Measurement of electromagnetic transition form factors in two-photon collisions at BESIII

Max Lellmann on behalf of the BESIII collaboration

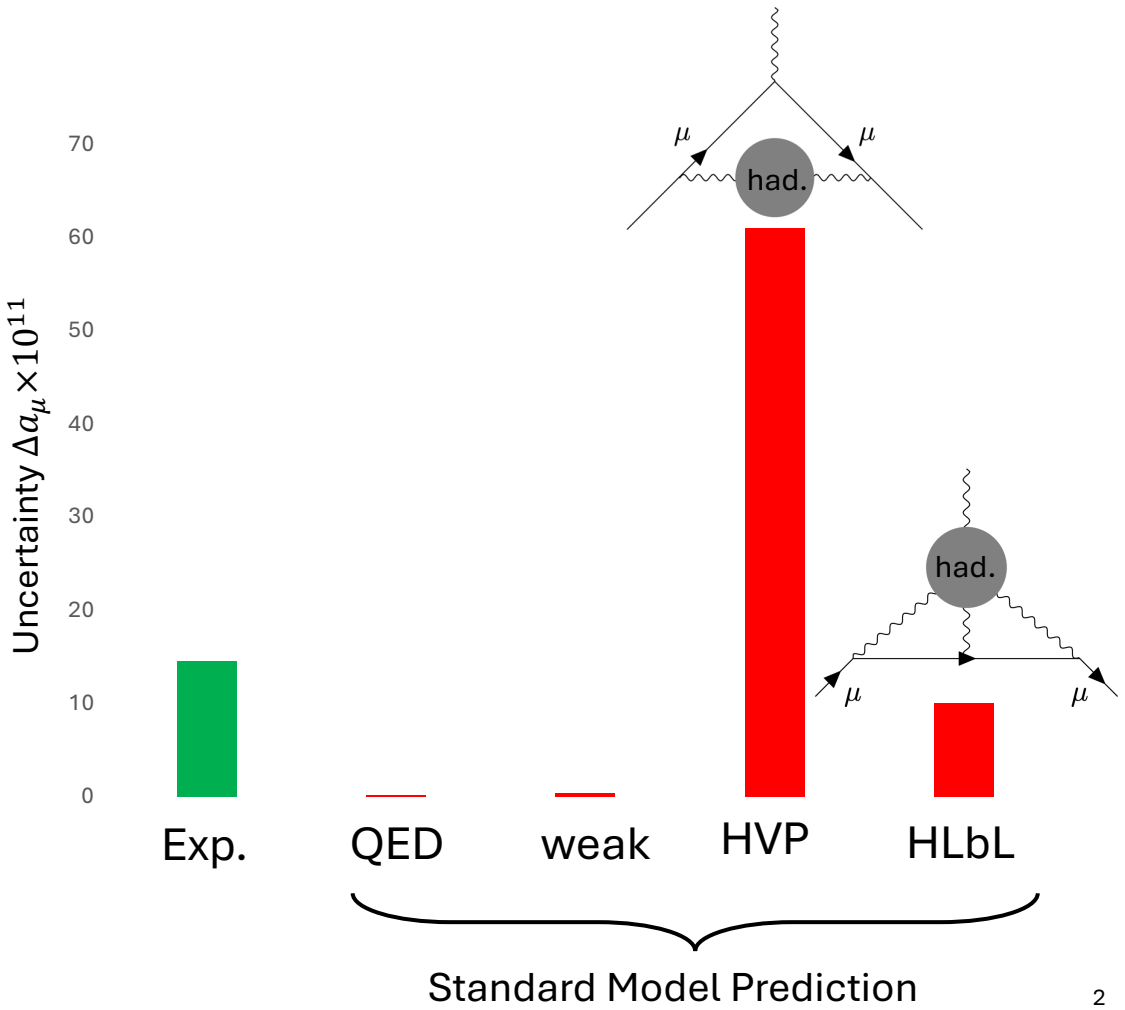
PhiPsi ‘26 Pisa

10.06.2026

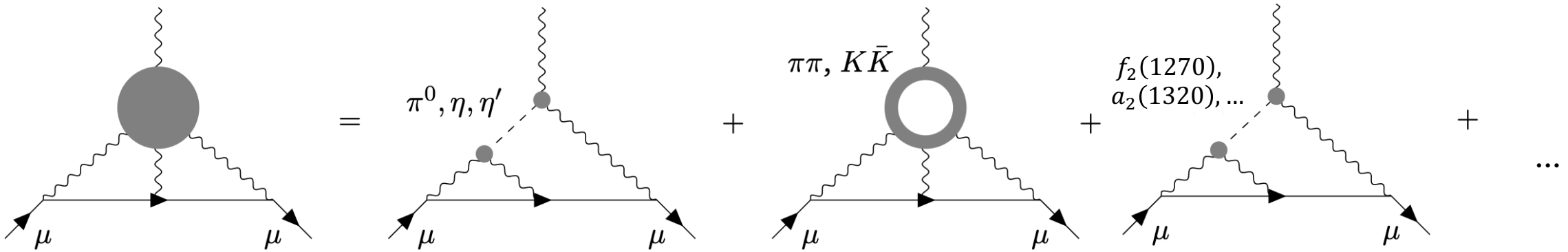
The Muon's Anomalous Magnetic Moment

- Anomalous magnetic moment of the muon
  - $a_\mu = \frac{(g-2)_\mu}{2}$
- Long standing discrepancy between experiment and Standard Model
- **Golden channel for precision tests of the Standard Model**
  - Experimentally known to 127 ppb (BNL & FNAL)
  - Standard Model's uncertainty much larger
  - Limited by hadronic effects

g-2 theory initiative, Physics Reports 1143 (2025) 1-158



The Hadronic Light-by-Light Contribution



One needs to know the coupling of hadrons to photons!

- Small energies especially relevant (pQCD impossible)
- Light mesons dominate
- Two-photon coupling described by Transition Form Factors $F(Q_1^2, Q_2^2)$

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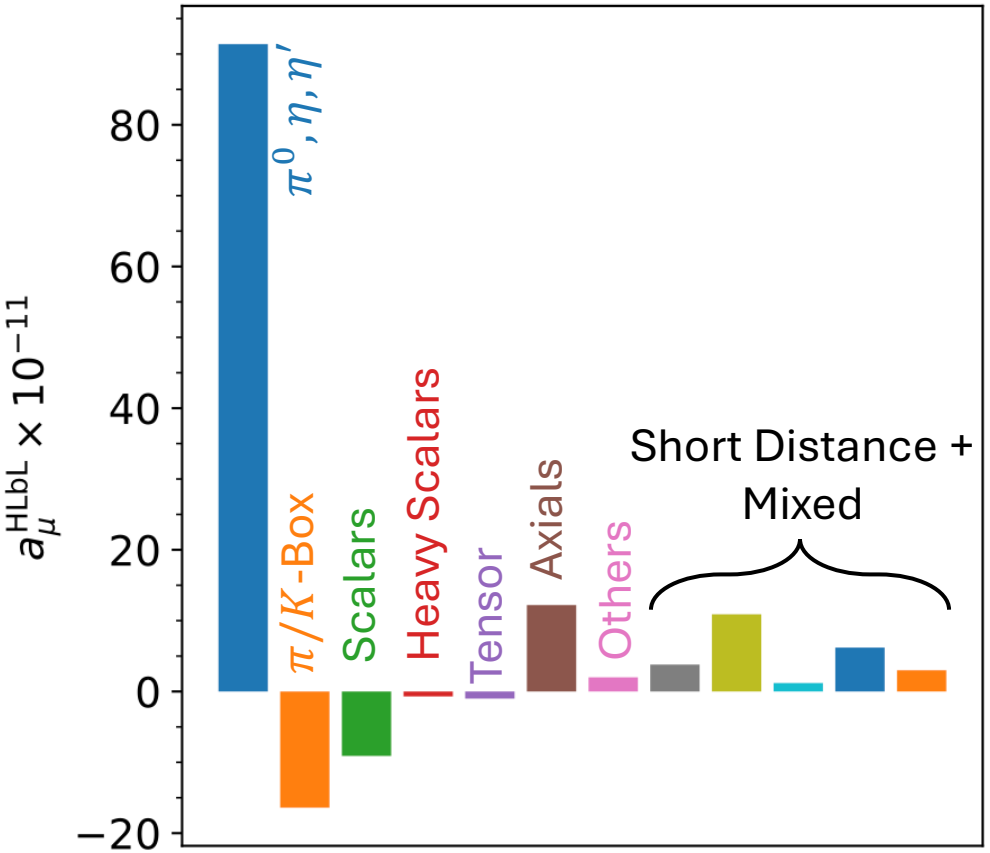

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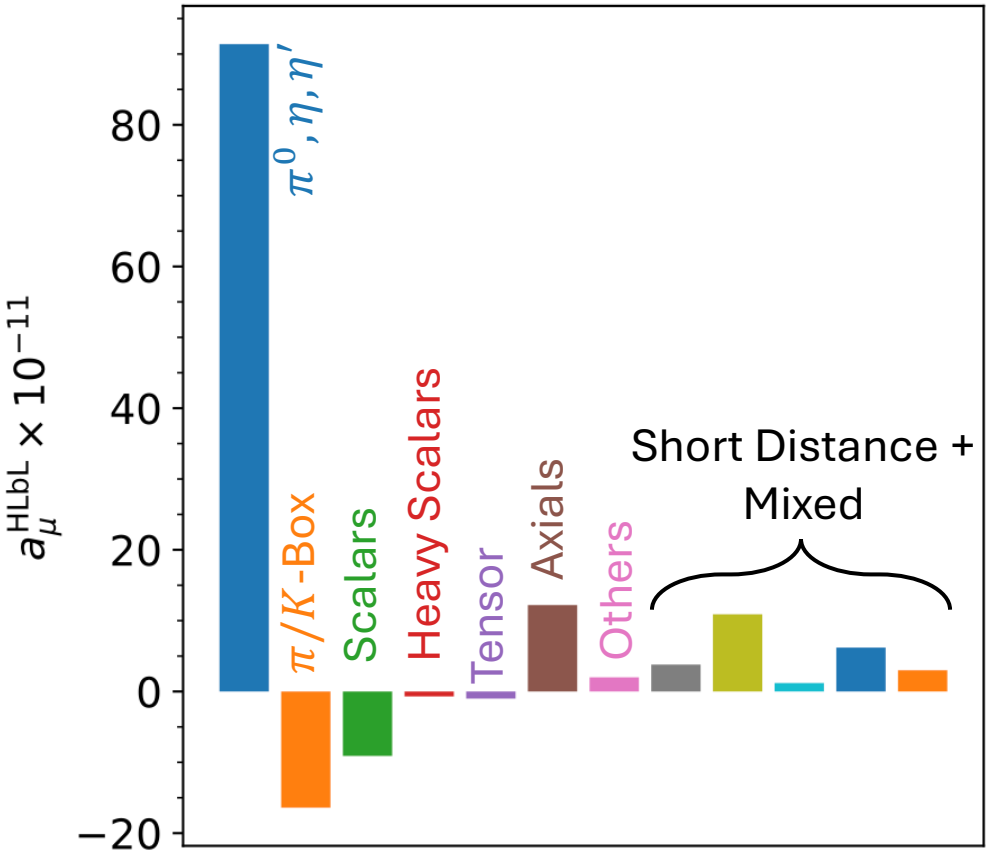

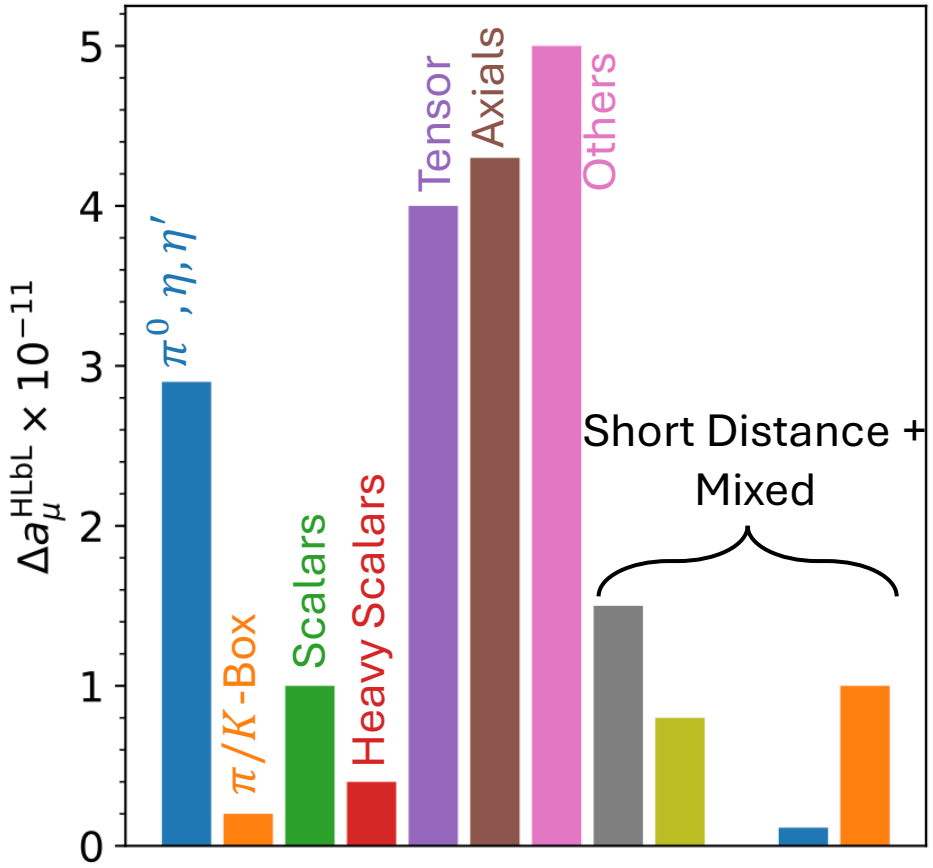

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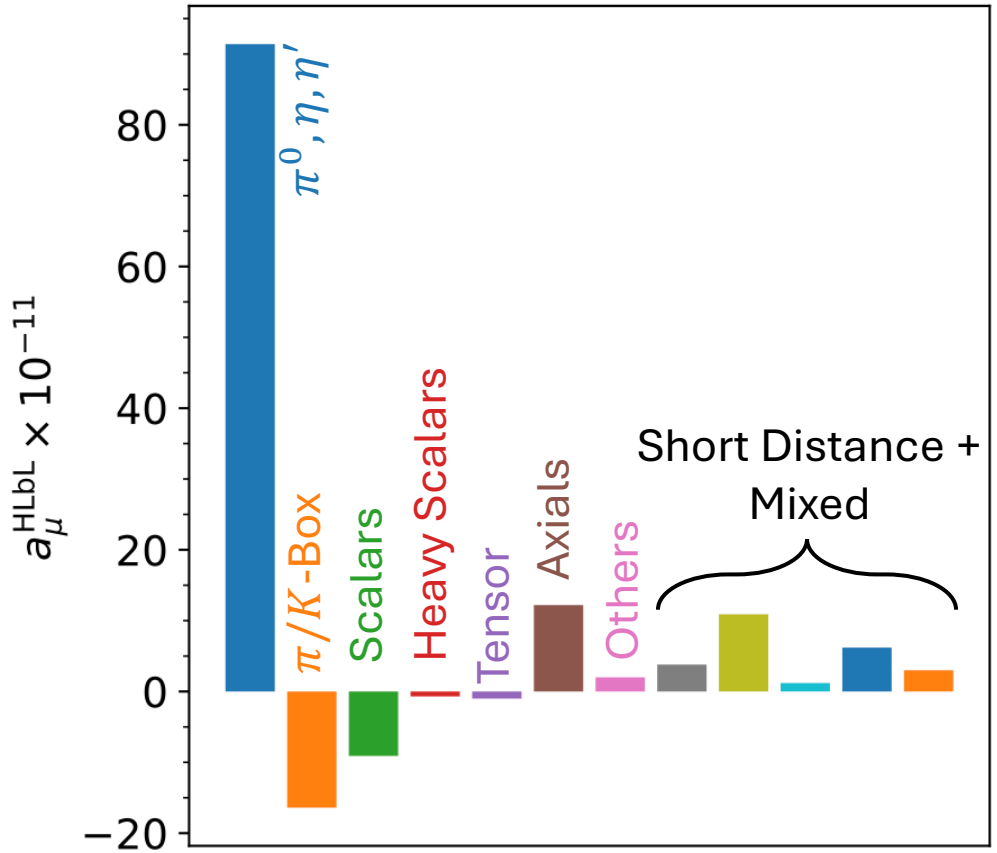
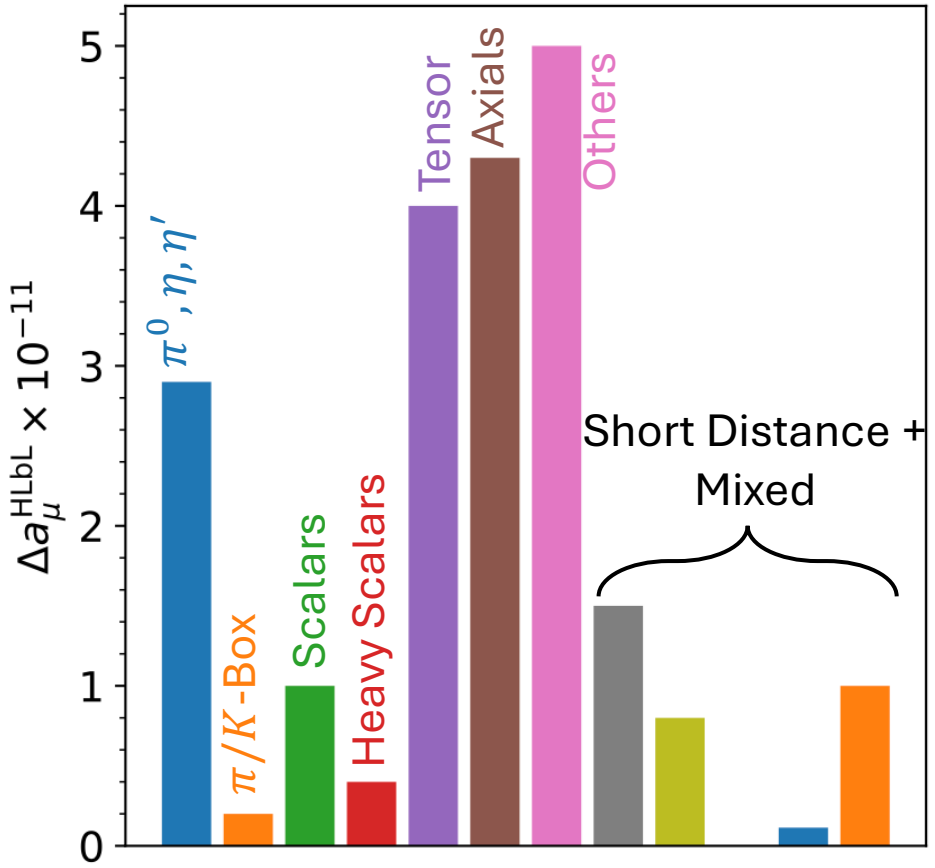


