



JOHANNES GUTENBERG
UNIVERSITÄT MAINZ



THE LOW-ENERGY FRONTIER
OF THE STANDARD MODEL



Measurement of meson transition form factors at **BESIII**

September 7, 2017 | Christoph Florian Redmer
for the BESIII collaboration

Hadronic Physics with Lepton and Hadron Beams

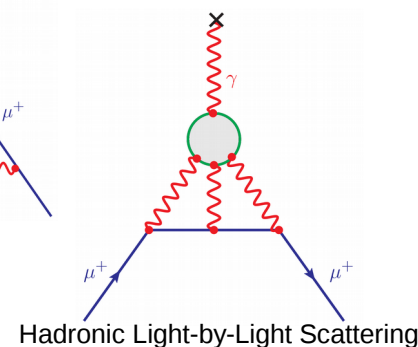
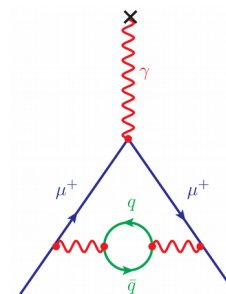
EM transition form factors – Coupling of light and matter

Important for the anomalous magnetic moment of the muon a_μ

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

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

Hadronic Vacuum Polarization

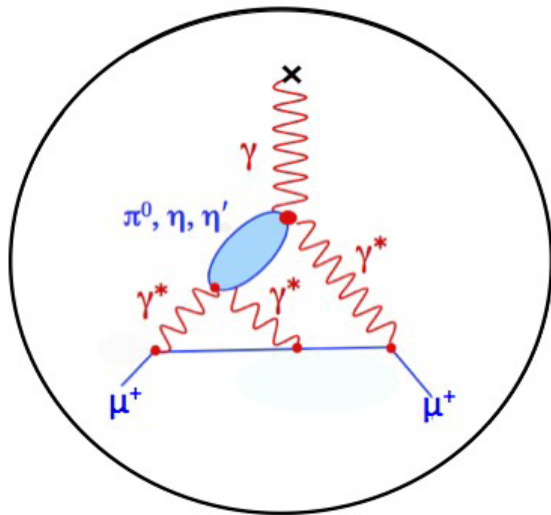


Test of Standard Model !

Prediction completely limited by hadronic contributions!

→ Use experimental input to improve theory!

a_{μ}^{hLBL} not directly related to measurable quantities



- Hadronic models
 - ChPT at lowest energies
 - pQCD at high energies
 - Intermediate region ?

Glasgow Consensus, arXiv:0901.0306
Jegerlehner/Nyffeler, Phys.Rept.477,1

- Data driven approaches
 - Based on dispersion relations
 - Reduce model dependency
 - Reliable error estimates

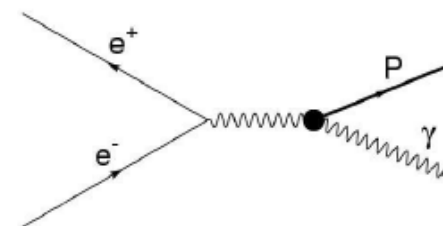
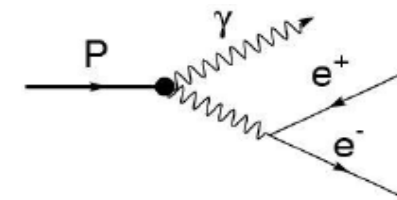
Collangelo, Hoferichter, et al. (Bern)
Vanderhaeghen, Pauk, et al. (Mainz)

- Transition form factors (TFF) as experimental input

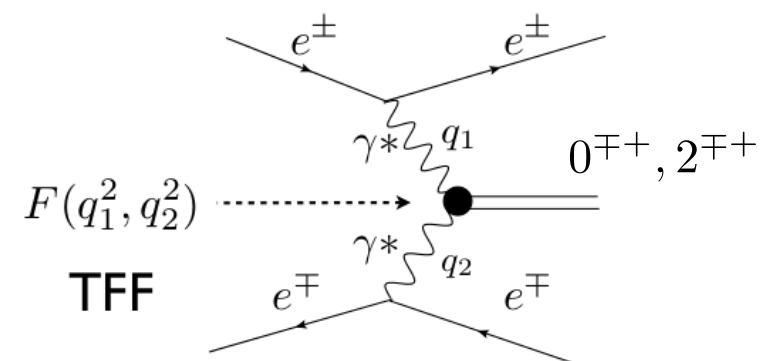
Time – like Transition Form Factors:

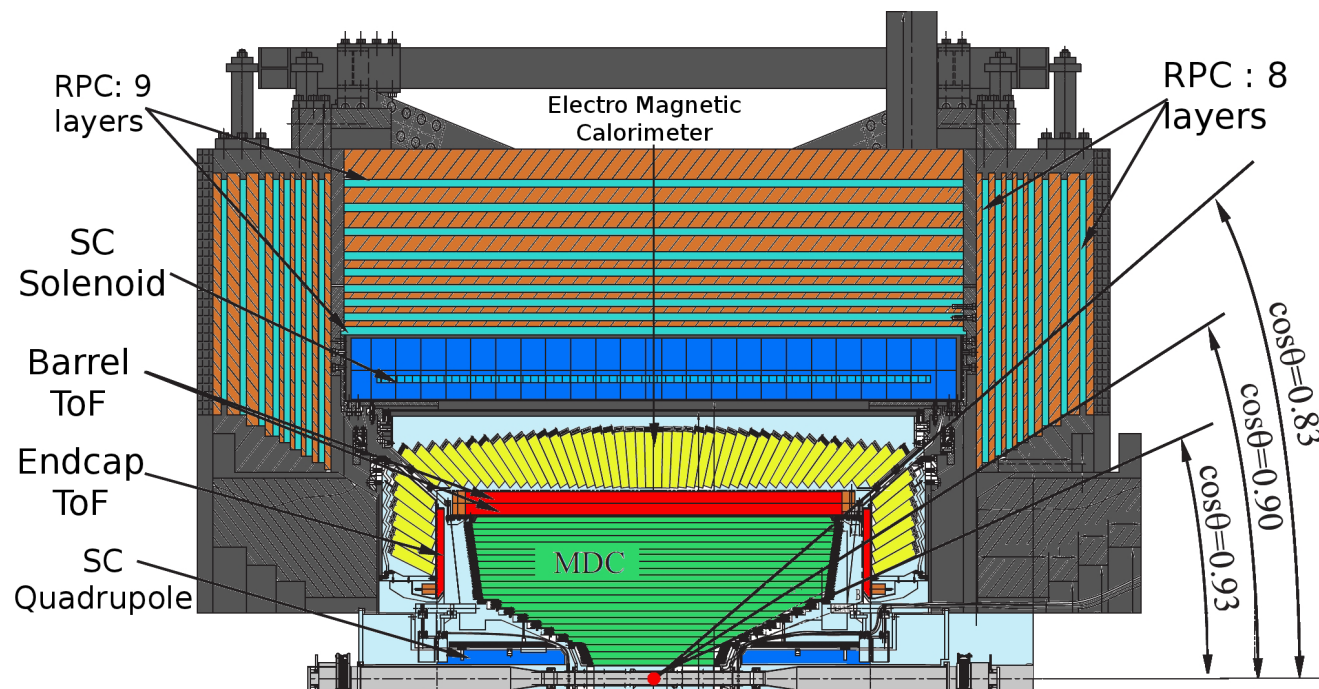
- Dalitz decays
 - $0 < q^2 < M^2$

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

Space – like Transition Form Factors:

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





- Main Drift Chamber (MDC)

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

- Time-of-flight system (TOF)

