R-Value Measurements at BESIII

11th International Workshop on Charm Physics (CHARM 2023) in Siegen

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for the BESIII Collaboration

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SFB 1044 THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

Cluster of Excellence PRiSMA+ Precision Physics, Fundamental Interactions and Structure of Matter

DFG Deutsche Forschungsgemeinschaft

BESIII

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

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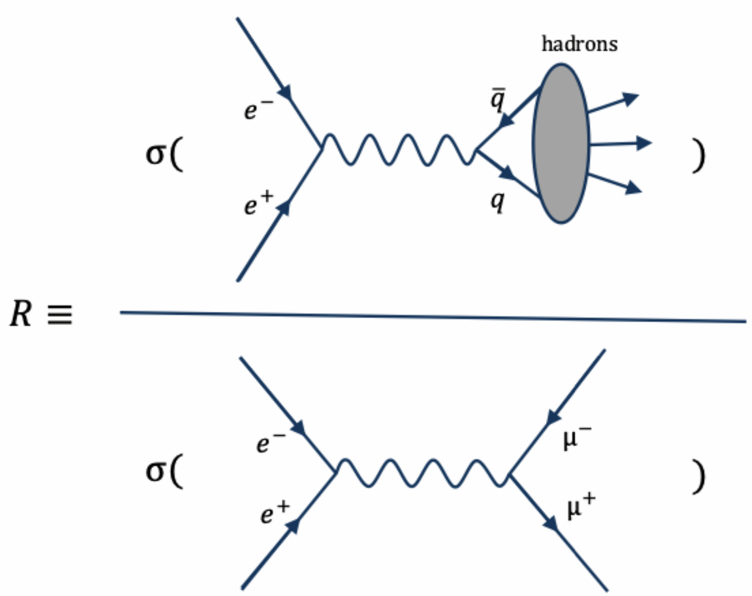
Definition of the R-Value

- Ratio of leading-order production cross section of hadrons and muon pairs 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 $\sigma^0_{\mu\mu}$ from QED:

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



→ **Important quantity in particle physics to test the Standard Model (SM)!**

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

- R-value contributes in determination of running QED coupling constant at Z pole → $\boldsymbol{\alpha(M_Z^2)}$

→ Precision test for the SM & essential for electroweak precision physics!

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

from perturbation theory

Hadronic Vacuum Polarisation contribution:

top quark contribution

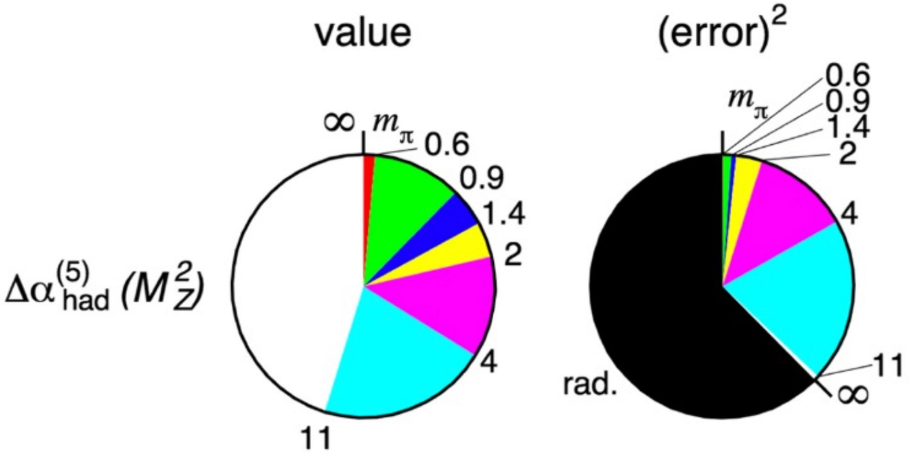
$$\Delta\alpha_{\text{had}}^{(5)}(s) = -\frac{\alpha s}{3\pi}\,\text{Re}\int_{E_{\text{th}}}^{\infty} \text{d}s' \frac{\boldsymbol{R(s')}}{s'(s'-s-i\varepsilon)}$$

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

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

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

Eur. Phys. J. 80 (2020) 241

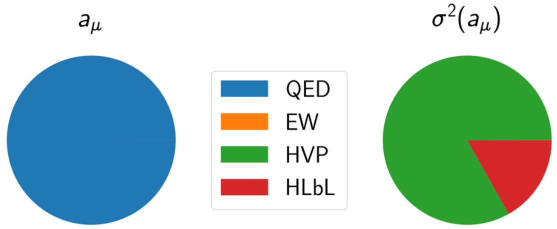


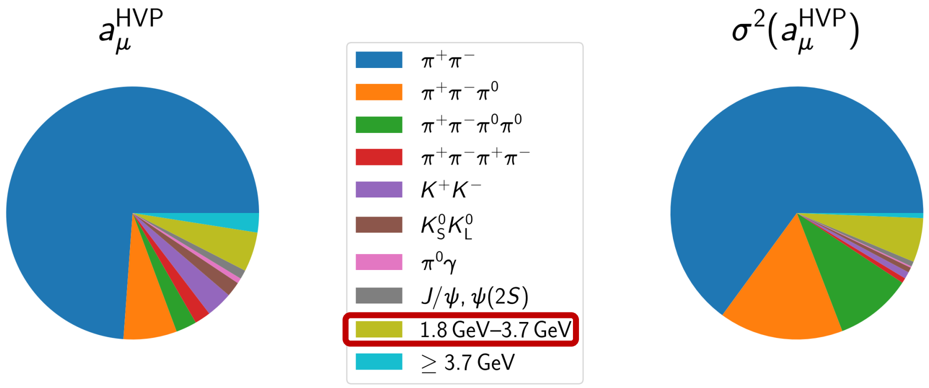
Phys. Rev. D97 (2019) 114025

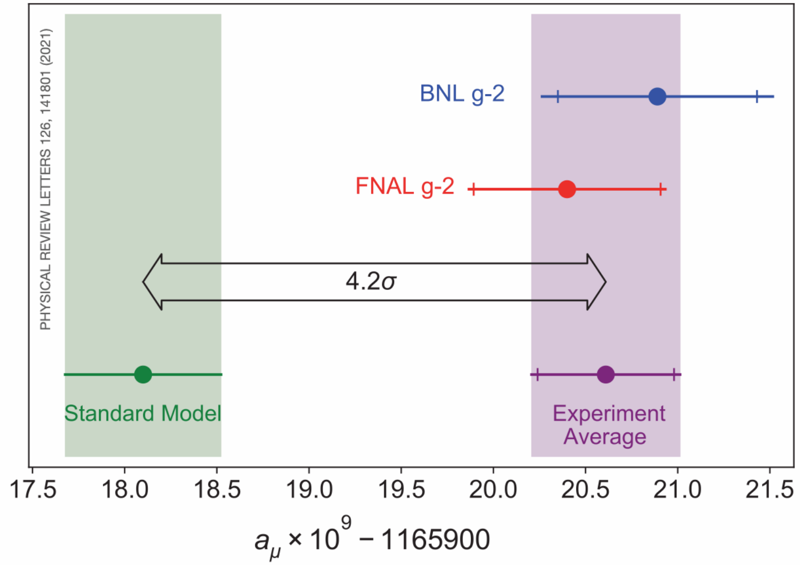
→ Over a wide energy range the **R-value is an important input!**

Anomalous Magnetic Moment of the Muon a_μ

- **Discrepancy of $4.2\ \sigma$** between SM prediction & direct measurements
- Hadronic contributions dominate by far the uncertainty of a_μ^{SM}
- **Hadronic Vacuum Polarisation (HVP):**
  - Dispersive approach: $a_\mu^{\mathrm{HVP}} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{2m_\pi}^{\infty} \mathrm{d}s\, \frac{\boldsymbol{R(s)}\, K(s)}{s^2}$
  - **R-value needed as experimental input**

