

# Unveiling Light-Quark Yukawa Flavor Structure via Dihadron Fragmentation at Lepton Colliders

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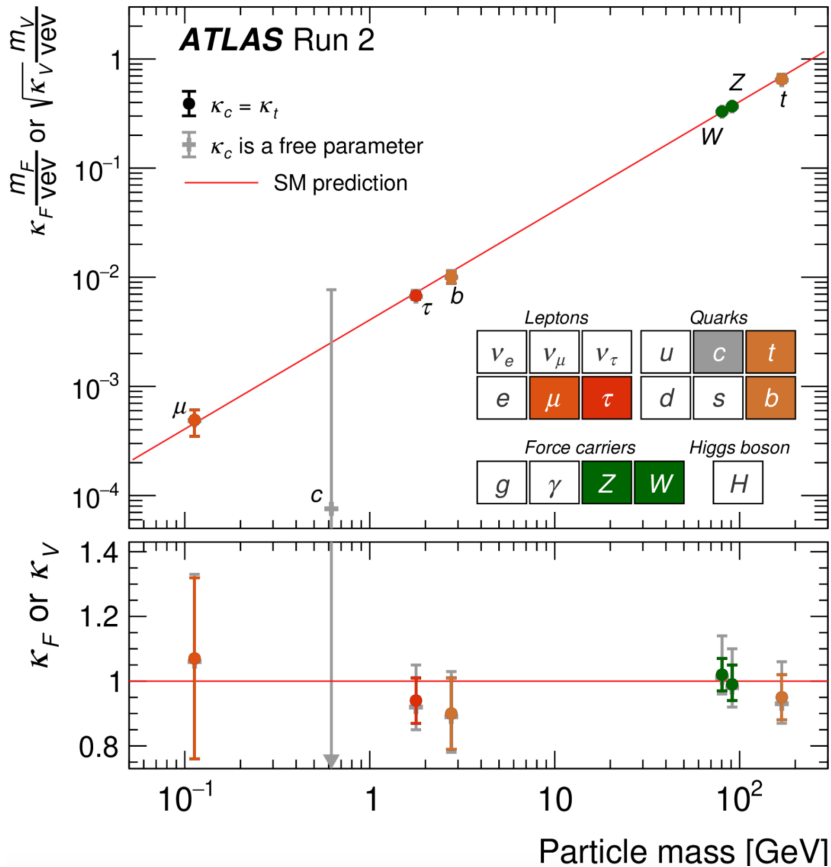
Base on: arXiv 2512.16492

In collaboration with: Qing-Hong Cao, Bin Yan, and Shu-Tao Zhang

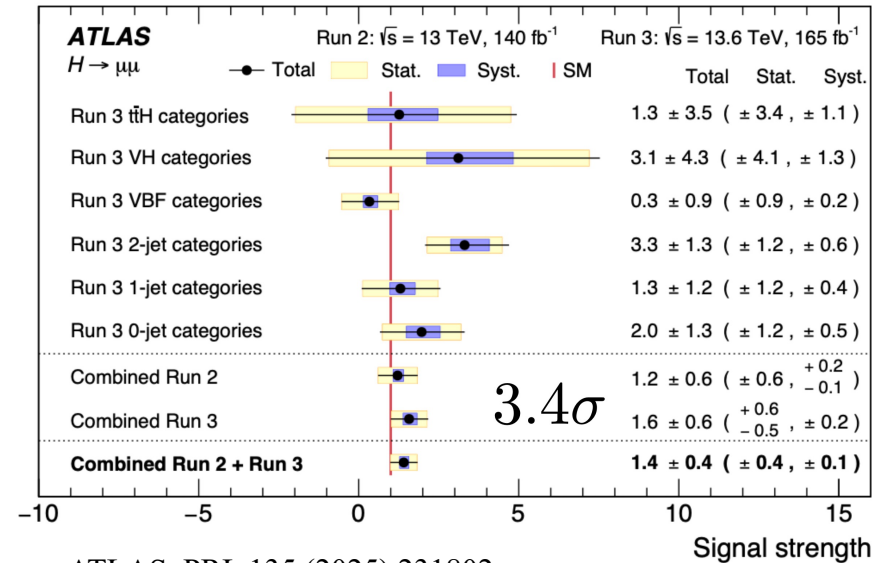
*2026/04/12, Guilin, Guangxi, China*

# EWSB and Higgs Mechanism

All fundamental particles get their mass from Higgs boson VEV via **Higgs mechanism**



