R value measurement and hadron fragmentation functions: recent results by the BESIII collaboration

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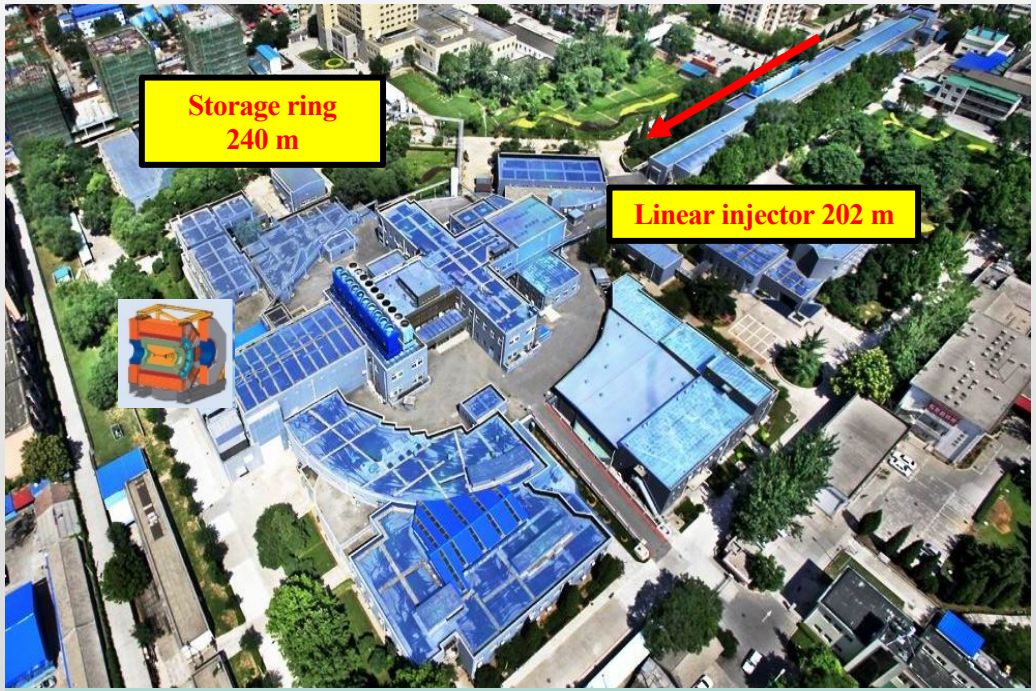
BEPCII and BESIII

Accelerator: BEPCII



Ecm= 1.84-4.95 GeV

Peak luminosity @3.770 GeV: ~1.1×10^{33} $cm^{-2}s^{-1}$

Detector: BESIII

Electromagnetic Calorimeter

CsI(Tl): L=28 cm

Barrel σ_E=2.5%

Endcap σ_E=5.0%

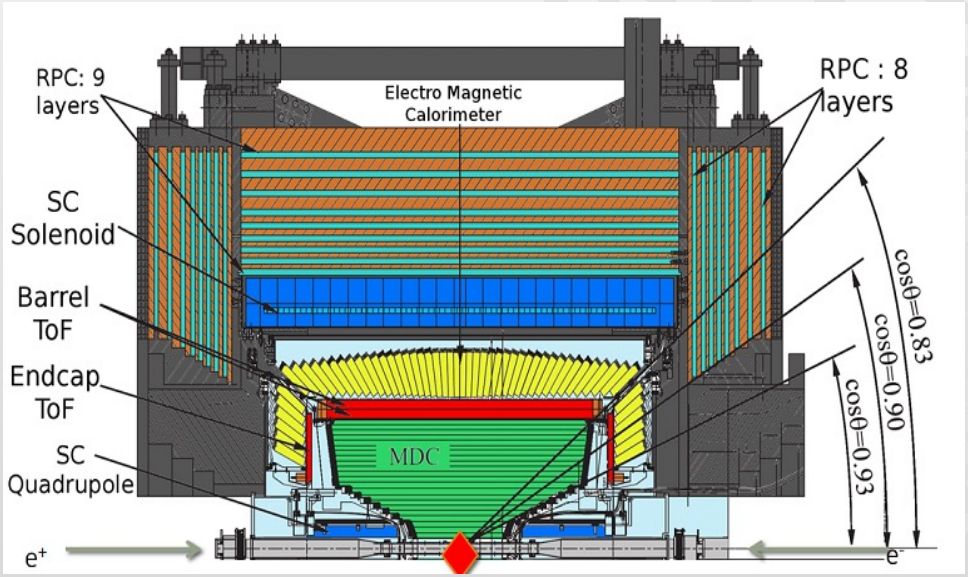
Muon Counter

RPC

Barrel: 9 layers

Endcap: 8 layers

$\sigma_{spatial}$=1.48 cm



Main Drift Chamber

Small cell, 43 layer

σ_{xy}=130 μm

dE/dx~6%

σ_p/p= 0.5% at 1 GeV

Time Of Flight

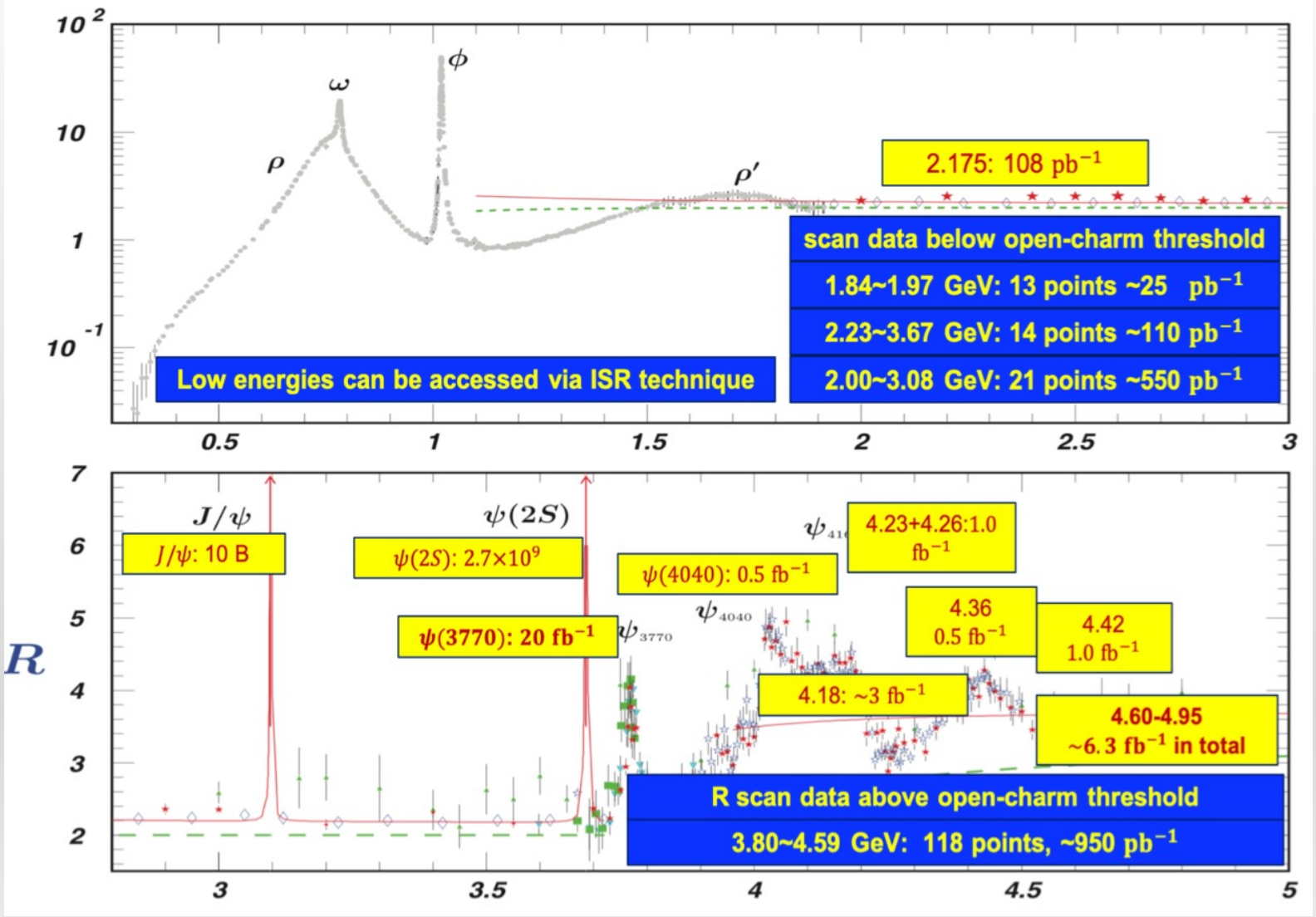
Plastic scintillator

σ_T(barrel)=68 ps

σ_T(endcap)=110 ps

(update to 65 ps with MRPC)

Data collected at BESIII



R-scan data:
- 1.84~4.95 GeV, ~170 points
- Extensive R ratio measurement
- Near-threshold Baryon pair-production mechanism

