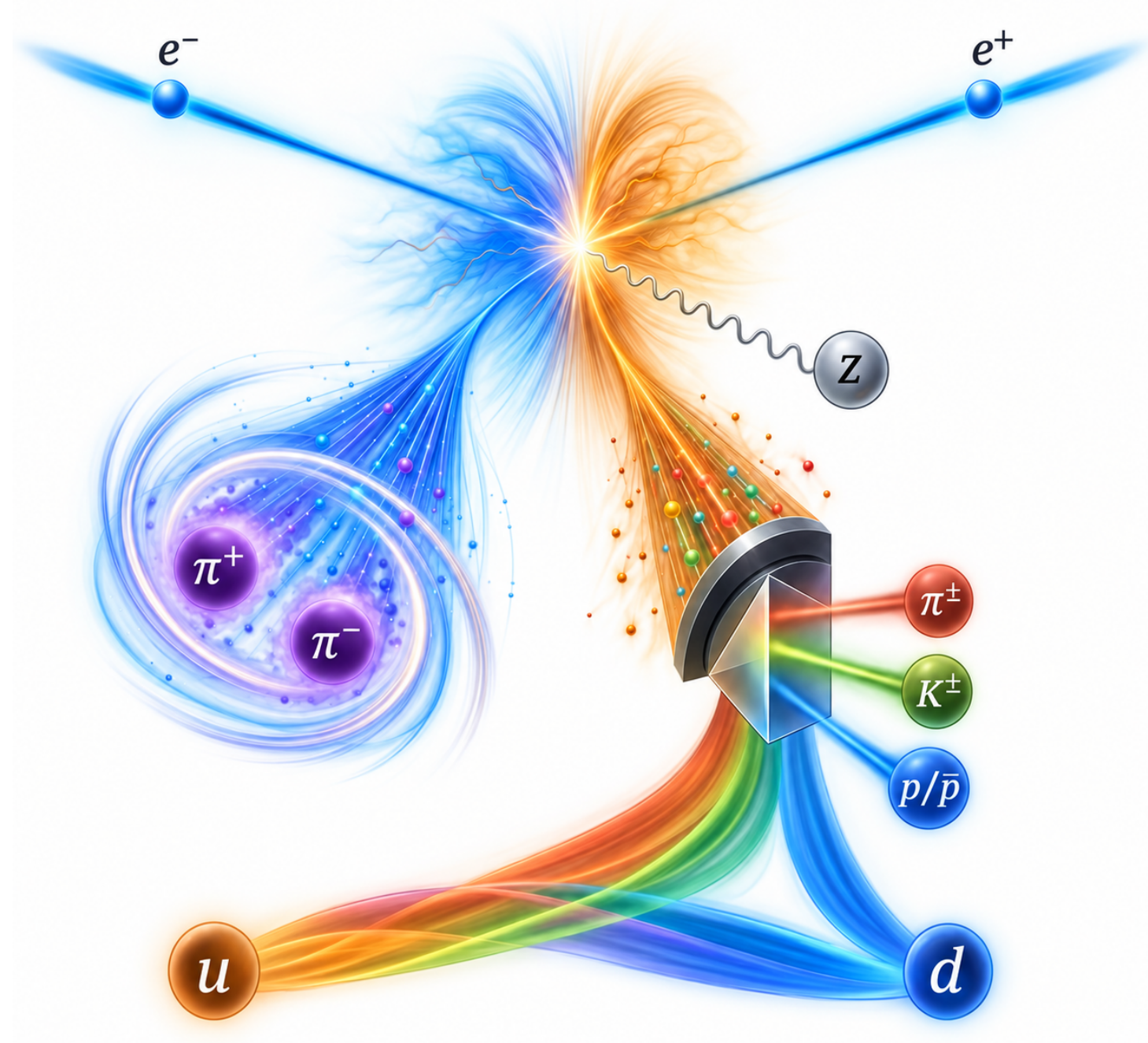
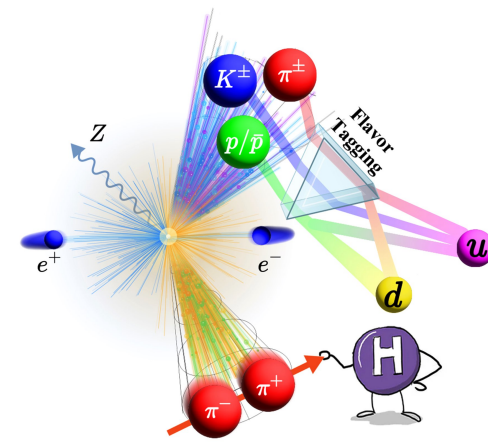


Unveiling *Light-Quark* Yukawa **Flavor** Structure via **Dihadron Fragmentation Function** at Lepton Colliders

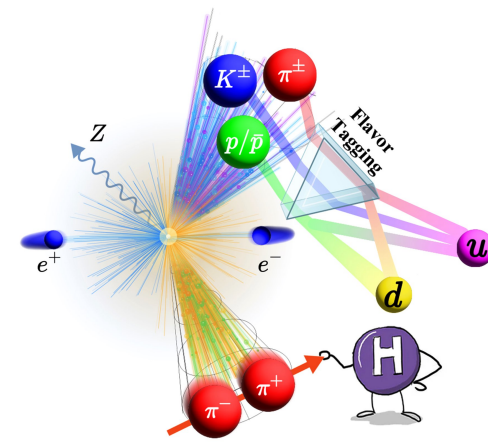


Shu-Tao Zhang
Peking University

The Second TeV & 33rd LHC Mini-Workshop
Sept. 19-20, 2026

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

Why are the *Light-Quark* Yukawa couplings important?



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

$$\Delta M = \Delta M_{\text{QCD}} + \Delta M_{\text{QED}}$$

+ 1.29 MeV

**Fine cancellation of
two large effects**

+ 2.52 MeV

$m_d > m_u$
Higgs Yukawa

- 1.00 MeV

**Proton is charged,
Coulomb self-energy**

48% of 2.52 MeV cancelled by QED

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

REPORTS

NUCLEAR PHYSICS

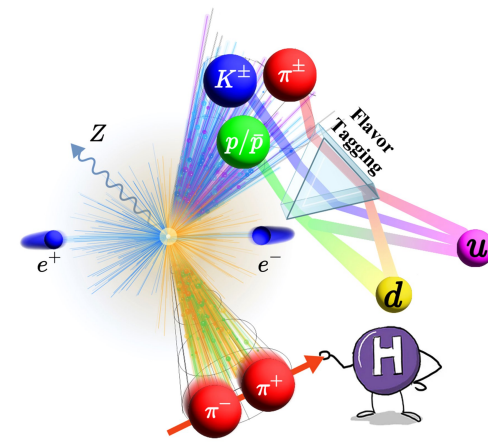
Ab initio calculation of the neutron-proton mass difference

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. Toth¹

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.

We need precise detection on the quark mass.

The missing *Light-Quark* Yukawa couplings

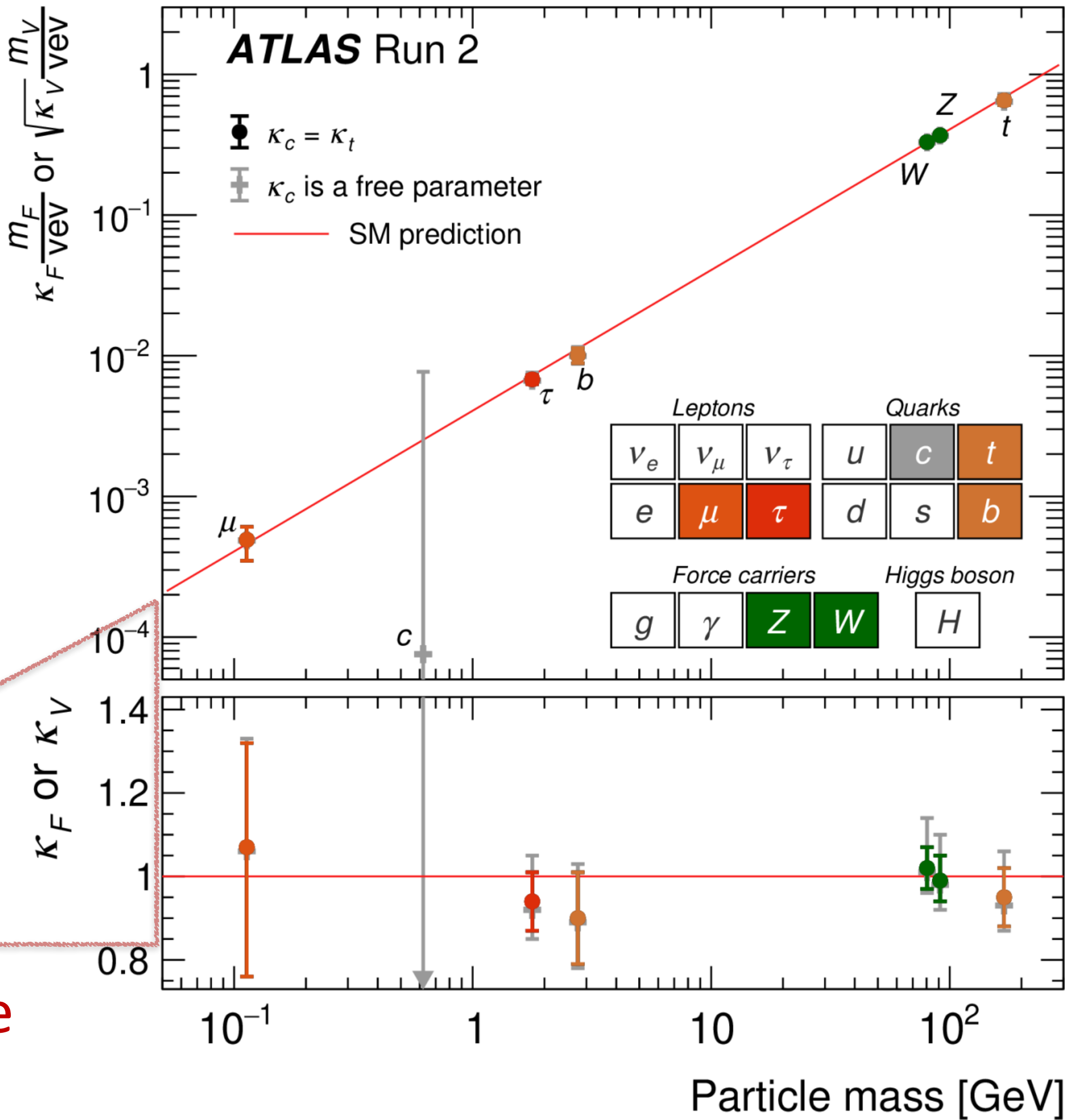


LHC sensitivity for *light-quark* Yukawa:

