QUARKS-2018

XXth International Seminar on High Energy Physics

Measurement of exclusive hadronic cross sections with the BABAR detector and implications on the g-2 of the muon

Peter A. Lukin

Budker Institute of Nuclear Physics and Novosibirsk State University

On behalf of BaBar Collaboration

Novosibirsk State University

*THE REAL SCIENCE

Outline

- Motivation
- Theory of $(g\text{-}2)_{\mu}/2$
- Collider, detector and method
- BaBar ISR measurements
- Conclusion

(g-2)/2 of muon (Experiment)

Magnetic moment of Dirac particle:

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

- Gyromagnetic factor g for
  - Point-like fermions: g = 2
  - Higher order contributions (QFT): g ≠ 2
- Muon anomaly
  - $a_\mu = (g-2)_\mu/2$

E821 Experiment @ BNL (1997-2001):

J. Muller et al., Annu. Rev. Nucl. Par S. Vo. 62(2012), 237

$a_\mu = (11\ 659\ 208.9 \pm 6.3)\ 10^{-10}$ (0.54 ppm)

E989 Experiment @ FNAL (2017-…):

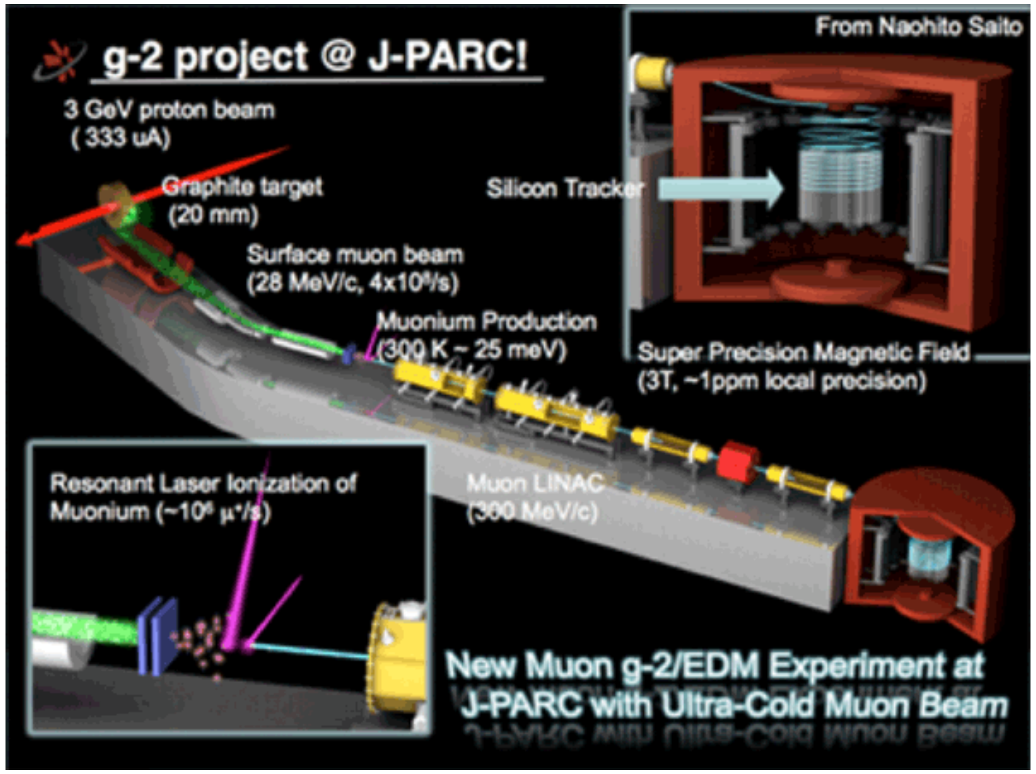
F. Gray et al., ArXiv 1510.003[physics.ins-det] (2015)

$a_\mu = \ldots$ (0.14 ppm)

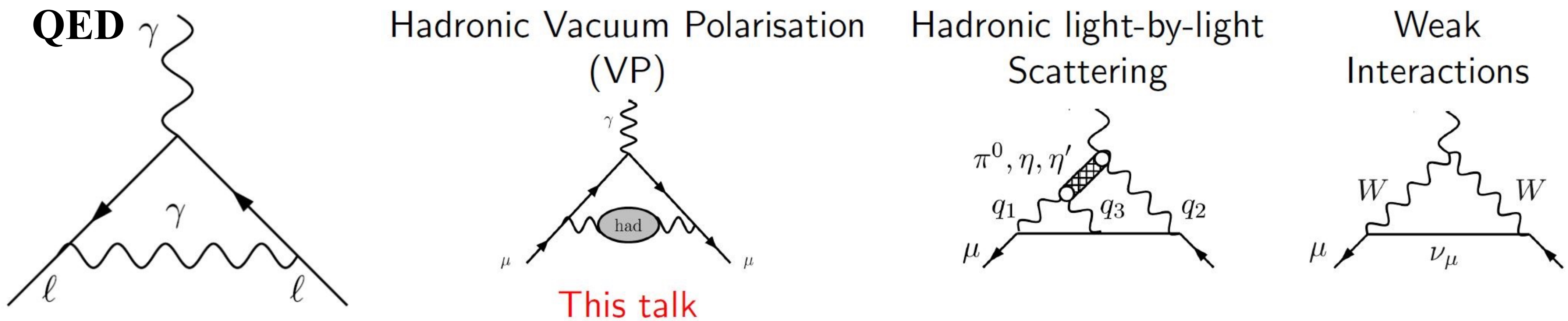
E34 Experiment @ J-PARC (????-…):

T. Mibe et al., Chin.Phys. C34 (2010) 745

$a_\mu = \ldots$ (0.1 ppm)

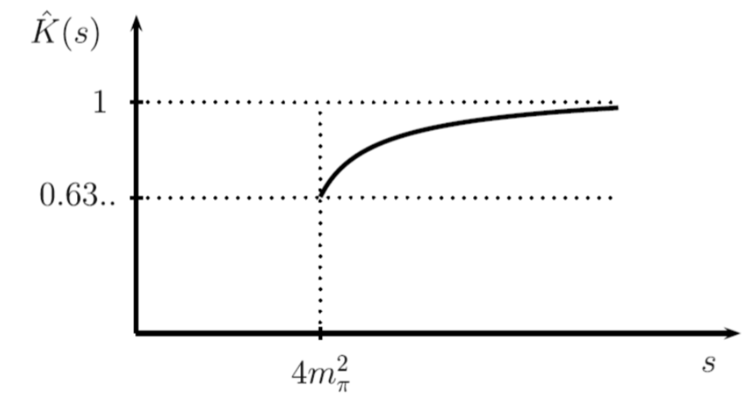


(g-2)/2 of muon (Theory)

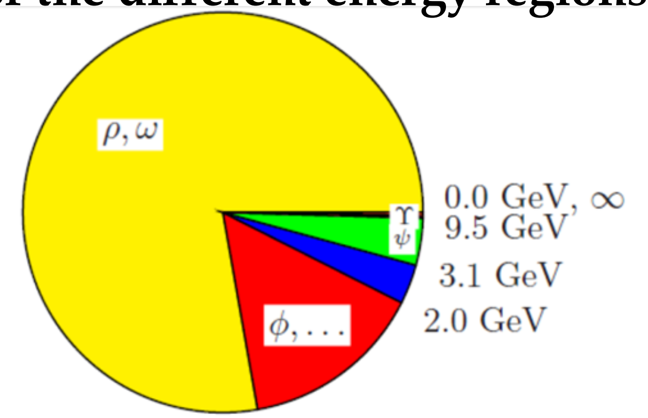


$$R(s) = \frac{\sigma(e^+e^- \to \gamma^* \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

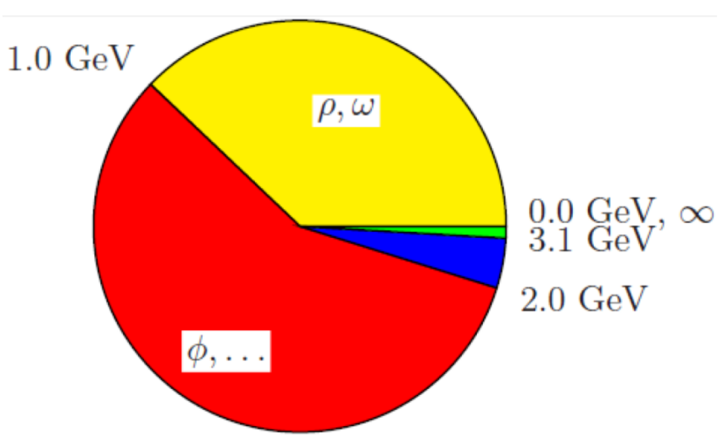
$$a_\mu^{had} = \frac{\alpha^2}{3\cdot\pi^2}\int_{4m_\pi^2}^{\infty} ds \cdot \frac{K(s)}{s} \cdot R(s)$$



Contributions of the different energy regions to:



a_μ integral



a_μ uncertainty

$$a_\mu^{theory(SM)} = a_\mu^{QED} + a_\mu^{had} + a_\mu^{weak}$$

$$a_\mu^{theo} \times 10^{10} = 11\,659\,180.2 \pm 4.9$$

$$a_\mu^{exp} \times 10^{10} = 11\,659\,208.9 \pm 6.3$$

$$\Delta a_\mu \times 10^{10} = 28.7 \pm 8.0$$

$$a_\mu^{EXP} - a_\mu^{SM} = 3.6\sigma$$

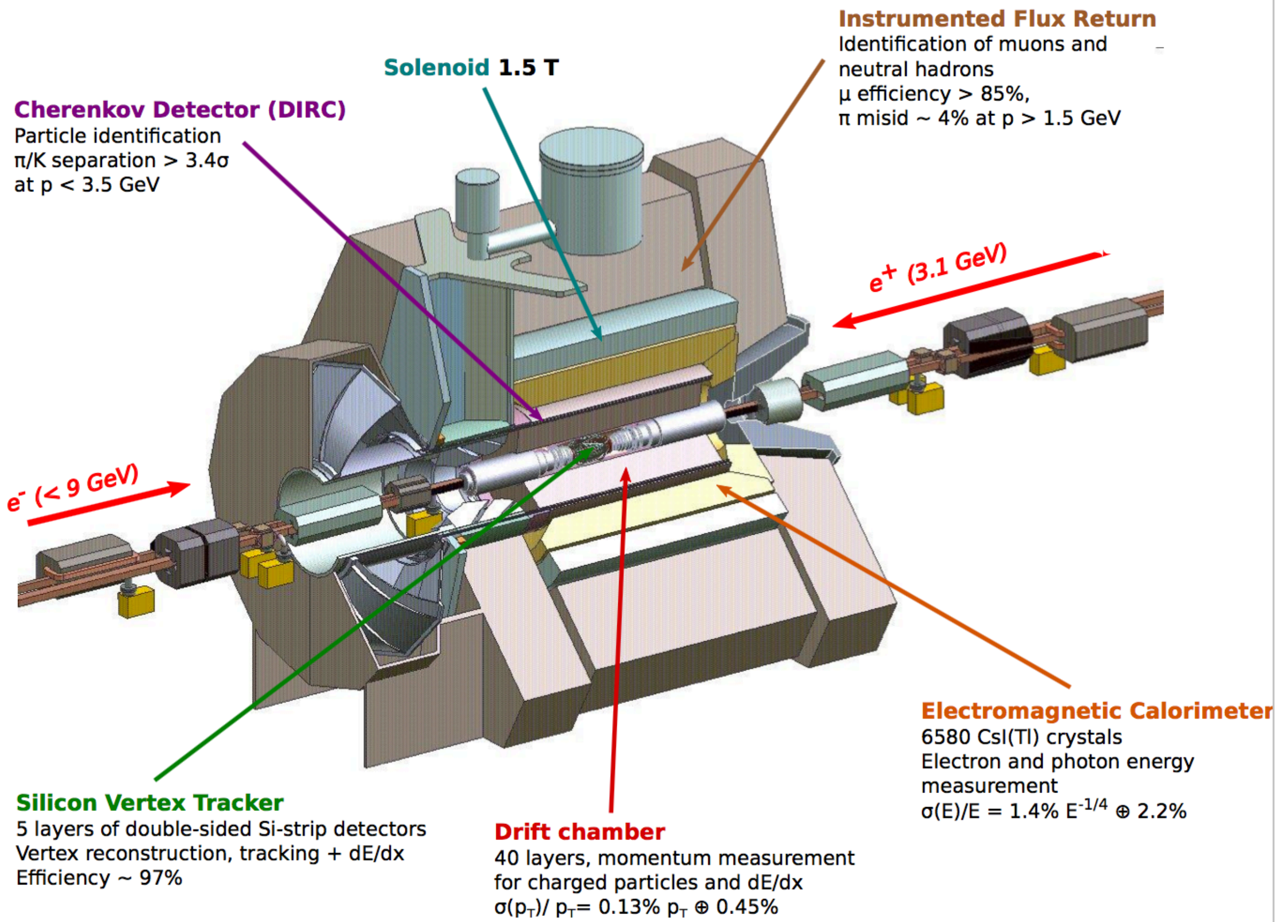
(M. Davier et al., EPJC71(2011)1515)

ISR @ BaBar

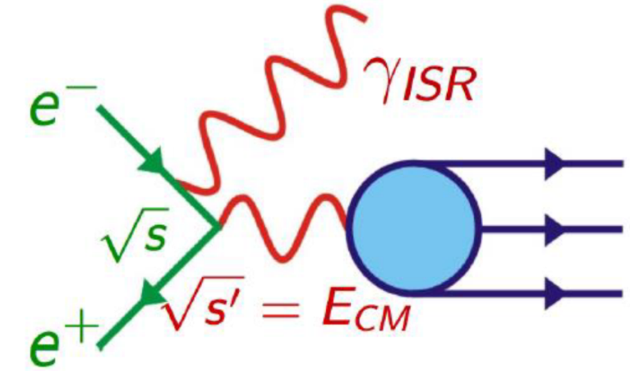
The BABAR experiment (1999-2008)

PEP-II: e^+e^- collider, 3.1×9 GeV^2

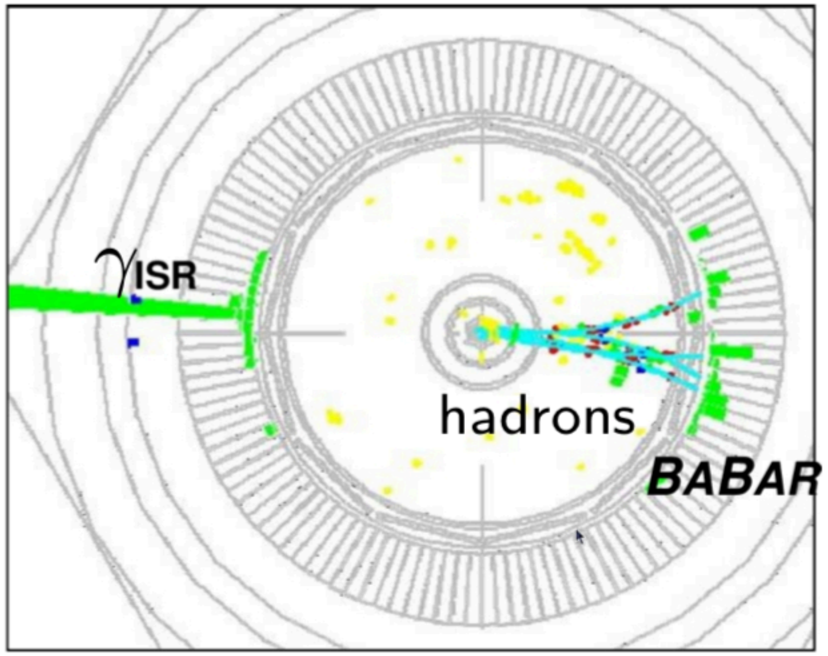
$\sqrt{s} = 10.58$ GeV $[\Upsilon(4S)]$



- High luminosity
  - $\mathcal{L}_{\text{peak}} = 12.069 \times 10^{33}\,\text{cm}^{-2}\,\text{s}^{-1}$
  - $513.7(18)\,\text{fb}^{-1}$ accumulated