The Higgs mechanism has been verified for the **third-generation fermions** and **gauge bosons**



ATLAS, PRL 135 (2025) 231802

**Higgs  $\rightarrow$  dimuon @ 2025**

It's time for the **second-generation fermions**

**How about light quarks ?**

Opportunity and Challenge !

# The Opportunity for Light Quark Case

Most existing studies rely on **indirect constraints** derived from precision measurements:

- Rare exclusive radiative decays:  $h \rightarrow V\gamma$  with  $V = \phi, \rho, \omega$  and  $J/\Psi$

G. T. Bodwin, F. Petriello, S. Stoynev, and M. Velasco, Phys. Rev. D 88, 053003 (2013)

A. L. Kagan, G. Perez, F. Petriello, Y. Soreq, S. Stoynev, and J. Zupan, Phys. Rev. Lett. 114, 101802 (2015)

M. König and M. Neubert, JHEP 08, 012 (2015)

- Rapidity or  $p_T$  distributions in Higgs production:

Y. Soreq, H. X. Zhu, and J. Zupan, JHEP 12, 045 (2016)

F. Bishara, U. Haisch, P. F. Monni, and E. Re, Phys. Rev. Lett. 118, 121801 (2017)

G. Bonner and H. E. Logan (2016)

W. Bizon', X. Chen, A. Gehrmann-De Ridder, T. Gehrmann, N. Glover, A. Huss, P. F. Monni, E. Re, L. Rottoli, and P. Torrielli, JHEP 12, 132 (2018)

X. Chen, T. Gehrmann, E. W. N. Glover, A. Huss, Y. Li, D. Neill, M. Schulze, I. W. Stewart, and H. X. Zhu, Phys. Lett. B 788, 425 (2019)

G. Billis, B. Dehnadi, M. A. Ebert, J. K. L. Michel, and F. J. Tackmann, Phys. Rev. Lett. 127, 072001 (2021)

- Global analyses and machine learning strategies:

L. Alasfar, R. Gröber, C. Grojean, A. Paul, and Z. Qian, JHEP 11, 045 (2022)

- Hadronic event shapes

J. Gao, JHEP 01, 038 (2018)

B. Yan and C. Lee, JHEP 03, 123 (2024)

- Lots of rate-approaches .....



