The $\gamma\gamma$ Physics Program at BESIII

September 20, 2016 | Christoph Florian Redmer
for the BESIII Collaboration

The 14th International Workshop on Tau Lepton Physics

Motivation

$$a_\mu = \frac{g_\mu - 2}{2} = \frac{\alpha}{2\pi} + ... = 0.001161...$$

$$a_\mu^{theo} = a_\mu^{QED} + a_\mu^{weak} + a_\mu^{hadr}$$

Contribution	Result in 10^{-10} units		
QED(leptons)	11658471.885	± 0.004	Kinoshita et al. (2012)
Weak	15.4	± 0.2	Czarnecki et al. (2003)
HVP(leading order)	692.3	± 4.2	Davier et al. (2011)
HVP(higher order)	-9.84	± 0.07	Hagiwara et al. (2009)
HLBL	11.6	± 4.0	Jegerlehner, Nyffler (2009)
Total	11659181.3	± 5.8	
Experiment	11659208.9	± 6.3	

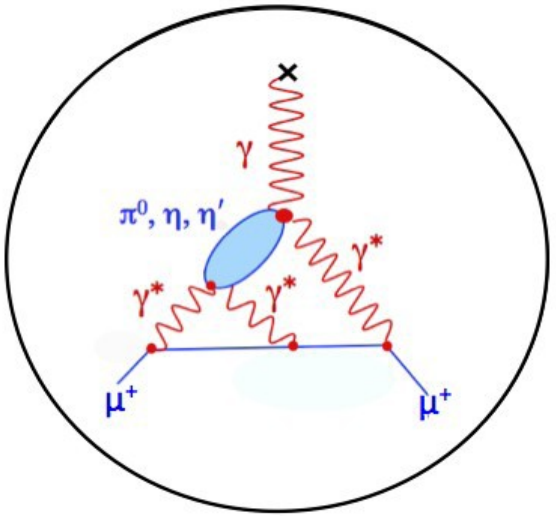
Prediction completely limited by hadronic contributions !

Challenge:

Perturbative methods cannot be applied in the relevant energy regime

Hadronic Light-by-Light

a_μ^{hLBL} not directly related to measurable quantities



- Interaction of virtual mesons with real/virtual photons
- Hadronic models
  - ChPT at lowest energies
  - pQCD at high energies
  - Intermediate region ?

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

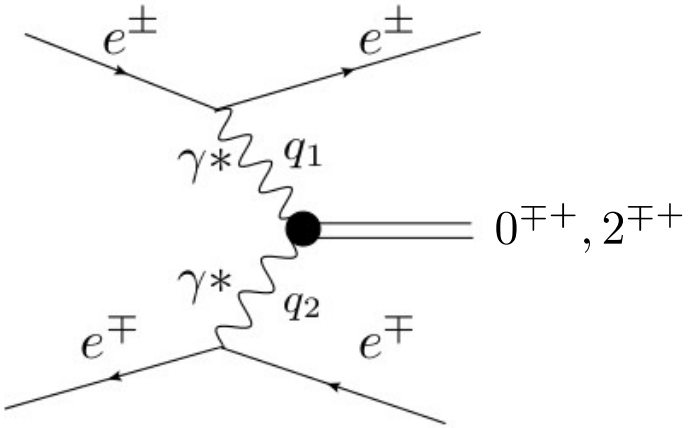
- Data driven approaches
  - Based on dispersion relations
  - Reduce model dependency
  - Reliable error estimates

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

- Transition form factors (TFF) as experimental input

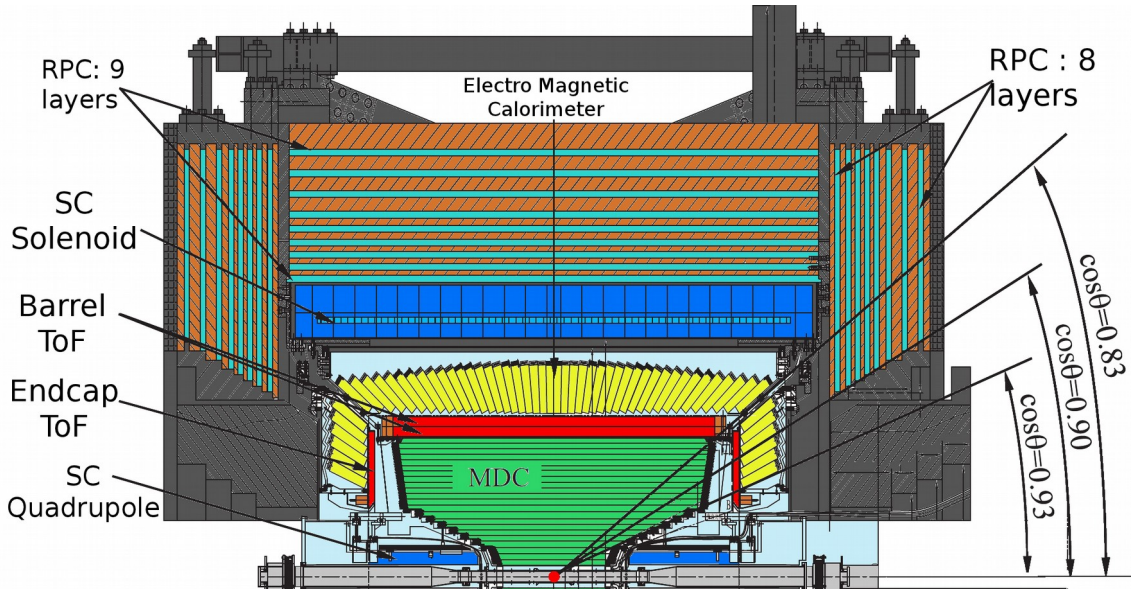
Two-Photon Collisions

- 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
  - Special tagging detectors recommended



