



Experimental Input for a_μ Light-by-Light

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Muon Anomaly

- Muon anomaly: $a_\mu = \frac{g_\mu - 2}{2} = \frac{\alpha}{2\pi} + \dots = 0.0011659 \dots$
- Experimental: $a_\mu^{\text{exp}} = 1165\ 920\ 8.9\ (6.3) \times 10^{-10}$ (0.54 ppm)

[BNL-E821: Phys. Rev. D 73 072003]

- Standard Model prediction: $a_\mu^{\text{SM}} = a_\mu^{\text{QED}} + a_\mu^{\text{weak}} + a_\mu^{\text{had}}$
 $= 1165\ 918\ 2.3\ (4.3) \times 10^{-10}$

[Eur. Phys. J. C 77 827 (2017)]

$$a_\mu^{\text{exp}} - a_\mu^{\text{SM}}: 26.8 \pm 7.6 (3.5\sigma)$$

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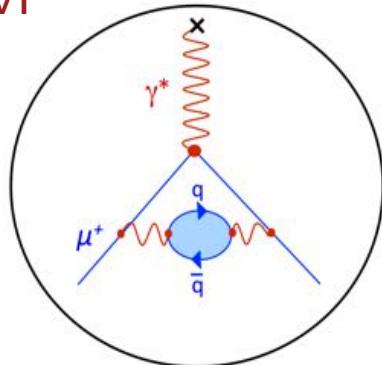
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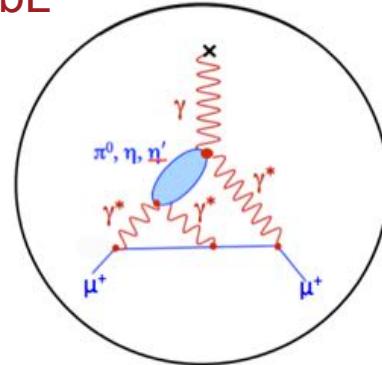
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HVP



HLbL



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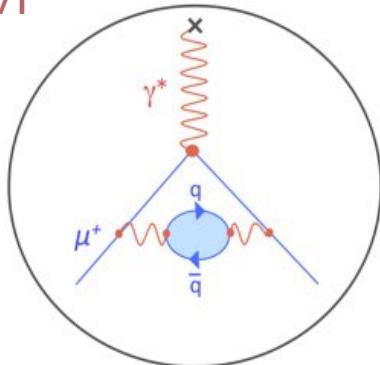
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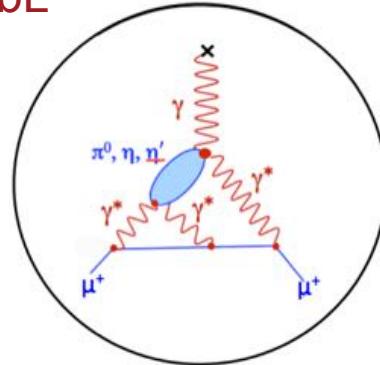
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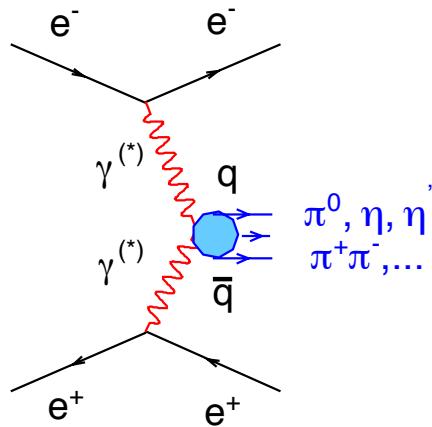


[Colangelo et al '14; '15; '17; Pauk, Vanderhaeghen '14; '15;
RBC-UKQCD; Mainz]

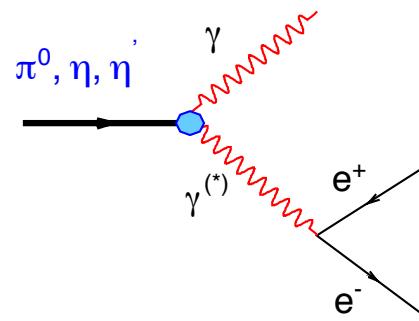
- Model calculations
- Data-driven approach
 - Reduce model dependency
(goal: 10..20%)
 - Reliable error estimations
- Lattice calculation

