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Experimental study of fragmentation functions at BESIII

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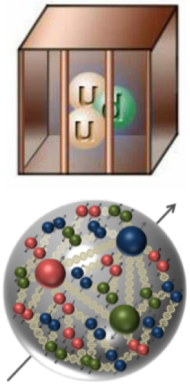
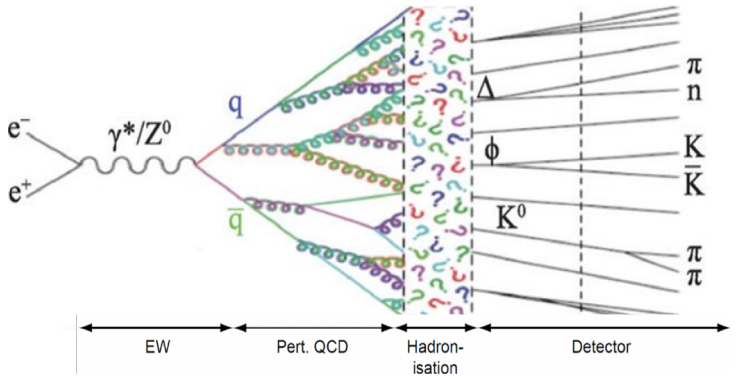
Several open questions about QCD and FF

- **Confinement**, no existing isolated quarks or gluons
- **Nucleon structure**, what is the origin of nucleon spin and mass in terms of quarks and gluons degree of freedom



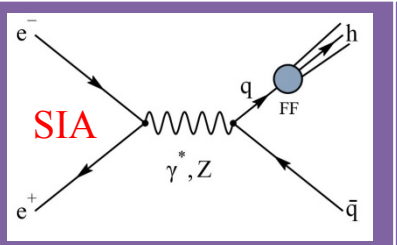
Fragmentation Functions (FFs):



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

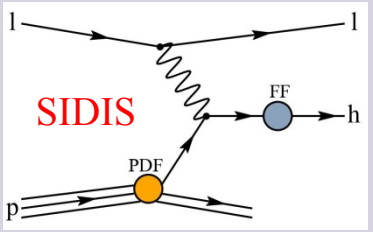
- ✓ Helps us understand the mechanism of color confinement.
- ✓ Extract accurately Parton Distribution Functions (PDFs).

Access FFs with QCD factorization



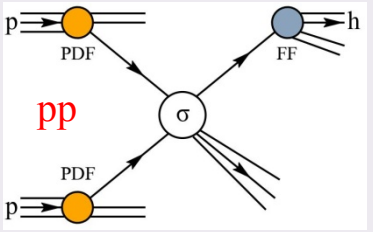
e^+e^-: $\sigma = \sum_q \sigma(e^+e^- \to q\bar{q}) \otimes FF$

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



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

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



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

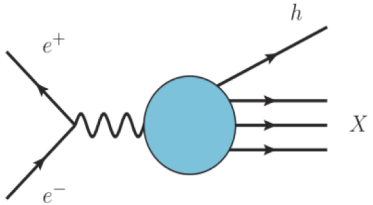
- Depend on unpolarized PDFs
- Leading access to gluon FF
- Parton momenta not directly known

- SIA @ e^+e^-: the cleanest input for FFs fitting

FFs @ e^+e^- Experment

Leading Quark TMDFFs — Hadron Spin, Quark Spin

		Quark Polarization		
		Un-Polarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Unpolarized (or Spin 0) Hadrons		D_1 = Unpolarized		$H_1^\perp$ = Collins
Polarized Hadrons	L		G_1 = Helicity	$H_{1L}^\perp$ =
	T	$D_{1T}^\perp$ = Polarizing FF	$G_{1T}^\perp$ =	H_1 = Transversity $H_{1T}^\perp$ =



Experimental observable

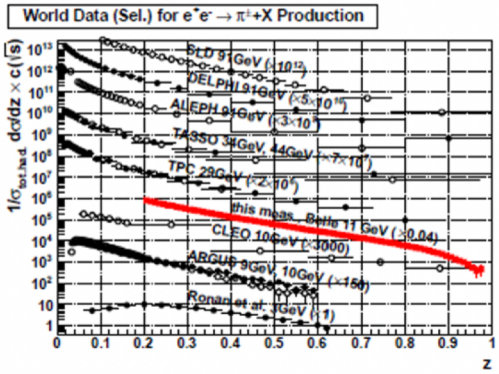
$$\frac{1}{\sigma_{had,tot}}\frac{d\sigma_h}{dz}$$

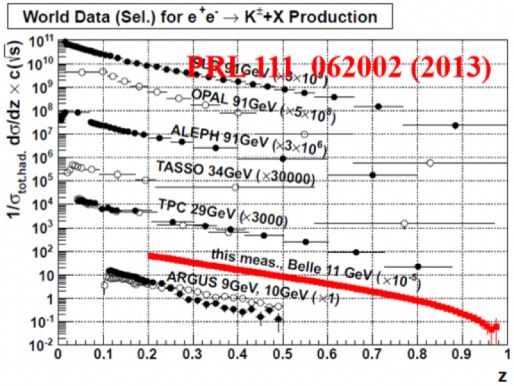
Leading order

- ✓ $e^+e^- \to hX \sim \sum_q e_q^2 \boldsymbol{D_1^{h/q}}(z)$
- ✓ $e^+e^- \to q\bar{q} \to h_1 h_2 X$

