Lam-Tung relation breaking effects and weak dipole moments at lepton colliders

based on arXiv: 2503.17663,
in collaboration with Xu Li, Bin Yan

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Institute of High Energy Physics

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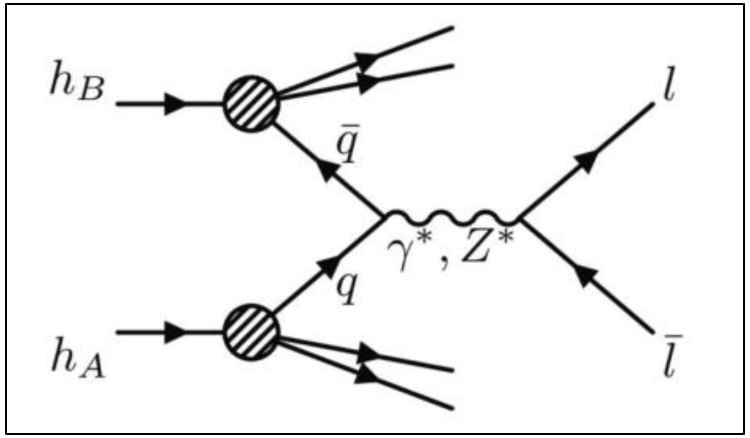
Angular Distribution in the Drell-Yan Process



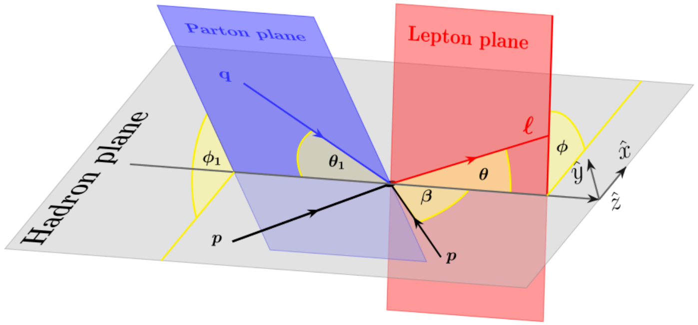
Drell-Yan process at the LHC with

- Large cross section
- Clean leptonic signature

which makes its measurement very precise

In the Collins-Soper frame, the angular dependence of the leptons can be expanded into a set of angular coefficients:

$$\frac{d\sigma}{d^4q\, d\cos\theta\, d\phi} = \frac{3}{16\pi}\frac{d\sigma^{\text{unpol.}}}{d^4q}\Big\{(1+\cos^2\theta) + \frac{1}{2}A_0\,(1-3\cos^2\theta)$$
$$+ A_1\,\sin(2\theta)\cos\phi + \frac{1}{2}A_2\,\sin^2\theta\,\cos(2\phi)$$
$$+ A_3\,\sin\theta\,\cos\phi + A_4\,\cos\theta + A_5\,\sin^2\theta\,\sin(2\phi)$$
$$+ A_6\,\sin(2\theta)\,\sin\phi + A_7\,\sin\theta\,\sin\phi\Big\},$$



Collins-Soper frame

J. C. Collins and D. E. Soper, Phys. Rev. D 16, 2219(1977).

Angular Moments

The angular coeffients can be extracted via their corresponding moments:

$$\langle \omega(\theta,\phi)\rangle = \frac{1}{\frac{d\sigma}{d^4q}} \int d\Omega \frac{d\sigma}{d^4q\, d\Omega} \omega(\theta,\phi)$$

$$\begin{aligned}
A_0 &= 4 - 10\langle \cos^2\theta\rangle, & A_1 &= 5\langle \sin 2\theta \cos\phi\rangle, \\
A_2 &= 10\langle \sin^2\theta \cos 2\phi\rangle, & A_3 &= 4\langle \sin\theta \cos\phi\rangle, \\
A_4 &= 4\langle \cos\theta\rangle, & A_5 &= 5\langle \sin^2\theta \sin 2\phi\rangle, \\
A_6 &= 5\langle \sin 2\theta \sin\phi\rangle, & A_7 &= 4\langle \sin\theta \sin\phi\rangle,
\end{aligned}$$

