中国科学院近代物理研究所
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Unpolarized Fragmentation Functions studies at BESIII

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（IMP）

碎裂函数和能量关联研讨会

2025.08.09, 兰州

Outline

- **Introduction of Fragmentation Functions**

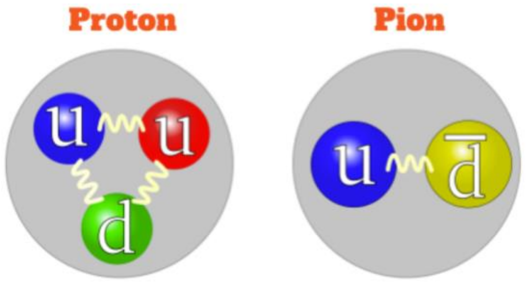
- **Existing studies at BESIII**
  - $e^+e^- \to \pi^0/K_S^0 + X$
  - $e^+e^- \to \eta + X$
  - $e^+e^- \to \pi^\pm/K^\pm + X$

- **Summary**

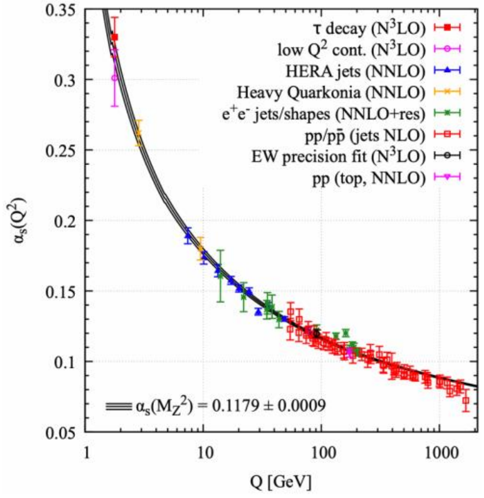
QCD: Confinement and Nucleon structure

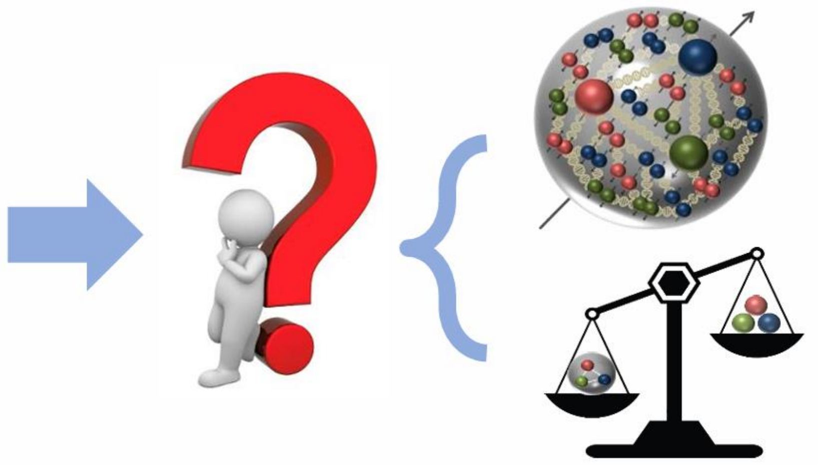
◆ Confinement

- Quarks and gluons can not be observed separately.
- They are perpetually confined within hadrons.



◆ Nucleon structure





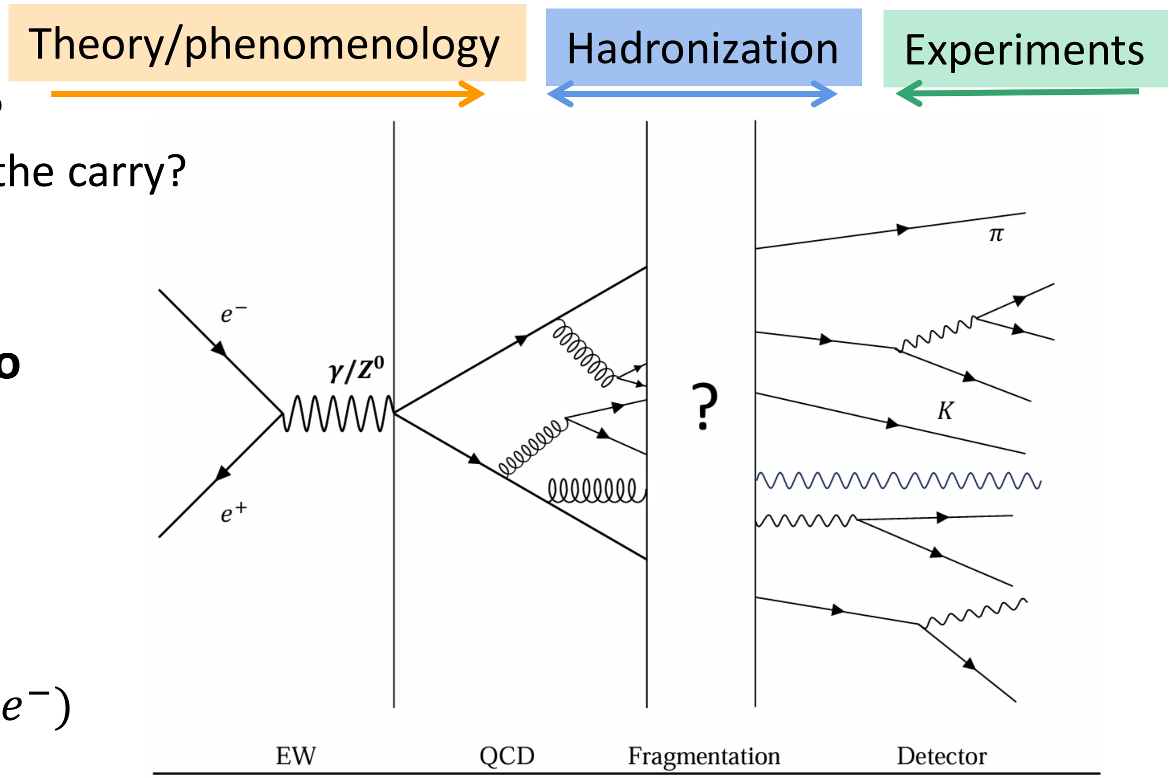
Spin: how does nucleon spin emerge

Mass: Higgs mechanism gives only a few %

QCD: Hadronization and Fragmentation functions

◆ Hadronization

- How many particles and how many jets created?
- What fraction of the initial parton momenta do the carry?



