R-Value Measurement at BESIII

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SFB 1044 THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

Cluster of Excellence PRiSMA+

BESIII

DFG Deutsche Forschungsgemeinschaft

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Definition of R-Value

Ratio of leading-order cross sections of hadron and muon pair production in e^+e^- annihilation

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

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

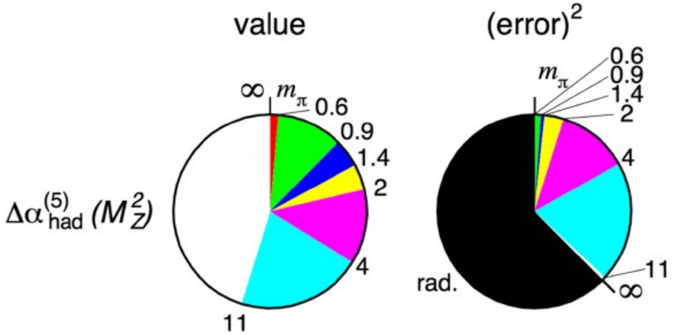
$$\Delta\alpha^{(5)}_{\text{had}}(s) = -\frac{\alpha s}{3\pi} P \int_{s_{th}}^{\infty} \mathrm{d}s' \frac{R(s')}{s'(s'-s)}$$

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

Eur.Phys.J. 80 (2020) 241

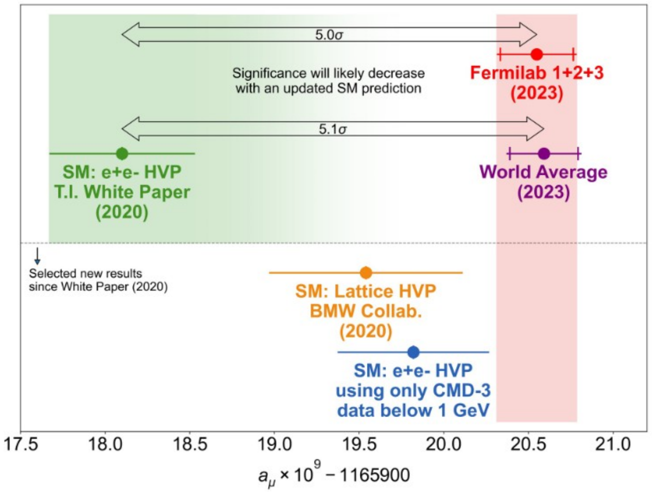
Phys.Rev.D97 (2019) 114025

R-Value over wide energy range important input:



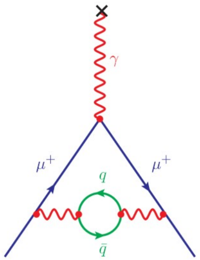
Anomalous Magnetic Moment of the Muon

Taken from James Mott: https://indico.fnal.gov/event/60738/



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

- Acuracy better than 0.5 ppm in experiment and theory
  - Exp: 116 592 059(22) × 10^{-11} (arXiv:2308.06230)
  - 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_μ^{SM}



Hadronic Vacuum Polarization contribution:

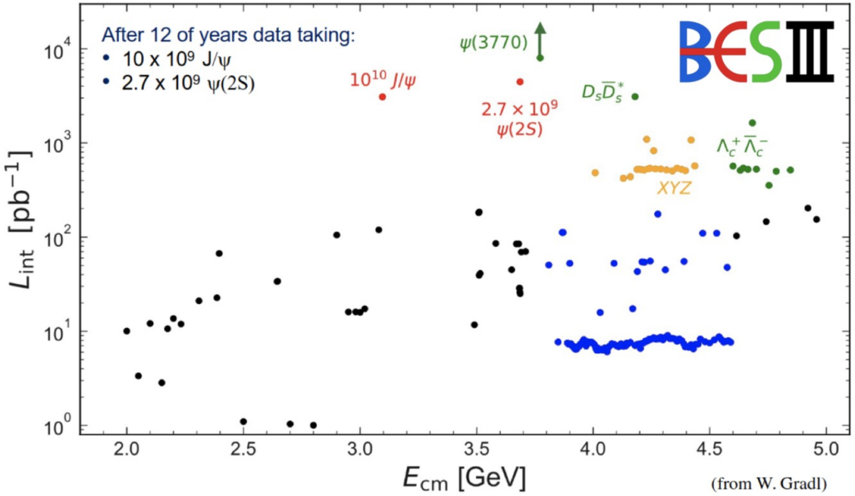
- Dispersion integral
- R-Value as experimental input

