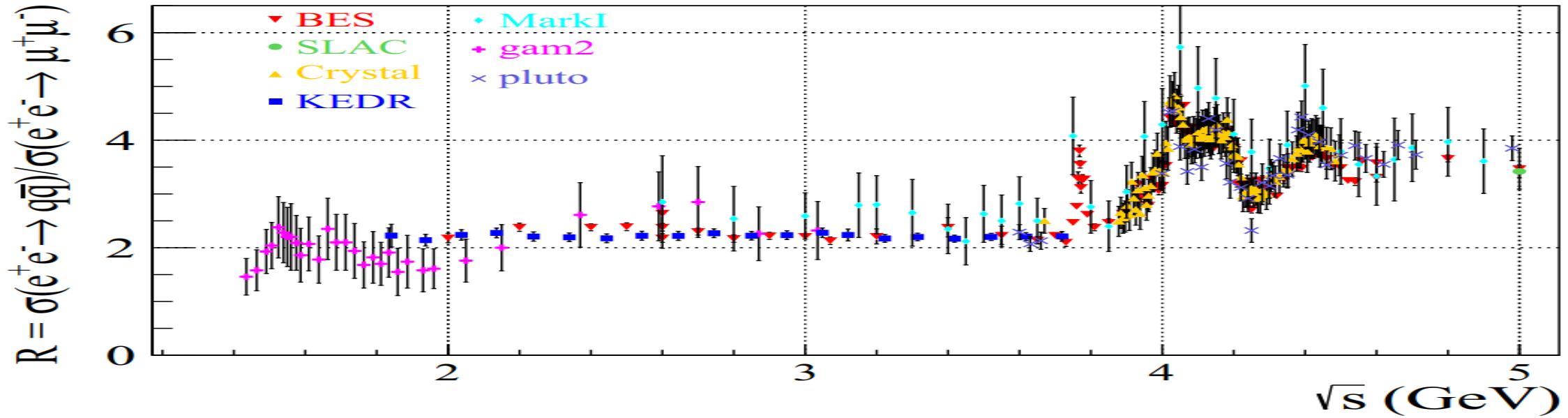


BESIII上R值与QCD实验 研究进展

周小蓉
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2023.4.20-23

QCD-studies at BESIII



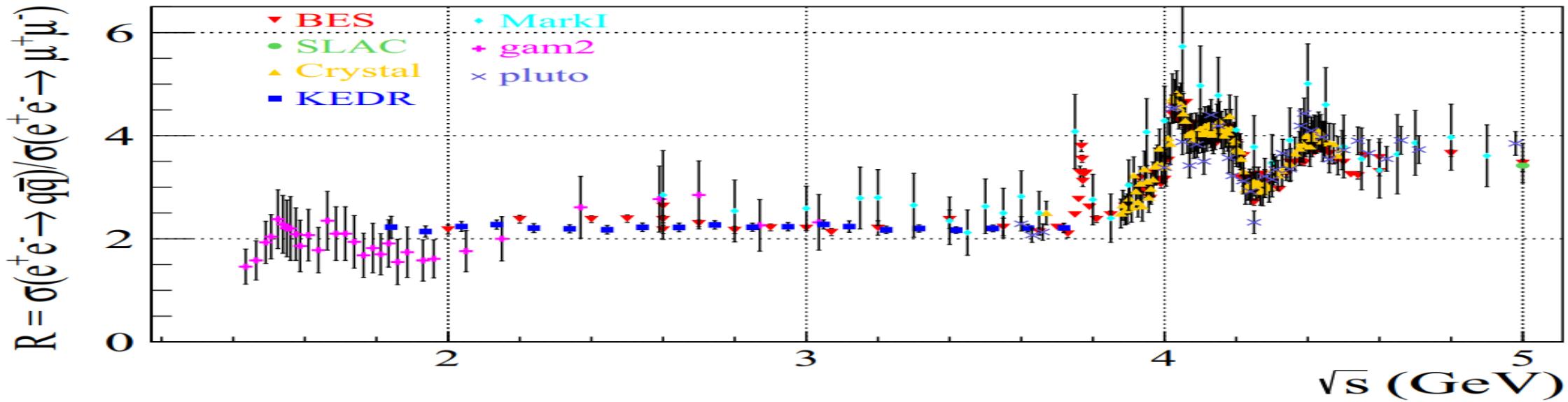
Precision Test of
the SM

Hadron
Structures

Hadron
Spectroscopy

Hadron Decay

QCD-studies at BESIII at low c.m.e



Precision Test of
the SM

$(g - 2)_\mu, \alpha_{EM}$
 $ISR e^+e^- \rightarrow \pi^+\pi^-, \pi^+\pi^-\pi^0$
 R-value measurement
Tau mass measurement

Hadron
Structures

Fragmentation Function
Baryon Form Factor
 Nucleon (p, n), Hyperon
 $(\Lambda, \Sigma, \Xi, \Lambda_c, \Delta, \Lambda^*, \Sigma^*, \Omega)$

Hadron
Spectroscopy

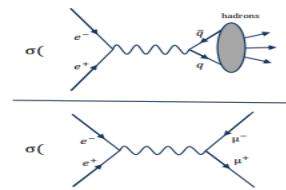
1⁻⁻ resonance in 2-3 GeV
 $e^+e^- \rightarrow K^+K^-, KK\pi\pi$
 $e^+e^- \rightarrow \phi\eta, \phi\eta', \omega\eta$
C even production

Hadron Decay

Phase in strong and EM
 $J/\psi \rightarrow p\bar{p}, \Sigma^{+/0} \bar{\Sigma}^{-/0}$
 $\Lambda\bar{\Lambda}, K^+K^-, \omega\pi^0 \dots$

Inclusive Measurements

R value



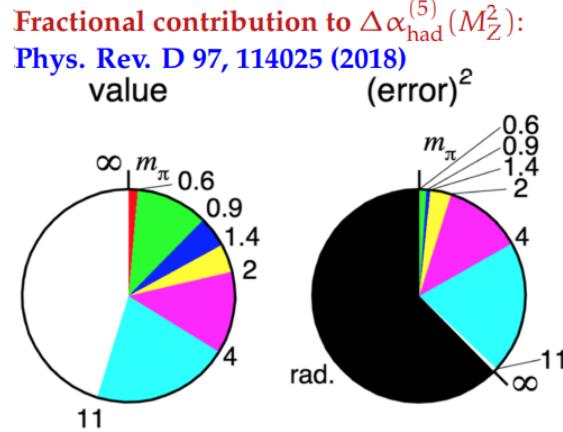
$$R \equiv \frac{\sigma^0(e^+e^- \rightarrow \text{hadrons})}{\sigma^0(e^+e^- \rightarrow \mu^+\mu^-)} \equiv \frac{\sigma_{\text{had}}^0}{\sigma_{\mu\mu}^0}$$

- Running of fine structure constant $\Delta\alpha_{\text{em}}$

$$\Delta\alpha(s) = 1 - \alpha(0)/\alpha(s) = \Delta\alpha_{\text{lepton}}(s) + \Delta\alpha_{\text{had}}^{(5)}(s) + \Delta\alpha_{\text{top}}(s)$$

Eur. Phys. J. C 80, 241 (2020)

Source	Contribution ($\times 10^{-4}$)
$\Delta\alpha_{\text{lepton}}(M_Z^2)$	314.979 ± 0.002
$\Delta\alpha_{\text{had}}^{(5)}(M_Z^2)$	276.0 ± 1.0
$\Delta\alpha_{\text{top}}(M_Z^2)$	-0.7180 ± 0.0054

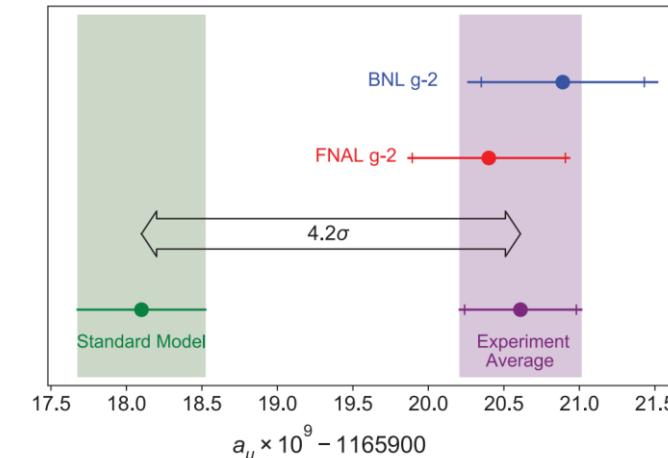


- $\Delta\alpha_{\text{had}}^{(5)}(s)$ should be calculated with R value:

$$\Delta\alpha_{\text{had}}^{(5)}(s) = -\frac{\alpha s}{3\pi} \text{Re} \int_{E_{\text{th}}}^{\infty} ds' \frac{R(s')}{s'(s' - s - i\varepsilon)}$$

- Muon anomalous magnetic moment a_μ

PRL126.141801 (2021)



- SM prediction: $a_\mu^{SM} = a_\mu^{QED} + a_\mu^{Weak} + a_\mu^{Had}$
 - Hadronic Vacuum Polarization (HVP) and Light-by-Light (HLbL) in a_μ^{Had} dominate uncertainty
- HVP contribution is calculated with R value with dispersion relation:

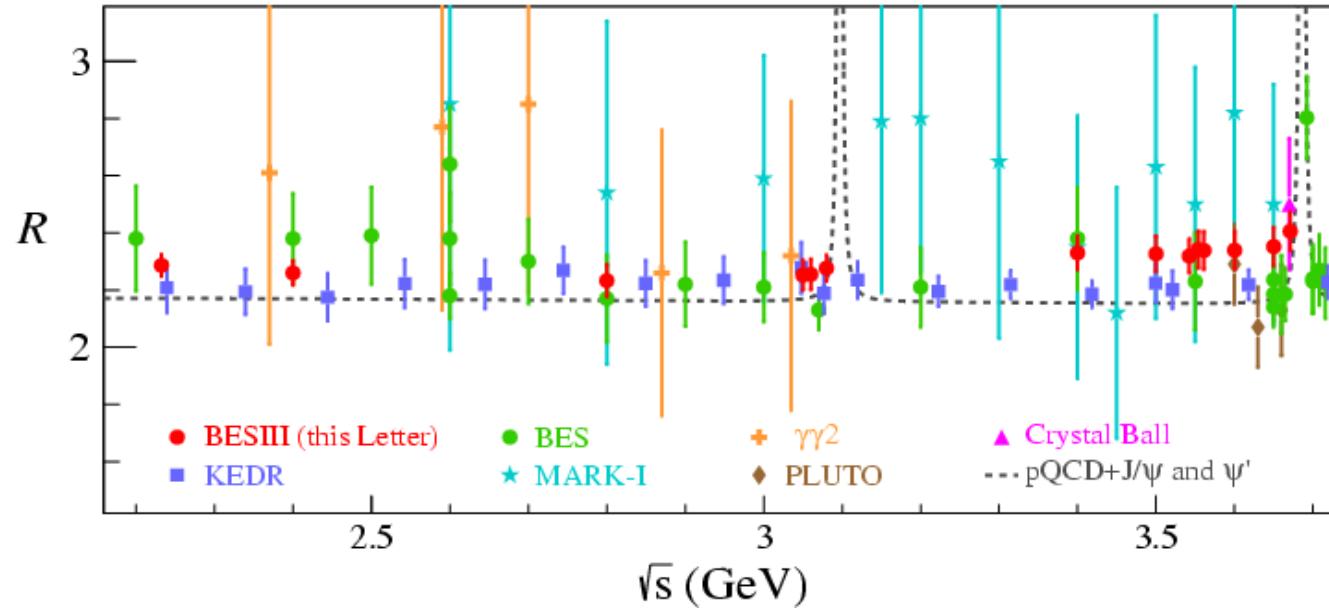
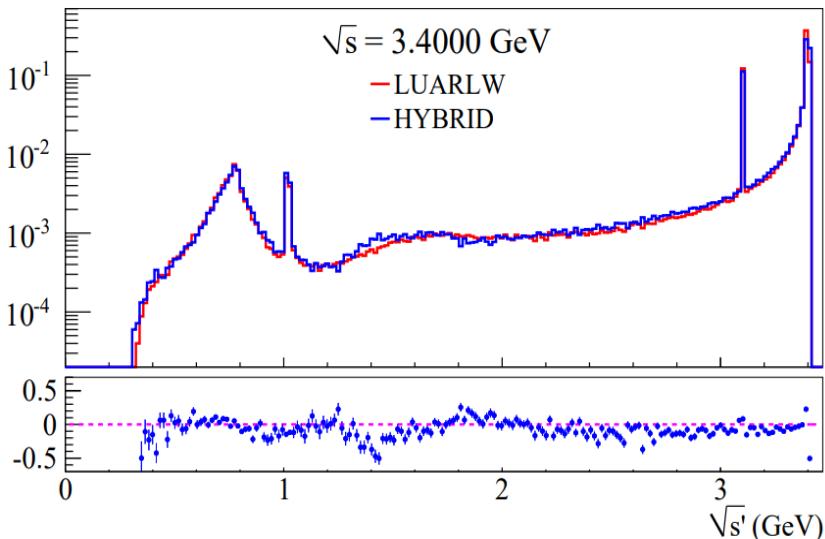
$$a_\mu^{\text{LO-HVP}} = \left(\frac{\alpha m_\mu}{3\pi} \right)^2 \int_{4m_\pi^2}^{\infty} ds \frac{R(s)K(s)}{s^2}$$

R value measurement at BESIII

PRL 128, 062004 (2022)

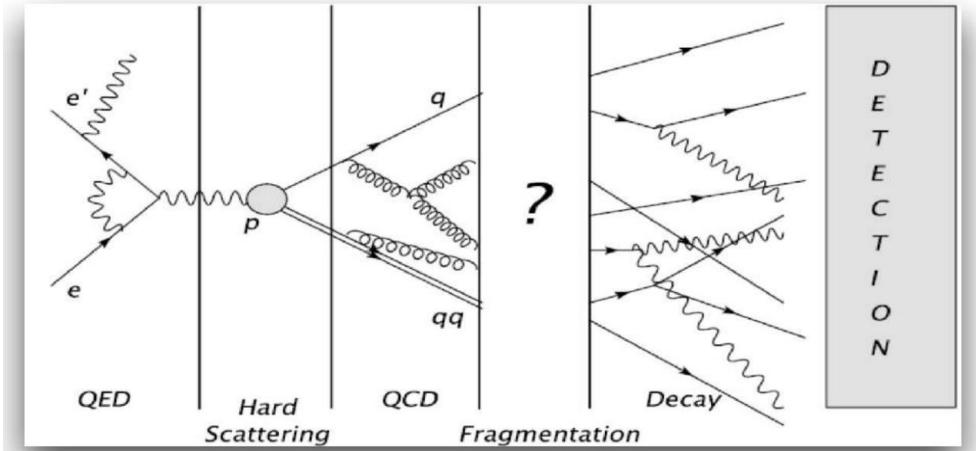
$$R = \frac{N_{\text{had}}^{\text{obs}} - N_{\text{bkg}}}{\sigma_{\mu\mu}^0 \mathcal{L}_{\text{int.}} \varepsilon_{\text{trig}} \varepsilon_{\text{had}} (1 + \delta)}$$

- Very challenging to determine ε_{had}
- Two simulation models developed, result in consistent ISR-return $\sqrt{s'}$ spectrum.



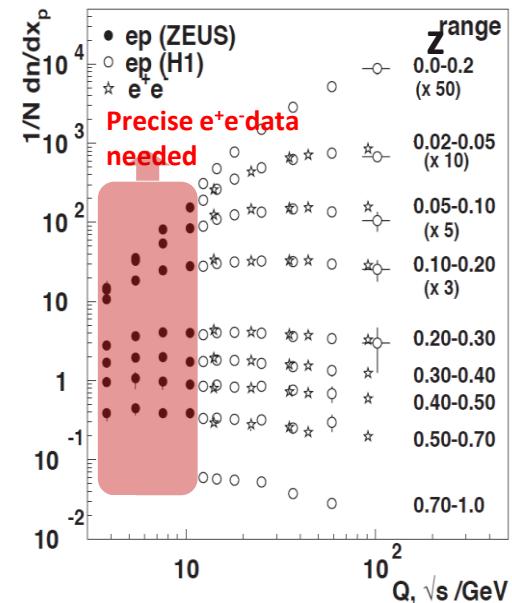
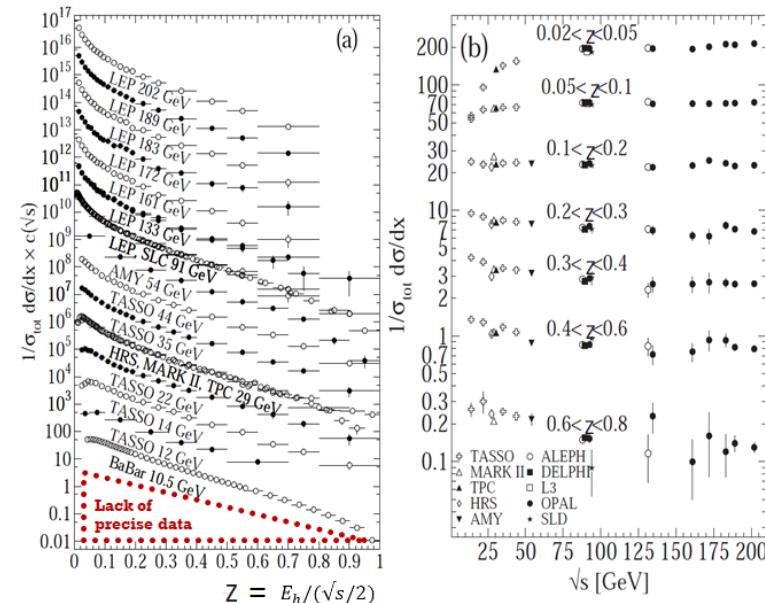
- R value measured at 14 c.m. energies from 2.2324 to 3.671 GeV.
- Accuracy better than 2.6% below 3.1 GeV and 3.0% above.
- Larger than the pQCD prediction by 2.7σ in $3.4 \sim 3.6$ GeV.

Inclusive π^0/K_s production

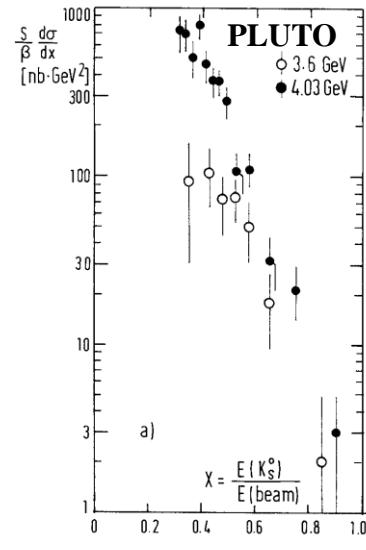
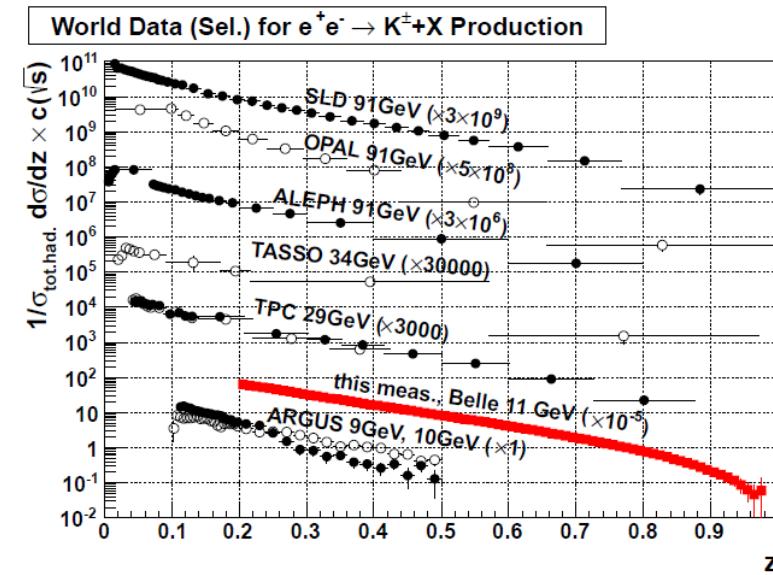


Fragmentation function $D_q^h(z)$: probability that hadron h is found in the debris of a hadron carrying a fraction $z=2E_h/\sqrt{s}$ of parton's momentum.