Experimental Input for HLbL

Transition form factors, Helicity amplitudes



Space-like



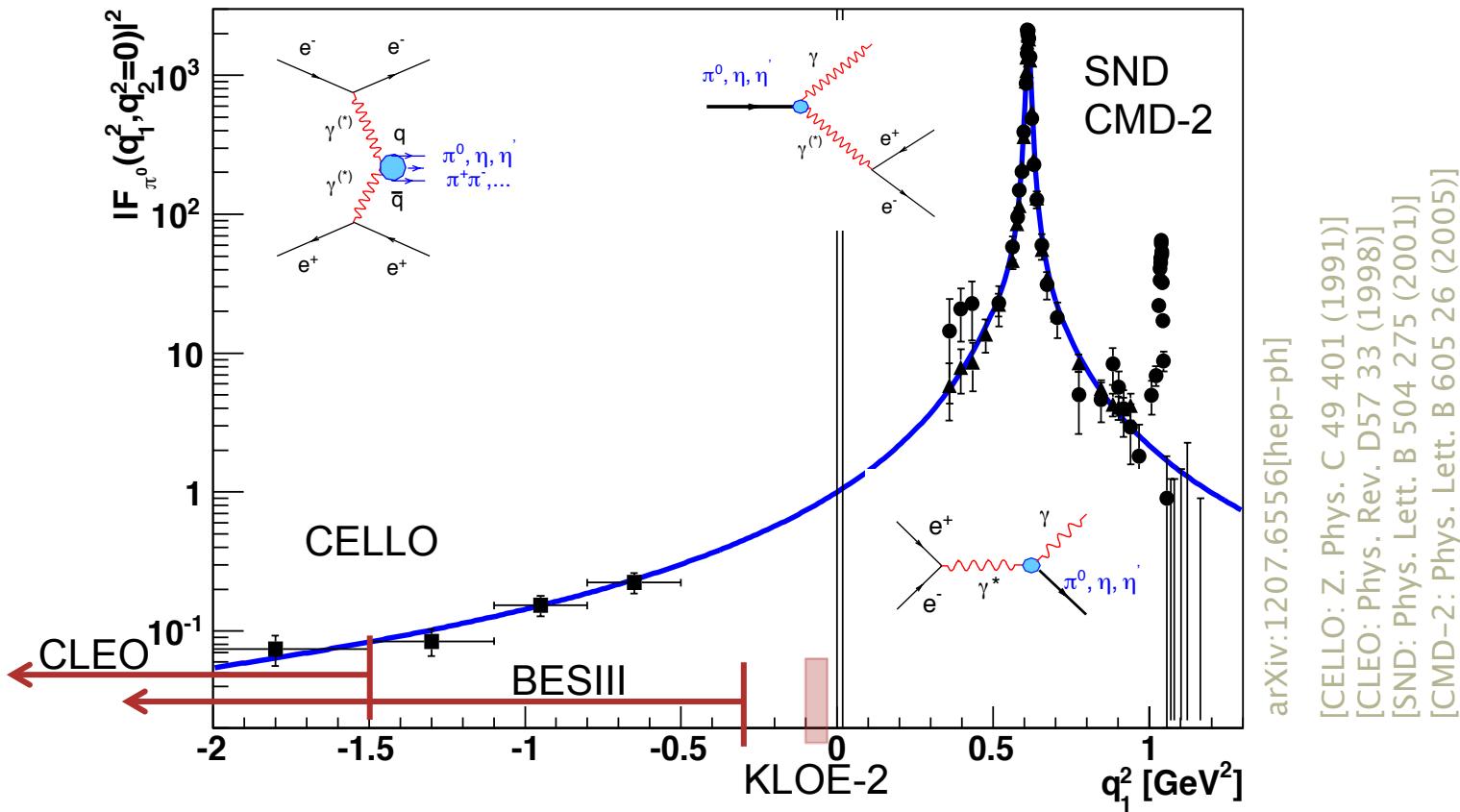
Time-like

*BaBar, Belle, BESIII, CELLO,
CLEO, ...*

A2, BESIII, NA60, CMD-2, SND, ...

Experimental Input for HLbL

Transition form factors, Helicity amplitudes



arXiv:1207.6556[hep-ph]

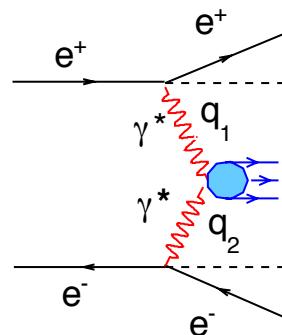
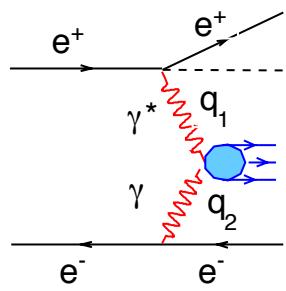
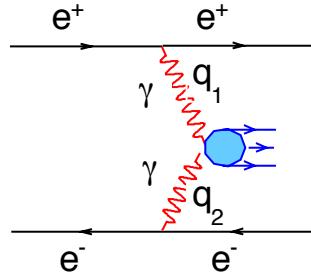
[CELLO: Z. Phys. C 49 401 (1991)]

[CLEO: Phys. Rev. D57 33 (1998)]

[SND: Phys. Lett. B 504 275 (2001)]

[CMD-2: Phys. Lett. B 605 26 (2005)]

Space-like TFFs



Untag:

- Only tag the hadron products, P_t -balance
- $F[Q_{1,2}^2 \sim 0]$

Single tag:

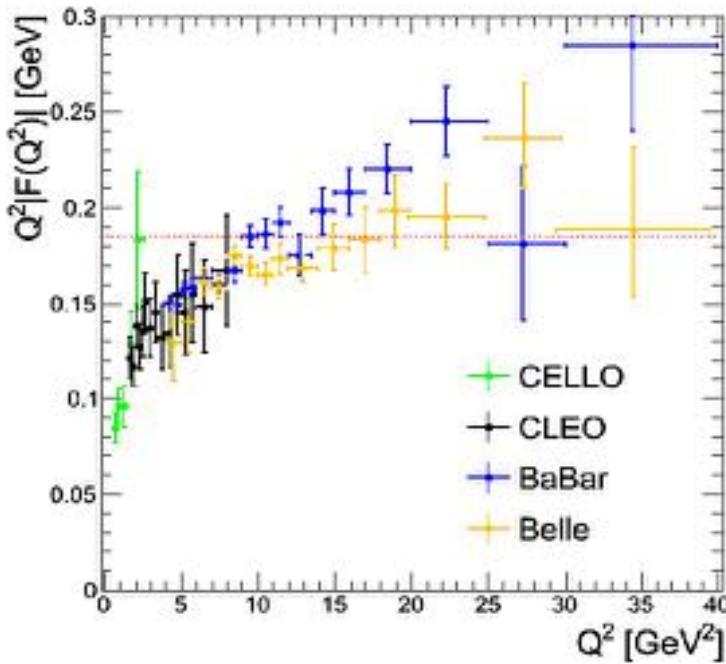
- Tag the hadron products
- Tag only one lepton, missing momentum direction
- $F[Q_1^2, Q_2^2 \sim 0]$

Double tag:

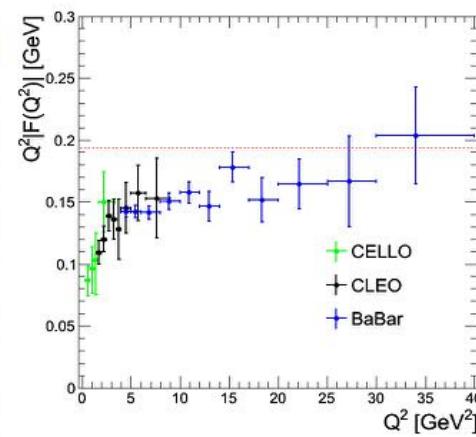
- Tag the hadron products
- Tag both leptons
- $F[Q_1^2, Q_2^2]$

