25th International Workshop on Deep Inelastic Scattering and Related Topics
Birmingham, England, April 3-7, 2017

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

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On behalf of BaBar Collaboration

Novosibirsk State University
*THE REAL SCIENCE

Outline

- Motivation: $(g-2)_\mu/2$
- Collider, detector and method
- Process $\pi^+\pi^-\pi^0\pi^0$
- Processes with η
- Processes with kaons and one π
- Processes with kaons and two π's
- Total $KK\pi(\pi)$ cross sections
- 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-…):

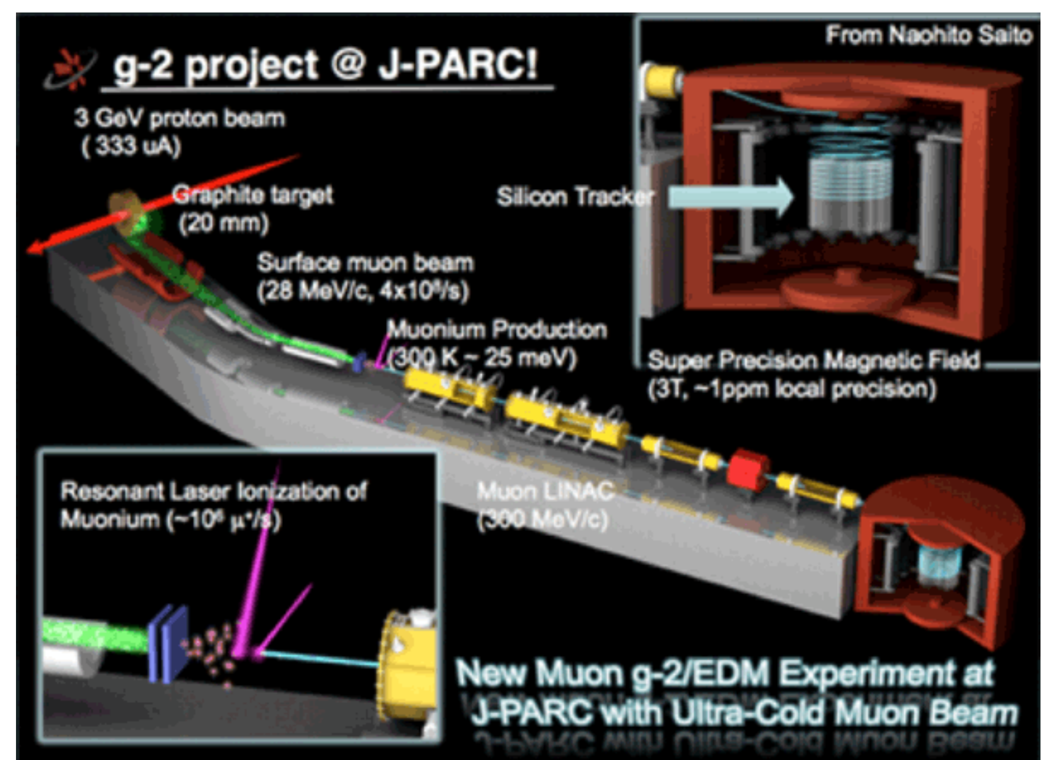
F. Gray et al., ArXiv 1510.003[physics.ins-det] (2015)

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

E34 Experiment @ J-PARC (????-…):

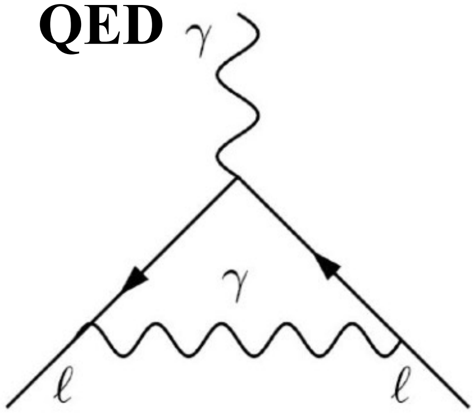
T. Mibe et al., Chin.Phys. C34 (2010) 745

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

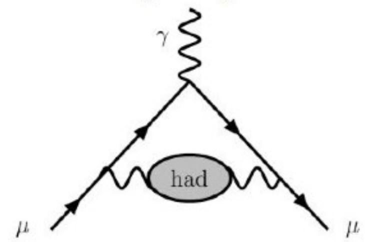


(g-2)/2 of muon (Theory)

QED

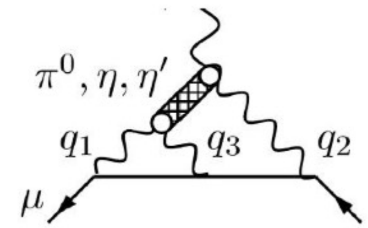


Hadronic Vacuum Polarisation (VP)

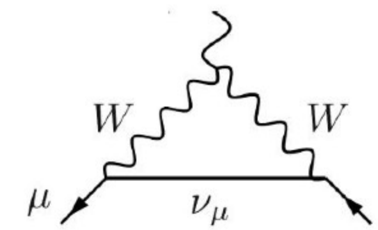


This talk

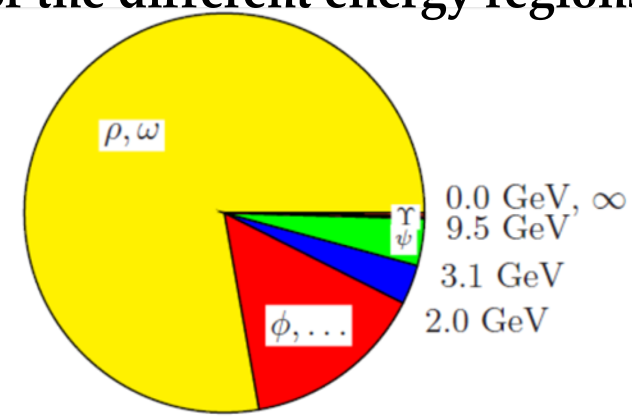
Hadronic light-by-light Scattering



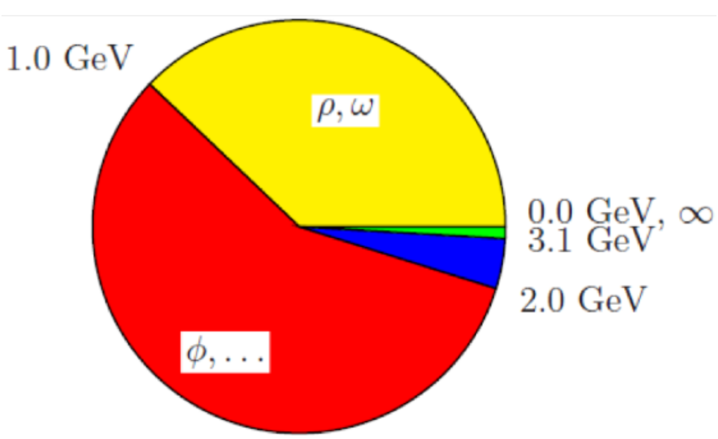
Weak Interactions



Contributions of the different energy regions to:



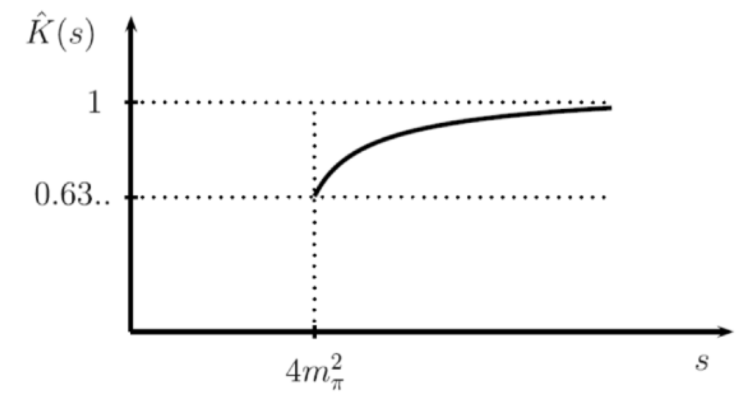
a_μ integral



a_μ uncertainty

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

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



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

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

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

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

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

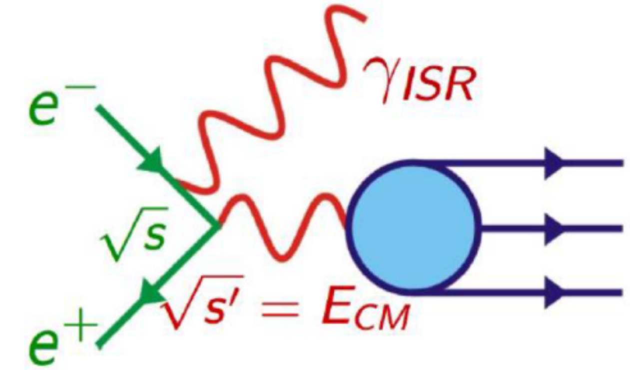
(M. Davier et al., EPJC71(2011)1515)