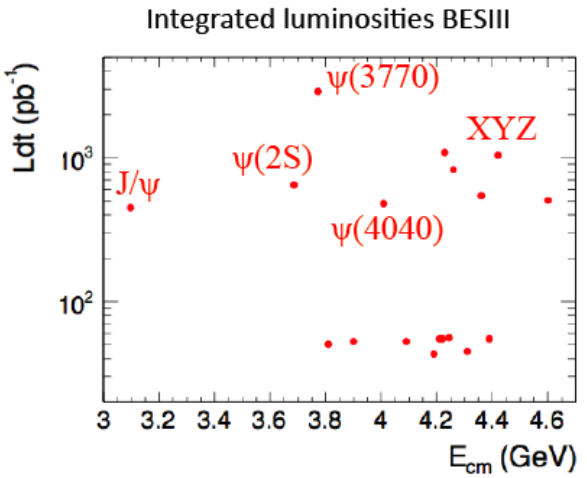
BESIII Detector

NIM A614 (2010) 345



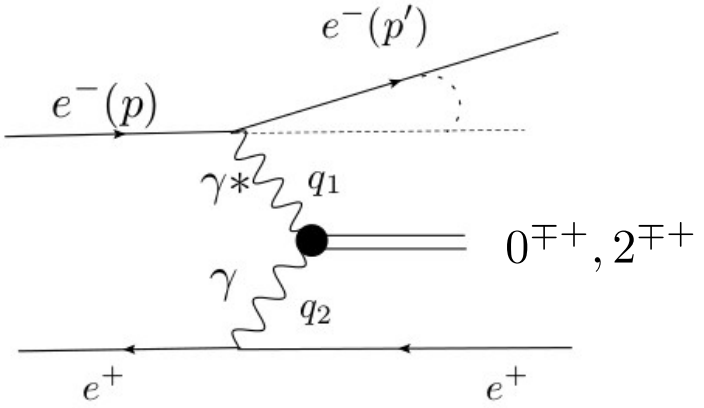
- Main Drift Chamber (MDC)
  - σ(p)/p = 0.5%
  - $\sigma_{dE/dx}$ = 6.0%
- Time-of-flight system (TOF)
  - σ(t) = 90ps (barrel)
  - σ(t) = 110ps (endcap)
- EMC
  - 6240 CsI(Tl) crystals
  - σ(E)/E = 2.5%
  - $\sigma_{Z,\Phi}$(E) = 0.5 – 0.7 cm
- Muon Chambers
  - 8 – 9 layers of RPC
  - p>400 MeV/c
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

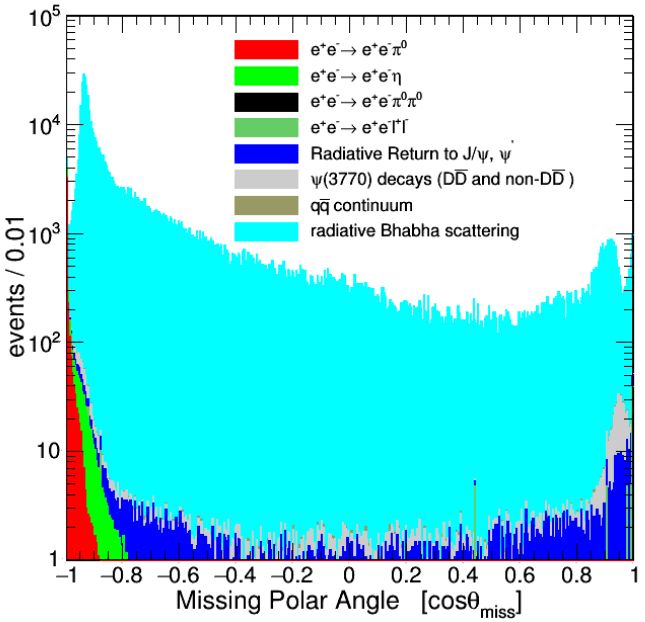
- Operated at BEPCII collider
  - $2.0 \leq \sqrt{s}\ [\mathrm{GeV}] \leq 4.6$
  - Design luminosity achieved
    - $\mathcal{L} = 1.0 \times 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ at $\psi(3770)$
- Large data sets for
  - Charmonium Spectroscopy
  - Charm Physics
  - Light hadrons
  - τ and R-Scan



Single-Tag Measurements

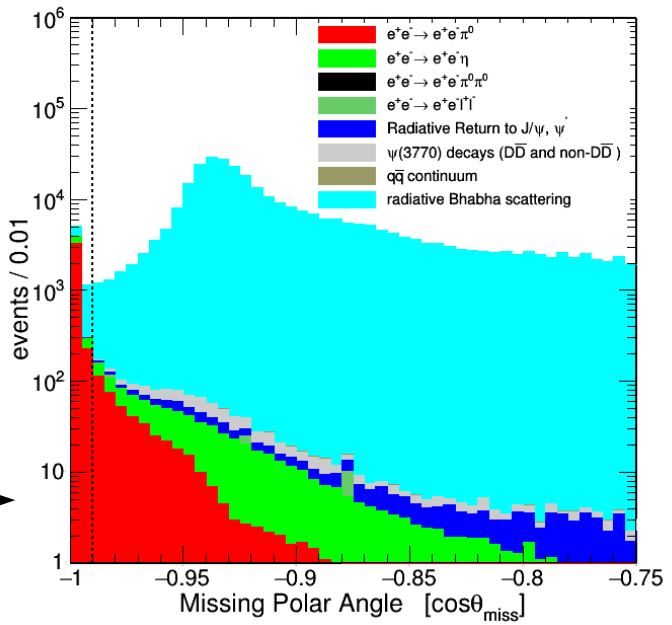
- Reconstruct
  - only one scattered lepton
  - Produced system
- Unmeasured lepton from momentum conservation
  - Require scattering angle to be small
  - Small virtuality
  - $F(q_1^2, q_2^2) \rightarrow F(q_1^2, 0) \rightarrow F(q^2)$





