Experimental Inputs to the Hadronic Light-by-Light Contribution to $(g-2)_\mu$ from BESIII

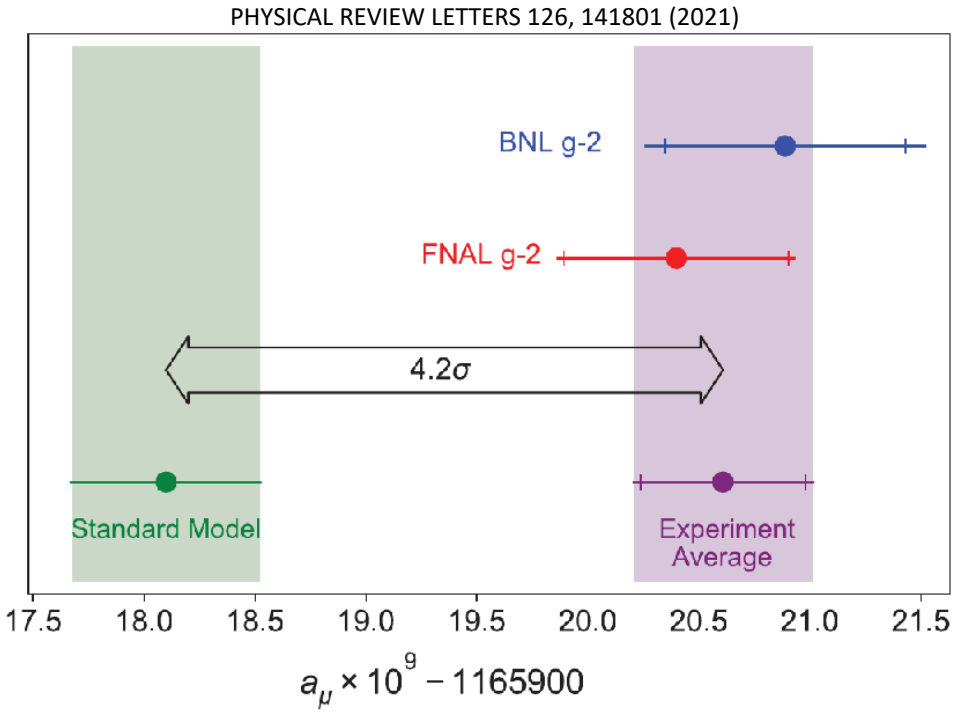
Max Lellmann

Frontiers and Careers in Nuclear and Hadronic Physics

05.08.2022

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

The Anomalous Magnetic Moment of the Muon



- Anomalous magnetic moment: $a_\mu = \frac{g_\mu - 2}{2}$
- Less than 0.5 ppm accuracy in experiment and theory
  - Exp.: $116\,592\,061(41) \times 10^{-11}$
    (PHYSICAL REVIEW LETTERS 126, 141801 (2021))
  - SM: $116\,591\,810(43) \times 10^{-11}$
    (PHYSICS REPORTS 887 (2020) 1–16)
- Discrepancy between SM prediction and experiment observed
- New measurements at FermiLab and J-PARC
  - Uncertainty of direct measurement will shrink by a factor of 4
- **SM prediction needs to be improved**

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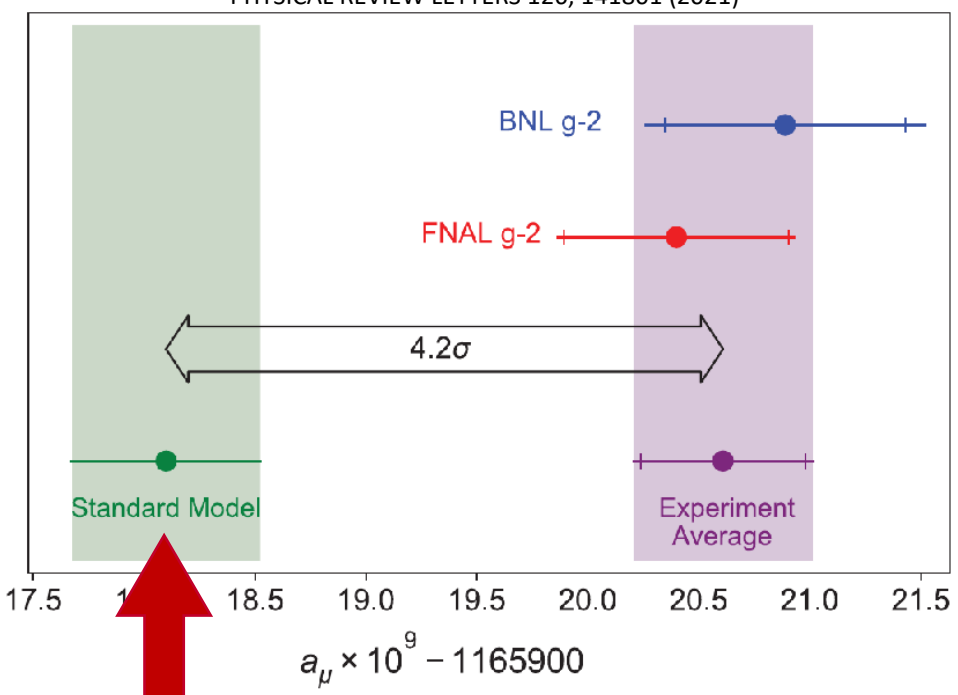
PHYSICAL REVIEW LETTERS 126, 141801 (2021)



$(g-2)_\mu$ Theory Initiative
PHYSICS REPORTS 887 (2020) 1–16

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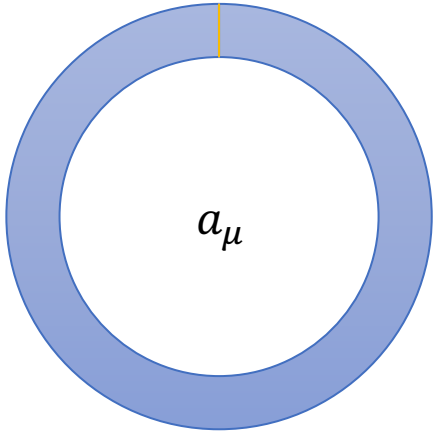
The Anomalous Magnetic Moment of the Muon

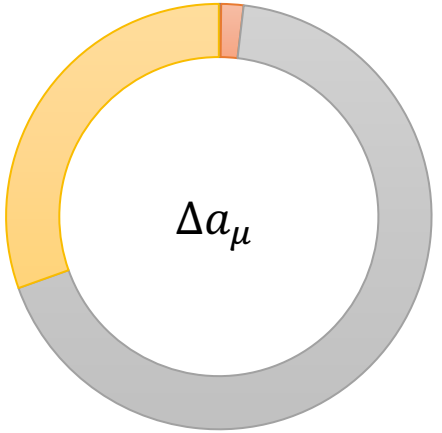
$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{Strong}$$

- **Hadronic contributions limit SM prediction**
- **Fix parameters using experimental input**

- Hadronic Vacuum Polarization (HVP)
  - Largest hadronic contribution to a_μ
  - Can be connected to hadronic R value
  - **See talk of Yasemin**

- Hadronic Light-by-Light scattering (HLbL)
  - Largest relative uncertainty of all contributions
  - Depends on the knowledge of hadrons coupling to photons





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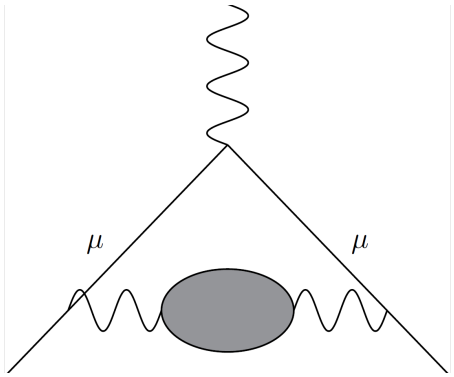
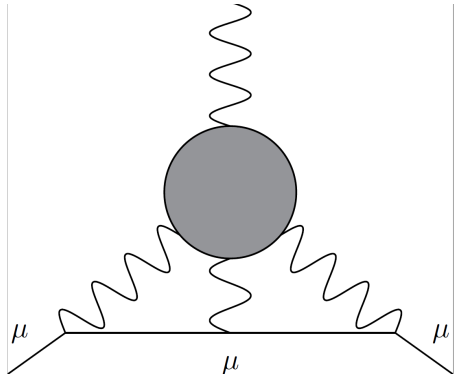


Hadronic Vacuum Polarization



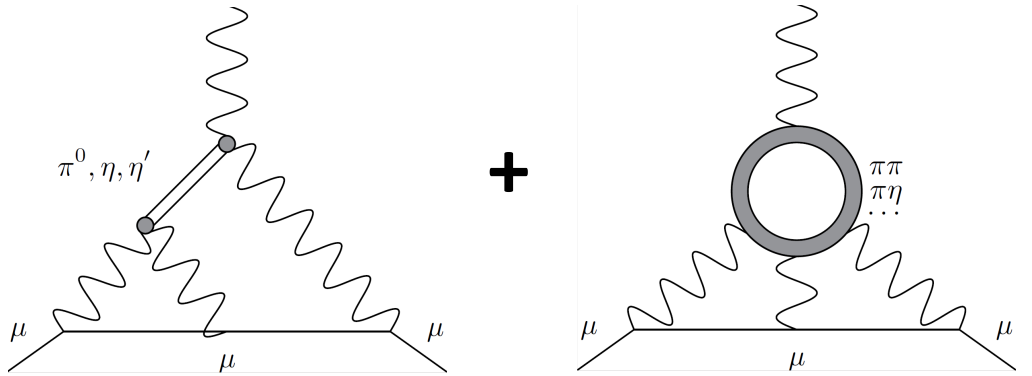
Hadronic Light-by-Light scattering

Relevant Processes for a_μ^{HLbL}

Counting Scheme: (de Rafael, Phys.Lett.B322, 239, 1994)

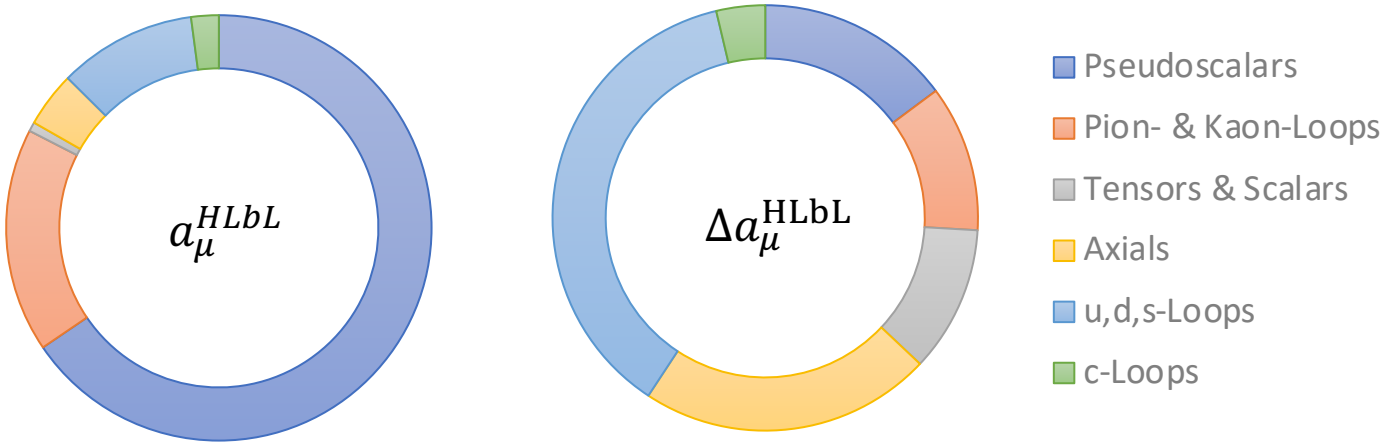
Dominant processes are:

- Pseudoscalar meson exchange
- Meson loop contribution



Similar sized uncertainties in numerous channels:

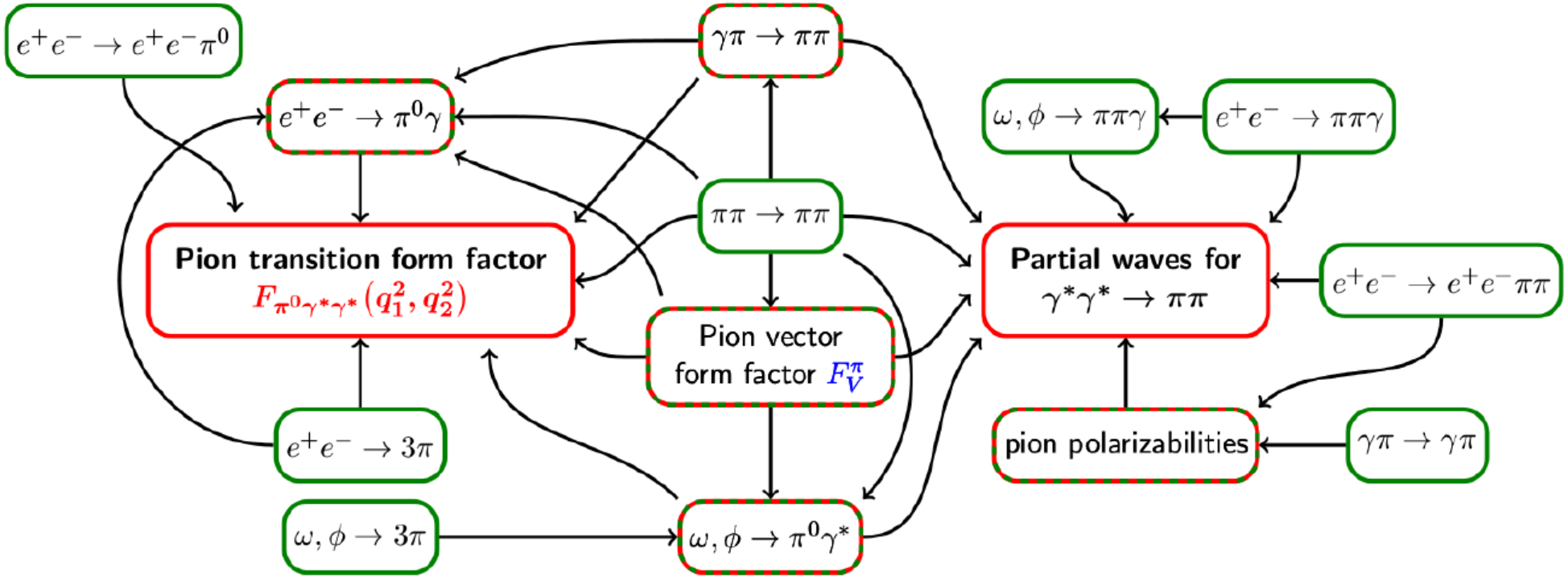
- Growing interest in the coupling of axials to photons



Information on photons coupling to hadrons necessary

(PHYSICS REPORTS 887 (2020) 1–16)

Relevant Processes for a_μ^{HLbL} (Dispersive Analysis)



Final ingredients to a_μ^{hLBL}
Input
Measurement/Calculation

Colangelo, Hoferichter, Kubis, Procura, Stoffer
Phys.Lett. B738 (2014) 6

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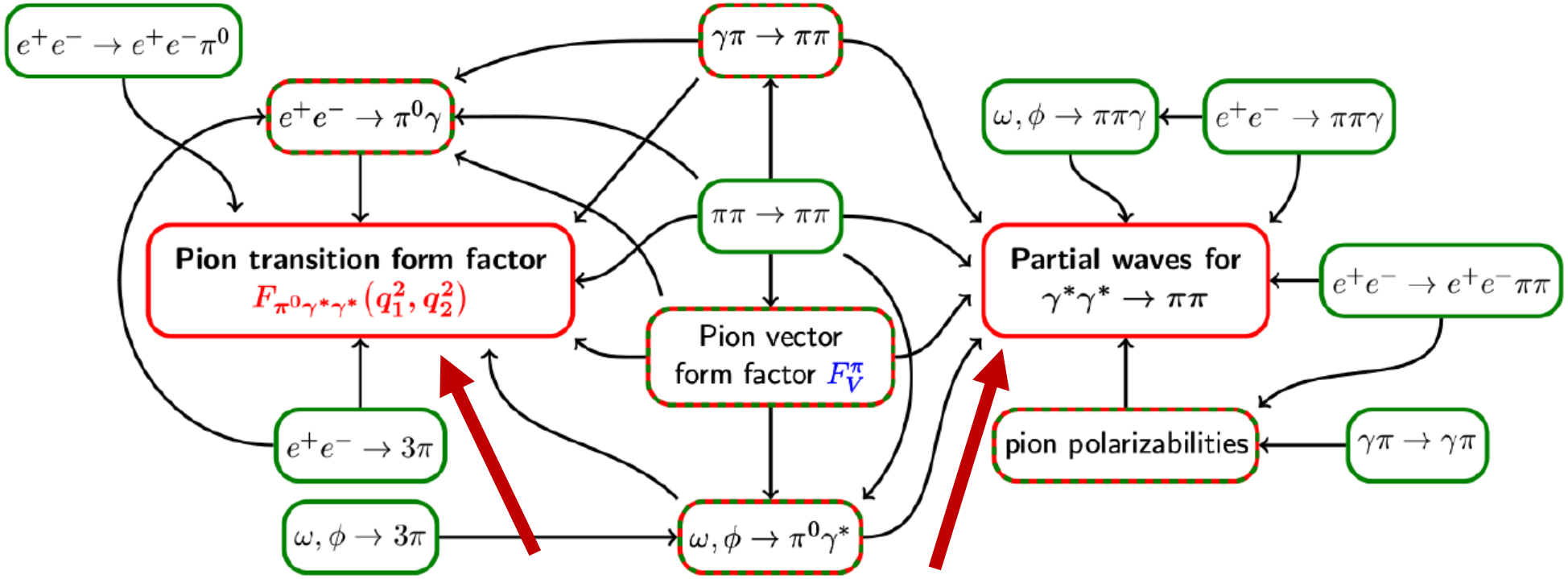


Final ingredients to a_μ^{hLBL}
Input
Measurement/Calculation

Perspectives for BESIII measurements (No Data)

Colangelo, Hoferichter, Kubis, Procura, Stoffer
Phys.Lett. B738 (2014) 6

Relevant Energies for a_μ^{HLbL}

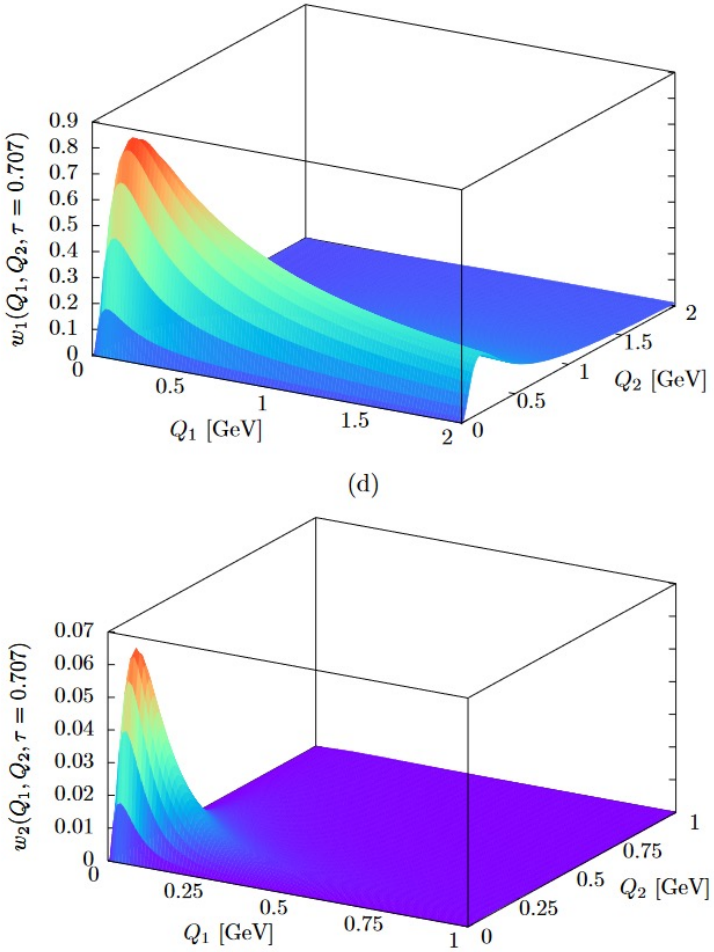
Example Single Pion Contribution (Phenomenological Approach):

- 3D integral over Transition Form Factor and weighting function
- Requires knowledge of Transition Form Factors in dependence on both photon virtualities

$$a_\mu^{\mathrm{HLbL};\pi^0(1)} = \int_0^\infty dQ_1 \int_0^\infty dQ_2 \int_{-1}^{1} d\tau\, w_1(Q_1, Q_2, \tau) \mathcal{F}_{\pi^0\gamma^*\gamma^*}(-Q_1^2, -(Q_1+Q_2)^2) \mathcal{F}_{\pi^0\gamma^*\gamma^*}(-Q_2^2, 0)$$

$$a_\mu^{\mathrm{HLbL};\pi^0(2)} = \int_0^\infty dQ_1 \int_0^\infty dQ_2 \int_{-1}^{1} d\tau\, w_2(Q_1, Q_2, \tau) \mathcal{F}_{\pi^0\gamma^*\gamma^*}(-Q_1^2, -Q_2^2) \mathcal{F}_{\pi^0\gamma^*\gamma^*}(-(Q_1+Q_2)^2, 0)$$

