Measurements of the R value at BESIII

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Definition of R value

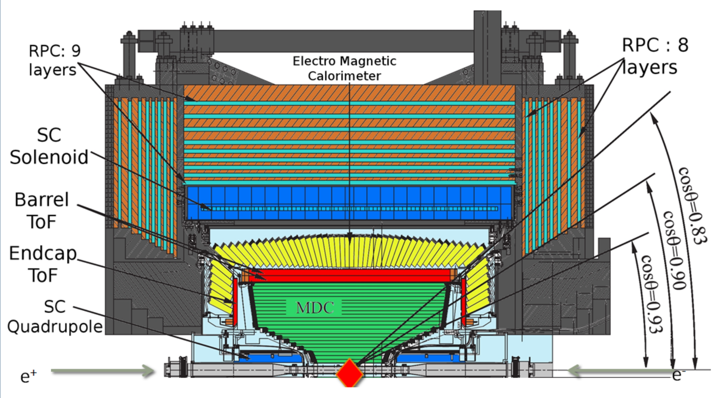
The $\boldsymbol{R}$ value is defined as the leading-order production cross section ratio of hadronic events and muon pairs in the e^+e^- annihilation:

$$\boldsymbol{R} \equiv \frac{\sigma^0(e^+e^- \to \text{hadrons})}{\sigma^0(e^+e^- \to \mu^+\mu^-)} \equiv \frac{\sigma^0_{\text{had}}}{\sigma^0_{\mu\mu}}$$

$$\sigma^0_{\mu\mu}(s) = \frac{4\pi\alpha^2}{3s}\frac{\beta_\mu(3-\beta_\mu^2)}{2}, \text{ with } \beta_\mu = \sqrt{1-4m_\mu^2/s}$$

Measurement of $\boldsymbol{R}$ value $\Longleftrightarrow$ Measurement of total cross section of hadron production

BEijing Spectrometer III (BESIII) at BEPCII



- MDC: Main Drift Chamber
- TOF: Time of Flight
- EMC: ElectroMagnetic Calorimeter
- SC: SuperConducting Magnet
- RPC: Muon Counter: Resistive Plate Chambers

Importance of R value

Anomalous magnetic moment of muon $g_\mu - 2$

$$a_l^{\text{SM}} = a_l^{\text{QED}} + a_l^{\text{weak}} + a_l^{\text{had}}$$

$$a_\mu^{\text{had, LO v.p.}} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^{\infty} ds \frac{K(s)}{s^2} R(s)$$

Source (α_μ)	Contribution ($\times 10^{-11}$)
QED	116584718.931 ± 0.104
Weak	153.6 ± 1.0
had,LO, (R-ratio)[1]	6931 ± 40
had,LO, (lattice)[2]	7075 ± 55
had,NLO	-98.3 ± 0.7
had,NNLO	12.4 ± 0.1
had,l-l	92 ± 18

[1] [Phys. Rep. 887, 1 (2020)]
[2] [Nature (London) 593, 51 (2021)]

Determination of running coupling constant of QED

$$\Delta\alpha(s) = \Delta\alpha_{\text{lepton}}(s) + \Delta\alpha_{\text{top}}(s) + \Delta\alpha^{(5)}_{\text{had}}(s)$$

