R Measurements and QCD Studies at future super τ-c factory

Guangshun Huang

University of Science and Technology of China

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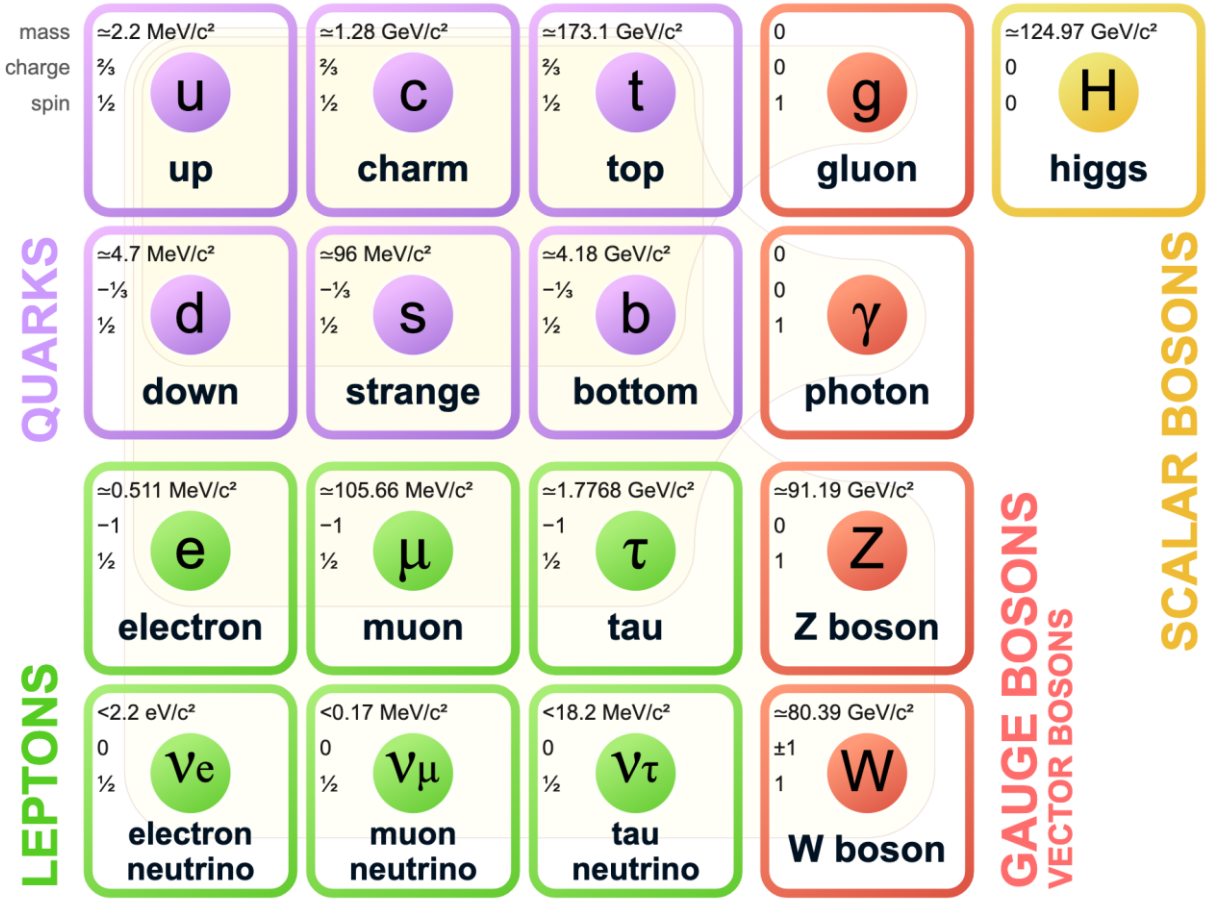
Outline

- Introduction
- R measurements at BESIII
- QCD studies at BESIII
  - Meson cross sections
  - Baryon form factors
- Summary

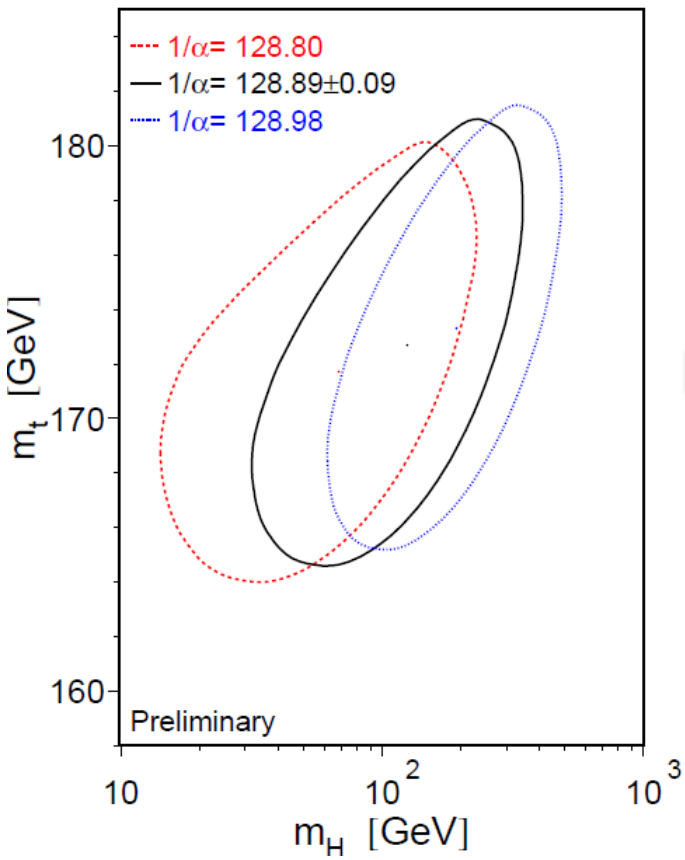
Standard Model

- Successful, but many parameters;
- Precision test needed!

