Recent BaBar results in light hadron spectroscopy

- $e^+e^- \to \pi^+\pi^-\pi^0\pi^0\pi^0$ and $\pi^+\pi^-\pi^0\pi^0\eta$
- $e^+e^- \to \pi^+\pi^-\eta$
- $e^+e^- \to e^+e^-\eta'$

BABAR

Novosibirsk State University
*THE REAL SCIENCE

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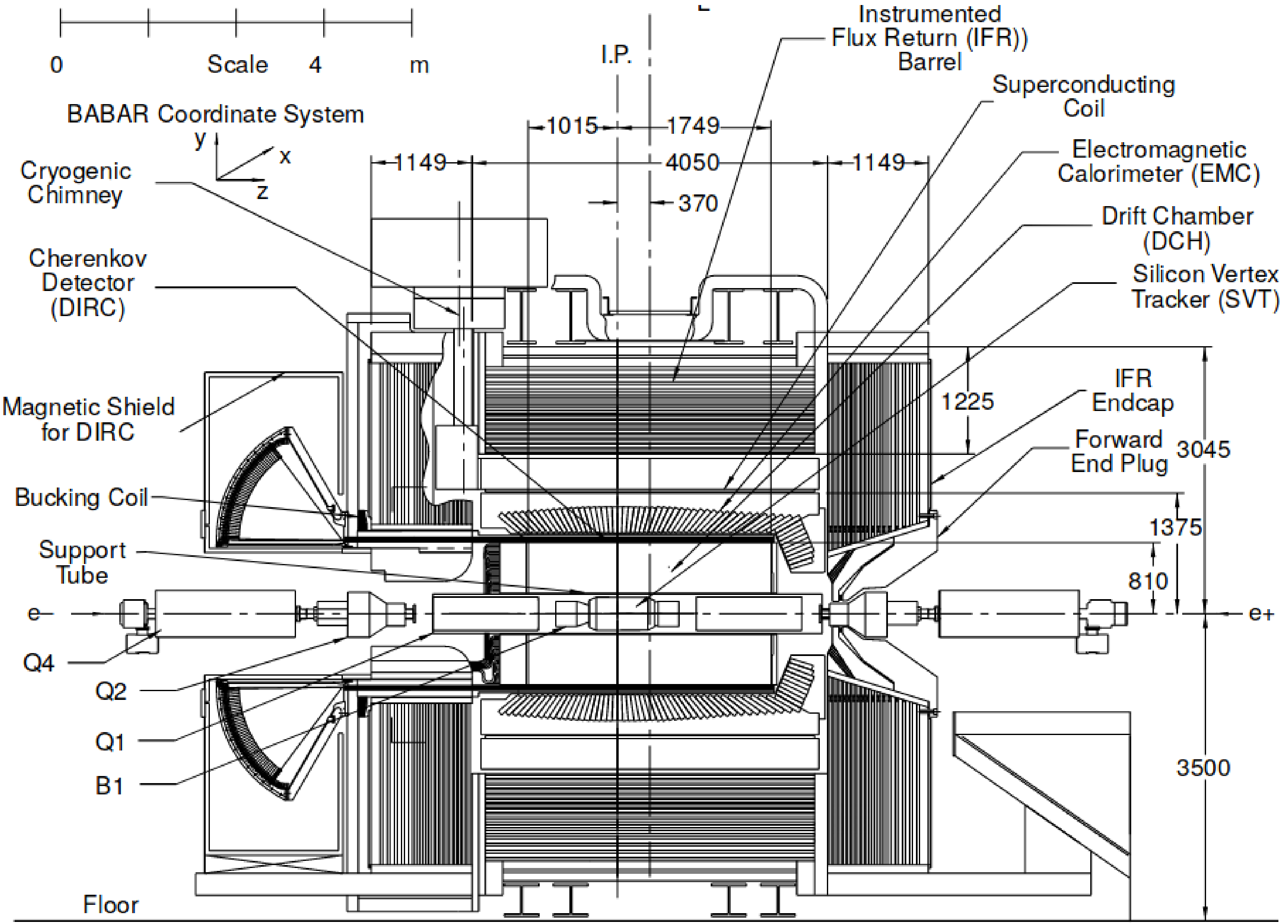
February 27, 2019

BABAR detector at center-of mass energy of 10.6 GeV at the e^+e^- collider PEP-II at SLAC

L = 468.6 fb^{-1}

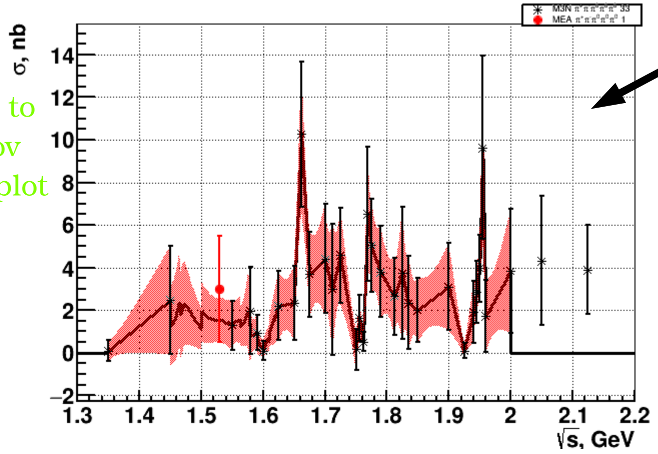


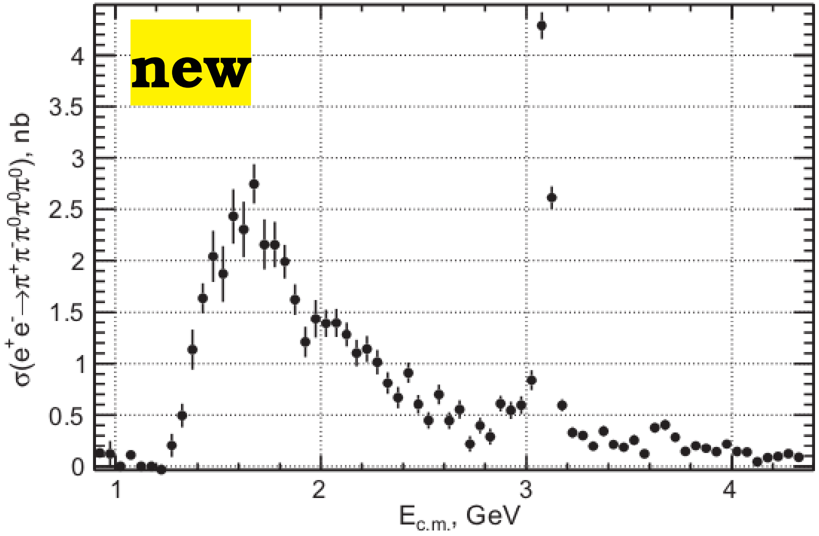
$e^+e^-\to\pi^+\pi^-\pi^0\pi^0\pi^0$

PHYSICAL REVIEW D 98, 112015 (2018)

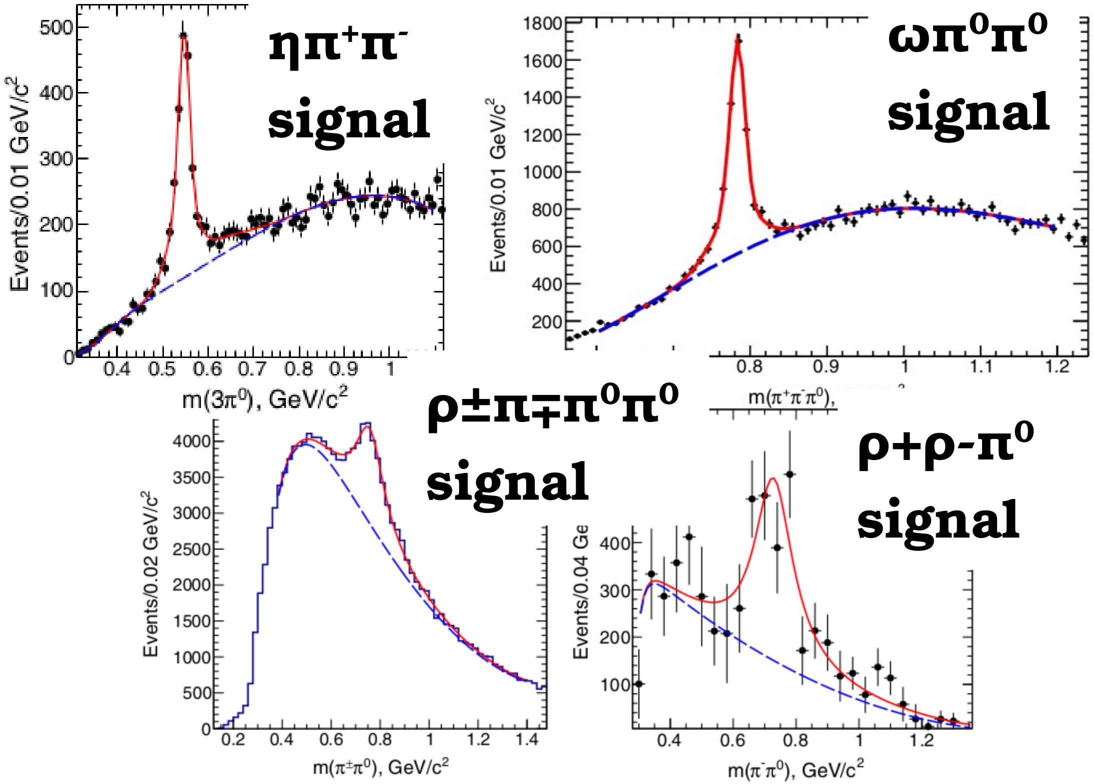
$\sigma(e^+e^-\to\pi^+\pi^-\pi^0\pi^0\pi^0)$

Thanks to F.Ignatov for the plot



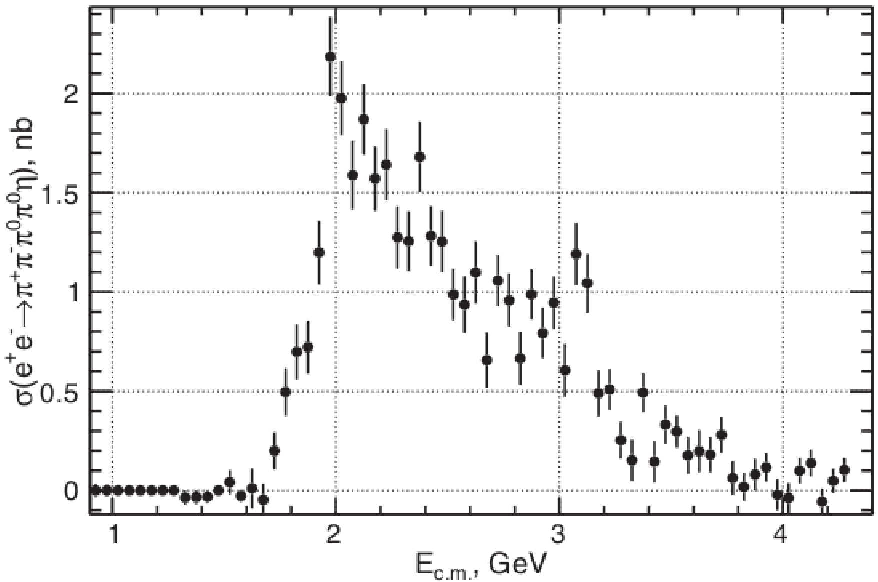


- Previous measurements (M3N, MEA) with very limited precision

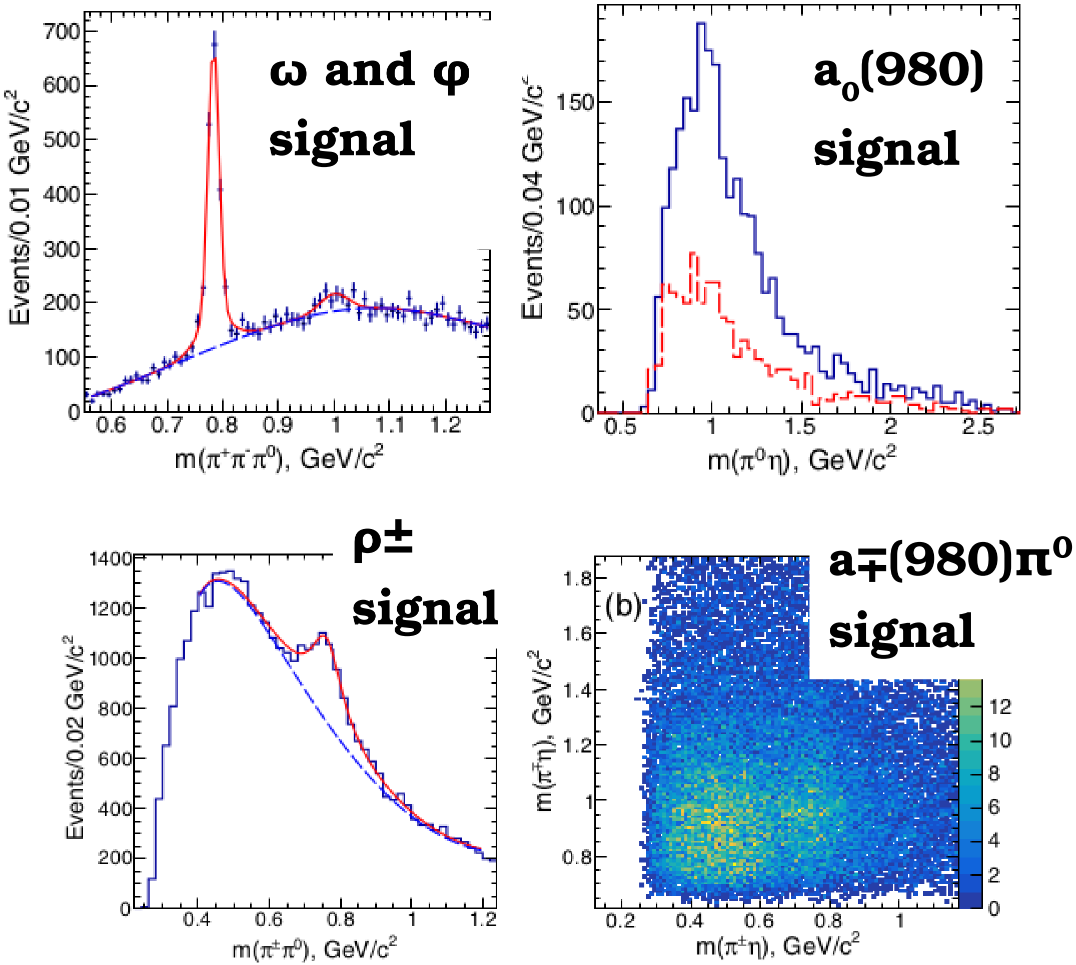


- The systematic uncertainty is typically between 10% and 13%.