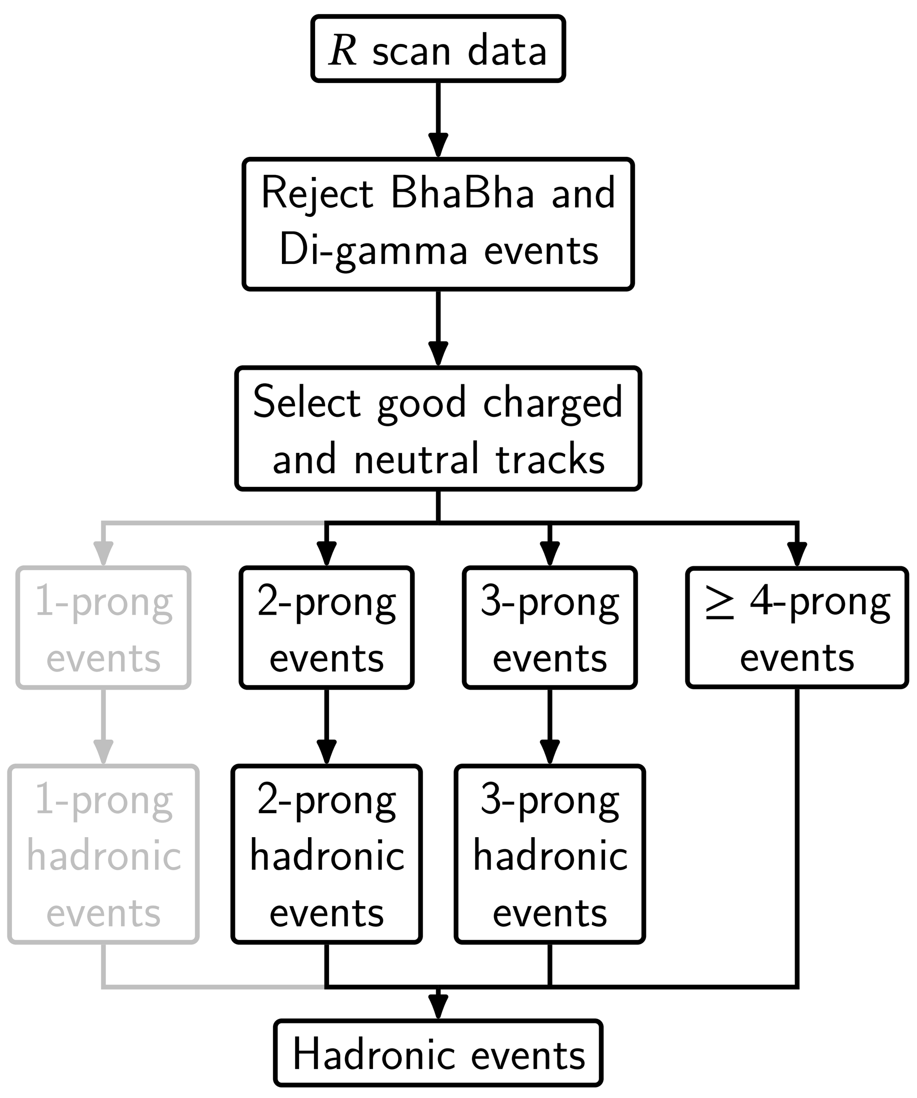
$$\Delta\alpha^{(5)}_{\text{had}}(s) = -\frac{\alpha s}{3\pi} Re \int_{4m_\pi^2}^{\infty} ds' \frac{R(s')}{s'(s'-s-i\epsilon)}$$

Source ($\Delta\alpha(M_Z^2)$)	Contribution ($\times 10^{-4}$)
Lepton	314.979 ± 0.002
Top	-0.7180 ± 0.0054
had$^{(5)}$[1]	276.1 ± 1.1

[1] [Phys. Rep. 887, 1 (2020)]

Signal Estimation

Selection of inclusive hadronic events



Determination of R value in experiment

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

- $N^{\text{obs}}_{\text{had}}$: Numbers of observed hadronic events
- N_{bkg}: Number of the residual background events
- $\sigma^0_{\mu\mu}(s)$: Leading order QED cross section for $e^+e^- \to \mu^+\mu^-$
- $\mathcal{L}_{\text{int}}$: Integrated luminosity measured by analyzing Bhabha events
- $\varepsilon_{\text{trig}}$: Trigger efficiency $\sim 100\%$
- ε_{had}: Detection efficiency of the hadronic events
- $1+\delta$: ISR correction factor

Systematic Uncertainty

- Uncertainty like Event selection, Background estimation, Signal simulation also included

$$\left(\frac{\Delta R}{R}\right)^2_{\text{sys}} = \left(\frac{\Delta\tilde{N}}{\tilde{N}}\right)^2 + \left(\frac{\Delta\mathcal{L}_{\text{int.}}}{\mathcal{L}_{\text{int.}}}\right)^2 + \left(\frac{\Delta\varepsilon_{\text{had}}}{\varepsilon_{\text{had}}}\right)^2 + \left(\frac{\Delta\varepsilon_{\text{trig}}}{\varepsilon_{\text{trig}}}\right)^2 + \left(\frac{\Delta(1+\delta)}{(1+\delta)}\right)^2$$

