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

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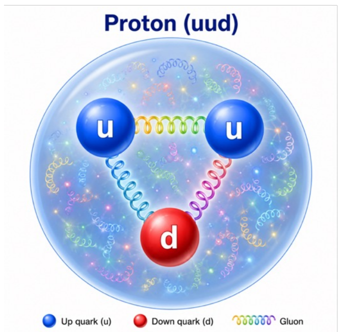
Qing-Hong Cao, Xin-Kai Wen, Bin Yan, Shutao Zhang, PRL 136 (2026) 231901

Why the Light quark Yukawa couplings

- The mass difference between proton and neutron—isospin



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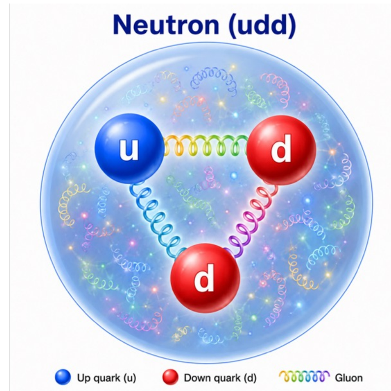
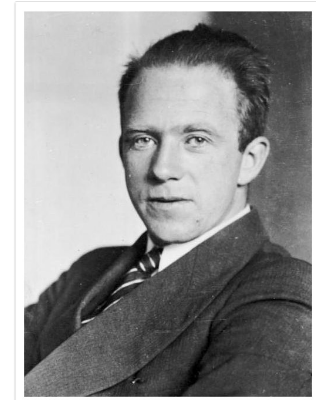




W. Heisenberg,
On the structure of atomic nuclei
Z. Phys. 77 (1932) 1-11

938.27231 MeV

939.56563 MeV

- BBN: primordial helium abundance

Thermal equilibrium: $$\frac{n_n}{n_p} = e^{-\Delta m_{np}/T_f}$$

$$Y_p = \frac{2\left(n_n/n_p\right)}{1 + n_n/n_p}$$

Why the Light quark Yukawa couplings

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

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

+ 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

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

REPORTS

Science

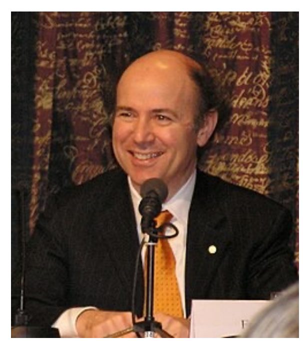
NUCLEAR PHYSICS

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.

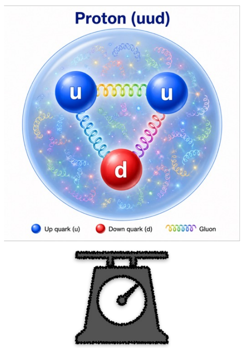
*"They have demonstrated, for the first time, that **fundamental theory gives the right sign** — not a trivial thing, because crude electrostatics gives the opposite result."*



— Frank Wilczek, Nature 520, 303 (2015)

