R value measurements at BESIII

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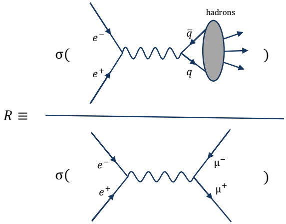
Definition of *R* value

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

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

That is, according to QCD,



A direct result from the QED theory:

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

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

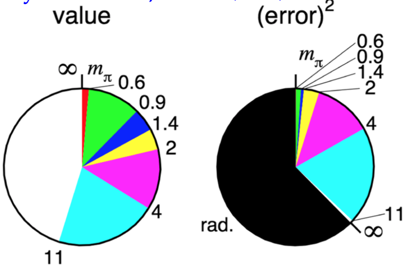
The contributions to $\Delta\alpha(s)$ can be distinguished to three pieces:

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

- $\Delta\alpha_{\text{lepton}}(s)$ 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).
- $\Delta\alpha^{(5)}_{\text{had}}(s)$ should be calculated by using the R value:

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

Fractional contribution to $\Delta\alpha^{(5)}_{\text{had}}(M_Z^2)$:
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
$\Delta\alpha^{(5)}_{\text{had}}(M_Z^2)$	276.0 ± 1.0
$\Delta\alpha_{\text{top}}(M_Z^2)$	-0.7180 ± 0.0054

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

Muon anomalous magnetic moment: a_μ

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

Anomalous Magnetic Moment:

1. Standard model prediction:

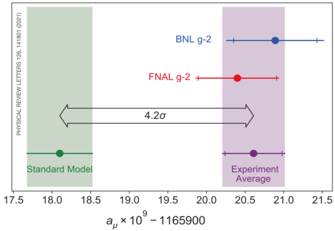
   $$\boxed{a_\mu^{\mathrm{SM}} = a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{QCD}} + a_\mu^{\mathrm{weak}}}$$

   Phys. Rep. 887, 1 (2020)
2. Direct measurement

   (Exp. average BNL & FNAL)

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

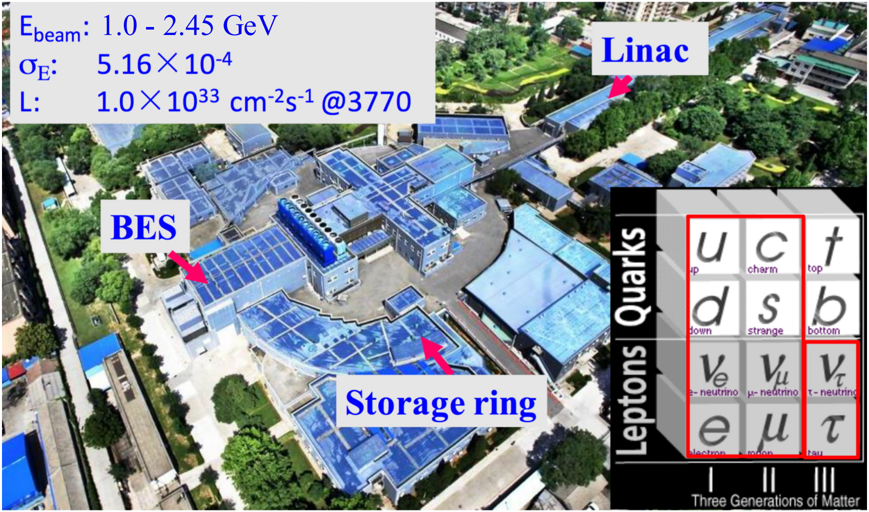
$\Rightarrow$ **Discrepancy of 4.2 σ!**



- 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:

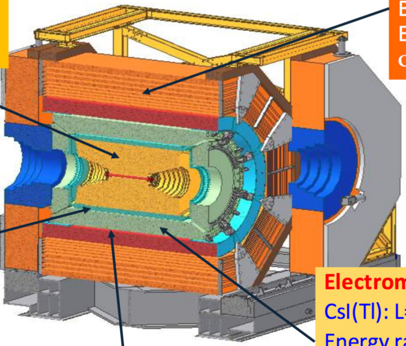
$$a_\mu^{\text{LO-HVP}} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^{\infty} \mathrm{d}s \frac{R(s)K(s)}{s^2}$$



