Measurements of fragmentation functions at BESIII

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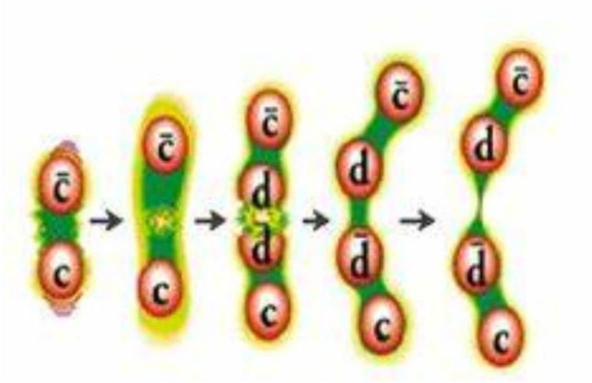
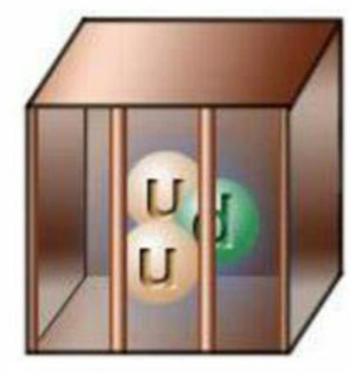
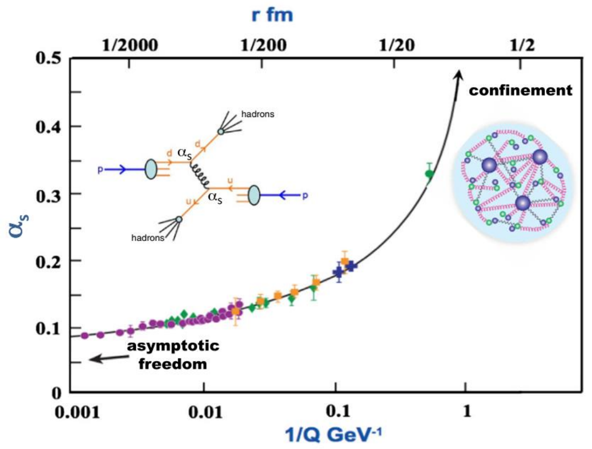
Several open questions about QCD

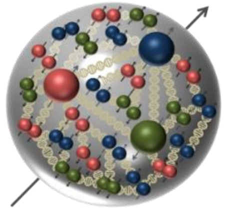
- **Confinement**, no existing isolated quarks or gluons





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

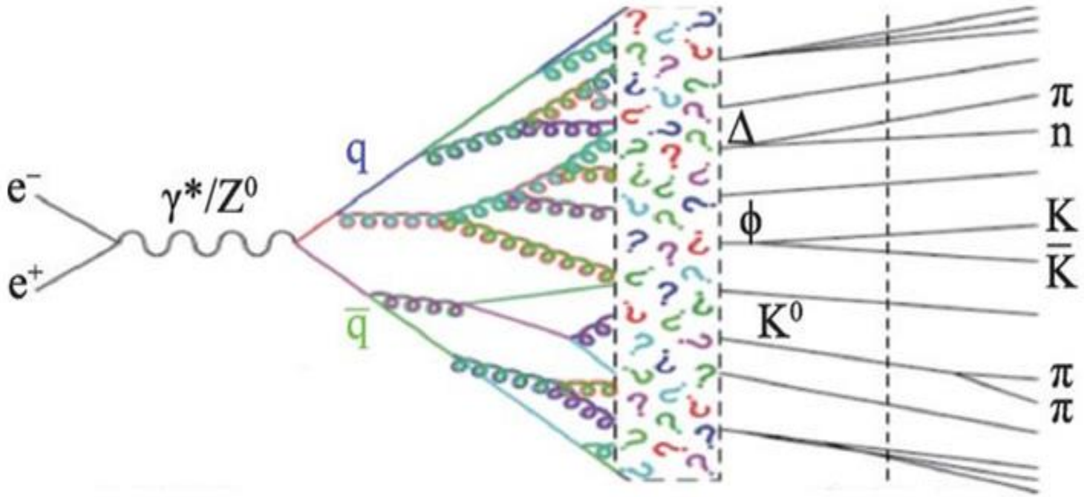




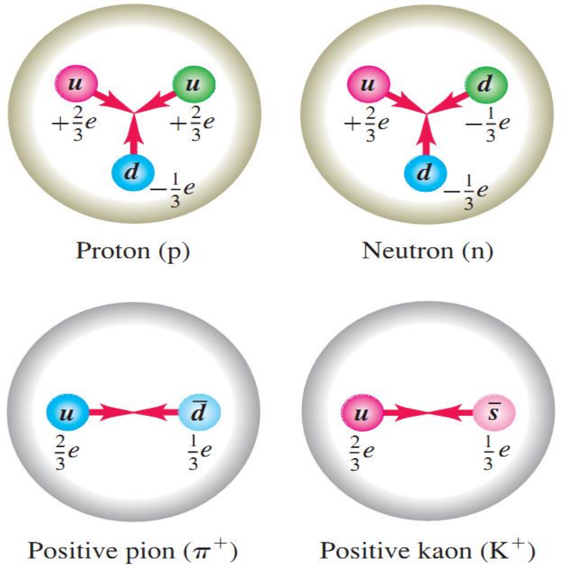
Spin:
How does nucleon spin emerge

Mass:
Higgs mechanism gives only ~few%

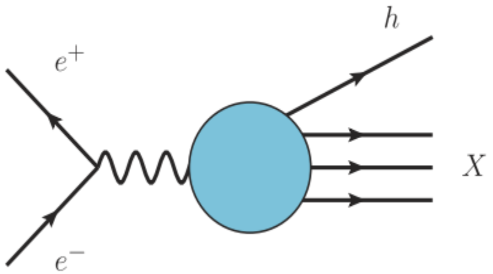
Fragmentation Functions (FFs)



$D_q^h(z)$

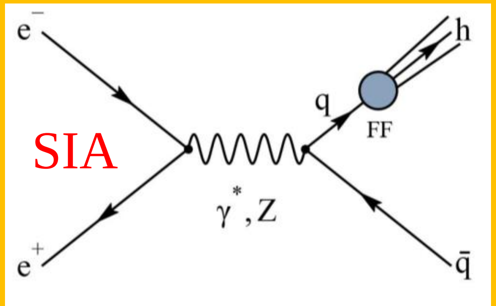


- $D_q^h(z)$: describe the fragmentation of an quark into an hadron, where the hadron carries a fraction $z = 2E_h/\sqrt{s}$ of parton's momentum



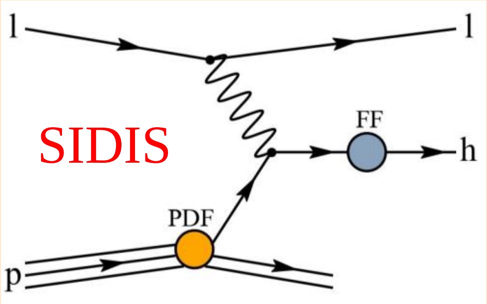
$$E_p \frac{d\sigma_{e^+e^-\to hX}}{d^3p}(s,p) = \sum_f \int \frac{dz}{z^2} D_{h/f}(z,\mu^2) \times E_k \frac{d\hat{\sigma}_{e^+e^-\to \hat{k}X}}{d^3\hat{k}}(s,\hat{k},\mu^2) + \mathcal{O}\left[\frac{\Lambda^2_{\mathrm{QCD}}}{Q^2}\right]$$

Access FFs with QCD factorization



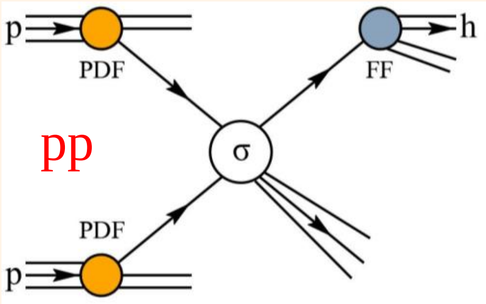
e^+e^-: $\sigma = \sum_q \sigma(e^+e^- \rightarrow q\bar{q}) \otimes FF$

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



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

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



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

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

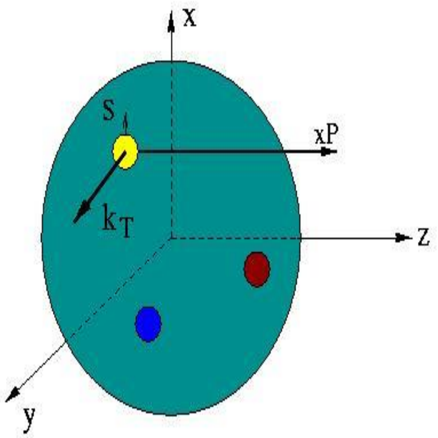
- SIA @ e^+e^-: the cleanest input for FFs fitting

Nucleon tomography

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

5D dist.

d^3r $d^2k_T \, dr_z$



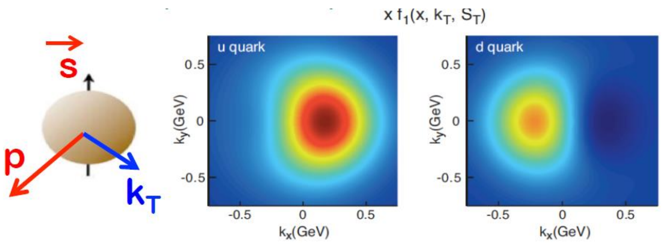
TMD PDFs

$f_1^u(x, k_T)$, ..

