LNF GENERAL SEMINAR

PHOTON PHOTON INTERACTION VIA PSEUDOSCALAR FIELDS

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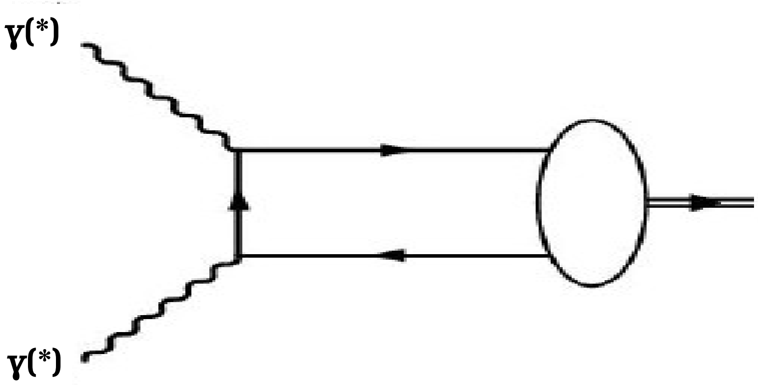


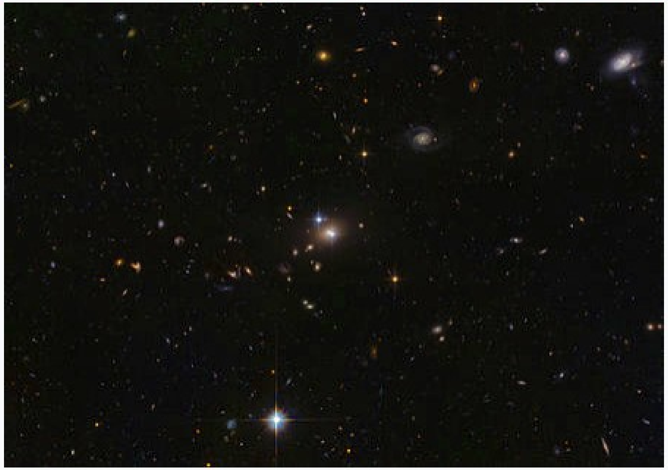
$J^{PC} = 0^{-+}$

November 28, 2018

Outline

- Introduction
  - **- Photon-photon interaction**
  - ***- The definition of $P\gamma\gamma$ transition form factor (TFF)***
  - ***- Theoretical aspects***
  - ***- Existing experimental data***
- The recent measurement of the TFF of η' meson with BaBar detector. Comparison with theoretical predictions
- Prospects for such investigations with KLOE-2
- Summary

The Twin Quasar Q0957+561



The Twin Quasar QSO 0957+561, which lies 7.8 billion light-years from Earth, is seen right in the center of this picture.[1]

$$\lambda \approx \frac{1}{n\sigma} \Rightarrow \sigma < \frac{1}{\lambda \cdot n} = \frac{1}{a \cdot 10^4} = \frac{1}{10 \cdot 10^9 \cdot 3 \cdot 10^8 \cdot \pi \cdot 10^7 \cdot 10^4} \approx \boxed{10^{-30}\, m^2}$$

$$\left.\begin{aligned} P_\odot &\approx 4 \cdot 10^{26}\, W \approx \frac{10^{45}\, \text{photons}}{s} \\ N_{stars} &\approx N_{galaxies} \cdot N^{stars}_{galaxy} \approx 10^9 \cdot 10^{10} \end{aligned}\right] \quad P_{total} \approx \frac{10^{65}\, \text{photons}}{s}$$

$$n \approx \frac{10^{65} \cdot 10 \cdot 10^9 \cdot 3 \cdot 10^7}{a^3} \approx 10^4\, \frac{\text{photons}}{m^3}$$

Introduction.

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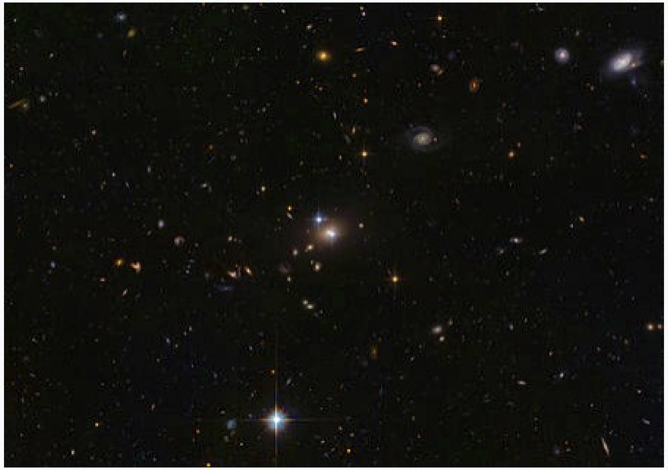

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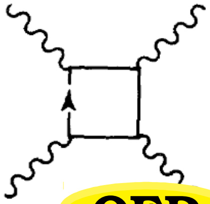

QED

10^{-68} m² for visible photons
10^{-34} m² for 100 GeV photons with CMB

The limit justifies that a photon does not interact with another photon in classical electrodynamics as a fact of the linearity of Maxwell equations.

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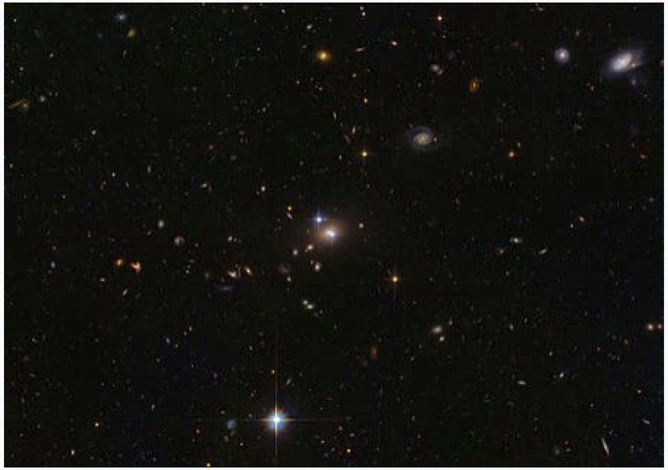

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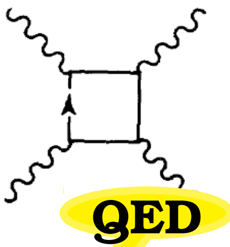

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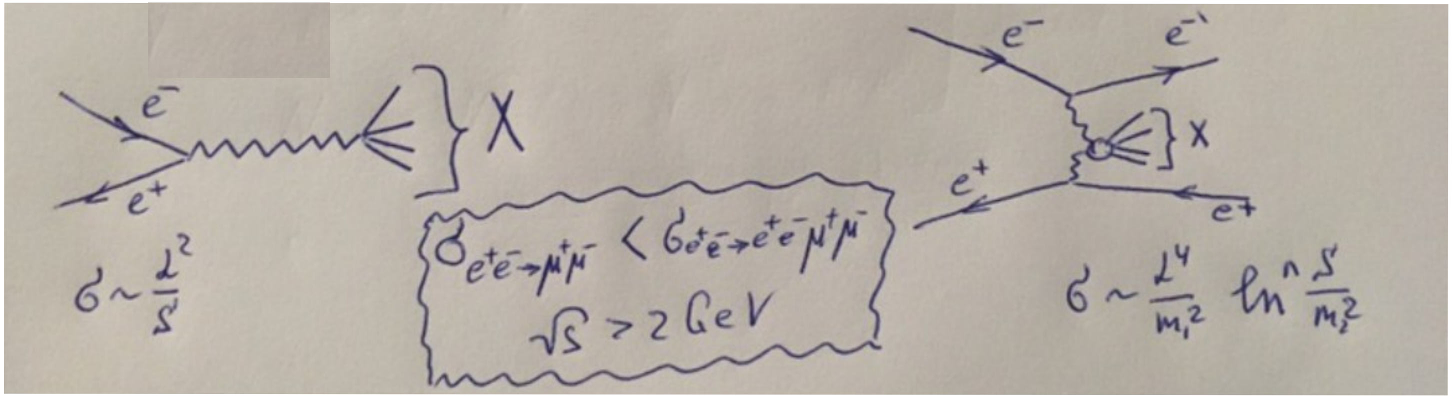
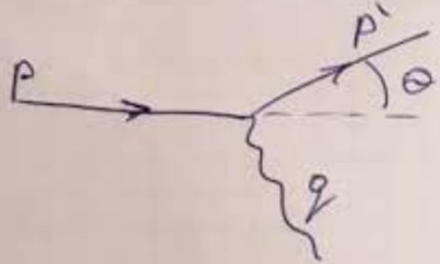
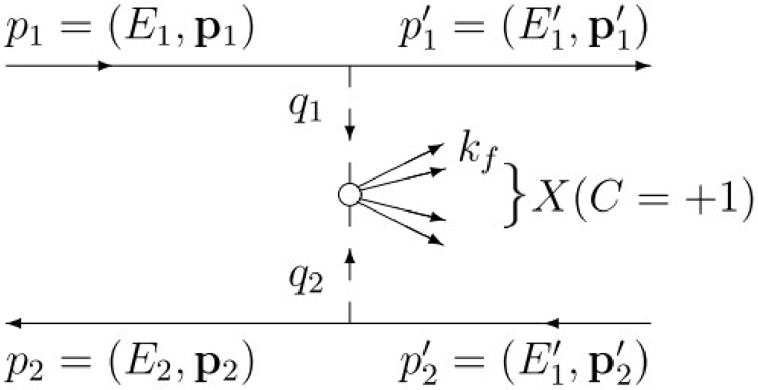




$$q = p - p'$$

$$q^2 = (p-p')^2 = p^2 + p'^2 - 2pp' = 2m_e^2 - 2\cdot(\varepsilon\varepsilon' - \bar{p}\cdot\bar{p}') \approx -2\varepsilon\varepsilon' \underbrace{(1-\cos\theta)}_{2\sin^2\frac{\theta}{2}}$$

$$Q^2 \equiv -q^2 = 4\varepsilon\varepsilon' \sin^2\frac{\theta}{2}$$



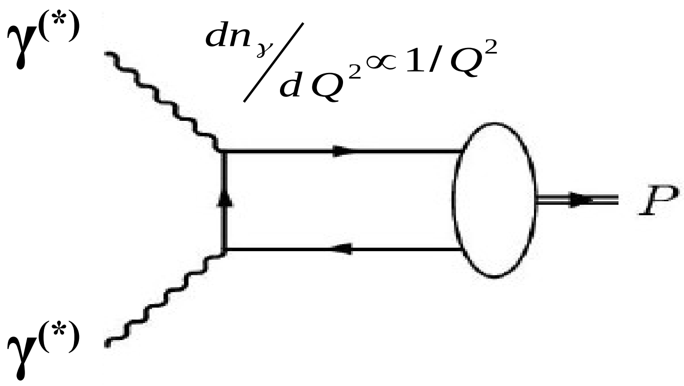
$$W^2 = (q_1 + q_2)^2 = k^2, \;\; k = \sum_f k_f.$$

$$d\sigma_{ee} = \frac{(4\pi\alpha)^2}{(q_1^2 q_2^2)^2}\, d\Sigma\, \frac{I}{I_{ee}}\, \frac{d^3p_1' d^3p_2'}{2E_1' 2E_2' (2\pi)^6},$$

$$I_{ee} = \sqrt{(p_1p_2)^2 - m_e^4}, \;\; I = \sqrt{(q_1q_2)^2 - q_1^2 q_2^2}$$

$$d\Sigma = \sum_{abcd} M_{cd}^* M_{ab}\, J_1^{ac} J_2^{bd}\, \frac{d\Gamma_X}{4I},$$

$$dn_\gamma(x, \mathbf{q}_\perp) = \frac{\alpha}{\pi^2}\left[1 - x + \frac{1}{2}x^2 - \frac{x^2(1-x)m_e^2}{\mathbf{q}_\perp^2 + m_e^2 x^2}\right] \frac{dx}{x} \frac{d^2 q_\perp}{\mathbf{q}_\perp^2 + m_e^2 x^2}$$



P — pseudoscalar meson

$e_{1,2}$ — photon polarization

$q_{1,2}$ — 4-momentum of photon

$-Q^2 = q^2$

The amplitude of the $\gamma^*\gamma^*\to P$ 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 are **no** measurements of the double **off-shell** transitions

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

The TFF gives the information about the composite structure of an object.

- The study of the TFF — as a probe of quark content and its interaction — sensitive to SU(3)-breaking effects, to test of the chiral anomaly of QCD, pQCD, ChPTs, decay constants and fundamental mixing parameters, N_c calculation ....

- Input for light-by-light scattering for muon (g-2) calculation

- Test for lattice calculations

- Test P, CP and C symmetries and search for new physics

All experimental and theoretical efforts can be divided in two parts:

The study of the TFF(0,0) (or equivalently $\Gamma_{\gamma\gamma}$)

The study of dynamics of TFF(q_1^2,q_2^2)

An example of how to reduce the entropy in the world of a huge number of models

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.

