

**EKHARA:**

a Monte Carlo tool for  $\gamma^* - \gamma^*$  physics

**H. CZYŻ, IF, UŚ, Katowice**



**MEETING**

**Frascati, March 2011**

## Based on:

H. Czyż, S. Ivashyn,

“EKHARA Monte Carlo generator for annihilation:

$$e^+e^- \rightarrow e^+e^-\pi^0 \text{ and } e^+e^- \rightarrow e^+e^-\pi^+\pi^-”$$

arXive 1009.1881 - CPC in press

H. Czyż, E. Nowak-Kubat

“The reaction  $e^+e^- \rightarrow e^+e^-\pi^+\pi^-$  and

the pion form factor measurements via the radiative return method”

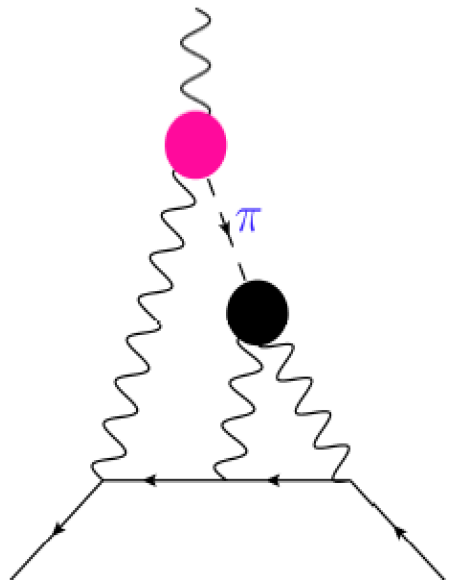
Phys. Lett. B634 (2006) 493.

H. Czyż, S. Ivashyn, A. Korchin, O. Shekhovtsova, in preparation

$$e^+e^- \rightarrow e^+e^-\eta \text{ and } e^+e^- \rightarrow e^+e^-\eta'$$

<http://www.us.edu.pl/~ekhara>

# Pion exchange in hadronic LbL

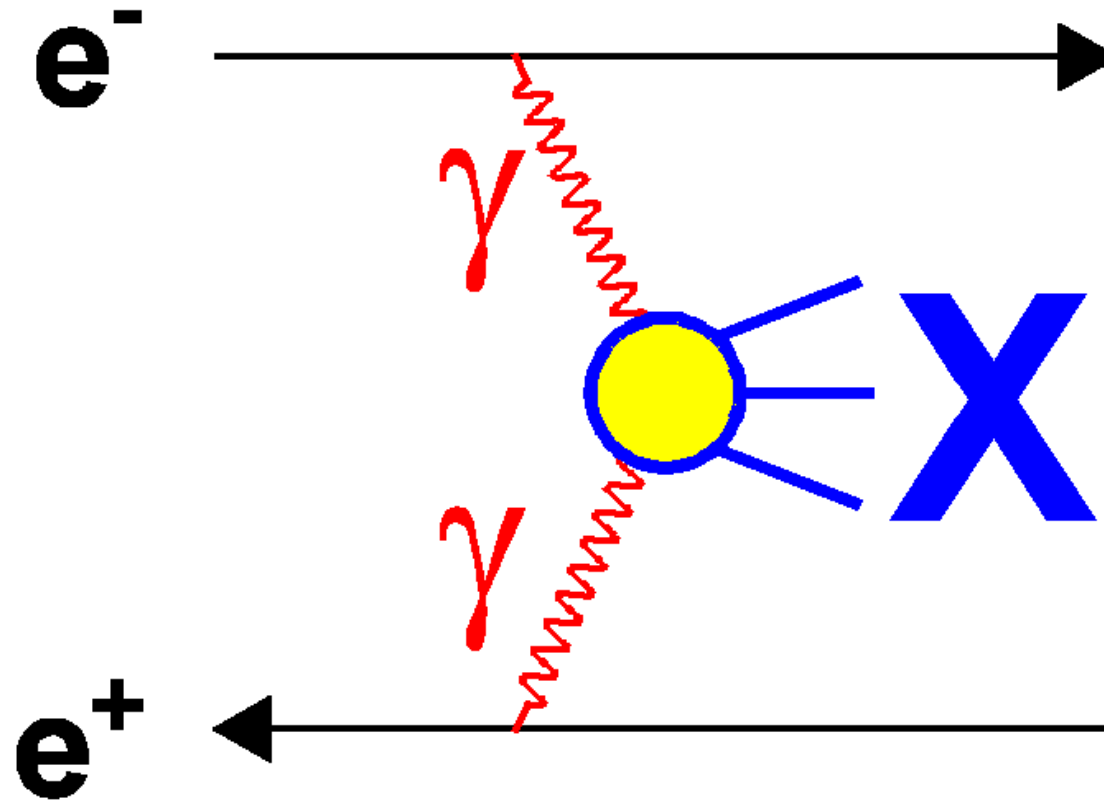


$F_{\pi^*\gamma^*\gamma^*}$  form factors are key objects

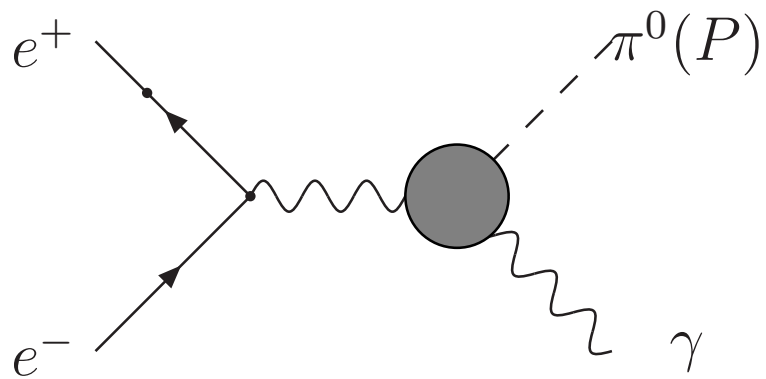
- external vertex :  $F_{\pi\gamma\gamma}(t_\pi, t_\pi, 0^2)$ 
  - ✓ far off-shell pion
  - ✓ zero-energy photon
- internal vertex :  $F_{\pi\gamma\gamma}(t_\pi, t_1, t_2)$ 
  - ✓ totally off-shell object

These form factors were never measured

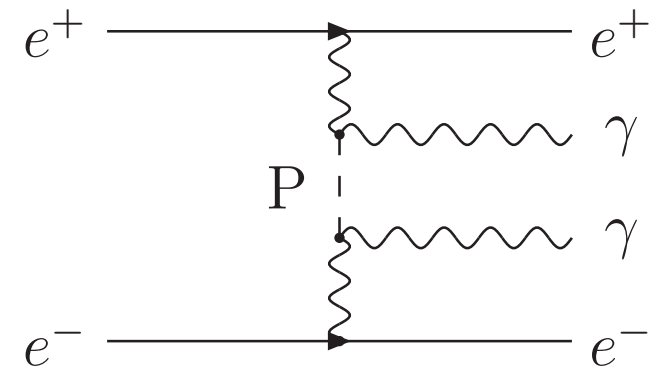
# Photon-photon interactions



# Photon-photon-P vertex



+ . . .



