Overview on QCD studies at BESIII

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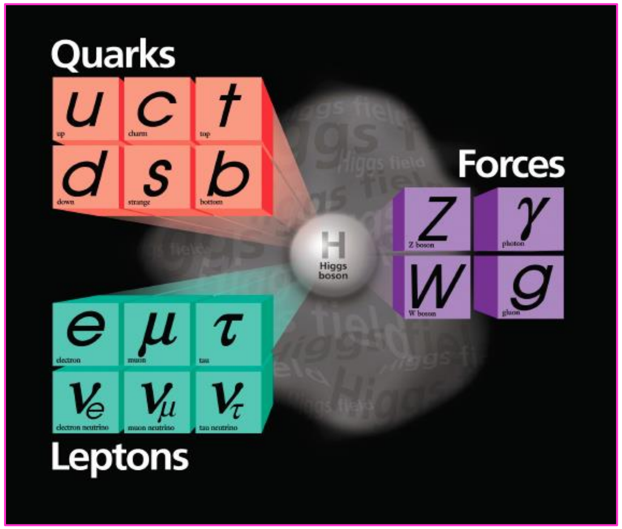
Limits of the Standard Model

The standard model of particle physics is a well-tested theoretical framework,

However, the SM has a number of issues need further investigation:

- ☐ The nature of quark confinement
- ☐ Matter-antimatter asymmetry of the Universe
- ☐ Gravity, dark matter, neutrino masses, numbers of flavors, etc.



19 free parameters of the SM

Masses

Parameter	Value	Method
m_u	1.9 MeV	Lattice
m_d	4.4 MeV	Lattice
m_s	87 MeV	Lattice
m_c	1.3 MeV	Collider
m_b	4.24 MeV	Collider
m_t	173 GeV	Collider
m_e	511 keV	Non-collider
m_μ	106 MeV	Non-collider
m_τ	1.78 GeV	Collider
m_z	91.2 GeV	Collider
m_H	125 GeV	Collider

Couplings

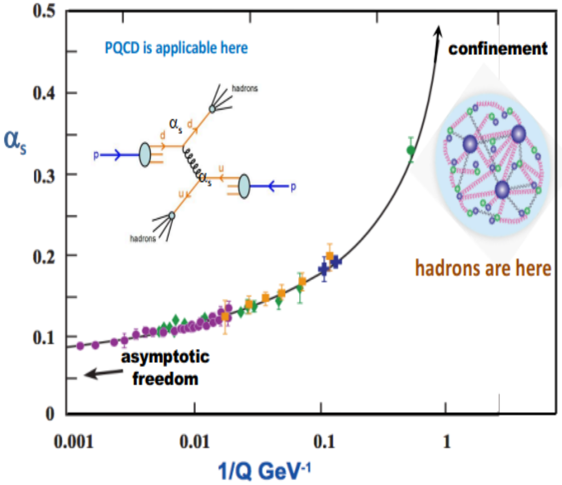
Parameter	Value	Method
α	0.0073	non-collider + collider
G_F	$1.17\text{x}10^{-5}$	Non-collider
α_s	0.12	Lattice + collider

Flavour and CP violation

Parameter	Value	Method
θ_{12} (CKM)	13.1°	Collider
θ_{23} (CKM)	2.4°	Collider
θ_{13} (CKM)	0.2°	Collider
δ (CKM-CPV)	0.995	Collider
θ (strong CP)	~0	Non-collider

Does not include neutrino masses and mixing angles

QCD coupling strength



QCD-related Topics to be Presented

Precision Test of the SM

$(g-2)_\mu$, α_{EM}

ISR $e^+e^- \to \pi^+\pi^-, \pi^+\pi^-\pi^0$

R-value measurement

Tau mass measurement

Hadron Structures

Fragmentation Function

Baryon Form Factor: Nucleon (p, n), Hyperon ($\Lambda, \Sigma, \Xi, \Lambda_c$)

Hadron Spectroscopy

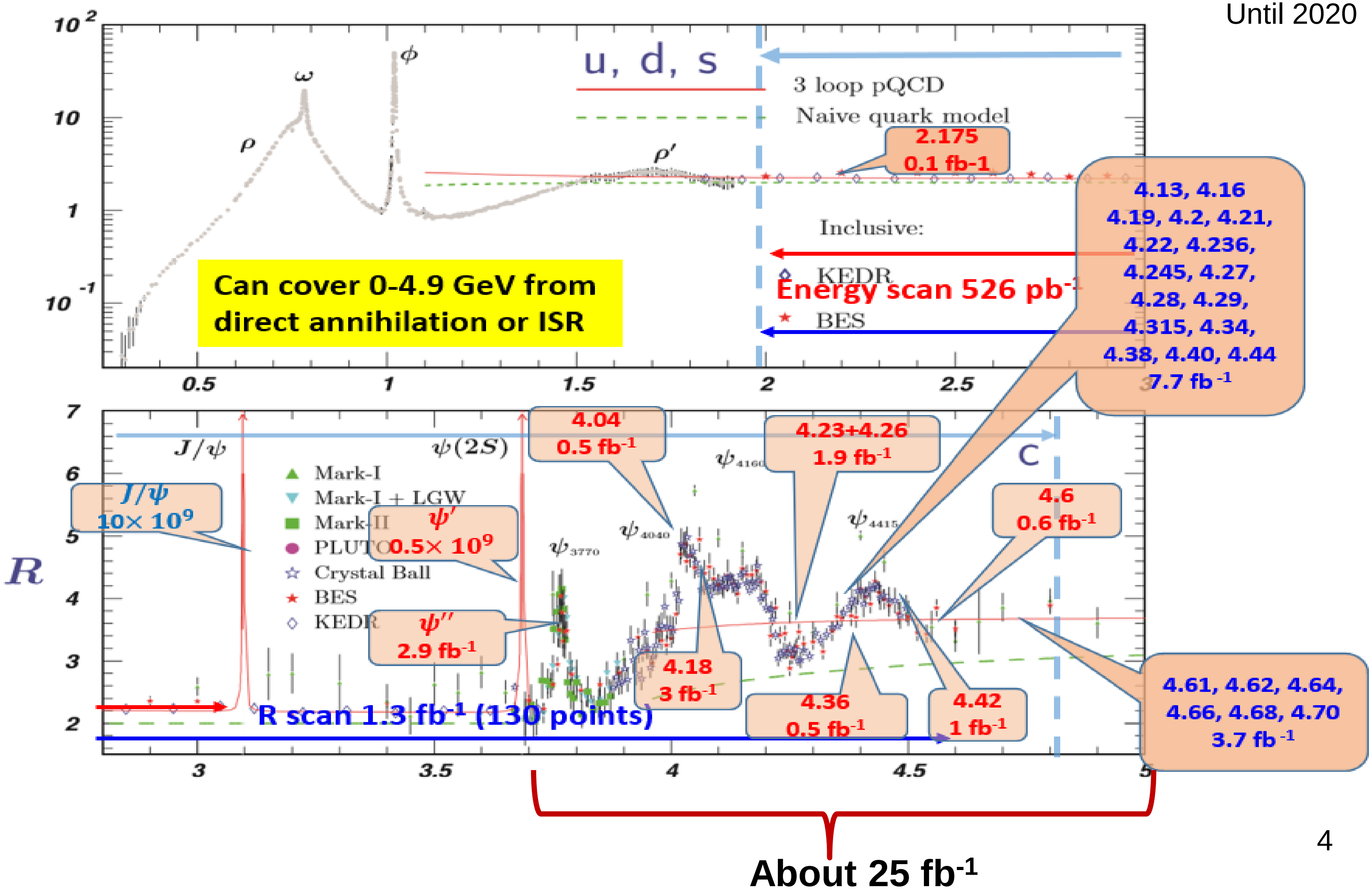
1^{--} resonance in 2-3 GeV

$e^+e^- \to K^+K^-, \phi KK, KK\pi\pi$

$e^+e^- \to \phi\eta, \phi\eta', \omega\eta$

Data Samples Collected at BESIII

Until 2020



Precision Test of the SM

$(g-2)_{\mu}$, α_{EM}:

ISR $e^+e^- \to \pi^+\pi^-, \pi^+\pi^-\pi^0$

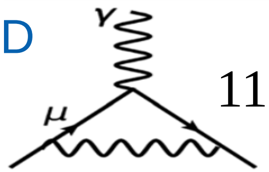
R-value measurement

Tau mass measurement

Muon g-2: SM contributions

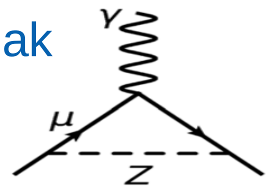
$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{Weak} + a_\mu^{Had.} = 116\,591\,810\,(43) \times 10^{-11}$$

QED



$116\,584\,718.9(1) \times 10^{-11}$

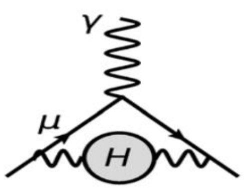
Weak



$153.6(1.0) \times 10^{-11}$

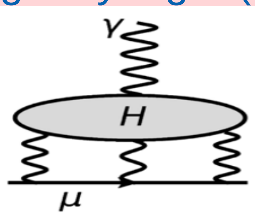
Hadronic…

Vacuum Polarization (HVP)



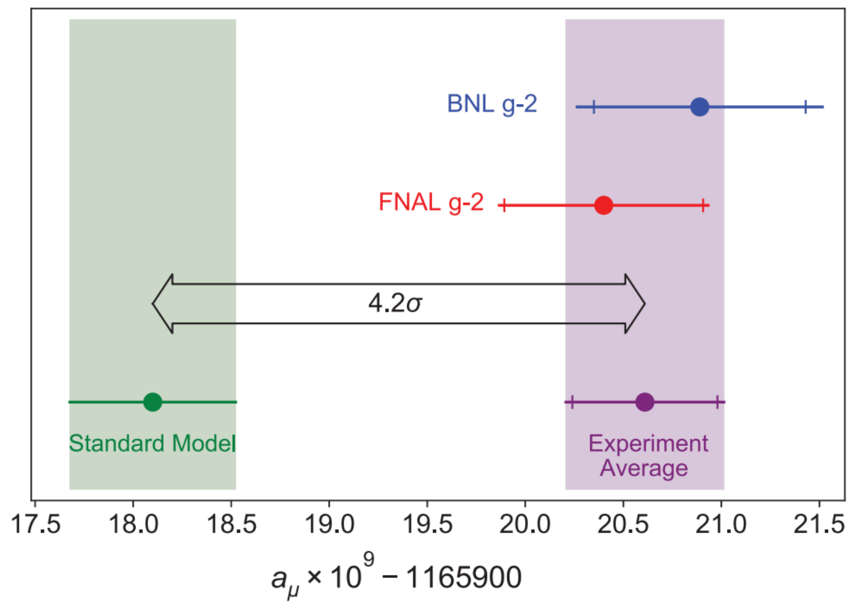
$6845(40) \times 10^{-11}$

Light-by-Light (HLbL)