◆ Fragmentation functions (FFs)

✓ **Describe how quarks or gluons transform into hadrons.**

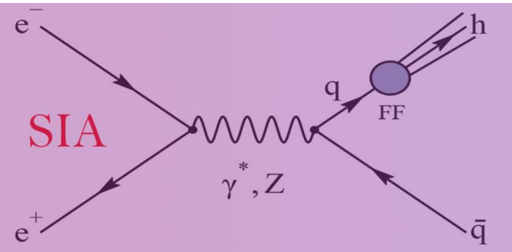
$$D_i^h(z, Q^2),$$

- i: quark, anti-quark or gluon
- h: hadrons like $\pi^{\pm}, K^{\pm}, p, \bar{p}$ etc..
- z: energy fraction of hadron. ($z = 2E_h/\sqrt{s}$ in e^+e^-)
- Q^2 : four momentum transfer in the reaction

✓ **Probability of a parton to fragment into a specific color-neutral hadron h.**

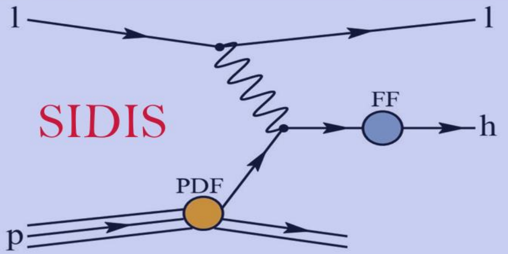
✓ **Provide a characterization of the non-perturbative aspects of hadronization.**

Accessing FFs in experiments



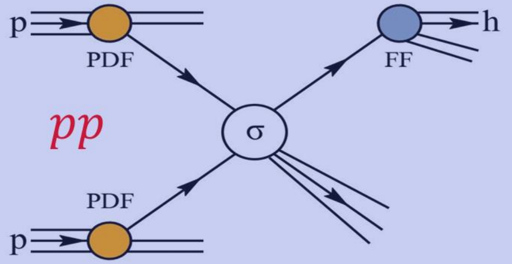
$e^+e^-: s = \sum_q \sigma(e^+e^- \to q\bar{q}) \otimes FF$

- 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

- e^+e^- experiments is the cleanest laboratory for the fragmentation function studies.
- FFs and PDF: Universal and non-perturbative objects
- Will known FFs are crucial for nucleon structure in ep experiments

Accessing FFs in e^+e^- annihilation

- Experimental observable in e^+e^- annihilation: normalized differential cross-section of the inclusive production of final state hadron "h"

$$\frac{1}{\sigma_{tot}(e^+e^- \to \text{hadrons})} \frac{d\sigma(e^+e^- \to h + X)}{dp_h}$$

  - At leading order in α_s, can be interpreted as:

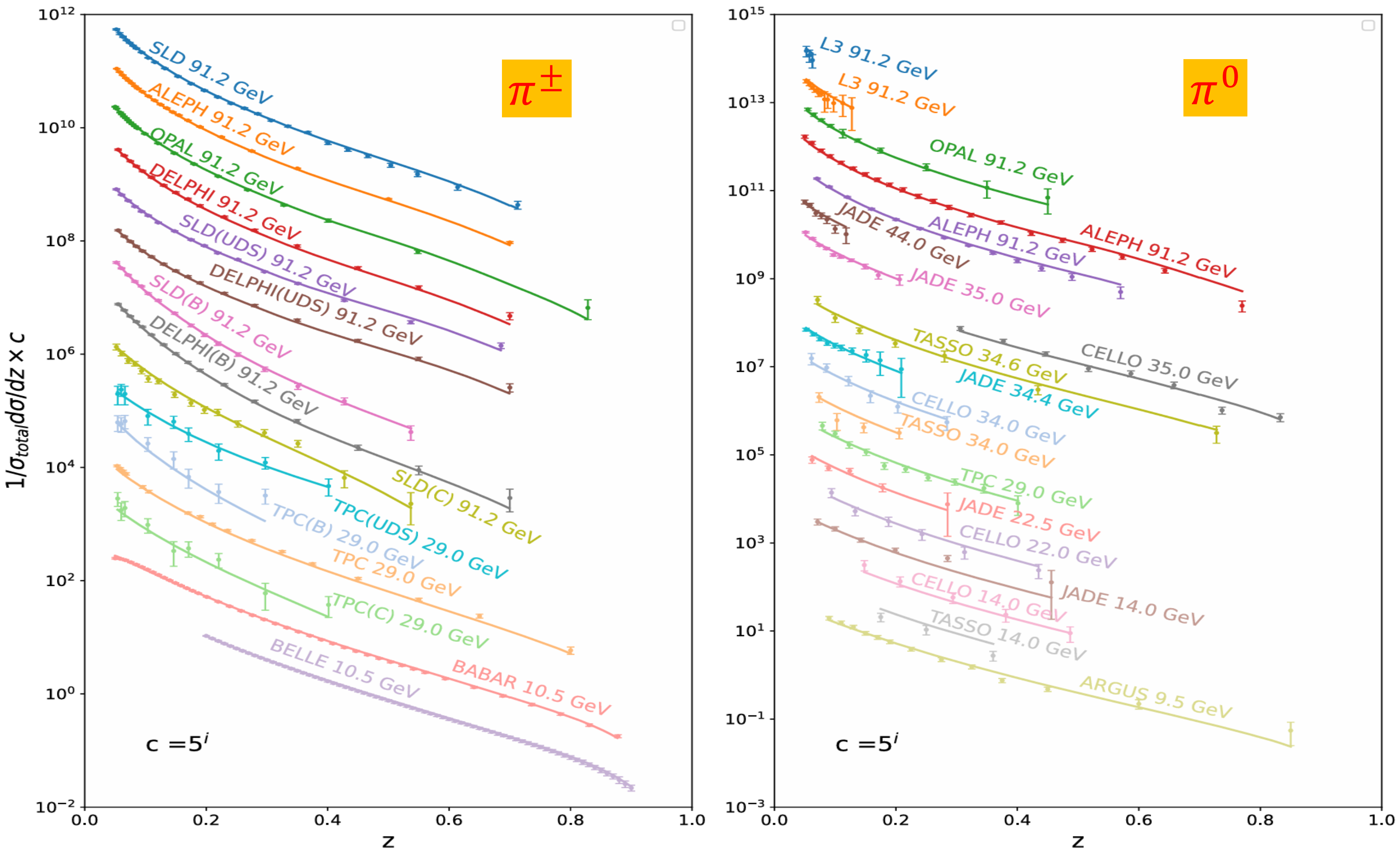
$$\sum e_q^2[D_q^h(z, Q^2) + [D_{\bar{q}}^h(z, Q^2)]]$$

FFs

$$z = \frac{2E_h}{\sqrt{s}}$$

Factorization scale (c.m. energies)

