Measurements of two-photon reactions - demands on event generators -

Workshop on Radiative Corrections and Monte Carlo simulations for electron-positron collisions

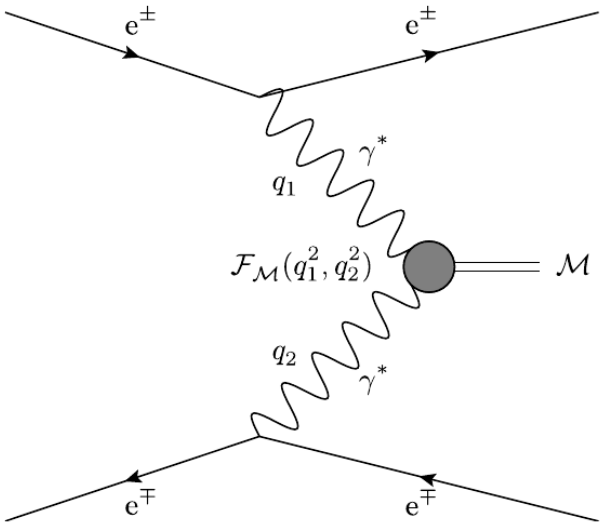
2025-05-07 | Christoph Florian Redmer

SFB 1044 THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL
Cluster of Excellence PRISMA+
DFG Deutsche Forschungsgemeinschaft
FOR5327
JOHANNES GUTENBERG UNIVERSITÄT MAINZ
JG|U

Two-photon Collisions

- C-even states in e+e- collisions
- Direct access to $J^{PC} = 0,2^{\pm+}$

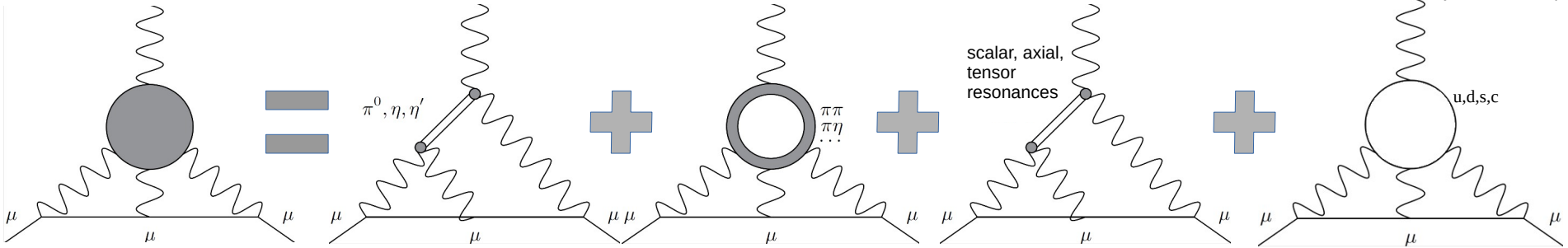
- Produced masses $m_X \ll \sqrt{s}$
- Energy dependence $\sigma \propto \alpha^2 \ln^2 E$
- Forward-peaked kinematics
- $\sigma = \sigma_{\text{point-like}} \cdot |\mathcal{F}(Q_1^2, Q_2^2)|^2, \qquad Q^2 = -q^2$



