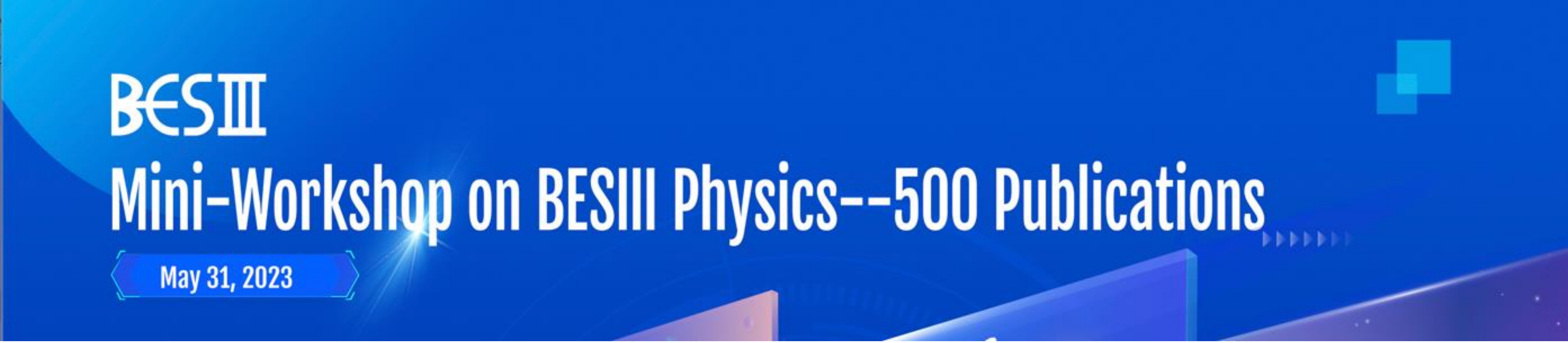


Highlight on R values and QCD

Xiaorong Zhou (on behalf of tau-QCD group)

2023.5.31, Beijing, IHEP

Tau-QCD related topics at BESIII

Precision Test of the SM

Tau mass measurement
$(g-2)_\mu$, α_{EM}
ISR $e^+e^- \to \pi^+\pi^-, \pi^+\pi^-\pi^0$
R-value 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
$e^+e^- \to K^+K^-, KK\pi\pi$
$e^+e^- \to \phi\eta, \phi\eta', \omega\eta$
C even production
$e^+e^- \to \chi_{c1}$

Hadron Decay

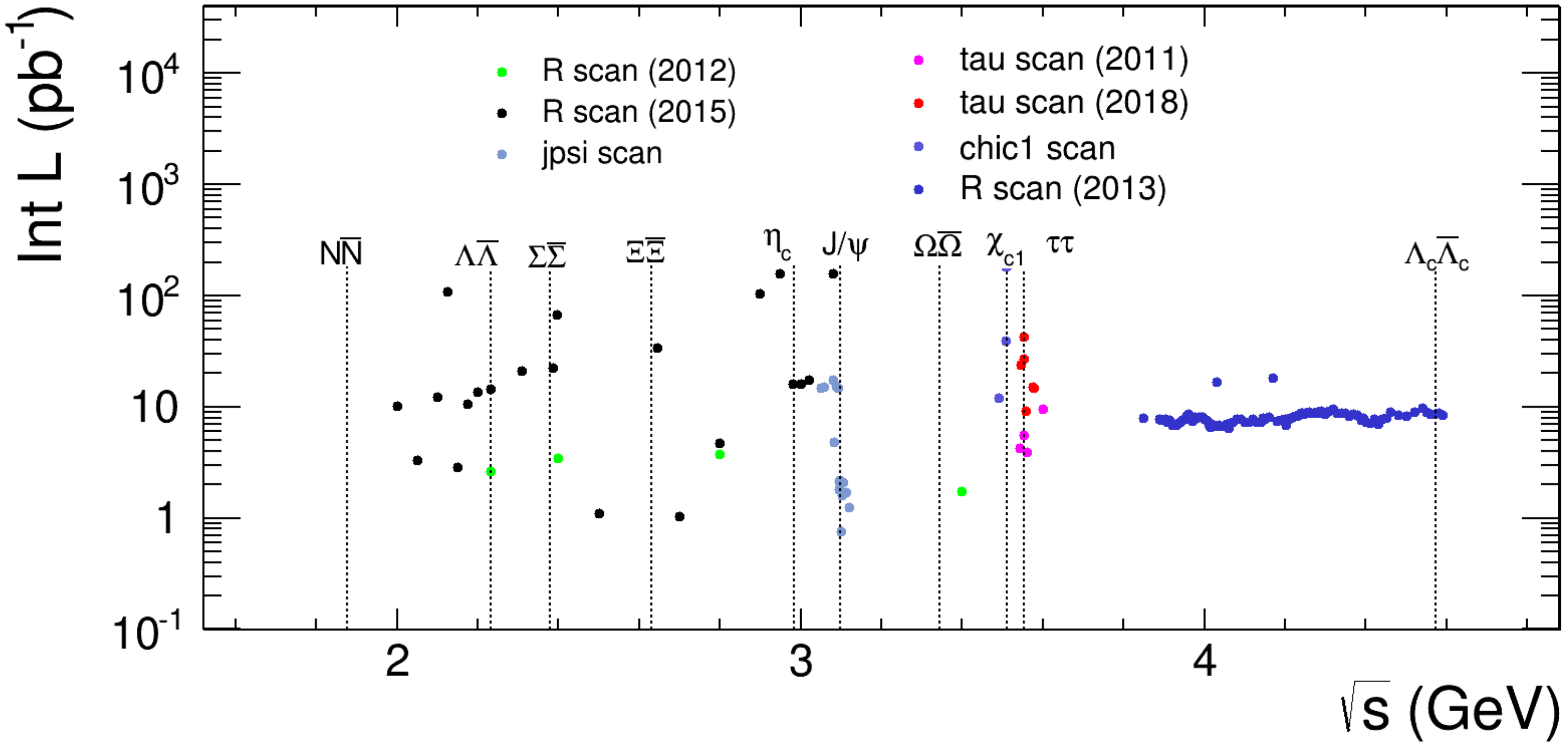
Phase in strong and EM in ψ decay
$J/\psi \to p\bar{p}, \Sigma^{+/0}\bar{\Sigma}^{-/0}$
$\Lambda\bar{\Lambda}, K^+K^-, \omega\pi^0$ ...

Some features:

- Two approaches used: ISR and energy scan
- Focus on the low q^2, production thresholds of pairs production
- Special request on the MC simulation, BEMS, theoretical inputs *etc.*

Dedicated data for Tau-QCD study

- **2011** tau scan: **11** days
- **2012** J/ψ phase scan: 3.05-3.10 GeV (**13** days); R scan: 2.2324, 2.4, 2.8, 3.4 GeV (**9** days)
- **2013-2014** R scan: 3.85-4.59 GeV, 104 points (**45** days)
- **2015** R scan: 21 points from 2.0 to 3.08 GeV (**120** days)
- **2017** chic1 scan: 3.49-3.51 GeV (**23** days)
- **2018** tau scan: **20** days



Precision Test of the SM

Free parameters of the SM

- 19 free parameters in SM that must be extracted from experimental measurements.
- BESIII contributes to tau mass m_τ , QED running coupling constant evaluated at the Z pole $\alpha(s)$, and SM calculation of muon anomalous magnetic moment a_μ. High precision measurement essential to test SM.

