R-Value Measurement at BESIII

Frederic Stieler for the BESIII collaboration

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SFB 1044 THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL
Cluster of Excellence PRISMA+
DFG Deutsche Forschungsgemeinschaft German Research Foundation
BESIII
JOHANNES GUTENBERG UNIVERSITÄT MAINZ
JG|U

Definition of R-Value

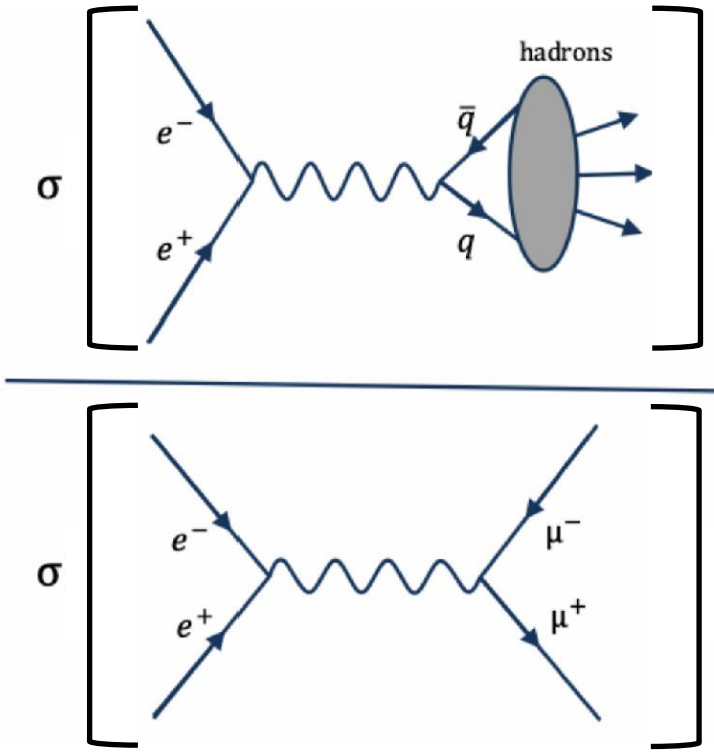
Ratio of leading-order cross section of hadron and muon pair production in e^+e^- annihilation

$$R \equiv \frac{\sigma^0(e^+e^- \to \text{hadrons})}{\sigma^0(e^+e^- \to \mu^+\mu^-)} \equiv \frac{\sigma^0_{\text{had}}}{\sigma^0_{\mu\mu}} \approx N_c \sum_f Q_f^2$$

with $\sigma^0_{\mu\mu}$ from QED:

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

$$R \equiv \frac{\sigma\left[e^+e^- \to \text{hadrons}\right]}{\sigma\left[e^+e^- \to \mu^+\mu^-\right]}$$



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

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

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

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

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

From perturbation theory

Hadronic Vacuum Polarisation Contribution

Top quark contribution

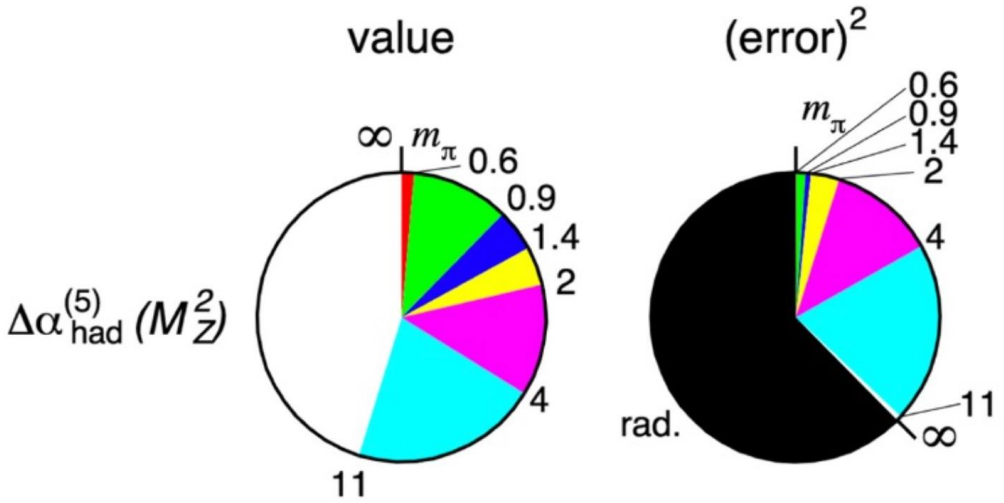
Running of the Fine Structure Constant: $\Delta\alpha_{em}$

Using the dispersive approach for the hadronic contribution

$$\Delta\alpha^{(5)}_{\text{had}}(s) = -\frac{\alpha s}{3\pi}\int_{s_{th}}^{\infty} ds' \frac{\boldsymbol{R(s')}}{s'(s'-s-i\epsilon)}$$

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

Eur. Phys. J. 80 (2020) 241

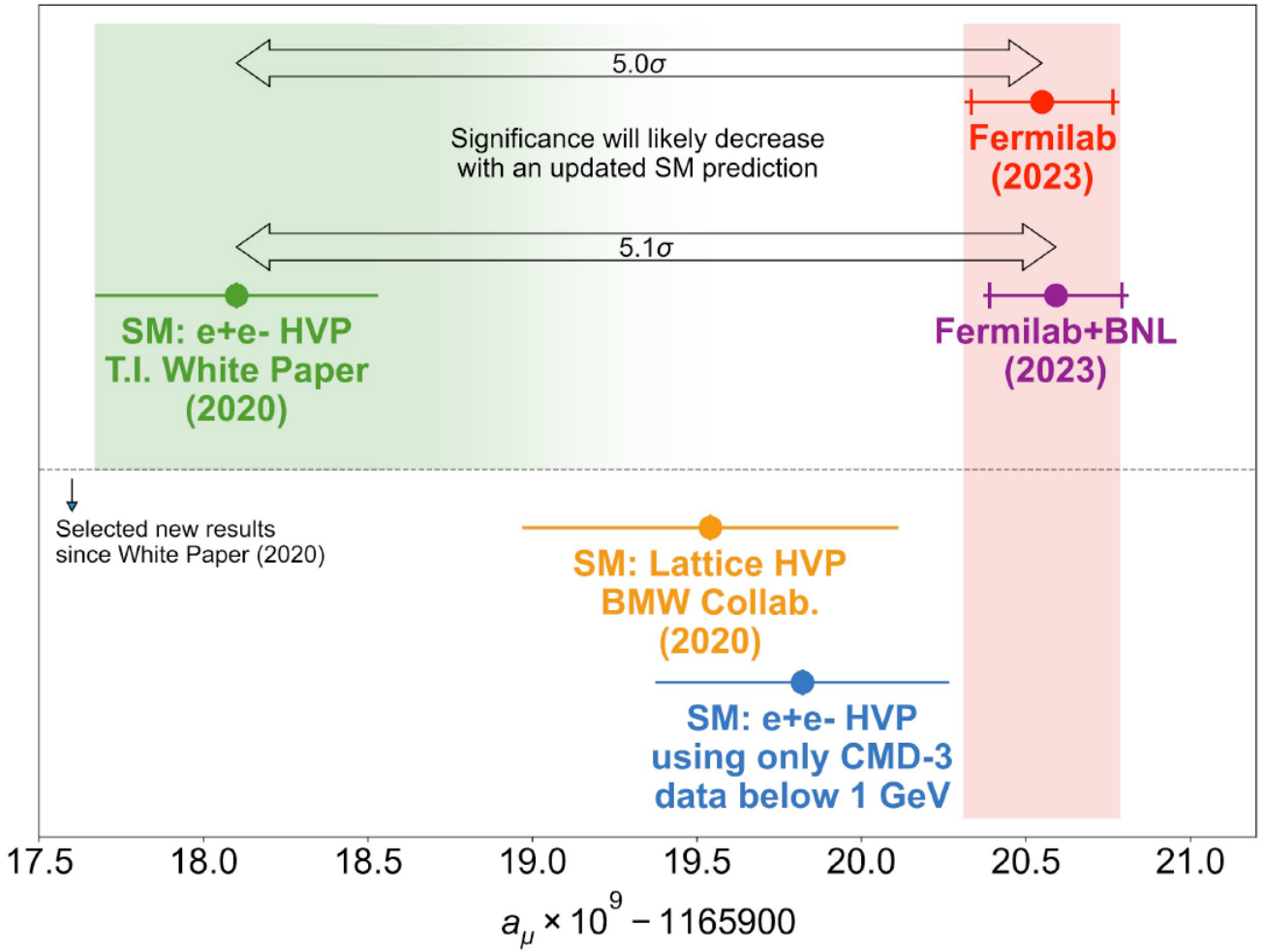


Phys. Rev. D97 (2019) 114025

➔ The R-Value is an important input over a wide energy range!