Existing Data: Space-like

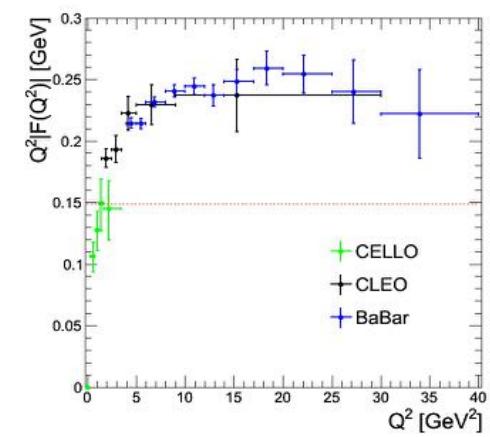
$e^+e^- \rightarrow e^+e^- \pi^0$



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



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



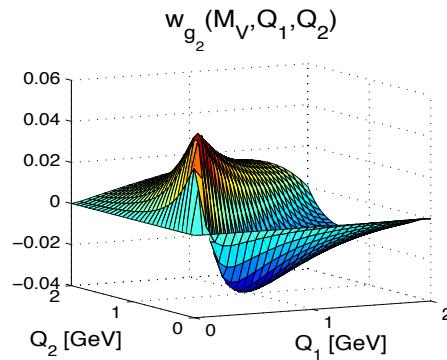
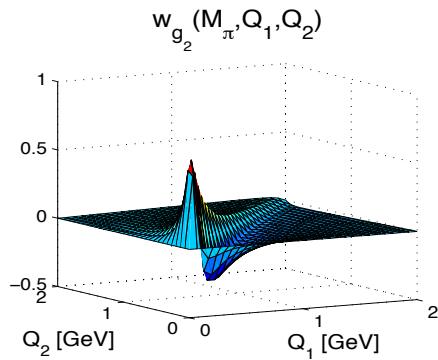
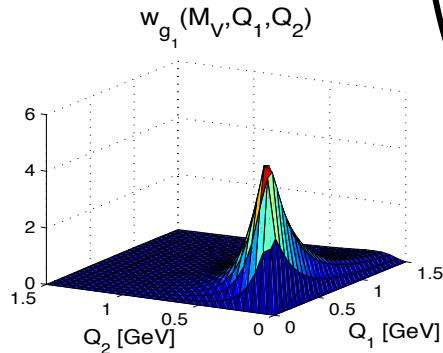
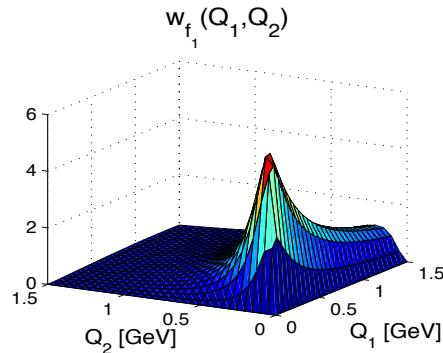
- [CELLO: Z. Phys. C 49 401 (1991)]
- [CLEO: Phys. Rev. D57 33 (1998)]
- [BaBar: Phys. Rev. D80 052002 (2009)]
- [Belle: Phys. Rev. D86 092007 (2012)]

- Recent results from BABAR and BELLE:
 $Q^2 > 4 \text{ GeV}^2$
- CLEO: $Q^2 > 1.5 \text{ GeV}^2$
- CELLO: $Q^2 < 1.5 \text{ GeV}^2$, very poor accuracy

Low Q^2 range not covered/precise

Relevant Q^2 Region

$$a_\mu^{\text{HLBL};\pi^0} = \int_0^\infty dQ_1 \int_0^\infty dQ_2 \sum_i w_i(Q_1, Q_2) f_i(Q_1, Q_2)$$



Form factor dependent

Universal weight functions

Relevant Q^2 region:

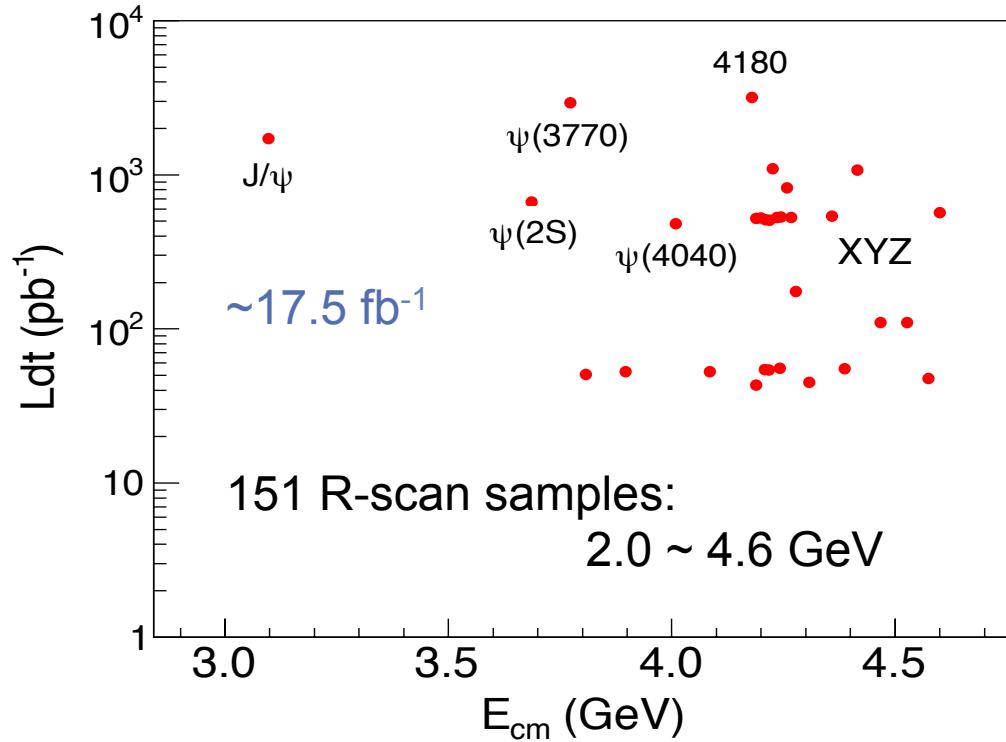
<1.5 GeV 2

Peak around 0.25 GeV 2

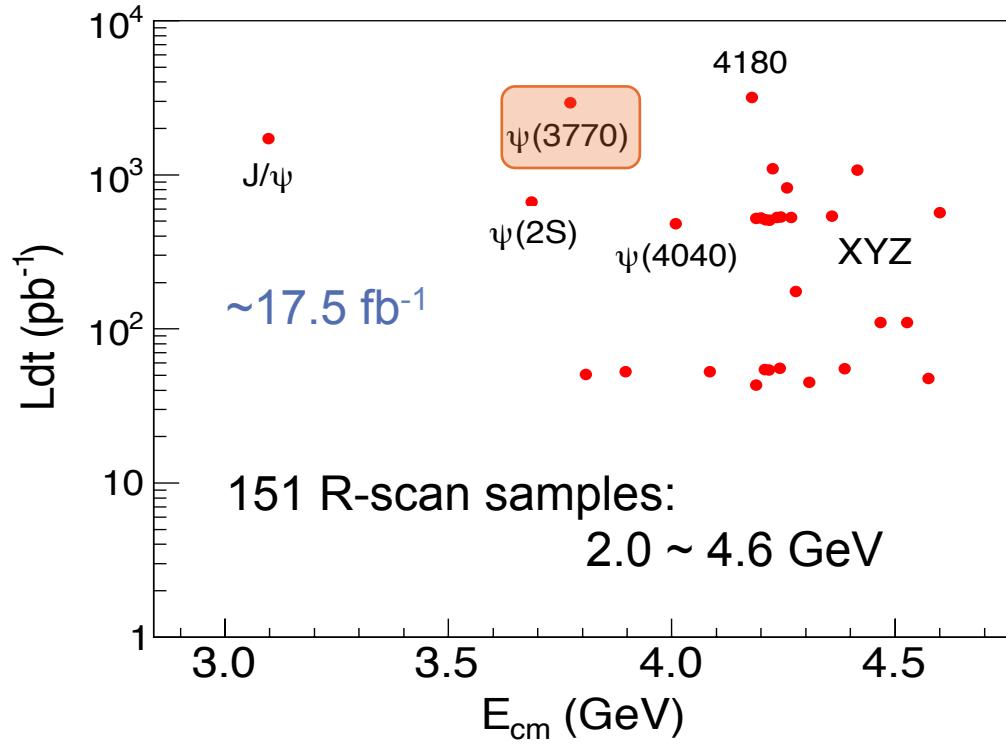
Double virtual form factor
needed!

