R value measurement at BESIII

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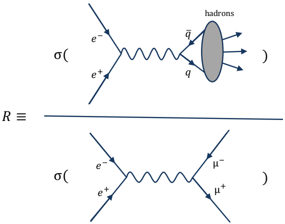
Definition of R value

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:

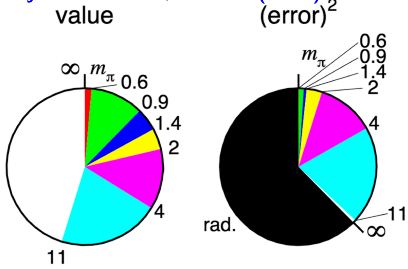
$$\Delta\alpha(s) = 1 - \alpha(0)/\alpha(s) = \Delta\alpha_{\text{lepton}}(s) + \Delta\alpha^{(5)}_{\text{had}}(s) + \Delta\alpha_{\text{top}}(s)$$

- $\Delta\alpha_{\text{lepton}}(s)$ 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: $\vec{\mu} = g_\mu \frac{e}{2m_\mu} \vec{S}$
- Dirac theory: $g_\mu = 2$ ⇒ Quantum Field Theory: $a_\mu = \frac{|g_\mu - 2|}{2}$ ⇒ **Muon Anomaly**

Anomalous Magnetic Moment:

1. Standard model prediction:

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

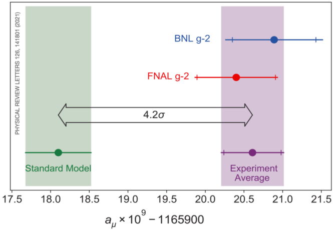
Phys. Rep. 887, 1 (2020)

2. Direct measurement

(Exp. average BNL & FNAL)

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

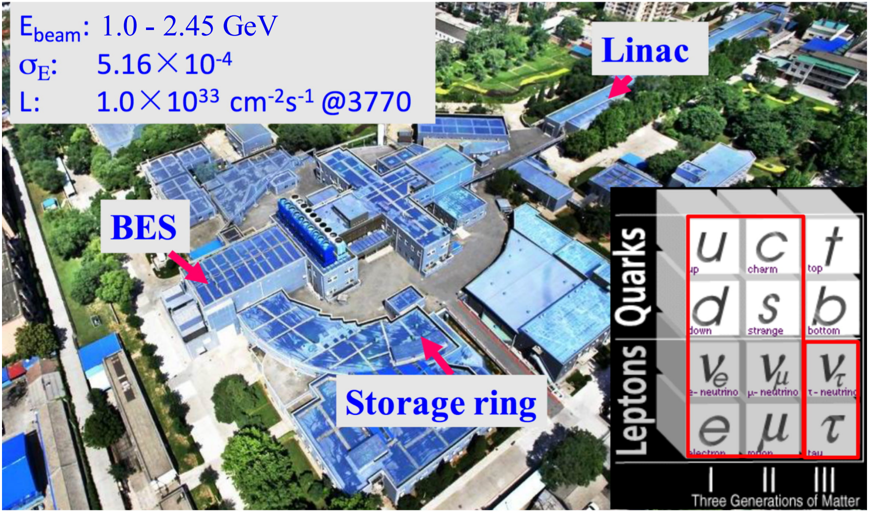
⇒ Discrepancy of 4.2 σ!



- 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 with R value by using dispersion relation:

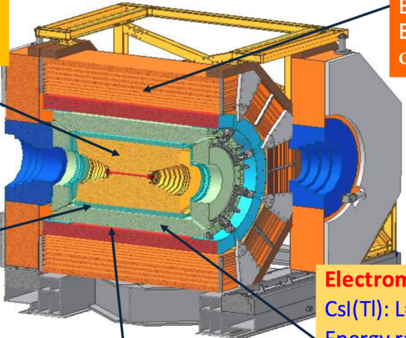
$$a_\mu^{\text{LO-HVP}} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^{\infty} ds \frac{R(s)K(s)}{s^2}$$



