Meson-pair Production in Two-Photon Collisions at Belle

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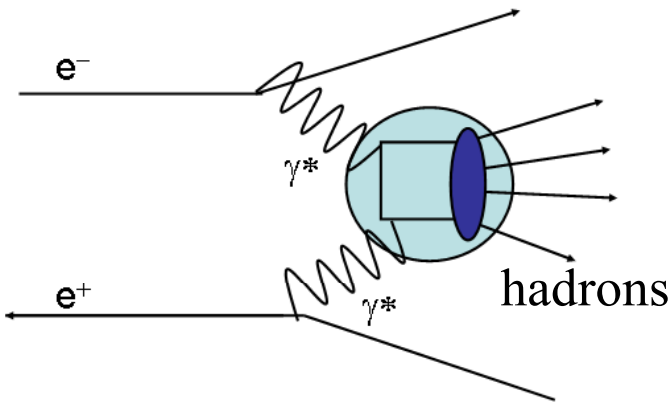
Hard Photon and Meson Production

GPD2010

Oct.10-15, 2010, ECT, Trento*

Two-Photon Collisions and QCD/Hadron Physics



Hadron production from collisions of virtual or quasi-real photons

- Perturbative/Non-perturbative QCD
- Hadron/Photon form factors
- Resonances

Wide energy region and various physics aspects can be studied simultaneously.

Incident photon -- dominated by quasi-real photon

$Q^2 \equiv |q^2| \lesssim 0.001\,\mathrm{GeV}^2$

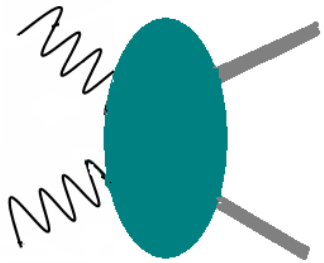
No-Tag:

with p_t-balance requirement, $|\Sigma\, p^*_t\,(\mathrm{hadrons})| < 0.05 - 0.3$ GeV/c

$Q^2 << W^2$ $(W \equiv W_{\gamma\gamma})$, $Q^2 << E^2_{QCD}$

Meson-pair production and QCD

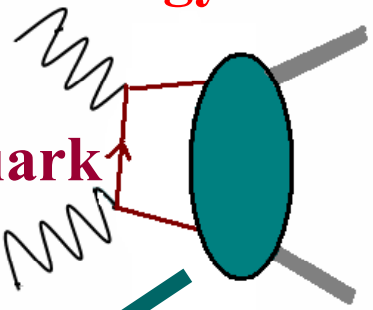
Low energy



Meson

Meson

High energy

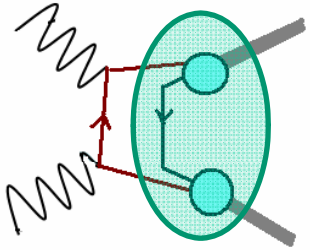


Meson

Meson

High energy

Brodsky and Lepage

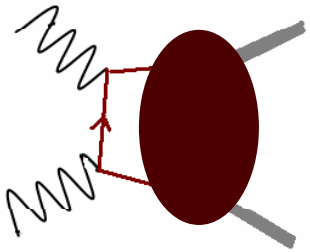


Perturbative QCD approach

for exclusive meson production

Works with refined form factors

S.J.Brodsky, G.P.Lepage, PRD 24, 1808 (1981)
M.Benayoun, V.L.Chernyak, NPB329,209(1990)



Kroll, Diehl and Vogt

Handbag model

with soft hadron exchange

M.Diehl, P.Kroll, and C. Vogt, PLB 532, 99 (2002)
M.Diehl, P.Kroll, PLB 683, 165 (2010)

Predicts…

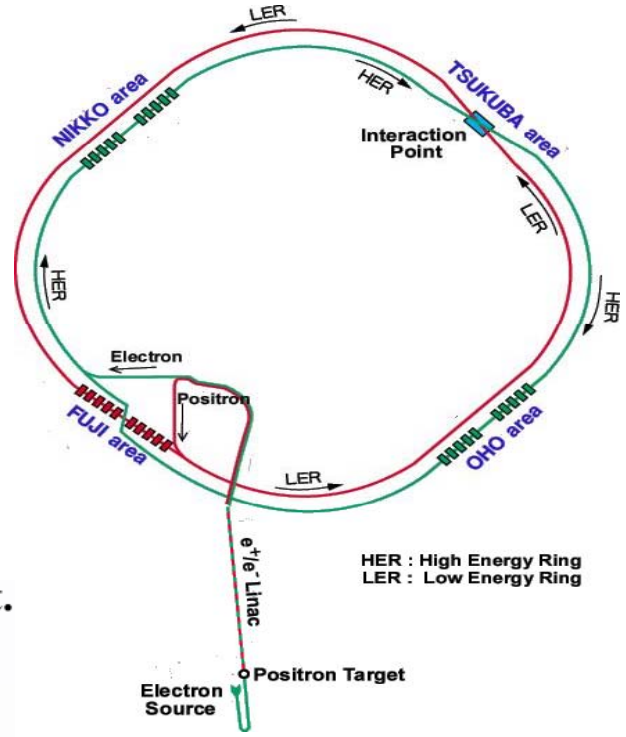
Scattering-angle (of meson) distribution,

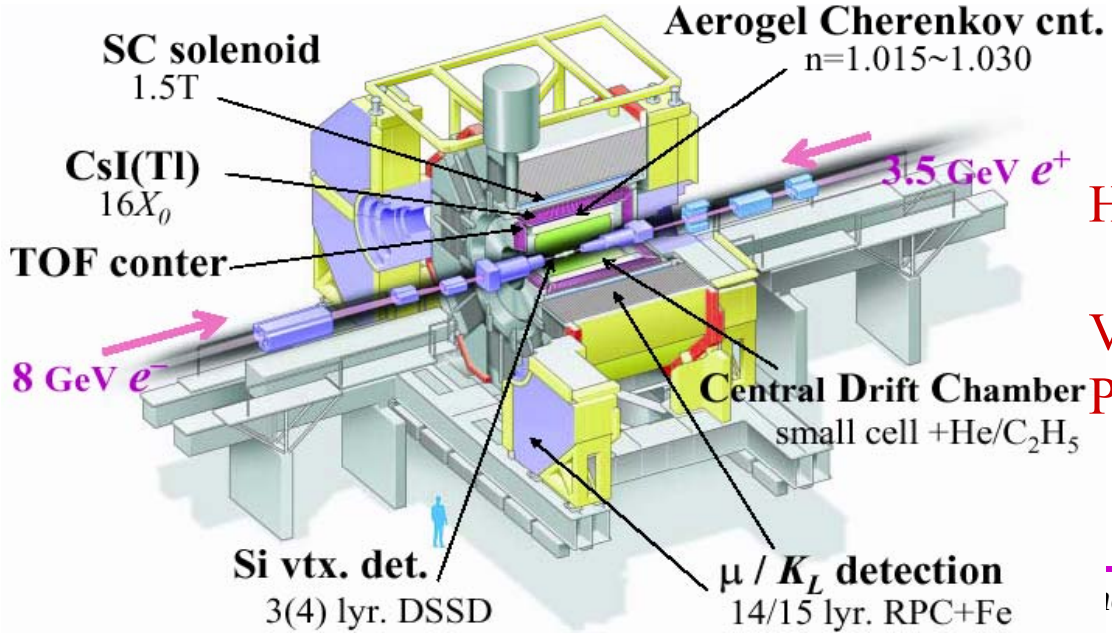
Energy -dependence

Cross section ratios under SU(3) sym.

KEKB Accelerator and Belle Detector

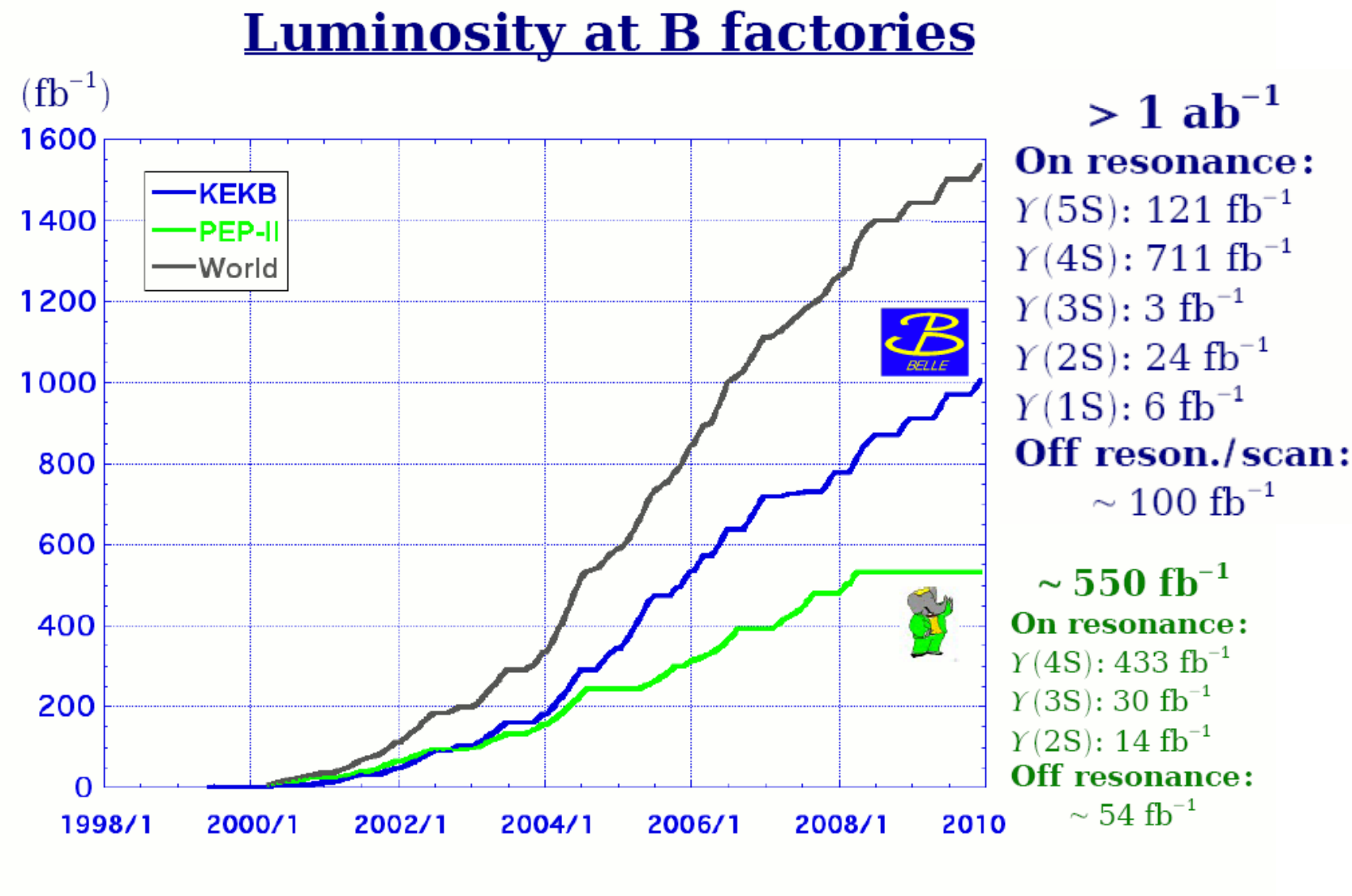
- **Asymmetric $e^- e^+$ collider**
  8 GeV e^- (HER) x 3.5 GeV e+ (LER)
  $\sqrt{s}$=10.58 GeV $\Leftrightarrow$ $\Upsilon(4S)$
- **Luminosity (World highest)**
  $L_{max}=2.1\times10^{34}\ cm^{-2}s^{-1}$
  $\int Ldt \sim 1040\ fb^{-1}$ (1999 - 2010)





High momentum/energy resolutions
CDC+Solenoid, CsI
Vertex measurement – Si strips
Particle identification
TOF, Si-aerogel, CDC-dE/dx,
RPC for K_L/muon

Integrated luminosities and beam energies



"$\gamma\gamma \rightarrow$ meson pair" measurements from Belle

Process	Reference	Int.Lum. (fb^{-1})	$\gamma\gamma$ c.m. Energy (GeV)	Physics covered: Light Mesons	QCD	Char-monia
$\pi^+\pi^-$	PLB 615, 39 (2005)	87.7	2.4 - 4.1		√	√
	PRD 75, 051101(R) (2007)	85.9	0.8 - 1.5	√		
	J. Phys. Soc. Jpn. 76, 074102 (2007)	85.9	0.8 – 1.5	√		
K^+K^-	EPJC 32, 323 (2003)	67	1.4 – 2.4	√		
	PLB 615, 39 (2005)	87.7	2.4 – 4.1		√	√
$\pi^0\pi^0$	PRD 78, 052004 (2008)	95	0.6 – 4.0	√		
	PRD 79, 052009 (2009)	223	0.6 – 4.0	√	√	√
$K^0_S K^0_S$	PLB 651, 15 (2007)	397.1	2.4 – 4.0		√	√
$\eta\pi^0$	PRD 80, 032001 (2009)	223	0.84 – 4.0	√	√	
$\eta\eta$	ArXiv:1007.3779[hep-ex](2010)	393	1.1 – 4.0	√	√	√

We, in principle, measure differential cross section **$d\sigma/d|\cos\theta^*|$** for these reaction processes.