Masses

Parameter	Value	Method
m_u	1.9 MeV	Lattice
m_d	4.4 MeV	Lattice
m_s	87 MeV	Lattice
m_c	1.3GeV	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

τ mass measurement at BESIII

- Lepton universality test:

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

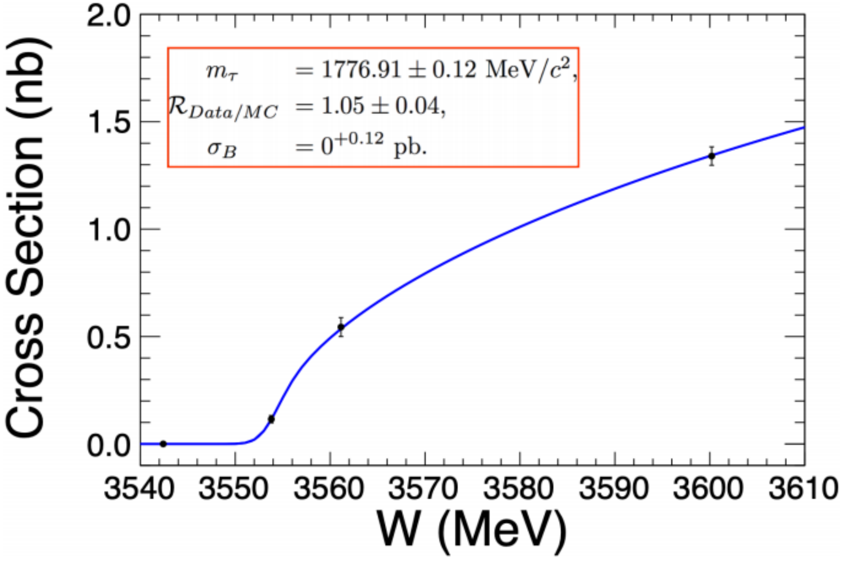
- Methods
  - Pseudomass technique: ARGUS, OPAL, BELLE and BABAR
  - Threshold scan method : DELCO, BES (92, 96), KEDR, BESIII
- BESIII obtains the most precise τ mass:
  - $m_\tau = 1776.91 \pm 0.12^{+0.10}_{-0.13}$ MeV/c^2

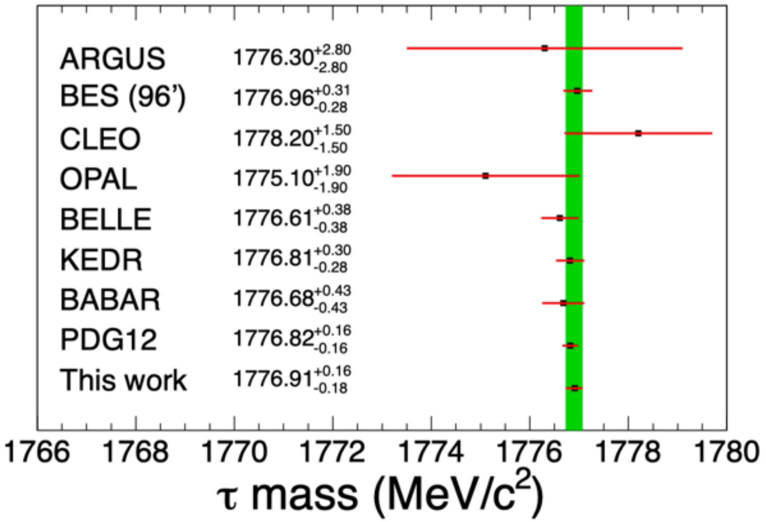
$$(g_\tau / g_\mu)^2 = 1.0016 \pm 0.0042$$

agrees at the 0.4σ level !

- New round of τ mass measurement expects a precision of less than 80 keV

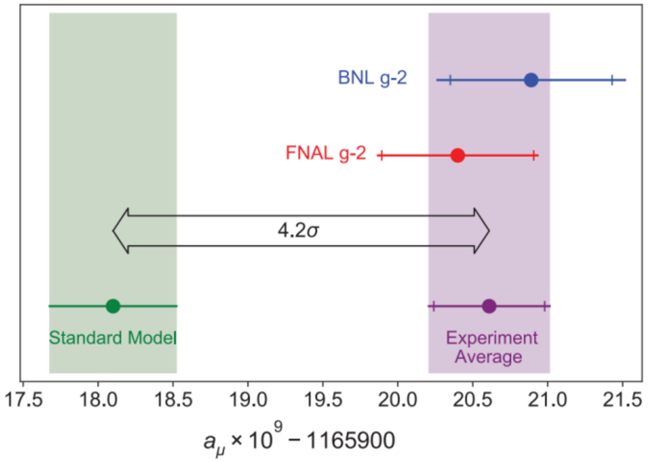
PRD 90, 012001 (2014)





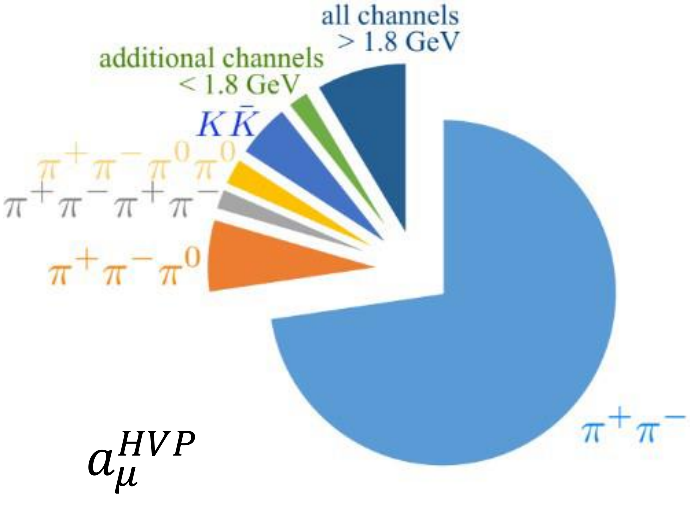
Muon anomalous magnetic moment a_μ

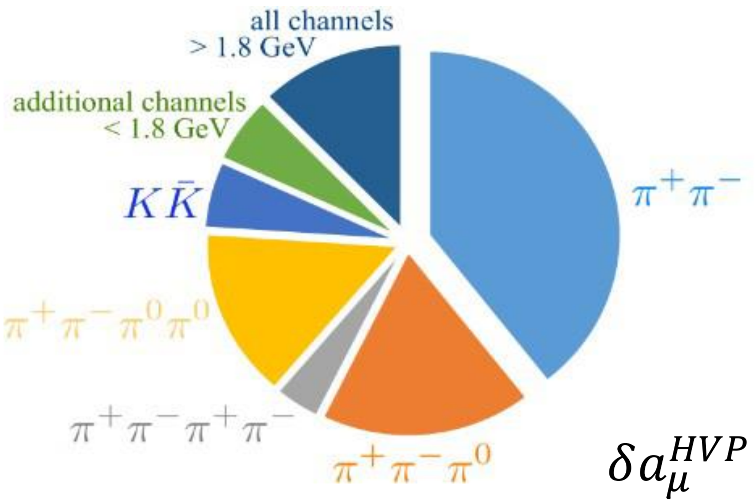
PRL126.141801 (2021)



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

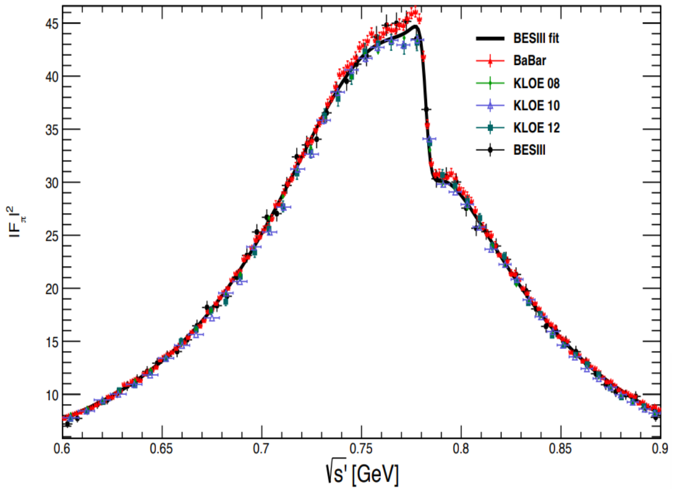
- SM prediction: $a_\mu^{SM} = a_\mu^{QED} + a_\mu^{Weak} + a_\mu^{Had}$
  - Hadronic Vacuum Polarization (HVP) and Light-by-Light (HLbL) in a_μ^{Had} dominate uncertainty
- The $\pi^+\pi^-$ channel accounts for 75% of the full a_μ^{Had}
  - Typical uncertainty around 0.6%-1.0%.
  - Large discrepancy among different experiments