$92(18) \times 10^{-11}$

PRL126.141801 (2021)



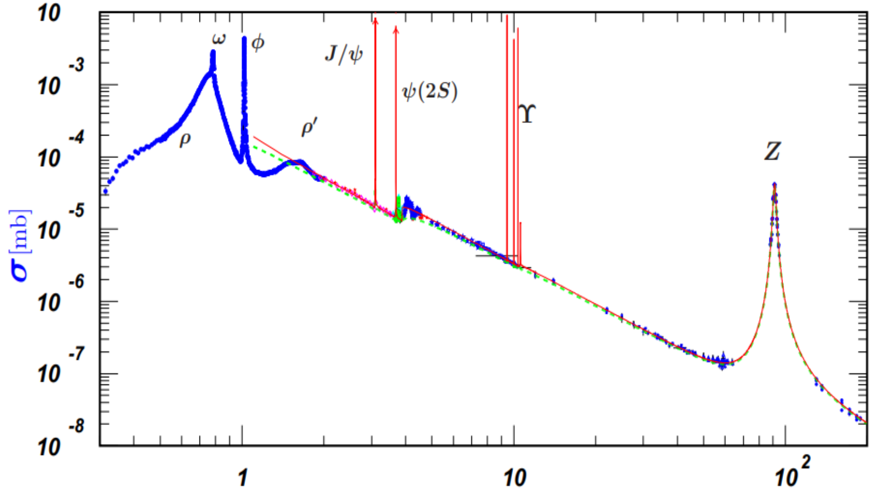
4.2σ discrepancy => Strong indication for physics beyond the SM?

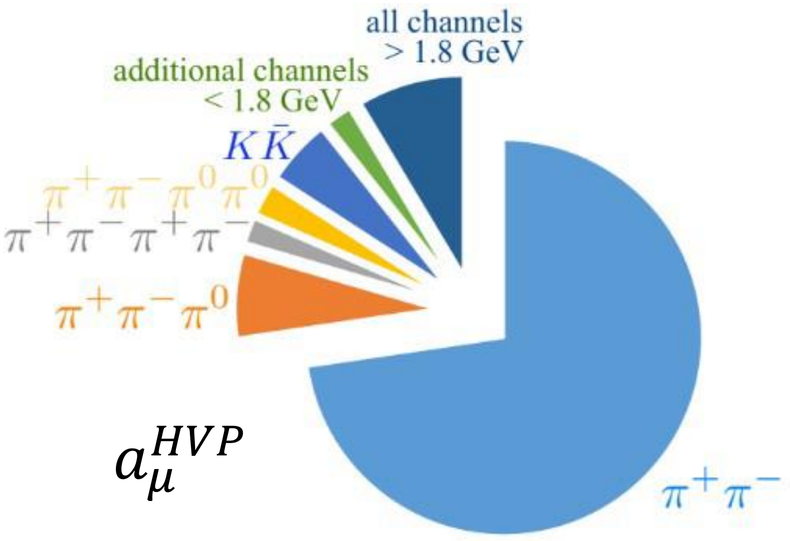
HVP contribution to $(g-2)_\mu$

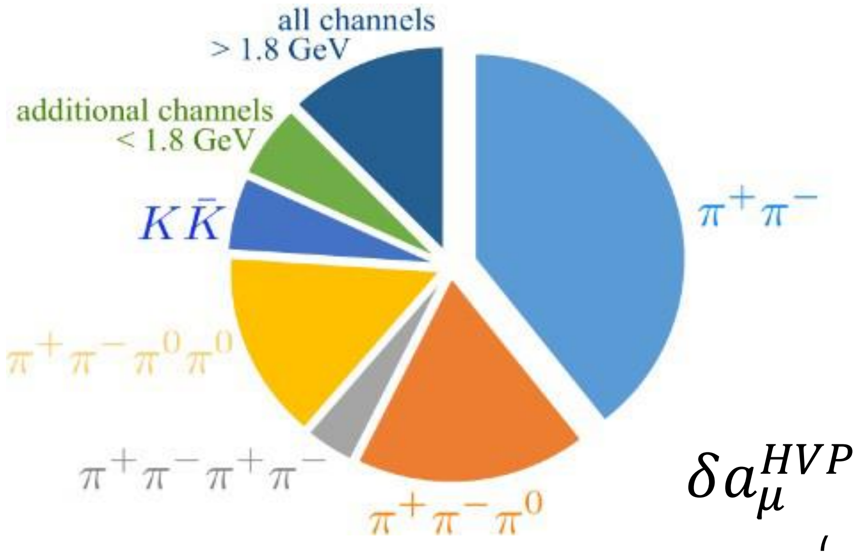
$$a_\mu^{had} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} ds\, \sigma_{had}^{(0)}(s)\, K(s)$$

$K(s)$ decreases monotonically with increasing s

$\sigma_{had} = \sigma(e^+e^- \to hadrons)$

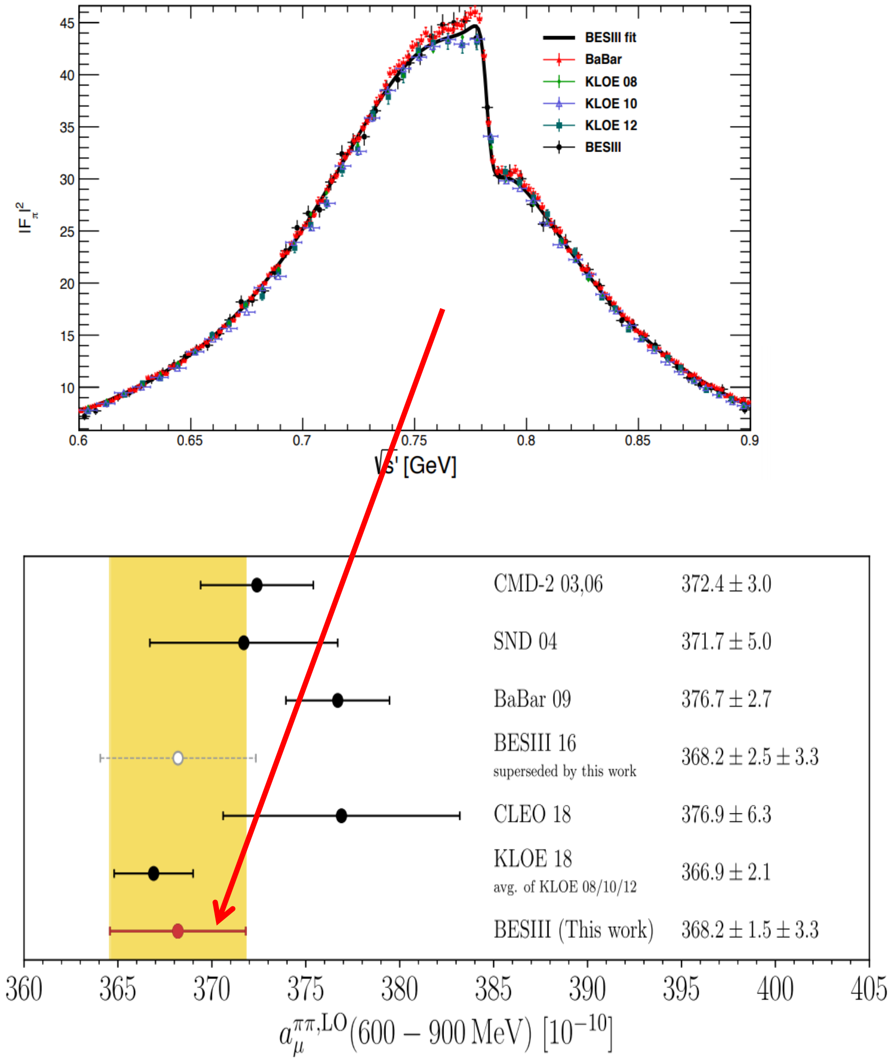




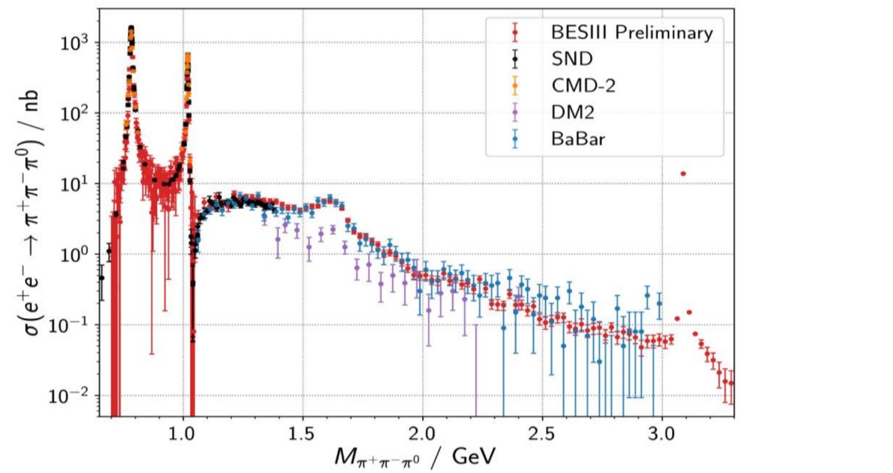


BESIII contributions to a_μ^{HVP}

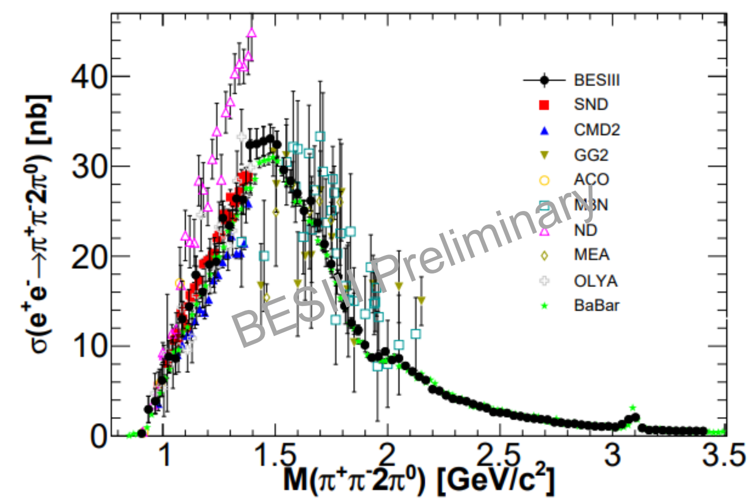
$e^+e^- \to \pi^+\pi^-$ Phys.Lett.B 753 (2016) 629-638, Phys.Lett.B 812 (2021) 135982 (erratum)



