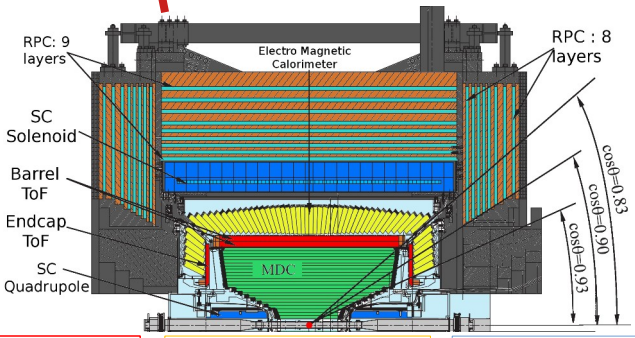
Experimental input from BESIII for the HLbL contribution

8th Plenary Workshop of the Muon g-2 Theory Initiative

2025-09-11 | Christoph Florian Redmer

SFB 1044 THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL
Cluster of Excellence PRISMA+
DFG Deutsche Forschungsgemeinschaft
FOR5327
Project TFF
Project XYZ
Project JRP
Project LBL
Project ALP
Photon-photon interactions in the Standard Model and beyond
JOHANNES GUTENBERG UNIVERSITÄT MAINZ
JG|U

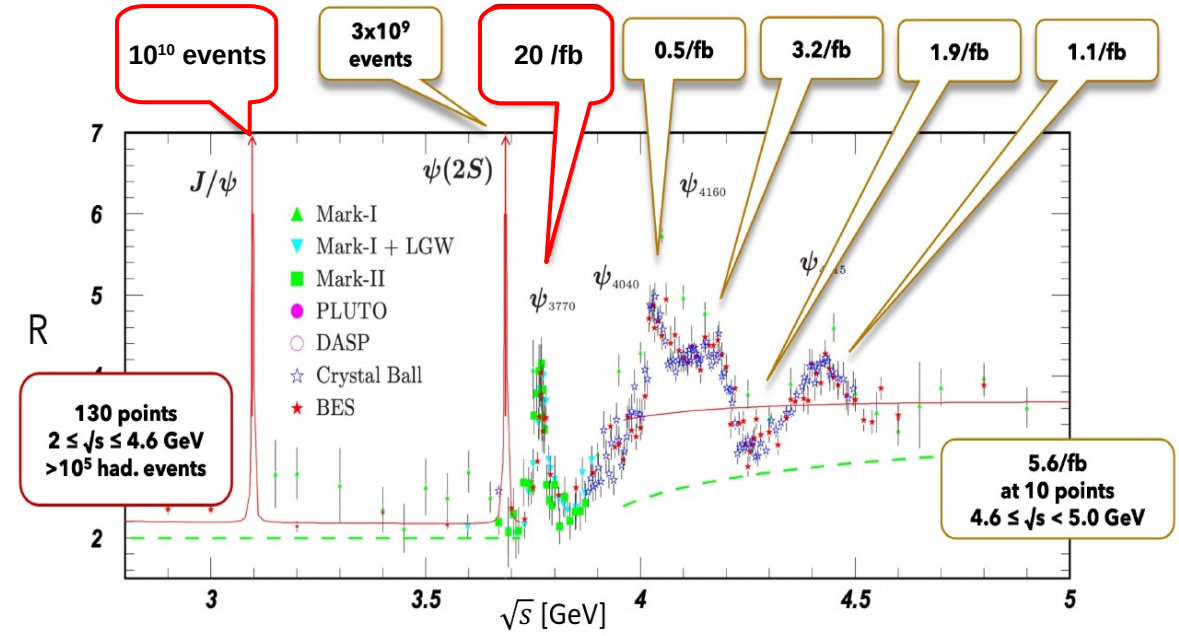
BESIII at BEPCII



Time of Flight | EM Calorimeter | Muon Counter

Drift Chamber | Solenoid

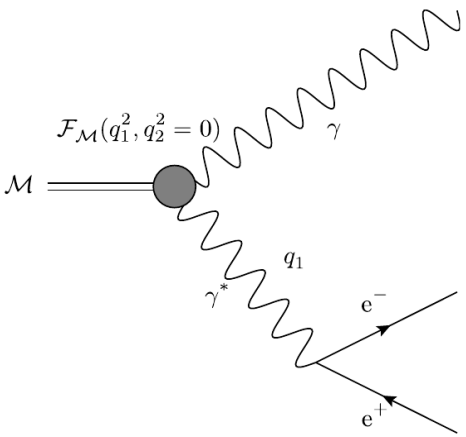
- Center-of-mass energies from 2 – 5 GeV
- Design luminosity exceeded: $1.1\times10^{33}\,cm^{-2}s^{-1}$ at 3.77 GeV



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

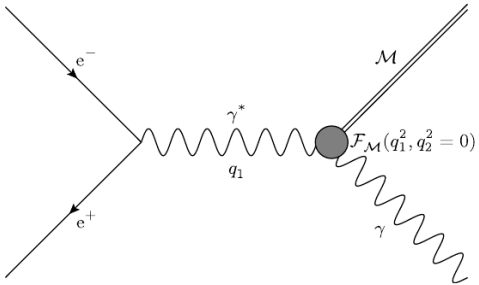
Experimental Access to TFFs

Meson Dalitz Decays



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

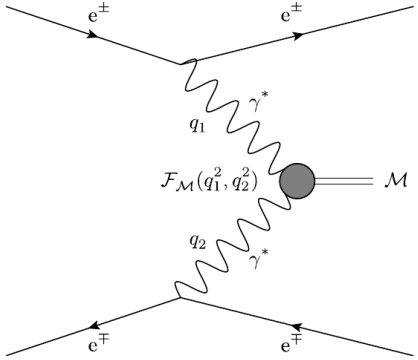
Radiative Meson Production



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

time-like

Two-photon collisions



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

space-like

“Wish Lists” from WPs 20 & 25

Table 14
Priorities for new experimental input and cross-checks.

