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BESIII

Unpolarized Fragmentation Functions studies at BESIII

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中国物理学会高能物理分会第十二届全国会员代表大会

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Outline

- ◆ **Introduction to Fragmentation Functions**

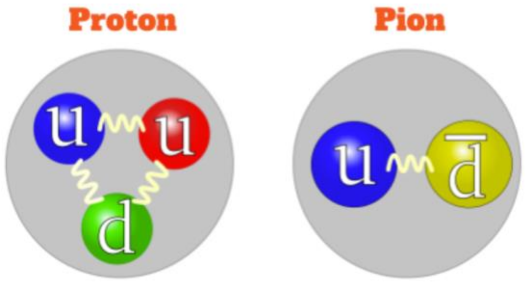
- ◆ **Existing studies at BESIII**
  - $e^+e^- \rightarrow \pi^0/K_S^0 + X$
  - $e^+e^- \rightarrow \eta + X$
  - $e^+e^- \rightarrow \pi^\pm/K^\pm + X$

- ◆ **Summary and Outlook**

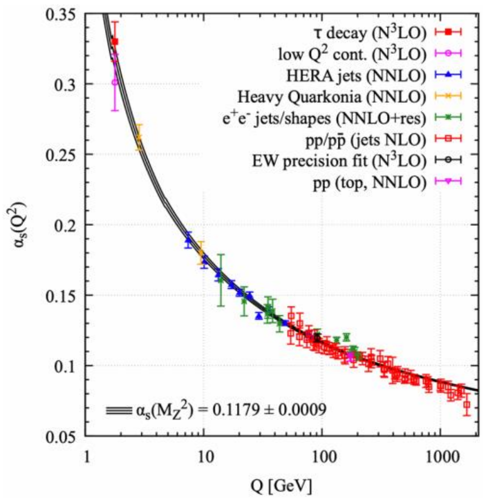
QCD Confinement and Nucleon structure

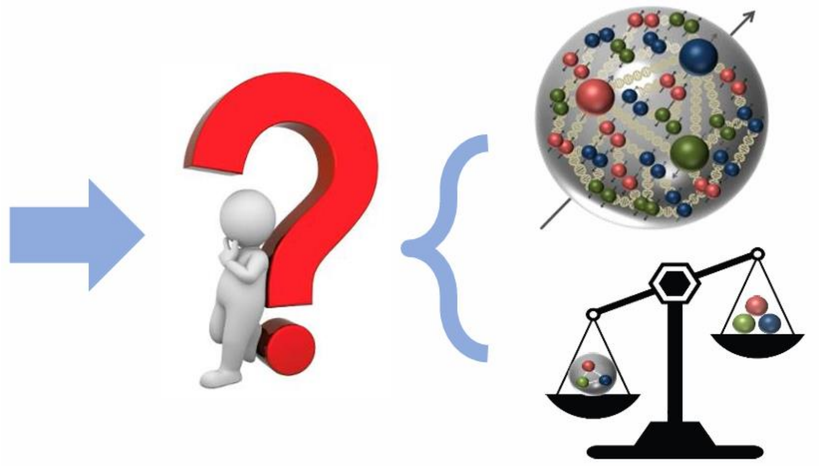
◆ Confinement

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



◆ Nucleon structure

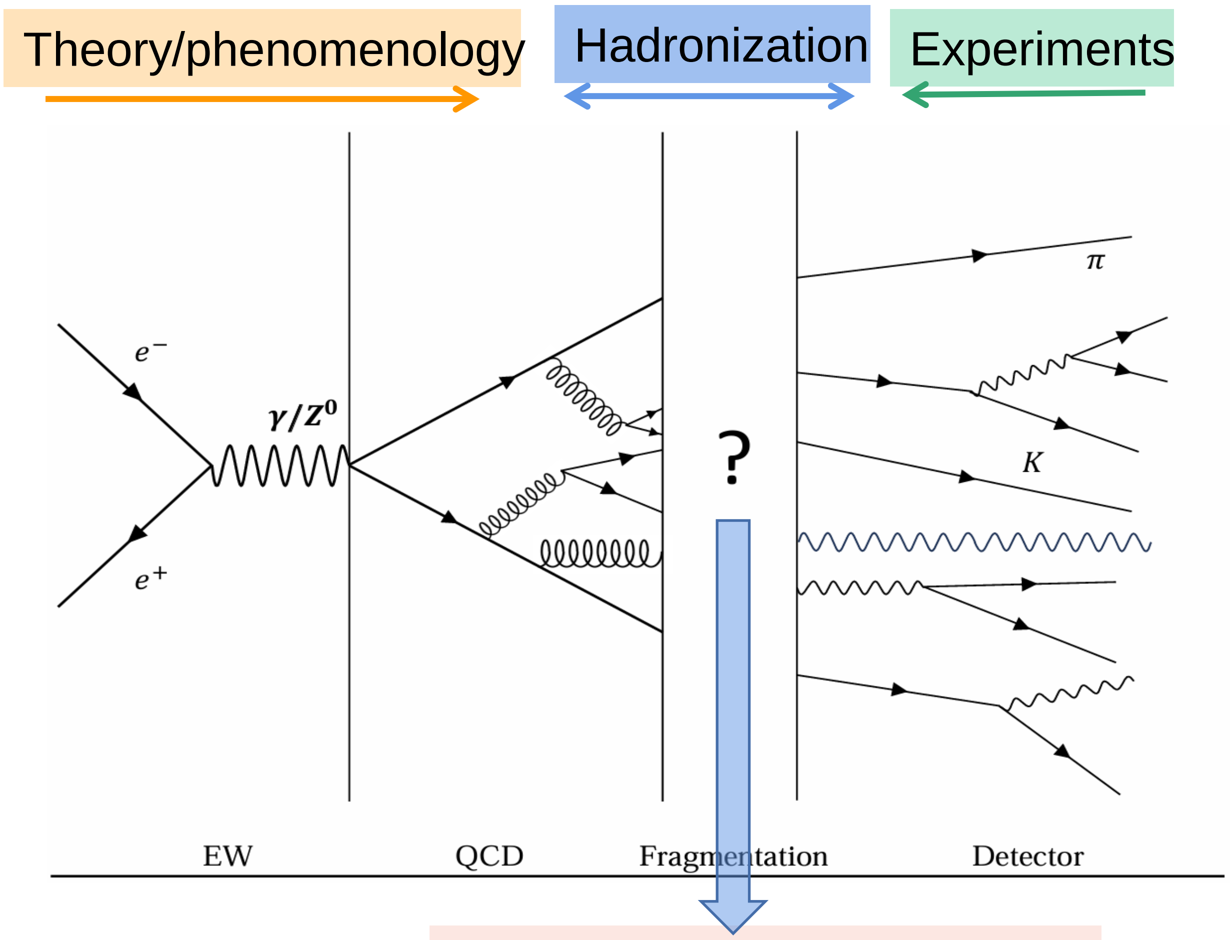




Spin: how does nucleon spin emerge

Mass: Higgs mechanism gives only a few %

Confinement and Hadronization

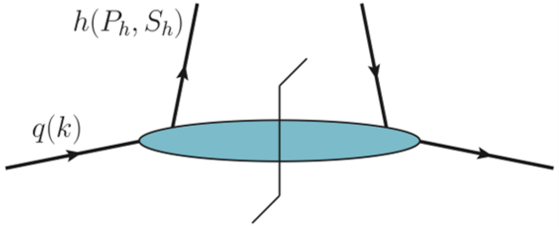


Fragmentation Functions FFs

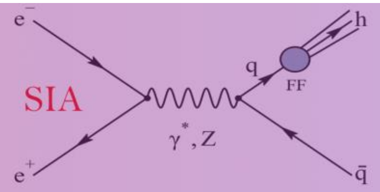
FFs: <u>describe how quarks or gluons transfer into hadrons</u>