ISR @ BaBar

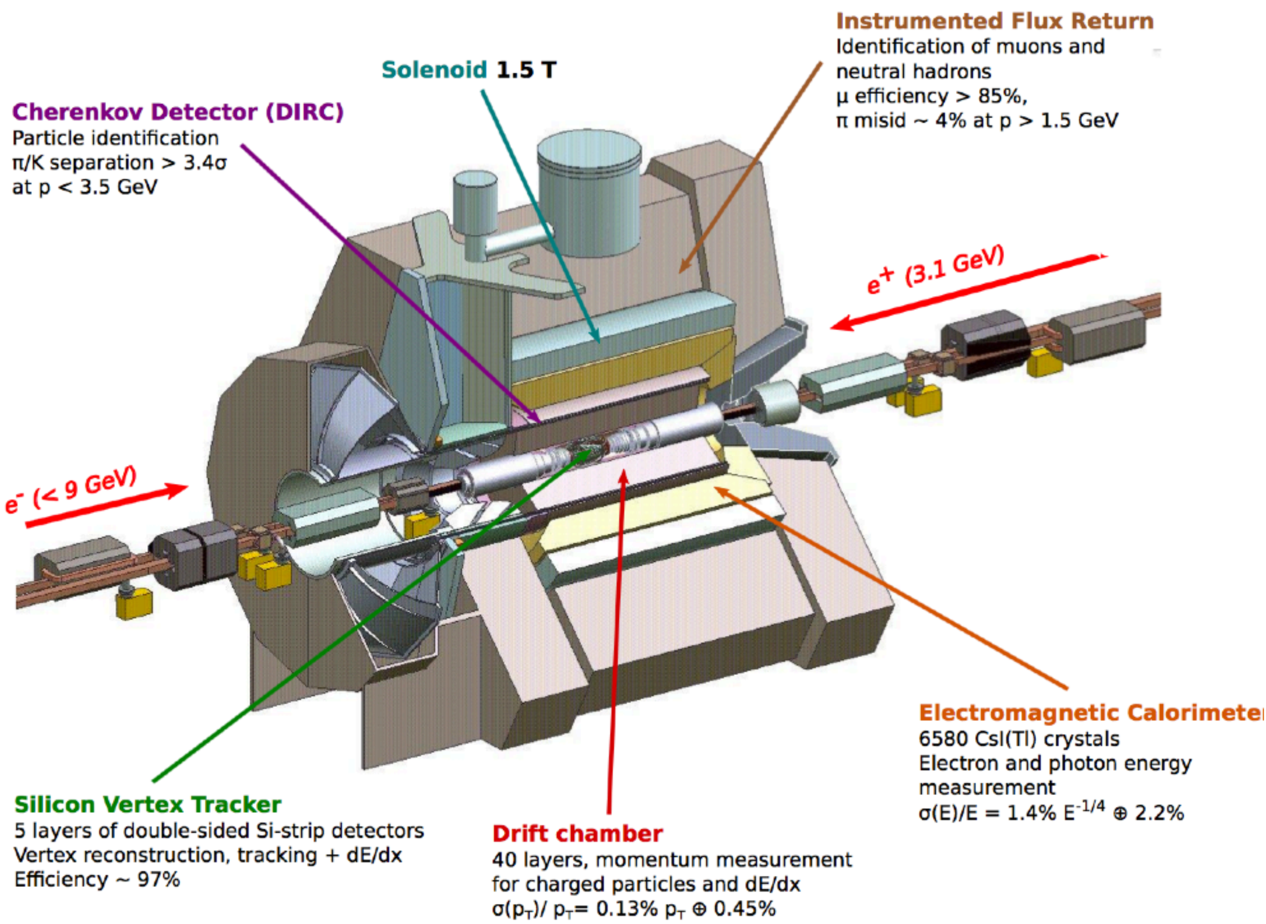
The *BABAR* experiment (1999-2008)

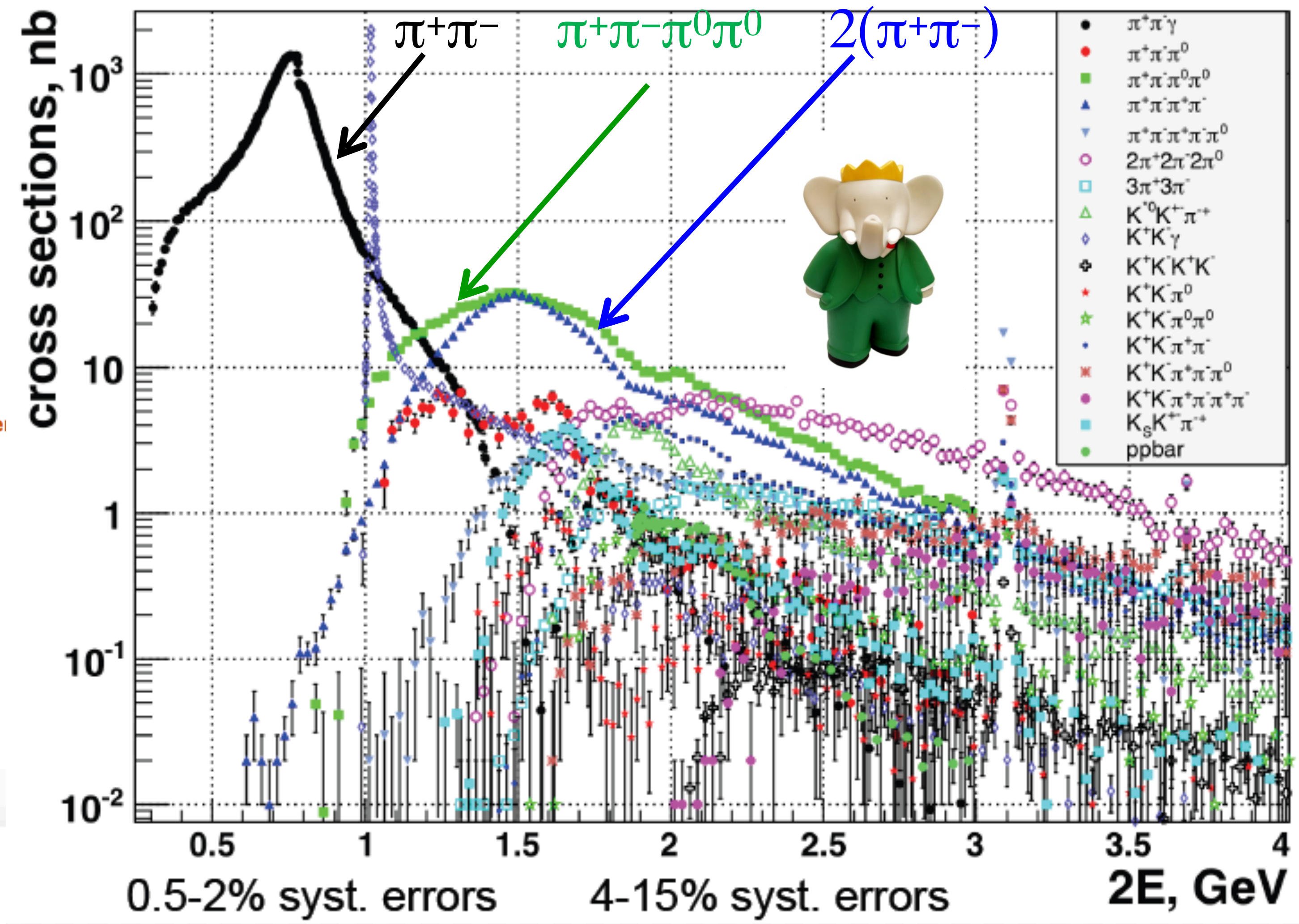
PEP-II: e^+e^- collider, 3.1×9 GeV^2

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



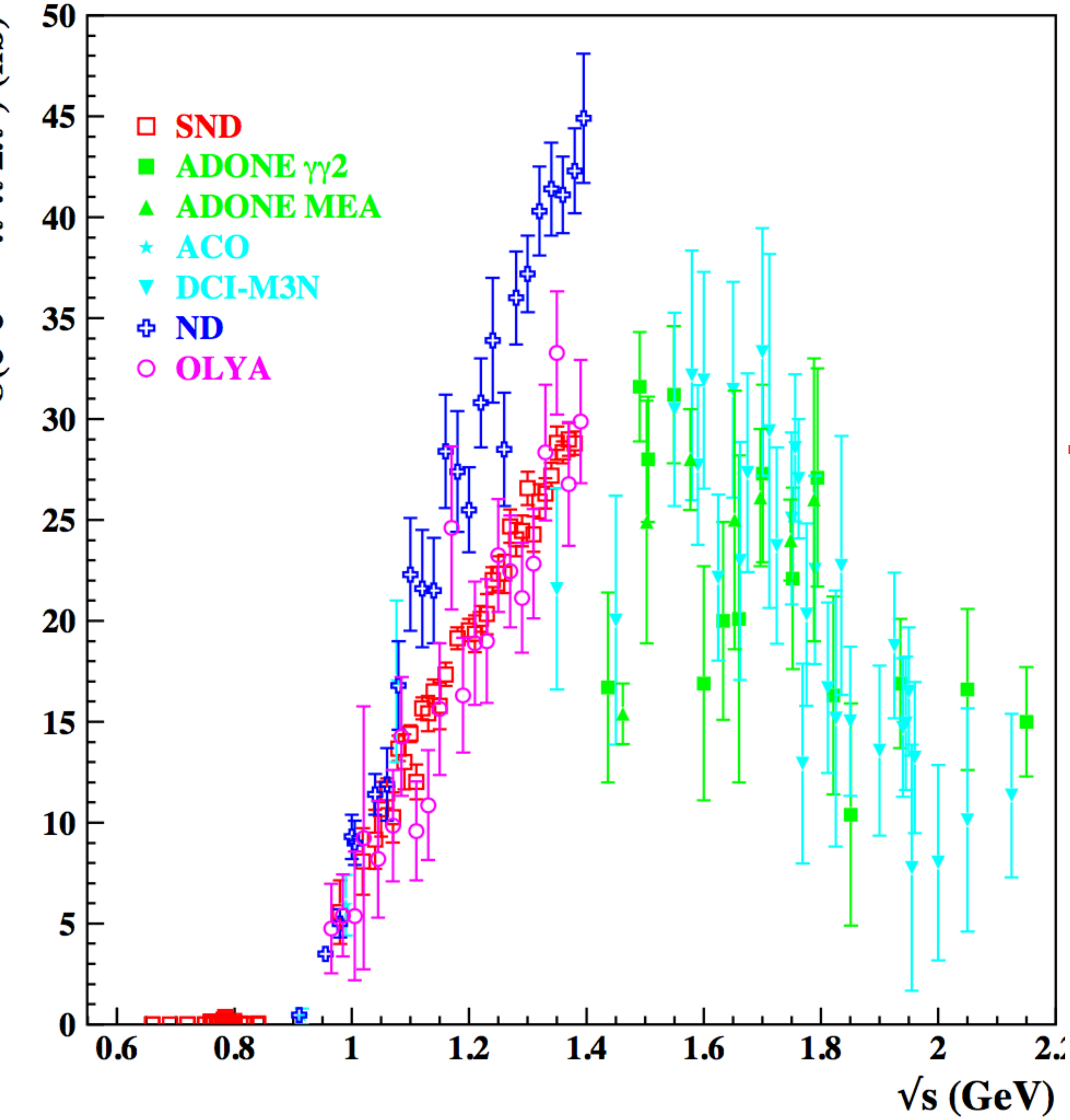
$$\frac{d\sigma_{[e^+e^-\to f\gamma]}}{ds'}(s') = \frac{2m}{s} W(s,x)\sigma_{[e^+e^-\to f]}(s')$$





