

R value measurements at BESIII

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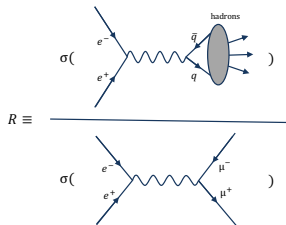
Bologna, Italy, 6–13 July 2022

Definition of R value

The R value is defined as the leading-order production cross section ratio of hadron and muon pairs in the electron-positron annihilation:

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

That is, according to QCD,



A direct result from the QED theory:

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

Running of QED coupling constant: $\Delta\alpha(s)$

The contributions to $\Delta\alpha(s)$ can be distinguished to three pieces:

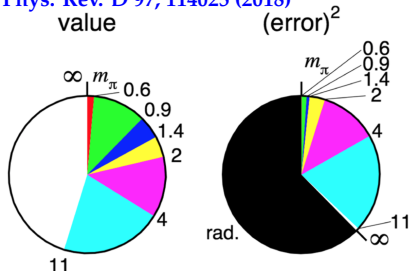
$$\Delta\alpha(s) = 1 - \alpha(0)/\alpha(s) = \Delta\alpha_{\text{lepton}}(s) + \Delta\alpha_{\text{had}}^{(5)}(s) + \Delta\alpha_{\text{top}}(s)$$

- $\Delta\alpha_{\text{lepton}}(s)$ can be calculated analytically using the perturbative theory.
- Since the top quark is heavy, $\Delta\alpha_{\text{top}}(s)$ is small ($10^{-7} \sim 10^{-10}$ for BESIII region).
- $\Delta\alpha_{\text{had}}^{(5)}(s)$ should be calculated by using the R value:

$$\Delta\alpha_{\text{had}}^{(5)}(s) = -\frac{\alpha s}{3\pi} \text{Re} \int_{E_{\text{th}}}^{\infty} ds' \frac{R(s')}{s'(s' - s - i\varepsilon)}$$

Fractional contribution to $\Delta\alpha_{\text{had}}^{(5)}(M_Z^2)$:

Phys. Rev. D 97, 114025 (2018)



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

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

$\Delta\alpha_{\text{had}}^{(5)}(s)$ is sensitive with the R value over all energy region!

Muon anomalous magnetic moment: a_μ

- Magnetic moment of the muon: $\vec{\mu} = g_\mu \frac{e}{2m_\mu} \vec{S}$
- Dirac theory: $g_\mu = 2 \Rightarrow$ Quantum Field Theory: $a_\mu = \frac{|g_\mu - 2|}{2} \Rightarrow$ **Muon Anomaly**

Anomalous Magnetic Moment:

- Standard model prediction:

$$a_\mu^{\text{SM}} = a_\mu^{\text{QED}} + a_\mu^{\text{QCD}} + a_\mu^{\text{weak}}$$

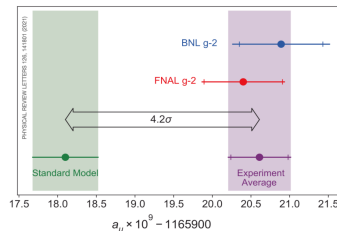
Phys. Rep. 887, 1 (2020)

- Direct measurement

(Exp. average BNL & FNAL)