[M. Knecht and A. Nyffeler: Phys. Rev. D 65, 073034 (2002)]

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



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

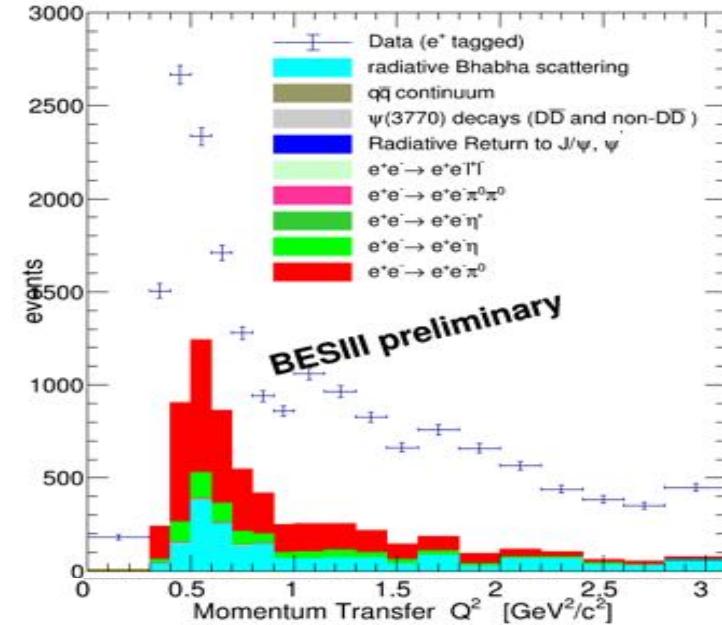
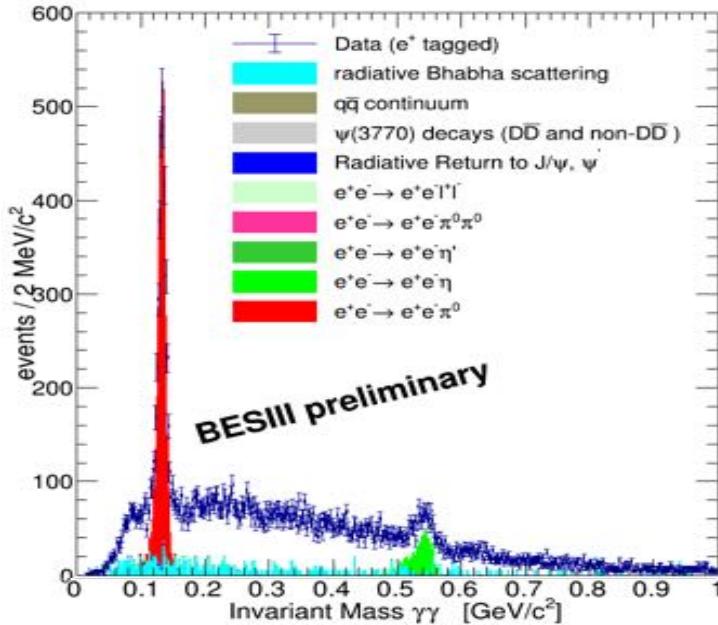


- 2.93 fb^{-1}
- Signal: EKHARA2.1 generator

Event Selection:

- Exactly one lepton candidate, $E/P > 0.8$
- At least two, max four photons
- Cut on angle of the missing momentum
- Helicity angle $\cos \theta_H < 0.8$
- Kinematic cuts to reject ISR background

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



Form Factor Calculation

Strategy: Count π^0 yield in bins of Q^2  $d\sigma/dQ^2$  Form factor $F(Q^2)$

Form Factor Calculation

Strategy:

Count π^0 yield in
bins of Q^2

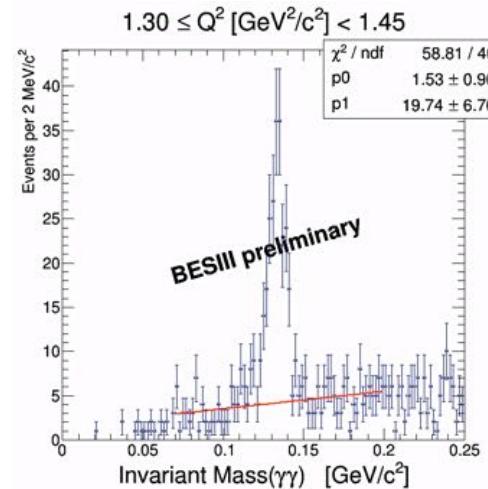
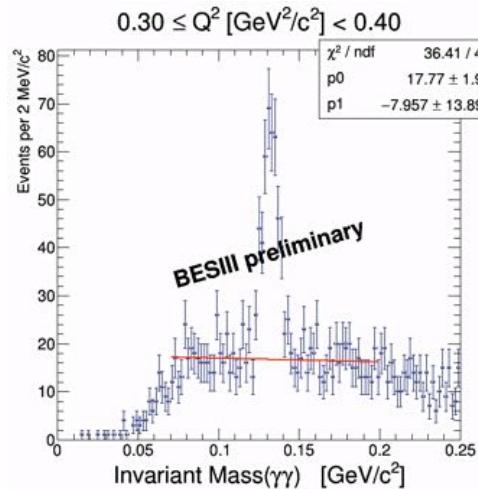


$d\sigma/dQ^2$



Form factor
 $F(Q^2)$

- Fit invariant mass distribution for each Q^2 bin
 - Exclude peak region from fit
 - Count number of events in peak region above fitted background



