



JOHANNES GUTENBERG
UNIVERSITÄT MAINZ



THE LOW-ENERGY FRONTIER
OF THE STANDARD MODEL



Cluster of Excellence
PRISMA+

Transition Form Factor Measurements at **BESIII**

June 3, 2019 | Christoph Florian Redmer
for the BESIII Collaboration

Photon2019 – International Conference on the Structure and the Interactions of the Photon

JG|U Anomalous Magnetic Moment of the μ

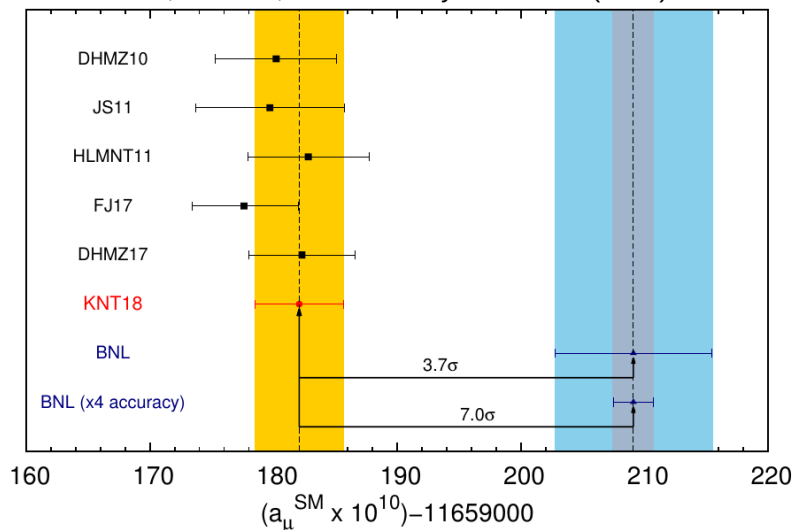
Muon anomaly: $a_\mu = \frac{g_\mu - 2}{2}$

- Known to 0.5 ppm in theory and experiment

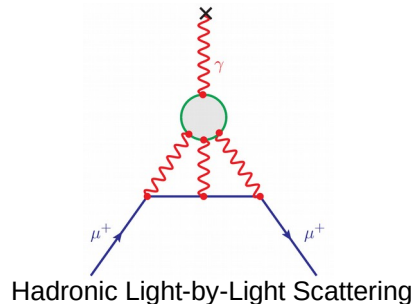
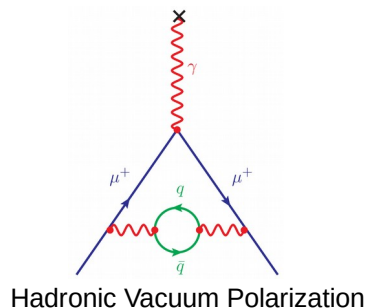
Standard Model (SM)	$(11659182.04 \pm 3.65) \cdot 10^{-10}$	Phys. Rev D97 (2018) 114025
Experiment (BNL)	$(11659208.9 \pm 6.3) \cdot 10^{-10}$	Phys. Rev. D73 (2006) 072003

- Discrepancy between SM prediction and measurement!
- New measurements at FermiLab and J-PARC
- Improvement of SM prediction necessary

Keshavarzi, Nomura, Teubner Phys.Rev. D79 (2018) 114025



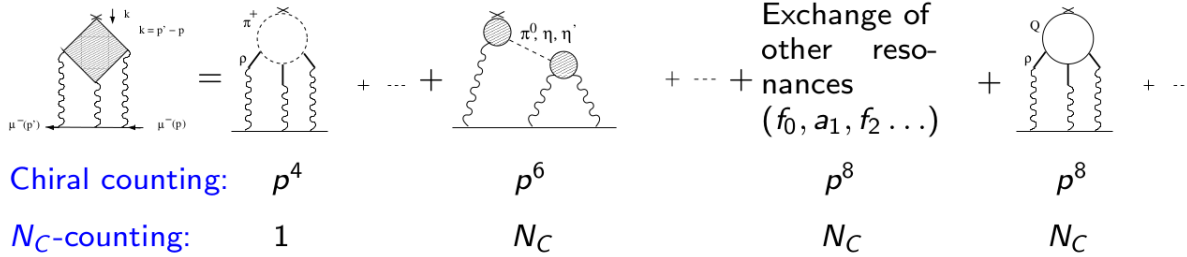
Uncertainty of SM prediction completely limited by hadronic contributions!



