



*14th Internazionale Workshop  
on  $e^+e^-$  Collisions from  
Phi to Psi 2026*

*Pisa, 8-11 June 2026*

# Fragmentation function study at BESIII

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On behalf of the **BESIII** Collaboration*

**Dipartimento  
di Fisica  
e Scienze della Terra**



# Outline

## **Introduction**

- *Fragmentation functions in  $e^+e^-$  annihilation experiments*
  - *world data for  $\pi$ ,  $K$  and  $\eta$*
- *The BESIII experiment*

## **Fragmentation function at BESIII:**

- *Experimental observables*
- *Inclusive  $\pi^0/K^0_S/\eta$  production*
- *Inclusive charged pions and kaons production*
- *Collins Fragmentation Function*

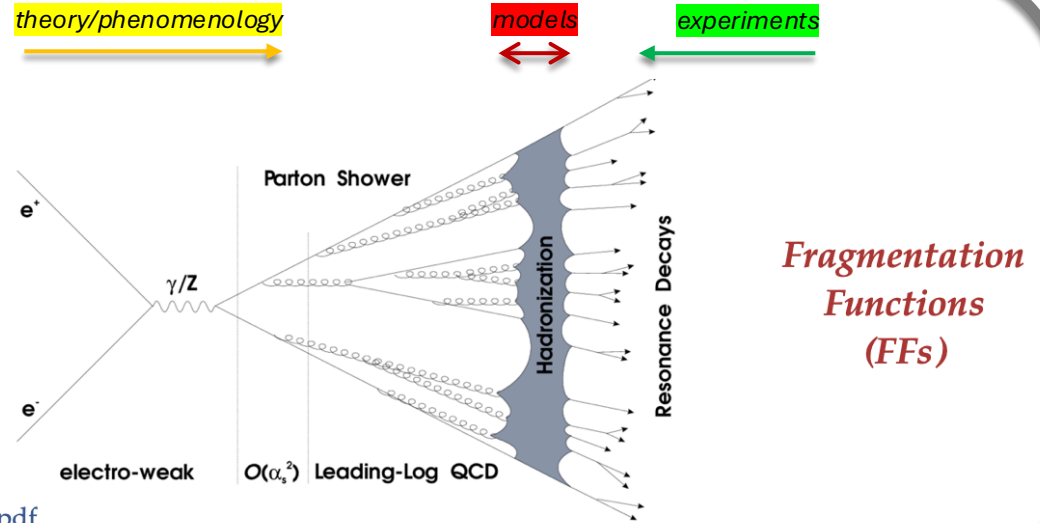
## **Summary and Conclusions**

# Fragmentation Functions

## Hadron formation

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

<https://pdg.lbl.gov/2019/reviews/rpp2019-rev-frag-functions.pdf>



Fragmentation Functions (FFs) are used for the distributions of hadrons that arise from partons exiting the hard scattering

- characterization of non-perturbative aspects of hadronization
- they depend on the fraction energy  $z$  of the initial parton's momentum acquired by the hadron  $h$

$$z = \frac{2P_h q}{Q^2} = \frac{2E_h}{\sqrt{s}}$$

# Fragmentation Functions

|                      |   | Quark polarization                   |                              |                              |
|----------------------|---|--------------------------------------|------------------------------|------------------------------|
|                      |   | Unpolarized (U)                      | Longitudinally polarized (L) | Transversely polarized (T)   |
| Nucleon polarization | U | $D_1 = \text{Unpol.}$                |                              | $H_1^\perp = \text{Collins}$ |
|                      | L |                                      | $G_1$                        | $H_{1L}^\perp$               |
|                      | T | $D_{1T}^\perp = \text{Polarized FF}$ | $G_{1T}^\perp$               | $H_1$<br>$H_{1T}^\perp$      |



**Transverse Momentum Dependent (TMD)**  
TMD independent

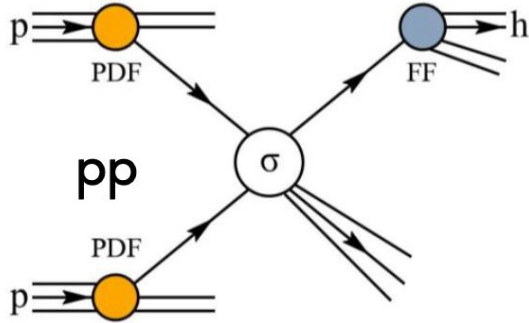
FFs classification:

- extending the integrated fragmentation function  $D_1$  to different quark and hadron polarizations
- including the dependence on the transverse momentum  $K_t$  of the hadron with respect to the parent quark

**Transverse Momentum Dependent** FFs ® to study the spin-dependent observables

- tools to investigate the 3D-structure of nucleons
- when only spinless hadrons ( $\pi$ ,  $K$ ) are considered, we have only  $D_1$  and  $H_1^\infty$
- TMDs evolution

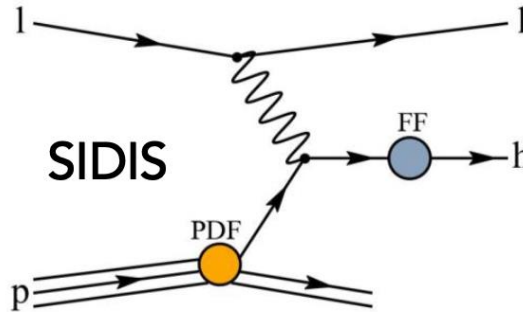
# Accessing FFs in experiments



pp

$$\sigma = \sum_q pdf \otimes pdf \otimes \sigma(q_1 q_2 \rightarrow q'_1 q'_2) \otimes FF$$

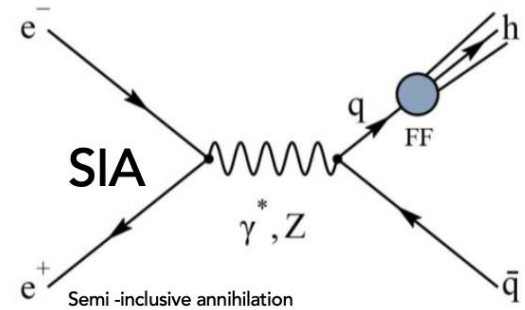
- Dependence from PDFs
- Leading access to gluon FF
- Parton momenta not known directly



SIDIS

$$\sigma = \sum_q pdf \otimes \sigma(eq \rightarrow e'q') \otimes FF$$

- Dependence from PDFs
- Direct access to flavour structure
- FFs and PDFs



SIA

$\gamma^*, Z$

Semi-inclusive annihilation

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

- No PDFs' knowledge necessary
- Calculations known up to NNLO
- Flavour structure not directly accessible

*Cleanest process for FFs studies*

PDFs and FFs: **Universal** and **non-perturbative** objects

# FFs in $e^+e^-$ annihilation

Experimental observable at  $e^+e^-$  annihilation experiments:

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

- $h$  is a particular type of hadron
- At leading order in  $\alpha_s$ , this observable can be interpreted as:

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

Unpolarized FF       $z = \frac{2E_h}{\sqrt{s}}$       Factorization scale  
(center-of-mass energy)

# FFs in $e^+e^-$ annihilation

Experimental observable at  $e^+e^-$  annihilation experiments:

$$\frac{1}{\sigma_{tot}(e^+e^- \rightarrow hadrons)} \frac{d\sigma(e^+e^- \rightarrow h + X)}{dP_h}$$

In practice



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

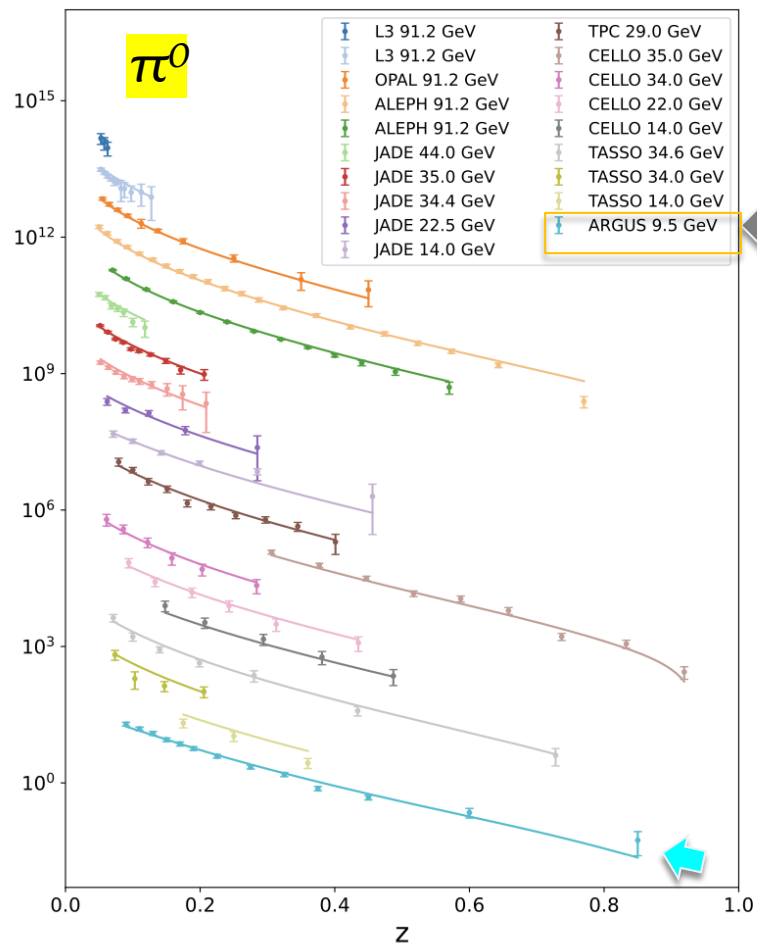
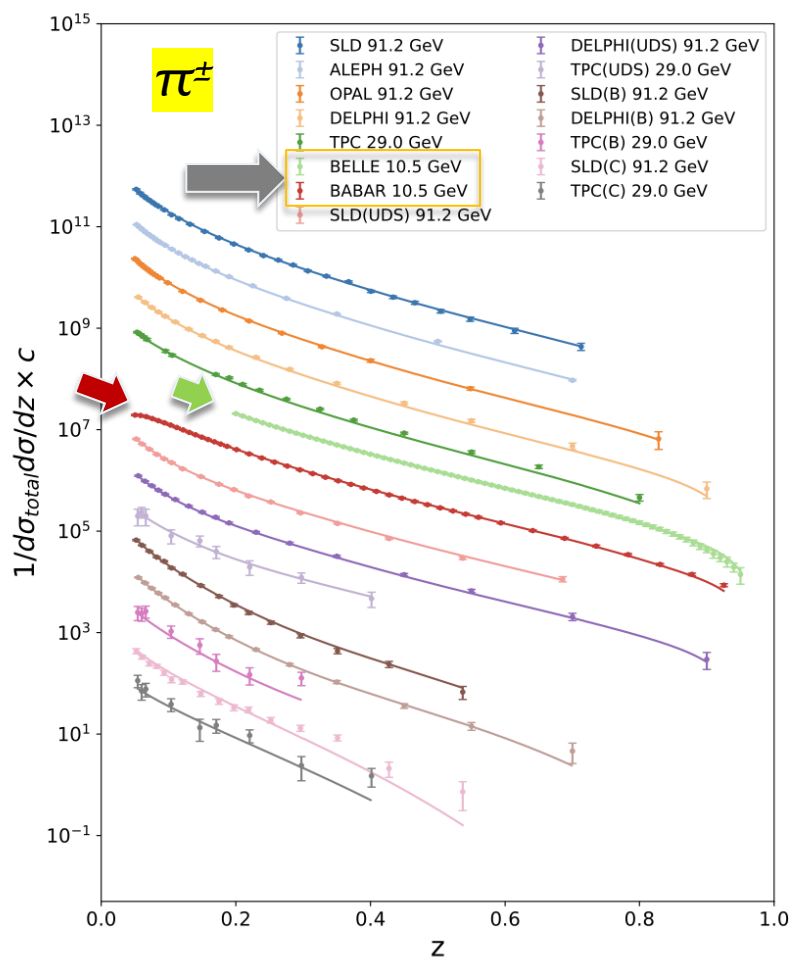
observed events with a specific momentum range  $\Delta p$

$$N_{had}^{obs} = N_{had}^{tot} - N_{bkg}$$

[see Weiping Wang presentation](#)

correction factor which accounts for detector acceptance, selection criteria, ISR, and vacuum polarization effects