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

- Tensions with latest Lattice QCD calculations and cross section measurements

Beijing e^+e^- Collider – BEPCII

- Center-of-mass energies from 2 – 5 GeV
- Design luminosity exceeded: $1.1\times10^{33}cm^{-2}s^{-1}$ at 3.77 GeV



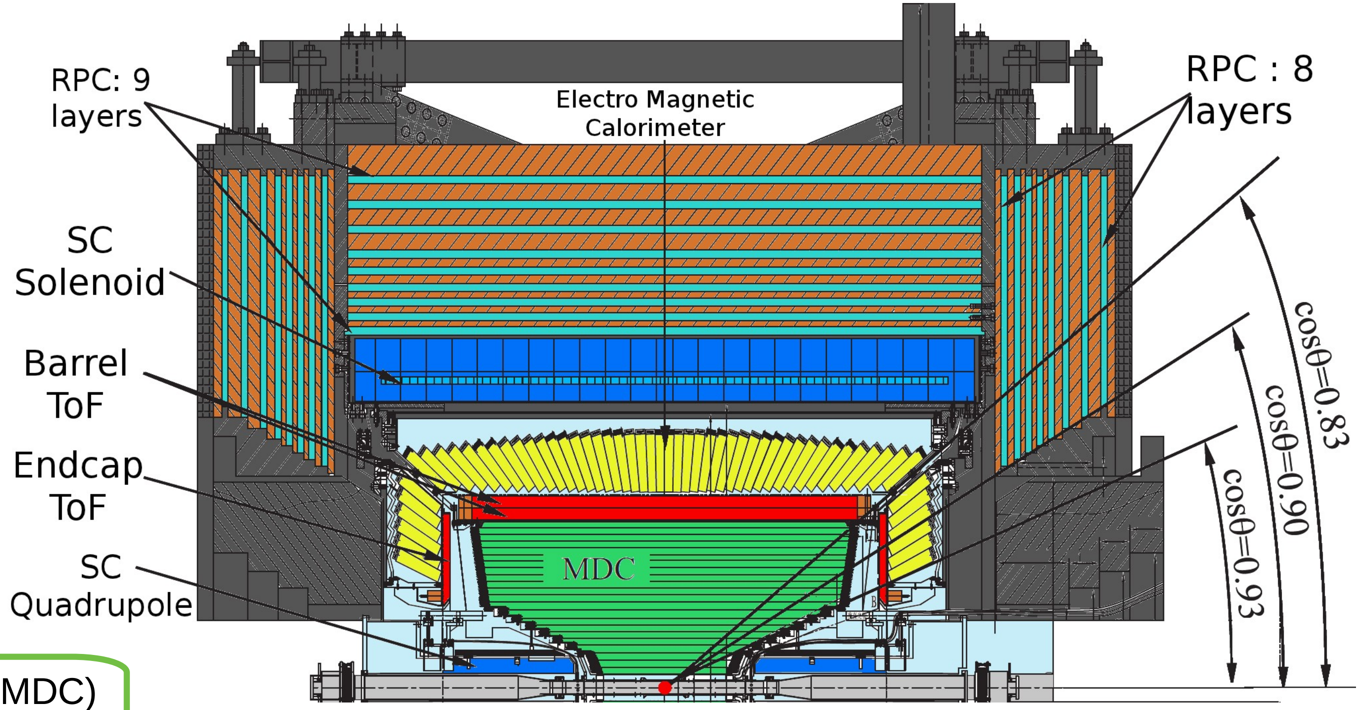
World's largest e+e- data sets at τ-charm energies

