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

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Base on: arXiv 2512.16492 (PRL 136 (2026) 23, 231901)

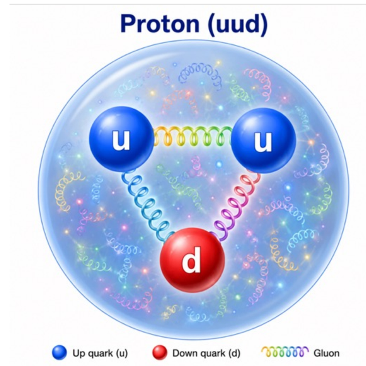
In collaboration with: Qing-Hong Cao, Bin Yan, and Shu-Tao Zhang

2026/07/29, Tsingtao, Shandong, China

Why the Light quark Yukawa couplings

- The mass difference between proton and neutron -- isospin

W. Heisenberg,
On the structure of atomic nuclei
Z. Phys. 77 (1932) 1-11



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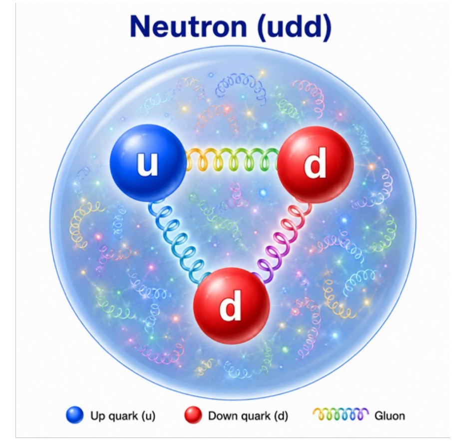


$$Q_u = +\frac{2}{3}\ ,\ Q_d = -\frac{1}{3}$$

938.27231 MeV **939.56563 MeV**

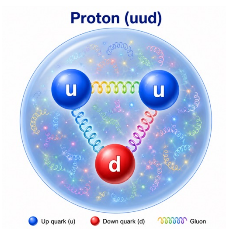
- BBN: primordial helium abundance

Thermal equilibrium:

$$\frac{n_n}{n_p} = e^{-\Delta m_{np}/T_f} \qquad Y_p = \frac{2\left(n_n/n_p\right)}{1 + n_n/n_p}$$

Why the Light quark Yukawa couplings

- The **0.14% Neutron-Proton Mass Difference** survives our fine-tuning Universe



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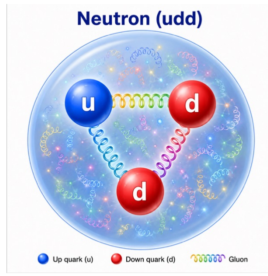


$Q_u = +\frac{2}{3}$, $Q_d = -\frac{1}{3}$

938.27231 MeV

939.56563 MeV

$$\Delta M = +1.29\text{MeV}$$

$$\frac{\Delta M}{M} \sim 0.14\%$$

DANGER ZONE I	HABITABLE CORRIDOR	DANGER ZONE II
$\Delta m < m_e$ H undergoes inverse β-decay ↓ No hydrogen	$\Delta m = 1.293\ \text{MeV}$ Our Universe	Neutron decays too fast ↓ No heavy element synthesis

0.0 — 0.5 — 1.8 — ΔM (MeV)

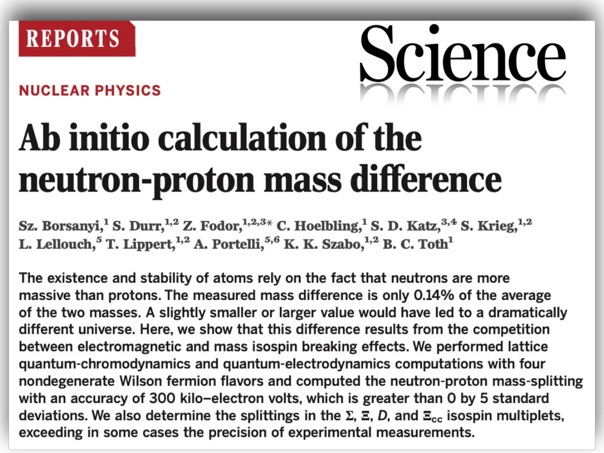
$$p + e^- \to n + \nu_e$$

$$n \to p + e^- + \bar{\nu}_e$$

Why the Light quark Yukawa couplings

- Neutron-proton mass difference: **quark Yukawa** and **electromagnetic interaction**

Borsanyi, et al. Science 347, 1452–1455 (2015)


REPORTS

Science

NUCLEAR PHYSICS

Ab initio calculation of the neutron-proton mass difference

Sz. Borsanyi,[1] S. Durr,[1,2] Z. Fodor,[1,2,3]* C. Hoelbling,[1] S. D. Katz,[3,4] S. Krieg,[1,2] L. Lellouch,[5] T. Lippert,[1,2] A. Portelli,[5,6] K. K. Szabo,[1,2] B. C. Toth[1]

The existence and stability of atoms rely on the fact that neutrons are more massive than protons. The measured mass difference is only 0.14% of the average of the two masses. A slightly smaller or larger value would have led to a dramatically different universe. Here, we show that this difference results from the competition between electromagnetic and mass isospin breaking effects. We performed lattice quantum-chromodynamics and quantum-electrodynamics computations with four nondegenerate Wilson fermion flavors and computed the neutron-proton mass-splitting with an accuracy of 300 kilo–electron volts, which is greater than 0 by 5 standard deviations. We also determine the splittings in the Σ, Ξ, D, and Ξ_{cc} isospin multiplets, exceeding in some cases the precision of experimental measurements.