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

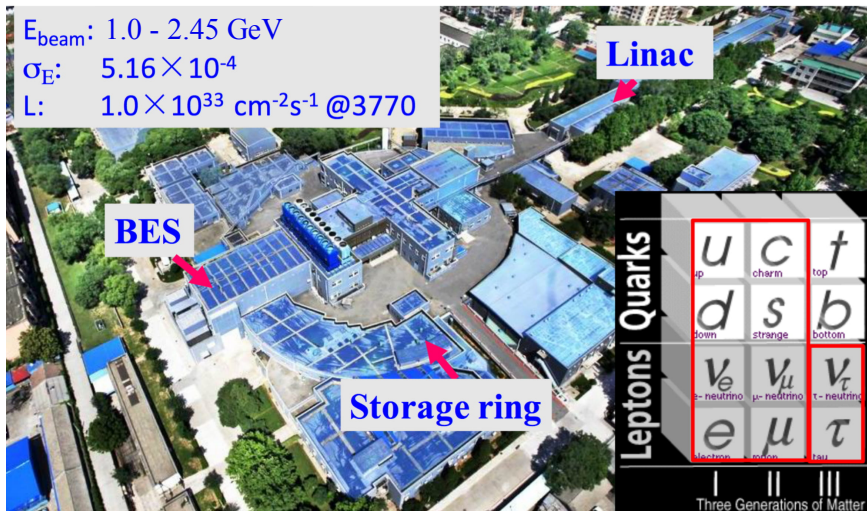
\Rightarrow **Discrepancy of 4.2σ !**



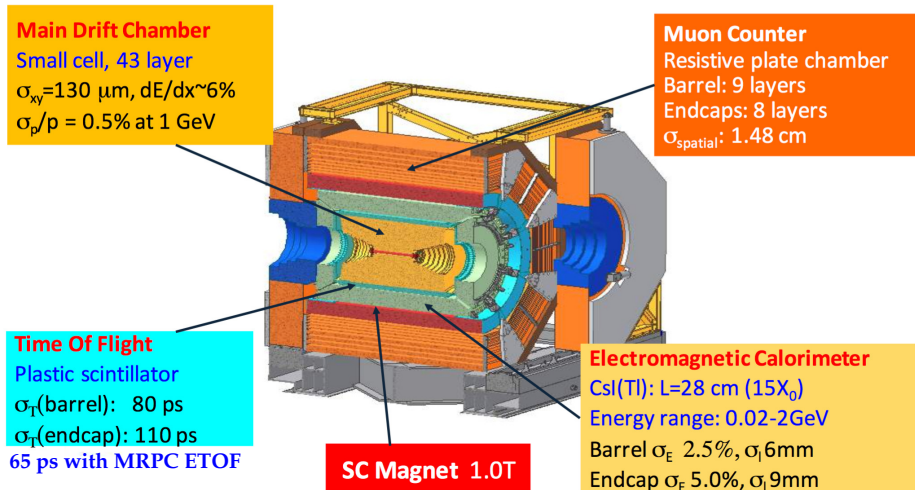
- Hadronic contributions dominate uncertainty of a_μ^{SM}
 - Hadronic Light-by-Light Scattering (HLbL) & **Hadronic Vacuum Polarization (HVP)**

The HVP contribution, i.e., $a_\mu^{\text{LO-HVP}}$, is calculated in terms of **R value** with the **dispersion relation**:

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



BEPC = Beijing Electron Positron Collider



BESIII = Beijing Spectrometer III

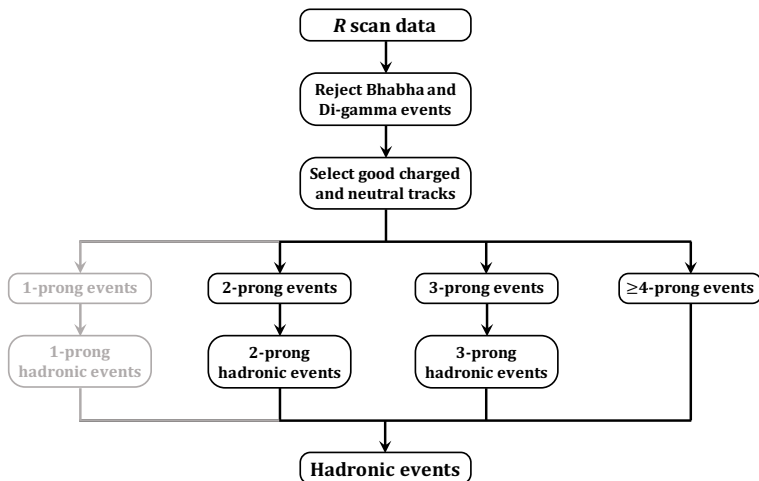
Determination of R value in experiment

Experimentally, the R value is determined by

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

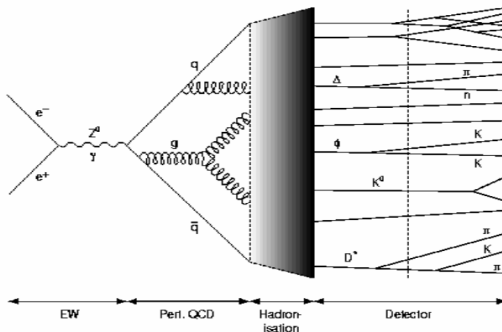
- $N_{\text{had}}^{\text{obs}}$: Numbers of observed hadronic events.
 - N_{bkg} : Number of the residual background events.
 - $\sigma_{\mu\mu}^0(s) = 86.85 \text{ nb/s}$: Leading order QED cross section for $e^+e^- \rightarrow \mu^+\mu^-$.
 - $\mathcal{L}_{\text{int.}}$: Integrated luminosity is measured by analyzing Bhabha events.
 - $\varepsilon_{\text{trig}}$: Trigger efficiency $\sim 100\%$.
 - ε_{had} : Detection efficiency of the hadronic events.
 - $(1 + \delta)$: ISR correction factor.
- **Determination of ε_{had} is the most challenging task!**
- **Two different signal simulation models are developed and investigated intensively.**