World data: Pion



World data: Kaon



Inclusive π^0/K_s production at BESIII

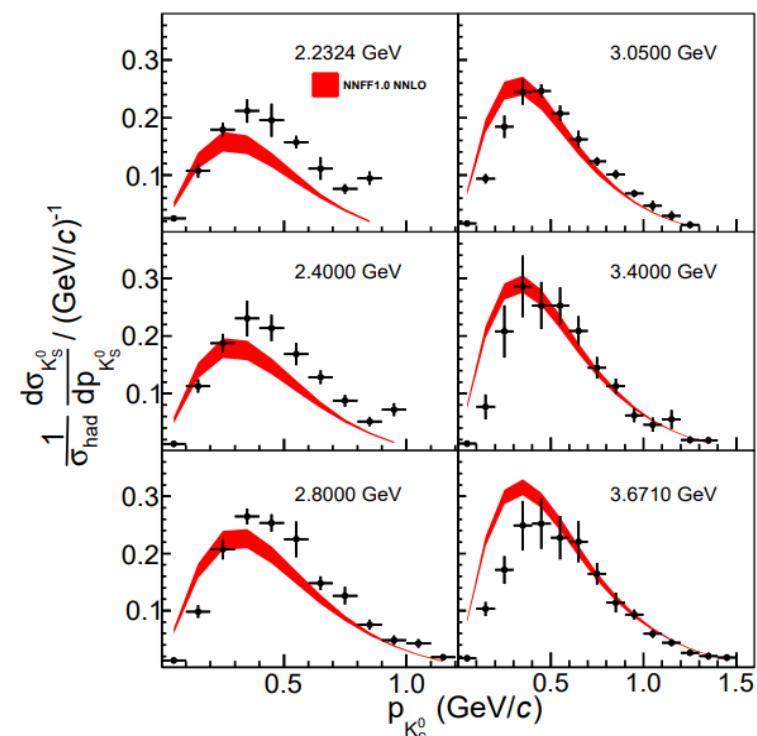
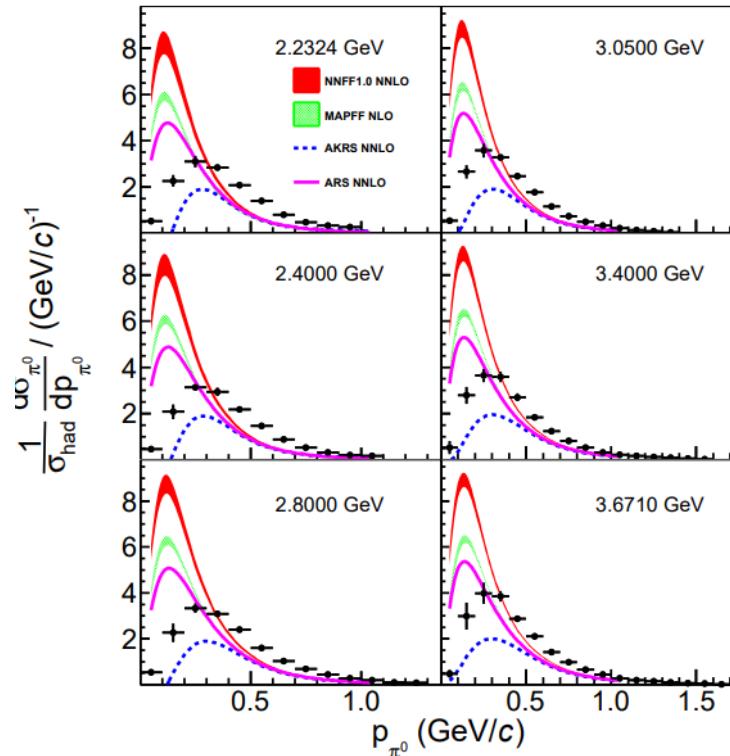
Normalized differential cross section:

$$\frac{1}{\sigma_{\text{had}}} \frac{d\sigma_{\pi^0}}{dp_{\pi^0}} = \frac{N_{\pi^0}}{N_{\text{had}}} \frac{1}{\Delta p_{\pi^0}}$$

Correction formula:

$$\frac{\text{Physical value}}{\frac{\bar{N}_{\pi^0}^{\text{truth}}(\text{off})}{\bar{N}_{\text{hadronic}}^{\text{truth}}(\text{off})}} = \frac{\frac{N_{\pi^0}^{\text{observable}}}{N_{\text{hadronic}}^{\text{observable}}}}{\frac{\bar{N}_{\pi^0}^{\text{observable}}(\text{on})}{\bar{N}_{\text{hadronic}}^{\text{observable}}(\text{on})}}}$$

\sqrt{s} (GeV)	\mathcal{L} (pb^{-1})	$N_{\text{had}}^{\text{tot}}$	N_{bkg}
2.2324	2.645	83227	2041
2.4000	3.415	96627	2331
2.8000	3.753	83802	2075
3.0500	14.89	283822	7719
3.4000	1.733	32202	843
3.6710	4.628	75253	6461

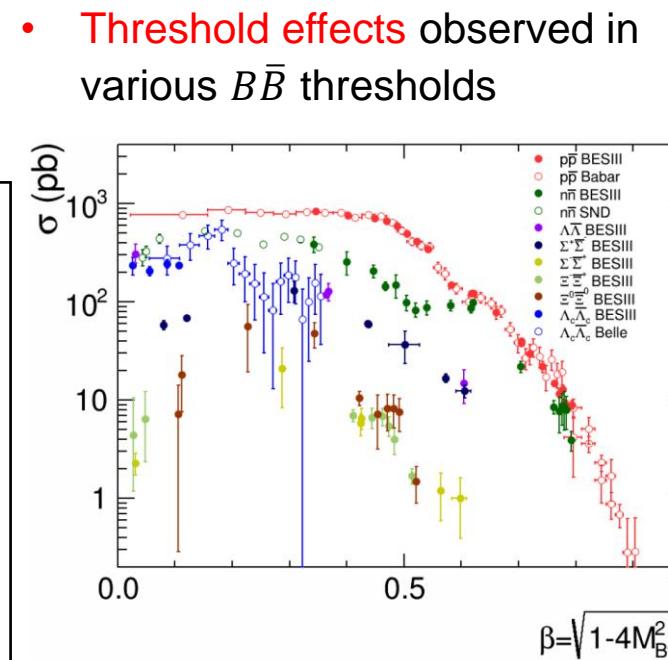
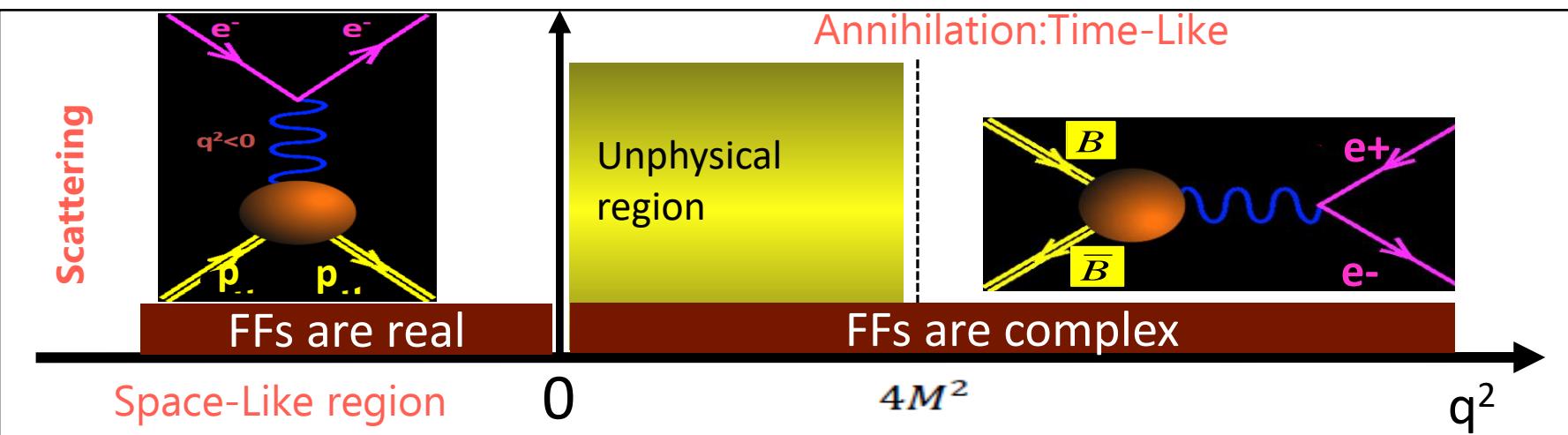


- Comparison of theoretical predictions using different evolution of existing FF world data are made.
- BESIII data can be used to improve the determine of FFs at low energy, fill the gap with $|Q^2| < 10 \text{ GeV}^2$
- The difference between the components of direct and indirect processes need to be considered.

