Physics Opportunities at Colliders

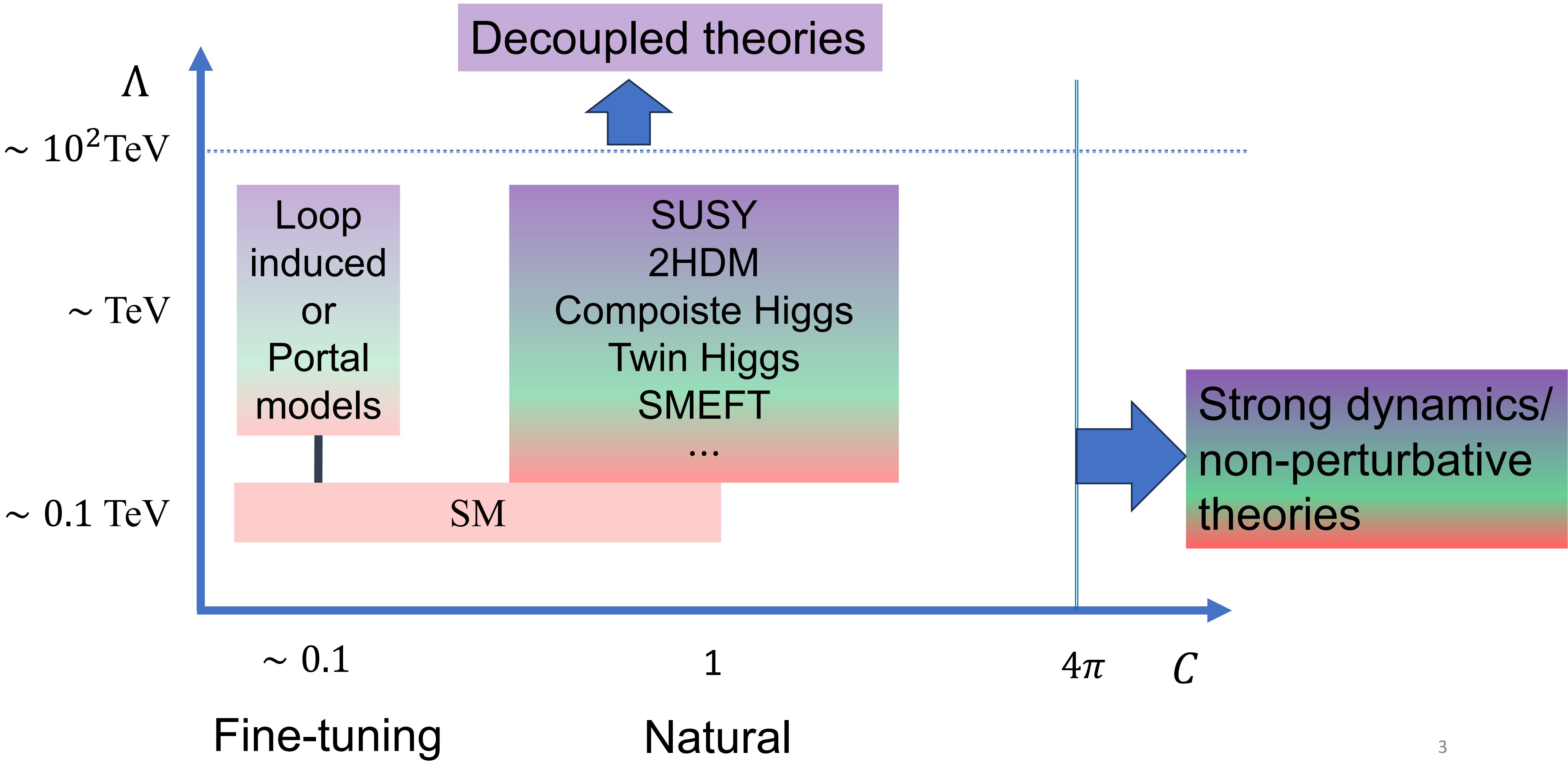
Yandong Liu

Beijing Normal University

