Study of Electromagnetic Dalitz Decays at BESIII

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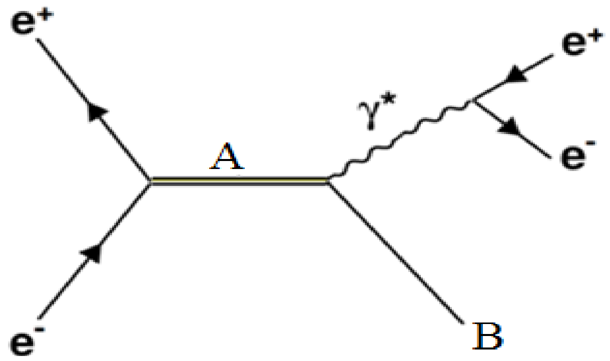
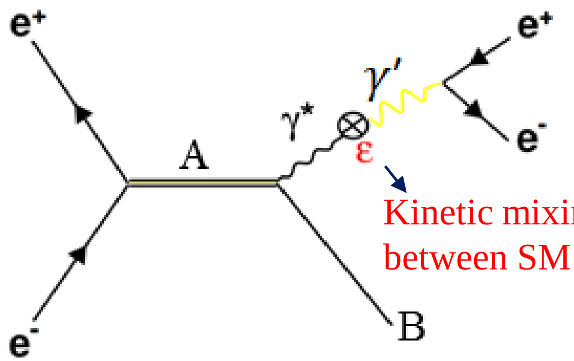
Motivation

- Electromagnetic (EM) Dalitz decays of A→e^+e^-B proceed via A→γ^*B, where the virtual photon γ^* converts into a lepton-pair in the final state.

- Study of EM Dalitz decays is important
  - ✓ Reveal the inner structure of hadrons and the interaction mechanism between photons and hadrons
  - ✓ Search for a hypothetical dark photon (γ') predicted by many models beyond the Standard Model (SM).

[Mod. Phys. Lett. A 27, 1250223 (2012)]





- Four-momentum transfer square ($q^2 = m^2_{e^+e^-}$) dependent decay rate A→e^+e^-B for the physical mesons is strongly modified by the transition form factor (TFF), $|F_{AB}(q^2)|^2$.

$$F_{AB}(q^2) = N \sum_{V'} \frac{m^2_{V'}}{m^2_{V'} - q^2 - i\Gamma_{V'} m_{V'}}$$

Within the vector meson dominance (VMD) model, the TFF is mainly governed by coupling of the γ^* to the A meson via an intermediate vector V' meson in the time-like region.

[Phys. Rept. 128, 301 (1985)]

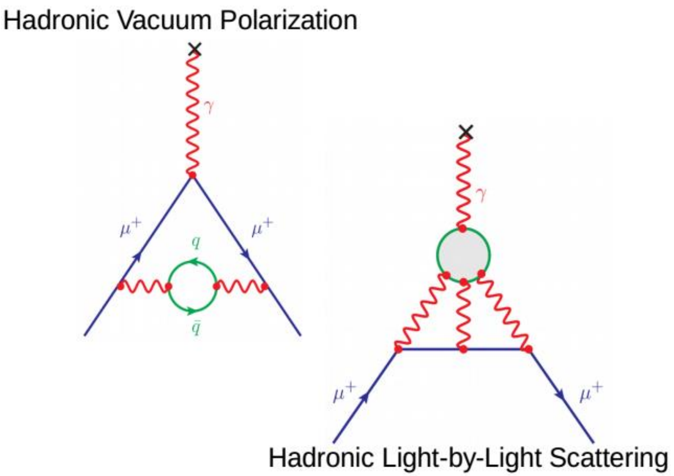
Motivation

- Experimental measurement of the TFF is important
  - ✓ Test the precision of VMD model **[Phys. Rept. 128, 301 (1985)]**
  - ✓ Test the theoretical precision of the anomalous magnetic moment of muon a_μ

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

Contribution	Result in 10^{-10} units
QED (leptons)	11658471.895 ± 0.008
Weak	15.4 ± 0.2
Hadronic	694.4 ± 5.8
Total (SM)	11659181.4 ± 5.8
BNL (E821)	11659208.9 ± 6.3
Difference	27.5 ± 8.6

Test of Standard Model !



Prediction is completely limited by the hadronic contribution.

TFF uses an input in the calculation of the hadronic Light-by-Light scattering corrections to the theoretical determination of a_μ. **[Phys. Lett. B 738, 6 (2014); JHEP 09,074 (2015)]**

BESIII Experiment

BESIII experiment is a symmetric electron positron collider experiment running as tau-charm region located at Institute of High Energy Physics, Beijing, China

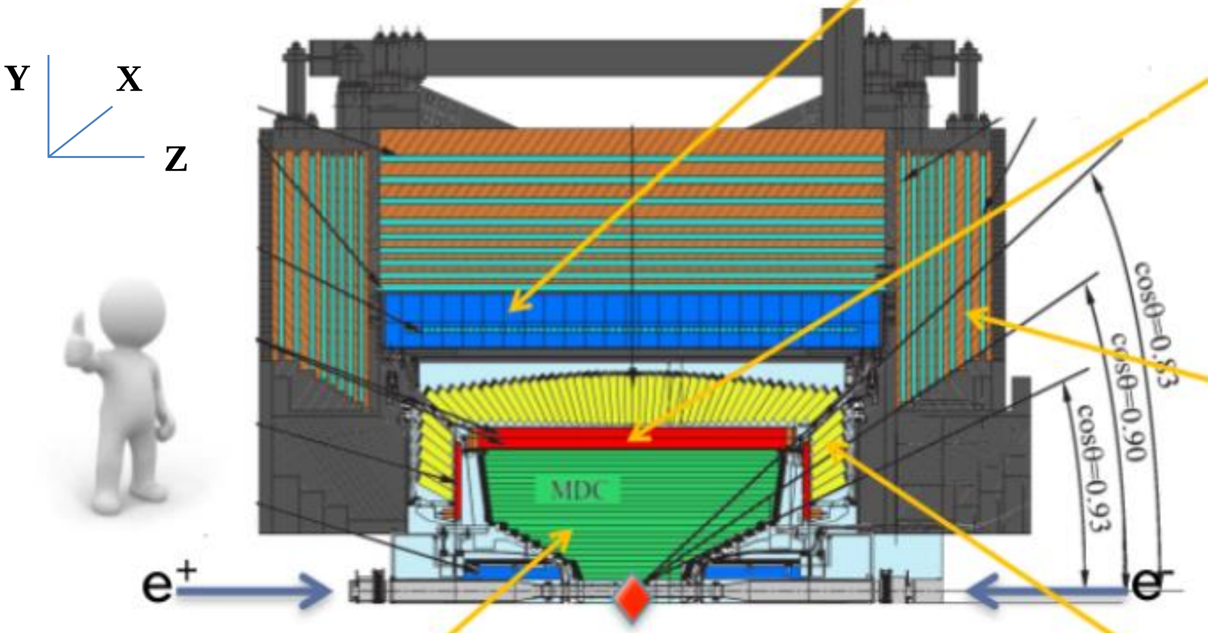
Super conducting magnet

✓ **1 Tesla**

[Nucl. Instrum. Meth. A614, 345-399 (2010)]

Time of Flight (TOF)

- **2 layer plastic scintillators**
- **σ_T = 90 ps (barrel)**
- **σ_T = 90 ps (endcap)**
- **Use for particle id**



