# R-Value Measurements at BESIII

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# Definition of R-Value

Ratio of leading-order production cross sections of muon pairs and hadrons in $e^+e^-$ collisions

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

With $\sigma^0_{\mu\mu}$ directly from QED: $\sigma^0_{\mu\mu} = \frac{4\pi\alpha}{3s}\frac{\beta_\mu(3-\beta_\mu^2)}{2}$ , with $\beta_\mu = \sqrt{1-\frac{4m_\mu^2}{s}}$

**Important input to current tests of Standard Model**

# Running of the Fine Structure Constant $\Delta\alpha_{em}$

$\alpha(m_Z^2)$ one of three essential observables for electroweak precision physics

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

From perturbation theory

top quark contribution

Hadronic Vacuum Polarization contribution

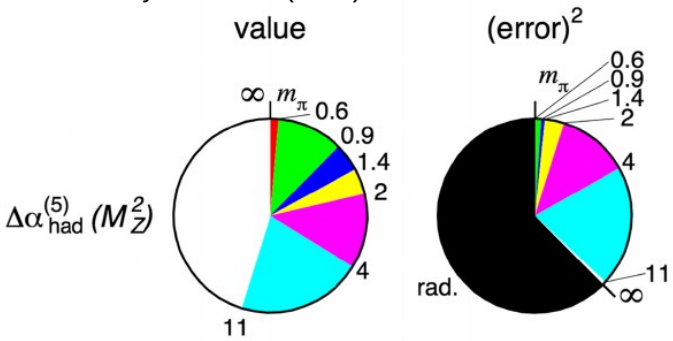
$$\Delta\alpha^{(5)}_{\text{had}}(s) = -\frac{\alpha s}{3\pi} P \int_{s_{th}}^{\infty} \mathrm{d}s' \frac{R(s')}{s'(s'-s)}$$

R-Value over wide energy range important input:

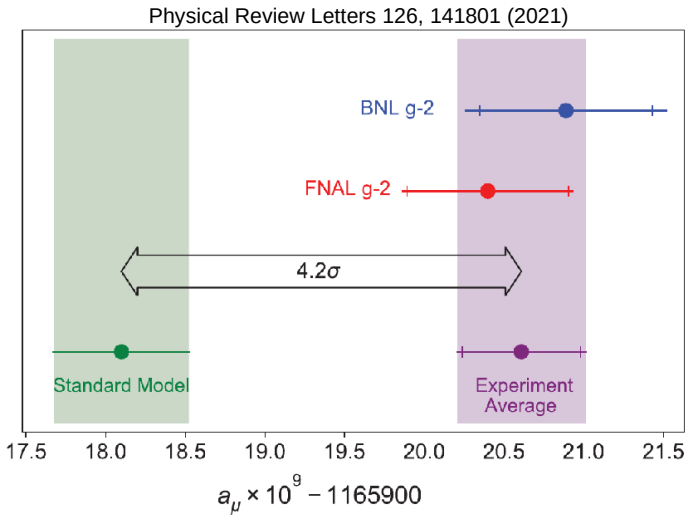
| Source | Contribution($\times 10^{-4}$) |
|---|---|
| $\Delta\alpha_{\text{lepton}}(M_Z^2)$ | $314.979 \pm 0.002$ |
| $\Delta\alpha^{(5)}_{\text{had}}(M_Z^2)$ | $276.0 \pm 1.0$ |
| $\Delta\alpha_{\text{top}}(M_Z^2)$ | $-0.7180 \pm 0.0054$ |

Eur.Phys.J. 80 (2020) 241

Phys.Rev.D97 (2019) 114025

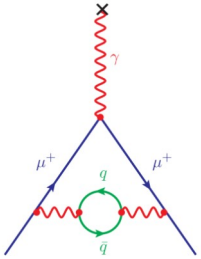


# Anomalous Magnetic Moment of the Muon




Muon anomaly $a_\mu = \dfrac{g_\mu - 2}{2}$

- Less than 0.5 ppm accuracy in experiment and theory
  - Exp: 116 592 061(41) × $10^{-11}$ (Physical Review Letters 126, 141801 (2021))
  - SM: 116 591 810(43) × $10^{-11}$ (Physics Reports 887 (2020) 1–16)
- Discrepancy between SM prediction and experiment
- Hadronic contributions dominate uncertainty of $a_\mu^{\mathrm{SM}}$