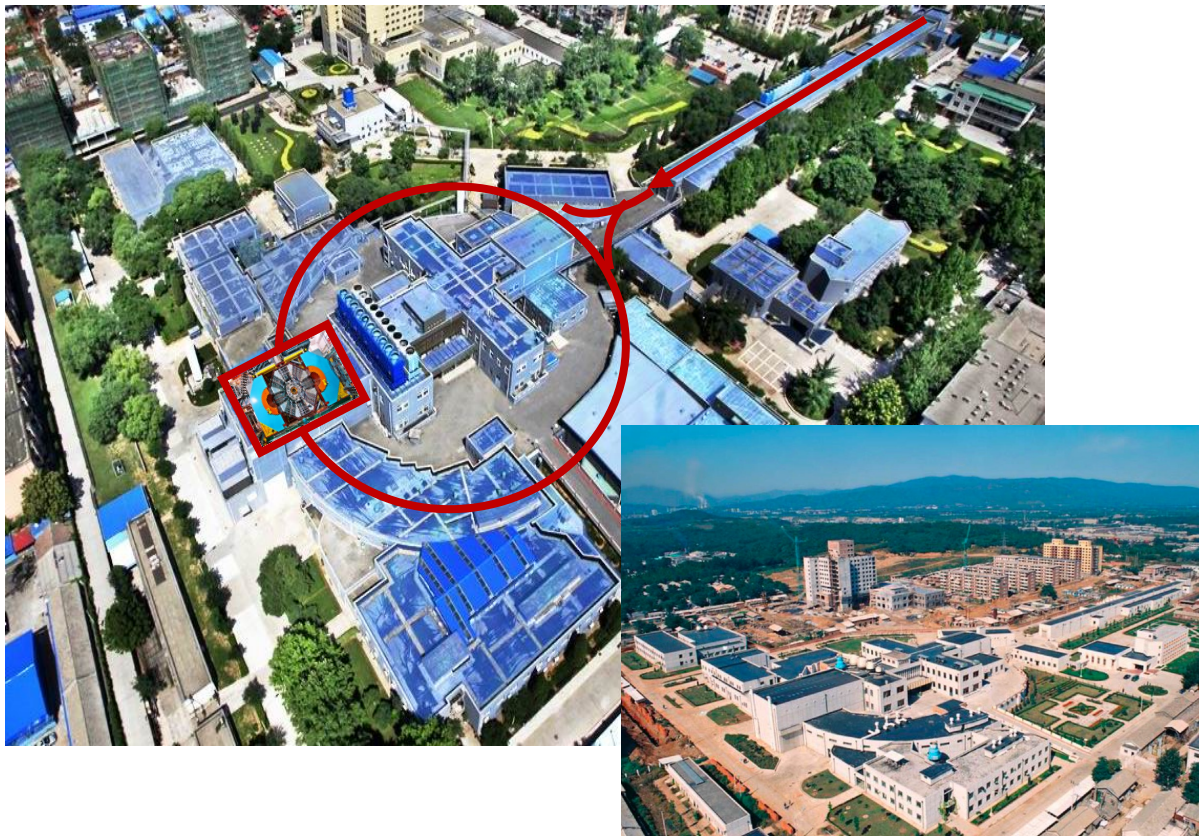


Provide experimental input for (pseudo-)scalar, tensor, and axial contributions!

g-2 theory initiative, Physics Reports 1143 (2025) 1-158

The BESIII Experiment

- Electron Positron Collisions in the τ-charm energy range
  - E_{cm} = 1.86-4.95 GeV
- Multi purpose detector
  - Tracking, TOF, Calorimetry, Magnet, Muon counters
- Design luminosity of 1.0 nb^{-1}/s exceeded
- Largest dataset of 20.3 fb^{-1} at 3.773 GeV
- **Perfectly suited for two-photon physics at small momentum transfers**



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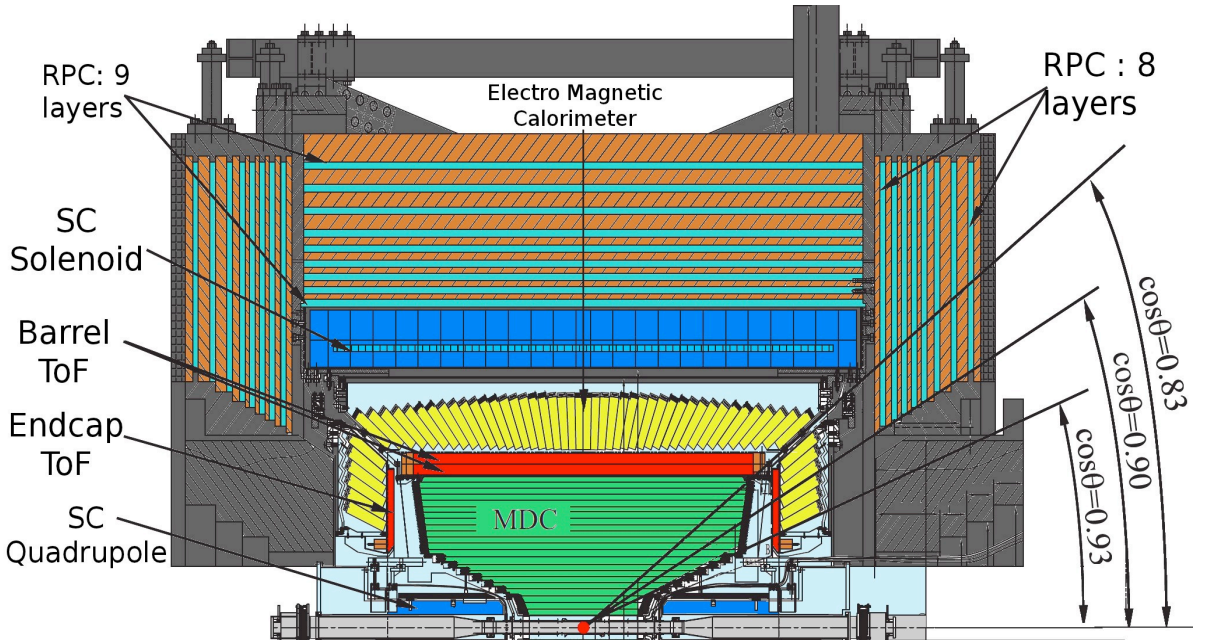


Muon Chambers

Superconducting Solenoid

Electromagnetic Calorimeter

Time-of-Flight System

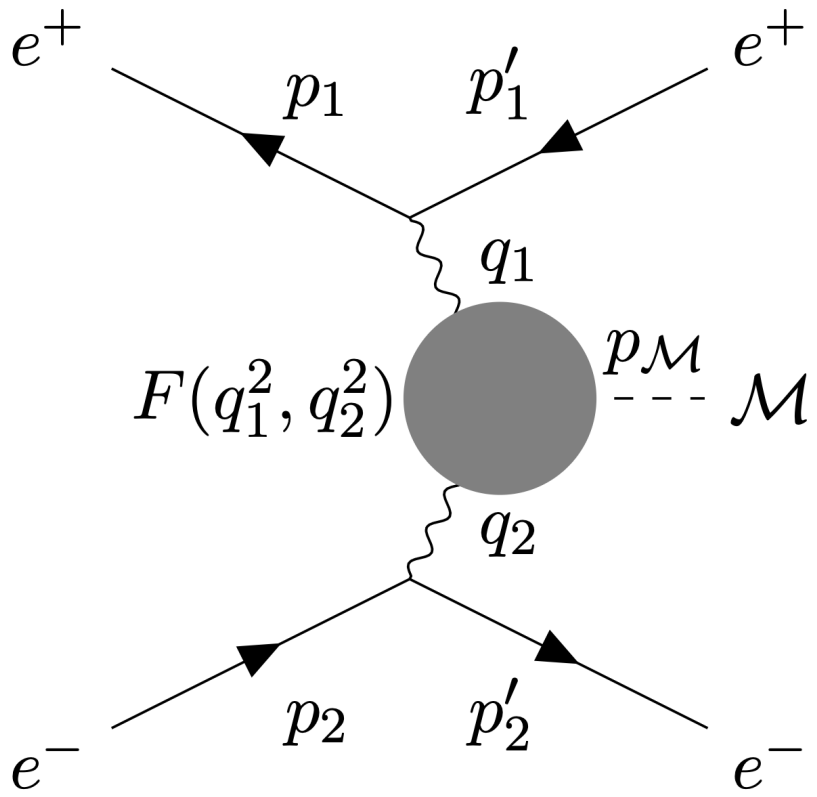
Drift Chamber

Collider Studies of Transition Form Factors

- Two-photon production of
  - … pseudoscalars ($M = \pi^0, \eta, \eta'$)
  - … scalars & tensors ($M = \pi\pi,\ \pi\eta,\ K\overline{K}$ …)
  - … axials ($M = \cancel{\pi\pi\pi}, \pi\pi\eta, KK\pi$ …)

- Transition form factors are functions of the photon virtualities Q^2
  - Requires production from off-shell photons
  - Virtualities equal lepton momentum transfers

$$Q^2 = -(p - p')^2 \approx 4EE' \sin^2 \frac{\theta}{2}$$



Collider Studies of Transition Form Factors

The $e^+e^- \to e^+e^-M$ cross sections can be related directly to different $\gamma^*\gamma^* \to M$ helicity cross sections and response functions

$$d\sigma = \frac{\alpha^2}{8\pi^4 Q_1^2 Q_2^2} \frac{\sqrt{X}}{s(1-4m^2/s)^{1/2}} \cdot \frac{d^3\vec{p}_1'}{E_1'} \cdot \frac{d^3\vec{p}_2'}{E_2'} \frac{4}{(1-\varepsilon_1)(1-\varepsilon_2)}$$
$$\times \left\{ \frac{1}{2}(\sigma_0 + \sigma_2) + \left[\varepsilon_1 + \frac{2m^2}{Q_1^2}(1-\varepsilon_1)\right]\left[\varepsilon_2 + \frac{2m^2}{Q_2^2}(1-\varepsilon_2)\right]\sigma_{\mathrm{LL}} \right.$$
$$+ \left[\varepsilon_2 + \frac{2m^2}{Q_2^2}(1-\varepsilon_2)\right]\sigma_{\mathrm{TL}} + \left[\varepsilon_1 + \frac{2m^2}{Q_1^2}(1-\varepsilon_1)\right]\sigma_{\mathrm{LT}} + \frac{1}{2}\varepsilon_1\varepsilon_2 \cos\left(2\tilde{\phi}\right)\tau_{\mathrm{TT}}$$
$$\left. + \left[\varepsilon_1(1+\varepsilon_1) + \frac{4m^2}{Q_1^2}\varepsilon_1(1-\varepsilon_1)\right]^{1/2}\left[\varepsilon_2(1+\varepsilon_2) + \frac{4m^2}{Q_2^2}\varepsilon_2(1-\varepsilon_2)\right]^{1/2} \cos\tilde{\phi}\,(\tau_0 + \tau_1) \right\}$$

[ML et. al. , arXiv:2511:12717]

Collider Studies of Transition Form Factors

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"Luminosity Functions"

$$\frac{d\sigma}{dQ_1^2\,dQ_2^2\,dW} = \frac{d^3L_{TT}}{dQ_1^2 dQ_2^2 dW}(\sigma_0 + \sigma_2) + \frac{d^3L_{LT}}{dQ_1^2 dQ_2^2 dW}\sigma_{LT} + \frac{d^3L_{TL}}{dQ_1^2 dQ_2^2 dW}\sigma_{TL} + \frac{d^3L_{LL}}{dQ_1^2 dQ_2^2 dW}\sigma_{LL} + \ldots$$

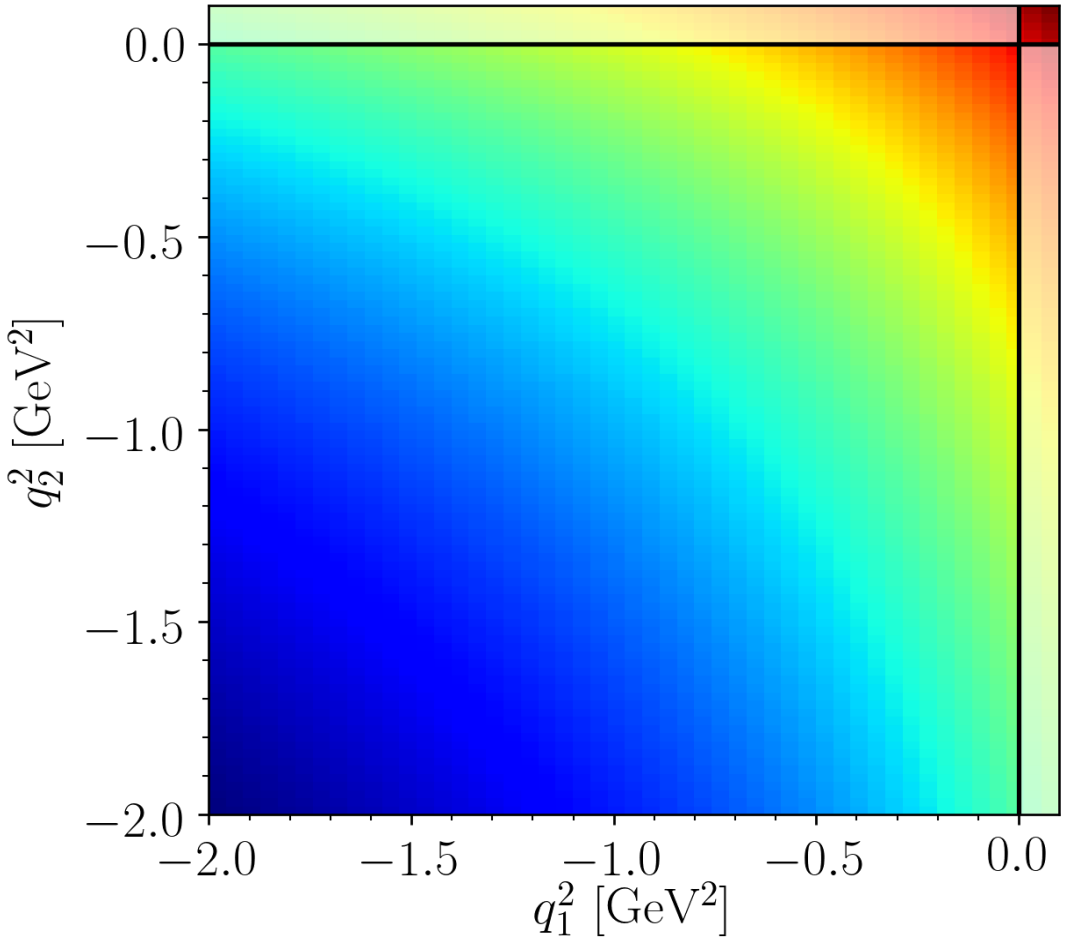
$$d\sigma = \frac{\alpha^2}{8\pi^4 Q_1^2 Q_2^2}\frac{\sqrt{X}}{s(1-4m^2/s)^{1/2}}\cdot\frac{d^3\vec{p}_1'}{E_1'}\cdot\frac{d^3\vec{p}_2'}{E_2'}\frac{4}{(1-\varepsilon_1)(1-\varepsilon_2)}$$
$$\times\left\{\frac{1}{2}(\sigma_0+\sigma_2) + \left[\varepsilon_1 + \frac{2m^2}{Q_1^2}(1-\varepsilon_1)\right]\left[\varepsilon_2 + \frac{2m^2}{Q_2^2}(1-\varepsilon_2)\right]\sigma_{\mathrm{LL}}\right.$$
$$+\left[\varepsilon_2 + \frac{2m^2}{Q_2^2}(1-\varepsilon_2)\right]\sigma_{\mathrm{TL}} + \left[\varepsilon_1 + \frac{2m^2}{Q_1^2}(1-\varepsilon_1)\right]\sigma_{\mathrm{LT}} + \frac{1}{2}\varepsilon_1\varepsilon_2\cos\left(2\tilde{\phi}\right)\tau_{\mathrm{TT}}$$
$$\left.+\left[\varepsilon_1(1+\varepsilon_1) + \frac{4m^2}{Q_1^2}\varepsilon_1(1-\varepsilon_1)\right]^{1/2}\left[\varepsilon_2(1+\varepsilon_2) + \frac{4m^2}{Q_2^2}\varepsilon_2(1-\varepsilon_2)\right]^{1/2}\cos\tilde{\phi}\,(\tau_0+\tau_1)\right\}$$

[ML et. al. , arXiv:2511:12717]

Collider Studies of Transition Form Factors

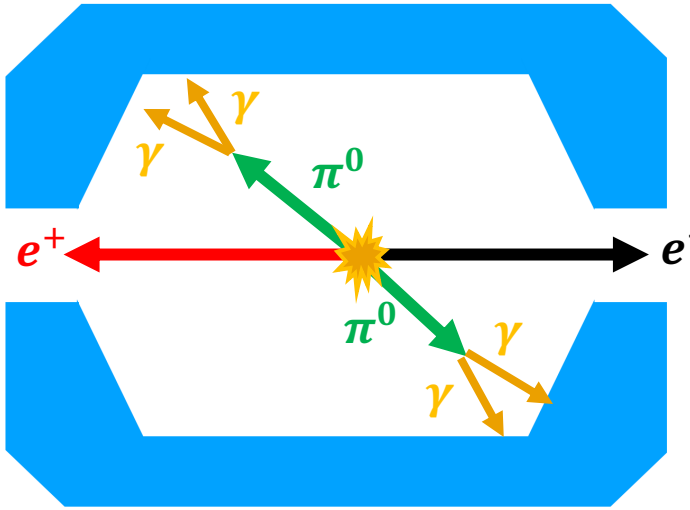
- Strong Q^2 dependence of transition form factor and cross sections
- Momentum transfer coupled to lepton scattering angles $Q^2 = -q^2 \approx 4EE' \sin^2 \frac{\theta}{2}$
  - Detectors do not cover full solid angle!
  - At BESIII: $\theta > 20°$
  - Restriction to Q^2