- 10^{10}J/ψ and 2.7×10^9ψ(2s) directly produced
- More than 40 fb^{-1} collected between 3.773 and 5 GeV
- Currently collecting 20 fb^{-1} at 3.773 GeV

This work:

- 14 R scan data points (~110 pb^{-1})
- 2.23 GeV – 3.67 GeV

Beijing Spectrometer – BESIII



Nucl.Instr.Meth. A614 (2010) 345

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

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

EM Calorimeter (EMC)
- 6240 CsI(Tl) crystals
- $\sigma(E)/E = 2.5\%$
- $\sigma_{z,\phi}(E) = 0.5 – 0.7$ cm

Time-of-flight system (TOF)
- $\sigma(t) = 60$ps

Superconducting Magnet
- 1 T magnetic field

Determination of R-Value

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

Leading-order QED cross section
$e^+e^- \to \mu^+\mu^-$

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

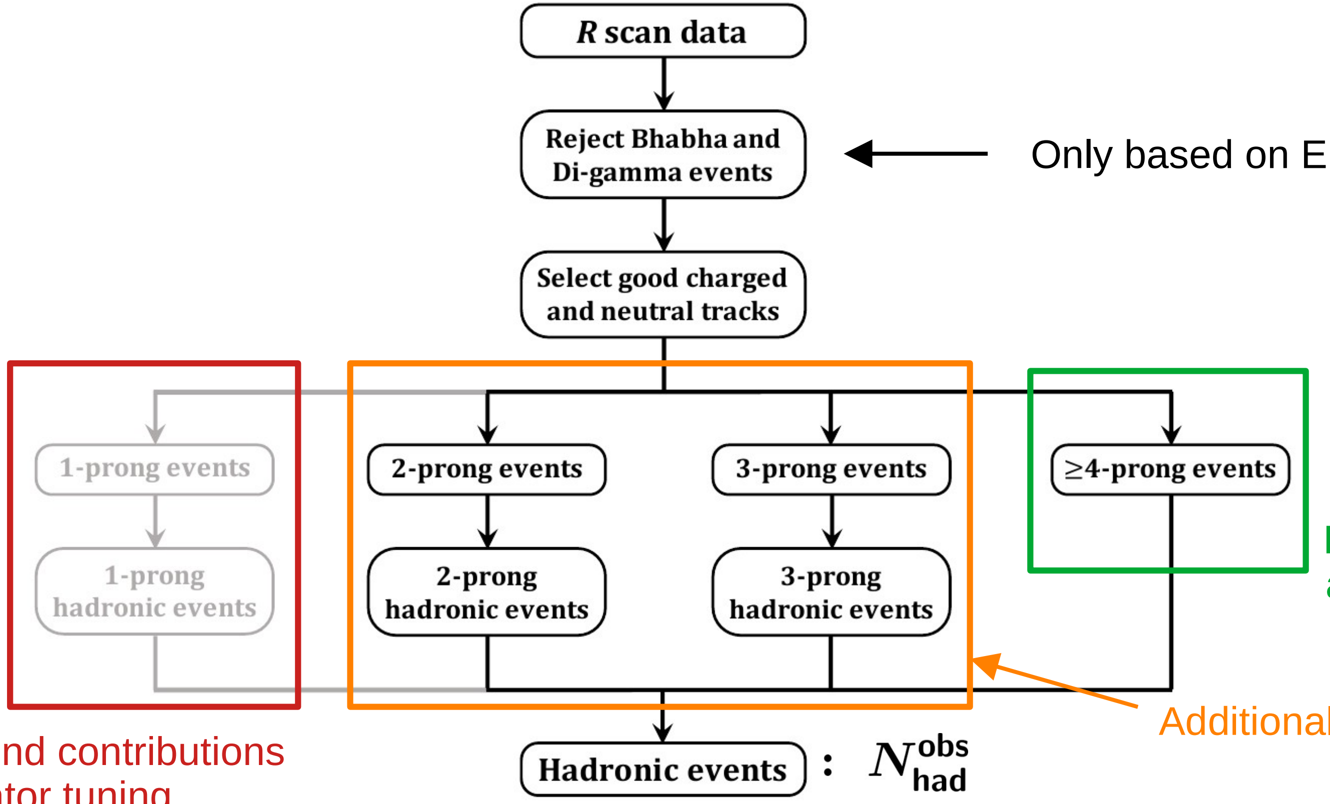
Integrated luminosity
- Determined from LA-Bhabha scattering
- 0.8% uncertainty