$\sigma(e^+e^- \to \pi^+\pi^-\pi^0\pi^0\eta)$



- Measured for the first time
- The systematic uncertainty is typically between 10% and 13%.



$\rho^\pm\rho^\mp\pi^0$ and $\eta(1285)\pi^-\pi^+$ are also seen

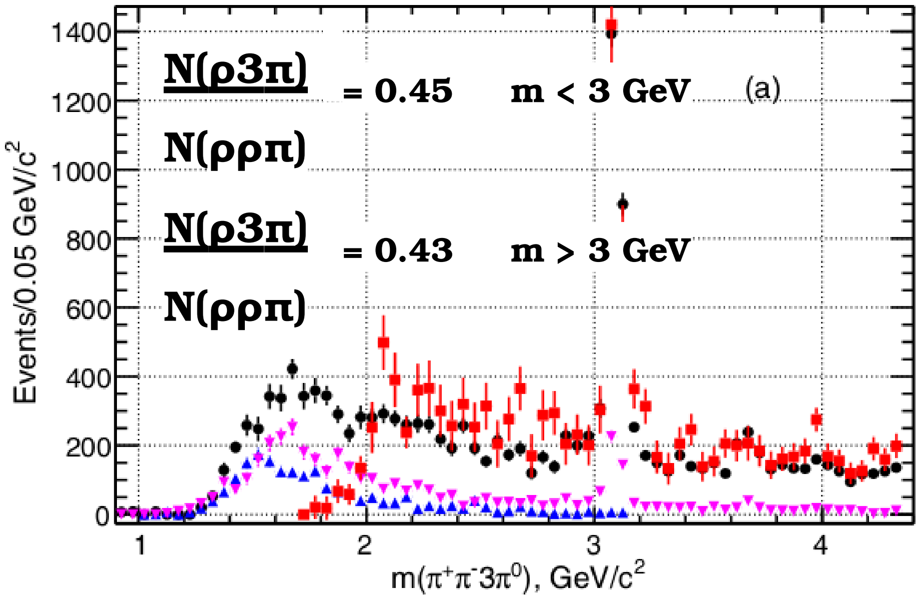
$e^+e^- \to \pi^+\pi^-\pi^0\pi^0\pi^0$

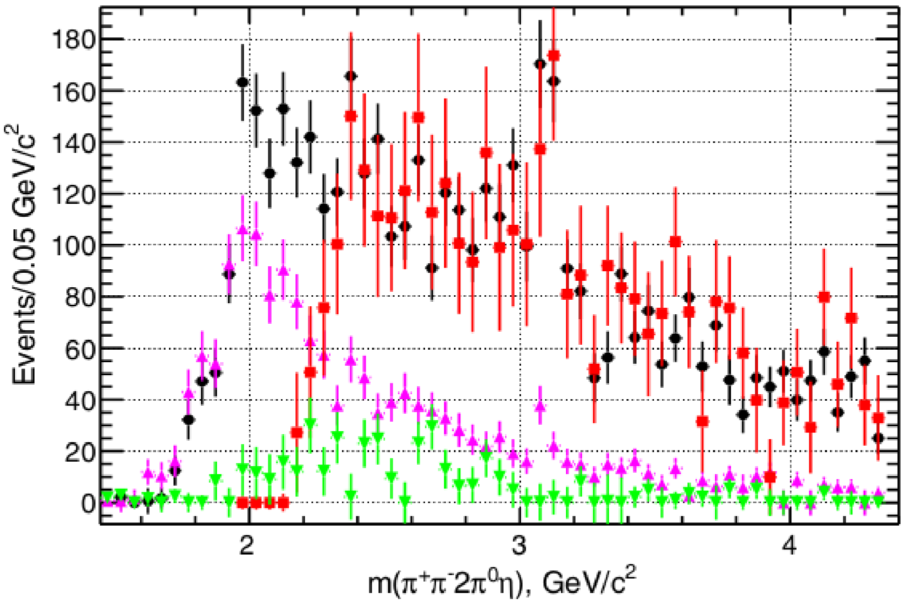
- $\eta(\to\pi^0\pi^0\pi^0)\rho(\to\pi^+\pi^-)$
- $\omega(\to\pi^+\pi^-\pi^0)\pi^0\pi^0$
- $\rho^\pm(\to\pi^\pm\pi^0)\pi^\mp\pi^0\pi^0$
- $\rho^\pm(\to\pi^\pm\pi^0)\rho^\mp(\to\pi^\mp\pi^0)\pi^0$

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

- $\omega(\to\pi^+\pi^-\pi^0)\pi^0\eta$
- $\varphi(\to\pi^+\pi^-\pi^0)\pi^0\eta$
- $\rho^\pm(\to\pi^\pm\pi^0)\pi^\mp\pi^0\eta$
- $\rho^\pm(\to\pi^\pm\pi^0)\rho^\mp(\to\pi^\mp\pi^0)\eta$

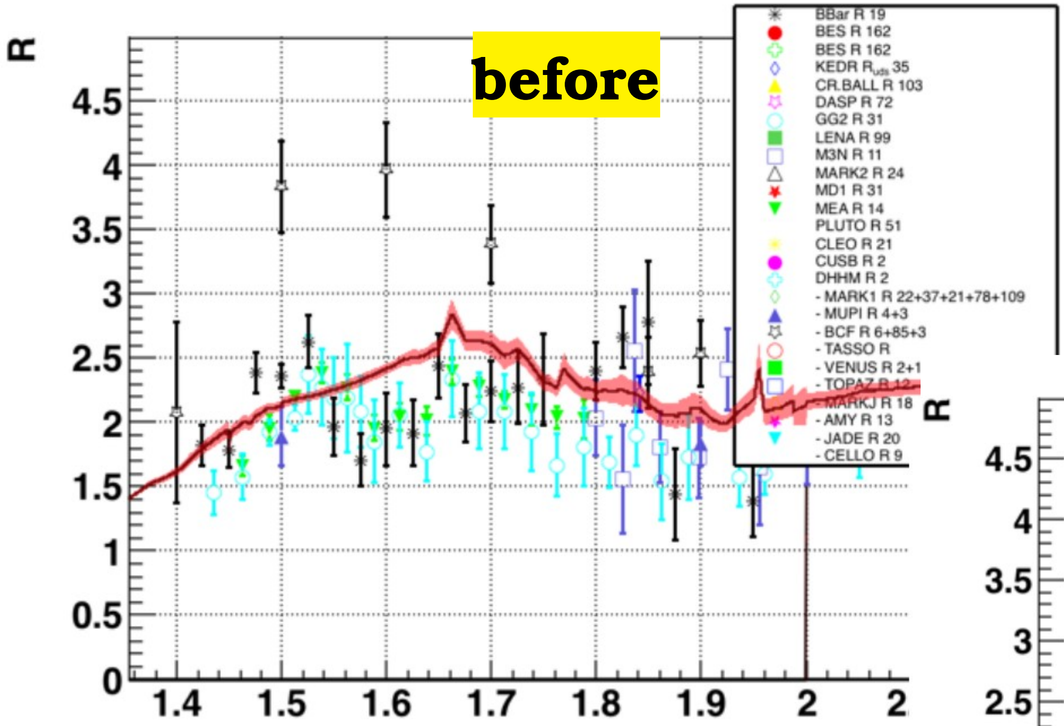
a(980) meson is seen in πη





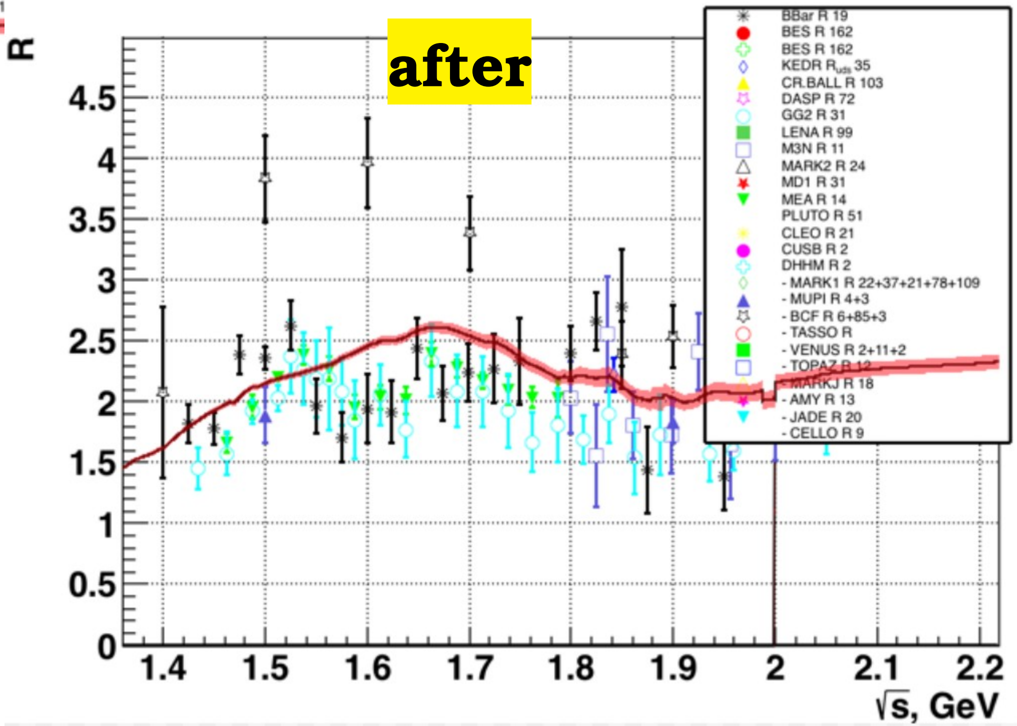
R value before and after this measurement

PHYSICAL REVIEW D 98, 112015 (2018)

