Two-Photon Interactions at BaBar and Belle

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Outline

1. General
2. $\gamma\gamma^* \to \pi^0$ transition form factor (BaBar)
3. $\gamma\gamma \to 2$ hadrons (Belle)
4. Conclusions

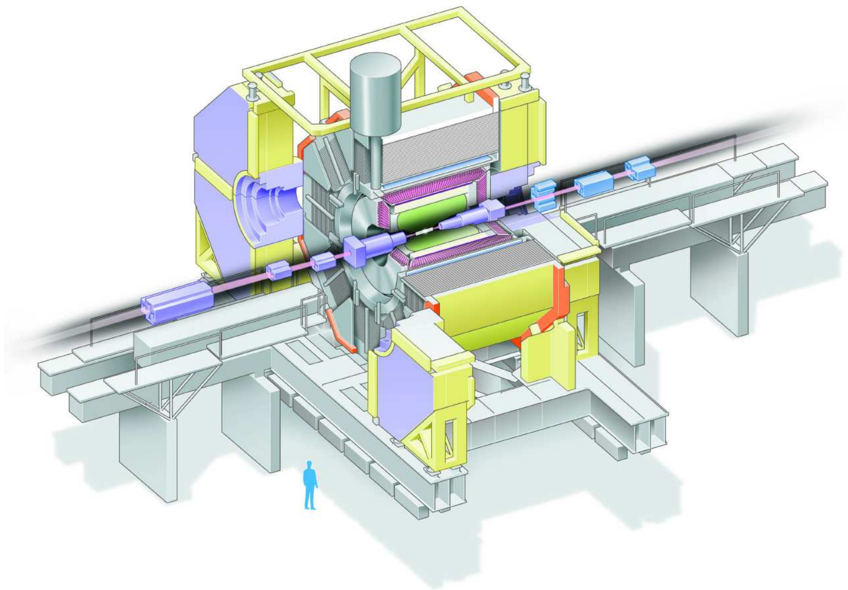
PEP-II and BaBar Detector

- PEP-II: 3.1 GeV $e^+ \times$ 9.0 GeV e^-
- $\mathcal{L}_{\rm max} = 1.21 \times 10^{34} {\rm cm}^{-2}{\rm s}^{-1}$
- Continuous injection $\to 0.91\,{\rm fb}^{-1}$/day
- $\int \mathcal{L}dt \approx 557\,{\rm fb}^{-1}$ Turned off in April 2008
- BaBar – 600 physicists from 75 Institutes in 10 countries

- Sil. vertex tracker
- Drift chamber
- DIRC
- CsI(Tl) calorimeter
- μK_L RPC

KEKB and Belle Detector

- KEKB: 3.5 GeV e^+ × 8.0 GeV e^-
- $\mathcal{L}_{\rm max} = 2.11 \times 10^{34} {\rm cm}^{-2}{\rm s}^{-1}$
- Continuous injection → $1.52\,{\rm fb}^{-1}$/day
- $\int \mathcal{L}dt \approx 948\,{\rm fb}^{-1}$ Operation continues
- Belle – 370 physicists from 60 Institutes in 15 countries

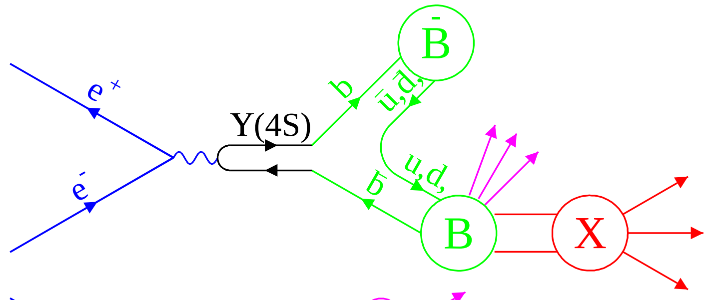


- Sil.VD: 3(4) layers DSSD
- CDC : small cells $He + C_2H_6$
- TOF counters
- Aerogel CC:$n = 1.015 \sim 1.030$
- CsI(Tl) 16 X_0
- SC solenoid 1.5 T
- μK_L detection 14-15 layers RPC+Fe

What And How Is Studied at B Factories

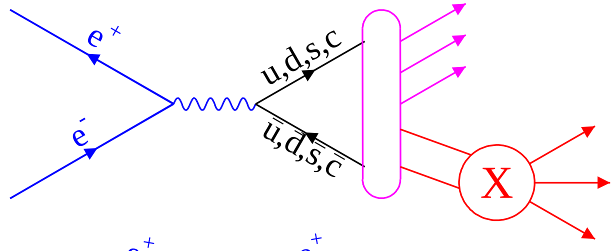
Production from B-decay

(broad D^{**}, D_{sJ}, $X(3872)$, $Y(3940)$)



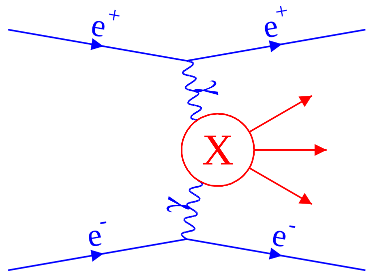
Production from continuum

(D_{sJ}, $\eta_c(2S)$, $X(3940)$, $\Sigma(2800)$)



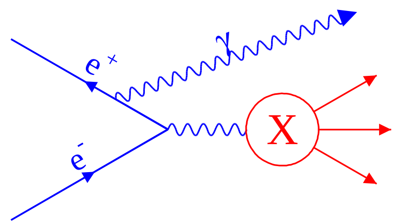
Two-photon production

($Z(3930)$ or $\chi_{c2}(2P)$)



Initial state radiation

($Y(4260)$)

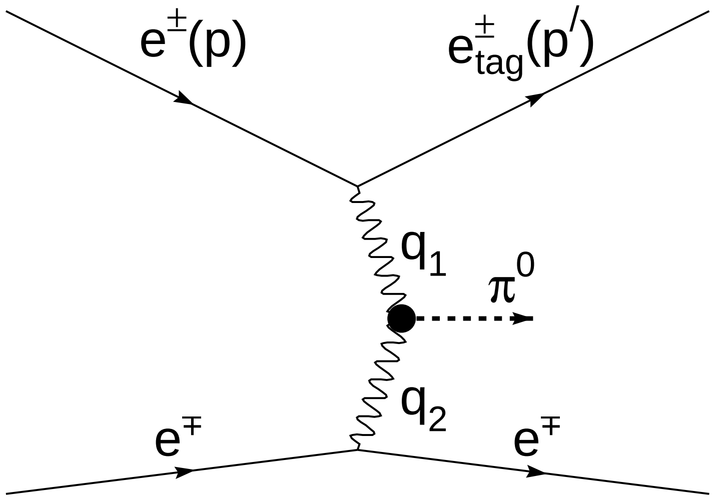


Two-photon Collisions

- Clean source of hadrons with positive C-parity
- Special kinematics:
  final $e^{\pm}$ fly in the same direction as initial $e^{\pm}$ and lose little energy;
  products of $\gamma\gamma$ have small transverse momentum
- Cross section grows as $\ln^3 E_{\rm CM}$
- No-tag: both $e^{\pm}$ undetected
  Single-tag: one $e^{\pm}$ detected
  Double-tag: both $e^{\pm}$ detected
- Excellent laboratory for QCD tests in $\gamma\gamma$ production
  of hadrons and hadronic resonances

$e^+e^- \to e^+e^-\pi^0$ at BaBar – I

Single-tag mode, $442\ \mathrm{fb}^{-1}$ at 10.54 and 10.58 GeV

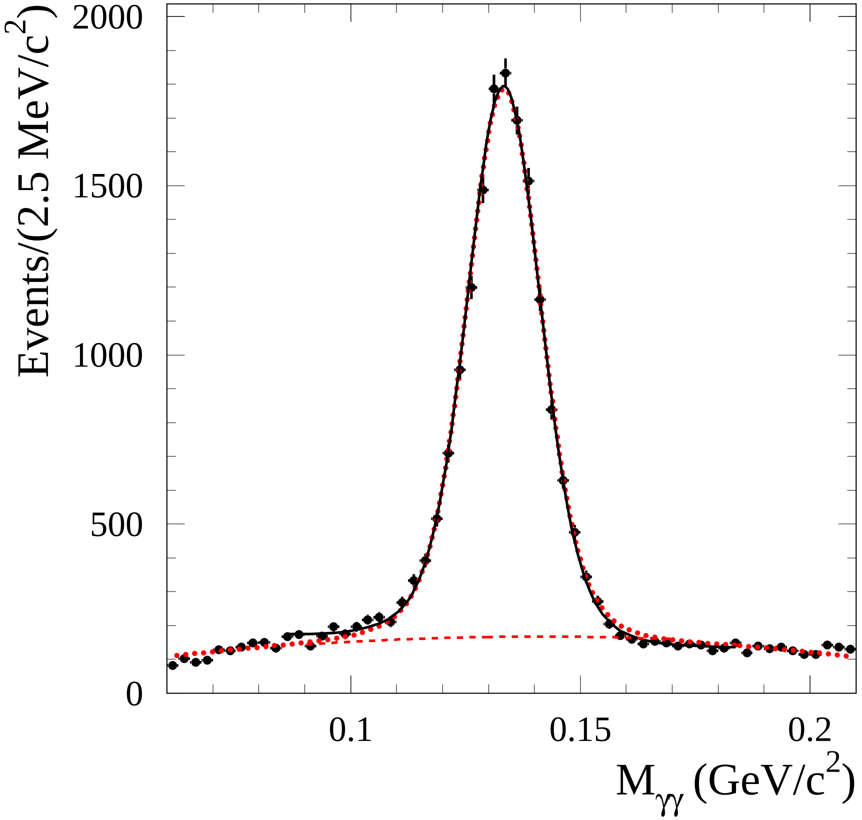


$$q_1^2 \equiv -Q^2 = (p-p')^2,\ \ 4 < Q^2 < 40\ \mathrm{GeV}^2, \quad q_2^2 \approx 0$$

Detector	Q^2, GeV^2	Year
CELLO	0.7 – 2.2	1991
CLEO	1.6 – 8.0	1998

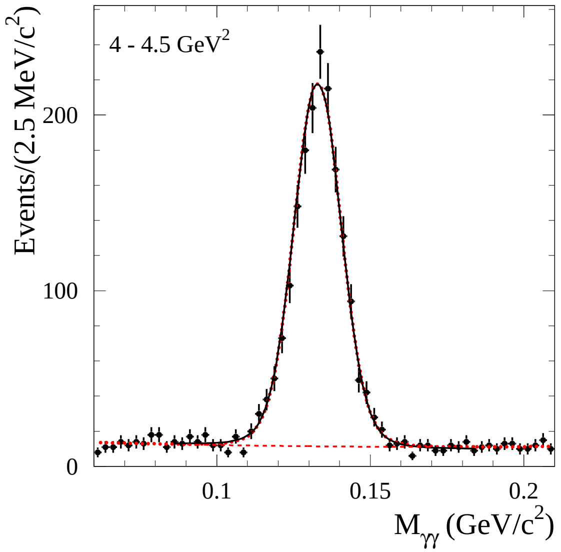
B. Aubert et al., arXiv:0905.4778

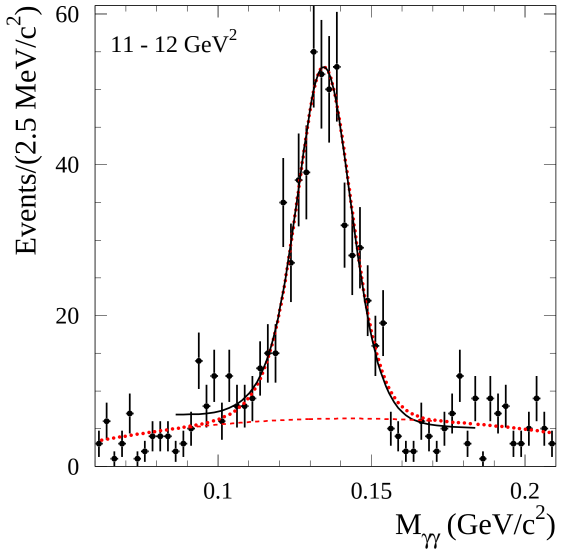
$e^+e^- \longrightarrow e^+e^-\pi^0$ at BaBar – II