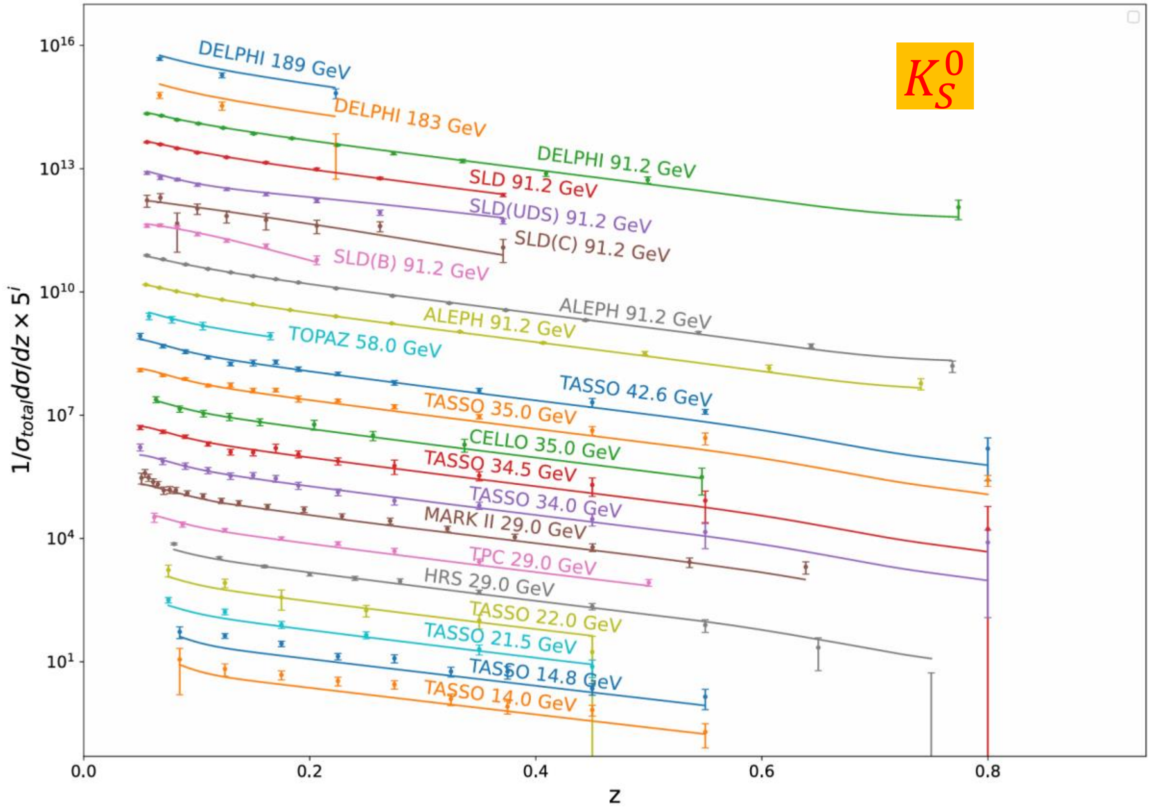
World data for $\pi^{\pm}/\pi^{0}$

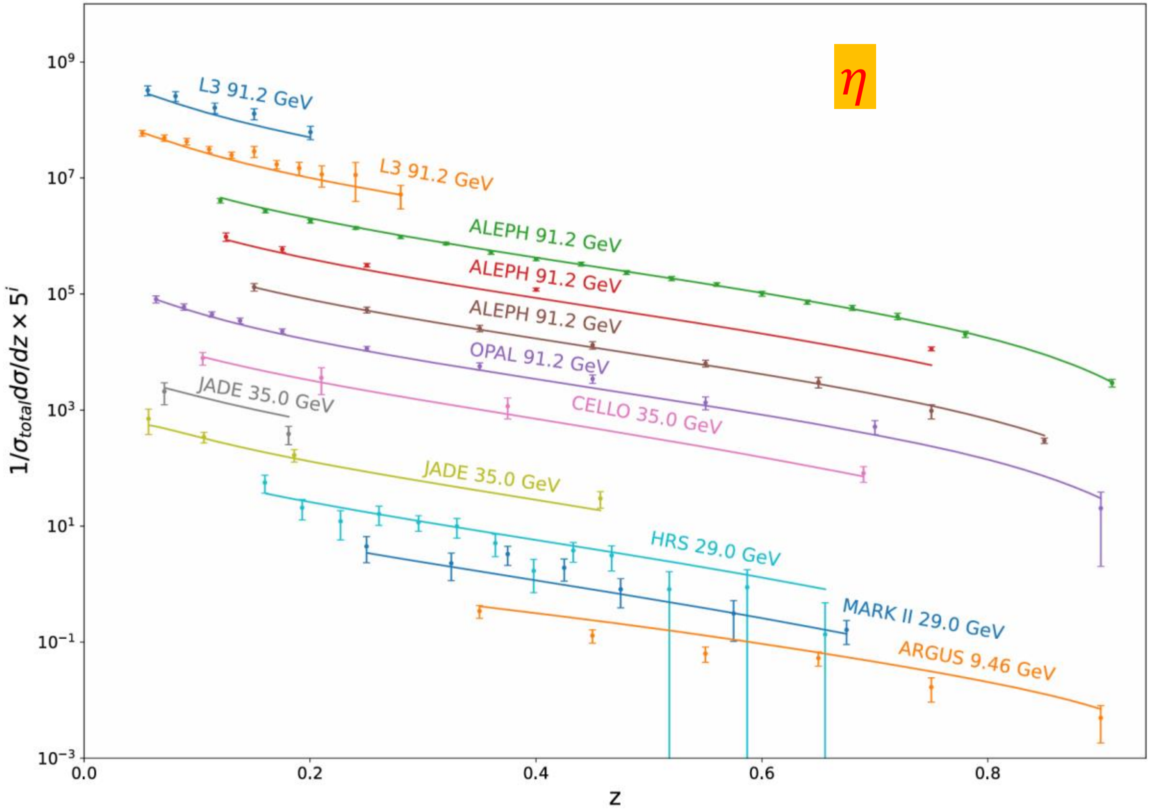


[Li, Anderle, Xing, Zhao PRD 111, 034030 (2025)]

- Precise data for $\pi^{\pm}/\pi^{0}$, most of them obtained at very high c.m. energies
- Lack of data at low energy, where BESIII can contribute

World data for K_S^0 and η





- Most of them obtained at very high c.m. energies
- Lack of data at low energy, where BESIII can contribute

Li, Anderle, Xing, Zhao
PRD 111, 034030 (2025)

Analysis at BESIII

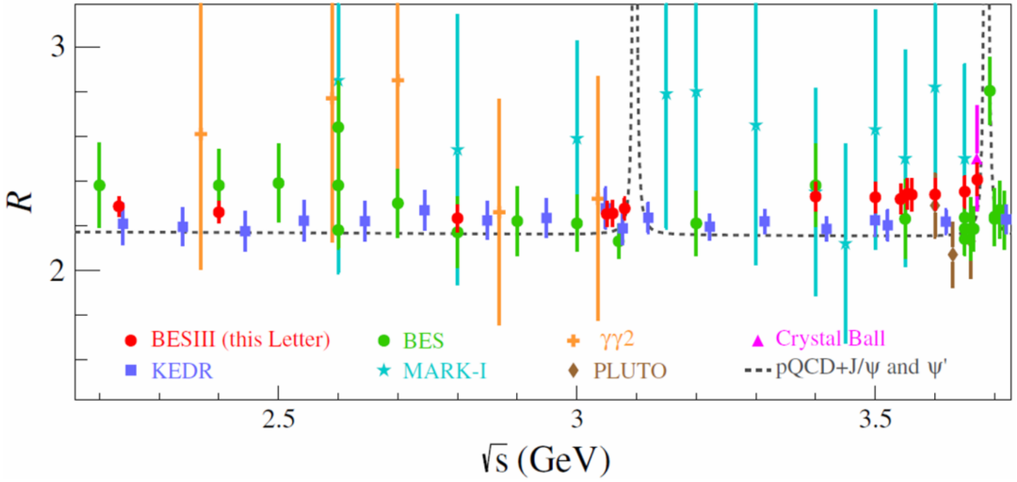
- Normalized differential cross-section:

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

- Based on dedicated MC generators development for R-value analysis:
- Luarlw, Hybrid

- Hadronic events:

[PRL 128, 062004 (2022)](PRL 128, 062004 (2022))

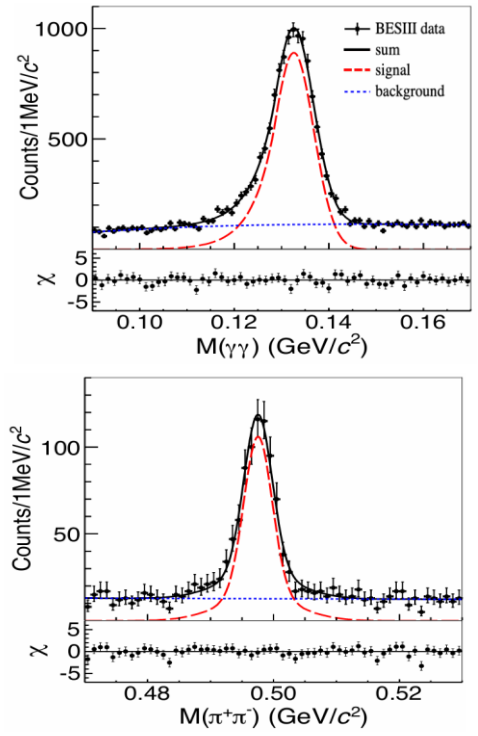


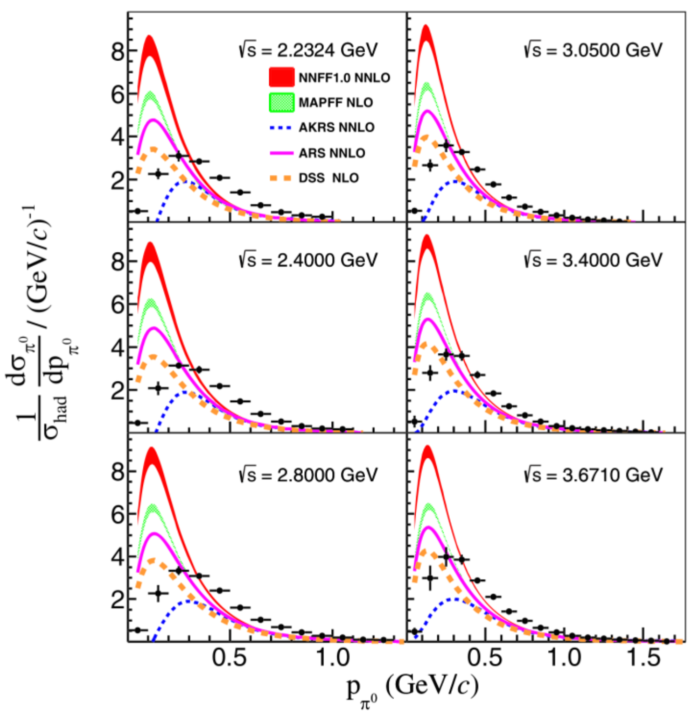
$\sqrt{s}$ (GeV)	$\mathcal{L}$ (pb^{-1})	$N_{\rm had}^{\rm tot}$
2.0000	10.074	350298 ± 592
2.2000	13.699	445019 ± 668
2.3960	66.869	1869906 ± 1368
2.6444	33.722	817528 ± 905
2.9000	105.253	2197328 ± 1483
3.0500	14.893	283822 ± 533
3.5000	3.633	62670 ± 251
3.6710	4.628	75253 ± 275

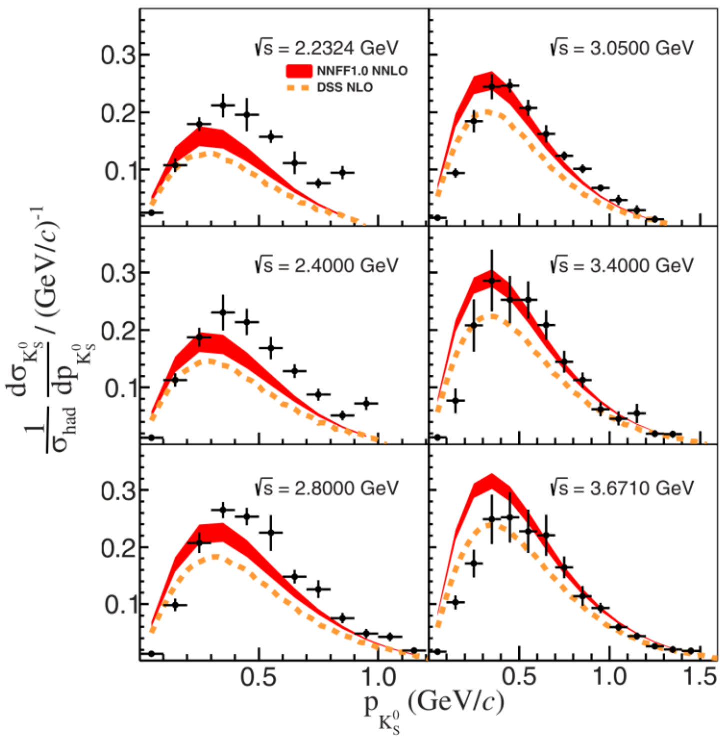
Inclusive production of π^0/K_S^0@ BESIII

$$\frac{N_h^{obs}}{N_{had}^{obs}}\frac{1}{\Delta p_h}f_h$$

PRL 130, 231901 (2023)