# LO amplitude

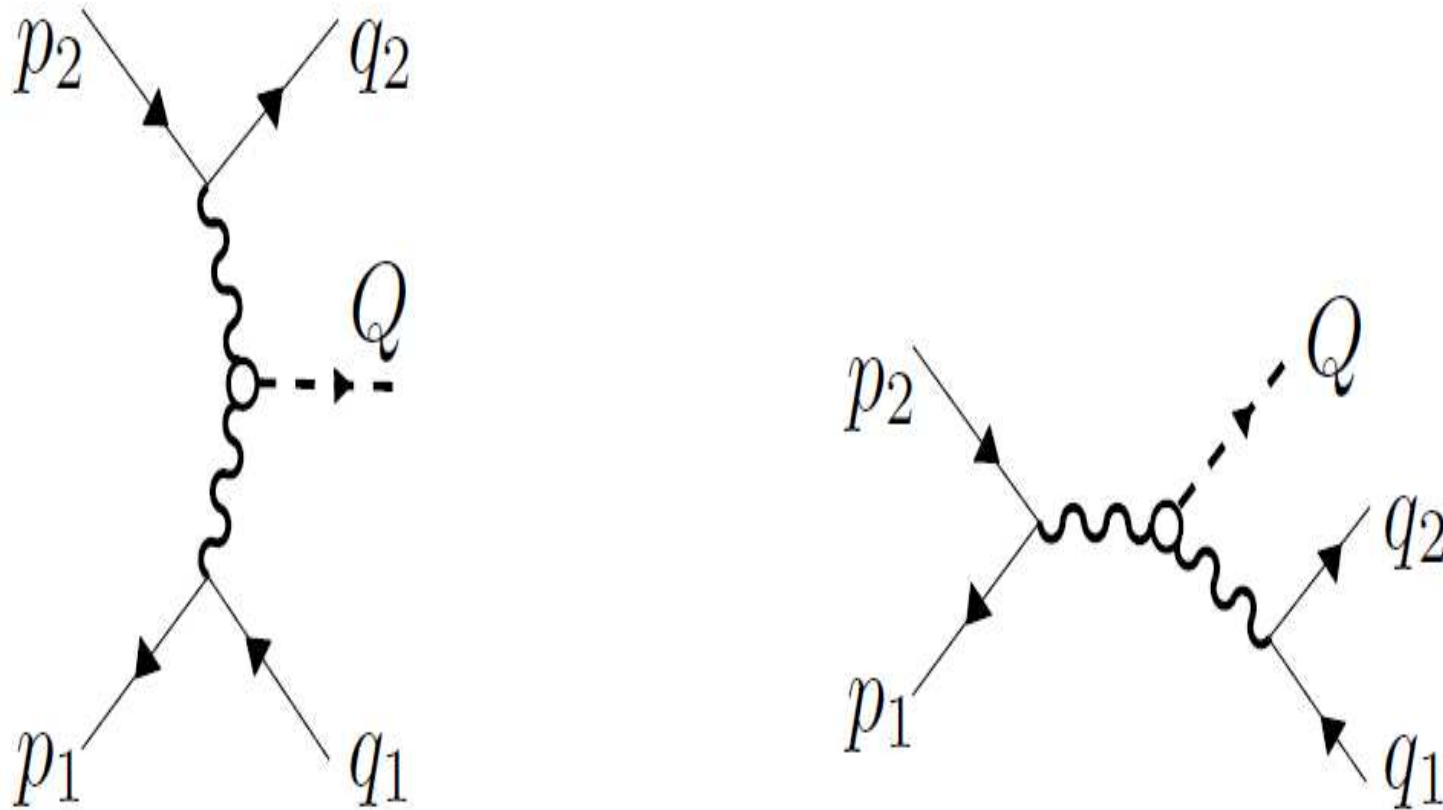


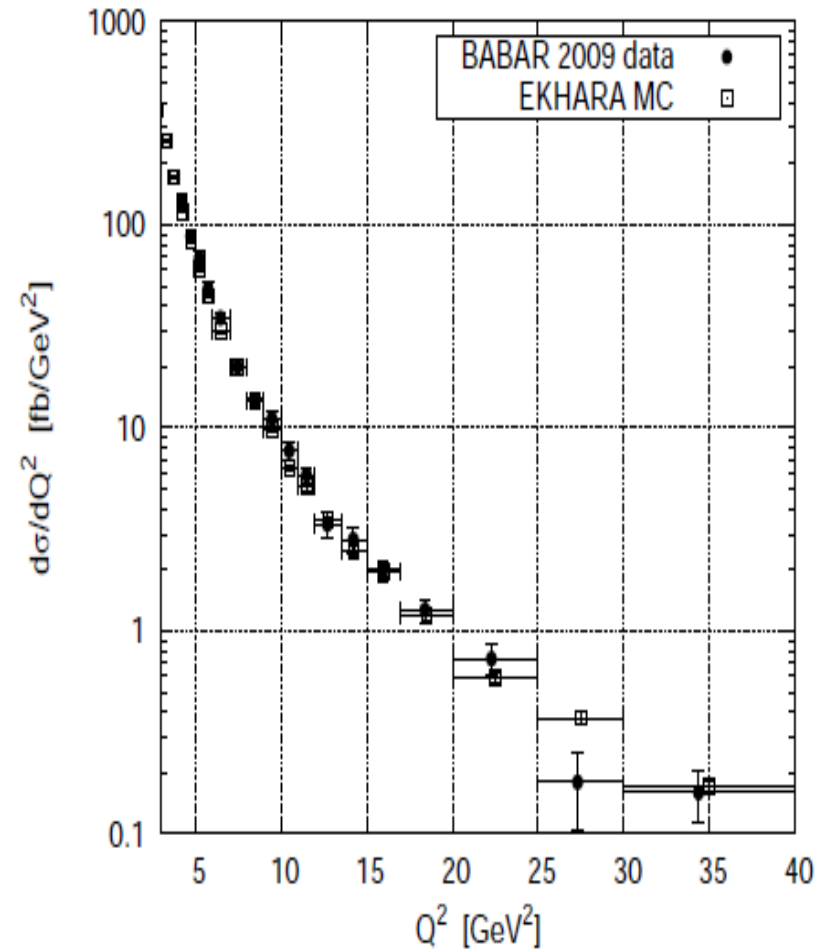
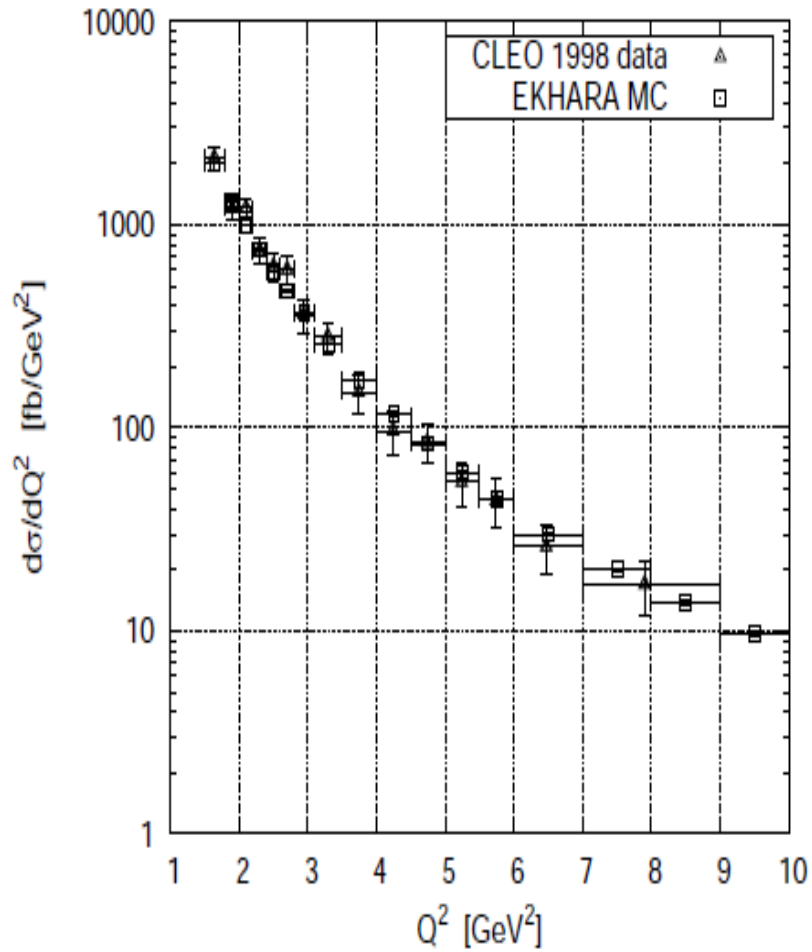
Figure 1: The  $t$ -channel (*left*) and the  $s$ -channel (*right*) diagrams for  $e^+e^- \rightarrow e^+e^-P$

# LO amplitude

$$\mathcal{M}_t = -\frac{4i\alpha^2}{f_\pi} F(t_1, t_2) \epsilon_{\mu\nu\alpha\beta} \frac{1}{t_1 t_2} (q_1 - p_1)^\alpha (q_2 - p_2)^\beta \\ \times (\bar{v}(p_1) \gamma^\mu v(q_1)) (\bar{u}(q_2) \gamma^\nu u(p_2)).$$

$$\mathcal{M}_s = \frac{4i\alpha^2}{f_\pi} F(s, (q_1 + q_2)^2) \epsilon_{\mu\nu\alpha\beta} \frac{1}{s (q_1 + q_2)^2} (p_1 + p_2)^\alpha (q_1 + q_2)^\beta \\ (\bar{v}(p_1) \gamma^\mu u(p_2)) (\bar{u}(q_2) \gamma^\nu v(q_1)).$$

# EKHARA vs. data

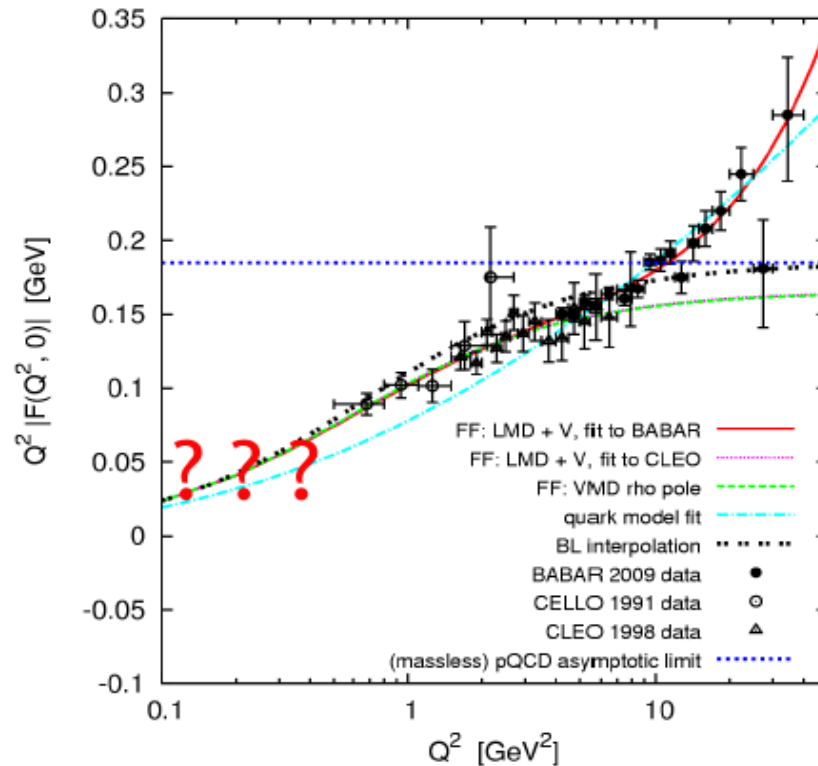


Form factor by A. Nyffeler (2009)



# Form factor

$$Q^2 F_{\pi^0 \gamma^* \gamma}(m_\pi^2, Q^2, 0)$$



## Theory:

[ A. Nyffeler, 0912.1441 ]

[ M. Knecht and A. Nyffeler,  
Phys. Rev. D65, 073034 (2002) ]

[ ibid. ]

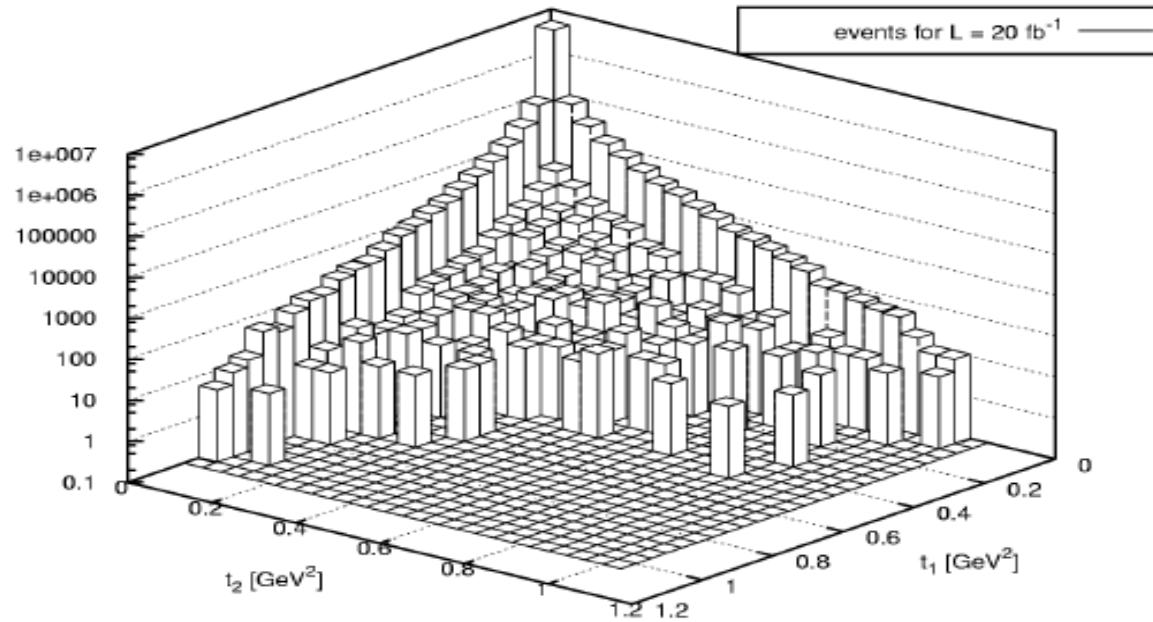
[ A. E. Dorokhov, 0905.4577 ]