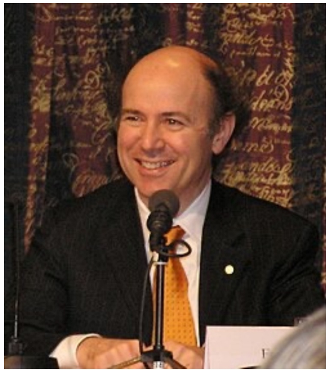
$$\Delta M \quad = \quad \Delta M_{\mathrm{QCD}} \quad + \quad \Delta M_{\mathrm{QED}}$$

ΔM	ΔM_{QCD}	ΔM_{QED}
+ 1.29 MeV	**+ 2.52 MeV**	**- 1.00 MeV**
Fine cancellation of two large effects	$m_d > m_u$ **Higgs Yukawa**	**Proton is charged, Coulomb self-energy**

48% of 2.52 MeV cancelled by QED

*"They have demonstrated, for the first time, that **fundamental theory gives the right sign** — not a trivial thing, because crude electrostatics gives the opposite result."*

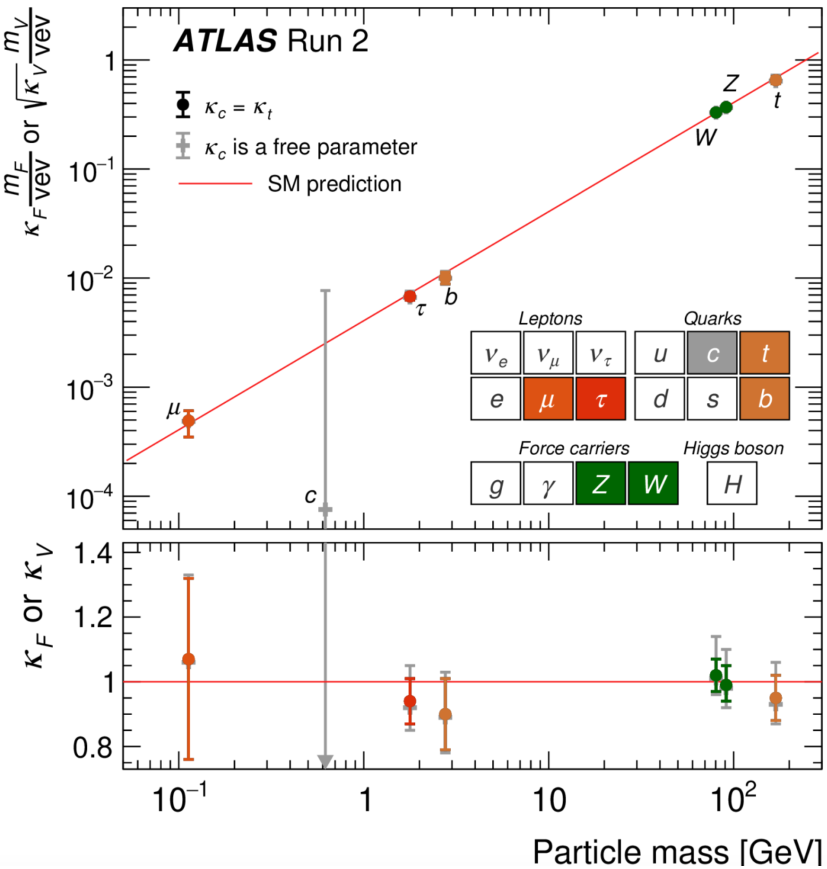
— Frank Wilczek, Nature 520, 303 (2015)