$h_1^u(x, k_T)$

GPDs/IPDs

3D imaging



d^2k_T

d^2r_T

dx & Fourier Transformation

PDFs

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

1D

Form Factors

$G_E(Q^2)$,

$G_M(Q^2)$

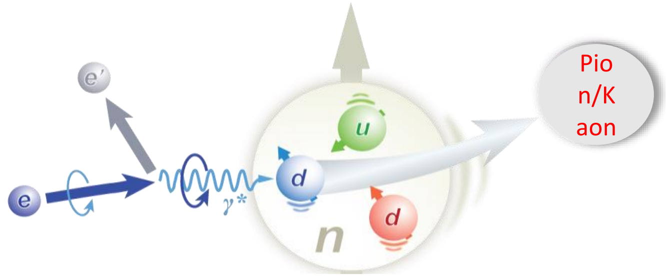
LO expansion of TMDs

		Quark polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon 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

Nucleon Spin *Quark Spin*

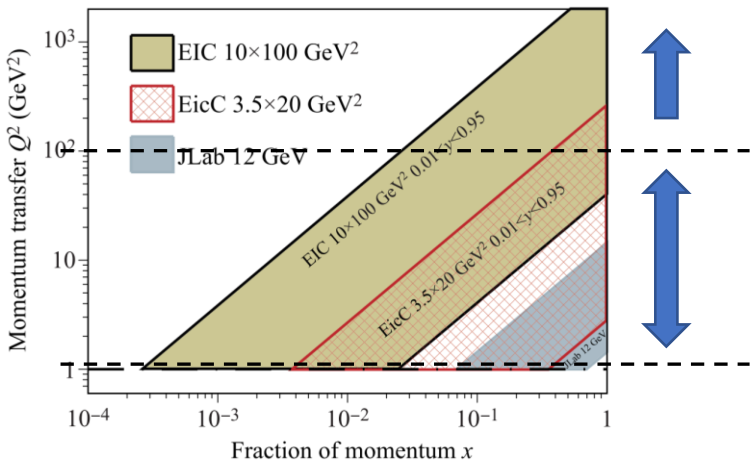
FFs studies at an unpolarized e^+e^- collider

- Separation of TMD factorization in SIDIS:



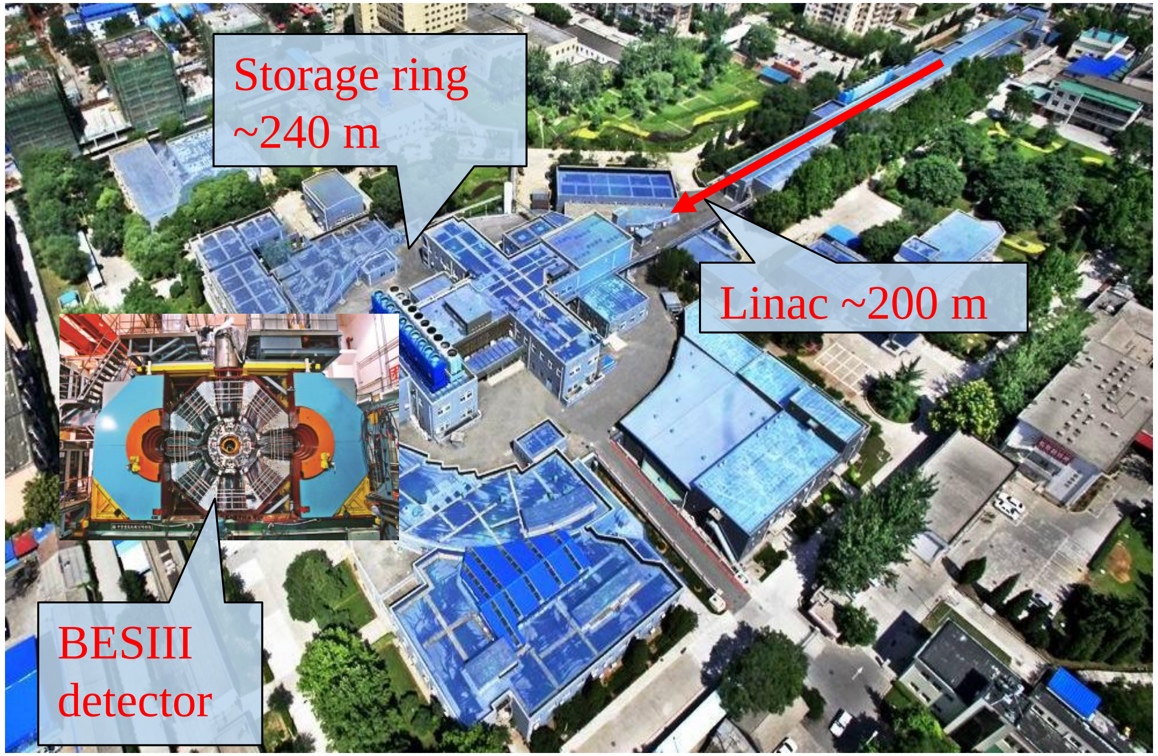
$$\sigma^{\ell N \to \ell h X} = \hat{\sigma} \otimes PDF \otimes FF$$

$$A_N^{\text{Sivers}} \propto \langle \sin(\phi_h - \phi_s) \rangle_{UT} \propto f_{1T}^{\perp} \otimes D$$
$$A_N^{\text{Collins}} \propto \langle \sin(\phi_h + \phi_s) \rangle_{UT} \propto h_1 \otimes H_1^{\perp}$$
$$A_N^{\text{Pretzelosity}} \propto \langle \sin(3\phi_h - \phi_s) \rangle_{UT} \propto h_{1T}^{\perp} \otimes H_1^{\perp}$$



- 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 $H_1^{\perp}$.