issue	experimental input [I] or cross-checks [C]
axials, tensors, higher pseudoscalars missing states	$\gamma^{(*)}\gamma^* \to 3\pi,\ 4\pi,\ K\bar{K}\pi,\ \eta\pi\pi,\ \eta'\pi\pi$ [I] inclusive $\gamma^{(*)}\gamma^* \to$ hadrons at 1–3 GeV [I]
dispersive analysis of $\eta^{(\prime)}$ TFFs	$e^+e^- \to \eta\pi^+\pi^-$ [I] $\eta' \to \pi^+\pi^-\pi^+\pi^-$ [I] $\eta' \to \pi^+\pi^-e^+e^-$ [I] $\gamma\pi^- \to \pi^-\eta$ [C]
dispersive analysis of π^0 TFF	$\gamma\pi \to \pi\pi$ [I] high accuracy Dalitz plot $\omega \to \pi^+\pi^-\pi^0$ [C] $e^+e^- \to \pi^+\pi^-\pi^0$ [C] $\omega, \phi \to \pi^0 l^+ l^-$ [C]
pseudoscalar TFF pion, kaon, $\pi\eta$ loops (including scalars and tensors)	$\gamma^{(*)}\gamma^* \to \pi^0, \eta, \eta'$ at arbitrary virtualities [I,C] $\gamma^{(*)}\gamma^* \to \pi\pi,\ K\bar{K},\ \pi\eta$ at arbitrary virtualities, partial waves [I,C]

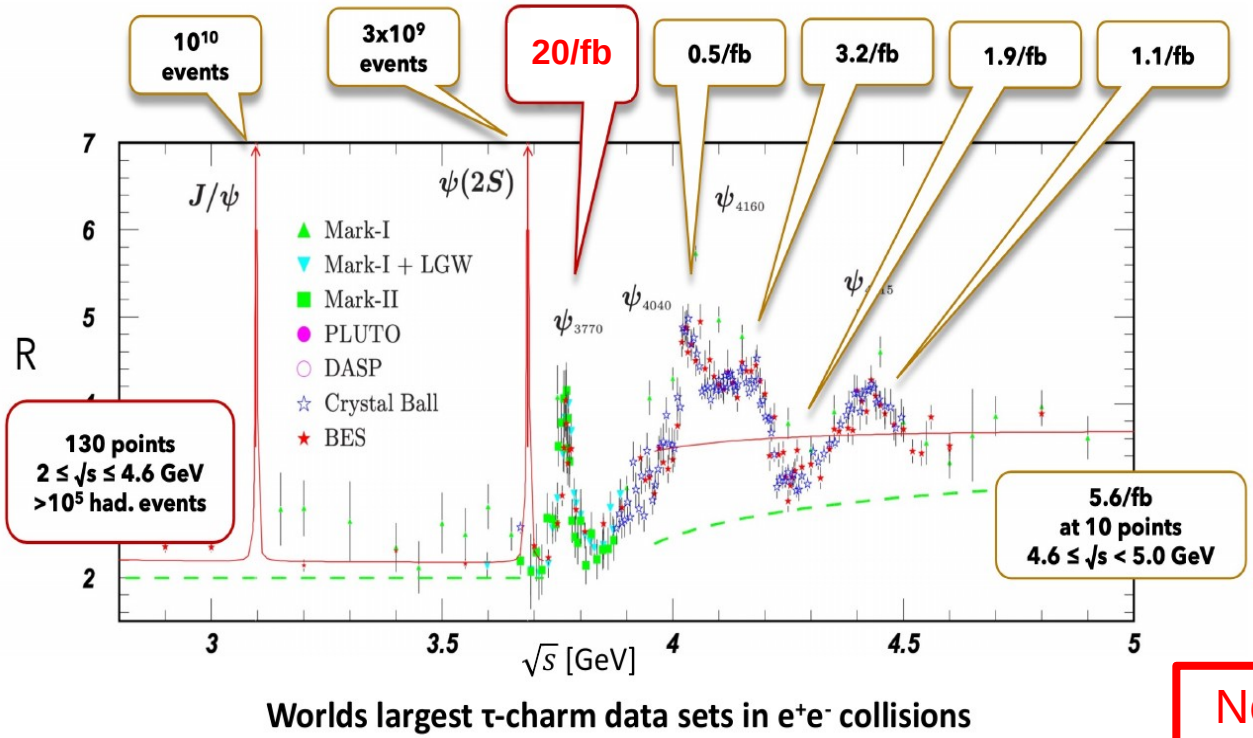
Phys.Rept. 887 (2020) 1 – 166

	Experimental input
Axial-vector TFFs	$e^+e^- \to e^+e^-A,\ A = f_1, f_1', a_1$ Radiative decays $A \to V\gamma,\ V = \rho, \omega, \phi$ Dilepton decays $A \to e^+e^-$
Scalar and tensor TFFs	$\gamma^*\gamma^{(*)} \to \pi\pi, \pi\eta, \bar{K}K, \pi\pi\pi$
Pseudoscalar TFFs	$\gamma\gamma \to \eta, \eta'$ $e^+e^- \to e^+e^-(\gamma^*\gamma^{(*)} \to \pi^0, \eta, \eta')$ $e^+e^- \to e^+e^-(\gamma\gamma \to P),\ P = \pi(1300), \eta(1295), \eta(1405)$

Table 30: Examples of useful experimental inputs related to the exclusive hadronic channels.

arXiv:2505.21476

$\gamma^{(*)}\gamma^*$ results to be expected from 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 3.77 GeV most relevant!