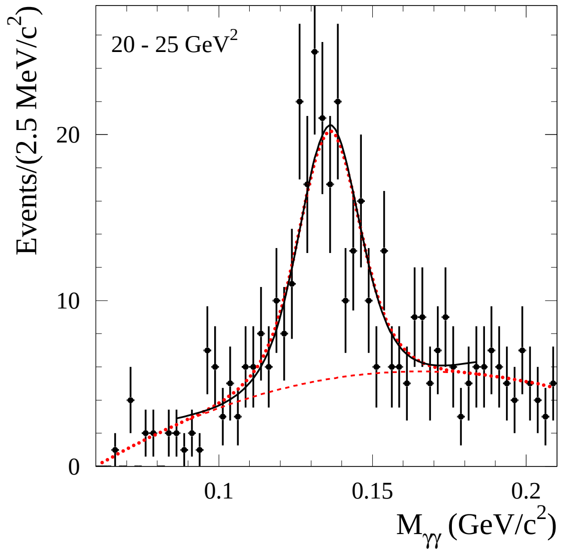


About 13200 events of $\gamma\gamma^* \rightarrow \pi^0$ at BaBar compared to 127 at CELLO and 1219 at CLEO

$e^+e^- \to e^+e^-\pi^0$ at BaBar – III





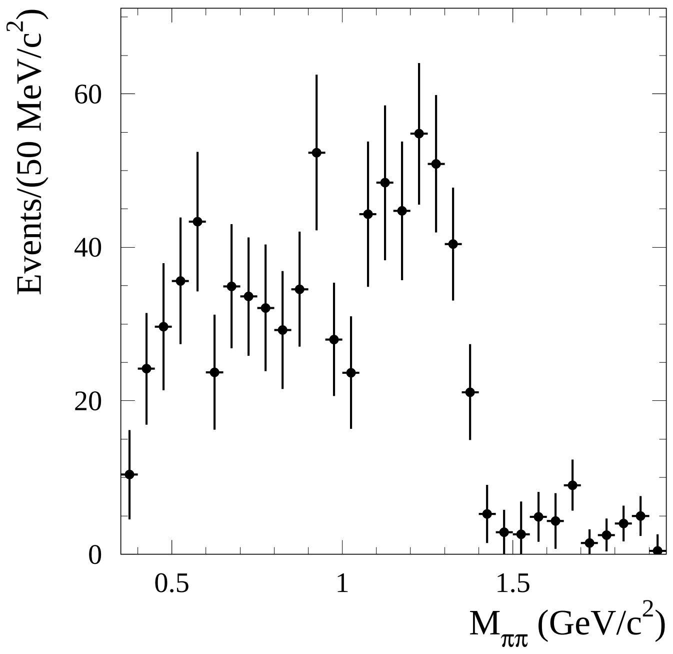


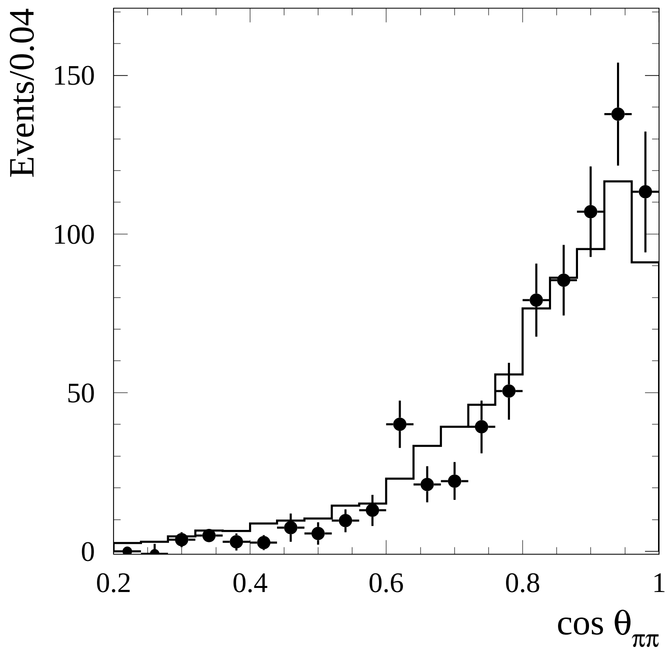
Q^2, GeV^2	4–10	10–15	15–20	20–40
$N_{\rm ev}$	10617	1803	504	274

$e^+e^- \to e^+e^-\pi^0$ at BaBar – IV

The main background comes from virtual Compton scattering, $e^+e^- \to e^+e^-\gamma$, with one final $e^\pm$ at small angles, while the other $e^\mp$ and γ scatter at large angles.

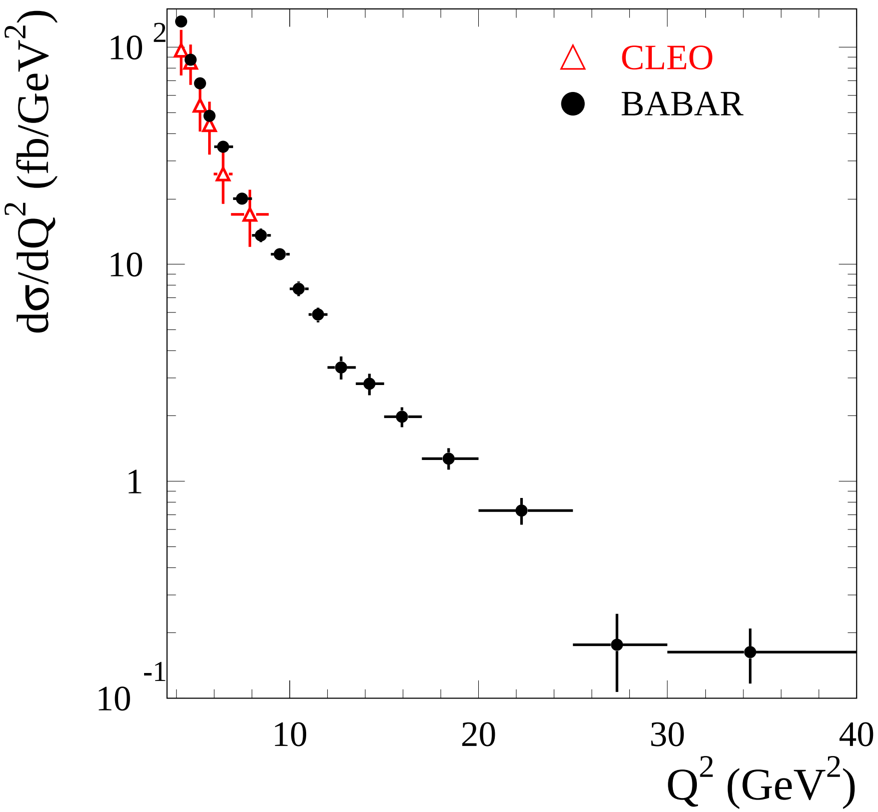
The major peaking background – $e^+e^- \to e^+e^-\pi^0\pi^0$, $\sim$ 1600 events detected





The fraction of the $2\pi^0$ background is 13% at $Q^2 < 10$ GeV^2 and (6-7)% above

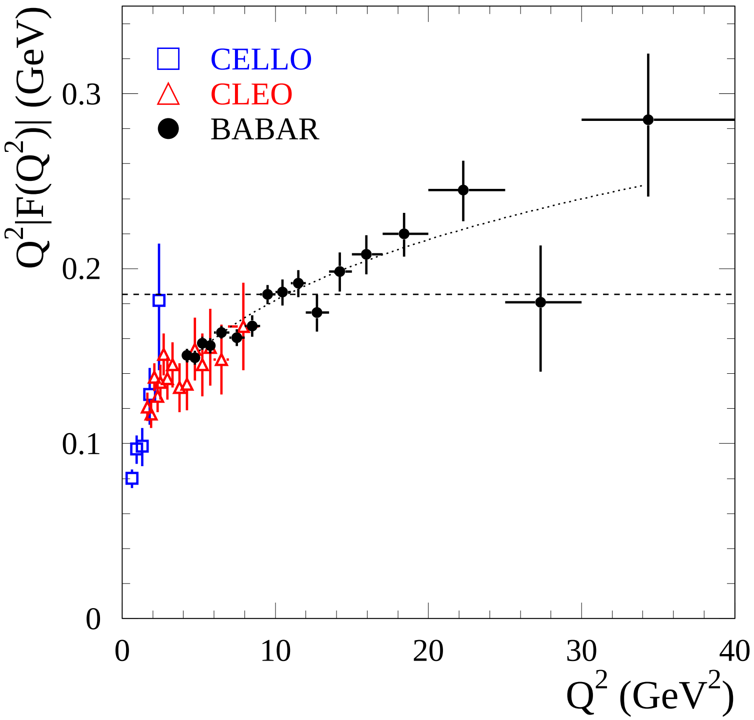
$e^+e^- \longrightarrow e^+e^-\pi^0$ at BaBar – V



The Q^2 resolution varies from 0.05 GeV^2 at 5 GeV^2 to 0.25 GeV^2 at 25 GeV^2

The Q^2-independent systematic error is 3% for $d\sigma/dQ^2$ and 2.3% for $F(Q^2)$