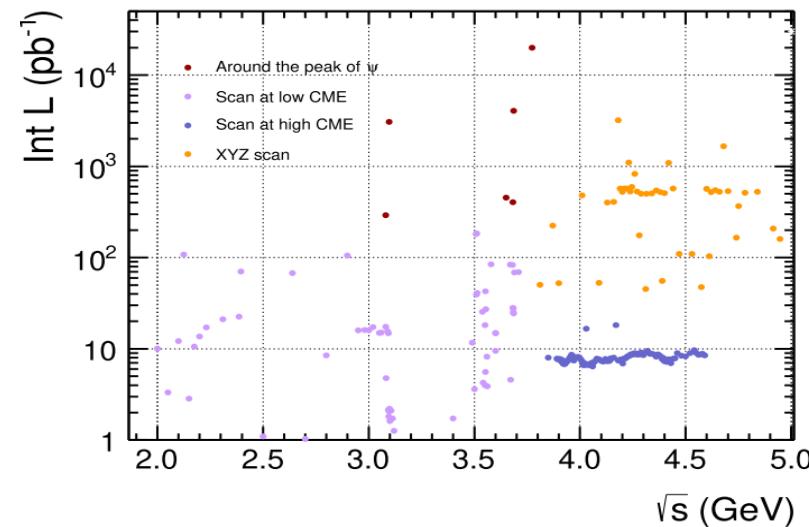
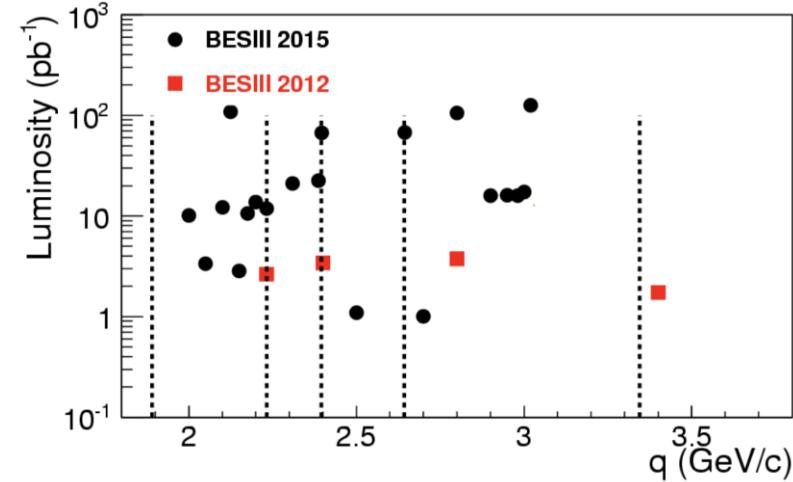
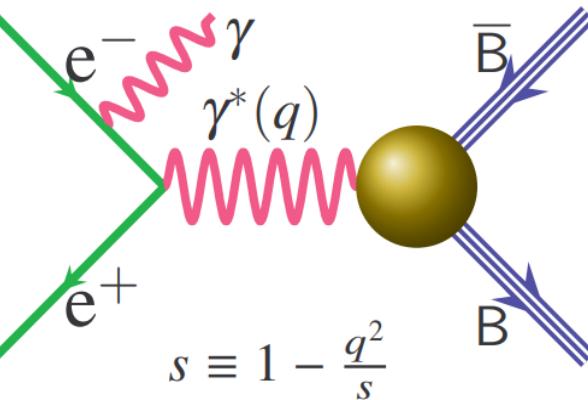
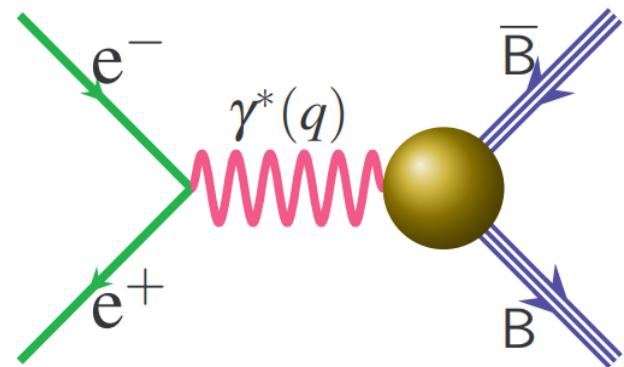
Exclusive Measurements

Timelike-Electromagnetic Form Factors

- Nucleons are composite objects with inner structure. At low Q^2 , perturbative QCD **not possible**
⇒ Nucleon structure must be measured **in experiments!**
- Electromagnetic Form Factors are fundamental properties of the nucleon
 - Connected to charge, magnetization distribution
 - Crucial testing ground for models of the nucleon internal structure



Experimental Access and Data Set at BESIII



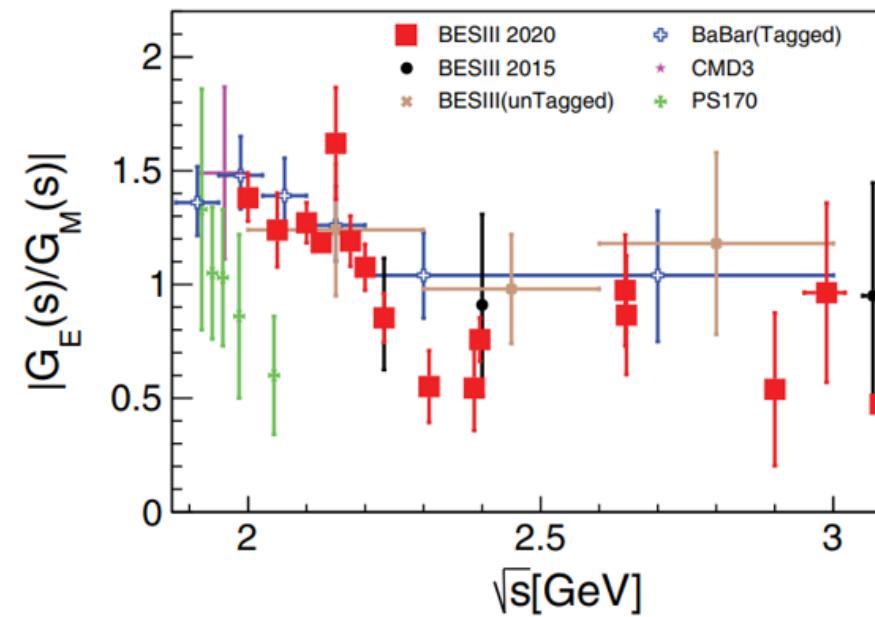
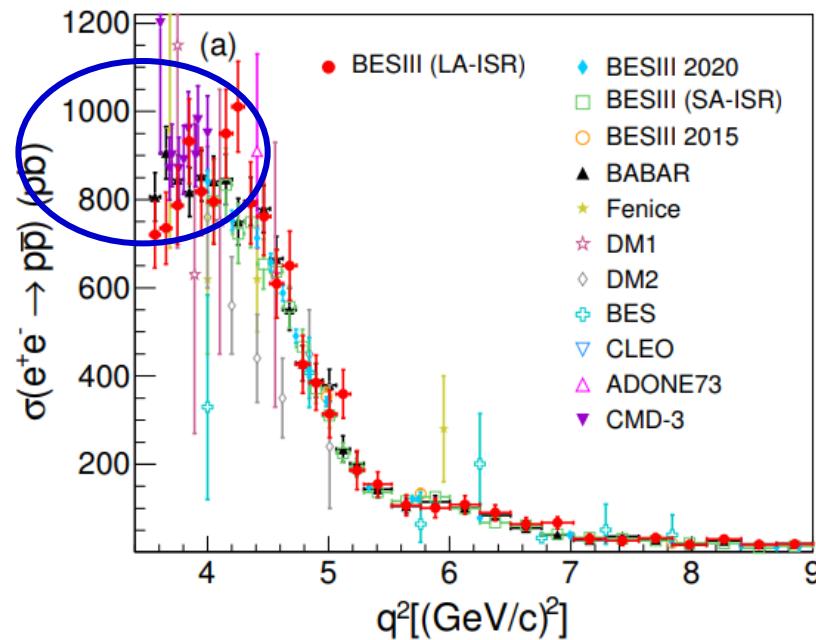
	Energy Scan	Initial State Radiation
\sqrt{s}	discrete	fixed
\mathcal{L}	low at each beam energy	high at one beam energy
σ	$\frac{d\sigma_{p\bar{p}}}{d(\cos \theta)} = \frac{\pi \alpha^2 \beta C}{2q^2} [G_M ^2 (1 + \cos^2 \theta) + \frac{4m_p^2}{q^2} G_E ^2 \sin^2 \theta]$	$\frac{d\sigma_{p\bar{p}\gamma}}{dq^2} = \frac{1}{s} W(s, x) \sigma_{p\bar{p}}(q^2)$ $W(s, x) = \frac{\alpha}{\pi x} (\ln \frac{s}{m_e^2} - 1) (2 - 2x + x^2)$
q^2	single at each beam energy	from threshold to s
	BESIII, CMD-3, ...	BaBar, BESIII, Belle, Belle-II, ...

ISR suppression factor: $\frac{\alpha}{\pi} \sim \frac{1}{400}$

Proton Form Factors

- ISR method with detected photon and undetected using 7.5 fb^{-1} data with $\sqrt{s} \geq 3.773 \text{ GeV}$.
- Scan technique from 2.0 to 3.08 GeV, using 688.5 pb^{-1} integrated luminosity.
- $|G_E/G_M|, |G_M|$ are determined with **high accuracy**, comparable to data in SL.