Hadronic Vacuum Polarization contribution:

- Dispersion integral
- R-Value as experimental input

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

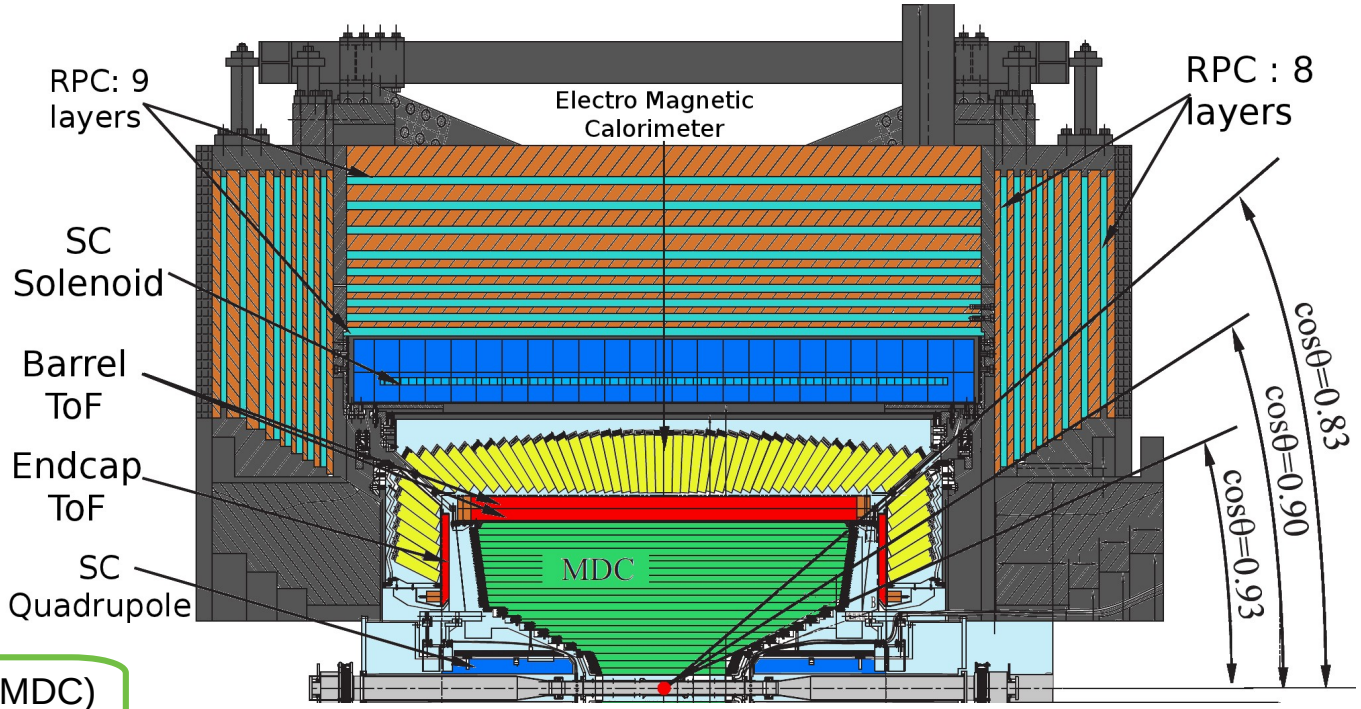
- Tension with latest Lattice QCD calculations

# Beijing $e^+e^-$ Collider – BEPCII

- Operated at BEPCII in Beijing, China
- Center-of-mass energies from 2 – 5 GeV
- Design luminosity $10^{33}cm^{-2}s^{-1}$ at 3.77 GeV

- World's largest e+e- data sets at τ-charm energies
  - $10^{10}$ J/ψ and $3\times10^{9}$ ψ(2s) directly produced
  - More than 40 $fb^{-1}$ collected between 3.773 and 5 GeV
  - Currently collecting 20 $fb^{-1}$ at 3.773 GeV