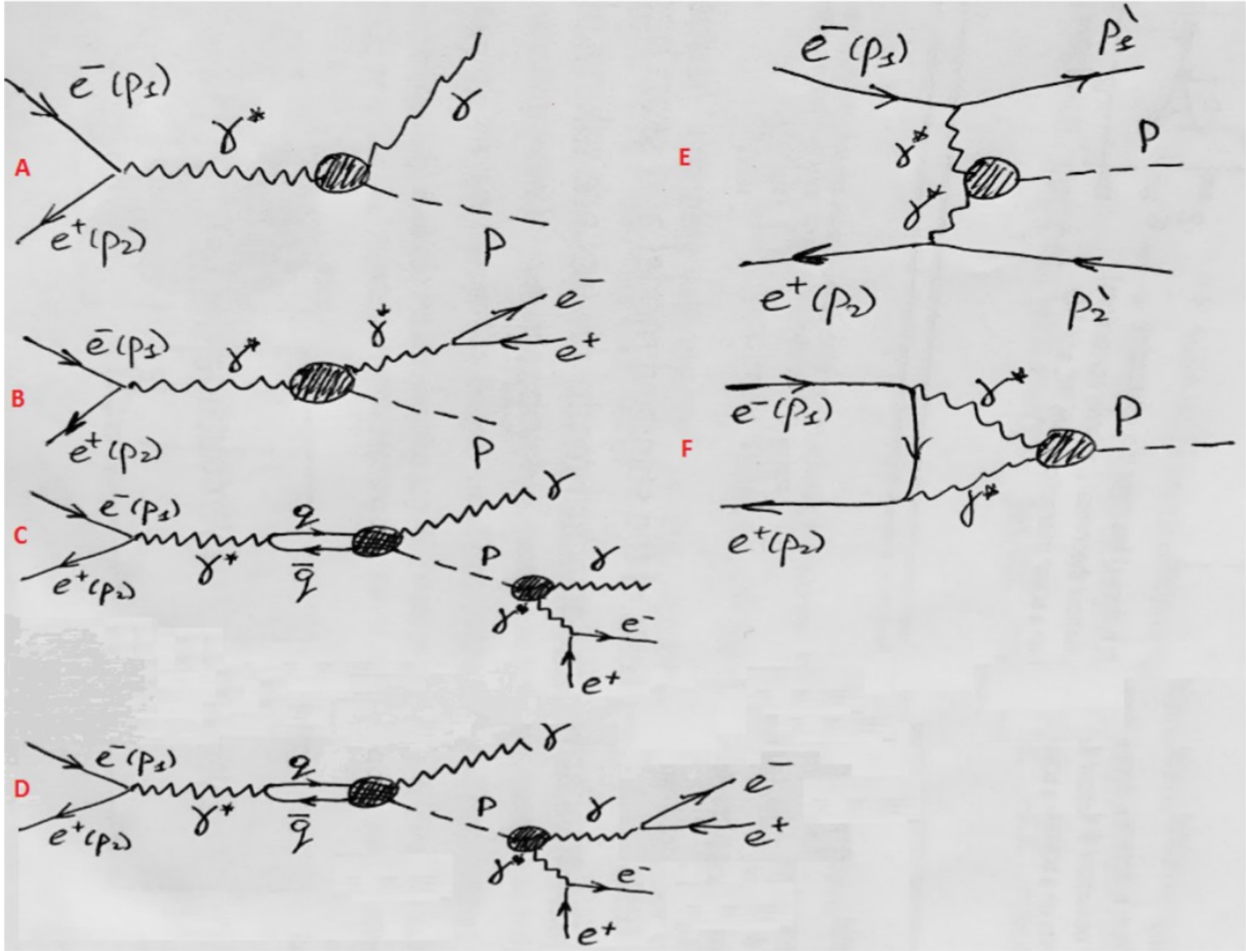
A.V. Radyushkin, R. Ruskov, Nuclear Physics B 481 (1996) 625-680:

	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: $q^2 \sim Q^2 \gtrsim 1\ \text{GeV}^2$, 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 $\varphi_\pi(x)$.

The most important two-photon processes, realized at the electron-positron low-energy collider



Дважды виртуальные фф легче мерить, меньше требований к качеству детектора, т. к. все частицы детектируются

- **η' deacay to real photons:**

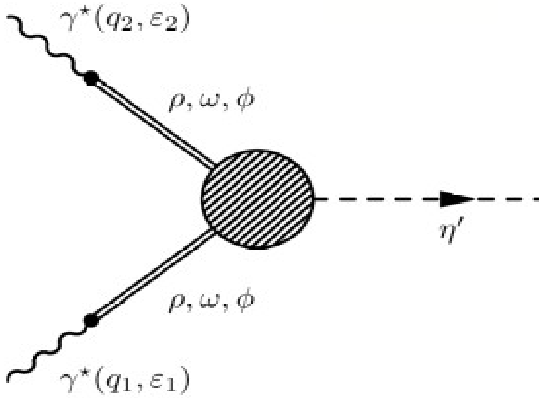
$$\Gamma_{\eta' \to 2\gamma} = \frac{\pi \alpha^2 m^3_{\eta'}}{4} |F(0,0)|^2 = 4.30 \pm 0.16 \text{ keV}$$

$$F(0,0) = 0.342 \pm 0.006 \text{ GeV}^{-1}.$$

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

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

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

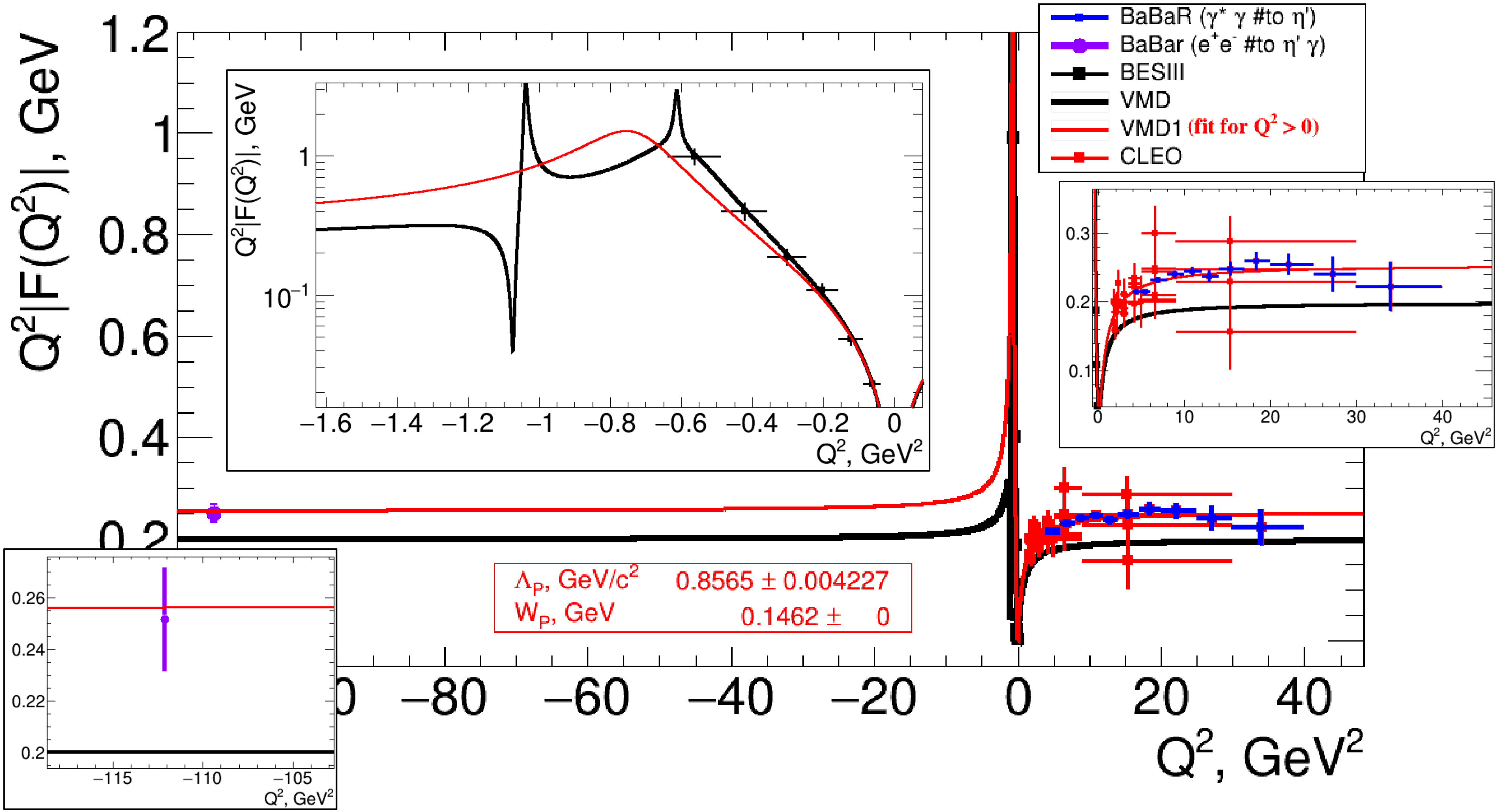


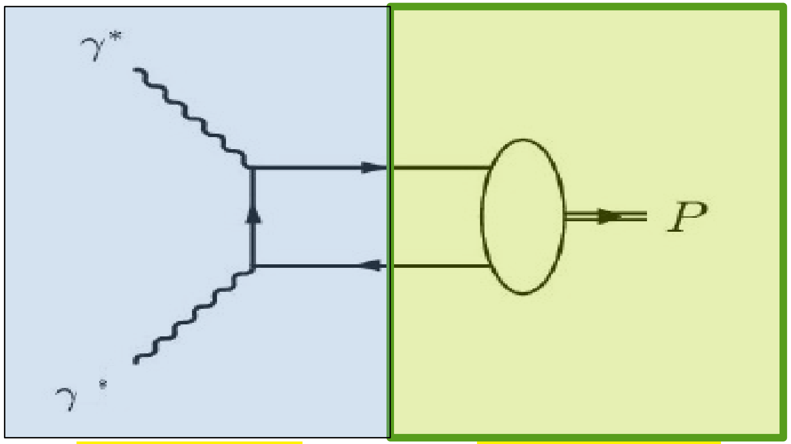
$$B(\phi \to \eta' \gamma) = (11,4^{+5,4}_{-4,4} \pm 2,0) \cdot 10^{-5}.$$

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

  where Λ_P — effective pole mass parameter

Introduction. Experimental data (with sist. uncert.) vs VMD.





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 → 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 $\boldsymbol{\varphi(x,Q^2_1,Q^2_2)}$ is unknown, but its evolution with $\boldsymbol{\mu^2 = Q^2_1+Q^2_2}$ is predicted by pQCD:

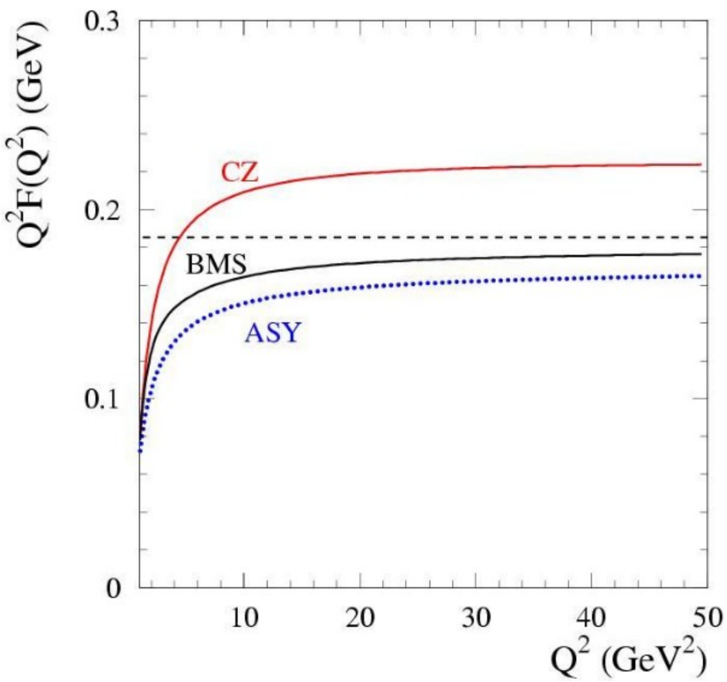
$$\mu^2\frac{d}{\mu^2}\phi(x,\mu) = \frac{\alpha_s(\mu)}{2\pi}\int_0^1 dyV(x,y)\phi(y,\mu)$$