Use input from experiments to improve SM prediction!

JGU Relevant Processes and Energies

Counting scheme for contributions to a_μ^{HLbL}



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

Dominating contributions:

- PS meson exchange
- Pion loops

3D integral representation for PS-pole contribution:

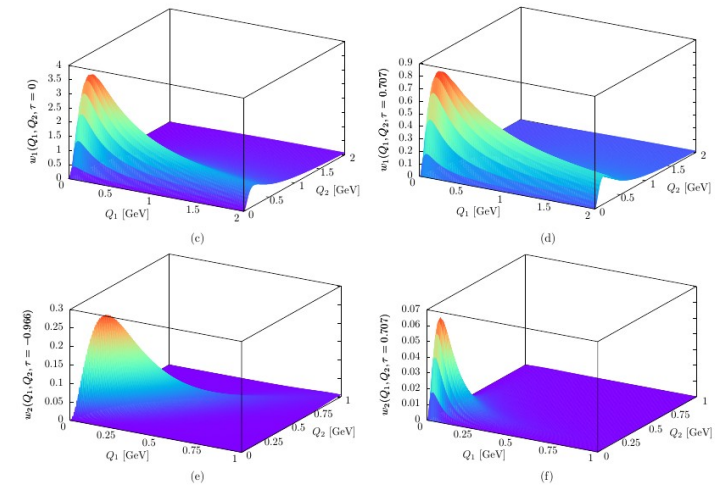
$$a_\mu^{\text{HLbL}; \pi^{0(1)}} = \int_0^\infty dQ_1 \int_0^\infty dQ_2 \int_{-1}^1 d\tau w_1(Q_1, Q_2, \tau) \mathcal{F}_{\pi^0 \gamma^* \gamma^*}(-Q_1^2, -(Q_1 + Q_2)^2) \mathcal{F}_{\pi^0 \gamma^* \gamma^*}(-Q_2^2, 0)$$

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

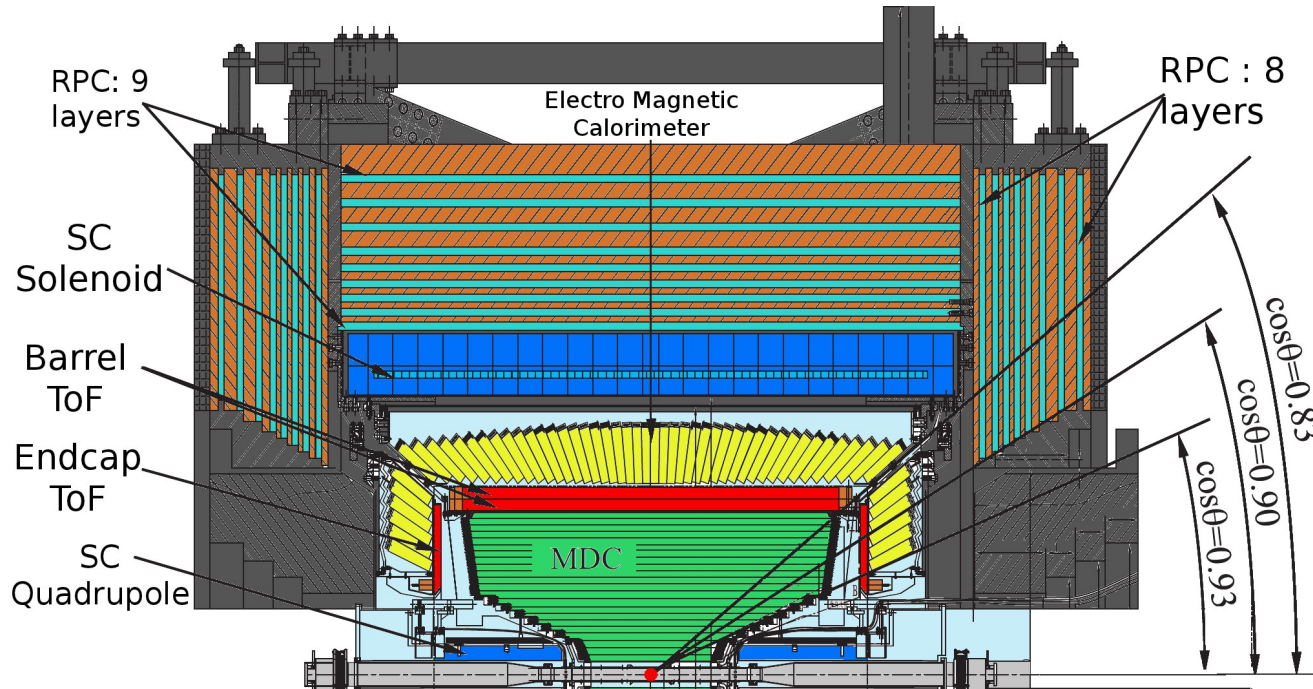
Universal weight functions w_1, w_2 Form factor dependence F