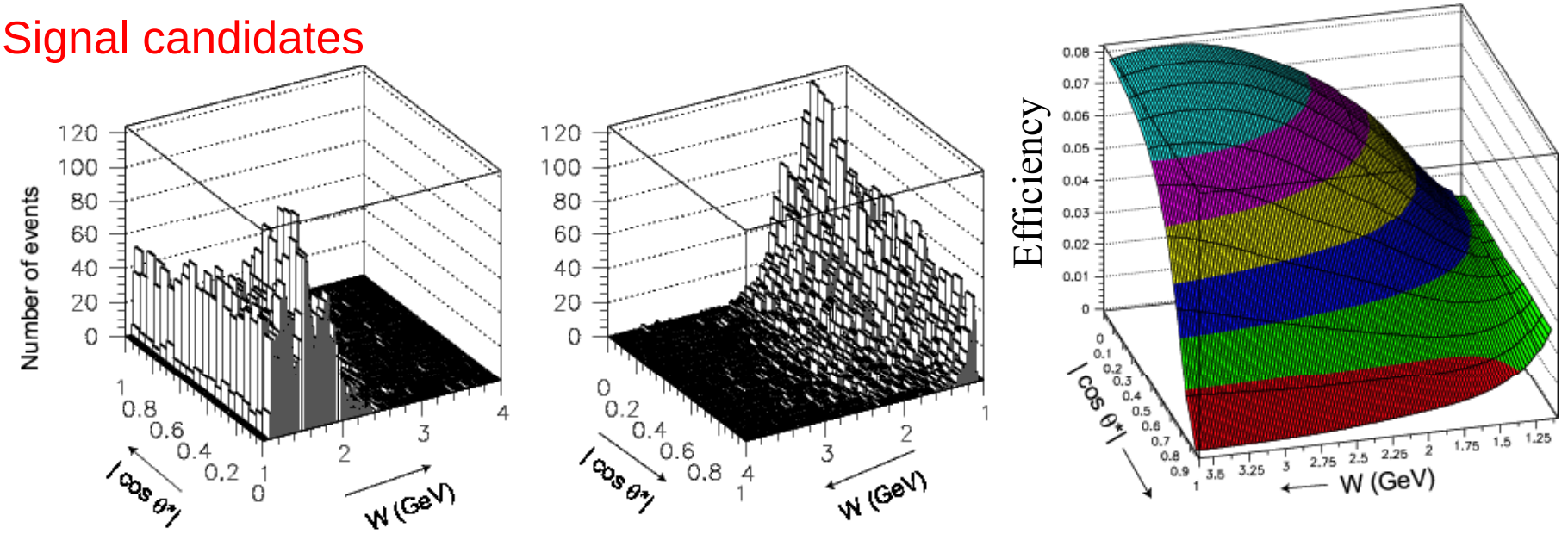
Experimental Analysis; $\gamma\gamma \rightarrow \eta\eta$

$\eta(548\text{MeV}) \rightarrow \gamma\gamma$ (Only 4 photons are visible in this process)

Triggered by ECL triggers

$\sqrt{s} = 9.4 - 11.0$ GeV $\int Ldt = 393$ fb^{-1}

Signal candidates



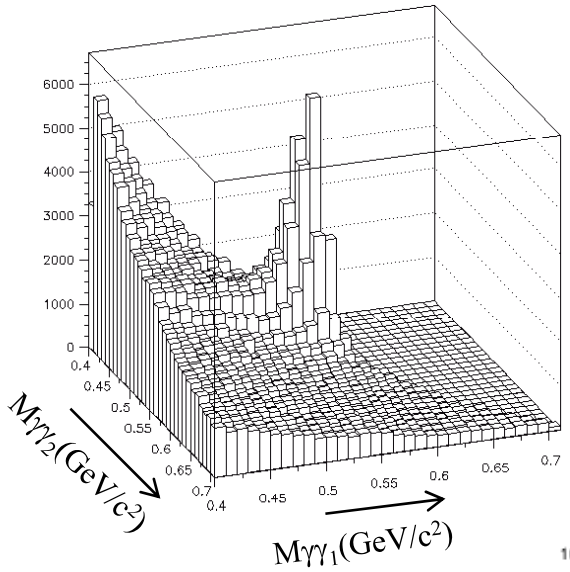
W: $\gamma\gamma$ energy in its c.m.s., θ^*: scattering angle of the meson in the $\gamma\gamma$ c.m.s.

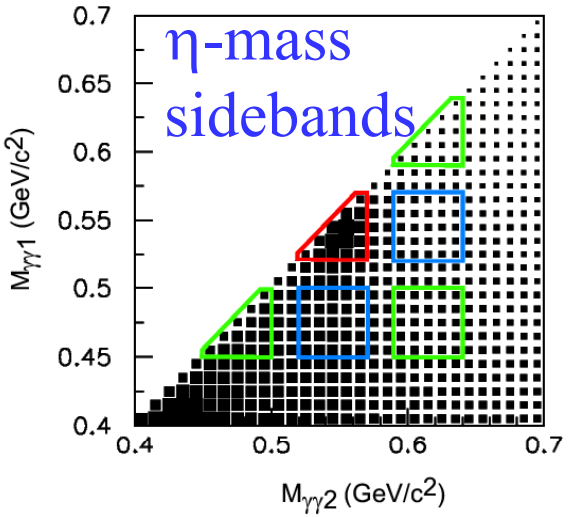
1.096GeV (mass threshold) < W < 3.8 GeV

$|\cos\theta^*| < 0.9$ or < 1.0

Signal candidates and backgrounds

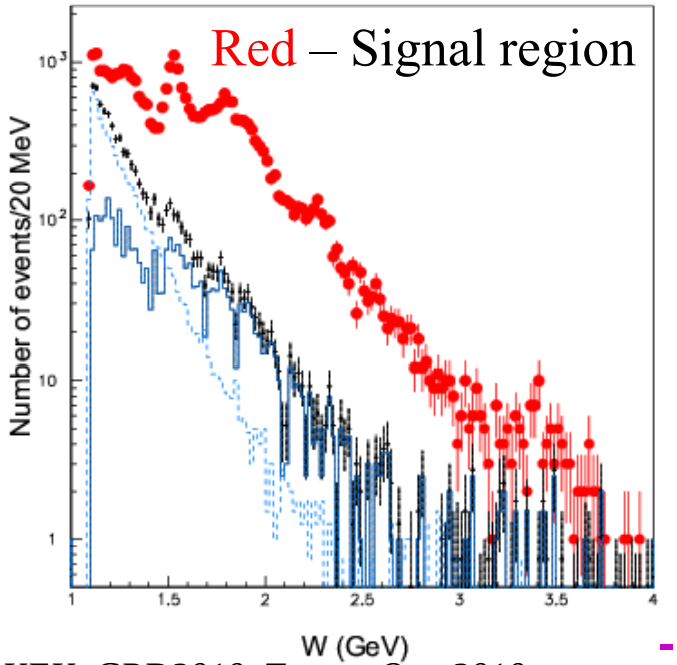
Clean ηη signal
in
$M(\gamma\gamma_1)$ vs $M(\gamma\gamma_2)$
with
non-negligible background





Blue – backgrounds
η non-η(solid)
non-η non-η (dashed)

Background sum (cross)
0.5(SB-A) – 0.25(SB-B)
--- 5% level except in low-W



Differential and integrated cross sections

$$\frac{d\sigma}{d|\cos\theta^*|} = \frac{\Delta Y}{\Delta W \,\Delta|\cos\theta^*| \int \mathcal{L}dt \; L_{\gamma\gamma}(W) \; \epsilon \; \mathcal{B}^2}$$

Yield: after the background subtraction

BF(η→γγ)