➢ **Different tagging methods**



Collider Studies of Transition Form Factors

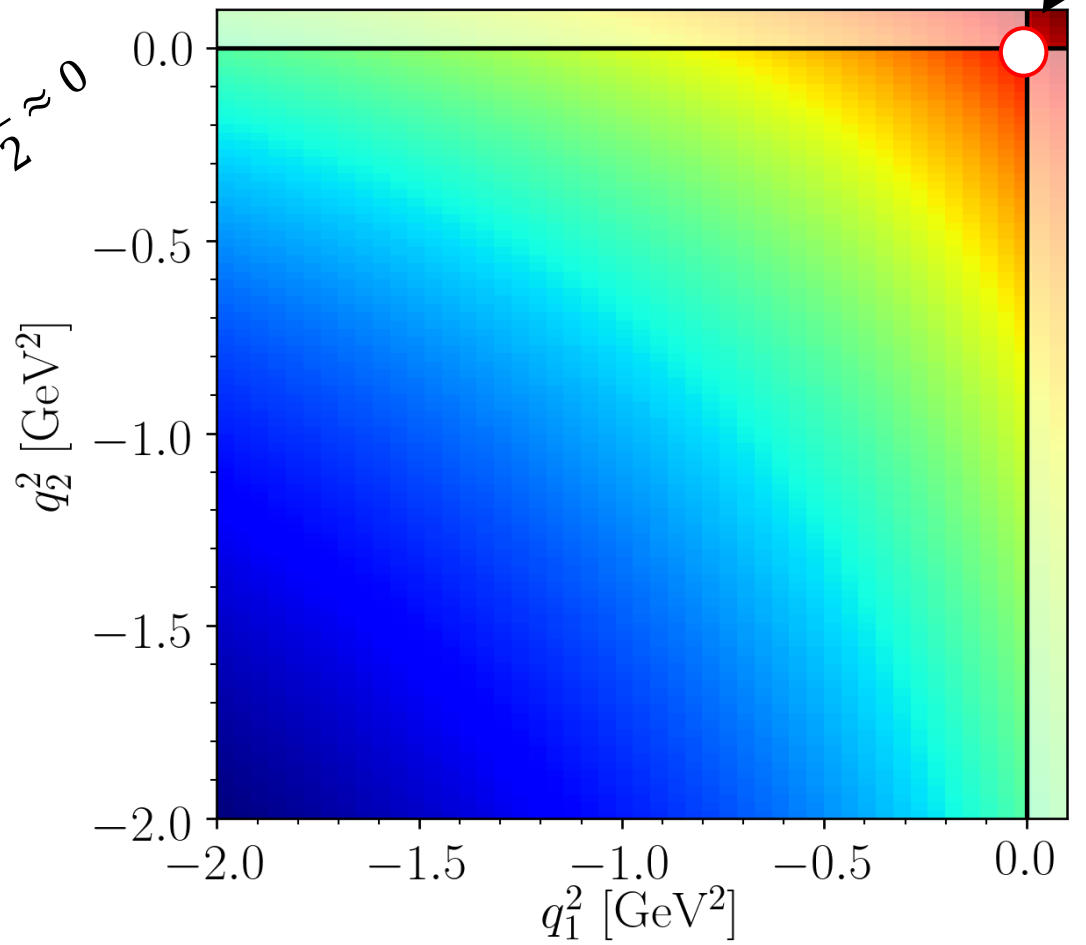
Untagged Studies



$Q^2 \approx 4EE' \sin^2 \frac{\theta}{2} \approx 0$

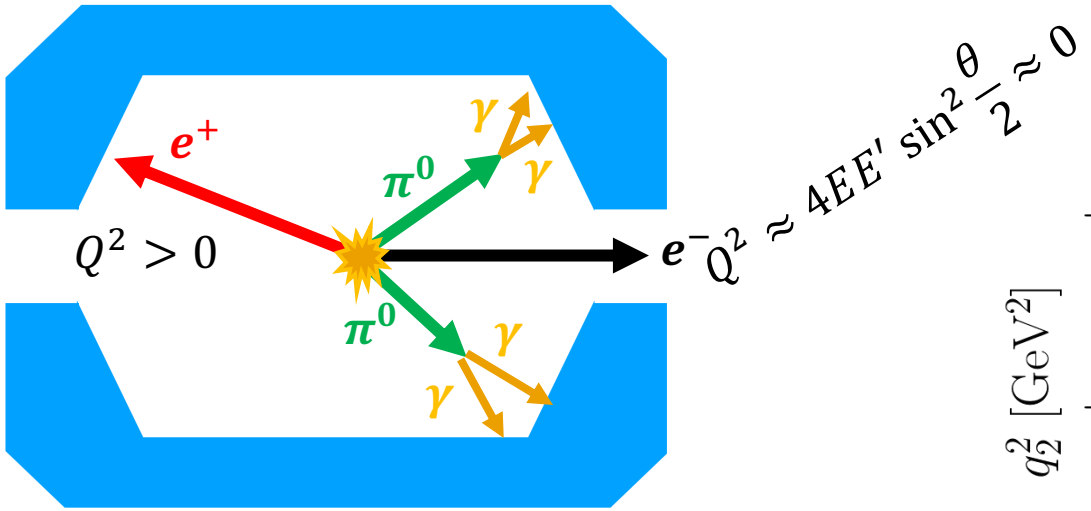
- Scattering of two on-shell photons
- Must be transversally polarized
  - ➢ Only helicity 0 and 2 contributions
- Study of radiative widths

Untagged Study



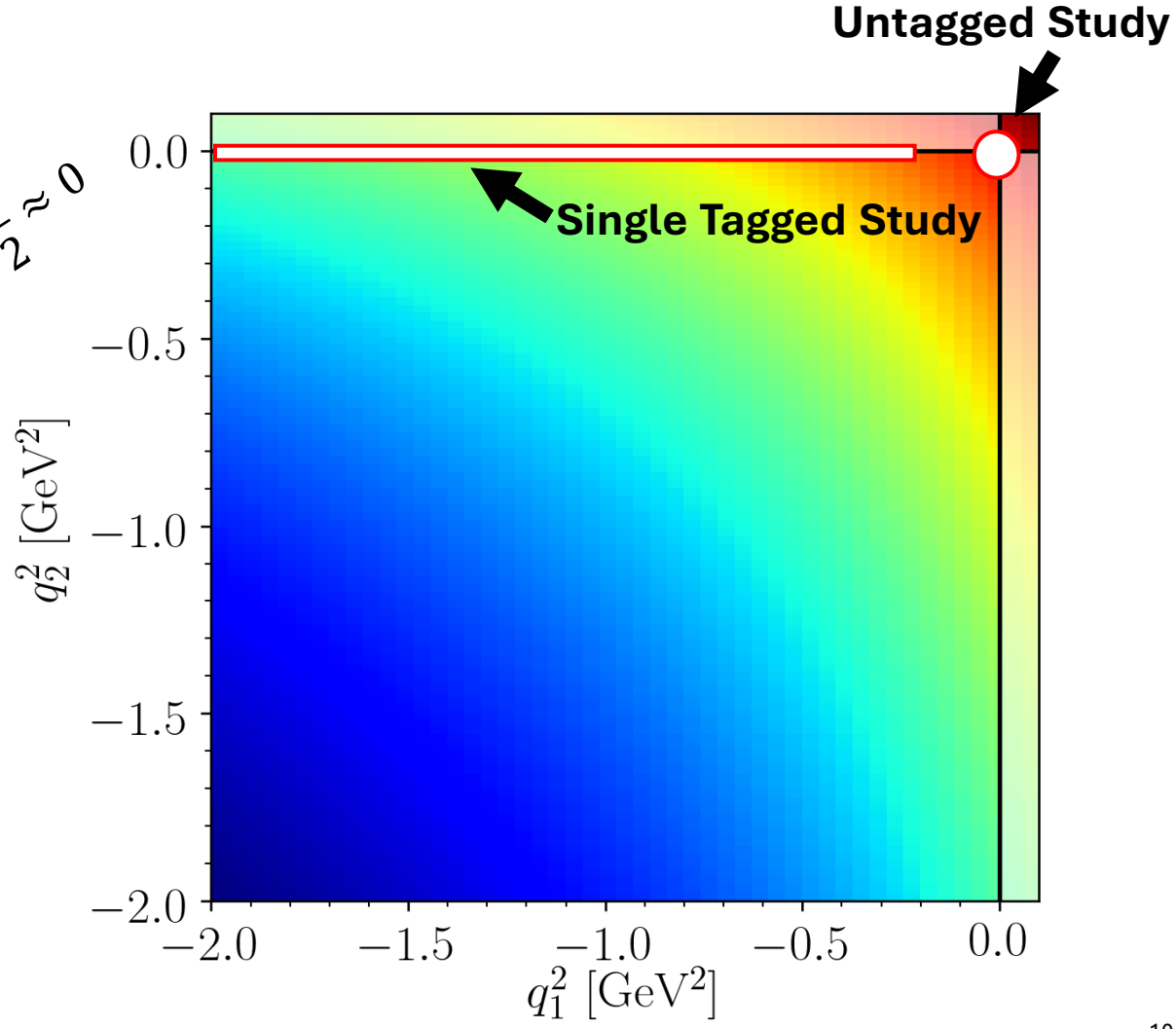
Collider Studies of Transition Form Factors

Single Tagged Studies



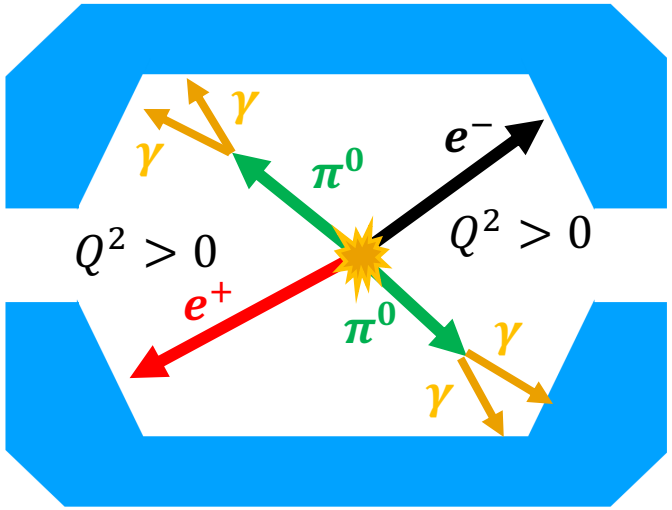
$Q^2 \approx 4EE' \sin^2 \frac{\theta}{2} \approx 0$

- One photon on-shell, one photon off-shell
  - Much smaller cross section
- TT and LT configurations
  - Helicity 0, 1, and 2
- Study TFFs as function of one Q^2

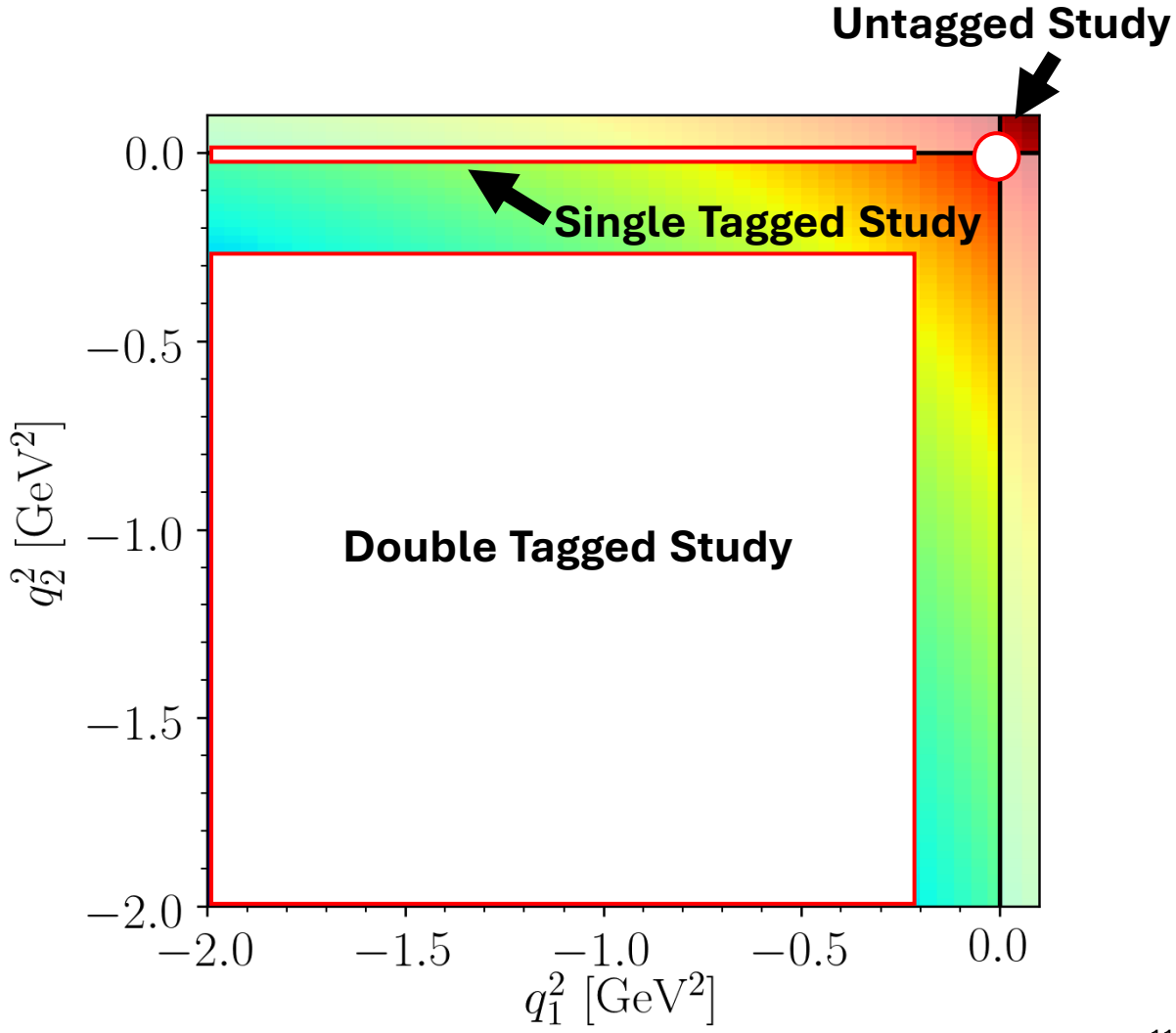


Collider Studies of Transition Form Factors

Double Tagged Studies



- Scattering of two off-shell photons
  - ➢ Tiny cross sections
- Study full functional dependence of TFFs on Q^2
- **Only one measurement: BaBar $\gamma^*\gamma^* \to \eta'$**

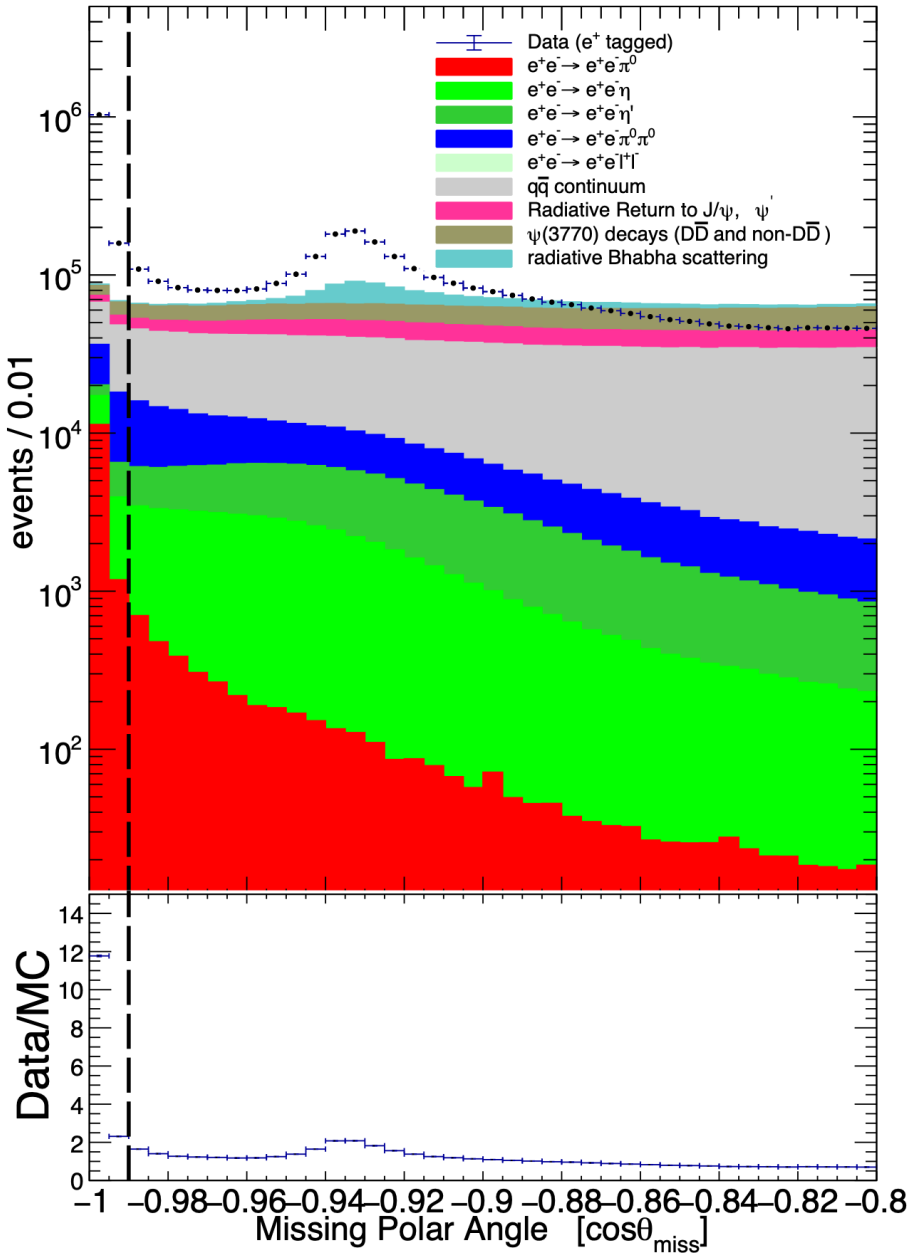


Study of $\gamma\gamma^* \to \pi^0$

- Single Tag Measurement (2.9 fb^{-1} @ 3.773 GeV)
  - Require quasi-real photon
- Select …

  … one final state lepton

  … require small scattering angle of missing momentum → small missing Q^2



arXiv:2509.07685

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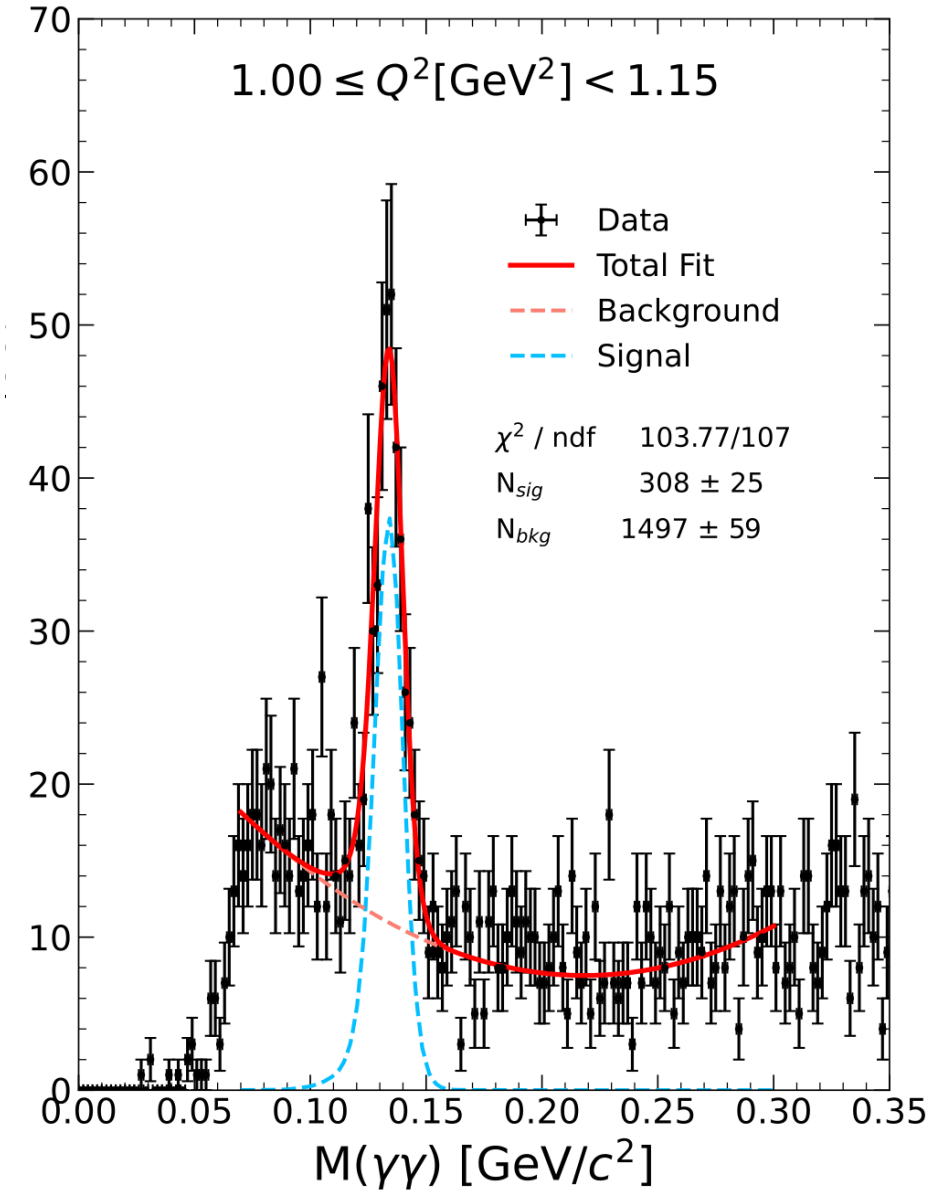
- Single Tag Measurement (2.9 fb^{-1} @ 3.773 GeV)
  - Require quasi-real photon
- Select …

