Fragmentation Functions study at BESIII/STCF

1

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Special thanks to:

Weiping Wang, Wenbiao Yan, Yateng Zhang, Xiaorong Zhou

Xiaorui Lv, Binlong Wang, Yangheng Zheng

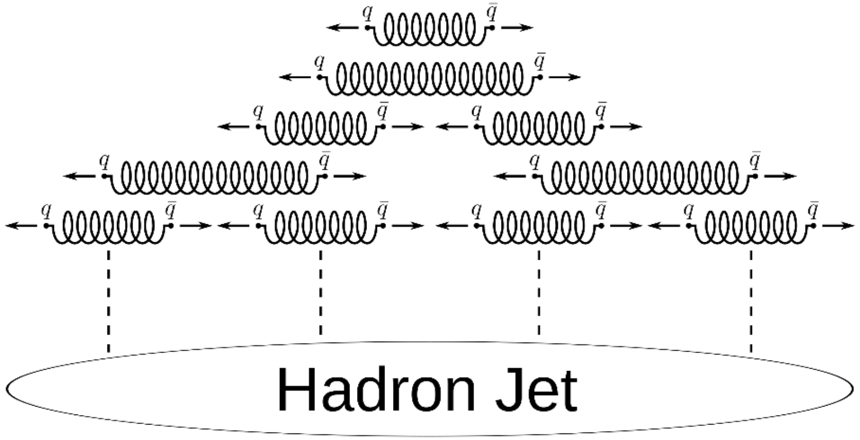
Outline

- Introduction of Fragmentation Functions
  - Existing studies at BESIII

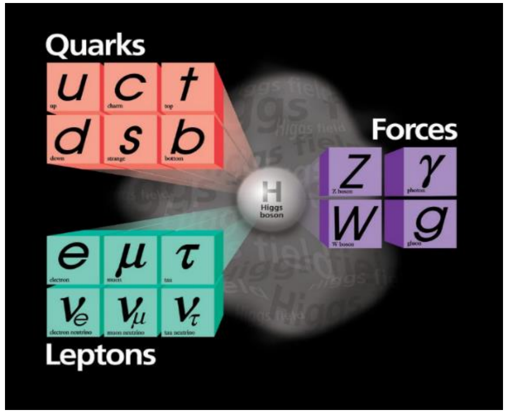
- Potential at STCF

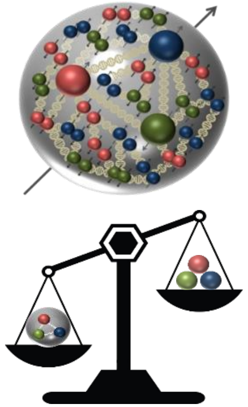
Several open questions about QCD

- 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

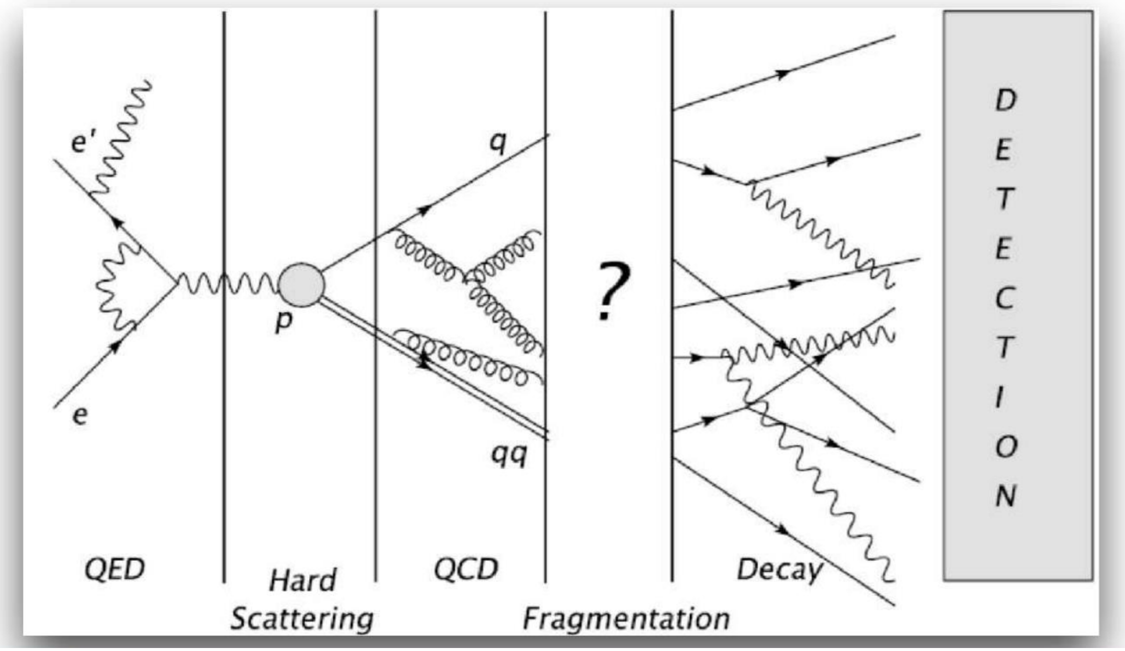




Spin:
How does nucleon spin emerge

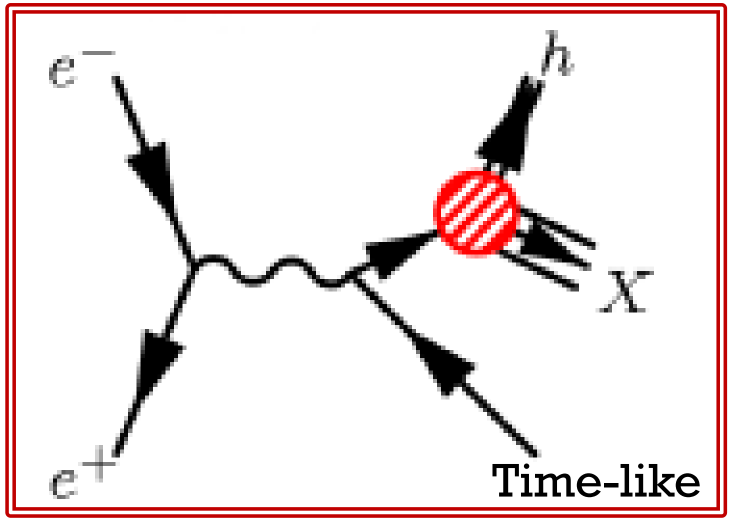
Mass:
Higgs mechanism gives only ~few%

FFs VS confinement

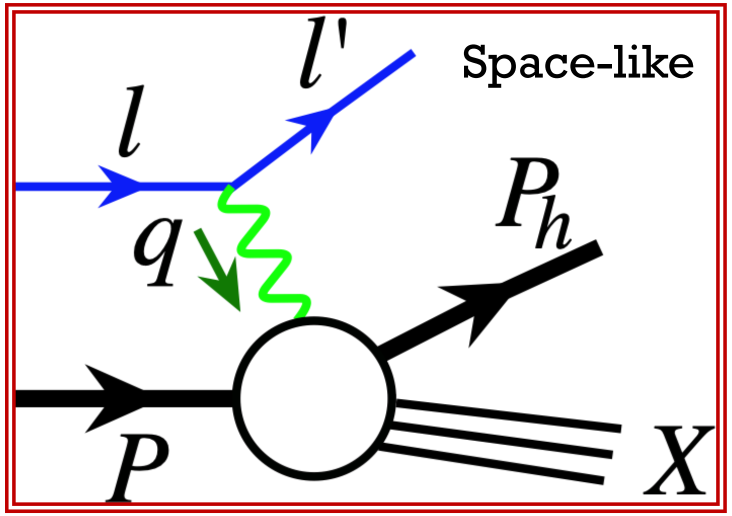


Non-perturbative QCD

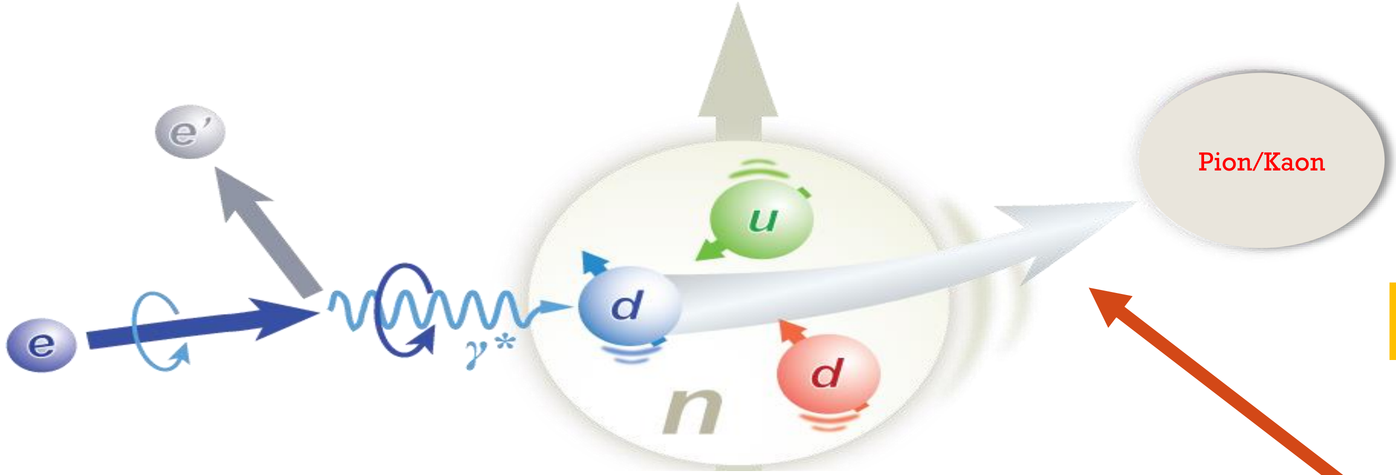
Without knowing how quarks fragment into hadrons,
we can't say we understand confinement