J/ψ and $\psi(2S)$ data:
- Largest sample in the world
- Light(exotic) hadron spectrum

$\psi(3770)$ data:
- 20 fb^{-1}
- Charm meson decays
- ISR technique for g-2 physics

XYZ data:
- Large open-charm samples
- Charmonium (-like) states

The definition of *R* value

Theoretical definition

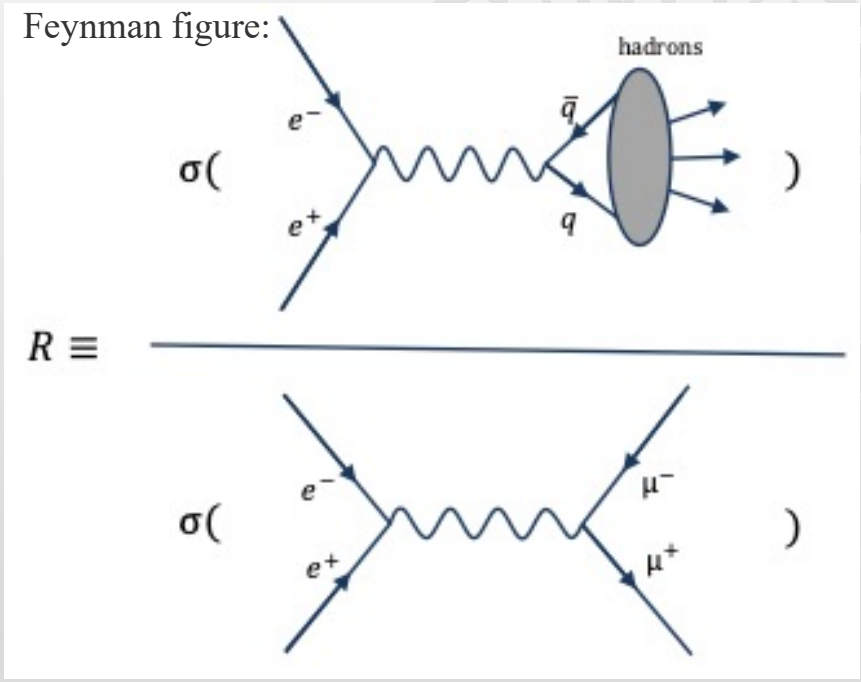
- The *R* value is defined as the leading-order production cross section ratio of hadrons and muon pairs in electron-positron annihilation:

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

A direct result from the QED theory:

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

Feynman figure:



Measurement of R value ⇐⇒ Measurement of total cross section of hadron production

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

Muon anomalous a_μ^{SM} & running $\Delta\alpha(s)$

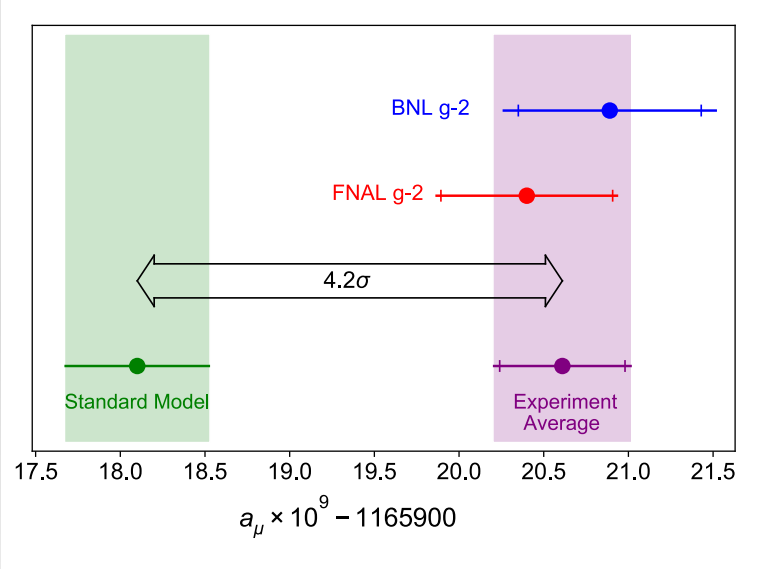
The anomalous magnetic moment of muon

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{Weak} + a_\mu^{had}$$

- a_μ^{QED} and a_μ^{Weak} can be calculated precisely
- $a_\mu^{had} = a_\mu^{LO-HVP} + a_\mu^{NLO-HVP} + a_\mu^{HLBL}$

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

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



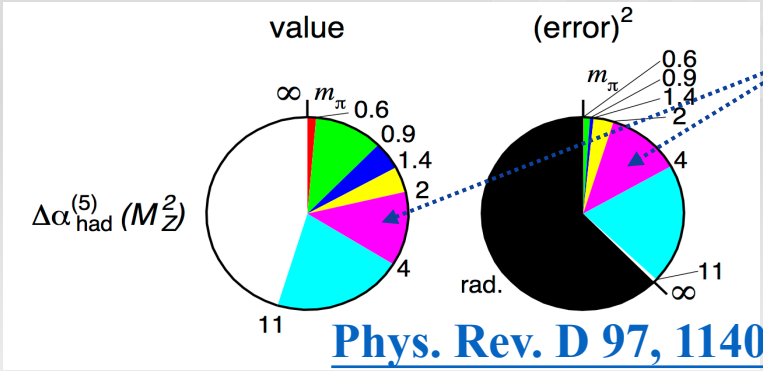
QED running coupling constant

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

- $\Delta\alpha_{lepton}(s)$ can be calculated analytically using perturbation theory
- $\Delta\alpha_{top}(s)$: is small(10^{-7}~10^{-10} for BESIII region), since the top quark is heavy
- $\Delta\alpha_{had}^{(5)}(s)$: should be calculated using R value at low energy

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

Fractional contribution to $\Delta\alpha_{had}^{(5)}(M_Z^2)$:



BEPC region

Phys. Rev. D 97, 114025 (2018)

Determination of R value in experiment

Inclusive method

Numbers of observed hadronic events

Number of the residual background events

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

- Leading order QED cross section for $e^+e^- \to \mu^+\mu^-$
- $\sigma_{\mu\mu}^{0}(s) = 86.85$ nb/s

