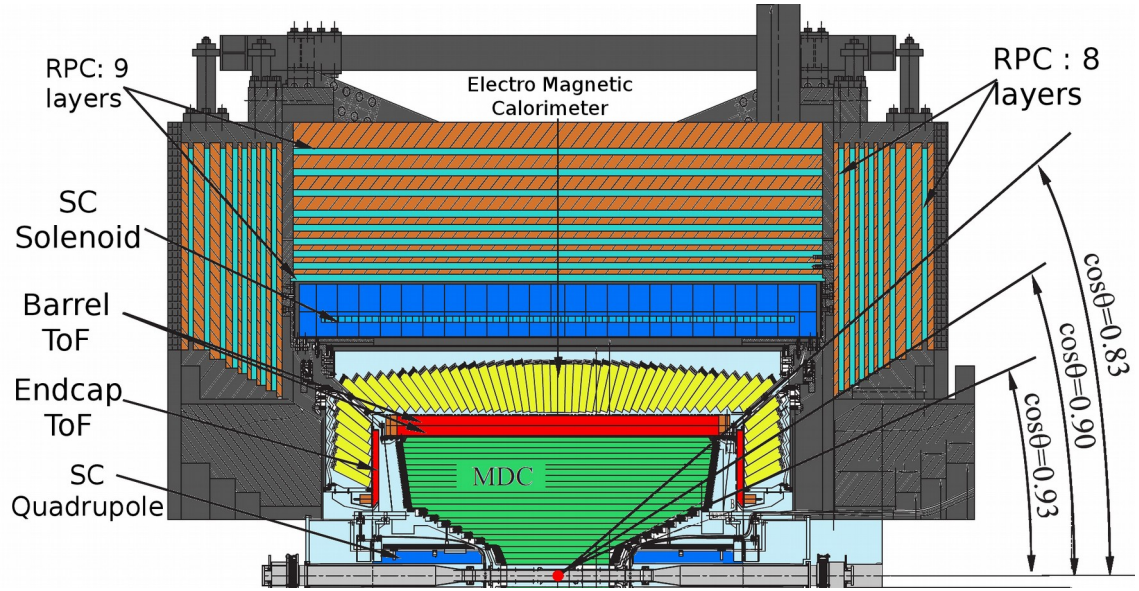
$\gamma\gamma$ Physics Program at BESIII

September 9, 2019 | Christoph Florian Redmer

3rd Workshop of the Muon g-2 Theory Initiative

BESIII Detector

NIM A614 (2010) 345



Muon Chambers
- 8 – 9 layers of RPC
- p>400 MeV/c
- δRΦ = 1.4 ~ 1.7 cm

Superconducting Magnet
- 1 T magnetic field

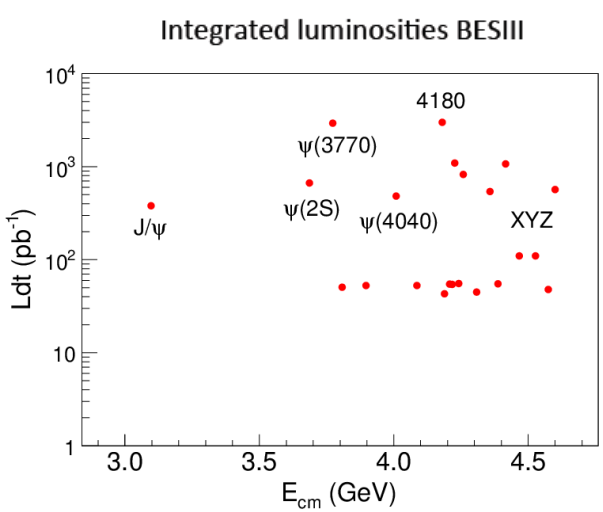
EM Calorimeter (EMC)
- 6240 CsI(Tl) crystals
- σ(E)/E = 2.5%
- $\sigma_{Z,\Phi}(E)$ = 0.5 – 0.7 cm

Time-of-flight system (TOF)
- σ(t) = 90ps (barrel)
- σ(t) = 110ps (endcap)

Drift Chamber (MDC)
- σ(p)/p = 0.5%
- $\sigma_{dE/dx}$ = 6.0%

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 hadron spectroscopy
  - τ mass and R-Scan

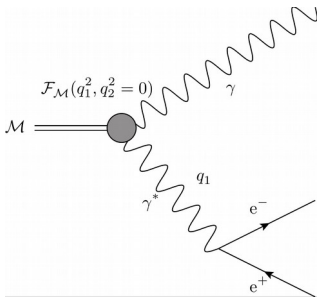


Transition Form Factors

Time – like Transition Form Factors:

Dalitz decays

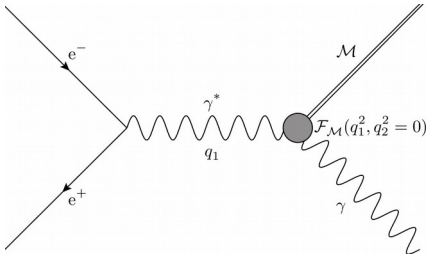
- $0 < q^2 < M^2$



$J/\psi \to \mathcal{P} e^+ e^-$	Phys. Rev. D89, 092008 (2014)
$\eta' \to \gamma e^+ e^-$	Phys. Rev. D92, 012001 (2015)
$\eta' \to \omega e^+ e^-$	Phys. Rev. D92, 051101(R) (2015)

