Sar WorS 2025 – 4th Sardinian Workshop on Spin

Fragmentation function studies at BESIII

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Dipartimento di Fisica e Scienze della Terra

11 – 13 June, 2025

Istituto Nazionale di Fisica Nucleare

Outline

Introduction

- *Open question in QCD*
- *Fragmentation functions in e+e- annihilation experiments*
  - *world data for π, K and η*
- *The BESIII experiment*

Fragmentation function at BESIII:

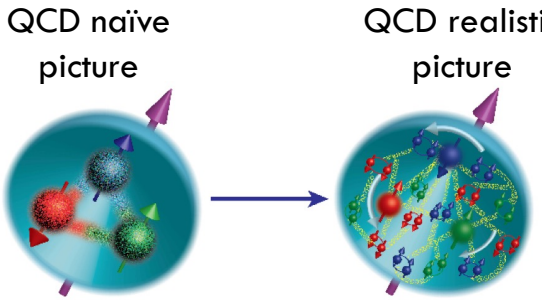
- *Normalized hadronic cross section*
- *Inclusive $\pi^0/K^0_S/\eta$ production*
- *Inclusive charged pions and kaons production*
- *Collins Fragmentation Function*

Summary and Conclusions

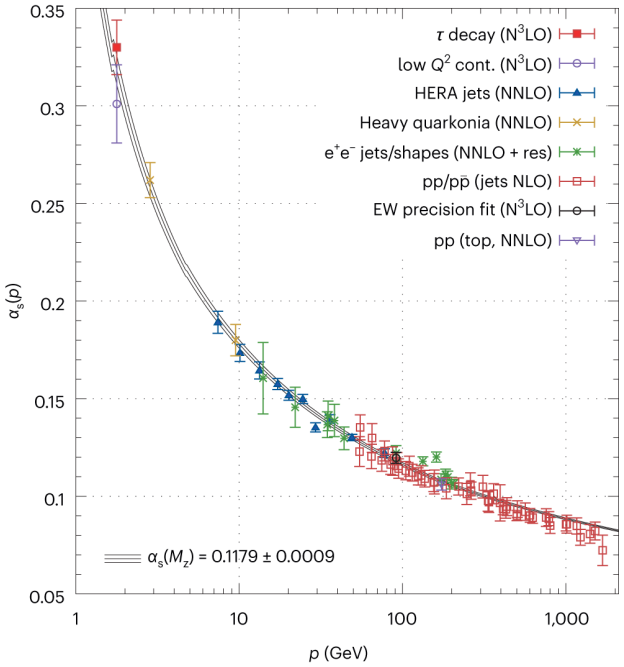
Open questions in QCD

Nucleon structure

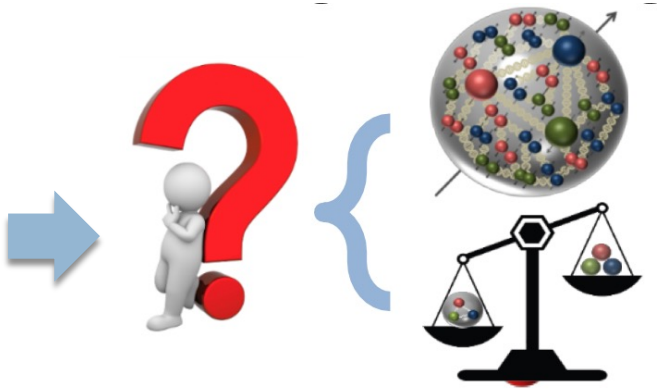
- ➢ Parton Distribution Functions (PDFs): related to the **probability densities** to find a parton carrying a momentum fraction *x* at a squared energy scale Q^2
- ❑ What is the origin of the nucleon spin and mass in terms of quarks and gluons degree of freedom?



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



Particle Data Group



How does nucleon spin emerge?

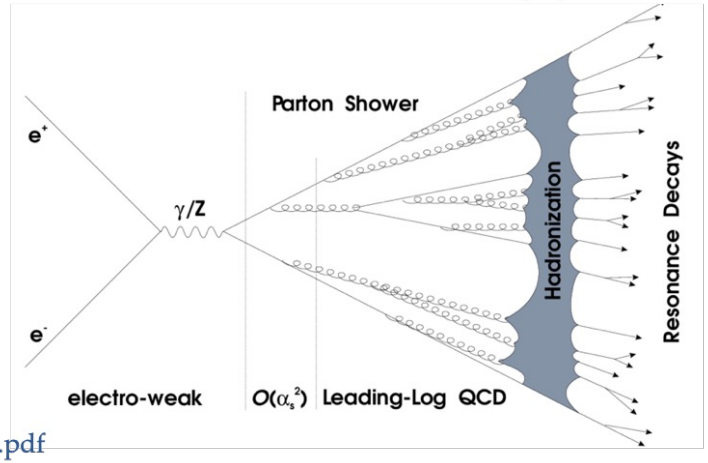
Higgs mechanism gives only ~ few %

Fragmentation Functions

theory/phenomenology → models ↔ experiments

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

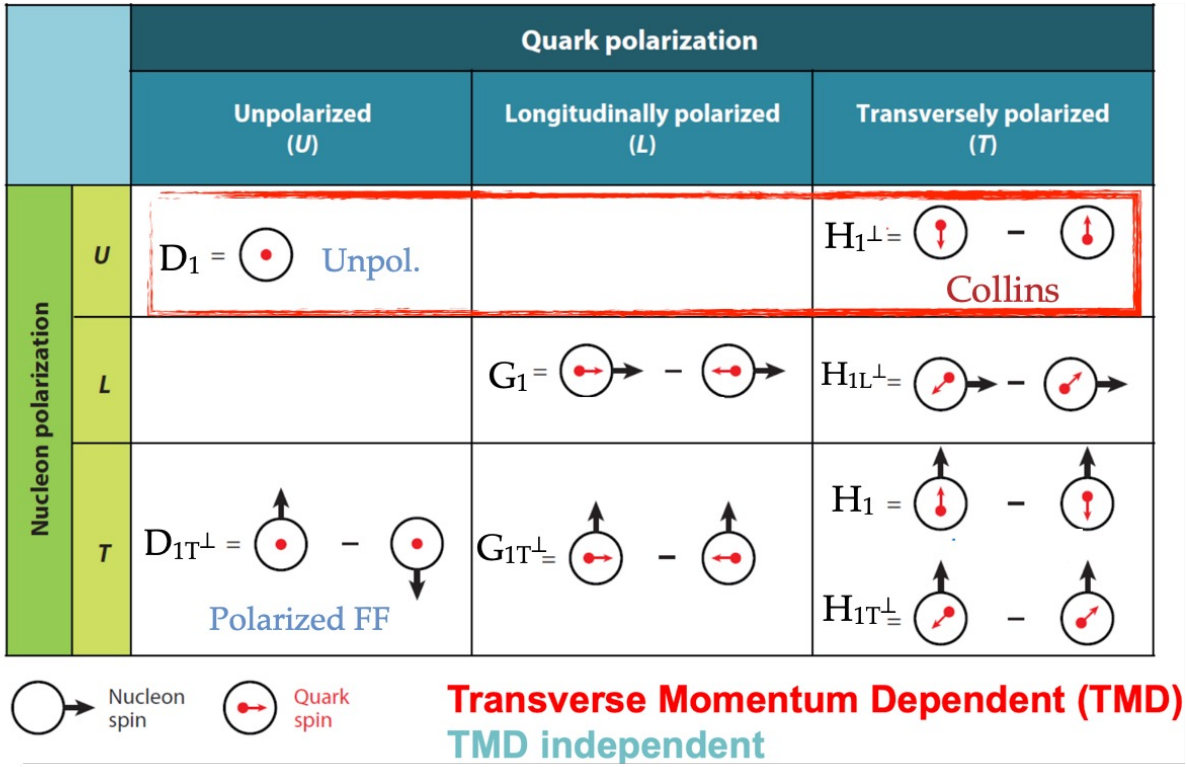
Fragmentation Functions (FFs)

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



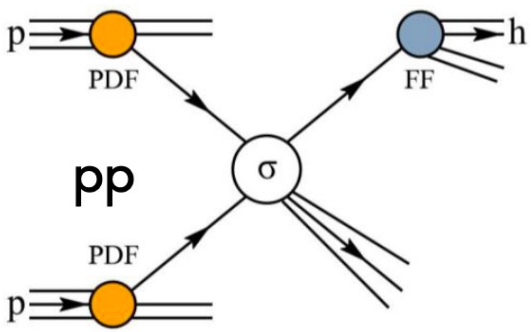
FFs classification:

- extending the integrated fragmentation function D1 to different quark and hadron polarizations
- including the dependence on the transverse momentum Kt of the hadron with respect to the parent quark

Transverse Momentum Dependent FFs ⇒ to study the spin-dependent observables

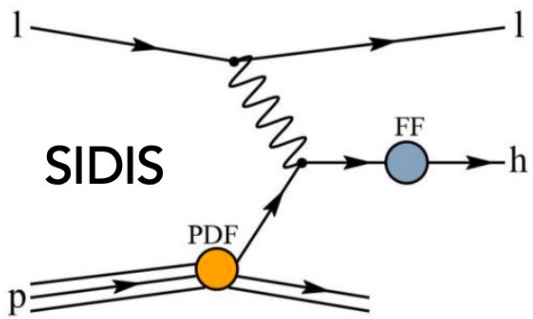
- tools to investigate the 3D-structure of nucleons
- when only spinless hadrons (π, K) are considered, we have only D_1 and $H_1^{\perp}$
- TMDs evolution

Accessing FFs in experiments



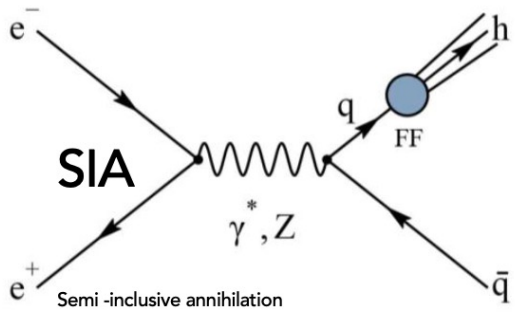
$$\sigma = \sum_q pdf \otimes pdf \otimes \sigma(q_1 q_2 \to q_1' q_2') \otimes FF$$