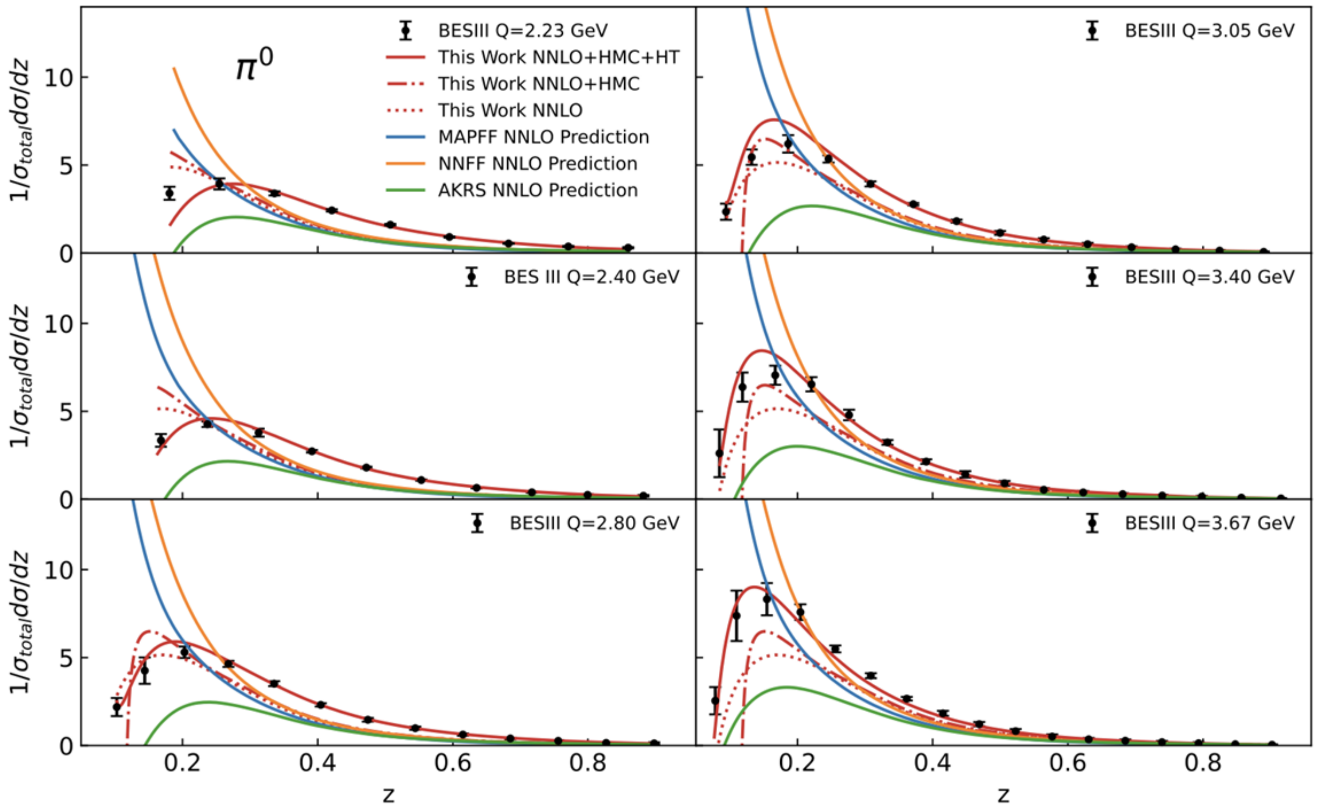




- Theory modes have different initial evolution scales and kinematic requirements on data
- Higher twits effect? Hadron mass effect?

Inclusive π^0 production

PRD 111, 034030 (2025)

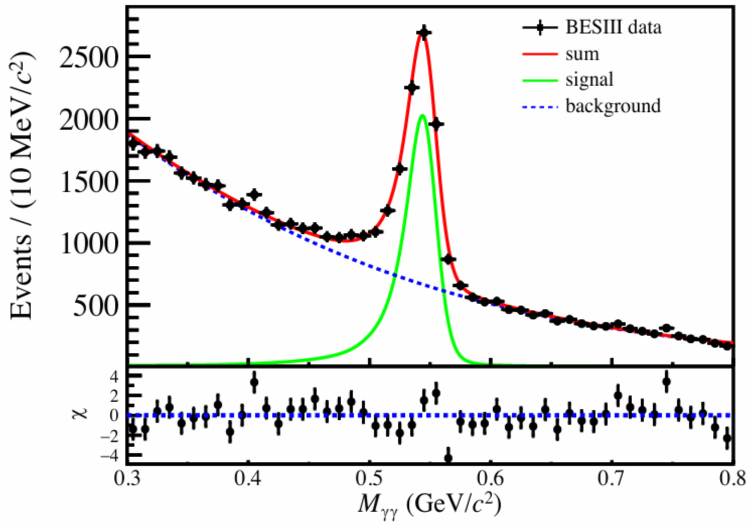


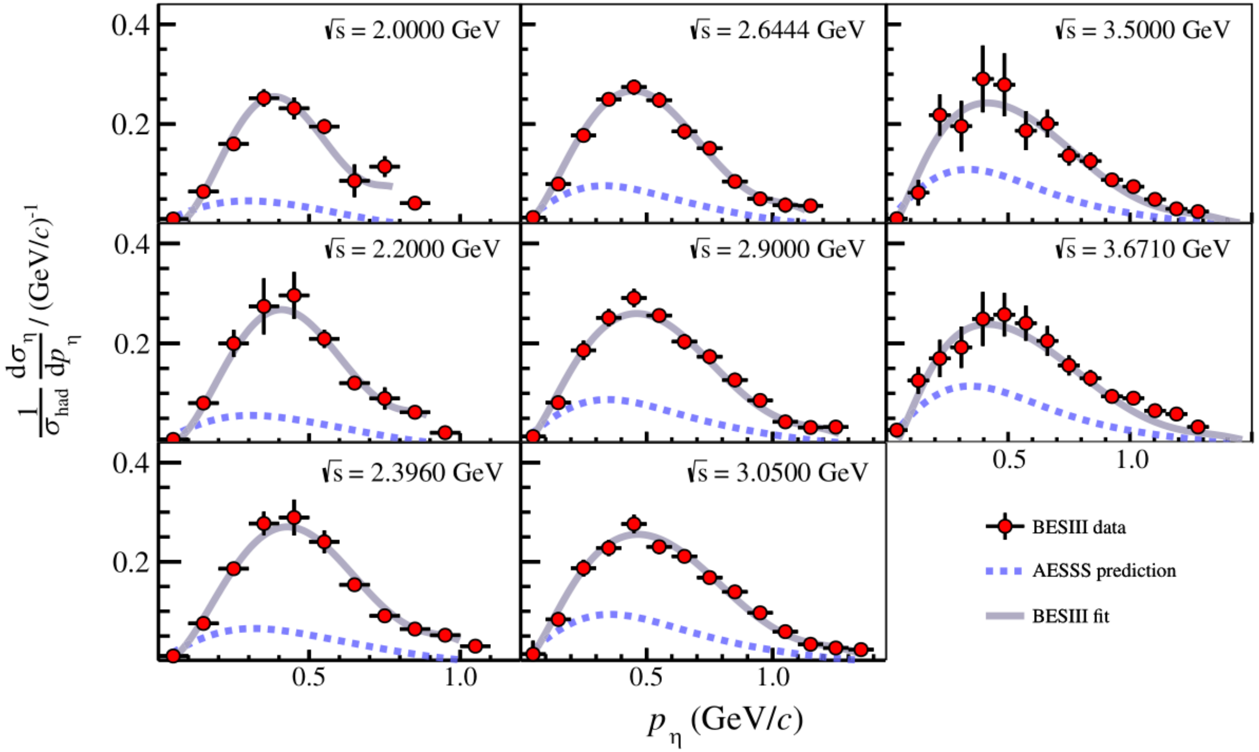
- NNLO accuracy, including hadron mass correction at higher-twits effects