**Current analyses:**  $|y_u| < 0.030$  and  $|y_d| < 0.026$

**HL-LHC:**  $|y_{u,d}| < 0.007$

# The Challenges for Light Quark Case

Directly measuring the light-quark Yukawa couplings is extremely challenging

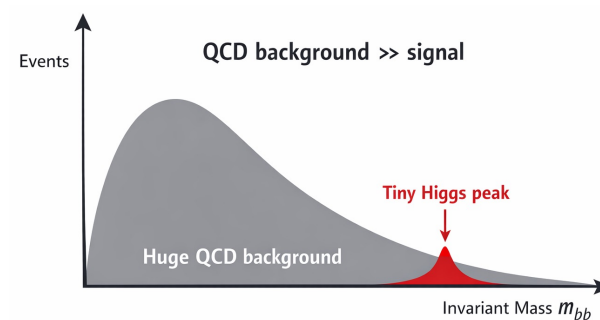
- Tiny couplings

$$y_{u,d}^{\text{SM}} \sim \mathcal{O}(10^{-6}) - \mathcal{O}(10^{-5})$$

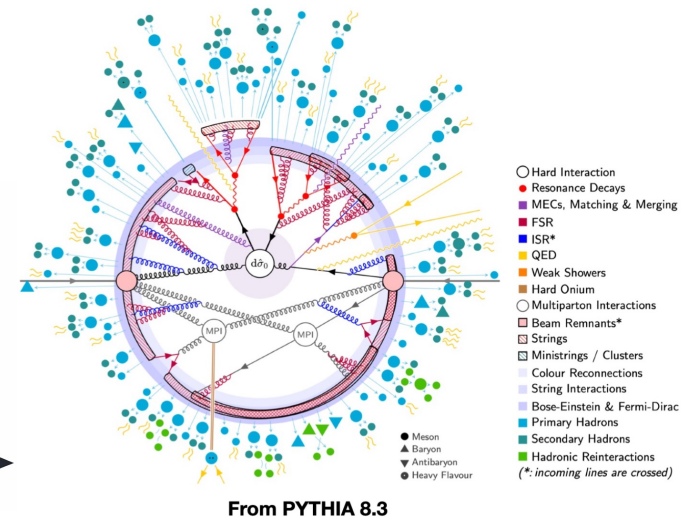
- The cross sections or decay rates proportional to  $y_q^2$  with  $y_q \ll 1$

**Yukawa couplings flip chirality**

- Huge QCD backgrounds



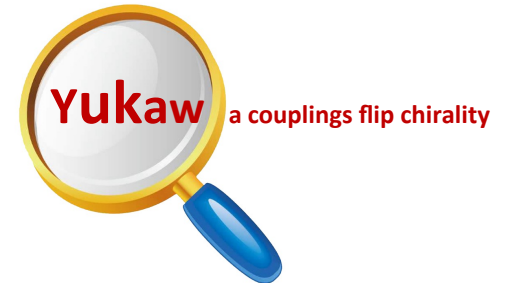
- QCD confinement



- No independent sensitivity to up- and down-quark Yukawa couplings

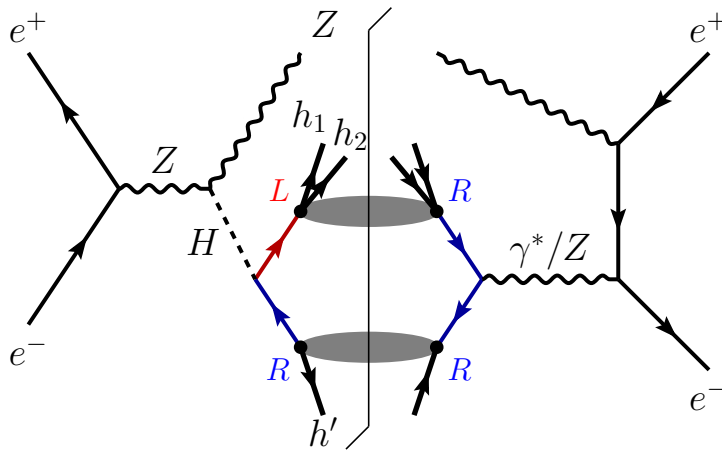
# Solution to the Challenges

- Tiny couplings → **Special and Unique Probe to “ZOOM IN”**
- Huge QCD backgrounds → **Lepton Collider, Spin Asymmetry**
- **The cross sections or decay rates:  $y_q^2$ , ( $y_q \ll 1$ )**



✓ **Quark transverse spin**  $\propto y_q$

**Chiral-flipping** Yukawa interactions generate **quark chiral-odd transverse spin** via the **interference between the different helicity** states of signal and background amplitudes



$$\rho = \frac{1}{2} (1 + \boldsymbol{\sigma} \cdot \mathbf{s}) = \frac{1}{2} \begin{pmatrix} 1 + \lambda & b_T e^{-i\phi_0} \\ b_T e^{i\phi_0} & 1 - \lambda \end{pmatrix}$$

$$\mathbf{s} = (b_1, b_2, \lambda) = (b_T \cos \phi_0, b_T \sin \phi_0, \lambda)$$