  … one final state lepton

  … require small scattering angle of missing momentum → small missing Q^2
- Background suppression and subtraction

$$|F(Q^2,0)|^2 = \frac{N}{\Delta Q^2\, L\, \varepsilon\, (1+\delta)} \left(\frac{d\sigma_{WZW}}{dQ^2}\right)^{-1}$$

- Normalize to luminosity, efficiency, point-like cross section, and corrections for radiative effects and **finite 2nd virtuality**



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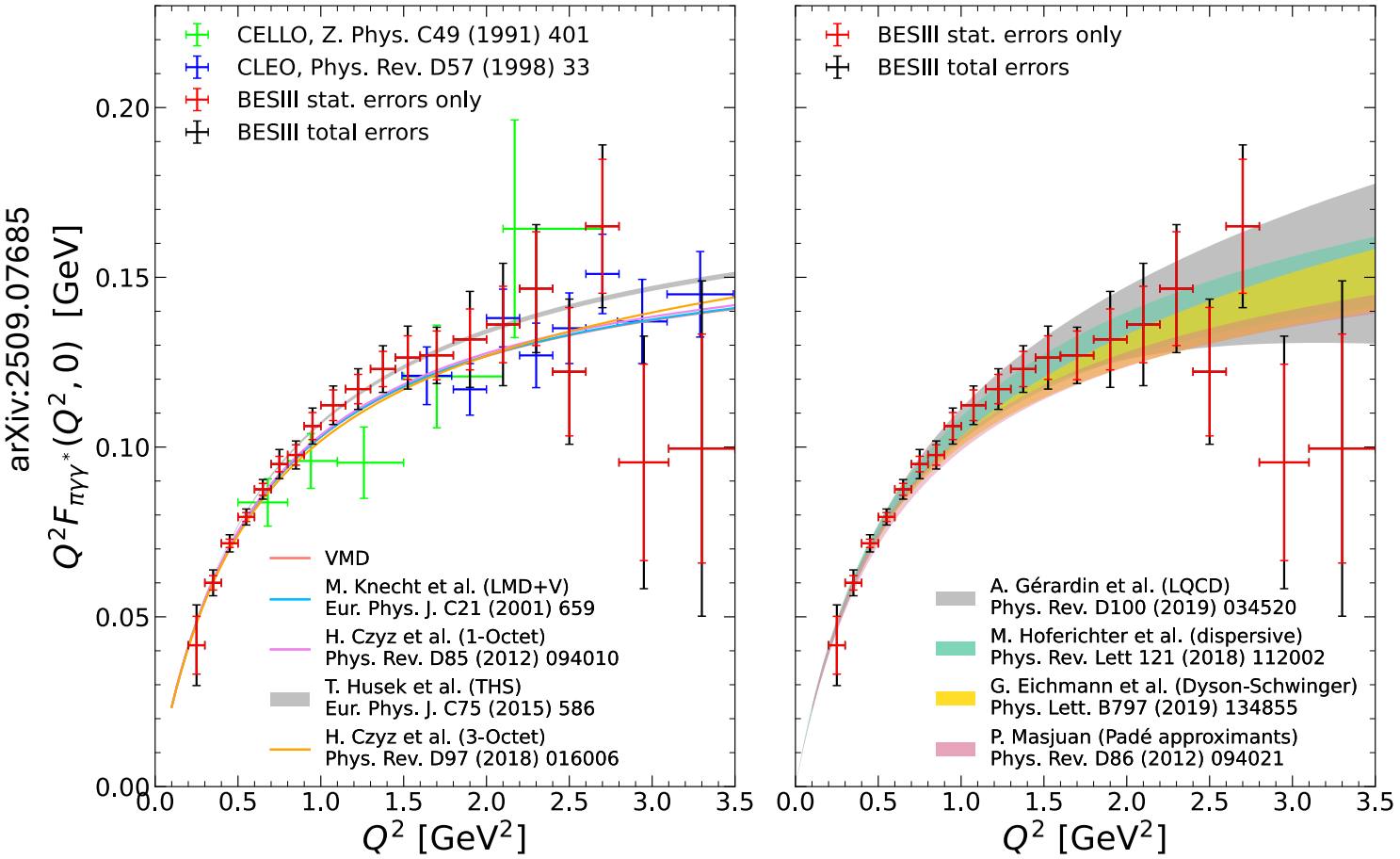


arXiv:2509.07685

- Good agreement with previous measurements
- Most precise measurement at small Q^2
- Excellent agreement with
  - Lattice QCD
  - Dispersive calculations
  - Dyson-Schwinger
- **To be repeated with 20 fb^{-1}!**
  - Also for η and η'

Study of $\gamma\gamma^* \to f_0/f_2 \to \pi^0\pi^0$

- Single Tag Measurement (20.3 fb^{-1} @ 3.773 GeV)
- Select …

  … one final state lepton

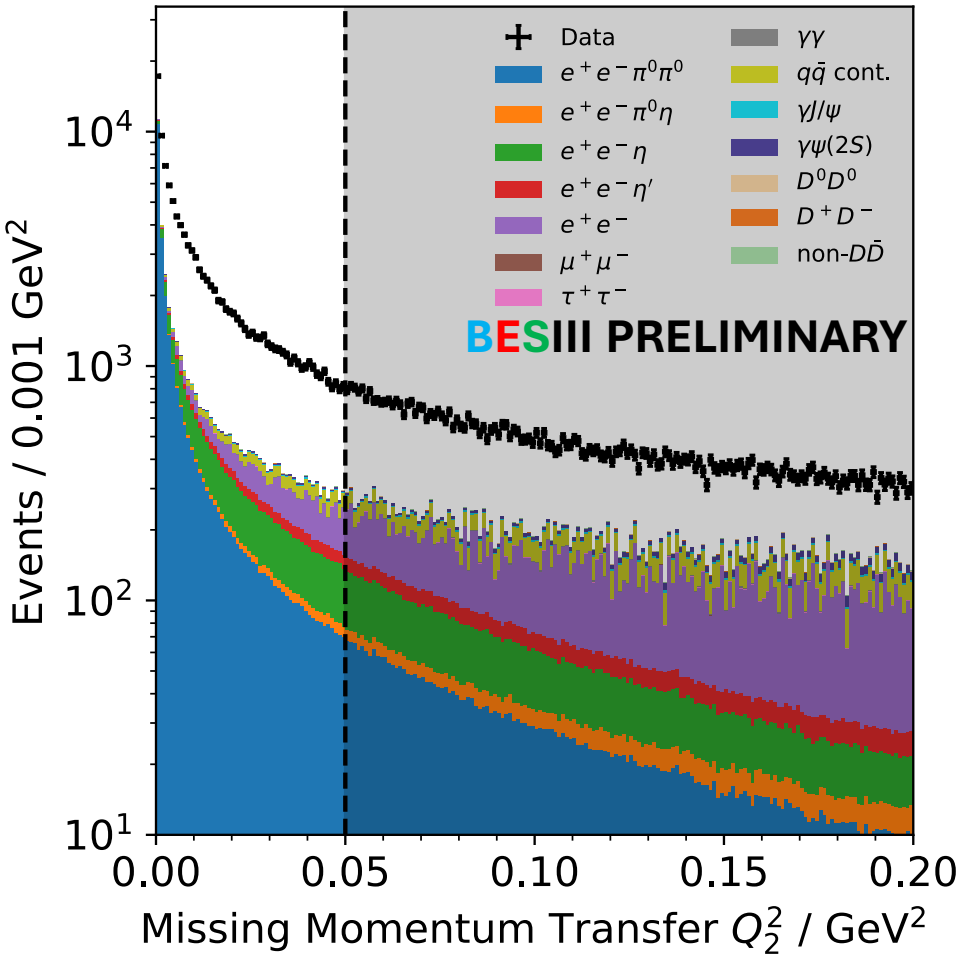
  … four photons (2x $\pi^0 \to \gamma\gamma$)

- Require vanishing second virtuality
  - Improved resolution of Q^2_{miss} using kin. fit

    → Direct constraint of Q^2_{miss}

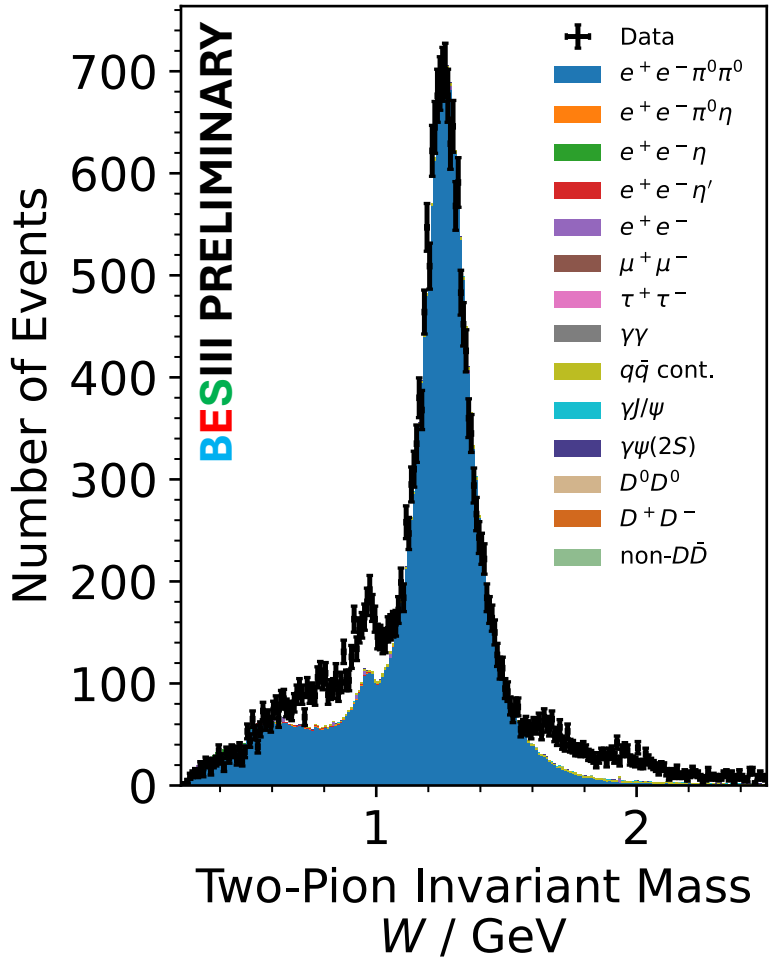
    → **Future measurement of double virtual cross section**

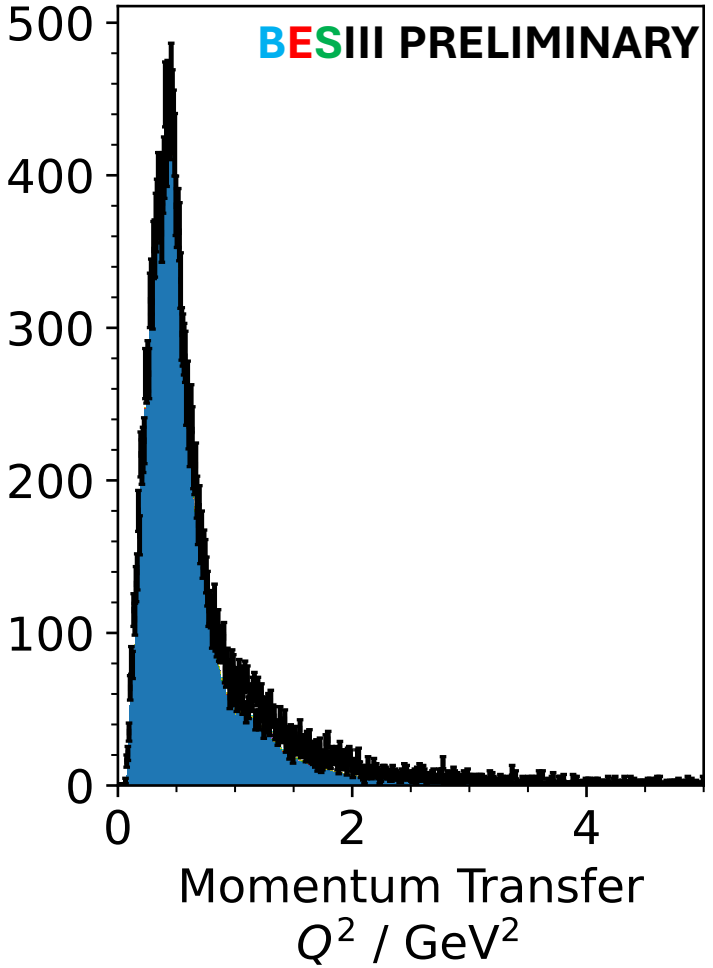
- Further suppression of background using kinematic constraints

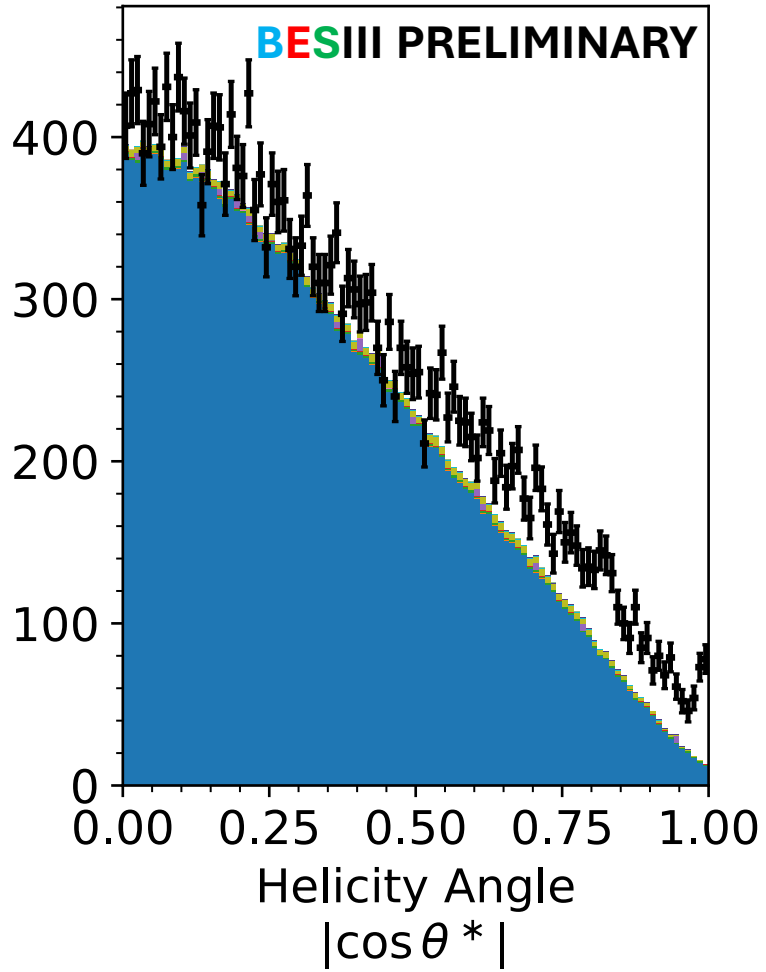


Study of $\gamma\gamma^* \to f_0/f_2 \to \pi^0\pi^0$

Simulations according to [ML et. al., arXiv:2511.12717]







Study of $\gamma\gamma^* \to f_0/f_2 \to \pi^0\pi^0$

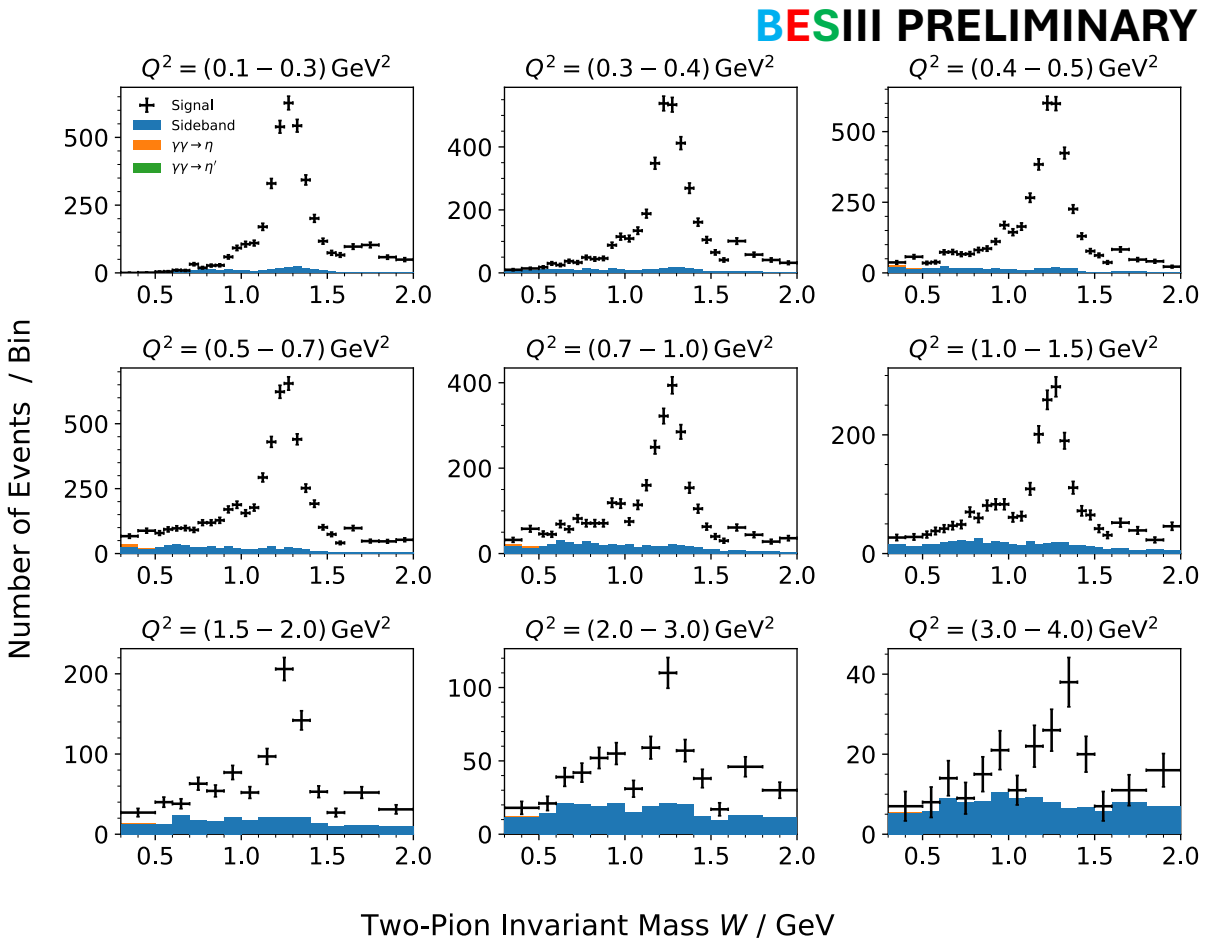
- Data driven background subtraction

$$\frac{d(\sigma_{TT} + \varepsilon\,\sigma_{LT})}{d|\cos\theta^*|} = \frac{N}{\Delta Q^2\,\Delta W\,\Delta|\cos\theta^*|\,L\,\epsilon}\left(\frac{d^2L_{TT}}{dQ^2\,dW^2}\right)^{-1}$$