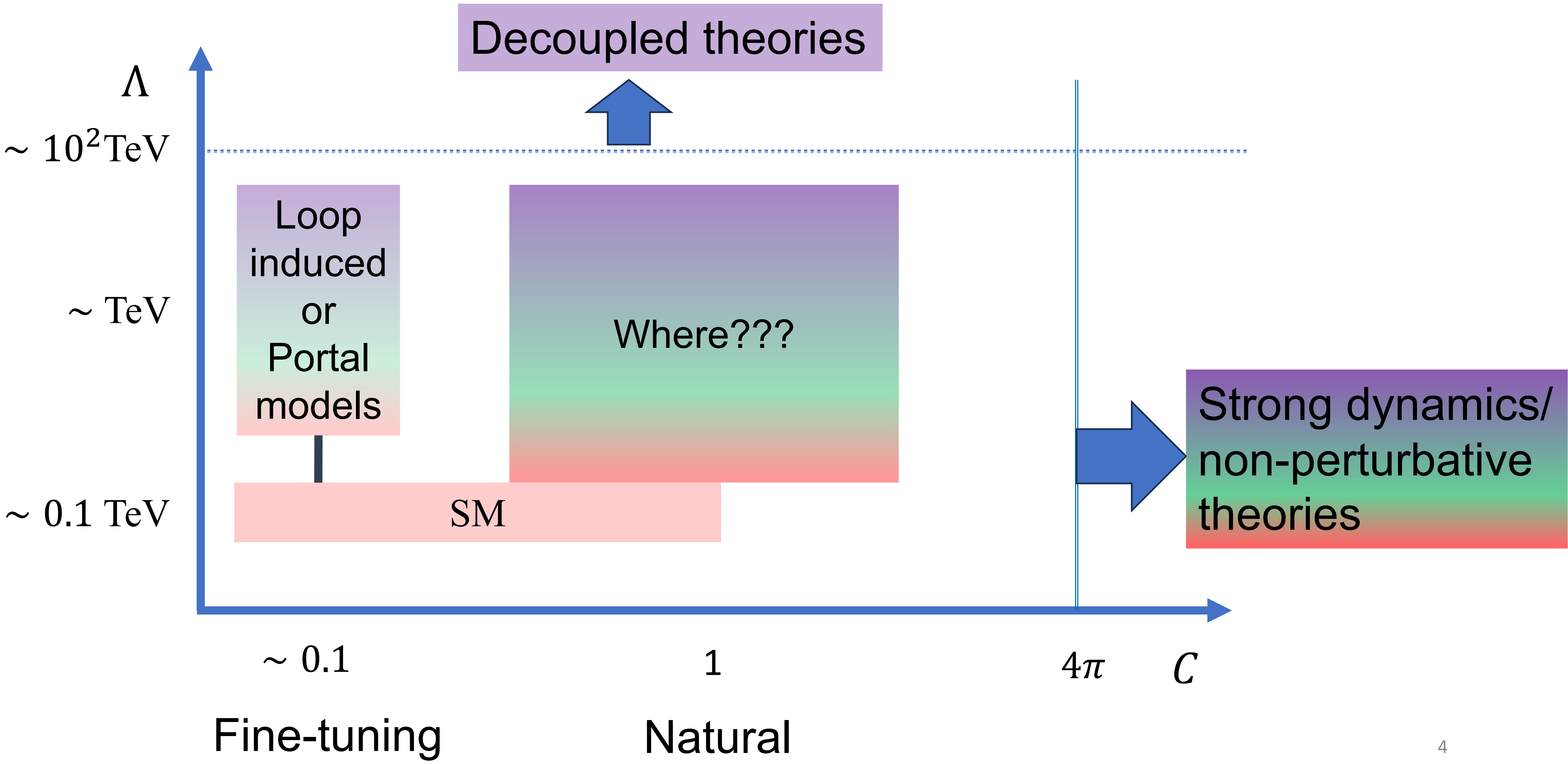
30/10/2025

Where and How can we find
new physics beyond the Standard Model
at colliders?