Integrated luminosity is measured by analyzing Bhabha events

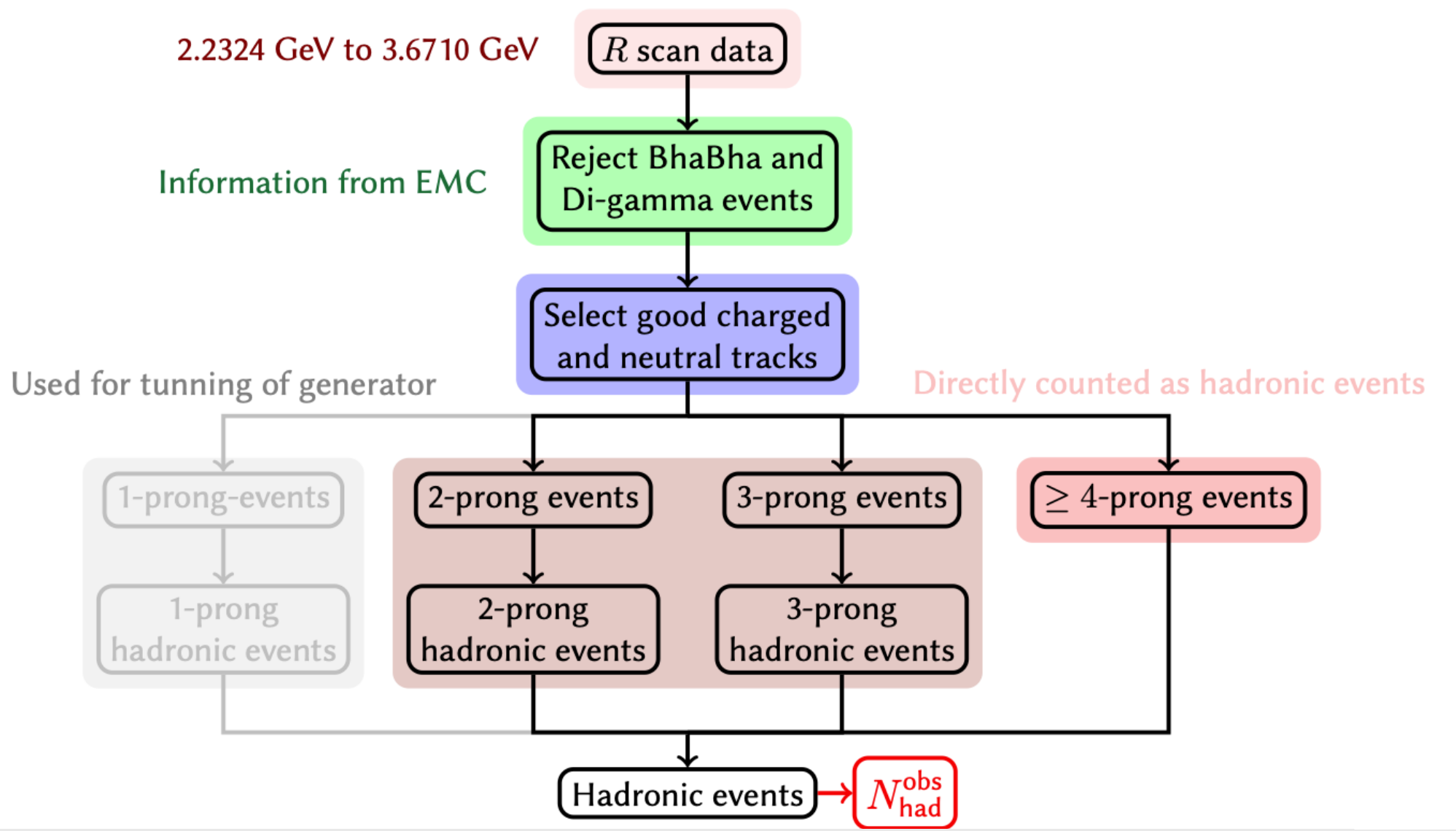
Trigger efficiency ~100%

Detection efficiency of the hadronic events

ISR correction factor

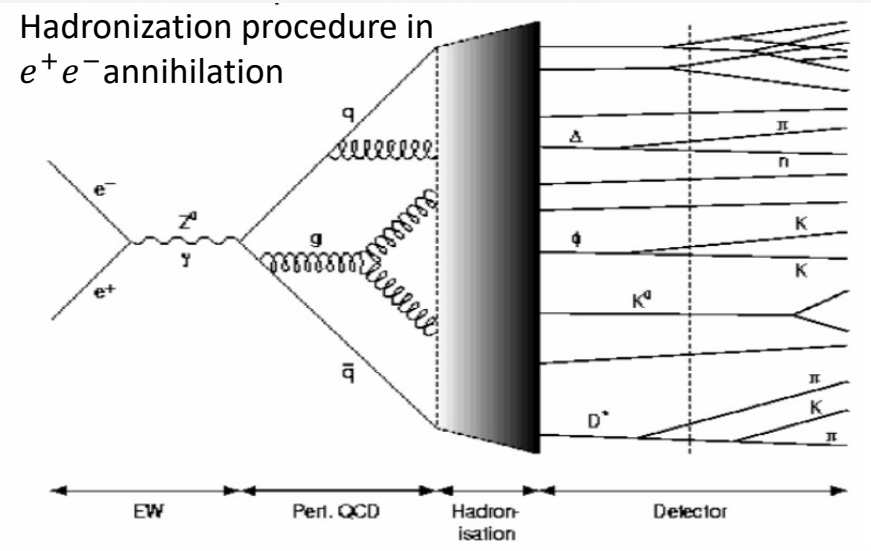
Determination of ε_{had} is the most challenging task!

Analysis strategy



Two MC simulation model: LUARLW and HYBRID

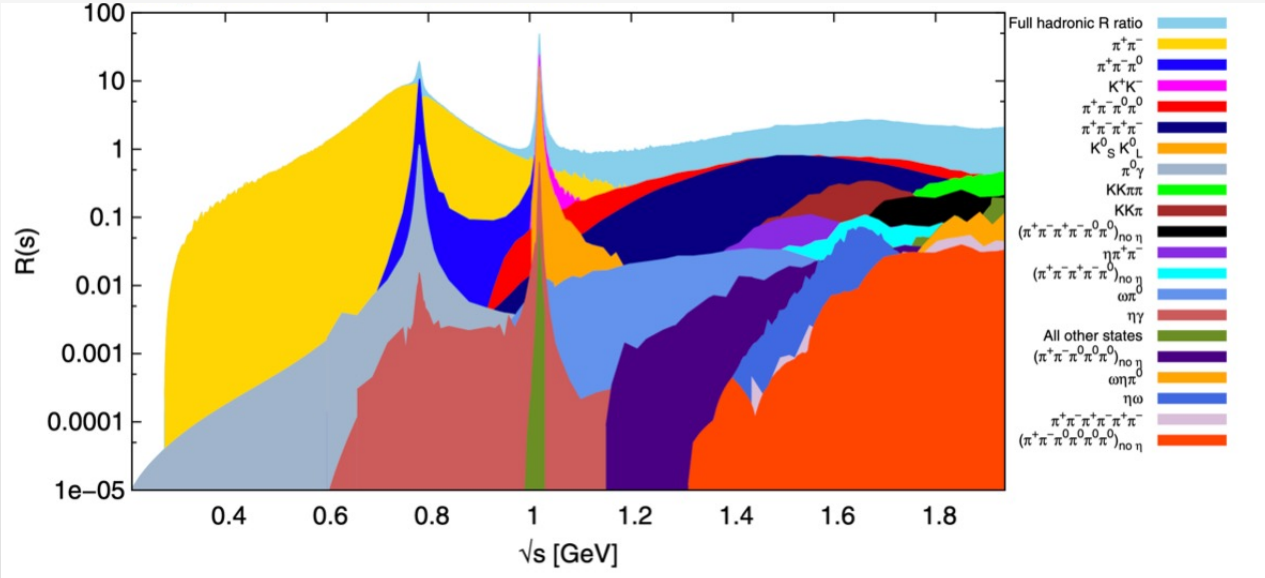
LUARLW model (nominal generator)



Main features of LUARLW:

- A self-consistent inclusive generator developed based on JETSET
- Initial-state radiation (ISR) process is implemented from $2m_\pi$ to $\sqrt{s}$
- Kinematic quantities of initial hadrons are sampled by the Lund area law
- Phenomenological parameters are tuned based on comparisons between data and MC

HYBRID model (alternative generator)

