JG|U

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

SFB 1044

THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

PRISMA

$\gamma\gamma$ physics – Experimental Overview

September 30, 2014 | Christoph Florian Redmer

MesonNet Meeting 2014, Frascati

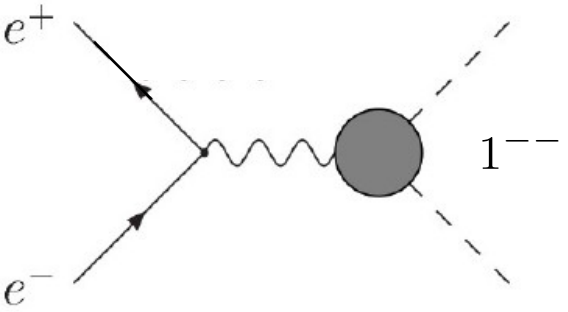
Outline

- Introduction
- Experimental Techniques
  - Space – like processes
  - Lightest pseudoscalar mesons
- Outlook
- Summary

Introduction

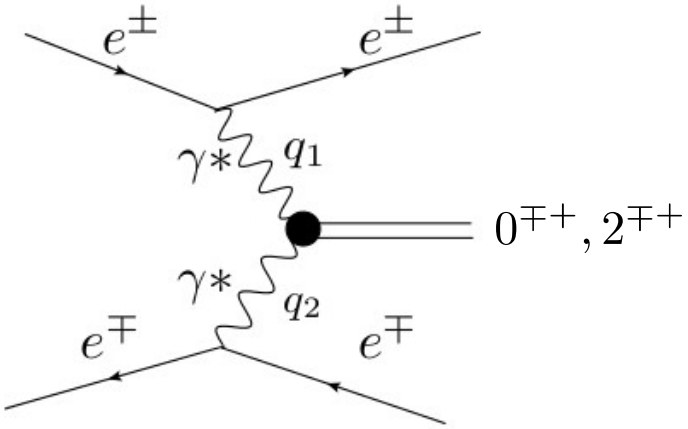
Usually at e+e- colliders: Annihilation

- Only vector states
- $M_x = \sqrt{s}$
- $\sigma \propto \frac{\alpha^2}{E^2}$



Here: Two-photon collisions

- Pseudoscalar, axial, and tensor states
- $M_x << \sqrt{s}$
- $\sigma \propto \alpha^2 \ln^2 E$
- Forward peaked kinematic



Features of two-photon process

- Production cross section

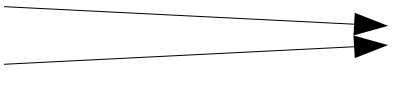
$$\sigma(e^+e^- \to e^+e^- X) = \int \sigma_{\gamma\gamma\to X}(q_1, q_2)\Phi(q_1, q_2)\frac{d\vec{q}_1}{dE_1}\frac{d\vec{q}_2}{dE_2}$$

- Differential $\gamma\gamma$ luminosity $\quad \Phi(q_1, q_2) \propto \frac{\alpha^2}{4\pi^2}\frac{\ln^2 E}{m_e^2}$

- Formation cross section
  - Here: narrow resonances with spin 0

$$\sigma_{\gamma\gamma\to X} = \frac{8\pi^2}{m_X}\Gamma_{X\to\gamma\gamma}\delta((q_1+q_2)^2 - m_X^2)|F(q_1^2, q_2^2)|^2$$

  - Radiative width $\Gamma_{X\to\gamma\gamma}$
  - Space-like transition form factor $F(q_1^2, q_2^2)$



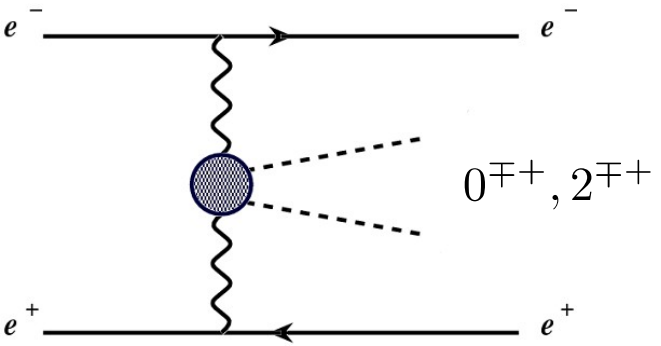
Structure of X

Tagging Techniques

Detectors without special tagging devices

Untagged Measurement

- Scattered leptons undetected
  - Both photons quasi-real
    - $F(q_1^2, q_2^2) \rightarrow F(0,0)$
- Produced system reconstructed
  - Small p_T



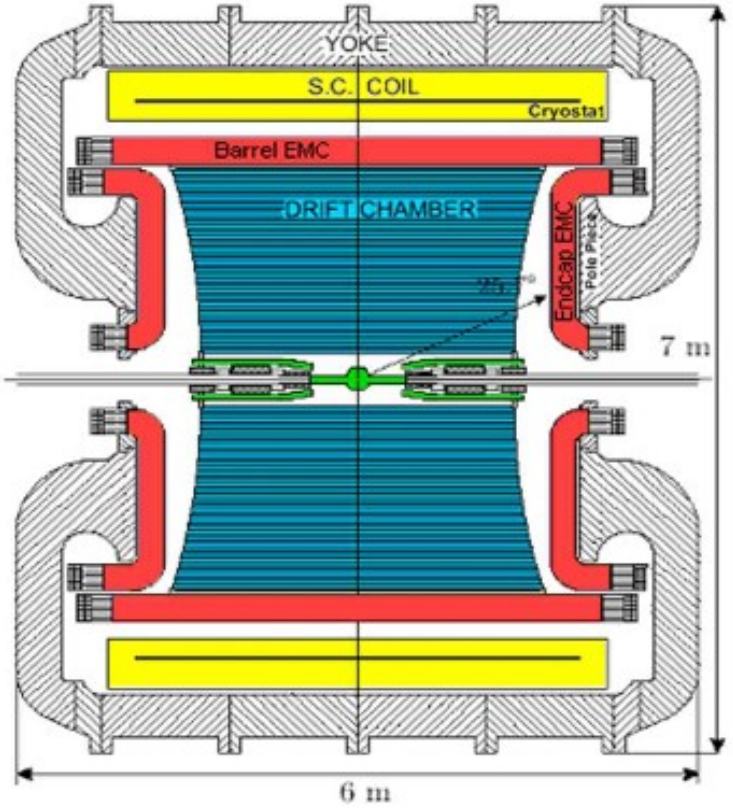
Single Tag Measurement

Double Tag Measurement

Example Analysis: $\Gamma_{\eta \to \gamma\gamma}$

- Analysis based on KLOE off-peak data
  - $\sqrt{s}$ = 1 GeV
  - L_{int} = 242.5 pb^{-1}

