A universal probe of spin through fragmentation energy correlator

Hua Xing Zhu
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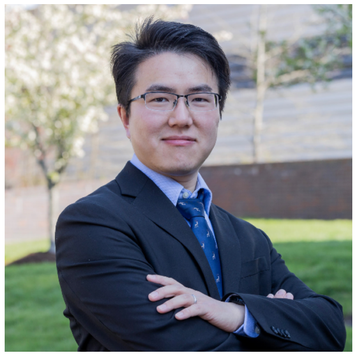
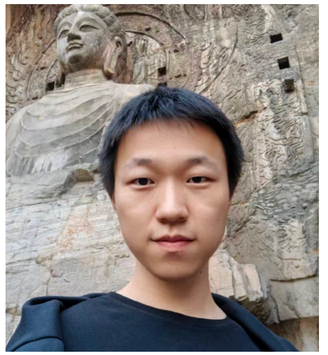
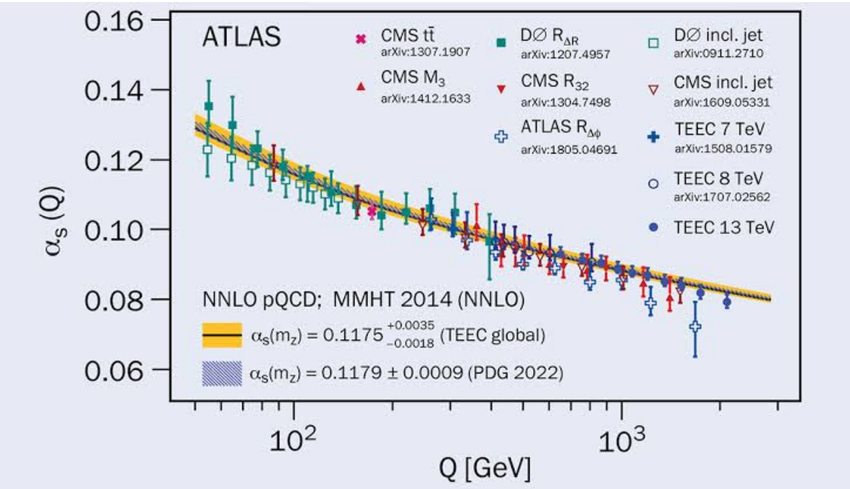
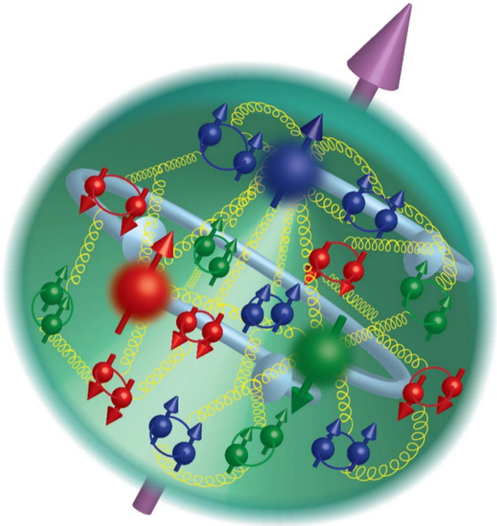
w. Qing-Hong Cao, Xiaohui Liu, Chien-Peng Yuan, Feng Yuan, Zhite Yu, Shutao Zhang
to appear on Monday, see also 2509.18892 JHEP

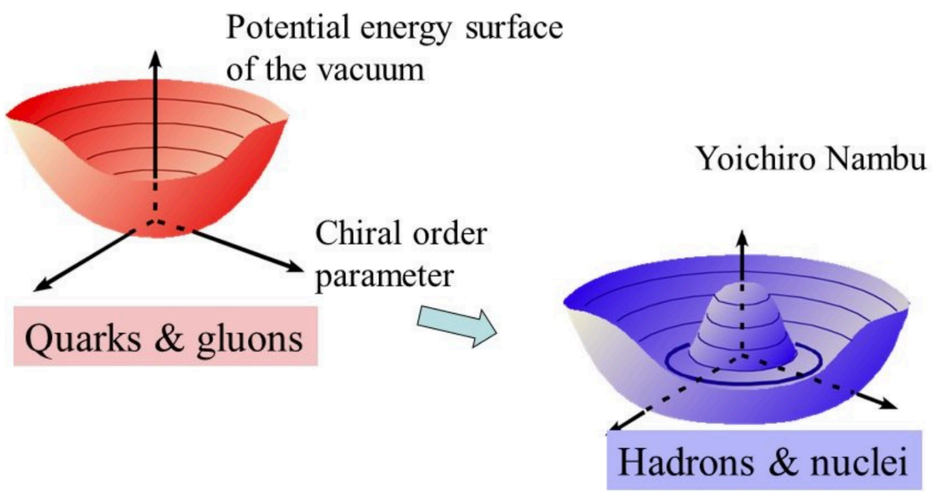



Quantum Entanglement Studies in Nuclear and Particle Physics
Fudan University, Oct. 25, 2026

Three remarkable facts of strong force







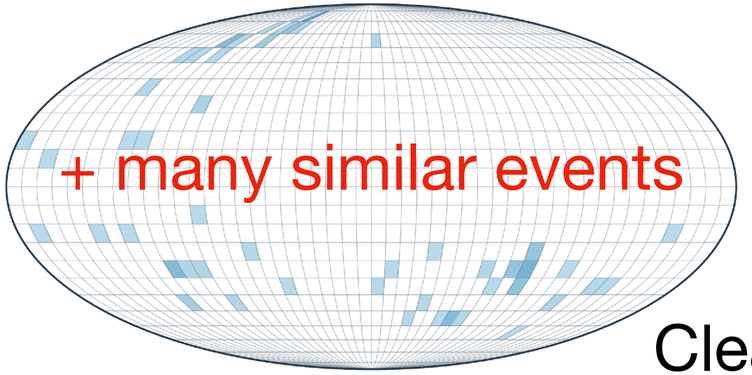
Asymptotic freedom

Confinement

Spontaneous chiral symmetry breaking

A new Quantum Frontier to explore the potential of collider experiment to shape a complete understanding of strong force (QCD)

What is energy correlator?



$$EEC(\chi) = \frac{1}{N_{\text{ev.}}} \sum_{\text{events}} \sum_{i,j \in X} \frac{E_i E_j}{Q^2} \Theta(\chi - \Delta\chi < \theta_{ij} < \chi + \Delta\chi)$$

Basham, Brown, Ellis, Love, 1978

Clean field theory definition

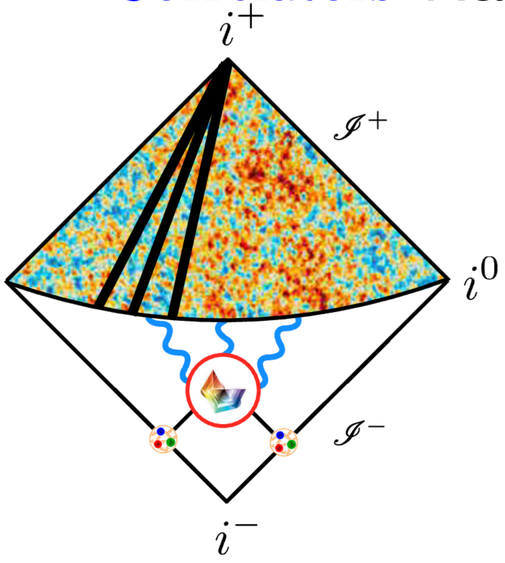
$$\mathcal{E}(\boldsymbol{n}) = \lim_{r\to\infty} r^2 \int_0^\infty dt\, n_i T_{0i}(t, r)$$

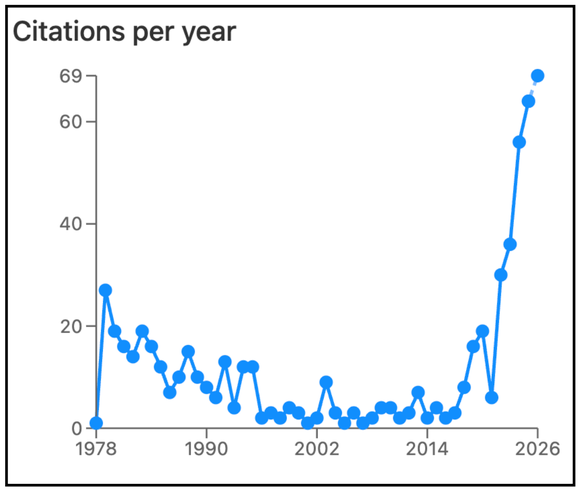
Energy Correlators

Natural language for quantum many body and QIS

$$p_a = \mathrm{Tr}(K_a^\dagger K_a\, \rho) \qquad \langle \mathcal{E} \rangle = \mathrm{Tr}(\mathcal{E}\, \rho)$$