Anomalous Magnetic Moment of the Muon

- Muon anomaly $\alpha_\mu = \frac{g_\mu - 2}{2}$
- Accuracy of 0.2 ppm in experiment and better than 0.5 ppm in theory
- Discrepancy between SM prediction and experiment
- Tensions with latest Lattice QCD calculations and cross section measurements

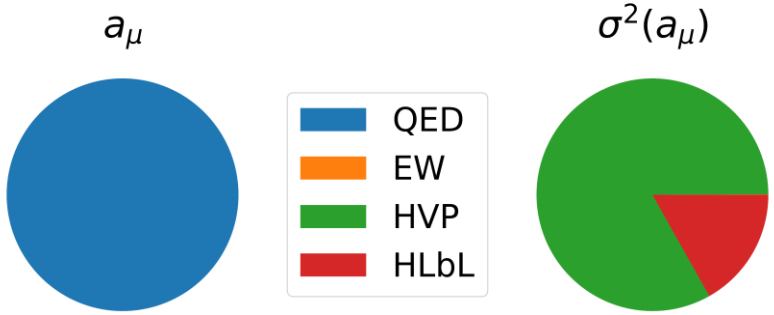


Fermilab [@Fermilab] (10.08.2023). Fermilab's new experimental result for muon g-2 differs from the 2020 theoretical prediction for muon #gminux2 at a significance of 5 sigma. [Tweet] https://twitter.com/Fermilab/status/1689665702582427648

Anomalous Magnetic Moment of the Muon

$$\alpha_\mu^{SM} = \alpha_\mu^{QED} + \alpha_\mu^{weak} + \alpha_\mu^{had}$$

Hadronic contributions dominate by far the uncertainty of α_μ^{SM}



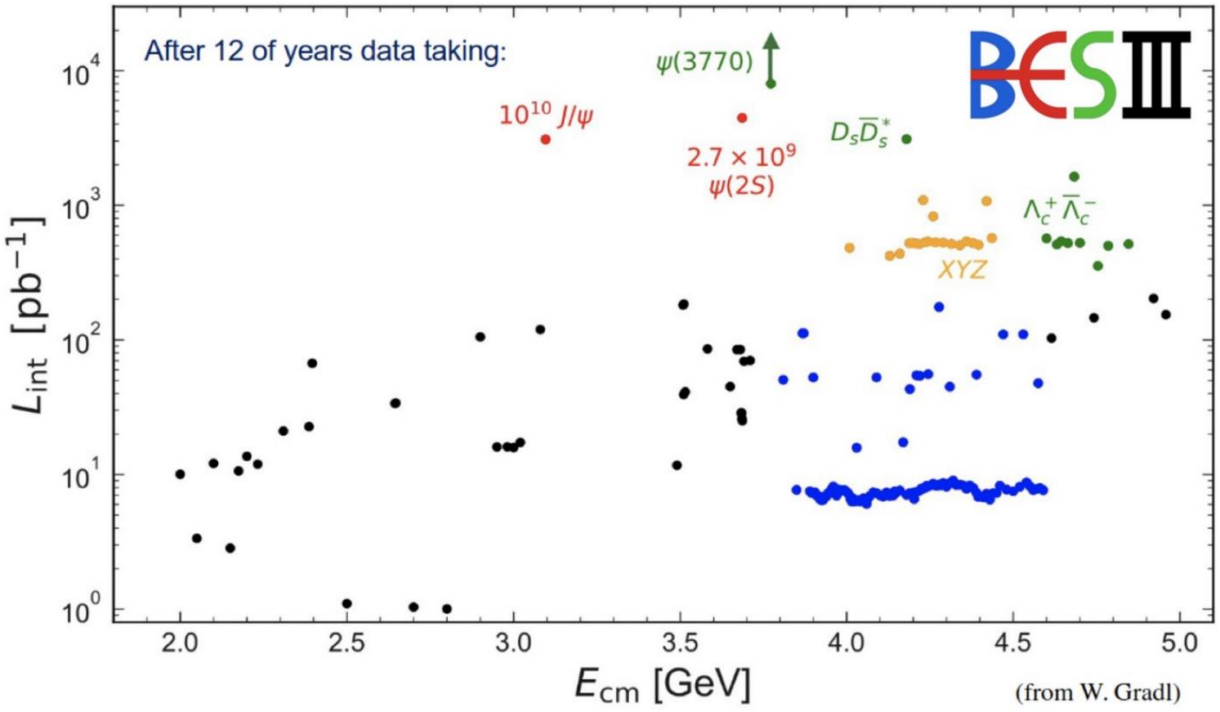
Hadronic Vacuum Polarisation (HVP) using dispersive approach:

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

R-Value needed as experimental input

Beijing Electron-Positron Collider II (BEPCII)

- Energy range: **2.0 GeV $\leq \sqrt{s} <$ 5.0 GeV**
- Design luminosity exceeded by 10 %
- World's largest τ-charm data set in e^+e^- annihilation!



Highlights of BESIII:

- 10^{10}J/ψ events
- $20\ \text{fb}^{-1}$ $\psi(3770)$
- $2.7 \cdot 10^9$ ψ(2S) events

This work:
- 14 data points ($\sim 110\ \text{pb}^{-1}$)
- $2.23\ \text{GeV} - 3.67\ \text{GeV}$