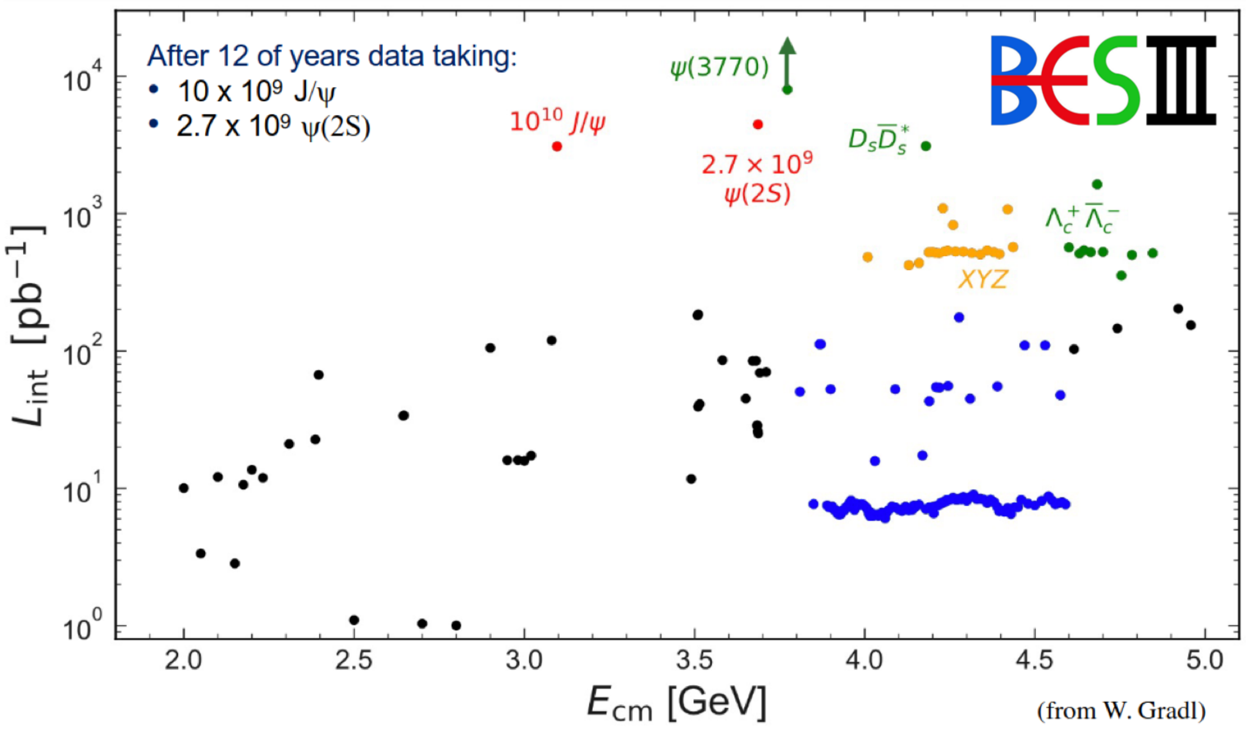






Beijing Electron-Positron Collider II (BEPCII)

- Energy range: **2.0 GeV $\leq \sqrt{s} < 5.0$ GeV**
- Peak luminosity reached: $\mathcal{L} = 1.1 \cdot 10^{33} \mathrm{cm}^{-2}\mathrm{s}^{-1}$ **at** $\psi(3770)$
- World‘s largest τ-charm data set in e^+e^- annihilation!



(from W. Gradl)

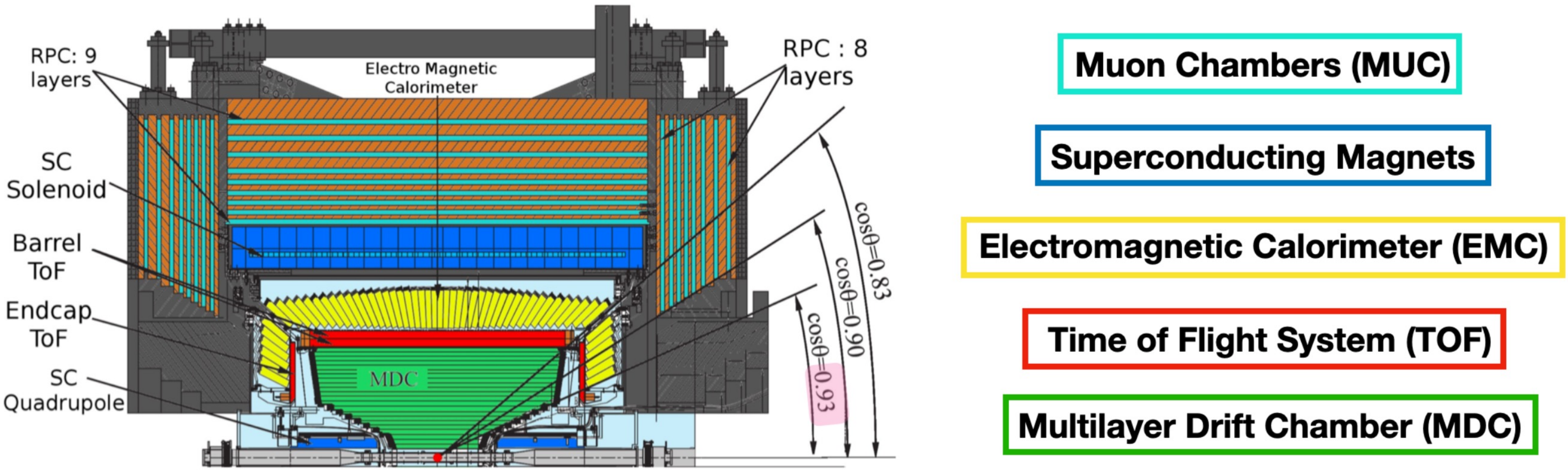
Highlights of BESIII:

- 10^{10} J/ψ events
- 2.7 x 10^9 $\psi(2S)$ events
- Currently upgrading **$\psi(3770)$ data set** 2.9 fb^{-1} → 20 fb^{-1}

This work:

- 14 R scan data points
- **2.23 GeV to 3.67 GeV**
- ~110 pb^{-1}

Beijing Spectrometer III (BESIII)



M. Ablikim et al., Nucl. Instrum. Meth. A 614, 345 (2010)

- Cylindrically shaped general purpose detector with four main layers
- Superconducting solenoid magnet providing a 1 Tesla magnetic field
- Can cover **93% of the full solid angle** → photons at polar angles above 21°

Determination of the R-Value

Integrated luminosity

- Determined from large angle Bhabha scattering
- 0.8% uncertainty

Residual background events

- MC simulation
- QED background processes
- Beam related contributions from data

