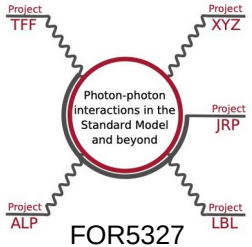
Project TFF — Experiment

Workshop of Research Unit FOR5327

2025-06-11 | Christoph Florian Redmer



DFG Deutsche Forschungsgemeinschaft

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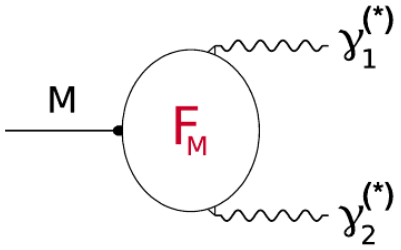
Transition Form Factors



- Coupling of photons to electrically neutral hadrons
- Scalar function of two virtualities $\mathcal{F}_M(q_1^2, q_2^2)$
- Normalized to radiative width of mesons $\Gamma_{M\to\gamma\gamma} = \frac{\pi\alpha^2 m_M^3}{4}|\mathcal{F}_M(0,0)|^2$
- Related to meson distribution amplitudes $\mathcal{F}_{\pi^0}(-Q_1^2, -Q_2^2) = \frac{2f_\pi}{6}\int_0^1 \phi(x) T_H(x, Q_1^2, Q_2^2)\mathrm{d}x$

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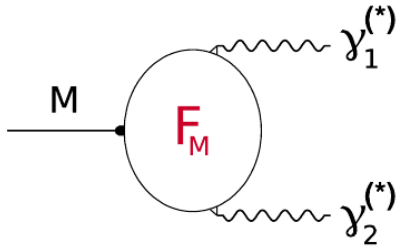

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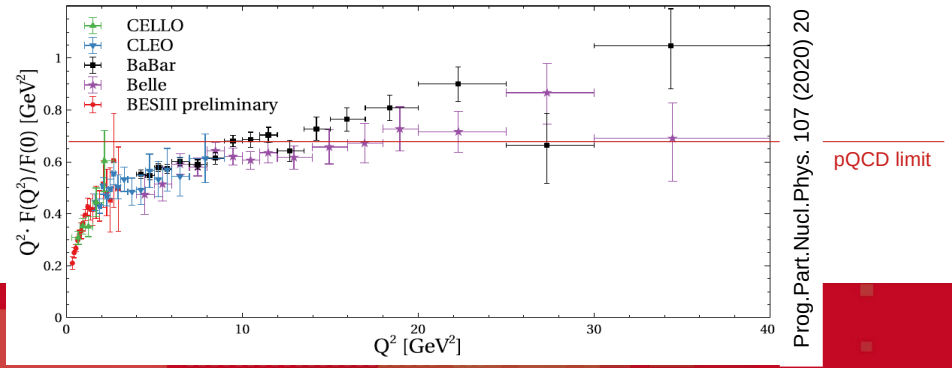
- Test of pQCD: Brodsky-Lepage limit



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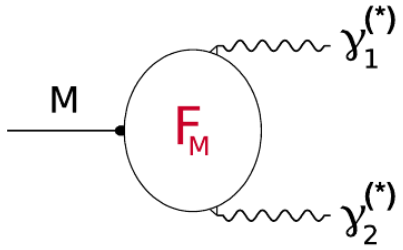

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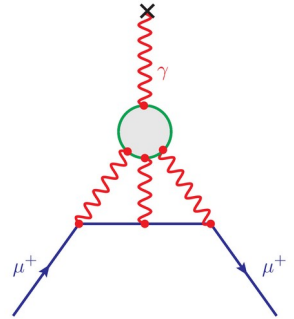
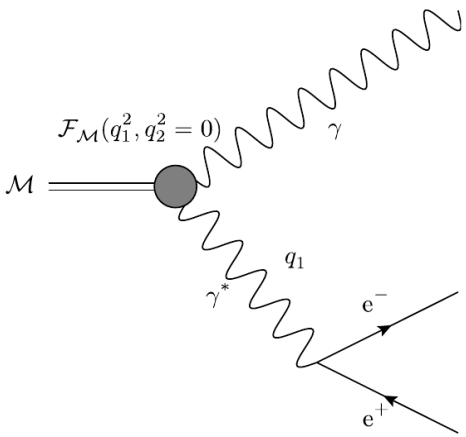
- Test of pQCD: Brodsky-Lepage limit
- Input and benchmark for phenomenology a_μ^{HLbL}



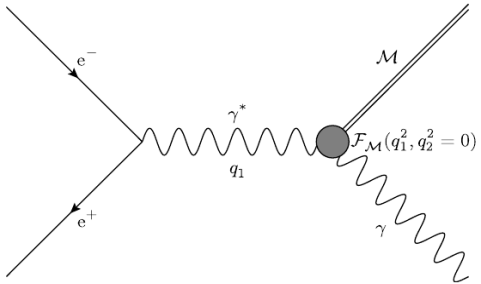
Experimental Access to TFF

Meson Dalitz Decays



$$m_{ll}^2 < q^2 < m_P^2$$

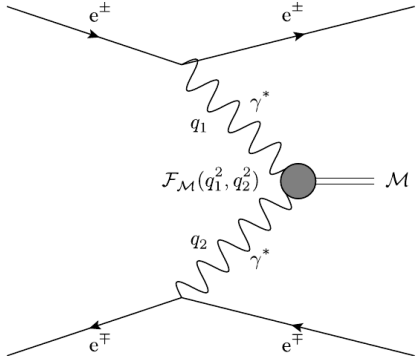
Radiative Meson Production



$$q^2 = s; \quad q^2 > m_P^2$$

time-like

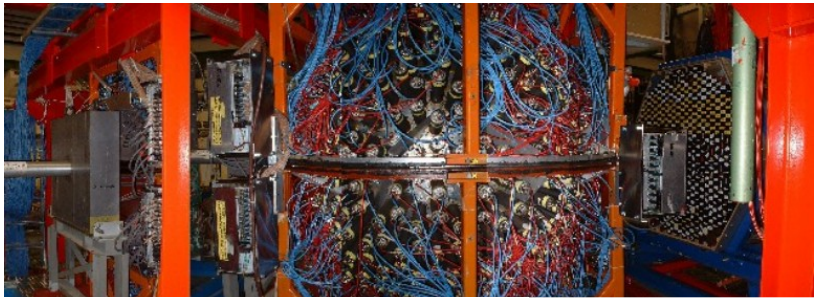
Two-photon collisions

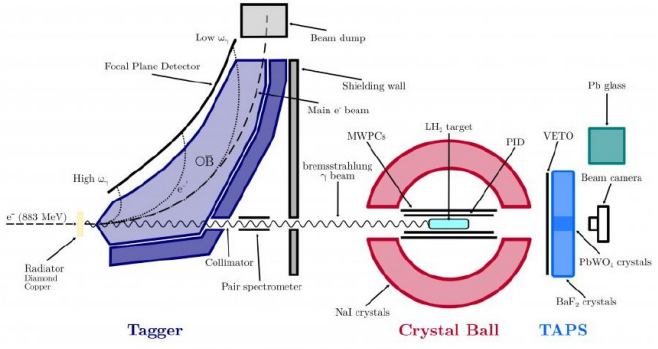


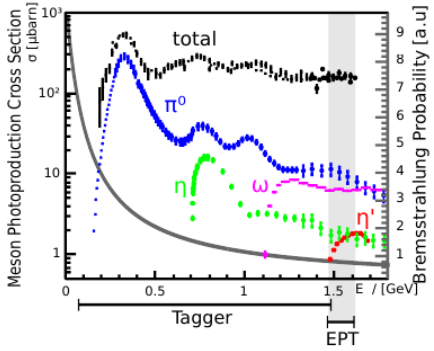
$$q_1^2 = -Q_1^2; \quad q_2^2 = -Q_2^2$$

space-like

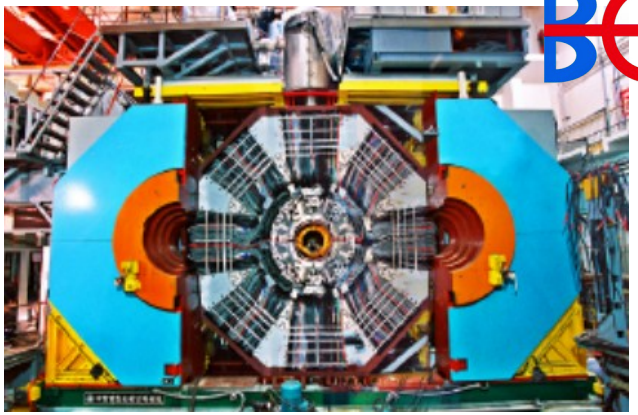
Exploit synergies of facilities







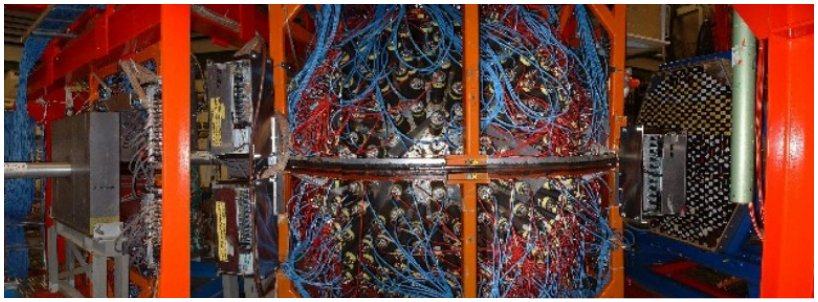
- Quasi-continuous electron beam at MAMI
- Tagged bremsstrahlung photon beam ($E_{max} \approx 1.6$ GeV)
- Non-magnetic spectrometer CB/TAPS

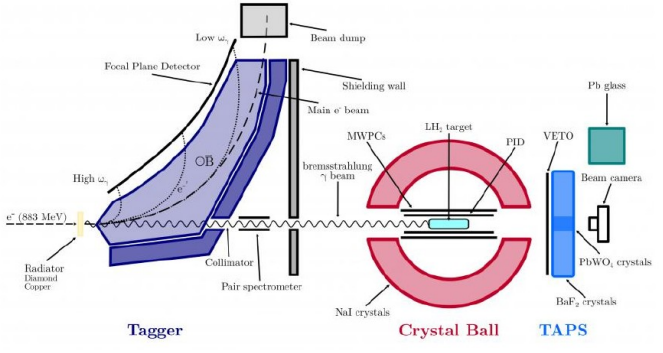


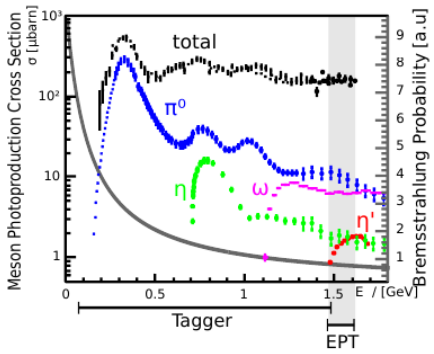
- e^+e^- collider
- $1.84 \leq \sqrt{s}\,[\mathrm{GeV}] \leq 5.0$
- Design luminosity exceeded $> 1 \frac{1}{\mathrm{nb} \cdot \mathrm{s}}$