# Unpolarized FF: world data for $\pi$ , K and $n$

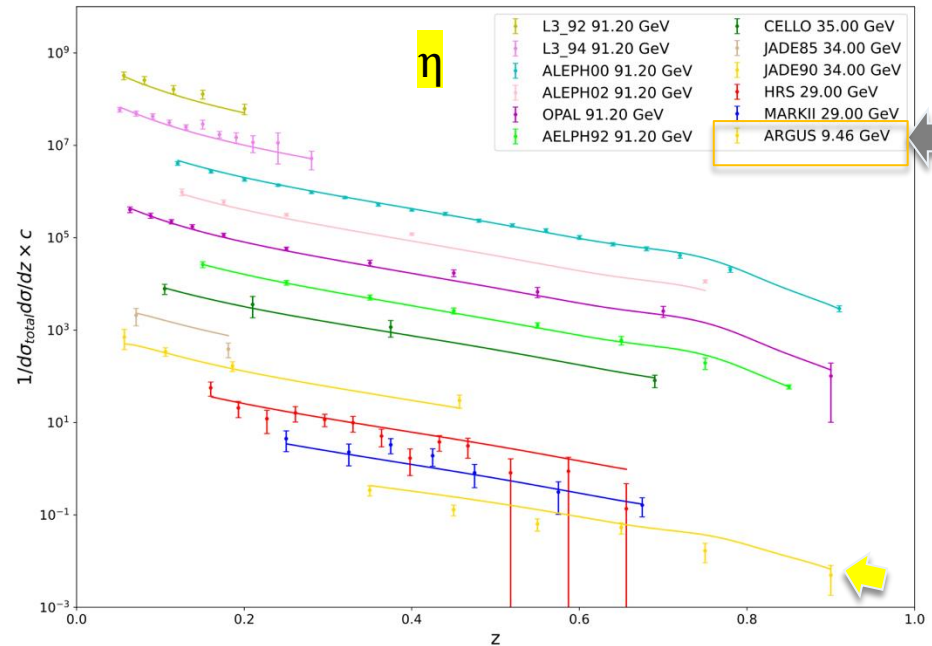
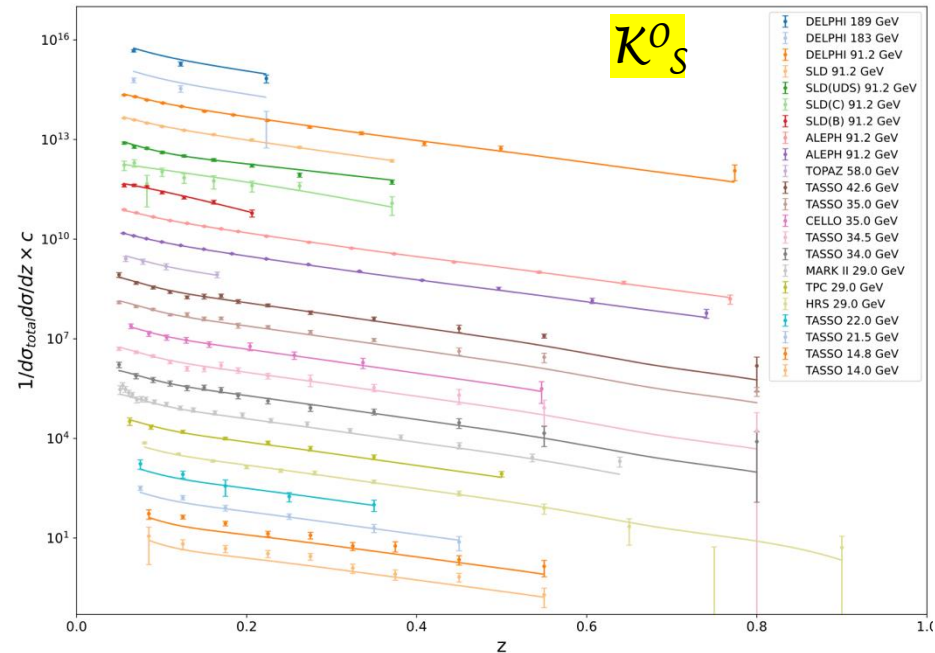


Li, Anderle, Xing, Zhao

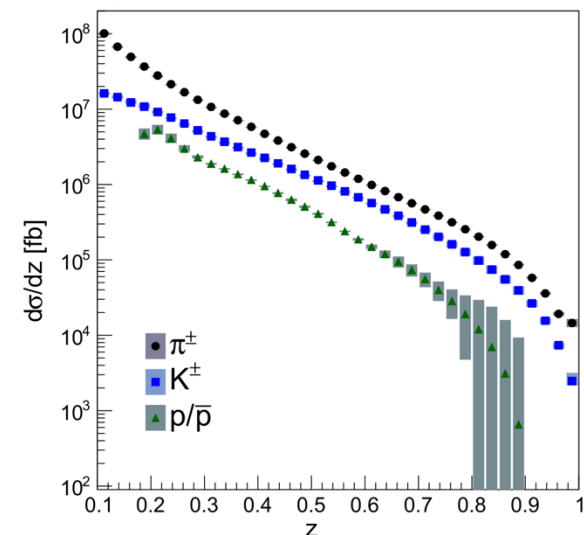
[Phys Rev. D 111,034030 \(2025\)](#)

# Unpolarized FF: world data for $\pi$ , $K$ and $\eta$

Li, Anderle, Xing, Zhao. [Phys Rev. D 111,034030 \(2025\)](#)

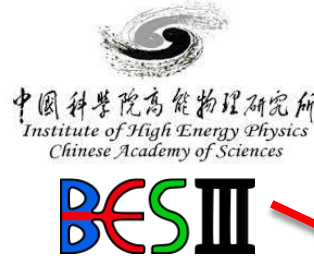
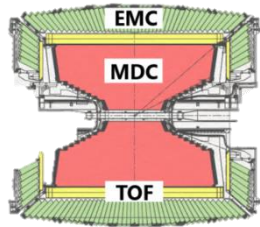


Belle Update: [PRD 101, 092004 \(2020\)](#)



- Precise data for charged kaons and pions, most of them obtained at very high center-of-mass energies
- Lack of data at low energy, where BESIII can contribute

# The BESIII experiment @ BEPCII



**Nucl. Instr. Meth. A614, 345 (2010)**

2004: started Beijing Electron Positron Collider II/BESIII construction

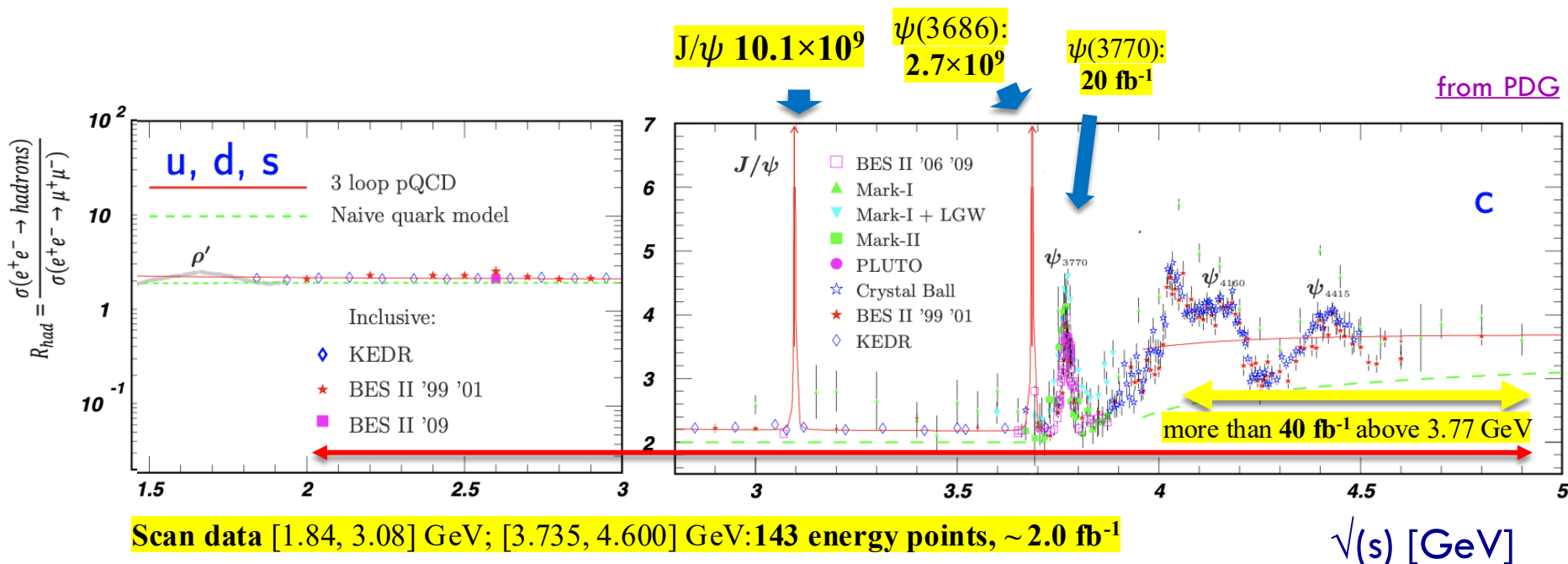
- ✓ Double rings
- ✓ Beam energy: 1 - 2.45 GeV
- ✓ Peak luminosity:  
 $1.05 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$  @  $\psi(3770)$ ,  
achieved in January 7<sup>th</sup>, 2023

2009 – today: BESIII physics runs



# BESIII dataset and physics program

*Optimised for flavour physics in the  $\tau$ -charm region*



- 130 points between 2 and 4.6 GeV ( $\sim 715 \text{ pb}^{-1}$  up to 3.08 GeV for  $\rho^*$ ,  $\omega^*$ ,  $\phi^*$ , ... studies)

- Light hadron spectroscopy
- $\eta/\eta'$  decays
- Hyperon physics
- Charmonium transitions

- $D^0 D^0$  pairs
- $D_{(s)}$  meson decays
- $D^*_{(s)}$
- ...

