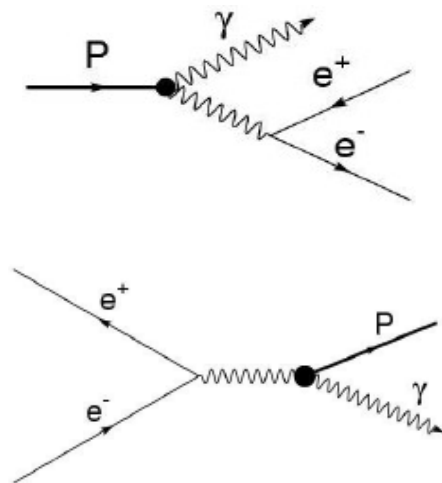# Measurement of meson transition form factors at BESIII

June 1, 2018 | Christoph Florian Redmer
for the BESIII collaboration

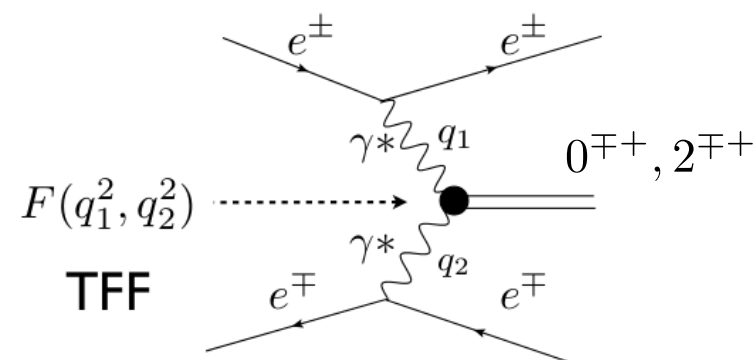CIPANP2018 – 13th Conference on the Intersections of Particle and Nuclear Physics

Coupling of light and matter

Time – like Transition Form Factors:
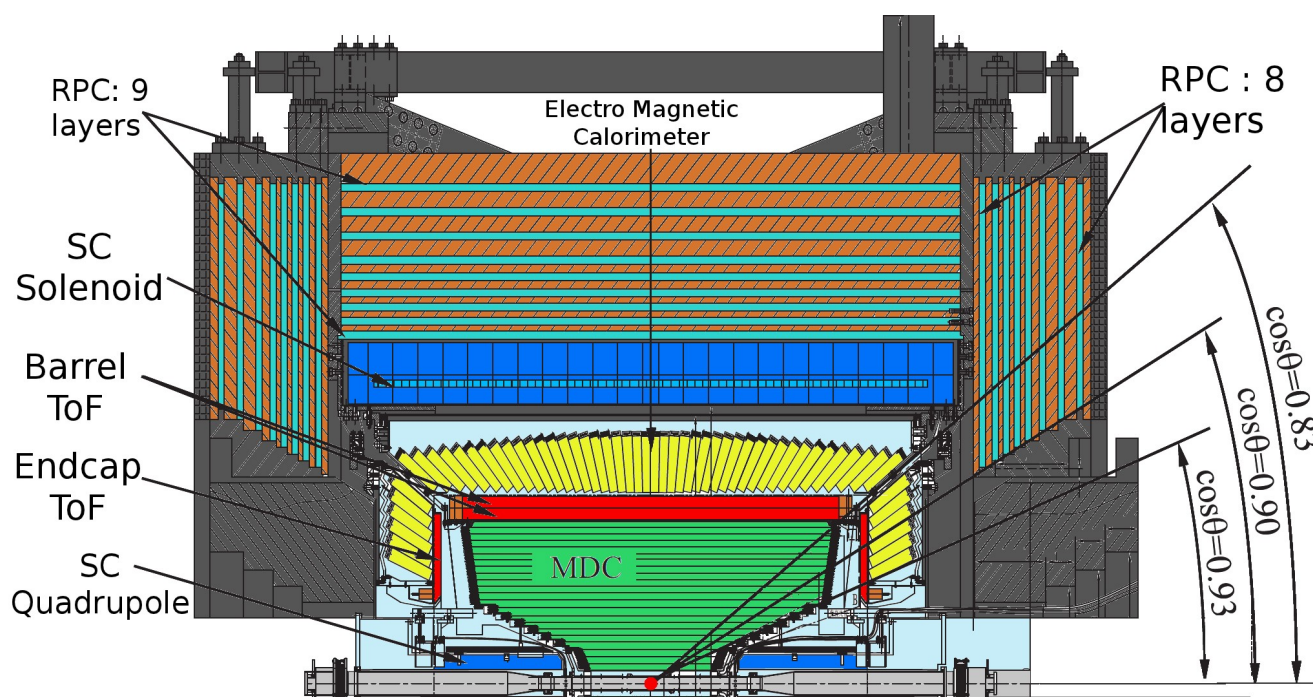
- Dalitz decays
  - $0 < q^2 < M^2$

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

Space – like Transition Form Factors:

- Two-photon production of mesons
  - $F(Q_1^2, Q_2^2), \quad Q^2 = -q^2$

BESIII Detector

NIM A614 (2010) 345

Muon Chambers
- 8 – 9 layers of RPC
- p>400 MeV/c
- $\delta R\Phi$ = 1.4 ~ 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)
- $\sigma(t)$ = 90ps   (barrel)
- $\sigma(t)$ = 110ps   (endcap)

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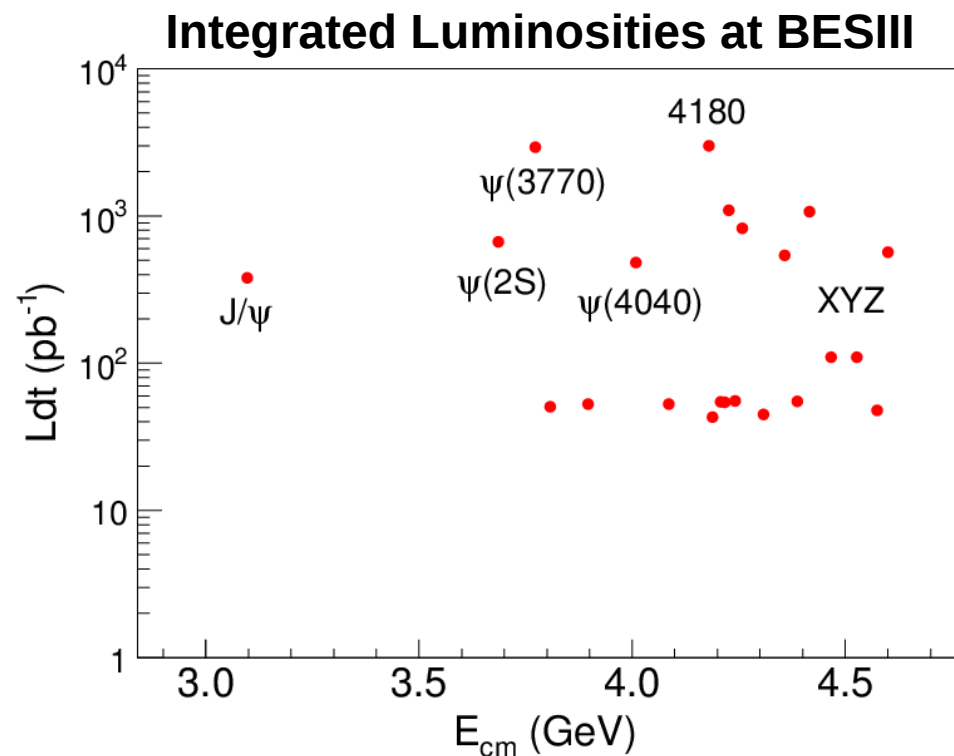- $\sigma_{dE/dx}$ = 6.0%

BESIII Data

Operated at BEPCII collider

- $2.0 \leq \sqrt{s}\,[\text{GeV}] \leq 4.6$

- Design luminosity achieved

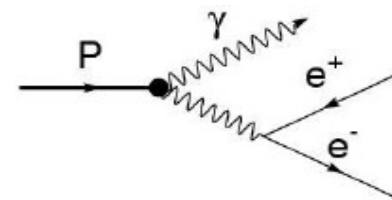 - $\mathcal{L} = 1.0 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}$ at $\psi(3770)$

