JOHANNES GUTENBERG UNIVERSITÄT MAINZ

SFB 1044 THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

PRISMA

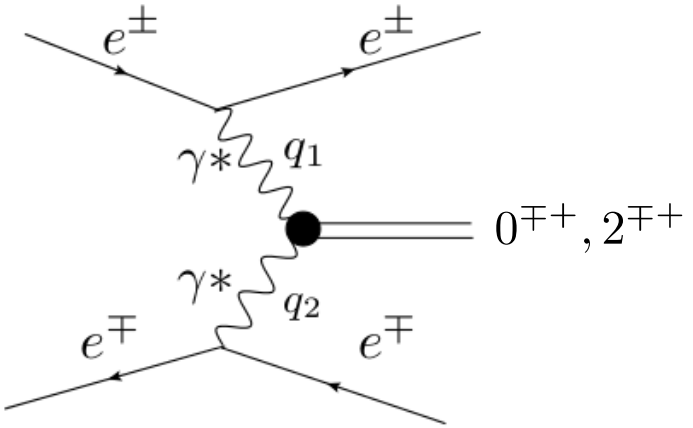
$\gamma\gamma$ Physics Program at BESIII

June 5, 2017 | Christoph Florian Redmer

First Workshop of the Muon g-2 Theory Initiative

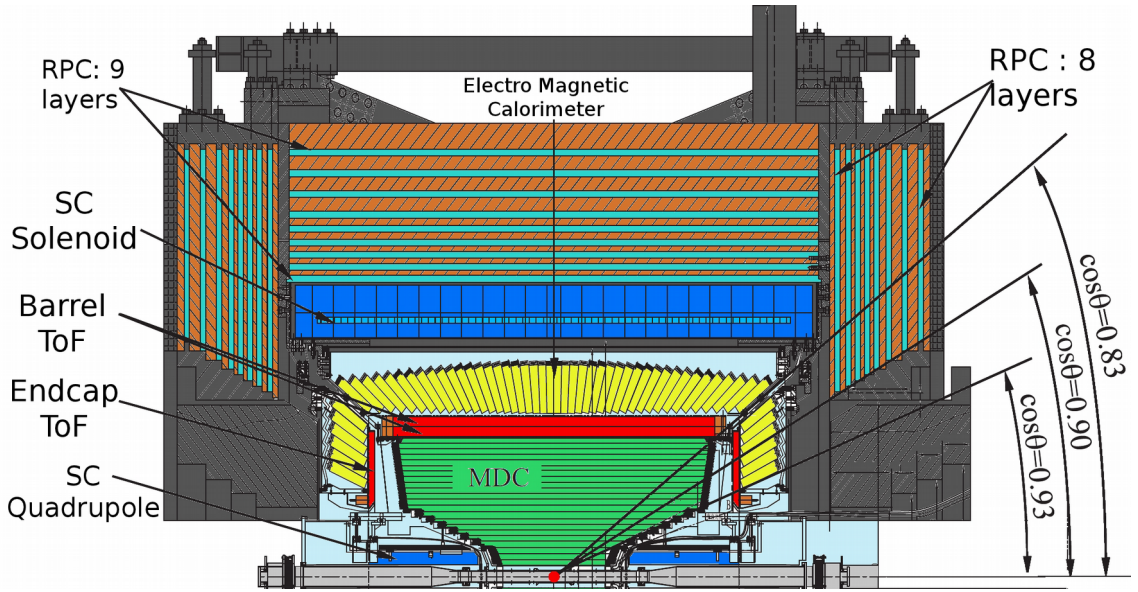
Two-Photon Collisions

- Exchange of two photons in e^+e^- collisions
- Pseudoscalar, axial, and tensor states accessible
- $M_X \ll \sqrt{s}$
- $\sigma \propto \alpha^2 \ln^2 E$
- $\sigma \propto F^2(Q_1^2, Q_2^2)$, with $Q_i^2 = -q_i^2$
- Forward peaked kinematic
  - Experimentally challenging
    - Untagged measurements
    - Single-tagged measurements
    - Double-tagged measurements