  $\sim \cos(2\phi_0)\, \boldsymbol{H_1^\perp(z_1) \otimes H_2^\perp(z_2)}$

World π 、 K & η data @ e^+e^-





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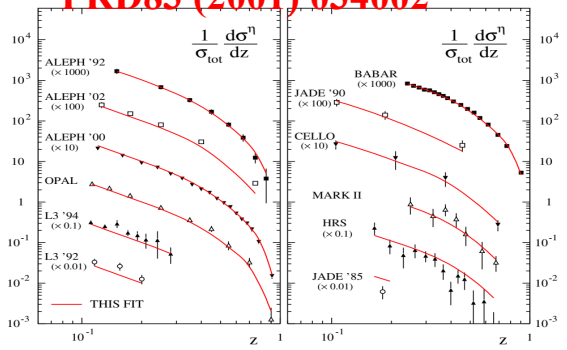
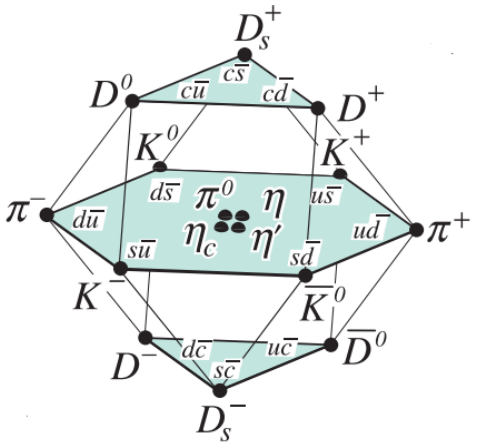
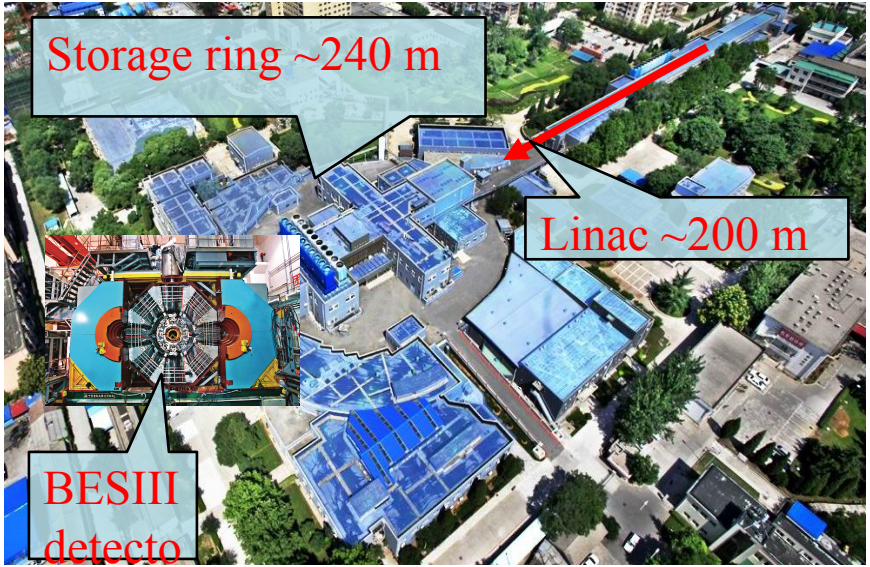
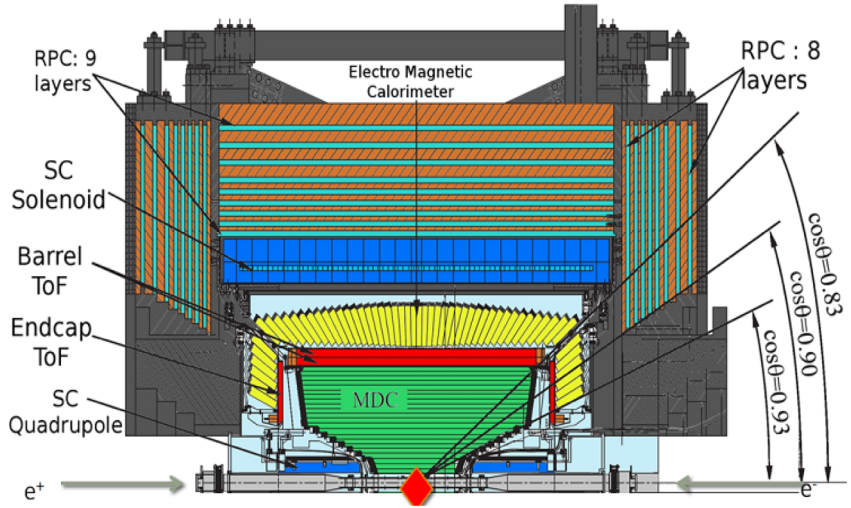


- Precision data includes charged π, K
- Data sets at $\sqrt{s} < 10$ GeV e^+e^- collision ?
  - high z data sets ?
- R scan data @ BESIII: ~10 pb^{-1} @ each $\sqrt{s}$