BEPC = Beijing Electron Positron Collider

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

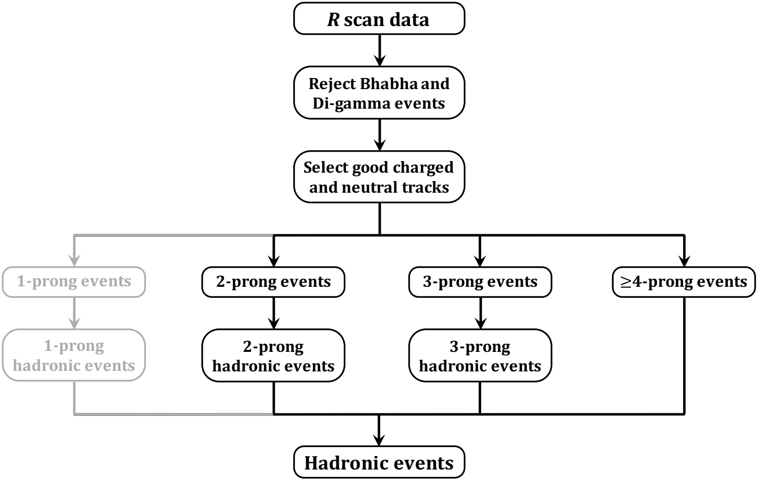
$$R = \frac{N_{\text{had}}^{\text{obs}} - N_{\text{bkg}}}{\sigma_{\mu\mu}^{0} \mathcal{L}_{\text{int.}} \varepsilon_{\text{trig}} \varepsilon_{\text{had}} (1+\delta)}$$

- $N_{\text{had}}^{\text{obs}}$: 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!**

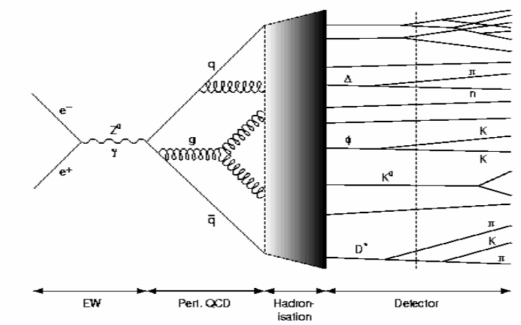
▶ **Two different signal simulation models are developed and investigated intensively.**

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 with the Feynman diagram scheme.
- 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 in R analysis

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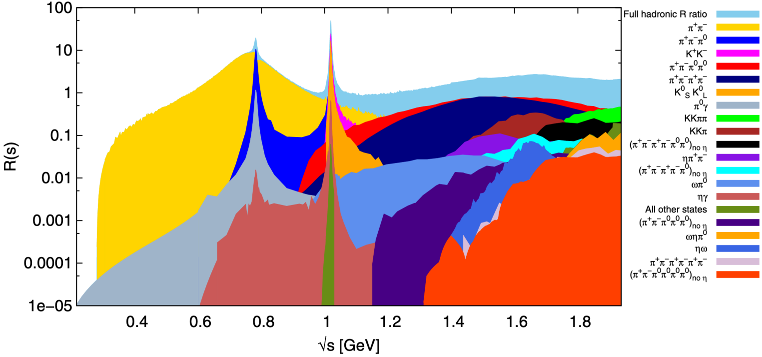


The main features of the HYBRID model:

- 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.

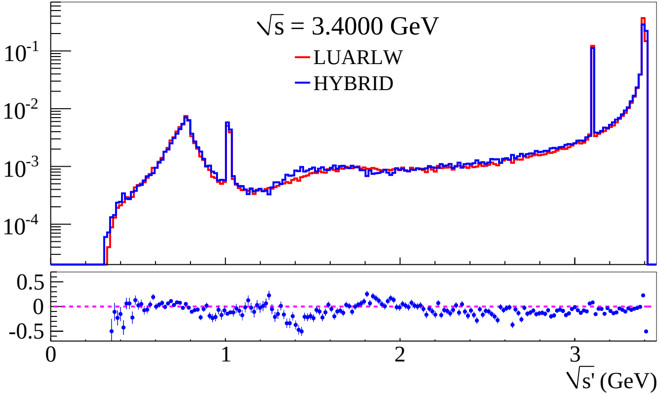
Construction of the HYBRID model

- The structure function scheme is used to simulate the ISR process in CONEXC.
- PHOKHARA is used to simulate 10 exclusive processes with known cross sections and intermediate states, $e^+e^- \to 2\pi, 3\pi, 4\pi$ etc..
- CONEXC simulates 47 exclusive processes with known cross sections according to PHSP model, such as $e^+e^- \to K^+K^-\pi^0$, $K_S^0K^\pm\pi^\mp$, $K^+K^-\pi\pi$, 5π, 6π and $\gamma_{\rm ISR}J/\psi$.
- As much as exclusive channels containing intermediate states are implemented in the CONEXC with their contributions to the related inclusive channels are excluded.
- LUARLW model is partially used to simulate remain unknown processes, in which a set of chosen parameters are tuned after comparing HYBRID simulations with data.
- Processes simulated by PHOKHARA or CONEXC are prohibited in LUARLW to avoid excessive generation of some specific processes.
- The residual double-generatings among the three components are negligible.

A lot of efforts have gone into engineering the HYBRID generator!