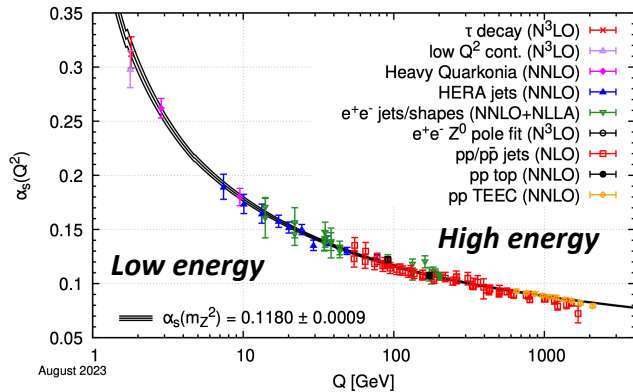
**How to Measure ?**

Qing-Hong Cao, Xin-Kai Wen, Bin Yan, and Shu-Tao Zhang, arXiv: 2512.16492

Xin-Kai Wen, Bin Yan, Zhite Yu, C.-P. Yuan, PRL 131 (2023) 241801, PRD112 (2025) 053004, 2408.07255

# Solution to the Challenges

- QCD confinement → QCD asymptotic freedom and factorization pave an avenue to study

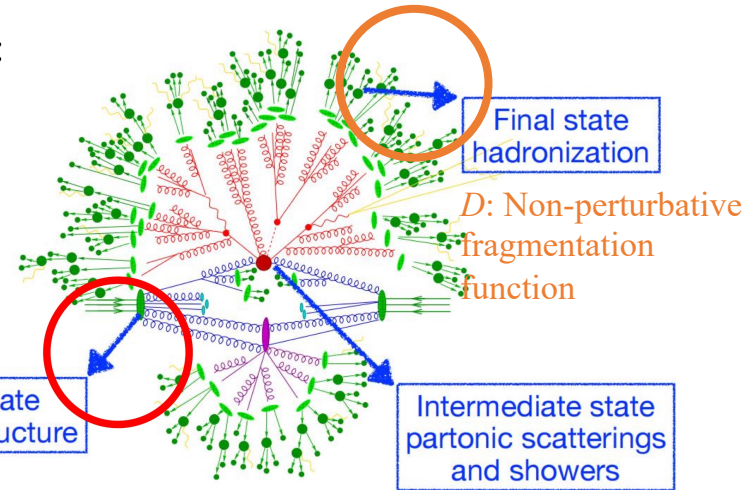


Particle Data Group, *Phys.Rev.D* 110 (2024) 3, 030001

QCD factorization:

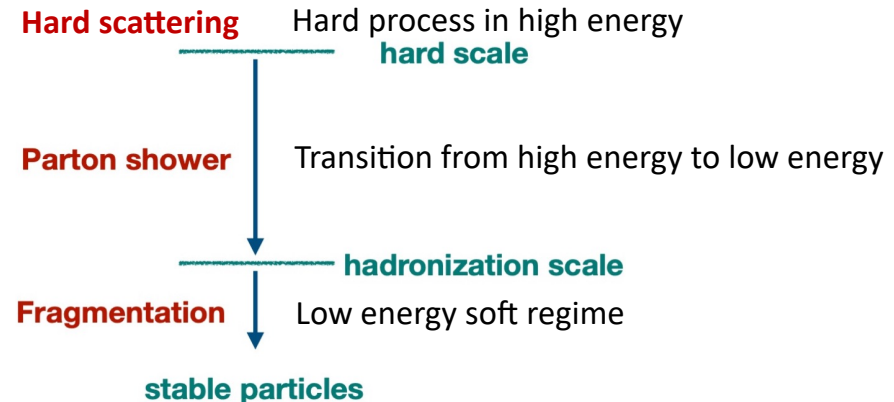
$$\sigma = f \otimes \hat{\sigma} \otimes D$$

$f$ : Non-perturbative parton distribution function




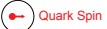
## How to probe the spin information of quarks?