BEPCII/BESIII

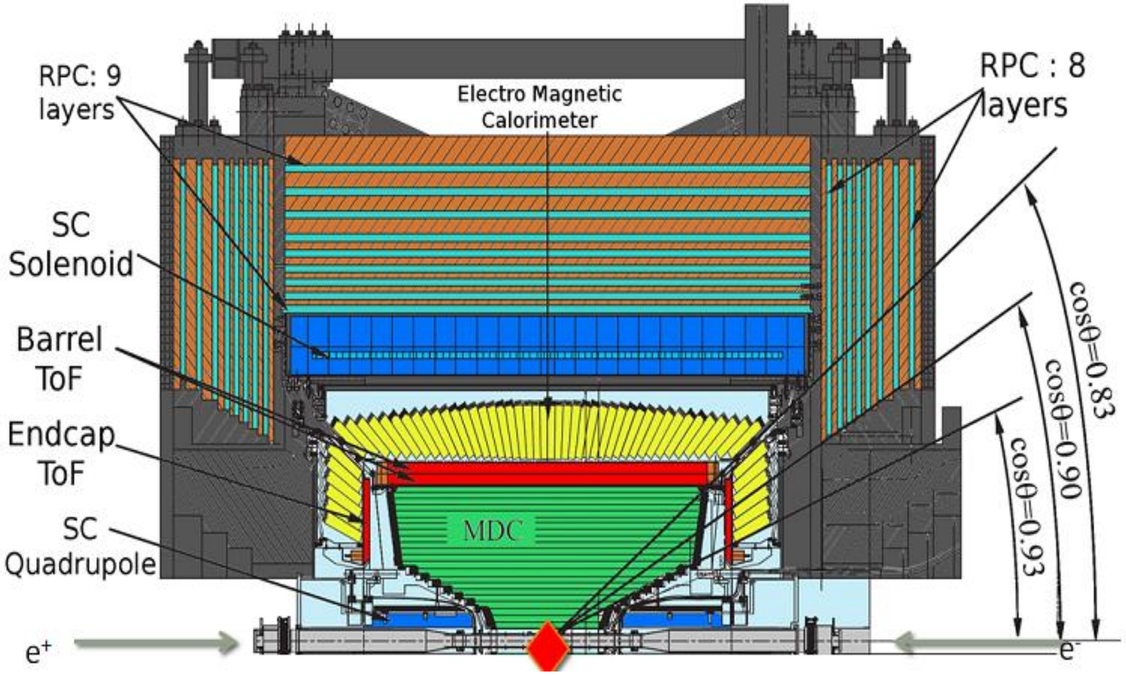


Double-ring, symmetry, multi-bunch $e^+ e^-$ collider

E_{cm}= 1.84 to 4.95 GeV

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

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



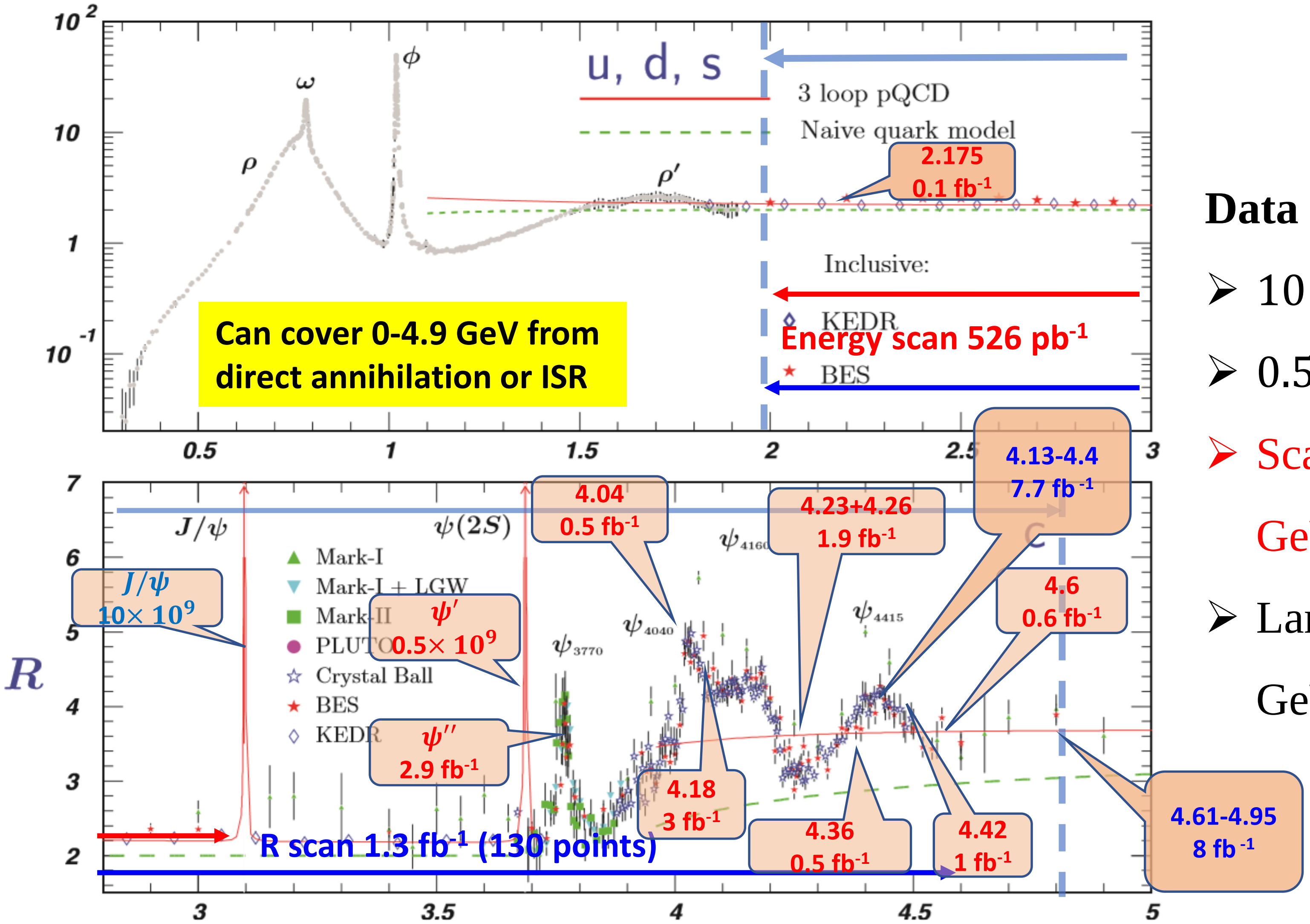
Main Drift Chamber
Small cell, 43 layer
σ_{xy}=130 μm
dE/dx~6%
σ_p/p= 0.5% at 1 GeV

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

Data samples collected at BESIII



Data sets collected so far include:

- 10×10^9 J/ψ events
- 0.5×10^9 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:

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

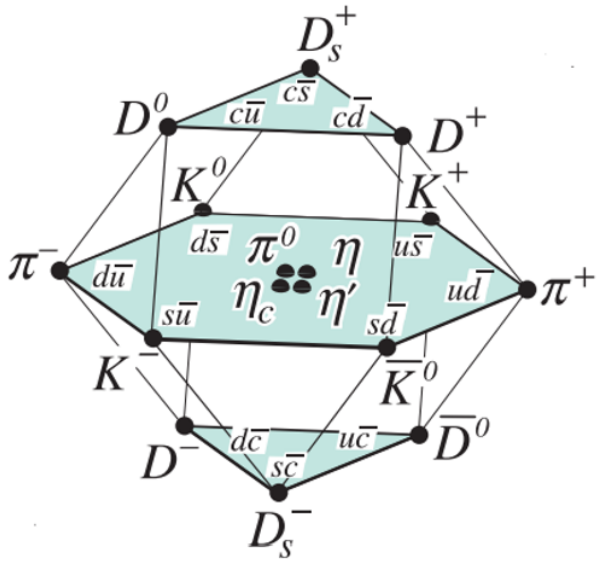
h is a particular type of hadron such as π^0, $\pi^{+/-}$, $K^{+/-}$ …

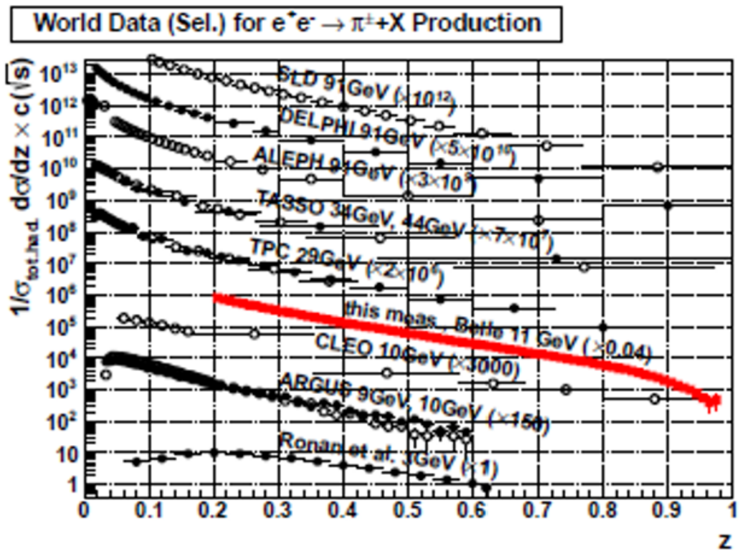
- At Leading order $\sim \sum_q e_q^2 D_1^{h/q}(z)$

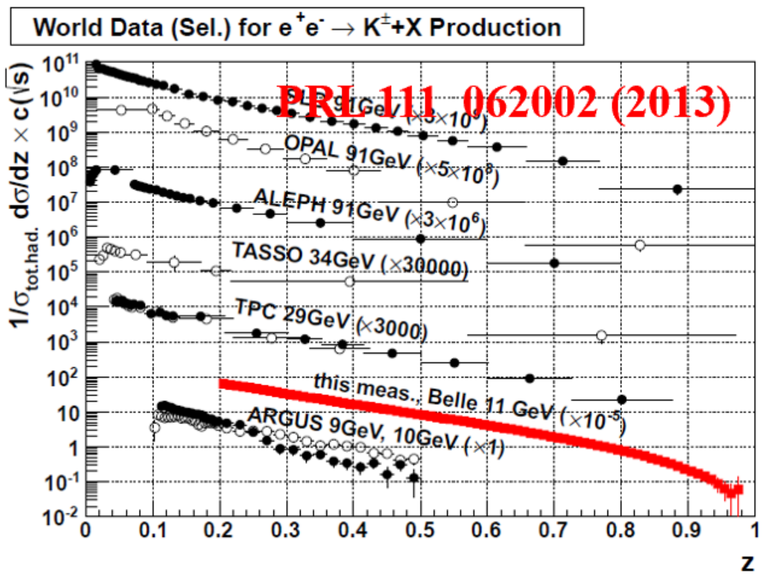
Unpolarized fragmentation function (*D*)