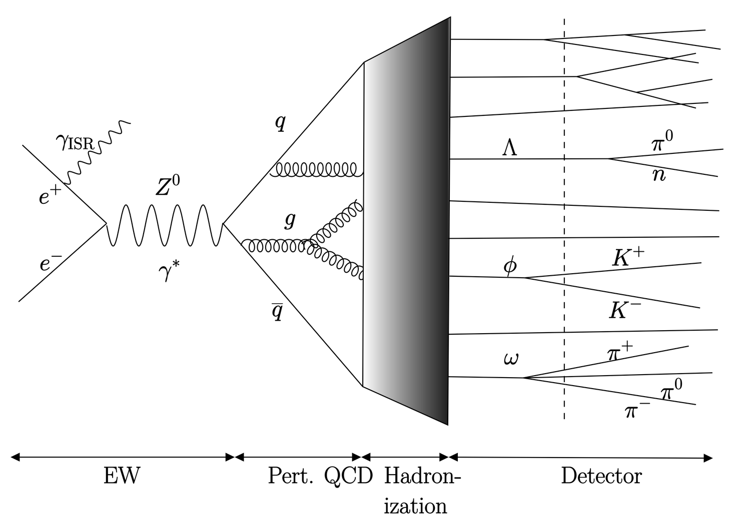
Main background process to the signal

- Bhabha $e^+e^- \to (\gamma)e^+e^-$
  - Two back-to-back charged tracks and energetic associated showers
  - No or less than one isolated photon
- Di-gamma $e^+e^- \to \gamma\gamma$
  - Two back-to-back energetic showers
  - No charged tracks
- Di-muon $e^+e^- \to \mu^+\mu^-$
  - Two back-to-back charged tracks with high momentum
  - No isolated photon
- Di-tau $e^+e^- \to \tau^+\tau^-$
  - Emerging only above $\sqrt{s} = 3.554$ GeV
  - Difficult rejected but accurately simulated
- Two-photon processes $e^+e^- \to e^+e^- + X$
  - $X = e^+e^-, \mu^+\mu^-, \pi^+\pi^-, K^+K^-, \eta, \eta'$
  - Low acceptance in the BESIII detector
  - No isolated photon for the first four channels
- Beam-associated process
  - Vertices of charged trks away from the interaction point
  - No or less than one isolated photon

Monte Carlo Simulation

Signal simulation: LUARLW model

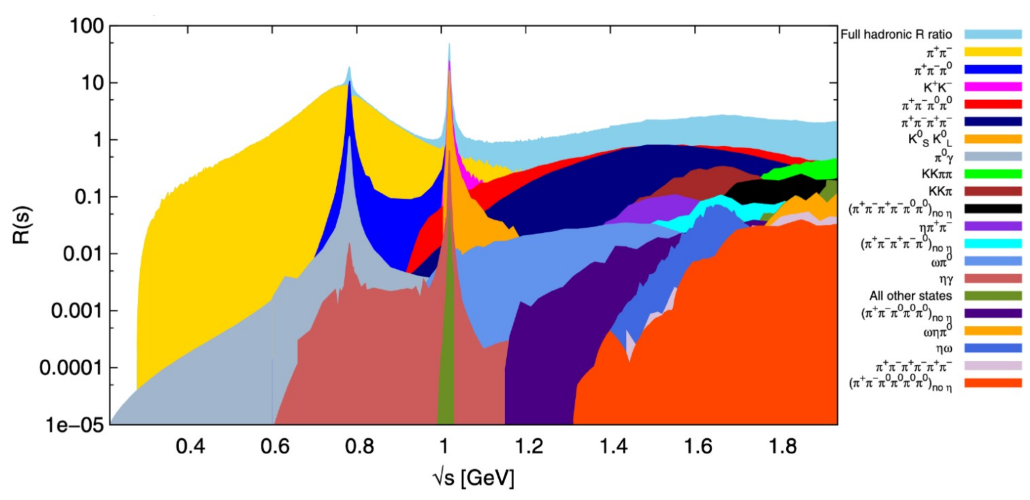
[arXiv:hep-ph/9910285]