- Multi-purpose spectrometer
- Recent upgrade of inner tracker

Exploit synergies of facilities







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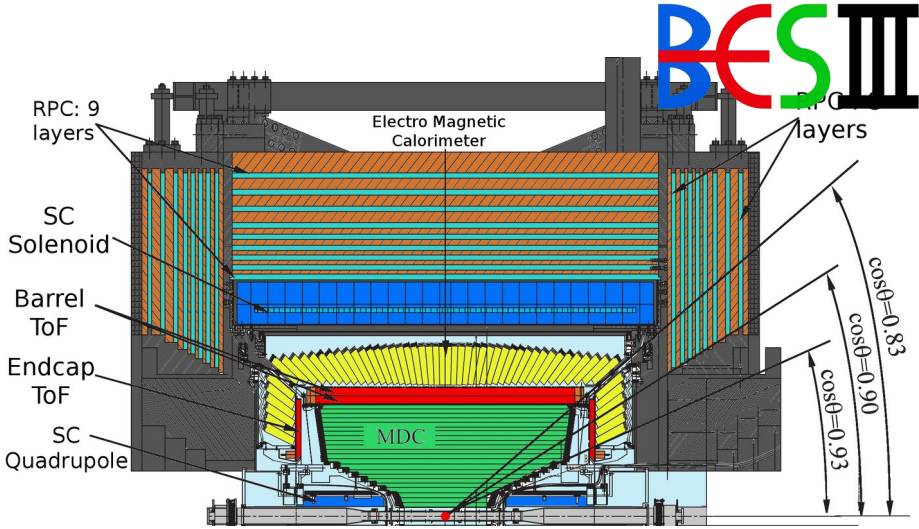

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RU Objectives

TFF-1: Measurement of space-like and time-like π^0 TFF

- World-leading time-like π^0 TFF measurement at A2/MAMI
- Preparation for high-statistics measurement of $\omega - \pi^0$ TFF
- Measurement of space-like π^0 TFF at low Q^2 at BESIII
- Preparation for a double-virtual measurement

TFF-2: $\gamma\gamma$ fusion to multi-meson final states

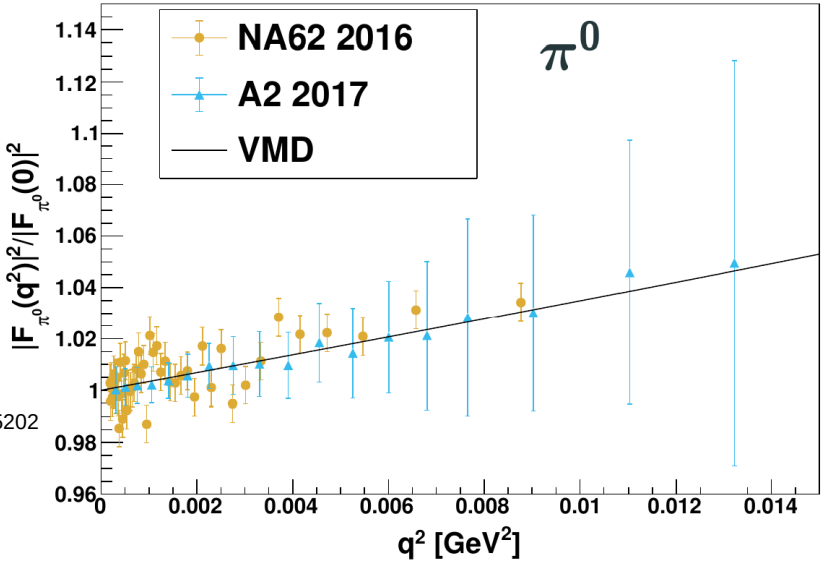
- First measurement of space-like TFF of $\pi^0\pi^0$ and $\pi^0\eta$ at BESIII
- Analysis of axial-vector meson TFFs in $\pi^+\pi^-\eta$ at BESIII

Pion TFF from Dalitz decays

- From decay rates

$$\frac{d\Gamma(A \to B\ell^+\ell^-)}{dq^2\Gamma(A \to B\gamma)} = [\mathrm{QED}] \left|\frac{\mathcal{F}_{AB}(q^2)}{\mathcal{F}_{AB}(0)}\right|^2 = [\mathrm{QED}] \left|F_{AB}(q^2)\right|^2$$

$$b_P = \left.\frac{dF_{AB}(q^2)}{dq^2}\right|_{q^2=0}$$



- A2/MAMI 0.4M events (photo-production) Phys.Rev. C95 (2017) 025202

$$b_\pi = 0.030 \pm 0.010_{\mathrm{tot}}$$

- NA62 1.11M events (kaon decays) Phys. Lett. B768 (2017) 38

$$b_\pi = 0.0368 \pm 0.0057_{\mathrm{tot}}$$

  - Both with radiative corrections Phys.Rev. D92 (2015) 054027

New Dalitz decay measurement at A2

- Additional data taken in 2018
  - Goal: 5.5 times increased statistics
- Analysis: $\gamma p \to e^+ e^- \gamma p$
  - Select events with three and four clusters
    - $\gamma/e^\pm$ cluster only in calorimeter
  - Kinematic fit $\gamma p \to 3\gamma p$
  - Identify e/p with hits on PID detector
  - Require hits in separate elements to suppress conversion
  - Subtract random and empty target background contributions

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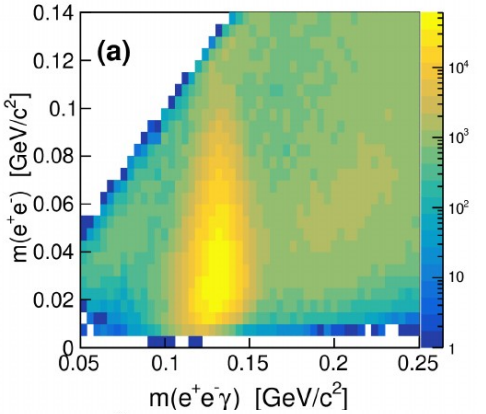
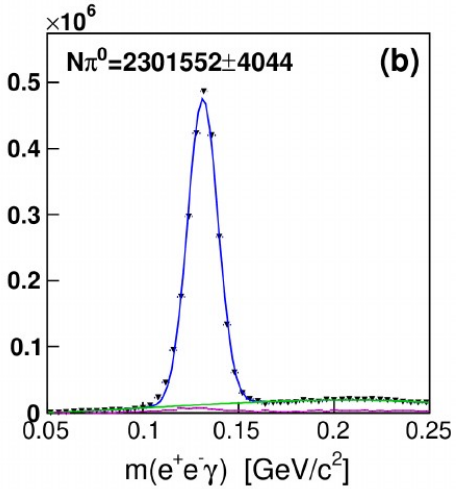
- 2.3 M events selected

Goal achieved !!





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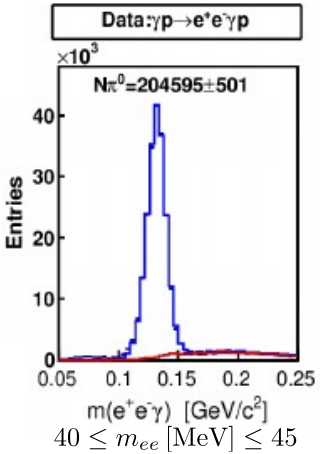
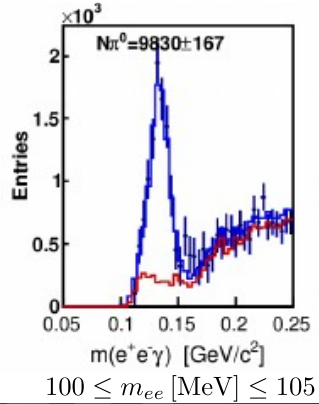
- Bin-wise background subtraction using MC distributions



$40 \leq m_{ee}\,[\mathrm{MeV}] \leq 45$



$100 \leq m_{ee}\,[\mathrm{MeV}] \leq 105$

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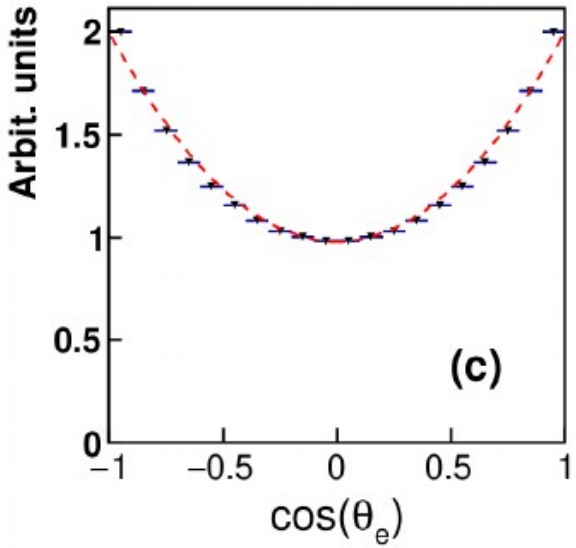
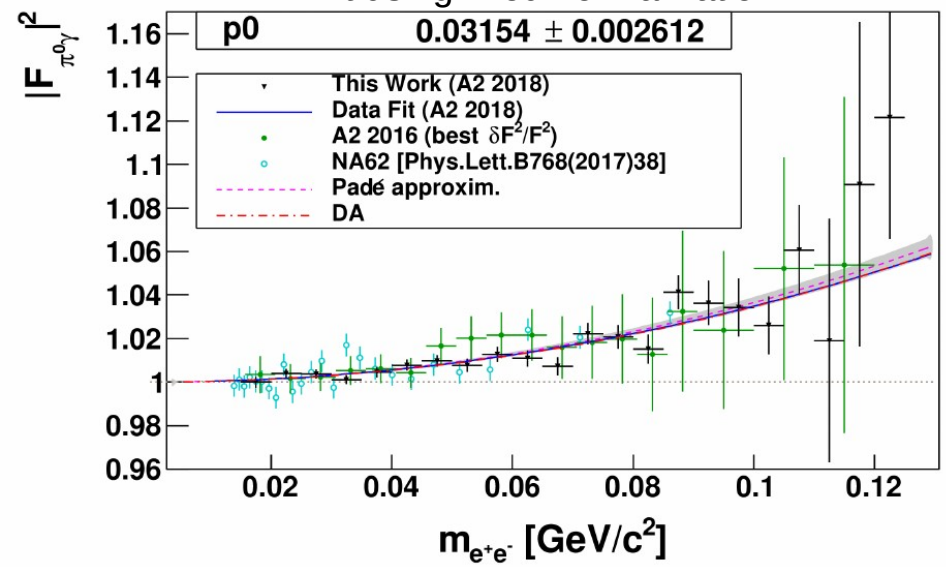
Cross check angular distribution of electrons