Universality



FFs VS Nucleon spin structure study



Important for flavor separations

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)

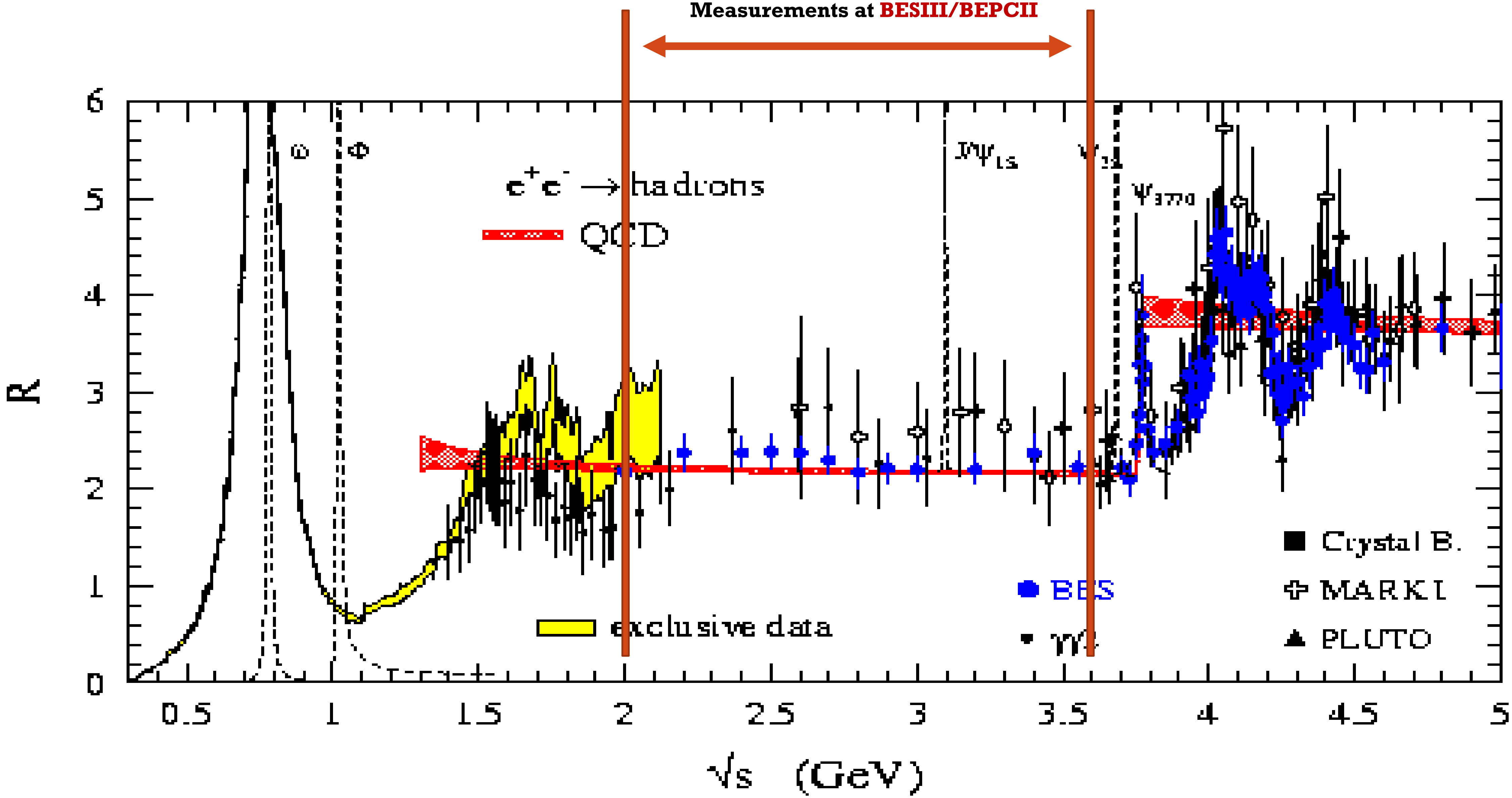
Extracted nucleon structure information: polarized PDFs (helicity distribution)

Fragmentation Functions studies at electron-positron colliders

PDG: "One of the cleanest ways to study FFs"

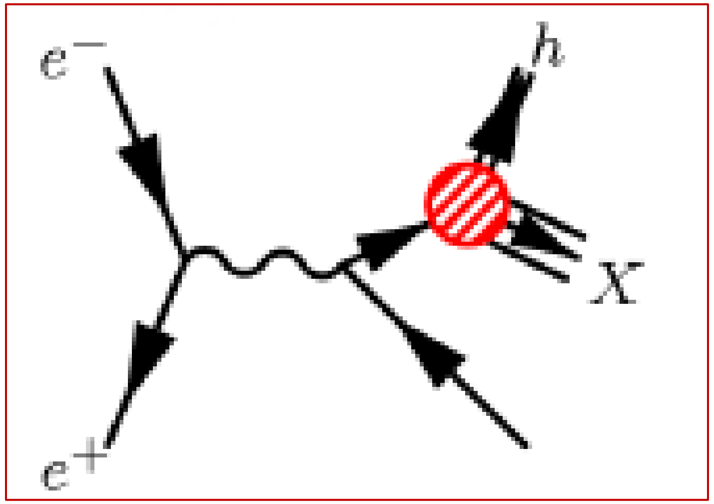
- Unpolarized fragmentation function (z, Pt dependence)
- Collins fragmentation function (Chiral odd)
- Spin-transfer fragmentation function (e.g., Lambda productions)
- Di-hadron fragmentation function (two hadron in a jet)
- TMD FFs in jet
- Higher-twist fragmentation function (multi-particle correlations in a jet)
- …

Measurements at BESIII/BEPCII

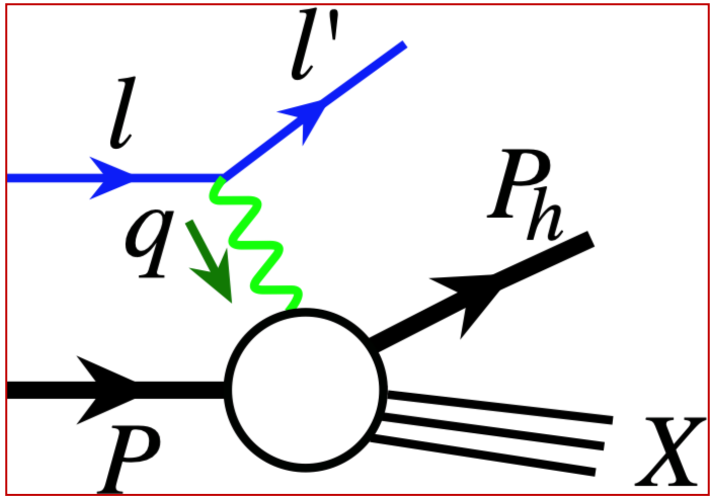


➤Unpolarized fragmentation function

Time-like



Space-like



Study unpolarized fragmentation functions at e^+e^- colliders

Experimental observable at e^+e^- colliders:

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

Multiplicity

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

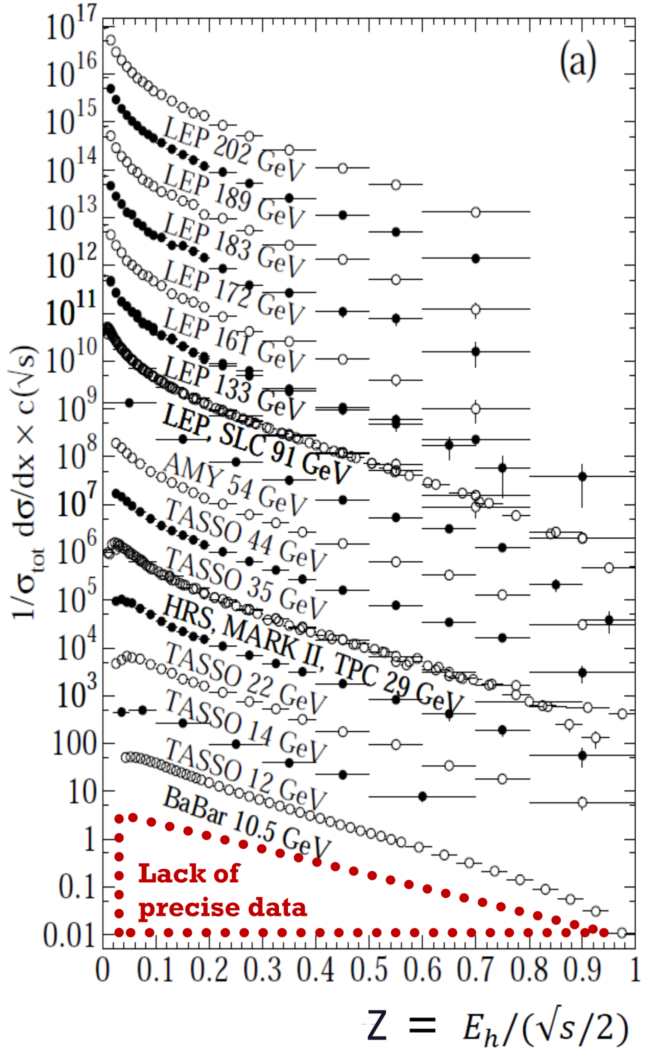
At Leading order $\sim \sum_q e_q^2 D_1^{h/q}(z)$

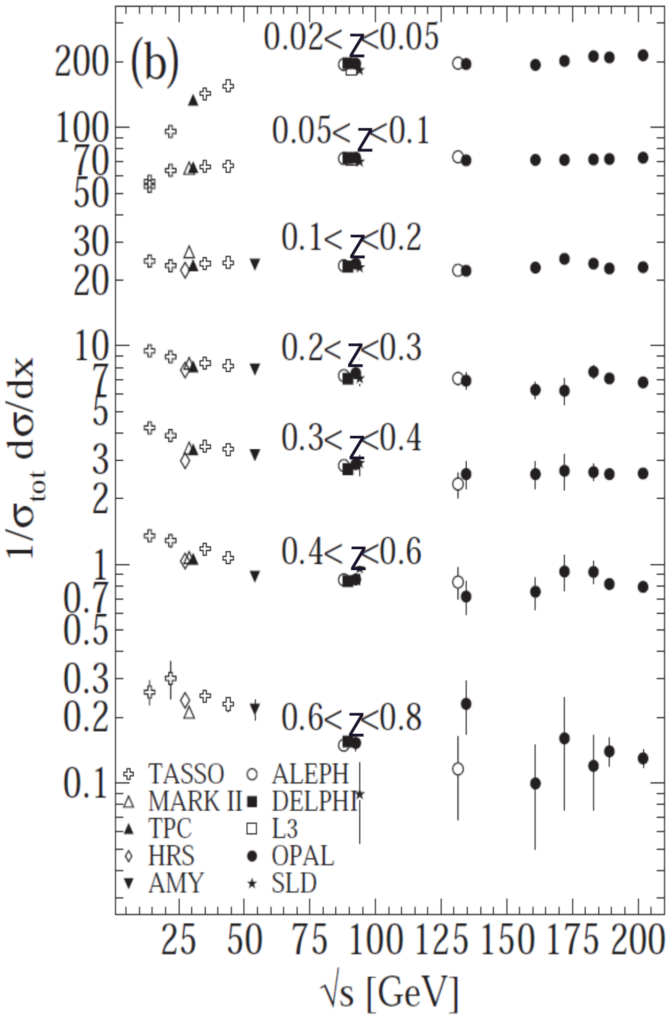
It can also be measured through electron-proton collisions by looking at multiplicities (Universality property)

World data

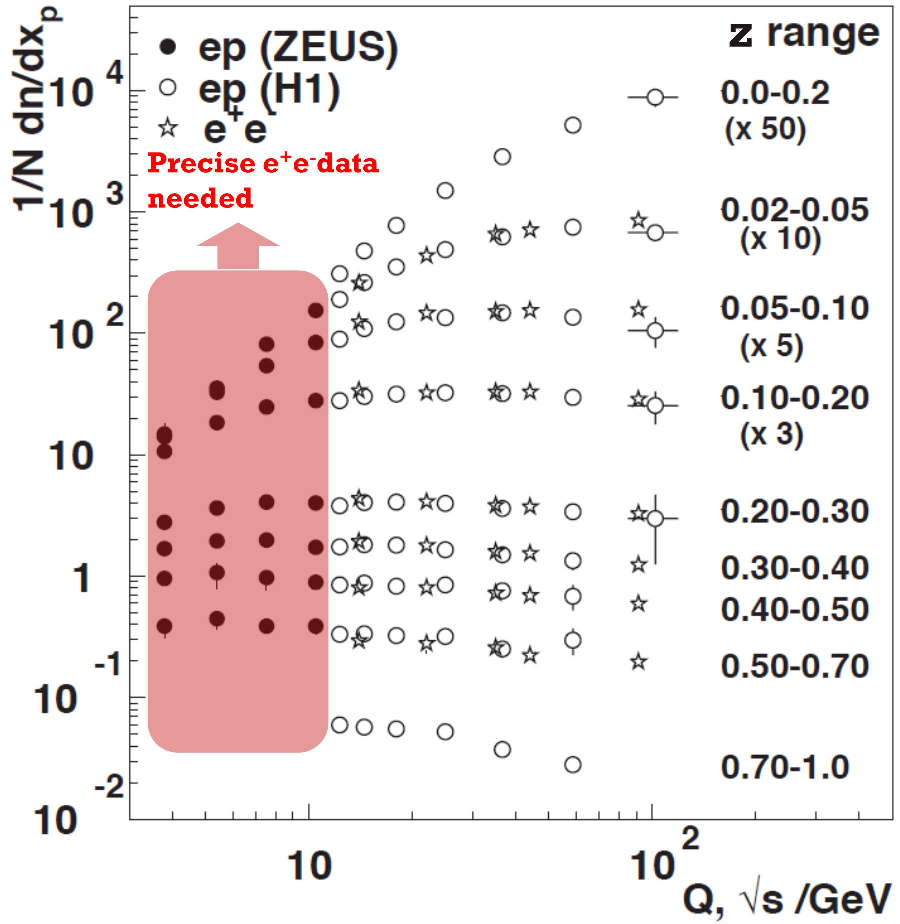
Lack of precise data at low energy region