Inclusive production of η@ BESIII

◆ Inclusive η @ BESIII

PRL 133, 021901 (2024)



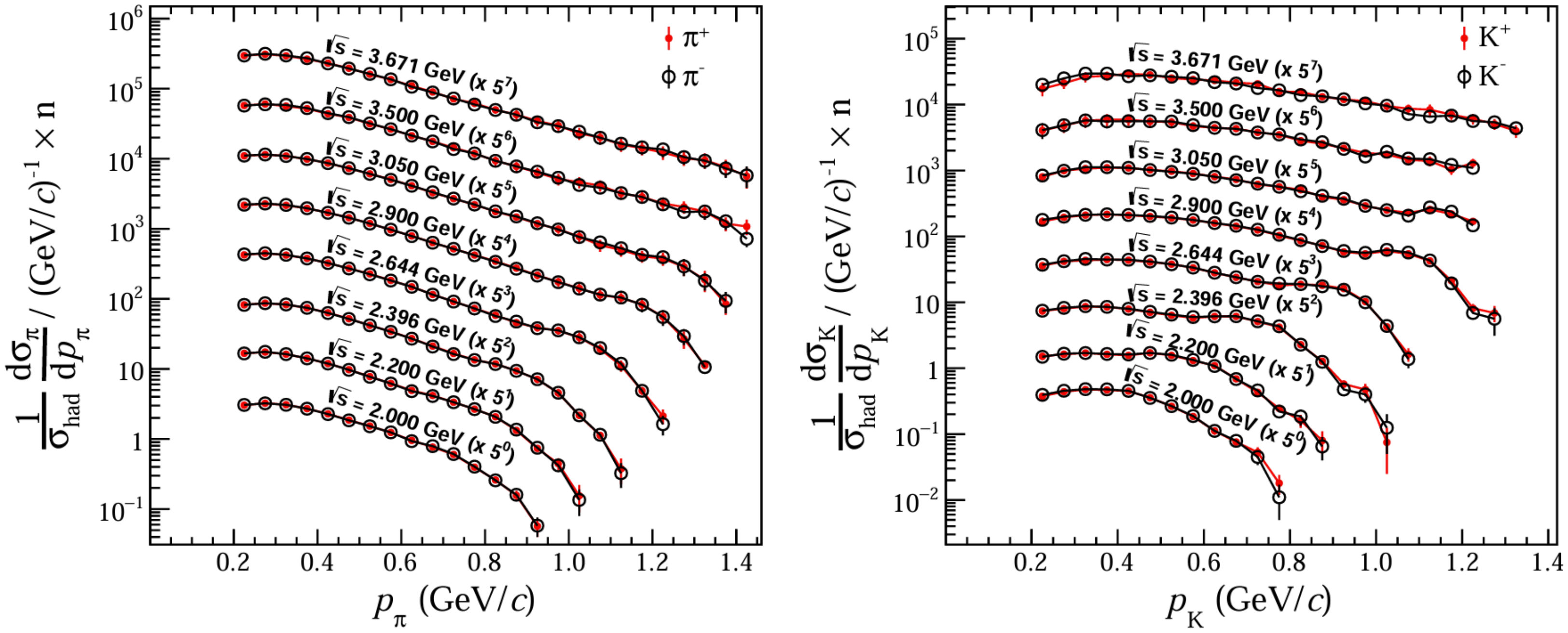


◆ BESIII fit: NNLO+hadron mass correction + high-twist

Inclusive production of $\pi^{\pm}/K^{\pm}$@ BESIII

◆ Normalized differential cross section of the inclusive process at 8 c.m. energies from 2.00 to 3.67 GeV

arXiv:2502.16084

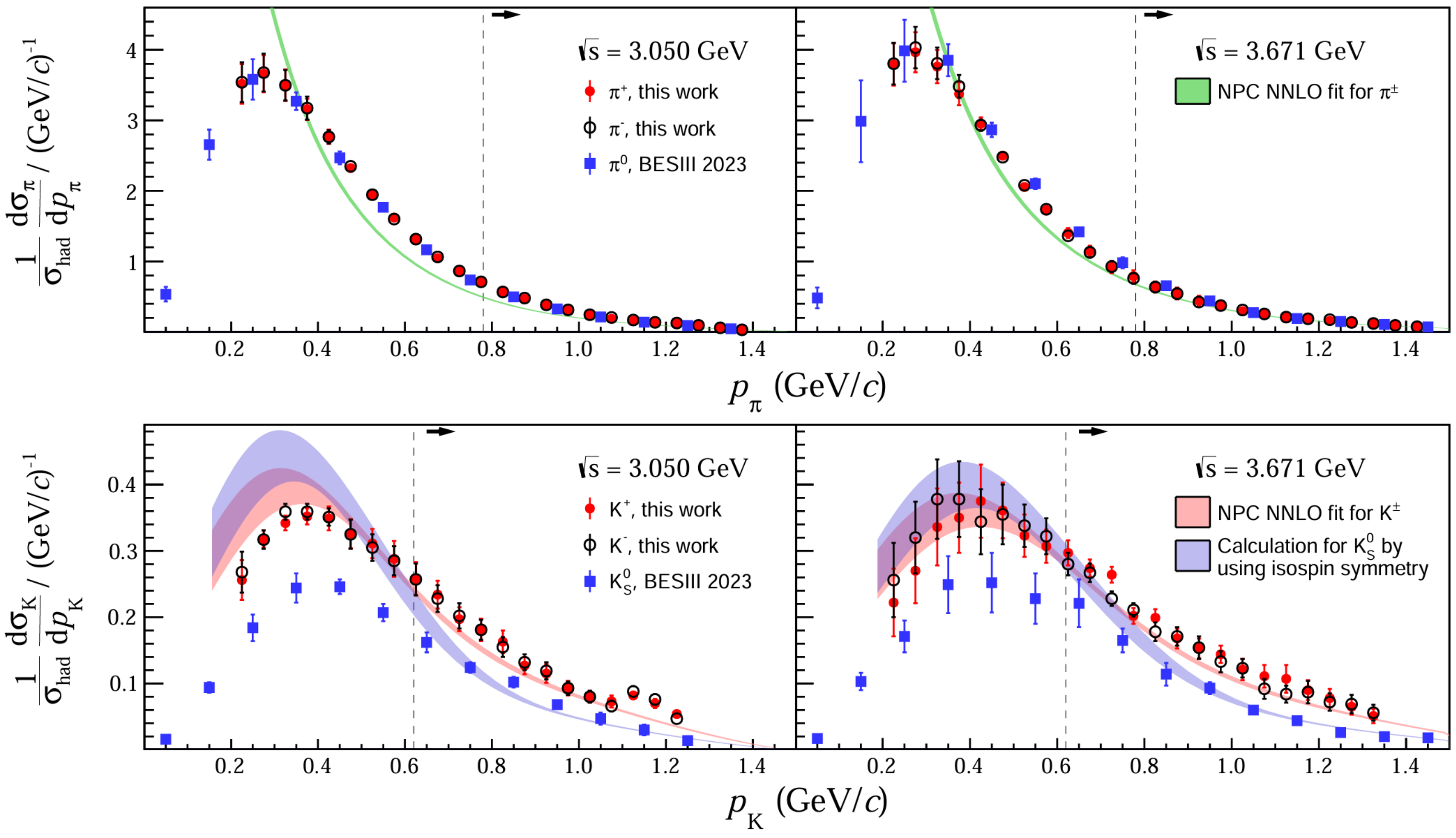


- Z coverage from 0.13-0.95
- Opportunity to test QCD factorization at low energy scale.