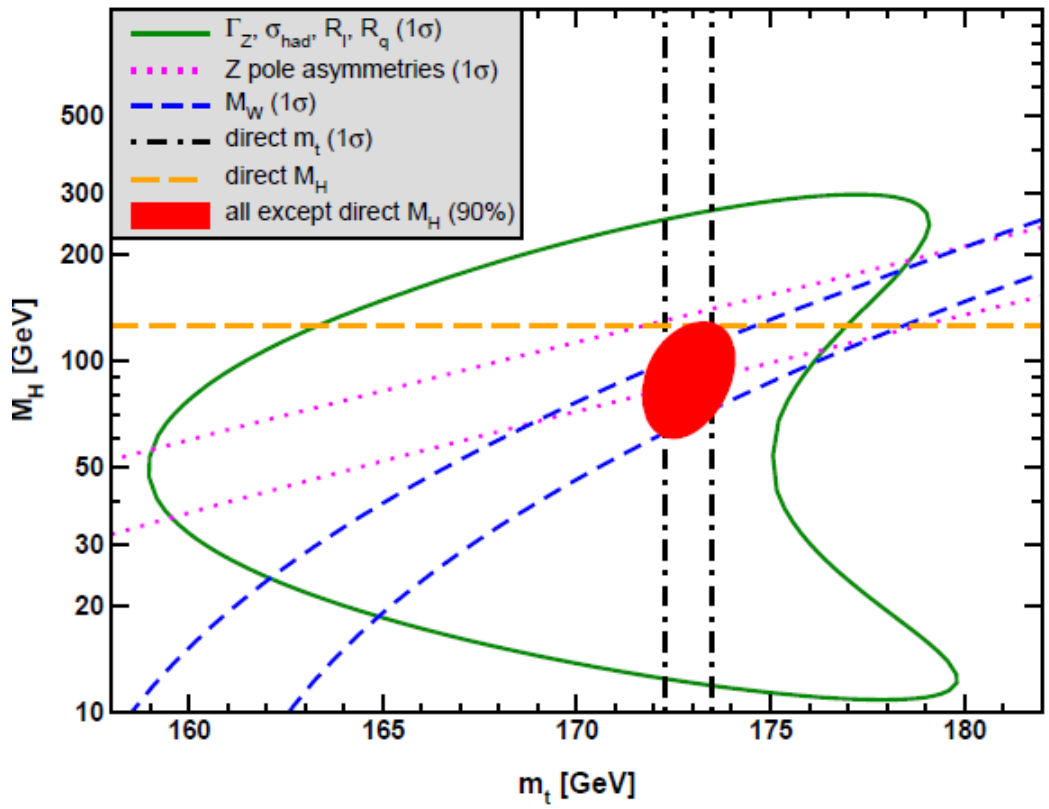


m_H, m_t and α in SM fit

EW Group 1997

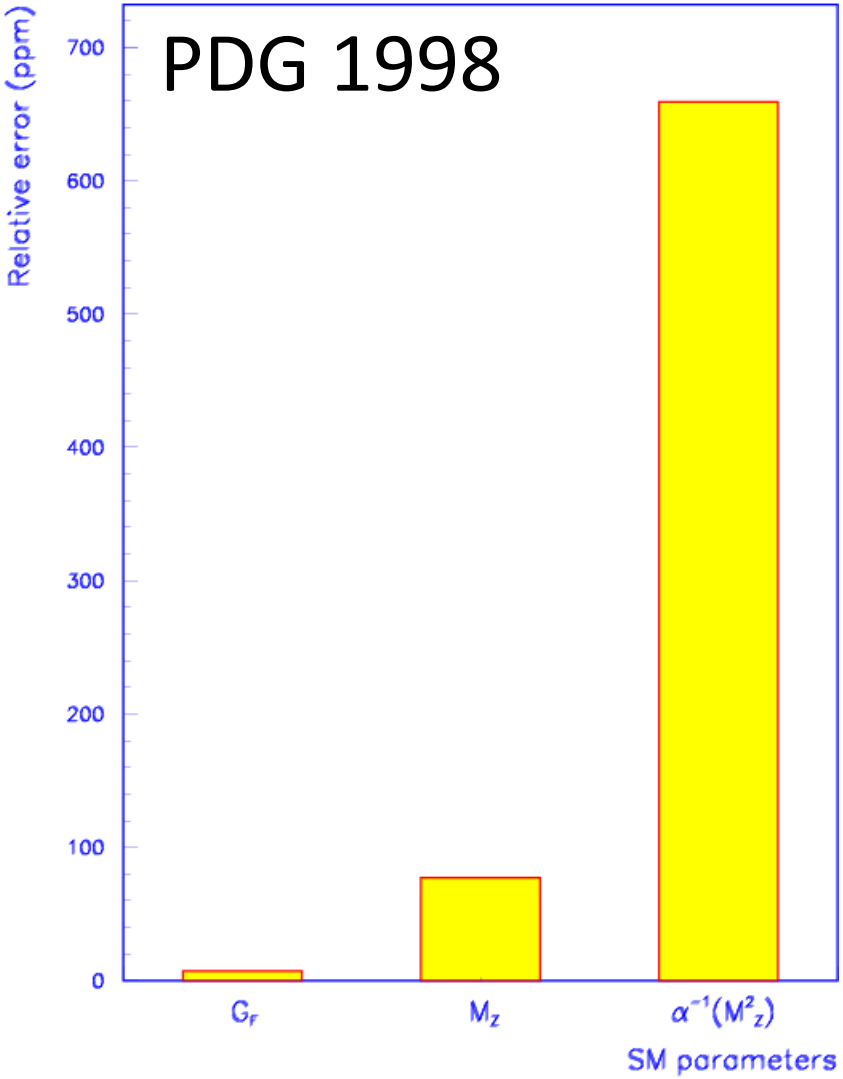


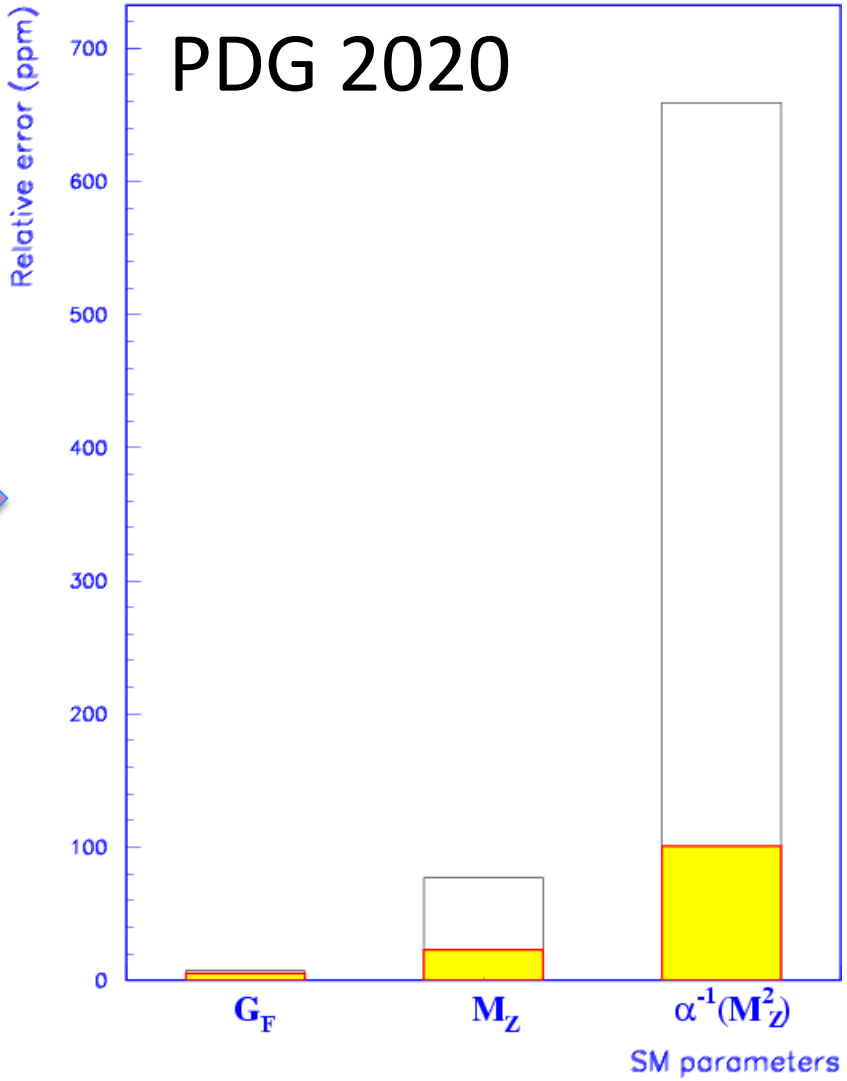
PDG 2022



Improvement due to better precision of α, …

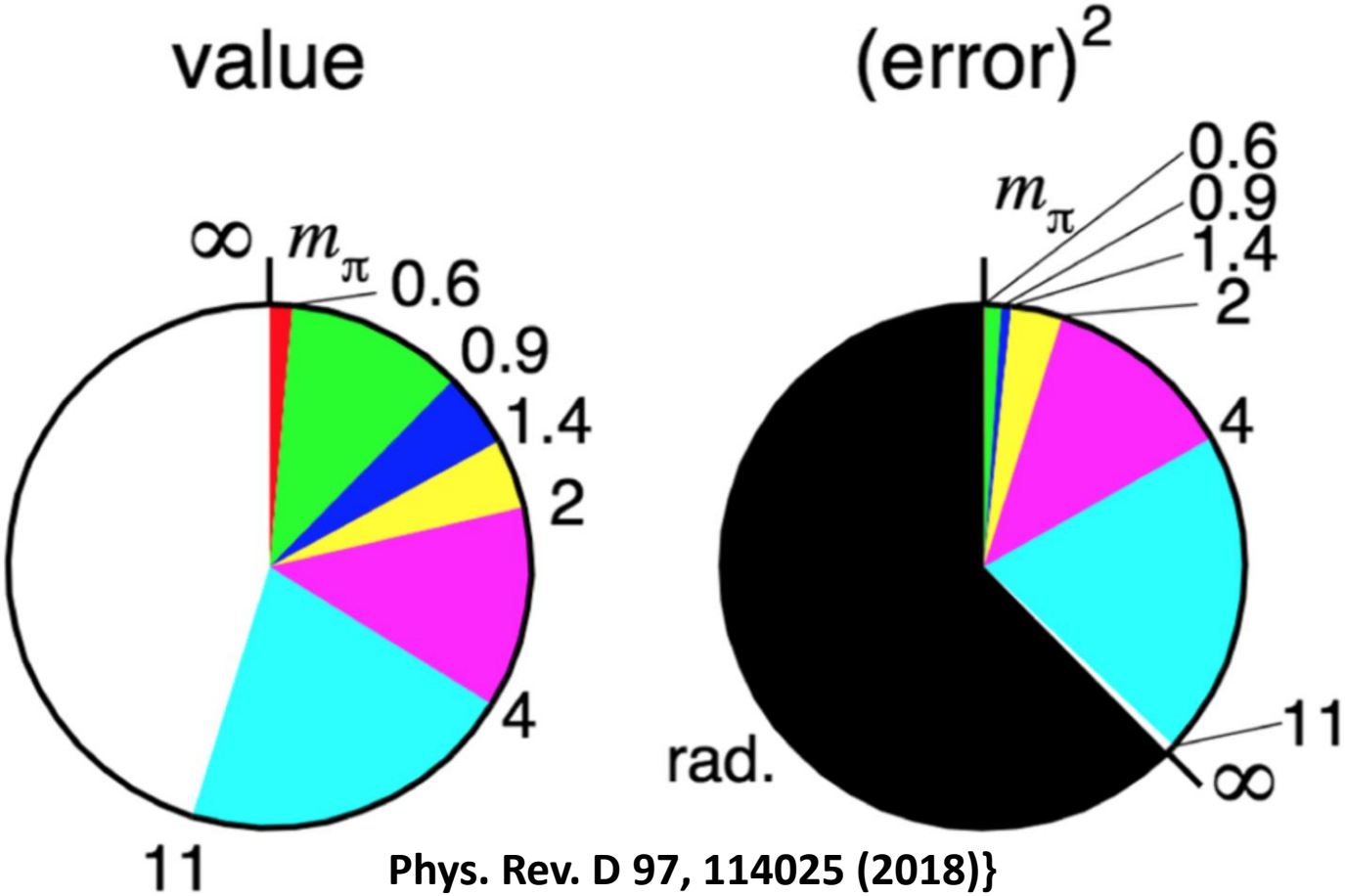
Uncertainties of SM parameters





$\Delta\alpha(M_Z^2)$

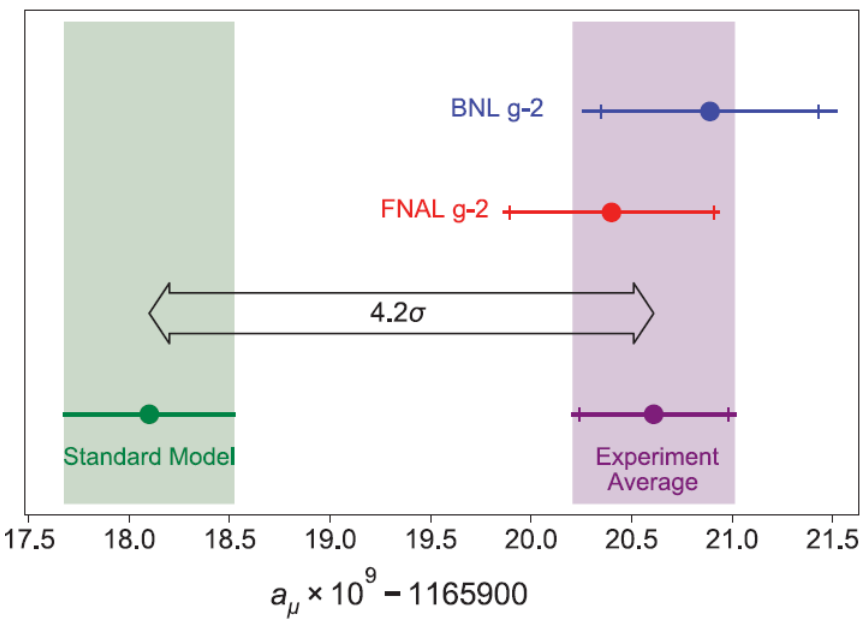
- $\Delta\alpha(s)=\Delta\alpha(s)_{lepton}+\Delta\alpha(s)_{top}+\Delta\alpha^{(5)}_{had}(s)$;
- Dominant: $\Delta\alpha^{(5)}_{\rm had}(s) = -\frac{\alpha s}{3\pi}\,{\rm Re}\int_{E_{\rm th}}^{\infty} ds'\,\frac{R(s')}{s'(s'-s-i\varepsilon)}$



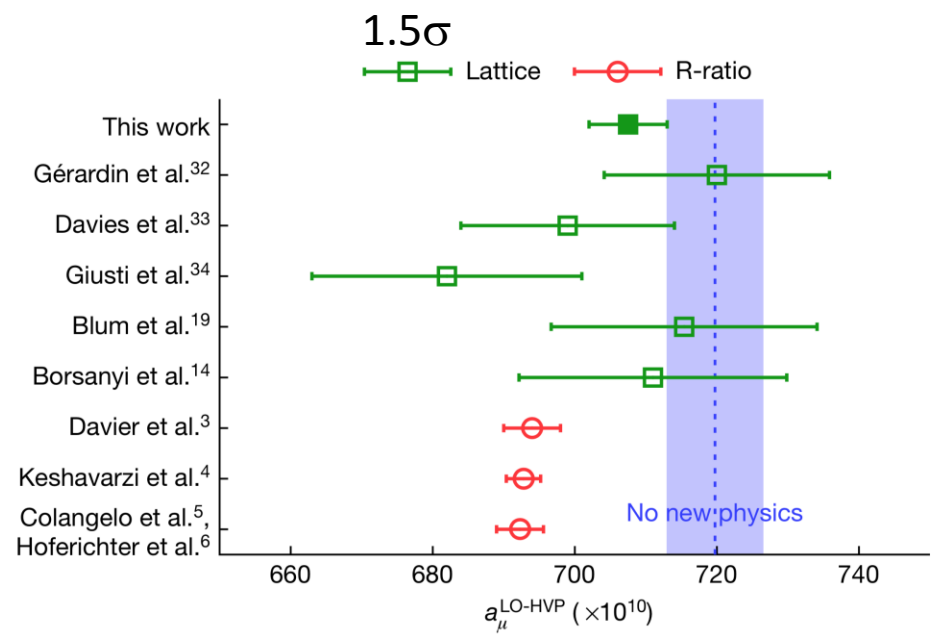
Phys. Rev. D 97, 114025 (2018)}

$a_\mu \equiv (g_\mu - 2)/2$

- 4.2σ discrepancy?



Phys. Rev. Lett. 126, 141801 (2021)



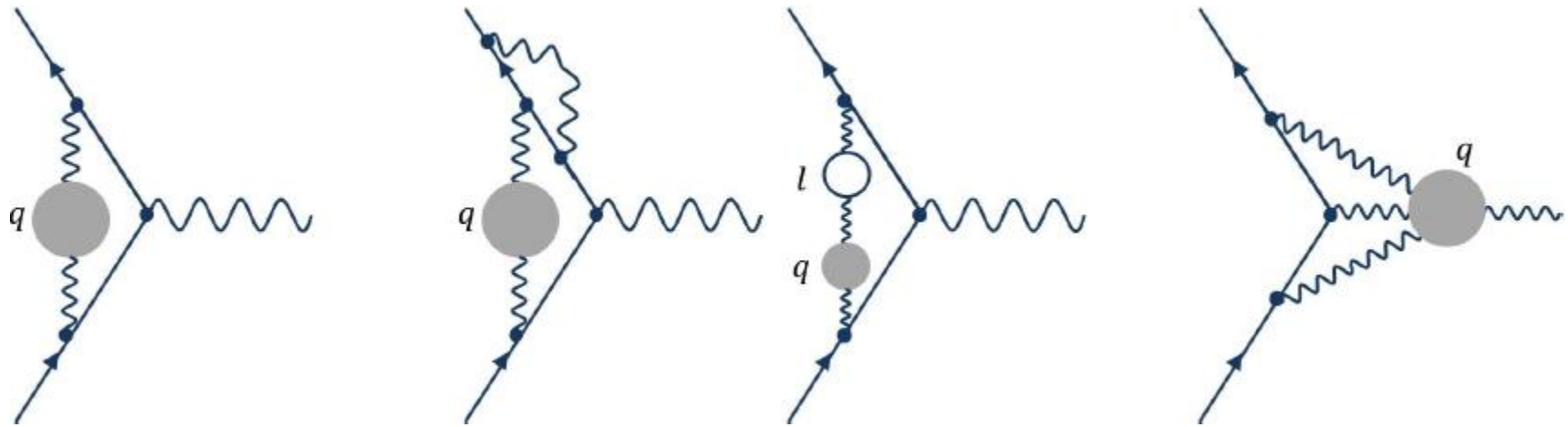
Nature 593, 51 (2021)

$a_\mu^{\text{LO-HVP}}$ (*R*-ratio) 6931 ± 40

$a_\mu^{\text{LO-HVP}}$ (lattice) 7075 ± 55

$a_\mu \equiv (g_\mu - 2)/2$

$$a_\ell^{\mathrm{SM}} = a_\ell^{\mathrm{QED}} \checkmark + a_\ell^{\mathrm{Weak}} \checkmark + a_\ell^{\mathrm{had}} \times$$

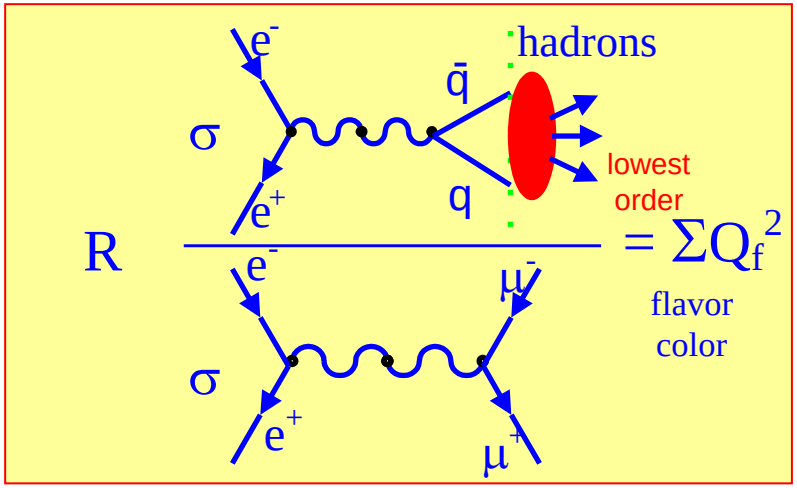


$$a_\ell^{\mathrm{had}} = a_\ell^{\mathrm{LO\text{-}HVP}} + a_\ell^{\mathrm{NLO\text{-}HVP}} + a_\ell^{\mathrm{HLbL}}$$

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

- R in low energy matters more!