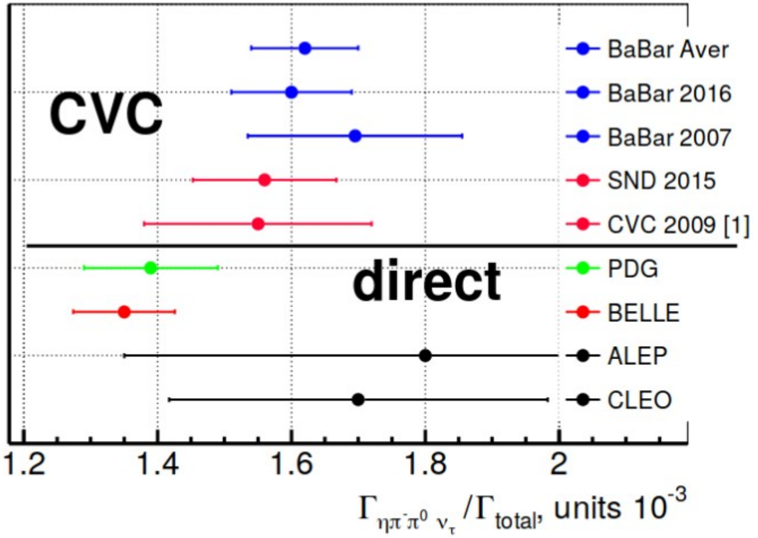


Line with error band – sum of exclusive channels

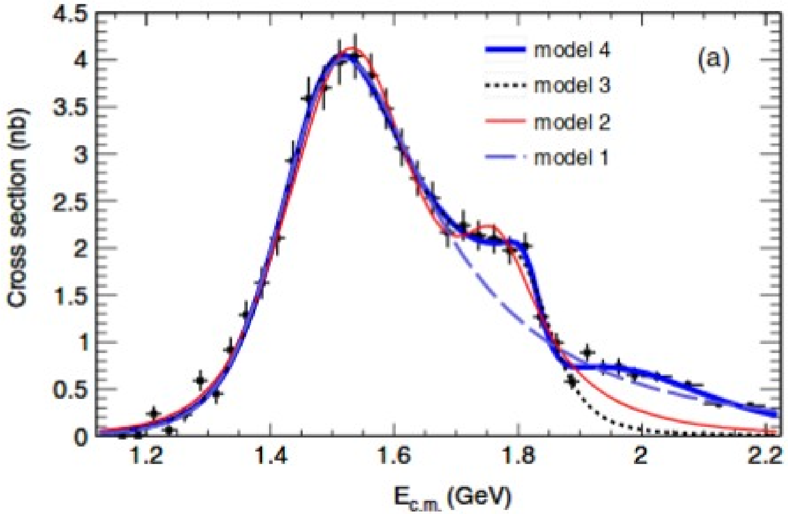
Points – inclusive measurements

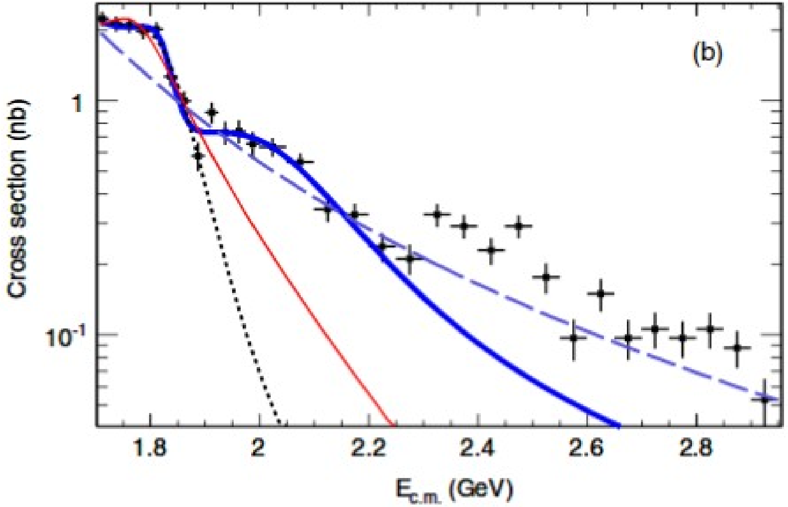


Thanks to F.Ignatov for these plots

- Systematic uncertainty ~ 5%
- $$\Gamma(\rho(1450) \to e^+e^-)\mathcal{B}(\rho(1450) \to \eta\pi^+\pi^-) = (210 \pm 24_{\mathrm{stat}} \pm 10_{\mathrm{syst}})\ \mathrm{eV}$$
$$\Gamma(\rho(1700) \to e^+e^-)\mathcal{B}(\rho(1700) \to \eta\pi^+\pi^-) = (84 \pm 26_{\mathrm{stat}} \pm 4_{\mathrm{syst}})\ \mathrm{eV}$$
- 

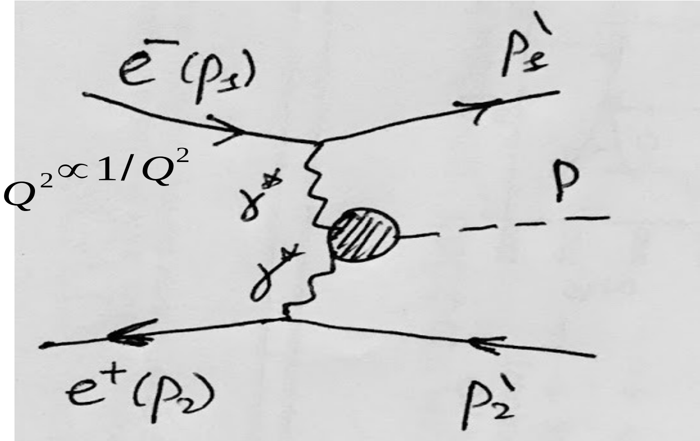
- BaBar and SND results with $\eta\to3\pi^0$ are not presented here





Transition form factor (TFF) of η'.

$$\frac{dn_\gamma}{dQ^2} \propto 1/Q^2$$



P — pseudoscalar meson

$e_{1,2}$ — photon polarization

$q_{1,2}$ — 4-momentum of photon

$-Q^2 = q^2$

	VMD	pQCD
$Q_1^2 \approx 0,\ Q_2^2 \to \infty$	$1/Q^2$	$1/Q^2$
$Q_1^2,\ Q_2^2 \to \infty$	$1/Q^4$	$1/Q^2$

The amplitude of the γ*γ*→P transition:

$$A = e^2 \varepsilon_{\mu\nu\alpha\beta} e_1^\mu e_2^\nu q_1^\alpha q_2^\beta F(q_1^2, q_2^2),$$

- There are a lot of experimental study of pseudoscalar meson production via the fusion of real (**on-shell**) and virtual (**off-shell**) photons

$\gamma^*\gamma \to$ P: π^0, η, η', η_c

- There is the first measurement of the double **off-shell** transition

$\gamma^*\gamma^* \to$ P

Let us see to $\mathbf{F_{\eta'}(q^2, 0)}$ from experimental and theoretical points

Introduction. $F(Q^2_1,Q^2_2)$ at low Q^2.

Phys. Rev. D 98, 112002

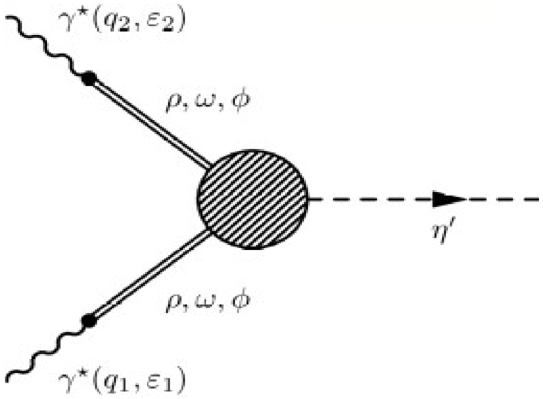
- **η' deacay to real photons:**

$$\Gamma_{\eta'\to 2\gamma} = \frac{\pi\alpha^2 m_{\eta'}^3}{4}|F(0,0)|^2 = 4.30 \pm 0.16\ \text{keV} \quad \Longrightarrow \quad F(0,0) = 0.342 \pm 0.006\ \text{GeV}^{-1}.$$

- The vector meson dominance model is commonly used to describe TFF at low Q^2:

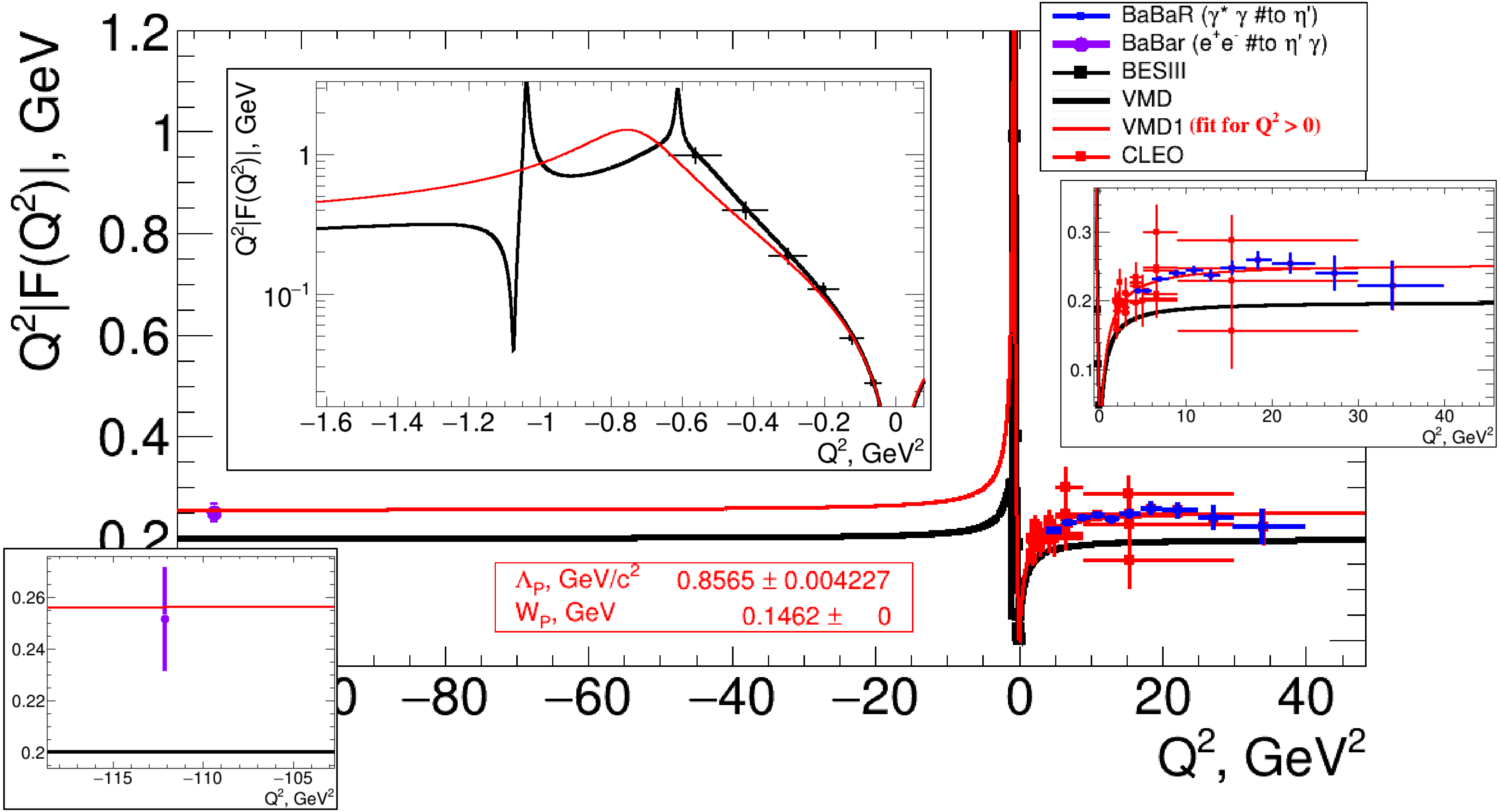
$$F(Q^2) = \frac{\sum_V \frac{f_{PV\gamma}}{f_V} \cdot \frac{m_V^2}{m_V^2 - q^2 - i W_V m_V} \cdot F(0)}{\sum_V \frac{f_{PV\gamma}}{f_V}} \quad \Longleftarrow$$

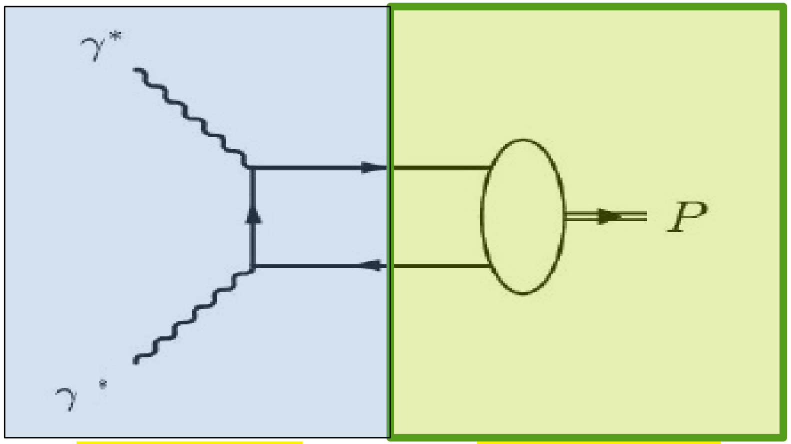
PDG
W(η'→ργ)
W(η'→ωγ)
W(φ→η'γ)
W(φ→ee)
W(ρ→ee)
W(ω→ee)



- In double off-shell case at $Q^2 > W_V m_V$: $F_{\eta'}(Q_1^2,Q_2^2) = \frac{F_{\eta'}(0,0)}{(1+Q_1^2/\Lambda_P^2)(1+Q_2^2/\Lambda_P^2)}$

  where Λ_P — effective pole mass parameter


BaBaR (γ* γ #to η')
BaBar (e+e- #to η' γ)
BESIII
VMD
VMD1 (fit for Q² > 0)
CLEO
Q²|F(Q²)|, GeV
Q², GeV²
Λ_P, GeV/c² 0.8565 ± 0.004227
W_P, GeV 0.1462 ± 0



Hard part *Warm part*

$$F(Q^2{}_1,Q^2{}_2) = \int \boxed{T(x,Q^2{}_1,Q^2{}_2)}\ \boxed{\varphi(x,Q^2{}_1,Q^2{}_2)}\ dx$$

x - is the fraction of the meson momentum carried by one of the quarks

$T(x,Q^2{}_1,Q^2{}_2)$ - hard scattering amplitude for $\gamma^*\gamma^* \to$ qqbar transition which is calculable in pQCD

$\varphi(x,Q^2{}_1,Q^2{}_2)$ - nonperturbative meson distribution amplitude (DA) describing transition P $\to$ qqbar

$$T_H(x,Q_1^2,Q_2^2) = \frac{1}{2}\cdot\frac{1}{xQ_1^2+(1-x)Q_2^2}\cdot\left(1+C_F\frac{\alpha_S(Q^2)}{2\pi}\cdot t(x,Q_1^2,Q_2^2)\right)+(x\to 1-x)+O(\alpha_s^2)+O(\Lambda^4_{QCD}/Q^4)$$

NLO correction [E. Braaten, Phys. Rev. D **28**, 3 (1983)]

- The shape (x dependence) of meson DA **$\varphi(x,Q^2{}_1,Q^2{}_2)$** is unknown.