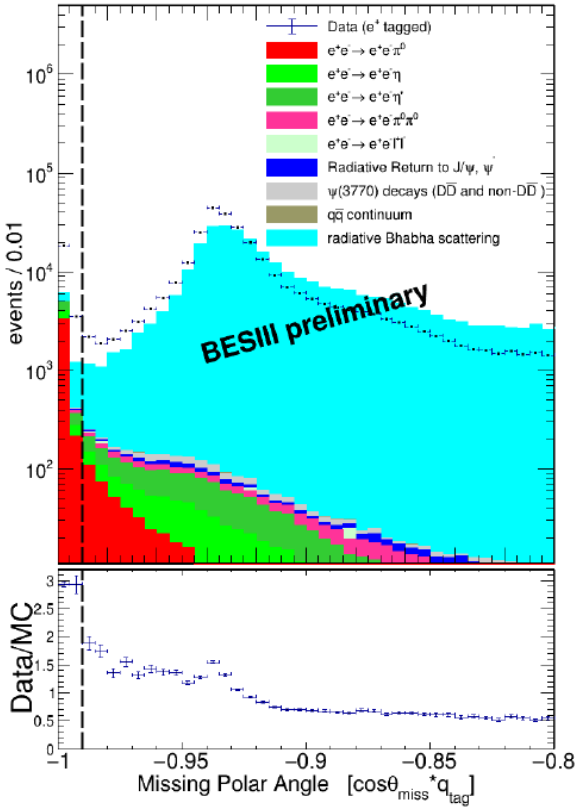
Data taking finished June 2024

$\gamma^{(*)}\gamma^* \to \pi^0, \eta, \eta'$

Two-photon collision events:

- Single-tag measurements
  - Require one quasi-real photon
- Select
  - One scattered lepton & meson decay products
  - Require small scattering angle of missing momentum

2.9 fb^{-1}, 3.773 GeV



$\gamma\gamma^* \to \pi^0$

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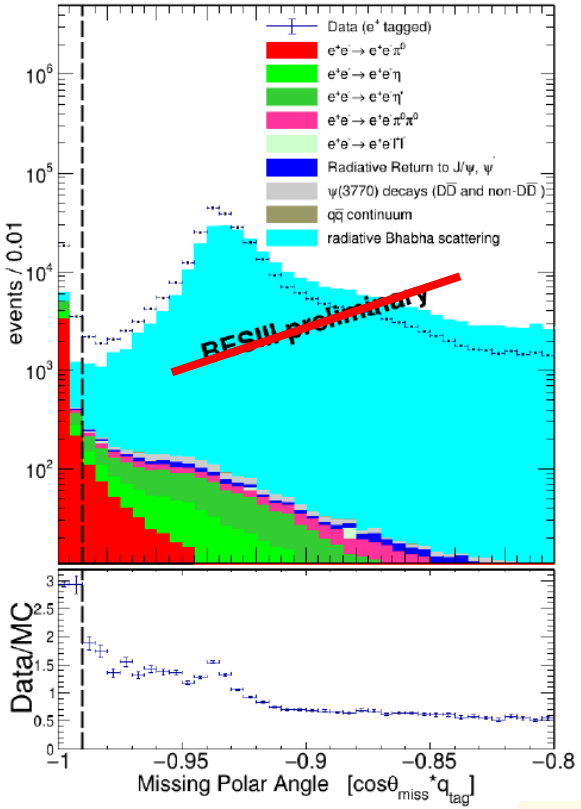

arXiv:2509.07685

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Two-photon collision events:

2.9 fb^{-1}, 3.773 GeV

- Single-tag measurements
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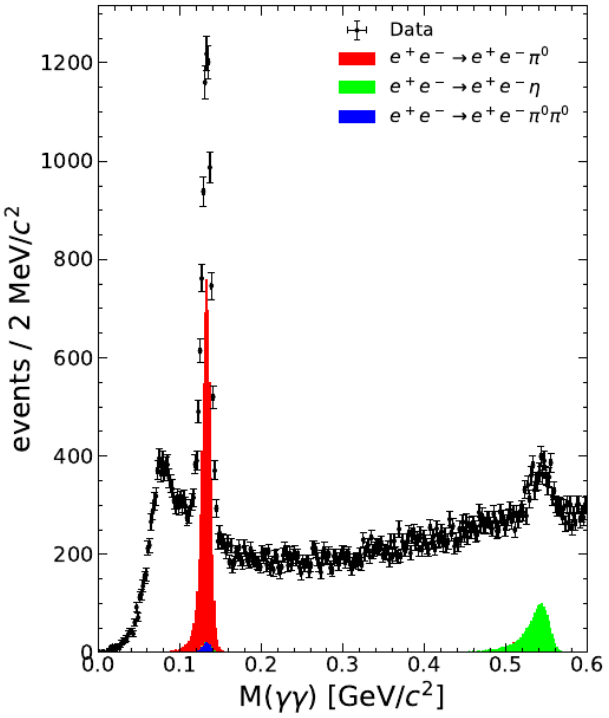
  - Require small scattering angle of missing momentum
- Reduce background by adequate conditions



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- Single-tag measurements
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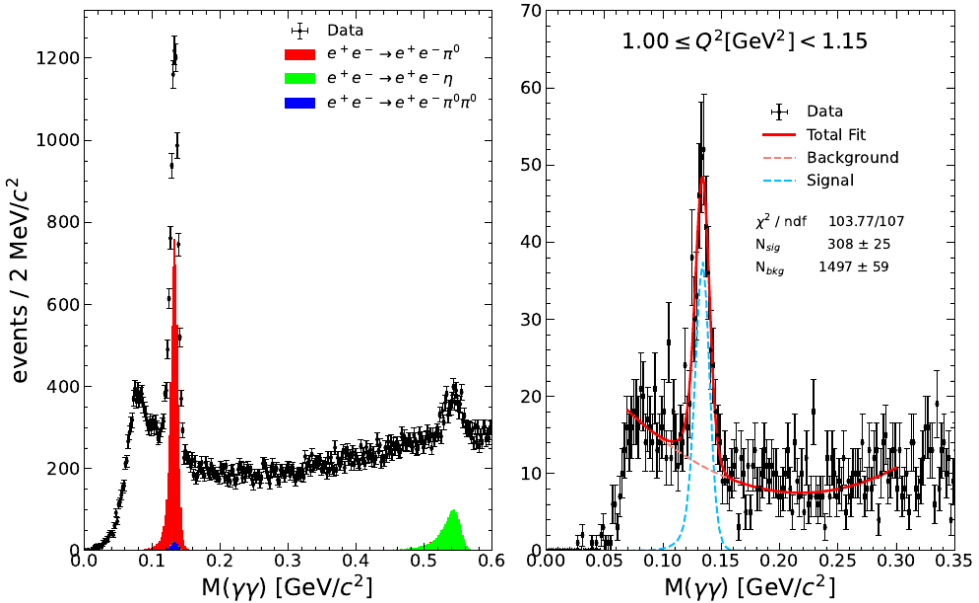