Definition of R:



- At lowest order

$$R \equiv \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} = \frac{\sum_q \sigma(e^+e^- \to q\bar{q})}{\sigma(e^+e^- \to \mu^+\mu^-)} = 3\sum_q Q_q^2$$

Number of quark colors

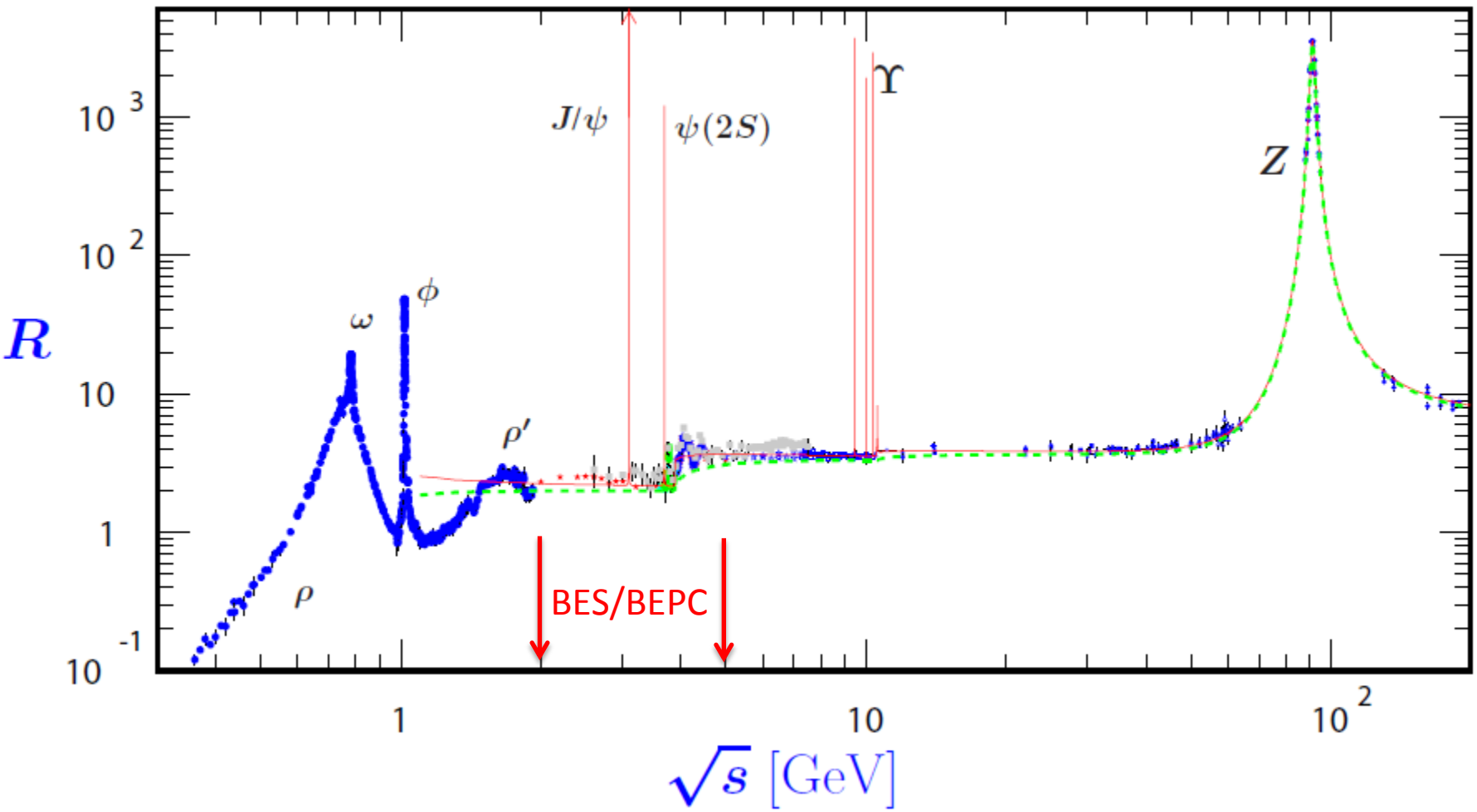
- At higher order

$$R = 3\, K_{QCD} \sum_q Q_q^2 ,$$

$$K_{QCD} = 1 + \frac{\alpha_S(\mu^2)}{\pi} + \sum_{n\geq 2} C_n \left(\frac{s}{\mu^2}\right) \left(\frac{\alpha_S(\mu^2)}{\pi}\right)^n$$

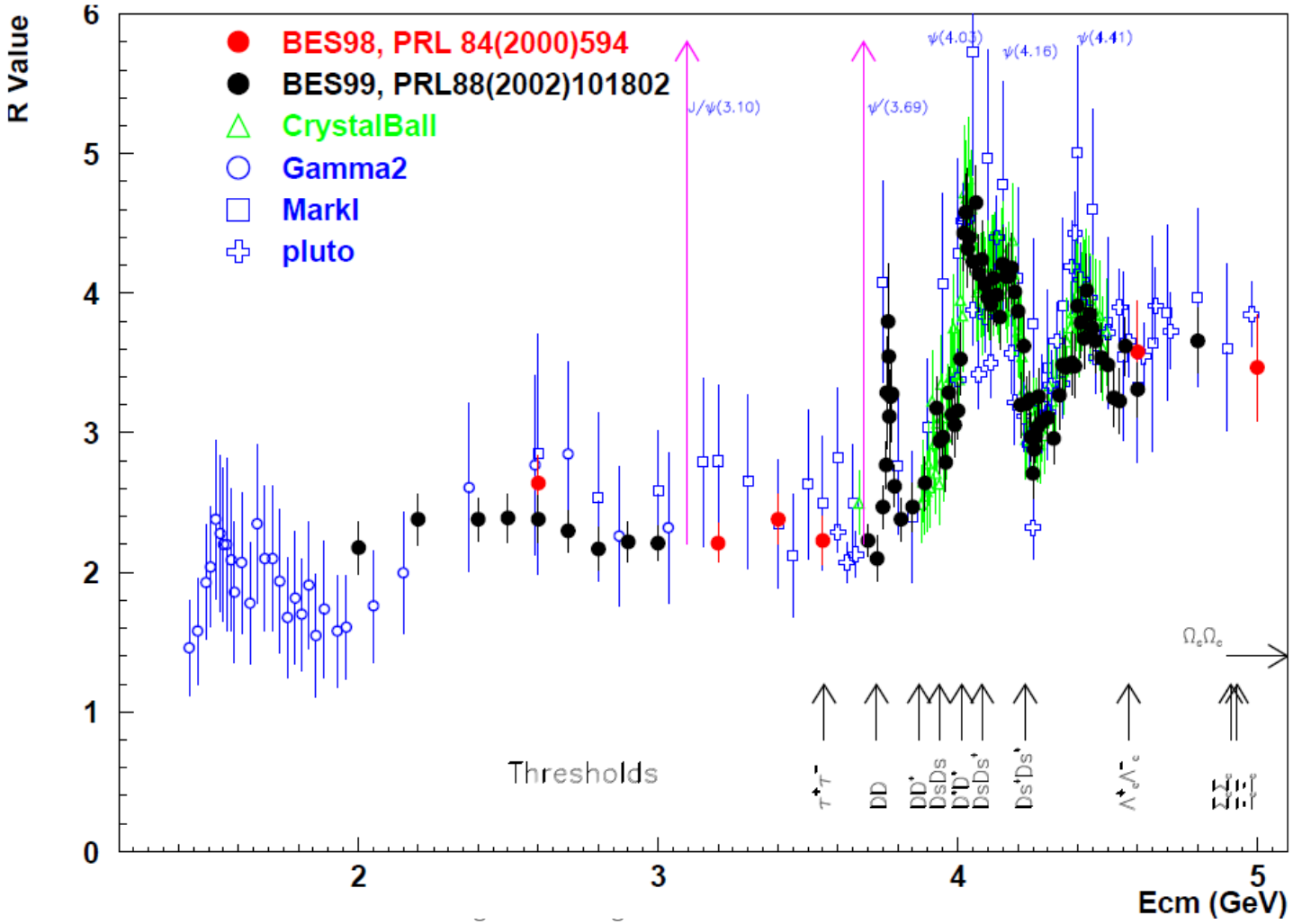
- R is one of the most fundamental quantities in particle physics that directly reflect the flavor and color of quarks.
- Directly test quark model & QCD, and discover new particles.

R: from threshold to Z

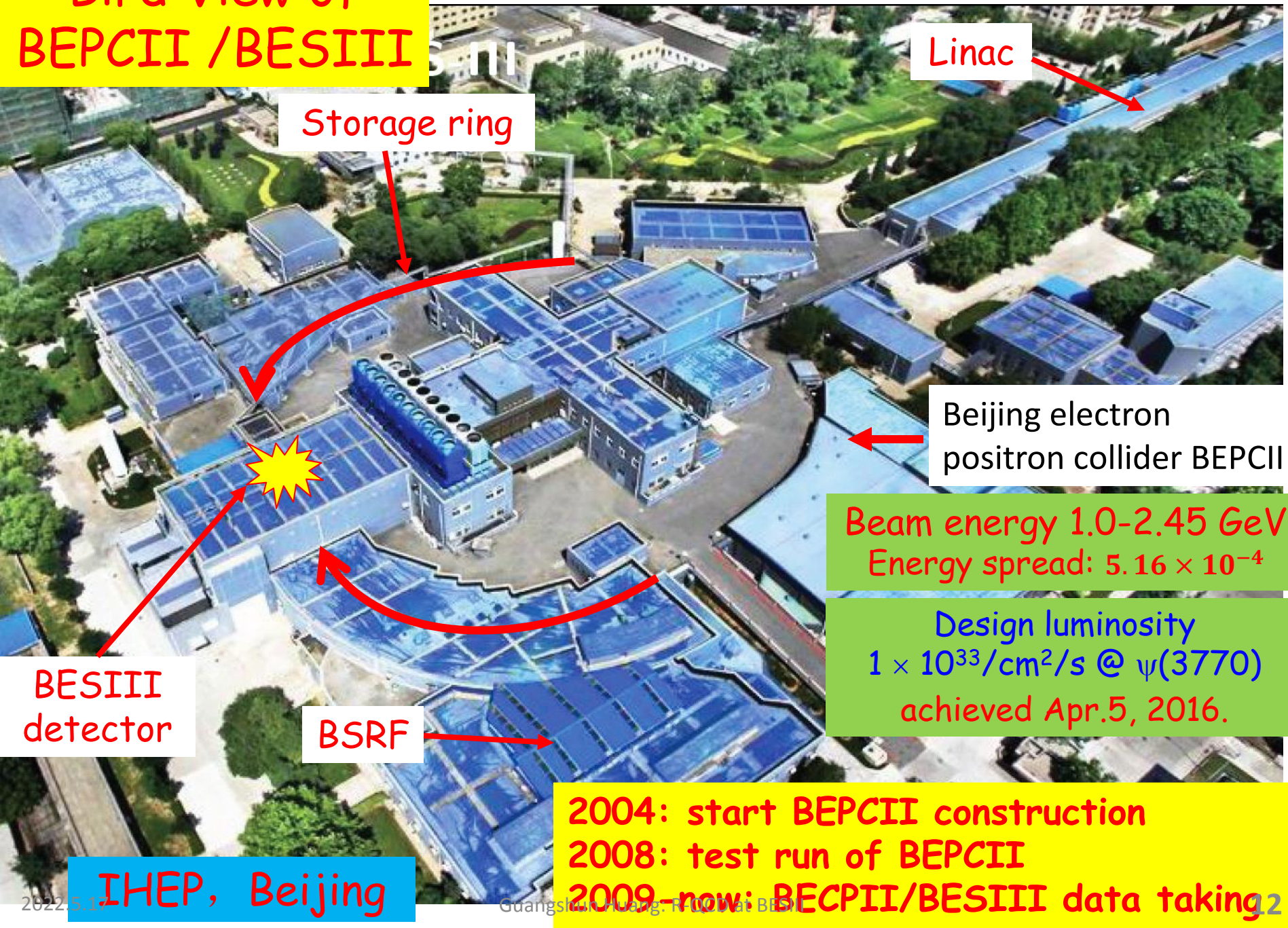


R Scans at BESII

- 6 + 85 energy points, total ~5 pb^{-1} data, average uncertainty 6.6% in [2 – 5] GeV.



Bird View of BEPCII /BESIII



Beam energy 1.0-2.45 GeV
Energy spread: 5.16×10^{-4}

Design luminosity
$1 \times 10^{33}/cm^2/s$ @ $\psi(3770)$
achieved Apr.5, 2016.