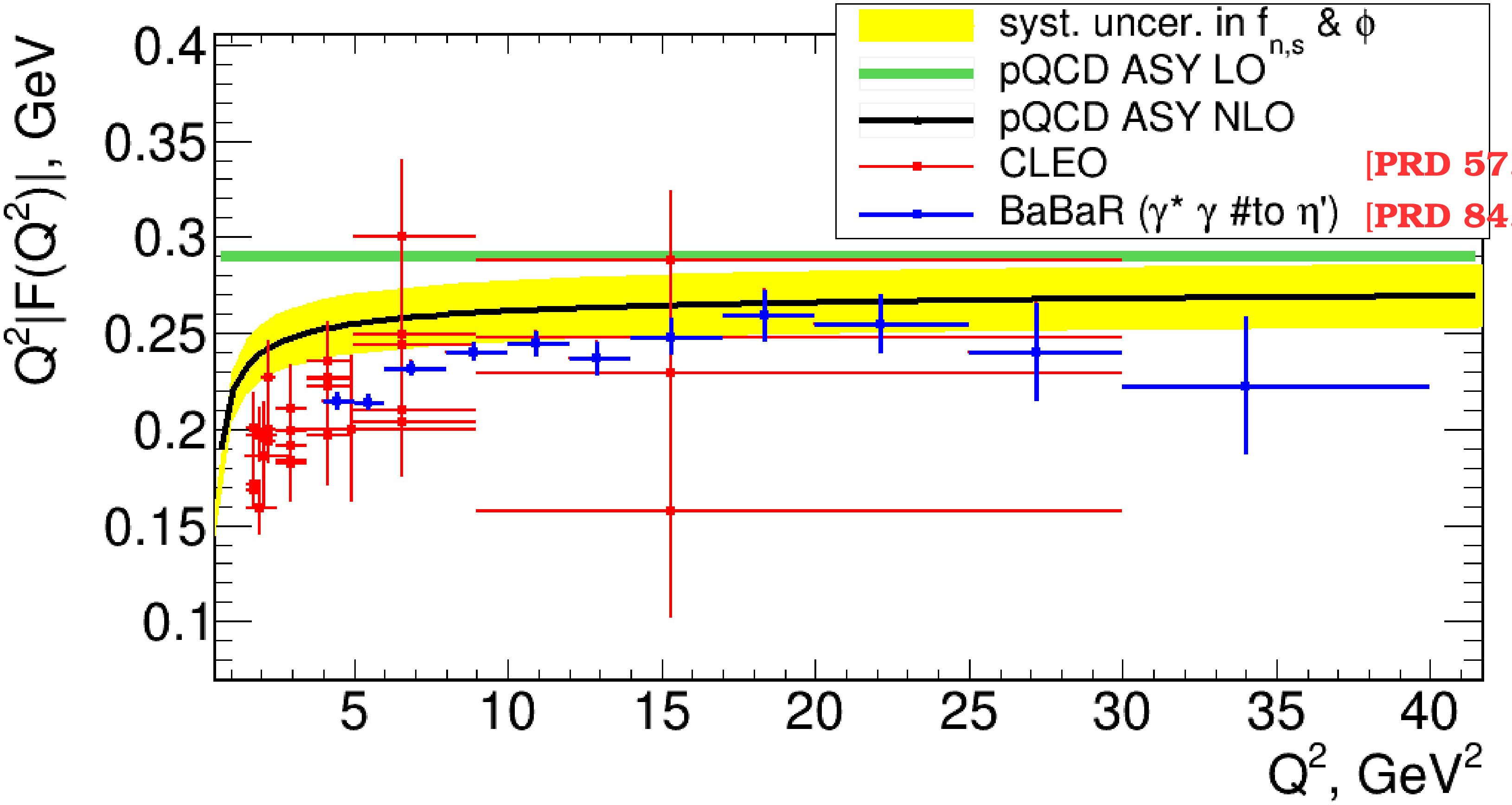
$$F_{\eta'}(Q_1^2,Q_2^2) = \left(\frac{5\sqrt{2}}{9}f_n\sin\phi+\frac{2}{9}f_s\cos\phi\right)\int_0^1 dx\frac{1}{2}\frac{\boxed{6x(1-x)}}{xQ_1^2+(1-x)Q_2^2}\left(1+C_F\frac{\alpha_s(\mu^2)}{2\pi}\cdot t(x,Q_1^2,Q_2^2)\right)+(x\to 1-x),$$

Master formula

The meson DA

NLO

Experimental data (with sist. uncert.) vs pQCD.

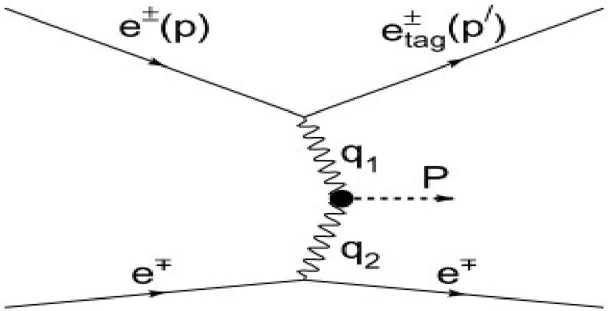


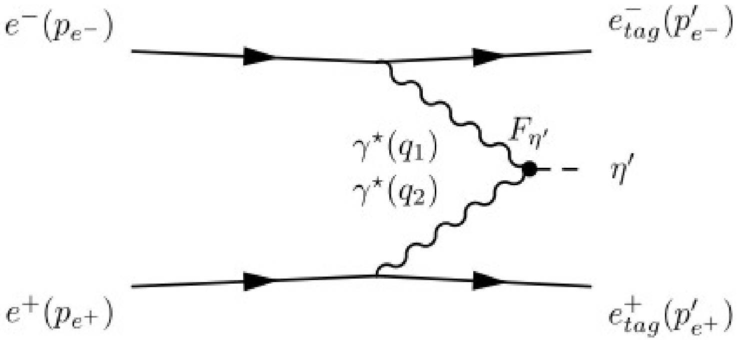
[PRD 57, 33 (1998)]
[PRD 84, 052001]

The $\gamma^*\gamma \to \eta$ Transition Form Factor

The analysis is based on the previous BaBar study [1].

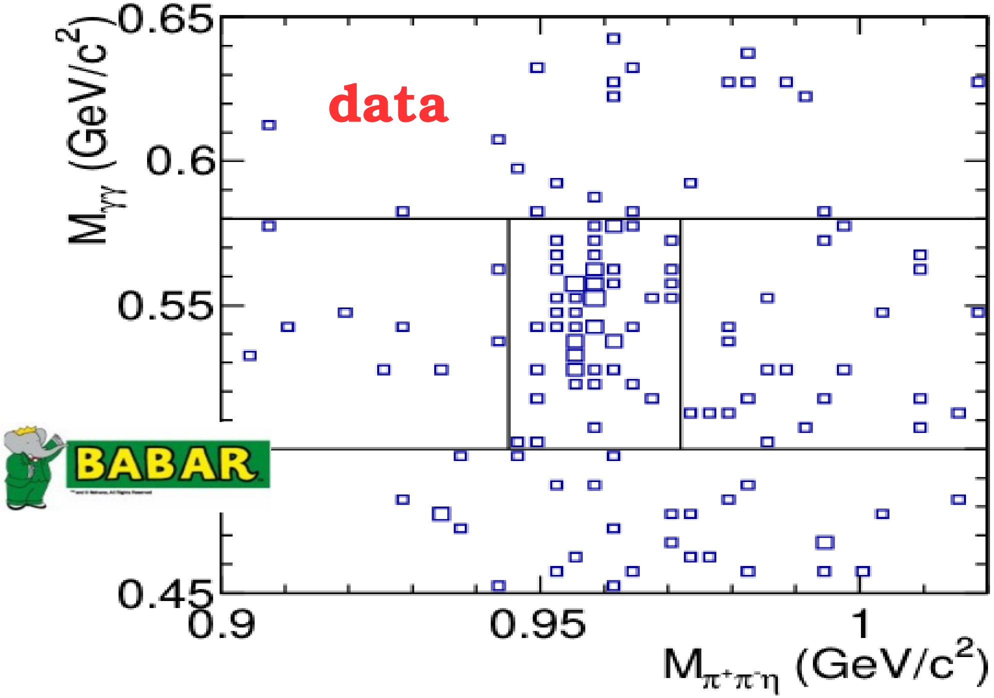
Previous	**New**
$\gamma\gamma^*\to\eta'$	$\gamma^*\gamma^*\to\eta'$
Single tagged	**Double tagged**
~ 5000 signal events	**46^{+8}_{-7} signal events**

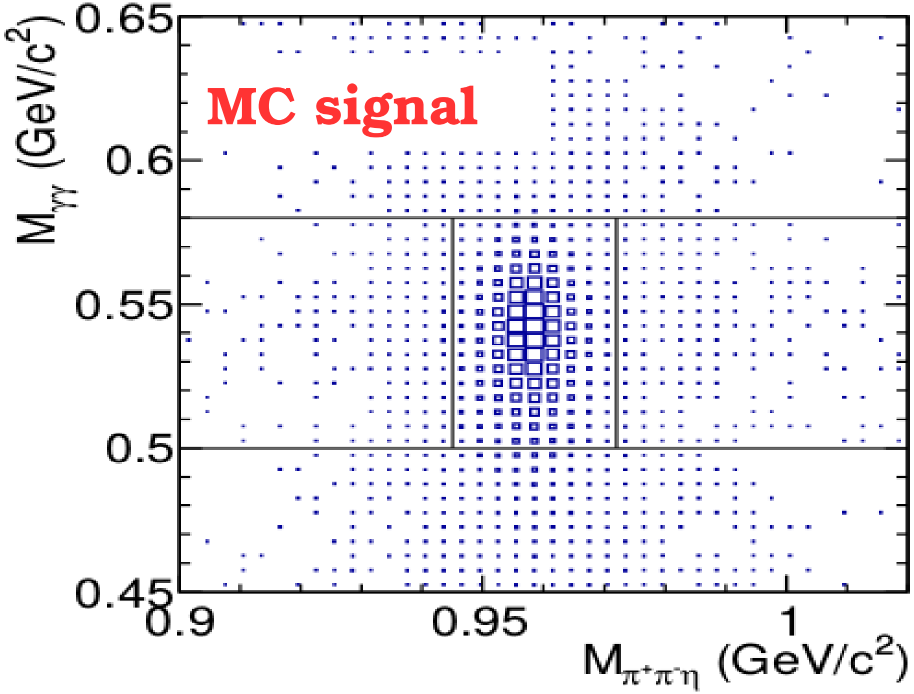




- **A large number of systematic uncertainties were studied in our previous work where the number of signal events was significantly larger.**

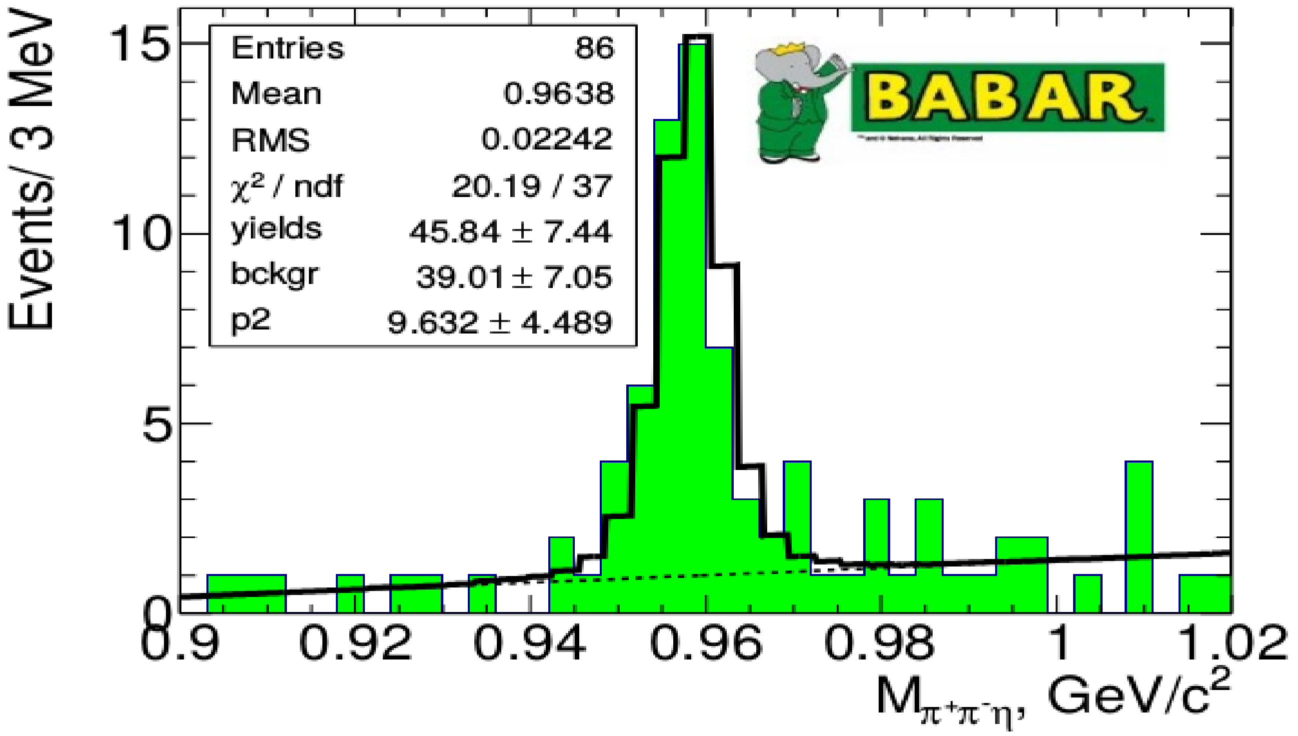
[1] [PRD 84, 052001]: P. del Amo Sanchez *et al. (BaBar collaboration)*, Phys. Rev. D 84, 052001 (2011) (> 126 citations).