BEPC = Beijing Electron Positron Collider

Main Drift Chamber
Small cell, 43 layer
σ_{xy}=130 μm, dE/dx~6%
σ_p/p = 0.5% at 1 GeV

Muon Counter
Resistive plate chamber
Barrel: 9 layers
Endcaps: 8 layers
$\sigma_{spatial}$: 1.48 cm



Time Of Flight
Plastic scintillator
σ_T(barrel): 80 ps
σ_T(endcap): 110 ps
65 ps with MRPC ETOF

SC Magnet 1.0T

Electromagnetic Calorimeter
CsI(Tl): L=28 cm ($15X_0$)
Energy range: 0.02-2GeV
Barrel σ_E 2.5%, σ_l 6mm
Endcap σ_E 5.0%, σ_l 9mm

BESIII = Beijing Spectrometer III

Determination of R value in experiment

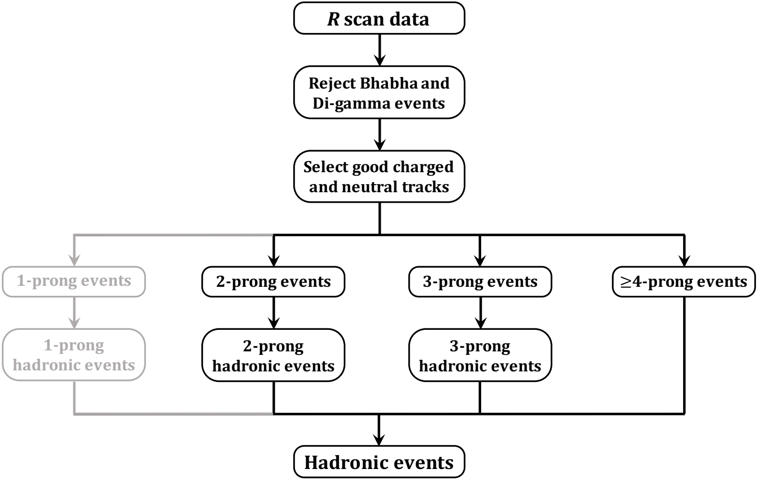
Experimentally, the R value is determined by

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

- $N_{\text{had}}^{\text{obs}}$: 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 $e^+e^- \to \mu^+\mu^-$.
- $\mathcal{L}_{\text{int.}}$: 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.

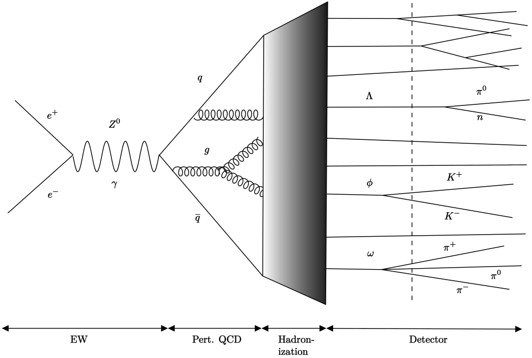
- **Determination of ε_{had} is the most challenging task!**
- **Two different signal simulation models are developed and investigated intensively.**