$e^+e^- \to e^+e^-\pi^0$ at BaBar – VI



$$Q^2|F(Q^2)| = A\left(\frac{Q^2}{10\ \mathrm{GeV}^2}\right)^{\beta},$$

$$A = 0.182 \pm 0.002\ \mathrm{GeV}, \quad \beta = 0.25 \pm 0.02$$

$F(Q^2) \sim 1/Q^{3/2}$ while in leading-order pQCD $\sim 1/Q^2$

Some Theory

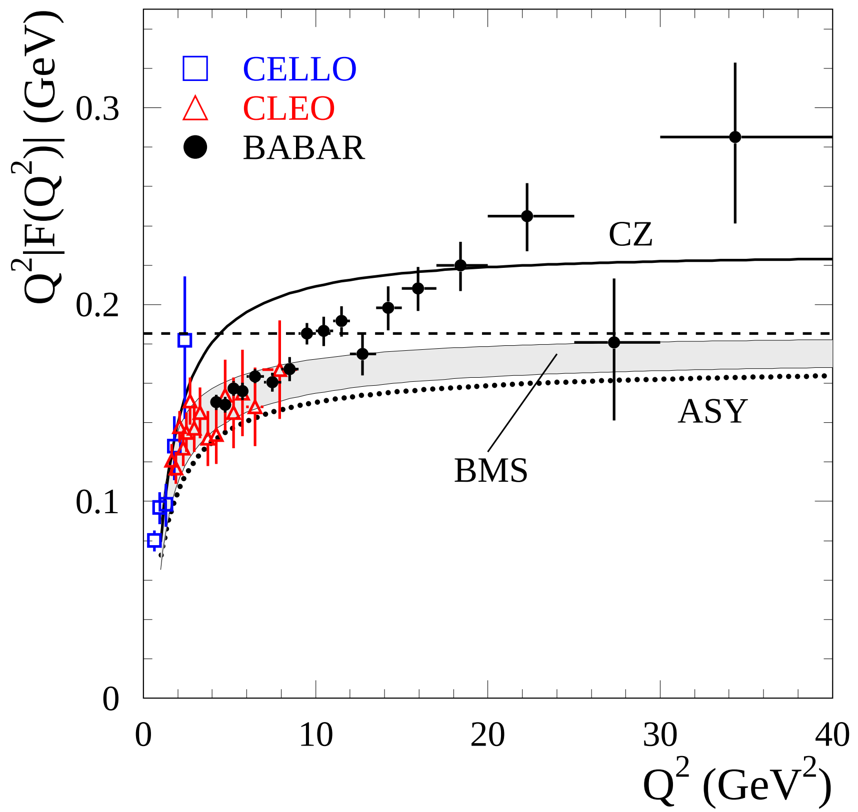
$$Q^2F(Q^2) = \frac{\sqrt{2}f_\pi}{3}\int_0^1 \frac{dx}{x}\phi_\pi(x,Q^2) + \mathcal{O}(\alpha_s) + \mathcal{O}(\Lambda^2_{\rm QCD}/Q^2)$$

$$\text{pQCD at } Q^2 \to \infty: \quad Q^2F(Q^2) = \sqrt{2}f_\pi \approx 0.185 \text{ GeV}$$

In most models for ϕ_π $F(Q^2)$ approaches asymptotics from below

Bakulev, Mikhailov, Stefanis (BMS) use light-cone sum rules
at NLO pQCD with twist-4 for three types of ϕ_π:
Chernyak-Zhitnitsky (CZ), ASY and BMS.

$e^+e^- \to e^+e^-\pi^0$ at BaBar – VII



For $Q^2 \lesssim 15$ GeV^2 the model is inadequate

At $Q^2 > 20$ GeV^2 the data are above ASY, consistent with CZ

More Theory: Postdictions

Several papers appeared after the recent BaBar publication:

- S.V. Mikhailov and N.G. Stefanis, arXiv:0905.4004,
  study the pion f/f with light-cone QCD sum rules and argue that growth of the f/f above 10 GeV^2 can NOT be explained in terms of NNLO higher-order perturbative corrections
- A.V. Radyushkin, arXiv:0906.0323,
  argues that with the flat pion distribution amplitude one can reproduce the Q^2 dependence of the f/f observed by BaBar
- M.V. Polyakov, arXiv:0906.0538,
  argues that the BaBar data support a flat shape of the pion distribution amplitude, which can be obtained in the effective chiral quark model. This implies that the standard DA expansion in Gegenbauer polynomials can be divergent.

QCD Tests in $\gamma\gamma$ Collisions

For the exclusive pair production $\gamma\gamma \to h_1 h_2$
in the leading order (quark-counting rule)

$$\frac{\mathrm{d}\sigma}{\mathrm{dt}} \propto \frac{f(\cos\theta^*)}{s^{n-2}},$$

where $s = W^2_{\gamma\gamma} = W^2$ and n is the number of “elementary” fields.

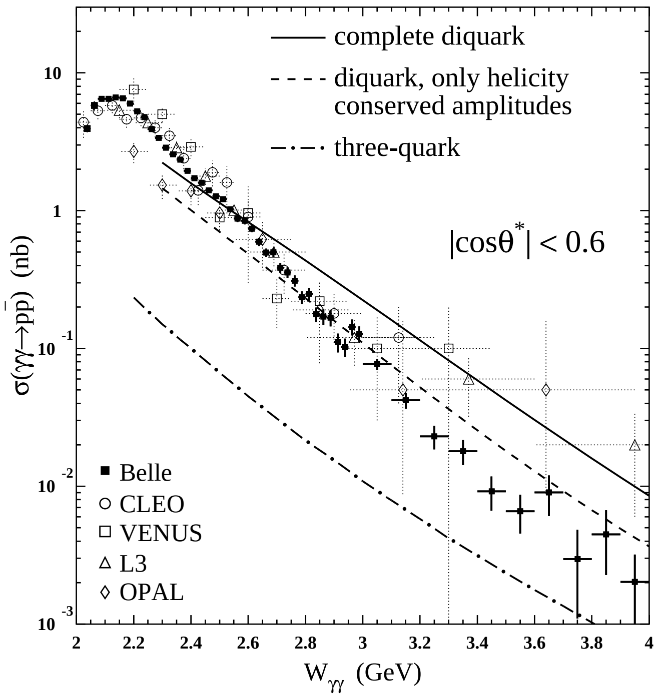
Scaling behaviour is expected in the QCD asymptotic regime $s \to \infty$
$\sigma \propto 1/s^3$ for mesons, $\sigma \propto 1/s^5$ for baryons

The hand-bag model: at intermediate energies
amplitudes are dominated by soft non-perturbative terms

Belle studied $\gamma\gamma \to p\bar{p}, \pi^+\pi^-, K^+K^-, K^0_S K^0_S, \pi^0\pi^0, \eta\pi^0$ at $3 < W < 4$ GeV

$\gamma\gamma \to p\bar{p}$ at Belle – I

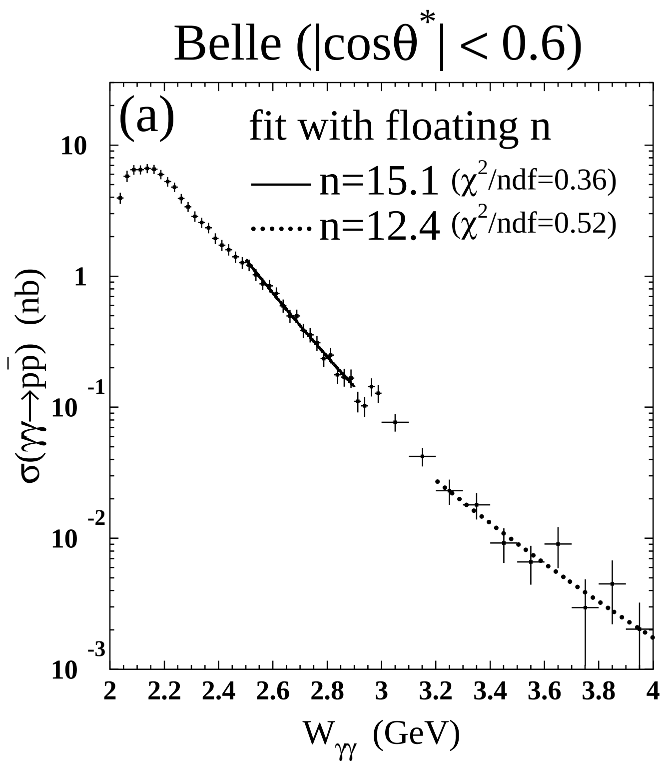
Belle studied $\gamma\gamma \to p\bar{p}$ with 89 fb^{-1} at 2.0 GeV $< W <$ 4.0 GeV

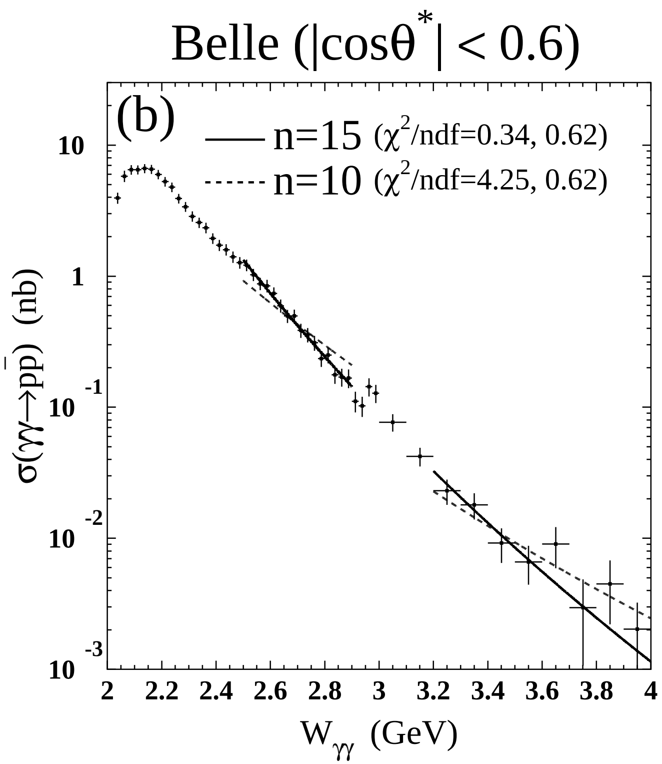


Diquark models fail to describe σ at high W

C.C. Kuo et al., Phys. Lett. B 621, 41 (2005)

$\gamma\gamma \to p\bar{p}$ at Belle – II



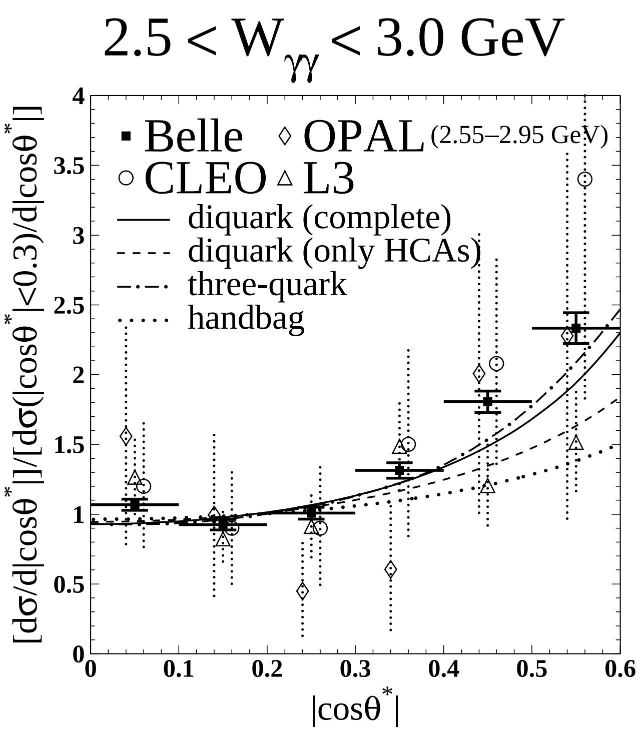


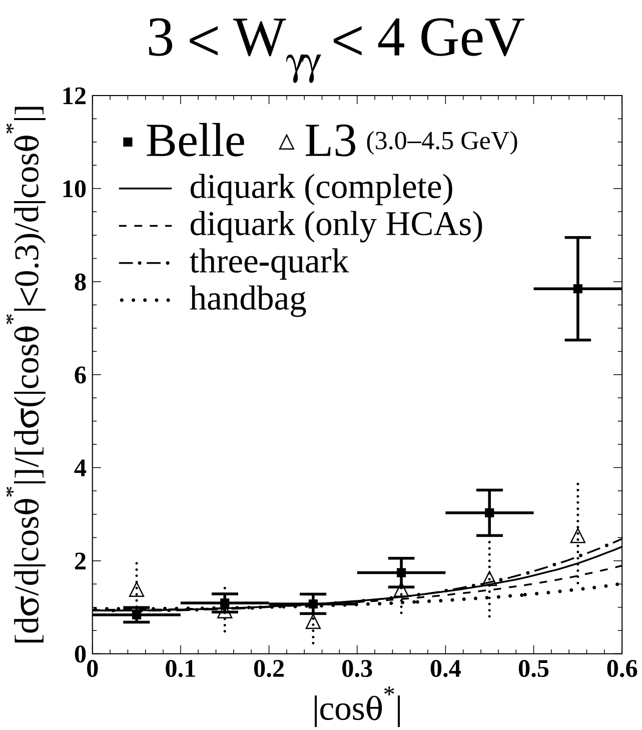
$n = 15.1^{+0.8}_{-1.1}$ at $2.5 < W < 2.9$ GeV,

$n = 12.4^{+2.4}_{-2.3}$ at $3.2 < W < 4.0$ GeV,

$n = 10$ works well above 3.2 GeV $\Rightarrow$ a transition to asymptotics?