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$$|\mathcal{F}(Q^2)|^2 = \frac{N_{\text{sig}}}{\Delta Q^2\, \mathcal{L}\, \varepsilon\, (1+\delta)\, \mathcal{B}_{\gamma\gamma}} \left(\frac{\mathrm{d}\sigma_{\text{WZW}}}{\mathrm{d}Q^2} \right)^{-1}$$

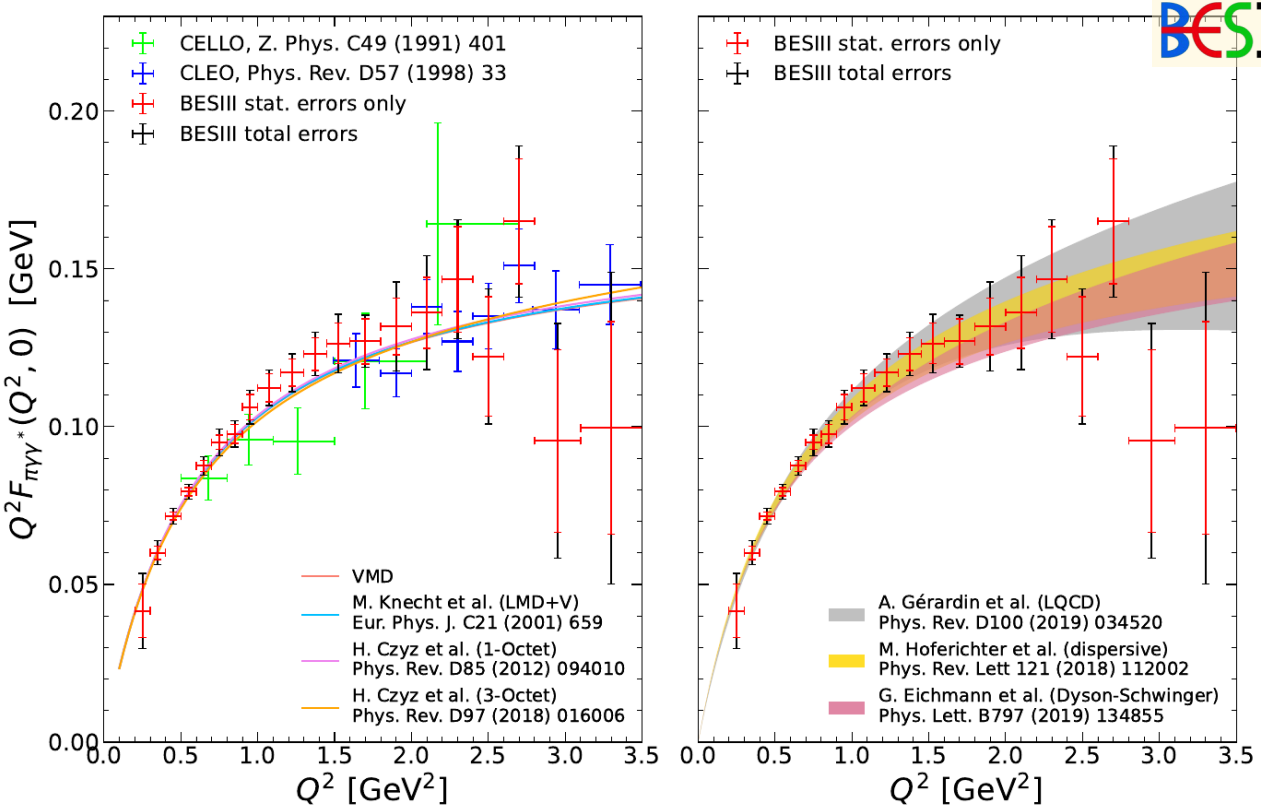
- Divide by point-like cross section
- Correct for radiative effects
- Correct for impact of finite 2nd virtuality

- Radiative effects at full NLO in Ekhara3.0
- NNLO calculations missing!
- Rule of thumb estimate suggested by Henryk:
  - 10% of reconstructed LO-NLO difference
- 1% uncertainty

- Comparison with TFF models for $|\mathcal{F}(Q^2, 0)|$
- Consistent deviation of 2% found

arXiv:2509.07685

$\gamma\gamma^* \to \pi^0$



2.9 fb^{-1}, 3.773 GeV

- Largest systematics at $Q^2 < 0.3; > 2.7\mathrm{GeV}^2$
- Statistically limited
- Agreement with previous measurements
- Significant improvement below 1.5 GeV²

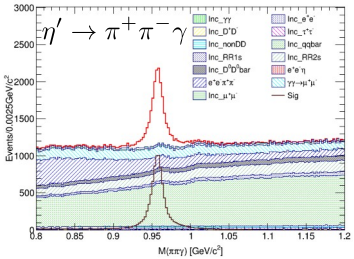
- models deviate around 1.2 GeV² by 1σ
- Good agreement with
  - Lattice QCD
  - Dispersive construction
  - Dyson-Schwinger

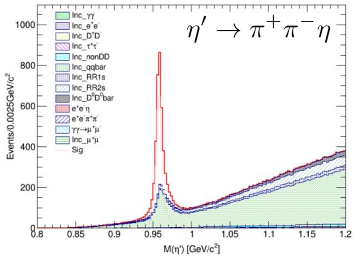
- To be repeated on full 20 fb^{-1} data set

arXiv:2509.07685

$\gamma\gamma^* \to \eta, \eta'$

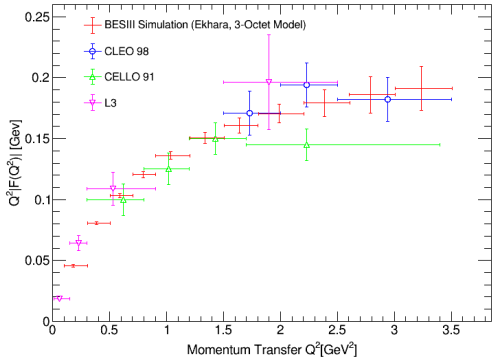
- Full 20 fb^{-1} data
- Single-tag analysis using kinematic fit
- Using two decay modes





Simulations using full 20 fb^{-1}

- Radiative corrections with Ekhara3.0
  - Rule-of-thumb estimate does not seem to work!
  - NNLO corrections needed!