- Access to Q^2 dependence by “tagging” scattered leptons

Hadronic Light-by-Light

Phys.Lett. B322 (1994) 239

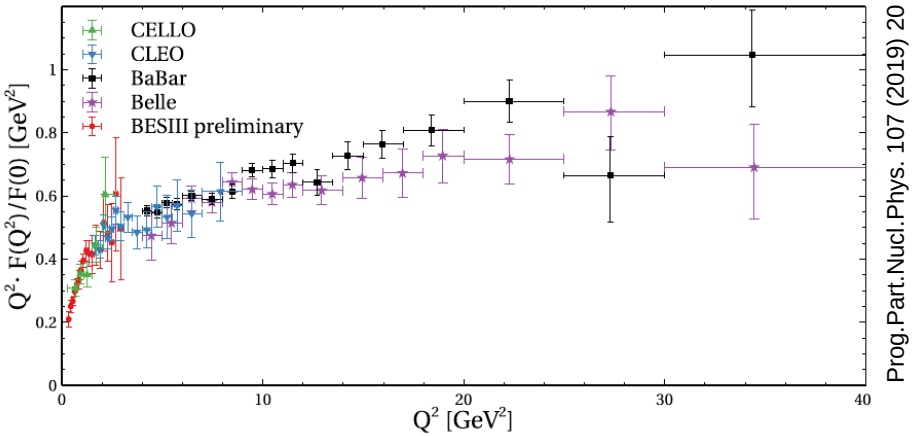


Contribution	$\times 10^{-11}$
Pseudoscalars	93.8 ± 4.0
π & K Loops/Boxes + *s*-wave rescattering	-24.4 ± 3
Tensors and Scalars	-1 ± 3
Axials	6 ± 6
u,d,s Loops / short distance	18 ± 11

Phys.Rept. 887 (2020) 1

- Pseudoscalar exchange and meson loops dominate
- Improvements using data-driven approaches
- More experimental input needed
  - ➔ Scalar, tensor, axial contributions

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



Prog.Part.Nucl.Phys. 107 (2019) 20

- Singletag measurements
  - Measure only one of the scattered leptons
  - Small scattering angle of missing lepton
- Most relevant for HLbL at $Q^2 \approx 1$ GeV^2

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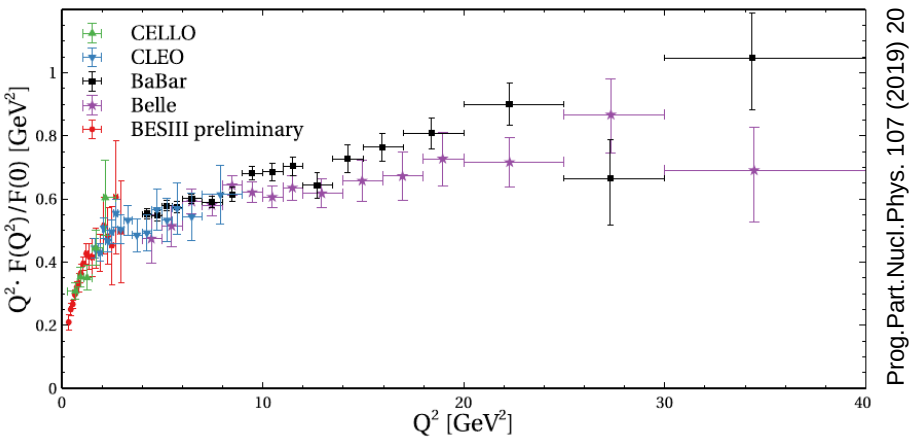

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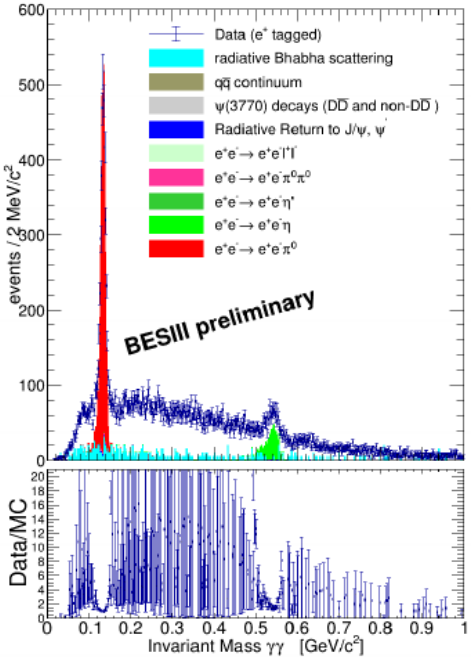
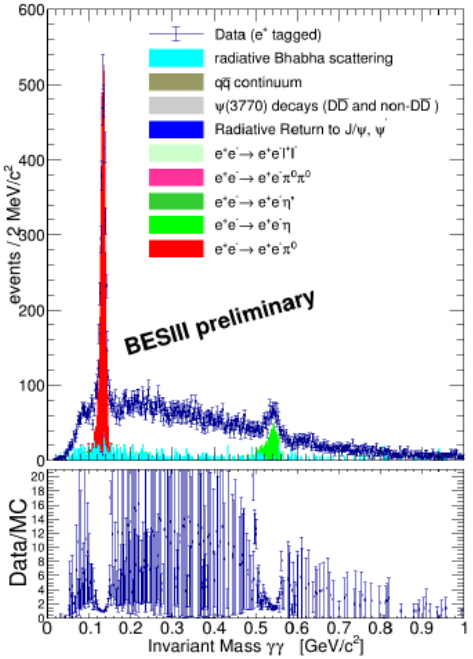