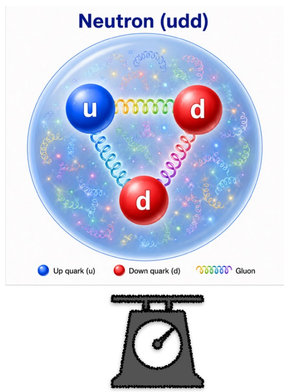
Why the Light quark Yukawa couplings

- ➢ Neutron-proton mass difference and our universe

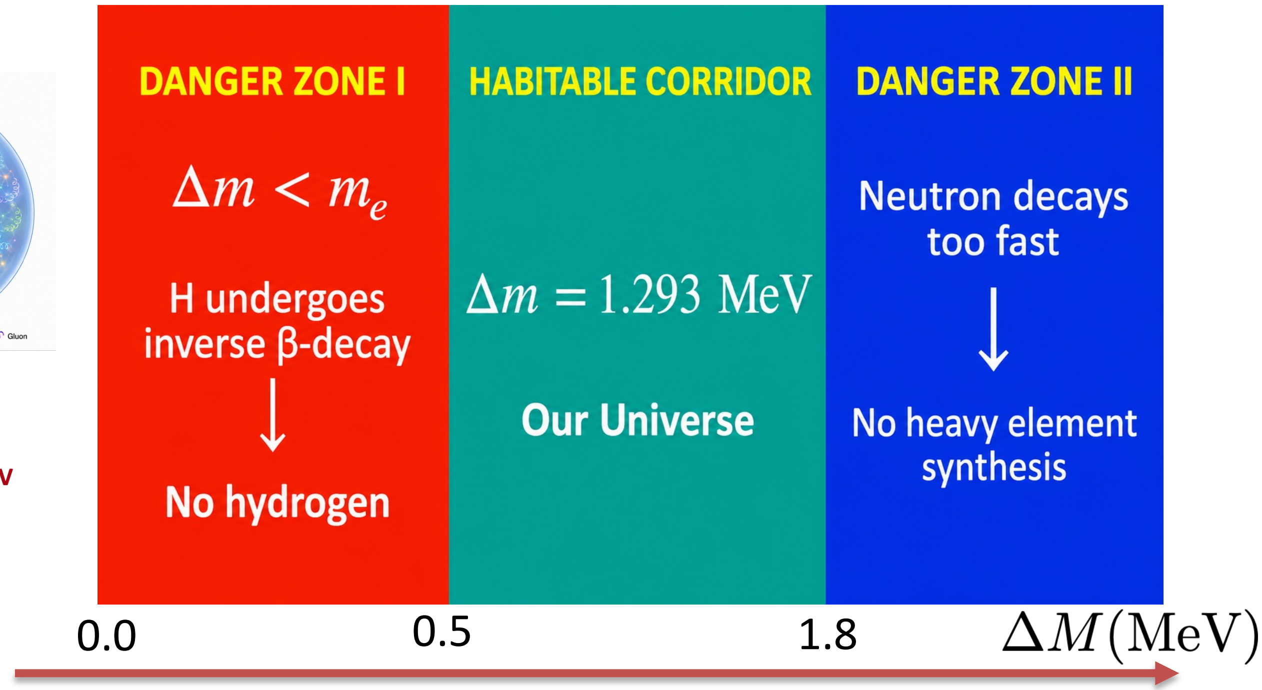


938.27231 MeV

$\neq$



939.56563 MeV



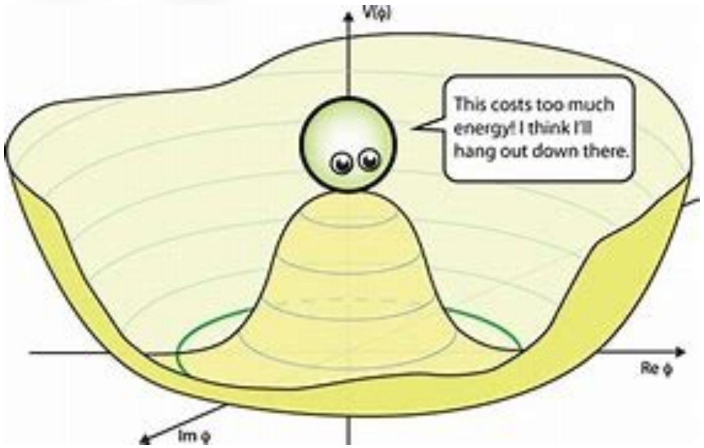
$$\frac{\Delta M}{M} \sim 0.14\%$$

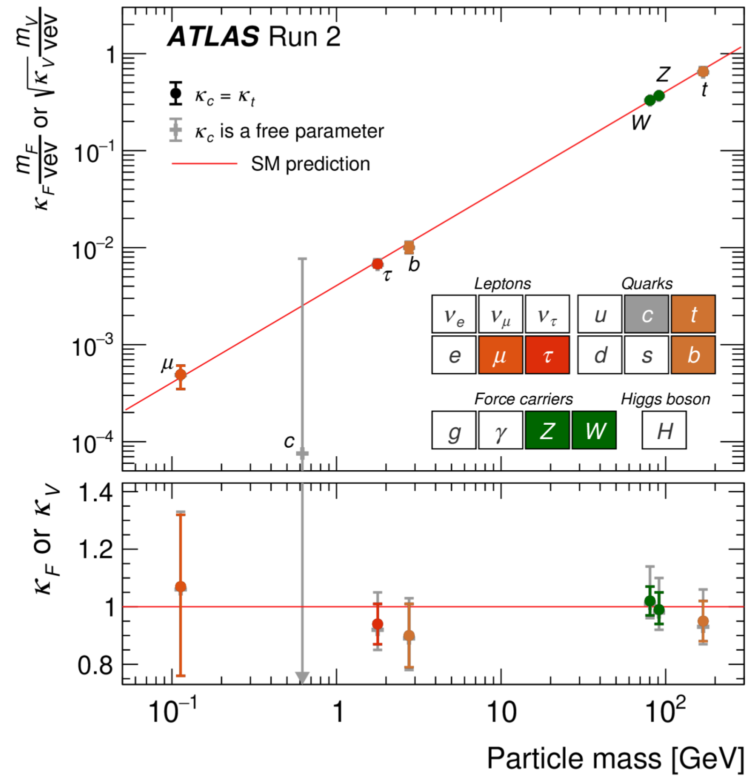
$p + e^- \to n + \nu_e$

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

- ➢ **Precisely determining the light-quark Yukawa couplings is crucial**

Higgs couplings and EWSB



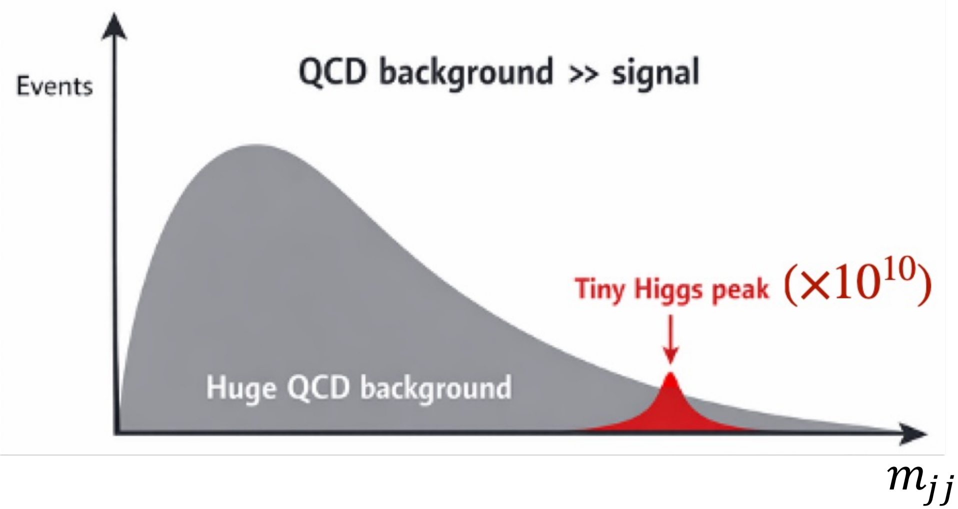


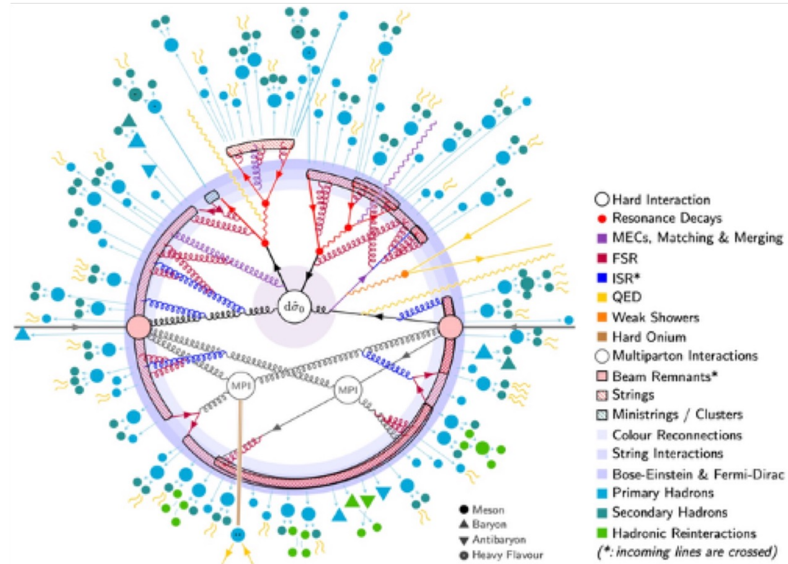
All fundamental particles get their mass from Higgs boson vev

- The Higgs mechanism has been verified for the third-generation fermions and gauge bosons
- The **university of the Higgs mechanism** for all fermion mass generation
- LHC sensitivity for light-quark Yukawa couplings: **No direct measurement**

Challenges for Light Quark Case

- Huge QCD backgrounds and blind to charge of u, d after confinement





From PYTHIA 8.3

- The cross sections or decay rates $\propto y_q^2$

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

- Current direct bounds three orders of magnitude above SM

$$|y_u| < 0.03, \ \ |y_d| < 0.026$$ CMS: PRL 132 (2024) 121901, PRD 112 (2025) 112001