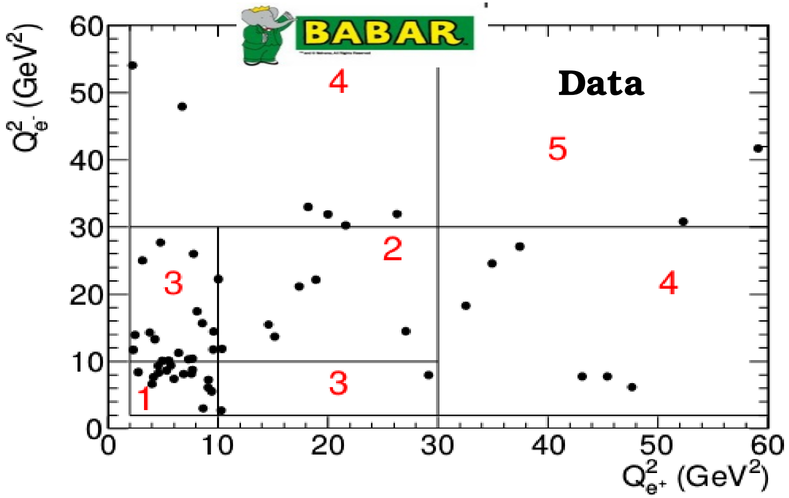


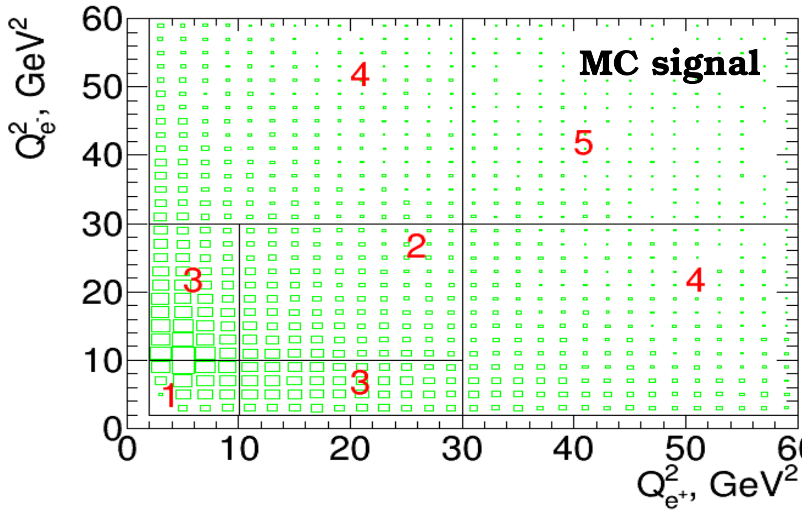
$m_{\gamma\gamma}$ *vs.* $m_{\pi+\pi-\eta}$

- We require $0.50 < m_{\gamma\gamma} < 0.58$ GeV/c^2



The $\pi^+\pi^-\eta$ mass spectra for data events. The open histogram is the fit result. The dashed line represents fitted background.





The Q^2_{e-} vs. Q^2_{e+} for events with $\mathbf{0.945 < m_{2\pi\eta} < 0.972}$ *GeV/c^2*

• The average momentum transfers for each region are calculated using the data spectrum normalized to the detection efficiency:

$$\overline{Q^2_{1,2}} = \frac{\sum_i Q^2_{1,2}(i)/\varepsilon(Q^2_1, Q^2_2)}{\sum_i 1/\varepsilon(Q^2_1, Q^2_2)}$$

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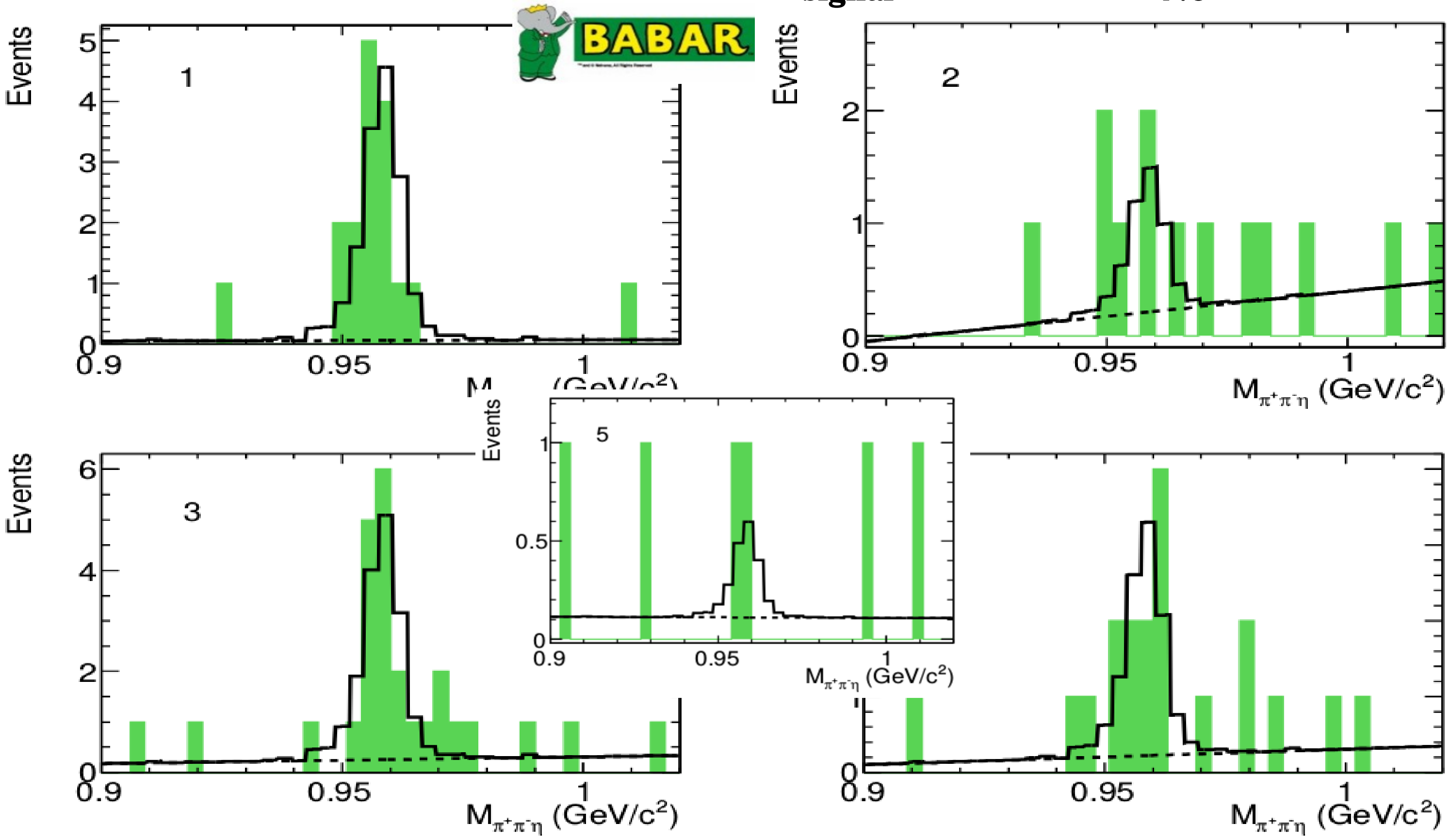
- The total number of signal events $\mathbf{N^{fit}_{signal} = 46.2^{+8.3}_{-7.0}}$



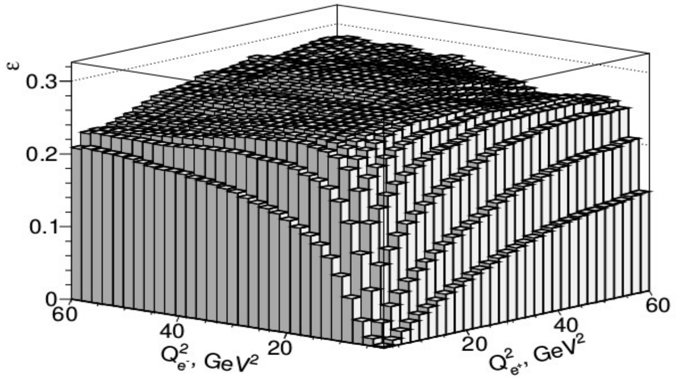
The $\pi^+\pi^-\eta$ mass spectra for data events for the five Q^2 ranges. The open histograms are the fit results. The dashed lines represent background.

Detection efficiency

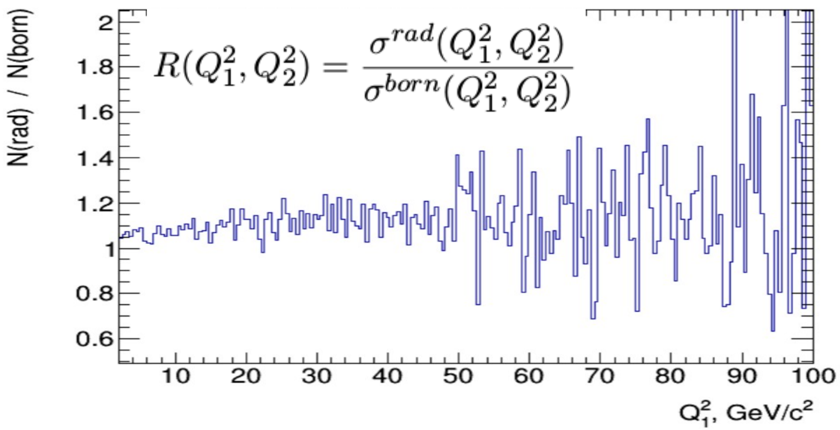
• The detector acceptance limits the detection of scattered fermions at small Q^2 . The minimum Q^2 equals to 2 GeV^2

$$\varepsilon_{true} = \frac{\int \varepsilon(Q_1^2, Q_2^2) F^2_{\eta'}(Q_1^2, Q_2^2) dQ_1^2 dQ_2^2}{\int F^2_{\eta'}(Q_1^2, Q_2^2) dQ_1^2 dQ_2^2}$$

($\boldsymbol{F}_{\eta'}$ from *master formula* at slide #7)



The dependence of detection efficiency on momentum transfers.



The ratio of generated spectra with rad. photons vs. without photons

• R leads to the decrease of the detection efficiency by ~10 %.

• The maximum energy of the photon emitted from the initial state is restricted by the requirement $E_\gamma < 0.05\sqrt{s}$, where $\sqrt{s}$ is the e^+e^- center-of-mass (c.m.) energy.

Cross section and Form Factor

- The differential cross section for $e^+e^- \to e^+e^-\eta'$ is calculated as

$$\boxed{\frac{d^2\sigma}{dQ_1^2 dQ_2^2} = \frac{1}{\varepsilon_{\rm true} R L B} \frac{d^2 N}{dQ_1^2 dQ_2^2}}$$

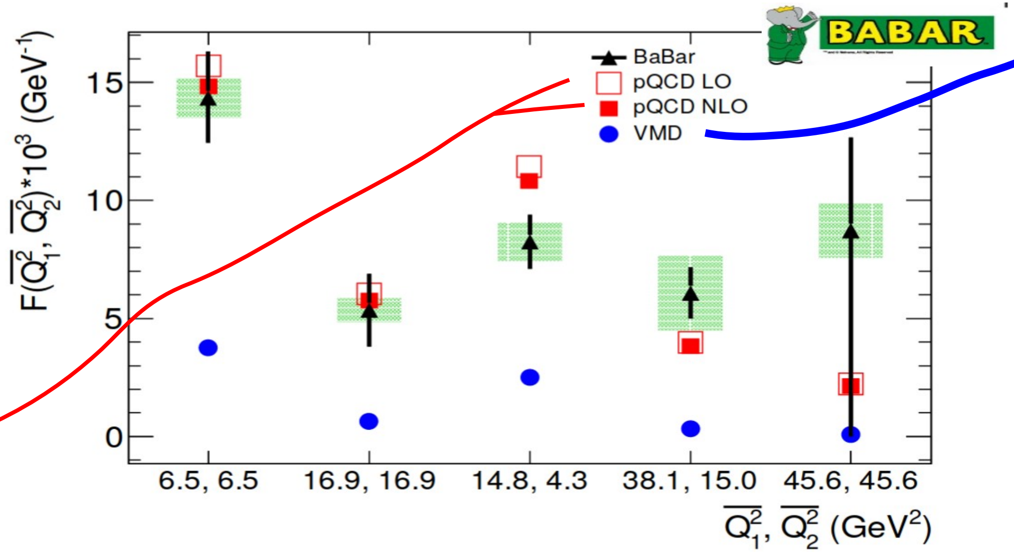
$$F^2(\overline{Q_1^2}, \overline{Q_2^2}) = \frac{(d^2\sigma/(dQ_1^2 dQ_2^2))_{data}}{(d^2\sigma/(dQ_1^2 dQ_2^2))_{MC}} F_{\eta'}^2(\overline{Q_1^2}, \overline{Q_2^2})$$

- From PDG: $B = B(\eta' \to \pi^+\pi^-\eta) \times B(\eta \to 2\gamma) = (0.3941 \pm 0.0020) \times (0.429 \pm 0.007) = 0.169 \pm 0.003$
- $\boldsymbol{\sigma_{e+e-\to e+e-\eta'}}$ **$(2 < Q_1^2, Q_2^2 < 60$ GeV$^2) = (11.4^{+2.8}_{-2.4})$ fb**

$\overline{Q_1^2}, \overline{Q_2^2}$, GeV^2	$\varepsilon_{\rm true}$	R	$N_{\rm events}$	$d^2\sigma/(dQ_1^2 dQ_2^2)$ $\times 10^4$, fb/GeV^4	$F(\overline{Q_1^2}, \overline{Q_2^2})$ $\times 10^3$, GeV^{-1}
6.48, 6.48	0.019	1.03	$14.7^{+4.3}_{-3.6}$	$1471.8^{+430.1}_{-362.9}$	$14.32^{+1.95}_{-1.89} \pm 0.83 \pm 0.14$
16.85, 16.85	0.282	1.10	$4.1^{+2.7}_{-2.7}$	$4.2^{+2.8}_{-2.8}$	$5.35^{+1.54}_{-1.54} \pm 0.31 \pm 0.42$
14.83, 4.27	0.145	1.07	$15.8^{+4.8}_{-4.0}$	$39.7^{+12.0}_{-10.2}$	$8.24^{+1.16}_{-1.13} \pm 0.48 \pm 0.65$
38.11, 14.95	0.226	1.11	$10.0^{+3.9}_{-3.2}$	$3.0^{+1.2}_{-1.0}$	$6.07^{+1.09}_{-1.07} \pm 0.35 \pm 1.21$
45.63, 45.63	0.293	1.22	$1.6^{+1.8}_{-1.1}$	$0.6^{+0.7}_{-0.6}$	$8.71^{+3.96}_{-8.71} \pm 0.50 \pm 1.04$

Statistical **Systematic** **Model**

- The statistical uncertainty is dominant



$$F_{\eta'}(Q_1^2, Q_2^2) = \frac{F_{\eta'}(0,0)}{(1 + Q_1^2/\Lambda_P^2)(1 + Q_2^2/\Lambda_P^2)}$$

The Λ_P is fixed at 849 MeV/c^2 from the approximation of $F_{\eta'}(Q^2, 0)$ with one off-shell photon [Phys. Rev. D 85, 057501 (2012)].