Muon system

- **9 layers of RPC**
- **P > 400 MeV/c**
- **$\delta R\phi$= 1.4 – 1.7 cm**

Multilayer drift chamber (MDC)

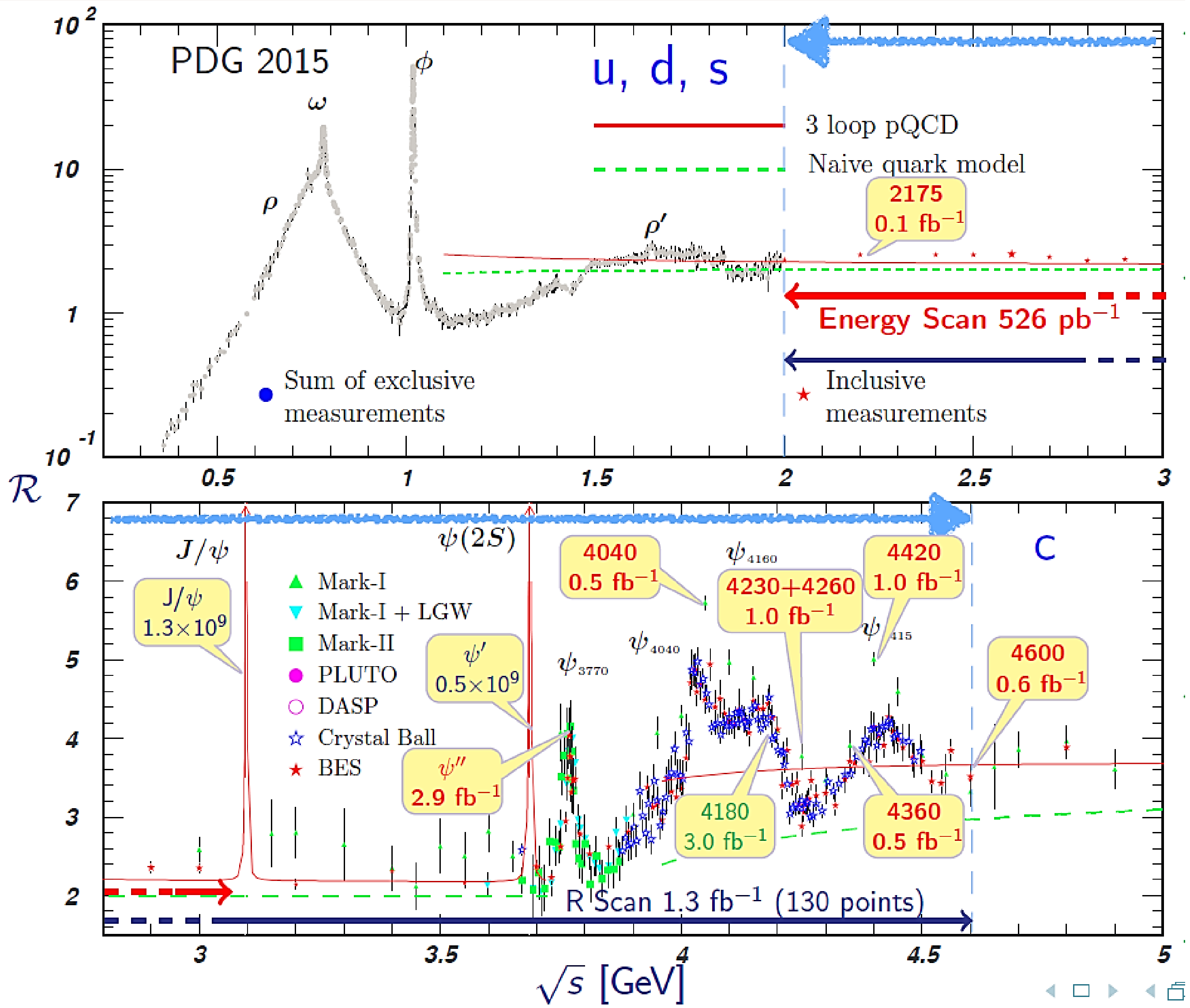
- **He/C_3H_8 (60/40)**
- **43 layers**
- **Momentum resolution σ_p/p = 0.5% @ 1 GeV**
- **Spatial resolution σ_{xy} = 130 μm.**

Electromagnetic calorimeter (EMC) (CsI(Tl))

→ 6240 crystals

- **$\sigma(E)/E$ = 2.5%**
- **$\sigma_{Z,\phi}(E)$ = 0.5 – 0.7 cm**

BESIII Data-set



World largest data for

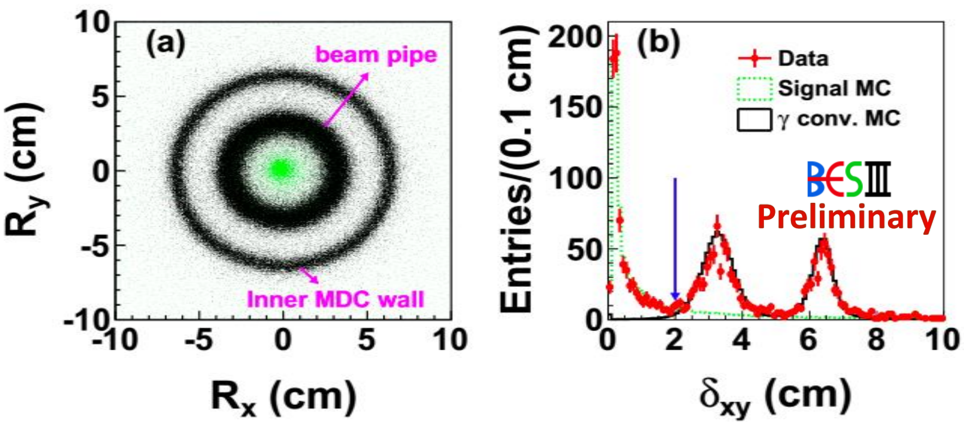
- ✓ Charmonium spectroscopy
- ✓ Charm physics
- ✓ Light hadrons
- ✓ τ and R scan

Dalitz studies are mainly based on the data samples collected at J/ψ and ψ(2S) resonances