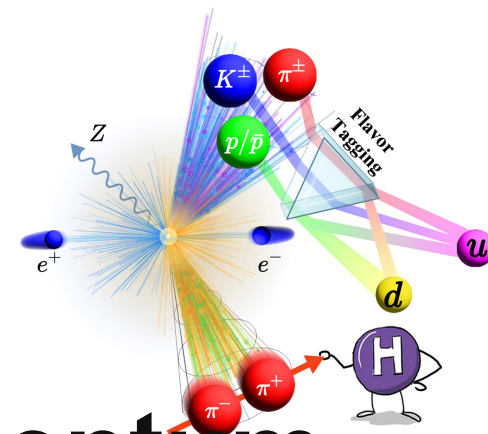
No Direct Measurement



universality of the Higgs mechanism

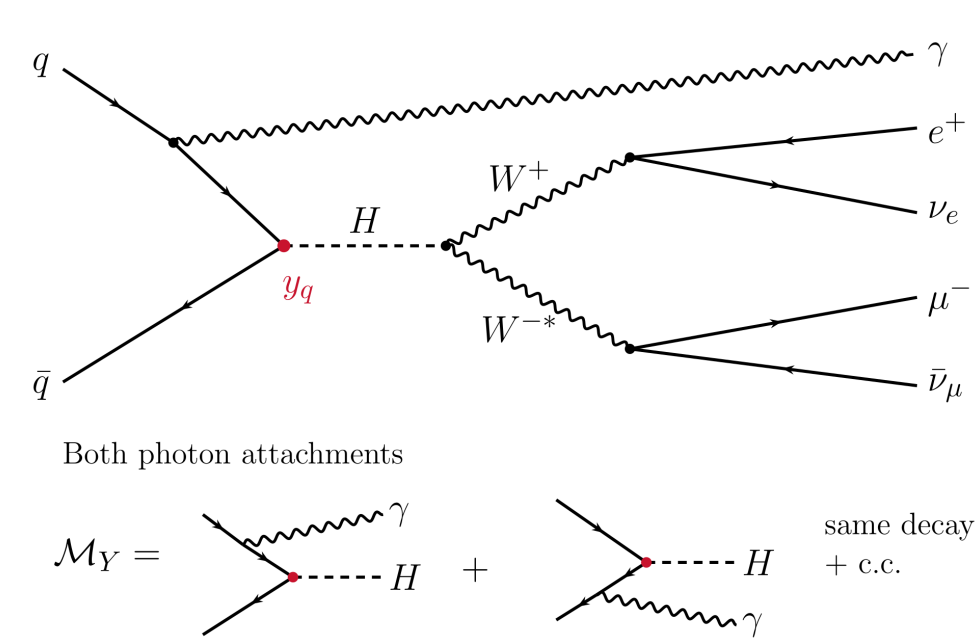


Current experiment constraints



Higgs plus photon

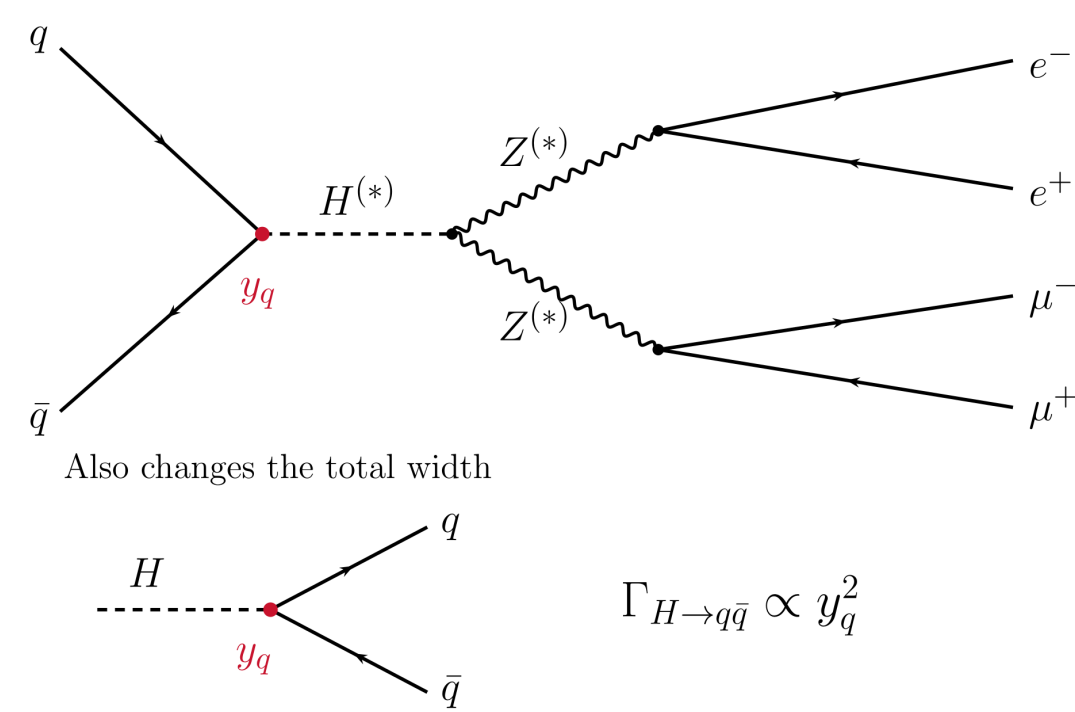
CMS, one coupling varied



CMS, PRL 132 (2024) 121901

On/off-shell four leptons

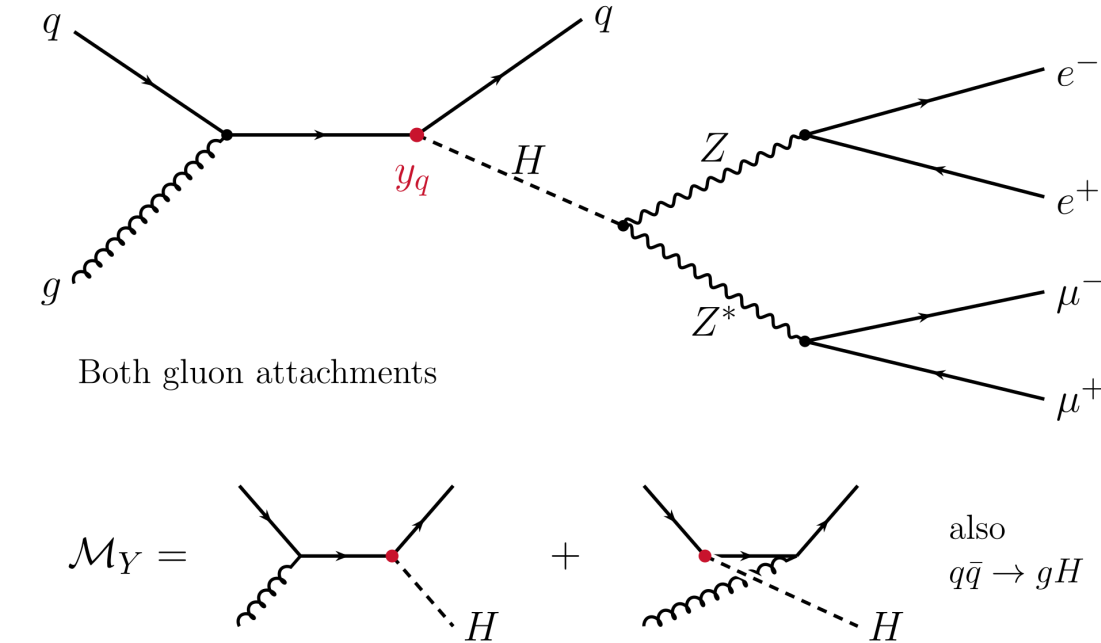
CMS, profiled light and vector couplings