The comparison of obtained form-factor with theoretical predictions. Error bars - statistical uncertainties. Shaded rectangles - quadratic sum of the systematic and model uncertainties.

NLO

$$F_{\eta'}(Q_1^2, Q_2^2) = \left(\frac{5\sqrt{2}}{9} f_n \sin\phi + \frac{2}{9} f_s \cos\phi\right) \int_0^1 dx \frac{1}{2} \frac{6x(1-x)}{xQ_1^2 + (1-x)Q_2^2} \left(1 + C_F \frac{\alpha_s(\mu^2)}{2\pi} \cdot t(x, Q_1^2, Q_2^2)\right) + (x \to 1-x),$$

- pQCD calculation is in good agreement with data (χ^2/n.d.f. = 6.2/5, Prob = 28%)
- VMD model exhibits a clear disagreement with the experiment.

Summary

- The new results on the measurements of $e^+e^-\to\pi^+\pi^-\pi^0\pi^0\pi^0$, $e^+e^-\to\pi^+\pi^-\pi^0\pi^0\eta$ and $e^+e^-\to\pi^+\pi^-\eta$ have been presented.

- The $\gamma^*\gamma^*\to\eta'$ transition form factor $F(Q^2_1, Q^2_2)$ have been measured for Q^2 range from 2 to 60 GeV^2 with ~ 50 events.

- The form factor is in reasonable agreement with the pQCD prediction. We propose a measurement of this quantity at BELLE II.

Thank you for your attention

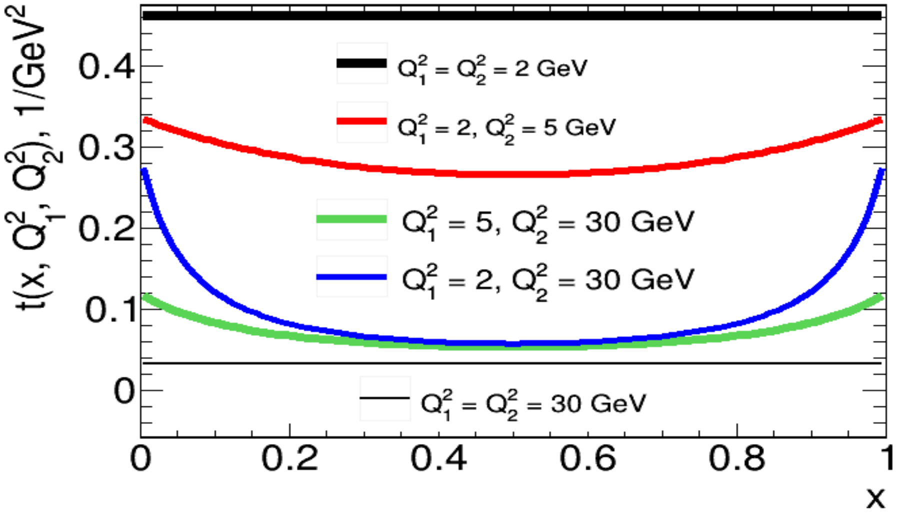
Back up slides

$$F_{\eta'}(Q_1^2,Q_2^2) = \left(\frac{5\sqrt{2}}{9} f_n \sin\phi + \frac{2}{9} f_s \cos\phi\right) \int_0^1 dx \frac{1}{2} \frac{\boxed{6x(1-x)}}{xQ_1^2 + (1-x)Q_2^2} \left(1 + C_F \frac{\alpha_s(\mu^2)}{2\pi} \cdot t(x,Q_1^2,Q_2^2)\right) + (x \to 1-x),$$

Master formula

The meson DA

NLO



- The double-virtual TFF is **less sensitive to NLO** than the single off-shell TFF.

- The form $\boxed{1/[xQ_1{}^2+(1\text{-}x)Q_2{}^2]}$ is not divergent, so double off-shell transition FF is **less sensitive to a shape of the meson DA** in comparison to the single off-shell FF.

Additionally, the study is motivated by g-2 puzzle

Pseudoscalar pole contribution to the hadronic light-by-light piece of aµ

Adolfo Guevara, Pablo Roig, JJ Sanz Cillero. Sep 17, 2018. 7 pp.

Conference: C18-06-25.2

e-Print: arXiv:1809.06175

is the largest one. A way to reduce such uncertainty could be by taking into account data form doubly off-shell TFF such as that given by BaBar for the η'-TFF [35]. Considering all possible contributions to the error we get

$$a_\mu^{P,HLbL} = (8.47 \pm 0.16_{\mathrm{sta}} \pm 0.09_{1/N_C}\, {}^{+0.5}_{-0}{}_{\mathrm{asym}}) \cdot 10^{-10}, \qquad (14)$$

where the first error (sta) comes from the fit of the TFF, the second from possible $1/N_C$ corrections and the last from the wrong asymptotic behavior estimated through the effects of heavier resonances in the TFF.

M. Poppe, Int. J. Mod. Phys. A 1, 545 (1986):

At present, a major interest of $\gamma\gamma$ physics concerns the answer to the question "do the photons resolve the hadron's structure or not?" In other words: is particle production in $\gamma\gamma$ interactions primarily the production of quark pairs or is the VDM interpretation correct that the photons turn into vector mesons before they interact? In the latter case, two-photon physics would be just a continuation of fixed target hadron scattering experiments, and we would not expect great news to appear.

A.V. Radyushkin, R. Ruskov, Nuclear Physics B 481 (1996) 625-680:

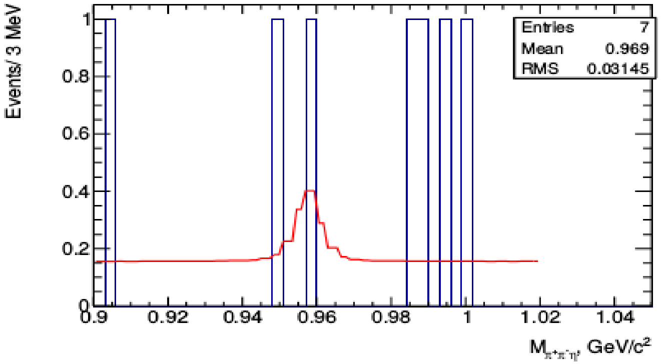
	VMD	pQCD
$Q_1^2 \approx 0,\ Q_2^2 \to \infty$	$1/Q^2$	$1/Q^2$
$Q_1^2,\ Q_2^2 \to \infty$	$1/Q^4$	$1/Q^2$

$$F^{LO}_{\gamma^*\gamma^*\pi^0}(q^2,Q^2) = \frac{4\pi}{3}\int_0^1 \frac{\varphi_\pi(x)}{xQ^2+\bar{x}q^2}\,dx,$$

where $\varphi_\pi(x)$ is the pion distribution amplitude and $x, \bar{x} \equiv 1-x$ are the fractions of the pion light-cone momentum carried by the quarks. In the region where both photon virtualities are large: $q^2 \sim Q^2 \gtrsim 1\ \mathrm{GeV}^2$, the pQCD predicts the overall $1/Q^2$ fall-off of the form factor, which differs from the naive vector meson dominance expectation $F_{\gamma^*\gamma^*\pi^0}(q^2,Q^2) \sim 1/q^2Q^2 \sim 1/Q^4$. Thus, establishing the $1/Q^2$ power law in this region is a crucial test of pQCD for this process. The study of $F_{\gamma^*\gamma^*\pi^0}(q^2,Q^2)$ over a wide range of the ratio q^2/Q^2 of two large photon virtualities can then provide non-trivial information about the shape of $\varphi_\pi(x)$.

Systematic uncertainty. Background subtraction.

- $e^+e^- \to e^+e^-\eta'\pi^0 \to e^+e^-\pi^-\pi^+\eta\pi^0$ - kinematically closest background for the process under study. Using the simulation of the $e^+e^- \to e^+e^- a_0(1450) \to e^+e^-\eta'\pi^0$ process we estimate the contribution $N_{\eta'\pi 0} < 0.16$ at 90% C.L.



The $\pi^+\pi^-\eta$ invariant mass spectrum

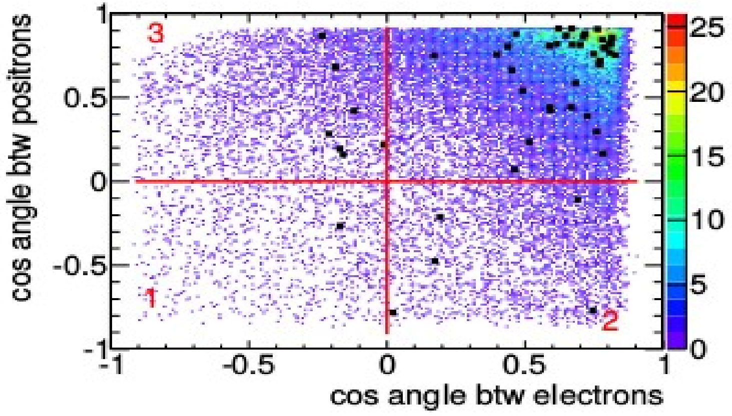
$$\Rightarrow \quad N^{signal}_{\eta'\pi^0} < 1.45 \text{ at } 90\% \text{ C.L.}$$

The detection efficiency for $e^+e^-\eta'\pi^0$ events to pass the selections of $\mathbf{e^+e^-\eta'}$.

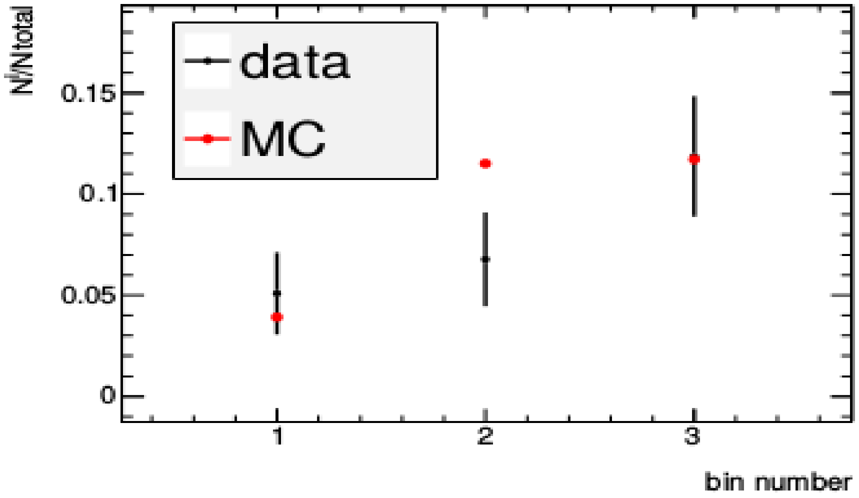
$$N_{bkgr} = \frac{N^{signal}_{\eta'\pi^0}\,\epsilon^{(2)}_{\eta'\pi^0}}{\epsilon^{(1)}_{\eta'\pi^0}} < 0.16 \text{ at } 90\% \text{ C.L.}$$

The detection efficiency for $e^+e^-\eta'\pi^0$ events to pass the selections of $\mathbf{e^+e^-\eta'\pi^0}$.

- $e^+e^-\to e^+e^-J/\psi(\varphi)\to e^+e^-\eta'\gamma$ is negligible according to [**PRD 84, 052001**].
- $e^+e^-\to\gamma^*\to X$:



The cosine of angle between scattered and initial electron (positron) in c.m.f.



The fraction of the events in the bins.

It is reasonable to assume that the $\cos(\alpha_{e\pm})$ spectrums must be symmetric in [-1:1] region for **annihilation processes**, while signal scattered electron (positron) prefers to fly in the about the same direction.

