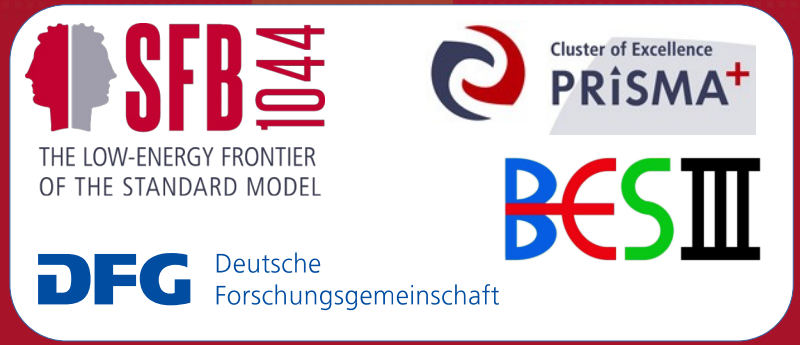
Status and Perspectives of the $\gamma\gamma$ Physics Program at BESIII

Christoph Florian Redmer for the BESIII Collaboration

13th International Workshop on e+e- Collisions from Phi to Psi

17.08.2022



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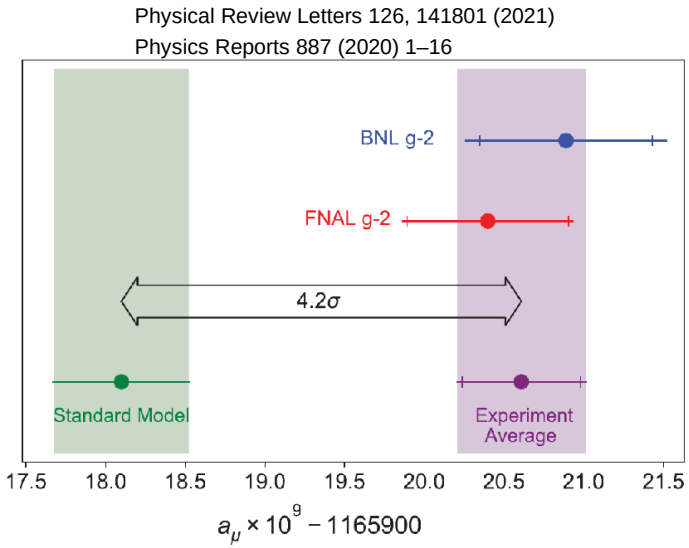
The Anomalous Magnetic Moment of the Muon

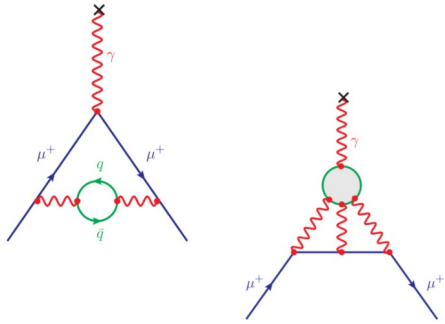


Muon anomaly $a_\mu = \dfrac{g_\mu - 2}{2}$

- Less than 0.5 ppm accuracy in experiment and theory
- Discrepancy between SM prediction and experiment
- New measurements at FermiLab and J-PARC
- **SM prediction needs to be improved**

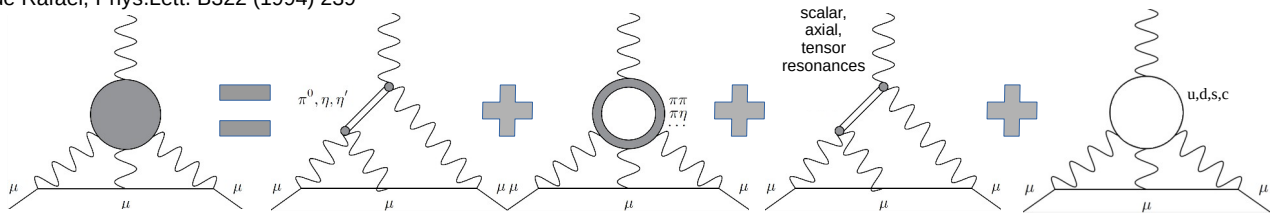
$$a_\mu^{\text{SM}} = a_\mu^{\text{QED}} + a_\mu^{\text{EW}} + a_\mu^{\text{had}}$$

  - Limited by hadronic contributions
  - Input from experiments needed



The Hadronic Light-by-Light Contribution

de Rafael, Phys.Lett. B322 (1994) 239



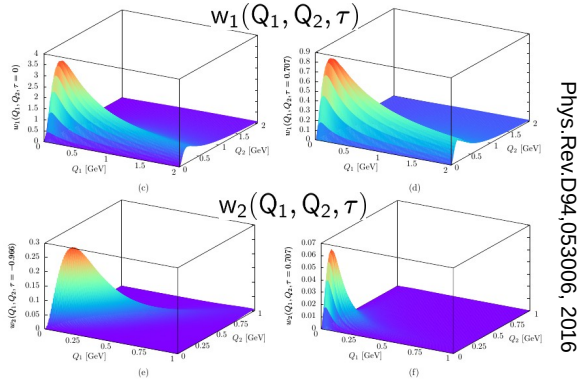
Phys.Rept. 887 (2020) 1

Contribution	$\times 10^{-11}$
Pseudoscalars	93.8 ± 4.0
π & K Loops/Boxes + *s*-wave rescattering	-24.4 ± 3
Tensors and Scalars	-1 ± 3
Axials	6 ± 6
u,d,s Loops / short distance	18 ± 11

- Dominating: Pseudoscalar exchange and meson loops
- Data driven estimates for individual contributions
- More experimental input on scalar, tensor, and axial contributions needed!