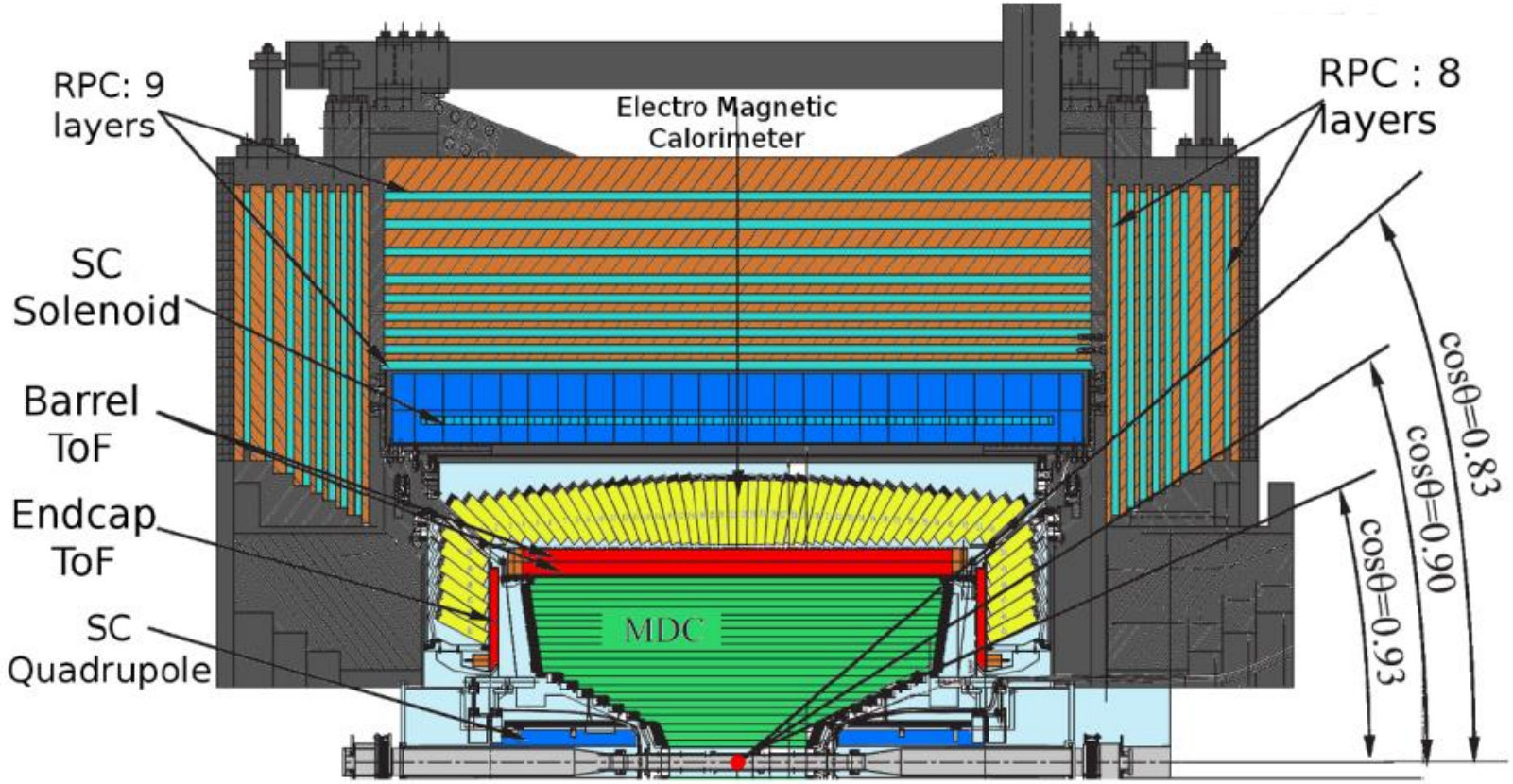
Beijing Spectrometer – BESIII

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

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

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

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



NIM A614 (2010) 345

Superconducting Magnet
- 1 T magnetic field

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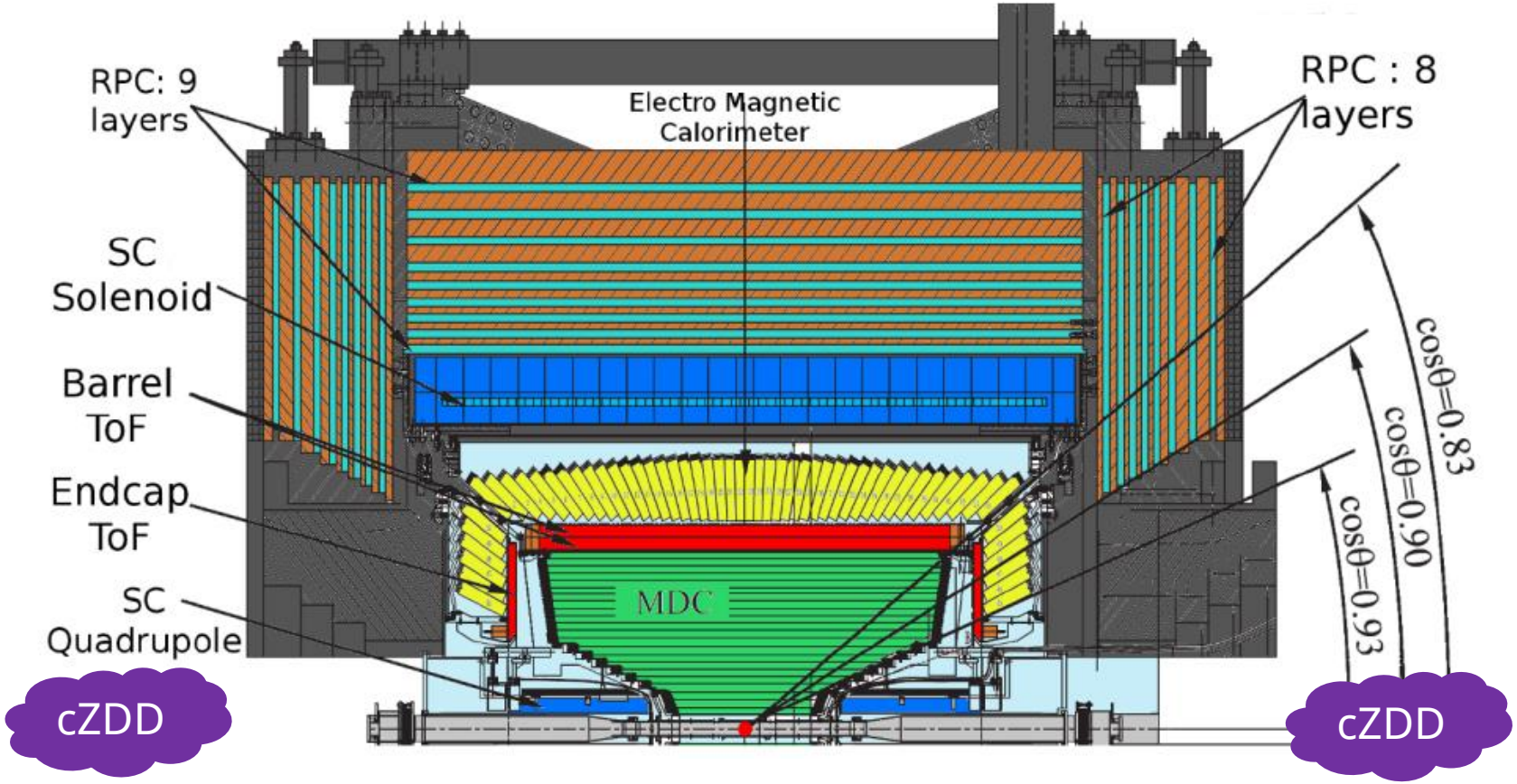


NIM A614 (2010) 345

Superconducting Magnet
- 1 T magnetic field

Crystal Zero Degree Detector (cZDD)
- ISR tagging at small angles

Determination of R-Value

Integrated luminosity
- Determined from large angle Bhabha scattering
- 0.8 % uncertainty

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

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

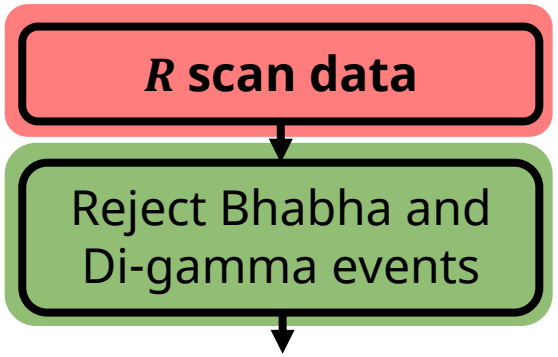
Radiative Corrections
- Feynman diagrams
- Structure functions
- Agreement better than 1.4 %

Trigger efficiency
for hadronic events ~ 100 %

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

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

Analysis Strategy



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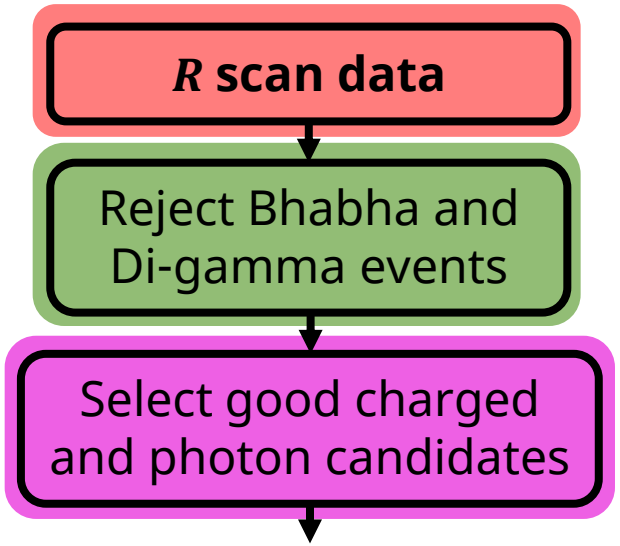

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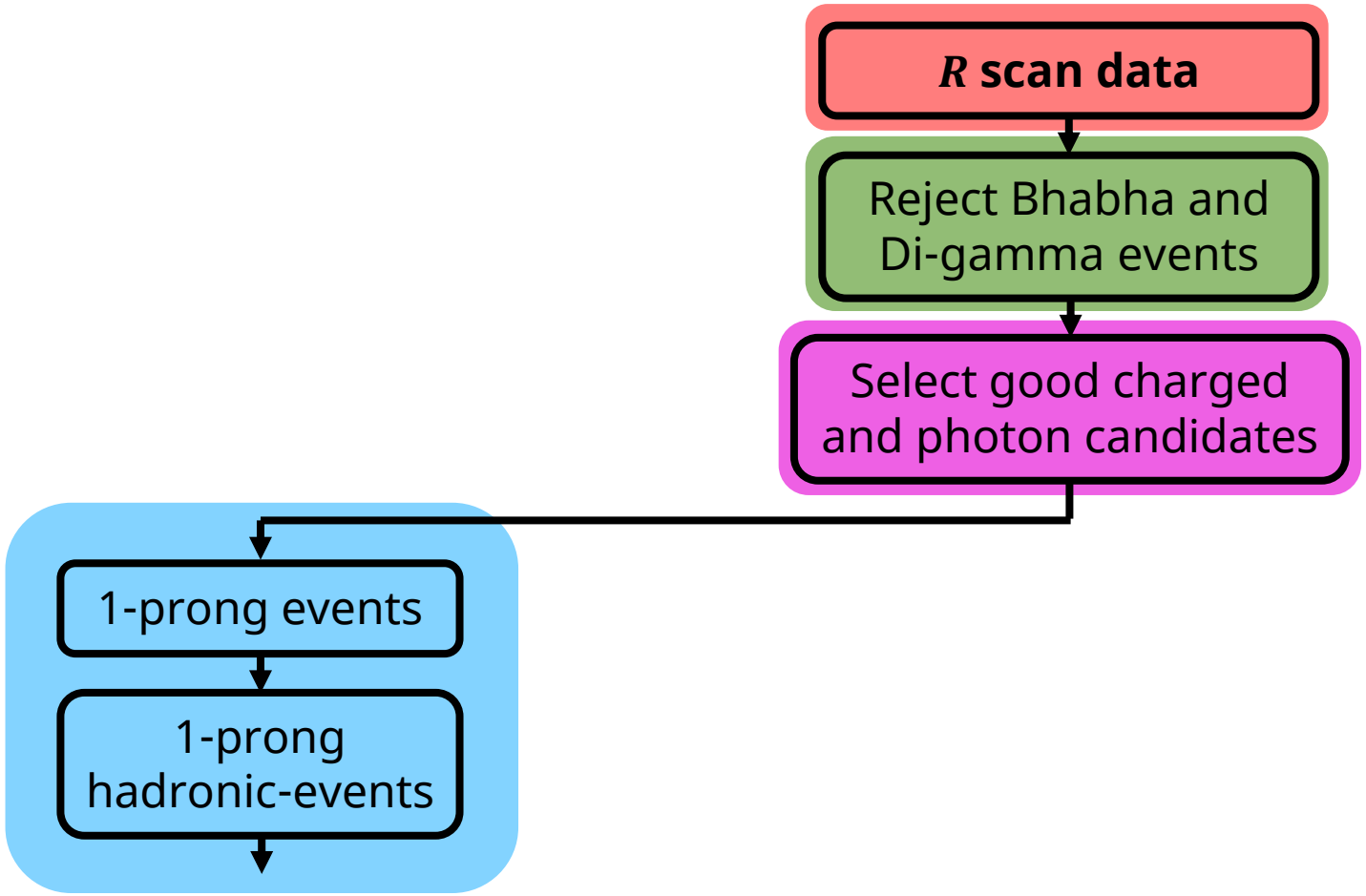

