Experimental study of fragmentation functions at BESIII

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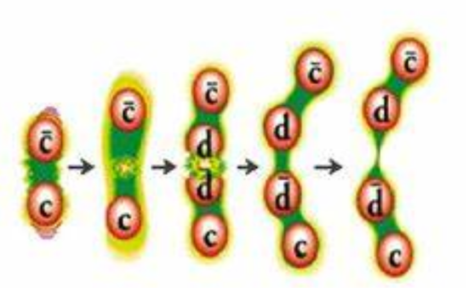
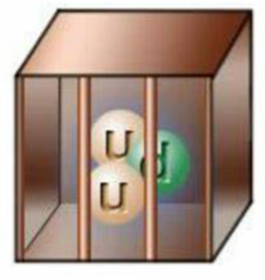
国家重点研发项目"粲强子衰变和标准模型的精确检验"2025年夏季年会

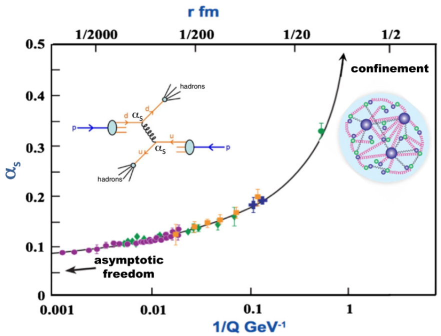
Several open questions about QCD

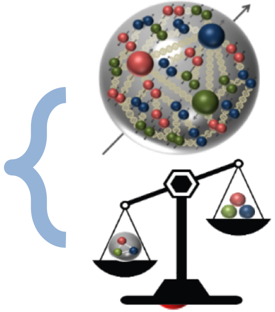
- **<u>Confinement</u>**, no existing isolated quarks or gluons





- **<u>Nucleon structure</u>**, what is the origin of nucleon spin and mass in terms of quarks and gluons degree of freedom

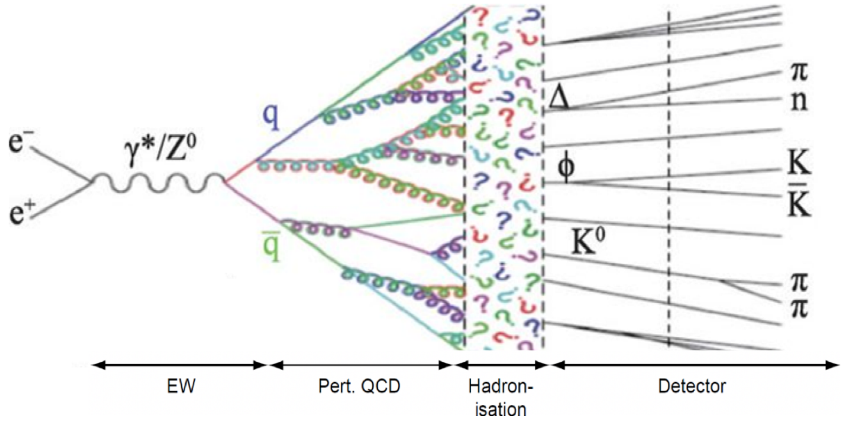


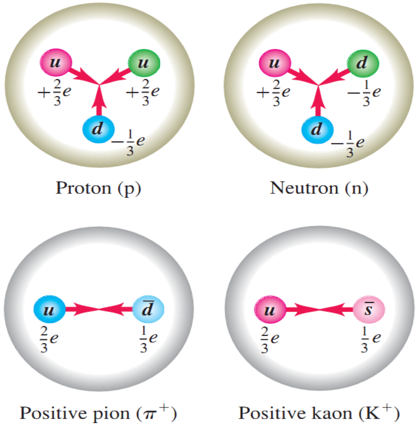


Spin:
How does nucleon spin emerge

Mass:
Higgs mechanism gives only ~few%

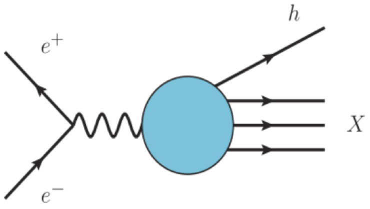
Fragmentation Functions (FFs)





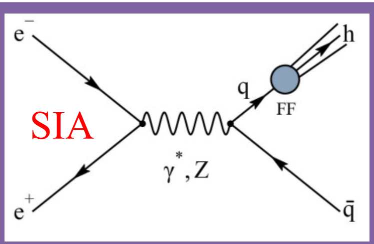
$D_q^h(z)$

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



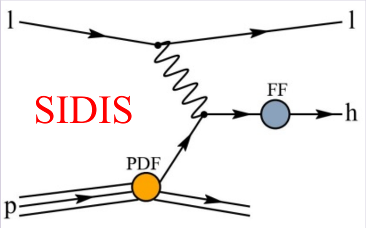
$$\sigma^{e^+e^-\to hX} = \hat{\sigma}_{e^+e^-\to i} \otimes D_{i\to h}$$

Access FFs with QCD factorization



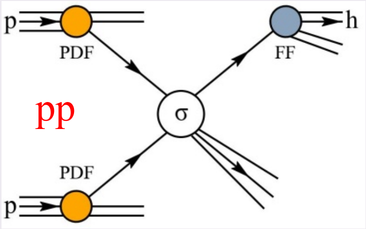
e⁺e⁻: $\sigma = \sum_q \sigma(e^+e^- \to q\bar{q}) \otimes FF$

- 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

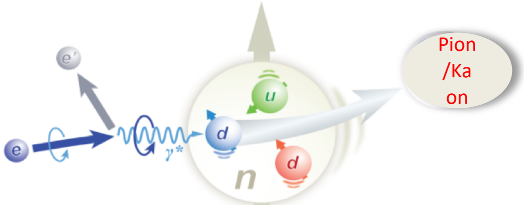


pp: $\sigma = \sum_q PDF \otimes PDF \otimes \sigma(q_1 q_1 \to q_1' q_2') \otimes FF$

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

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

FFs studies at an unpolarized e^+e^- collider



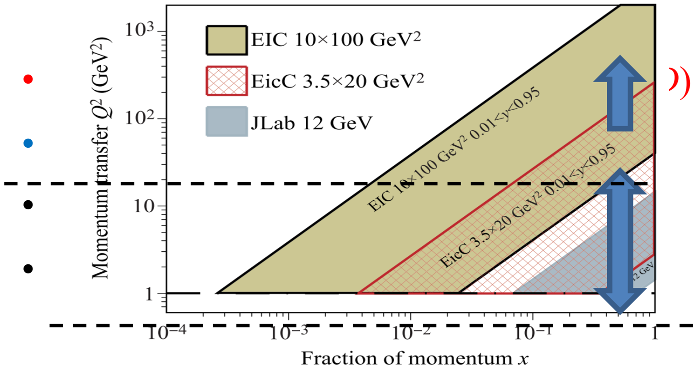
- Separation of TMD factorization in SIDIS:

$$\sigma^{\ell N \to \ell h X} = \hat{\sigma} \otimes PDF \otimes FF$$

$$A_N^{\text{Sivers}} \propto \langle \sin(\phi_h - \phi_s) \rangle_{UT} \propto f_{1T}^{\perp} \otimes D$$

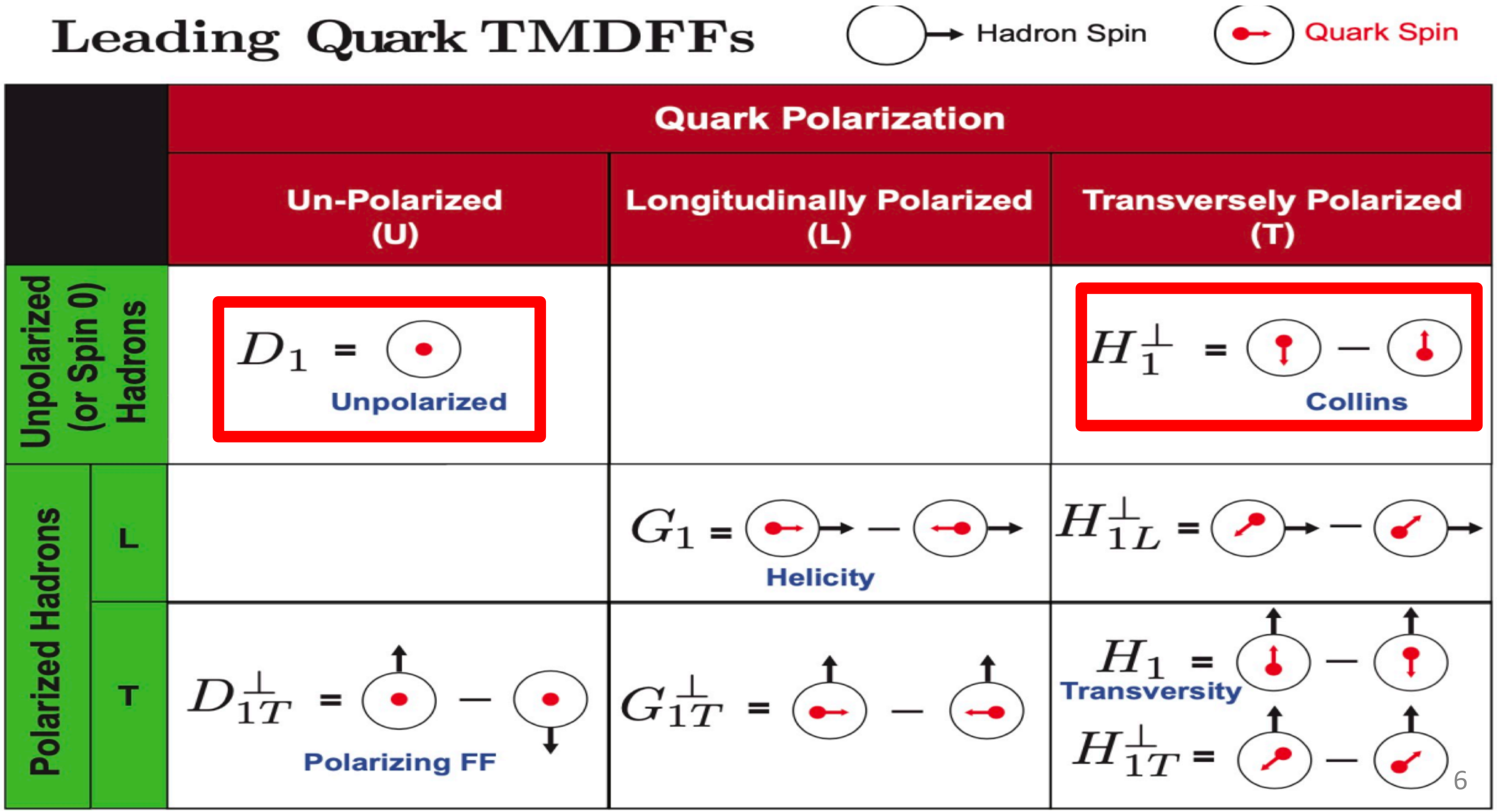
$$A_N^{\text{Collins}} \propto \langle \sin(\phi_h + \phi_s) \rangle_{UT} \propto h_1 \otimes H_1^{\perp}$$