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

Initial State Radiation (ISR) correction factor

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

Trigger efficiency for hadronic events ~ 100%

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

Detection efficiency for inclusive hadronic events

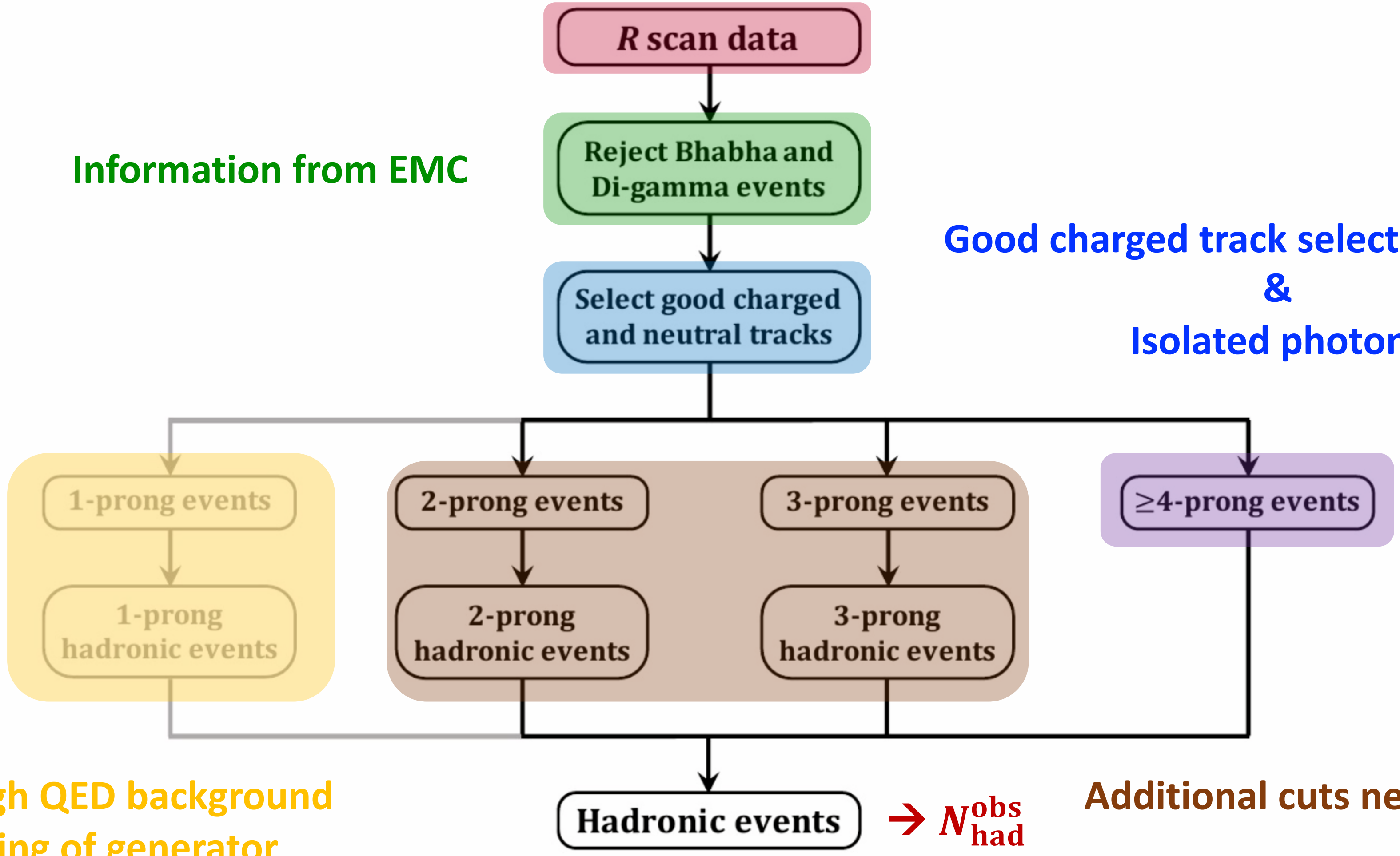
- **Most crucial source for uncertainties!**
- Evaluated using two different generator models

Analysis Workflow

2.23 GeV to 3.67 GeV

Information from EMC

Good charged track selection (prongs)
&
Isolated photons



→ N_{had}^{obs}

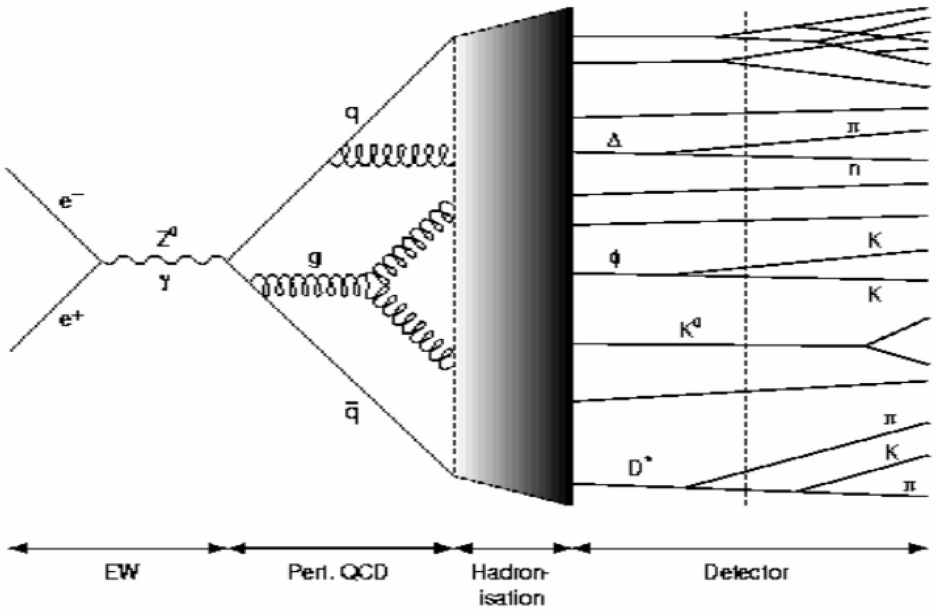
Directly counted as hadronic events

Not used due to high QED background
→ Used for tuning of generator

Additional cuts needed

LUARLW: Nominal Model for Signal Simulation

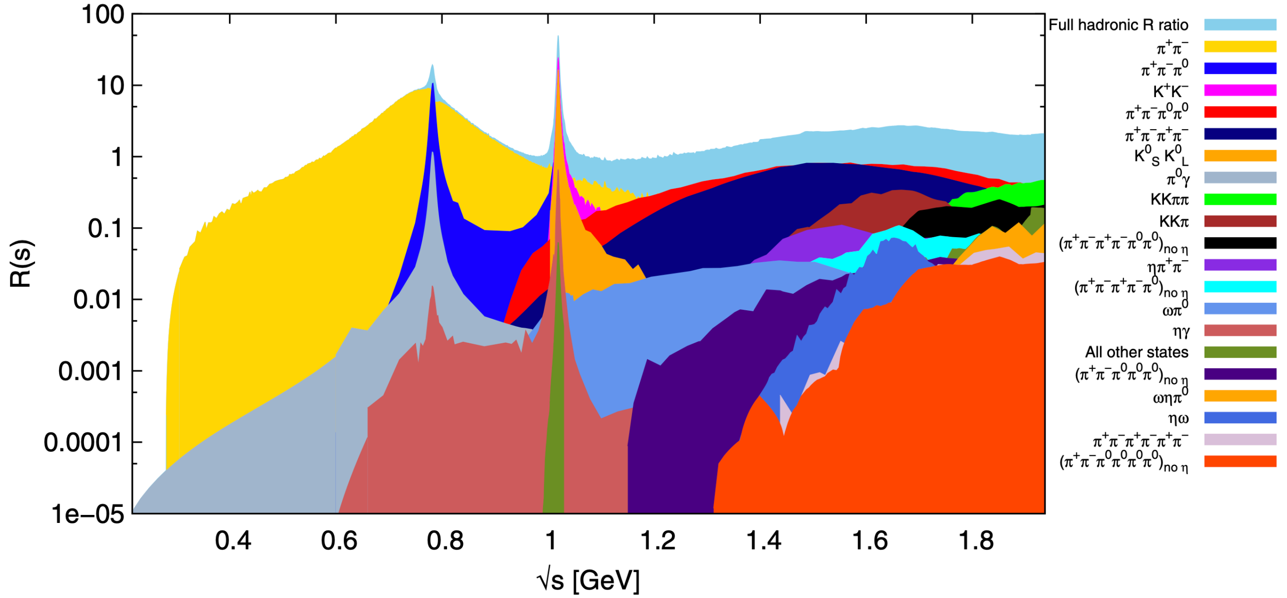
- Self consistent **inclusive generator**
- Based on **JETSET** for low energies
- Kinematics of initial hadrons determined from **Lund area law** [arXiv:hep-ph/9910285]
- Generation of resonant and continuum states
- **ISR** implemented from $m_{\pi\pi}$ to $\sqrt{s}$
- Phenomenological parameters tuned to data
- Used in most previous R-value measurements



Hadronisation procedure in e^+e^- annihilation

Alternative Model: HYBRID Generator

- New event generator with **as much experimental input as possible**
- Combination of three established event generators:
  - **Phokhara:** 10 exclusive channels, hadronic models tuned to experiment
  - **ConExc:** 47 channels with cross sections from experiment
  - **LUARLW:** remaining unknown processes