- Kinematic quantities of initial hadrons sampled by the Lund area law
- Initial-state radiation (ISR) implemented from $2m_\pi$ to $\sqrt{s}$

HYBRID model as an alternative generator

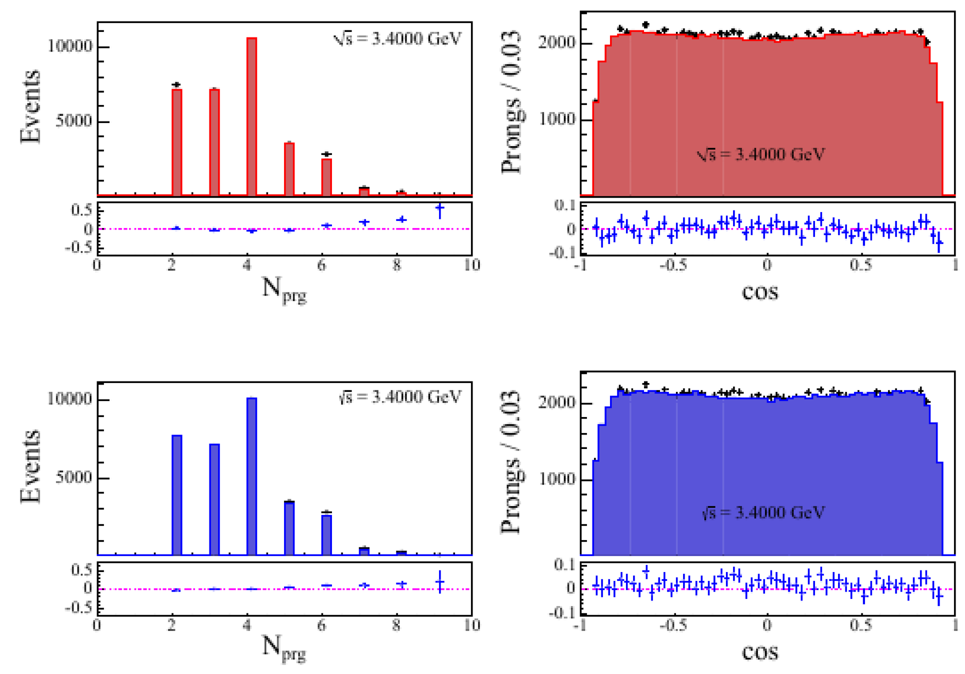
[Phys. Rev. D 97, 114025 (2018)]



- Hybrid with combination: CONEXEC, PHOKHARA, and LUARLW
- As much as experimental knowledges used in CONEXEC
- Different ISR and VP correction schemes

Monte Carlo vs Data @ 3.4 GeV

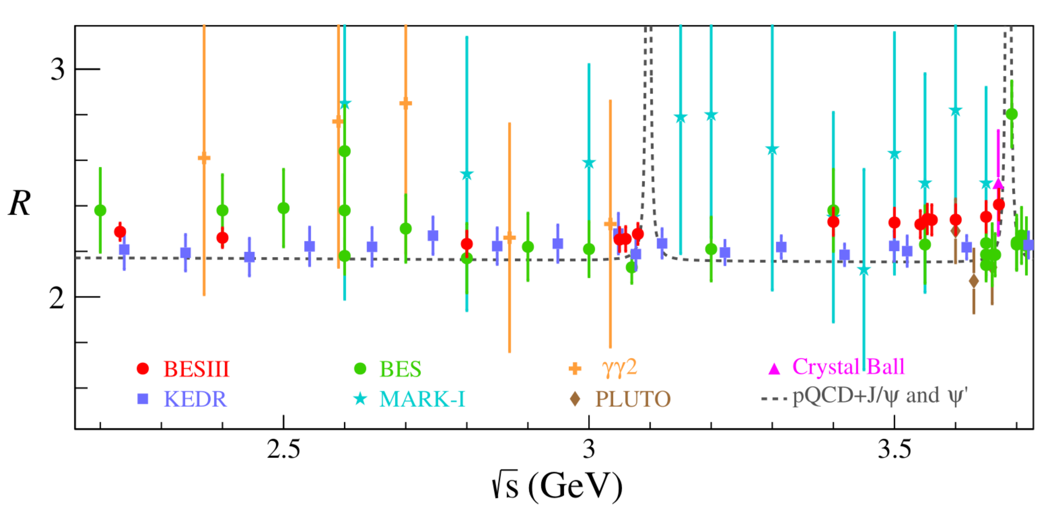
- Both LUARLW and HYBRID give good consistency
  - N_{prg}: number of good charged tracks (prong)
  - $\cos\theta$: polar angle of each prong