# Beijing Spectrometer – BESIII




Nucl.Instr.Meth. A614 (2010) 345

**Drift Chamber (MDC)**
- σ(p)/p = 0.5%
- $\sigma_{dE/dx}$ = 6.0%

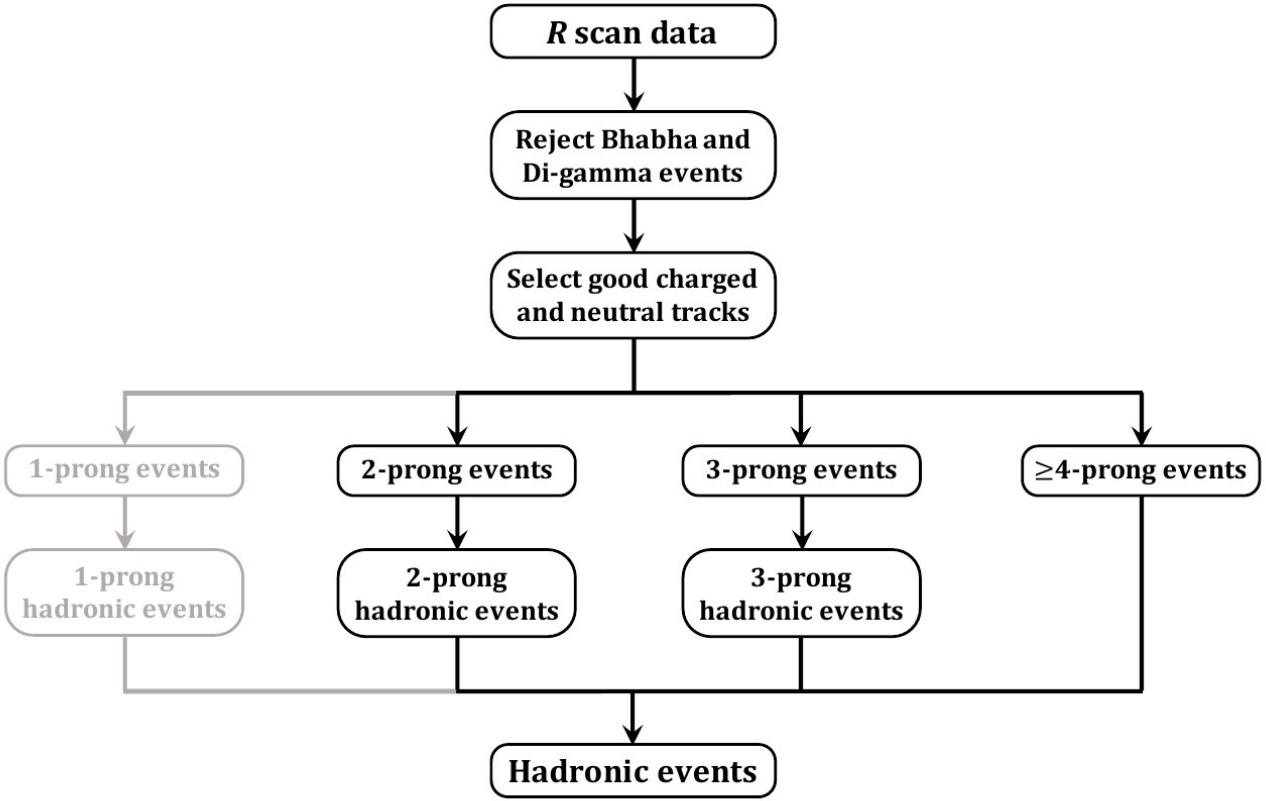
**Time-of-flight system (TOF)**
- σ(t) = 60ps

**Superconducting Magnet**
- 1 T magnetic field

**EM Calorimeter (EMC)**
- 6240 CsI(Tl) crystals
- σ(E)/E = 2.5%
- $\sigma_{Z,\Phi}$(E) = 0.5 – 0.7 cm

**Muon Chambers**
- 8 – 9 layers of RPC
- p > 400 MeV/c
- δRΦ = 1.4 ~ 1.7 cm

# Analysis Stategy



# Determination of R-Value

Leading-order QED cross section

$$\sigma^0_{\mu\mu}(s) = 86.85\frac{\text{nb}}{s}$$

Residual background contributions
- MC simulations
- Beam related contributions from data