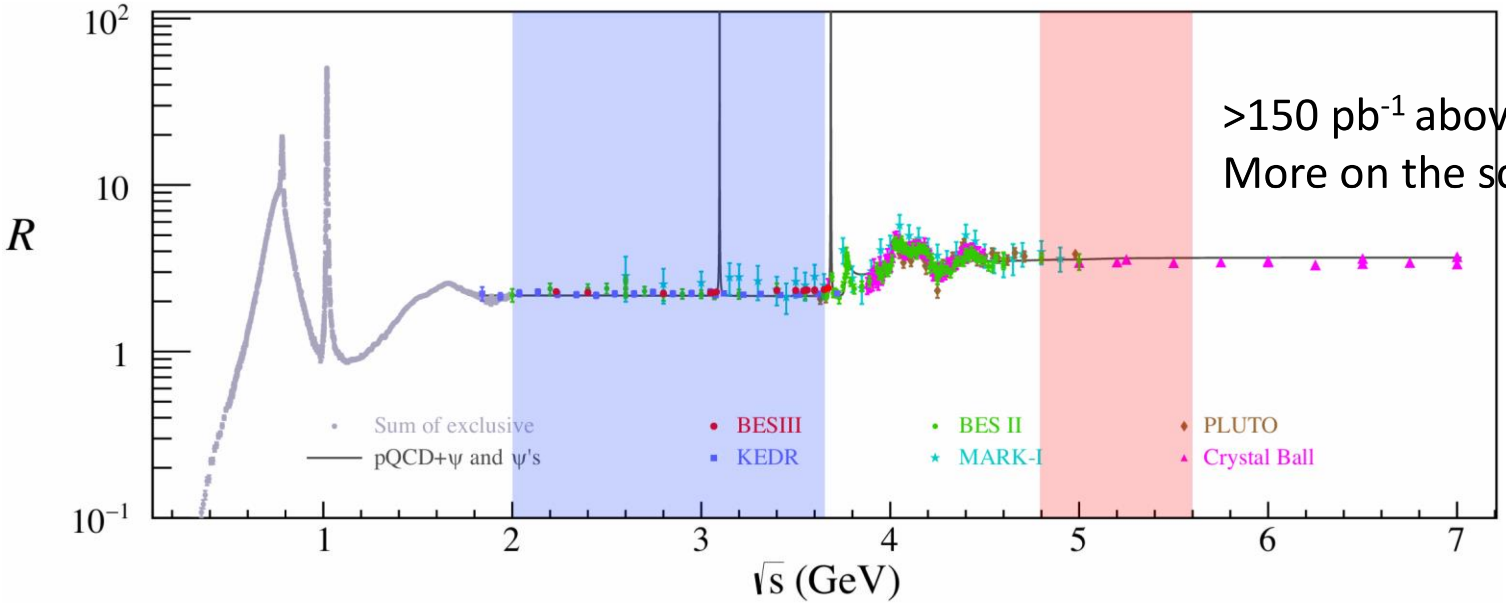
Inclusive production of $\pi^{\pm}/K^{\pm}$@ BESIII

- The measured $\pi^{\pm}$cross sections are consistent with that of π^0.
- The measured $K^{\pm}$ cross sections are systematically higher than that of K_S^0.
- New global data fit is performed at NNLO under Nonperturbative Physics Collaboration (NPC) framework [PRD110, 114019; PRL132,261903]($\sqrt{s} > 3$ GeV & $E_h > 0.8$ GeV)
- $D_i^{\pi^0} = \frac{1}{2}\left(D_i^{\pi^+} + D_i^{\pi^-}\right)$
- $D_q^{K_S^0} = \frac{1}{2}\left(D_{q'}^{K^+} + D_{q'}^{K^-}\right)$($q' = u, d$ if $q = d, u$)
- First support for isospin symmetry at <10 GeV in π and K fragmentation processes

arXiv:2502.16084



Further Measurements @ BESIII



>150 pb^{-1} above 4.8 GeV
More on the schedule

Collinear FFs D_1^h

$e^+e^- \to (\pi\pi) + X$

$e^+e^- \to \phi/K^*(892) + X$

$e^+e^- \to \eta' + X$

$e^+e^- \to \Lambda(\overline{\Lambda}) + X$

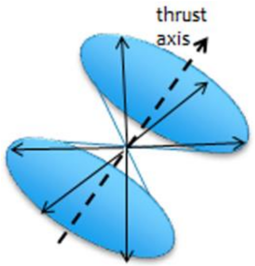
$e^+e^- \to \Sigma + X$

TMD FFs $D_{1T}^{\perp h}$

$e^+e^- \to \pi^\pm/\pi^0 + X$

$e^+e^- \to \eta/K^\pm/K_S^0 + X$

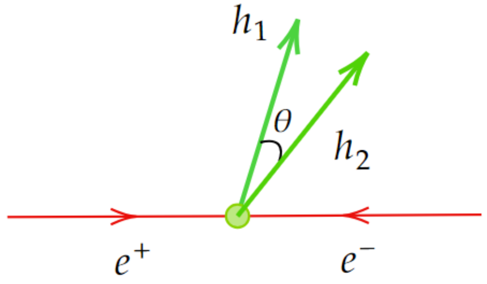
$e^+e^- \to h_1 h_2 + X$
(back-to-back pair)



Many results will be ready soon

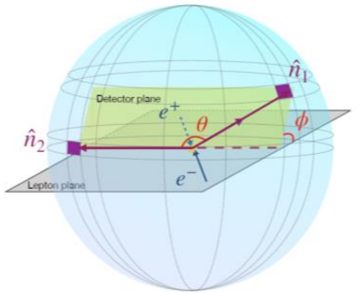
FFs vs Energy-Energy correlator (EEC)

- Energy-weighted two particle angular correlation



$$\mathrm{EEC}(\chi) = \frac{1}{\sigma_{\mathrm{tot}}} \sum_{i,j} \int d\sigma_{e^+e^- \to ijX} \frac{E_i E_j}{Q^2} \delta(\cos\theta_{ij} - \chi)$$