$\gamma\gamma \to p\bar{p}$ at Belle – III



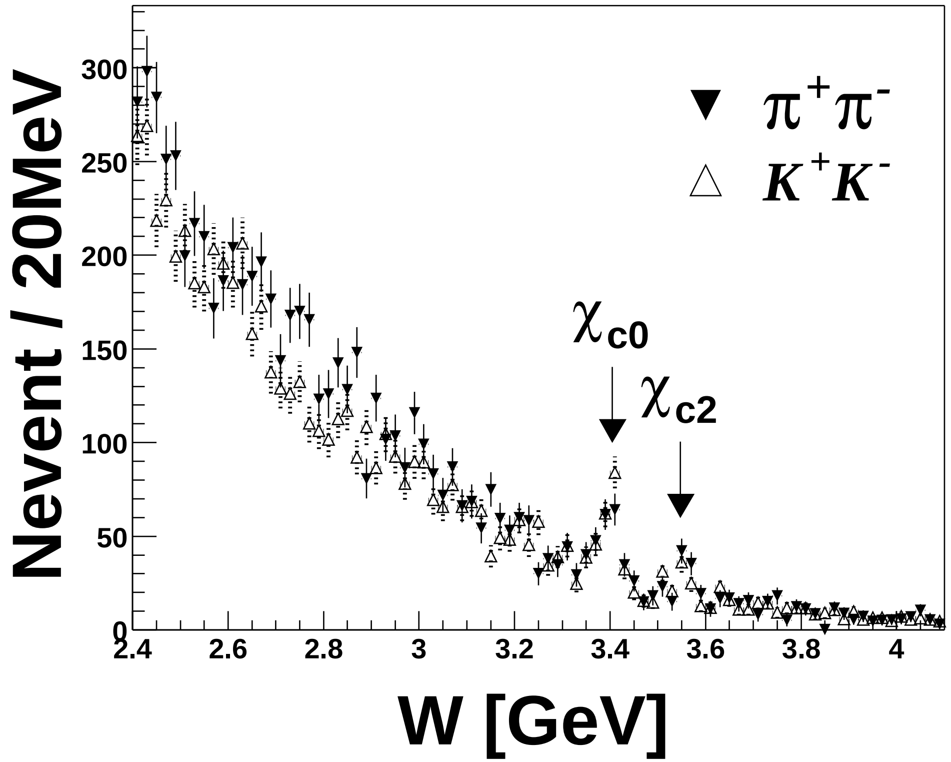


The deviation of the LO QCD from the data at $2.5 < W < 4.0$ GeV implies that power corrections are still important (close threshold)

Diquark and handbag models specially developed for the intermediate energy fail

$\gamma\gamma \to \pi^+\pi^-,\ K^+K^-$ at Belle – I

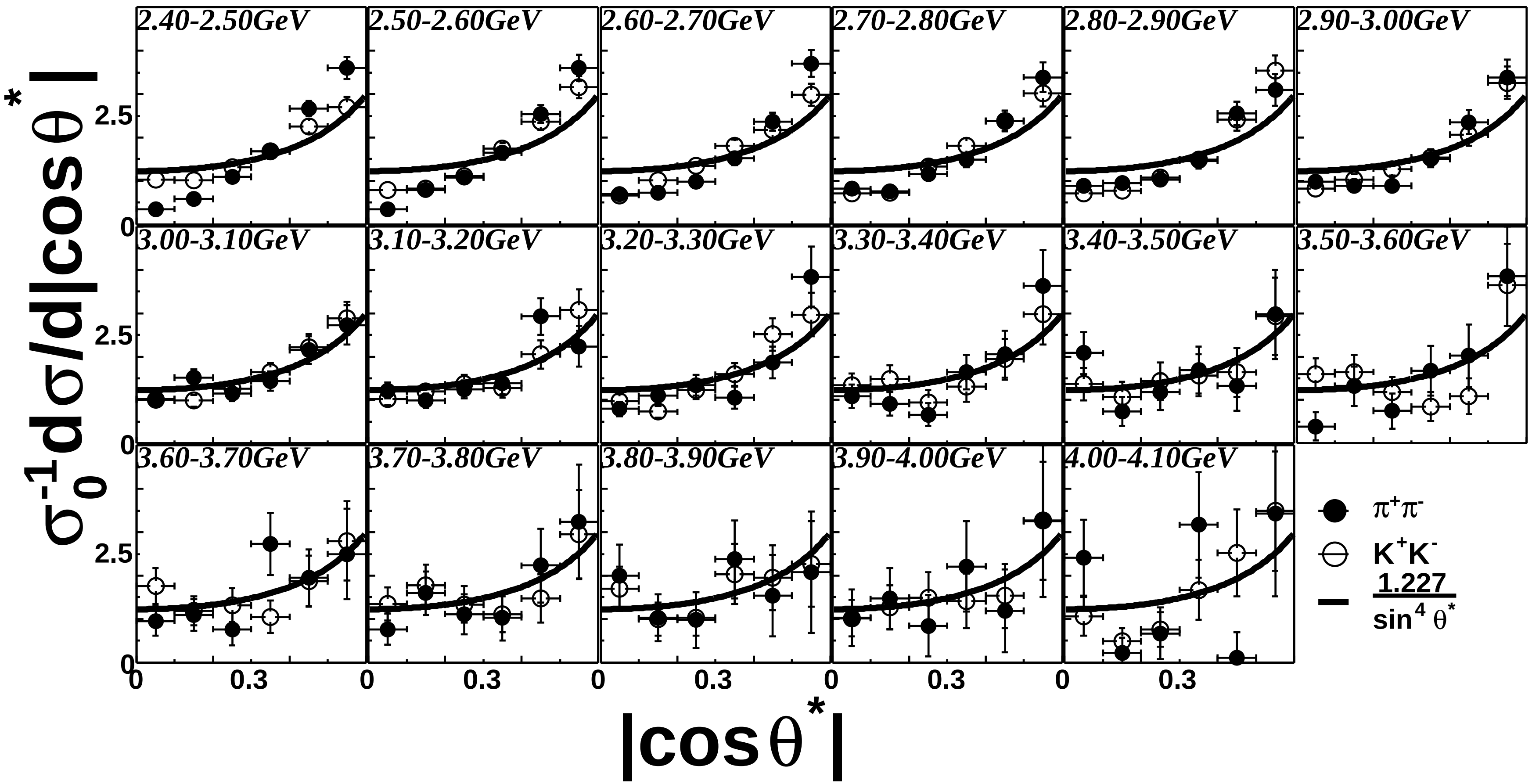
Belle studied $\gamma\gamma \to \pi^+\pi^-,\ K^+K^-$ with 87.7 fb^{-1} at 2.4 GeV $< W <$ 4.0 GeV



H. Nakazawa et al., Phys. Lett. B 615, 39 (2005)

$\gamma\gamma \to \pi^+\pi^-,\ K^+K^-$ at Belle – II

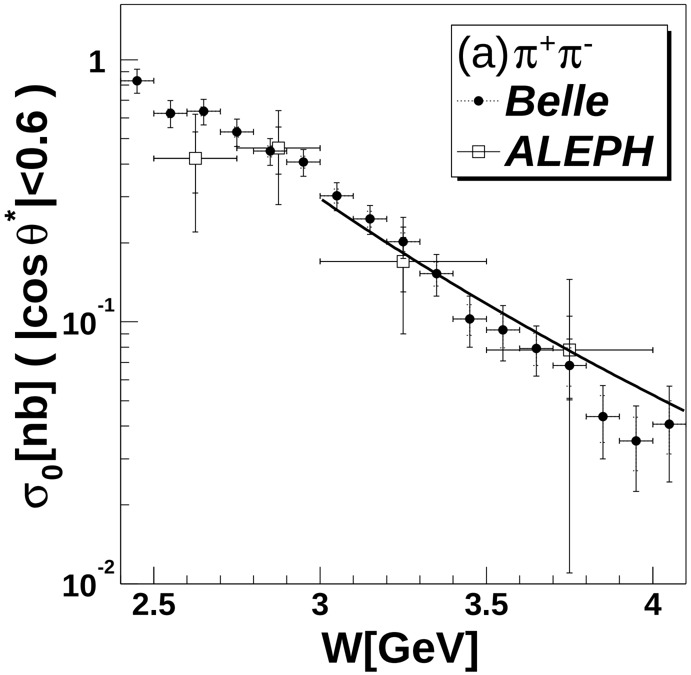
Theory: $d\sigma/dt \propto 1/\sin^4\theta^*$