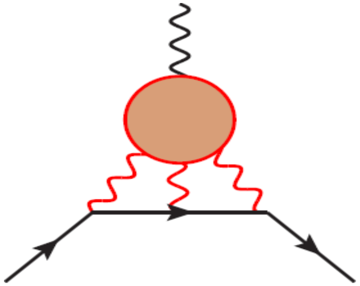
$e^+e^- \to \pi^+\pi^-\pi^0$ arXiv:1912.11208[hep-ex]



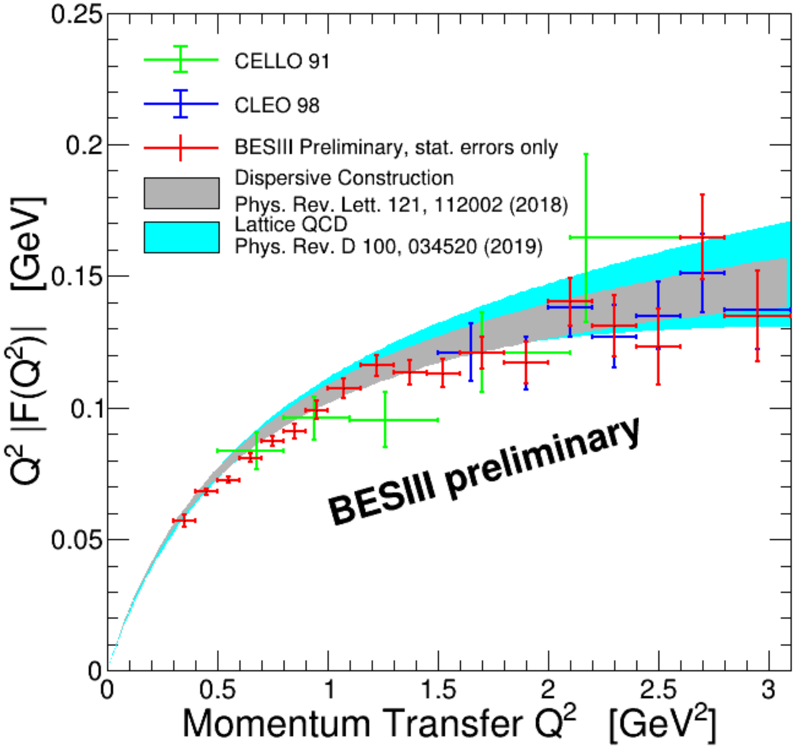
$e^+e^- \to \pi^+\pi^-\pi^0\pi^0$



BESIII contributions to a_μ^{HLbL}



- $\gamma\gamma^* \to \pi^0$ (shown right), ongoing studies: $\eta(')$, $\pi^+\pi^-$, $\pi^0\pi^0$, $\pi^0\eta$, $f_1(1285)$ ...
- Less relevant, but unique Q^2 range at BESIII;
- More important, to confirm calculations(LQCD, dispersion) which are used in a_μ^{HLbL} predictions.



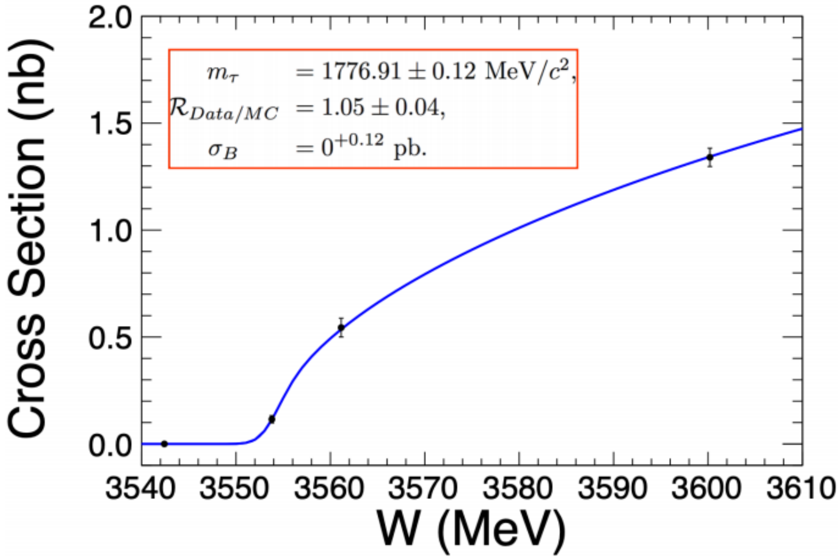
τ mass measurement at BESIII

- The τ-lepton mass is a fundamental parameter of the Standard Model
- Lepton universality test:

$$\left(\frac{g_\tau}{g_\mu}\right)^2 = \frac{\tau_\mu}{\tau_\tau}\left(\frac{m_\mu}{m_\tau}\right)^5 \frac{B(\tau \to e\nu\bar{\nu})}{B(\mu \to e\nu\bar{\nu})}$$

Universality is sensitive to: m_τ^5
For e, μ, $\Delta m/m \sim 10^{-8}$, , for τ, $\Delta m/m \sim 10^{-4}$, need more precise measurements.

- Methods
  - Pseudomass technique: ARGUS, OPAL, BELLE and BABAR
  - Threshold scan method : DELCO, BES (92, 96), KEDR and BESIII



τ mass measurement at BESIII

- $m_\tau = 1776.91 \pm 0.12^{+0.10}_{-0.13} MeV/c^2$
- Calculate g_τ with B(τ→eννbar) and τ_τ from PDG

$$g_\tau = (1.1650 \pm 0.0034) \times 10^{-5} GeV^{-2}$$

- The ratio of squared coupling constants:

$$\left(g_\tau / g_\mu\right)^2 = 1.0016 \pm 0.0042$$

agrees at the 0.4σ level !

PRD 90, 012001

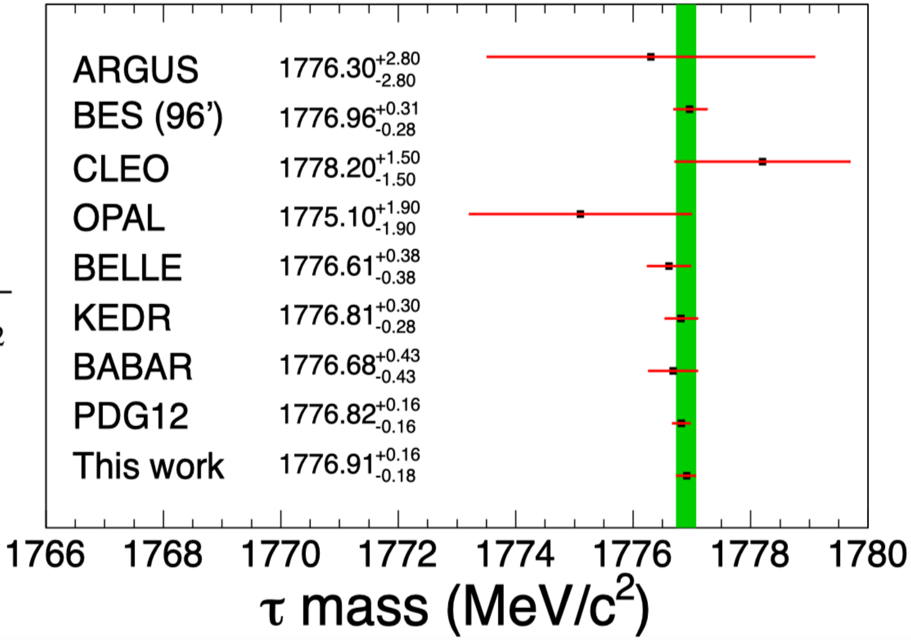
Compatible with previous determination
Dominant uncertainty still comes from Δm_τ

- Yoshio Koide equality testing

$$m_e + m_\mu + m_\tau = \frac{2}{3}(\sqrt{m_e} + \sqrt{m_\mu} + \sqrt{m_\tau})^2$$

$$\Delta f_m = \sqrt{\sum_{i=e,\mu,\tau} (m_i - \frac{2}{3} \sum_{k=e,\mu,\tau} \sqrt{m_i m_k})^2 \times (\frac{\delta m_i}{m_i})^2}$$

The error: $\Delta f_m \approx \frac{1}{3} \delta m_\tau \approx 60 keV$



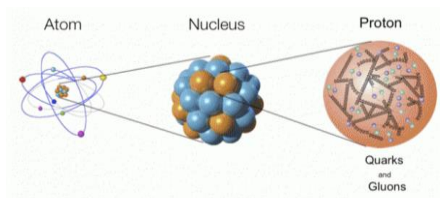
Nucleon structure

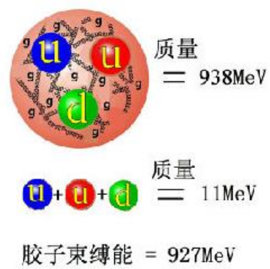
Fragmentation Function
Baryon EM form factors:
Nucleon (p, n), Hyperon (Λ, Σ, Ξ, Λ_c)

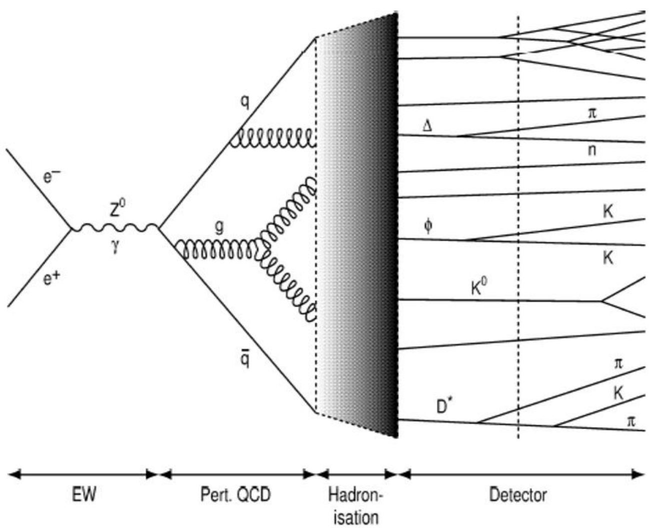
Fragmentation Function

- **Nucleons are composite objects with inner structure. At low Q, perturbative QCD not possible (expansion of coupling constant $\boldsymbol{\alpha_s}$)**

  ⇒ Nucleon structure must be measured in experiments!