New Physics beyond Standard Model



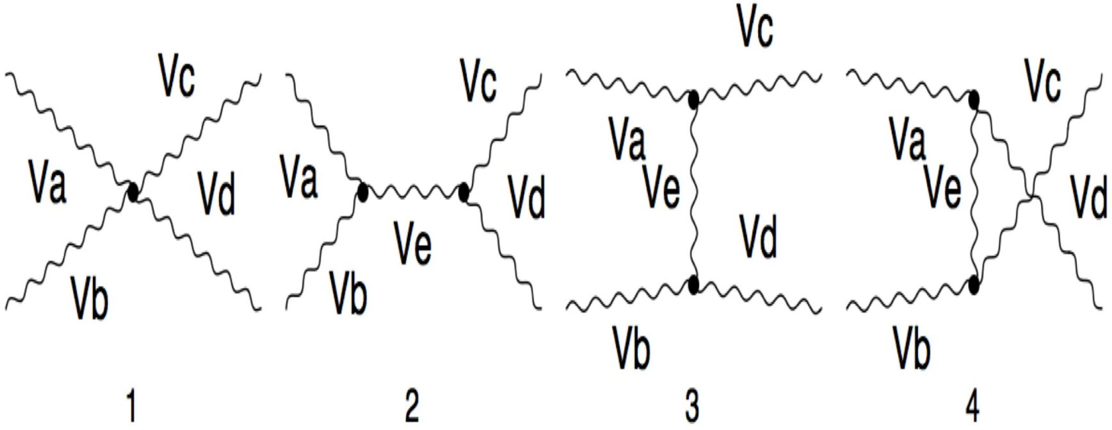
New Physics beyond Standard Model



What might we have missed?

Cancellation in WW Scattering and Di-Higgs Production

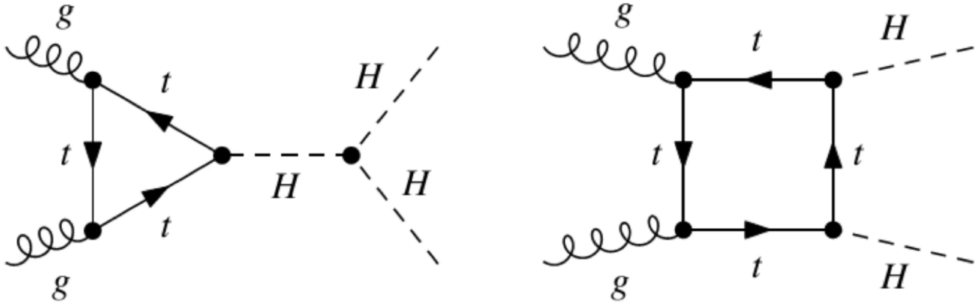
$$W^{\pm}W^{\mp} \to W^{\pm}W^{\mp}$$



$$M_{\pm\pm,\pm\pm} = 0 * S^2 + 0 * S^{\frac{3}{2}} + \cdots$$

Gauge symmetry protection👍

$$gg \to HH$$



$$-\frac{\alpha_s}{24\pi} G^{a,\mu\nu} G^a_{\mu\nu} \sum_n \frac{y_t^n h^n}{n!} \frac{\partial^n}{\partial m_t^n} \log\left(\frac{\Lambda_{UV}^2}{m_t^2}\right)$$

