QCD studies at BESIII

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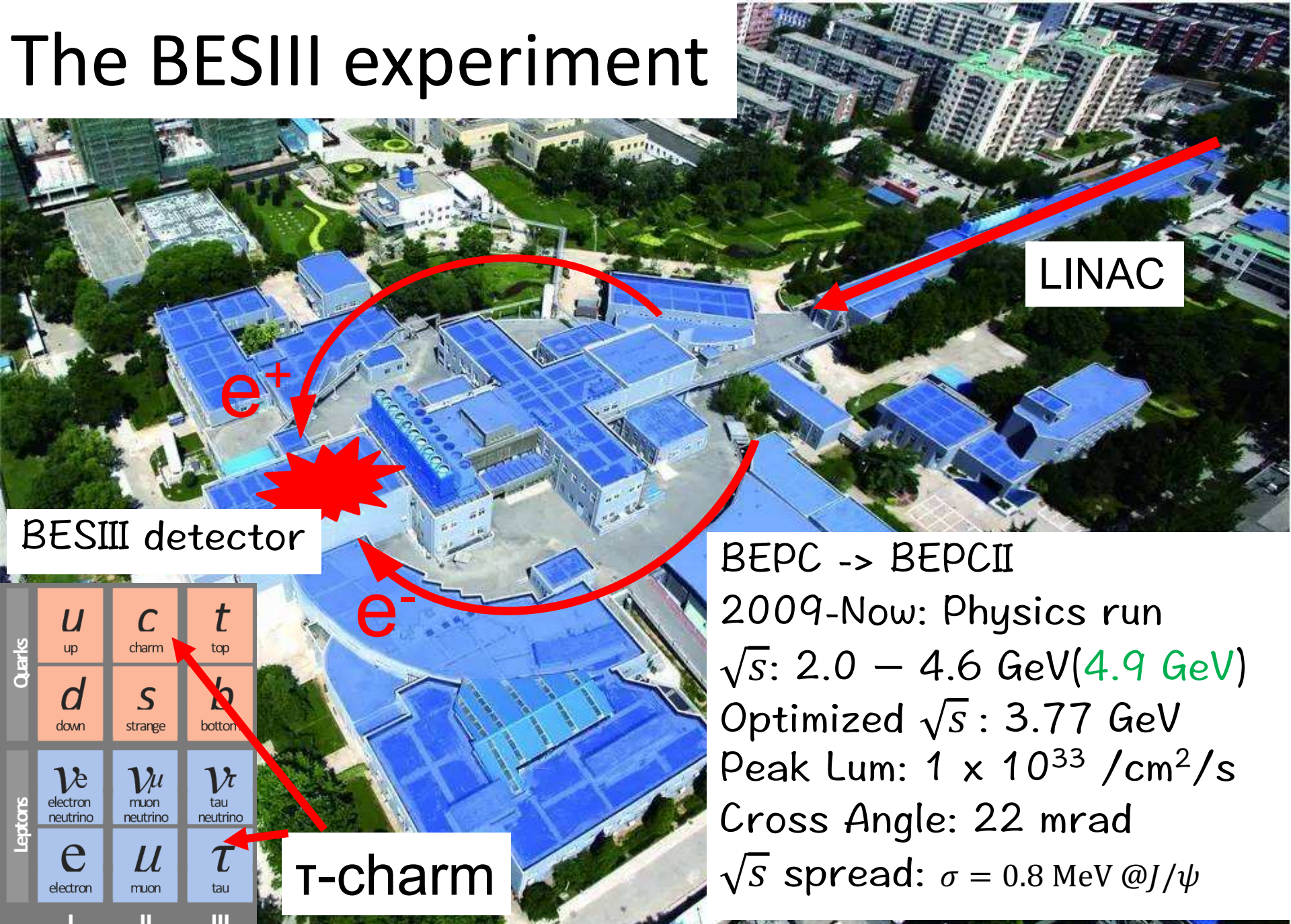
Outline

- The BESIII experiment
- Baryon structure, form factor measurement
- ϕ(2170) related studies
- Precision test on a_μ
- Summary

The BESIII experiment



BEPC -> BEPCII

2009-Now: Physics run

$\sqrt{s}$: 2.0 – 4.6 GeV(4.9 GeV)

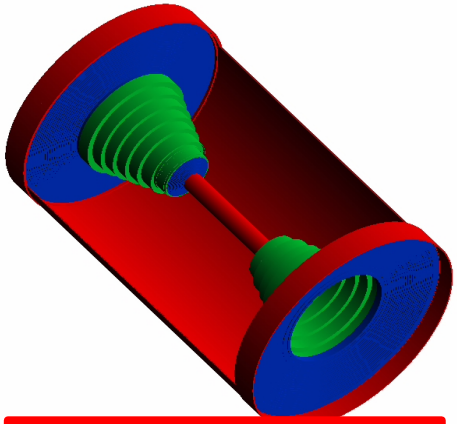
Optimized $\sqrt{s}$: 3.77 GeV

Peak Lum: 1 x 10^{33} /cm^2/s

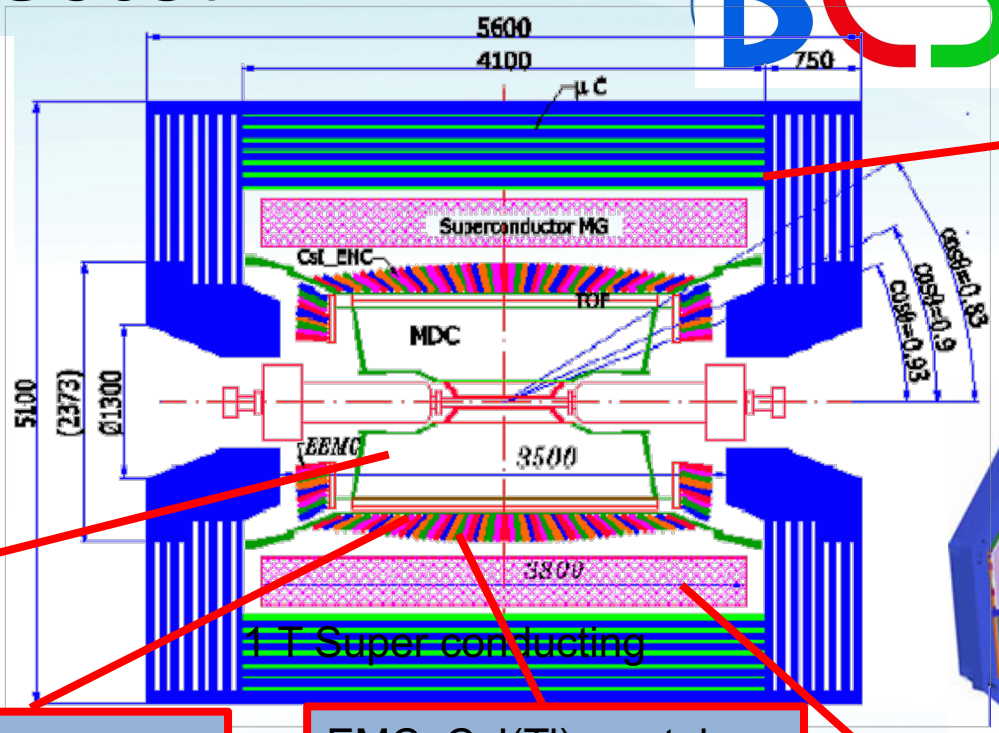
Cross Angle: 22 mrad

$\sqrt{s}$ spread: $\sigma = 0.8$ MeV @J/ψ

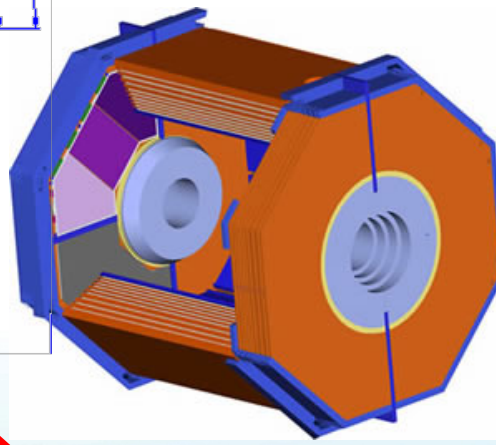
BESIII detector



MDC:
σ_p/p=0.5% @1 GeV,
$\sigma_{dE/dx}$=6%
σ_{xy}=130 μm

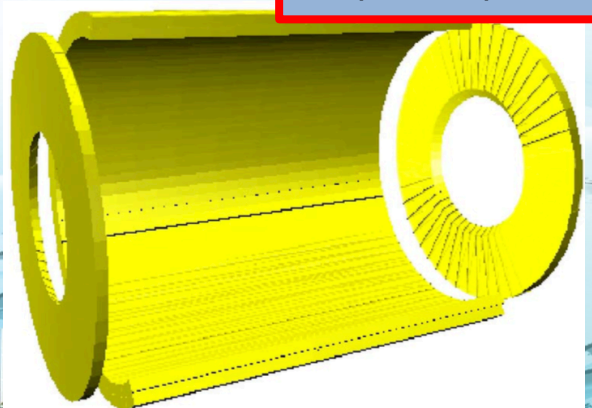


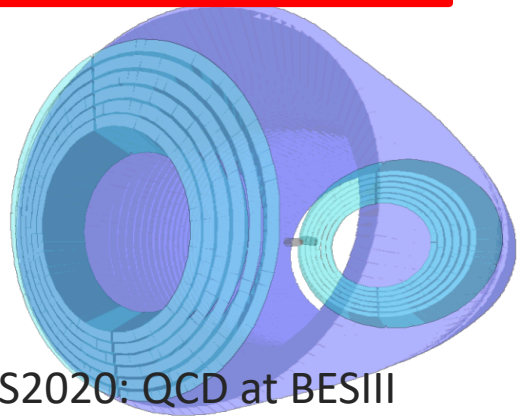
Muon ID: RPCs
Barrel: 9 layers
Endcap: 8 layers
$\sigma_{spatial}$=1.48 cm