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

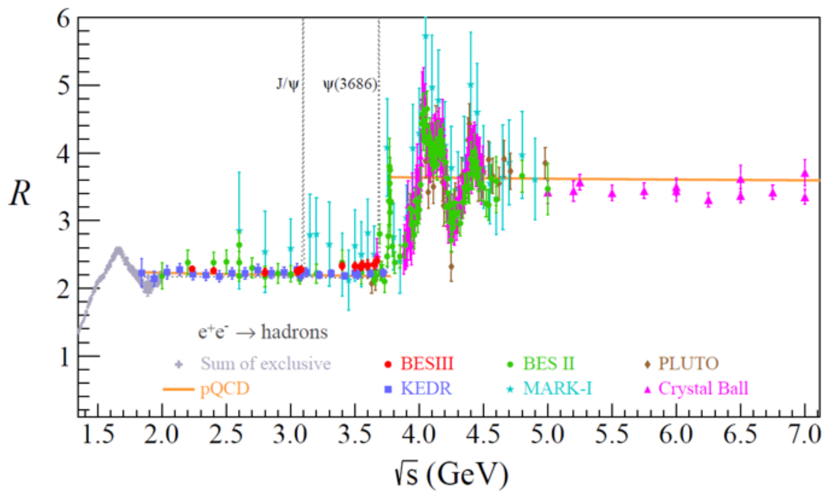
World π & K data on e^+e^-



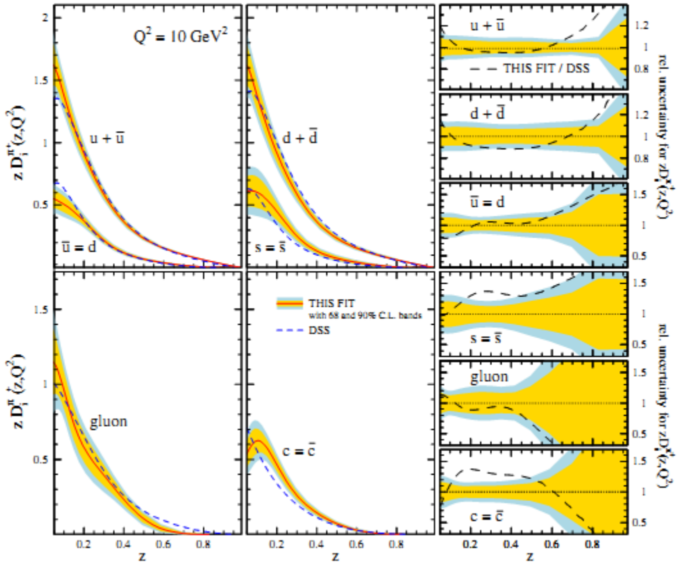




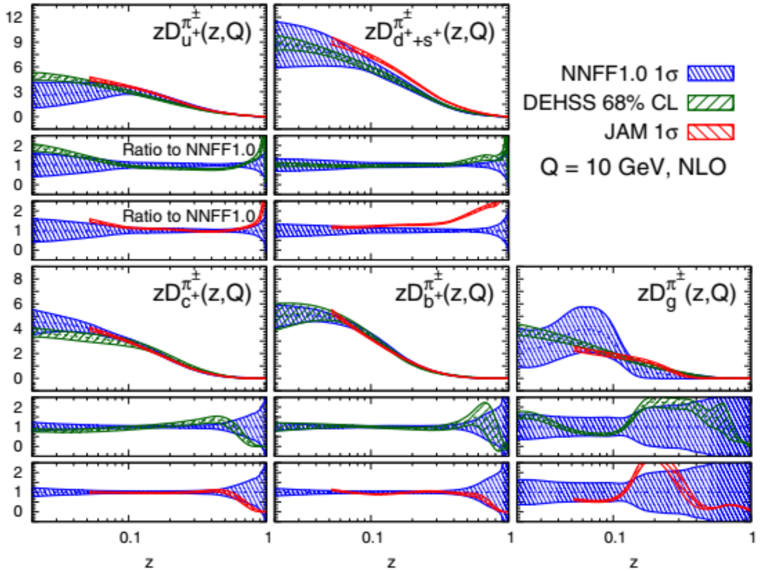
- Precision data includes charged π, K
- Data sets at $\sqrt{s}$ < 10 GeV e^+e^- collision ?
    - high z data sets ?
- R scan data @ BESIII: ~10 pb^{-1} @ each $\sqrt{s}$



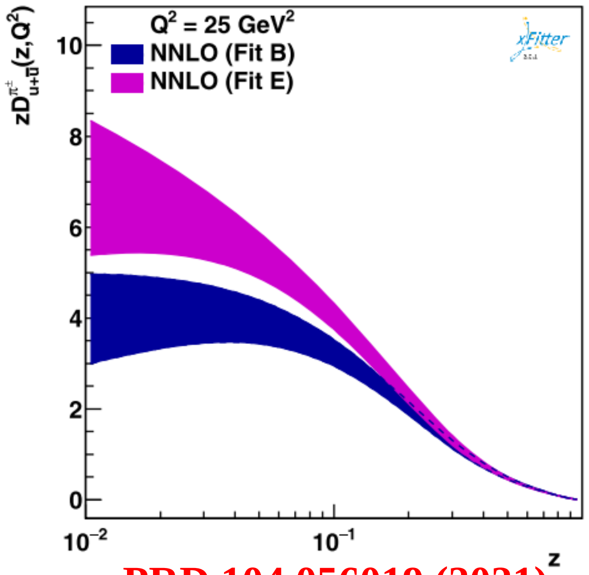
Pion FF: Best known FF



PRD 91 014015 (2015)

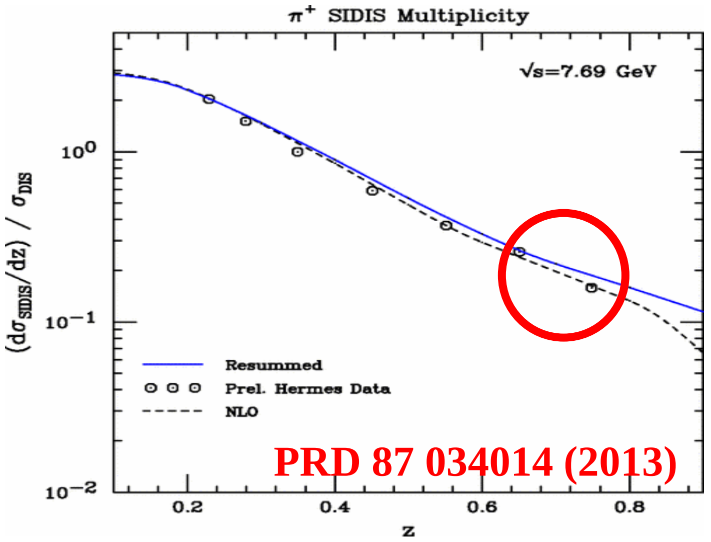


Eur.Phys.J.C77 516 (2017)



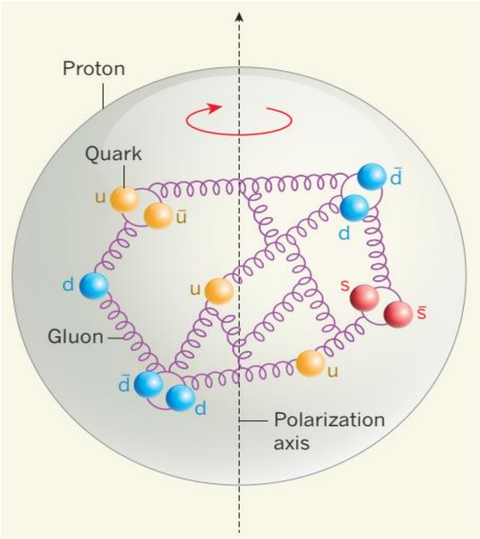
PRD 104 056019 (2021)

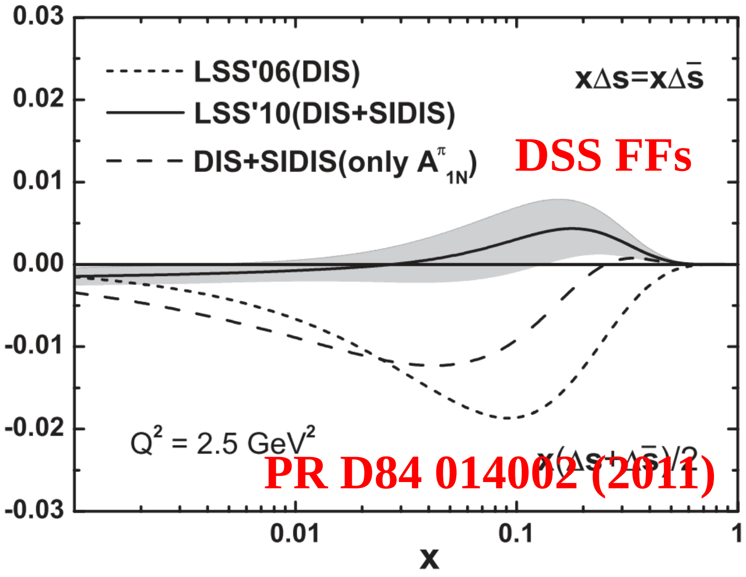
- For $z \geq 0.8$, uncertainty rapidly increase because of the lack of experimental data
- Xfitter: data at $\sqrt{s}$ > 10 GeV e^+e^-
  - Low $\sqrt{s}$ e^+e^- data ?
- Large z re-summation
  - High z data ?

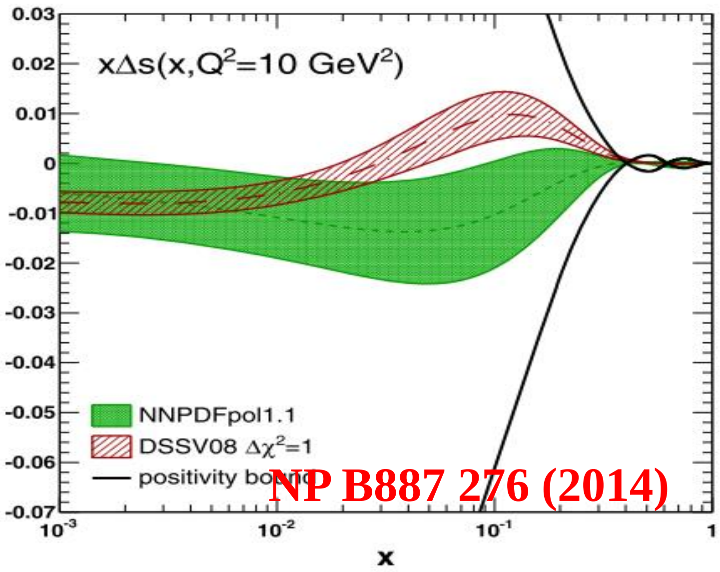


PRD 87 034014 (2013)

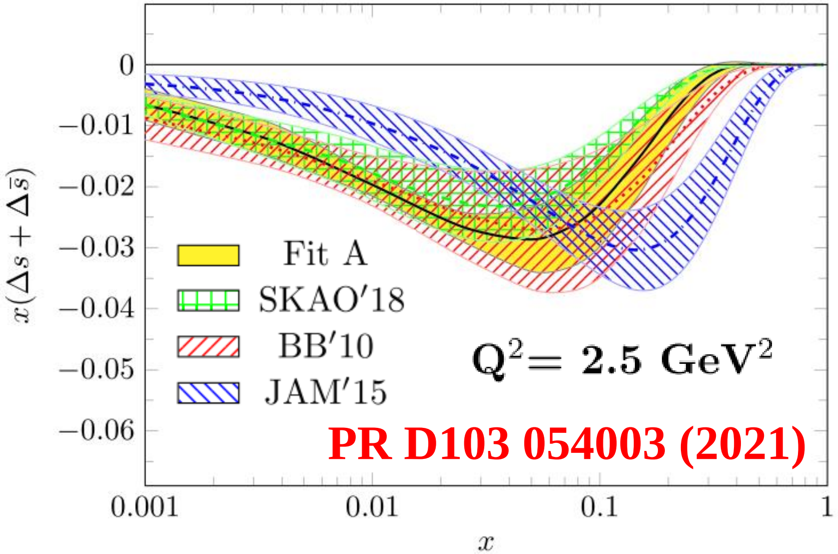
Strange quark polarization puzzle







- Strange quark density function: Δs(x)+Δs̄(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