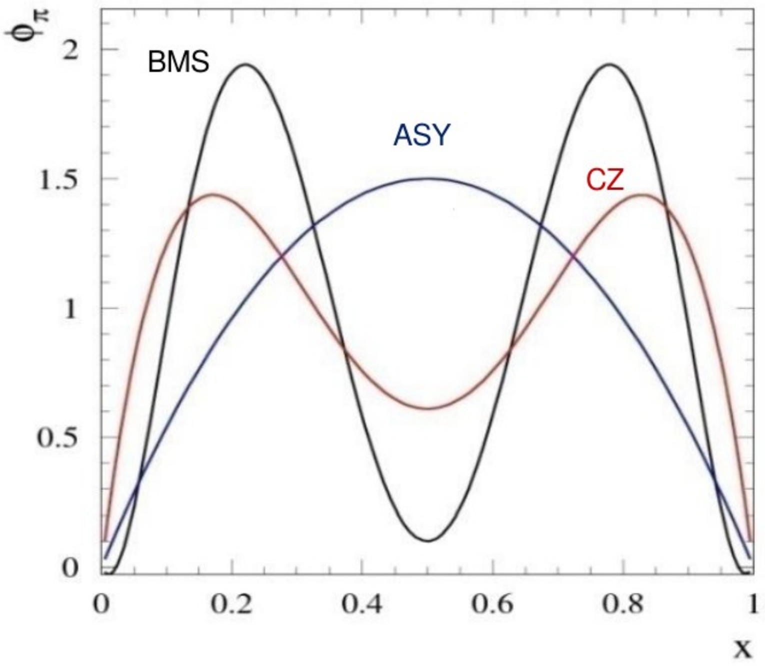
At the limit $\boldsymbol{\mu\to\infty}$

$$\phi_P(x,\mu) = A_P 6x(1-x)(1+O(\Lambda^2_{QCD}/\mu^2))$$

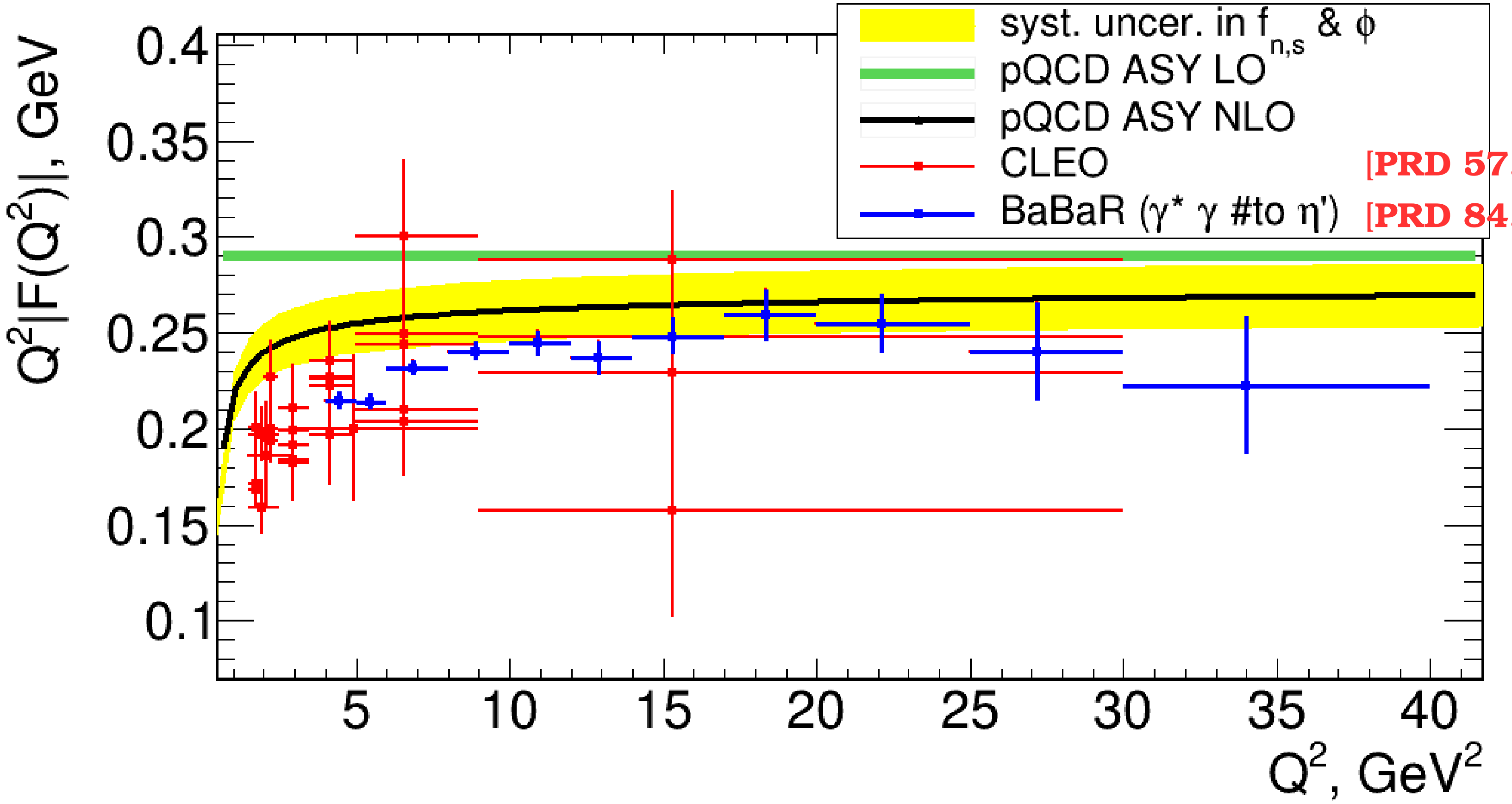
[S. J. Brodsky and G. P. Lepage, Phys. Rev. D 24, 7 (1981)]

ASY: G. P. Lepage and S. J. Brodsky, Phys. Lett. B 87, 359 (1979)
CZ: V. L. Chernyak and A. R. Zhitnitsky, Nucl. Phys. B 201, 492 (1982)
BMS: A. P. Bakulev, S. V. Mikhailov, and N. G. Stefanis, Phys. Lett. B 508, 279 (2001)





- The QCD evolution of the DA is very slow.
- Wider DA corresponds to a higher level of $Q^2F(Q^2)$ at large Q^2



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

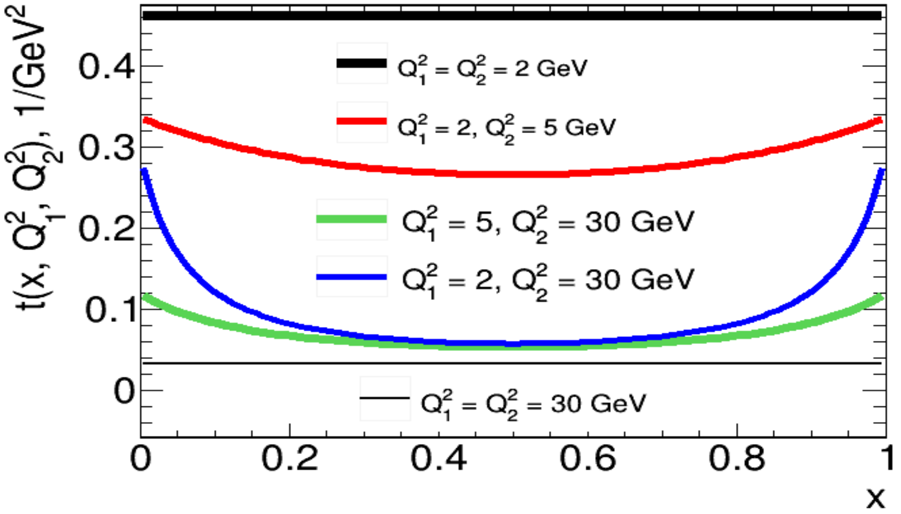
The $\gamma^*\gamma \to \eta'$ Transition Form Factor

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

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.

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

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

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.

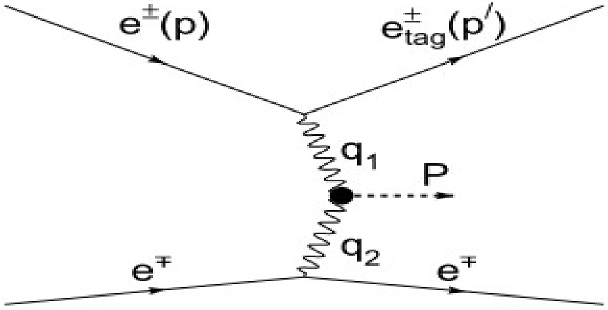
The analysis is based on the previous BaBar study [1].

Previous

$\gamma\gamma^* \to \eta'$

Single tagged

~ 5000 signal events

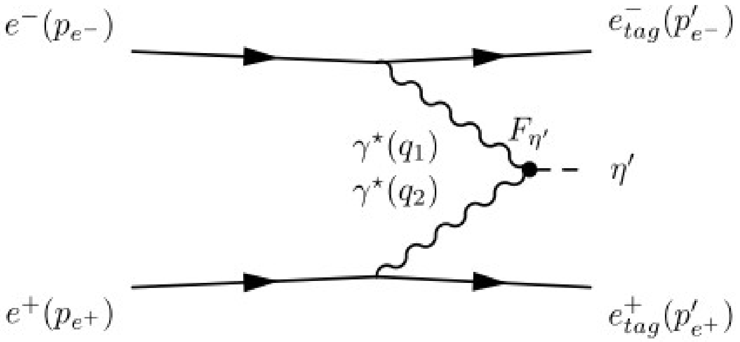


New

$\gamma^*\gamma^* \to \eta'$

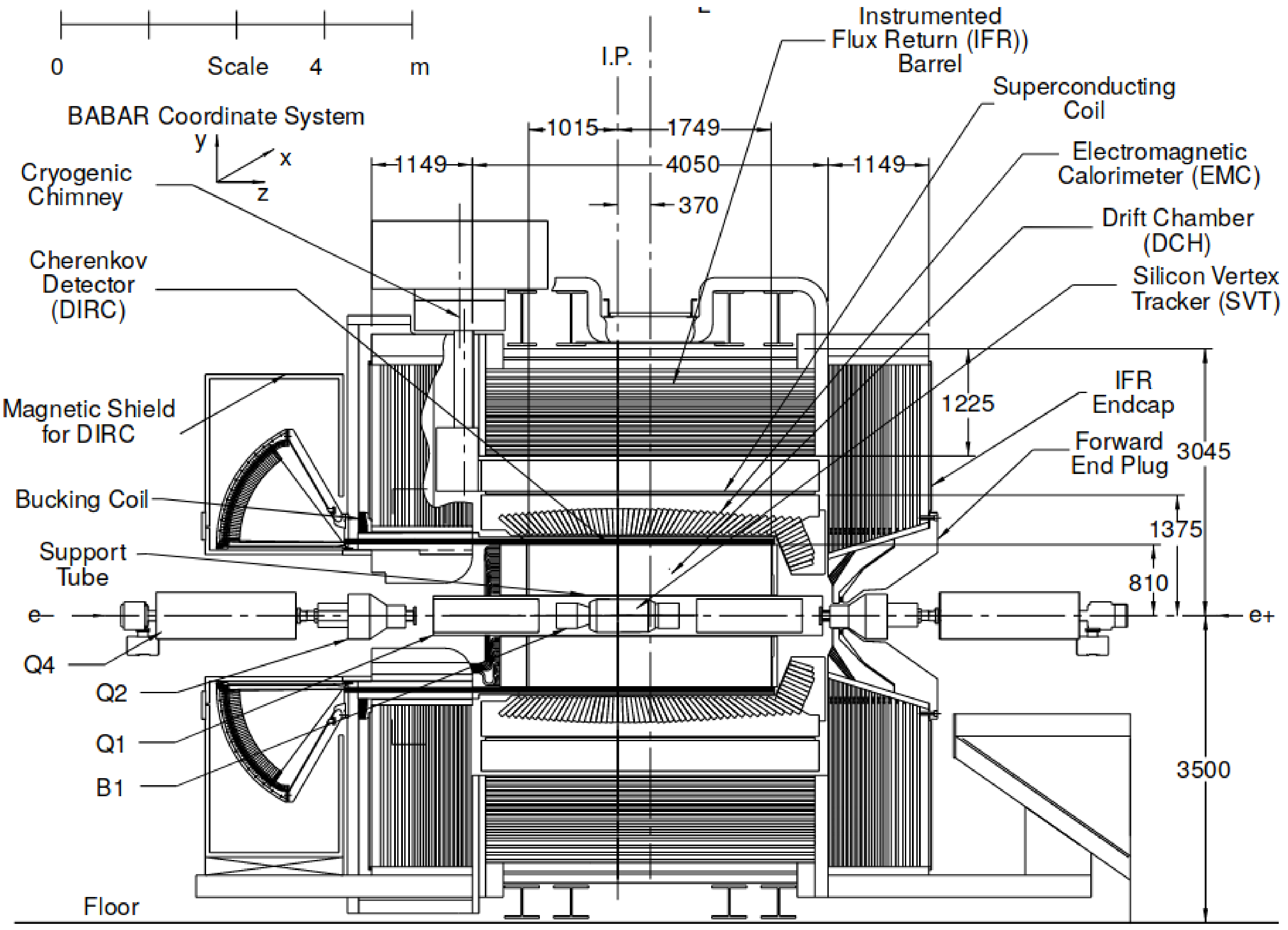
Double tagged

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).