TOF:
barrel: σ_T=68 ps P.S.,
endcaps: P.S.->MRPC
110ps->65 ps

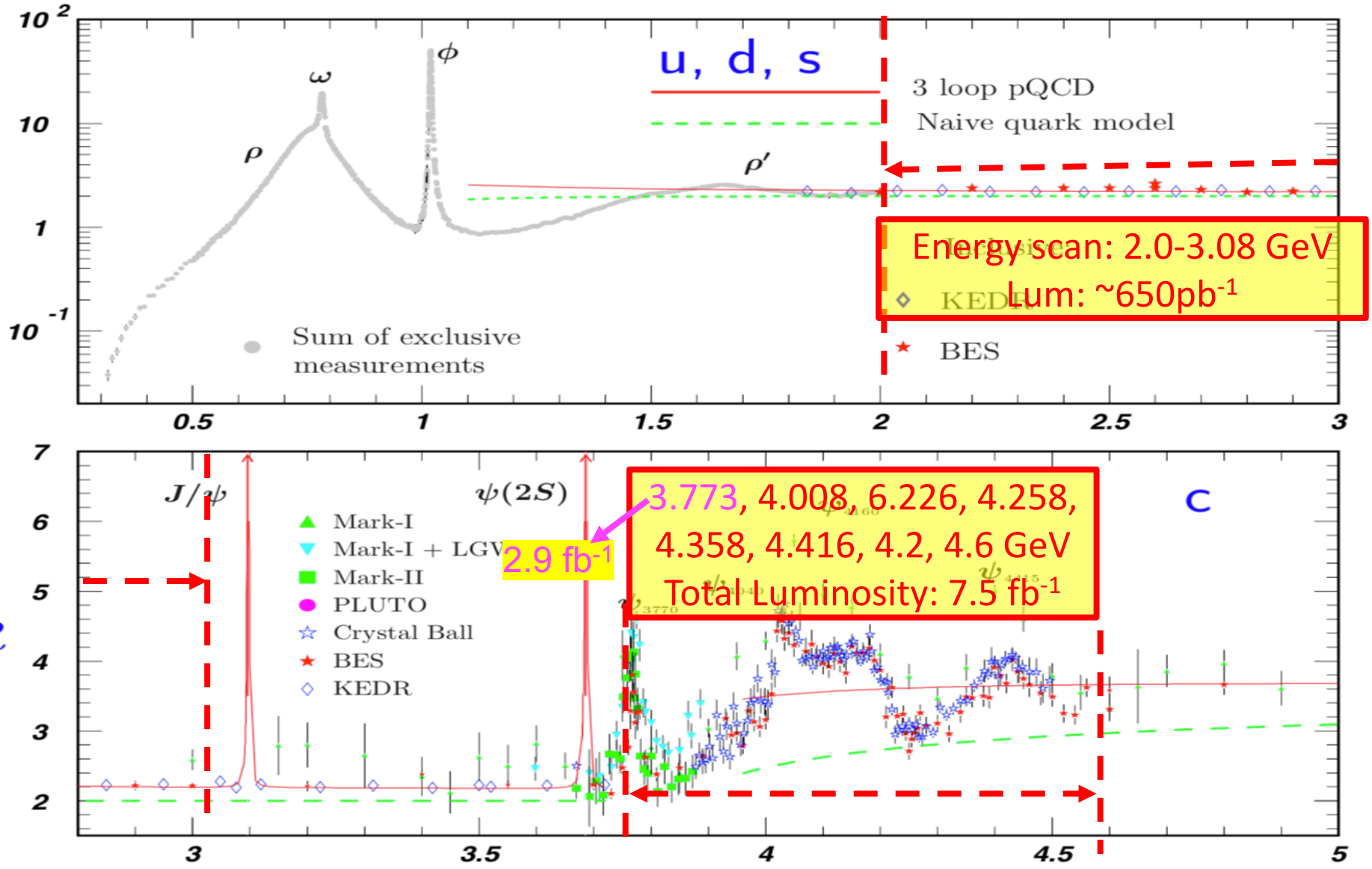
EMC: CsI(Tl) crystal,
ΔE/E = 2.5% @1 GeV
σ_X ~ 6mm@1GeV





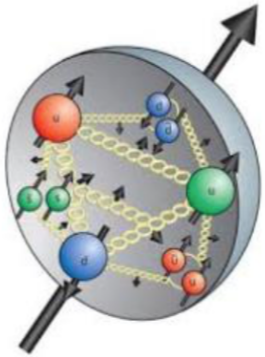
Magnet: 1T

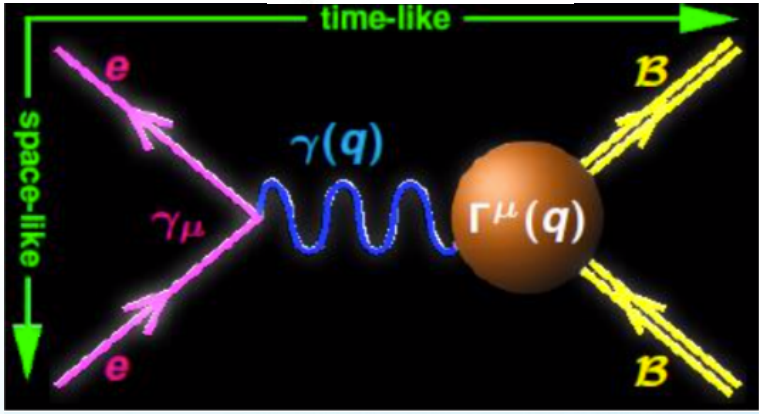
Data sets


u, d, s
3 loop pQCD
Naive quark model
ρ
ω
φ
ρ′
Sum of exclusive measurements
KEDR
BES
Energy scan: 2.0-3.08 GeV
Lum: ~650pb-1
R
J/ψ
ψ(2S)
Mark-I
Mark-I + LGW
Mark-II
PLUTO
Crystal Ball
BES
KEDR
2.9 fb-1
3.773, 4.008, 6.226, 4.258,
4.358, 4.416, 4.2, 4.6 GeV
Total Luminosity: 7.5 fb-1
c

Baryon form factor

- Baryons are non-point like particles
  - Quarks, gluons
- Structure of baryons
  - Electromagnetic form factors
  - Parton distribution functions
  - Generalized parton distributions
  - Other functions
- Space-like (scattering) and time-like (annihilation) experiments
- Electromagnetic form factors
  - FF characterize the internal structure and dynamics of baryons
  - For a particle spin S, 2S+1 FFs are required





Baryon form factor

- Spin 1/2 baryons
  - Vertex Γ_μ

$$\Gamma_\mu = \gamma_\mu F_1^B(q^2) + \frac{i\sigma_{\mu\nu}q^\nu}{2M} F_2^B(q^2)$$

  - Dirac FF: $F_1^B(q^2)$; Pauli FF: $F_2^B(q^2)$
  - Relation of EM FF with Sachs FF

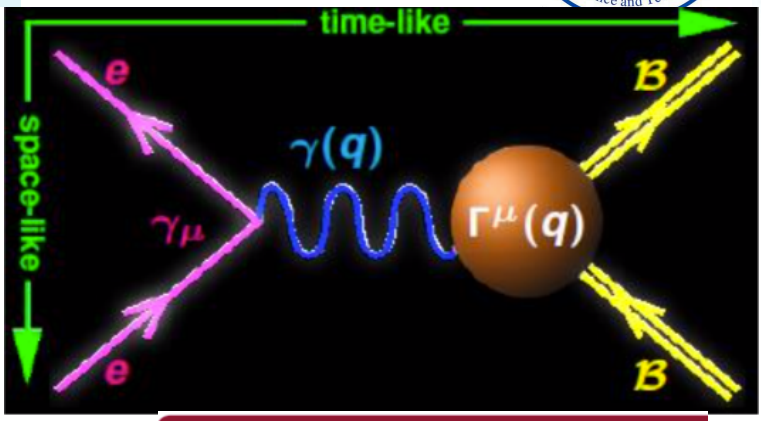
$$G_E(q^2) = F_1(q^2) + \frac{q^2}{4m^2}\kappa F_2(q^2)$$

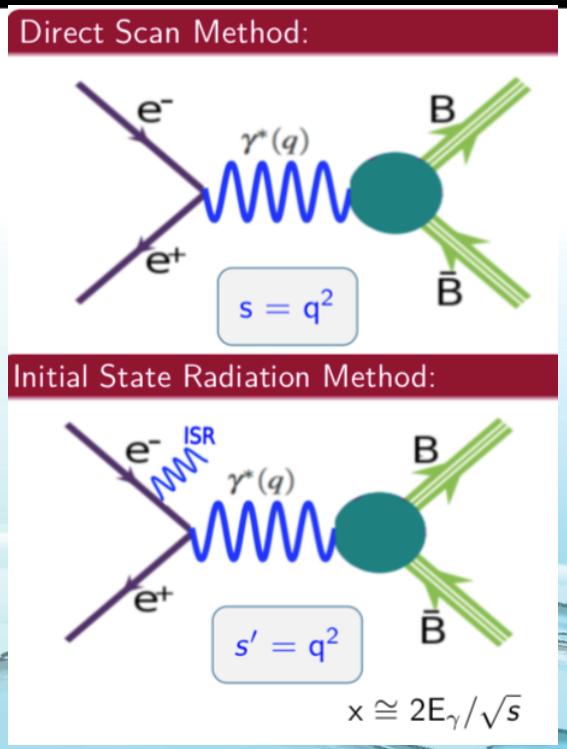
$$G_M(q^2) = F_1(q^2) + \kappa F_2(q^2)$$

  - G_E & G_M: related to the spatial distributions of charge and magnetization of baryon
  - Cross section

$$\sigma_{BB}(q^2) = \frac{4\pi\alpha^2 C\beta}{3q^2}\left[|G_M(q^2)|^2 + \frac{2m^2}{q^2}|G_E(q^2)|^2\right]$$

    - C: Coulomb factor, $\frac{\pi\alpha}{\beta}\frac{1}{1-\exp(-\frac{\pi\alpha}{\beta})}$ for $B^{\pm}$, 1 for B^0.