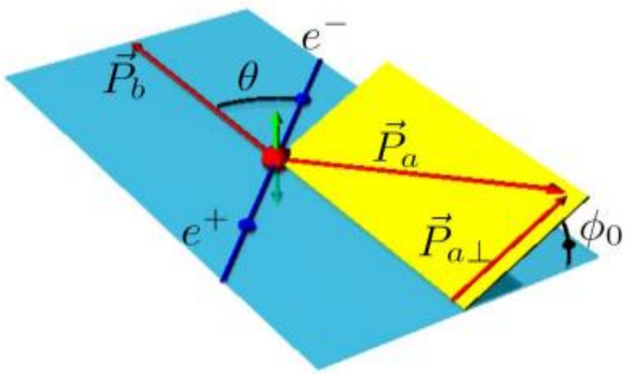






- **Fragmentation functions can be studied at BESIII:**
  - **Unpolarized fragmentation function**
  - **Collins fragmentation function (chiral odd)**
  - **Di-hadron fragmentation function**

Collins Fragmentation Functions



$$\frac{d^6\sigma^{e^+e^-\to h_a h_b X}}{d\Omega\, dz_a\, dz_b\, d^2\vec{P}_{a\perp}} = \frac{3\,\alpha_{\rm em}^2}{Q^2}\, z_a^2 z_b^2 \Big(A(y)\, \mathcal{C}_{e^+e^-}[D_1 \bar{D}_1]$$

$$+ B(y)\, \cos(2\phi_0)\, \mathcal{C}_{e^+e^-}\Big[\frac{2\hat{h}\cdot\vec{k}_{aT}\,\hat{h}\cdot\vec{k}_{bT} - \vec{k}_{aT}\cdot\vec{k}_{bT}}{M_a M_b}\, H_1^\perp \bar{H}_1^\perp\Big]\Big),$$

where we use the convolution integral

$$\mathcal{C}_{e^+e^-}[wD\bar{D}] = \sum_q e_q^2 \int d^2\vec{k}_{aT}\, d^2\vec{k}_{bT}\, \delta^{(2)}(\vec{k}_{aT} + \vec{k}_{bT} + \vec{P}_{aT}/z_a)$$

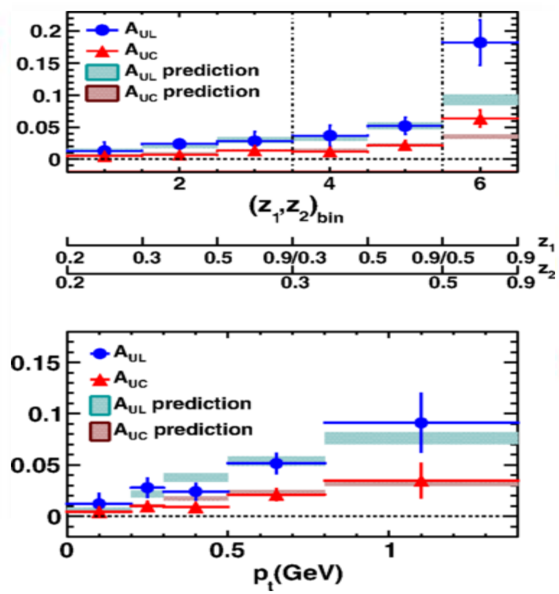
$$\times\, w(\vec{k}_{aT}, \vec{k}_{bT})\, D^{h_a/q}(z_a, z_a^2\vec{k}_{aT}^2)\, D^{h_b/\bar{q}}(z_b, z_b^2\vec{k}_{bT}^2) + \{q \leftrightarrow \bar{q}\}\,.$$

To avoid detection-related effects, experimentally, a double ratio measurement was proposed:

U: pi+&pi- or pi-&pi+

L: pi+&pi+ or pi-&pi-

$$\frac{R^U}{R^{L(C)}} = A\cos(2\phi_0) + B,$$



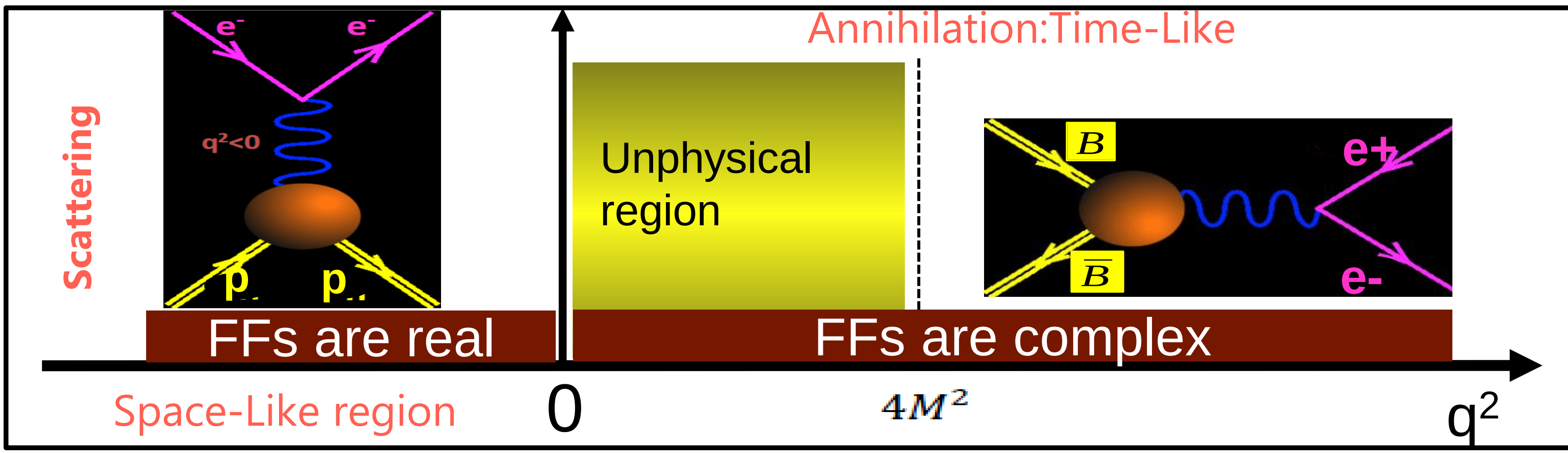
BESIII measurement

Clearly see the modulation

PRL 116, 042001 (2016)

Electromagnetic Form Factors

- **Fundamental properties of the nucleon**
  - **Connected to charge, magnetization distribution**
  - **Crucial testing ground for models of the nucleon internal structure**



The nucleon electromagnetic vertex Γ_μ describing the hadron current:

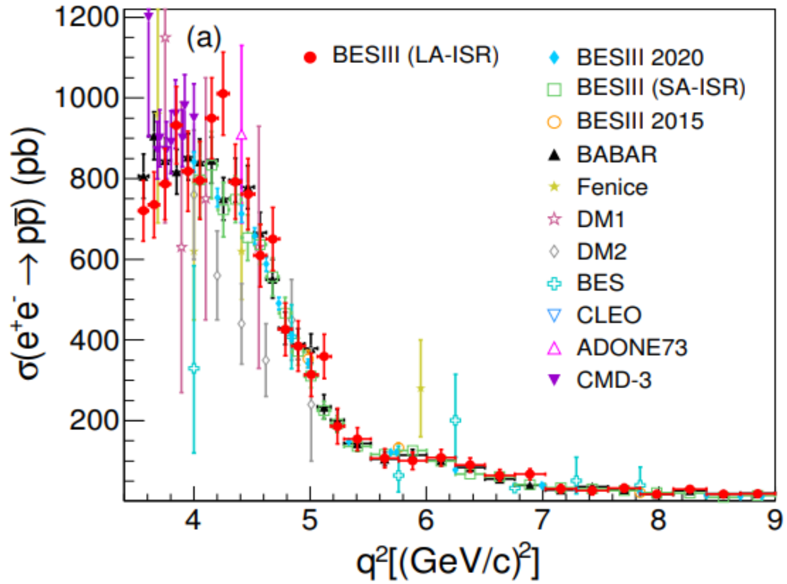
$$\Gamma_\mu(p', p) = \gamma_\mu F_1(q^2) + \frac{i\sigma_{\mu\nu}q^\nu}{2m_p} F_2(q^2)$$

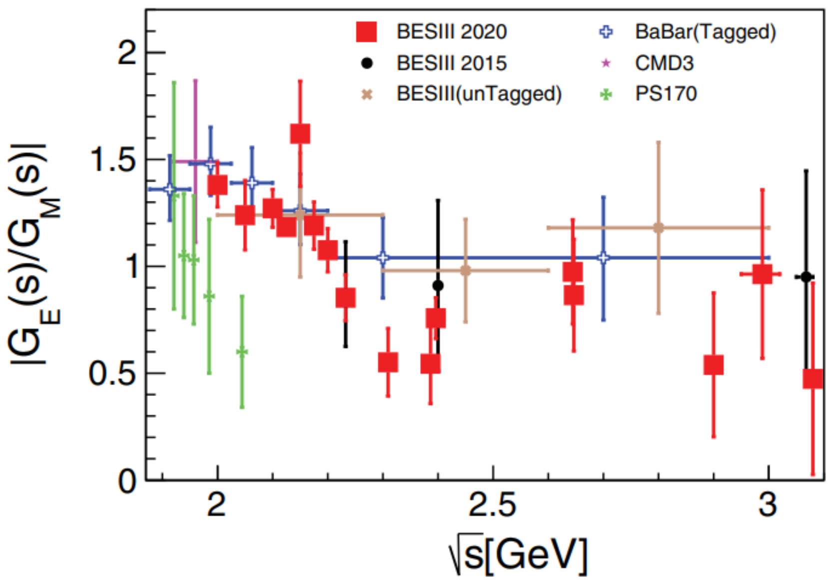
Sachs FFs: $G_E(q^2) = F_1(q^2) + \tau\kappa_p F_2(q^2),\ G_M(q^2) = F_1(q^2) + \kappa_p F_2(q^2)$

Proton Form Factors

PRL 124, 042001 (2020)
PRD 91, 112004 (2015)
SA-ISR: PRD 99, 092002 (2019)
LA-ISR: arXiv:2102.10337, submit to PLB

- Both scan and ISR technique applied
- From threshold to q^2=4.0 GeV^2, average cross section 840 pb (close to point-like cross section at threshold)
- $|G_E/G_M|$, $|G_M|$ are determined with **high accuracy**, comparable to data in SL.