Example: BESIII (2.9 fb^{-1} at 3.773 GeV)

- Select
  - Exactly one lepton
  - At least two photons
- Dominating background: (hard) radiative Bhabha

Radiative effects in $\gamma\gamma^* \to \pi^0$



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- Signal MC: Ekhara 2 (H. Czyz *et al.*) Comput.Phys.Commun. 182 (2011) 1338
  - Matrix elements using exact equations
  - Double-Octet TFF model
- MC overestimates signal content ! (also observed for η,η')

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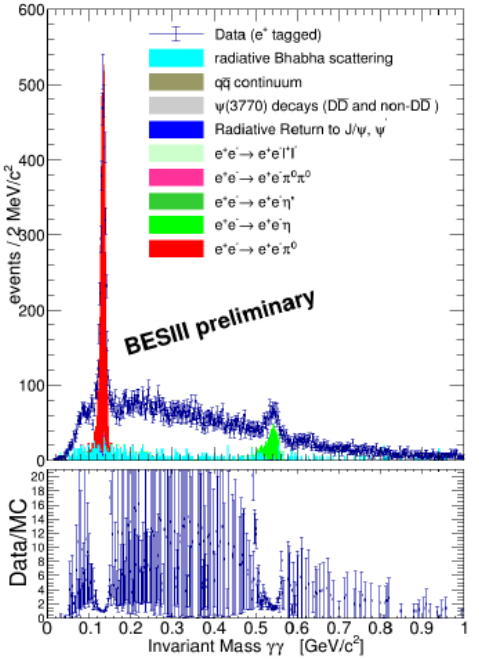

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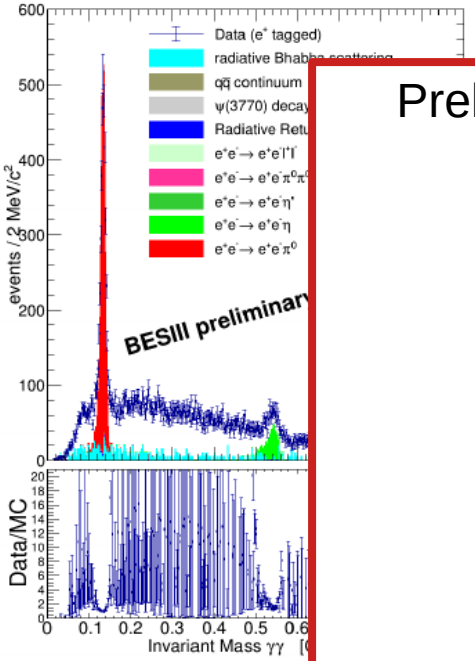
- MC overestimates signal content ! (also observed for η,η')
- Ekhara 3.0 (H. Czyz *et al.*) Comput.Phys.Commun. 234 (2019) 245
  - Full NLO QED corrections considered
  - Leads to negative event weights!
- Reasonable estimate of signal content!