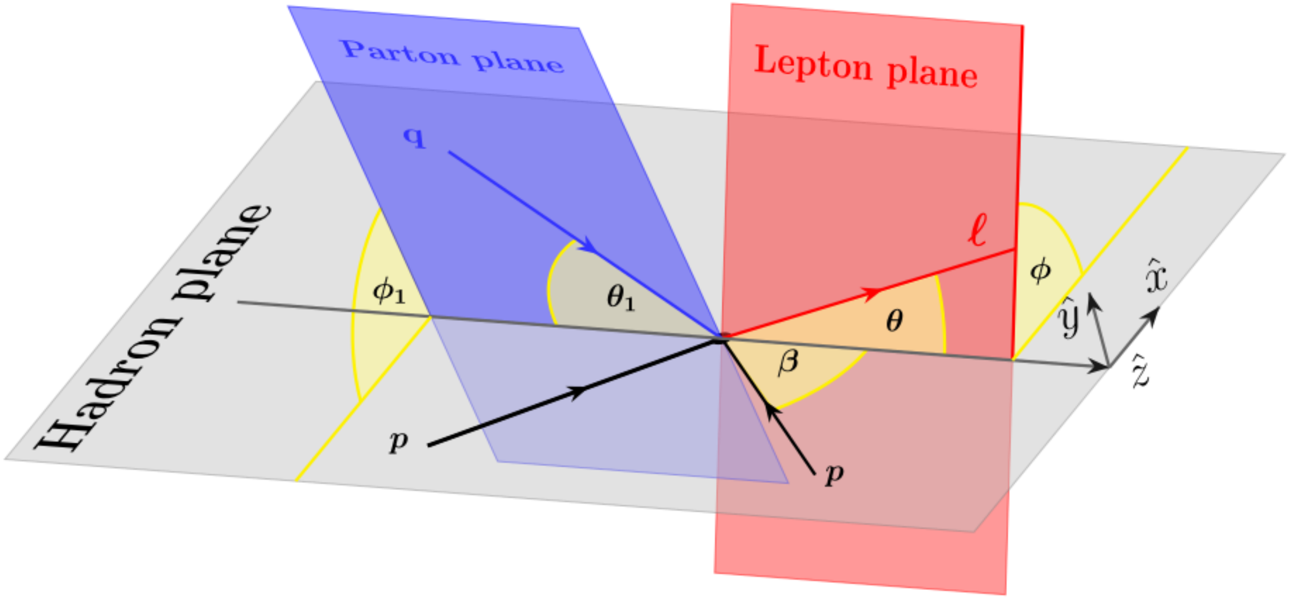
Lam-Tung Relation

Lam-Tung Relation: $A_0 = A_2$

C. S. Lam and W.-K. Tung, Phys. Rev. D 21, 2712(1980).

Spin ½ nature of quarks @ LO
Vector coupling of spin-1 gluon @ NLO
Violation @ NNLO and beyond

Jen-Chieh Peng et al. 1511.08932



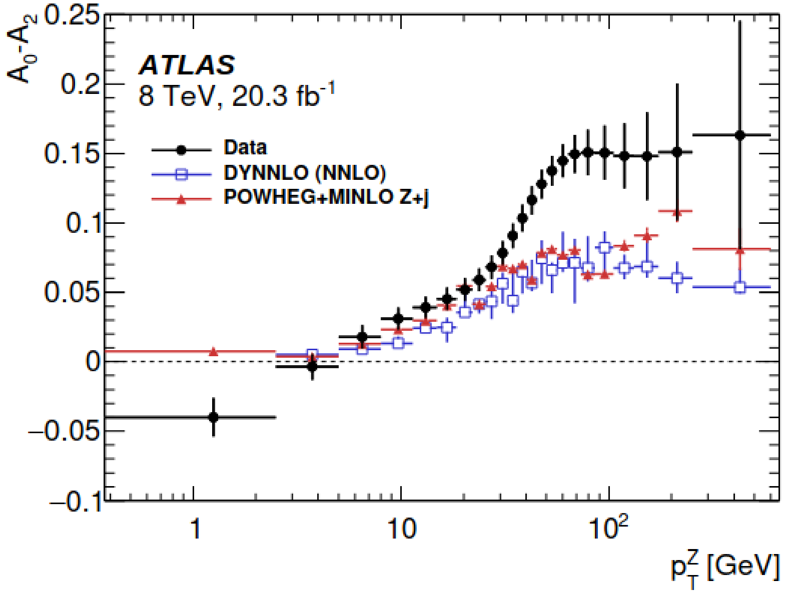
Collins-Soper frame

$$\frac{d\sigma}{d\Omega} = a\cos\hat{\theta} + b\cos^2\hat{\theta} + c\cos^3\hat{\theta} + d$$