CMS, arXiv:2607.23352
PRD 112 (2025) 112001

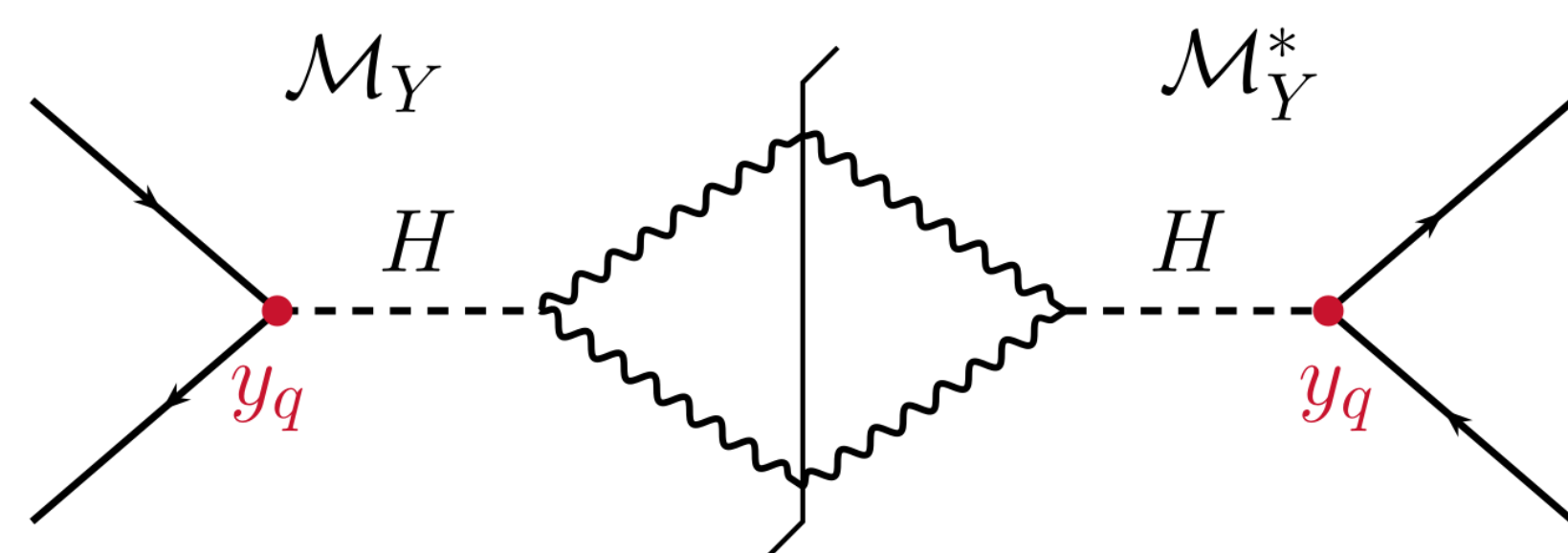
Higgs transverse momentum

ATLAS data, theory recast

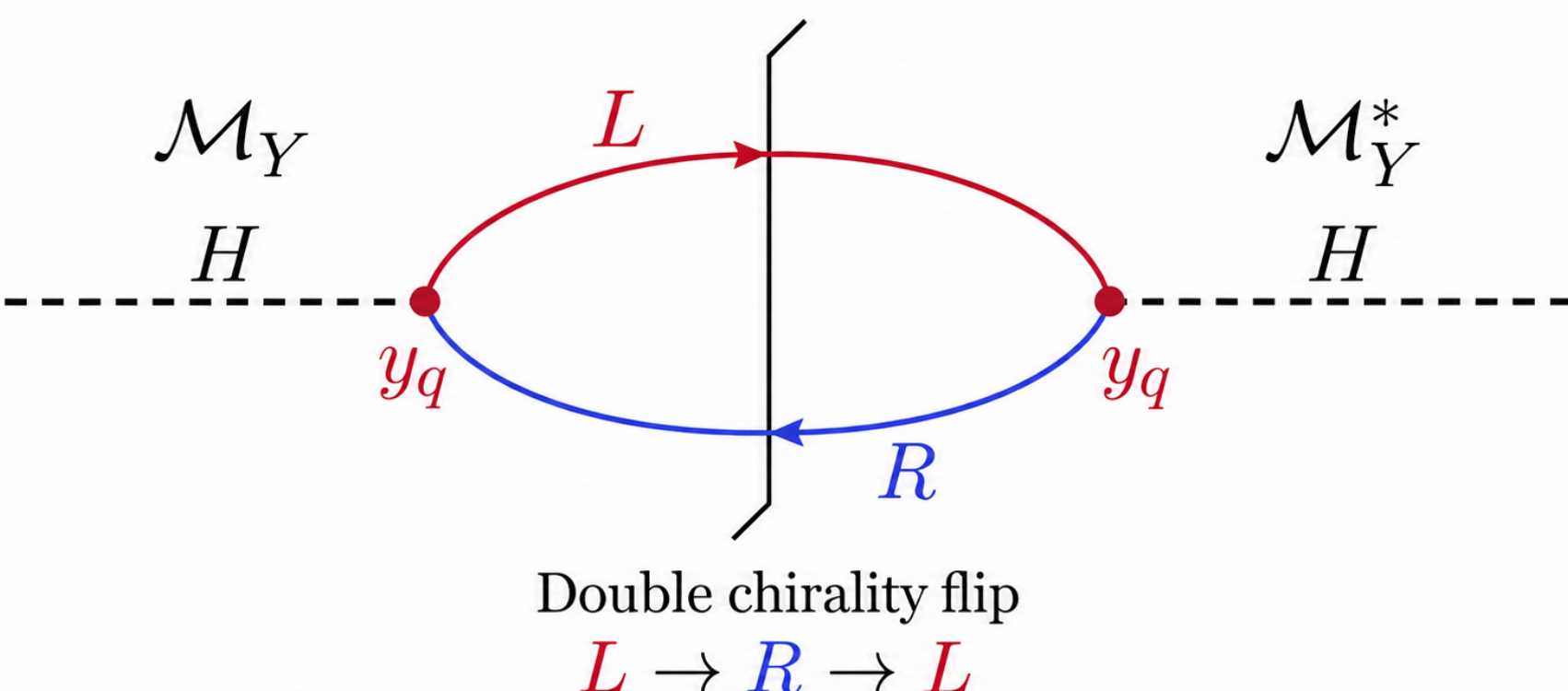


Soreq, Zhu, Zupan, JHEP 12 (2016) 045
ATLAS, PRL 115 (2015) 091801

Best Constrains: $|y_u| < 0.03, |y_d| < 0.026$



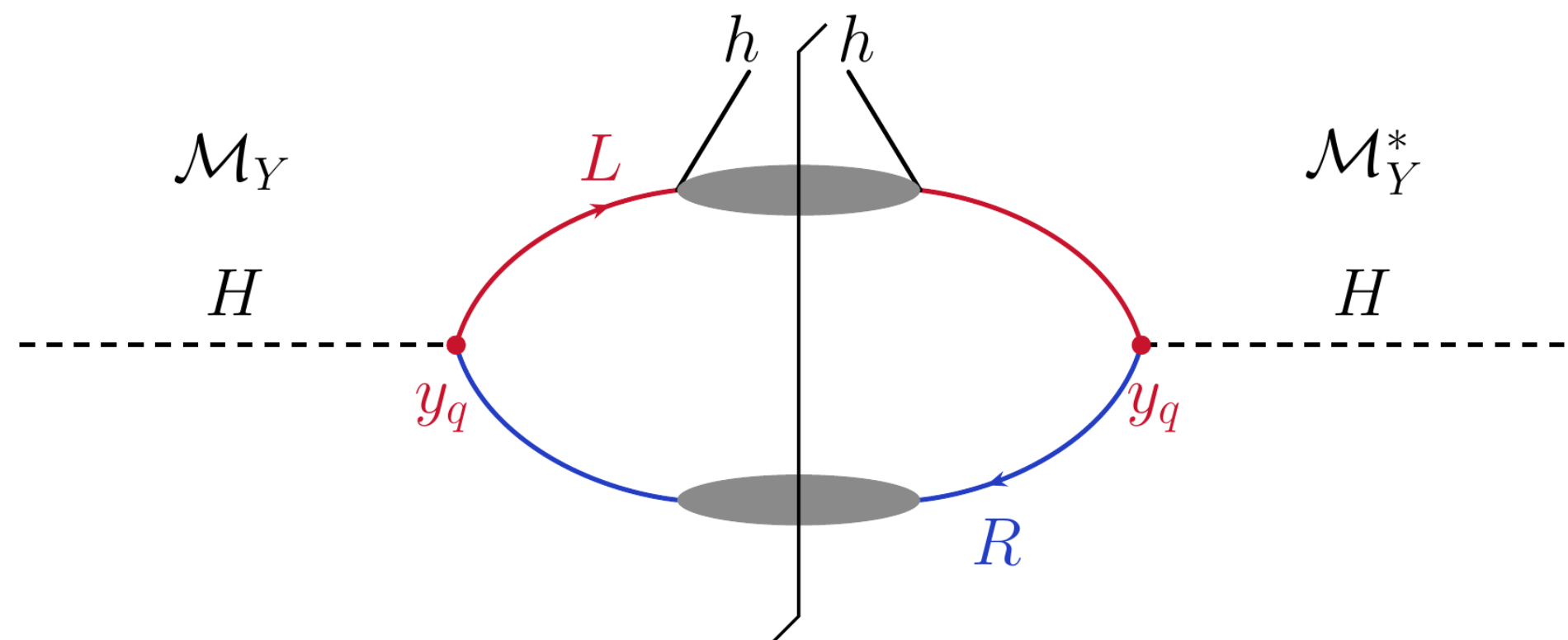
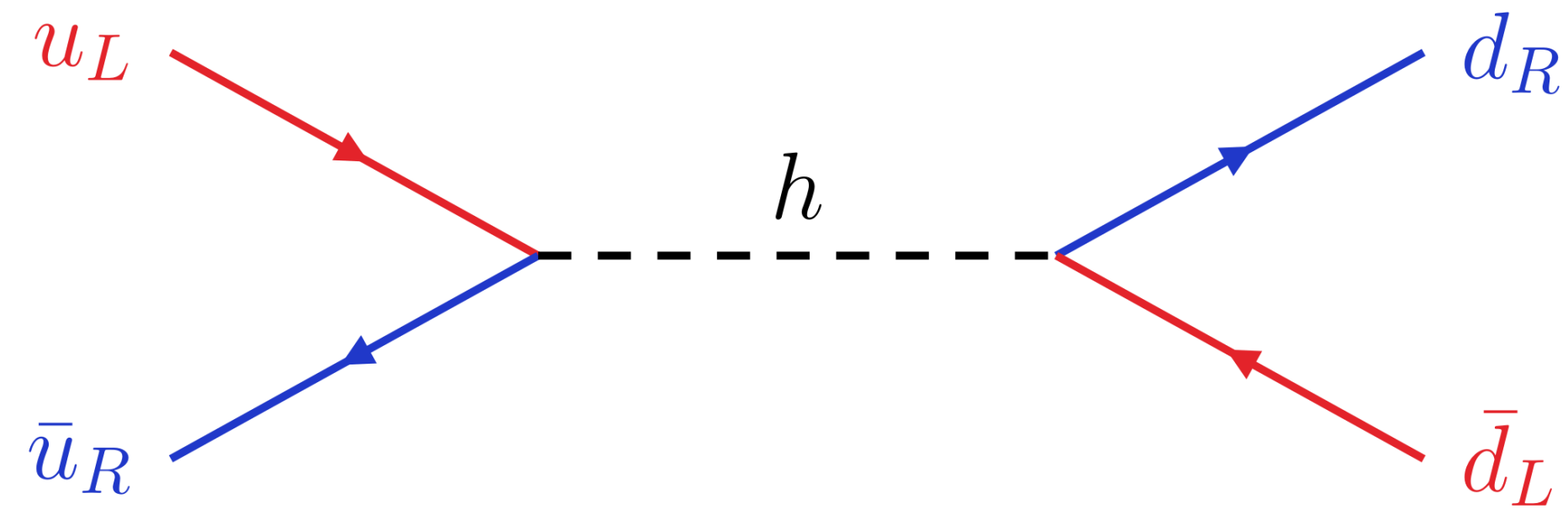
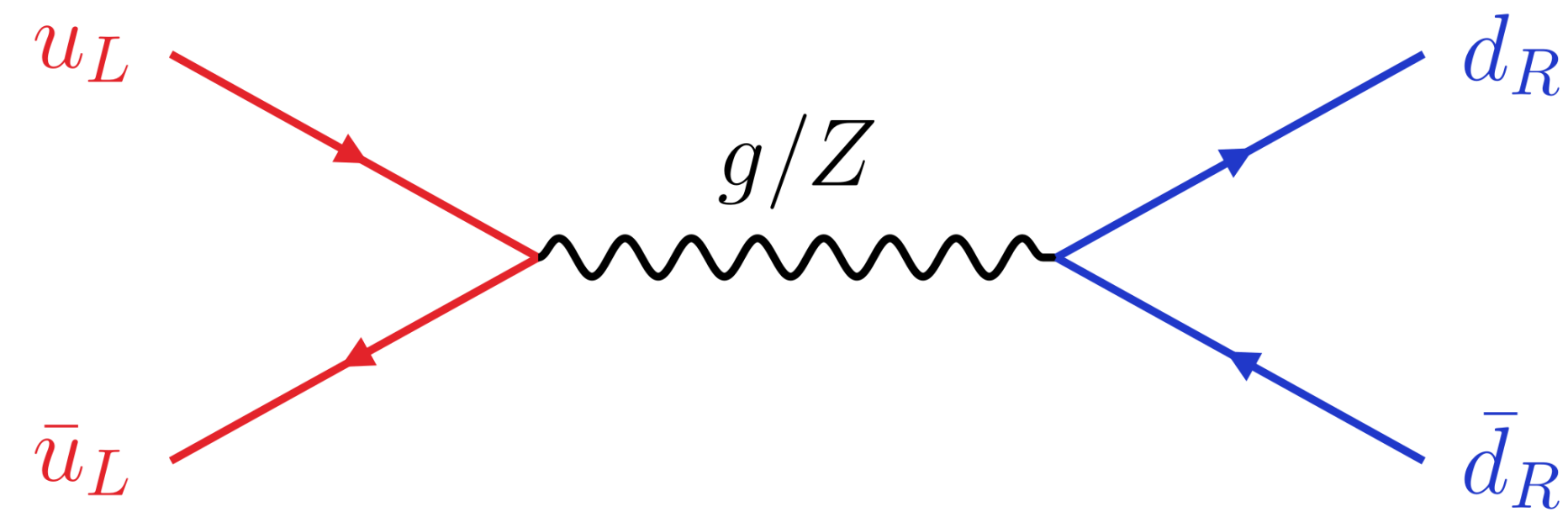
$$|\mathcal{M}_Y|^2 \propto y_q^2$$