Radiative effects in $\gamma\gamma^* \to \pi^0$



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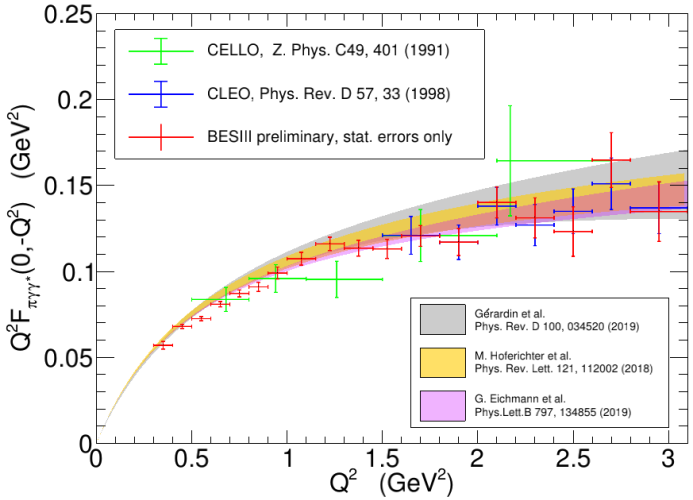
Preliminary TFF result without radiative corrections



Radiative corrections “enlarge” transition form factor

► better agreement with theory predictions

ommun. 182 (2011) 1338

erved for η,η’)

ommun. 234 (2019) 245

Radiative effects in event generators

Ekhara 3.0 (H. Czyz *et al.*) Comput.Phys.Commun. 234 (2019) 245

- Full NLO QED corrections considered
- Only applied in t-channel

GGResRC (Druzhinin, Kardapoltsev, Tayursky) Comput.Phys.Commun. 185 (2014) 236

- Structure function approach
- Corrections only for tagged particle

TREPS (Uehara *et al.*) arXiv:1310.0157

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Effects of corrections on untagged particle are significant!

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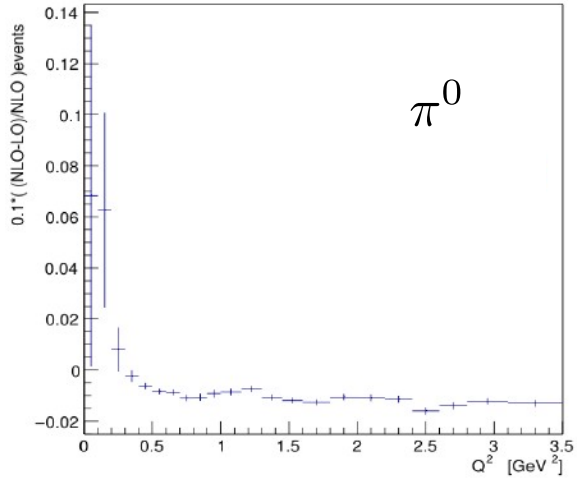
- Uncertainty is 1% or less
- Untagged particle can be neglected

Uncertainty of radiative effects

No statement on uncertainty of radiative corrections in Ekhara 3.0!

Suggestion by Henryk:

- 10% of relative difference of LO and NLO cross sections maybe a good (conservative) estimate
- Corrections depend on analysis conditions, use reconstructed values
  - Estimate seems to work reasonably well for π^0 : $\delta \sim 1\%$
  - Unexpected behavior for η, η' : $\delta > 15 - 20\%$
    (already at generator level)



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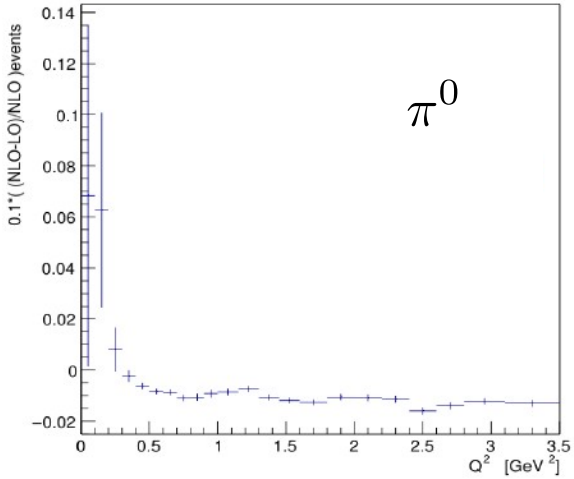

