



JOHANNES GUTENBERG
UNIVERSITÄT MAINZ



THE LOW-ENERGY FRONTIER
OF THE STANDARD MODEL



Measurement of electromagnetic transition form factors in two-photon collisions at **BESIII**

June 29, 2017 | Christoph Florian Redmer
for the BESIII collaboration

11th International Workshop on e+e- Collisions from Phi to Psi
Schloss Waldthausen

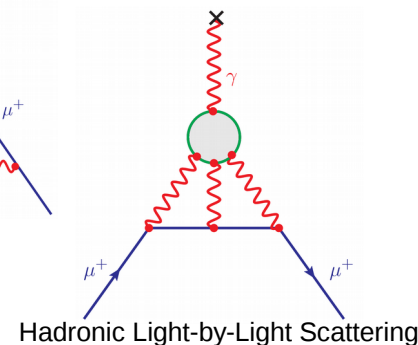
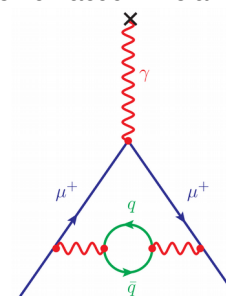
EM transition form factors – Coupling of light and matter

Important for the anomalous magnetic moment of the muon a_μ

$$a_\mu = \frac{g_\mu - 2}{2} = a_\mu^{\text{QED}} + a_\mu^{\text{weak}} + a_\mu^{\text{hadr}}$$

Contribution	Result in 10^{-10} units	
QED(leptons)	11658471.895	± 0.008
Weak	15.4	± 0.2
Hadronic	694.1	± 5.8
Total (SM)	11659181.4	± 5.8
BNL (E821)	11659208.9	± 6.3
Difference	27.5	± 8.6

Hadronic Vacuum Polarization

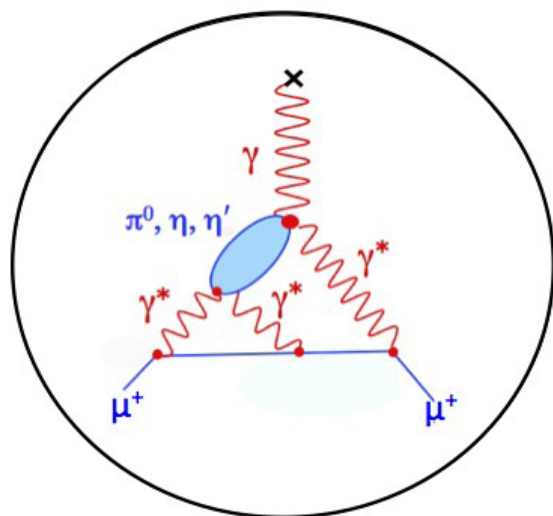


Test of Standard Model !

Prediction completely limited by hadronic contributions!

—————▶ Use experimental input to improve theory!

a_{μ}^{hLBL} not directly related to measurable quantities



- Hadronic models
 - ChPT at lowest energies
 - pQCD at high energies
 - Intermediate region ?

Glasgow Consensus, arXiv:0901.0306
Jegerlehner/Nyffeler, Phys.Rept.477,1

- Data driven approaches
 - Based on dispersion relations
 - Reduce model dependency
 - Reliable error estimates

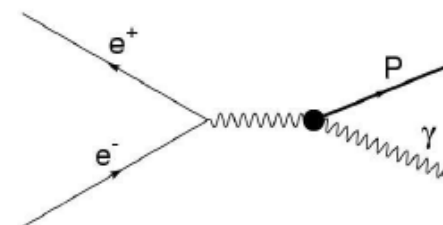
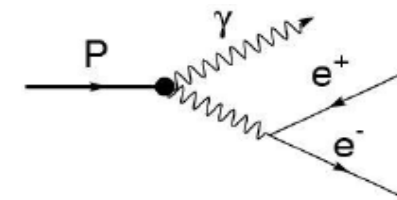
Collangelo, Hoferichter, et al. (Bern)
Vanderhaeghen, Pauk, et al. (Mainz)

- Transition form factors (TFF) as experimental input

Time – like Transition Form Factors:

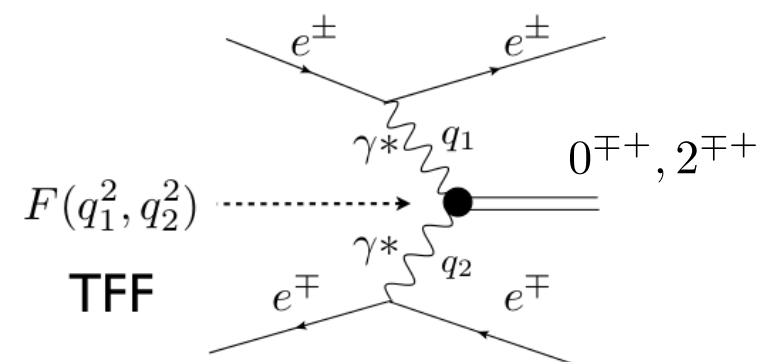
- Dalitz decays
 - $0 < q^2 < M^2$

- Annihilation process
 - $q^2 = s > M^2$

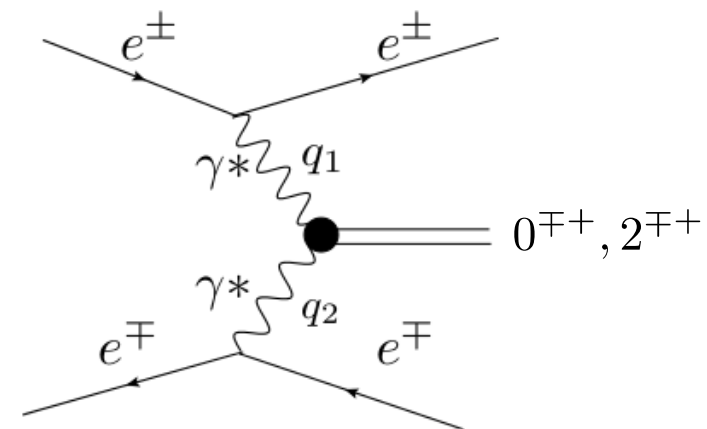


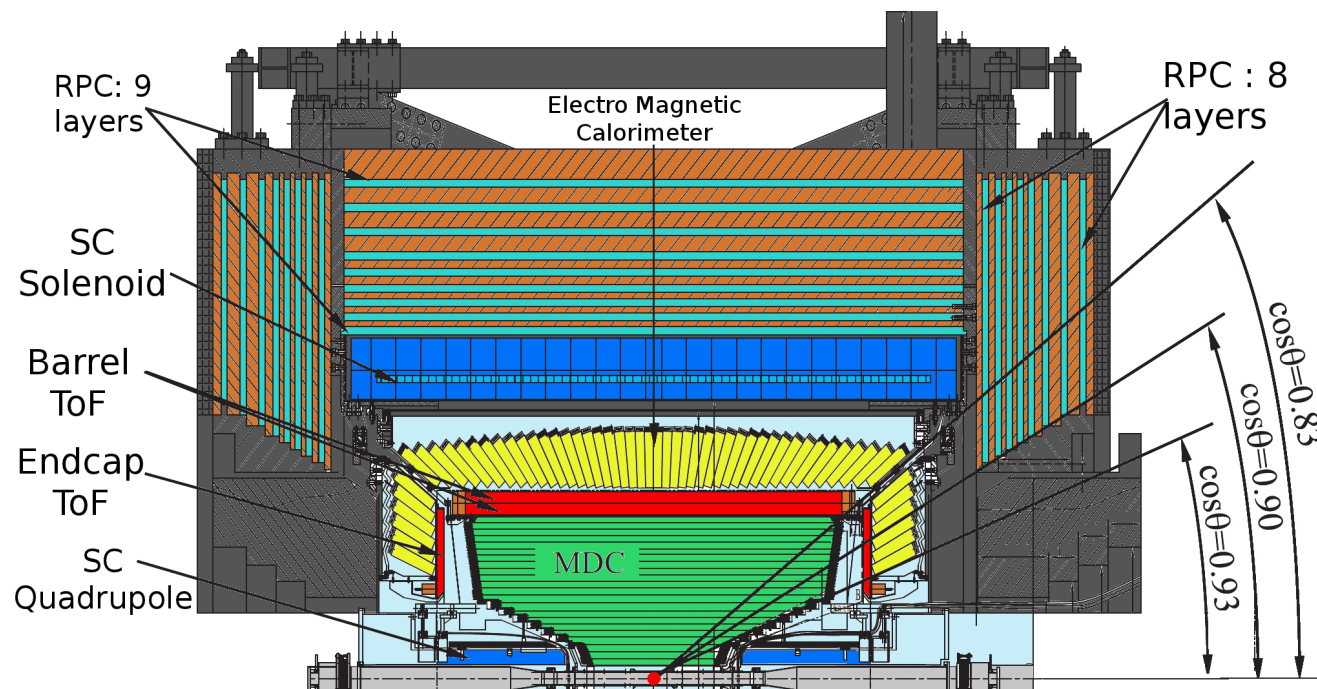
Space – like Transition Form Factors:

- Two-photon production of mesons
 - $F(Q_1^2, Q_2^2), \quad Q^2 = -q^2$



- 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
 - Special tagging detectors recommended





- Main Drift Chamber (MDC)

- $\sigma(p)/p = 0.5\%$
- $\sigma_{dE/dx} = 6.0\%$

- Time-of-flight system (TOF)

- $\sigma(t) = 90\text{ps}$ (barrel)
- $\sigma(t) = 110\text{ps}$ (endcap)

- EMC

- 6240 CsI(Tl) crystals
- $\sigma(E)/E = 2.5\%$
- $\sigma_{z,\phi}(E) = 0.5 - 0.7 \text{ cm}$

- Muon Chambers

- 8 – 9 layers of RPC
- $p > 400 \text{ MeV}/c$
- $\delta R\Phi = 1.4 \sim 1.7 \text{ cm}$

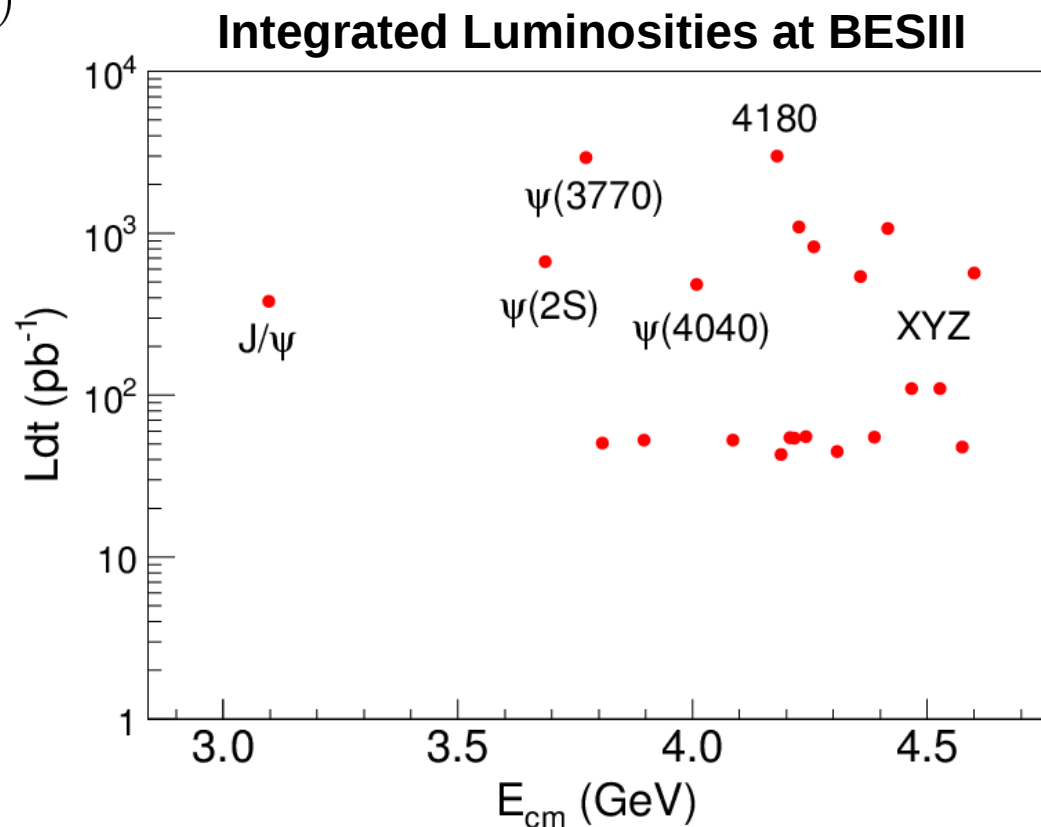
- Superconducting Magnet

- 1 T magnetic field

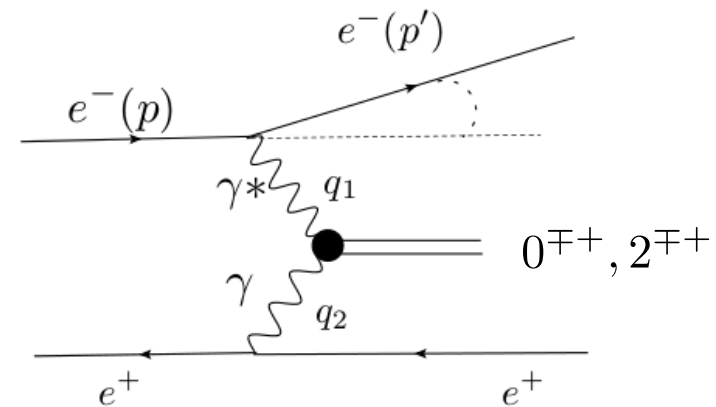
- Operated at BEPCII collider
 - $2.0 \leq \sqrt{s}$ [GeV] ≤ 4.6
 - Design luminosity achieved
 - $\mathcal{L} = 1.0 \times 10^{33} \text{cm}^{-2} \text{s}^{-1}$ at $\psi(3770)$

- Large data sets for
 - Charmonium spectroscopy
 - Charm physics
 - Light hadrons
 - τ and R-scan

$\gamma\gamma$ studies mainly on 2.9 fb^{-1} at $\psi(3770)$



- Reconstruct
 - only one scattered lepton
 - Produced system
- Unmeasured lepton from momentum conservation
 - Require scattering angle to be small
 - Small virtuality
- $F(q_1^2, q_2^2) \rightarrow F(q_1^2, 0) \rightarrow F(q^2)$