Large data sets for
- Charmonium spectroscopy
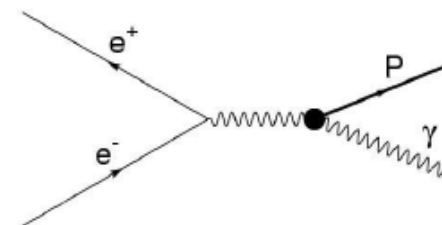- Charm physics
- Light hadrons
- τ and R-scan

Integrated Luminosities at BESIII

Dalitz Decays

$J/\psi \to \mathcal{P}e^+e^-$	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)

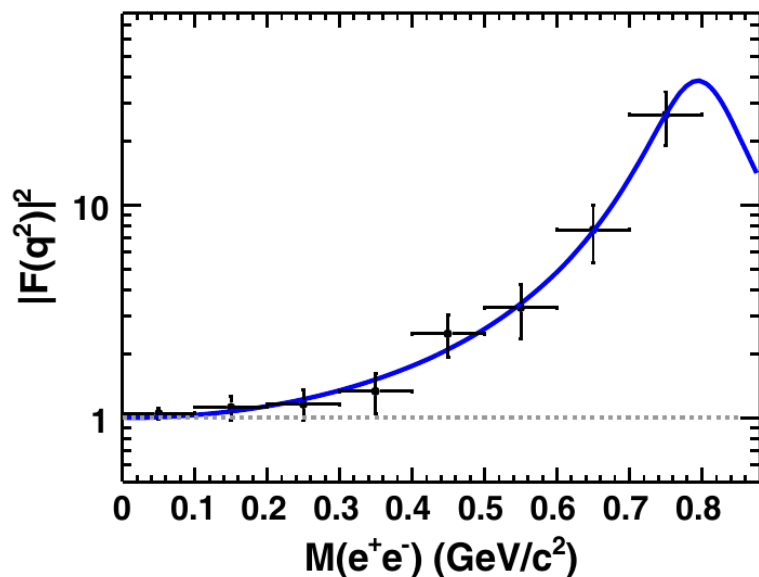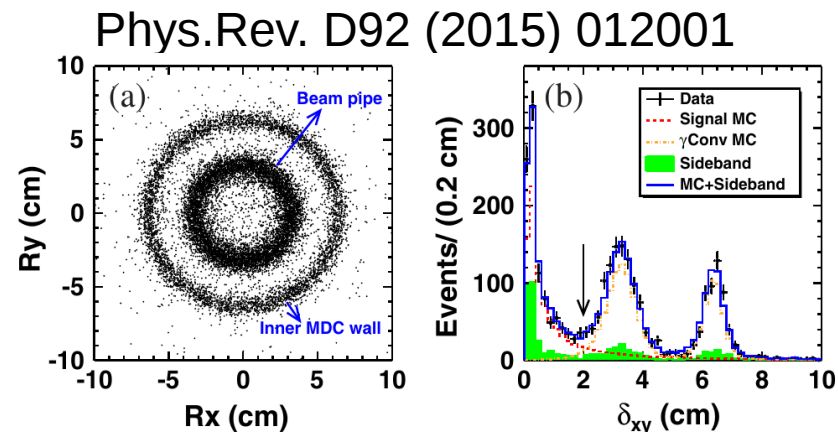## Radiative Decays / Production

$\psi' \to \mathcal{P}\gamma$	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)

$\eta' \rightarrow e^+ e^- \gamma$

- Reconstructed from $J/\psi \rightarrow \gamma\eta'$

- Using $1.3 \cdot 10^9 \, J/\psi$ decays

- 864 ± 36 Dalitz events detected
  - **First measurement!**

- Main Background: Photon conversion

Phys.Rev. D92 (2015) 012001

$$|F(q^2)|^2_{\eta'} = \frac{\Lambda^2(\Lambda^2 - \gamma^2)}{(\Lambda^2 - q^2)^2 - \Lambda^2\gamma^2}$$

$$\Lambda = (0.79 \pm 0.04_{\text{stat}} \pm 0.02_{\text{syst}})\,\text{GeV}$$
$$\gamma = (0.13 \pm 0.06_{\text{stat}} \pm 0.03_{\text{syst}})\,\text{GeV}$$
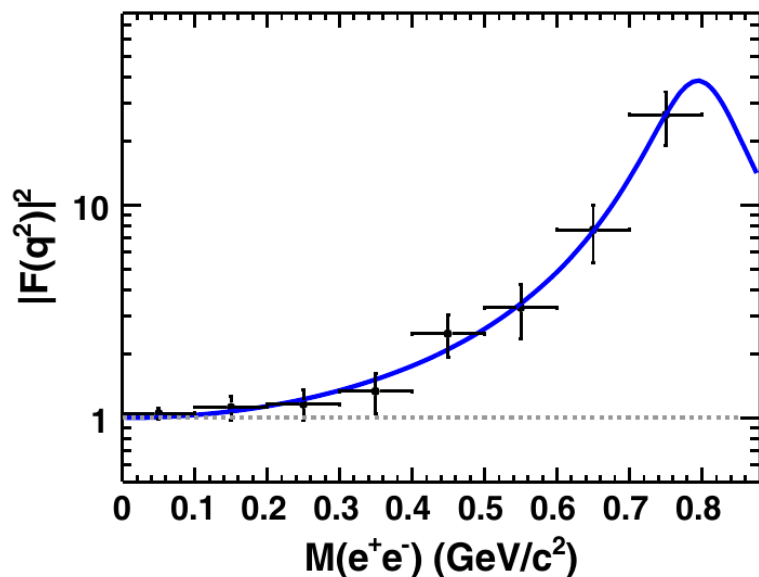
- Precision on the level of space-like extrapolation

- Improvement over muon Dalitz decays

$\eta' \to e^+ e^- \gamma$

- Reconstructed from $J/\psi \to \gamma\eta'$

- Using $1.3 \cdot 10^9 \, J/\psi$ decays

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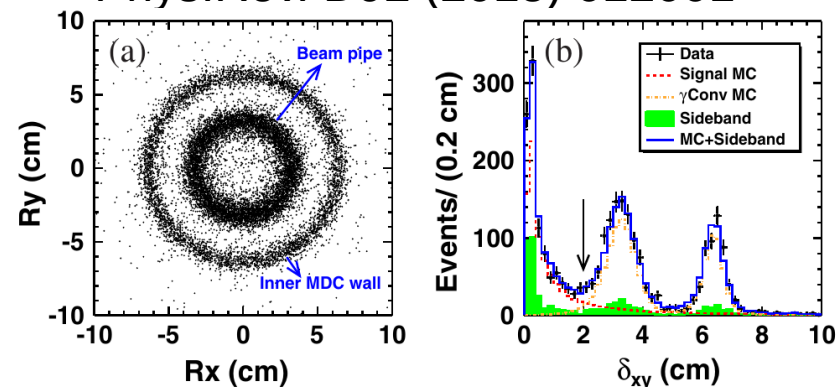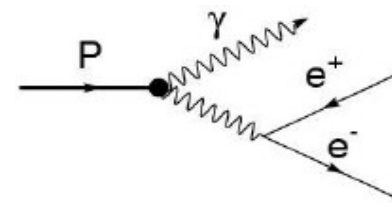$$\gamma = (0.13 \pm 0.06_{\text{stat}} \pm 0.03_{\text{syst}})\text{GeV}$$

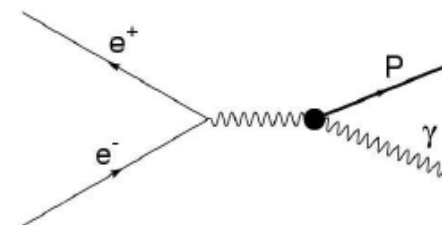New measurements expected from:

- A2 (Mainz)

- CLAS12 (JLab)

Some recent results

Dalitz Decays

$$J/\psi \to \mathcal{P}e^+e^-$$
$$\eta' \to \gamma e^+e^-$$
$$\eta' \to \omega e^+e^-$$

Phys. Rev. D89, 092008 (2014)

Phys. Rev. D92, 012001 (2015)

Phys. Rev. D92, 051101(R) (2015)