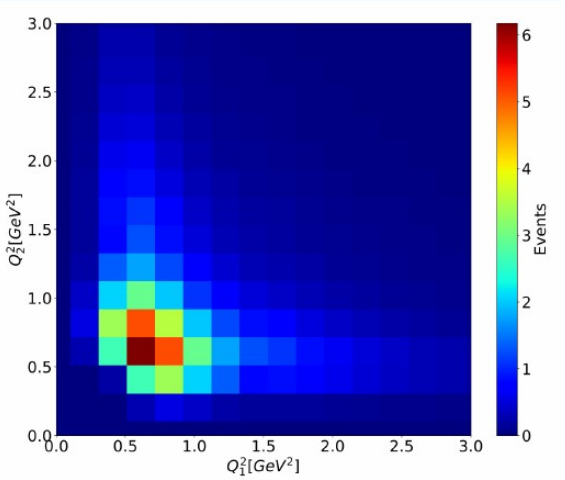
- First direct measurement at Q^2<0.3 GeV^2
- Significant improvement compared to existing data expected

$\gamma^*\gamma^* \to \pi^0, \eta, \eta'$

- Full 20 fb^{-1} data
- Begin with $\gamma^*\gamma^* \to \eta, \eta'$
  - Favorable background situation
- Feasibility studies performed
- Results at $Q_1^2 \approx Q_2^2 \approx 1\,\mathrm{GeV}^2$ expected
- s-channel process needs to be understood

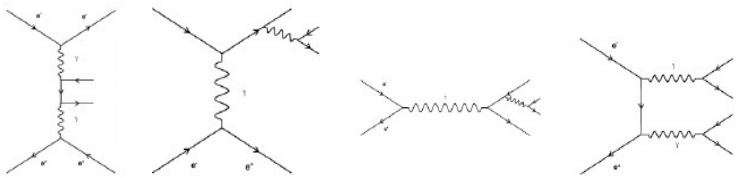
- Data analysis ongoing for $\gamma^*\gamma^* \to \eta, \eta'$
- Follow-up: $\gamma^*\gamma^* \to \pi^0$

Simulation of expected yields
for 13 fb^{-1} of data at $\sqrt{s} \geq 3.773\,\mathrm{GeV}$

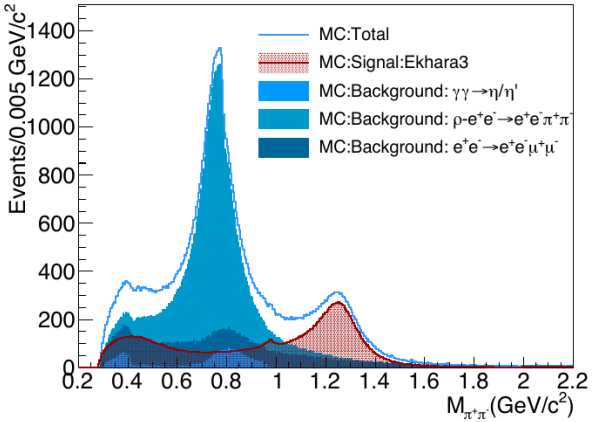


$\gamma\gamma^* \to \pi^+\pi^-$

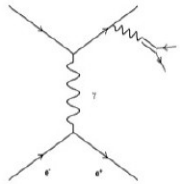
- Classic single-tag event selection
- Background
  - Muon production



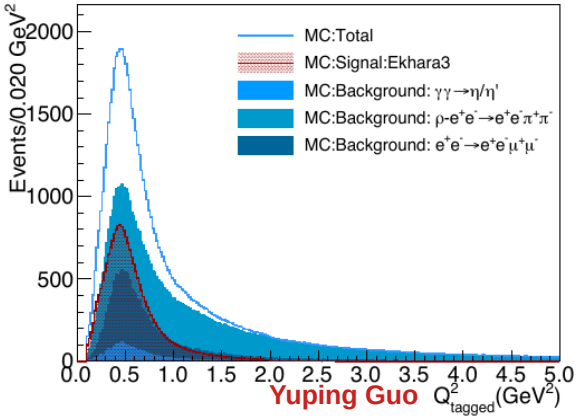
$e^+e^- \to e^+e^-\mu^+\mu^-$



  - Time-like pion production



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

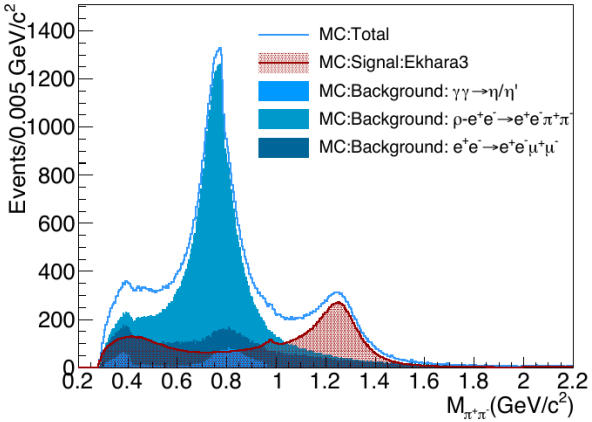


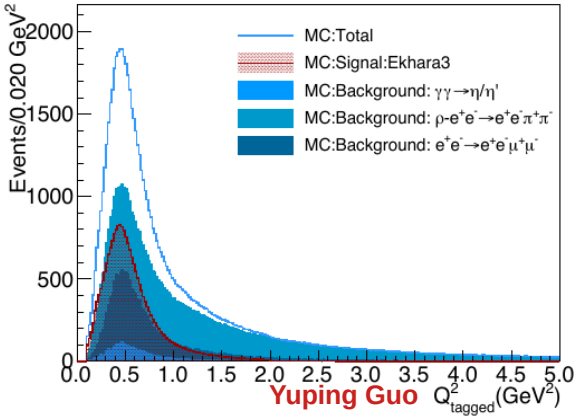
$\gamma\gamma^* \to \pi^+\pi^-$

- Classic single-tag event selection
- Background
  - Muon production → machine learning for separation
  - Time-like pion production → precise/tuned event generators to subtract distributions