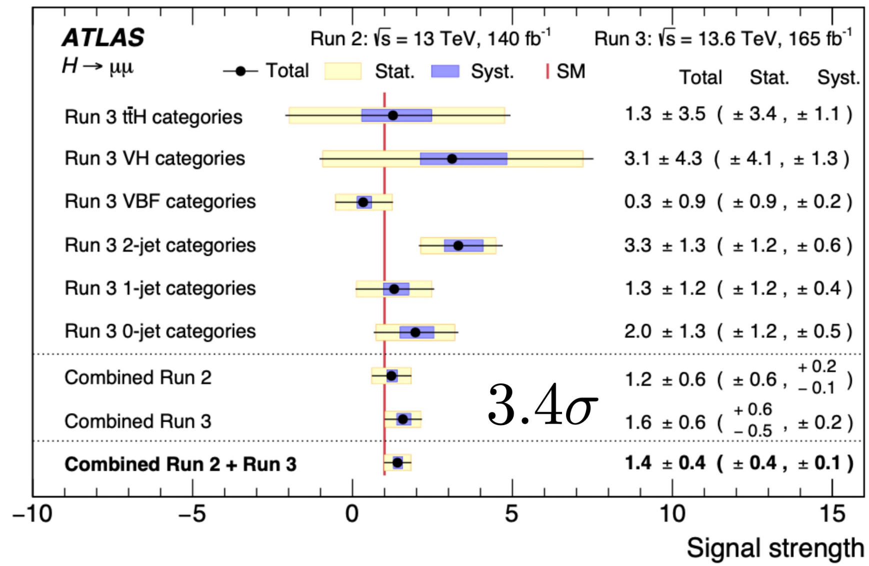
Precisely determining the light-quark Yukawa couplings is crucial

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



Higgs → dimuon @ 2025 ATLAS, PRL 135 (2025) 231802

It's time for the second-generation fermions

How about light quarks ?

LHC sensitivity for light-quark Yukawa couplings:
No Direct Measurement

Opportunity and Challenge !

Opportunity for Light Quark Case

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

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

  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. Bizoń, 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 ……

Three orders of magnitude above SM

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

CMS: PRL 132 (2024) 121901, PRD 112 (2025) 112001

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

Challenges for Light Quark Case

Directly measuring the light-quark Yukawa couplings is extremely challenging

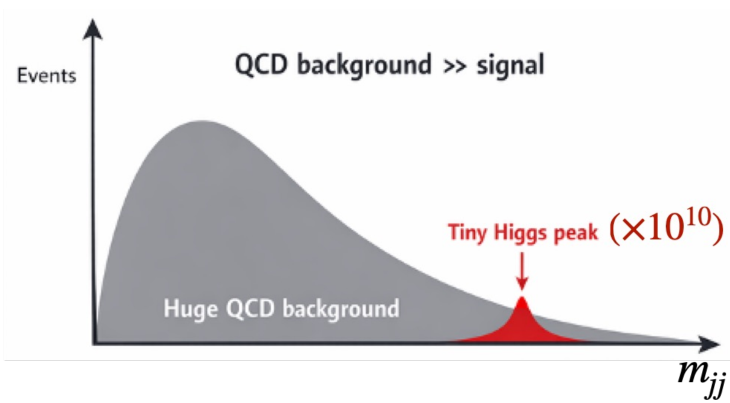
- Tiny couplings

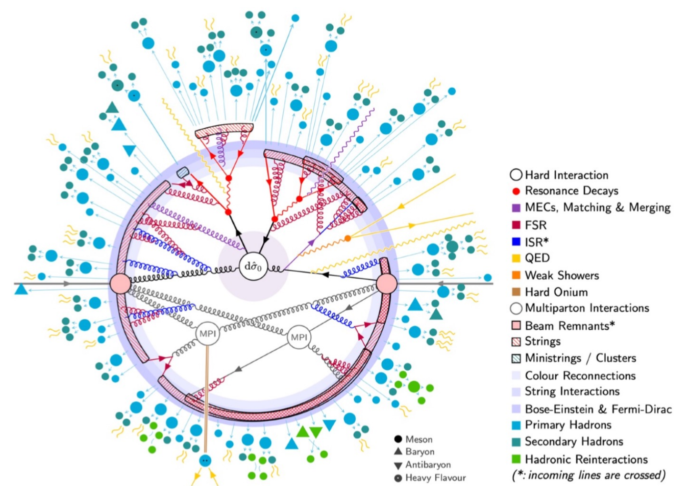
$$y_{u,d}^{\mathrm{SM}} \sim \mathcal{O}(10^{-6}) - \mathcal{O}(10^{-5})$$