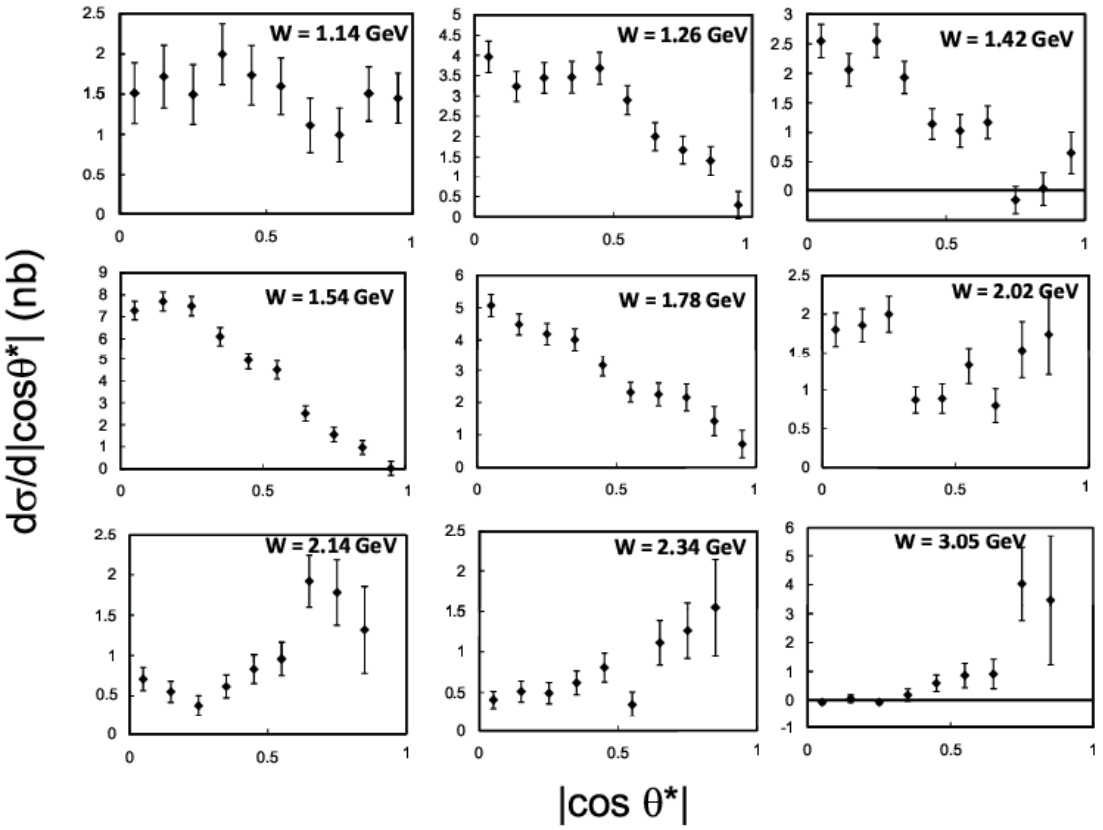
Bin sizes

ΔW=40MeV/c, Δ|cosθ*|=0.1

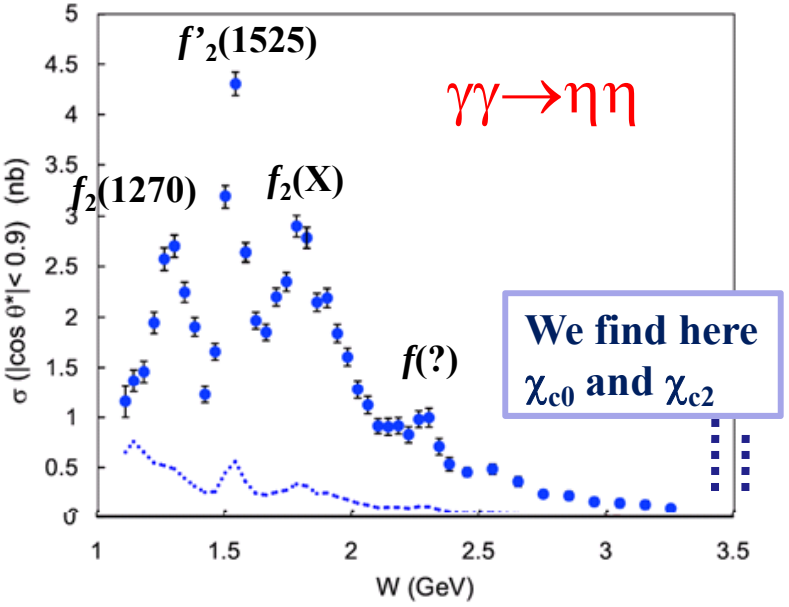
Integrated luminosity

Efficiency

Two-photon luminosity function

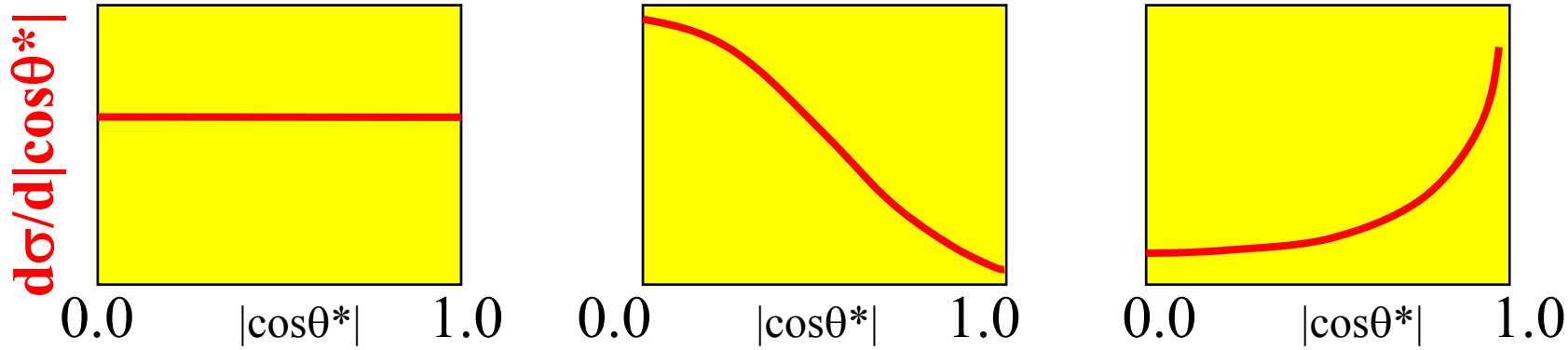


σ(|cosθ*|<0.9) = Σ (dσ/d|cosθ*|)Δ|cosθ*|



Angular dependences in $\gamma\gamma \to MM'$

General tendency in meson pair production processes



Low energy
Near the mass threshold
or Scalar resonance

Intermediate energy
Tensor resonance

High energy
pQCD
Quark line mediates

Predictions for High Energy

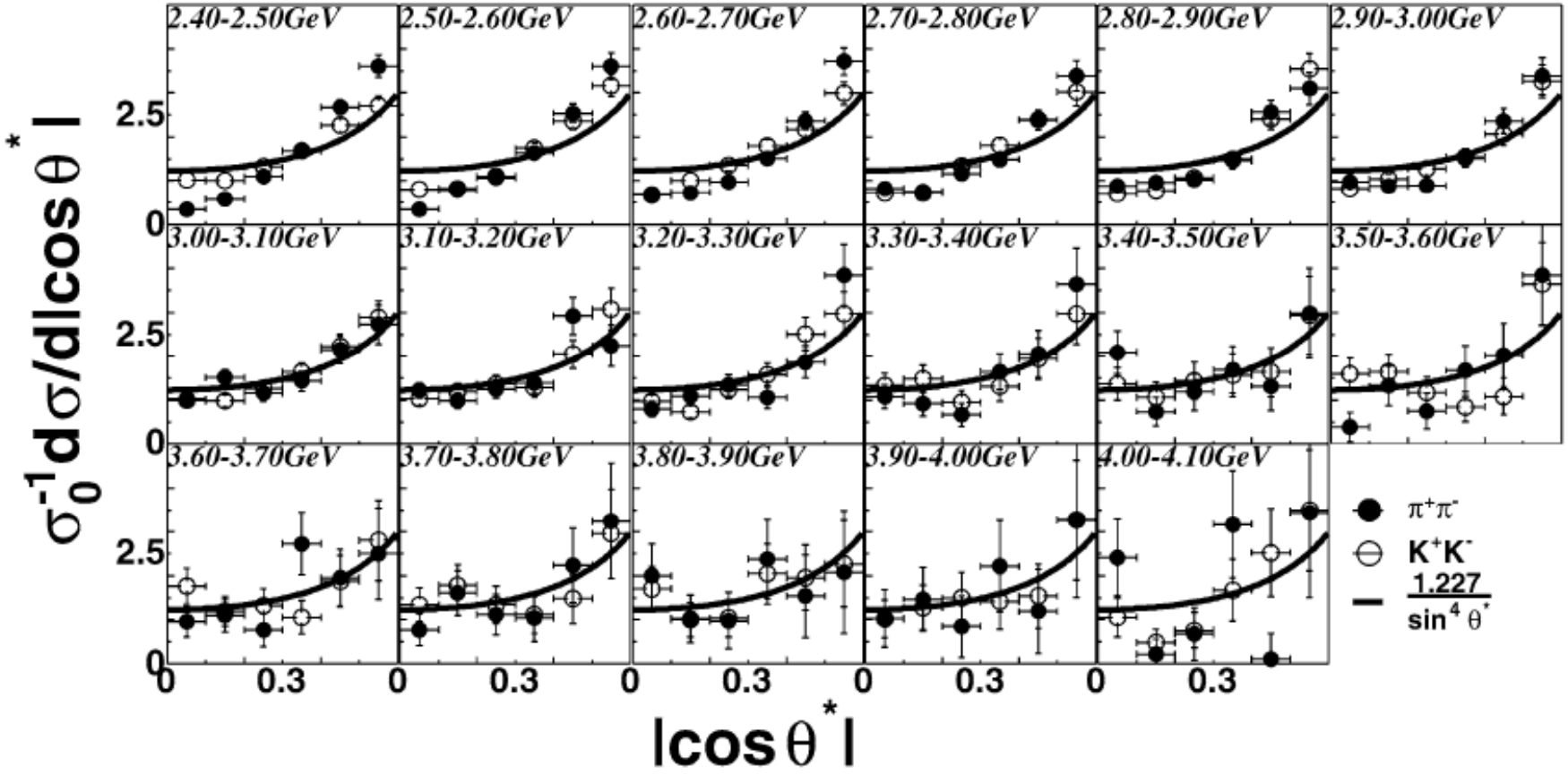
pQCD: **$\sim 1/\sin^4\theta^*$** for a charged-meson pair

(no definite prediction for a neutral-meson pair)

Handbag: $\sim 1/\sin^4\theta^*$ dep. , for BOTH charged and neutral

$\gamma\gamma \rightarrow \pi^+\pi^-$ and $\gamma\gamma \rightarrow K^+K^-$

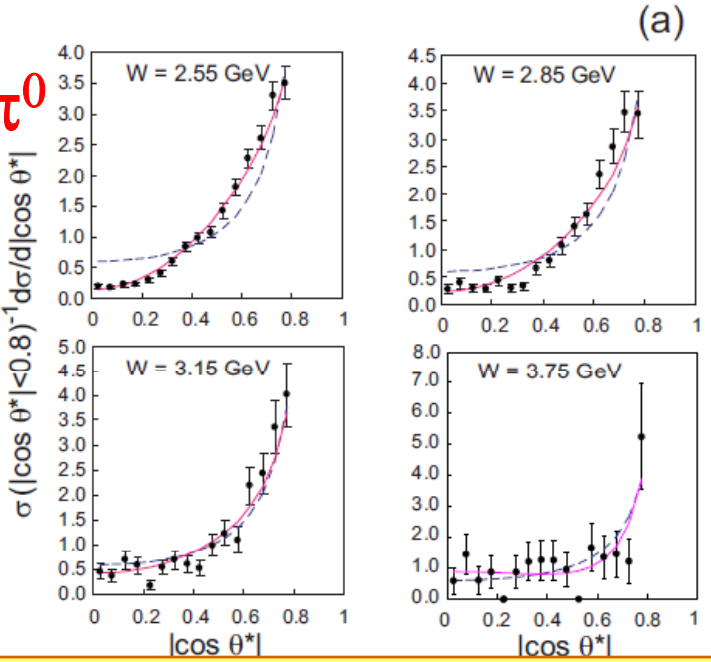
Black circles $\pi^+\pi^-$; White circles K^+K^-



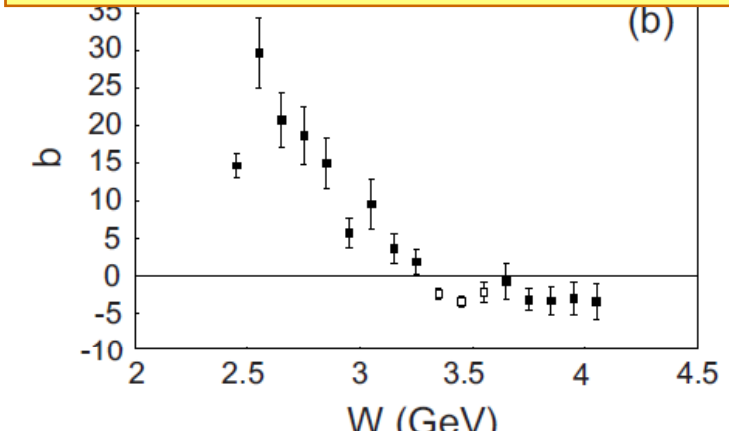
The **~1/sin⁴θ*** dependence is valid above W>3.0 GeV for these processes

$\pi^0\pi^0$ and $K_S{}^0K_S{}^0$

$\pi^0\pi^0$

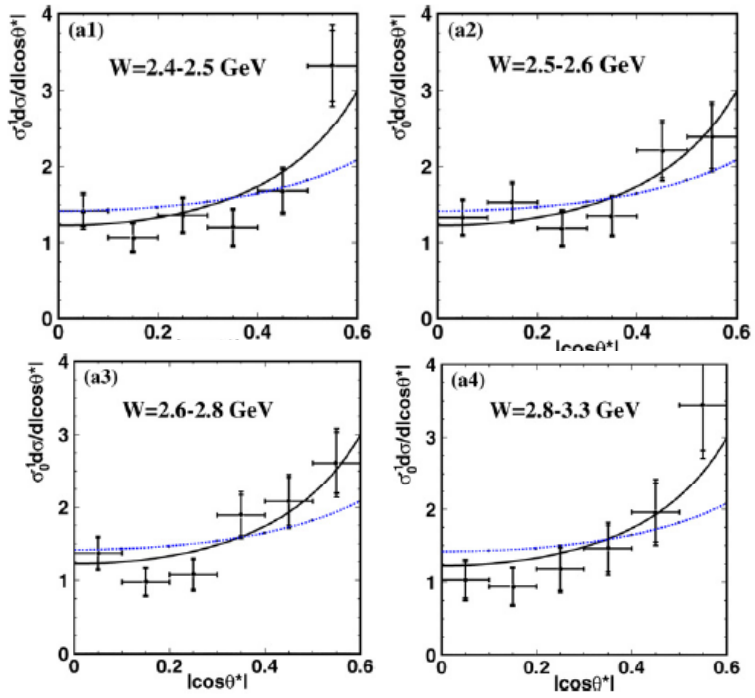


$$d\sigma/d|\cos\theta^*| = a(\sin^{-4}\theta^* + b\cos^2\theta^*).$$



$\sim 1/\sin^4\theta^*$ valid above W>3.1 GeV

$K_S{}^0K_S{}^0$



Angular dependence available only for W<3.3 GeV

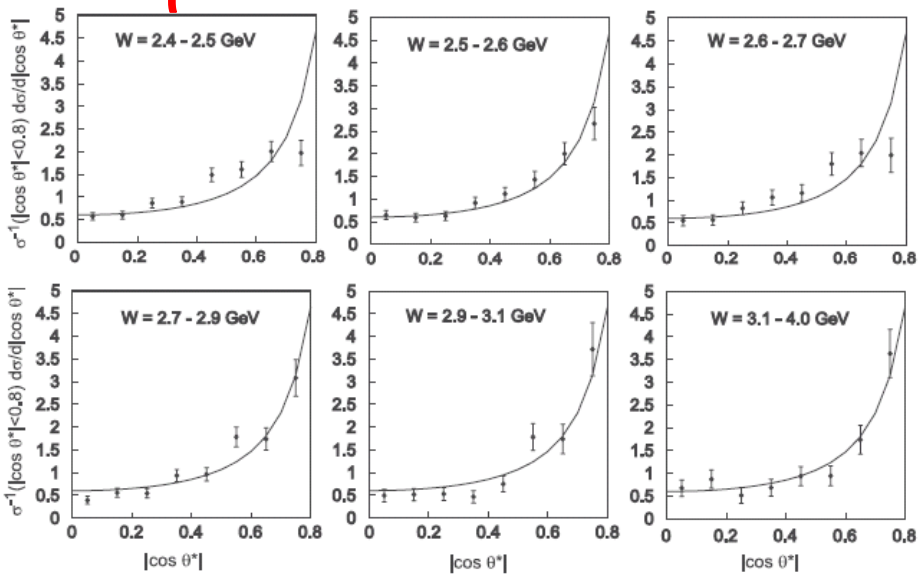
Black solid: Handbag ($\sim 1/\sin^4\theta^*$)

Blue dotted: Benayoun & Chernyak

Not bad within errors

$\pi^0\eta$ and $\eta\eta$

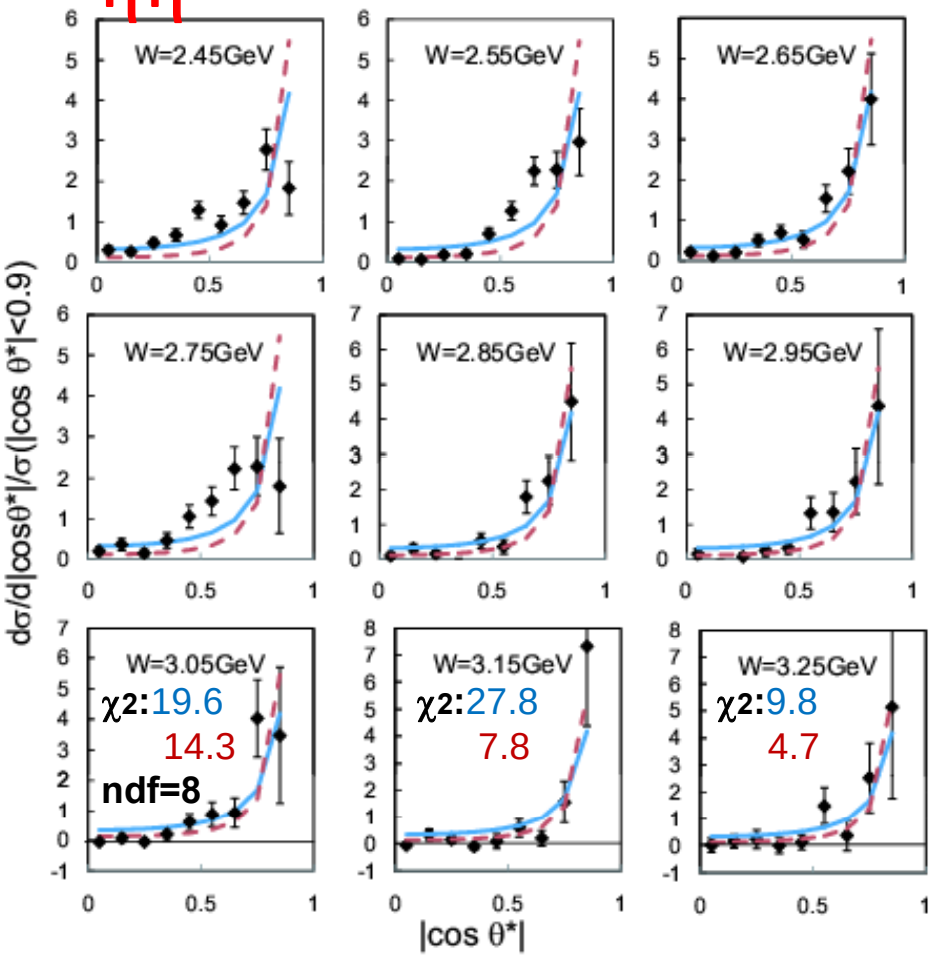
$\pi^0\eta$



The agreement with $1/\sin^4\theta^*$ is good for W>2.7GeV

The reactions **except** $\eta\eta$ show an agreement with $\sim 1/\sin^4\theta^*$ above W> 2.4 - 3.1 GeV.