Relevant Energies:
0.25 GeV – 1.25 GeV



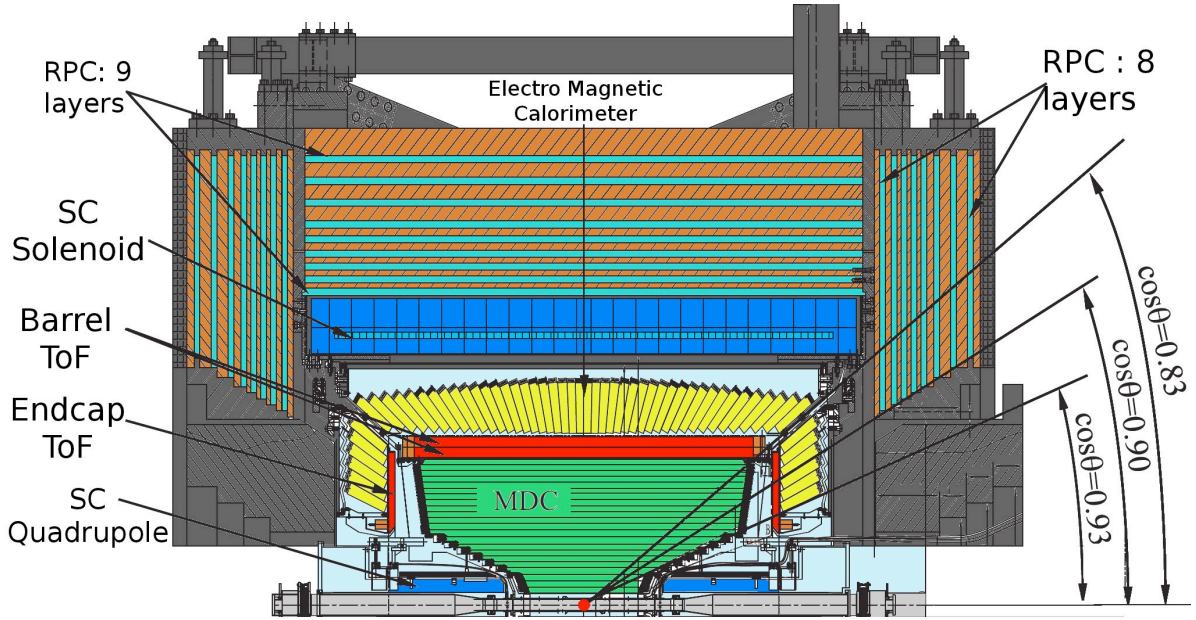
Nyffeler, Phys.Rev.D94,053006, 2016

The BESIII Experiment

- Located at the BEPCII collider (Beijing, China)
- Symmetric e^+e^- beams
- Center-of-Mass energies between 2 and 5 GeV
- Maximum luminosity: 1 nb^{-1}/s
- 93% solid angle coverage

Largest τ-charm data sets collected in e^+e^- collisions

- 10^{10} J/ψ and 3x 10^9 ψ(2S) directly produced
- More than 20 fb^{-1} of data collected between 3.773 GeV and 5 GeV
- Soon: 20 fb^{-1} at 3.773 GeV



Superconducting Solenoid:
- 1T magnetic field

Time-of-Flight System:
- 90 – 110 ps resolution

Drift Chamber:
- 0.5% momentum resolution
- 6% dE/dx resolution

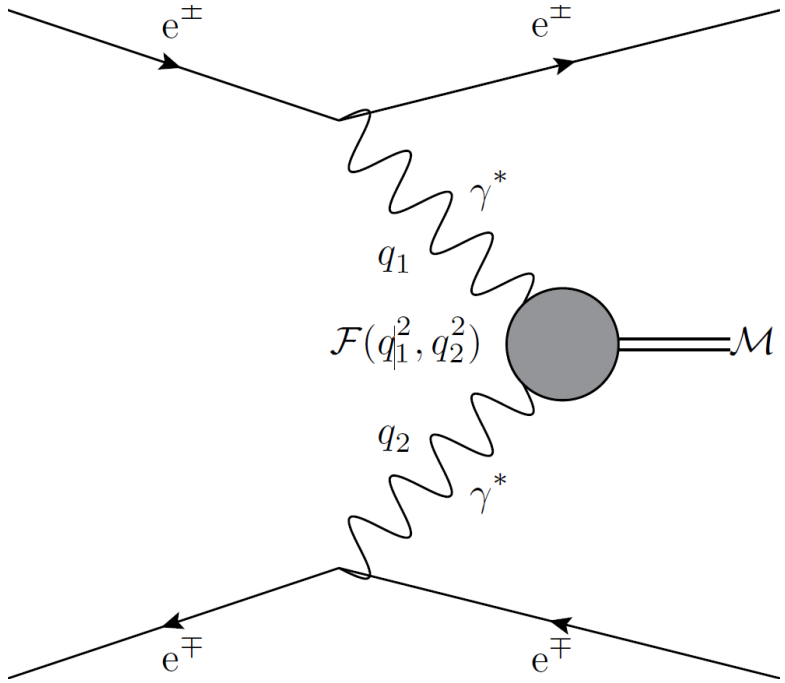
Muon Chambers:
- 8-9 layers of RPCs
- 1.4-1.7 cm resolution
- P > 400 MeV

Electromagnetic Calorimeter:
- 6240 CsI(Tl) crystals
- 2.5% energy resolution
- 0.5 – 0.7 cm spatial resolution

NIM A614 (2010) 345

Space-Like TFFs at BESIII

- Scattering process of two (potentially) virtual photons
- Photon fusion into a hadronic state
- Cross section depends on center-of-mass energy, mass of the produced state, and virtuality of photons
  - Additional dependencies like helicity angle for higher multiplicity final states
- Very strong dependency on photon virtuality
  - Rapid drop of the cross section with $Q^2 \approx 4EE' \sin^2 \theta/2$



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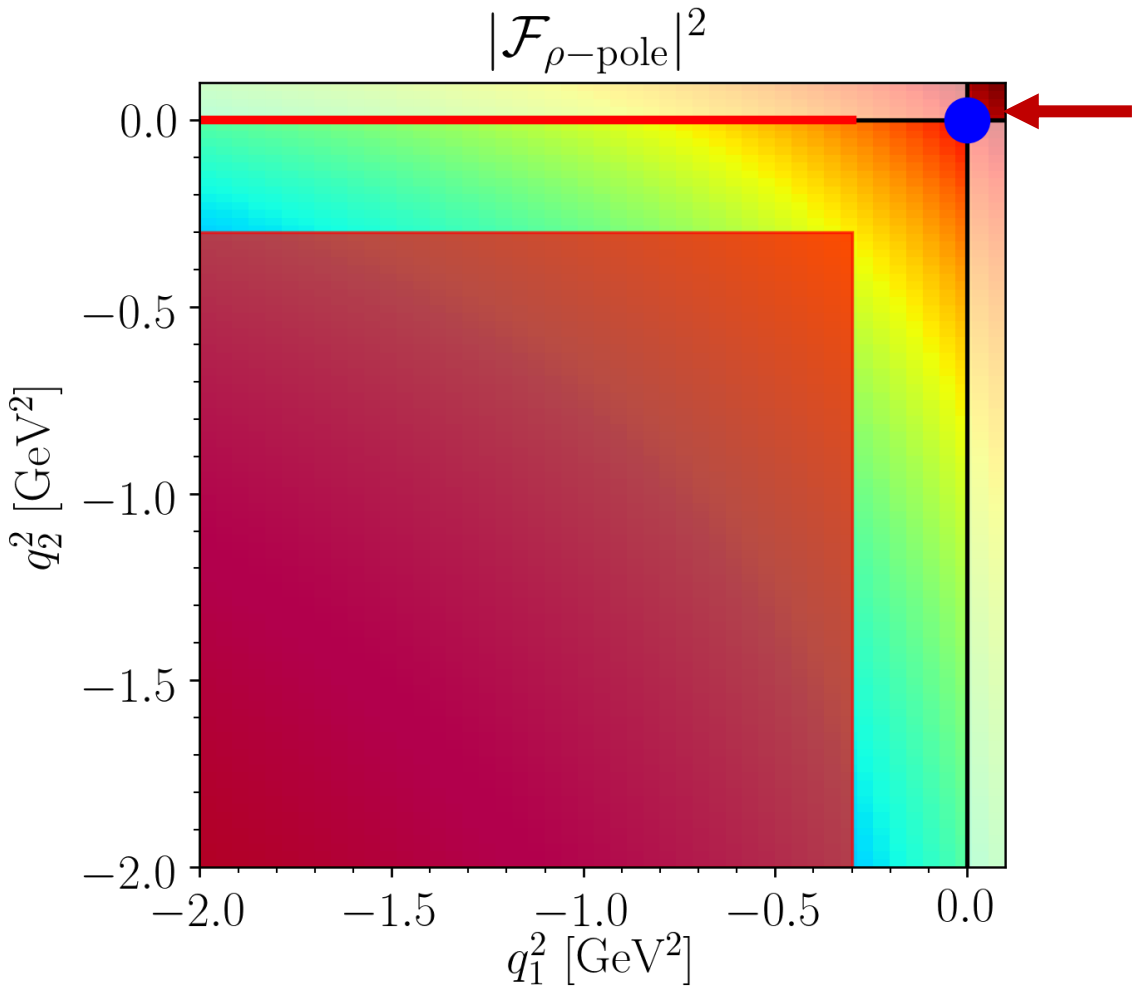

Three different lepton kinematics $(q^2 = -4EE'sin^2\,\theta/2)$

1. **Untagged Measurements**
   - Both leptons escape the detector at small angles
   - $q_1^2 = q_2^2 = 0 \rightarrow$ Two on-shell photons scatter
   - Large cross sections
   - Spectroscopy purposes

2. **Single-tagged Measurements**
   - One leptons escapes the detector at small angles
   - Remaining lepton is tagged
   - $q_1^2 = (p - p')^2 \quad q_2^2 = 0 \rightarrow$ One on- and one off-shell photon scatter
   - Smaller cross section but q^2 dependence can be mapped out

3. **Double-tagged Measurements**
   - Both leptons are measured
   - Complete dependence of the TFFs from photon virtualities can be measured
   - Tiny cross section

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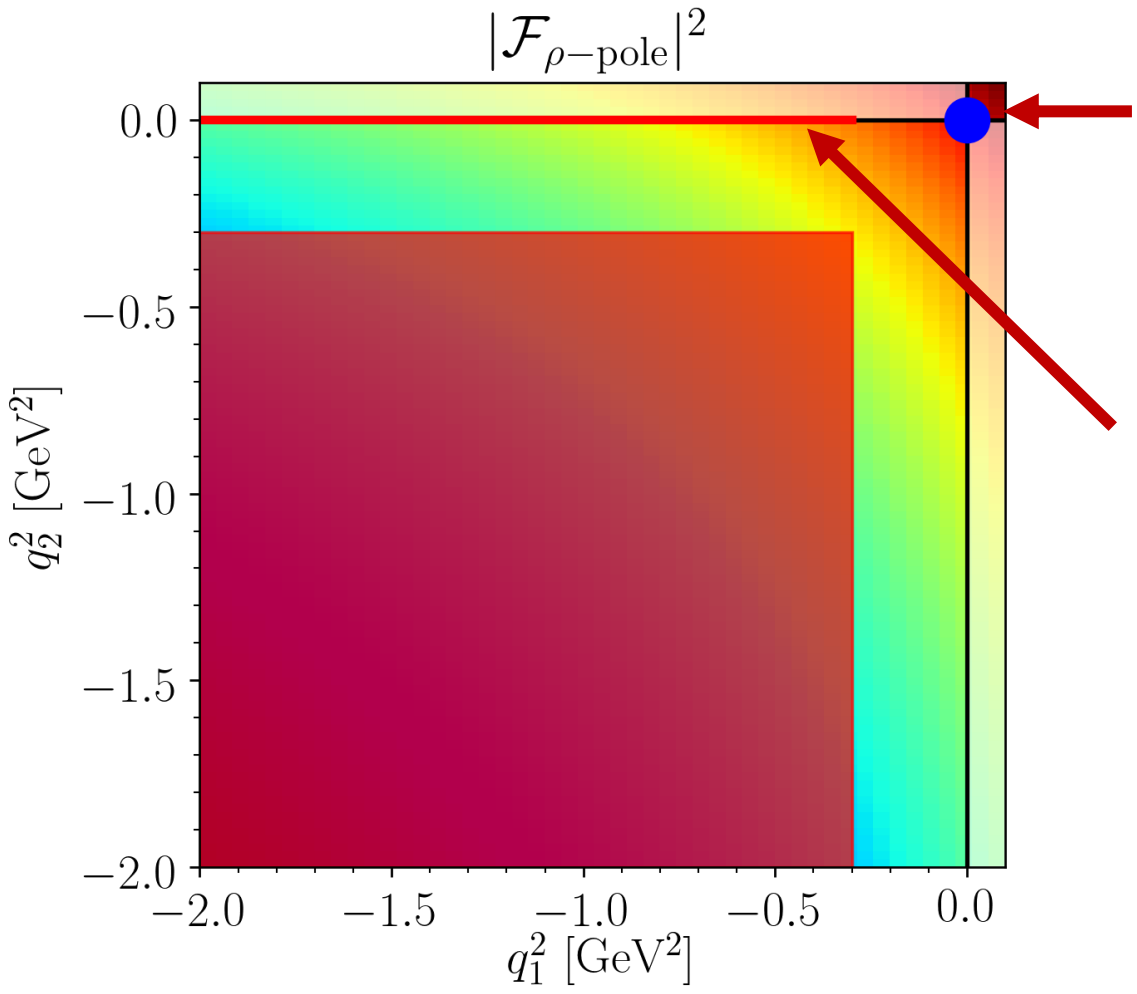