- Relevant momentum region: $Q_i^2 \leq 1\,\mathrm{GeV}^2$
  - From 3D integral representation of PS contribution

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

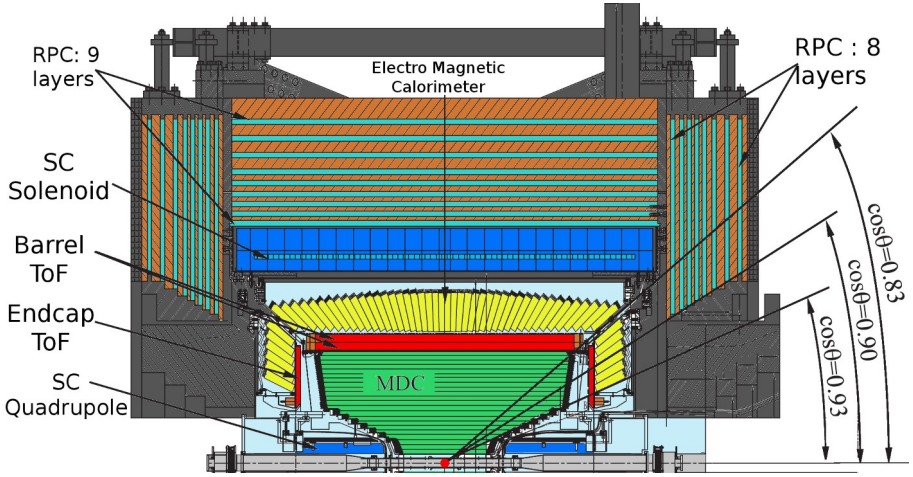


Phys.Rev.D94,053006, 2016

BESIII Experiment

- Operated at BEPCII in Beijing, China
- Center-of-mass energies from 2 – 5 GeV
- Design luminosity $10^{33}cm^{-2}s^{-1}$ at 3.773 GeV

- World's largest e+e- data sets at τ-charm energies
- 10^{10} J/ψ and 3×10^{9} ψ(2s) directly produced
- More than 20 fb^{-1} collected between 3.773 and 5 GeV
- Currently collecting 20 fb^{-1} at 3.773 GeV



