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

H. CZYŻ, IF, UŚ, Katowice

INT Workshop on Hadronic Light-by-Light Contribution to the Muon Anomaly

SEATTLE, 2011

Based on:

H. Czyż, S. Ivashyn,
"EKHARA Monte Carlo generator for annihilation:
$e^+e^- \rightarrow e^+e^-\pi^0$ and $e^+e^- \rightarrow e^+e^-\pi^+\pi^-$"
arXive 1009.1881 - CPC in press

H. Czyż, E. Nowak-Kubat
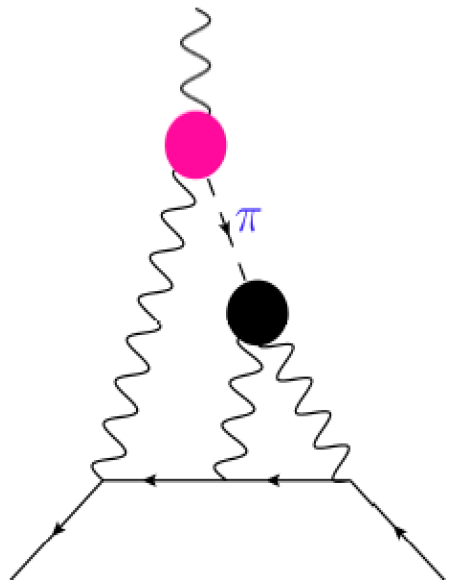"The reaction $e^+e^- \rightarrow e^+e^-\pi^+\pi^-$ and
the pion form factor measurements via the radiative return method"
Phys. Lett. B634 (2006) 493.

H. Czyż, S. Ivashyn, A. Korchin, O. Shekhovtsova, in preparation
$e^+e^- \rightarrow e^+e^-\eta$ and $e^+e^- \rightarrow e^+e^-\eta'$
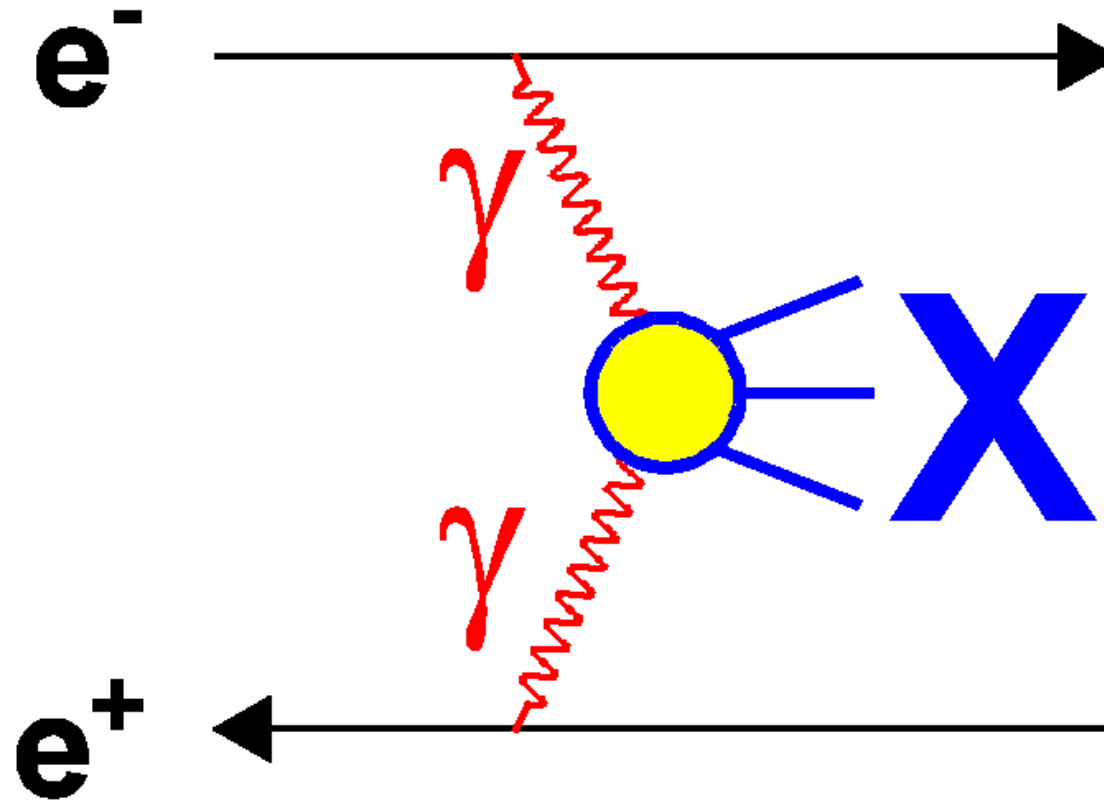
Pion exchange in hadronic LbL

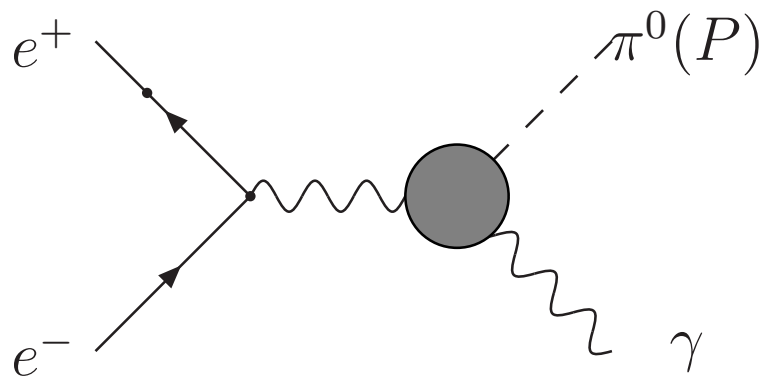$F_{\pi^*\gamma^*\gamma^*}$ form factors are key objects