- Invariant masses from threshold to 2 GeV
- $0.2 \leq Q^2[\mathrm{GeV}^2] \leq 3$
- Full coverage of helicity angle

- Analysis transferred to new 20fb^{-1} data set
  - Reduced systematic effects
  - New training of PID time consuming

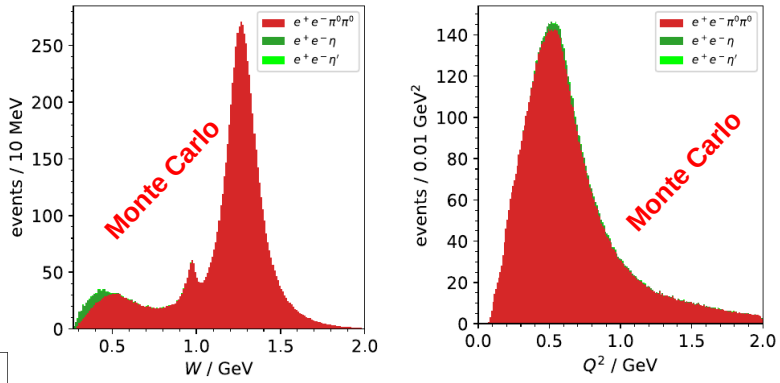


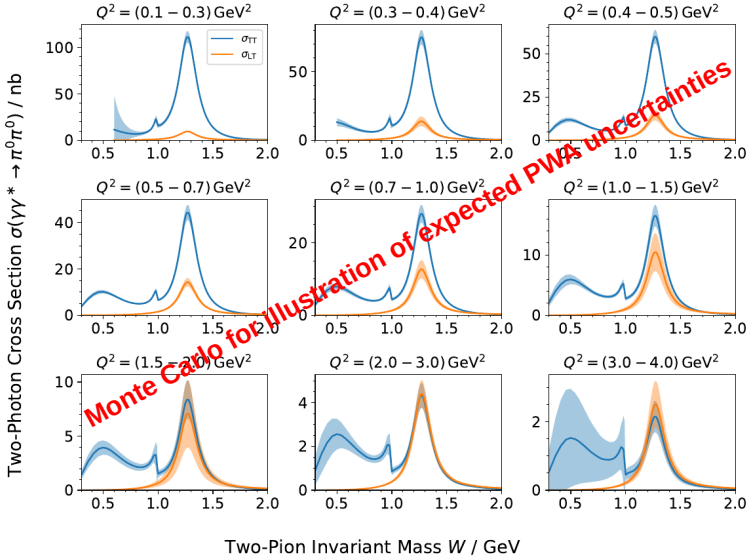


$\gamma\gamma^* \to \pi^0\pi^0$

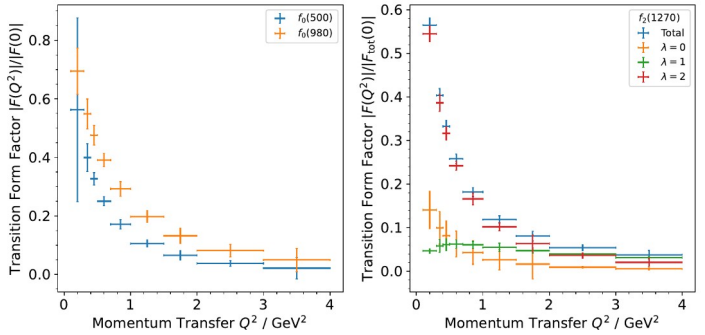
- Full new 20 fb^{-1} data
- New strategy: Kinematic fit with missing track
  - improved resolution of 2nd virtuality

- Similar parameter ranges as for $\gamma\gamma^* \to \pi^+\pi^-$
  - $0.3 \leq W[\mathrm{GeV}] \leq 2$
  - $0.1 \leq Q^2[\mathrm{GeV}^2] \leq 4$
  - $|\cos\theta^*| \leq 1$





ρ-pole TFF model for illustration of expected uncertainties



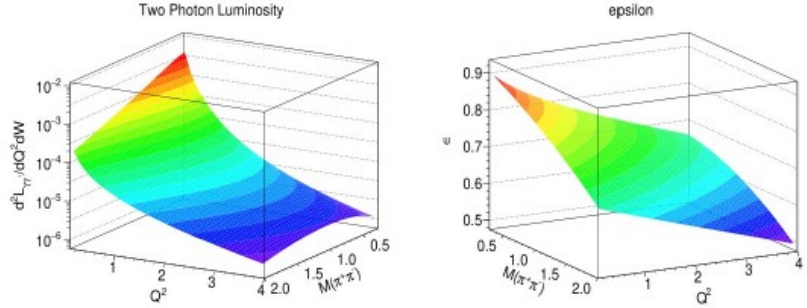
Two-photon cross section

Luminosity function needed to determine relevant cross sections

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

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

Analytic evaluation:



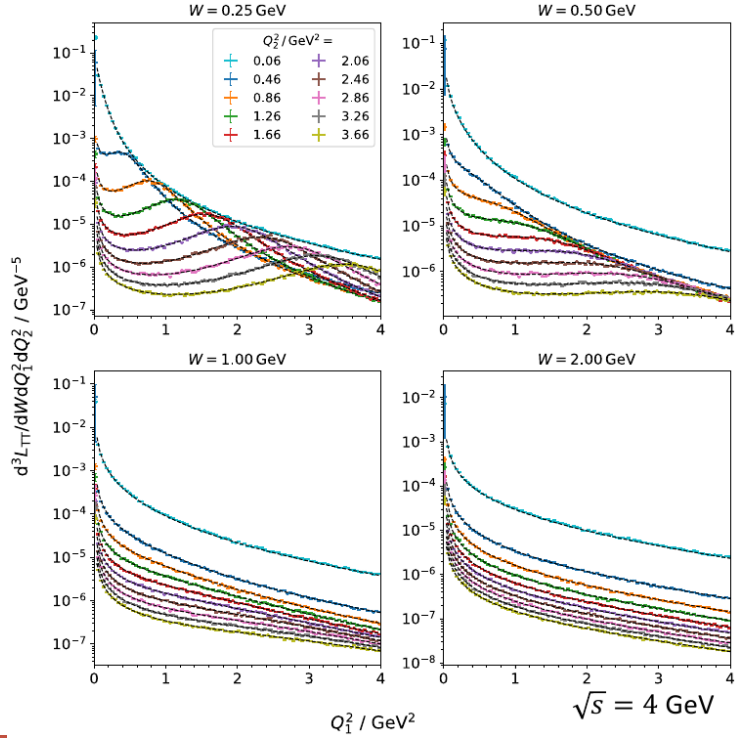
Using:
Phys. Rept. 15 (1975) 181
Nucl.Phys. B54 (1973) 573

Model dependent assumptions for finite 2nd virtuality necessary

Two-photon cross section

Numerical approach:

- 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

Two-photon cross section

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

Two-photon cross section

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

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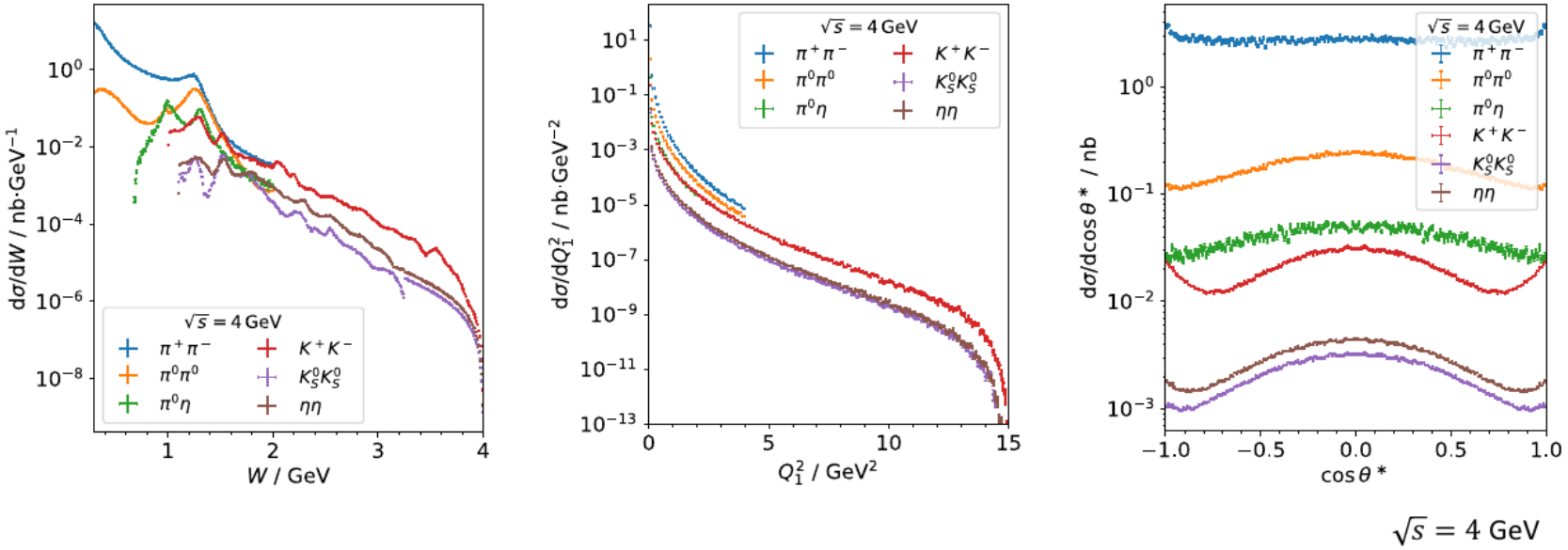
- Need input for two-photon cross sections
  - $\gamma\gamma \to \pi^+\pi^-/\pi^0\pi^0$ from dispersive analysis (Danilkin *et al*., Phys.Rev.D 101 (2020) 054008)
  - $\gamma\gamma \to \pi^0\eta$ from dispersive analysis (Deneika *et al*., Phys.Rev.D 111 (2025) 034009)
  - $\gamma\gamma \to \pi^+\pi^-\eta$ from phenomenology (Ren *et al*., Phys. Rev. D 110 (2024) 094043)
  - 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

Two-photon cross section

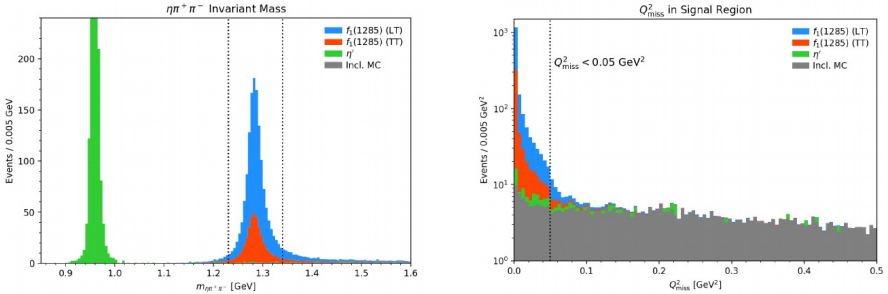
New event generator: **HadroTOPS**



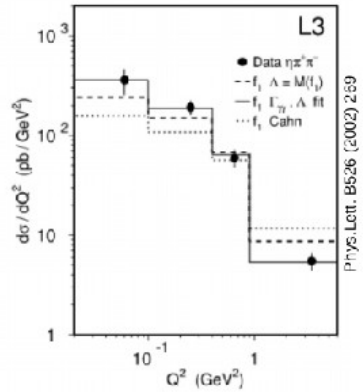
- Essential, since development of established generator (Ekhara) came to an end
- Publication in preparation