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

Yukawa couplings flip chirality

- Huge QCD backgrounds and QCD confinement





From PYTHIA 8.3

Blind to charge of u, d after confinement

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

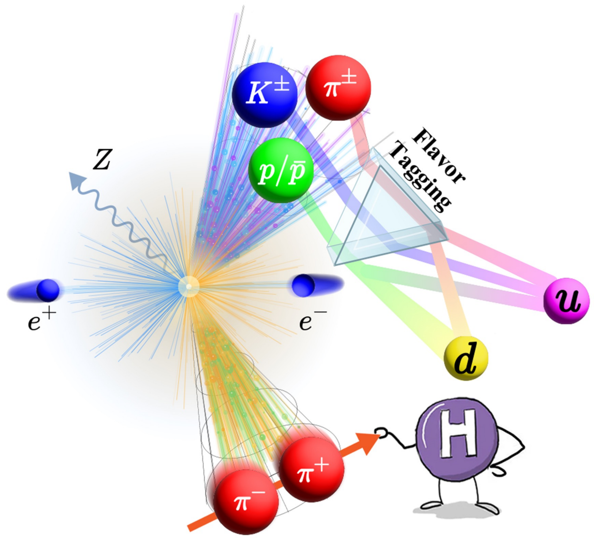
Solution to the Challenges

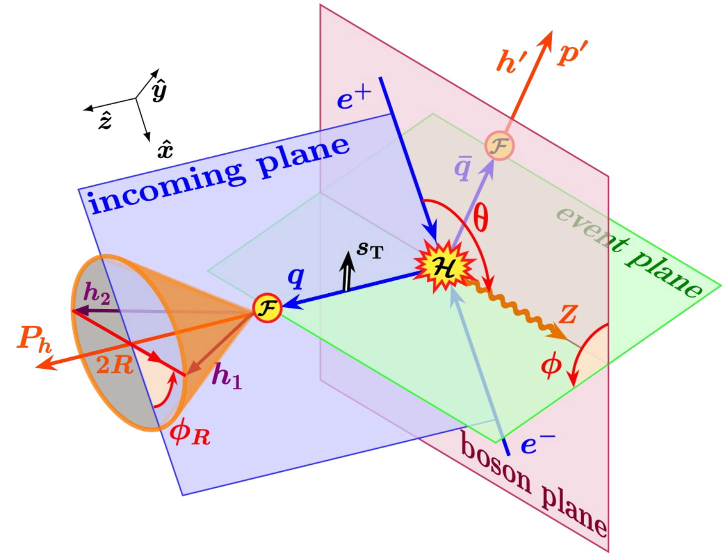
a couplings flip chirality

- 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 $\propto y_q$

Chirality-flipping Yukawa interactions generate **quark chiral-odd transverse spin**



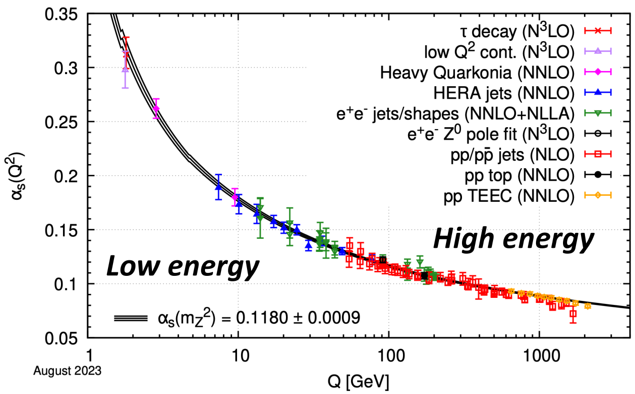


Qing-Hong Cao, Xin-Kai Wen, Bin Yan, and Shu-Tao Zhang, PRL. 136 (2026) 23, 231901

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

Solution to the Challenges--QCD Spin

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

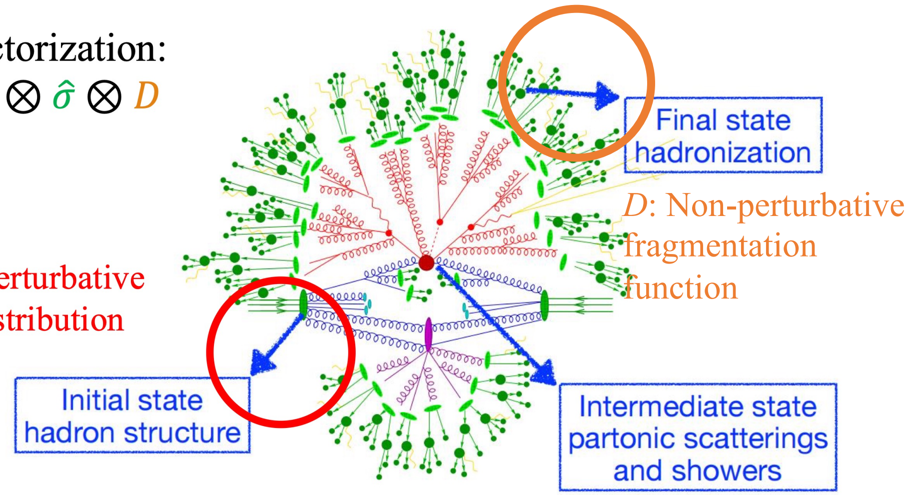


Particle Data Group, *Phys.Rev.D* 110 (2024) 3, 030001

QCD factorization:

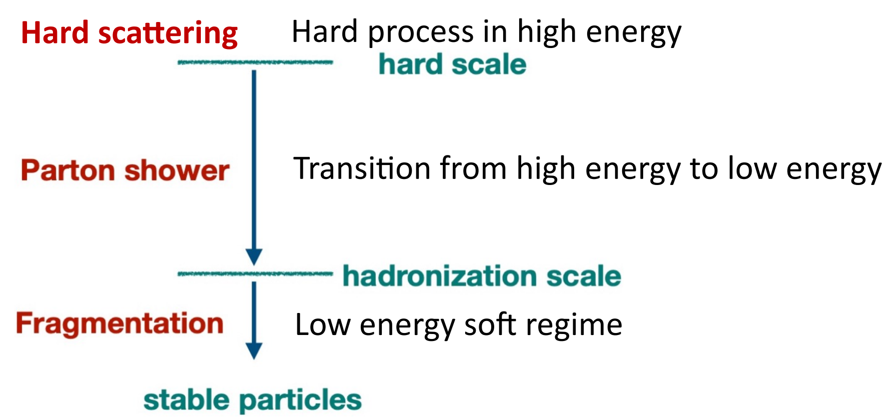
$$\sigma = f \otimes \hat{\sigma} \otimes D$$

f: Non-perturbative parton distribution function



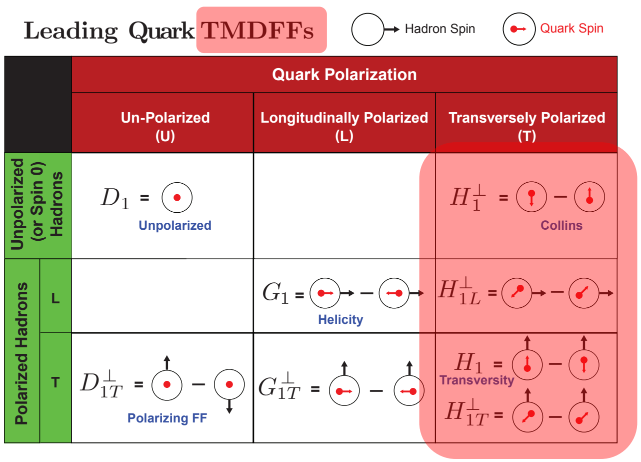
How to probe the spin information of quarks?

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



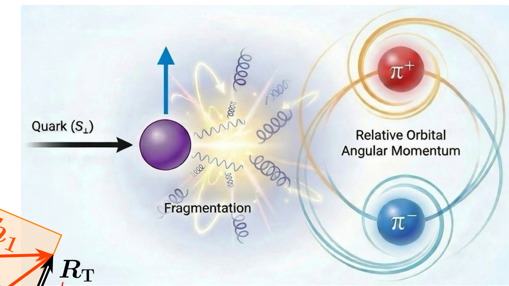
QCD Spin Probe and Dihadron FFs

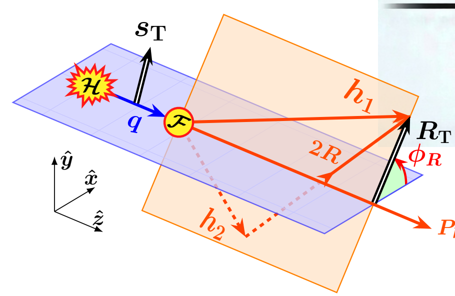
- **Spin-dependent** **Chiral-odd FFs** project out **Chiral-odd quark transverse spin**



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; ......

✓ ***Dihadron FFs:*** Independent of hadron spin in collinear factorization

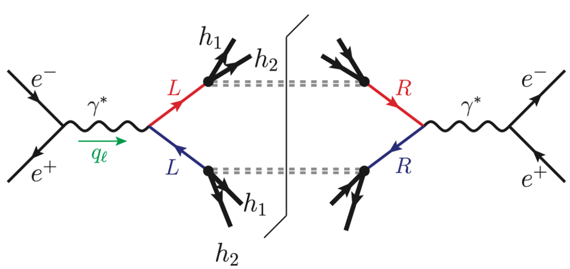




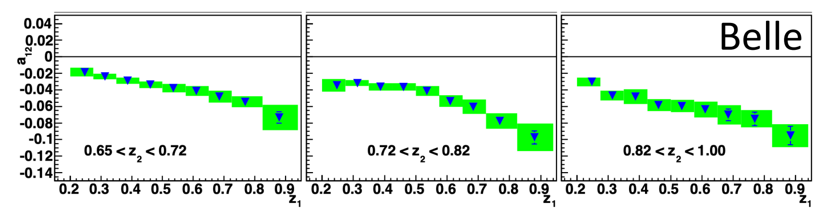
Quark transverse spin turns into the relative orbital angular momentum of a pion pair in fragmentation