- external vertex : $F_{\pi\gamma\gamma}(t_\pi, t_\pi, 0^2)$

  ? ✓ far off-shell pion **?**

  ✓ zero-energy photon

- internal vertex : $F_{\pi\gamma\gamma}(t_\pi, t_1, t_2)$

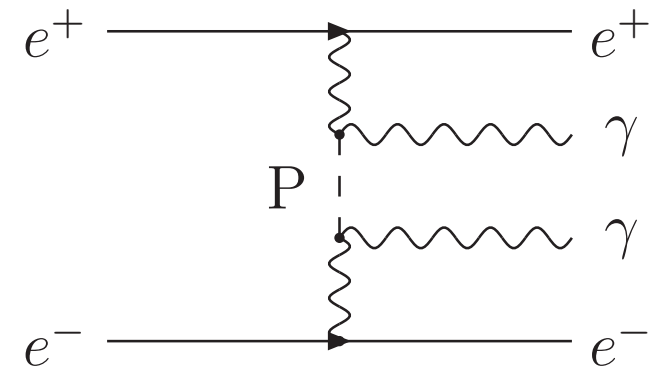 ✓ totally off-shell object

These form factors were never measured

Photon-photon interactions

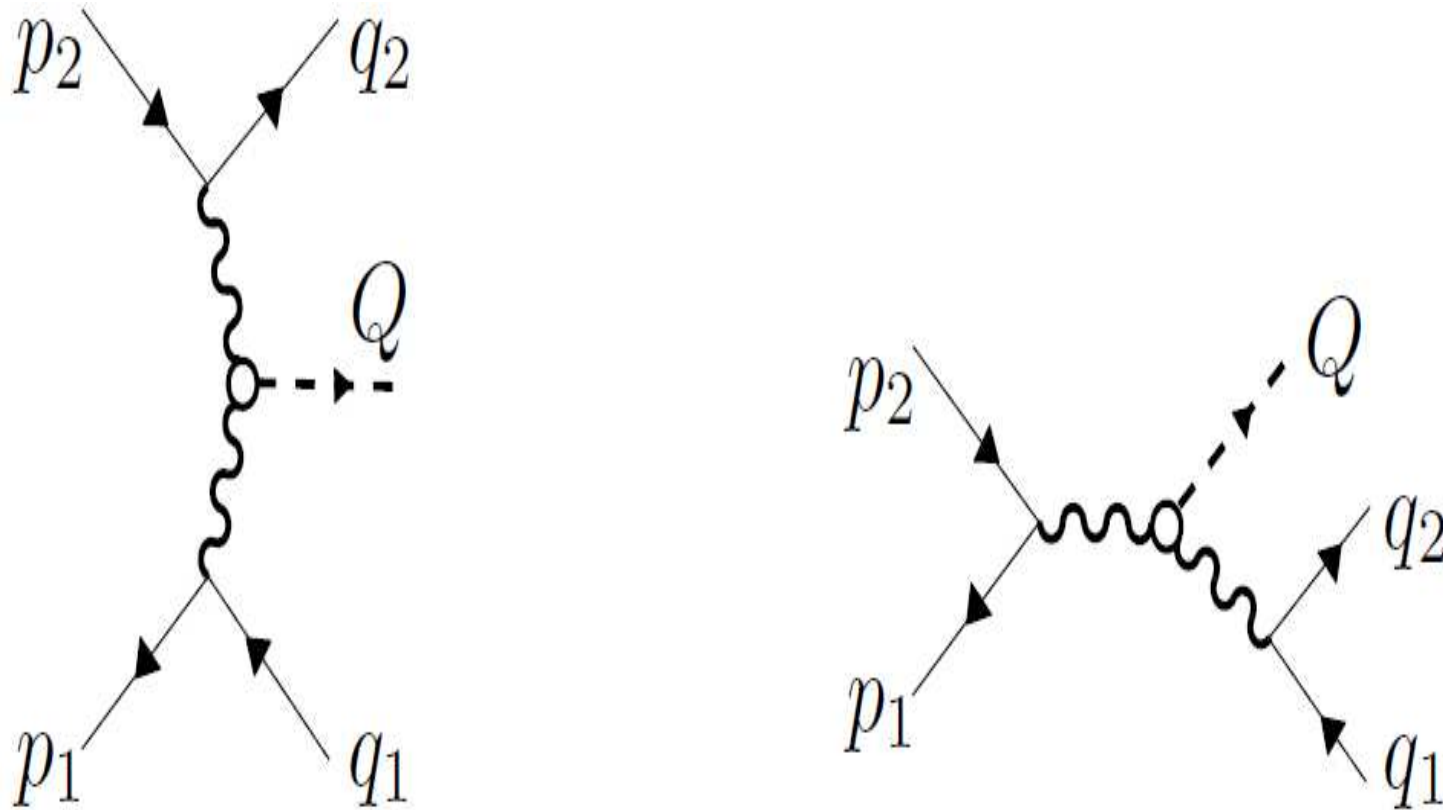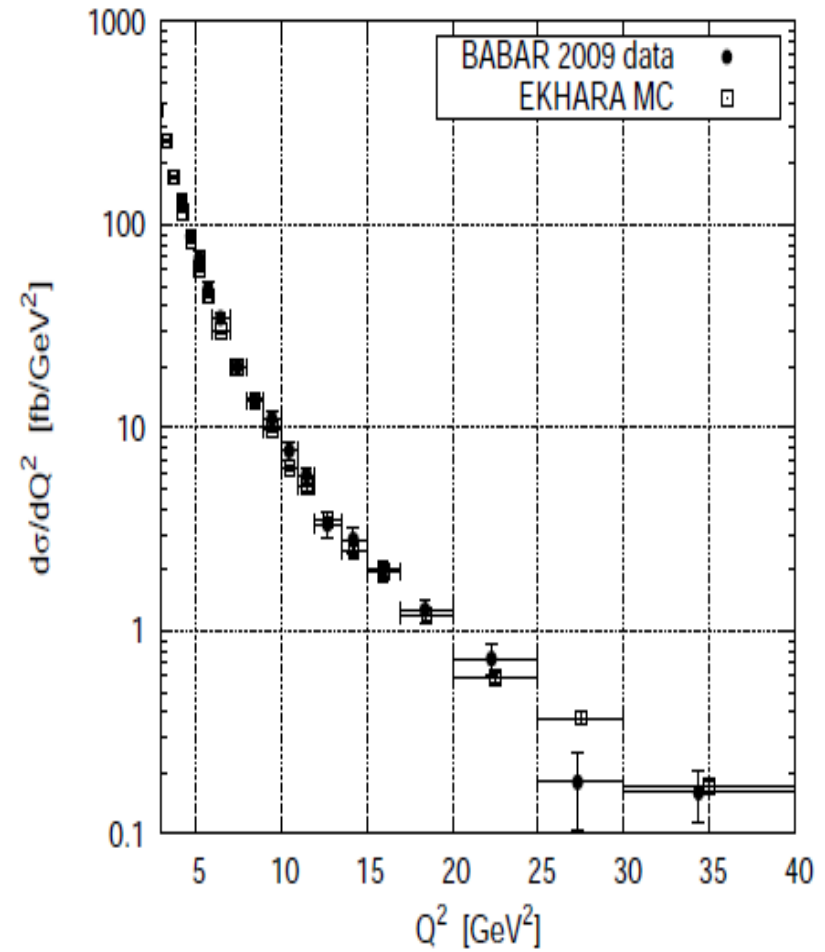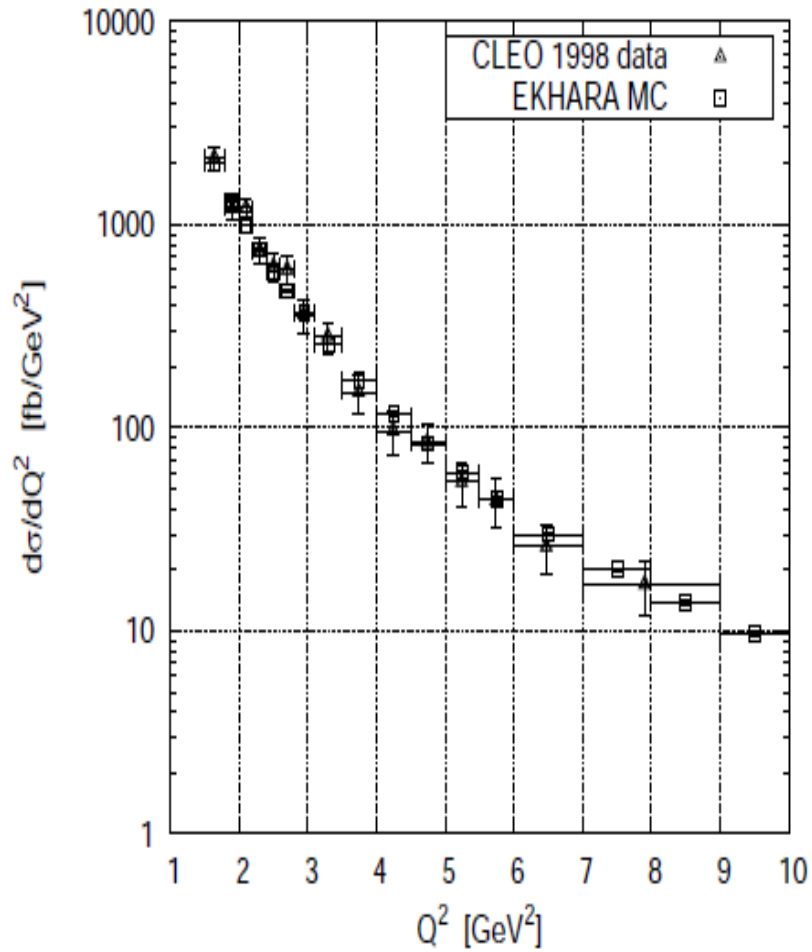# Photon-photon-P vertex

$$+ \cdots$$

LO amplitude

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

LO amplitude

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

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

EKHARA vs. data

Form factor by A. Nyffeler (2009)

Form factor

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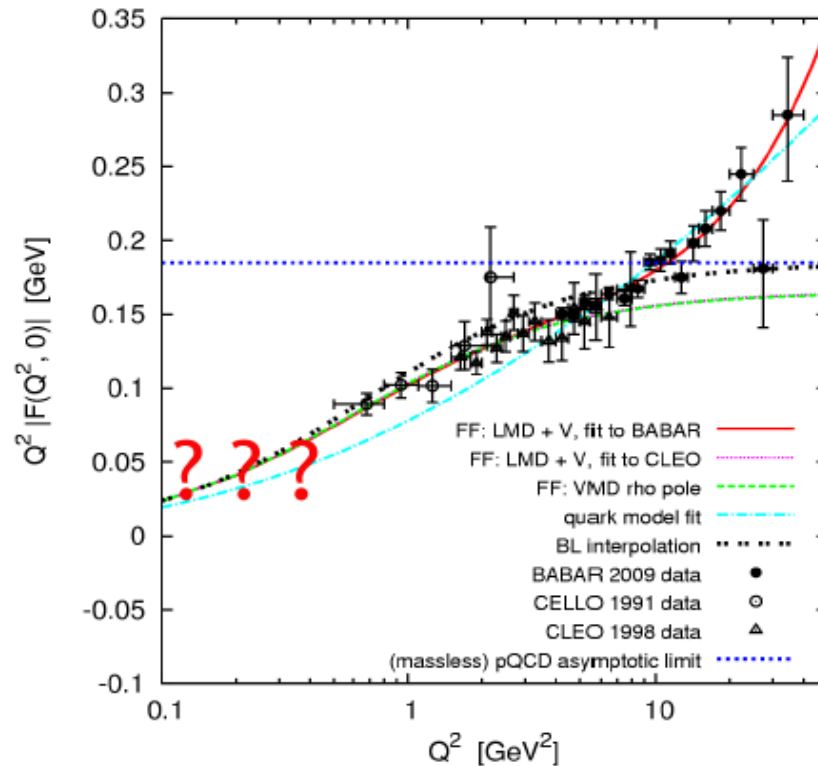
Theory:

[A. Nyffeler, 0912.1441]

[M. Knecht and A. Nyffeler,

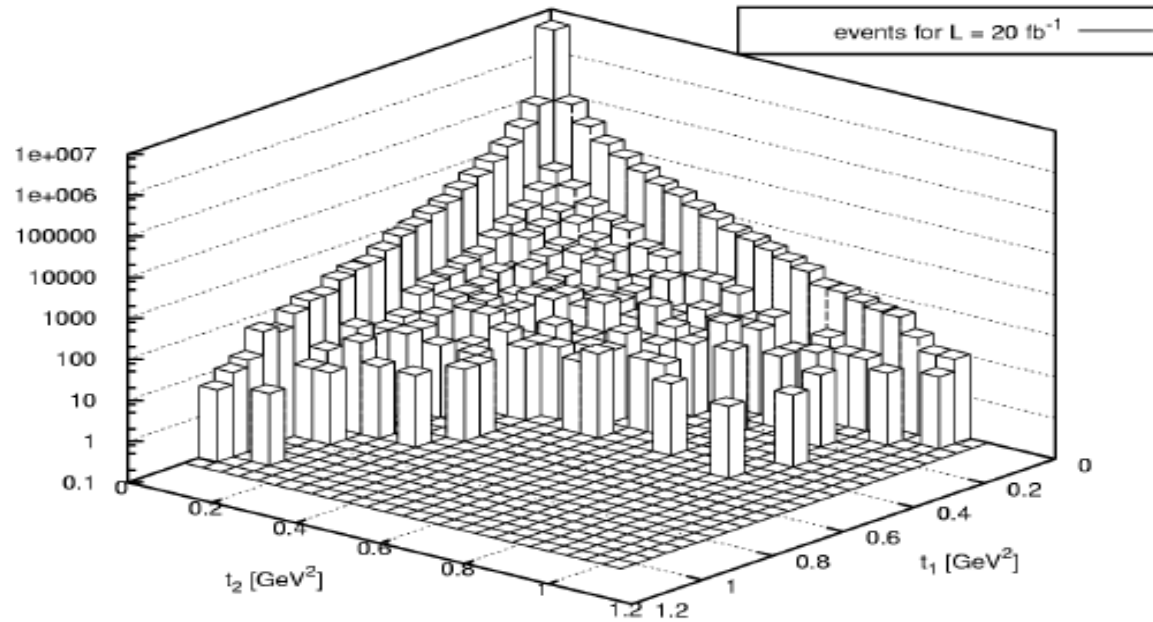Phys. Rev. D**65**, 073034 (2002)]

[ibid.]