- **PLUTO: more than 40 years ago**
- **Stat. uncertainty: 18-41%**



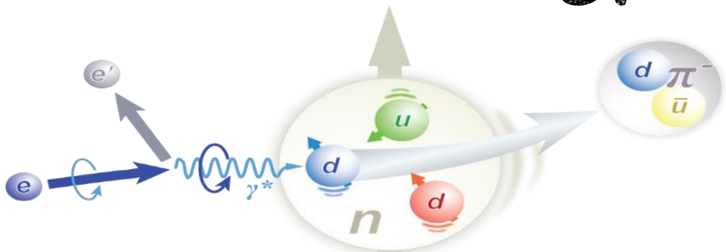


Bjorken scaling

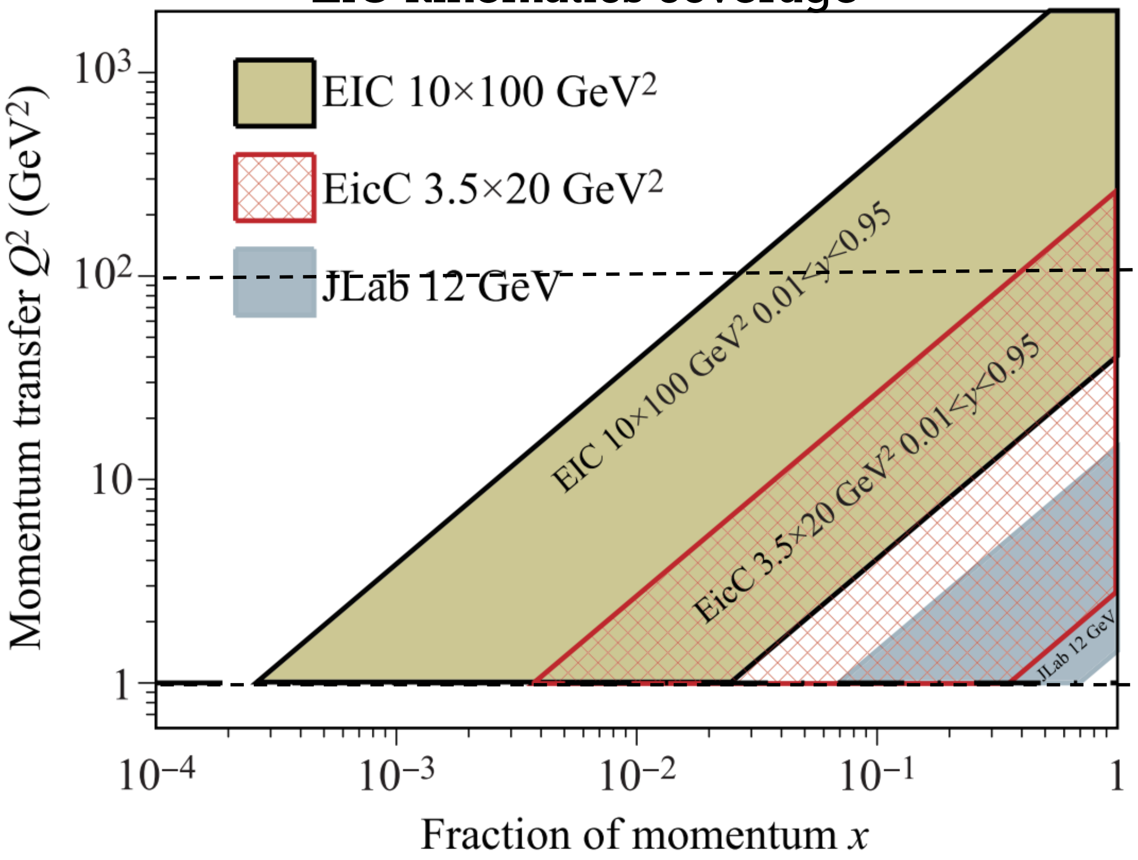


Universality check

FFs in the low energy region is important for EIC



EIC kinematics coverage



Measurements in e^+e^-

BELLE, BaBar, TASSO, LEP …

Almost no precision data on FF

Keep in mind: QCD back evolution is not reliable
This has been demonstrated for PDFs study

https://journal.hep.com.cn/fop/EN/10.1007/s11467-021-1062-0

Global data fit and "Universality"

- Parameterization are fitted to particles that reached detectors

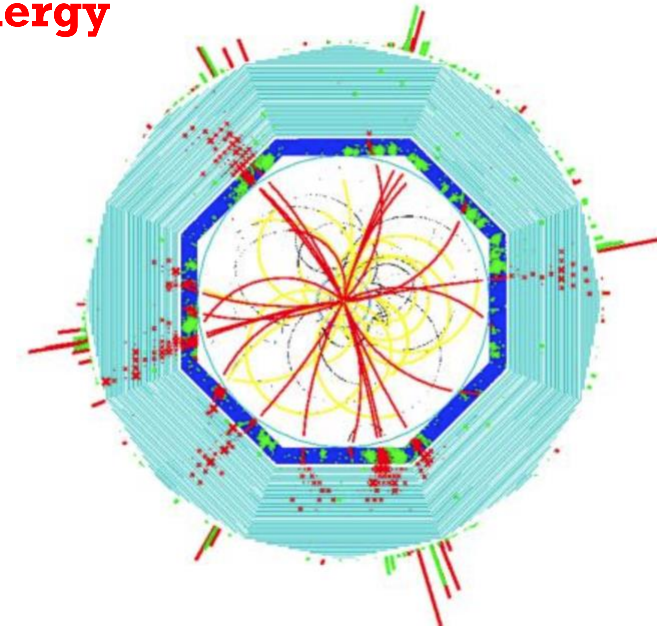
A good parameterization:

Depend on collider energy

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

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

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



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

Global data fit on unpolarized FFs

R.D. Field R.P. Feynman, *Phys.Rev.D* 15, 2590 1977
J.F. Owens E. Reya. M.Gluck, *Phys.Rev.D* 18, 1501 1978
R. Baier, J. Engels and B. Petersson, *Z.Phys.C 2*, 265 1979
M. Anselmino, P. Kroll E. Leader, *Z.Phys.C 18*, 307 1983
…

"model estimates consistent with data"

LO groundbreaking

P. Chiappeta et al. , *Nuc.Phys.B 412*, 3 1994	π^0	CGGRW94
J. Binneweis. B. Kniehl, G. Kramer, *Z. Phys. B 65*, 471 1995	"$\pi^\pm$, $K^\pm$"	BKK95
J. Binneweis. B. Kniehl, G. Kramer, *Phys. Rev. D 52*, 4947 1995	"$\pi^\pm$, $K^\pm$LEP"	
J. Binneweis. B. Kniehl, G. Kramer, *Phys. Rev. D 53*, 3553 1996	K^0	
D. de Florian. M.Stratmann, W.Vogelsang, *Phys. Rev. D 57*, 5811 1998	Λ^0	DSV97
L. Bourhis et al. , *Eur. Phys. J.C 19*, 89 2001	$h^\pm$	BFGW00
B. Kniehl G. Kramer, B. Potter, *Nuc. Phys. B 582*, 514 2000	" $\pi^\pm$ $K^\pm$, $p/\bar{p}$ "	KKP00
S. Kretzer, *Phys. Rev. D 62*, 4001 2000	"flavor tagging"	KRE00
S. Albino, S. Kniehl, G. Kramer, *Nuc. Phys. B 785*, 181 2005	"OPAL tagging"	AKK05
M. Hirai, et al., *Phys. Rev. D 75*, 4009 2007	"uncertainties "	HKNS07

… heavy flavors, hadron mass effects, resummations, …

NLO e^+e^- paradigm

C.o.M. energy > 10 GeV

D. de Florian, R.S., M. Stratmann , *Phys. Rev. D 75*, 4010 2007	"e^+e^-, pp, $SIDIS$"	DSS07
S. Albino, S. Kniehl, G. Kramer, *Nuc. Phys. B 803*, 42 2008	"e^+e^-, pp"	AKK08
R.S., M. Stratmann, P. Zurita , *Phys. Rev. D 81*, 054001 2010	" nFFs"	SSZ10
C. Aidala, et al., *Phys. Rev. D 83*, 034002 2011	" η "	AESS11
E. Leader, A.V. Sidorov, D. Stamenov, *arXiv:1312.5200*	"$SIDIS$ only"	LSS13
M. Soleymaninia et al., *Phys. Rev. D 88*, 054019 2013	"e^+e^-, $pSIDIS$ "	SKMNA13
D. de Florian et al. , *Phys. Rev. D 91*, 4035 2015, D 95 094019 2017	" $\pi^\pm$ $K^\pm$, update"	DSS14/17
E. Leader, A.V. Sidorov, D. Stamenov, *Phys. Rev. D96*, 074026 2016	" $SIDIS$ only"	LSS15