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

- EMC

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

- Muon Chambers

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

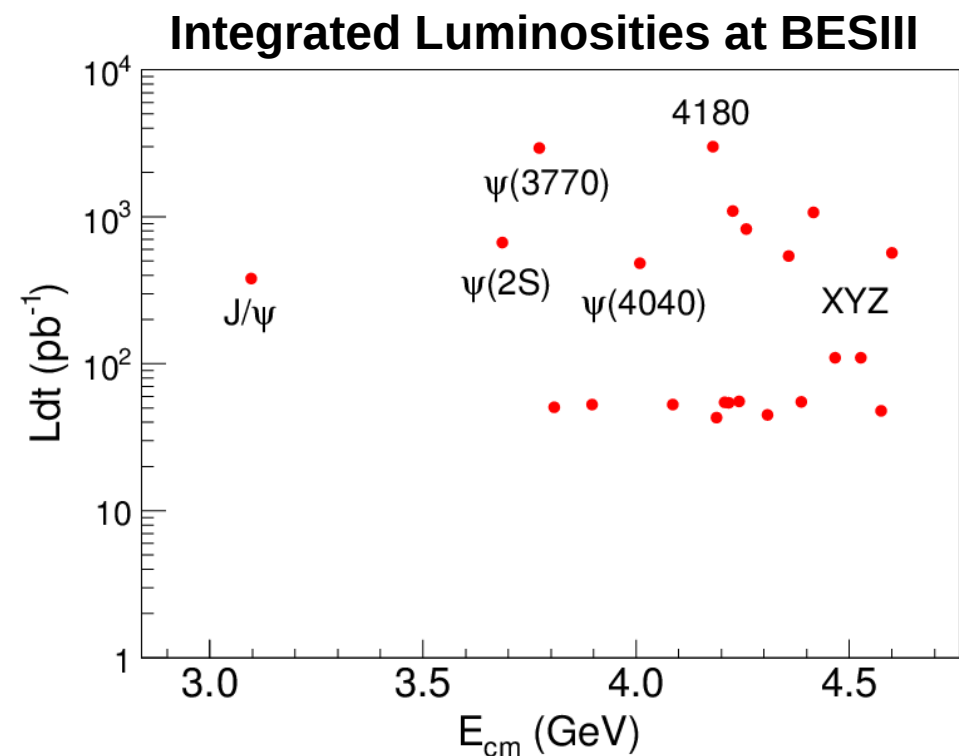
- Superconducting Magnet

- 1 T magnetic field

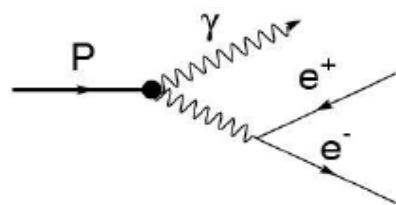
- Operated at BEPCII collider
 - $2.0 \leq \sqrt{s} \text{ [GeV]} \leq 4.6$
 - Design luminosity achieved
 - $\mathcal{L} = 1.0 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ at $\psi(3770)$

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

$\gamma\gamma$ studies mainly on 2.9 fb^{-1} at $\psi(3770)$



Dalitz Decays



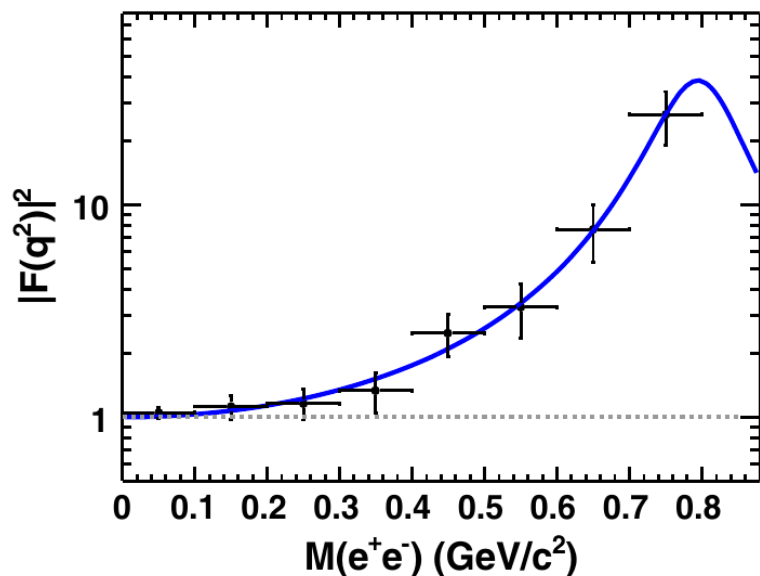
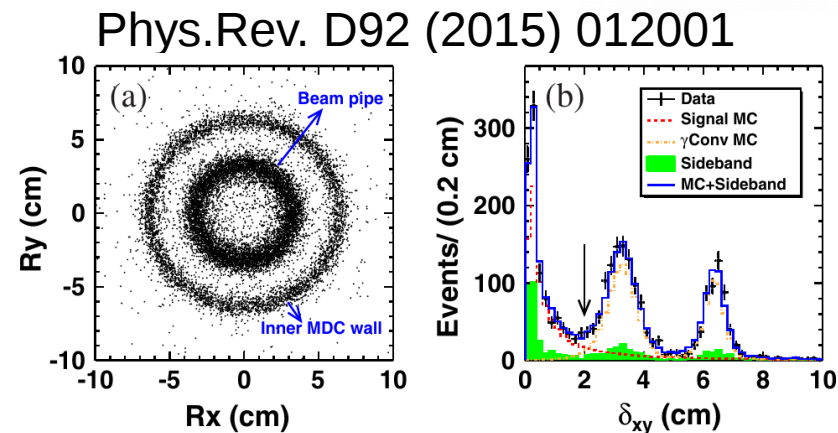
$J/\psi \rightarrow \mathcal{P}e^+e^-$ Phys. Rev. D89, 092008 (2014)

$\eta' \rightarrow \gamma e^+e^-$ Phys. Rev. D92, 012001 (2015)

$\eta' \rightarrow \omega e^+e^-$ Phys. Rev. D92, 051101(R) (2015)

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

- 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



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

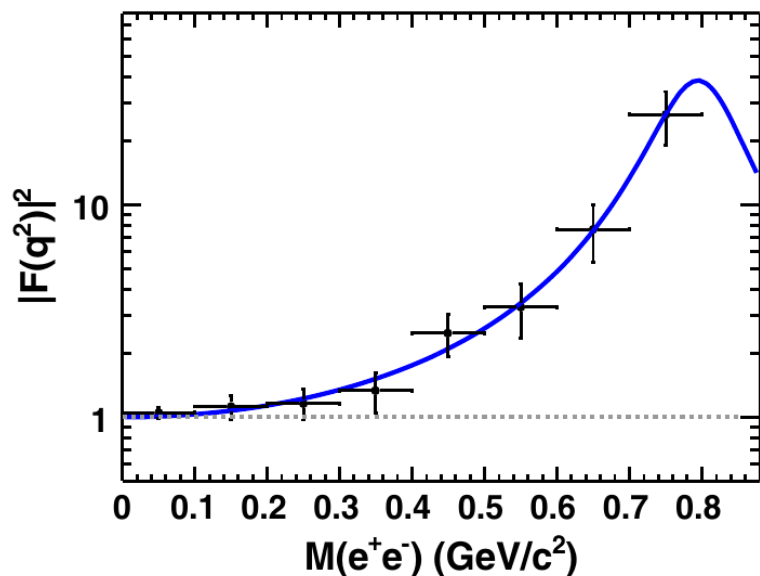
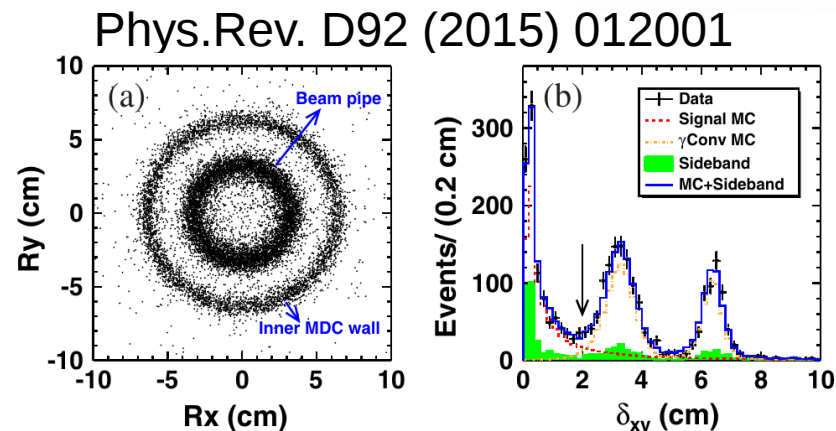
$$\Lambda = (0.79 \pm 0.04_{\text{stat}} \pm 0.02_{\text{syst}}) \text{ GeV}$$