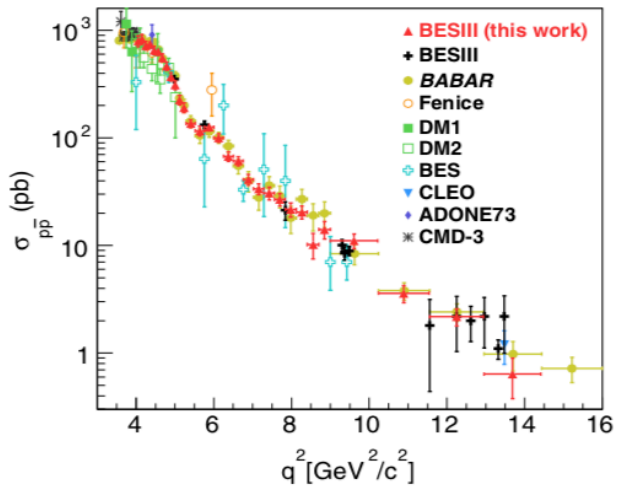


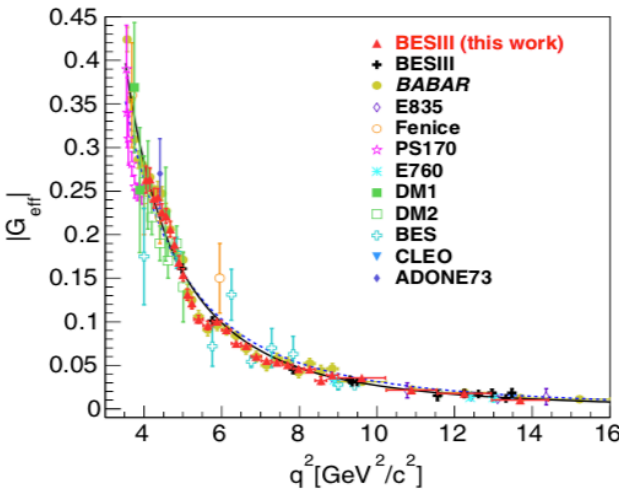
Baryon form factor

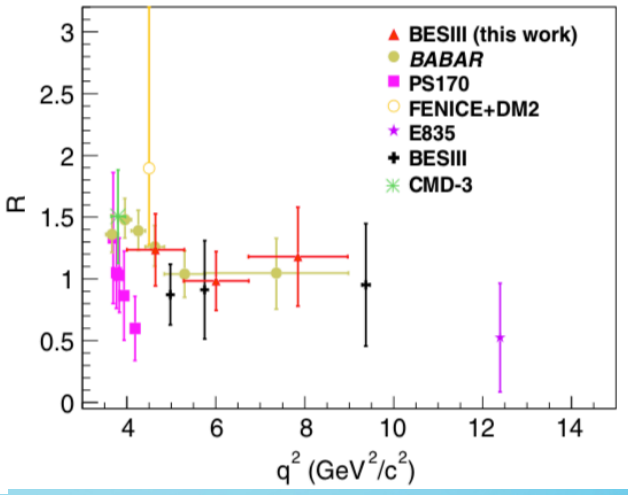
- Nucleon
  - $e^+e^- \to p\bar{p}$ (ISR method) [PRD 99, 092002(2019)]
    - Combined data sets between 3.773 and 4.6 GeV: 7.5 fb^{-1}
    - ISR technique, untagged analysis (ISR photon not detected)
    - Precision on $|G_{eff}|$: 4.1 – 28.7%

$$|G_{eff}| = \sqrt{\frac{\sigma_{p\bar{p}}}{\frac{4\pi\alpha^2\beta C}{3s}\left(1+\frac{2m^2}{s}\right)}}$$

    - R=$|G_E/G_M|$ measured in three q^2 intervals, consistent with Babar's result

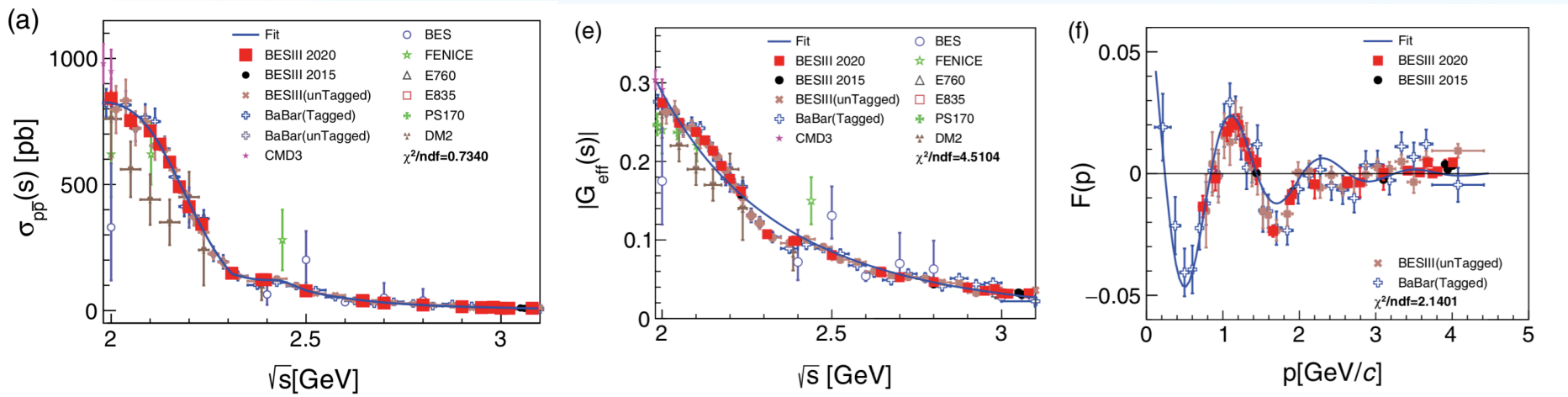






Baryon form factor

- Nucleon
  - $e^+e^- \to p\bar{p}$ (scan method) [PRL 124, 042001(2020)]
    - Precise measurement of cross section $e^+e^- \to p\bar{p}$ at 22 points from 2.0 – 3.08 GeV
    - Effective form factor (EFF) is extracted with uncertainty ~ 1.7-11.8%
    - Oscillating structures observed in the EFF minus modified dipole parameterization
      - Rescattering process in the final state? [PRL 114, 232301 (2015)]
      - Independent resonant structure?



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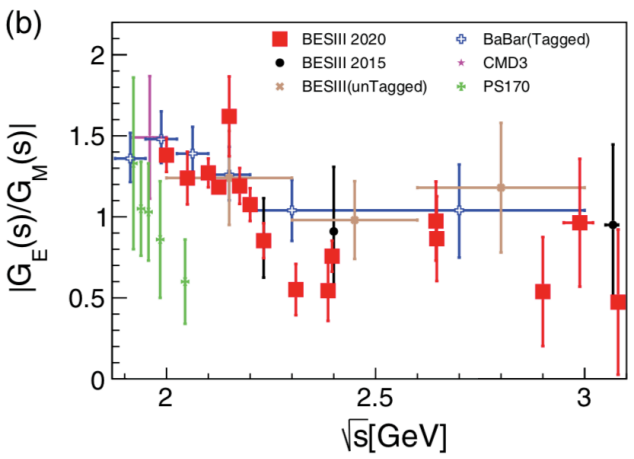
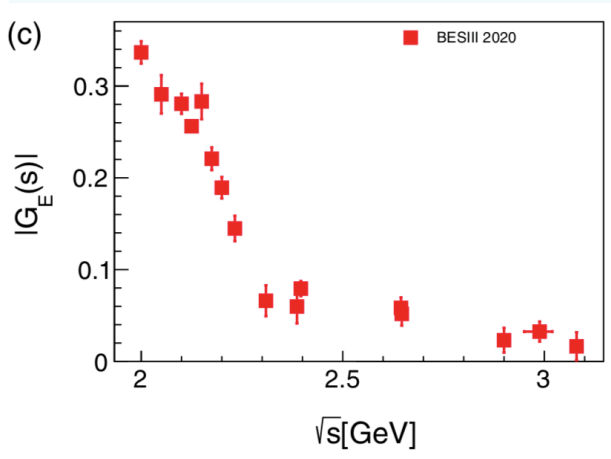
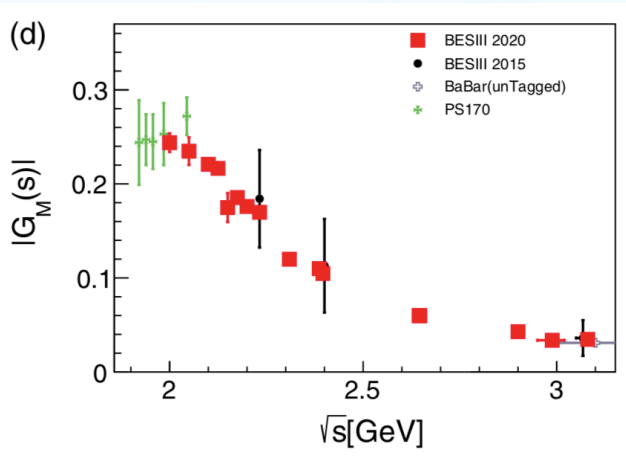
    - Precise measurement of cross section $e^+e^- \to p\bar{p}$ at 22 points from 2.0 – 3.08 GeV
    - Effective form factor (EFF) is extracted with uncertainty ~ 1.7-11.8%
    - $|G_E/G_M|$, $|G_M|$ are determined with high accuracy, with uncertainty comparable to data in space-like experiments
    - $|G_E|$ is measured for the first time in time-like region

$$\frac{dN}{\epsilon(1+\delta)\times d\cos\theta_p} = \frac{\mathcal{L}\hbar c\pi\alpha^2\beta C}{2s}|G_M|^2\left[(1+\cos^2\theta_p)+\frac{4m_p^2}{s}\left|\frac{G_E}{G_M}\right|^2(1-\cos^2\theta_p)\right]$$

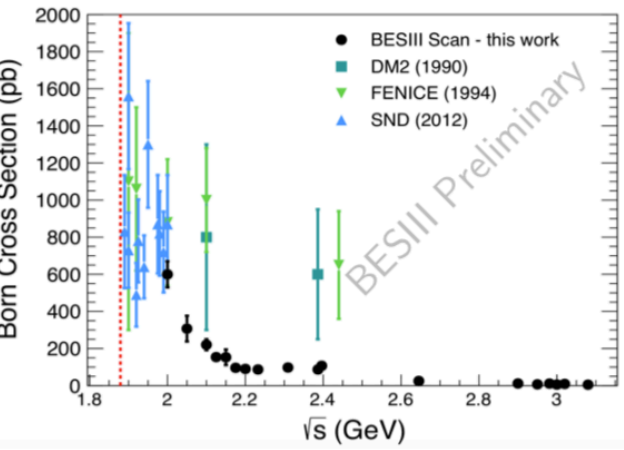


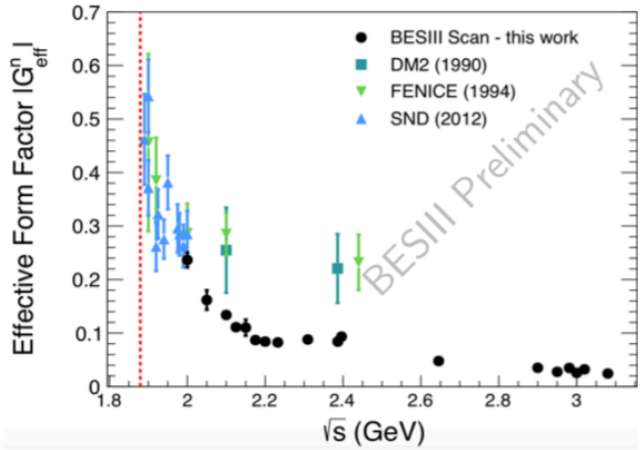


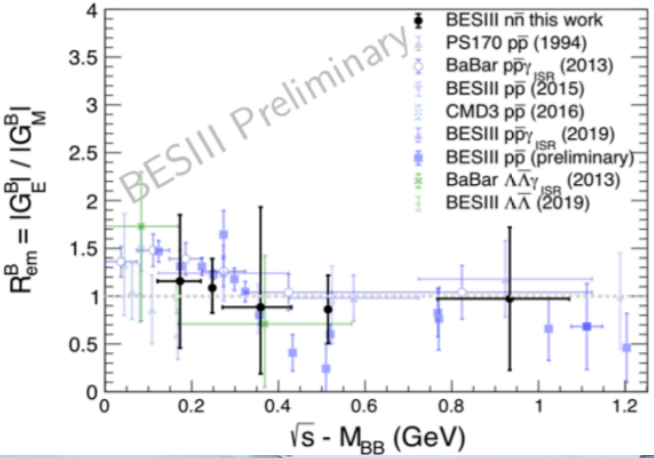


Baryon form factor

- Nucleon
  - $e^+e^- \to n\bar{n}$ (scan method)
    - The Born cross sections are determined in a wide rage with unprecedented precision, ~10%, (best at 2.396 GeV with 7.3% uncertainty)
    - Agree with FENICE and SND at 2.0 GeV
    - Differ by 2σ with FENICE at 2.396 GeV.
    - R=$|G_E/G_M|$ have been determined for the first time in time-like region