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

Trigger efficiency
for hadronic events ~100%

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

Analysis Stategy



Only based on EMC information

Directly considered as hadronic events

Additional conditions applied

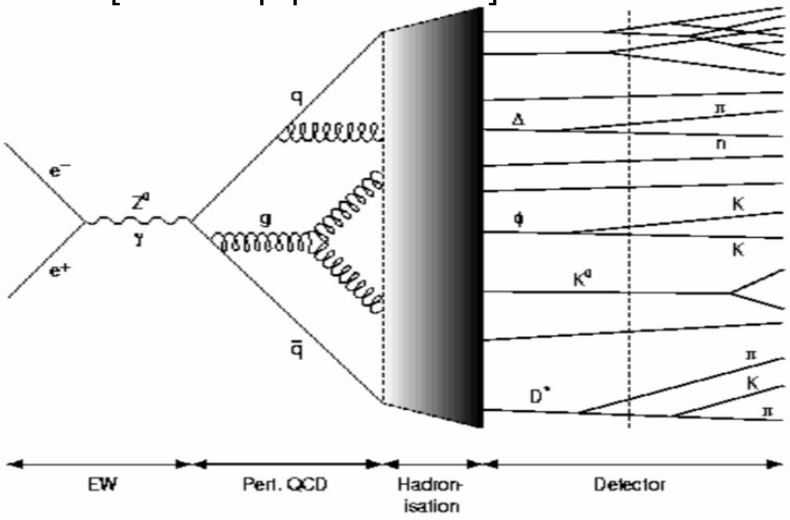
High QED background contributions
Only used in generator tuning

LUARLW: Nominal Model for Signal Simulation

- Inclusive event generator
- 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

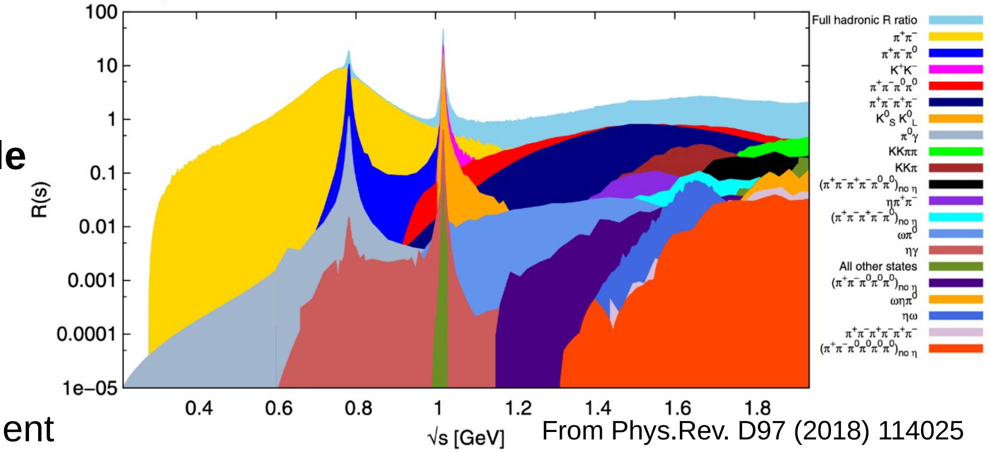
[arXiv:hep-ph/9910285]



Alternative Model: “Hybrid Generator”