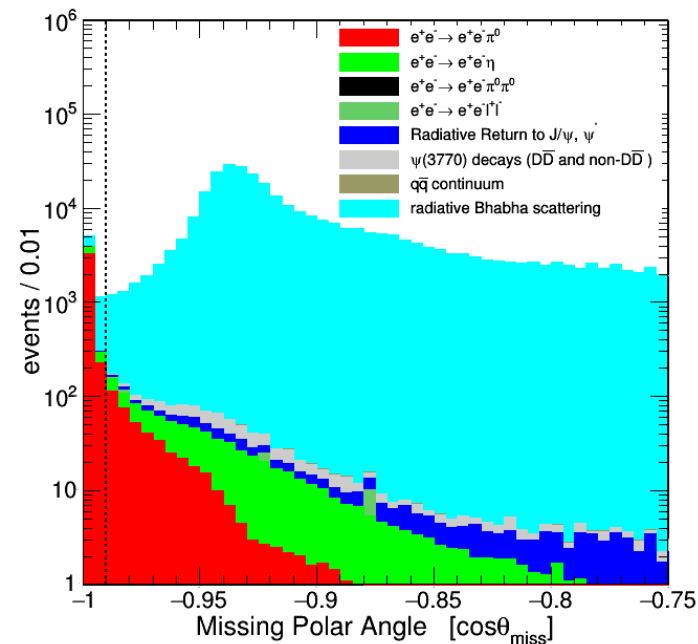


Example: π^0 transition form factor at BESIII

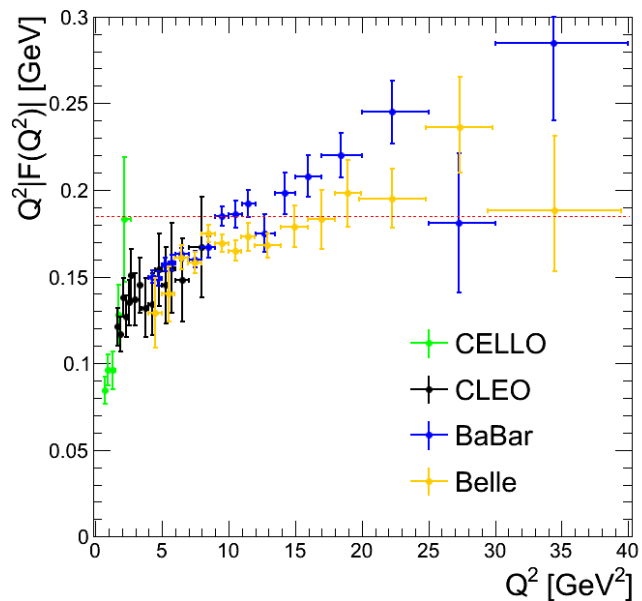
Monte Carlo, $L_{\text{int}} : 2.93 \text{ fb}^{-1} @ \Psi(3770)$

Tagged Lepton: e^+

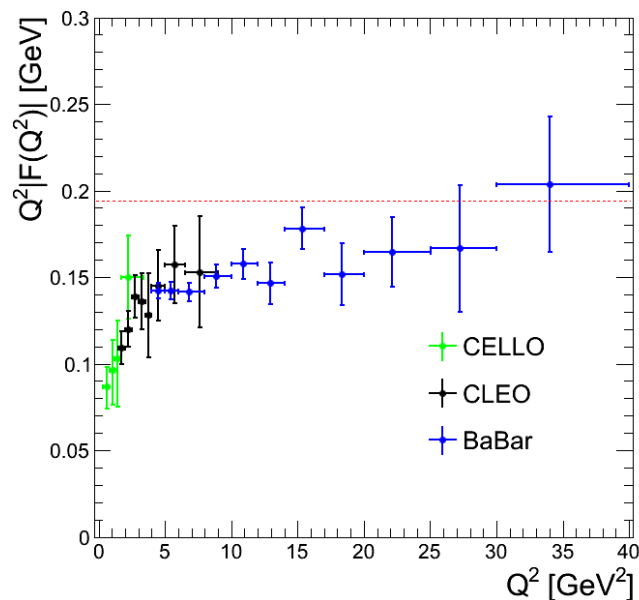
Reconstructed decay: $\pi^0 \rightarrow \gamma\gamma$



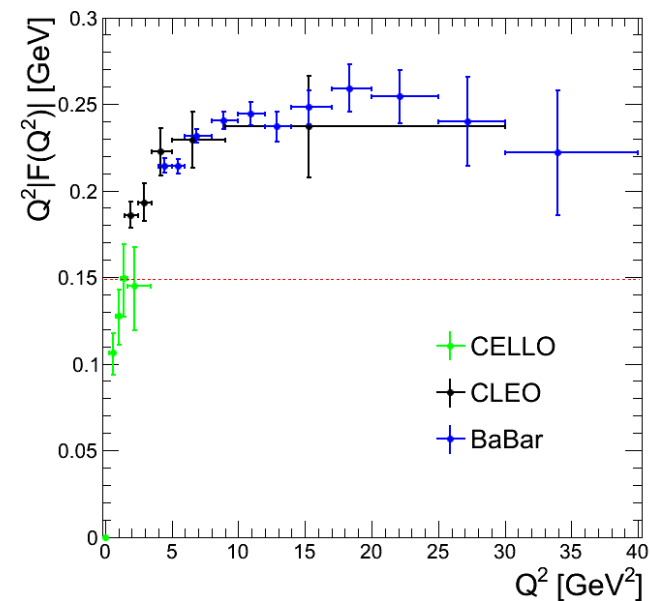
$$e^+e^- \rightarrow e^+e^- \pi^0$$



$$e^+e^- \rightarrow e^+e^- \eta$$



$$e^+e^- \rightarrow e^+e^- \eta'$$



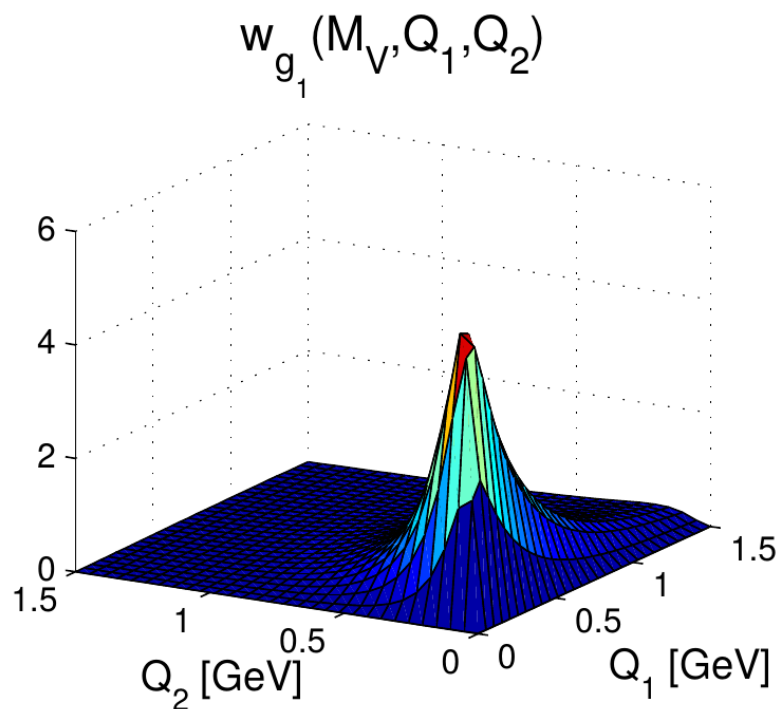
- Recent results from B-factories cover only large Q^2 ($5 < Q^2 [\text{GeV}^2] < 40$)
- Discrepancy for π^0 between BaBar and Belle
- Data scarce at lowest Q^2
- Region of relevance for $(g-2)_\mu$