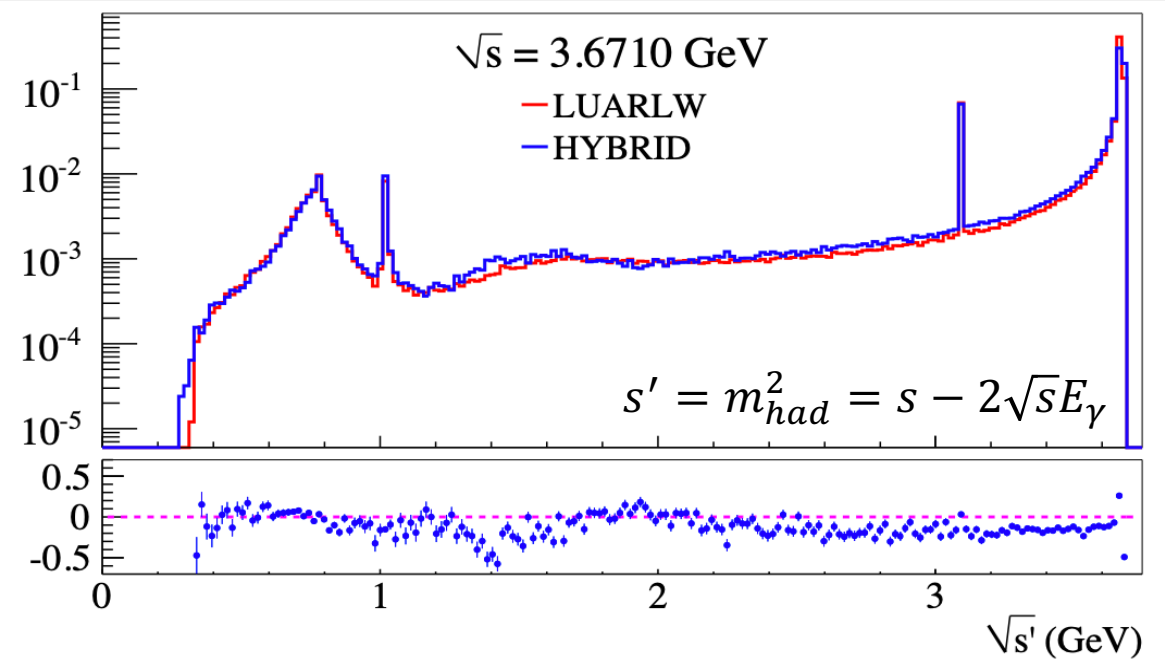


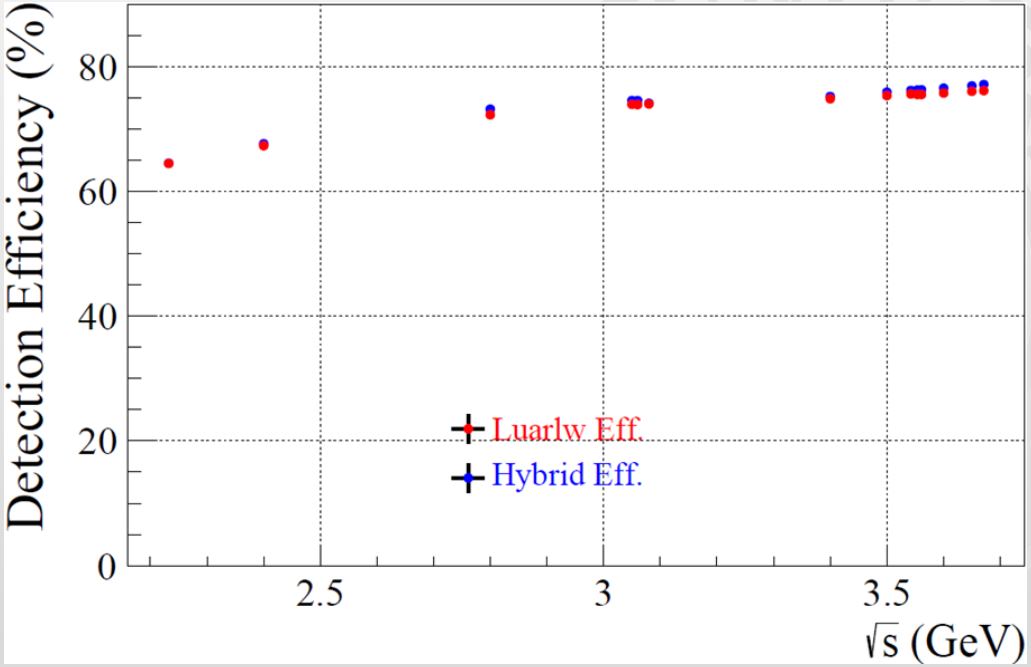
Main features of HYBRID:

- The first attempt of exclusive simulations in determination of hadronic efficiency
- Combination of THREE different well-established simulation models
- As much as currently known experimental knowledges are implemented.
- Different ISR and VP correction schemes are adopted.

HYBRID-LUARLW comparison: effective energy

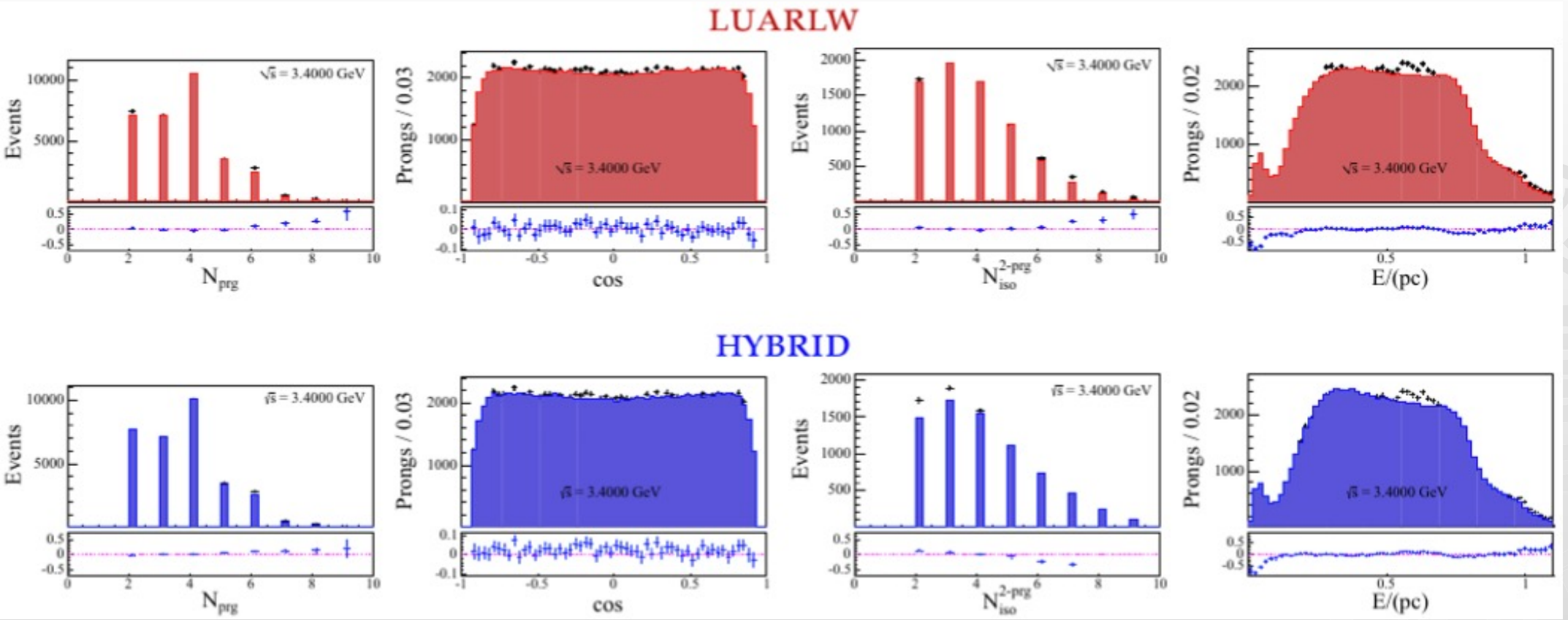
- The comparisons of the $\sqrt{s'}$ spectrum between LUARLW and HYBRID
- The $\sqrt{s'}$ spectrum directly reflect the fraction of the ISR-returned processes





These two different simulation schemes result in consistent $\sqrt{s'}$ spectra!

Comparison between MC and data



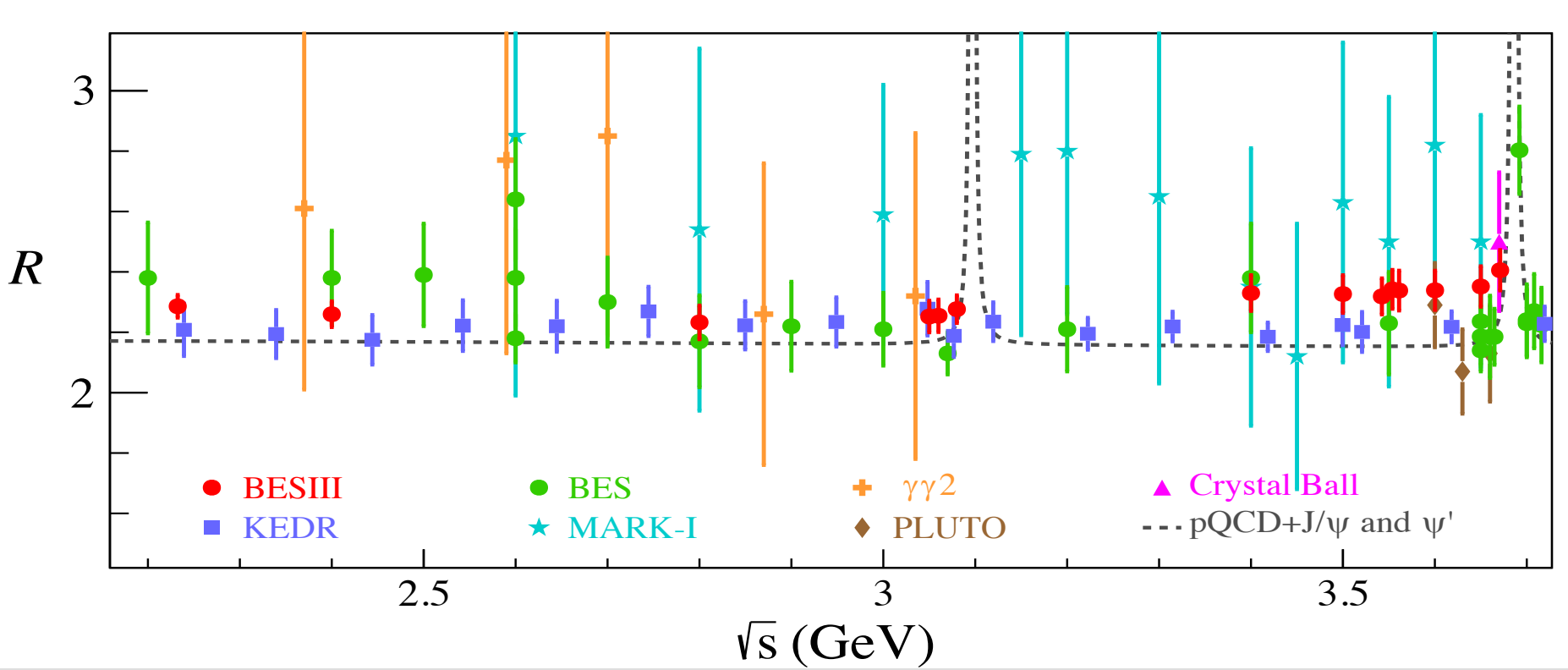
- N_{prg}, θ: Number and polar angle of selected charged tracks
- N_{iso}^{2-prg}: Number of isolated clusters in 2-prong events
- $E/(pc)$: Ratio of deposited energy and measured momentum per track

Good agreement of both generator models and data

R-value measurements in 2.2-3.7 GeV

Comparing BESIII *R* values with previously published results:

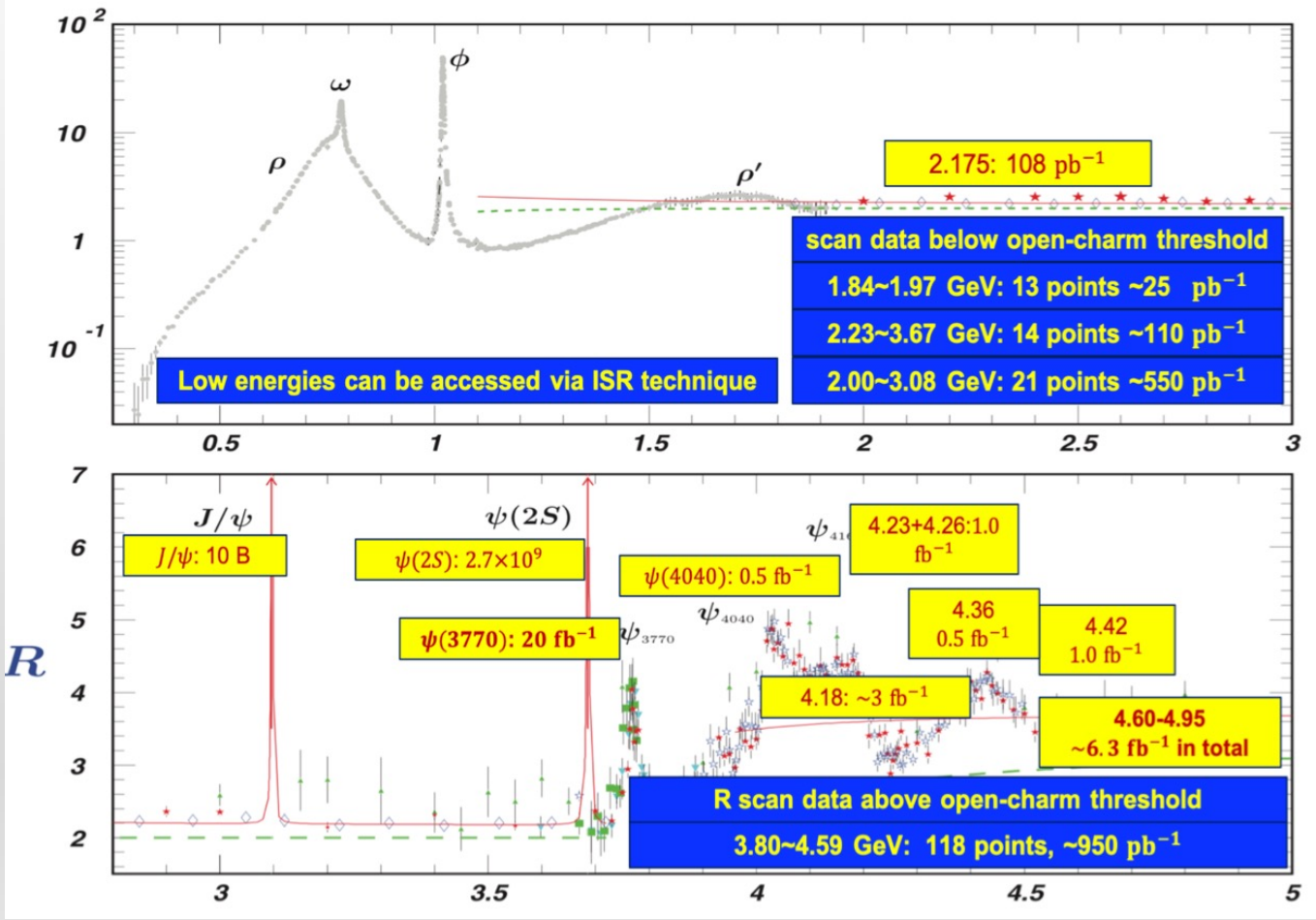
Phys. Rev. Lett. 128, 06200(2022)



- The accuracy is better than 2.6% below 3.1 GeV and 3.0% above
- Larger than the pQCD prediction by 2.7σ between 3.4~3.6 GeV

Prospect of the R value at BESIII

More additional data already collected (2.0-4.96 GeV, below 2.0 GeV also obtained)



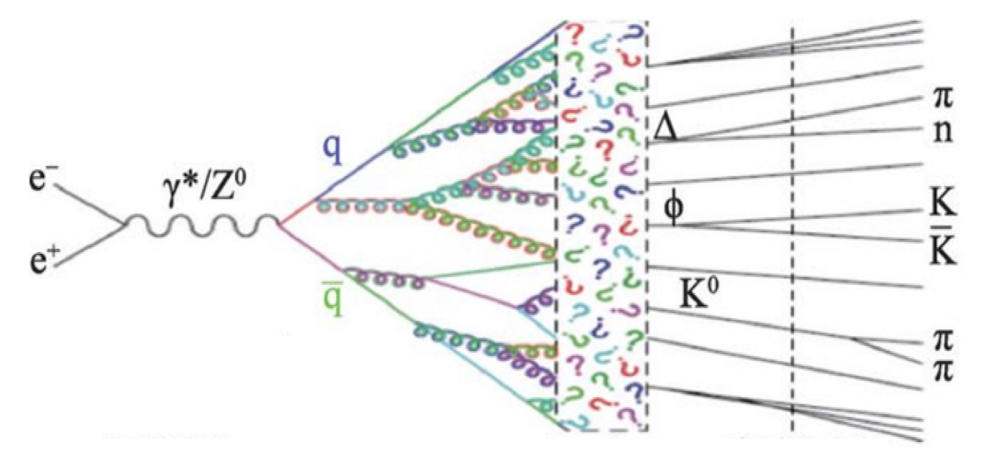
Different methods:

- @≤2.0 GeV: exclusive
- @≥2.0 GeV: inclusive
- ISR technique: taking advantage of BESIII $\psi(3770)$ data, the R value from $\pi^+\pi^-$ threshold to continuum region can be accessed

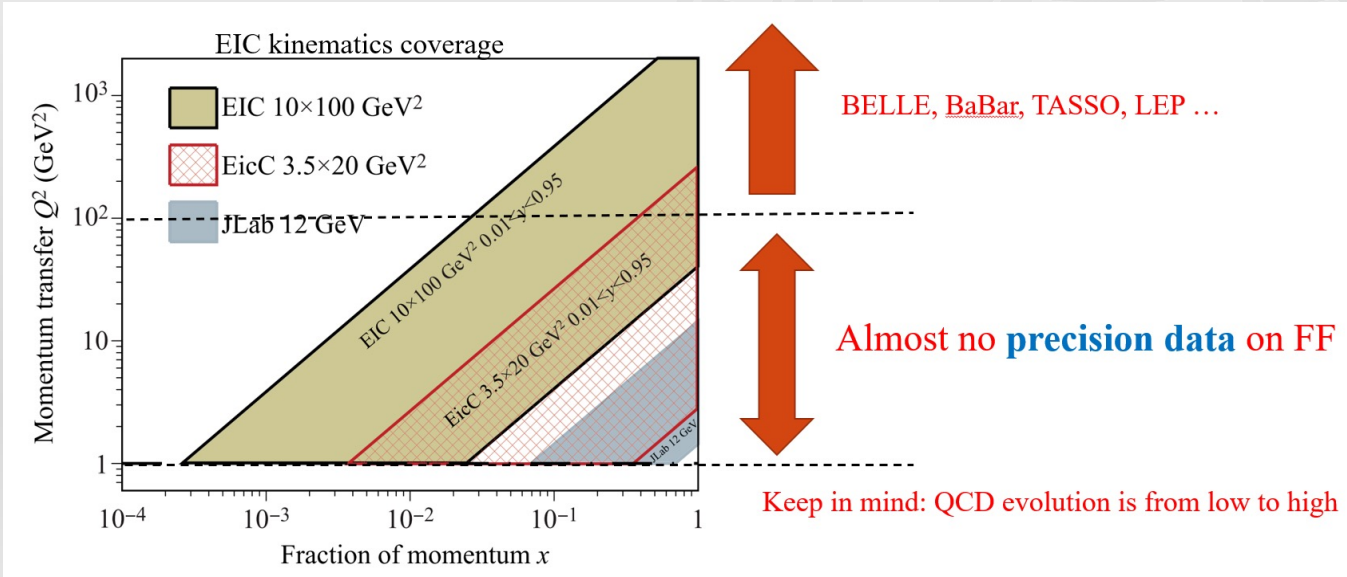
More results of R measurement at BESIII are coming soon!