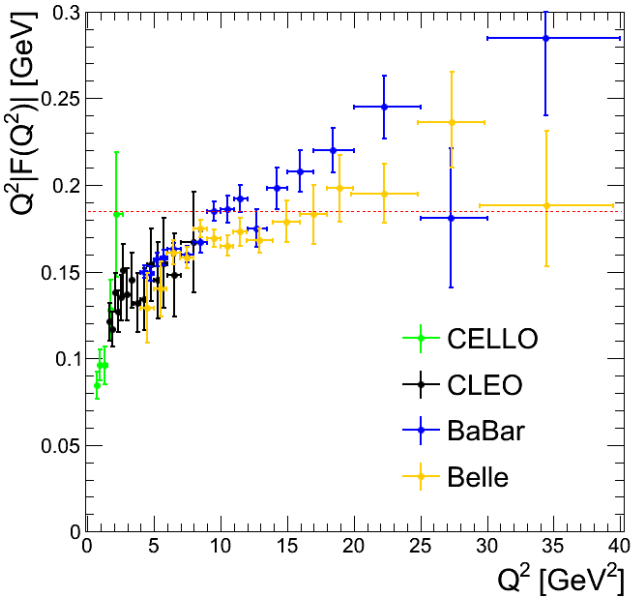
Example: π^0, η
BESIII Monte Carlo,
L_{int}: 2.93 fb^{-1} @ Ψ(3770)
Tagged Lepton: e$^+$

zoom

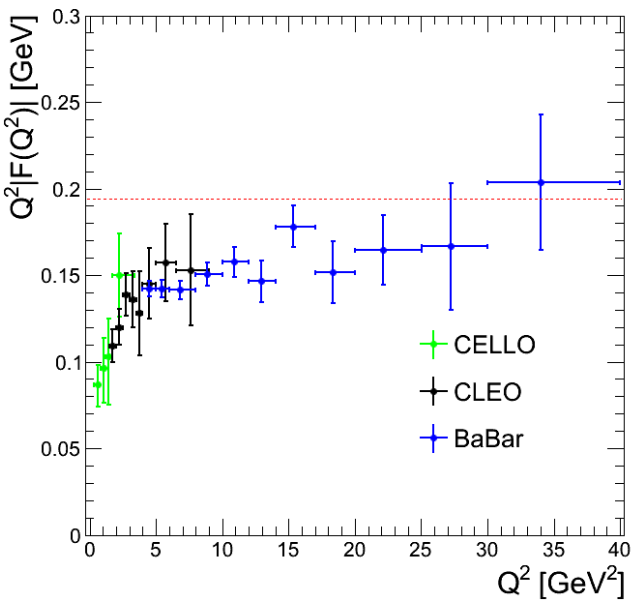


Existing Data

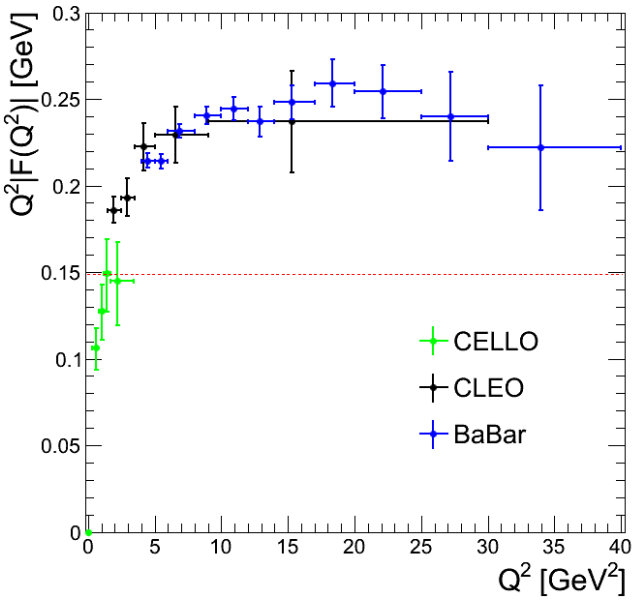
$e^+e^- \rightarrow e^+e^- \pi^0$



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



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



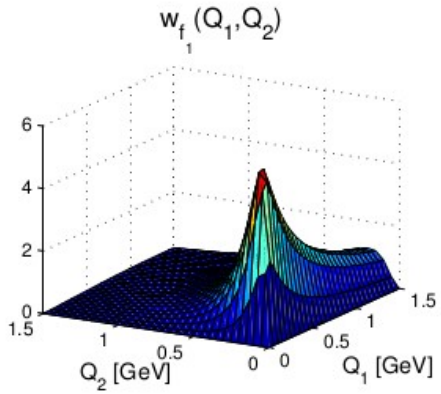
- Recent results from B-factories cover only large Q^2 ($5 < Q^2$ [GeV^2] < 40)
  - Discrepancy for π^0 between BaBar and Belle
- Data scarce at lowest Q^2
  - Region of relevance for (g-2)μ

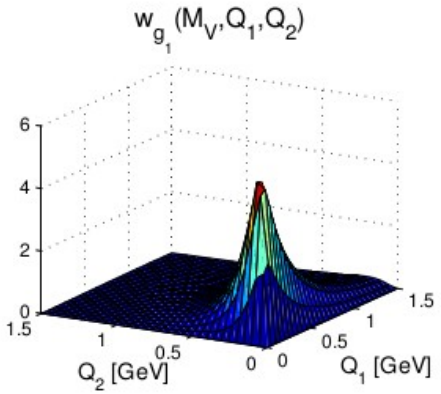
CELLO: Z.Phys.C49 (1991) 401
CLEO: Phys.Rev.D57 (1998) 33
BaBar: Phys.Rev.D80 (2009) 052002
Phys.Rev.D84 (2011) 052001
Belle: Phys.Rev.D86 (2012) 092007