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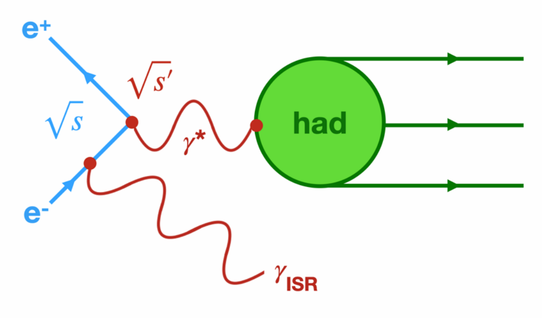
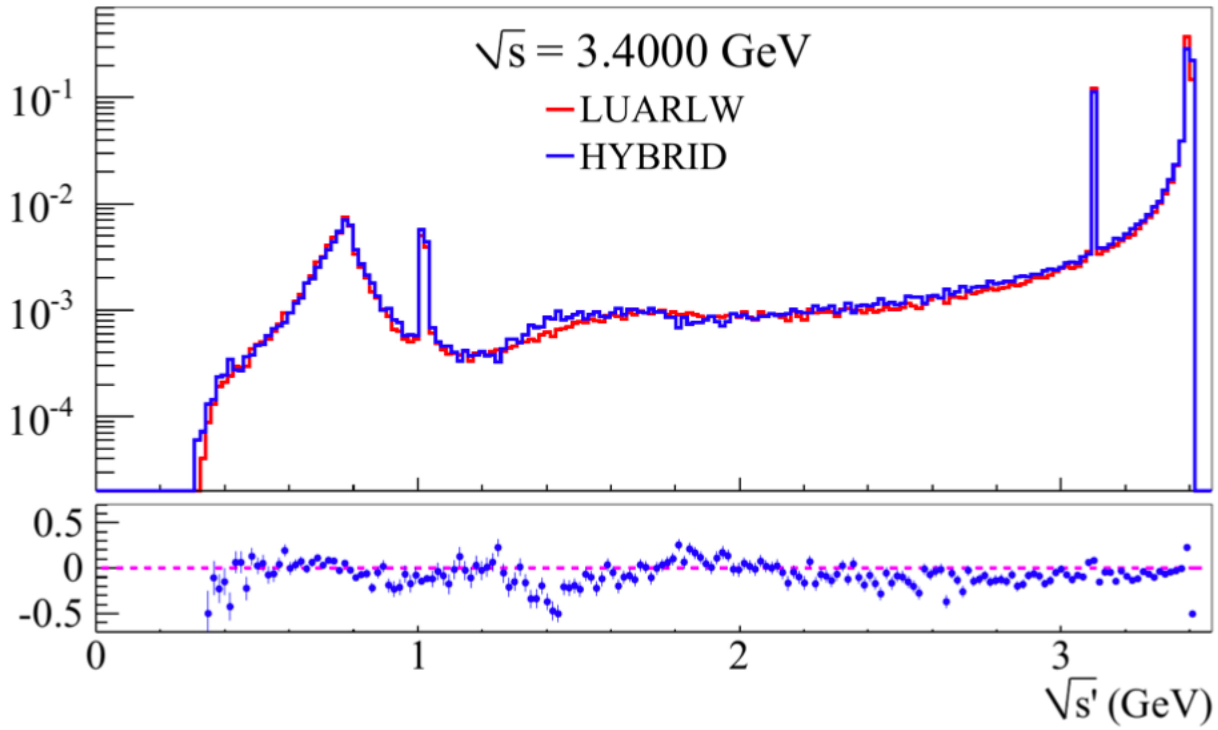
Comparison of LUARLW and HYBRID Generator

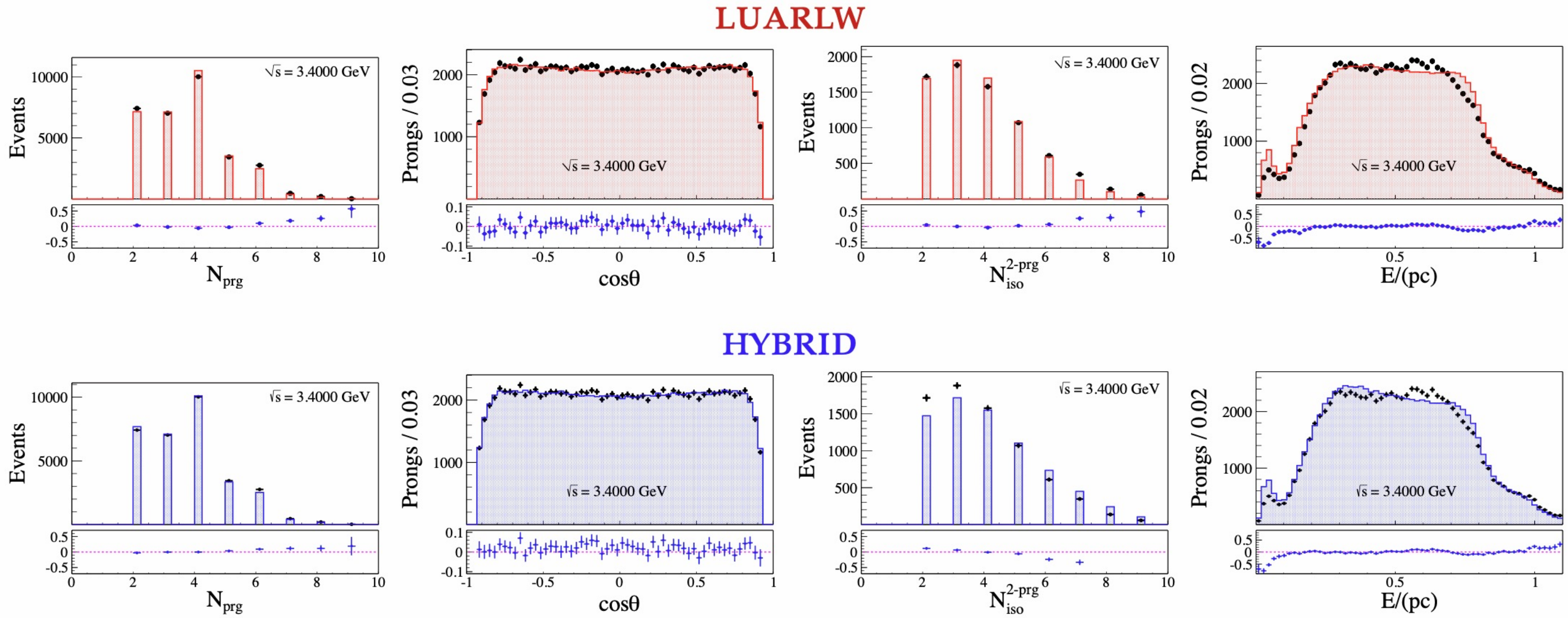




- Effective energy spectrum of simulated ISR processes at $\sqrt{s} = 3.4$ GeV
- LUARLW and HYBRID generators
- $\sqrt{s'}$ spectrum directly reflects the **fraction** of ISR-returned processes