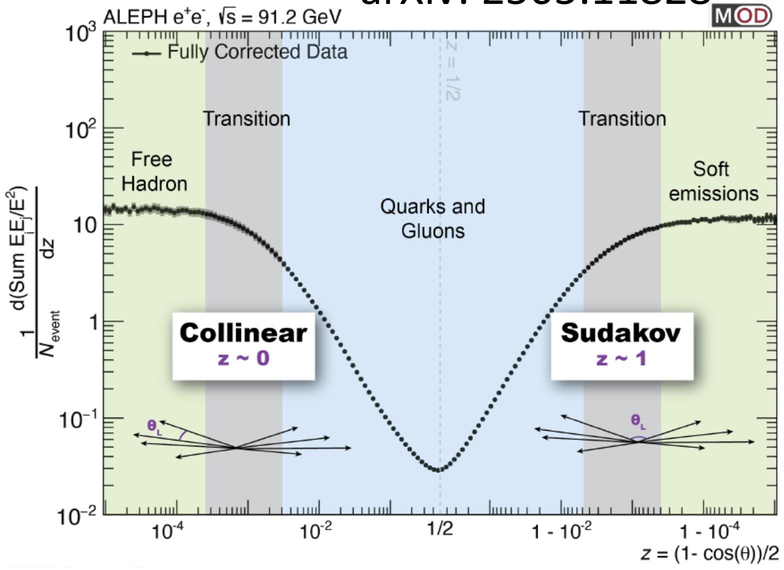
$$\frac{1}{\sqrt{s}\cdot\sqrt{s}} \frac{\sum_i^{N_{h_{12}}} E_{h_1 h_2}}{N_{had}} \frac{1}{\Delta\cos\theta}$$



$$\frac{\sum_i^{N_{12}} (z_1 \cdot z_2)}{N_{had}} \frac{1}{\Delta\phi}$$

BESIII results will ready soon

arXiv: 2505.11828



FFs vs Energy-Energy correlator (EEC)

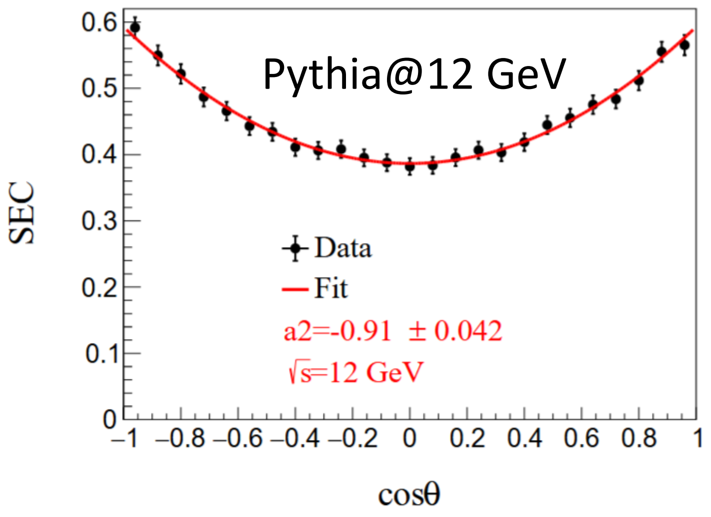
◆ One point energy correlation

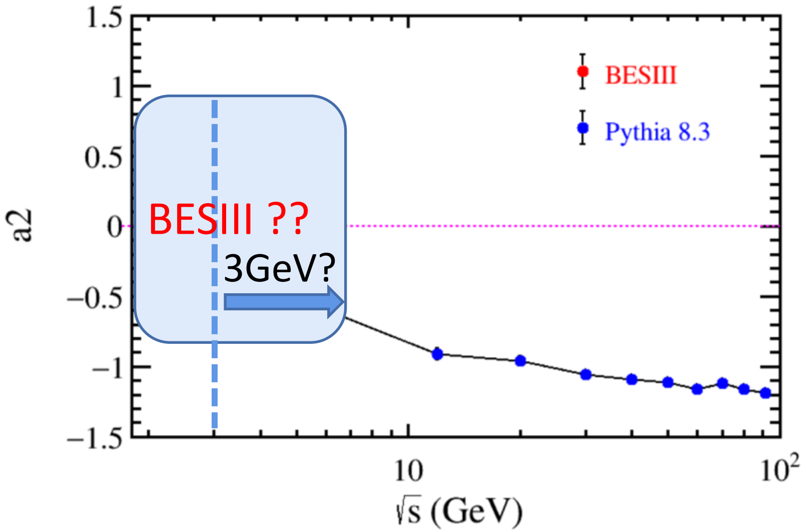
(θ : polar angle)

Fit to the cosθ distribution to extract the a_2 parameter

$$\frac{1}{\sqrt{s}}\frac{\sum_i^N E_h}{N_{had}}\frac{1}{\Delta\cos\theta}$$

$$\langle\mathcal{E}(\vec{n})\rangle = \frac{\sum_s \langle 0|(\epsilon_s^* \cdot j^\dagger)\,\mathcal{E}(\vec{n})\,(j\cdot\epsilon_s)|0\rangle}{\sum_s \langle 0|(\epsilon_s^* \cdot j^\dagger)\,(j\cdot\epsilon_s)|0\rangle} = \frac{q}{4\pi}\left[1 + a_2\left(\frac{1}{2}\sin^2\theta_b - \frac{1}{3}\right)\right] \qquad 3 \geq a_2 \geq -\frac{3}{2}$$





Summary

- Precise knowledge of FFs are important for the understanding of non-perturbative QCD dynamics.
- In e^+e^-annihilation experiments, which serve as the cleanest laboratory for FFs studies, BESIII has provided extensive data at lower energy regimes.
  - $\boldsymbol{e^+e^- \to \pi^0/K_S^0 + X}$
  - $\boldsymbol{e^+e^- \to \eta + X}$
  - $\boldsymbol{e^+e^- \to \pi^\pm/K^\pm + X}$

Thanks for your attention!

- More results of , and EEC-related results will be ready soon at BESIII

$e^+e^- \to (\pi\pi) + X$

$e^+e^- \to \phi/K^*(892) + X$

$e^+e^- \to \eta' + X$

$e^+e^- \to \Lambda(\bar{\Lambda}) + X$

$e^+e^- \to \Sigma + X$

$e^+e^- \to \pi^\pm/\pi^0 + X$

$e^+e^- \to \eta/K^\pm/K_S^0+X$

$e^+e^- \to h_1h_2 + X$
(back-to-back pair)

Back up

Fragmentation functions

- **Final results**

$$\frac{1}{\sigma_{\text{had}}}\frac{d^2\sigma_{\pi^+}}{\text{d}p\text{d}p_t} = f_{correct}\frac{N_{\pi^+}^{obs}}{N_{\text{had}}^{obs}}\frac{1}{\Delta p\Delta p_t}$$