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

- Precision on the level of space-like extrapolation
- Improvement over muon Dalitz decays

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

- Reconstructed from $J/\psi \rightarrow \gamma \eta'$
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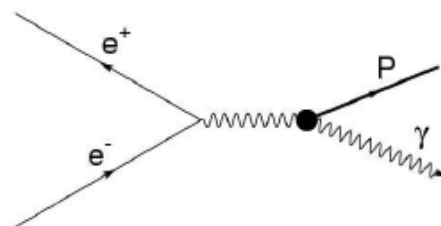
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New measurements expected from:

- A2 (Mainz)
- CLAS12 (JLab)

Annihilation Reactions



$$\psi' \rightarrow \mathcal{P}\gamma$$

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

$$\psi' \rightarrow \gamma\eta_c$$

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

$$\psi(3770) \rightarrow \gamma\eta_c$$

Phys. Rev. D 89, 112005 (2014)

$$e^+e^- \rightarrow \gamma\eta_c$$

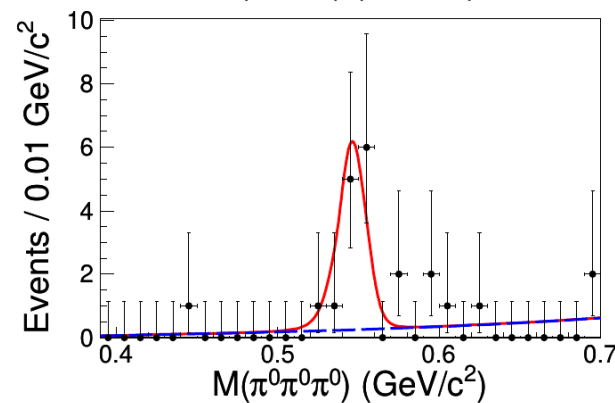
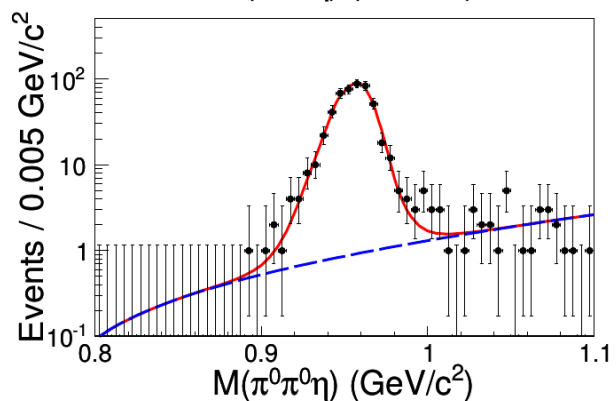
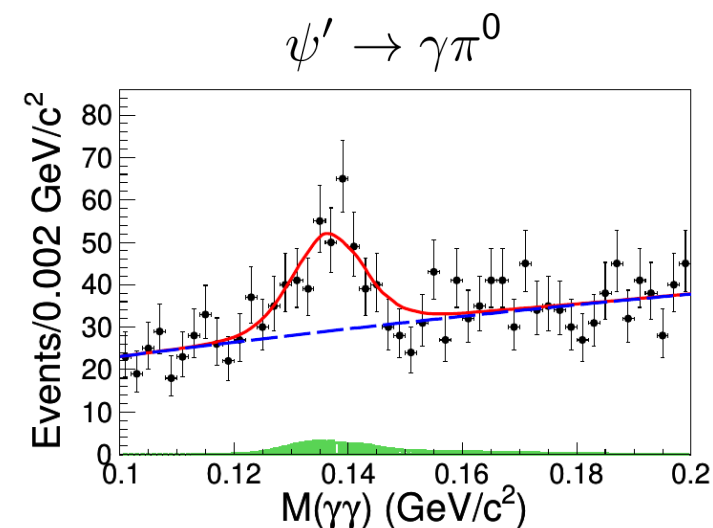
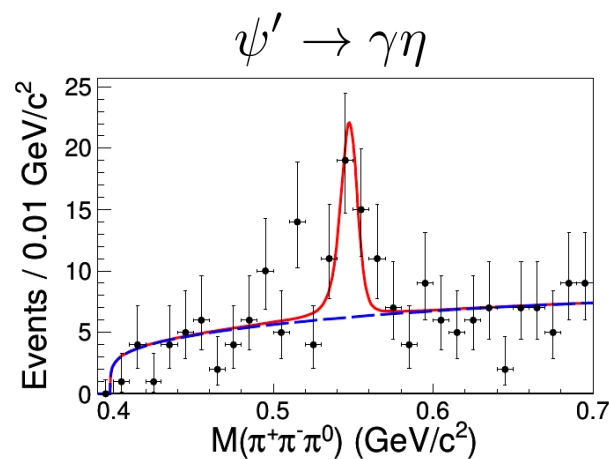
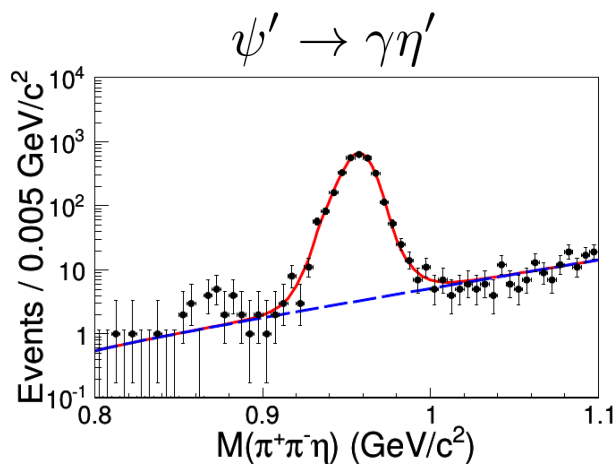
arXiv:1705.06853, accepted by Phys. Rev. D

$$\psi' \rightarrow \mathcal{P}\gamma$$

arXiv:1708.03103, accepted by Phys. Rev. D

$$\psi' \rightarrow \gamma \pi^0, \eta, \eta'$$

- 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



arXiv:1708.03103, accepted by PRD

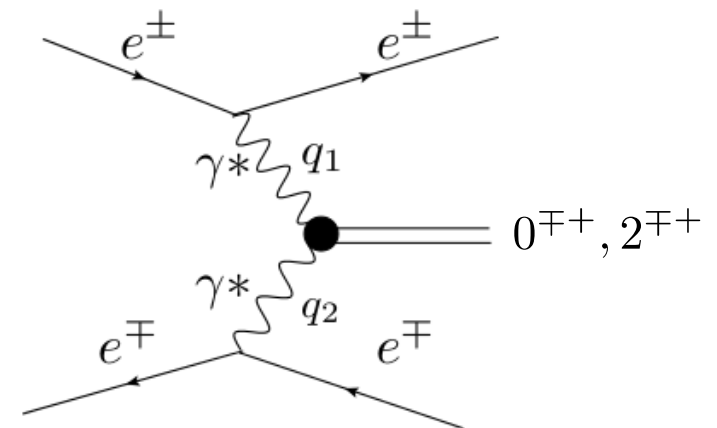
$$\psi' \rightarrow \gamma\pi^0, \eta, \eta'$$

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	$(0.95 \pm 0.16 \pm 0.05) \times 10^{-6}$