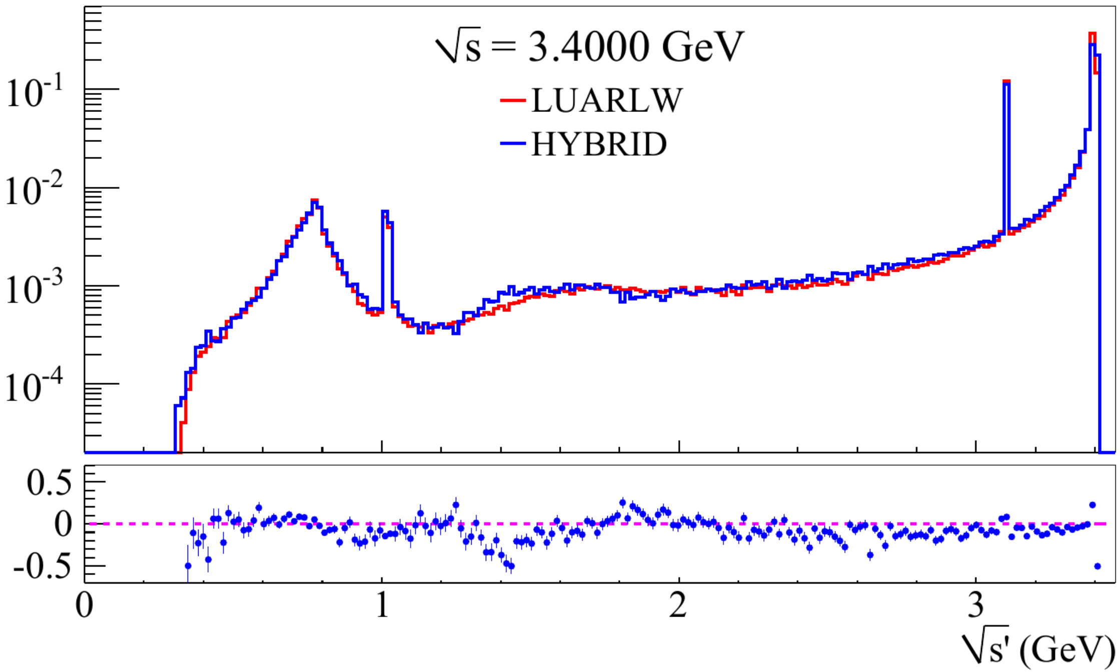
New event generator developed:

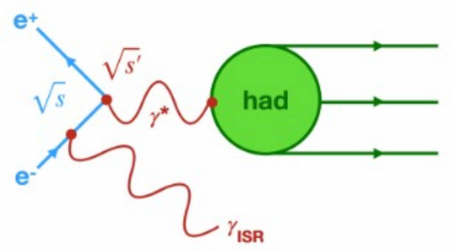
- Idea: **Use as much experimental information as possible**
- Combination of three established event generators
  - Phokhara
    - 10 exclusive channels, hadronic models tuned to experiment
  - ConExc
    - More than 50 channels with cross sections from experiment
  - LUARLW
- Alternative ISR and VP correction schemes implemented



