Measurement of R Value at BESIII

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August 22, 2022 - 兰州 - BESIII 实验上粲强子、QCD 及新物理研讨会

The Definition of R Value

The R is defined as the ratio of the leading-order production cross section ratio of hadron and muon pairs in e^+e^- collisions:

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

With $\sigma^0_{\mu\mu}$ directly from QED:

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

Muon anomalous a_μ^{SM} & running $\Delta\alpha(s)$

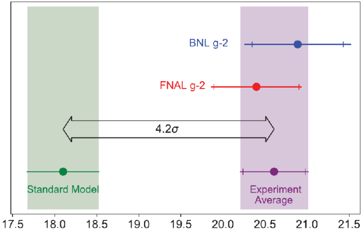
The Anomalous Magnetic Moment

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

- a_l^{QED} and a_l^{weak}: can be calculated precisely.
- $a_l^{\mathrm{had}} = a_l^{\text{had, LO v.p.}} + a_l^{\text{had, NLO v.p.}} + a_l^{\text{had, l-l}}$

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

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



Electromagnetic Running Coupling Constant of QED

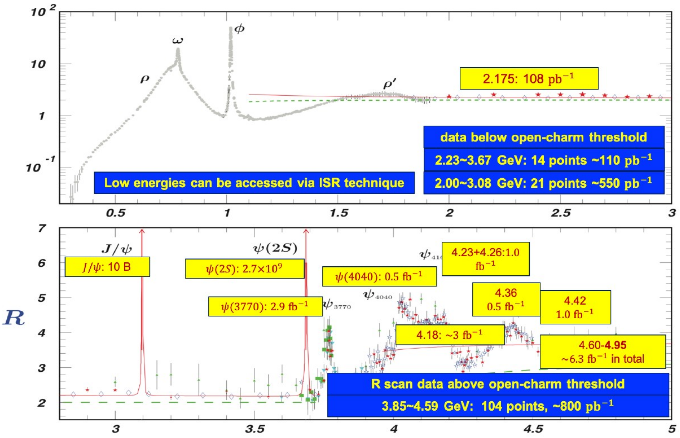
$$\Delta\alpha(s) = \Delta\alpha_{\mathrm{lepton}}(s) + \Delta\alpha_{\mathrm{top}}(s) + \Delta\alpha_{\mathrm{had}}^{(5)}(s)$$

- $\Delta\alpha_{\mathrm{lepton}}(s)$ can be calculated precisely using the pertubative theory.
- $\Delta\alpha_{\mathrm{top}}(s)$ is small ($10^{-7} \sim 10^{-10}$ for BESIII region), since the top quark is heavy.
- $\Delta\alpha_{\mathrm{had}}^{(5)}(s)$ should be calculated by using R value at low energy.

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

The R program at BESIII

- First data in 2012
  - 4 energy points, 2.2324 ~ 3.4 GeV
  - 10 more energy points in 2011 ~ 2013
  - 1.7 ~ 3.7 pb^{-1} luminosity
  - 30k ~ 100k hadronic events
- Second data in 2013 ~ 2014
  - 104 energy points, 3.85 ~ 4.60 GeV
  - 8 pb^{-1} luminosity
  - 150k hadronic events
- Third data in 2015
  - 21 energy points, 2.00 ~ 3.08 GeV
  - 1 ~ 100 pb^{-1} luminosity
  - 20k ~ 2000k hadronic events



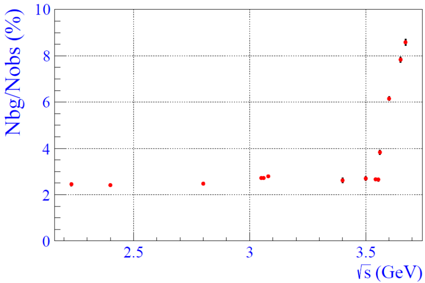
- Large amounts of data (139 energy points) already collected
- More data at the $\psi(3770)$ peak are on the way