- **Artru-Collins asymmetry** and **dihadron FF:** a powerful tool

Also see Gunaghui's talk and Yu-Jie's talk



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



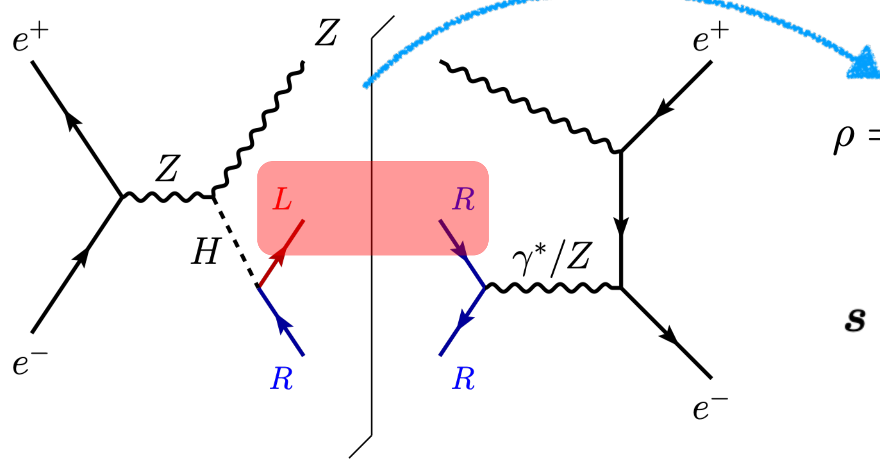
Belle Collaboration, *Phys. Rev. Lett.* **107** (2011) 072004
JAM Collaboration, *Phys. Rev. Lett* **132** (2024) 091901
JAM Collaboration, *Phys. Rev. D* **109** (2024) 034024

Linear Sensitivity via Interference

- Higgs-mediated amplitude interference with the SM background

$$\left|M_{\mathrm{SM}}+M_H\right|^2=\left|M_{\mathrm{SM}}\right|^2+2\,\mathrm{Re}\left(M_{\mathrm{SM}}^{*}M_H\right)+\left|M_H\right|^2$$

$$\propto y_q \qquad\qquad \propto y_q^2\sim 10^{-10}$$



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

$$\boldsymbol{s}=(b_1,b_2,\lambda)=(b_{\mathrm{T}}\cos\phi_0,b_{\mathrm{T}}\sin\phi_0,\lambda)$$

$e^++e^-\to Z+H(\to q\bar{q})$ $\qquad$ $e^++e^-\to Z+Z/\gamma^*(\to q\bar{q})$ $\qquad$ $y_q^2\to y_q$

- Dihadron Fragmentation Functions (DiFFs) projected out this interference effects

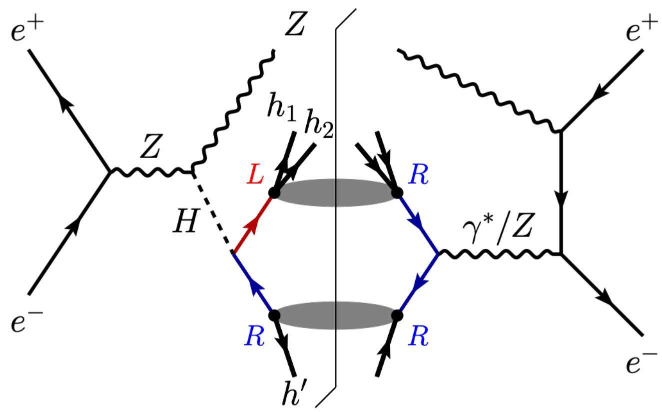
Yukawa couplings flip chirality:
transverse spin of quark

Yukawa vertex (chiral-odd) $\xrightarrow[\text{chiral-even observable}]{\text{pair up}}$ DiFF $H_q^{\pi^+\pi^-}$ (chiral-odd) $\qquad q\to\pi^+\pi^-$

Single-hadron tagging lifts degeneracy

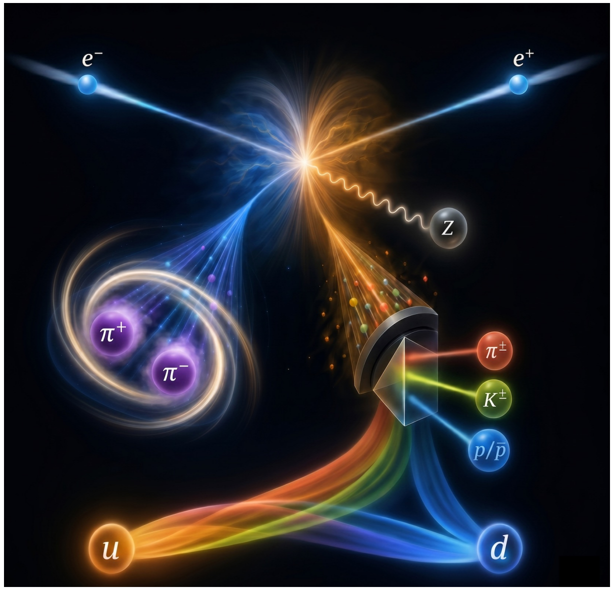
- **Yukawa interactions** generate **transverse spin of quark** through interference between different helicity states of signal and backgrounds **rising y_q^2 to y_q**
- Dihadron interference FFs provide a direct azimuthal probe **linear** in the Yukawa couplings