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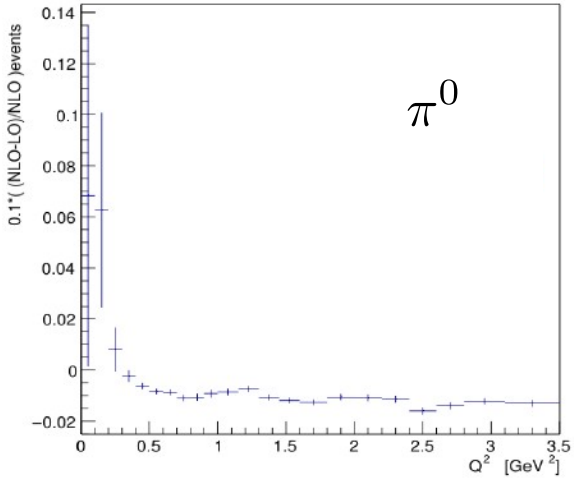

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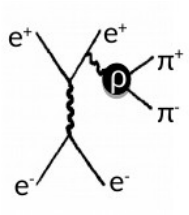
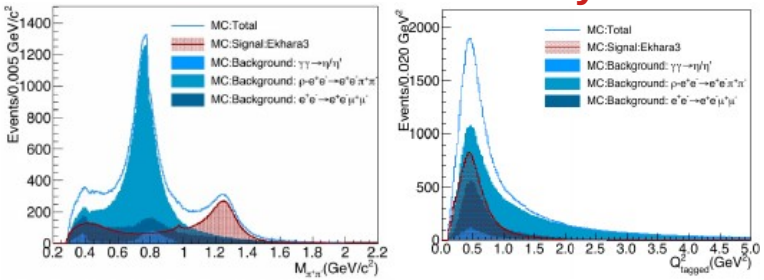
Even more important for doubletag measurements !?

Higher Multiplicities

- $\pi\pi/K\bar{K}$ pairs provide information on polarizabilities, scalar & tensor resonances
  - Different helicity amplitudes
  - Momentum transfer dependence
  - Interference with background
  - Luminosity function



$e^+e^- \to e^+e^-\pi^+\pi^-$ MC study at BESIII



- Ekhara >3.1 includes most of the requirements
  - Exact matrix elements
  - $s + t + \gamma\gamma$ channels included
  - Resonances numerically included from dispersive analysis (Phys.Rev. D101 (2020) 054008)

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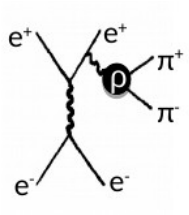

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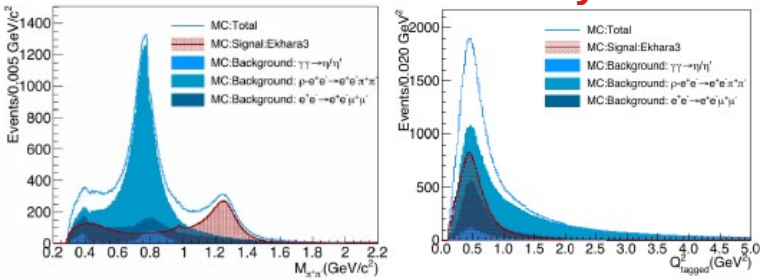

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Unfortunately, Henryk retired!