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

Integrated luminosity
- Determined from LA-Bhabha scattering
- 0.8% uncertainty

Trigger efficiency ~100%

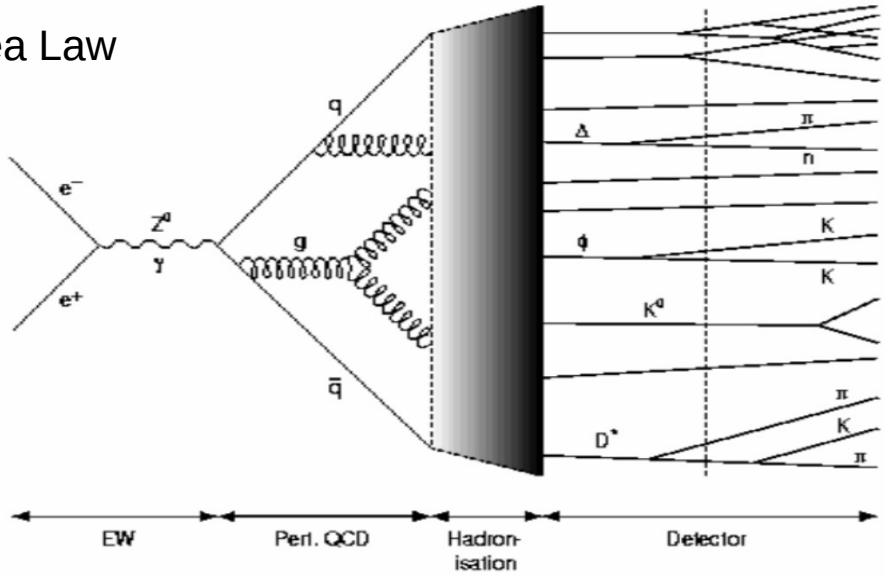
Radiative corrections
- Feynman diagrams
- Structure functions
- Agreement better than 1.4%

Detection efficiency for hadronic events
- Most crucial source of uncertainties
- Evaluated using two different generator models

# Nominal Model for Signal Simulation: LUARLW

- Self-consistent model
- Developed from JETSET for low energies
- Kinematics of initial hadrons determined from Lund Area Law
- Generation of resonant and continuum states
- Initial state radiation implemented from $m_{\pi\pi}$ to $\sqrt{s}$
- Phenomenological Parameters tuned to data

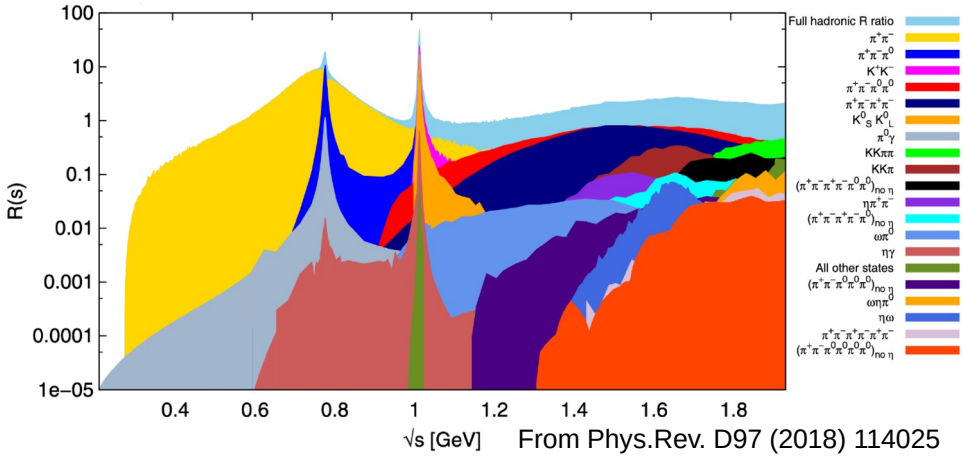
- Used in most previous R-Value measurements