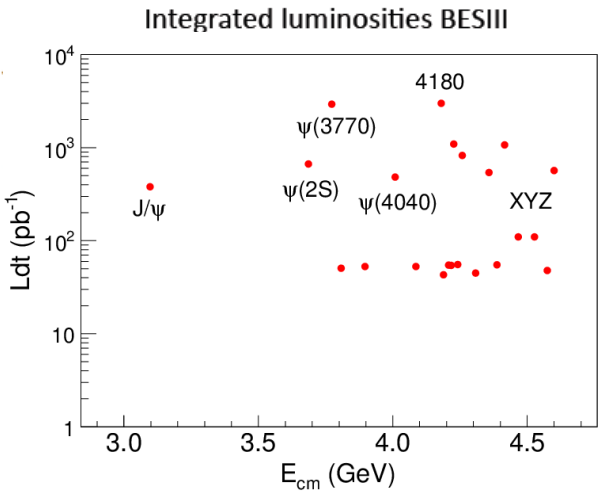
BESIII Detector

NIM A614 (2010) 345



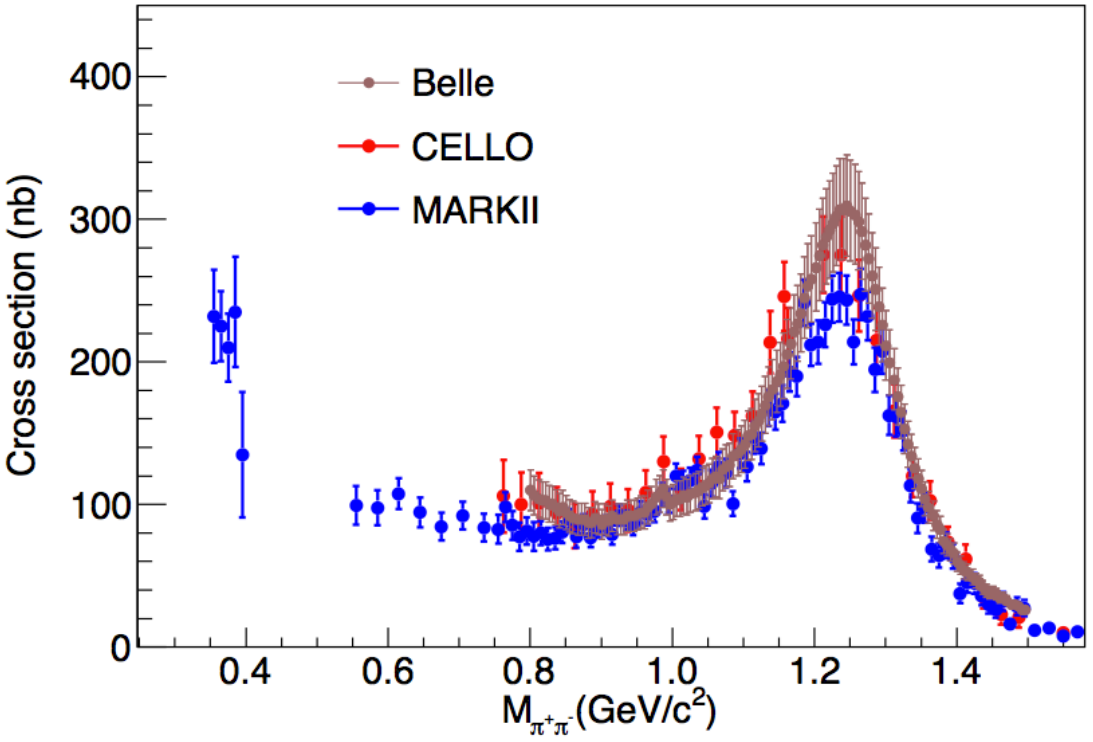
- Main Drift Chamber (MDC)
  - σ(p)/p = 0.5%
  - $\sigma_{dE/dx}$ = 6.0%
- Time-of-flight system (TOF)
  - σ(t) = 90ps (barrel)
  - σ(t) = 110ps (endcap)
- EMC
  - 6240 CsI(Tl) crystals
  - σ(E)/E = 2.5%
  - $\sigma_{Z,\Phi}$(E) = 0.5 – 0.7 cm
- Muon Chambers
  - 8 – 9 layers of RPC
  - p>400 MeV/c
  - δRΦ = 1.4 ~ 1.7 cm
- Superconducting Magnet
  - 1 T magnetic field

- Operated at BEPCII collider
  - $2.0 \leq \sqrt{s}\ [\mathrm{GeV}] \leq 4.6$
  - Design luminosity achieved
    - $\mathcal{L} = 1.0 \times 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ at $\psi(3770)$
- Large data sets for
  - Charmonium Spectroscopy
  - Charm Physics
  - Light hadrons
  - τ and R-Scan



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

- Previous measurements:



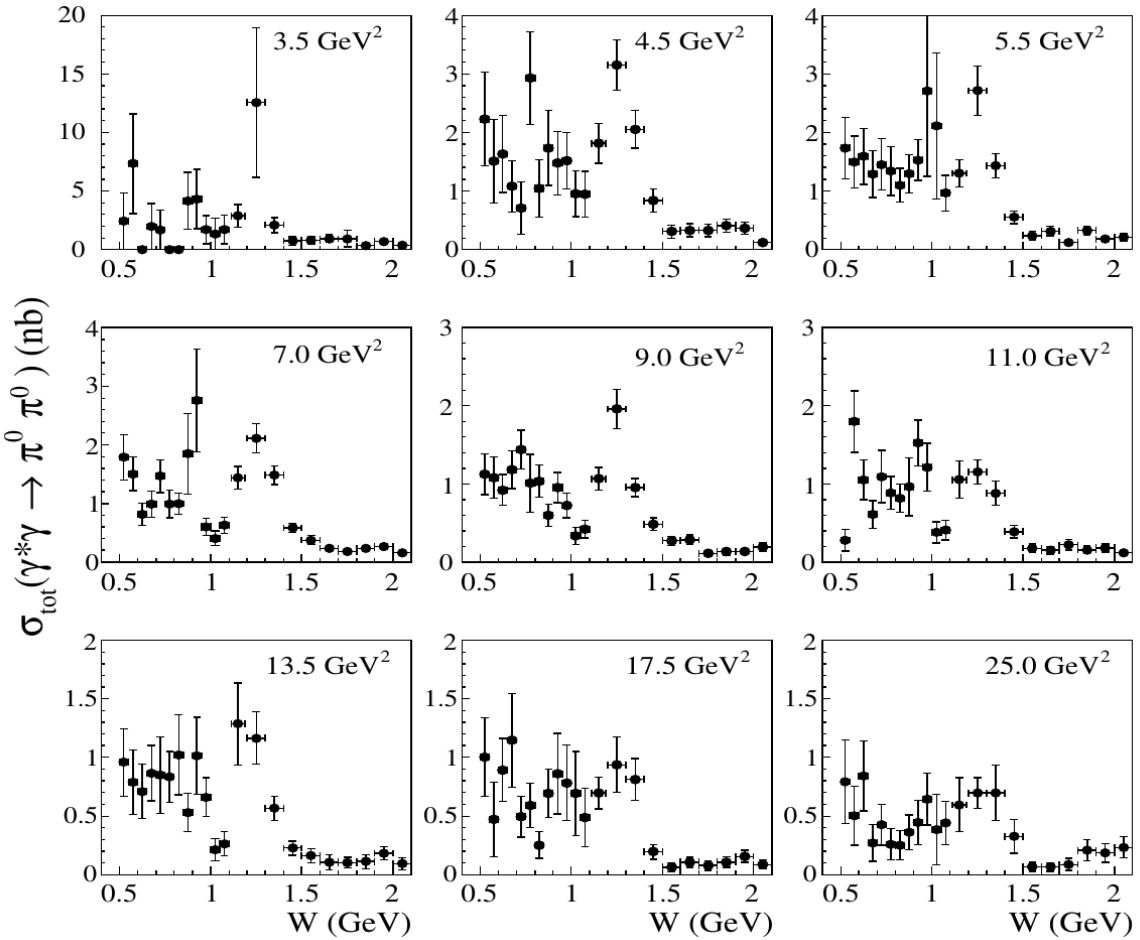
$$\gamma\gamma \to \pi^+\pi^-$$

- Only untagged measurements
- Data scarce at small $\mathrm{m}_{\pi^+\pi^-}$

- MARKII: $209\ \mathrm{pb}^{-1}, \quad 0.35 \leq \mathrm{m}_{\pi\pi}[\mathrm{GeV/c}^2] \leq 1.6$ Phys. Rev. D42 (1990) 1350
- CELLO: $86\ \mathrm{pb}^{-1}, \quad 0.75 \leq \mathrm{m}_{\pi\pi}[\mathrm{GeV/c}^2] \leq 1.9$ Z. Phys. C56 (1992) 381
- Belle: $85.9\ \mathrm{fb}^{-1}, \quad 0.8 \leq \mathrm{m}_{\pi\pi}[\mathrm{GeV/c}^2] \leq 1.5$ Phys. Rev D75 (2007) 051101

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

- Previous measurements:



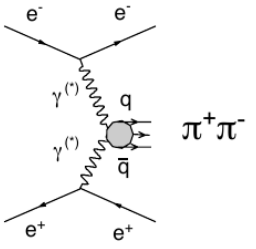
$$\gamma\gamma^* \to \pi^0\pi^0$$

- First single-tagged measurement
  - Belle [Phys. Rev. D93 (2016) 032003]

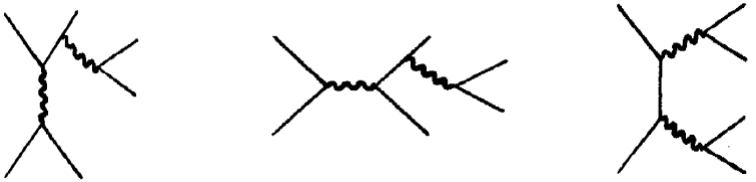
- 759 fb^{-1} data
- $3 < Q^2\ [\mathrm{GeV}^2] < 30$
- $0.5 < W\ [\mathrm{GeV}/c^2] < 2.1$
- $|\cos\theta^*| < 1.0$
- Determination of partial-wave amplitudes
- Measurement of TFF for $f_2(1270)$ and $f_0(980)$

MC Generators

- Signal: $\gamma^{(*)}\gamma^{(*)} \to \pi^+\pi^-$
  - Modified Galuga2.0 (ChPT prediction only)



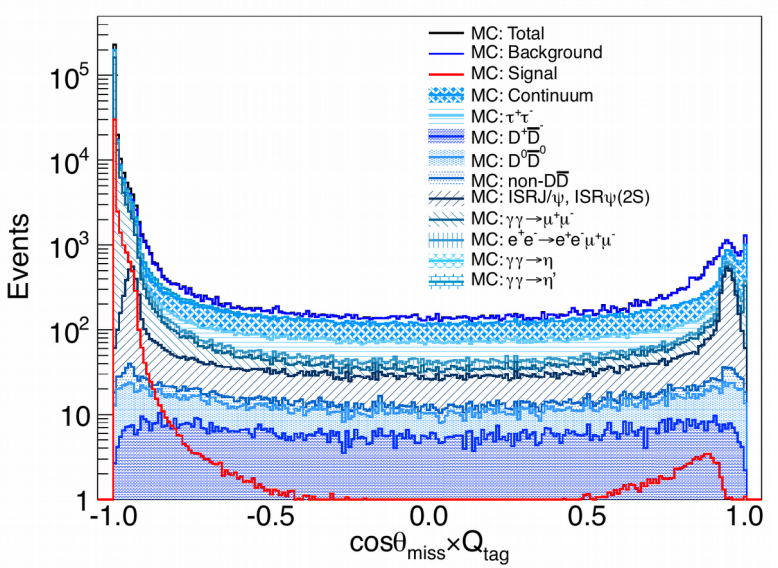
- Background
  - Same final state: $e^+e^- \to e^+e^-\pi^+\pi^-$
    - Generator under development
    - Measured form factor as input