Relevant momentum region: 0.25 – 1.25 GeV

(Nyffeler, Phys.Rev.D94,053006, 2016)



NIM A614 (2010) 345



Muon Chambers

- 8 – 9 layers of RPC
- $p > 400$ MeV/c
- $\delta R\Phi = 1.4 \sim 1.7$ cm

Superconducting Magnet

- 1 T magnetic field

EM Calorimeter (EMC)

- 6240 CsI(Tl) crystals
- $\sigma(E)/E = 2.5\%$
- $\sigma_{z,\phi}(E) = 0.5 - 0.7$ cm

Time-of-flight system (TOF)

- $\sigma(t) = 90$ ps (barrel)
- $\sigma(t) = 110$ ps (endcap)

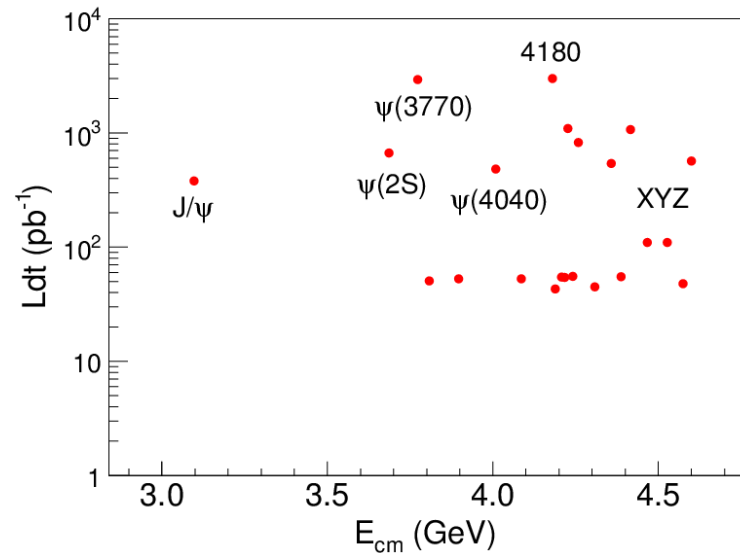
Drift Chamber (MDC)

- $\sigma(p)/p = 0.5\%$
- $\sigma_{dE/dx} = 6.0\%$



- Data taking for
 - Charmonium spectroscopy
 - Charm physics
 - Light hadrons
 - τ and R-scan

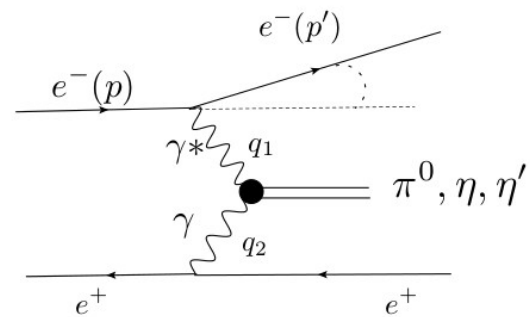
- Operated at BEPCII collider
 - $2.0 \leq \sqrt{s}$ [GeV] ≤ 4.6
 - Design luminosity achieved
 - $\mathcal{L} = 1.0 \times 10^{33} \text{cm}^{-2} \text{s}^{-1}$ at $\psi(3770)$