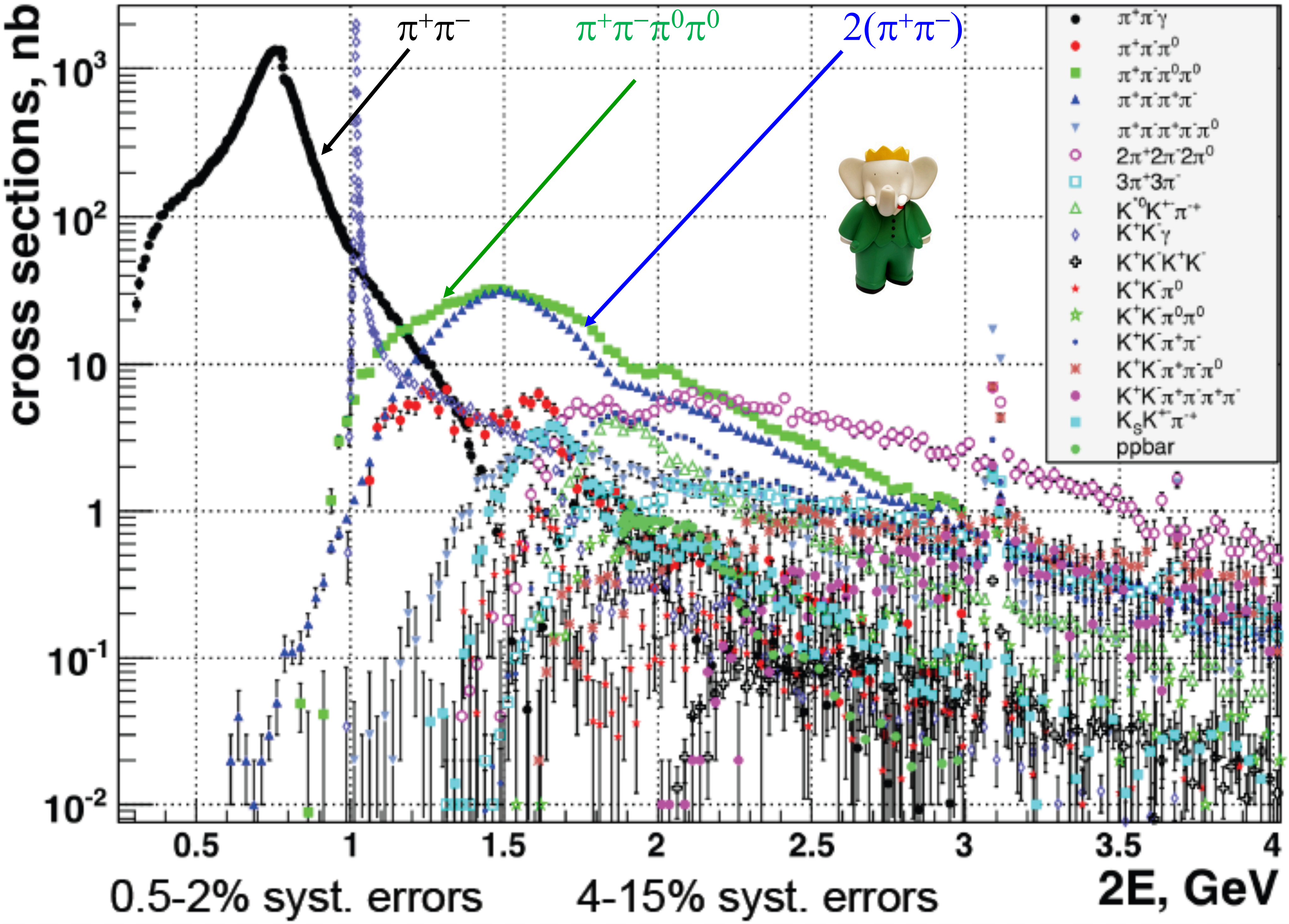
$$\frac{d\sigma_{[e^+e^-\to f\gamma]}}{ds'}(s') = \frac{2m}{s} W(s,x)\sigma_{[e^+e^-\to f]}(s')$$



ISR selection

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

ISR @ BaBar



$\pi^+\pi^-$
$\pi^+\pi^-\pi^0\pi^0$
$2(\pi^+\pi^-)$
cross sections, nb
10^3
10^2
10
1
10^{-1}
10^{-2}
0.5
1
1.5
2
2.5
3
3.5
4
2E, GeV
0.5-2% syst. errors
4-15% syst. errors
$\pi^+\pi^-\gamma$
$\pi^+\pi^-\pi^0$
$\pi^+\pi^-\pi^0\pi^0$
$\pi^+\pi^-\pi^+\pi^-$
$\pi^+\pi^-\pi^+\pi^-\pi^0$
$2\pi^+2\pi^-2\pi^0$
$3\pi^+3\pi^-$
$K^{*0}K^{+-}\pi^{-+}$
$K^+K^-\gamma$
$K^+K^-K^+K^-$
$K^+K^-\pi^0$
$K^+K^-\pi^0\pi^0$
$K^+K^-\pi^+\pi^-$
$K^+K^-\pi^+\pi^-\pi^0$
$K^+K^-\pi^+\pi^-\pi^+\pi^-$
$K_SK^{+-}\pi^{-+}$
ppbar

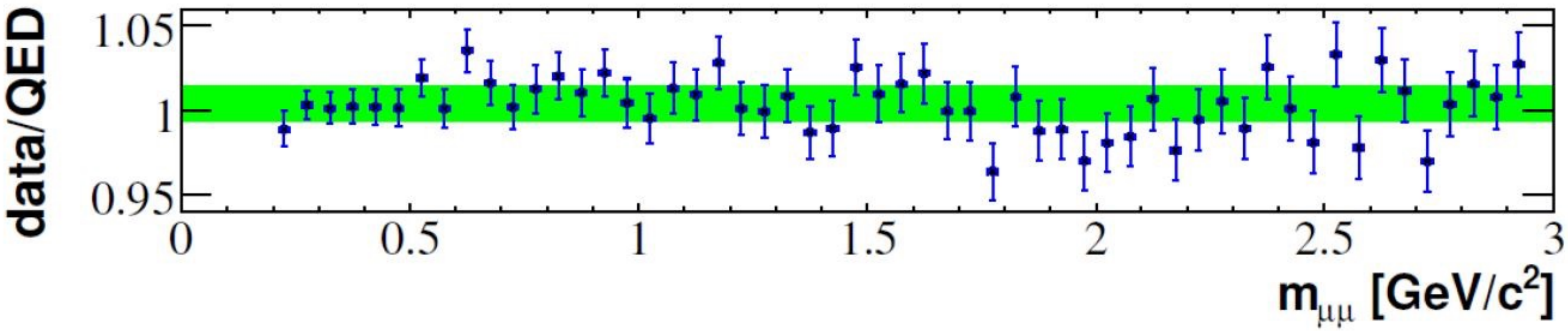
$e^+e^- \rightarrow \pi^+\pi^-(\gamma)\gamma$

- Systematics mastered at the 10^{-3} level for first time in BaBar
- ISR γ in EMC (thus: at large angle)
- Good quality tracks, particle identification (PID)
- Kinematic Fit (using only direction of ISR γ)
  - Possibly including 1 additional γ: NLO!
- All efficiencies (trigger, filter, tracking, PID, fit) from data. $\pi^+\pi^-/\ \mu^+\mu^-$ ratio:
  - Cancelation of ee luminosity, additional ISR, VP, ISR γ efficiency
- Correct for lowest order FSR in $\mu^+\mu^-$ and for ISR + additional FSR, both calc. in QED and checked in data

$$R_{\mathrm{exp}}(s') = \frac{\sigma_{[\pi\pi\gamma(\gamma)]}(s')}{\sigma_{[\mu\mu\gamma(\gamma)]}(s')} = \frac{\sigma^0_{[\pi\pi(\gamma)]}(s')}{(1+\delta^{\mu\mu}_{\mathrm{FSR}})\sigma^0_{[\mu\mu(\gamma)]}(s')} = \frac{R(s')}{(1+\delta^{\mu\mu}_{\mathrm{FSR}})(1+\delta^{\mu\mu}_{add,FSR})}$$

BaBar sanity check: comparision μμ spectra with QED

Phys.Rev.Lett. 103 (2009) 231801, Phys.Rev.D86 (2012) 032013

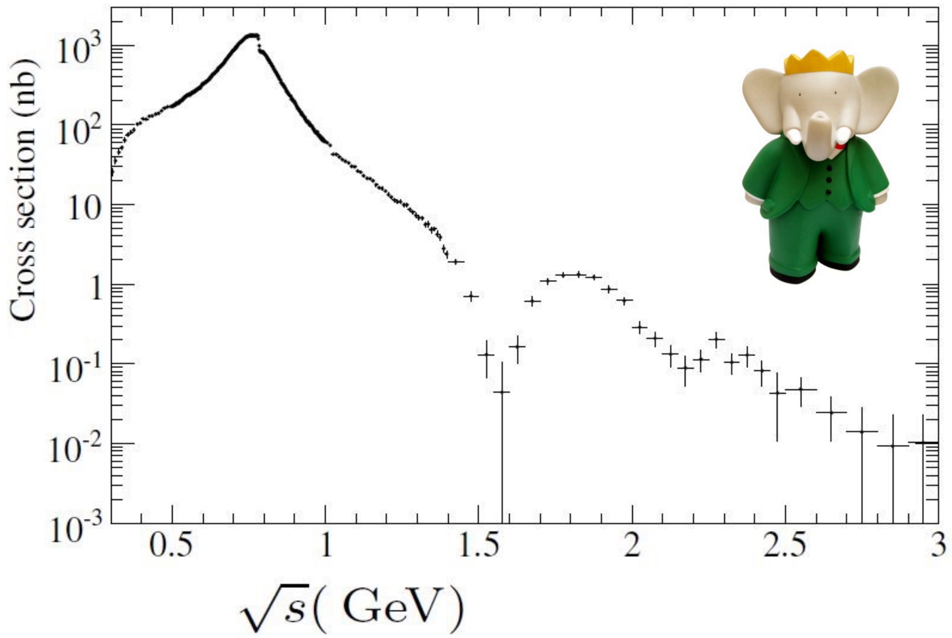


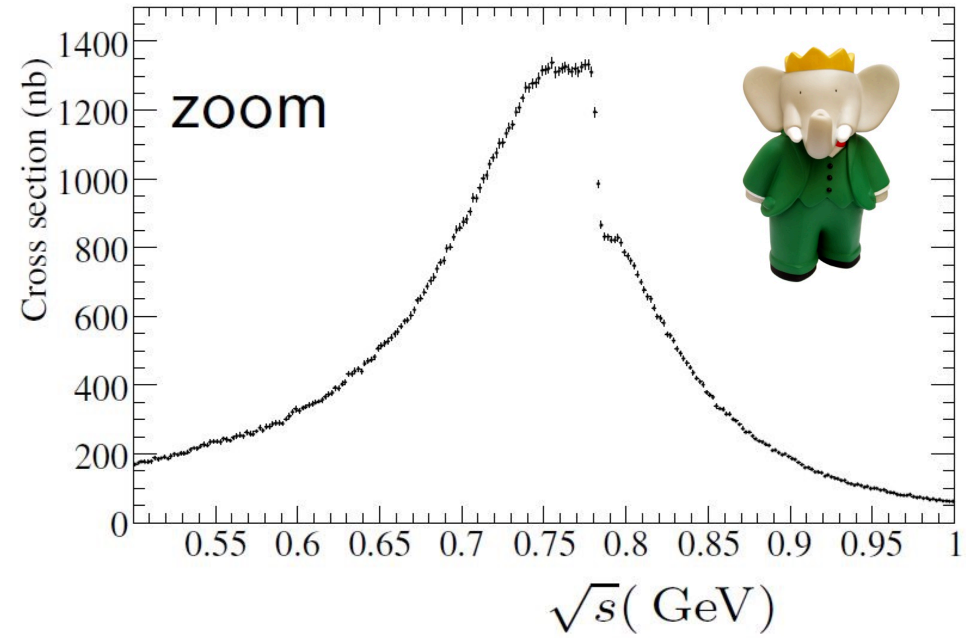
- **Here the radiator function and the collider integrated luminosity are needed**
- **MC simulation corrected for all known MC/data dierences.**
  - **ISR γ efficiency measured in data, from μμ-only reco'ed evts.**
  - **MC corrected for known NLO deciencies by comparing to PHOKHARA**

Good agreement within (0.4 ± 1.1)% ; Dominated by L_{ee} (± 0.9%)

$e^+e^- \to \pi^+\pi^-(\gamma)\gamma$ Cross Section

Phys.Rev.Lett. 103 (2009) 231801, Phys.Rev.D86 (2012) 032013





Bare (incl. additional FSR, VP removed) unfolded $\sigma(e^+e^- \to \pi^+\pi^-)$ 232 fb^{-1} @ $\sqrt{s}$ = 10.6 GeV

Excellent precision down to threshold:

$$a_\mu^{\pi^+\pi^-}[2m_\pi, 1.8\,\text{GeV}] = (514.1 \pm 2.2 \pm 3.1) \times 10^{-10}$$