- **Serve as a bridge to understand hadronization**

Determination of FFs: Global data fits

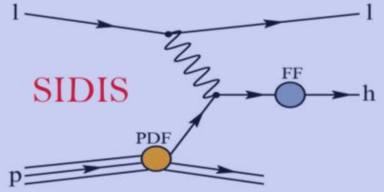


$$D_{h/q}(z) = \frac{z}{4}\sum\!\!\!\!\!\!\!\int_X \int \frac{d\xi^+}{2\pi} e^{iP_h^- \xi^+/z}\,\mathrm{Tr}\Big[\langle 0\,|\,\mathcal{W}(\infty^+,\xi^+)\;\psi_q(\xi^+,0^-,\vec{0}_T)\,|\,P_h,S_h;X\rangle$$
$$\times\,\langle P_h,S_h;X\,|\,\bar{\psi}_q(0^+,0^-,\vec{0}_T)\;\mathcal{W}(0^+,\infty^+)\,|\,0\rangle\;\gamma^-\Big]$$



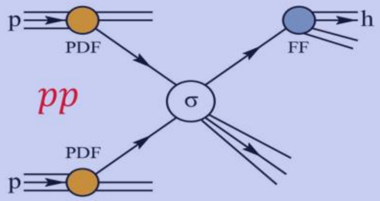
e^+e^-: $s = \sum_q \sigma(e^+e^- \to q\bar{q}) \otimes FF$

- 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



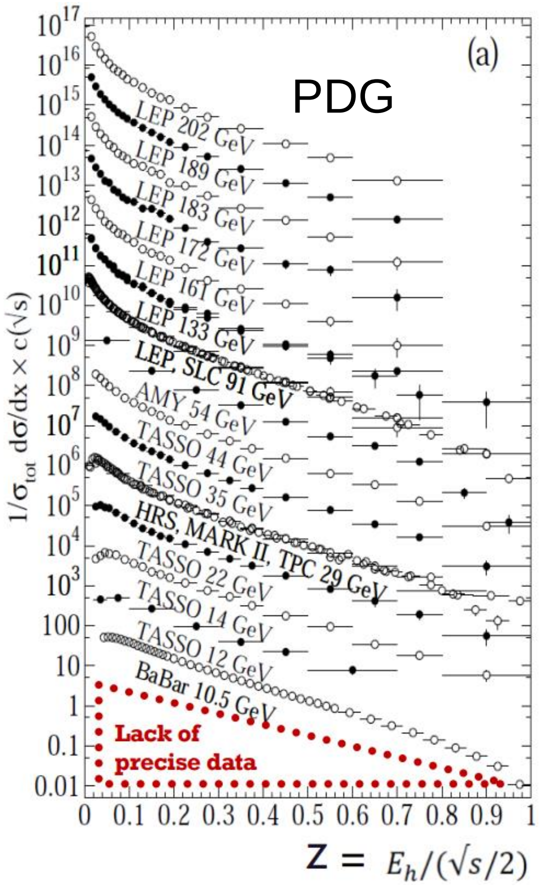
pp: $s = \sum_q PDF \otimes PDF \otimes \sigma(q_1 q_1 \to q_1' q_2') \otimes FF$

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

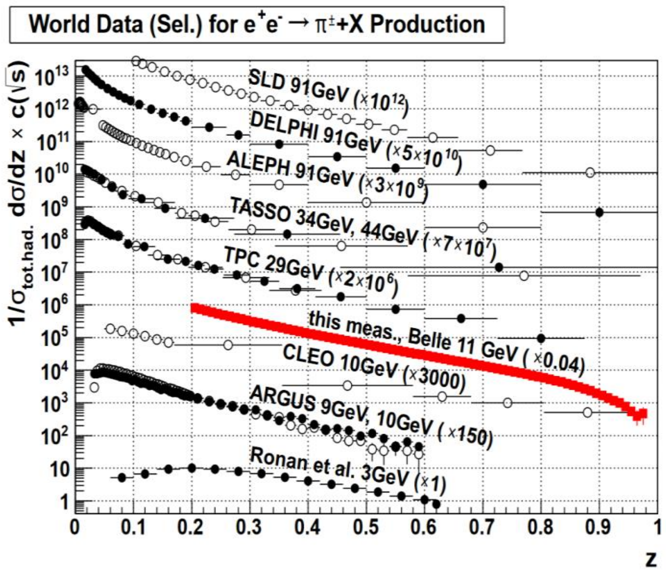
- e^+e^- experiments is the cleanest laboratory for the fragmentation function studies.
- FFs and PDF: Universal and non-perturbative objects
- Well known FFs are crucial for nucleon structure in ep experiments