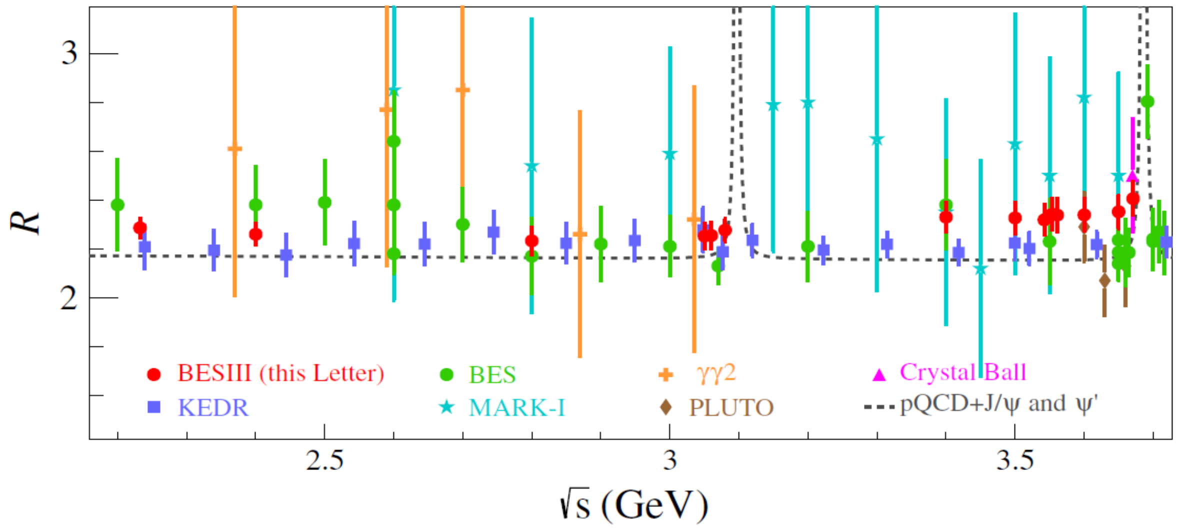


Analysis at BESIII

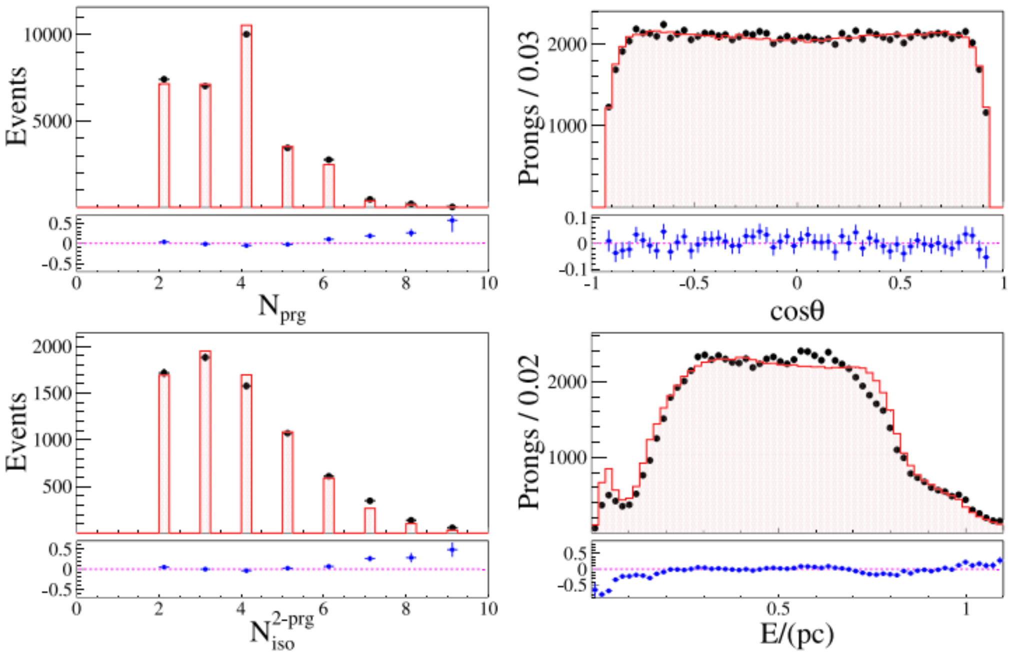
- Normalized differential cross section (take π^0 as an example):

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

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

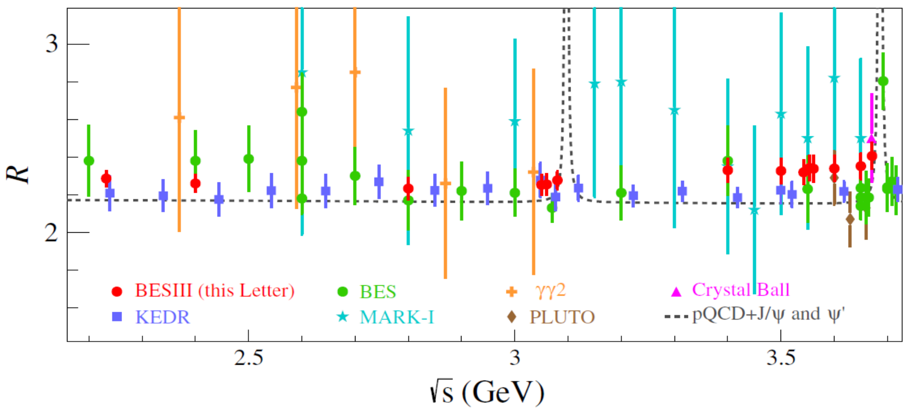


PRL 128 062004(2022)

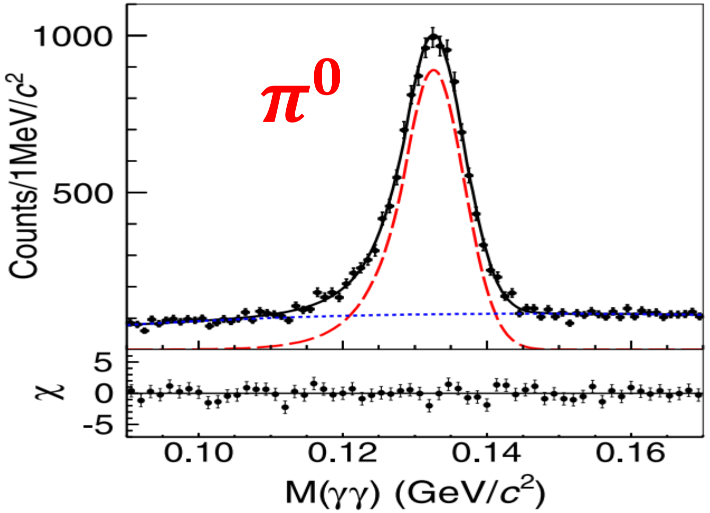


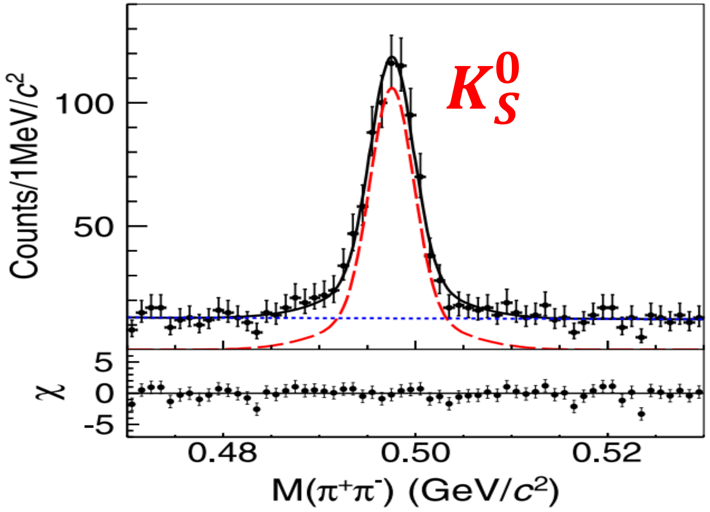
LUARLW MC generator

Inclusive π^0/K_S^0 production

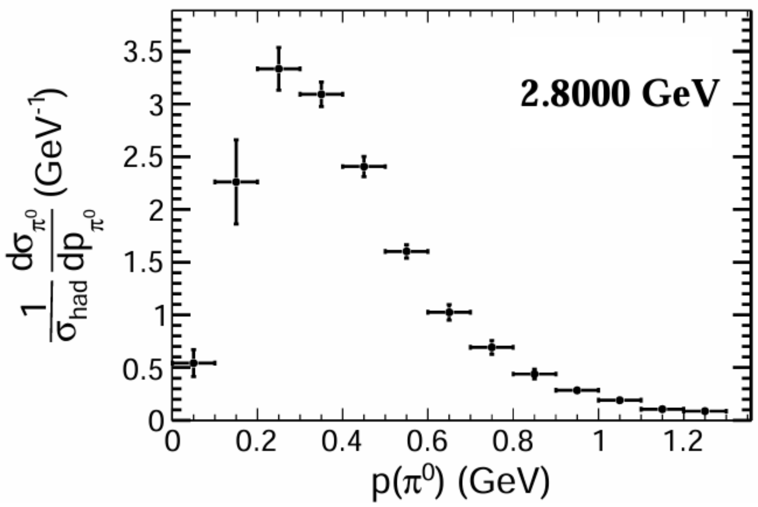


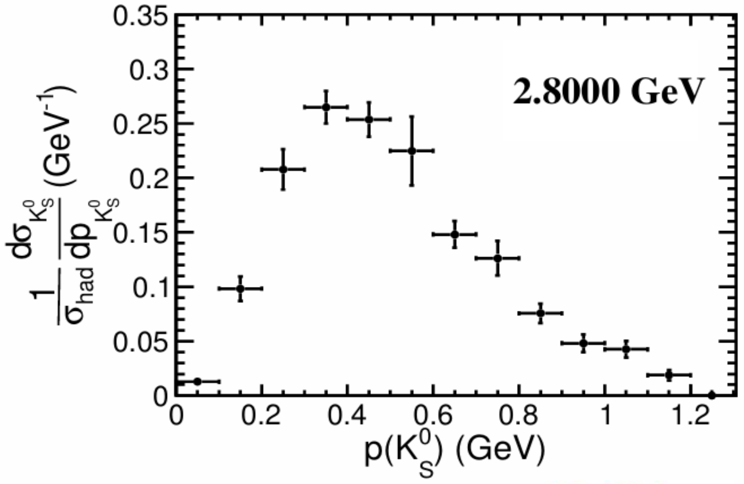
$p \in (0.4, 0.5)$ GeV





$\sqrt{s}$ (GeV)	$\mathcal{L}$ (pb^{-1})	$N_{\text{had}}^{\text{tot}}$	N_{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