CELLO: Z.Phys.C49 (1991) 401
 CLEO: Phys.Rev.D57 (1998) 33
 BaBar: Phys.Rev.D80 (2009) 052002
 Phys.Rev.D84 (2011) 052001
 Belle: Phys.Rev.D86 (2012) 092007

2D integral representation for pion-pole contribution by Knecht, Nyffeler (2002):

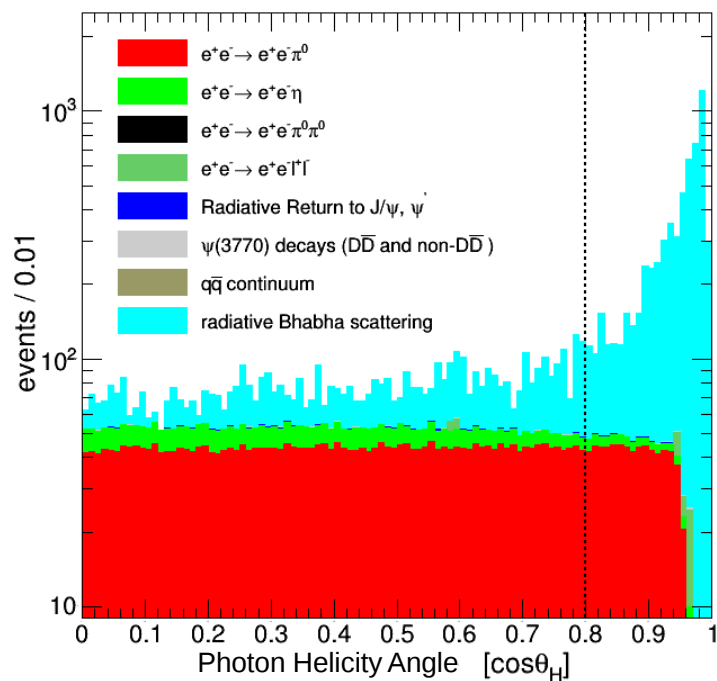
$$a_{\mu}^{\text{HLbL};\pi^0} = \int_0^{\infty} dQ_1 \int_0^{\infty} dQ_2 \sum_i w_i(Q_1, Q_2) f_i(Q_1, Q_2)$$

- Universal weight functions w_i
- Form factor dependence f_i



Relevant momentum region:

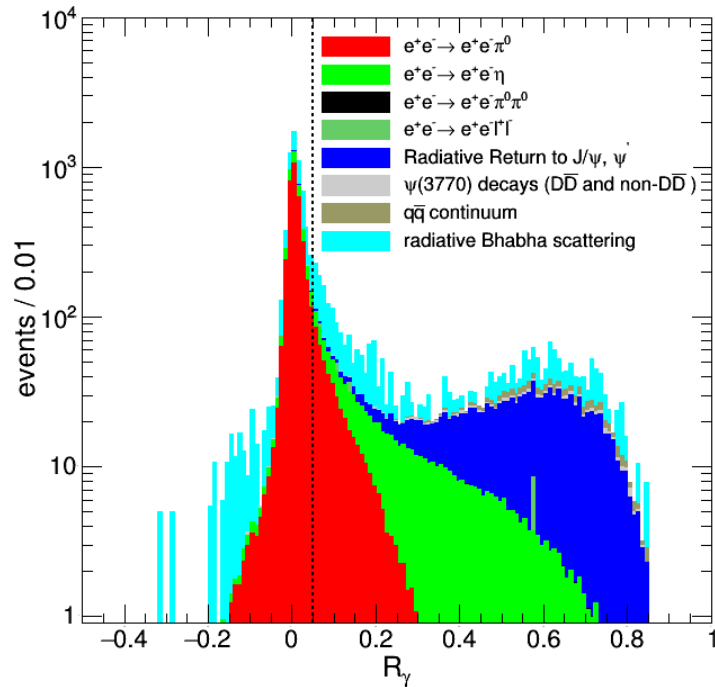
0.25 – 1.25 GeV

BESIII Monte Carlo, $\Psi(3770)$ $L_{\text{int}} : 2.93 \text{ fb}^{-1}$, Tagged Lepton: e^+ 

- Exactly one lepton
- Two to four photons
- $\cos\theta_{\text{untagged}} < -0.99$
- $\cos\theta_{\text{Helicity}} < 0.8$

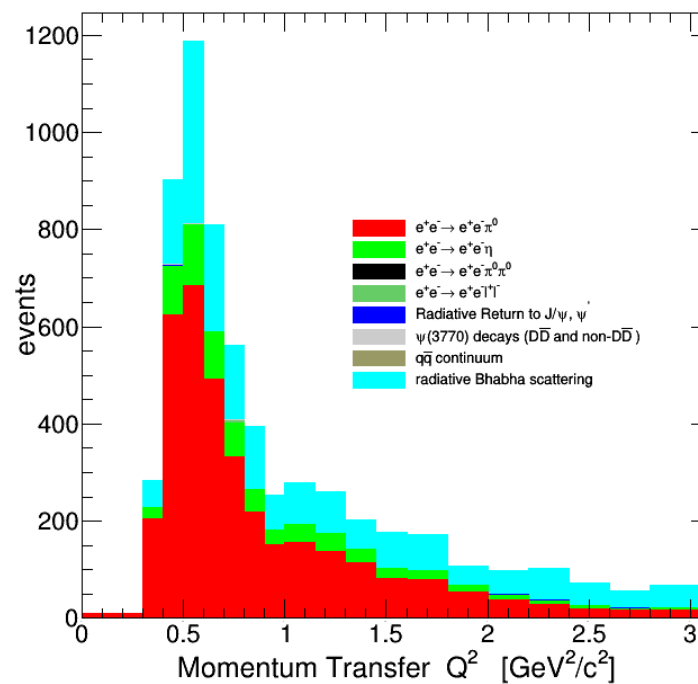
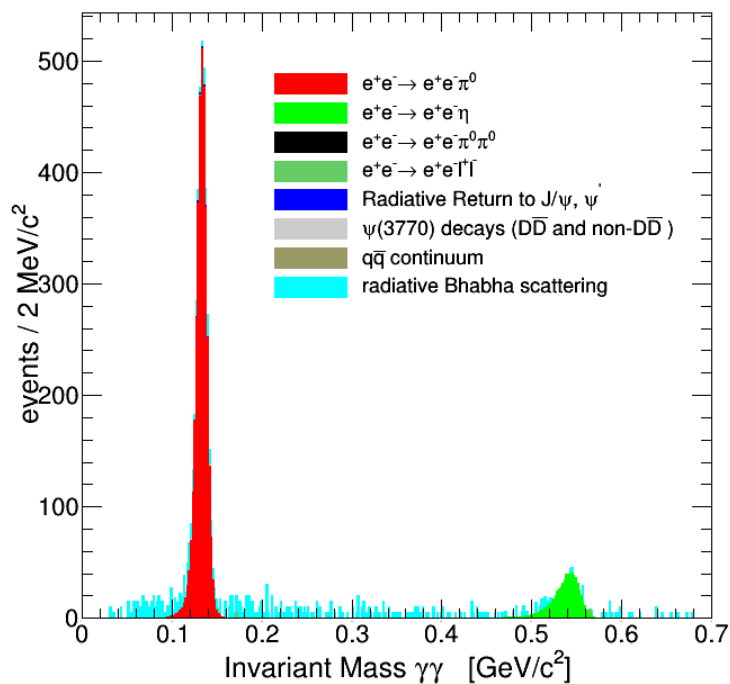
- Angle between γ in π^0 rest frame and π^0 in lab