[A. E. Dorokhov, 0905.4577]

[G. P. Lepage and S. J. Brodsky,

Phys. Rev. D **22**, 2157 (1980)]

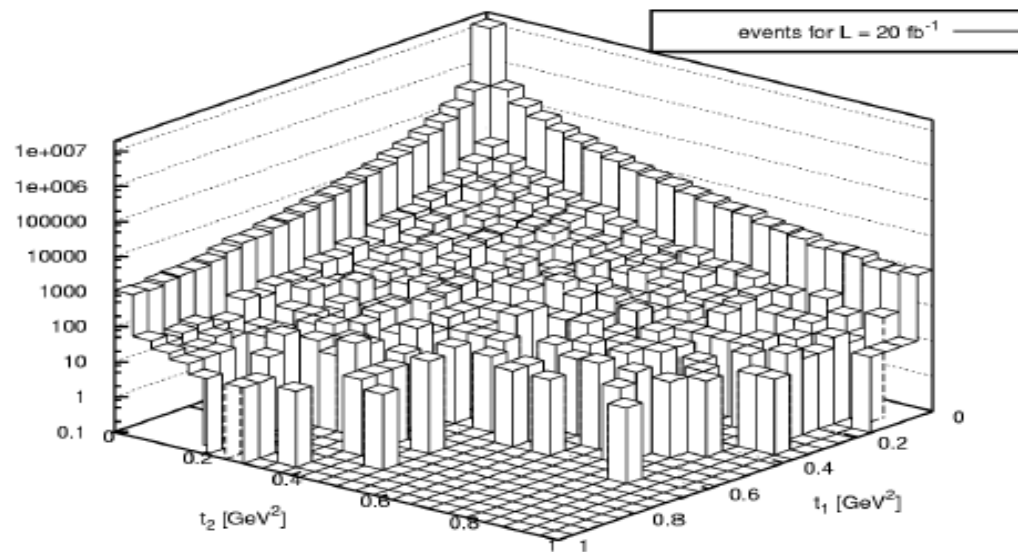No data at $0.02 \text{ GeV}^2 < Q^2 < 0.4 \text{ GeV}^2$

KLOE2

no cuts

- both invariants are well populated

BES-III

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

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

BES-III

BES-III at high Q^2
example: no cuts
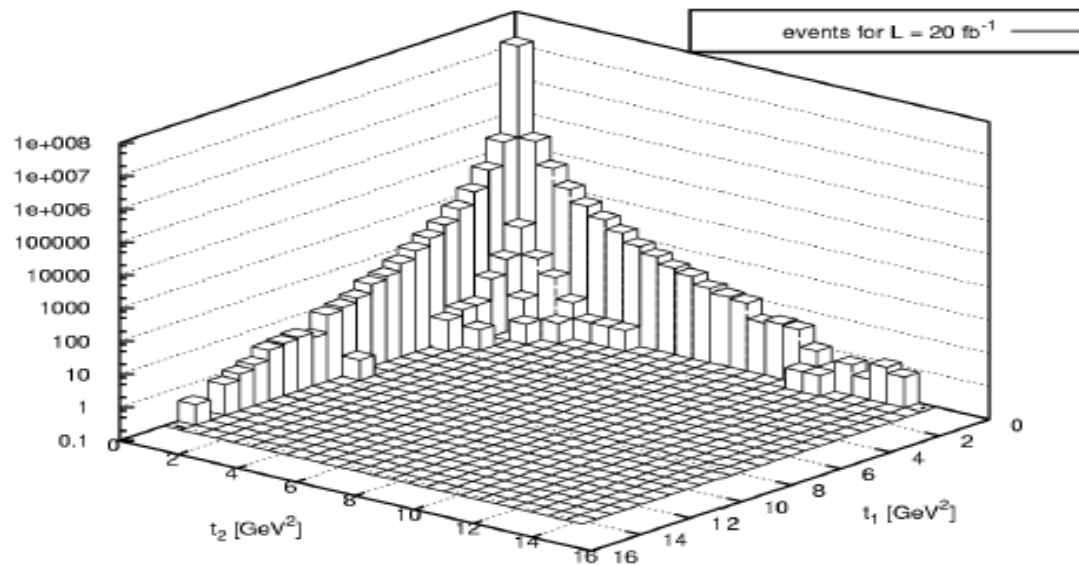
- $\sqrt{s} = 3.770$ GeV, $\int \mathscr{L} dt = 20$ fb^{-1}
  (~ 9 months at $\mathscr{L} = 10^{33}$ cm^{-2} s^{-1})
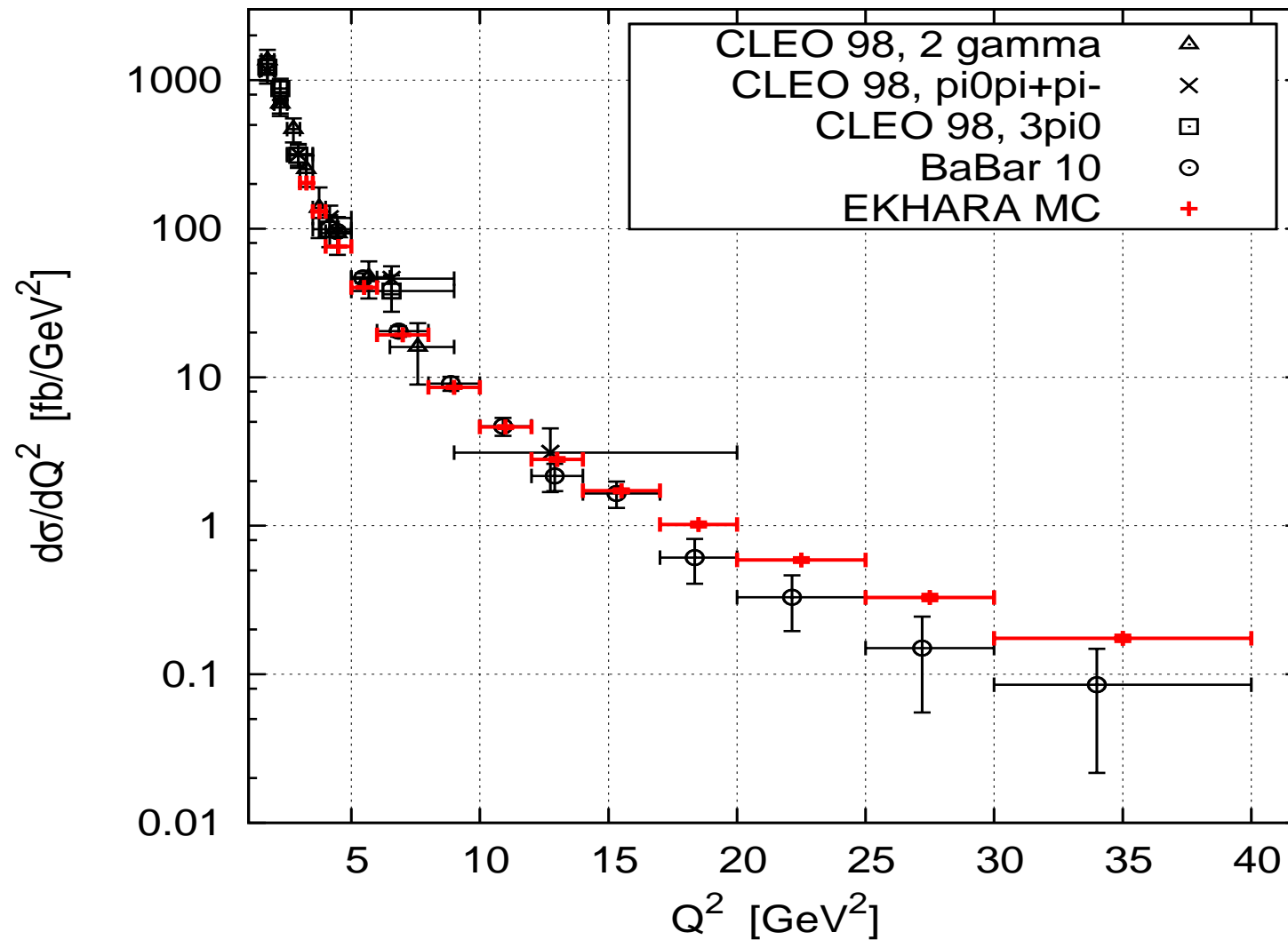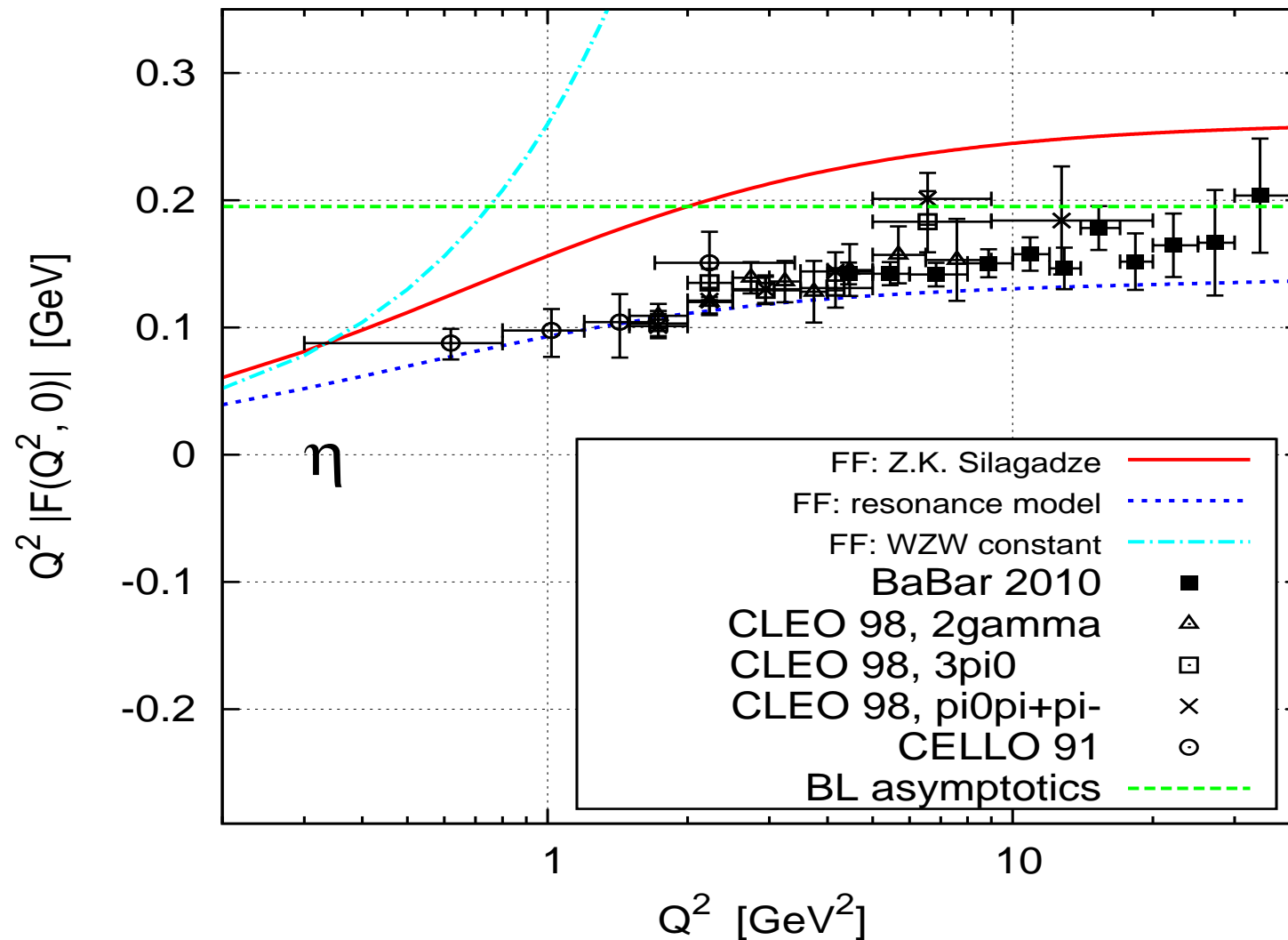
η in EKHARA