# Alternative Model: “Hybrid Generator”

New event generator developed:

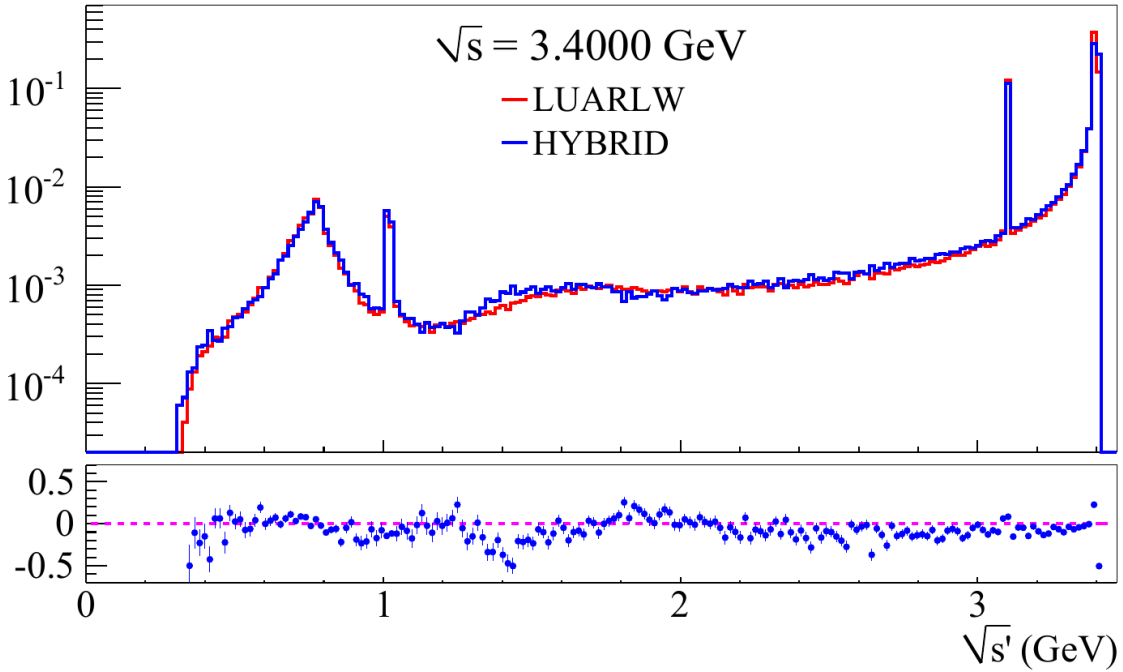
- Idea: Use as much experimental information as possible



From Phys.Rev. D97 (2018) 114025

- Combination of established event generators
  - Phokhara
    - 10 exclusive channels, hadronic models tuned to experiment
  - ConExc
    - More than 50 channels with cross sections from experiment
  - LUARLW
- Alternative ISR and VP correction schemes implemented