- Heavy quarks: **decay products**
- Light quarks: **non-perturbative functions**, i.e., the PDFs and the fragmentation functions



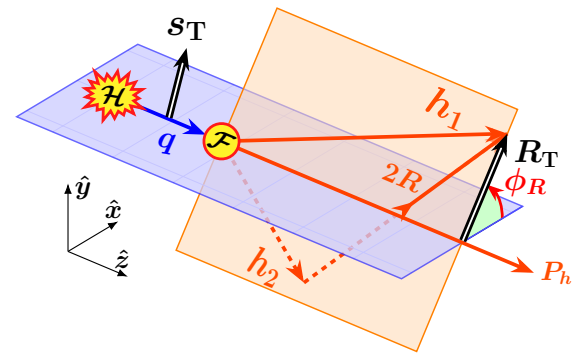
# QCD Spin Probe and Dihadron FFs

➤ Spin-dependent **Chiral-odd FFs** project out **Chiral-odd quark transverse spin**

Leading Quark **TMDFFs**  Hadron Spin  Quark Spin

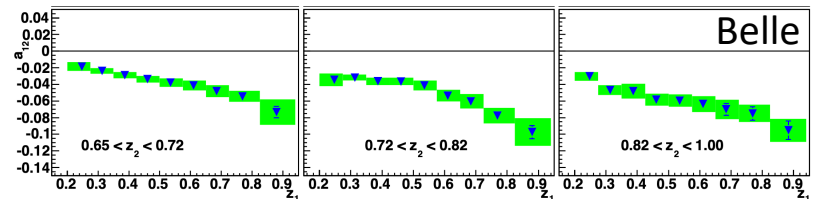
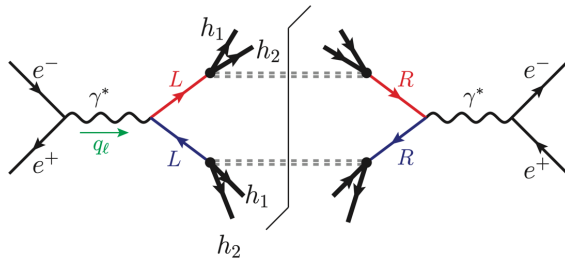
		Quark Polarization		
		Un-Polarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Unpolarized (or Spin 0) Hadrons		$D_1 = \text{Unpolarized}$		$H_1^\perp = \text{Collins}$
	L		$G_1 = \text{Helicity}$	$H_{1L}^\perp$
Polarized Hadrons	T	$D_{1T}^\perp = \text{Polarizing FF}$	$G_{1T}^\perp$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

Independent of hadron spin?  
Collinear factorization?  
✓ **Dihadron FFs!**



Kang, Prokudin, Sun, Yuan, *Phys.Rev.D* **93** (2016) 014009;  
Zeng, Dong, Liu, Sun, Zhao, *Phys.Rev.D* **109** (2024) 056002;  
TMD Handbook, *arXiv*: 2304.03302; .....