$$A_N^{\text{Pretzelosity}} \propto \langle \sin(3\phi_h - \phi_s) \rangle_{UT} \propto h_{1T}^{\perp} \otimes H_1^{\perp}$$

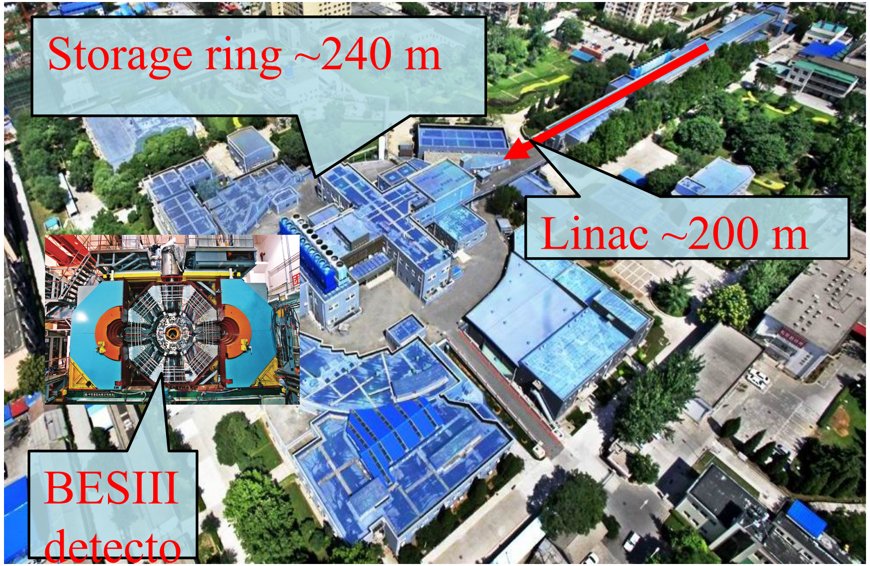


- To accurately extract Parton Distribution Functions (PDFs), more precise FFs are required.
- Two types of fragmentation functions can be studied at an unpolarized e^+e^- collider: D and $H_1^{\perp}$.

Leading quark TMDFFS



BEPCII/BESIII

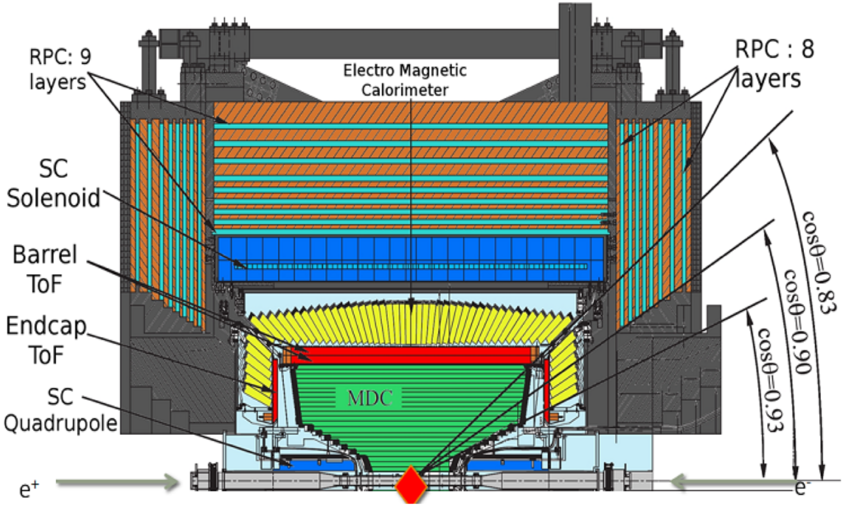


Double-ring, symmetry, multi-bunch e⁺ e⁻ collider

E_{cm}= 1.84 to 4.95 GeV

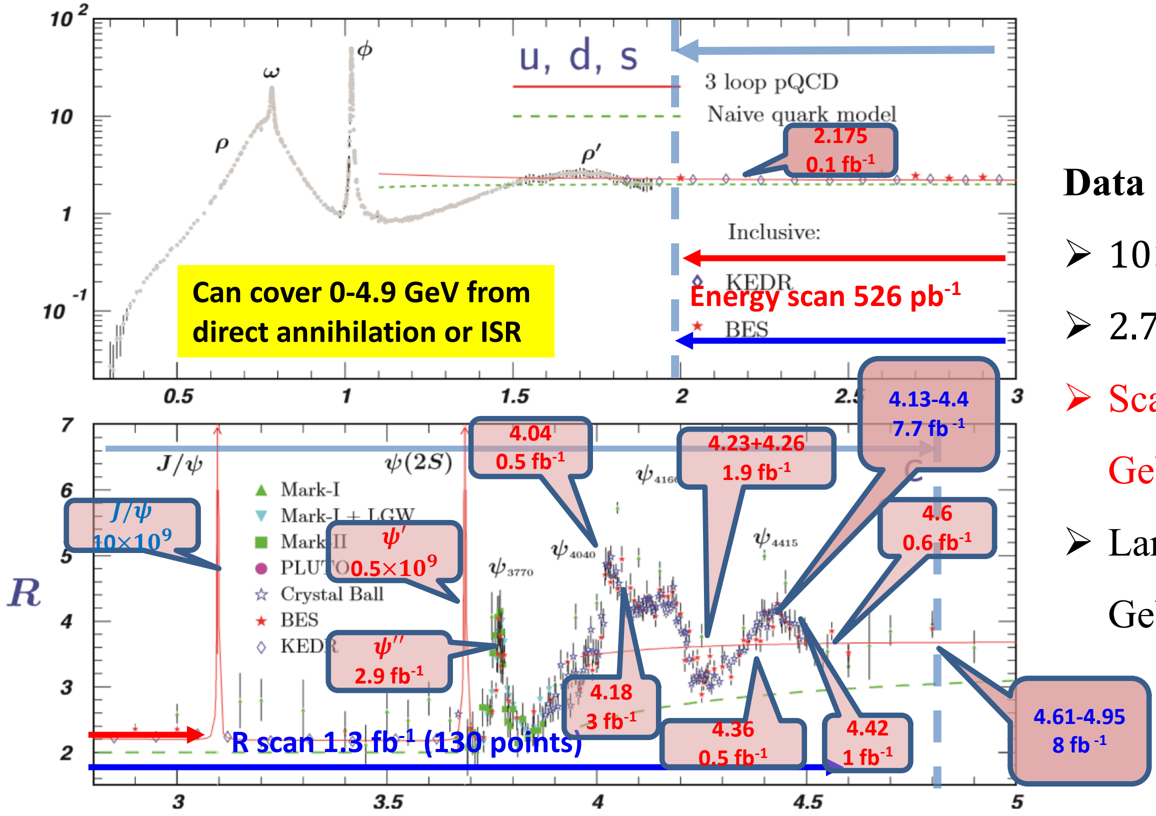
Energy spread: $\Delta E \approx 5\times10^{-4}$

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}

Unpolarized FFs measurements at BESIII

Experimental observable at e^+e^- colliders:

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

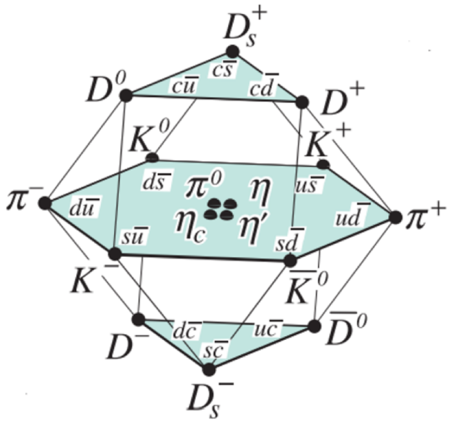
h is a particular type of hadron such as π^0, $\pi^{+/-}$, $K^{+/-}$ …