- Normalize event yield to
  - Bin widths
  - Integrated luminosity
  - Reconstruction efficiency
  - Luminosity Function

    → TT luminosity function → correct LT term

    → correction for finite second Q^2



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[Phys. Rev. D, vol. 101, no. 5, p. 054008, 2020, Phys. Lett. B, vol. 789, pp. 366–372, 2019, Prog. Part. Nucl. Phys., vol. 107, pp. 20–68, 2019]

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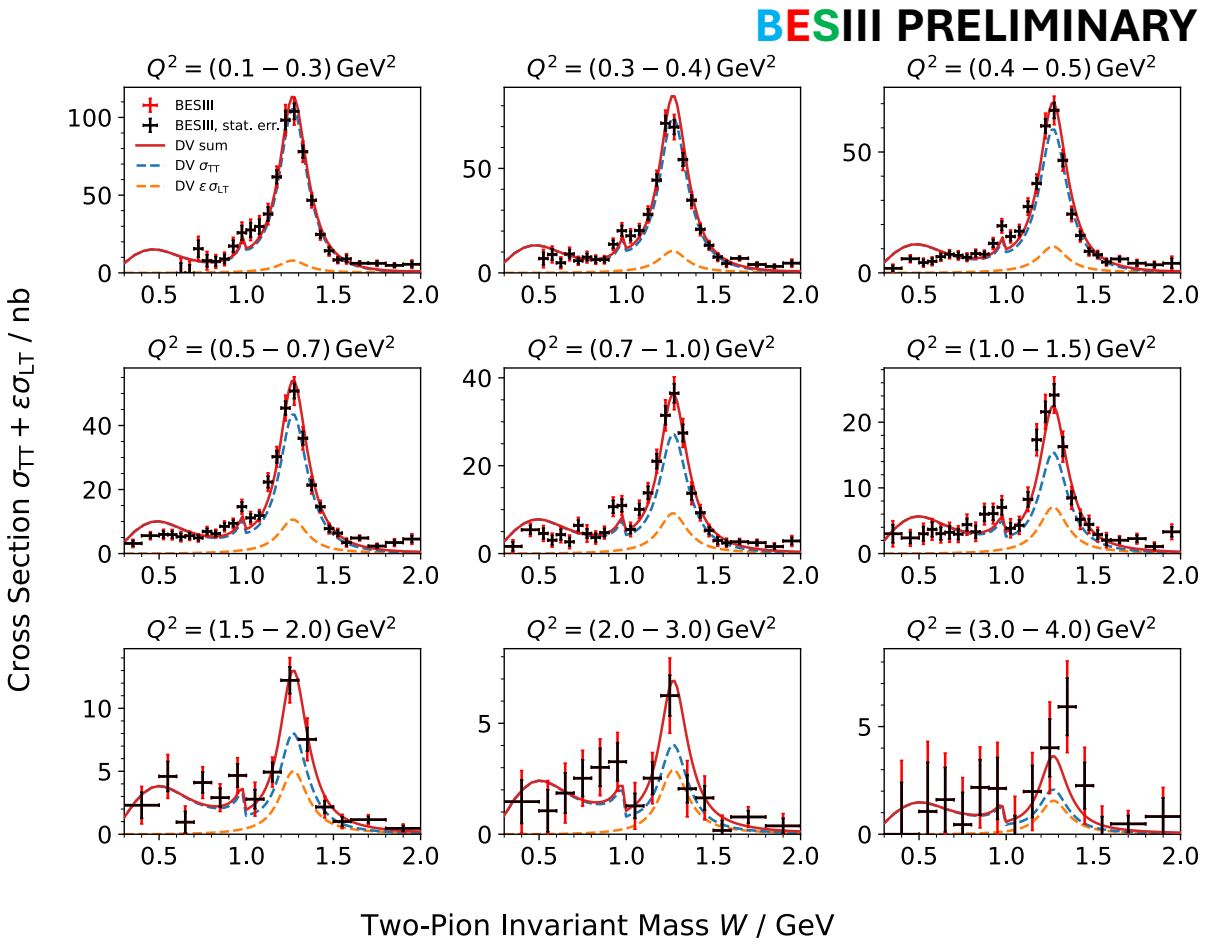

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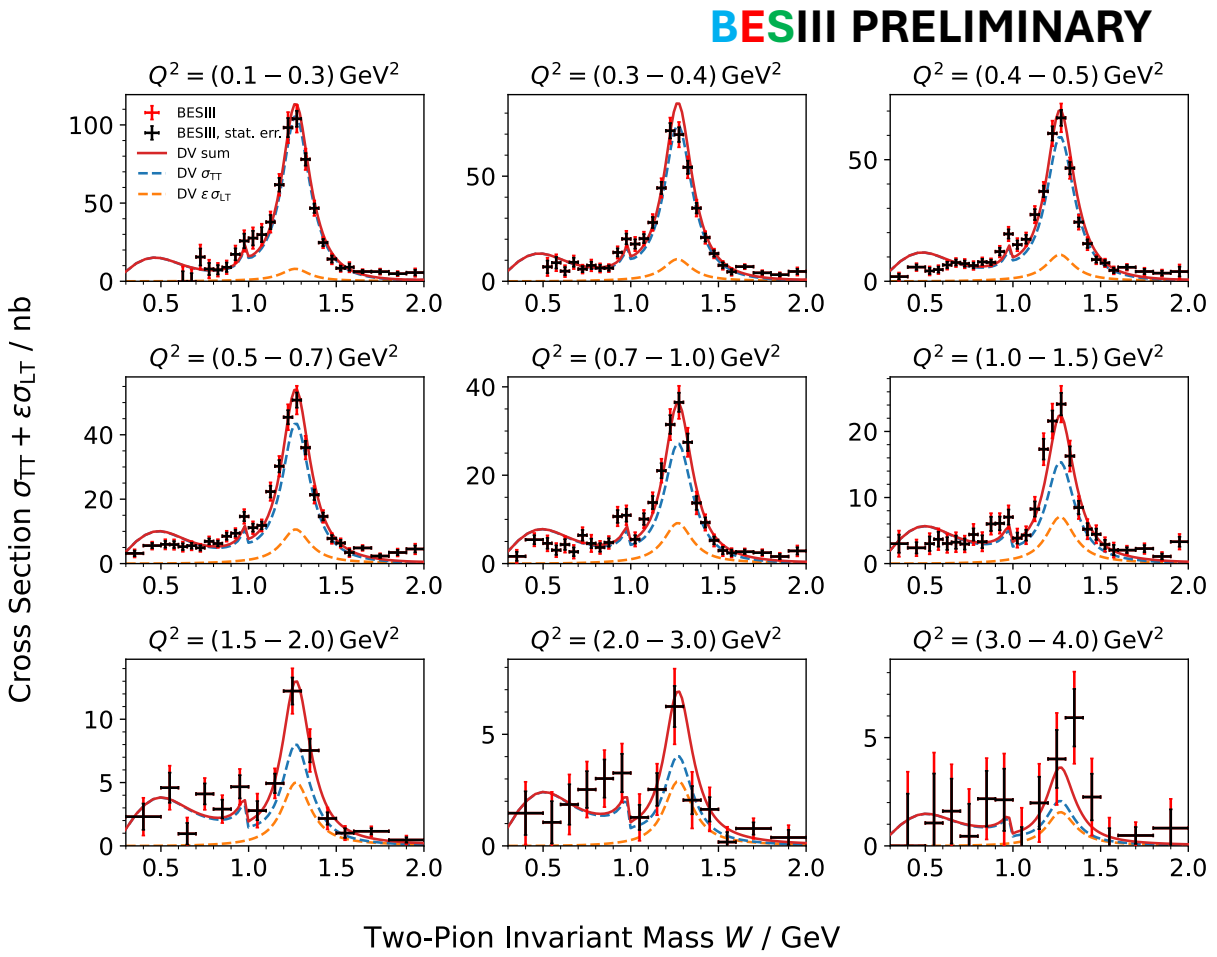
- The cross sections contain information on Transition Form Factors
- Different resonances:
  - Scalars: $f_0(500)$ & $f_0(980)$
  - Tensor: $f_2(1270)$
  - Others statistically irrelevant
- Extraction of TFFs through partial wave analysis



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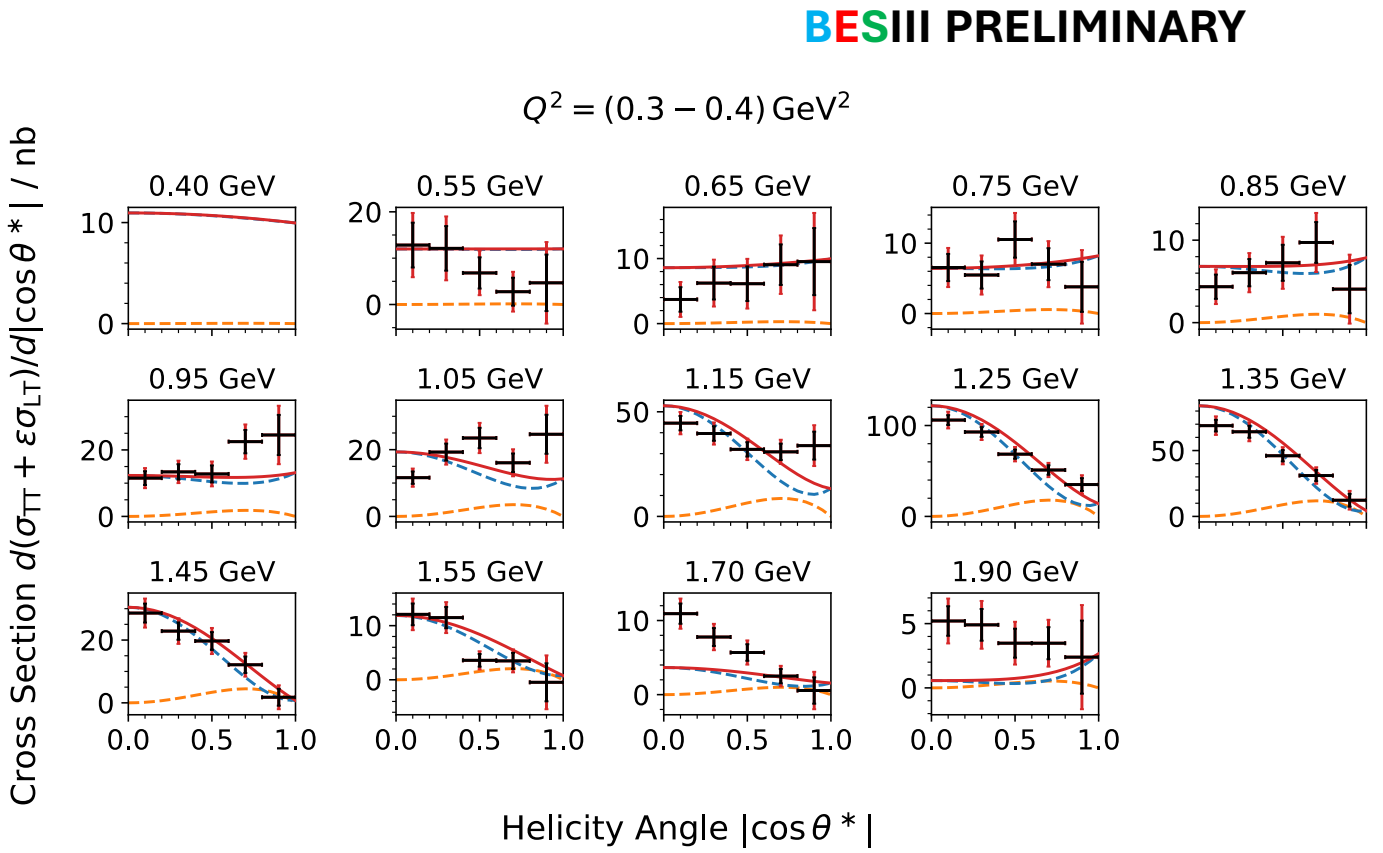

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- Extraction of TFFs through partial wave analysis

- Cross section‘s dependence on partial waves

$$\frac{d\sigma}{d|\cos\theta^*|} = 4\pi\left(1+\frac{Q^2}{W^2}\right)\left(\left|S\,Y_0^0 + D_0 Y_2^0 e^{i\phi}\right|^2 + 2\varepsilon\left|D_1 Y_2^1\right|^2 + \left|D_2 Y_2^2\right|^2\right)$$

- Parameterization of S wave using Omnès function
  - Provided by Danilkin et. al.

- Parameterization of $f_2(1270)$ by relativistic Breit-Wigner

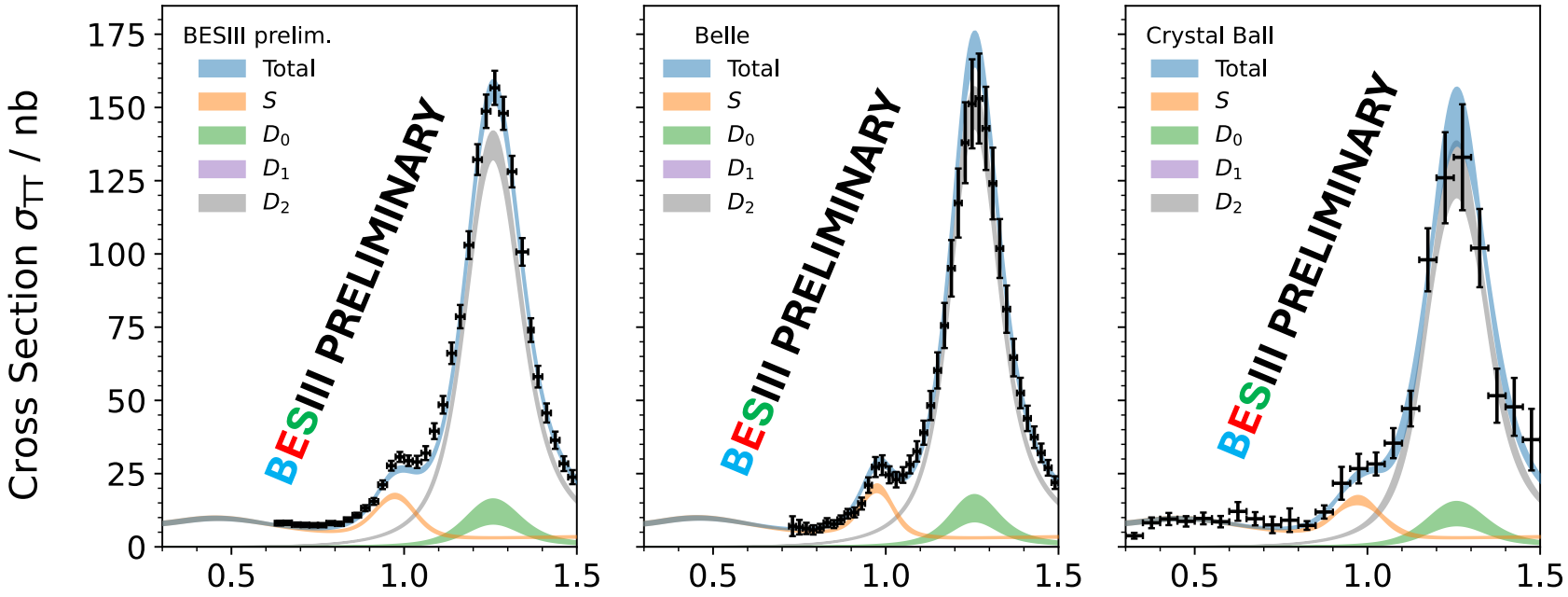
- TFFs are given by the ratio of amplitudes at Q^2 and Q^2=0
  - Normalization needs to be determined
  - Combined fit with untagged data

Study of $\gamma\gamma^* \to f_0/f_2 \to \pi^0\pi^0$

Fix normalization at $Q^2=0$ using untagged data!