Translate energy scan to angular scan





Rethinking jets with energy correlators: Tracks, resummation, and analytic continuation

2004.11381

Hao Chen,[1,*] Ian Moult,[2,†] XiaoYuan Zhang,[1,‡] and Hua Xing Zhu[1,§]

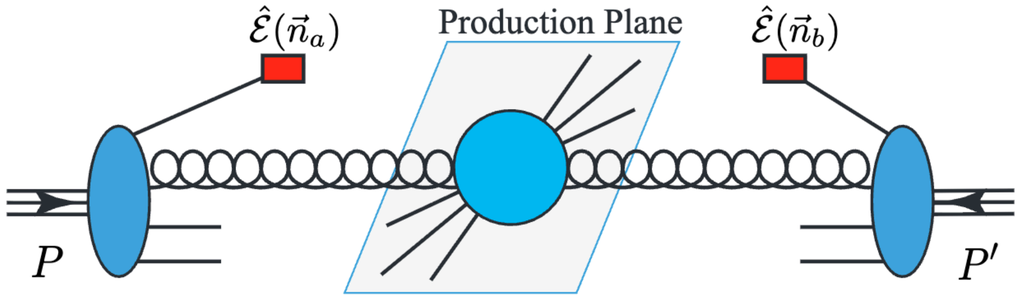
For a review: Moult, HXZ, 2506.09119

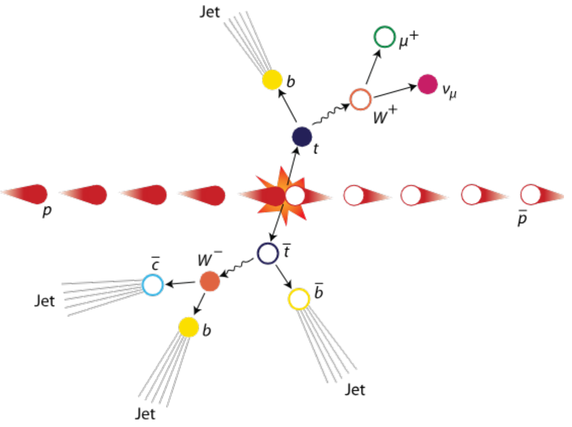
Relation to quantum correlation

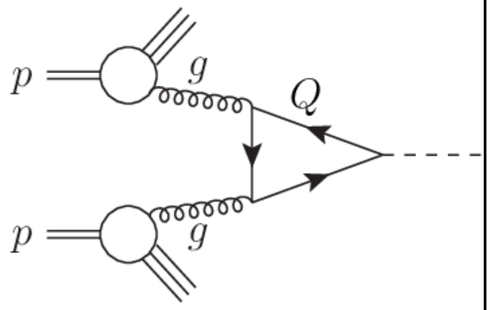
Long Range Azimuthal Correlation, Entanglement and Bell Inequality Violation by Spinning Gluons at the LHC

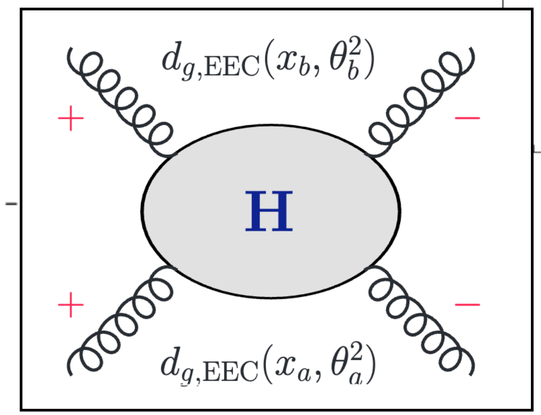
2406.05880

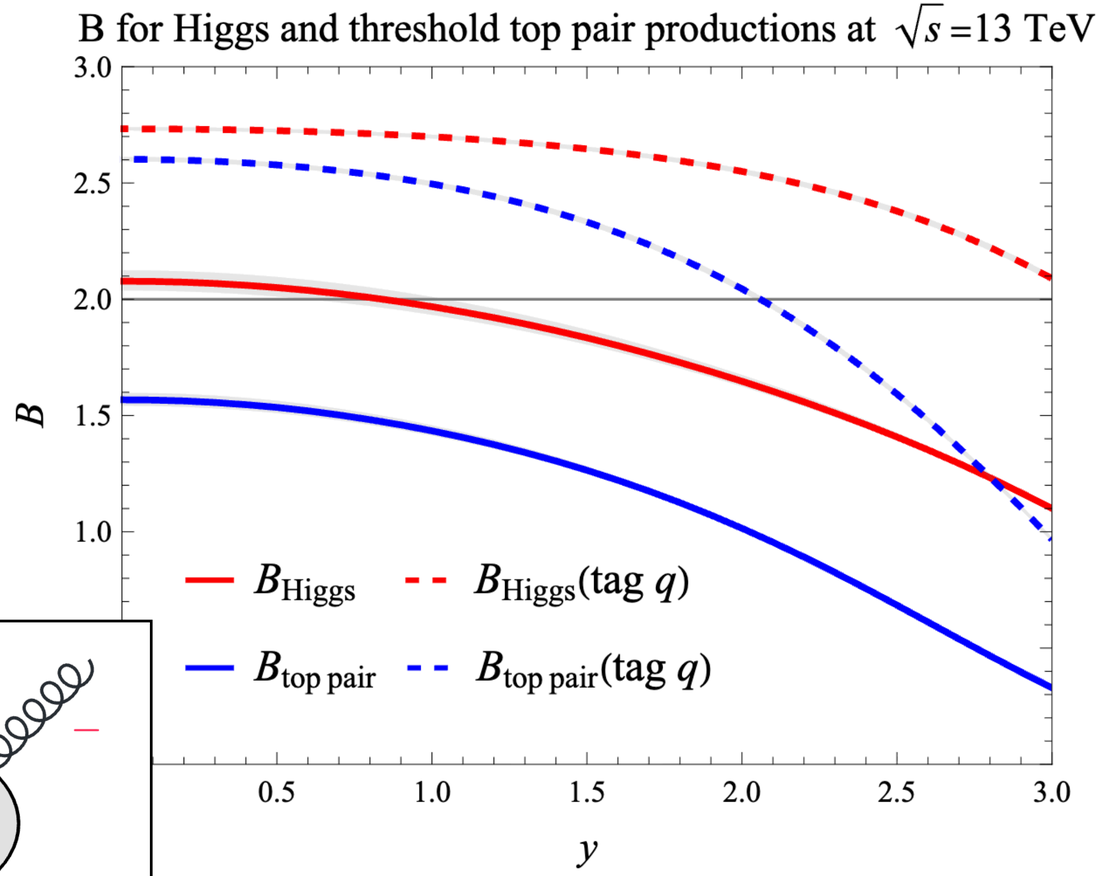
Yuxun Guo,[1,*] Xiaohui Liu,[2,3,†] Feng Yuan,[1,4,‡] and Hua Xing Zhu[5,6,§]



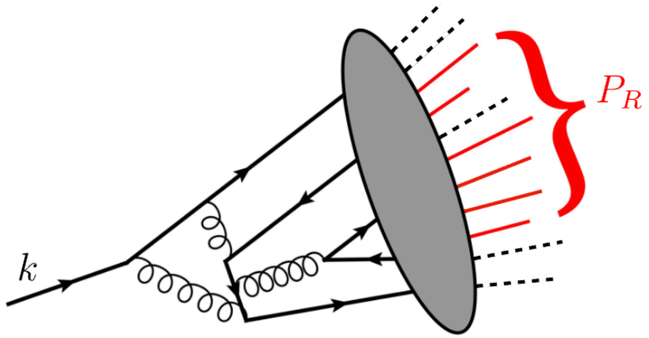




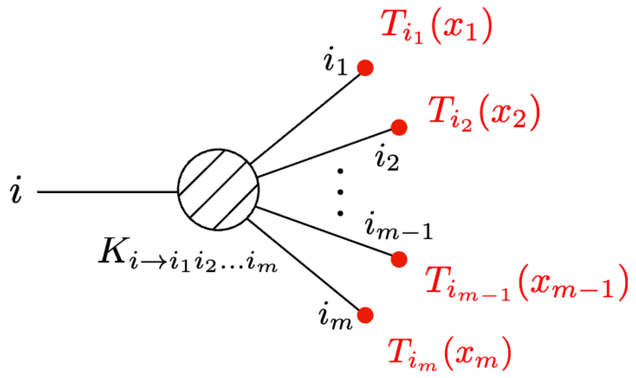




Central moment of track function



(a)