BESIII contributions to a_μ^{HVP}

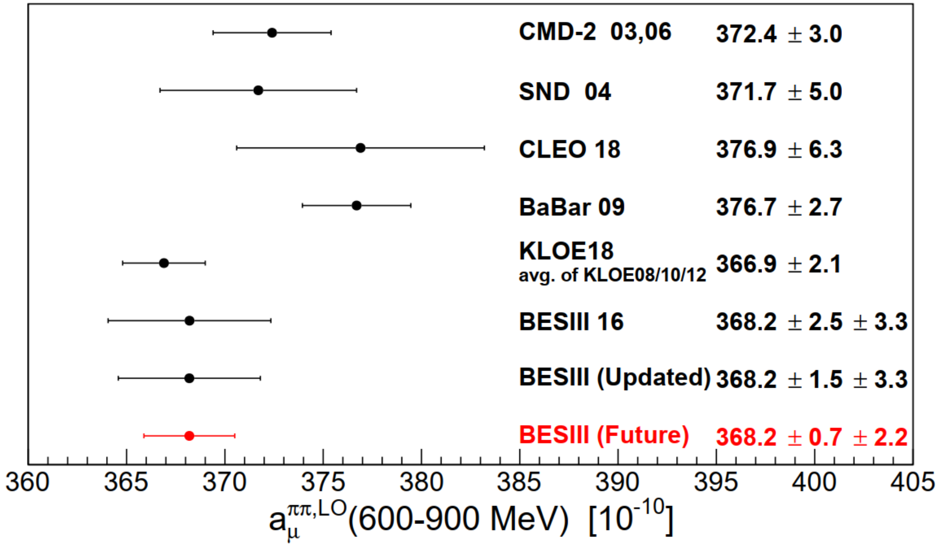
- $e^+e^- \to \pi^+\pi^-$ at BESIII with ISR method:
  - Systematic uncertainty: 0.9% .
  - Dominate uncertainty: luminosity (0.5%), radiator function (0.5%)



PLB 753 (2016) 629-638,
PLB 812 (2021) 135982 (erratum)

Source	Uncertainty (%)
Photon efficiency correction	0.2
Pion tracking efficiency correction	0.3
Pion ANN efficiency correction	0.2
Pion e-PID efficiency correction	0.2
ANN	negl.
Angular acceptance	0.1
Background subtraction	0.1
Unfolding	0.2
FSR correction δ_{FSR}	0.2
Vacuum polarization correction δ_{vac}	0.2
Radiator function	0.5
Luminosity $\mathcal{L}$	0.5
Sum	**0.9**

- With 20 fb^{-1} $\psi(3770)$ data
  - New technique applied by measuring cross section ratio of $e^+e^- \to \pi^+\pi^-$ to $e^+e^- \to \mu^+\mu^-$
  - Uncertainty from luminosity, radiator function, VP correction will be canceled
  - Expect systematic uncertainty: 0.5%



QED running coupling constant $\alpha(s)$

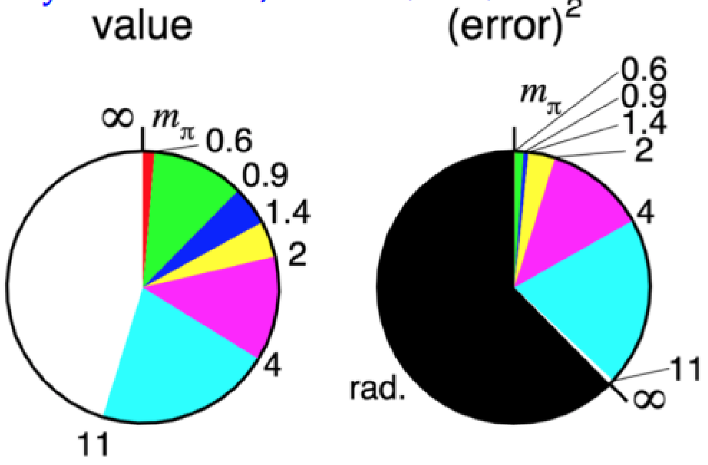
- $\alpha(s)$ is one of the most important QED parameters
- The contribution to $\Delta\alpha(s)$ can be distinguished to three pieces

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

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

$$\Delta\alpha^{(5)}_{\mathrm{had}}(s) = -\frac{\alpha s}{3\pi}\,\mathrm{Re}\int_{E_{\mathrm{th}}}^{\infty} \mathrm{d}s' \frac{R(s')}{s'(s'-s-i\varepsilon)}$$

Fractional contribution to $\Delta\alpha^{(5)}_{\mathrm{had}}(M_Z^2)$:
Phys. Rev. D 97, 114025 (2018)



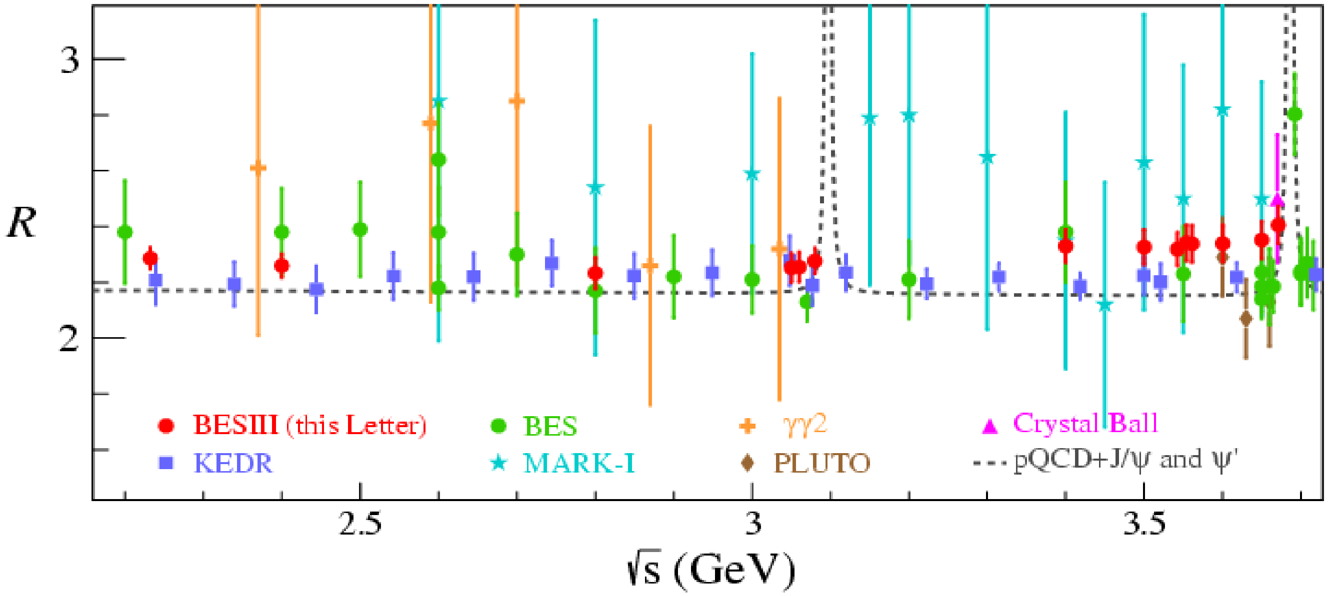
Eur. Phys. J. C 80, 241 (2020)

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

R value measurement at BESIII

- Precision measurements of the R contributes to SM prediction of a_μ^{HVP} and determination of the QED running coupling constant $\alpha(s)$ evaluated at the Z pole.