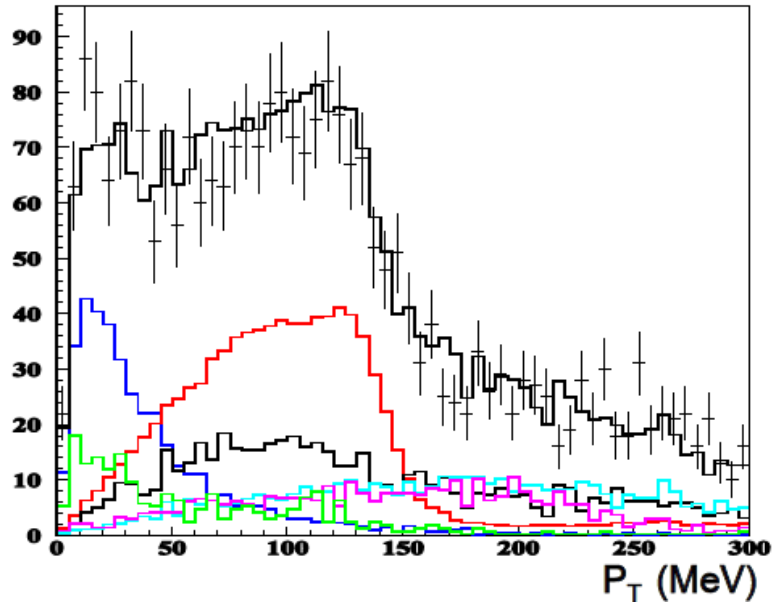
- using charged and neutral 3π decays
- Main background $e^+e^- \to \eta\gamma$
- TFF description from VMD

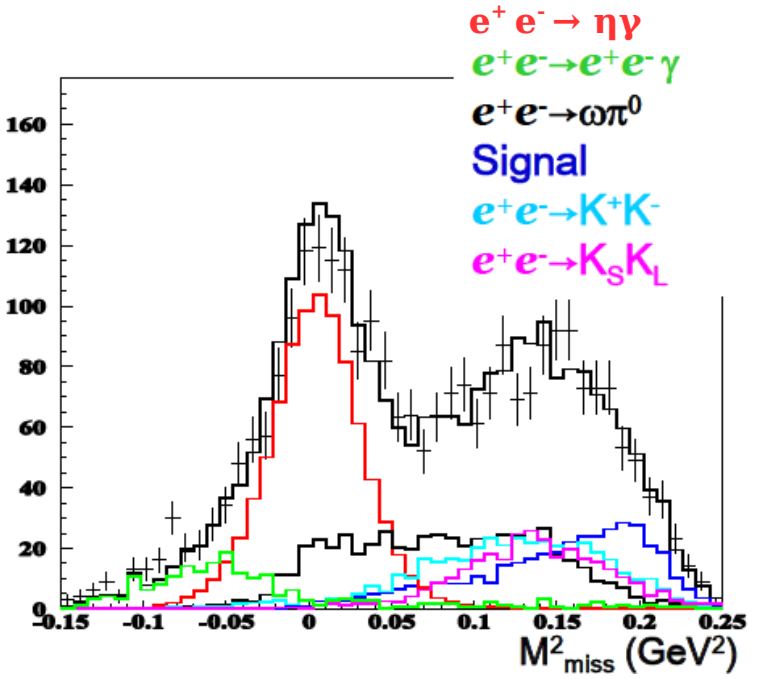


Example Analysis: $\Gamma_{\eta \to \gamma\gamma}$

Tagging $\eta \to \pi^+\pi^-\pi^0$

- Two prompt photons
- Two charged tracks
- Kinematic fit $M_{\pi\pi\gamma\gamma} = M_\eta$





- Combined fit to transverse momentum and missing mass distributions of $\pi\pi\gamma\gamma$
- 394 ± 29 signal events

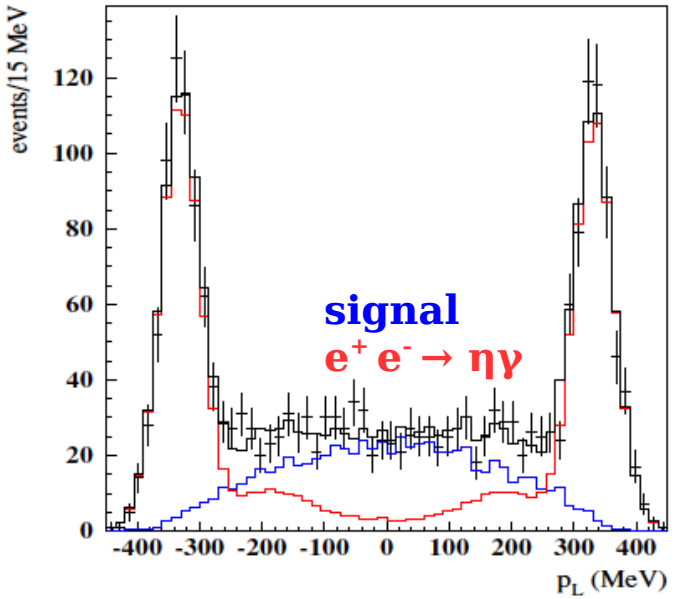
JHEP1301(2013)119

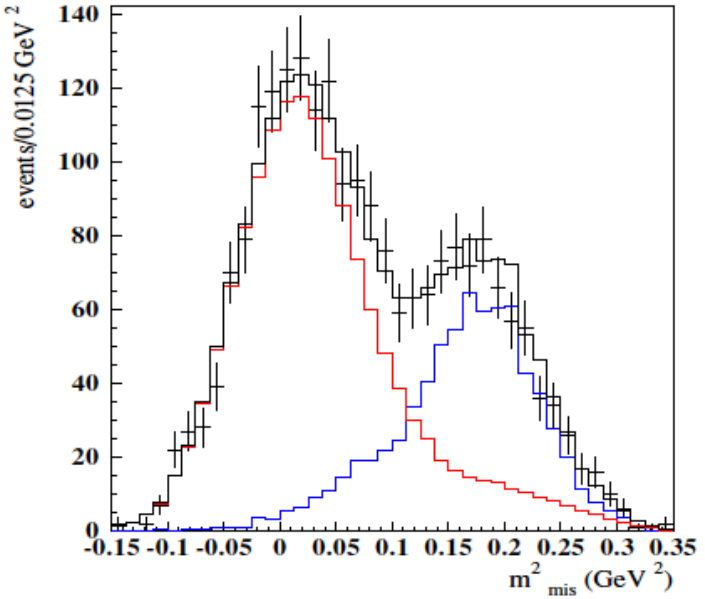
$$\sigma(e^+e^- \to e^+e^-\eta) = (34.5 \pm 2.5_{stat} \pm 1.0_{syst} \pm 0.7_{FF} \pm 0.4_{BR})pb$$

Example Analysis: $\Gamma_{\eta \to \gamma\gamma}$

Tagging $\eta \to \pi^0\pi^0\pi^0$

- six prompt photons
- no charged tracks
- Kinematic fit $M_{6\gamma} = M_\eta$





- Combined fit of longitudinal momentum and missing mass distributions of 6γ
- 2166 events in distribution (33.4 ± 1.5) %signal

JHEP1301(2013)119

$$\sigma(e^+e^- \to e^+e^-\eta) = (32.0 \pm 1.5_{stat} \pm 0.9_{syst} \pm 0.2_{FF} \pm 0.2_{BR})pb$$

Example Analysis: $\Gamma_{\eta \to \gamma\gamma}$

Combined result:

- $\sigma(e^+e^- \to e^+e^-\eta) = (32.7 \pm 1.3_{stat} \pm 0.7_{syst})pb$

- Extracting radiative width from cross section
  - $F(q_1, q_2) = \frac{1}{1 - bq_1^2} \frac{1}{1 - bq_2^2}$, with b = (1.94 ± 0.15) GeV^{-2}

$$\Gamma_{\eta \to \gamma\gamma} = (520 \pm 20_{stat} \pm 13_{syst})eV$$

JHEP1301(2013)119

Most precise measurement to date!

