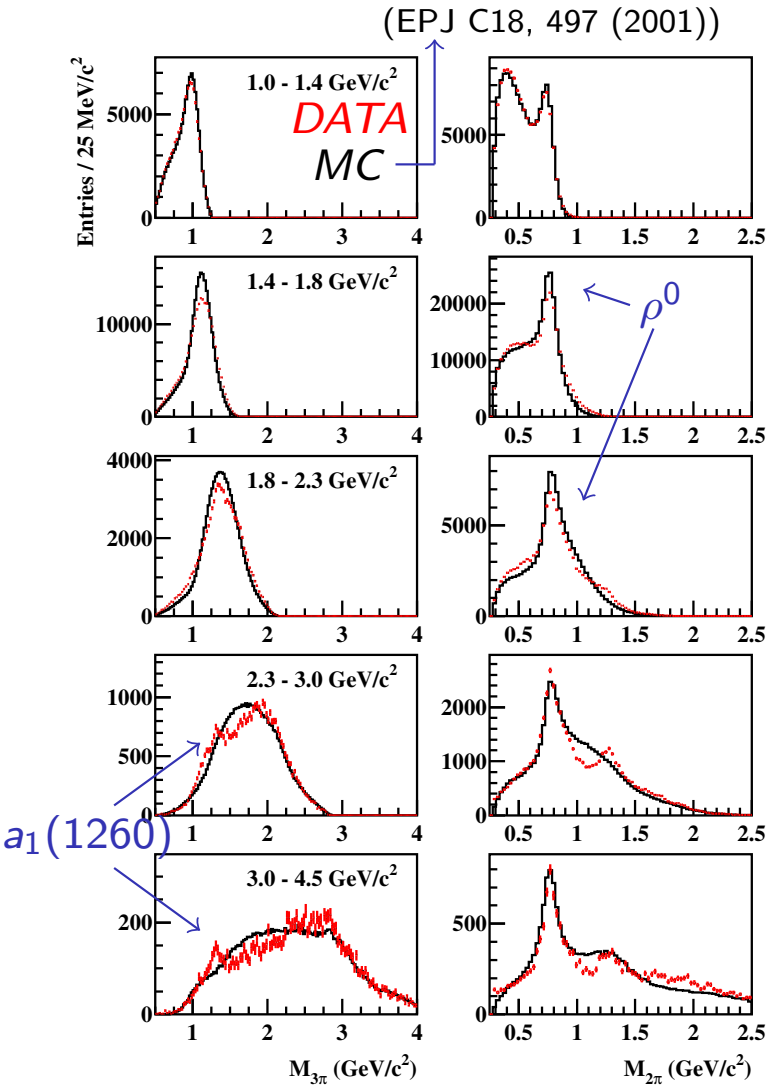
Internal structure in various E_{CM} energy slices



First column (4 entries/event):

$a_1(1260)$

Internal structure in various E_{CM} energy slices



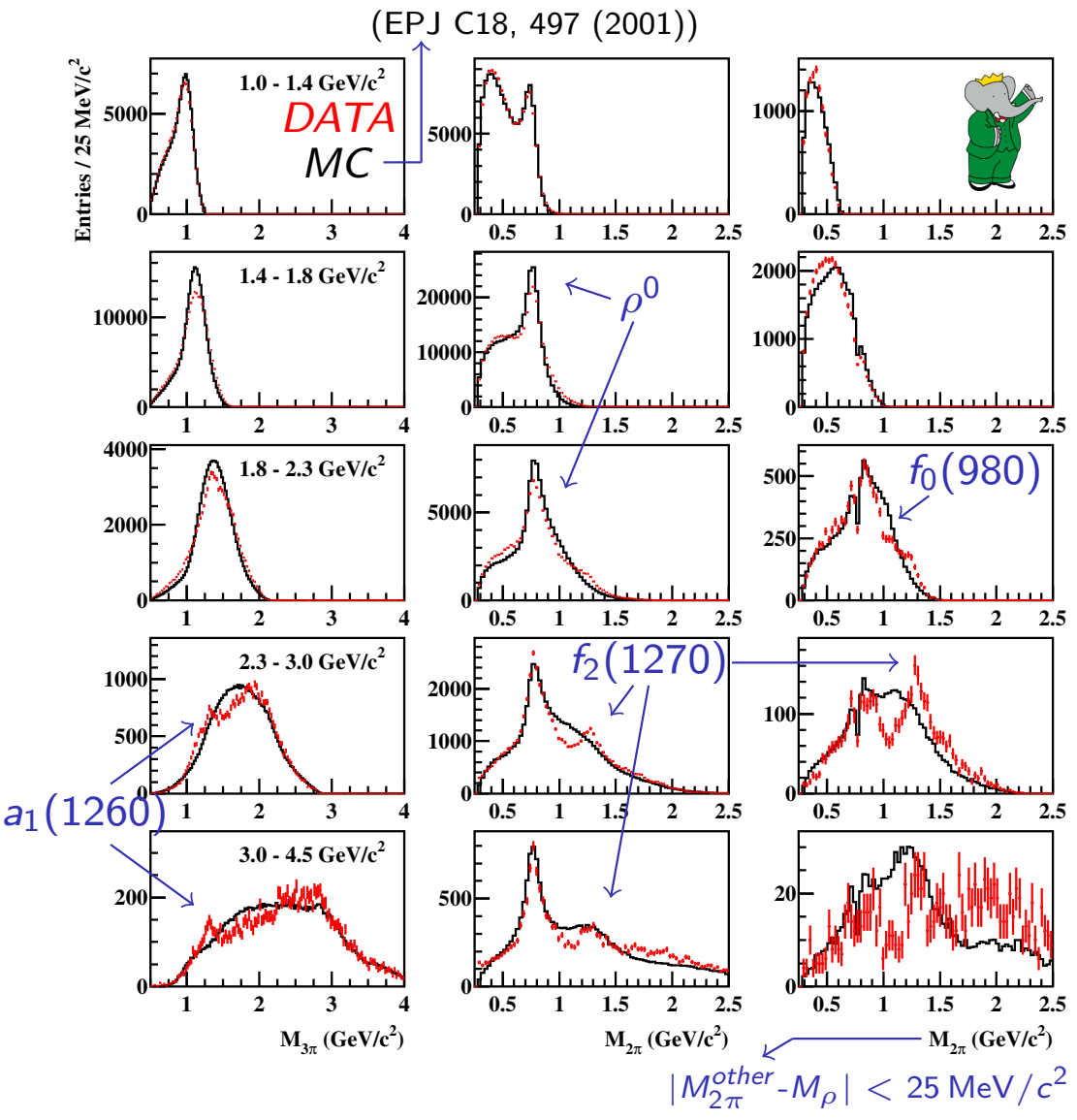
First column (4 entries/event):