Annihilation process

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

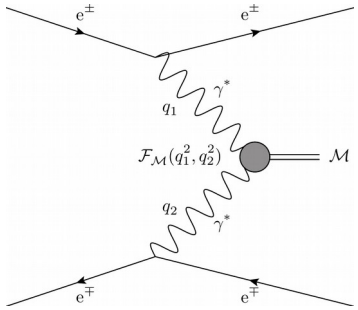


$\psi' \to \mathcal{P}\gamma$	Phys. Rev. Lett. 105, 261801 (2010)
$\psi' \to \gamma\eta_c$	Phys. Rev. Lett. 109, 042003 (2012)
$\psi(3770) \to \gamma\eta_c$	Phys. Rev. D 89, 112005 (2014)
$e^+e^- \to \gamma\eta_c$	Phys. Rev. D 96, 051101 (2017)
$\psi' \to \mathcal{P}\gamma$	Phys. Rev. D 96, 052003 (2017)

Space – like Transition Form Factors:

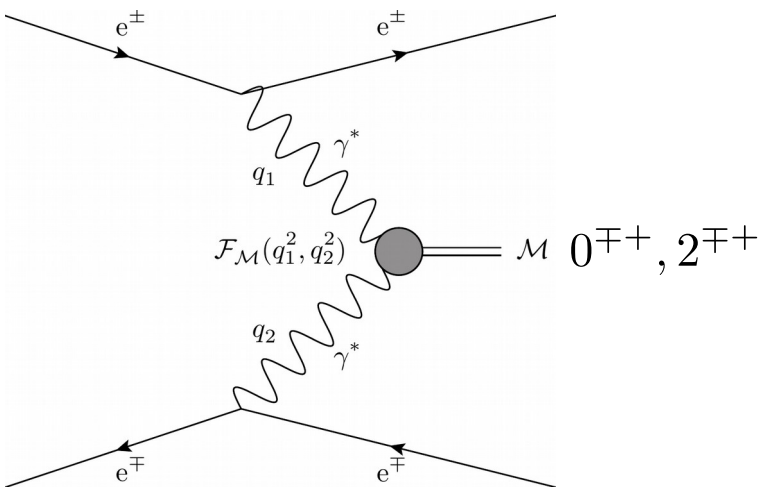
Two-photon production of mesons

- $F(Q_1^2, Q_2^2), \quad Q^2 = -q^2$



Two-Photon Collisions

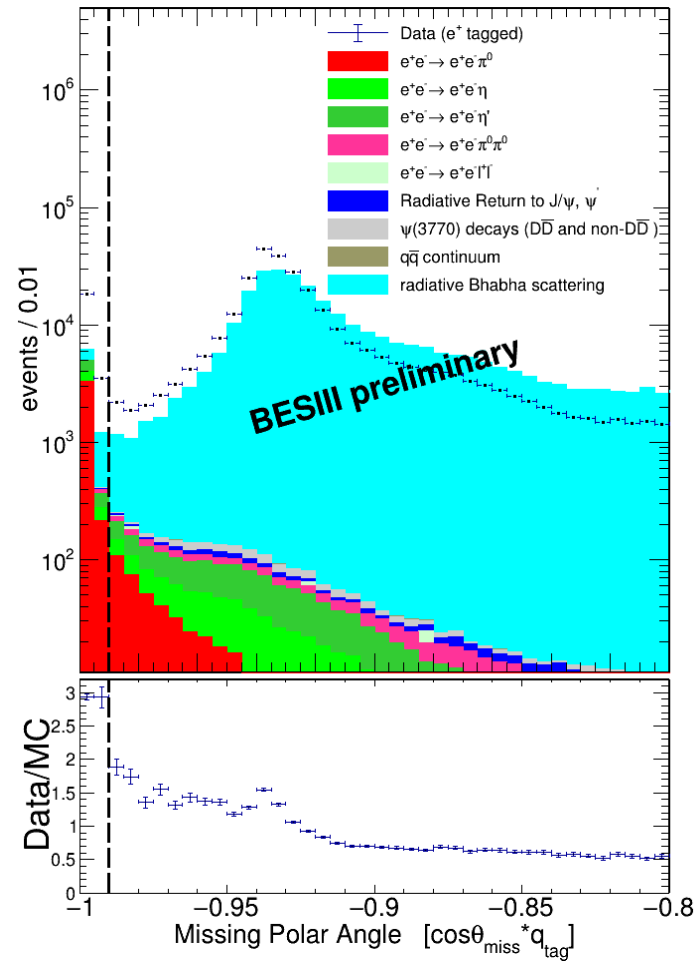
- Exchange of two photons in e^+e^- collisions
- Pseudoscalar, axial, and tensor states accessible
- $M_X << \sqrt{s}$
- $\sigma \propto \alpha^2 \ln^2 E$
- $\sigma \propto F^2(Q_1^2, Q_2^2)$, with $Q_i^2 = -q_i^2$
- Forward peaked kinematic
  - Experimentally challenging
    - Untagged measurements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



Single-tagged Measurements

A feasible approach to study the momentum dependence of meson transition form factors

- Reconstruct:
  - only one scattered lepton
  - produced system
  - unmeasured lepton from momentum conservation
- Require scattering angle of missing momentum to be small
  - Small virtuality of exchanged photon
  - $F(Q_1^2, Q_2^2) \rightarrow F(Q_1^2, 0) \rightarrow F(Q^2)$