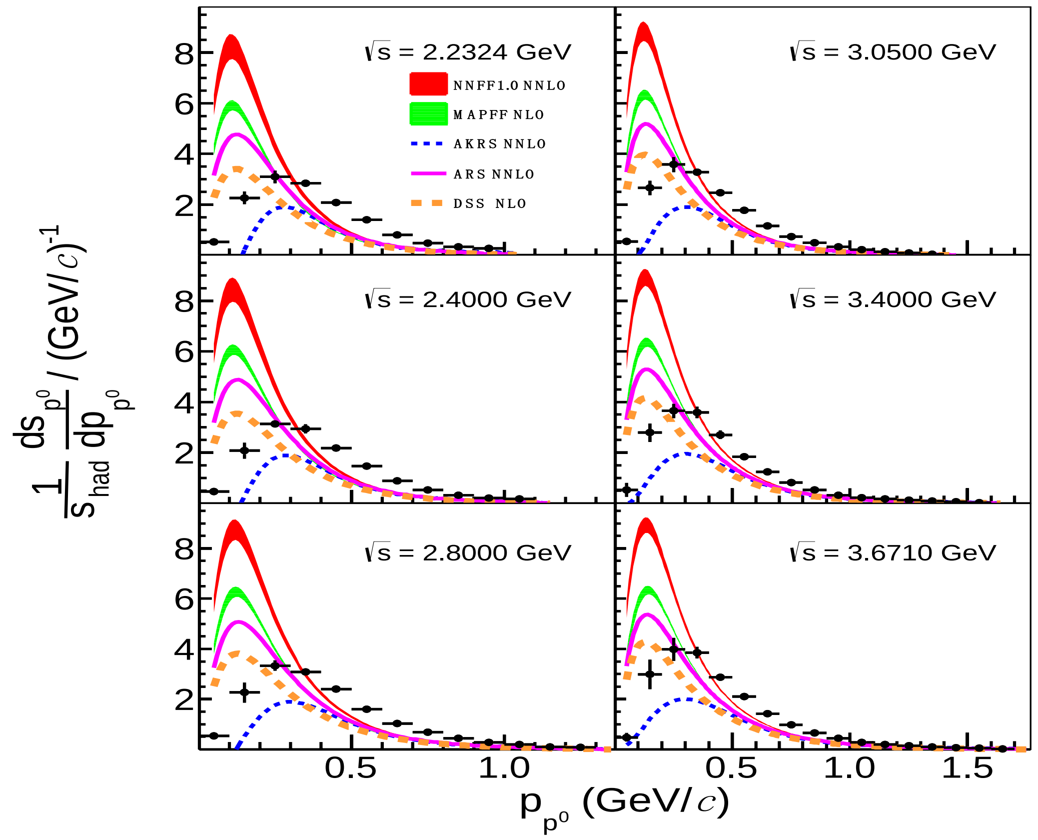
PRL 130 231901(2023)

Results: inclusive π^0/K_s^0

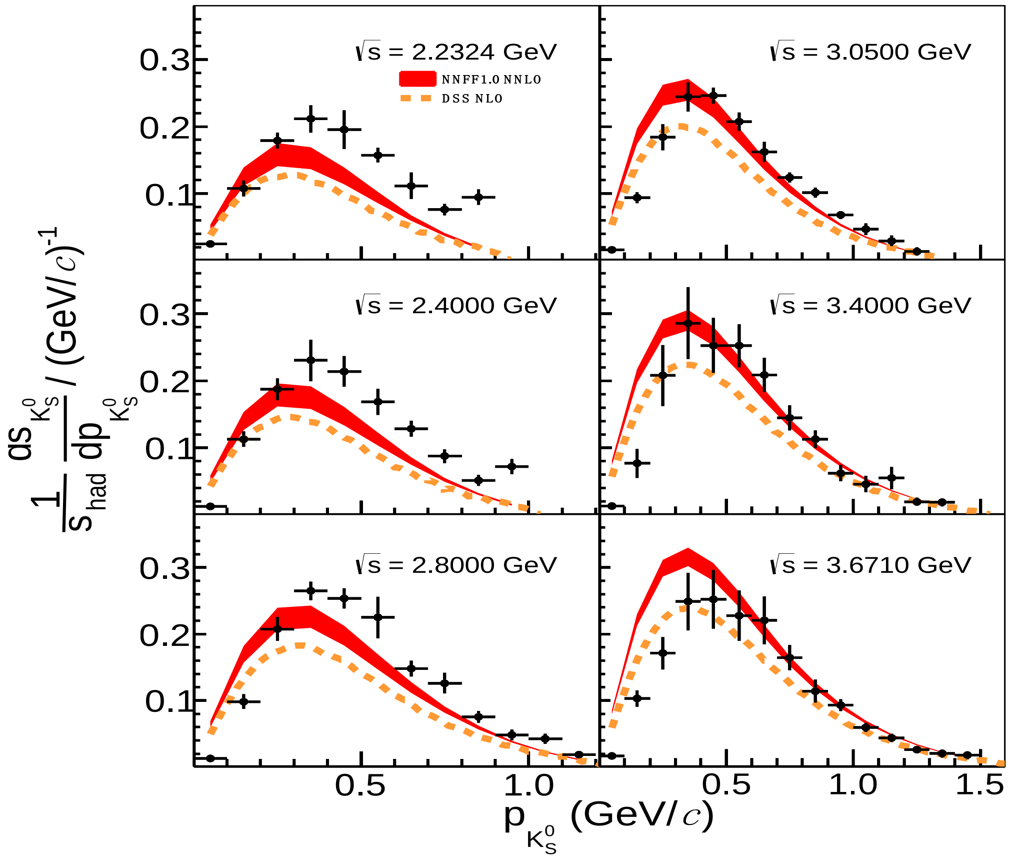
Theory support: Hongxi Xing, Daniele Anderle