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

Time-of-flight system (TOF)
- σ(t) = 60ps

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

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

Nucl.Instr.Meth. A614 (2010) 345

Experimental Access to TFFs

Time-like

- Meson Dalitz decays

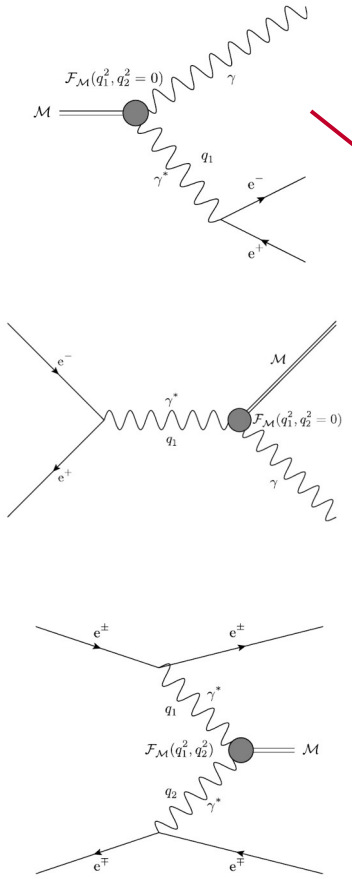
$$m_{ll}^2 < q^2 < m_P^2$$

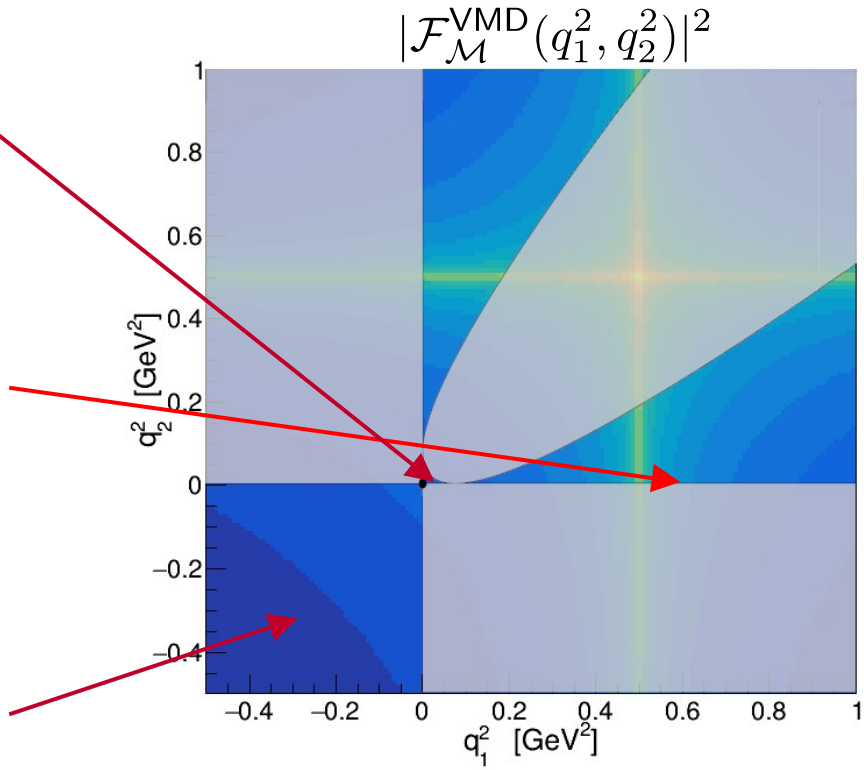
- Radiative production

$$q^2 = s; \quad q^2 > m_P^2$$

Space-like

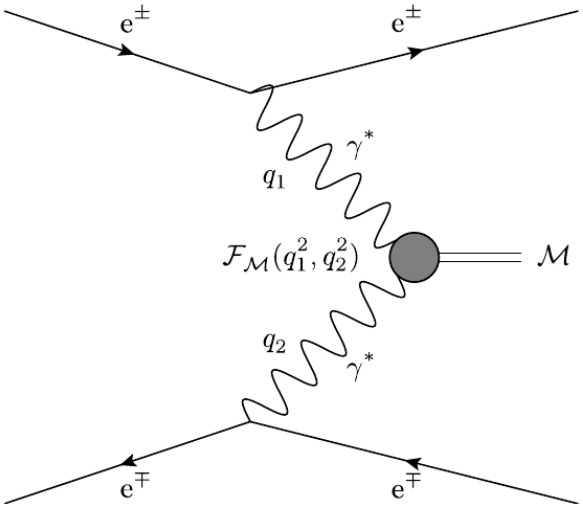
- Two-photon collisions





Space-Like TFF at BESIII

- Scattering of two (virtual) photons
- Photon-fusion to hadronic states
- Production of C-even states in e+e- collisions
- Direct access to $J^{PC} = 0,2^{\pm+}$

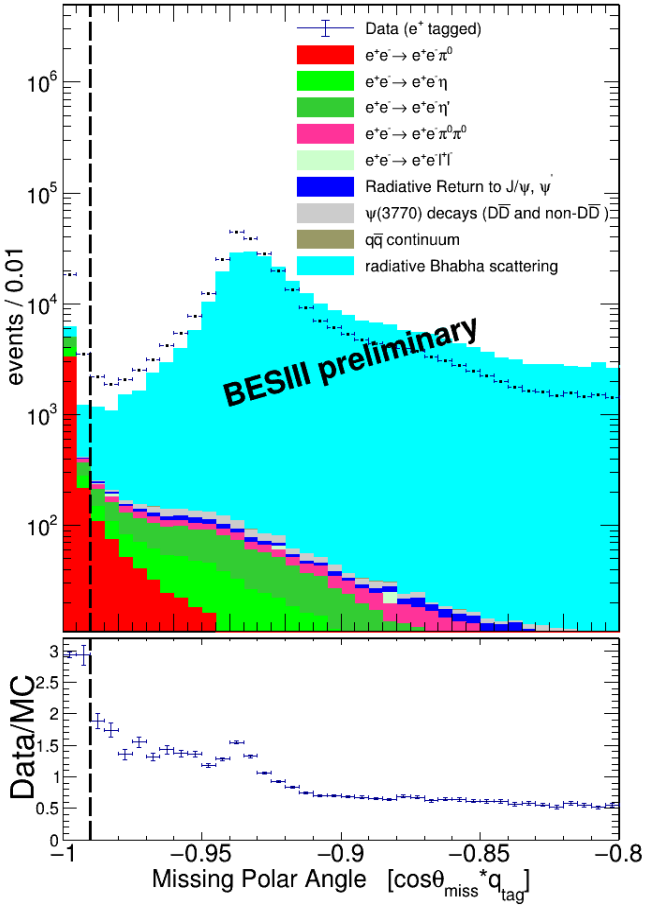


- Produced masses $m_X \ll \sqrt{s}$
- Energy dependence $\sigma \propto \alpha^2 \ln^2 E$
- Forward-peaked kinematics
- $\sigma = \sigma_{\text{point-like}} |F(Q_1^2, Q_2^2)|^2, \qquad Q^2 = -q^2$

- Access to Q^2 by “tagging” of scattered leptons

Space-like $\gamma\gamma^* \to \pi^0$ TFF at BESIII

- Based on 2.9 fb^{-1} at 3.773 GeV
- Select:
  - Exactly one lepton
  - At least two photons
- missing lepton from energy-momentum conservation
- Require small scattering angle of missing lepton
  - “single-tag condition”
  - Small virtuality of exchanged photon $q_{\text{tag}} \cdot \cos\theta_{\text{miss}} < -0.99$

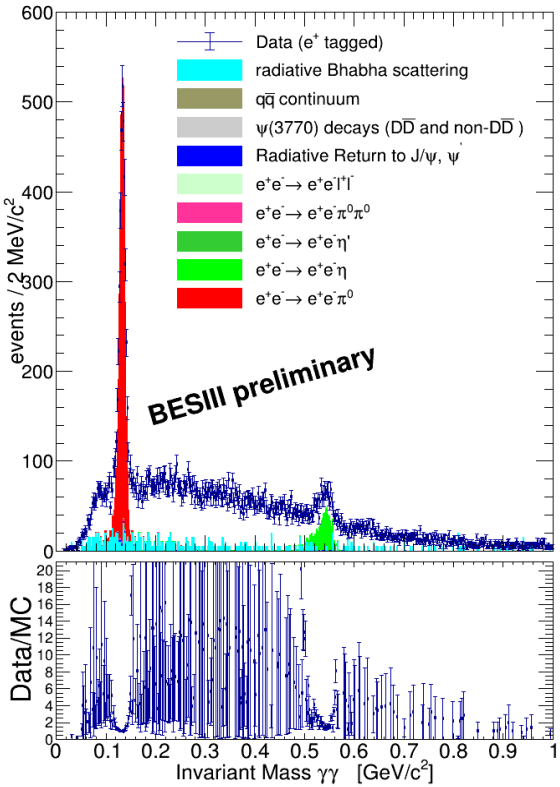


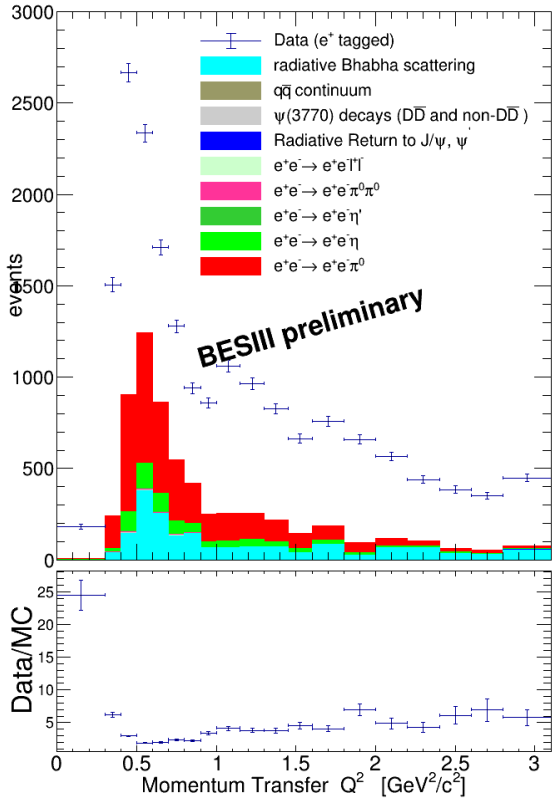
Space-like $\gamma\gamma^* \rightarrow \pi^0$ TFF at BESIII