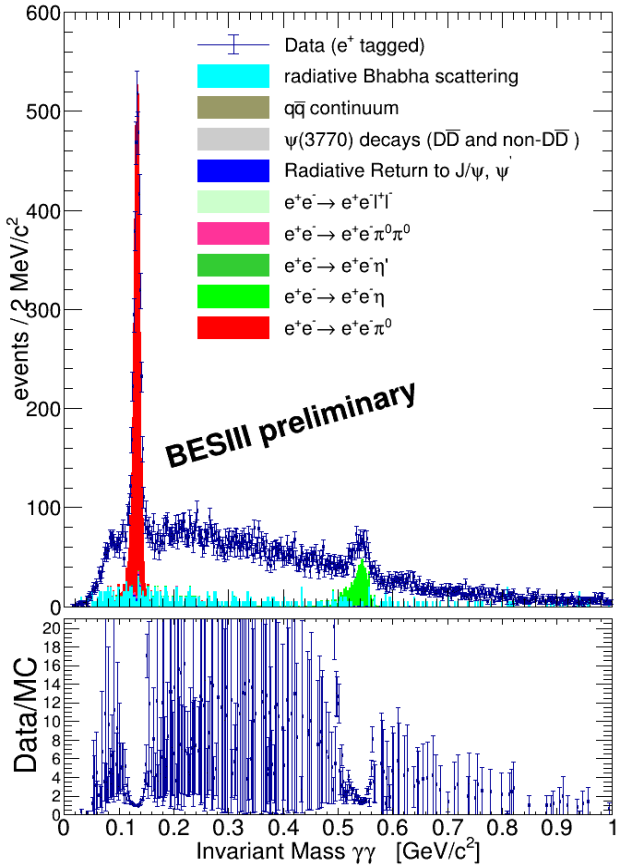
Here: π^0 transition form factor analysis at 3.773 GeV

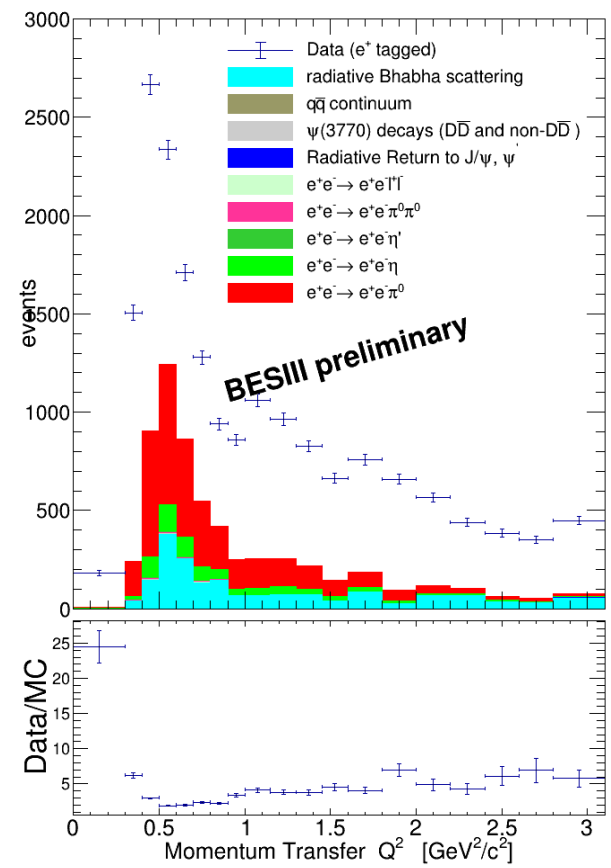
Reject events with $q_{\text{tag}} \cdot \cos(\theta_{\text{miss}}) > -0.99$

q_{tag} : Charge of tagged lepton in units of [e]

Spacelike π^0 Transition Form Factor

- Based on 2.9 fb^{-1} at 3.773 GeV
- Select:
  - Exactly one lepton
  - At least two photons
- Apply:
  - Single-tag condition
  - Helicity angle of photons
  - $R_\gamma = \frac{\sqrt{s} - E^{\text{CMS}}_{e^\pm\pi^0} - p^{\text{CMS}}_{e^\pm\pi^0}}{\sqrt{s}} > 0.05$
- Clear signals of π^0 and η
- Incomplete MC description
  - Data-driven background subtraction
- Divide out point-like cross section using MC distributions