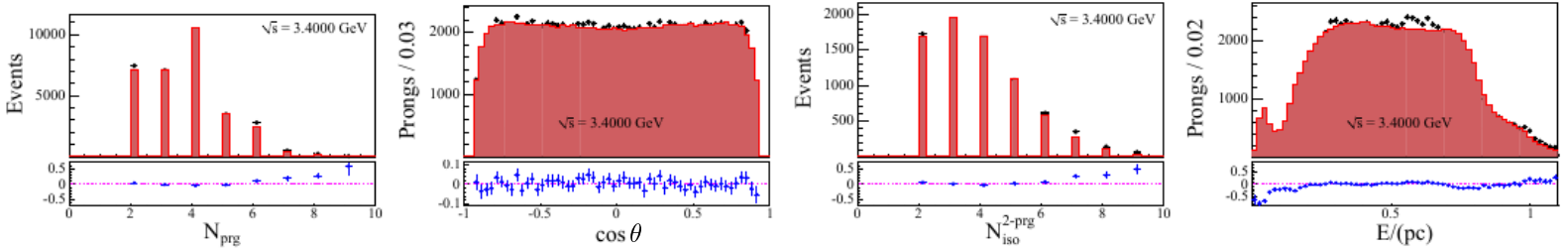
# Comparison of the two Generators



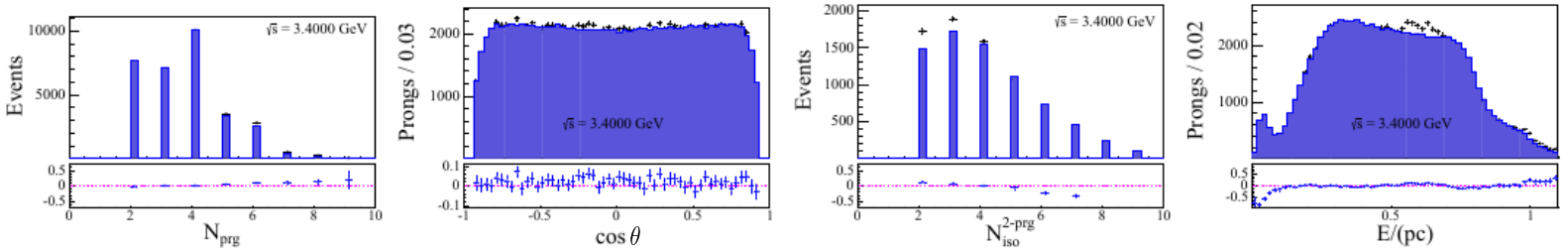

- Effective energy spectrum of simulated ISR processes
- Consistent spectra from two different generators (different ISR schemes)