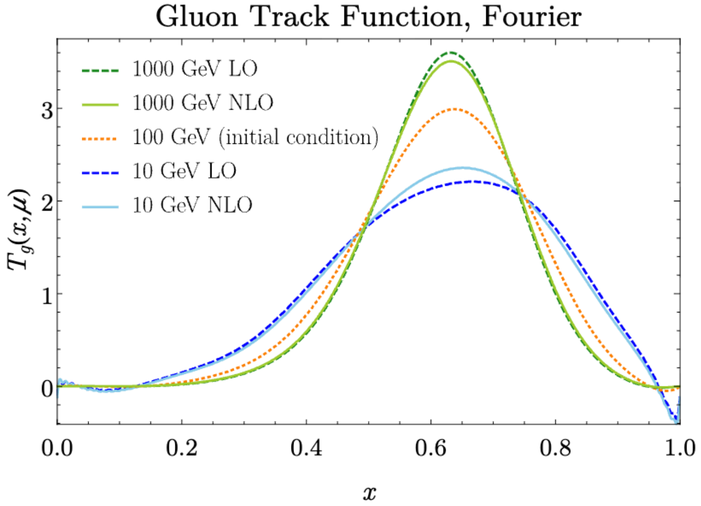


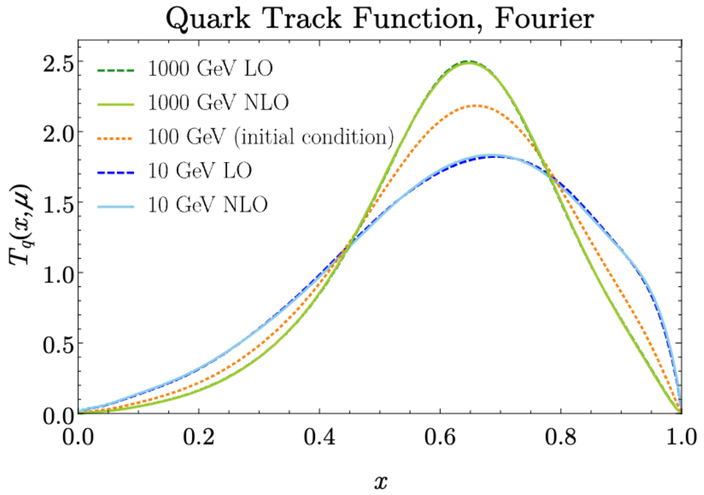
(b)

$$\sigma(n,\mu) = \int_0^1 \mathrm{d}x\ (x - \langle x \rangle)^n\ T(x,\mu)$$

$$T_q(x) = \int \mathrm{d}y^+ \mathrm{d}^{d-2} y_\perp e^{ik^- y^+/2} \sum_X \delta\left(x - \frac{P_R^-}{k^-}\right) \frac{1}{2N_c} \mathrm{tr}\left[\frac{\gamma^-}{2} \langle 0|\psi(y^+,0,y_\perp)|X\rangle\langle X|\bar{\psi}(0)|0\rangle\right]$$

Renormalization group equation for cumulant central moment



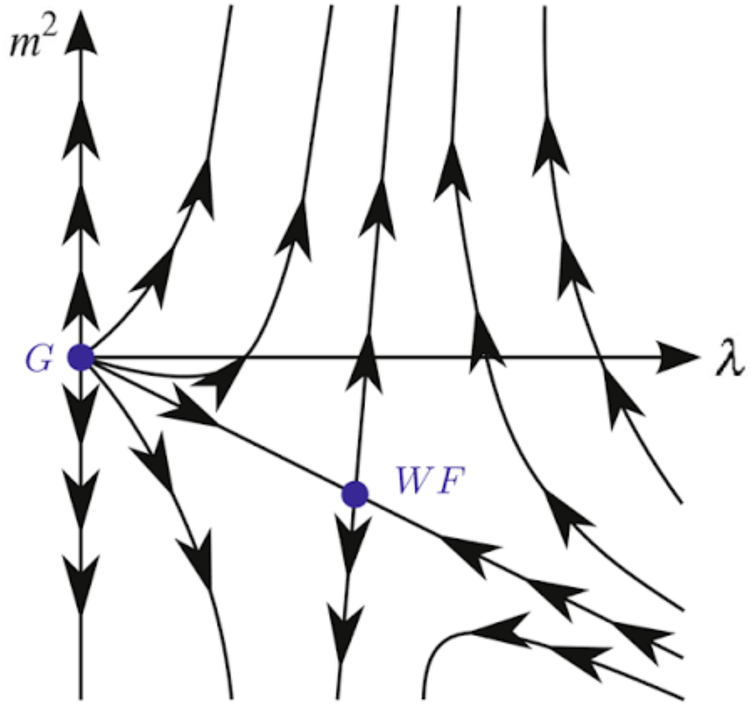


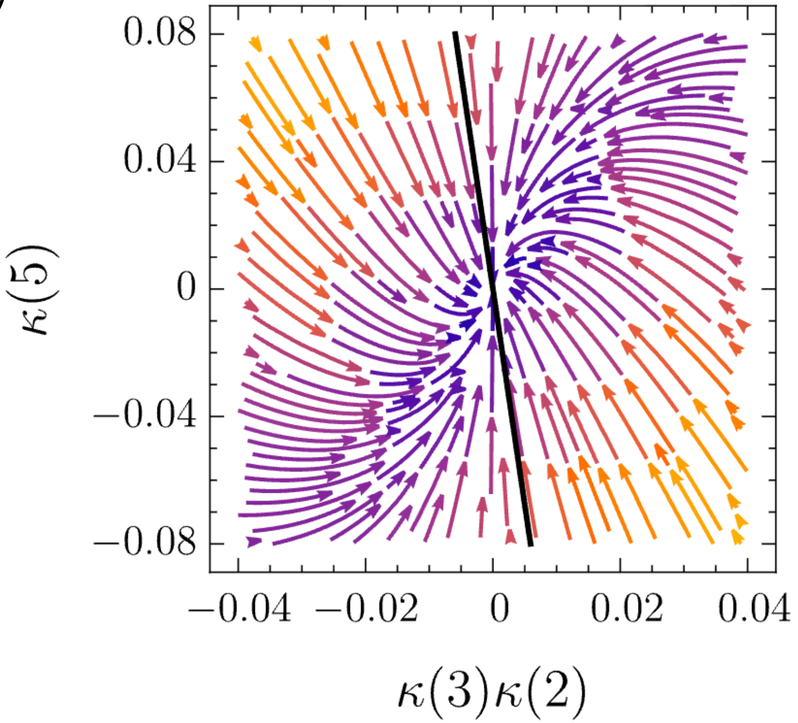
$$\frac{\mathrm{d}}{\mathrm{d}\ln\mu^2}\kappa(4) = -\gamma_{gg}(5)\kappa(4) + \gamma_{\kappa_2\kappa_2}\kappa^2(2)\ ,$$

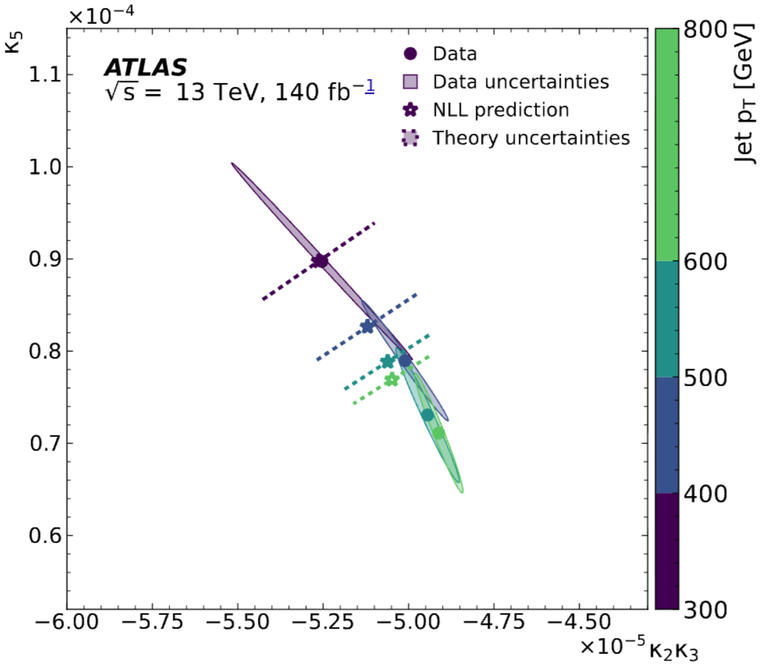
$$\frac{\mathrm{d}}{\mathrm{d}\ln\mu^2}\kappa(5) = -\gamma_{gg}(6)\kappa(5) + \gamma_{\kappa_3\kappa_2}\kappa(3)\kappa(2)$$