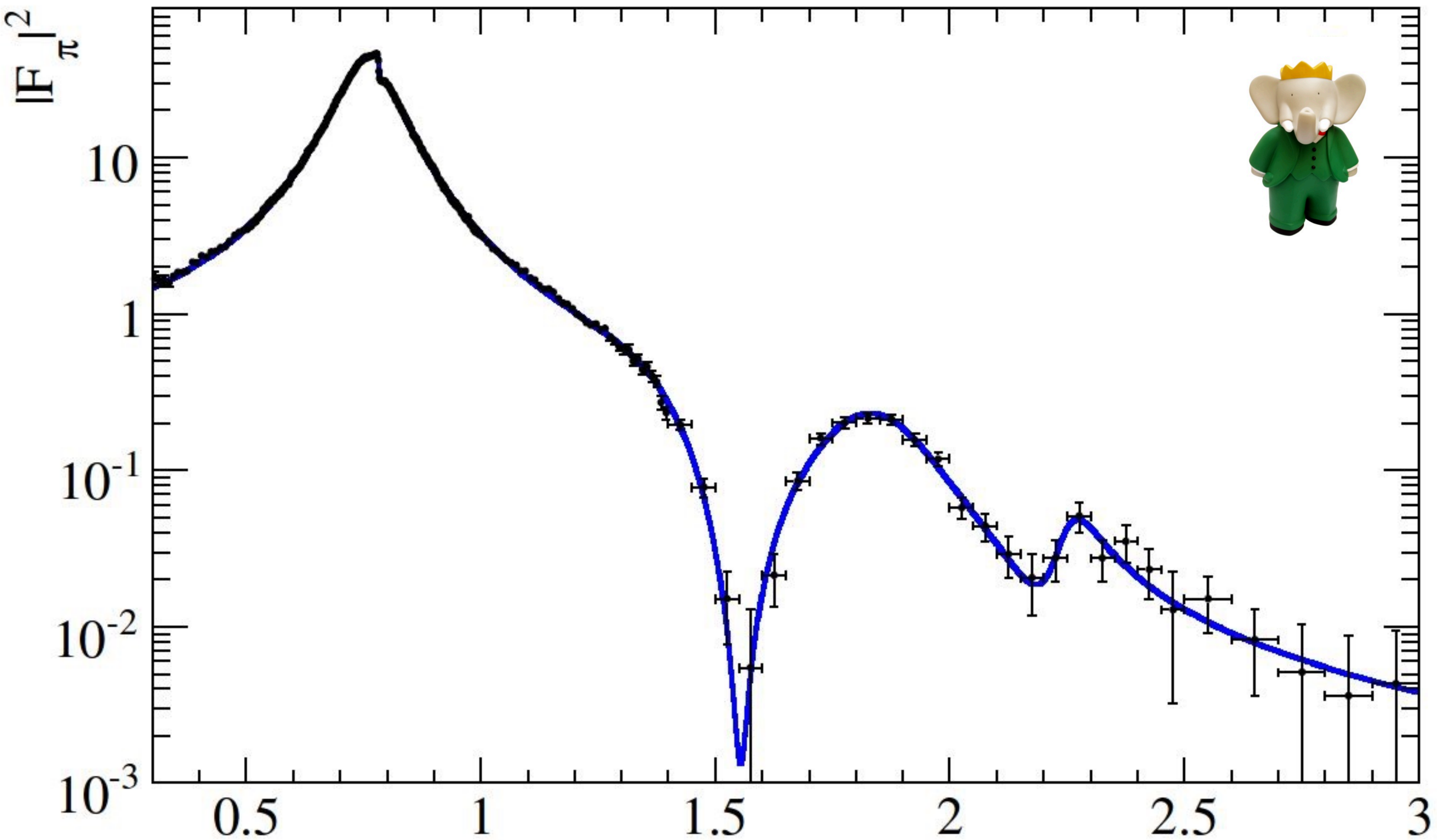
Similar precision as combination of previous e^+e^- results:

$$a_\mu^{\pi^+\pi^-}[2m_\pi, 1.8\,\text{GeV}] = (503.5 \pm 4.5) \times 10^{-10}$$

1.7 σ **larger than previous e^+e^- average:** $\Delta = +(10.6 \pm 5.9) \times 10^{-10}$

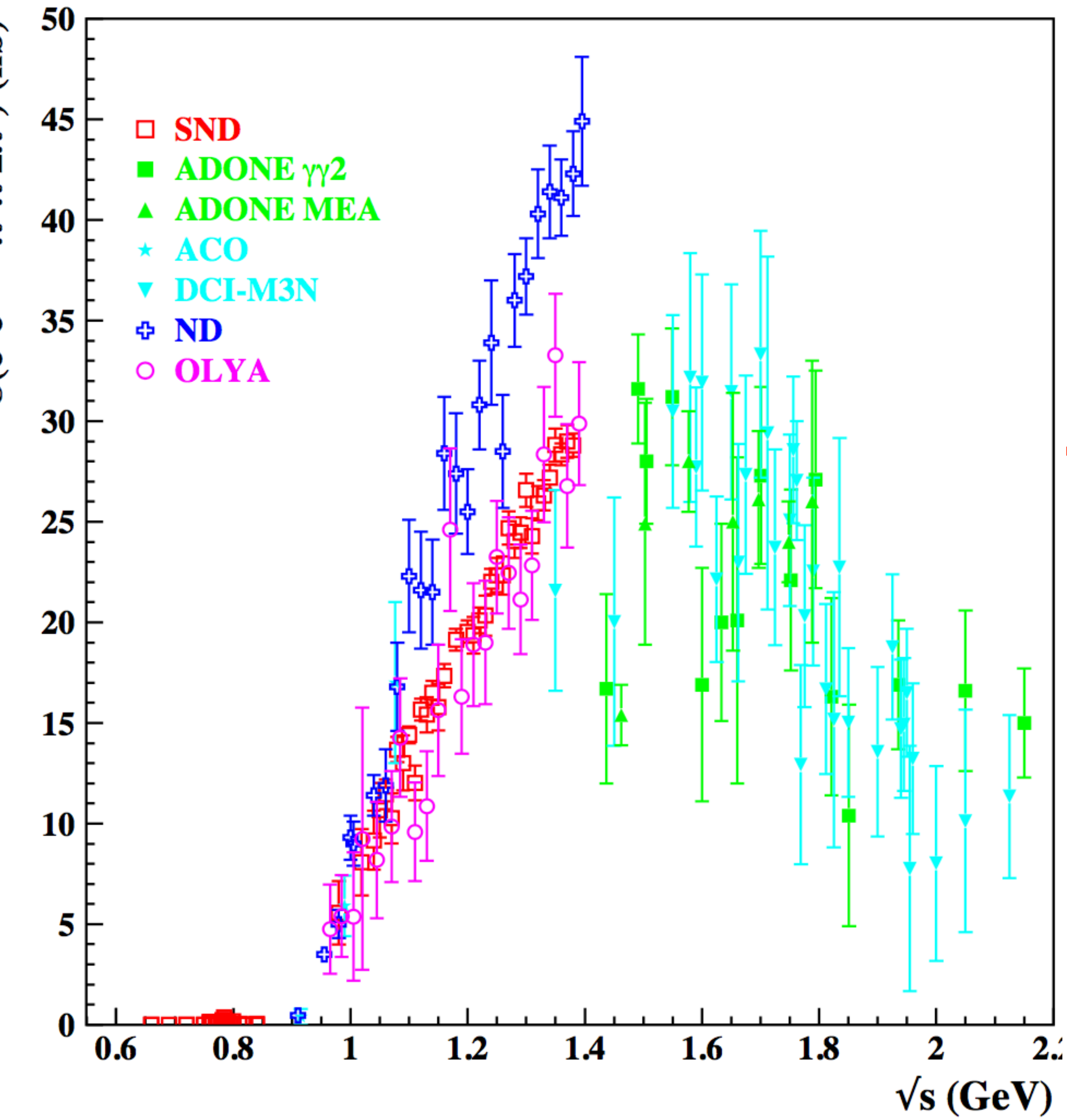
$e^+e^- \rightarrow \pi^+\pi^-(\gamma)$: VDM Fit of $|F_\pi(s)|^2$

Phys.Rev.Lett. 103 (2009) 231801, Phys.Rev.D86 (2012) 032013



- |Form Factor|^2 fitted with a vector dominance model ρ, ρ′, ρ″, ω′
- ρ′ s described by the Gounaris-Sakurai model χ^2/n.d.f = 334/323

Process $\pi^+\pi^-\pi^0\pi^0$ (Before BABAR)



Before the BaBar measurement:

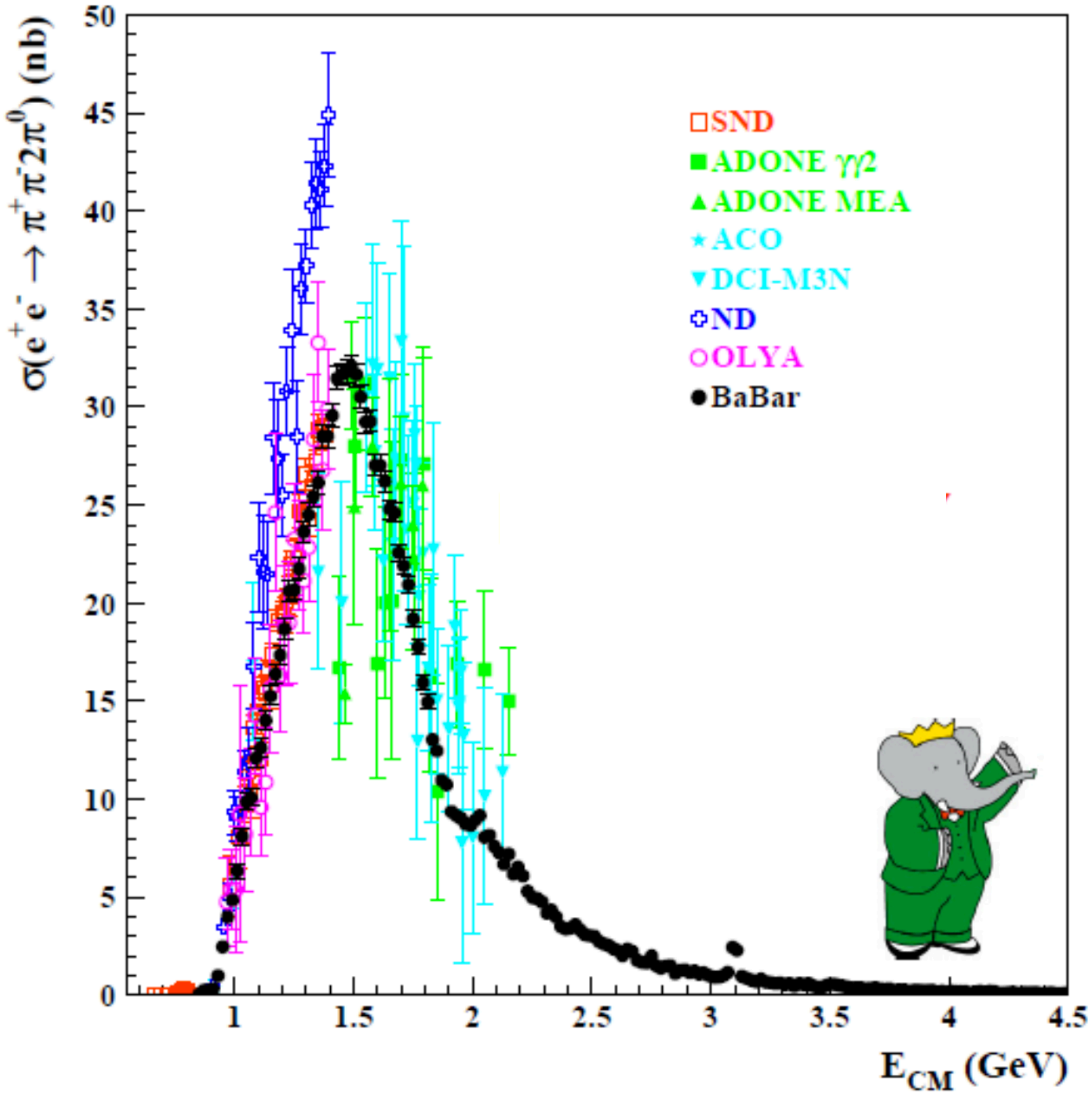
- Limited precision
- Big disagreement between experiments
- Small energy ranges

K.Hagiwara et al., arXiv:1105.3149 [hep-ph] (2011)

Channel	$a_\mu^{\rm had,LO}$ $[10^{-10}]$
$\pi^0\gamma$	$4.42 \pm 0.08 \pm 0.13 \pm 0.12$
$\eta\gamma$	$0.64 \pm 0.02 \pm 0.01 \pm 0.01$
$\pi^+\pi^-$	$507.80 \pm 1.22 \pm 2.50 \pm 0.56$
$\pi^+\pi^-\pi^0$	$46.00 \pm 0.42 \pm 1.03 \pm 0.98$
$2\pi^+2\pi^-$	$13.35 \pm 0.10 \pm 0.43 \pm 0.29$
$\pi^+\pi^-2\pi^0$	$18.01 \pm 0.14 \pm 1.17 \pm 0.40$
$2\pi^+2\pi^-\pi^0$ (η excl.)	$0.72 \pm 0.04 \pm 0.07 \pm 0.03$
$\pi^+\pi^-3\pi^0$ (η excl., from isospin)	$0.36 \pm 0.02 \pm 0.03 \pm 0.01$
$3\pi^+3\pi^-$	$0.12 \pm 0.01 \pm 0.01 \pm 0.00$
$2\pi^+2\pi^-2\pi^0$ (η excl.)	$0.70 \pm 0.05 \pm 0.04 \pm 0.09$
$\pi^+\pi^-4\pi^0$ (η excl., from isospin)	$0.11 \pm 0.01 \pm 0.11 \pm 0.00$
$\eta\pi^+\pi^-$	$1.15 \pm 0.06 \pm 0.08 \pm 0.03$
$\eta\omega$	$0.47 \pm 0.04 \pm 0.00 \pm 0.05$
$\eta 2\pi^+2\pi^-$	$0.02 \pm 0.01 \pm 0.00 \pm 0.00$
$\eta\pi^+\pi^-2\pi^0$ (estimated)	$0.02 \pm 0.01 \pm 0.01 \pm 0.00$
$\omega\pi^0$ ($\omega \to \pi^0\gamma$)	$0.89 \pm 0.02 \pm 0.06 \pm 0.02$
$\omega\pi^+\pi^-, \omega 2\pi^0$ ($\omega \to \pi^0\gamma$)	$0.08 \pm 0.00 \pm 0.01 \pm 0.00$
ω (non-$3\pi, \pi\gamma, \eta\gamma$)	$0.36 \pm 0.00 \pm 0.01 \pm 0.00$
K^+K^-	$21.63 \pm 0.27 \pm 0.58 \pm 0.36$
$K_S^0K_L^0$	$12.96 \pm 0.18 \pm 0.25 \pm 0.24$
ϕ (non-$K\bar{K}, 3\pi, \pi\gamma, \eta\gamma$)	$0.05 \pm 0.00 \pm 0.00 \pm 0.00$
$K\bar{K}\pi$ (partly from isospin)	$2.39 \pm 0.07 \pm 0.12 \pm 0.08$
$K\bar{K}2\pi$ (partly from isospin)	$1.35 \pm 0.09 \pm 0.38 \pm 0.03$
$KK3\pi$ (partly from isospin)	$-0.03 \pm 0.01 \pm 0.02 \pm 0.00$
$\phi\eta$	$0.36 \pm 0.02 \pm 0.02 \pm 0.01$
$\omega K\bar{K}$ ($\omega \to \pi^0\gamma$)	$0.00 \pm 0.00 \pm 0.00 \pm 0.00$

Process $\pi^+\pi^-\pi^0\pi^0$(After BABAR)

Phys.Rev. D96 (2017) no.9, 092009



BaBar measurement:

- **Much more precise**
- **Larger energy range**

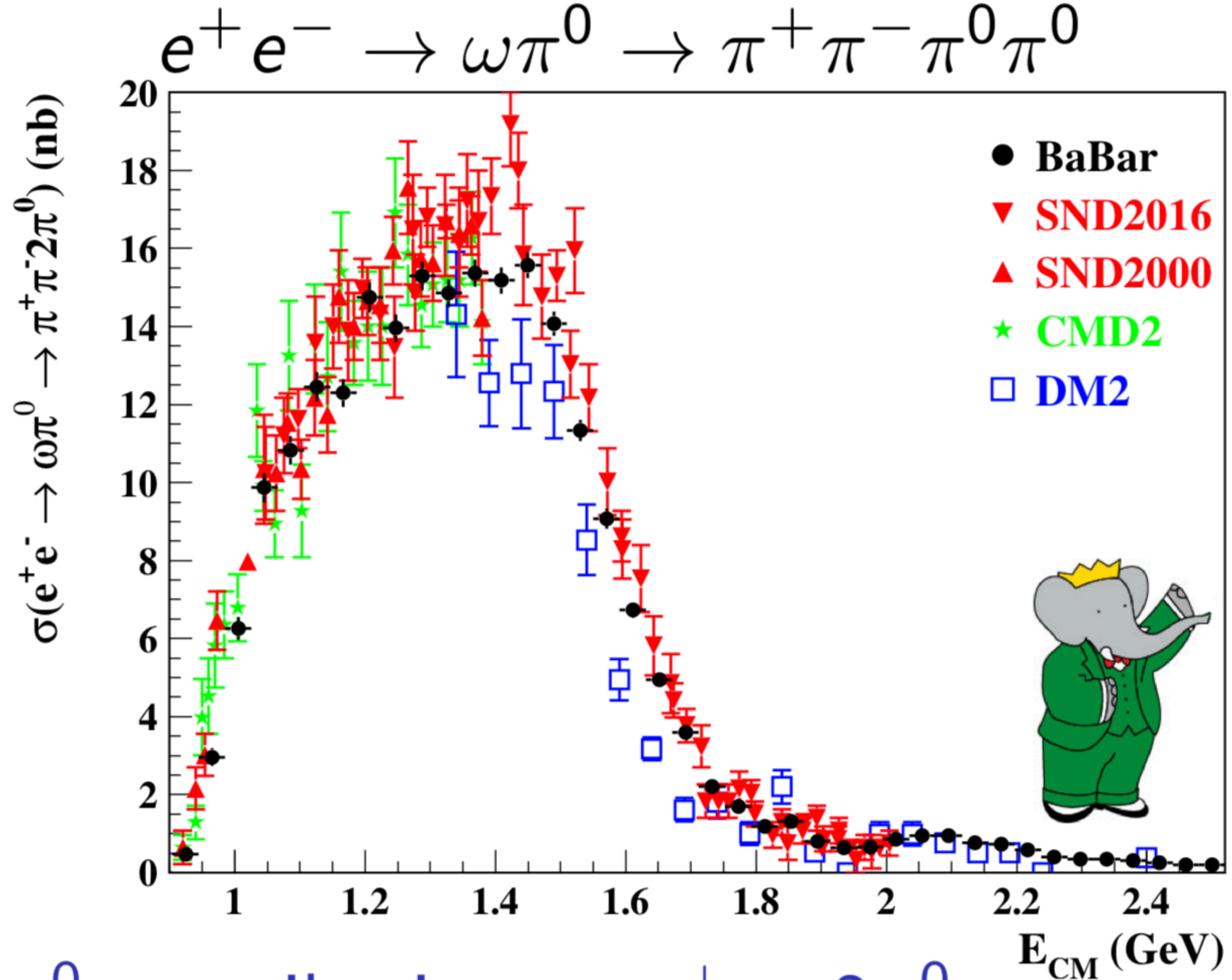
From 0.85 to 1.8 GeV:

- **Relative precision 3.3%**
- **Improved by factor 2.5**

$$a_\mu(\pi^+\pi^-2\pi^0) = (17.9 \pm 0.1 \pm 0.6)\ 10^{-10}$$

Process $\omega\pi^0$

Phys.Rev. D96 (2017) no.9, 092009



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

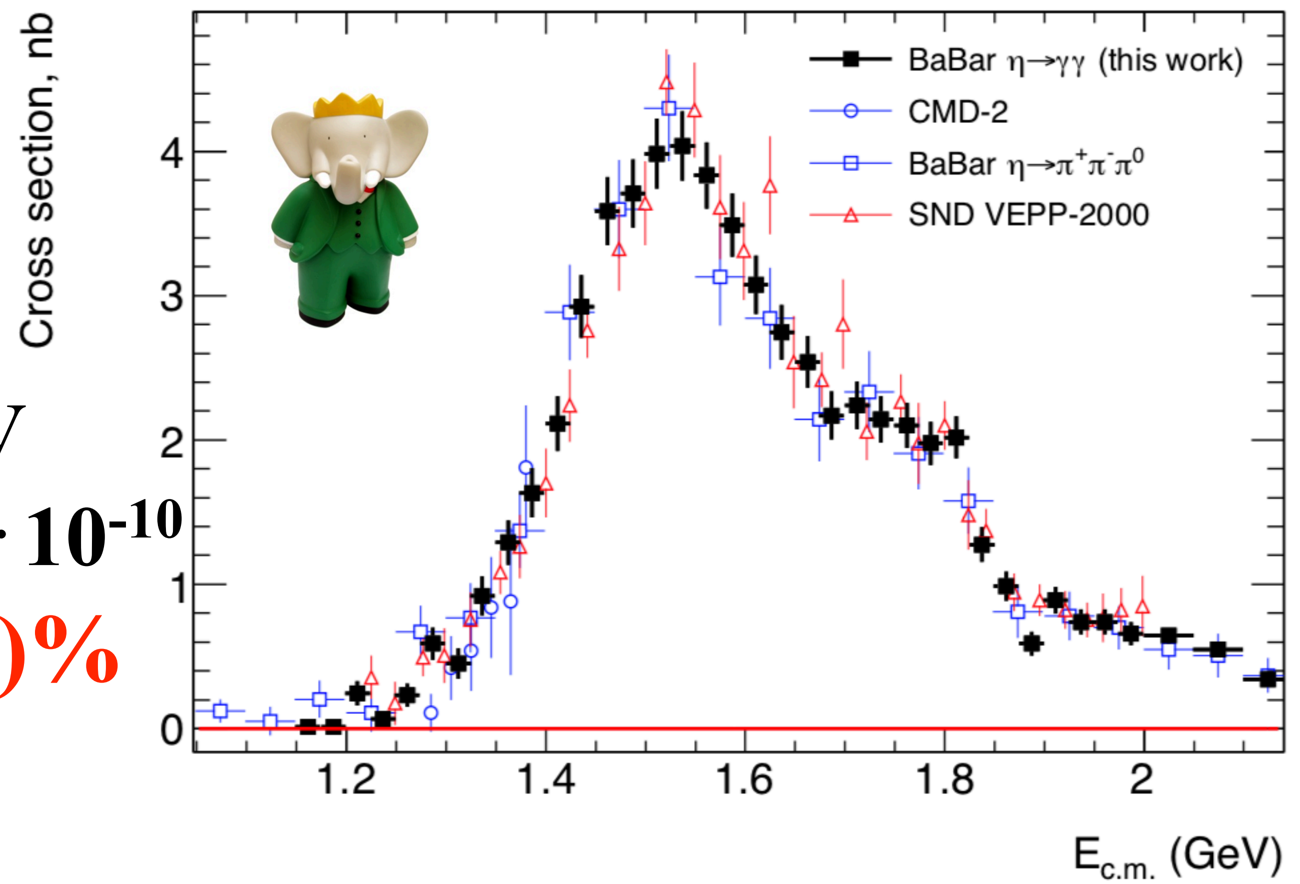
$(32.1 \pm 0.2_{\text{stat}} \pm 2.6_{\text{syst}})\,\%$

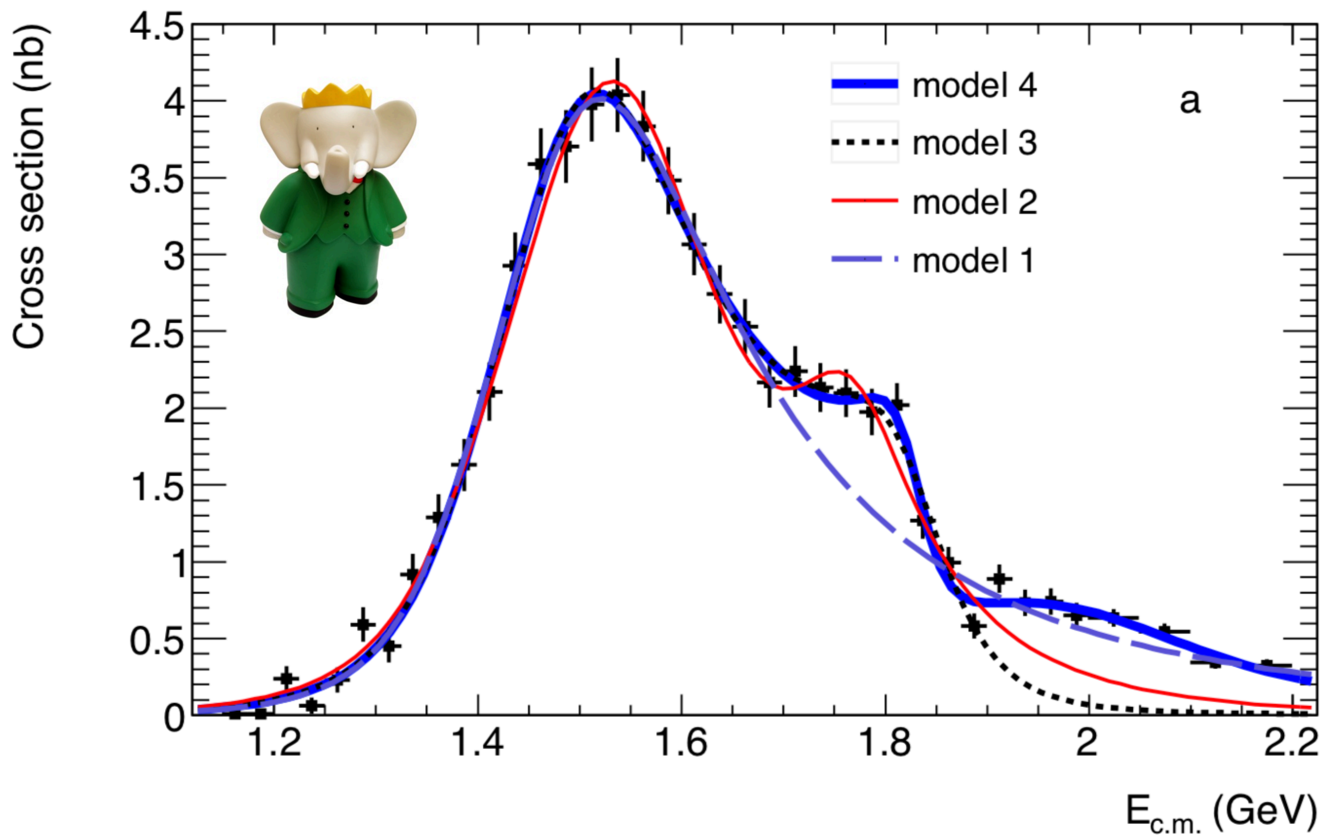
Process $\pi^+\pi^-\eta$

Phys.Rev. D97 (2018) 052007

- **$\eta \to \gamma\gamma$ decay is used**
- **The most precise measurement**
- **Extending energy range up 3.5 GeV**
- **$a_\mu^{had\ LO}(\sqrt{s} < 1.8\ GeV) = (1.18 \pm 0.06) \cdot 10^{-10}$**

Systematic uncertainty is (4.5-12)%

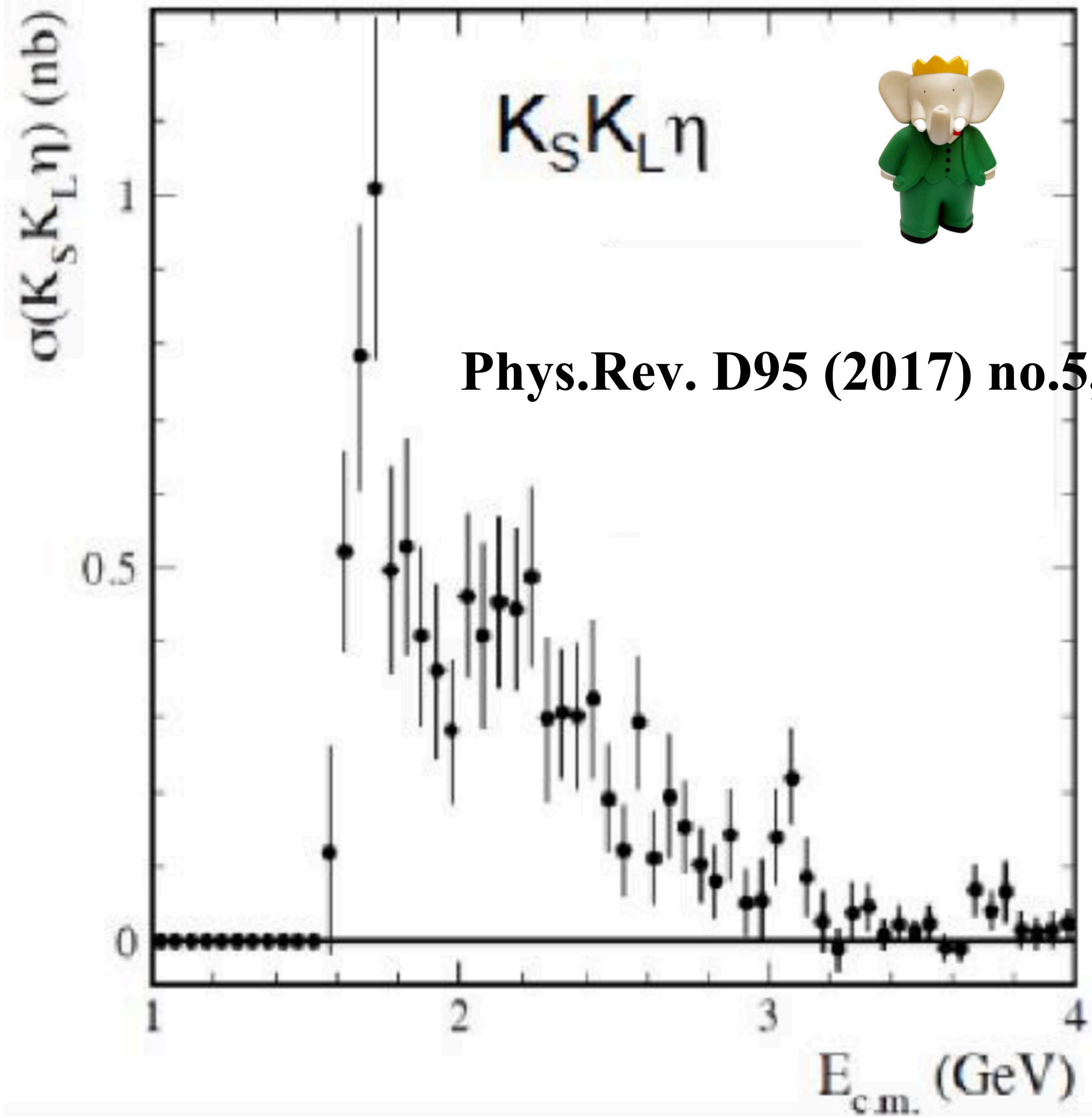




model	Resonance model	Good fit for
0	ρ(770) + ρ(1450)	Doesn't fit
1	ρ(770) − ρ(1450)	E_{cm} < 1.7 GeV
2	ρ(770) − ρ(1450) − ρ(1700)	E_{cm} < 1.9 GeV
3	ρ(770) − ρ(1450) + ρ(1700)	E_{cm} < 1.9 GeV
4	ρ(770) − ρ(1450) + ρ(1700) + ρ(2150)	E_{cm} < 2.2 GeV