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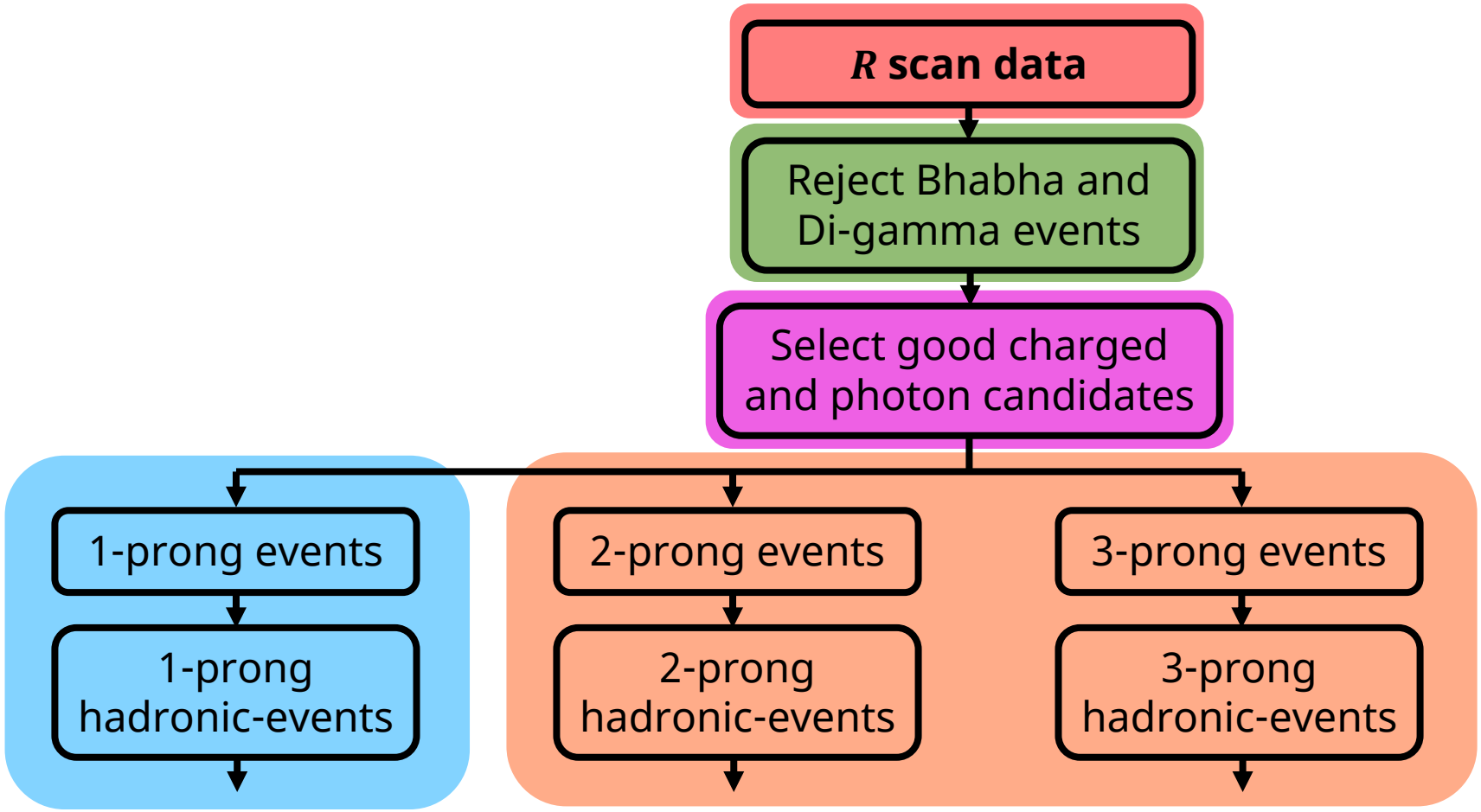

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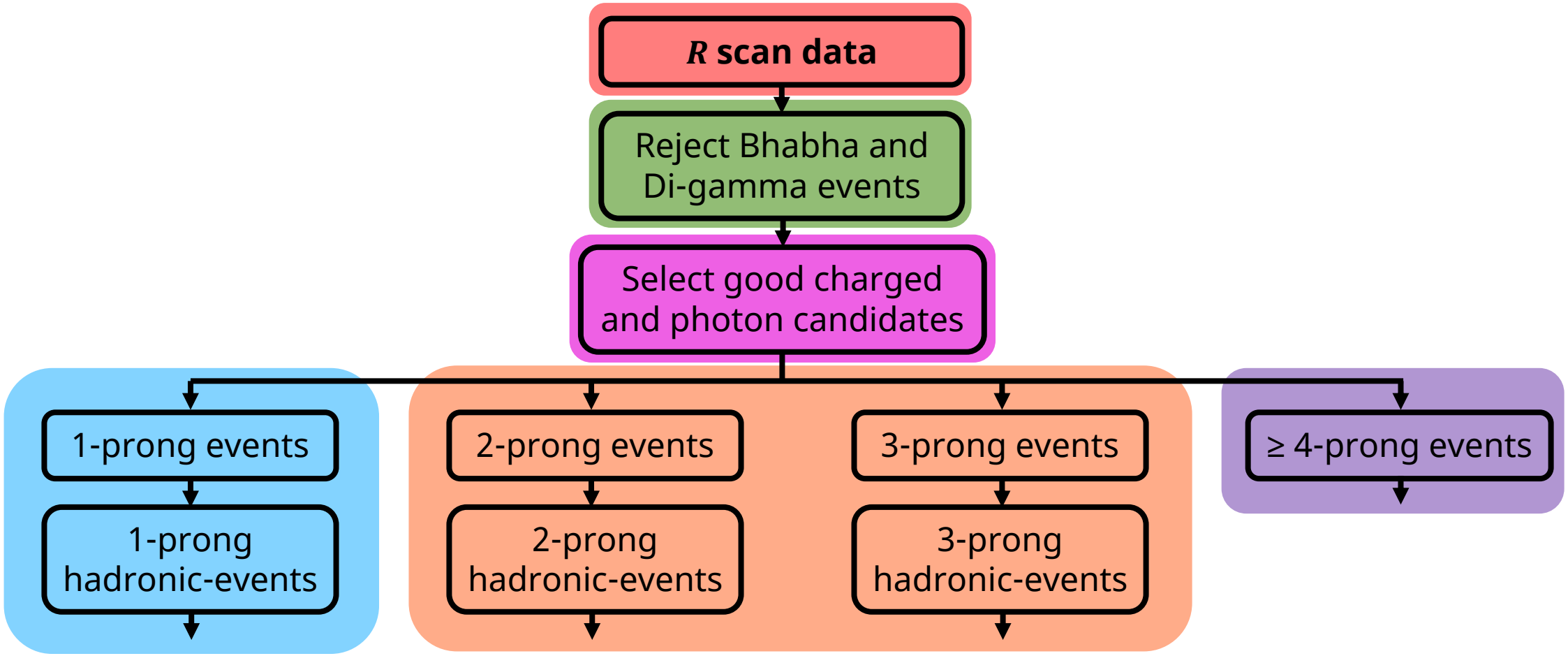

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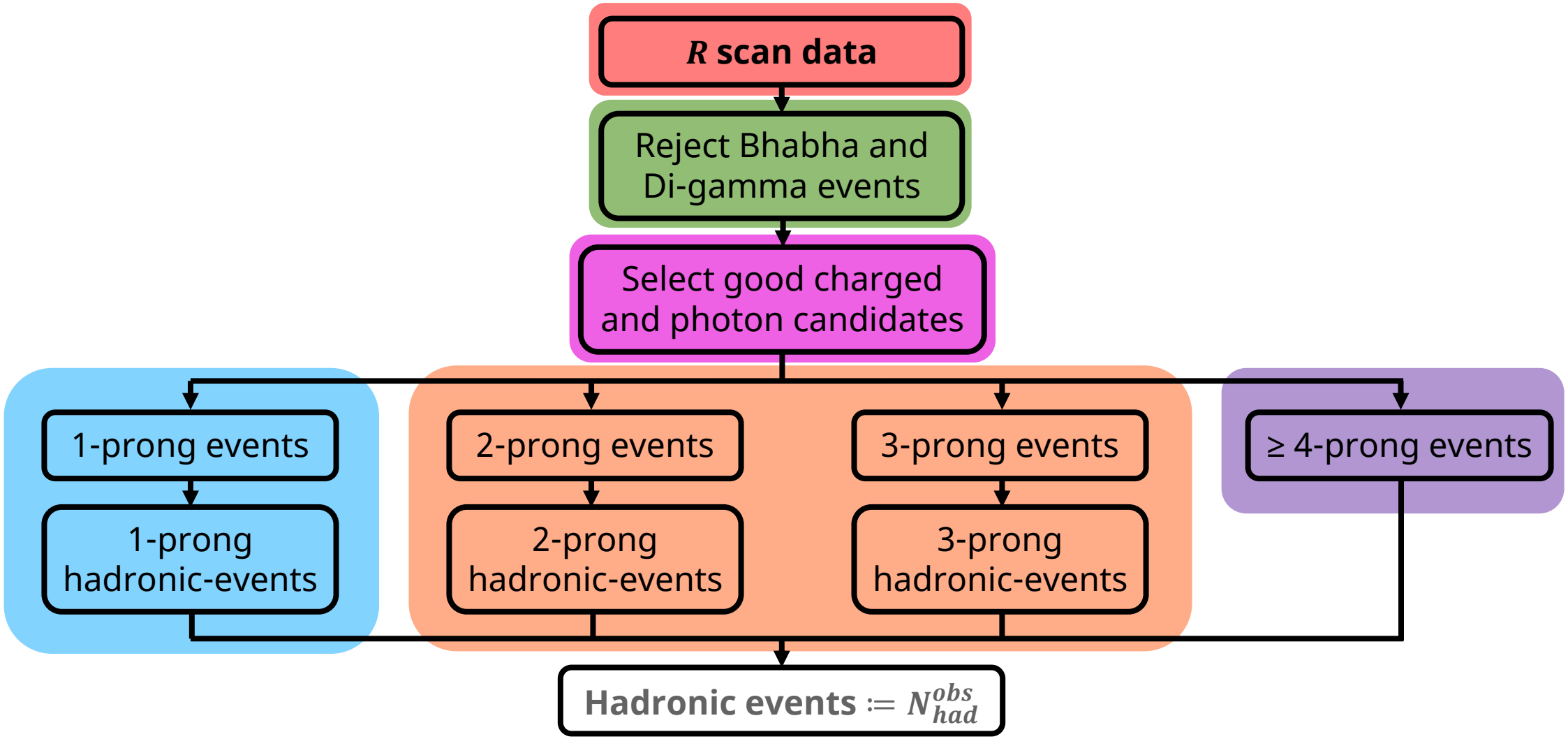
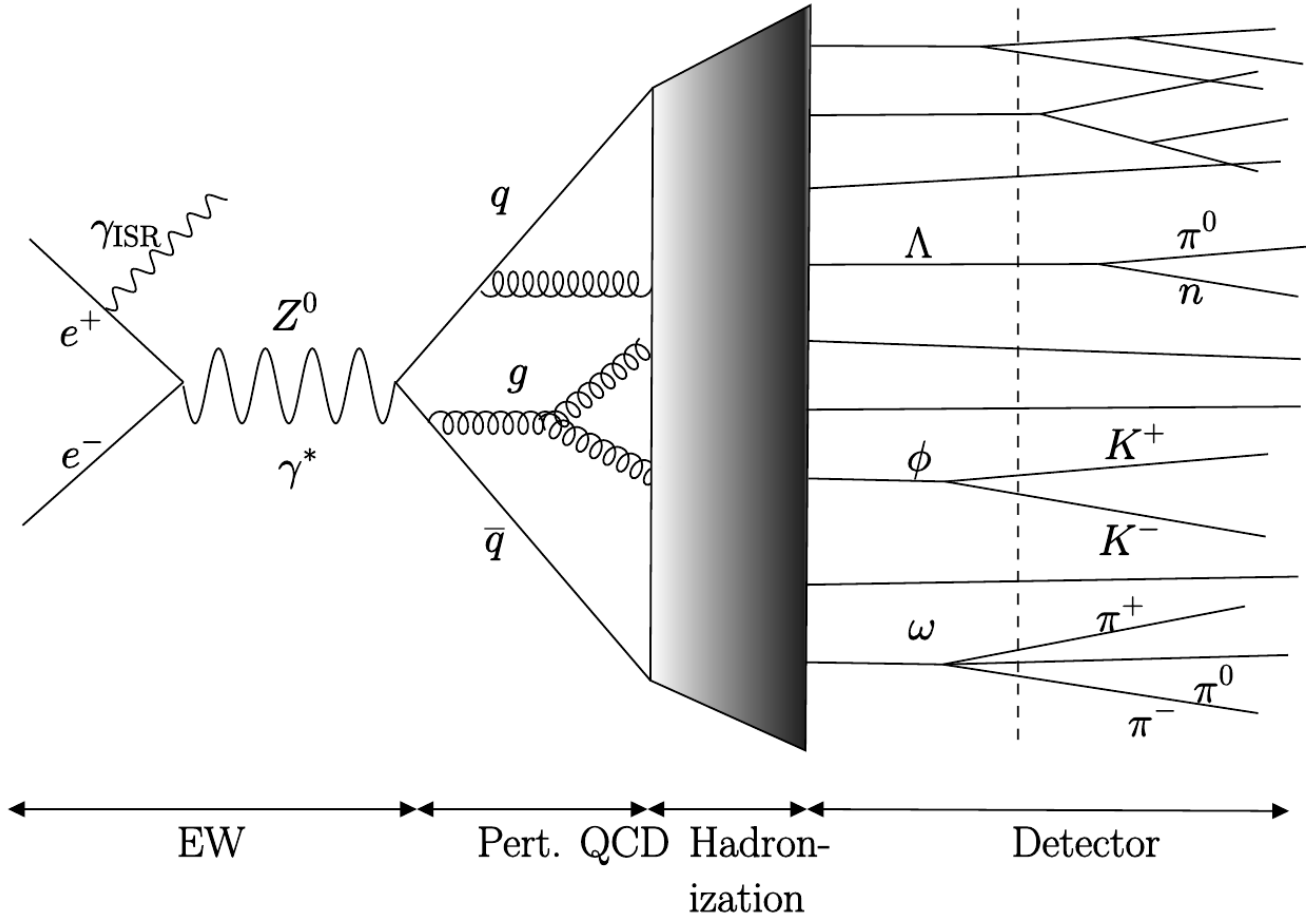