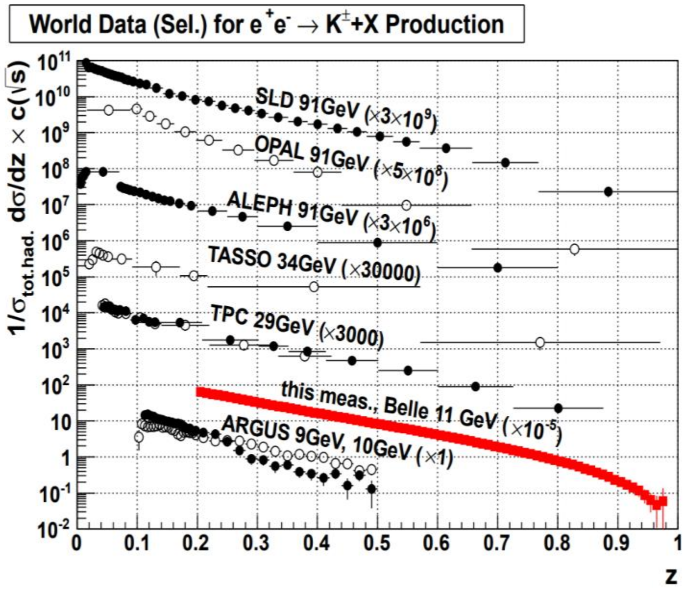
Word data from e^+e^- experiments

PDG



PRL 111 062002 (2013)

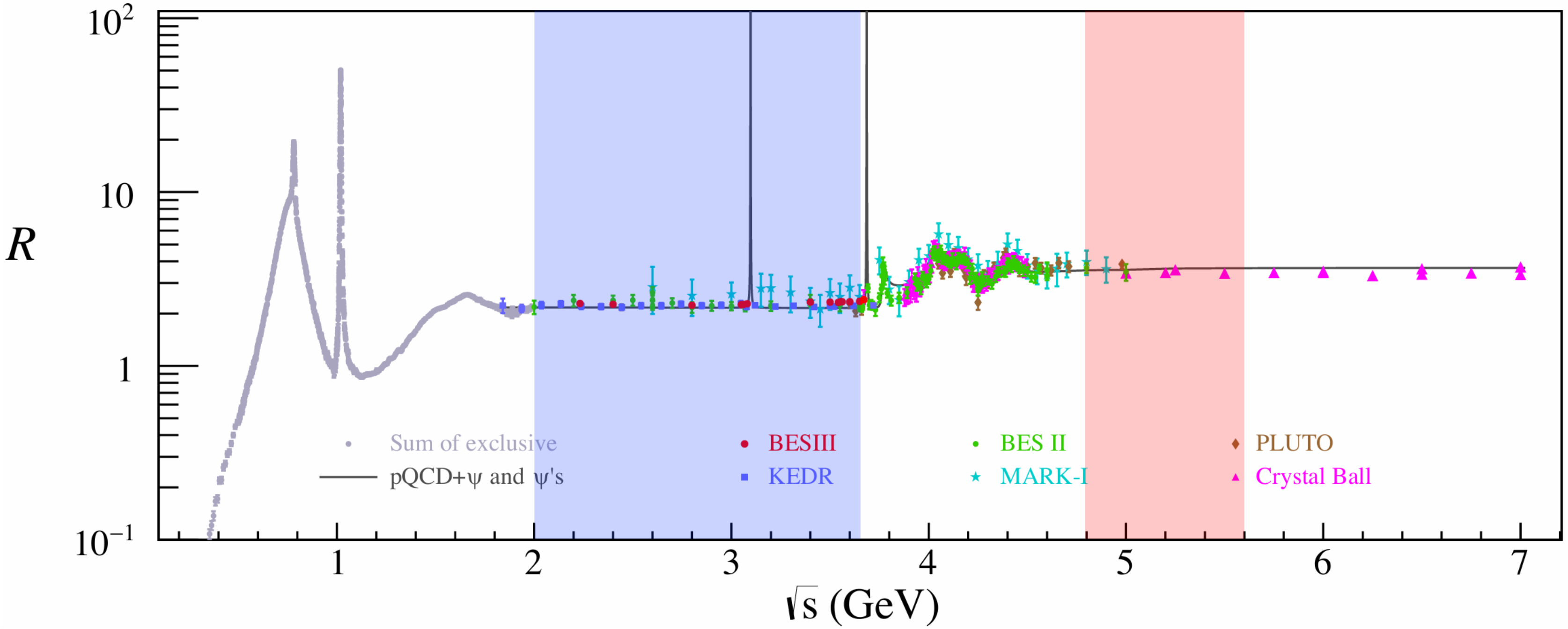


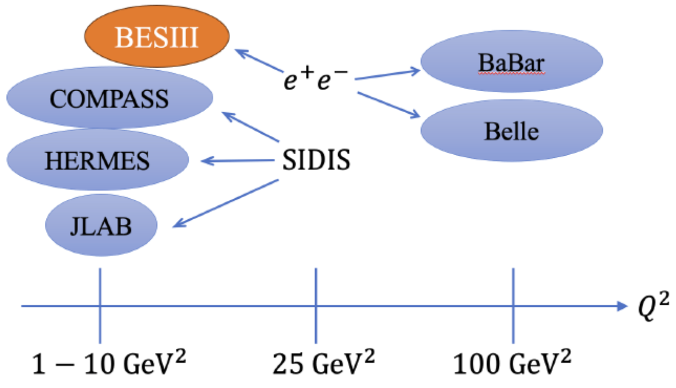


Lack of precise data @ $\sqrt{s} < 10$ GeV !