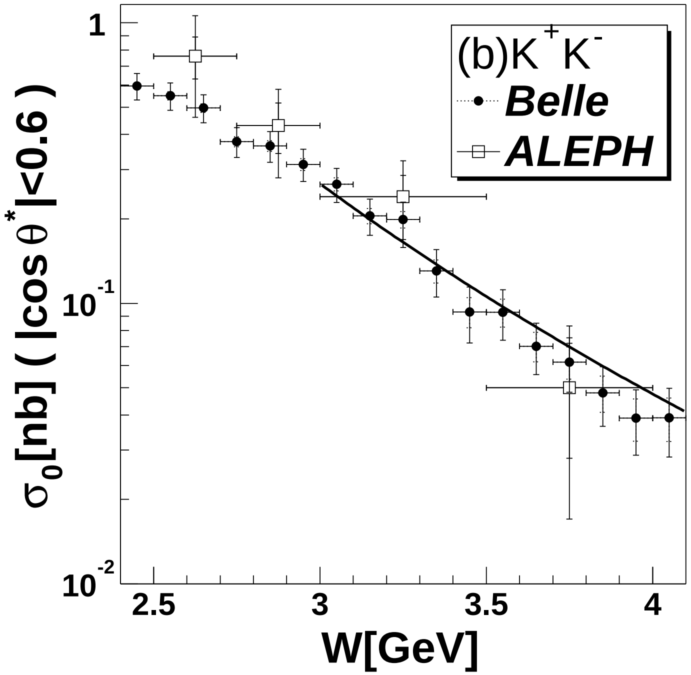


Works well above 3 GeV, but resonances distort the picture at $W < 3$ GeV

$\gamma\gamma \to \pi^+\pi^-$, K^+K^- at Belle – III

ALEPH data agree with $\sigma \propto 1/W^6$, Belle fits $\sigma \propto W^n$



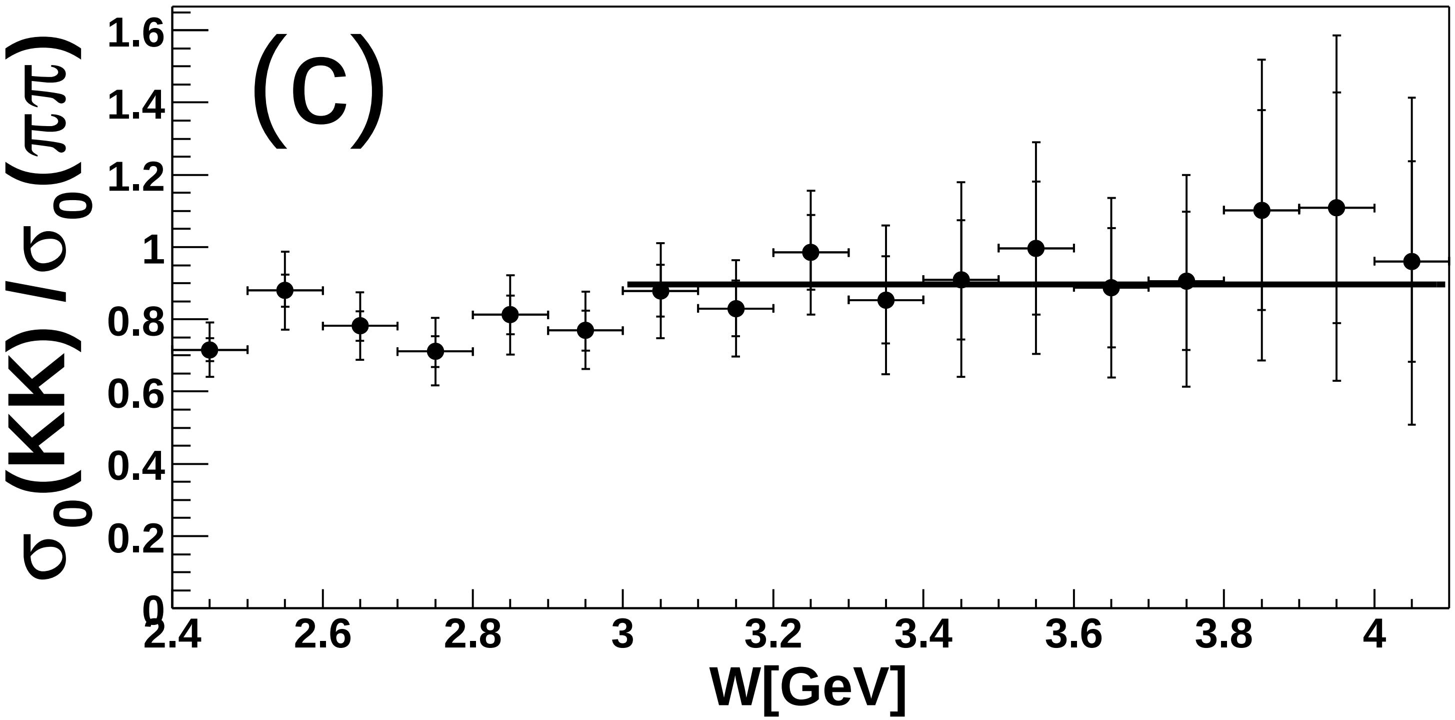


$n = -7.9 \pm 0.4 \pm 1.5$ $n = -7.3 \pm 0.3 \pm 1.5$

ALEPH observed 318 $\pi^+\pi^-$ and 165 K^+K^- events vs. 6900 and 6200 at Belle

$\gamma\gamma \to \pi^+\pi^-,\ K^+K^-$ at Belle – IV

$r = \sigma(K^+K^-)/\sigma(\pi^+\pi^-) = 0.89 \pm 0.04 \pm 0.15$

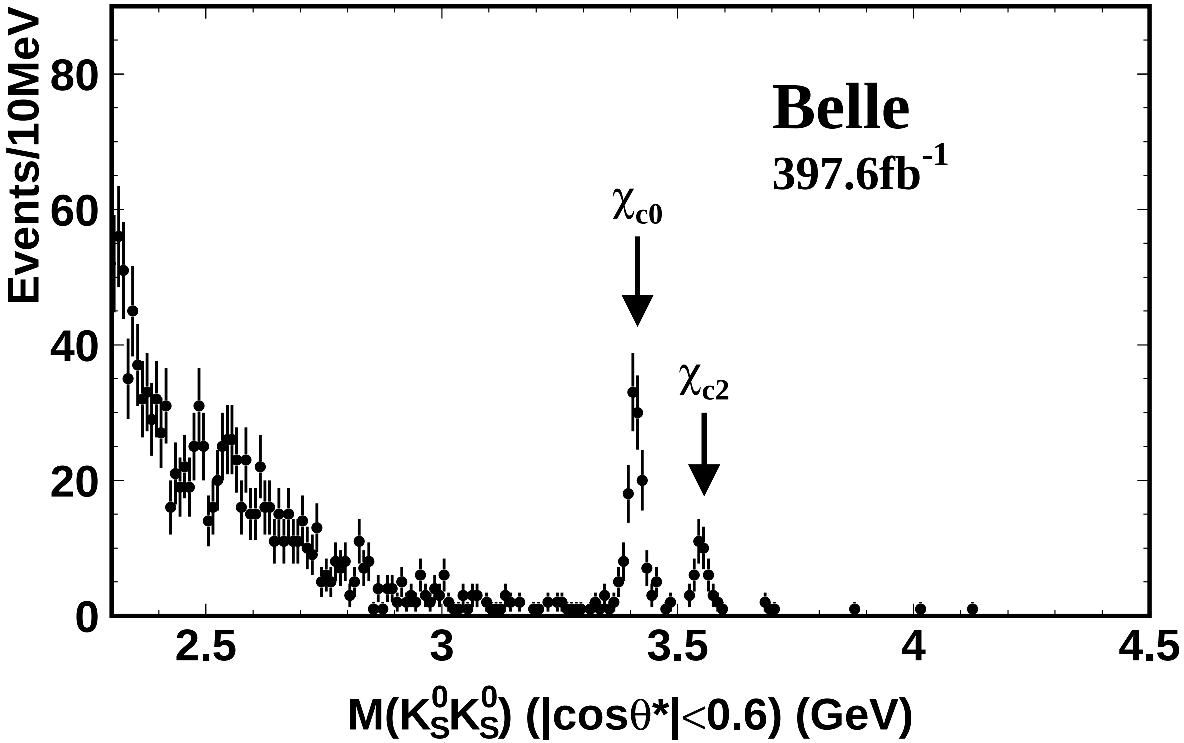


Brodsky, Lepage, 1981: $r = (f_{K^+}/f_{\pi^+})^4 = 2.23$ from $\mathcal{W}_\pi = \mathcal{W}_K$

Benayoun, Chernyak, 1990: r=1.08 with $\mathcal{W}_{\pi(K)}$ from QCD SR and full SU(3) breaking

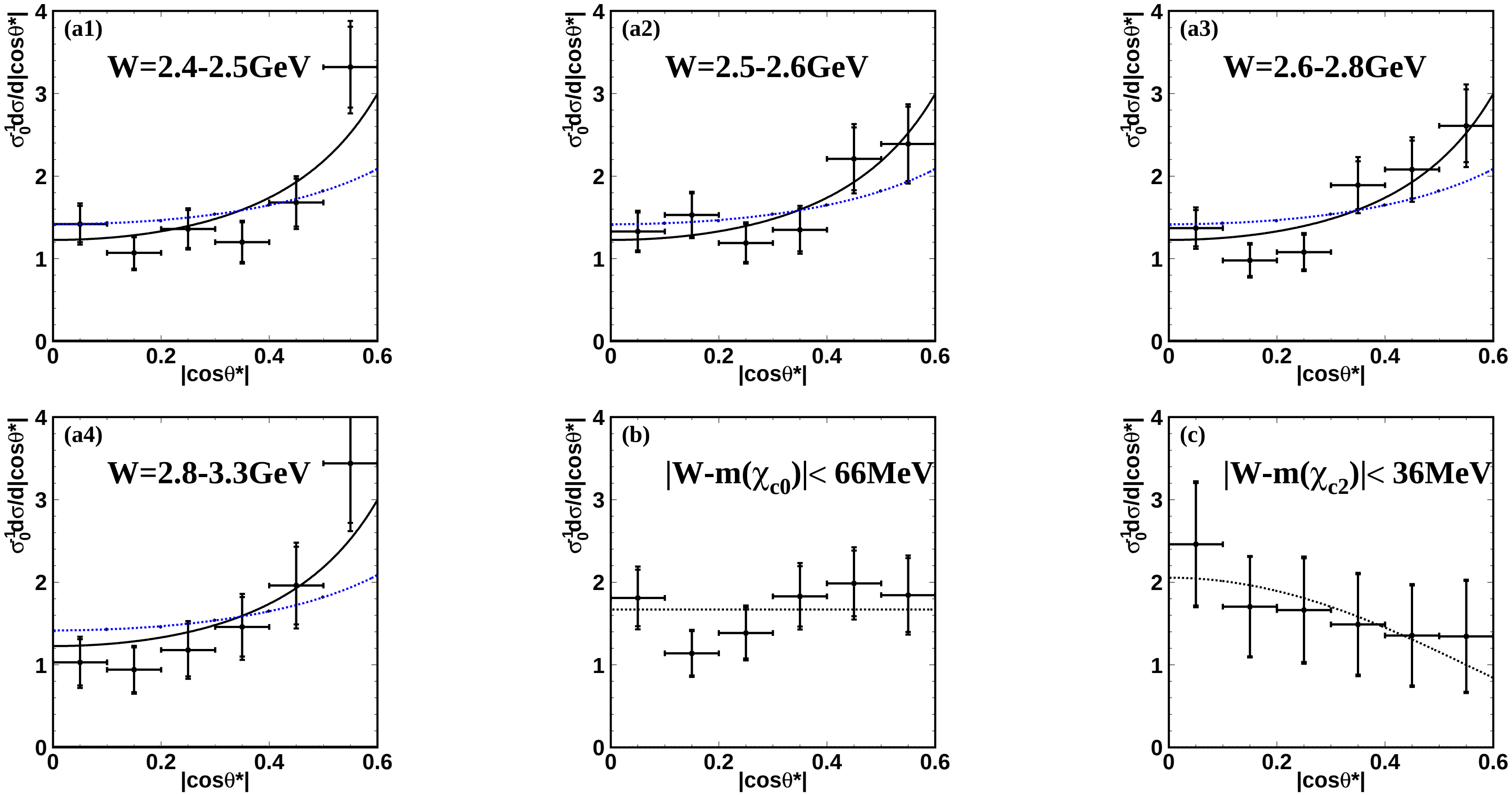
$\gamma\gamma \to K^0_S K^0_S$ at Belle – I