Process $K_L K_S \eta$

First measurement of this cross section

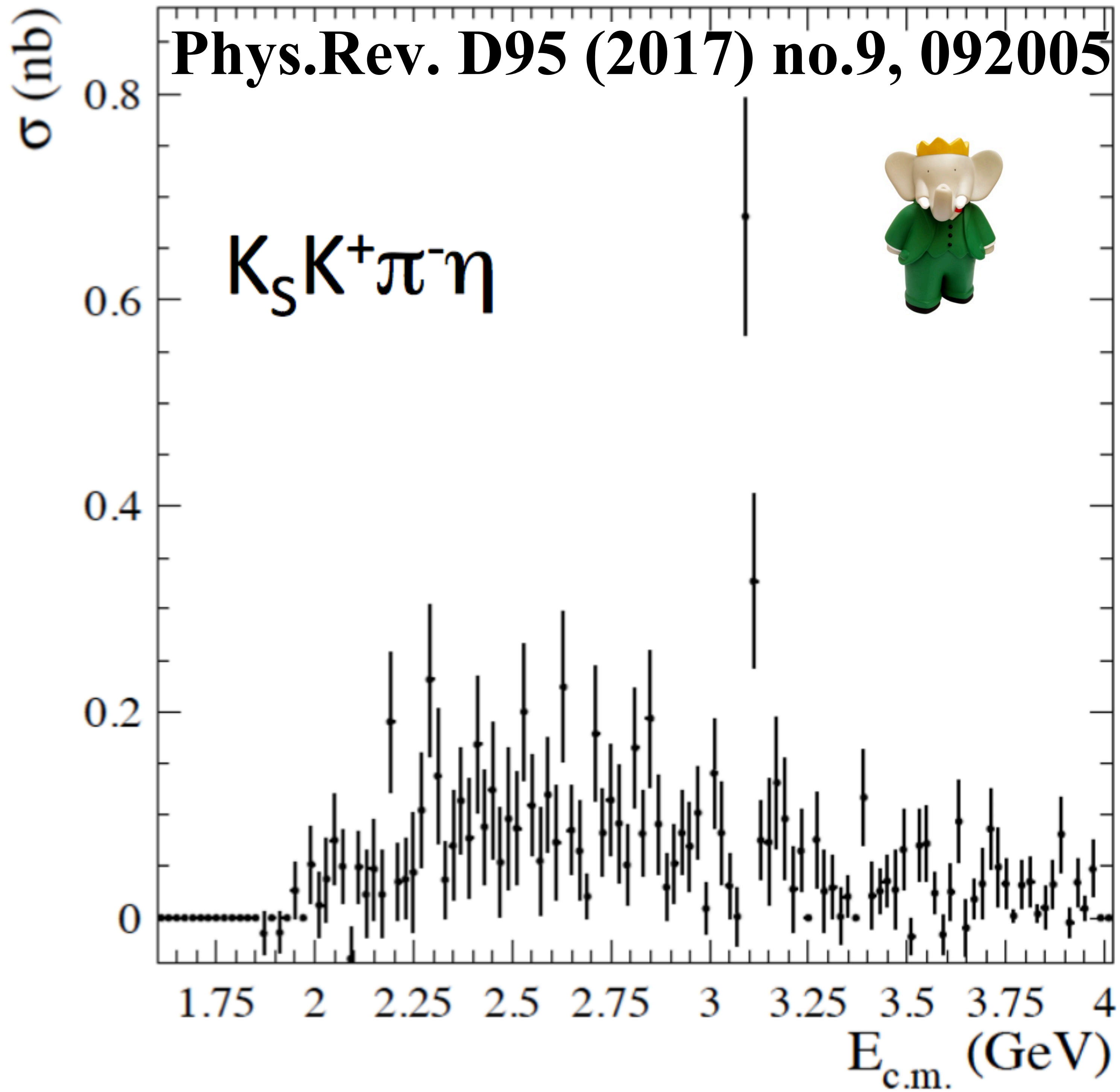


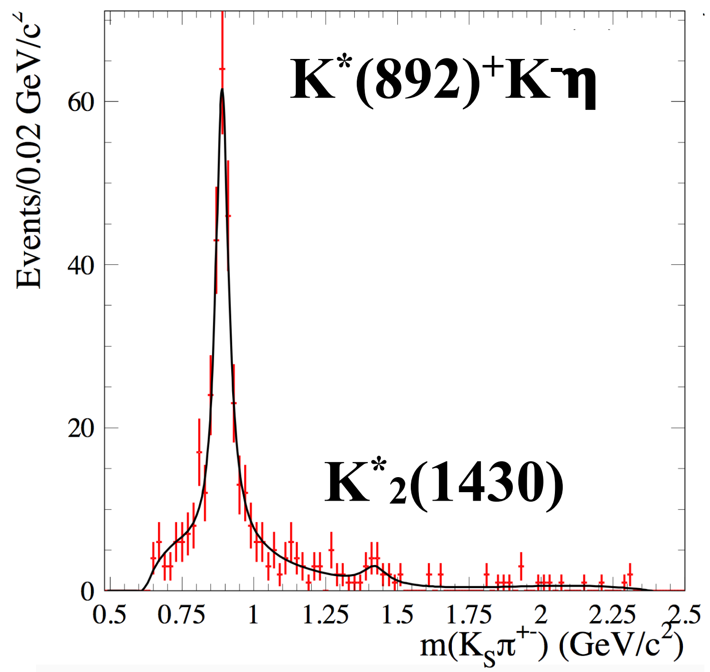
Phys.Rev. D95 (2017) no.5, 052001

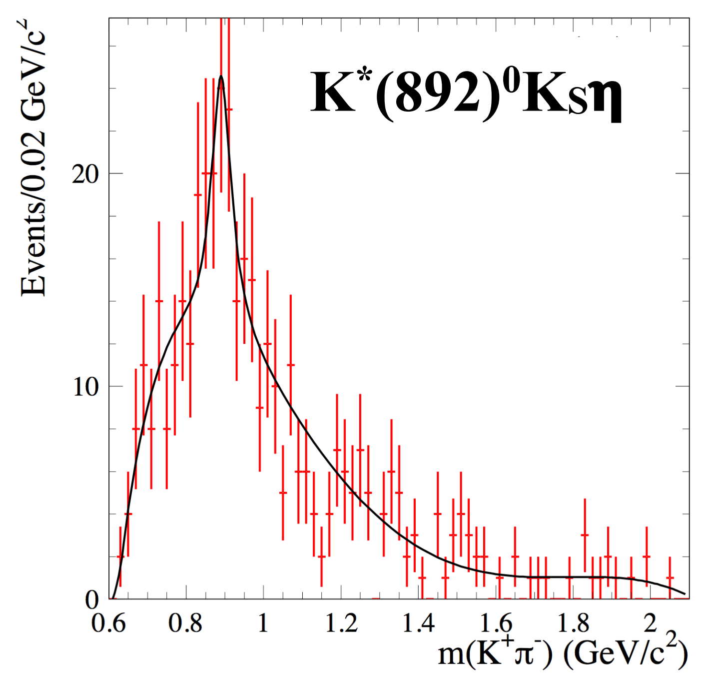
Systematic uncertainty is (15-100)%

Process $K_S K^{\pm}\pi^{\mp}\eta$

First measurement of this cross section





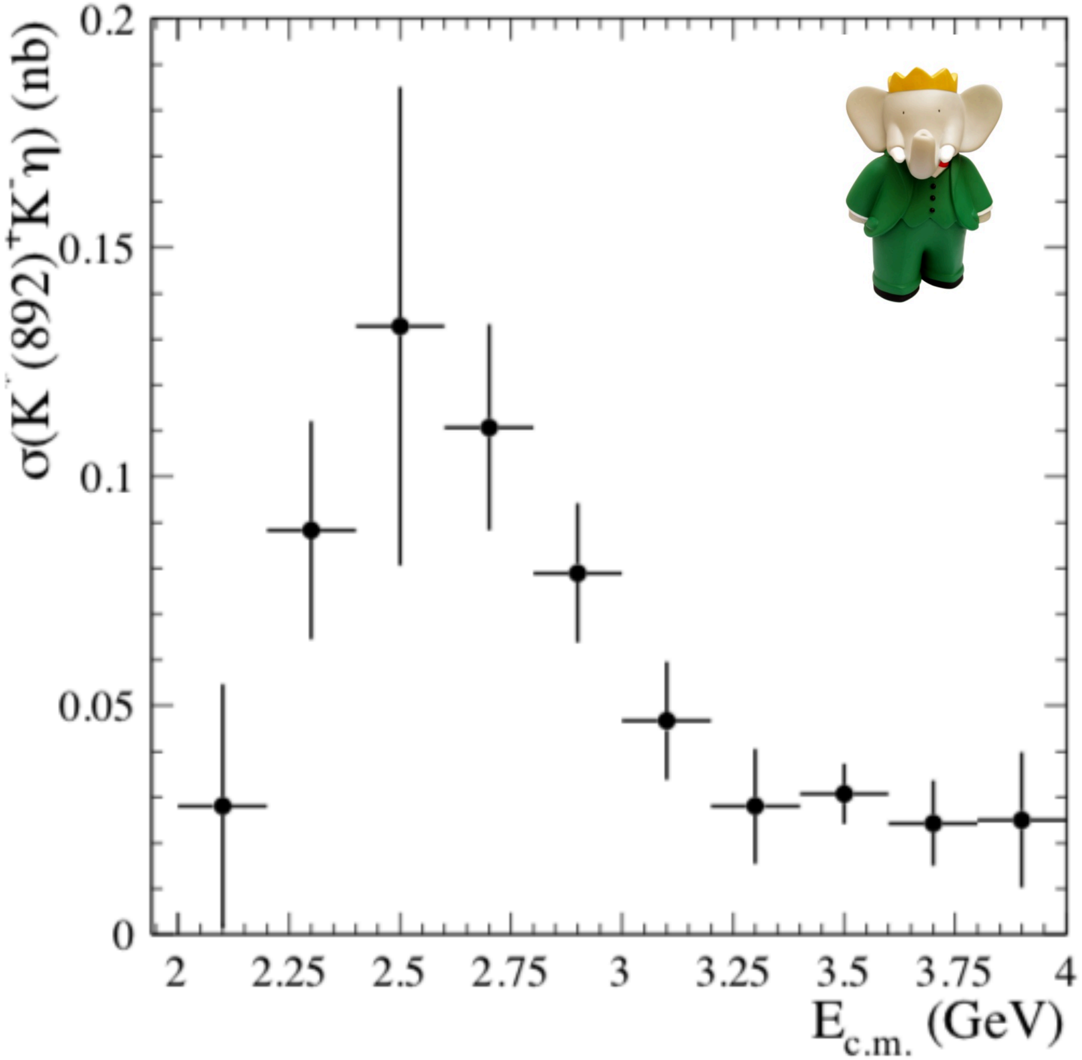


Systematic uncertainty is (12-19)%

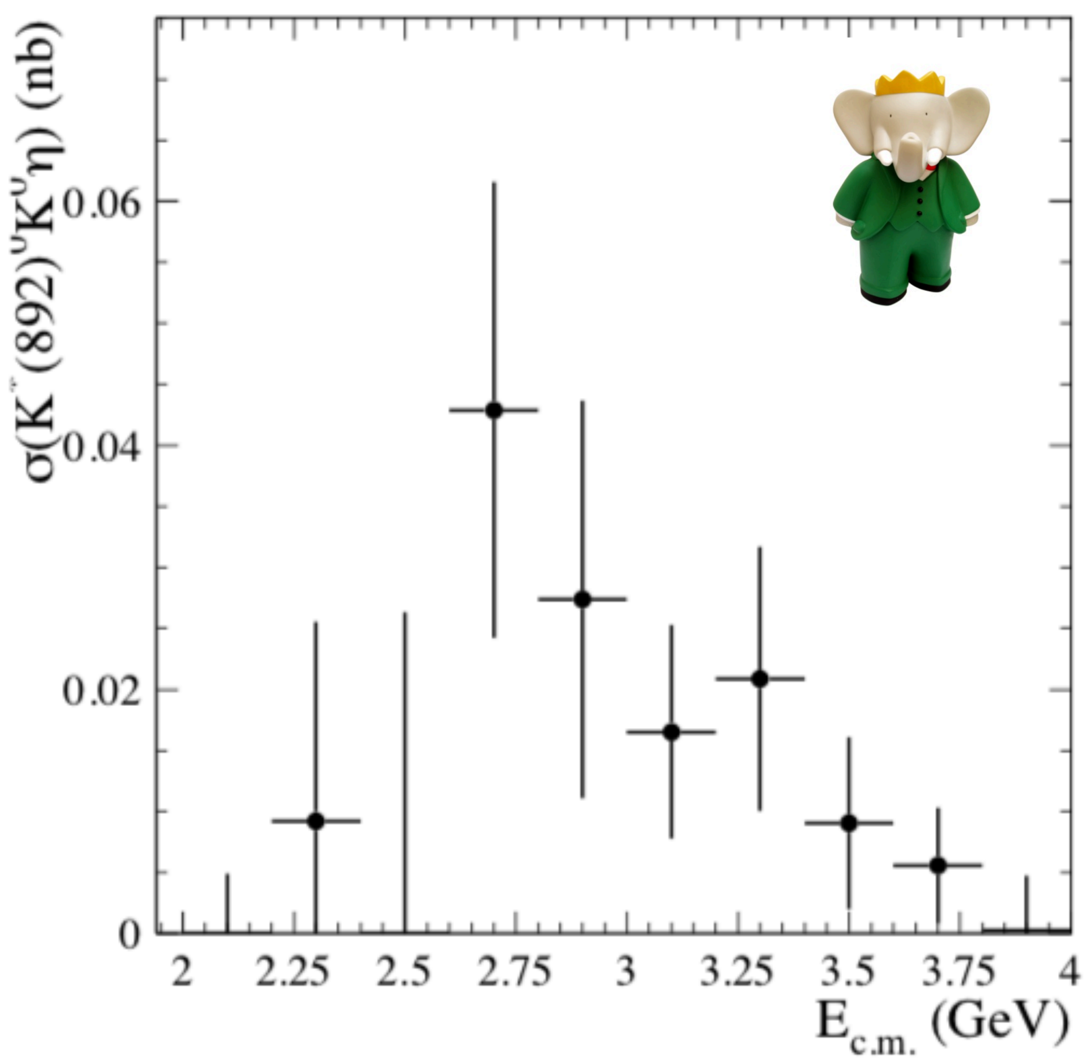
Processes K*(892)Kη

Phys.Rev. D95 (2017) no.9, 092005

Charged K*(892)

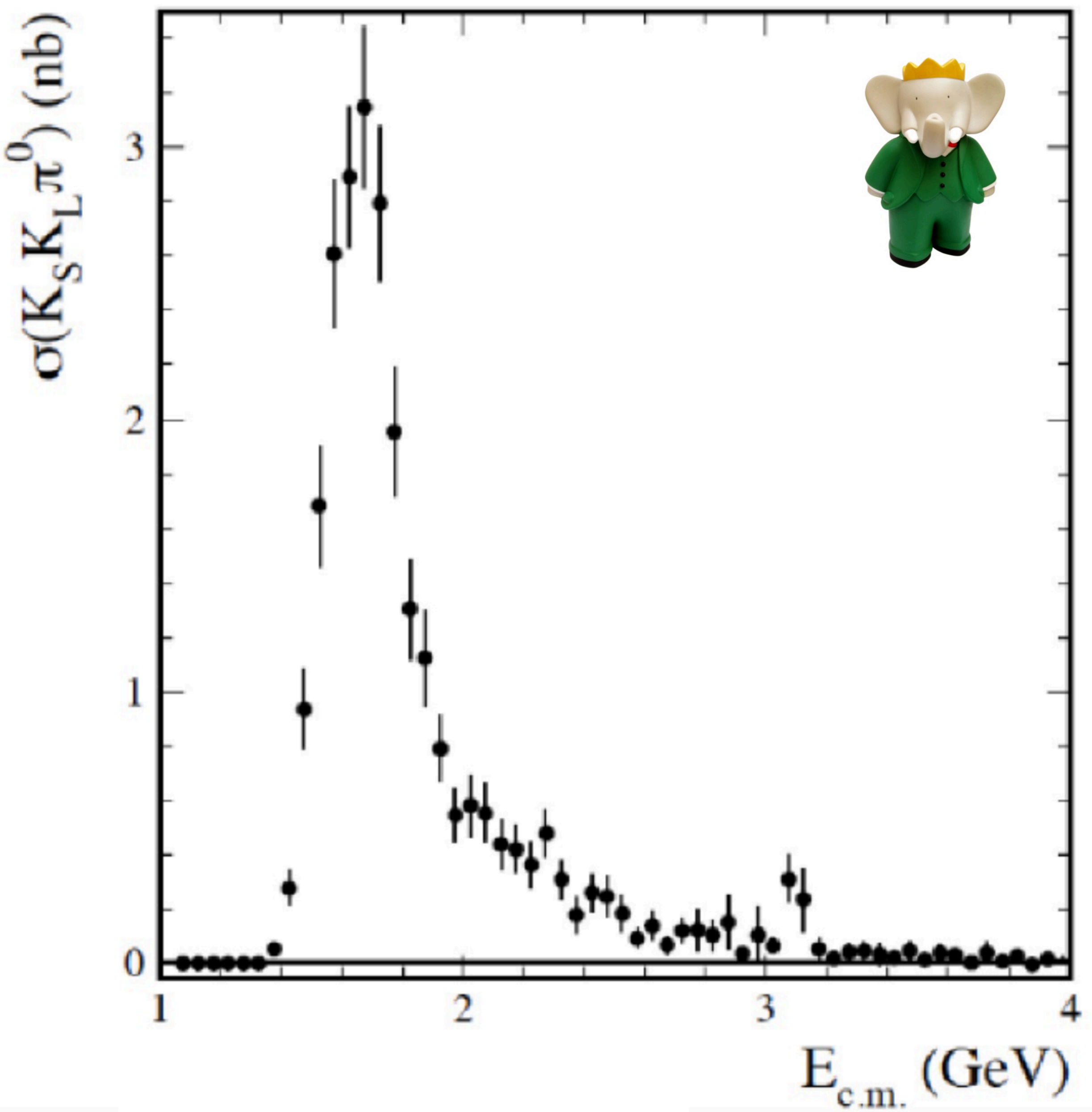


Neutral K*(892)