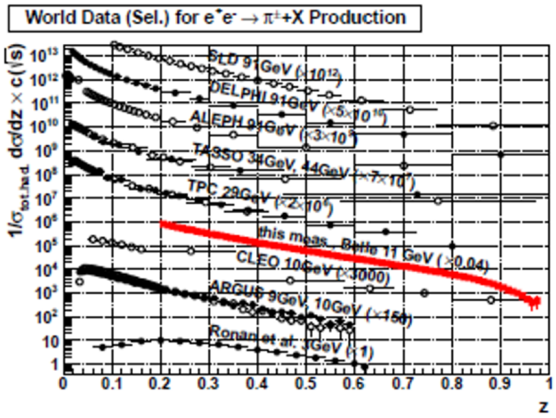
- At Leading order $\sim \sum_q e_q^2 D_1^{h/q}(z)$

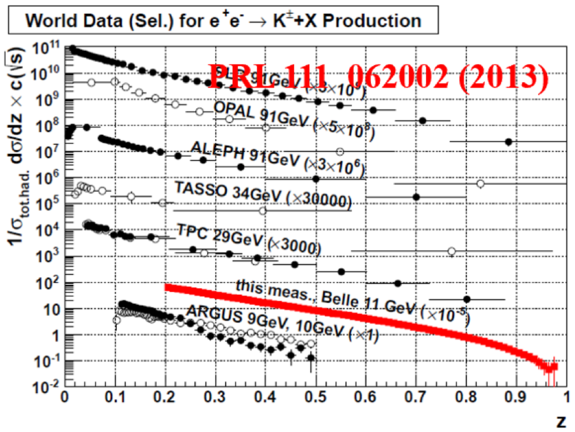
Unpolarized fragmentation function (D)

Fractional energy of hadron $z = 2E_h/\sqrt{s}$

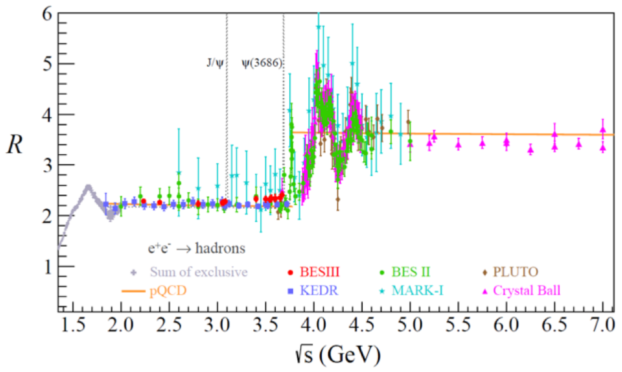
World π & K data on e^+e^-



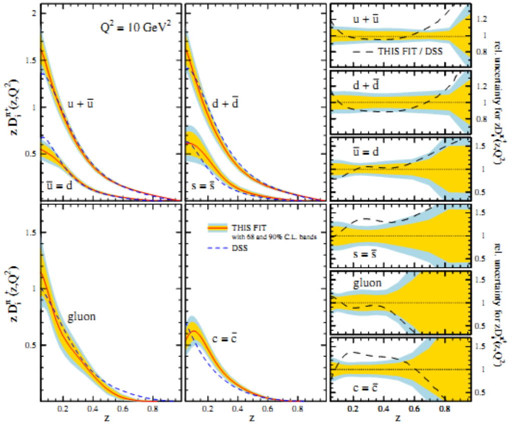




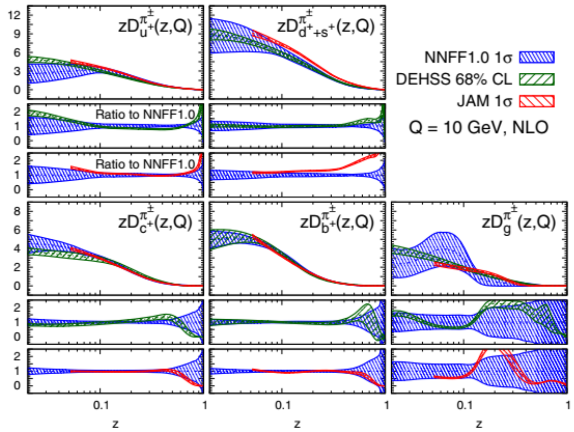
- Precision data includes charged π, K
- Data sets at $\sqrt{s} < 10$ GeV e^+e^- collision ?
  - high z data sets ?
- R scan data @ BESIII: ~10 pb^{-1} @ each $\sqrt{s}$



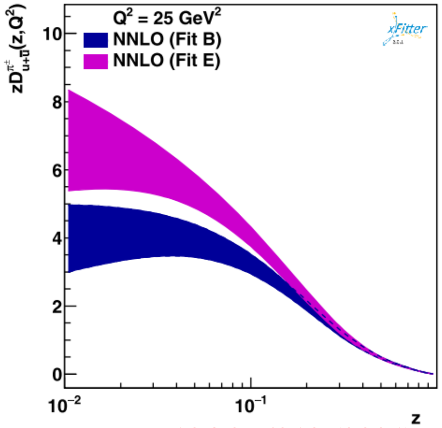
Pion FF: Best known FF



PRD 91 014015 (2015)

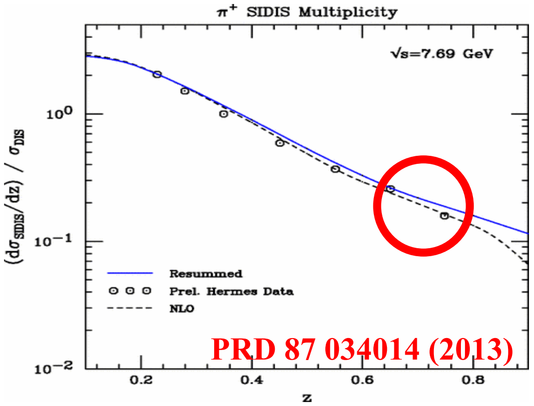


Eur.Phys.J.C77 516 (2017)



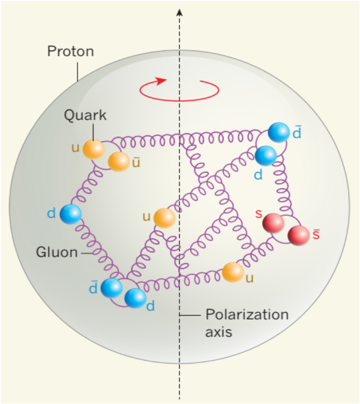
PRD 104 056019 (2021)

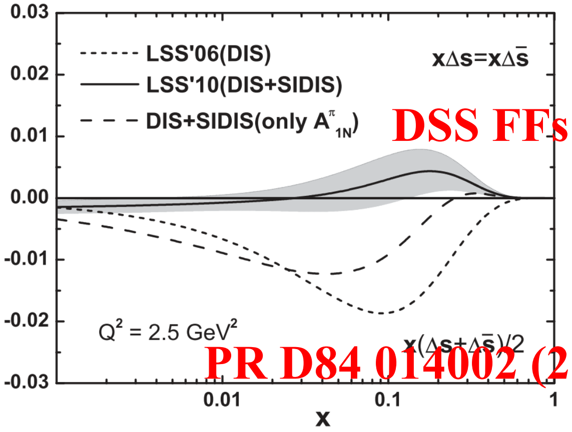
- For $z \geq 0.8$, uncertainty rapidly increase because of the lack of experimental data
- Xfitter: data at $\sqrt{s} > 10$ GeV e^+e^-
  - Low $\sqrt{s}$ e^+e^- data ?
- Large z re-summation
  - High z data ?



PRD 87 034014 (2013)

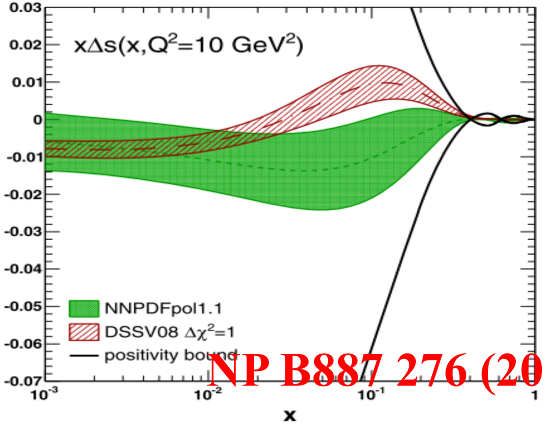
Strange quark polarization puzzle





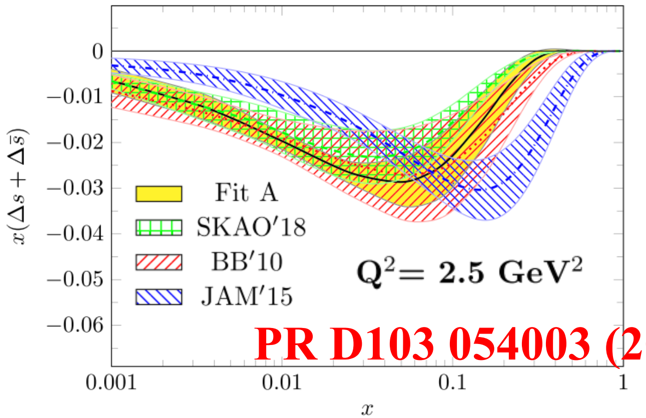
DSS FFs

PR D84 014002 (201



NP B887 276 (2014)

- Strange quark density function: ∆s(x)+∆s̄(x)
  - Inclusive DIS: only proton PDF
    - negative for all values of x
  - Semi-inclusive DIS: proton PDF & kaon FF
    - DSS FFs: positive for most of measured x
    - HKNS FF: negative
    - JAM FFs: negative
- Reliable FFs knowledge ? Need more efforts