- Background rejection:
  - Single-tag condition
  - Helicity angle of photons
  - Energy/momentum conservation w.r.t radiative effects

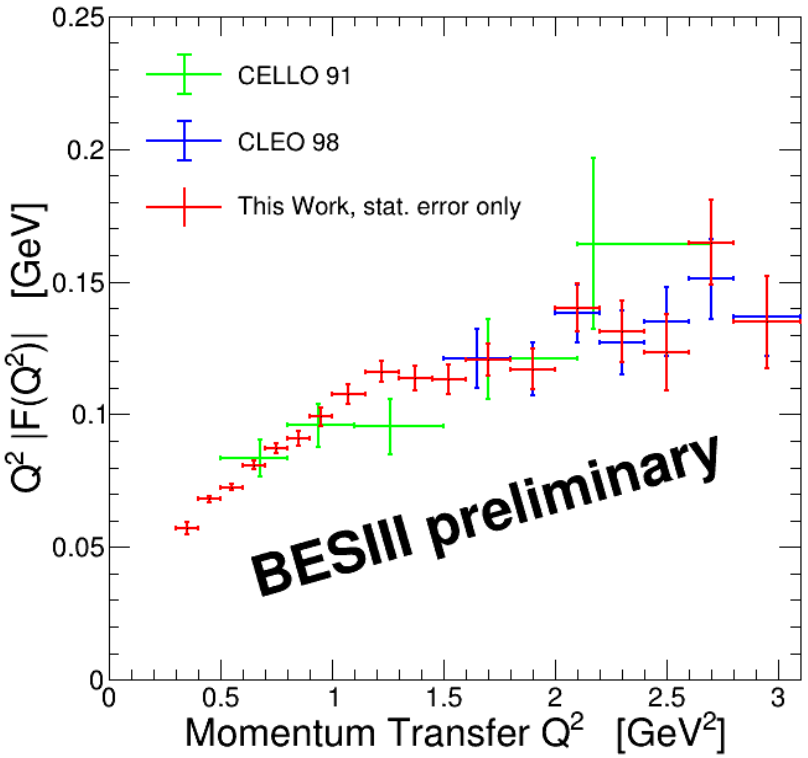
- Clear signals of π^0 and η
- Incomplete MC description
  - Data-driven background subtraction

- Differential cross section w.r.t Q^2
- Divide out point-like cross section using MC distributions





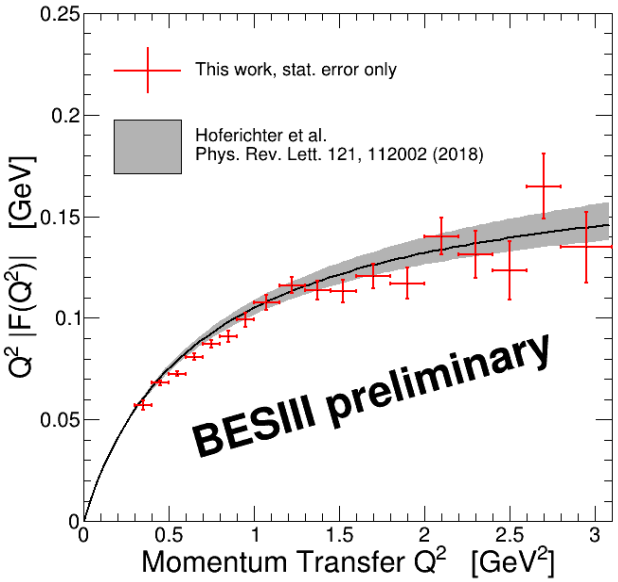
Space-like $\gamma\gamma^* \to \pi^0$ TFF at BESIII



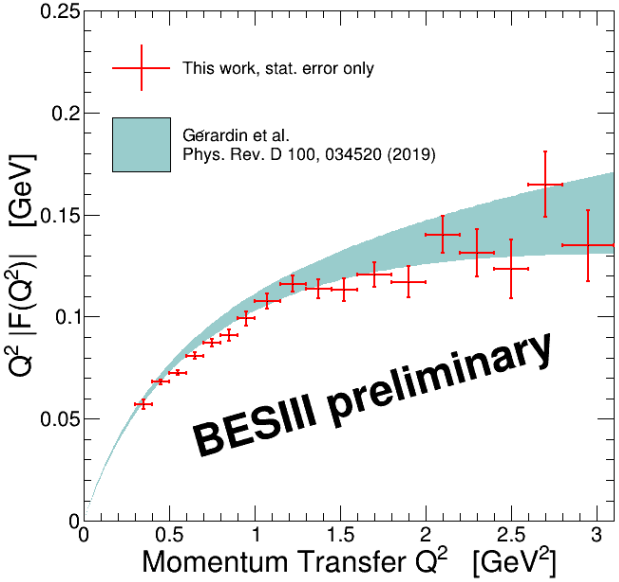
- Covers relevant range of Q^2 for a_μ
- Unprecedented accuracy for $Q^2 < 1.5$ GeV^2
- Competitive accuracy up to 3.1 GeV^2
- First measurement below 0.5 GeV^2
  - Limited by acceptance for $\pi^0 \to \gamma\gamma$
- More data sets to be analyzed
- Analysis to be extended to TFFs of η and η'