PRL 128, 062004 (2022)



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

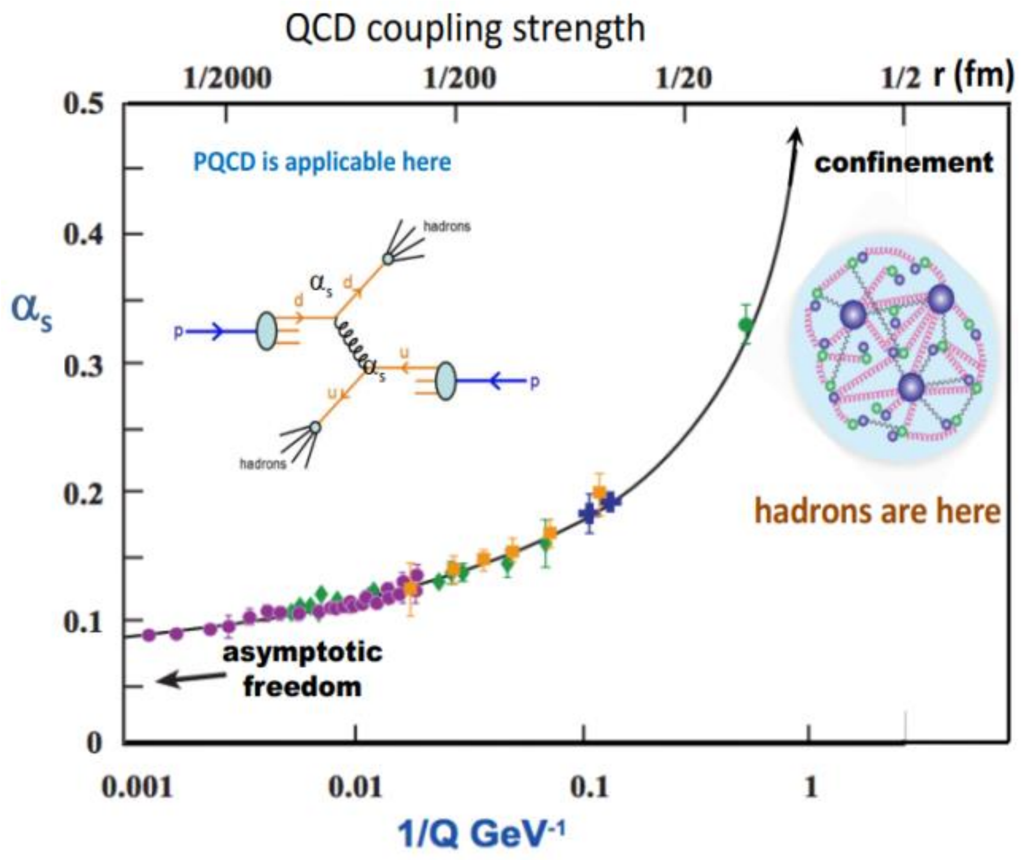
Hadron Structures

Hadron structures

- 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!

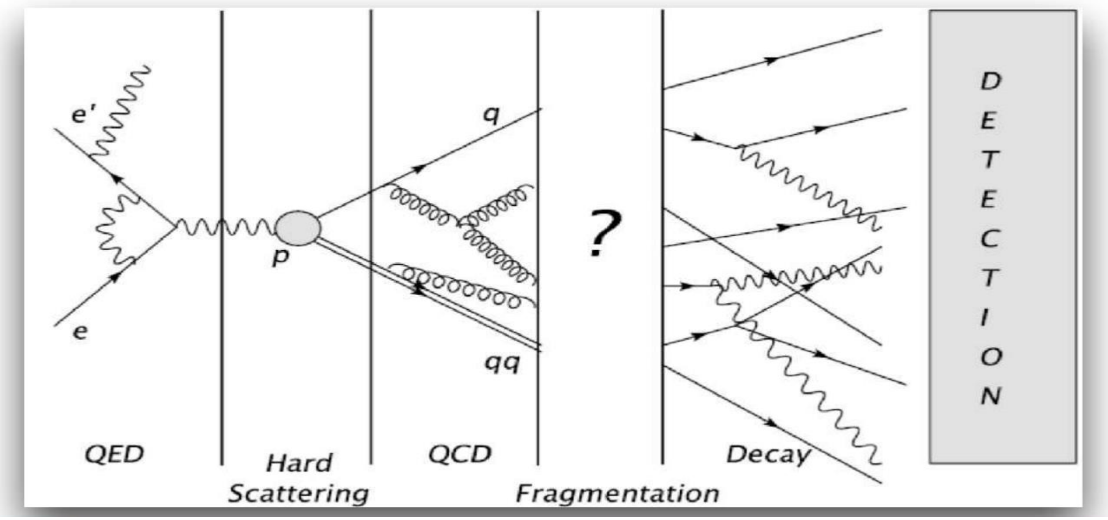
- BESIII contribute to the nucleon structure by studying fragmentation functions (=>help extract the structure function) and electromagnetic form factors

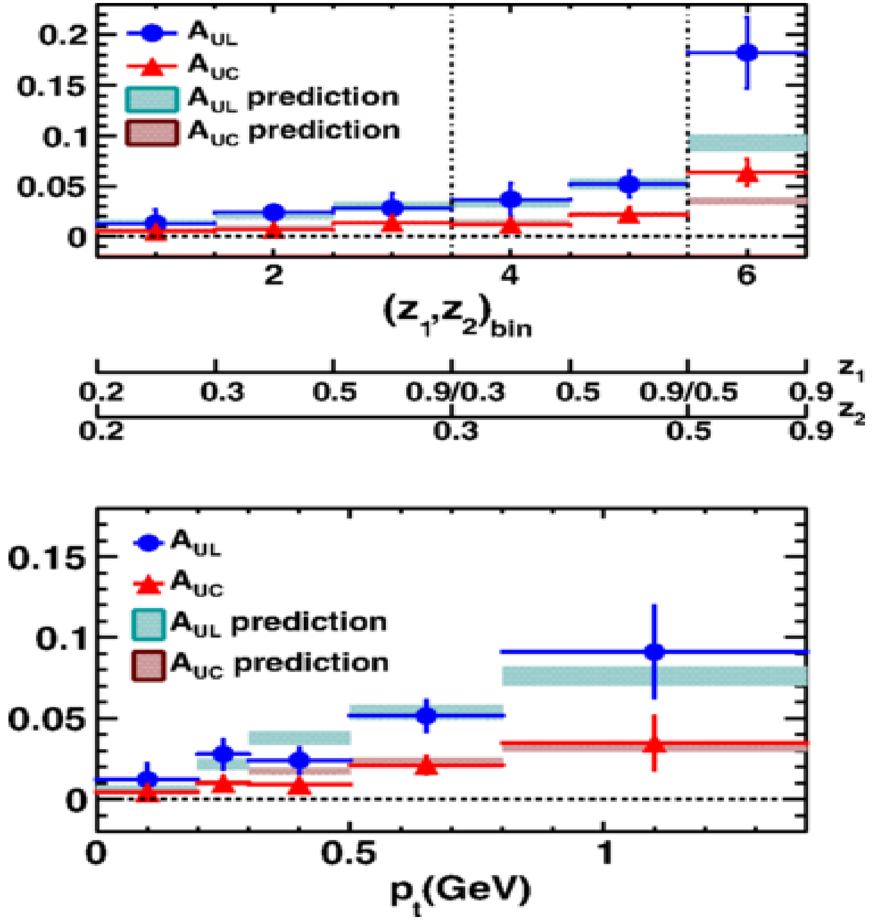


Fragmentation Functions

- Fragmentation function : probability that hadron *h* is found in the debris of a hadron carrying a fraction of parton's momentum
- Help understand confinement of QCD and essential input to the structure function of nucleons

PRL 116, 042001(2016)