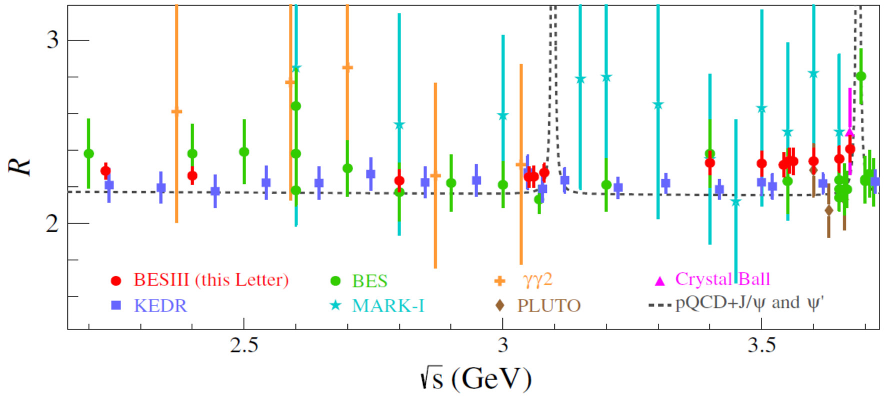
PR D103 054003 (2021)

Analysis at BESIII

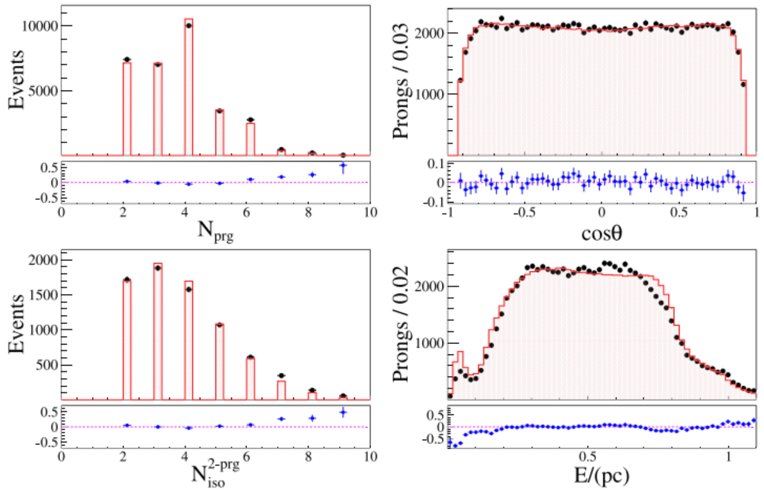
- Normalized differential cross section (take π^0 as an example):

$$\frac{1}{\sigma_{\text{had}}}\frac{d\sigma_{\pi^0}}{dp_{\pi^0}}=\frac{N_{\pi^0}}{N_{\text{had}}}\frac{1}{\Delta p_{\pi^0}}$$

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

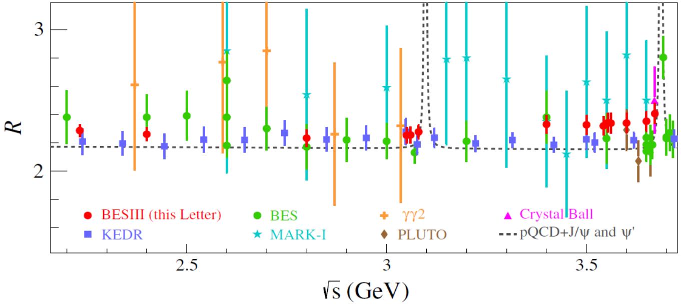


PRL 128 062004(2022)



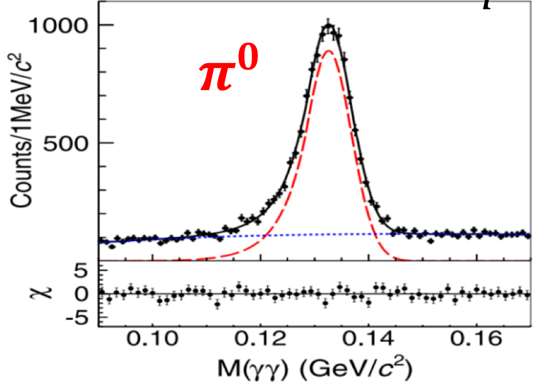
LUARLW MC generator

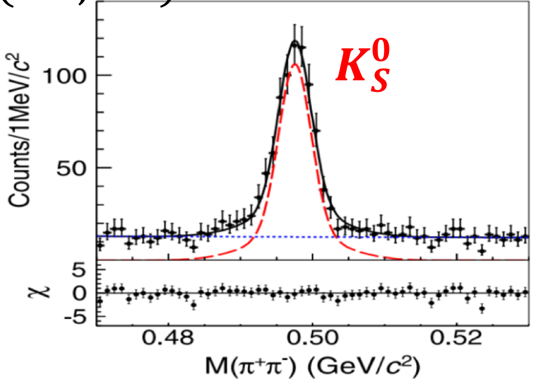
Inclusive π^0/K_S^0 production

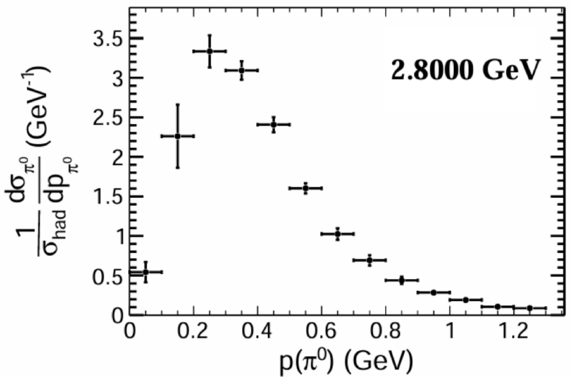


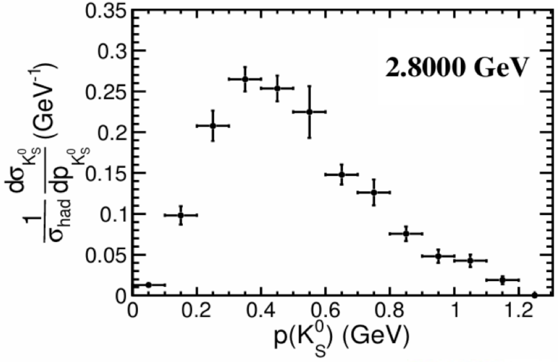
$\sqrt{s}$ (GeV)	$\mathcal{L}$ (pb^{-1})	$N_{\rm had}^{\rm tot}$	$N_{\rm bkg}$
2.2324	2.645	83227	2041
2.4000	3.415	96627	2331
2.8000	3.753	83802	2075
3.0500	14.89	283822	7719
3.4000	1.733	32202	843
3.6710	4.628	75253	6461

$p \in (0.4, 0.5)$ GeV







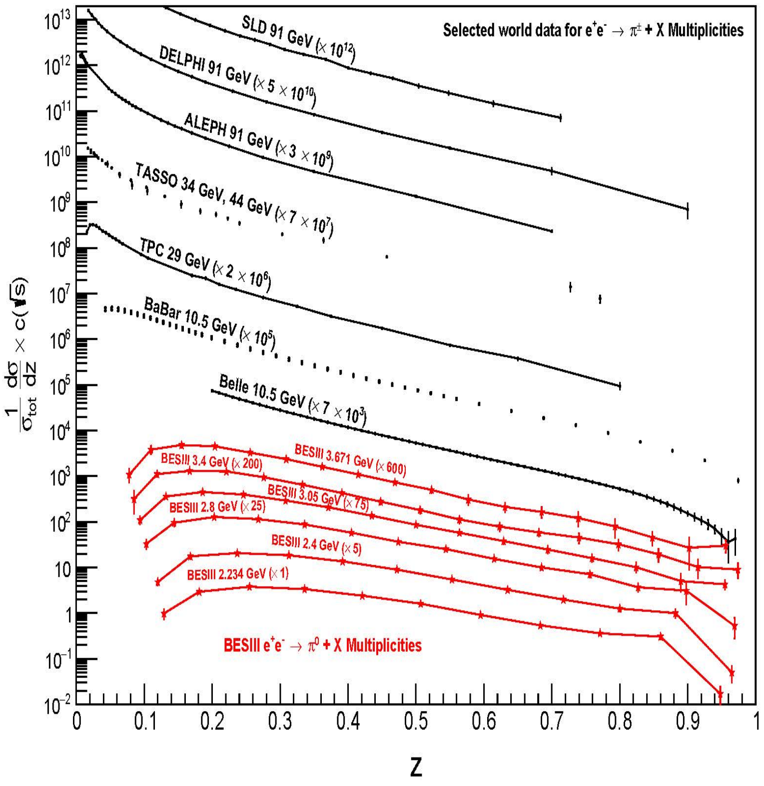


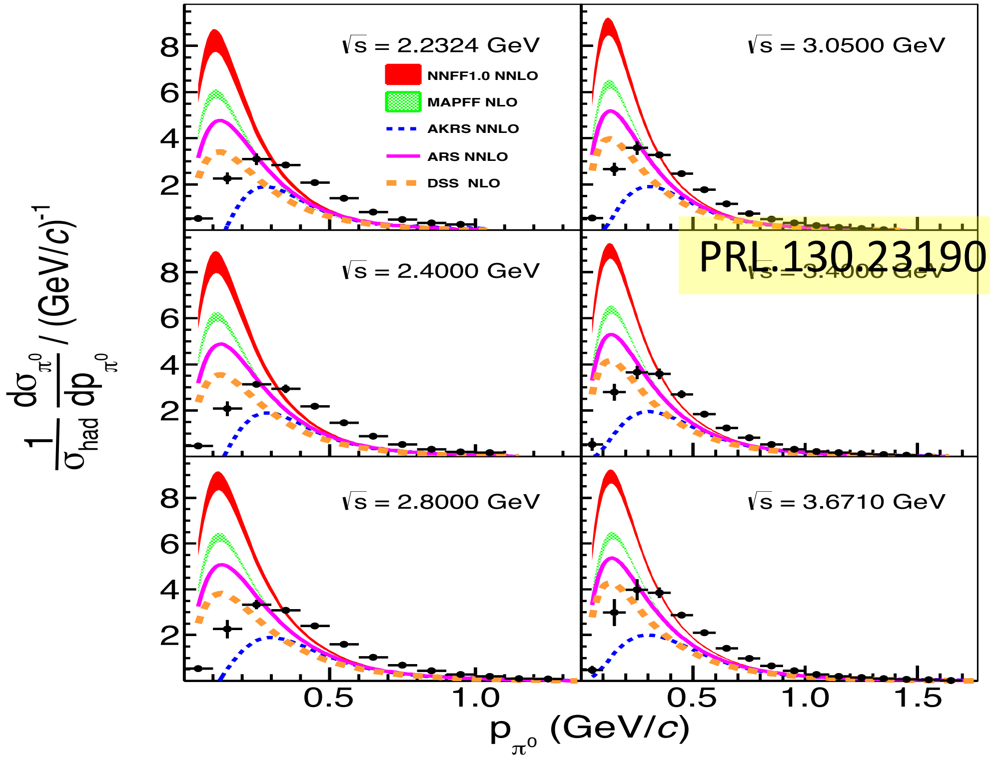
PRL 130 231901(2023)