Double chirality flip
 $L \rightarrow R \rightarrow L$

Chirality at gauge and Yukawa vertices

Massless limit of a high-energy quark line



Gauge interactions

$$\Gamma_g^{a,\mu} = ig_s T^a \gamma^\mu$$

$$\Gamma_Z^\mu = i\gamma^\mu (g_L P_L + g_R P_R)$$

$$L \rightarrow L \quad R \rightarrow R$$

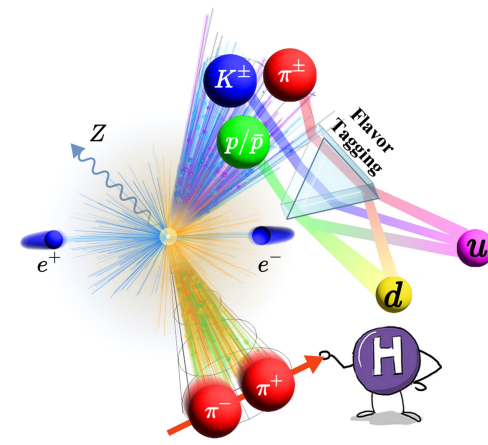
Yukawa interaction

$$\Gamma_h = -i y_q / \sqrt{2}$$

$$h(\bar{q}_L q_R + \bar{q}_R q_L)$$

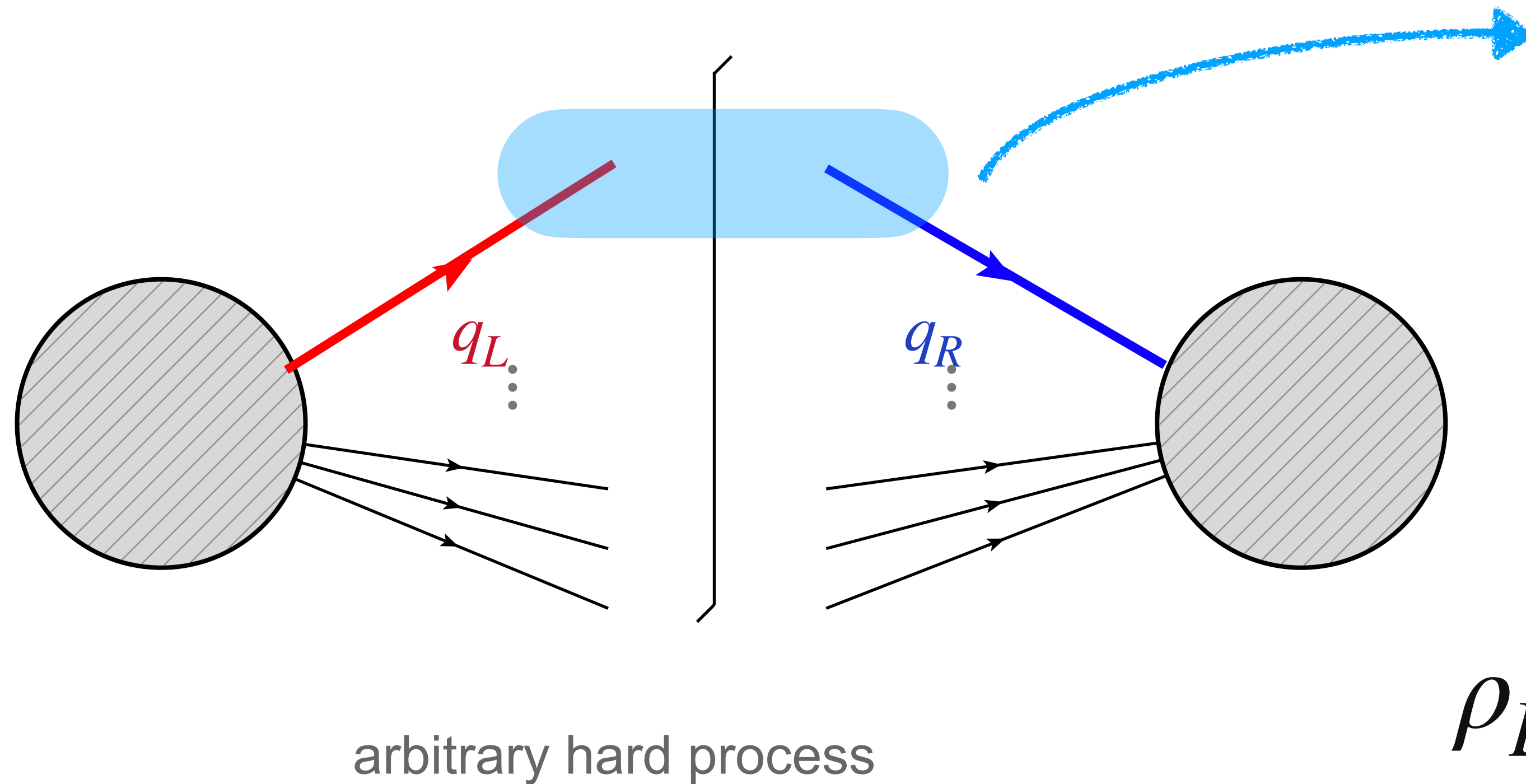
$$L \leftrightarrow R$$

Traditionally no chiral odd fragment



Transverse spin resolves chiral interference

Keep the outgoing-quark spin indices open.

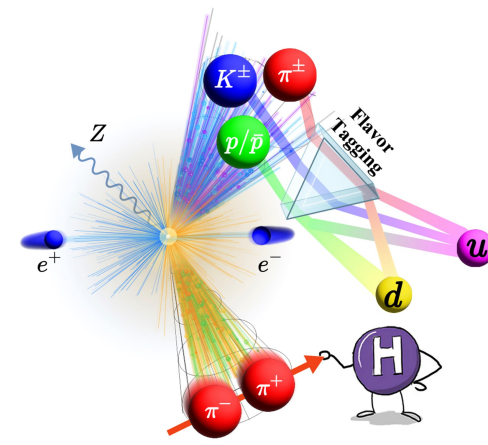


$$\rho = \frac{1}{2} \begin{pmatrix} 1 + s_z & s_x - i s_y \\ s_x + i s_y & 1 - s_z \end{pmatrix}$$