0
Scale
4
m
BABAR Coordinate System
y
x
z
I.P.
Instrumented
Flux Return (IFR))
Barrel
Superconducting
Coil
Electromagnetic
Calorimeter (EMC)
Drift Chamber
(DCH)
Silicon Vertex
Tracker (SVT)
IFR
Endcap
Forward
End Plug
Cryogenic
Chimney
Cherenkov
Detector
(DIRC)
Magnetic Shield
for DIRC
Bucking Coil
Support
Tube
e−
e+
Q4
Q2
Q1
B1
Floor
1015
1749
1149
4050
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1375
810
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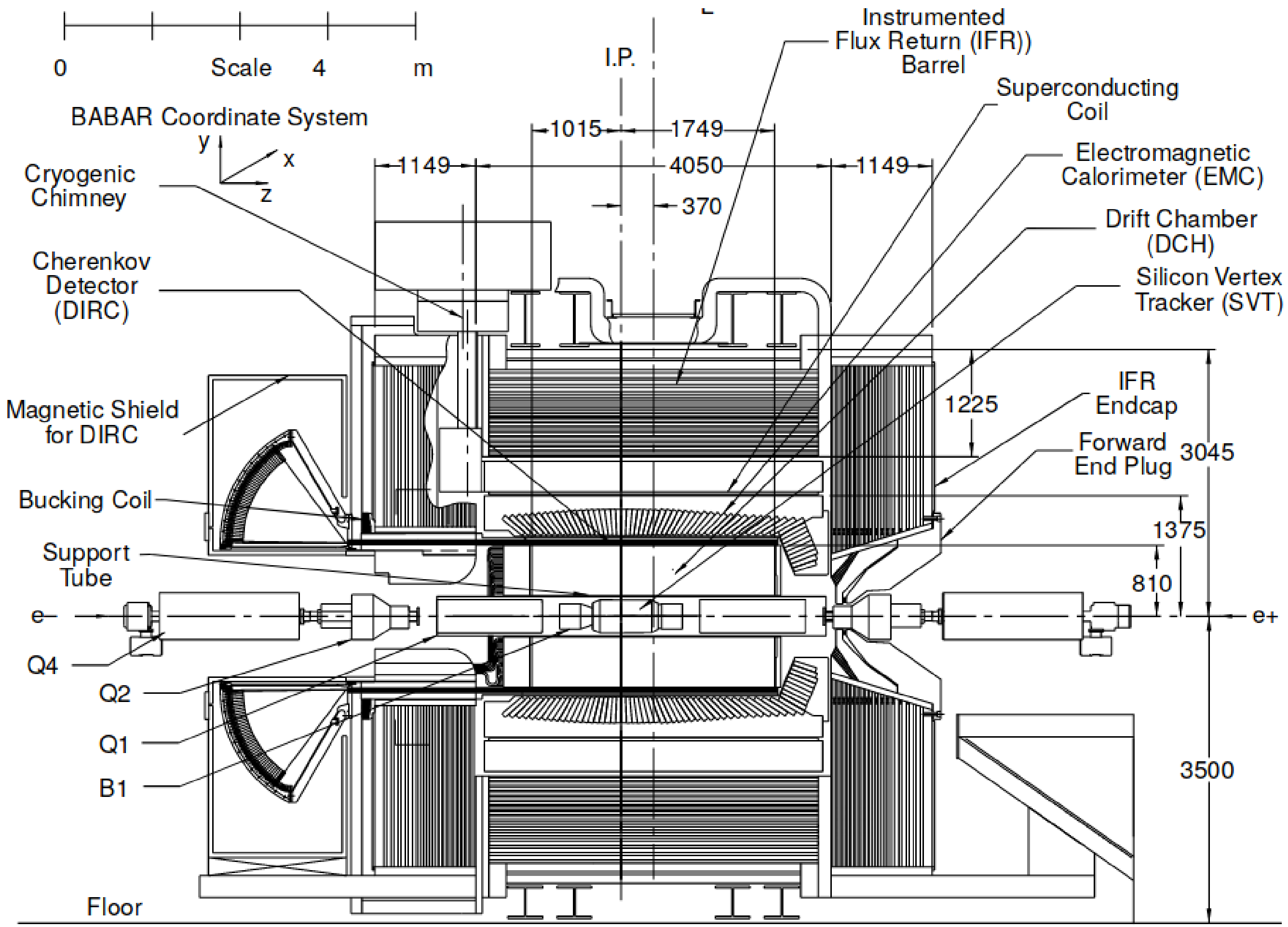
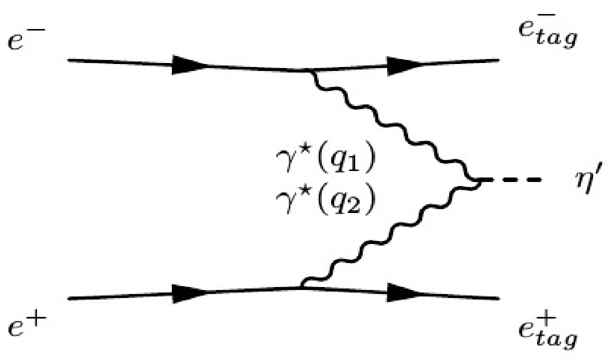


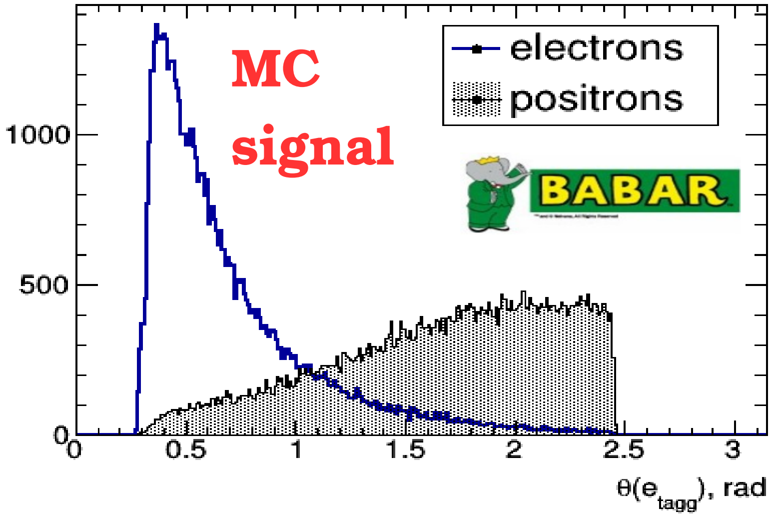
Synergistic effect: $|dA/dt| > |dE/dt + dE/dt|$

Technique

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



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



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

We require the presense

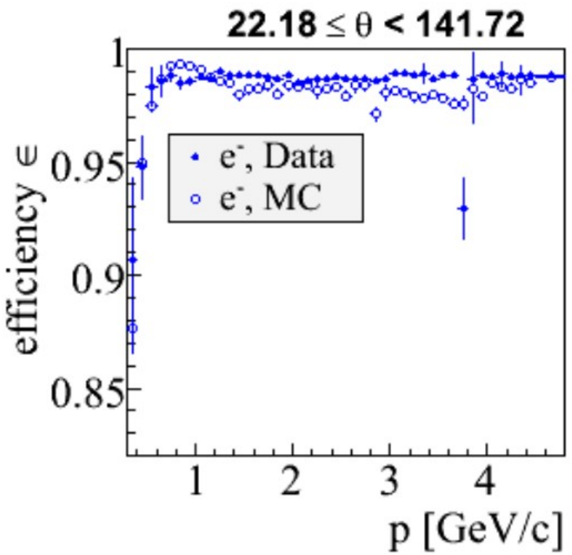
- at least **two tracks** from *GoodTrackLoose* list passed *LooseElectronMicroSecection*
- at least **two tracks** from *GoodTrackLoose* list passed *TightKMPionMicroSelection*
- at least **two photons** from *GoodPhotonLoose* list

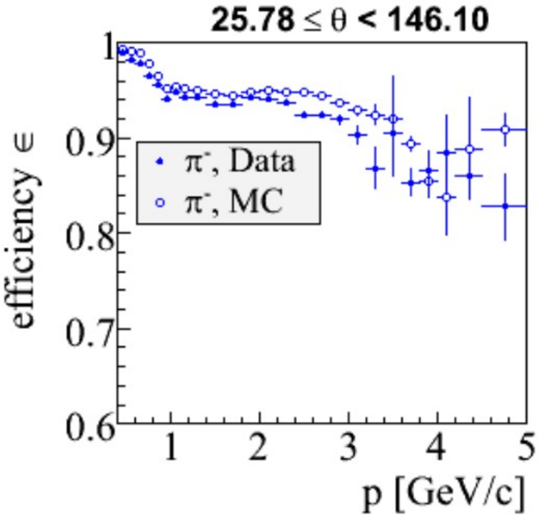
  -ε_{γ} > 30 MeV

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

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

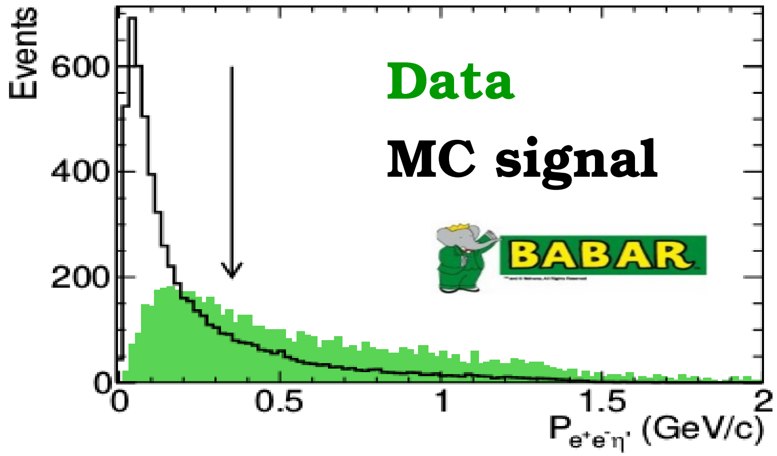
- The η candidate and a pair of oppositely-charged pion candidates are fitted with a η' mass constraint.



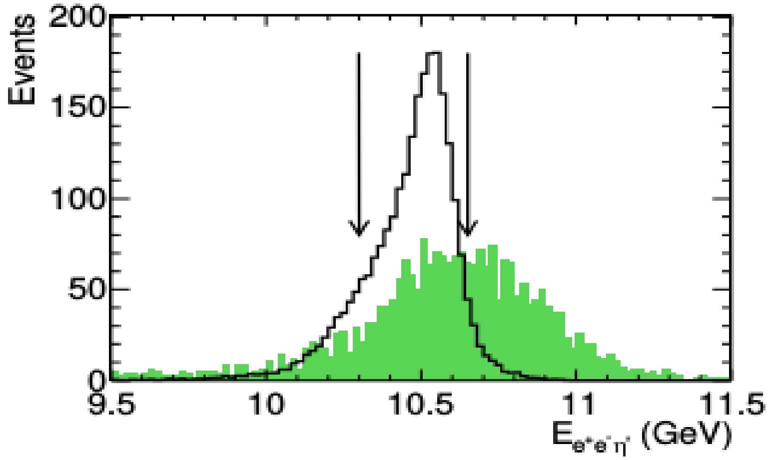


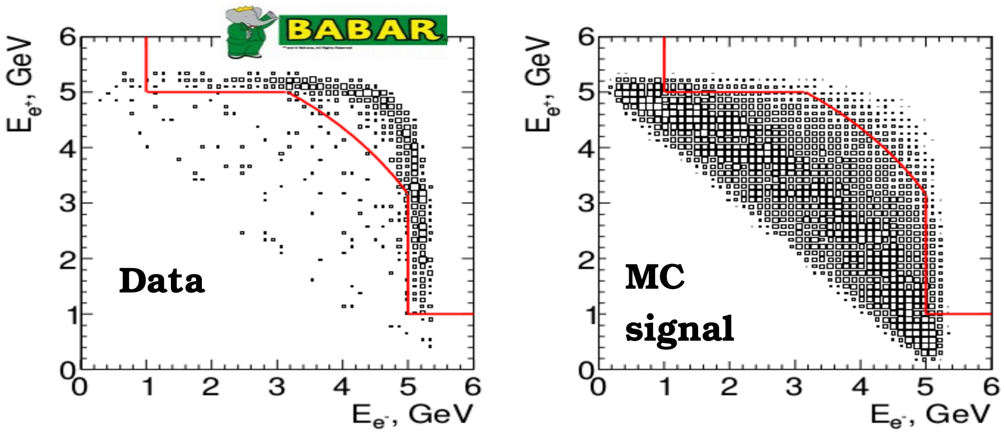
Event selection

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



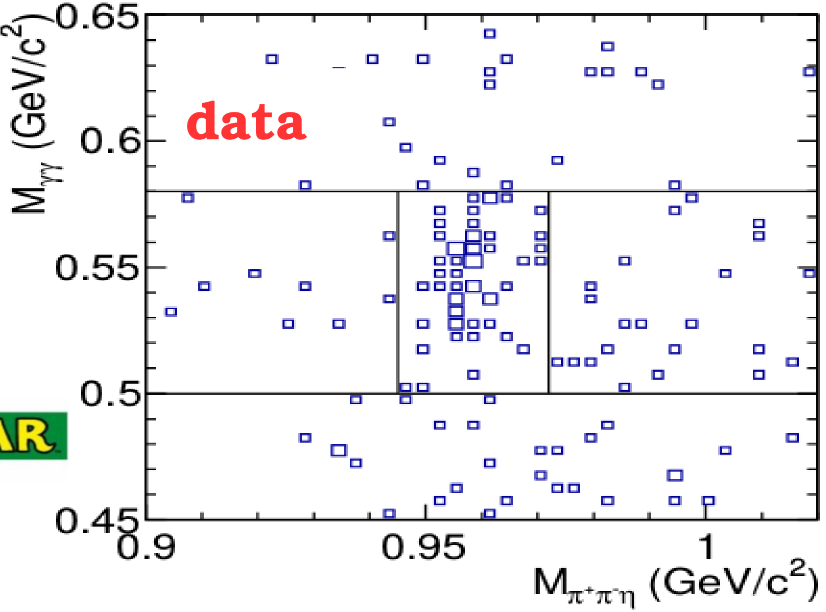
- $10.3 < E_{c.m.}(e^+e^-\pi^+\pi^-\eta) < 10.7$ GeV