Space-like $\gamma\gamma^* \to \pi^0$ TFF at BESIII

Comparison to: Dispersive Construction



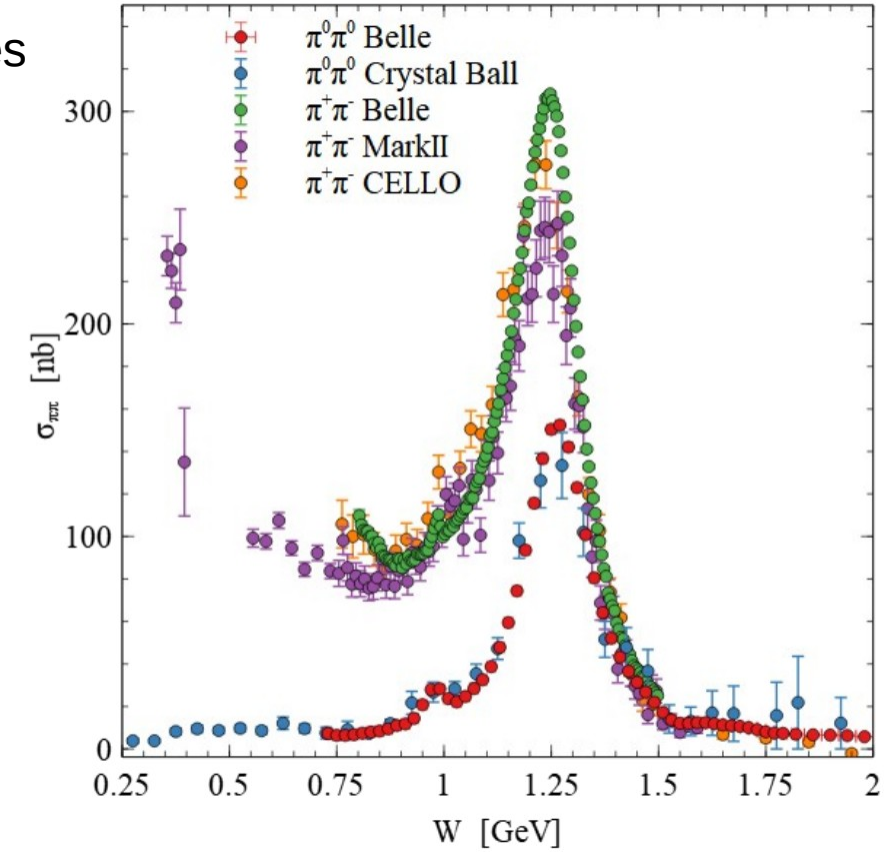
Lattice QCD



BESIII measurement confirms theory calculations used for recent estimate of a_μ^{HLbL}

Partial waves of space-like $\gamma\gamma^* \to \pi\pi$

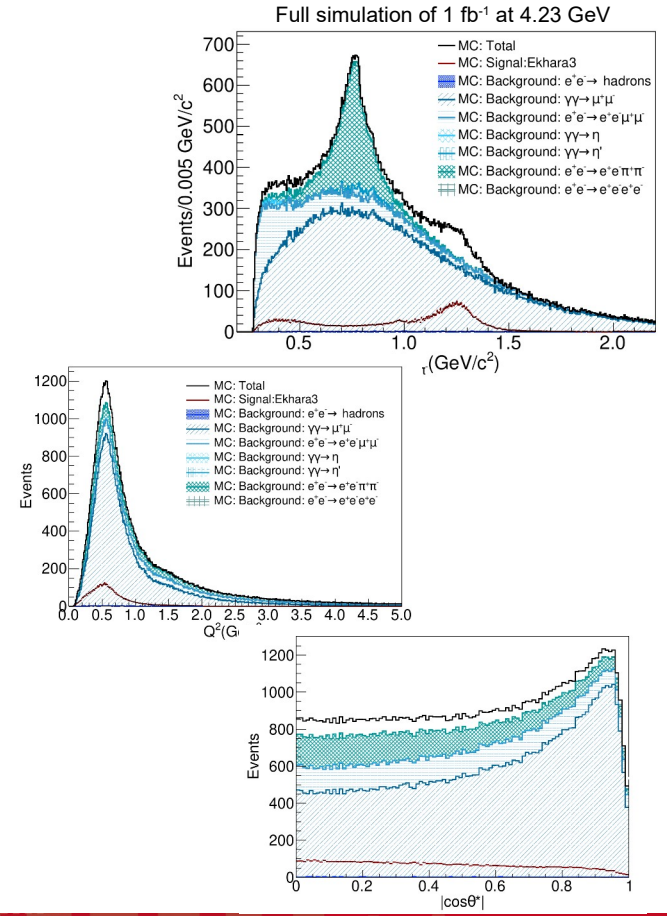
- Relevant for spectroscopy and polarizabilities
- Previous Measurements
  - Mostly untagged, i.e. $\gamma\gamma \to \pi\pi$
  - Limited coverage of helicity angles
  - Data scarce at small masses
- Only one single-tagged result available
  - Belle: $\gamma\gamma^* \to \pi^0\pi^0$
  - Full helicity angle coverage
  - M > 0.5 GeV
  - $Q^2 > 3$ GeV^2



Partial waves of space-like $\gamma\gamma^* \to \pi^+\pi^-$

- Combine 7.5 fb^{-1} from 3.773 GeV to 4.6 GeV
- Event selection analogous to single pseudoscalar analysis
- Machine learning tools to suppress $e^+e^- \to e^+e^-\mu^+\mu^-$
- Subtraction of ρ contribution in $e^+e^- \to e^+e^-\pi^+\pi^-$
  - Fit peak in data using shape from theory
- Conversion to photon-based cross section
- Study $\pi^+\pi^-$ invariant mass in bins of Q^2 and $\cos\theta^*$