Radiative Decays / Production

$$\psi' \to \mathcal{P}\gamma$$
$$\psi' \to \gamma\eta_c$$
$$\psi(3770) \to \gamma\eta_c$$
$$e^+e^- \to \gamma\eta_c$$
$$\psi' \to \mathcal{P}\gamma$$

Phys. Rev. Lett. 105, 261801 (2010)

Phys. Rev. Lett. 109, 042003 (2012)

Phys. Rev. D 89, 112005 (2014)
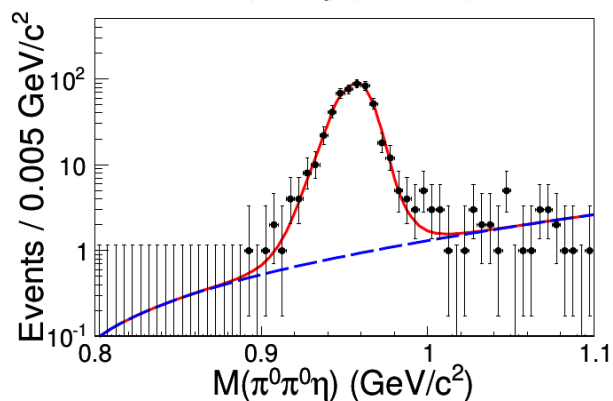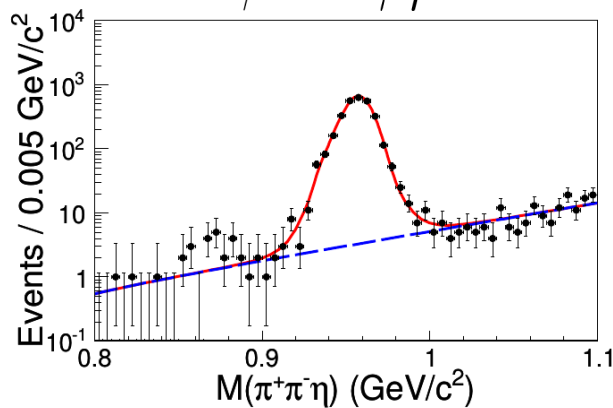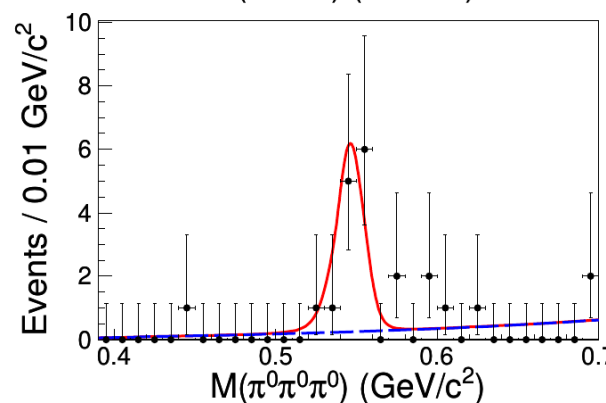
Phys. Rev. D 96, 051101 (2017)

Phys. Rev. D 96, 052003 (2017)

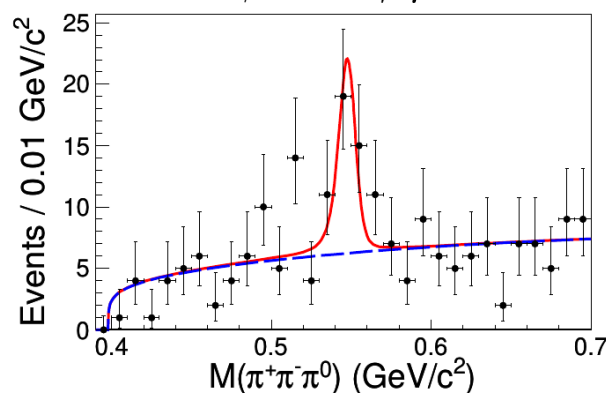# $\psi' \to \gamma\pi^0, \eta, \eta'$

- radiative transitions of vector charmonium to pseudoscalars

- Using $448 \cdot 10^6 \psi'$ decays

- Background well under control
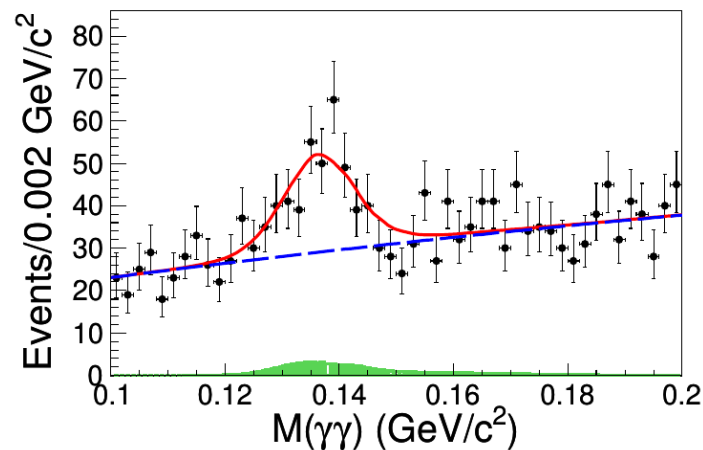 - Photon conversion rejected by counting hits in drift chamber

$\psi' \to \gamma\eta'$

$\psi' \to \gamma\eta$

$\psi' \to \gamma\pi^0$

Phys. Rev. D96 (2017) 052003

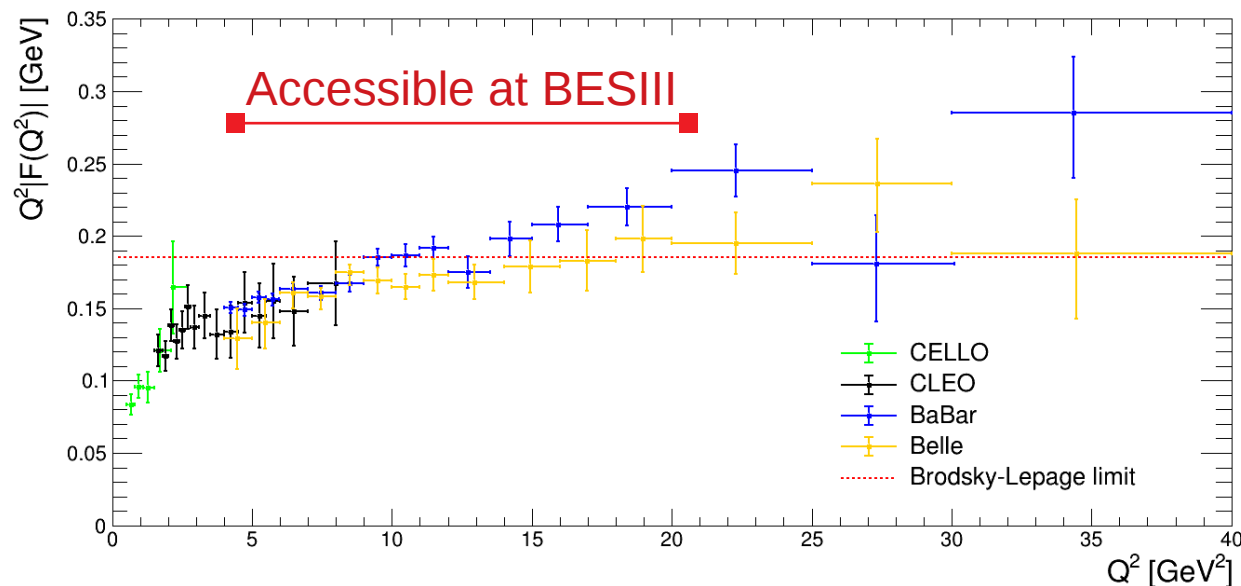| Decay mode	Significance	$N_{\text{sig}}^{\text{cor}}$	$\mathcal{B}(\psi(3686) \rightarrow \gamma\eta'/\eta/\pi^0)$
$\psi(3686) \rightarrow \gamma\eta'$	$> 10\sigma$	56053.5 ± 980.8	$(125.1 \pm 2.2 \pm 6.2) \times 10^{-6}$
$\psi(3686) \rightarrow \gamma\eta$	7.3σ	382.5 ± 78.9	$(0.85 \pm 0.18 \pm 0.04) \times 10^{-6}$
$\psi(3686) \rightarrow \gamma\pi^0$	6.7σ	423.4 ± 71.4	$(0.95 \pm 0.16 \pm 0.05) \times 10^{-6}$