[ G. P. Lepage and S. J. Brodsky,  
Phys. Rev. D 22, 2157 (1980) ]

No data at  $0.02 \text{ GeV}^2 < Q^2 < 0.4 \text{ GeV}^2$

# KLOE2

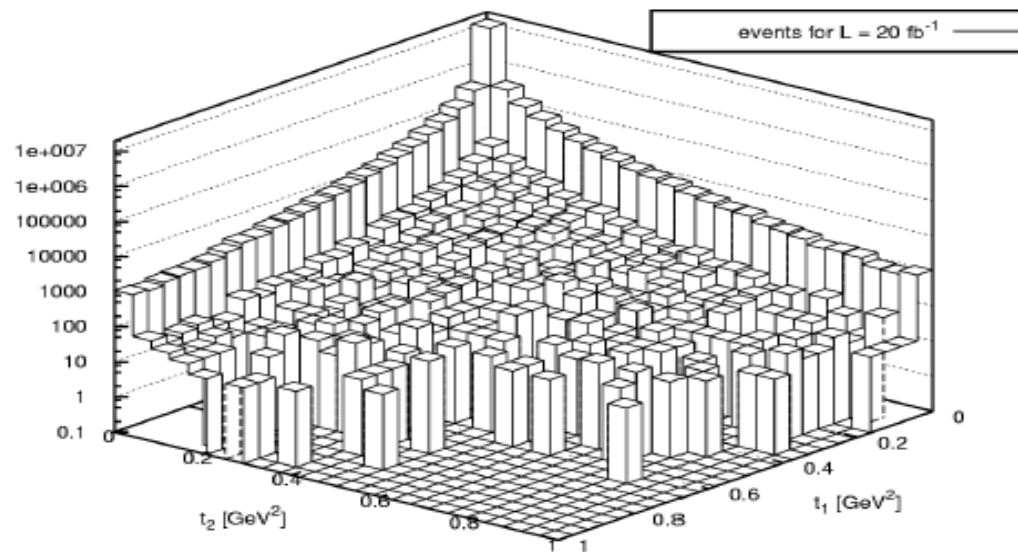
no cuts



- both invariants are well populated

# BES-III

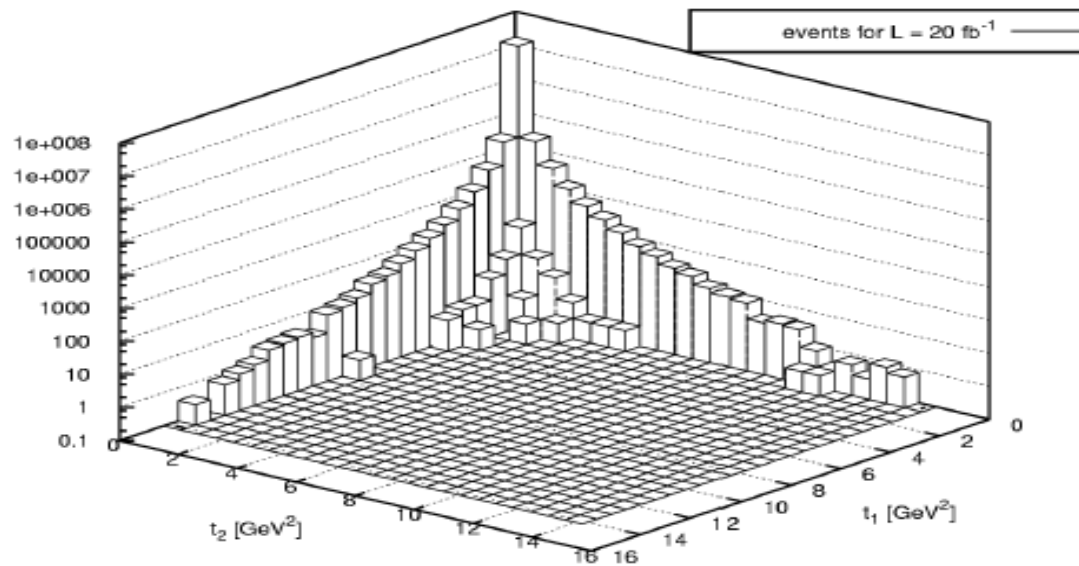
## BES-III at small $Q^2$ example: no cuts



- $\sqrt{s} = 3 \text{ GeV}$ ,  $\int \mathcal{L} dt = 20 \text{ fb}^{-1}$   
( $\sim 9$  months at  $\mathcal{L} = 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ )

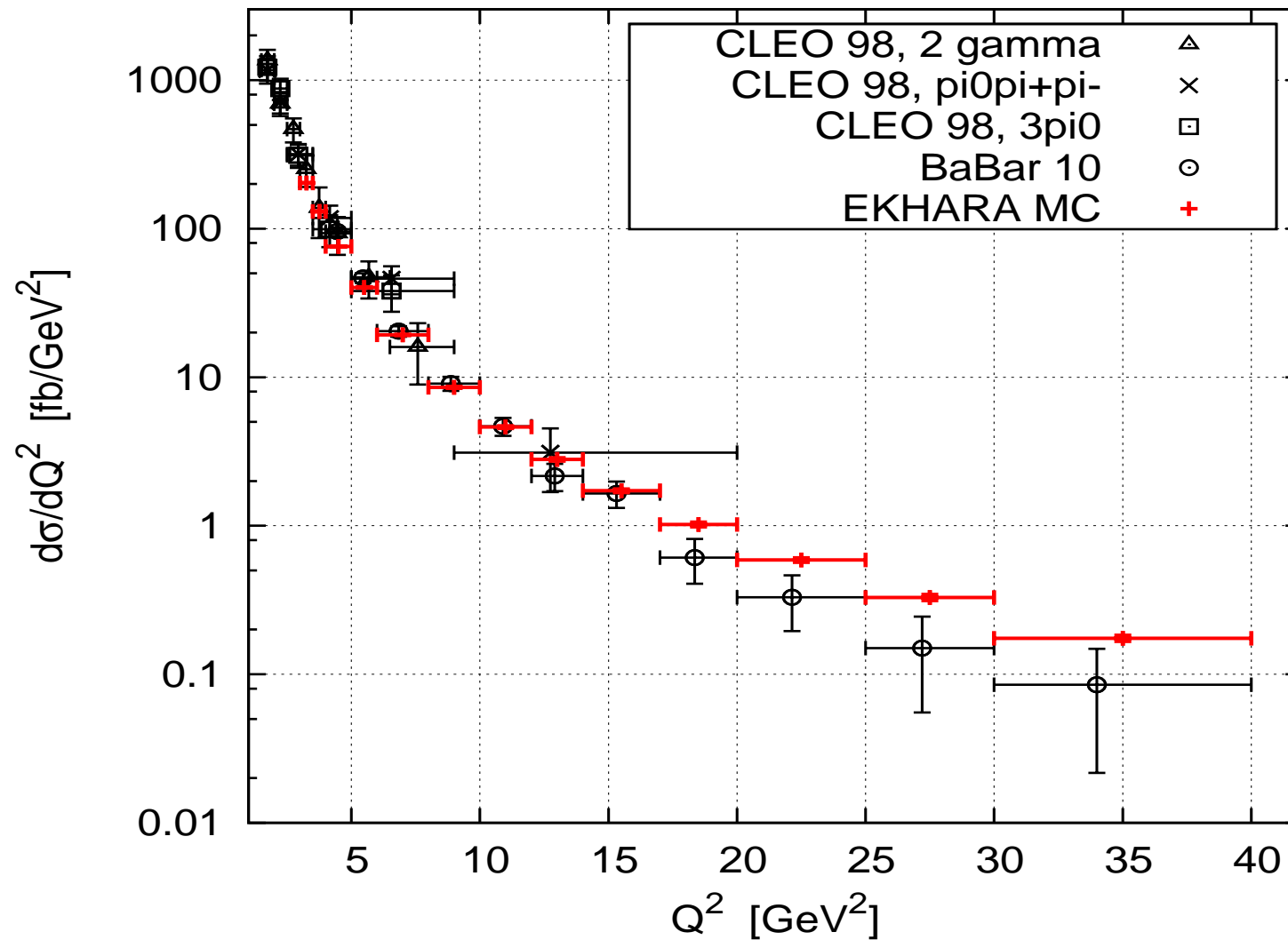
# BES-III

## BES-III at high $Q^2$ example: no cuts



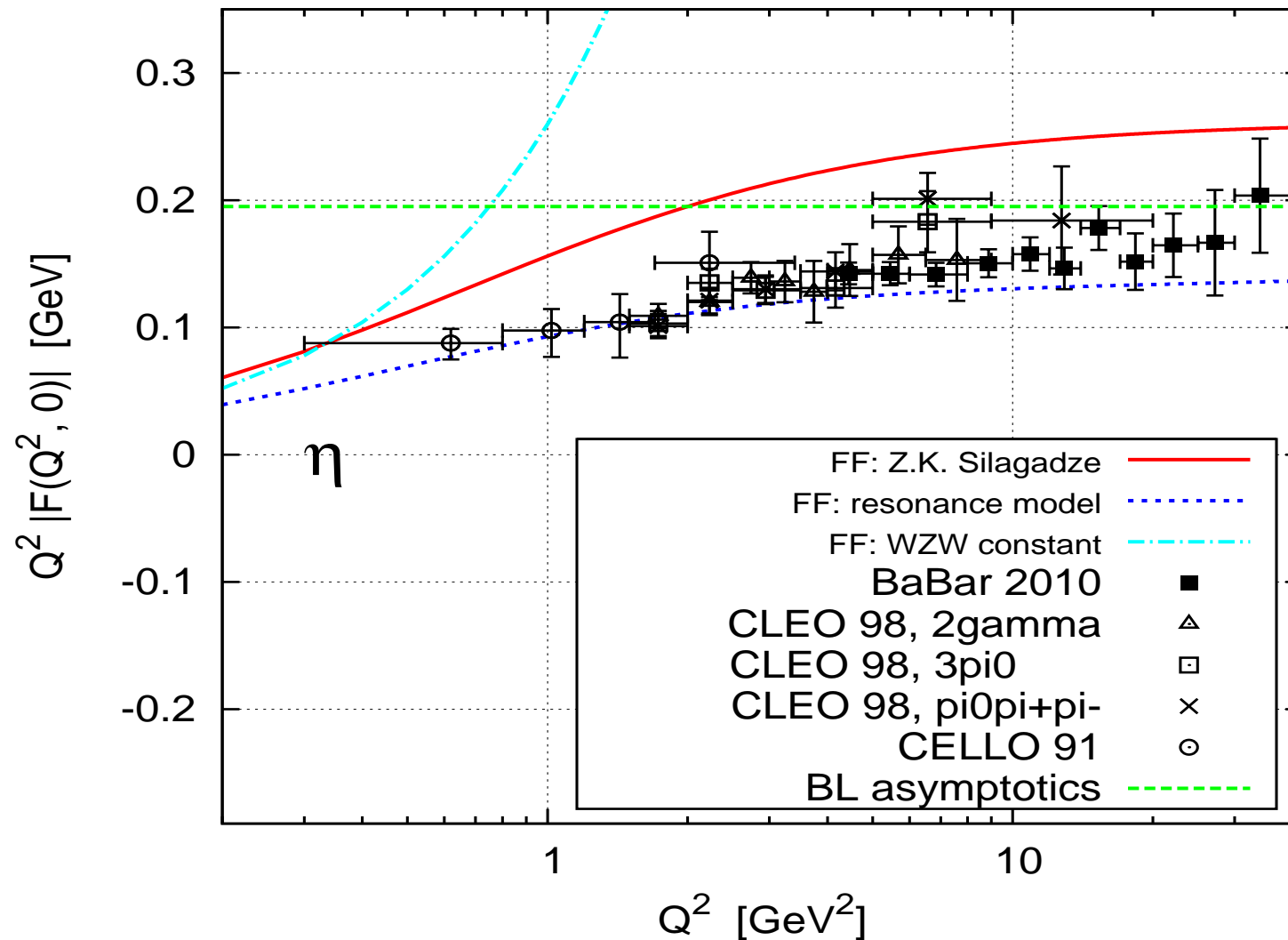
- $\sqrt{s} = 3.770 \text{ GeV}$ ,  $\int \mathcal{L} dt = 20 \text{ fb}^{-1}$   
( $\sim 9$  months at  $\mathcal{L} = 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ )

# $\eta$ in EKHARA



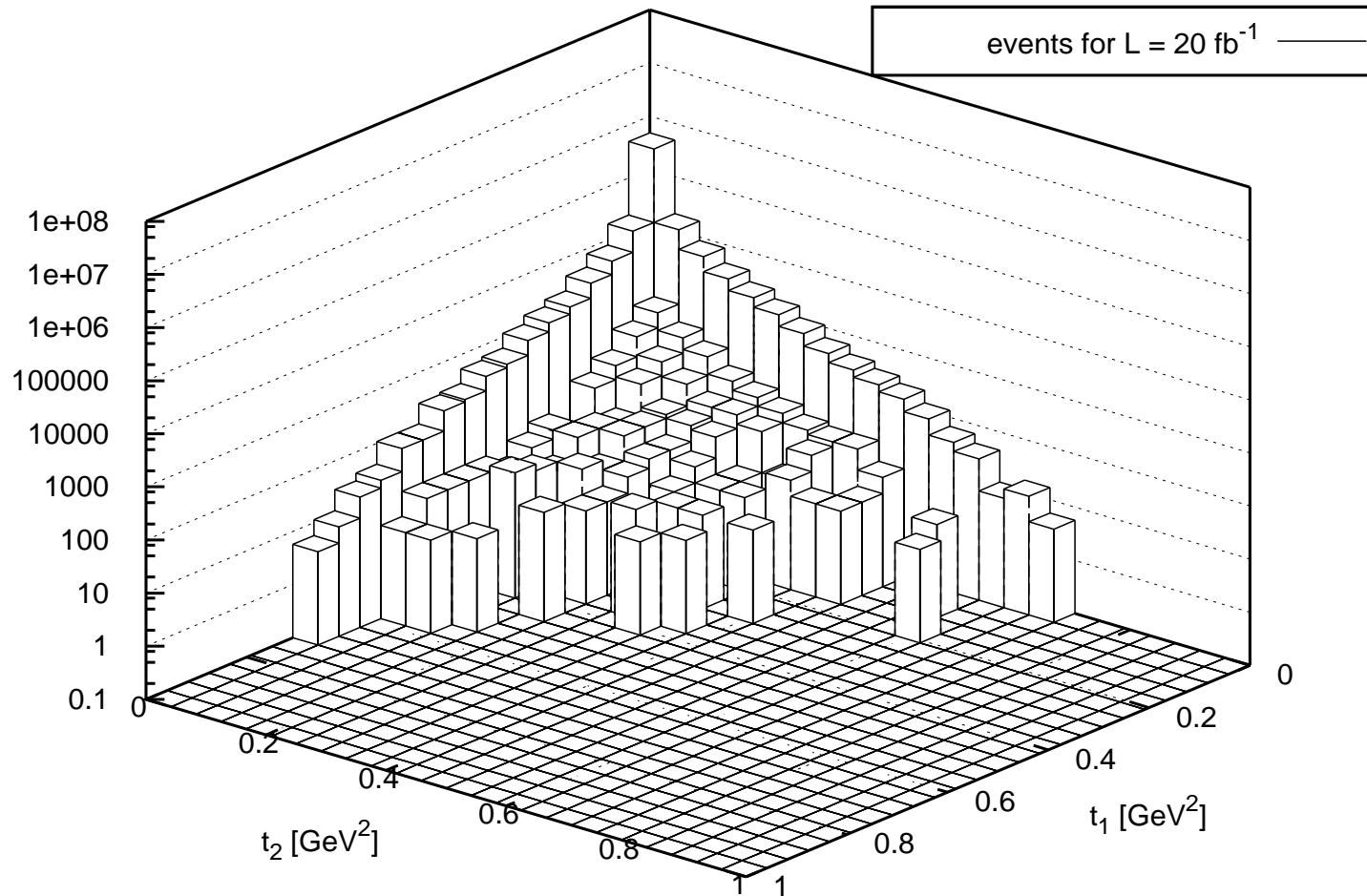
Model based on RCHPT

# $\eta$ in EKHARA



Model based on RCHPT

# $\eta$ in EKHARA

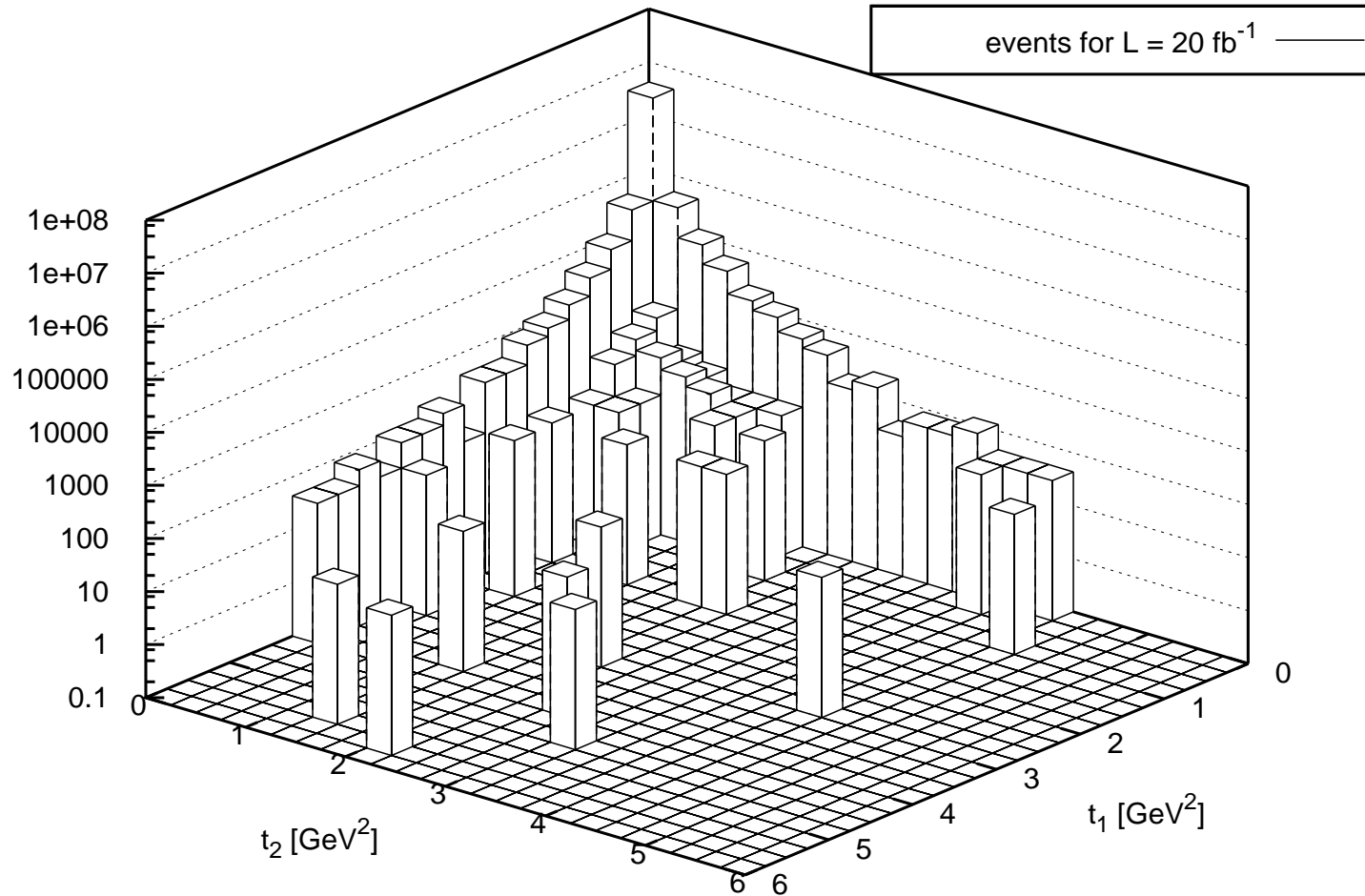


KLOE

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EKHARA 2.0+ ...