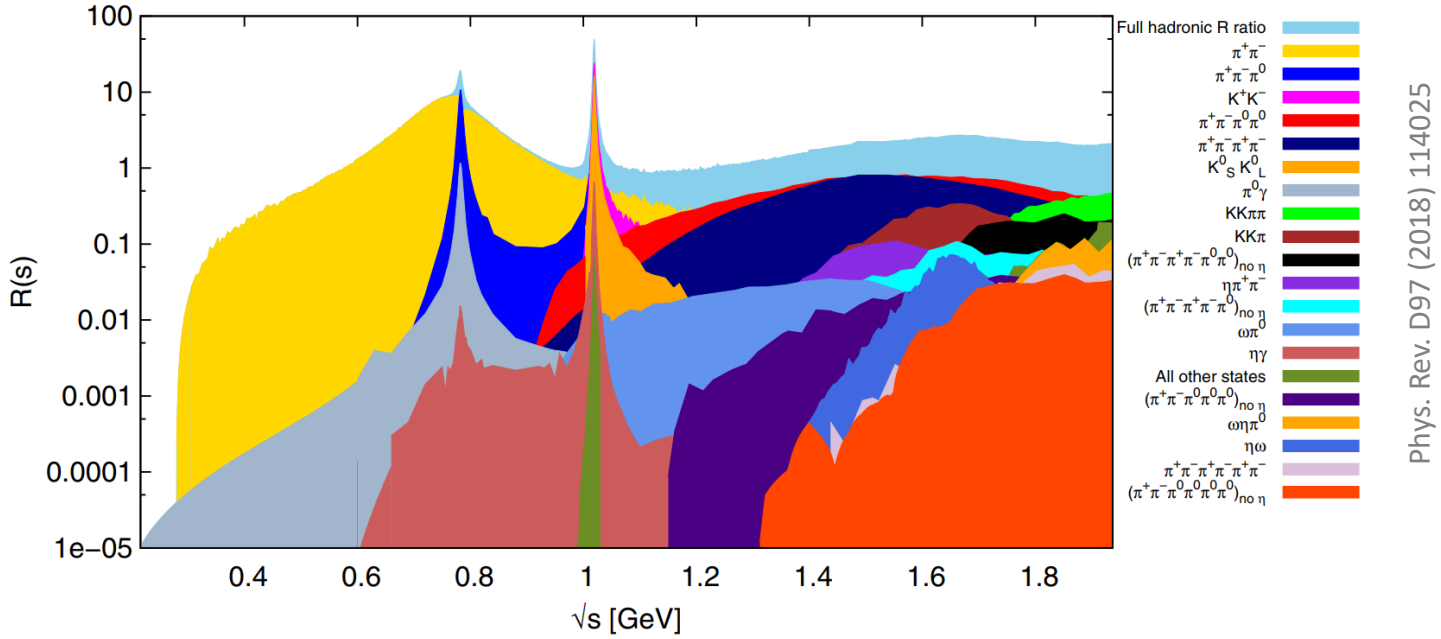
LUARLW: Nominal Model for Signal Simulation

- Self consistent **inclusive generator**
- Developed from **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 $2m_\pi$ to $\sqrt{s}$
- Phenomenological parameters tuned to data
- Used in most previous R-value measurements



Alternative Model: “Hybrid Generator”

- New event generator with **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**: remaining unknown processes



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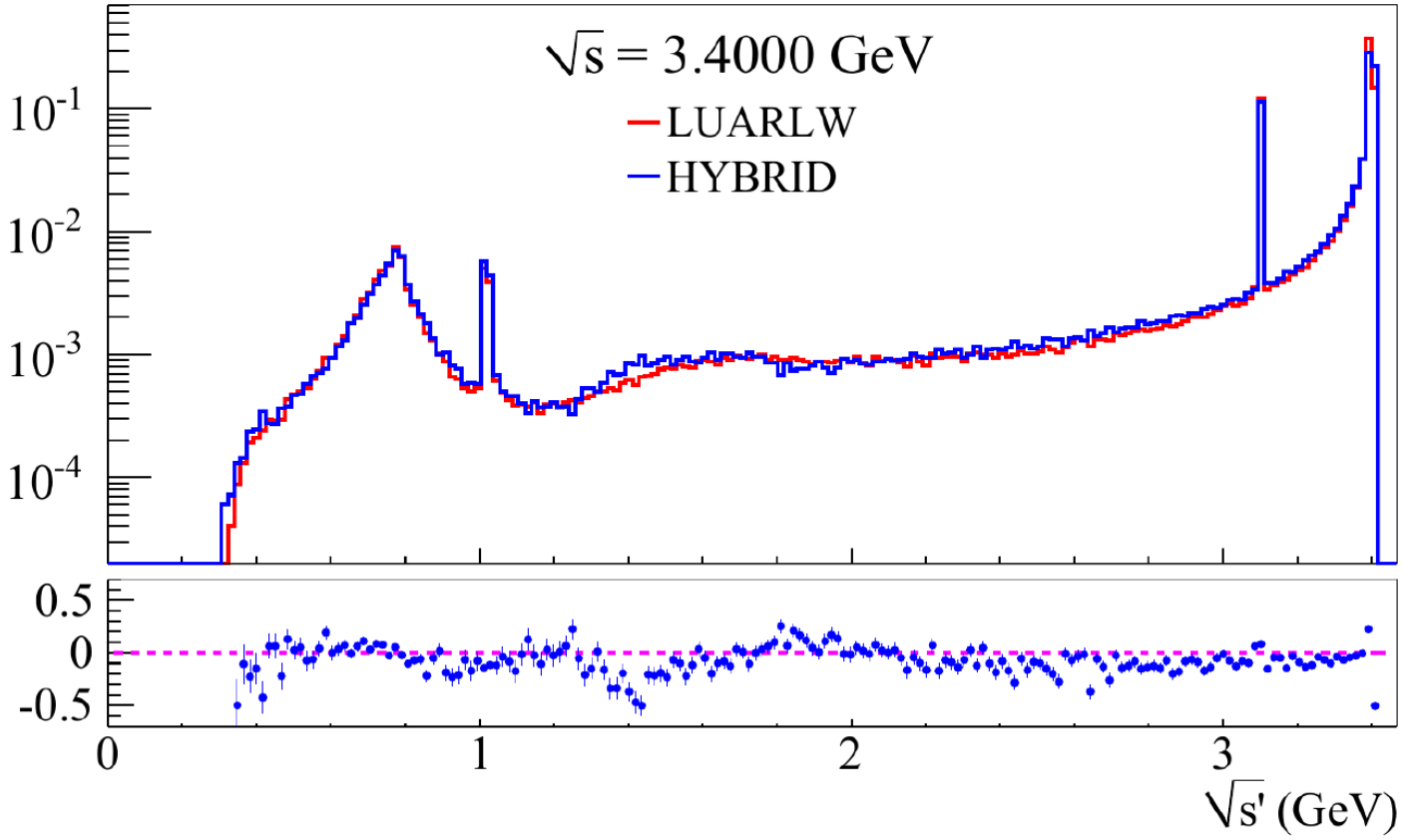
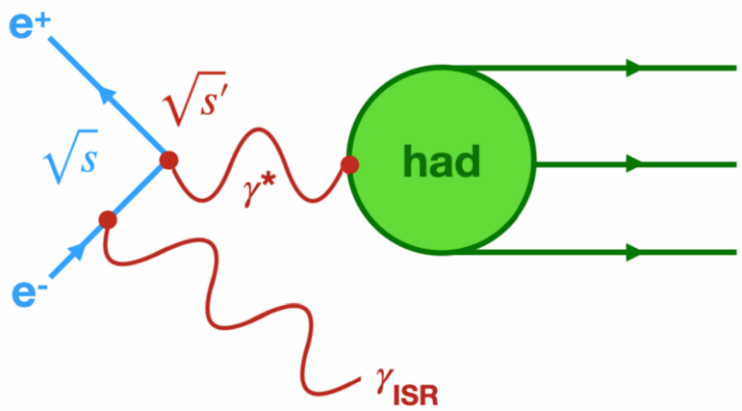
Comparison of LUARLW and Hybrid Generator