Measuring the RG flow

$$S = \int d^3x \left(\frac{1}{2}(\partial\phi)^2 + \frac{1}{2}m^2\phi^2 + \frac{1}{4!}\lambda\phi^4 \right)$$



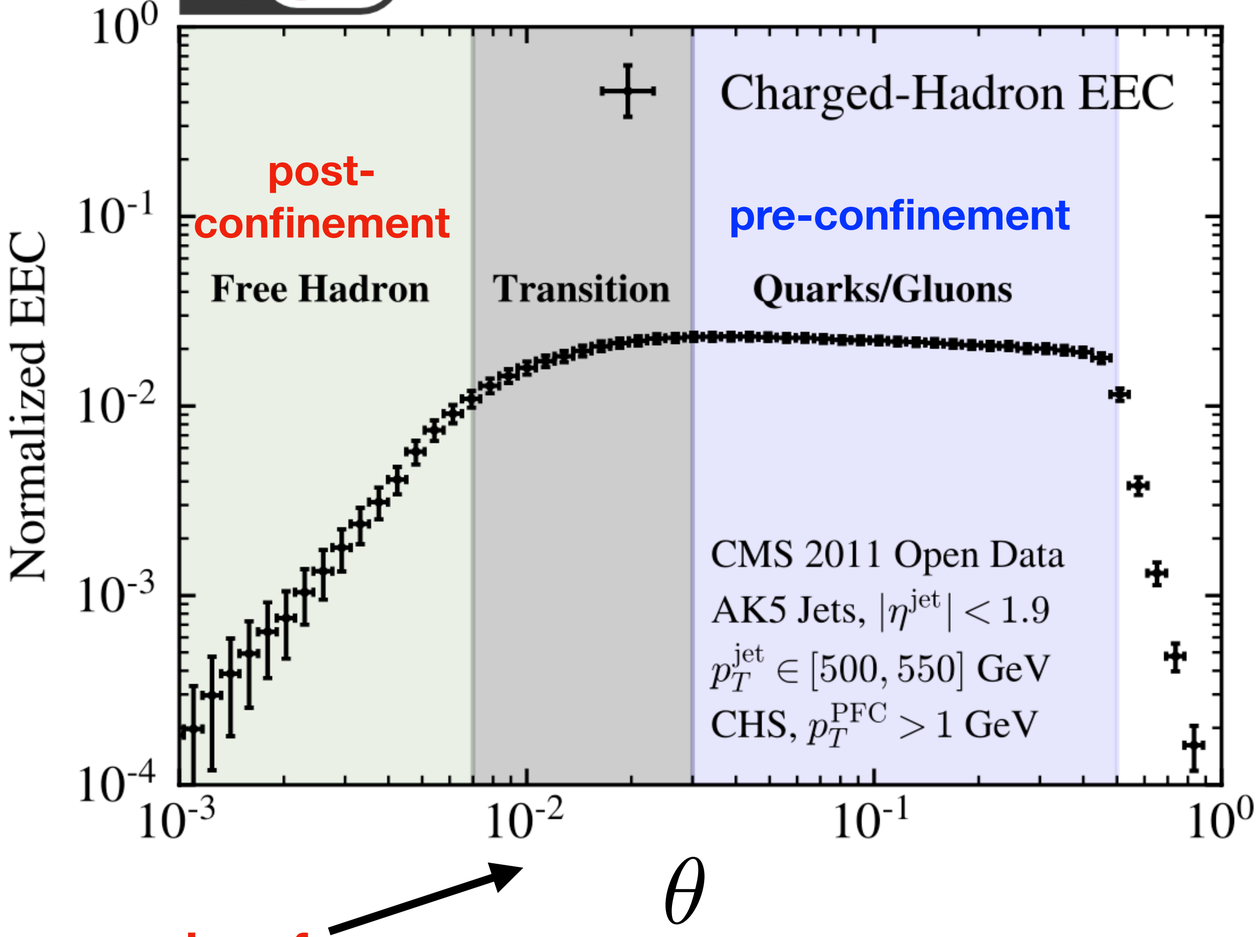




Jaarsmax, Y.B. Li, Moult, Waalewijn, HXZ, 2022

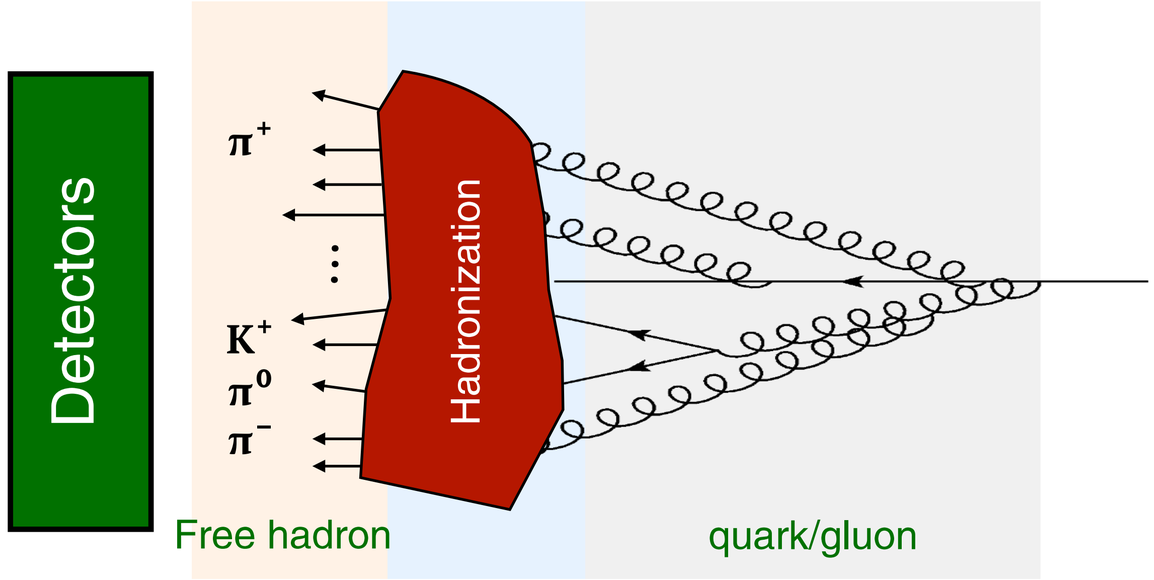
The scale of confinement from energy correlator

MOD Komiske, Moult, Thaler, HXZ, 2022



a probe of "confinement" scale

Angular resolution helps!



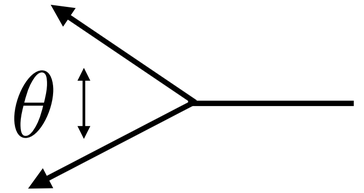
low energy

late time

$$\Delta p_T \sim \langle E \rangle \theta$$

high energy

early time



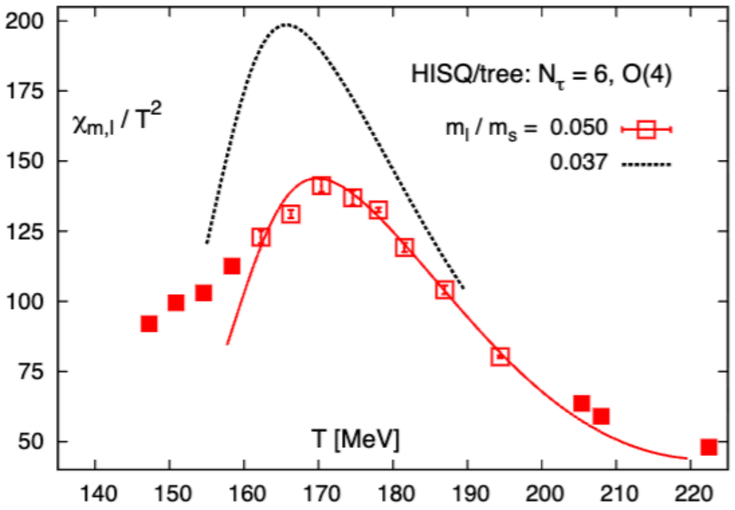
The scale of chiral symmetry breaking

What is the scale of chiral symmetry breaking?

How is it different from confinement scale?

$$\chi_{m,l}(T) = 2\frac{\partial\langle\bar{\psi}\psi\rangle_{l,\tau}}{\partial m_l}$$

Bazavov et.al., 1111.1710



Is it possible to probe the scale of chiral symmetry breaking at zero temperature?