Determination of R value in experiment

Inclusive method

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

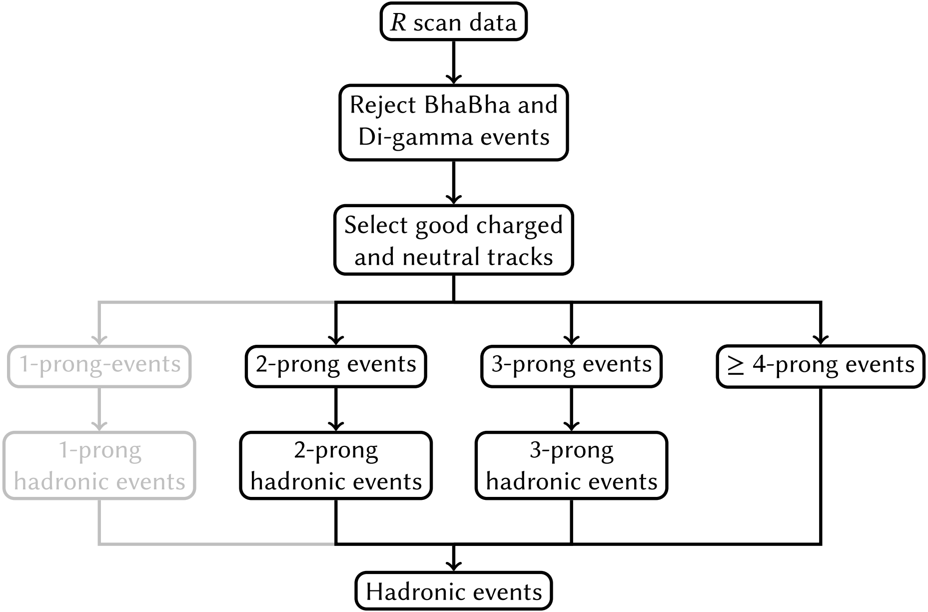
- $N_{\mathrm{had}}^{\mathrm{obs}}$: Numbers of observed hadronic events
- N_{bkg}: Number of the residual background events
- $\sigma_{\mu\mu}^{0}(s)$: Leading order QED cross section for $e^+e^- \to \mu^+\mu^-$
- $\mathcal{L}_{\mathrm{int}}$: Integrated luminosity measured by analyzing Bhabha events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



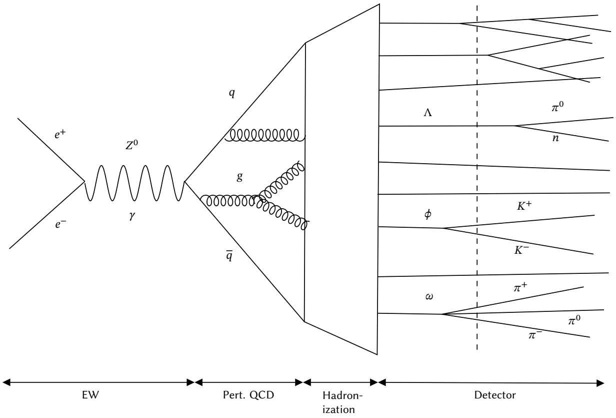
Exclusive method

$$R = \frac{\sigma^0(e^+e^- \to N\bar{N} + \mathrm{n}\pi + \mathrm{n}K + \mathrm{n}\pi\mathrm{m}K + \cdots)}{\sigma_{\mu\mu}^{0}}$$

Analysis strategy of inclusive method



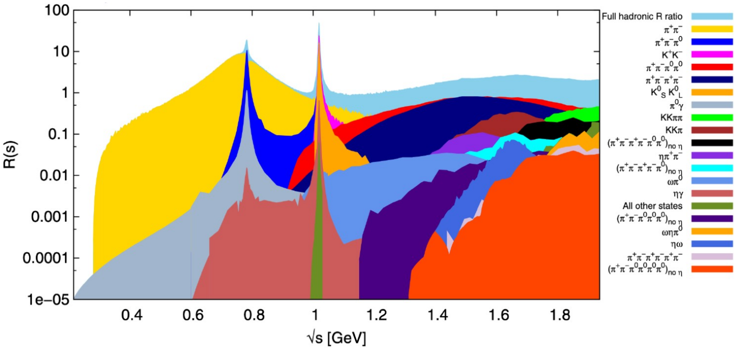
Nominal model for signal simulation: LUARLW



- A self-consistent inclusive generator developed based on **JETSET**
- **Initial-state radiation (ISR)** process implemented from $2m_\pi$ to $\sqrt{s}$
- Kinematic quantities of initial hadrons are sampled by the **Lund area law**
- Phenomenological parameters are tuned based on comparisons between data and MC