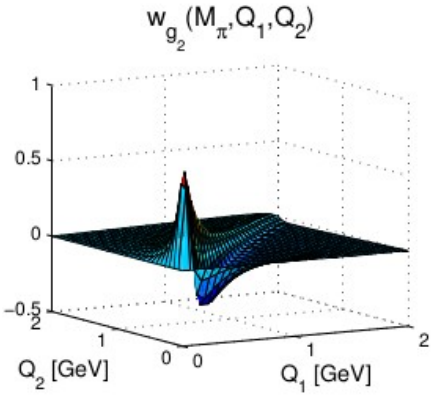
Relevant Energy Range

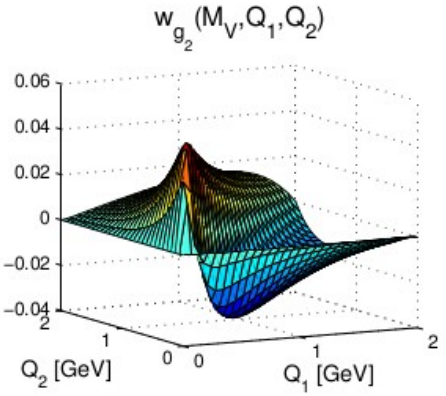
2D integral representation for pion-pole contribution by Knecht, Nyffeler (2002):

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









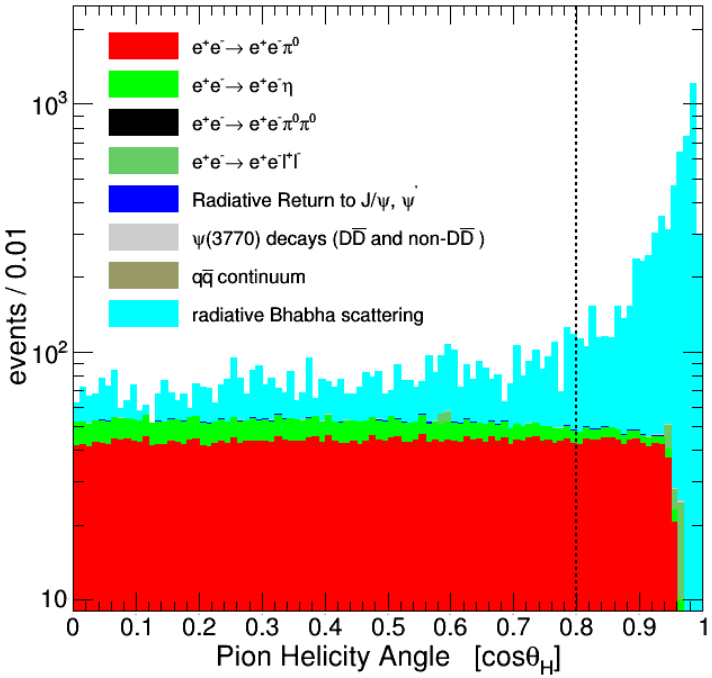
- Universal weight functions w_i
- Form factor dependence f_i

Relevant momentum regions:

0.25 – 1.25 GeV

Space-like π^0 Transition Form Factor

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



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

- Angle between γ in π^0 rest frame and π^0 in lab
- Flat for signal
- Peaked for background
- Reject events with $\cos(\theta_H) > 0.8$

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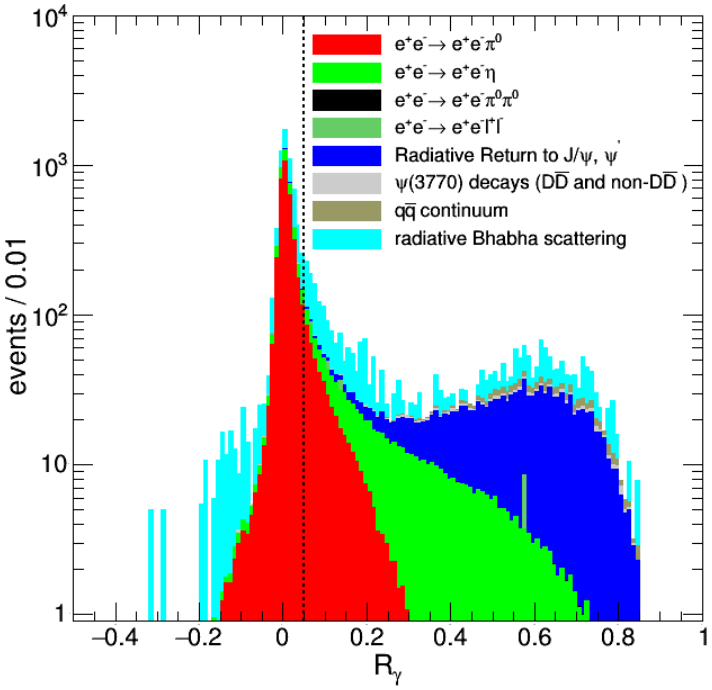

- ISR results in wrong Q^2
- Useful observable: $R_\gamma = \frac{\sqrt{s} - E^{CMS}_{e^\pm \pi^0, \eta} - p^{CMS}_{e^\pm \pi^0, \eta}}{\sqrt{s}}$
- If ISR, $R_\gamma = \frac{2E_\gamma}{\sqrt{s}}$
- Reject events with $R_\gamma > 0.05$