Dalitz decay of $J/\psi \to e^+e^-\eta$

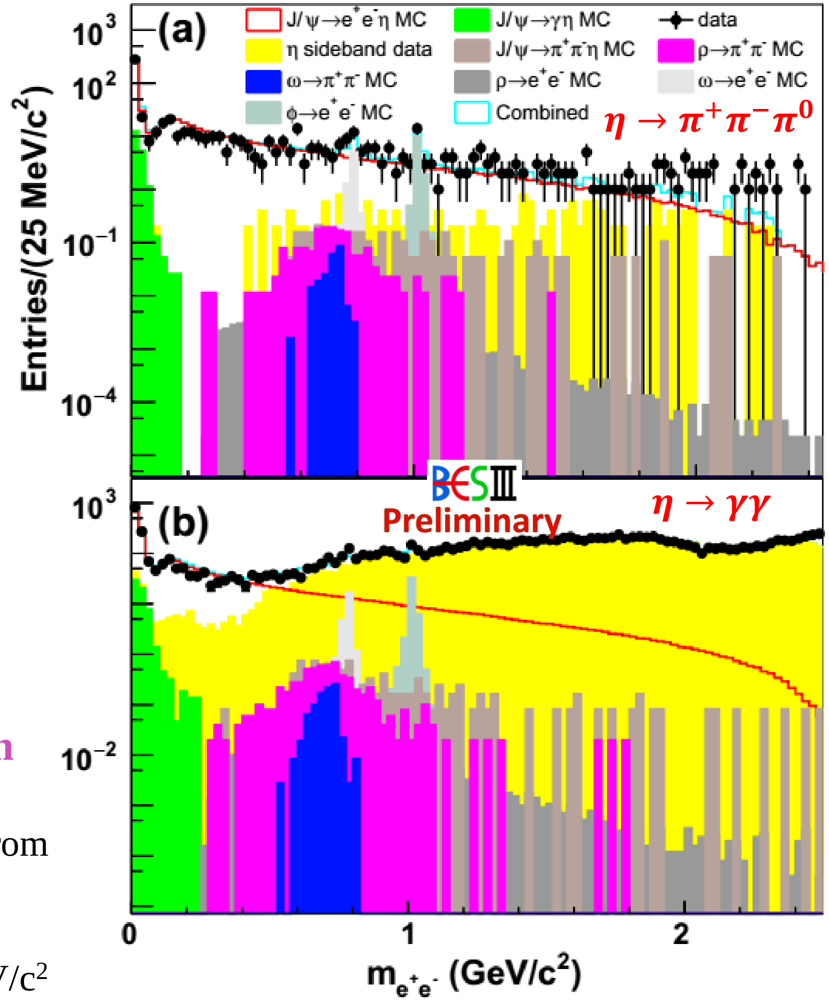
BESIII **Preliminary**

- BESIII previously measured $B(J/\psi \to e^+e^-\eta) = (1.16 \pm 0.07(stat) \pm 0.06(syst)) \times 10^{-5}$ using **225 million J/ψ events**. **[Phys. Rev. D 89, 092008 (2014)]**
- The new measurement is based on **$(1310.6 \pm 7.0) \times 10^6$ J/ψ events**.
- Main peaking background: Photon conversion **[Chin. Phys. C 36, 742 (2012)]**



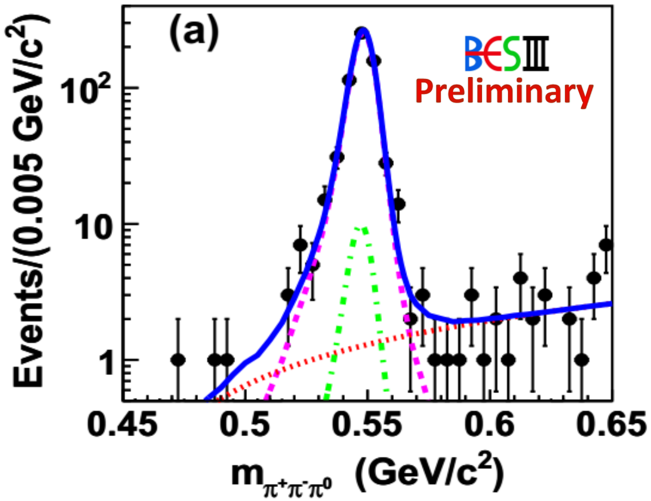
✓ **Further selection criteria for the branching fraction measurement**

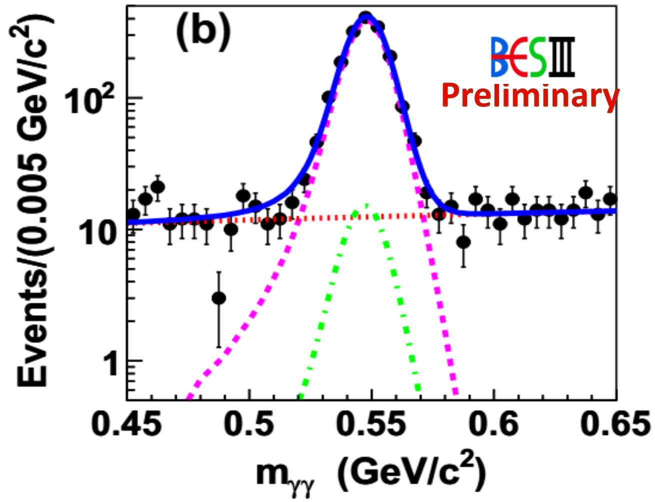
- $m_{e^+e^-} < 0.5$ GeV/c^2 in $\eta \to \gamma\gamma$ decay (to suppress background from radiative Bhabha process $e^+e^- \to \gamma e^+e^-$)
- Discard the events in the regions of $0.65 < m_{e^+e^-} < 0.90$ GeV/c^2 and $0.96 < m_{e^+e^-} < 1.08$ GeV/c^2 in $\eta \to \pi^+\pi^-\pi^0$ decay.



Dalitz decay of $J/\psi \to e^+e^-\eta$

BESIII Preliminary





- Signal: MC shape ⊗ Gaussian
- Non-peaking background: Chebychev Polynomial
- Peaking background: MC shape (γ conversion, $J/\psi \to V\eta$, $V=e^+e^-$, $\pi^+\pi^-$)

	$\eta \to \pi^0\pi^+\pi^-$	$\eta \to \gamma\gamma$
Signal Yield	594.9 ± 25.3	1623.4 ± 43.6
Efficiency (%)	15.2	24.9
$B(J/\psi \to \eta e^+e^-)$ (10^{-5})	$1.32 \pm 0.06_{stat} \pm 0.07_{syst}$	$1.26 \pm 0.03_{stat} \pm 0.06_{syst}$
Combined result (10^{-5})	$\mathbf{1.28 \pm 0.03_{stat} \pm 0.06_{syst}}$	

BESIII Preliminary

Precision is improved by a factor of **1.4** over the **previous BESIII measurement**.

[Phys. Rev. D 89, 092008 (2014)]

Dalitz decay of $J/\psi \to e^+e^-\eta$: TFF study

BESIII **Preliminary**

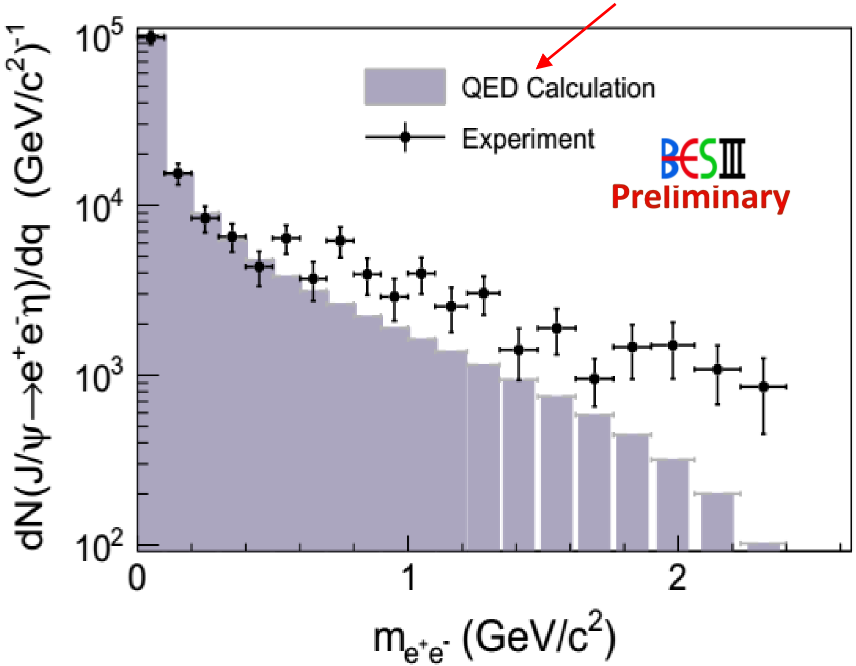
- Due to large contamination of radiative Bhabha background in $\eta \to \gamma\gamma$, only the data sample of $\eta \to \pi^+\pi^-\pi^0$ is used for the **TFF study**.