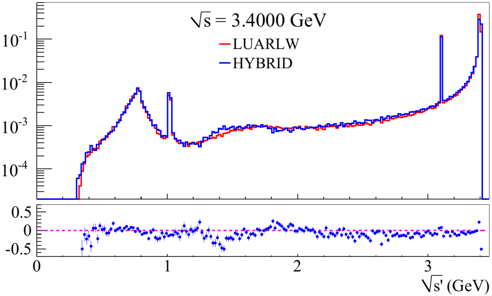
Alternative Model: "HYBRID" Generator

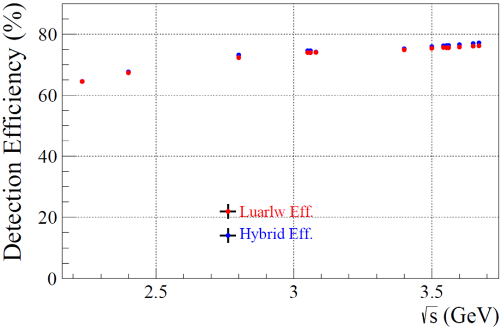
Phys. Rev. D 97, 114025 (2018)



- "HYBRID" of three well-established simulation models: **CONEXC**, **PHOKHARA**, and **LUARLW**
- As much as well currently known **experimental knowledges** are implemented
- different **ISR** and **VP** correction schemes are adopted

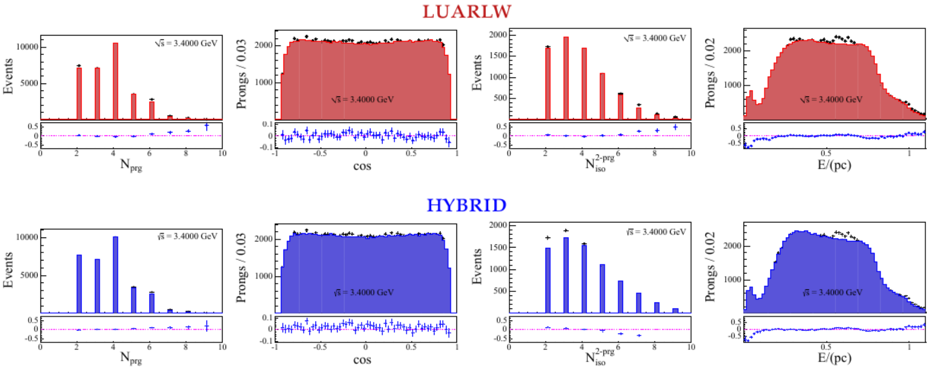
Comparison between LUARLW and HYBRID





- The $\sqrt{s'}$ spectrum directly reflect the **fraction** of the ISR-returned processes.
- These two different simulation schemes result in consistent $\sqrt{s'}$ spectra!
- These two generators also result in consistent efficiency

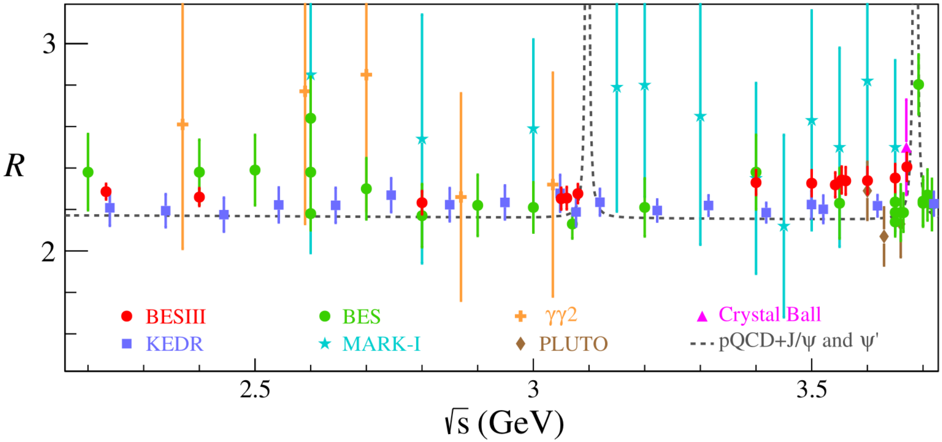
Comparison between MC and data



- $N_{\mathrm{prg},\theta}$: Number and polar angle of selected charged tracks
- $N_{\mathrm{iso}}^{\text{2-prg}}$: Number of isolated clusters in 2-prong events
- $E/(pc)$: Ratio of deposited energy and measured momentum per track

Good agreement of both generator models and data

Phys. Rev. Lett. 128, 062004 (2022)