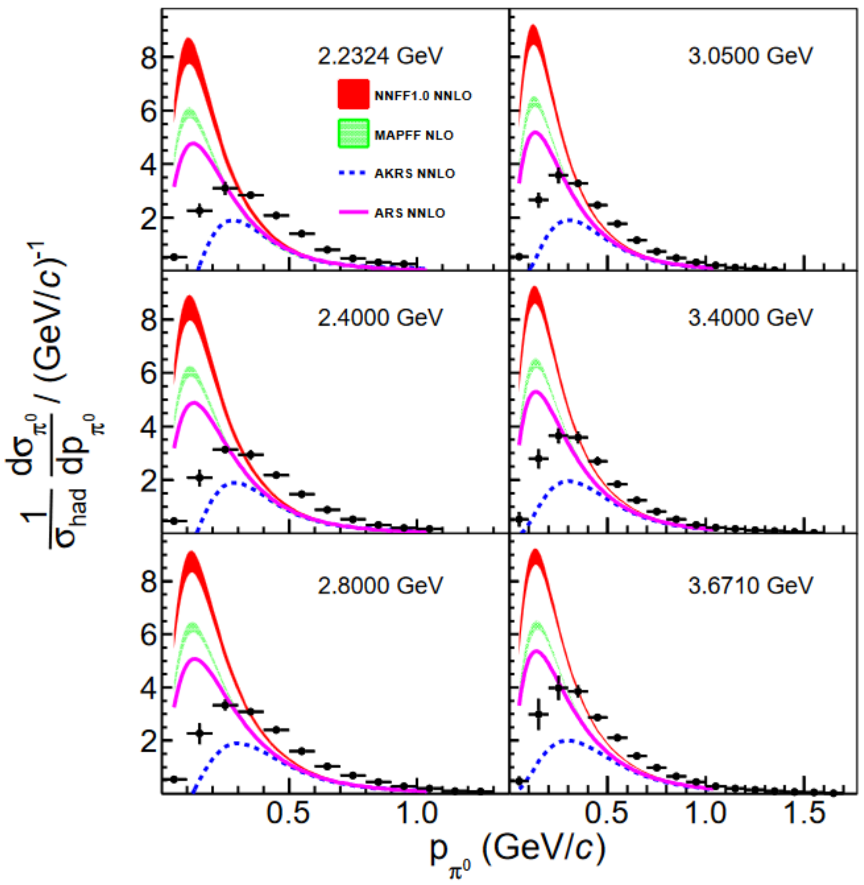
Global paradigm

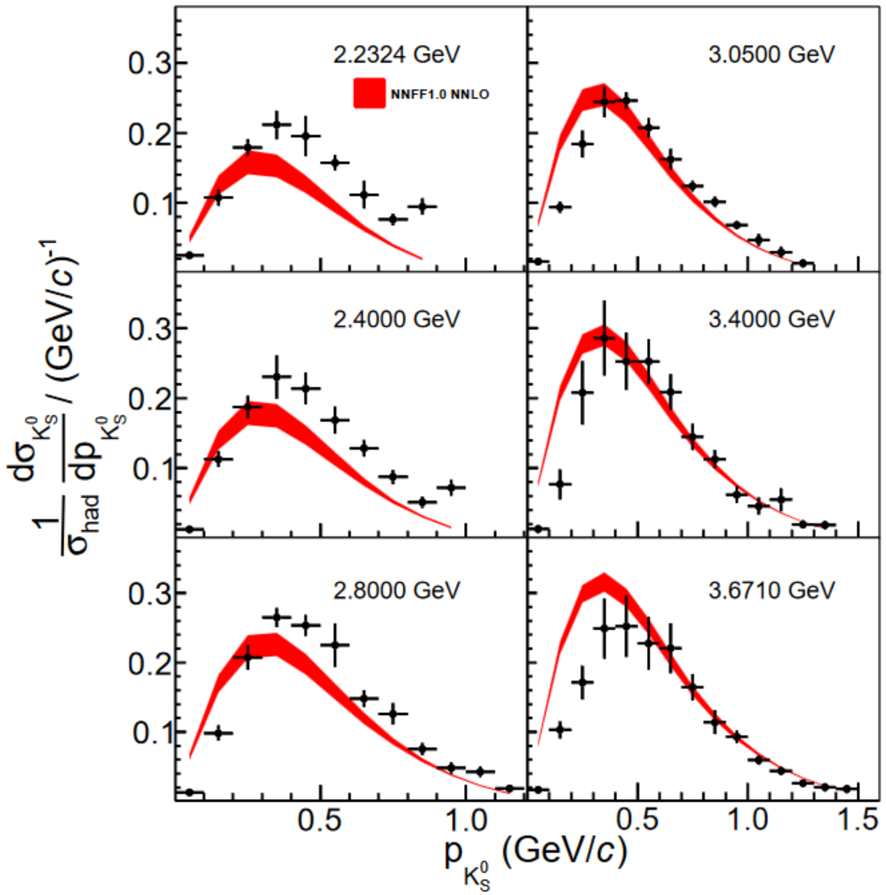
BESIII measurements

W. P. Wang, Y. T. Zhang, Y. X. Zhao, J. Zu
X. L. Gao, X. R. Zhou, W. B. Yan, G. S. Huang

arxiv: 2211.11253

Theory support: Hongxi Xing, Daniele Anderle





- Data VS theoretical predictions with FFs extracted using high energy collision data (C. o. M. > 10 GeV)
- A discrepancy has been observed, dependent on C. o. M. energy → higher energy at 5-7 GeV?
- A few more analyses are ongoing…

- **Collins fragmentation function (Chiral odd)**

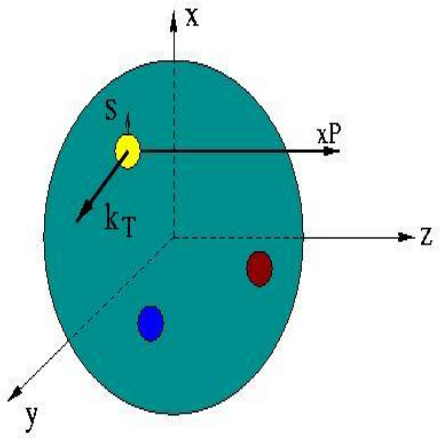
We have very little data from e^+e^- machine

3D-imaging of the nucleon

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

5D Dist.

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



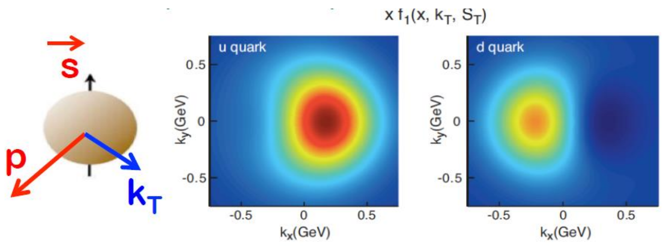
TMD PDFs

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

GPDs/IPDs

3D imaging

dx &
Fourier
Transformation



d^2k_T $\qquad$ d^2r_T

PDFs

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

1D

Form Factors

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

Leading-Twist 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

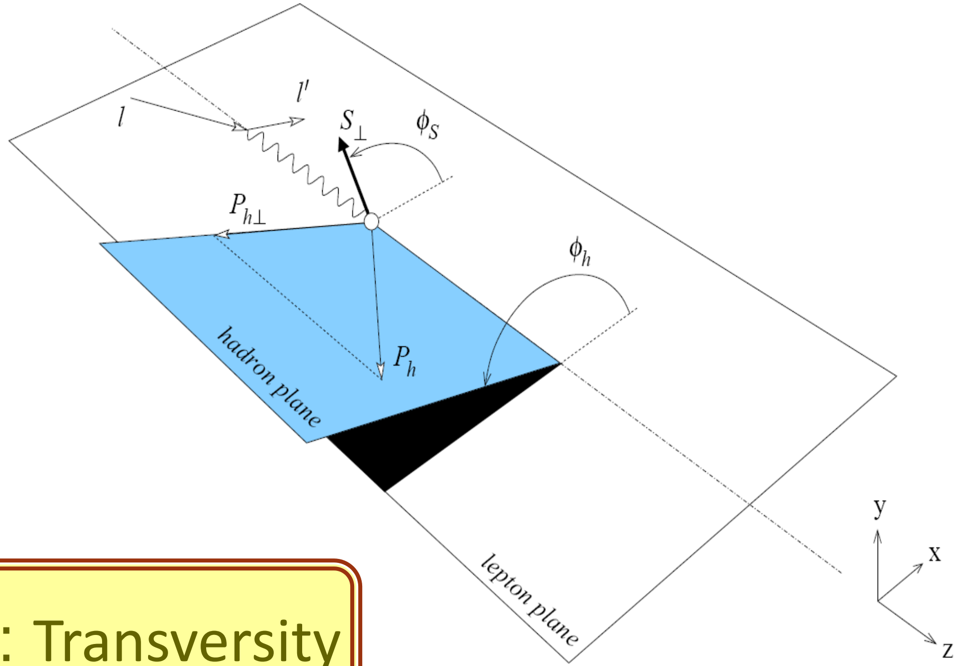
Survive the k_T integration, yield 1D pdfs

Separation of Collins, Sivers and Pretzelosity through azimuthal angular dependence

$$A_{UT}(\varphi_h^l, \varphi_S^l) = \frac{1}{P}\frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}$$

$$= A_{UT}^{Collins}\sin(\phi_h + \phi_S) + A_{UT}^{Sivers}\sin(\phi_h - \phi_S)$$

$$+ A_{UT}^{Pretzelosity}\sin(3\phi_h - \phi_S)$$



UT: **U**npolarized beam + **T**ransversely polarized target

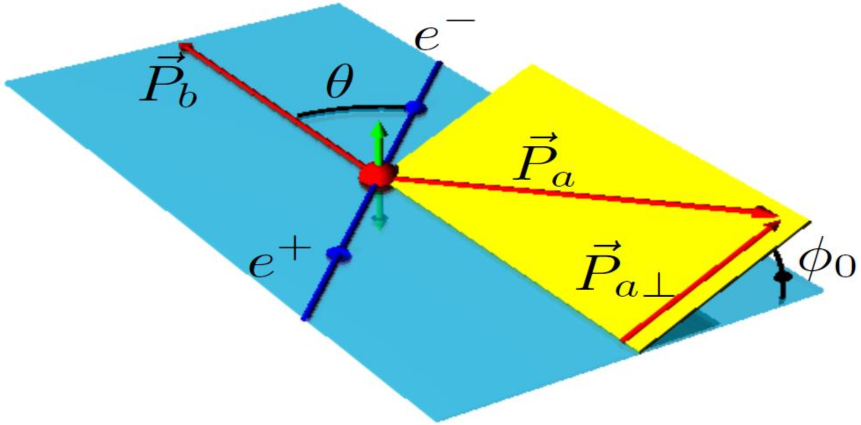
$$A_{UT}^{Collins} \propto \langle \sin(\phi_h + \phi_S) \rangle_{UT} \propto h_1 \otimes H_1^{\perp}$$ →TMD: Transversity

$$A_{UT}^{Sivers} \propto \langle \sin(\phi_h - \phi_S) \rangle_{UT} \propto f_{1T}^{\perp} \otimes D_1$$ →TMD: Sivers

$$A_{UT}^{Pretzelosity} \propto \langle \sin(3\phi_h - \phi_S) \rangle_{UT} \propto h_{1T}^{\perp} \otimes H_1^{\perp}$$ →TMD: Pretzelosity