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

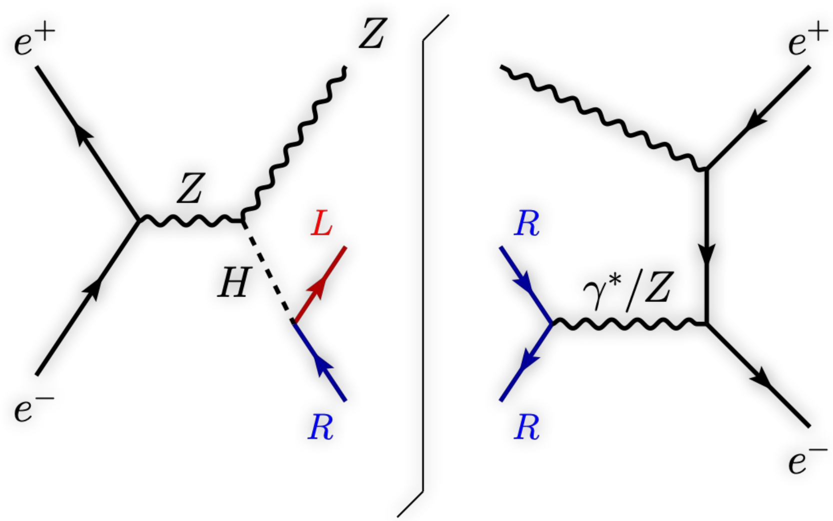
Linear sensitivity via interference

- Higgs-mediated amplitude interference with the SM background

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

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

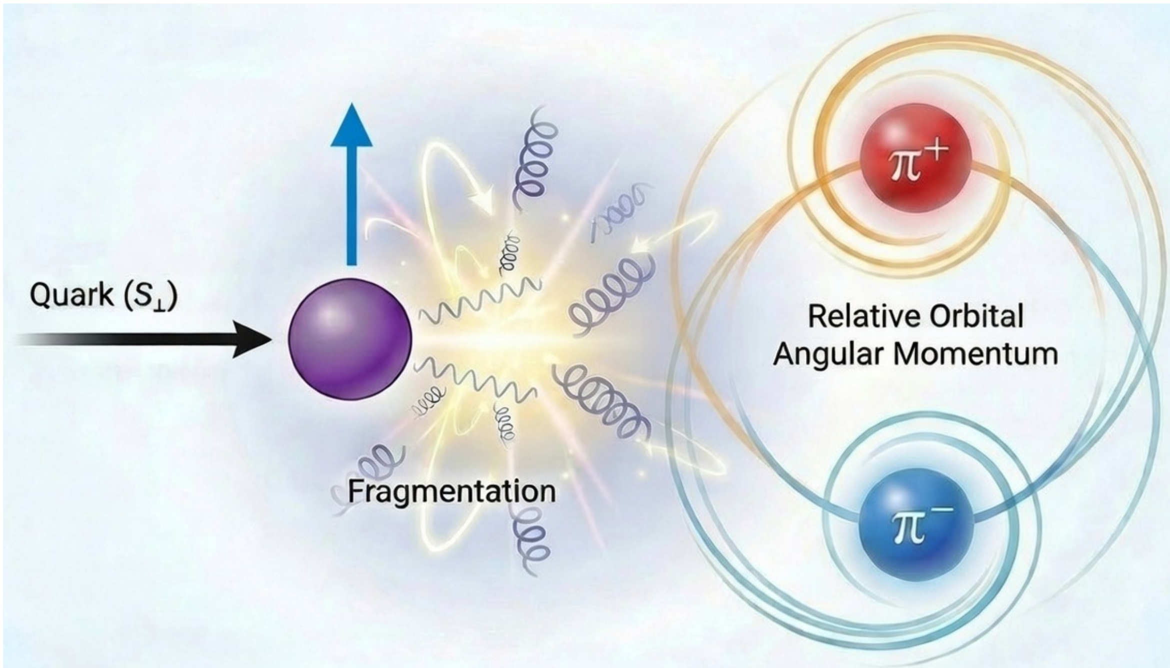
$e^+ + e^- \to Z + H(\to q\bar{q}) \qquad e^+ + e^- \to Z + Z/\gamma^*(\to q\bar{q})$



- The interference effects could be projected out by the Dihadron Fragmentation Functions (DiFFs)