Fragmentation of Transversely Polarized Quarks Probed in Transverse Momentum Distributions

John Collins

Physics Department, Penn State University,
University Park, PA 16802, U.S.A.

The new fragmentation function is sensitive to the coupling of the fragmentation process to (spontaneous) chiral symmetry breaking.

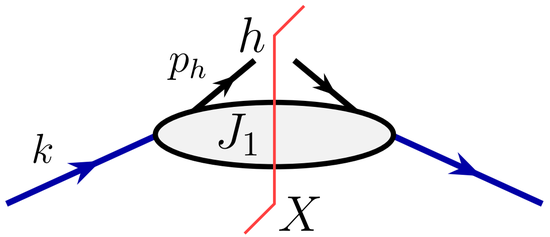
Collins, hep-ph/9208213

Fragmentation energy correlator

❑ Fragmentation function (FF)

$$D_{h/q}(z;\mu) = \frac{z}{4N_c}\sum_X \int \frac{dw^-}{2\pi}\, e^{ip_h^+ w^-/z}\, \mathrm{Tr}\Big[\gamma^+ \langle 0|\, \psi_q(w^-)\, |h,X\rangle\, \langle h,X|\, \bar{\psi}_q(0)\, |0\rangle\Big]$$

unpolarized quark state

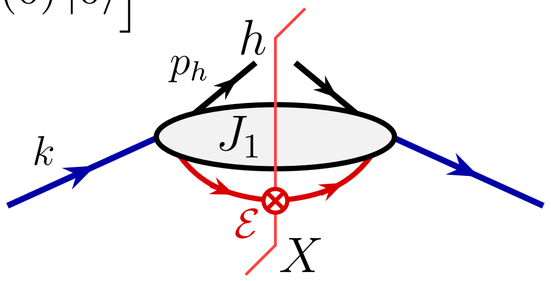


❑ Fragmentation energy correlator (FEC)

$$\mathcal{D}_{h/q}(z,\Omega;\mu) = \frac{z}{4N_c}\sum_X \int \frac{dw^-}{2\pi}\, e^{ip_h^+ w^-/z}\, \mathrm{Tr}\Big[\gamma^+ \langle 0|\, \psi_q(w^-)\, \hat{\mathcal{E}}(\Omega)\, |h,X\rangle\, \langle h,X|\, \bar{\psi}_q(0)\, |0\rangle\Big]$$

FEC collects the collinear pinches, along with the energy flow

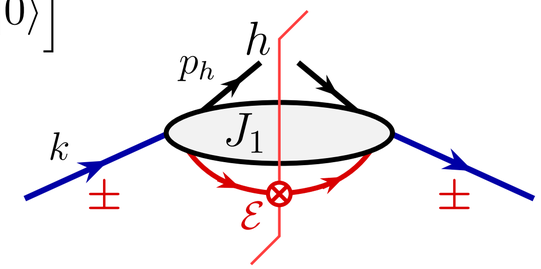
$$\hat{\mathcal{E}}(\Omega)\, |h,X\rangle = \sum_{j\in X} E_j\, \delta(\cos\theta - \cos\theta_j)\, \delta(\phi - \phi_j)\, |h,X\rangle$$



Spin dependence and Collins FEC

- γ^+ projector $\longrightarrow$ Unpolarized FEC: uniform ϕ distribution

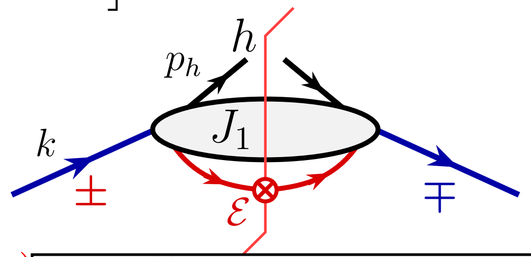
$$\mathcal{D}_{h/q}(z,\Omega;\mu) = \frac{z}{4N_c}\sum_X \int \frac{dw^-}{2\pi}\, e^{ip_h^+ w^-/z}\, \mathrm{Tr}\Big[\gamma^+ \langle 0|\, \psi_q(w^-)\, \hat{\mathcal{E}}(\Omega)\, |h,X\rangle\, \langle h,X|\, \bar{\psi}_q(0)\, |0\rangle\Big]$$
$$\equiv \mathcal{D}_{h/q}(z,\theta;\mu)$$



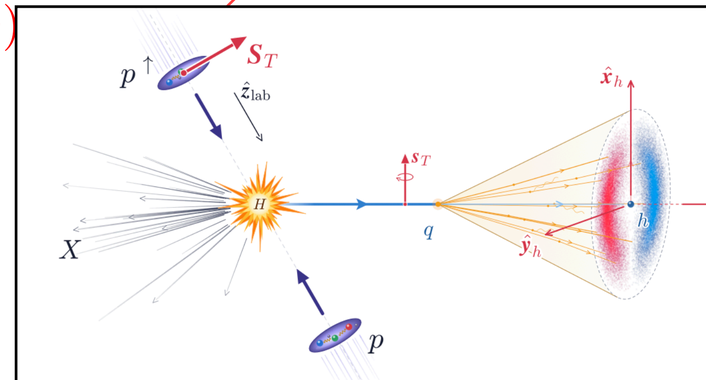
- $\gamma^+\gamma^i_\perp\gamma_5$ projector $\longrightarrow$ Collins FEC: anisotropic ϕ distribution

$$\mathcal{H}_{h/q}(z,\Omega;\mu) = \frac{z}{4N_c}\sum_X \int \frac{dw^-}{2\pi}\, e^{ip_h^+ w^-/z}\, \mathrm{Tr}\Big[\gamma^+\gamma^i_\perp\gamma_5 \langle 0|\, \psi_q(w^-)\, \hat{\mathcal{E}}(\Omega)\, |h,X\rangle\, \langle h,X|\, \bar{\psi}_q(0)\, |0\rangle\Big]$$
$$\equiv (-\sin\phi, \cos\phi)^i\, \mathcal{H}_{h/q}(z,\theta;\mu)$$

$\hat{p}_h \times \hat{n}$

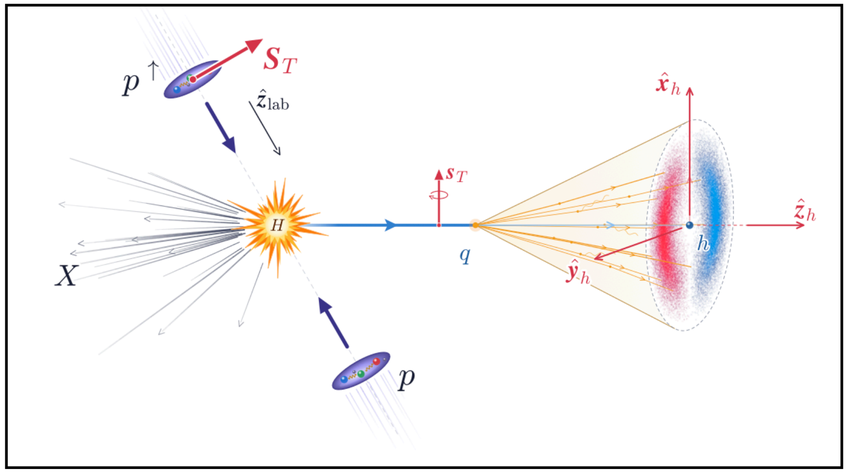


- Transverse quark spin s_T gives **azimuthal asymmetry** $s_T \cdot (\hat{p}_h \times \hat{n}) \propto s_T \sin(\phi - \phi_S)$
- Holds for **unpolarized** hadron h → **"Collins effect"**
- Originates from **flipped** helicity interference → **Chiral symmetry breaking**



Advantage of FECs

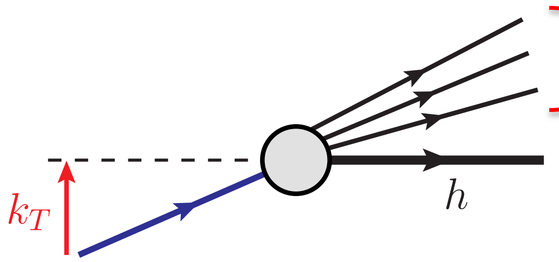
- Fragmentation energy correlator as probe chiral spin effects
- Introduce explicit scale dependence
- Allow chiral odd contributions
- Perturbative controllable: absent of Sudakov effect
- Universality among e+e-, ep, and pp
- Quantum entanglement