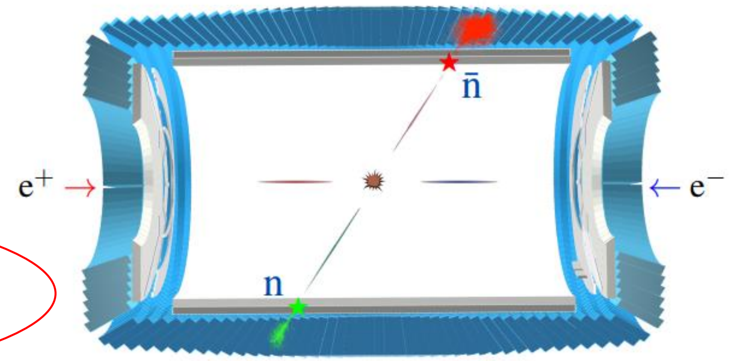




Neutron Form Factors

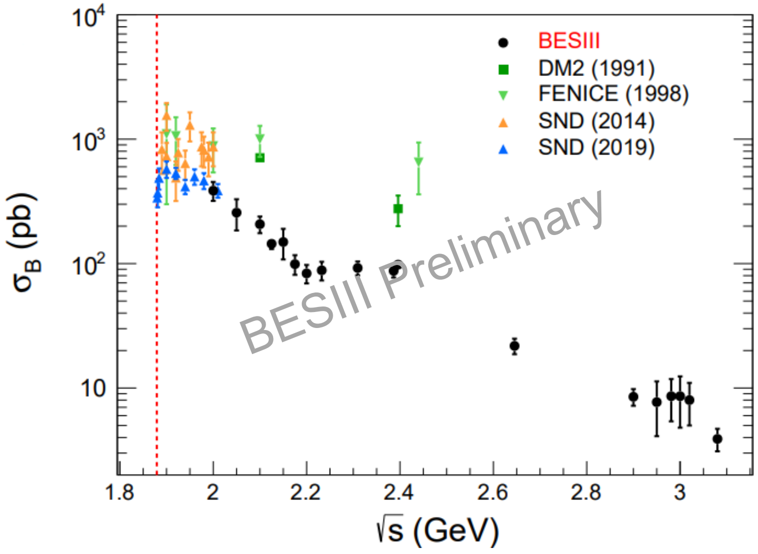
arXiv:2103.12486

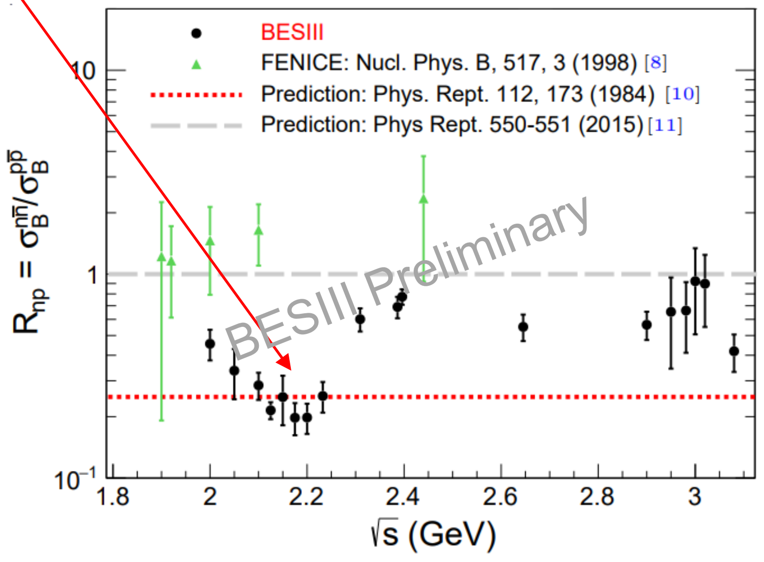
- Born cross section measured over wide $\sqrt{s}$ with unprecedented precision.
- Clarify the "puzzle" that photon-neutron coupling larger than photon-proton coupling.



V. L. Chernyak and A. R. Zhitnitsky, Phys. Rept. 112, 173 (1984)

$$\sigma(e^+e^- \to B\bar{B}) \propto |\sum_{q\in B} Q_q a_q^B(s)|^2, \quad \frac{\sigma(e^+e^- \to p\bar{p})}{\sigma(e^+e^- \to n\bar{n})} \to \frac{Q_u^2}{Q_d^2} = 4$$

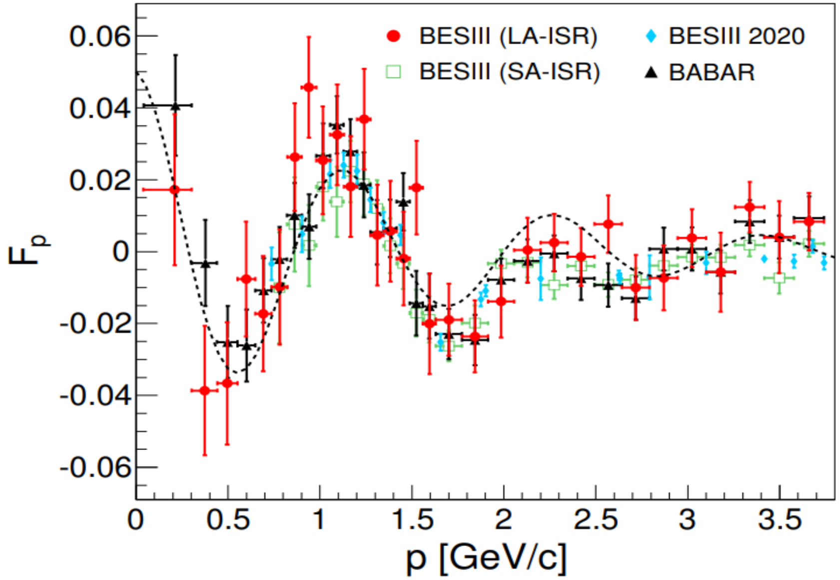


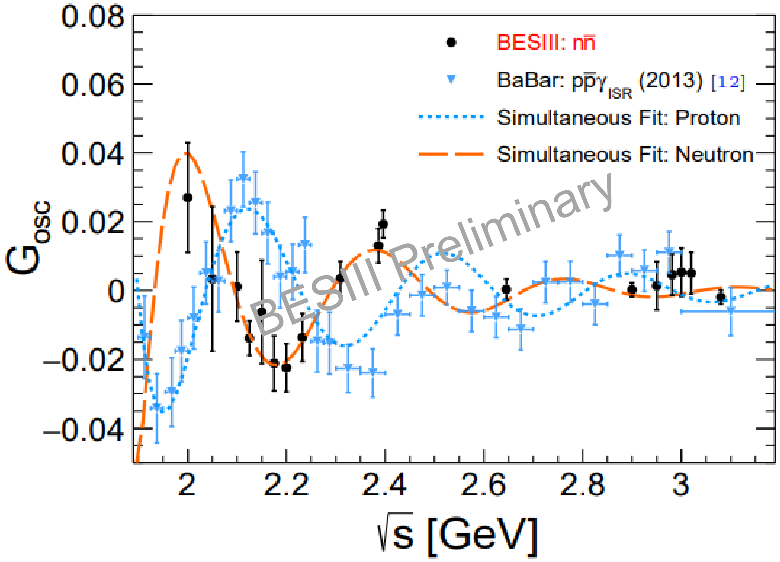


Oscillation Structure in Form Factor

- Periodic behavior of $|G_p|$ for the proton observed at Babar and confirmed at BESIII. Can we see a similar effect in the neutron channel?

$$F^{osc}_{sim} = A \cdot \exp(-B|p|) \cdot \cos(C_{shared}|p| + D)$$



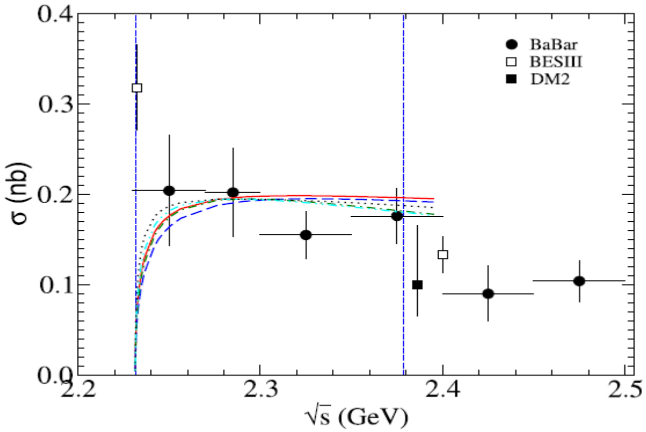


- Oscillation of |G| observed in **neutron data**
- Simultaneous fit of proton and neutron data, **shared frequency** C=(5.55 $\pm$ 0.28) GeV^{-1}
- Almost orthogonal behavior with **large phase difference** $\Delta D=|D_p - D_n|=(125 \pm 12)^{\circ}$

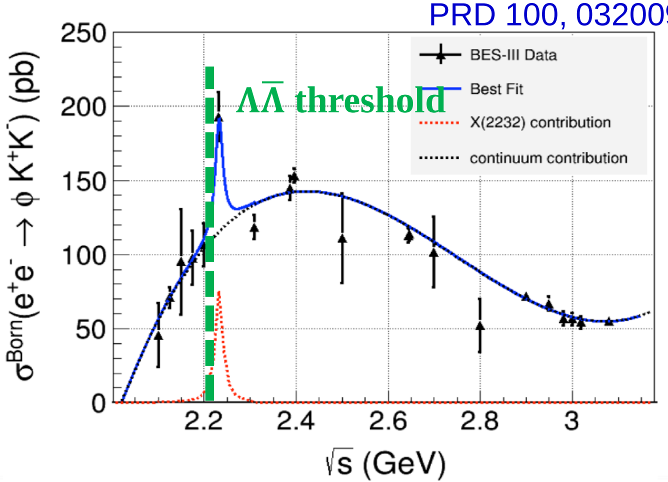
Threshold effect on $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ and $e^+e^- \to \Lambda\bar{\Lambda}$