$a_1(1260)$

Second column (4 entries/event):

strong ρ^0 contribution
e.g. for $M_{4\pi} > 1.4\,\mathrm{GeV}/c^2$:
$1/4th$ of entries in ρ^0 peak
$\rho^0\rho^0$ is forbidden
$\to$ ρ^0 in each event!

Internal structure in various E_{CM} energy slices



First column (4 entries/event):

$a_1(1260)$

Second column (4 entries/event):

strong ρ^0 contribution
e.g. for $M_{4\pi} > 1.4\,\mathrm{GeV}/c^2$:
$1/4th$ of entries in ρ^0 peak
$\rho^0\rho^0$ is forbidden
$\to$ ρ^0 in each event!

Third column (1 entry/event):

2π lie within ρ^0 mass
$\to$ other $\pi^+\pi^-$'s mass plotted

$f_2(1270)$, $a_1(1260)$, $f_0(980)$ . . .?

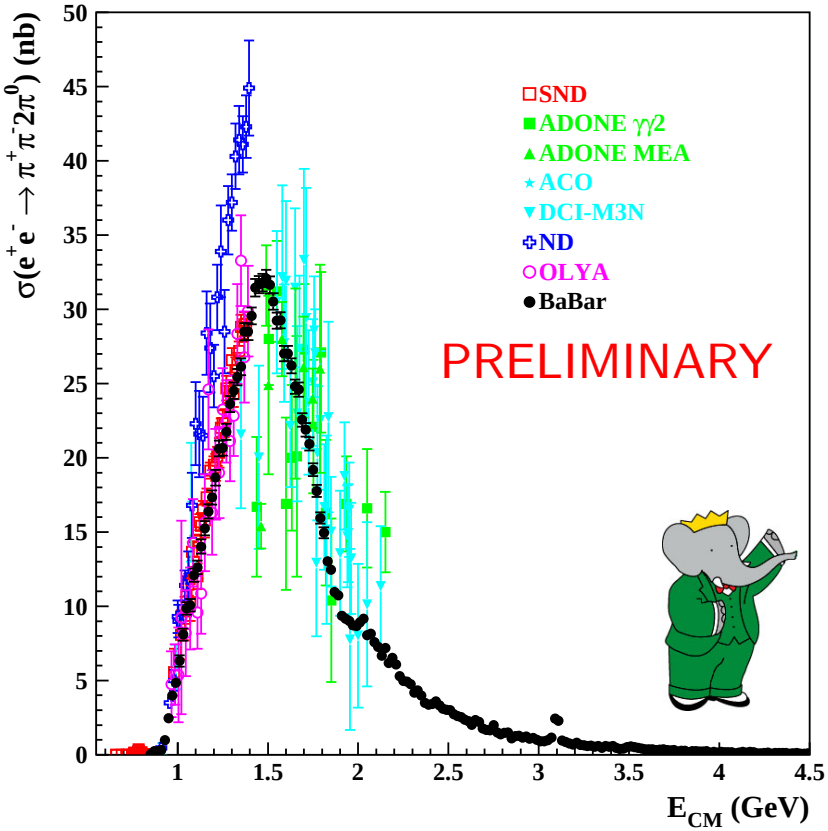
$\to$ Partial Wave Analysis needed

$e^+e^- \to \pi^+\pi^-\pi^0\pi^0$

PRELIMINARY
submitted to PRD, arXiv:1709.01171

Resulting cross section

$$e^+e^- \to \pi^+\pi^-\pi^0\pi^0$$



$E_{\rm CM}$(GeV)	Syst. unc.
1.2 – 2.7	3.1%
2.7 – 3.2	6.7%
> 3.2	7.1%

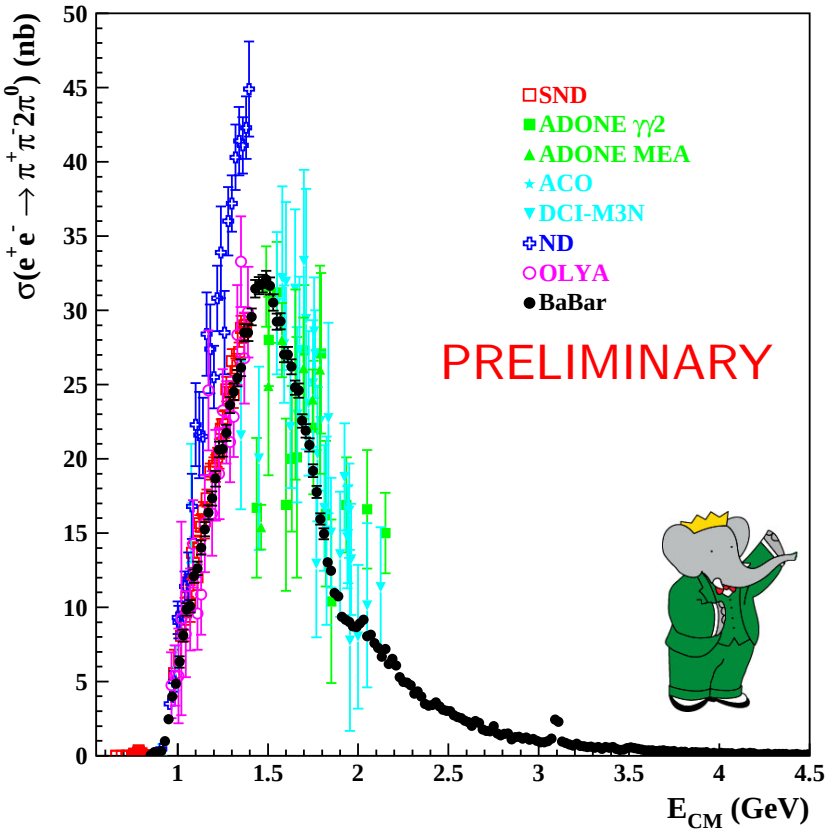
- dominant ISR-bkg $\pi^+\pi^-3\pi^0$ removed using data
- most precise measurement to date
- widest energy range $0.85 < E_{\rm CM} < 4.5\,\text{GeV}$

Contribution to $g_\mu - 2$

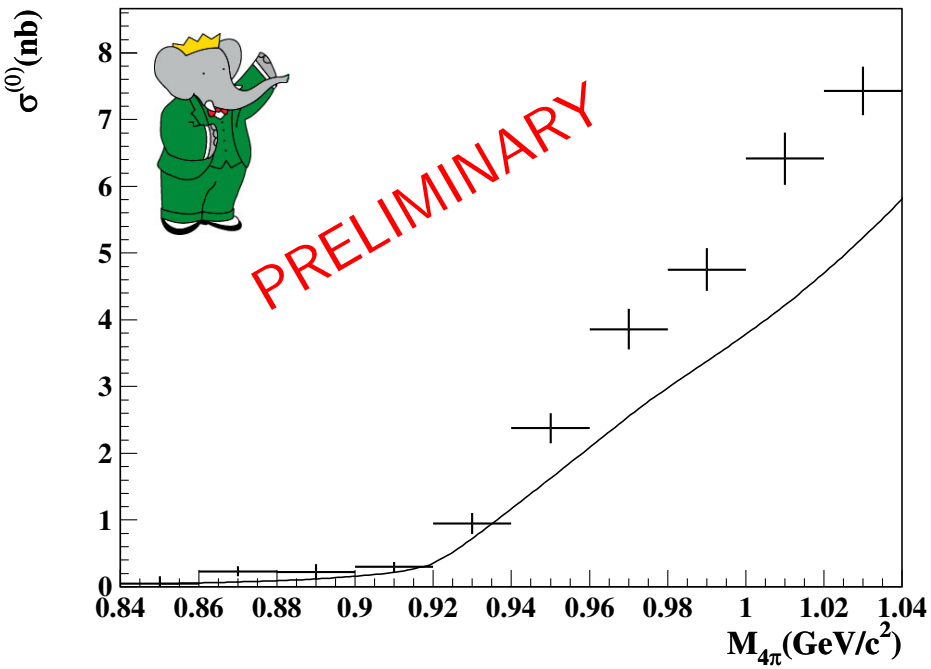
$a_\mu(0.85 < \sqrt{s} < 1.8\,\text{GeV}) =$
$(17.9 \pm 0.1_{\rm stat} \pm 0.6_{\rm syst}) \times 10^{-10}$