Phys. Rev. D96 (2017) 052003

Data analysis is being extended to continuum regions: $e^+e^- \rightarrow \gamma\mathcal{P}$

- Study time-like transition form factor for $4 \leq q^2[\text{GeV}^2] \leq 21.16$

  - BaBar-Belle puzzle

Two-Photon Collisions

- Exchange of two photons in e^+e^- collisions

- Pseudoscalar, axial, and tensor states accessible

- $M_x \ll \sqrt{s}$

- $\sigma \propto \alpha^2 \ln^2 E$

- $\sigma \propto F^2(Q_1^2, Q_2^2)$, with $Q_i^2 = -q_i^2$

- Forward peaked kinematic

Two-Photon Collisions

- Exchange of two photons in e⁺e⁻ collisions

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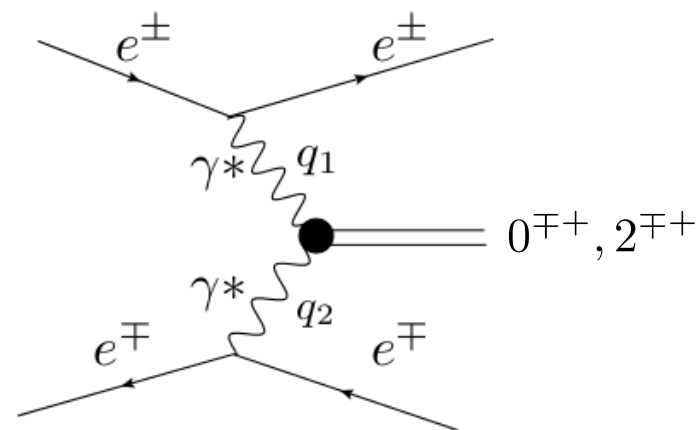
- $\sigma \propto F^2(Q_1^2, Q_2^2)$, with $Q_i^2 = -q_i^2$
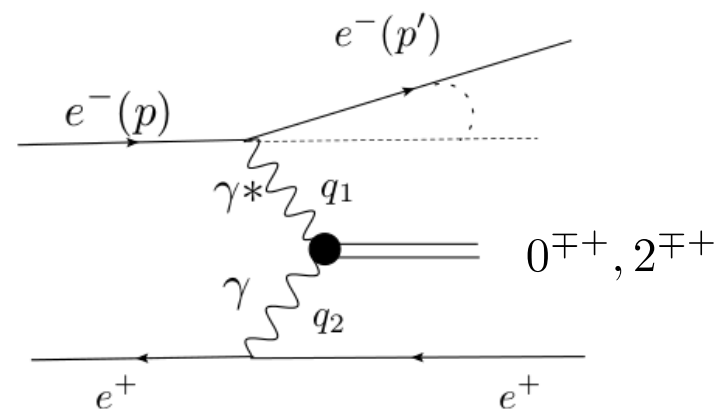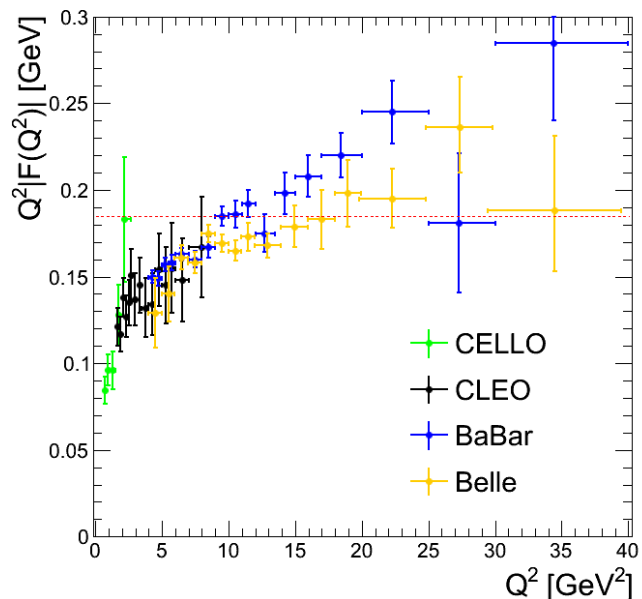
- Forward peaked kinematic
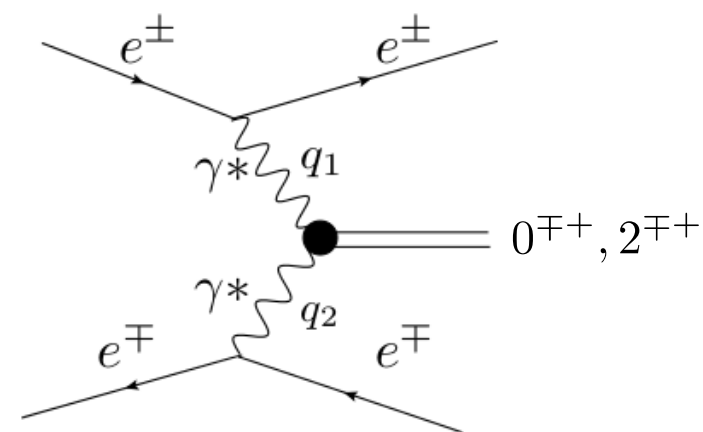
- Single-tagged measurements
  - Measure produced meson and only one scattered lepton
  - Missing lepton from momentum conservation
  - Require small scattering angle

$$F(Q_1^2, Q_2^2) \to F(Q_1^2, 0) \to F(Q^2)$$

Existing Data
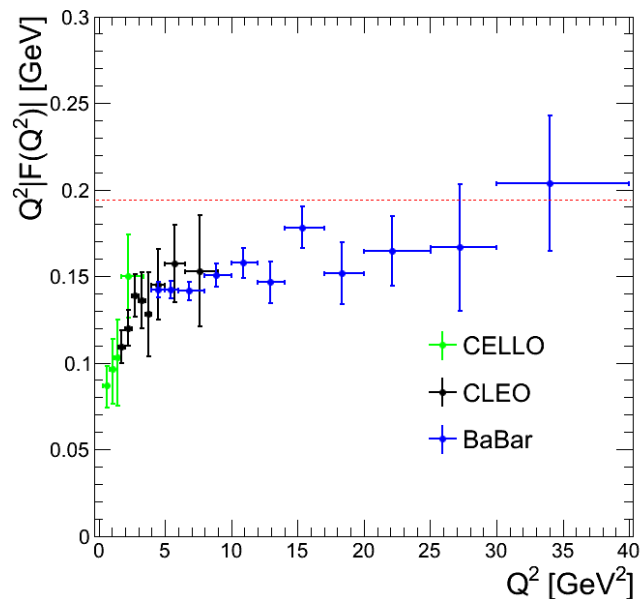
$e^+e^- \to e^+e^- \pi^0$ $e^+e^- \to e^+e^- \eta$ $e^+e^- \to e^+e^- \eta'$
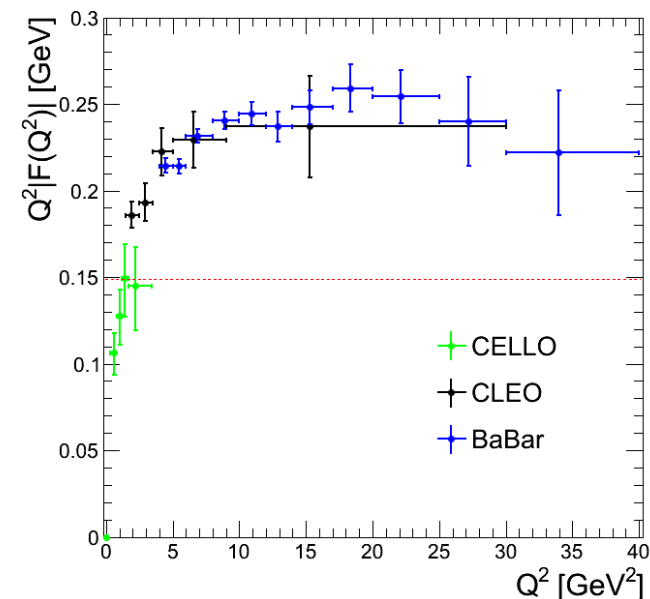
- Recent results from B-factories cover only large Q^2 ($5 < Q^2$ [GeV²] < 40)