# $\eta$ in EKHARA

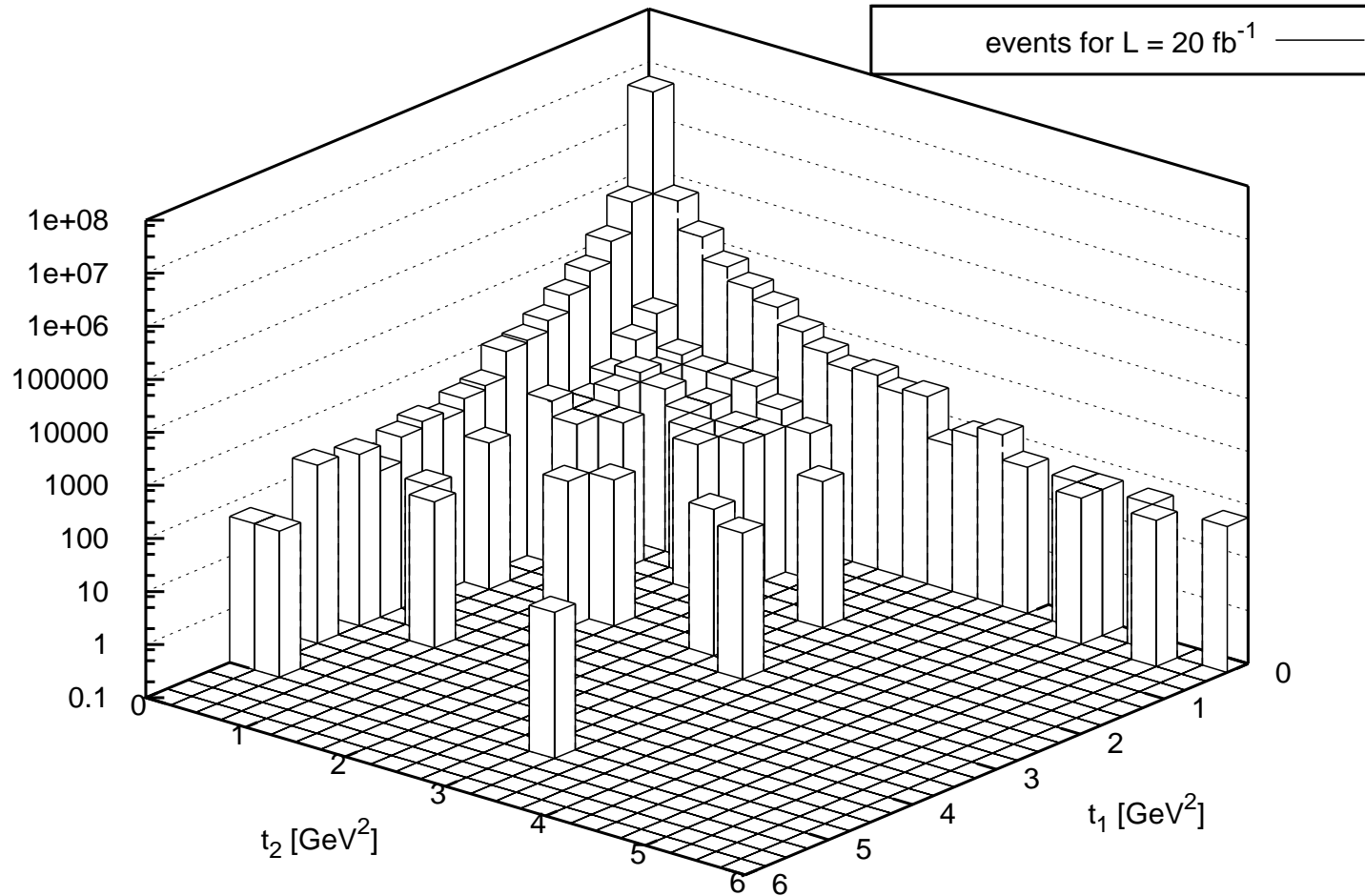


BES-III,  $\sqrt{s} = 3 \text{ GeV}$

H. Czyż, IF, UŚ, Katowice, EKHARA 2.0+ ...



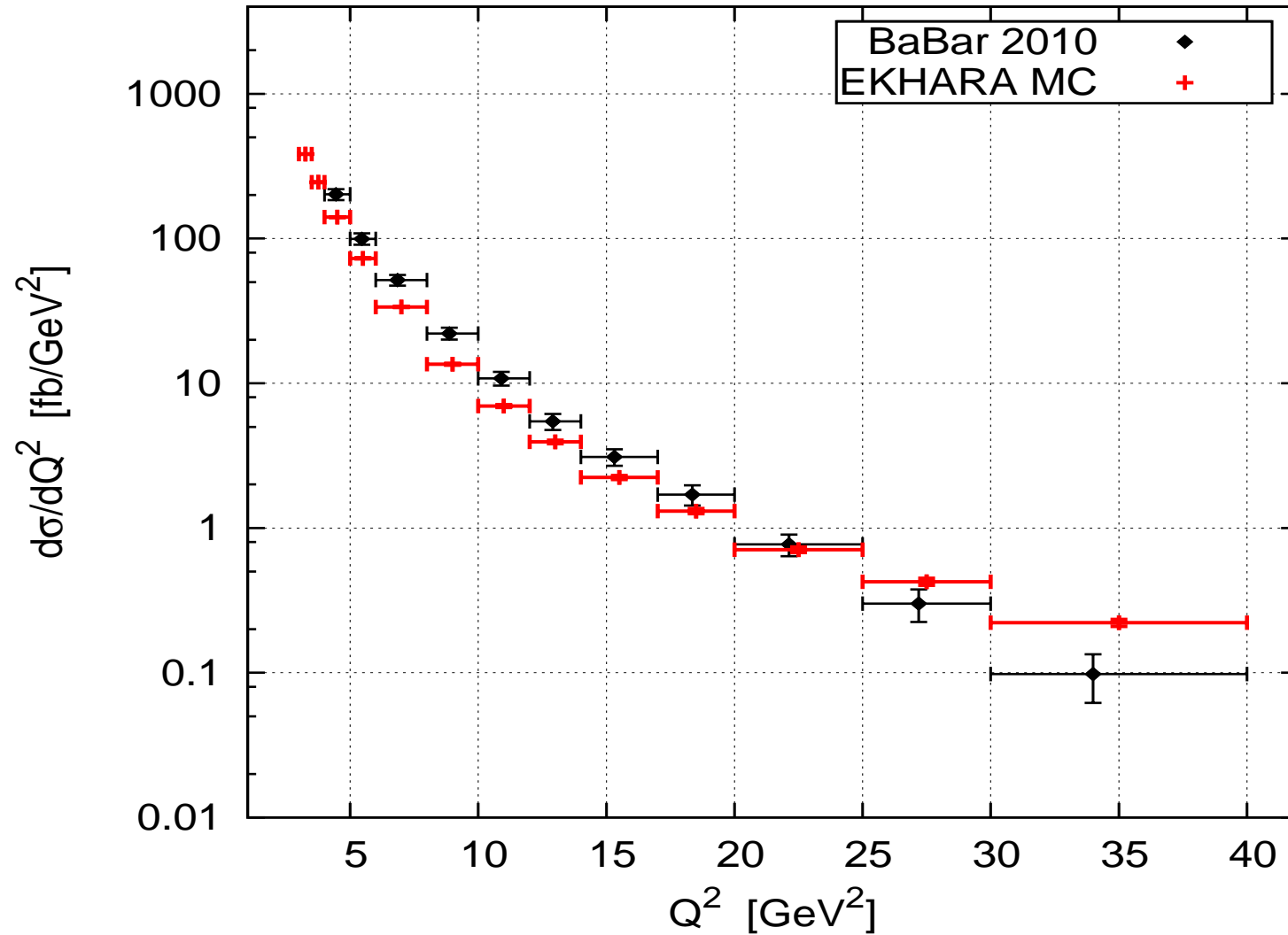
# $\eta$ in EKHARA



BES-III,  $\sqrt{s} = 3.77 \text{ GeV}$

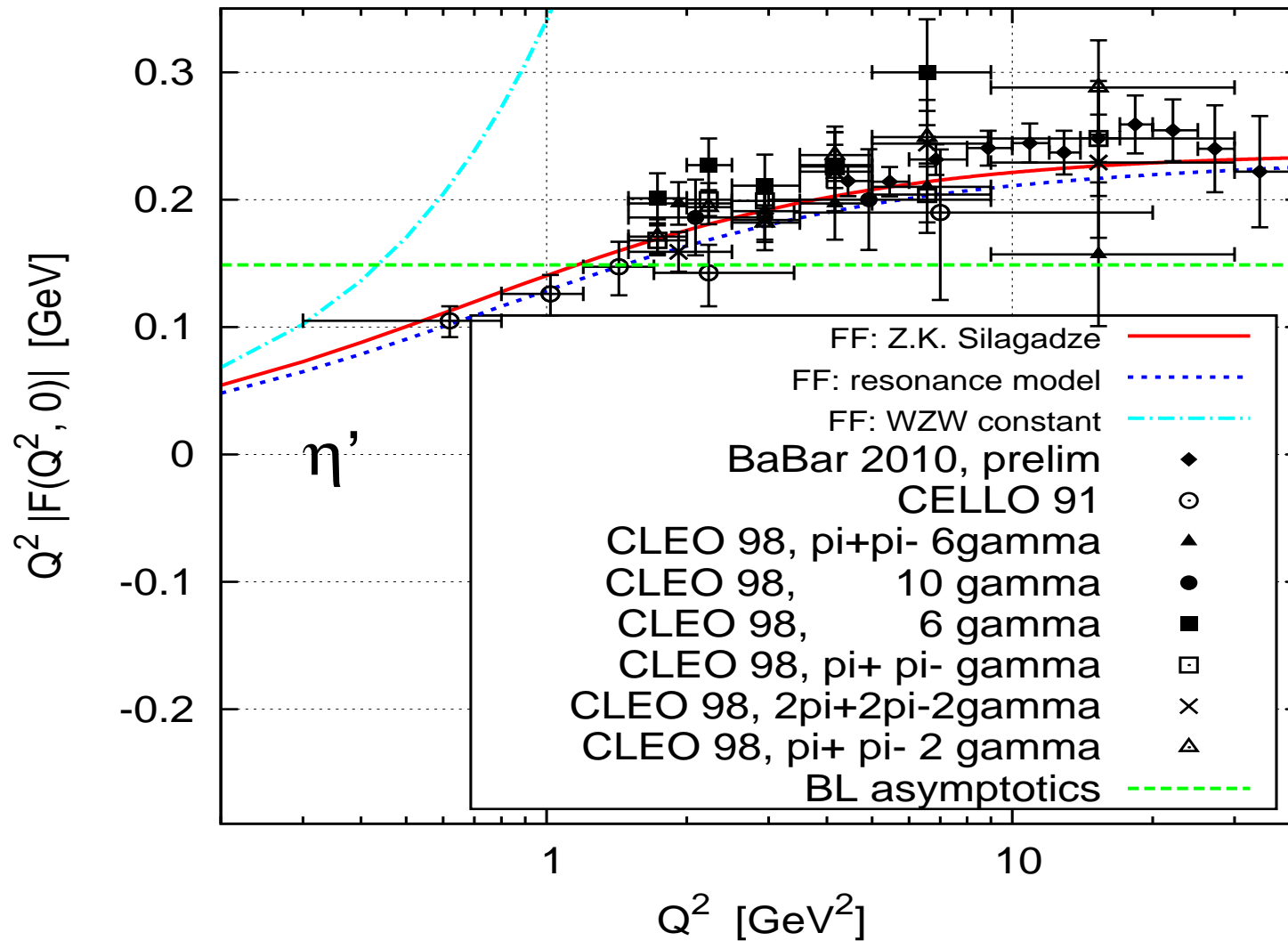
H. Czyż, IF, UŚ, Katowice, EKHARA 2.0+ ...