Relation to TMD fragmentation function

❑ Understanding TMD FF from fragmentation remnants

Liu and Zhu, 2403.08874



In "hadron frame", parton $\boldsymbol{k}_T$ = fragmentation remnants' $\boldsymbol{k}_T$

$$d_{h/q}^{[\Gamma]}(z,-z\boldsymbol{k}_T)=\frac{1}{4zN_c}\sum_X\int\frac{dw^-}{2\pi}\,e^{ip_h^+w^-/z}\,\mathrm{Tr}\Big[\Gamma\,\langle 0|\,\psi_q(w^-)\times\delta^{(2)}\Big(\boldsymbol{k}_T-\int d\Omega\,\hat{\mathcal{E}}(\boldsymbol{n})\,\boldsymbol{n}_T\Big)\,|h,X\rangle\,\langle h,X|\,\bar{\psi}_q(0)\,|0\rangle\Big]$$

$$z^2\int d^2\boldsymbol{k}_T\,k_T^i\,\underbrace{d_{h/q}^{[\Gamma]}(z,-z\boldsymbol{k}_T)}_{\text{TMD FF}}=\int d\Omega\,n_T^i\,\underbrace{\mathcal{D}_{h/q}^{[\Gamma]}(z,\Omega)}_{\text{FEC}}$$

- "FEC ⇔ TMD" at integral (moment) level.
- Generalizable to N-point FEC.

❑ Only $\Gamma=\gamma^+\gamma_\perp^i\gamma_5$ gives non-vanishing results

$$\int_0^\pi d\theta\,\sin^2\theta\,\underbrace{\mathcal{H}_{h/q}(z,\theta)}_{\text{Collins FEC}}=-z^2\int\frac{dk_T^2}{2m_h}\,k_T^2\,\underbrace{H_{h/q}(z,zk_T)}_{\text{Collins TMD FF}}$$

Modified FEC definition with boost invariance

Q.-H. Cao, et al., JHEP 02 (2026) 244

Lack of Lorentz covariance due to explicit dependence on E and θ

❑ Modified energy flow operator

$+/-$ components and rapidity η defined w.r.t. hadron h

$$\mathcal{E}_L(\eta,\phi)|X;\text{out}\rangle = \sum_{i\in X} p_i^+ \delta(\eta-\eta_i)\delta(\phi-\phi_i)|X;\text{out}\rangle$$

$$\mathcal{E}_L(\eta,\phi) = \frac{1+\tanh\eta}{\sqrt{2}\cosh^2\eta}\mathcal{E}(\theta,\phi)$$

Boost covariantly: $U(\alpha)\,\mathcal{E}_L(\eta,\phi)\,U^{-1}(\alpha) = e^{-\alpha}\mathcal{E}_L(\eta+\alpha,\phi)$

❑ Boost-invariant FEC definition

$$\Delta^{[\Gamma]}_{h/q}(z,\Lambda_F^2,\phi\,;\mu) = \frac{1}{2\Lambda_F^2}\frac{z}{4N_c}\sum_X\int\frac{dw^-}{2\pi\,p_h^+}\,e^{ip_h^+w^-/z}\,\text{Tr}\Big[\Gamma\,\langle 0|\,\psi_q(w^-)\,\hat{\mathcal{E}}_L(\eta,\phi)\,|h,X\rangle\,\langle h,X|\,\bar{\psi}_q(0)\,|0\rangle\Big]$$

$\Lambda_F = m_h\,e^{y_h-\eta} = \sqrt{2}\,p_h^+ e^{-\eta}$ is a **boost-invariant scale**. $\Lambda_F \simeq E_h\theta$ in small-θ limit.

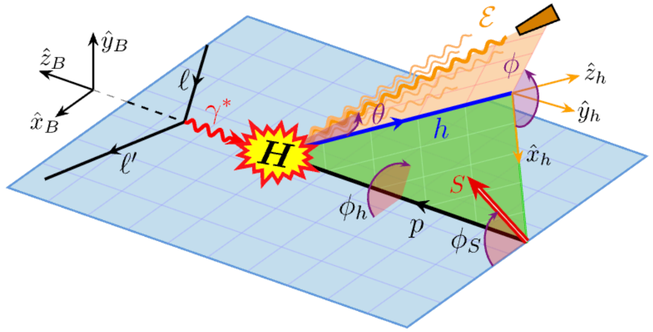
- $\Gamma = \gamma^+ \longrightarrow \mathcal{D}_{h/q}(z,\Lambda_F^2)$
- $\Gamma = \gamma^+\gamma_\perp^i\gamma_5 \longrightarrow \mathcal{H}_{h/q}(z,\Lambda_F^2)$

Factorization in different processes

$$\frac{d\Sigma_i}{d\Lambda_F^2 d\Phi_i} \propto \begin{cases} U_i + S_T V_i \sin\Phi_i, & i = ep, pp, \\ U_i + V_i \cos\Phi_i, & i = ee. \end{cases}$$

$ep^\uparrow \to e\,h + X$

$$\Phi_{ep} = \phi - \phi_S$$



$$U_{ep} = \sum_q e_q^2 f_q(x_B)\, \mathcal{D}_{h/q}(z, \Lambda_F^2),$$

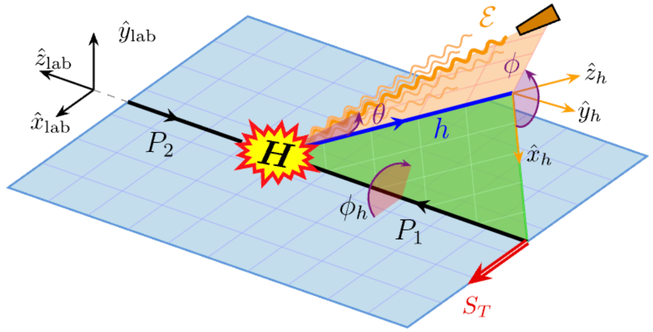
$$V_{ep} = \frac{2(1-y)}{1+(1-y)^2} \sum_q e_q^2 h_q(x_B) \times \mathcal{H}_{h/q}(z, \Lambda_F^2).$$

f_q : unpolarized PDF

h_q : chiral-odd transversity

$p^\uparrow p \to h + X$

$$\Phi_{pp} = \phi + \phi_h$$



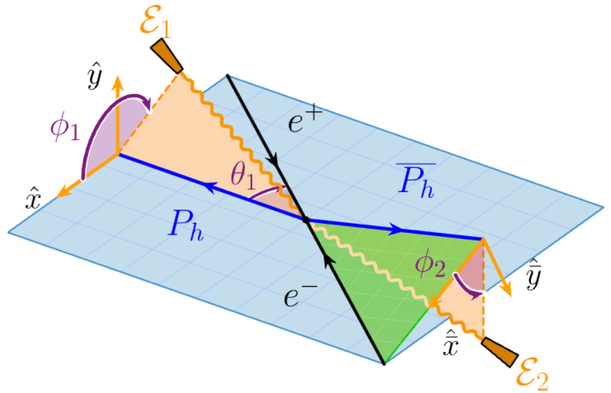
$$U_{pp} = \sum_{a,b,c} \int \frac{dx_1\, dx_2}{x_1^2 x_2^2 \bar{z}} f_a(x_1) f_b(x_2) \times C_{abc}(\hat{y})\, \mathcal{D}_{h/c}(\bar{z}, \Lambda_F^2),$$

$$V_{pp} = \sum_{a,b,c} \int \frac{dx_1\, dx_2}{x_1^2 x_2^2 \bar{z}} h_a(x_1) f_b(x_2) \times T_{abc}(\hat{y})\, \mathcal{H}_{h/c}(\bar{z}, \Lambda_F^2).$$

$$\hat{y} = y_h - \frac{1}{2}\ln\frac{x_1}{x_2}, \qquad \bar{z} = \frac{2p_{hT}\cosh\hat{y}}{\sqrt{x_1 x_2 s}}$$

$e^+e^- \to h_1 h_2 + X$

$$\Phi_{ee} = \phi_2 - \phi_1$$



$$U_{ee} = \sum_q e_q^2\, \mathcal{D}_{h_1/q}(z_1, \Lambda_F^2) \mathcal{D}_{h_2/\bar{q}}(z_2, \bar{\Lambda}_F^2),$$

$$V_{ee} = \frac{\sin^2\theta_1}{1+\cos^2\theta_1} \sum_q e_q^2\, \mathcal{H}_{h_1/q}(z_1, \Lambda_F^2) \times \mathcal{H}_{h_2/\bar{q}}(z_2, \bar{\Lambda}_F^2).$$