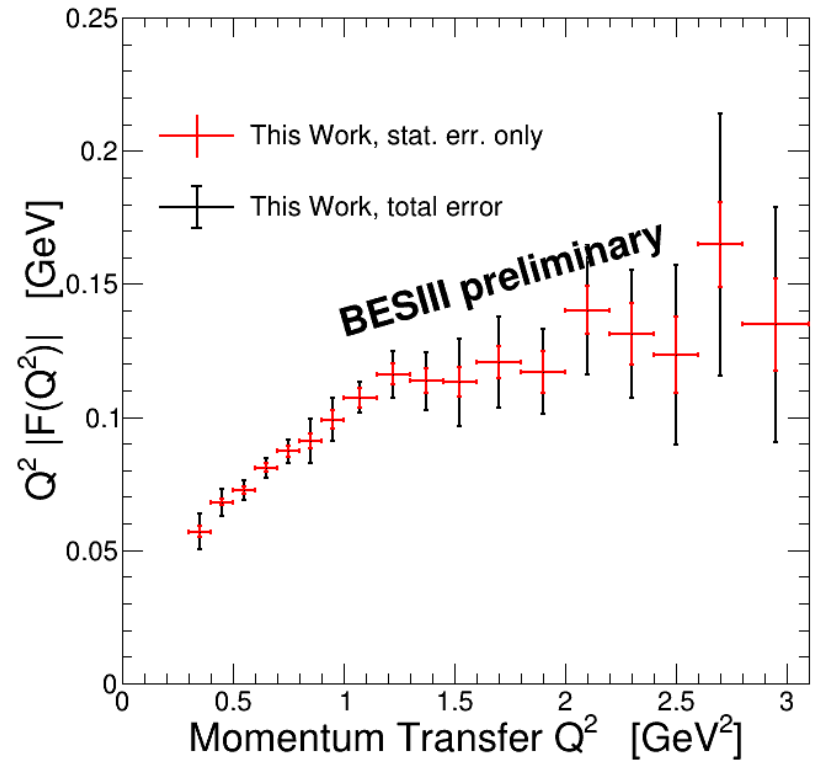


Spacelike π^0 Transition Form Factor

Systematic Uncertainties of $|F(Q^2)|$

Error propagation: $\Delta|F(Q^2)|_i = \frac{1}{2}\frac{1}{\sqrt{(|F(Q^2)|^2)}}\Delta(|F(Q^2)|^2)_i$

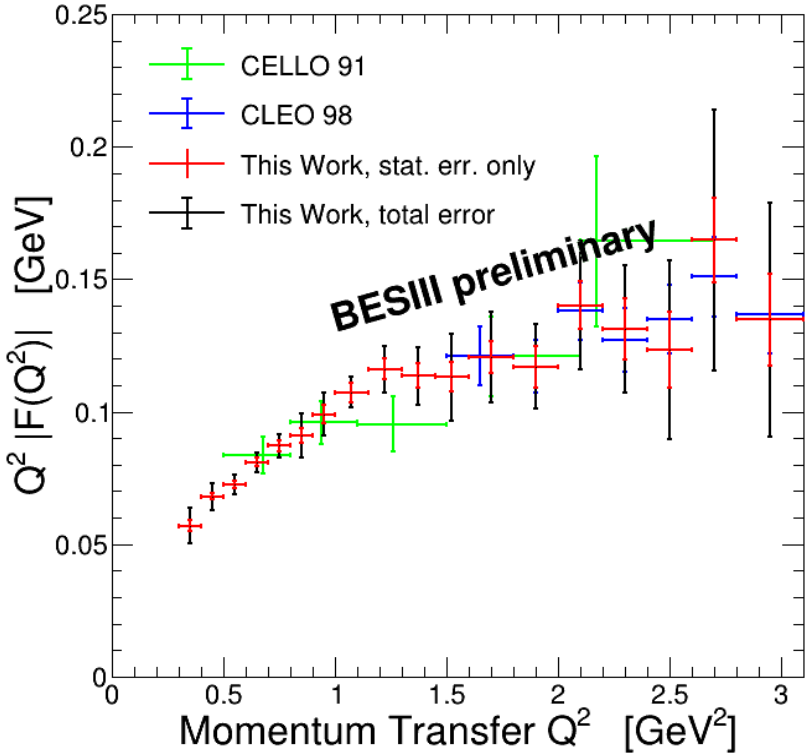
	Source	Contribution
External	Tracking efficiency	0.25%
	Photon detection efficiency	1%
	Luminosity	0.25%
Analysis	$q_{\text{tag}} \cdot \cos\theta_{\text{miss}} < -0.99$	0.1% – 3.1%
	$\cos\theta_{\text{H}} < 0.8$	0.2% – 4.5%
	$\lvert\Delta\phi_{\gamma\gamma}\rvert < \frac{\pi}{2}$	negligible
	$\lvert\Delta\theta_{\gamma\gamma} - 0.01 q_{\text{tag}}\rvert > 0.02$	0.3% – 9.8%
	$R_\gamma < 0.05$	1.0% – 7.7%
	Reconstruction efficiency	1.6% – 17.2%
Background subtraction	Signal shape	0.1% – 1.9%
	Event counting	0.1% – 11.1%
	Background shape	0.2% – 21.0%
Total		**3.9% – 30.0%**



- Contributions added in quadrature
- Full correlation between contributions of analysis conditions and background subtraction assumed
- Error estimate does not consider radiative effects
  - To be evaluated with recently released Ekhara 3.0