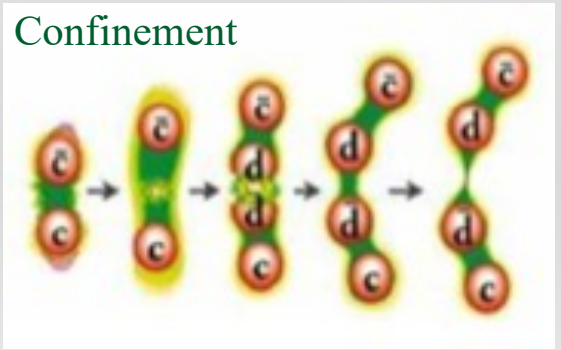
Fragmentation functions (FFs) $D_q^h(z)$

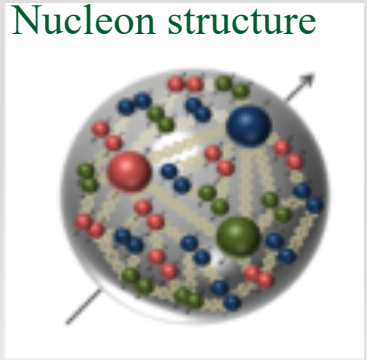
- $D_q^h(z)$: describe the fragmentation of an unpolarized quark into an unpolarized hadron, where the hadron carries a fraction $z = 2E_h/\sqrt{s}$ of parton's momentum



- Better knowledge of $D_q^h(z)$ needed to exploit full potential of future facilities(EIC & EicC)

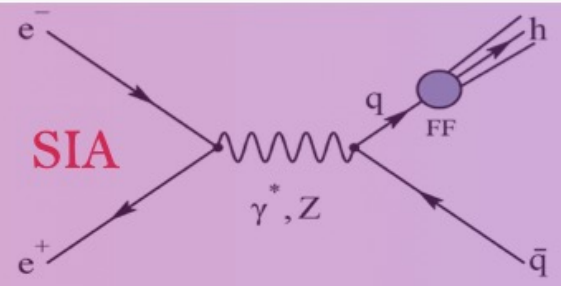






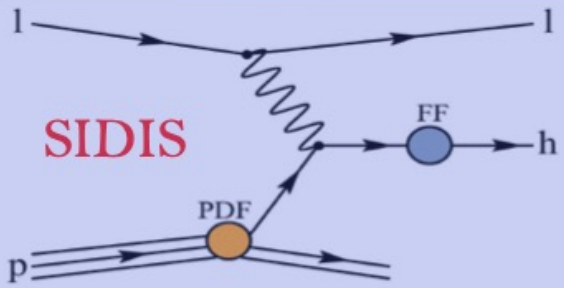
Several open questions about QCD

Access FFs with QCD factorization



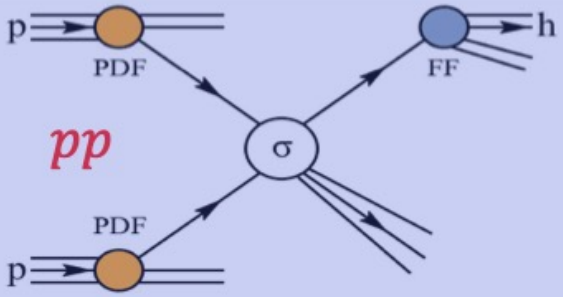
$e^+e^-: s = \sum_q \sigma(e^+e^- \to q\bar{q}) \otimes FF$

- No PDFs necessary
- Calculations know at NNLO
- Flavor structure not directly accessible



SIDIS: $s = \sum_q PDF \otimes \sigma(eq \to e'q') \otimes FF$

- Depend on unpolarized PDFs
- Flavor structure directly accessible
- FFs and PDFs



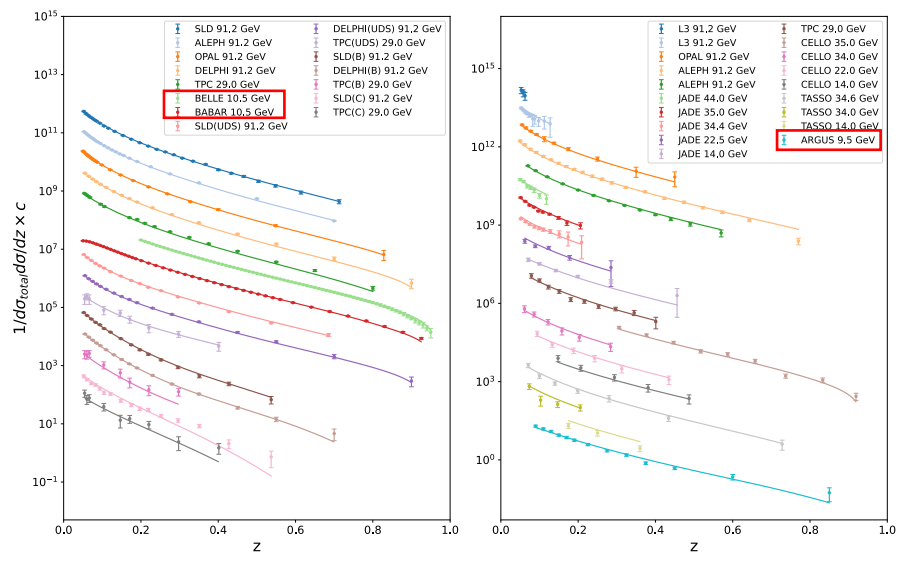
$pp: s = \sum_q PDF \otimes PDF \otimes \sigma(q_1 q_1 \to q_1' q_2') \otimes FF$

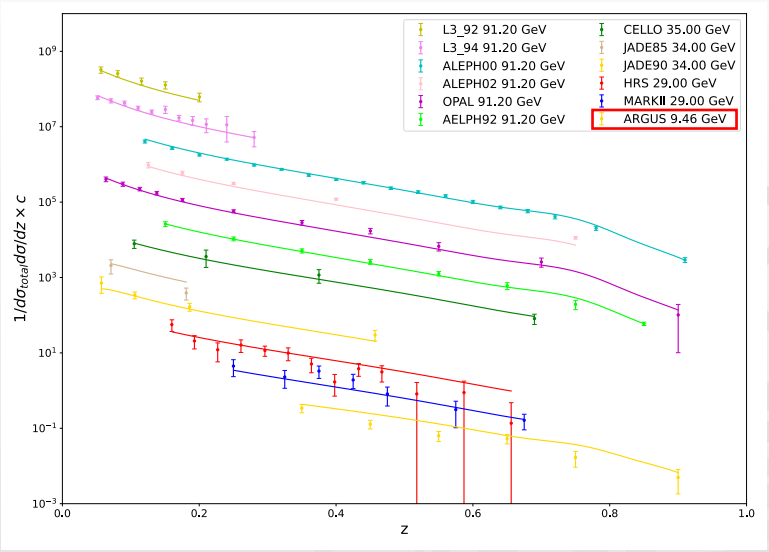
- Depend on unpolarized PDFs
- Leading access to gluon FF
- Parton momenta not directly known

SIA @ e^+e^- : the cleanest process for FFs studying

World data: $\pi^{\pm}$, π^{0}, η, K_S^0, $K^{\pm}$

arxiv:2404.11527





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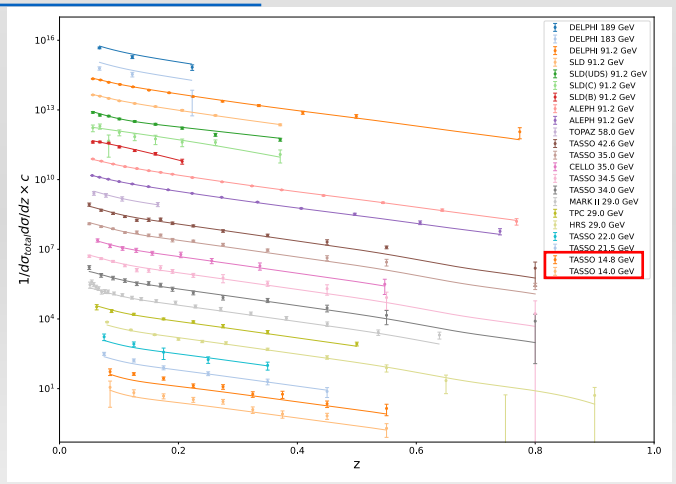
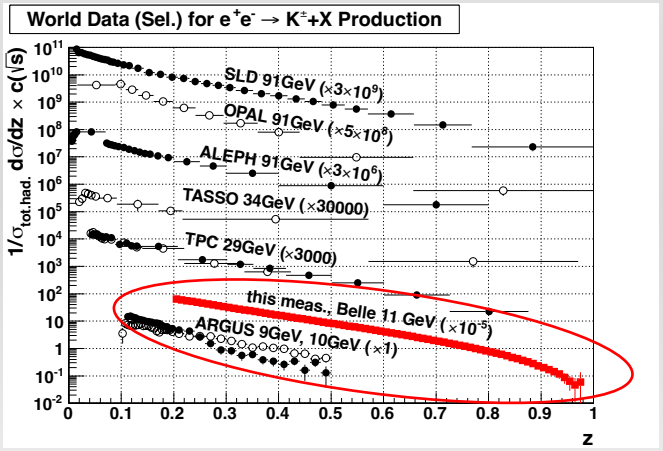


PRL **111** 062002 (2013)