- XYZ decays and spectroscopy
- Open charm production
- Charmed baryons
- ...

# Inclusive $\pi^0$ and $K^0_S$ production @ BESIII

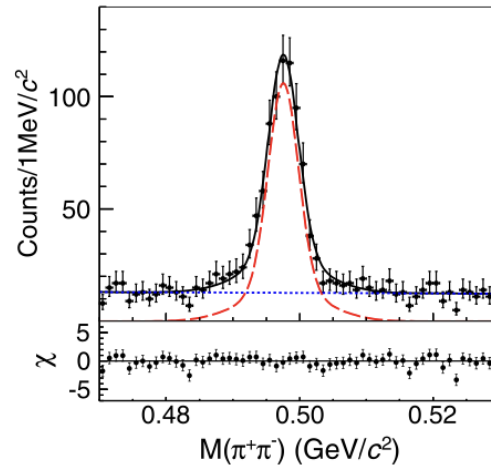
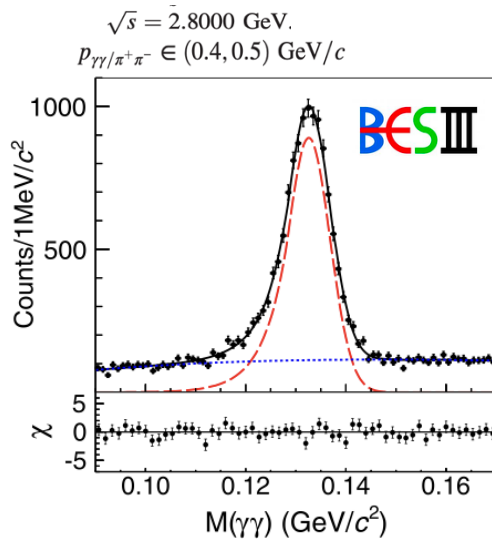
PRL 130, 231901 (2023)

Suppl. Material

$e^+e^- \rightarrow \pi^0/K^0_S + X$  studied at six c.m. energies from 2.2324 to 3.6710 GeV

- $M(\gamma\gamma)$  and  $M(\pi^+\pi^-)$  spectra divided into  $\Delta p_{\pi/K}=0.1$  GeV/c intervals in order to extract the corresponding number of signal events
- Normalized differential cross section:

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



- The  $M(\gamma\gamma)$  and  $M(\pi^+\pi^-)$  spectra are divided into the momentum intervals with a step of 0.1 GeV/c, (5 times the momentum resolutions)
- Unbinned maximum likelihood fits are performed on the  $M(\gamma\gamma)$  and  $M(\pi^+\pi^-)$  spectra in each momentum interval to determine the corresponding numbers of signal events

Correction:

$$f_h = \frac{\bar{N}_h^{\text{tru}}(\text{off})}{\bar{N}_{\text{had}}^{\text{tru}}(\text{off})} \bigg/ \frac{\bar{N}_h^{\text{obs}}(\text{on})}{\bar{N}_{\text{had}}^{\text{obs}}(\text{on})}$$

on/off: ISR effect  
 tru/obs: gen/det level

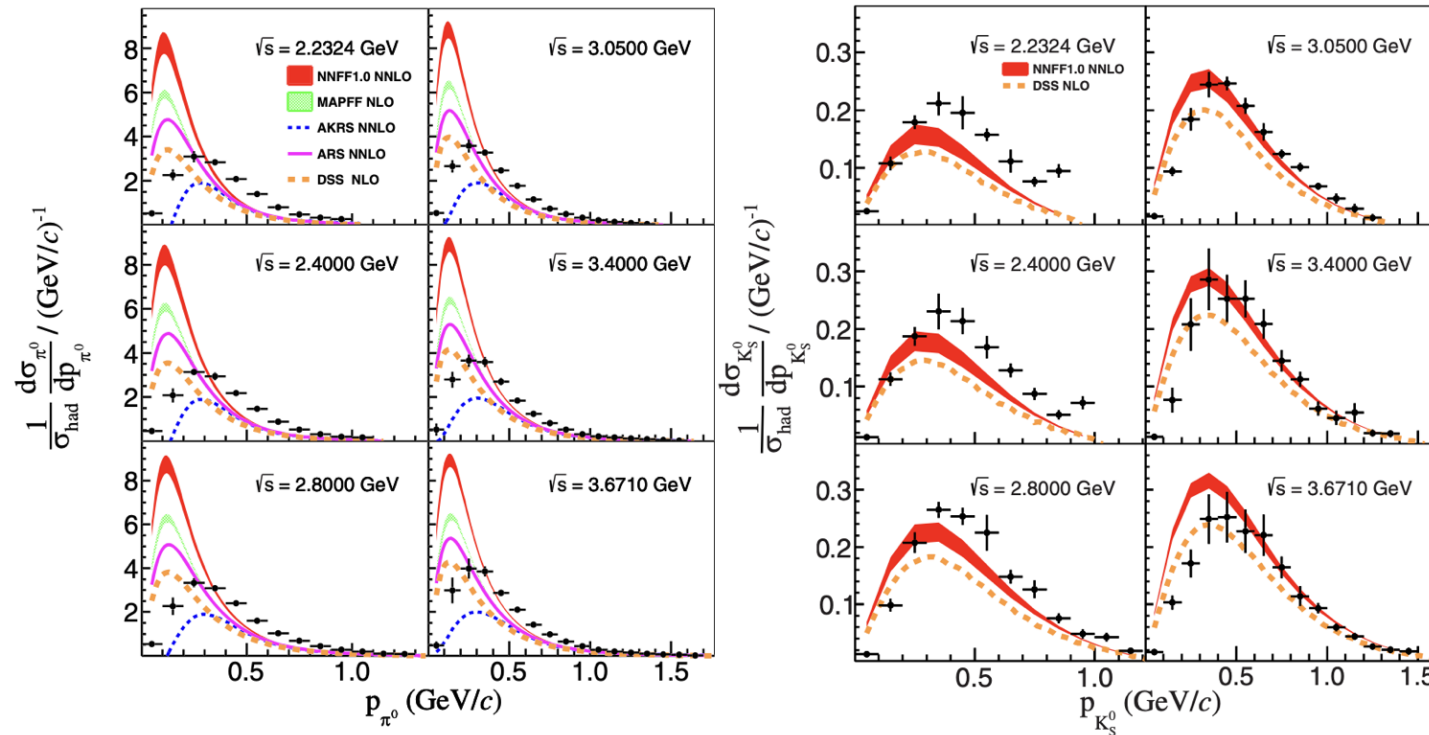
# Inclusive $\pi^0$ and $K^0_S$ production @ BESIII: RESULTS



PRL 130, 231901 (2023)

Suppl. Material

Theory support: Hongxi Xing, Daniele Anderle



NNFF1.0, ARS, AKRS:  
inclusive e+e- data at NNLO accuracy

MAPFF:  
+ Lepton-proton fixed target

DSS:  
+ Lepton-proton fixed target and proton-proton collision

*Disagreement observed to depend on both c.m energy and hadron momentum*

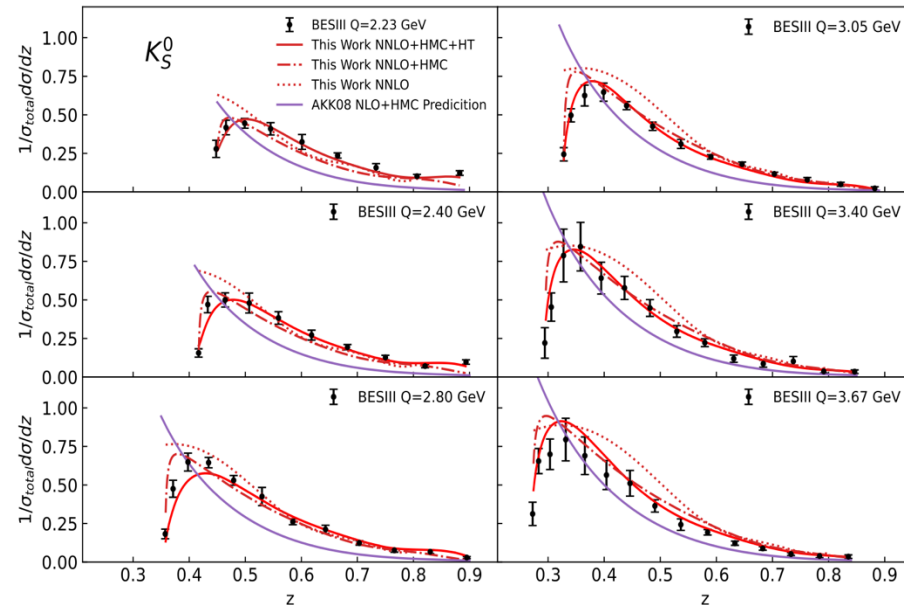
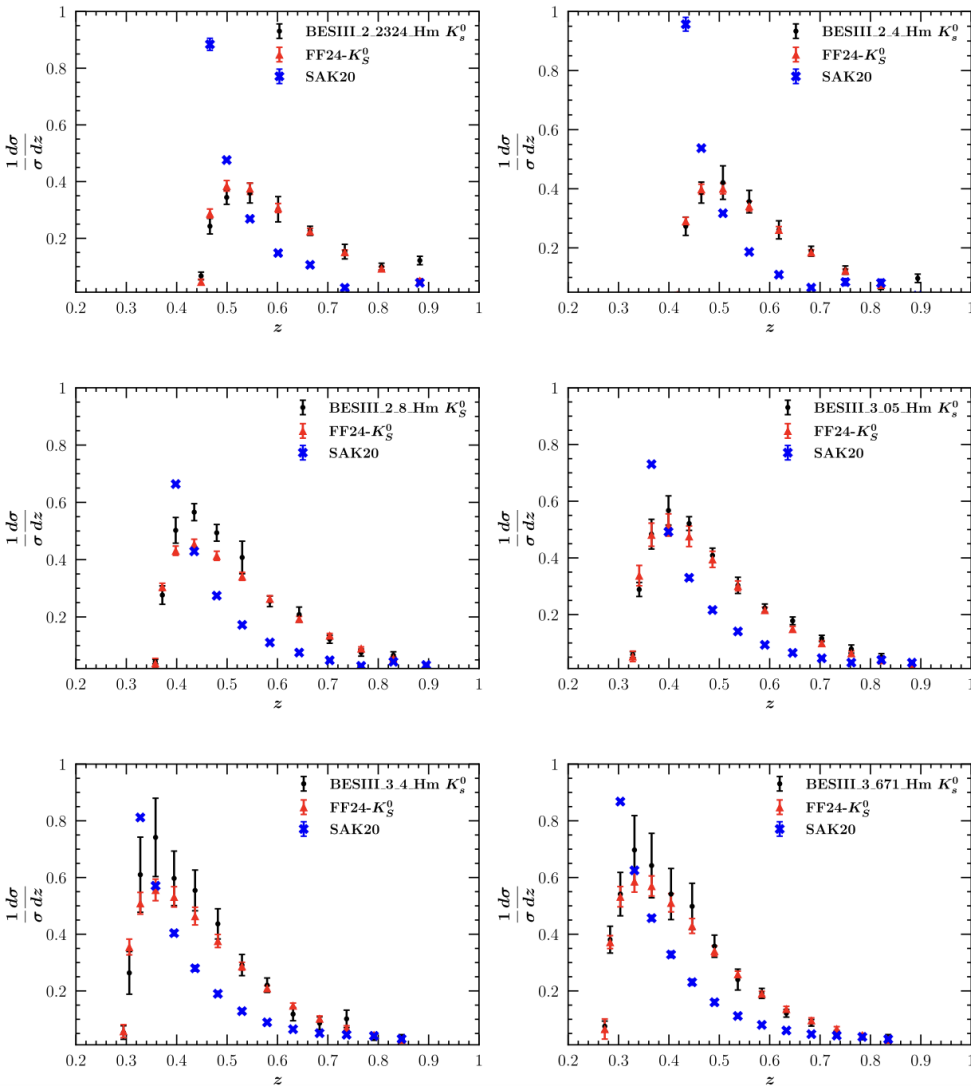
This result