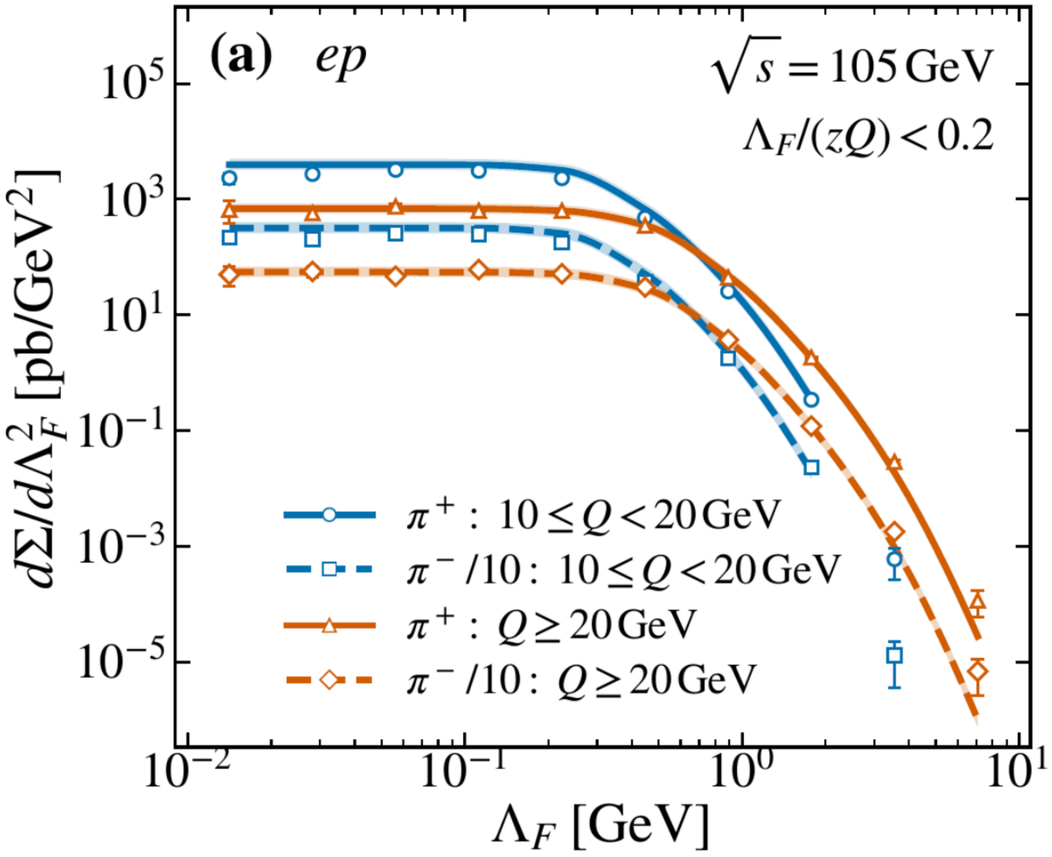
C_{abc} : $ab \to cX$

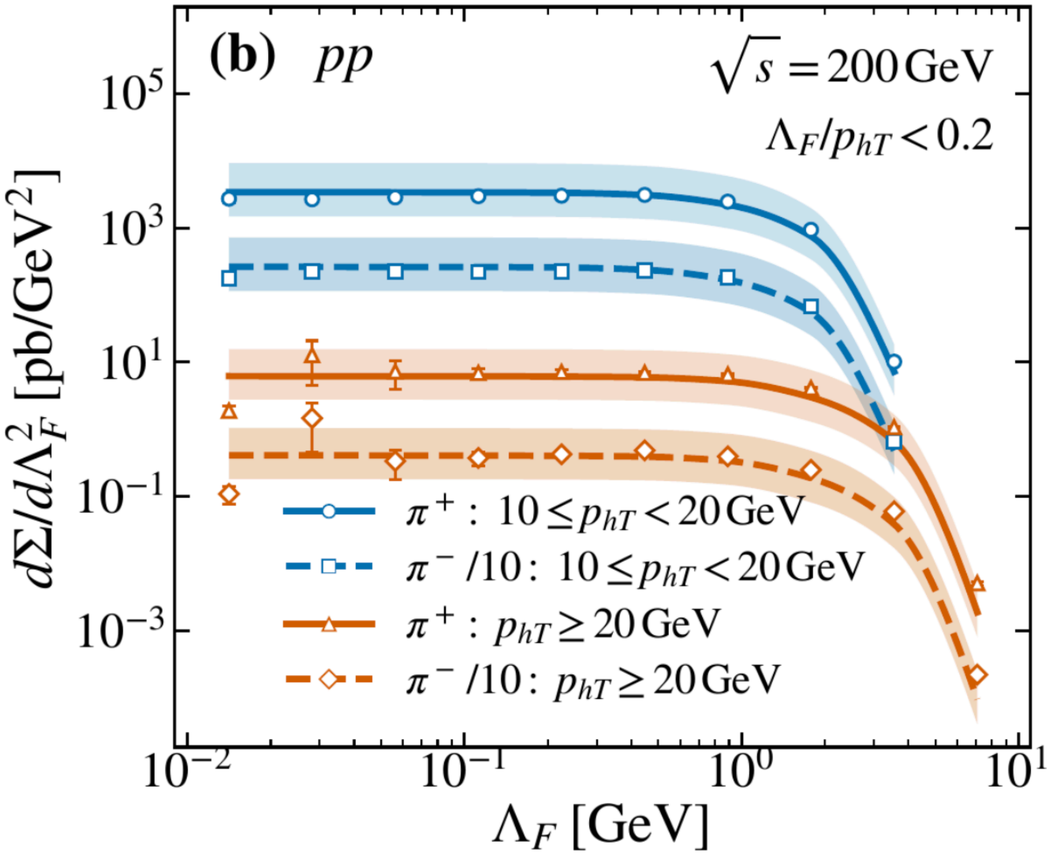
T_{abc} : $a^\uparrow b \to c^\uparrow X$

Universality test of Unpolarized FEC

With Pythia

Predict from e^+e^- extraction



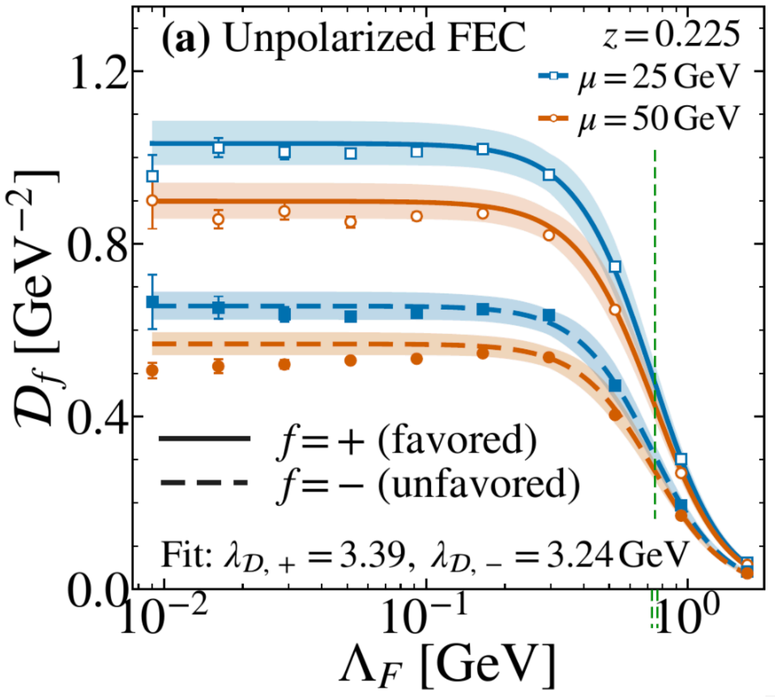


No need for jet algorithm!