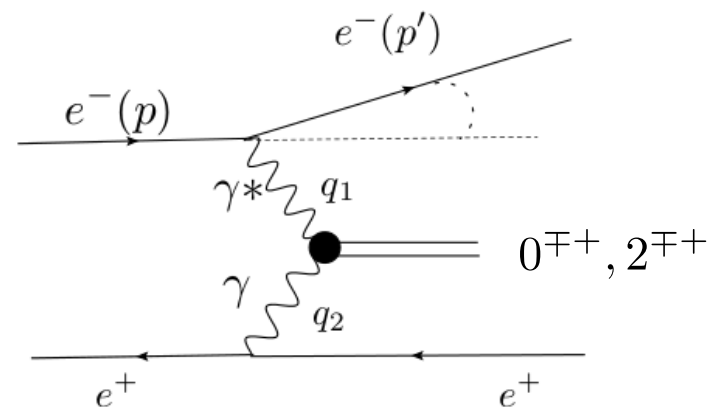
arXiv:1708.03103, accepted by PRD

- Data analysis is being extended to continuum regions: $e^+e^- \rightarrow \gamma\mathcal{P}$
 - Study time-like transition form factor for $4 \leq q^2[\text{GeV}^2] \leq 21.16$
 - QCD tests
 - BaBar-Belle puzzle

- 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
 - Experimentally challenging



- Reconstruct
 - only one scattered lepton
 - Produced system
- Unmeasured lepton from momentum conservation
 - Require scattering angle to be small
 - Small virtuality
- $F(q_1^2, q_2^2) \rightarrow F(q_1^2, 0) \rightarrow F(q^2)$

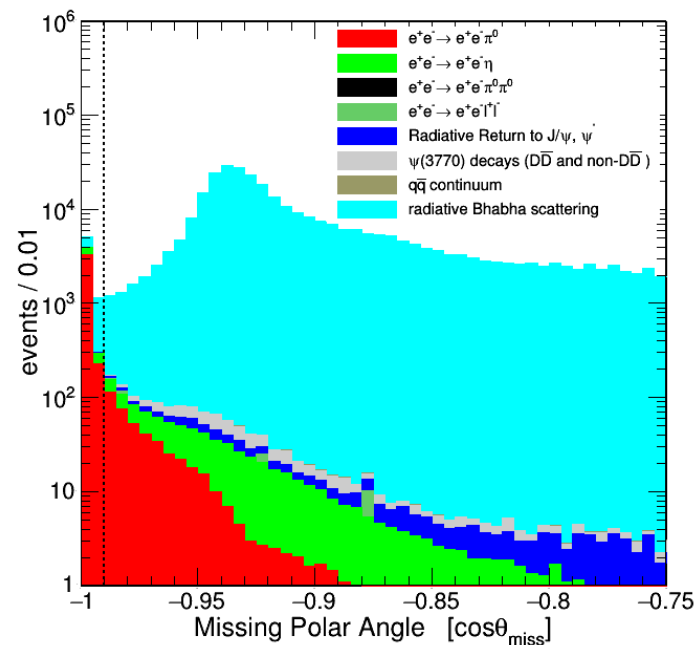


Example: π^0 transition form factor at BESIII

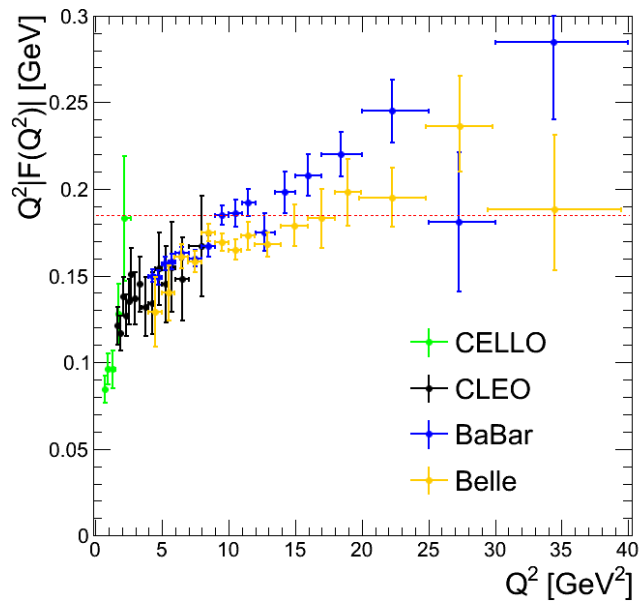
Monte Carlo, $L_{\text{int}} : 2.93 \text{ fb}^{-1} @ \Psi(3770)$

Tagged Lepton: e^+

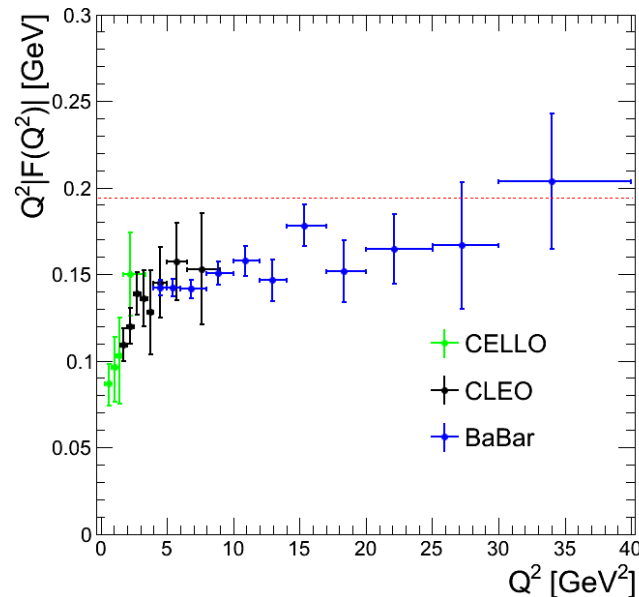
Reconstructed decay: $\pi^0 \rightarrow \gamma\gamma$



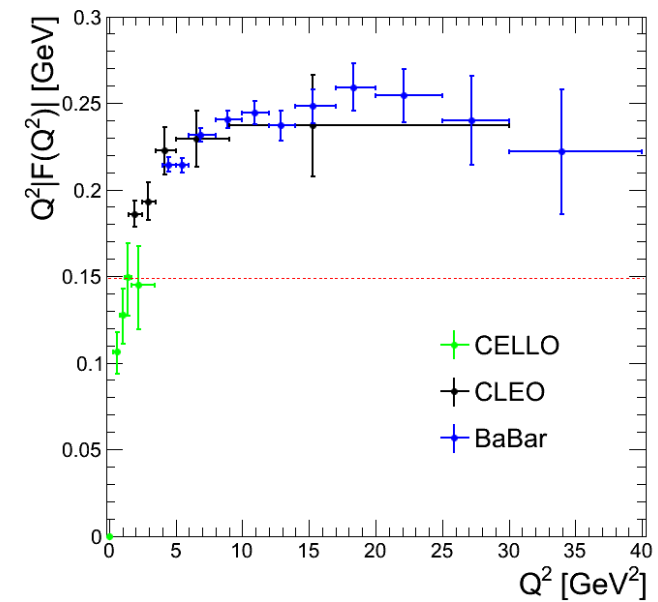
$$e^+e^- \rightarrow e^+e^- \pi^0$$



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



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



- Recent results from B-factories cover only large Q^2 ($5 < Q^2 [\text{GeV}^2] < 40$)
- Discrepancy for π^0 between BaBar and Belle
- Data scarce at lowest Q^2
- Region of relevance for $(g-2)_\mu$