Comp. Phys. Commun. 234 (2019) 245

Spacelike π^0 Transition Form Factor

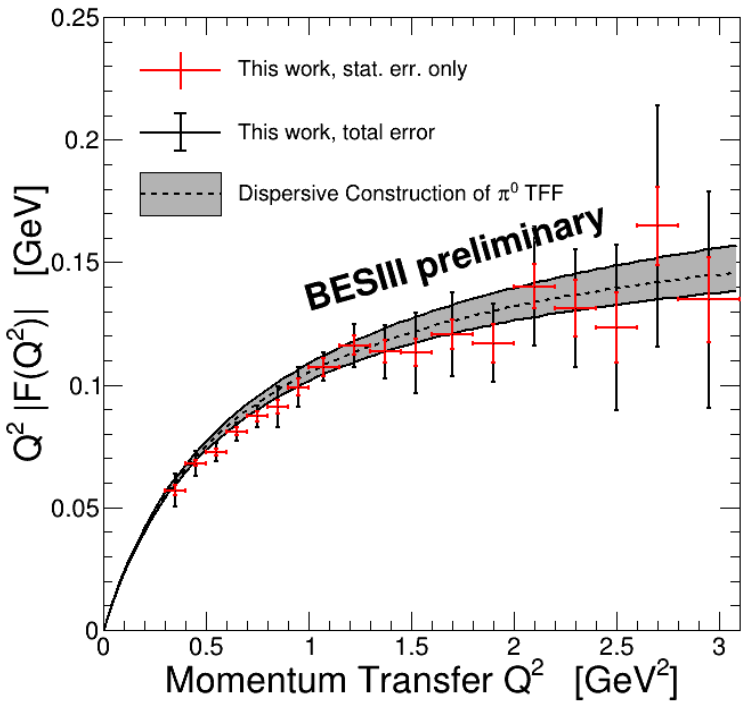


CELLO: Z. Phys. C49 (1991) 401
CLEO: Phys. Rev. D57 (1998) 33

- Competitive accuracy up to 3.1 GeV²
- Unprecedented accuracy below Q^2 =1.5 GeV²
- First data provided below 0.5 GeV²
  - Limited by photon acceptance

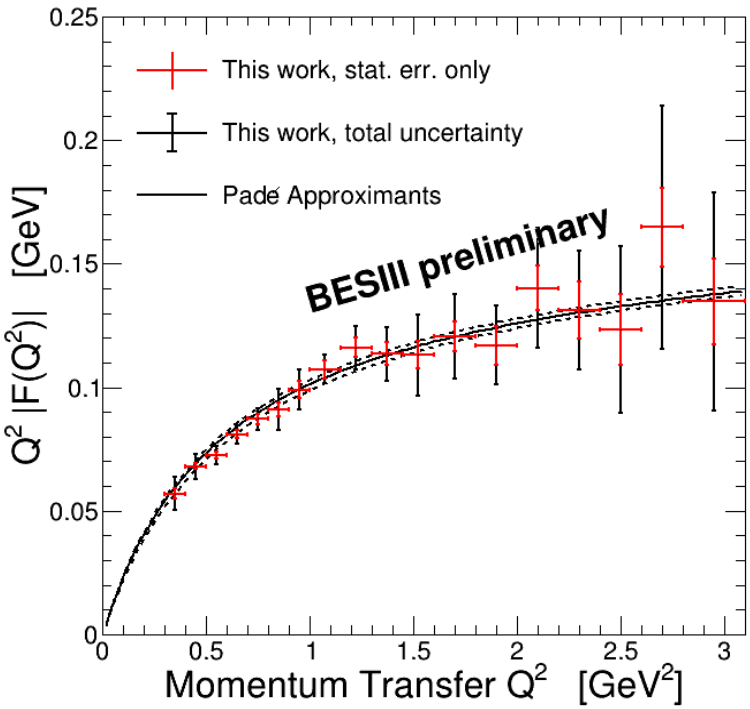
Spacelike π^0 Transition Form Factor

Comparison to Theory: Data-driven Approaches



Construction of space-like TFF using time-like experimental results in dispersive calculations

Hoferichter et al., Phys. Rev. Lett. 121 (2018) 112002



Fit previous measurements with Padé approximants

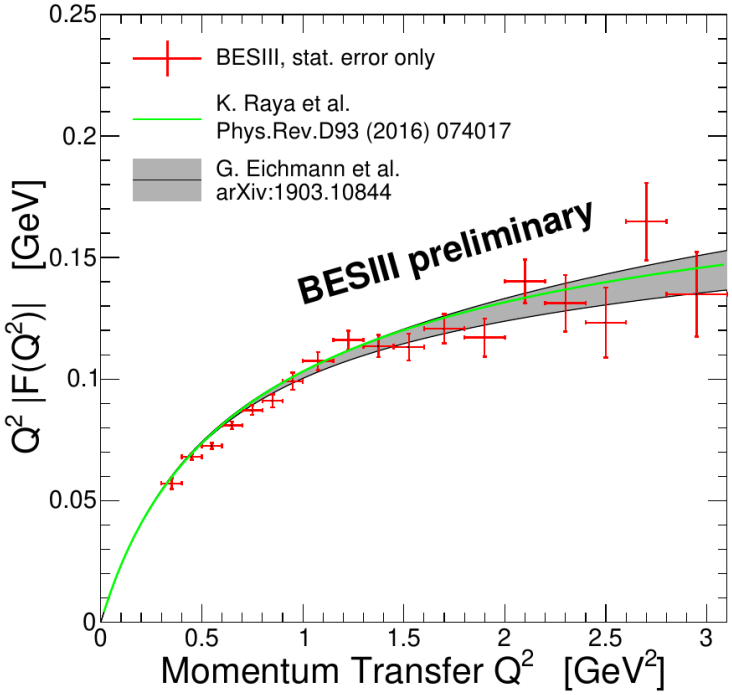
Masjuan et al., Phys. Rev. D86 (2012) 094021

Model independent (mathematical technique)
Provides estimate of systematic uncertainties