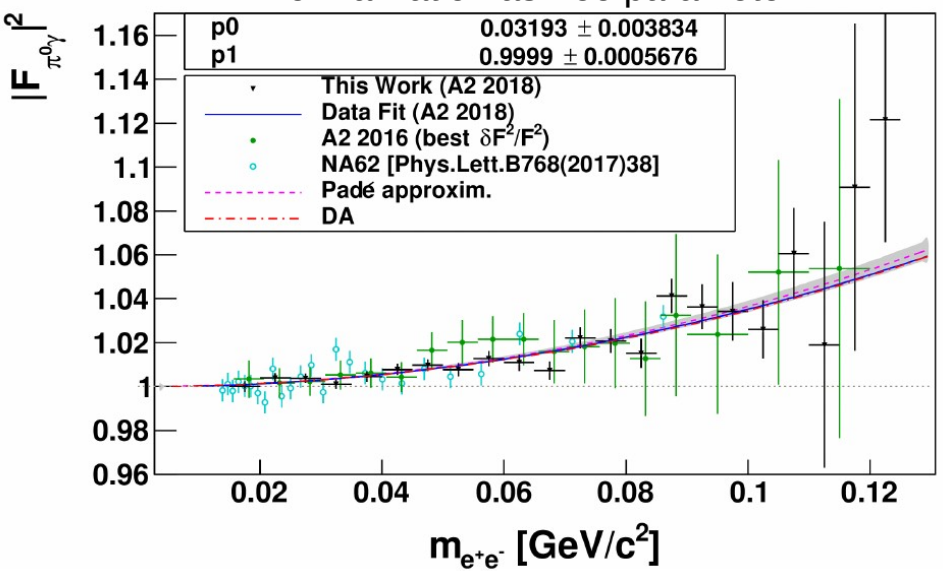


New Dalitz decay measurement at A2

Fit using fixed normalization



Normalization as free parameter



New A2 result (preliminary): $b_\pi = 0.0315 \pm 0.0026_{\mathrm{stat}} \pm 0.0010_{\mathrm{syst}}$

Previous result: $b_\pi = 0.030 \pm 0.010_{\mathrm{tot}}$

NA62: $b_\pi = 0.0368 \pm 0.0057_{\mathrm{tot}}$

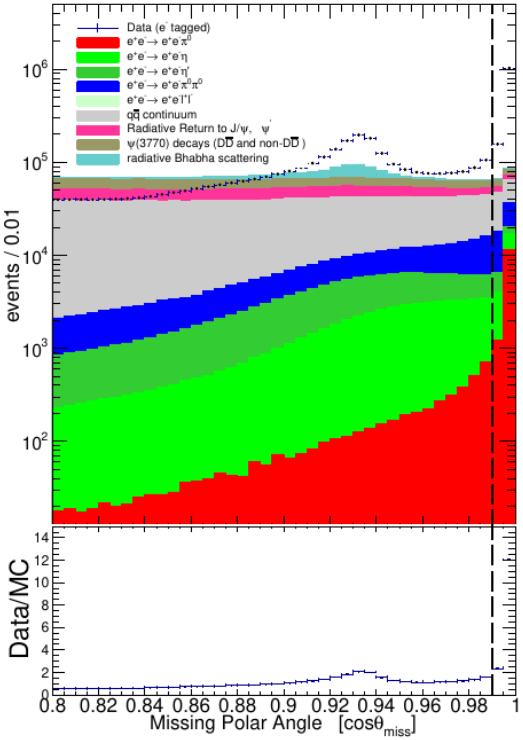
4 x improvement w.r.t A2(2017)

2 x improvement w.r.t NA62

Space-like TFF at BESIII

Two-photon collision events:

- Single-tag measurements $\mathcal{F}(Q_1^2, Q_2^2) \rightarrow \mathcal{F}(Q^2)$
  - Require one quasi-real photon
- Select
  - One scattered lepton & meson decay products
  - Require small scattering angle of missing momentum



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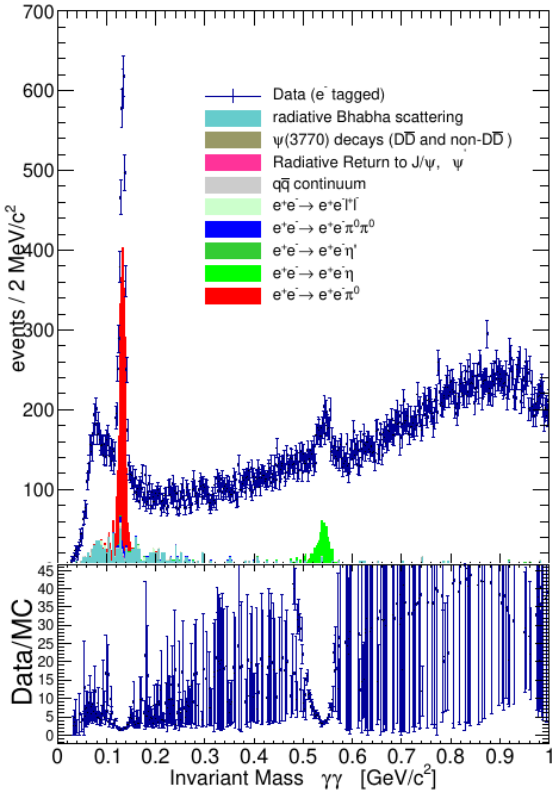

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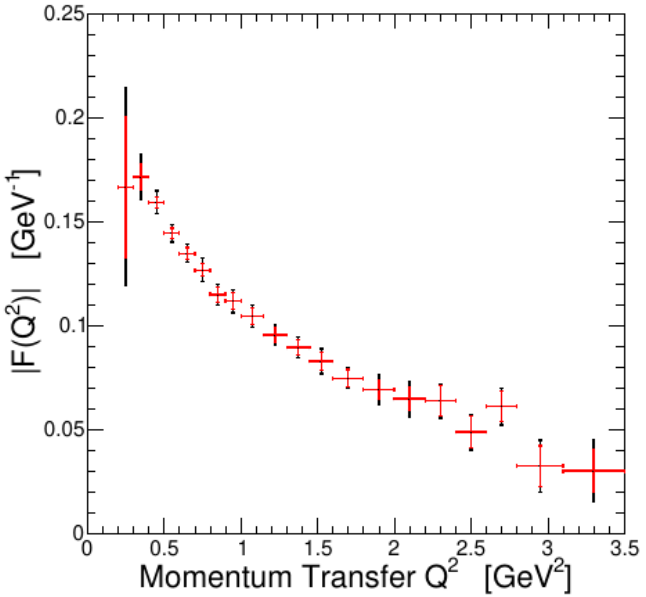
- Divide by point-like cross section
- Correct for radiative effects

Here: based on 2.9 fb^{-1} taken at 3.773 GeV



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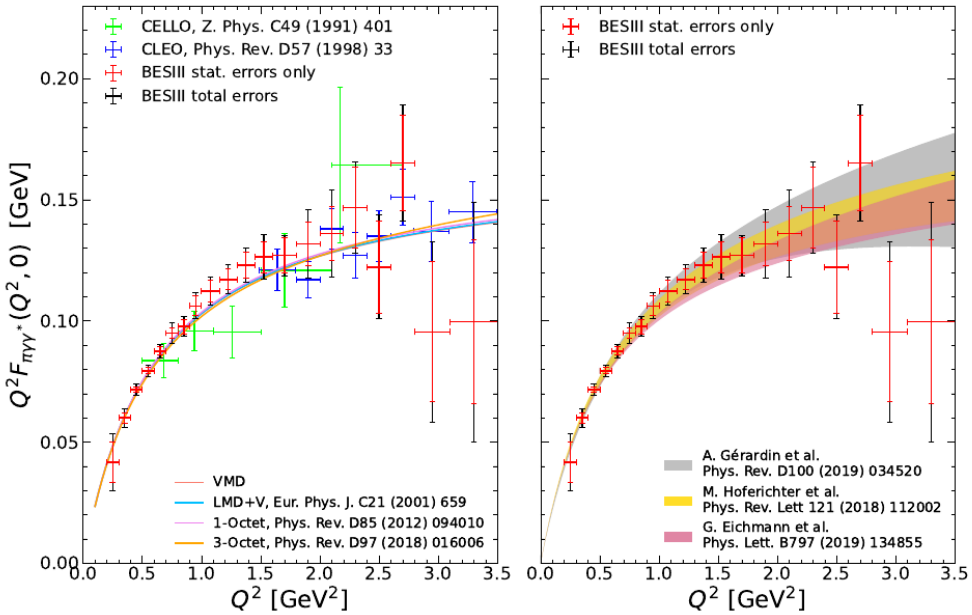

Access smaller momentum transfer

First π^0 TFF analysis finalized

- Systematic effects reduced
- Radiative corrections included
- Larger momentum transfer range accessible $0.3\,\mathrm{GeV}^2 \rightarrow 0.2\,\mathrm{GeV}^2$

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In the meantime: Measurements of η and η' TFFs started!