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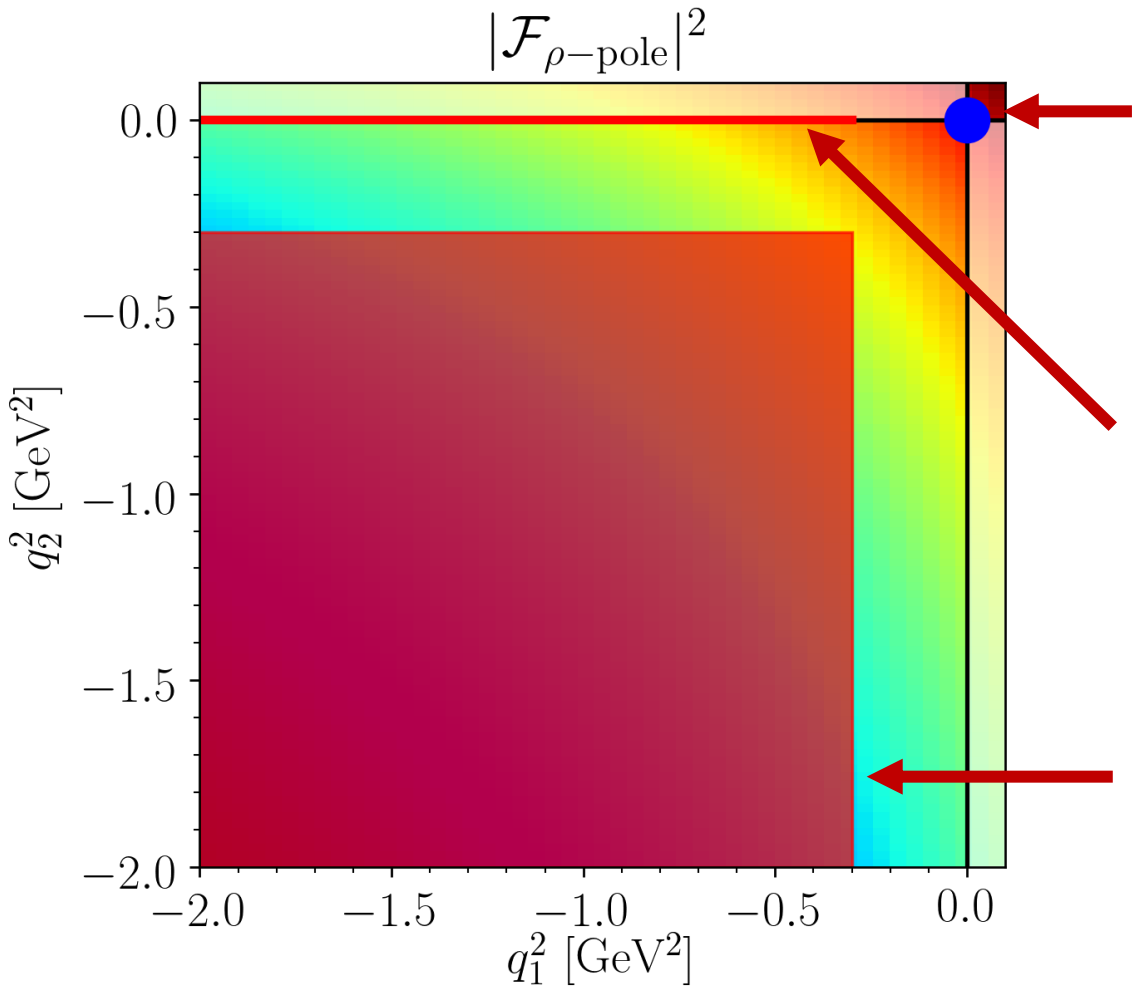

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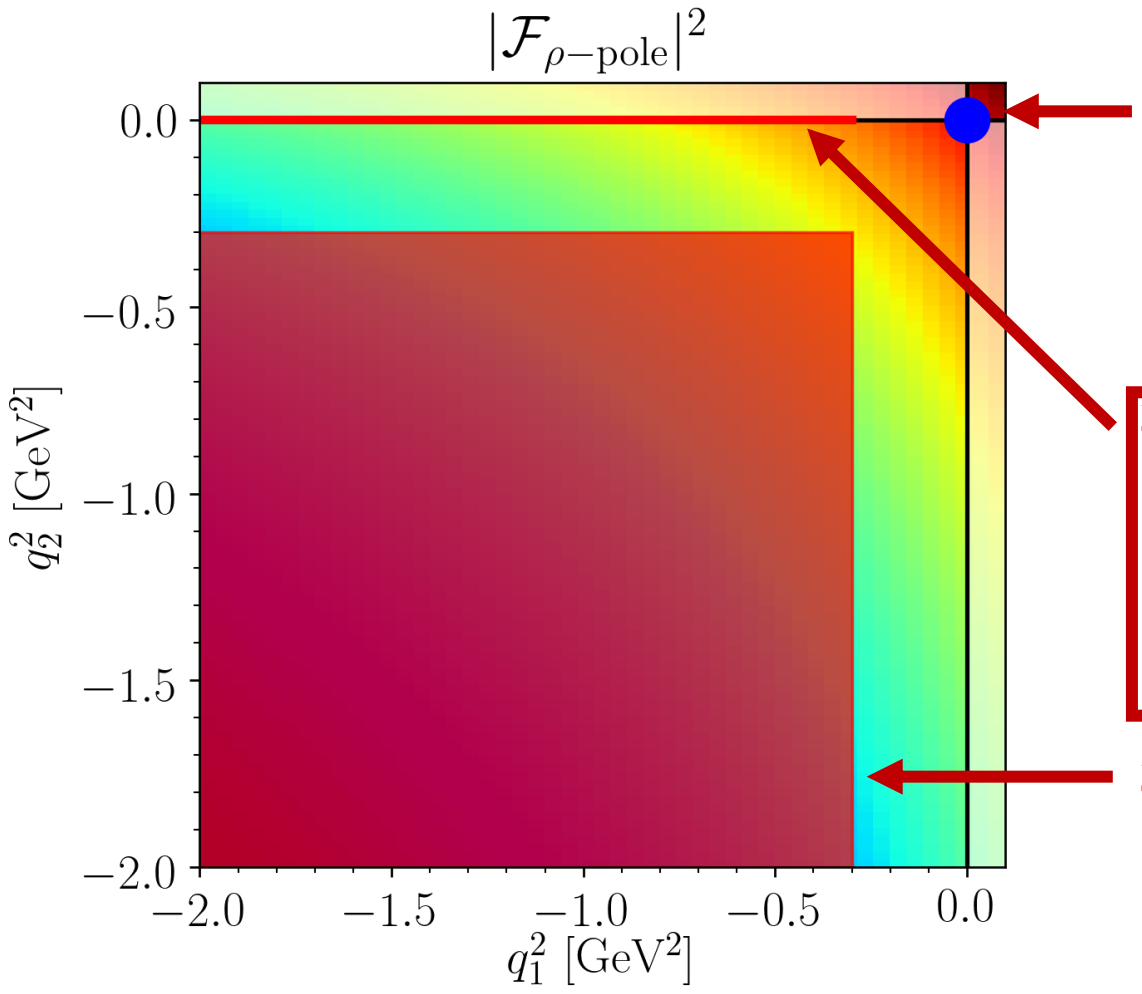