- ✓ help to fill the region with c.m. energy < 10 GeV
- ✓ provide broad z coverage from 0.1 to 0.9 with precision of around 3% at z ~ 0.4.
- ✓ provide new ingredients for FF global data fits, in which almost no single inclusive annihilation data measured in this energy region has been included

# Inclusive $K_S^0$ production

PRD 110, 014019 (2024)

PRD 111, 034030 (2025)

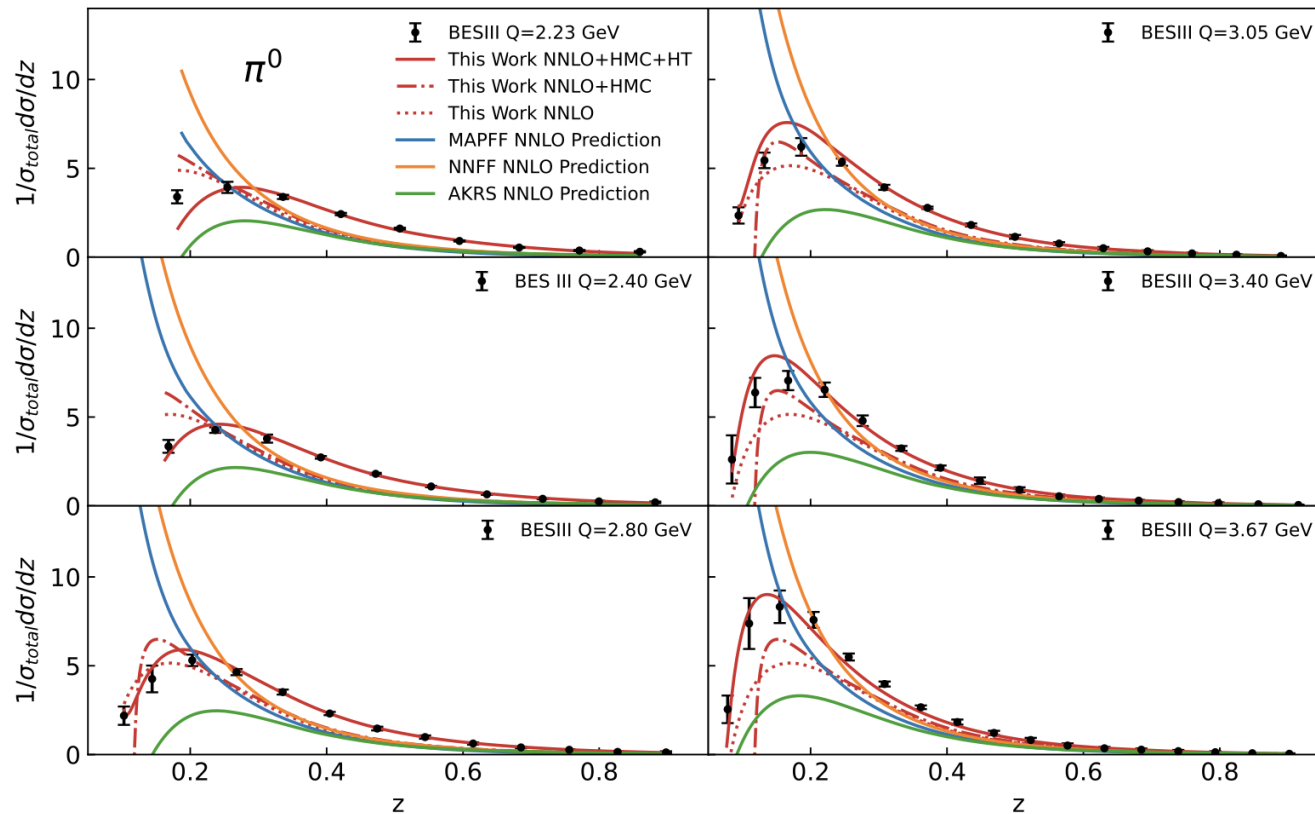


**NNLO accuracy & higher twist  
& hadron mass contributions**

**NLO and NNLO accuracy  
& hadron mass correction for  $K_S^0$**

# Inclusive $\pi^0$ production

PRD 111, 034030 (2025)

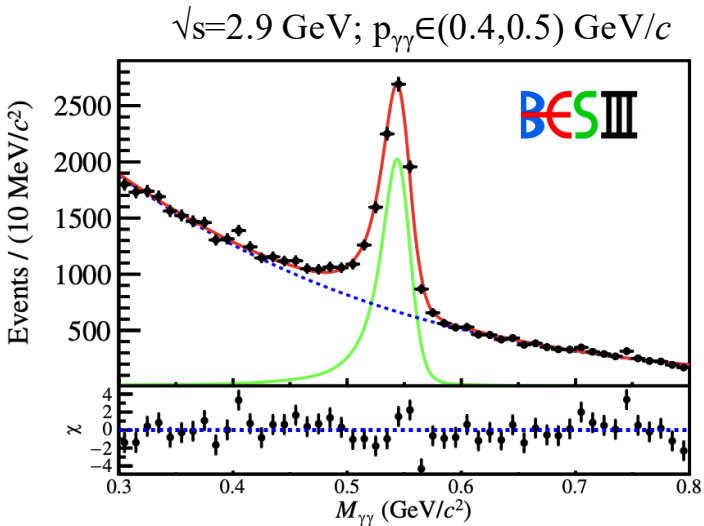


## NNLO accuracy, including hadron mass correction at higher-twist effects

Despite SIA being the cleanest process for the determination of FFs, it carries limited information on flavor separation and lacks the ability to distinguish between quark and antiquark FFs → updates with proton-proton collisions and SIDIS processes in order to address these limitations

# Inclusive $\eta$ production @ BESIII

PRL 133,021901 (2024)



Normalized cross section of the inclusive process  $e^+e^- \rightarrow \eta + X$  measured at 8 c.m. energies from 2.000 to 3.6710 GeV

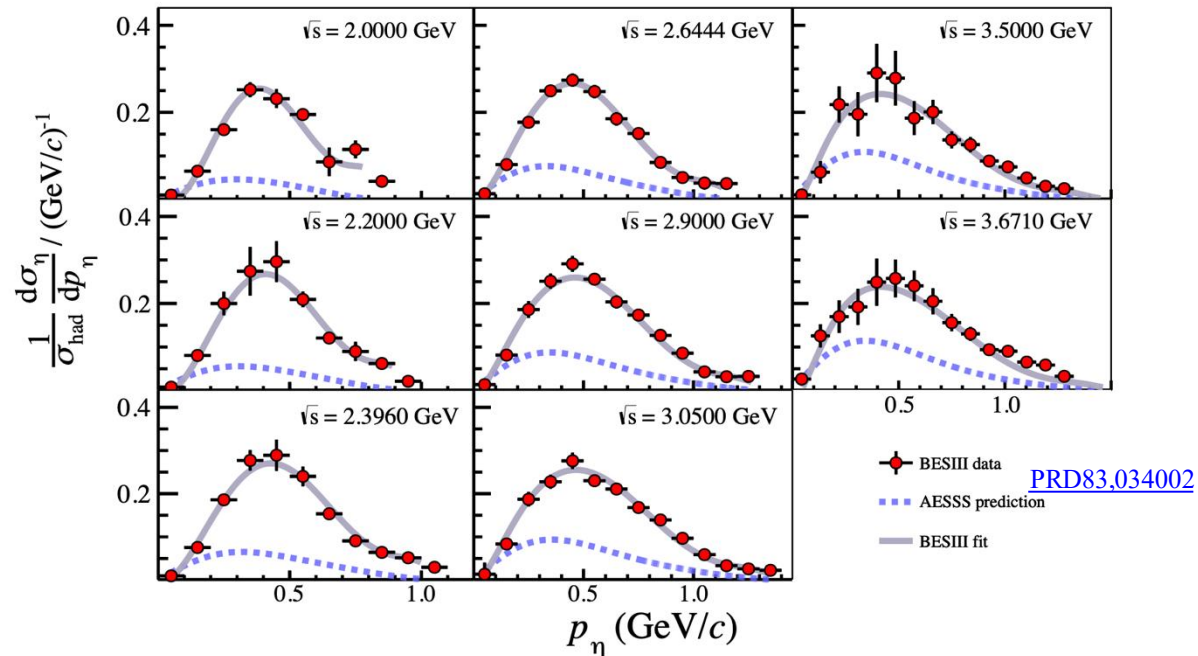
- more info on the hadronization process since the  $\eta$  wave function contains all light quarks and antiquarks

BESIII

Experimental observation:

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

- AESSS prediction: NLO, pp data and  $e^+e^-$  data from  $\sqrt{s} > 10 \text{ GeV}$
- **Huge tension with BESIII data**
- BESIII fit:  $e^+e^-$  data from  $\sqrt{s} > 10 \text{ GeV}$  (except unpublished BaBar data) + BESIII data + NNLO + higher twist effects + hadron mass corrections