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

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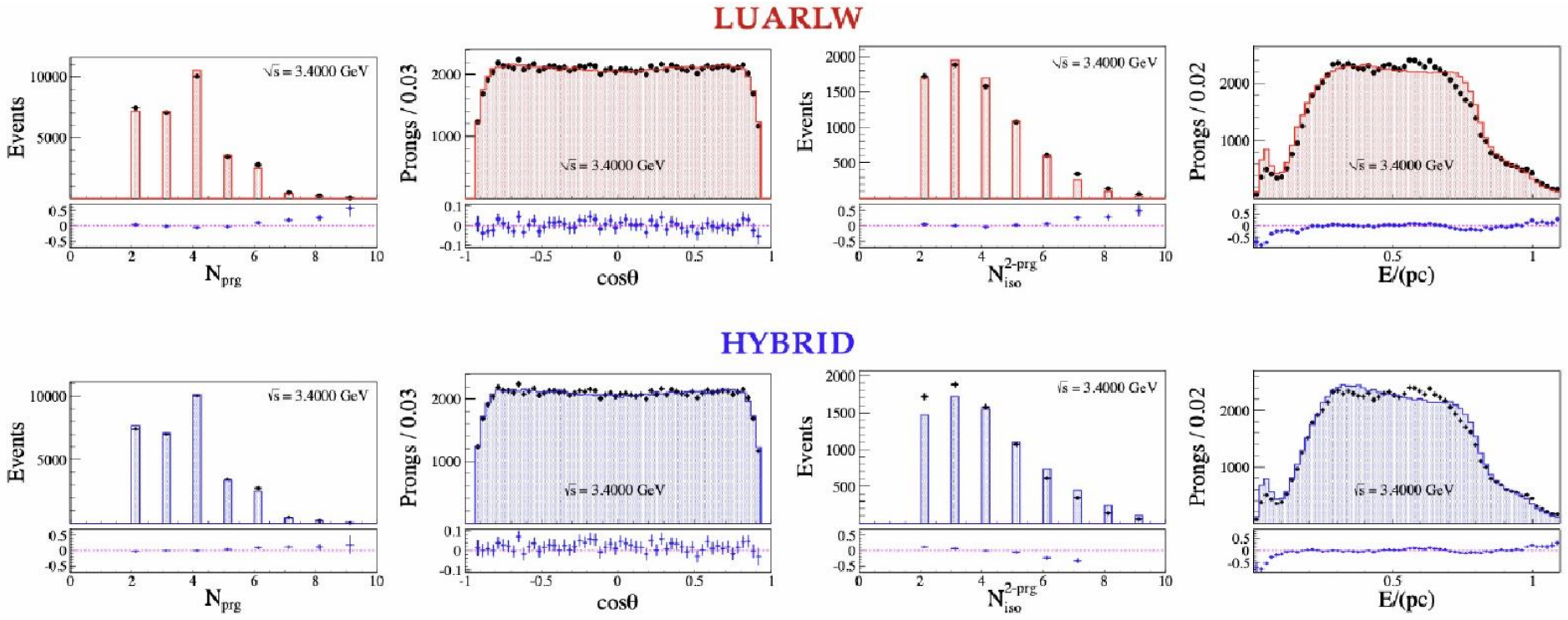
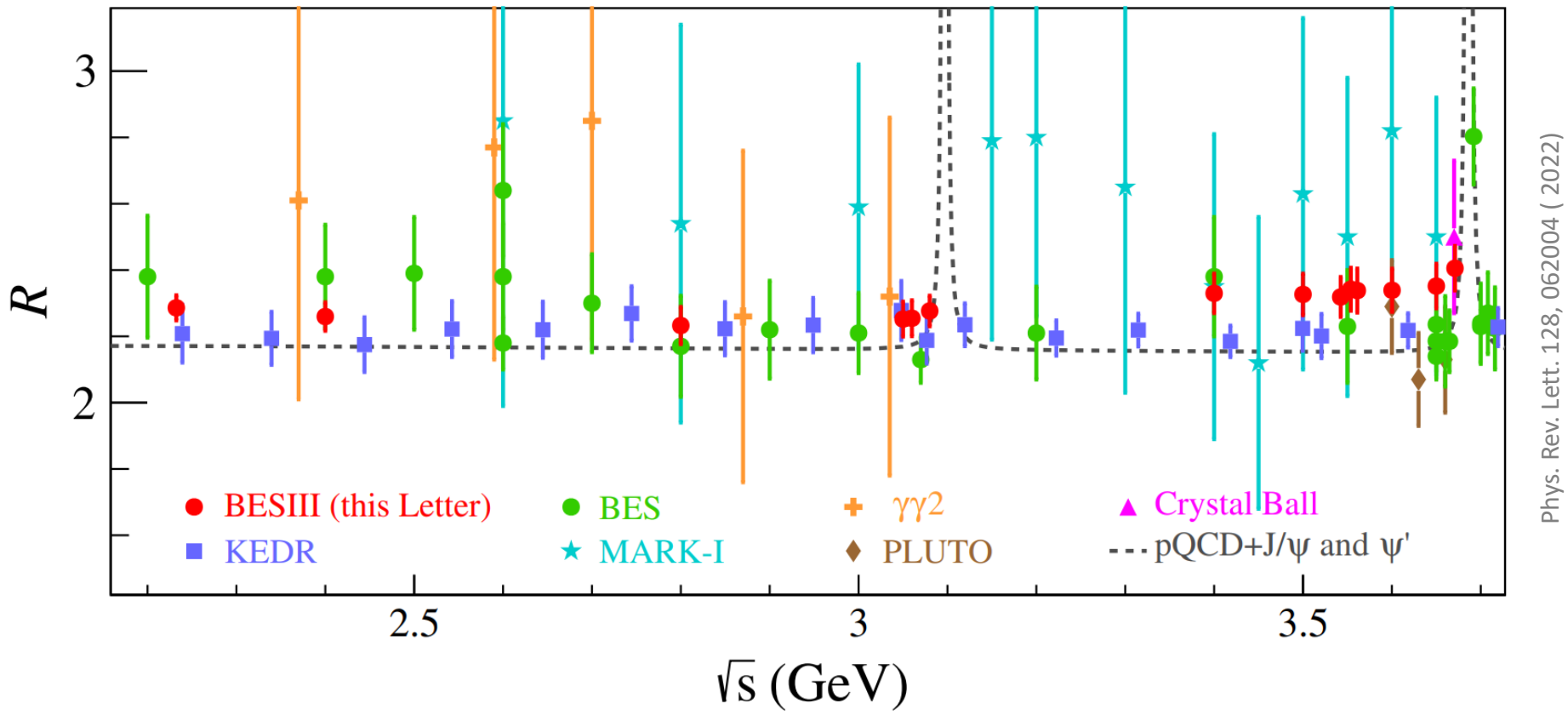


- $\mathrm{N_{prg}}$: Number of good charged tracks (prong)
- $\mathrm{N_{iso}^{2prg}}$: Number of isolated cluster in 2-prong events
- $\cos(\theta)\,, E, p$: Polar angle, EMC deposited energy, and measured momentum in MDC

Good agreement of both generator models and data!