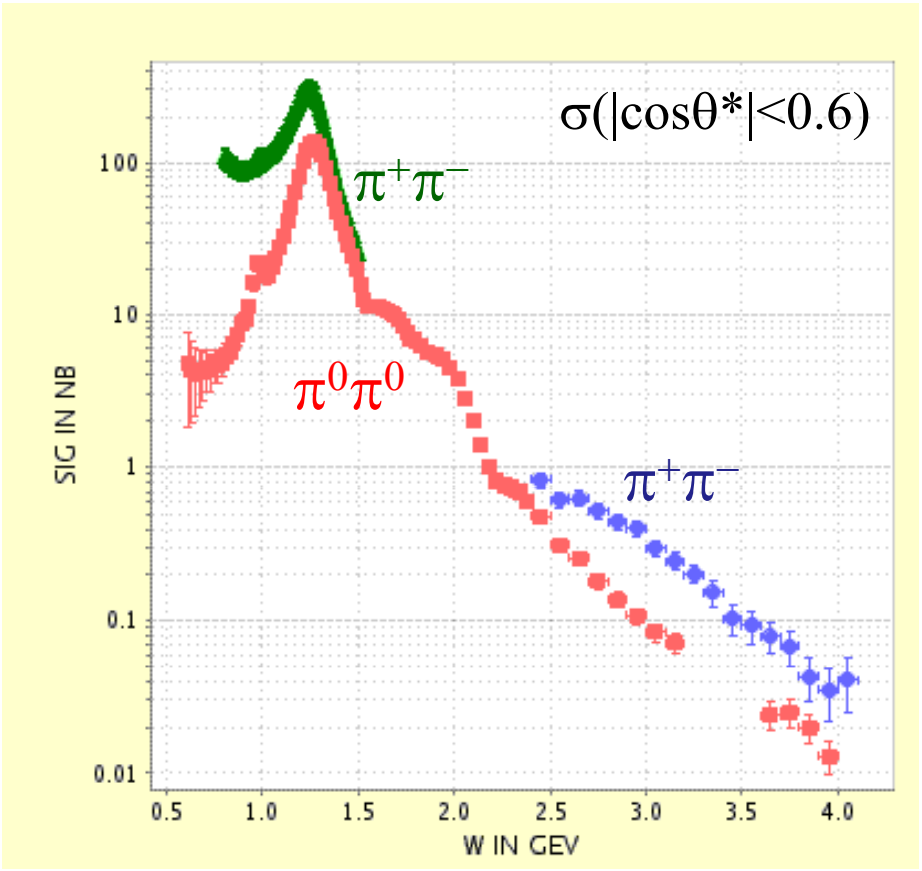
$\eta\eta$

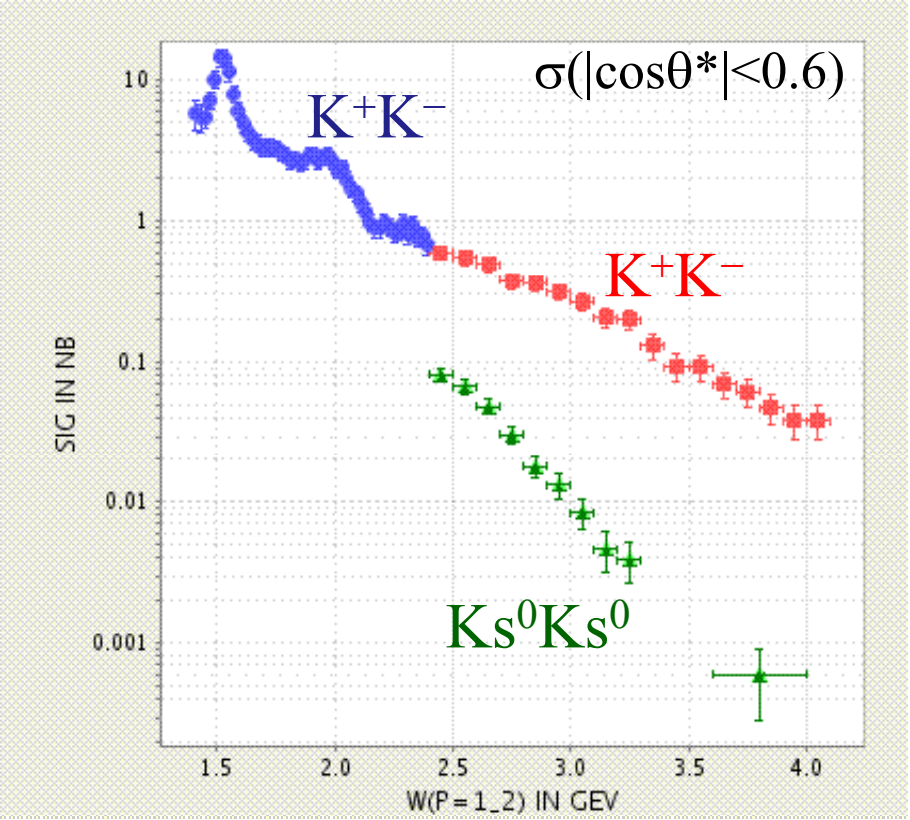


—— $\sim 1/\sin^4\theta^*$ is not good anywhere.

- - - $\sim 1/\sin^6\theta^*$ is better for W>3.0 GeV

Cross sections integrated over angle

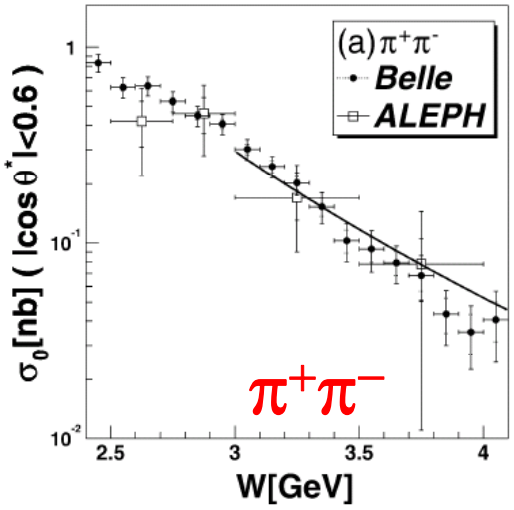


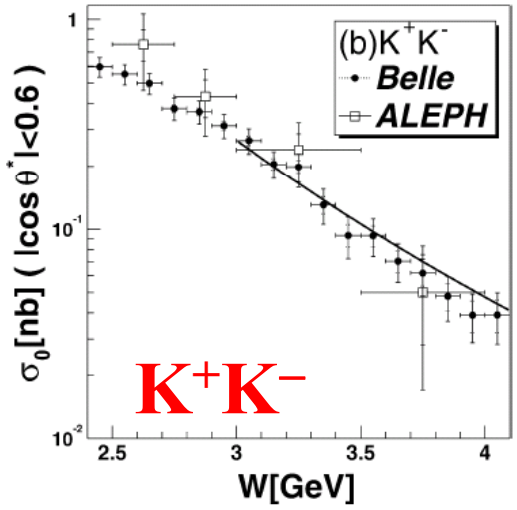


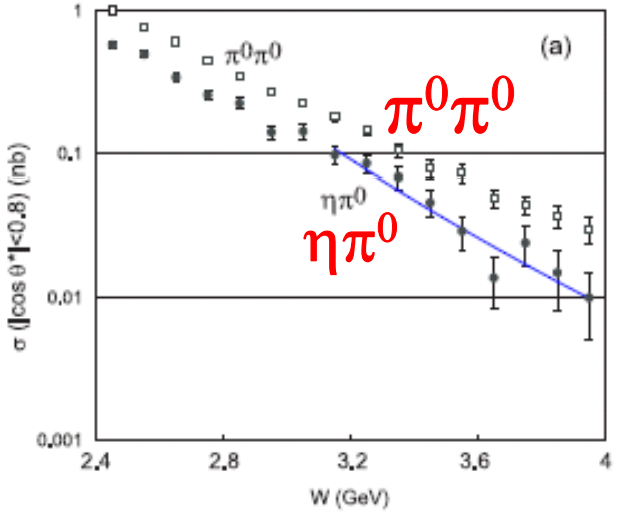
♠Those for $\eta\pi^0$ and $\eta\eta$ are shown in other slides

W-dependences at high energies

Assume or expect $\sigma(W) \sim W^{-n}$

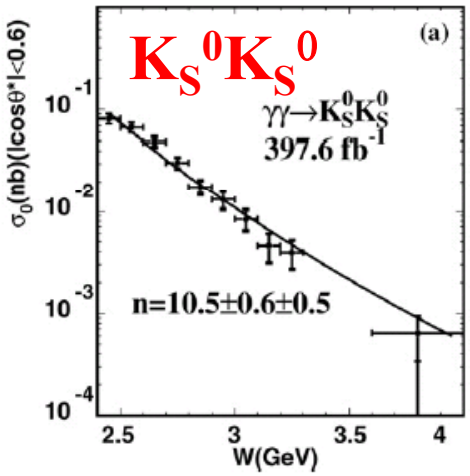


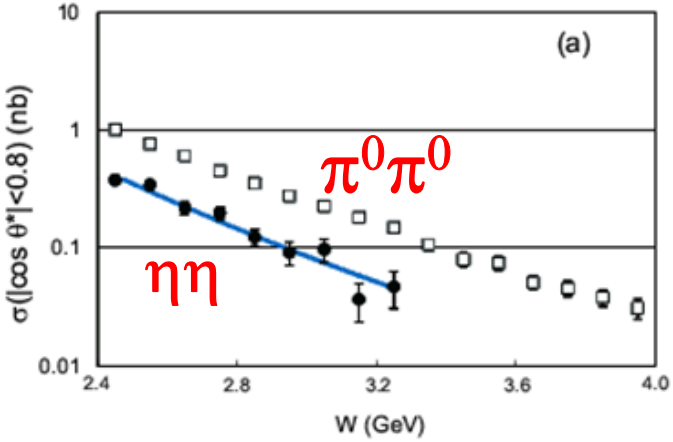




Fitted and reproduced
Slope parameter **n** different
among the reactions

Charmonium contributions
not included/removed





W-dependence: Summary

Process	n	W range (GeV)	$\lvert\cos\theta^*\rvert$ range
$\eta\eta$	$7.8 \pm 0.6 \pm 0.4$	2.4 – 3.3	< 0.8
$\eta\pi^0$	$10.5 \pm 1.2 \pm 0.5$	3.1 – 4.1	< 0.8
$\pi^0\pi^0$	$8.0 \pm 0.5 \pm 0.4$	3.1 – 4.1 (3.3 – 3.6 excluded)	< 0.8
$K^0_S K^0_S$	$10.5 \pm 0.6 \pm 0.5$	2.4 – 4.0 (3.3 – 3.6 excluded)	< 0.6
$\pi^+\pi^-$	$7.9 \pm 0.4 \pm 1.5$	3.0 – 4.1	< 0.6
K^+K^-	$7.3 \pm 0.3 \pm 1.5$	3.0 – 4.1	< 0.6

pQCD, in the enough high energies

Dimensional counting rule predicts -- n = 6

Handbag model introduces annihilation form factor,

n = 6 --- R(s) ~ 1/s

Slightly steeper than n = 6

Power corrections ? (mainly for $s\bar{s}$ component) (by DK)

Effects from resonance tail around 2.3GeV?

Baryon-pair result

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

n=15.1 $\pm^{0.8}_{1.1}$ @ 2.5 – 2.9 GeV

n=12.4 $\pm^{2.4}_{2.3}$ @ 3.2 – 4.0 GeV

Dimensional counting rule:

n= 10

PLB 621, 41 (2005)

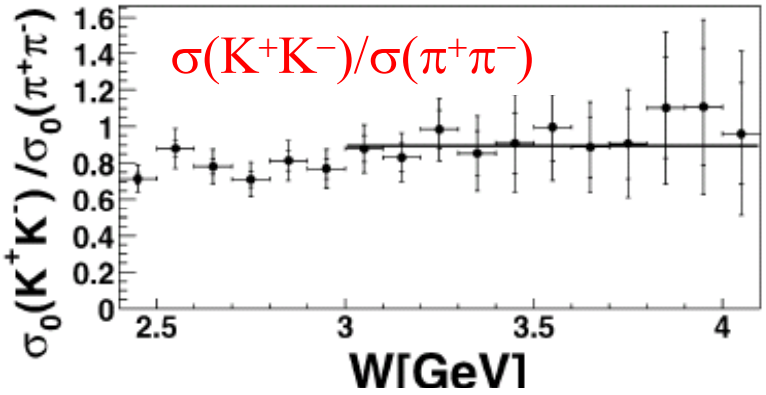
Cross-section ratios: K vs π or Charged vs Neutral

$\sigma(K^+K^-)/\sigma(\pi^+\pi^-) = 0.89 \pm 0.04(stat.) \pm 0.15(syst.)$ $|\cos\theta^*|<0.6$

--- slightly smaller than unity

Close to Benayoun-Chernyak(1.08),

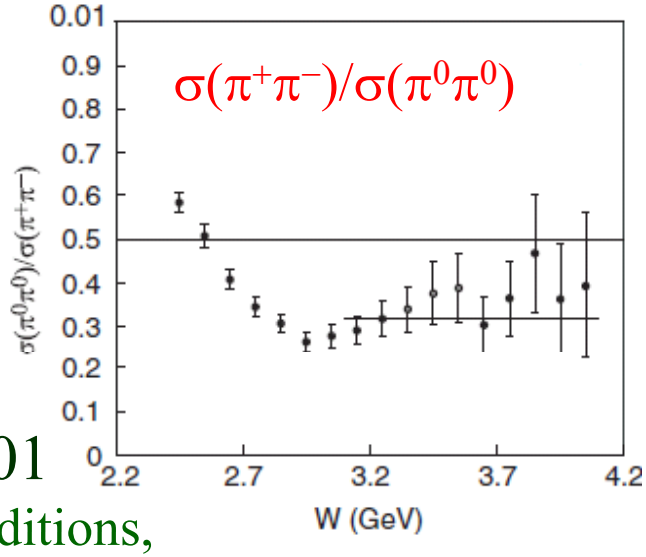
Difference between π and K form factors

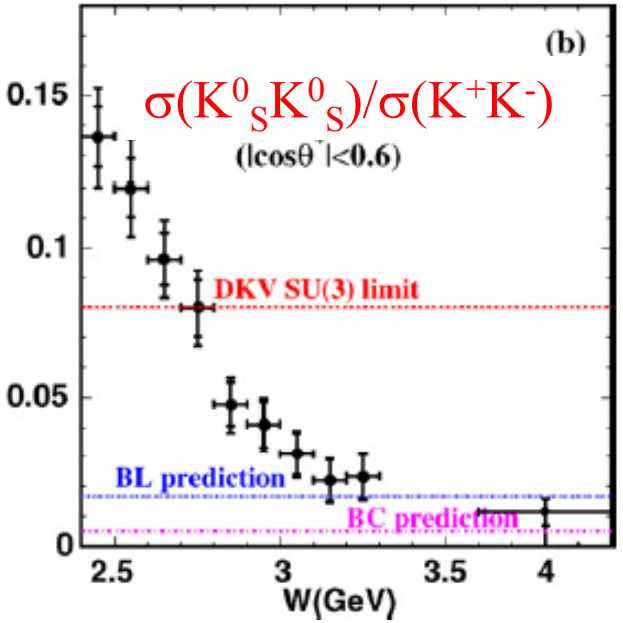


$\sigma(\pi^0\pi^0)/\sigma(\pi^+\pi^-) = 0.32\pm 0.03\pm 0.05,$

Larger than LO- pQCD (<~0.1)