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

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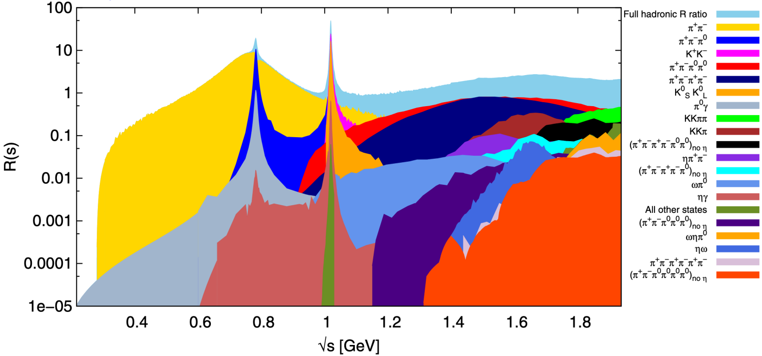
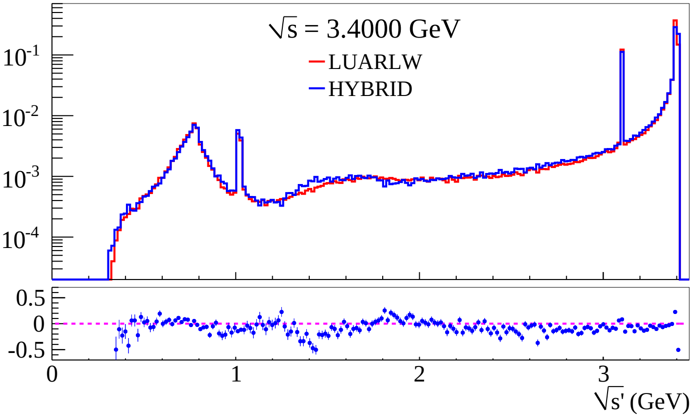


The main features of the HYBRID model:

- 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

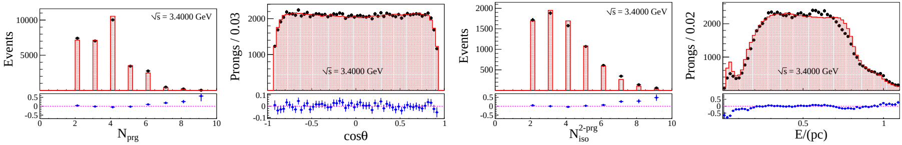


- Both in the LUARLW and HYBRID models, the ISR process is simulated.
- The $\sqrt{s'}$ spectrum directly reflect the fraction of the ISR-returned processes.
- **These two different simulation schemes result in consistent $\sqrt{s'}$ spectrum!**

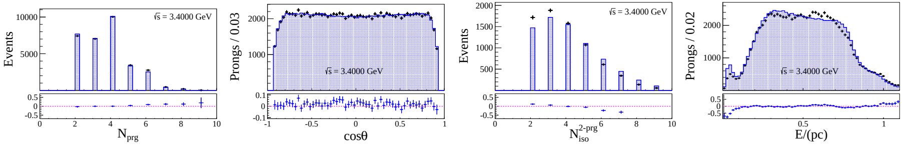
Comparison between MC and data in a few observables:

- 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.
- $N_{\text{iso}}^{\text{2-prg}}$: the number of isolated photons of two-prong events.

LUARLW



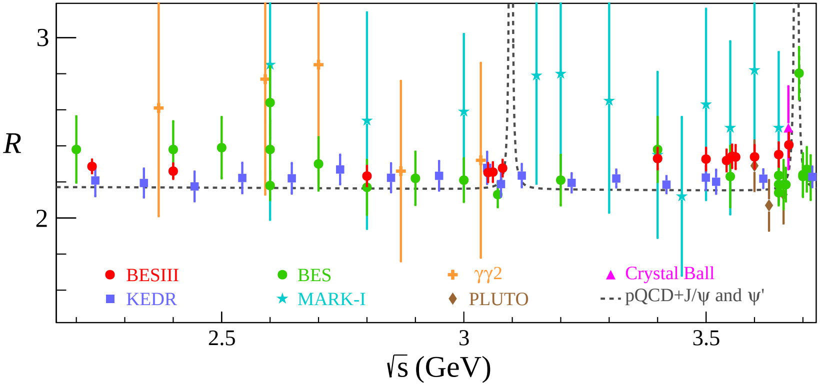
HYBRID



Both the two simulation models give good consistency with data!