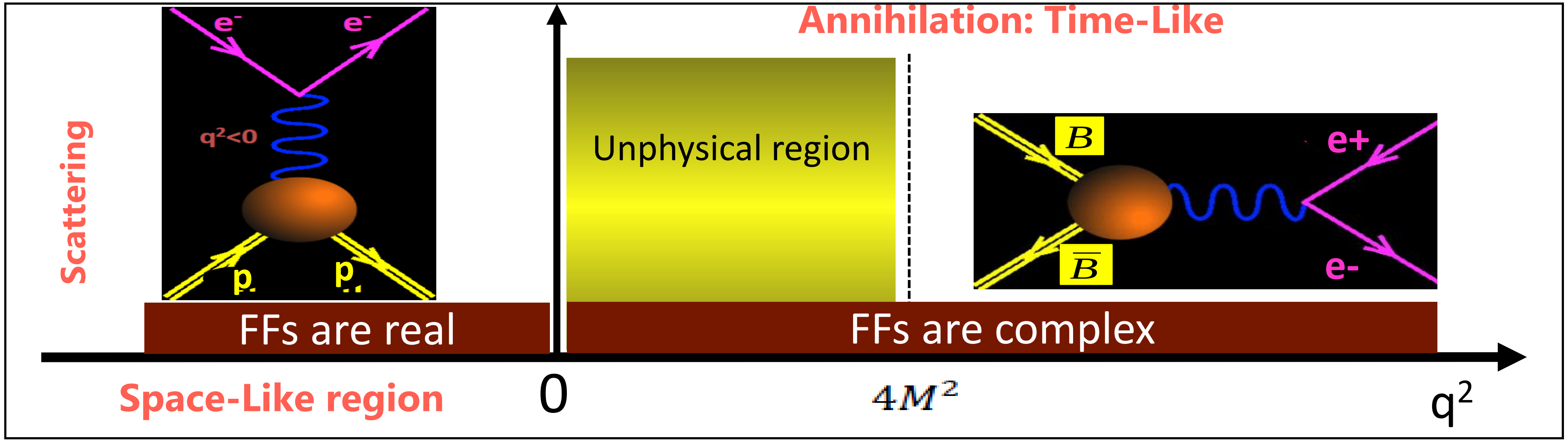




- Fragmentation functions can be studied at BESIII:
  - ✓ Unpolarized fragmentation function
  - ✓ Collins fragmentation function (chiral odd)
  - Di-hadron fragmentation function

Electromagnetic Form Factors

- Electromagnetic Form Factors are fundamental properties of the nucleon
  - Connected to charge, magnetization distribution
  - Crucial testing ground for models of the nucleon internal structure



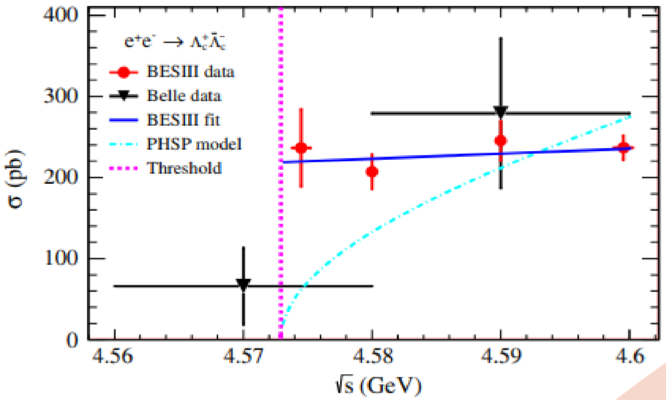
The nucleon electromagnetic vertex Γ_μ describing the hadron current:

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

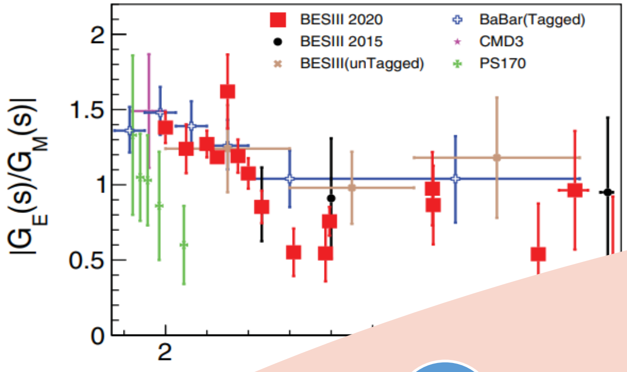
Sachs FFs: $G_E(q^2) = F_1(q^2) + \tau\kappa_p F_2(q^2)$, $G_M(q^2) = F_1(q^2) + \kappa_p F_2(q^2)$

Baryon EMFFs at BESIII

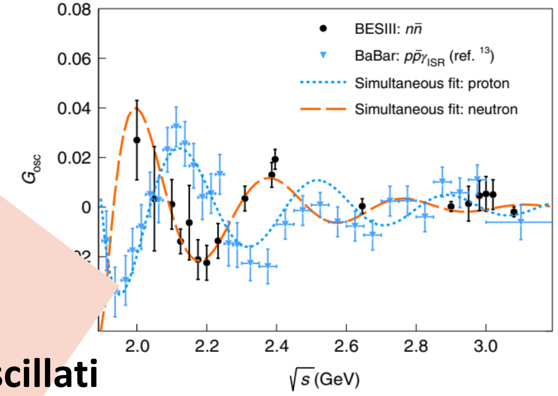
PRL 120, 131001 (2018)



PRL 124.042001(2020)



Nat. Phys. 17, 1200 (2021)



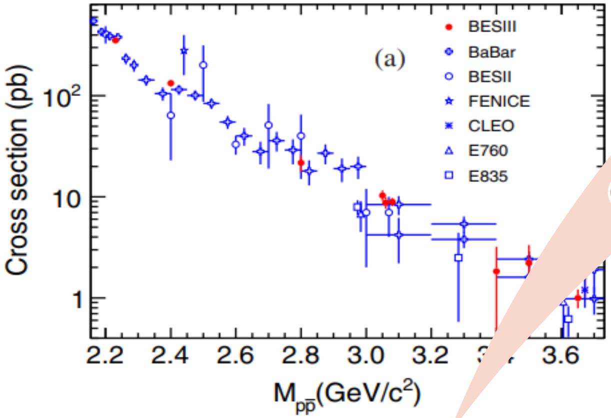
2015, first proton EMFFs

2018, threshold effect observed

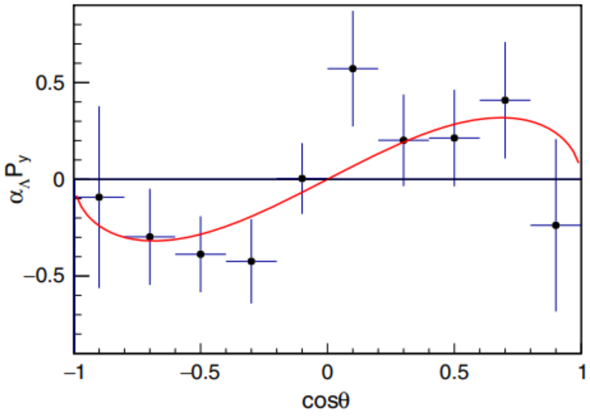
2019, complete Lambda EMFF

2020, most precise proton EMFF

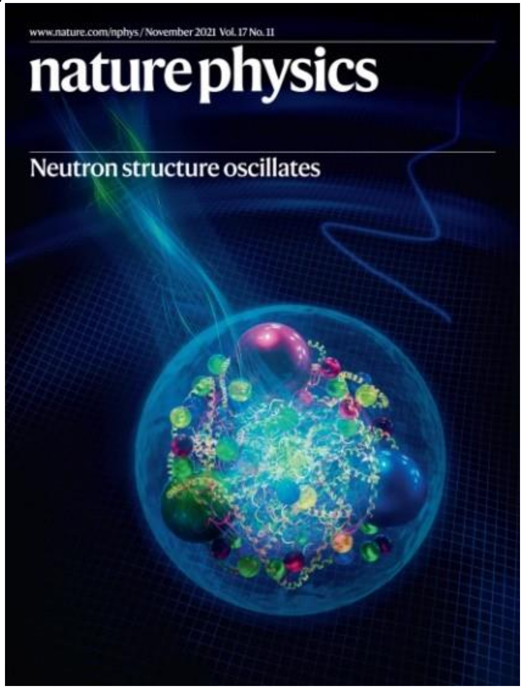
2021,Oscillation in neutron Effective FF