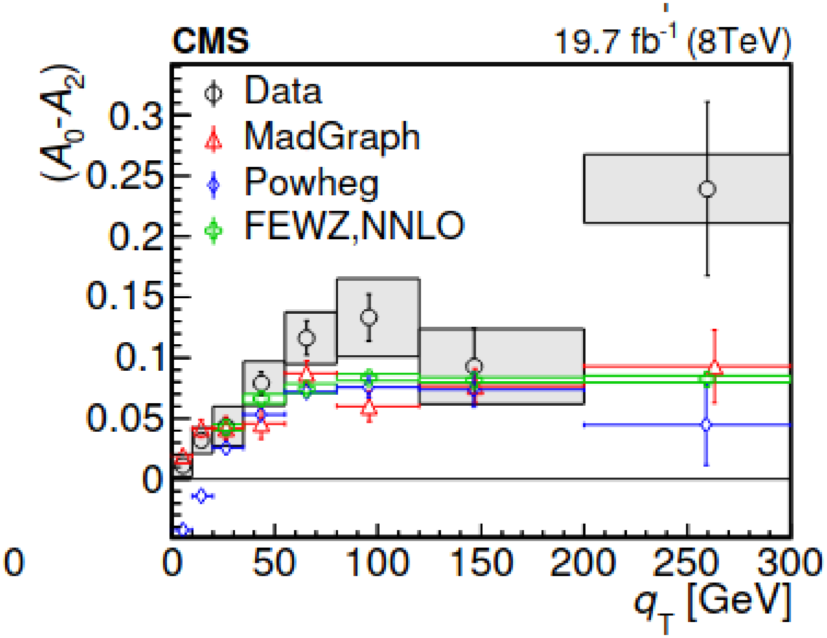
$$A_0 - A_2 = \left\langle 2\frac{d-b}{b+3d} \right\rangle$$

Lam-Tung Relation

The experiments showed discrepancies from SM predictions at NNLO:



1606.00689



1504.03512

Various effects in the SM have been considered

perturbative QCD at $\mathcal{O}(\alpha_s^3)$ R. Gauld et al. 1708.00008

electroweak corrections Rikkert Frederix,Timea Vitos, 2007.08867

non-perturbative effects Ian Balitsky, 2105.13391 et al.

Lam-Tung Relation breaking in the SMEFT

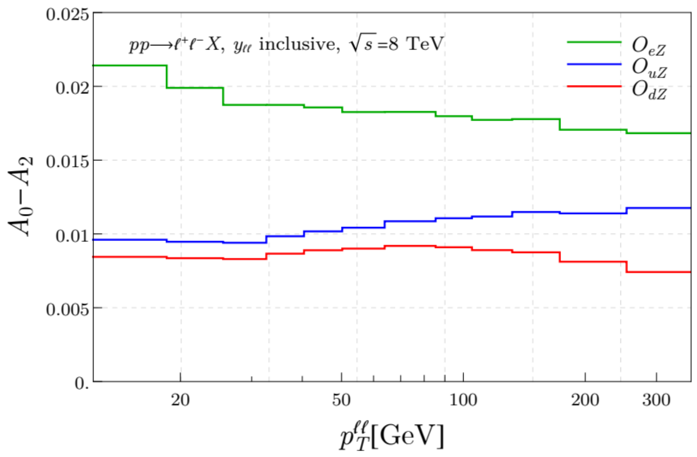
The possibility of new physics in the L-T relation breaking was discussed in the framework of the Standard Model Effective Field Theory(SMEFT).