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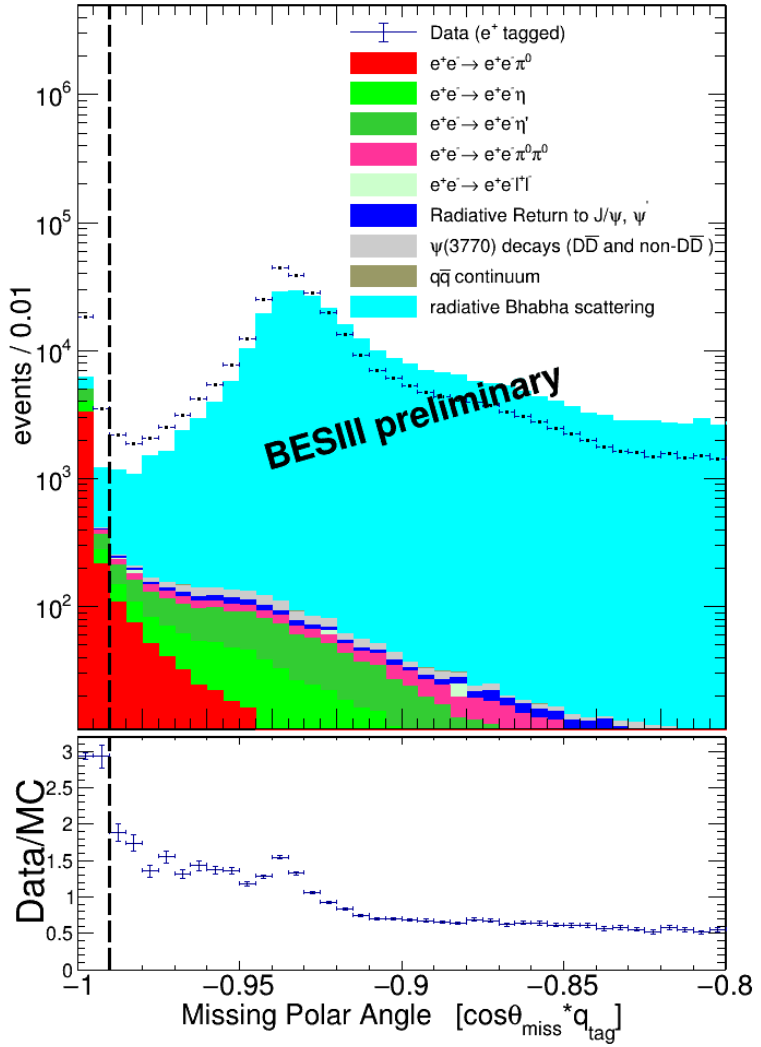
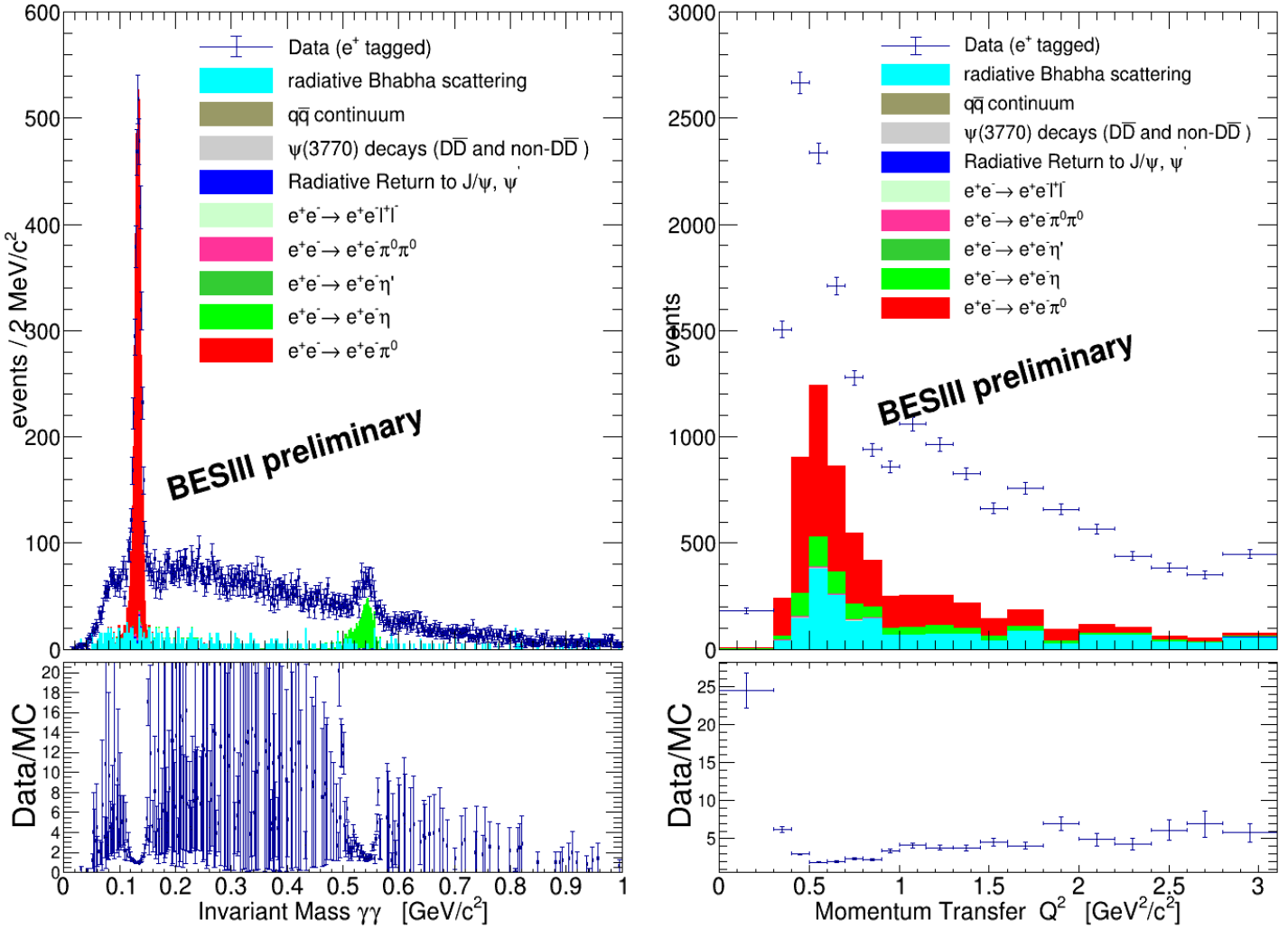
Space-Like $\gamma\gamma^* \rightarrow \pi^0$ Transition Form Factor

- Based on 2.9 fb^{-1} at 3.773 GeV
- Reconstruct:
  - One charged track identified as a lepton
    - Constraints on acceptance and vertex position
    - Particle ID based on ratio of energy deposited in the calorimeter and momentum measured in the wire chamber
  - At least two good photon candidates:
    - Constraints on acceptance, timing, and minimum energy deposition
  - Unmeasured lepton from energy-momentum-conservation
- Require angle of missing lepton to be small
  - „Single-tag-condition“ $\cos\theta > 0.99$
  - Small virtuality for one of the exchange photons



Space-Like $\gamma\gamma^* \rightarrow \pi^0$ Transition Form Factor

- Background suppression:
  - Single-tag condition
  - Photon helicity angle
  - Radiative effects:
    - $R_\gamma = \frac{\sqrt{s}-E^*-p^*}{\sqrt{s}} > 0.05$
- Clear signals of π^0 and η visible
- Incomplete MC description of data
  - Data driven background subtraction
- Relevant q^2 range for a_μ^{HLbL} covered
- Transition form factor determined by dividing q^2dependent cross section by point-like cross section from MC



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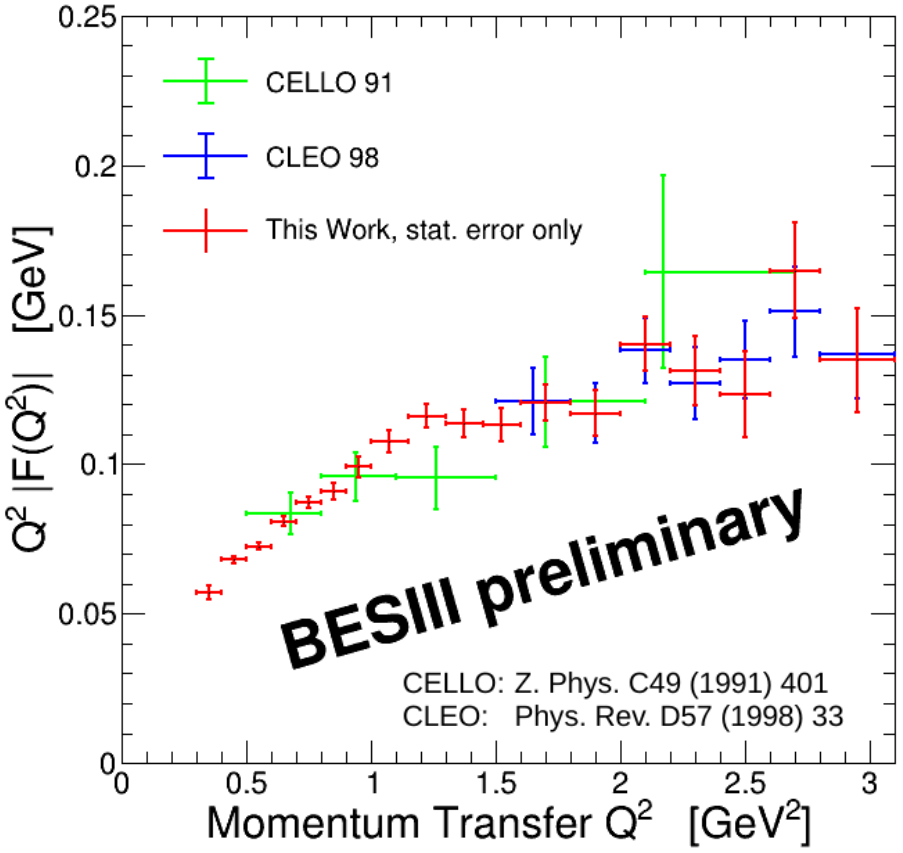
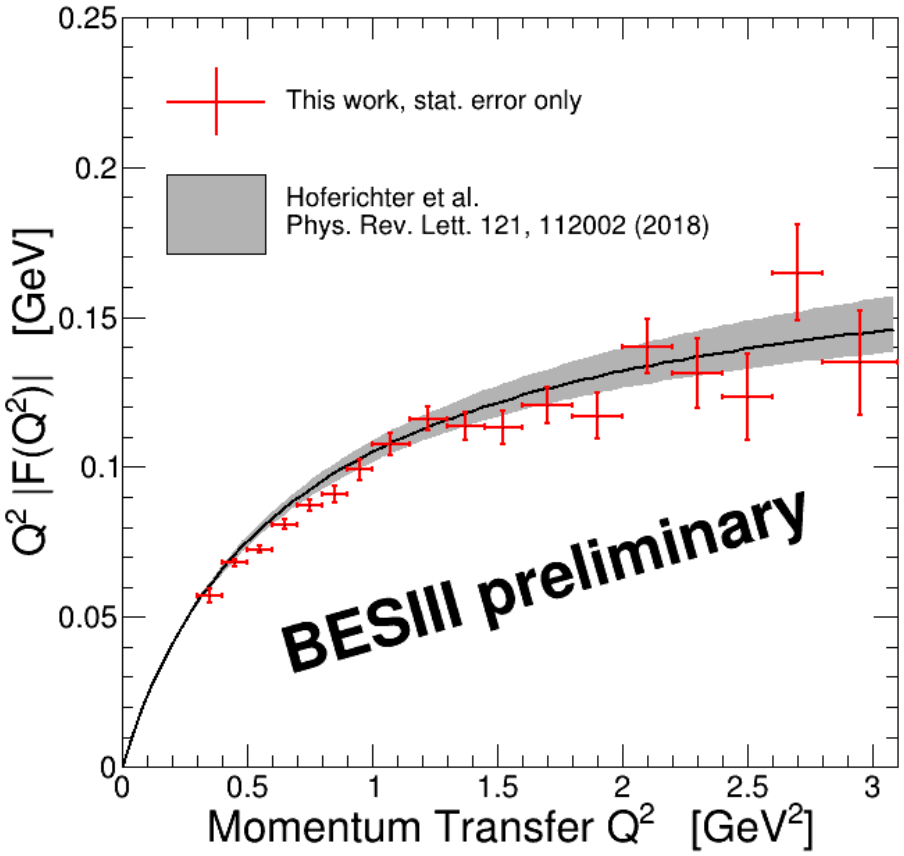


- First measurement below 0.5 GeV²
  - Limited due to photon efficiency
  - Smaller virtualities might be possible at other energy points
- Unprecedented accuracy up to 1.5 GeV²
- Competitive between 1.5 GeV² and 3.1 GeV²

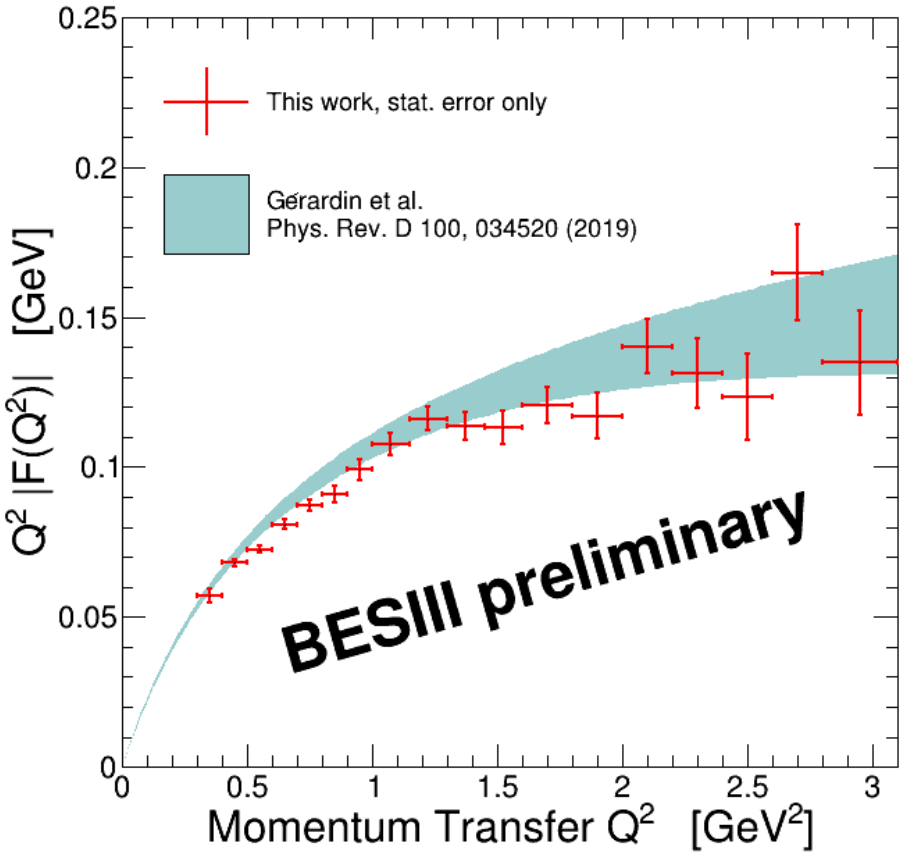
- More data available to be analysed
- Analysis will be extended to measure the η TFF