  - Discrepancy for π^0 between BaBar and Belle

- Data scarce at lowest Q^2

  - Region of relevance for (g-2)μ

CELLO: Z.Phys.C49 (1991) 401
CLEO: Phys.Rev.D57 (1998) 33
BaBar: Phys.Rev.D80 (2009) 052002
        Phys.Rev.D84 (2011) 052001
Belle: Phys.Rev.D86 (2012) 092007

Anomalous magnetic moment of μ

$$a_\mu = \frac{g_\mu - 2}{2} = a_\mu^{QED} + a_\mu^{weak} + a_\mu^{hadr}$$

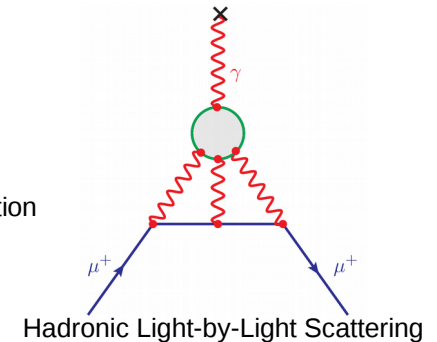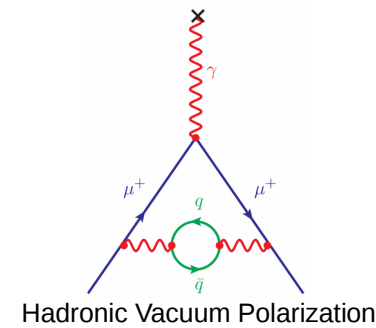| Contribution	Result in 10^{-10} units	
QED(leptons)	11658471.895	± 0.008
Weak	15.4	± 0.2
Hadronic	694.1	± 5.8
Total (SM)	11659181.4	± 5.8
BNL (E821)	11659208.9	± 6.3
Difference	27.5	± 8.6

Prediction completely limited by hadronic contributions!

Hadronic Vacuum Polarization

Hadronic Light-by-Light Scattering

Hadronic Light-by-Light scattering contribution a_μ^{hLBL}

- **Hadronic models**
  - Glasgow Consensus, arXiv:0901.0306
  - Jegerlehner/Nyffeler, Phys.Rept.477,1

- **Data-driven approaches**
  - Based on dispersion relations
  - Reduce model dependence
  - Collangelo, Hoferichter, et al. (Bern)
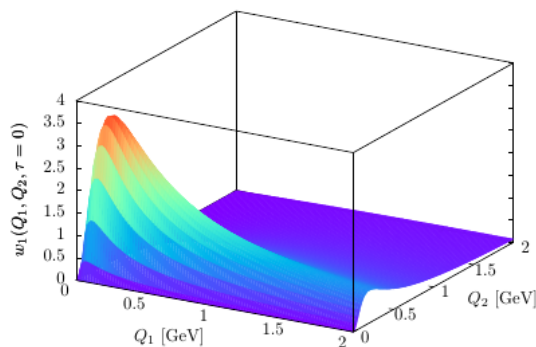 - Vanderhaeghen, Pauk, et al. (Mainz)

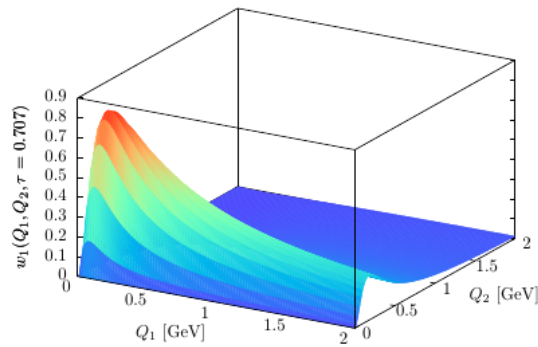**TFF as experimental input to improve theory!**

Relevant Energy Range

3D integral representation for PS-pole contribution: (Nyffeler, PRD94,053006, 2016)

$$a_\mu^{\text{HLbL};\pi^{0}(1)} = \int_0^\infty dQ_1 \int_0^\infty dQ_2 \int_{-1}^1 d\tau \, w_1(Q_1, Q_2, \tau) \mathcal{F}_{\pi^0\gamma^*\gamma^*}(-Q_1^2, -(Q_1+Q_2)^2)\mathcal{F}_{\pi^0\gamma^*\gamma^*}(-Q_2^2, 0)$$
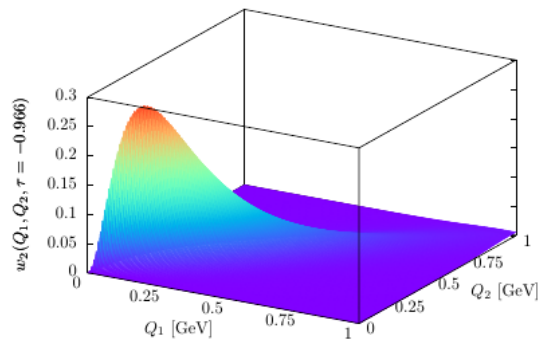
$$a_\mu^{\text{HLbL};\pi^{0}(2)} = \int_0^\infty dQ_1 \int_0^\infty dQ_2 \int_{-1}^1 d\tau \, w_2(Q_1, Q_2, \tau) \mathcal{F}_{\pi^0\gamma^*\gamma^*}(-Q_1^2, -Q_2^2)\mathcal{F}_{\pi^0\gamma^*\gamma^*}(-(Q_1+Q_2)^2, 0)$$
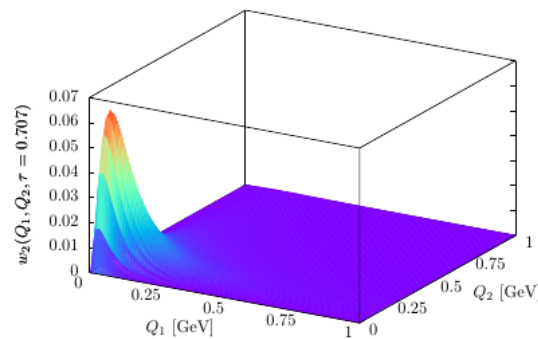

- Universal weight functions w_1, w_2
- Form factor dependence F

Relevant momentum region:

Q = 0.25 – 1.25 GeV/c
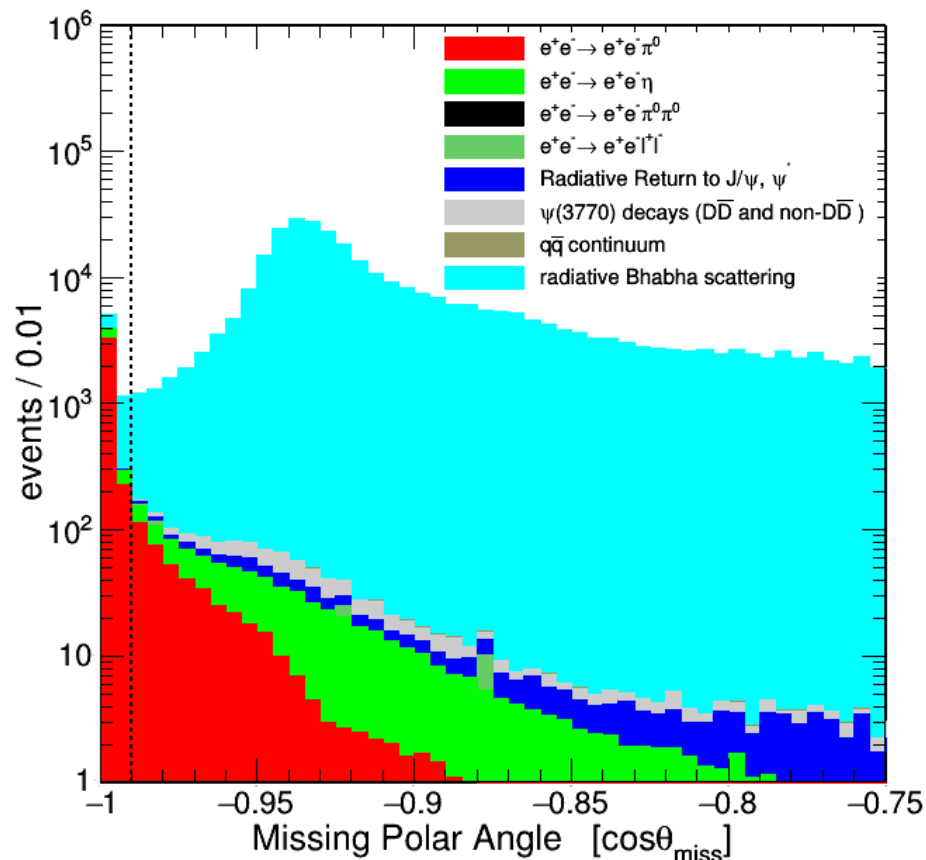
Space-like π^0 Transition Form Factor