Smaller than 0.5 suggested by I=0



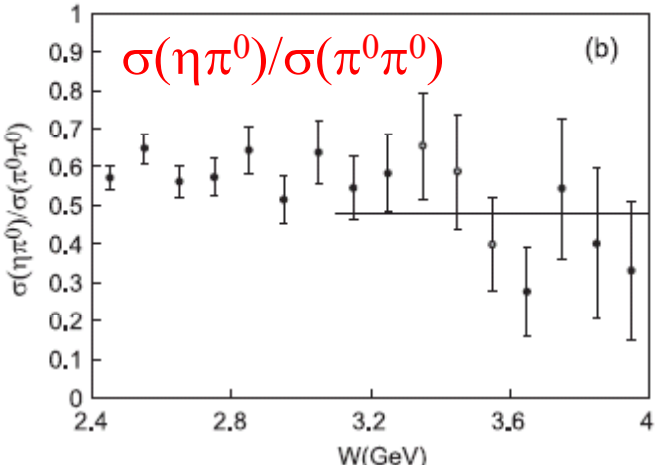


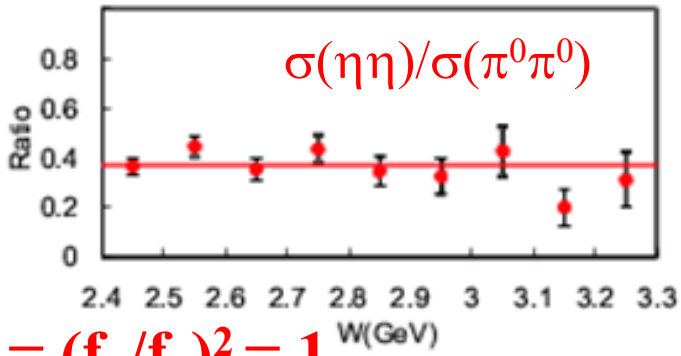
$\sigma(K^0_SK^0_S)/\sigma(K^+K^-)$ changes ~ 0.13 to ~ 0.01

Approaches the pQCD preditions,

Much smaller than Handbag prediction in HE

Cross-section ratios: Among neutral pairs





Comparison with pQCD – $q\bar{q}$ model

η in SU(3)	$\sigma(\pi^0\pi^0) : \sigma(\eta\pi^0) : \sigma(\eta\eta)$
octet	$1 : 0.24R_f : 0.36R_f^2$

S.J.Brodsky, G.P.Lepage, PRD 24, 1808 (1981)

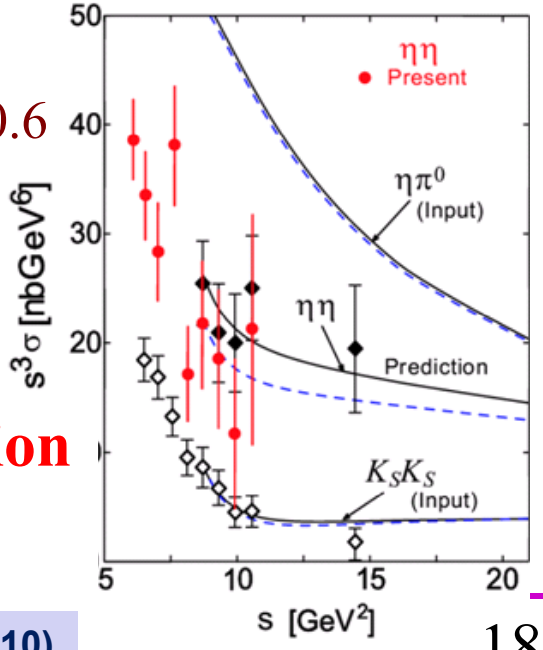
$\theta_P = -18°$	$1 : 0.46R_f : 0.62R_f^2$

1: (0.48±0.06) : (0.37±0.04)

↑ Belle Measurement

$|\cos\theta^*|<0.8$

$|\cos\theta^*|<0.6$



$R_f = (f_\eta/f_\pi)^2 = 1$

reproduces $\eta\pi^0/\pi^0\pi^0$ but does not $\eta\eta/\pi^0\pi^0$

Comparison with the Handbag model prediction

Based on SU(3)-flavor symmetry

and Belle measurements for different processes

M. Diehl, P.Kroll, PLB 683, 165 (2010)

Summary on the QCD part

Angular dependence of the differential cross sections

Steeply increasing to forward angle in all the processes,

Consistent with $\sim 1/\sin^4\theta^*$ except the $\eta\eta$ process.

(W region depends on process)

W-dependence

Slope parameter depends on process: $n = 7 - 11$

No clear explanation for the differences

Cross-section Ratio

Not completely reproduced by either pQCD or handbag predictions

Partially explained by these models

More detailed comparisons/considerations are necessary.

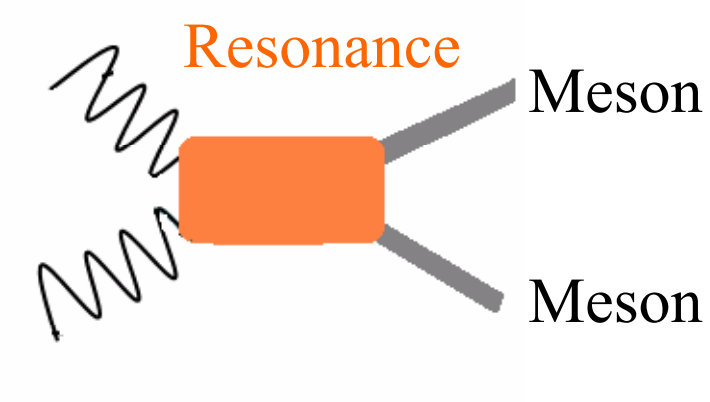
Take kinematical regions into account

Non-valence quark components

Resonance production

Resonance production and quantum numbers

Resonance formation or **partial-waves**



$Q = 0$, **C = +,**

$J^P = 0^+, 0^-, 2^+, 2^-, 3^+, 4^+, 4^-, 5^+ \ldots.$

$(\text{even})^{\pm}$, $(\text{odd} \neq 1)^+$

Strict constraints for quantum numbers

Pseudoscalar-pair production: $J^P = (\text{even})^+$ only

$\Gamma\gamma\gamma$, two-photon partial decay width of the resonance,

from the cross-section measurement,

important information for the **meson's internal structure**

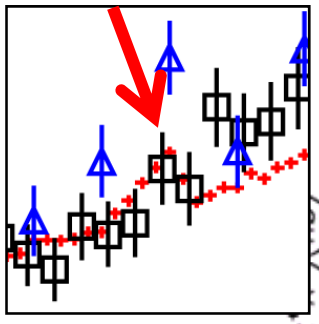
Decay properties

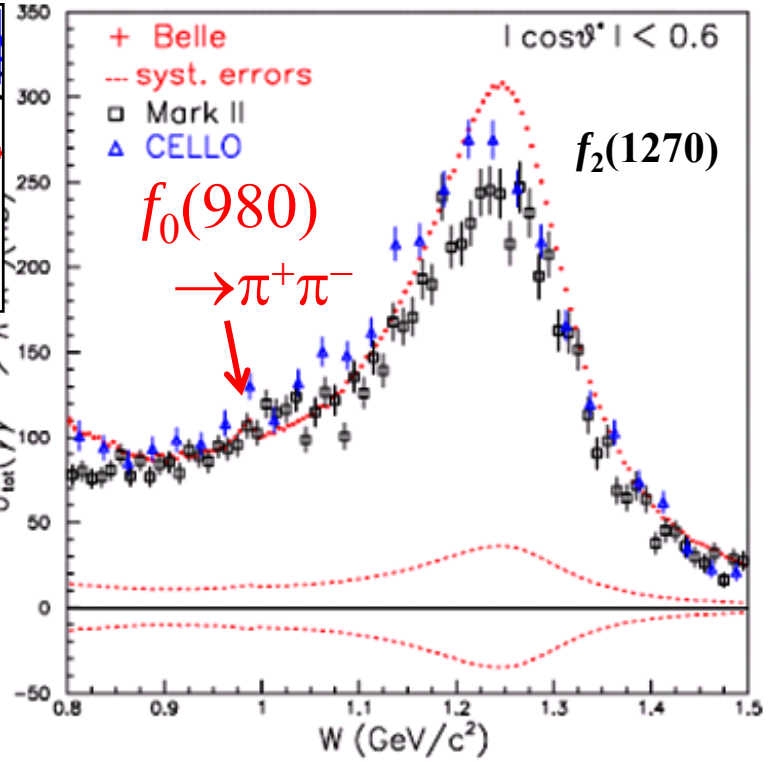
Searches/Discoveries of **new resonances, including *"XYZ"***

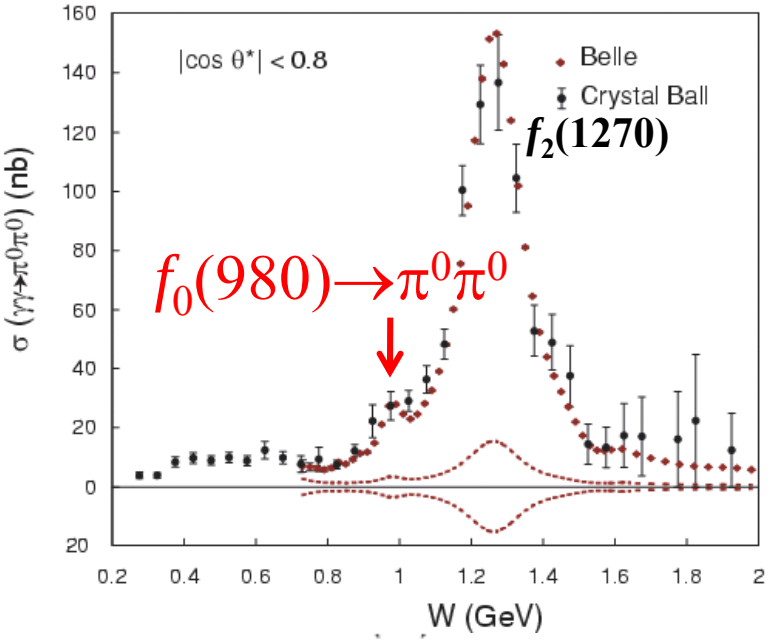
Confirmations of $f_0(980)$ and $a_0(980)$

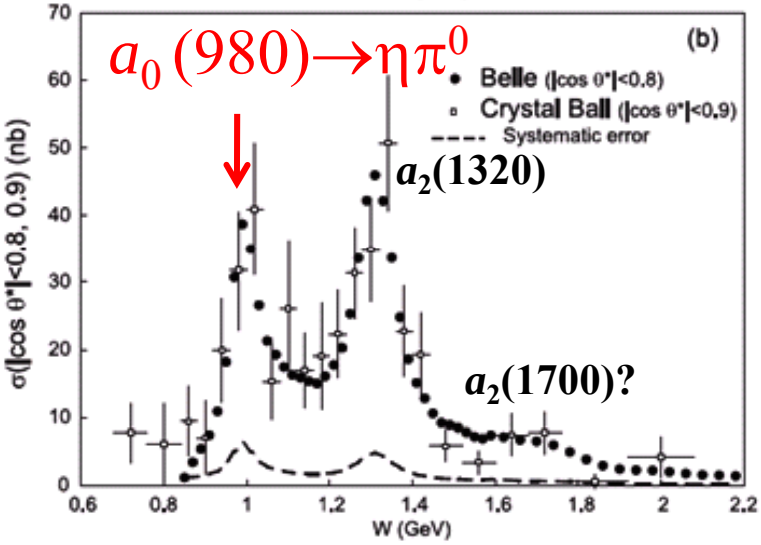
True nature of **$f_0(980)$ and $a_0(980)$**
is not clarified, well.