A new event generator: HadroTOPS

- Uses full cross section formula
- Inherits highly efficient $e^+e^- \to e^+e^- X$ phase space generation algorithm from Galuga/Ekhara
- Produces flat phase space decay of X to any kinematically allowed particle combination
- Two-photon cross sections as input

Work done by **Max Lellmann**

$$e^+e^- \to e^+e^- M$$

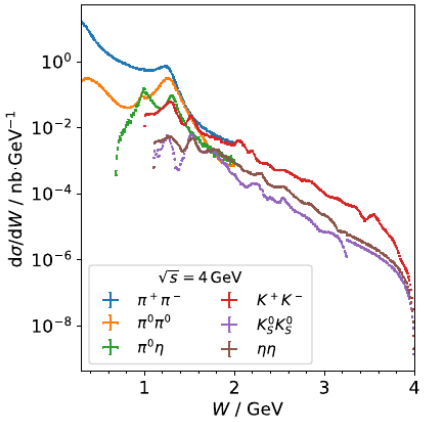
$$\begin{aligned} d\sigma = & \frac{\alpha^2}{16\pi^4 Q_1^2 Q_2^2} \frac{2\sqrt{X}}{s_{ee}(1-4m_e^2/s_{ee})^{1/2}} \cdot \frac{d^3\vec{p}_1'}{E_1'} \cdot \frac{d^3\vec{p}_2'}{E_2'} \\ & \times \{4\rho_1^{++}\rho_2^{++}\sigma_{TT} + \rho_1^{00}\rho_2^{00}\sigma_{LL} + 2\rho_1^{++}\rho_2^{00}\sigma_{TL} + 2\rho_1^{00}\rho_2^{++}\sigma_{LT} \\ & + 2(\rho_1^{++}-1)(\rho_2^{++}-1)\cos(2\tilde{\phi})\tau_{TT} \\ & + 8\left[\frac{(\rho_1^{00}+1)(\rho_2^{00}+1)}{(\rho_1^{++}-1)(\rho_2^{++}-1)}\right]^{1/2}\cos\tilde{\phi}\,\tilde{\tau}_{TL} \qquad \gamma\gamma \to M \\ & + h_1 h_2\, 4\left[(\rho_1^{00}+1)(\rho_2^{00}+1)\right]^{1/2}\tilde{\tau}_{TT} \\ & + h_1 h_2\, 8\left[(\rho_1^{++}-1)(\rho_2^{++}-1)\right]^{1/2}\cos\tilde{\phi}\,\tau_{TL}\}, \end{aligned}$$

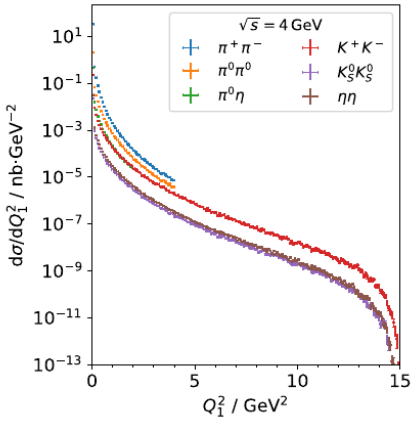
Generate

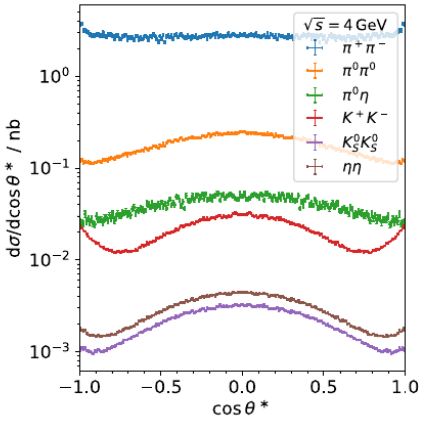
- Luminosity functions
- Luminosity function weighted phase space (useful for PWAs)
- Events according to simple models (efficiency estimates)
- Events according to numerical cross section input

A new event generator: HadroTOPS

Work done by **Max Lellmann**







$\sqrt{s} = 4$ GeV

Theory input:

$\pi^+\pi^-/\pi^0\pi^0$	Phys.Rev. D101 (2020) 054008
$\pi^0\eta$	Phys.Rev. D96 (2017) 114018

Experimental input:

K^+K^-	BESIII PhD thesis
$K_SK_S, \eta\eta$	Belle

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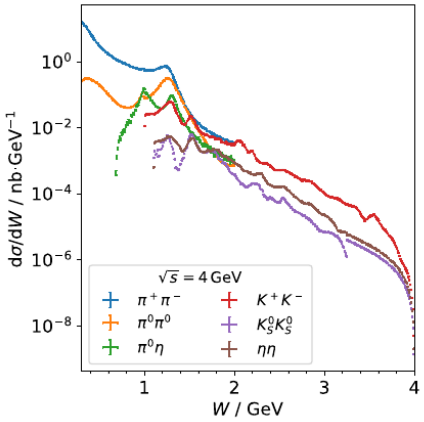

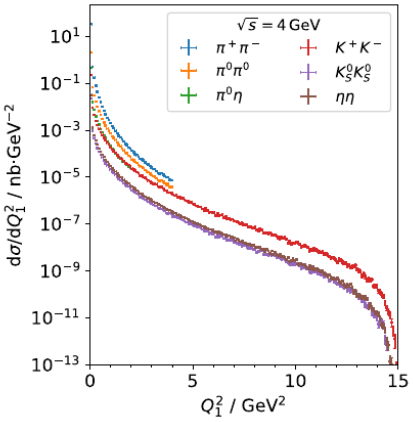

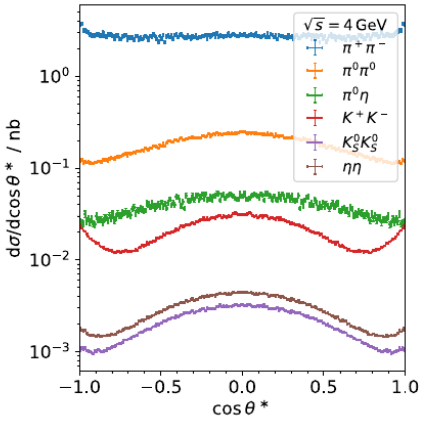

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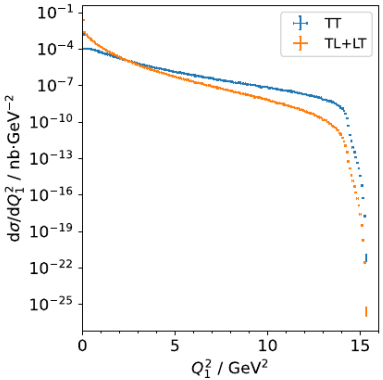

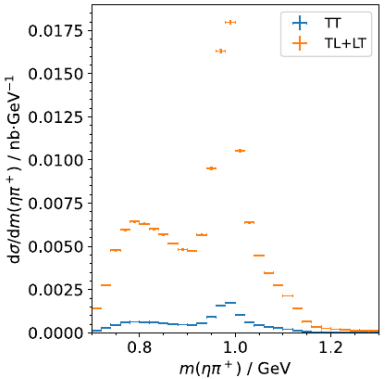

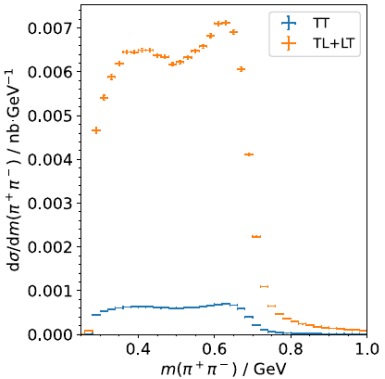

Also axial vector mesons:

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

Theory input: Phys.Rev. D110 (2024) 094043

Summary

- Two-photon reactions in e+e- important for spectroscopy, meson structure, and HLbL
- MC event generators essential
  - Efficiency estimates and background studies
  - Radiative corrections
- Latest developments by Henryk Czyz
- New, flexible event generator prepared: HadroTOPS
  - Numerical input for cross section models
  - Luminosity functions accessible
  - No interference with background
  - No radiative effects

New activities highly desired to make full use of new data at BESIII and Belle-2 !