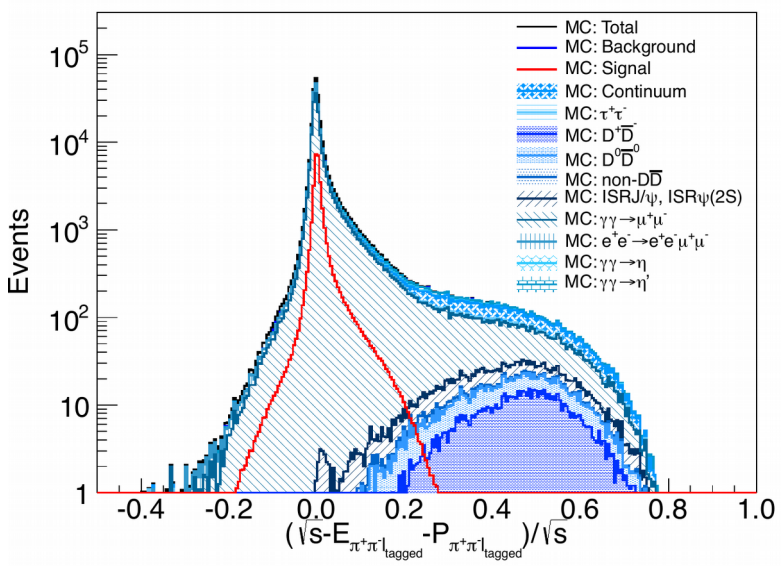


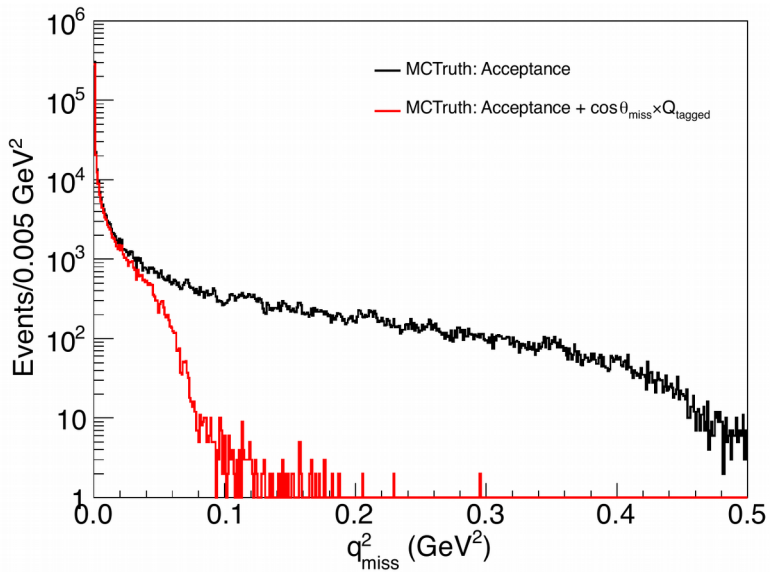
  - Similar final state: $e^+e^- \to e^+e^-\mu^+\mu^-$
    - BesBdkRc (developed from RADCOR) CPC 40 (1986) 271
      - Partly consideres radiative effects
    - DIAG36 CPC 40 (1986) 285
    - Helac-Phegas CPC 180 (2009) 1942
  - Other:
    - $\gamma^{(*)}\gamma^{(*)} \to \eta, \eta'$ (Ekhara) PRD 85 (2012) 094010
    - QED processes, Radiative Return, DD decays, hadronic continuum

Single-tag measurement of $\pi^+\pi^-$ at BESIII

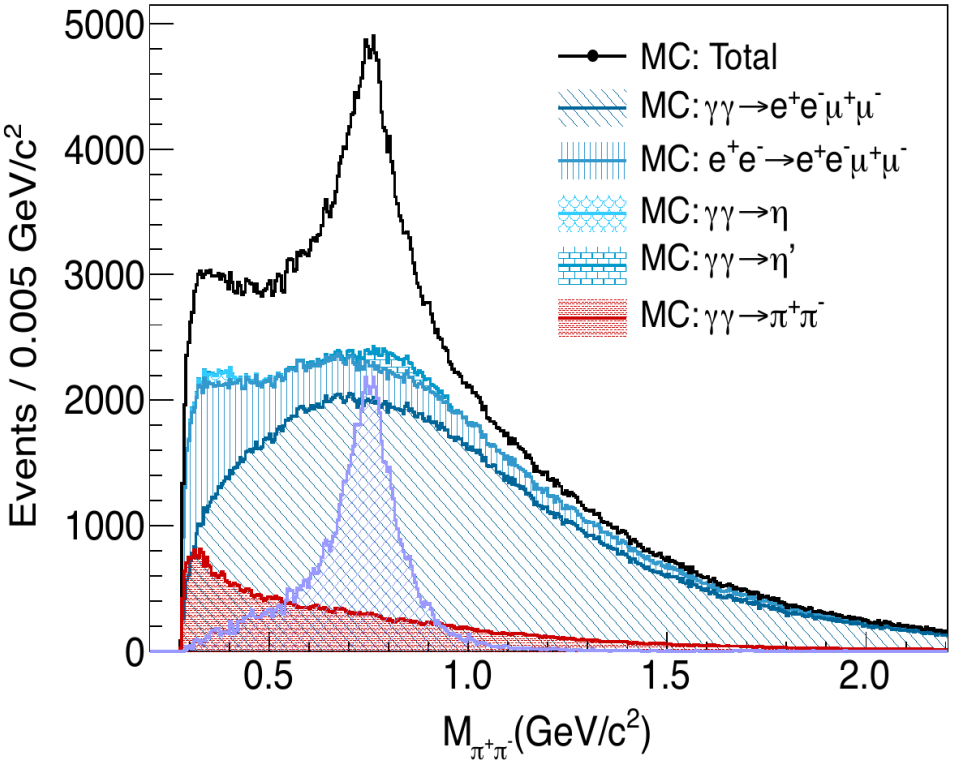
- Event selection:
  - Two oppositely charged tracks, identified as $\pi^{\pm}$
  - One charged track identified as $e^{\pm}$ by $\frac{E_{Cal}}{p_{MDC}}$
  - Missing momentum: $q_{tag} \cdot \cos\theta_{miss} < -0.99$
  - $R_\gamma = \frac{\sqrt{s} - E^{CMS}_{e^{\pm}\pi^0} - p^{CMS}_{e^{\pm}\pi^0}}{\sqrt{s}} < 0.15$



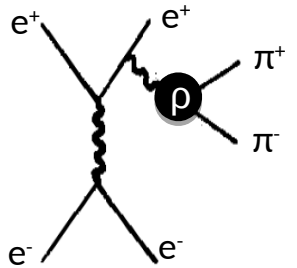




Background Conditions



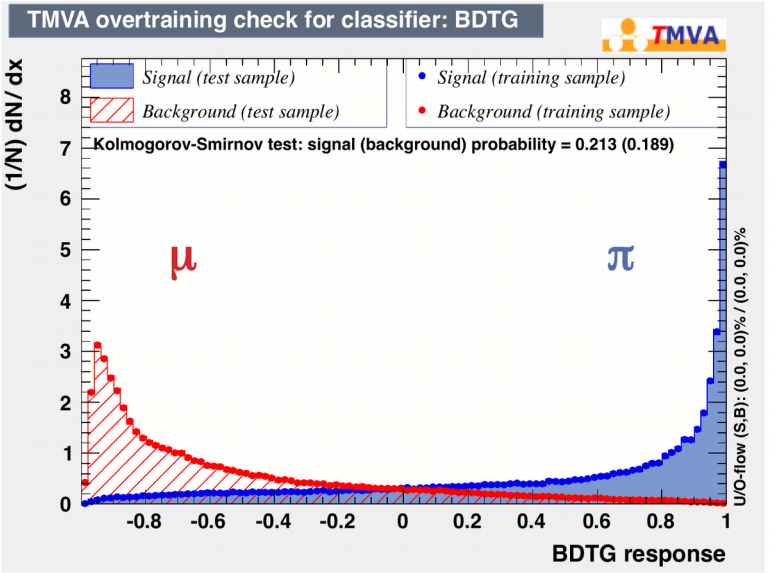
- Dominating background
  - $e^+e^- \to e^+e^-\mu^+\mu^-$
    - Cross section six times larger than signal process
    - Good μ/π separation needed
  - $e^+e^- \to e^+e^-\pi^+\pi^-$
    - Irreducible background
    - Peak in $\mathrm{m}_{\pi\pi}$
    - Can be subtracted