BESIII Monte Carlo, $\Psi(3770)$
 $L_{\text{int}} : 2.93 \text{ fb}^{-1}$, Tagged Lepton: e^+

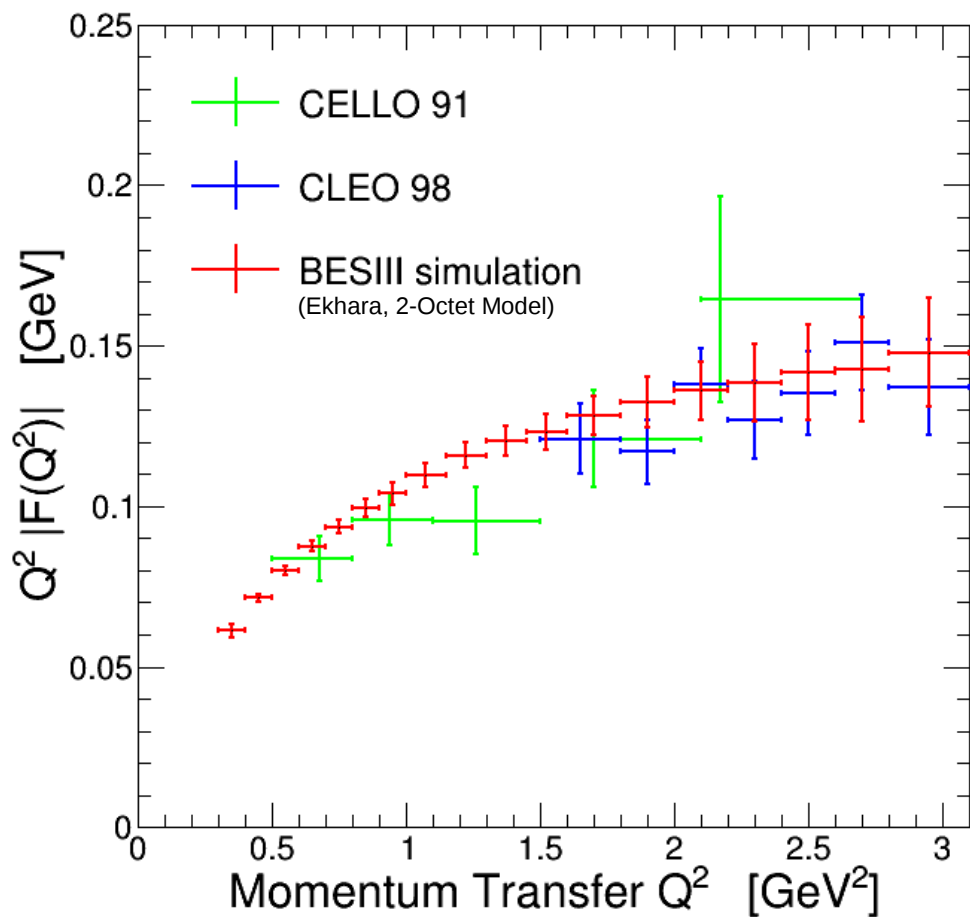


- Exactly one lepton
- Two to four photons
- $\cos\theta_{\text{untagged}} < -0.99$
- $\cos\theta_{\text{Helicity}} < 0.8$
- Reject hadronic background

- Radiative effects result in wrong Q^2
- Useful observable:
$$R_\gamma = \frac{\sqrt{s} - E_{e^\pm \pi^0}^{\text{CMS}} - p_{e^\pm \pi^0}^{\text{CMS}}}{\sqrt{s}}$$
- Reject events with $R_\gamma > 0.05$

BESIII Monte Carlo, $\Psi(3770)$ $L_{\text{int}} : 2.93 \text{ fb}^{-1}$, Tagged Lepton: e^+ 

- Analysis useful for π^0 and η
- Monte Carlo description of background incomplete
- Bkg subtr. by counting π^0 yield per Q^2 bin
- Divide out point-like cross section for $|F(Q^2)|^2$



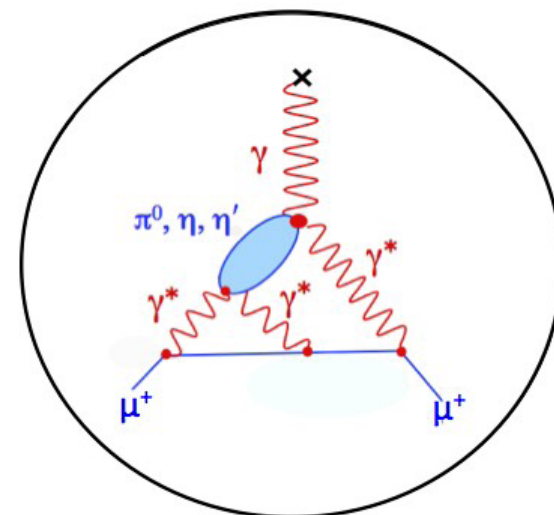
- 2.9 fb $^{-1}$ at $\Psi(3770)$ analyzed
- Covering $0.3 \leq Q^2 [\text{GeV}^2] \leq 3.1$
- Unprecedented accuracy below 1.5 GeV 2
 - Important for a_μ^{hLbL}
- Competitive accuracy up to 3.1 GeV 2
- Soon to be published

- Current accuracy of a_μ : $\sim 6.3 \times 10^{-10}$
- Contribution of π^0 : $\sim 7 \times 10^{-10}$ Knecht, Nyffeler
Phys.Rev.D65 (2002) 073034
- Expected accuracy of new experiments at FNAL and J-PARC: $\sim 1.6 \times 10^{-10}$
- Contributions of η and η' relevant!