$\gamma\gamma \to K^0_S K^0_S$ studied for the first time
with 397.6 fb^{-1} at 2.4 GeV $< W <$ 4.0 GeV



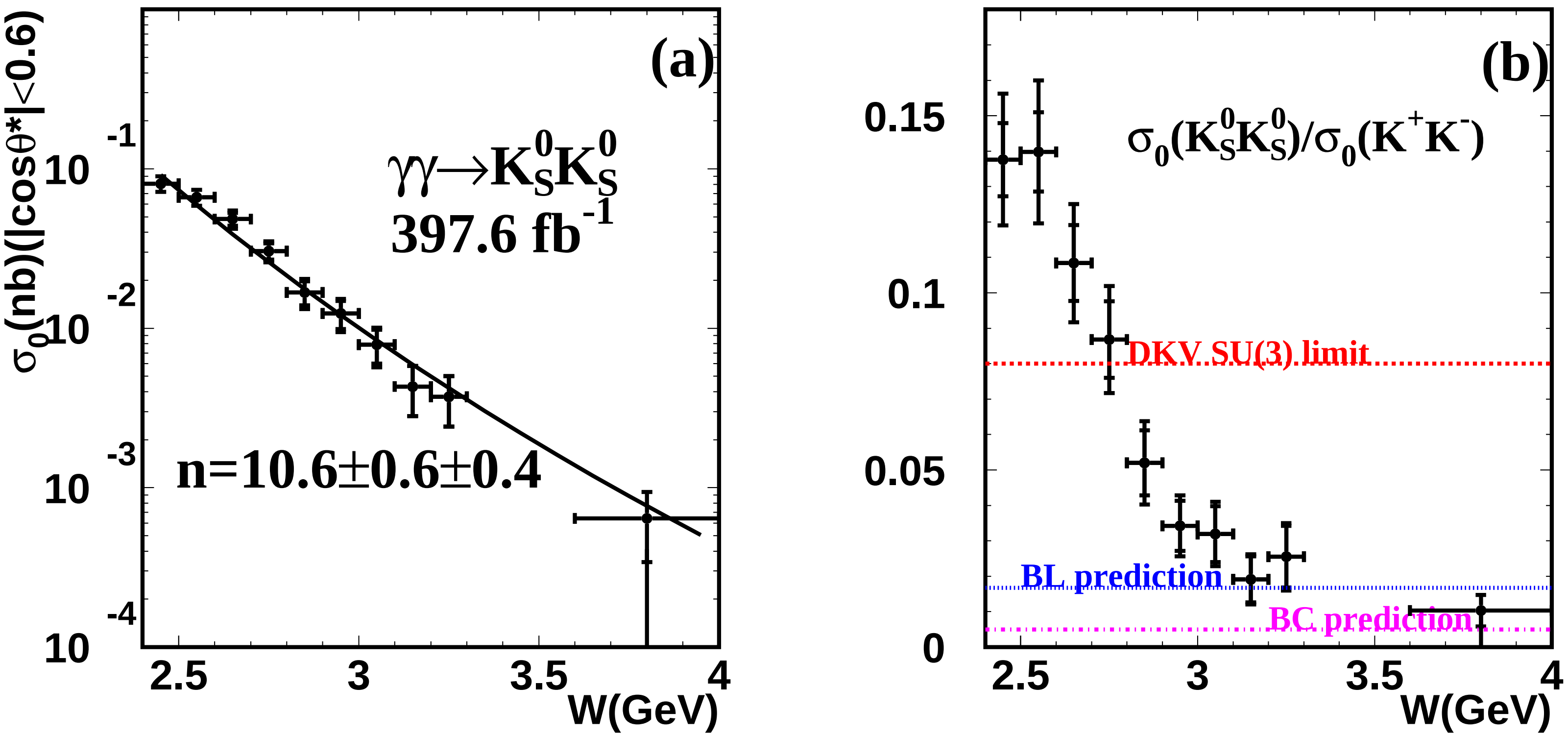
W.T. Chen et al., Phys. Lett. B 651, 15 (2007)

$\gamma\gamma \to K_S^0 K_S^0$ at Belle – II



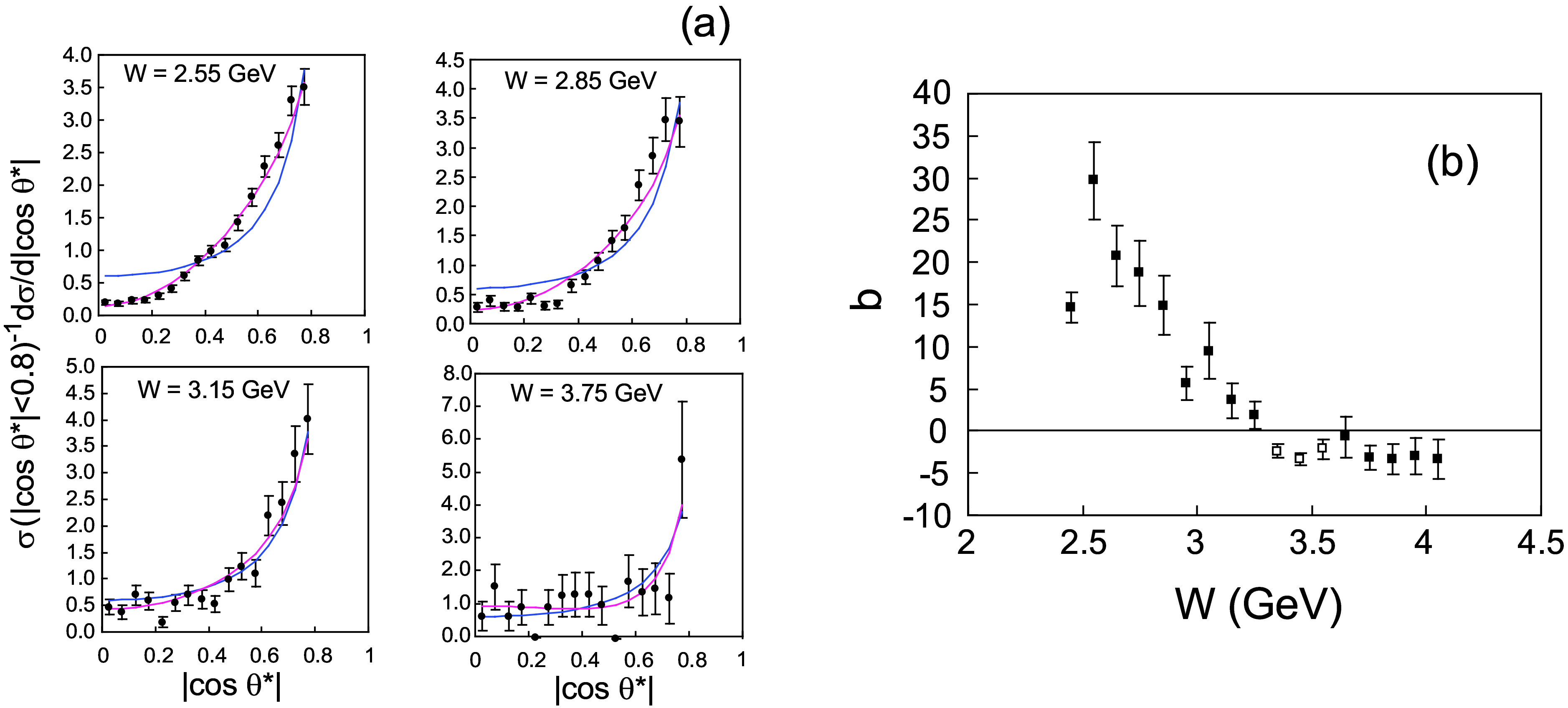
Angular distributions are compatible with both $\sin^{-4}\theta^*$ and BC predictions

$\gamma\gamma \to K_S^0 K_S^0$ at Belle – III



A fit of W^{-n} gives $n = 10.5 \pm 0.6 \pm 0.5$ and suggests that the leading term $\propto 1/s$ is small and the term $\propto 1/s^2$ dominates resulting in $1/W^{10}$

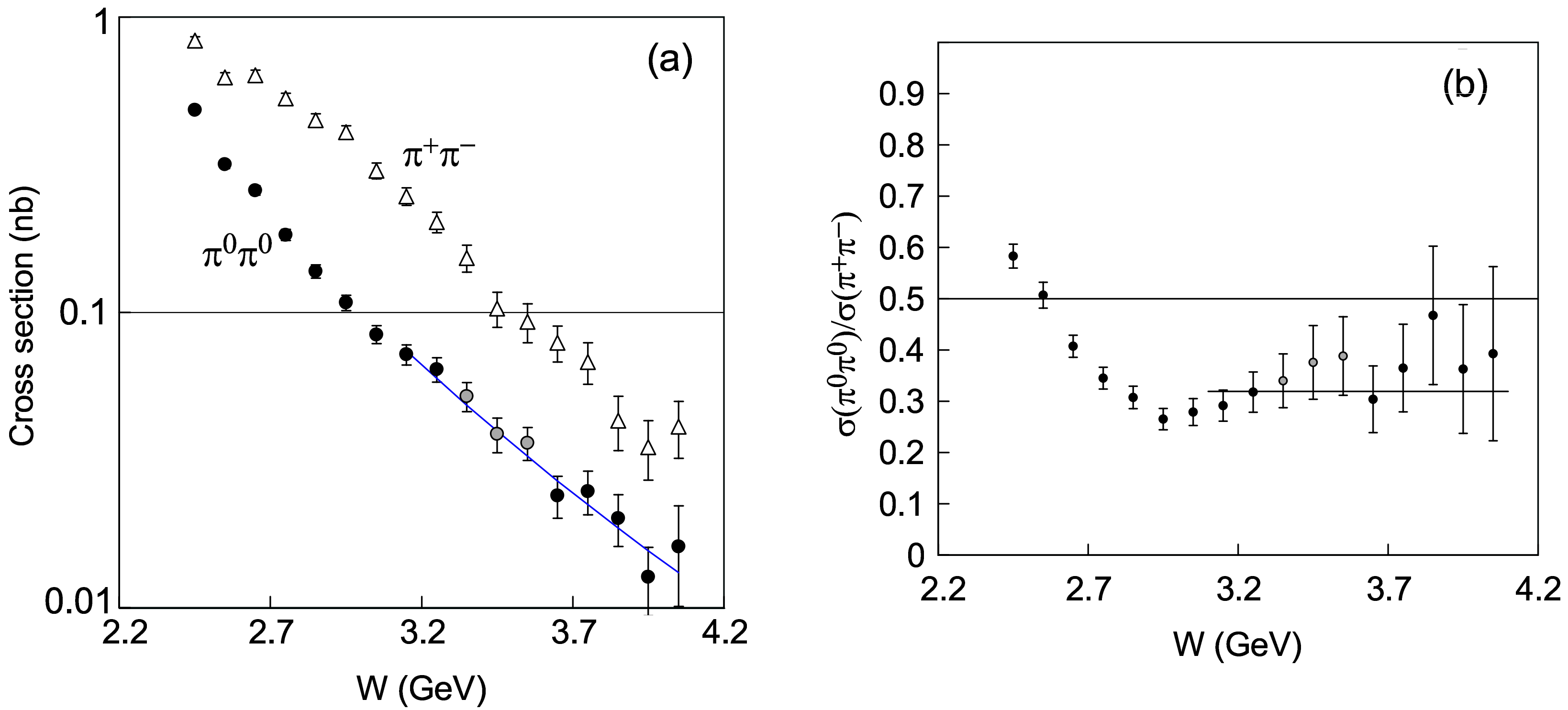
$\gamma\gamma \to \pi^0\pi^0$ at Belle – I