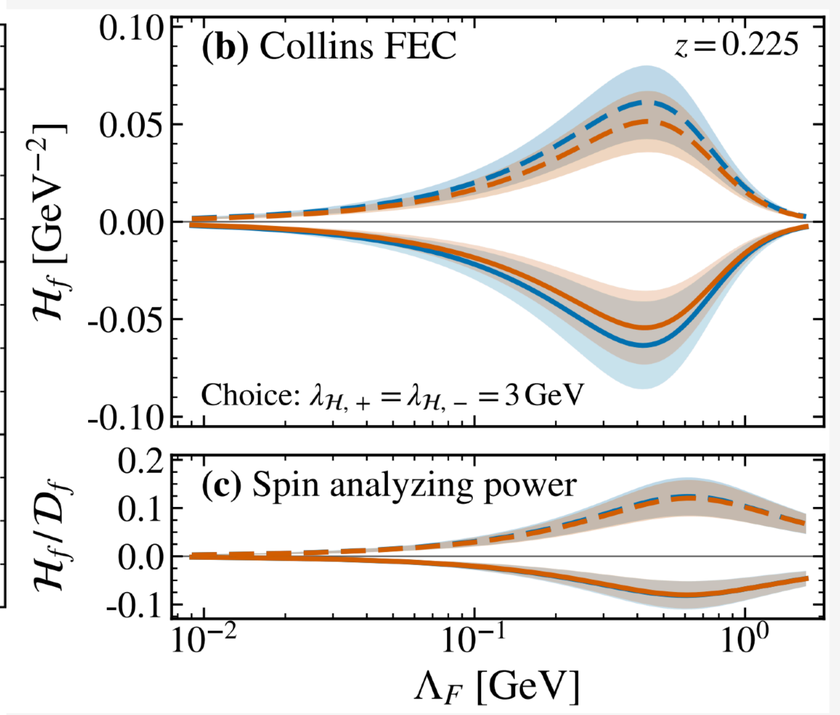
Parameterizing the transition

$$\mathcal{D}_f(z,\Lambda_F^2;\mu_0) = N_{\mathcal{D},f}(z) \times \left[1+\left(\frac{\Lambda_F}{z\lambda_{\mathcal{D},f}}\right)^{\kappa_{\mathcal{D},f}(z)}\right]^{-\frac{2+\gamma_{\mathcal{D},f}(z)}{\kappa_{\mathcal{D},f}(z)}}$$

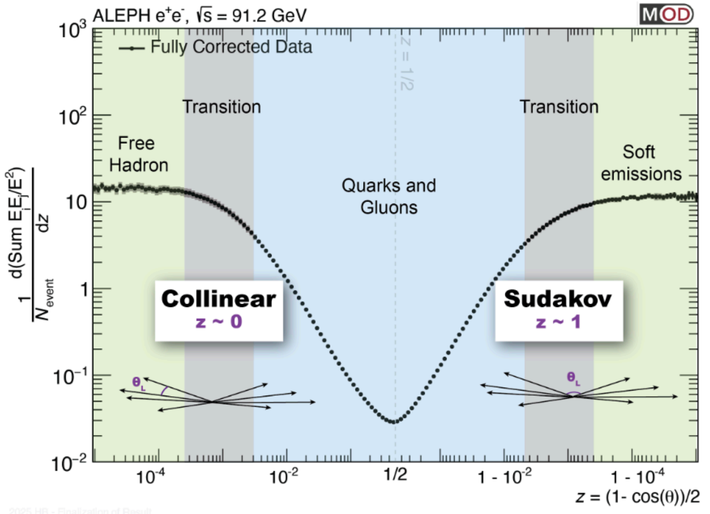
$$\mathcal{H}_f(z,\Lambda_F^2;\mu_0) = N_{\mathcal{H},f}(z)\frac{\Lambda_F}{z\lambda_{\mathcal{H},f}} \times \left[1+\left(\frac{\Lambda_F}{z\lambda_{\mathcal{H},f}}\right)^{\kappa_{\mathcal{H},f}}\right]^{-\frac{4+\gamma_{\mathcal{H},f}}{\kappa_{\mathcal{H},f}}}$$



$z\lambda_{\mathcal{D},\pm}$



$z\lambda_{\mathcal{H}}$



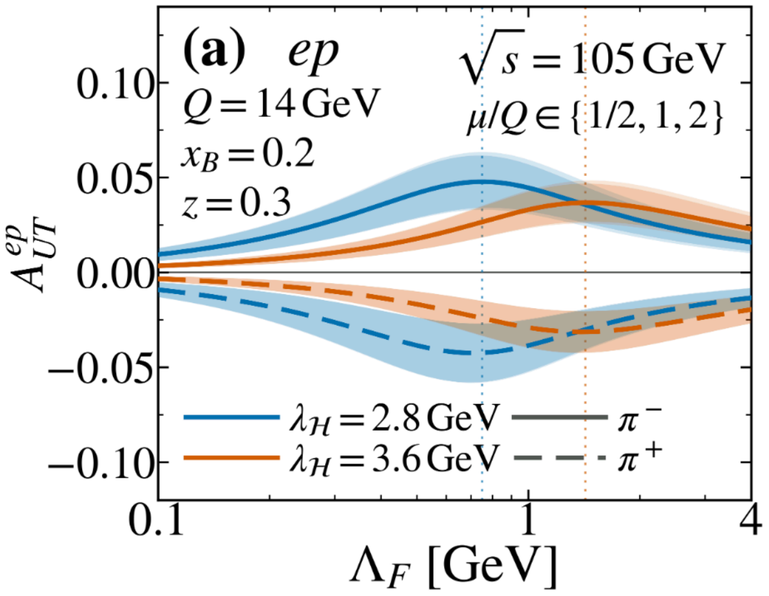
Bossi et al., 2505.11828

EEC already resolves this transition

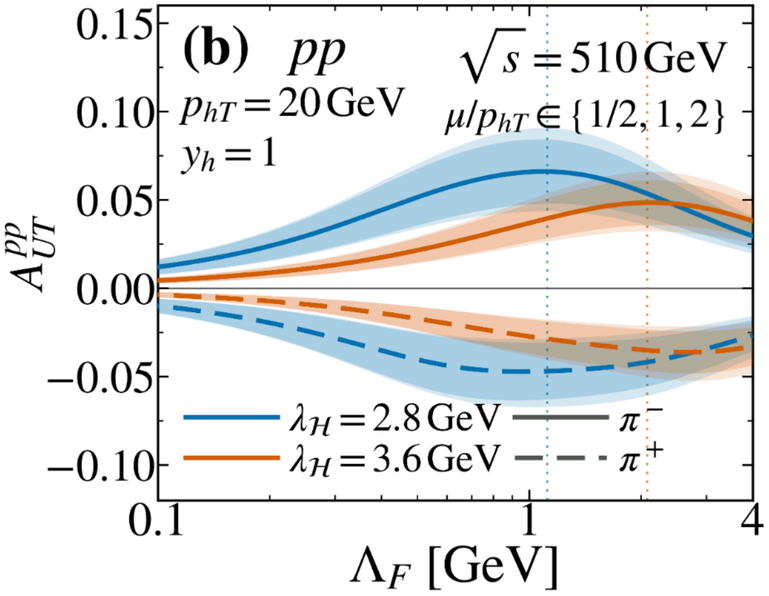
Will experiment help resolve the ‘chiral breaking’ sale?

Asymmetry

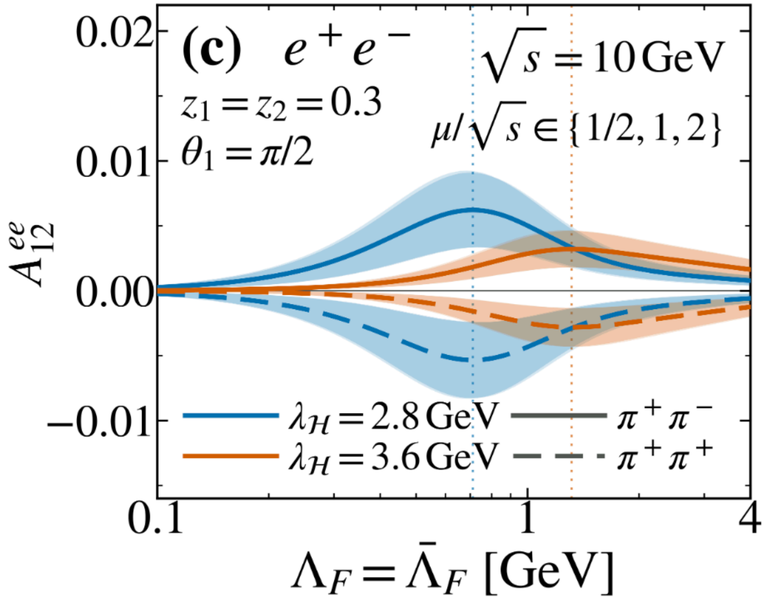
$$A_{UT}^{ep} = \frac{V_{ep}}{U_{ep}}$$



$$A_{UT}^{pp} = \frac{V_{pp}}{U_{pp}}$$



$$A_{12}^{ee} = \frac{V_{ee}}{U_{ee}}$$



Comparable to measured spin asymmetries

STAR, 2604.15543
Belle, 1104.2425

The Λ_F **spectrum** is sensitive to $\lambda_{\mathcal{H}}$

Summary

1. **Universal** collinear factorization **without jet algorithms**.

2. Energy correlators for **quark spin** and spin correlations.

3. Probing the **nonperturbative scales** of QCD.

Thank You !