Model based on RCHPT

η in EKHARA

Model based on RCHPT

η in EKHARA

KLOE

η in EKHARA

events for L = 20 fb^{-1}

t_2 [GeV^2]

t_1 [GeV^2]
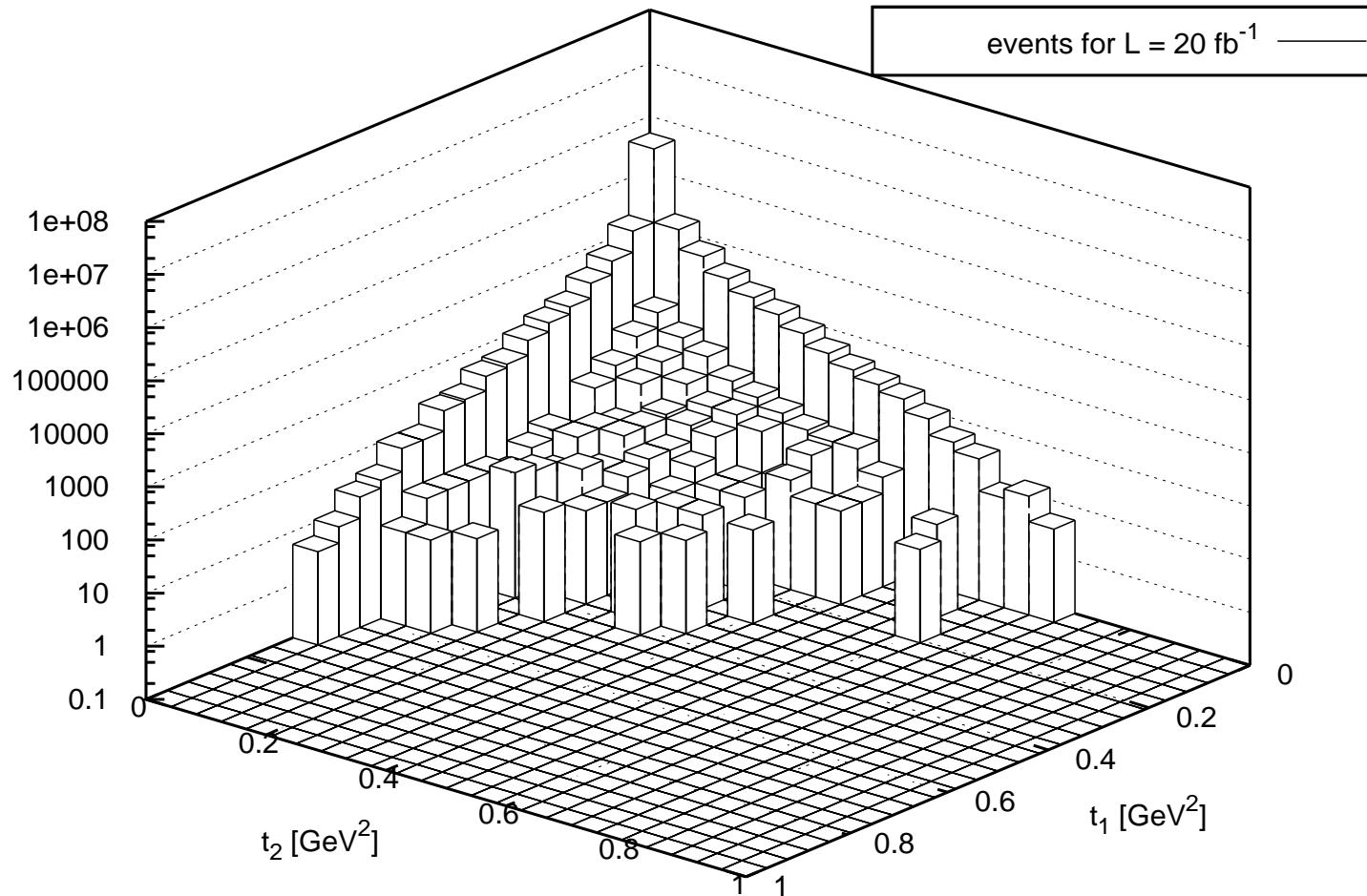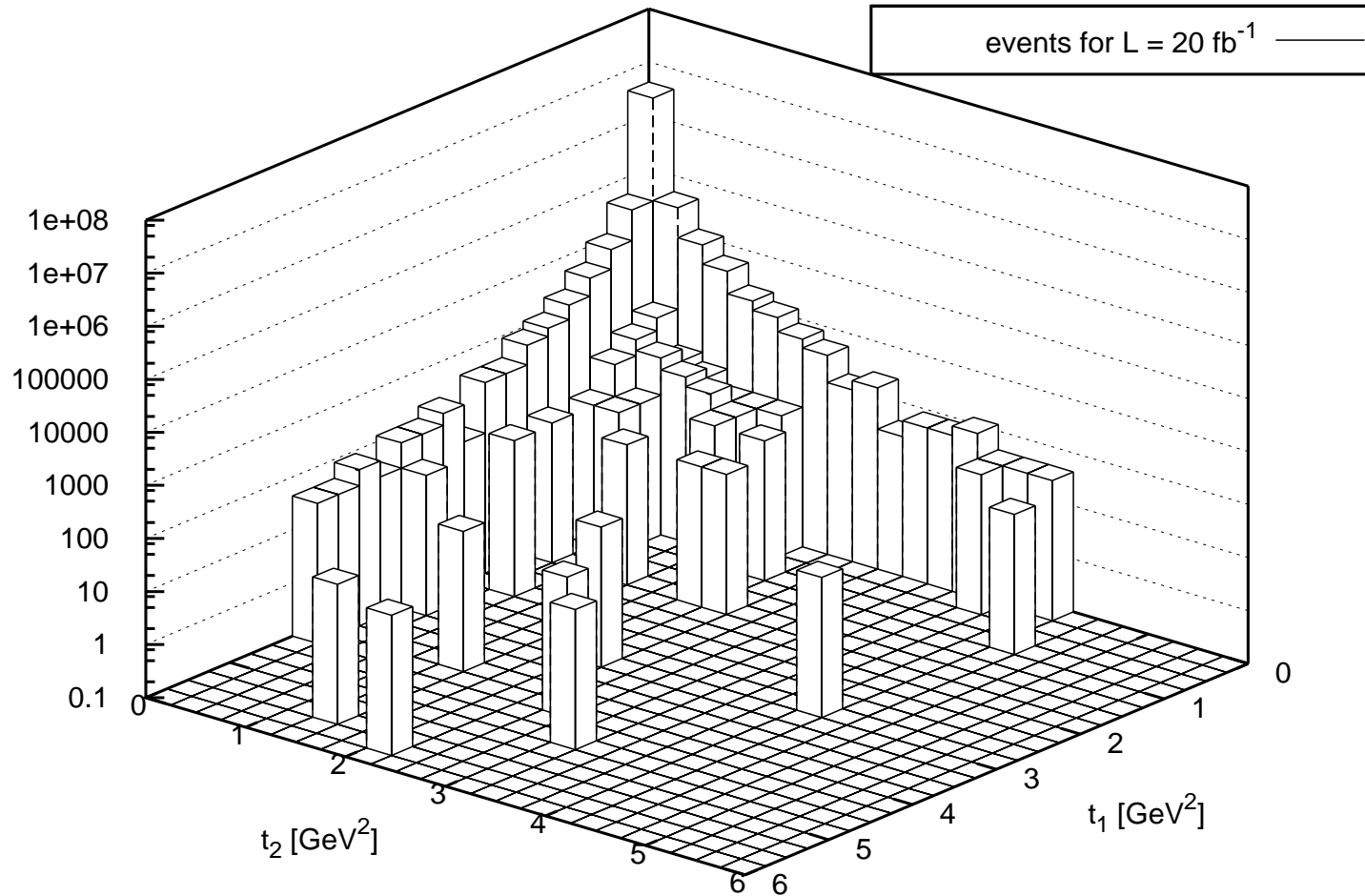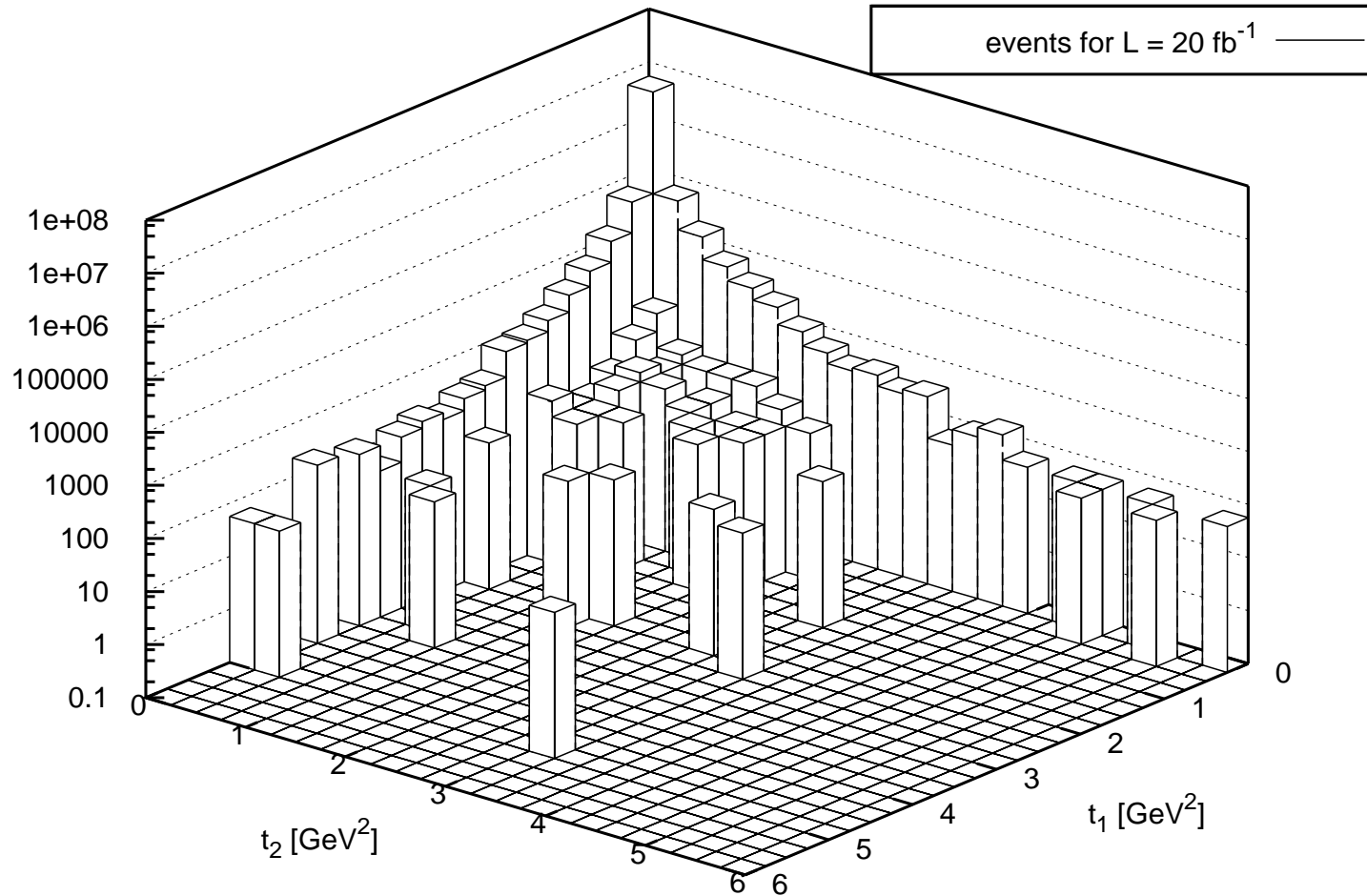
BES-III, $\sqrt{s}=$ 3 GeV