Compared with theoretical estimation

π^0

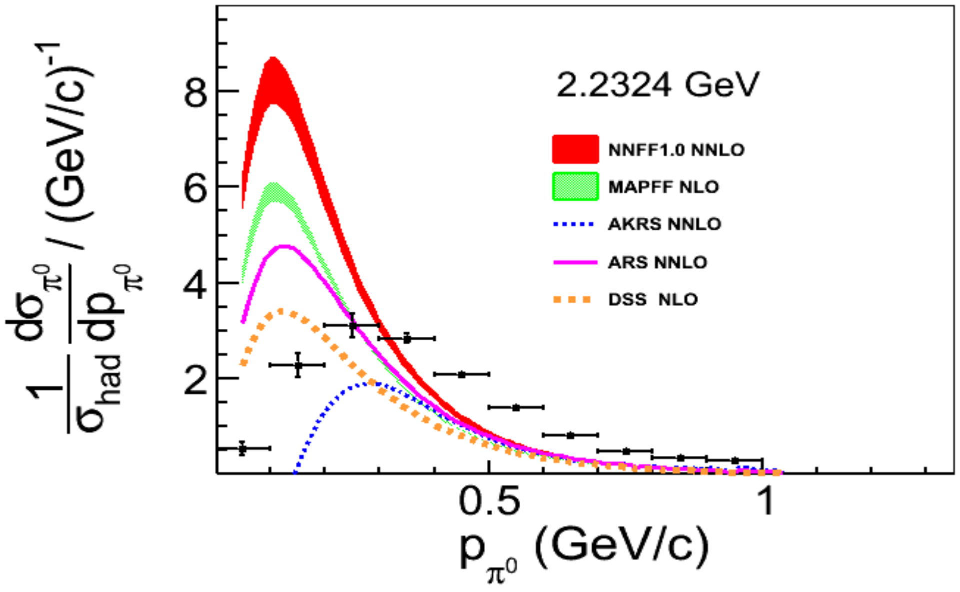


K_S^0



PRL 130 231901(2023) BESIII

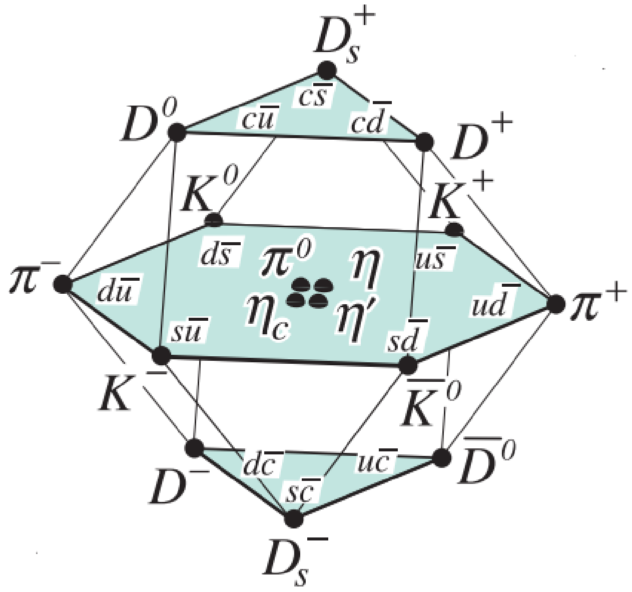
Results: inclusive π^0/K_s^0



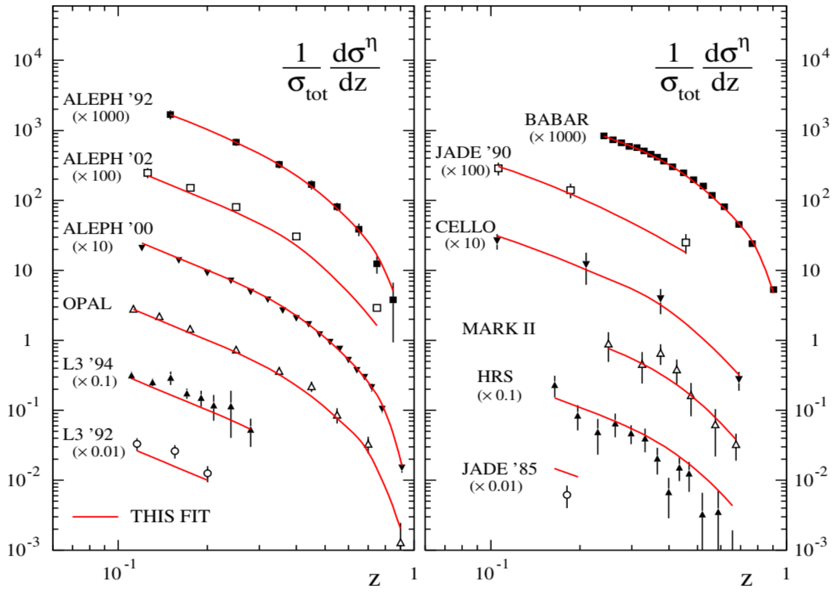
PRL 130 231901(2023)

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

World η data on e^+e^-

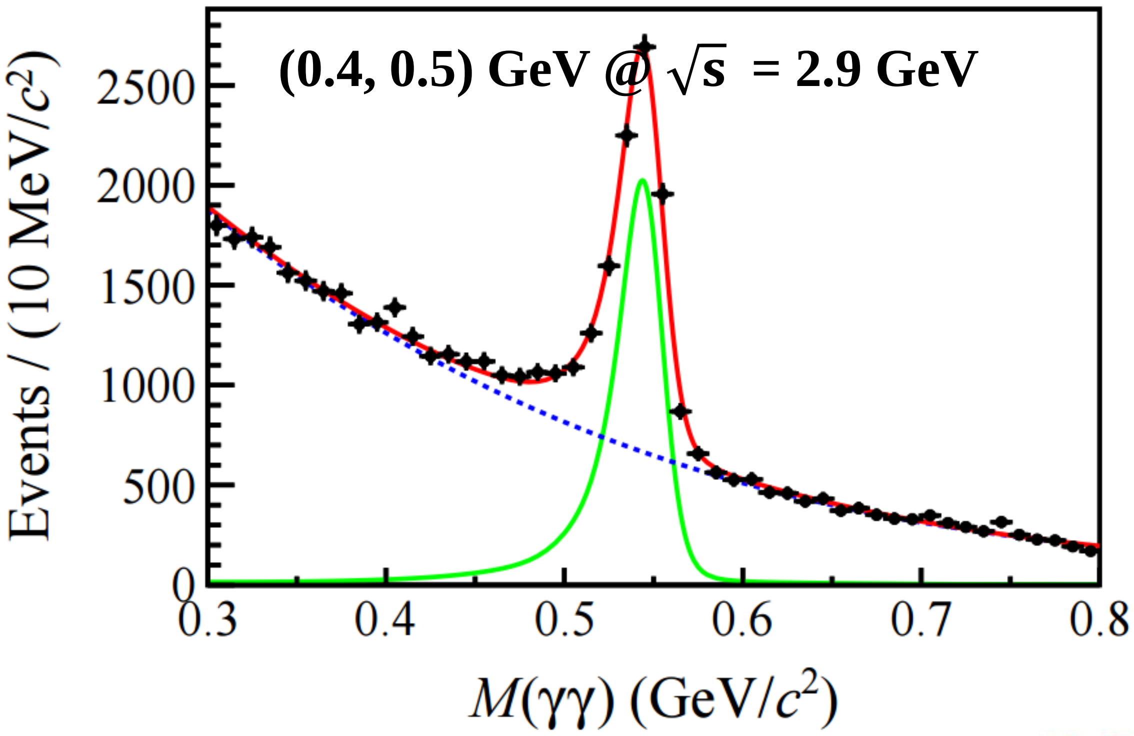


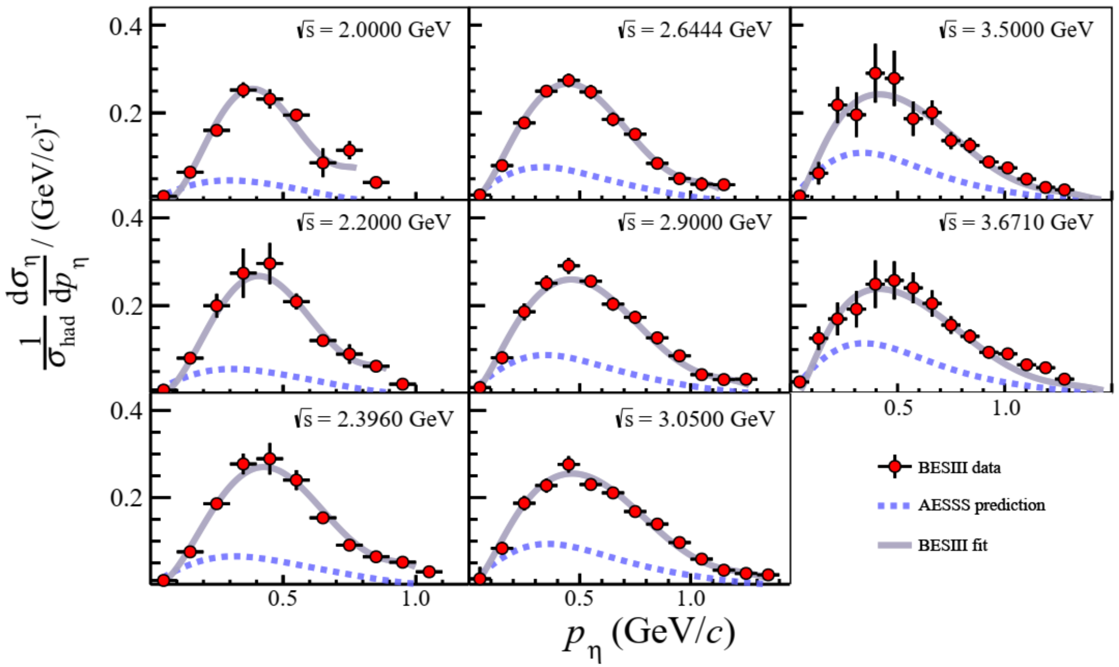
PRD83 (2001) 034002



- η FF @ NLO: data at $\sqrt{s}$ > 10GeV 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 at BESIII



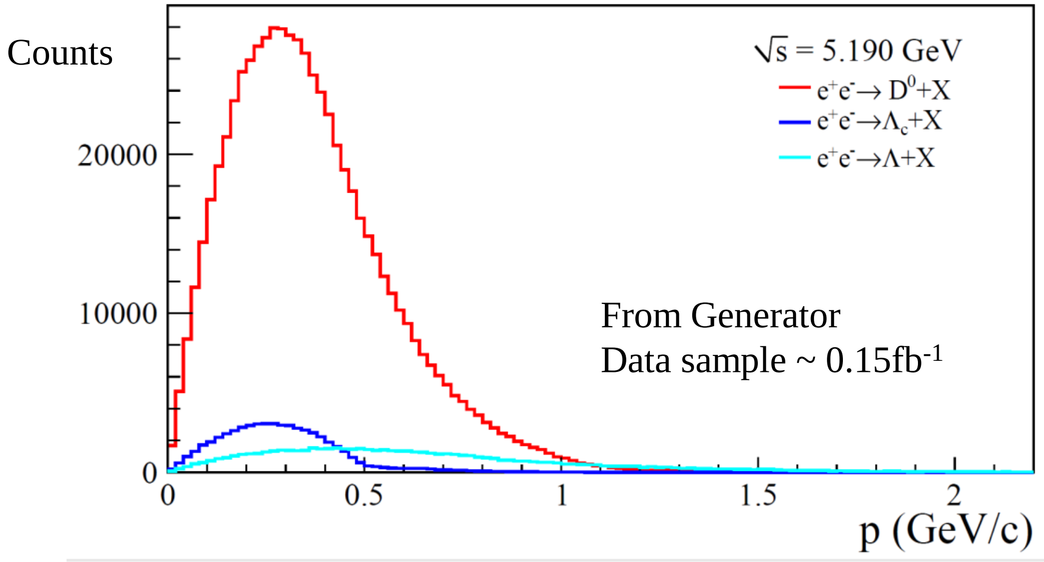


arXiv:2401.17873, accepted by PRL

- PRD83 (2001) 034002 prediction vs. BESIII data: tension !
- BESIII fit: detail @ arXiv:2404.11527
  - $\sqrt{s}$ > 10GeV e^+e^- data + BESIII data
  - NNLO accuracy, hadron mass correction & higher twist contributions