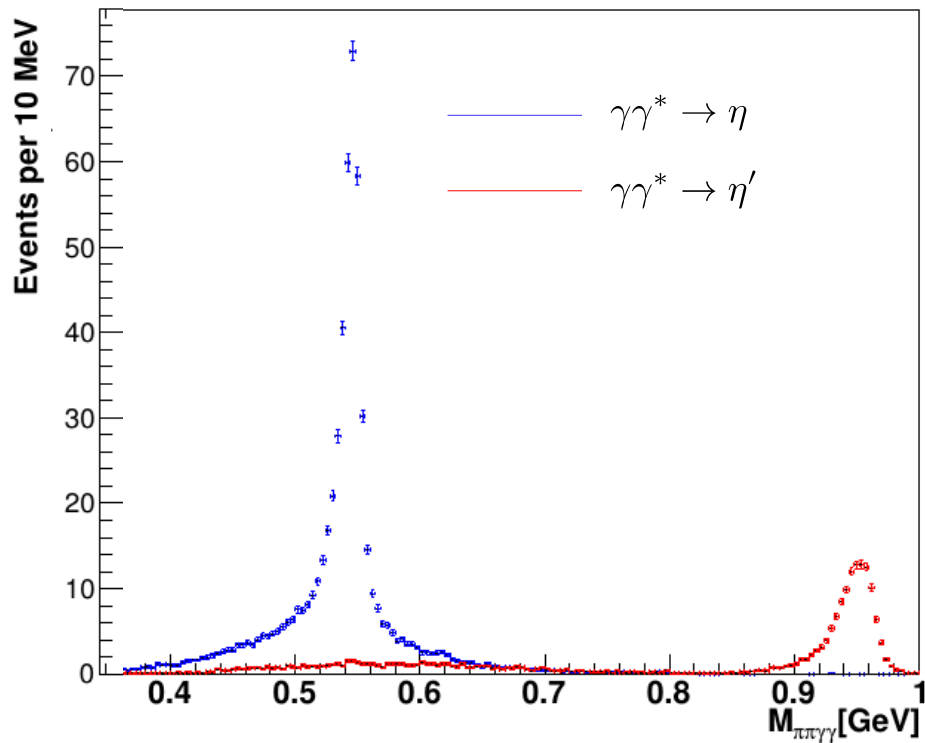
$$\eta \sim 1.5 \times 10^{-10}$$

$$\eta' \sim 1.5 \times 10^{-10}$$

Knecht, Nyffeler
Phys.Rev.D65 (2002) 073034



BESIII Simulation: $2.9 fb^{-1}$ @ 3.773 GeV

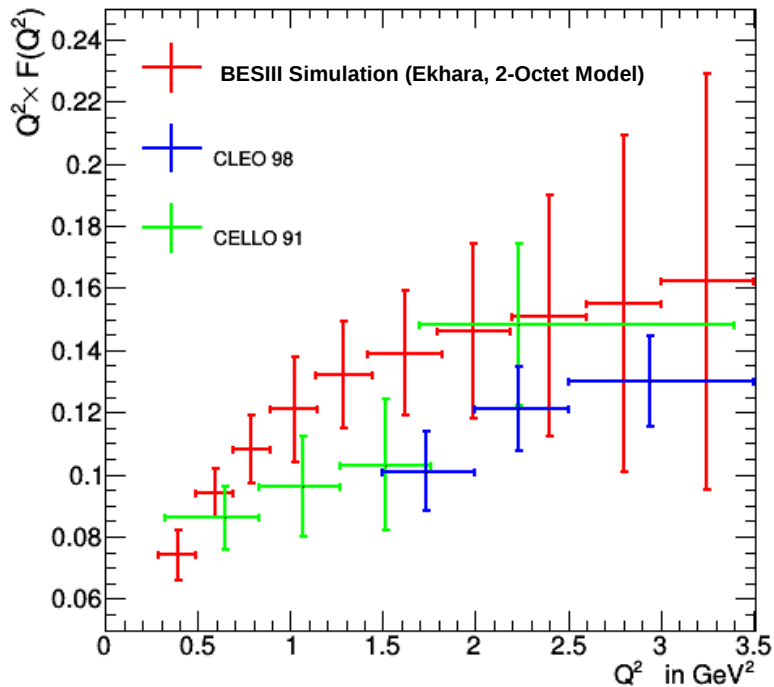


- $\eta \rightarrow \pi^+ \pi^- \pi^0$
- $\eta' \rightarrow \pi^+ \pi^- \eta$
- Select:
 - one electron or positron
 - two oppositely charged pions
 - two photons
- $\cos\theta_{\text{untagged}} > 0.99$
- Reject hadronic background
- Mass window cuts on $\gamma\gamma$ invariant mass
- Kinematic fit
- Relatively small background contamination

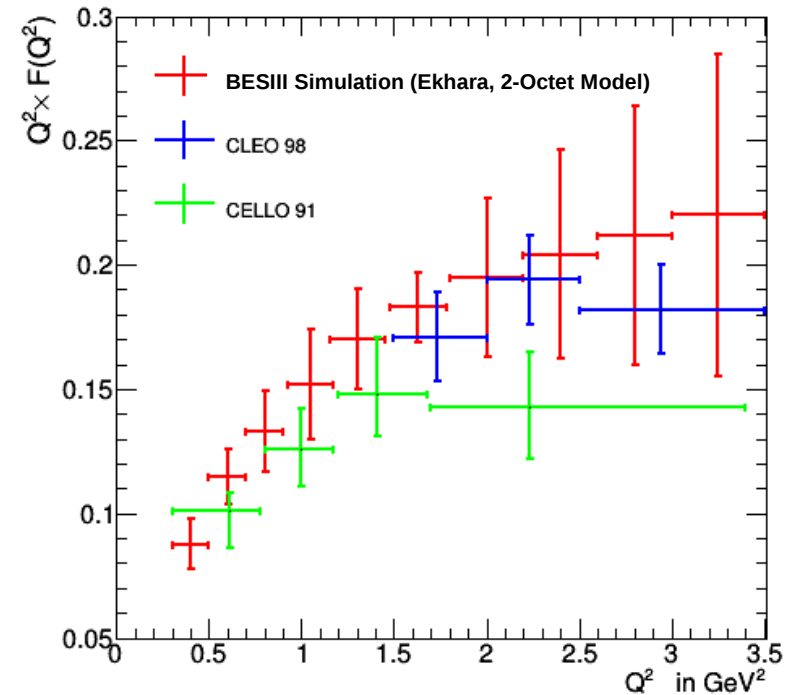
JGU Space-like η, η' Transition Form Factor



$$F_{\eta, \gamma, \gamma^*}(Q^2)$$



$$F_{\eta', \gamma, \gamma^*}(Q^2)$$

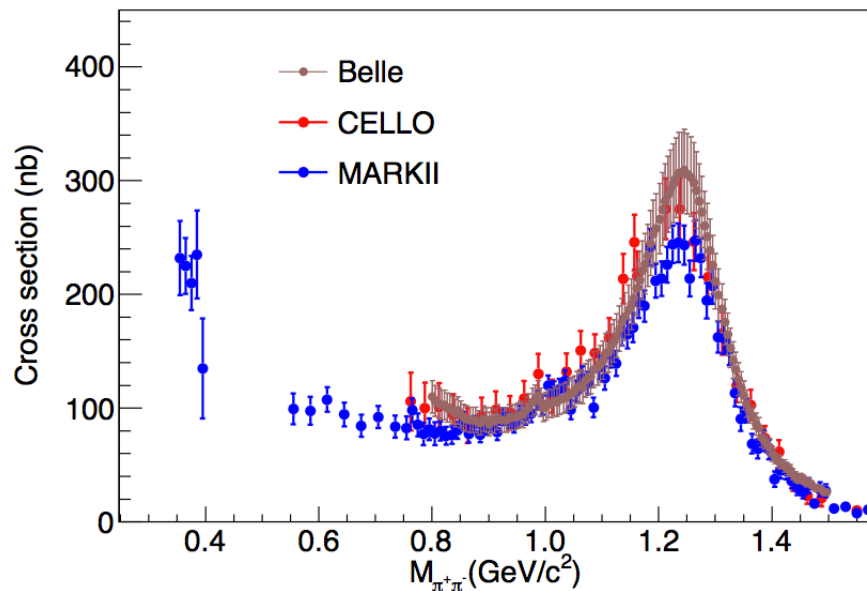


- Statistics compatible to previous measurements
 - only one decay channel of η and η' analyzed at BESIII
 - more data available ($\times 3.5$)
- Systematic studies to be done