$\gamma\gamma^* \to f_1(1285)$

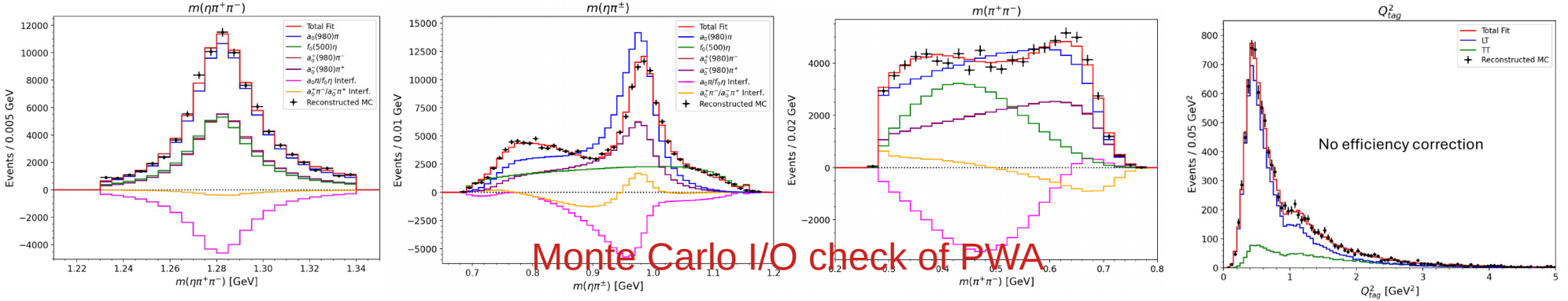
- Reconstructing $f_1(1285) \to \pi^+\pi^-\eta$



Only available data:



- Possibility to separate helicity states from fit to angular distributions
- PWA required due to inseparable intermediate states $a_0^{\pm}(980)\pi^{\mp} \longleftrightarrow f_0(500)\eta$
  - Amplitude based on Phys. Rev. D 110 (2024) 094043



Monte Carlo I/O check of PWA

$\gamma\gamma^* \to f_1(1285)$

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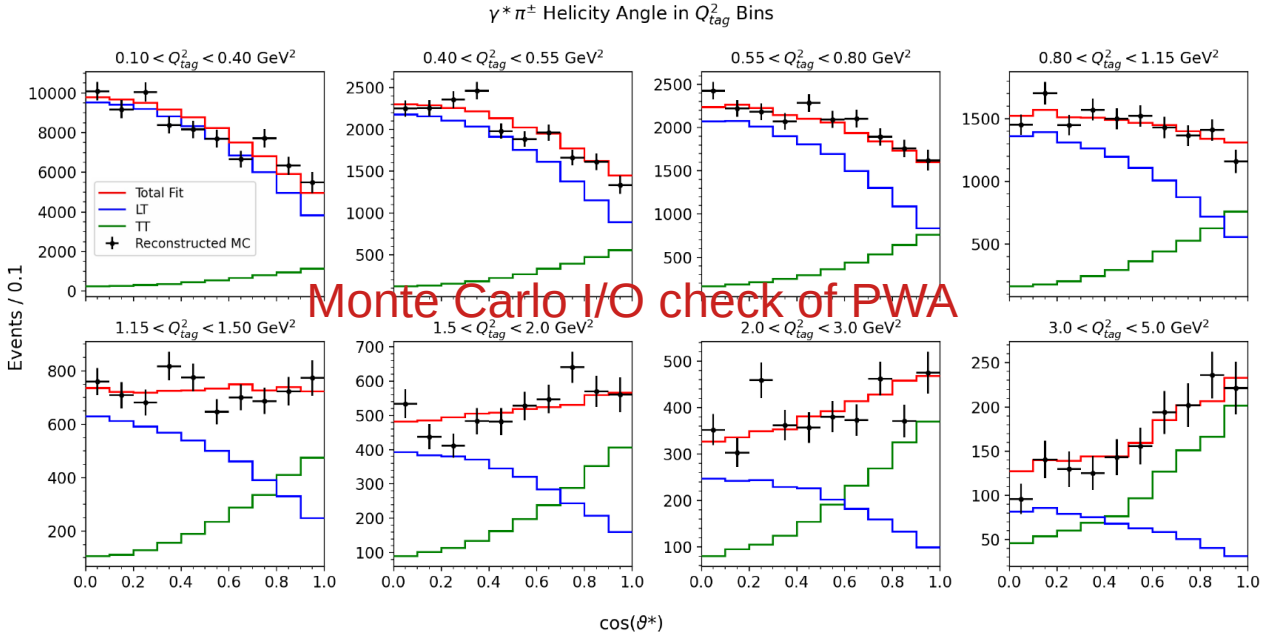

Monte Carlo I/O check of PWA

- Applied on full 20 fb^{-1} data
- Systematic uncertainties under evaluation

See Poster of Jan Muskalla

Summary

BESIII is an ideal laboratory to study two-photon reactions at $Q^2 \approx 1\ \mathrm{GeV}^2$

- Single pseudocalar meson TFFs
  - Single-tag measurements
    - $0.1 \leq Q^2[\mathrm{GeV}^2] \leq 5.0$
    - First TFF measurement released **arXiv:2509.07685**
    - High statistics results on π^0, η, η' in preparation
  - Double-tag measurements of π^0, η, η' in preparation
- Multi meson systems
  - Single-tag measurements
    - $\pi^0\pi^0/\pi^+\pi^-$
      - masses from threshold to 2 GeV
      - virtualities from 0.2 to 2 GeV²
      - full helicity angle coverage
    - $f_1(1285) \to \pi^+\pi^-\eta$ with PWA to separate helicity amplitudes of TFF

Development of new MC Generator facilitates studies of further multi meson systems

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Preliminary results by the end of this year!

Development of new MC Generator facilitates studies of further multi meson systems