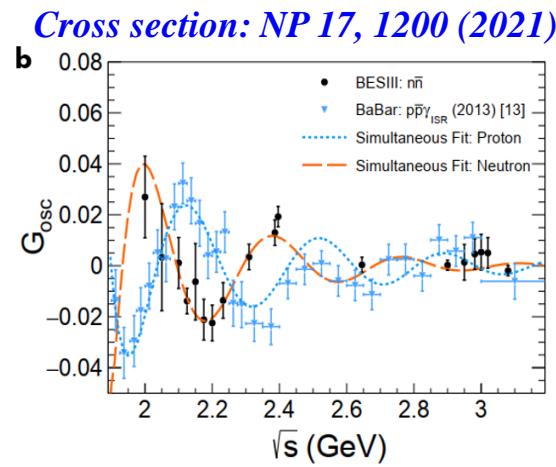
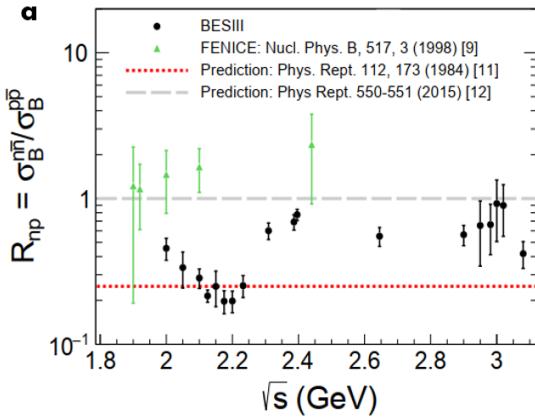
$SA\text{-ISR}$: PRD 99, 092002 (2019)
 $LA\text{-ISR}$: PLB 817, 136328 (2021)
 $Scan$: PRL 124, 042001 (2020)
 $Scan$: PRD 91, 112004 (2015)



- From threshold to $q^2=4.0 \text{ GeV}^2$, average cross section 840 pb.
- $|G_E/G_M|$ measured, consistent with BaBar near threshold, oscillation with \sqrt{s} is observed.

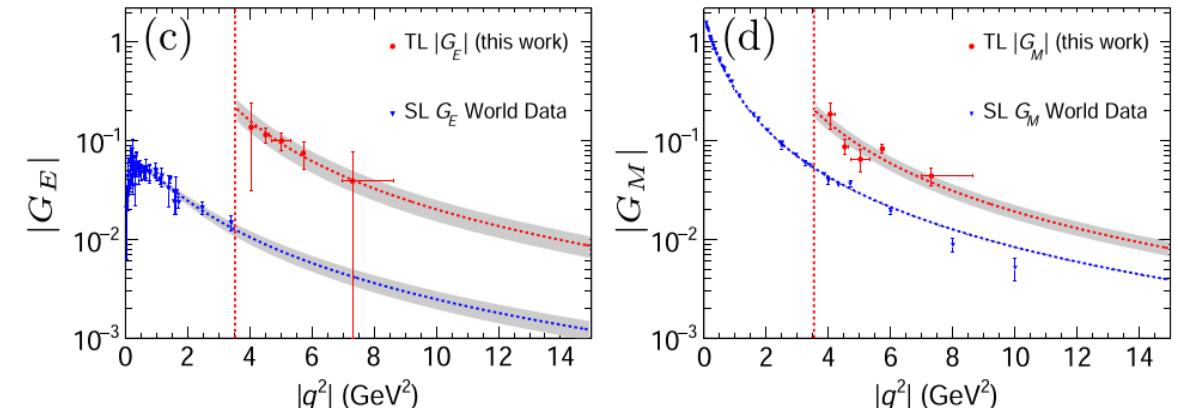
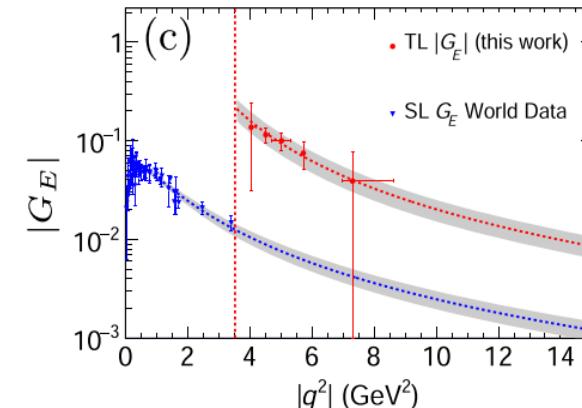
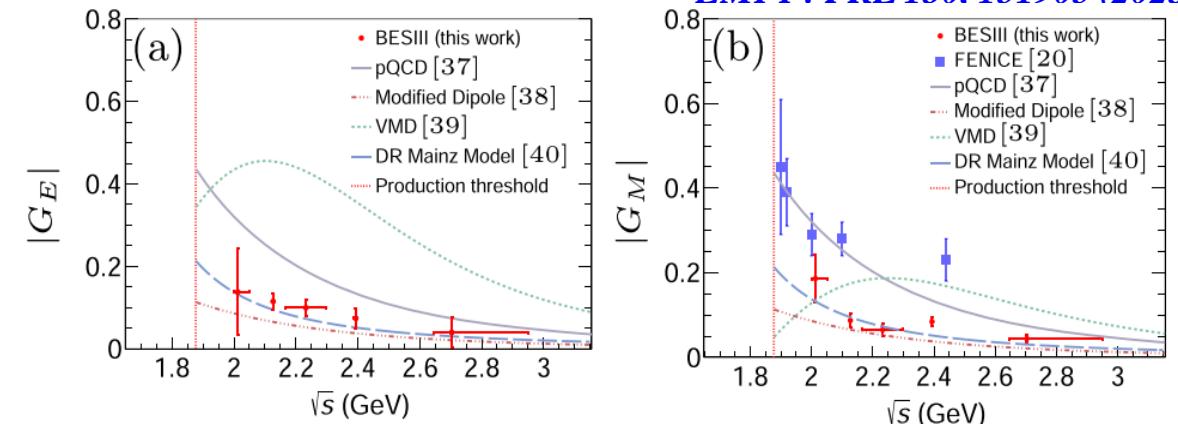
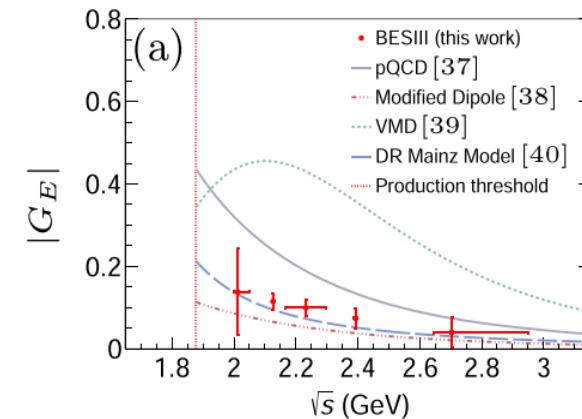
Neutron Form Factors

- Cross section measurement of $e^+e^- \rightarrow n\bar{n}$
 - $\gamma - p$ coupling larger than $\gamma - n$ coupling
 - Oscillation of reduced-|G| observed in neutron with a phase orthogonal to that of proton



\sqrt{s} (GeV)	\mathcal{L} (pb $^{-1}$)	R_{em}	$ G_M (\times 10^{-2})$	$ G_E (\times 10^{-2})$
2.0000	10.1	$0.9 \pm 0.7 \pm 0.4$	$18.6 \pm 5.0 \pm 3.1$	$17.2 \pm 8.3 \pm 4.7$
2.0500	3.34	$1.3 \pm 0.4 \pm 0.3$	$8.7 \pm 1.2 \pm 0.8$	$11.2 \pm 1.7 \pm 1.1$
2.1250	108	$1.5 \pm 0.6 \pm 0.2$	$6.5 \pm 1.5 \pm 0.4$	$9.8 \pm 1.9 \pm 0.6$
2.1500	2.84			
2.1750	10.6			
2.2000	13.7			
2.2324	11.9			
2.3094	21.1			
2.3864	22.5			
2.3960	66.9	$0.9 \pm 0.3 \pm 0.2$	$8.3 \pm 0.9 \pm 0.4$	$7.3 \pm 2.1 \pm 1.0$
2.6454	67.7	$0.6 \pm 0.9 \pm 0.7$	$4.4 \pm 0.8 \pm 0.3$	$2.5 \pm 2.9 \pm 2.9$
2.9500	15.9			

- Differential cross-sections measured and the separated electric and magnetic FFs of the neutron is obtained
- Results is compared with various models

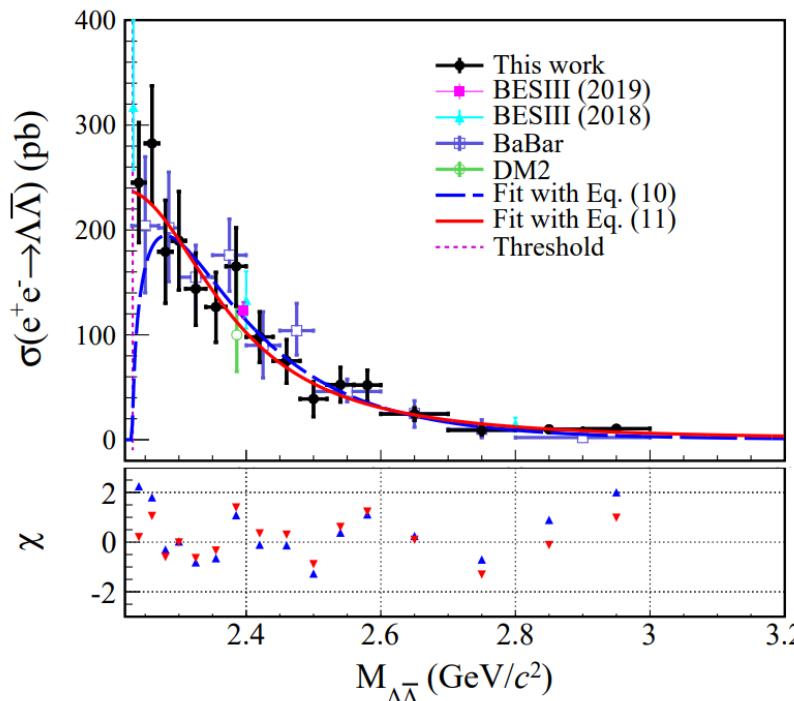


EMFF: PRL 130, 151905 (2023)