Resulting cross section

$$e^+e^- \to \pi^+\pi^-\pi^0\pi^0$$



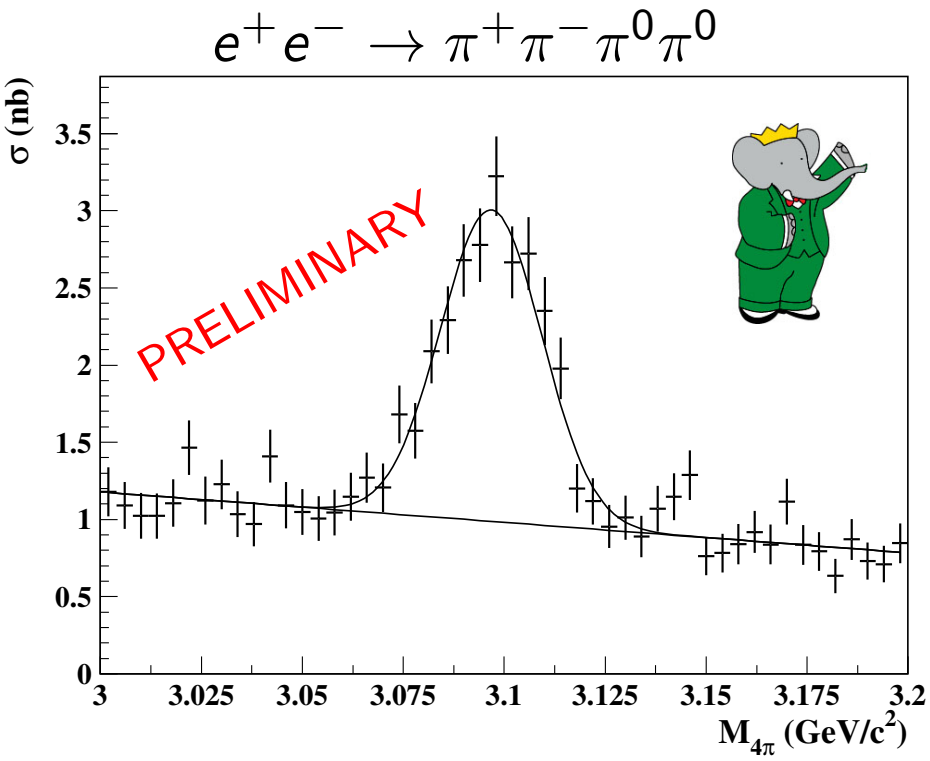
E_{CM}(GeV)	Syst. unc.
1.2 – 2.7	3.1%
2.7 – 3.2	6.7%
> 3.2	7.1%



Comparison to Chiral Pert. Theo.

(Eur.Phys.J., C24:535–545, 2002 [7])

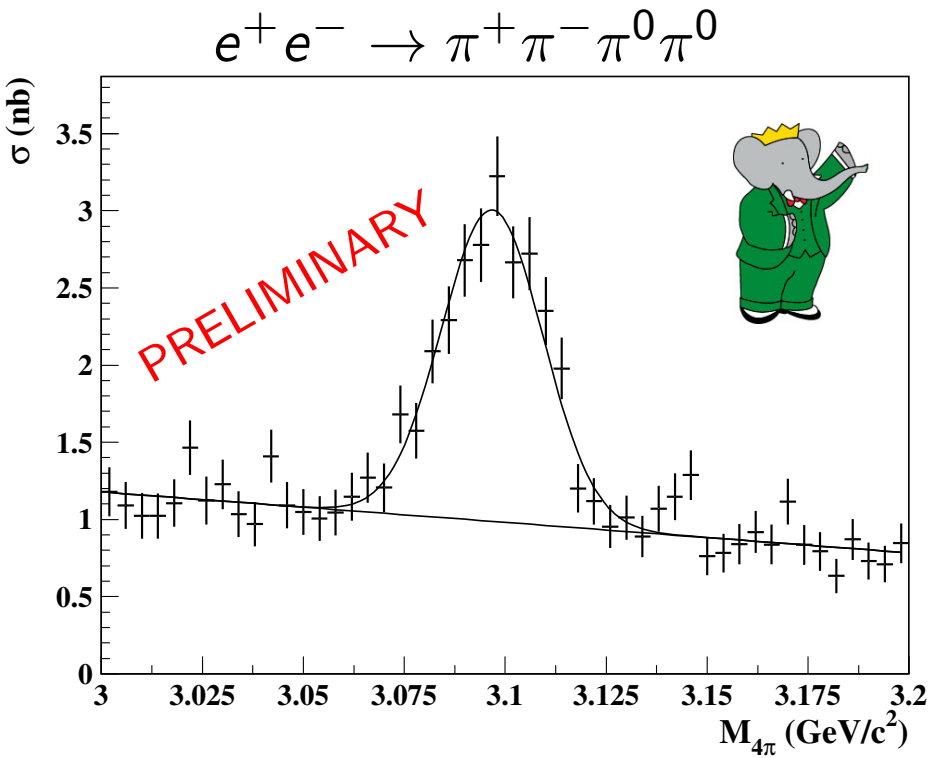
Intermediate resonances $J/\psi \to \pi^+\pi^-\pi^0\pi^0$