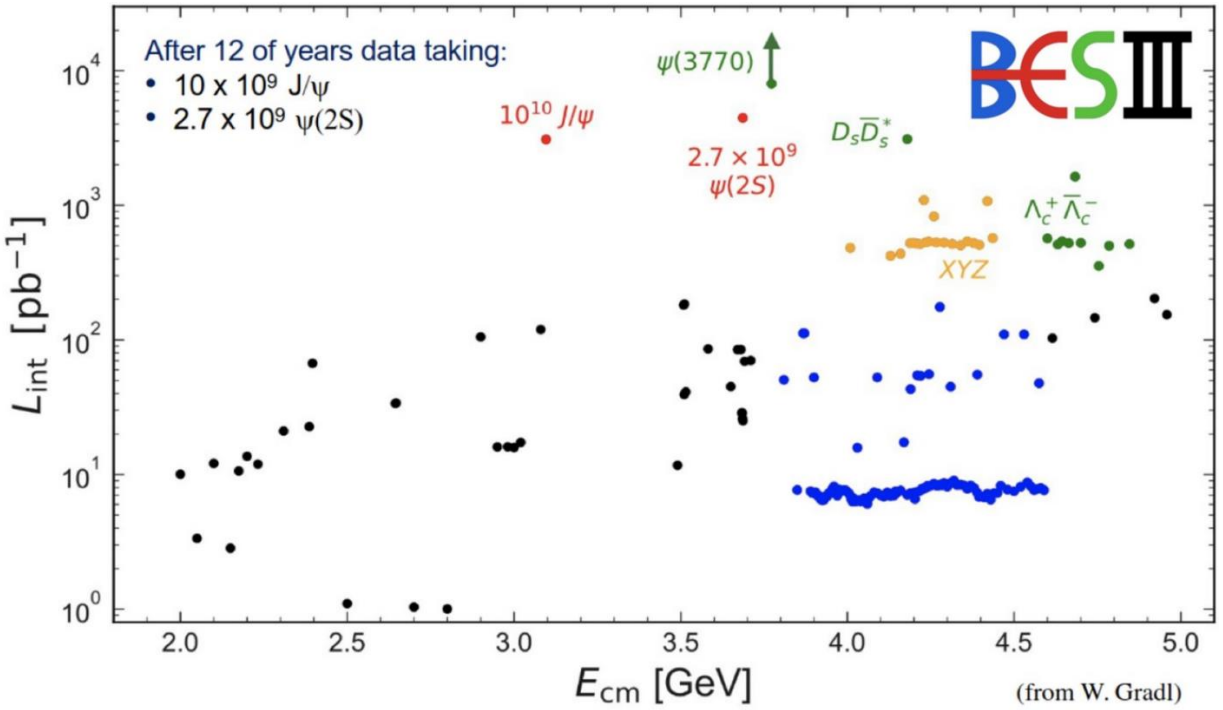
Results of R-Value Measurements



Phys. Rev. Lett. 128, 062004 (2022)

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

Further R-Value Measurements at BESIII



This work:

- 14 data points
- **2.23 to 3.67 GeV**
- $\sim 110\ \mathrm{pb}^{-1}$

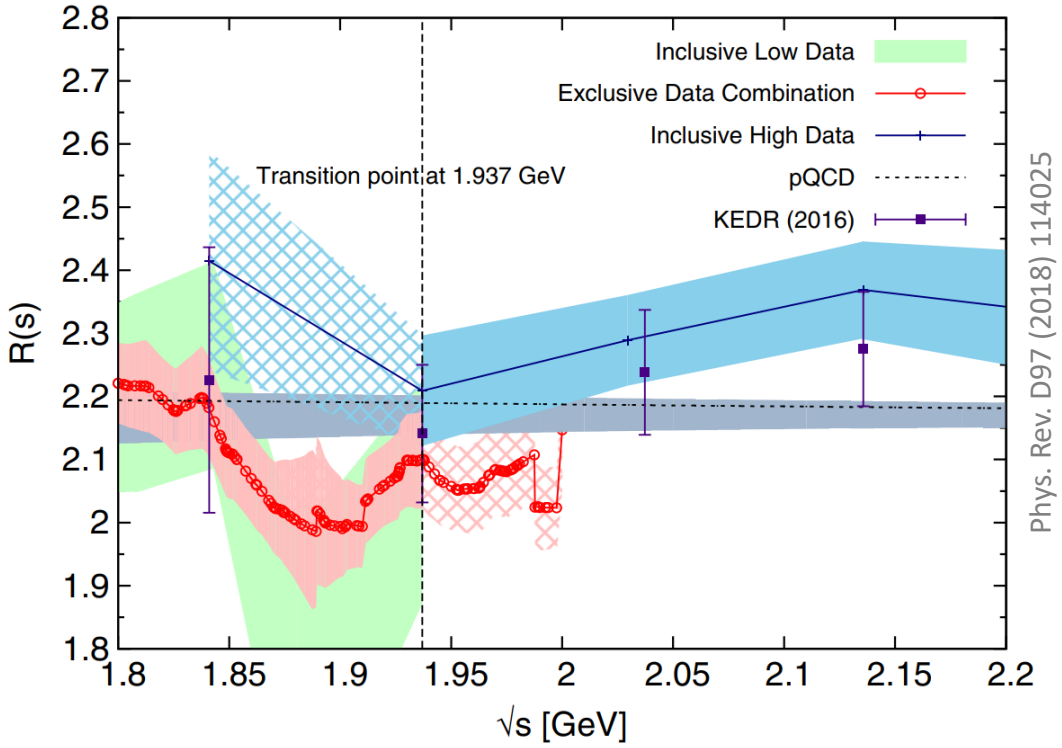
For future analyses:

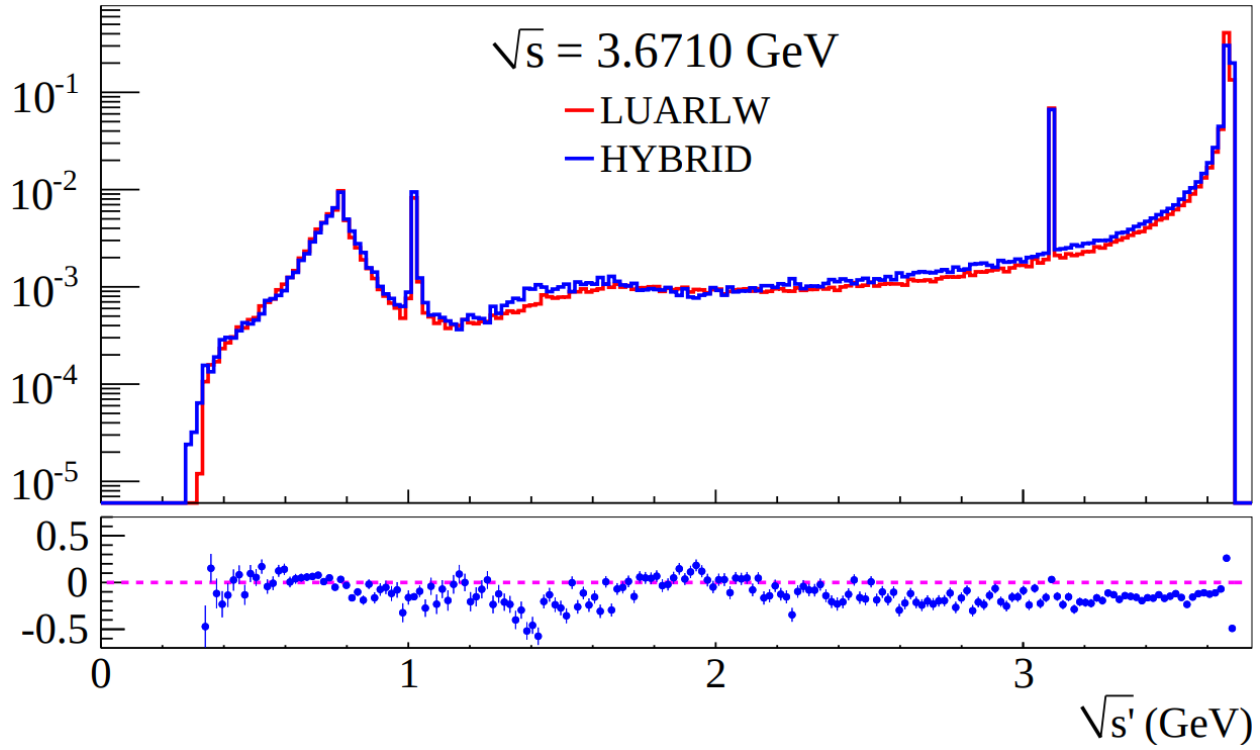
- 21 data points
- **2.00 to 3.08 GeV**
- $\sim 550\ \mathrm{pb}^{-1}$
- 104 data points
- **3.85 to 4.59 GeV**
- $\sim 800\ \mathrm{pb}^{-1}$

- Large amounts of **additional data available**

  ➔139 energy scan points with > 10^5 hadrons each
- High accuracy R-value measurements in continuum and open-charm region

Alternative Approaches to R-Value Measurement





- **Exclusive** measurements for $\sqrt{s}$ < 2 GeV
- **Inclusive** measurements for $\sqrt{s}$ > 2 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 & exclusive measurements

Summary & Outlook

- **High accuracy determination of R-Value important for Standard Model tests**
  - Running of $\Delta\alpha_{\mathrm{em}}(M_Z^2)$
  - Muon anomaly α_μ

- **Pilot R-Value measurement at BESIII published in 2022** (Phys. Rev. Lett. 128 (2022) 062004)
  - 2.2324 GeV $\leq \sqrt{s} \leq$ 3.6710 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