JGU Two-photon Physics at BESIII

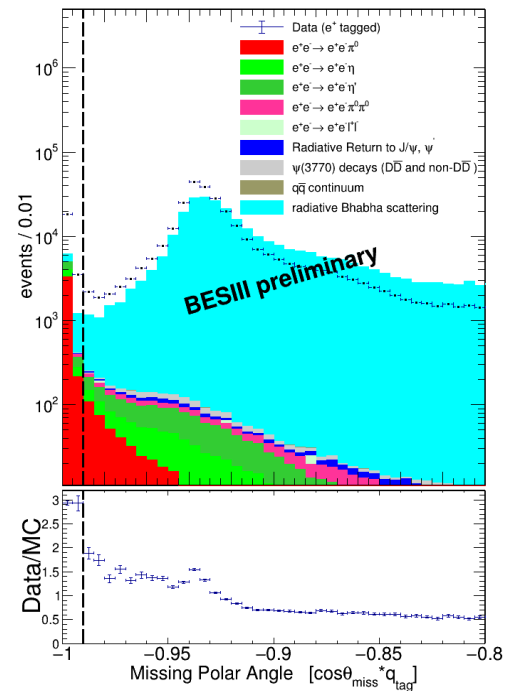


- Determine transition form factors (TFF) as input for HLbL calculations
- Cross section of $\gamma\gamma$ processes proportional to square of TFF
- Single-tagged measurements to study momentum dependence of TFFs



- 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
 - $F(Q_1^2, Q_2^2) \rightarrow F(Q_1^2, 0)$

Reject events with $q_{\text{tag}} \cdot \cos(\theta_{\text{miss}}) > -0.99$
 q_{tag} : Charge of tagged lepton in units of [e]



JGU Space-like π^0 Transition Form Factor



- Based on 2.9 fb^{-1} at 3.773 GeV

- Select:

- Exactly one lepton
- At least two photons

- Apply:

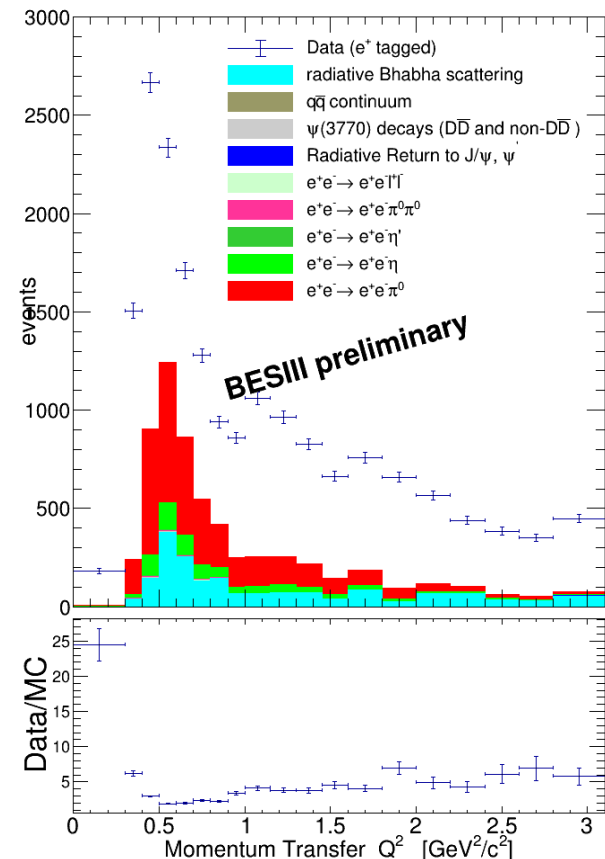
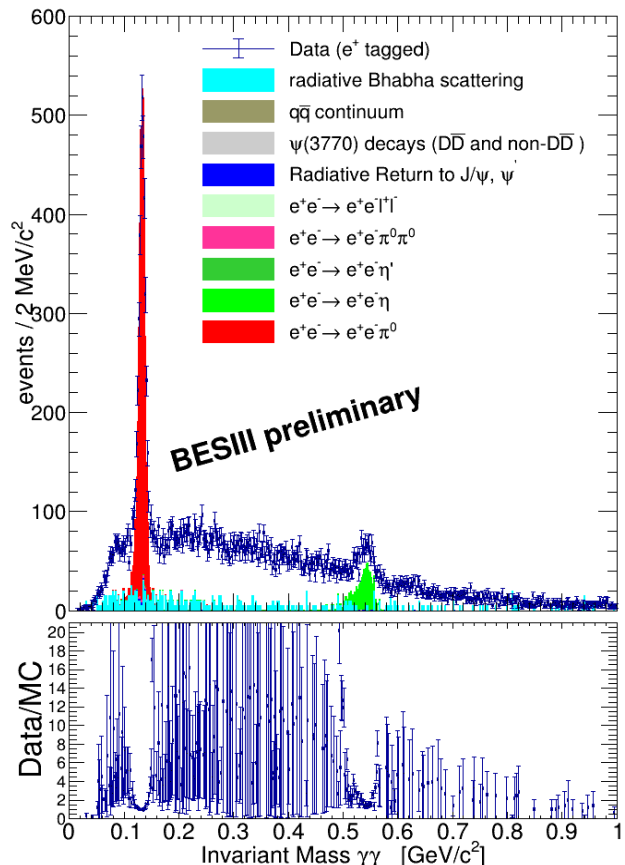
- Single-tag condition
- Helicity angle of photons