$Q^2 = 0 \qquad |\cos\theta^*| < 0.8$

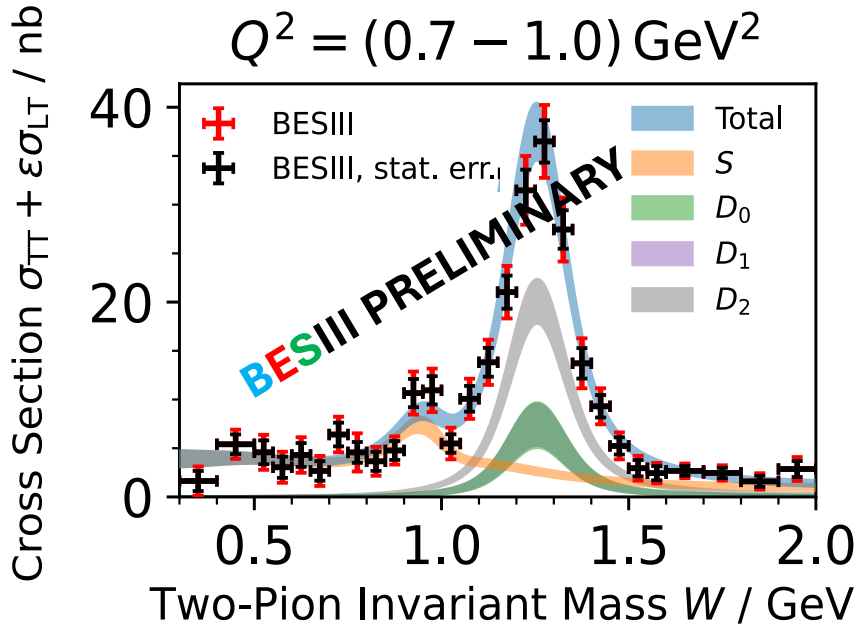
EPJ Web Conf., vol. 291 (2024), p. 01002 | Phys.Rev.D 79 (2009) 052009 | Phys.Rev.D 41 (1990) 3324

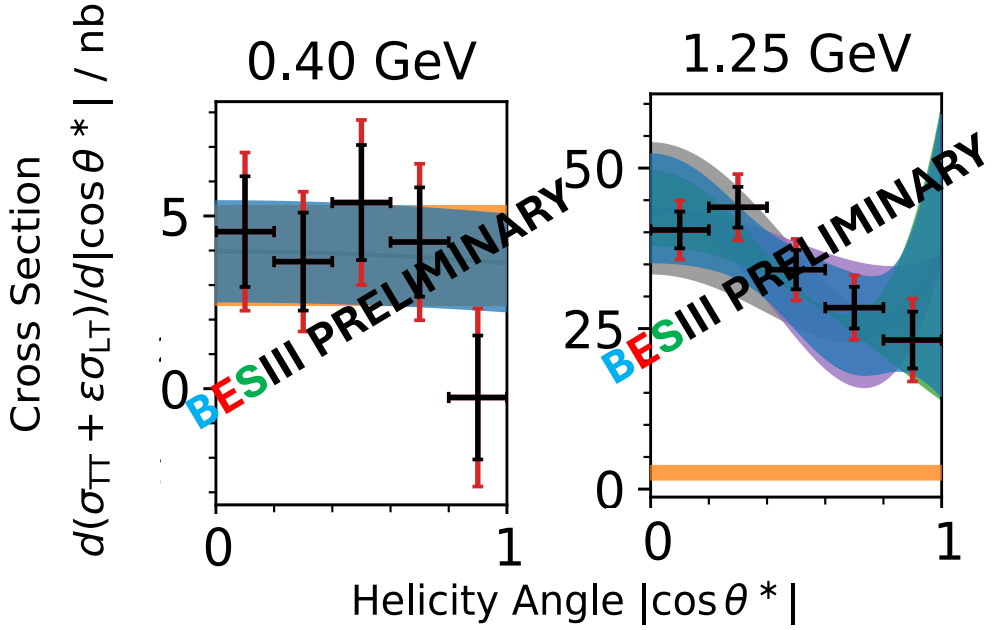


Convolution of the fit function with Gaussian function to compensate smearing effects

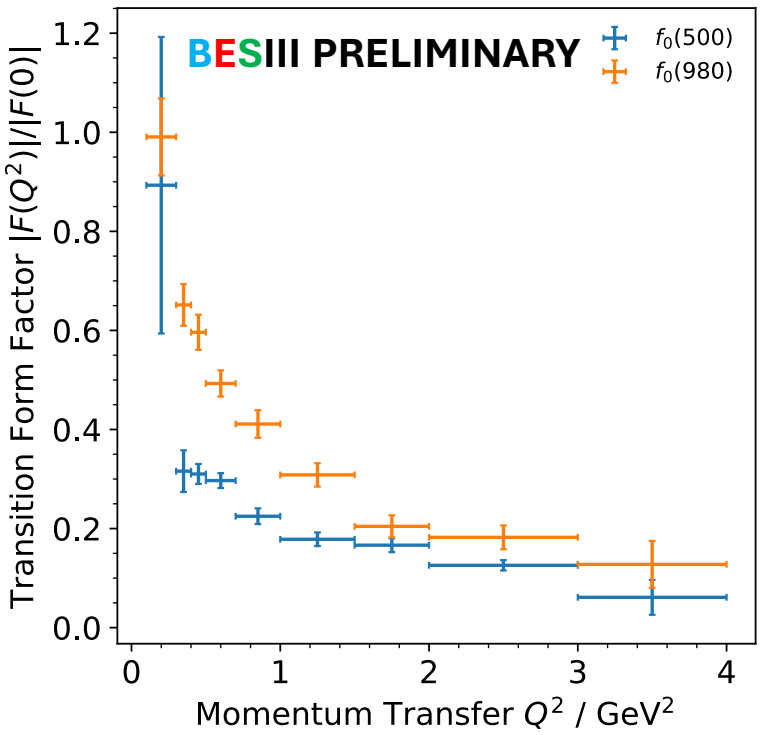
Study of $\gamma\gamma^* \to f_0/f_2 \to \pi^0\pi^0$

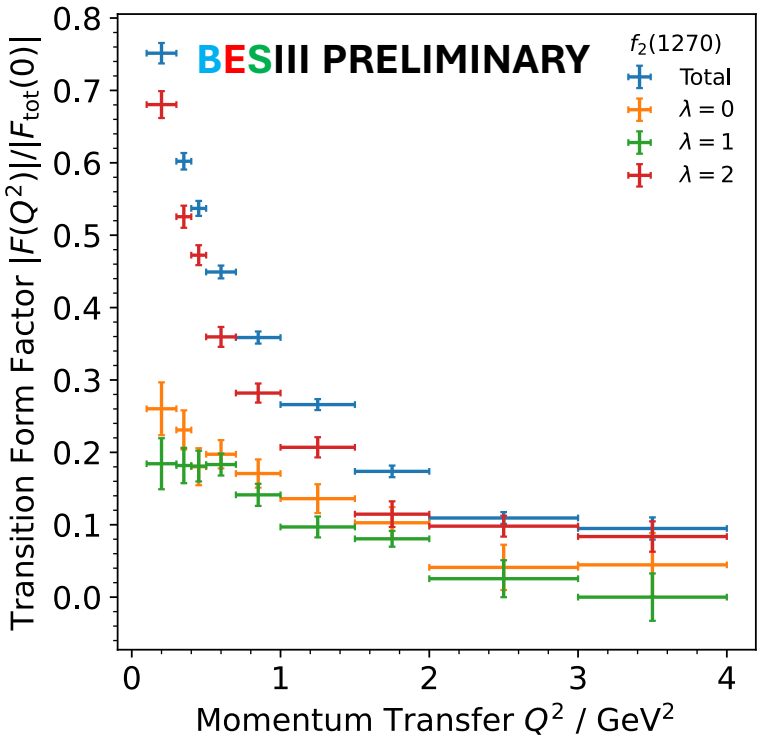
- Fit to single tagged data to extract Q^2 dependence of TFFs
- Angular modulations used to differentiate resonance
- Smearing effects taken into account





Study of $\gamma\gamma^* \to f_0/f_2 \to \pi^0\pi^0$

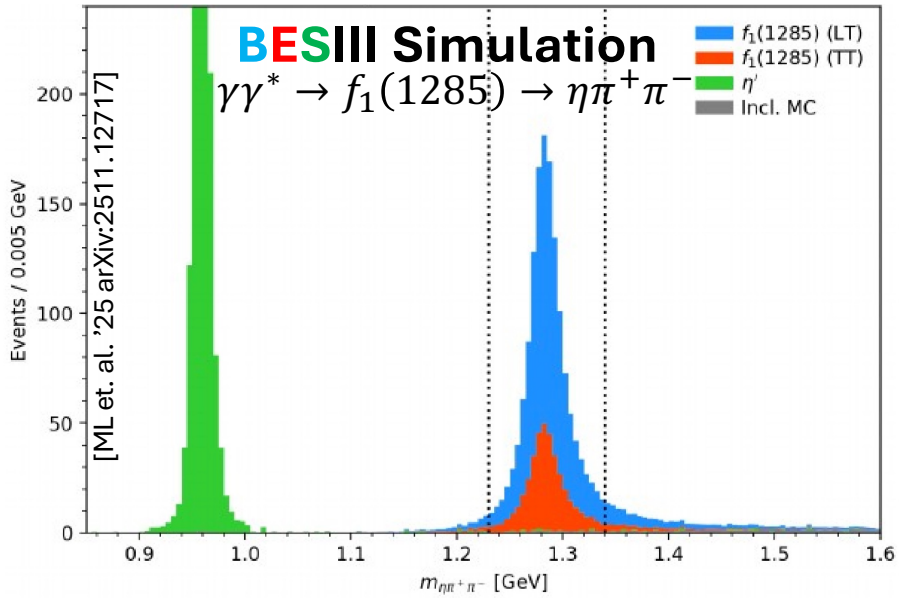


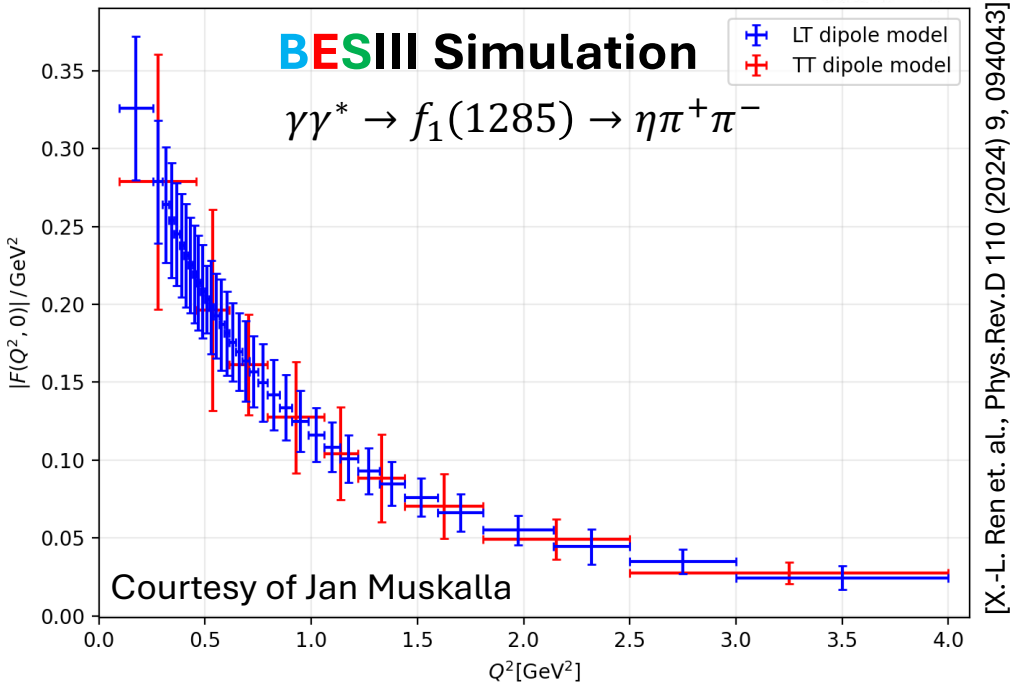


- First extraction of TFFs in a_μ relevant Q^2 range
- First measurement of $f_0(500)$ TFF
- Lowest Q^2 and most precise measurement of $f_0(980)$ and $f_2(1270)$ TFFs
  - Compatible with high Q^2 Belle data!

Conclusion and Outlook

- BESIII is perfectly suited to provide data on space-like TFFs at small to intermediate Q^2
- World best measurement of π^0,$f_0(500)$, $f_0(980)$, and $f_2(1270)$ TFFs
- Several measurements in preparation
  - $\gamma\gamma^* \to \pi^0, \eta, \eta', \pi^+\pi^-, \pi^0\eta$ …
  - $\boldsymbol{\gamma\gamma^* \to f_1(1285) \to a_0(980)\pi / f_0(500)\eta}$
  - $\gamma^*\gamma^* \to \pi^0, \eta, \eta', \pi^0\pi^0$
  - Study of azimuthal angular dependencies
  - …
- **More data to come: 10 fb^{-1} @ 4.68 GeV**





Conclusion and Outlook

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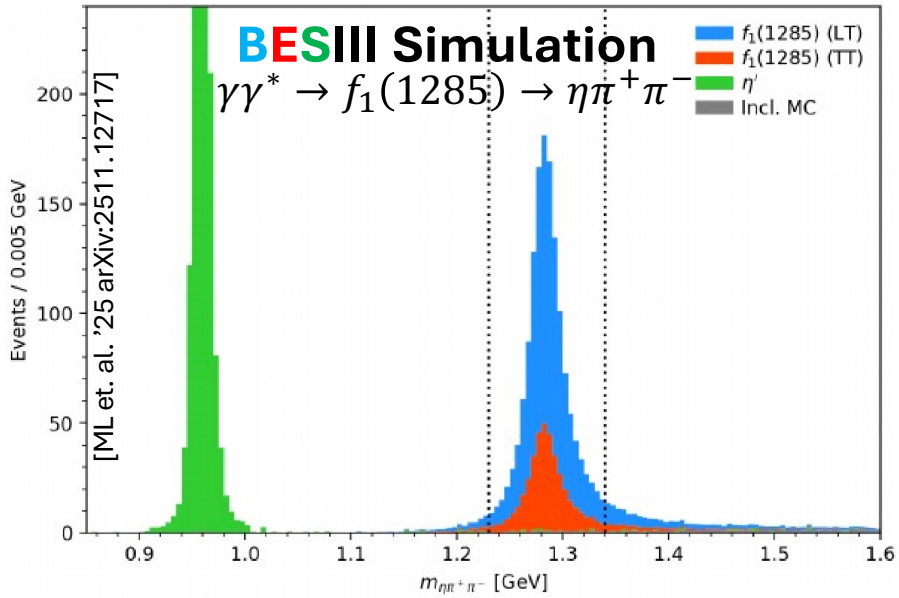

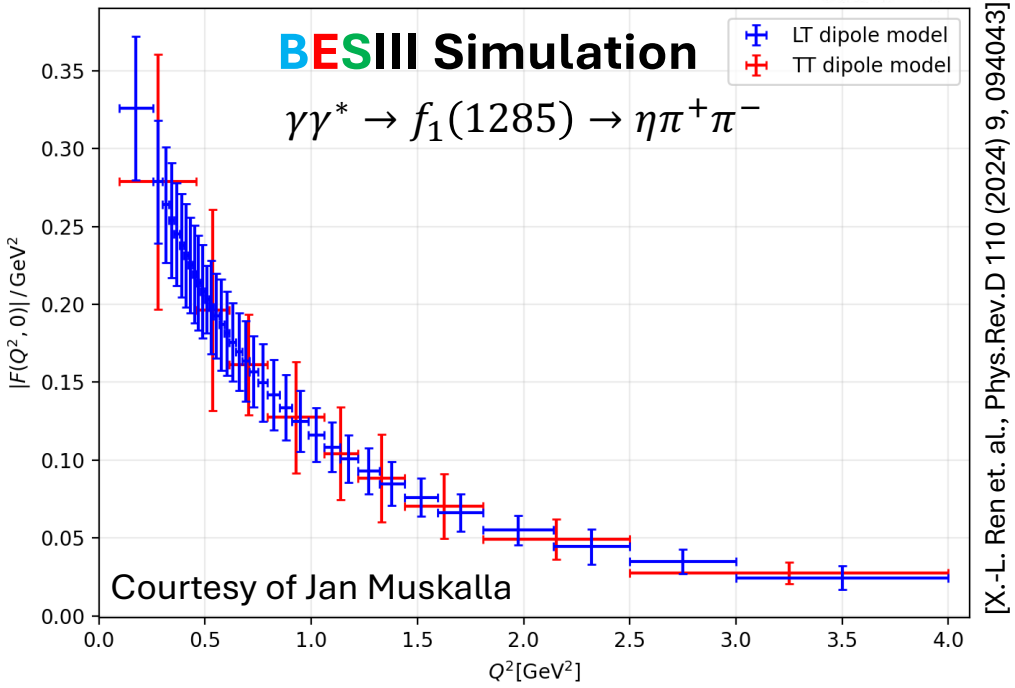

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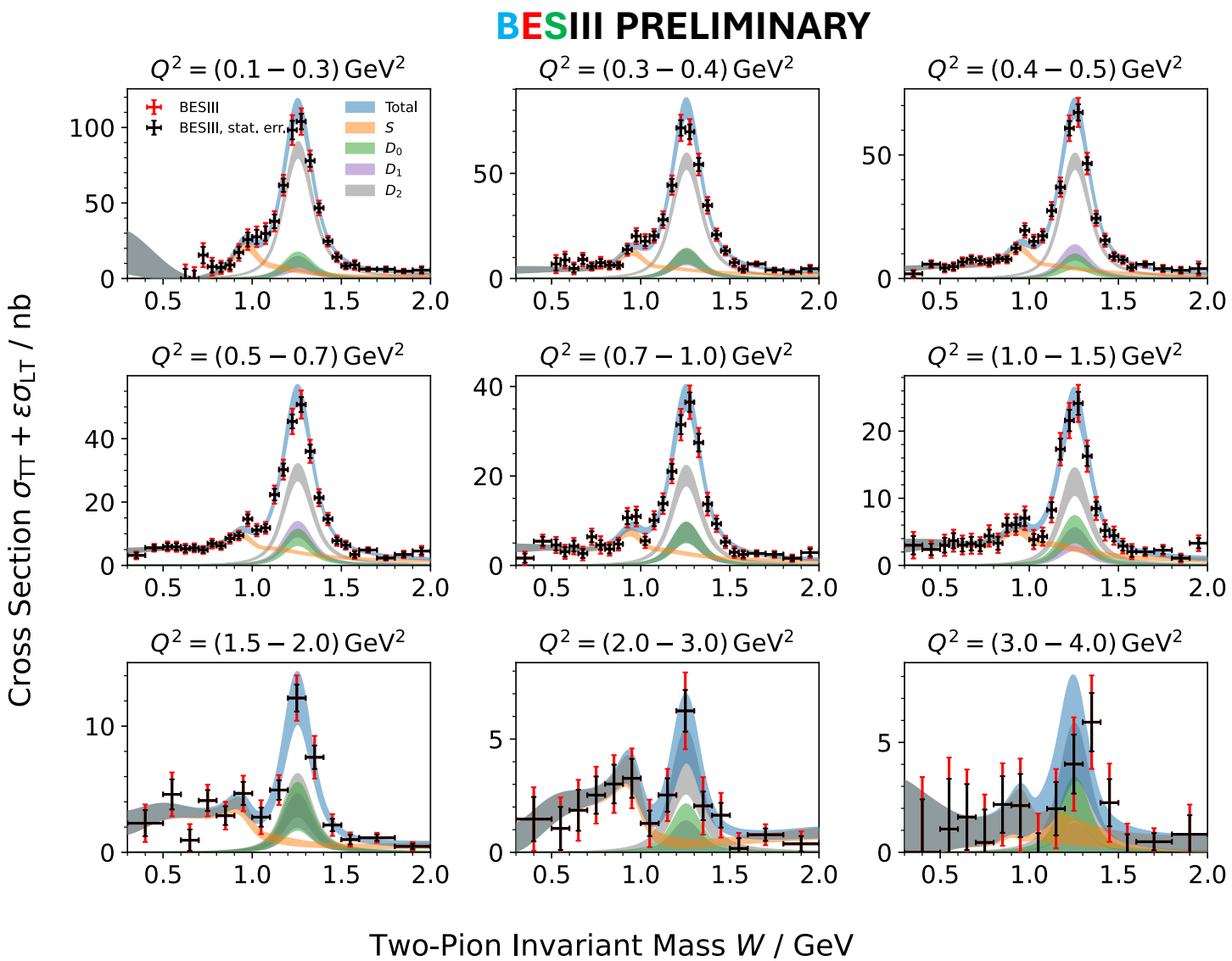
Backup