BESIII Data Sets

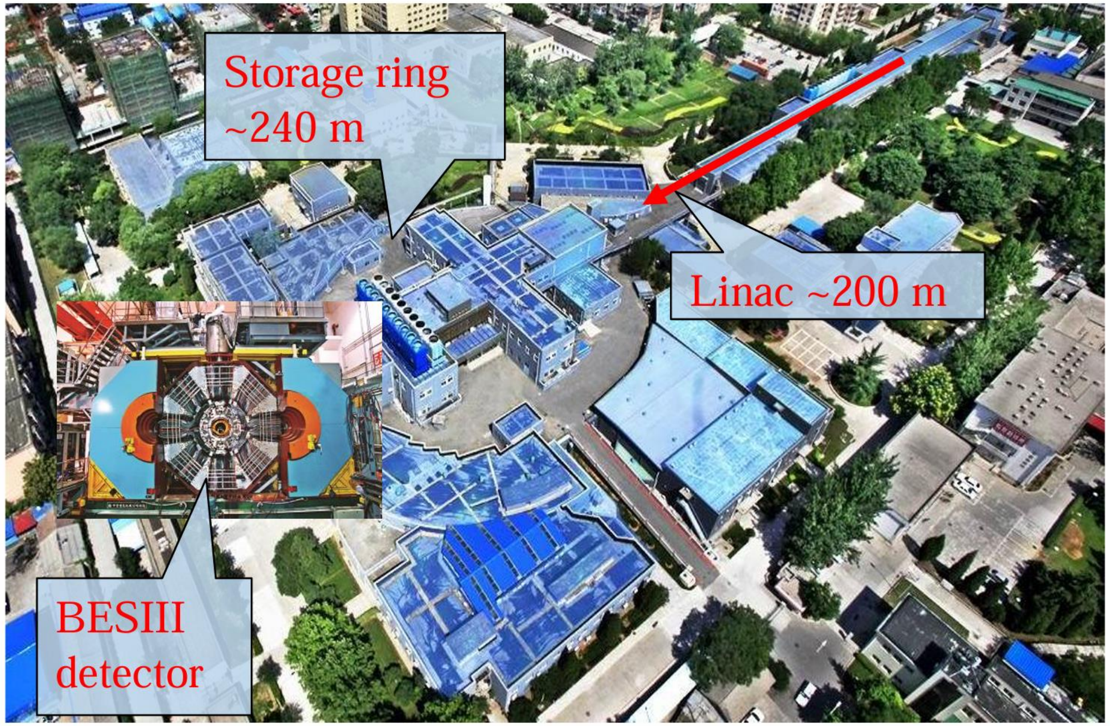
- **BESIII : 1.84-4.95 (5.6) GeV**

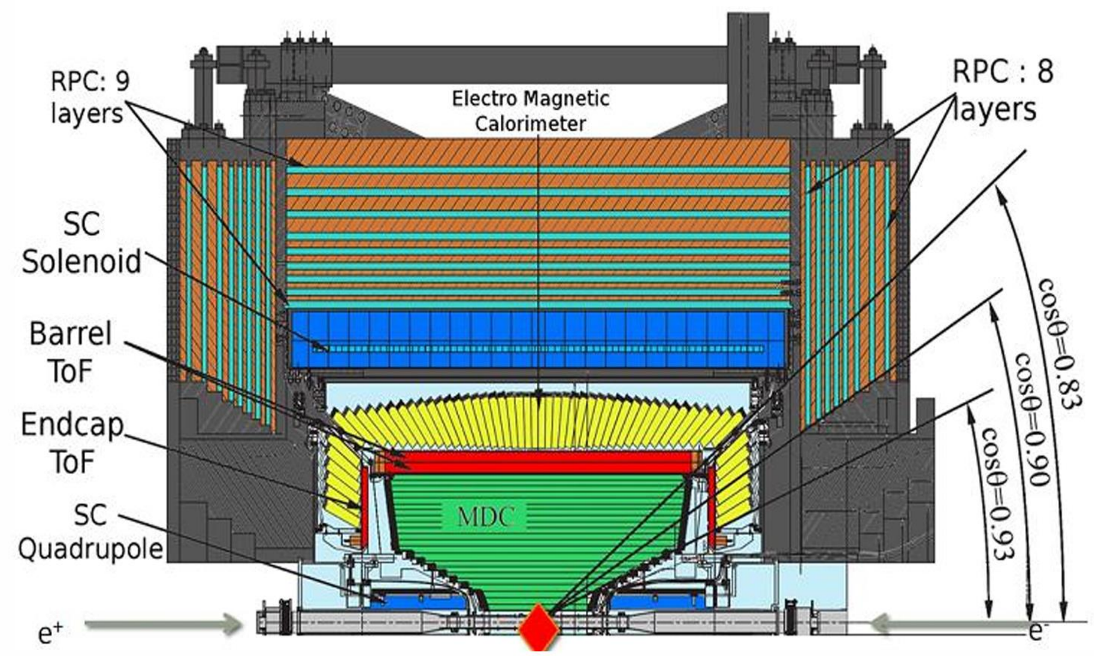




- **New opportunities at new energy scale with BESIII data**

BEPCII and BESIII





Double-ring, symmetry, multi-bunch e+ e- collider

E_{cm}= 1.84 to 4.9 GeV

Energy spread: $\Delta E \approx 5 \times 10^{-4}$

Peak luminosity in continuously operation @E_{cm}= 3.77 GeV: 1.1×10^{33} cm^{-2}s^{-1}

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): 65 ps
σ_T(endcap): 110 ps
(update to 60 ps with MRPC)

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

Accessing FFs in e^+e^- annihilation experiments

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

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

  - 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)

Analysis at BESIII

◆ Normalized differential cross-section:

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

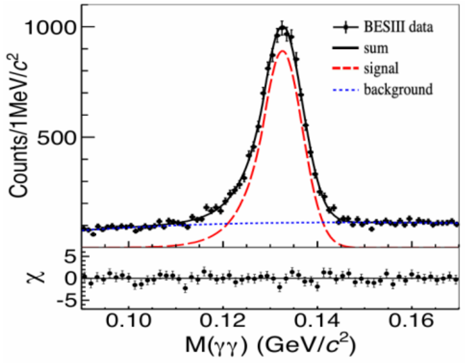
$$\frac{1}{\sigma_{had}}\frac{d\sigma(e^+e^-\to h+X)}{dp_h}=\frac{N_h}{N_{had}}\frac{1}{\Delta p_h}=\frac{N_h^{obs}}{N_{had}^{obs}}\frac{1}{\Delta p_h}f_h$$

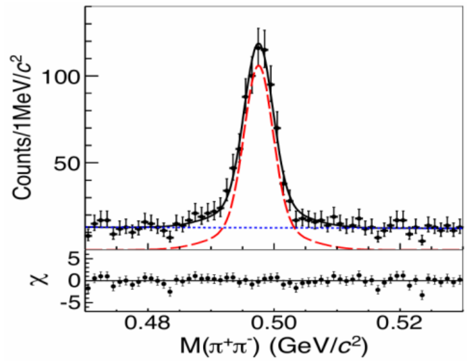
e^+e^- data

$e^+e^-\to q\bar{q}$ selection

$\pi^0/K_S^0/\eta/\pi^\pm/K^\pm$(photon, PID, second vertex fit)