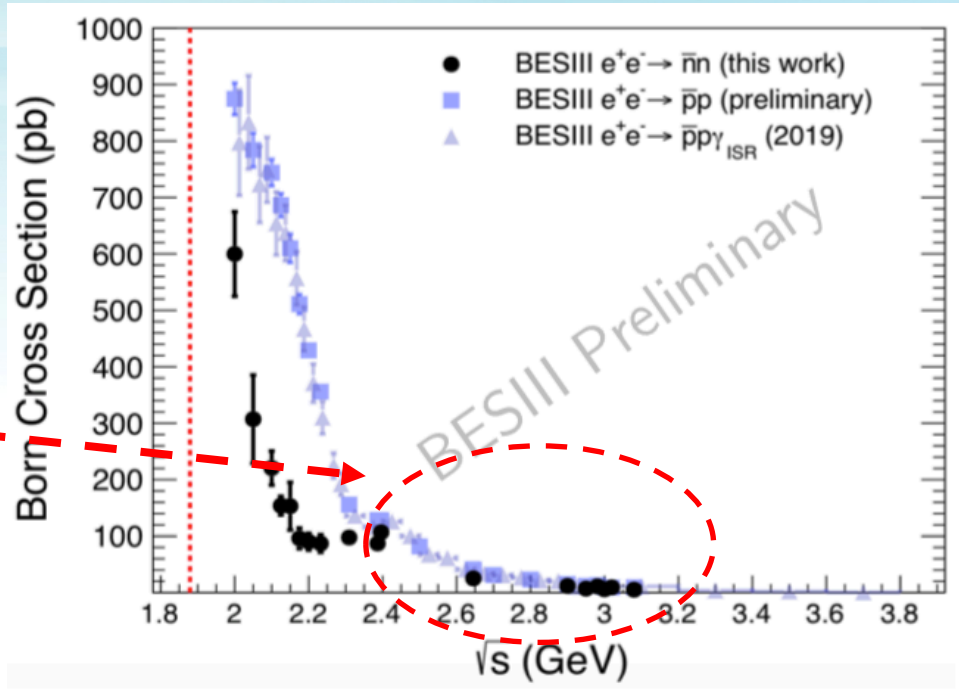


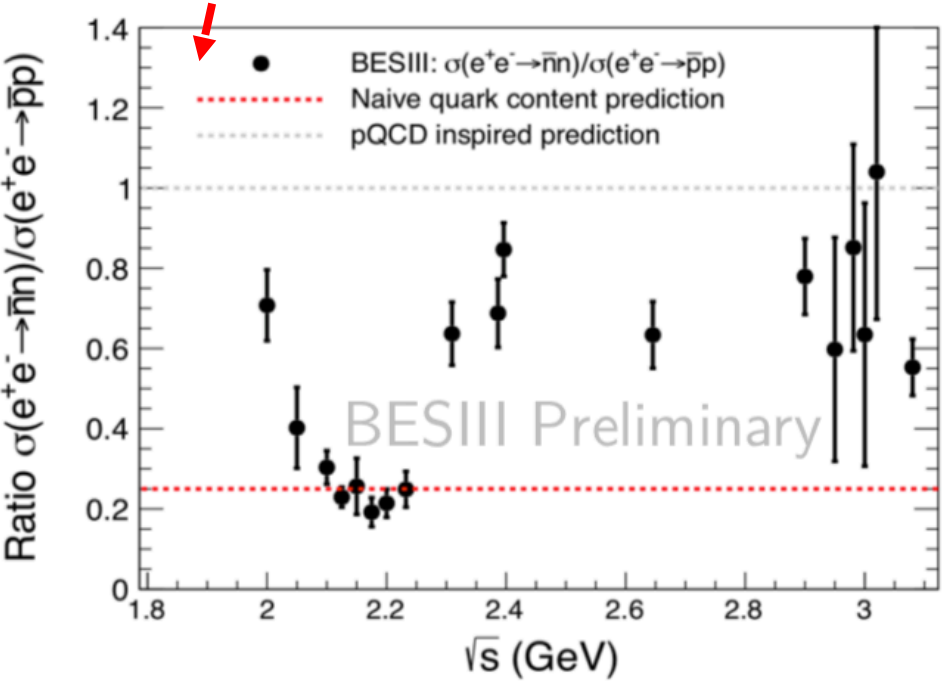


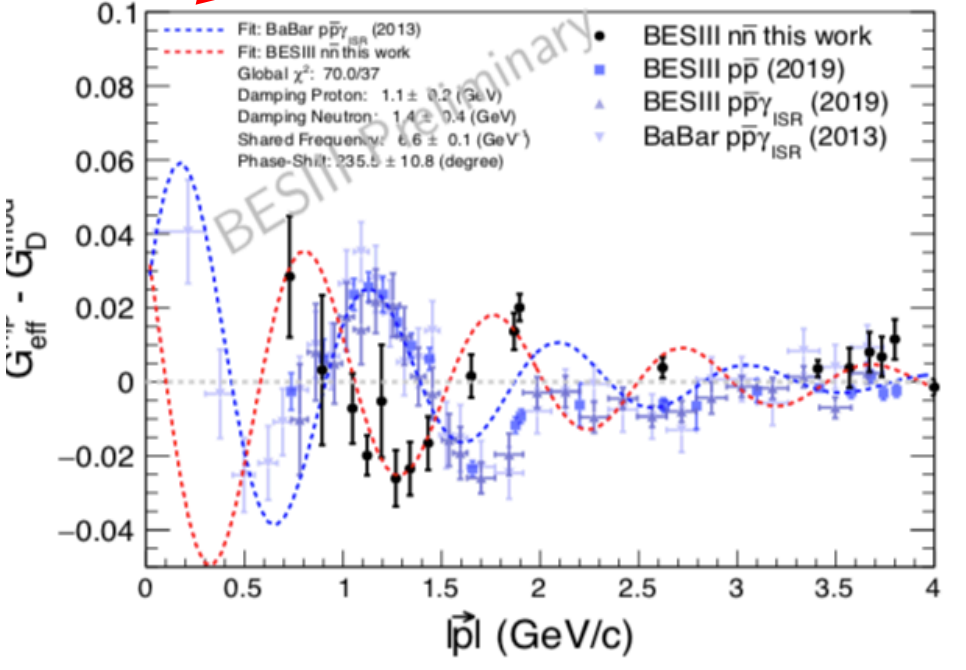


Baryon form factor

- Nucleon
  - Compare with $p\bar{p}$ process
    - σ: Similar above 2.4 GeV
    - σ_{pp}/σ_{nn}:
      - $R_{np} \cong \left|\frac{q_d}{q_u}\right|^2 \cong 0.25$→ EM interaction?
      - $R_{np} < 1$ → strong interaction?
    - G_{eff}: relative phase shift, ~235°







Baryon form factor

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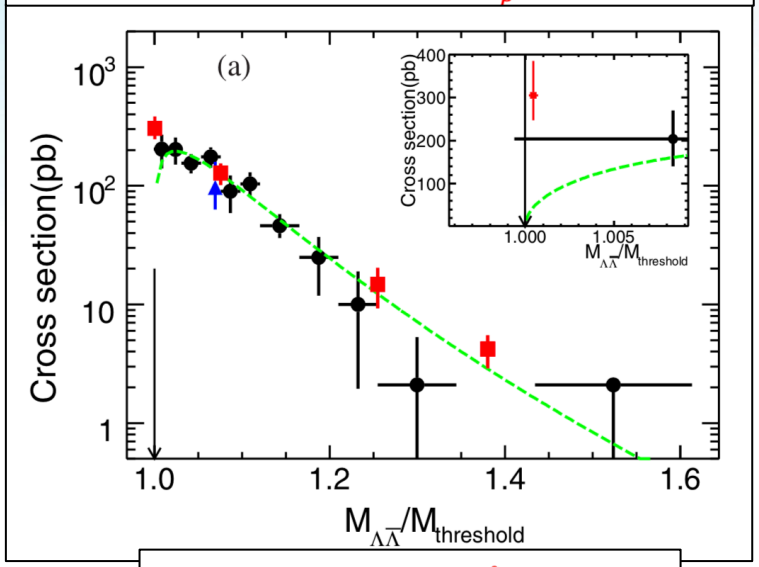
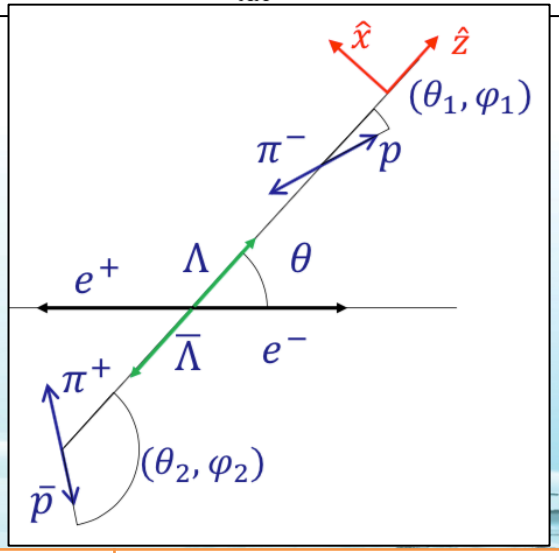
- C: Coulomb factor, $\frac{\pi\alpha}{\beta}\frac{1}{1-\exp(-\frac{\pi\alpha}{\beta})}$ for $B^{\pm}$, 1 for B^0.