We observe them as a peak very clearly
in two-photon production for the first time
- Measurements of $\Gamma\gamma\gamma$

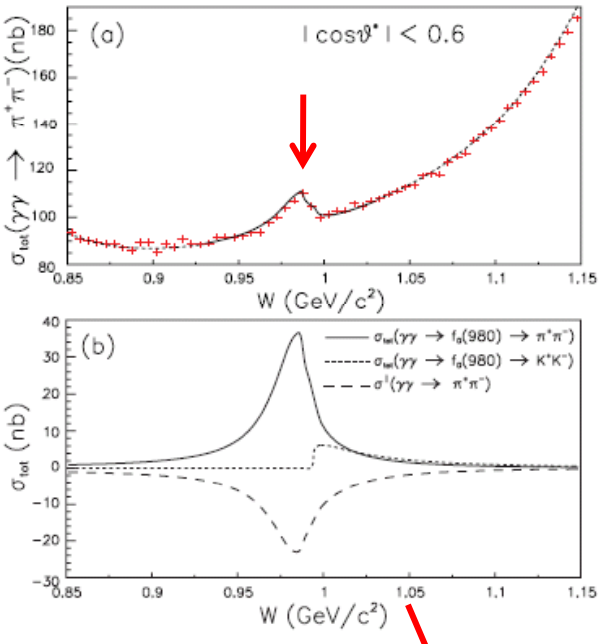


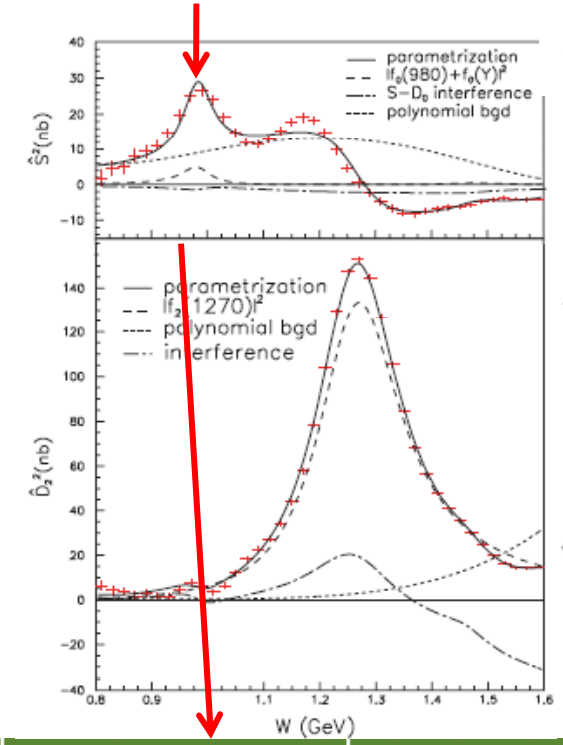




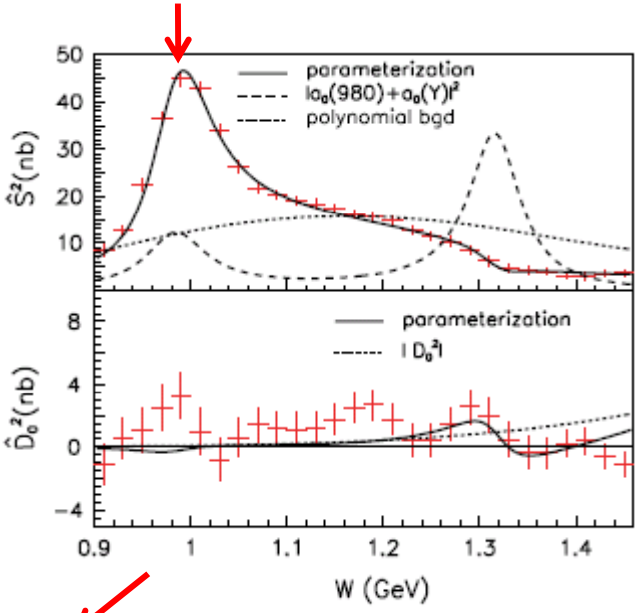


Two-photon decay width of $f_0(980)$ and $a_0(980)$





$$\frac{d\sigma}{d\Omega} = \hat{S}^2\left|Y_0^0\right|^2 + \hat{D}_0^2\left|Y_2^0\right|^2 + \hat{D}_2^2\left|Y_2^2\right|^2$$



Meson	$f_0(980)$	$f_0(980)$	$a_0(980)$
M[MeV/c^2]	$985.6^{+1.2+1.1}_{-1.5-1.6}$	$982.2 \pm 1.0^{+8.1}_{-8.0}$	$982.3^{+0.6+3.1}_{-0.7-4.7}$
$\Gamma_{\pi\pi/tot}$[MeV]	$51.3^{+20.9+13.2}_{-17.7-3.8}$	$66.9^{+13.9+8.8}_{-11.8-2.5}$	$75.6 \pm 1.6^{+17.4}_{-10.0}$
$\Gamma_{\gamma\gamma}$[eV]	$205^{+95+147}_{-83-117}$	$286 \pm 17^{+211}_{-70}$	$128^{+3+502}_{-2-43} / \mathcal{B}_{\pi^0\eta}$
Channel	$\gamma\gamma \rightarrow \pi^+\pi^-$	$\gamma\gamma \rightarrow \pi^0\pi^0$	$\gamma\gamma \rightarrow \pi^0\eta$
Reference	PRD75, 051101(2007)	PRD78, 052004(2008)	PRD80, 032001(2009)

Predictions

Model	$\Gamma_{\gamma\gamma}$ [eV]
*uu*bar,*dd*bar	1300 – 1800
*ss*bar	300 – 500
*KK*bar molecule	200 – 600
Four-quark	270

Summary of resonances seen in $\gamma\gamma \to MM'$

$f_0(980) \to \pi^+\pi^-, \pi^0\pi^0$ **$a_0(980) \to \eta\pi^0$**

The 1^3P_2 tensor-meson triplet **$f_2(1270)$, $f'_2(1525)$, $a_2(1320)$**

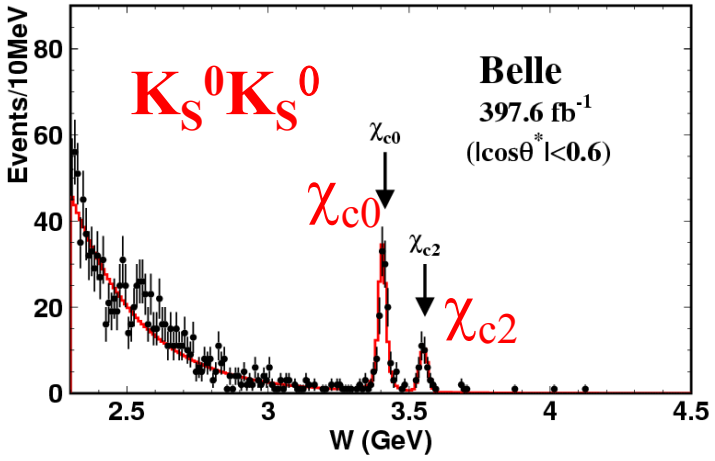
$f_0(Y) \to \pi^+\pi^-, \pi^0\pi^0, \eta\eta$ unidentified in 1.2 – 1.5 GeV

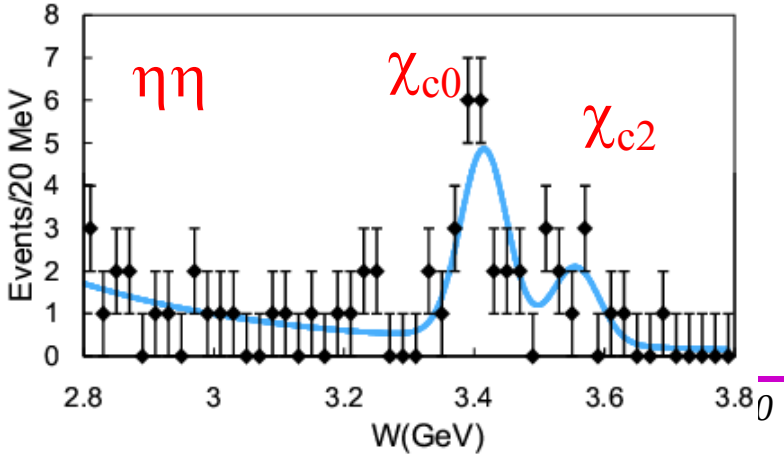
$a_0(Y) \to \eta\pi^0$ unidentified in 1.2 – 1.5 GeV

$f_2(X) \to \pi^0\pi^0, \eta\eta$ unidentified in 1.7 – 2.0 GeV

Signatures of $a_2(1700)$?, f_4, a_4, and/or others? seen in 1.7 – 2.3 GeV in $\pi^0\pi^0$, $\eta\pi^0$, $\eta\eta$ and K^+K^-

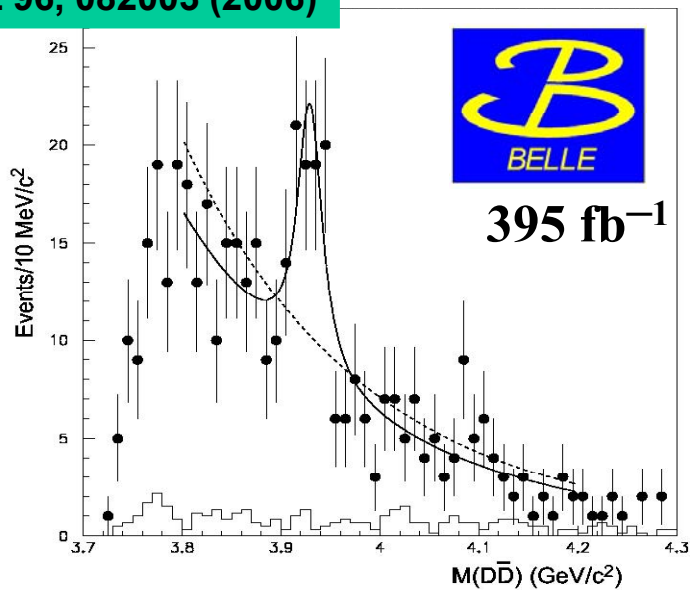
χ_{c0}, χ_{c2} $\to \pi^+\pi^-, K^+K^-, \pi^0\pi^0, K^0_SK^0_S, \eta\eta$

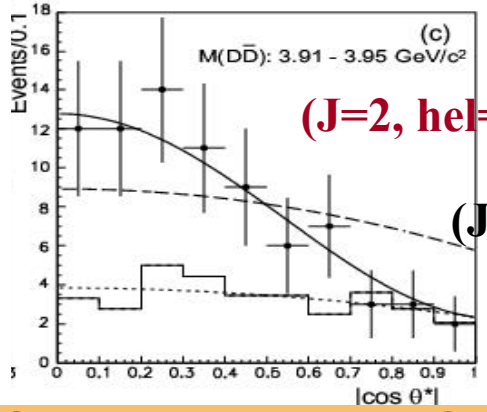




$\gamma\gamma \rightarrow Z(3930) \rightarrow D\bar{D}$ discovered /confirmed

PRL 96, 082003 (2006)





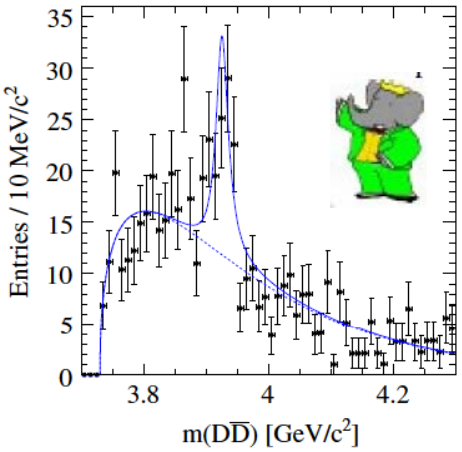
(J=2, hel=2)

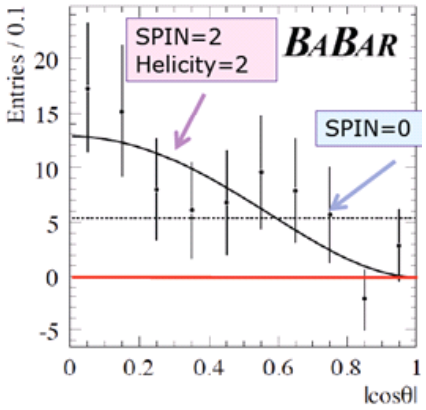
(J=0)

$m(3930)=3929\pm5\pm2$ MeV/c^2
$\Gamma(3930)=29\pm10\pm2$ MeV
$\Gamma_{\gamma\gamma}\cdot BF(Z(3930\rightarrow D\bar{D}))=0.18\pm0.05\pm0.03$ keV

BaBar, PRD 81, 092003 (2010)

384 fb^{-1}



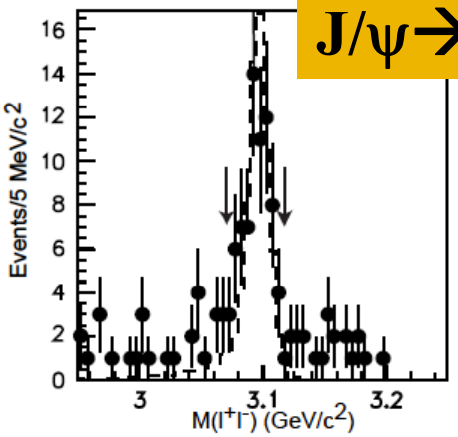


$m(3930)=3926.7\pm2.7\pm1.1$ MeV/c^2
$\Gamma(3930)=21.3\pm6.8\pm3.6$ MeV
$\Gamma_{\gamma\gamma}\cdot BF(Z(3930\rightarrow D\bar{D}))=0.24\pm0.05\pm0.04$ keV