Form Factor Calculation

Strategy: Count π^0 yield in bins of Q^2  $d\sigma/dQ^2$  Form factor $F(Q^2)$

- Normalize background subtracted data to detection efficiency and luminosity

Form Factor Calculation

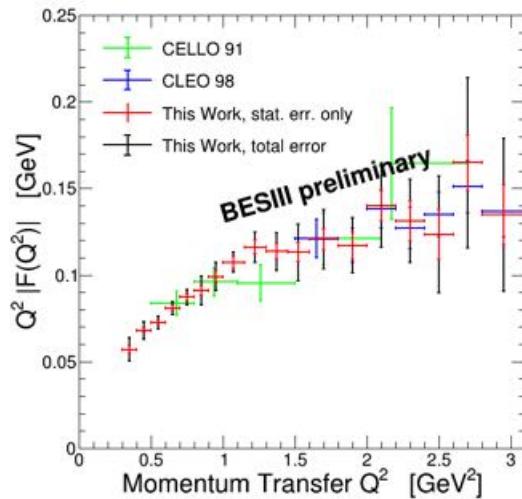
Strategy: Count π^0 yield in bins of Q^2  $d\sigma/dQ^2$  Form factor $F(Q^2)$

- Normalize background subtracted data to detection efficiency and luminosity
- Divide by point-like cross section to obtain TFF

Form Factor Calculation



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- Divide by point-like cross section to obtain TFF

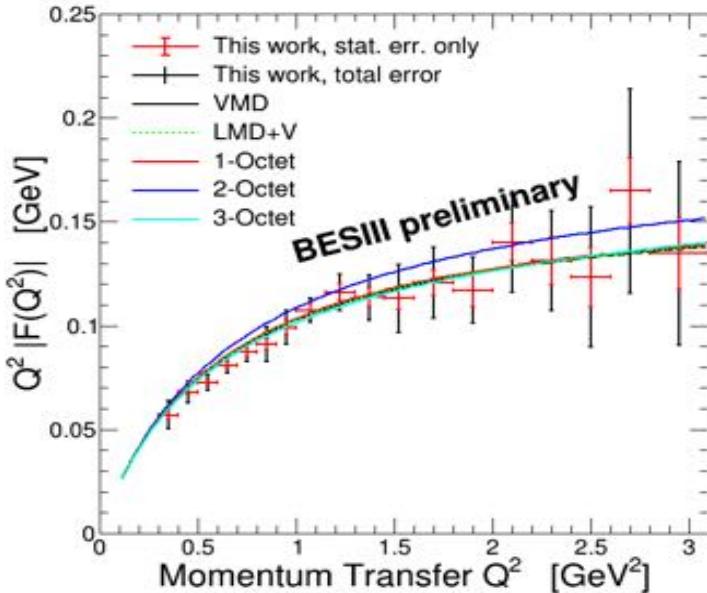


- First Measurement below 0.5 GeV^2
- Unprecedented accuracy below 1.5 GeV^2
- Competitive accuracy up to 3.1 GeV^2

[CELLO: Z. Phys. C 49 401 (1991)]
[CLEO: Phys. Rev. D57 33 (1998)]

Comparison to Theory

Models:



- Parameters fixed according to publications
- Agreement with result:

$$\left. \begin{array}{l} \chi^2_{\text{VMD}} = 8.48 \\ \chi^2_{\text{LMD+V}} = 8.62 \\ \chi^2_{\text{1-Octet}} = 9.54 \\ \chi^2_{\text{2-Octet}} = 24.14 \\ \chi^2_{\text{3-Octet}} = 5.94 \end{array} \right\} n.d.f = 18$$

$$F_{\text{VMD}}(Q^2) = -\frac{N_c}{12\pi^2 F_\pi} \frac{M_V^2}{M_V^2 + Q^2}$$

$$F_{\text{LMD+V}}(Q^2) = -\frac{F_\pi}{3} \frac{h_1 Q^4 - h_5 Q^2 + h_7}{(M_{V1}^2 + Q^2)(M_{V1}^2 + Q^2) M_{V1}^2 M_{V2}^2}$$

$$F_{\text{n=1,2-Octet}}(Q^2) = -\frac{N_c}{12\pi^2 F_\pi} + \sum_{i=1}^n \frac{4\sqrt{2}h_{Vi}f_{Vi}}{3F_\pi} Q^2 (D_{\rho_i} - D_{\omega_i})$$

$$F_{\text{3-Octet}}(Q^2) = -\frac{N_c}{12\pi^2 F_\pi} + \sum_{i=1}^3 \frac{4\sqrt{2}h_{Vi}f_{Vi}}{3F_\pi} Q^2 (D_{\rho_i} + F_{\omega_i} H_{\omega_i} D_{\omega_i} + A_i^{\pi^0} F_{\phi_i} D_{\phi_i})$$

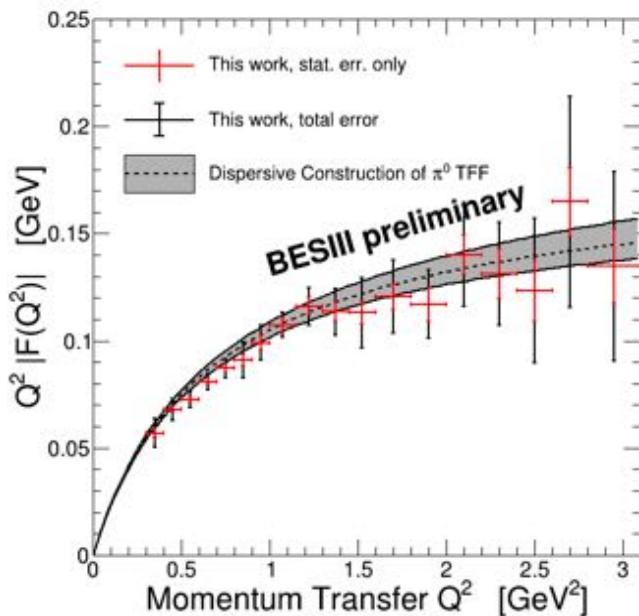
[Knecht,Nyffeler Phys. Rev. D65 073034 (2002)]

[Czyz et al. Phys. Rev. D55 094010 (2012)]

[Czyz et al. Phys. Rev. D97 016006 (2018)]

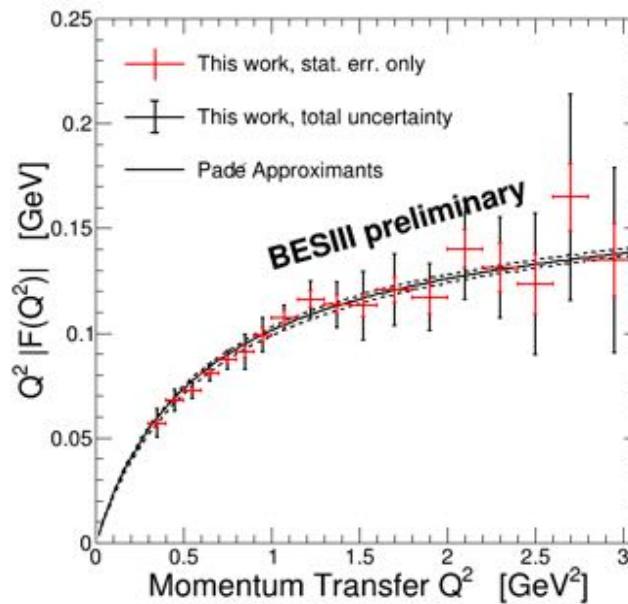
Comparison to Theory

Data-driven Approaches:



[Hoferichter et al., Phys. Rev. Lett. 121 112002 (2018)]

- Construction of space-like TFF using time-like experimental results in dispersive calculations
- Agreement with result: $\chi^2_{\text{center}} = 11.52$

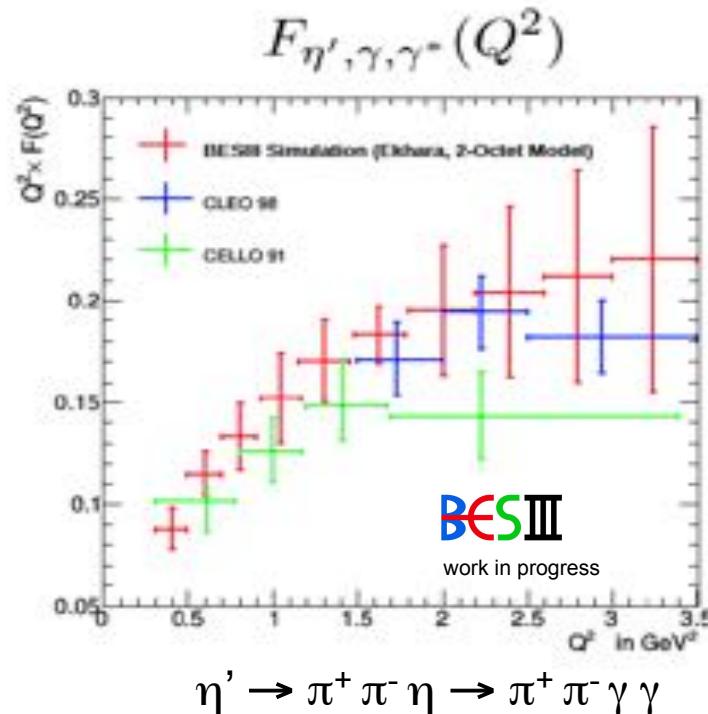
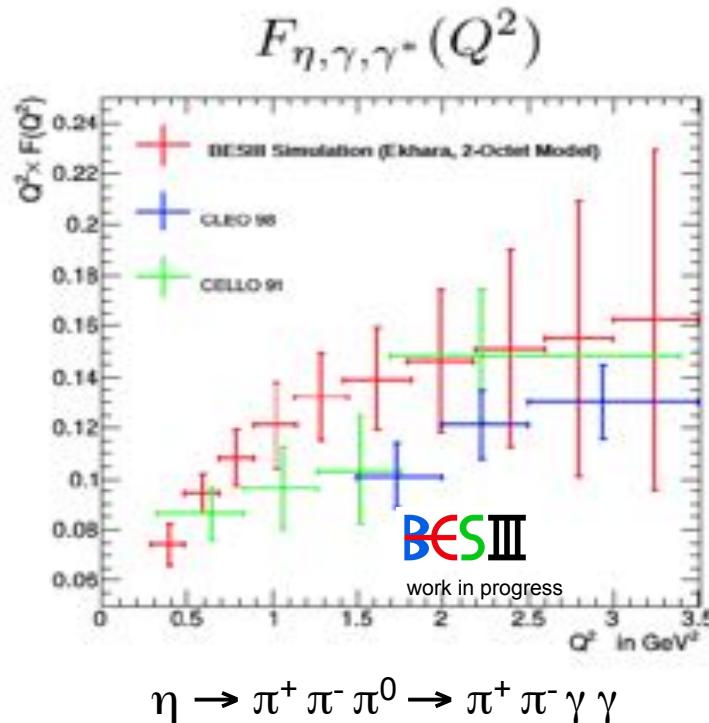


[Masjuan et al., Phys. Rev. D 86 094021]

- Padé approximants
 - Fit previous measurements
 - Model independent
 - Estimation of systematic uncertainty
- Agreement with result: $\chi^2_{\text{center}} = 5.74$

Space-like TFF: η / η'

MC only, $\psi(3770)$ statistics: 2.93 fb^{-1}

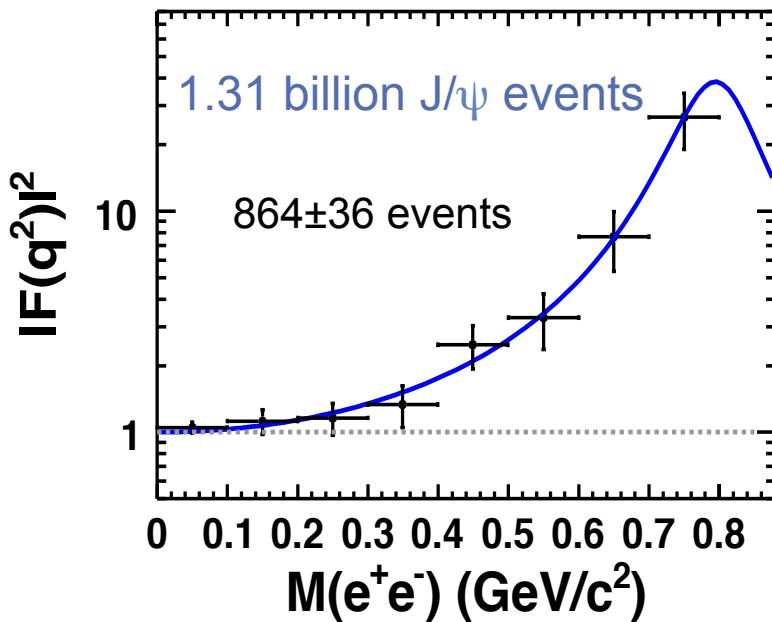


- Results competitive to previous measurement
- More data and more decay modes → order of magnitude improvement

Time-like TFF: η'

$$\frac{d\Gamma(\eta' \rightarrow \gamma l^+ l^-)}{dq^2 \Gamma(\eta' \rightarrow \gamma\gamma)} = [\text{QED}(q^2)] \times |F(q^2)|^2$$

↑
Point-like



Vector meson dominance model:

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

$$\Lambda^{-2} = (1.60 \pm 0.17 \pm 0.08) \text{ GeV}^{-2}$$

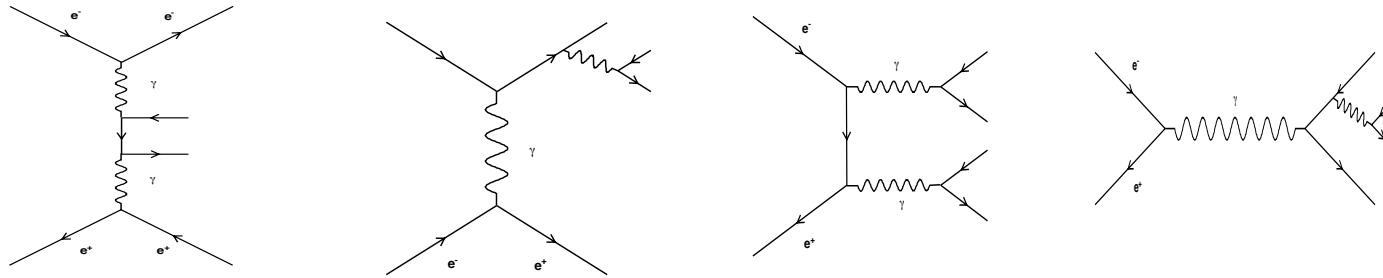
Agrees with VMD prediction

Space-like result

[BESIII: Phys. Rev. D92 012001 (2015)]

Space-like $\pi^+\pi^-$

- First single-tag measurement, 7.5fb^{-1} data sample
- Event selection similar to pesudoscalar analysis
- Dominate background:
 - $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$
 - QED process, dedicated μ/π separation, remaining estimated with precise MC simulation BdkRc + DIAG36-ABC
 - $e^+e^- \rightarrow e^+e^-\pi^+\pi^-$ (not two photon process)
 - Same final states as signal, radiative Bhabha scattering couples to vector resonance (ρ), extract using fit method



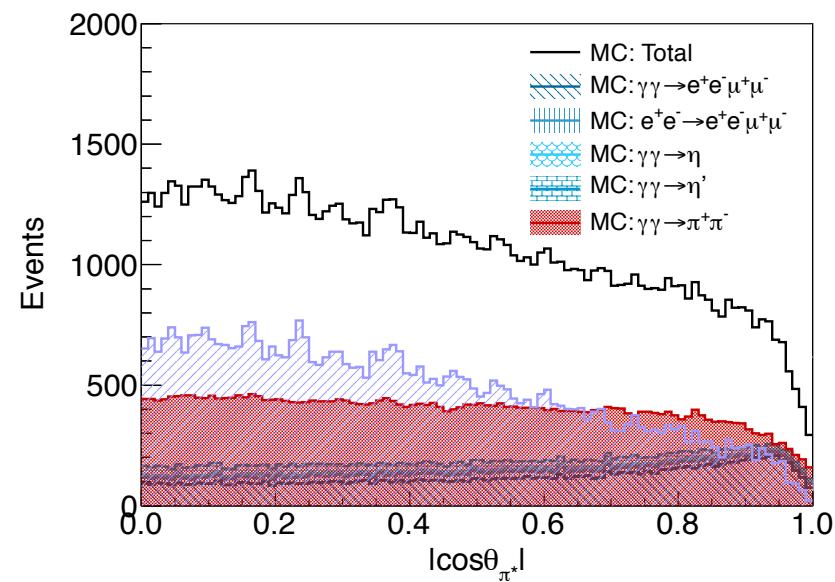
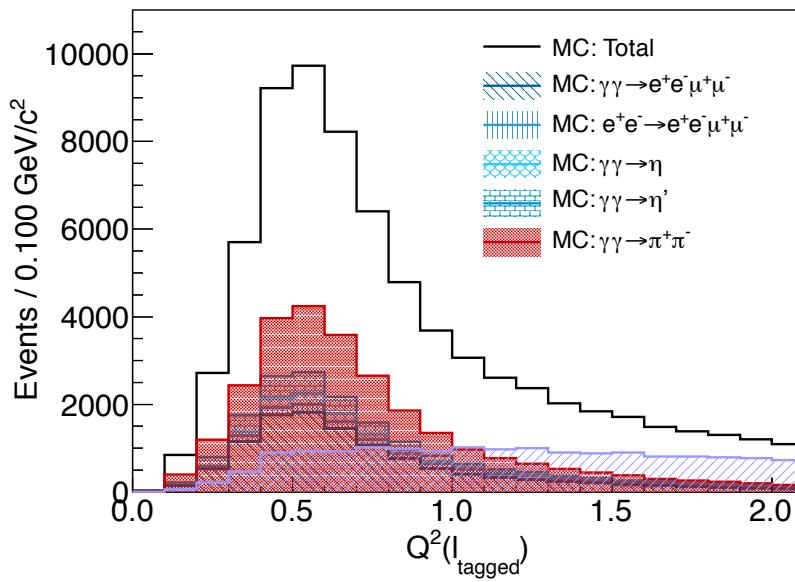
Available region

- Extract cross section in bins of W , Q^2 and $\cos\theta^*$

Access to: Q^2 region: 0.1 - 4.0 GeV^2

W : threshold - 2.0 GeV/c^2

$|\cos\theta^*|$: 0.0 - 1.0



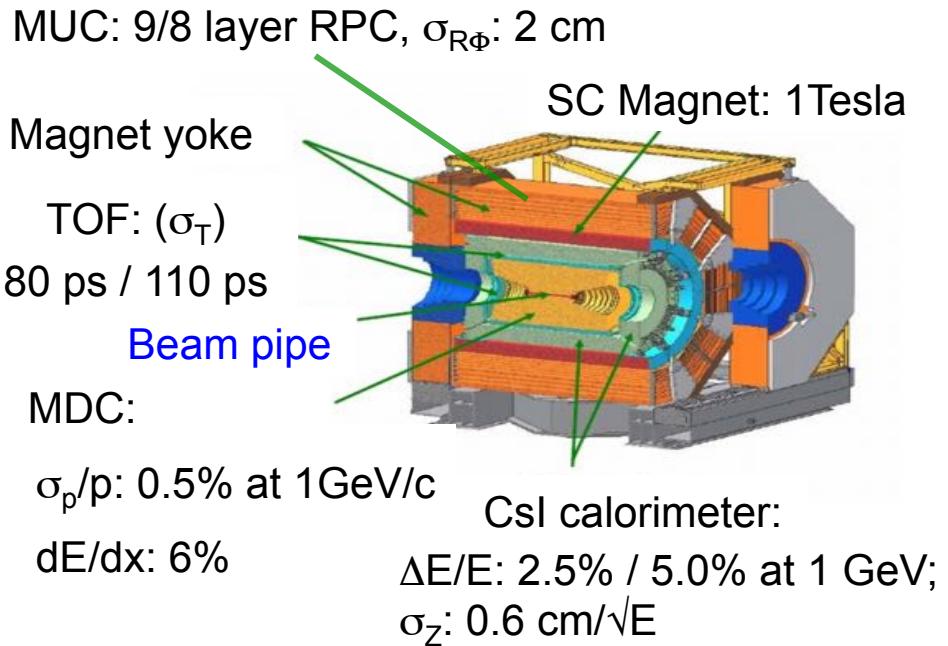
Conclusion and Outlook

Input for HLbL:

- Transition form factors of π^0 , η , η' in relevant Q^2 region
 - Unprecedented accuracy for $Q^2 < 1.5 \text{ GeV}^2$
- First measurement of single tag $\gamma\gamma \rightarrow \pi^+\pi^-$
 - Start from 2π invariant mass threshold, access to low Q^2 , cover full helicity angle
 - To be extended to neutral pion pair final state
- Double tag study of π^0 possible using BESIII statistics

THANK YOU FOR YOUR ATTENTION!