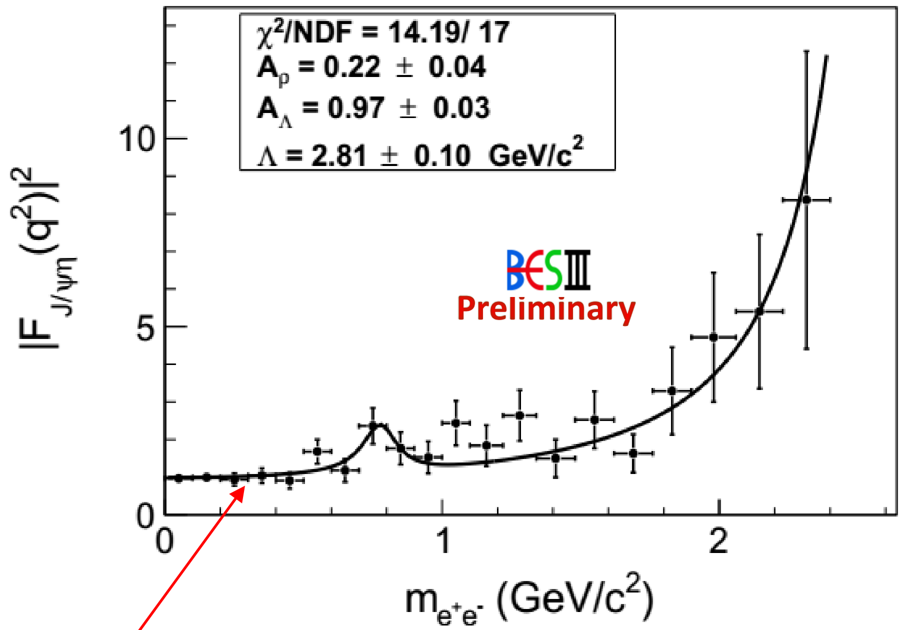
✓ Four momentum transfer square ($q^2 = m^2_{e^+e^-}$) dependent decay rate

$$\frac{d\Gamma(J/\psi \to e^+e^-\eta)}{d\Gamma(J/\psi \to \gamma\eta)} = \frac{\alpha}{3\pi}|F_{J/\psi\eta}(q^2)|^2\left(1-\frac{4m_e^2}{q^2}\right)^{1/2}\frac{2}{q}\left(1+\frac{2m_e^2}{q^2}\right)\left[\left(1+\frac{q^2}{m^2_{J/\psi}-m^2_\eta}\right)^2-\frac{4m^2_{J/\psi}q^2}{(m^2_{J/\psi}-m^2_\eta)^2}\right]^{3/2}$$

$$= |F_{J/\psi P}(q^2)|^2 \times [QED(q^2)]$$

First measurement



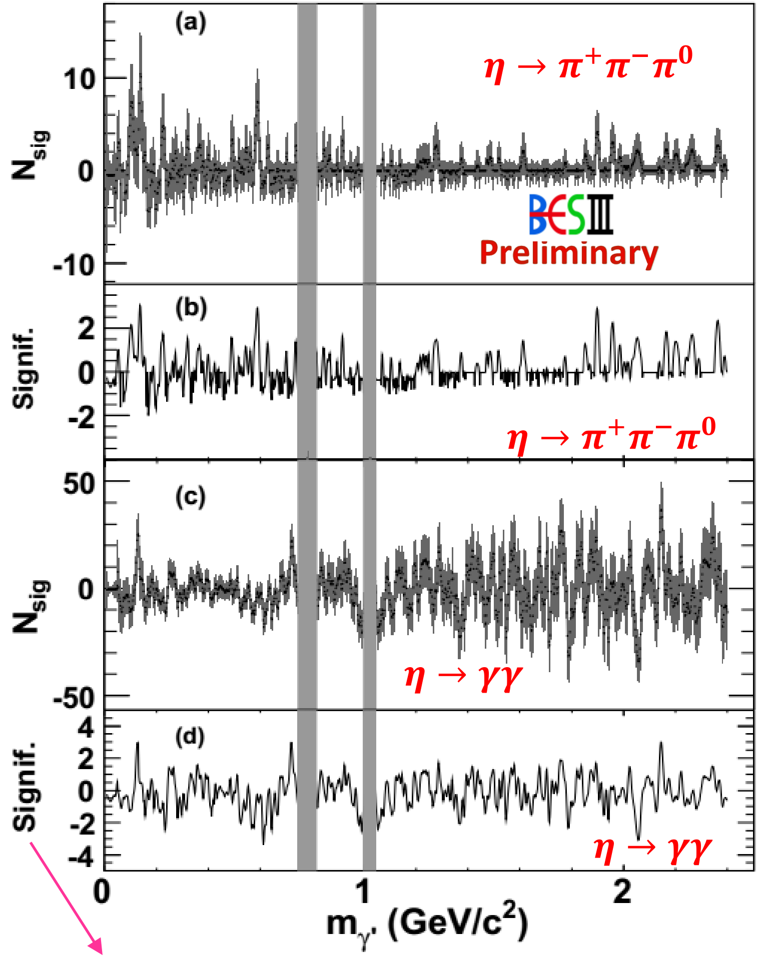


Deviation from the QED spectrum= Form Factor

$$|F_{J/\psi\eta}(q^2)|^2 = |A_\rho|^2\left(\frac{m_\rho^2}{(m_\rho^2-q^2)^2+\Gamma_\rho^2 m_\rho^2}\right)^2 + |A_\Lambda|^2\left(\frac{\Lambda^2}{\Lambda^2-q^2}\right)^2$$

Dalitz decay of $J/\psi \to e^+e^-\eta$: dark photon search

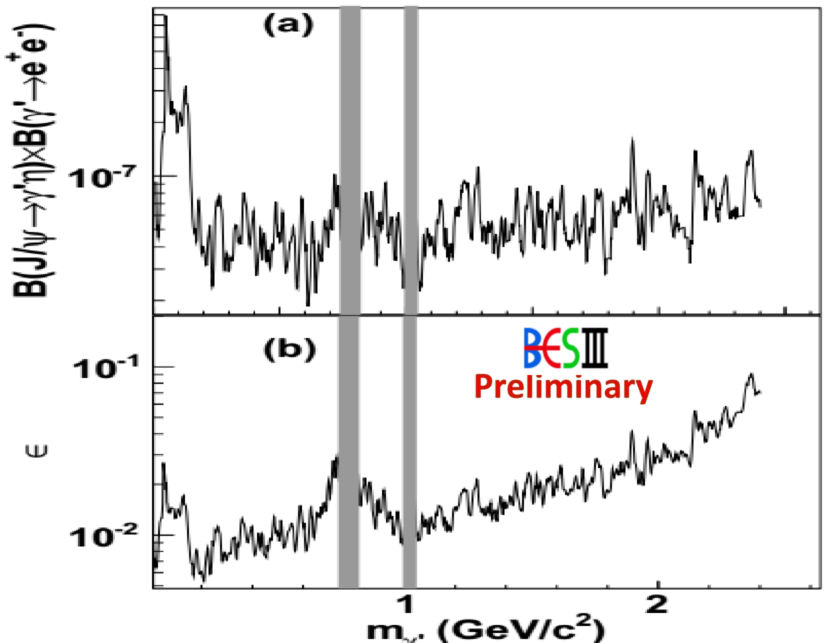
- Search for a narrow resonance of dark photon (γ') in the step of 2 MeV/c^2 using the surviving event candidates within the η mass window of [0.52, 0.57] GeV/c^2



$S = sign(Nsig)\sqrt{-2lnL_0/L_{max}}$

No evidence of γ´ production is found.