# $\eta'$ in EKHARA



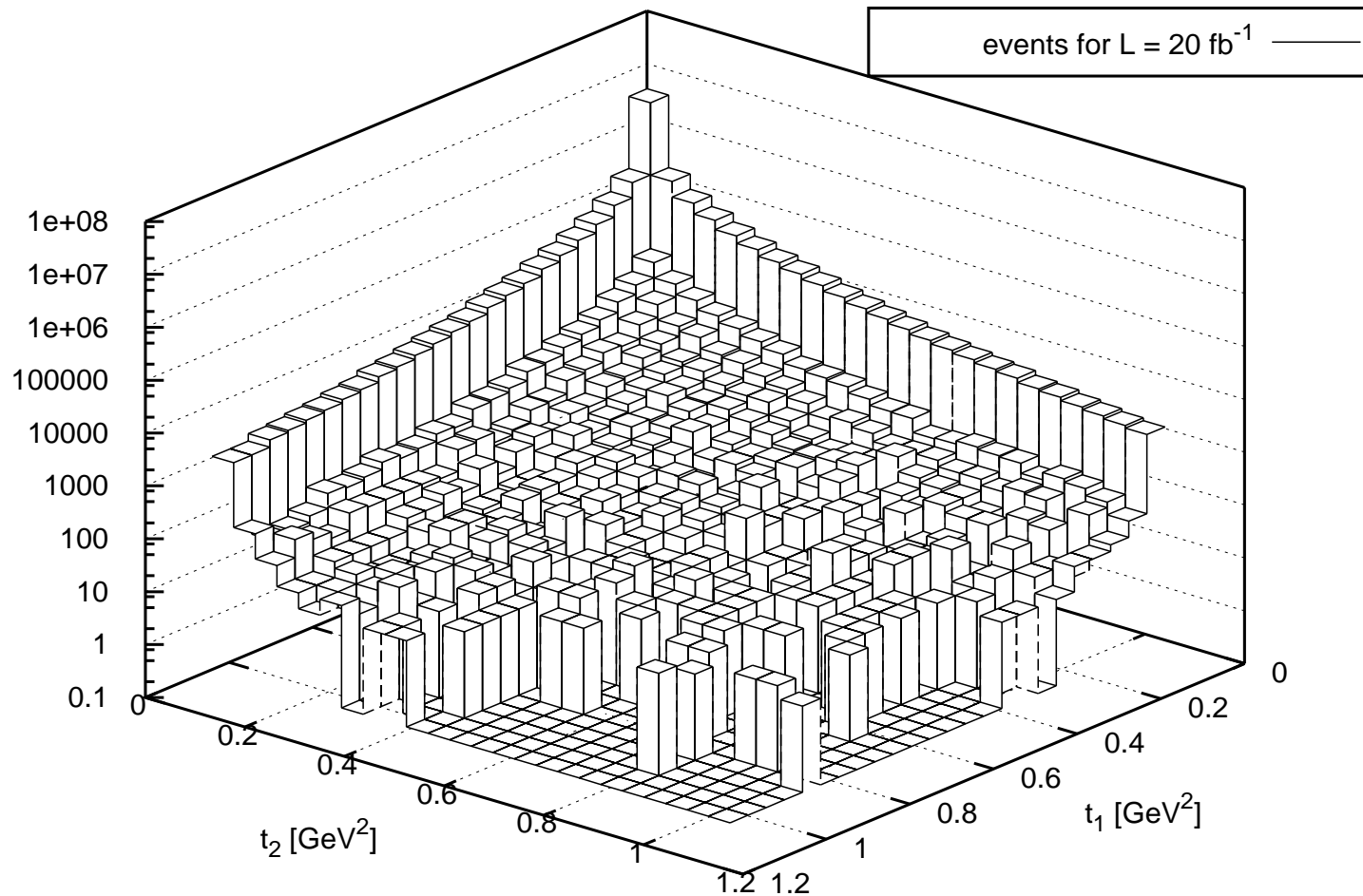
Model based on RCHPT

# $\eta'$ in EKHARA



Model based on RCHPT

# $\eta'$ in EKHARA

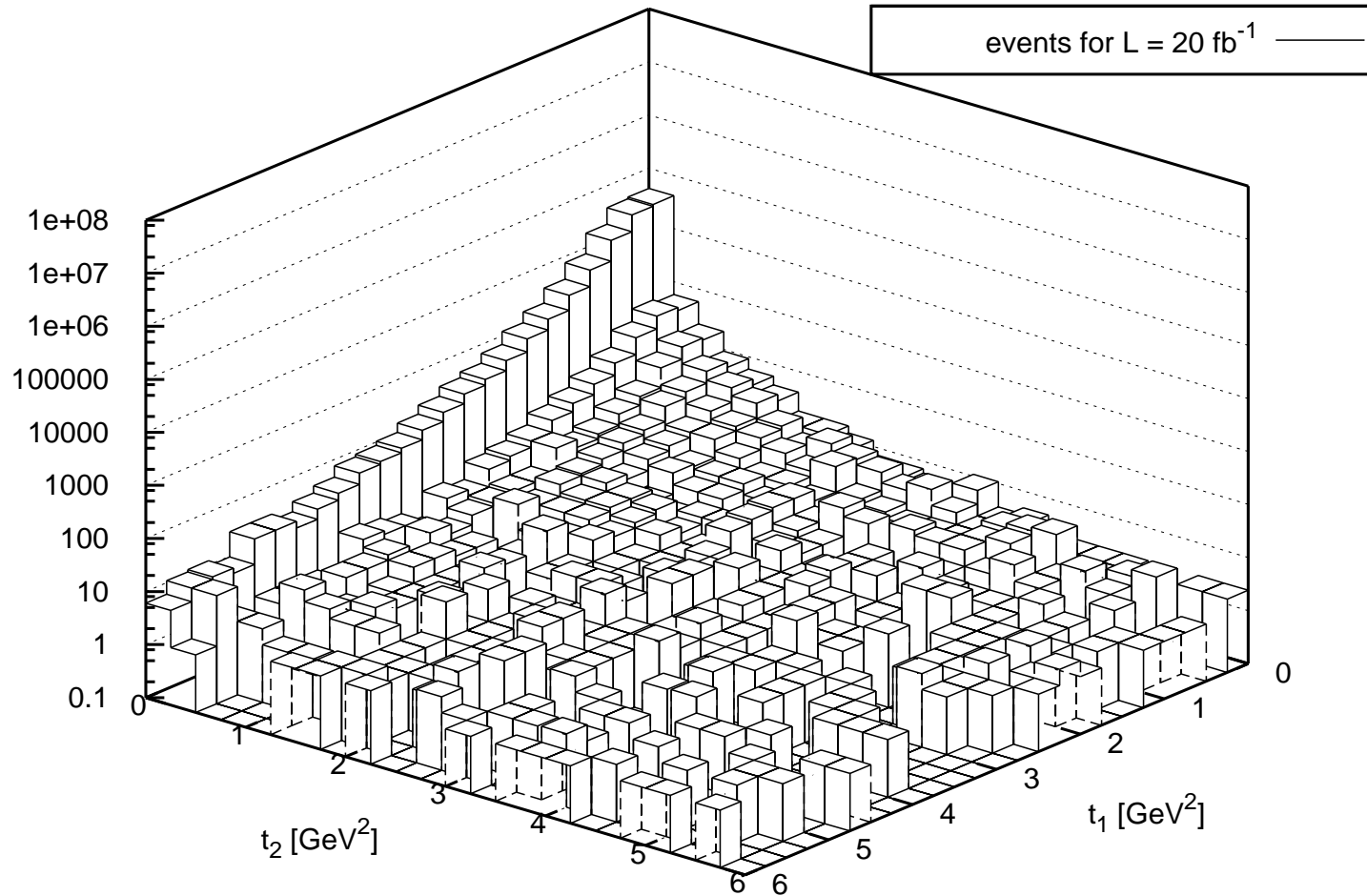


Model based on RCHPT, BES-III,  $\sqrt{s} = 3.77 \text{ GeV}$

# Tests of the program

- volume calculation
- Matrix element - trace vs. helicity amplitudes

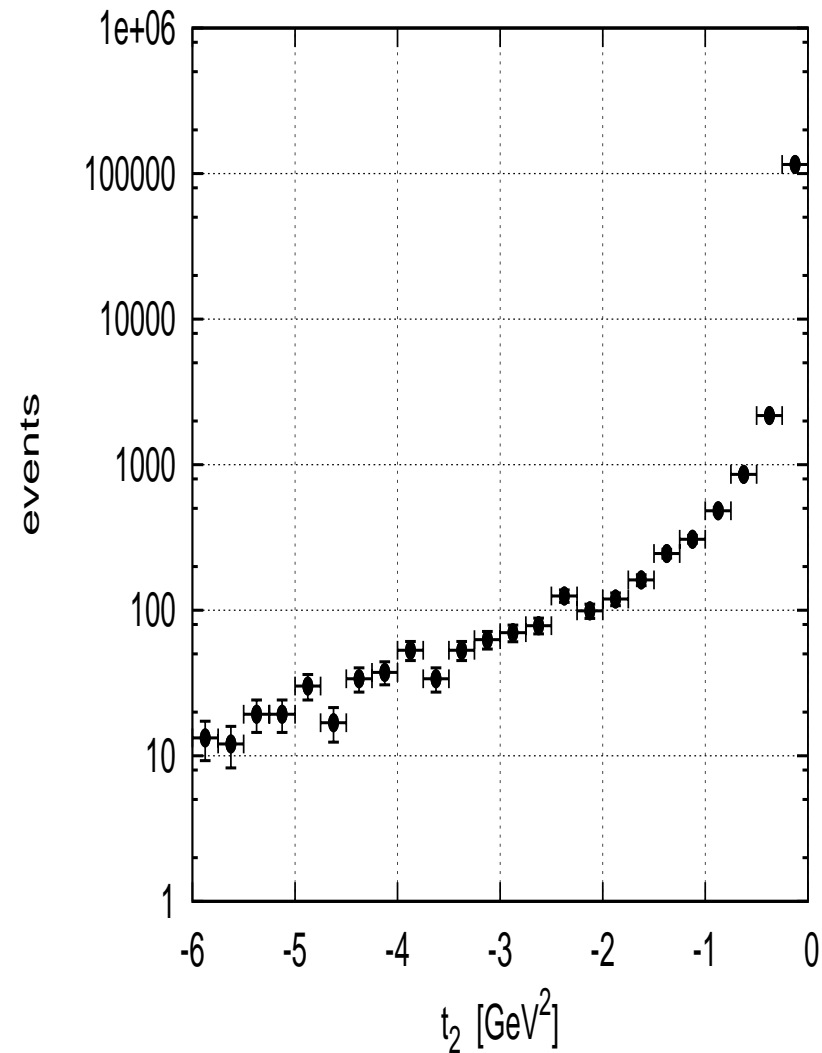