Results: inclusive π^0

Theory support: Hongxi Xing, Daniele Anderle

Compared with theoretical estimation





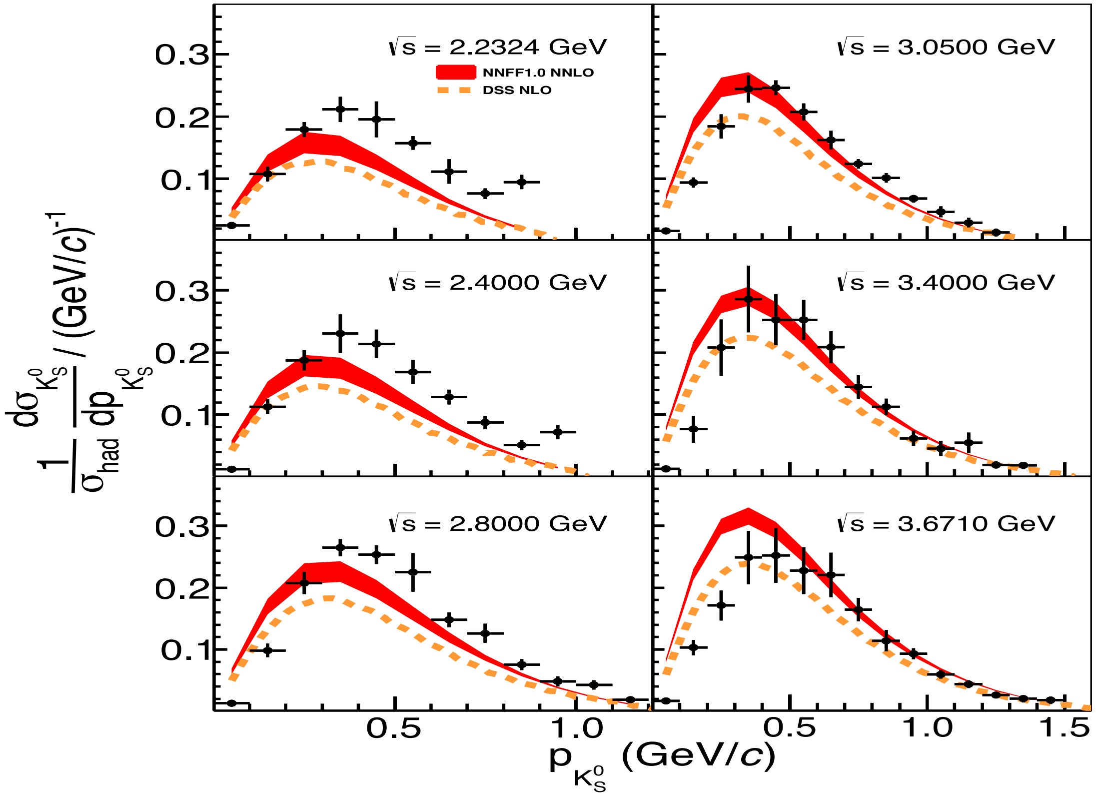
PRL.130.231901

Uncertainties ~ less 10%

Results: Inclusive K_S^0

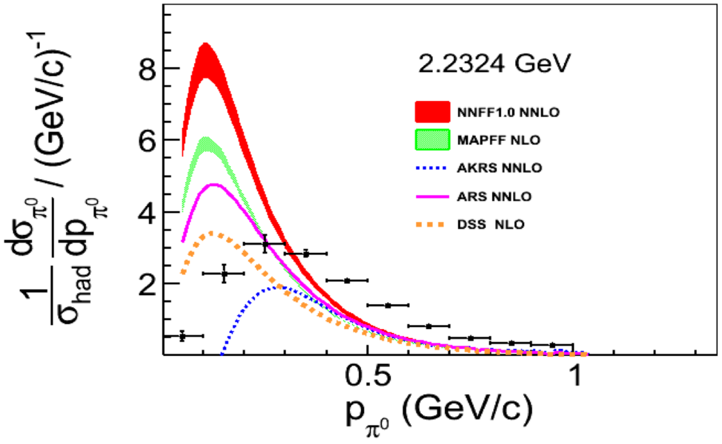
Compared with theoretical estimation

Theory support: Hongxi Xing, Daniele Anderle



PRL.130.231901

Results: inclusive π^0/K_s^0

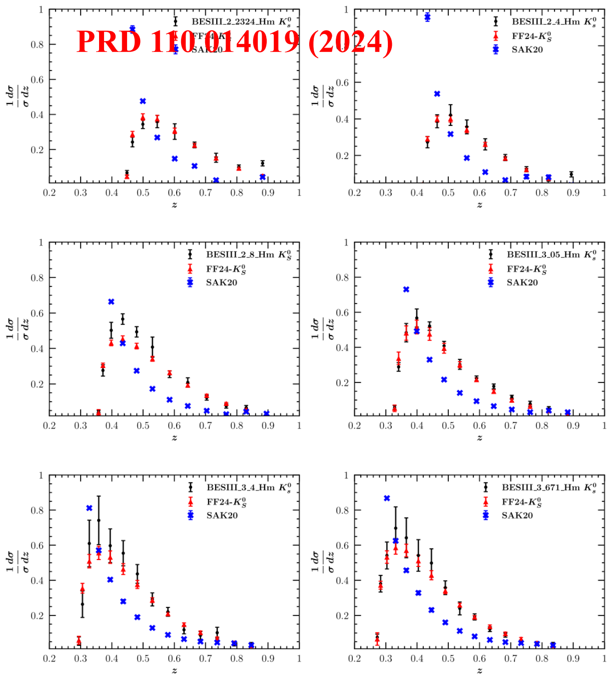


PRL 130 231901(2023) BESIII

- 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^*
  - $\Longrightarrow e^+ e^- \rightarrow \rho^*/\omega^*/\phi^* \rightarrow h + X$

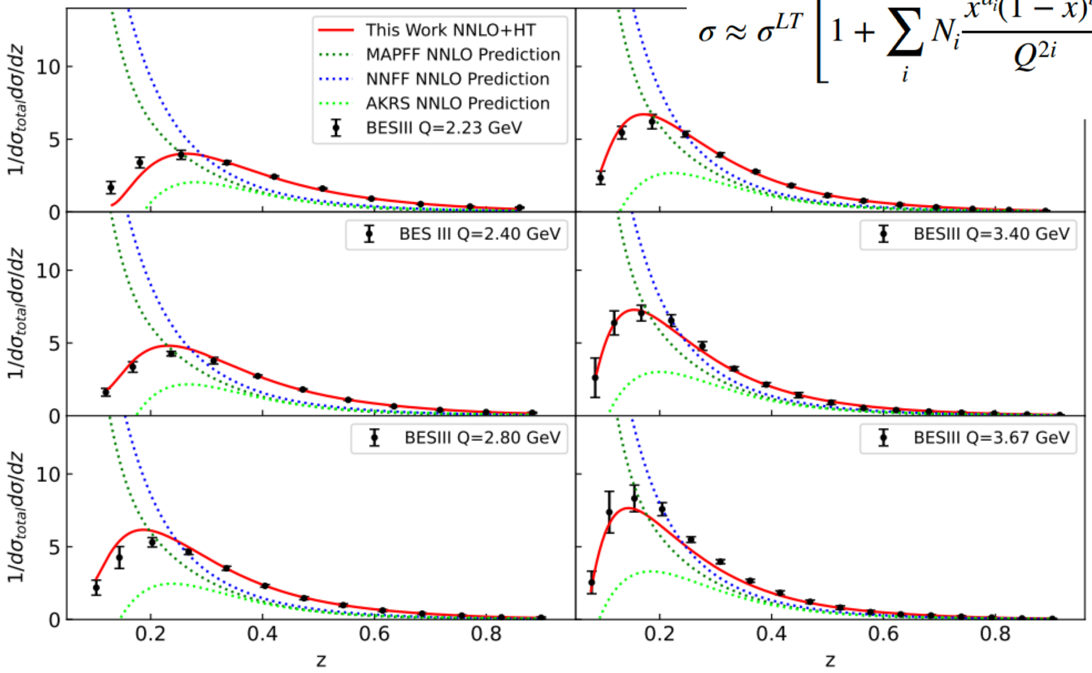
Results: inclusive π^0/K_s^0

PRD 110 014019 (2024)



theory

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



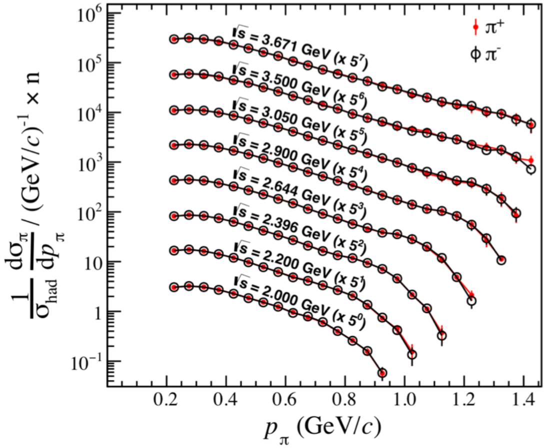
- **PRD 110 014019 (2024): NNLO & hadron mass correction for K_S**
- **arXiv:2404.11527: NNLO & higher twist contribution for π^0**