Set 90% confidence level (C.L.) on the product branching fraction $B(J/\psi \to \gamma'\eta) \times B(\gamma' \to e^+e^-)$ for the **first time,** as well as kinematic strength between SM photon and dark photon.



$$\frac{B(J/\psi \to \gamma'\eta)}{B(J/\psi \to \gamma\eta)} = \epsilon^2\, |F_{J/\psi\eta}(m_{\gamma'}^2)|^2 \frac{\Lambda'^{\frac{3}{2}}(m_{J/\psi}^2, m_\eta^2, m_{\gamma'}^2)}{\Lambda'^{\frac{3}{2}}(m_{J/\psi}^2, m_\eta^2, 0)}$$ [JHEP 0907, 051 (2009)]

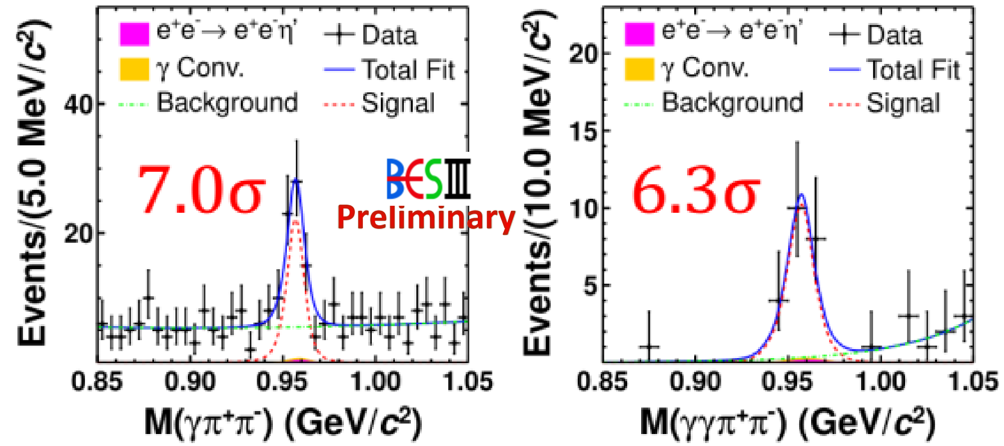
Where, $\Lambda(m_1^2, m_2^2, m_3^2) = (1 + \frac{m_3^2}{m_1^2 - m_2^2})^2 - \frac{4m_1^2 m_3^2}{(m_1^2 - m_2^2)^2}$

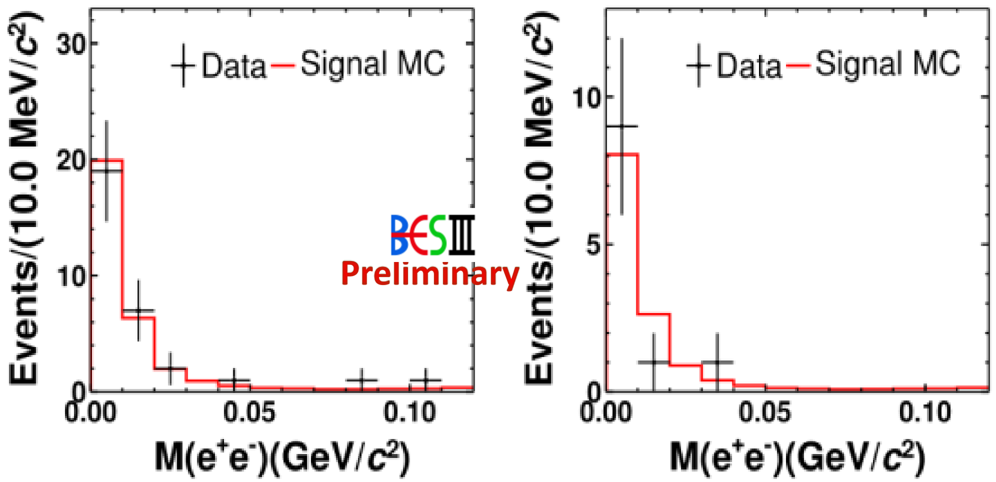
$|F_{J/\psi\eta}(m_{\gamma'}^2)|^2 = \frac{\Lambda^2}{\Lambda^2 - m_{\gamma'}^2}$ is $m_{\gamma'}$ dependent TFF, where $\Lambda = m_{\psi(2S)}$

$B(J/\psi \to \gamma'\eta)$ is computed by dividing the $B(J/\psi \to \gamma'\eta) \times B(\gamma' \to e^+e^-)$ by expected $B(\gamma' \to e^+e^-)$ [Phys. Rev. D 79, 115008 (2009)]

Dalitz decay of $\psi(2S) \to e^+e^-\eta'$

BESIII Preliminary





First measurement

	$\eta' \to \gamma\pi^+\pi^-$	$\eta' \to \pi^+\pi^-\eta$
Signal yield	57.4 ± 9.6	20.2 ± 4.3
Background yield	224.1 ± 16.2	12.0 ± 3.6
ϵ (%)	25.25	17.70
Significance (σ)	7.0	6.3
$\mathcal{B}$ ($\times 10^{-6}$)	$1.75 \pm 0.29 \pm 0.11$	$1.51 \pm 0.33 \pm 0.11$

BESIII Preliminary

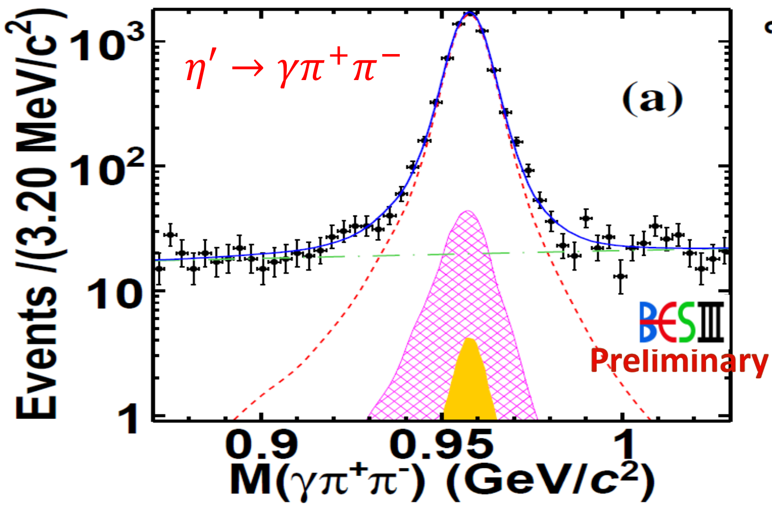
- The two modes of η' decay are combined by considering correlated and uncorrelated systematic uncertainties.