- Hyperon
  - $e^+e^- \to \Lambda\bar{\Lambda}$ [PRD 97, 032013(2018)]
    - Near threshold production and small PHSP in $\Lambda/\bar{\Lambda}$ decays
    - Anomalous behavior differing from the pQCD prediction at threshold is observed
  - Complete Λ form factor [PRL123, 122003(2019)] (@2.396GeV)
    - Formula

$$\mathcal{W}(\xi) = \mathcal{T}_0(\xi) + \eta\mathcal{T}_5(\xi) - \alpha_\Lambda^2\left(\mathcal{T}_1(\xi) + \sqrt{1-\eta^2}\cos(\Delta\Phi)\mathcal{T}_2(\xi) + \eta\mathcal{T}_6(\xi)\right) + \alpha_\Lambda\sqrt{1-\eta^2}\sin(\Delta\Phi)\left(\mathcal{T}_3(\xi) - \mathcal{T}_4(\xi)\right).$$

$$R = |G_E/G_M|, \Delta\Phi = \Phi_E - \Phi_M, \eta = \frac{\tau - R^2}{\tau + R^2}$$



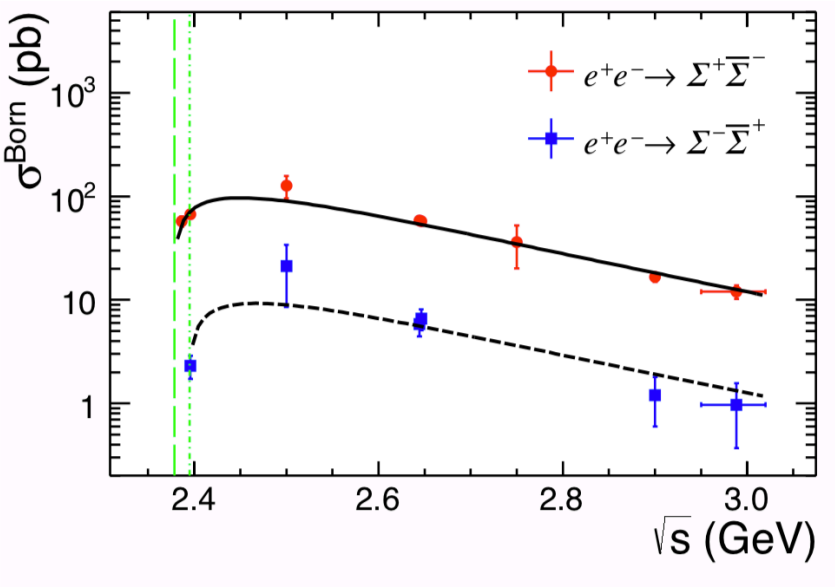
R	$0.96 \pm 0.14 \pm 0.02$
Δϕ	$37^o \pm 12^o \pm 6^o$

Baryon form factor

- Hyperon
  - $e^+e^- \to \Sigma^+\bar{\Sigma}^-$ and $\Sigma^-\bar{\Sigma}^+$ [arxiv: 2009.01404]
    - Nonzero cross section near threshold
    - The lineshape is well described by pQCD motivated model
    - $\sigma(e^+e^- \to \Sigma^+\bar{\Sigma}^-)/\sigma(e^+e^- \to \Sigma^-\bar{\Sigma}^+)$: 9.7 ± 1.3, which is inconsistent with prediction from various models
    - $|G_E/G_M|$ of Σ^+ is significantly higher than 1 near threshold, and consistent with 1 at higher c.m. energies.

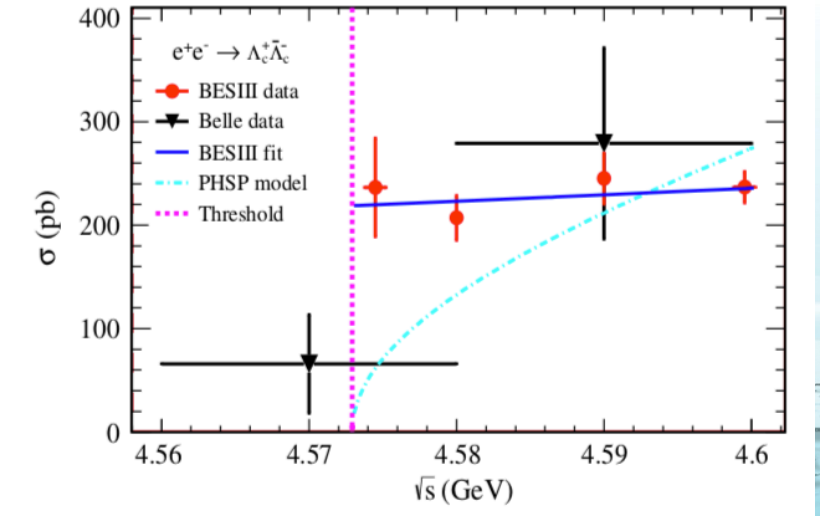
Energy (GeV)	$\lvert G_E/G_M \rvert$
2.3960	$1.83 \pm 0.26 \pm 0.24$
2.6454	$0.66 \pm 0.15 \pm 0.11$
2.9000	$1.06 \pm 0.36 \pm 0.09$

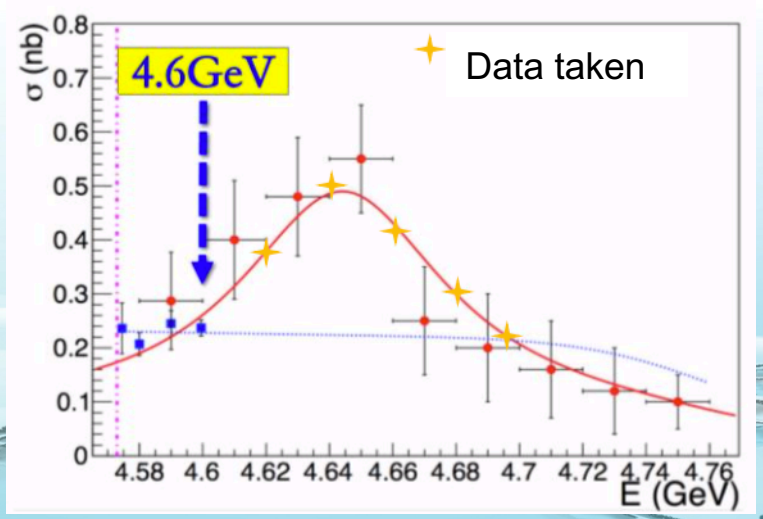
    - $|G_E/G_M|$ of Σ^- : data not enough



Baryon form factor

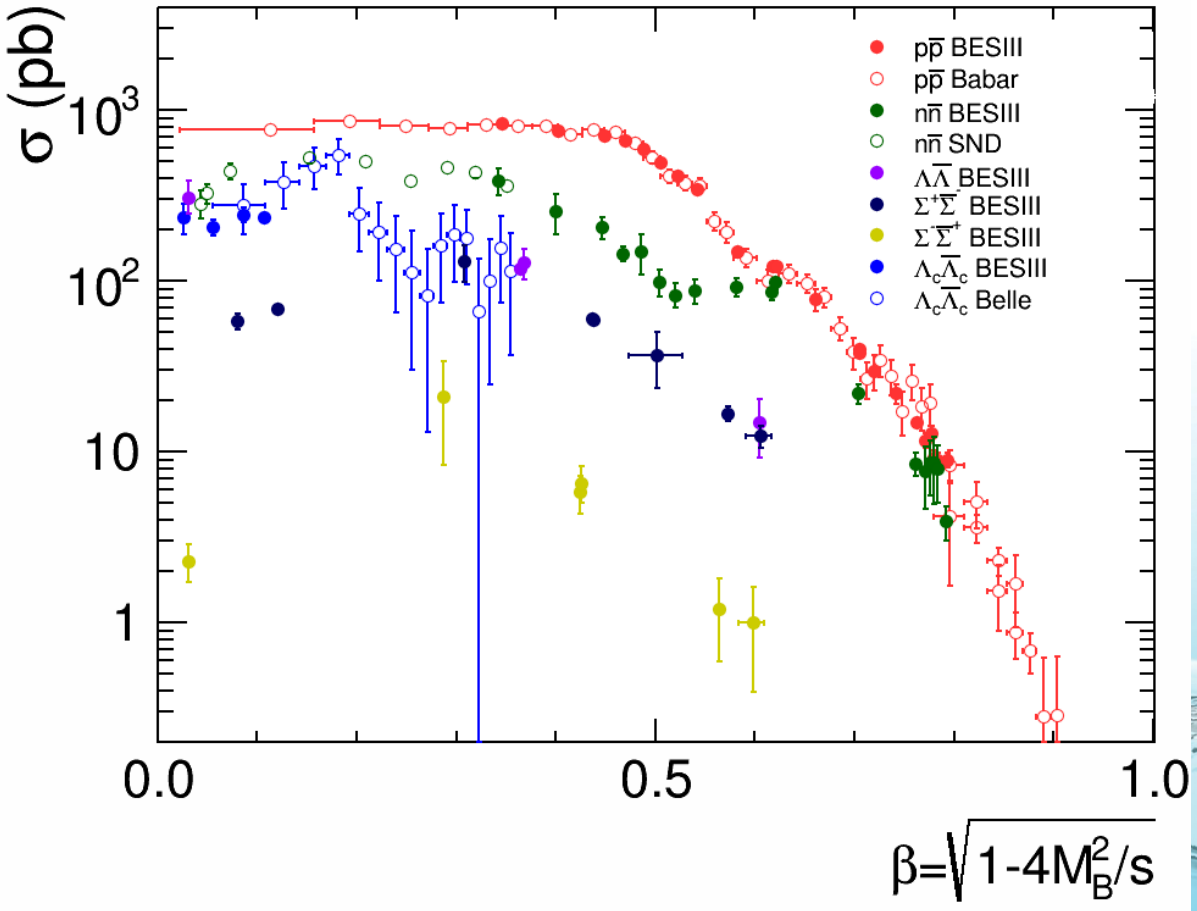
- Charmed baryon
  - $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ [PRL120, 132001(2018)]
    - Ten decay modes of Λ_c^+ are reconstructed
    - Measurement of Born cross section at 4 energies below 4.6 GeV with unprecedented statistical accuracy (~1.3% at 4.6 GeV)
    - Threshold enhancement is observed
    - Data has been taken above 4.6 GeV