n=1

$$\frac{\alpha_s}{12\pi v} G^{a,\mu\nu} G^a_{\mu\nu} h$$

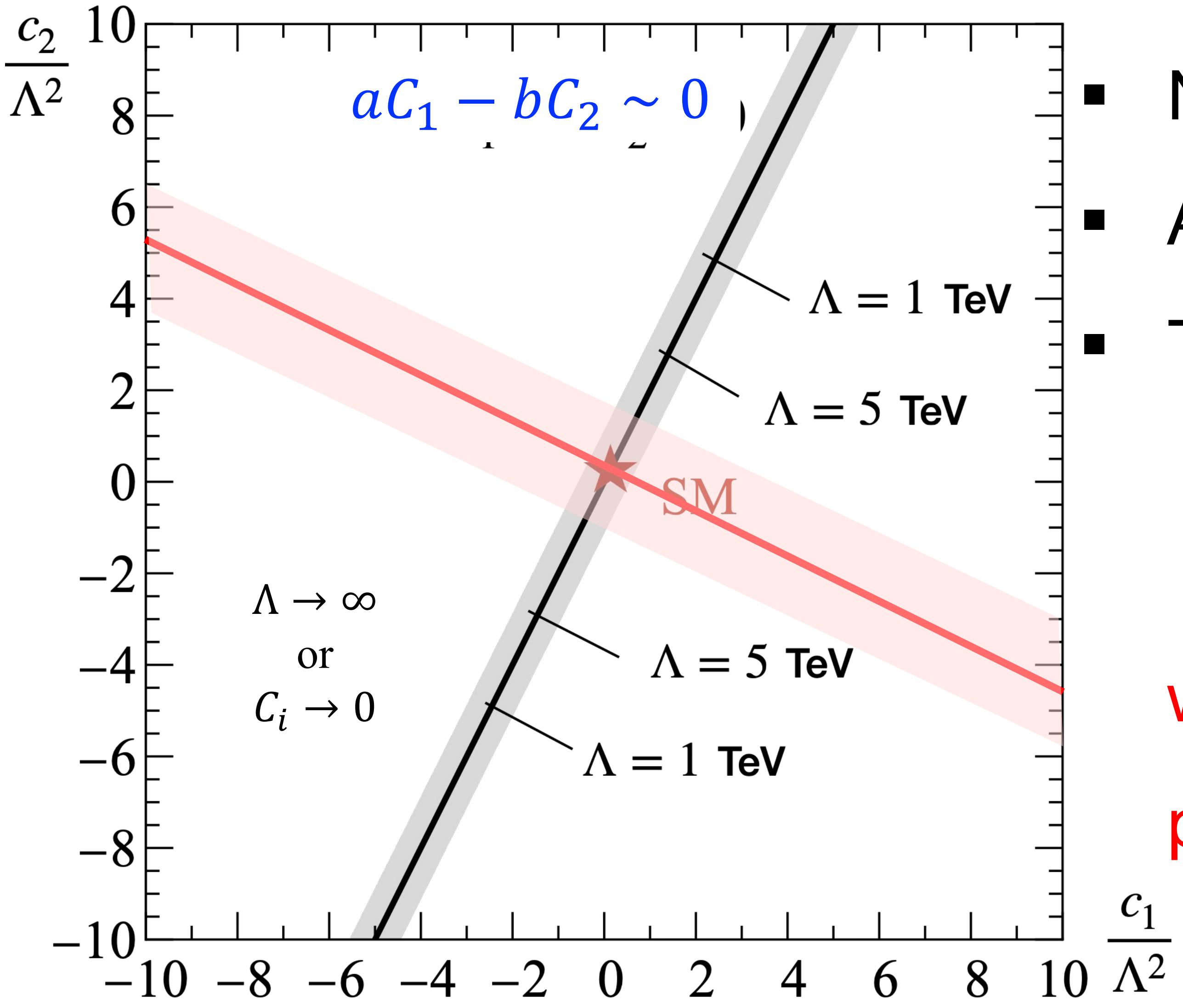
n=2

$$-\frac{\alpha_s}{24\pi v^2} G^{a,\mu\nu} G^a_{\mu\nu} h^2$$

Higgs low energy theorem😱

Operator correlation: shedding/hiding light on NP