Legend:
- $e^+e^- \to e^+e^-\pi^0$
- $e^+e^- \to e^+e^-\eta$
- $e^+e^- \to e^+e^-\pi^0\pi^0$
- $e^+e^- \to e^+e^-l^+l^-$
- Radiative Return to $J/\psi,\ \psi'$
- $\psi(3770)$ decays ($D\bar{D}$ and non-$D\bar{D}$)
- $q\bar{q}$ continuum
- radiative Bhabha scattering

BESIII Monte Carlo, $\Psi(3770)$
L_{int}: 2.93 fb^{-1} , Tagged Lepton: e^+

Event selection:

- Exactly one lepton

- Two to four photons

- Single-tag requirement
  - $\cos\theta_{untagged} < -0.99$

- Dominated by Bhabha scattering

Space-like π^0 Transition Form Factor
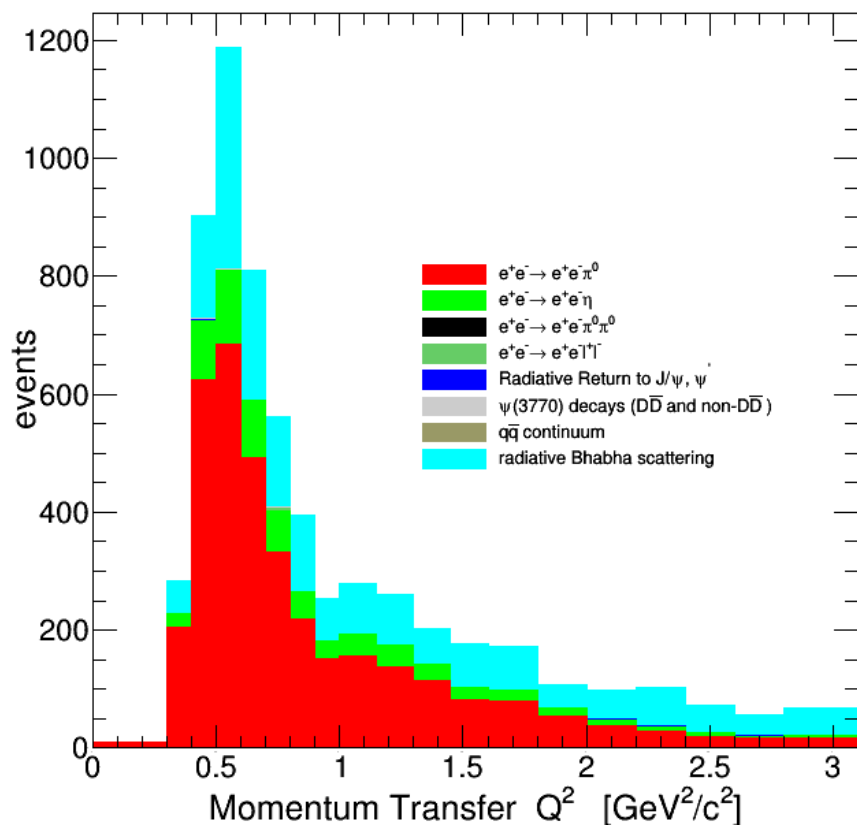

BESIII Monte Carlo, $\Psi(3770)$
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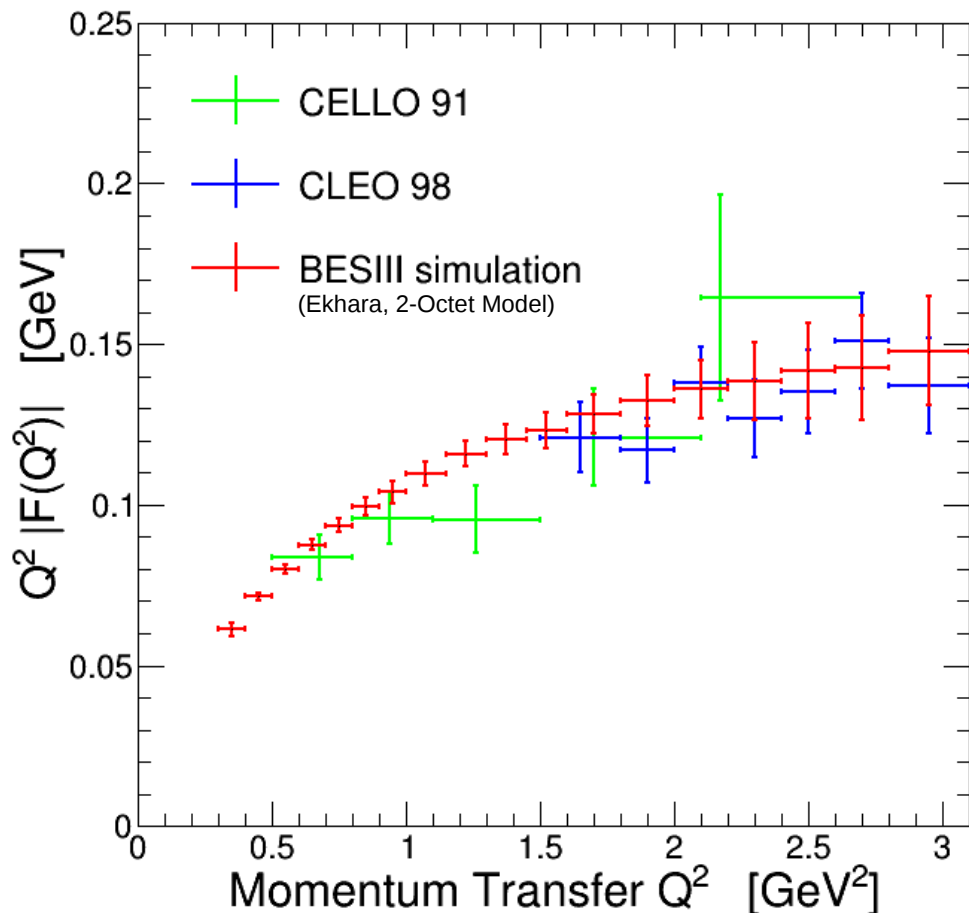 - $\cos\theta_{untagged} < -0.99$

- Dominated by Bhabha scattering

- Bin-wise background subtraction

- Divide out point-like cross section for $|F(Q^2)|^2$

Space-like π^0 Transition Form Factor

- 2.9 fb^{-1} at $\Psi(3770)$ analyzed

- Covering $0.3 \leq Q^2[\text{GeV}^2] \leq 3.1$

- Unprecedented accuracy below 1.5 GeV²

  - Relevant for a_μ^{hLbL}

- Competitive accuracy up to 3.1 GeV²

- Soon to be published

Analogous studies performed for TFFs of η and η'!