Collins FF

Collins FF study at e^+e^- colliders



$$\frac{d^5\delta^{e^+e^-\to h_1h_2+X}}{dz_1dz_2d^2P_{h\perp}d\cos\theta} = \frac{N_c\pi\alpha_{em}^2}{2Q^2}\left[(1+\cos^2\theta)Z_{uu}^{h_1h_2} + \sin^2\theta\cos(2\phi_0)Z_{collins}^{h_1h_2}\right]$$
$$= \frac{N_c\pi\alpha_{em}^2}{2Q^2}(1+\cos^2\theta)Z_{uu}^{h_1h_2}\left[R^{h_1h_2}(z_1,z_2,\theta,P_{h\perp})\right]$$

$$R^{h_1h_2}(z_1,z_2,\theta,P_{h\perp}) = 1+\cos(2\phi_0)\frac{\sin^2\theta}{1+\cos^2\theta}\frac{Z_{collins}^{h_1h_2}}{Z_{uu}^{h_1h_2}}$$

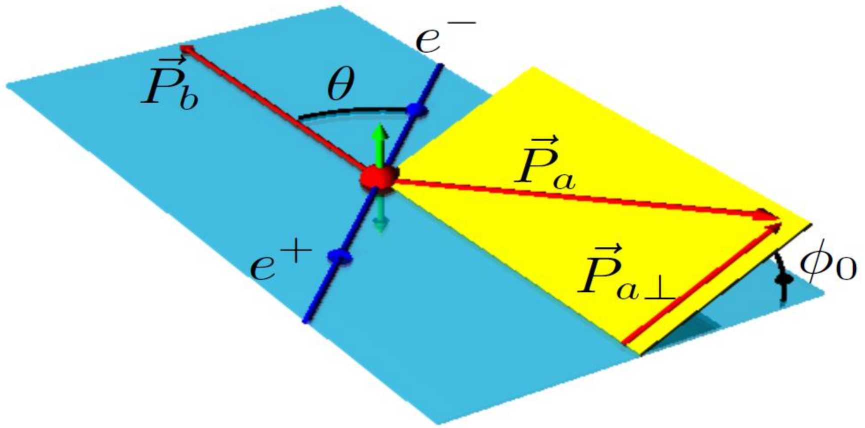
To avoid detection-related effects, experimentally, a double ratio measurement was proposed:

arxiv:1505.05589

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

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

Collins fragmentation functions



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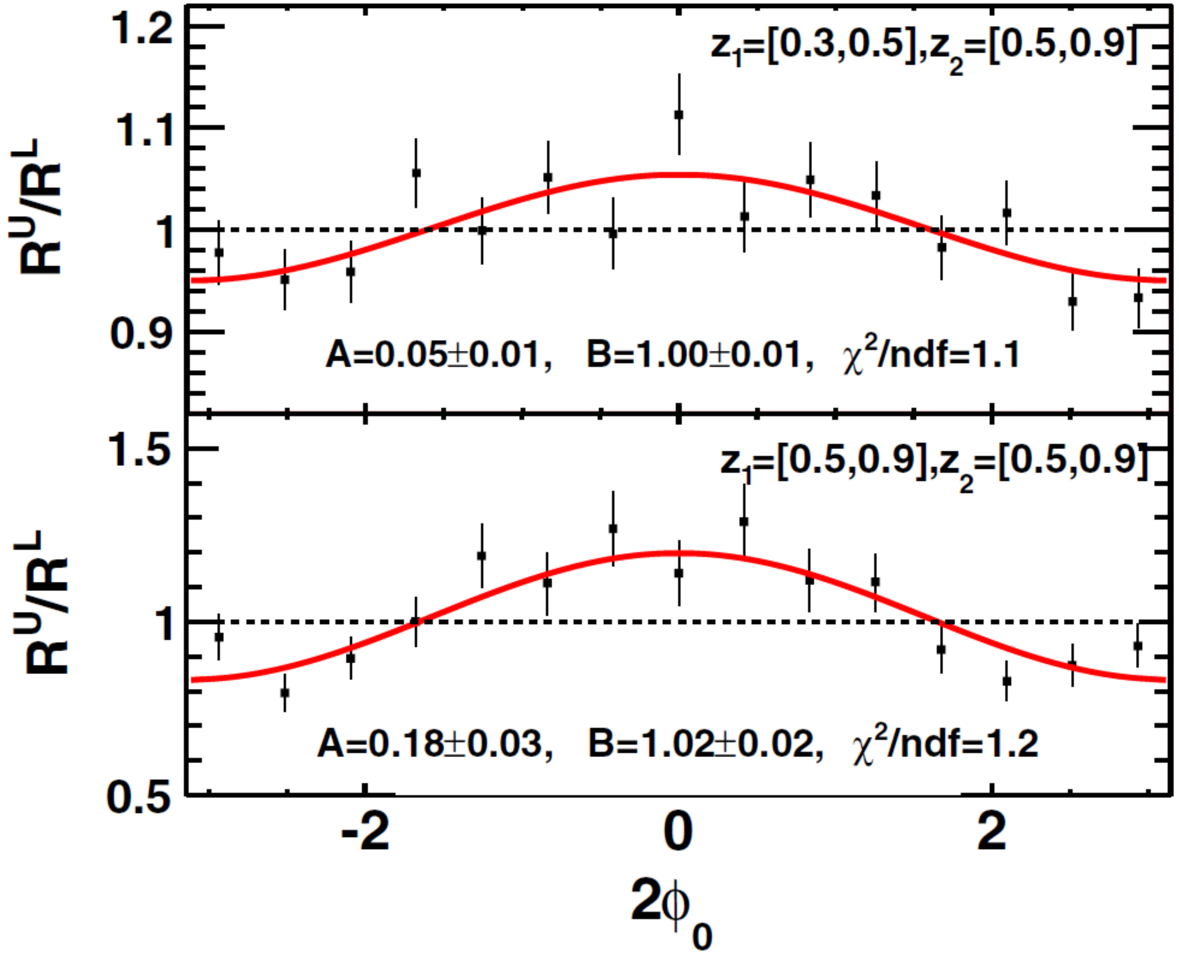


BESIII measurement, exploratory study
Clearly see the modulation
PRL 116, 042001 (2016)

World data fit to extract Collins FFs and Transversity TMDs

C. H. Zeng, H. X. Dong, T. B. Liu, P. Sun, Y. X. Zhao

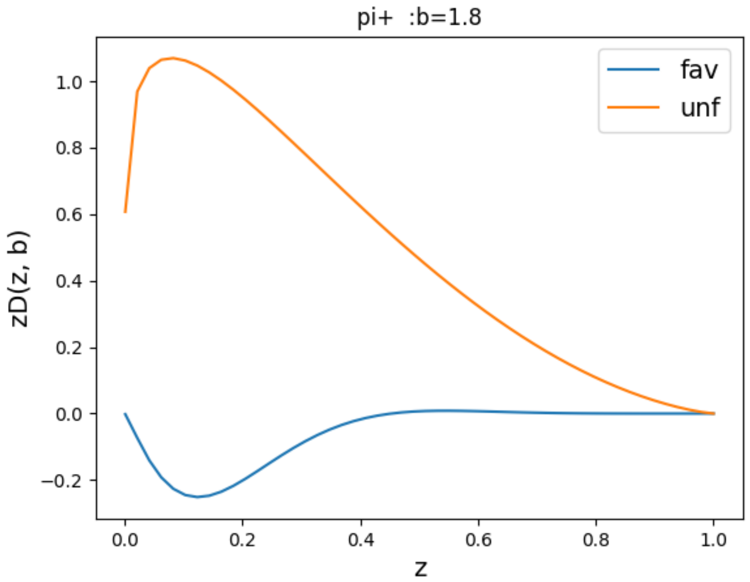
TABLE I: World SIDIS data used in our analysis. The numbers in parentheses are the original number of data points before applying δ cut.