--the LHC inverse problem in SMEFT



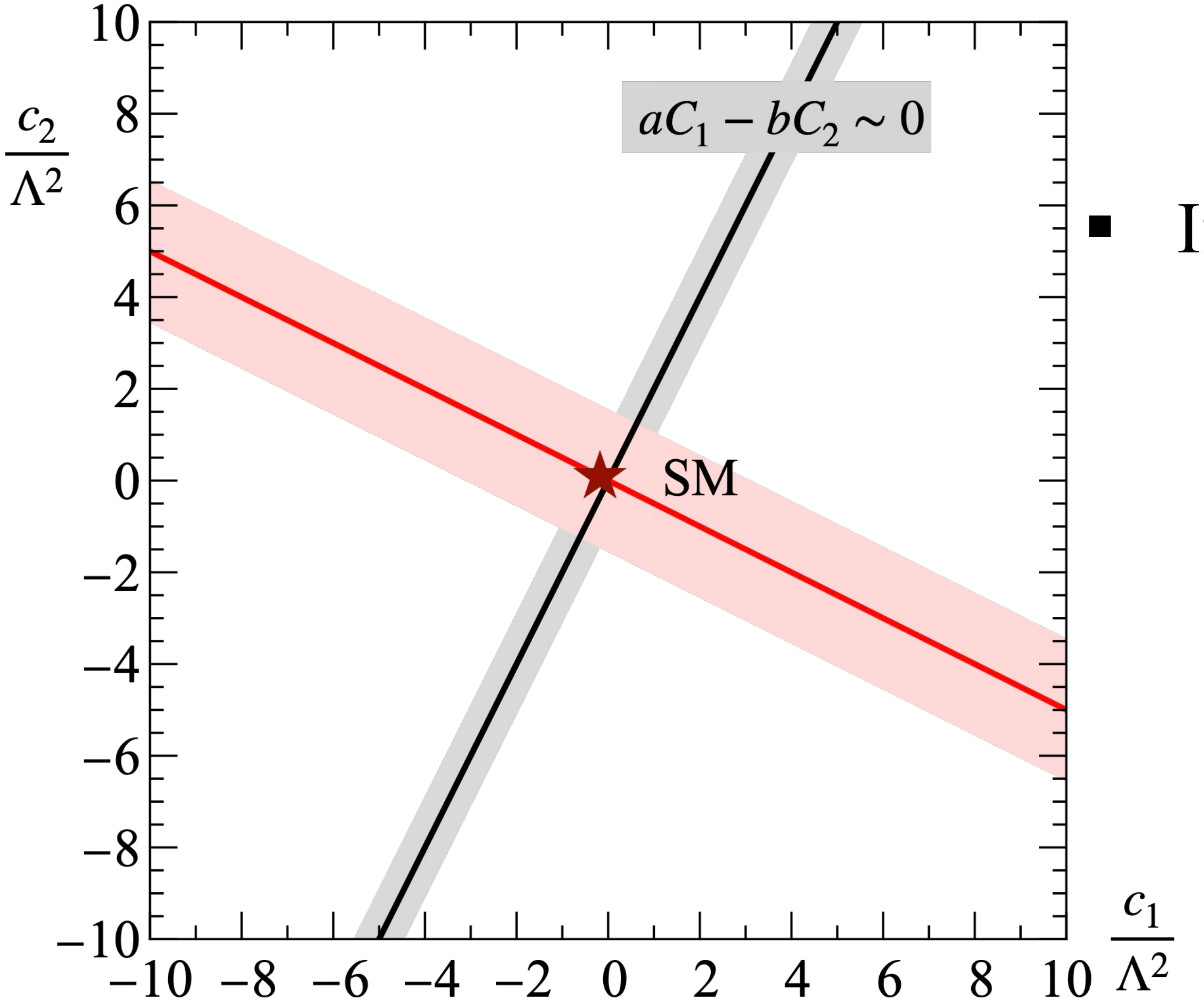
- NP effect: $\delta\sigma^{obs1} = (aC_1 - bC_2)/\Lambda^2$
- A blind direction exists: $aC_1 - bC_2 = 0$
- The orthogonal direction