Comparison in truth level

The effective energy ($\sqrt{s'}$) spectra of LUARLW and HYBRID after ISR process



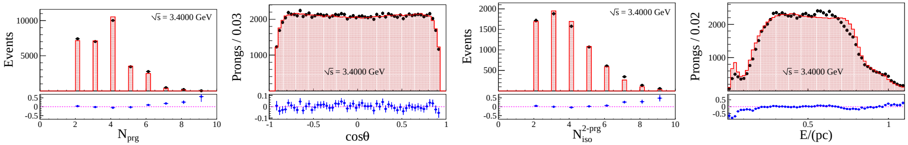
- In LUARLW and HYBRID, the ISR process is simulated in different ways.
- The $\sqrt{s'}$ spectrum directly reflect the fraction of the ISR-returned processes.
- **These two different simulation schemes result in consistent $\sqrt{s'}$ spectrum!**

Comparison in observable level

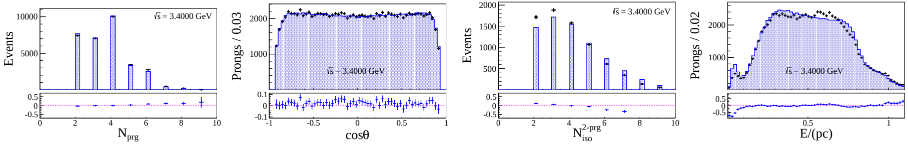
Comparison between MC and data in a few observables:

- 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



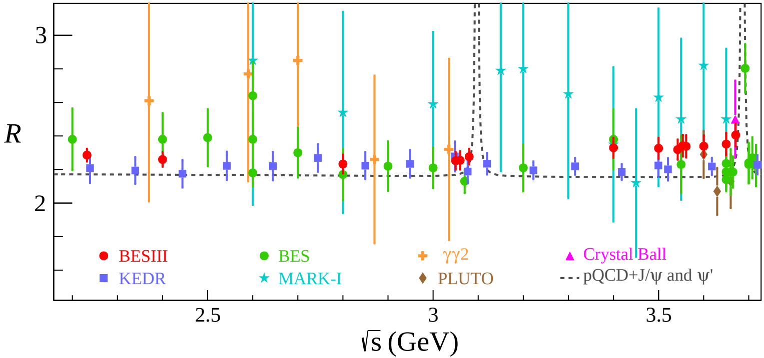
HYBRID



Both the two simulation models give good consistency with data!

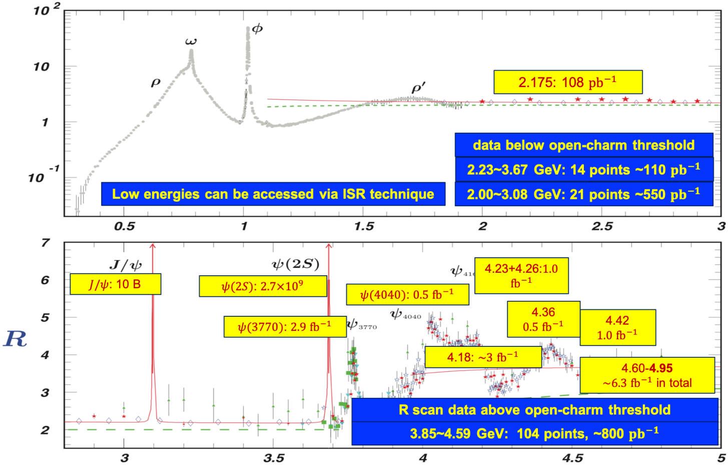
Measured R values between $2.2 \sim 3.7$ GeV

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 $3.4 \sim 3.6$ GeV:**
  - Lager $a_\mu^{\text{LO-HVP}}$ which is close to a_μ calculated by the lattice QCD?
  - Contributions from new, long-lived neutral hadrons? [arXiv:2206.13460].

More measurements using the BESIII data



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

Different methods and different physics?

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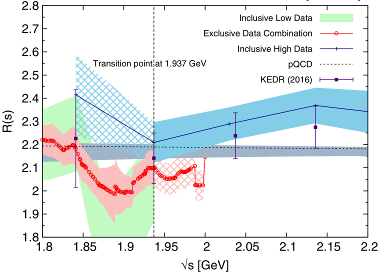
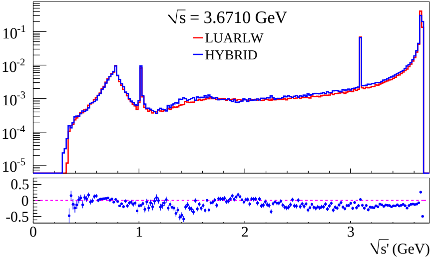


The $\sqrt{s'}$ spectrum after ISR at 3.67 GeV



- 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 and the HYBRID model, 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.