➤ **Artru-Collins asymmetry and dihadron FF**



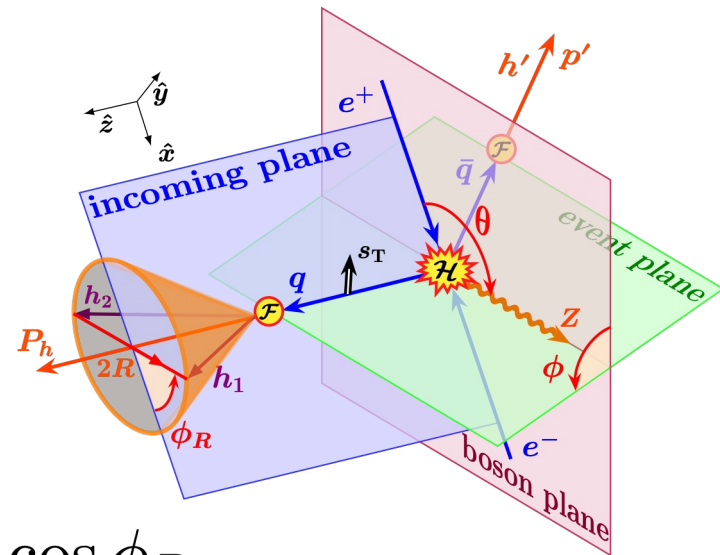
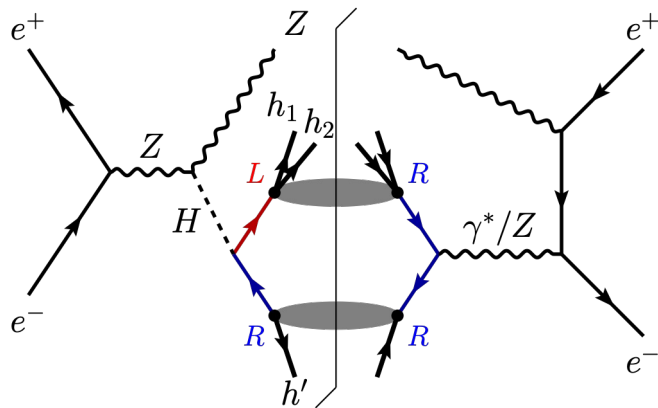
$$A^{e^+e^-} = \frac{\sin^2 \theta \sum_q e_q^2 H_1^{\langle, q}(z, M_h) H_1^{\langle, \bar{q}}(\bar{z}, \bar{M}_h)}{(1 + \cos^2 \theta) \sum_q e_q^2 D_1^q(z, M_h) D_1^{\bar{q}}(\bar{z}, \bar{M}_h)}$$

Belle Collaboration, *Phys. Rev. Lett.* **107** (2011) 072004  
JAM Collaboration, *Phys. Rev. Lett.* **132** (2024) 091901  
JAM Collaboration, *Phys. Rev. D* **109** (2024) 034024

# Dihadron FFs and Yukawa coupling

Yukawa interactions generate **transverse spin of quark** through interference between different helicity states of signal and backgrounds **rising  $y_q^2$  to  $y_q$**

$$e^-(\ell) + e^+(\ell') \rightarrow [h_1(p_1) + h_2(p_2)] + h'(p') + Z(P_Z) + X$$



$$(\hat{\mathbf{s}}_{T,q} \times \hat{\mathbf{R}}_T)^z = s_q^x \sin \phi_R - s_q^y \cos \phi_R$$

**Dihadron interference FFs** provide a direct azimuthal probe **linear** in the Yukawa couplings

**Single-hadron tagging lifts degeneracies** among up- and down-quark Yukawa couplings

Qing-Hong Cao, Xin-Kai Wen, Bin Yan, and Shu-Tao Zhang, arXiv: 2512.16492

# Dihadron FFs and Yukawa coupling

$e^+ e^- \rightarrow q \bar{q} Z$  three-body kinematics

$$\frac{d\sigma}{dx_q dx_{\bar{q}} d\cos\theta d\phi dz d\bar{z} dM_h d\phi_R} = \frac{1}{64(2\pi)^5} \sum_{q, q \rightarrow \bar{q}} C_q D_{\bar{q}}^{h'}(\bar{z})$$

$$\times \left[ D_q^{h_1 h_2}(z, M_h) - (\mathbf{s}_{T,q} \times \hat{\mathbf{R}}_T)^z H_q^{h_1 h_2}(z, M_h) \right].$$