Prospects of FFs at BESIII

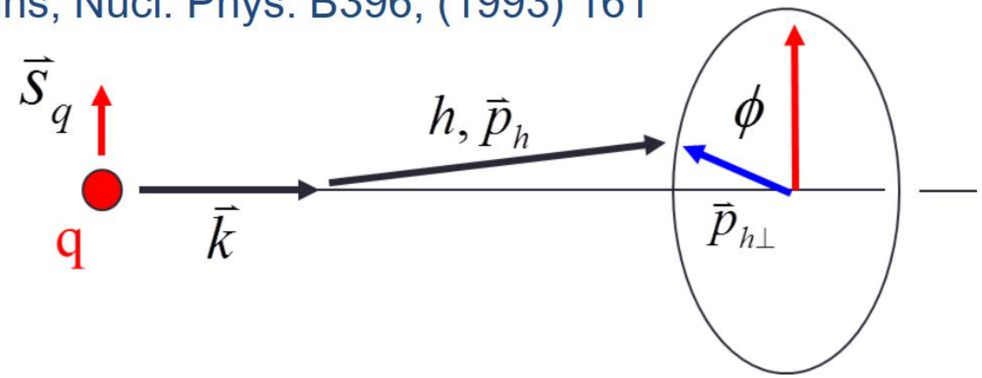
- **Higher center-of-mass energy**
  - Broader hard scale Q coverage
  - heavy flavors: Λ, Λ_c, D^0
  - Hadron mass correction is smaller



- **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)

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

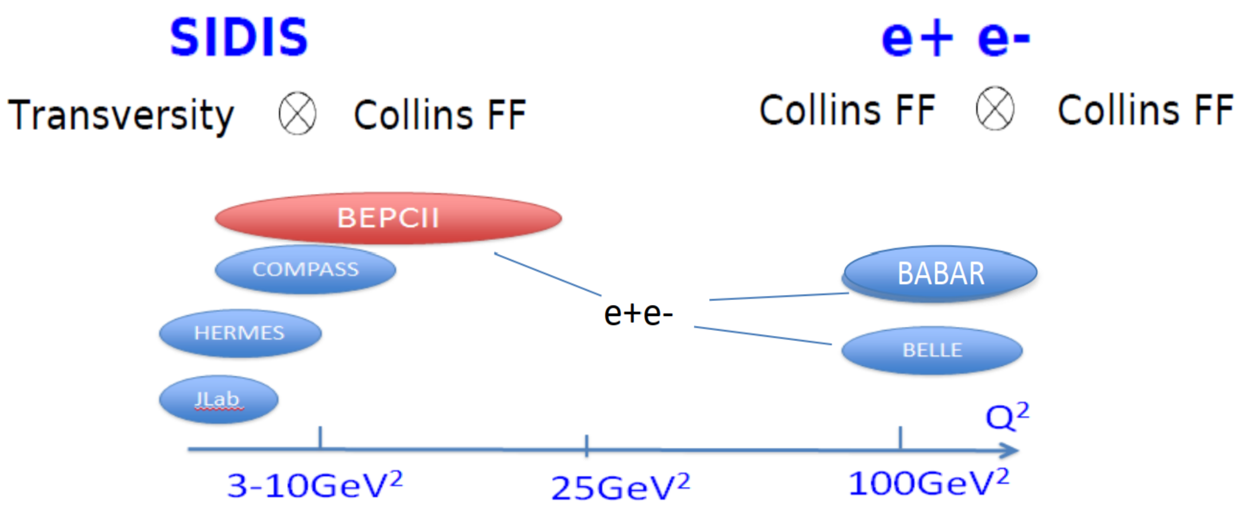
- The possibilities for finding a hadron produced from a transversely polarized quark:

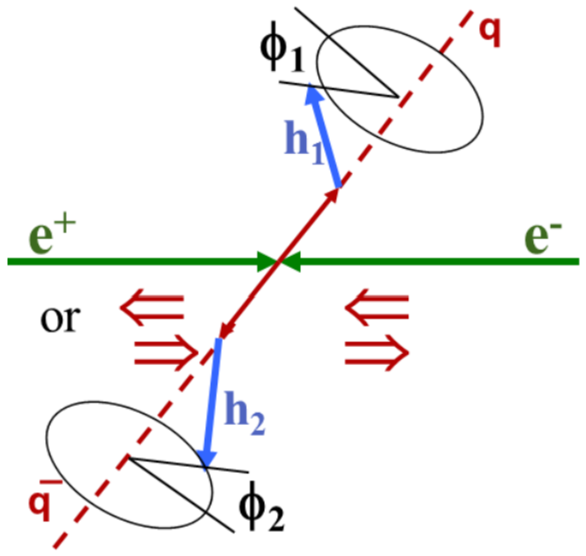
$$D_{hq^\uparrow}(z, P_{h\perp}) = D_1^q(z, P_{h\perp}^2) + H_1^{\perp q}(z, P_{h\perp}^2) \frac{(\hat{\mathbf{k}} \times \mathbf{P}_{h\perp}) \cdot \mathbf{S}_q}{z M_h},$$

- 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



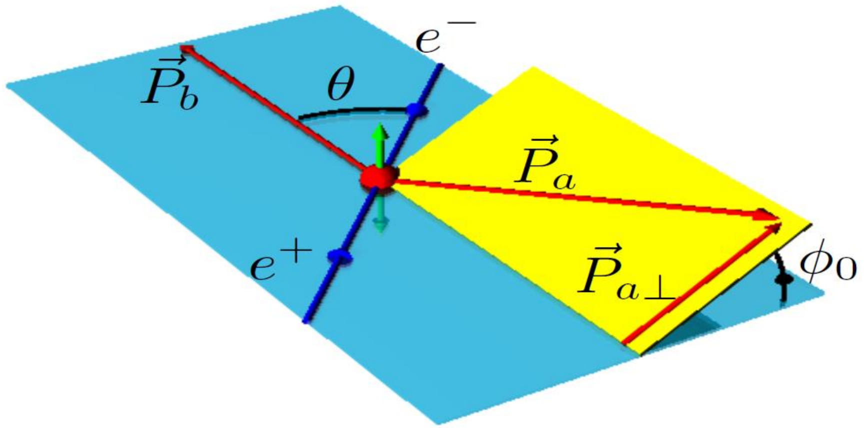


- At BESIII, the correlation of quark and anti-quark Collins functions are searched with back-to back hadrons:

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

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

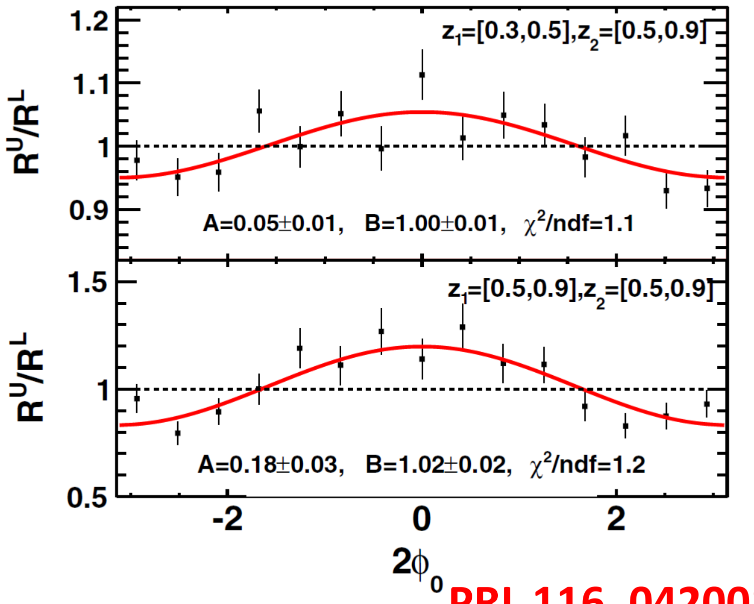
Collins effects at BESIII

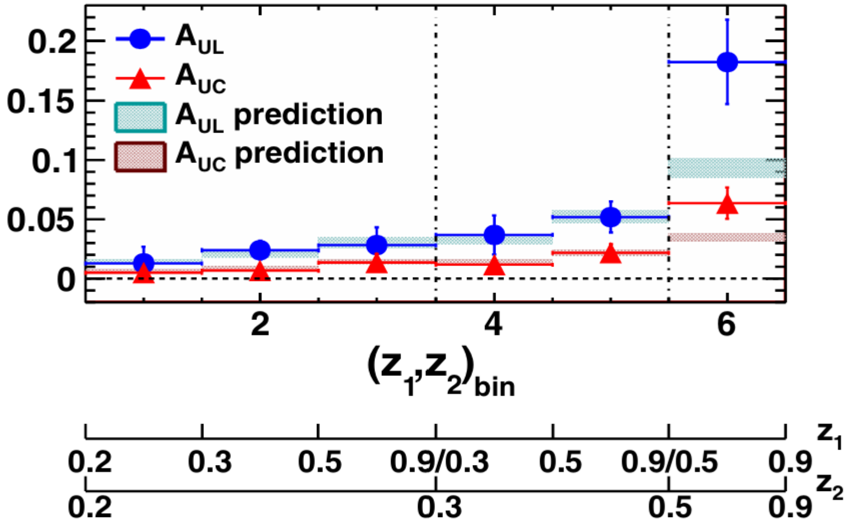


To avoid detection-related effects, experimentally, a double ratio measurement was proposed:

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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BESIII

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 charged π/K and heavy flavor
  - ➢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