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



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

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



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

- 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*

Accessing FFs in e^+e^- annihilation

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

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

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

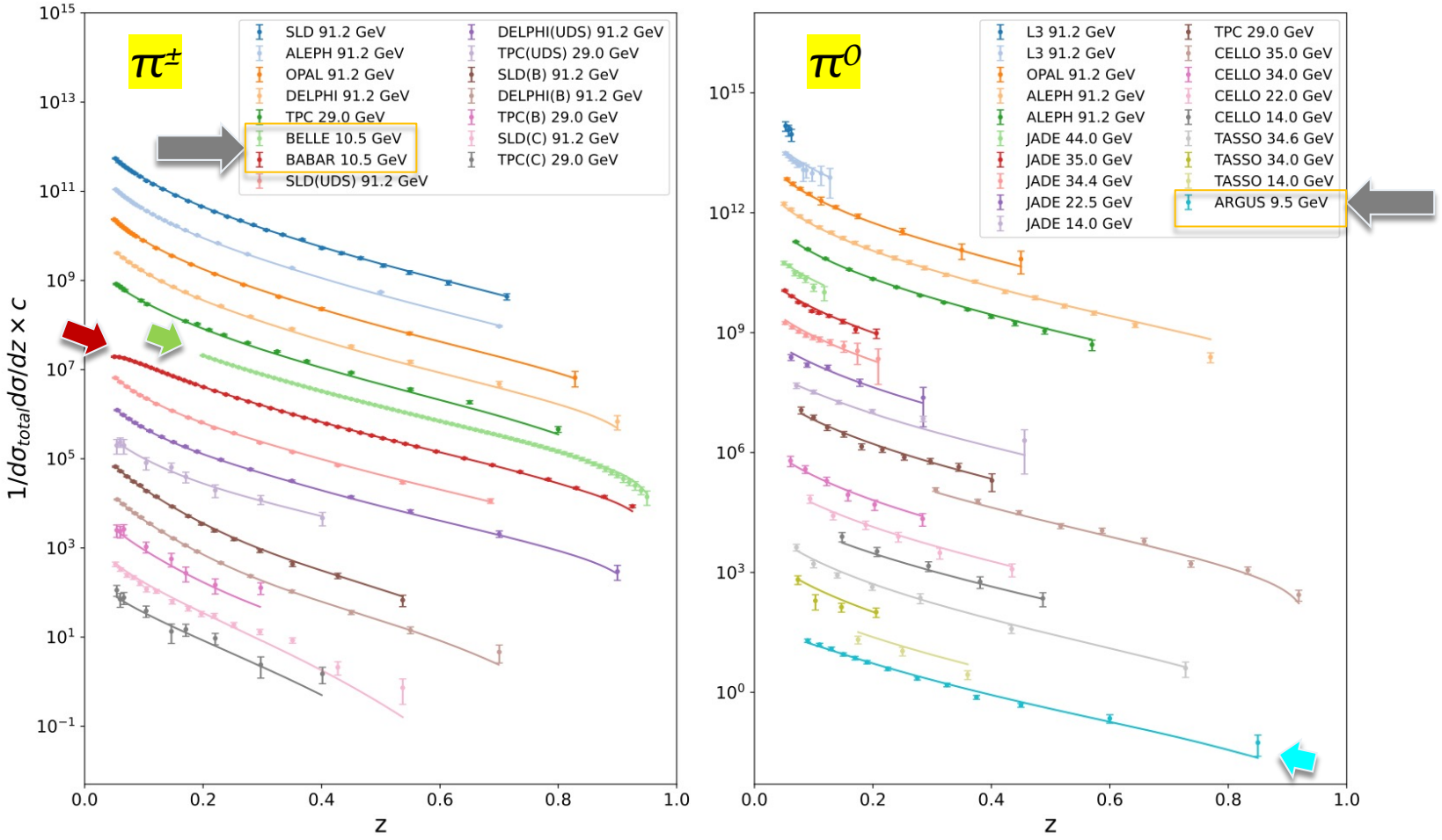
$$\sum_q e_q^2 [D_q^h(z,\mu) + D_{\bar{q}}^h(z,\mu)]$$

Unpolarized FF

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

Factorization scale (center-of-mass energy)

Unpolarized FF: world data for π, K and η

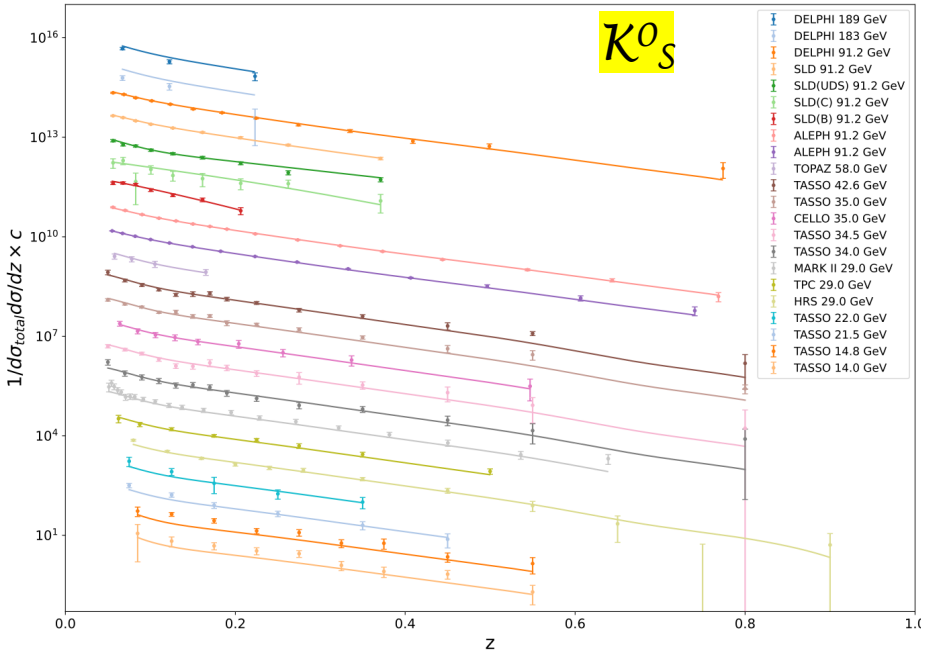


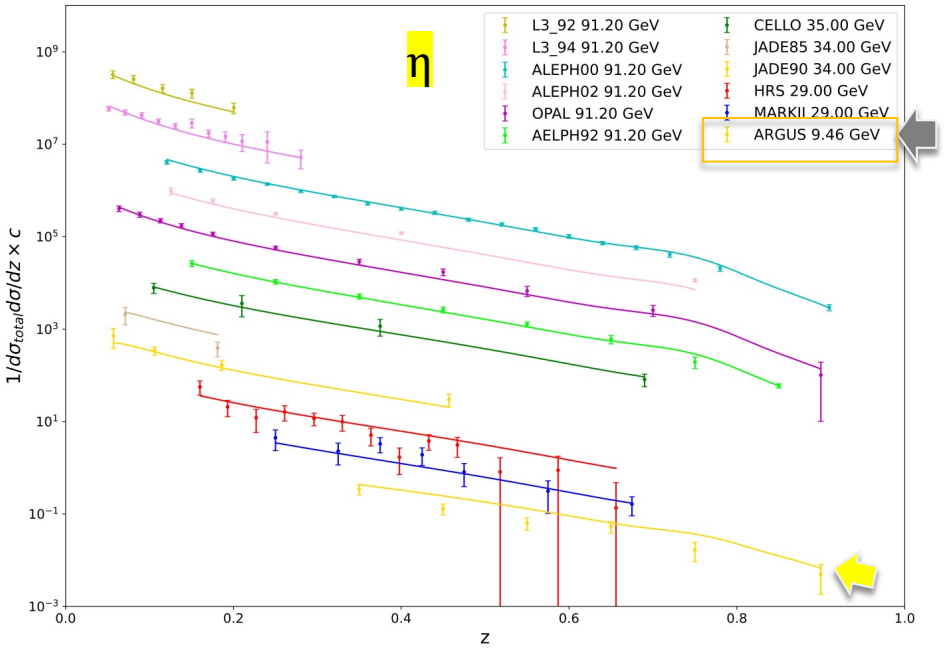
Li, Anderle, Xing, Zhao

Phys Rev. D 111,034030 (2025)

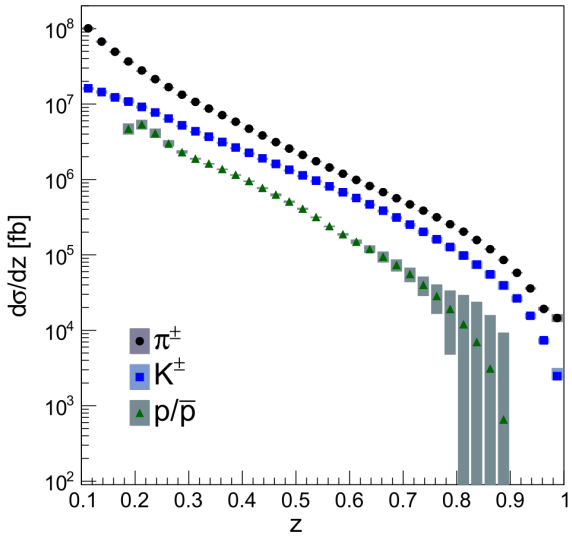
Unpolarized FF: world data for π, K and η

Li, Anderle, Xing, Zhao. Phys Rev. D 111,034030 (2025)



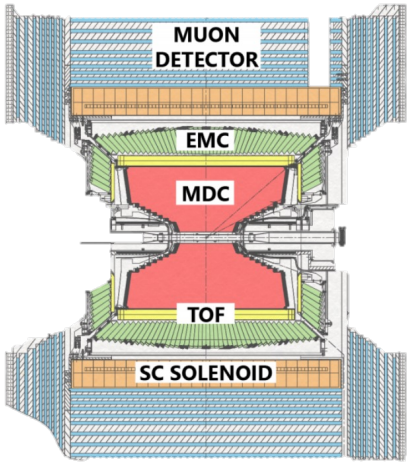


Belle Update: PRD 101, 092004 (2020)



- 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



中國科學院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

BESIII

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

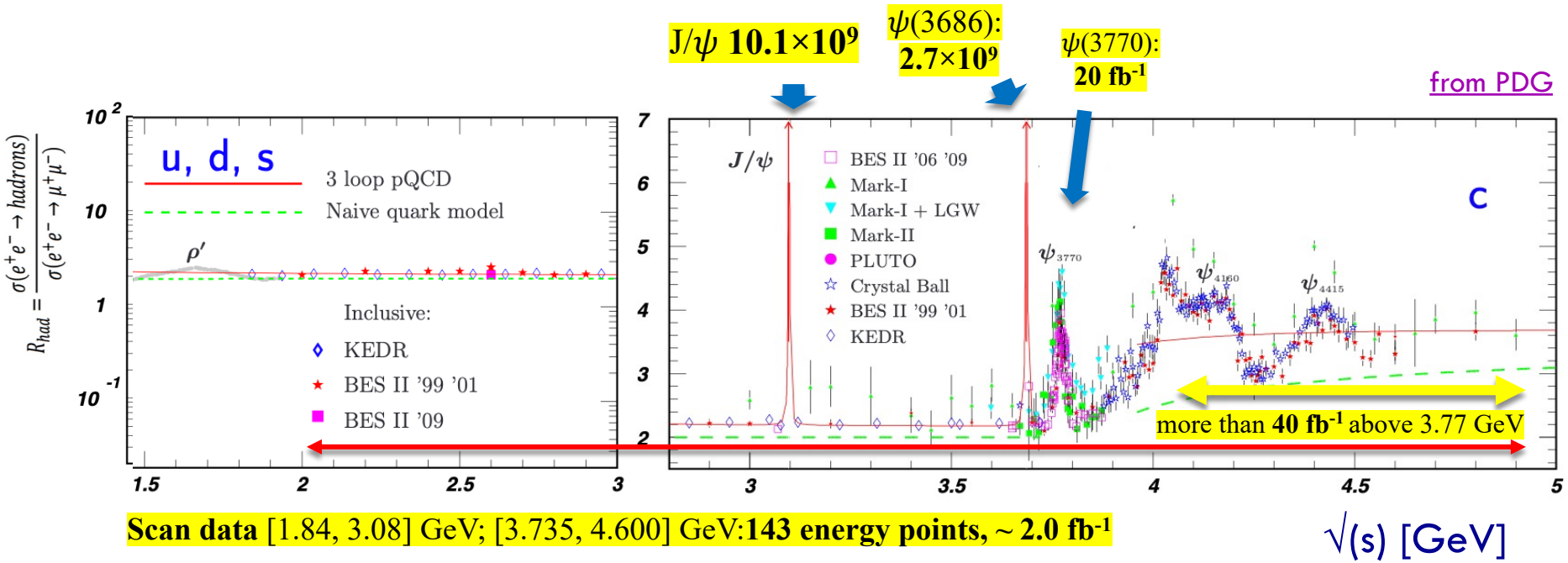
2004: started Beijing Electron Positron Collider II/BESIII construction

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

2009 – today: BESIII physics runs

BESIII dataset and physics program

Optimised for flavour physics in the τ-charm region



- 130 points between 2 and 4.6 GeV (~715 pb^{-1} up to 3.08 GeV for ρ*, ω*, ϕ*,… studies)

- Light hadron spectroscopy
- η/η' decays
- Hyperon physics
- Charmonium transitions

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

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

Normalized Hadronic Cross Section

PRL 128, 062004 (2022)

BESIII

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

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

Residual background events
- MC simulations
- Beam related contributions from data(SB)

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

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

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

Integrated luminosity (by LA-Bhabha) 0.8% uncertainty

Detection efficiency

Trigger efficiency ~ 100%.