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

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



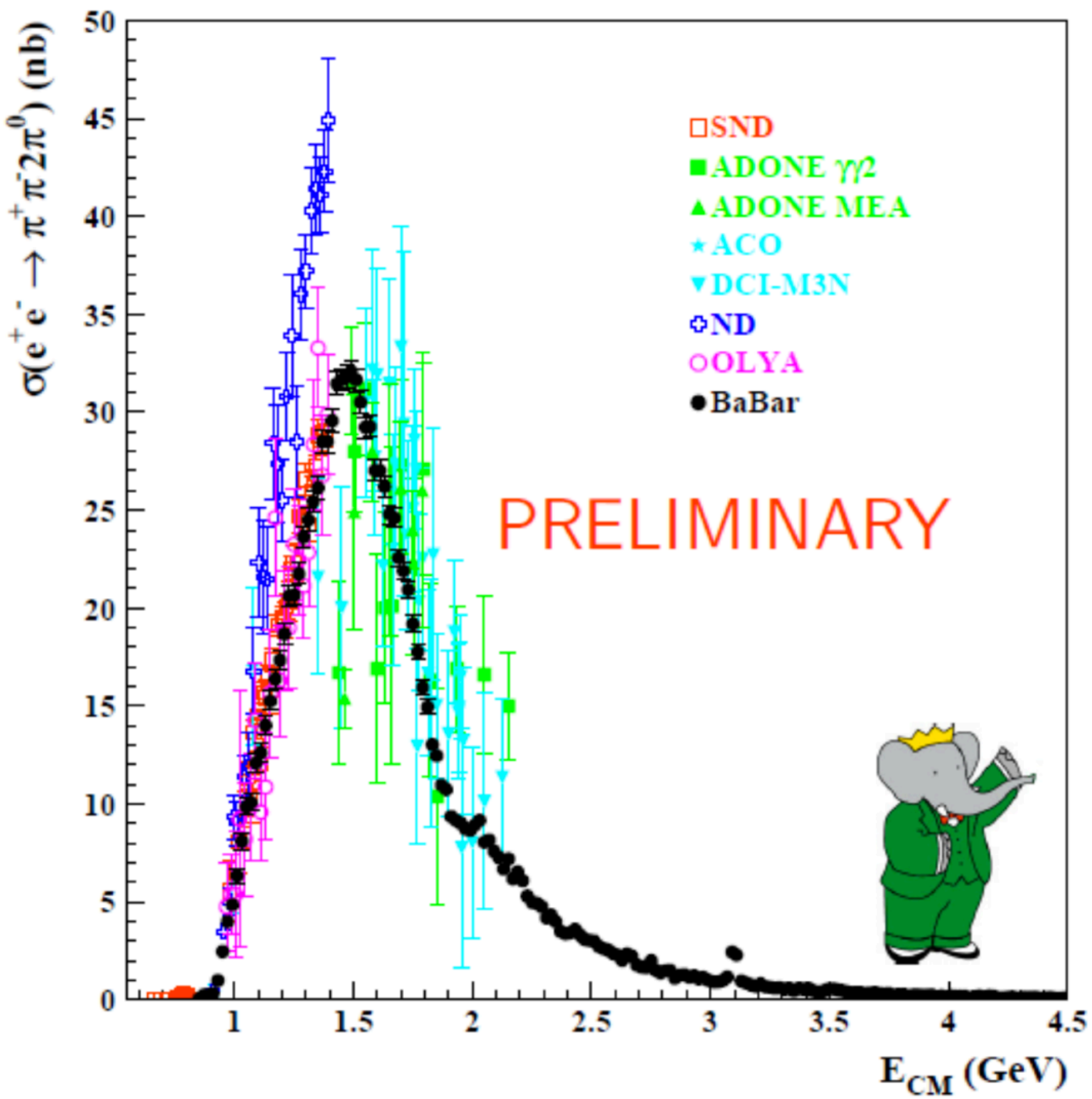
K.Hagiwara et al., arXiv:1105.3149 [hep-ph] (2011)

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)	$-0.03 \pm 0.01 \pm 0.02 \pm 0.00$
$\phi\eta$	$0.36 \pm 0.02 \pm 0.02 \pm 0.01$
$\omega K\bar{K}$ ($\omega \to \pi^0\gamma$)	$0.00 \pm 0.00 \pm 0.00 \pm 0.00$

Before the BaBar measurement:

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

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

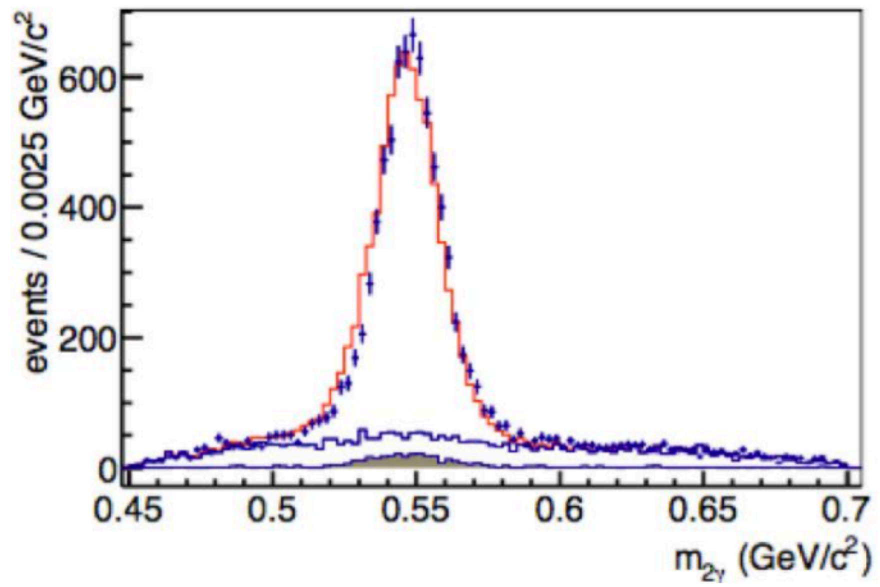


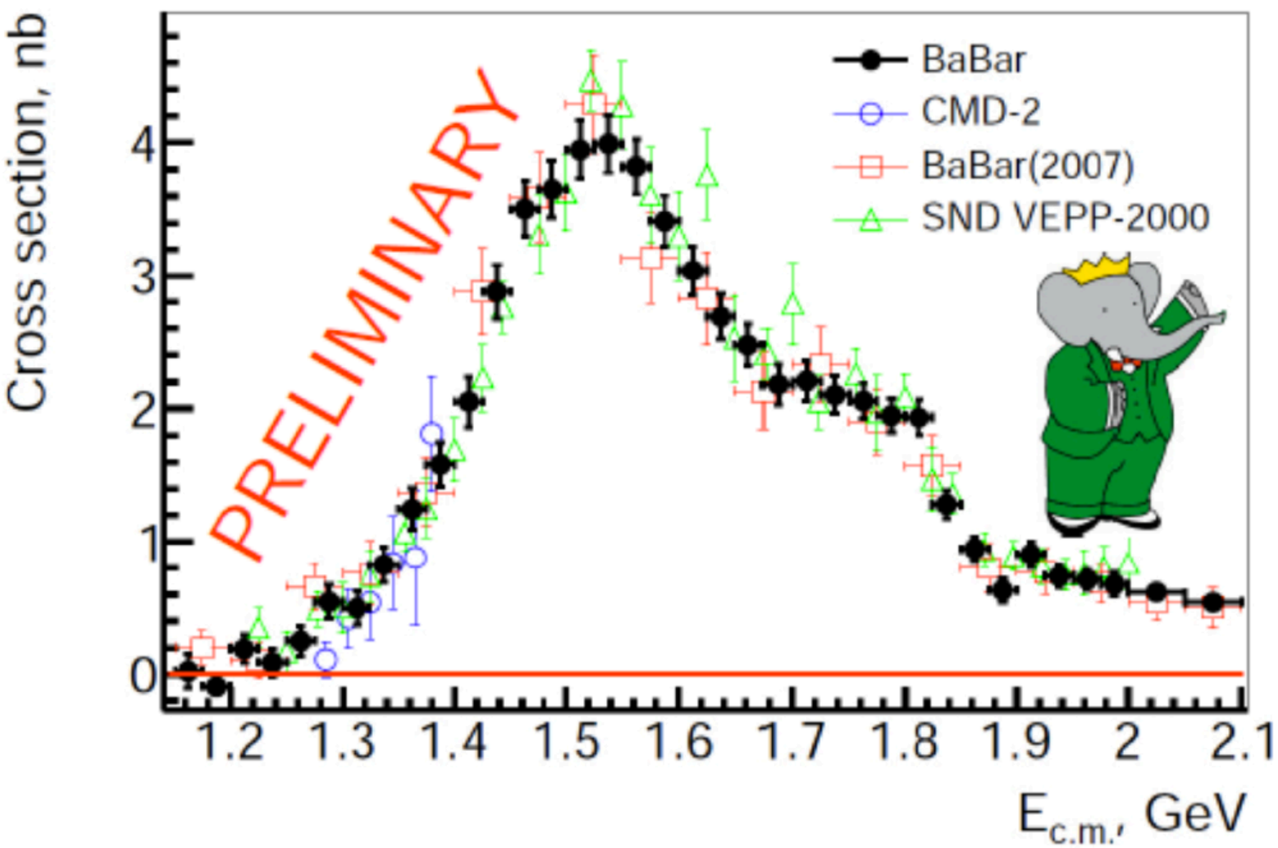
- BaBar measurement:
  - Much more precise
  - Larger energy range
- From 0.85 to 1.8 GeV:
  - Relative precision 3.3%
  - Improved by factor 2.5

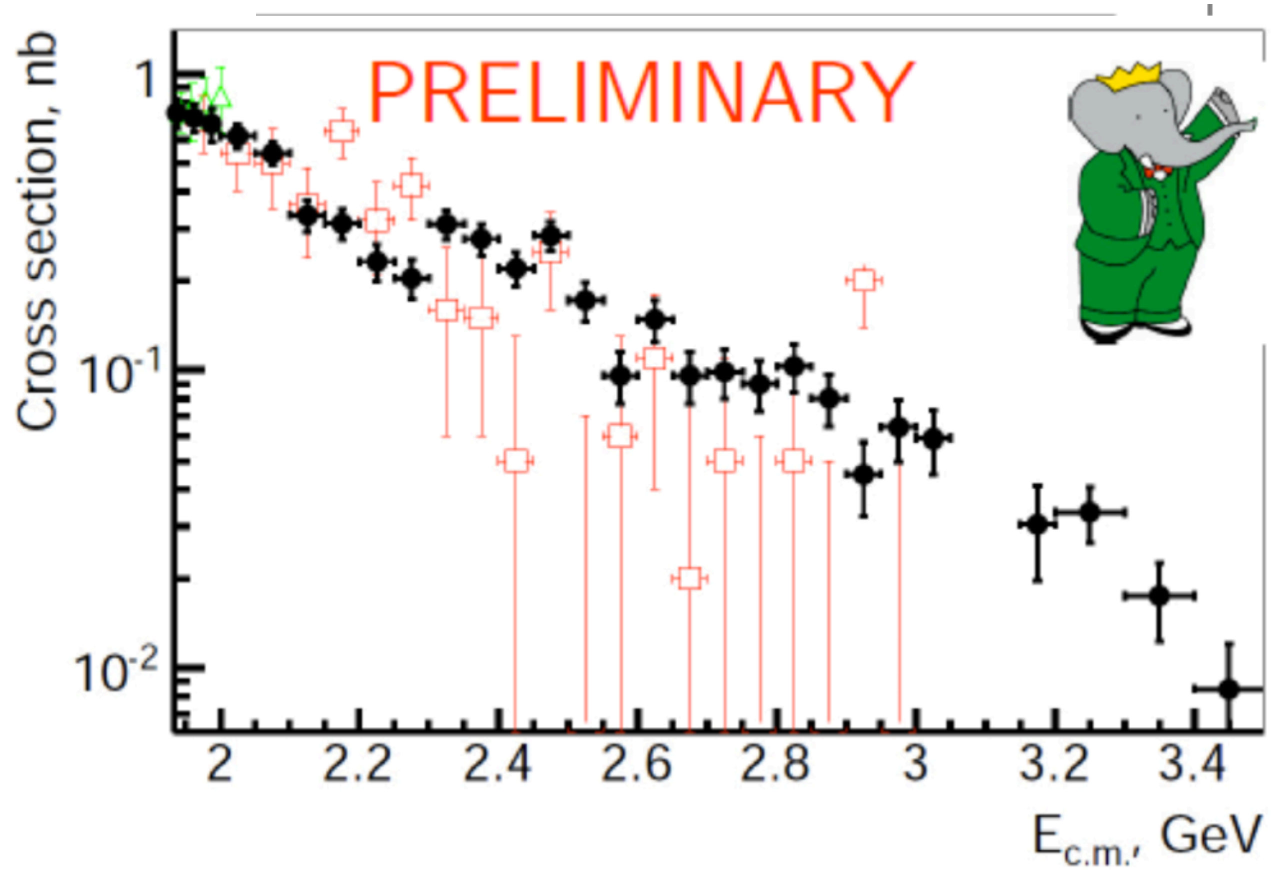
$$a_\mu(\pi^+\pi^-2\pi^0) = (17.9 \pm 0.1 \pm 0.6)\ 10^{-10}$$