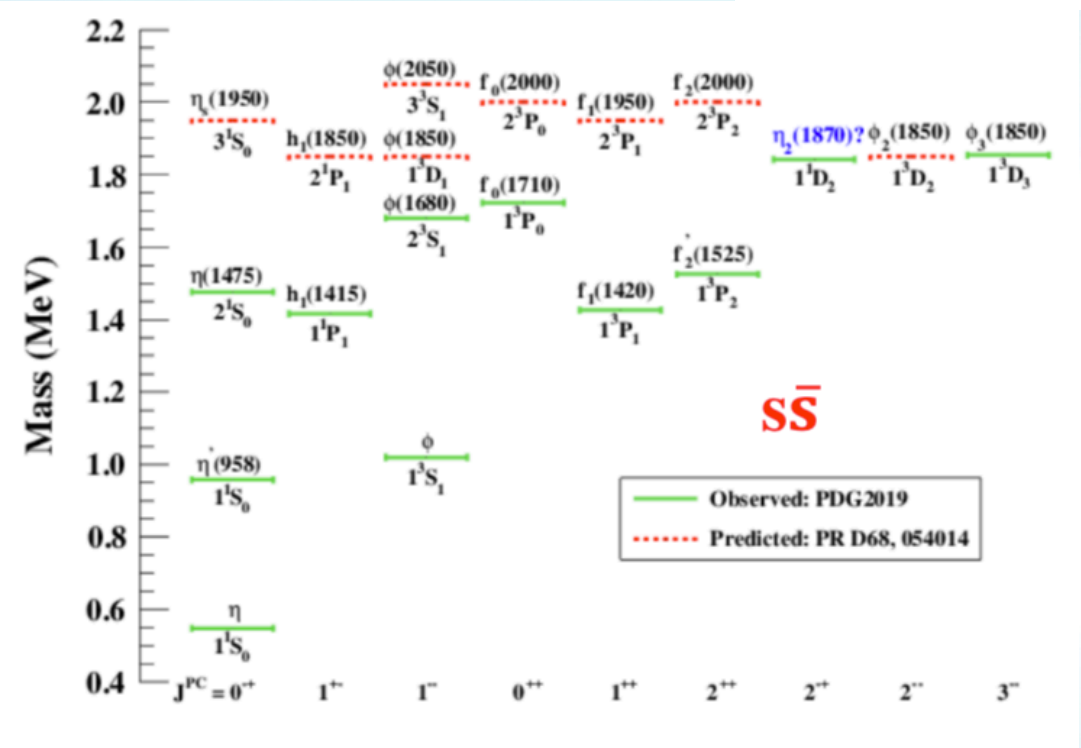


Baryons

- $p\bar{p}$, $n\bar{n}$, $\Lambda\bar{\Lambda}$, $\Sigma^{+}\bar{\Sigma}^{-}$, $\Sigma^{-}\bar{\Sigma}^{+}$, $\Lambda_c^{+}\bar{\Lambda}_c^{-}$ are studied with good accuracy
- Threshold enhancements
- Oscillation in effective form factor of nucleons



Strange quarkonium



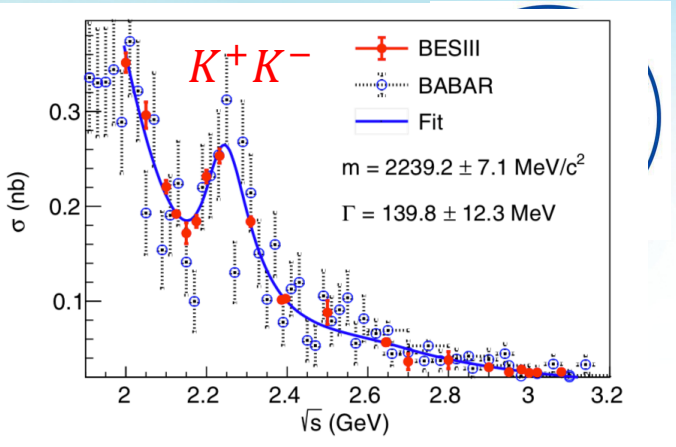
- Compared with $c\bar{c}$ and $b\bar{b}$, $s\bar{s}$ is a terra incognita
- XYZ particles with strange quark as well?
- A bridge between light and heavy quark
- The nature of ϕ(2170) is unclear

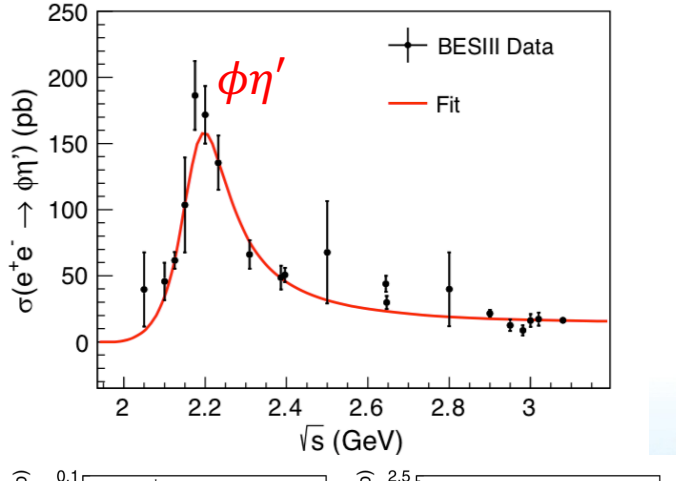
Nature of $\phi(2170)$
$s\bar{s}g$ hybrid,
2^3D_1 or 3^3S_1 $s\bar{s}$,
tetraquark,
molecular state $\Lambda\bar{\Lambda}$,
three body ϕKK

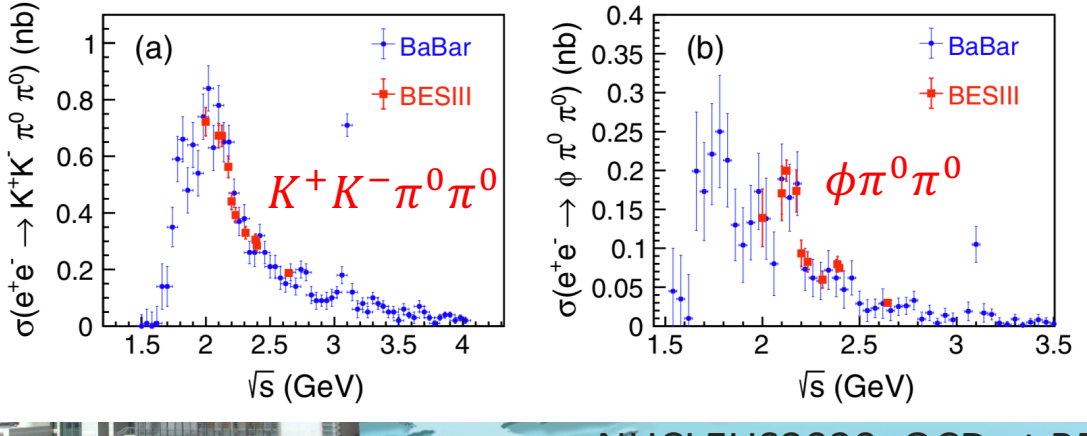
$\phi(2170)$ related studies

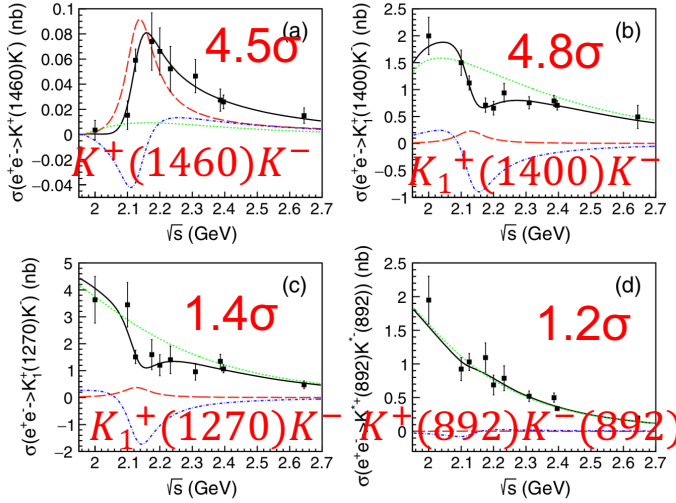
- $e^+e^- \to K^+K^-$ [PRD99, 032001(2019)]
- $e^+e^- \to \phi\eta'$[PRD102, 012008(2020)]
- $e^+e^- \to K^+K^-\pi^0\pi^0$ [PRL124, 112001(2020)]

Process	Mass(MeV/c²)	Width(MeV)
$e^+e^- \to K^+K^-$	2239.2±7.1±11.3	139.8±12.3±20.6
$e^+e^- \to \phi\eta'$	2177.5±4.8±19.5	149.0±15.6±8. 9
$e^+e^- \to K^+K^-\pi^0\pi^0$	2126.5±16.8±12.4	106.9±32.1±28.1