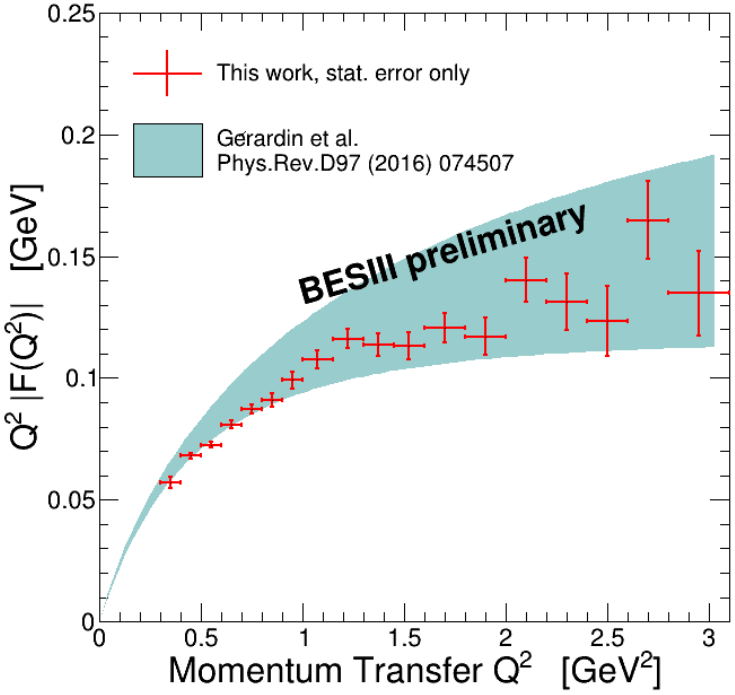
Spacelike π^0 Transition Form Factor

Comparison to Theory

Dyson - Schwinger

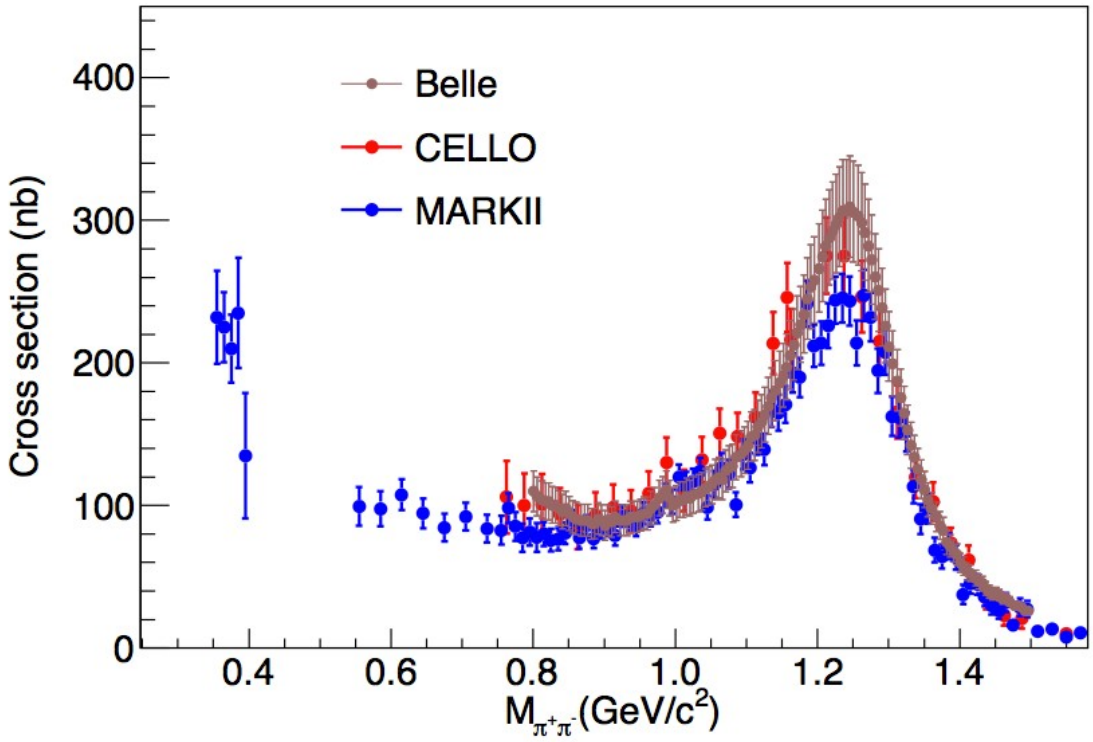


Lattice



Single-tagged Measurement of $\pi^+\pi^-$

Previous measurements:



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

- Only untagged measurements
- Data scarce at small $m_{\pi^+\pi^-}$

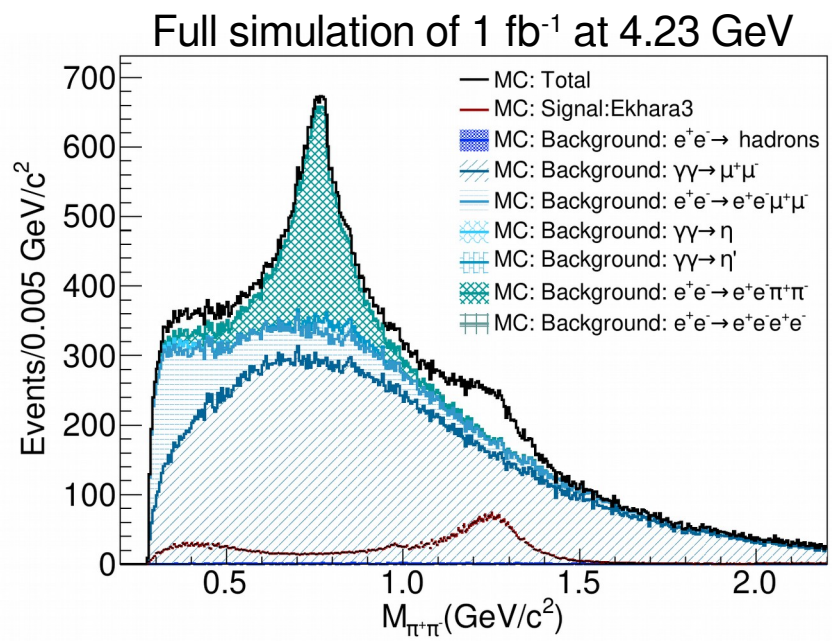
- MARKII: $209\ \mathrm{pb}^{-1}, \quad 0.35 \leq m_{\pi\pi}[\mathrm{GeV/c^2}] \leq 1.6$ — Phys. Rev. D42 (1990) 1350
- CELLO: $86\ \mathrm{pb}^{-1}, \quad 0.75 \leq m_{\pi\pi}[\mathrm{GeV/c^2}] \leq 1.9$ — Z. Phys. C56 (1992) 381
- Belle: $85.9\ \mathrm{fb}^{-1}, \quad 0.8 \leq m_{\pi\pi}[\mathrm{GeV}/c^2]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