Normalized Hadronic Cross Section

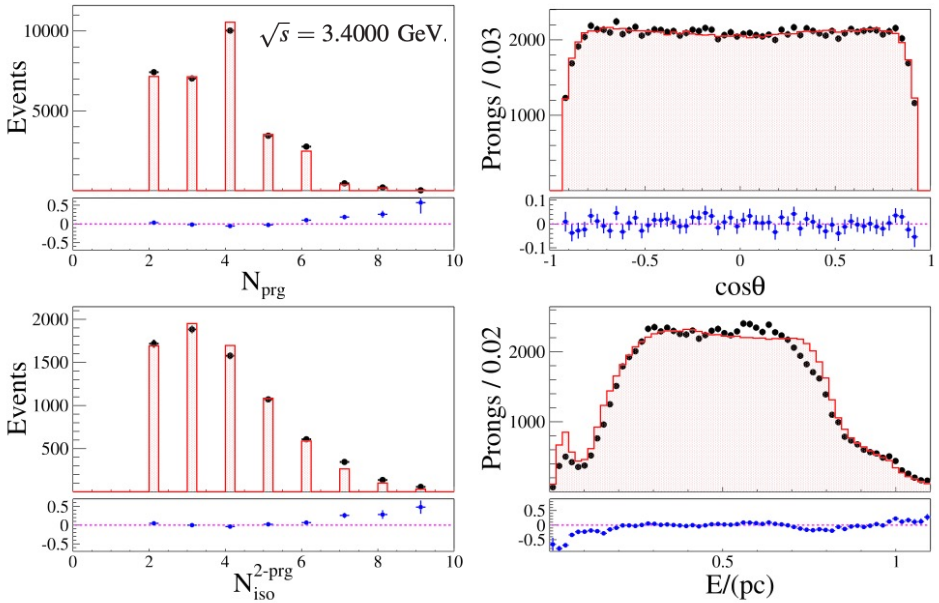
PRL 128, 062004 (2022)

BESIII

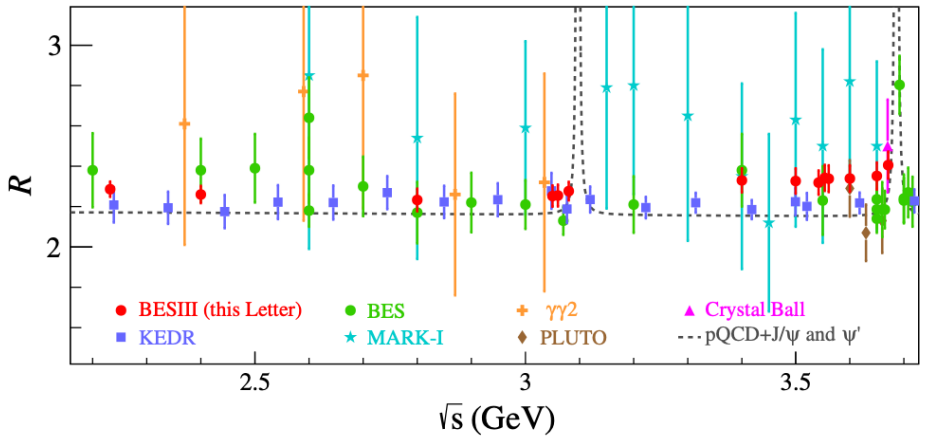
$$\frac{1}{\sigma_{\rm had}}\frac{d\sigma\left(e^+e^-\to h+X\right)}{dp_h}=\frac{N_h}{N_{\rm had}}\frac{1}{\Delta p_h}=\frac{N_h^{\rm obs}}{N_{\rm had}^{\rm obs}}\frac{1}{\Delta p_h}f_h$$

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

LUARLW MC reasonably reproduce the data



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



- 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 1.9σ and 2.7σ

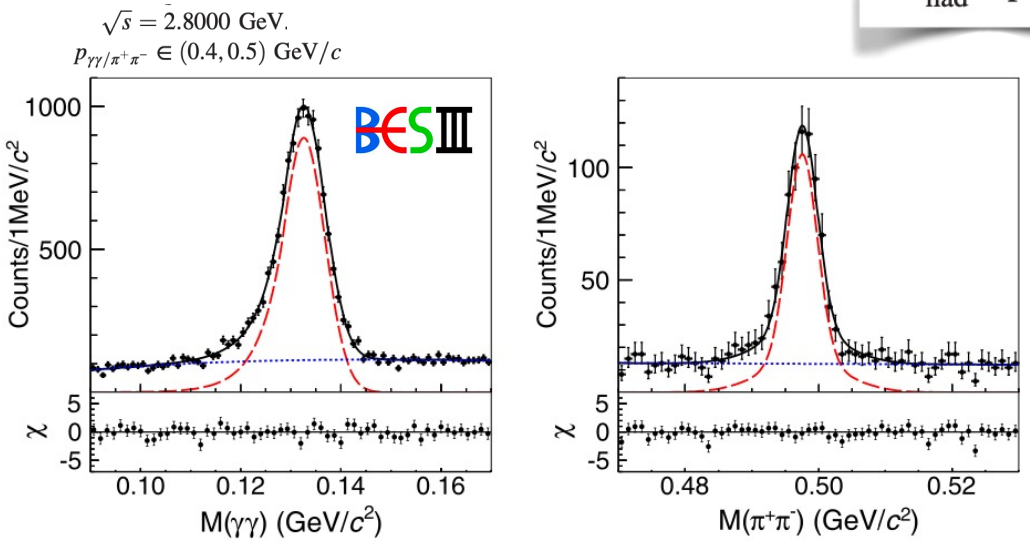
Inclusive π^0 and K^0_S production @ BESIII

PRL 130, 231901 (2023)
Suppl. Material

$e^+e^- \to \pi^0/K^0_S + X$ 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:

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



- The M(γγ) 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(γγ) and M($\pi^+\pi^-$) spectra in each momentum interval to determine the corresponding numbers of signal events

Correction:

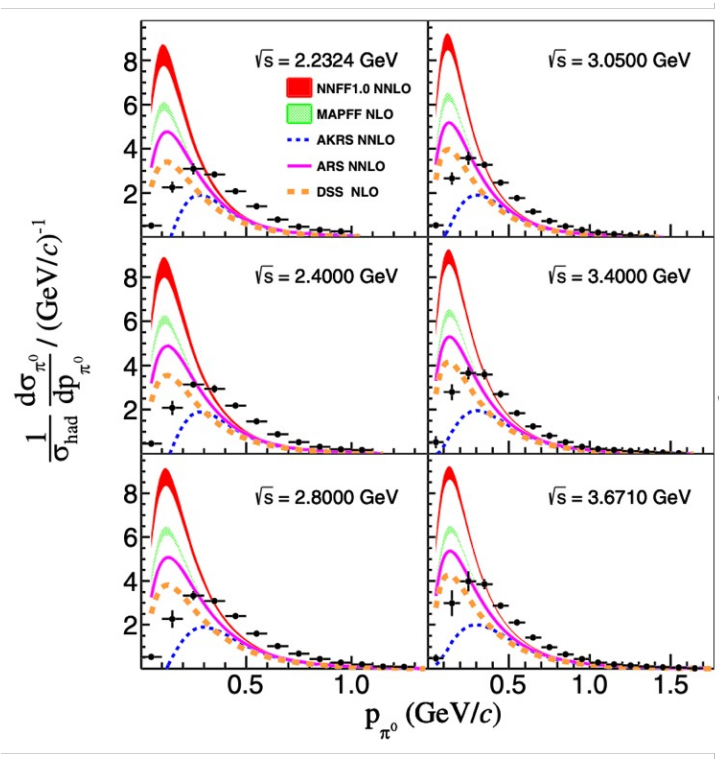
$$f_h = \frac{\bar{N}_h^{\rm tru}({\rm off})}{\bar{N}_{\rm had}^{\rm tru}({\rm off})} \Big/ \frac{\bar{N}_h^{\rm obs}({\rm on})}{\bar{N}_{\rm had}^{\rm obs}({\rm on})}$$

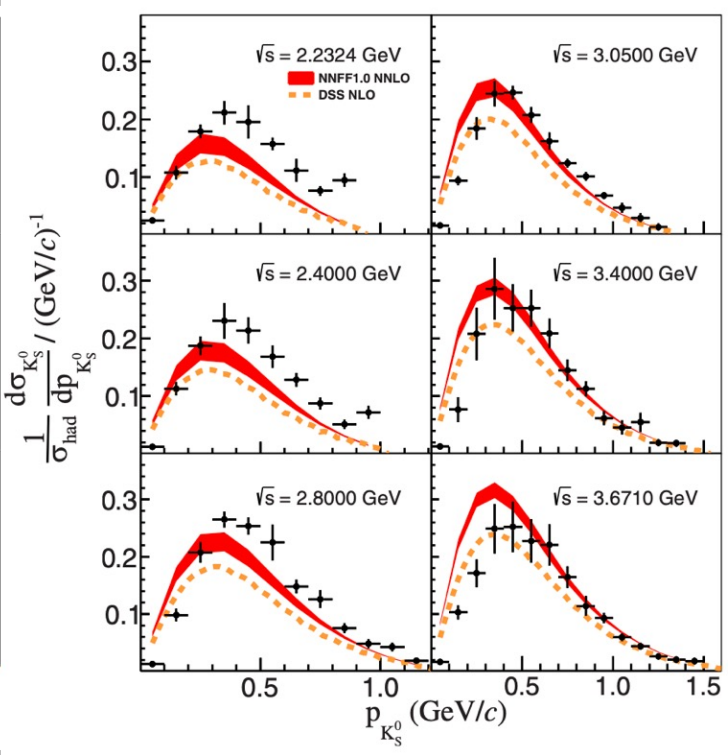
on/off: ISR effect
tru/obs: gen/det level