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First π^0 TFF analysis finalized

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- Radiative corrections included
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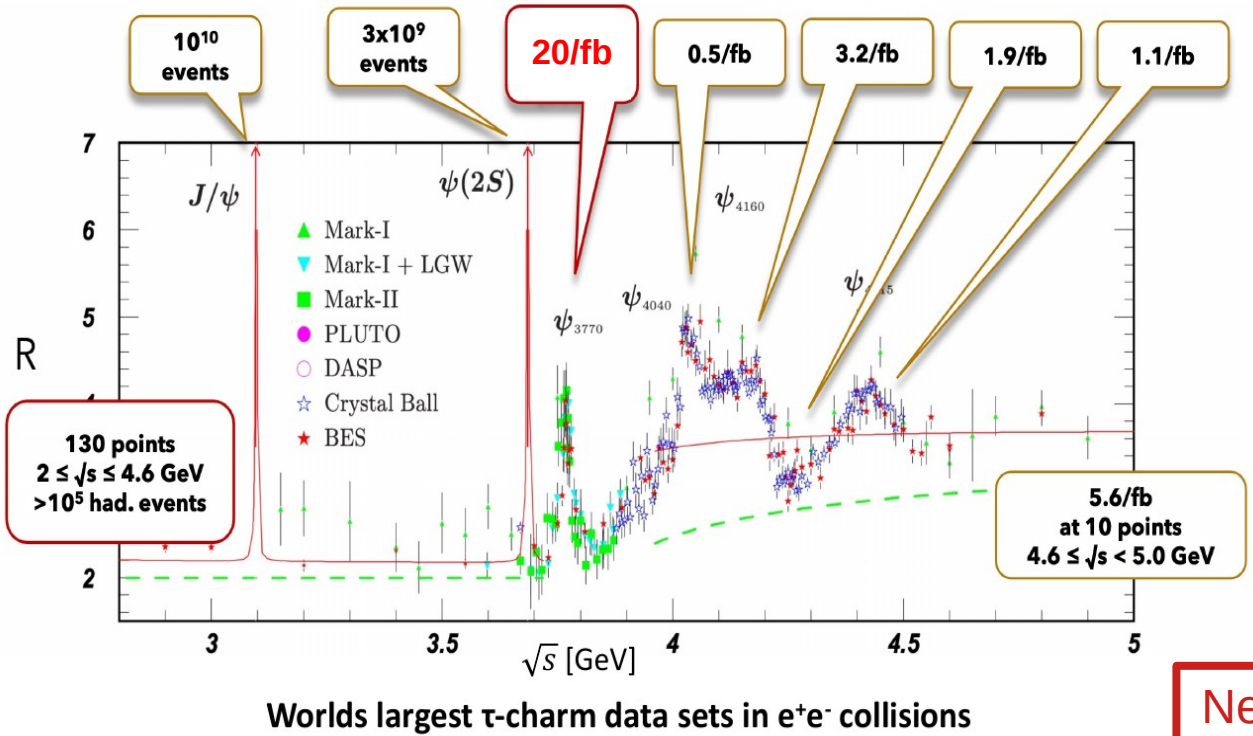
In the meantime: Measurements of η and η' TFFs started!

- Reconstruction efficiency improves with lower $\sqrt{s}$
  - Tests at 2.125 GeV
  - Q^2 range can be extended to 0.1 GeV^2
  - Small integrated luminosities available (~100 pb^{-1})

Data available at BESIII



Worlds largest τ-charm data sets in e^+e^- collisions

- Richest data above open charm threshold
  - Access to
    - Hadronic masses up to 2 GeV
    - $0.2 \leq Q^2[\mathrm{GeV}^2] \leq 3$
- Access to smaller Q^2 values at $\sqrt{s} \approx 2\,\mathrm{GeV}$ (limited statistics)

New data at 3.773 GeV most relevant!

Data taking finished June 2024

Preparation of double-tagged measurements

- Original plan: $\mathcal{F}_\pi(Q_1^2, Q_2^2)$
  - Dominating background contributions from Bhabha scattering
  - Reliability of MC limited for hard radiation Bhabha
- Alternative: $\mathcal{F}_{\eta,\eta'}(Q_1^2, Q_2^2)$ with charged decays modes
  - Better resolution
  - Better background situation
  - BaBar published successful measurement

Phys.Rev. D98 (2018) 112002

Study decay modes: $\eta \to \pi^+\pi^-\pi^0$

$\eta' \to \pi^+\pi^-\eta$

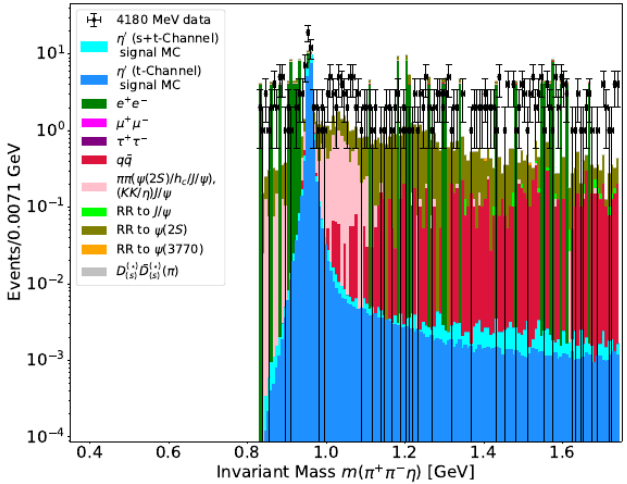
$\eta' \to \pi^+\pi^-\gamma$

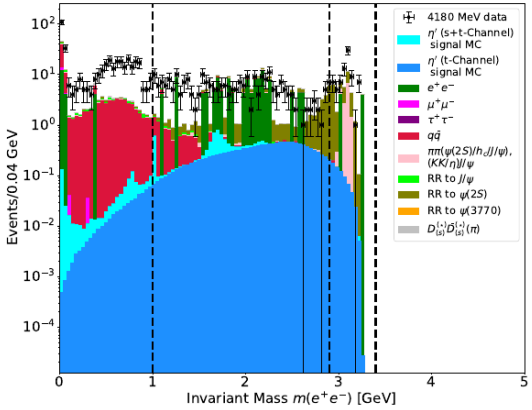
B.Sc. Thesis of Maurice Anderson

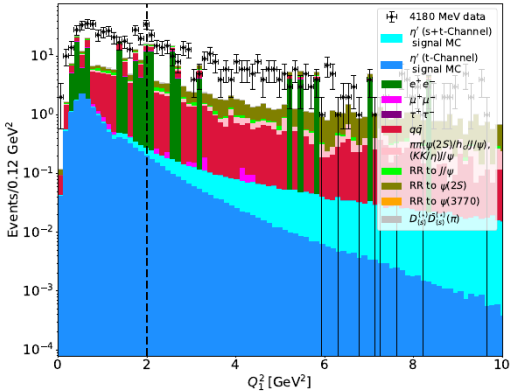
Preparation of double-tagged measurements

Example: $\eta' \to \pi^+\pi^-\eta$

- Combine 13.5 fb^{-1} at energies ≥ 3.773 GeV
- Select 3 tracks and at least 2 photons
- 4C/5C kinematic fit
- Reject background from
  - Charmonium transitions
  - Timelike two-photon production







Preparation of double-tagged measurements

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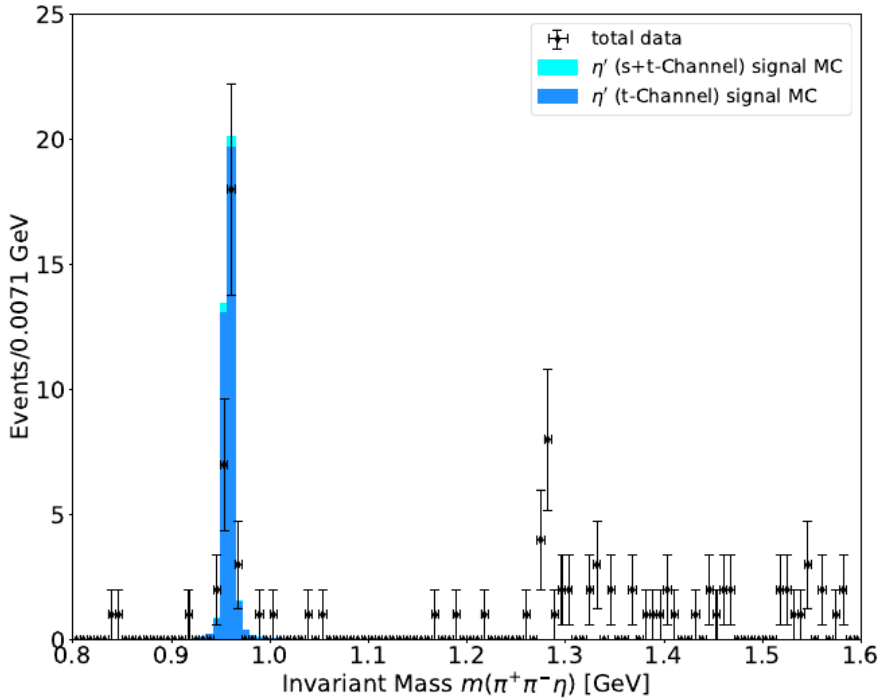
28.4 ± 5.5 signal events identified!

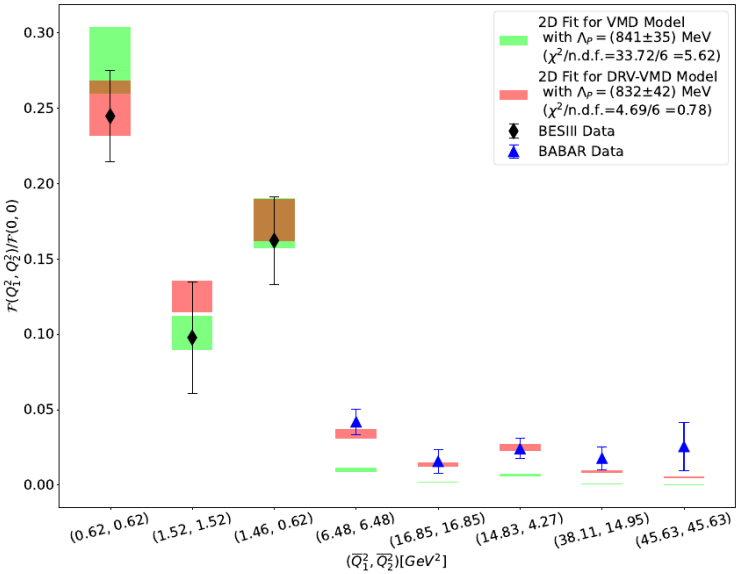
Potential for double-tagged $f_1(1285)$?

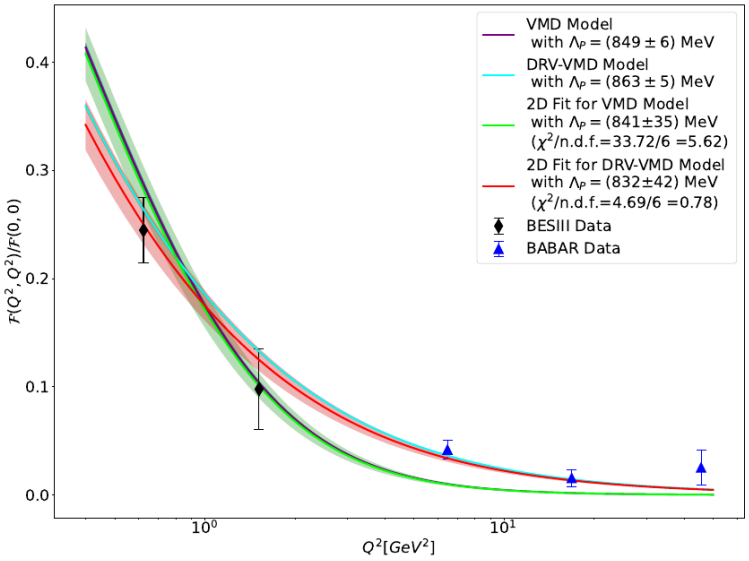


Preparation of double-tagged measurements

Analysis of $\eta' \to \pi^+\pi^-\eta$ and $\eta' \to \pi^+\pi^-\gamma$ yields 47.2 ± 7.4 events!