Lambda EMFFs

- Using scan method, cross section of $e^+e^- \rightarrow \Lambda\bar{\Lambda}$ at $\sqrt{s} = 2.2324$ GeV is $305 \pm 45^{+66}_{-36}$ pb
- Using ISR method (11.9 fb^{-1}), cross section in $[2.231, 2.250]$ GeV and $[2.25, 2.27]$ GeV is $245 \pm 56 \pm 14$ pb and $283^{+53}_{-55} \pm 15$ pb
- Threshold effects observed in both scan and ISR methods

Scan: PRD 97, 032013 (2018)
ISR: PRD 107, 072005 (2023)



Lineshape is fitted with:

➤ pQCD prediction

$$\sigma(s) = \frac{c_0 \cdot \beta(s) \cdot C}{(\sqrt{s} - c_1)^{10}},$$

➤ Consider strong interaction near threshold

$$\sigma(s) = \frac{e^{a_0} \pi^2 \alpha^3}{s \left[1 - e^{-\frac{\pi \alpha s}{\beta}} \right] \left[1 + \left(\frac{\sqrt{s} - 2m_\Lambda}{a_1} \right)^{a_2} \right]}.$$

➤ Relativistic Breit-Wigner with a mass-dependent width

$$BW(M_{\Lambda\bar{\Lambda}}) \propto \frac{1}{M_{\Lambda\bar{\Lambda}}^2 - m^2 - im\Gamma_X}.$$

Sigma/Xi EMFFs

- Born cross sections of $e^+e^- \rightarrow \Sigma^+\bar{\Sigma}^-, \Sigma^-\bar{\Sigma}^+, \Sigma^0\bar{\Sigma}^0$ are measured from threshold to 3.02 GeV

- The cross sections can be well described by pQCD-motivated functions

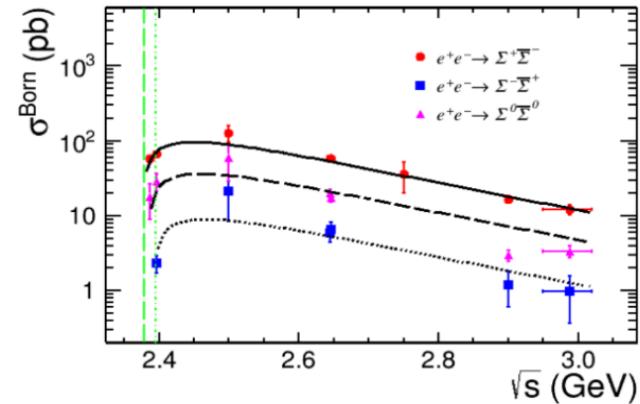
$$\sigma^B(s) = \frac{\beta C}{s} \left(1 + \frac{2m_B^2}{s}\right) \frac{c_0}{(s - c_1)^4 (\pi^2 + \ln^2(s/\Lambda_{\text{QCD}}^2))^2}$$

- An asymmetry in cross sections for Σ isospin triplets: $9.7 \pm 1.3 : 3.3 \pm 0.7 : 1$

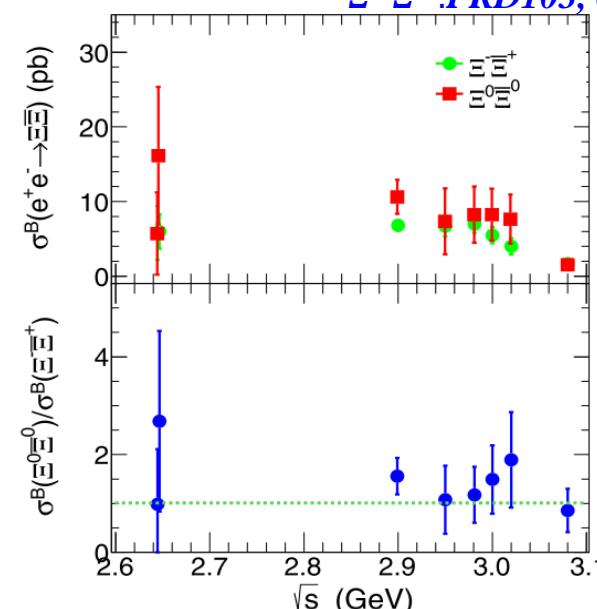
- Born cross sections of $e^+e^- \rightarrow \Xi^0\bar{\Xi}^0$ and $\Xi^-\bar{\Xi}^+$ are measured from threshold to 3.08 GeV

- No obvious threshold enhancement observed.
- The ratio of Born cross sections for both modes agrees with the expectation of isospin symmetry.

$\Sigma^\pm\bar{\Sigma}^\mp$:PLB 814, 136110 (2021)
 $\Sigma^0\bar{\Sigma}^0$:PLB 831, 137187 (2022)



$\Xi^0\bar{\Xi}^0$:PLB. 820, 136557 (2021)
 $\Xi^-\bar{\Xi}^+$:PRD103, 012005(2021)



Omega EMFFs

PRD 107, 052003, 2023

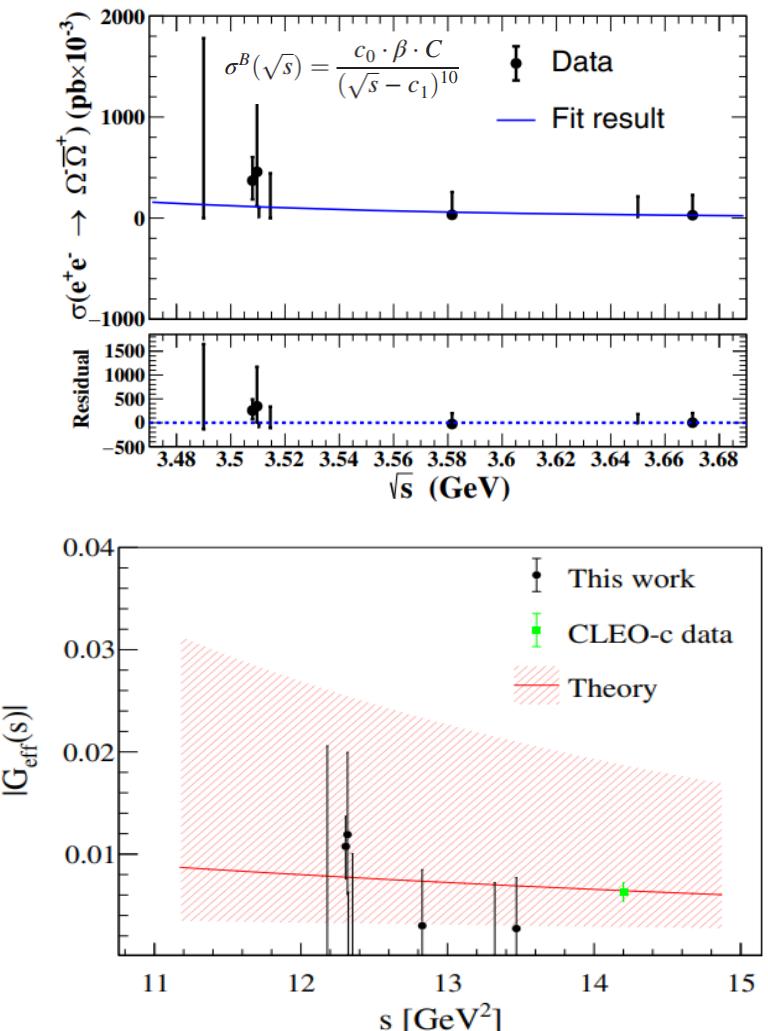
- Born cross sections of $e^+e^- \rightarrow \Omega^-\bar{\Omega}^+$ at 8 energy points between 3.49 and 3.67 GeV
 - No threshold effect observed
 - Upper limit of the effective FF is consistent with theoretical prediction

$$|G_{\text{eff}}(s)| = \sqrt{\frac{2 \times \frac{s}{4m^2} |G_M^*(s)|^2 + |G_E^*(s)|^2}{2 \times \frac{s}{4m^2} + 1}}$$

$$|G_E^*(s)|^2 = 2|G_{E0}|^2 + \frac{8}{9} \left(\frac{s}{4m^2}\right)^2 |G_{E2}|^2,$$

$$|G_M^*(s)|^2 = \frac{10}{9} |G_{M1}|^2 + \frac{32}{5} \left(\frac{s}{4m^2}\right)^2 |G_{M3}|^2$$

- More studies of EMFFs on spin 3/2 baryon are undergoing:
 $\Delta(1232)$, $\Lambda(1520)$, $\Sigma(1385)$, Λ_c^* ...



Light flavor mesons

□ Experimental information of $\phi(2170)$

- Limited decay modes
- Inconsistence on Mass & Width

□ Theoretical explain of $\phi(2170)$

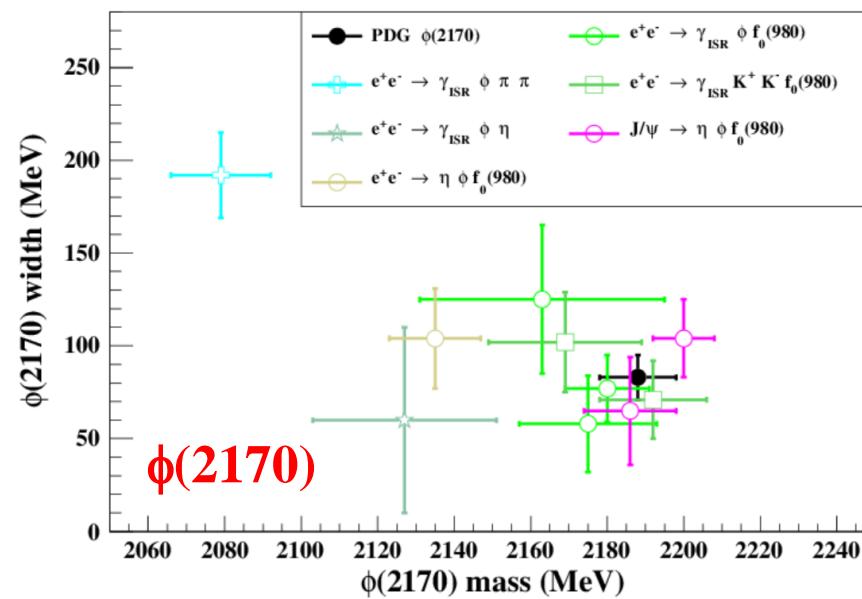
- $s\bar{s}g$ hybrid
- 2^3D_1 or 3^3S_1 $s\bar{s}$
- Tetraquark
- Molecular state $\Lambda\bar{\Lambda}$
- ...