η in EKHARA

BES-III, $\sqrt{s}$ = 3.77 GeV
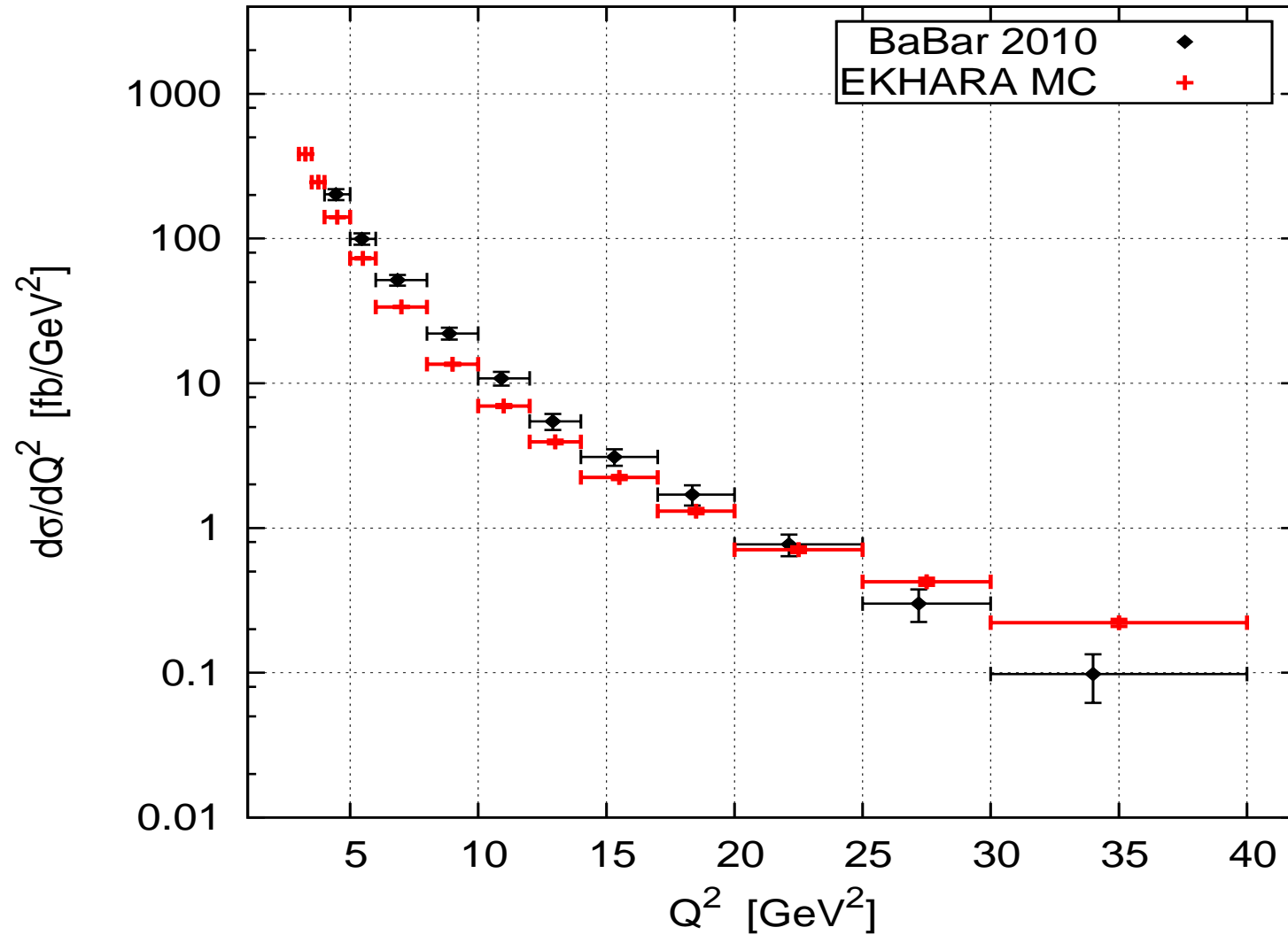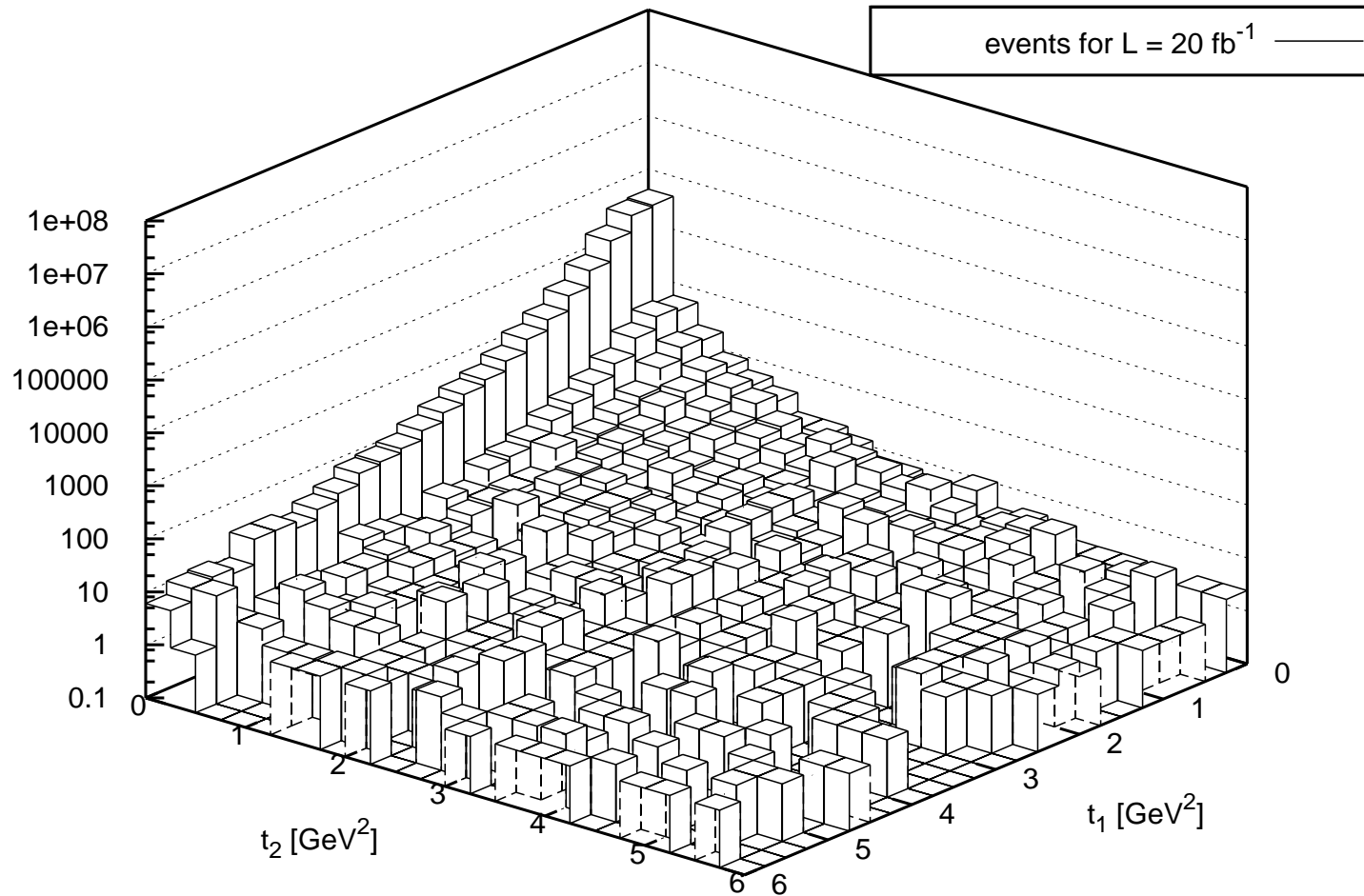
η' in EKHARA