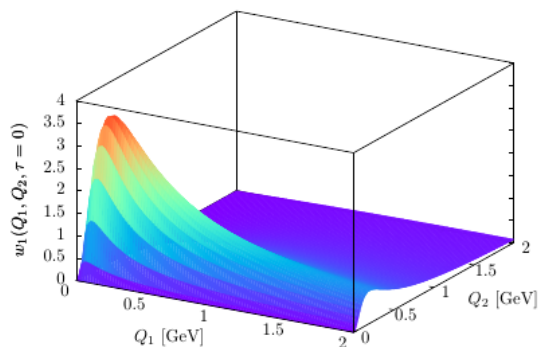
CELLO: Z.Phys.C49 (1991) 401
 CLEO: Phys.Rev.D57 (1998) 33
 BaBar: Phys.Rev.D80 (2009) 052002
 Phys.Rev.D84 (2011) 052001
 Belle: Phys.Rev.D86 (2012) 092007

Relevant Energy Range

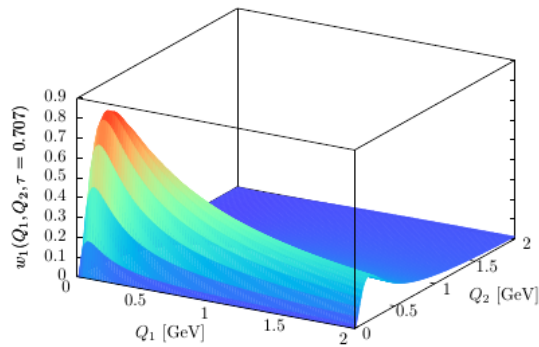
3D integral representation for PS-pole contribution: (Nyffeler, PRD94,053006, 2016)

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

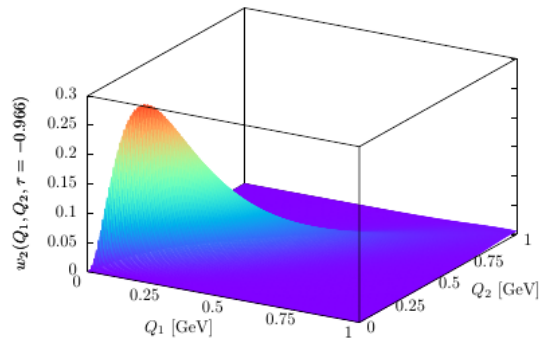
$$a_{\mu}^{\text{HLbL};\pi^{0(2)}} = \int_0^{\infty} dQ_1 \int_0^{\infty} dQ_2 \int_{-1}^1 d\tau w_2(Q_1, Q_2, \tau) \mathcal{F}_{\pi^0\gamma^*\gamma^*}(-Q_1^2, -Q_2^2) \mathcal{F}_{\pi^0\gamma^*\gamma^*}(-(Q_1 + Q_2)^2, 0)$$



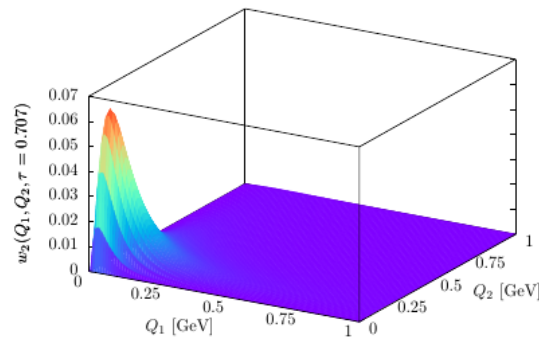
(c)



(d)



(e)



(f)

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

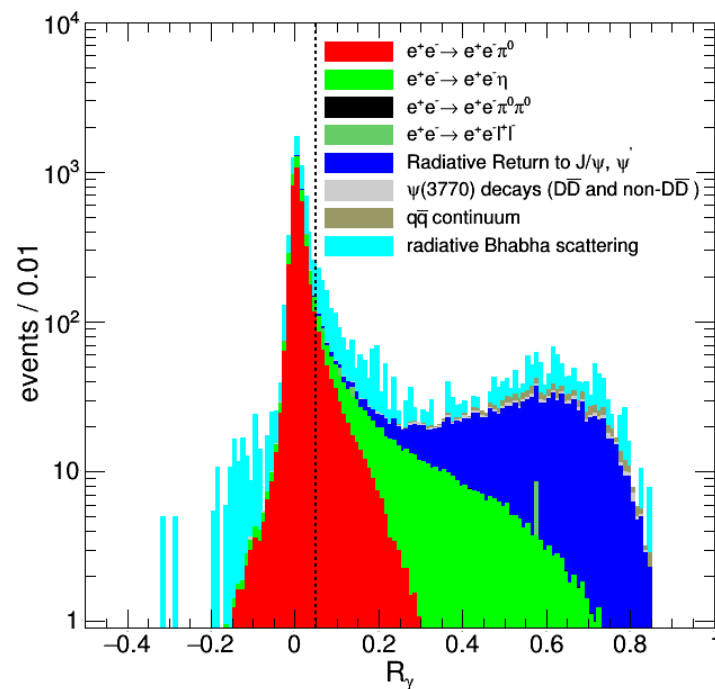
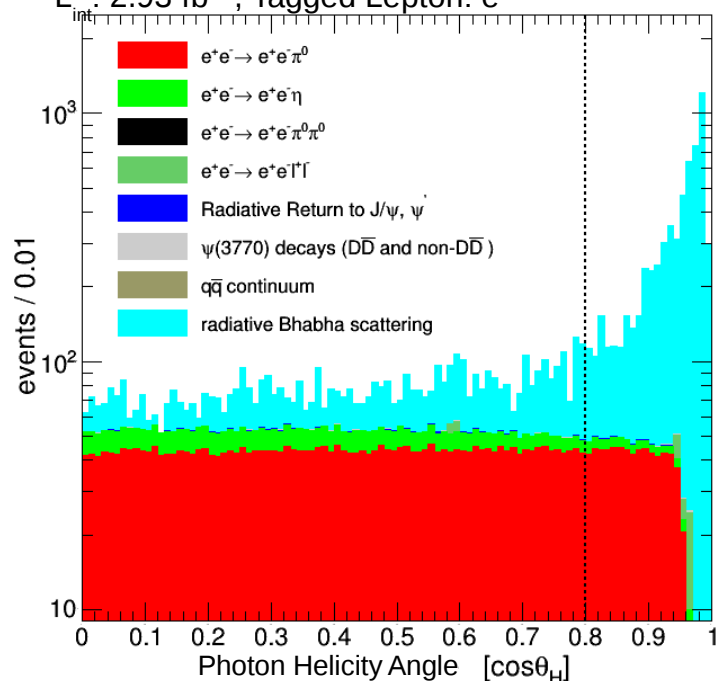
Relevant momentum region:

0.25 – 1.25 GeV

- Event selection:
- Exactly one lepton
 - Two to four photons

$$\cos\theta_{\text{untagged}} < -0.99$$

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



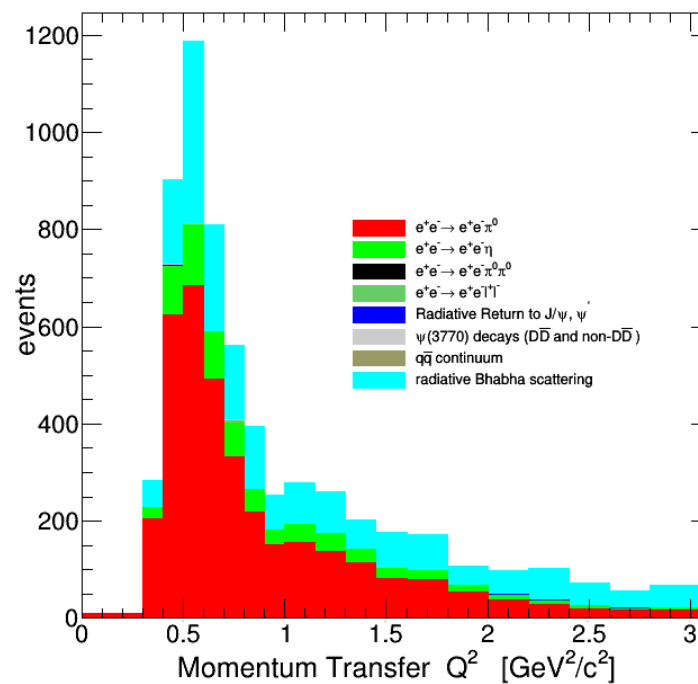
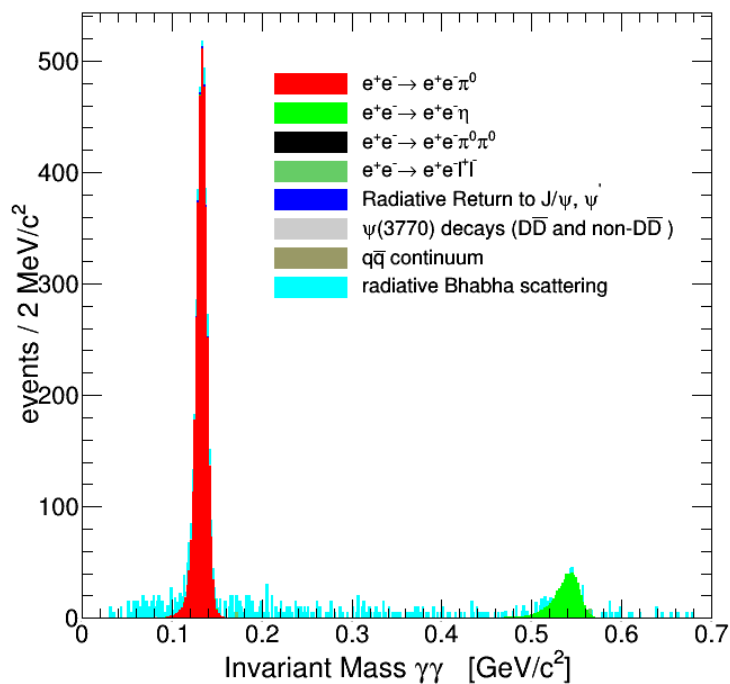
- Angle between γ in π^0 rest frame and π^0 in lab

$$\cos\theta_{\text{Helicity}} < 0.8$$

- Radiative effects result in wrong Q^2

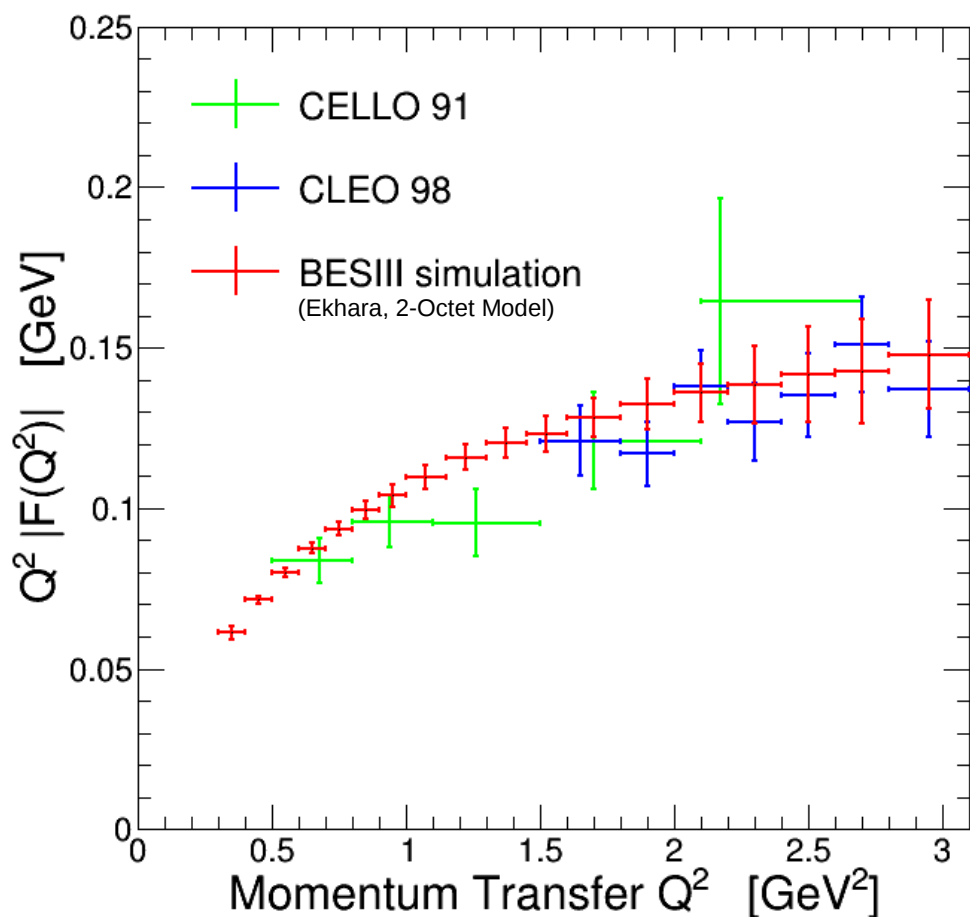
$$\text{Useful observable: } R_\gamma = \frac{\sqrt{s} - E_{e^\pm\pi^0}^{\text{CMS}} - p_{e^\pm\pi^0}^{\text{CMS}}}{\sqrt{s}}$$

- Reject events with $R_\gamma > 0.05$

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

- Analysis useful for π^0 and η
- Monte Carlo description of background incomplete

- Bkg subtr. by counting π^0 yield per Q^2 bin
- Divide out point-like cross section for $|F(Q^2)|^2$



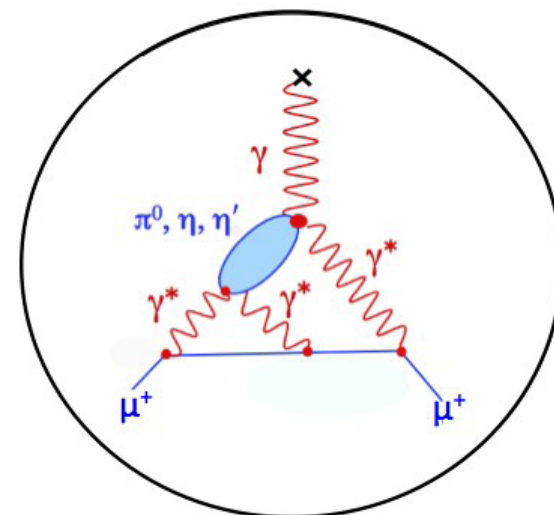
- 2.9 fb $^{-1}$ at $\Psi(3770)$ analyzed
- Covering $0.3 \leq Q^2 [\text{GeV}^2] \leq 3.1$
- Unprecedented accuracy below 1.5 GeV 2
 - Important for a_μ^{hLbL}
- Competitive accuracy up to 3.1 GeV 2
- Soon to be published

- 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!