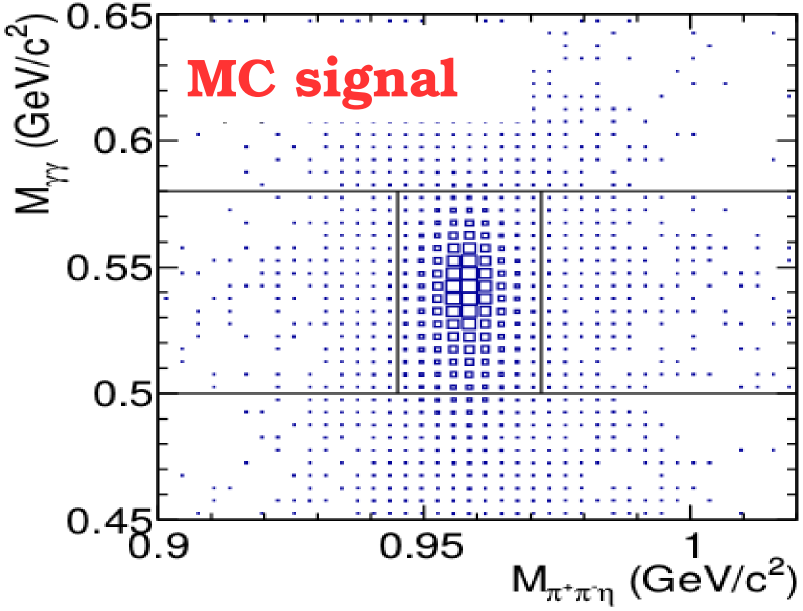




The positron c.m. energy vs the electron c.m. energy

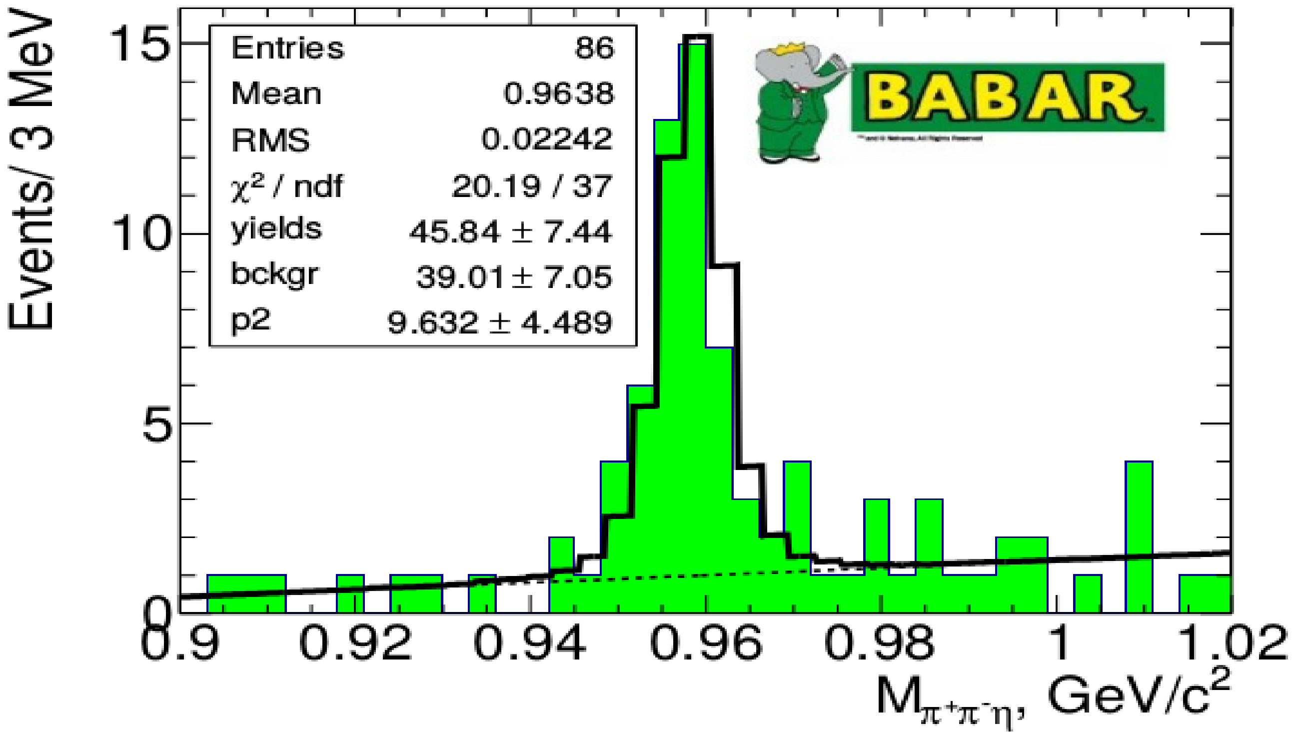
- Events that lie above and on the right of the lines (mostly, Bhabha scattering) are rejected.



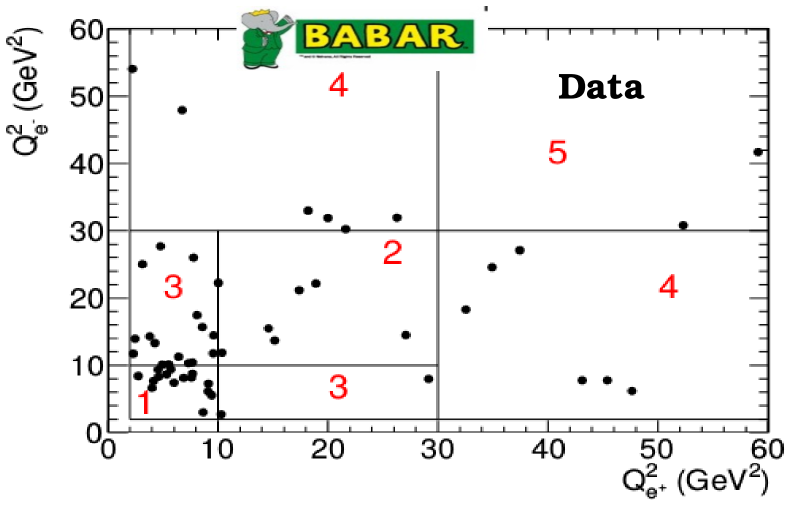


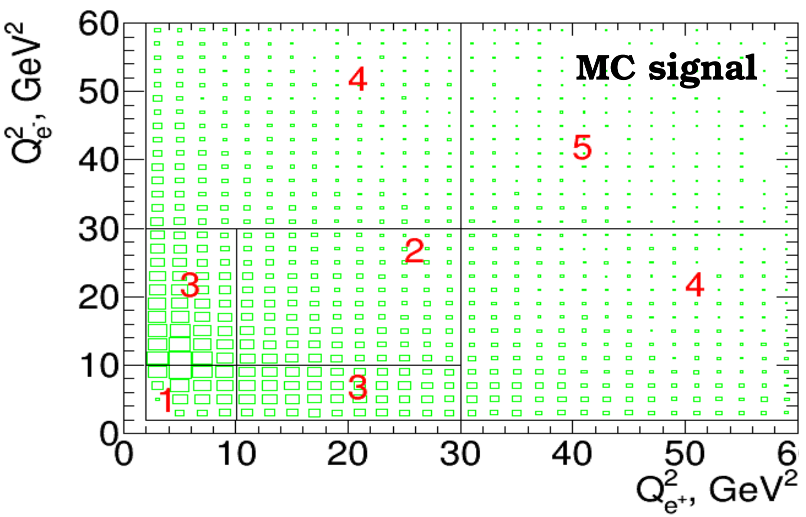
$$m_{\gamma\gamma}\ vs.\ m_{\pi+\pi-\eta}$$

- 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.*





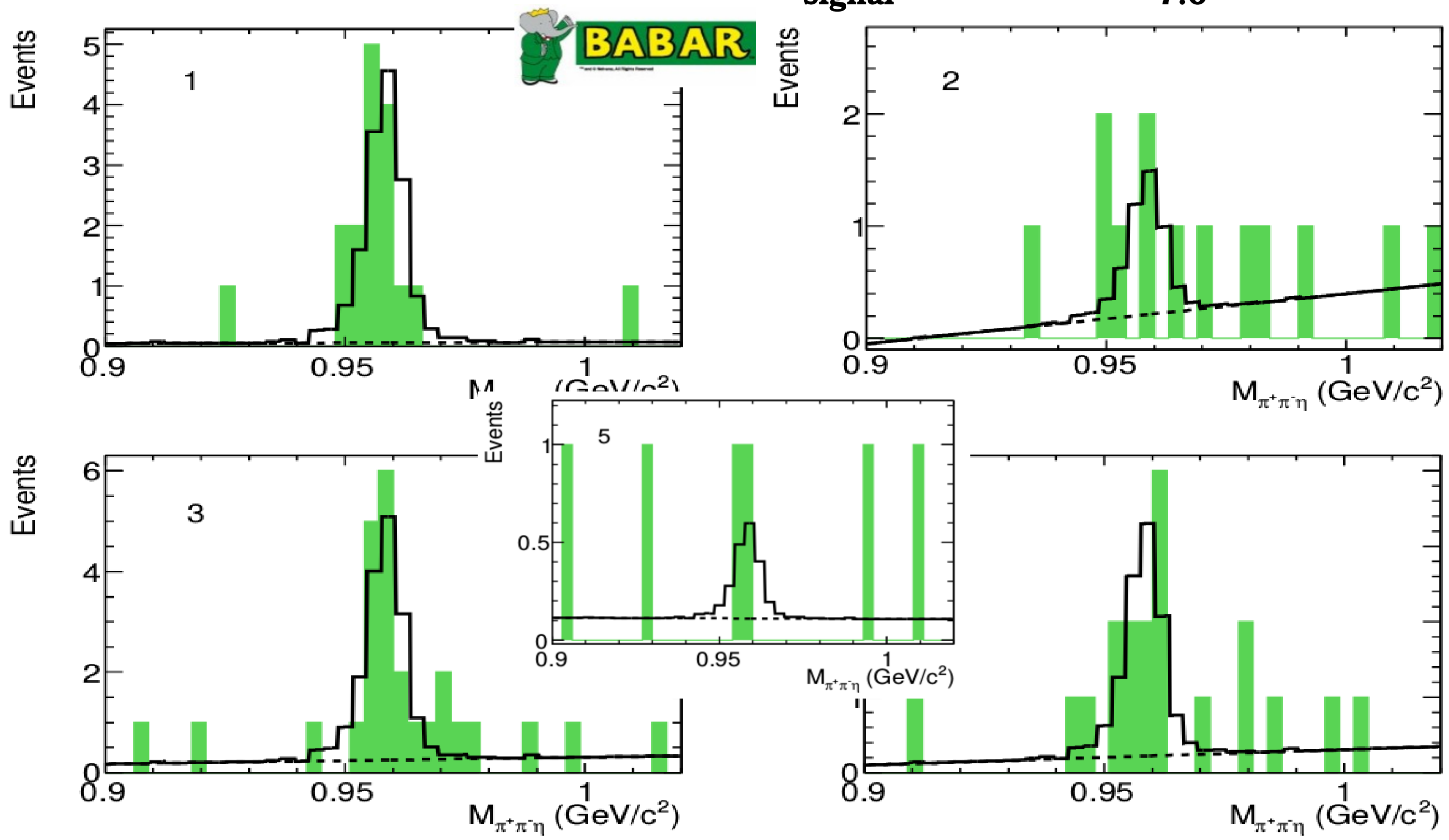
The Q^2_{e-} vs. Q^2_{e+} for events with $\mathbf{0.945 < m_{2\pi\eta} < 0.972}$ *GeV/c²*

- New definition: $Q_1^2 = \max(Q^2_{e+}, Q^2_{e-}),\ Q_2^2 = \min(Q^2_{e+}, Q^2_{e-})$

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

$$\overline{Q^2_{1,2}} = \frac{\sum_i Q^2_{1,2}(i)/\varepsilon(Q_1^2, Q_2^2)}{\sum_i 1/\varepsilon(Q_1^2, Q_2^2)}$$

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

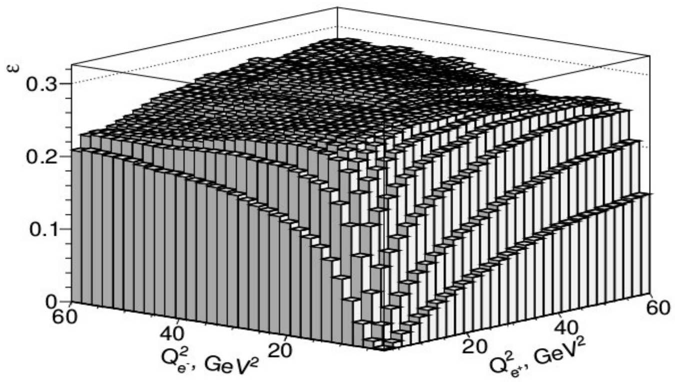


The $\pi^+\pi^-\eta$ mass spectra for data events for the five Q^2 ranges. The open histograms are the fit results. The dashed lines represent background.