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



$$\bar{q} \to h$$

New flavor tagging: single hadron



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

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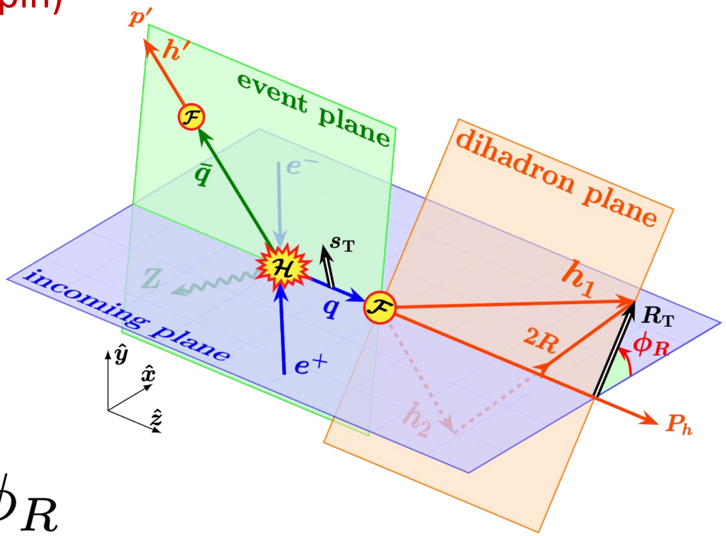
Yukawa coupling at lepton colliders

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

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

Unpolarized DiFFs   Interference DiFFs (transverse spin)



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

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

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

$$s_q^x\, \mathcal{C}_q = 2\,\mathrm{Re}\,\mathcal{H}_{+-}^q = \omega_q\, y_q + \tilde{\omega}_q\, \tilde{y}_q$$
$$s_q^y\, \mathcal{C}_q = 2\,\mathrm{Im}\,\mathcal{H}_{+-}^q = \tilde{\omega}_q\, y_q - \omega_q\, \tilde{y}_q$$

Distinguish CP or not ?

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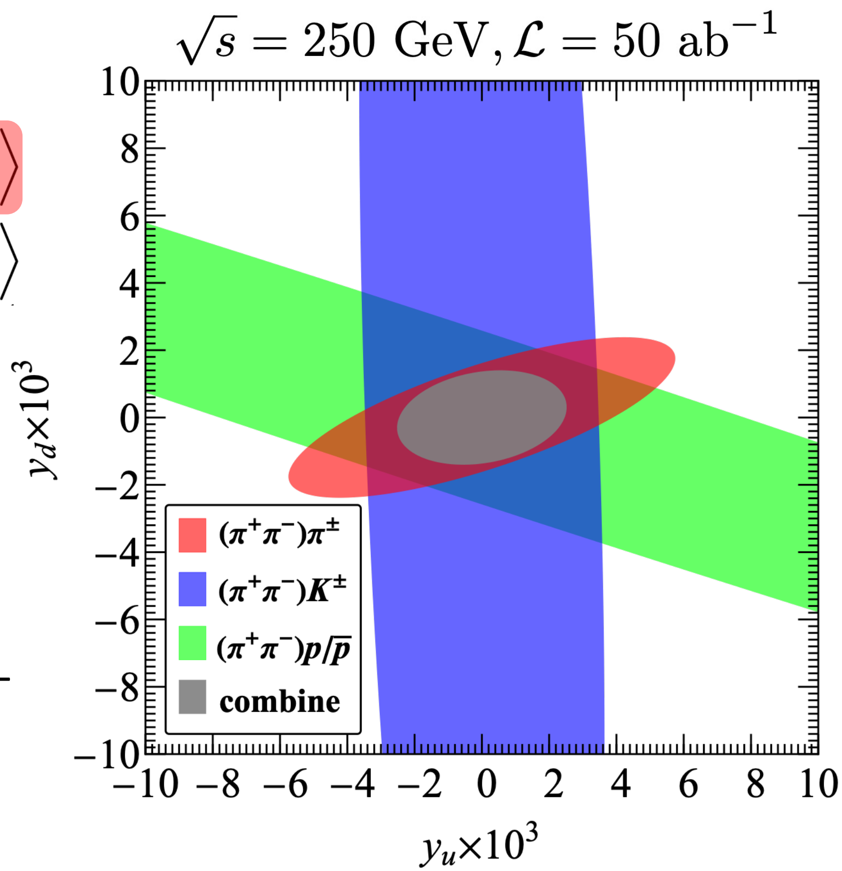
CP-even Yukawa couplings at lepton colliders

Collinear and Leading order

$$2\pi \frac{d\sigma}{d\phi_R} = \sum_{q=u,d} \langle \mathcal{C}_q \rangle \left\langle D_q^{h_1 h_2} \right\rangle \left\langle D_{\bar{q}}^{h'} + D_q^{h'} \right\rangle$$
$$- \left[y_q \sin\phi_R + \tilde{y}_q \cos\phi_R \right] \langle \omega_q \rangle \left\langle H_q^{h_1 h_2} \right\rangle \boxed{\left\langle D_{\bar{q}}^{h'} - D_q^{h'} \right\rangle}$$
$$- \left[\tilde{y}_q \sin\phi_R - y_q \cos\phi_R \right] \langle \tilde{\omega}_q \rangle \left\langle H_q^{h_1 h_2} \right\rangle \left\langle D_{\bar{q}}^{h'} + D_q^{h'} \right\rangle$$