Lack of precise data at low energy, where BESIII could contribute

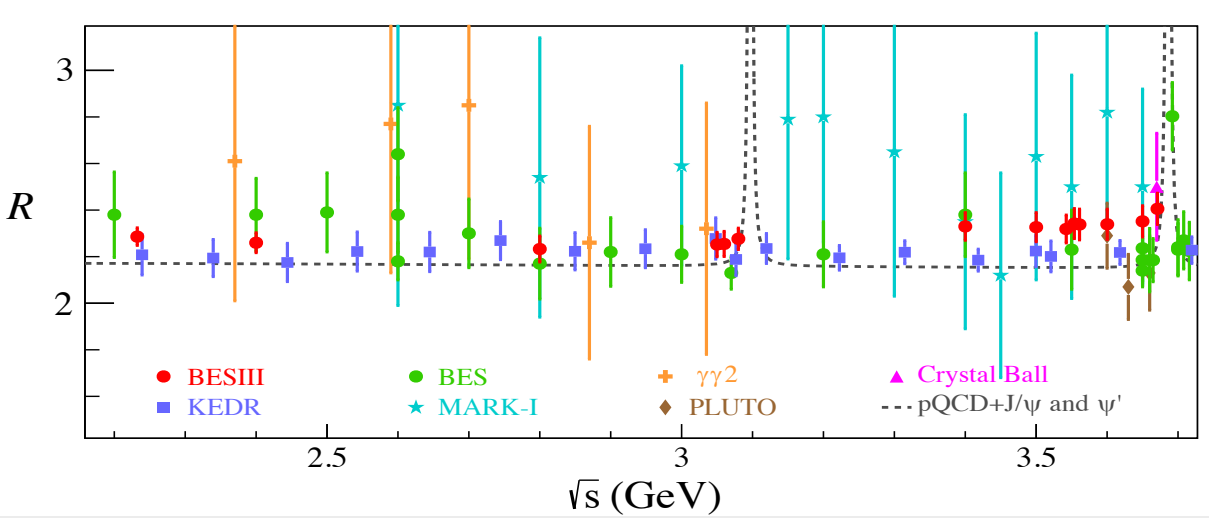
Measurement strategy at BESIII

- Normalized differential cross section (h as the hadron under investigation):

$$\frac{1}{\sigma_{\mathrm{had}}}\frac{d\sigma(e^+e^-\to h+X)}{dp_h} = \frac{N_h}{N_{\mathrm{had}}}\frac{1}{\Delta p_h} = \frac{N_h^{\mathrm{obs}}}{N_{\mathrm{had}}^{\mathrm{obs}}}\frac{1}{\Delta p_h} f_h$$

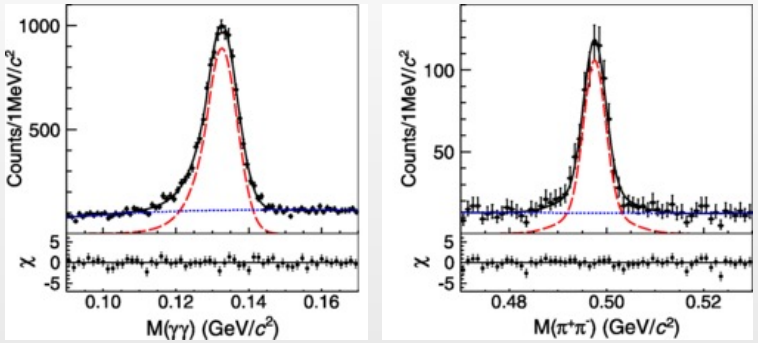
- Hardronic events N_{had}: using the same criteria as those applied in the R value measurement
- Δp_h: Bin width in a momentum bin
- Two relatively independent inclusive MC models are developed to determine f_h

Phys. Rev. Lett. 128, 06200(2022)



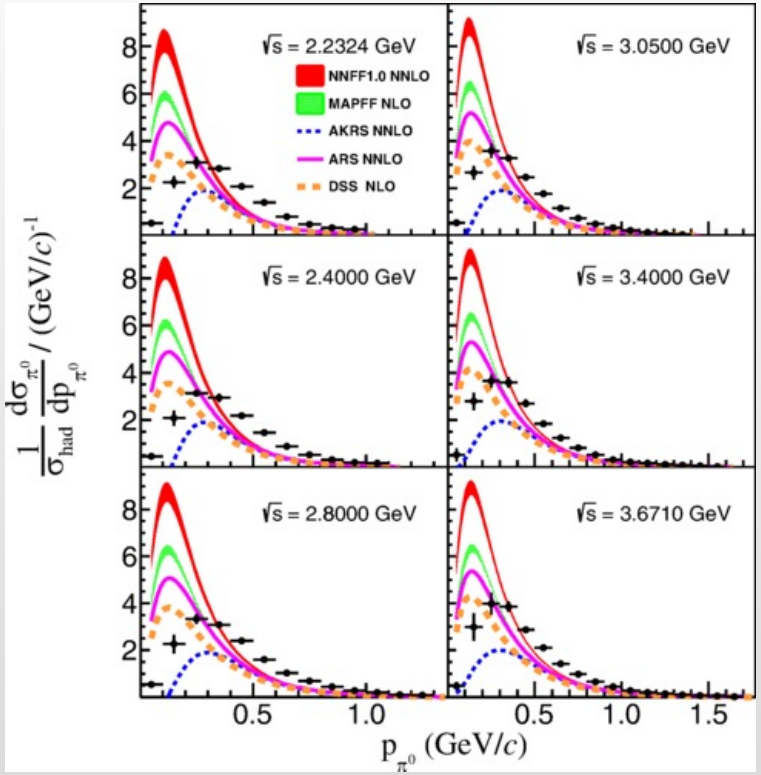
Results for π^0 and K_S^0

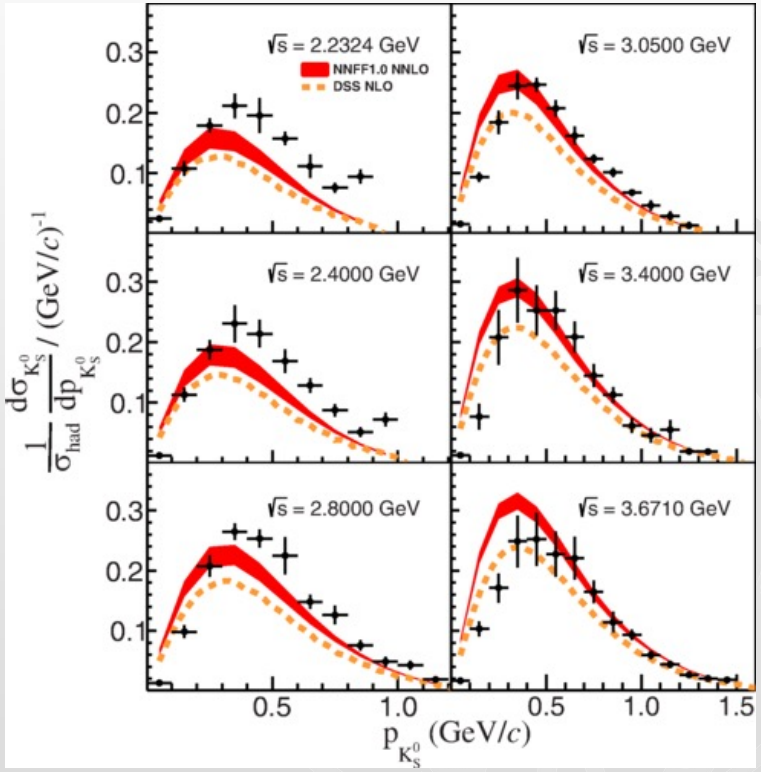
PRL 130 231901 (2023)



$P \in (0.4, 0.5)$ GeV/c

- Hadrons reconstructed from daughters
- Background suppression:
  - Helicity angle cut
  - Secondary vertex fit

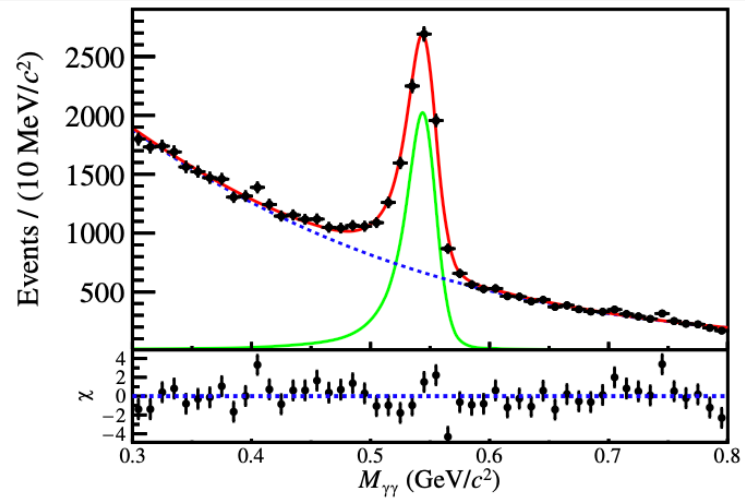




- Dominant uncertainty is from simulation of $e^+e^- \to \pi^0/K_S^0 + X$
- Disagreement between FF fits and data depends on both $\sqrt{s}$ and p_h
- Leading twist calculation not sufficient? quark and hadron mass correction? small-z resumption? problem in the extrapolation of FFs to lower energy?