Chiral-odd FFs: Transverse spin of quark

- Sizeable DiFF replaces the y_q- suppressed chiral flip

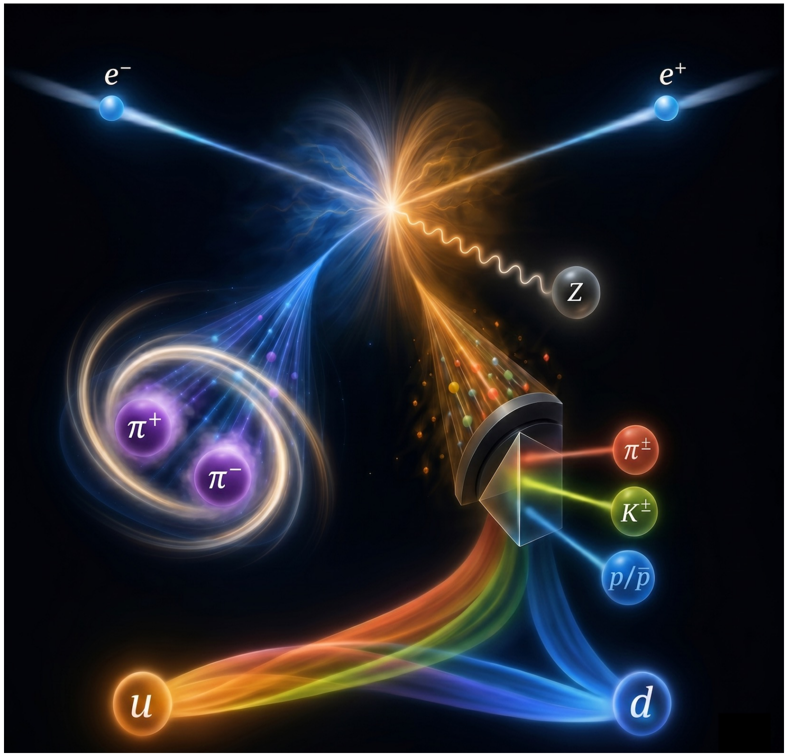


Quark transverse polarization turns into the relative orbital angular momentum of a pion pair during fragmentation

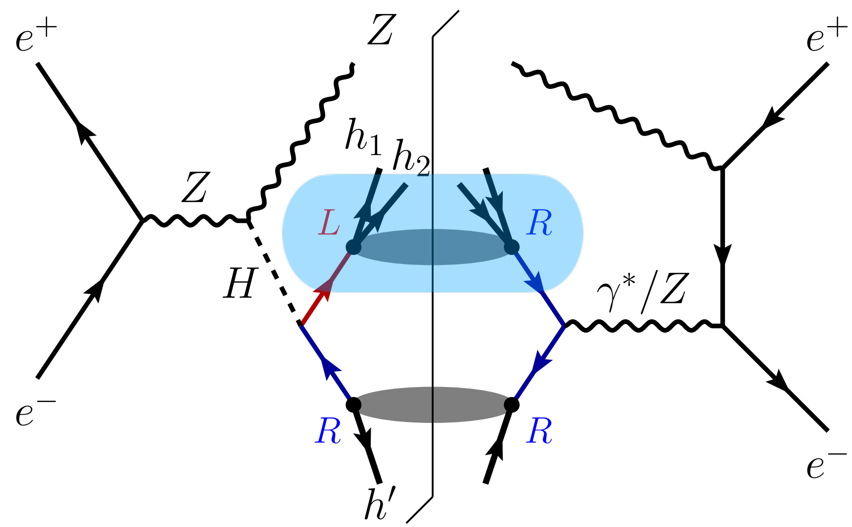
$$\boxed{\begin{array}{c}\text{Yukawa vertex}\\ \text{(chiral-odd)}\end{array}} \xrightarrow[\text{chiral-even observable}]{\text{pair up}} \boxed{\begin{array}{c}\text{DiFF } H_q^{\pi^+\pi^-}\\ \text{(chiral-odd)}\end{array}}$$

Linear sensitivity via interference

- Yukawa couplings flip chirality: transverse polarization of quark $q \to \pi^+\pi^-$



$$\rho = \frac{1}{2}(1 + \mathbf{s}\cdot\sigma) = \begin{pmatrix} 1+s_z & s_x - is_y \\ s_x + is_y & 1-s_z \end{pmatrix}$$