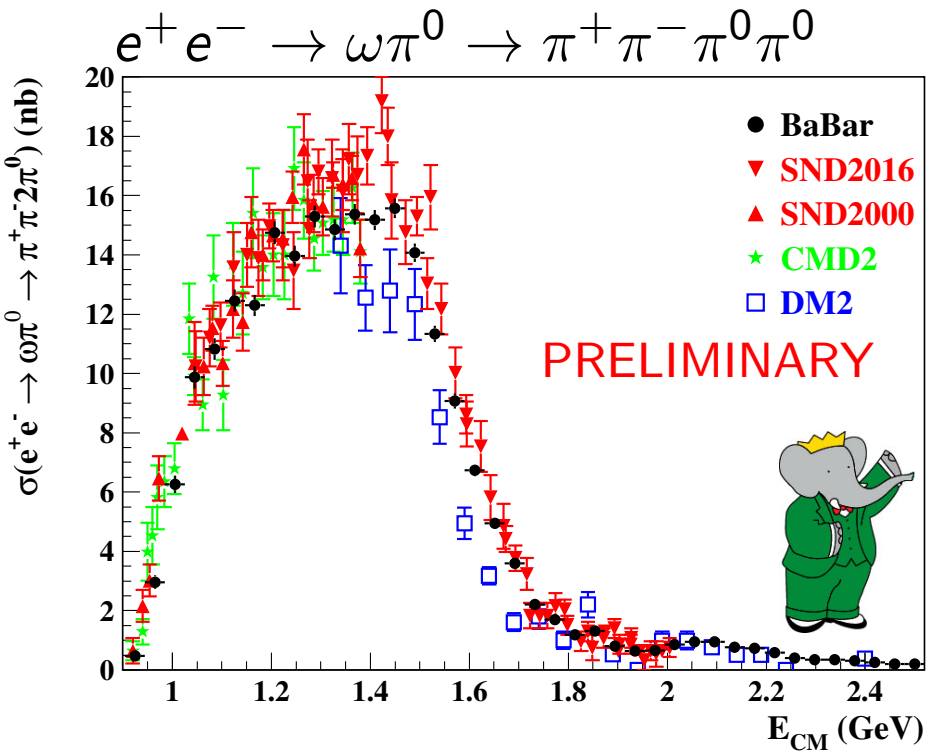


J/ψ branching fraction

$$\mathcal{B}(J/\psi \to 2\pi 2\pi^0) = (0.51 \pm 0.05)\,\%$$

Intermediate resonances $J/\psi\,, \omega\pi^0 \to \pi^+\pi^-\pi^0\pi^0$





J/ψ branching fraction

$$\mathcal{B}(J/\psi \to 2\pi 2\pi^0) = (0.51 \pm 0.05)\,\%$$

$\omega\pi^0$ contribution to $\pi^+\pi^-2\pi^0$

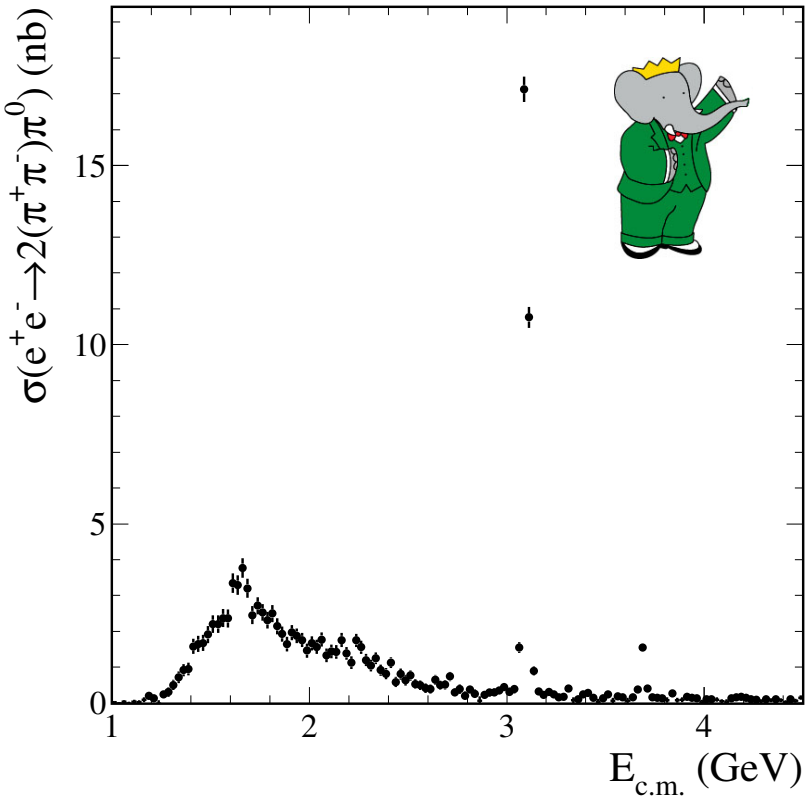
$$(32.1 \pm 0.2_{\text{stat}} \pm 2.6_{\text{syst}})\,\%$$

$$e^+e^- \longrightarrow \pi^+\pi^-\pi^+\pi^-\pi^0$$

Phys.Rev. D76 (2007) 092005 [3]