- A hint for resonance around $\Lambda\bar{\Lambda}$ **threshold** in $e^+e^- \to KKKK$ cross section: Mass=2232±3.5 MeV, width≈20 MeV

PRD 97, 032013 (2018)

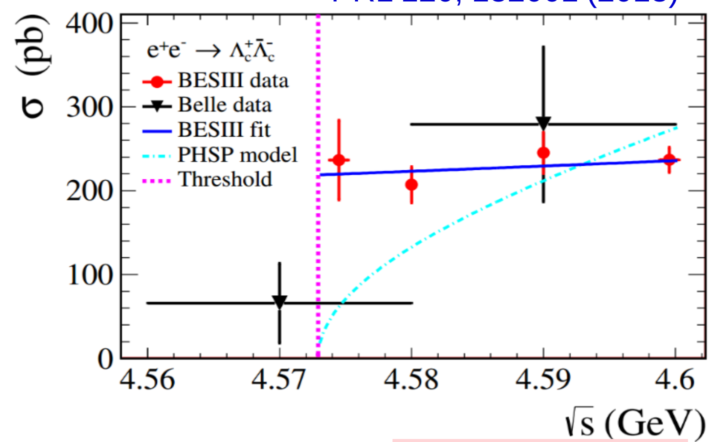


PRD 100, 032009 (2019)

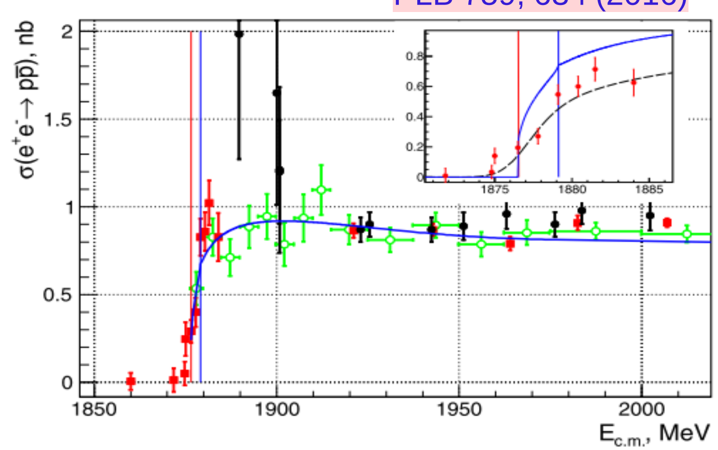


- The BESIII measurements indicate that there is indeed a step in $\Lambda_c^+\bar{\Lambda}_c^-$, similar to $p\bar{p}$, followed by a plateau.

PRL 120, 132001 (2018)



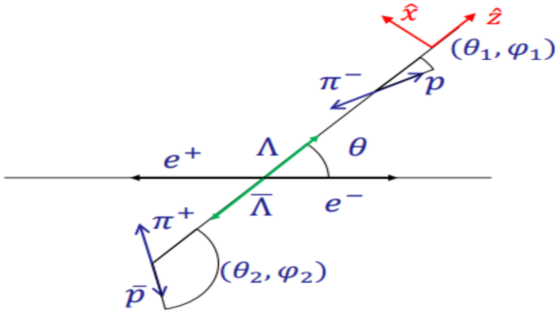
PLB 759, 634 (2016)

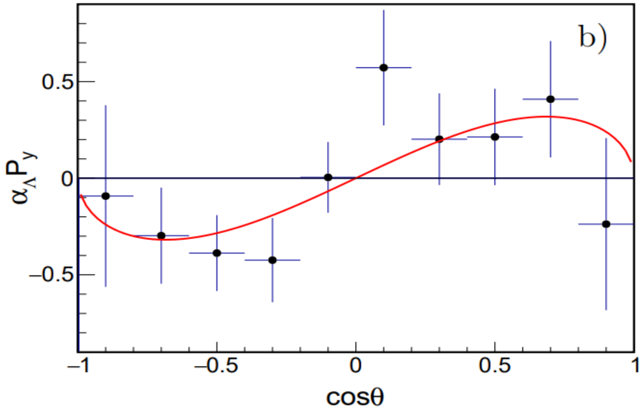


Determination of the Relative phase of Λ FFs

- **Complex form** of FFs:
  - $G_E = |G_E|e^{i\Phi_E}$, $G_M = |G_M|e^{i\Phi_M}$
  - Relative phase: $\Delta\Phi = \Phi_E$-Φ_M
- A non-zero phase has **polarization** effect on the Baryons:
  - $\boldsymbol{P_y \propto \sin\Delta\Phi}$
- The **angular** distribution of daughter baryon from Hyperon weak decay is:
  - $\boldsymbol{\frac{d\sigma}{d\Omega} \propto 1 + \alpha_\Lambda P_y \cdot \hat{q}}$
  - α_Λ: asymmetry parameter
  - $\hat{q}$: unit vector along the daughter baryon in hyperon rest frame

PRL 123, 122003 (2019)





$$\left|\frac{G_E}{G_M}\right| = 0.96 \pm 0.14(\text{stat.}) \pm 0.02(\text{sys.})$$

$$\Delta\Phi = 37^\circ \pm 12^\circ(\text{stat.}) \pm 6^\circ(\text{sys.})$$

Confirm the complex form of EMFFs !

PDG Update

R = $|G_E/G_M|$ in $\Lambda \to p\pi^-, \bar{\Lambda} \to \bar{p}\pi^+$

VALUE	DOCUMENT ID		TECN	COMMENT
0.96±0.14±0.02	[1] ABLIKIM	19BF	BES3	$e^+e^- \to \bar{\Lambda}\Lambda$ at $\sqrt{s}$ = 2.396 GeV

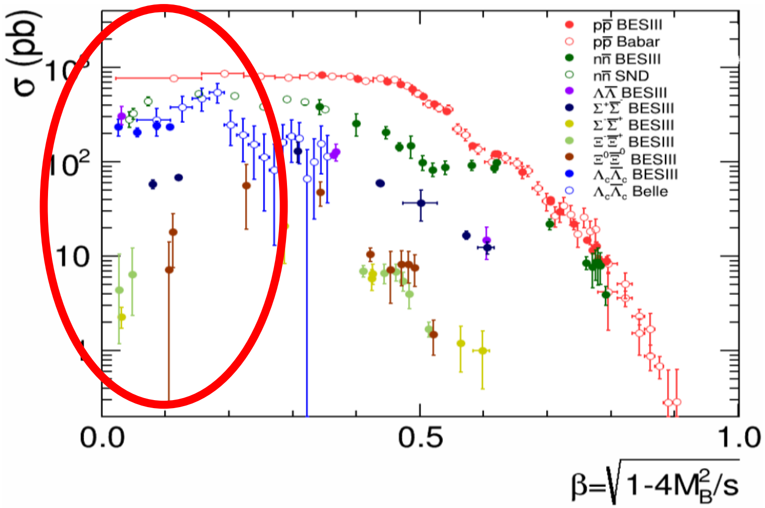
[1] Determined using the latest BES-III value on the asymmetry parameter $\alpha = 0.750 \pm 0.010$.

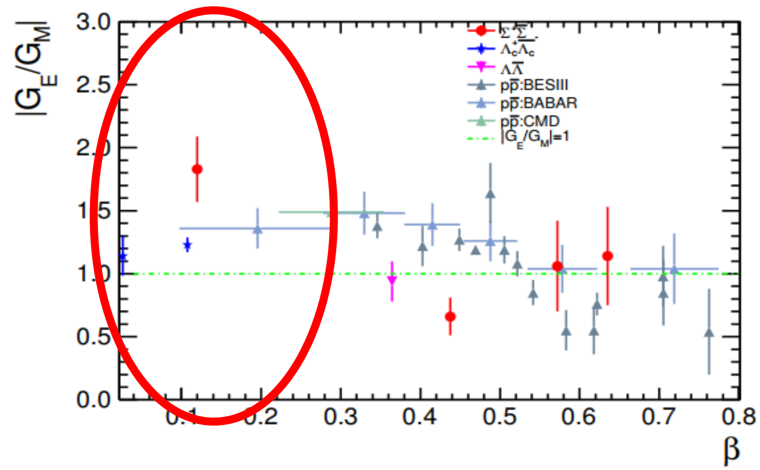
$\Delta\Phi = \Phi_E - \Phi_M$ in $\Lambda \to p\pi^-, \bar{\Lambda} \to \bar{p}\pi^+$

VALUE (degrees)	DOCUMENT ID		TECN	COMMENT
37±12±6	[1] ABLIKIM	19BF	BES3	$e^+e^- \to \bar{\Lambda}\Lambda$ at $\sqrt{s}$ = 2.396 GeV

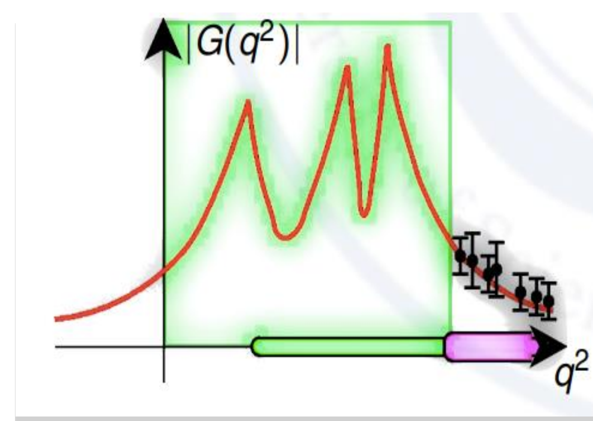
[1] Relative phase between GE and GM, determined using the latest BES-III value on the asymmetry parameter $\alpha = 0.750 \pm 0.010$.

Baryon pair production at Continuum





- As no meson-cloud contribution, abundant theoretical prediction on the form factors in SL, *e.g.* Lattice QCD. But corresponding experiments for hyperons are limited due to their unstable nature.
- A lot results of TL form factors appears for hyperons. Possible to combine the TL and SL via dispersion relation in a unified frame?