2004: start BEPCII construction
2008: test run of BEPCII
2009-now: BECPII/BESIII data taking

IHEP, Beijing

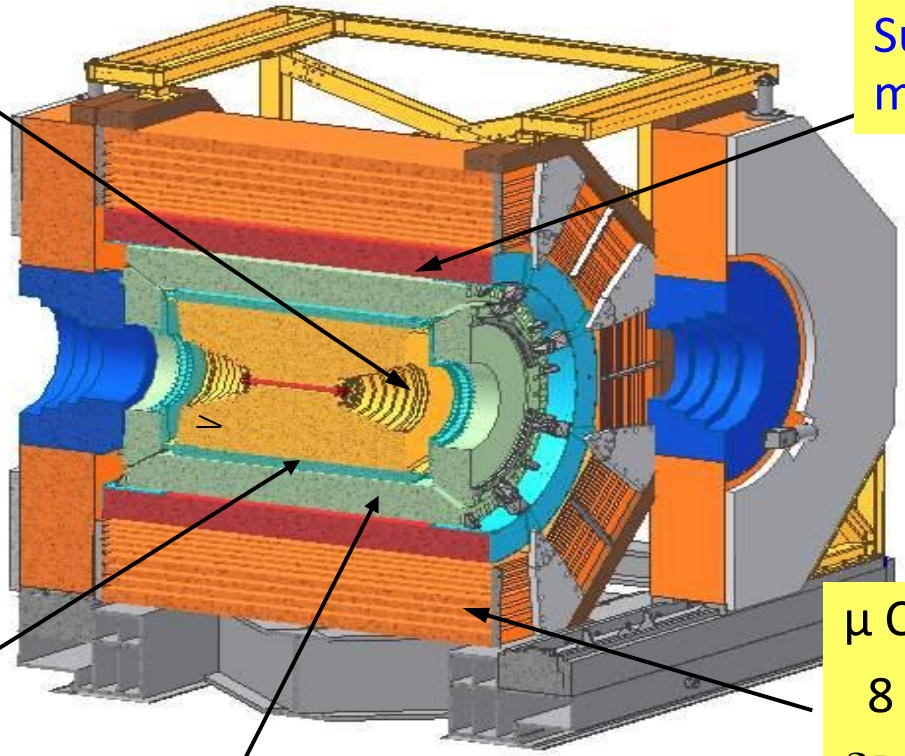
The BESIII Detector

Drift Chamber (MDC)

$\sigma p/p$ ($^0/_0$) = 0.5%(1GeV)

$\sigma_{dE/dx}$ ($^0/_0$) = 6%

Super-conducting magnet (1.0 Tesla)



Time of Flight (TOF)

σ_T : 90 ps for Barrel;

110 ps $\rightarrow$ 65 ps for Endcaps

μ Counter

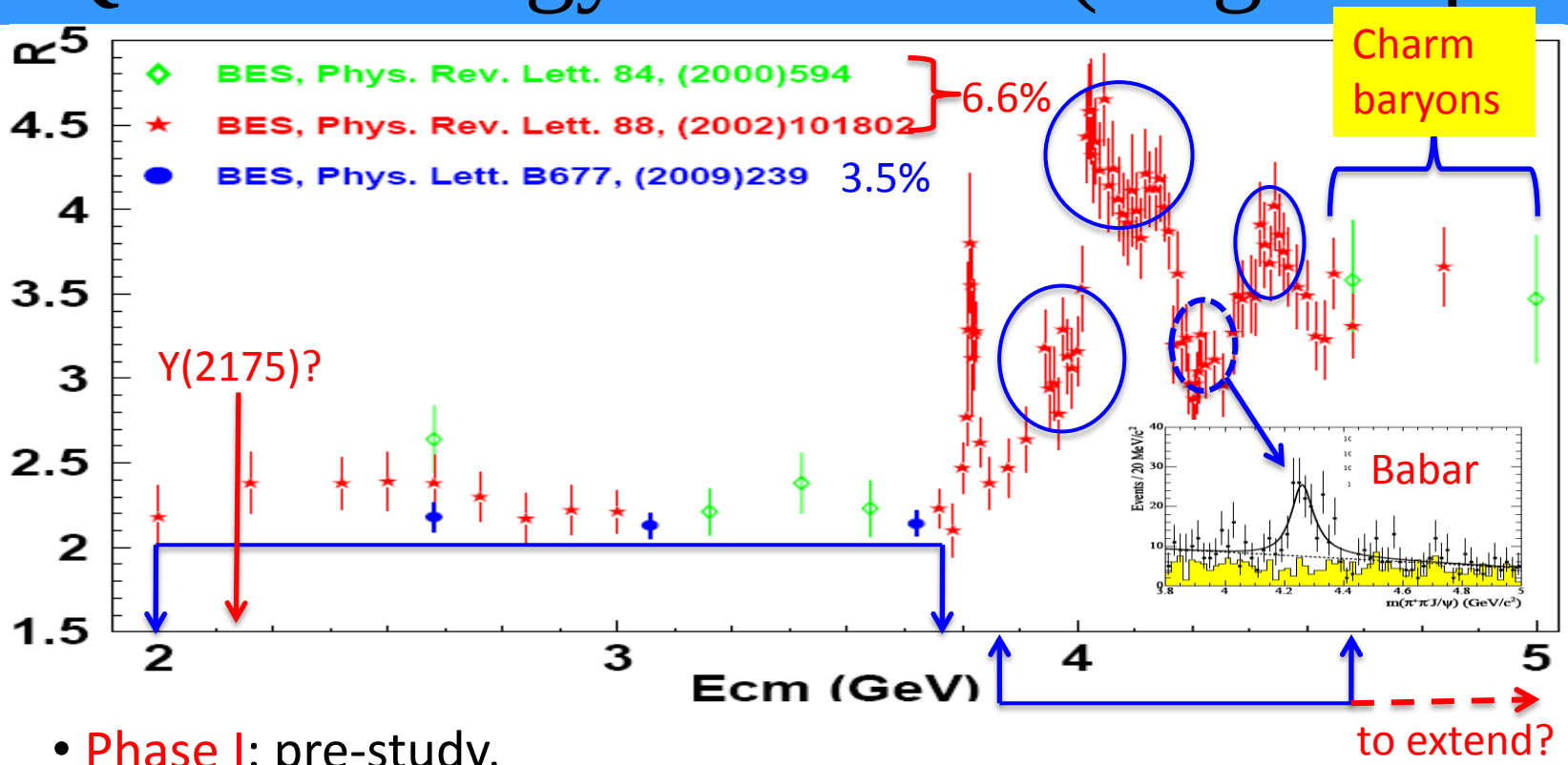
8 - 9 layers RPC

δR=1.4 cm~1.7 cm

EMC: $\sigma E/\sqrt{E}$($^0/_0$) = 2.5 % (1 GeV)

(CsI) $\sigma_{z,\phi}$(cm) = 0.5 - 0.7 cm/$\sqrt{E}$

R-QCD Strategy at BESIII (original plan)



- Phase I: pre-study,
  Machine study at 2.0, 2.5 and 4.2(4.6) GeV, MC tuning, …
- Phase II: scan continuum region,
  15 points in 2.0–3.6 GeV, step 100 MeV, 100k+ hadrons<3 GeV.
- Phase III: scan resonance region,
  ~100 points in 3.8–4.6 GeV, 100k events, step 2, 5,10, 20 MeV.
  (10^8 hadrons at 4040, 4160, 4415 for radiative decay search?)

Measurement of R Values

$$R = \frac{1}{\sigma_{\mu+\mu-}} \cdot \frac{N_{had} - N_{bg}}{L \cdot \varepsilon_{had} \cdot (1+\delta)}$$

N_{had}: observed hadronic events

N_{bg}: background events

L: integrated luminosity

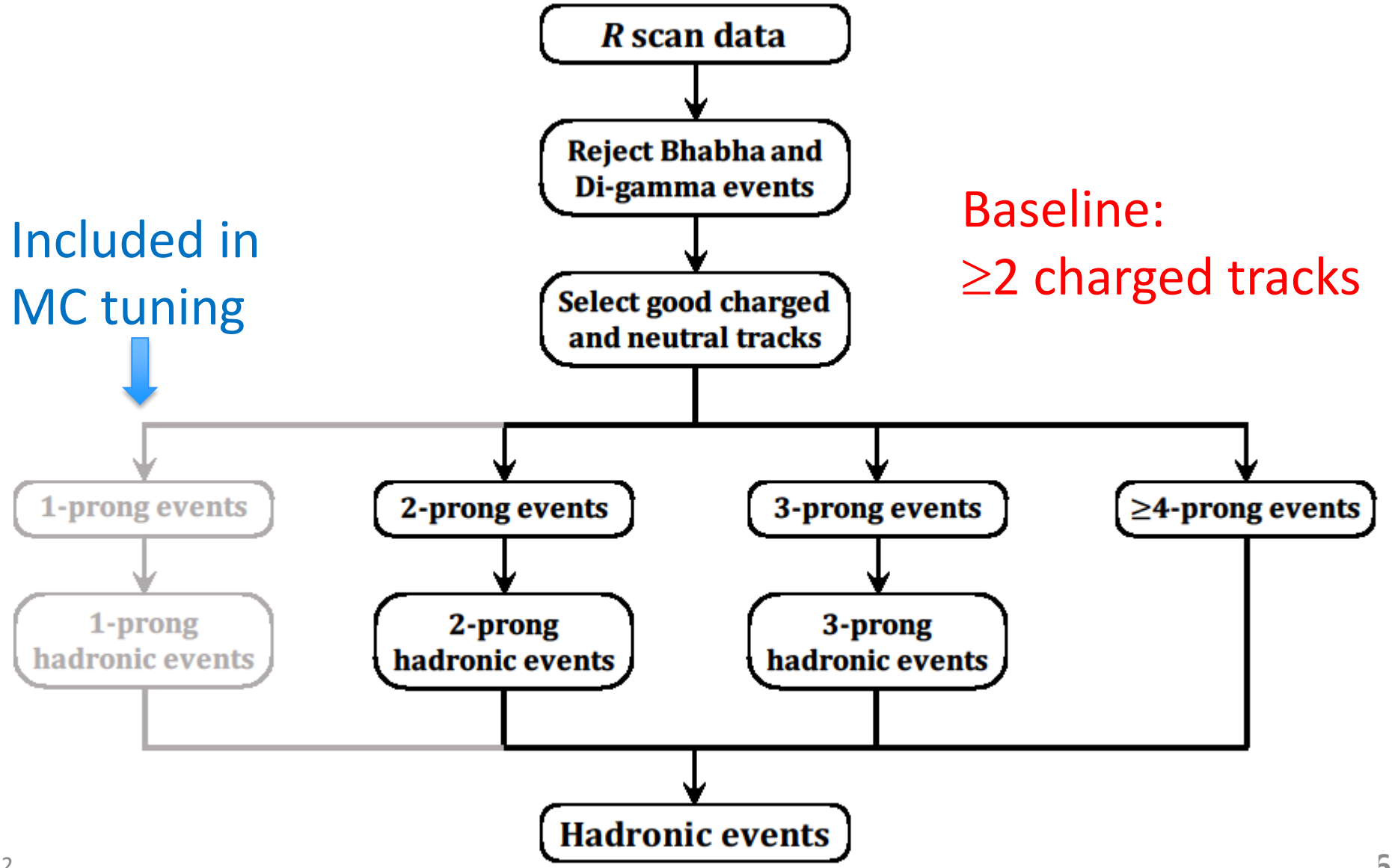
ε_{had}: detection efficiency for N_{had}

δ: radiative correction factor

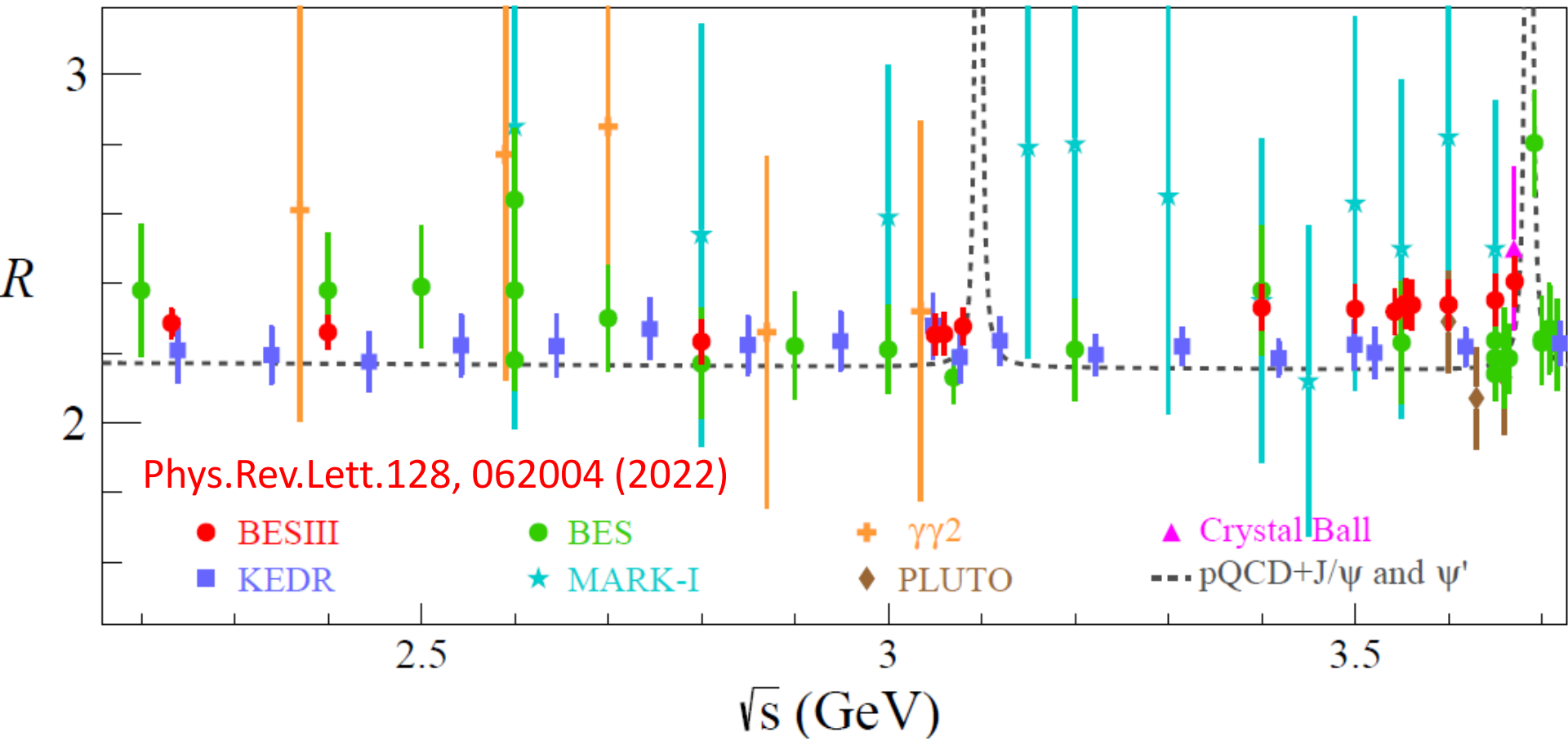
$\sigma_{\mu\mu}$: can be precisely calculated(QED). Measurement of R is to measure the total $\sigma(e^+e^- \rightarrow \text{hadrons})$

Except for controlling each item to the precision requested, stable long term machine and detector performance is crucial.