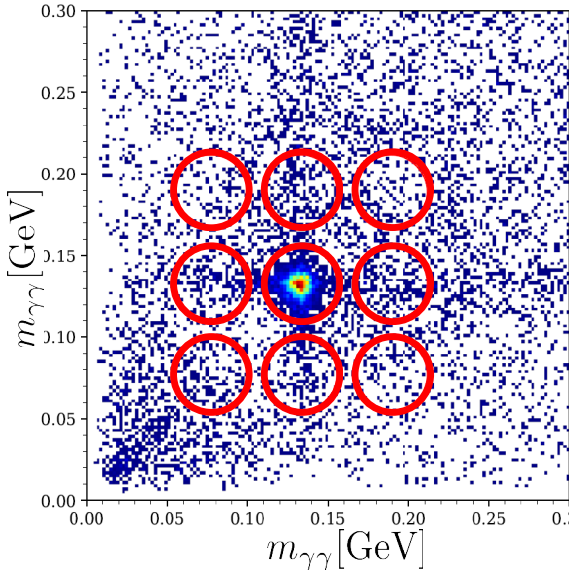
- First single-tag measurement of $\pi^+\pi^-$!
  - Access to:
    - low momentum transfers $0.2 < Q^2\,[\mathrm{GeV}^2] < 2.0$
    - low invariant masses $2m_{\pi^+} < M\,[\mathrm{GeV}] < 2.0$
    - full coverage of $\cos\theta^*$



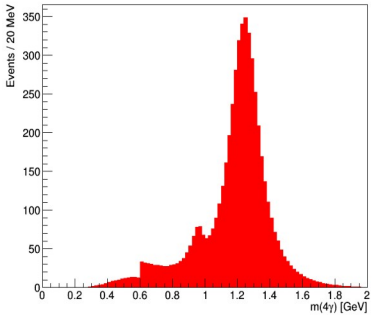
Partial waves of space-like $\gamma\gamma^* \to \pi^0\pi^0$

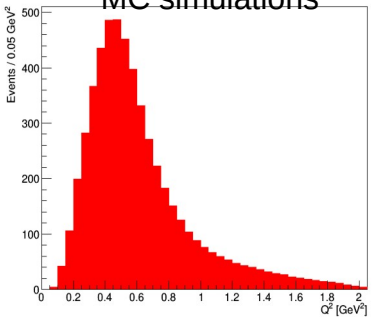
- Combine 9 fb^{-1} from 3.773 GeV to 4.6 GeV
- Event selection analogous to single pseudoscalar analysis
- Background subtraction using 2D sidebands
- Unfolding of mass bins necessary

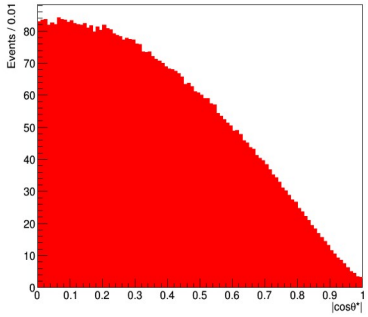
- First single-tagged measurement at $Q^2 < 2$ GeV^2
  - low momentum transfers $0.2 < Q^2$ [GeV^2] < 2.0
  - low invariant masses $2m_\pi < M$ [GeV] < 2.0
  - full coverage of cosθ*



MC simulations

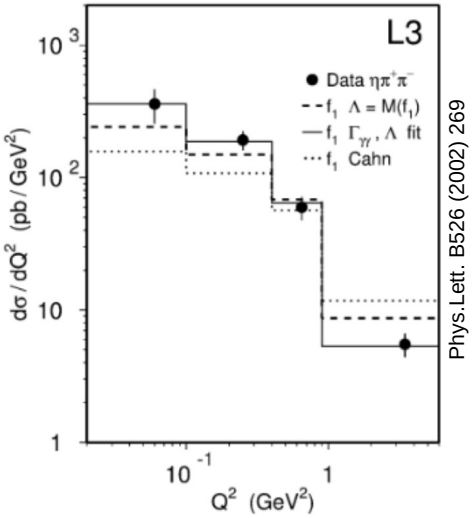


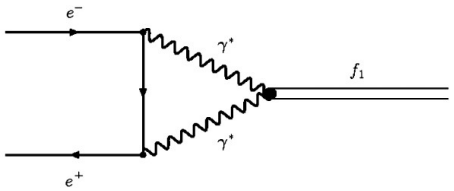




Space-like $\gamma\gamma^* \to f_1(1285)$ TFF at BESIII

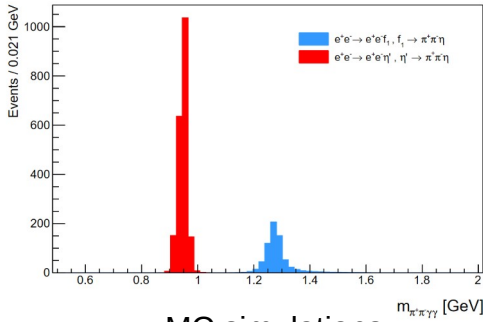
- Spin-1 meson
  - Virtual photon needed for production
  - Helicity amplitudes sensitive to photon polarizations
- Latest measurement from L3 at LEP
  - Very small Q^2
  - Only total cross section provided
- Alternative approach: direct production in e+e- annihilation
  - Rare two-photon process
  - Recently observed by SND