# Comparison of the two Generators

LUARLW




HYBRID

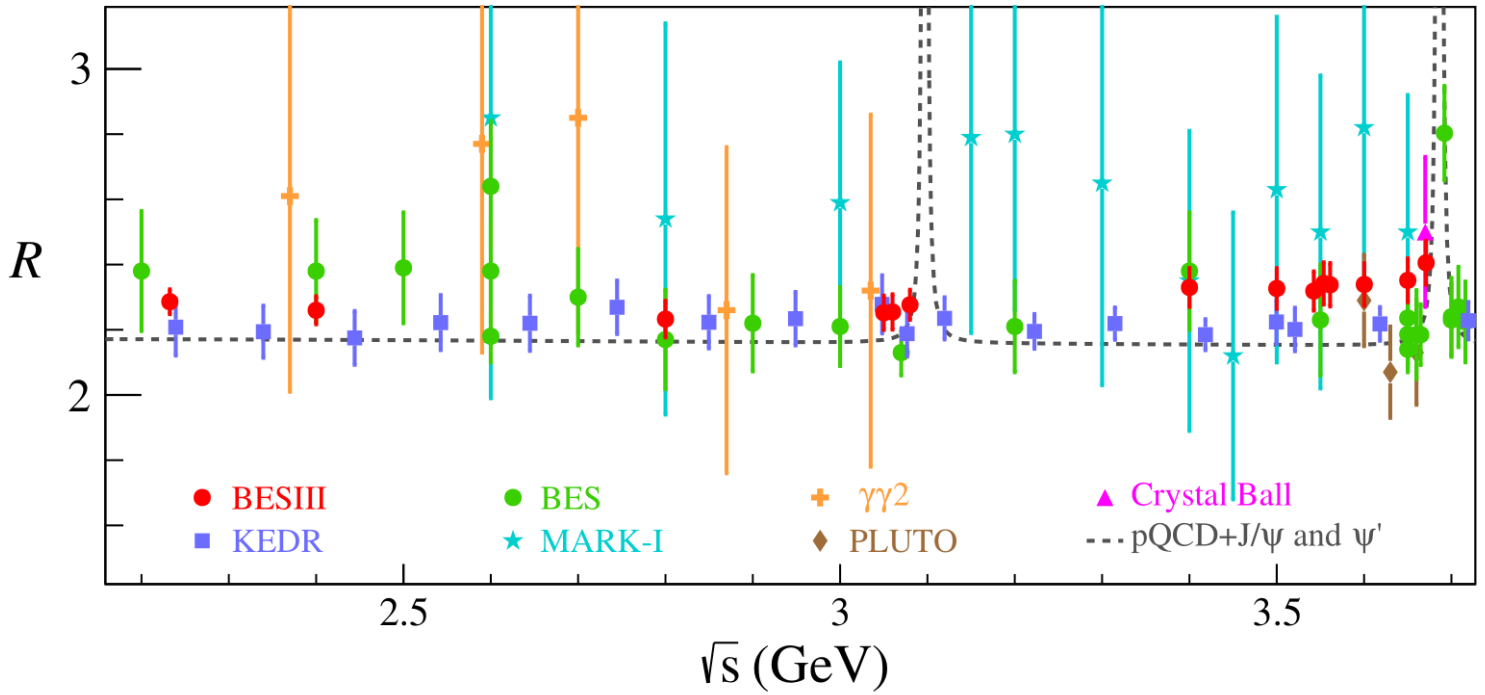



Comparison with data:

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

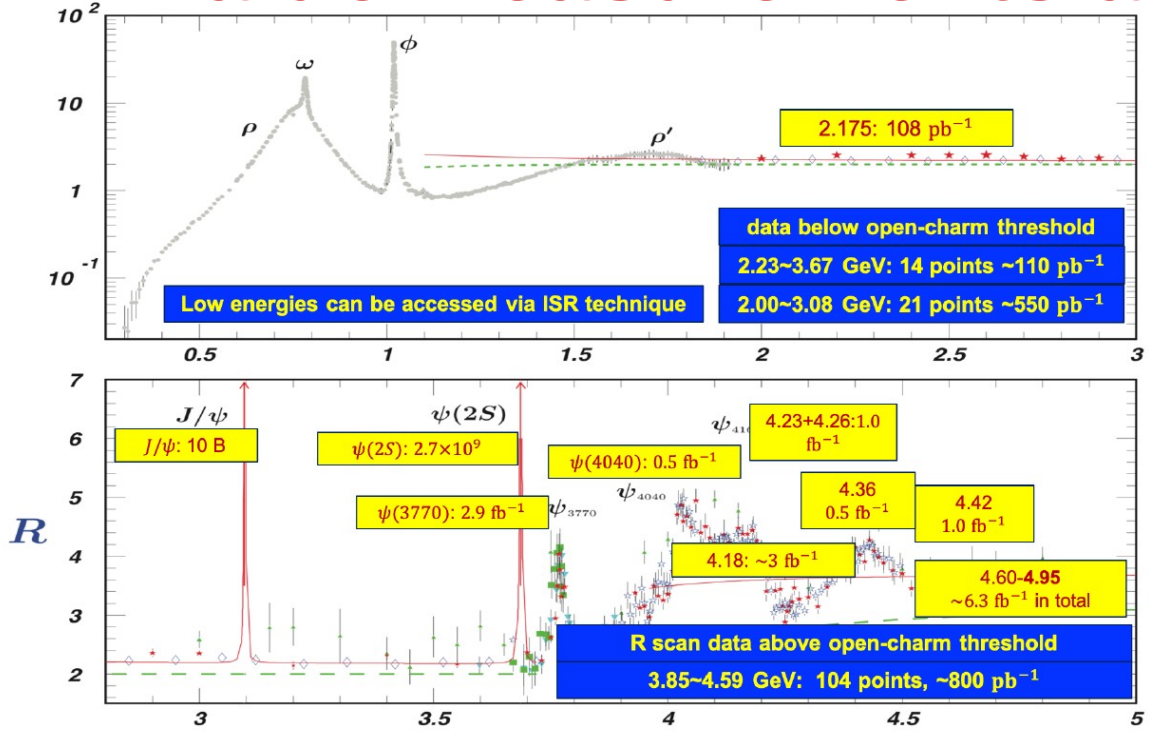
**Good agreement of both generator models and data**