Inclusive π^0 and K^0_S production @ BESIII: RESULTS

BESIII 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

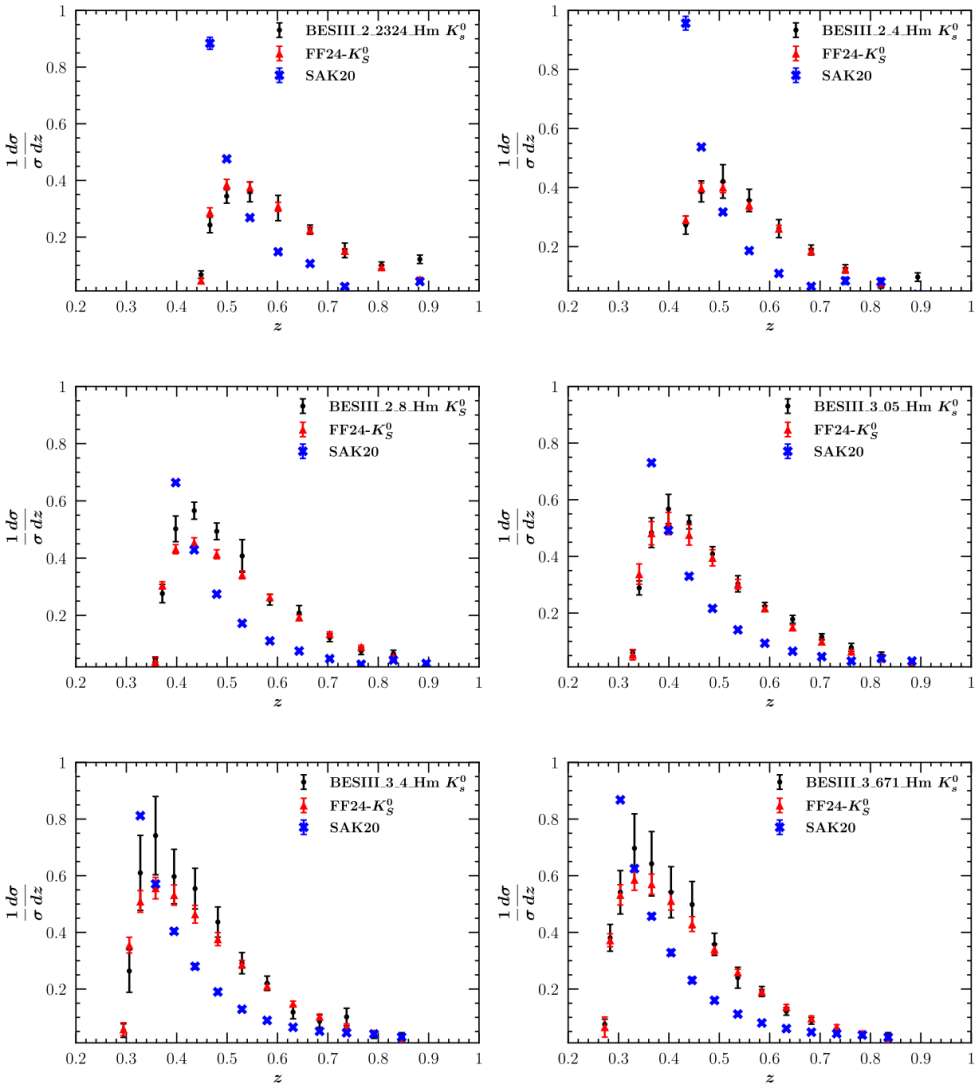
Disagreement observed to depend on both c.m energy and hadron momentum

This result

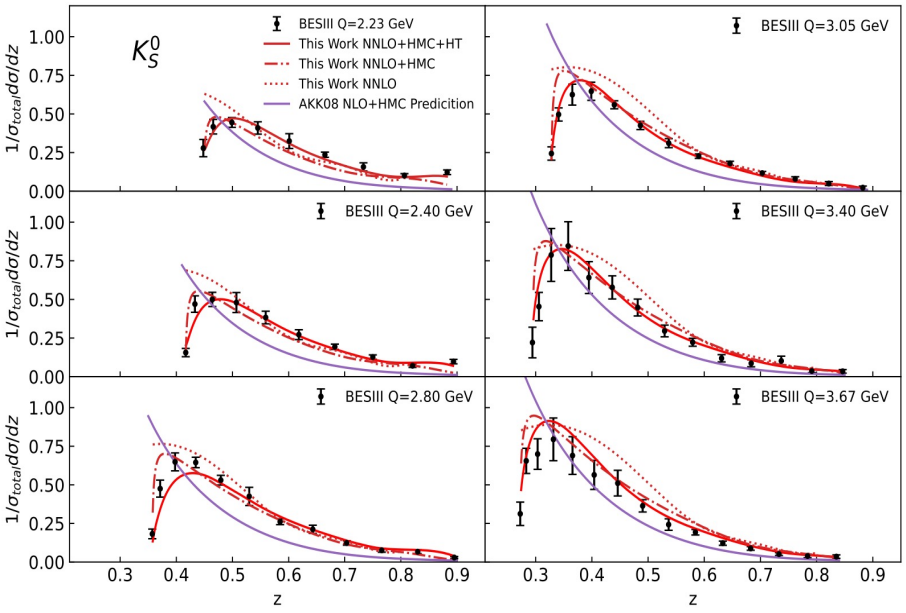
- ✓ help to fill the region with c.m. energy < 10 GeV
- ✓ provide broad z coverage from 0.1 to 0.9 with precision of around 3% at z ~ 0.4.
- ✓ provide new ingredients for FF global data fits, in which almost no single inclusive annihilation data measured in this energy region has been included

Inclusive K^0_S production

PRD 110, 014019 (2024)



PRD 111, 034030 (2025)

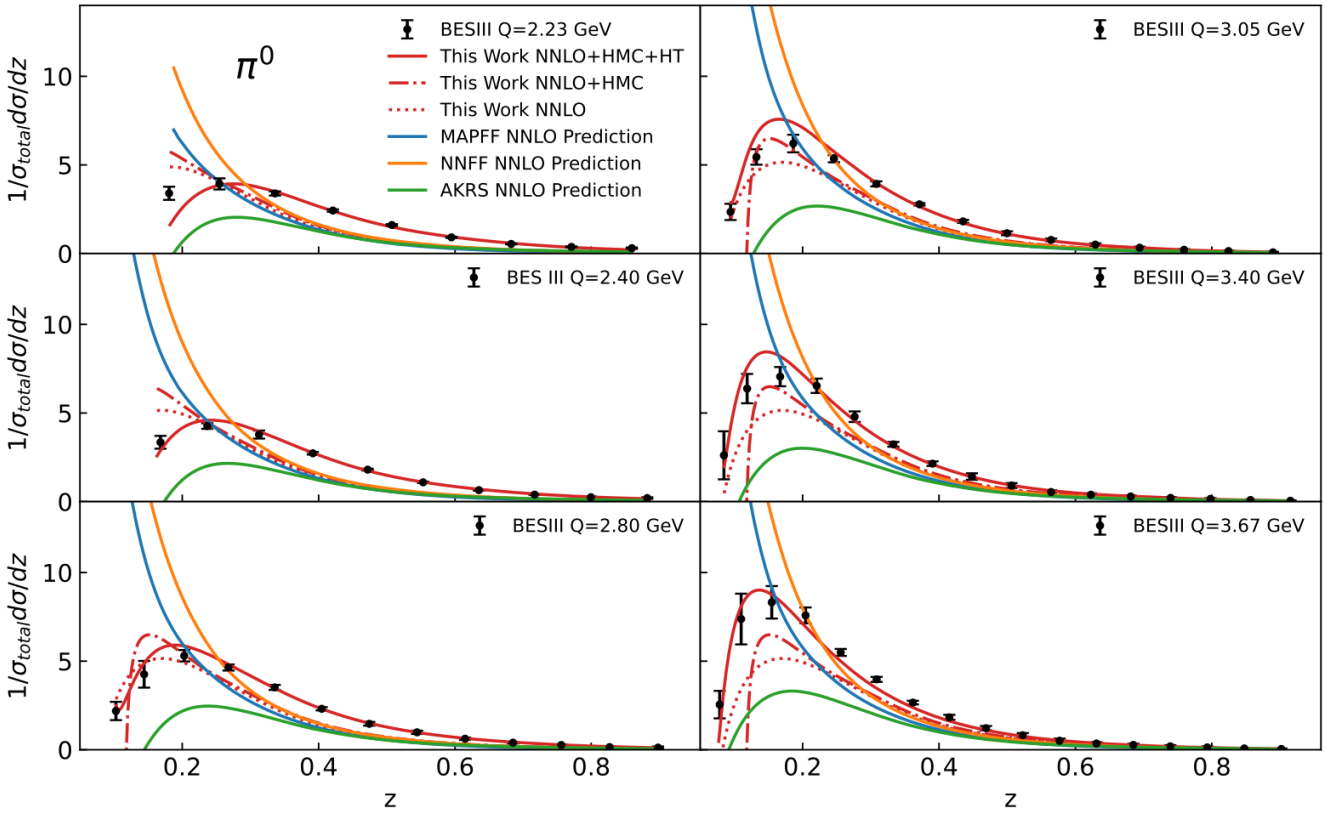


NNLO accuracy & higher twist & hadron mass contributions

NLO and NNLO accuracy & hadron mass correction for K^0_S

Inclusive π^0 production

PRD 111, 034030 (2025)

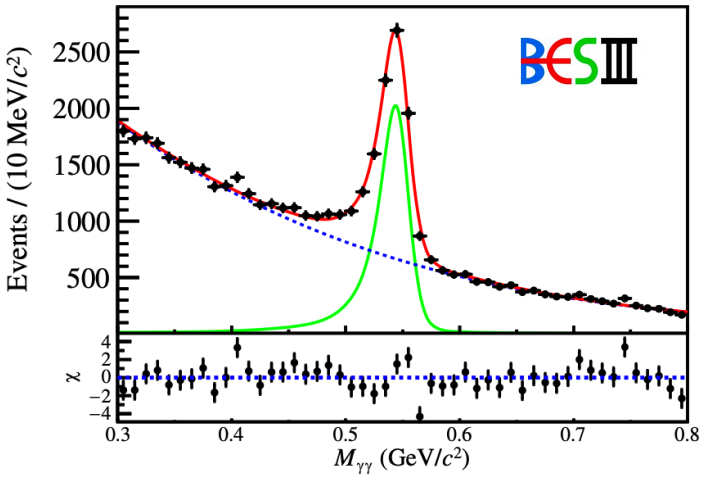


NNLO accuracy, including hadron mass correction at higher-twist effects

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 η production @ BESIII

√s=2.9 GeV; $p_{\gamma\gamma}$∈(0.4,0.5) GeV/c



Experimental observation:

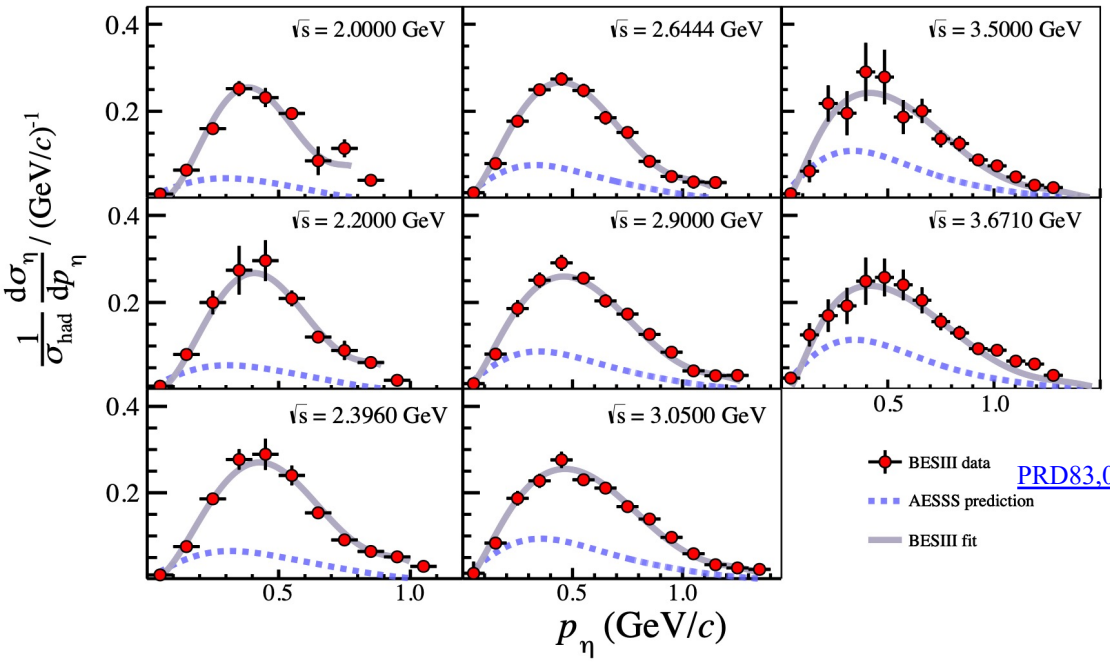
$$\frac{N_h^{\rm obs}}{N_{\rm had}^{\rm obs}}\frac{1}{\Delta p_h} f_h$$

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

PRL 133,021901 (2024)

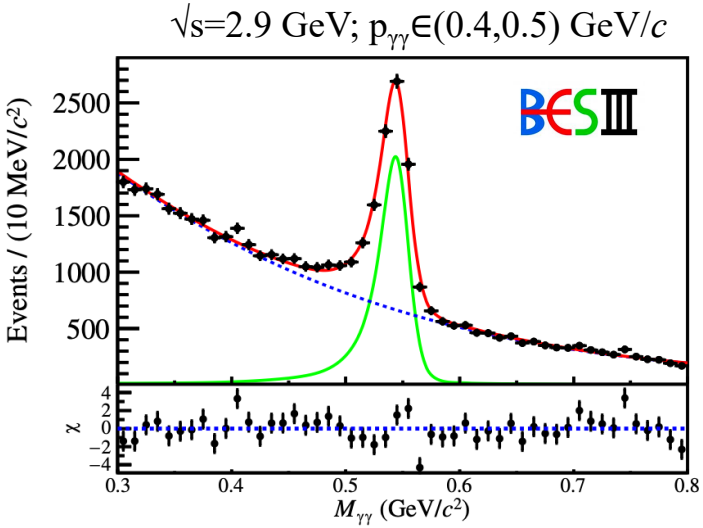
Normalized cross section of the inclusive process $e^+e^-\to\eta+X$ measured at 8 c.m. energies from 2.000 to 3.6710 GeV

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



PRD83,034002

Inclusive η production @ BESIII



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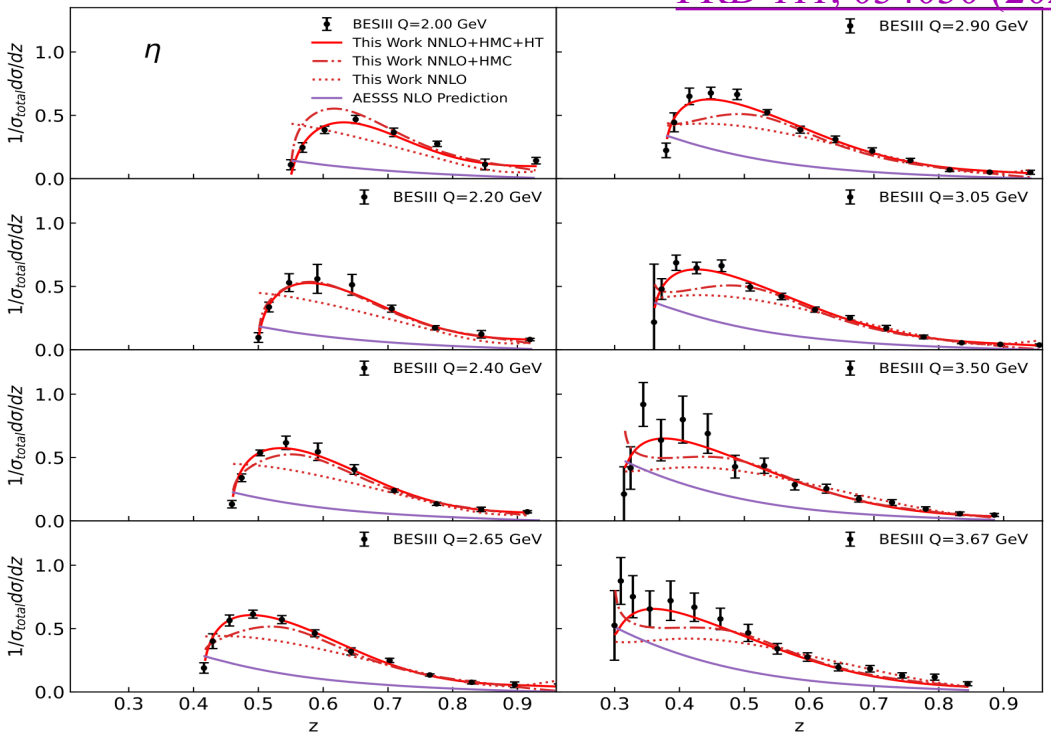
PRD 111, 034030 (2025)



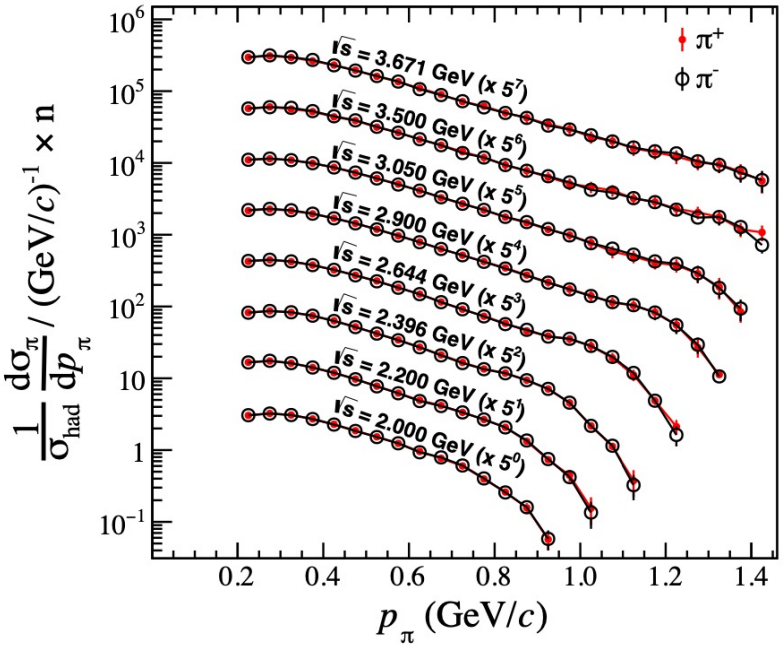
Inclusive $\pi^{\pm}$ and $K^{\pm}$ production @ BESIII

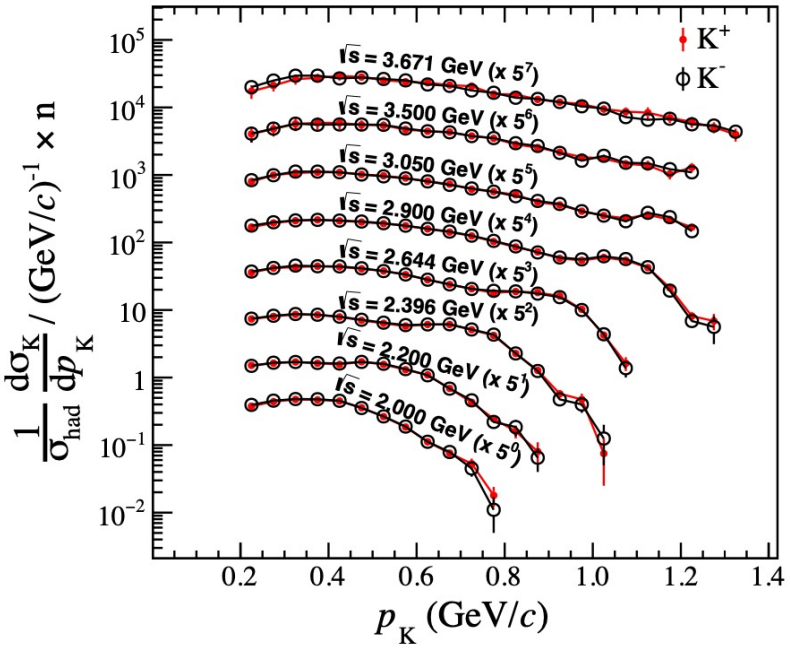
ArXiV:2502.16084

Normalized differential cross section of the inclusive process $e^+e^- \to \pi^{\pm}/K^{\pm} + X$ 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 $e^+e^- \to K^{\pm} + X$ process may be attributed to the $e^+e^- \to K^*_2(1430)^{\pm}K^{\mp}$