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

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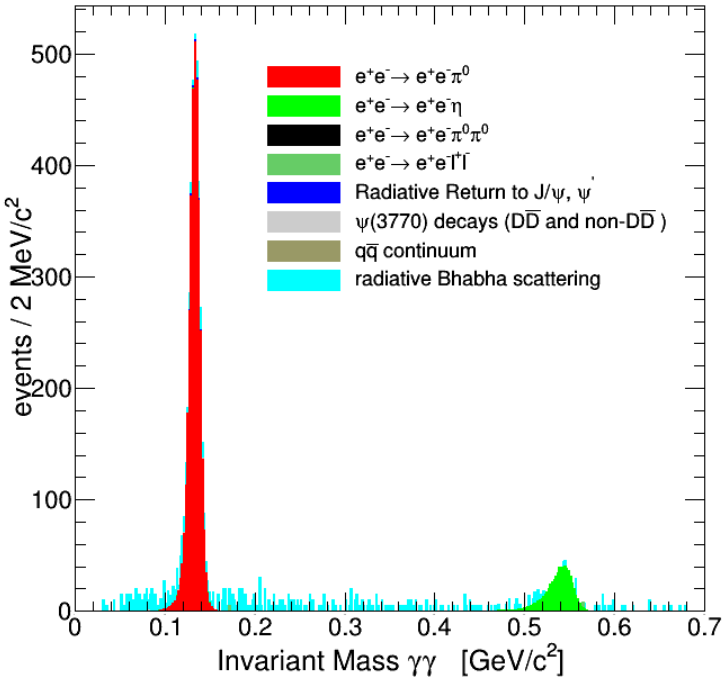
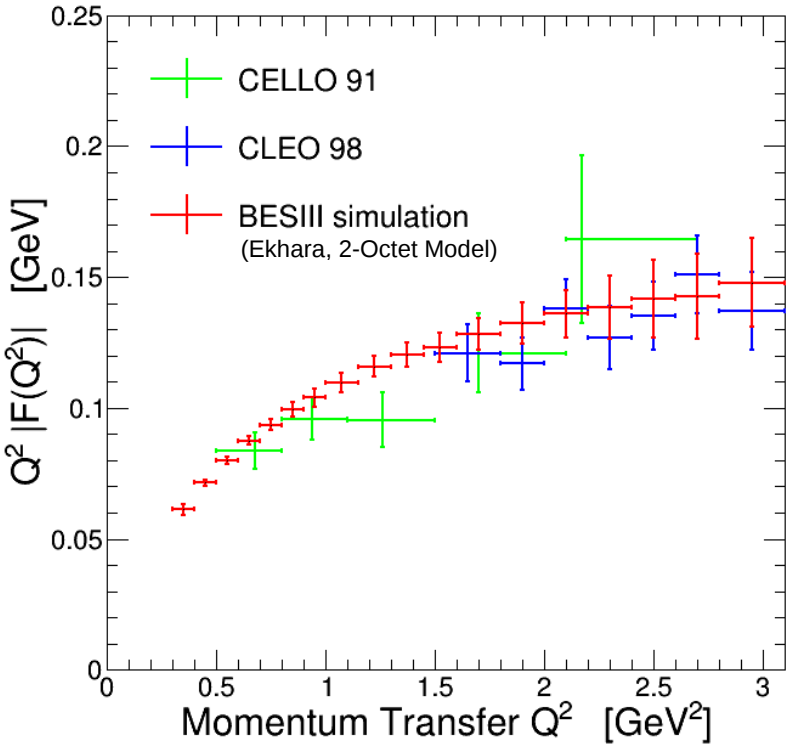


- Exactly one lepton
- Two to four photons
- $\cos\theta_{untagged} < -0.99$
- $\cos\theta_{Helicity} < 0.8$
- Reject hadronic background

- Analysis useful for π^0 and η
- Monte Carlo description of background incomplete

Space-like π^0 Transition Form Factor



- Only statistical errors shown
- Systematic uncertainty dominated by background subtraction

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

- Bkg subtr. by counting π^0 yield per Q^2 bin
- $|F(Q^2)|^2$ extracted by division by WZW-MC

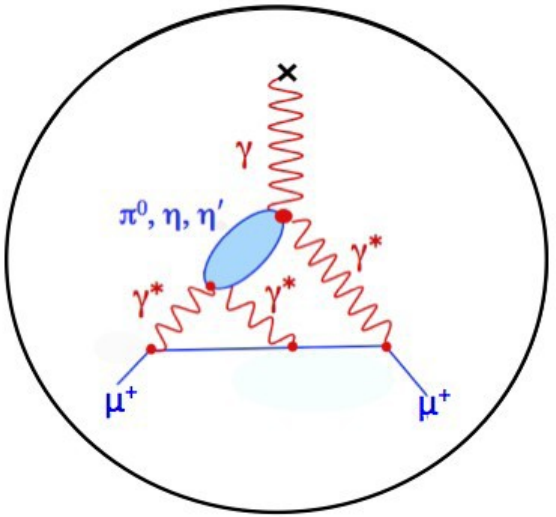
- Full BESIII $\Psi(3770)$ data set analyzed
- Competitive accuracy up to 3.1 GeV^2
- Unprecedented accuracy below Q^2 =1.5 GeV^2

Contribution to a_μ

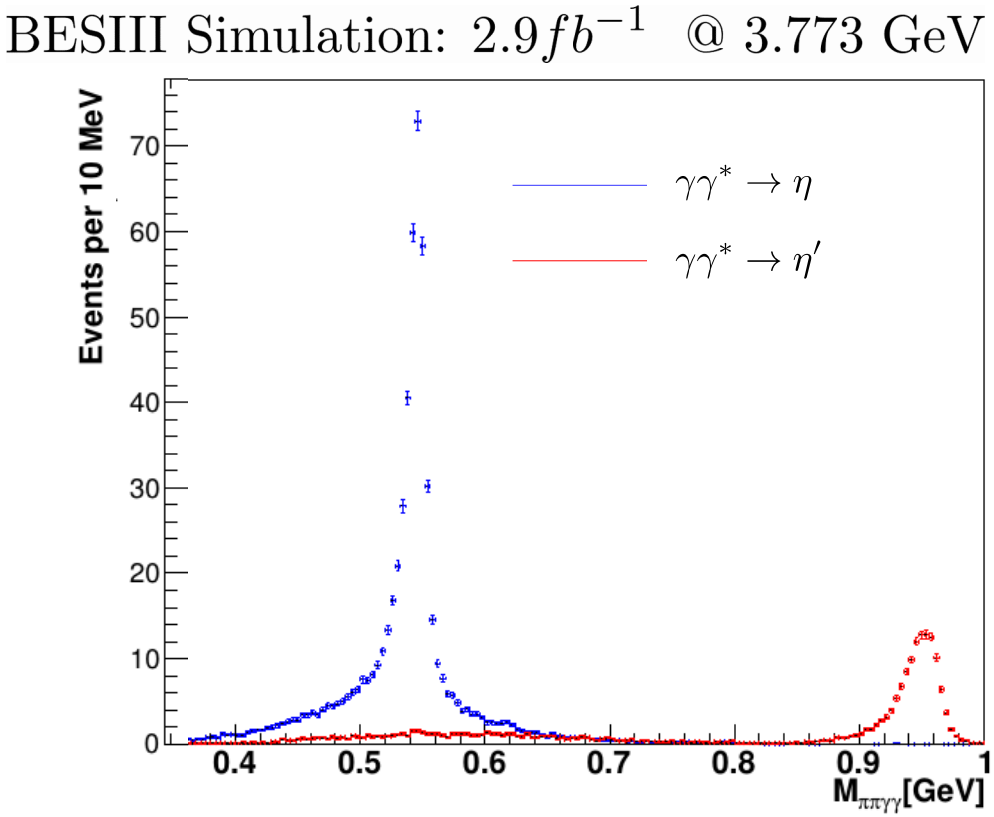
- Current accuracy of a_μ : $\sim 6.3 \times 10^{-10}$
- Contribution of π^0 : $\sim 7 \times 10^{-10}$ Knecht,Nyffeler Phys.Rev.D65 (2002) 073034
- Expected accuracy of new experiments at FNAL and J-PARC: $\sim 1.6 \times 10^{-10}$
- Contributions of η and η' relevant!