JG|U Space-like $\pi^+\pi^-$ Transition Form Factor

- Additional motivations:
 - Resonance parameters
 - Pion polarizabilities, pion structure
 - Essential for dispersive frameworks
 - Rescattering effects in low mass region
- Until recently only untagged measurements:

Collangelo, Hoferichter, Procura, Stoffer
JHEP 1409,091; JHEP1509,074



MarkII, Phys. Rev. D42 (1990) 5
CELLO, Z. Phys. C56 (1992) 381
Belle, Phys. Rev D75 (2007) 051101

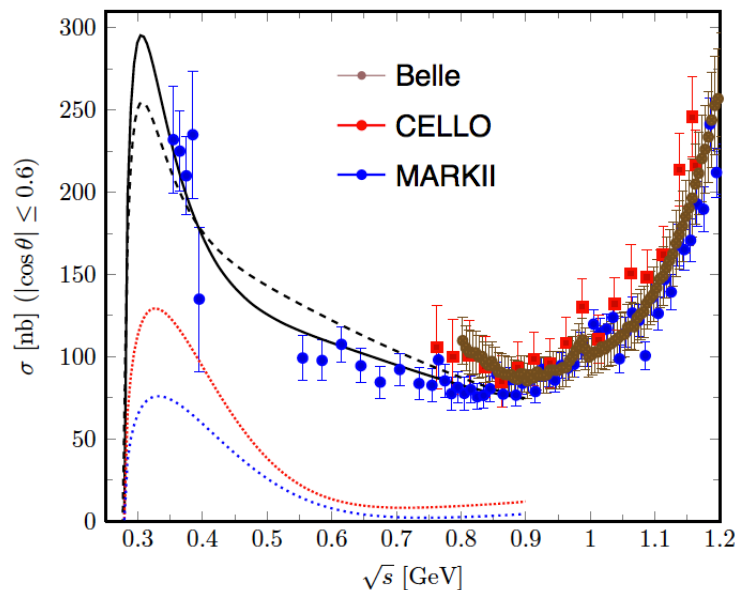
- First single-tagged result on $\pi^0\pi^0$ by Belle

Phys. Rev. D93 (2016) 032003

JG|U Space-like $\pi^+\pi^-$ Transition Form Factor

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Calculations by
Assmussen, Masjuan, and Vanderhaeghen:

Untagged

Single-Tag ($Q_1^2 = 0.5 \text{ GeV}^2$)

Double-Tag ($Q_1^2 = Q_2^2 = 0.5 \text{ GeV}^2$)

- First single-tagged result on $\pi^0\pi^0$ by Belle

Phys. Rev. D93 (2016) 032003

- At BESIII: Single-Tag measurement

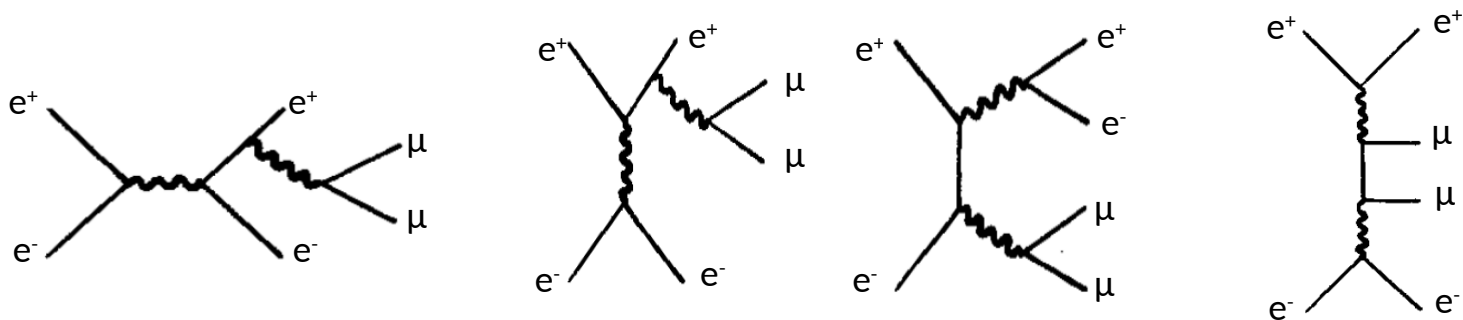
- Event selection analogous to single pseudoscalar analysis

- Major Backgrounds:

- $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$

- Includes two-photon production of muon pairs

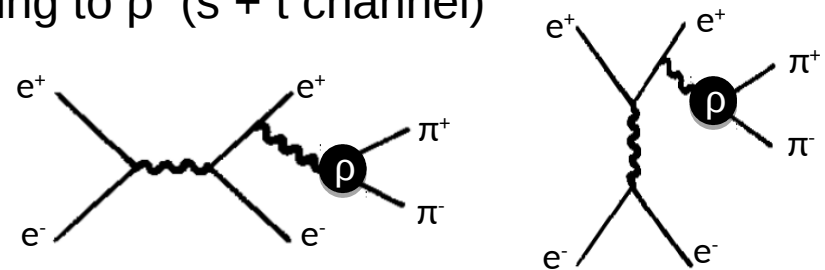
- Precise MC generators available from LEP era (BdkRC + Diag36ABC)



- $e^+e^- \rightarrow e^+e^-\pi^+\pi^-$

- Radiative Bhabha scattering coupling to ρ (s + t channel)

- MC generators being developed



- Training multivariate methods to suppress muon background
 - To be replaced with multivariate method trained for muon suppression

- Subtract ρ contribution

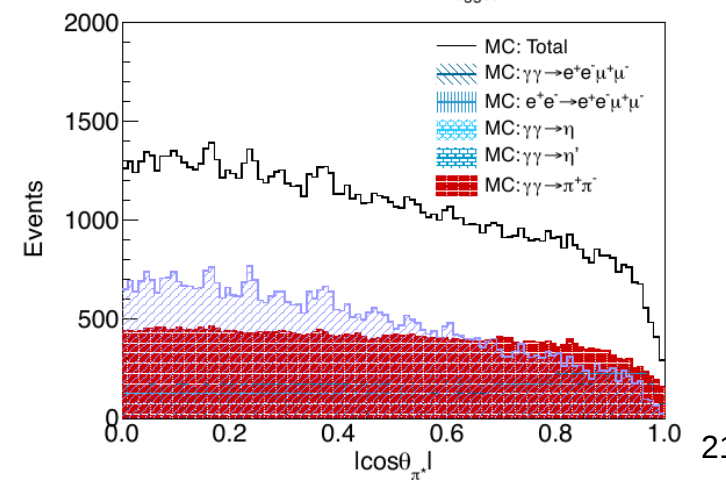
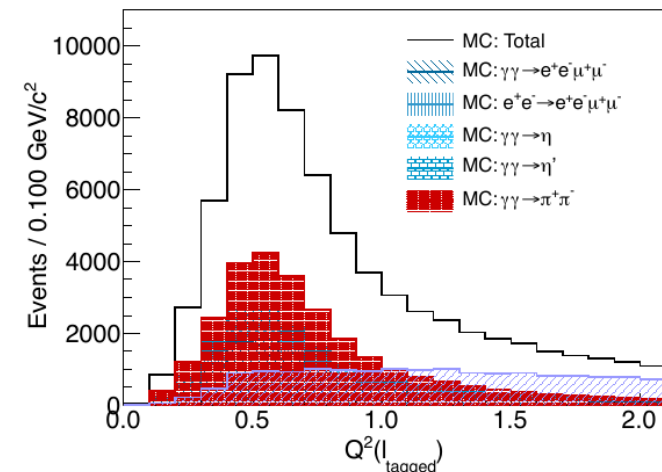
- Fit peak in data using shape from theory

- Study $\pi^+\pi^-$ invariant mass in bins of Q^2 and $\cos\theta^*$

- First single-tag measurement of $\pi^+\pi^-$!