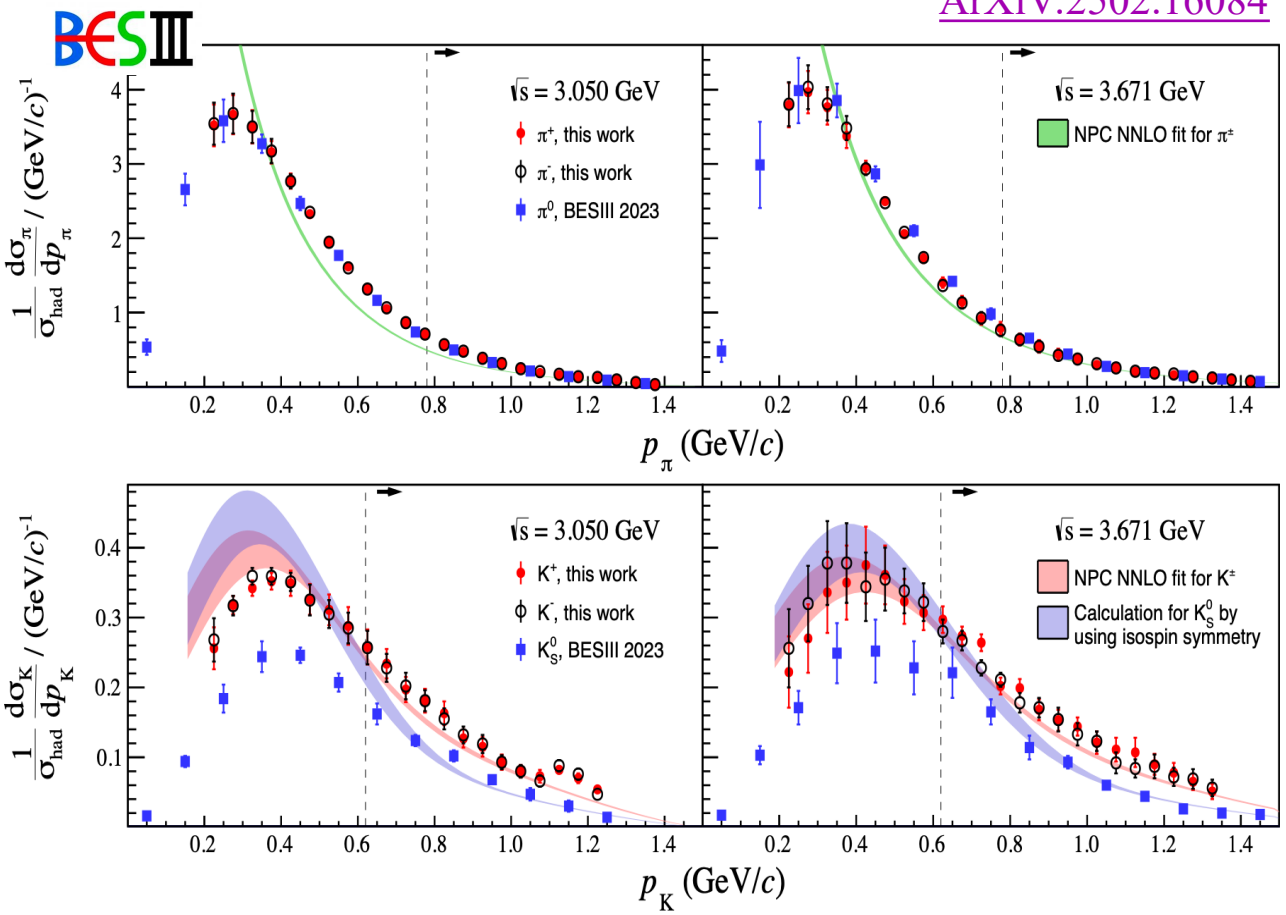
Inclusive $\pi^{\pm}$ and $K^{\pm}$ production @ BESIII

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

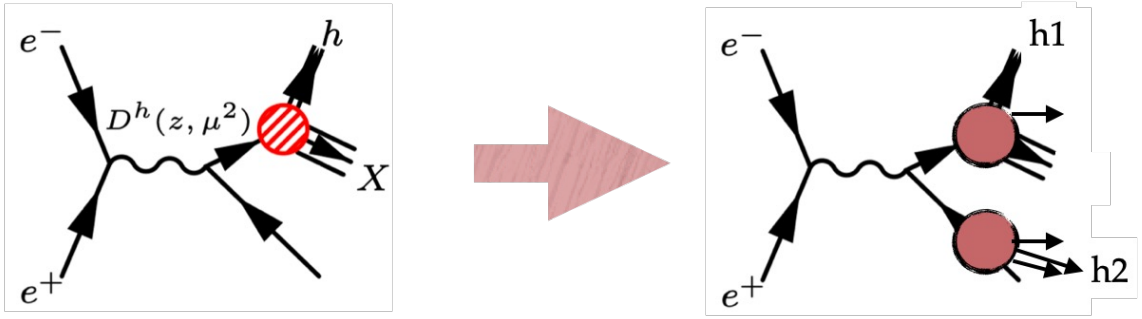
- $\sqrt{s}$>3 GeV & E_h>0.8 GeV to ensure validity of factorization and pQCD calculation for BESIII measurements

ArXiV:2502.16084

- ✓ 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 π and K fragmentation process



Collins @ BESIII



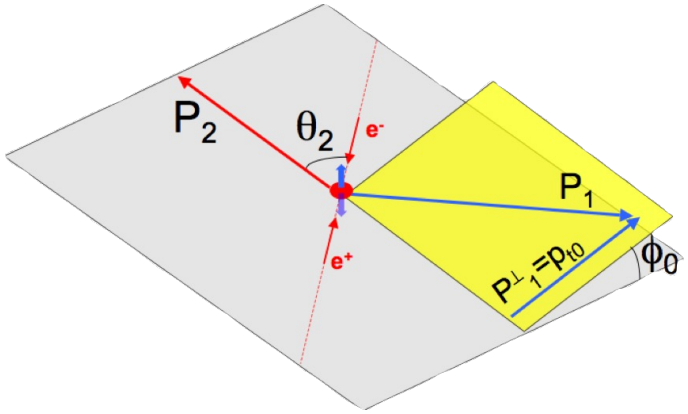
q↑→hX: $$D_1^{q\uparrow}(z,\mathbf{P}_\perp;s_q) = D_1^q(z,P_\perp) + \frac{P_\perp}{zM_h} H_1^{\perp q}(z,P_\perp)\, \mathbf{s}_q \cdot (\mathbf{k}_q \times \mathbf{P}_\perp)$$

Unpolarized FF

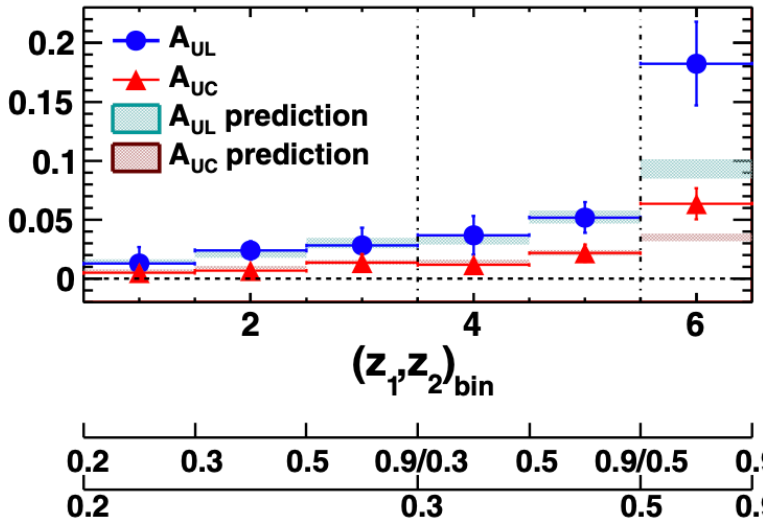
Collins FF [NP**B 396**, 161 (1993)]: related to the probability that a transversely polarized quark (q↑) fragments into a spinless hadron

- 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

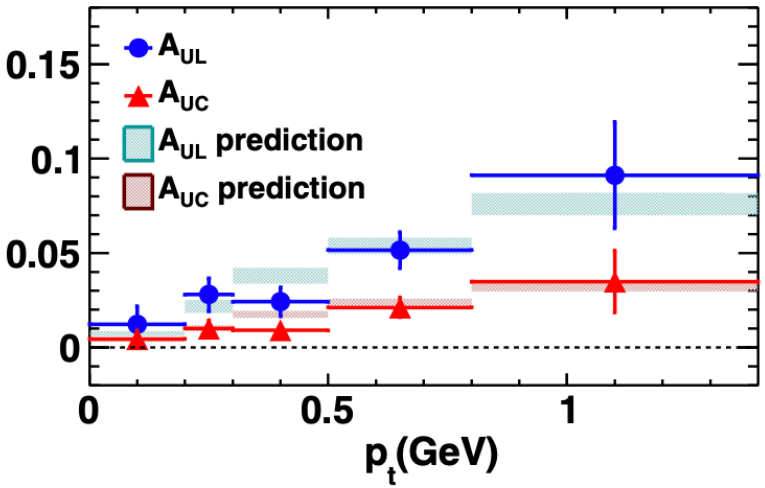


BESIII PRL 116,042001 (2016)



Double ratio of asymmetries performed in order to avoid detector acceptance effect:

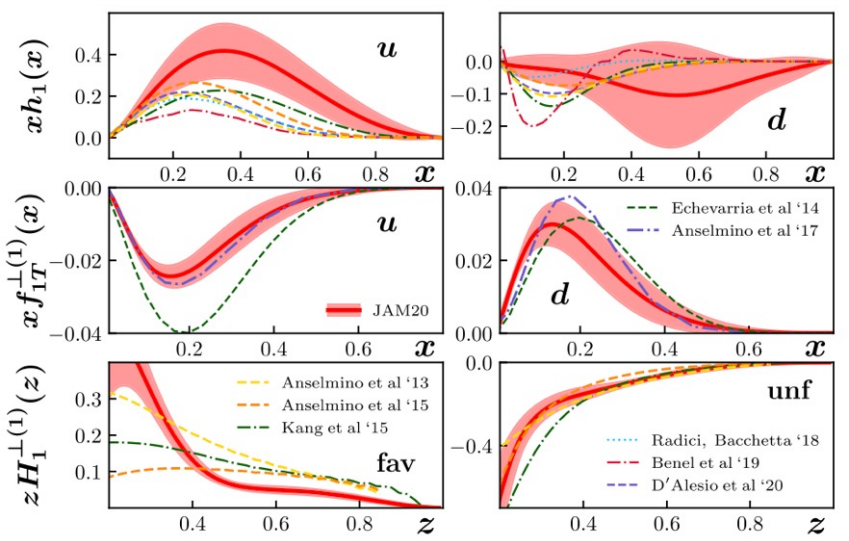
$$A_{UL} = \frac{\left[\pi^+ \; u_{fav} \; e^+ \; \bar{u}_{fav} \; \pi^-\right] \text{ or } \left[\pi^- \; u_{dis} \; e^+ \; \bar{u}_{dis} \; \pi^+\right]}{\left[\pi^+ \; u_{fav} \; e^+ \; \bar{u}_{dis} \; \pi^+\right] \text{ or } \left[\pi^- \; u_{dis} \; e^+ \; \bar{u}_{fav} \; \pi^-\right]}$$



Collins FFs @ BESIII: First Global Analysis

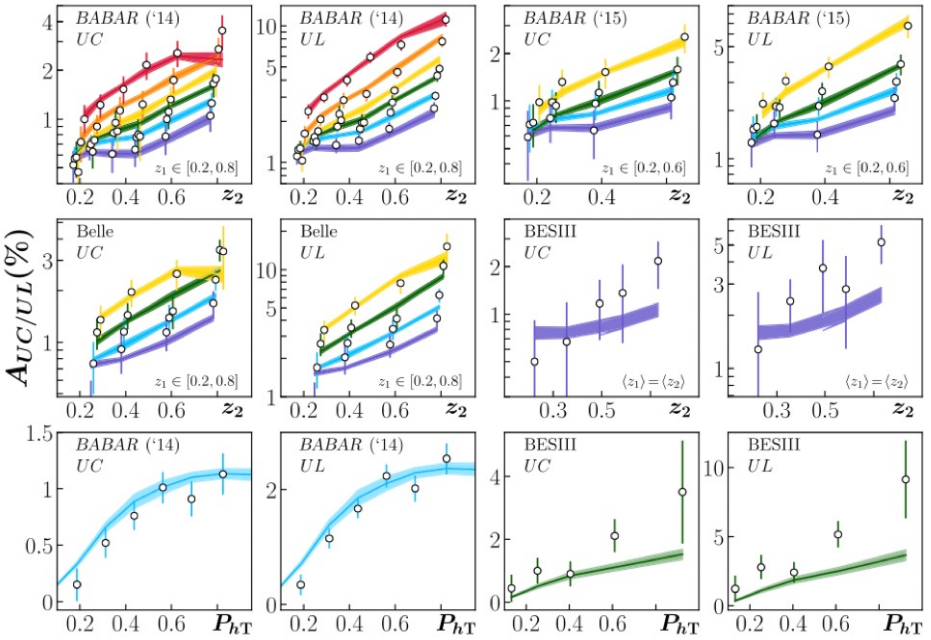
First simultaneous QCD global analysis with SIDIS, semi-inclusive e+e- annihilation, Drell-Yan and proton-proton collisions