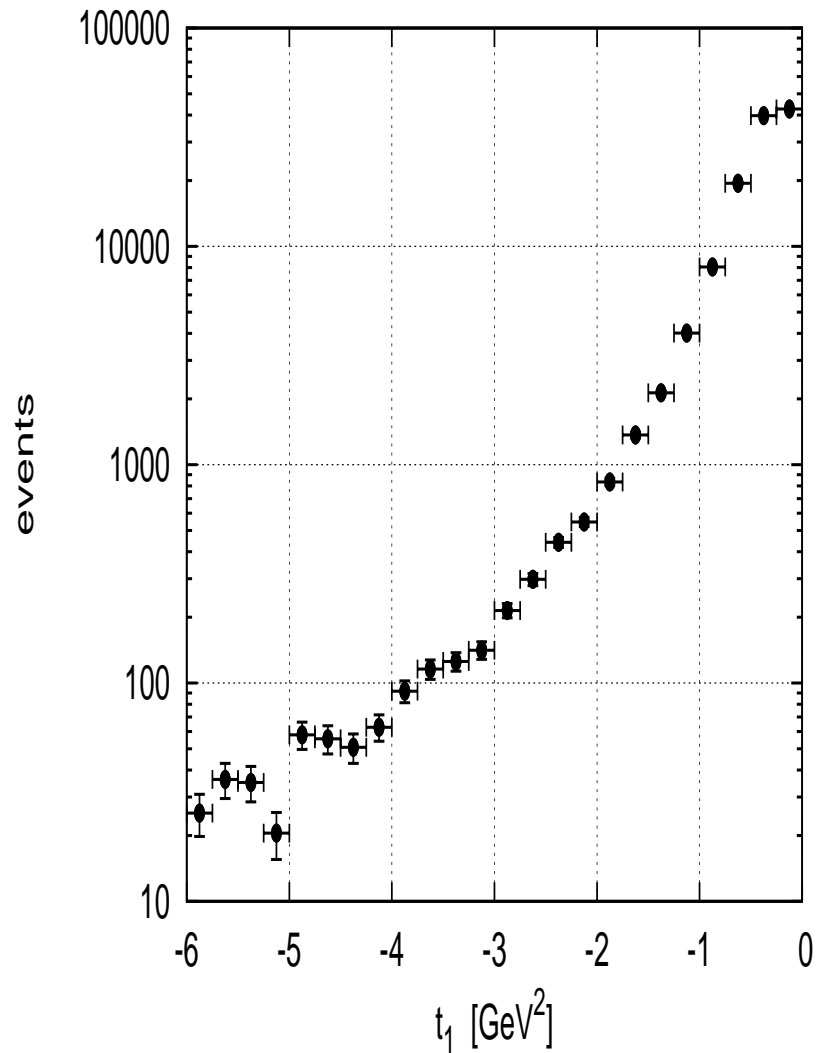
# $\eta$ in EKHARA



BES-III,  $\sqrt{s} = 3.77 \text{ GeV}$ ;  $20^\circ < \theta_{e^+} < 160^\circ$

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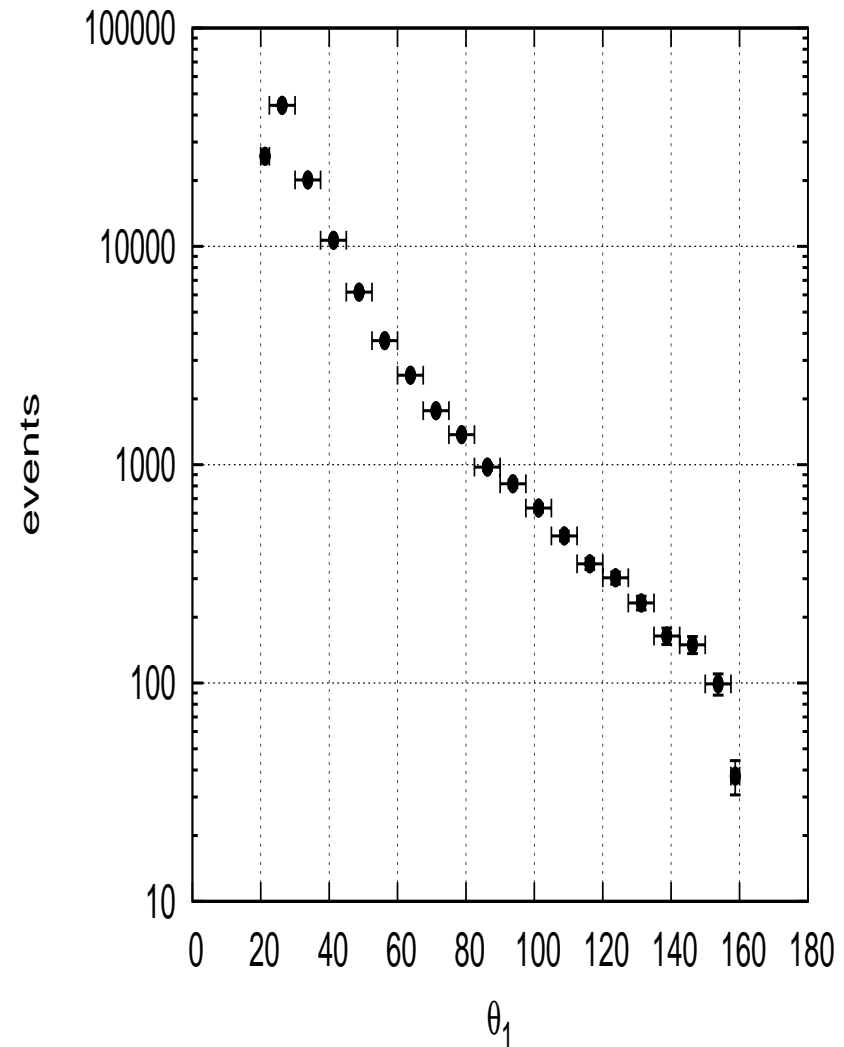
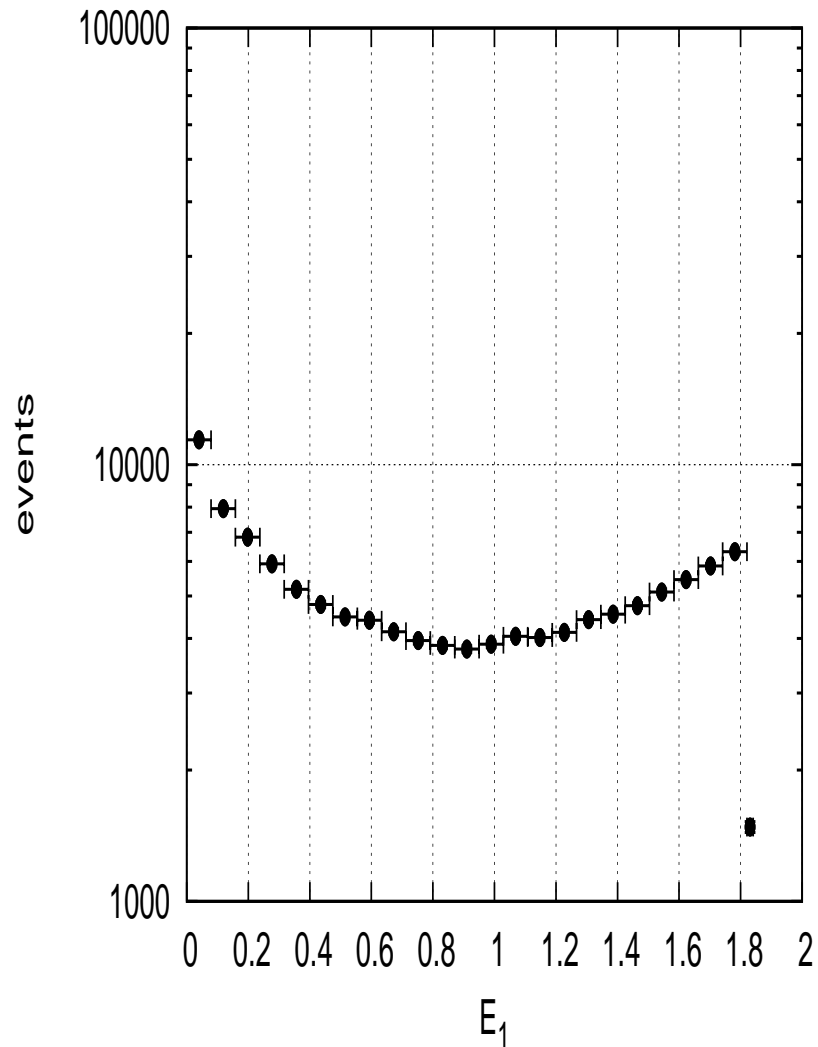
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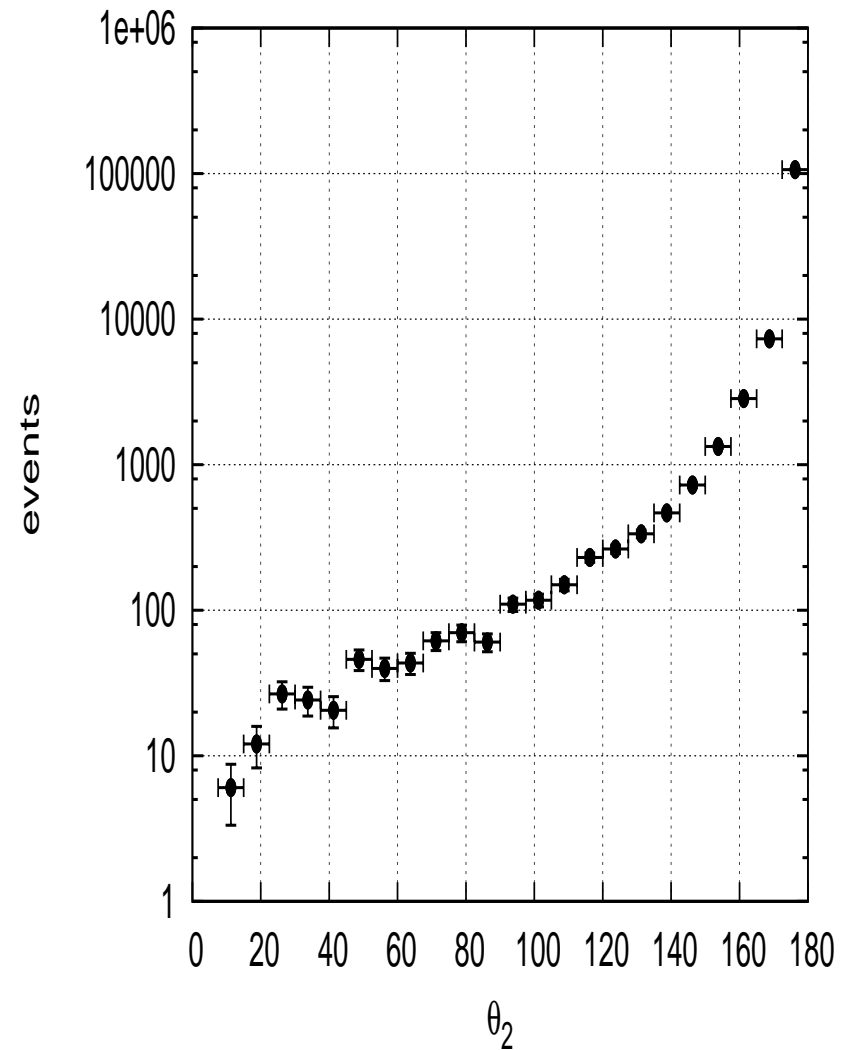
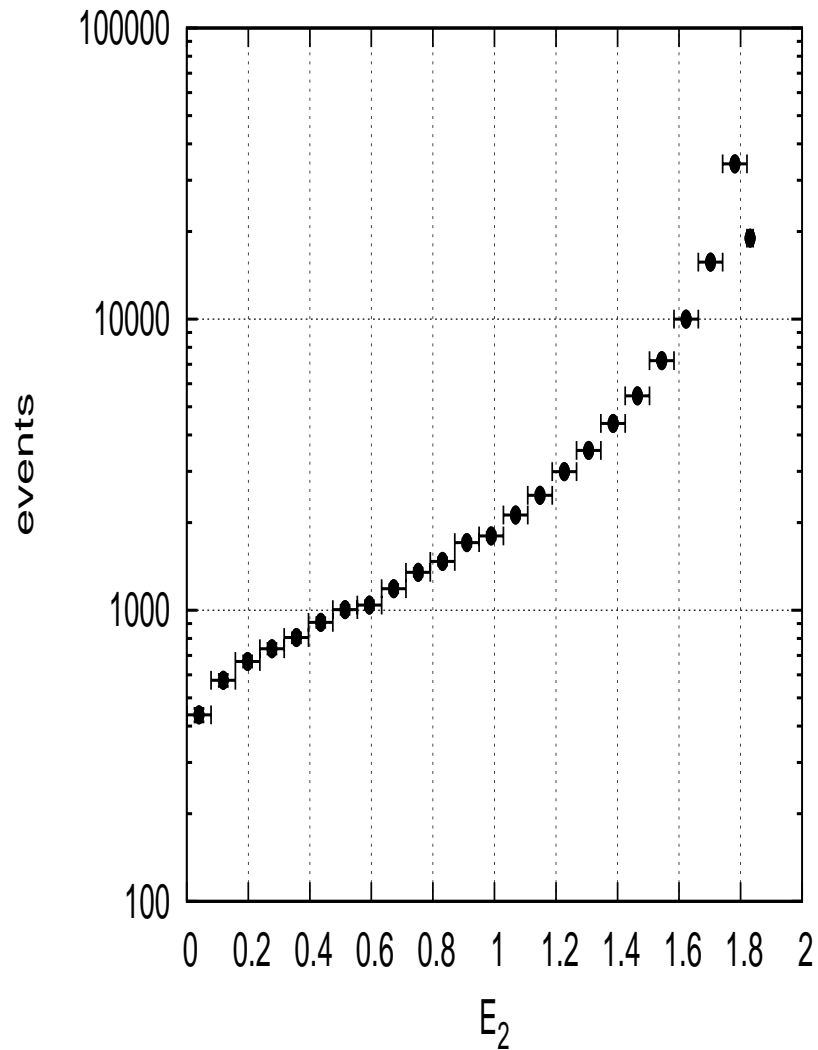