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

- Additional motivations:

  - Essential for dispersive frameworks
  - Resonance parameters
  - Pion polarizabilities, pion structure
  - Rescattering effects in low mass region

Collangelo, Hoferichter, Procura, Stoffer
JHEP 1409,091; JHEP1509,074

- Until recently only untagged measurements:
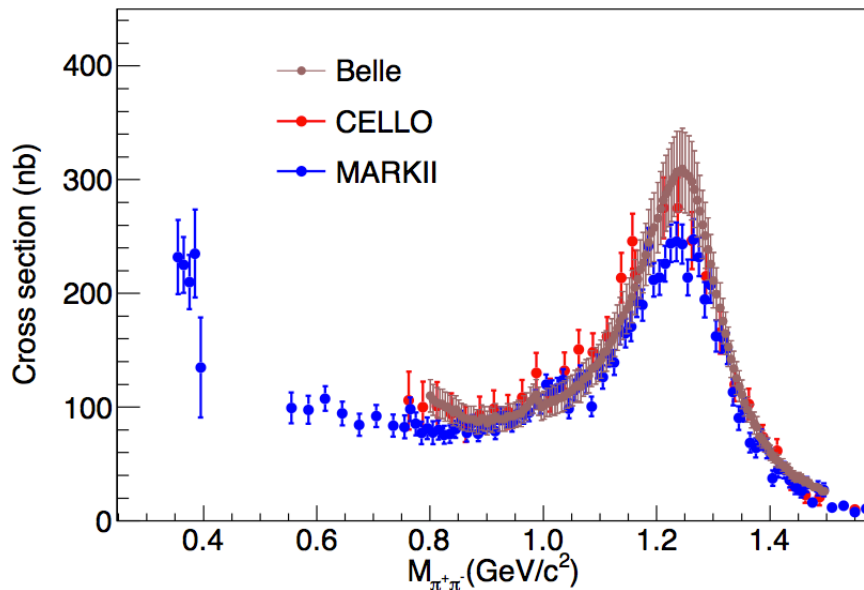
MarkII, Phys. Rev. D42 (1990) 5

CELLO, Z. Phys. C56 (1992) 381

Belle, Phys. Rev D75 (2007) 051101

- First single-tagged result on $\pi^0\pi^0$ by Belle
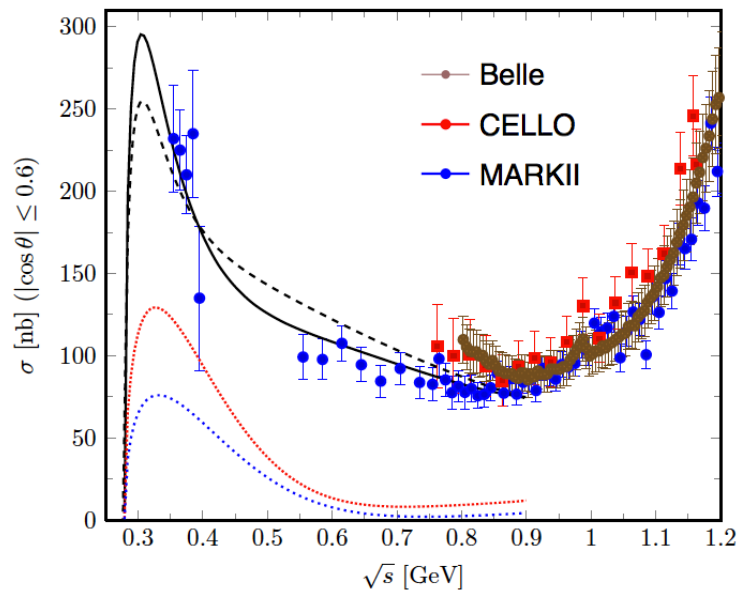
Phys. Rev. D93 (2016) 032003

- **Additional motivations:**

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Collangelo, Hoferichter, Procura, Stoffer
JHEP 1409,091; JHEP1509,074

- **Until recently only untagged measurements:**

Untagged

Single-Tag $\quad \left(Q_1^2 = 0.5\,\mathrm{GeV}^2\right)$

Double-Tag $\quad \left(Q_1^2 = Q_2^2 = 0.5\,\mathrm{GeV}^2\right)$

Calculations by
Assmussen, Masjuan, and Vanderhaeghen

- **First single-tagged result on $\pi^0\pi^0$ by Belle**

Phys. Rev. D93 (2016) 032003

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

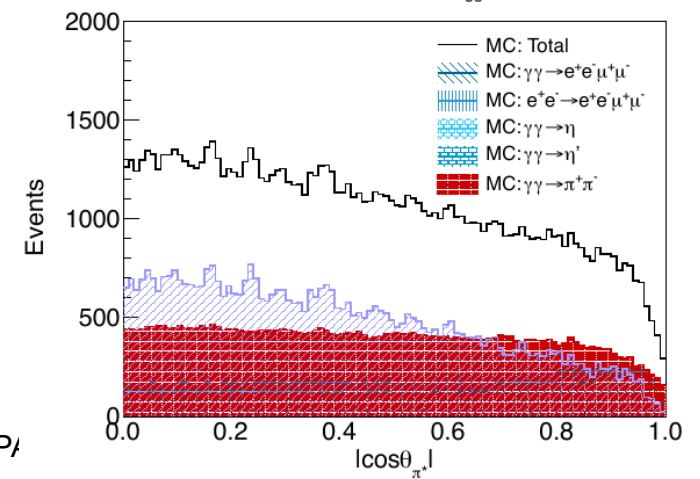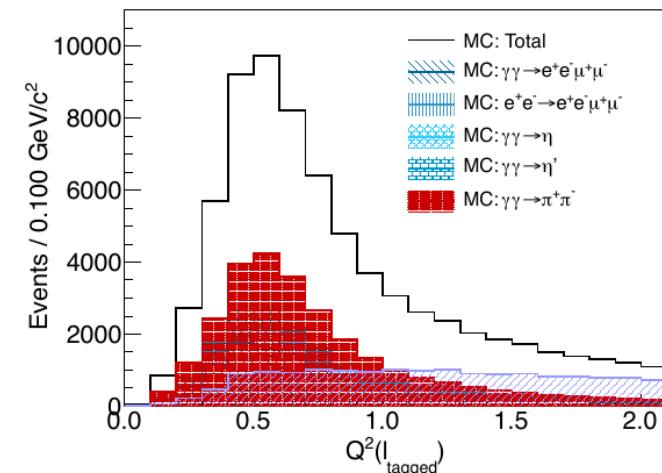## Single-Tag measurement

- Event selection analogous to single pseudoscalar analysis

- Multivariate methods to suppress muon background $e^+e^- \to e^+e^-\mu^+\mu^-$

- Subtraction of ρ contribution in $e^+e^- \to e^+e^-\pi^+\pi^-$
    - Fit peak in data using shape from theory

- 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 $0.2 < Q^2$ [GeV^2] < 2.0
        - low invariant masses $m_{\pi+\pi-} < M$ [GeV] < 2.0
        - full coverage of $\cos\theta*$

- Measurement of $F_{\gamma^*\gamma^*\pi^0}(Q_1^2, Q_2^2)$ never done before!
  - Contains full information
  - model independent input

- BESIII collected > 10 fb^{-1} at 3.77 < √s [GeV] < 4.6
  - Double-tag measurement possible

    - Low statistics expected
    - 1st Step: Test TFF models
      - e.g. VMD vs. LMD+V
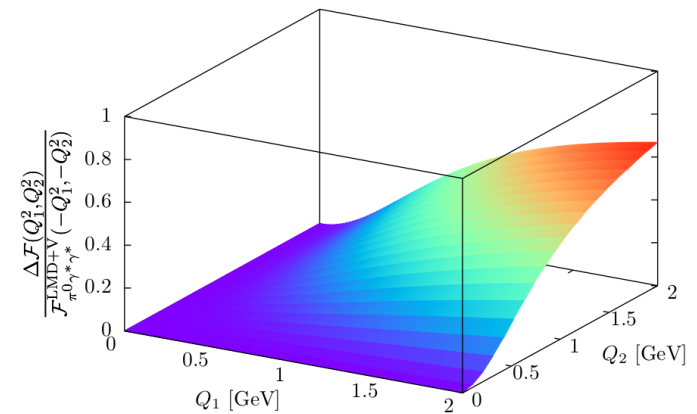
Calculations: A. Nyffeler
Phys.Rev. D94, 2016, 053006

Summary

Transition form factors at BESIII measured in time- and space-like region

- Dalitz decays: Study $\mathcal{P}\gamma$ and $\mathcal{P}V$ transitions

- e^+e^- annihilation into a pseudoscalar and a photon / vector meson

- Two-photon physics program

  - Single-tag measurements

    - π^0, η, and η' transition form factors with unprecedented accuracy ($Q^2 < 1.5$ GeV^2)

    - $\pi^+\pi^-$
      - First measurement at low Q^2
      - Covers masses from threshold and the full helicity angle
      - To be extended to neutral final states