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

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

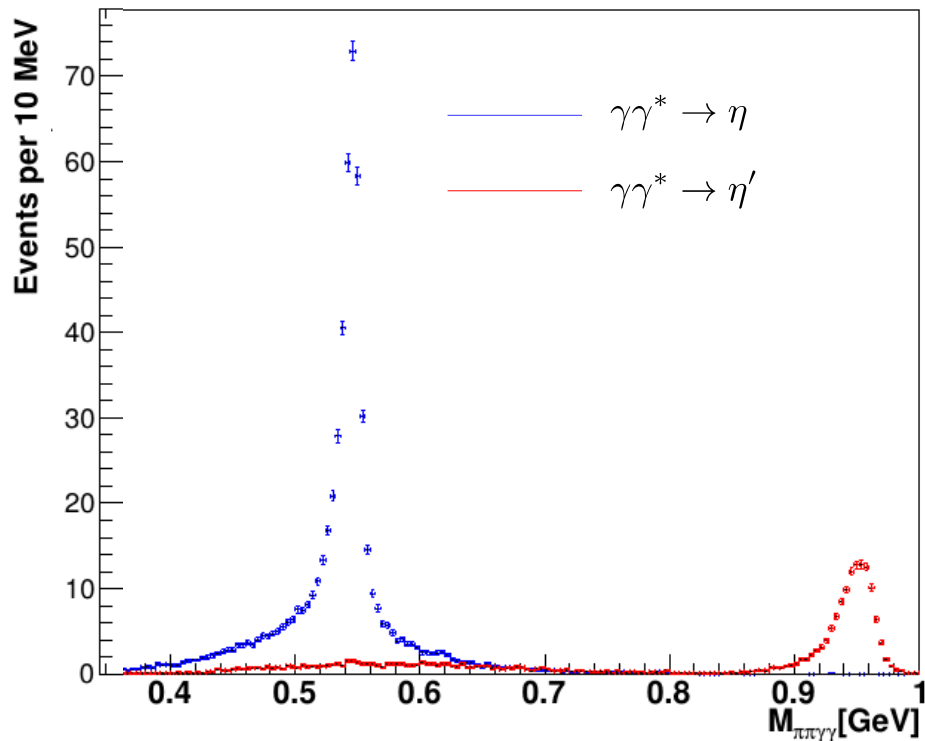
Knecht, Nyffeler
Phys.Rev.D65 (2002) 073034



JGU Space-like η, η' Transition Form Factor



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



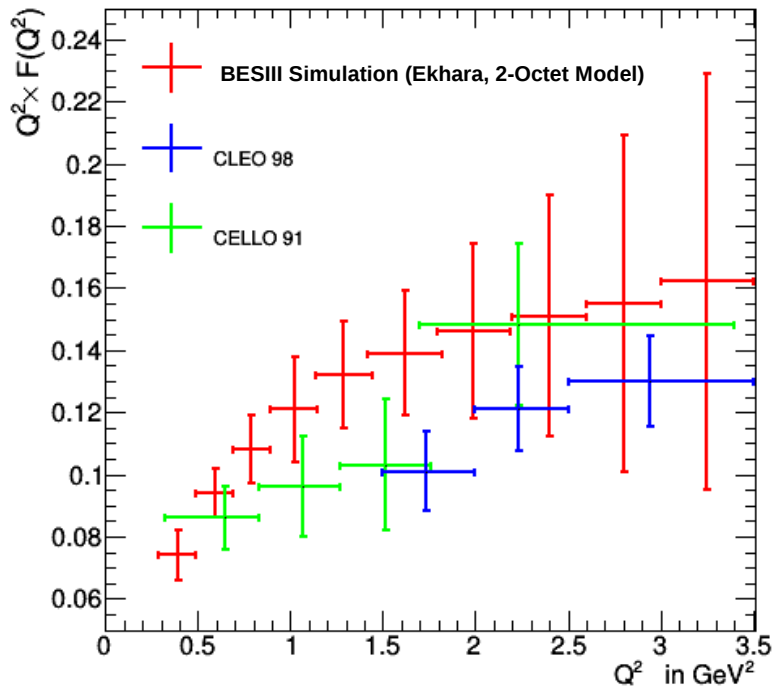
- $\eta \rightarrow \pi^+ \pi^- \pi^0$
- $\eta' \rightarrow \pi^+ \pi^- \eta$
- Select:
 - one electron or positron
 - two oppositely charged pions
 - two photons
- $\cos\theta_{\text{untagged}} > 0.99$
- Reject hadronic background
- Mass window cuts on $\gamma\gamma$ invariant mass
- Kinematic fit

- Relatively small background contamination

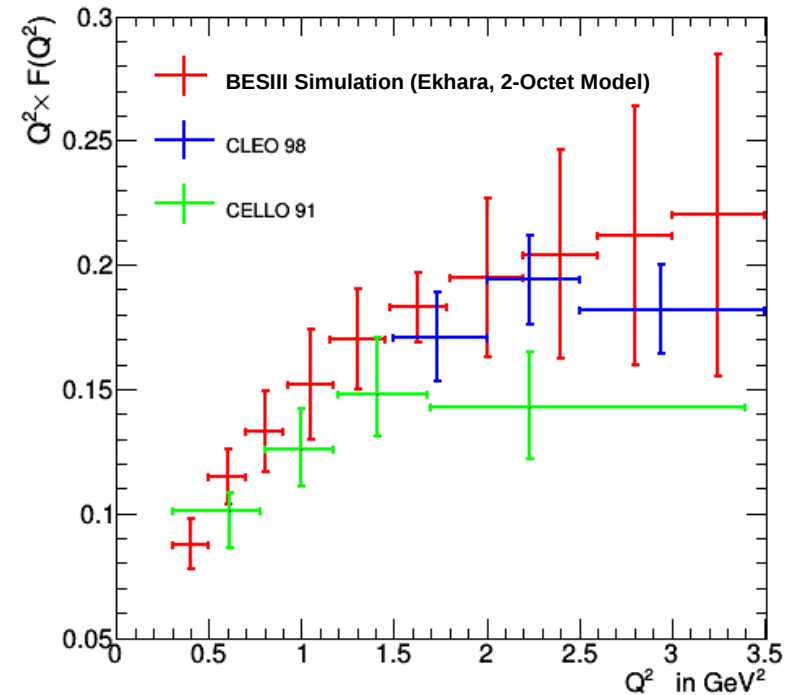
JGU Space-like η, η' Transition Form Factor

BESIII

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



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



- Statistics compatible to previous measurements
 - only one decay channel of η and η' analyzed at BESIII
 - more data available ($\times 3.5$)
- Systematic studies to be done

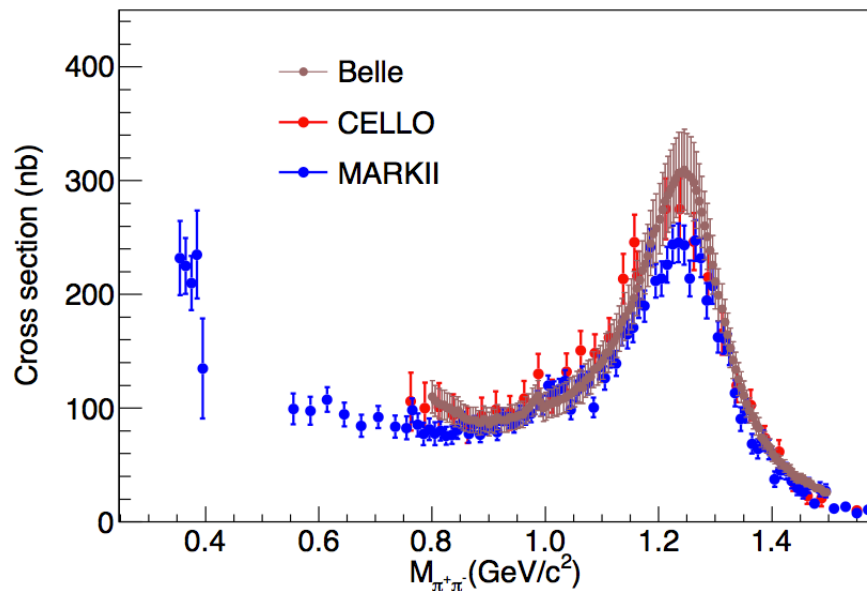
JGU Space-like $\pi^+\pi^-$ Transition Form Factor