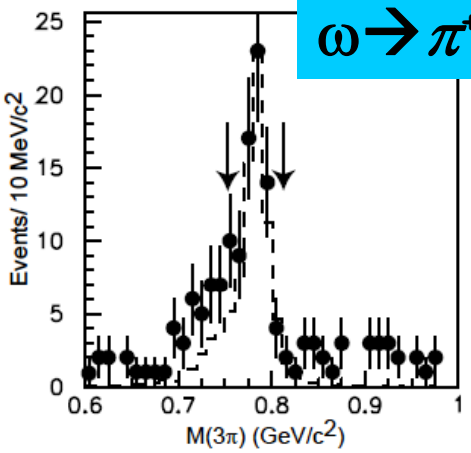
Belle and Babar results are consistent

Confirms that Z(3930) = $\chi_{c2}(2P)$

Peak in $\gamma\gamma \rightarrow \omega J/\psi$

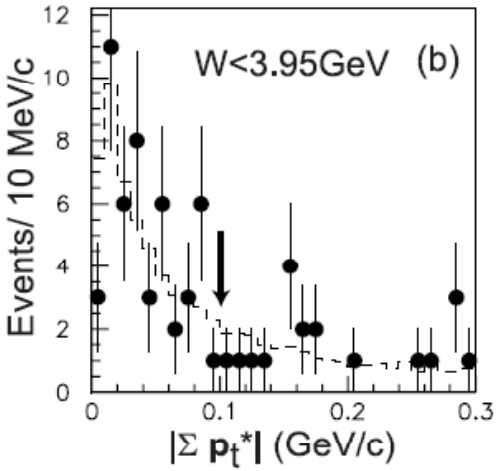


$J/\psi \rightarrow l^+l^-$

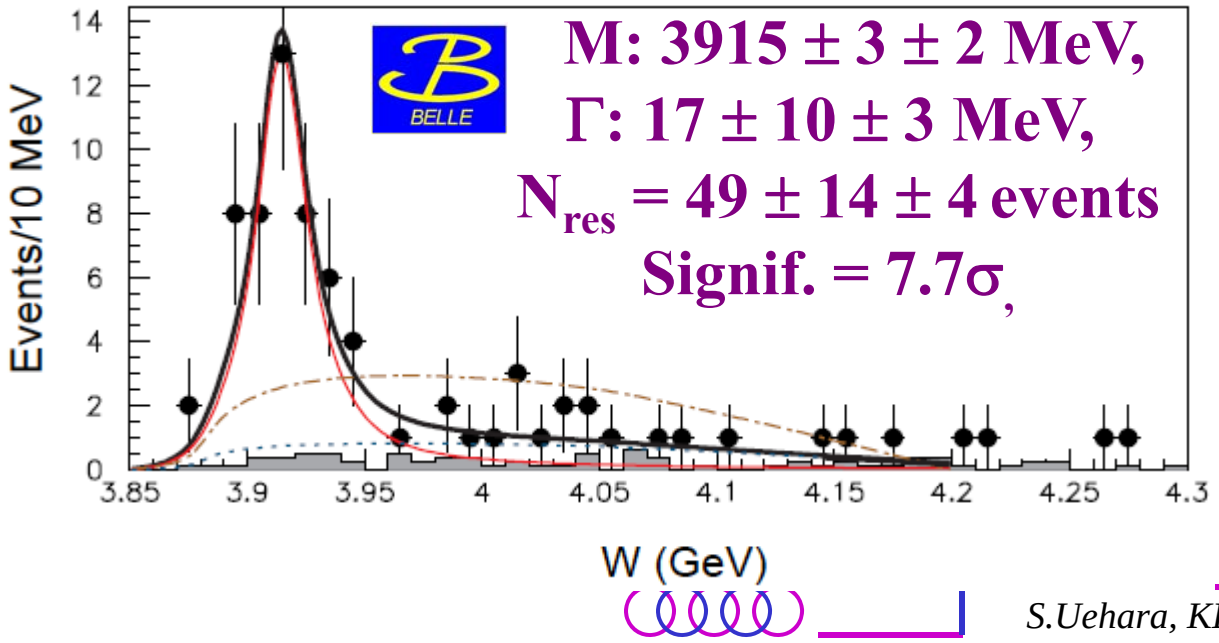


$\omega \rightarrow \pi^+\pi^-\pi^0$

PRL 104, 092001 (2010)



694 fb^{-1}

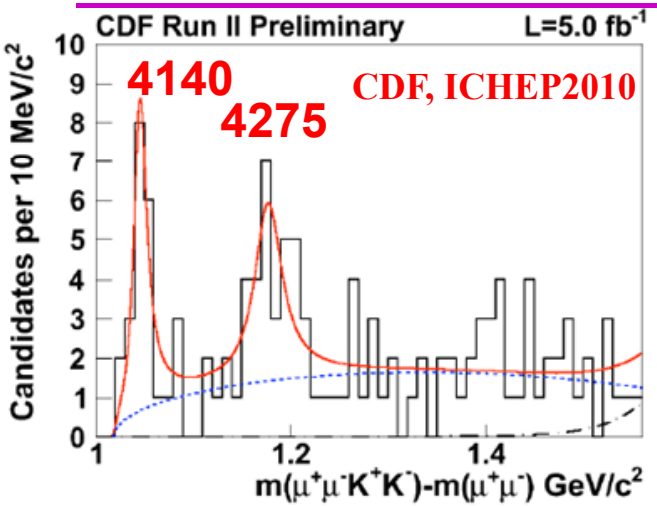


Two-photon production of Y(3940) ?
reported in B decay

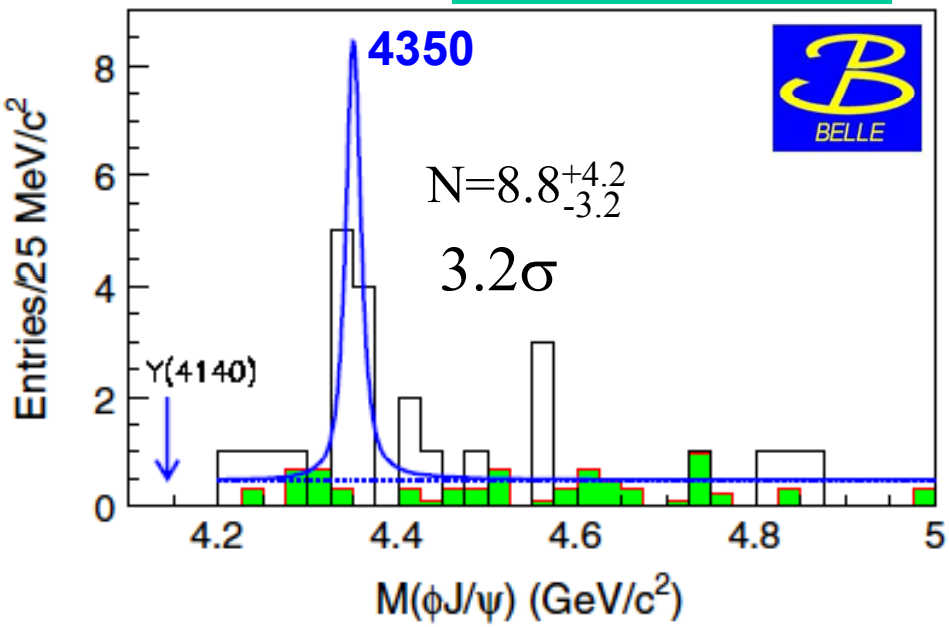
or

New decay mode of $Z(3930)/\chi_{c2}(2P)$?

$\gamma\gamma \rightarrow \phi\, J/\psi$



PRL 104,112004 (2010)

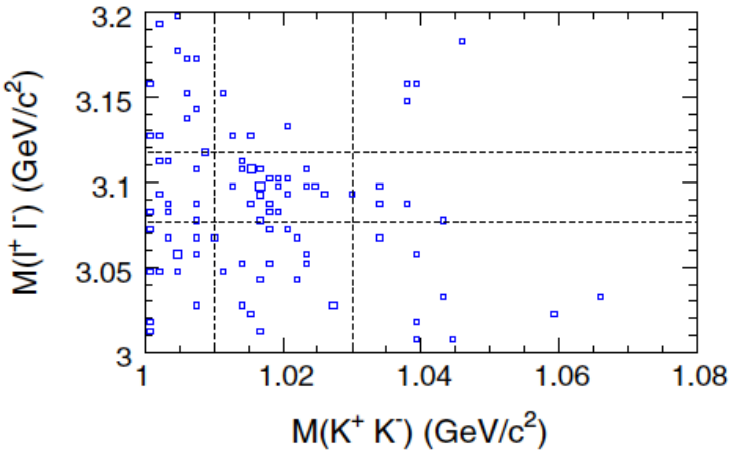


Y(4140), reported by CDF in B-meson decays, is NOT seen in two-photon process by Belle.

Instead, a **new peak** is seen at around 4.35 GeV in the same process

$M = 4350.6\ ^{+4.6}_{-5.1} \pm 0.7$ MeV/c^2

$\Gamma = 13\ ^{+18}_{-9} \pm 4$ MeV



Summary

Many meson-pair production processes from two-photon collisions are studied at Belle.

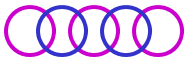
- Cross sections in the 2 – 4 GeV region are compared with predictions based on QCD, systematically.
- Any comprehensive reproducibility by theoretical models is not obtained, yet.

  Further comparison with theories is now possible.
- Belle discovers/confirms several interesting meson states produced in two-photon fusion:

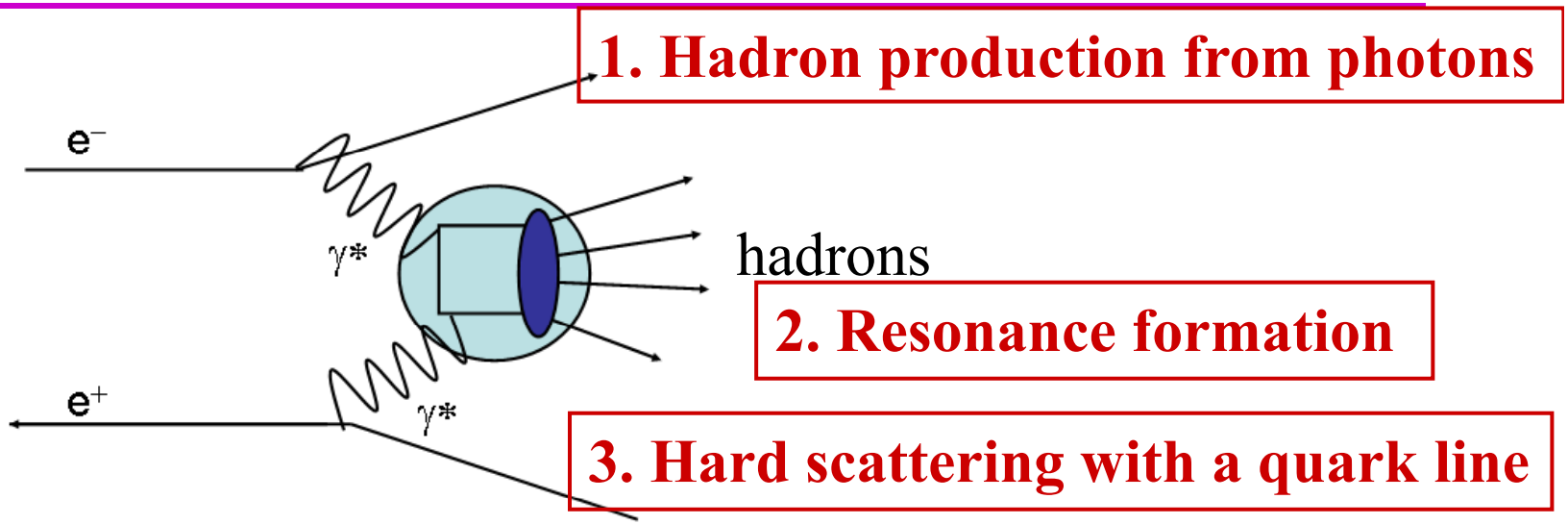
  $\Gamma\gamma\gamma$ for $f_0(980)$ and $a_0(980)$ are measured

  New charmonium-like states are found

  $Z(3930) = \chi_{c2}(2P)$, X(3915)=Y(3940)?, X(4350)



Two-Photon Collisions and QCD/Hadron Physics



Hadron production from collision of virtual or quasi-real photons

Perturbative/Non-perturbative QCD

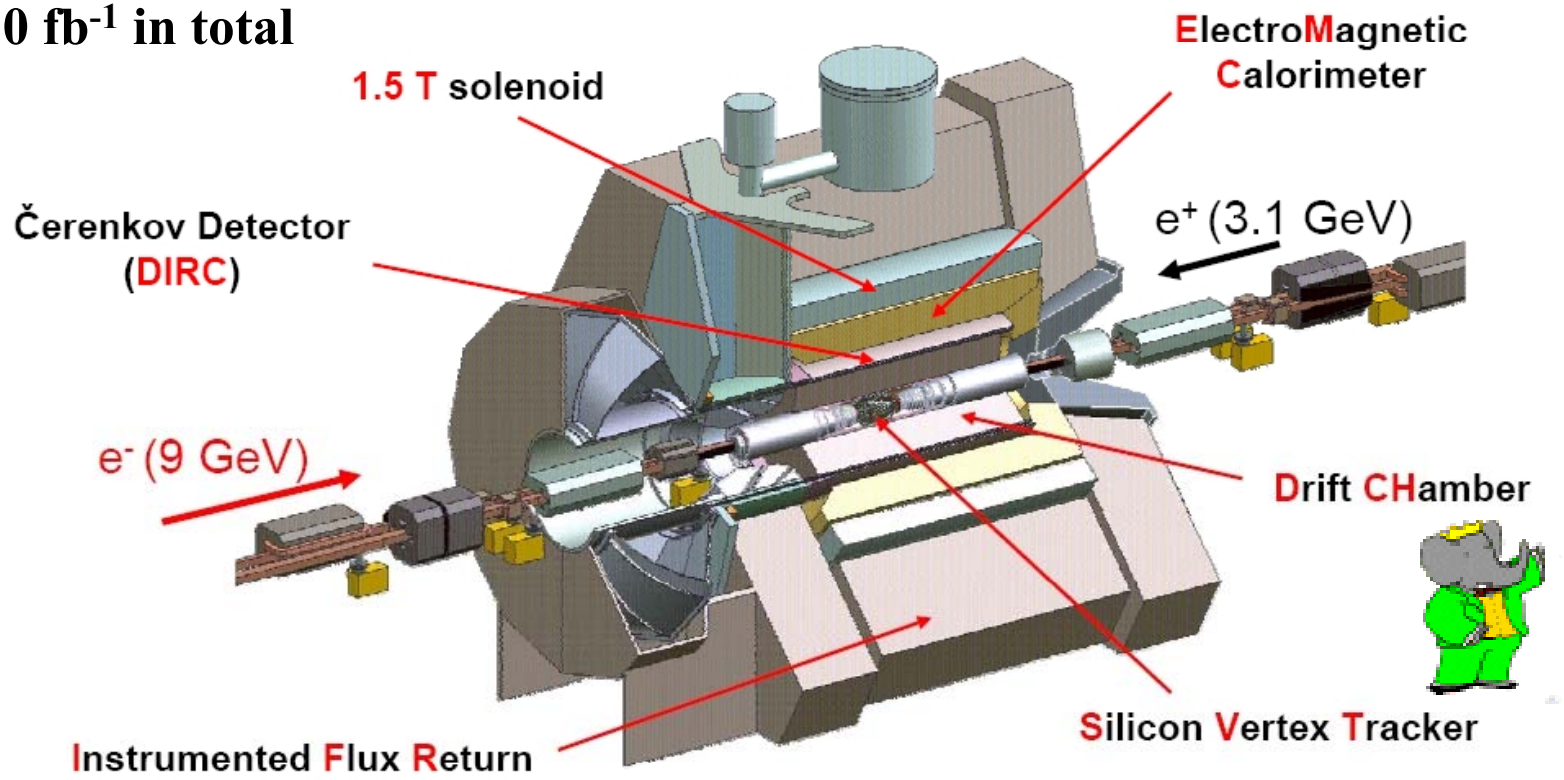
Hadron/Photon form factors

Wide energy region --- Various physics aspects
can be studied simultaneously.