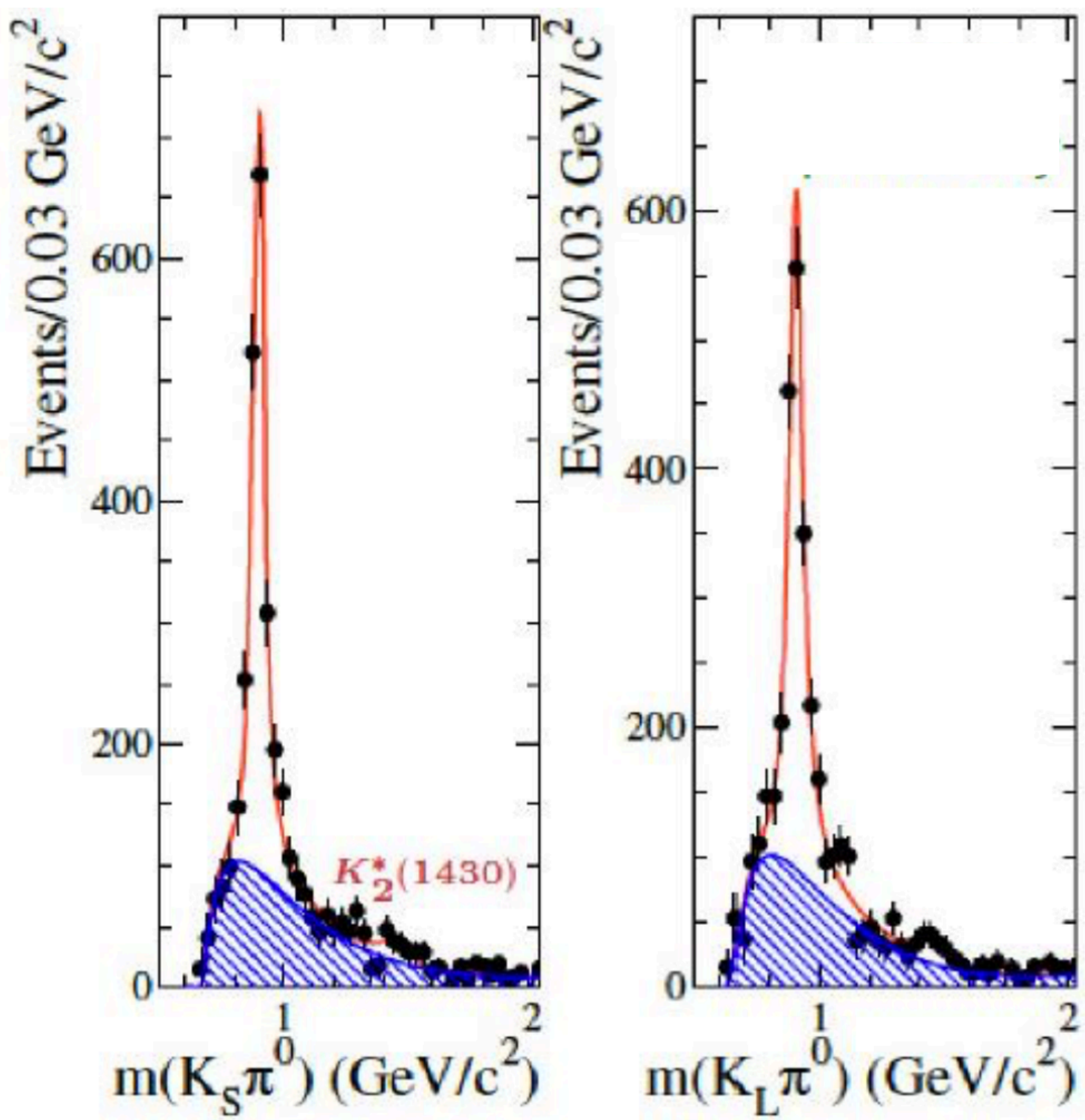


Process $K_L K_S \pi^0$

First measurement of this cross section



Phys.Rev. D95 (2017) no.5, 052001



Systematic uncertainty is (10-30)%

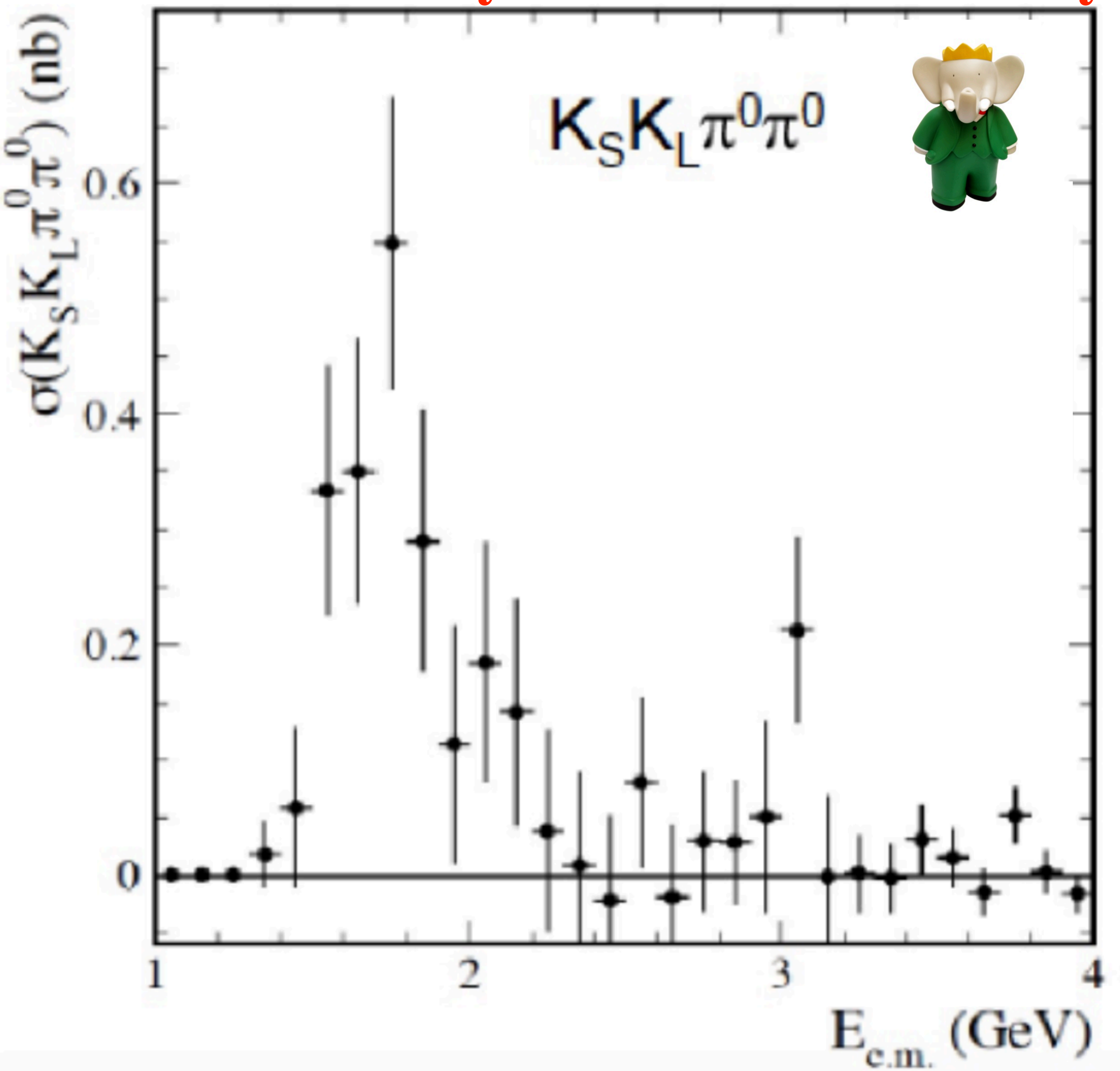
Dominant $K^*(892)^0\overline{K}^0$

Small $K^*(1430)^0\overline{K}^0, \phi\pi^0$

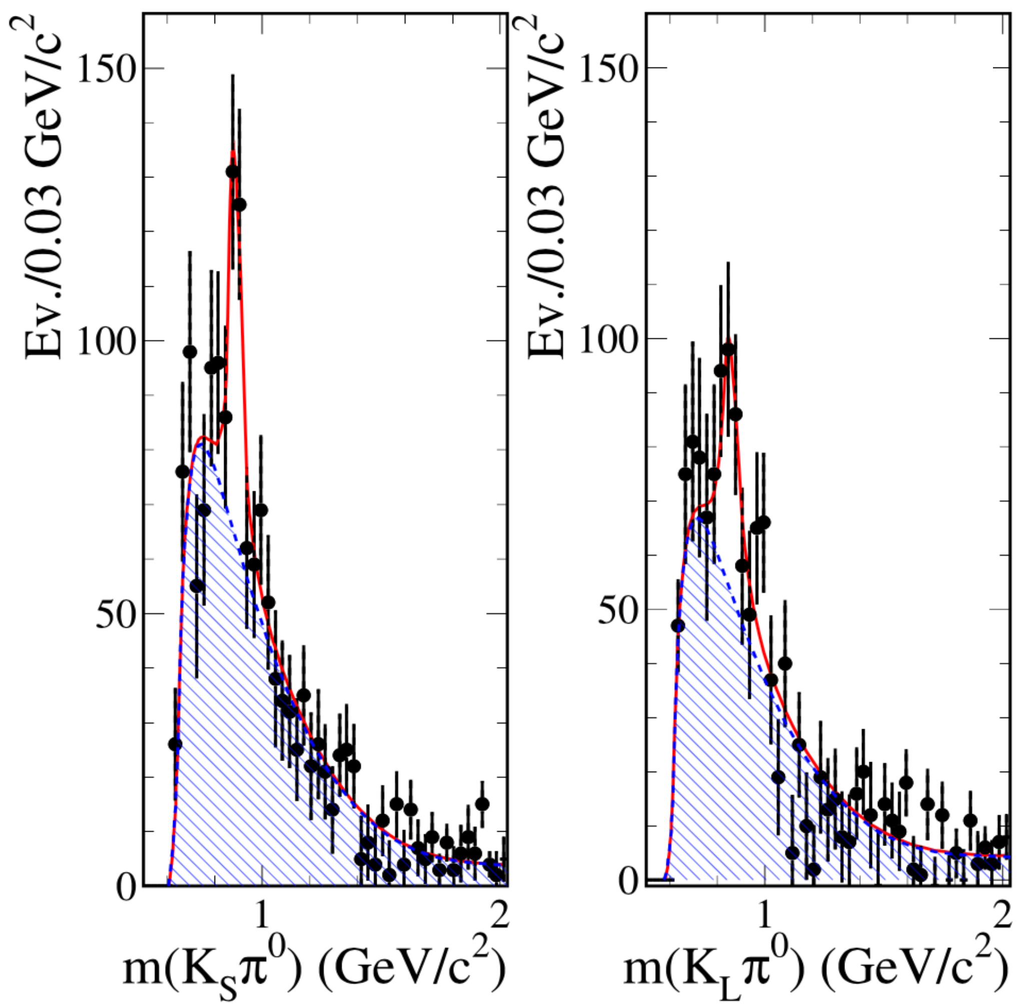
Process $K_L K_S \pi^0 \pi^0$

First measurement of this cross section

Systematic uncertainty is (25-100)%



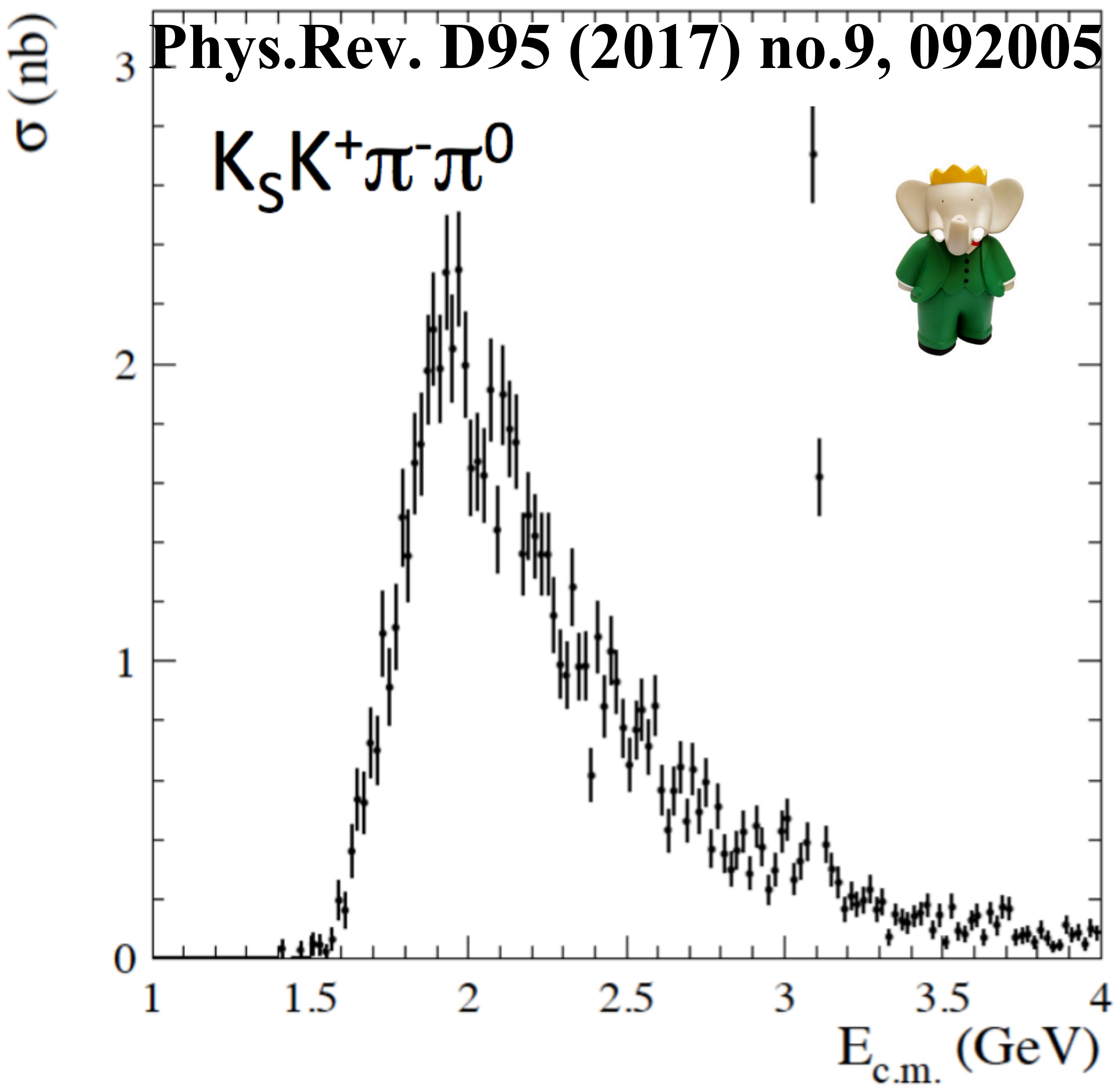
Phys.Rev. D95 (2017) no.5, 052001



Process $K_S K^{\pm}\pi^{\mp}\pi^0$

First measurement of this cross section

Phys.Rev. D95 (2017) no.9, 092005



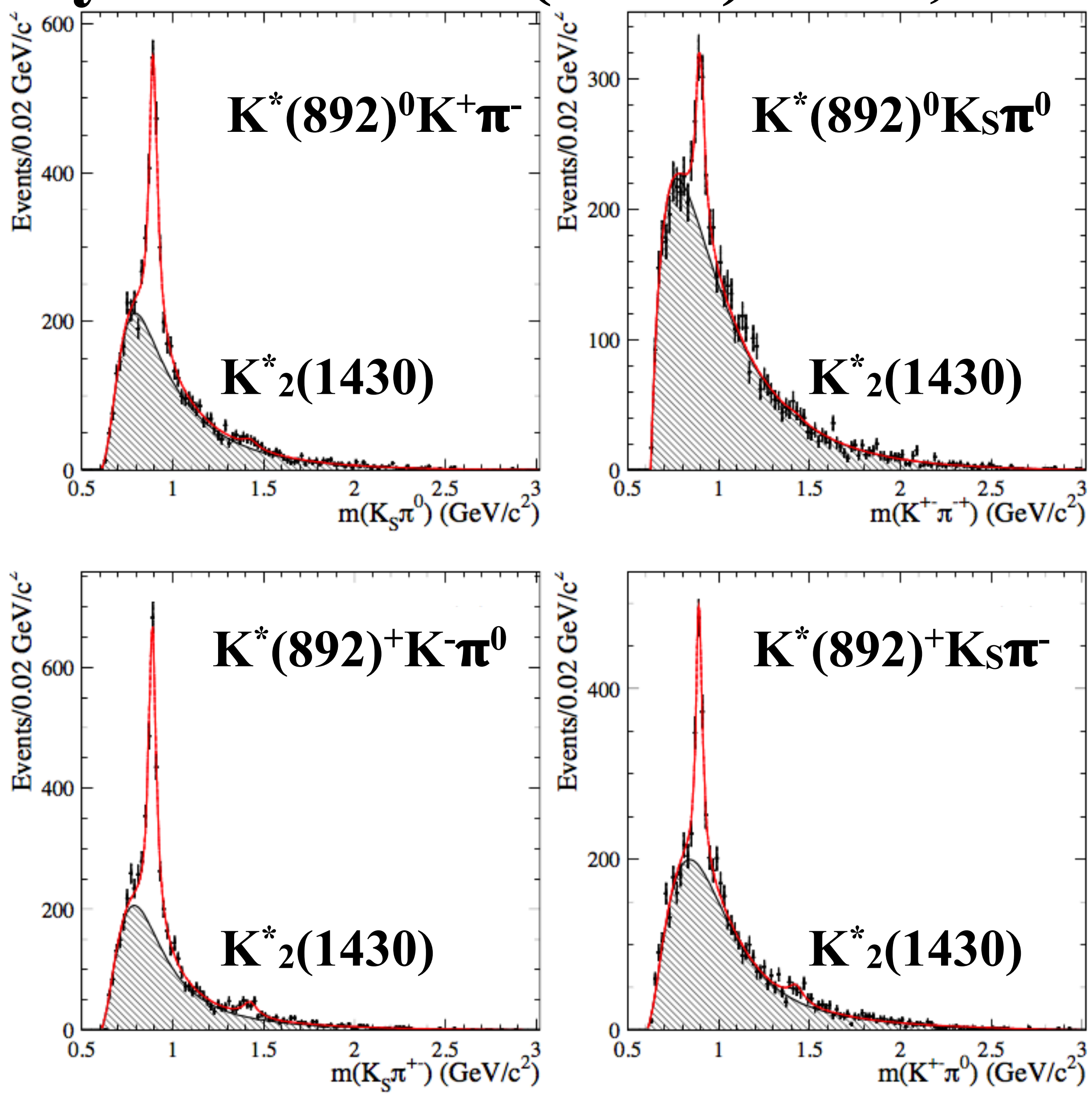
More than 10 intermediate states