- Babar: $46.2^{+8.3}_{-7.0}$





Analysis being repeated on full 20 fb^{-1} data set at 3.773 GeV !

TFF2: Multi-meson final states

More degrees of freedom make analysis more involved

Assuming unpolarized lepton beams:

$$d\sigma_{ee} = \frac{\alpha^2}{16\pi^4 q_1^2 q_2^2}\sqrt{\frac{(q_1\cdot q_2)^2 - q_1^2 q_2^2}{(p_1\cdot p_2)^2 - m_e^4}}\left[4\rho_1^{++}\rho_2^{++}\sigma_{TT} + 2|\rho_1^{+-}\rho_2^{+-}|\tau_{TT}\cos 2\tilde{\phi} + 2\rho_1^{++}\rho_2^{00}\sigma_{TL} + 2\rho_1^{00}\rho_2^{++}\sigma_{LT} + \rho_1^{00}\rho_2^{00}\sigma_{LL} - 8|\rho_1^{+0}\rho_2^{+0}|\tau_{TL}\cos\tilde{\phi}\right]\frac{d^3p_1' d^3p_1'}{E_1' E_2'}$$

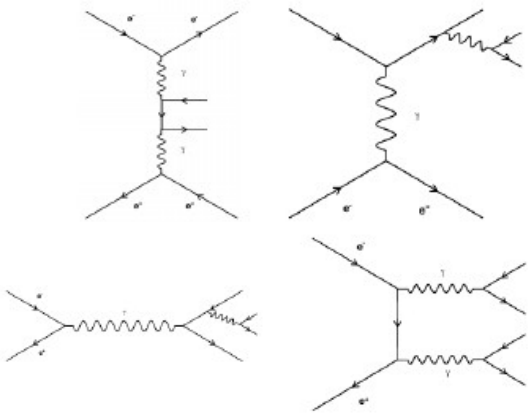
$p_i, p_i', q_i = (p_i - p_i')$	Momenta of incoming and outgoing leptons and photons
$\sigma_{TT}, \sigma_{TL}, \sigma_{LT}, \sigma_{LL}$	Two-photon cross sections for Transversely and Longitudinally polarized photons
τ_{TT}, τ_{TL}	Two-photon cross sections correlation terms
ρ_i^{ab}	Elements of photon density matrix for helicities a,b=+,-,0; functions of q_i
$\tilde{\phi}$	Angle between planes of incoming and outgoing leptons in two-photon c.m.s

TFF2: Multi-meson final states

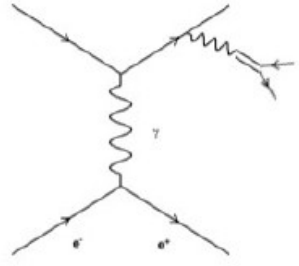
Yuping Guo
Kangshuai Zhu

Previously momentum dependent information on $\gamma^{(*)}\gamma^{(*)} \to \pi\pi$ scarce

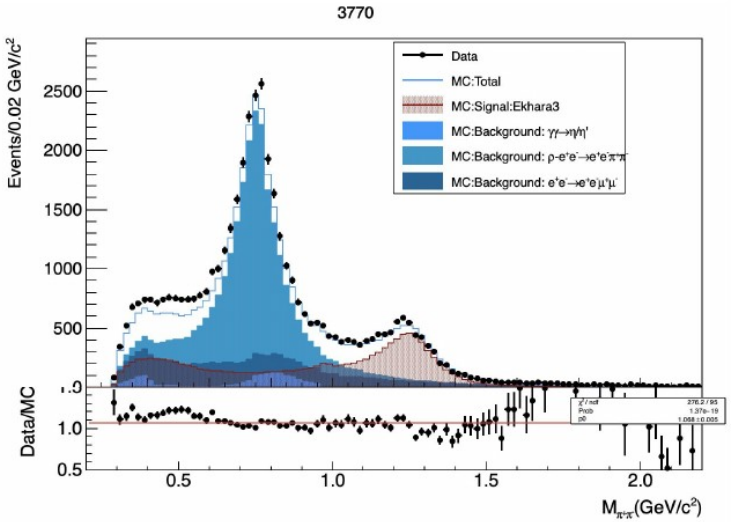
- Preliminary work: $\pi^+\pi^-$
  - Originally combined 7fb^{-1} of data, now moving to new 3.773 GeV data
  - Single-tag analysis
  - Background from pion and muon production



$e^+e^- \to e^+e^-\mu^+\mu^-$



$e^+e^- \to e^+e^-\rho$



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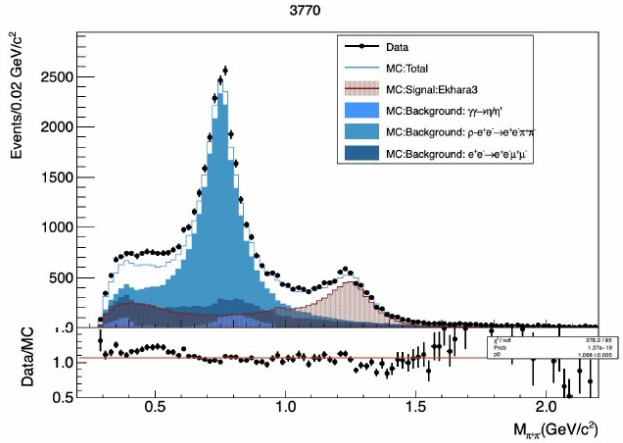

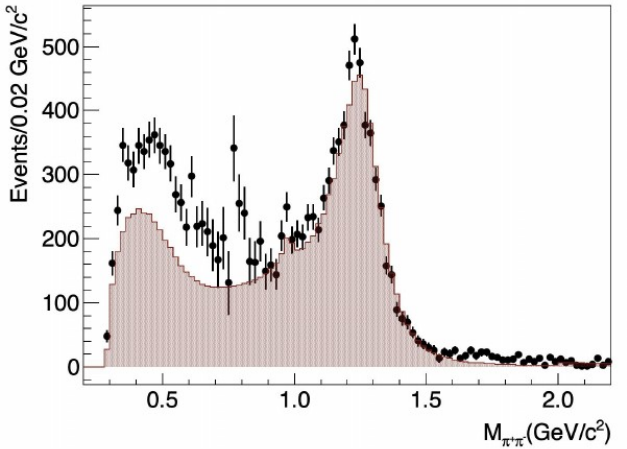

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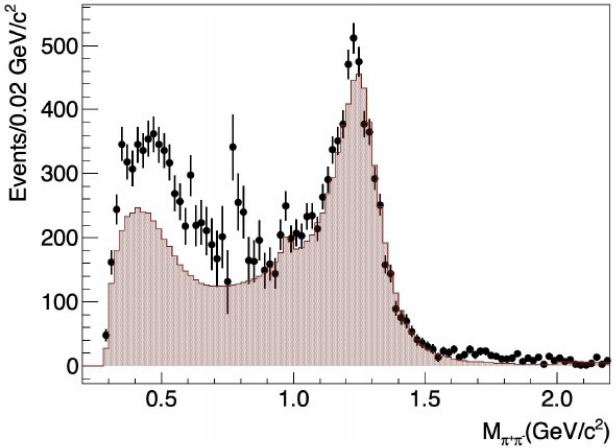
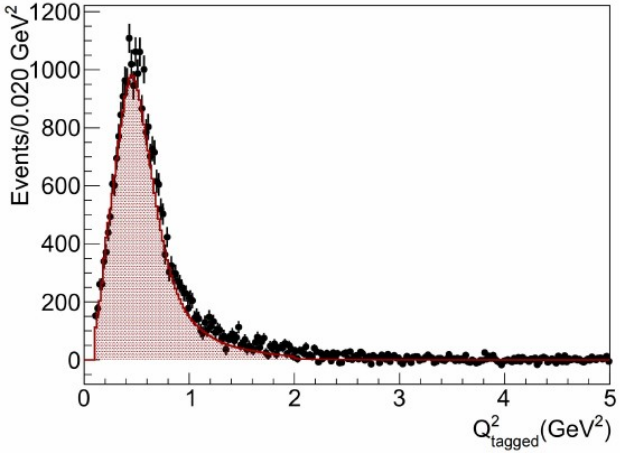


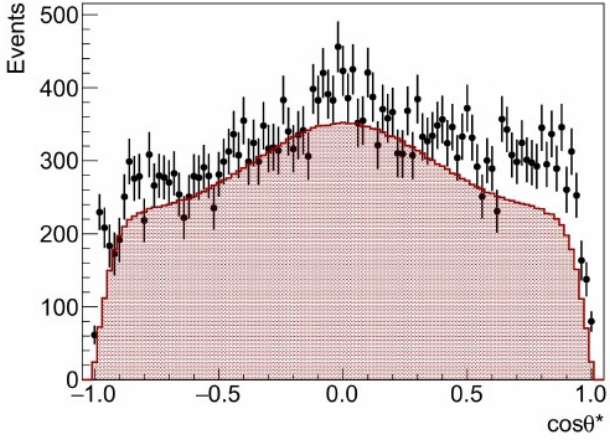
Final result covers:

$$m_{2\pi} \leq W[\mathrm{GeV}] \leq 2$$

$$0.2 \leq Q^2[\mathrm{GeV}^2] \leq 2$$

$$|\cos\theta^*| \leq 1$$





TFF2: Multi-meson final states

Max Lellmann

Analysis of neutral system: $\pi^0\pi^0$

- Using full new 20 fb^{-1} data set
- New approach for single-tag analysis: Kinematic fit with missing track
  - Better resolution of missing Q²
- Only conditions on χ^2_{KF} and Q^2_{miss}

$$m_{2\pi} \leq W[\mathrm{GeV}] \leq 2$$
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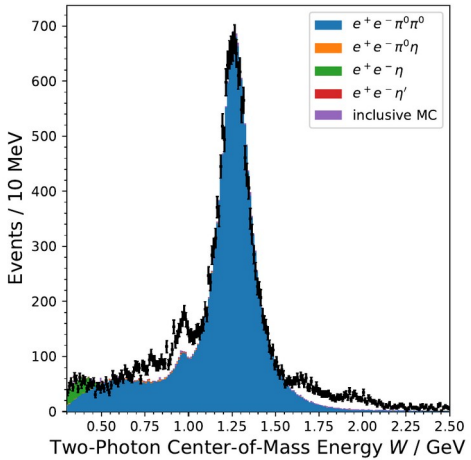
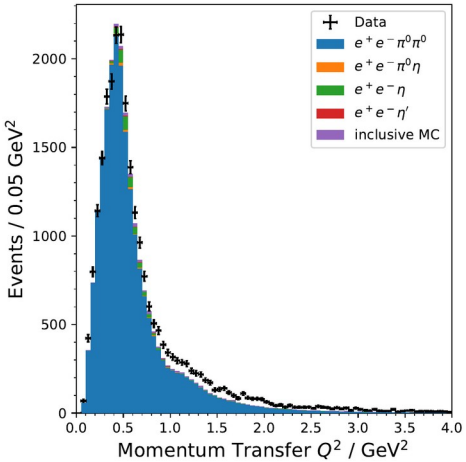
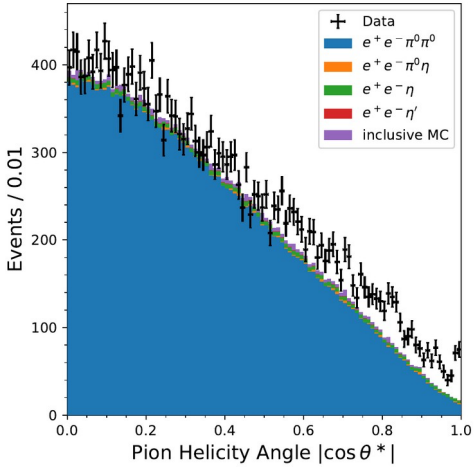
$f_0(980)$ not reproduced by dispersive result !