# Resulting R-Values



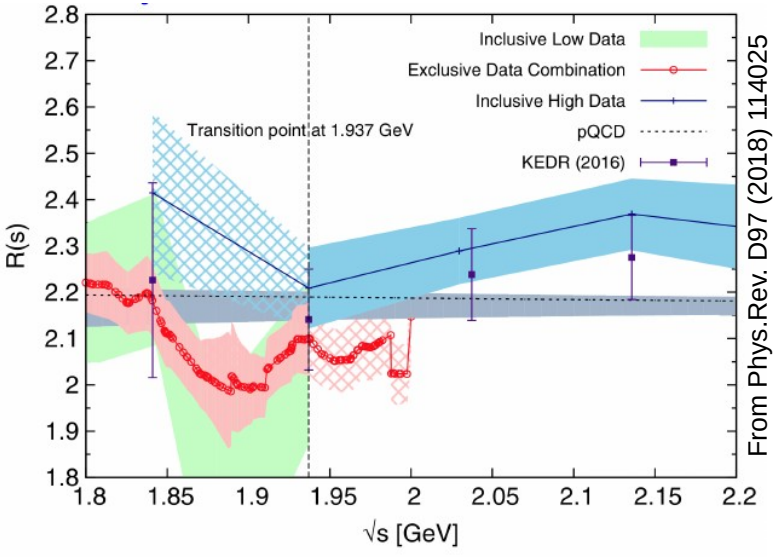

- Accuracy better than 2.6% for $\sqrt{s} < 3.1$GeV and better than 3% above
- Exceeding pQCD prediction by 2.7σ between 3.4 and 3.6 GeV

# Further R-Value Measurements at BESIII



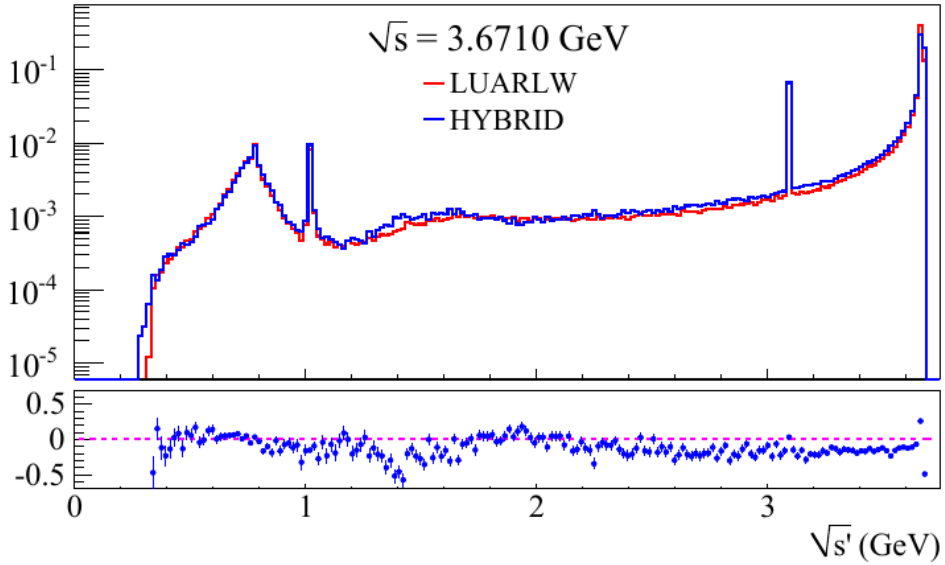

- Large amounts of additional data already collected
  - 130 energy scan points with >$10^5$ hadrons
- High accuracy R-Value measurements in continuum and open-charm region

# Alternative Approach to R-Value Measurement




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

- Use ISR for R-Value measurement
- Exploit large charmonium data sets at BESIII
- Better $\varepsilon_{\text{had}}$ due to ISR kinematics
- Comparison of inclusive and exclusive measurements



# Summary

- High accuracy determination of R-Value important for Standard Model tests
  - Running of $\alpha_{\mathrm{em}}(M_Z^2)$
  - Muon anomaly $a_\mu$
- First R-Value measurement at BESIII published
  - $2.2324 \leq \sqrt{s}[\mathrm{GeV}] \leq 3.6710$
  - Accuracy better than
    - 2.6% below 3.1 GeV
    - 3% above

Phys. Rev. Lett. 128 (2022) 062004

- Further high statistics energy scan data acquired
- Alternative approach exploiting ISR being developed