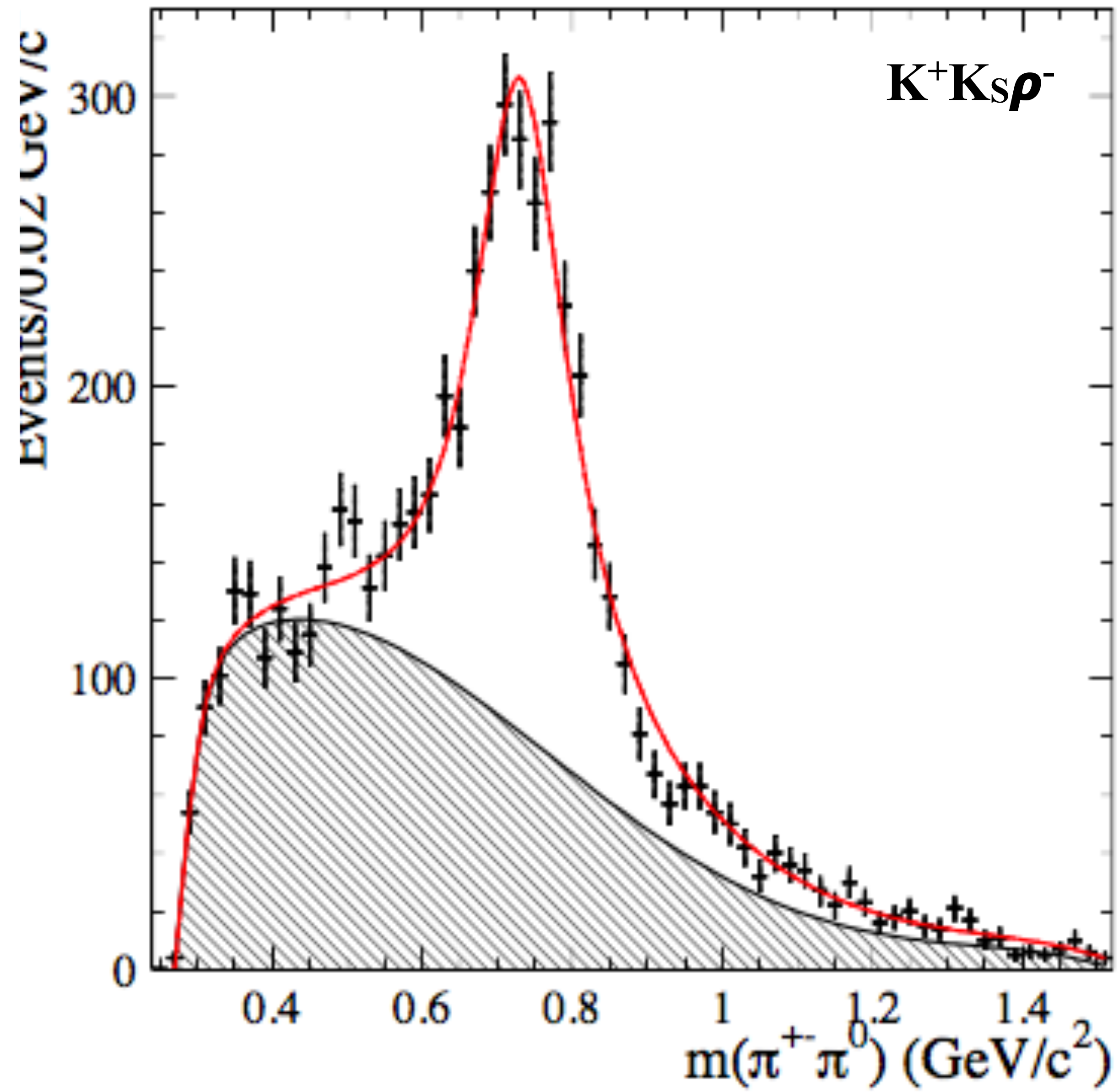
Intermediate state
$K^{*0} K^0_S \pi^0$
$K^{*0} K^{\pm} \pi^{\mp}$
$K^*_2(1430)^0 K^0_S \pi^0$
$K^*_2(1430)^0 K^{\pm} \pi^{\mp}$
$K^*(892)^{\pm} K^0_S \pi^{\mp}$
$K^*(892)^{\pm} K^{\mp} \pi^0$
$K^*_2(1430)^{\pm} K^0_S \pi^{\mp}$
$K^*_2(1430)^{\pm} K^{\mp} \pi^0$
$K^{*0} \overline{K}^{*0}$
$K^*(892)^+ K^*(892)^-$
$K^0_S K^{\pm} \rho(770)^{\mp}$

Systematic uncertainty is (6-12)%

Substructures in $K_S K^{\pm} \pi^{\mp} \pi^0$

Phys.Rev. D95 (2017) no.9, 092005

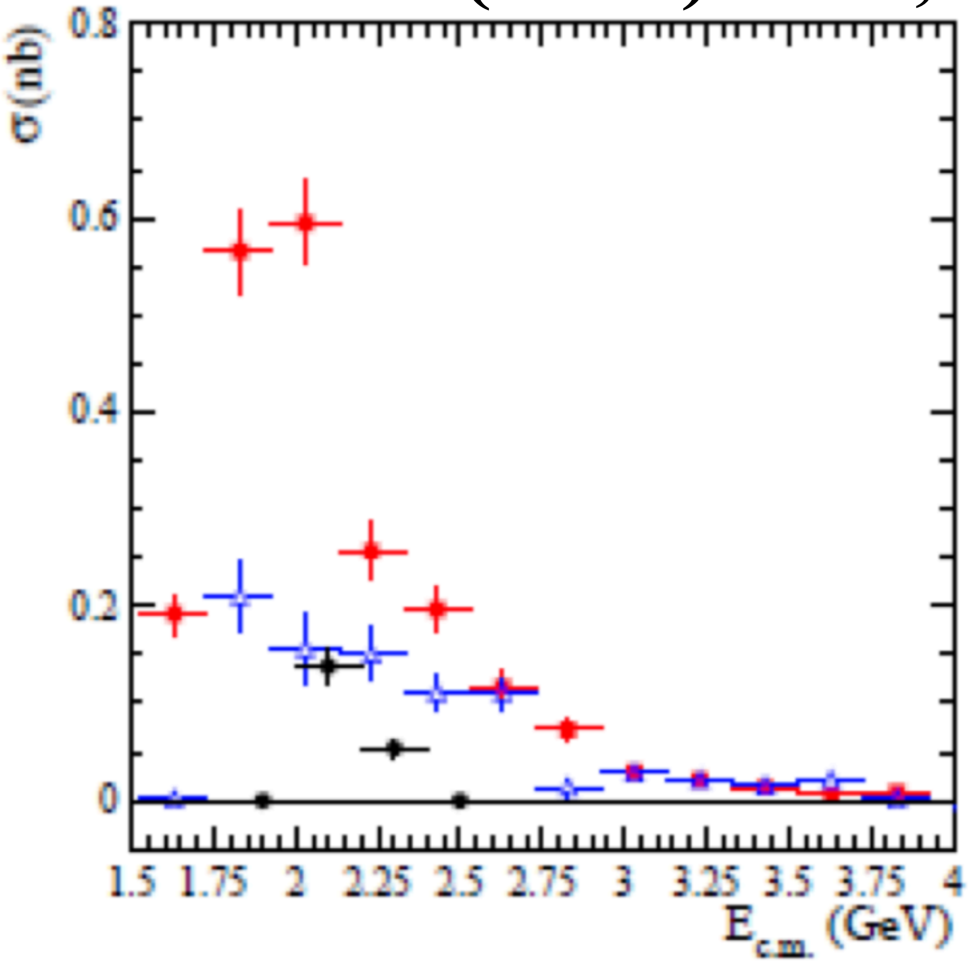


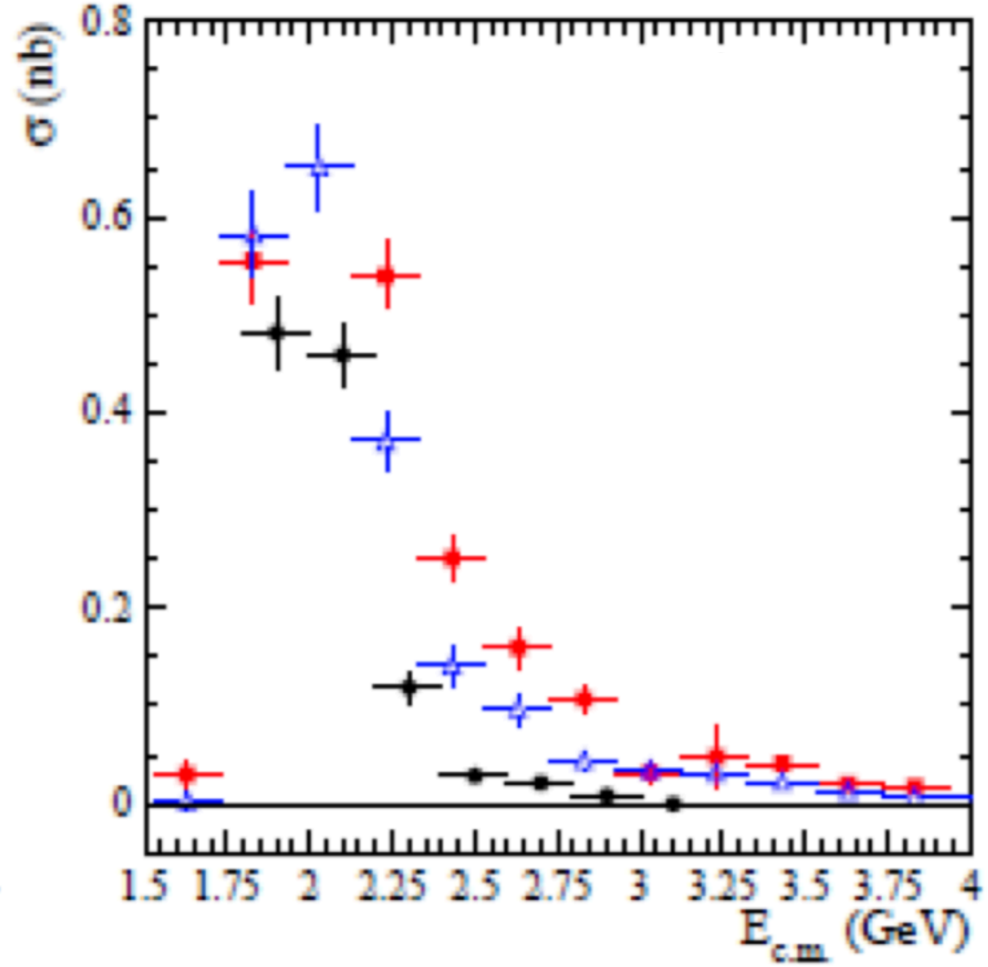


All $K^*(892)K\pi$ signals include also signals from $K^*(892)K^*(892)$

Processes K*(892)$K_S\pi$ and K*(892)Kπ

Phys.Rev. D95 (2017) no.9, 092005





Neutral K*(892)