(R, L) basis

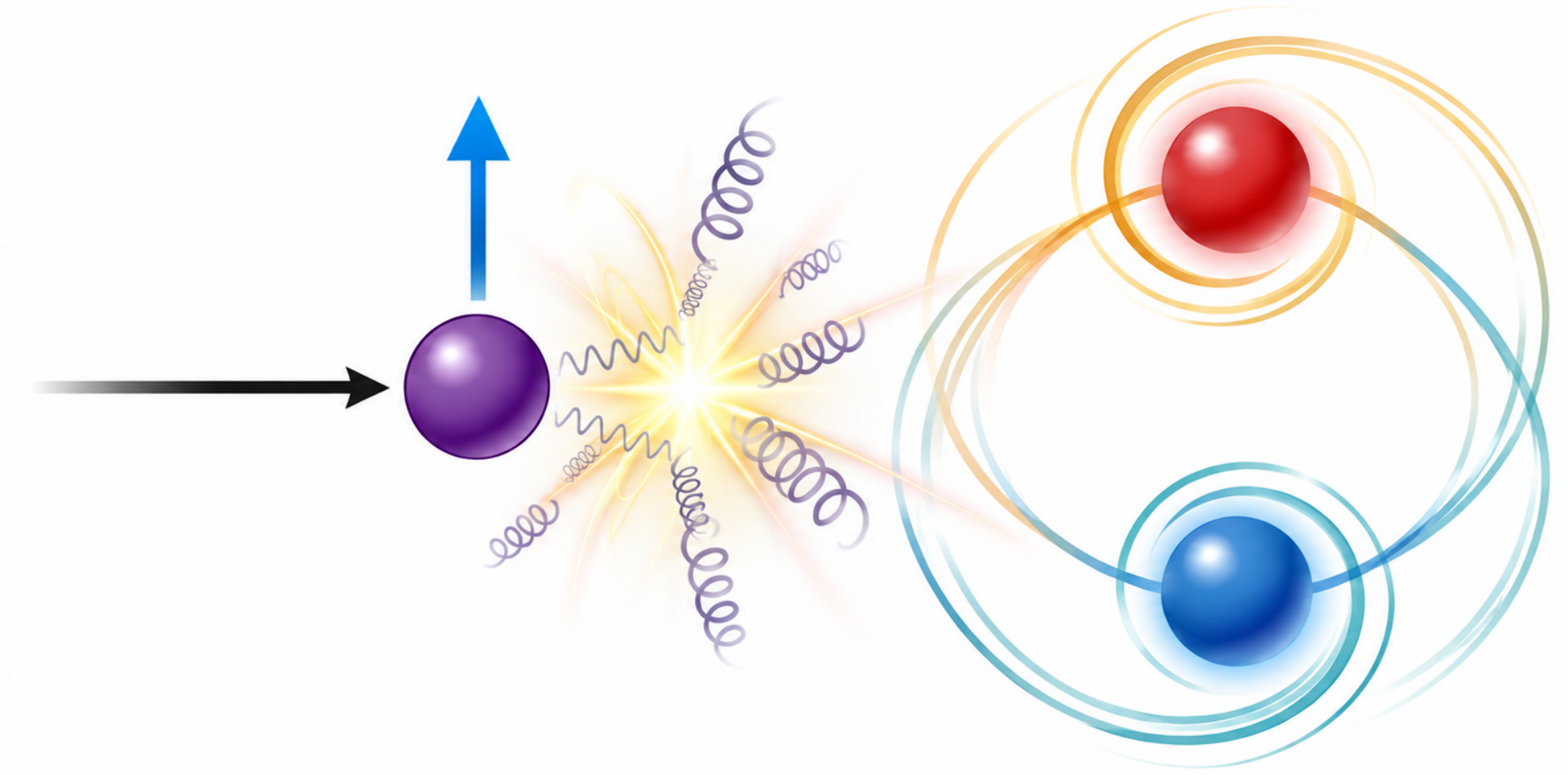
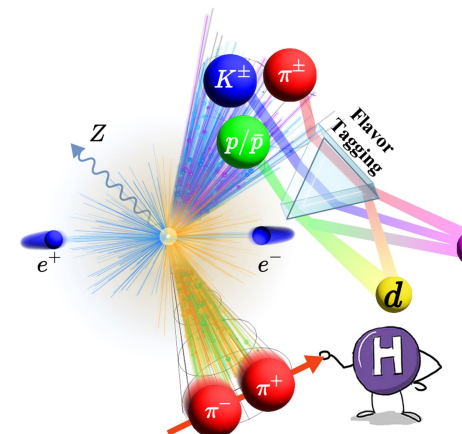
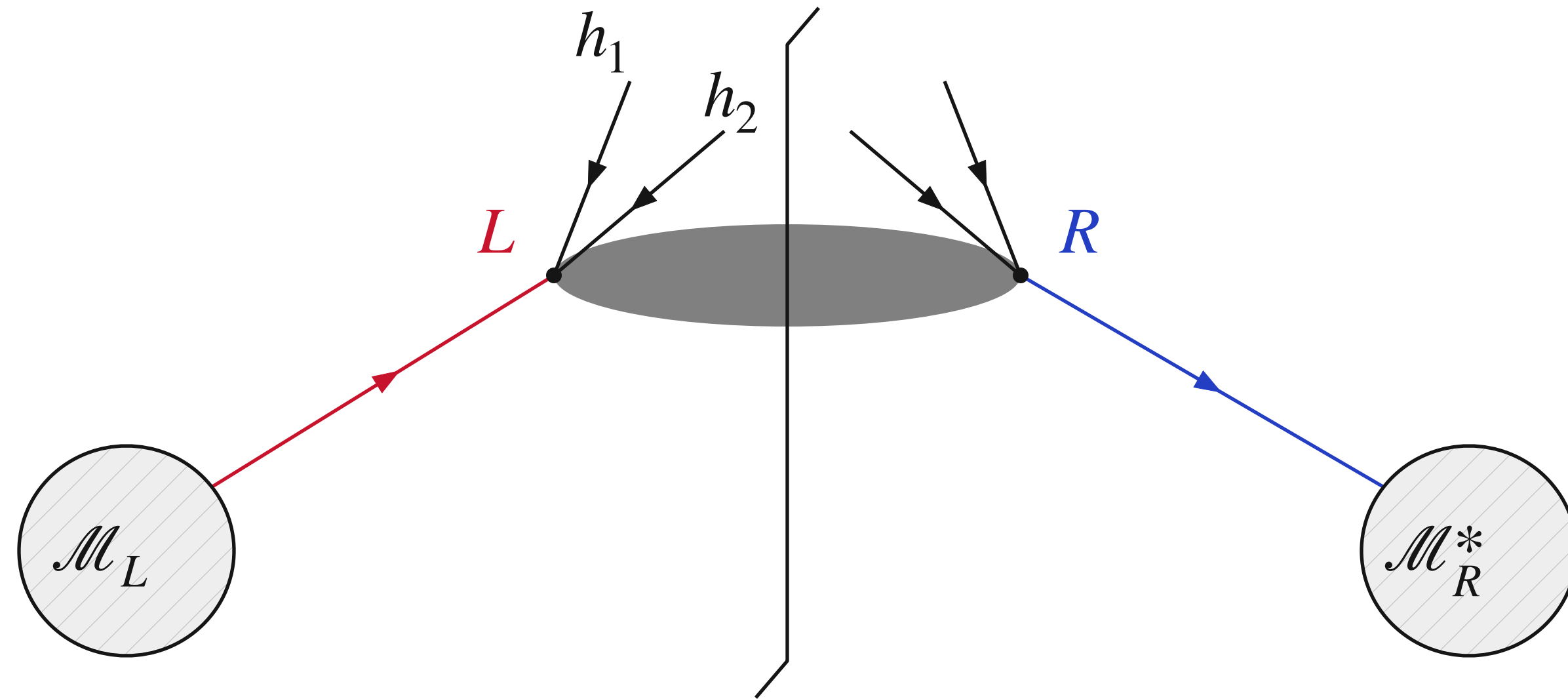
$$\rho_{LR} \propto \sum_X \mathcal{M}_L(X) \mathcal{M}_R^*(X)$$