BEPCII/BESIII





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

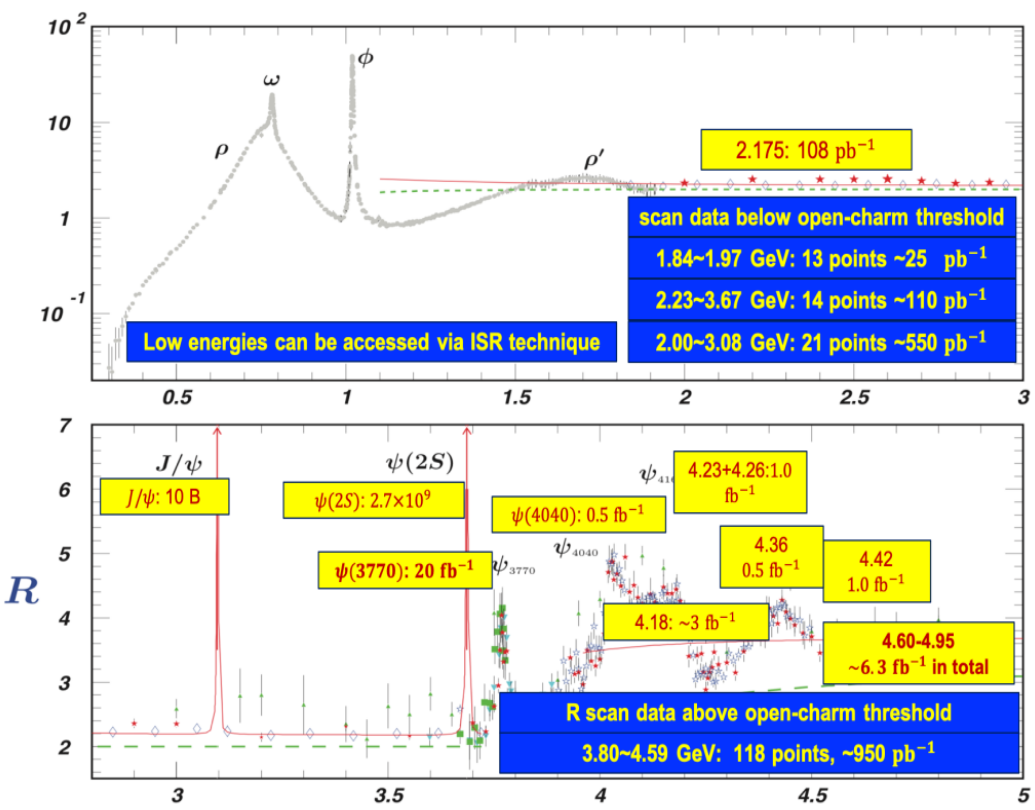
E_{cm}= 1.84 to 4.95 GeV

Energy spread: $\Delta E \approx 5\times10^{-4}$

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

Main Drift Chamber	Time Of Flight	Electromagnetic Calorimeter	Muon Counter
Small cell, 43 layer	Plastic scintillator	CsI(Tl): L=28 cm	RPC
σ_{xy}=130 μm	σ_T(barrel): 65 ps	Barrel σ_E=2.5%	Barrel: 9 layers
dE/dx~6%	σ_T(endcap): 110 ps (update to 60 ps with MRPC)	Endcap σ_E=5.0%	Endcap: 8 layers
σ_p/p= 0.5% at 1 GeV			$\sigma_{spatial}$: 1.48 cm

Data samples collected at BESIII



Data sets collected so far include:

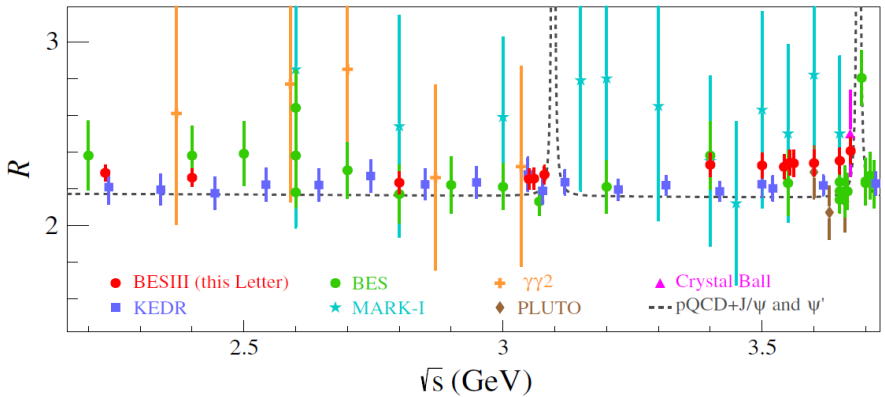
- 10×10^9 J/ψ events
- 2.7×10^9 ψ' events
- Scan data [2.0, 3.08] GeV; [3.735, 4.600] GeV, 130 energy points, about 2.0 fb^{-1}
- Large data sets for XYZ study above 4.0 GeV about 22 fb^{-1}

Analysis at BESIII

- Normalized differential cross section (take h as an example):

$$\frac{1}{\sigma_{\mathbf{had}}}\frac{d\sigma_h}{dp_h} = \frac{N_h}{N_{\mathbf{had}}}\frac{1}{\Delta p_h} f$$

- Hardronic events $N_{\mathbf{had}}$: $R \equiv \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$



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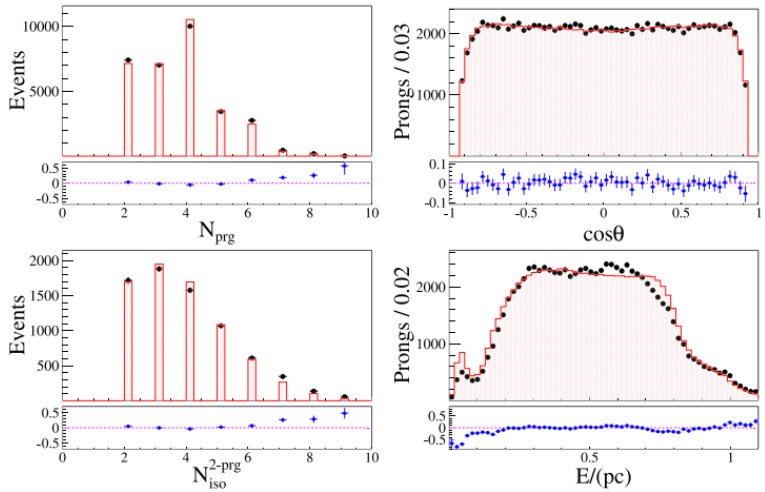
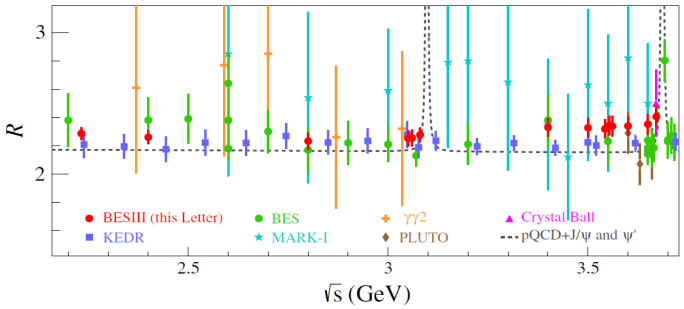