Summary

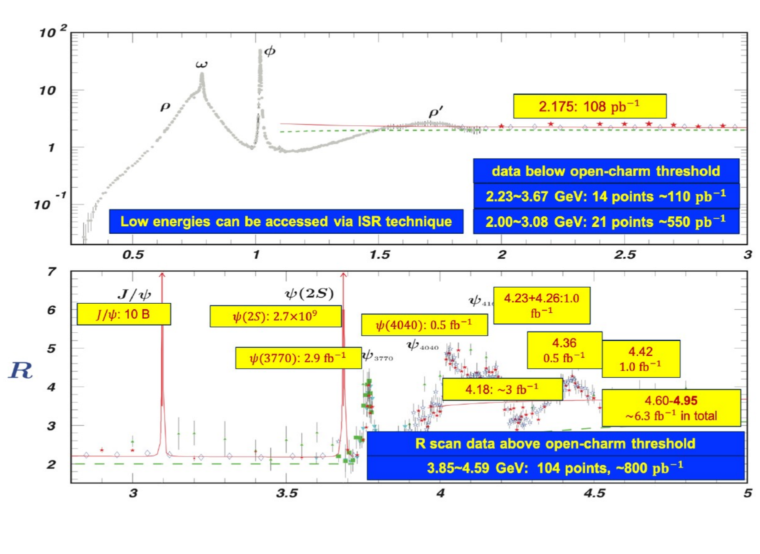
R value measurement at BESIII

- Precision better than 2.6% below 3.1 GeV and 3.0% above [Phys. Rev. Lett. 128, 062004 (2022)]



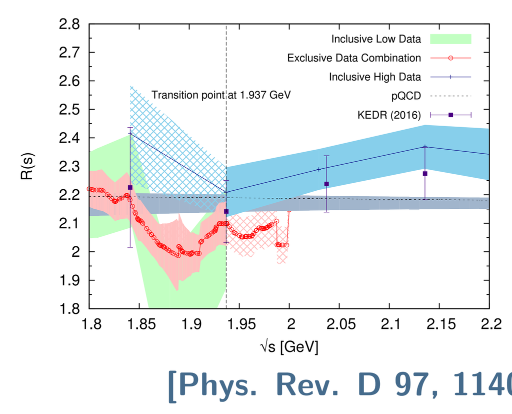
Outlook

Large statistics available



- BESIII has collected data from 2.00 to 4.95 GeV for R measurement

Exploring different methods



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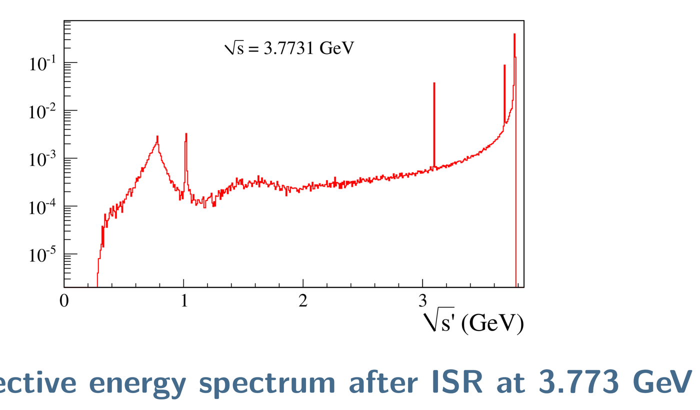

Effective energy spectrum after ISR at 3.773 GeV

- R measurement via exclusive method gives a check on the tension between inclusive R and exclusive R measurement at or below 2.0 GeV
- R measurement via ISR technique exploits large $\psi(3770)$ data and allows measurement from $\pi^+\pi^-$ threshold to continuum region