Hadron spectroscopy

1^{--} resonance in 2-3 GeV

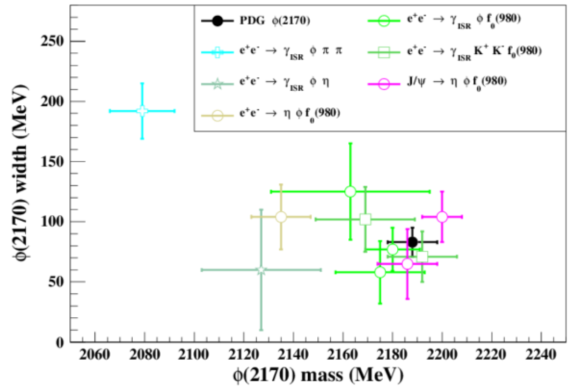
$e^+e^- \to K^+K^-, \phi KK, KK\pi\pi$

$e^+e^- \to \phi\eta, \phi\eta', \omega\eta$

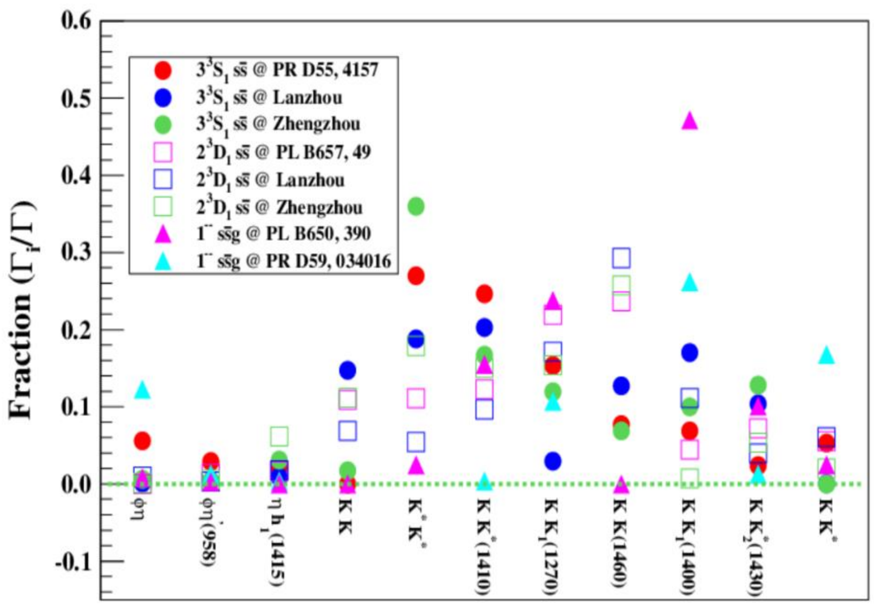
The nature of $\phi(2170)$

PDG2020 $\phi(2170)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	e^+e^-	seen
Γ_2	$\phi\eta$	
Γ_3	$\phi\pi\pi$	
Γ_4	$\phi f_0(980)$	seen
Γ_5	$K^+K^-\pi^+\pi^-$	
Γ_6	$K^+K^- f_0(980) \to K^+K^-\pi^+\pi^-$	seen
Γ_7	$K^+K^-\pi^0\pi^0$	
Γ_8	$K^+K^- f_0(980) \to K^+K^-\pi^0\pi^0$	seen
Γ_9	$K^{*0}K^\pm\pi^\mp$	not seen
Γ_{10}	$K^*(892)^0\overline{K}^*(892)^0$	not seen



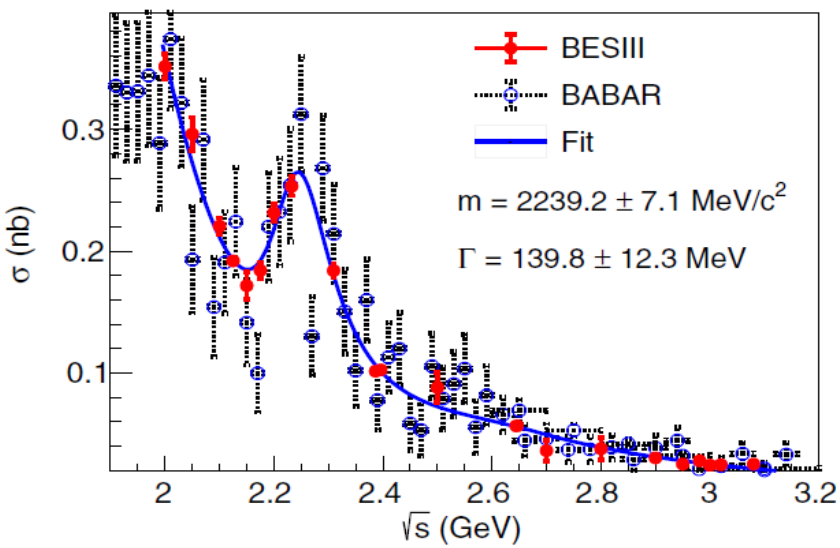
- Experimental information of $\phi(2170)$
  - Limited decay modes
  - Inconsistence on Mass & Width



- Theoretical explain of $\phi(2170)$
  - $s\bar{s}g$ hybrid
  - 2^3D_1 or 3^3S_1 $s\bar{s}$
  - Tetraquark
  - Molecular state $\Lambda\bar{\Lambda}$
  - $\phi f_0(980)$ resonance with FSI
  - Three body system ϕKK

The nature of $\phi(2170)$ is still not fully understood

$e^+e^- \to K^+K^-$



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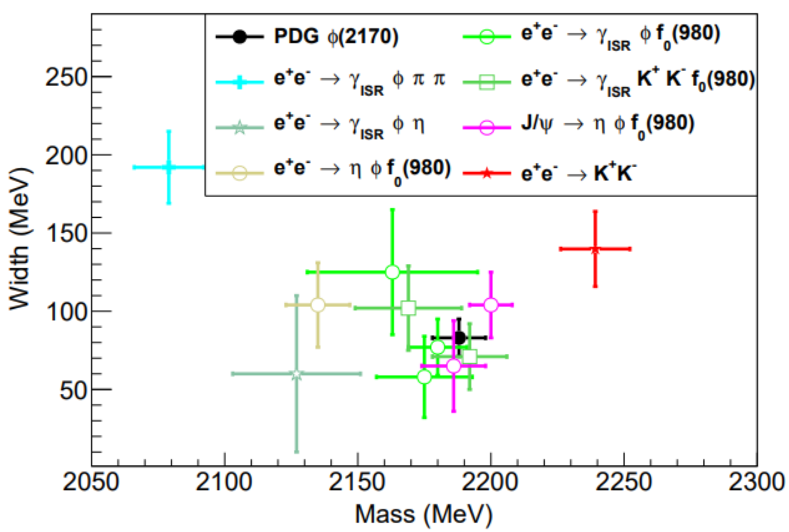
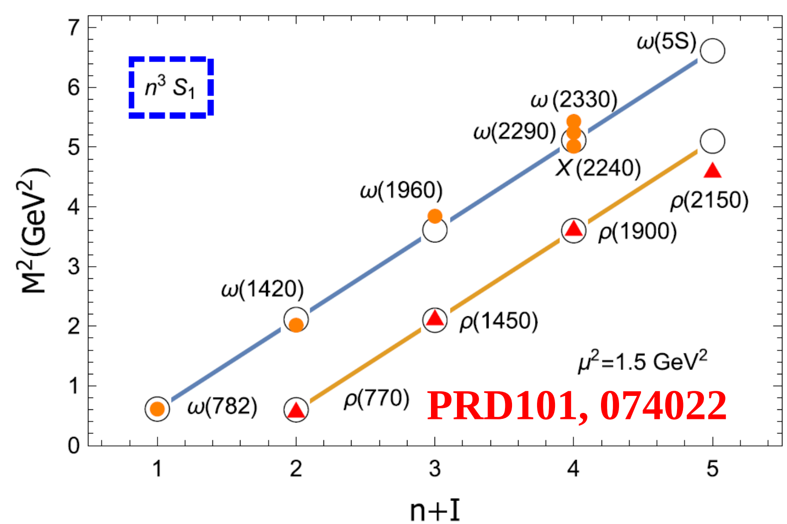
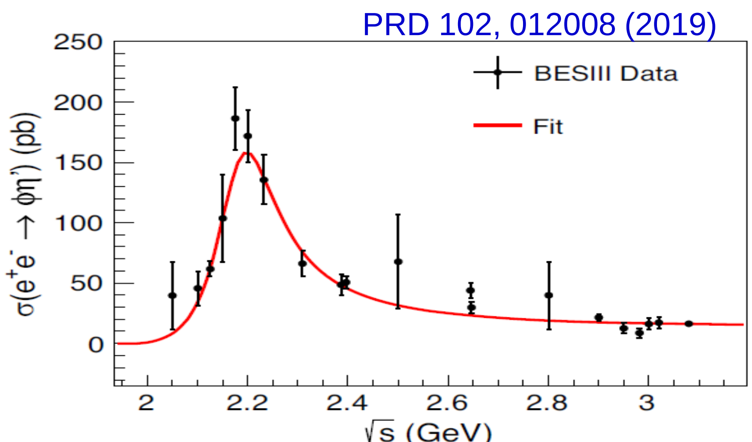
- 1^{--} resonance observed in K^+K^- lineshape:
  - Differs from the world average parameters of $\phi(2170)$ by more than 3σ in mass and more than 2σ in width
  - Interpreted as isoscalar : $\omega^*, \phi(2170)$