Space-Like $\gamma\gamma^* \to \pi^0$ Transition Form Factor

Comparison to a dispersive construction of the TFF



Comparison to a Lattice calculation of the TFF



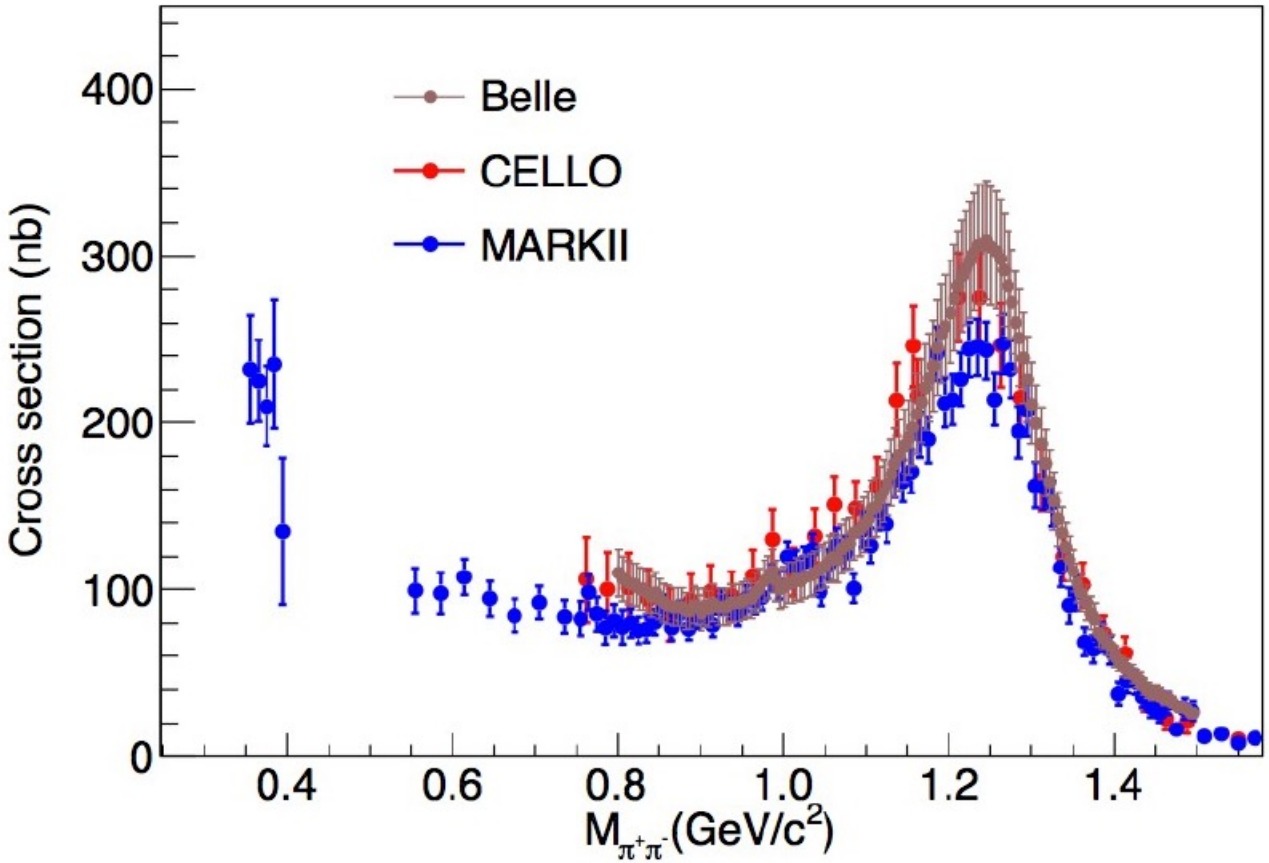
Space-Like $\gamma\gamma^* \to \pi^+\pi^-$ Partial Waves

Previous Measurements:

- Belle: $0.8 < m(\pi^+\pi^-)/\mathrm{GeV} < 1.5$
  Phys. Rev D75 (2007) 051101
- Cello: $0.75 < m(\pi^+\pi^-)/\mathrm{GeV} < 1.9$
  Z. Phys. C56 (1992) 381
- MARKII: $0.35 < m(\pi^+\pi^-)/\mathrm{GeV} < 1.6$
  Phys. Rev. D42 (1990) 1350

All of them are untagged measurements

- $\gamma\gamma \to \pi^+\pi^-$
- Data sparse at small masses and angles



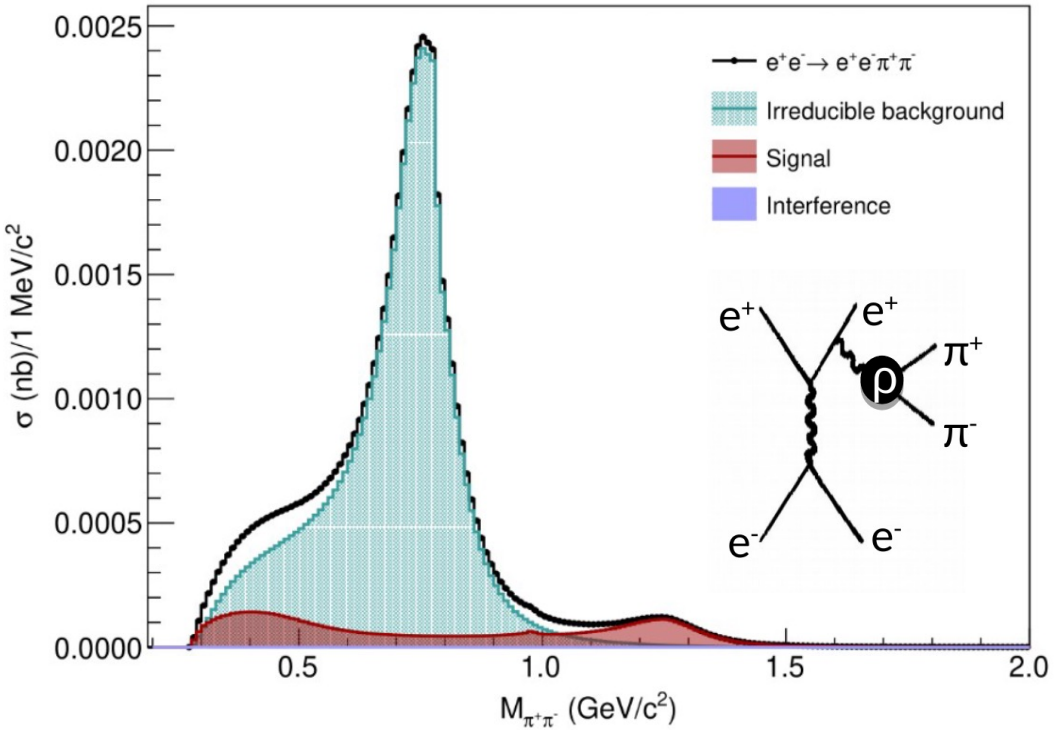
Space-Like $\gamma\gamma^* \to \pi^+\pi^-$ Partial Waves

- Analysis based on 7fb^{-1} of data between 3.773 GeV and 4.6 GeV

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

- Event selection:
  - Three good charged tracks
  - One of them identified as an electron/positron
  - Other two oppositely charged

- Main background contributions
  - $e^+e^- \to e^+e^-\mu^+\mu^-$
    Suppressed using MVA tools (random forests)
  - $e^+e^- \to e^+e^-\pi^+\pi^-$
    Subtracted using fits and special simulations



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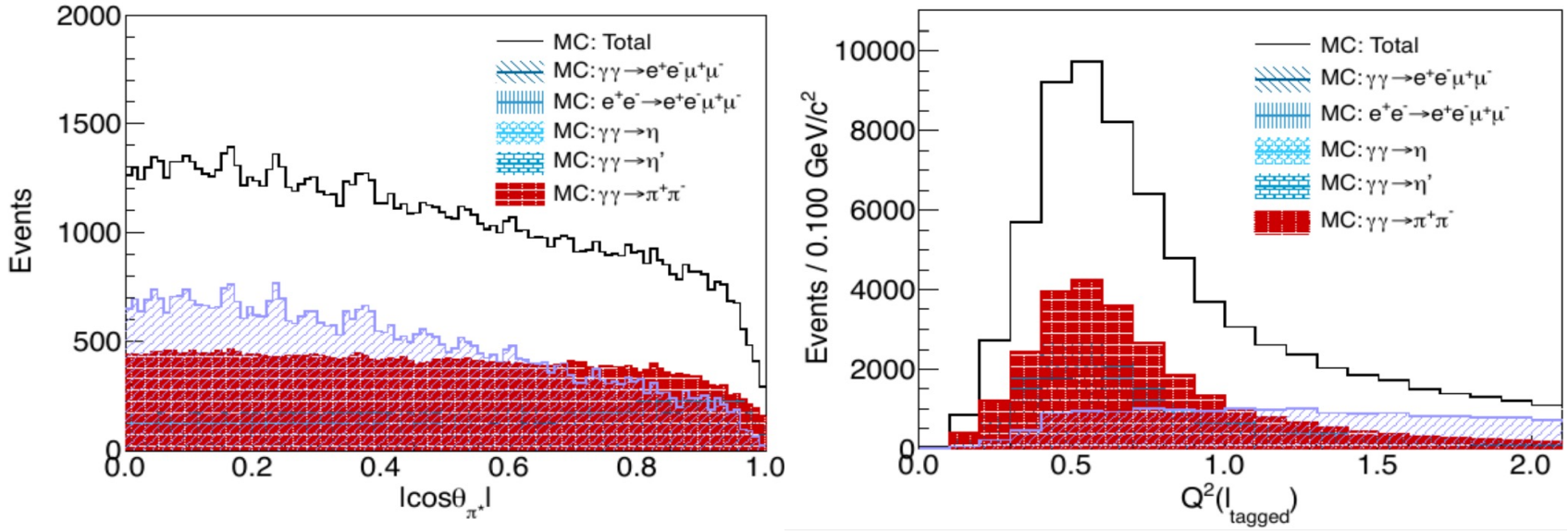


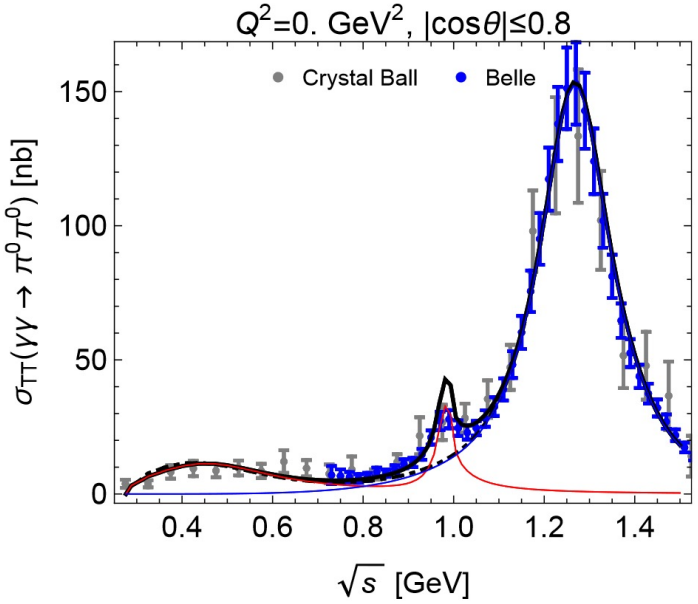
First single-tagged measurement of this channel

- Small momentum transfers 0.1 GeV² < Q² < 2 GeV²
- Full helicity angle coverage
- Mass coverage from threshold to 2 GeV

Space-Like $\gamma\gamma^* \to \pi^0\pi^0$ Partial Waves

Goal of this measurement: Cover the so far unmeasured Q^2 region in between!