New PDG average: $\Gamma_{\eta \to \gamma\gamma} = (516 \pm 18)eV$

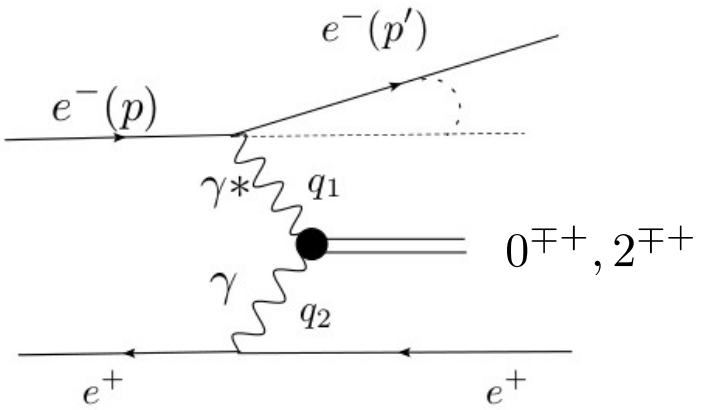
Tagging Techniques

Detectors without special tagging devices

Untagged Measurement

Single Tag Measurement

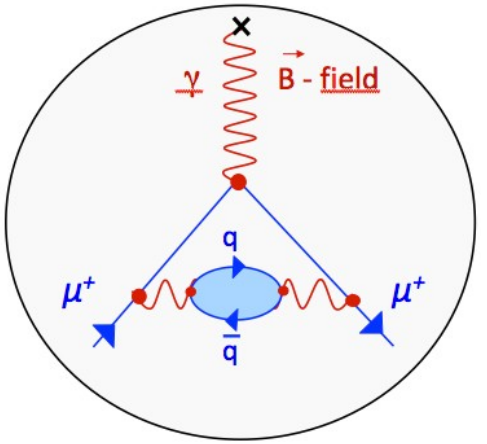
- Reconstruct one scattered lepton
  - one photon quasi-real
    - $F(q_1^2, q_2^2) \rightarrow F(q_1^2, 0) \rightarrow F(q^2)$
- Produced system reconstructed

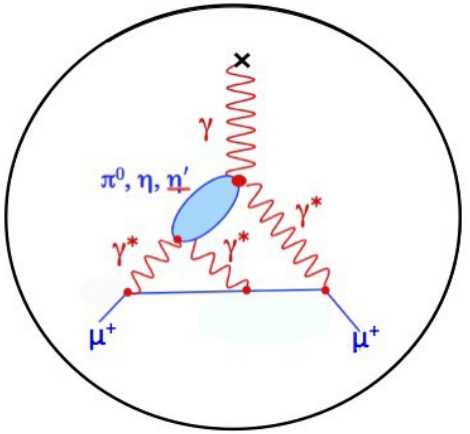


Double Tag Measurement

Motivation

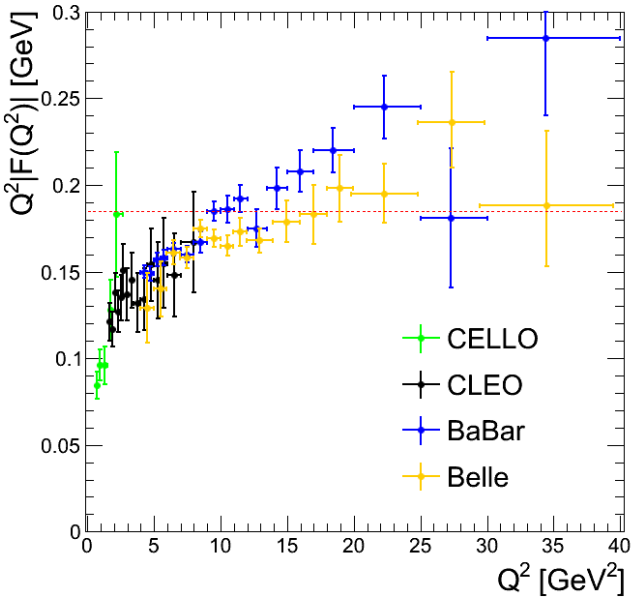
- Hadronic Contributions to Anomalous magnetic moment of the muon:
  - Dominating the uncertainty of the prediction of a_μ
  - Perturbative methods not applicable
  - Hadronic vacuum polarization
    - evaluate dispersion integrals
    - $\sigma(e^+e^- \rightarrow \text{hadr})$ needed as input
  - Hadronic Light-by-Light Scattering
    - Virtual mesons, real and virtual photons
    - Modeled using sum rules, Pade approximants,...
    - TFF's as input