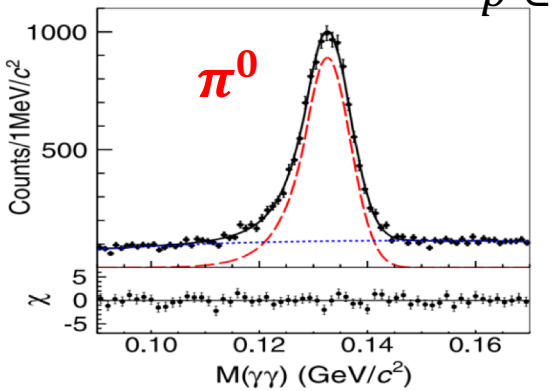
LUARLW MC generator

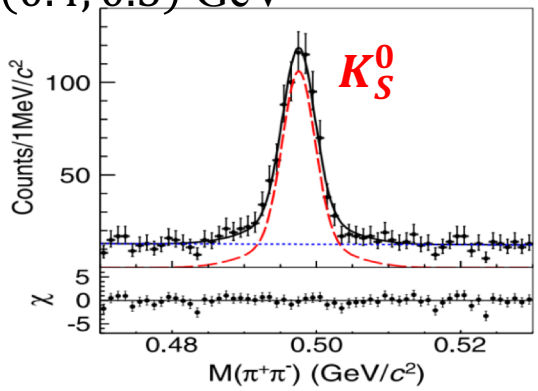
Inclusive π^0/K_S^0 production

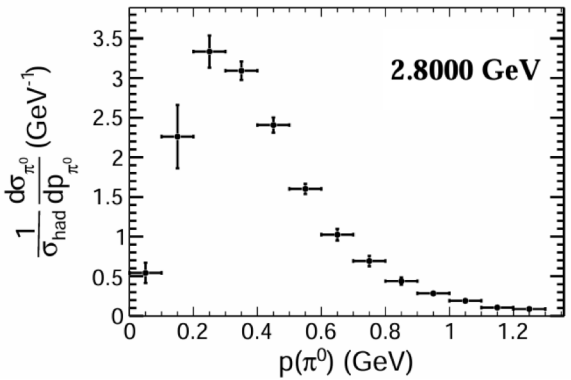


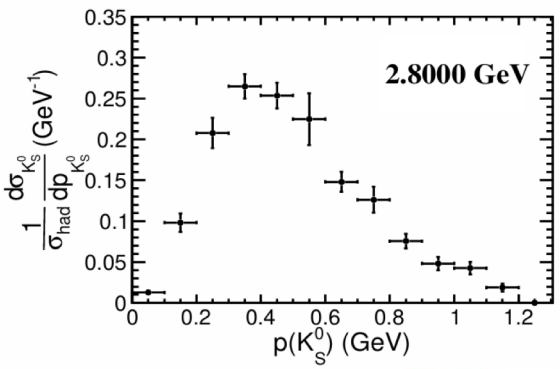
$\sqrt{s}$ (GeV)	$\mathcal{L}$ (pb^{-1})	$N_{\rm had}^{\rm tot}$	$N_{\rm bkg}$
2.2324	2.645	83227	2041
2.4000	3.415	96627	2331
2.8000	3.753	83802	2075
3.0500	14.89	283822	7719
3.4000	1.733	32202	843
3.6710	4.628	75253	6461

$p \in (0.4, 0.5)$ GeV









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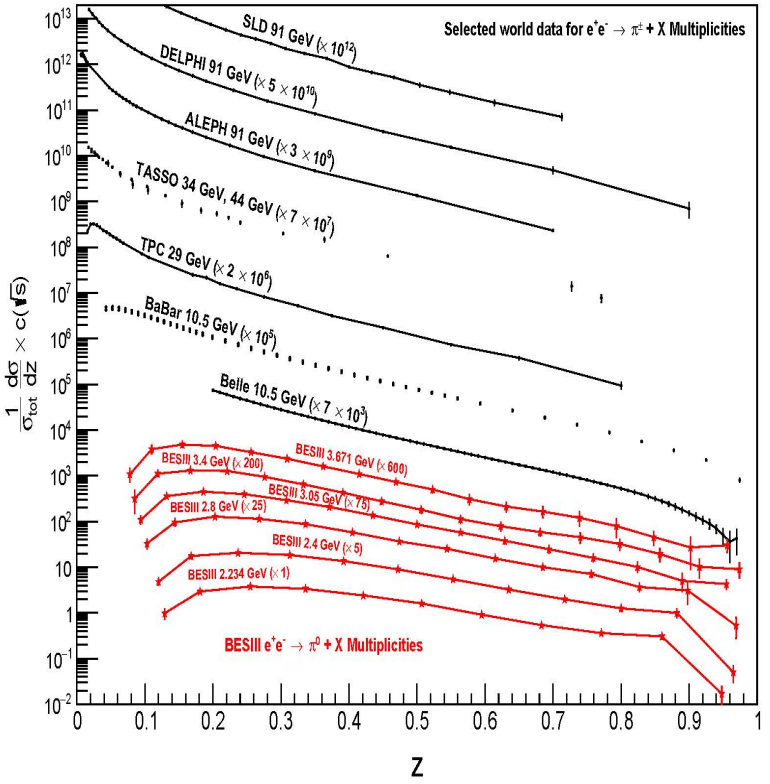
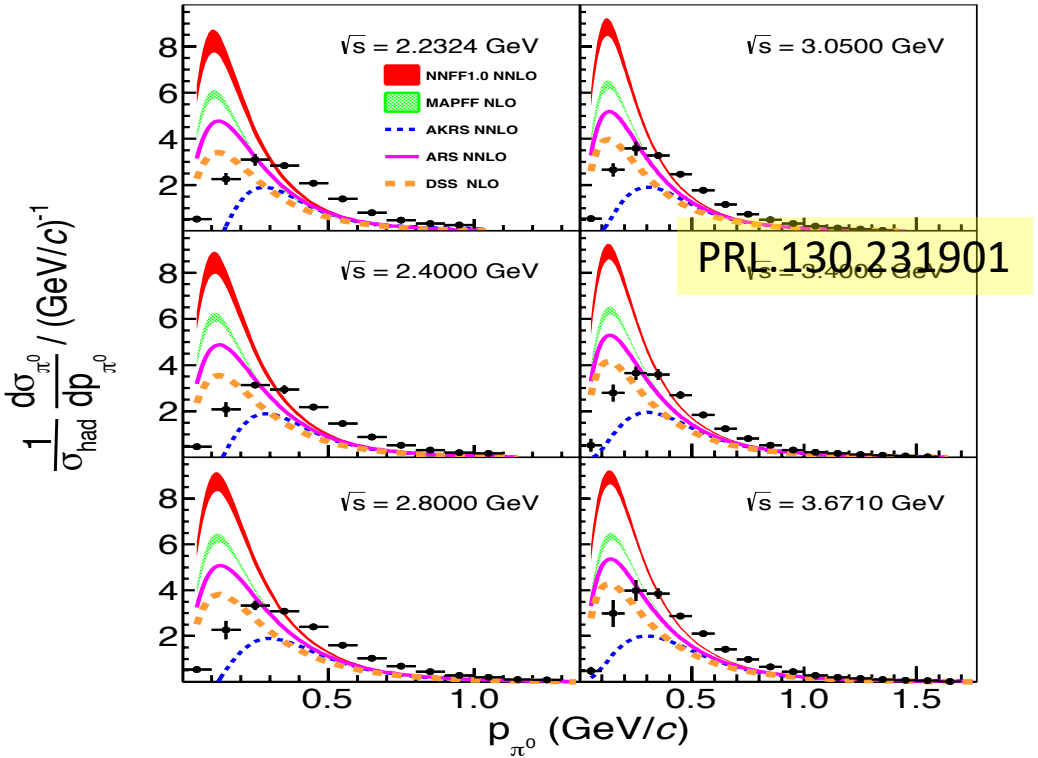
Results: inclusive π^0