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

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



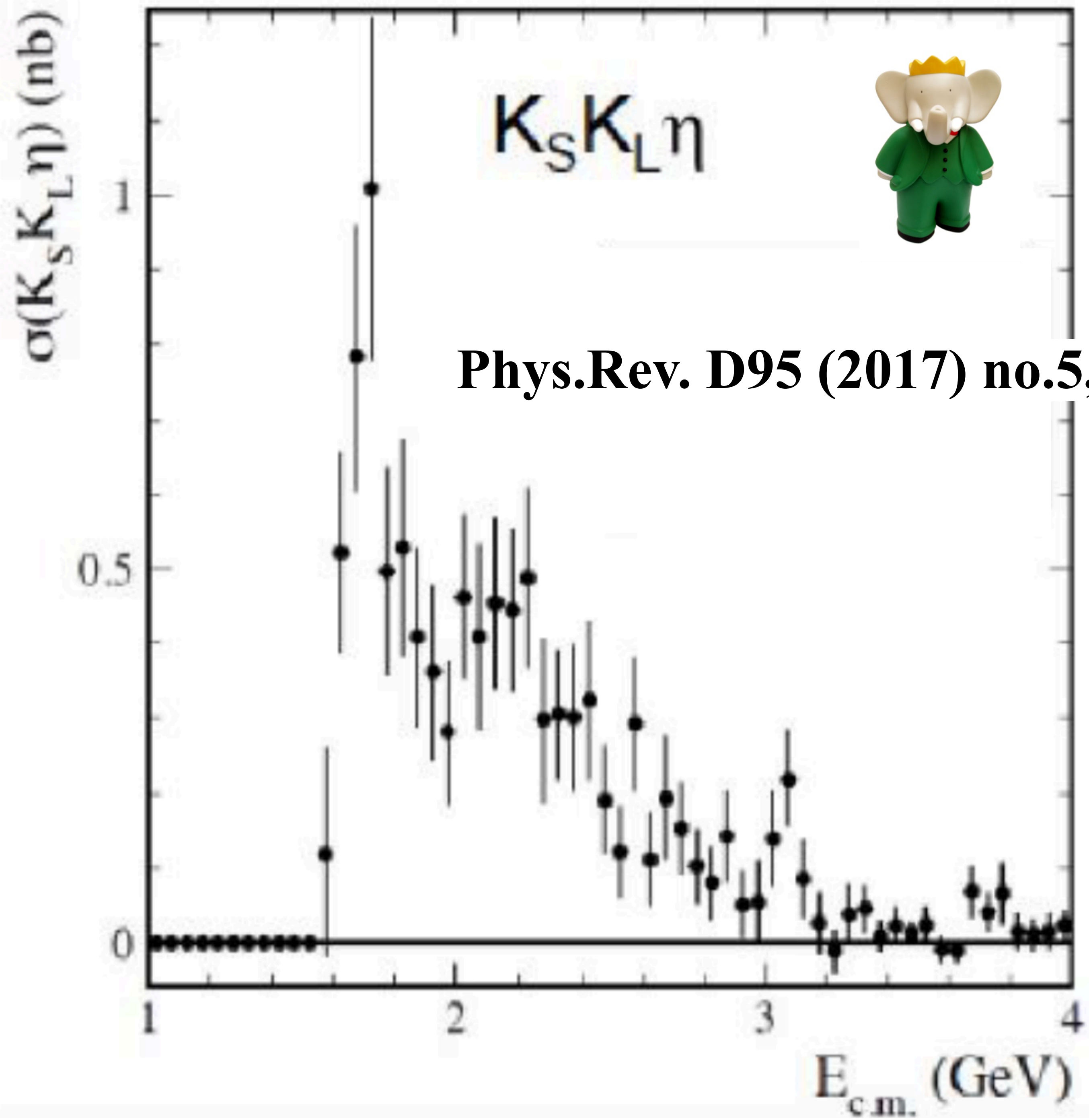




Systematic uncertainty is (4.5-12)%

Process $K_L K_S \eta$

First measurement of this cross section

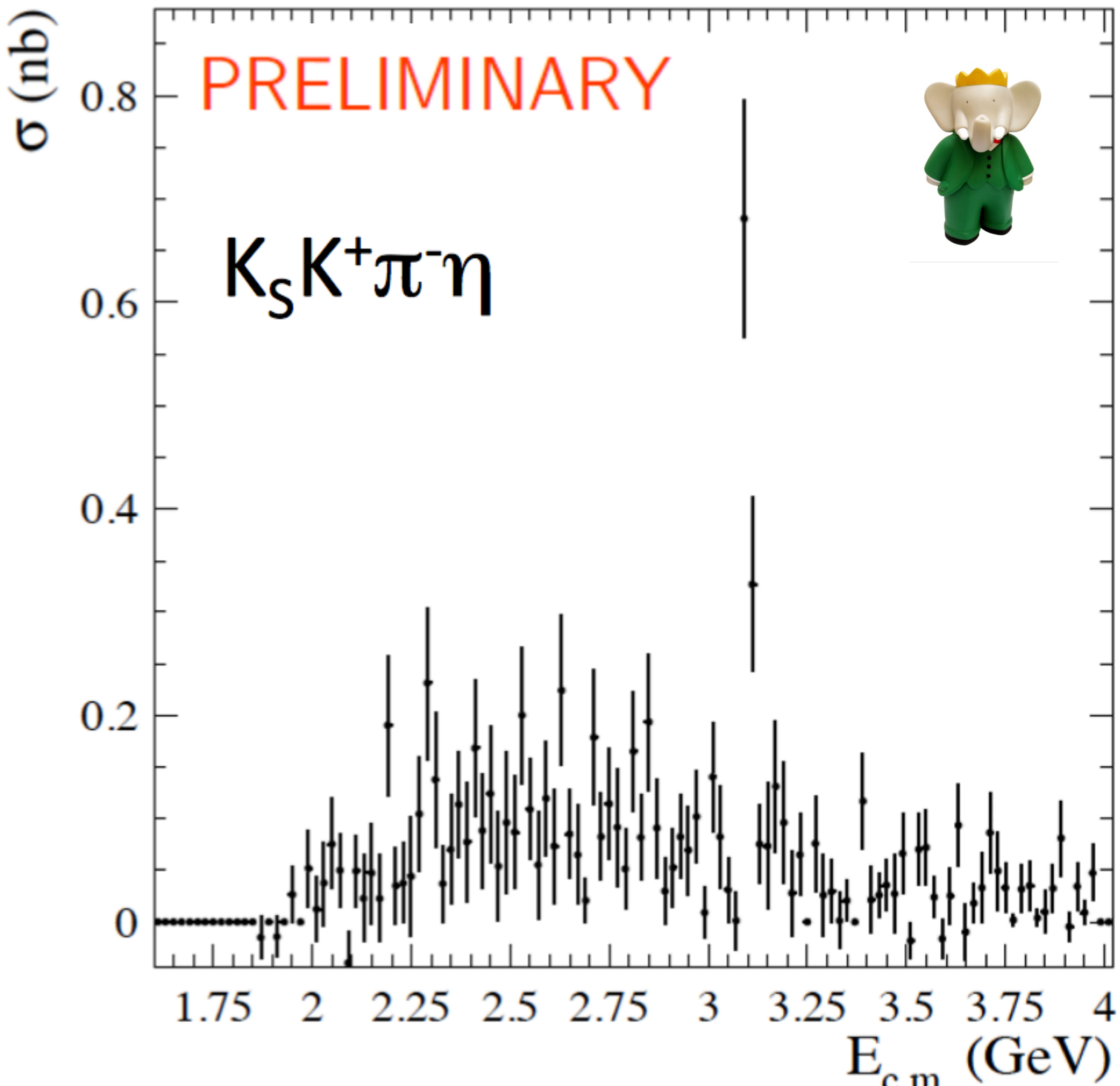


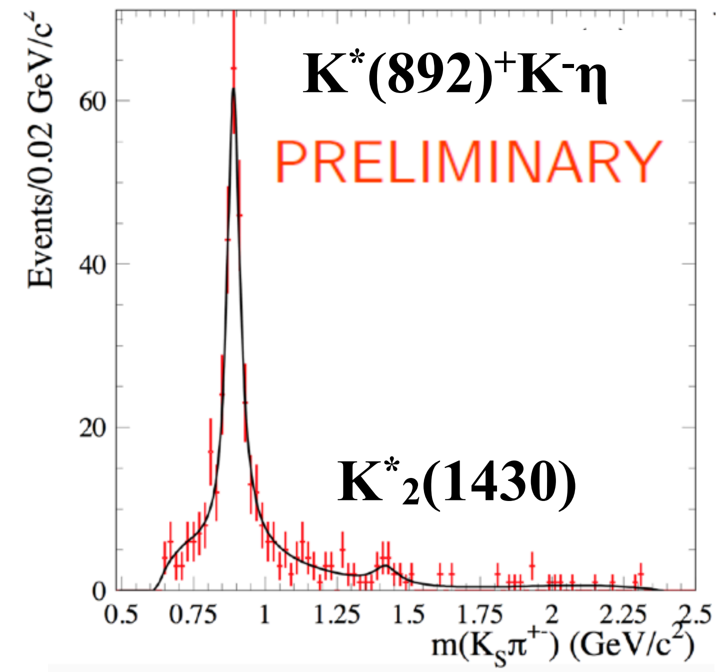
Phys.Rev. D95 (2017) no.5, 052001

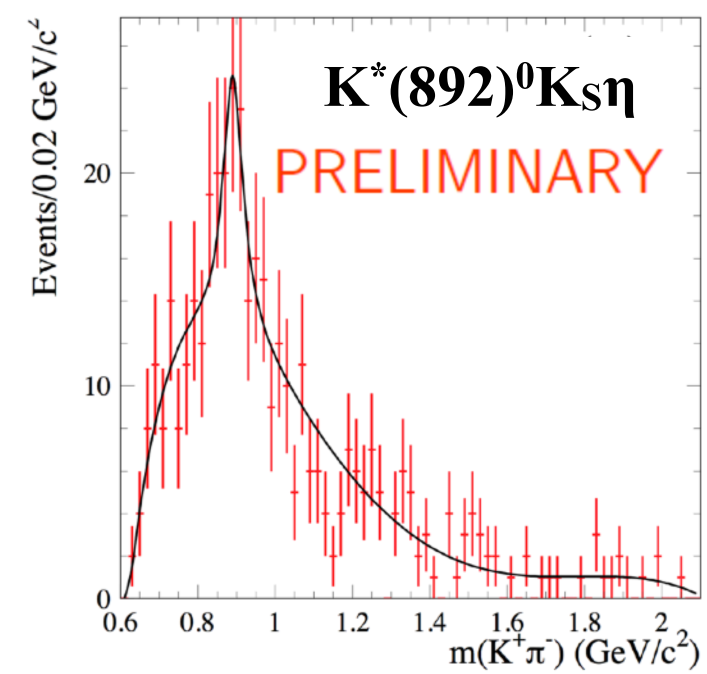
Systematic uncertainty is (15-100)%

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