Model based on RCHPT
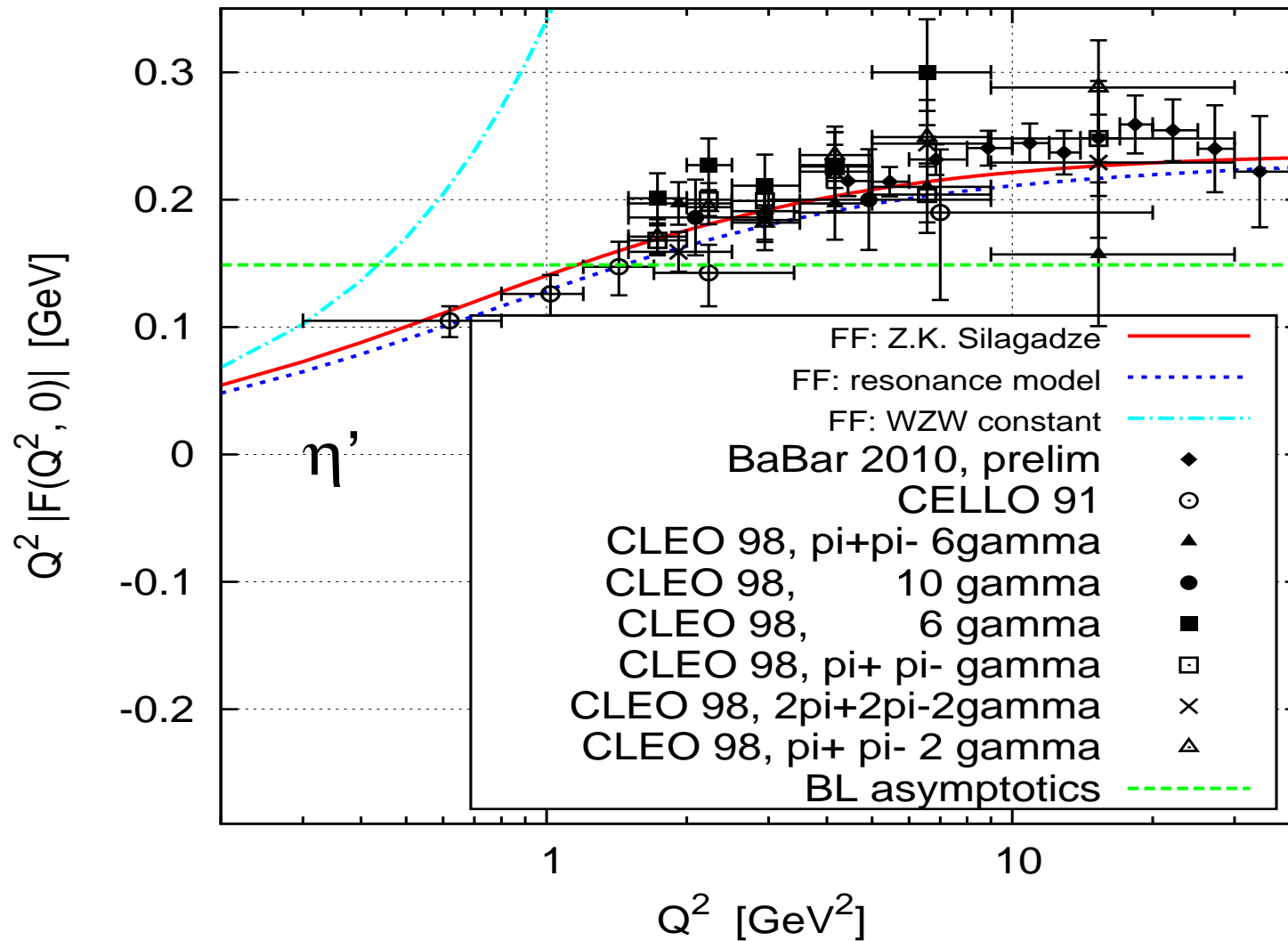
η′ in EKHARA

Model based on RCHPT

Tests of the program

- volume calculation

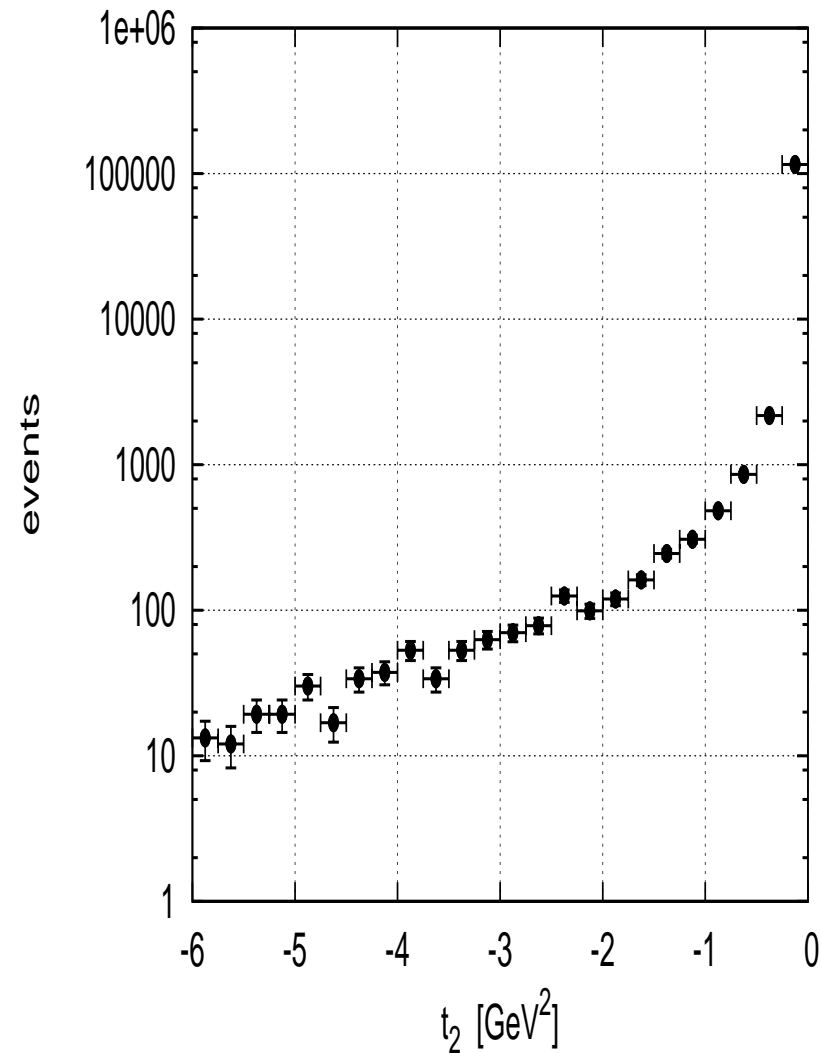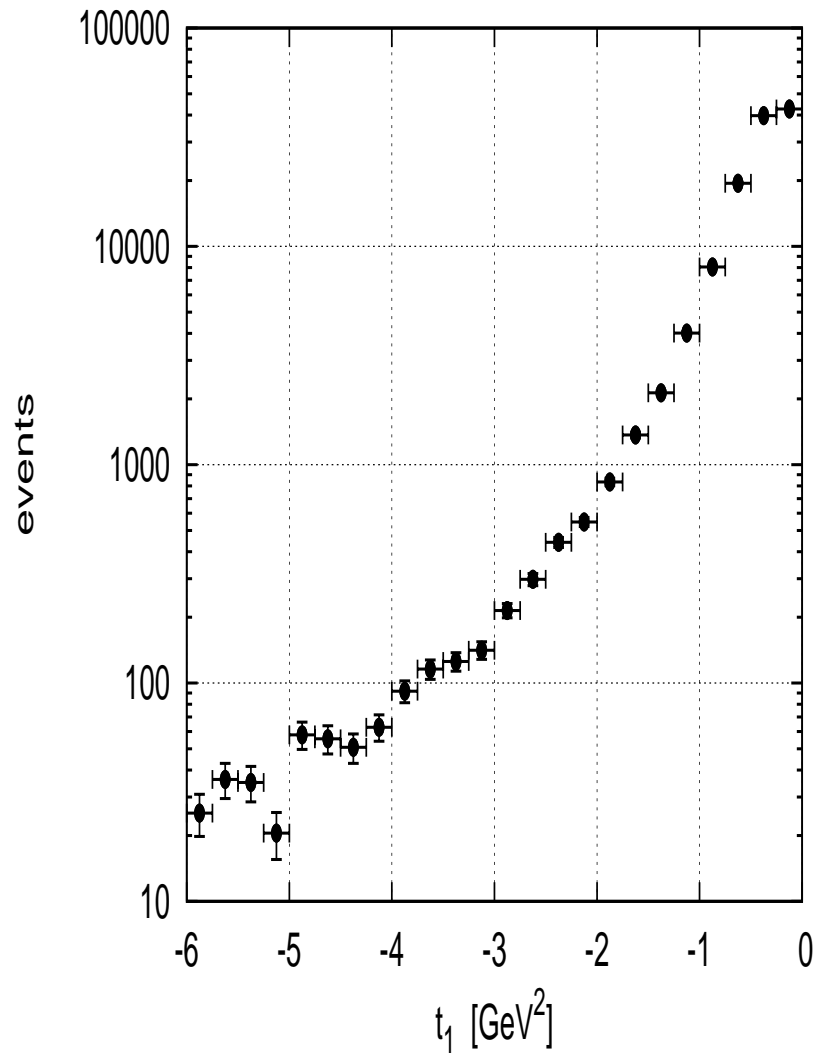- Matrix element - trace vs. helicity amplitudes