- $R_\gamma = \frac{\sqrt{s} - E_{e^\pm\pi^0}^{\text{CMS}} - p_{e^\pm\pi^0}^{\text{CMS}}}{\sqrt{s}} > 0.05$

- Clear signals of π^0 and η

- Incomplete MC description
 - Data-driven background subtraction

- Divide out point-like cross section using MC distributions



JGU Space-like π^0 Transition Form Factor

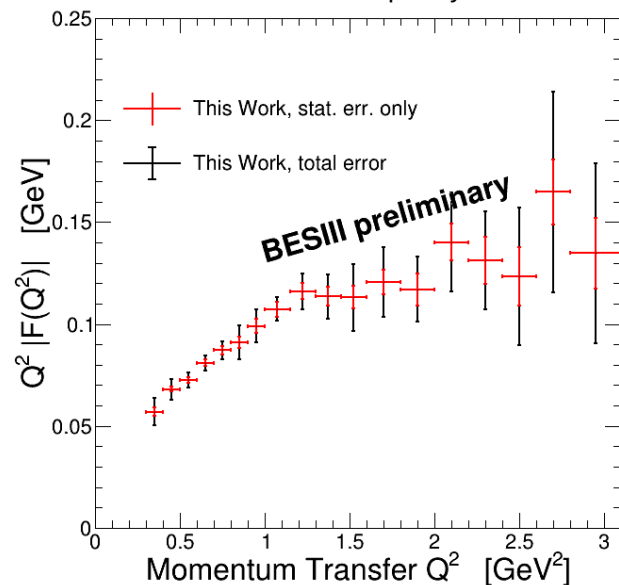


Systematic Uncertainties of $|F(Q^2)|$

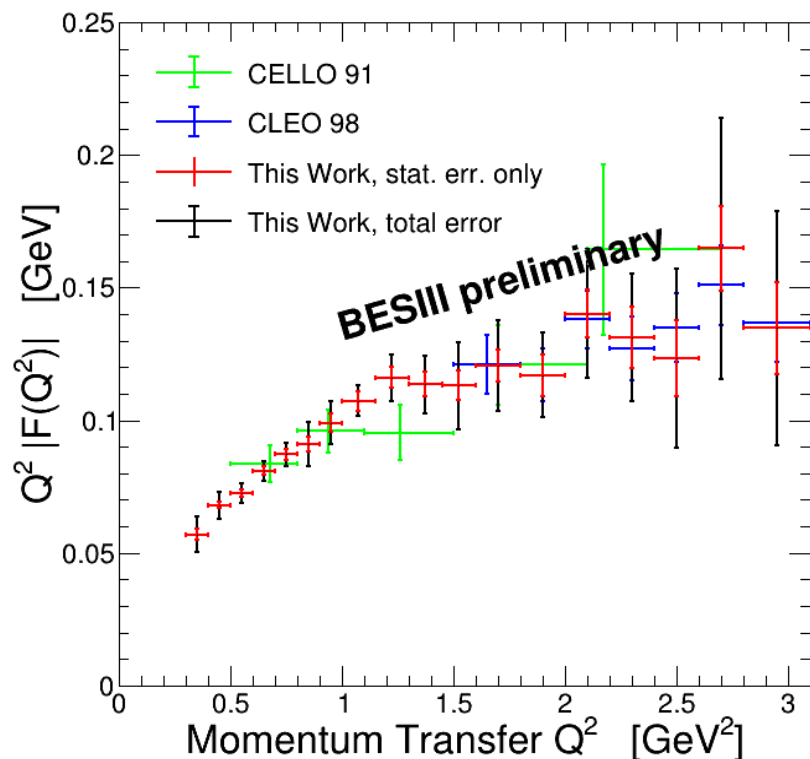
Error propagation: $\Delta|F(Q^2)|_i = \frac{1}{2} \frac{1}{\sqrt{(|F(Q^2)|^2)_i}} \Delta(|F(Q^2)|^2)_i$