- 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'Alesio'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 Kπ+X and KK+X
- Collinear dihadron FFS
  - new results ready soon

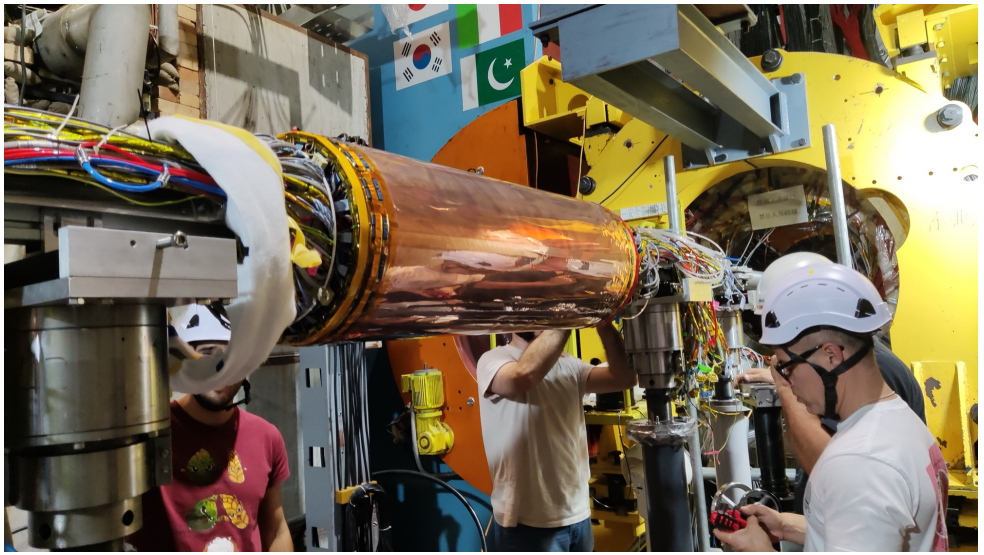
$$\frac{1}{\sigma_{tot}(e^+e^- \to hadrons)} \frac{d^2\sigma(e^+e^- \to (h_1h_2) + X)}{dzdM_h}$$

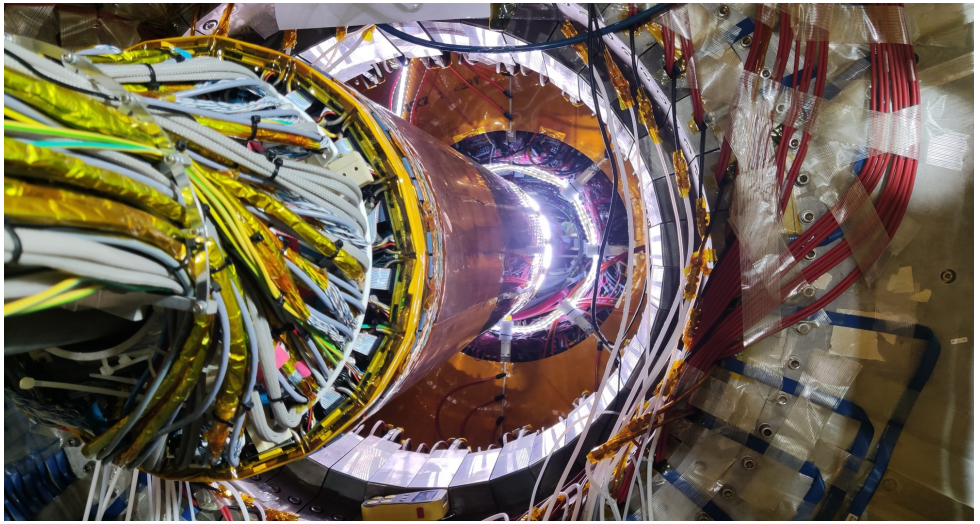
Conclusions

Detector and BEPCII upgrade

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

- Opportunities to study other charmed baryons (Σ_c, Ξ_c, Ω_c) in the BEPCII-U
- Remove the inner MDC and replace it with CGEM



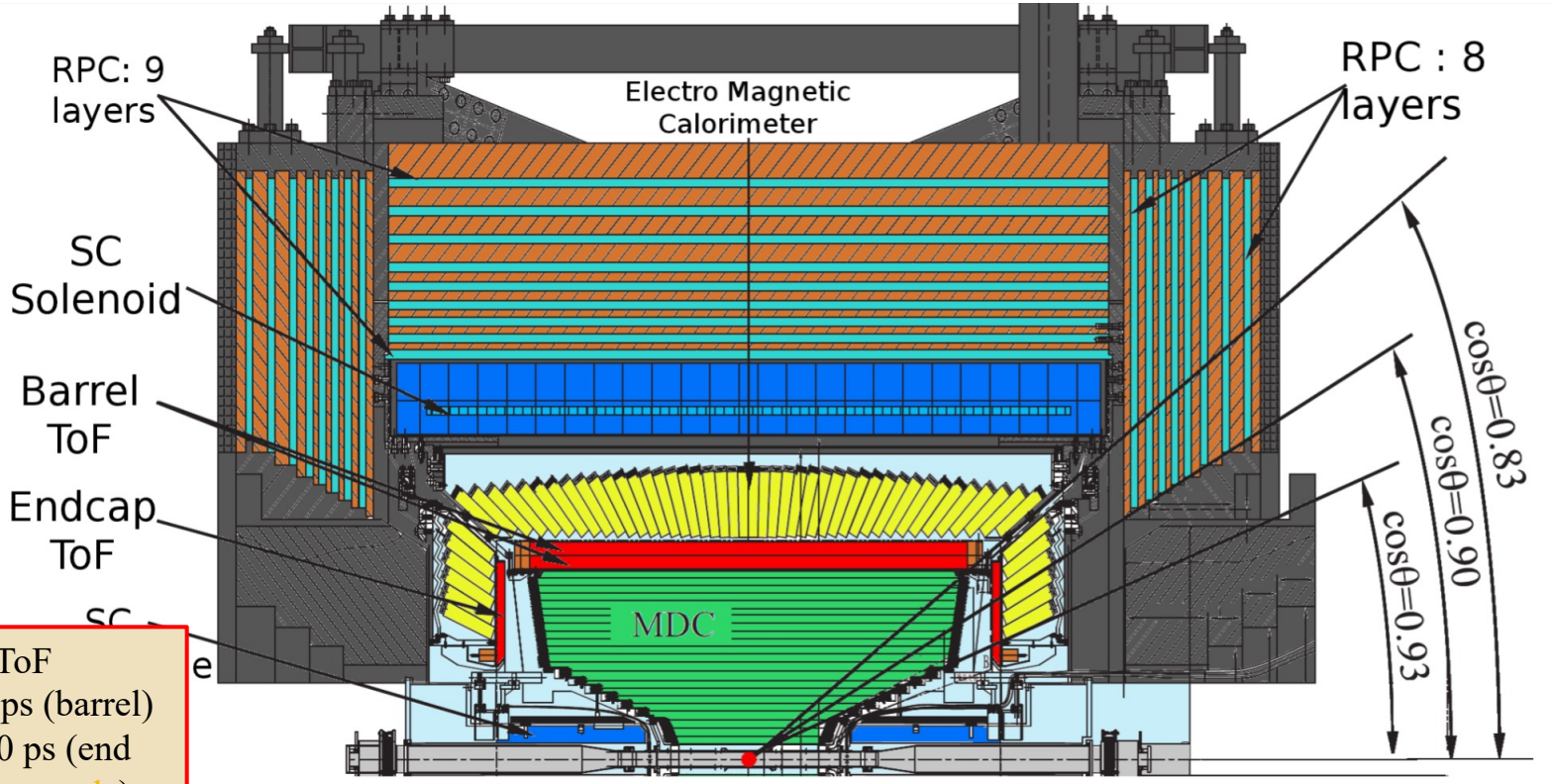


Thank you for your attention

Back-up slides

The BESIII Detector

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



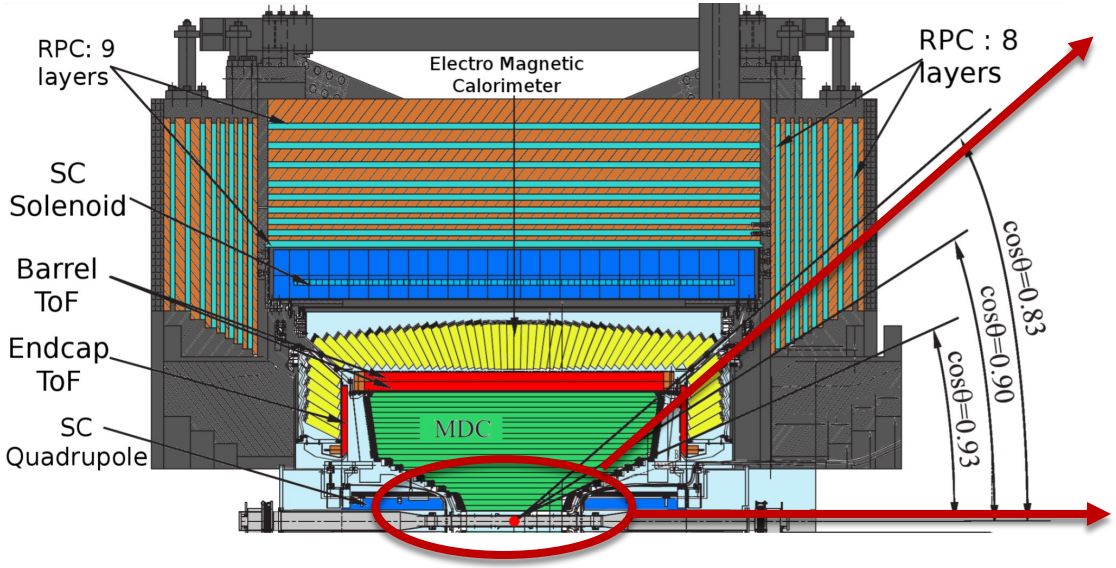
ToF
$\sigma_t \sim 68$ ps (barrel)
$\sigma_t \sim 60$ ps (end caps, upgrade)