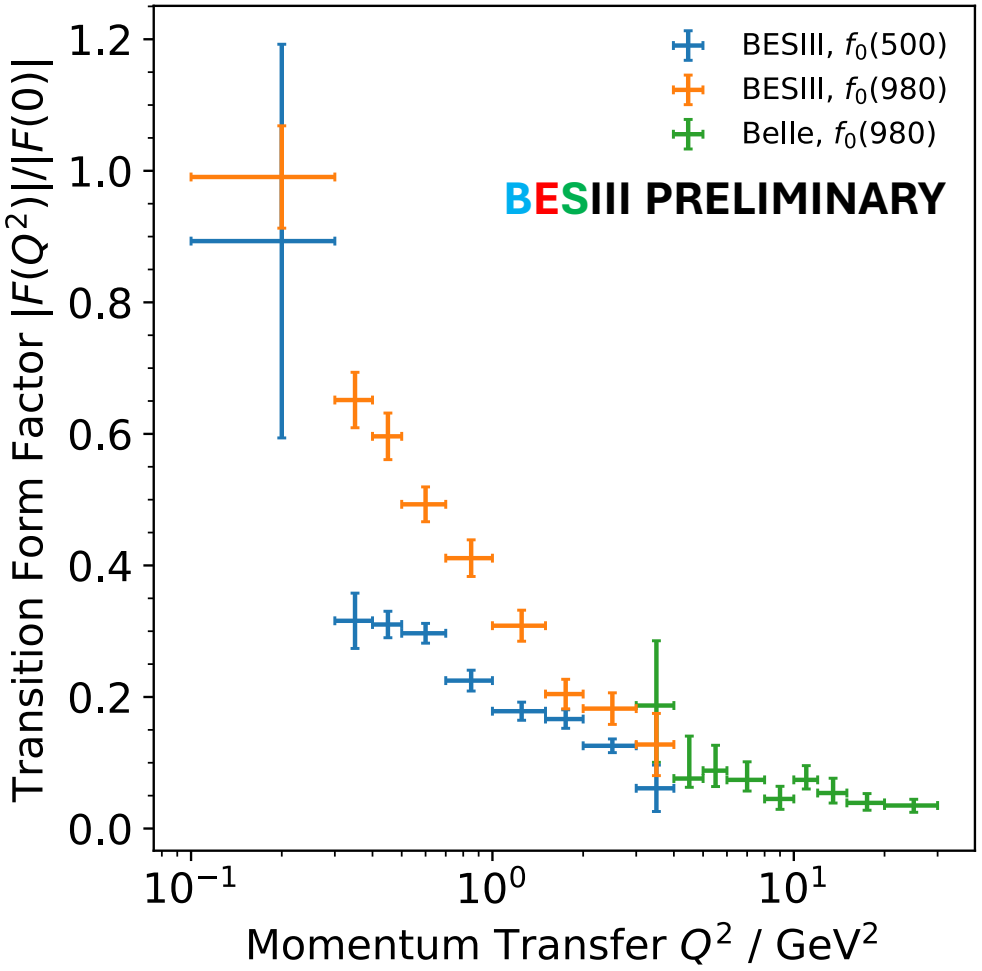
Fit Results

- Fit converges with $\chi^2/ndf = 736/1449$
  - Large systematic uncertainties of untagged Belle measurement
- Good description of all structures
- Normalization mostly fixed by untagged Belle results
- BESIII preliminary and Crystal Ball untagged results necessary to fix smearing and normalization of $f_0(500)$ and $f_0(980)$ TFFs



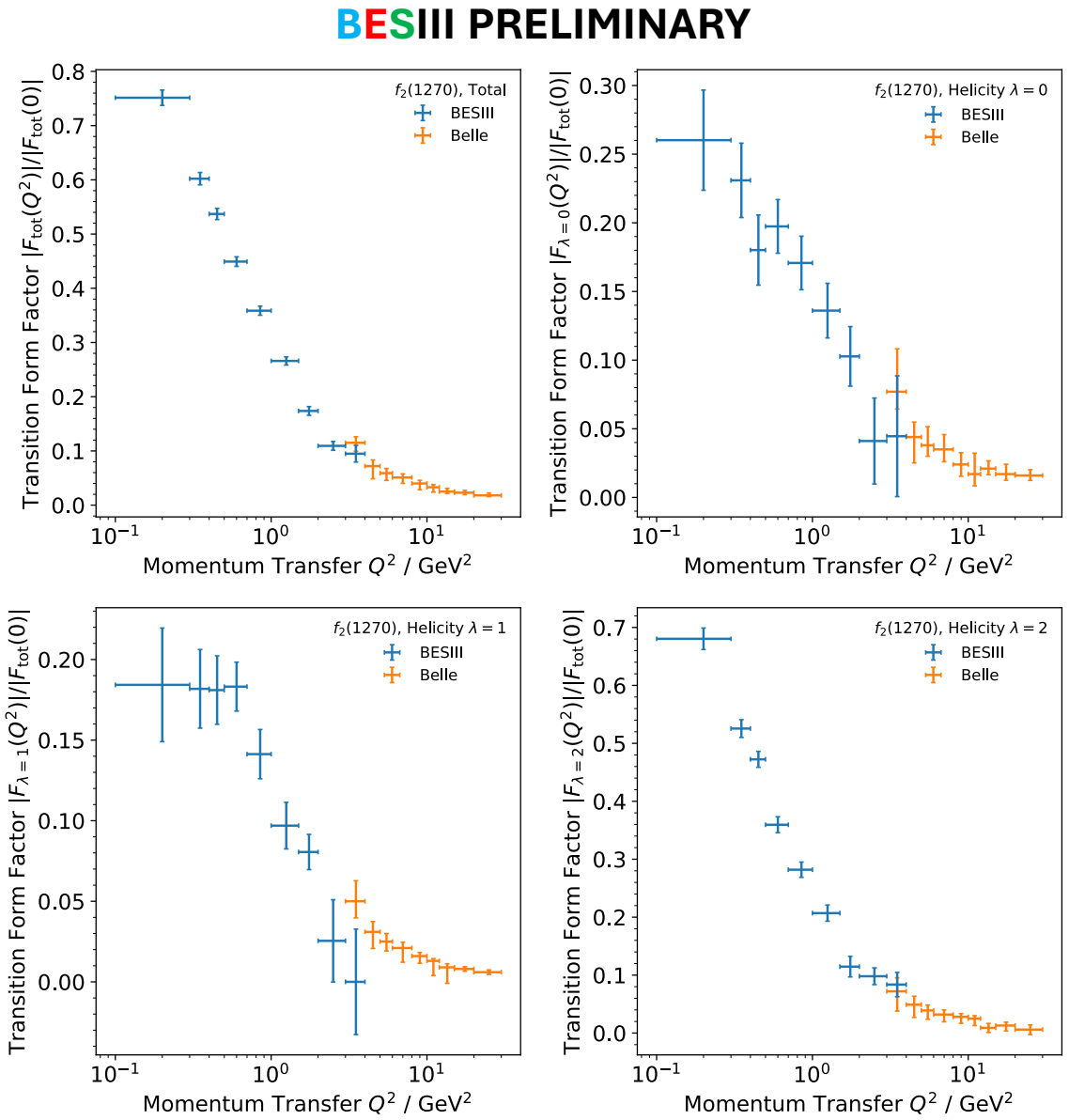
Comparison To Belle

- First determination of $f_0(500)$ TFF!
- First measurement of $f_0(980)$ TFF below 3 GeV^2
- Good agreement to Belle $f_0(980)$ data
- Large uncertainty of $f_0(500)$ TFF at small momentum transfers
  - ➢ Missing constraints at small W and small Q^2

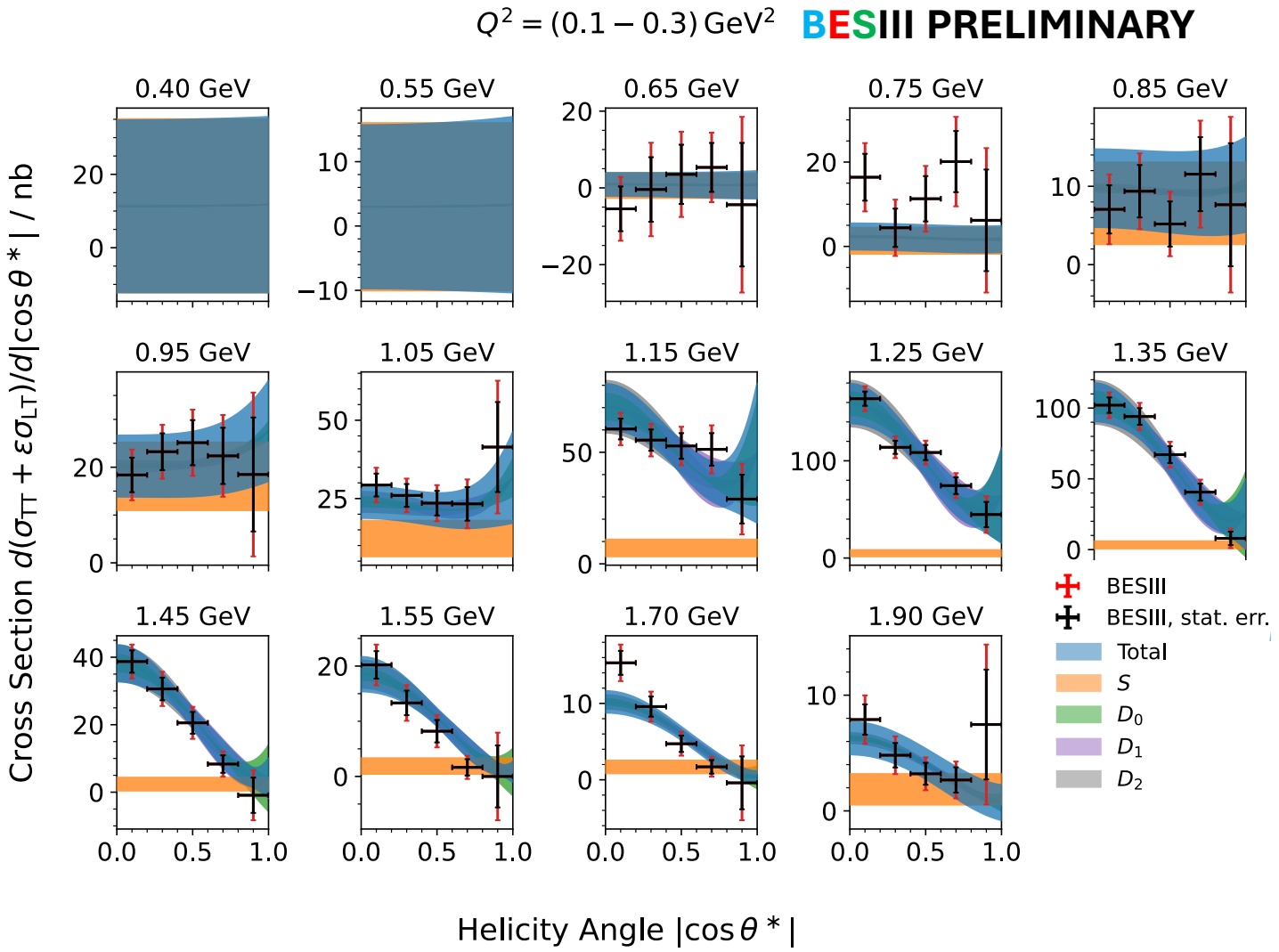


Comparison To Belle

- First measurement below 3 GeV^2
- Helicity-2 component dominant
- Very slight tension to existing helicity-1 Belle data
- Otherwise the data seems to be described by a smooth distribution
- ”Plateau” in helicity-1 TFF
  - Drop towards zero required by Landau-Yang?



Fits to Single Tagged Data



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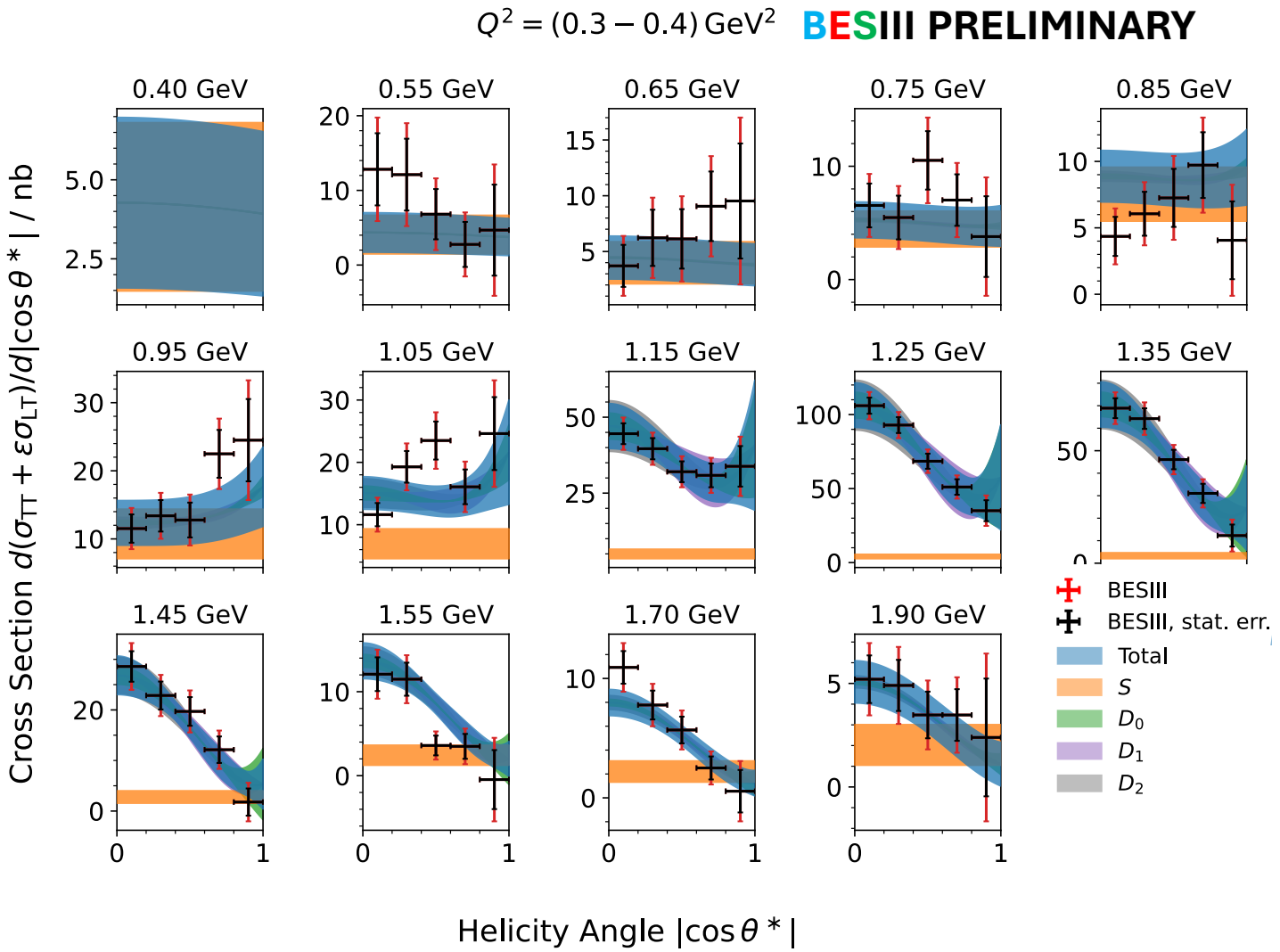

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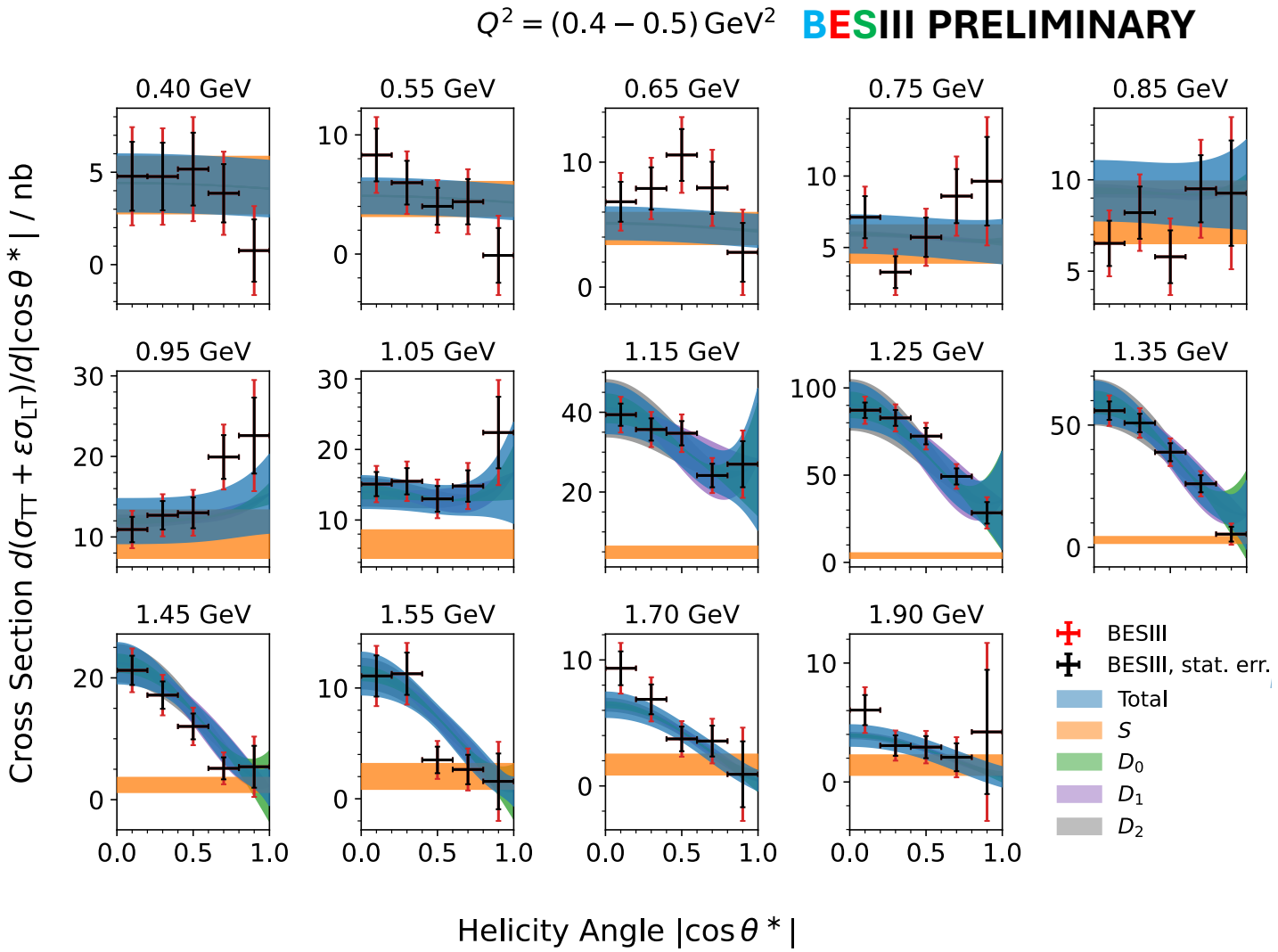