- Other background < 0.5%

μ/π separation

- Boosted-Decision-Tree
  - Apply to individual tracks
  - Use variables independent of kinematics
  - Trained with $\gamma^{(*)}\gamma^{(*)} \to \mu^+\mu^-$ and $e^+e^- \to e^+e^-\mu^+\mu^-$ MC
  - Correction of data/MC efficiency differences
  - Selection validated with muons



- Select π : $y_{BDT} > 0.58$
  - Efficiency π : 56.2%
  - Efficiency μ : 2.9%
- Select μ : $y_{BDT} < -0.6$
  - Efficiency π : 5%
  - Efficiency μ : 60%

μ/π separation

- Boosted-Decision-Tree
  - Apply to individual tracks
  - Use variables independent of kinematics
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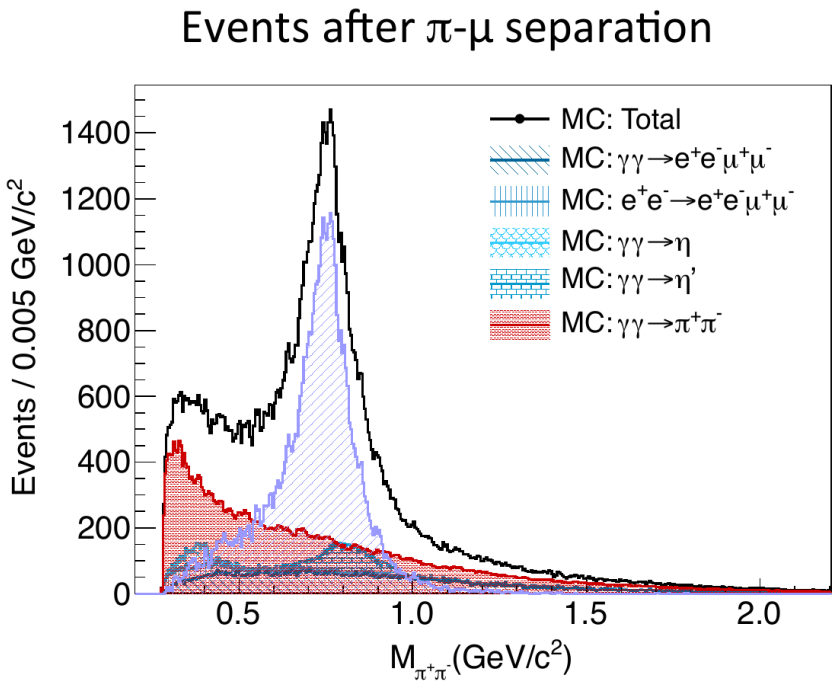

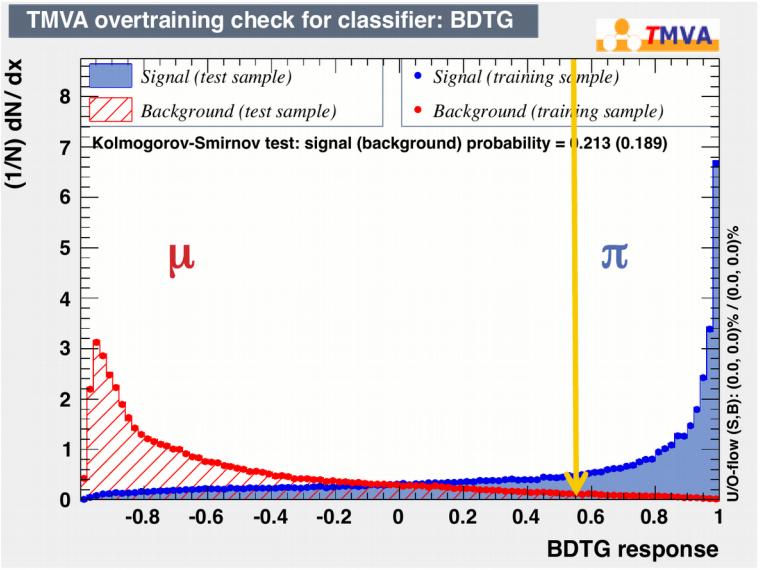

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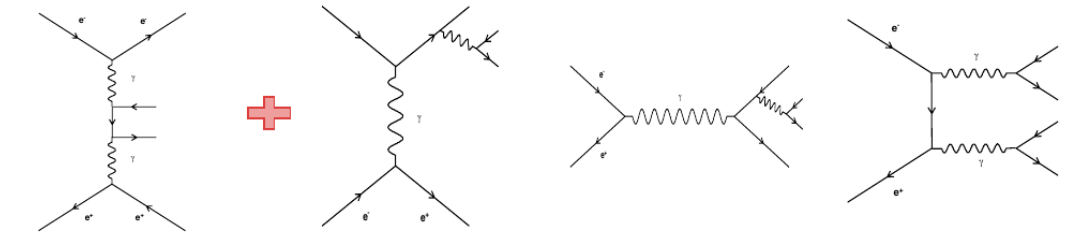
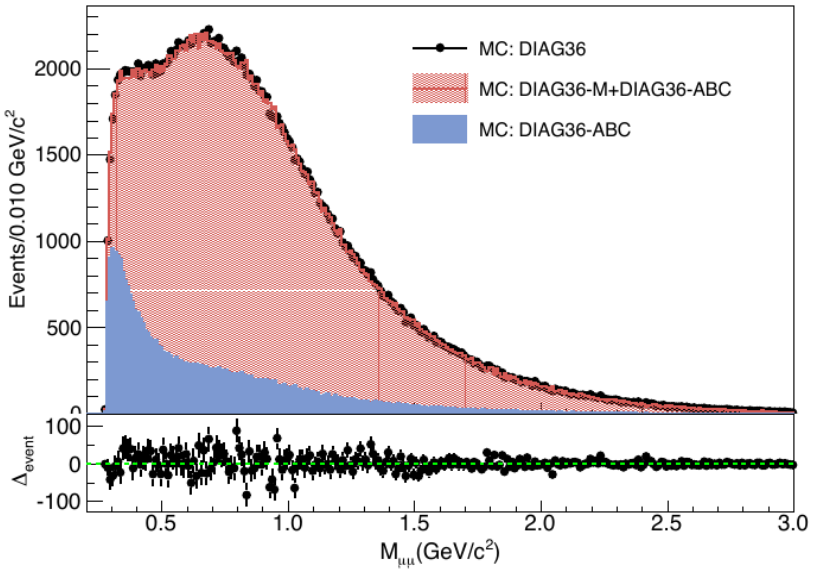
Background from $e^+e^- \to e^+e^-\mu^+\mu^-$