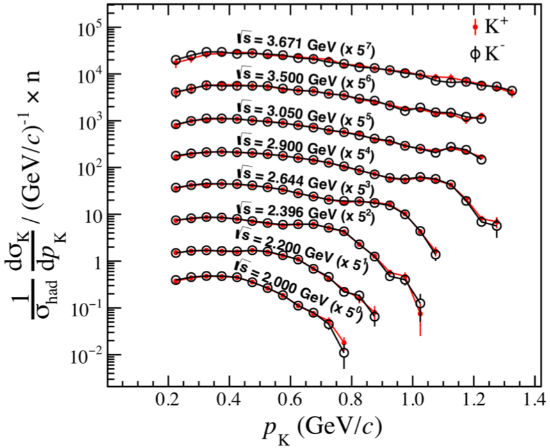
Inclusive $\pi^{\pm}/K^{\pm}$ production

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

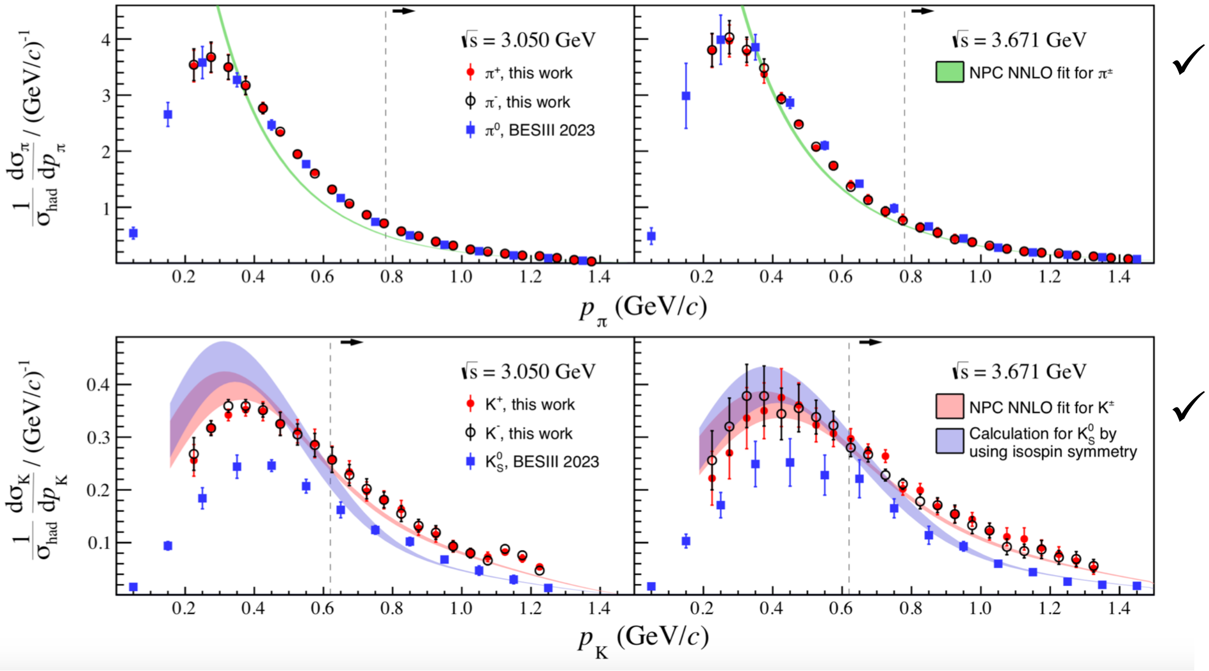




- ✓ Center-of-mass energies: 2.0 – 3.671 GeV, 8 energy points
- ✓ z coverage: 0.13 to 0.95 for $\pi^{\pm}$, 0.30 to 0.95 for $K^{\pm}$
- ✓ Highest experimental precision ~ 1(2)% at z ~ 0.3 – 0.5 for $\pi^{\pm}$ and $K^{\pm}$

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

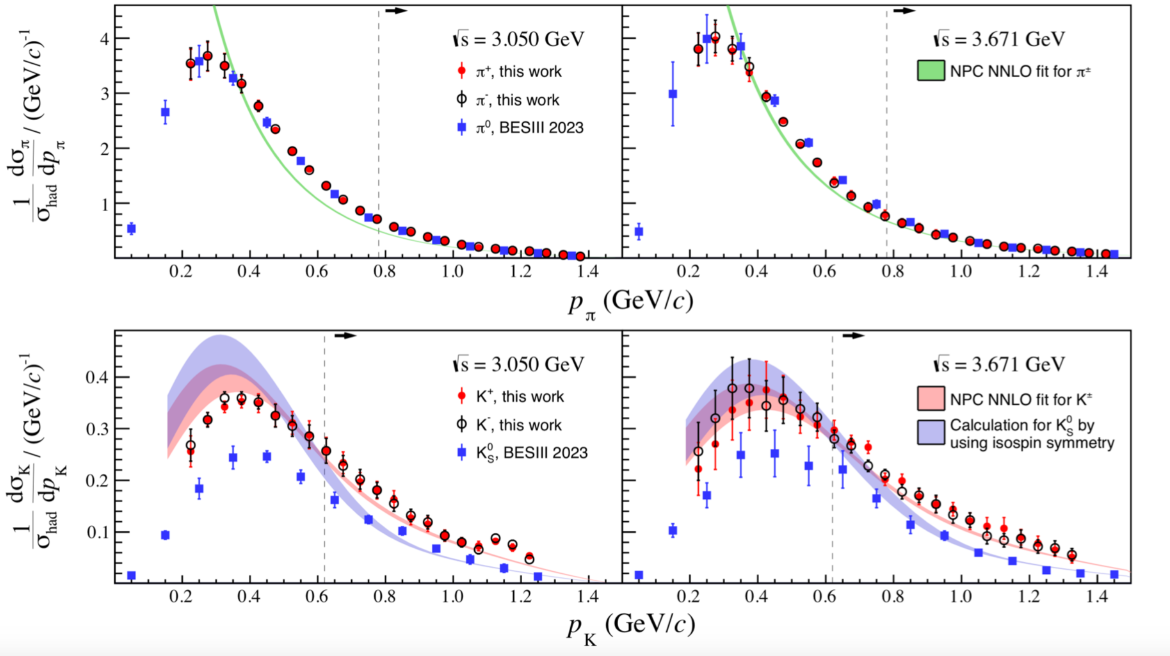
arXiv: 2502.16084



- ✓ 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

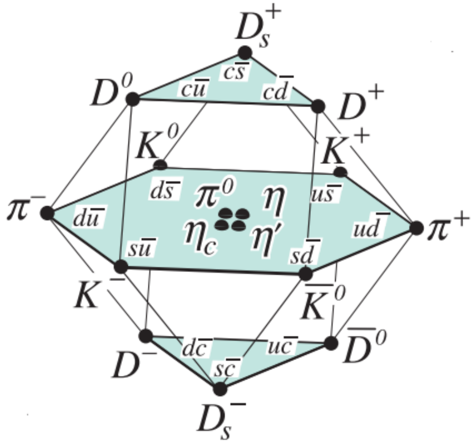


- $\sqrt{s}$ > 3.0 GeV， E_h > 0.8 GeV
- Charge conjugation symmetry and flavor symmetries among favored (unfavord) quark FFs assumed
- s quark FF shares the same shape as the $\bar{u}$ quark FF