□ Rich vector resonances around 2.0 GeV:

- At BESIII, $\phi(2170)$ is systematically studied by K^+K^- , $K_S K_L$, $K^+K^-\pi\pi$, $\phi\eta^{(\prime)}$, $K^+K^-\pi^0$...
- ω^* is observed in $\omega\eta$, $\omega\pi^0\pi^0$ and $\omega\pi^+\pi^-$...
- ρ^* is observed in $\omega\pi^0$, $\eta'\pi^+\pi^-$...

PDG2018 $\phi(2170)$ DECAY MODES

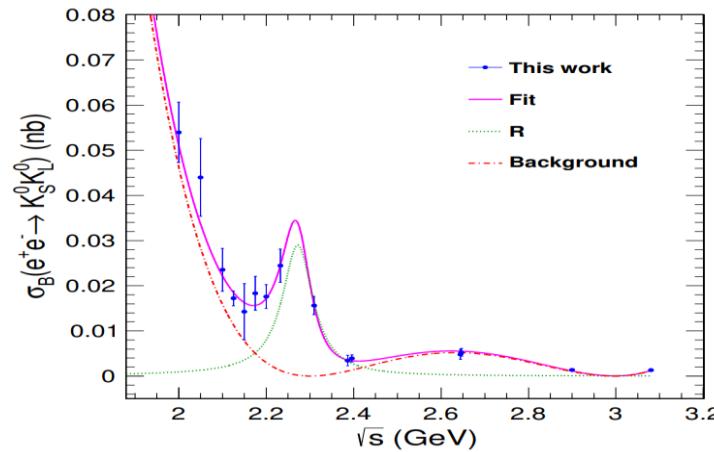
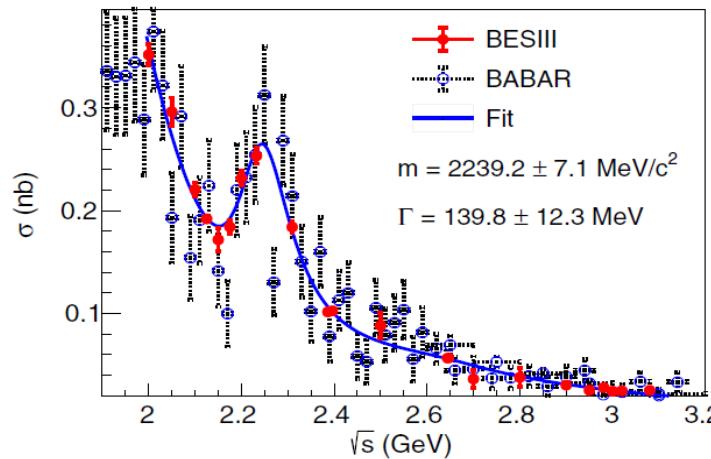
Mode	Fraction (Γ_i/Γ)
$\Gamma_1 e^+e^-$	seen
$\Gamma_2 \phi\eta$	
$\Gamma_3 \phi\pi\pi$	
$\Gamma_4 \phi f_0(980)$	seen
$\Gamma_5 K^+K^-\pi^+\pi^-$	
$\Gamma_6 K^+K^-f_0(980) \rightarrow K^+K^-\pi^+\pi^-$	seen
$\Gamma_7 K^+K^-\pi^0\pi^0$	
$\Gamma_8 K^+K^-f_0(980) \rightarrow K^+K^-\pi^0\pi^0$	seen
$\Gamma_9 K^{*0}K^\pm\pi^\mp$	not seen
$\Gamma_{10} K^*(892)^0\bar{K}^*(892)^0$	not seen



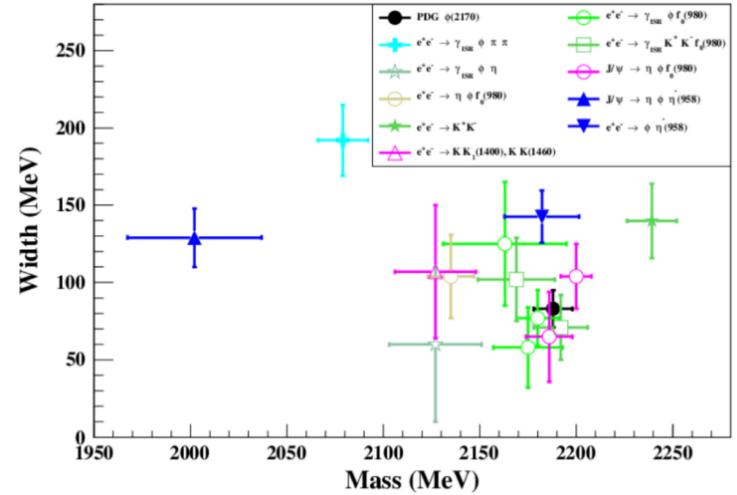
$e^+e^- \rightarrow K^+K^-$ and K_sK_L

□ 1^{--} resonance observed in K^+K^- and K_sK_L lineshapes:

- Differs from the world average parameters of $\phi(2170)$ over 3σ in mass and over 2σ in width
- Interpreted as isoscalar : ω^* , $\phi(2170)$ or isovector : $\rho(2150)$
- The width of $\Gamma_{ee}\text{Br}$ of K^+K^- is about 10 times that of K_sK_L



K^+K^- : PRD 99, 032001 (2019)
 K_sK_L : PRD 104, 092014 (2021)

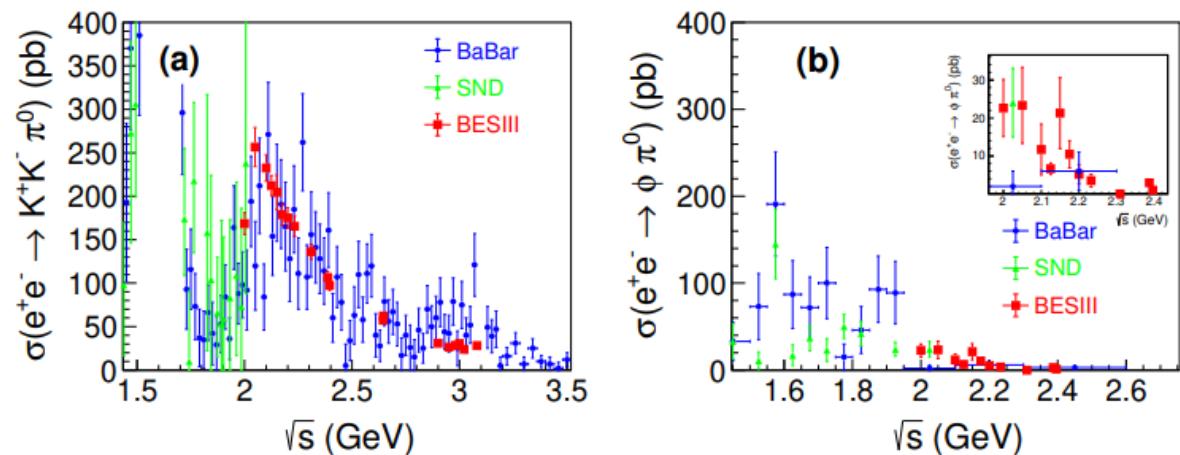


	K^+K^-	K_sK_L
Mass (MeV/c ²)	$2239.2 \pm 7.1 \pm 11.3$	$2273.7 \pm 5.7 \pm 19.3$
Width (MeV)	$139.8 \pm 12.3 \pm 20.6$	$86 \pm 44 \pm 51$
$\Gamma_{ee}\text{Br}$ (eV)		$0.9 \pm 0.6 \pm 0.7$

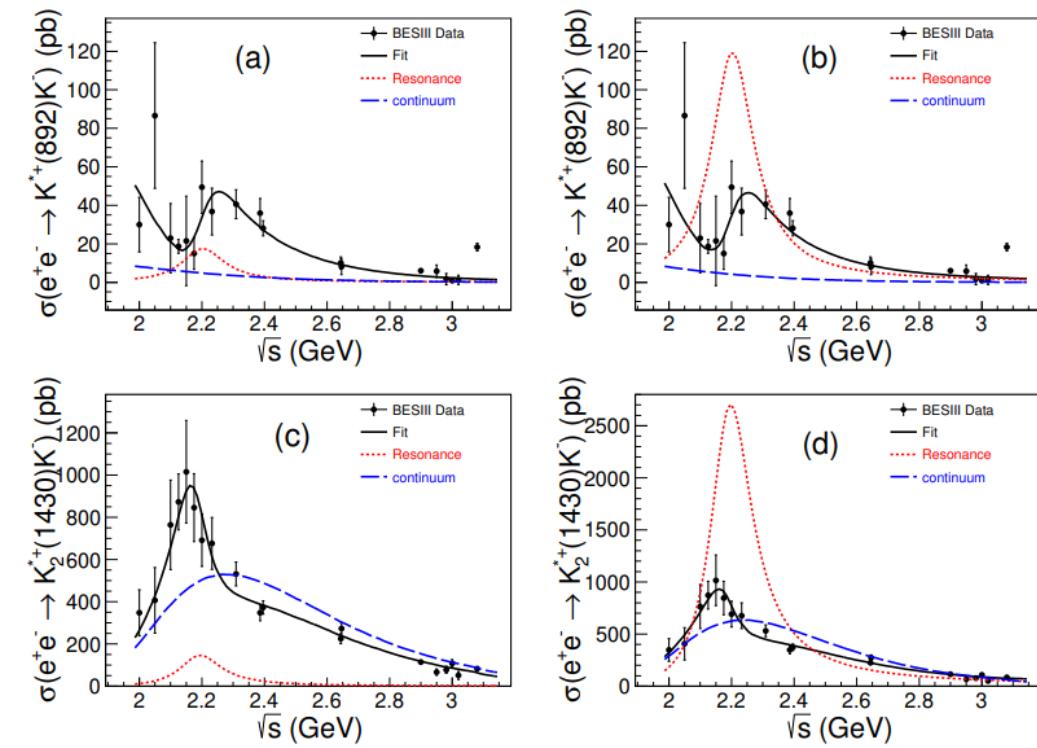
$e^+e^- \rightarrow K^+K^-\pi^0$

- $e^+e^- \rightarrow K^+K^-\pi^0$ measured at 19 energy points
- Intermediate processes $e^+e^- \rightarrow \phi\pi^0, K^{*+}(892)K^-$ and $K_2^{*+}(1430)K^-$ are measured by PWA
- Improved precision for cross section of $e^+e^- \rightarrow K^+K^-\pi^0$ and $\phi\pi^0$