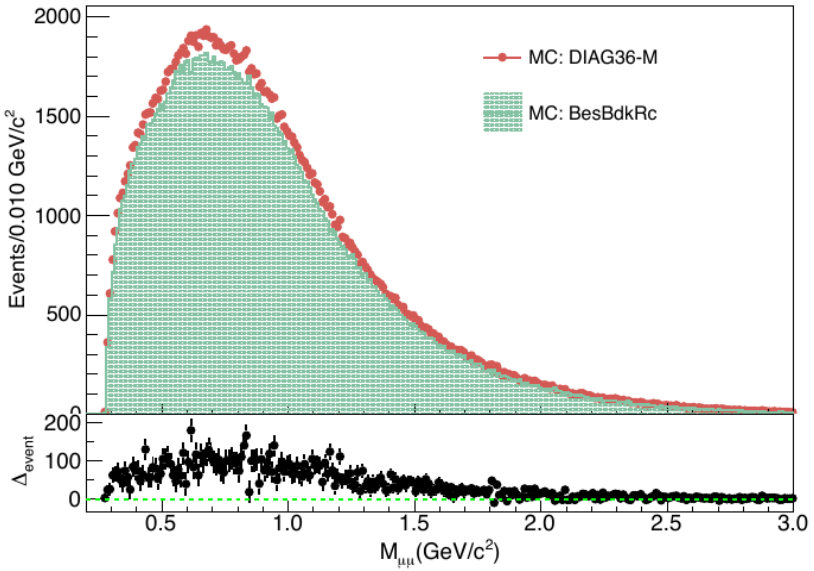
- Interference Effects (0.3%)
  - Between two-photon process and others
- Radiative Corrections (4.6% - 6.2%)
  - Only in two-photon process



DIAG36 (w/o RC)
BdkRc (w/RC)

DIAG36

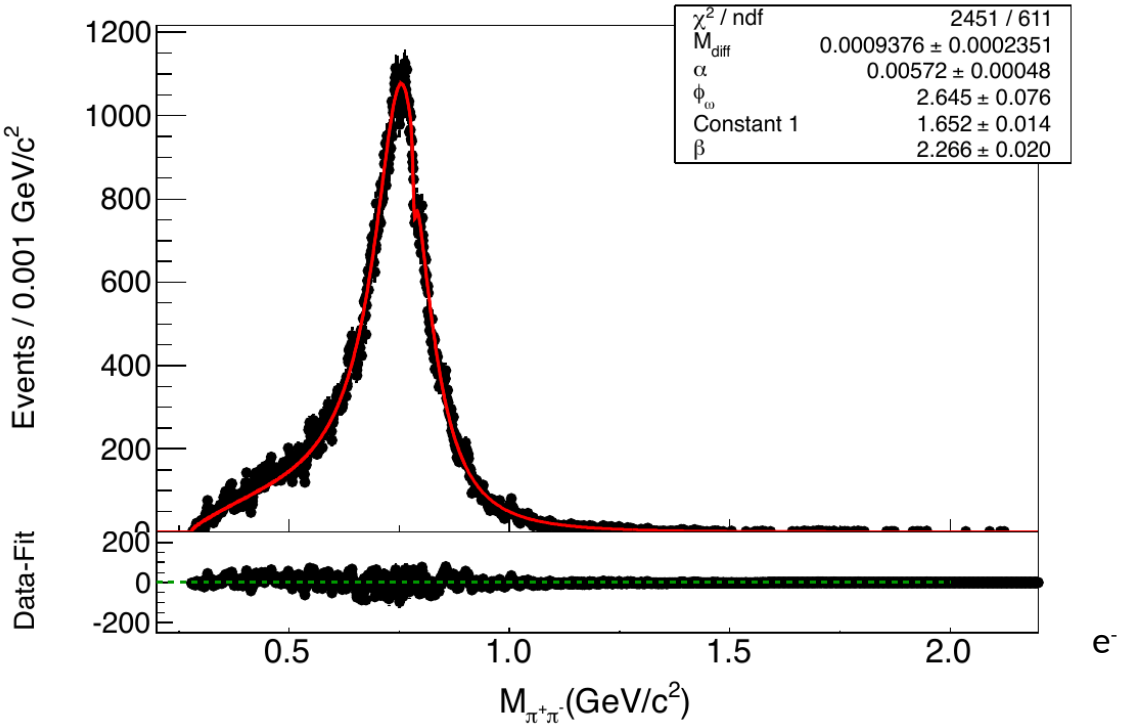




Background from $e^+e^- \to e^+e^-\pi^+\pi^-$

- Fit peak in $\mathrm{m}_{\pi\pi}$ and subtract from spectrum
  - Gounaris-Sakurai parameterization of
  - Obtain fit parameters from simulation
  - Line-shape fixed when fitting data

$$|\mathrm{BW}^{\mathrm{GS}} + \alpha \cdot e^{i\phi}\mathrm{BW}|\sqrt{1-\frac{4m_\pi^2}{M^2_{\pi^+\pi^-}}}\,e^{\beta\left(1-\frac{4m_\pi^2}{M^2_{\pi^+\pi^-}}\right)}\,\frac{1}{M^2_{\pi^+\pi^-}}$$