- 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

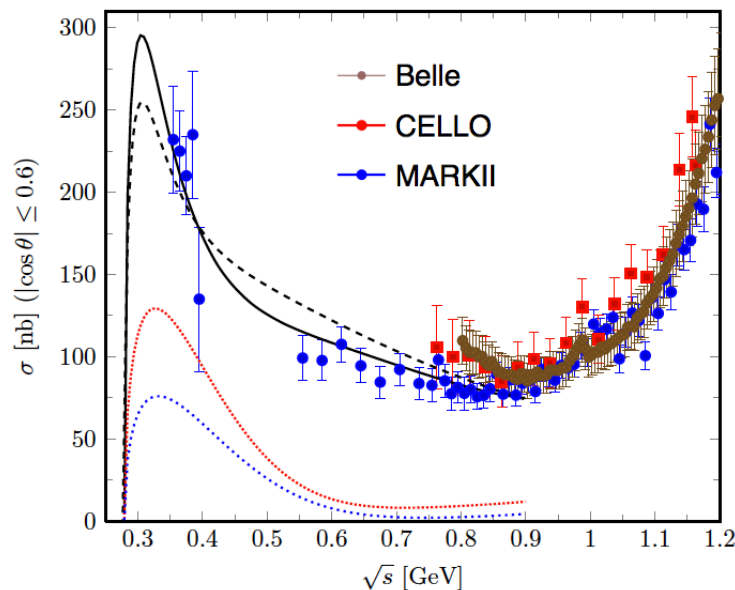
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■ Until recently only untagged measurements:



Calculations by
Assmussen, Masjuan, and Vanderhaeghen:

Untagged

Single-Tag ($Q_1^2 = 0.5 \text{ GeV}^2$)

Double-Tag ($Q_1^2 = Q_2^2 = 0.5 \text{ GeV}^2$)

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

Phys. Rev. D93 (2016) 032003

- At BESIII: Single-Tag measurement

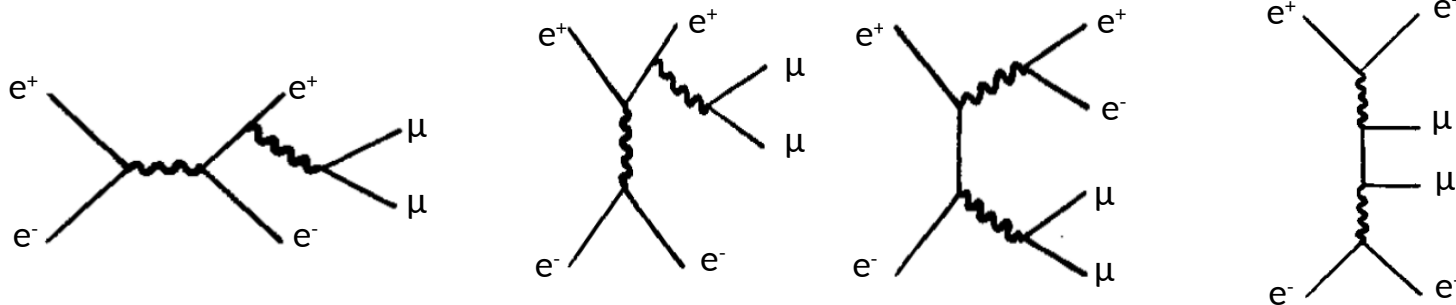
- Event selection analogous to single pseudoscalar analysis

- Major Backgrounds:

- $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$

- Includes two-photon production of muon pairs

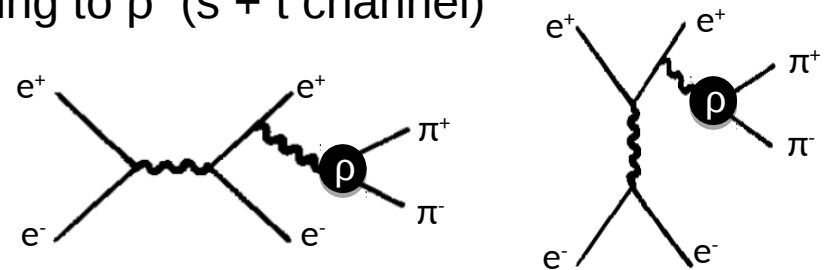
- Precise MC generators available from LEP era (BdkRC + Diag36ABC)



- $e^+e^- \rightarrow e^+e^-\pi^+\pi^-$

- Radiative Bhabha scattering coupling to ρ (s + t channel)

- MC generators being developed



- Training multivariate methods to suppress muon background
 - Improves statistical accuracy

- Subtract ρ contribution

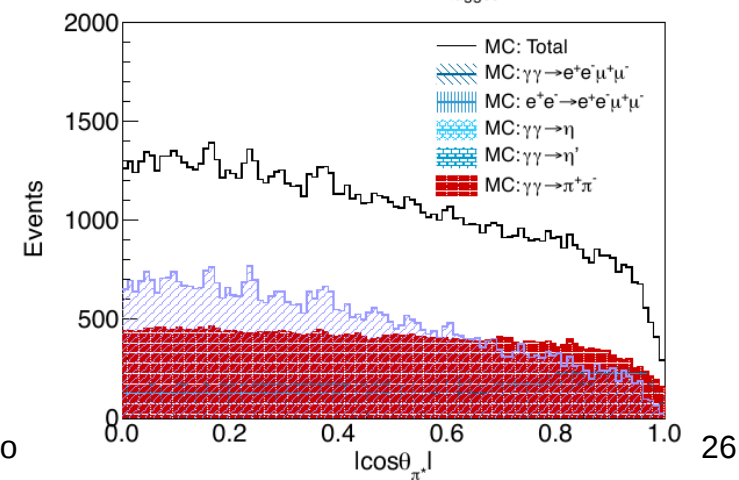
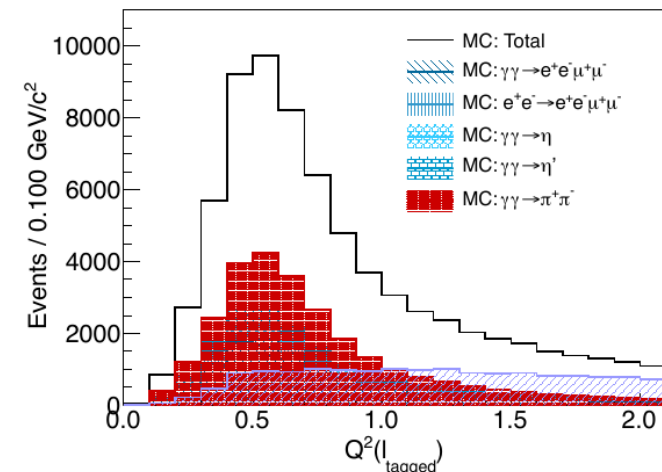
- Fit peak in data using shape from theory

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

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

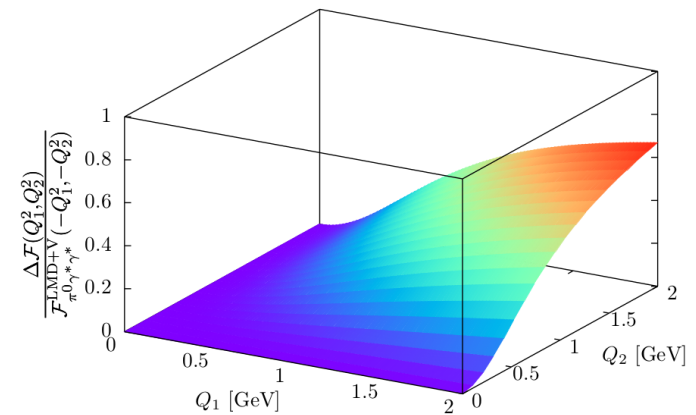
- Access to:

- low momentum transfers $0.2 < Q^2 [\text{GeV}^2] < 2.0$
 - low invariant masses $m_{\pi^+\pi^-} < M [\text{GeV}] < 2.0$
 - 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 $> 10 \text{ fb}^{-1}$ at $3.77 < \sqrt{s} [\text{GeV}] < 4.6$
 - Double-tag measurement possible
 - Low statistics expected
 - 1st Step: Test TFF models
 - e.g. VMD vs. LMD+V



Calculations: A. Nyffeler
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- 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 started
 - Single-tag measurements
 - π^0 , η , and η' transition form factors with unprecedented accuracy ($Q^2 < 1.5 \text{ GeV}^2$)
 - $\pi^+\pi^-$
 - 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 $\gamma^*\gamma^* \rightarrow \pi^0$ started