From Phys.Rev. D97 (2018) 114025

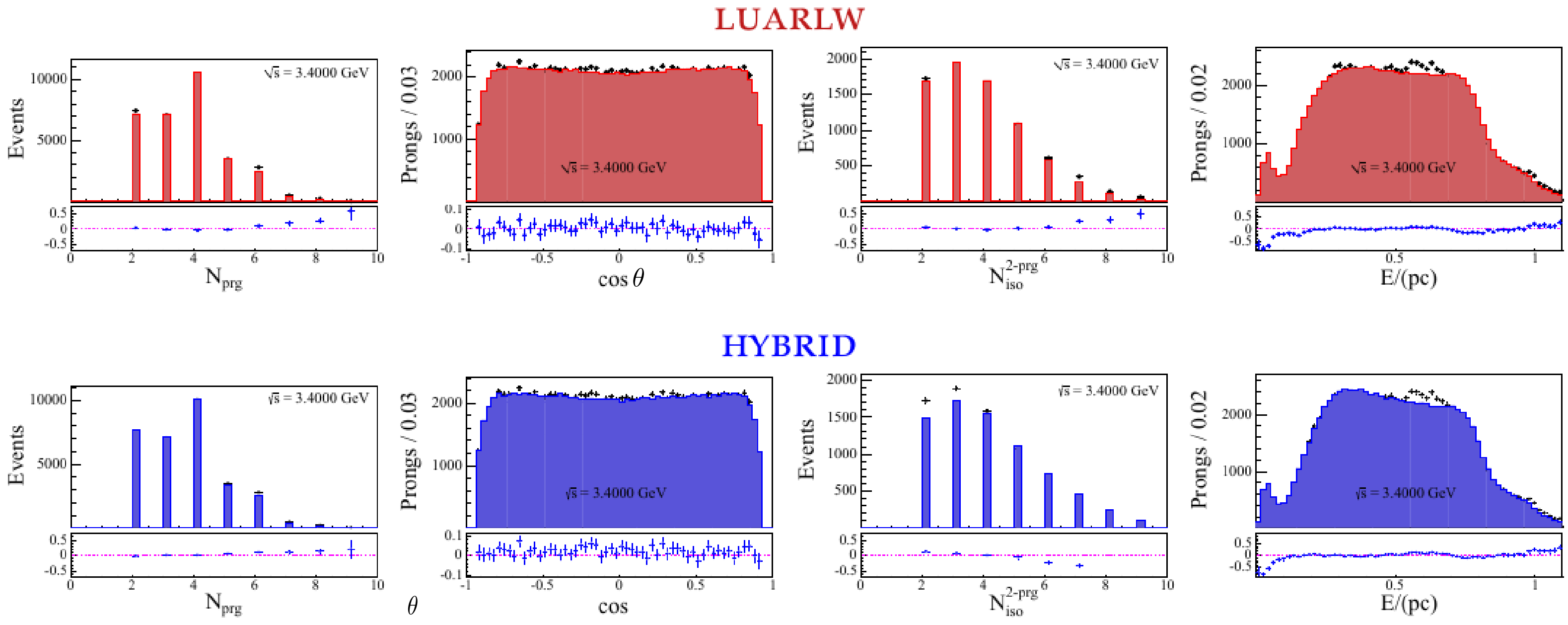
Comparison of the two Generators





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

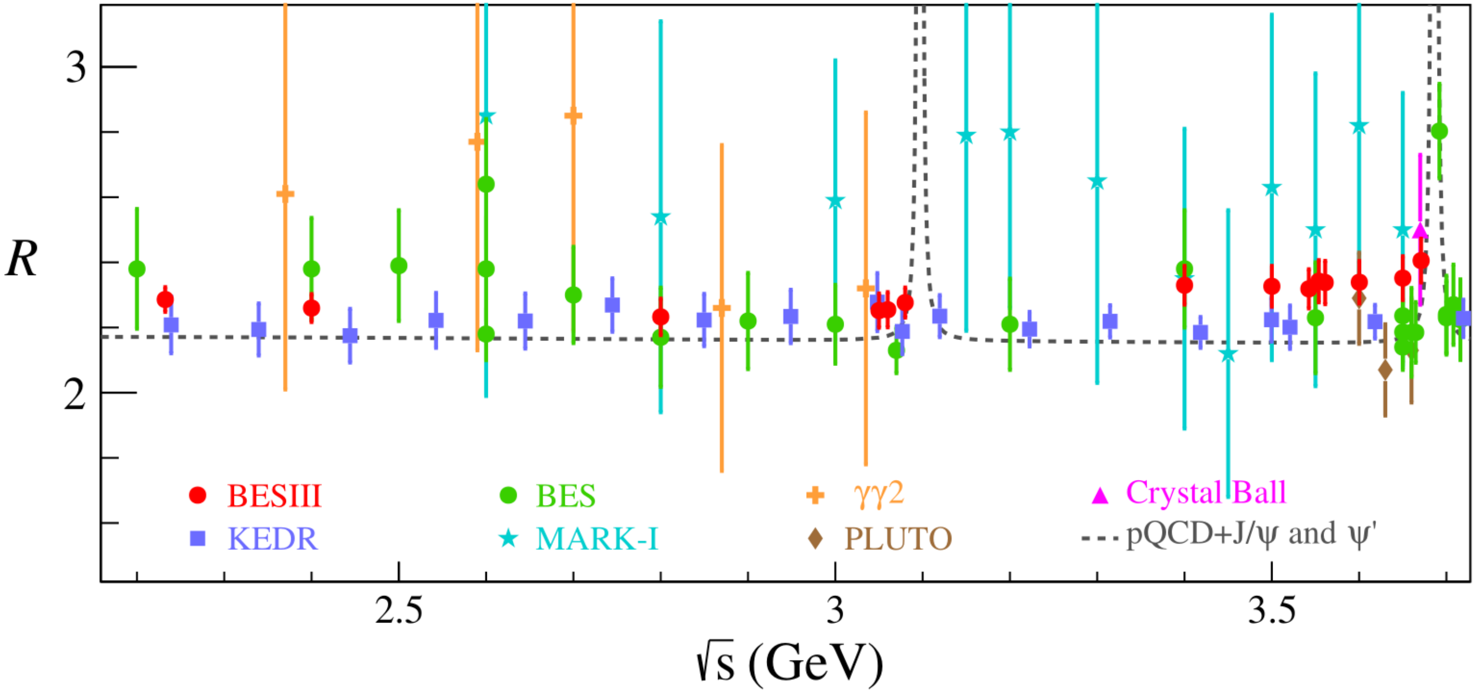