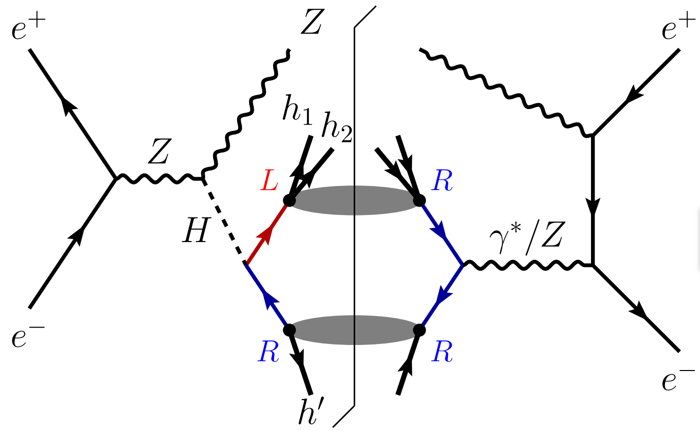


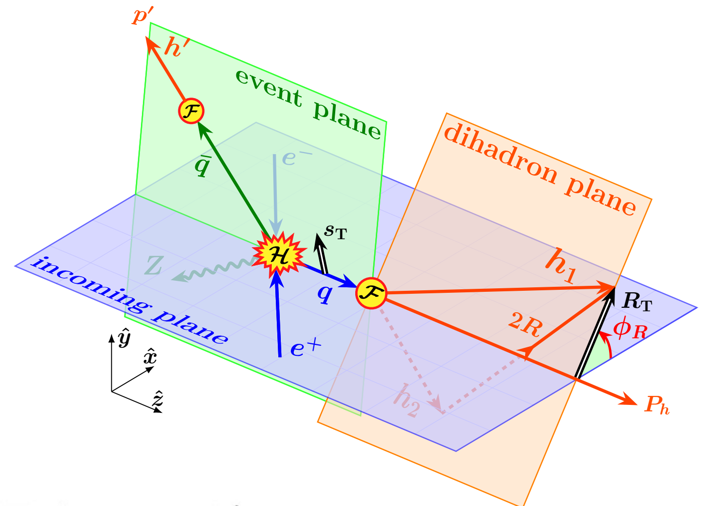
QHC, XKW, BY, STZ, PRL 136 (2026) 231901

$y_q^2 \to y_q$

- New flavor tagging: single hadron $\bar{q} \to h$

Transverse spin effects of quark @ CEPC





$$\frac{d\sigma}{dx_q\, dx_{\bar{q}}\, d\cos\theta\, d\phi\, dz\, d\bar{z}\, dM_h\, d\phi_R} = \frac{1}{64(2\pi)^5} \sum_{q,\, q\to\bar{q}} \mathcal{C}_q D_{\bar{q}}^{h'}(\bar{z})$$
$$\times \left[D_q^{h_1 h_2}(z, M_h) - (\boldsymbol{s}_{T,q} \times \hat{\boldsymbol{R}}_T)^z H_q^{h_1 h_2}(z, M_h) \right].$$