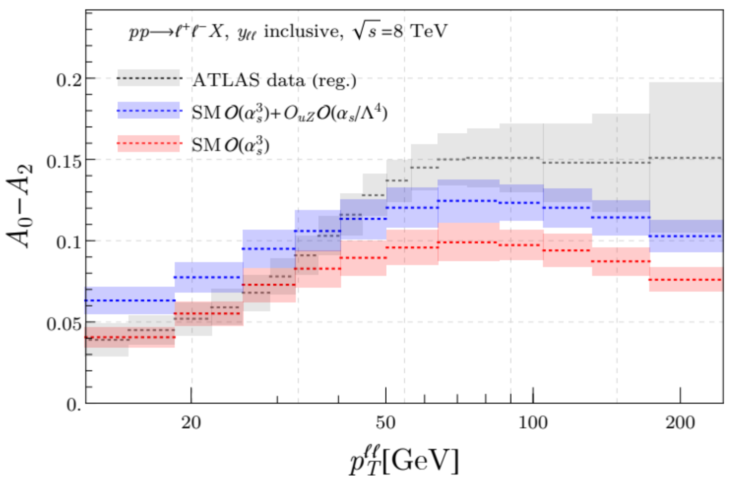
W. Buchmuller and D. Wyler, Nucl. Phys. B 268, 621(1986).

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{C_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_i \frac{C_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \dots$$

The effects from dim-6 dipole operators were found to demonstrate in the breaking:

$$O_{fZ} = \frac{v}{\sqrt{2}}\bar{f}_L\sigma^{\mu\nu}f_R Z_{\mu\nu}, \quad O_{fA} = \frac{v}{\sqrt{2}}\bar{f}_L\sigma^{\mu\nu}f_R A_{\mu\nu},$$



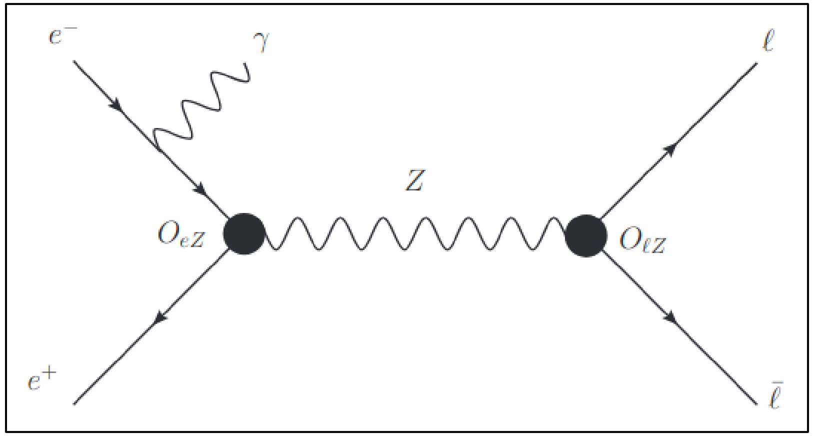


X. Li, B. Yan, and C. P. Yuan (2024), 2405.04069.

Lam-Tung Relation at Lepton Colliders

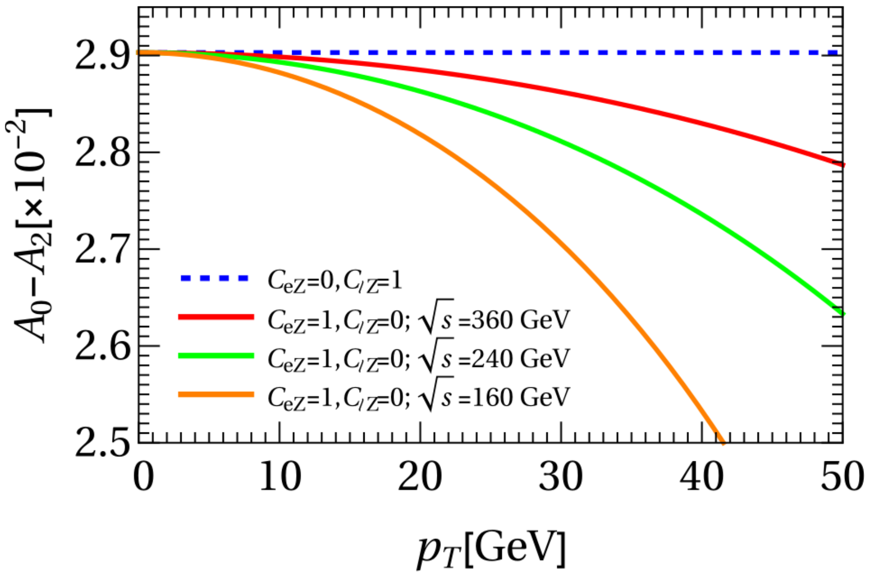
The lepton process of different final states are concerned with different dipole operators,