JHEP 07, 045 (2022)



	$K_2^{*+}(1430)K$	$K^{*+}(892)K$
Mass (MeV/c ²)		$2208 \pm 19 \pm 24$
Width (MeV)		$168 \pm 24 \pm 30$
$G_{ee}Br$ (eV)	12.6 ± 2.4 161.1 ± 20.6	1.0 ± 0.3 7.1 ± 0.9



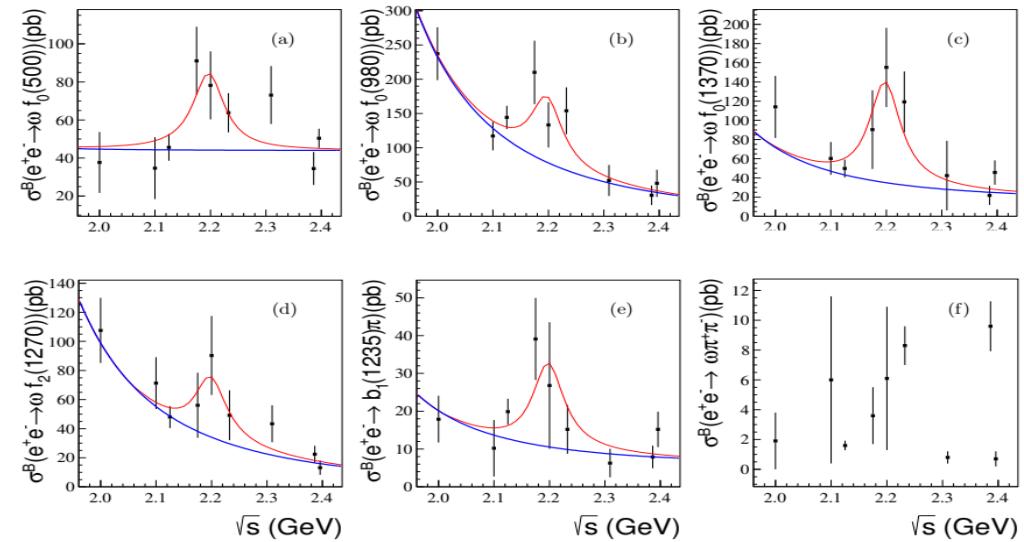
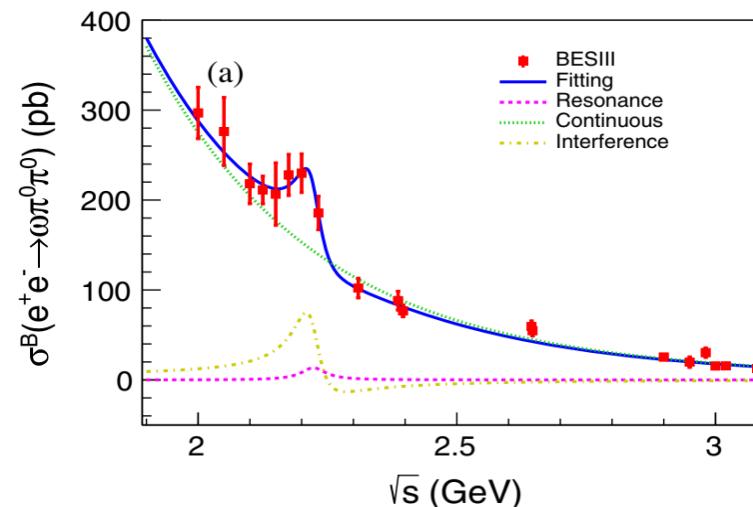
- The fitted mass is consistent with $\phi(2170)$ and deviates from $\rho(2170)$ and $\omega(2170)$ over 3σ

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

□ $e^+e^- \rightarrow \omega\pi\pi$ measured at 19 energy points

➤ Structure around 2.20 GeV observed in cross section of $e^+e^- \rightarrow \omega\pi^0\pi^0$, and in intermediate states of $e^+e^- \rightarrow \omega\pi^+\pi^-$: $\omega f_0(500)$, $\omega f_0(980)$, $\omega f_0(1370)$, $\omega f_2(1270)$, $b_1(12235)\pi$

$\omega\pi^0\pi^0$: PRD 105, 032005 (2022)
 $\omega\pi^+\pi^-$: JHEP01, 111 (2023)



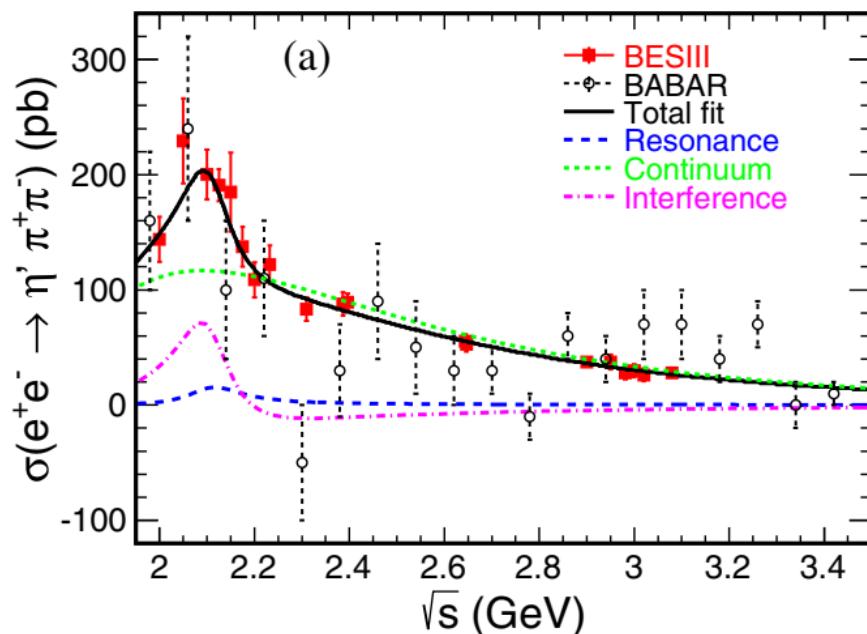
Parameter	Solution (a)	Solution (b)
$M_r(\text{MeV}/c^2)$	2222 ± 7	
$\Gamma_r(\text{MeV})$	59 ± 30	
ϕ_r	2.4 ± 0.3	-1.7 ± 0.1
$\Gamma_{ee}^r \text{Br}(\text{eV})$	0.3 ± 0.1	13.8 ± 6.6
$a(\times 10^3)$	1.3 ± 0.2	
b	5.0 ± 0.1	
Significance		5.3σ

Parameter	Solution I	Solution II
$m_r(\text{MeV}/c^2)$	2250 ± 25	
$\Gamma_r(\text{MeV})$		125 ± 23
$\Gamma_{ee}^r \cdot \text{Br}(\text{eV})$	0.9 ± 0.4	52.9 ± 17.0
$\phi(\text{rad.})$	2.4 ± 0.3	-1.8 ± 0.1
$a(10^3)(\text{pb}^{1/2})$	1.1 ± 0.2	
b		4.4 ± 0.1
Significance		10.3σ

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

- $e^+e^- \rightarrow \eta'\pi^+\pi^-$ measured at 19 energy points, dominant component $\rho\eta'$
- Resonance structure observed around 2.1 GeV with significance over 6σ , with parameters consistent with $e^+e^- \rightarrow \omega\pi^0$ by BESIII

$\eta'\pi^+\pi^-$: PRD103 072007 (2021)
 $\omega\pi^0$: PLB 813, 136059 (2021)



Parameter	Solution 1	Solution 2
M_R (MeV/c ²)	$2111 \pm 43 \pm 25$	
Γ_R^{tot} (MeV)	$135 \pm 34 \pm 30$	
$\mathcal{B}_R \Gamma_R^{ee}$ (eV)	$0.64 \pm 0.49 \pm 0.42$	$23.3 \pm 5.3 \pm 3.3$
ϕ (rad)	$2.24 \pm 0.73 \pm 0.48$	$4.46 \pm 0.06 \pm 0.10$
$n(n')$	$4.42 \pm 0.22 \pm 0.20$	$(1.66 \pm 0.12 \pm 0.07)$
$C_0(C'_0)$	$921 \pm 240 \pm 114$	$(53.0 \pm 13.2 \pm 0.1)$

- More analysis on $e^+e^- \rightarrow \eta\pi^+\pi^-$ and $e^+e^- \rightarrow \pi^+\pi^-\pi^0$ are undergoing
- The intermediate results will give an impact in the theoretical calculation of muon g-2

Summary

□ **Inclusive measurement at BESIII show great potential**

- R value has been measured with best precise in 2.0 to 3.671 GeV
- Inclusive π^0/K_s production are measured with $|Q^2| < 10 \text{ GeV}^2$

□ **Fruitful physics results of exclusive hadronic channels in $\sqrt{s} = 2.0$ to 3.0 GeV at BESIII**

- SU(3) octet baryon: cross section near threshold, electromagnetic form factor
- Light flavor vectors: improved knowledge for excited light flavor vector states

Summary