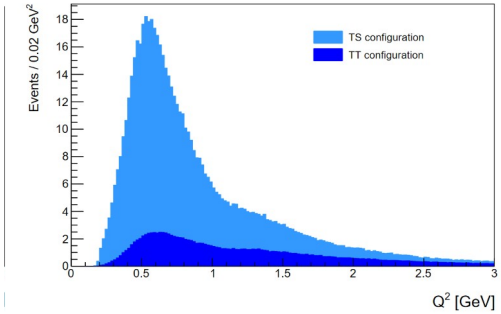


Space-like $\gamma\gamma^* \to f_1(1285)$ TFF at BESIII

- Reconstruction via $f_1(1285) \to \pi^+\pi^-\eta$
- Event selection:
  - Three charged tracks, identified as $e^\pm, \pi^+, \pi^-$
  - At least two photons
  - Single-tag condition $q_{\text{tag}} \cdot \cos\theta_{\text{miss}} < -0.99$
  - Minimum lepton energy
  - Energy-momentum conservation
- Clean signal of η' and $f_1(1285)$
- Remaining background subtracted with sidebands
- $0.2 \leq Q^2[\text{GeV}^2] \leq 3.0$

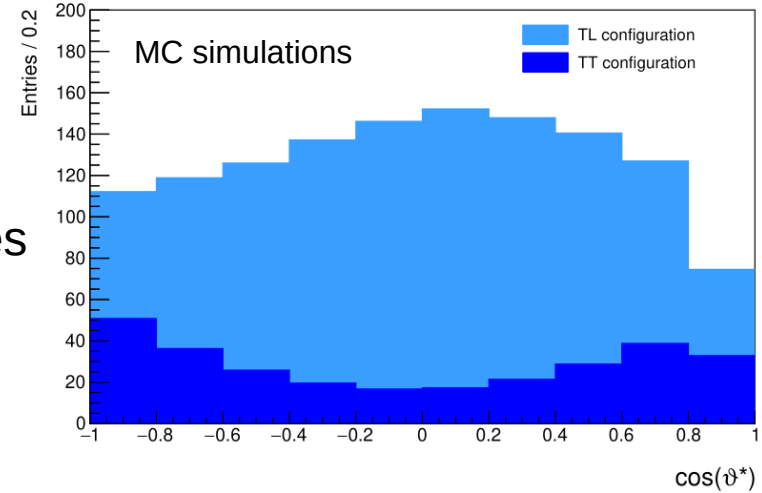


MC simulations



Space-like $\gamma\gamma^* \to f_1(1285)$ TFF at BESIII

- TL and LL polarized photons contribute
- $a_0^{\pm}\pi^{\mp}$ intermediate state dominates $f_1(1285)$ decay
- Use helicity angle distribution to disentangle amplitudes

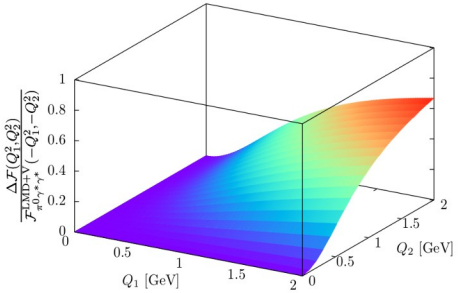


First measurement of TFFs for individual helicity states of $f_1(1285)$

- Extending efforts to $f_1'(1420)$

Double-tagged TFF Measurements at BESIII

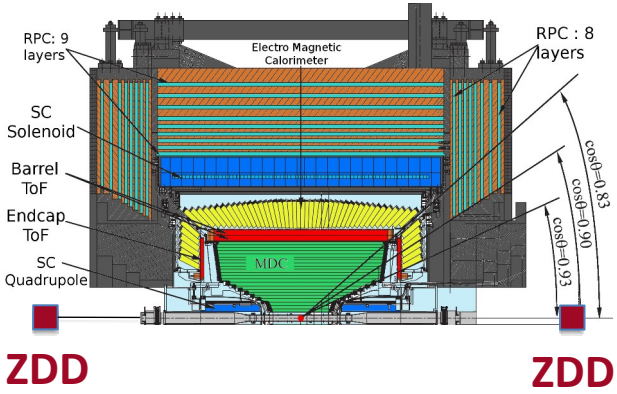
- Access to full TFF information
- Challenging measurements due to small cross section
  - Chance to validate popular models already with limited statistics

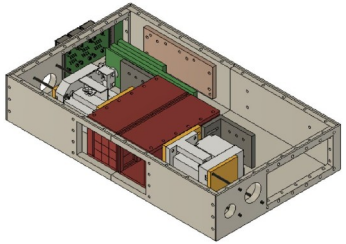


Calculations: A. Nyffeler
Phys.Rev. D94, 2016, 053006

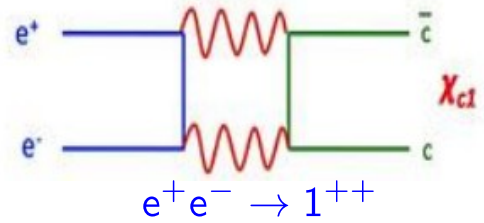
Tagging detectors to be installed at BESIII

- Arrays of LYSO crystals covering 1 – 10 mrad





C-even Resonances in e+e- Collisions



- Can be produced directly through a process with two virtual photons
- Production rate proportional to electronic width Γ_{ee}
- Experimental null searches:

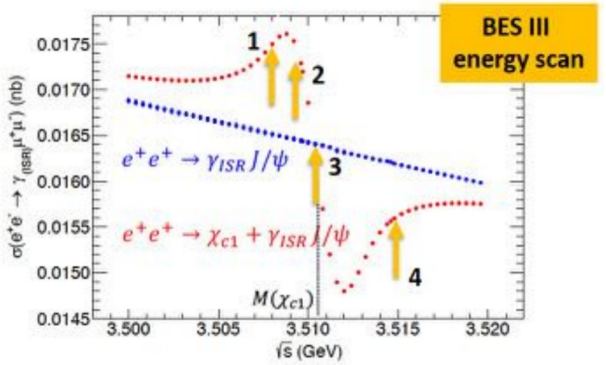
  $\eta, \eta', f_0(980), f_2(1270), a_0(980), a_2(1320)$, and $X(3872)$ from Novosibirsk and BEPCII
- Recent evidence for direct $f_1(1285)$ production at SND (VEPP-2000)