Comparing BESIII R values with previously published results

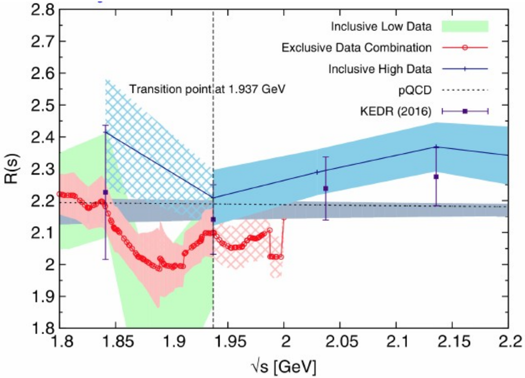
- The accuracy is better than 2.6% below 3.1 GeV and 3.0 % above
- Larger than the pQCD prediction by 2.7σ between 3.4 ~ 3.6 GeV

Exclusive method at 2.0 GeV

- Exclusive measurements for $\sqrt{s} < 2\,\mathrm{GeV}$
- Inclusive measurements for $\sqrt{s} > 2\,\mathrm{GeV}$
- Tensions in transition region

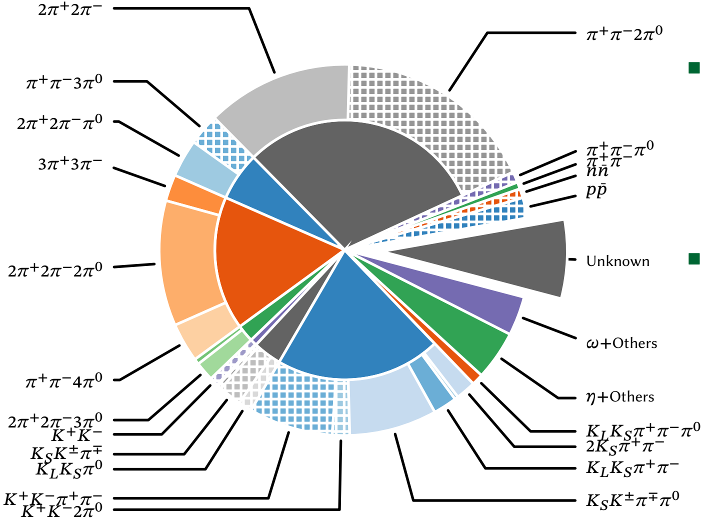
- Only $p\bar{p}$, $n\bar{n}$, multi-π, K and ω, η, ρ, ϕ, $\cdots$ at 2.0 GeV
- Any $p\bar{p}+X$ or $n\bar{n}+X$ is excluded
- Beyond $2K^+2K^-$ are excluded
- 10.1 pb^{-1} luminosity, ~ 47 nb total hadronic cross section, and ~ 350K hadronic events
- For process which has 0.1 nb (2‰) cross section and only 10% efficiency, still have 100 signal events, the 10% stat. uncern. contributes little to the uncertainty of R.

Phys. Rev. D 97, 114025 (2018)



List of exclusive processes

Considering the published work and very simple overlay situation, the total hadronic cross section at 2.0 GeV is > 95% with assumption that R at 2.0 GeV is 2.2.



- Not included:
  - Neutral channels like $\gamma\pi^0$
  - Multi-π channels like 8π, 9π, $\cdots$
  - Other unmeasured channels

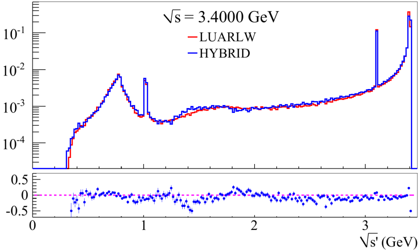
- Observable in current dataset (10.1 pb^{-1})
  - $3\pi^+3\pi^-$
  - $3\pi^+3\pi^-\pi^0$, $2\pi^+2\pi^-3\pi^0$, $\pi^+\pi^-5\pi^0$
  - $K^+K^-\pi^+\pi^-$, $K^+K^-\pi^+\pi^-\pi^0$

Summary and outlook

- Improving accuracy determination of R value important for Standard Models tests
  - Anomalous Magnetic Moment of the Muon
  - Running of QED coupling constant

- The First round measurement of R value at BESIII published
  - Phys. Rev. Lett. 128, 062004 (2022)
  - $2.2324 \leq \sqrt{s}$ [GeV] ≤ 3.6710
  - Accuracy better than 2.6% below 3.1 GeV and 3.0% above

- Many possibilities of R measurement at BESIII, and more works are ongoing.
  - Exclusive way at 2.0 GeV
  - Inclusive way by ISR



Thanks for your attention!