The main source of systematic uncertainty of cross section

Source	Uncertainty (%)
$\pi^{\pm}$ identification	$\boxed{1.0}$
$e^{\pm}$ identification	$\boxed{1.0}$
Other selection criteria	11
Track reconstruction	$\boxed{0.9}$
$\eta \to 2\gamma$ reconstruction	$\boxed{2}$
Trigger, filters	$\boxed{1.3}$
Background subtraction	3.7
Radiative correction	1.0
Luminosity	1.0
Total	12%

$\boxed{}$ from previous BaBar study of γ*γ→η′ **[PRD 84, 052001]**

selection	$N_{signal}/\varepsilon_{true}$	deviation from standard criteria
standard selection criteria	985 ± 197	
$P_{e^+e^-\eta'}$ is less than 1 GeV/c instead of 0.35 GeV/c	1052 ± 273	6.8
$10.20 < E_{e^+e^-\eta'} < 10.75$ GeV instead of $10.3 < E_{e^+e^-\eta'} < 10.65$ GeV	942 ± 235	-4.3
without the restrictions on E_{e^+} and E_{e^-}	1061 ± 280	7.7
$0.48 < m_{2\gamma} < 0.60$ GeV/c^2 instead of $0.50 < m_{2\gamma} < 0.58$ GeV/c^2	958 ± 181	-2.7
total		11

Model uncertainty

- **$(d^2\sigma/(dQ^2_1\ dQ^2_2))_{MC}$ and ε_{true} depends on model.**

Repeating the calculations with a constant TFF we estimate the model uncertainty.

For the cross section - about 60% due to the strong dependence of ε_{true} on the input model for TFF at small values of Q^2_1 and Q^2_2.

The TFF is much less sensitive to the model.

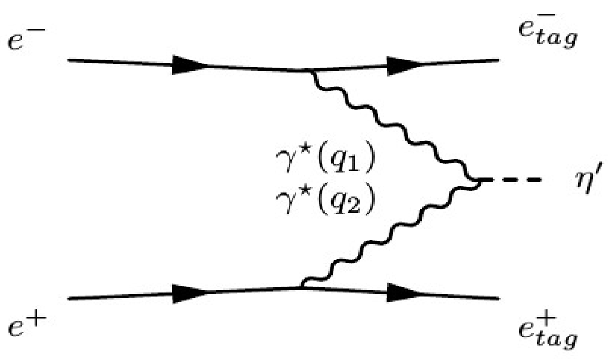
TABLE V: $\frac{d^2\sigma}{dQ_1^2 dQ_2^2}$ obtained with different models for TFF

	1	2	3	4	5
QCD	$1471.8^{+430.136}_{-362.91}$	$4.17^{+2.75}_{2.75}$	$39.72^{+11.98}_{-10.18}$	$2.98^{+1.17}_{-0.96}$	$0.62^{+0.69}_{-0.62}$
const	$637.10^{+186.19}_{-157.09}$	$4.15^{+2.74}_{2.74}$	$33.30^{+10.05}_{-8.54}$	$2.76^{+1.08}_{-0.89}$	$0.62^{+0.69}_{-0.62}$
deviation, %	60	0.6	15	7	1.

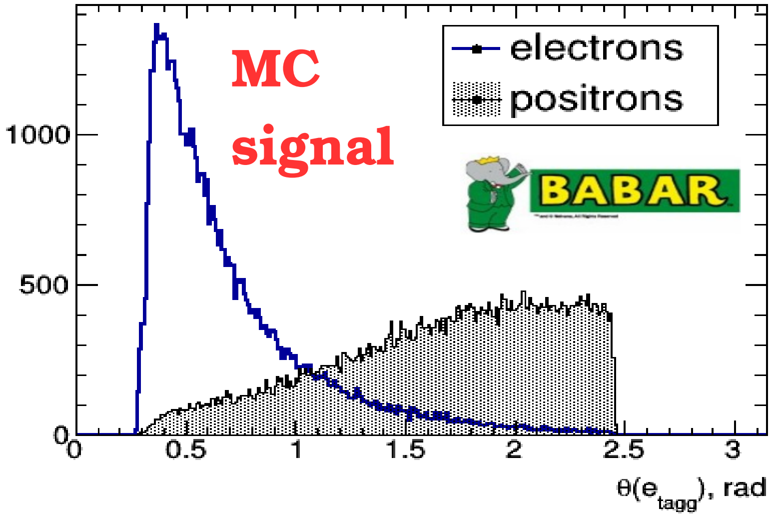
TABLE VI: TFF obtained with different models for TFF

	1	2	3	4	5
QCD	$14.32^{+1.95}_{-1.89}$	$5.35^{+1.54}_{-1.54}$	$8.24^{+1.16}_{-1.13}$	$6.07^{+1.09}_{-1.07}$	$8.71^{+3.96}_{-8.71}$
const	$14.61^{+1.99}_{-1.92}$	$5.62^{+1.62}_{-1.62}$	$7.24^{+1.02}_{-0.99}$	$7.24^{+1.30}_{-1.28}$	$10.02^{+4.55}_{-10.02}$
deviation %	1	8	8	20	12

$$q^2_{e^-} = -Q^2_{e^-} = (p_{e^-} - p'_{e^-})^2$$



$$q^2_{e^+} = -Q^2_{e^+} = (p_{e^+} - p'_{e^+})^2$$



Polar angle distribution for tagged electrons (positrons)

- The decay chain $\eta' \to \pi^+\pi^-\eta \to \boldsymbol{\pi^+\pi^-2\gamma}$ is used
- A total integrated luminosity L = 469 fb^{-1}
- GGResRc event generator is used [arXiv:1010.5969]. Initial and final state radiative corrections as well as vacuum polarization effects are included. The form factor is fixed to the constant value F(0,0).

The strategy: $dN/dQ^2 \Rightarrow d\sigma/dQ^2 \Rightarrow |F(Q^2)|$

Event selection

We require the presense

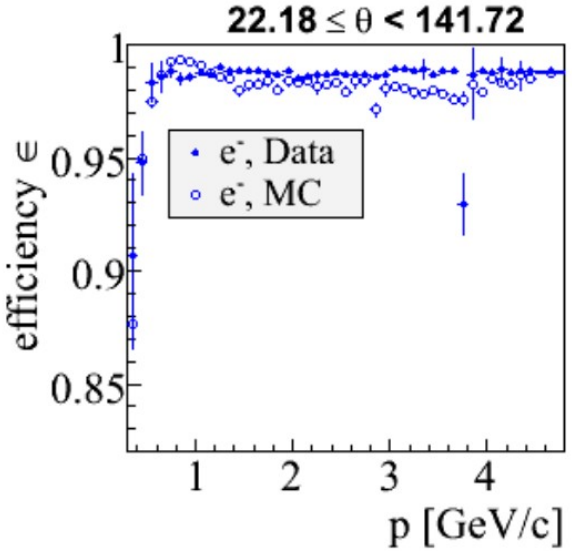
- at least **two tracks** from *GoodTrackLoose* list passed *LooseElectronMicroSecection*
- at least **two tracks** from *GoodTrackLoose* list passed *TightKMPionMicroSelection*
- at least **two photons** from *GoodPhotonLoose* list

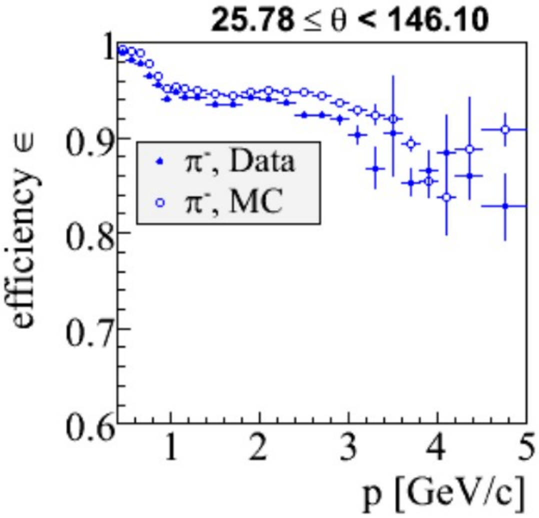
  -ε_γ > 30 MeV

  -0.45 < $m_{\gamma\gamma}$ <0.65 GeV/c^2

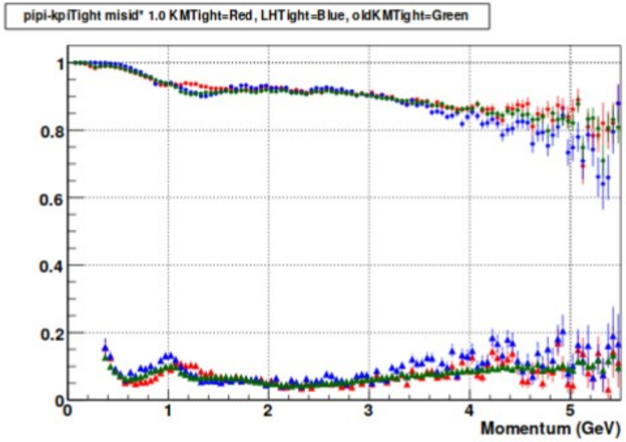
  -The photon candidates are fitted with a η mass constraint.

- The η candidate and a pair of oppositely-charged pion candidates are fitted with a η' mass constraint.

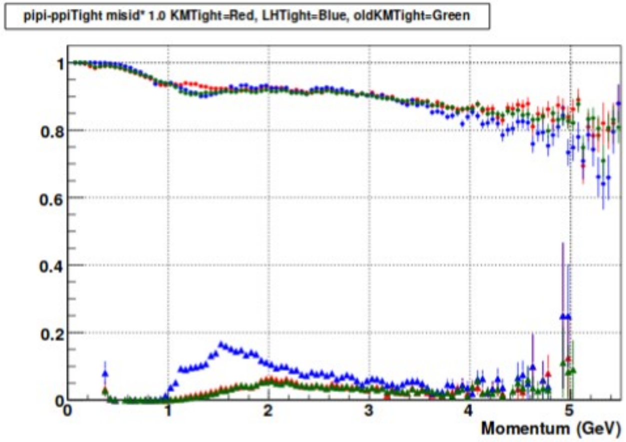




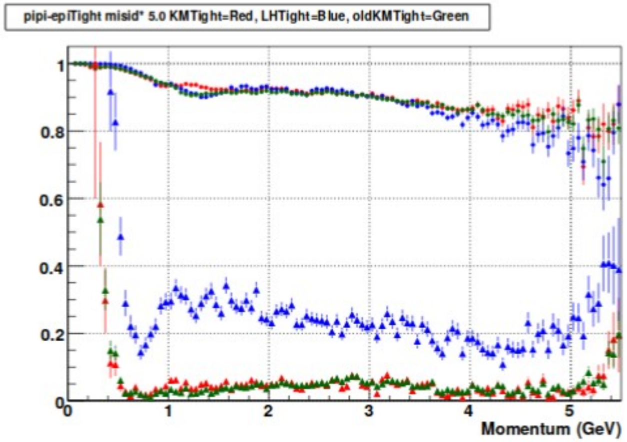
Pions misedentification with *TightKMPionMicroSelection:*



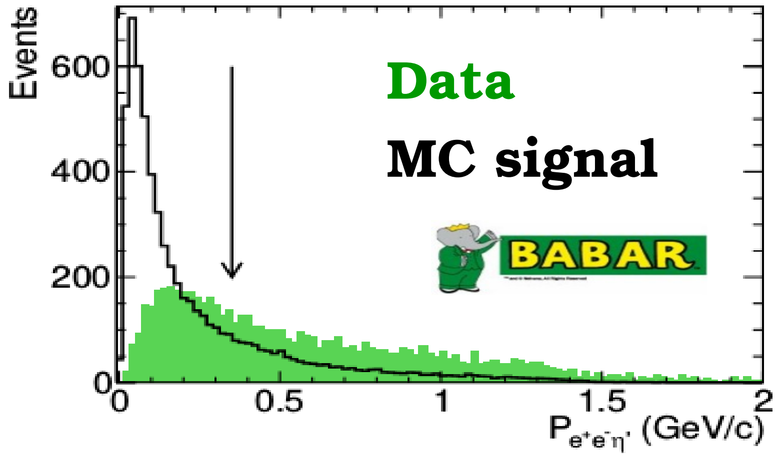
(a) K as π mis-id*1



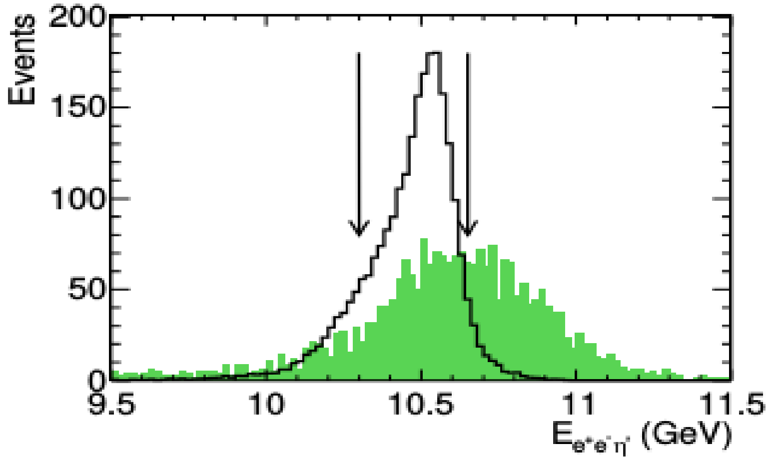
(b) p as π mis-id*1



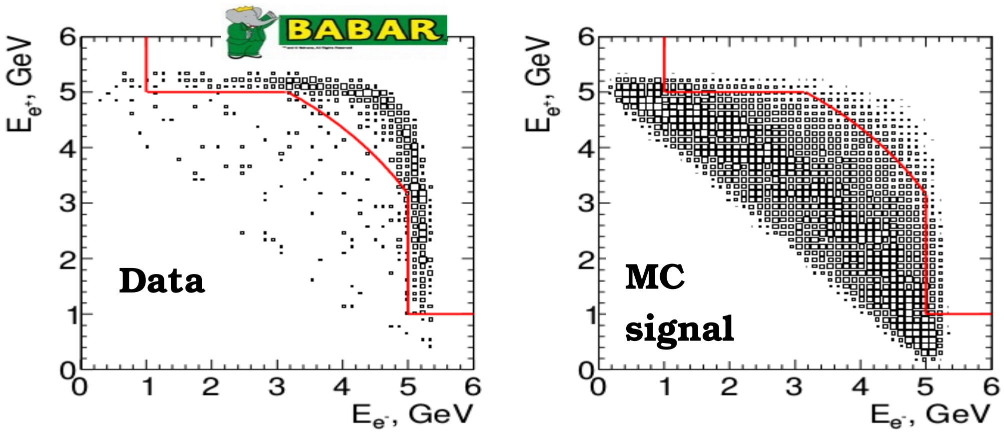
- $P_{c.m.}(e^+e^-\pi^+\pi^-\eta) < 0.35$ GeV/c.