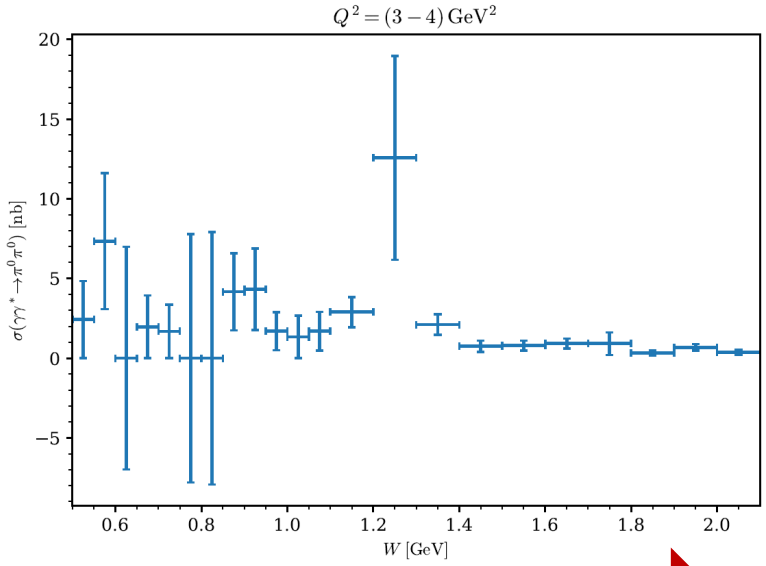
Minimum virtuality



This work

BESIII

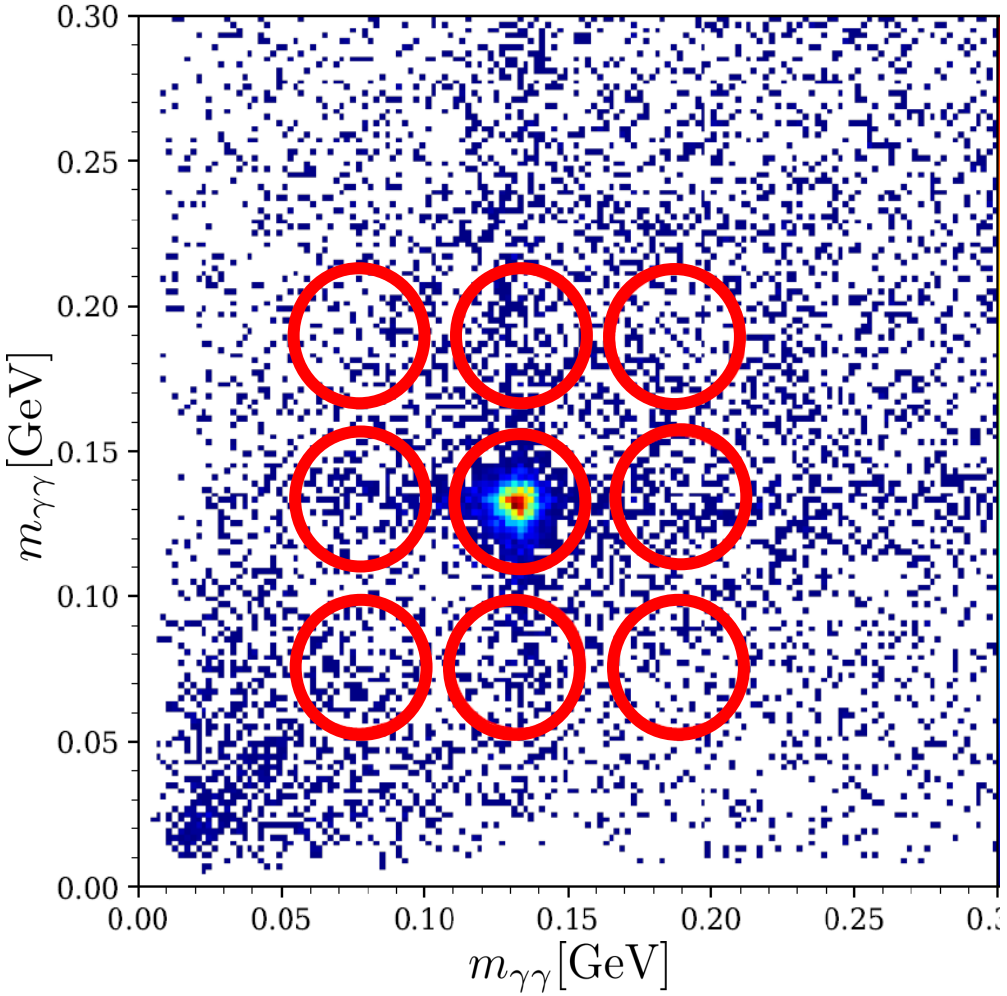
High virtuality



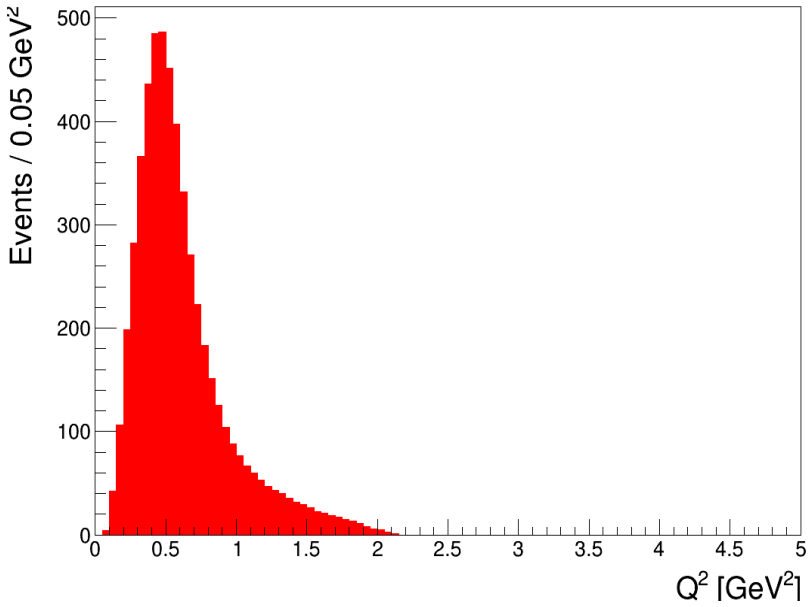
Momentum transfer Q²

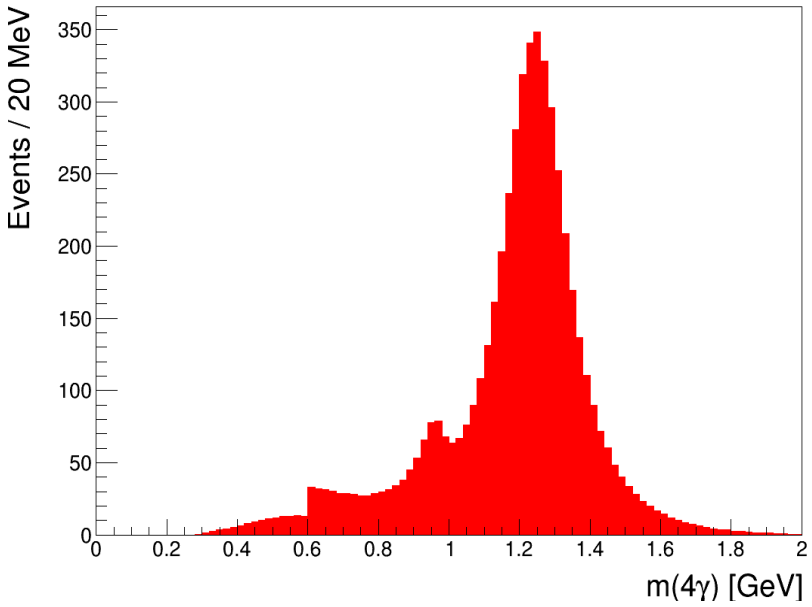
Space-Like $\gamma\gamma^* \to \pi^0\pi^0$ Partial Waves

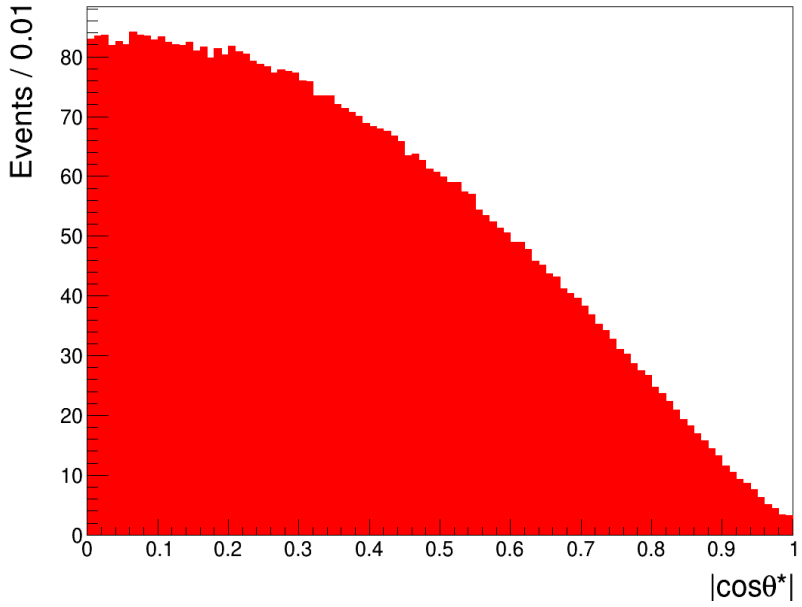
- Analysis based on 9 fb^{-1} of data between 3.773 GeV and 4.6 GeV
- $e^+e^- \to e^+e^-\pi^0\pi^0$
  - $\pi^0 \to \gamma\gamma$
- Event selection:
  - One charged track identified as electron/positron
  - At least four photons
- Background suppression:
  - Single-tag condition
  - $R_\gamma = \frac{\sqrt{s}-E^*-p^*}{\sqrt{s}} < 0.05$
  - Photon helicity angle
  - Mass dependent condition on total transverse momentum
- Background subtraction using 2D sidebands