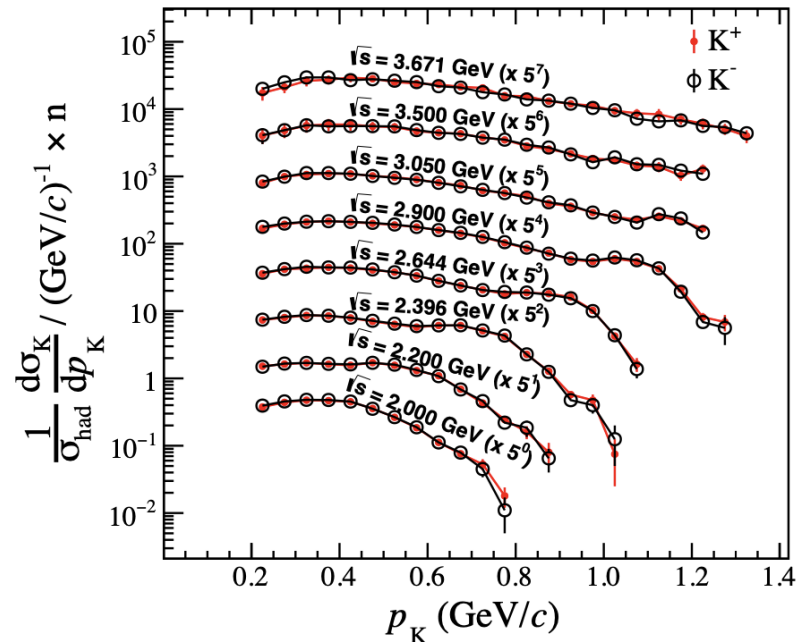
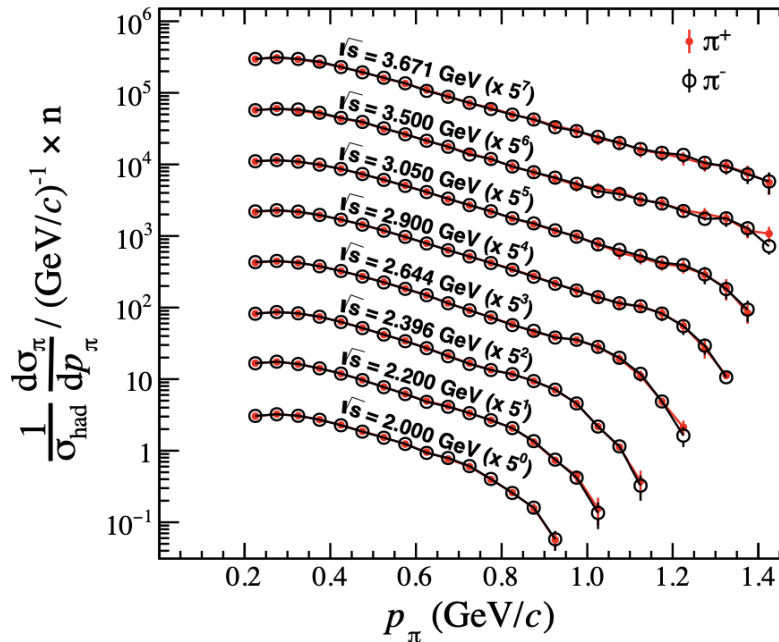
# Inclusive $\pi^\pm$ and $K^\pm$ production @ BESIII

PRL135, 151901(2025)

Normalized differential cross section of the inclusive process  $e^+e^- \rightarrow \pi^\pm/K^\pm + X$  measured at 8 c.m. energies from 2.000 to 3.6710 GeV

- z coverage from 0.13 to 0.95
- opportunity to test QCD factorization at low energy scales and consistency of charged hadron production between  $e^+e^-$  annihilations and SIDIS

\* observables scaled by random factor



BESIII

- Enhancements observed in the high-momentum region for the  $e^+e^- \rightarrow K^\pm + X$  process may be attributed to the  $e^+e^- \rightarrow K^*(1430)^\pm K^\mp$

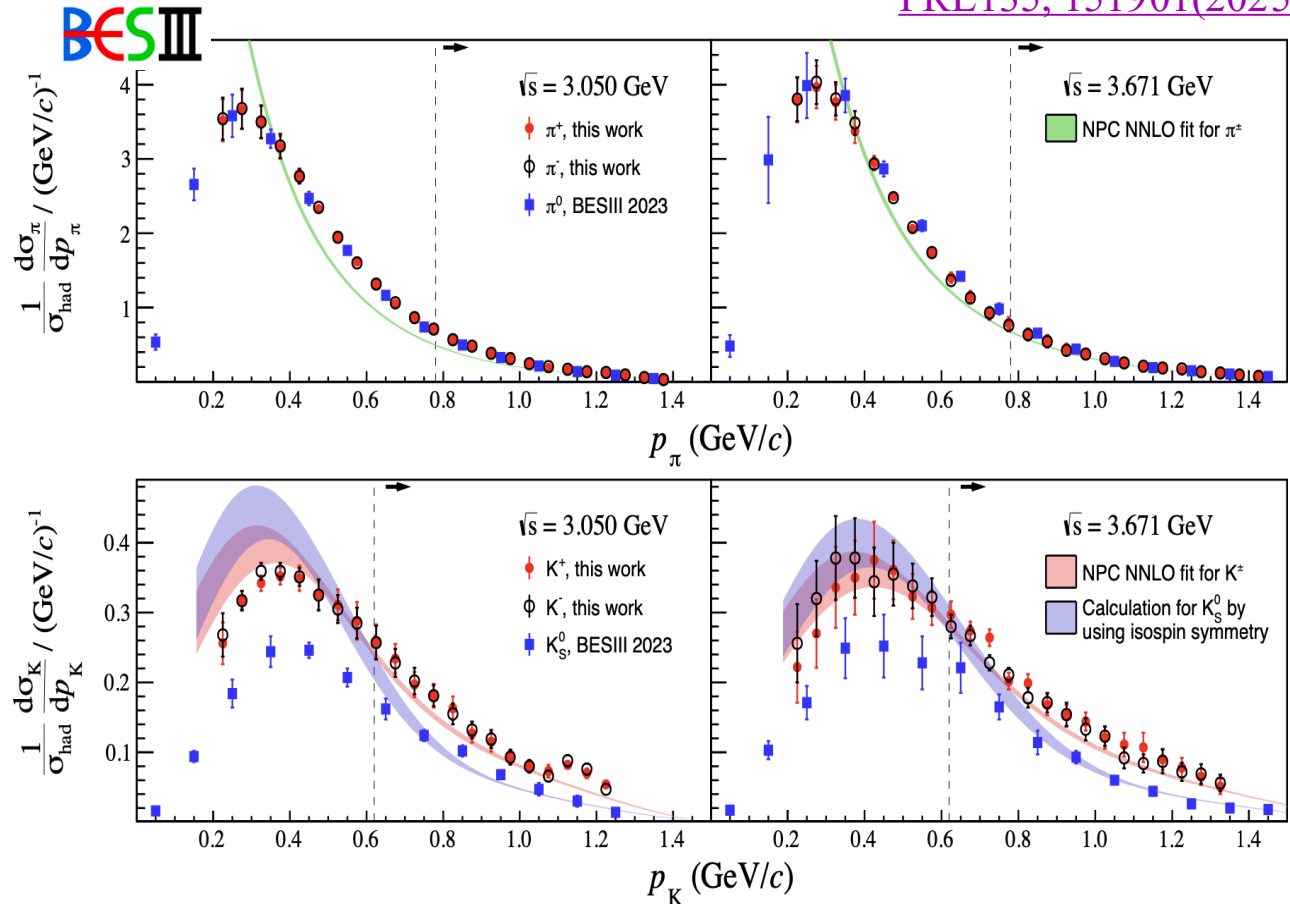
# Inclusive $\pi^\pm$ and $K^\pm$ production @ BESIII

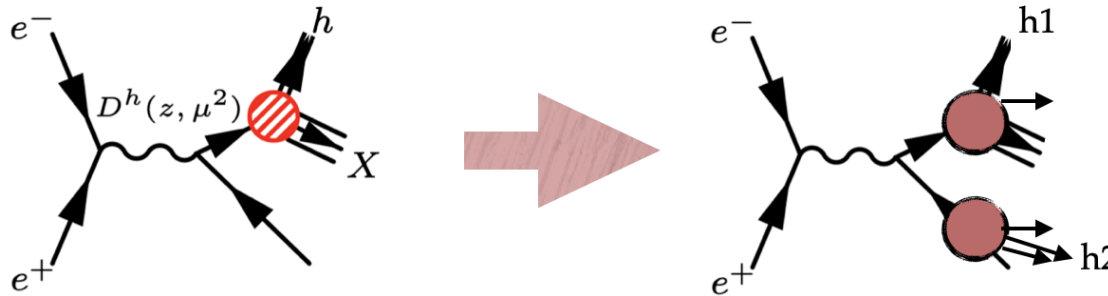
New global data fit is performed at NNLO under Nonperturbative Physics Collaboration (NPC) framework [PRD110, 114019; PRL132,261903]

- $\sqrt{s} > 3 \text{ GeV}$  &  $E_h > 0.8 \text{ GeV}$  to ensure validity of factorization and pQCD calculation for BESIII measurements

- ✓ reasonable agreement in the region where BESIII data are included
- ✓ validity of QCD factorization and pQCD calculation at c.m. energy down to 3 GeV
- ✓ higher twist contribution and small z-logarithmic enhancement in the low-momentum region
- ✓ first support for isospin symmetry at energy scale below 10 GeV in  $\pi$  and K fragmentation process

PRL135, 151901(2025)





$$q^\uparrow \rightarrow hX: \quad D_1^{q^\uparrow}(z, \mathbf{P}_\perp; s_q) = D_1^q(z, P_\perp) + \frac{P_\perp}{zM_h} \underline{H}_1^{\perp q}(z, P_\perp) \mathbf{s}_q \cdot (\mathbf{k}_q \times \mathbf{P}_\perp)$$

Unpolarized FF

**Collins FF** [NPB 396, 161 (1993)]:  
related to the probability that a transversely polarized quark ( $q^\uparrow$ ) fragments into a spinless hadron