Theory support: Hongxi Xing, Daniele Anderle

Compared with theoretical estimation





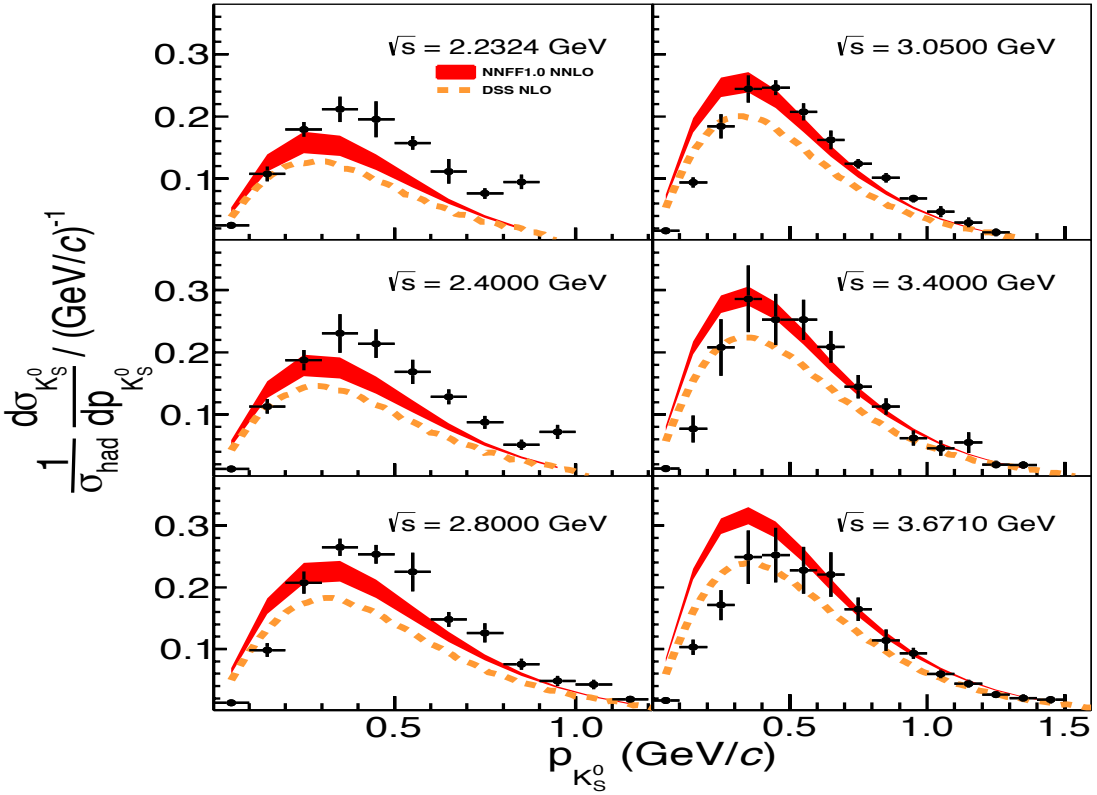
PRL 130 231901

Uncertainties ~ less 10%

Results: Inclusive K_s^0

Compared with theoretical estimation

Theory support: Hongxi Xing, Daniele Anderle



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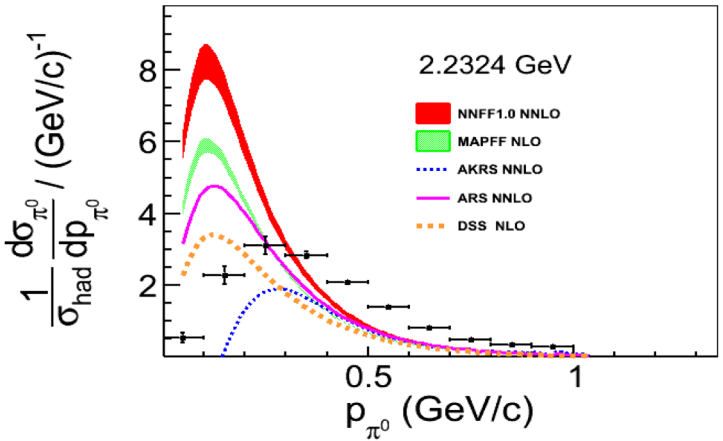
Results: inclusive π^0/K_s^0