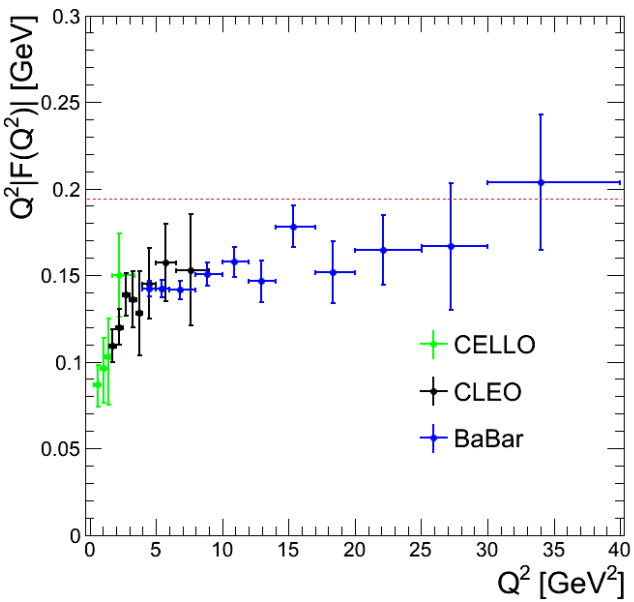


Previous Measurements

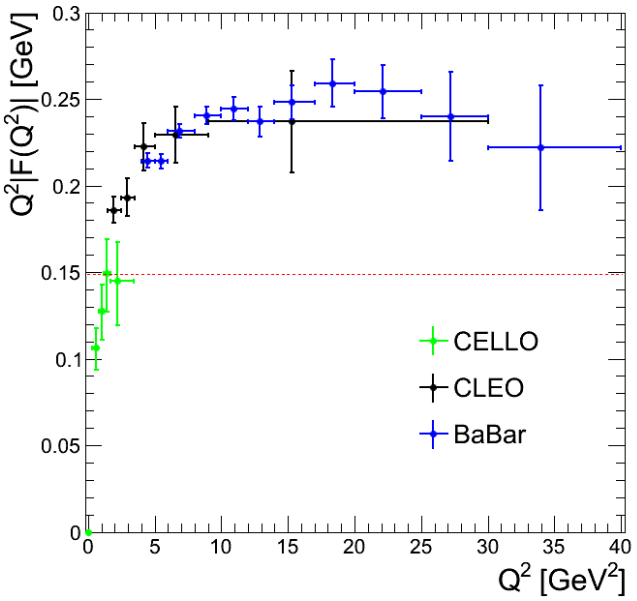
$e^+e^- \rightarrow e^+e^- \pi^0$



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



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

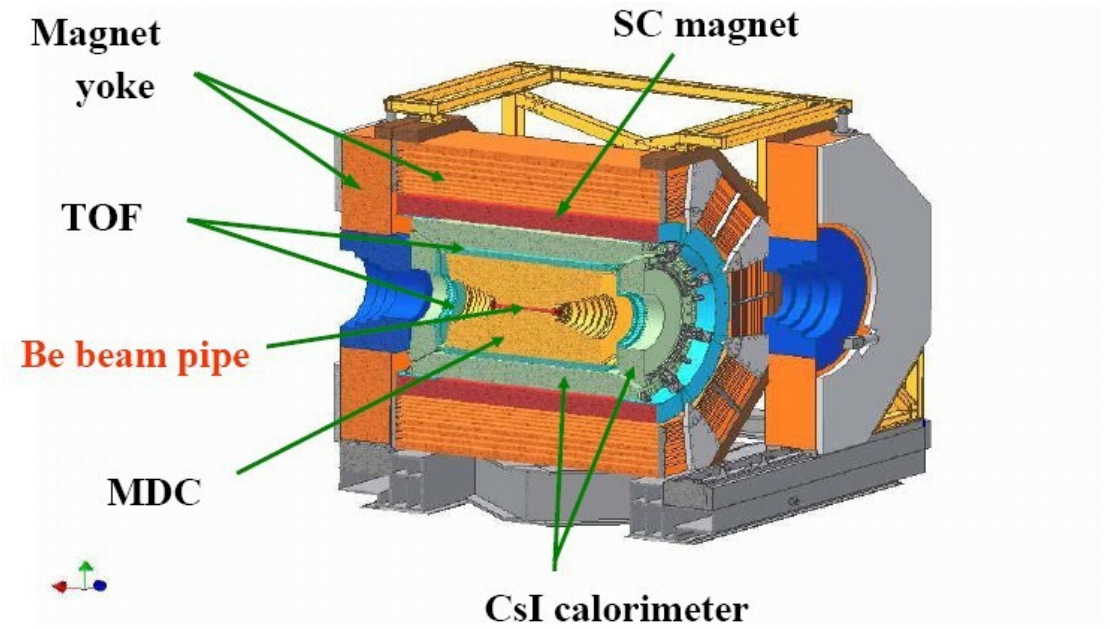


- Recent results from B-factories cover only large Q^2 ($5 < Q^2$ [GeV^2] < 40)
  - Discrepancy for π^0 between BaBar and Belle
- Data scarce at lowest Q^2
  - Region of relevance for (g-2)μ

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

BESIII Detector

NIM A614 (2010) 345



World's largest data samples of J/Ψ, Ψ(2S), Ψ(3770), and 4 GeV < √s < 4.6 GeV

- 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

Analysis Example: π^0 / η

Data

- Ψ(3770) on-peak, available: 2.92 fb^{-1}

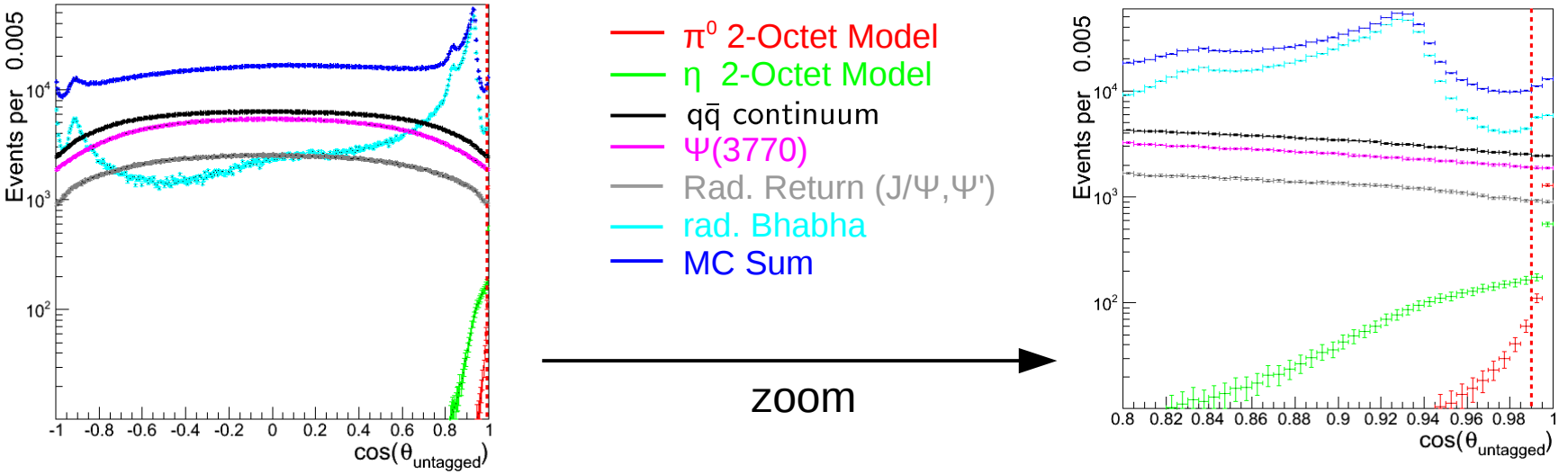
Event Selection:

- exactly one lepton candidate
- At least two, max four photons

Single-Tag Condition

- Reconstruct untagged lepton from missing four-momentum
- Require small scattering angle → small virtuality

Example: Monte Carlo, Ψ(3770), L_{int}: 927 pb^{-1} , Tagged Lepton: e^-

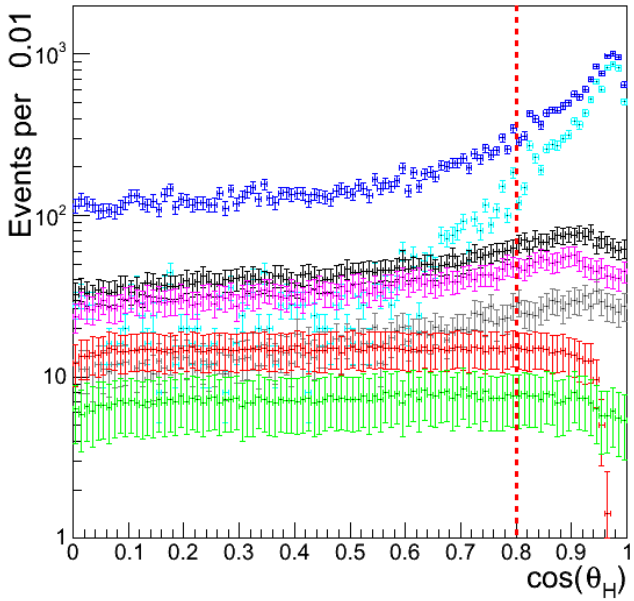


Analysis Steps

Helicity Condition for π^0

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

L_{int}: 927 pb^{-1} , Tagged Lepton: e^-

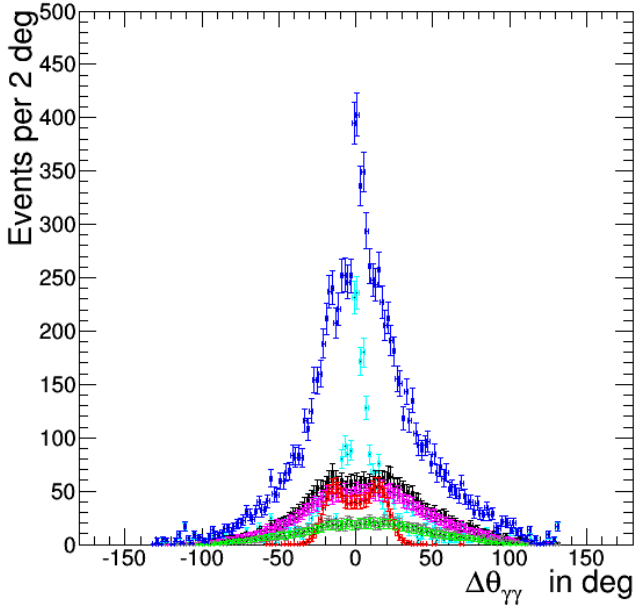


- reduction of QED background

Polar angle difference of γ pair

- Strongly peaked for QED background
- Flat for hadronic background
- Dip for signal
- Reject events with $|\Delta\theta_{\gamma\gamma}| < 1.5°$