η in EKHARA
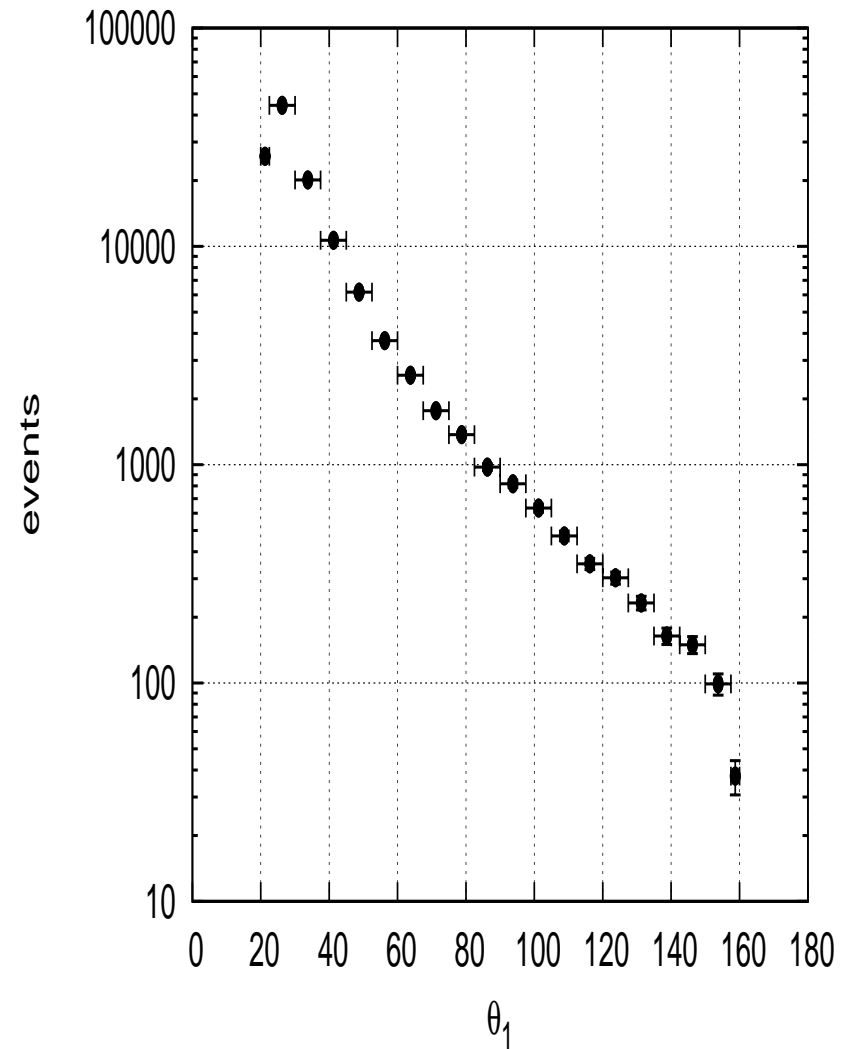

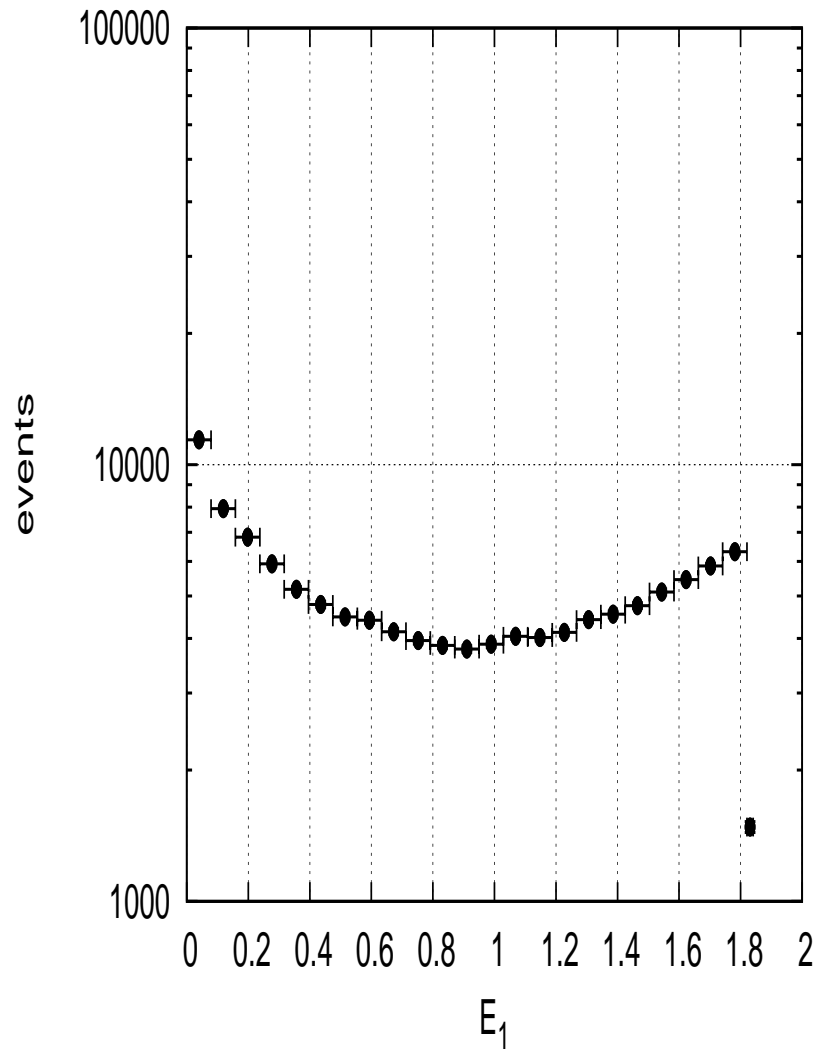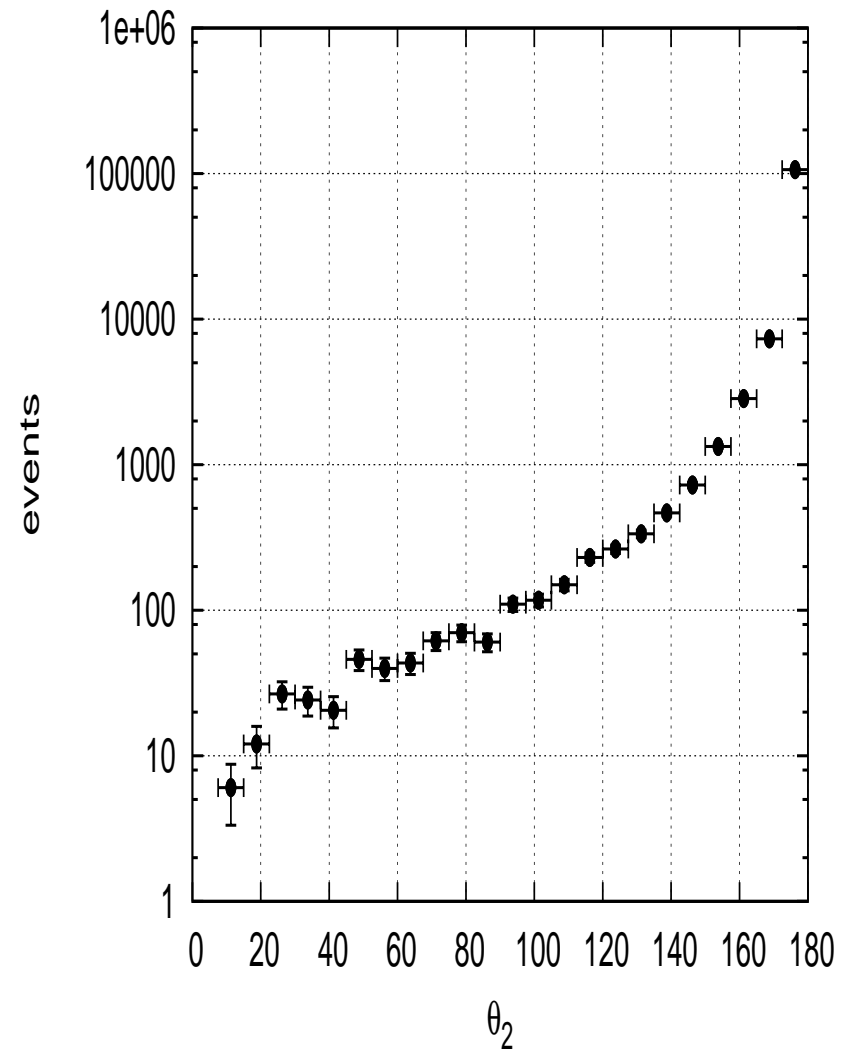BES-III, $\sqrt{s}=$ 3.77 GeV; $20° < \theta_{e+} < 160°$
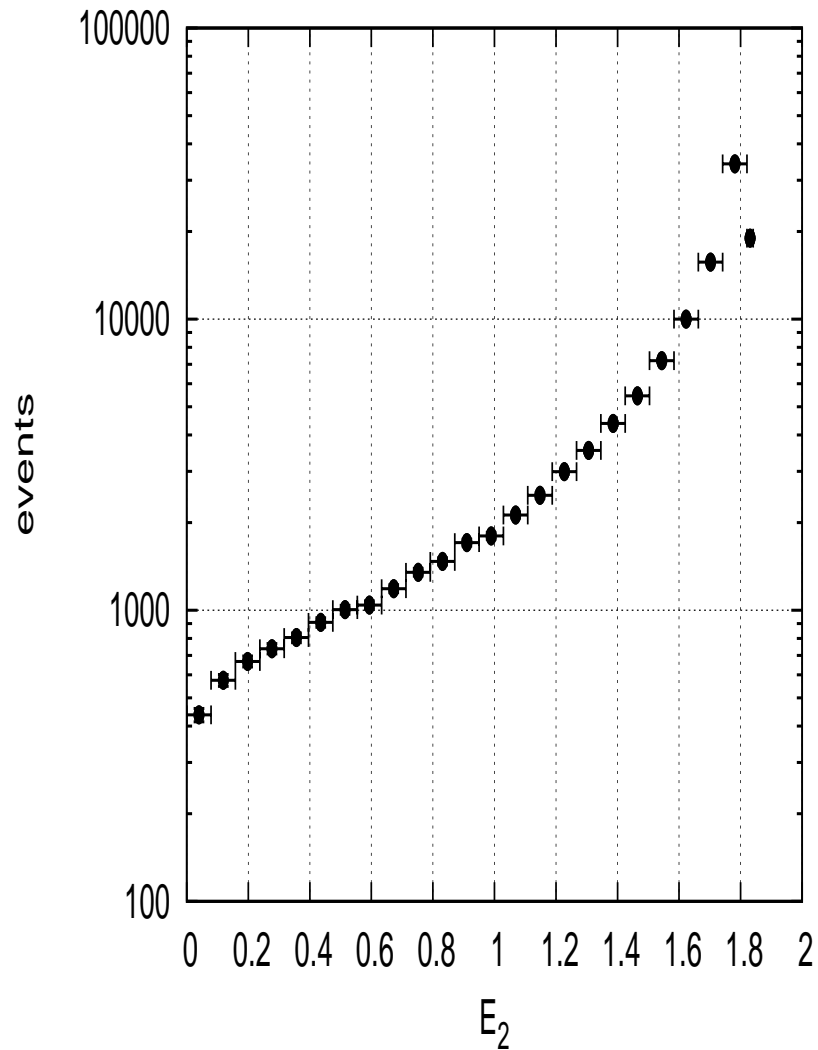
η in EKHARA