Unpolarized DiFFs

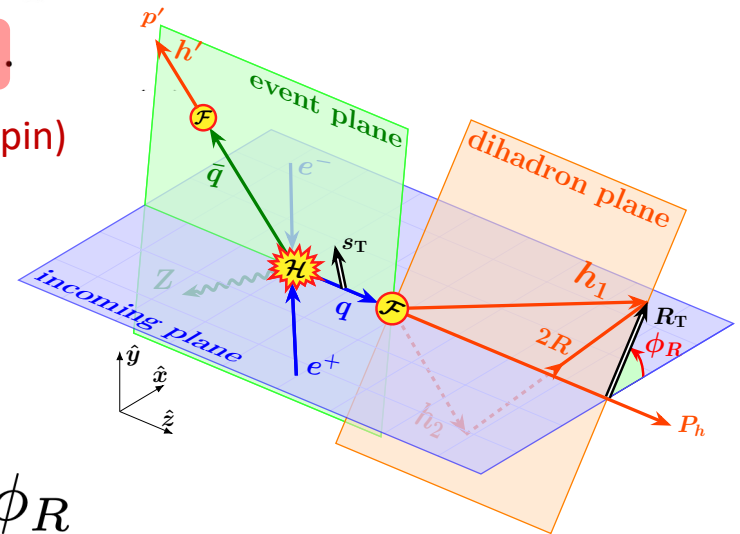
Interference DiFFs (transverse spin)

Different spin and CP dependence due to three-body nontrivial property

$$\left( \mathbf{s}_{T,q} \times \hat{\mathbf{R}}_T \right)^z = s_q^x \sin\phi_R - s_q^y \cos\phi_R$$

$$s_q^x C_q = 2 \operatorname{Re} \mathcal{H}_{+-}^q = \omega_q y_q + \tilde{\omega}_q \tilde{y}_q$$

$$s_q^y C_q = 2 \operatorname{Im} \mathcal{H}_{+-}^q = \tilde{\omega}_q y_q - \omega_q \tilde{y}_q$$



Distinguish CP or not ?

# Dihadron FFs and Yukawa coupling

Collinear and LO: the integration of the hard coefficients and FFs can be **factorized**

$$\langle \mathcal{O} \rangle \equiv \int dx_q dx_{\bar{q}} d \cos \theta d\phi \mathcal{O}_{\text{hard}}(x_q, x_{\bar{q}}, \cos \theta, \phi)$$

$$\langle \mathcal{O} \rangle \equiv \int dz d\bar{z} dM_h \mathcal{O}_{FF}(z, \bar{z}, M_h),$$

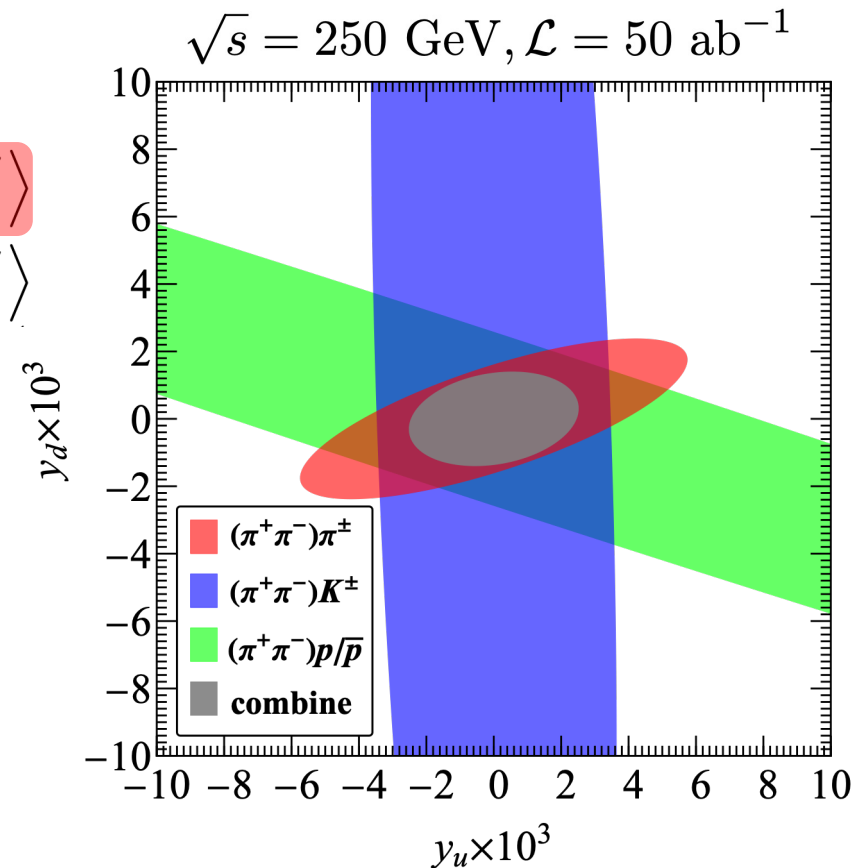
$$2\pi \frac{d\sigma}{d\phi_R} = \sum_{q=u,d} \langle \mathcal{C}_q \rangle \langle D_q^{h_1 h_2} \rangle \langle D_{\bar{q}}^{h'} + D_q^{h'} \rangle$$