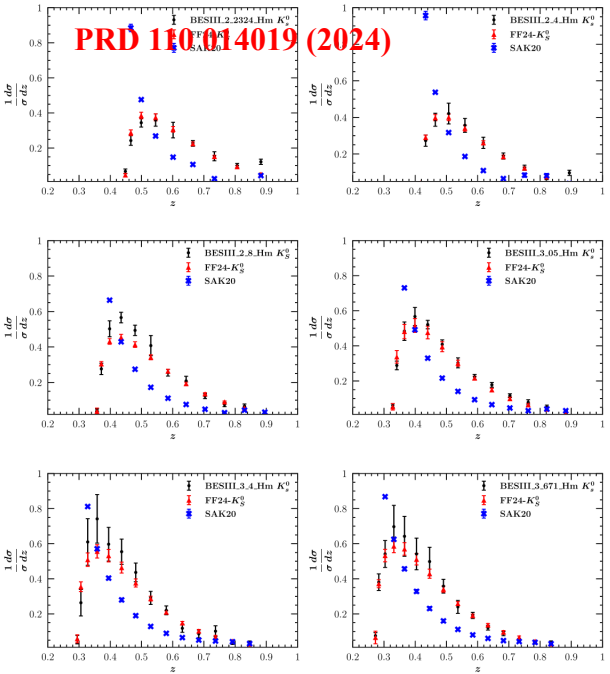


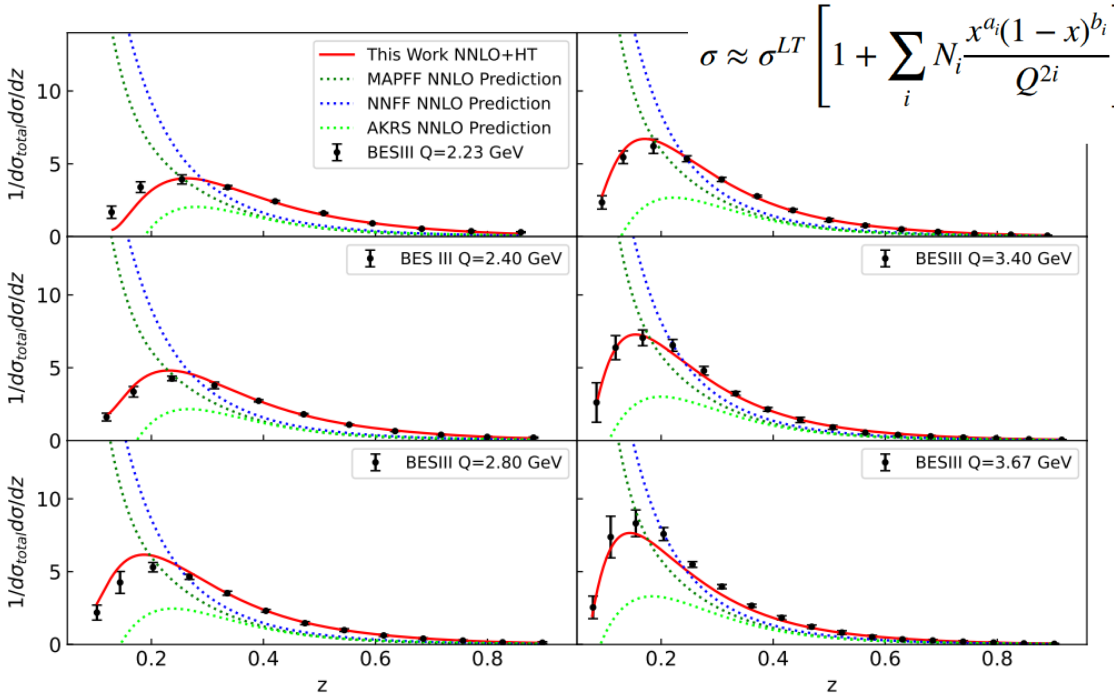
PRL 130 231901(2023) BESIII

- From theory side: fitting with BESIII data, hadron mass effect, large *z* re-summation, and so on
- From experimental side
  - Primary hadron vs from resonance decay
    $\Longrightarrow$ measure $e^+ e^- \rightarrow \rho(\omega, \phi) + X$, and so on
  - Contribution of vector states ρ^*, ω^* and ϕ^*
    $\Longrightarrow e^+ e^- \rightarrow \rho^*/\omega^*/\phi^* \rightarrow h + X$

Results: inclusive π^0 / K_S^0

theory

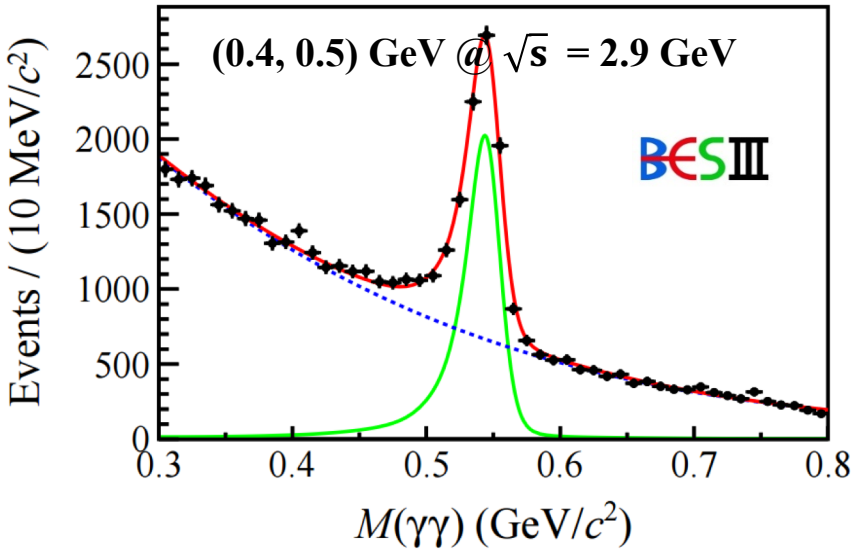


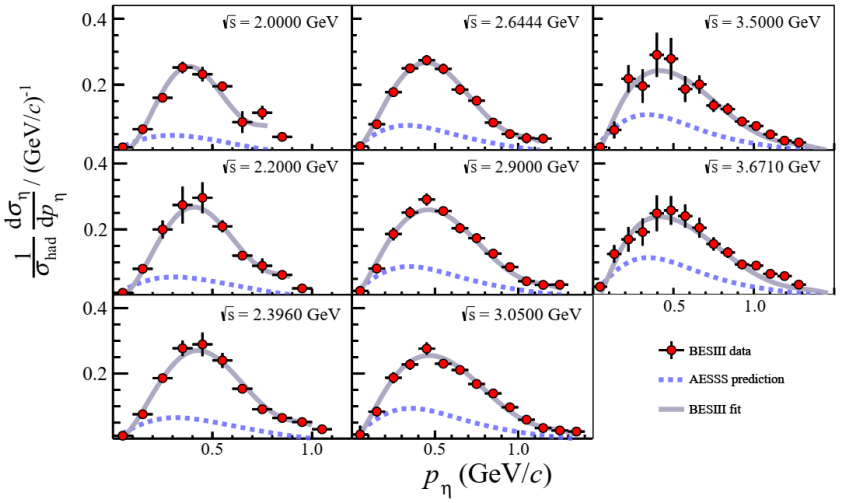


$$\sigma \approx \sigma^{LT}\left[1+\sum_i N_i \frac{x^{a_i}(1-x)^{b_i}}{Q^{2i}}\right]$$

- PRD 110 014019 (2024): NNLO & hadron mass correction for K_S
- arXiv:2404.11527: NNLO & higher twist contribution for π^0

Inclusive η production





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$$\sigma \approx \sigma^{LT}\left[1+\sum_i N_i \frac{x^{a_i}(1-x)^{b_i}}{Q^{2i}}\right]$$

- PRD83 (2001) 034002 prediction vs. BESIII data: tension !