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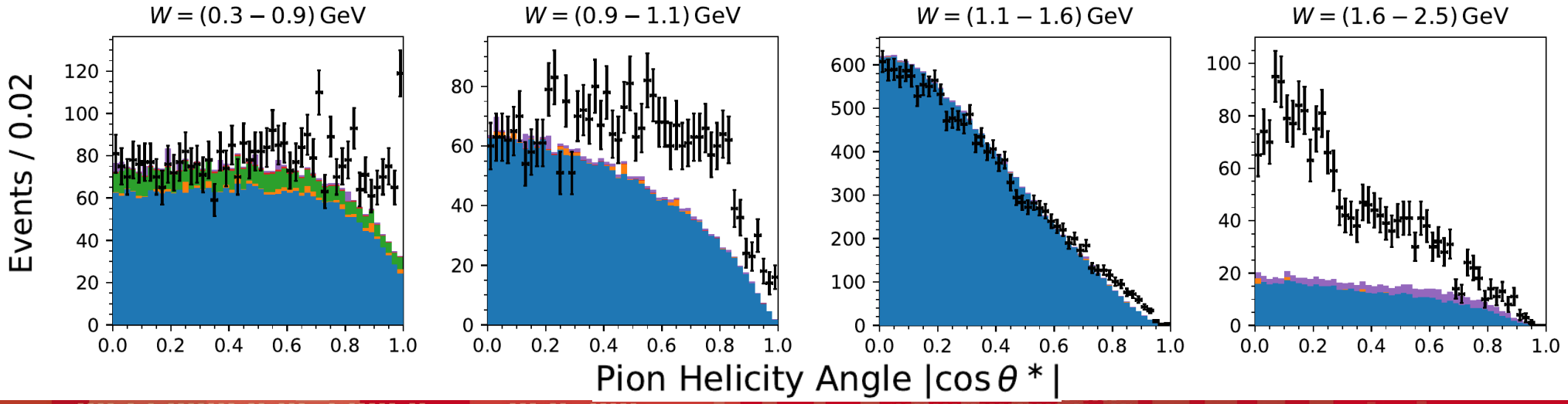

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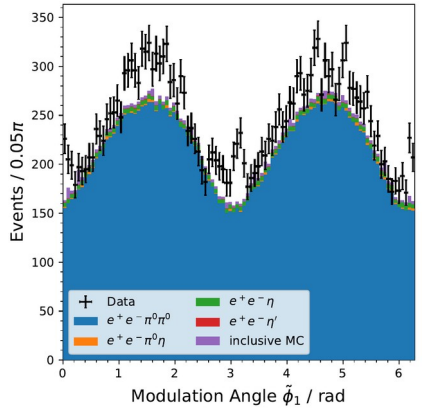
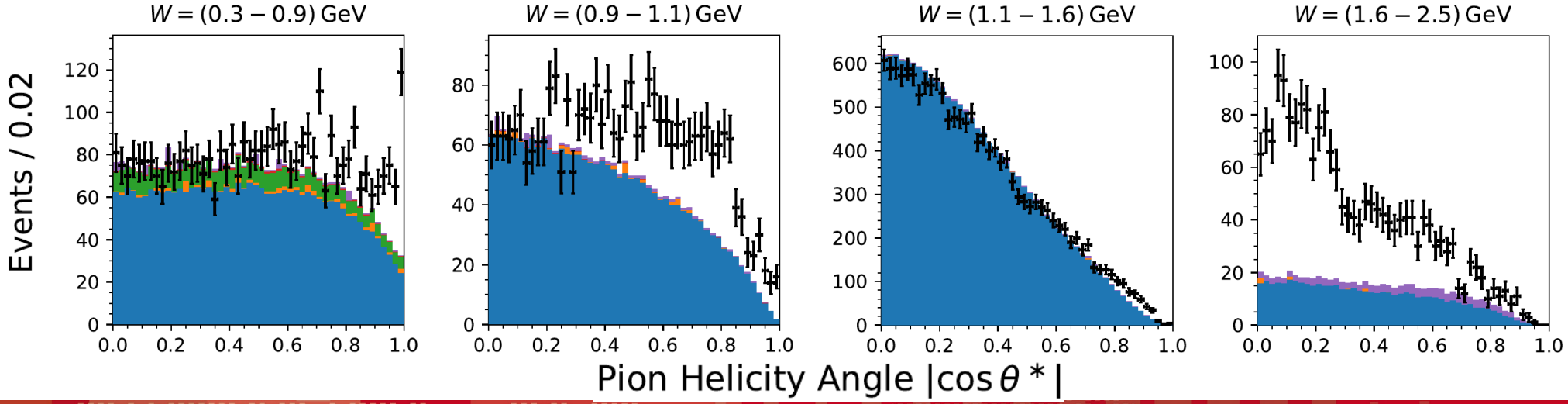


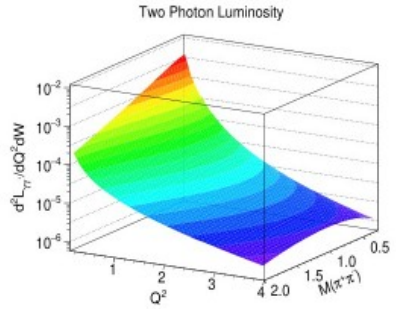


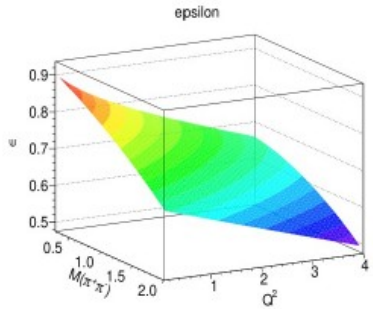
TFF2: Multi-meson final states

Luminosity function needed to determine relevant cross sections

$$d\sigma_{ee} = \frac{\alpha^2}{16\pi^4 q_1^2 q_2^2}\sqrt{\frac{(q_1\cdot q_2)^2 - q_1^2 q_2^2}{(p_1\cdot p_2)^2 - m_e^4}}\left[4\rho_1^{++}\rho_2^{++}\sigma_{TT} + 2\rho_1^{++}\rho_2^{00}\sigma_{TL} + 2\rho_1^{00}\rho_2^{++}\sigma_{LT}\right]\frac{d^3p_1' d^3p_1'}{E_1' E_2'}$$

$$\frac{d^2\sigma_{ee}}{dQ^2 dW} = \frac{d\mathcal{L}_{\gamma\gamma}}{dQ^2 dW}\left(\sigma_{TT}(Q^2, 0, W) + \varepsilon\sigma_{TL}(Q^2, 0, W)\right)$$





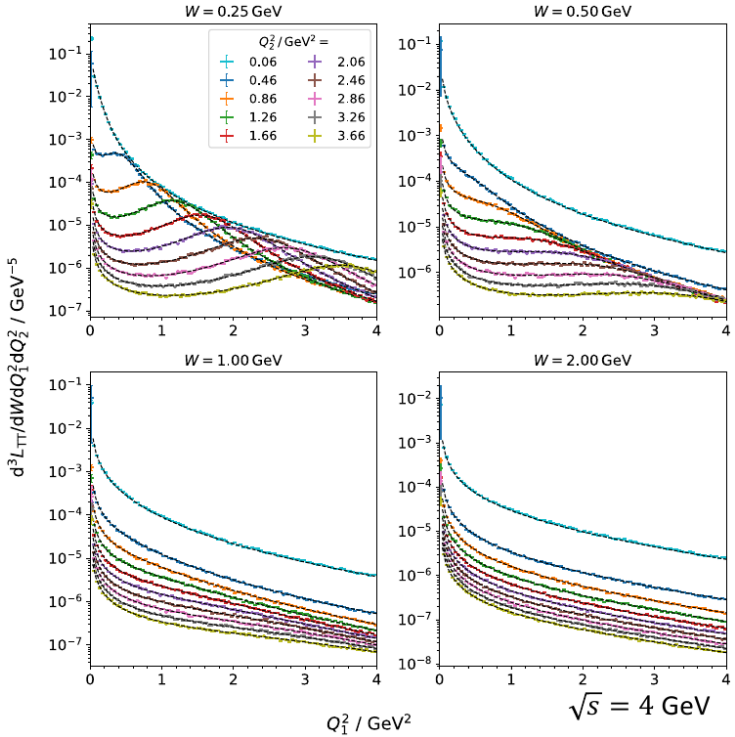
Using:
Phys. Rept. 15 (1975) 181
Nucl.Phys. B54 (1973) 573

- Analytic evaluation by Yuping
- Model dependent assumptions for finite 2nd virtuality necessary

TFF2: Multi-meson final states

Max preferred to do it numerically:

- Combine cross section equation with phase space generation algorithm by Schuler *et al.*



Agreement with analytic determination for all

- Energies
- Ranges of Q^2
- Hadronic masses

TFF2: Multi-meson final states

Extend it to be an event generator for Hadron production in Two-Photon Scattering

- Allow for any number of particles
- Assume flat phase space distribution
- Need input for two-photon cross sections

TFF2: Multi-meson final states

Extend it to be an event generator for Hadron production in Two-Photon Scattering