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

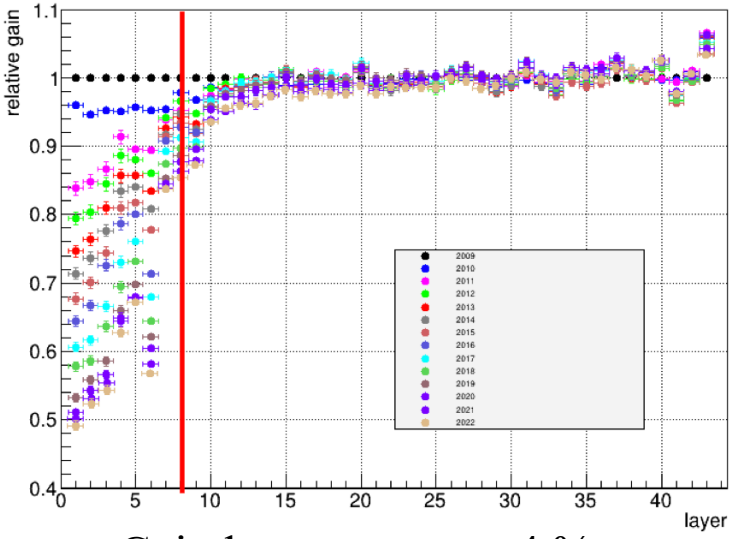
Electromagnetic CsI(Tl) Calorimeter
$\sigma_E/E < 2.5\%$ @ 1 GeV (barrel)
$\sigma_E/E < 5\%$ @ 1 GeV (end caps)
$\sigma_{xy} \sim (6\text{ mm})/E^{1/2}$ @ 1 GeV

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

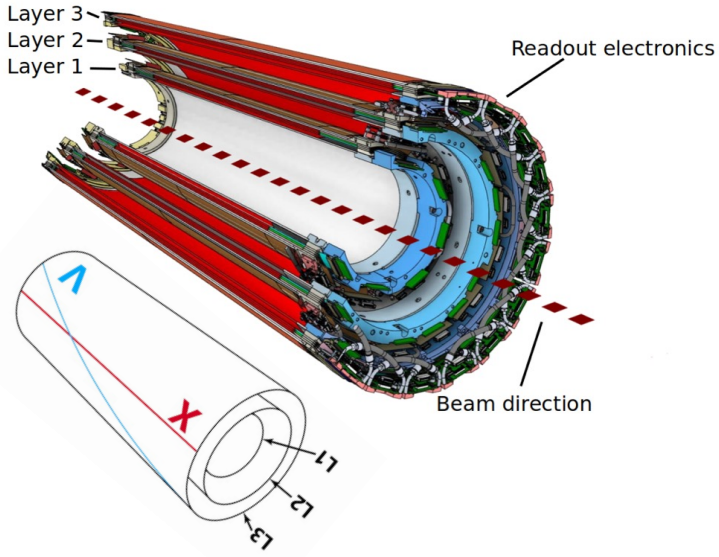
Why CGEM-IT ?



Gain loss of the inner MDC



Gain loss per year ~ 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 ~1.5% of X_0 in total
- Spatial resolution of 130-150 μm with charge and time readout

BESIII physics programme

Light hadron physics

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

XYZ meson physics

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

QCD and τ

- Precision R measurement
- τ decay

Charm physics

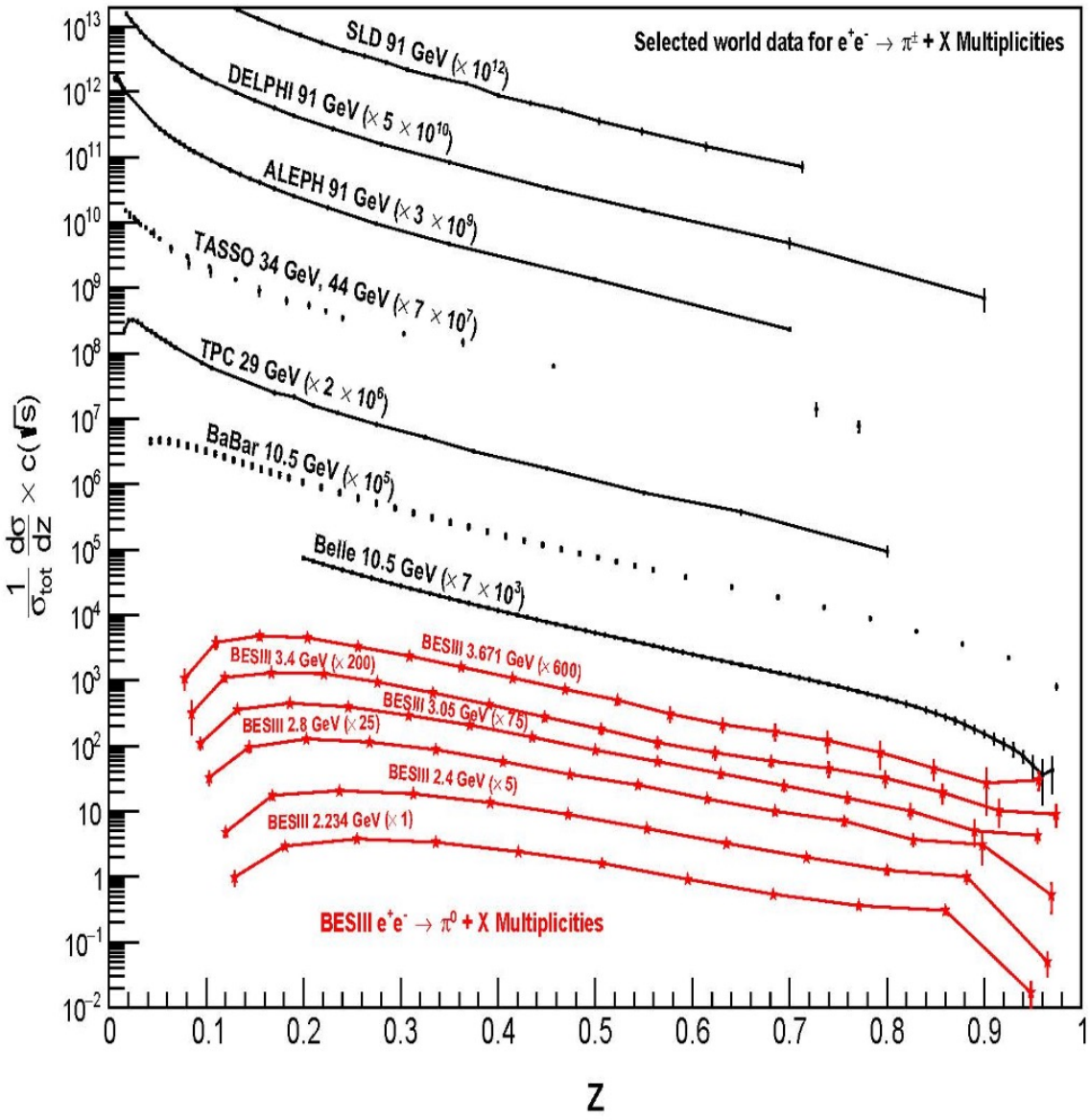
- Semi-leptonic form factors
- Decay constants f_D and f_{Ds}
- CKM matrix: $|V_{cd}|$ and $|V_{cs}|$
- D^0-$\overline{D}^0$ mixing, CPV
- Strong phases

Charmonium physics

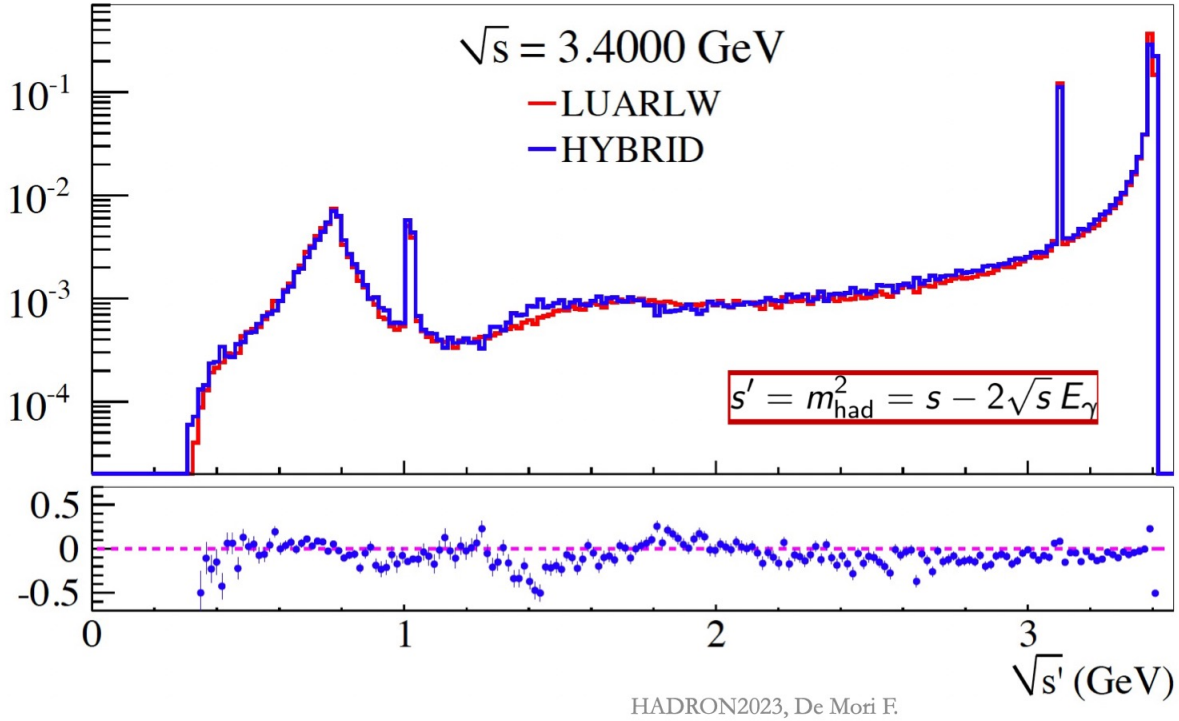
- Precision spectroscopy
- Transitions and decays

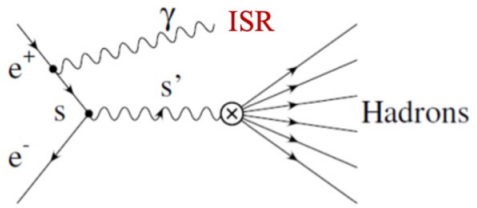
Precision mass measurements

- τ mass
- D, D^* mass


Selected world data for $e^+e^- \to \pi^\pm$ + X Multiplicities
SLD 91 GeV (× 10^{12})
DELPHI 91 GeV (× 5 × 10^{10})
ALEPH 91 GeV (× 3 × 10^9)
TASSO 34 GeV, 44 GeV (× 7 × 10^7)
TPC 29 GeV (× 2 × 10^6)
BaBar 10.5 GeV (× 10^5)
Belle 10.5 GeV (× 7 × 10^3)
BESIII 3.671 GeV (× 600)
BESIII 3.4 GeV (× 200)
BESIII 3.05 GeV (× 75)
BESIII 2.8 GeV (× 25)
BESIII 2.4 GeV (× 5)
BESIII 2.234 GeV (× 1)
BESIII $e^+e^- \to \pi^0$ + X Multiplicities
$\frac{1}{\sigma_{tot}} \frac{d\sigma}{dz} \times c(\sqrt{s})$
Z

The $\sqrt{s'}$ spectrum directly reflect the fraction of the ISR-returned processes





ISR process is simulated with different schemes

The results are consistent
For effective energy spectrum!

maximum difference of the calculated ISR corr. factor between HYBRID and LUARLW simulations is 1.4%,

from F. De Mori