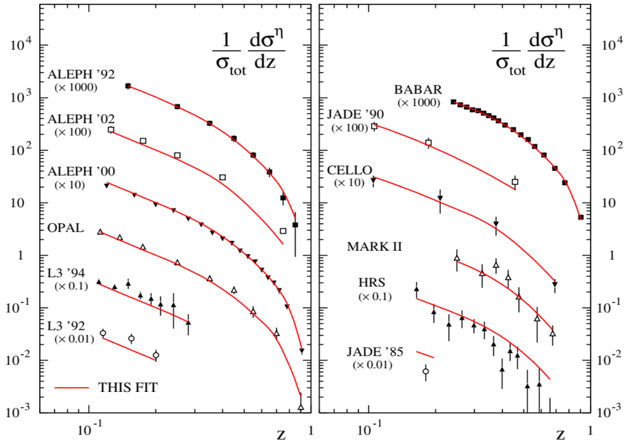
✓ Consistent with NPC fit results

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

World η data on e^+e^-

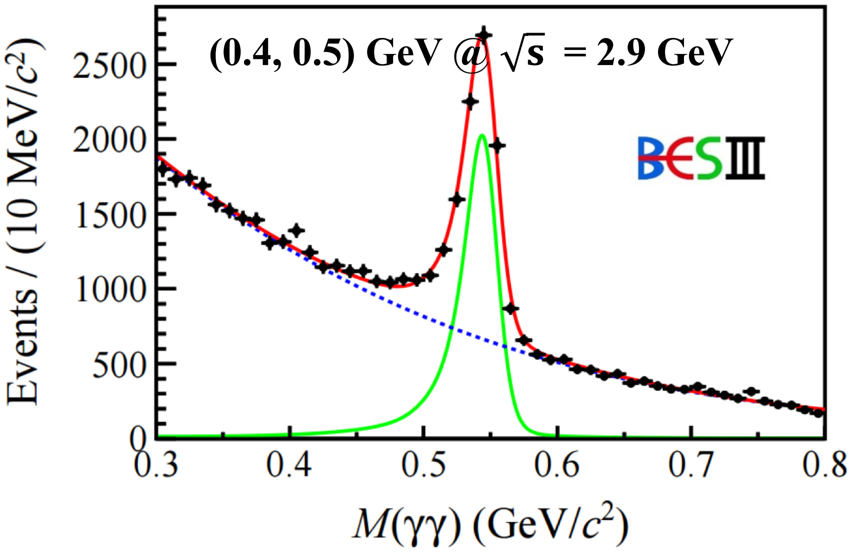


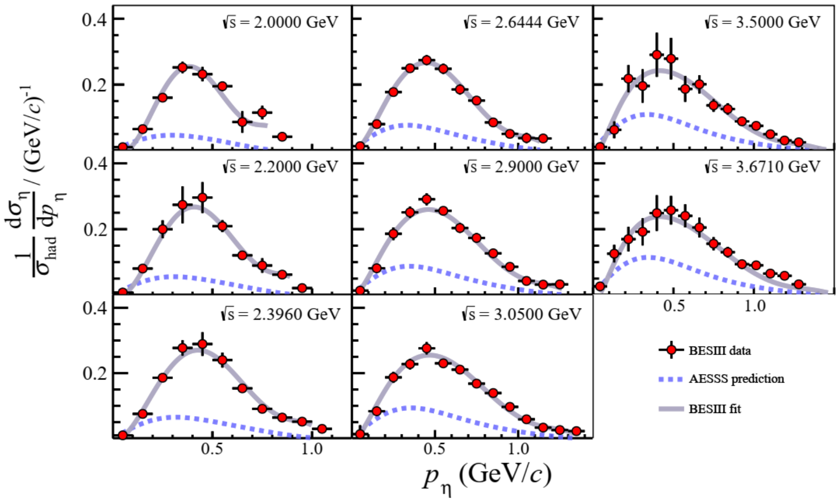
PRD83 (2001) 034002



- η FF @ NLO: data at $\sqrt{s} > 10$GeV e^+e^- collision
  - Missing theory uncertainty
- Theory improvement:
  - NNLO accuracy, hadron mass correction & higher twist contributions
- BESIII results and its possible impact ?

Inclusive η production





PRL 133, 021901 (2024)

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

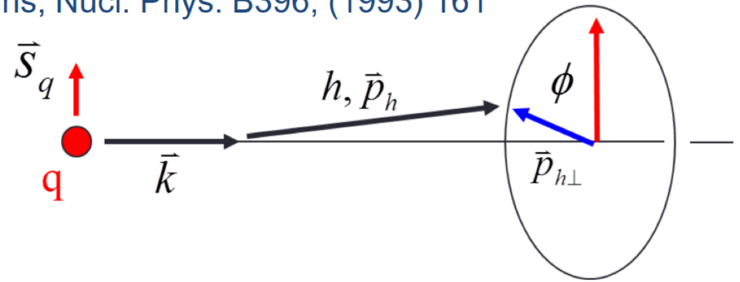
- PRD83 (2001) 034002 prediction vs. BESIII data: tension !

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

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

Collins FFs

J. Collins, Nucl. Phys. B396, (1993) 161



- Spin of quark correlates with hadron transverse momentum

➔translates into azimuthal anisotropy of final state hadrons

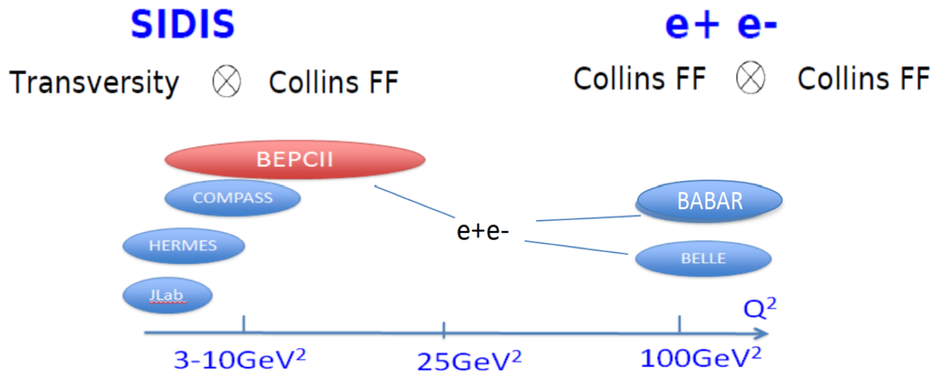
- The possibilities for finding a hadron produced from a transversely polarized quark:

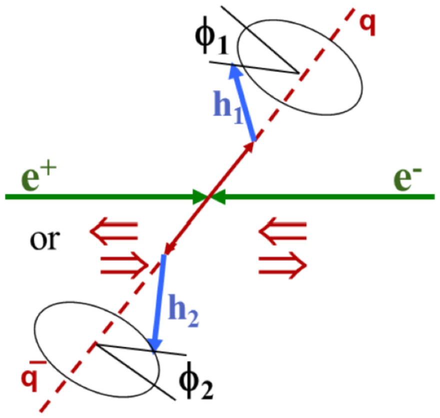
$$D_{hq^\uparrow}(z, P_{h\perp}) = D_1^q(z, P_{h\perp}^2) + \boxed{H_1^{\perp q}(z, P_{h\perp}^2)} \frac{(\hat{\mathbf{k}} \times \mathbf{P}_{h\perp}) \cdot \mathbf{S}_q}{zM_h},$$

- Unpolarized fragmentation function (D)
- Collins fragmentation function ($H_1^\perp$)

- Fractional energy of hadron $z = 2E_h/\sqrt{s}$
- Transverse momentum of the hadron $P_{h\perp}$

Collins effects in e^+e^- annihilation



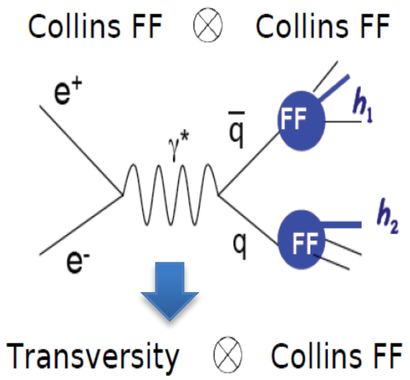


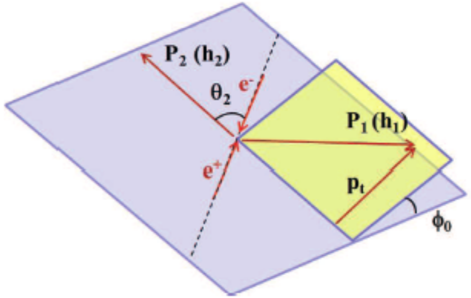
- At BESIII, the correlation of quark and anti-quark Collins functions are searched with back-to back hadrons:

$$e^+e^- \to q\bar{q} \to h_1 h_2 X$$

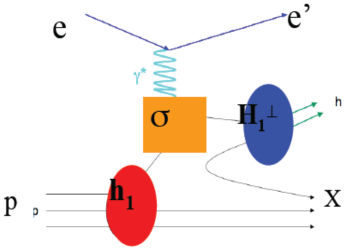
$$\Rightarrow \sigma \propto \cos(2\phi_0)\, H_1^\perp(z_1) \otimes H_2^\perp(z_2)$$

Collins effects in e^+e^- annihilation





- Normalized ratio $R = N(2\phi_0)/\langle N_0 \rangle$
  - ✓ $N(2\phi_0)$: di-pion yield in each $2\phi_0$ bin
  - ✓ $\langle N_0 \rangle$: averaged bin content
  - ✓ R^U: unlike sign ($\pi^\pm\pi^\mp$);
  - ✓ R^L: like sign ($\pi^\pm\pi^\pm$)
  - ✓ R^C: all pion pair



- Double ratio: reduce acceptance and radiation effect

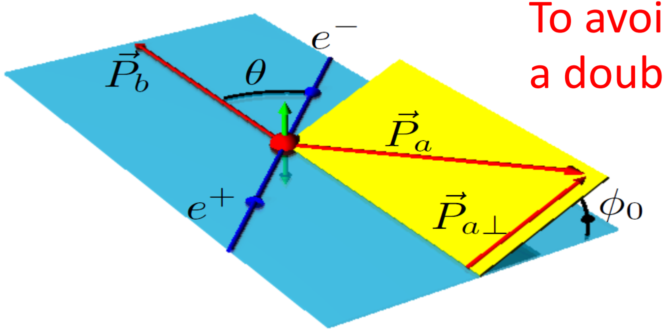
$$\frac{R^U}{R^{L(C)}} = 1 + \cos(2\phi_0) \cdot \frac{\sin^2\theta_2}{1+\cos^2\theta_2} \frac{\mathcal{F}(H_1^\perp(z_1)\bar{H}_1^\perp(z_2)/M_1M_2)}{D_1(z_1)\bar{D}_1(z_2)} = 1 + \cos(2\phi_0) \cdot A^{UL(UC)}$$