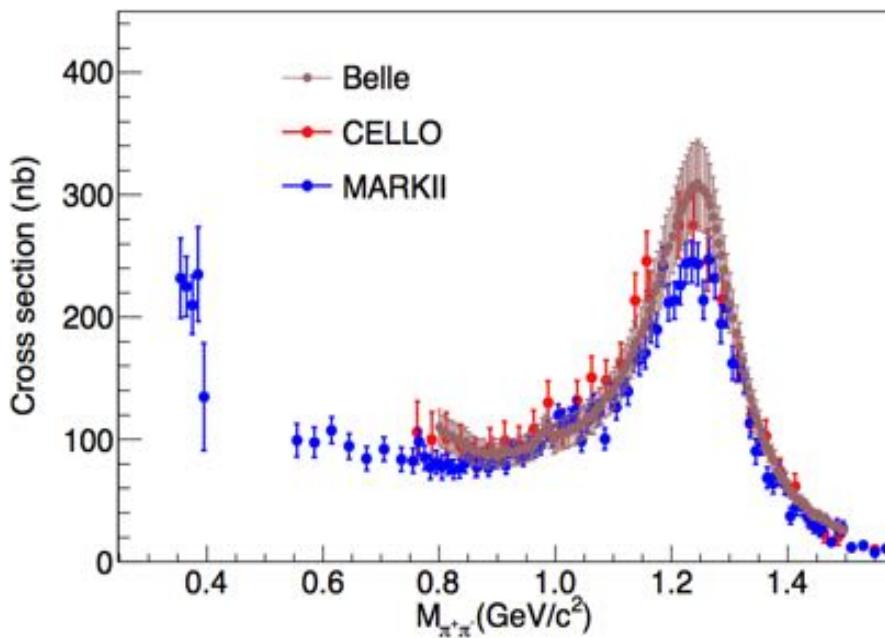
Beijing Electron Positron Collider-II



BEPCII: τ -charm factory
Beam energy:
1-2.3 GeV
Design luminosity:
 $1 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ (April 2016)
Data taking from 2009 to present

Previous Measurement

- MarkII: 209 fb^{-1} @ 29 GeV cover W from 0.35 to 1.60 GeV
[PRD42, 5, 1990]
- Cello: 86 fb^{-1} cover W from 0.75 to 1.9 GeV
[Z.Phys.C56, 381, 1992]
- Belle: 85.9 fb^{-1} @ 10.52-10.58 GeV cover W from 0.8 to 1.5 GeV
[PRD75, 051101(R), 2007]



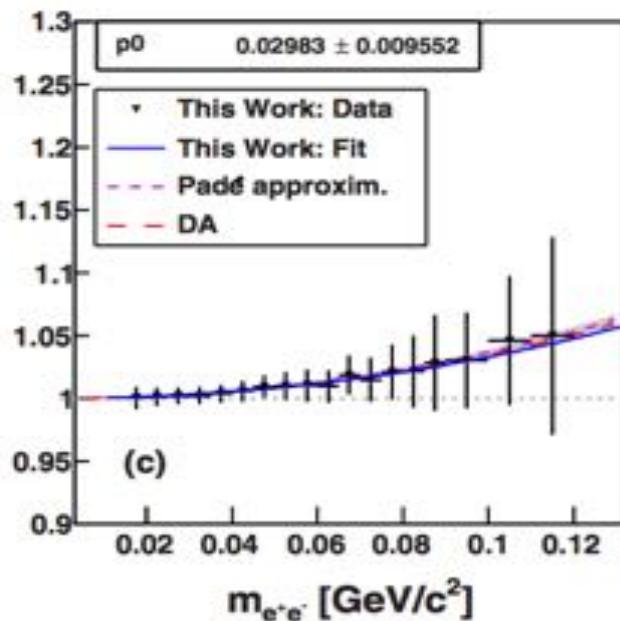
- All in two real photon case:
 $\gamma\gamma \rightarrow \pi^+\pi^-$
- In low mass region, only measurement come from MarkII

Systematic Uncertainties

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

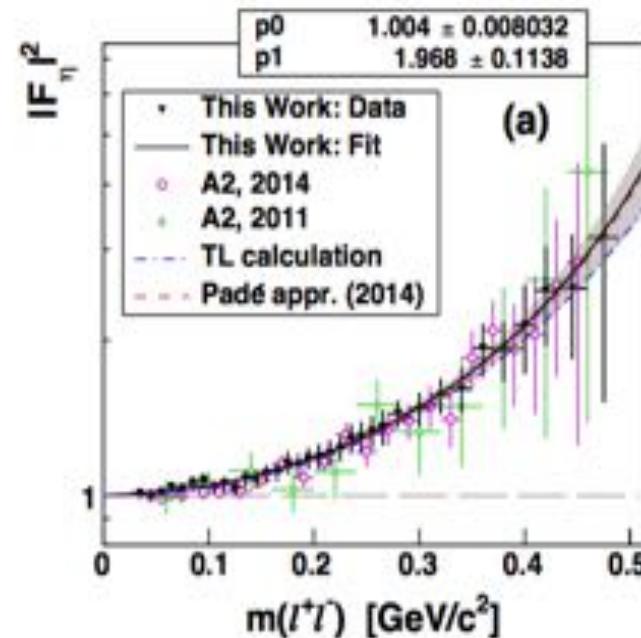
	Source	Contribution
External	Tracking efficiency	0.25%
	Photon detection efficiency	1%
	Luminosity	0.25%
Analysis	$q_{\text{tag}} \cdot \cos \theta_{\text{miss}} < -0.99$	0.1% – 3.1%
	$\cos \theta_H < 0.8$	0.2% – 4.5%
	$ \Delta\phi_{\gamma\gamma} < \frac{\pi}{2}$	negligible
	$ \Delta\theta_{\gamma\gamma} - 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%

Time-like TFF: A2



4.0×10^5 dalitz decays; $a_\pi = 0.030(10)_{\text{tot}}$

[Phys. Rev. C 95 025202 (2017)]



$$\Lambda^{-2} = 1.97(13)_{\text{tot}} \text{ GeV}^{-2}$$

[Phys. Rev. C 95 035208 (2017)]