总结

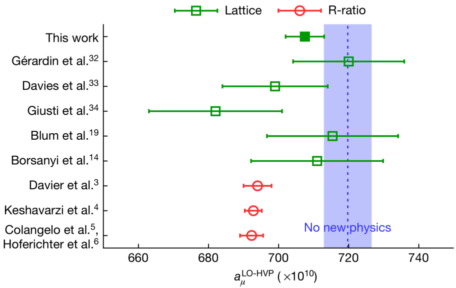
- 实验上不断提高 R 值的精度对检验标准模型，尤其是理解当前与缪子反常磁矩有关的疑难问题具有重要意义。
- 基于大量细致的分析和检查，BESIII 测量得到的连续能区的 R 值具有目前世界上最好的精度和可靠性。
- BESIII 上正在开展基于不同方法的 R 值测量工作，包括单举方法、遍举方法以及ISR 方法，这些工作将对粒子物理领域提供高质量的基础实验数据。

Thanks for your attention!

Muon anomalous magnetic moment: a_μ

New calculation of $a_\mu^{\text{LO-HVP}}$ from the lattice QCD approach decreases the discrepancy between a_μ^{SM} and a_μ^{exp}:

Nature (London) 593, 51 (2021)



Source	Contribution($\times 10^{-11}$)
a_μ^{QED}	116584718.931 ± 0.104
a_μ^{Weak}	153.6 ± 1.0
$a_\mu^{\text{LO-HVP}}$ (R-ratio)	6931 ± 40
$a_\mu^{\text{LO-HVP}}$ (lattice)	7075 ± 55
$a_\mu^{\text{NLO-HVP}}$	-98.3 ± 0.7
$a_\mu^{\text{NNLO-HVP}}$	12.4 ± 0.1
a_μ^{HLbL}	92 ± 18
a_μ^{SM}	116591954 ± 58
a_μ^{exp}	116592061 ± 41
Δa_μ	107 ± 71 (1.5σ)

The R-ratio approach still gives the best prediction to $a_\mu^{\text{LO-HVP}}$.

Additional checks on the R value

- Inclusion of one-prong events: R changes by 0.8% at most.
- Exclusion of two-prong events: A maximum of 2.2% differences of R is observed.
- The LUARLW generator is quantitatively checked in a few exclusive channels, by replacing the corresponding production fractions (f) and inclusive efficiencies (ε^{inc})
    - $\pi^+\pi^-$: $f_{2\pi}$ and $\varepsilon^{\text{inc}}_{2\pi}$ replaced by that of HYBRID, ε_{had} changes by 2.1% at most.
    - $\pi^+\pi^-\pi^0$: $f_{3\pi}$ and $\varepsilon^{\text{inc}}_{3\pi}$ replaced by that of HYBRID, ε_{had} changes by 0.6% at most.
    - $\pi^+\pi^-\pi^+\pi^-$: $f_{4\pi}$ replaced by that extracted from experimental data and $\varepsilon^{\text{inc}}_{4\pi}$ by that of HYBRID, ε_{had} differs from the nominal value by 1.1% at most.
    - $\pi^+\pi^-\pi^0\pi^0$: $f_{4\pi}$ replaced by that extracted from experimental data and $\varepsilon^{\text{inc}}_{4\pi}$ by that of HYBRID, the resulted differences in ε_{had} is less than 0.6%.
    - $\gamma_{\text{ISR}}J/\psi$: $f_{J/\psi}$ and $\varepsilon^{\text{inc}}_{J/\psi}$ replaced by that of HYBRID, the maximum changement in ε_{had} is 0.2% at $\sqrt{s} = 3.4$ GeV.

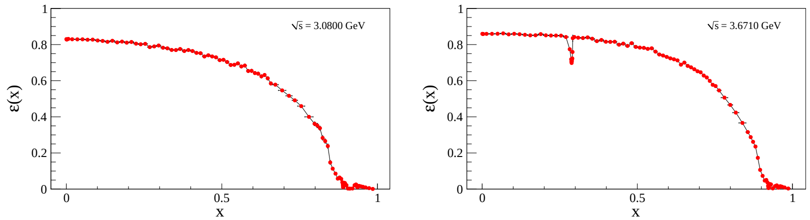
An alternative treatment of ISR process

In previous R measurement works, a different treatment of ISR process is adopted:

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

where the $\varepsilon_{\mathrm{had}}(0)$ stands for the detection efficiency of events without radiating ISR photon.

$$1+\delta_{\mathrm{obs}} = \frac{\delta_{\mathrm{vert}}}{|1-\Pi(s)|^2} + \frac{1}{\sigma_{\mathrm{had}}^{0}(s)\varepsilon_{\mathrm{had}}(0)}\int_0^{x_m}\frac{x^{\beta}}{x}(1-x+\frac{x^2}{2})\frac{\sigma_{\mathrm{had}}^{0}(s')\varepsilon_{\mathrm{had}}(x)}{|1-\Pi(s')|^2}\mathrm{d}x.$$



The maximum difference in R value resulted by this treatment is 0.8%.