Resulting cross section

$$e^+e^- \to \pi^+\pi^-\pi^+\pi^-\pi^0$$



$E_{\rm CM}$(GeV)	Syst. unc.
1.5 – 1.8	7%
1.8 – 3.5	20%
> 3.5	50%

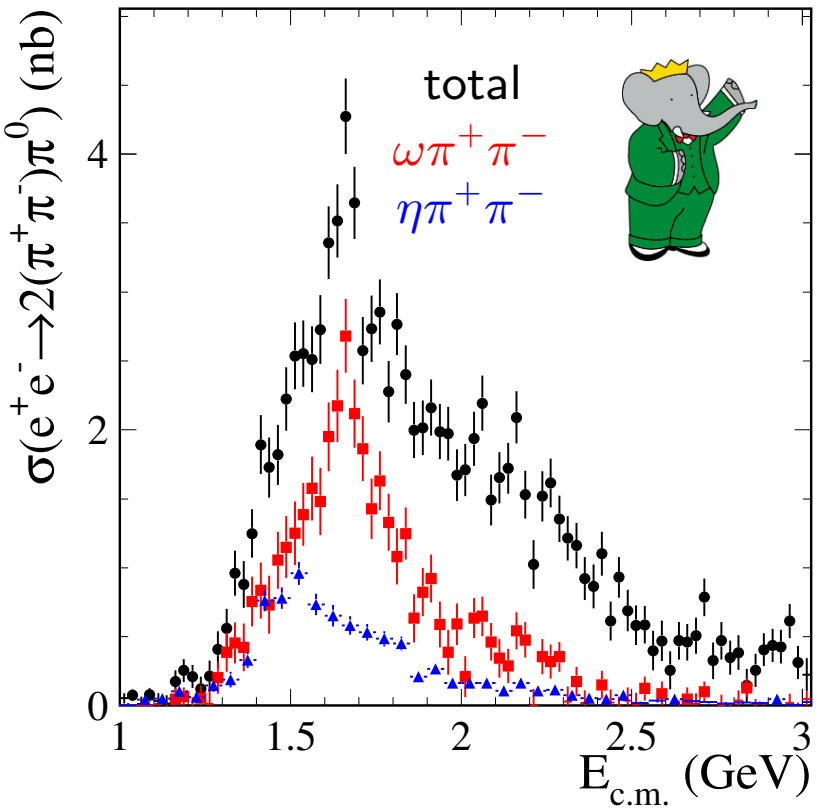
- dominant bkgs $K^+K^-\pi^+\pi^-\pi^0$ and $K^0_S K^\pm\pi^\mp\pi^0$
- most precise measurement to date
- energy range $1 < E_{\rm CM} < 4.5\,\text{GeV}$

Contribution to $g_\mu - 2$ (comp. [6])

$a_\mu(\sqrt{s} < 1.8\,\text{GeV}) =$
$(0.96 \pm 0.09) \times 10^{-10}$

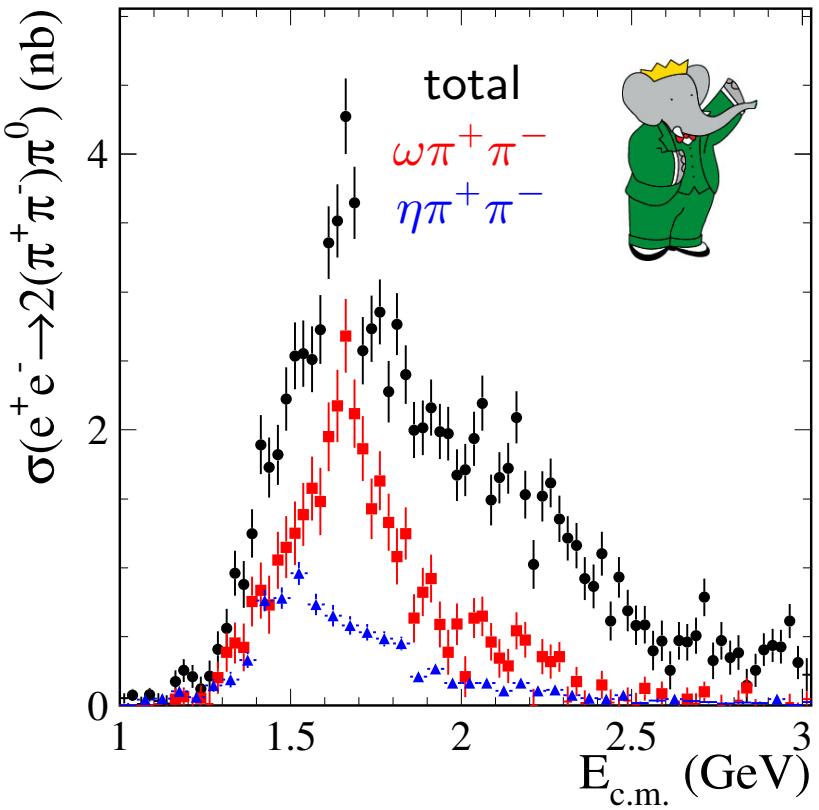
Intermediate resonances: $\omega/\eta\pi^+\pi^-$