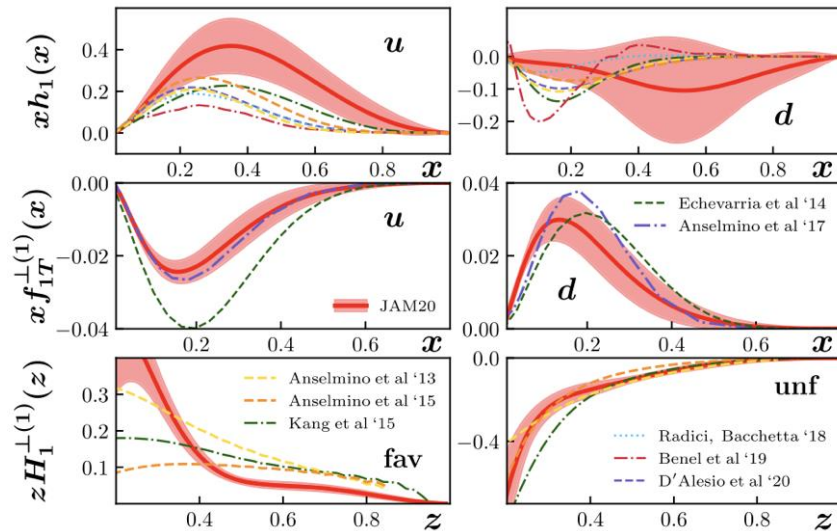
- Evolution of TMD objects
- Global analysis (PRD 78,032011 (2007); PRD 87,094019 (2013), PRD 91,014034 (2015)):
  - combines Semi Inclusive Deep Inelastic Scattering (SIDIS) and  $e^+e^-$  data
  - extraction of  $H_{\perp 1}$  and transversity parton distributions  $h_1$  for the “u” and “d” quarks



# Collins FFs @ BESIII: First Global Analysis

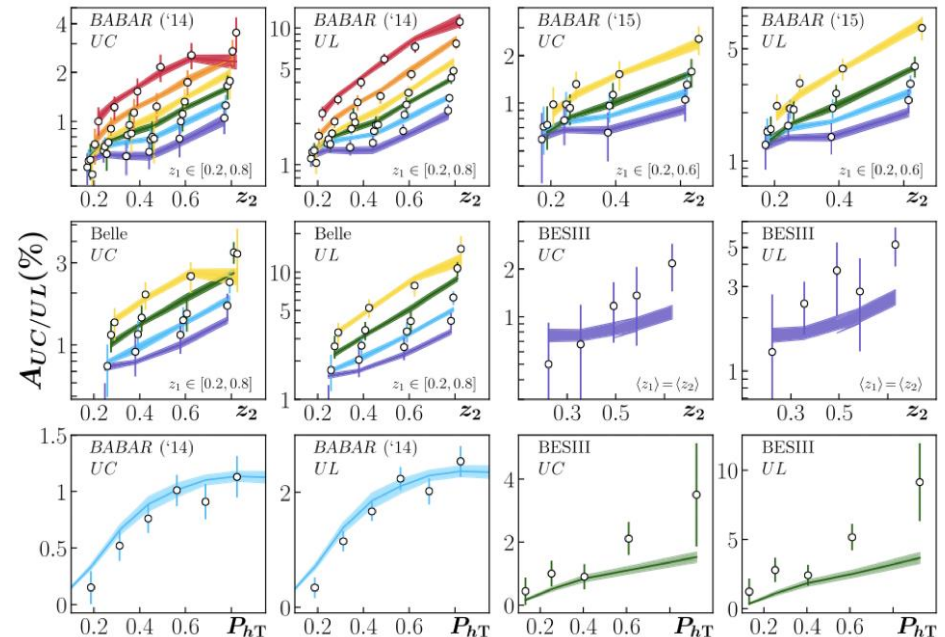
First simultaneous QCD global analysis with SIDIS, semi-inclusive e+e- annihilation, Drell-Yan and proton-proton collisions

- Test of universality
- Indication that transverse-spin asymmetries in high-energy collisions have a common origin
- Extracted quark tensor charges are in excellent agreement with lattice QCD



[Anselmino '13](#), [Anselmino '15](#), [Anselmino '17](#), [Benel '19](#),  
[D'Alessio '20](#), [Echevarria '14](#), [Kang '15](#), [Radici-Bacchetta '18](#)

[PRD 102, 054002 \(2020\)](#)



Comparison between theory and data  
 ([BaBar](#), [Belle](#), [BESIII](#))

# Conclusions

The knowledge of FFs is an important ingredient in our understanding of **non-perturbative QCD dynamics**, and  $e^+e^-$  annihilation experiments provide the **cleanest** environment to measure FFs

@BESIII:

- **Unpolarized fragmentation functions**
  - Unique  $Q < 10$  GeV data
  - New results from charged pions and kaons
- **Collins fragmentation functions**
  - Input in the 3D imaging era of the nucleon structure study
  - More results for  $K\pi+X$  and  $KK+X$
- **Collinear di-hadron FFS**
  - New results ready soon

$$\frac{1}{\sigma_{tot}(e^+e^- \rightarrow hadrons)} \frac{d^2\sigma(e^+e^- \rightarrow (h_1h_2) + X)}{dzdM_h}$$

**Thank you for your attention**

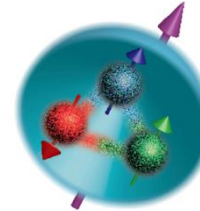
*Back-up slides*

# Open questions in QCD

## Nucleon structure

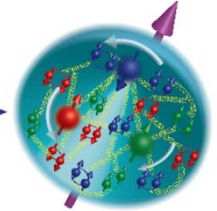
- Parton Distribution Functions (PDFs): related to the **probability densities** to find a parton carrying a momentum fraction  $x$  at a squared energy scale  $Q^2$
- ❑ What is the origin of the nucleon spin and mass in terms of quarks and gluons degree of freedom?

QCD naïve picture

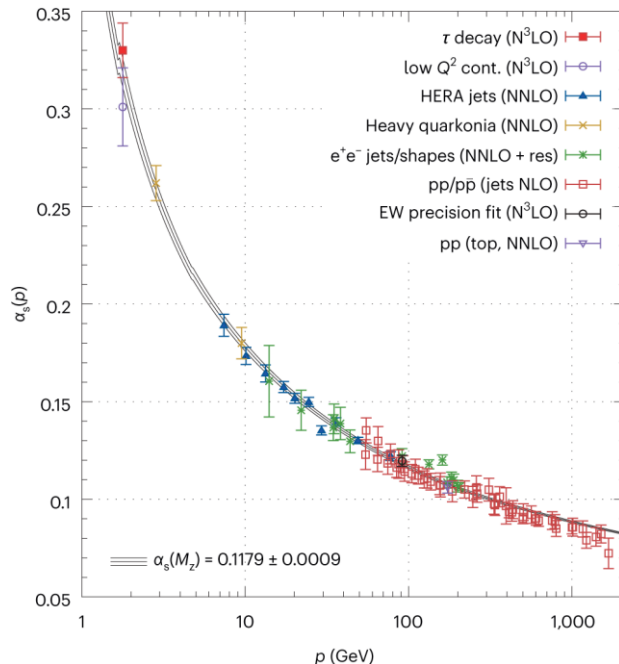


*three non-relativistic quarks*

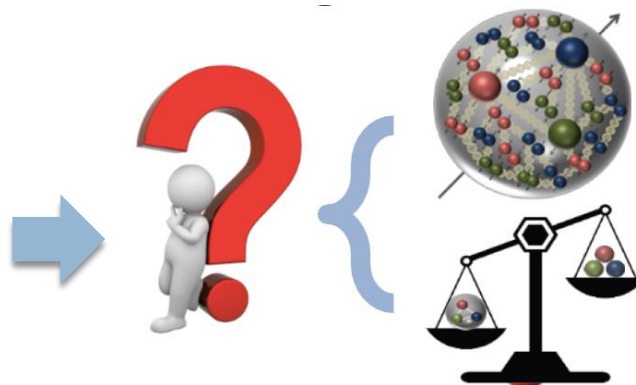
QCD realistic picture



*infinite number of relativistic quarks and gluons*



*Particle Data Group*



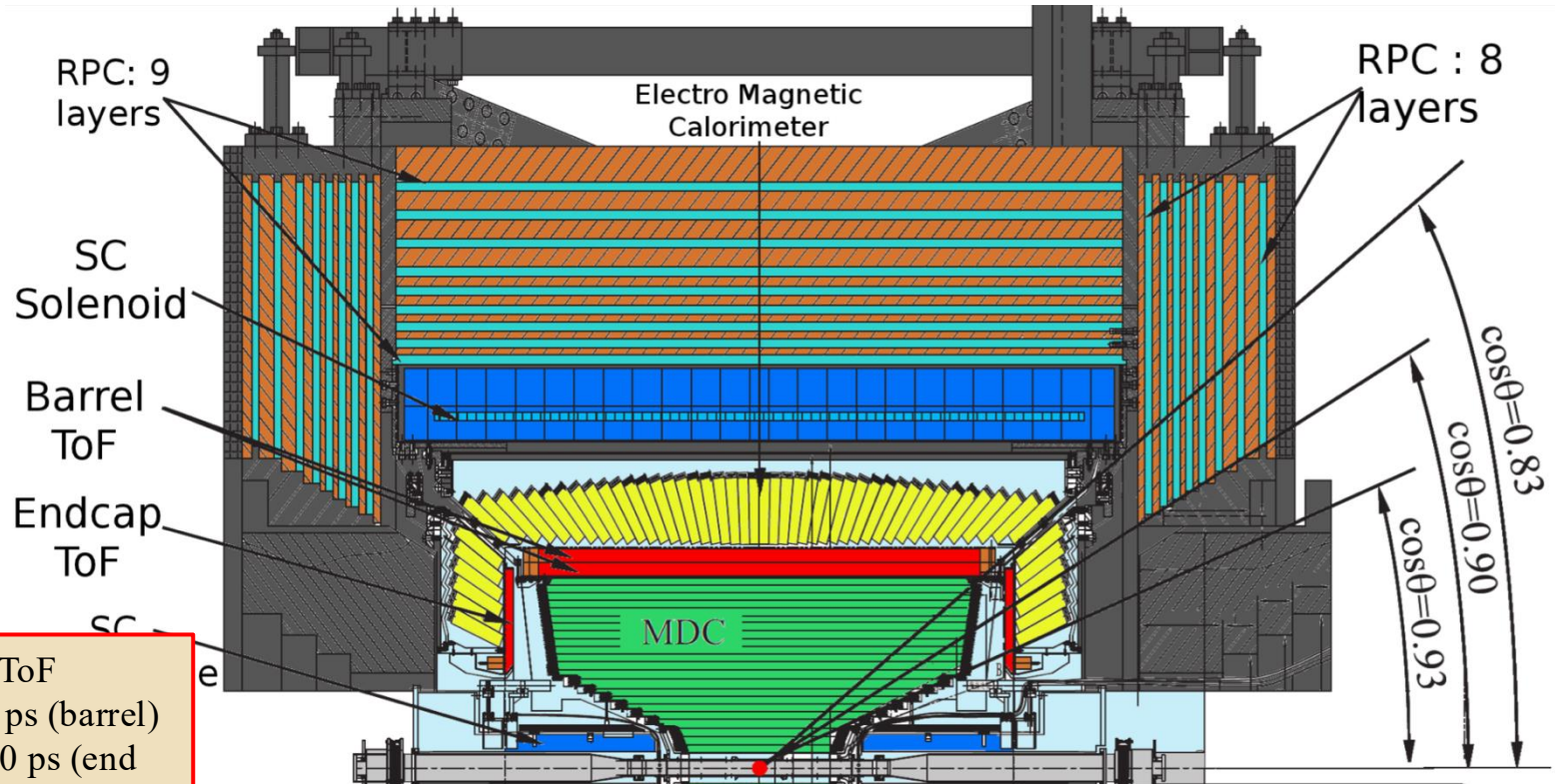
Annual Reviews Vol. 70, 43-76 (2020)

How does nucleon spin emerge?