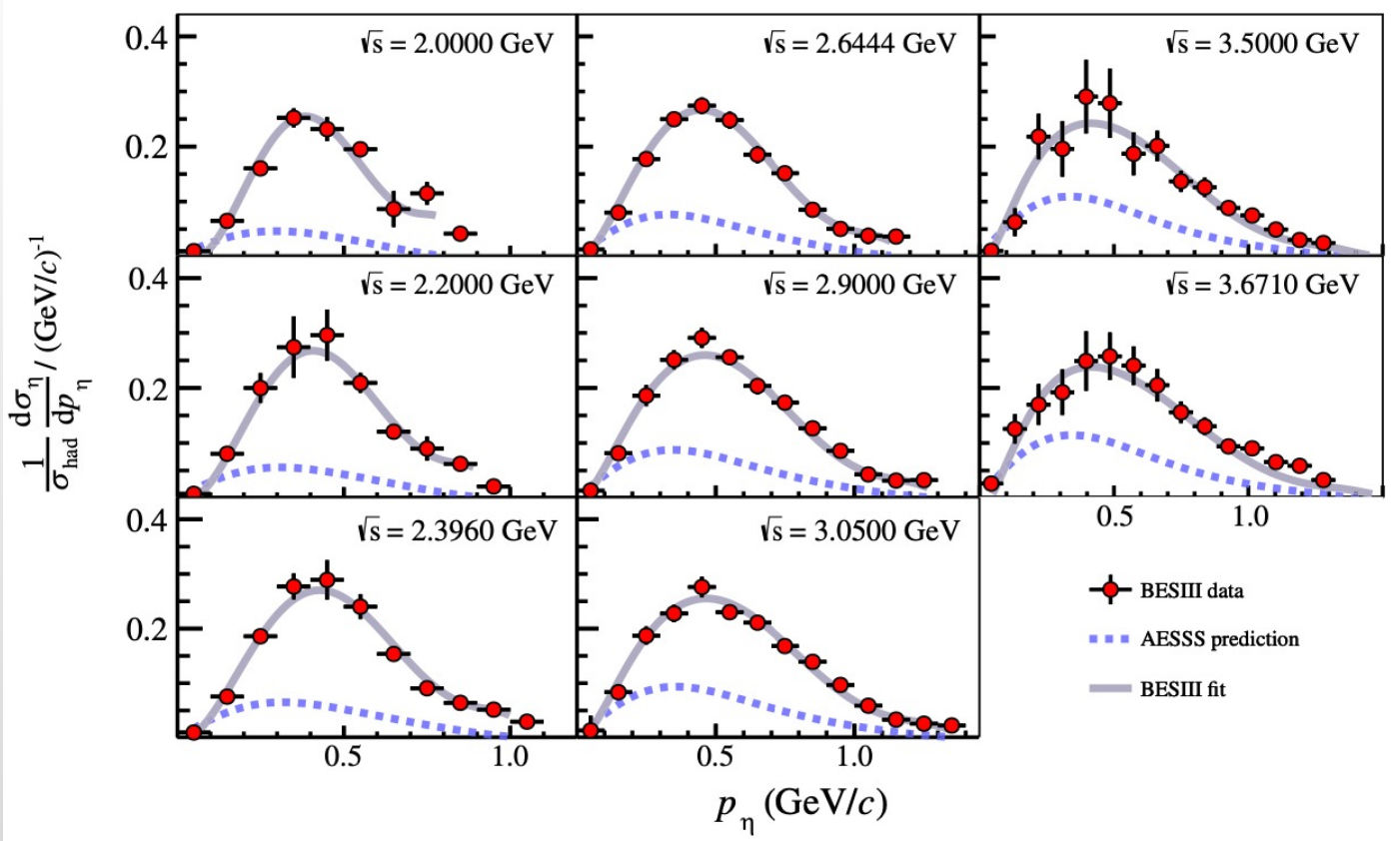
Results for η

PRL **133** 021901 (2024)



(0.4, 0.5) GeV/c @ $\sqrt{s}$ = 2.9 GeV

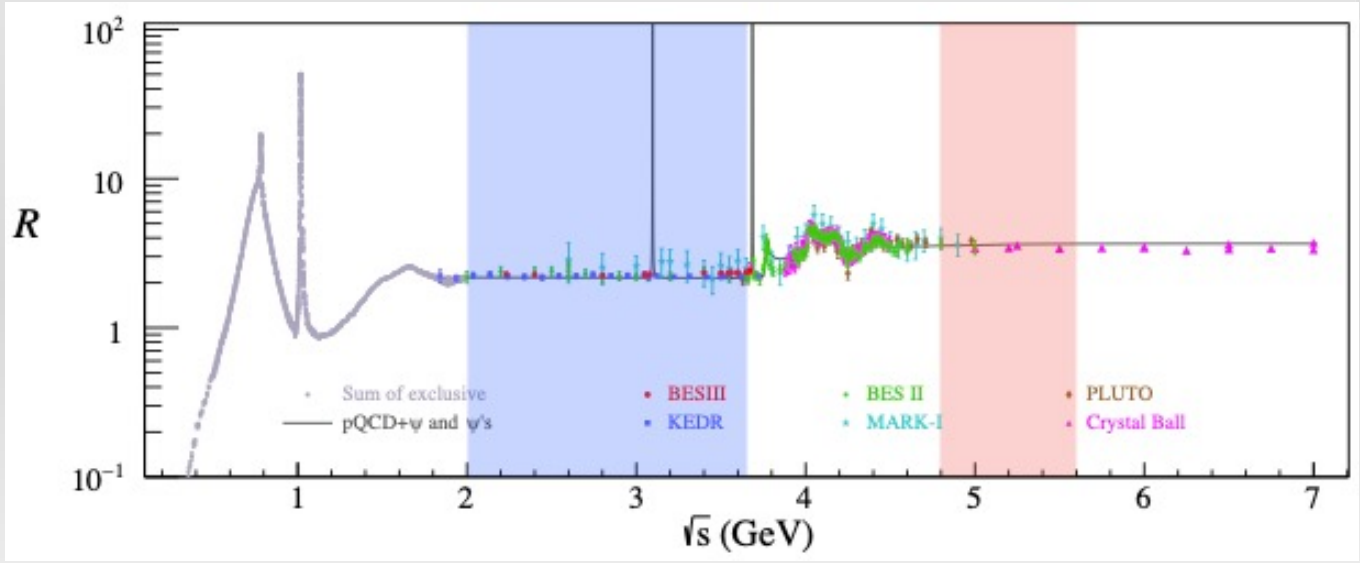
- Hadrons reconstructed from daughters
- Helicity angle cut for background suppression



- Significant disagreement between FF fits given in PRD 83, 034002 (2011) and data
- A new fit performed (arXiv: 2404.11527):
  - Incorporated new BESIII data and previous world e^+e^- data with $\sqrt{s} > 10$ GeV
  - Implemented higher-twist effects and hadron mass correction in NNLO accuracy

More results are ongoing

- In continuum region 2.00 ~ 3.67 GeV:
  - 1D and 2D (p v.s. p_t) inclusive production of charged particles: $e^+e^- \to \pi^\pm/K^\pm + X$
  - Search for spin-alignment effect for vector mesons: $e^+e^- \to \phi K^* + X$
- In higher-energy region above 4.8 GeV:
  - High luminosity data: $> 150\ \mathrm{pb}^{-1}$ on the tape and more on the schedule
  - Possible to measuring heavier strange meson and hyperons: $e^+e^- \to \eta'/\Lambda/\Sigma + X$



Summary

■R value

- ➢ Improving accuracy determination of R value important for Standard Models tests
- ➢ The First round measurement of R value at BESIII published (Phys. Rev. Lett. 128, 06200(2022))
  - ✓ $2.2324\ \text{GeV} \leq \sqrt{s} \leq 3.6710\ \text{GeV}$
  - ✓ Accuracy better than 2.6% below 3.1 GeV and 3.0% above

⇒ Other high statistics samples available

⇒ Other approaches on-going @ BESIII Stay tuned !!!!

■Fragmentation functions

- ➢ Precise knowledge of FFs helps us to understand the non-perturbative QCD dynamics
- ➢ The e^+e^- annihilation experiments provide the cleanest environment to measure FFs
- ➢ BESIII contributes to the study of unpolarized FFs at $\sqrt{s} < 5$ GeV
  - ✓ Normalized differential cross sections of inclusive $\pi^0/\mathrm{K}_S^0/\eta$ production are measured
  - ✓ The results provide broad z coverage from 0.1 to 0.9 with precision of 3% at z ~ 0.4
  - ✓ Large discrepancy from predictions of the existing fragmentation functions are observed, which requires more study

⇒ More results for $\pi^{\pm}, K^{\pm}, \phi, K^*$ at continuum region and $\eta'/\Lambda/\Sigma$ at higher energy region are currently in progress

Thank you!