PRD 91, 112004 (2015)

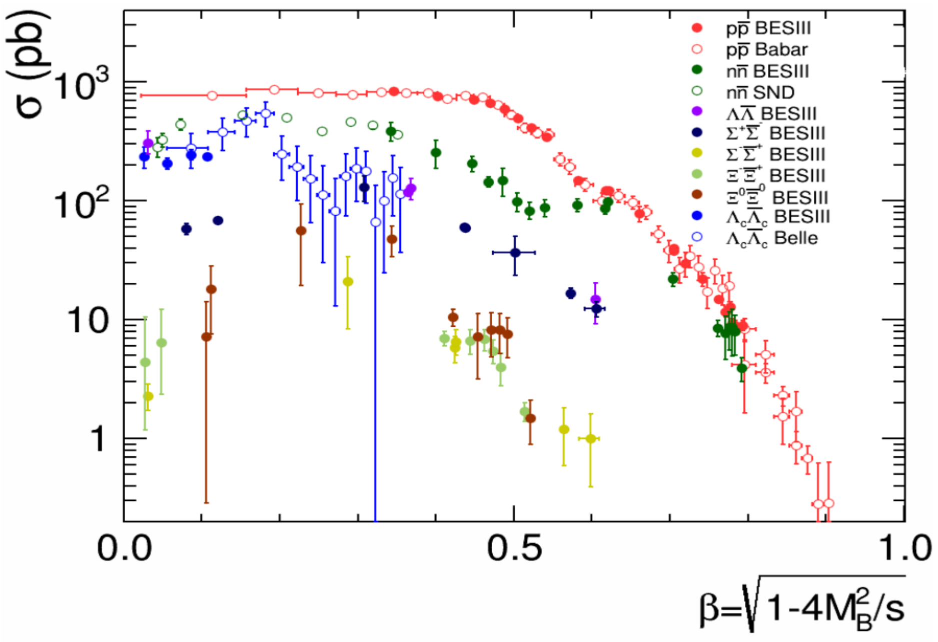


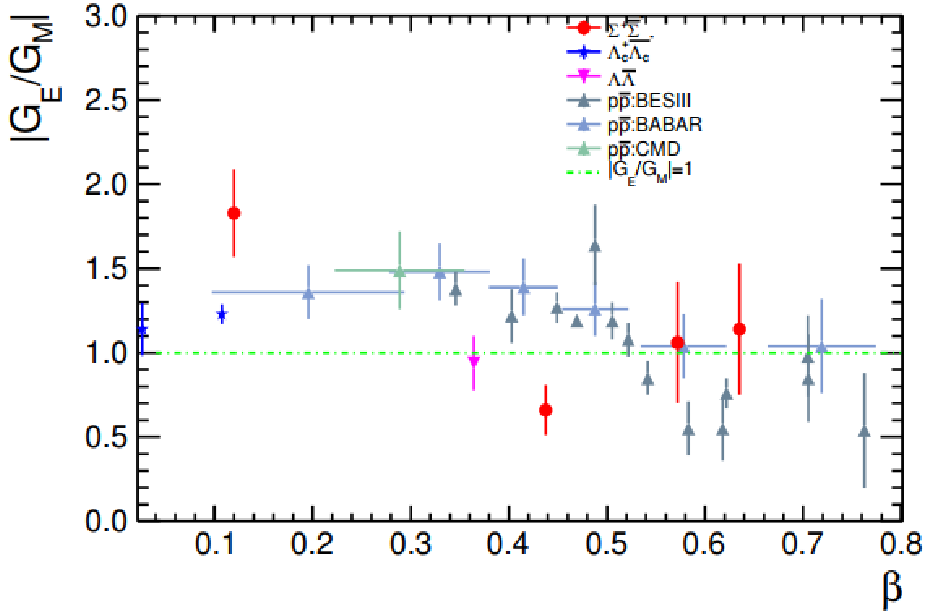
PRL 123, 122003 (2019)



Baryon EMFFs at BESIII

Nat.Sci.Rev. 8 (2021) 11, nwab187





- Abnormal threshold effects observed in various baryon pair production: $p\bar{p}$, $\Lambda\bar{\Lambda}$, $\Lambda_c^+\bar{\Lambda}_c^-$ …
- Oscillation structures observed in $p\bar{p}$, $n\bar{n}$
- $|G_E/G_M|$ ratio significantly larger than 1 at low beta for p, Λ_c^+, Σ^+, indicating large D-wave near threshold
- Relative phase angle of form factor $\Delta\phi(\sin\Delta\phi)$ measured for Λ, Λ_c^+

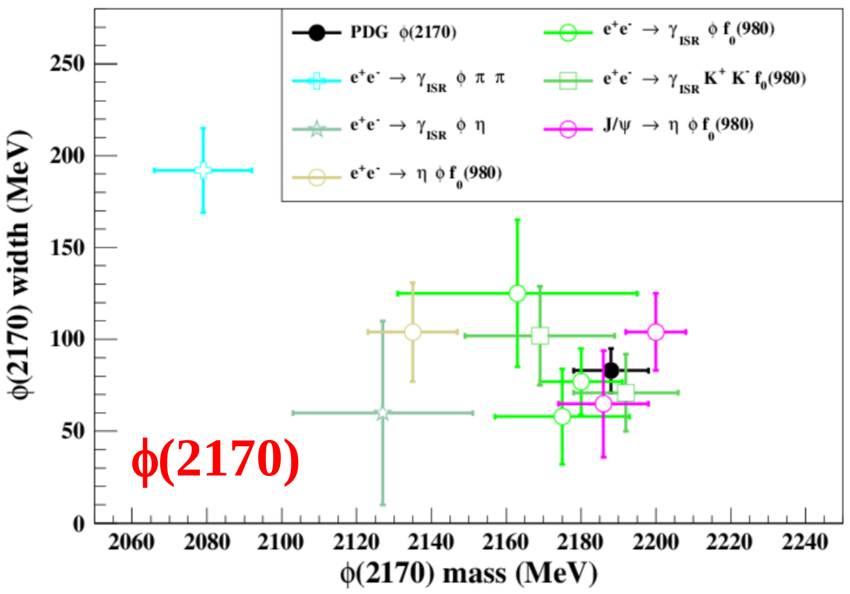
Hadron Spectroscopy

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_SK_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 $\omega\pi^0$, $\eta'\pi^+\pi^-$…

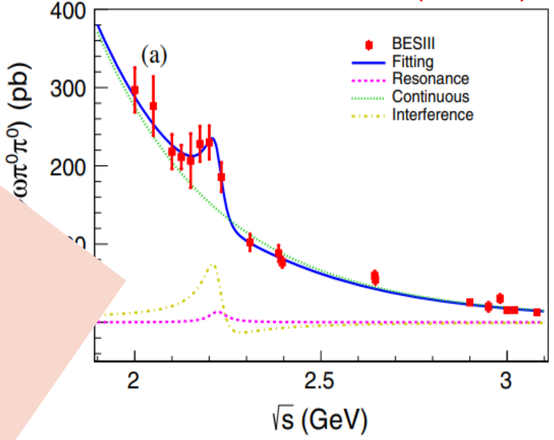
PDG2018 $\phi(2170)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
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