L_{int}: 927 pb^{-1} , Tagged Lepton: e^-



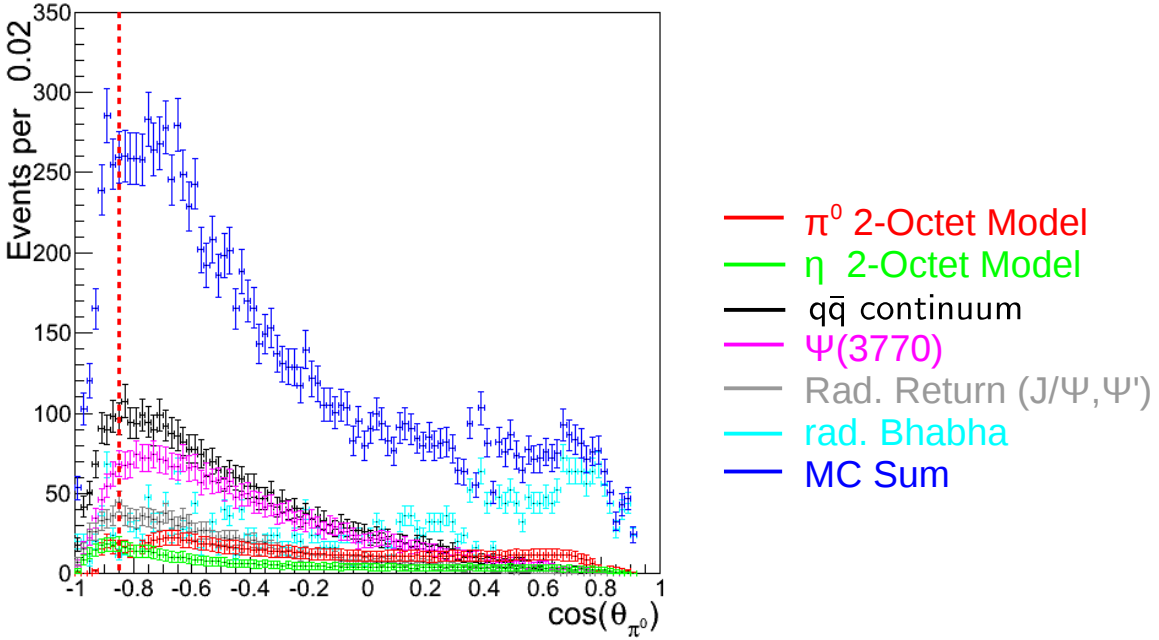
- reduction of QED background

Analysis Steps

Polar angle of π^0

- Background enhanced at large $\cos(\theta_\pi)$
- Signal almost evenly distributed
- Reject events with $\cos(\theta_\pi) \cdot q_{tagged} > 0.8$

L_{int}: 927 pb^{-1} , Tagged Lepton: e^-

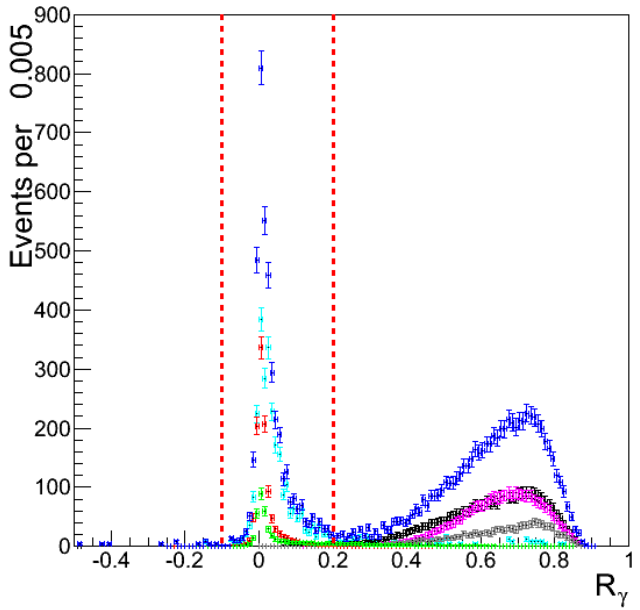


- Data/MC difference
- QED background reduced

Condition on ISR

- 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 $r_\gamma < -0.1$ and $r_\gamma > 0.2$

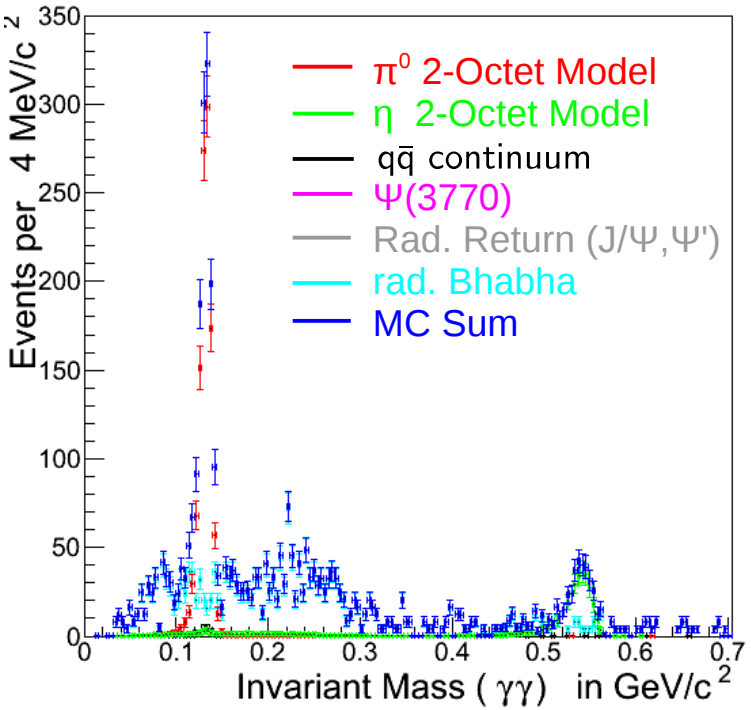
L_{int}: 927 pb^{-1} , Tagged Lepton: e^-