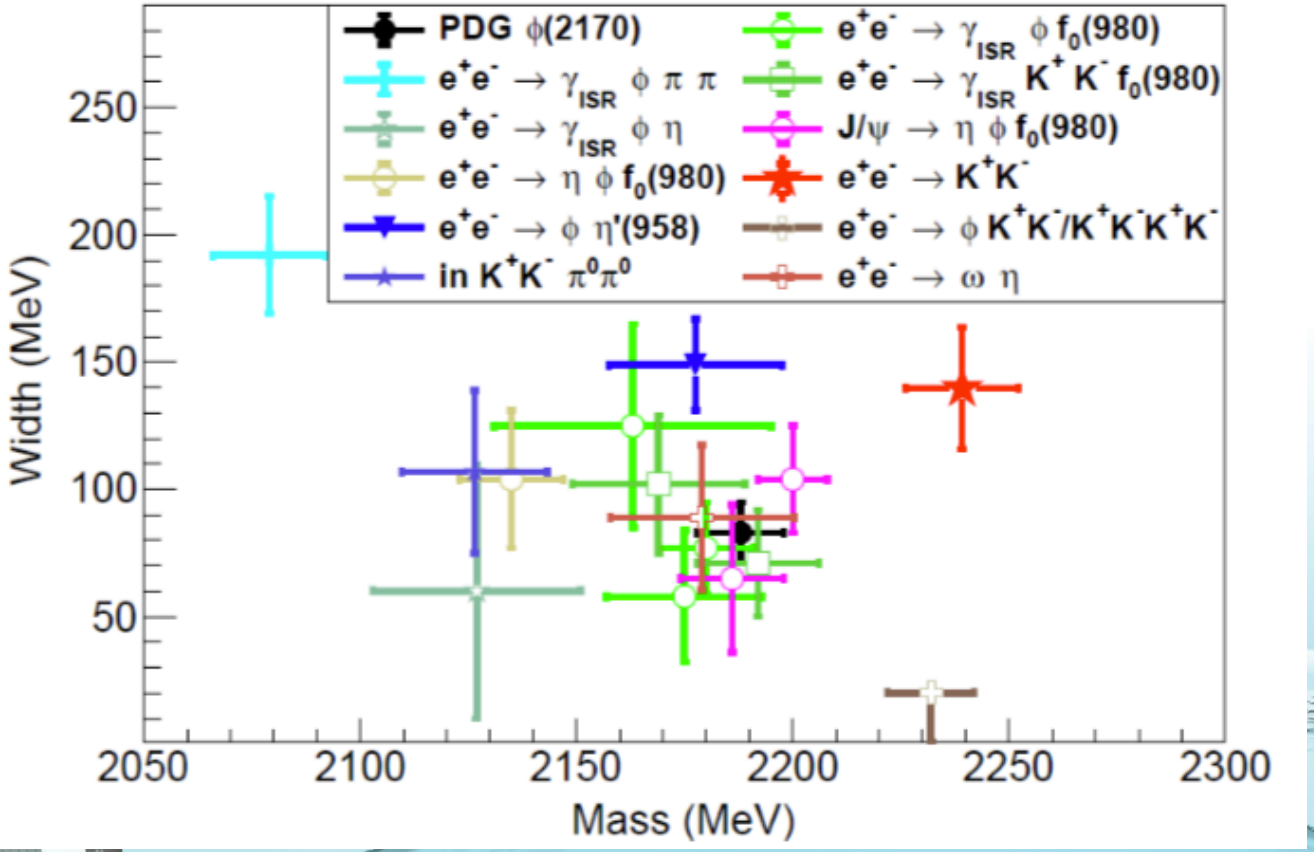






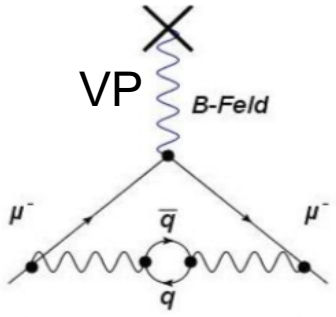
ϕ(2170) related studies

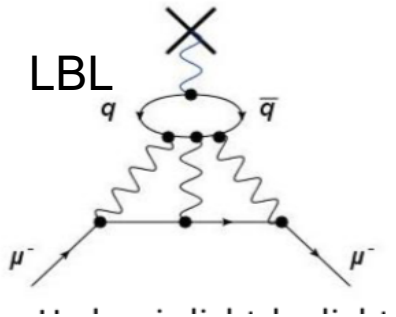
- ϕ(2170) in multi channels
  - Results vary in channels
  - Nature of the ϕ(2170) state is worth of discussion



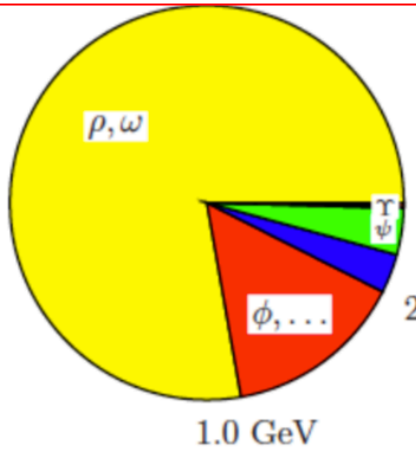
Precision tests of SM

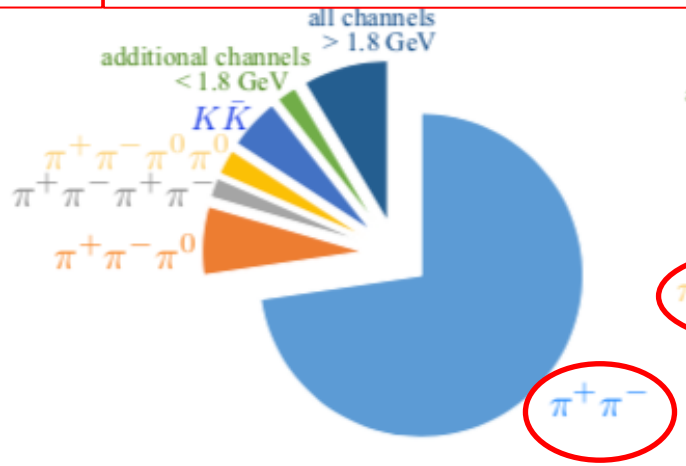
- $a_\mu = \frac{g_\mu - 2}{2}$ [CPC 44, 040001 (2020)]
  - 3.6σ SM vs Experiments
- $a_\mu^{SM} = a_\mu^{QED} + a_\mu^{Weak} + a_\mu^{Hadr}$
  - a_μ^{Hadr} can not be calculated by means of perturbative calculations
    - $a_\mu^{Hadr} = a_\mu^{Hadr,VP} + a_\mu^{Hadr,LBL}$, $a_\mu^{Hadr,VP} = (692.2 \pm 4.2)\times 10^{-10}$, $a_\mu^{Hadr,LBL} = (10.5 \pm 2.6)\times 10^{-10}$
    - $a_\mu^{Hadr,LO} = \frac{\alpha^2(0)}{3\pi^2}\int_{4m_\pi^2}^{\infty} ds \frac{K(s)}{s} R(s)$, $R(s) = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$

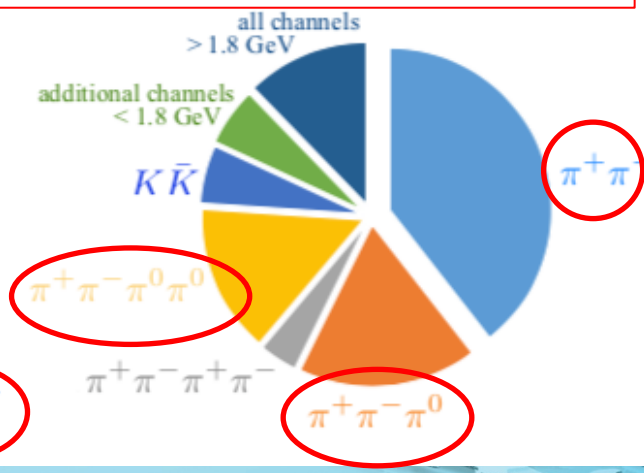




Contribution in energy regions	Contribution in channels, left: value, right: uncertainty

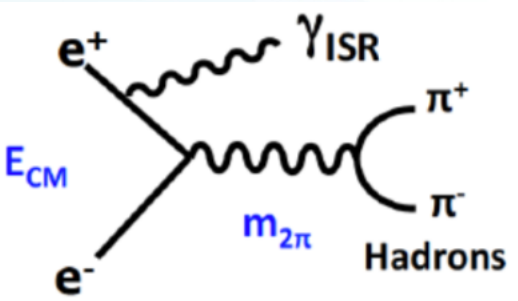




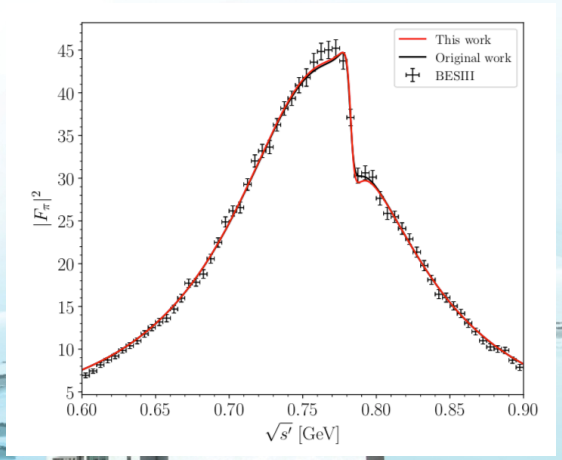


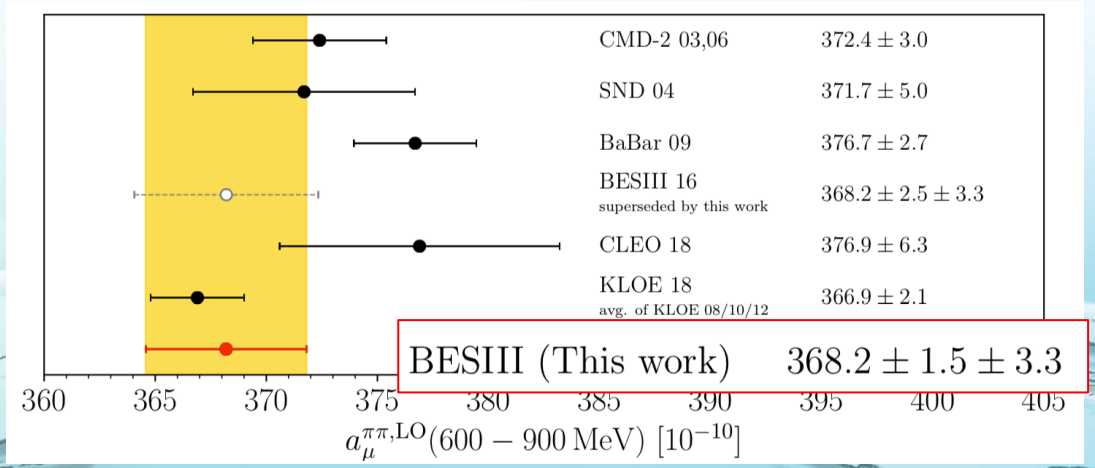
Precision tests of SM

- $e^+e^- \to \gamma_{ISR}\pi^+\pi^-$ [arxiv: 2009.05011][PLB 753 (2016) 629]
  - Data: 2.9 fb^{-1} @3.773 GeV
  - ISR method with neutral network technique
  - uncertainty of σ at 1% level
  - Contribution to the hadronic contribution of a_μ



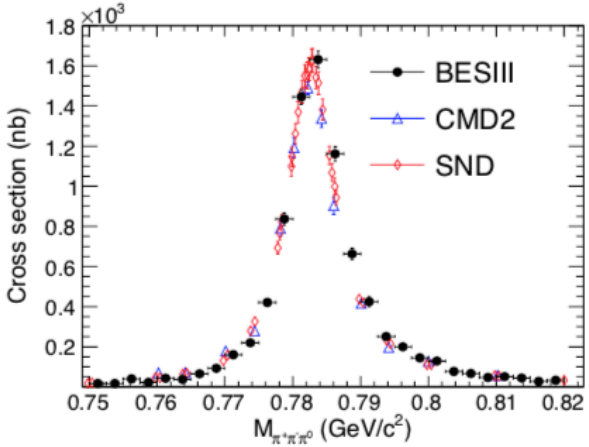
  - $a_\mu^{\pi\pi,LO}(0.6-0.9\ \mathrm{GeV}) = \frac{1}{4\pi^3}\int_{0.6}^{0.9} dsK(s)\sigma_{\pi\pi}^{bare}$, $\sigma_{\pi\pi(\gamma_{\mathrm{FSR}})}^{bare} = \frac{N_{\pi\pi\gamma}(1+\delta_{FSR}^{\pi\pi})}{L\varepsilon H(s)\delta_{vac}}$
  - Confirmed the more than 3σ deviation with SM prediction