Comparison of the two Generators



- 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

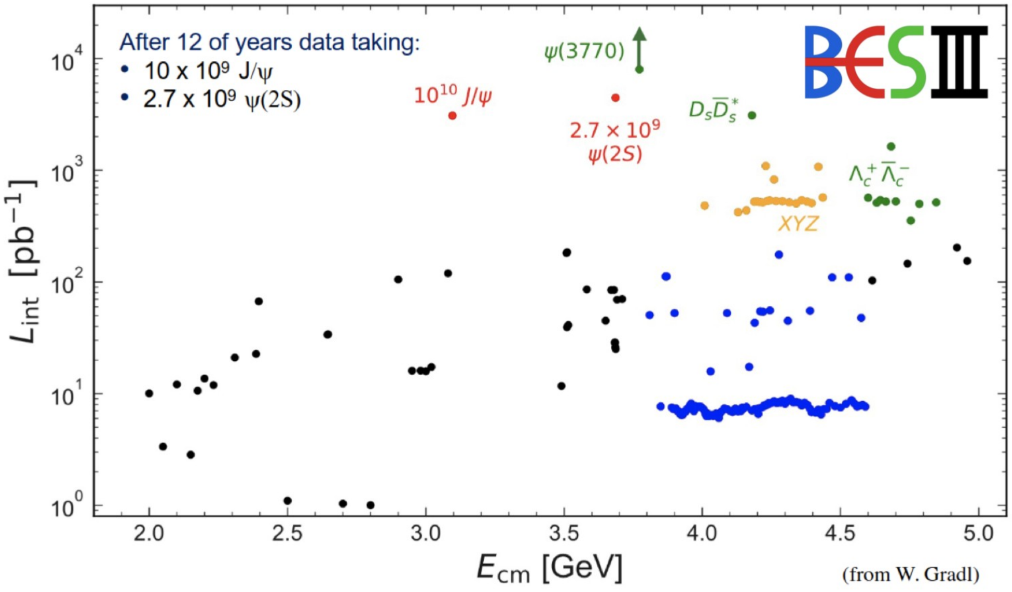
Good agreement of both generator models and data !