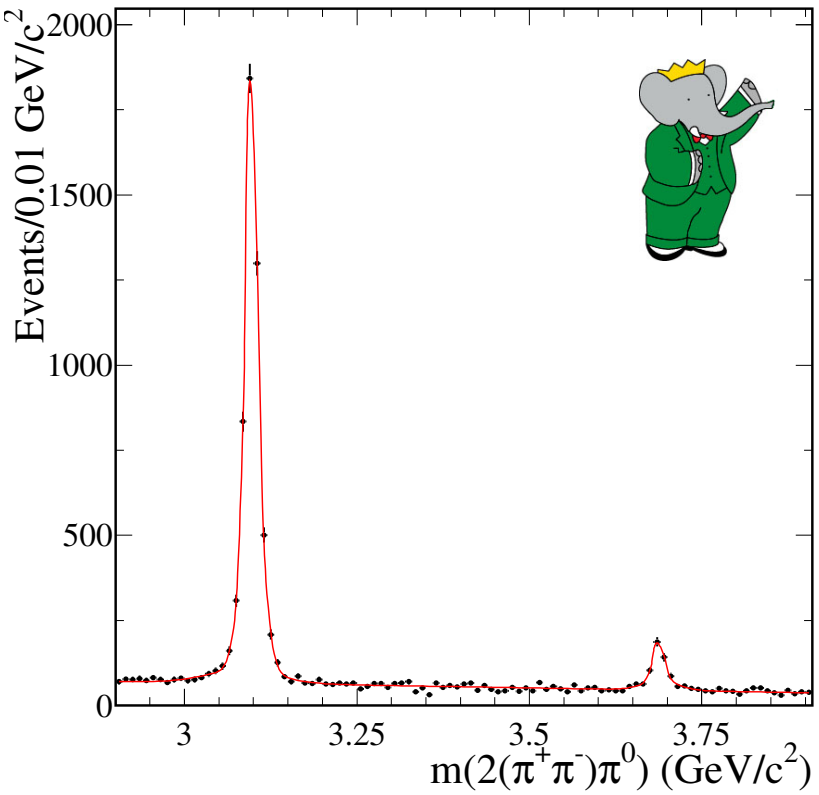
$$e^+e^- \to \pi^+\pi^-\pi^+\pi^-\pi^0$$