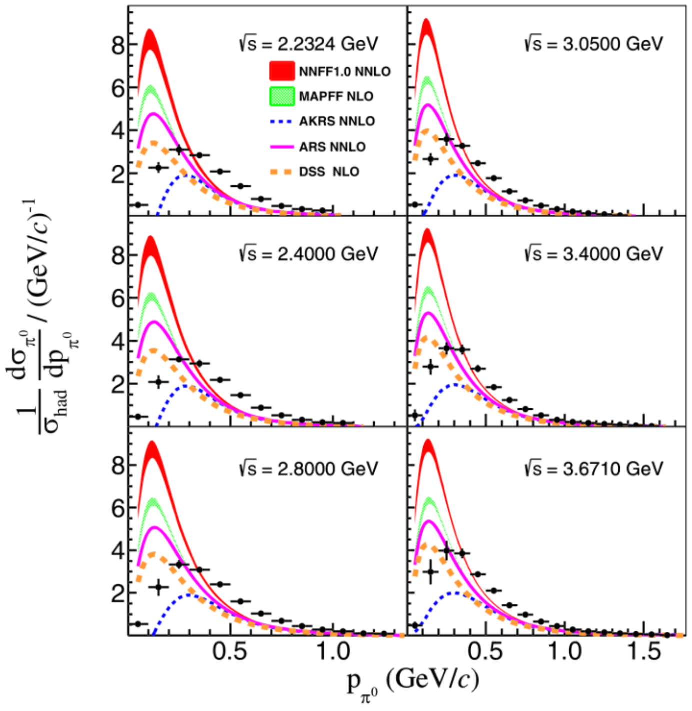
Efficient and ISR correction

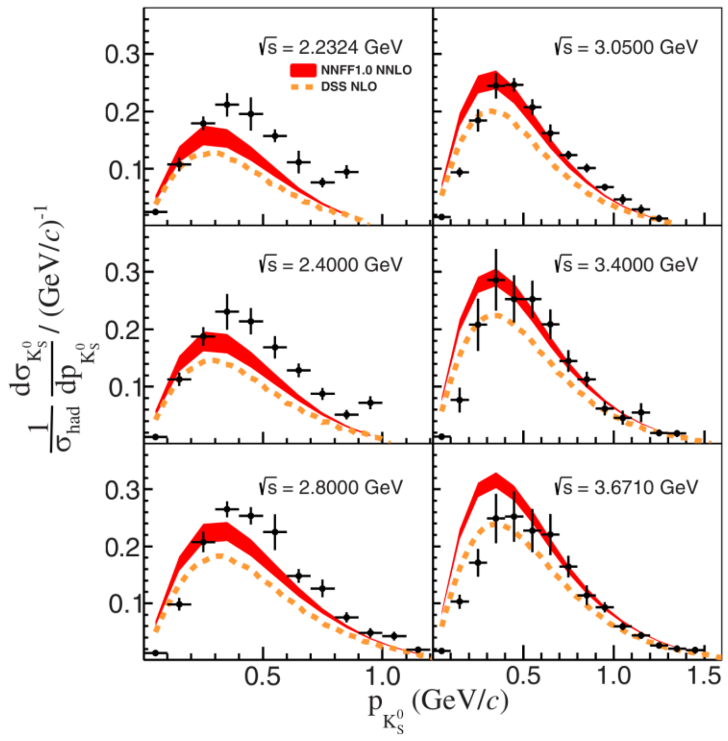




Inclusive production of π^0/K_S^0@ BESIII

[PRL 130, 231901 (2023)]