Unpolarized FFs

Polarized FFs

Energy fractions of quarks $x_q, x_{\bar{q}}$; hadrons $z, \bar{z}$

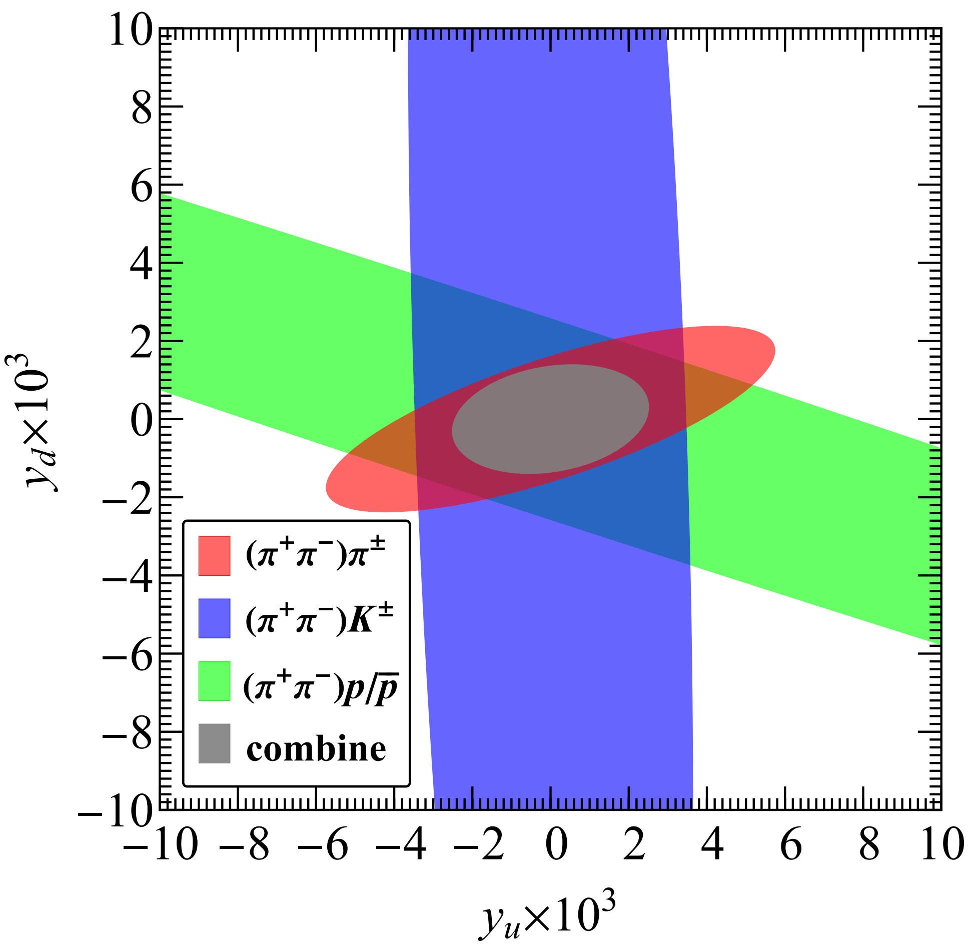
$$(\boldsymbol{s}_{T,q} \times \hat{\boldsymbol{R}}_T)^z = s_q^x \sin\phi_R - s_q^y \cos\phi_R$$

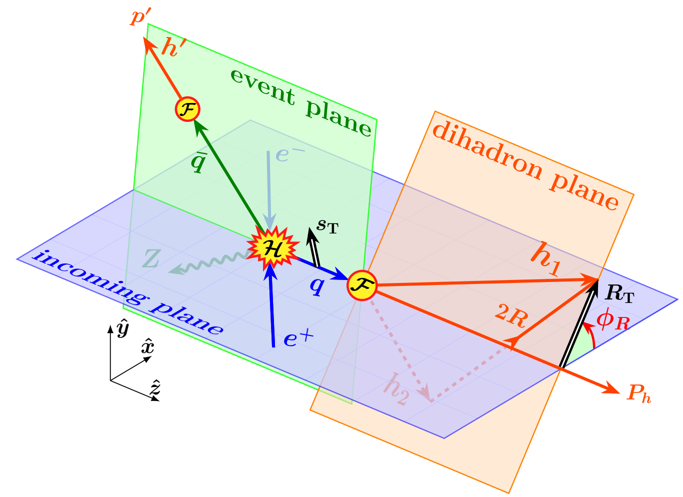
$$s_q^{x,y} \propto y_q$$

CP even Yukawa couplings @ CEPC

$$A_{UD}^{h'} = \frac{\sigma^{h'}(\sin\phi_R > 0) - \sigma^{h'}(\sin\phi_R < 0)}{\sigma^{h'}(\sin\phi_R > 0) + \sigma^{h'}(\sin\phi_R < 0)}$$

$$A_{LR}^{h'} = \frac{\sigma^{h'}(\cos\phi_R > 0) - \sigma^{h'}(\cos\phi_R < 0)}{\sigma^{h'}(\cos\phi_R > 0) + \sigma^{h'}(\cos\phi_R < 0)}$$





$$\sqrt{s} = 250\ \text{GeV}, \mathcal{L} = 50\ \text{ab}^{-1}$$

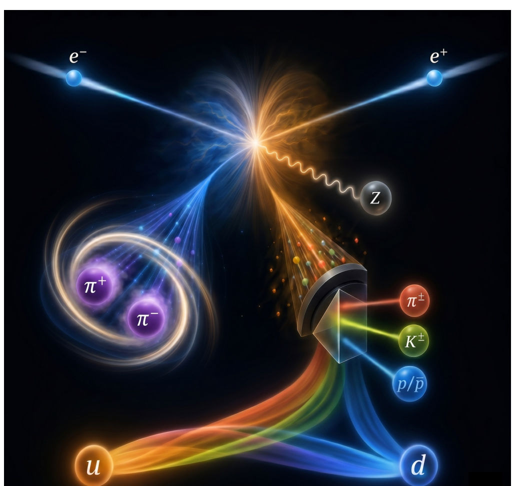
- Yukawa couplings $O(10^{-4} - 10^{-3})$
- Single-hadron channels enable flavor separation