First measurement of this cross section





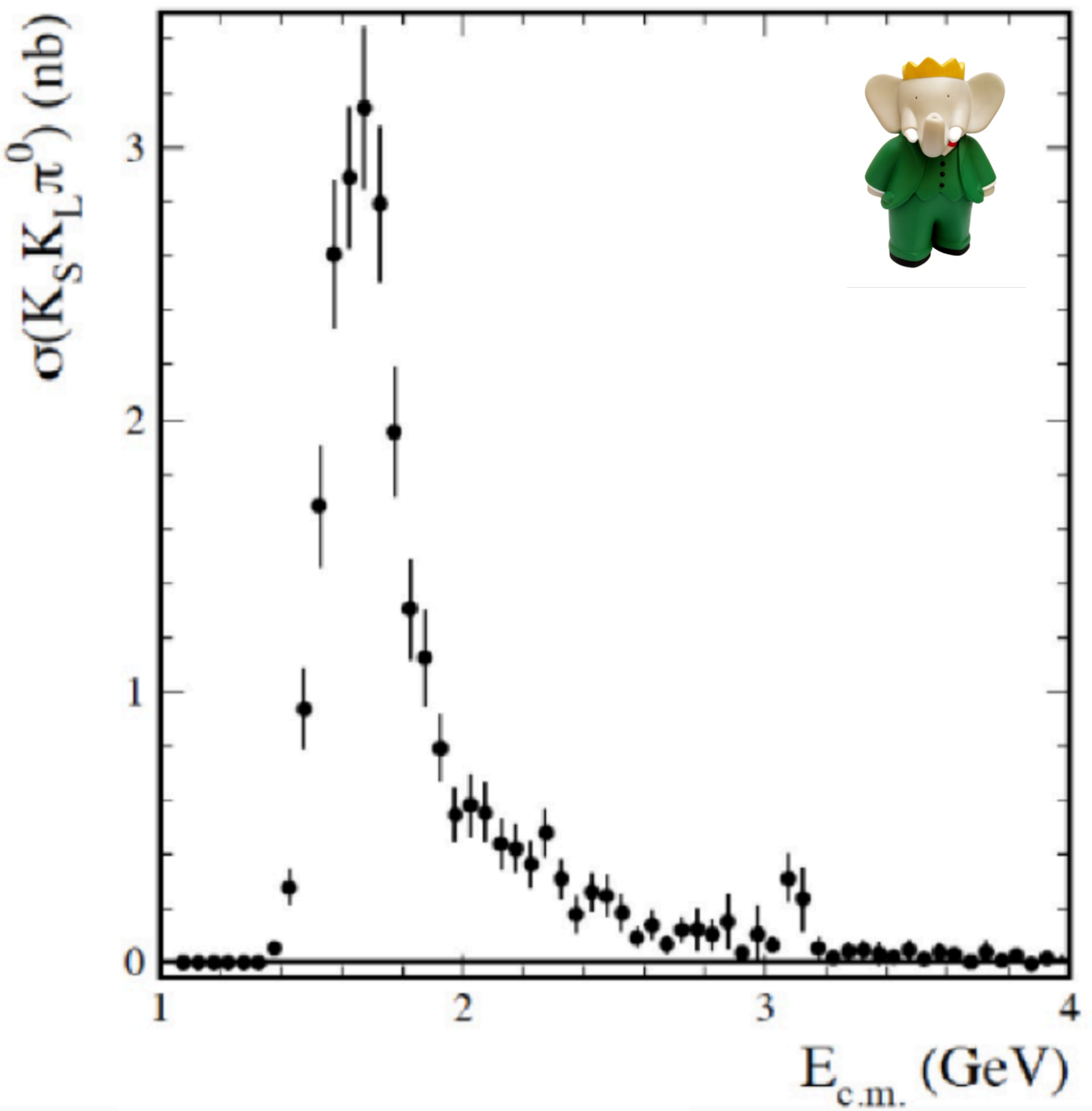


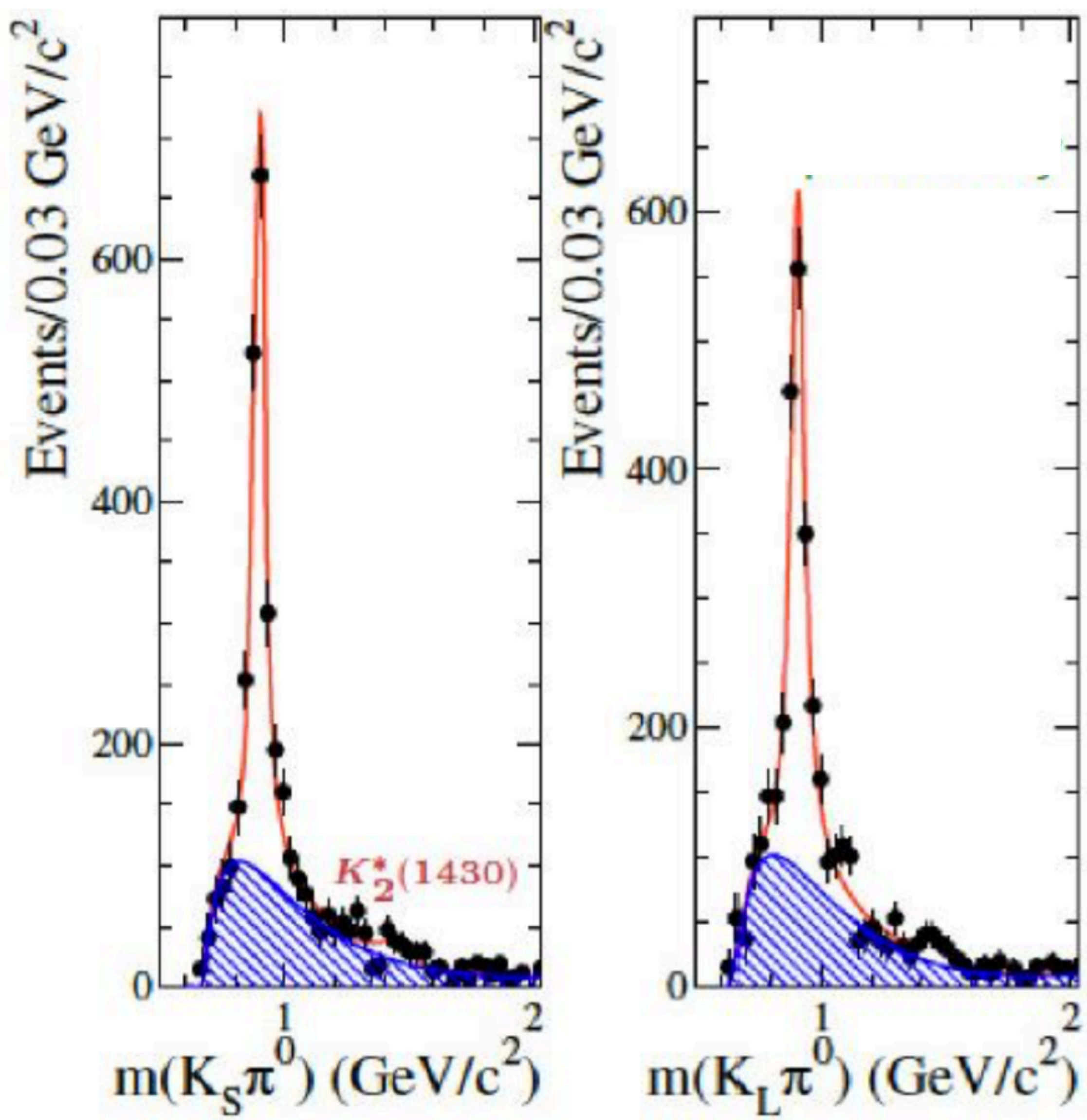
Systematic uncertainty is (12-19)%

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)%

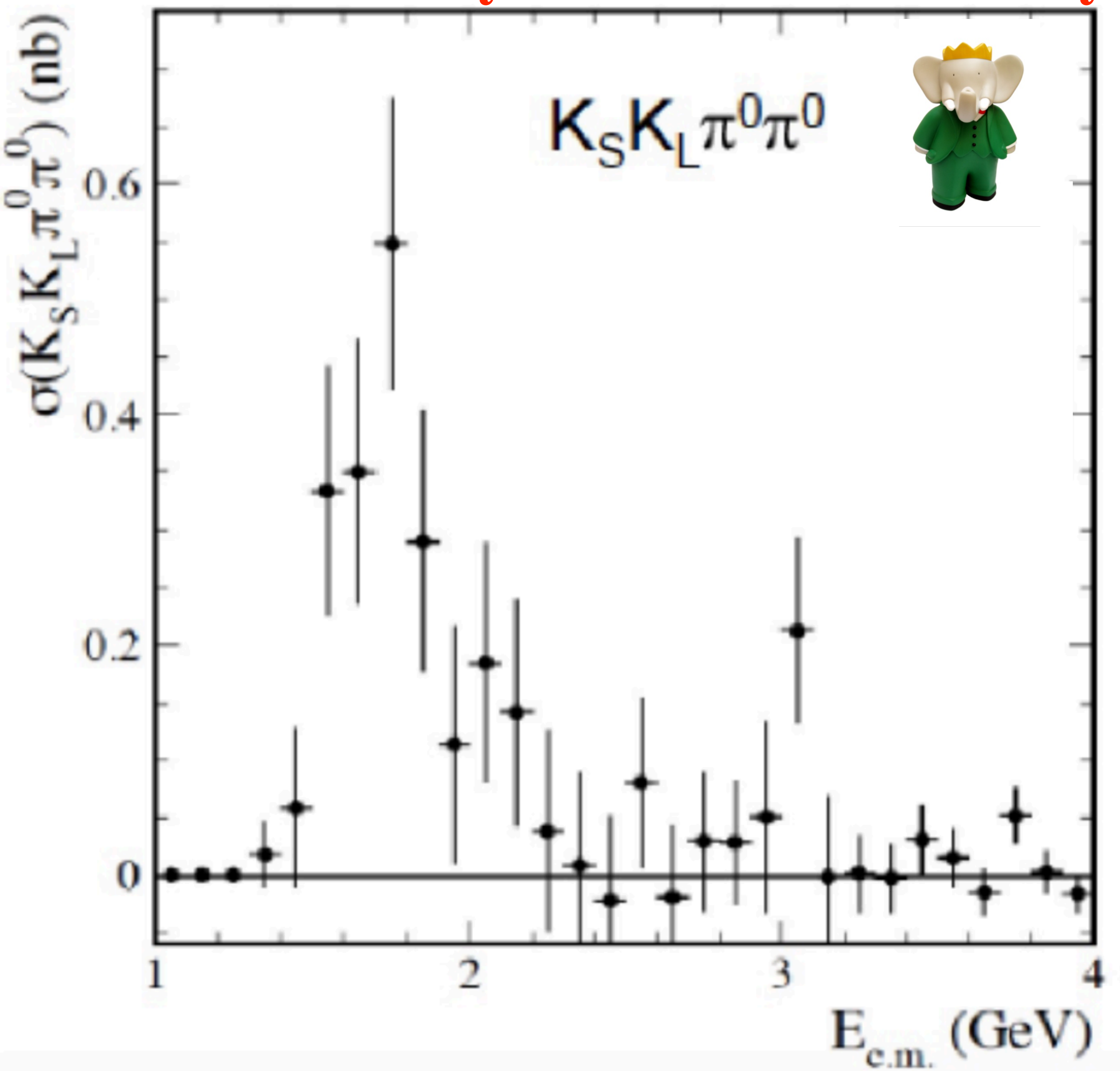
Dominant $K^*(892)^0\overline{K}^0$

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

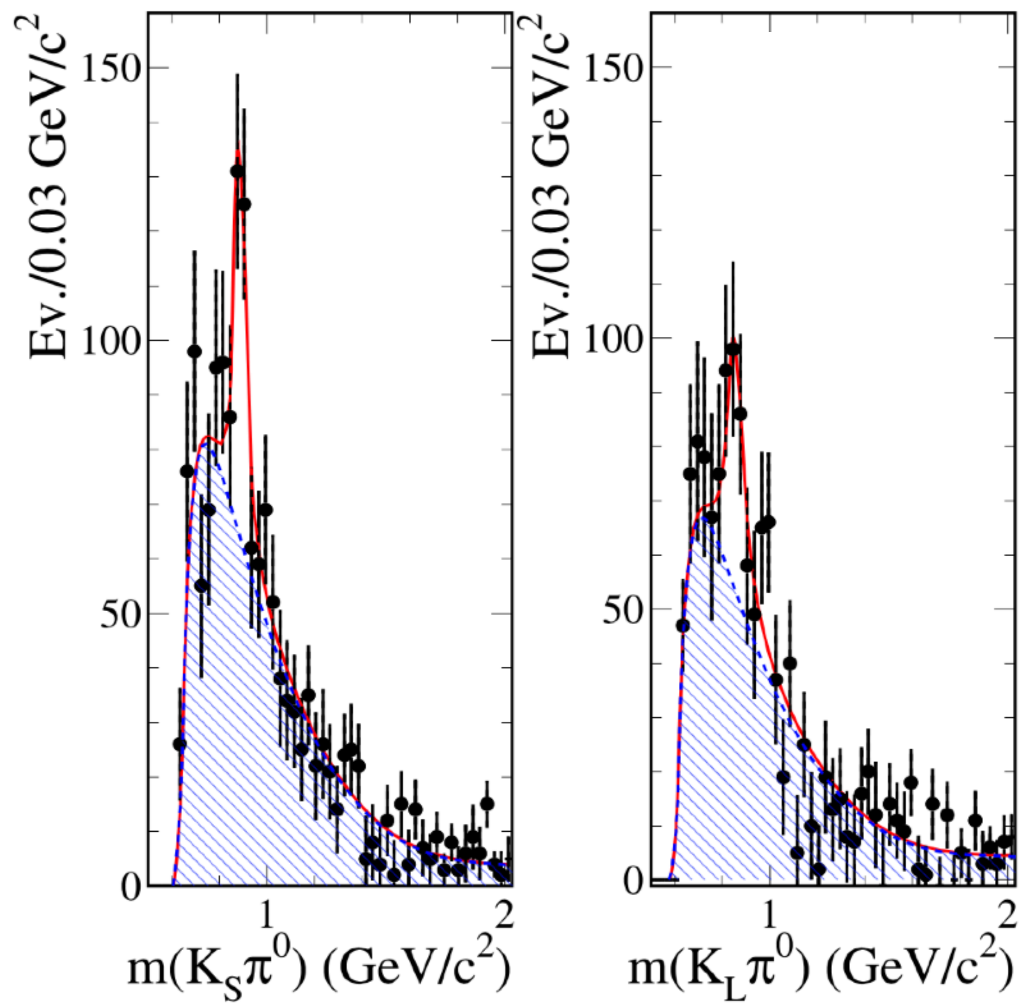
Process $K_L K_S \pi^0 \pi^0$

First measurement of this cross section

Systematic uncertainty is (25-100)%

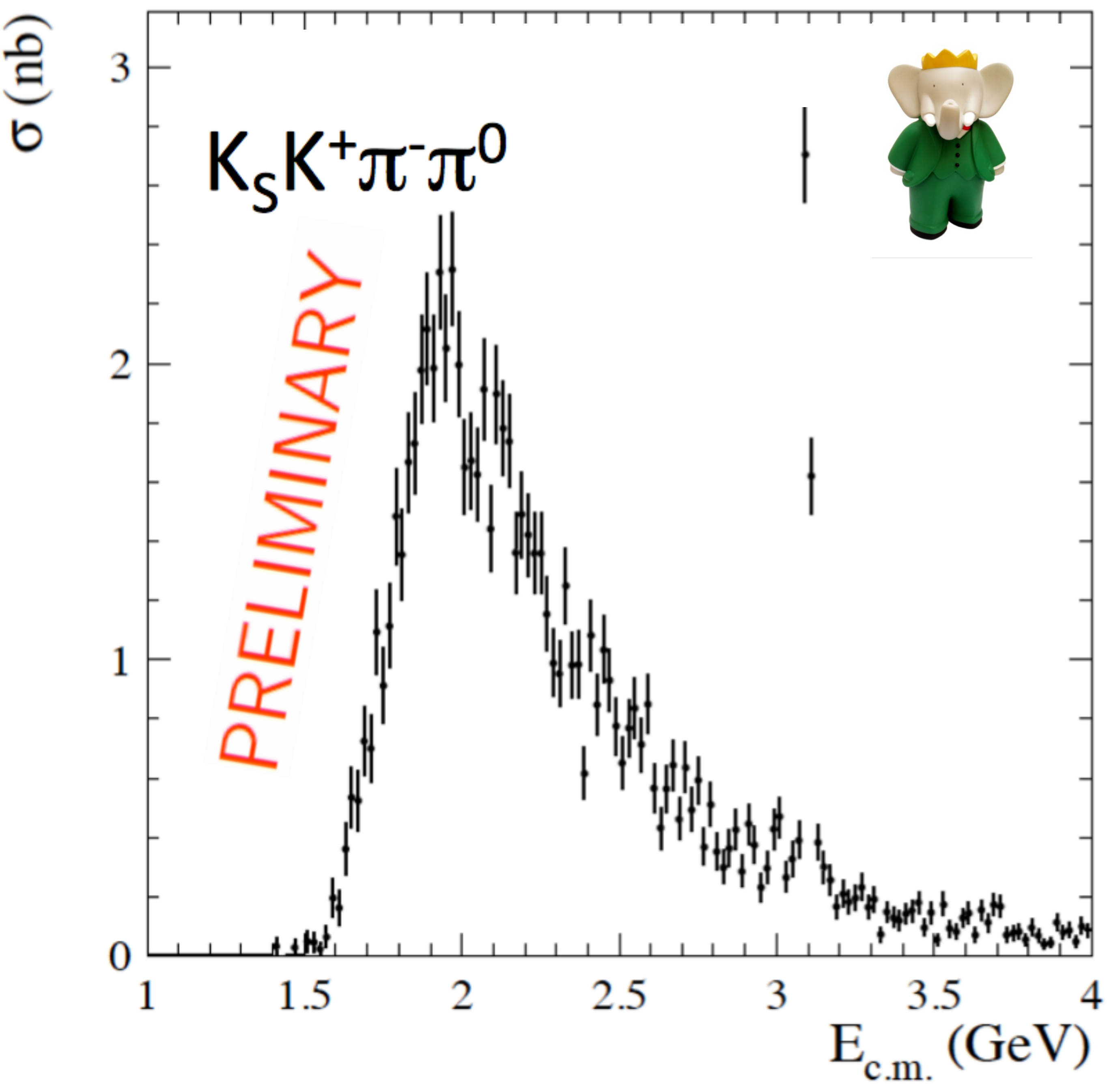