Data set	Target	Beam	Data points	Reaction	measurement
COMPASS [5]	^{6}LiD	160 GeV μ^+	9(36)	$\mu^+ d \to \mu^+ \pi^+ X$ $\mu^+ d \to \mu^+ \pi^- X$ $\mu^+ d \to \mu^+ K^+ X$ $\mu^+ d \to \mu^+ K^- X$	$A_{UT}^{Collins}/\epsilon$
COMPASS [6]	NH_3	160 GeV μ^+	10(36)	$\mu^+ p \to \mu^+ \pi^+ X$ $\mu^+ p \to \mu^+ \pi^- X$ $\mu^+ p \to \mu^+ K^+ X$ $\mu^+ p \to \mu^+ K^- X$	$A_{UT}^{Collins}/\epsilon$
HERMES [4]	H_2	27.6 GeV $e^\pm$	104(256)	$e^\pm p \to e^\pm \pi^+ X$ $e^\pm p \to e^\pm \pi^- X$ $e^\pm p \to e^\pm K^+ X$ $e^\pm p \to e^\pm K^- X$	$A_{UT}^{Collins}/\epsilon$
JLab [7]	^{3}He	5.9 GeV e^-	4(8)	$e^- n \to e^- \pi^+ X$ $e^- n \to e^- \pi^- X$	$A_{UT}^{Collins}$
Jlab [8]	^{3}He	5.9 GeV e^-	2(5)	$e^- {}^3\text{He} \to e^- K^+ X$ $e^- {}^3\text{He} \to e^- K^- X$	$A_{UT}^{Collins}$

TABLE II: World SIA data used in our analysis.

Data set	Energy	dependence	Data points	Reaction
BELLE [9]	10.58 GeV	z	16	$e^+e^- \to \pi\pi X$
BABAR [10]	10.6 GeV	z	36	$e^+e^- \to \pi\pi X$
		P_{ht}	9	$e^+e^- \to \pi\pi X$
BABAR [11]	10.6 GeV	z	48	$e^+e^- \to \pi\pi X$
		z		$e^+e^- \to \pi K X$
		z		$e^+e^- \to K K X$
BESIII [12]	3.68 GeV	z	6	$e^+e^- \to \pi\pi X$
		P_{ht}	5	$e^+e^- \to \pi\pi X$

SIA		chi2/N	data
Babar2014	z	0.98	36
	pt	1.13	9
BESIII	z	1.90	6
BESIII	pt	1.46	5



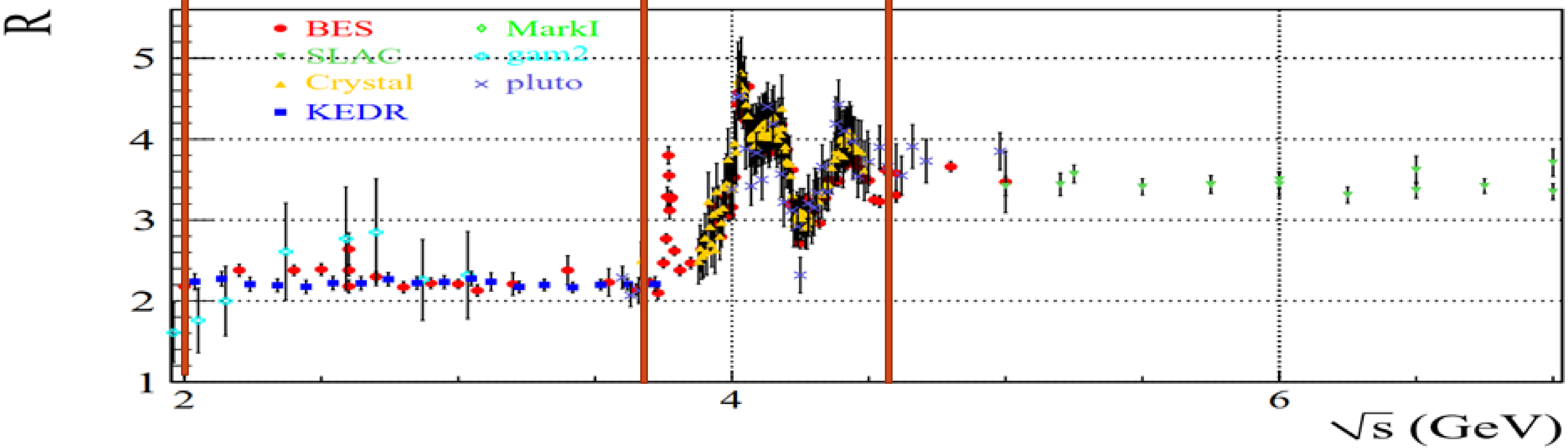
Polarized SIDIS data + SIA data

Outline

- Introduction of Fragmentation Functions
  - Existing studies at BESIII
- Potential at STCF

BESIII coverage

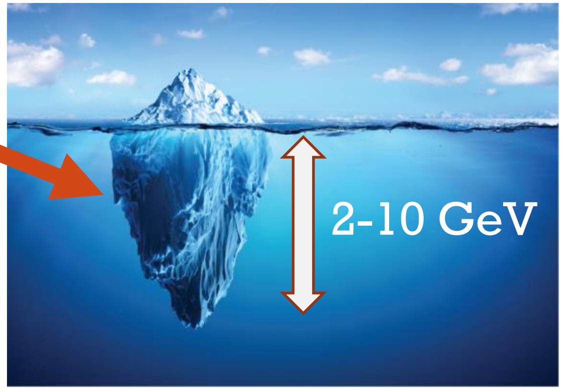
High CoM energy, High Lumi.



STCF coverage

A few highlights in the high CoM region

- **Higher center of mass energy available at STCF**
  - Broader hard scale Q coverage
  - heavy particles
    - Lambda, Lambda_C, D0

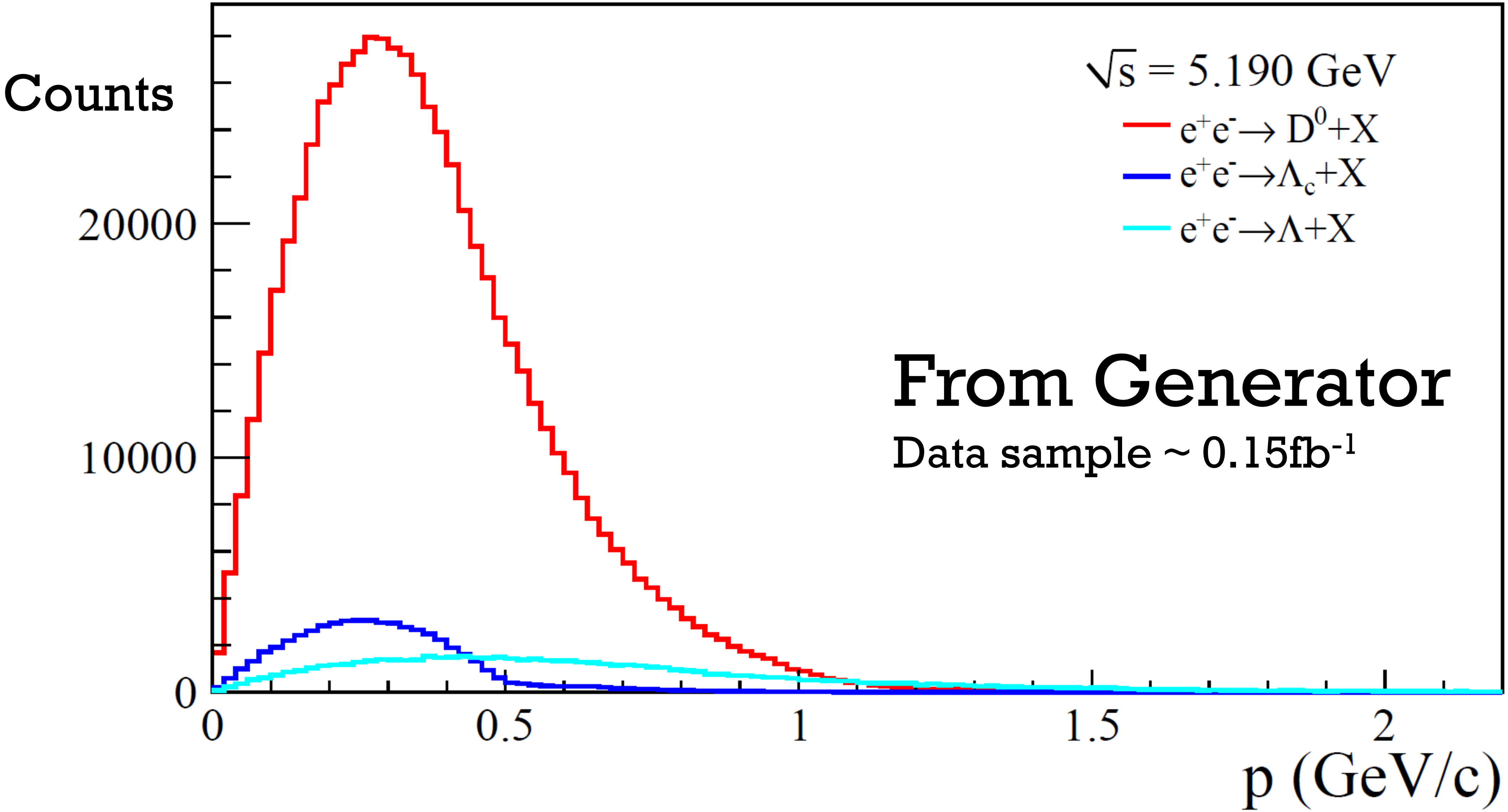


Transition from Pert. to Non-pert.