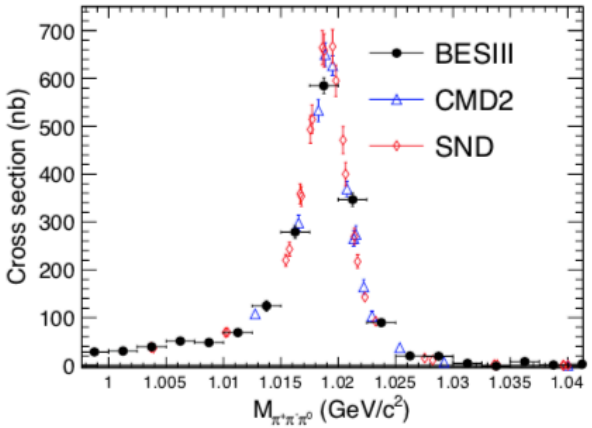


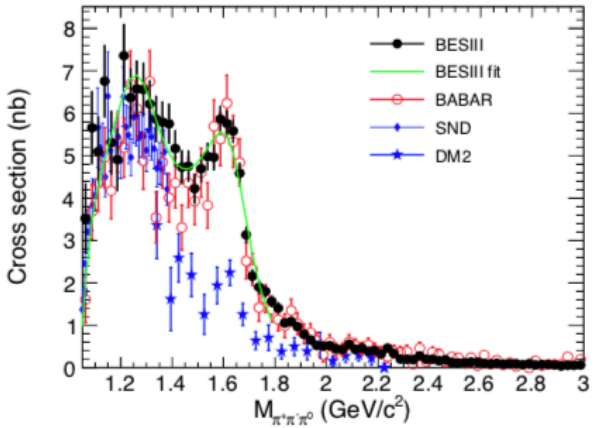


Precision tests of SM

- $e^+e^- \to \gamma_{ISR}\pi^+\pi^-\pi^0$ [arxiv:1912.11208]
  - Data: 2.9 fb^{-1} @3.773 GeV, ISR method
  - $a_\mu^{3\pi}(0.7-3.0\ \text{GeV})$ determined to be (49.77$\pm$0.53$\pm$0.17) x 10^{-10}

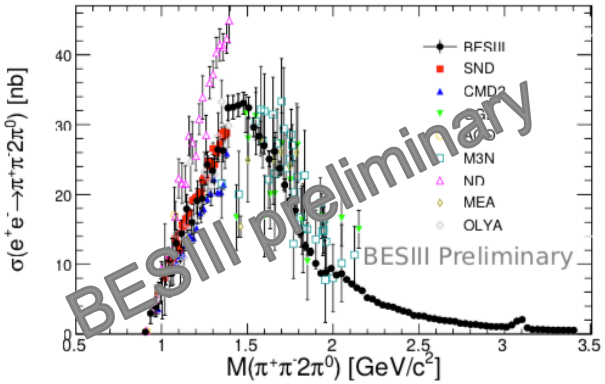






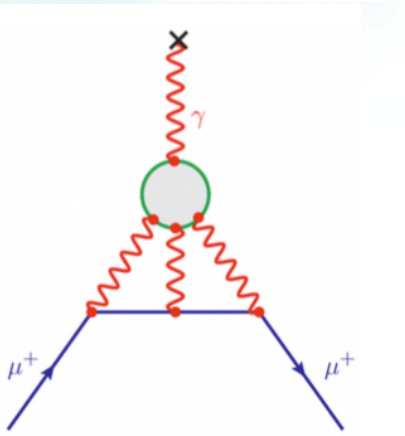
- $e^+e^- \to \gamma_{ISR}\pi^+\pi^-\pi^0\pi^0$
  - Data: 2.9 fb^{-1} @3.773 GeV, ISR method
  - $a_\mu^{\pi^+\pi^-\pi^0\pi^0}(4m_\pi - 1.8\ \text{GeV})$

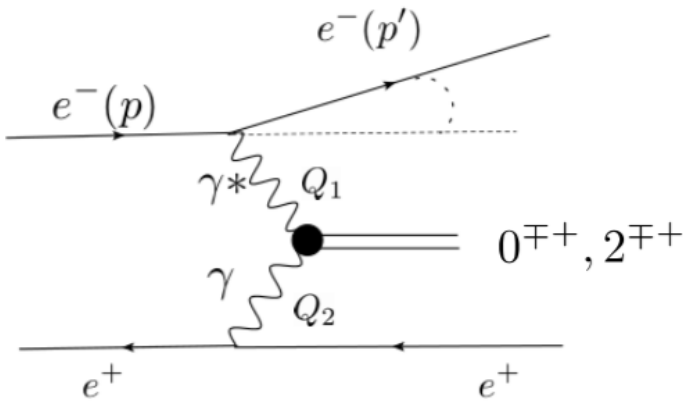
	$a_\mu^{\pi^+\pi^-2\pi^0,\text{LO}}/10^{-10}$
BESIII (preliminary)	$18.63 \pm 0.27 \pm 0.57$
BABAR (preliminary)	$17.9 \pm 0.1 \pm 0.6$

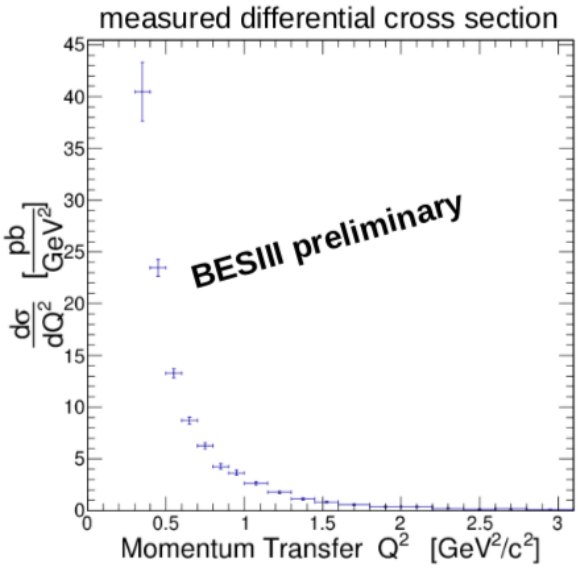


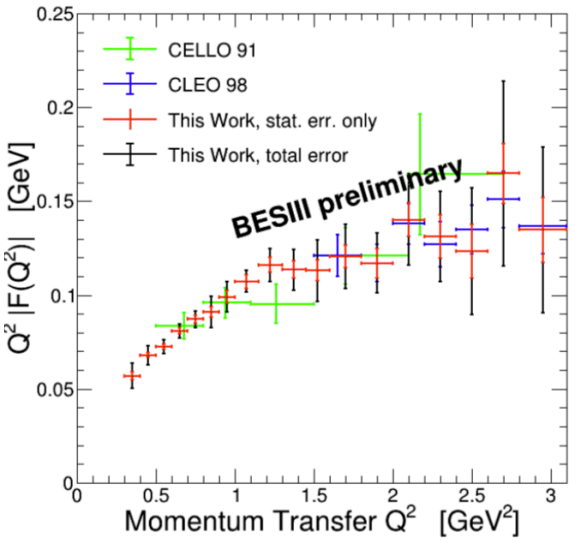
Precision tests of SM

- $\gamma\gamma \to \pi^0$
  - $a_\mu^{Hadr,LBL}$ is not directly related to measurable quantities
    - Transition form factors (TFF) as experimental input
  - Single tag measurement (tag one scattered lepton)
    - First measurement below 0.5 GeV^2
    - Unprecedented accuracy below 1.5 GeV^2
    - Competitive accuracy up to 3.1 GeV^2









Summary

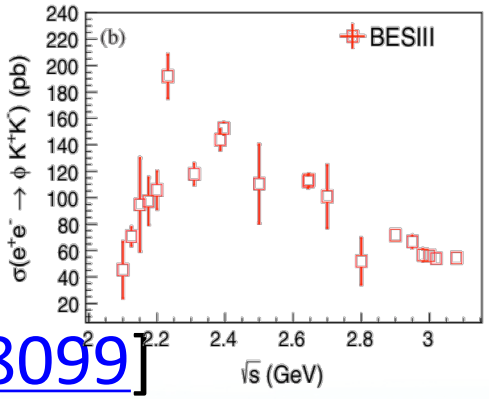
- Fruitful results from e+ e- annihilation at BESIII, both energy scan and ISR methods are performed.
- More precise baryon form factor on proton, neutron, Λ, $\Sigma^{\pm}$ and Λ_c^+
  - Threshold enhancement effect
  - Electromagnetic form factors are measured
  - Oscillation of the effective form factor of nucleons.
- Several exclusive channels are analyzed to study the property of ϕ(2170). Resonant structures are observed.
- ISR method is used to study $\pi^+\pi^-$, $\pi^+\pi^-\pi^0$ and $\pi^+\pi^-\pi^0\pi^0$ to study the anomalous μ magnetic moment.
- π transition form factor is measured via two-photon process.

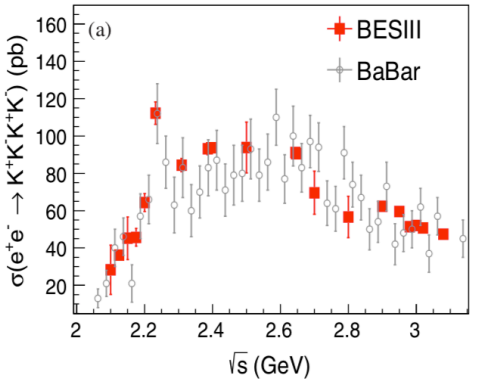
Thank you!

backup

ϕ(2170) related studies

- $e^+e^- \to \phi K^+K^-$ and $K^+K^-K^+K^-$ [PRD100, 032009(2019)]
  - Born cross sections are measured with improved precision
  - A jump at 2.232 GeV is observed, but very narrow
    - Three body system ϕK^+K^-?
    - $\Lambda\bar{\Lambda}$ threshold effect?
    - Other explanations?





- $e^+e^- \to \omega\eta$ [arxiv:2009.08099]
  - A resonance at 2.2 GeV with significance more than 5σ

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