	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%
	$\cos \theta_H < 0.8$	0.2% – 4.5%
	$ \Delta\phi_{\gamma\gamma} < \frac{\pi}{2}$	negligible
	$ \Delta\theta_{\gamma\gamma} - 0.01q_{\text{tag}} > 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



JGU Space-like π^0 Transition Form Factor



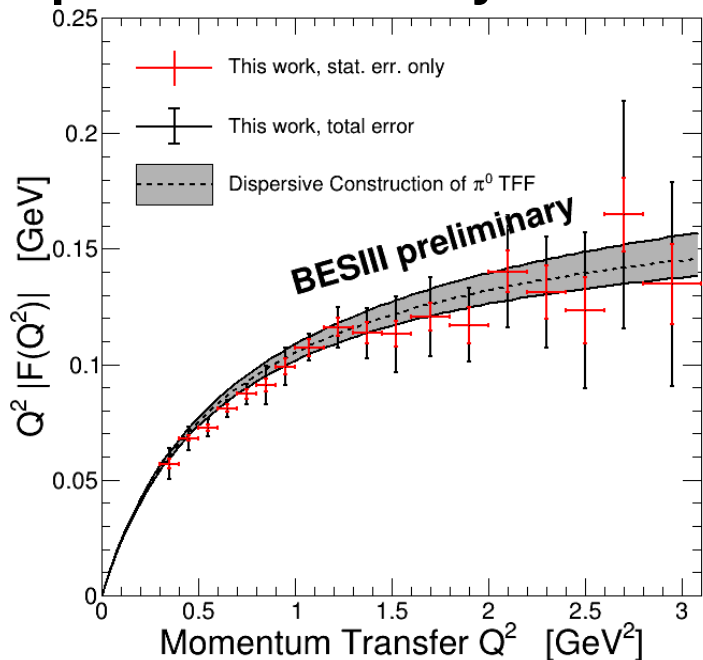
Comparison to previous measurements:

- First measurement below 0.5 GeV^2
- Unprecedented accuracy below $Q^2 = 1.5 \text{ GeV}^2$
- Competitive accuracy up to 3.1 GeV^2

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

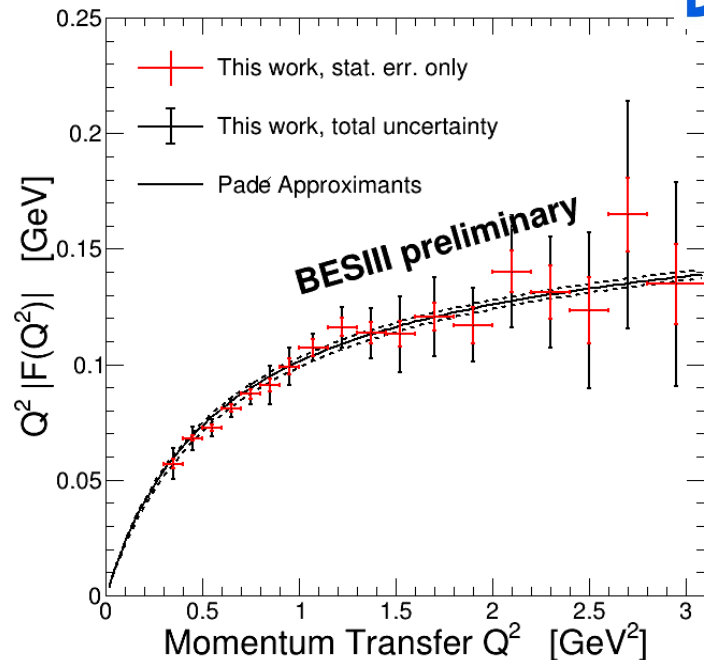
JG|U Space-like π^0 Transition Form Factor

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

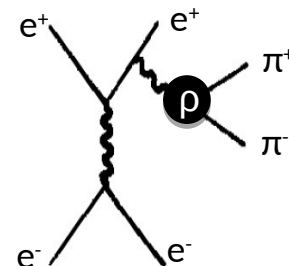
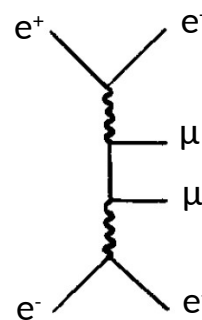
JGU Space-like $\pi^+\pi^-$ Transition Form Factor