- Hadronic background almost completely removed

Analysis Steps

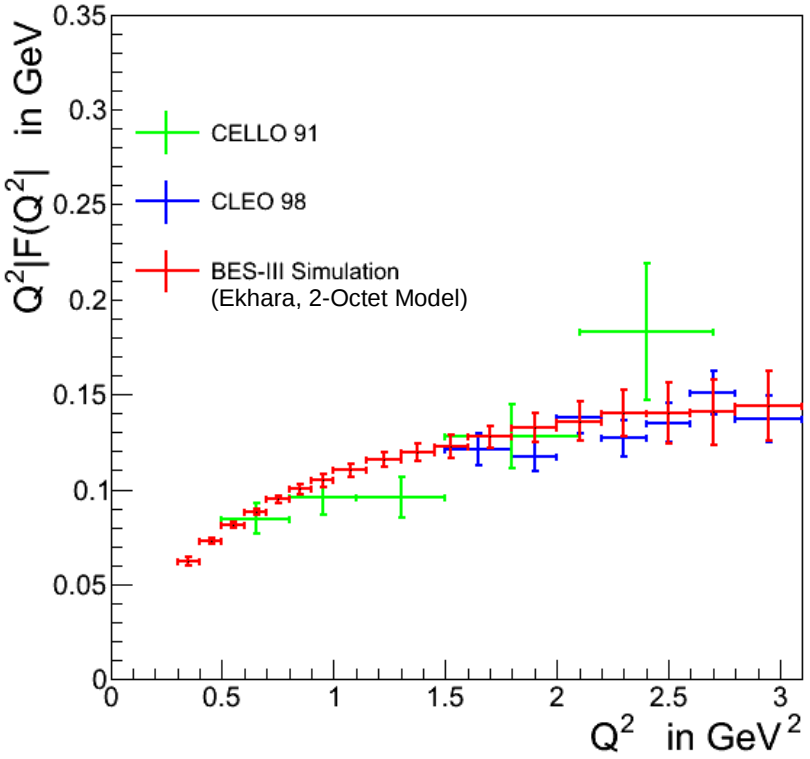
L_{int}: 927 pb^{-1} , Tagged Lepton: e^-



- Clear signals from π^0 / $\eta \rightarrow \gamma\gamma$
- Data: Background underestimated
  - ➔ Use better MC generators

- Study differential cross section $d\sigma/dQ^2$
- Bin wise back ground subtraction
- Statistics from Ψ(3770) data only sufficient for π^0 TFF up to $Q^2 = 3$ GeV^2

Expectations for π^0 TFF



- Full Simulation
  - L_{int}: 2.92 fb^{-1}
  - Single Tag with both, $e^{\pm}$
- Extract TFF for $0.3 \leq Q^2[GeV^2] \leq 3.1$
- Expected statistical precision:
  - Unprecedented below $Q^2 = 1.5$ GeV^2
    - ➔ Important for $(g-2)_\mu$
  - Compatible with CLEO

Next steps:

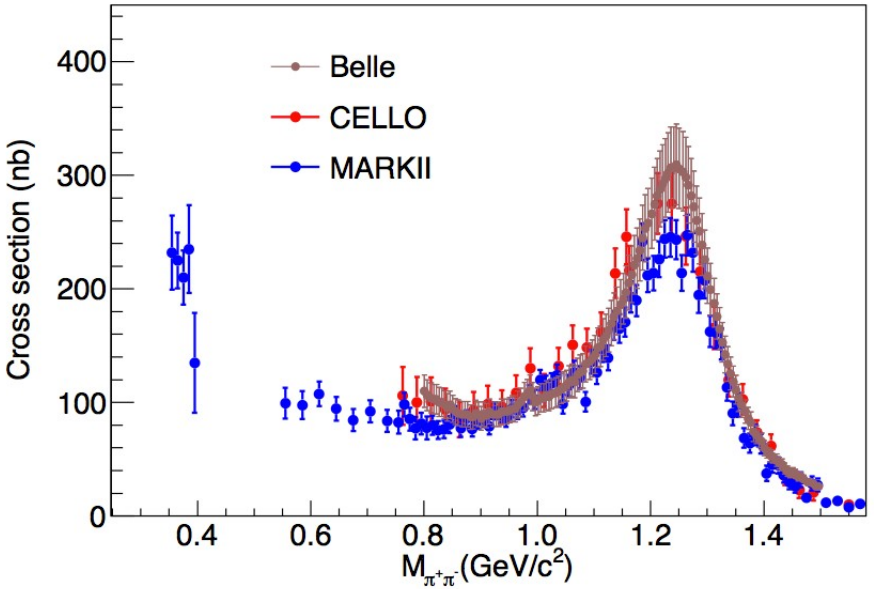
- Finalize systematic studies
  - Largest contribution expected from background subtraction
- Other final states

Analysis Example: $\pi^+\pi^-$

- Additional Motivations:
  - Resonance parameters
  - Pion polarizabilities, pion structure
  - Dispersive framework developed
  - Rescattering effects in low mass region

Collangelo, Hoferichter, Procura, Stoffer
arXiv:1402:7081

- Only untagged measurements so far



MarkII, Phys. Rev. D42 (1990) 5

CELLO, Z. Phys. C56 (1992) 381

Belle, Phys. Rev D75 (2007) 051101

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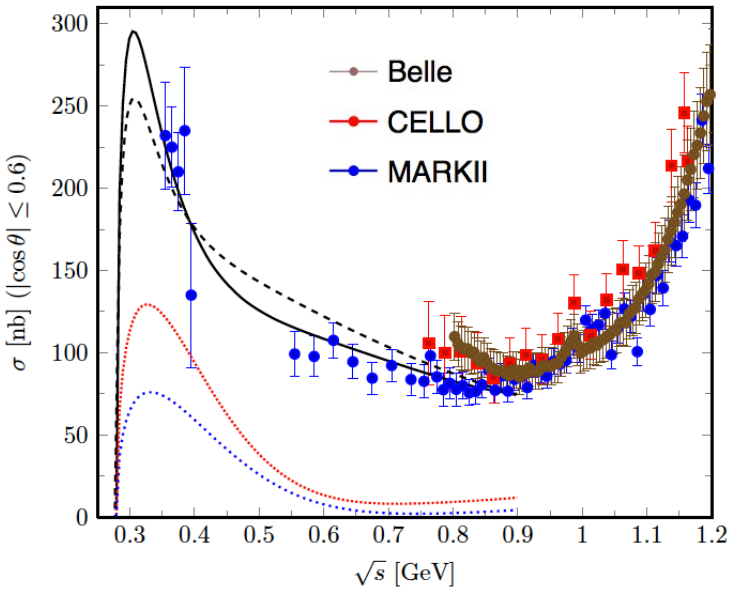


Calculations by Assmussen, Masjuan, and Vanderhaegen:

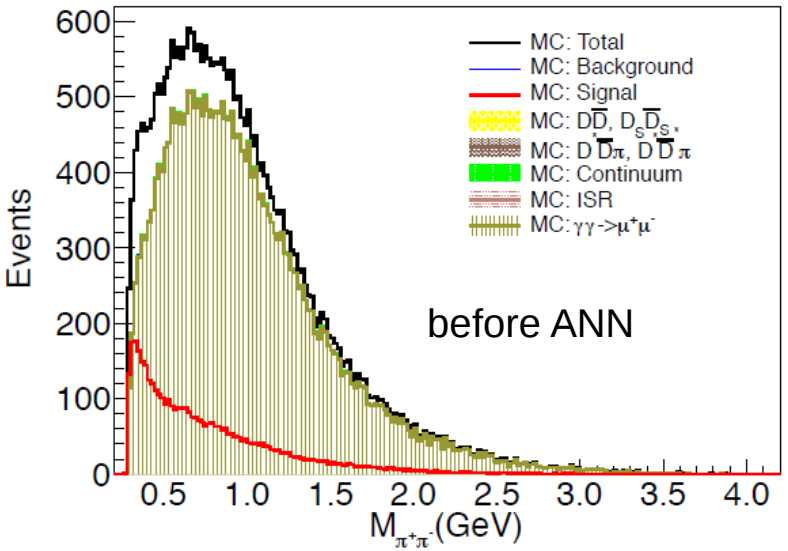
Untagged

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

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

Analysis Example: $\pi^+\pi^-$

- At BESIII: Single-Tag measurement
  - Using 1 fb^{-1}, collected at √s = 4360 MeV
  - Event selection analogous to single pseudoscalar analysis
  - Major Backgrounds:
    - $e^+e^- \to \pi^+\pi^-$ (s + t channel)
    - $\gamma\gamma^{(*)} \to \mu^+\mu^-$
      - Use ANN to suppress muon background: S/B≈ 1/6 → S/B≈ 3/1



- Expectations:
  - About 9000 events at √s = 4360 MeV
  - Access to:
    - low momentum transfers 0.2 < Q^2 [GeV^2] < 2.0
    - low invariant masses $m_{\pi^+\pi^-}$ < M [GeV] < 2.0

Tagging Techniques

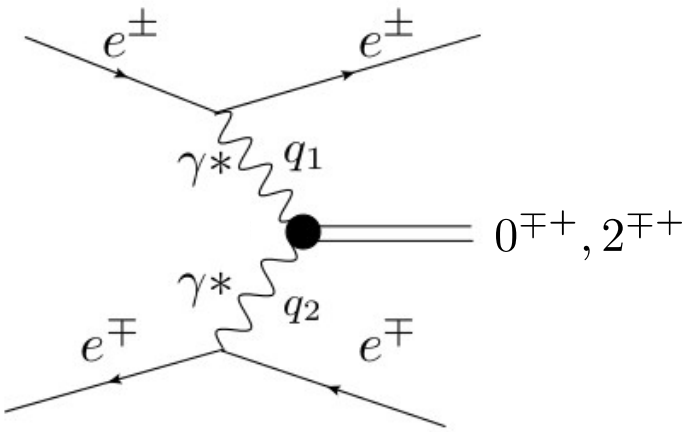
Detectors without special tagging devices

Untagged Measurement

Single Tag Measurement

Double Tag Measurement

- Exclusive measurement
  - Two large virtualities
  - $F(q_1^2, q_2^2)$



Double Tagged Measurements

- **Data are very scarce**

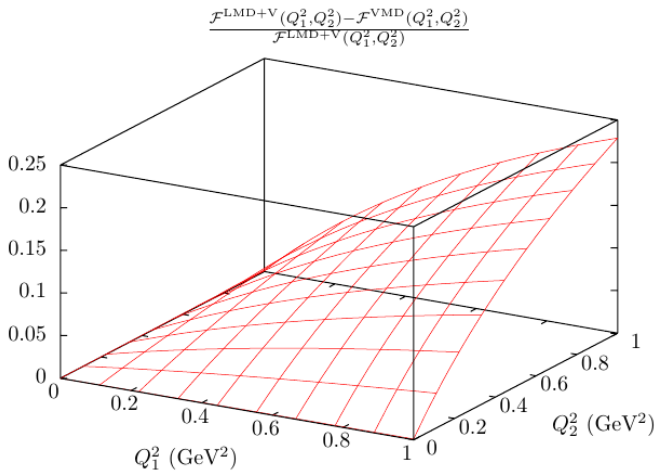
Double Tagged Measurements

- **Data are very scarce**

- **Outlook:**

  - **Plans for BESIII**
    - More than 7.7fb^{-1} on disk at 3.77 < √s [GeV] < 4.6
    - Double-tag measurements possible
      - Test TFF models
      - Test polarization in $\gamma\gamma$ production

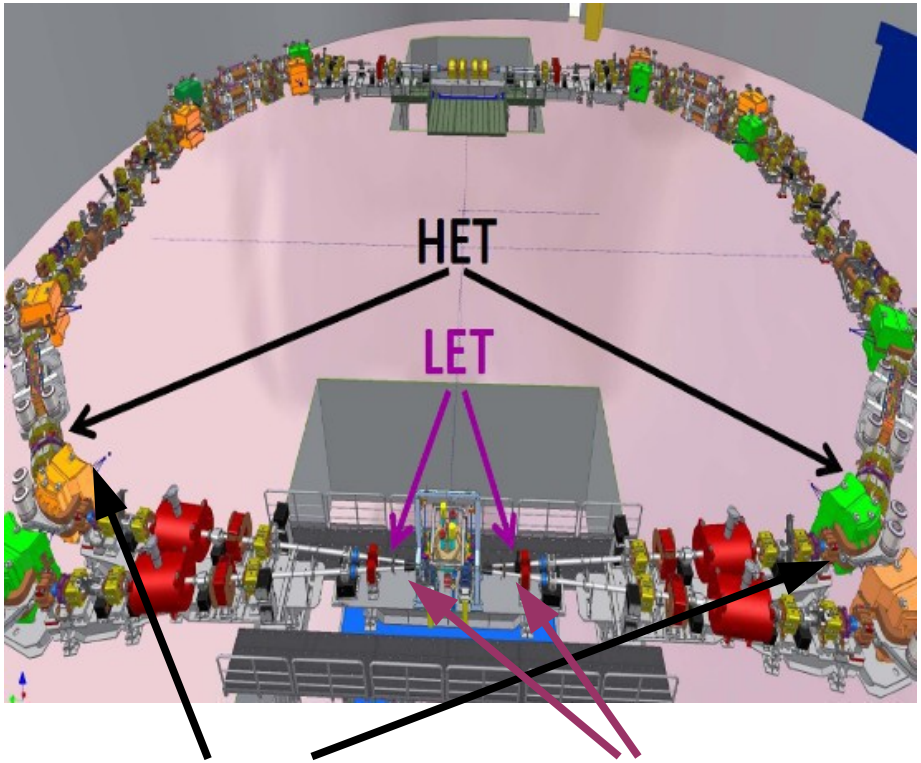
    - Equip BESIII with tagging detectors

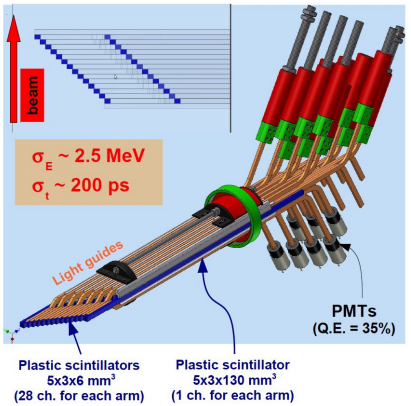


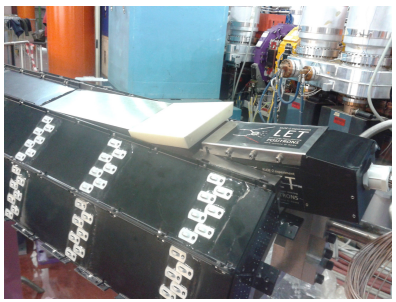
Calculations: A. Nyffeler

KLOE-2 Tagger

- **Low Energy Tagger**
  - 2 x 40 LYSO Crystals
  - 1.5 m from the IP
  - $150 < E_{e\pm}[MeV] < 350$
  - σ(E)/E < 10%
- **High Energy Tagger**
  - Scintillator hodoscope
  - 11m from the IP
  - DAPHNE dipole as spectrometer
  - $420 < E_{e\pm}[MeV] < 495$