Differential Cross Section

$$\frac{d^3\sigma_{ee\to ee\pi^+\pi^-}}{d|\cos\theta^*|dWdQ^2} = \frac{N^{\mathrm{sig}}(|\cos\theta^*|, W, Q^2)}{\varepsilon(|\cos\theta^*|, W, Q^2)\Delta W \Delta|\cos\theta^*|\Delta Q^2 \mathcal{L}}$$

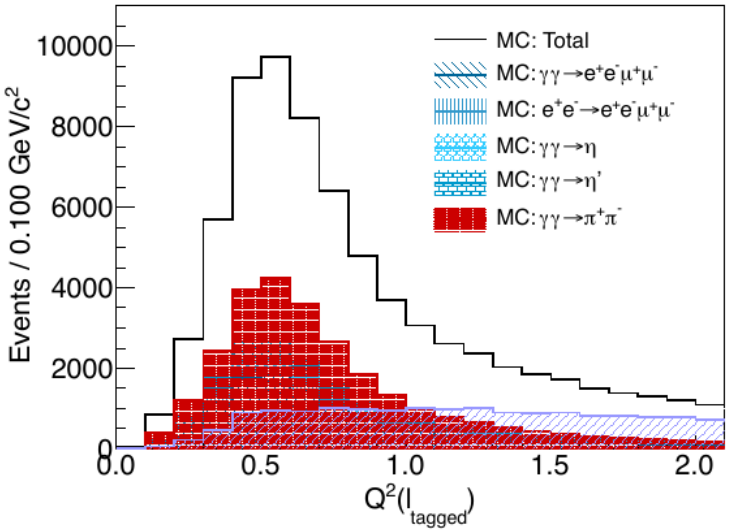
- Integrated Luminosity $\mathcal{L}$
- Efficiency $\varepsilon(|\cos\theta^*|, W, Q^2)$
- Bin width
  - $\Delta|\cos\theta^*| = 0.1$
  - $\Delta W = 0.005\ \mathrm{GeV/c^2}$
  - $\Delta Q^2 = 0.2 - 0.3\ \mathrm{GeV}^2$

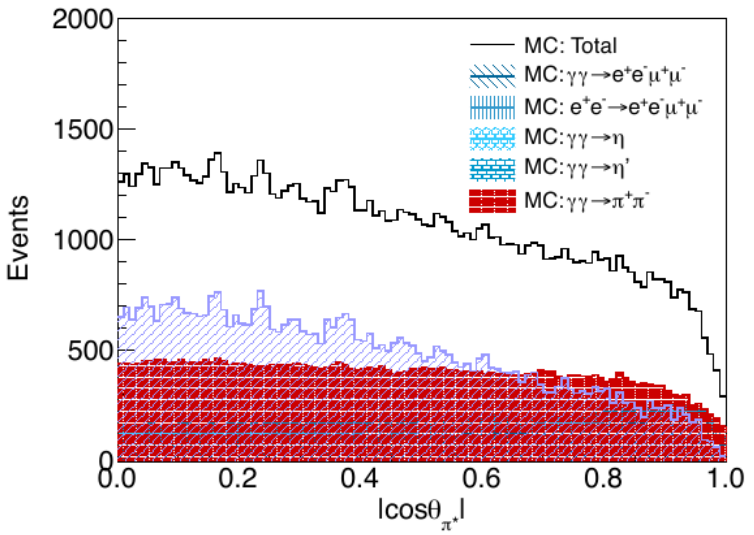
- Number of signal events $N^{sig}(|\cos\theta^*|, W, Q^2)$: Interference needs to be considered!

$$\mathcal{S} \quad + \quad \mathcal{B}\ (\mathrm{peak}) \quad + \quad \mathcal{B}\ (\mathrm{ee}\mu\mu)$$

$\mathcal{S}$	$\mathcal{B}$ (peak)	$\mathcal{B}$ (eeμμ)
smooth curve polynomial, or exponential, or theoretical formula	fix line-shape	fix line-shape normalization

Single-tag measurement of $\pi^+\pi^-$ at BESIII

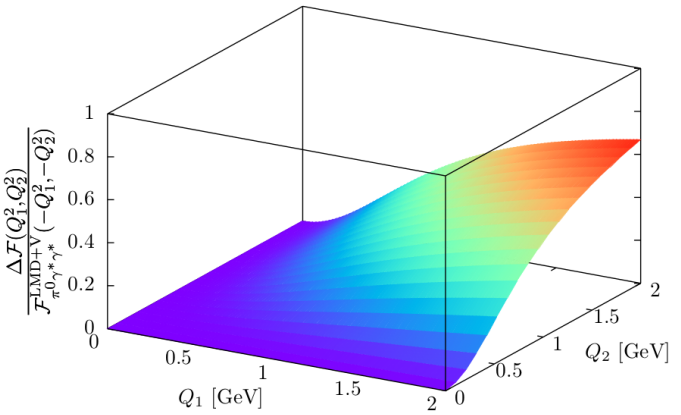




- First single-tag measurement of $\pi^+\pi^-$!
  - Access to:
    - low momentum transfers $0.2 < Q^2\ [\mathrm{GeV}^2] < 2.0$
    - low invariant masses $m_{\pi^+\pi^-} < M\ [\mathrm{GeV}] < 2.0$
    - full coverage of $|\cos\theta^*|$

Outlook: Double-Tagged Measurements

- Measurement of $F_{\gamma^*\gamma^*\pi^0}(Q_1^2, Q_2^2)$ never done before!
  - BESIII collected > 10 fb^{-1} at 3.77 < √s [GeV] < 4.6
  - Double-tag measurement possible
    - 1st Step: Test TFF models
      - e.g. VMD vs. LMD+V