Strategy of hadron selection



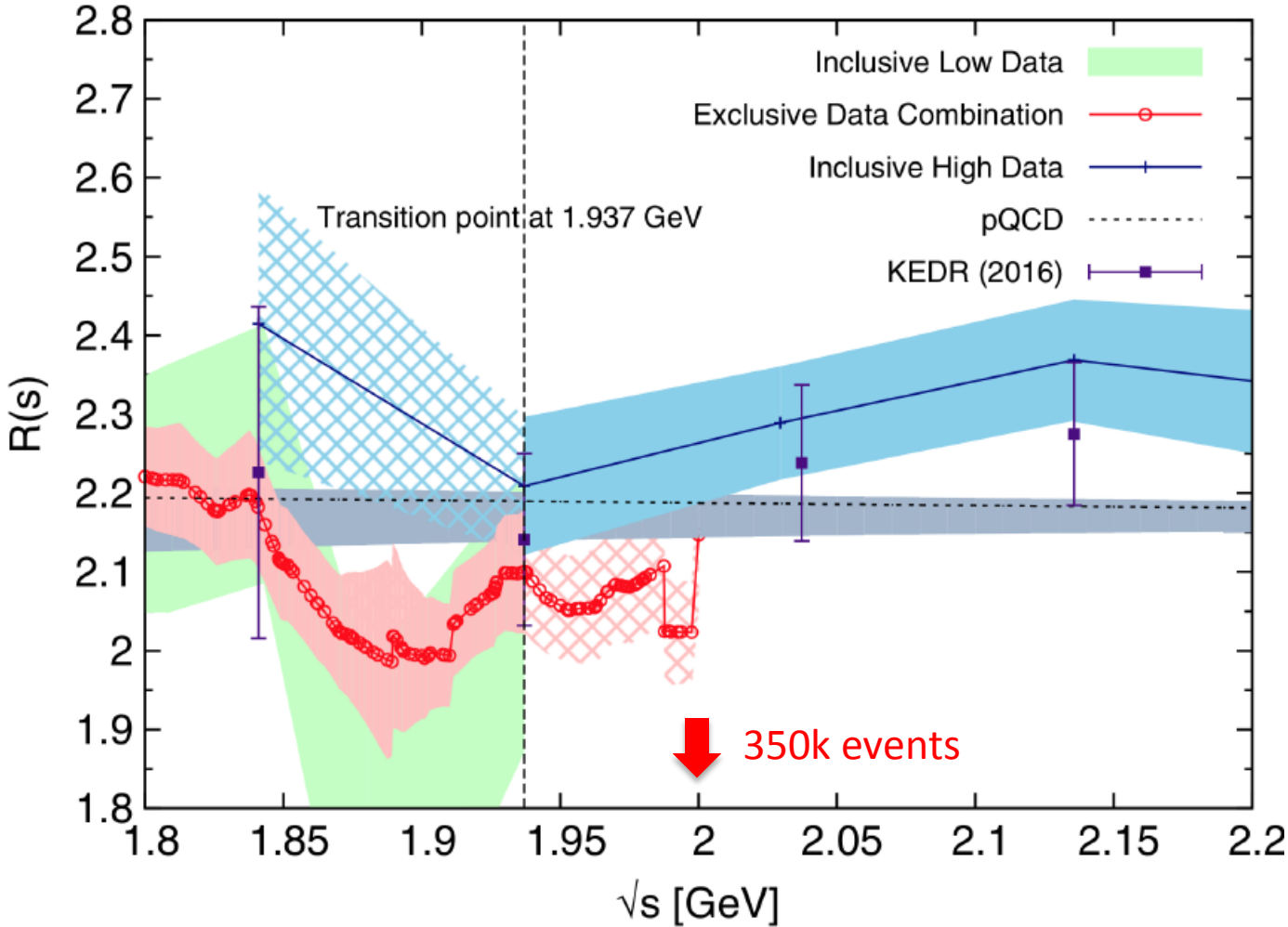
R value in [2.2324, 3.671] GeV



- Precision better than 3%;
- Larger than pQCD by 2.7σ in [3.4, 3.7] GeV.

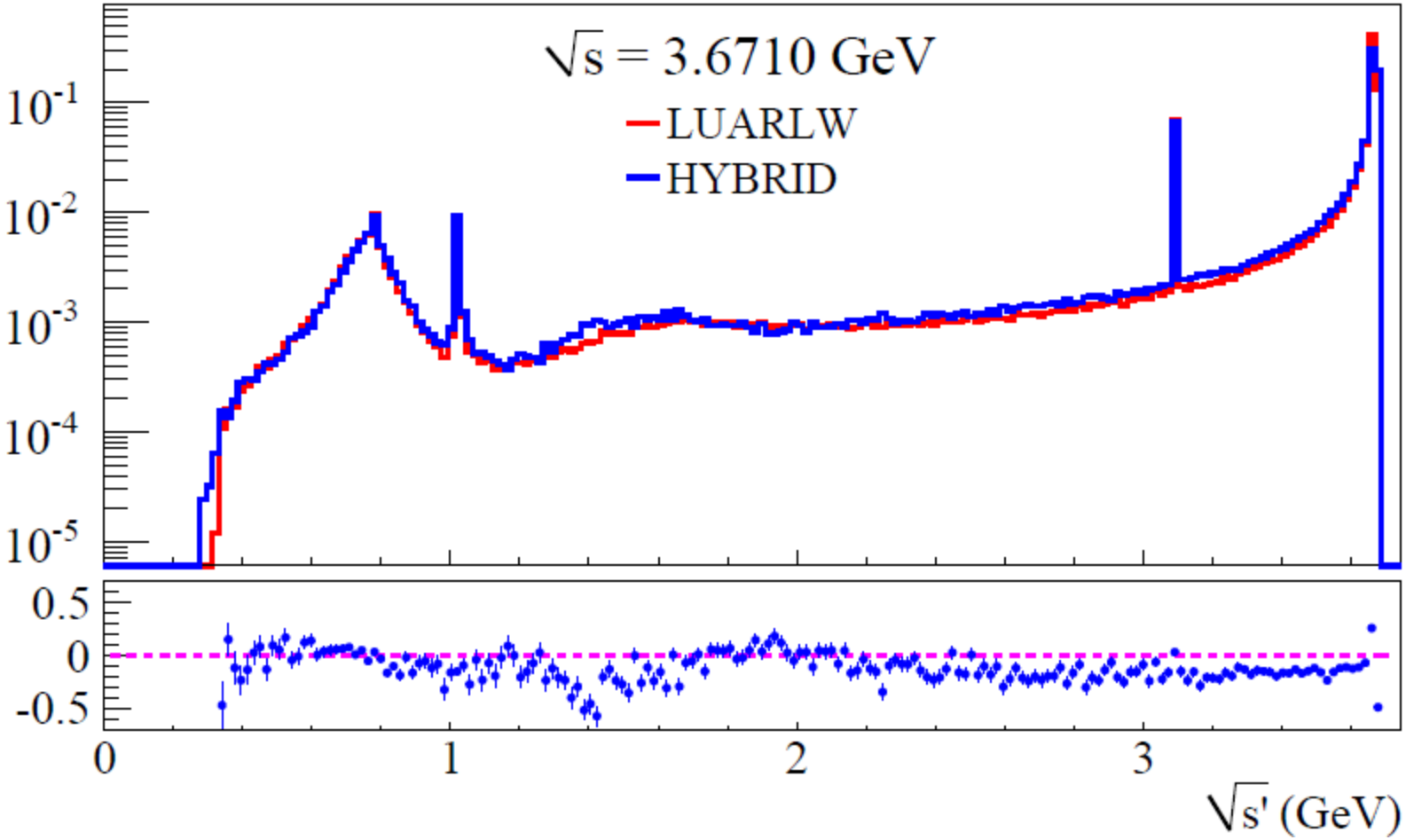
R: ongoing studies and prospects

- R value in the full energy range [2.0, 4.6] GeV;
- Comprehensive measurement at 2.0 GeV:



R: ongoing studies and prospects

- R via ISR technique down to $\pi^+\pi^-$ threshold!



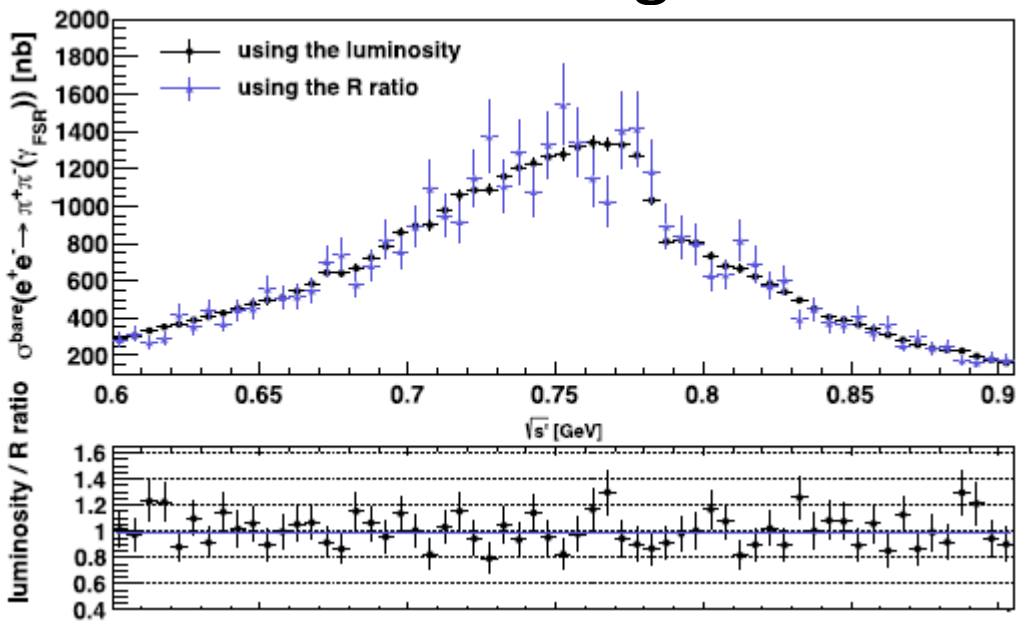
- To take data in [1.8, 2.0] GeV.

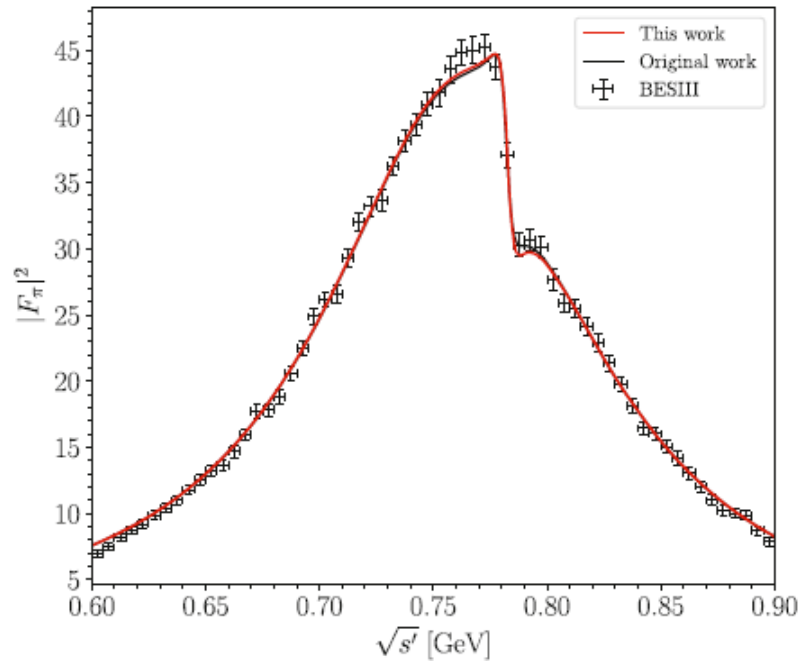
Meson cross section & form factor

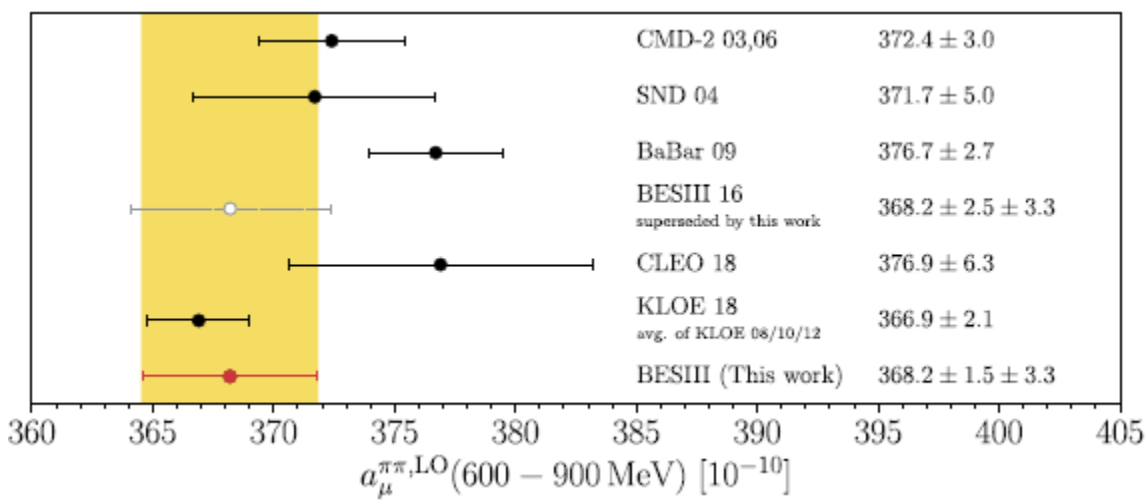
- Energy scan data in [2.0 - 3.08] GeV;
- With high-statistics data at higher energies, Initial State Radiation (ISR) technique allows access below 2.0 GeV;
- Lot of channels studied: $e^+e^- \rightarrow \pi^+\pi^-$, $\pi^+\pi^-\pi^0$, $\omega\pi^0/\eta$, $\eta'\pi^+\pi^-$, $\omega\pi^+\pi^-$, $\omega\pi^0\pi^0$, $\gamma\eta$, $\omega\eta'$, K^+K^-, K_SK_L, $2(K^+K^-)$, $\phi\pi^+\pi^-$, $\phi\pi^0$, $\phi\eta/\eta'$, ωK^+K^-, ...