Analysis strategy



Nominal signal simulation model: LUARLW

Hadronization procedure in electron-positron annihilation:

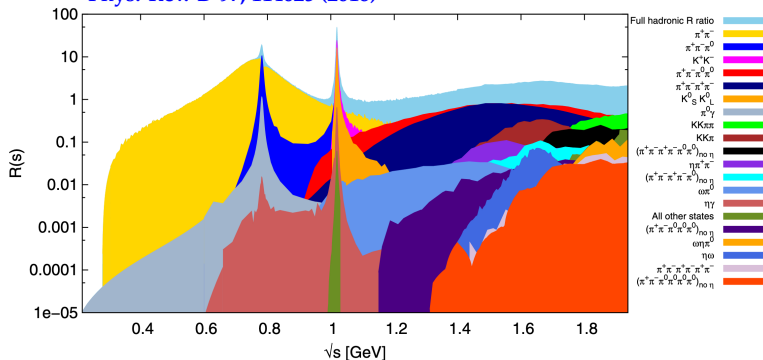


Main features of the **LUARLW** model:

- ▶ A self-consistent inclusive generator developed based on **JETSET**.
- ▶ **Initial-state radiation (ISR)** process is 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: first exclusive attempt

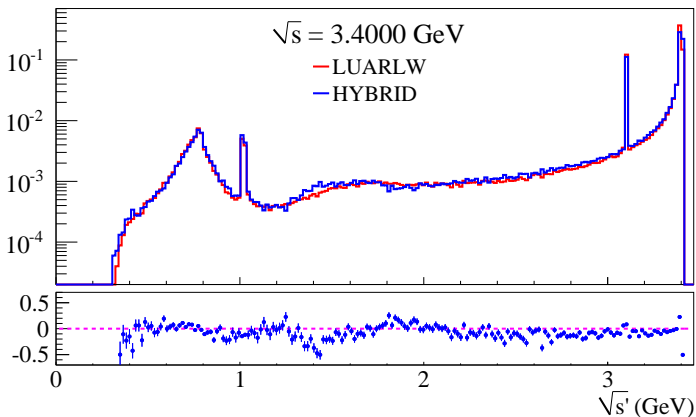
Phys. Rev. D 97, 114025 (2018)



The main features of the **HYBRID** model:

- Combination of **THREE** well-established models: **CONEXC**, **PHOKHARA**, and **LUARLW**.
- As much as currently known **experimental knowledges** are implemented.
- Different **ISR** and **VP** correction schemes from the nominal ones are adopted.

Comparison of effective energy ($\sqrt{s'}$) spectrum between LUARLW and HYBRID

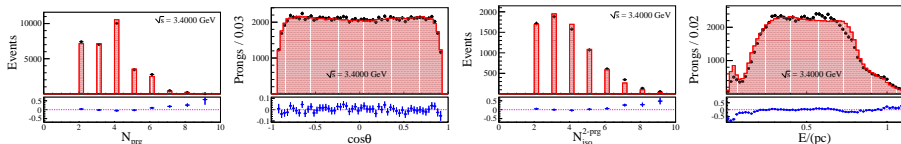


- Both in the LUARLW and HYBRID models, the ISR process is simulated.
- The $\sqrt{s'}$ spectrum directly reflect the **fraction** of the ISR-returned processes.
- **These two different simulation schemes result in consistent $\sqrt{s'}$ spectrum!**

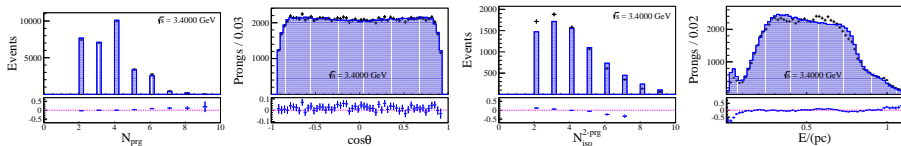
Comparison between MC and data in a few observables:

- N_{prg} : the number of detected the good charged tracks (**prong**).
- $\cos \theta$, E , and p : polar angle, deposited energy in EMC, and measured momentum in MDC.
- $N_{\text{iso}}^{2\text{-prg}}$: the number of isolated photons of two-prong events.