$$d\sigma/d\cos\theta^* \propto \sin^{-4}\theta^* + b\cos^2\theta^*.$$

S. Uehara et al., Phys. Rev. D 79, 052004 (2009)

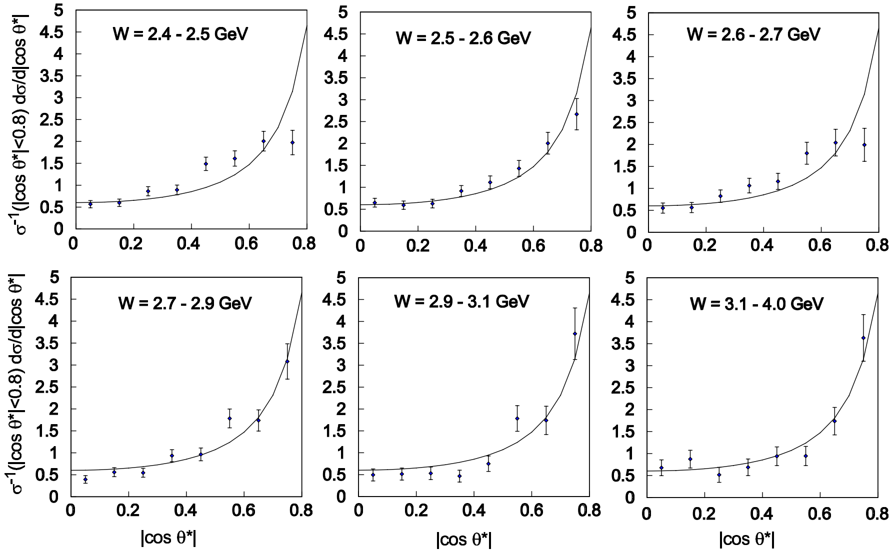
$\gamma\gamma \to \pi^0\pi^0$ at Belle – II



A fit of W^{-n} gives $n = 6.9 \pm 0.6 \pm 0.7$ at $|\cos\theta^*| < 0.6$

$\sigma(\pi^0\pi^0)/\sigma(\pi^+\pi^-) = 0.32 \pm 0.03 \pm 0.05$, much higher than 0.04 at $|\cos\theta^*| = 0.6$ (BC)

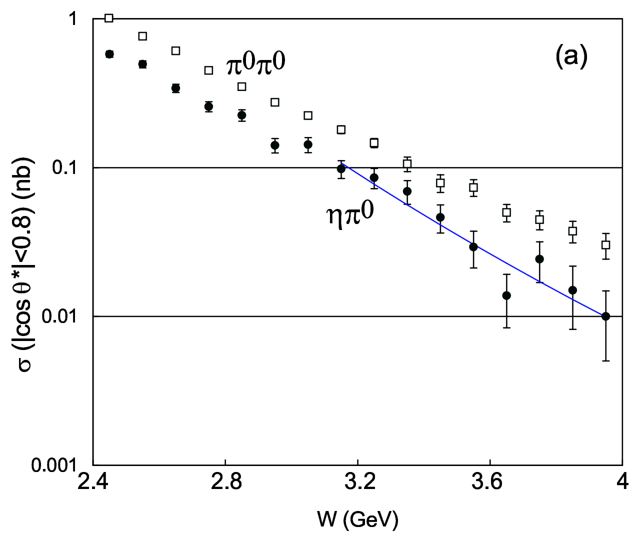
$\gamma\gamma \to \eta\pi^0$ at Belle – I

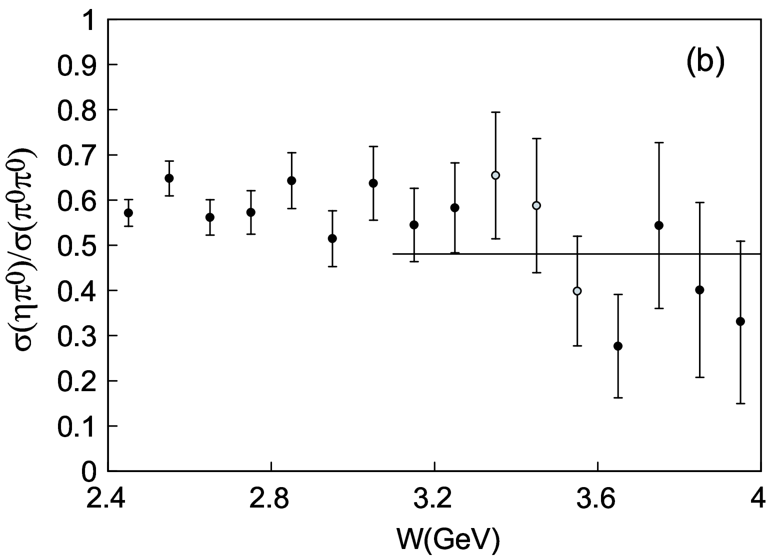


At $W > 2.7$ GeV the angular dependence agrees with $1/\sin^4\theta^*$

S. Uehara et al., arXiv:0906.1464

$\gamma\gamma \to \eta\pi^0$ at Belle – II





A fit with W^{-n} gives $n = 10.5 \pm 1.2 \pm 0.5$ compatible with $K_S^0 K_S^0$, but higher than for $\pi^0\pi^0$.

A fit of the ratio gives $0.48 \pm 0.05 \pm 0.04$ with 0.46 predicted

Summary of W Dependence Studies at Belle

Mode	n	$\int L\ dt$, fb^{-1}	W range, GeV	$\|\cos\theta^*\|$ range
$\pi^+\pi^-$	$7.9 \pm 0.4 \pm 1.5$	87.7	[3.0,4.1]	$<$ 0.6
K^+K^-	$7.3 \pm 0.3 \pm 1.5$	87.7	[3.0,4.1]	$<$ 0.6
$K_S^0 K_S^0$	$10.5 \pm 0.6 \pm 0.5$	397.6	[2.4,3.3],[3.6,4.0]	$<$ 0.6
$\pi^0\pi^0$	$6.9 \pm 0.6 \pm 0.7$	223	[3.1,3.3],[3.6,4.1]	$<$ 0.6
$\pi^0\pi^0$	$8.0 \pm 0.5 \pm 0.4$	223	[3.1,3.3],[3.6,4.1]	$<$ 0.8
$\eta\pi^0$	$10.5 \pm 1.2 \pm 0.5$	223	[3.1,4.1]	$<$ 0.8
$p\bar{p}$	$15.1^{+0.8}_{-1.1}$	89	[2.5,2.9]	$<$ 0.6
	$12.4^{+2.4}_{-2.3}$	89	[3.2,4.0]	$<$ 0.6

There are indications of rather early pQCD regime in W dependence

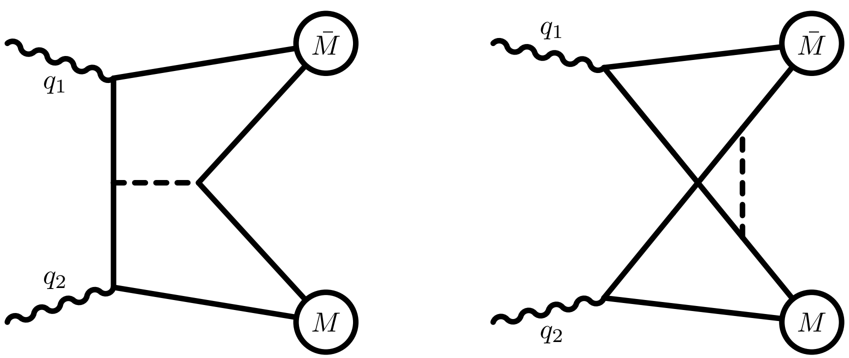
Is there anything special in the $\pi^0\pi^0$ mode?

Conclusions

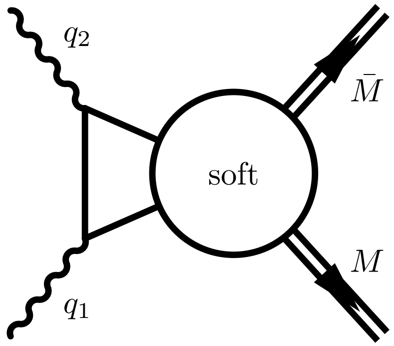
- Huge integrated luminosity collected at B factories has already resulted in high-statistics studies of the rare phenomena
- BaBar measured the $\gamma\gamma^* \to \pi^0$ transition f/f from 4 to 40 GeV^2; below 15 GeV^2 the NLO pQCD with twist-4 is inadequate, above 20 GeV^2 the data lie above the asymptotic limit; η_c f/f to appear soon; η, η' f/f in progress important for models of f/f in $a_\mu^{\mathrm{had,LBL}}$
- Belle performed tests of QCD at $3 < W < 4$ GeV with $\gamma\gamma \to p\bar{p}$, $\pi^+\pi^-$, K^+K^-, $K^0_S K^0_S$, $\pi^0\pi^0$, $\eta\pi^0$; $\eta\eta$ in progress; for $\sigma(W) \sim W^{-n}$ n follows pQCD
- Also many interesting studies of hadronic resonances: f_0's in $\pi^+\pi^-$, $\pi^0\pi^0$, a_0's in $\eta\pi^0$, f_2's in K^+K^- at Belle; η_c and $\eta_c(2S)$ at BaBar and Belle, $\chi_{c2}(2P)$ discovered at Belle in $\gamma\gamma \to D\bar{D}$
- High-statistics $\gamma\gamma$ production has good potential for discovering new states, measuring transition form factors and $\mathcal{B}$'s, testing QCD predictions