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

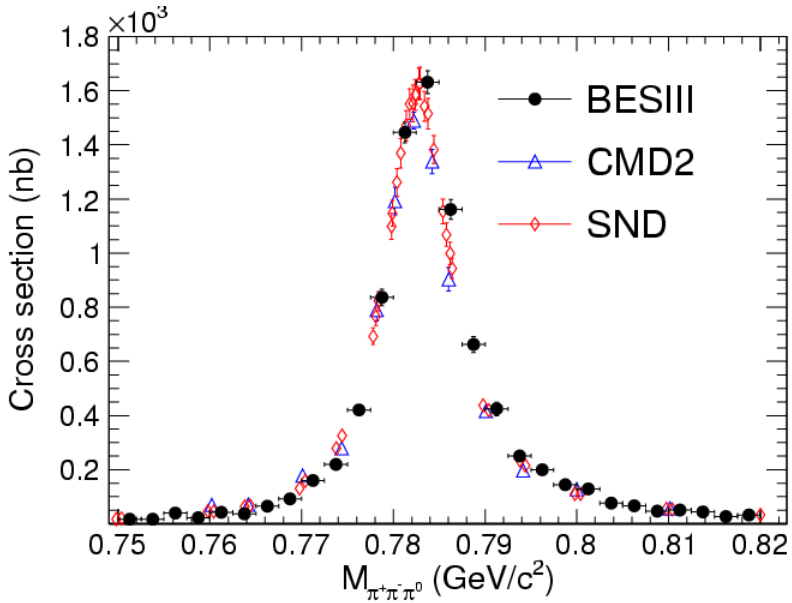
- PLB 753, 629 (2016); Erratum: 812, 135982 (2021).
- New effort to go > 1GeV.

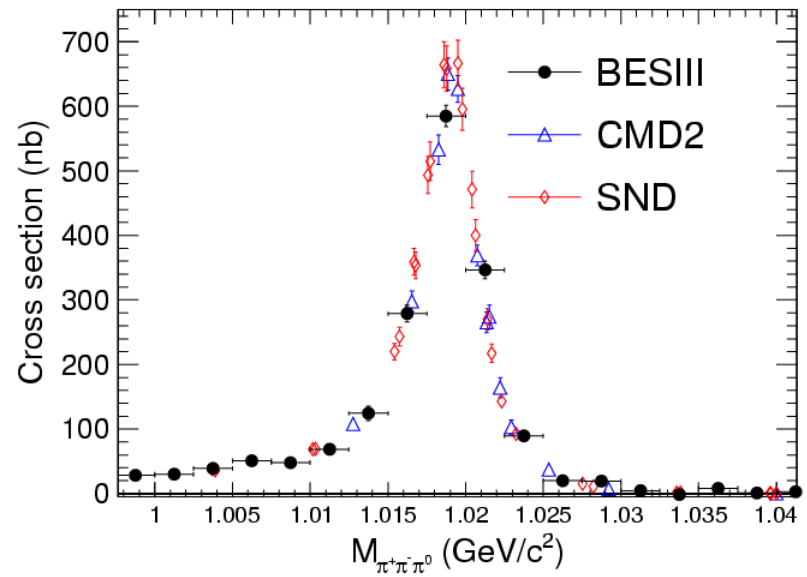


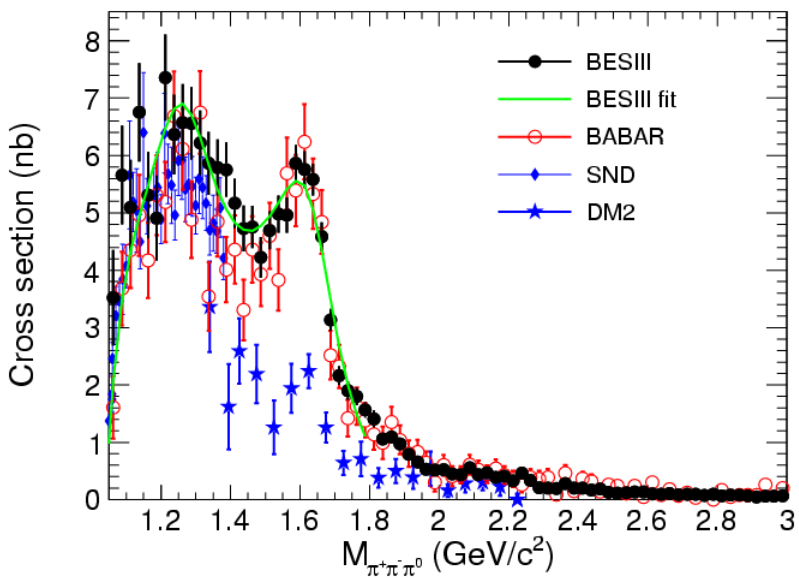




ISR $e^+e^- \to \pi^+\pi^-\pi^0$



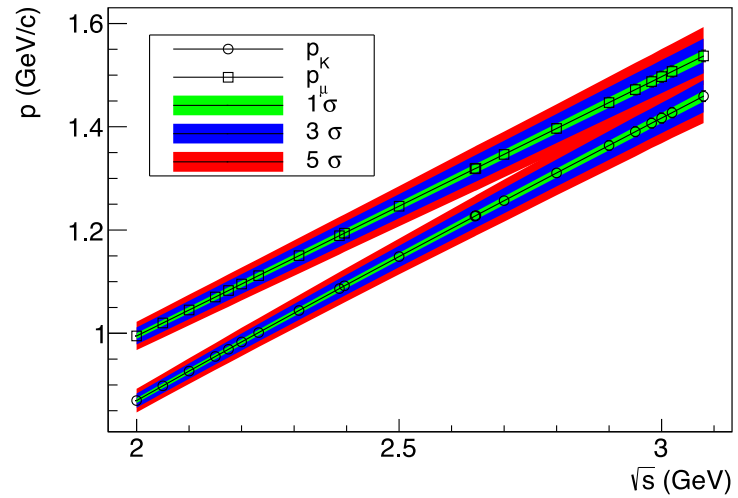


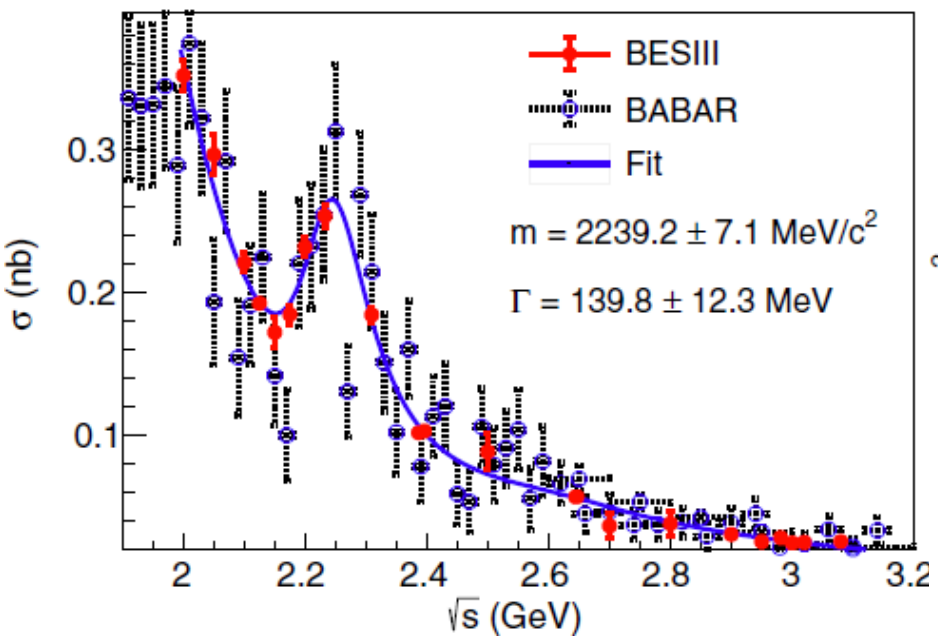


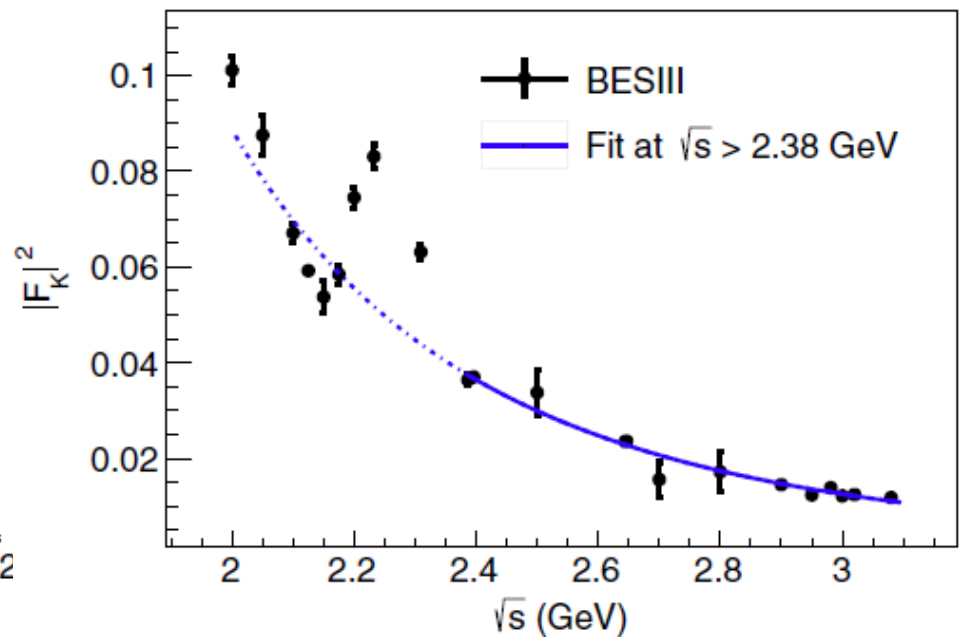
- Tagged & untagged analyses;
- 0.7 ~ 3.0 GeV, 1st result from a single experiment;
- arXiv:1912.11208.

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

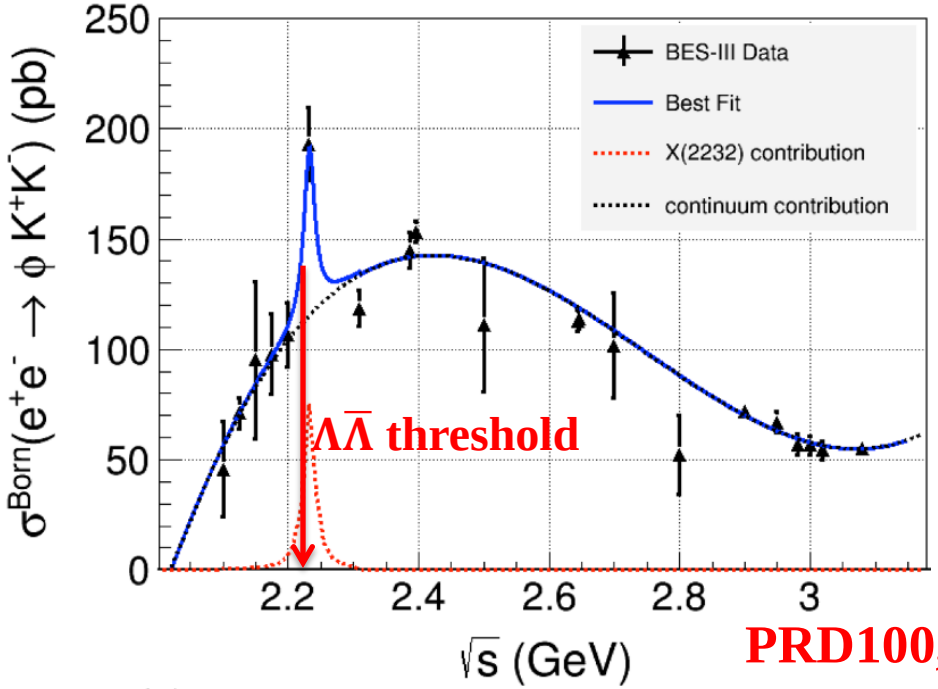
- Signal & background well separated;
- Much better precision than BaBar;
- Shape of FF agrees with pQCD 1/s;
- Unknown structure at 2.23 GeV;
- Phys. Rev. D 99, 032001 (2019).