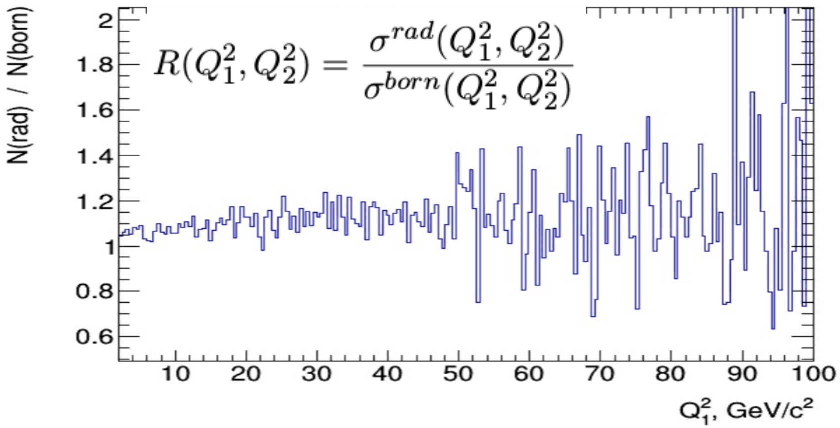
Detection efficiency

- The detector acceptance limits the e^-e^+ detection efficiency at small Q^2. The minimum Q^2 equals to 2 GeV^2.

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



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.

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

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

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

- $B=B(\eta' \to\pi^+\pi^-\eta)\times B(\eta\to2\gamma)=(0.3941 \pm 0.0020)\times(0.429 \pm 0.007) = 0.169 \pm 0.003$
- $\boldsymbol{\sigma_{e+e-\to e+e-\eta'} (2 < Q_1^2, Q_2^2 < 60\ \mathrm{GeV}^2)= (11.4^{+2.8}_{-2.4})\ \mathrm{fb}}$

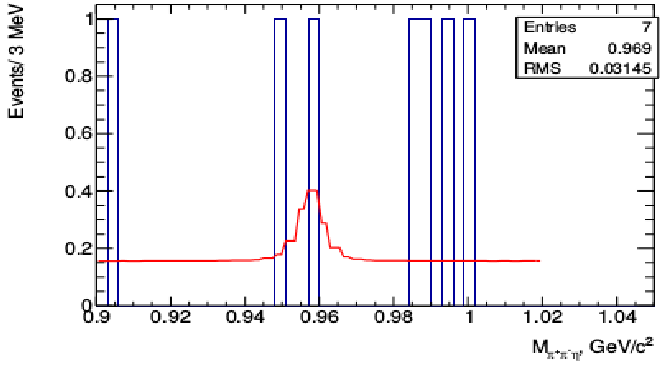
$\overline{Q_1^2}$, $\overline{Q_2^2}$, GeV^2	$\varepsilon_{\rm true}$	R	$N_{\rm events}$	$d^2\sigma/(dQ_1^2dQ_2^2)$ $\times10^4$, fb/GeV^4	$F(\overline{Q_1^2}, \overline{Q_2^2})$ $\times10^3$, GeV^{-1}
6.48, 6.48	0.019	1.03	$14.7^{+4.3}_{-3.6}$	$1471.8^{+430.1}_{-362.9}$	$14.32^{+1.95}_{-1.89} \pm 0.83 \pm 0.14$
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

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 $N_{\eta'\pi0} < 0.16$ at 90% C.L.



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

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

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

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

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

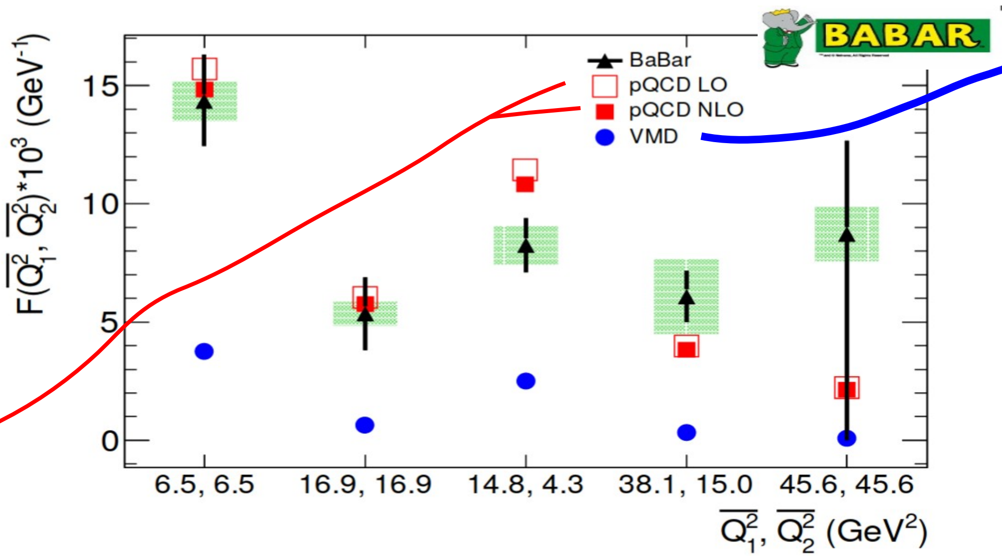
Systematic uncertainty.

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%

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



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

The Λ_P is fixed at 849 MeV/c² from the approximation of $F_{\eta'}(Q^2, 0)$ with one off-shell photon [Phys. Rev. D 85, 057501 (2012)].

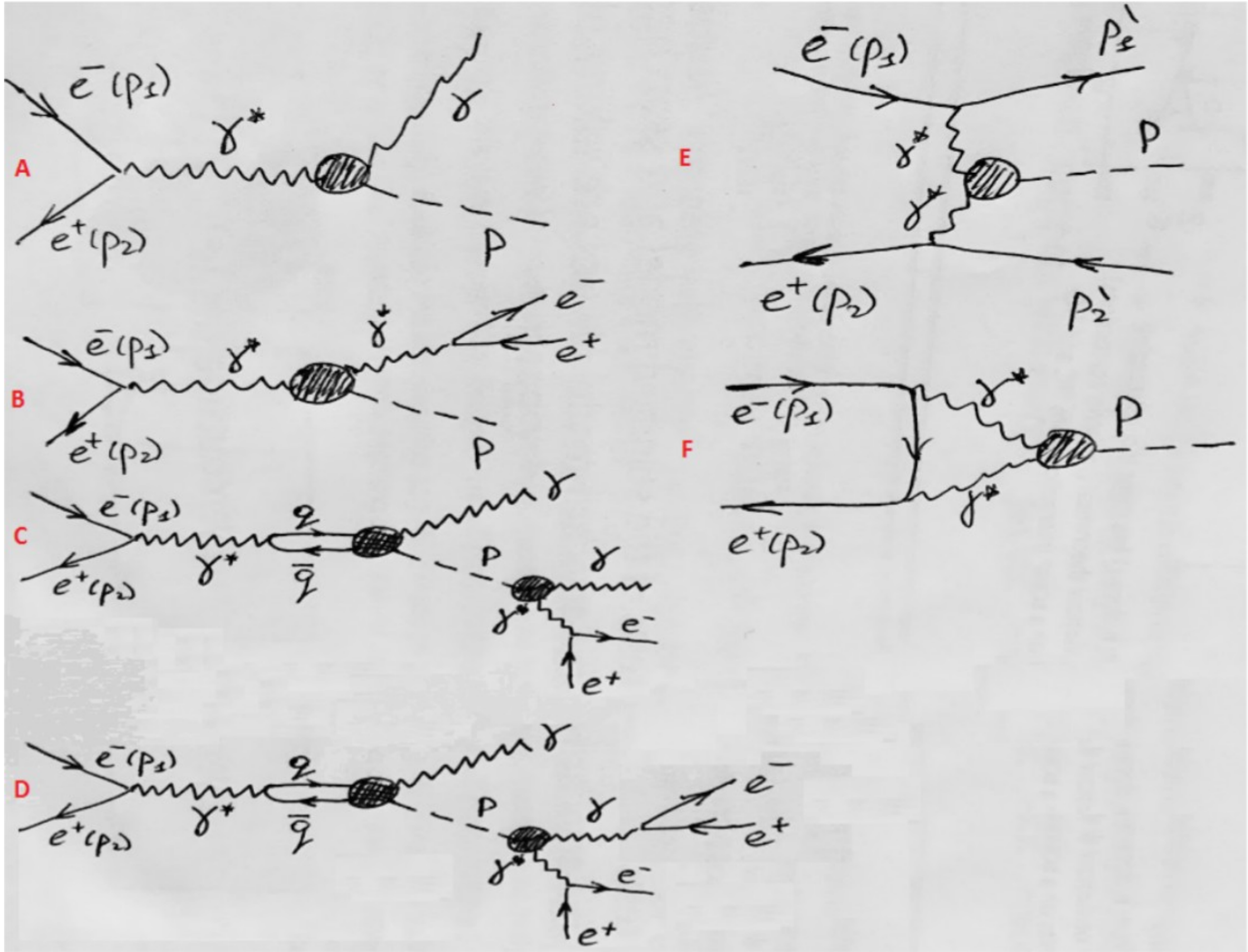
The comparison of obtained form-factor with theoretical predictions. Error bars - statistical uncertainties. Shaded rectangles - quadratic sum of the systematic and model uncertainties.

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.

The most important two-photon processes, realized at the electron-positron low-energy collider



Дважды виртуальные фф легче мерить, меньше требований к качеству детектора, т. к. все частицы детектируются

It is promising to use the magnetic dipole decay $\varphi \to P\gamma$ with following decay chains **$P \to l^+l^-$, $l^+l^-\gamma$, $l^+l^-l^+l^-$**, that are sensitive to $TFF_P(q_1^2 > \sim 0, q_2^2 > \sim 0)$.

decay	π^0	η	η'
e^+e^-	$(6.46 \pm 0.33) \cdot 10^{-8}$	$< 2.3 \cdot 10^{-6}$	$< 5.6 \cdot 10^{-9}$
$\mu^+\mu^-$	forbidden	$(5.8 \pm 0.8) \cdot 10^{-6}$	no search
$e^+e^-\gamma$	$(1.174 \pm 0.035) \cdot 10^{-2}$	$(6.9 \pm 0.4) \cdot 10^{-3}$	$(4.73 \pm 0.30) \cdot 10^{-4}$
$\mu^+\mu^-\gamma$	forbidden	$(3.1 \pm 0.4) \cdot 10^{-4}$	$(1.09 \pm 0.27) \cdot 10^{-4}$
$e^+e^-e^+e^-$	$(3.34 \pm 0.16) \cdot 10^{-5}$	$(2.40 \pm 0.22) \cdot 10^{-5}$	no search
$\mu^+\mu^-\mu^+\mu^-$	forbidden	$< 3.6 \cdot 10^{-4}$	no search
$e^+e^-\mu^+\mu^-$	forbidden	$< 1.6 \cdot 10^{-4}$ ~2 10^{-7}	no search
$\sigma(ee \to P\gamma)_{\sqrt{s}=m_\phi} \times 5fb^{-1}$	$26 \cdot 10^6$	$111 \cdot 10^6$	$0.7 \cdot 10^6$

Experimental results on the photo leptonic decays of pseudoscalar mesons [PDG].

The last line corresponds to the produced sample of the mesons with integrated luminosity around 5 fb^{-1}.