BESIII fit: detail @ Phys. Rev. D 111, 034030 (2025)

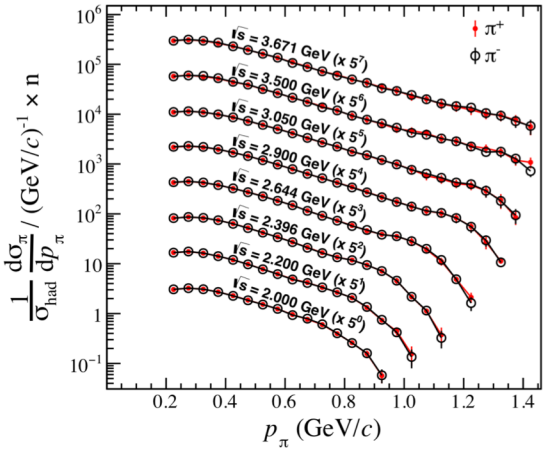
- $\sqrt{s}$ > 10GeV e^+e^- data + BESIII data
- NNLO accuracy, hadron mass correction & higher twist contributions

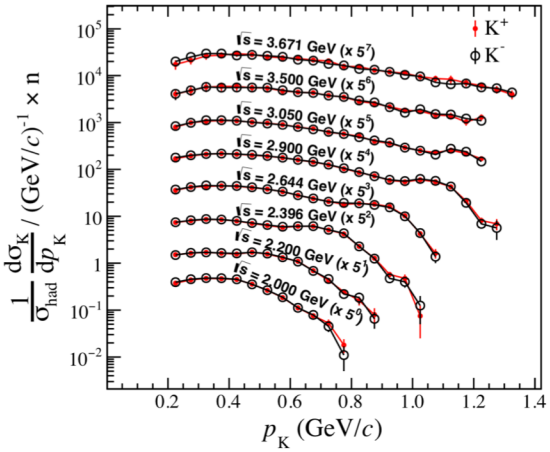
Inclusive $\pi^{\pm}/K^{\pm}$ production

arXiv: 2502.16084

TABLE I. The integrated luminosities and the numbers of total selected hadronic and residual background events in different c.m. energies.

$\sqrt{s}$ (GeV)	$\mathcal{L}$ (pb^{-1})	$N_{\rm had}^{\rm tot}$	$N_{\rm bkg}$
2.0000	10.074	350298 ± 592	8722 ± 94
2.2000	13.699	445019 ± 668	10737 ± 104
2.3960	66.869	1869906 ± 1368	47550 ± 219
2.6444	33.722	817528 ± 905	21042 ± 146
2.9000	105.253	2197328 ± 1483	56841 ± 239
3.0500	14.893	283822 ± 533	7719 ± 88
3.5000	3.633	62670 ± 251	1691 ± 42
3.6710	4.628	75253 ± 275	6461 ± 81

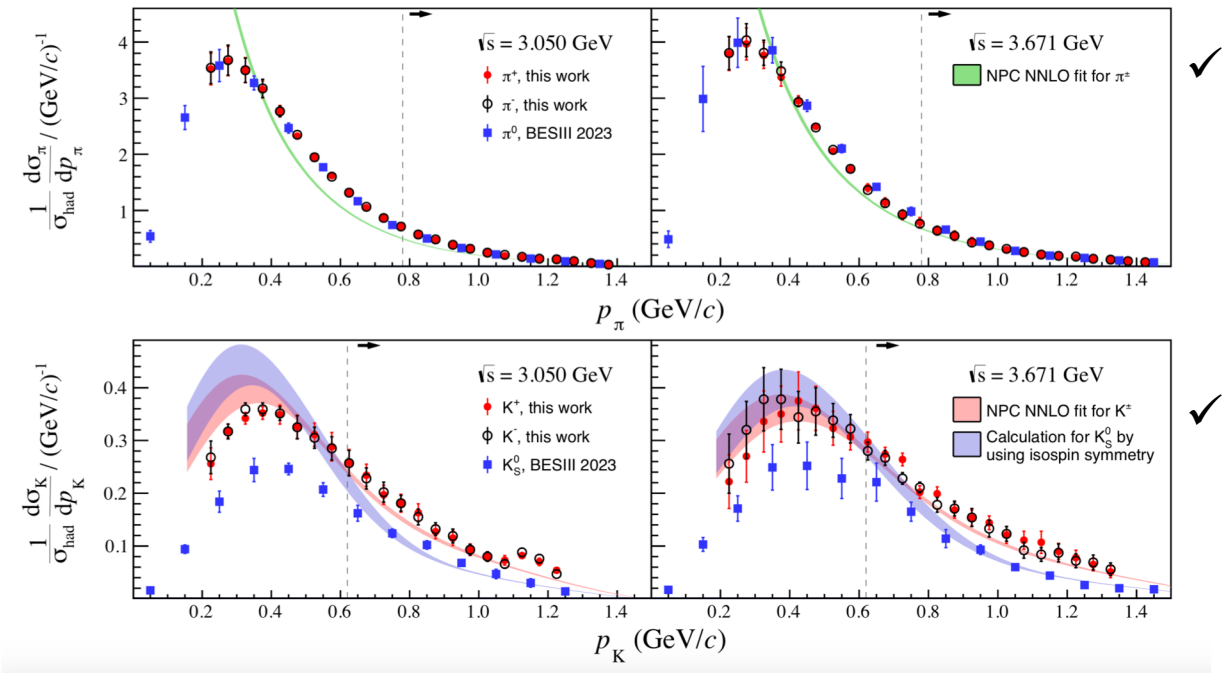




- ✓ Center-of-mass energies: 2.0 – 3.671 GeV, 8 energy points
- ✓ z coverage: 0.13 to 0.95 for $\pi^{\pm}$, 0.30 to 0.95 for $K^{\pm}$
- ✓ Highest experimental precision ~ 1(2)% at z ~ 0.3 – 0.5 for $\pi^{\pm}$ and $K^{\pm}$