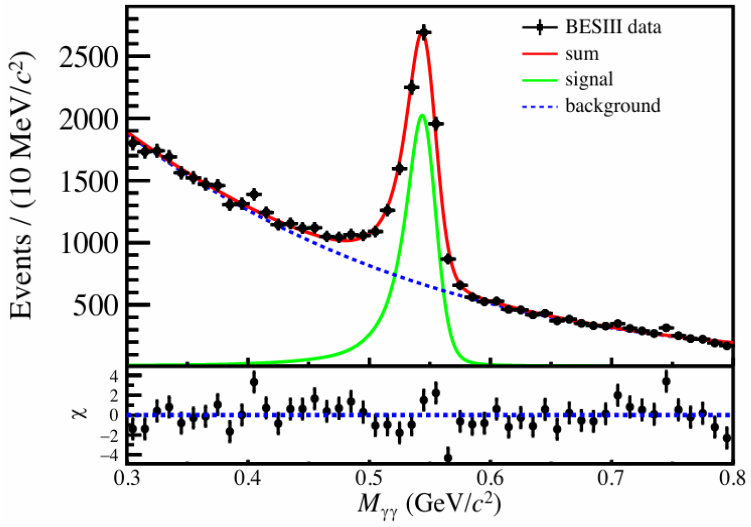


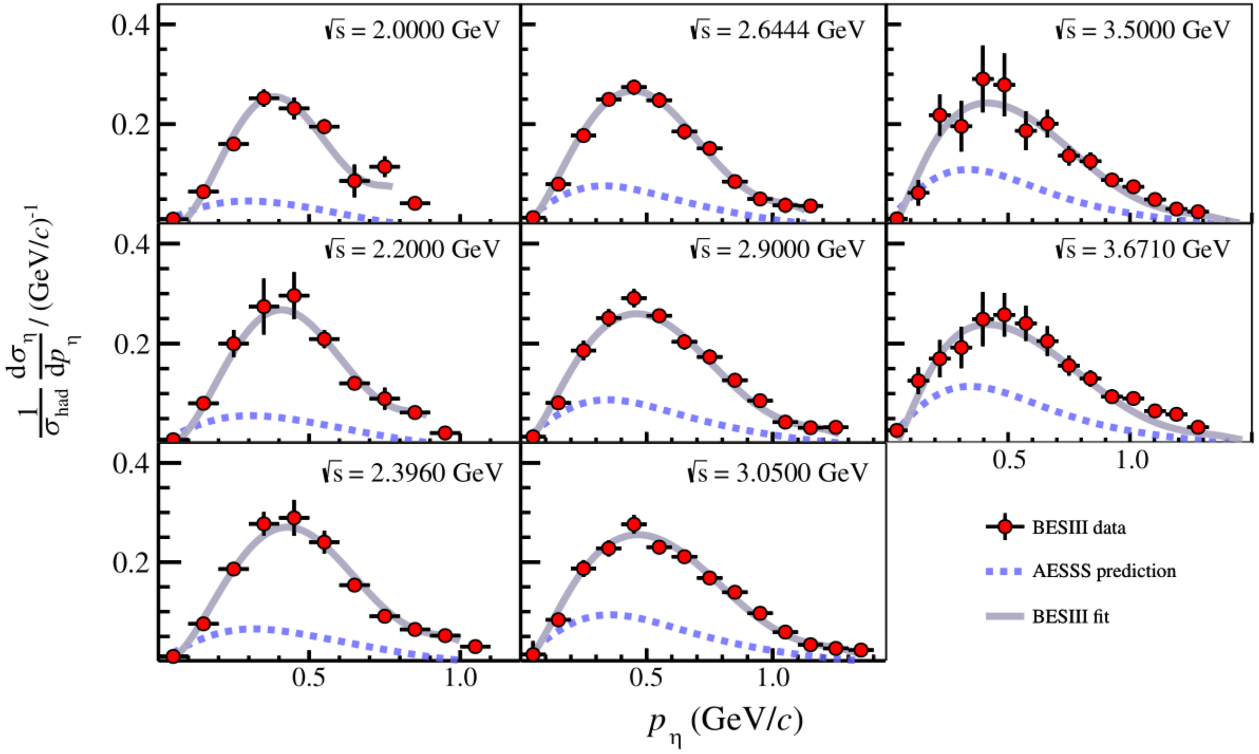


- Theory modes have different initial evolution scales and kinematic requirements on data
- Higher twits effect? Hadron mass effect?

Inclusive production of η@ BESIII

PRL 133, 021901 (2024)



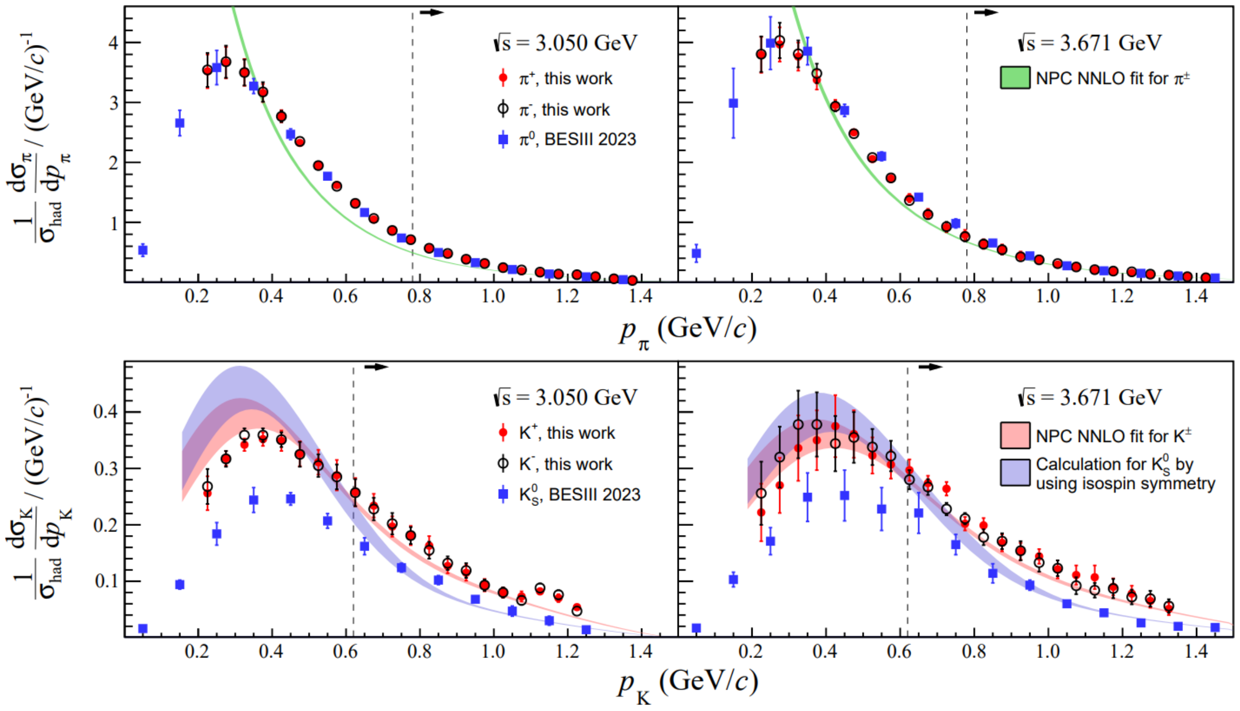


- BESIII fit: NNLO + hadron mass correction + high-twist

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

- $\pi^{\pm}$ is consistent with π^{0}.
- $K^{\pm}$ is systematically higher than that of K_S^0.
- New global data fit at NNLO under (NPC) framework ($\sqrt{s} >$ 3 GeV & $E_h >$ 0.8 GeV)

Phys. Rev. Lett. 135, 151901 (2025)