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

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



Space-like η,η' Transition Form Factor

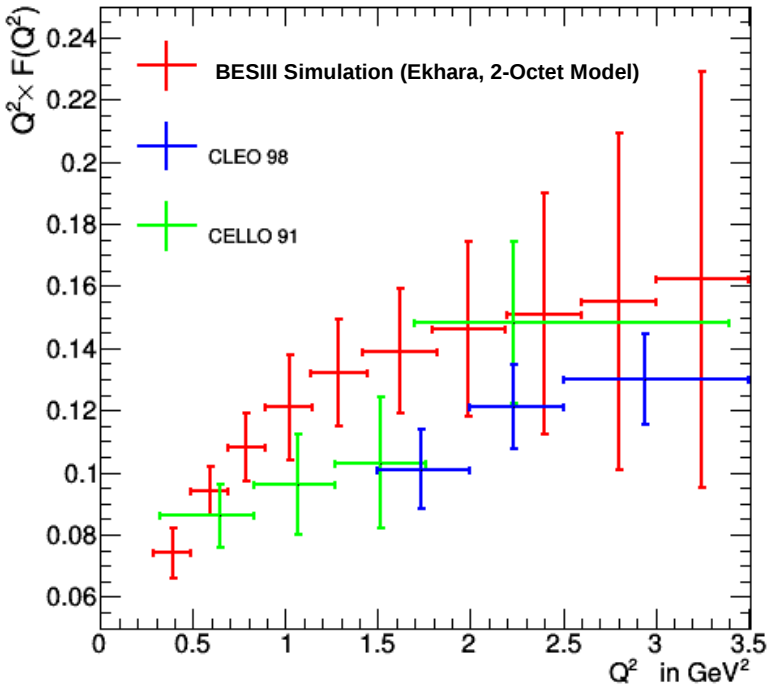


- $\eta \to \pi^+\pi^-\pi^0$
- $\eta' \to \pi^+\pi^-\eta$
- Any combination of
  - one positron
  - two charged pions
  - two photons
- $\cos\theta_{untagged} > 0.99$
- reject hadronic background
- Mass window cuts on yy invariant mass
- Kinematic fit

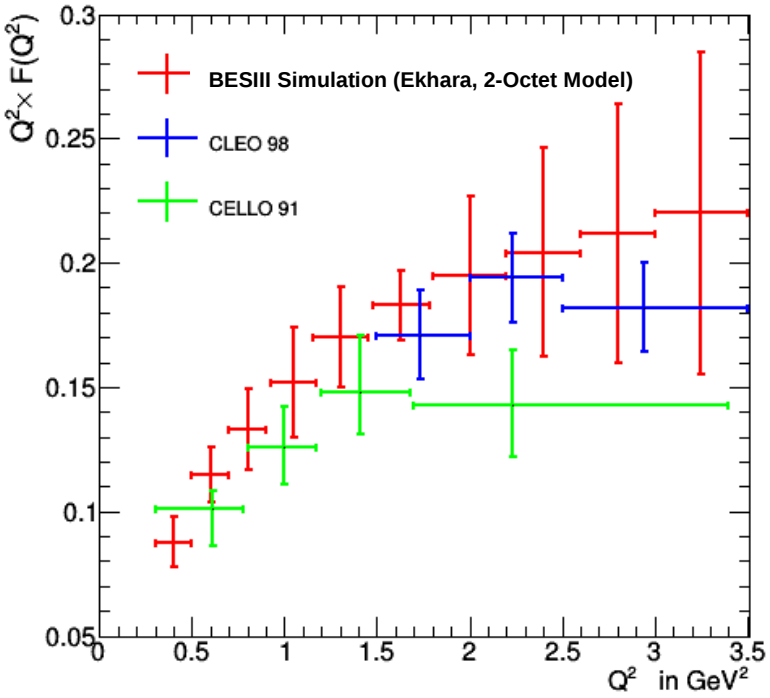
- Relatively low background conditions

Space-like η,η' Transition Form Factor

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



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



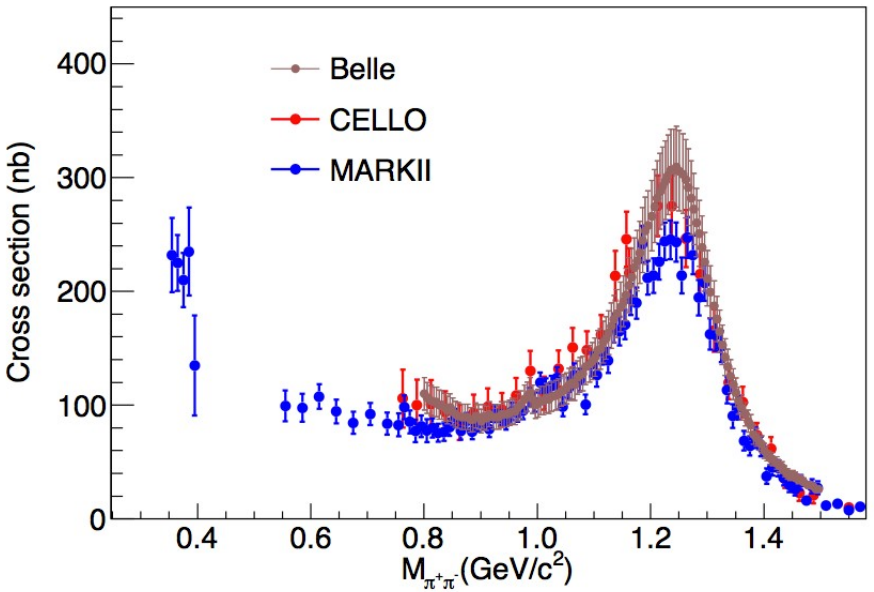
- Full BESIII Ψ(3770) data set analyzed
- statistics compatible to previous measurements
  - only one decay channel of η and η' analyzed at BESIII
  - more data available
- Systematic studies to be done