Space-Like $\gamma\gamma^* \to \pi^0\pi^0$ Partial Waves







First single-tagged measurement below 2 GeV²

- Momentum transfers between 0.1 GeV² and 2 GeV²
- Mass range covered from threshold to 2 GeV
- Full coverage of helicity angle

Summary

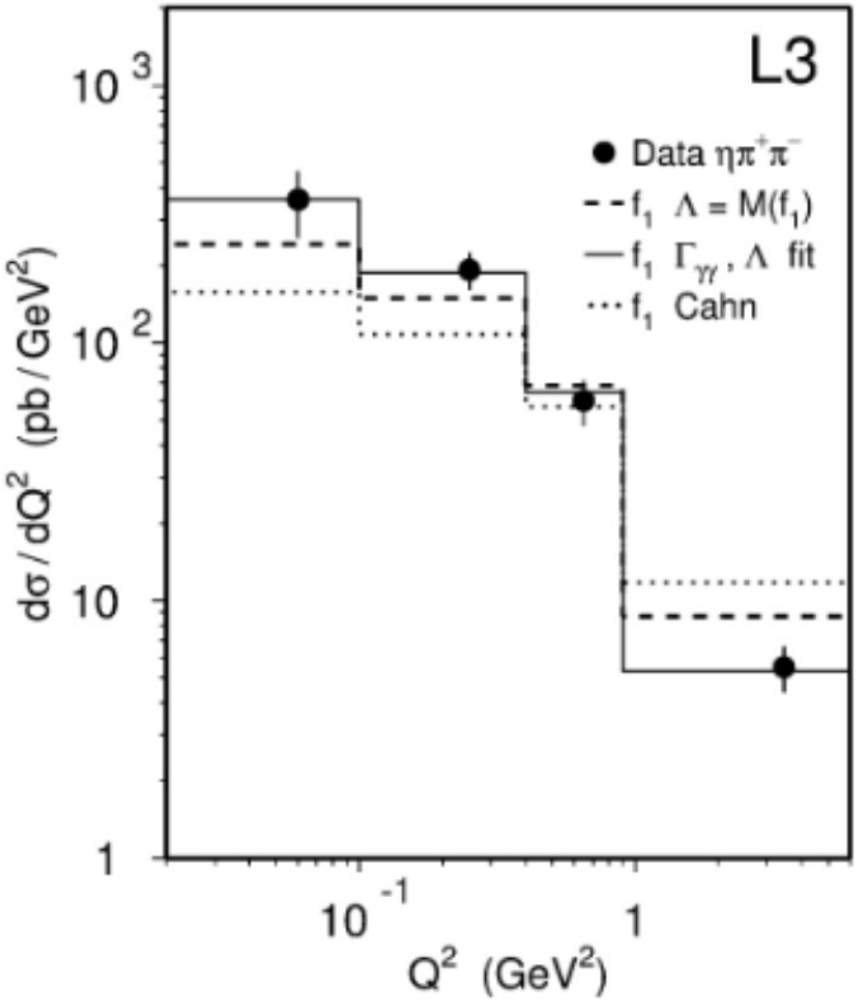
- BESIII is a great laboratory for the study of hadronic two photon scattering in the $(g-2)_\mu$ relevant energy region
- Measurement of the π^0, η, and η' transition form factor with unprecedented accuracy ($Q^2 < 1.5$ GeV^2)
- Measurements of the $\pi^+\pi^-$ and $\pi^0\pi^0$ partial waves…
  - … cover the mass region from threshold to 2 GeV
  - … cover virtualities between 0.1 GeV^2 and 2 GeV^2
  - … cover the full helicity angle range
- **Large 20 fb^{-1} data set will improve all measurements**
- **Double-tagged measurements will become feasible eventually**

Thank you for your attention!

Space-Like $\gamma\gamma^* \rightarrow f_1(1285)$ Transition Form Factors

- Spin-1 Meson
  - Only accessible in single-tagged or double-tagged configurations
  - In singletagged configuration two different helicity amplitudes accessible TT and TL

- Previously measured by L3/LEP
  - No direct tagging
  - Only total cross section measured
  - TT dominates over TL contribution at large energies



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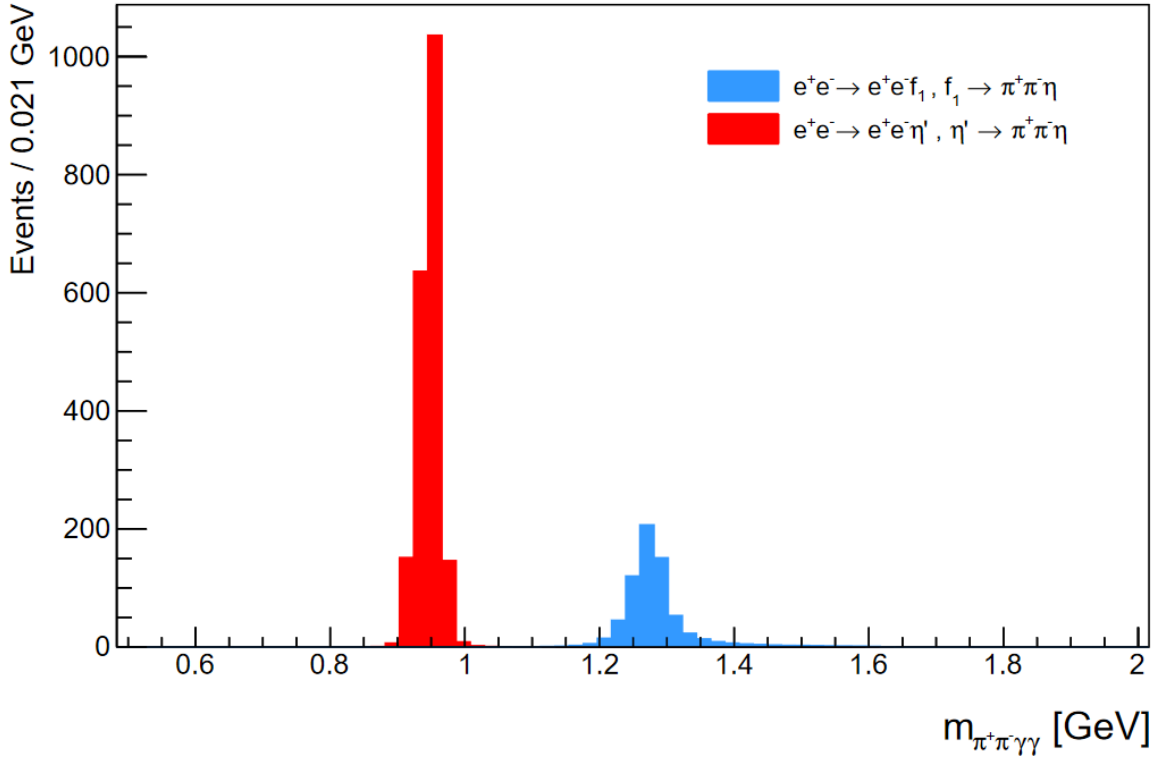
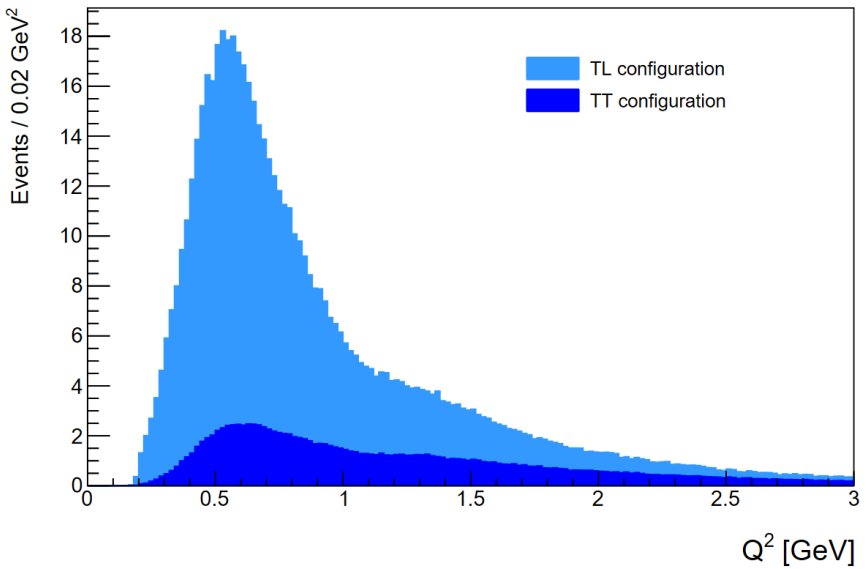
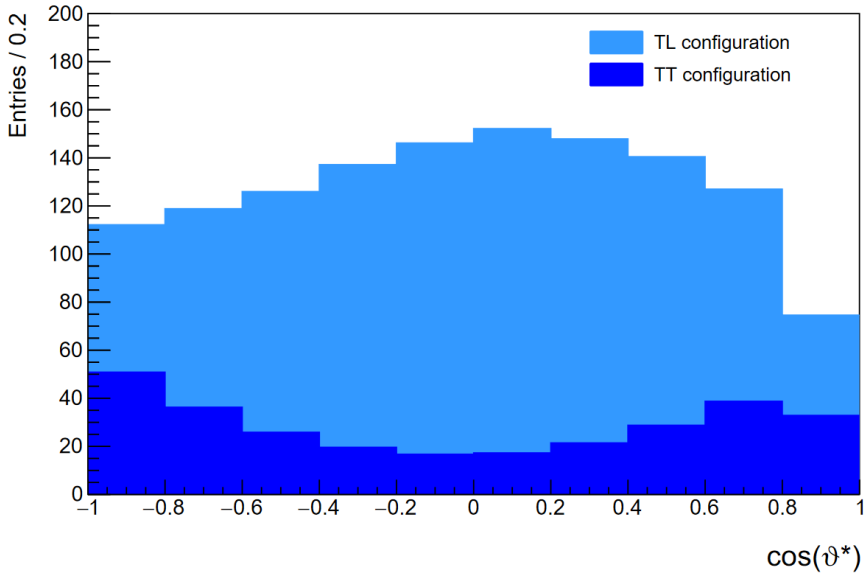
Space-Like $\gamma\gamma^* \to f_1(1285)$ Transition Form Factors

- Events selection ($f_1(1285) \to \pi^+\pi^-\eta$)
  - Three good charged tracks
  - One track identified as electron/positron
  - Two oppositely charged tracks identified as pion
- Background suppression:
  - Single-tag condition $|\cos\theta| > 0.99$
  - Radiative effects:
    - $R_\gamma = \frac{\sqrt{s}-E^*-p^*}{\sqrt{s}} < 0.05$
  - Lepton energy > 500 MeV
- Very clean channel
  - Remaining background subtracted using sideband subtraction
- Clear signals for η' and $f_1(1285)$



Space-Like $\gamma\gamma^* \rightarrow f_1(1285)$ Transition Form Factors





- $(g-2)_\mu$ relevant q² region covered
  - 0.24 GeV² < Q² < 3 GeV²
- Relevant contributions from TT and TL helicity configurations
  - Separable by partial wave analysis

First measurement of different helicity state $f_1(1285)$ TFFs