Phys.Rev. D95 (2017) no.5, 052001



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

First measurement of this cross section

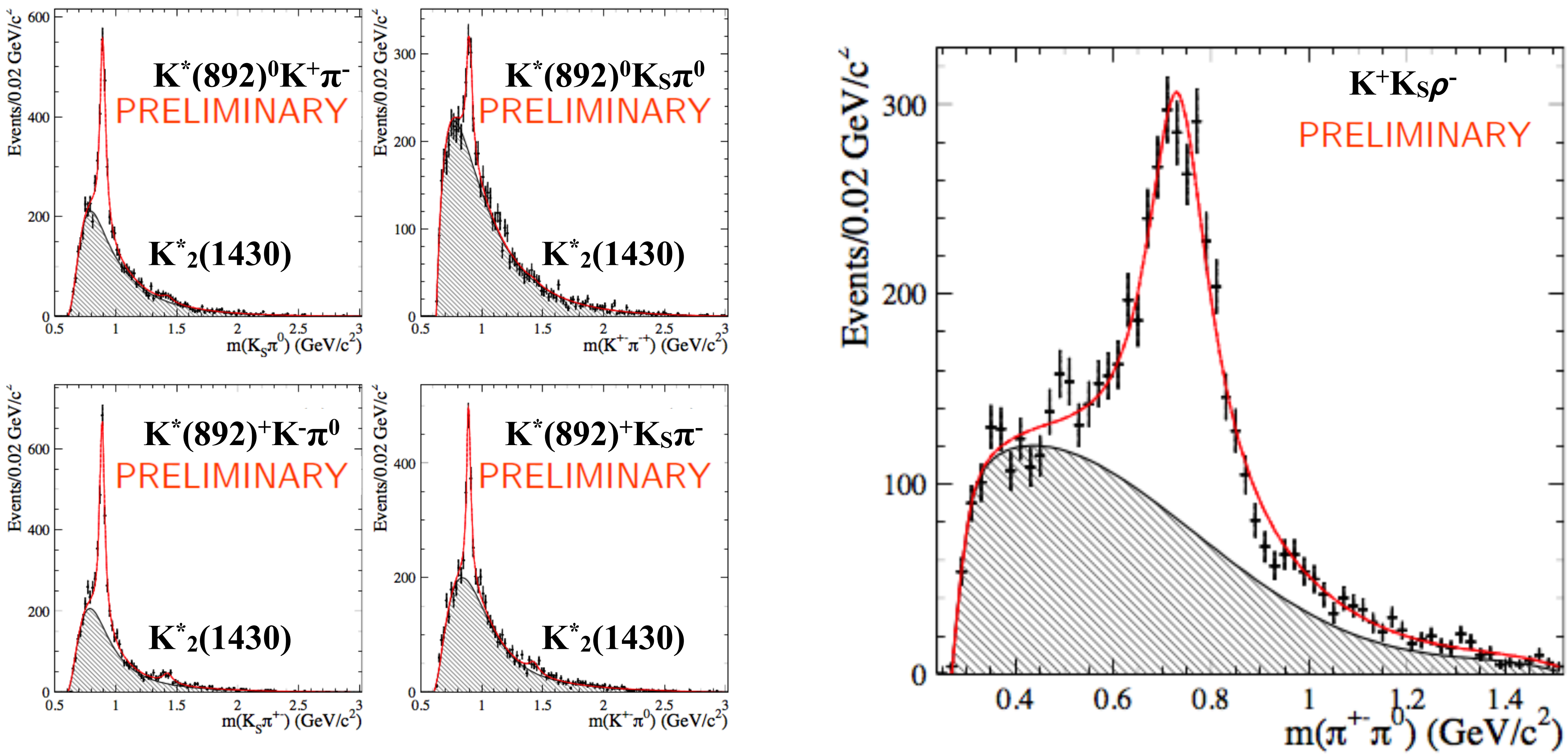


More than 10 intermediate states

Intermediate state
$K^{*0} K^0_S \pi^0$
$K^{*0} K^{\pm} \pi^{\mp}$
$K_2^*(1430)^0 K^0_S \pi^0$
$K_2^*(1430)^0 K^{\pm} \pi^{\mp}$
$K^*(892)^{\pm} K^0_S \pi^{\mp}$
$K^*(892)^{\pm} K^{\mp} \pi^0$
$K_2^*(1430)^{\pm} K^0_S \pi^{\mp}$
$K_2^*(1430)^{\pm} K^{\mp} \pi^0$
$K^{*0} \overline{K}^{*0}$
$K^*(892)^+ K^*(892)^-$