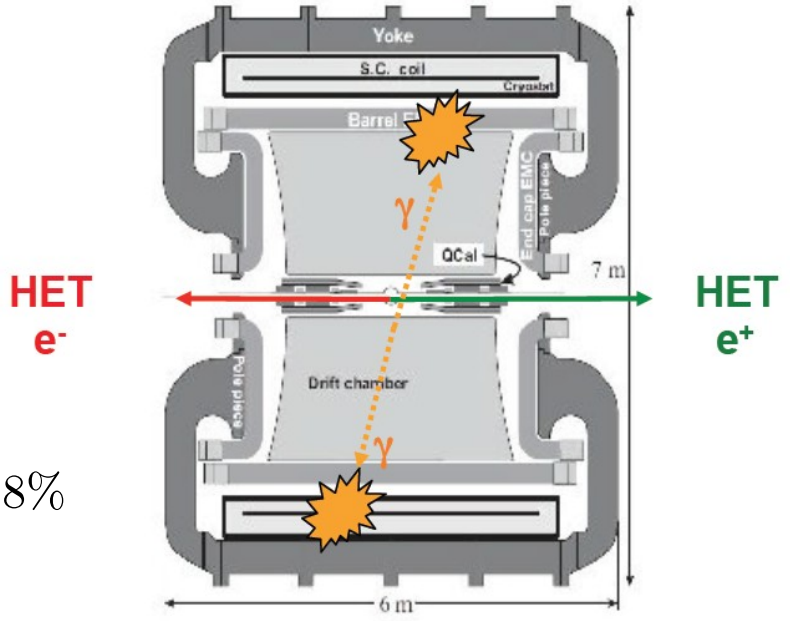
KLOE-2 Tagger

EPJC72(2012)1917

- **Radiative Width of π^0**
  - Both leptons in HET → untagged configuration
    - $Q^2 < 10^{-3}$ GeV
  - 2000 events/fb^{-1} expected
  - with L_{int} = 5fb : $\delta\Gamma(\pi^0 \to \gamma\gamma) \approx 1\%$ achievable

$$\Gamma(\pi^0 \to \gamma\gamma)_{Theory} = (8.09 \pm 0.11) \Rightarrow 1.4\%$$

$$\Gamma(\pi^0 \to \gamma\gamma)_{PrimExJLab} = (7.84 \pm 0.14 \pm 0.17) eV \Rightarrow 2.8\%$$



- **Transition Form Factor of π^0**
  - Leptons in KLOE and HET → single-tag configuration
    - $Q^2 < 0.1$ GeV^2
    - with L_{int} = 5fb : 6% uncertainty at each point
  - Unmeasured region of momentum transfer
  - Check TFF parameterizations

KLOE-2 Tagger

EPJC72(2012)1917

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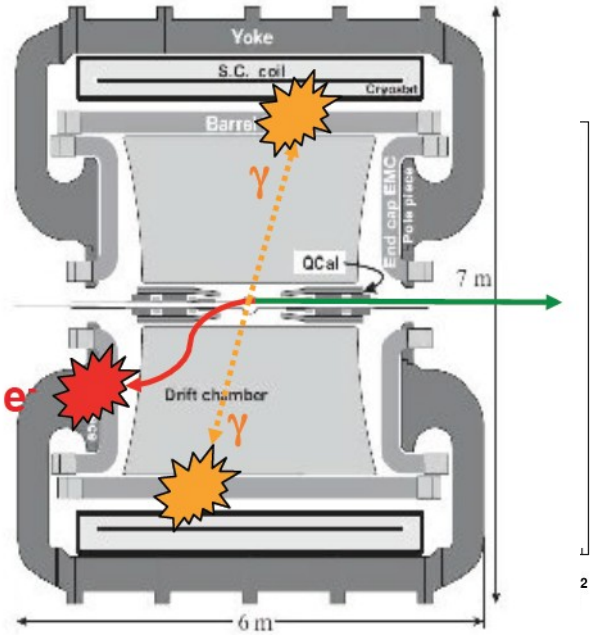
  - Leptons in KLOE and HET → single-tag configuration
    - $Q^2 < 0.1$ GeV^2
    - with L_{int} = 5fb : 6% uncertainty at each point
  - Unmeasured region of momentum transfer
  - Check TFF parameterizations



KLOE-2 Tagger

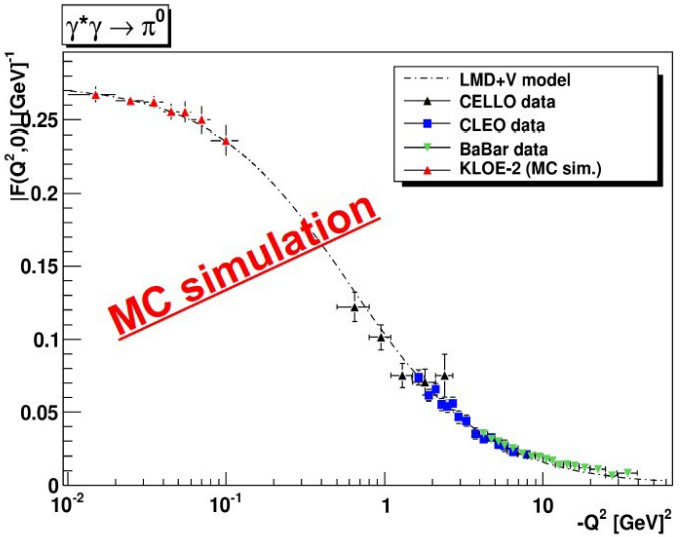
EPJC72(2012)1917

- **Radiative Width of π^0**
  - Both leptons in HET → untagged configuration
    - $Q^2 < 10^{-3}$ GeV
  - 2000 events/fb^{-1} expected
  - with L_{int} = 5fb : $\delta\Gamma(\pi^0 \to \gamma\gamma) \approx 1\%$ achievable

$$\Gamma(\pi^0 \to \gamma\gamma)_{Theory} = (8.09 \pm 0.11) \Rightarrow 1.4\%$$

$$\Gamma(\pi^0 \to \gamma\gamma)_{PrimExJLab} = (7.84 \pm 0.14 \pm 0.17) eV \Rightarrow 2.8\%$$

- **Transition Form Factor of π^0**
  - Leptons in KLOE and HET → single-tag configuration
    - $Q^2 < 0.1$ GeV^2
    - with L_{int} = 5fb : 6% uncertainty at each point
  - Unmeasured region of momentum transfer
  - Check TFF parameterizations



Summary

- $\gamma\gamma$ physics at e^+e^- colliders provides access to
  - radiative width
  - (space-like) transition form factors

- Kinematics limit feasibility
- Successfully performed at various facilities (Babar, Belle, KLOE, BESIII,....)

- Fascinating prospects from dedicated exp. Programs (KLOE-2, BESIII,....)

- Provide valuable input to hadronic Light-by-Light scattering calculations