It is promising to study $\mathbf{e^+e^- \to e^+e^-P}$, that are sensitive to $\mathbf{TFF_P(q_1^2<0,q_2^2<0)}$.

single tagged: $\mathbf{0.4 < \theta_{e\pm} < \pi - 0.4}$ **rad**

double tagged: $\mathbf{0.4 < \theta_{e-}, \theta_{e+} < \pi - 0.4}$ **rad**

Large angle scattering is suppresed by factor $\mathbf{1/(k_{tr}^2 + m^2x)}$ in each photon flux, but in case of η and η': $\mathbf{x \sim 0.5}$

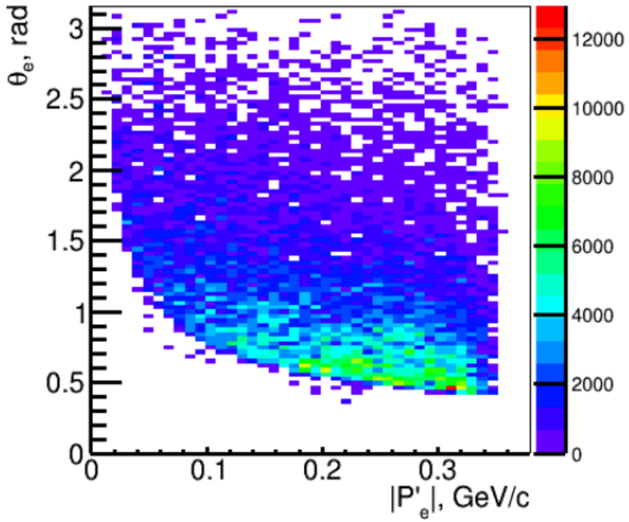
mode\meson	π, pb	η, pb	η′, pb
no tagged	284	32	2
single tagged	17	5.2	0.7
double tagged	1.7	0.8	0.2

The calculation is performed by using the EKHARA generator, the answer does not strongly depend on input model for TFF:

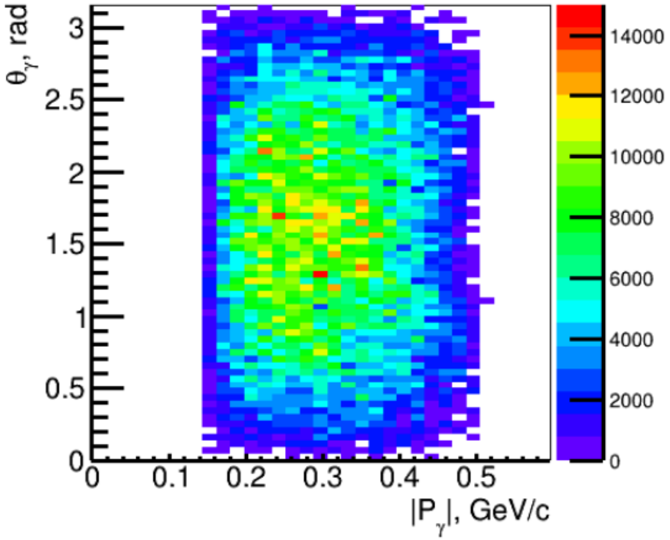
H. Czyż, S. Ivashyn, Comput. Phys. Commun**182**, (2011), 1338–1349.

Additionally to previous proposal [D. Babusci et al., EPJ C72, 1917 (2012)] to measure the width $\Gamma_{\pi 0 \to \gamma\gamma}$ and the $\pi^0\gamma\gamma^*$ form factor $F(Q^2 < 0.1\ \mathrm{GeV}^2)$ it is interesting to make, for the first time, **double tagged** studies with less statistics.

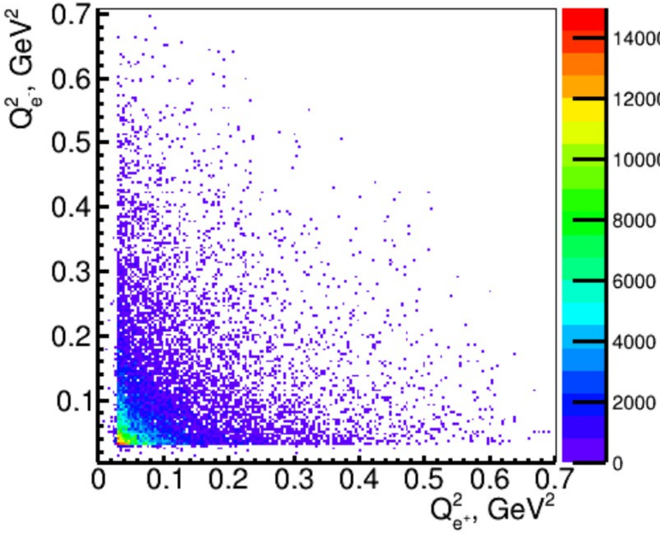
Additional plots for $\mathbf{e^+e^- \to e^+e^-P \to \eta e^+e^- \to \gamma\gamma\ e^+e^-}$ at $E_{c.m.} = 1.02$ GeV with the restriction ($Q^2_{1,2} > 0.03$ GeV^2):



The polar angle vs momentum of scattered fermion in c.m.f.



The polar angle vs momentum of photonsfrom the decay $\eta \to 2\gamma$

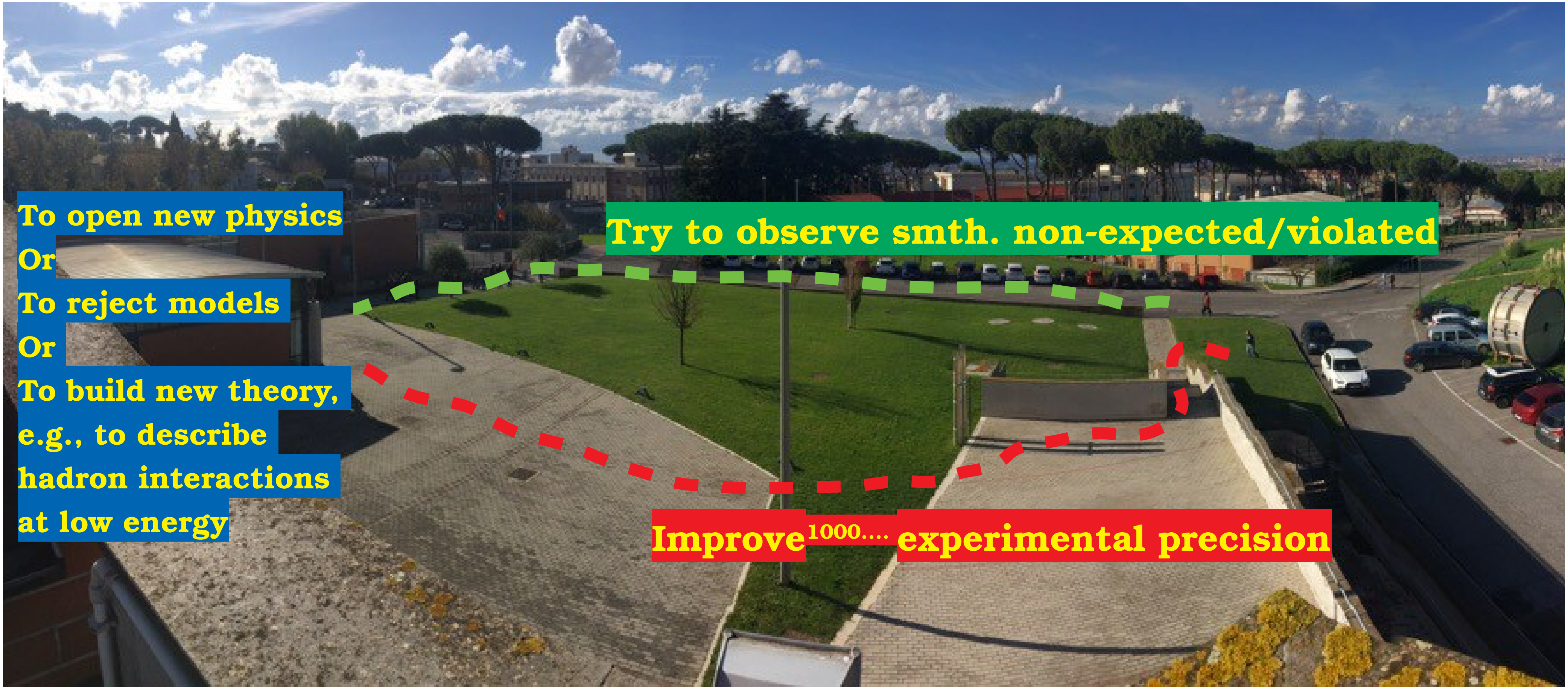


The Q^2_{e-} vs Q^2_{e+} distribution for generated events

GGResRc event generator is used [arXiv:1010.5969]

- About 46 events of $e^+e^- \to e^+e^-\eta'$ were observed in the BABAR double tagged mode for the first time with BaBar detector.
- 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.
- The form factor is in reasonable agreement with the pQCD prediction.
- I propose a measurement of this quantity at BELLE II.
- It is promising to perform competitive studies of $\gamma^*\gamma^*\to P$ with KLOE-(2), however deep efforts to study of background processes are required.

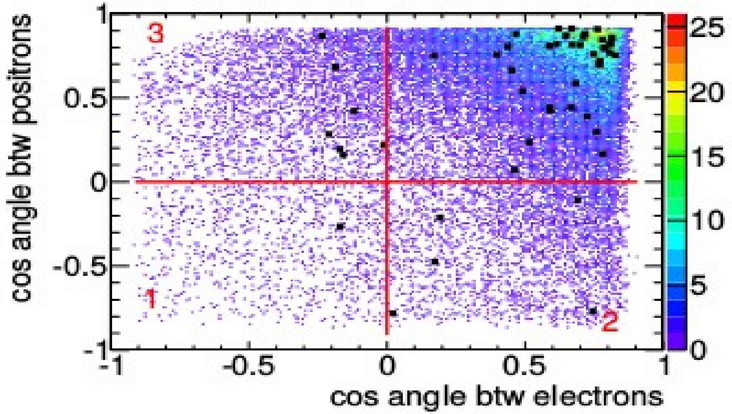
There are alternatives ways:



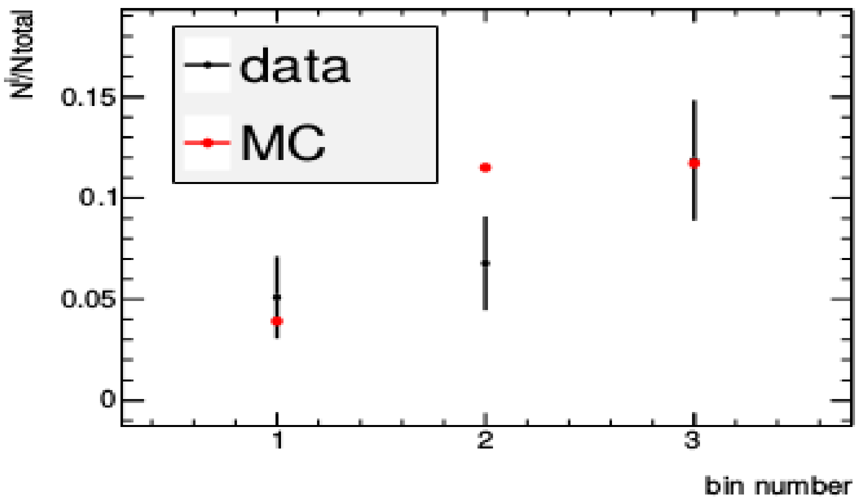
Thank you for your attention

Back up slides

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

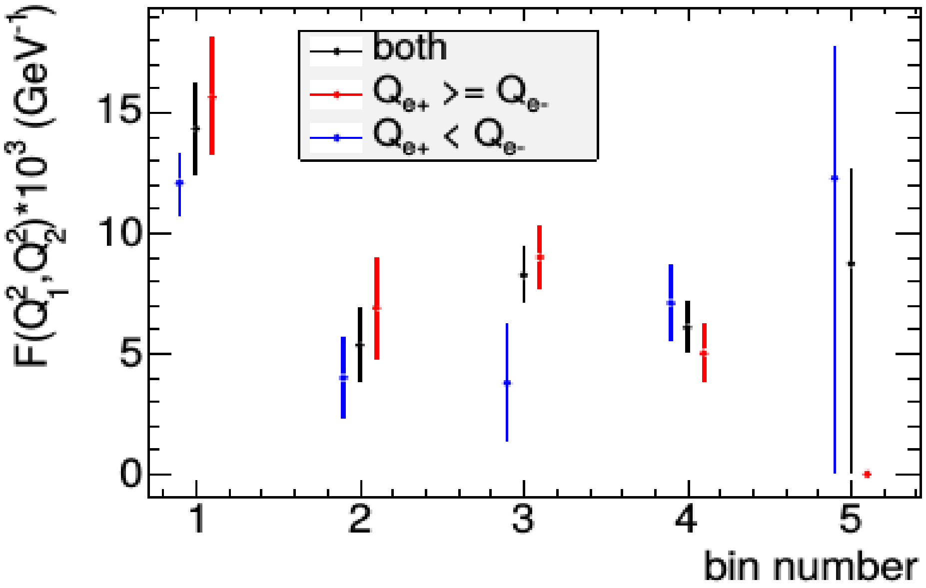


The cosine of angle between scattered and initial electron (positron) in c.m.f.



The fraction of the events in the bins.