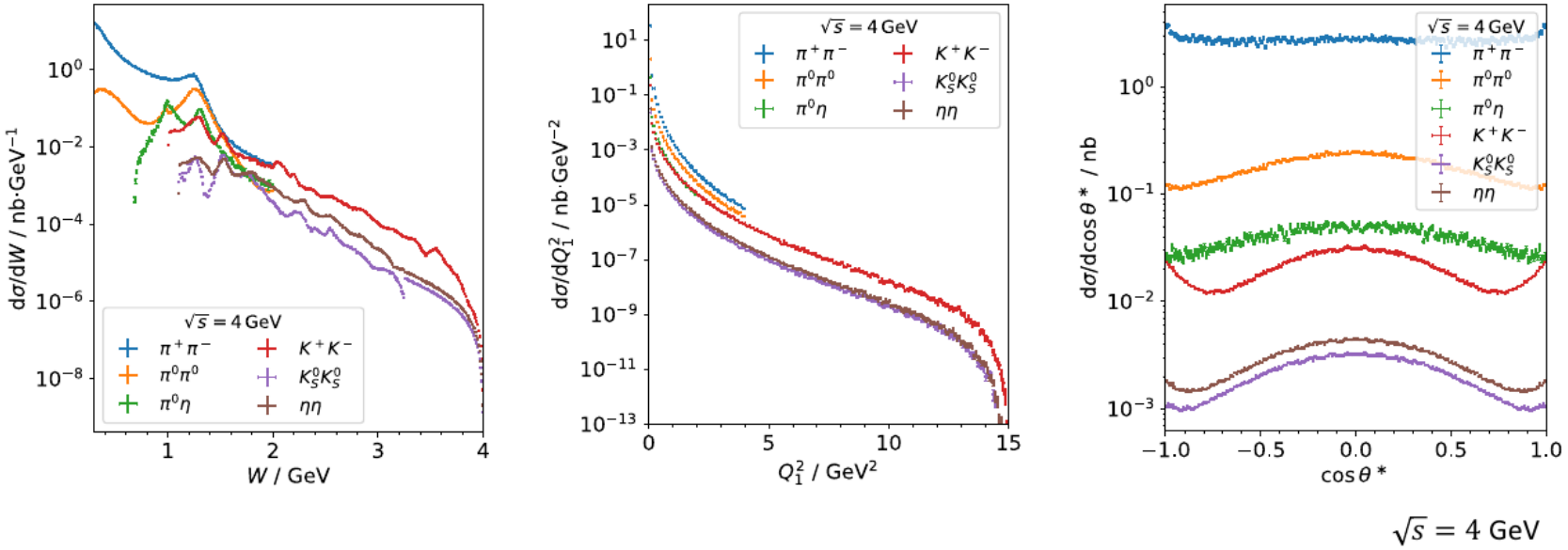
- Allow for any number of particles
- Assume flat phase space distribution
- Need input for two-photon cross sections
  - $\gamma\gamma \to \pi^+\pi^-/\pi^0\pi^0$ from dispersive analysis (Danilkin, Vanderhaeghen)
  - $\gamma\gamma \to \pi^0\eta$ from dispersive analysis (Danilkin, Deneika, Vanderhaeghen)
  - $\gamma\gamma \to \pi^+\pi^-\eta$ from phenomenology (Ren, Danilkin, Vanderhaeghen)
  - Experimental results from Belle and BESIII on $K\bar{K}, \eta\eta$

Additional degree of freedom for two-body final states

- Formalism previously established for $e^+e^- \to e^+e^-X$
- Extended in collaboration with Marc Vanderhaeghen

TFF2: Multi-meson final states

New event generator: **HadroTOPS**

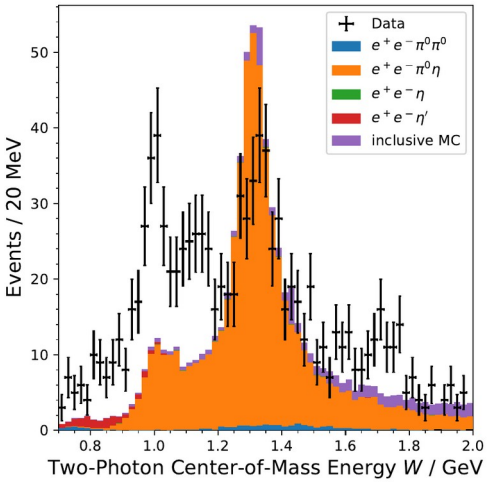


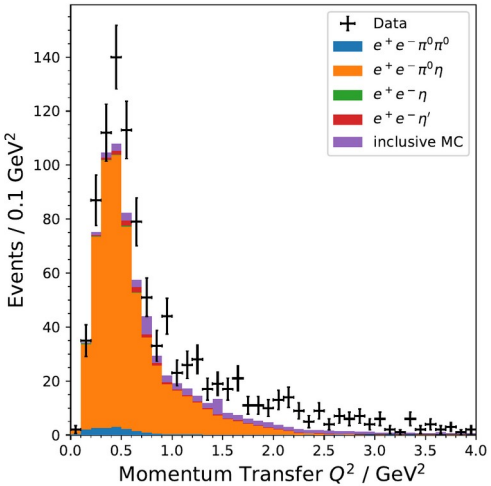
- Essential, since development of established generator (Ekhara) came to an end
- Publication in preparation

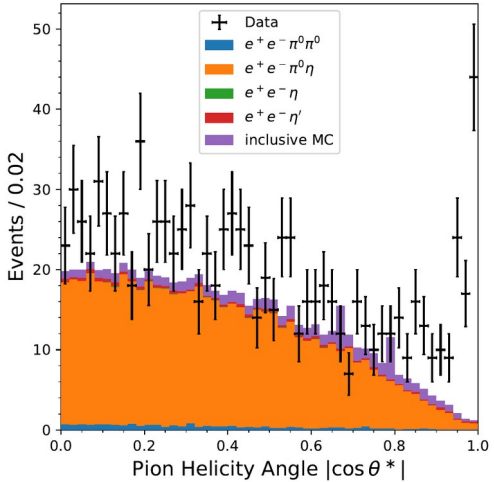
TFF2: Multi-meson final states

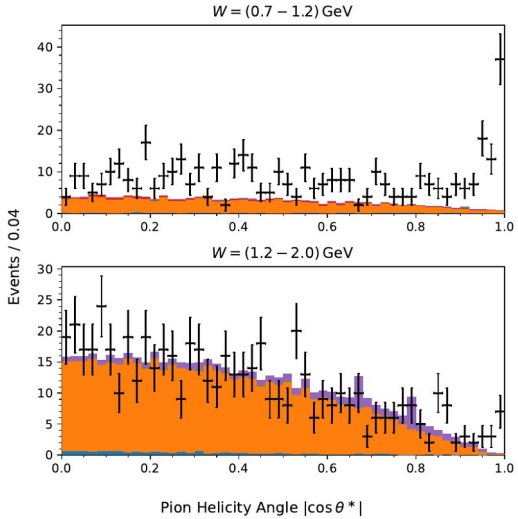
Analysis of $\gamma\gamma^* \to \pi^0\eta$

- Analogous procedure to $\pi^0\pi^0$ analysis









$a_0(980)$ not reproduced by dispersive result !

Results will cover

$$\begin{cases} m_{2\pi} \leq W[\mathrm{GeV}] \leq 2 \\ 0.2 \leq Q^2[\mathrm{GeV}^2] \leq 2 \\ |\cos\theta^*| \leq 1 \end{cases}$$

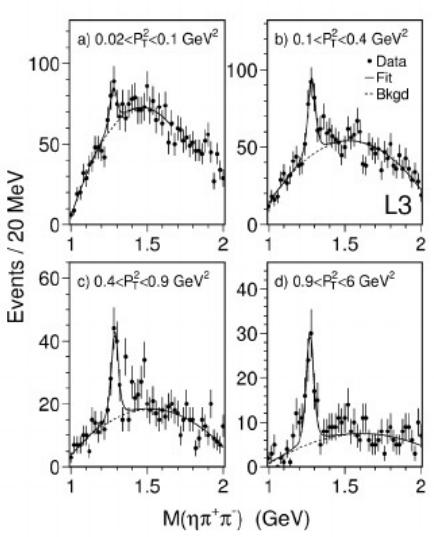
TFF2: Multi-meson final states

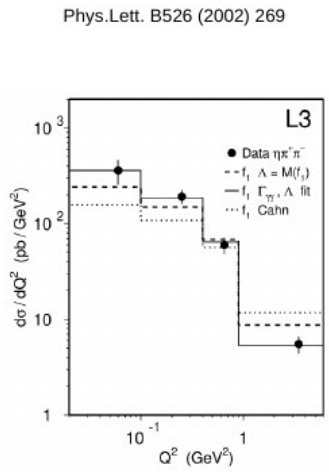
$$\gamma\gamma^* \to f_1(1285) \to \pi^+\pi^-\eta$$

- Axial-vector mesons can be produced due to virtuality of tagged lepton
  - Otherwise forbidden due to Landau-Yang theorem
- Only experimental information on Q^2 dependence of TFF from L3
  - Q^2 dependence inferred from MC
  - Effective TFF model fitted to data
  - Data published as lepton-based cross section at 91 GeV

At BESIII

- Accessible in single-tagged analysis
  - Confirmed by absence of signal in untagged measurement





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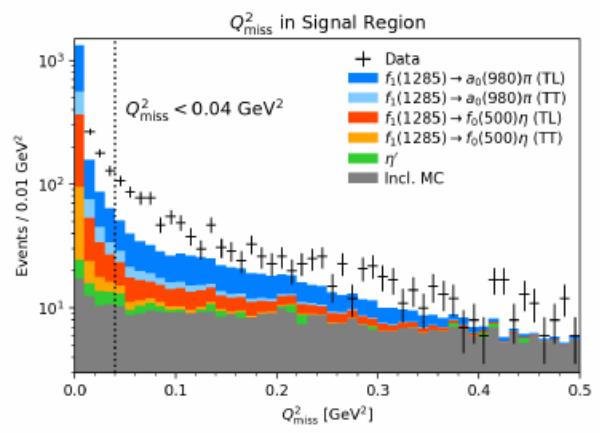
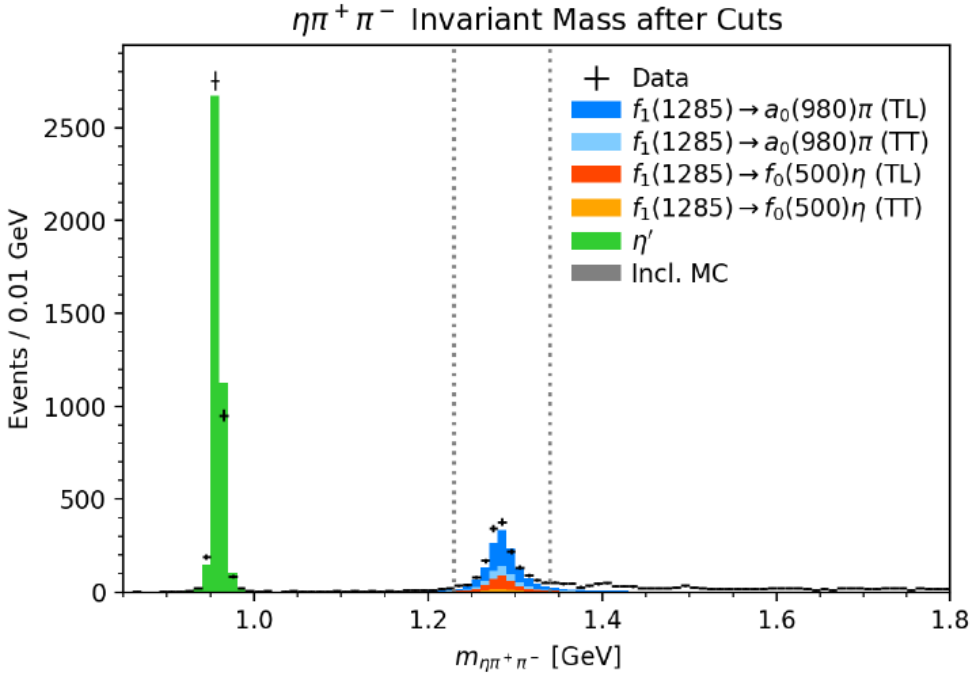
$$\gamma\gamma^* \to f_1(1285) \to \pi^+\pi^-\eta$$