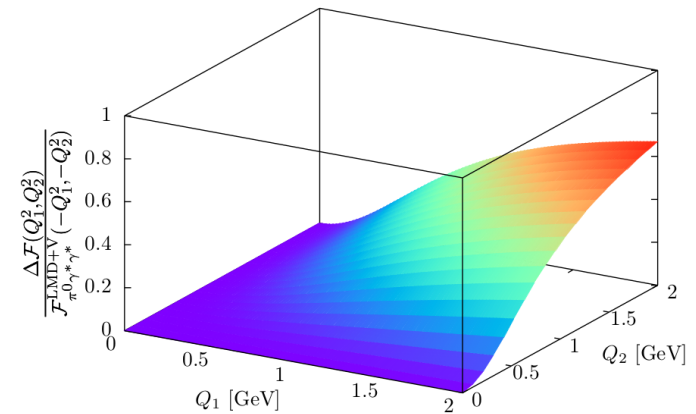
- Access to:

- low momentum transfers $0.2 < Q^2 [\text{GeV}^2] < 2.0$
 - low invariant masses $m_{\pi^+\pi^-} < M [\text{GeV}] < 2.0$
 - full coverage of $\cos\theta^*$



- Measurement of $F_{\gamma^* \gamma^* \pi^0}(Q_1^2, Q_2^2)$ never done before!

- BESIII collected $> 10 \text{ fb}^{-1}$ at $3.77 < \sqrt{s} [\text{GeV}] < 4.6$
- 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

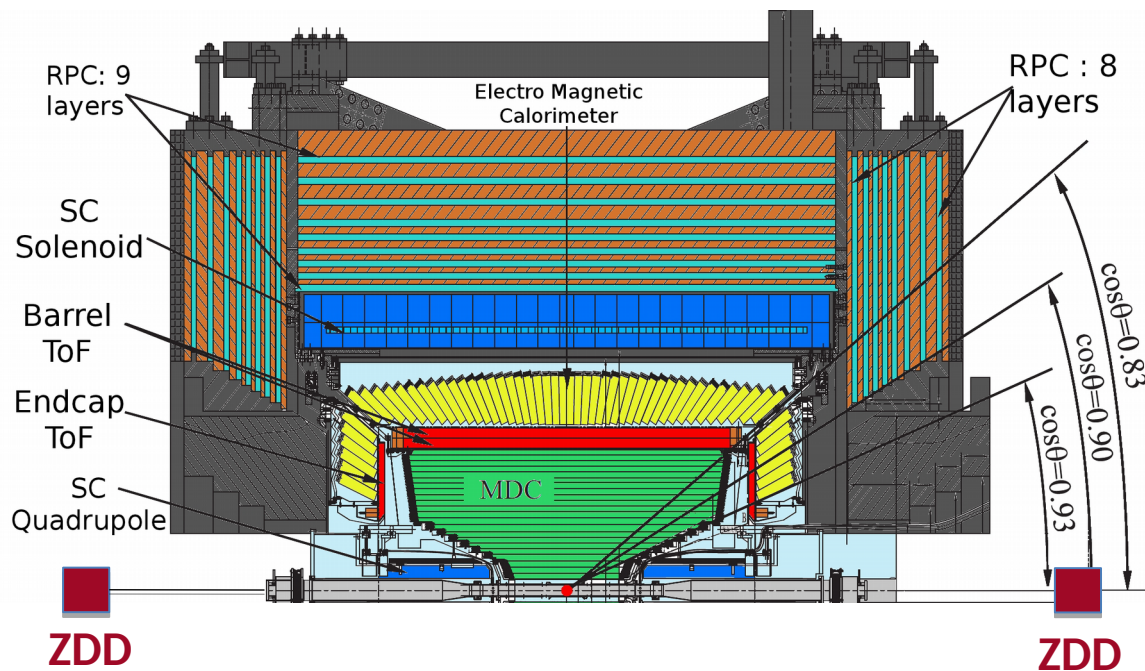
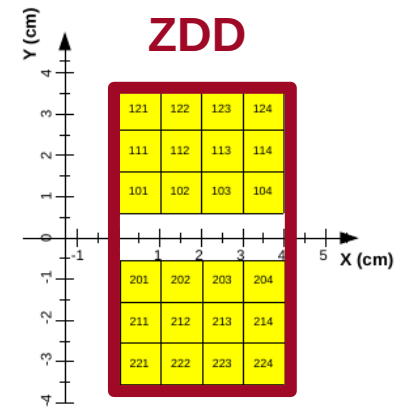
- General two-photon cross section:

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

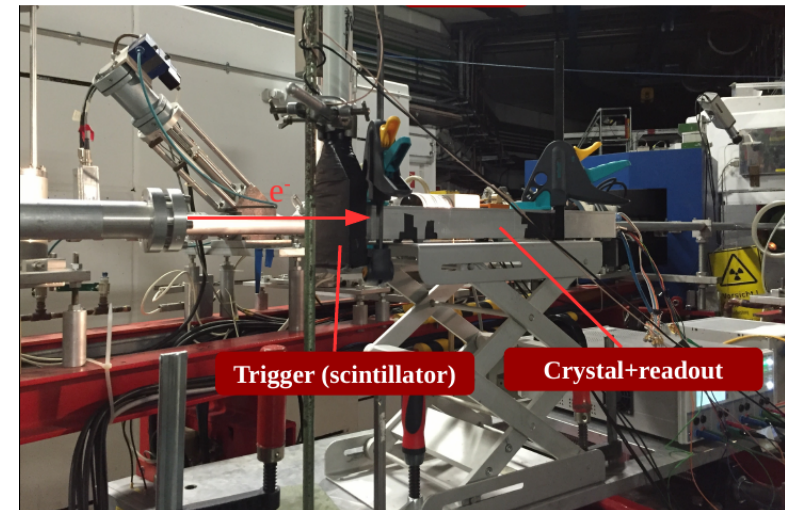
- $\tilde{\phi}$: azimuthal angle between lepton planes in $\gamma^* \gamma^*$ rest frame
 - Allows to disentangle form factor contributions of multi-meson and tensor states
 - Requires precise measurement of angles and high statistics

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: Two arrays of 12 LYSO crystals on each side



In-beam tests at MAMI (Mainz)



- Two-photon physics program established at BESIII
 - Single-tag measurements of π^0 , η , and η' transition form factors
 - Unprecedented accuracy for $Q^2 < 1.5 \text{ GeV}^2$
 - Single-tag measurement of $\pi^+\pi^-$
 - First measurement
 - low Q^2 , masses from threshold, full helicity angle coverage
 - To be extended to neutral final states
 - First double-tagged measurement $\gamma^*\gamma^* \rightarrow \pi^0$ started
 - New prospects from tagging detectors
 - Untagged measurements for light hadron spectroscopy