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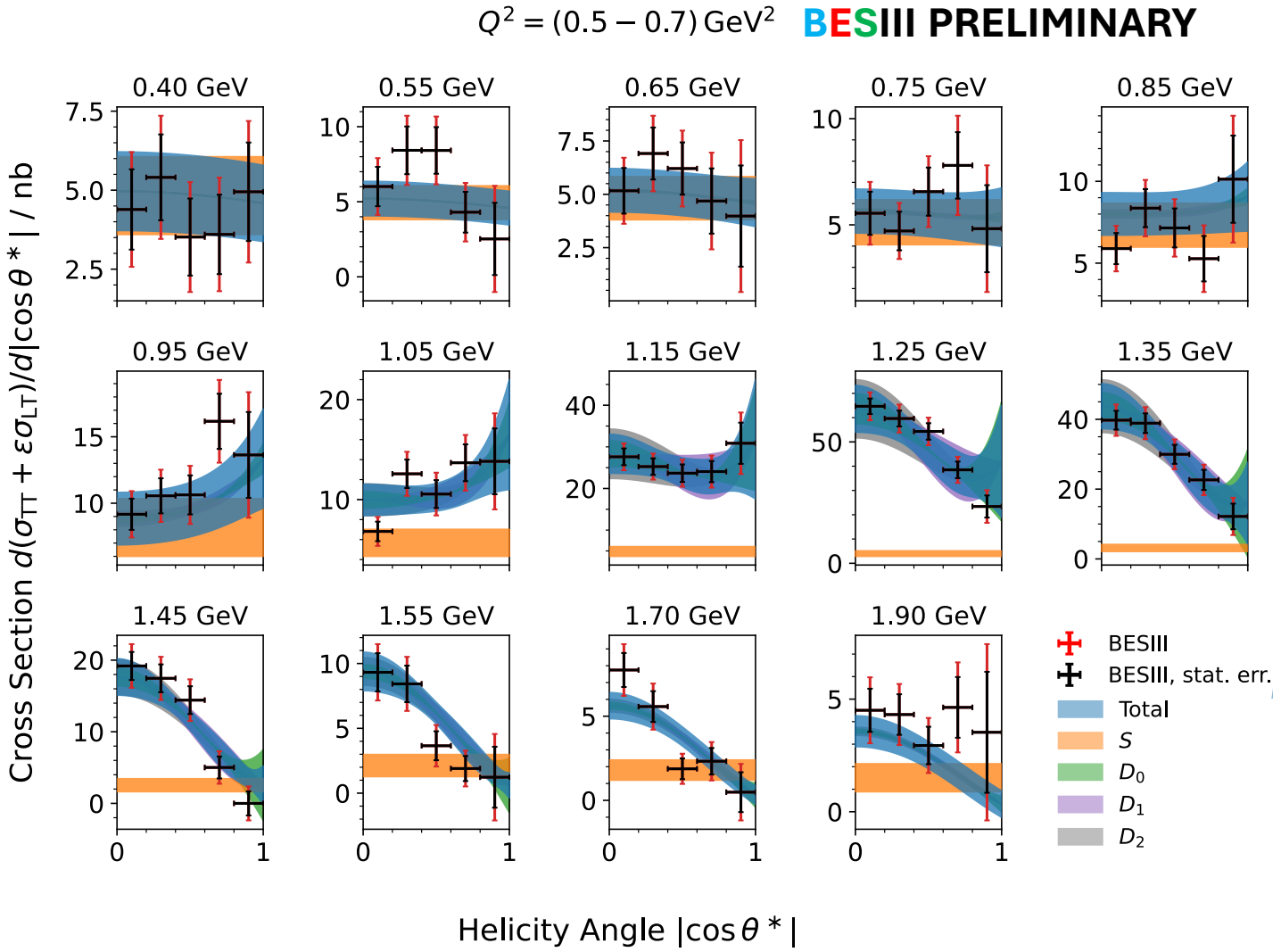

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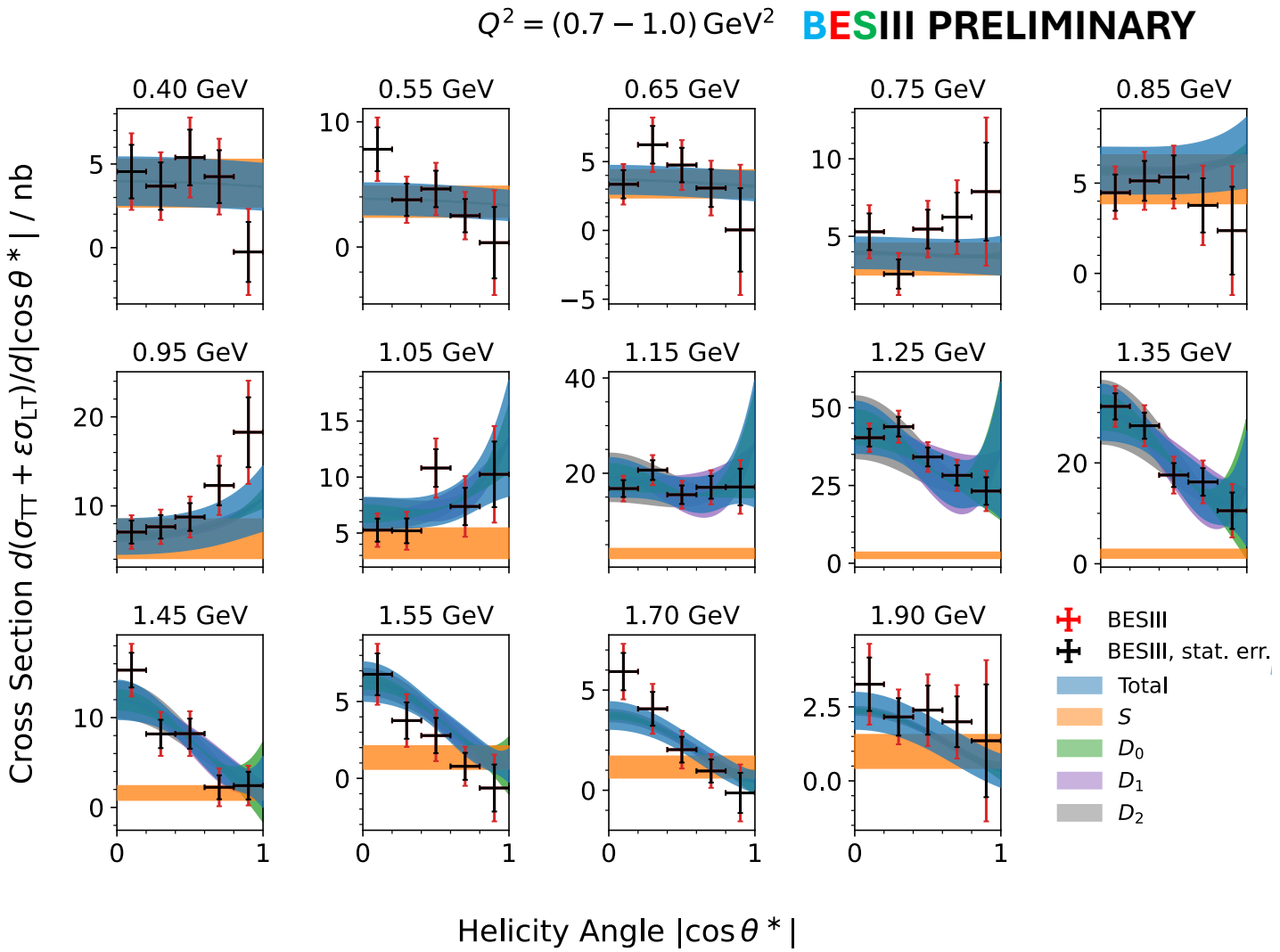

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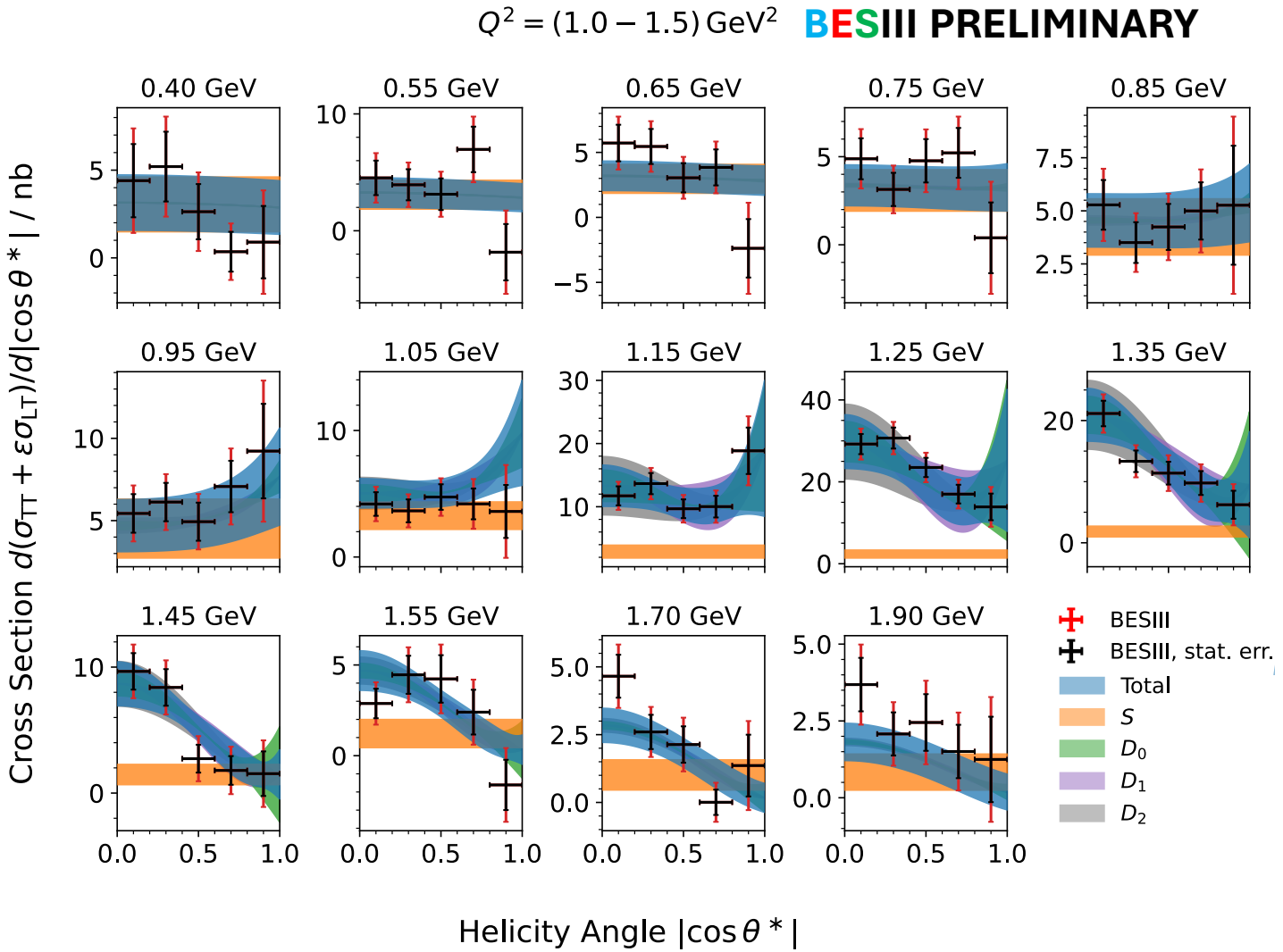

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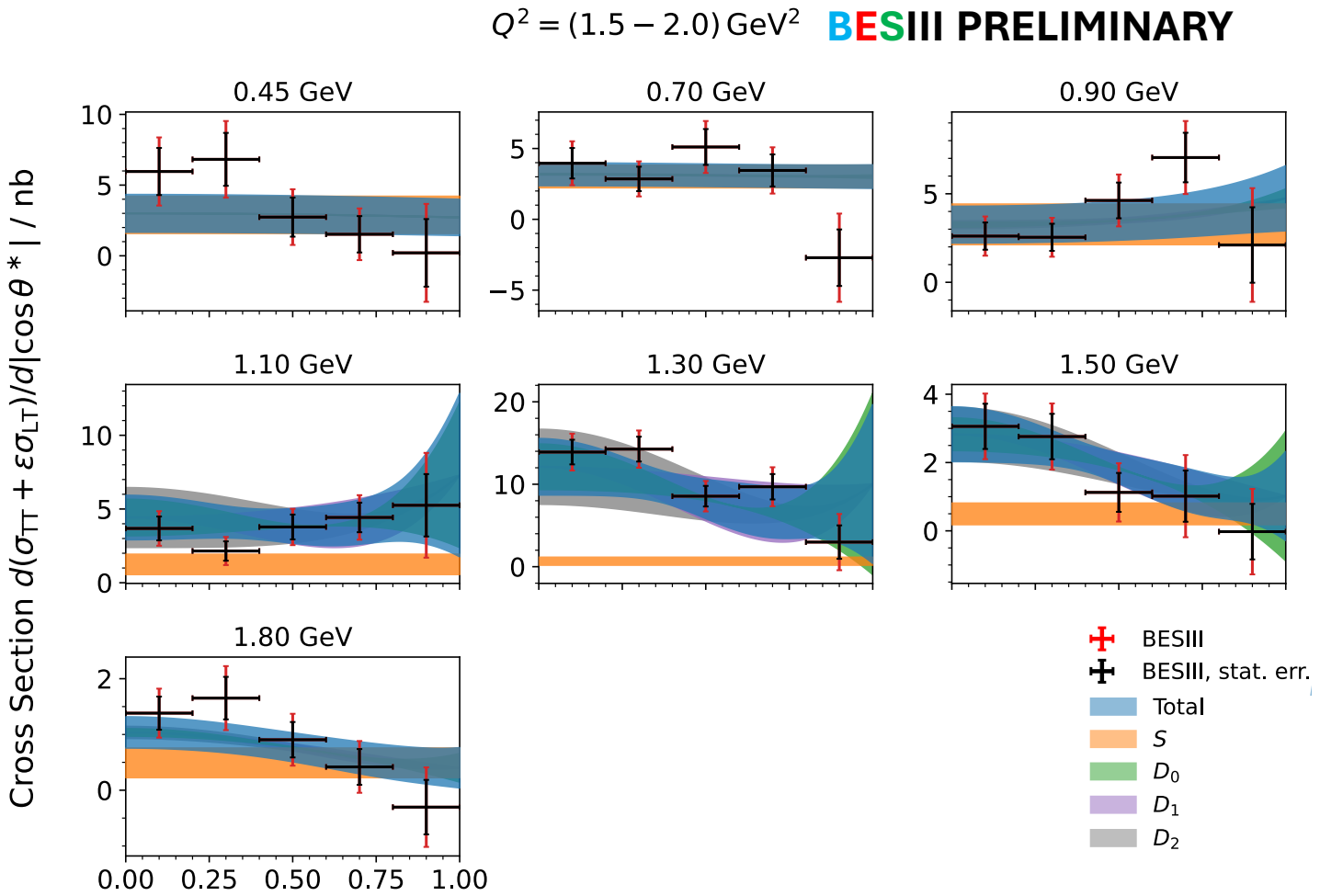
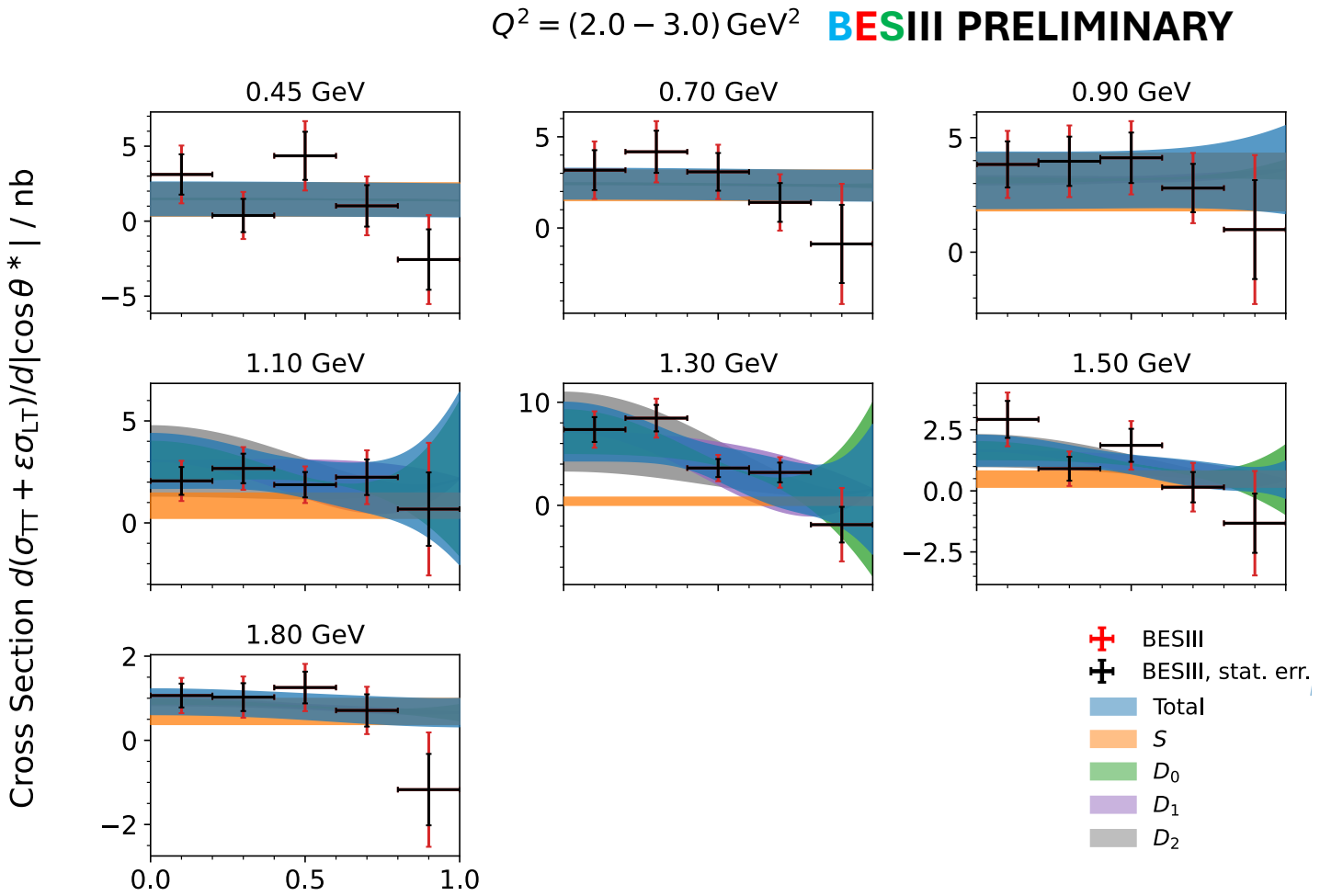


Fits to Single Tagged Data



Fits to Single Tagged Data