Transverse spin measures **off-diagonal coherence**



Dihadron fragmentation analyzes transverse spin

A collider analogue of a Stern–Gerlach spin analyzer



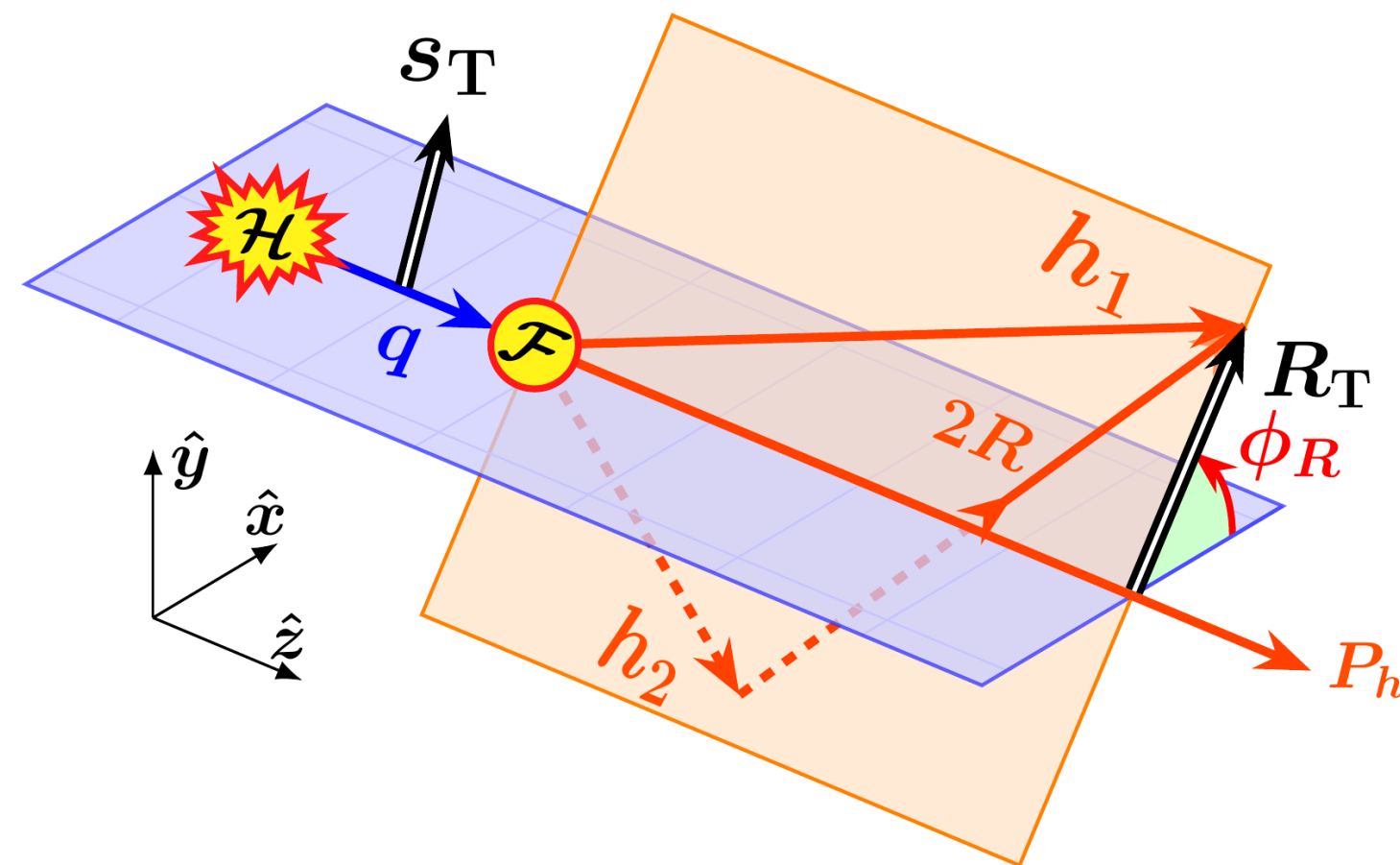
$$q(s_T) \rightarrow \pi^+ \pi^- + X$$

Chiral-odd spin analyzer

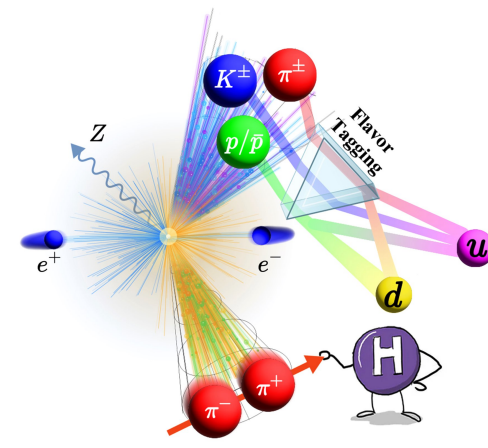
$$H_q^{\triangleleft} \sin(\phi_R - \phi_s)$$

The pair azimuth reads transverse spin.

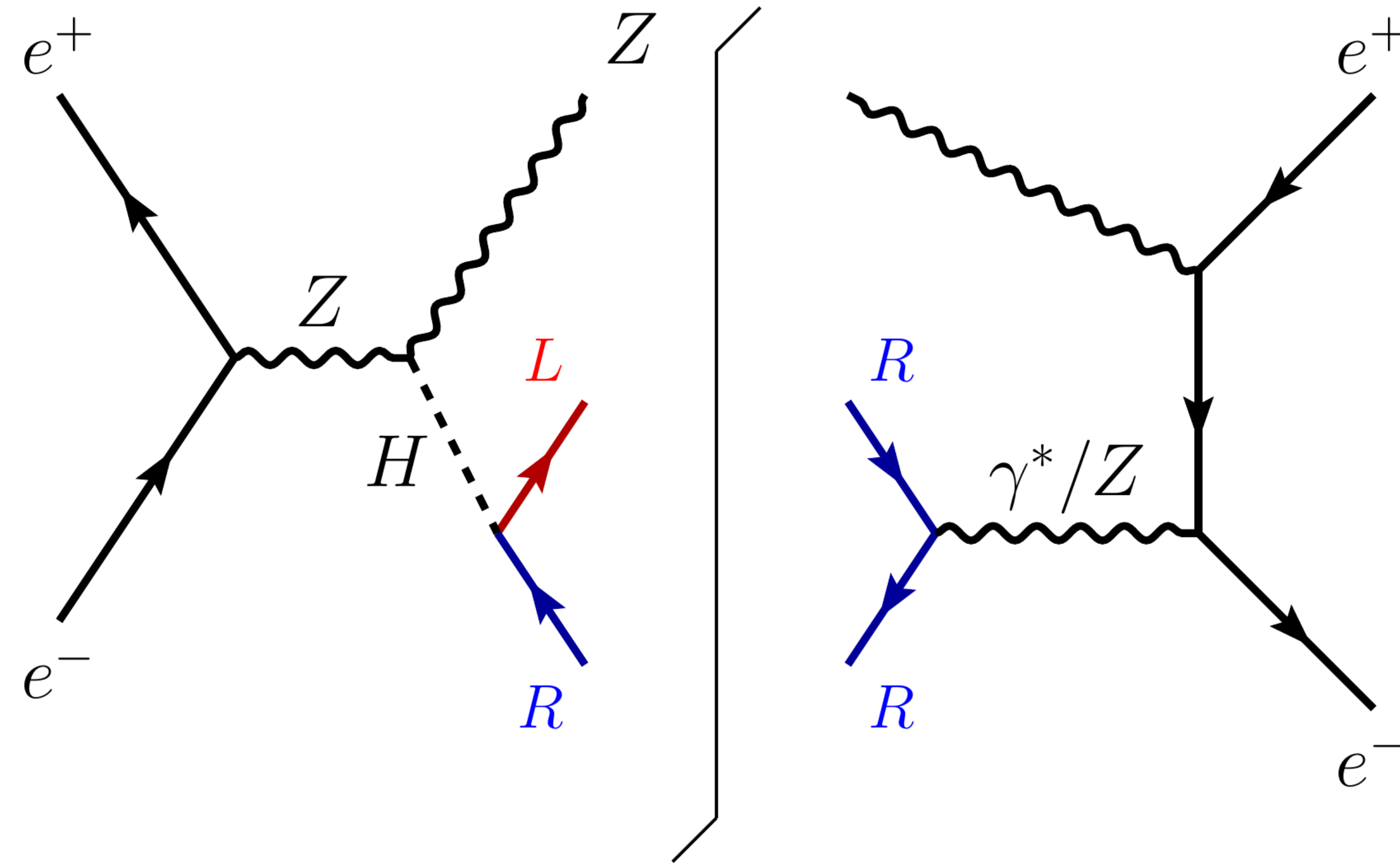
No extra light-quark Yukawa factor.



Three-body production and Yukawa interference



$$e^+e^- \rightarrow Zq\bar{q}$$



One light-quark Yukawa insertion

$$\mathcal{H}_{LR} \propto y_q$$

Higgs recoil peak

$$M_{\text{rec}}^2 = s + m_Z^2 - 2\sqrt{s} E_Z$$

$$\simeq m_h^2$$

Keep the two sides of the Higgs peak in separate bins.

[illegible]

Dihadron spin analyzer

$$q \rightarrow (\pi^+ \pi^-) + X$$

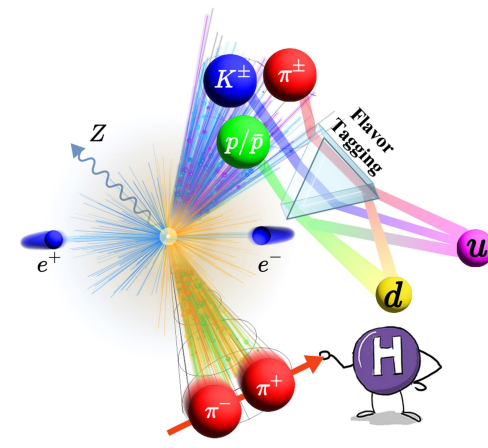
$$H_q^{\triangleleft}$$

Identified recoil hadron sensitive to Flavor

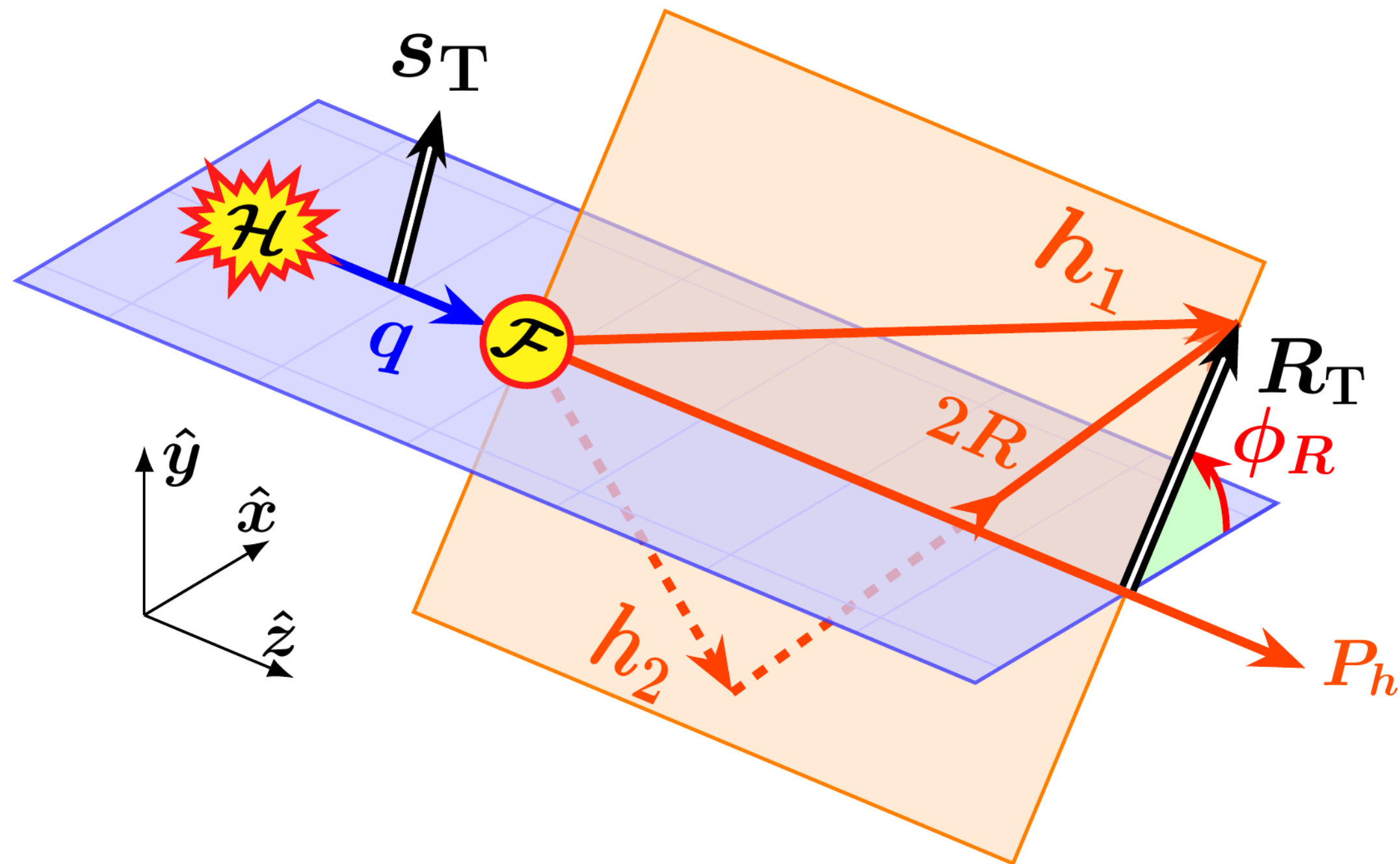
$$\bar{q} \rightarrow h' + X$$

$$D_{\bar{q}}^{h'}$$

Azimuthal asymmetries and Yukawa sensitivity



The pion-pair plane converts spin into an azimuthal modulation.