LUARLW



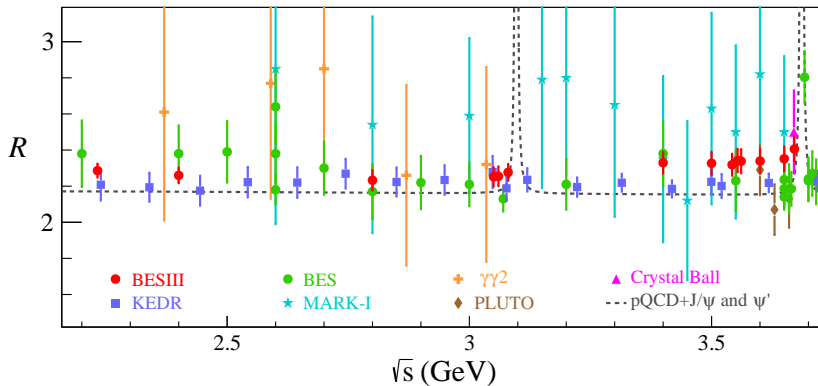
HYBRID



Both the two simulation models give good consistency with data!

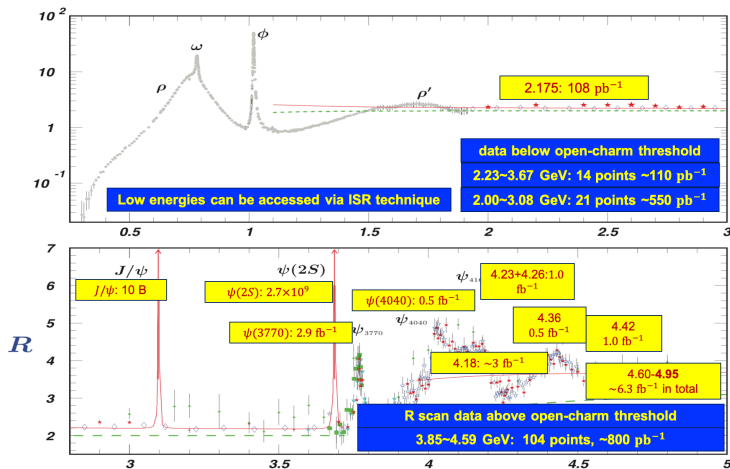
Measured R values between 2.2 ~ 3.7 GeV

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.

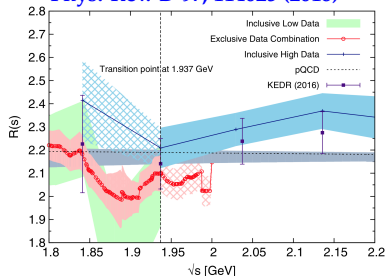
More measurements using the BESIII data



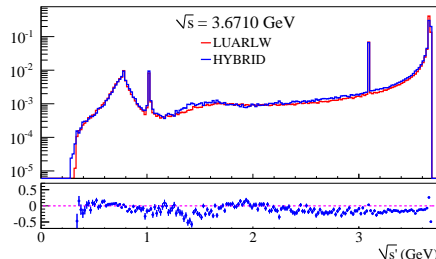
- ▶ BESIII has collected data from 2.00 to 4.95 GeV, which can be used for R measurement.
- ▶ R measurement both in the continuum and open-charm regions has significant impacts.

Different methods?

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Effective energy spectrum after ISR at 3.67 GeV



- ▶ R measured **inclusively** and **exclusively** at or below 2.0 GeV, and a comparison between them would be interesting.
- ▶ R measured via the **ISR technique** taking advantage of BESIII $\psi(3770)$ data, the R value from $\pi^+\pi^-$ threshold to continuum region can be accessed.
- ▶ Both of these two attempts will contribute to understanding the discrepancy of muon anomaly between SM calculation and experiment measurement.

Summary and outlook

- Improving the accuracy of R value is of great importance for precision prediction of muon anomaly.
- The first round measurement of R value at BESIII is published in **Phys. Rev. Lett. 128, 062004 (2022)** with the accuracy better than 2.6% below 3.1 GeV and 3.0% above.
- There are many possibilities of R measurement at BESIII, and more works are ongoing.

Thanks for your attention!