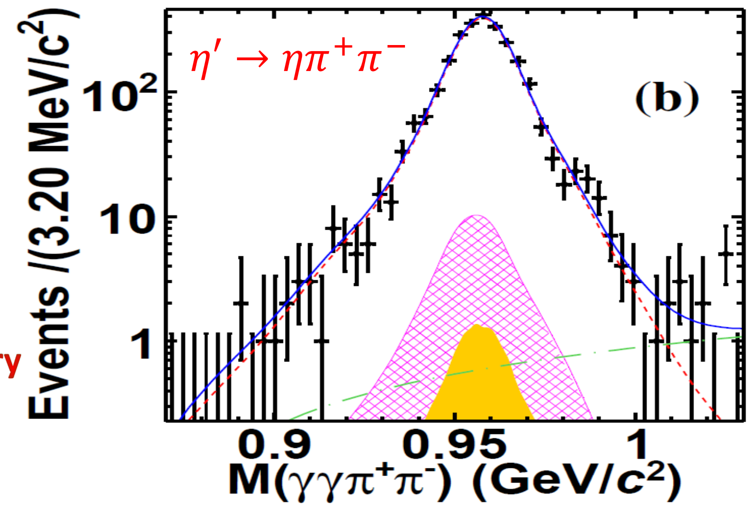
Combined result of $B(\psi(3686) \to \eta' e^+ e^-)$:
$(1.64 \pm 0.22_{stat} \pm 0.09_{syst}) \times 10^{-6}$

- The M(ee) distributions of data and signal MC generated based on a monopole TFF agree well with each other.

Dalitz decay of $J/\psi \to e^+e^-\eta'$

BESIII Preliminary





- Signal: MC shape ⊗ Gaussian
- Peaking background: MC shape (γ conversion/ $J/\psi \to \Phi\eta'$)
- Non-peaking background: Chebychev Polynomial

	$\eta' \to \gamma\pi^+\pi^-$	$\eta' \to \eta\pi^+\pi^-$
Signal Yield	6436.9 ± 87.1	2494.4 ± 51.3
Background Yield	981.4 ± 43.8	27.3 ± 10.0
Efficiency (%)	28.21	19.94
$B(J/\psi \to \eta' e^+e^-)$ (10^{-5})	$5.98 \pm 0.08_{stat} \pm 0.32_{syst}$	$5.65 \pm 0.12_{stat} \pm 0.33_{syst}$
Combined result(10^{-5})	$5.81 \pm 0.07_{stat} \pm 0.29_{syst}$	

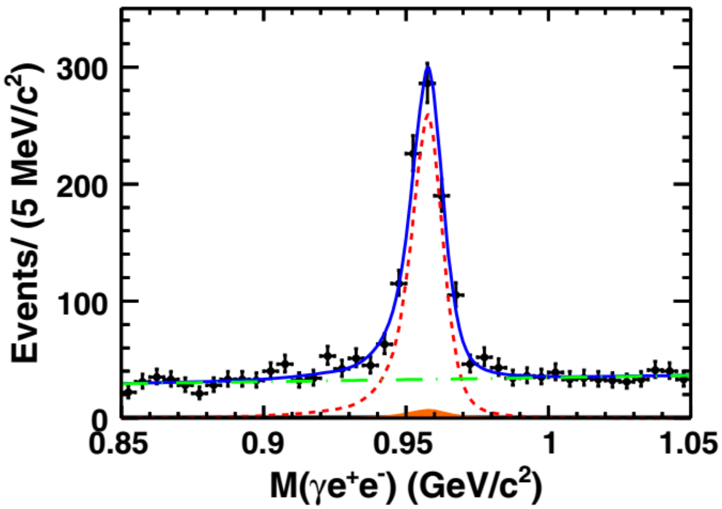
BESIII Preliminary

Improves on the **previous BESIII measurement** of $B(J/\psi \to \eta' e^+e^-)$ **[Phys. Rev. D 89, 092008 (2014)]**

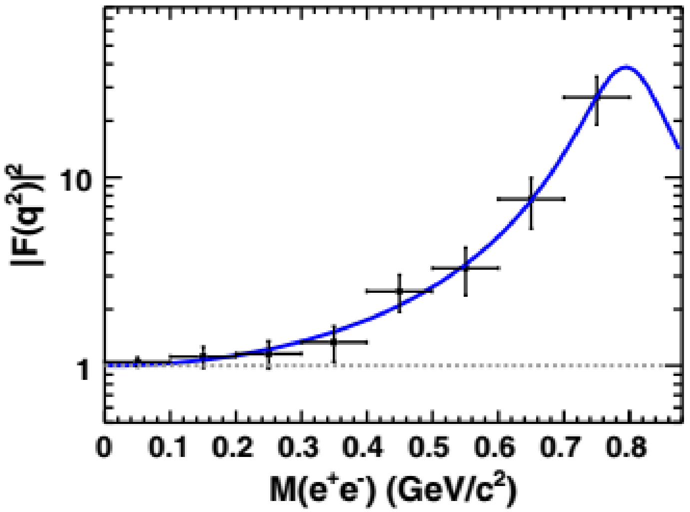
Dalitz decay of $\eta' \to e^+e^-\gamma$

Phys. Rev. D92, 012001 (2015)

- Reconstructed from $J/\psi \to \gamma\eta'$
- Using 1.3 billion J/ψ decays
- 864 ± 36 Dalitz events detected
- Measured quantities:
  - $\frac{\Gamma(\eta' \to \gamma e^+ e^-)}{\Gamma(\eta' \to \gamma\gamma)} = (2.13 \pm 0.09(stat) \pm 0.07(syst)) \times 10^{-2}$
  - $B(\eta' \to \gamma e^+ e^-) = (4.69 \pm 0.20(stat) \pm 0.23(syst)) \times 10^{-4}$



First measurement!



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

$$\Lambda_{\eta'} = (0.79 \pm 0.04(\text{stat}) \pm 0.02(\text{sys}))\ \text{GeV}$$

$$\gamma_{\eta'} = (0.13 \pm 0.06(\text{stat}) \pm 0.03(\text{sys}))\ \text{GeV}$$

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

Observation of ψ(2S)→$e^+e^-\chi_{cJ}$ and χ_{cJ}→ e^+e^- J/ψ

Phys. Rev. Lett. 118, 221802 (2017)