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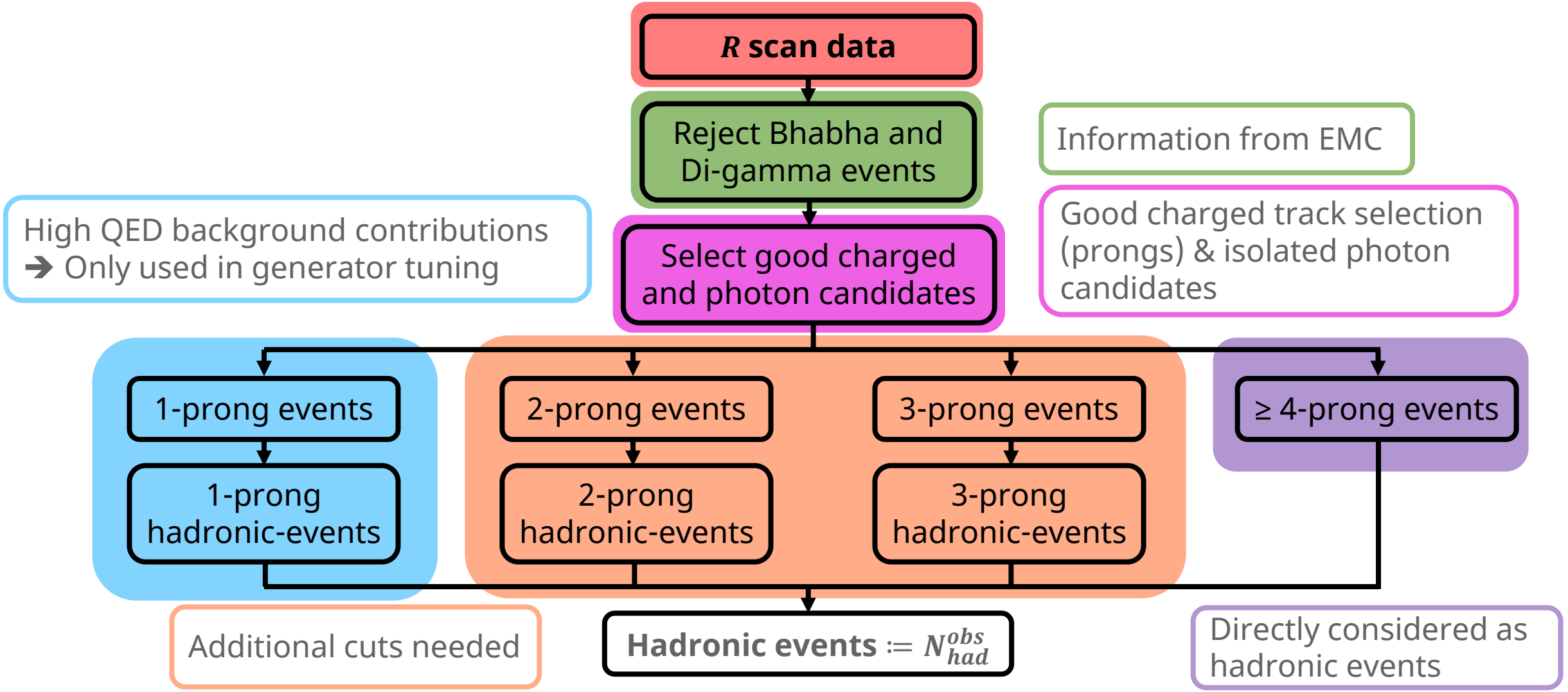
Thank you for your attention!

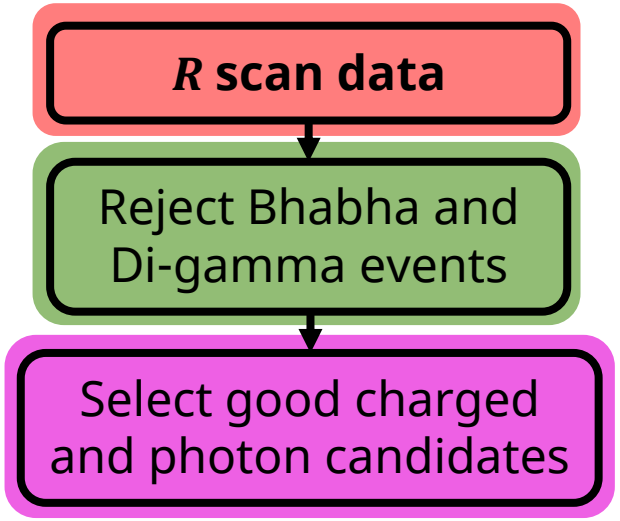
Appendix

Analysis Strategy



Analysis Strategy

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



Good charged hadronic tracks (prongs)

- $V_Z < 5$ cm & $V_r < 0.5$ cm & $|\cos\theta| < 0.93$
- $\chi_p = (dE/dx - dE/dx_p)/\sigma_p < 10$
- $p < 0.94 p_{\text{beam}}$
- Remove when $E/(pc) > 0.8$ & $p > 0.65 p_{\text{beam}}$
- Remove when for both tracks $E/(pc) > 0.8$ & inv. mass < 0.1 GeV/c^2 & opening angle < 15°

Isolated photon candidates

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

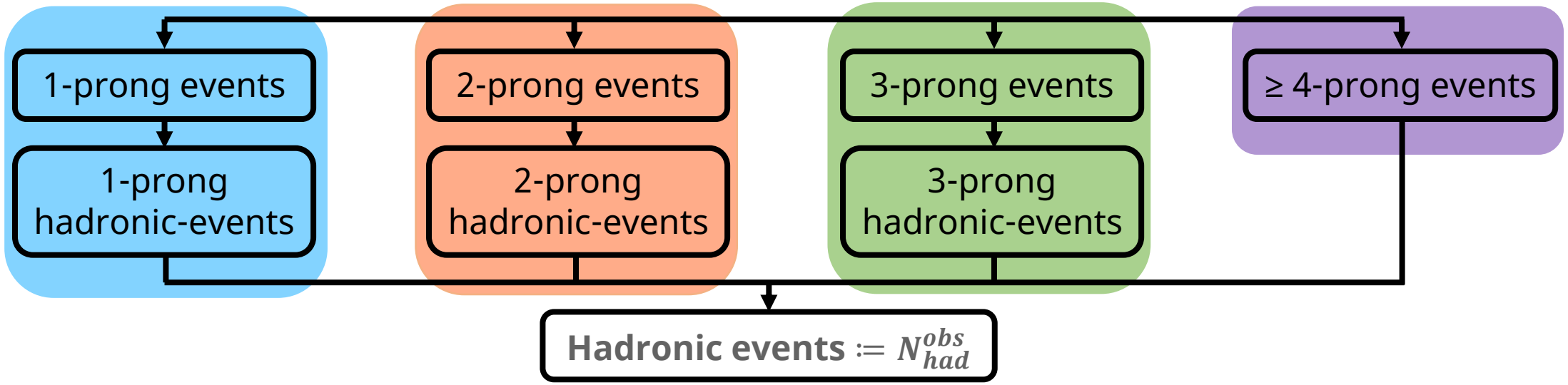
Analysis Strategy

1-prong events:
- At least two charged tracks
- Used to tune generator

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
- Less than two charged tracks with $E/(pc) > 0.8$
- Less than two charged tracks with $r_{\mathrm{PID}} > 0.25$

≥4-prong events:
- Events with more than 3-prongs count directly as hadronic events



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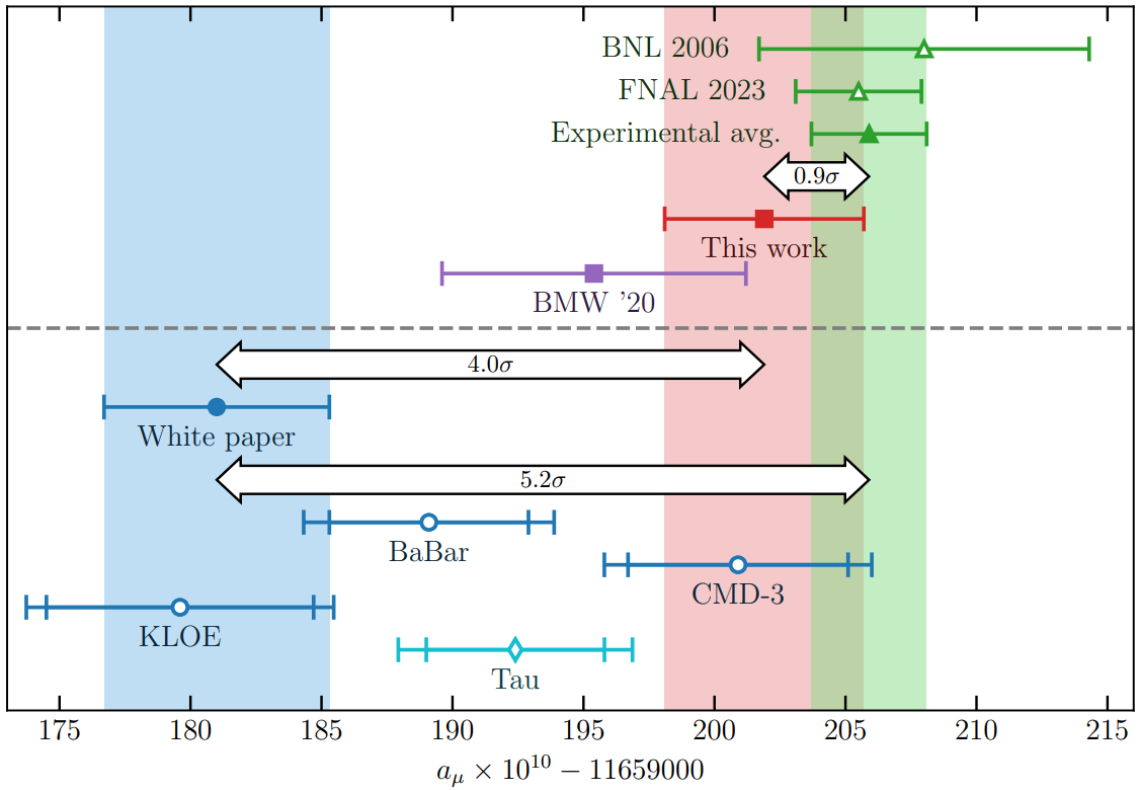

arXiv: 2407.10913