Inclusive $\pi^{\pm}/K^{\pm}$ production

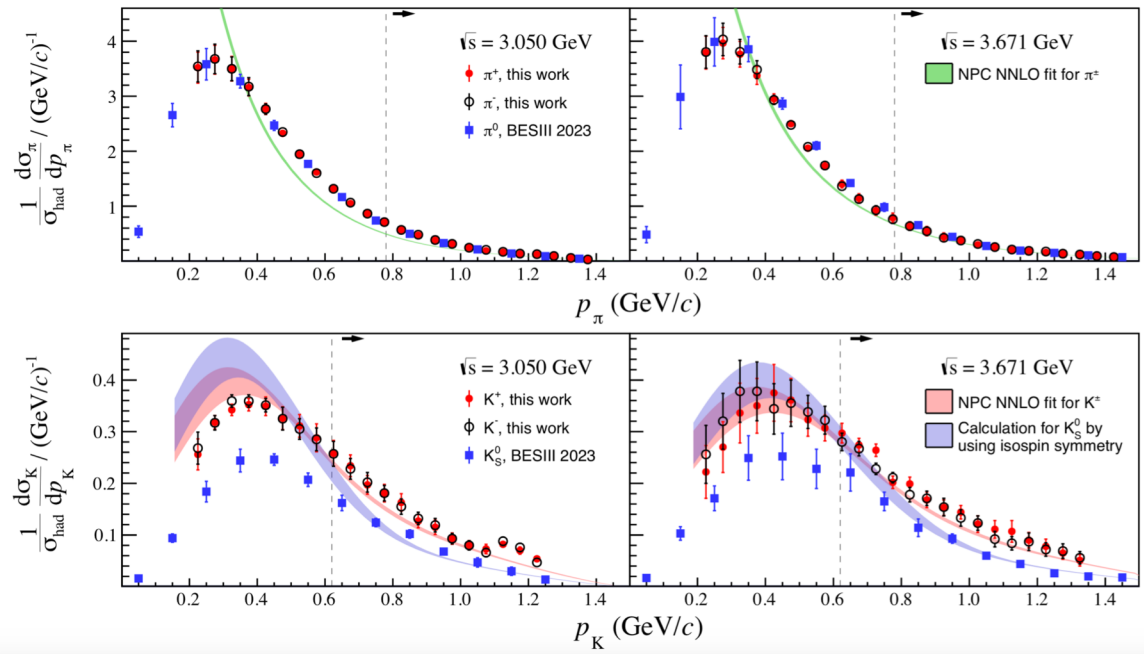
arXiv: 2502.16084



- ✓ The measured $\pi^{\pm}$ cross sections are consistent with the previously reported π^0 cross-sections by BESIII
- ✓ The $K^{\pm}$ cross sections are systematically higher than the K_S^0 cross sections by a factor of approximately 1.4.

Results: inclusive $\pi^{\pm}/K^{\pm}$

arXiv: 2502.16084



- $\sqrt{s}$ > 3.0 GeV, E_h > 0.8 GeV
- Charge conjugation symmetry and flavor symmetries among favored (unfavord) quark FFs assumed
- s quark FF shares the same shape as the $\bar{u}$ quark FF

$$D_i^{\pi^0} = \frac{1}{2}\left(D_i^{\pi^+} + D_i^{\pi^-}\right)$$
$$D_q^{K_S^0} = \frac{1}{2}\left(D_{q'}^{K^+} + D_{q'}^{K^-}\right)$$

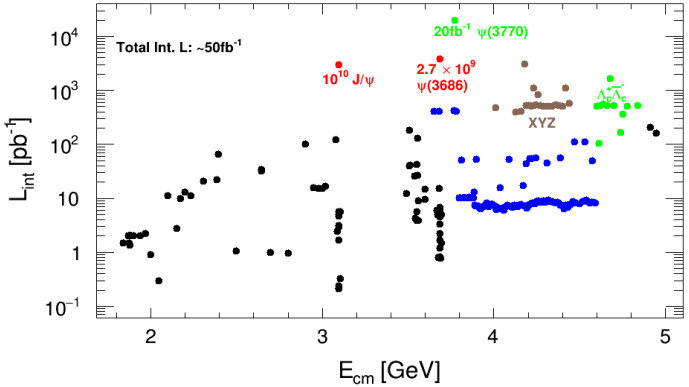
✓ Consistent with NPC fit results

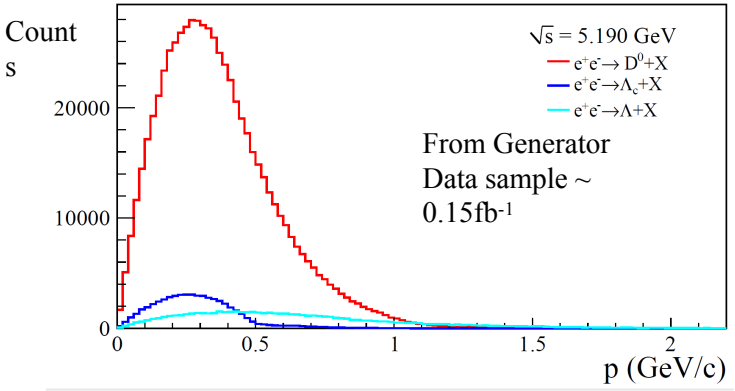
✓ Support isospin symmetry of $K^{\pm}$ and K_S^0

Prospects of FFs at BESIII

- **Higher center-of-mass energy**
  - Broader hard scale Q coverage
  - heavy flavors: Λ, D^0
  - Hadron mass correction is smaller

- **High luminosity**
  - From exploratory to precision measurements
  - Multi-dimensional binning of the measurements
    - Currently mainly on z and Q^2, P_t of hadron is crucial (now with Gaussian assumption)





Summary

- The knowledge of FFs is an important ingredient in our understanding of non-perturbative QCD dynamics. e^+e^- annihilation experiments provide the cleanest environment to measure FFs.
- Two types of fragmentation functions can be studied at BEPCII/BESIII
  - ➢ Unpolarized fragmentation function
    - ✓ Unique Q<10 GeV data
    - ✓ More results from Λ, Σ
  - ➢ Collins fragmentation function
    - ✓ Essential input in the 3D imaging era of the nucleon structure study
    - ✓ More results from $K\pi + X$ and $KK + X$

Thanks