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



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

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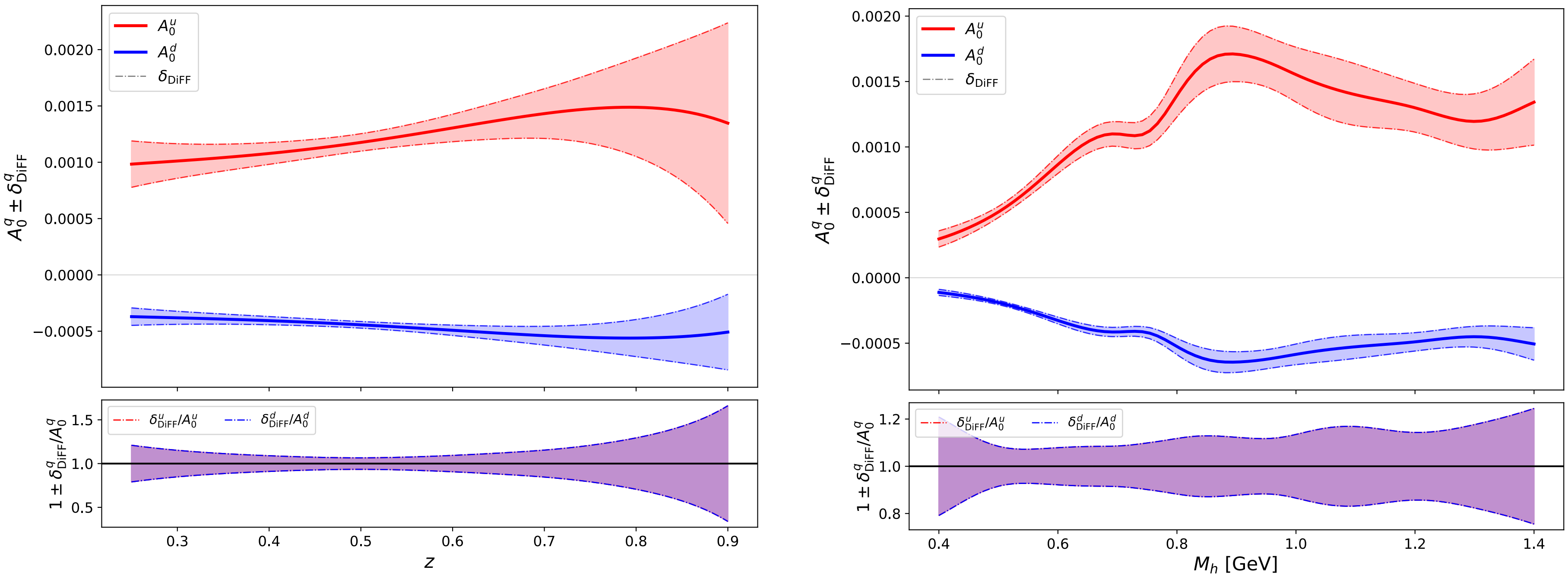
Uncertainties from DiFFs

- Benchmark: $(\pi^+\pi^-)\pi^+$ channel with $y_{u,d} = 0.01$

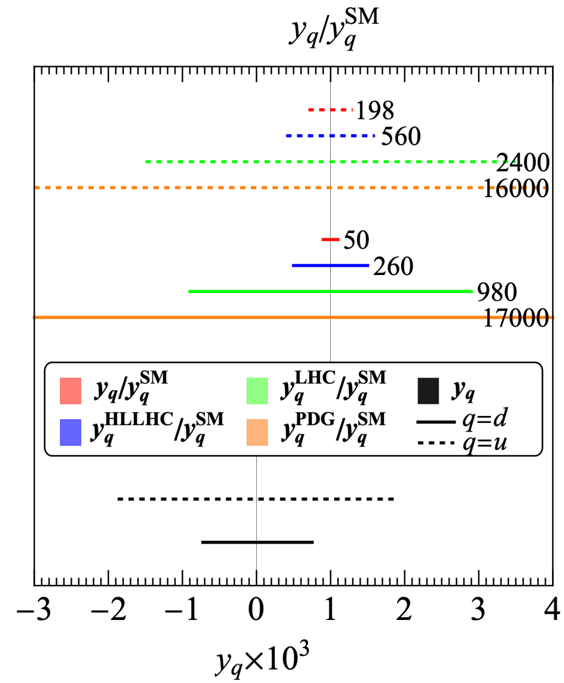


DiFF uncertainties: $\delta_{DiFF}/A_0^q \leq 20\,\%$

- The DiFF uncertainties are under control and can be further improved in the future!

Summary

- ✓ Light quark Yukawa couplings are poorly measured due to tiny size, QCD background, quark confinement, and quadratic effect y_q^2 at conventional 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
- ✓ Recoiling 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