- Single-tag analysis of full 20 fb^{-1} data set
  - 2C kinematic fit (missing electron & fixed eta mass)
  - Conditions on missing Q² and sideband in χ^2_{2C}
- Previously event generator from BaBar used





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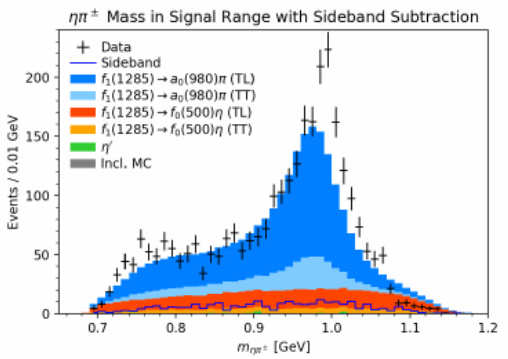

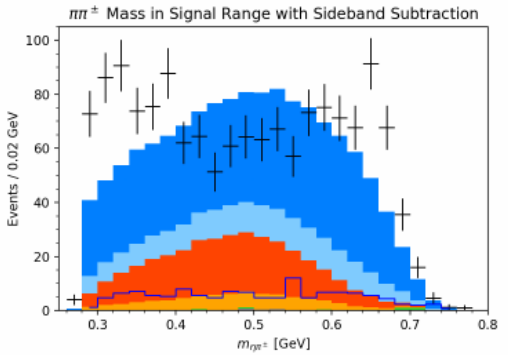

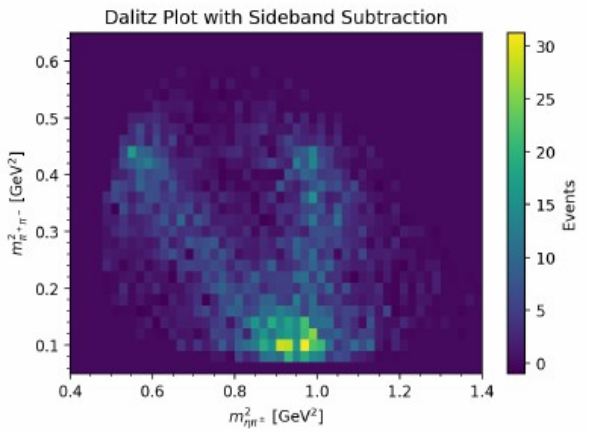

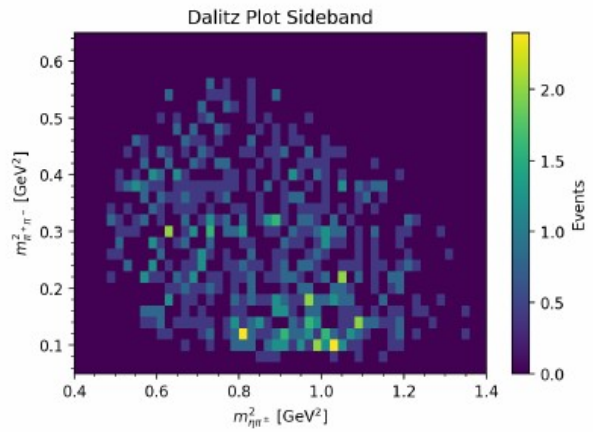

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- Previously event generator from BaBar used
  - Not able to describe intermediate masses
- Perform PWA
  - Use amplitude developed in work of Ren, Danilkin, Vanderhaeghen
  - Use HadroTOPS for two-photon phase space description
  - Use AmpTools to fit experimental distributions (masses and widths of f_1 & a_1, and TFFs as free parameters)

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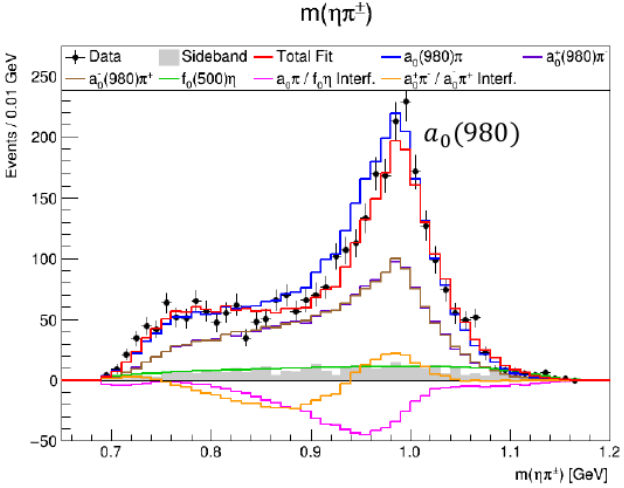

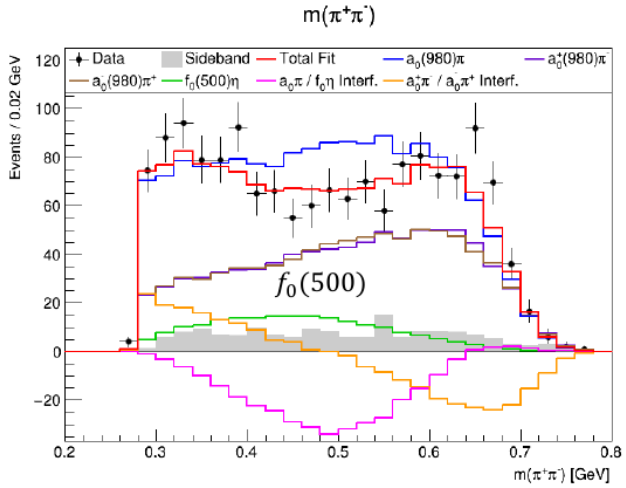

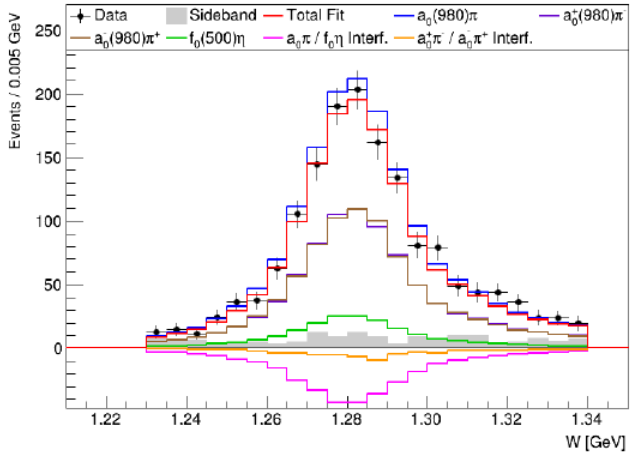

TFF2: Multi-meson final states

$\gamma\gamma^* \to f_1(1285) \to \pi^+\pi^-\eta$

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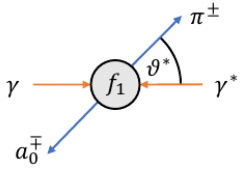

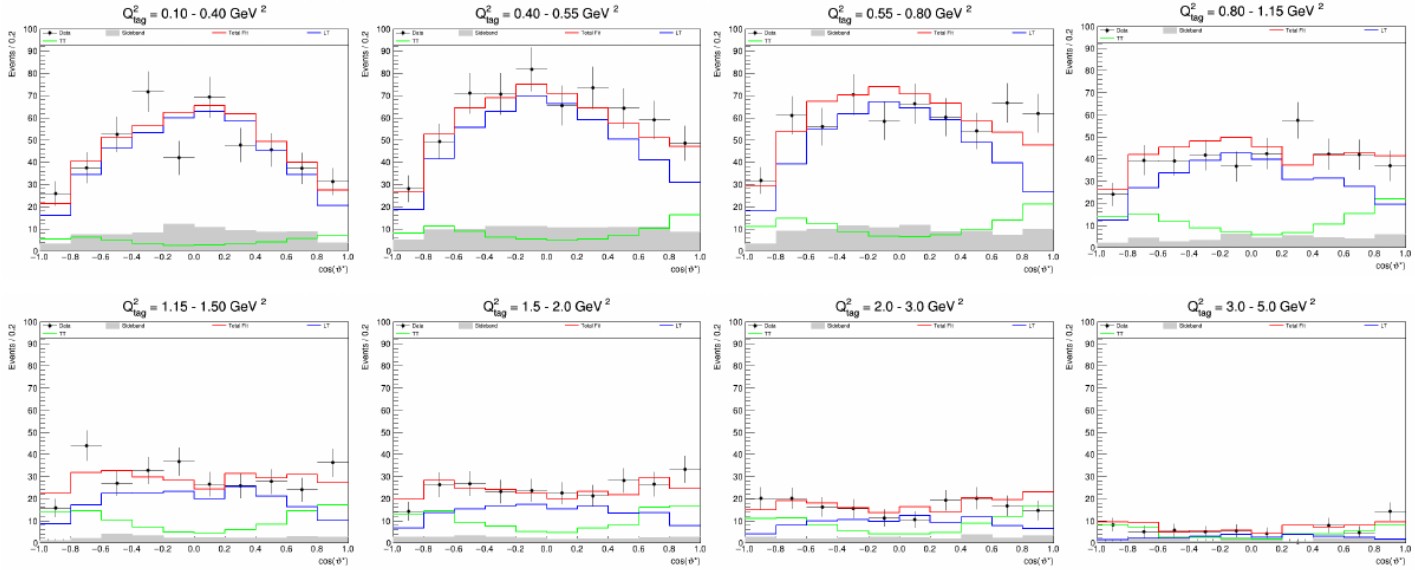

Summary

TFF-1

- New π^0 TFF analysis from Dalitz decays at A2/MAMI, world leading statistics
- Space-like π^0 TFF at reduced Q^2
- Exploratory double-tagged TFF measurements of η, η'

TFF-2:

- Single-tag measurements $\pi\pi, \pi^0\eta$ close to finalization
- New event generator developed
- Single-tag measurement with PWA of $f_1(1285)$ decay to determine axial-vector meson TFFs