Intermediate resonances: $\omega/\eta\pi^+\pi^-$, J/ψ

$$e^+e^- \to \pi^+\pi^-\pi^+\pi^-\pi^0$$



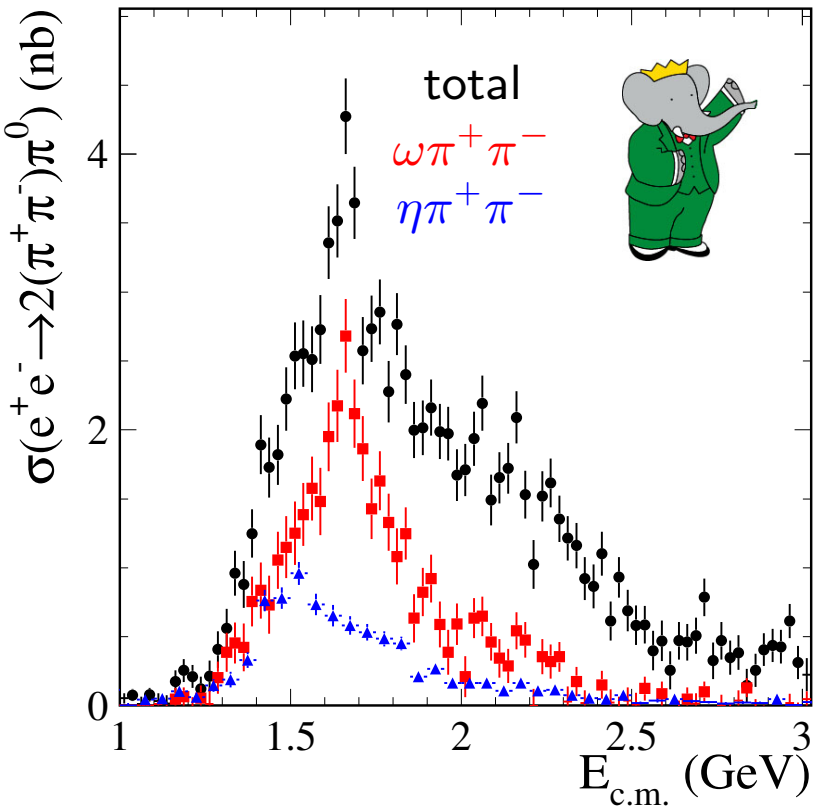


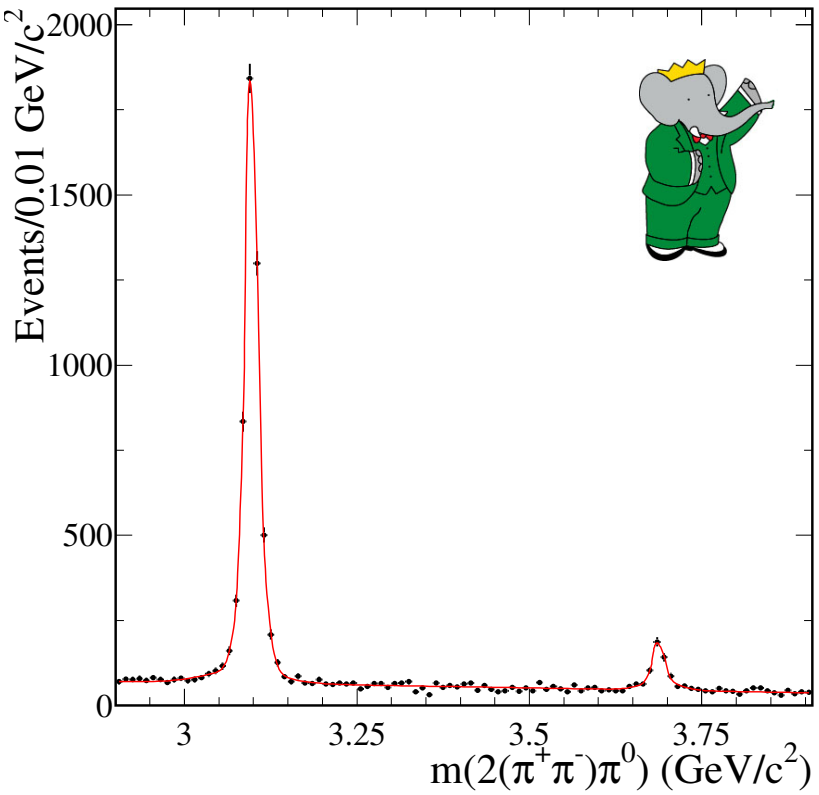
J/ψ branching fraction

$$\mathcal{B}(J/\psi \to 4\pi\pi^0) = (5.46 \pm 0.35)\,\%$$

Intermediate resonances: $\omega/\eta\pi^+\pi^-$, J/ψ, and $\psi(2S)$

$$e^+e^- \to \pi^+\pi^-\pi^+\pi^-\pi^0$$





$\psi(2S)$ branching fraction

$$\mathcal{B}(\psi(2S) \to 4\pi\pi^0) = (1.2 \pm 1.1)\,\%$$

Summary

- ISR physics has proven to be a very productive field even years after the end of data taking at the B-factories
- Precision measurements of hadronic cross sections have greatly improved a_μ^{SM} & more final states in preparation. Shown today:
  - ⋆ $e^+e^- \to \pi^+\pi^-$ Phys. Rev. D86 (2012) 032013 [13]
  - ⋆ $e^+e^- \to \pi^+\pi^-\pi^0$ Phys. Rev. D70 (2004) 072004 [2]
  - ⋆ $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$ Phys. Rev. D85 (2012) 112009 [12]
  - ⋆ $e^+e^- \to \pi^+\pi^-\pi^0\pi^0$ submitted to PRD, arXiv:1709.01171
  - ⋆ $e^+e^- \to \pi^+\pi^-\pi^+\pi^-\pi^0$ Phys.Rev. D76 (2007) 092005 [3]
- New results from *BABAR* forthcoming:
  - ⋆ $e^+e^- \to \pi^+\pi^-\eta$
  - ⋆ $e^+e^- \to \pi^+\pi^-$ (new method, full dataset)

Thank you!

Any questions?

References

References I

[1] T. Aoyama, M. Hayakawa, T. Kinoshita, and M. Nio.
Complete tenth-order qed contribution to the muon $g-2$.
Phys. Rev. Lett., 109:111808, Sep 2012.

[2] B. Aubert et al.
Study of $e^+e^- \to \pi^+\pi^-\pi^0$ process using initial state radiation with BaBar.
Phys.Rev., D70:072004, 2004.

[3] B. Aubert et al.
The e+ e- —¿ 2(pi+ pi-) pi0, 2(pi+ pi-) eta, K+ K- pi+ pi- pi0 and K+ K- pi+ pi- eta Cross Sections Measured with Initial-State Radiation.
Phys. Rev., D76:092005, 2007.