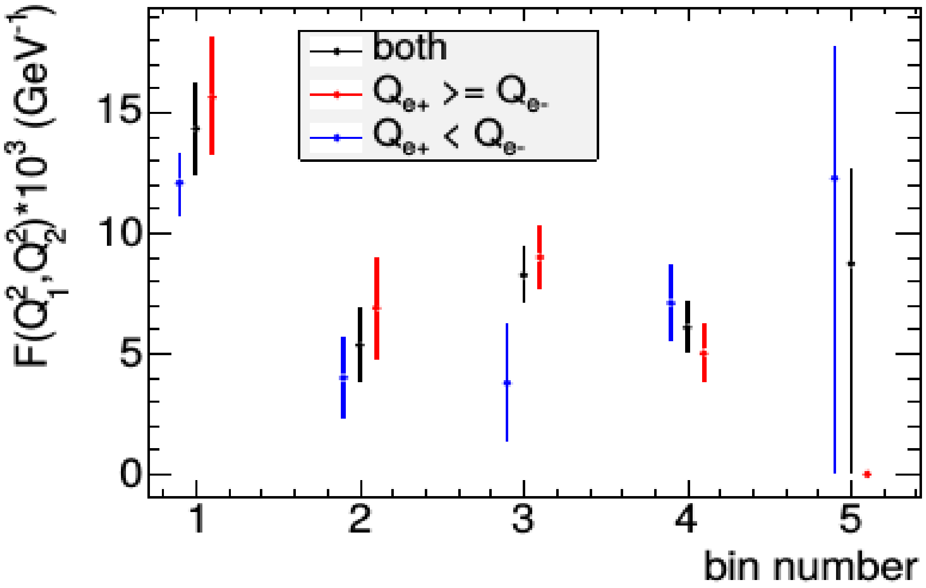
- $10.3 < E_{c.m.}(e^+e^-\pi^+\pi^-\eta) < 10.7$ GeV



- Events that lie above and on the right of the lines (mostly, Bhabha scattering) are rejected.

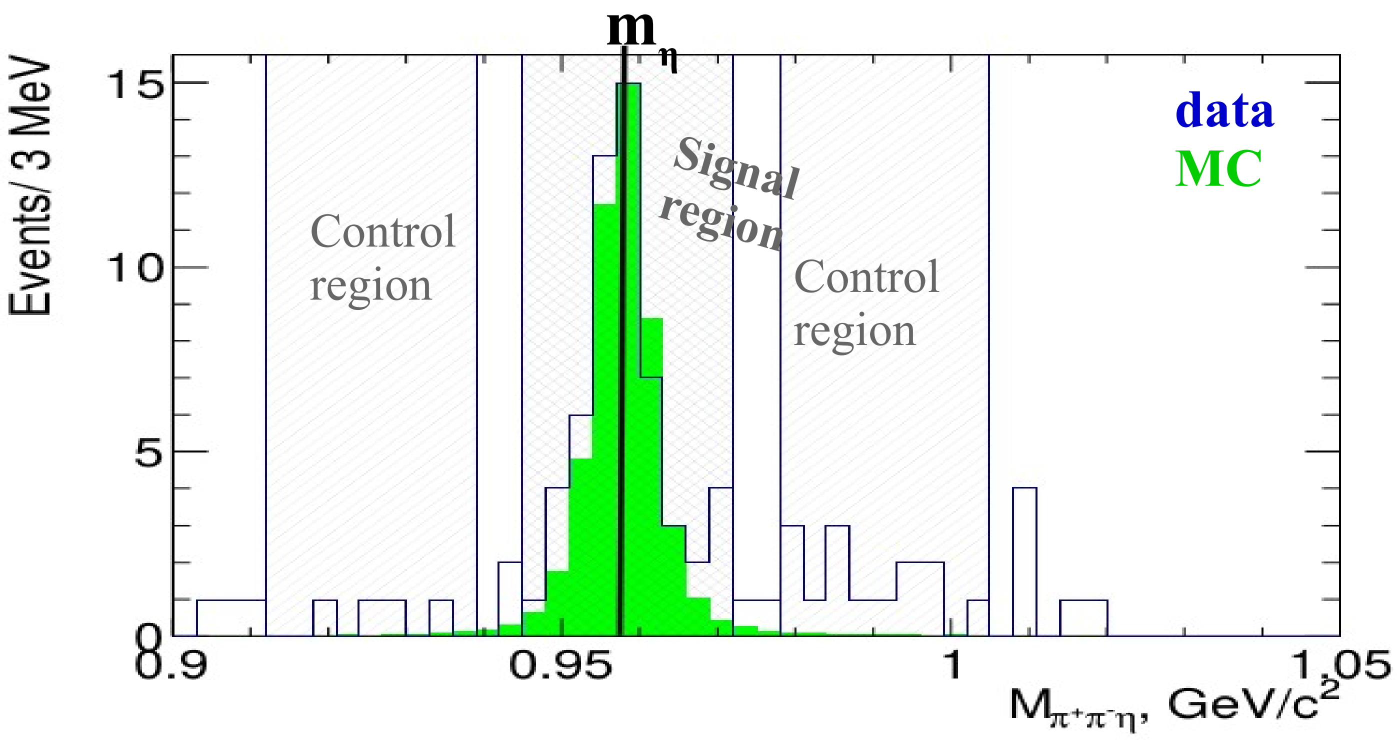


The positron c.m. energy vs the electron c.m. energy



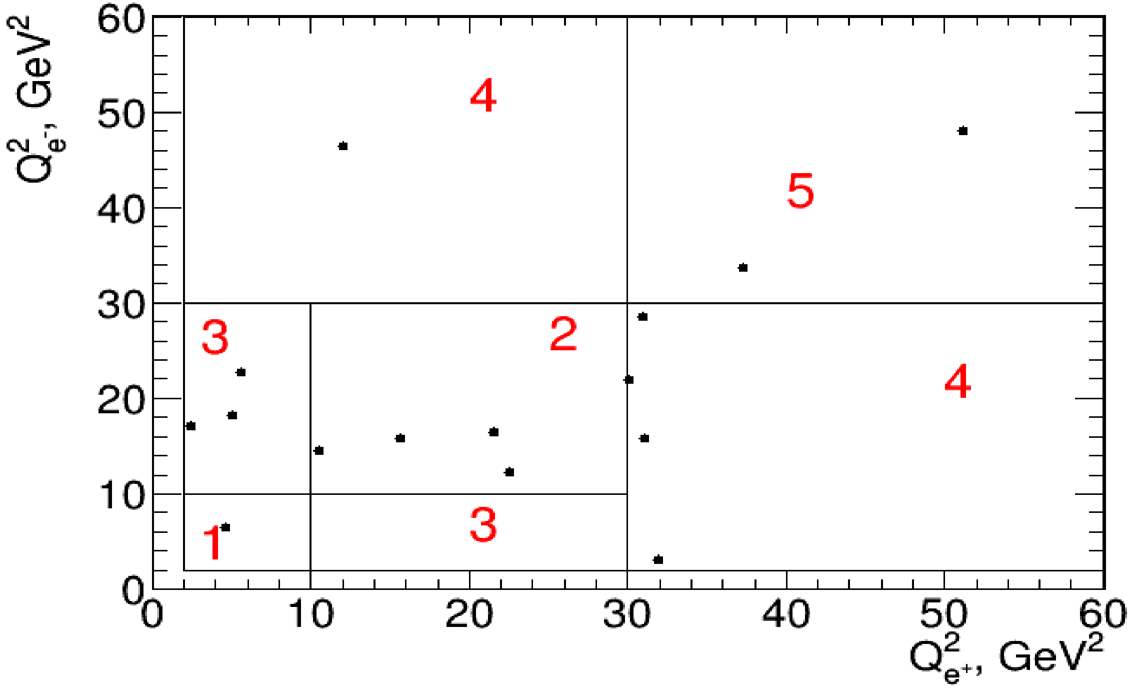
The comparison of the measured η′ TFF with
$Q^2_{e+} < Q^2_{e-}$, $Q^2_{e+} >= Q^2_{e-}$ *and without the restriction.*

Event selection



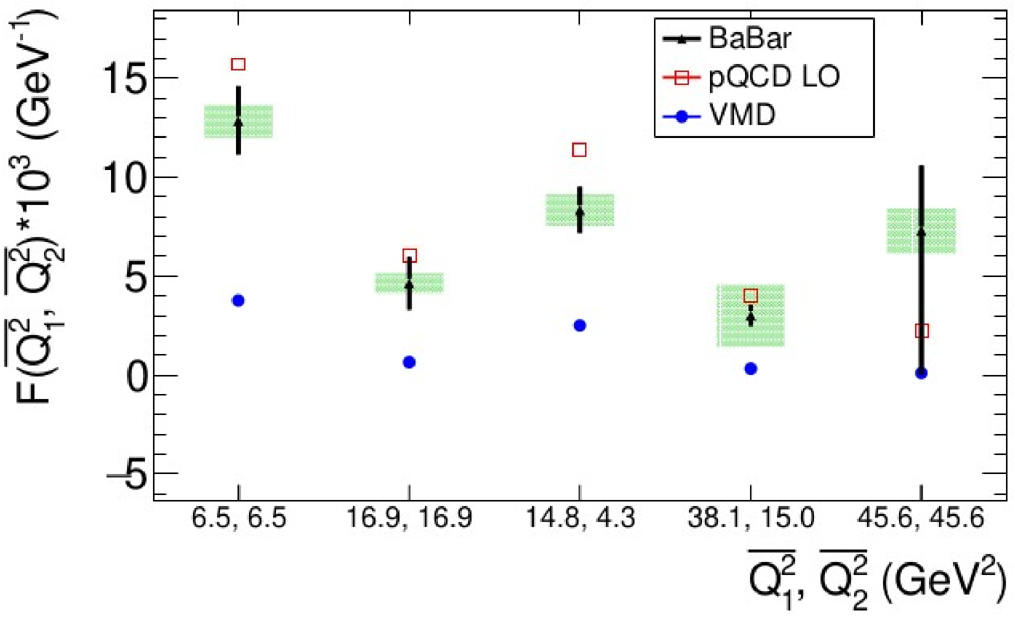
The data-MC comparison of ππη invariant mass distribution. The MC histogram is normalized to central bin of data distribution.

The expected number of signal $N^{side}_{signal} = 55 - 18/2 = 46$



The Q^2_{e-} vs. Q^2_{e+} for events from control side-band regions

If $(d^2\sigma/(dQ^2{}_1\ dQ^2{}_2))_{MC}$ and ε_{true} is made using VMD TFF:



The comparison of obtained form-factor with theoretical predictions. The Error bars - statistical uncertainties. Shaded rectangles - quadratic sum of the systematic and model uncertainties.

$$|\eta'> = \sin\phi\ |n> + \cos\phi\ |s>$$

$$F_{\eta'} = \sin\phi\ F_n + \cos\phi\ F_s$$

$$|n> = \frac{1}{\sqrt{2}}(|\bar{u}u> + |\bar{d}d>)$$
$$|s> = |\bar{s}s>$$
$$|\eta'> = sin\phi|n> + cos\phi|s>$$

- $\lim_{Q^2\to\infty} F_n(Q^2) = \frac{5\sqrt{2}}{3Q^2} f_n;\ \lim_{Q^2\to\infty} F_s(Q^2) = \frac{2}{3Q^2} f_s$

Master formula

- $$F_{\eta'}(Q_1^2, Q_2^2) = (\frac{5\sqrt{2}}{9} \cdot f_n \cdot \sin\phi + \frac{2}{9} \cdot f_s \cdot \cos\phi) \cdot \int_0^1 dx \frac{3x(1-x)}{xQ_1^2 + (1-x)Q_2^2}(1 + C_F \frac{Q^2}{2\pi} \cdot t(x, Q_1^2, Q_2^2)) + (x \to 1-x)$$

- at which scale of Q^2 the asymptotic pQCD perdiction starts to be valid?

- In the case of $\gamma\gamma^* \to P$:

$$F_{\eta'}(Q^2) = F_{\eta'}(Q^2, 0) = \frac{\frac{5\sqrt{2}}{9} \cdot f_n \cdot \sin\phi + \frac{2}{9} \cdot f_s \cdot \cos\phi}{Q^2} \cdot \left(1 - \frac{5}{2} C_F \frac{\alpha_S(Q^2)}{2\pi}\right)$$