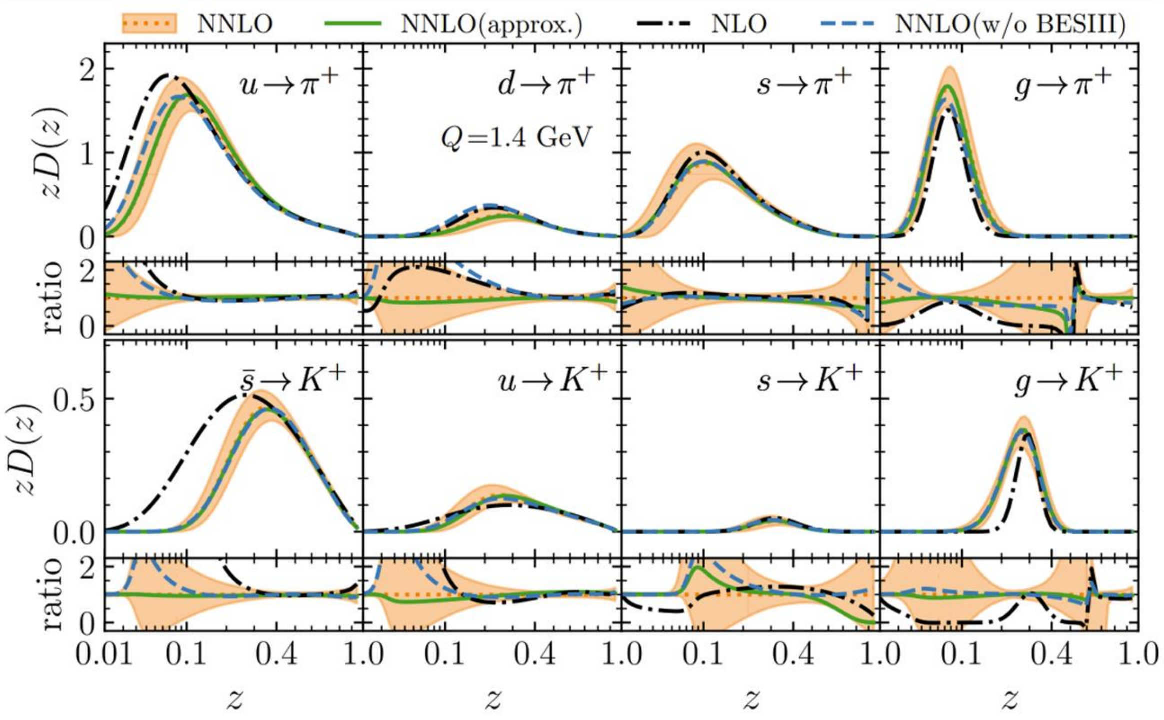
Global analysis with BESIII data

- FFs at NNLO with BESIII data

First university test of FFs at Q~ 3 GeV

exp.	$\sqrt{s}$/GeV	lum.(n_Z)	year	final states	hadrons
DELPHI	189	157.7 pb^{-1}	2002	inc. had.	$\pi^\pm$,$K^\pm$
OPAL	m_Z	780 000	1994	$Z\to q\bar{q}$	$\pi^\pm$,$K^\pm$
ALEPH	m_Z	520 000	1995	$Z\to q\bar{q}$	$\pi^\pm$, $K^\pm$
DELPHI	m_Z	1 400 000	1998	$Z\to q\bar{q}$	$\pi^\pm$,$K^\pm$
				$Z\to b\bar{b}$	$\pi^\pm$,$K^\pm$
SLD	m_Z	400 000	2004	$Z\to q\bar{q}$	$\pi^\pm$,$K^\pm$
				$Z\to b\bar{b}$	$\pi^\pm$, $K^\pm$
				$Z\to c\bar{c}$	$\pi^\pm$,$K^\pm$
TASSO	44	34 pb^{-1}	1989	inc. had.	$\pi^\pm$, π^0
TASSO	34	77 pb^{-1}	1989	inc. had.	$\pi^\pm$,$K^\pm$
TPC/2γ	29	70 pb^{-1}	1988	inc. had.	$\pi^\pm$,$K^\pm$
Belle	10.52	68 fb^{-1}	2013	inc. had.	$\pi^\pm$, $K^\pm$
BaBar	10.54	0.91 fb^{-1}	2013	inc. had.	$\pi^\pm$,$K^\pm$
BESIII	2.0-3.671	253 pb^{-1}	2025	inc. had.	$\pi^\pm$, $K^\pm$

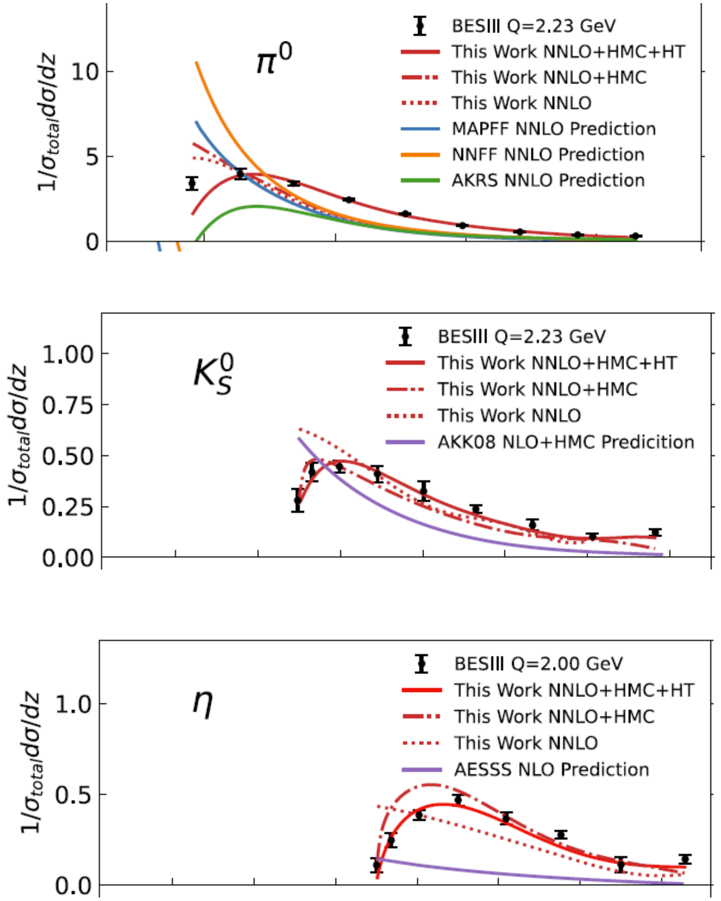
[Gao, **XS**, Xing, Zhao, Zhou, ***PRL 135, 041902***, 2025]