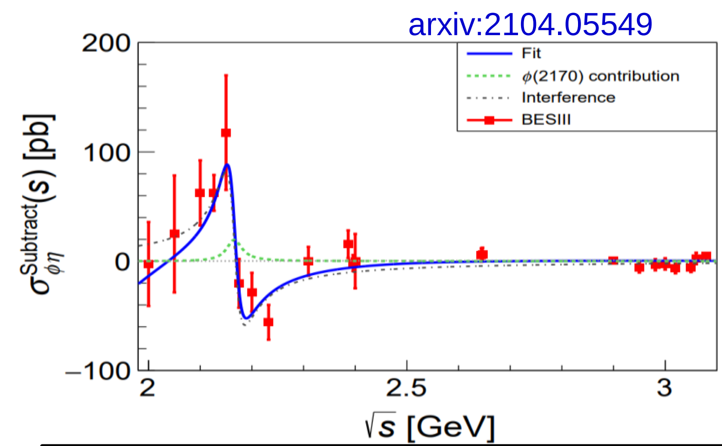
Or isovector : $\rho(2150)$





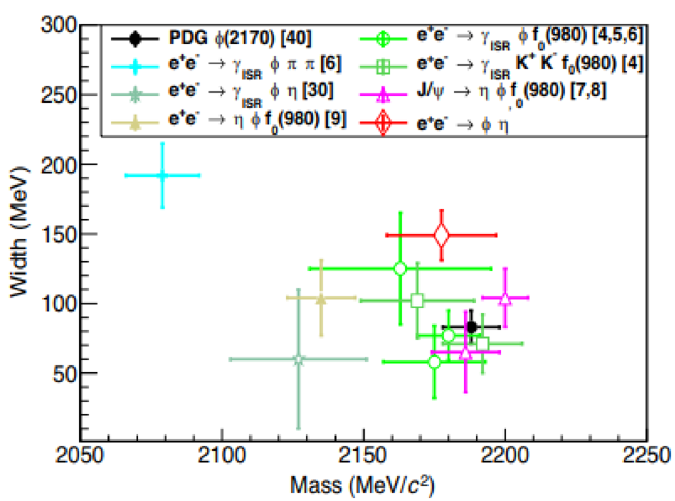
$e^+e^- \to \phi\eta'$ and $\phi\eta$





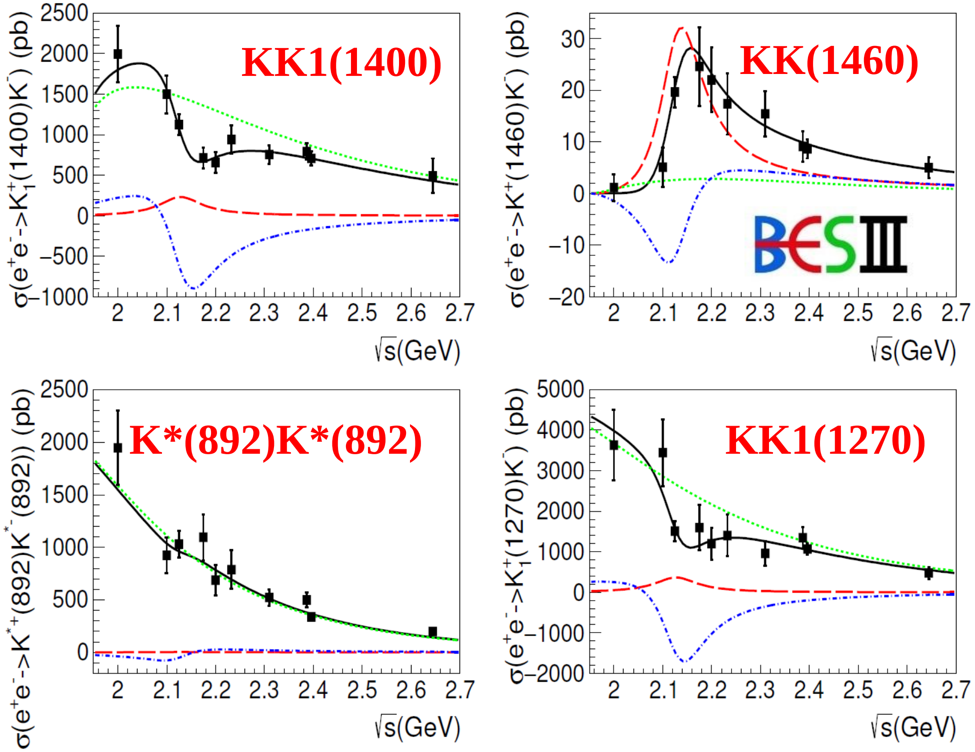
$$M = 2177.5 \pm 4.8 \pm 19.5\ \text{MeV}/c^2$$
$$\Gamma = 149.0 \pm 15.6 \pm 8.9\ \text{MeV}$$
$$\mathcal{B}_{\phi\eta'}\Gamma_{ee} = 7.1 \pm 0.7 \pm 0.7\ \text{eV}$$

$$M = 2165.5 \pm 5.8 \pm 1.5\ \text{MeV}/c^2$$
$$\Gamma = 36.4^{+31.4}_{-15.3} \pm 2.1\ \text{MeV}$$
$$\mathcal{B}_{\phi\eta}\Gamma_{ee} = 0.23^{+0.37}_{-0.06}\ \text{eV}$$



- **1^{--} resonance observed in $\phi\eta$ and $\phi\eta'$**
  - Isoscalar ω^* is suppressed due to OZI rule
  - Conflict with $s\bar{s}g$ hybrid prediction on $\mathcal{B}_{\phi\eta}/\ \mathcal{B}_{\phi\eta'}$

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



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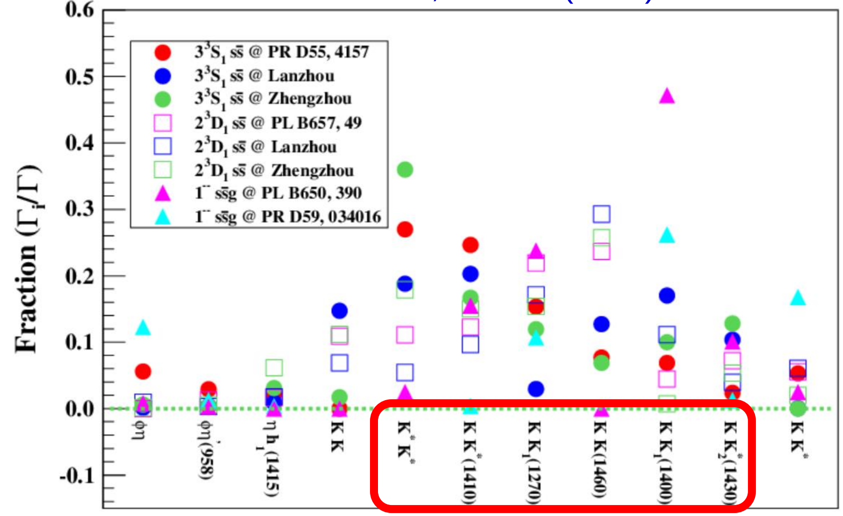
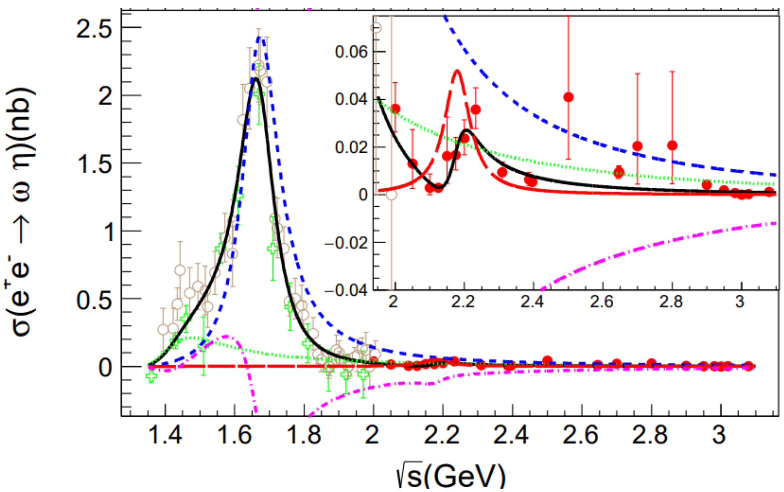


Table 22: Fitting parameters.

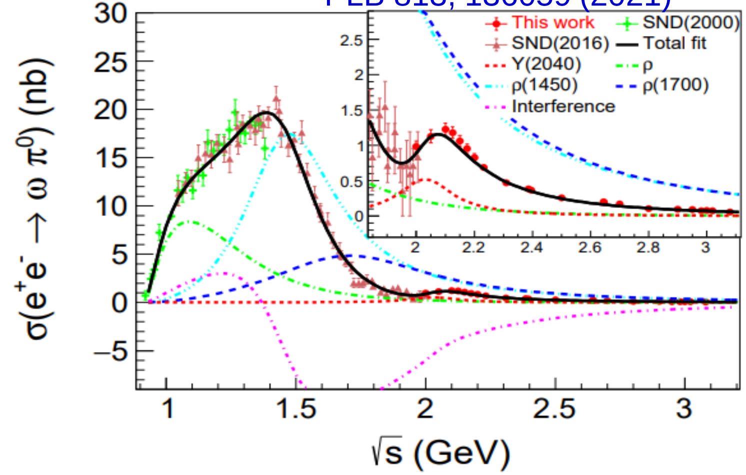
channel	$e^+e^- \to K_1^+(1400)K^-$		$e^+e^- \to K^+(1460)K^-$	$e^+e^- \to K_1^+(1270)K^-$		$e^+e^- \to K^{*+}K^{*-}$
Mass (MeV/c^2)	2126.5 ± 16.8					
Width (MeV)	106.9 ± 32.1					
	Solution1	Solution2		Solution1	Solution2	
$\mathcal{B}_R\Gamma^{e^+e^-}$ (eV)	7.6 ± 3.7	152.6 ± 14.2	1.0 ± 1.3	4.7 ± 3.3	98.8 ± 7.8	0.04 ± 0.2
ϕ (rad)	3.7 ± 0.4	4.5 ± 0.3	5.6 ± 1.5	4.0 ± 0.2	4.5 ± 0.1	5.8 ± 1.9
Significance(σ)	4.8		4.5	1.4		1.2

- PWA for $e^+e^- \to K^+K^-\pi^0\pi^0$ at multiple energy points
- Cross section lineshapes for intermediate states => **essential input to clarify the nature of $\phi(2170)$**

$e^+e^- \to \omega\eta$ and $\omega\pi^0$



PLB 813, 136059 (2021)



parameters	solution I	solution II
$m_{Y(2180)}(\mathrm{MeV}/c^2)$	2179 ± 21	
$\Gamma_{Y(2180)}(\mathrm{MeV})$	89 ± 28	
$\Gamma^{ee} \cdot B^{\omega\eta}(\mathrm{eV})$	0.50 ± 0.16	1.50 ± 0.44
φ	2.7 ± 0.3	1.9 ± 0.2
significance	6.1σ	

$$M = 2034 \pm 14 \pm 9\ \mathrm{MeV}/c^2$$
$$\Gamma = 234 \pm 30 \pm 25\ \mathrm{MeV}$$
$$\mathcal{B}_{\omega\pi^0}\Gamma_{ee} = 34 \pm 11 \pm 16\ \mathrm{eV}$$

- Resonance in ωη lineshape: ω^* or $\phi(2170)$
- Resonance in $\omega\pi^0$ lineshape: $\rho(2000)$ or $\rho(2150)$

Unique place at BESIII to study 1^{--} resonance between $\sqrt{s}$ =2.0 to 3.0 GeV. However, there are still questions and puzzles!

Summary

- BESIII is a good platform for the non-perturbative QCD with the unique energy region.
- BESIII has a lot progress in the QCD researches at low q^2 to precisely test the SM, study hadron structure and spectroscopy, etc.
- There is still results which cannot be well explained, e.g. abnormal threshold effect, nature of phi(2170)…Work more closely with theory is necessary.