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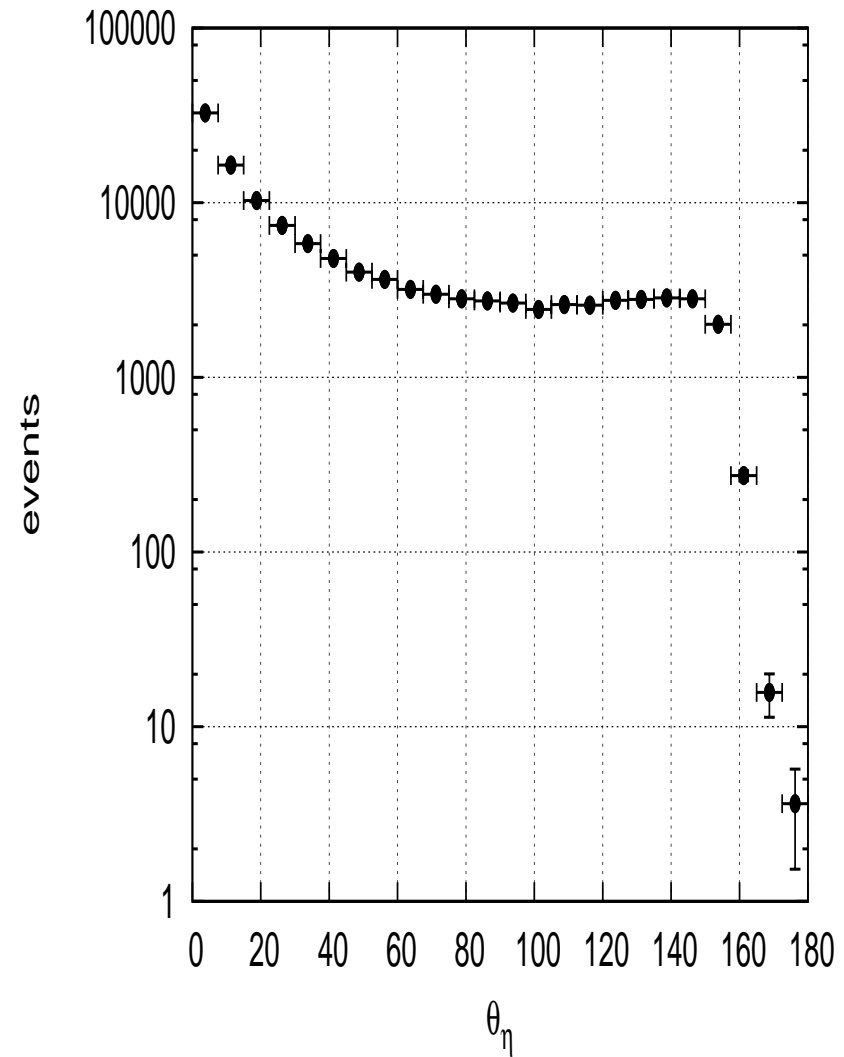
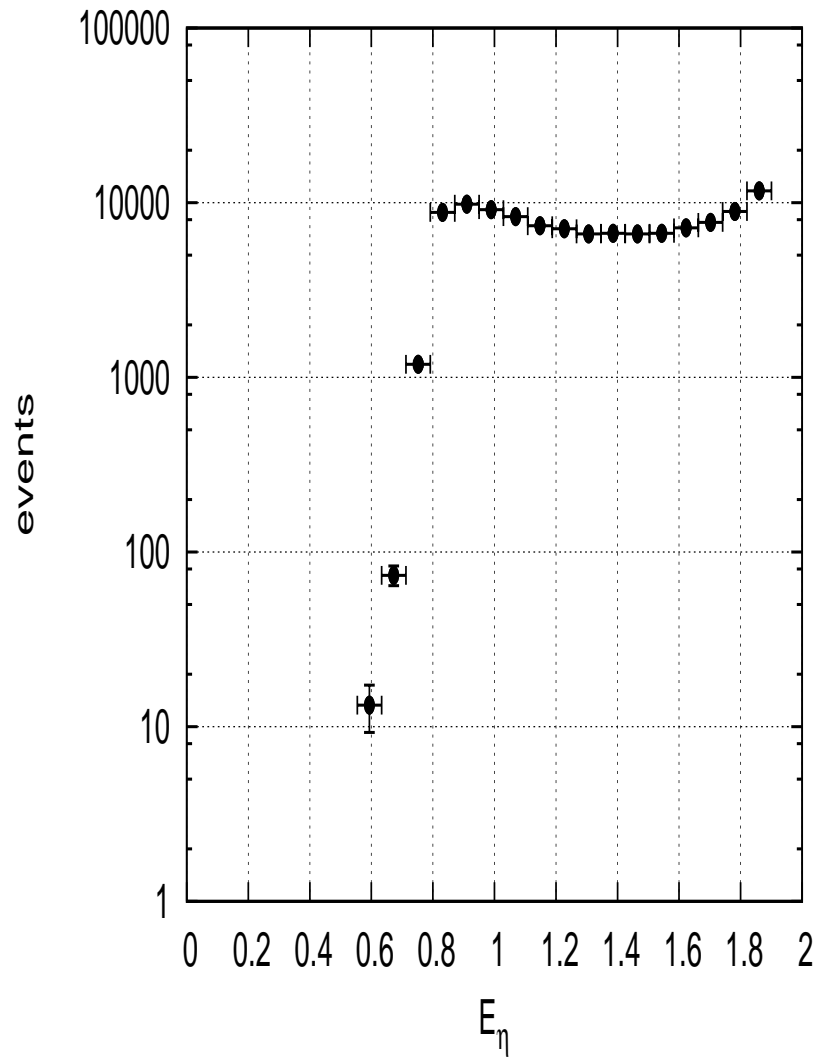
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# Planned upgrades

- finalize  $\eta$  and  $\eta'$
- radiative corrections to be added
- further work on  $\pi^+\pi^-$