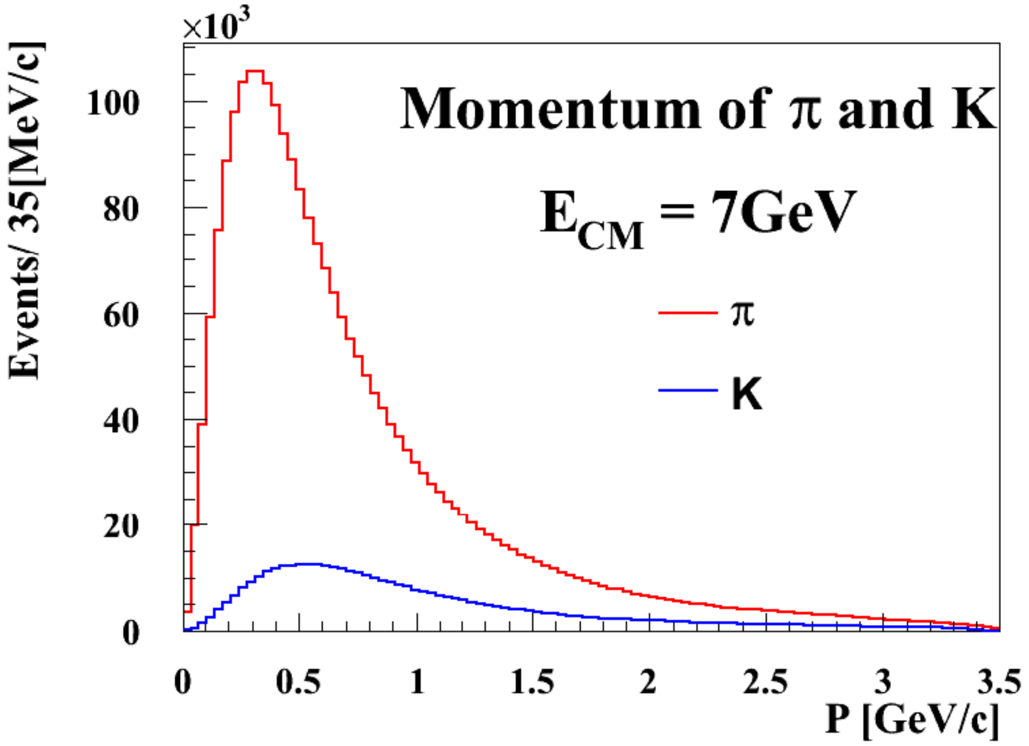
Many interesting effects

- **High lumi.**
  - 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)

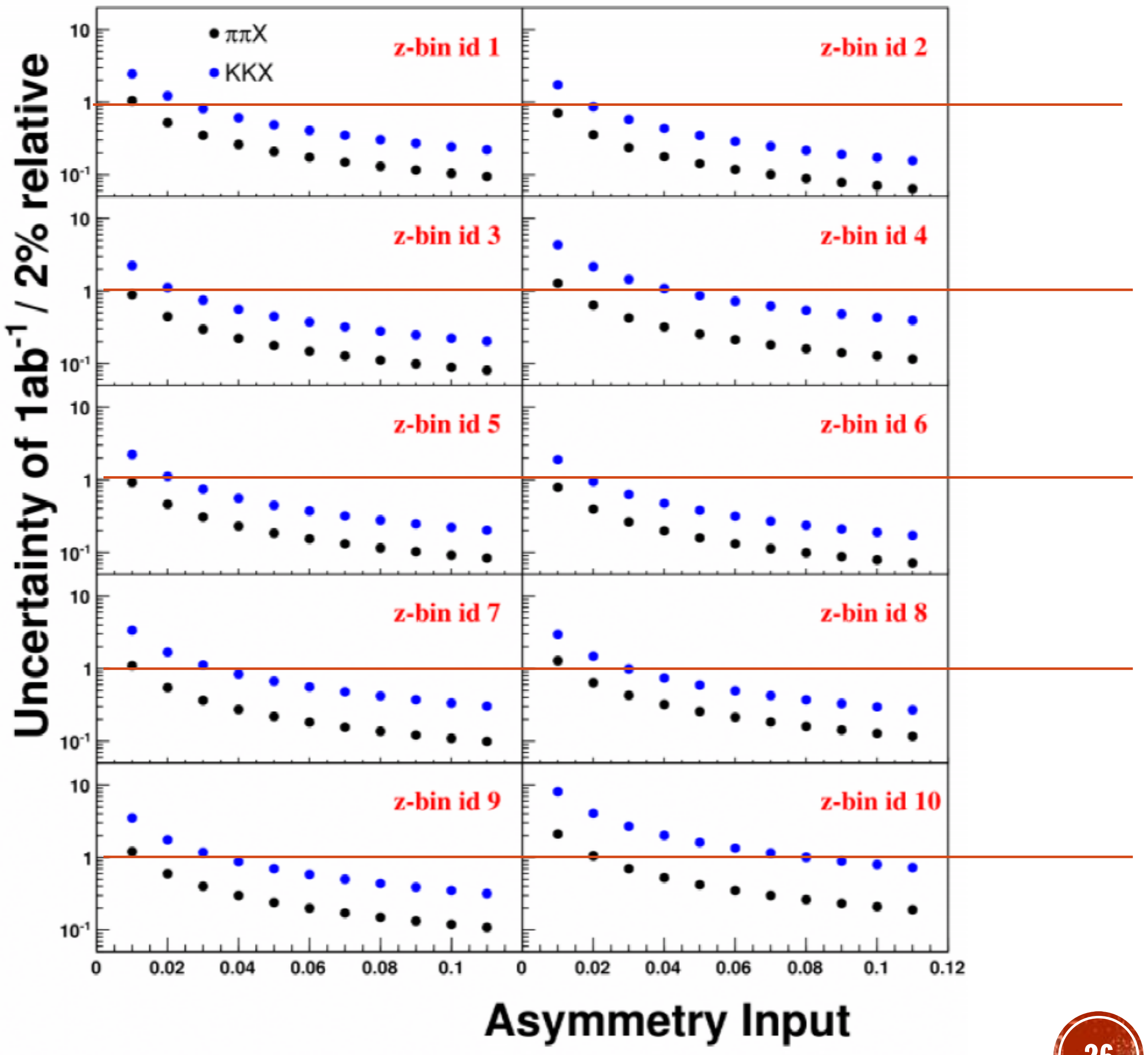
Example of heavy particles



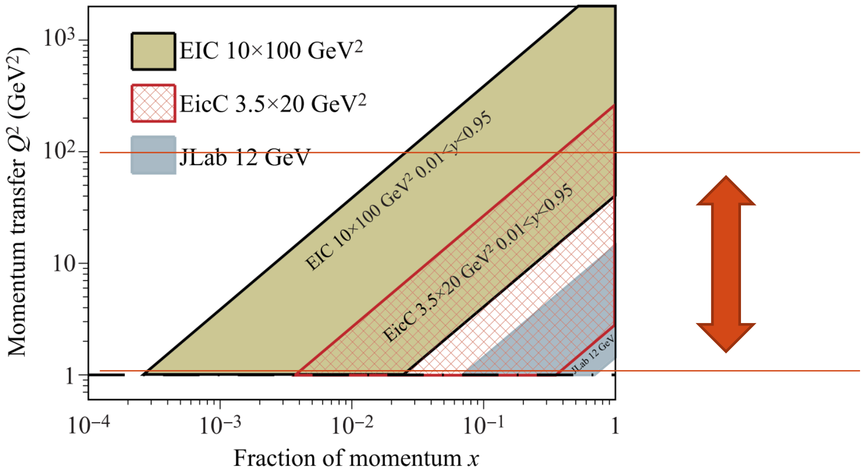
Example of Collins



A simulation at STCF



Summary



- **Unpolarized fragmentation function**
  - ✓Unique Q<10 GeV data
  - ✓Hadronization in a "non-pert. → pert." region
- **Collins fragmentation function**
  - ✓Important inputs in the 3D imaging era of the nucleon structure study, especially EIC is becoming real
  - ✓Very little data in e^+e^- machine
- Heavy particles are possible compared to BESIII
- Jet ?

Thanks