[Erratum: Phys. Rev.D77,119902(2008)].

References II

[4] G. Colangelo, M. Hoferichter, A. Nyffeler, M. Passera, and P. Stoffer.
Remarks on higher-order hadronic corrections to the muon $g-2$.
Phys.Lett., B735:90–91, 2014.

[5] M. Davier, A. Hoecker, B. Malaescu, and Z. Zhang.
Reevaluation of the Hadronic Contributions to the Muon $g-2$ and to $\alpha(M_Z)$.
Eur.Phys.J., C71:1515, 2011.

[6] M. Davier, A. Hoecker, B. Malaescu, and Z. Zhang.
Reevaluation of the hadronic vacuum polarisation contributions to the Standard Model predictions of the muon g-2 and alpha(mZ) using newest hadronic cross-section data.
2017.

References III

[7] G. Ecker and R. Unterdorfer.
Four-Pion Production in e^+e^- Annihilation.
Eur. Phys. J., C24:535–545, 2002.

[8] C. Gnendiger, D. Stöckinger, and H. Stöckinger-Kim.
The electroweak contributions to $(g-2)_\mu$ after the Higgs boson mass measurement.
Phys.Rev., D88(5):053005, 2013.

[9] G. J. Gounaris and J. J. Sakurai.
Finite width corrections to the vector meson dominance prediction for $\rho \to e^+e^-$.
Phys. Rev. Lett., 21:244–247, 1968.

References IV

[10] F. Jegerlehner and A. Nyffeler.
The Muon g-2.
Phys.Rept., 477:1–110, 2009.

[11] A. Kurz, T. Liu, P. Marquard, and M. Steinhauser.
Hadronic contribution to the muon anomalous magnetic moment to next-to-next-to-leading order.
Phys.Lett., B734:144–147, 2014.

[12] J. Lees et al.
Initial-State Radiation Measurement of the $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$ Cross Section.
Phys.Rev., D85:112009, 2012.

References V

[13] J. P. Lees et al.
Precise Measurement of the $e^+e^- \to \pi^+\pi^-(\gamma)$ Cross Section with the Initial-State Radiation Method at BABAR.
Phys. Rev., D86:032013, 2012.

[14] K. Olive et al.
Review of Particle Physics.
Chin.Phys., C38:090001, 2014.