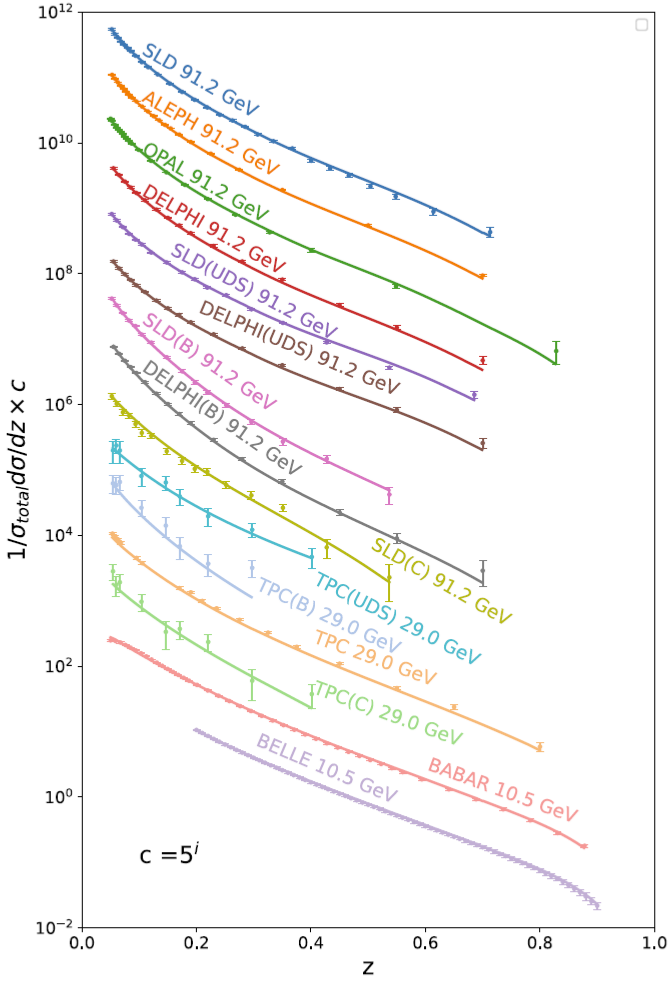


Global analysis with BESIII data

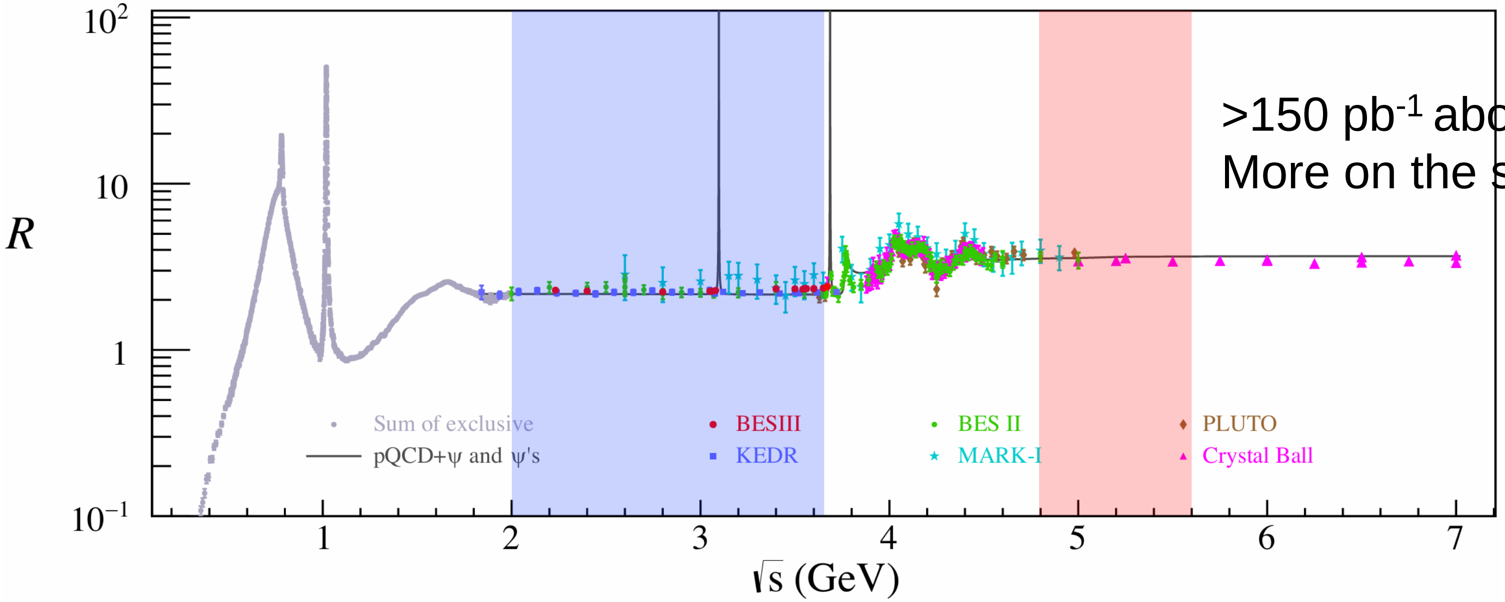
- FFs at NNLO with BESIII data can explain both existing high-energy world data and the BESIII new measurements

Exp (π^0)	$\sqrt{s}$ [GeV]	N_{dp}	χ^2/N_{dp}
L3 [61]	91.2	3	0.82
L3 [62]	91.2	12	2.27
OPAL [60]	91.2	10	0.60
ALEPH [58]	91.2	21	1.83
ALEPH [59]	91.2	13	2.53
JADE [57]	44.0	7	1.60
JADE [57]	35.0	10	3.09
CELLO [54]	35.0	8	0.64
TASSO [52]	34.6	7	1.47
JADE [56]	34.4	10	1.17
TASSO [51]	34.0	4	2.51
CELLO [53]	34.0	7	0.34
TPC [55]	29.0	10	1.29
JADE [56]	22.5	5	1.79
CELLO [53]	22.0	7	1.41
CELLO [53]	14.0	6	2.39
JADE [56]	14.0	6	1.77
TASSO [51]	14.0	4	1.62
ARGUS [50]	9.46	13	1.47
BESIII [9]	3.67	16	2.23
BESIII [9]	3.40	15	0.65
BESIII [9]	3.05	14	1.77
BESIII [9]	2.80	13	0.53
BESIII [9]	2.40	10	1.41
BESIII [9]	2.23	9	4.73
TOTAL		568	1.09





Further Measurements @ BESIII



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

Collinear FFs D_1^h

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

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

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

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

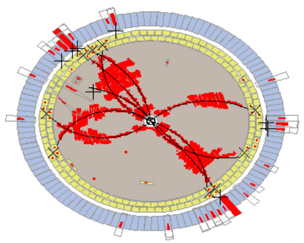
$e^+e^- \to \Sigma + X$

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

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

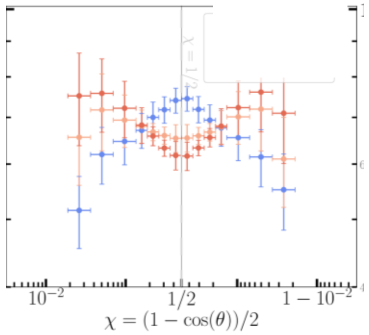
$e^+e^- \to \eta/K^\pm/K_S^0 + X$

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



EECs

E1C
E2C
TMD EEC
…



Many results will be ready soon

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 and have good constrains on FFs.
  - $\boldsymbol{e^+e^- \to \pi^0/K_S^0 + X}$
  - $\boldsymbol{e^+e^- \to \eta + X}$
  - $\boldsymbol{e^+e^- \to \pi^\pm/K^\pm + X}$

Thanks for your attention!

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

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

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

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

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

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

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

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

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

E1C
E2C
TMD EEC
…

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Backup