→ **Consistent $\sqrt{s'}$ spectra!**

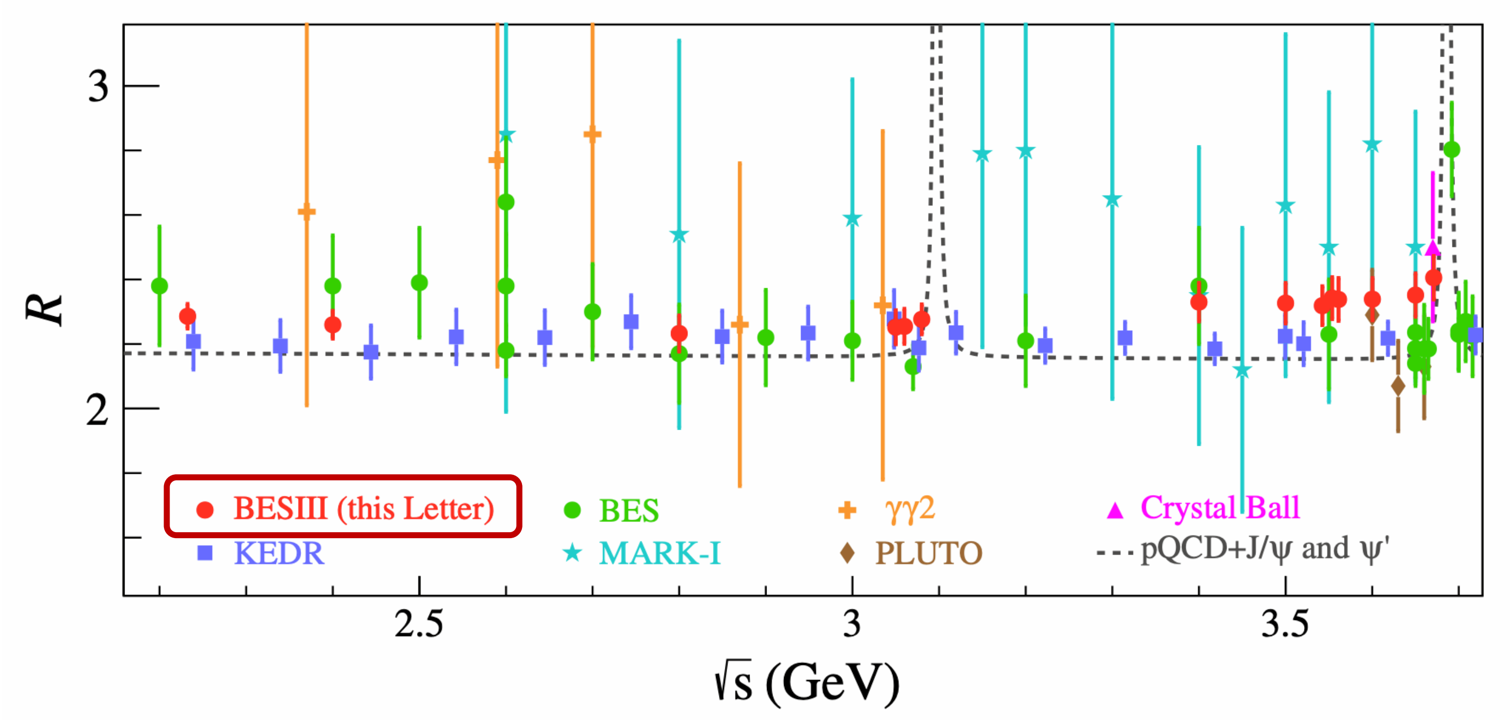
Comparison of LUARLW and HYBRID Generator with Data



- $\boldsymbol{N_{\mathrm{prg}}}$: Number of good charged tracks (prong)
- $\boldsymbol{N_{\mathrm{iso}}^{\mathrm{2prg}}}$: Number of isolated clusters in 2-prong events
- $\boldsymbol{\cos(\theta)}, \boldsymbol{E}$, and $\boldsymbol{p}$: polar angle, EMC deposited energy, and measured momentum in MDC

Good agreement of both generator models & data!

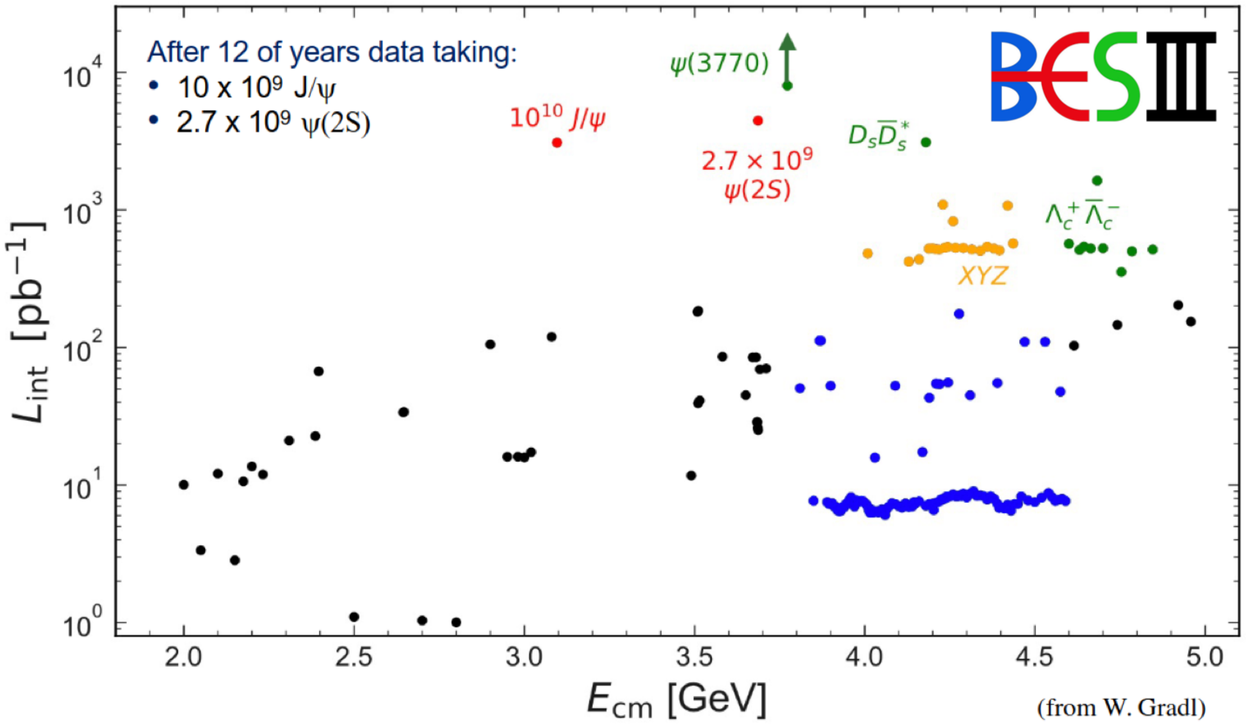
Results of R-Value Measurements between 2.2 and 3.7 GeV



Phys. Rev. Lett. 128 (2022) 062004

- Accuracy better than **2.6%** below 3.1 GeV & better than **3%** above
- In the energy region from 3.4 to 3.6 GeV:
  - **Larger than KEDR** result by 1.9σ & **larger than pQCD prediction** by 2.7σ

Further R-Value Measurements at BESIII



This work:

- 14 R scan data points
- **2.23 to 3.67 GeV**
- ~110 pb^{-1}

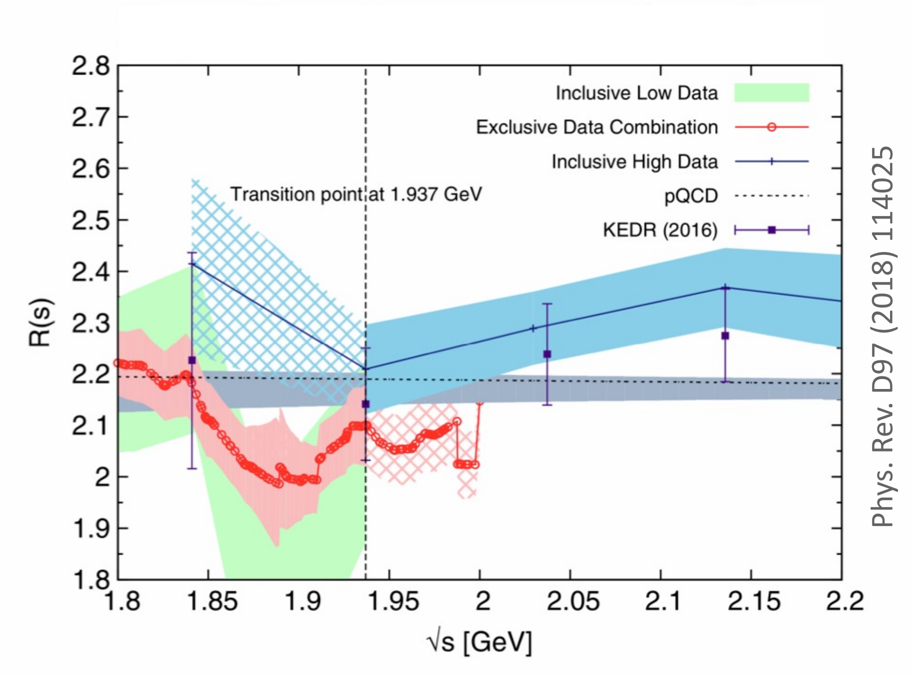
For future analyses:

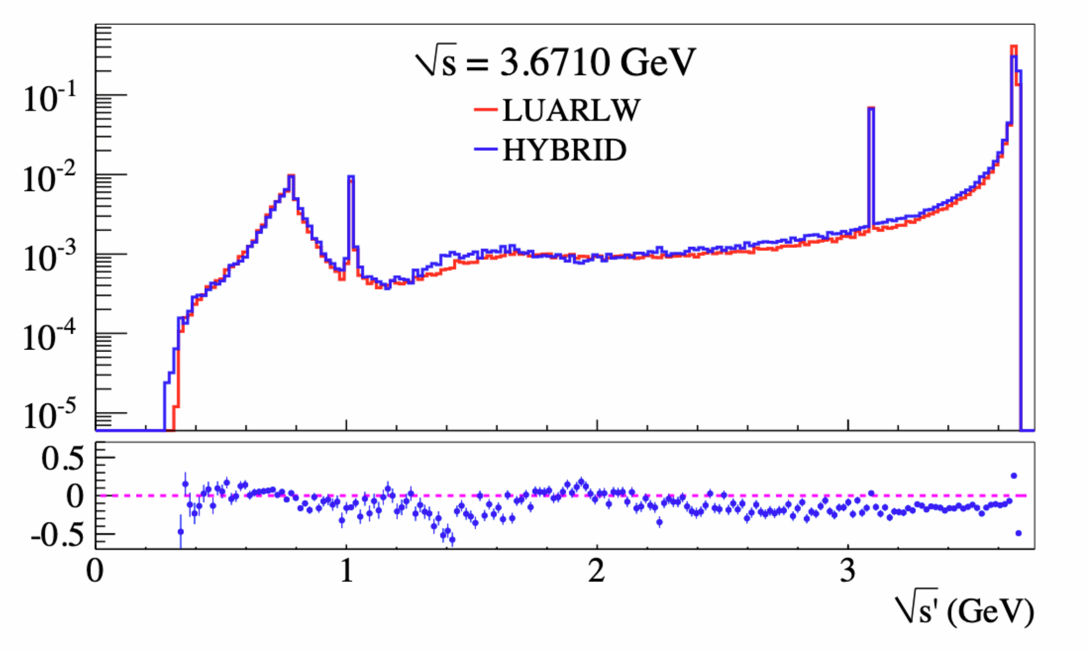
- 21 R scan data points
- **2.00 to 3.08 GeV**
- ~550 pb^{-1}

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

- Large amounts of **additional data available** (139 scan data points with $> 10^5$ hadrons each)
- High accuracy R-value measurements in continuum and open-charm region

Alternative Approaches for further R-Value Measurements





- **Exclusive** measurement below 2 GeV
- **Inclusive** measurement above 2 GeV
- Tensions in transition region

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

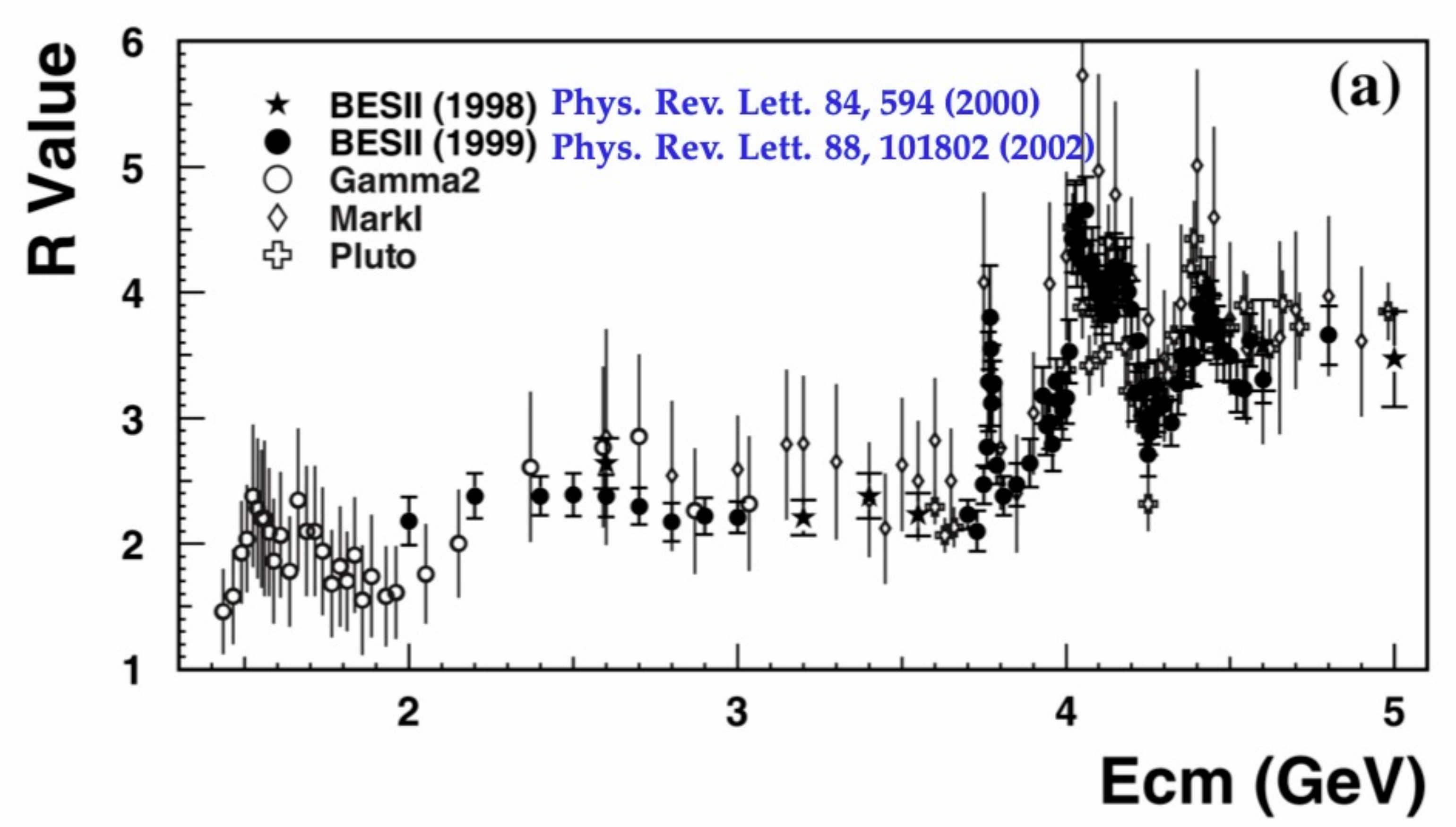
Summary & Outlook

- **High accuracy R-value measurements important to test the SM**
  - 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)
  - $2.2324 \text{ GeV} \leq \sqrt{s} \leq 3.6710 \text{ GeV}$
  - Accuracy better than
    - 2.6% below 3.1 GeV
    - 3% in the region above
- **Additional high statistics data samples available**
- Alternative approach exploiting ISR being developed at BESIII

Thank you for your attention!