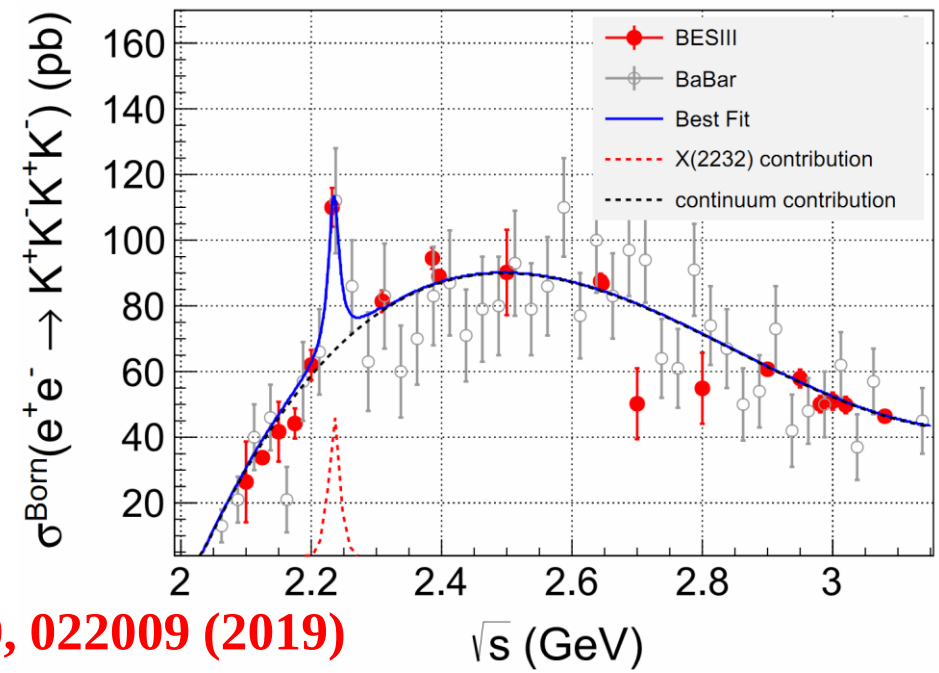




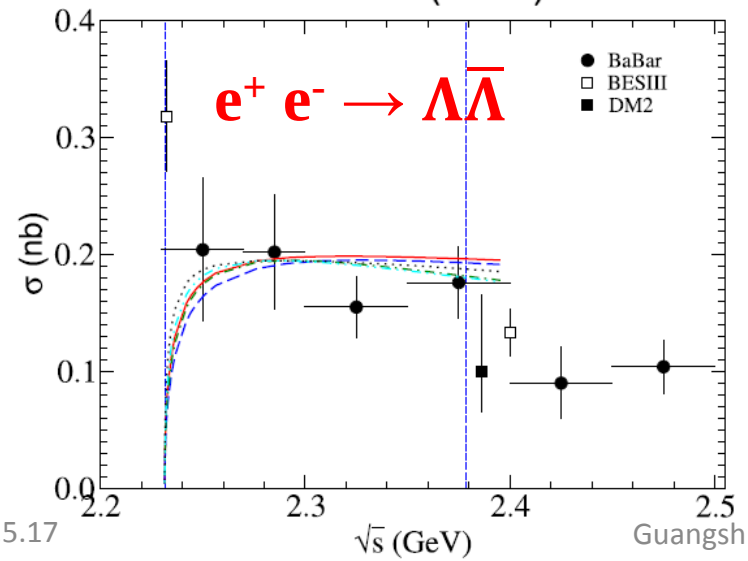


Scan $e^+ e^- \rightarrow 2(K^+ K^-)$





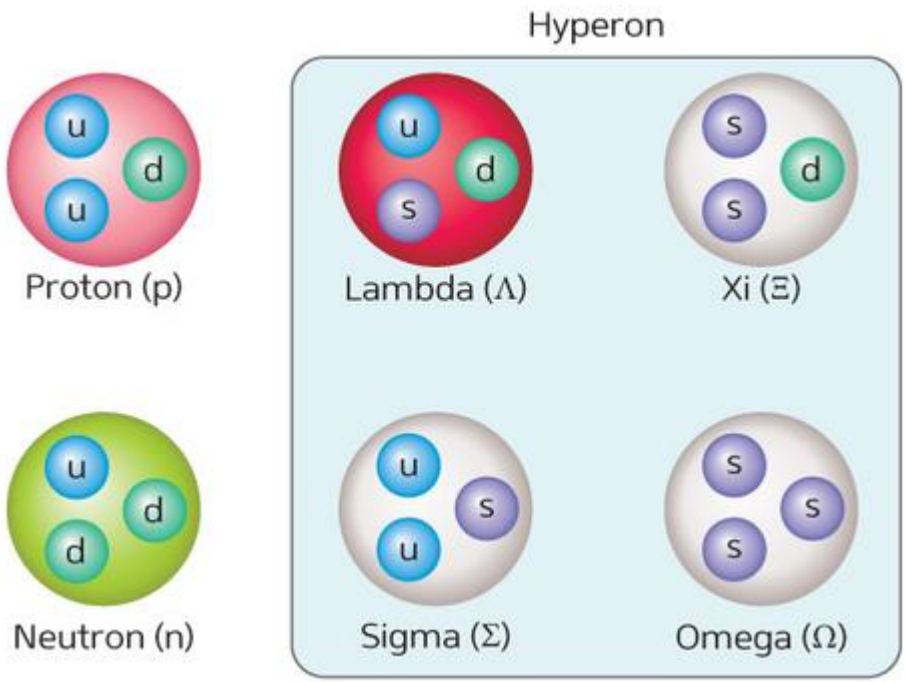
PRD100, 022009 (2019)

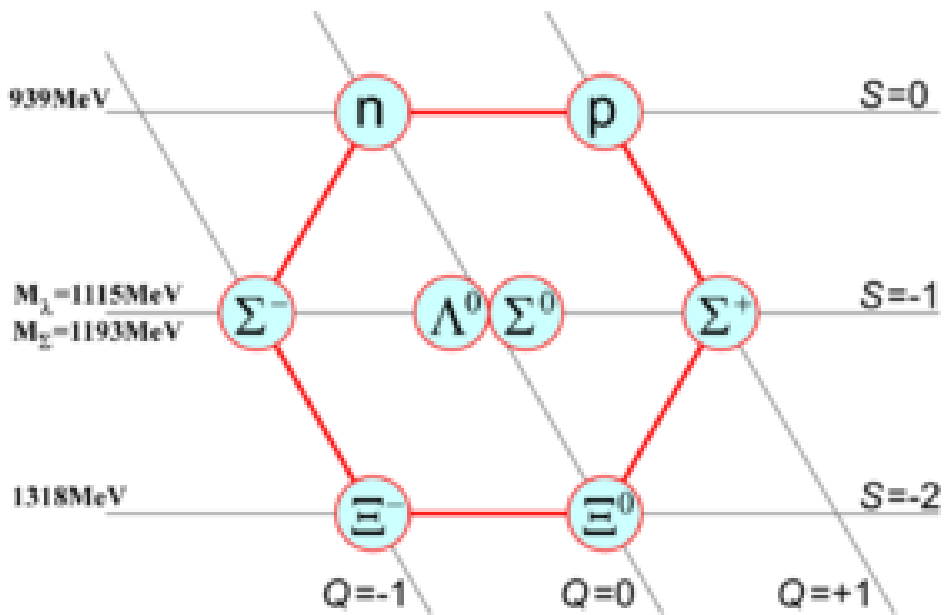


- **Both ϕK^+K^- and $2(K^+K^-)$ show similar enhancement around 2.2324 GeV;**
- **$\Lambda\bar{\Lambda}$ threshold effect?**
- **Any other explanations?**

Baryon form factor

- $p\bar{p}$: PRD 91, 112004 (2015); PRL 124, 042001 (2020);
- $n\bar{n}$: Nature Physics 17, 1200 (2021);
- $\Lambda\bar{\Lambda}$: Phys. Rev. D 97, 032013 (2018);
- $\Sigma^+\bar{\Sigma}^-/\Sigma^-\bar{\Sigma}^+$: Phys. Lett. B814, 136110 (2021);
- $\Sigma^0\bar{\Sigma}^0$: Phys. Lett. B (accepted);
- $\Xi^-\bar{\Xi}^+$: Phys. Rev. D103, 012005 (2021);
- $\Xi^0\bar{\Xi}^0$: Phys. Lett. B820, 136557 (2021). → ½$^+$ octet all covered!





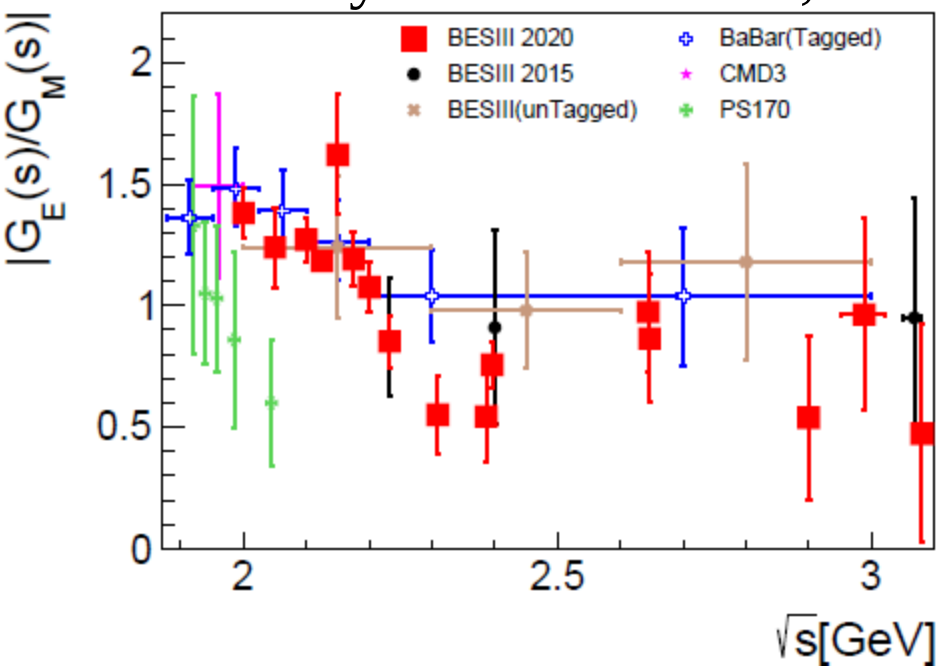
$\Omega^-\bar{\Omega}^+$, $\Lambda_c^+\bar{\Lambda}_c^-$ as well

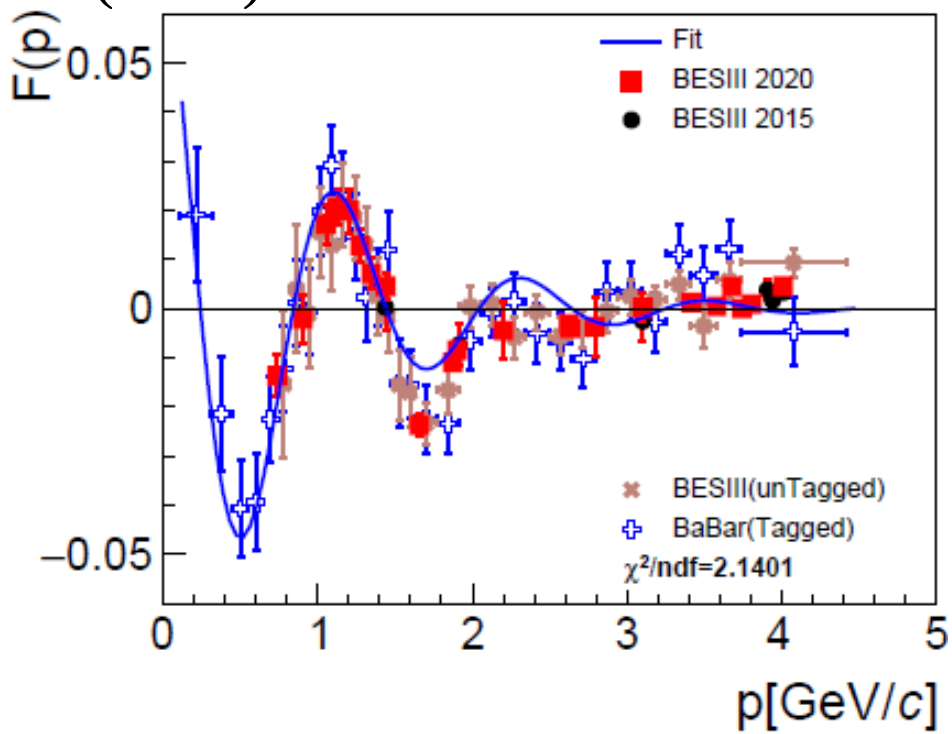
Spin $\frac{1}{2}^+$ SU(3) octet

Proton form factors

- Oscillation seen in the effective form factor $F^{osc}(p)=|G_{eff}|-F^0$ (F^0: regular shape)

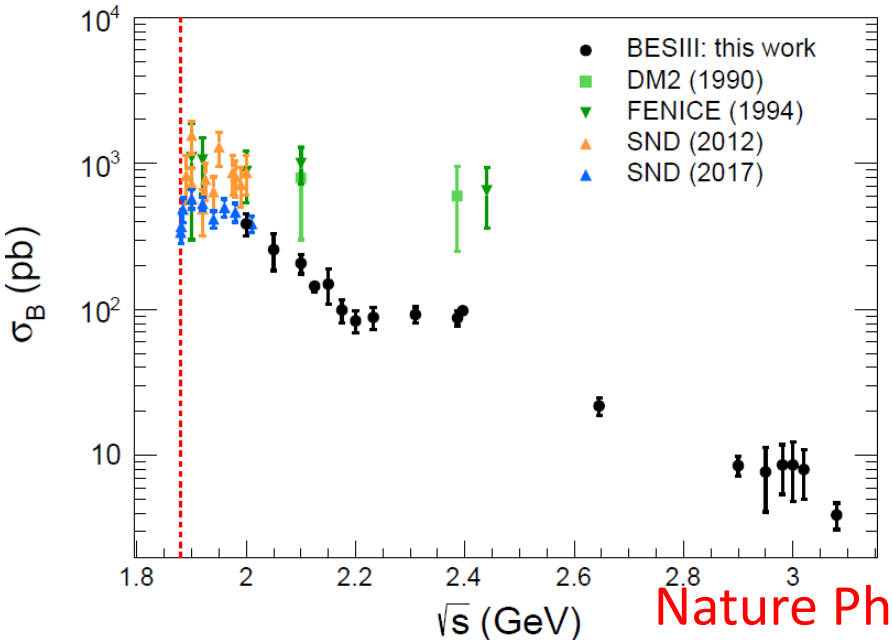
Phys. Rev. Lett. 124, 042001 (2020)