Higgs mechanism gives only ~ few %

# The BESIII Detector

Nucl. Instr. Meth. A614, 345 (2010)



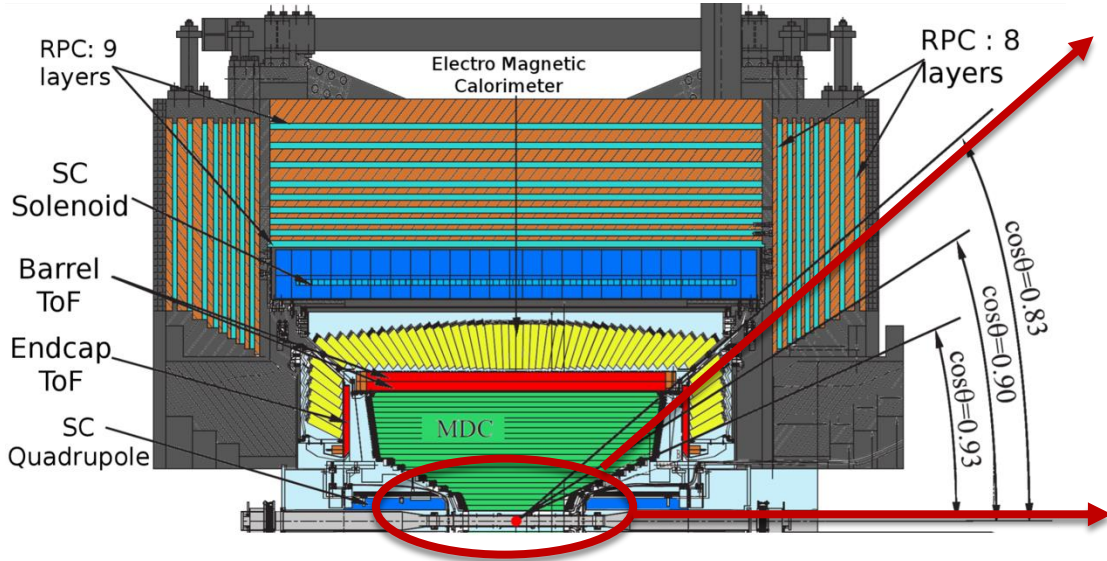
ToF  
 $\sigma_t \sim 68$  ps (barrel)  
 $\sigma_t \sim 60$  ps (end caps, upgrade)

Drift Chamber  
 $\sigma_{r\phi} \sim 130$   $\mu\text{m}$  (single wire)  
 $\sigma_{pt}/p_t \sim 0.5$  % @ 1 GeV

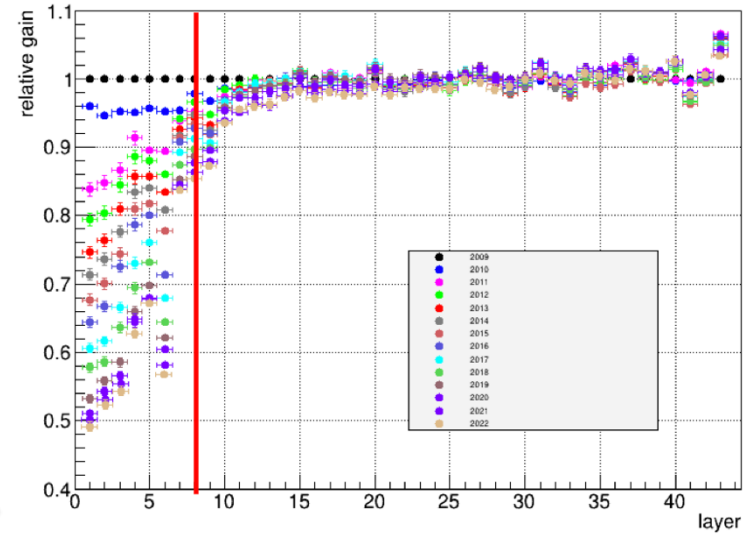
Electromagnetic CsI(Tl) Calorimeter  
 $\sigma_E/E < 2.5$  % @ 1 GeV (barrel)  
 $\sigma_E/E < 5$  % @ 1 GeV (end caps)  
 $\sigma_{xy} \sim (6 \text{ mm})/E^{1/2}$  @ 1 GeV

RPC Muon Detector  
 $\Delta\Omega/4\pi=93$  %

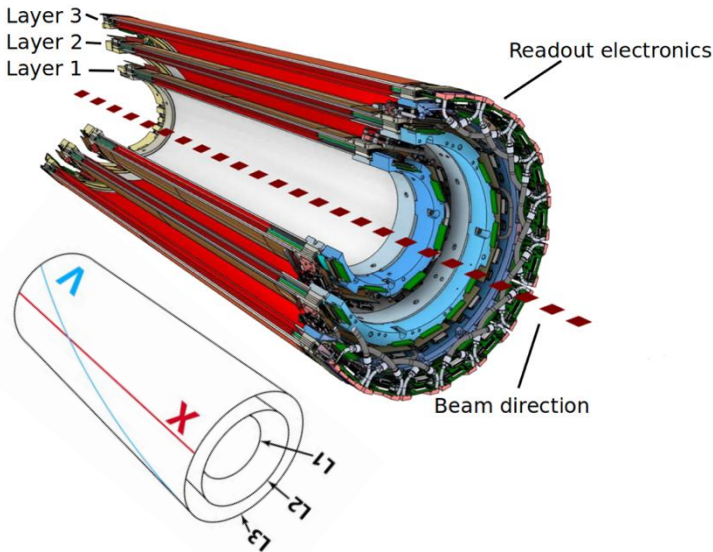
# Why CGEM-IT ?



## Gain loss of the inner MDC



Gain loss per year  $\sim 4\%$



- Replace the inner MDC with 3 layers of cylindrical triple-GEM detectors
- Improve rate capability, aging and secondary vertex reconstruction, while retaining the current momentum and tracking performance

Main system requirements:

- Low Material budget  $\sim 1.5\%$  of  $X_0$  in total
- Spatial resolution of 130-150  $\mu\text{m}$  with charge and time readout

# BESIII physics programme

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## Light hadron physics

- Meson and baryon spectroscopy
- Multiquark states
- Threshold effects
- Glueballs and hybrids
- two-photon physics
- Form factors

## QCD and $\tau$

- Precision R measurement
- $\tau$  decay

## Charmonium physics

- Precision spectroscopy
- Transitions and decays

## XYZ meson physics

- $Y(4260)$ ,  $Y(4360)$  properties
- $Z_c(3900)^+$ , ...

## Charm physics

- Semi-leptonic form factors
- Decay constants  $f_D$  and  $f_{D_s}$
- CKM matrix:  $|V_{cd}|$  and  $|V_{cs}|$
- $D^0$ - $\bar{D}^0$  mixing, CPV
- Strong phases

## Precision mass measurements

- $\tau$  mass
- $D$ ,  $D^*$  mass

# Fragmentation Functions

|                      |   | Quark polarization                  |                              |                               |
|----------------------|---|-------------------------------------|------------------------------|-------------------------------|
|                      |   | Unpolarized (U)                     | Longitudinally polarized (L) | Transversely polarized (T)    |
| Nucleon polarization | U | $D_1 = \text{Unpol.}$               |                              | $H_{1\perp} = \text{Collins}$ |
|                      | L |                                     | $G_1$                        | $H_{1L\perp}$                 |
|                      | T | $D_{1T\perp} = \text{Polarized FF}$ | $G_{1T\perp}$                | $H_1, H_{1T\perp}$            |

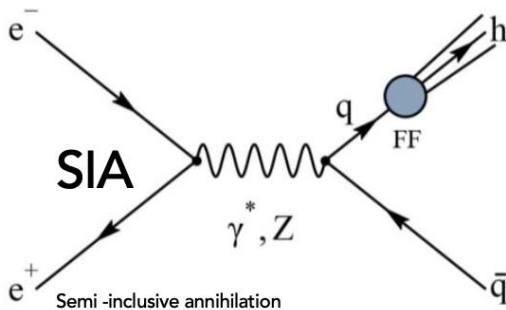


**Transverse Momentum Dependent (TMD)**  
**TMD independent**

FFs classification:

- including the dependence on the transverse momentum  $K_t$  of the hadron with respect to the parent quark → TMD
- tools to investigate the 3-D structure of nucleons
- when only spinless hadrons ( $\pi, K$ ) are considered, we have only  $D_1$  and  $H_{1\perp}$

Cleanest process for FFs studies



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

- No PDFs' knowledge necessary
- Calculations known up to NNLO
- Flavour structure not directly accessible

# Normalized Hadronic Cross Section

PRL 128, 062004 (2022)

BESIII

see Weiping Wang presentation

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

$$R \equiv \sigma(e^+e^- \rightarrow \text{hadrons}) / \sigma(e^+e^- \rightarrow \mu^+\mu^-)$$

Number of hadronic events directly counted from data

Residual background events remaining after all selection requirements

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

$\frac{4\pi\alpha(0)^2}{3s}$  is the leading order QED Born cross section for  $e^+e^- \rightarrow \mu^+\mu^-$

Integrated luminosity

Trigger efficiency

Detection efficiency

Radiative corrections (Feynman diagrams, structure functions) – agreement better than 1.4%

# Normalized Hadronic Cross Section

PRL 128, 062004 (2022)