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

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

- Until recently only untagged measurements:



MarkII, Phys. Rev. D42 (1990) 5

CELLO, Z. Phys. C56 (1992) 381

Belle, Phys. Rev D75 (2007) 051101

- First single-tagged result by Belle

Phys. Rev. D93 (2016) 032003

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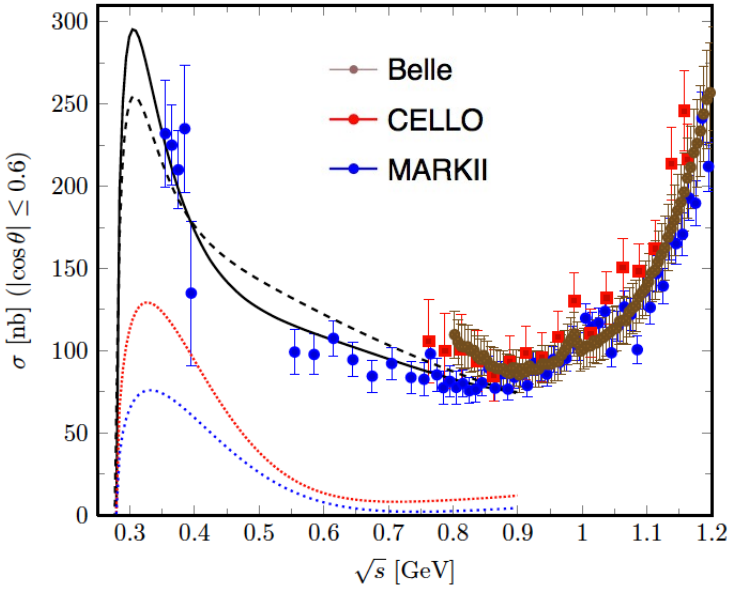


Calculations by
Assmussen, Masjuan, and Vanderhaeghen:

Untagged

Single-Tag $(Q_1^2 = 0.5\,GeV^2)$

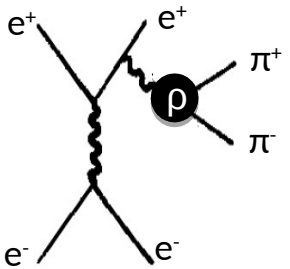
Double-Tag $(Q_1^2 = Q_2^2 = 0.5\,GeV^2)$

- First single-tagged result by Belle

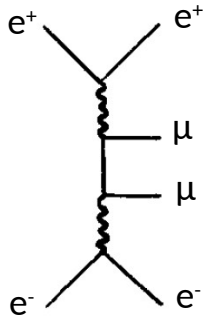
Phys. Rev. D93 (2016) 032003

Space-like $\pi^+\pi^-$ Transition Form Factor

- At BESIII: Single-Tag measurement
  - Using 1 fb^{-1}, collected at $\sqrt{s}$ = 4360 MeV
  - Event selection analogous to single pseudoscalar analysis
  - Major Backgrounds:
    - $e^+e^- \to e^+e^-\pi^+\pi^-$
      - Radiative Bhabha scattering coupling to ρ (s + t channel)
      - MC generators missing



    - $\gamma\gamma^{(*)} \to \mu^+\mu^-$
      - Two-photon production of muon pairs
      - Precise MC generators available from LEP era (BdkRC + Diag36ABC)
      - Train ANN to suppress muon background

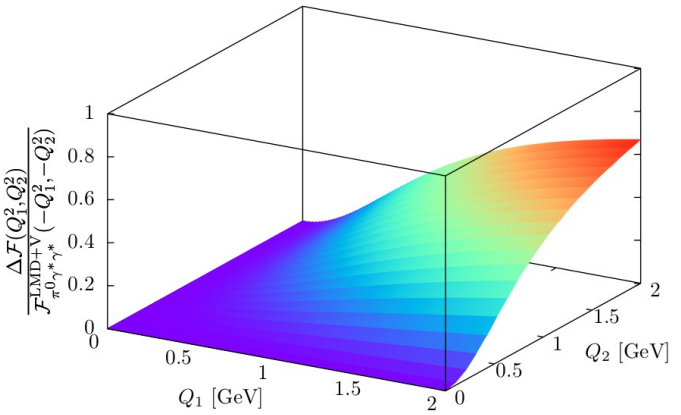


Space-like $\pi^+\pi^-$ Transition Form Factor

- Subtract muon background using MC distributions
  - To be replaced with ANN trained for muon suppression
- Subtract ρ contribution
  - Fit with Kühn-Santamaria parameterization
- Study pion mass in bins of Q^2 and $\cos\theta^*$
- Expectations:
  - About 5000 signal events at $\sqrt{s}$ = 4360 MeV
  - Access to:
    - low momentum transfers $0.2 < Q^2\ [\mathrm{GeV}^2] < 2.0$
    - low invariant masses $m_{\pi^+\pi^-} < M\ [\mathrm{GeV}] < 2.0$

Outlook: Double-Tagged Measurements

- More than 7.7fb^{-1} on disk at 3.77 < √s [GeV] < 4.6
  - Double-tag measurement possible
    - Measure $F_{\gamma^*\gamma^*\pi^0}(Q_1^2, Q_2^2)$
    - 1st Step: Test TFF models
      - e.g. VMD vs. LMD+V