Calculations: A. Nyffeler
Phys.Rev. D94, 2016, 053006

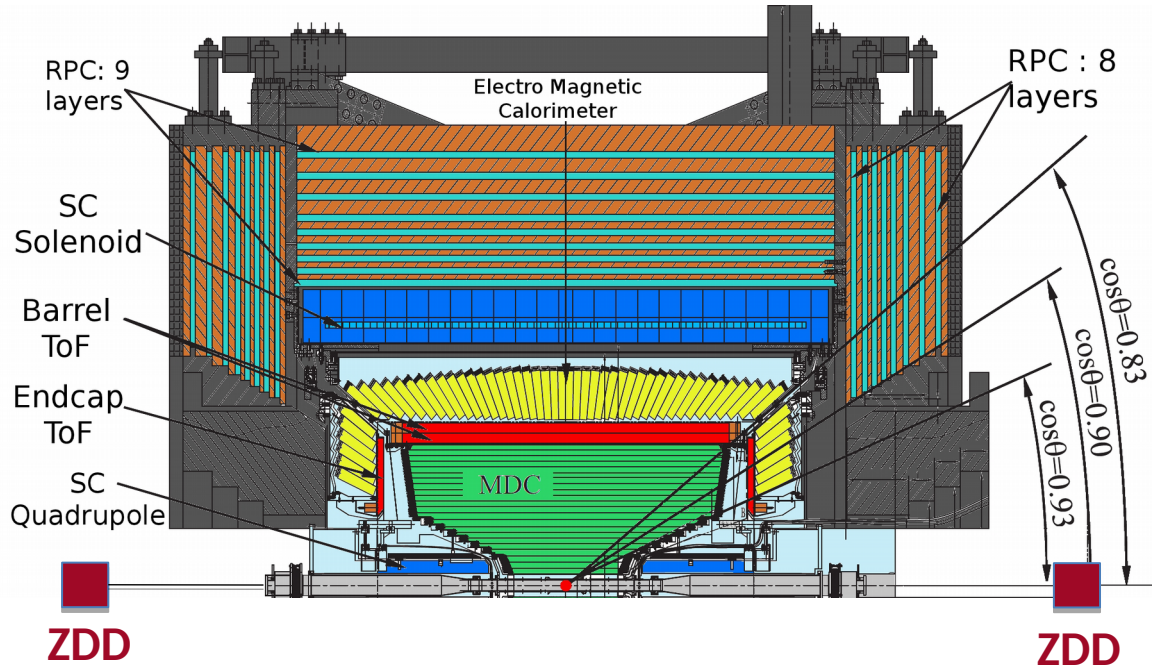
- Test polarization effects in $\gamma\gamma$ production
  - General two-photon cross section:

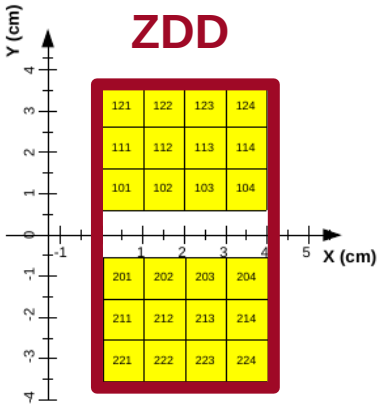
$$d\sigma = F\Big\{v_{TT}\,\sigma_{TT} + v'_{TT}\cos(2\tilde{\phi})\,(\sigma_{\parallel} - \sigma_{\perp}) + h_1 h_2 v''_{TT}\,\frac{1}{2}\,(\sigma_0 - \sigma_2)$$
$$+ v_{LL}\,\sigma_{LL} + v_{TL}\,\sigma_{TL} + v_{LT}\,\sigma_{LT} + v'_{TL}\cos(\tilde{\phi})\,\tau_{TL} + h_1 h_2 v''_{TL}\cos(\tilde{\phi})\,\tau^a_{TL}\Big\}.$$

    - $\tilde{\phi}$: azimuthal angle between lepton planes in $\gamma^*\gamma^*$ rest frame
      - Allows to disentangle form factor contributions of multi-meson and tensor states
      - Requires precise measurement of angles and high statistics

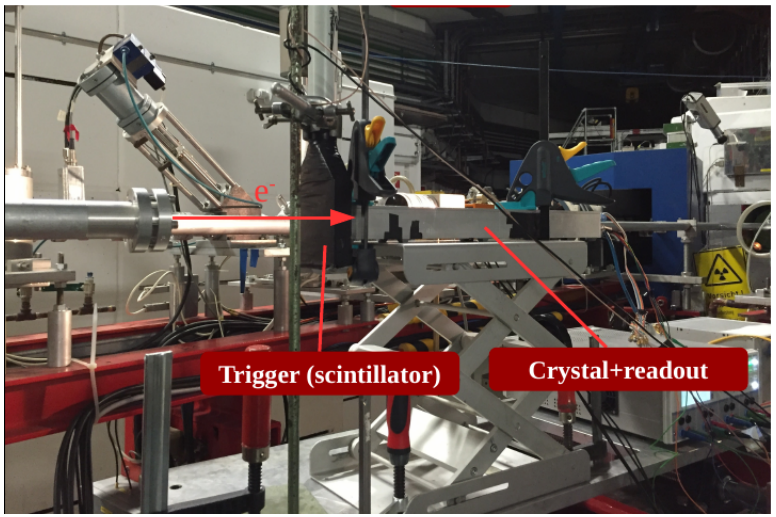
Outlook: Zero Degree Detector

- Tagging of photons and electrons at small angles
  - Polar angle range: 1 – 10 mrad
- Current design: Pb-SciFi, one sided
- Upgrade: Arrays of 48 crystals (PbWO, LYSO) on both sides





In-beam tests at MAMI (Mainz)



Summary

- Two-photon physics at BESIII
  - Untagged measurements for light hadron spectroscopy
  - Single-tag measurements of pseudoscalars for transition form factors
    - Here: $\gamma\gamma^* \to \pi^+\pi^-$
    - Requires good PID, treatment of interferences
    - First measurement at low Q^2, low mass, and full $|\cos\theta^*|$
    - To be extended to neutral final states
  - First double-tagged measurement $\gamma^*\gamma^* \to \pi^0$ started
  - New prospects from tagging detectors