Single-tagged Measurement of $\pi^+\pi^-$

Based on 7.5 fb^{-1} from 3.773 GeV to 4.6 GeV

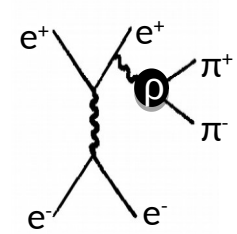
Event selection:

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



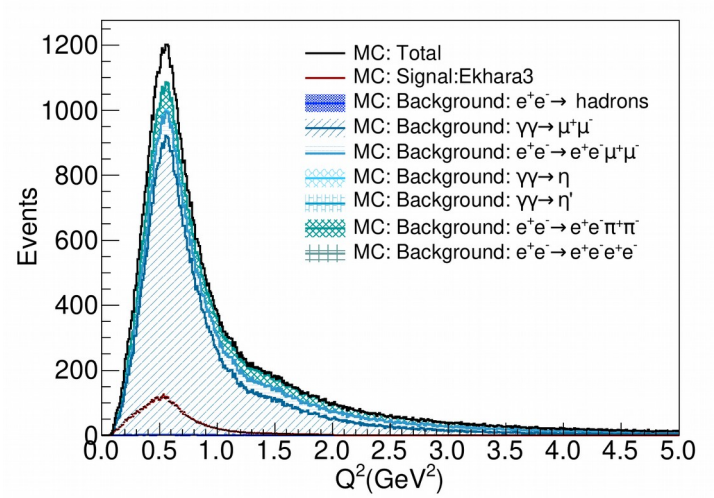
Dominating background contributions

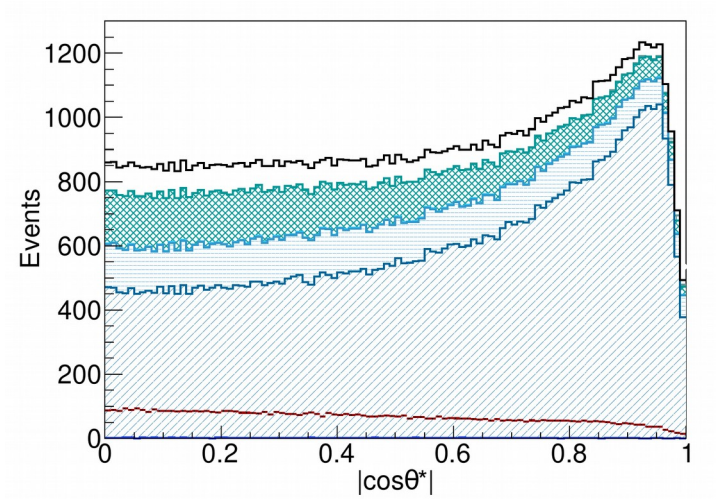
- $e^+e^- \to e^+e^-\mu^+\mu^-$
  - π/μ separation using machine learning techniques
- $e^+e^- \to e^+e^-\pi^+\pi^-$
  - Subtract with parametrization or MC distributions



Single-tagged Measurement of $\pi^+\pi^-$

Full simulation of 1 fb^{-1} at 4.23 GeV





- First single-tag measurement of $\pi^+\pi^-$!
  - Providing access to:
    - small momentum transfers $0.1 < Q^2$ [GeV²] < 2.0
    - small invariant masses $m_{\pi+\pi-} < M$ [GeV] < 2.0
    - full coverage of $|\cos\theta^*|$

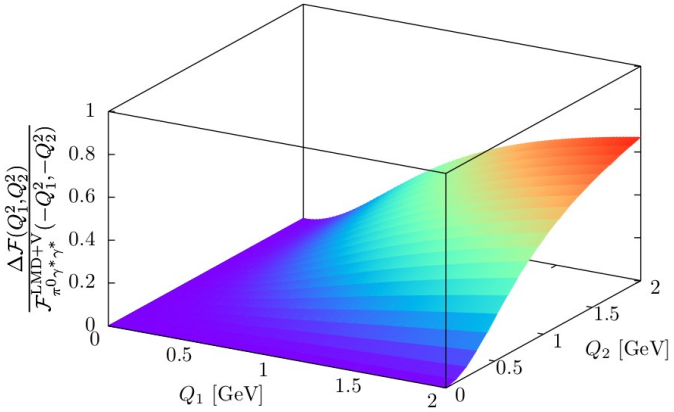
Outlook: Single-Tagged Measurements

- Final publication of π^0 measurement at 3.773 GeV
- Measurement of η and η'
  - Different decay modes used for tagging mesons
- Final publication of $\pi^+\pi^-$
- Measurement of $\pi^0\pi^0$ in preparation
  - To be extended to $\pi^0\eta, \eta\eta$
- First test of axial and tensor meson measurements successful
  - Clear signals of $f_1(1285)$ or $a_2(1320)$
- Consider data sets between 2.0 GeV and 3.773 GeV
  - reduced boost on hadronic system
  - Better detection efficiency
  - First test for π^0: Q^2 down to 0.1 GeV^2 accessible!