Backup Slides

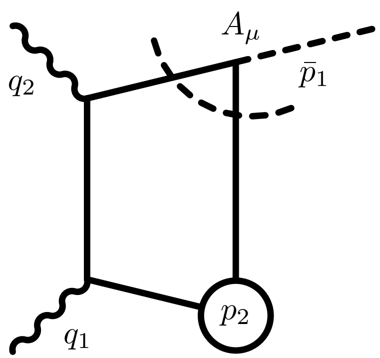
Some Diagrams



Leading order hard contributions



The hand-bag contribution



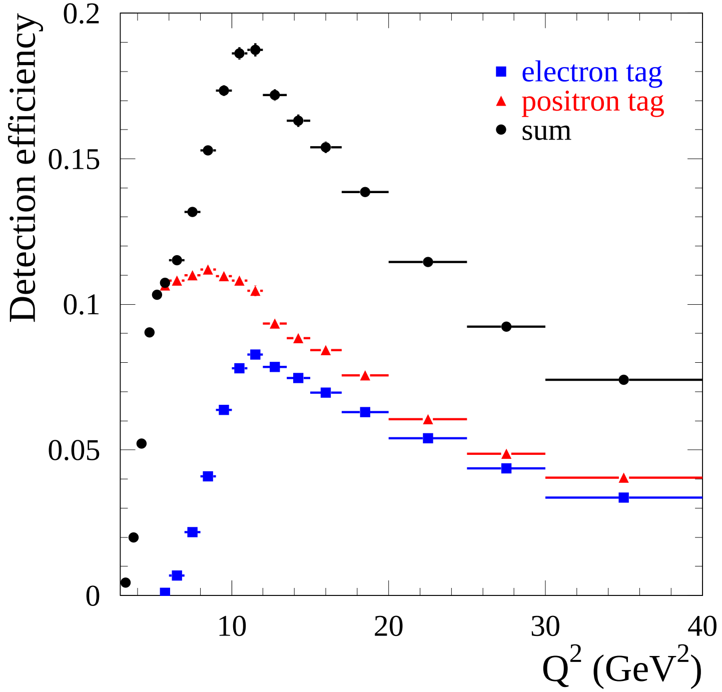
The light cone sum rule

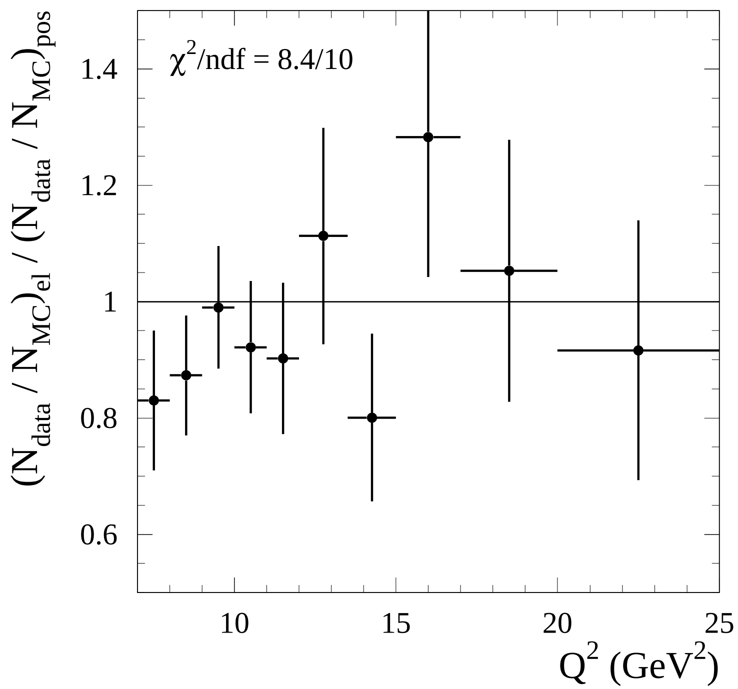
Selection of $e^+e^- \to e^+e^-\pi^0$ at BaBar

- The VirtualCompton filter (VCS – $e^+e^- \to e^+e^-\gamma$)
  a track with $p^*/\sqrt{s} > 0.1$, an EMC cluster with $E^*/\sqrt{s} > 0.1$
- For $e^\pm$ $0.376 < \theta_e^* < 2.450$, $E_e^{\mathrm{lab}} > 2$ GeV;
  For π^0 two photons with $E_\gamma > 50$ MeV, $E_{1\gamma}^{\mathrm{lab}} + E_{2\gamma}^{\mathrm{lab}} > 1.5$ GeV,
  $0.06 < m_{\gamma\gamma} < 0.21$ GeV
- VCS is rejected by $|\cos\theta_h| < 0.8$, $|\cos\theta_\pi^*| < 0.8$
- Misreconstructed QED (noisy EMC, tracks close to π^0, close γ)
- Kinematics ($|\cos\theta_{e\pi}^*| > 0.99$ and suppression of extra γ's)

Comparison of e^- and e^+ Tags at BaBar

Because of asymmetry of e^+e^- collisions the efficiency is different for electron and positron tags





Efficiency corrections for $e^+e^- \to e^+e^-\pi^0$ at BaBar – I

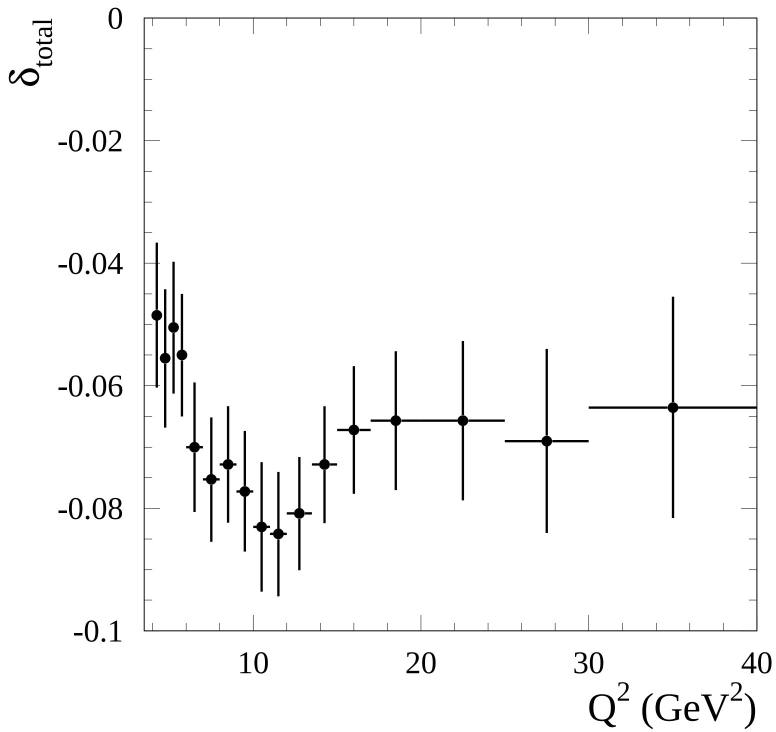
The data distribution should be corrected for data-MC difference in detector response: $N_i^{\rm cor} = N_i/\Pi_{j=1}^4(1+\delta_j^i)$.

The efficiency corrections take into account:

- π^0 reconstruction (from -1.5% to -4.5%, 1% to syst.)
- Electron identification (from -1.50% to 0.25%)
- Trigger (-2% for e^+, from -8% to -1.5% for e^-, 2% to syst.)
- Selection (1% to syst.)

Efficiency corrections for $e^+e^- \to e^+e^-\pi^0$ at BaBar – II

The total efficiency correction vs. Q^2



The Q^2-independent systematic error is 2.5%

F/F Model Dependence for $e^+e^- \to e^+e^-\pi^0$ at BaBar

The measured form factor is determined from

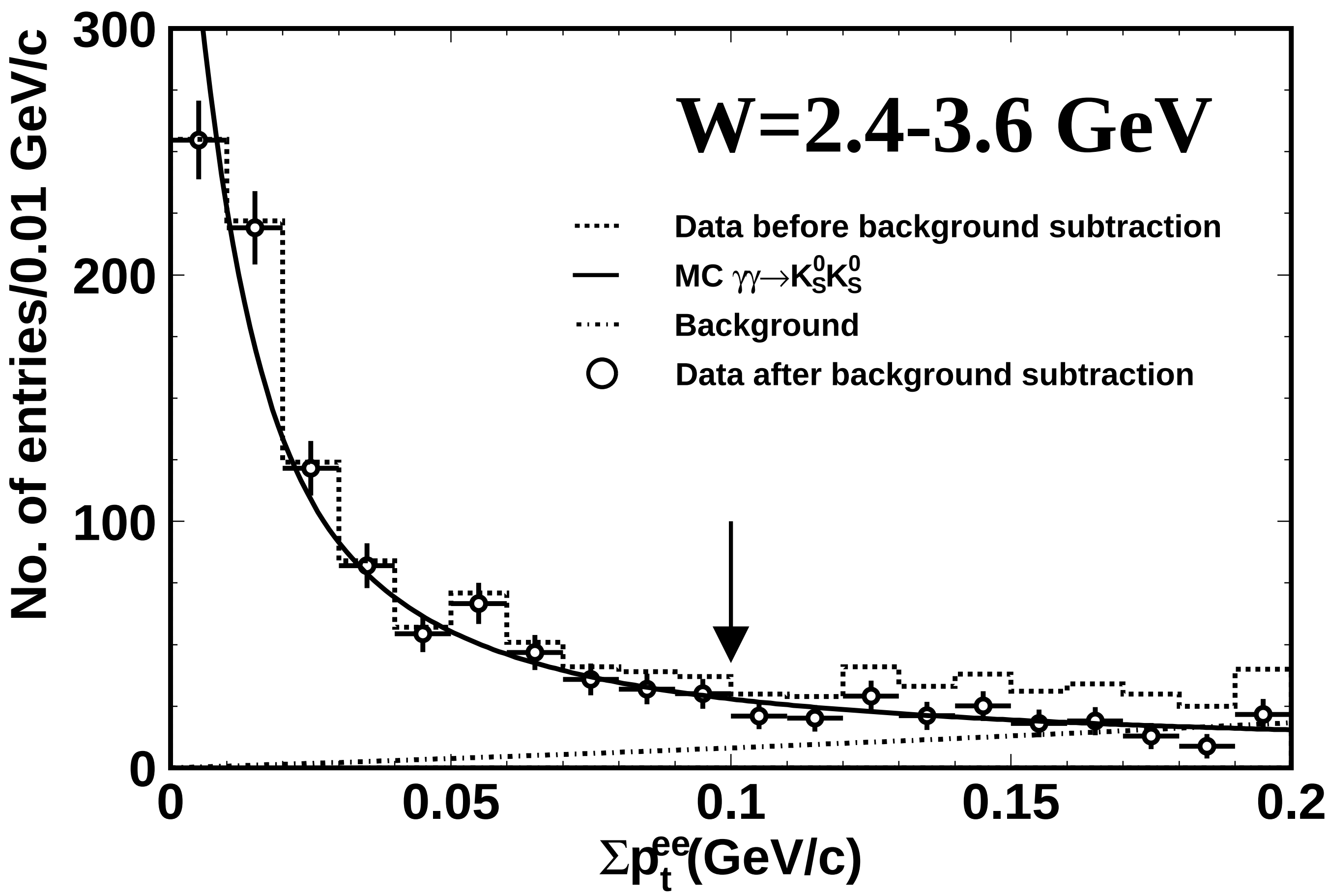
$$F^2(Q^2) = \frac{(d\sigma/dQ^2)_{\rm data}}{(d\sigma/dQ^2)_{\rm MC}} F^2_{\rm MC}.$$

$F^2_{\rm MC}$ uses the QCD-inspired model

$$F(q_1^2, q_2^2) \propto 1/(q_1^2 + q_2^2) \approx 1/q_1^2.$$

If VDM is used with $F(q_2^2) \propto 1/(1 - q_2^2/m_\rho)$, σ decreases by 3.5%.
This is valid for $|q_2^2| < 0.18$ GeV^2.

Background Determination in $\gamma\gamma$ Analysis at Belle



$\gamma\gamma \to p\bar{p}$ at Belle