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

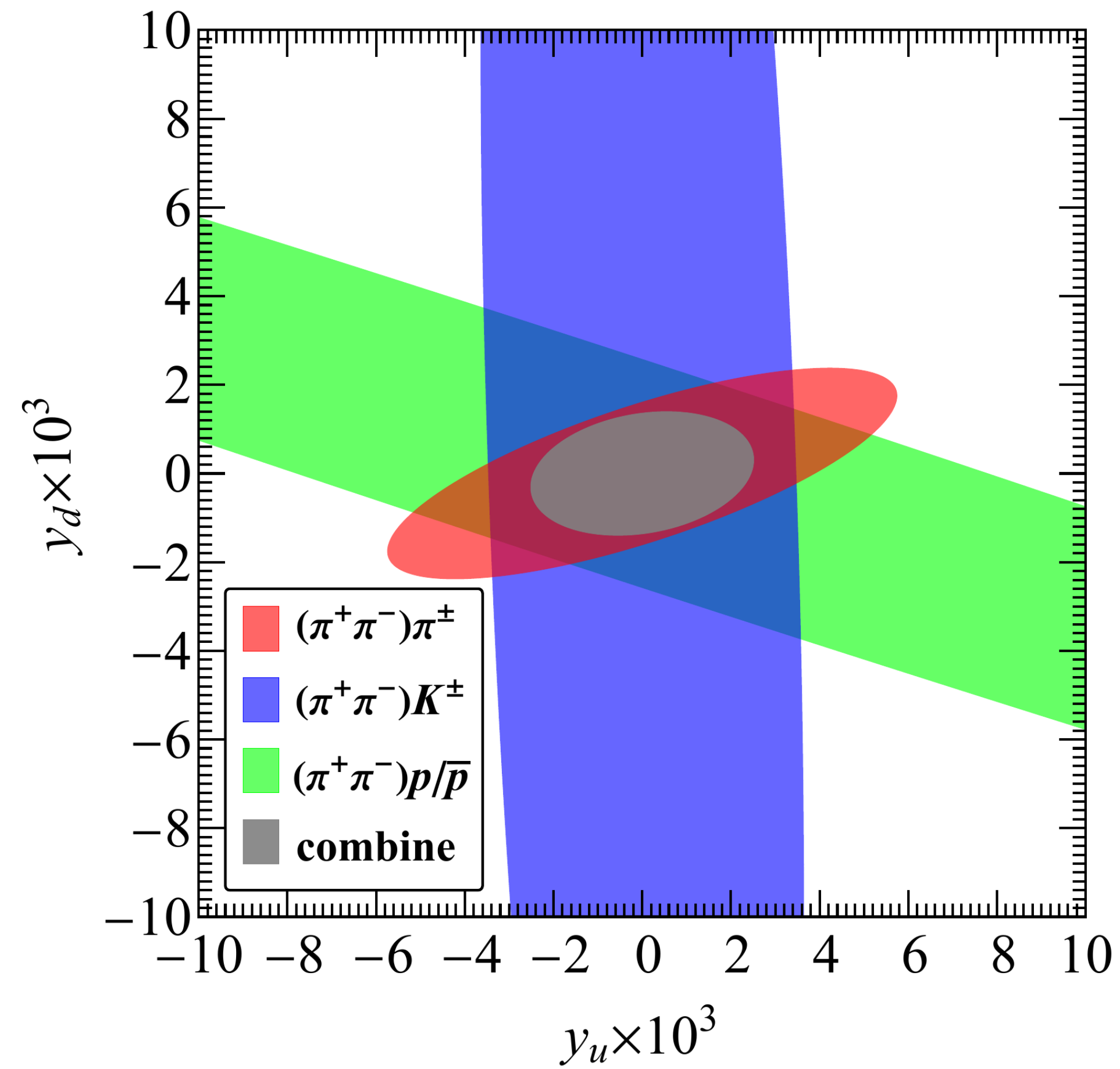
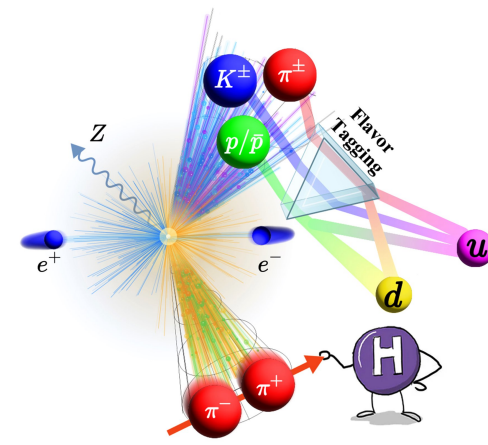
The harmonics include fragmentation weights.

$$A_{\text{UD}} = \frac{2S_x}{\pi} \quad A_{\text{LR}} = \frac{2S_y}{\pi}$$

$$d\sigma_{\text{spin}} \sim \sum_q \mathcal{H}_{LR}^q \otimes H_q^{\leftarrow, q} \otimes D_{\bar{q}}^{h'} \quad (\text{see backups})$$

Fit both modulations across the identified-hadron channels.