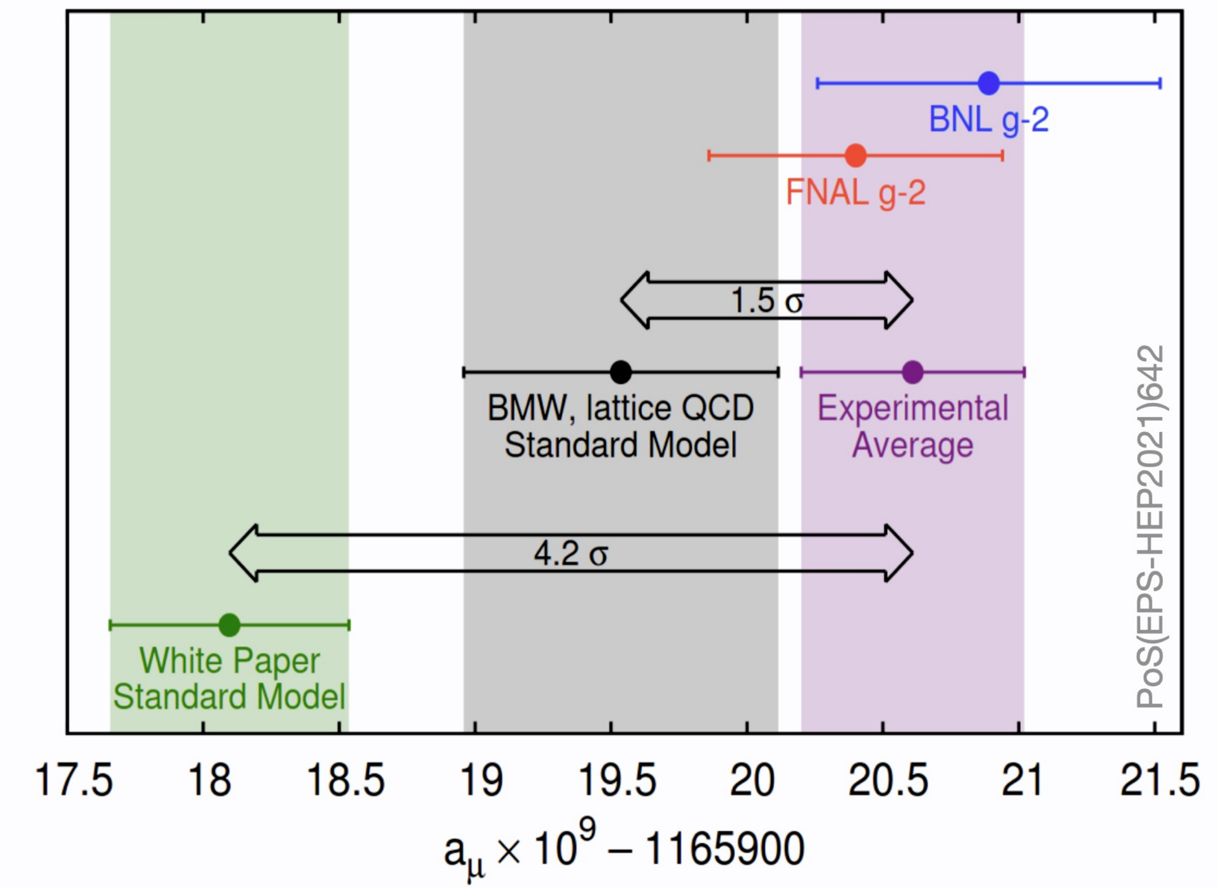
Backup

R-Value Measurements at BESII



- BESII improved the precision of R from 15-20% to 6%!

Lattice QCD Result for a_μ^{SM}

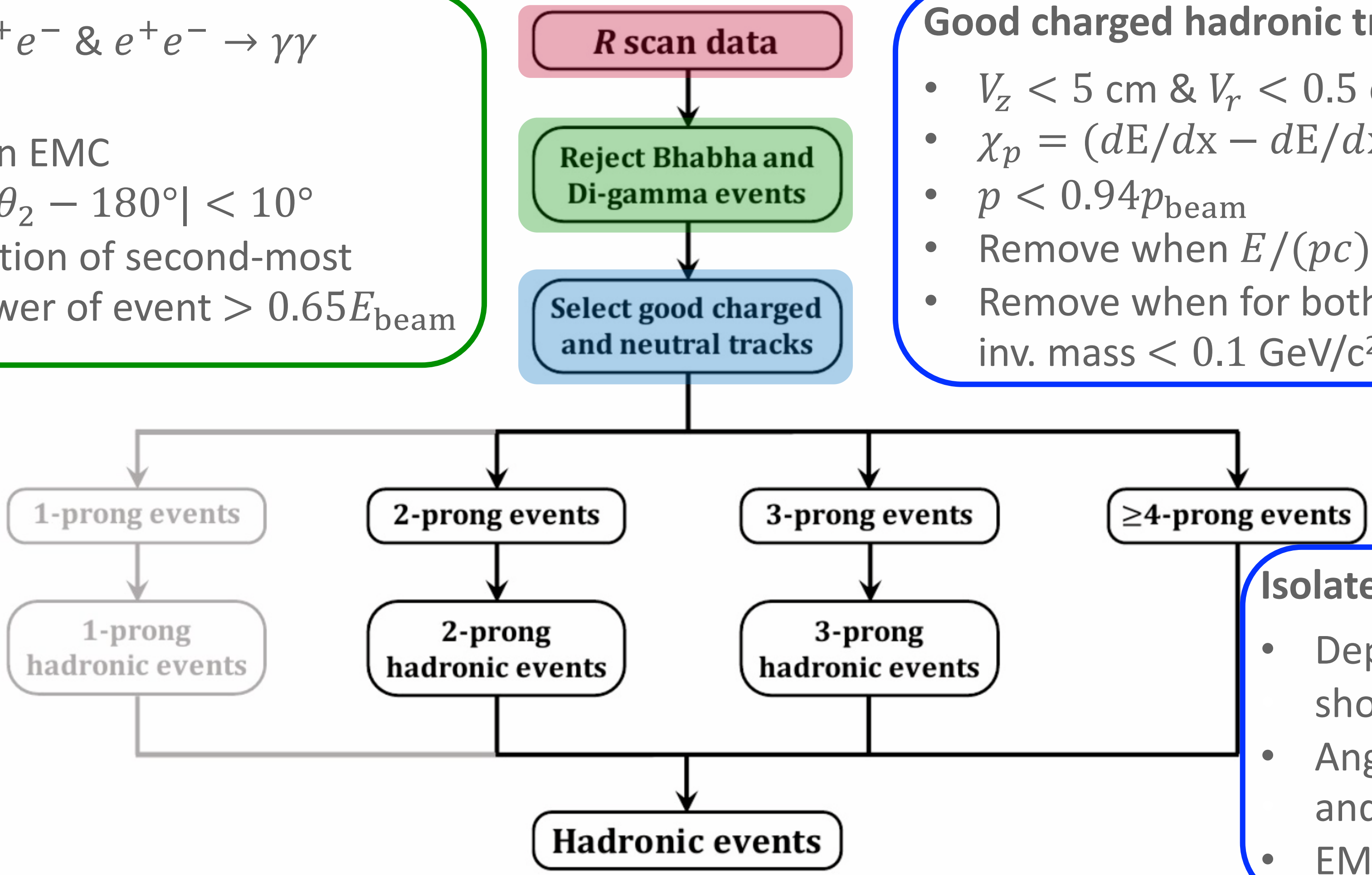


- Discrepancy between a_μ^{SM} and a_μ^{exp}: $4.2\ \sigma$
- In tension with latest lattice QCD result from BMW collaboration: $1.5\ \sigma$

Analysis Workflow

- Identify $e^+e^- \to e^+e^-$ & $e^+e^- \to \gamma\gamma$
- Reject them by:
  - $\geq$ 2 showers in EMC
  - $|\Delta\theta| = |\theta_1 + \theta_2 - 180°| < 10°$
  - Energy deposition of second-most energetic shower of event $> 0.65E_{\text{beam}}$

2.23 GeV to 3.67 GeV



Good charged hadronic tracks (prongs)

- $V_z < 5$ cm & $V_r < 0.5$ cm & $|\cos\theta| < 0.93$
- $\chi_p = (dE/dx - dE/dx_p)/\sigma_p < 10$
- $p < 0.94p_{\text{beam}}$
- Remove when $E/(pc) > 0.8$ & $p > 0.65p_{\text{beam}}$
- Remove when for both tracks $E/(pc) > 0.8$ & inv. mass < 0.1 GeV/c² & opening angle $< 15°$