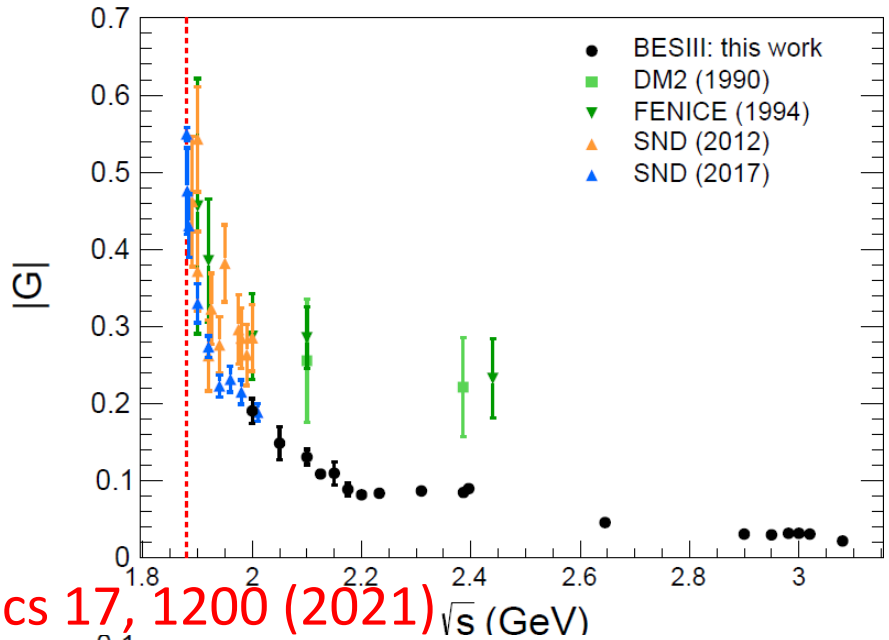




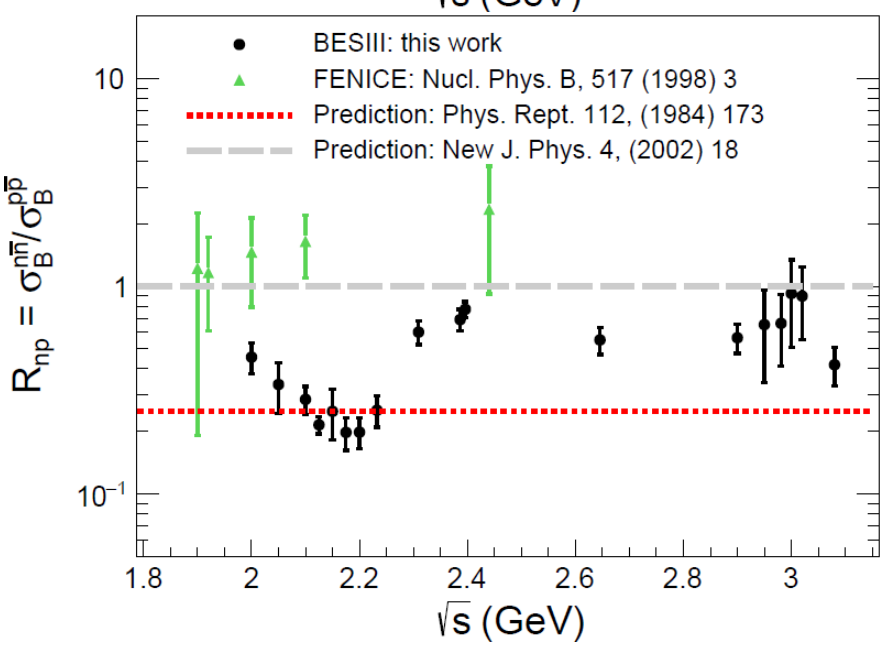
p is the 3-momentum of proton in the frame of anti-proton. Re-scattering effect?

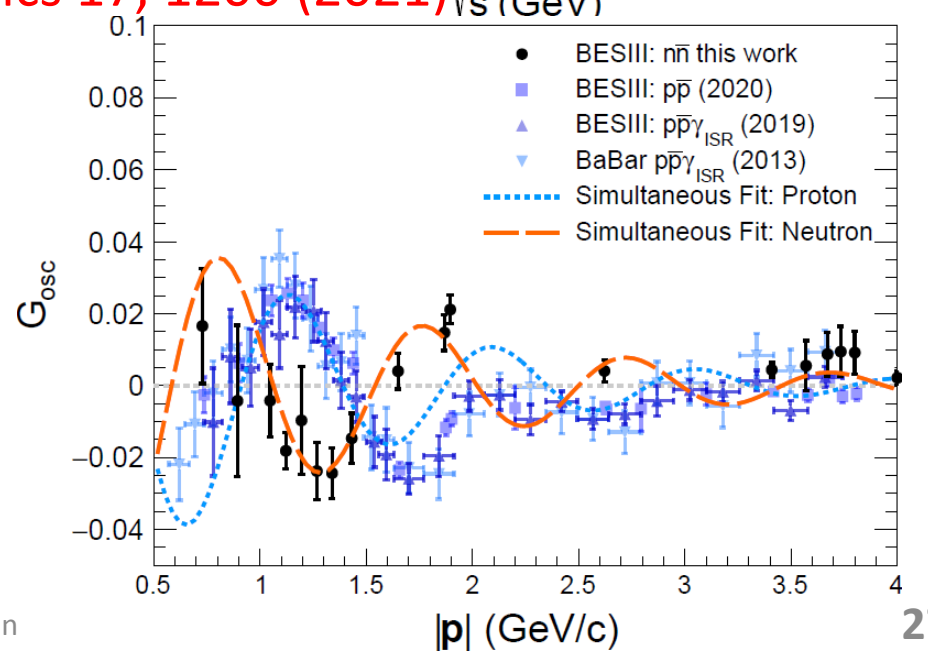
Neutron form factors





Nature Physics 17, 1200 (2021)





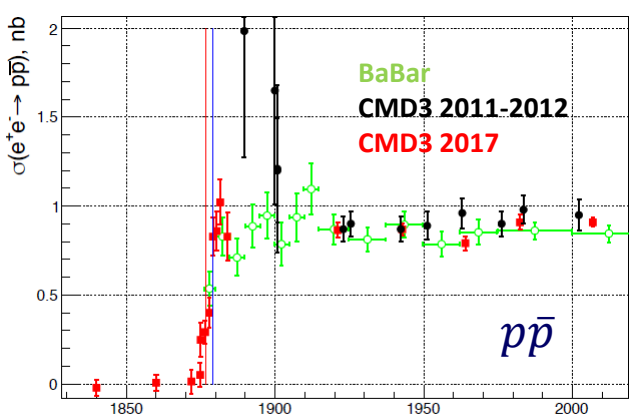
Baryon-pair production near threshold

$\bar{p}p$,	$\bar{\Lambda}\Lambda$,	$\bar{\Sigma}^-\Sigma^+$,	$\bar{\Sigma}^0\Sigma^0$,	$\bar{\Sigma}^-\Sigma^+$,	$\bar{\Xi}^0\Xi^0$,	$\bar{\Xi}^+\Xi^-$,	$\bar{\Omega}^+\Omega^-$,	$\bar{\Lambda}_c^-\Lambda_c^+$
	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$
	$p\pi^-$	$p\pi^0$	$\Lambda\gamma$	$n\pi$	$\Lambda\pi^0$	$\Lambda\pi$	ΛK	$\Lambda\pi$
	64%	52%	$\approx 100\%$	$\approx 100\%$	$\approx 100\%$	$\approx 100\%$	68%	$\approx 1\%$

$e^+e^- \to \gamma^* \to B\bar{B}$ production cross section:

$$\sigma_{B\bar{B}}(m) = \frac{4\pi\alpha^2 C\beta}{3m^2}\left[|G_M(m)|^2 + \frac{1}{2\tau}|G_E(m)|^2\right]$$

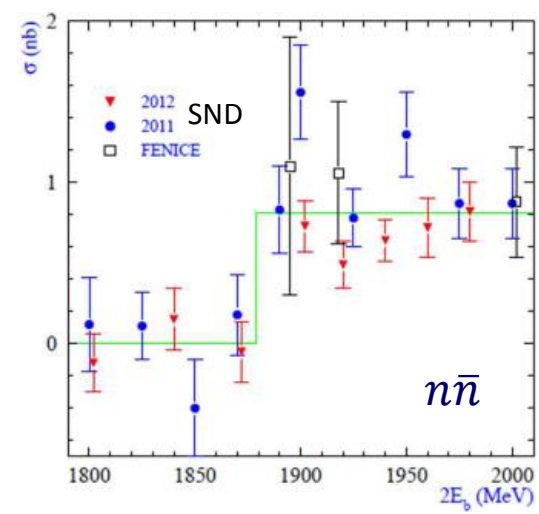
Coulomb factor $C = \begin{cases} \frac{\pi\alpha}{\beta}\frac{1}{1-\exp(-\frac{\pi\alpha}{\beta})}, & \text{for charged } B\bar{B} \\ 1, & \text{for neutral } B\bar{B} \end{cases}$



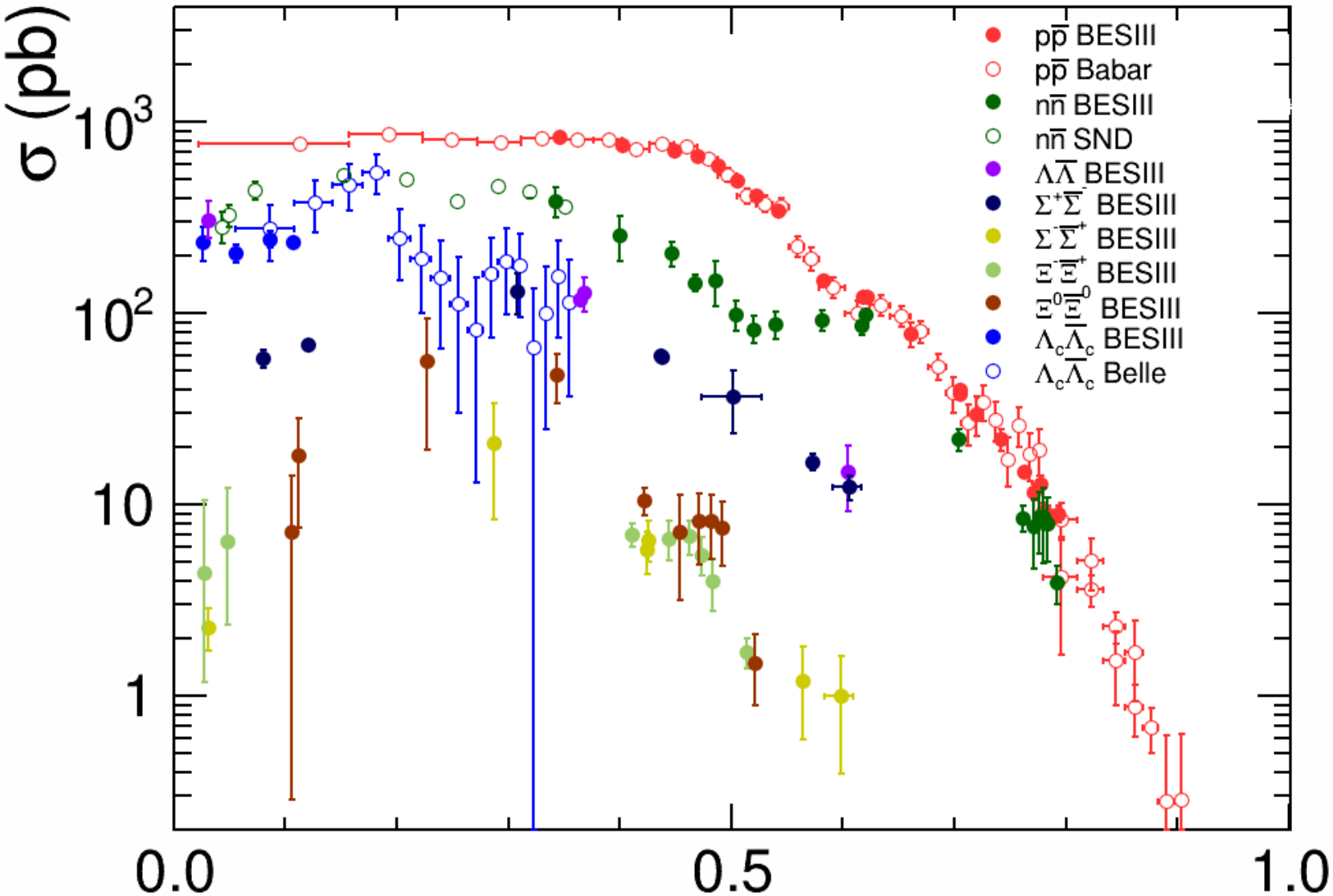
$p\bar{p}$、$n\bar{n}$ should be different, but poor precision for latter.

How about other baryon-pairs?

0 expected at threshold!



Baryon-pair production in a glance



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$$\beta=\sqrt{1-4M_B^2/s}$$

Summary

- High-quality data for R-QCD at BESIII in 2.0–4.6 GeV: 1.5 fb^{-1}
- BESIII First R values with uncertainties <3% at 14 energies in [2.2324, 3.671] GeV published;
- Meson cross sections measured for precision test;
- Form factors measured and threshold production behavior studied for various baryons;
- Prospects at a future super τ-c factory:
  - Inclusive R: ~2% (generator model, radiative correction);
  - Exclusive measurements down to meson production threshold;
  - Insight into structure of hadrons.