Separating up- and down-quark Yukawa couplings



Projection

$$\sqrt{s} = 250 \text{ GeV}$$

$$\mathcal{L} = 50 \text{ ab}^{-1}$$

68% CL, CP-even fit

$\pi^\pm$: largest yield

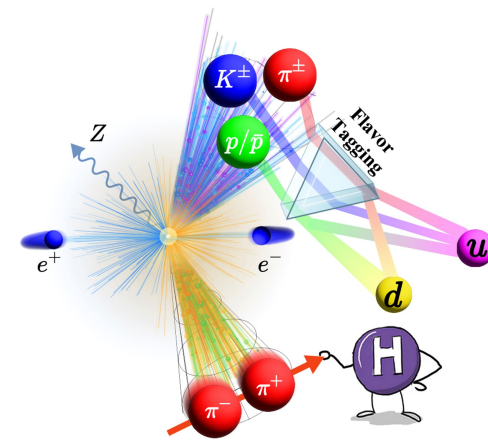
$K^\pm$: u sensitivity

$p/\bar{p}$: different band direction

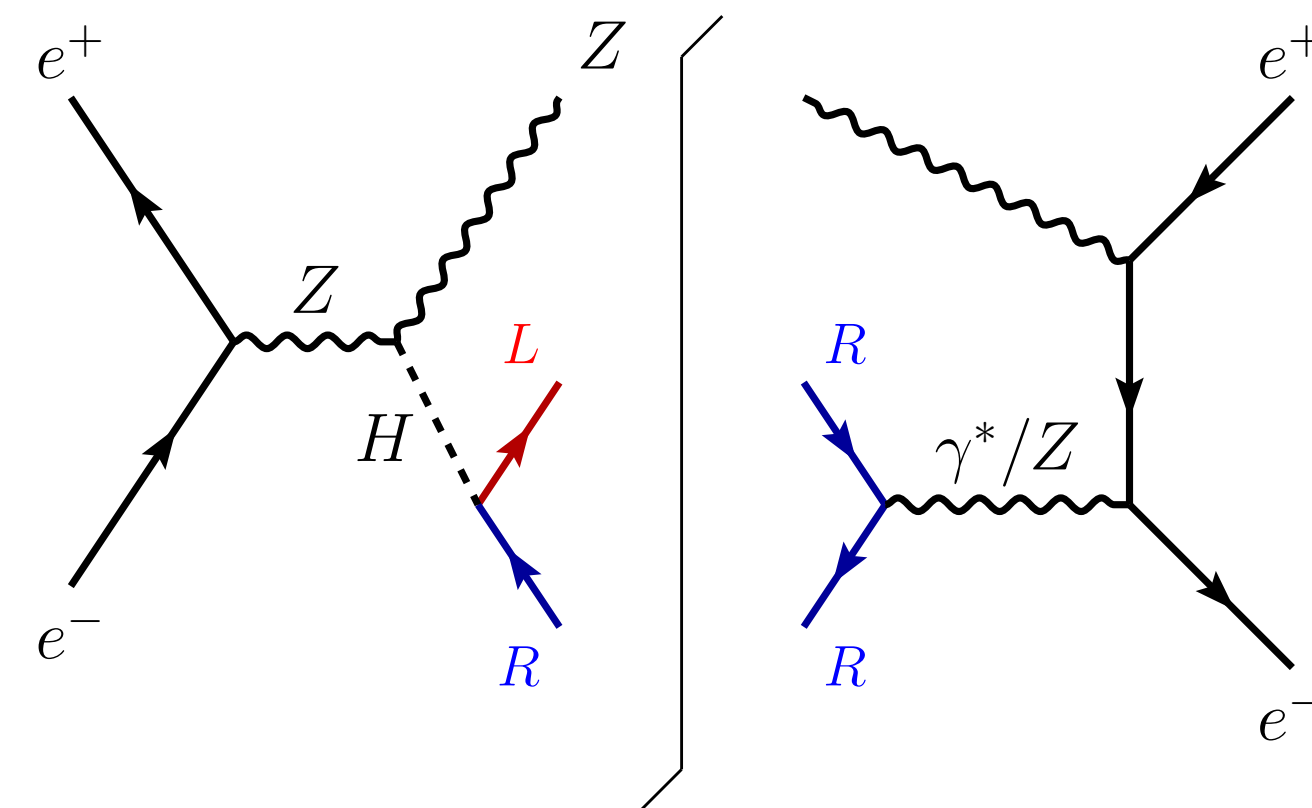
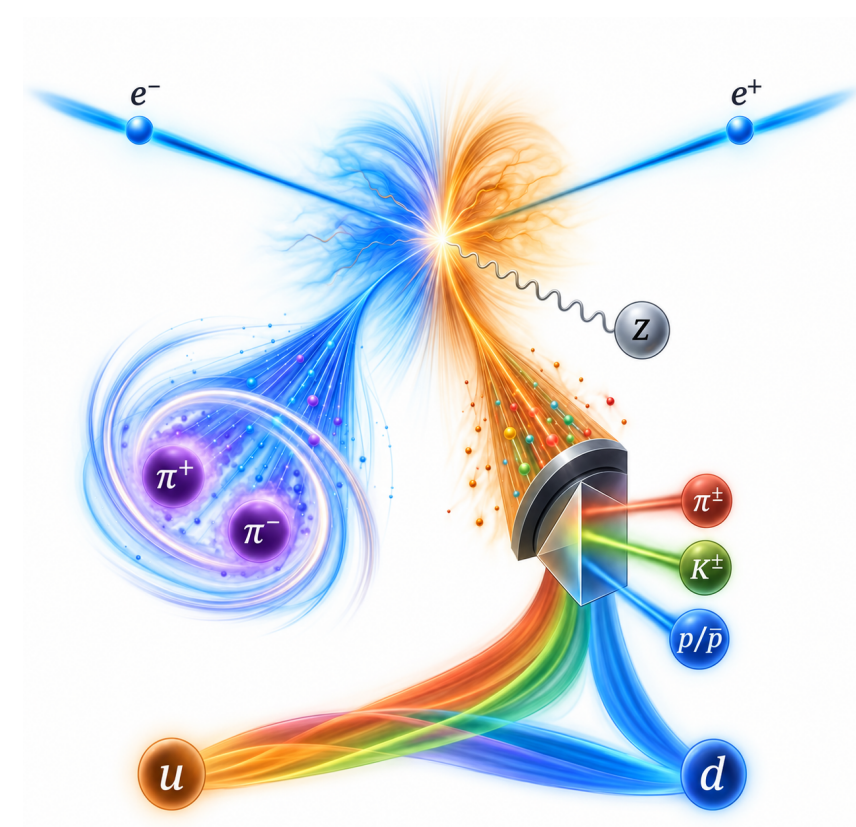
Combined: $\mathcal{O}(10^{-4} - 10^{-3})$

Combine the flavor weights to separate the two couplings.

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!

BackUps

Transverse spin effects of quark @ CEPC

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

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

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

Unpolarized DiFFs

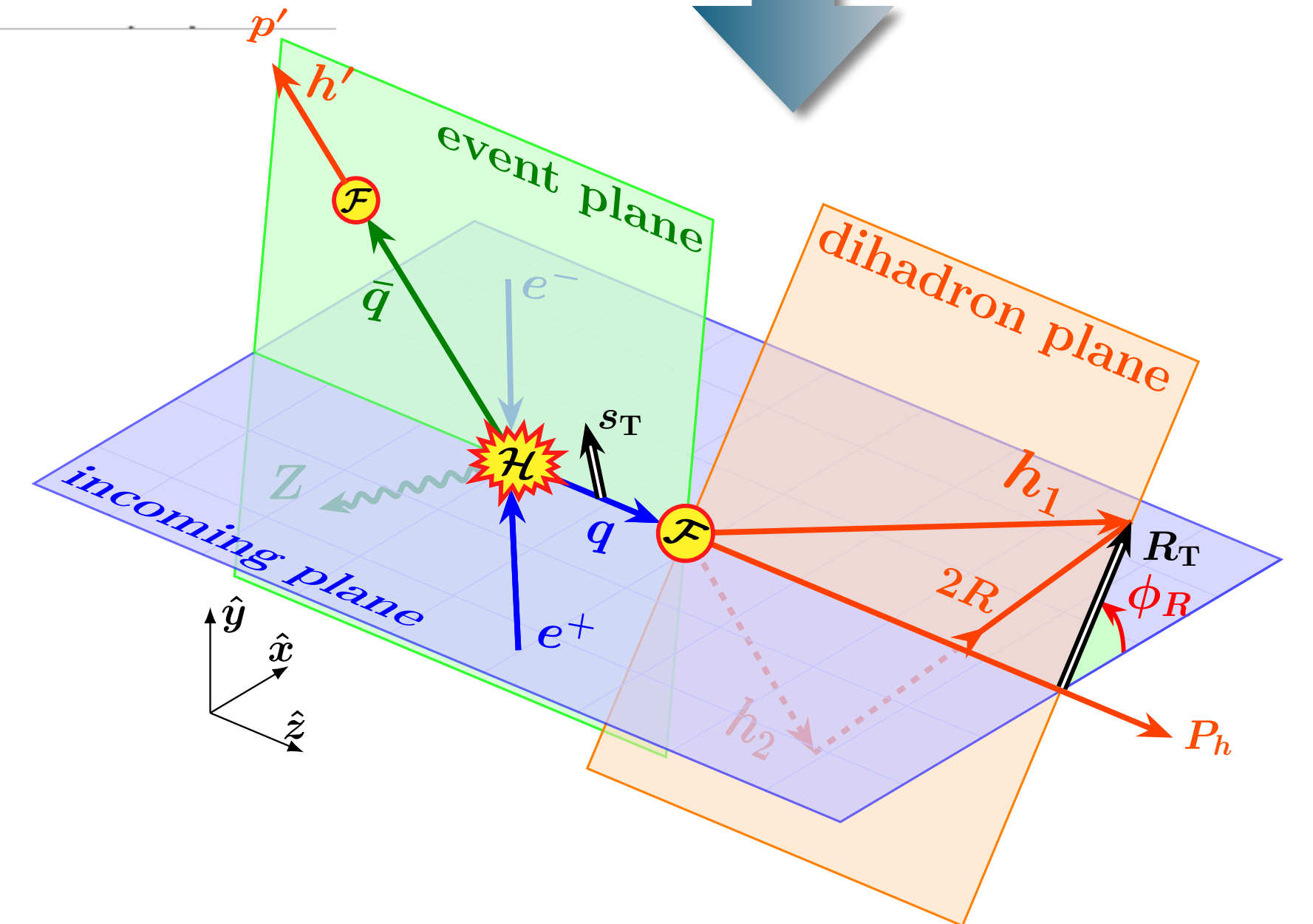
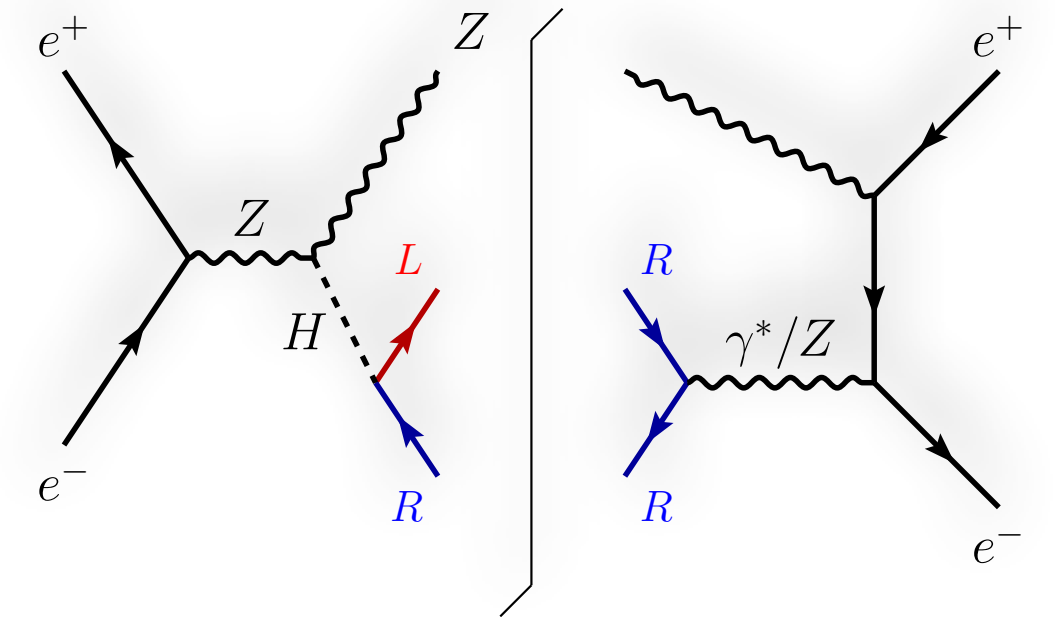
Interference DiFFs (transverse spin)

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

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

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

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



Transverse spin effects of quark @ CEPC

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

$$\begin{aligned} \mathcal{N} \frac{d\sigma}{d\phi_R} = & \sum_{q=u,d} \langle \text{Tr } \mathcal{H}^q \rangle \langle D_q^{h_1 h_2} \rangle \langle \Sigma D_q^{h'} \rangle \\ & - [y_q \sin \phi_R + \tilde{y}_q \cos \phi_R] \langle \omega_q \rangle \langle H_q^{h_1 h_2} \rangle \langle \Delta D_q^{h'} \rangle \\ & - [\tilde{y}_q \sin \phi_R - y_q \cos \phi_R] \langle \tilde{\omega}_q \rangle \langle H_q^{h_1 h_2} \rangle \langle \Sigma D_q^{h'} \rangle, \end{aligned}$$

Proton

valence: u, d

Pion

$u, \bar{d}$