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



(from W. Gradl)

This work:

- 14 R scan data points (~110 pb^{-1})
- 2.23 GeV – 3.67 GeV

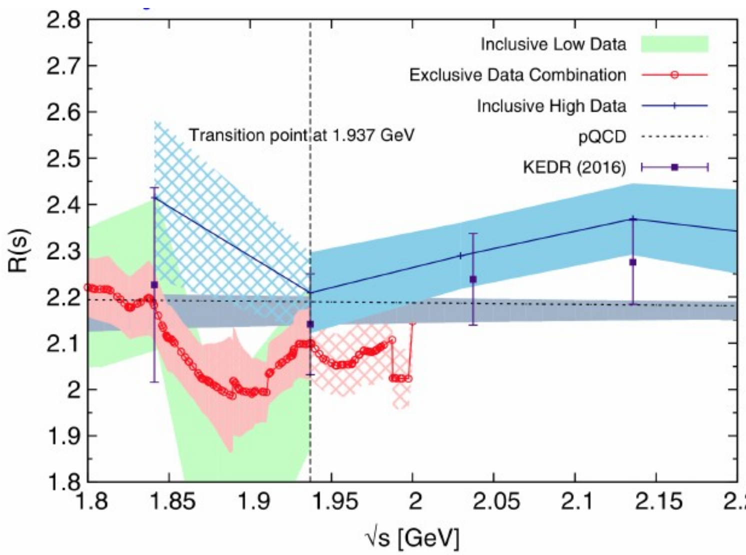
For future analysis:

- 21 R scan data points
- 2.00 GeV – 3.08 GeV
- ~550 pb^{-1}

- 104 R scan data points
- 3.85 GeV – 4.59 GeV
- ~800 pb^{-1}

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

Alternative Approach to R-Value Measurement



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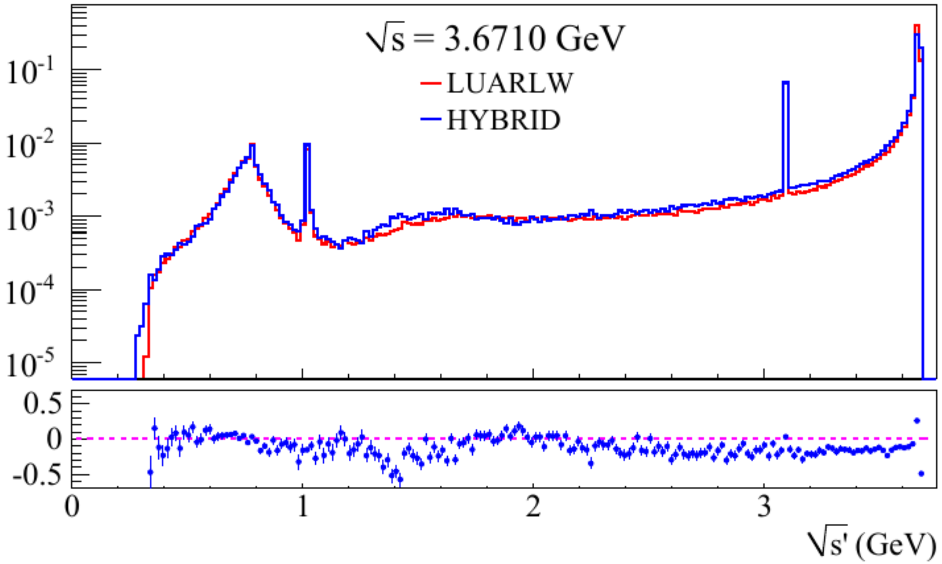

- **Exclusive** measurements for $\sqrt{s} < 2\,\text{GeV}$
- **Inclusive** measurements for $\sqrt{s} > 2\,\text{GeV}$
- Tensions in transition region

- Use **ISR technique**
- Exploit large charmonium data sets at BESIII
- **Better detection efficiency** due to ISR kinematics
- Comparison of inclusive and exclusive measurements

Summary

High accuracy determination of R-Value important for Standard Model tests

- Running of $\alpha_{\text{em}}(M_Z^2)$
- Muon anomaly a_μ

Pilot R-Value measurement at BESIII published in 2022

Phys. Rev. Lett. 128 (2022) 062004

- $2.2324 \leq \sqrt{s}[\mathrm{GeV}] \leq 3.6710$
- Accuracy better than
  - 2.6% below 3.1 GeV
  - 3% in the region above

- Additional high statistics energy scan data samples available
- Alternative approach exploiting ISR being developed at BESIII

See poster by T. Lenz