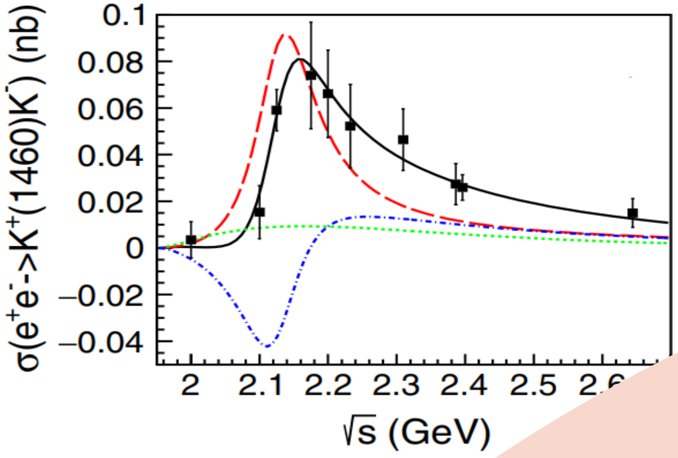


Light flavor vector states as BESIII

PRD 105, 032005 (2022)



PRL 124, 112001 (2020)

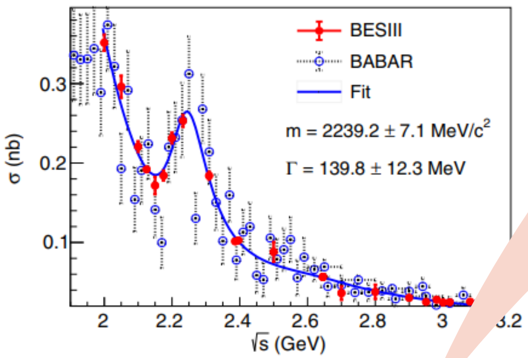


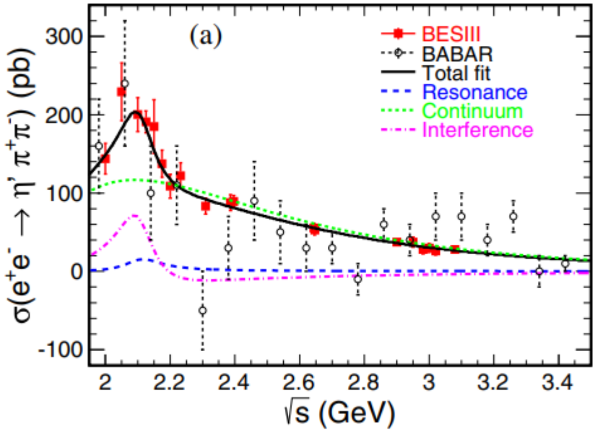
2022, resonance in ωππ(ω*)

2021, resonance in η’π⁺π⁻(ρ*)

2020, PWA in K⁺K⁻π⁰π⁰

2019,resonance in K⁺K⁻

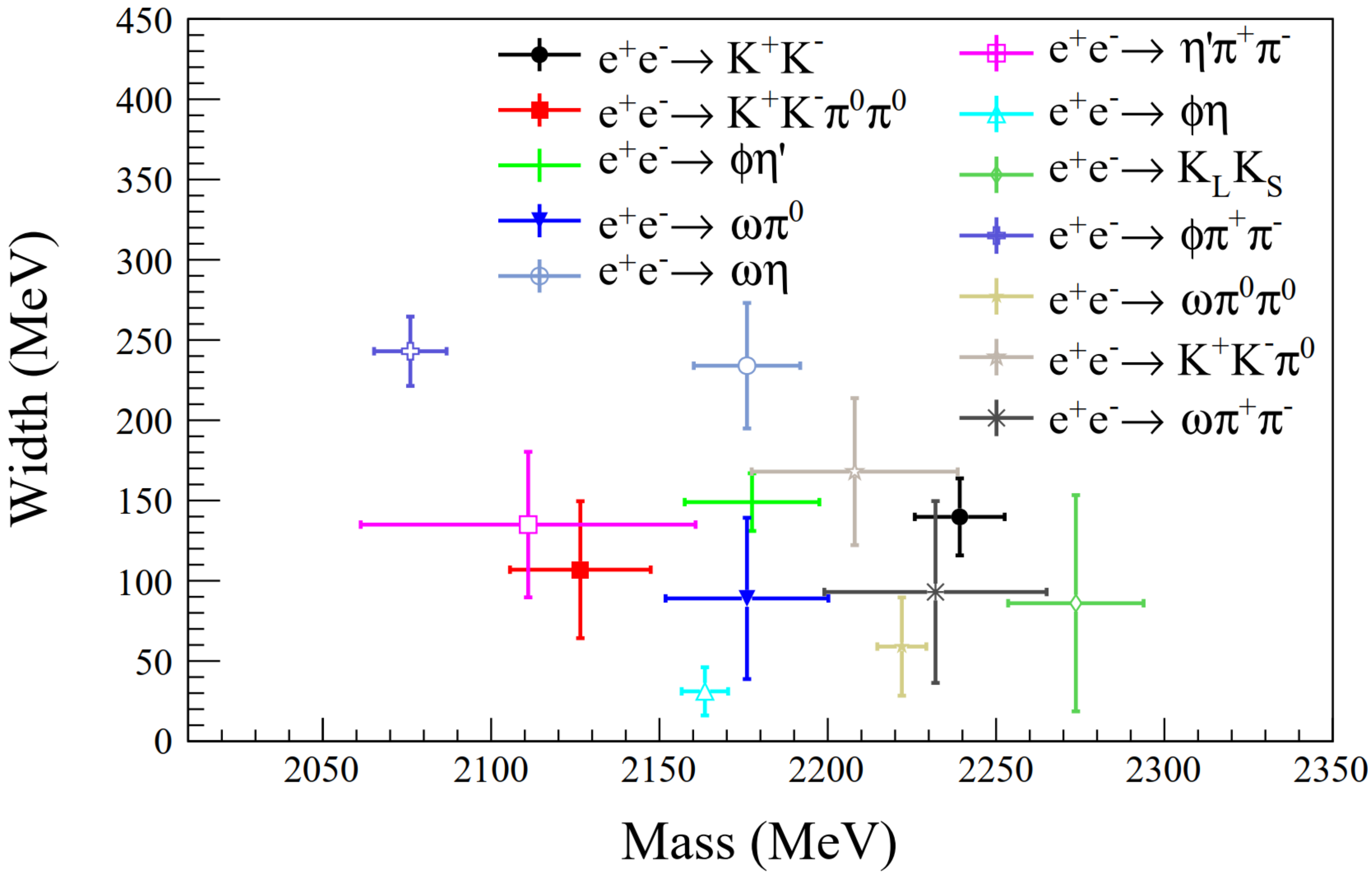




PRD 103, 072007 (2021)

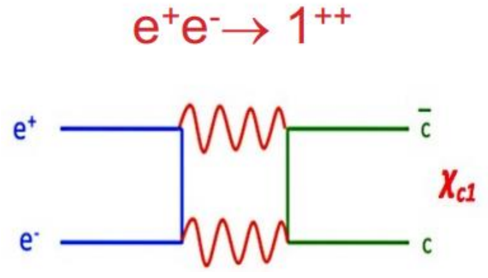
PRD 99, 032001 (2019)

Light flavor vector states as BESIII



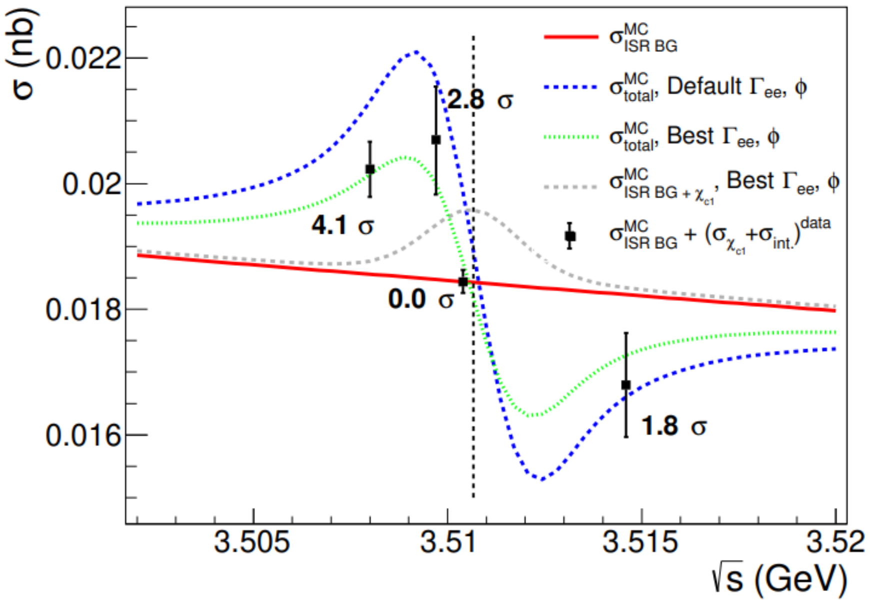
Direct C-even production in e^+e^- annihilation