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

η in EKHARA

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

η in EKHARA

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

η in EKHARA
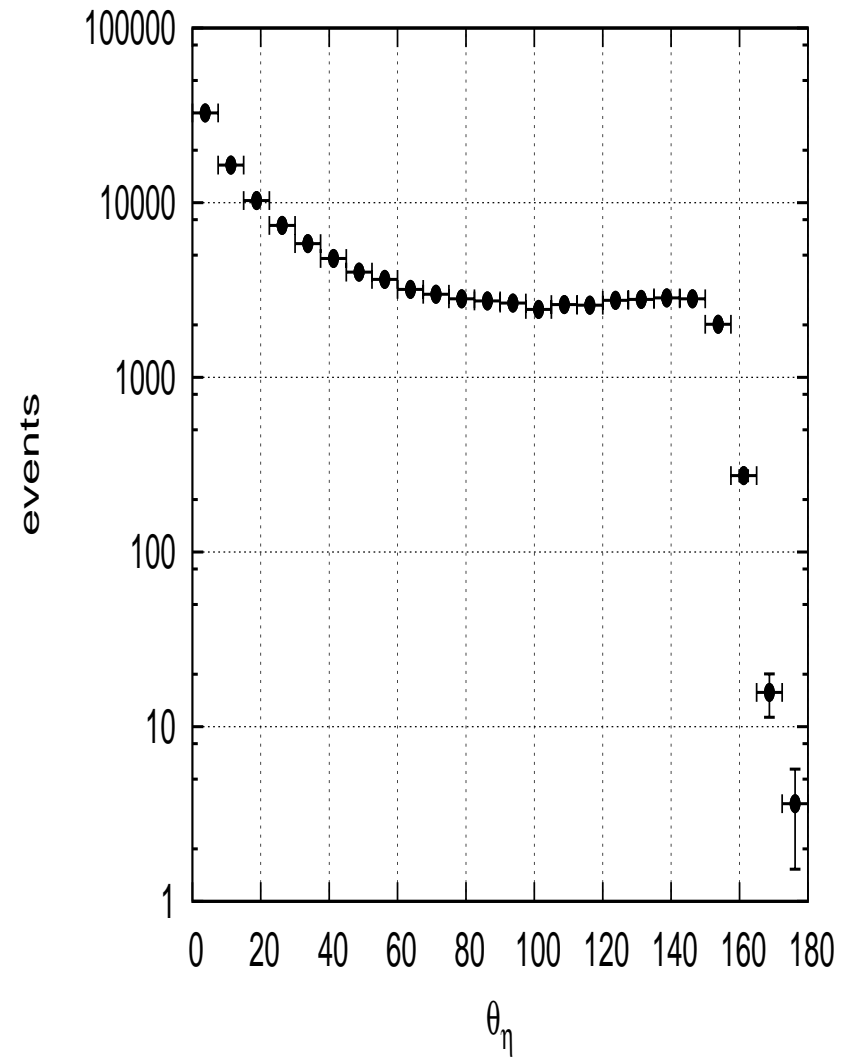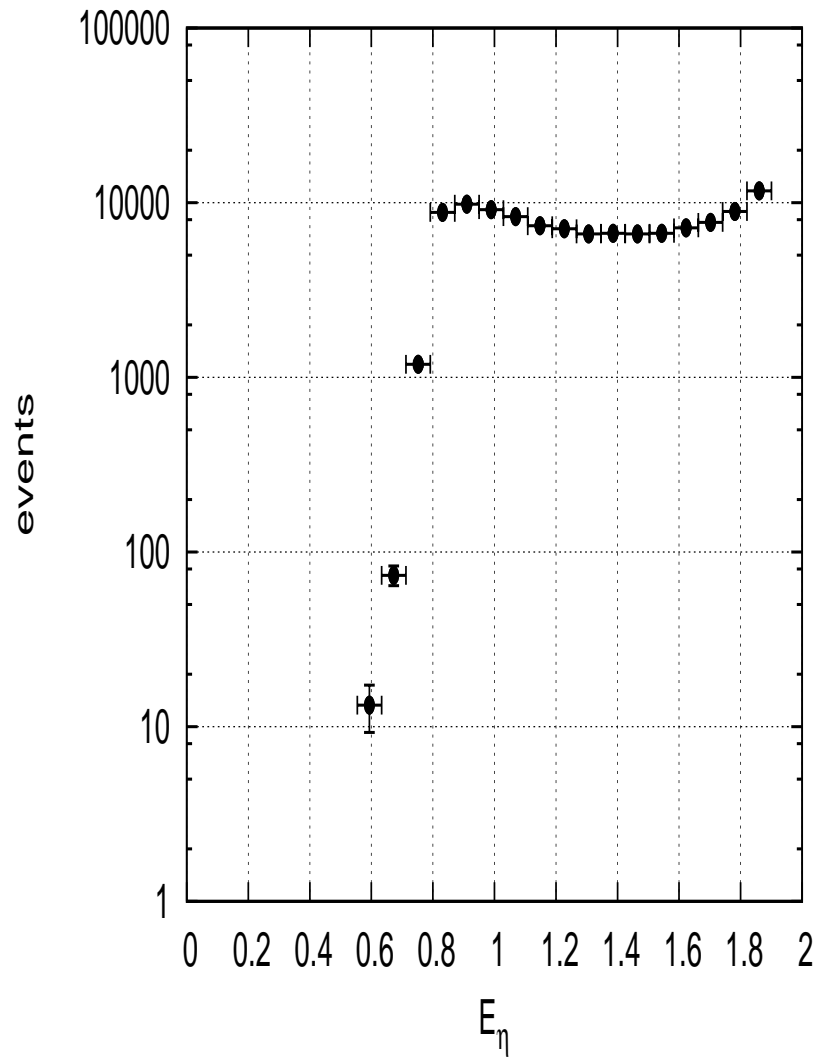
BES-III, $\sqrt{s}$= 3.77 GeV; $20° < \theta_{e+} < 160°$

Planned upgrades

- finalize η and η'

- radiative corrections to be added

- further work on $\pi^+\pi^-$