Outlook: Double-Tagged Measurements

Only available data: $F_{\gamma^*\gamma^*\eta'}(Q_1^2, Q_2^2)$ by BaBar at large Q^2

- BESIII collected > 15 fb^{-1} at 3.77 < √s [GeV] < 4.6
  - First test on 10 fb^{-1} yields $\mathcal{O}(10^2)\pi^0$event candidates
  - Q^2 dependence investigation for $Q^2_{1,2}$ in [0.3 GeV^2;2.0 GeV^2]
  - η and η' candidates found



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

The BESIII Collaboration plans to collect additional 20 fb^{-1} at 3.773 GeV

- $F_{\gamma^*\gamma^*\pi^0}(Q_1^2, Q_2^2)$ measurement with high statistical accuracy

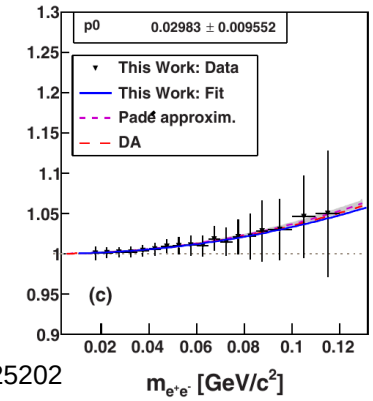
Summary

Two-photon physics at BESIII offers valuable input for data-driven approaches

- Single-tag measurements
  - relevant momentum range
  - Unprecedented accuracy
- Flagship measurements: $\gamma\gamma^* \to \pi^0$ and $\gamma\gamma^* \to \pi^+\pi^-$
  - Studies of further mesons and meson systems in preparation
- First double-tagged measurement started: $\gamma^*\gamma^* \to \pi^0$
- Tagging detectors in development

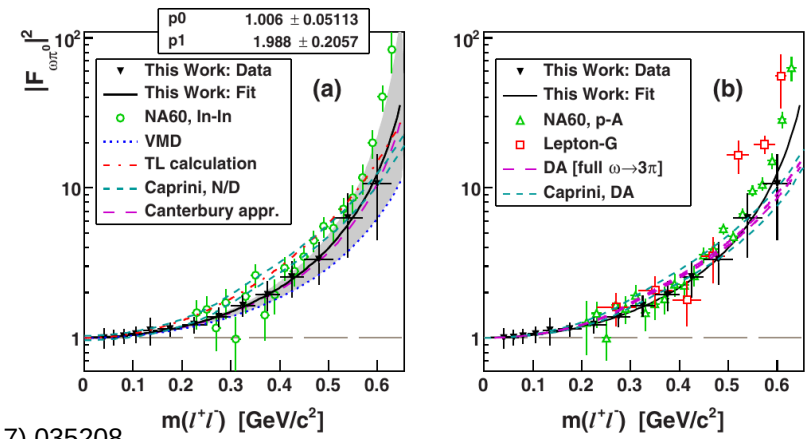
Reminder: The A2 Results

- Non-magnetic spectrometer
- Photon-induced meson production

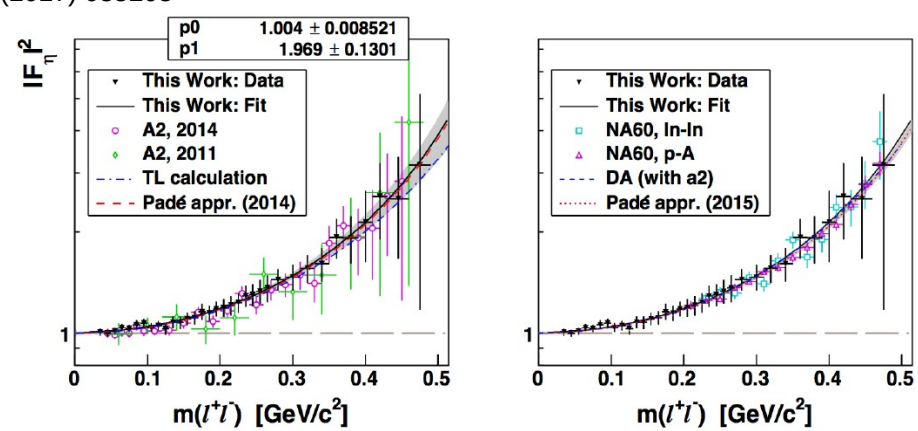


Phys. Rev. C95 (2017) 025202

- π^0 Dalitz Decay $\pi^0 \to \gamma e^+ e^-$
  - Slope parameter: $a_\pi = 0.030 \pm 0.010_{\text{tot}}$
  - New Data being analyzed



Phys. Rev. C95 (2017) 035208

- η Dalitz Decay $\eta \to \gamma e^+ e^-$
  - Slope parameter: $\Lambda_{\eta\gamma}^{-2} = (1.97 \pm 0.13_{\text{tot}})\text{GeV}^{-2}$

- ω Dalitz Decay $\omega \to \pi^0 e^+ e^-$
  - Slope parameter: $\Lambda_{\omega\pi^0}^{-2} = (1.99 \pm 0.21_{\text{tot}})\text{GeV}^{-2}$
  - New data taking later this year