Motivation:

- Essential for dispersive approaches to HbL contribution to a_μ
- Previous measurements mostly with quasi-real photons
- Data scarce at small invariant masses and momentum transfer

At BESIII:

- Single-Tag measurement
- Event selection analogous to single pseudoscalar analysis
- Multivariate methods to suppress muon background
- Subtraction of ρ contribution in $e^+e^- \rightarrow e^+e^-\pi^+\pi^-$
 - Fit peak in data using shape from theory



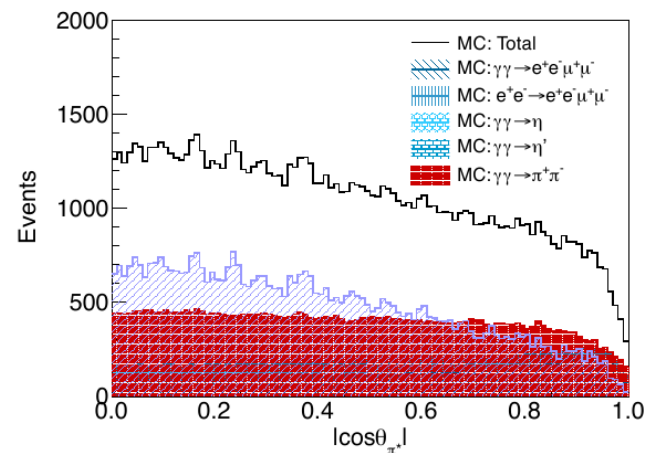
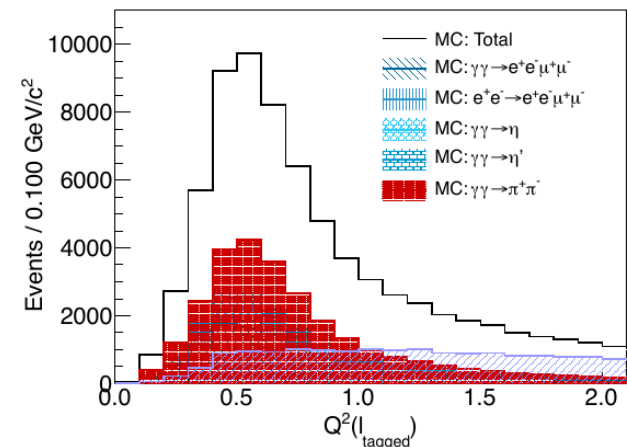
JGU Space-like $\pi^+\pi^-$ Transition Form Factor

Study $\pi^+\pi^-$ invariant mass in bins of Q^2 and $\cos\theta^*$

First single-tag measurement of $\pi^+\pi^-$!

Access to:

- Small momentum transfers $0.2 < Q^2 [\text{GeV}^2] < 2.0$
- Small invariant masses $m_{\pi^+\pi^-} < M [\text{GeV}] < 2.0$
- Full coverage of $\cos\theta^*$



Single-tagged measurements

- Complete TFF studies of single mesons (η, η')
- Extend two-meson studies to neutral channels ($\pi^0\pi^0, \pi^0\eta, \eta\eta$)
- Investigate higher multiplicity final states ($3\pi, 4\pi, \dots$)
 - Axial and tensor contributions to a_μ

Double-tagged measurements

- Complementary to BaBar measurement of η' TFF
- Cover all single pseudoscalar states for $Q^2 < 2 \text{ GeV}^2$
- Feasibility studies successful
- Development and installation of dedicated taggers

BESIII established a competitive two-photon physics program

- Motivated by the data-driven calculations for a_{μ}^{HLbL}
- Single-tag measurements
 - π^0 , η , and η' transition form factors with unprecedented accuracy ($Q^2 < 1.5 \text{ GeV}^2$)
 - $\pi^+\pi^-$, $\pi^0\pi^0$, $\pi^0\eta$, $\eta\eta$
 - First measurement at low Q^2
 - Covers masses from threshold and the full helicity angle
 - Higher multiplicities to study axial and tensor mesons
- Double-tagged measurement $\gamma^*\gamma^* \rightarrow \pi^0$ started
- Untagged measurements for spectroscopy purposes