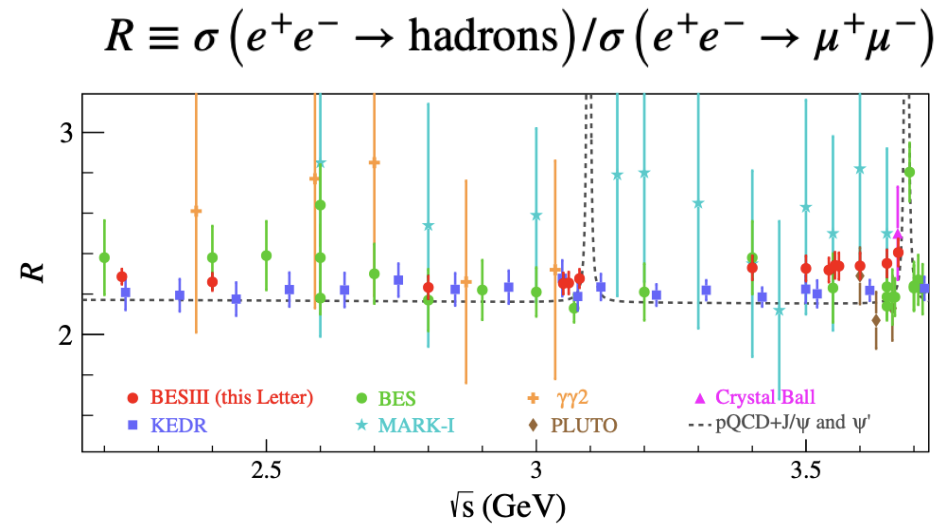
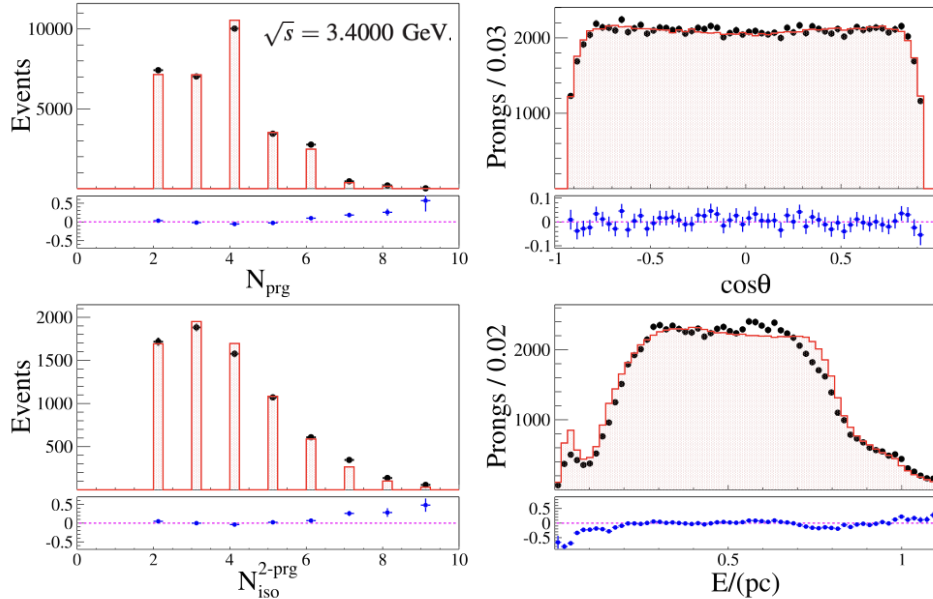
BESIII

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

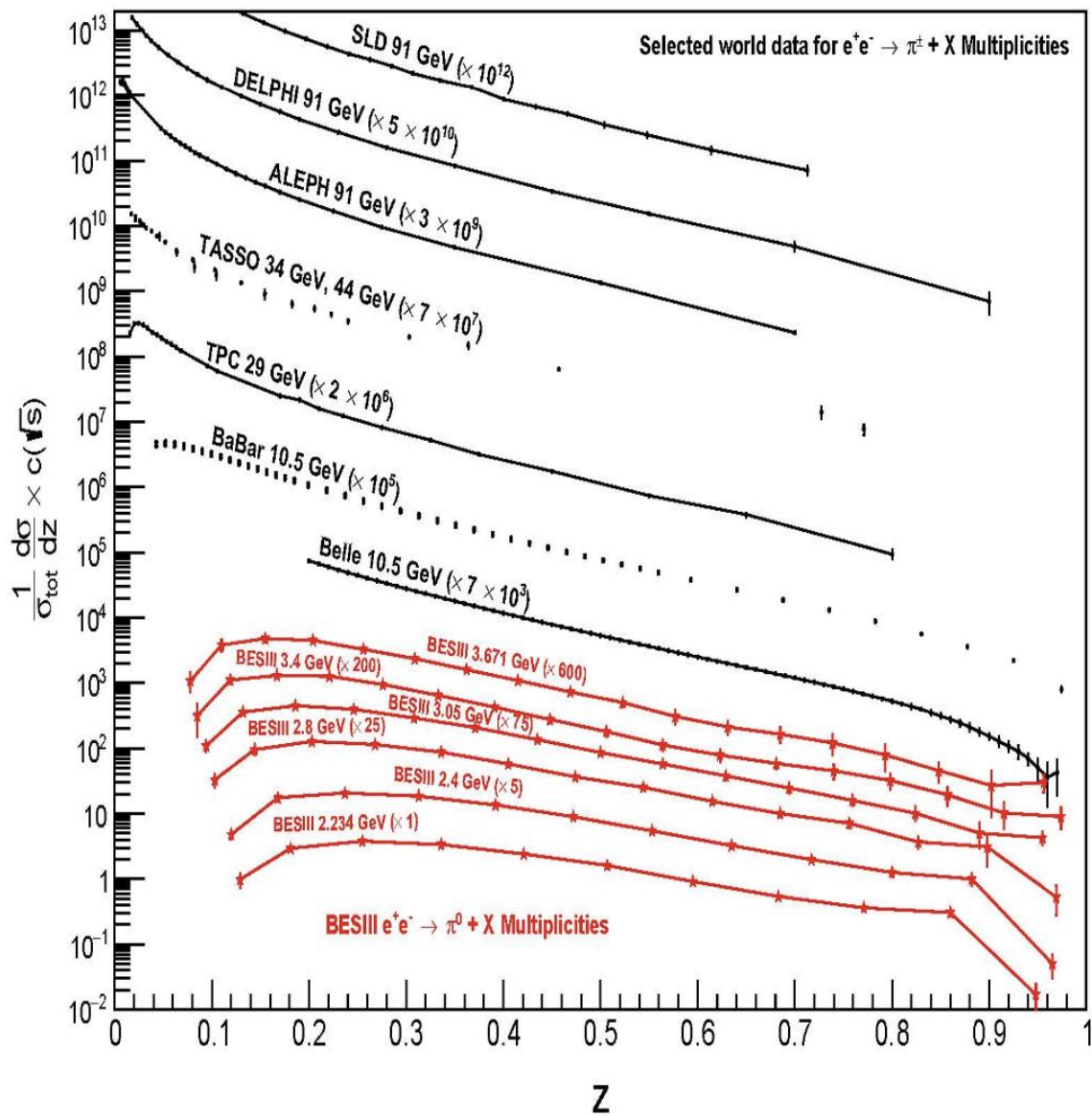
see Weiping Wang  
presentation

R value is measured at 14 c.m. energies from 2.2324 to 3.6710 GeV

LUARLW MC reasonably reproduce the data

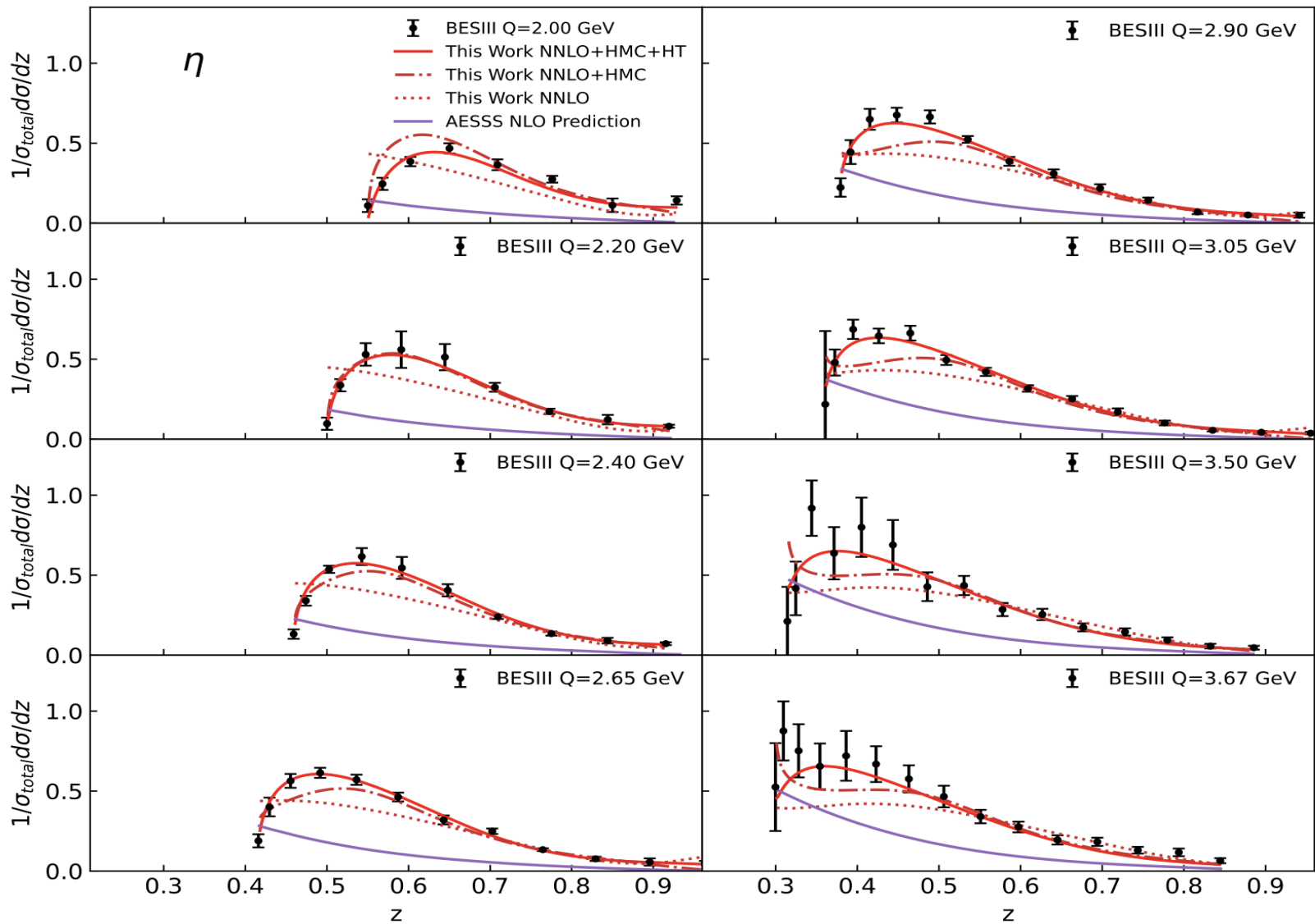


- Accuracy better than 2.6% below 3.1 GeV and 3.0% above
- The average R value in the c.m. energy range 3.4 – 3.6 GeV obtained by BESIII is larger than the corresponding KEDR result and theoretical expectation by  $1.9\sigma$  and  $2.7\sigma$



# Inclusive $\eta$ production @ BESIII

PRD 111, 034030 (2025)



## Detector and BEPCII upgrade

Upgrade in energy (5.6 GeV)  
and luminosity (BEPCII-U, 3x)

- Opportunities to study other charmed baryons ( $\Sigma_c$ ,  $\Xi_c$ ,  $\Omega_c$ ) in the BEPCII-U
- Remove the inner MDC and replace it with CGEM