- Distinguish different operators
- Accessible for heavy quarks



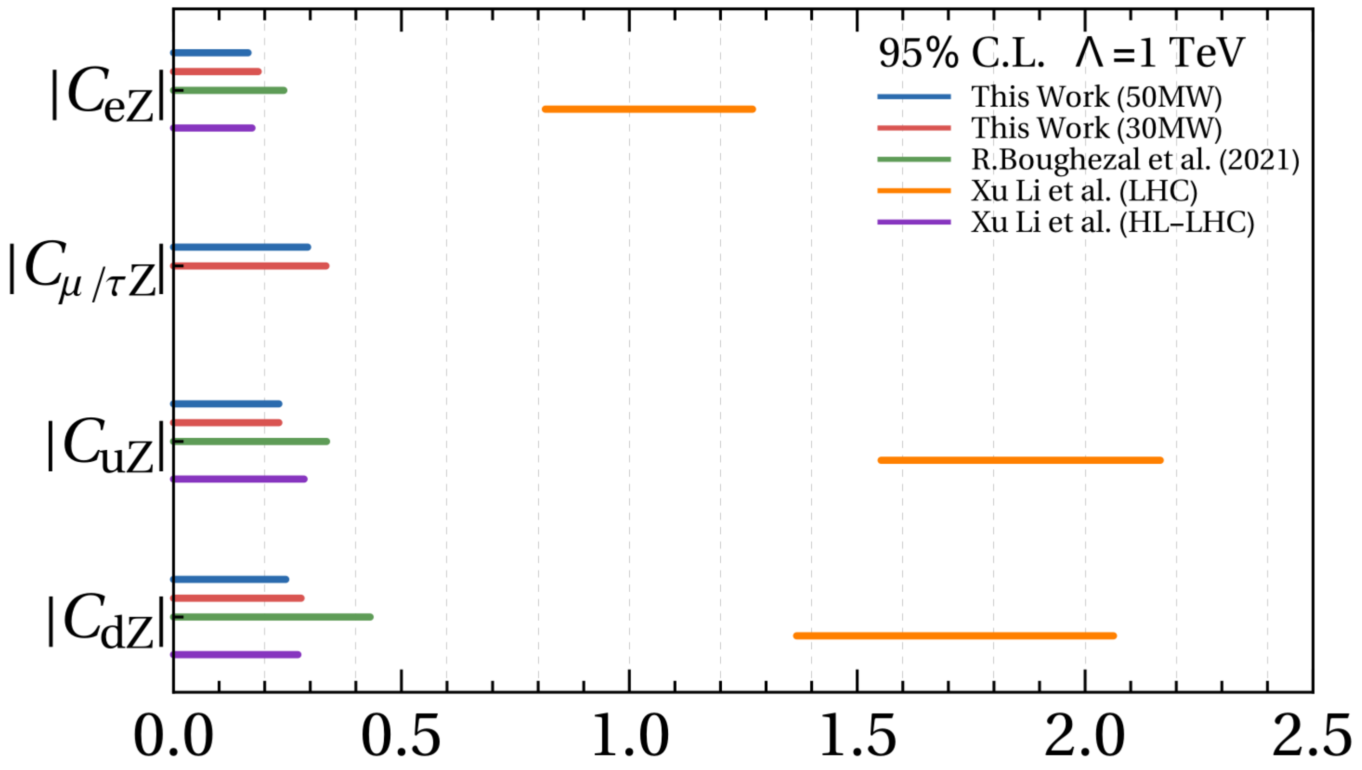
Without the contribution of PDF, the effects from dipole operators can be expressed analytically:

$$(A_0 - A_2)_\ell = \frac{4v^2 m_{\ell\bar{\ell}}^2}{(g_L^2 + g_R^2)} \times \left[\frac{C_{eZ}^2}{\Lambda^4} \left(1 - \frac{2sp_T^2}{m_{\ell\bar{\ell}}^4 - 2sp_T^2 + s^2} \right) + \frac{C_{\ell Z}^2}{\Lambda^4} \right].$$



Numerical Results

By assuming the existence of one single dipole operators, we give the individual bounds for each operator.



distinguishing ability, heavy quarks…

SUMMARY

Lam-Tung Relation Breaking

- High signaficace
- Few contributed operators

Lepton Colliders

- More observables
- Clear dependence of operators