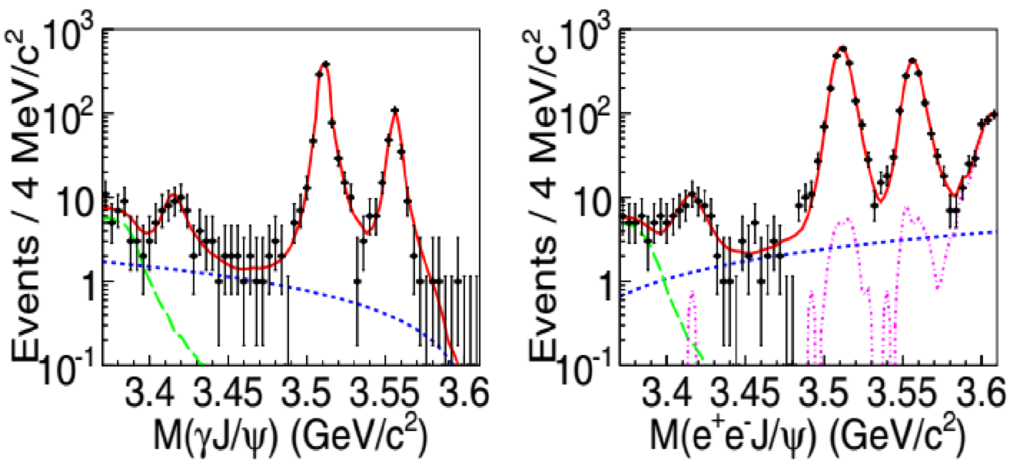
- Analyze the cascade decays

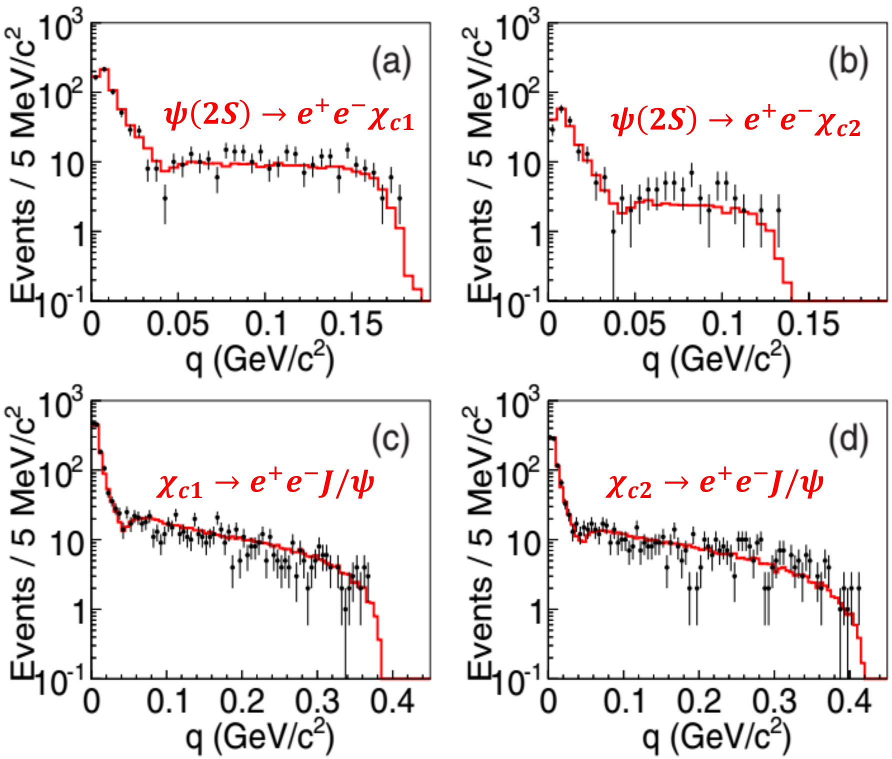
$$\psi(2S) \to e^+e^-\chi_{cJ}, \chi_{cJ} \to \gamma J/\psi, J/\psi \to l^+l^-$$

$$\psi(2S) \to \gamma\chi_{cJ}, \chi_{cJ} \to e^+e^-J/\psi, J/\psi \to l^+l^-$$

where $l = e, \mu$ and J = 0, 1, 2

- Using 447.9 million ψ(2S) decays





$$B(\psi(2S) \to e^+e^-\chi_{cJ}) = (11.7 \pm 2.5(stat) \pm 1.0(syst)) \times 10^{-4}, (8.6 \pm 0.3(stat) \pm 0.6(syst)) \times 10^{-4}, (6.9 \pm 0.5(stat) \pm 0.6(syst)) \times 10^{-4}$$

for J = 0, 1, 2

$$B(\chi_{cJ} \to e^+e^-J/\psi) = (1.51 \pm 0.30(stat) \pm 0.13(syst)) \times 10^{-4}, (3.73 \pm 0.09(stat) \pm 0.25(syst)) \times 10^{-3}, (2.48 \pm 0.08(stat) \pm 0.16(syst)) \times 10^{-3}$$

for J = 0, 1, 2

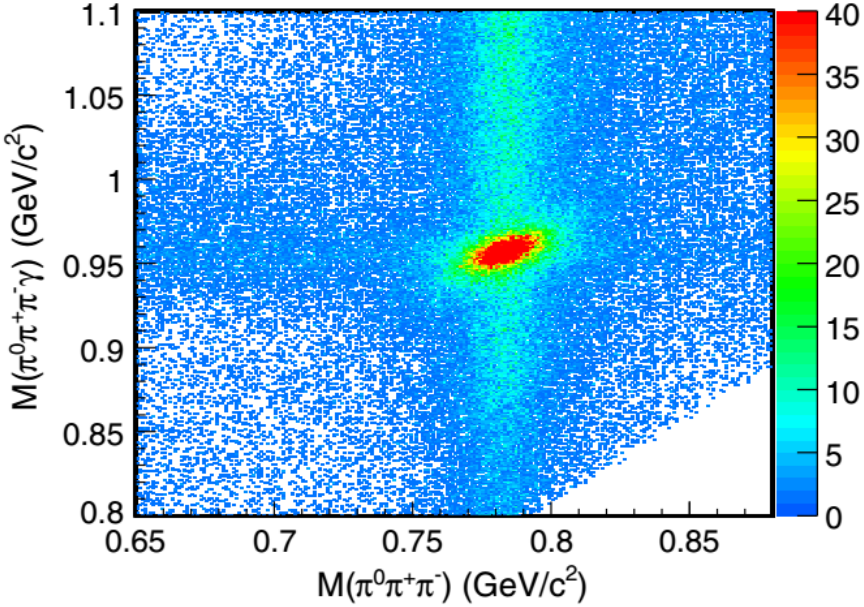
First measurement!

Observation of the Decay $\eta' \to \omega e^+e^-$

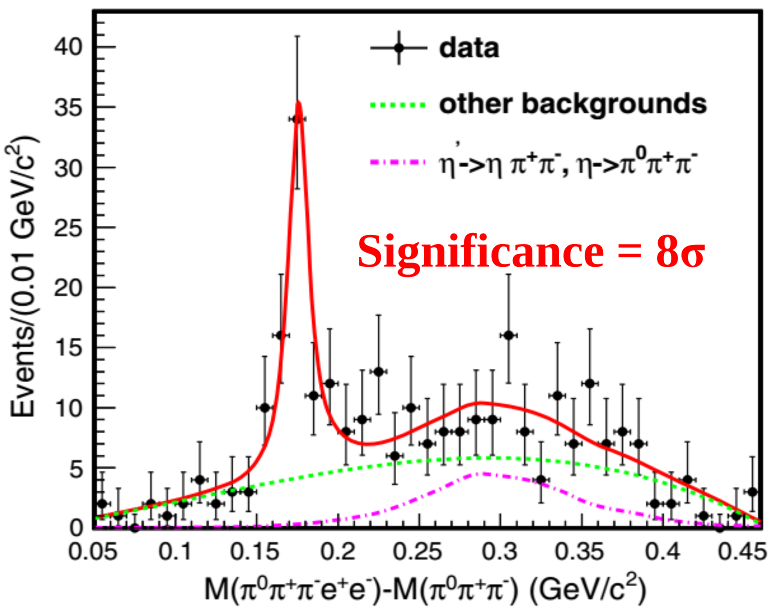
Phys. Rev. D 92, 051101 (R) (2015)

- Reconstructed from $J/\psi \to \gamma\eta'$ using 1.3 billion J/ψ decays

Normalization $\eta' \to \omega\gamma$



First observation



$$B(\eta' \to \omega e^+e^+) = (1.97 \pm 0.34(stat) \pm 0.17(syst)) \times 10^{-4}$$

First measurement ever

$$B(\eta' \to \omega\gamma) = (2.55 \pm 0.03(stat) \pm 0.16(syst)) \times 10^{-2}$$

in agreement with previous world average

Summary

- BESIII has updated branching fractions of $J/\psi \to e^+e^-\eta$ and $J/\psi \to e^+e^-\eta'$ using 1.3 billion J/ψ decays, and measured the TFF of $J/\psi \to e^+e^-\eta$ for the first time.