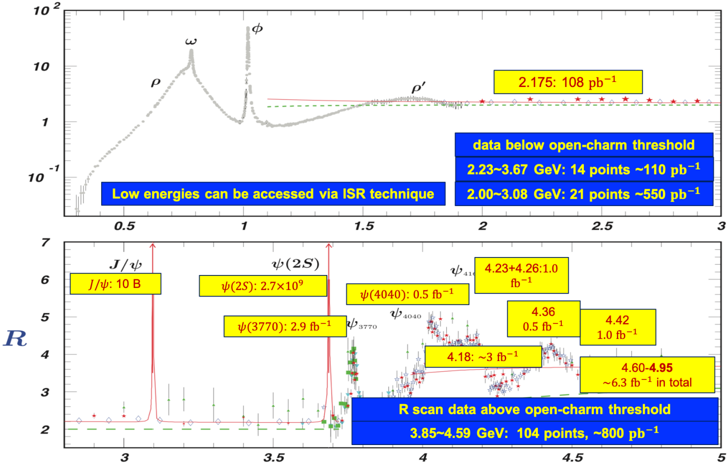
Measured *R* values between 2.2 ~ 3.7 GeV

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 R 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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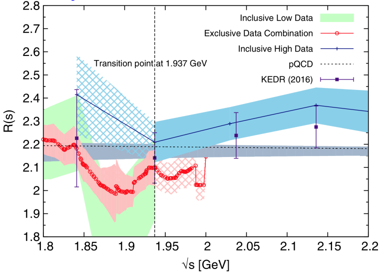
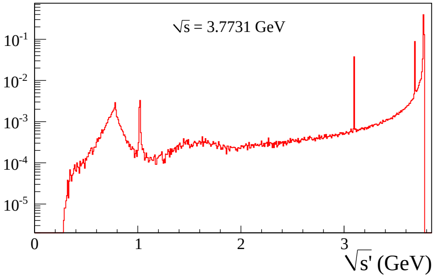


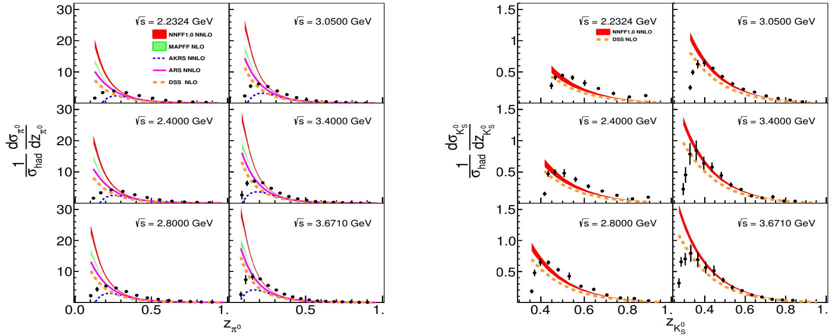
Effective energy spectrum after ISR at 3.67 GeV



- 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 with sufficient statistics.
- Both of these two attempts will contribute to understanding the discrepancy of muon anomaly between SM calculation and experiment measurement.

More possibility: Fragmentation function

arXiv:2211.11253



- Normalized differential cross section of inclusive π^0/K_S^0 production in e^+e^- annihilation at the center-of-mass energy of a few GeV.
- Broad z coverage from 0.1 to 0.9 with precision of around 3% at $z \sim 0.4$.
- Significant deviation between data and predictions of current FF calculations.

Summary and outlook

- Improving the accuracy of R value is of great importance for precision prediction of muon anomaly and the standard model.
- First bounch of R value measurement at BESIII is achieved with the accuracy better than 2.6% below 3.1 GeV and 3.0% above.
- There are many possibilities of R measurement at BESIII: at broader center-of-mass energy region, with different approaches.
- More works based on the R value measurement are ongoing: FF study of hadrons, TMD measurement, BEC effects etc..

Thanks for your attention!