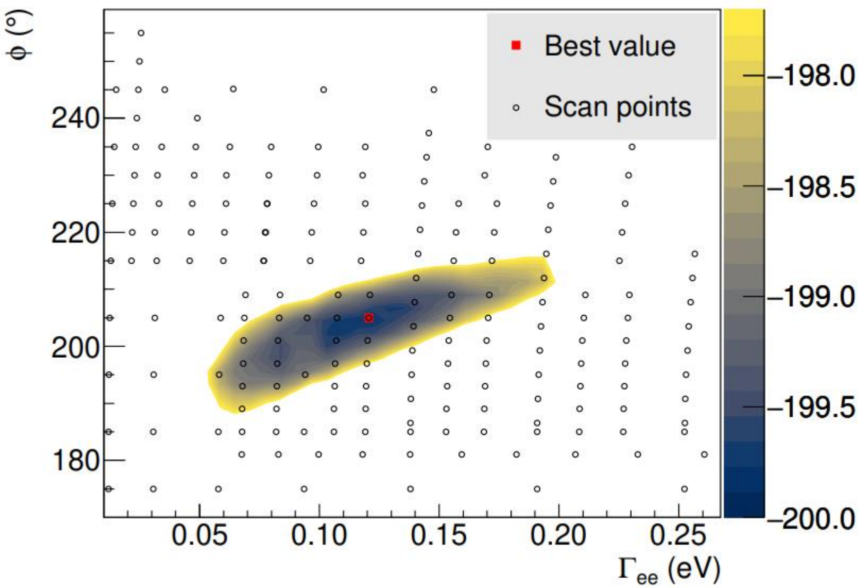
- The C-even states, *i.e.* $\eta, f_1(1285), \chi_c, X(3872)$, can be produced directly from e^+e^- annihlation through two virtual photons or neutral current reaction.
- Revisit calculation with large interference effects distortion of the total cross section *(PRD 94, 034033 (2016))* .



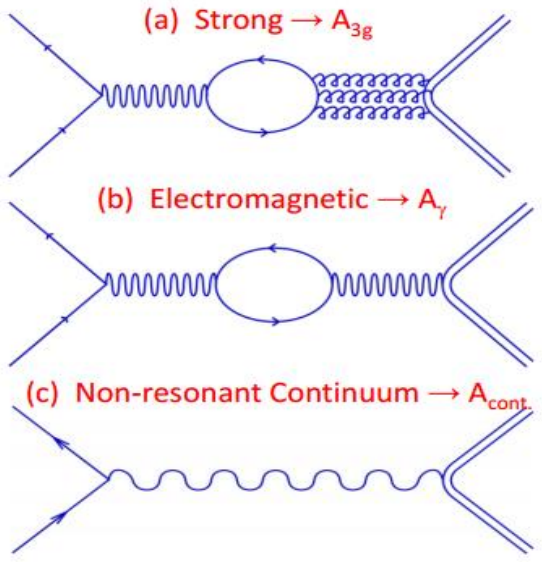
- χ_{c1} is observed with significance over 5σ. First observation of a C-even state in e^+e^- annihilation.

PRL129.122001(2022)





Phase in strong and EM amplitudes



(a) $e^+e^- \to J/\psi \to$ hadrons via strong mechanism;

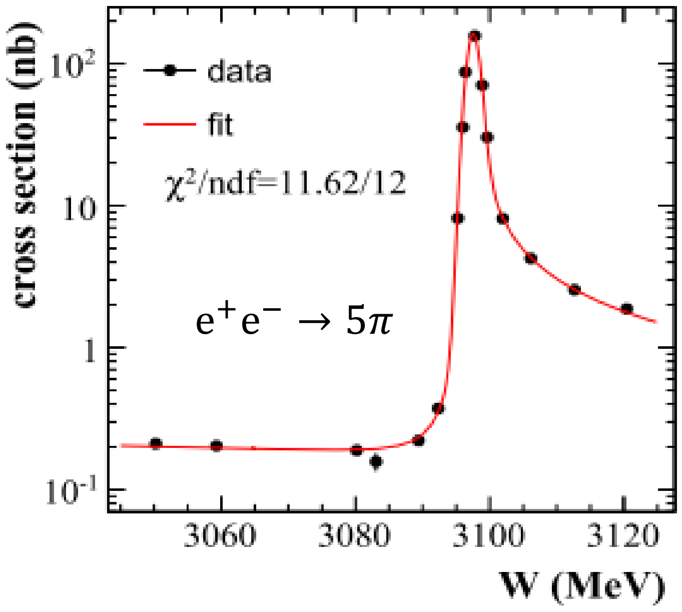
(b) $e^+e^- \to J/\psi \to$ hadrons via EM mechanism;

(c) non-resonant $e^+e^- \to$ hadrons via a virtual photon.

$$\sigma_{Born} = |A_{3g} + A_\gamma + A_{cont}|^2$$
$$= \left| |A_{3g}| e^{i\Phi_{3g,EM}} + |A_\gamma| e^{i\Phi_{\gamma,cont.}} + |A_{cont.}| \right|^2$$

- First measurement of the $\Phi_{3g,EM}$ in J/ψ decay using multihadron final state with the production line-shape.

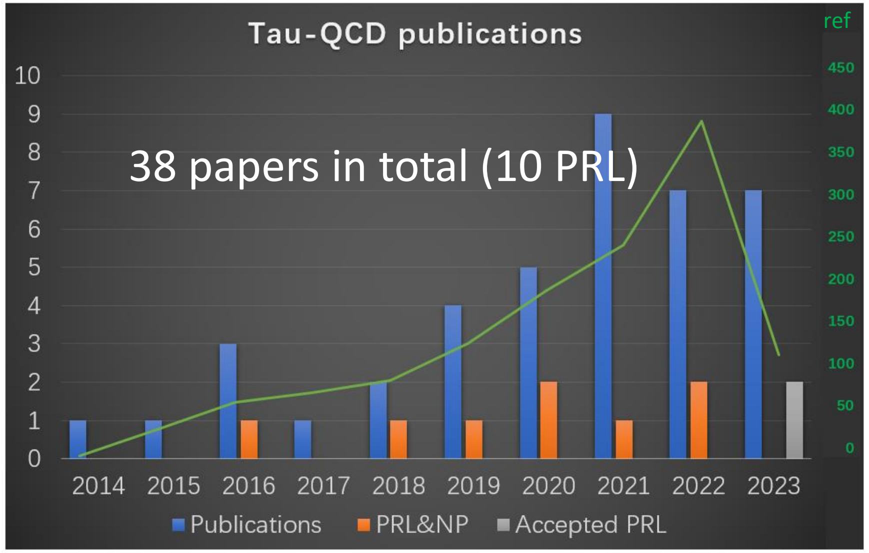
PLB 791, 375(2019)



	$\Phi_{g,EM}$	$\mathcal{B}_{5\pi}$ (%)	χ^2/ndf
Solution I	$(84.9 \pm 3.6)°$	4.73 ± 0.44	11.62/12
Solution II	$(-84.7 \pm 3.1)°$	4.85 ± 0.45	11.62/12

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. Work more closely with theorist is necessary and more data at low q^2 is required.**