- Dalitz decays of $J/\psi \to e^+e^-\eta(')$ are also utilized to search for a dark gauge boson predicted by many models beyond the SM.

- The branching fraction and TFF of $\eta' \to \gamma e^+e^-$ are also measured for the first time.

- Also measured the branching fractions of the following Dalits decays for the first time:
  - $\psi(2S) \to e^+e^-\eta'$
  - $\psi(2S) \to e^+e^-\chi_{cJ}$ and $\chi_{cJ} \to e^+e^- J/\psi$
  - $\eta' \to \omega e^+e^-$
  - $J/\psi \to e^+e^-\pi^0$

- This year, BESIII is collecting 10 times more statistics of the present existing J/ψ data, which can be utilized to measure several new Dalitz decays, and improve the precision of measured Dalitz decays.

Thank you!

Back up Slide

Dalitz decay of $J/\psi \to e^+e^-\eta$

BESIII **Preliminary**

Systematic Uncertainties

Source	$J/\psi \to e^+e^-\eta$			$J/\psi \to \gamma'\eta$	
	$\eta \to \gamma\gamma$	$\eta \to 3\pi$	TFF measurement	$\eta \to \gamma\gamma$	$\eta \to 3\pi$
Additive systematic uncertainties (events)					
Signal	negligible	0.9	negligible	0.0 – 1.0	0.0 – 0.6
Non-peaking background	13.0	1.4	0.0 – 0.6	0.0 – 12.0	0.0 – 5.0
Fit Bias	1.6	0.1	0.1	0.1	0.1
Total	13.1	1.7	0.1-0.6	0.1 – 12.0	0.1 – 5.0
Multiplicative systematic uncertainties (%)					
Charged tracks (* for e track only)	2.4	4.4	4.4	2.4	4.4
$e^{\pm}$ PID*	1.2	1.2	1.2	1.2	1.2
Photon detection efficiency*	2.0	2.0	2.0	2.0	2.0
χ^2_{4C}	0.9	0.9	0.9	0.9	0.9
η/π^0 mass window requirement	—	1.0	1.0	1.0	2.0
Veto of gamma conversion*	1.0	1.0	0.0 – 1.5	0.0 – 1.5	0.0 – 1.5
$\cos\theta_\gamma^{hel}$	1.9	—	—	1.9	—
TFF	1.5	0.9	—	1.5	0.9
$\mathcal{B}(\eta \to \gamma\gamma)$	0.5	—	—	0.5	—
$\mathcal{B}(\eta \to \pi^+\pi^-\pi^0)$	—	1.2	1.2	—	1.2
$\mathcal{B}(J/\psi \to \gamma\eta)$	—	—	3.1	3.1	3.1
$\mathcal{B}(\gamma' \to e^+e^-)$*	—	—	—	0.0 – 14.0	0.0 – 14.0
J/ψ event number*	0.5	0.5	0.5	0.5	0.5
Total	4.4	5.5	6.2 – 6.3	5.4 – 15.1	6.5 – 15.5

The terms with asterisks are correlated systematic uncertainties between the decay modes of $\eta \to \pi^+\pi^-\pi^0$ and $\eta \to \gamma\gamma$

Dalitz decay of $J/\psi \to e^+e^-\eta$

BESIII **Preliminary**

Transition form factor (TFF) study

The value of $|F(q^2)|^2$ for each bin of $m_{e^+e^-}$, where the first uncertainty is statistical and second systematic.

$m_{e^+e^-}$ (GeV/c^2)	$[2m_e,\ 0.1]$	$[0.1,\ 0.2]$	$[0.2,\ 0.3]$	$[0.3,\ 0.4]$
$\|F(q^2)\|^2$	$0.97 \pm 0.06 \pm 0.06$	$1.00 \pm 0.13 \pm 0.06$	$0.94 \pm 0.15 \pm 0.06$	$1.04 \pm 0.18 \pm 0.07$
$m_{e^+e^-}$ (GeV/c^2)	$[0.4,\ 0.5]$	$[0.5,\ 0.6]$	$[0.6,\ 0.7]$	$[0.7,\ 0.8]$
$\|F(q^2)\|^2$	$0.91 \pm 0.20 \pm 0.06$	$1.68 \pm 0.30 \pm 0.11$	$1.18 \pm 0.29 \pm 0.09$	$2.36 \pm 0.45 \pm 0.17$
$m_{e^+e^-}$ (GeV/c^2)	$[0.8,\ 0.9]$	$[0.9,\ 1.0]$	$[1.0,\ 1.1]$	$[1.1,\ 1.22]$
$\|F(q^2)\|^2$	$1.77 \pm 0.41 \pm 0.12$	$1.53 \pm 0.41 \pm 0.10$	$2.44 \pm 0.57 \pm 0.17$	$1.84 \pm 0.53 \pm 0.13$
$m_{e^+e^-}$ (GeV/c^2)	$[1.22,\ 1.34]$	$[1.34,\ 1.48]$	$[1.48,\ 1.62]$	$[1.62,\ 1.76]$
$\|F(q^2)\|^2$	$2.64 \pm 0.65 \pm 0.18$	$1.50 \pm 0.49 \pm 0.10$	$2.52 \pm 0.74 \pm 0.17$	$1.63 \pm 0.48 \pm 0.16$
$m_{e^+e^-}$ (GeV/c^2)	$[1.76,\ 1.90]$	$[1.90,\ 2.06]$	$[2.06,\ 2.23]$	$[2.23,\ 2.40]$
$\|F(q^2)\|^2$	$3.29 \pm 1.14 \pm 0.23$	$4.72 \pm 1.69 \pm 0.32$	$5.40 \pm 2.01 \pm 0.37$	$8.37 \pm 3.90 \pm 0.64$

Dalitz decay of $\psi(2S) \to e^+e^-\eta'$

BESIII **Preliminary**

Systematic Uncertainties

Sources	$\eta' \to \gamma\pi^+\pi^-$	$\eta' \to \pi^+\pi^-\eta$
MDC tracking *	4.0	4.0
Photon detection *	0.6	1.2
PID *	0.6	0.6
$E/p > 0.8$	0.2	–
Veto of γ conversion *	1.0	1.0
4C kinematic fit	0.8	0.5
η reconstruction	–	1.0
$RM(\pi^+\pi^-)$ requirement	0.2	1.8
Form factor	0.2	0.9
Signal shape	2.6	0.5
Fit range and background shape	2.8	4.5
Fixed peaking background	1.3	0.7
Number of $\psi(3686)$ events*	0.6	0.6
Quoted branching fractions	1.7	1.7
Total	6.2	7.0

- The uncertainties denoted with asterisk refer to the correlated terms between the two η' decay modes.

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