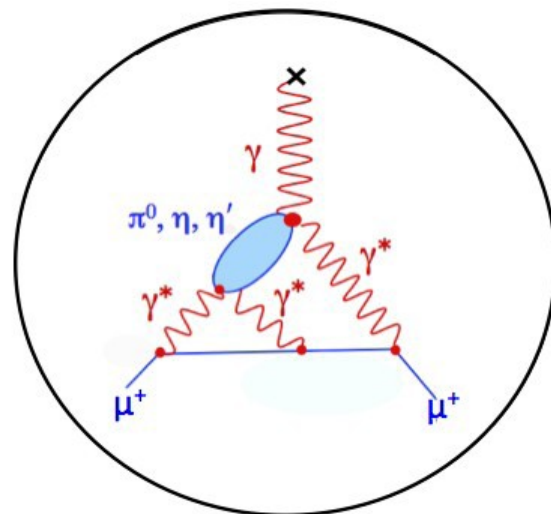 - First double-tagged measurement $\gamma^*\gamma^* \to \pi^0$ started

Backup

Contribution to a_μ

- Current accuracy of a_μ : $\sim 6.3 \times 10^{-10}$

- Contribution of π^0 : $\sim 7 \times 10^{-10}$ Knecht,Nyffeler
  Phys.Rev.D65 (2002) 073034

- Expected accuracy of new experiments at FNAL and J-PARC: $\sim 1.6 \times 10^{-10}$

- Contributions of η and η' relevant!

$$\eta \sim 1.5 \times 10^{-10}$$
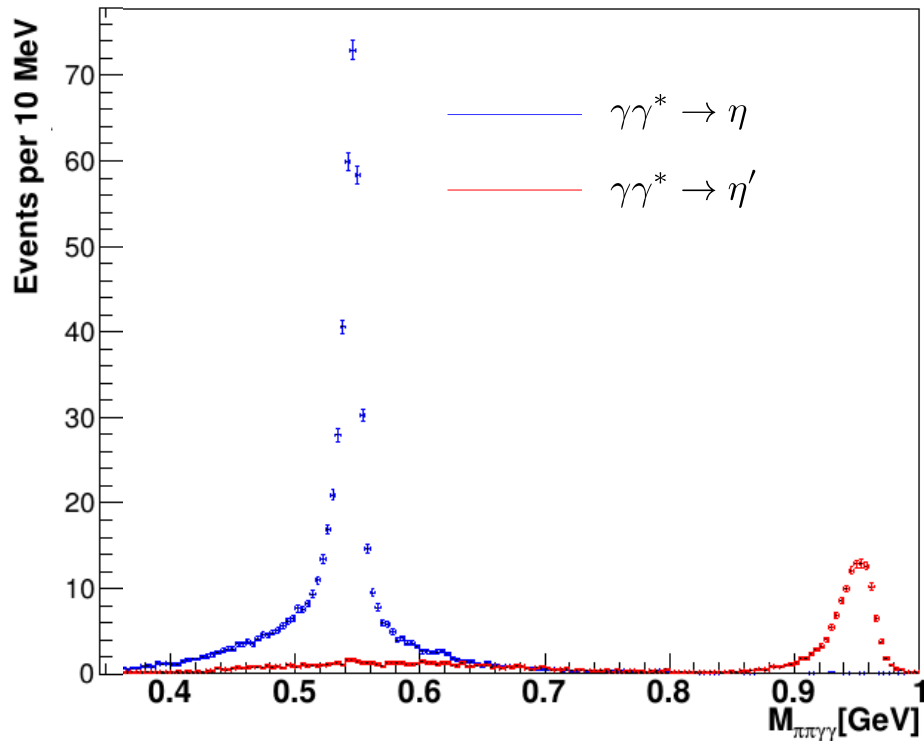$$\eta' \sim 1.5 \times 10^{-10}$$

Knecht,Nyffeler
Phys.Rev.D65 (2002) 073034

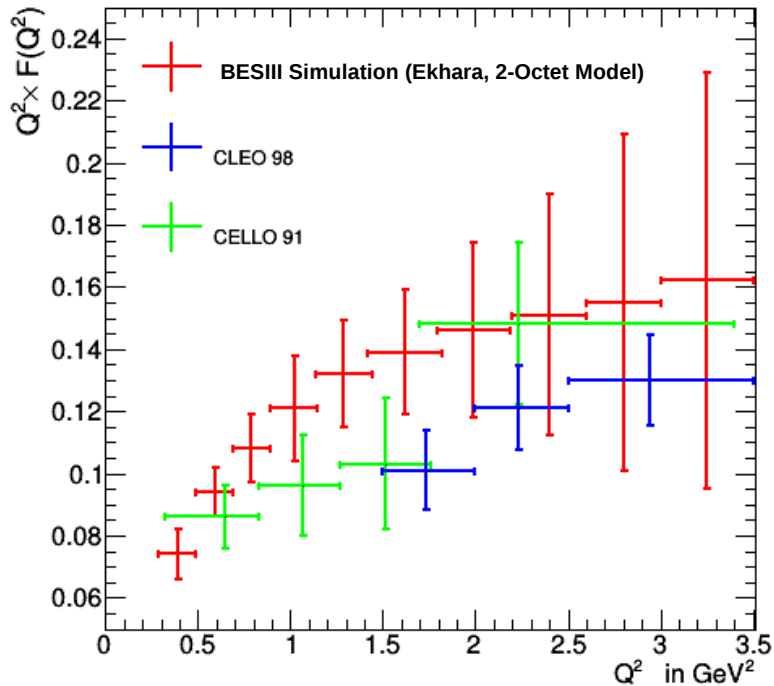**JG|U**

BES III

BESIII Simulation: $2.9 fb^{-1}$ @ 3.773 GeV

- $\eta \to \pi^+\pi^-\pi^0$

- $\eta' \to \pi^+\pi^-\eta$

- Select:

  - one electron or positron
  - two oppositely charged pions
  - two photons

- $\cos\theta_{untagged} > 0.99$

- Reject hadronic background

- Mass window cuts on $\gamma\gamma$ invariant mass

- Kinematic fit
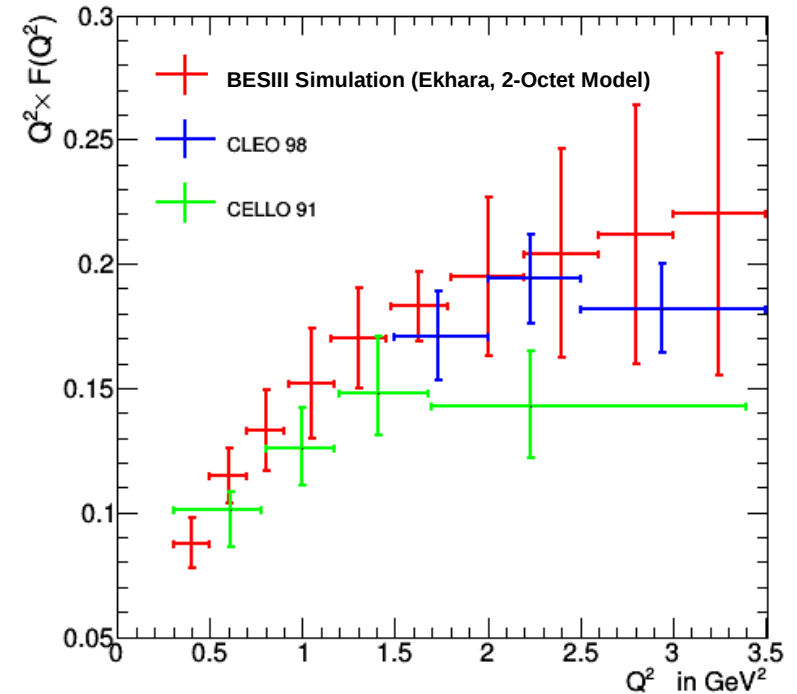
- Relatively small background contamination

Space-like η,η' Transition Form Factor

$$F_{\eta,\gamma,\gamma^*}(Q^2)$$

$$F_{\eta',\gamma,\gamma^*}(Q^2)$$

- Statistics compatible to previous measurements
    - only one decay channel of η and η' analyzed at BESIII
    - more data available (×3.5)

- Systematic studies to be done