Calculations: A. Nyffeler
hep-ph:1602.03398

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

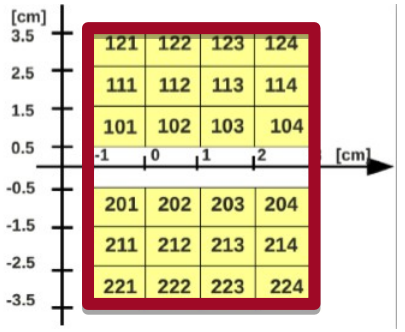
$$d\sigma = F\Big\{v_{TT}\,\sigma_{TT} + v'_{TT}\cos(2\tilde{\phi})\,(\sigma_{\parallel} - \sigma_{\perp}) + h_1 h_2 v''_{TT}\,\frac{1}{2}\,(\sigma_0 - \sigma_2)$$
$$+ v_{LL}\,\sigma_{LL} + v_{TL}\,\sigma_{TL} + v_{LT}\,\sigma_{LT} + v'_{TL}\cos(\tilde{\phi})\,\tau_{TL} + h_1 h_2 v''_{TL}\cos(\tilde{\phi})\,\tau^a_{TL}\Big\}\,.$$

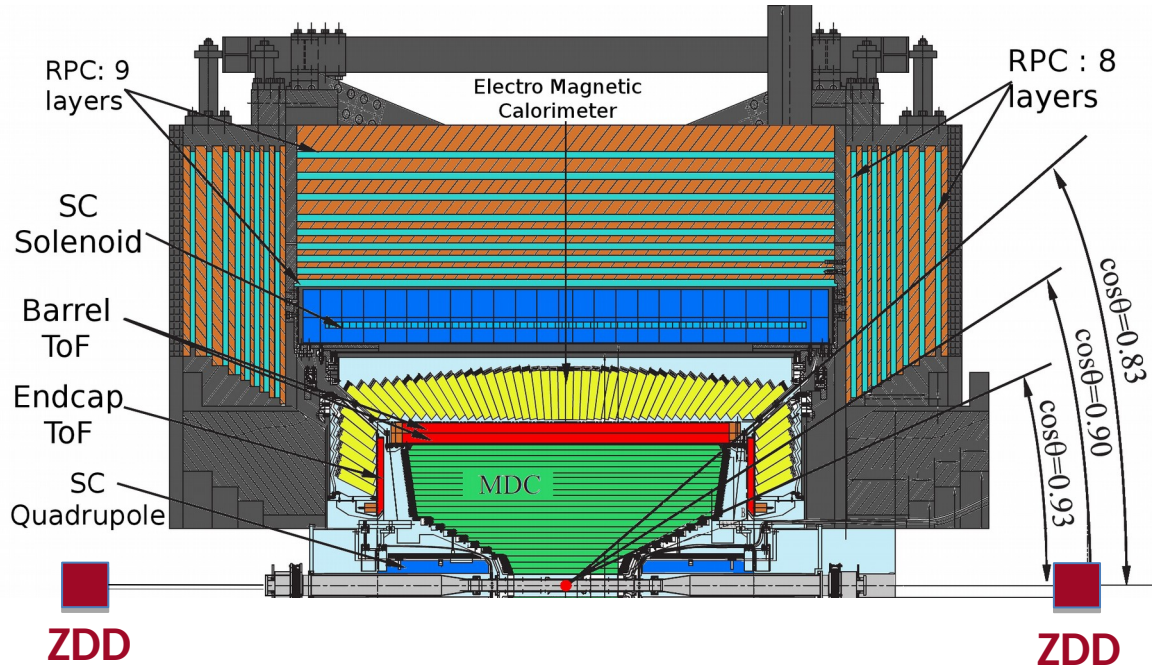
  - $\tilde{\phi}$: azimuthal angle between lepton planes in $\gamma^*\gamma^*$ CMS
    - Allows to disentangle form factor contributions of multi-meson and tensor states
    - Requires precise measurement of angles

Outlook: Zero Degree Detector

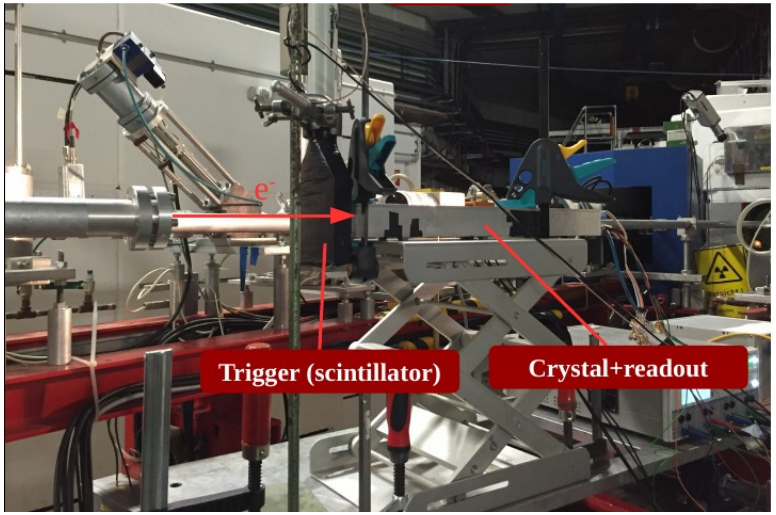
- Tagging of photons and electrons at small angles
  - Polar angle range: 1 – 10 mrad
- Current design: Pb-SciFi, one sided
- Upgrade: Arrays of 48 crystals (PbWO, LYSO) on both sides

ZDD





In-beam tests at MAMI (Mainz)



Summary

- Two-photon physics program established at BESIII
  - Single-tag measurements of π^0, η, and η' transition form factors
    - Unprecedented accuracy for $Q^2 < 1.5$ GeV^2
  - Single-tag measurement of $\pi^+\pi^-$
    - First measurement at low Q^2, low mass
    - To be extended to neutral final states
  - First double-tagged measurement $\gamma^*\gamma^* \to \pi^0$ started
  - New prospects from tagging detectors