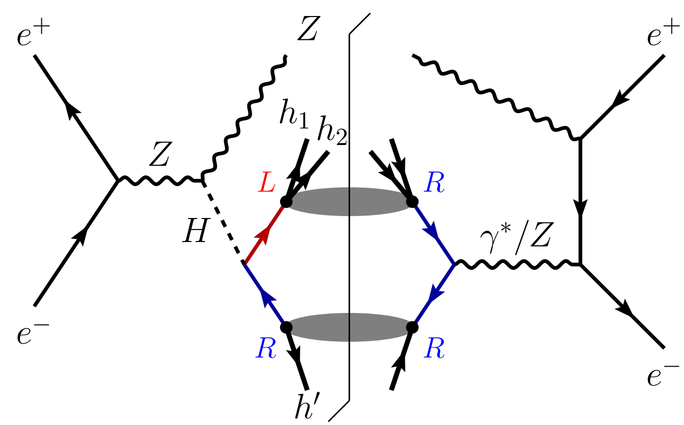
Summary

- Light quark Yukawa couplings are extremely small and poorly constrained; conventional observables scale as y_q^2 and lack sensitivity

- The signal and background interference induces quark transverse polarization and the chiral-odd dihadron fragmentation functions, yielding azimuthal asymmetries linear in y_q

- Recoiling single-hadron could be used for flavor discrimination and break $y_u - y_d$ degeneracy

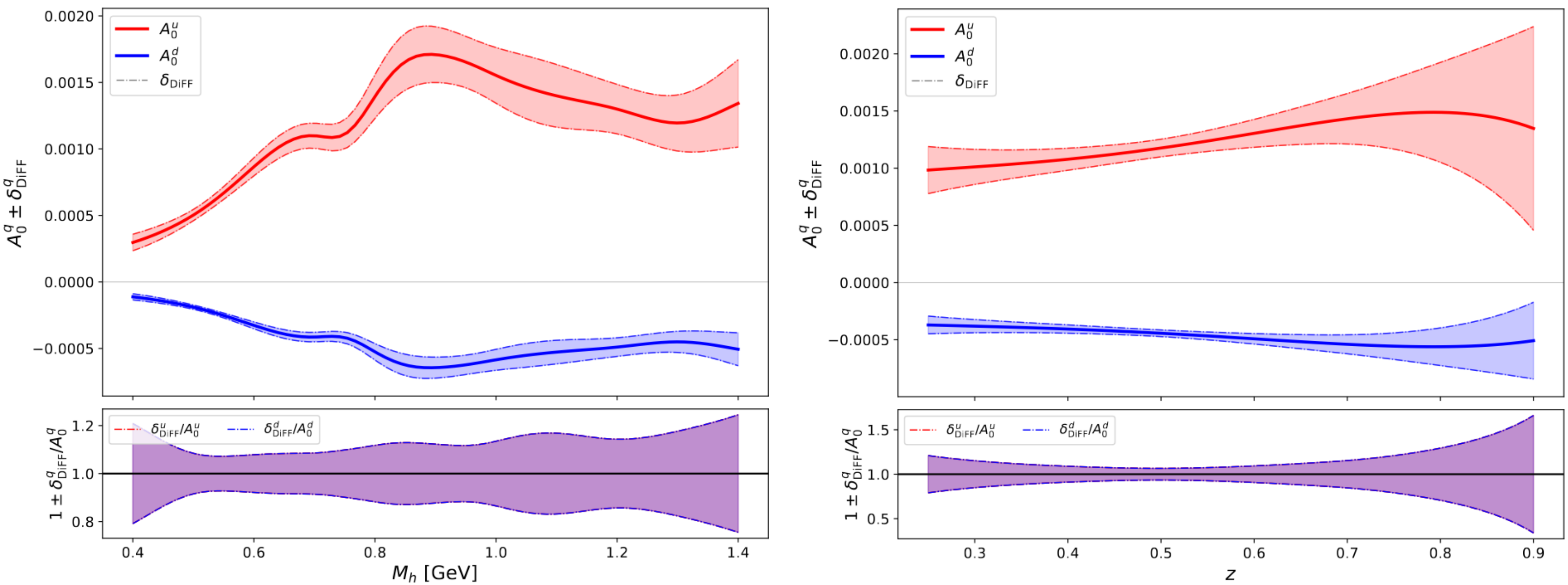




Thank you!

DiFF uncertainties

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



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

- The DiFF uncertainties are well under controlled!