BaBar at PEP-II

$e^+e^- \rightarrow Y(4S)$ and nearby continuum: $E_{cms} \sim 10.6$ GeV

530 fb^{-1} in total



No-tag $\gamma\gamma$ measurements at B-factories

Production from two quasi-real photon

(Dominated by $\mathbf{Q^2} \equiv |q^2| < 0.001\,\mathrm{GeV}^2$)

p_t- balance requirement,

$$\mathbf{|\Sigma\, p^*_t\,(hadrons)| < 0.05 \sim 0.3\ GeV/c}$$

Exclusive processes $\mathbf{W} \equiv W_{\gamma\gamma} \sim 0.6$ - 4.5 GeV

$\gamma\gamma$ c.m. energy = invariant mass of the hadron system

Translate the cross section $\sigma_{ee} \rightarrow \sigma_{\gamma\gamma}$

with Equivalent Photon Approximation

$\mathbf{\sigma_{\gamma\gamma} = (d\sigma_{ee}/dW)/L_{\gamma\gamma}(W)}$ Two-photon luminosity function calculated by QED

"$\gamma\gamma \to$ meson pair" measurements from Belle

$\pi^+\pi^-$: **PLB 615, 39 (2005)** 87.7fb^{-1}, 2.4 - 4.1GeV, QCD, Charmonia
PRD 75, 051101(R) (2007) 85.9fb^{-1}, 0.8 - 1.5 GeV, light-quark resonance
J. Phys. Soc. Jpn. 76, 074102 (2007) 85.9fb^{-1}, 0.8 - 1.5 GeV, light-quark resonances

K^+K^-: **EPJC 32, 323 (2003)** 67fb^{-1}, 1.4 - 2.4 GeV, light-quark resonances
PLB 615, 39 (2005) 87.7fb^{-1}, 2.4 - 4.1GeV, QCD, Charmonia

$\pi^0\pi^0$: **PRD 78, 052004 (2008)** 95fb^{-1}, 0.6 - 4.0 GeV, light-quark resonances
PRD 79, 052009 (2009) 223 fb^{-1}, 0.6 - 4.0 GeV, light-quark resonances, QCD, Charmonia

$K^0_S K^0_S$: **PLB 651, 15 (2007)** 397.6fb^{-1}, 2.4 - 4.0GeV, QCD, Charmonia

$\eta\pi^0$: **PRD 80, 032001 (2009)** 223 fb^{-1} , 0.84 - 4.0 GeV, light-quark resonances, QCD

$\eta\eta$: **ArXiv:1007.3779[hep-ex](2010)** 393 fb^{-1} , 1.1- 4.0 GeV, light-quark resonances, QCD, Charmonia

We, in principle, measure differential cross section **$d\sigma/d|\cos\theta^*|$** for these reaction processes.

Experimental Analysis; $\gamma\gamma \rightarrow \eta\eta$

$\eta(548\text{MeV}) \rightarrow \gamma\gamma$ (Only 4 photons are visible in this process)

Triggered by ECL triggers ($\Sigma E > 1.1$GeV or ≥ 4 clusters)

$\sqrt{s} = 9.4 - 11.0$ GeV $\quad \int Ldt = 393$ fb^{-1}

Selection of $\eta\eta$ signal events

-Just 4 γ's with $E\gamma > 100$ MeV, No π^0 candidate

η reconstruction

-Two 2γ sets each satisfying

$0.52 < M\gamma\gamma < 0.57$GeV

- Apply energy correction for each η, scaling to the nominal mass

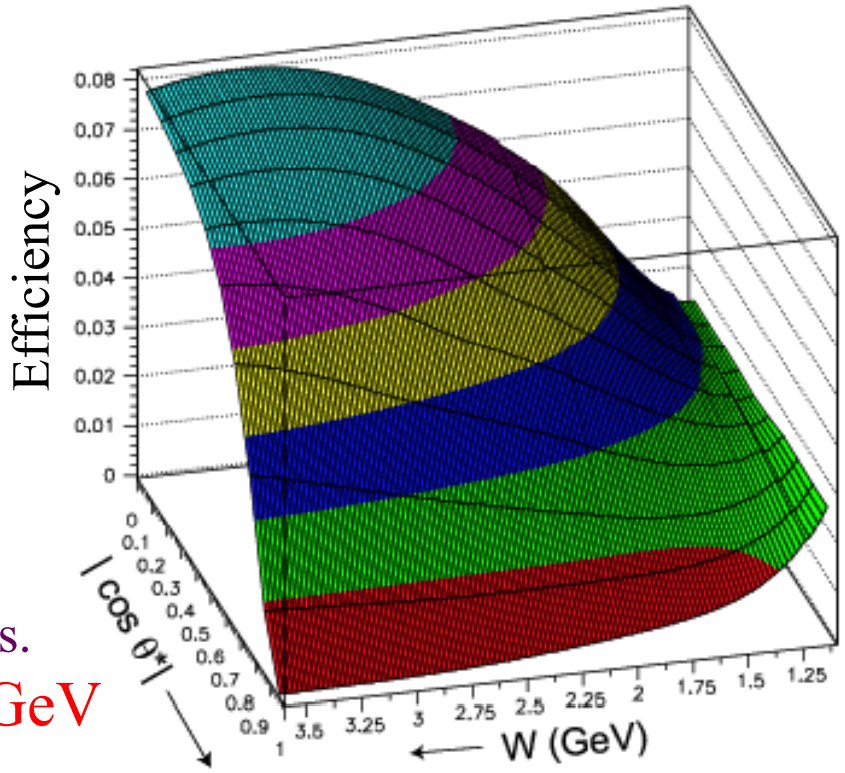
-p_t-balance <50 MeV/c

W: $\gamma\gamma$ energy in its c.m.s.

θ^*: scattering angle of the meson in the $\gamma\gamma$ c.m.s.

1.096GeV (mass threshold) < W < 3.8 GeV

$|\cos\theta^*| < 0.9$ or < 1.0



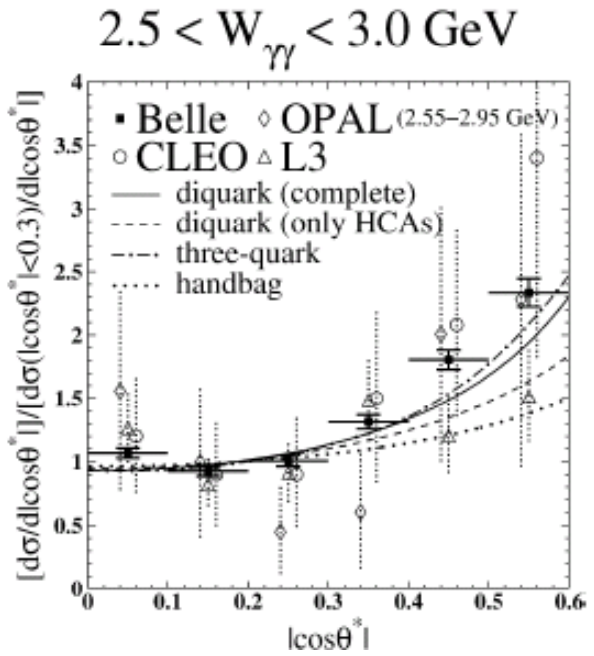
Baryon pair: $\gamma\gamma \to p\bar{p}$

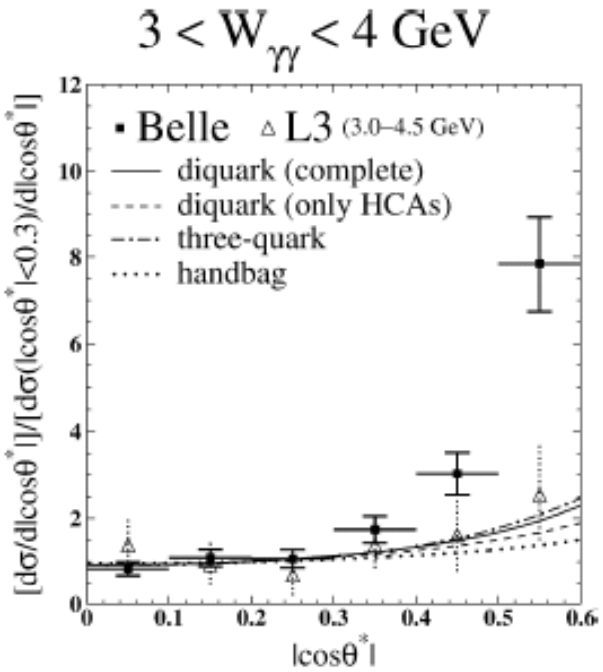
PLB 621, 41 (2005)

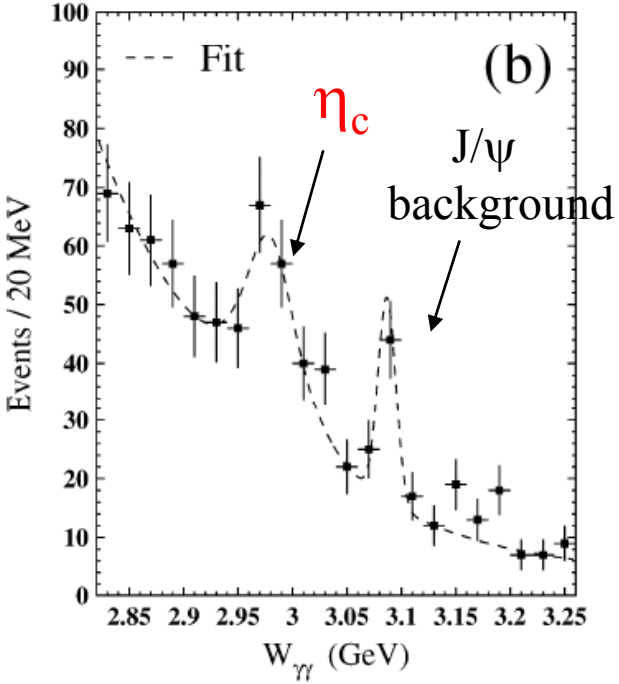
Baryon production mechanism

Couple with a single quark?.. or a diquark?

Angular and W dependences, Cross-section size







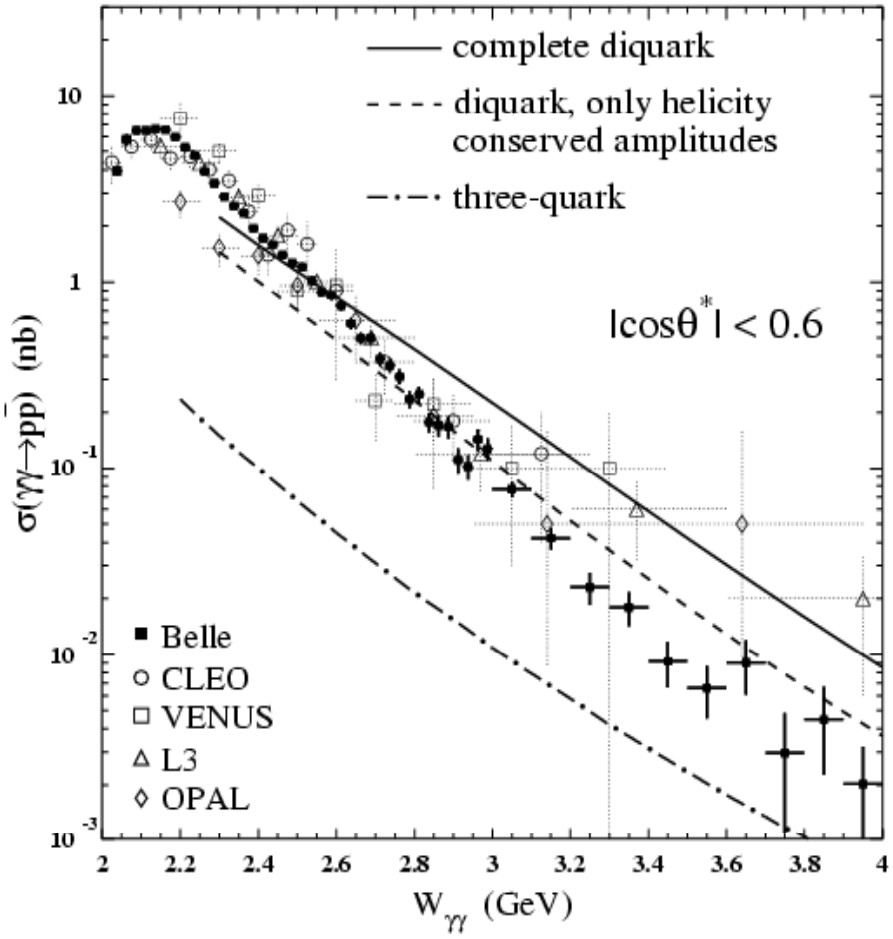
Model predictions are normalized for $|\cos\theta^*|<0.3$.

Agreement is not very good in W>3 GeV

η_c :observation in this proces

Subtract charmonium contributions

Cross sections; W dependence



$W_{\gamma\gamma}^{-n}$ dependence

$n=15.1 \pm^{0.8}_{1.1}$ @ 2.5 – 2.9 GeV

$n=12.4 \pm^{2.4}_{2.3}$ @ 3.2 – 4.0 GeV

Might agree with a
QCD prediction n= 10
at some energy above 3.1 GeV

Slope – steeper than meson pairs