Fit function $\frac{R^U}{R^{L(C)}} = A\cos(2\phi_0) + B$

$A^{UL/UC}$ mainly contains Collins effect

B should be consistent with unity

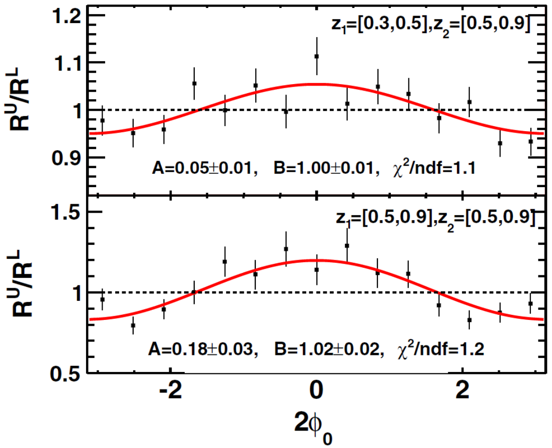
Collins effects at BESIII

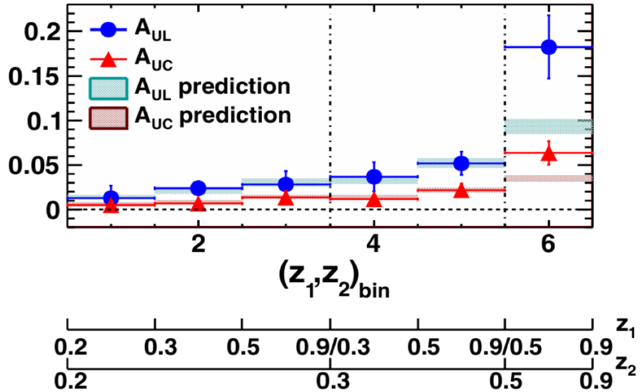


To avoid detection-related effects, experimentally, a double ratio measurement was proposed:

U: pi+&pi- or pi-&pi+
L： pi+&pi+ or pi-&pi-

$$\frac{R^U}{R^{L(C)}} = A\cos(2\phi_0) + B,$$





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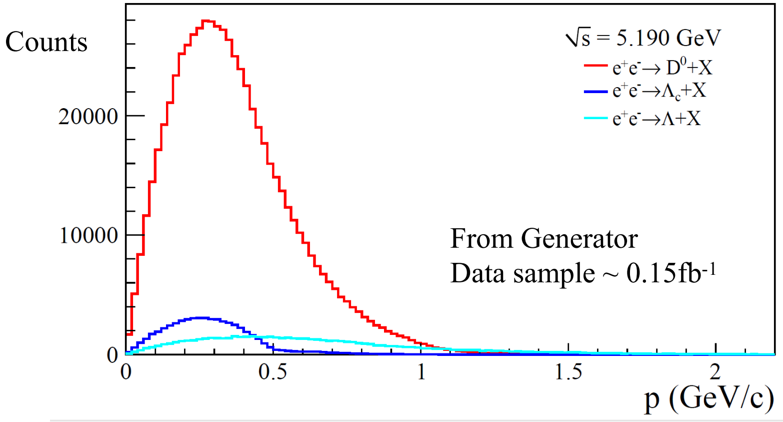
Prospects of FFs at BESIII

- **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)

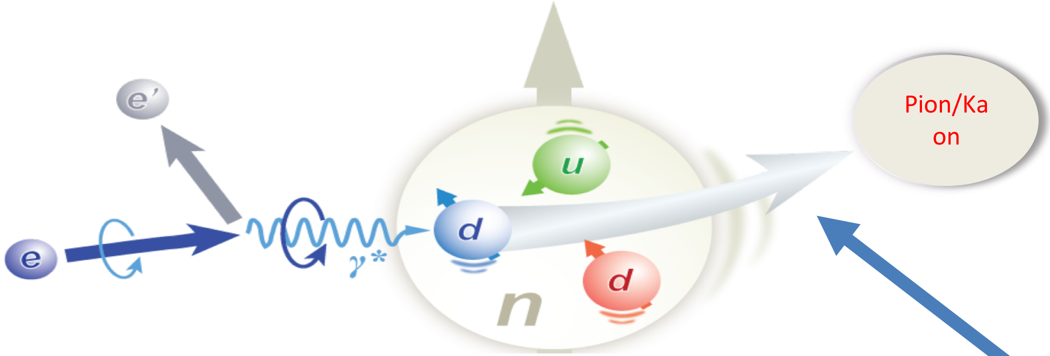


Summary

- 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

FFS VS Nucleon spin structure study



Fragmentation functions

Experimental observable: polarized structure functions g1

input

input

$$g_1^h(x,Q^2,z) = \frac{1}{2}\sum_q e_q^2 \left[\Delta q(x,Q^2) D_q^h(z,Q^2) + \Delta\bar{q}(x,Q^2) D_{\bar{q}}^h(z,Q^2)\right]$$

(LO picture)

Extracted nucleon structure information: polarized PDFs (helicity distribution)

Wigner distribution $W_\Gamma(\vec{r}, k)$ 7 variables

Integrating out $\boldsymbol{k^-}$

Reduced Wigner distribution $W_\Gamma(\vec{r}, \vec{k})$ 6 variables

Integrating out $\vec{\boldsymbol{k}}_\perp$

Integrating out $\vec{\boldsymbol{r}}$

$\tilde{f}_{\gamma^+}(\vec{r}, k^+)$ or $f_{\gamma^+}(\vec{r}, x)$ 4 variables

3D density in the rest frame of the proton

$f(x, \vec{k}_\perp)$ 3 variables

Transverse-momentum dependent parton distributions

Integrating out $\boldsymbol{z}$

Fourier transformation

$f_{\gamma^+}(\vec{r}_\perp, x)$ 3 variables

Impact parameter space distribution

$F_{\gamma^+}(x, \xi, t)$ 3 variables

Generalized parton distribution

Integrating out $\vec{\boldsymbol{k}}_\perp$

Integrating out $\vec{\boldsymbol{r}}_\perp$

Taking $\boldsymbol{\xi, t = 0}$

$f(x)$ 1 variables

Parton distribution function

Nucleon tomography

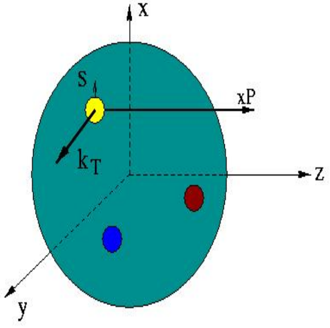
$W_p^u(x,k_T,r)$ *Wigner distributions*

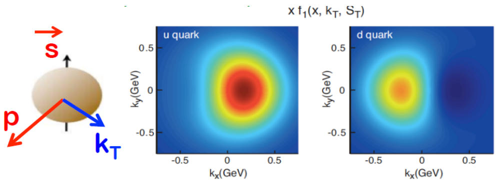
5D dist.

d^3r → **TMD PDFs** $f_1^u(x,k_T)$, .. $h_1^u(x,k_T)$

$d^2k_T\,dr_z$ → **GPDs/IPDs**

3D imaging





TMD PDFs → d^2k_T → PDFs

GPDs/IPDs → d^2r_T → PDFs

GPDs/IPDs → *dx & Fourier Transformation* → Form Factors

PDFs $f_1^u(x)$, .. $h_1^u(x)$

1D

Form Factors $G_E(Q^2)$, $G_M(Q^2)$

Leading quark TMDPDFS

		Quark polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Hadron Polarization	U	$f_1 =$		$h_1^{\perp} =$ − Boer-Mulders
	L		$g_1 =$ − Helicity	$h_{1L}^{\perp} =$ − Worm Gear
	T	$f_{1T}^{\perp} =$ − Sivers	$g_{1T} =$ − Worm Gear	$h_1 =$ − Transversity $h_{1T}^{\perp} =$ − Pretzelosity

Hadron Spin *Quark Spin*

Results: inclusive π^0/K_s^0

experimental

- Parameterization are fitted to particles that reached detectors

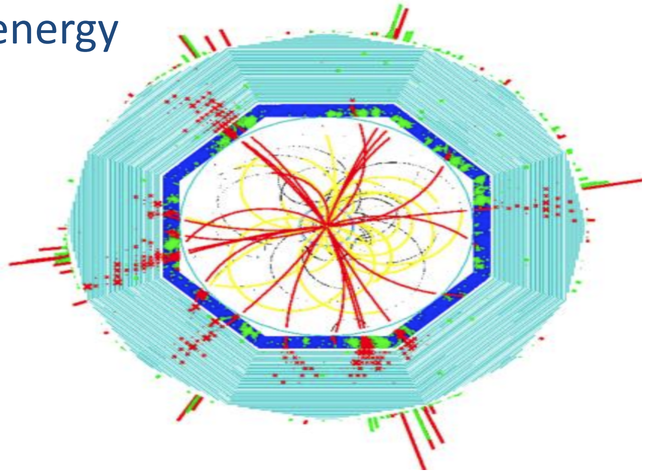
A good parameterization should be

Depend on collider energy

$$D_{1q}^{h}(z) = D_{1q}^{h,\mathrm{dir}}(z) + D_{1q}^{h,\mathrm{dec}}(z),$$

$$D_{1q}^{h,\mathrm{dec}}(z) = \sum_{h_j} D_{1q}^{h,h_j}(z),$$

$$D_{1q}^{h,h_j}(z) = Br(h,h_j)\int dz' K_{h,h_j}(z,z') D_{1q}^{h_j}(z'),$$



Resonance decay from $\frac{1}{2}^+, \frac{1}{2}^+, 1^-, 0^-$ multiplet was proposed by Yu-kun Song, K.B.Chen, Z.T.Liang, Y.L.Pan and S.Y.Wei to explain BELLE data

How to interpret data will help us to understand QCD