$$- [y_q \sin \phi_R + \tilde{y}_q \cos \phi_R] \langle \omega_q \rangle \langle H_q^{h_1 h_2} \rangle \langle D_{\bar{q}}^{h'} - D_q^{h'} \rangle$$

$$- [\tilde{y}_q \sin \phi_R - y_q \cos \phi_R] \langle \tilde{\omega}_q \rangle \langle H_q^{h_1 h_2} \rangle \langle D_{\bar{q}}^{h'} + D_q^{h'} \rangle$$

$$\frac{2\pi}{\sigma^{h'}} \frac{d\sigma^{h'}}{d\phi_R} = 1 + S_x^{h'} \sin \phi_R + S_y^{h'} \cos \phi_R$$

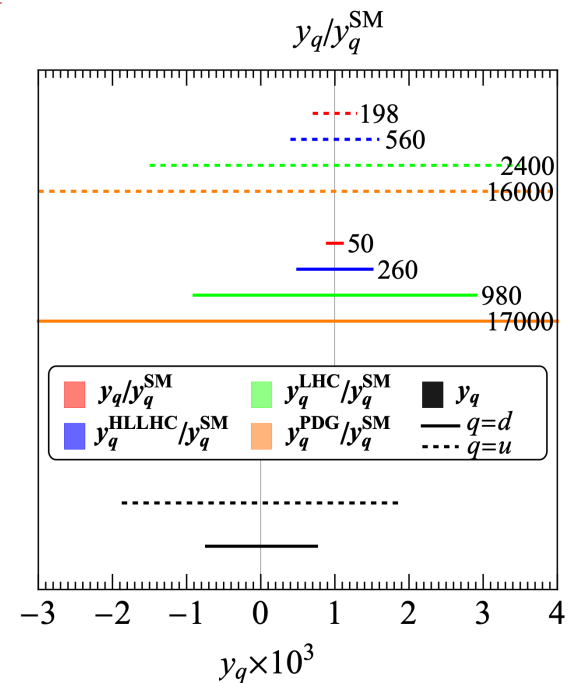
- ✓ The **single hadron as flavor tags** for up- and down-quarks, **enabling flavor separation**
- ✓ Yukawa couplings:  $\mathcal{O}(10^{-4} - 10^{-3})$



Qing-Hong Cao, Xin-Kai Wen, Bin Yan, and Shu-Tao Zhang, arXiv: 2512.16492

# Summary

- ✓ The light quark Yukawa couplings are poorly measured due to tiny size, QCD background, quark confinement, and quadratic effect  $y_q^2$  at rate-based methods
- ✓ **Chiral-odd dihadron fragmentation** projects out the **quark transverse spin** sourcing from the **linear interference effect**  $y_q$  between Yukawa signal and background amplitudes
- ✓ Spin-independent **single-hadron tagging disentangles the quark flavor structure** and resolves degeneracy between  $y_u$  and  $y_d$
- ✓ This azimuthal asymmetry achieve  $O(10^{-4} - 10^{-3})$  bound on Yukawa couplings, much stronger than current results at  $O(10^{-3} - 10^{-2})$
- ✓ It is flexible to extend to probe the potential CP-violation Yukawa interactions



Thank you