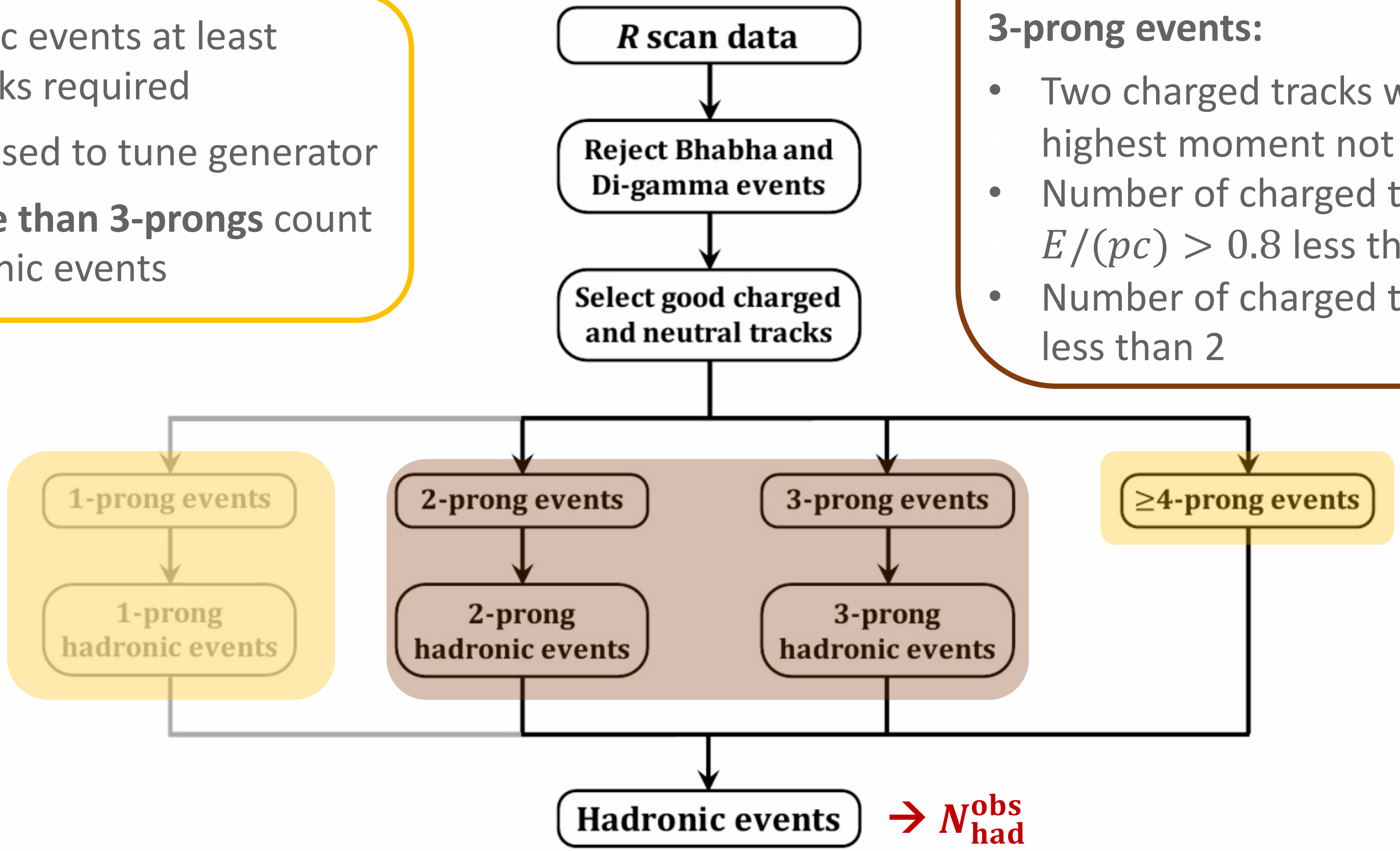
Isolated photons

- Deposited energy of shower > 0.1 GeV
- Angle between shower and nearest track > 20°
- EMC timing: $0 \leq T \leq 700$ ns

Analysis Workflow

- To select hadronic events at least two charged tracks required
- **1-prong events** used to tune generator
- Events with **more than 3-prongs** count directly as hadronic events

2.23 GeV to 3.67 GeV



→ N_{had}^{obs}

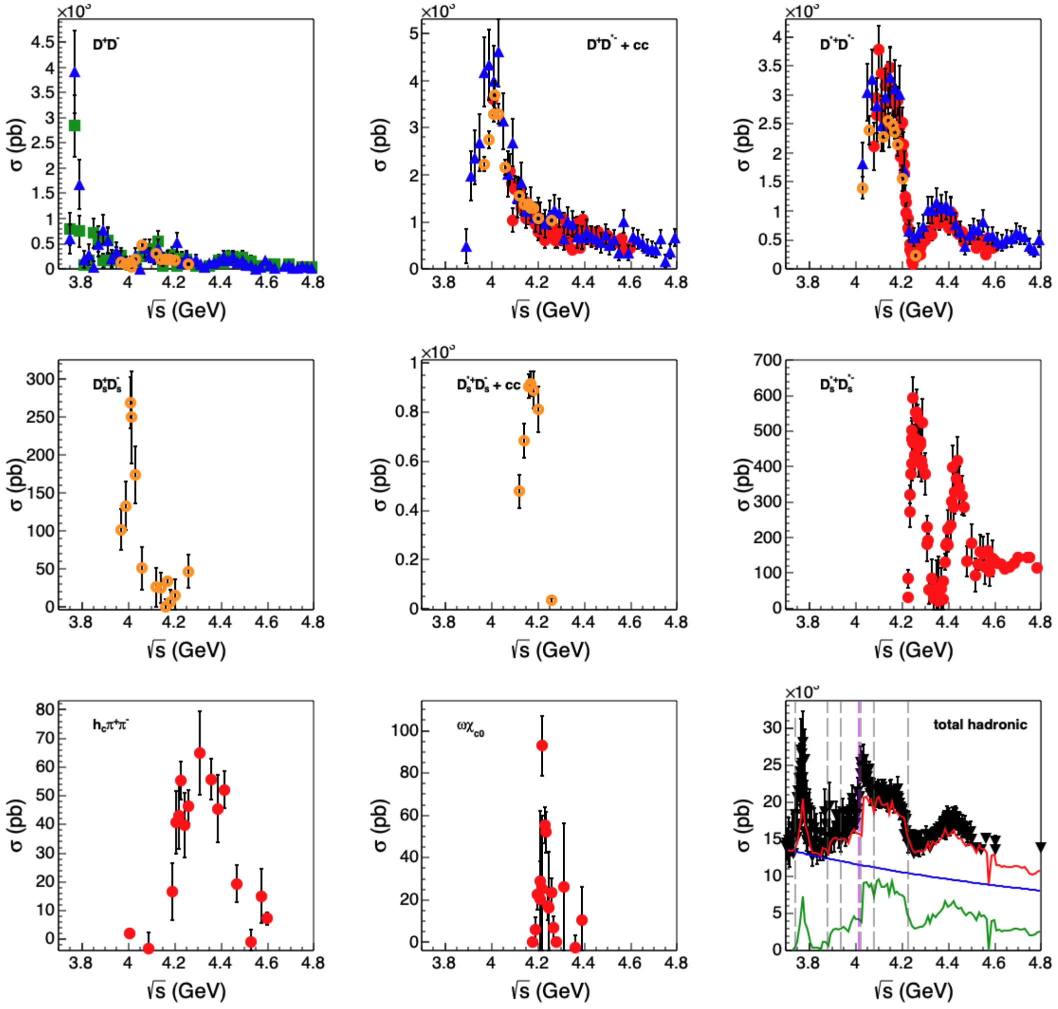
2-prong events:

- Two charged tracks not back-to-back
- Number of isolated photons > 1

3-prong events:

- Two charged tracks with highest & second highest moment not back-to-back
- Number of charged tracks with $E/(pc) > 0.8$ less than 2
- Number of charged tracks with $r_{\mathrm{PID}} > 0.25$ less than 2

CC Cross Sections



Individual channels:

- Red: BESIII
- Blue: Belle
- Green: BaBar
- Yellow: CLEO
- Black: PDG

by Nils Hüsken

Total hadronic:

- Green: Sum of exclusive channels
- Blue: pQCD for $R_{uds} \cdot \sigma_{\mu\mu}$
- Red: Sum