$K^0_S K^{\pm} \rho(770)^{\mp}$

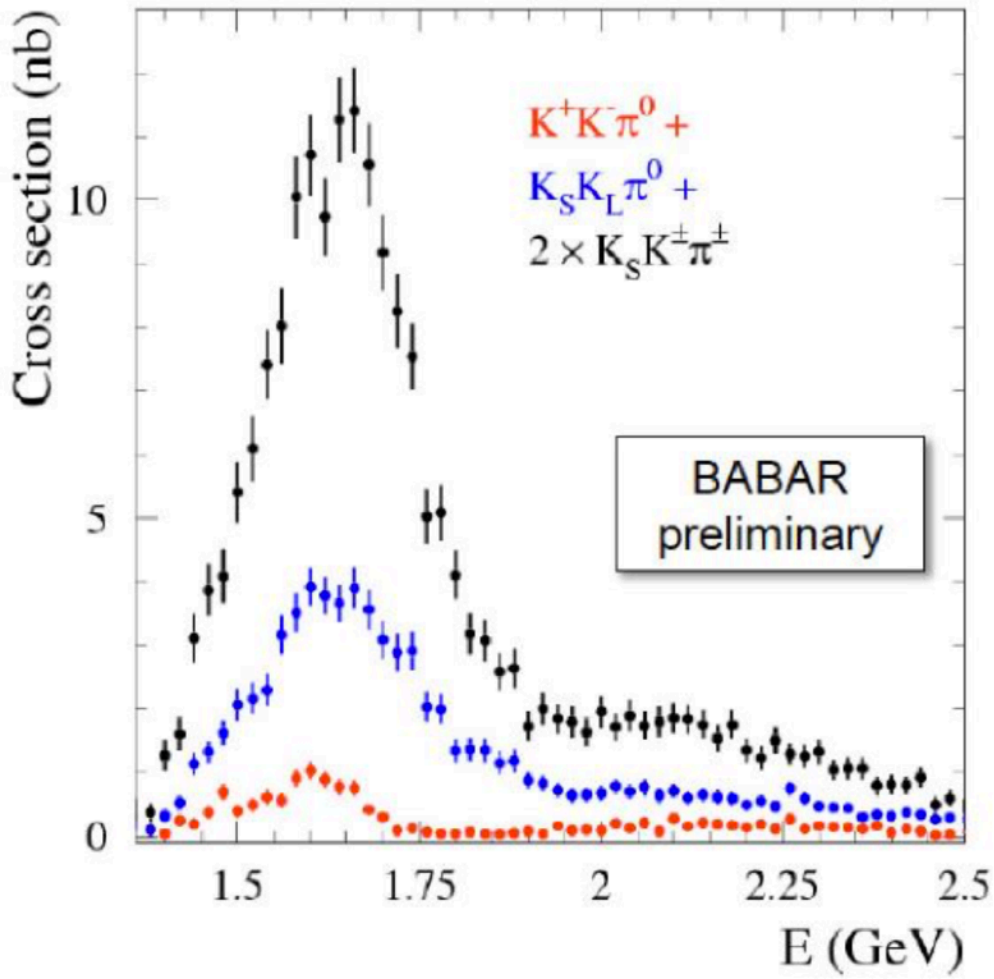
Systematic uncertainty is (6-12)%

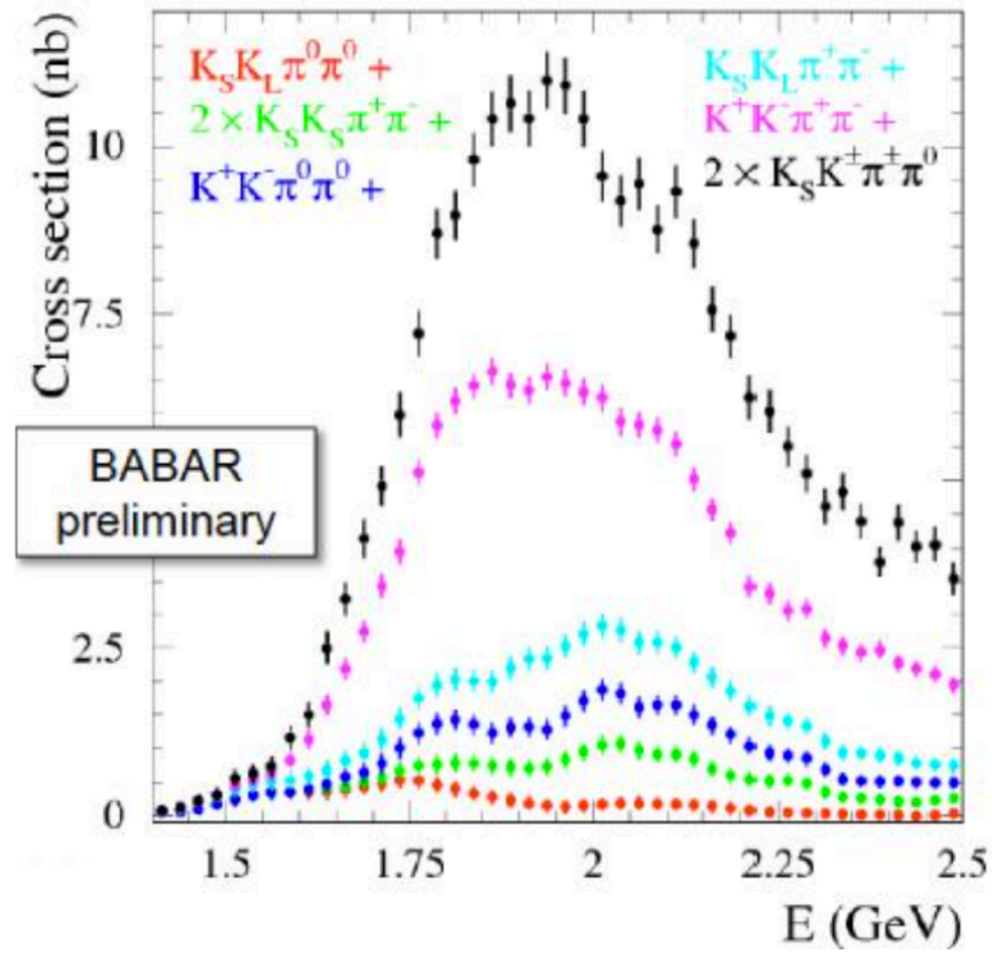
Substructures in $K_S K^{\pm}\pi^{\mp}\pi^0$



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

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:**

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

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

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

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