- Predictions for χ_{c1}
  - Unitary limit: $\Gamma_{ee} > 0.044\,\text{eV}$ — Kaplan, Kühn Phys.Lett. B78 (1978) 252
  - Vector Dominance Model: $\Gamma_{ee} > 0.46\,\text{eV}$ or $\Gamma_{ee} \sim 0.1\,\text{ev}$ — Hühn, Kaplan, Safiani Nucl.Phys. B157 (1979) 125; Denig, Guo, Hanhart, Nefediev Phys.Lett B736 (2014) 221
  - Non-relativistic QCD: $\Gamma_{ee} \sim 0.1\,\text{eV}$ — Kivel, Vanderhaeghen JHEP 2 (2016) 32
  - Latest prediction: $\Gamma_{ee} \sim 0.43\,\text{eV}$ (interference) — Czyz, Kühn, Trasz Phys.Rev. D94 (2016) 034033

C-even Resonances in e+e- Collisions

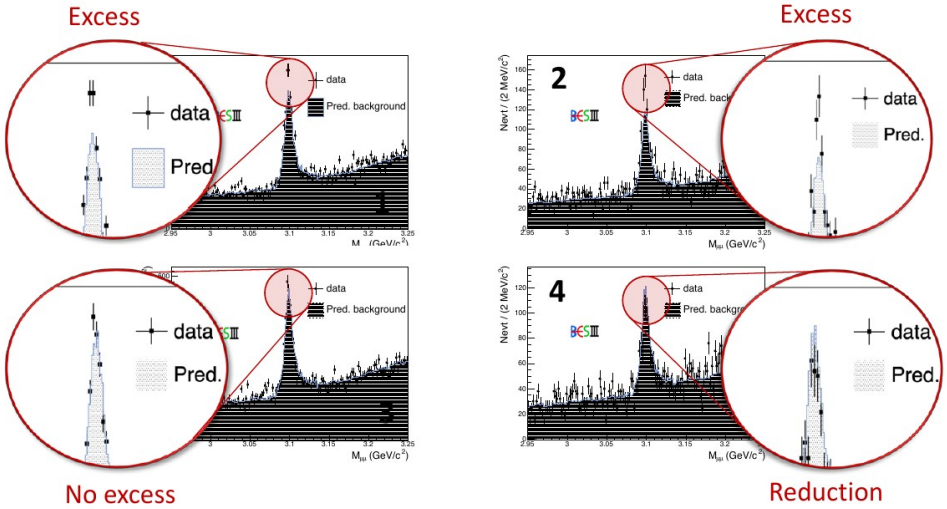
- Search $e^+e^- \to \chi_{c1}$ at BESIII
  - Exploit main decay channel $\chi_{c1} \to \gamma J/\psi$
  - Large interference effects
  - Implemented in PHOKHARA event generator
- Energy scan around χ_{c1} mass
- Validate ISR background simulation using high statistics data samples
- Search for excess or lack of events in muon mass and angular distributions

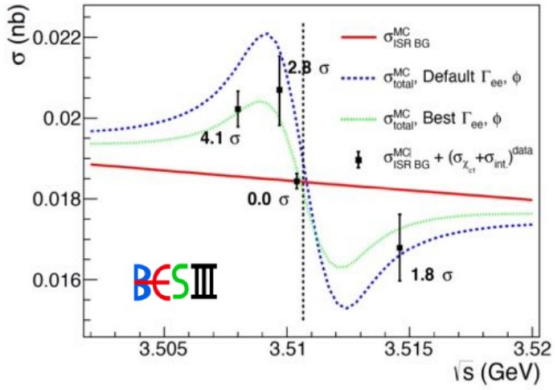
Data Sample	E_{cms} [GeV]*	Lumi. [1/pb]
1	3.5080	181.79±0.04±1.04
2	3.5097	39.29±0.02±0.22
3	3.5104	183.64±0.04±1.05
4	3.5146	40.92±0.02±0.23



MC event generator by H. Czyż *et al.*

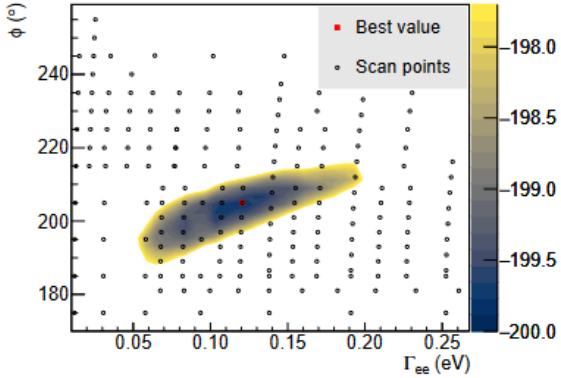
C-even Resonances in e+e- Collisions





First observation of non-vector resonance in e+e- annihilation

- Combination of 4 scan points yields significance of 5.1σ
- First measurement of Γ_{ee} by common fit to all scan points



$$\Gamma_{ee} = 0.12^{+0.13}_{-0.08}\text{eV}, \qquad \phi = 205^{\circ}{}^{+15.4^{\circ}}_{-22.4^{\circ}}$$

Accepted for publication by Phys. Rev. Lett.
arXiv: 2203.13782

Summary

BESIII ideally suited to study two-photon reactions

- Single-tagged two-photon collisions
  - Provide important input for a_μ^{HLbL}
  - Access to virtualites $Q^2 < 3\ \mathrm{GeV}^2$
  - Measurements of TFF of with unprecedented accuracy
  - Measurements of $\pi^+\pi^-$ and $\pi^0\pi^0$ partial waves cover
    - Masses from threshold to 2 GeV
    - Virtualities from 0.2 to 2 GeV^2
    - Full range of helicity angle
  - Access to different helicity states in TFF of $f_1(1285)$
  - Double-tagged measurements in preparation
  - Significant benefits from currents data taking expected
- First measurement of a 1^{++} state in e+e- annihilation