$e^+e^- \to K^{*0}K^{\pm}\pi^{\mp}$

$e^+e^- \to K^{*0}K_S\pi^0$

$e^+e^- \to K^{*0}\overline{K}^{*0}$

Charged K*(892)

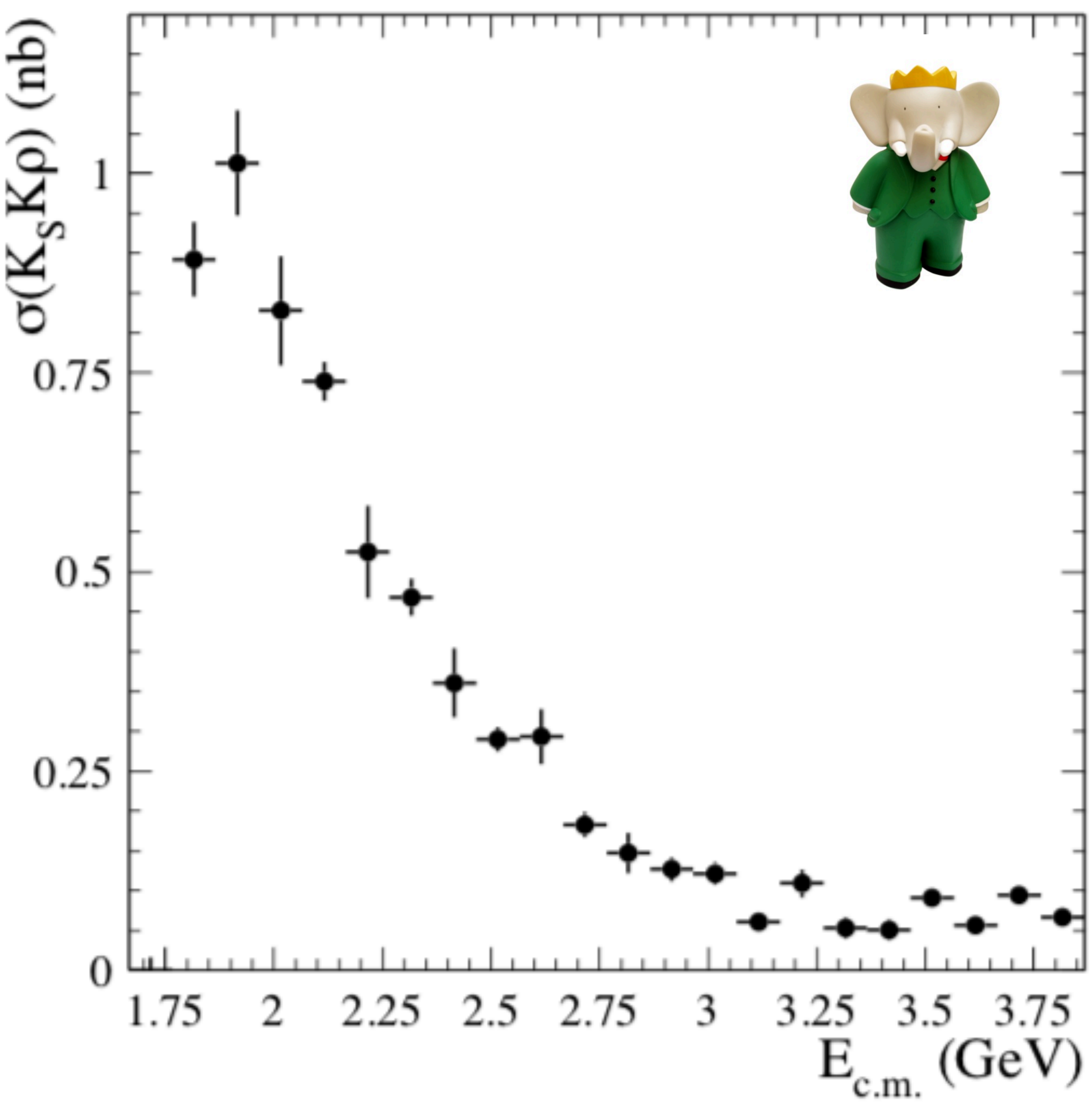
$e^+e^- \to K^{*\pm}K_s\pi^{\mp}$

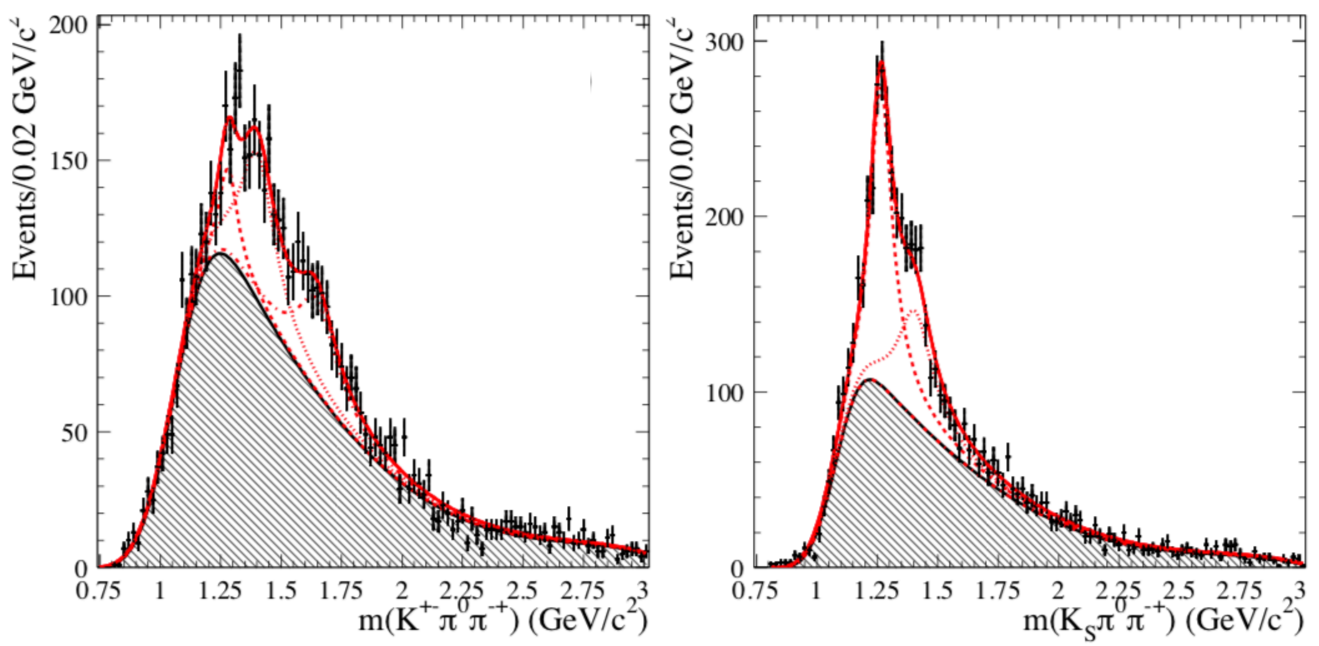
$e^+e^- \to K^{*\pm}K^{\mp}\pi^0$

$e^+e^- \to K^{*+}K^{*-}$

Process $KK_S\rho$

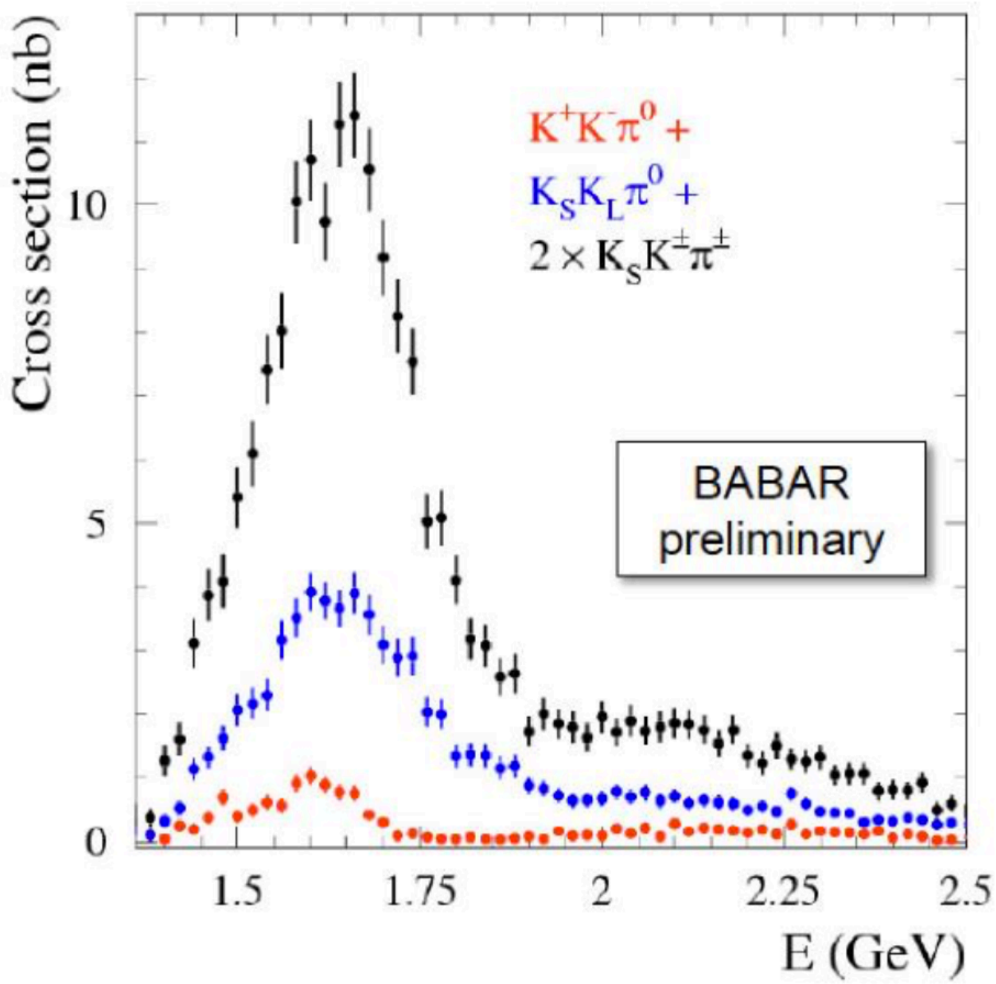
Phys.Rev. D95 (2017) no.9, 092005

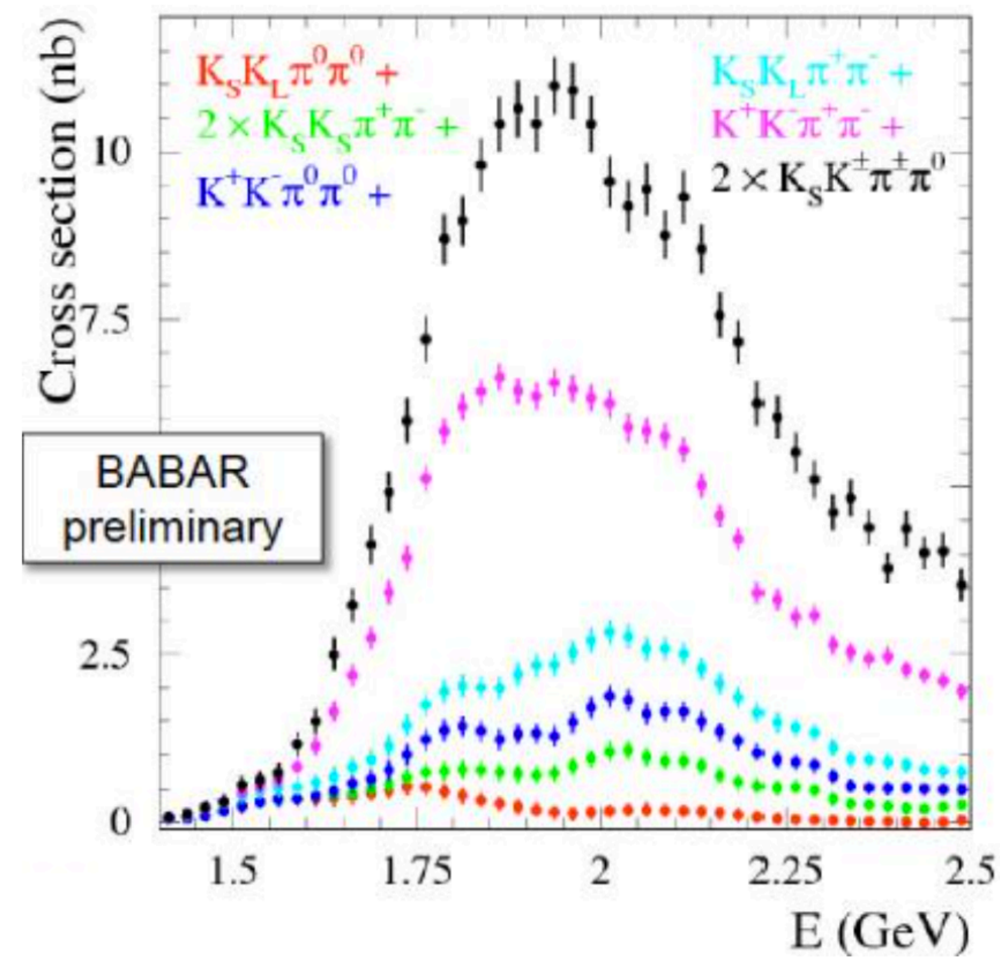




Cross section may contain contributions from $K_1 \to K\rho$, where $K_1 = K_1(1270), K_1(1400), K_1(1650)$

Total KKπ(π) cross sections





- **All modes have now been measured by BABAR**
- **KKπ is about 12% of the total cross section for E_{cm} = 1.65 GeV**
- **KKππ is about 25% of the total cross section for E_{cm} = 2.0 GeV**
- **Precision on (g-2)/2 improved (no reliance on isospin)**

$a_\mu(KK\pi) = (2.45 \pm 0.15)\ 10^{-10}$ $\quad$ $a_\mu(KK\pi\pi) = (0.85 \pm 0.05)\ 10^{-10}$

Conclusion

- **Using ISR technique BABAR does precision studies of low energy e^+e^- annihilation.**
- **All $KK\pi$ and $KK\pi\pi$ modes now directly measured by BABAR. No isospin relations needed any more for cross sections and dispersion relations.**
- **Resonant substructures explored with $\mathcal{O}(10^2\text{-}10^3)$ events.**
- **Contributions to a_μ:**

  $a_{\mu(\pi^+\pi^-\pi^0\pi^0)} = (17.4\pm0.6)\ 10^{-10}$

  $a_{\mu(KK\pi)} = (2.45\pm0.15)\ 10^{-10}$ $a_{\mu(KK\pi\pi)} = (0.85\pm0.05)\ 10^{-10}$

- **Improvement of the total $a_\mu^{\text{had LO}}$ prediction:**

DHMZ 2011	Tau2016 Conference
$(692.3\pm4.2)\ 10^{-10}$	$(692.8\pm3.3)\ 10^{-10}$