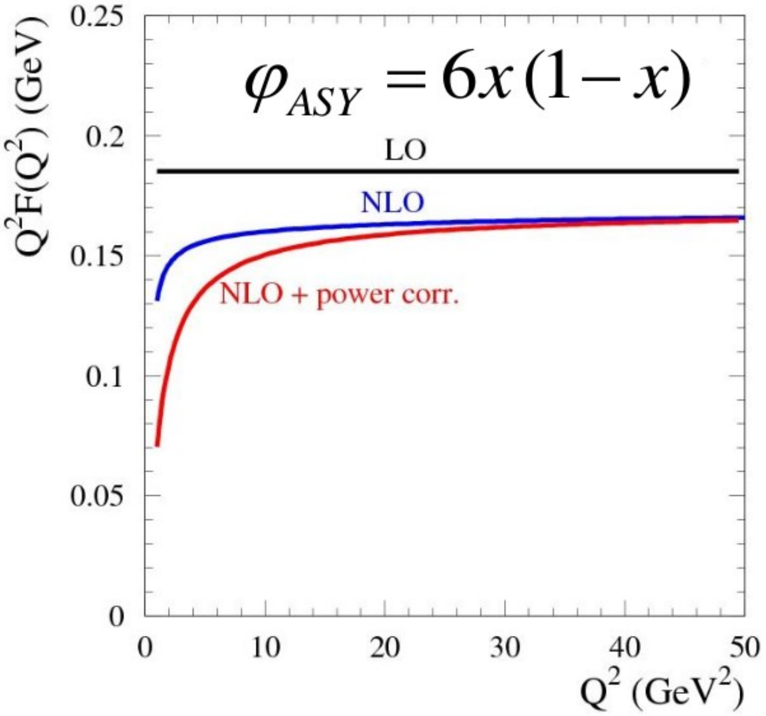
It is reasonable to assume that the cos($\alpha_{e\pm}$) spectrums must be symmetric in [-1:1] region for **annihilation processes**, while signal scattered electron (positron) prefers to fly in the about the same direction.



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

The leading contribution:

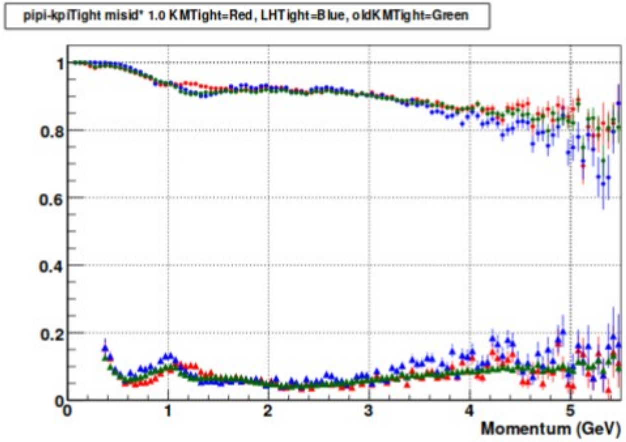
$$Q^2F(Q^2)=\frac{\sqrt{2}f_\pi}{3}\int_0^1\frac{dx}{x}\varphi_\pi(x,Q^2)+O(\alpha_s)+O(\Lambda^2_{QCD}/Q^2)$$



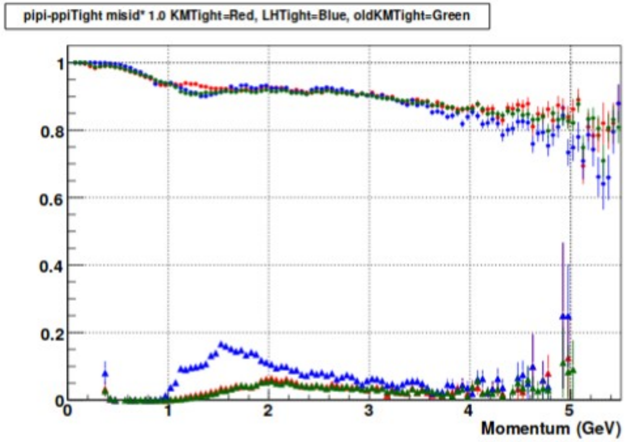
A.P.Bakulev, S.V.Mikhailov and N.G.Stefanis, Phys.Rev. D 67, 074012: light-cone sum rule method at NLO

- NLO and power corrections are large: 30, 20,10 % at 4,10,50 GeV^2.
- Power corrections are 7% at 10 GeV^2 (twist-4 + due to hadronic component of the quasi-real photon).
- What is the model uncertainty of the power corrections?

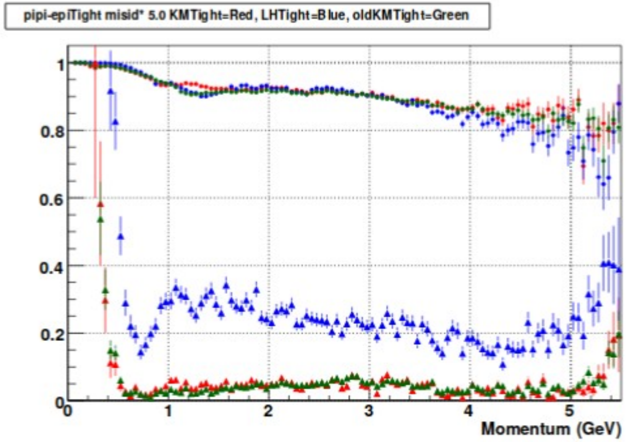
Pions misedentification with *TightKMPionMicroSelection:*



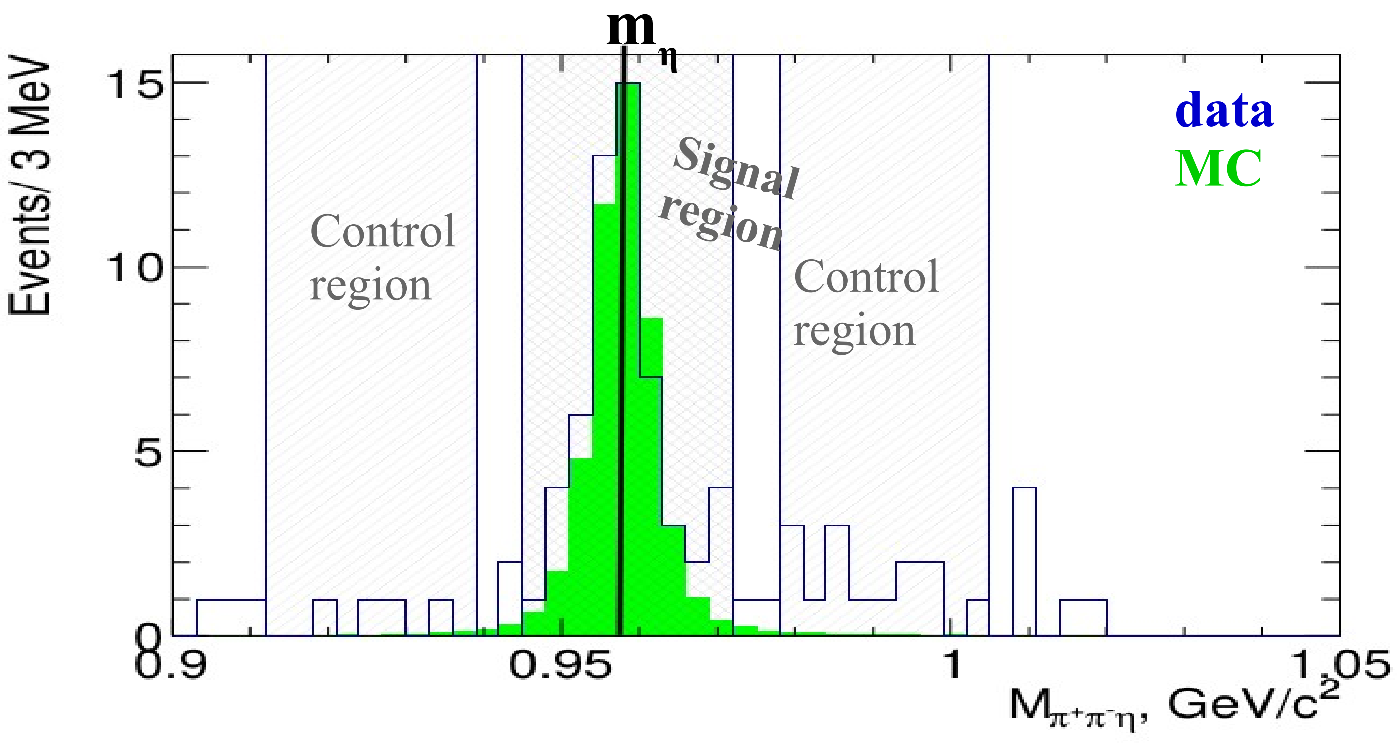
(a) K as π mis-id*1



(b) p as π mis-id*1

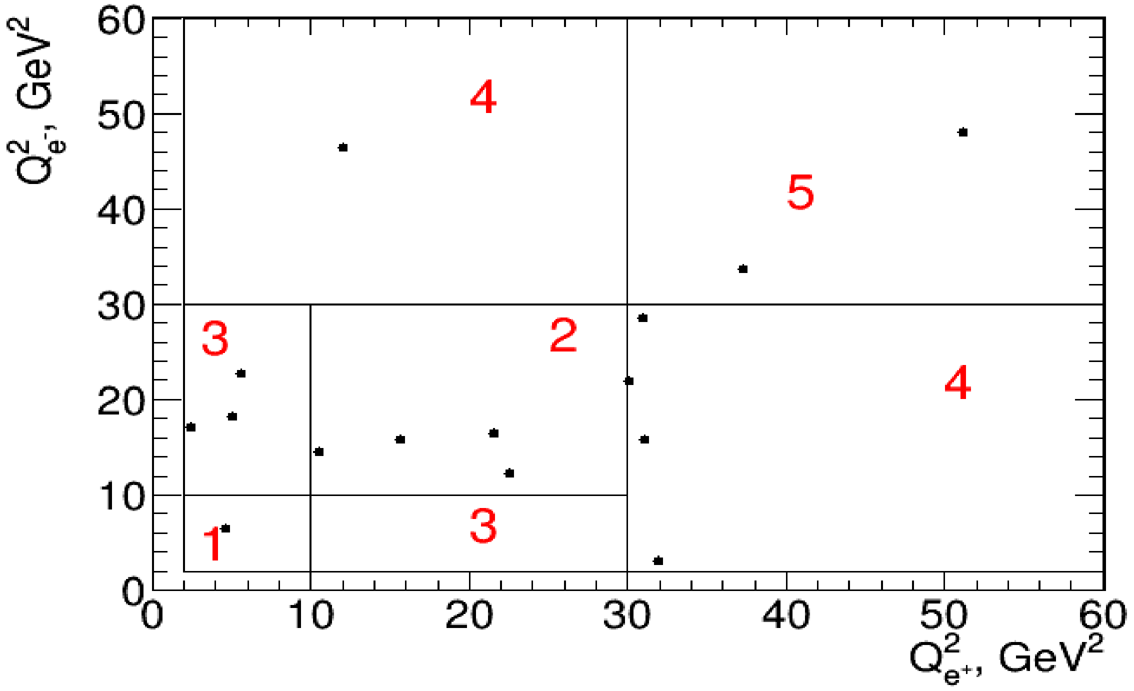


Event selection



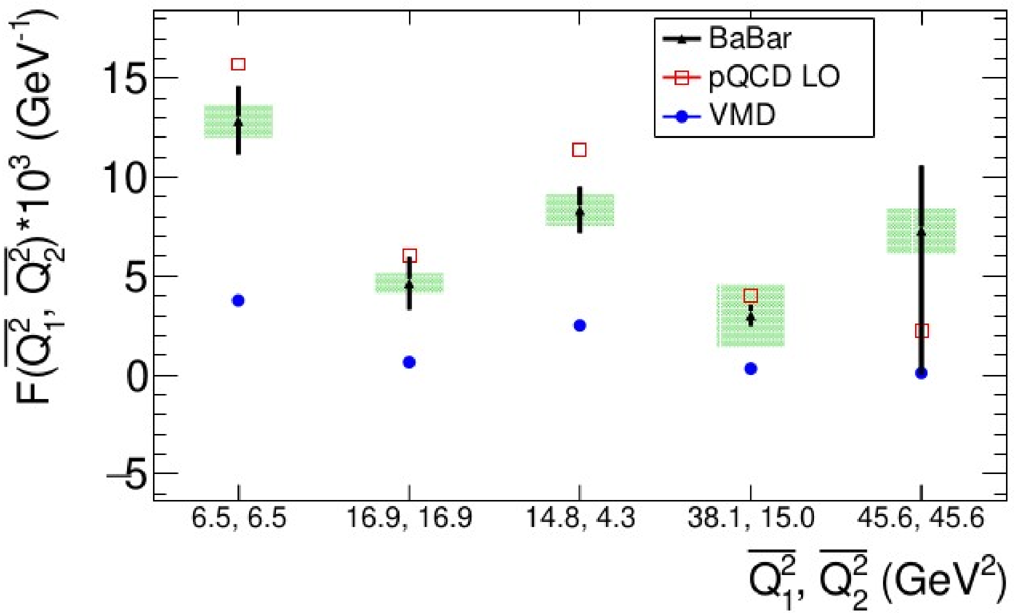
The data-MC comparison of ππη invariant mass distribution. The MC histogram is normalized to central bin of data distribution.

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



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

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

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

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

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