$$\delta\sigma^{obs2} = \frac{mC_1 + nC_2}{\Lambda^2}$$

which is the most efficient channel to probe or rule out new physics

Operator correlation shedding/hiding light on NP

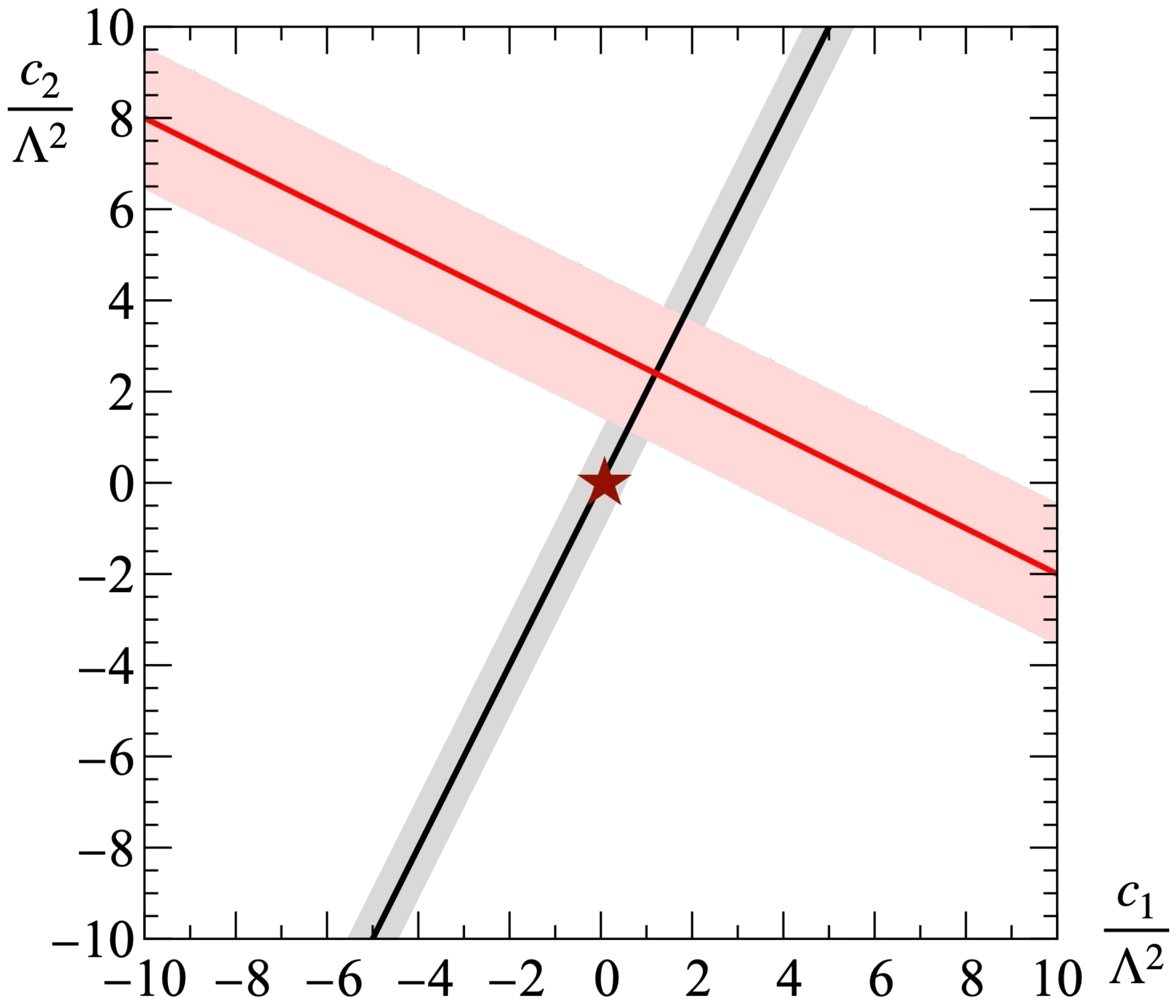
--the LHC inverse problem in SMEFT



- If $(mC_1 + nC_2)/\Lambda^2 = 0$
  - NP is far away from us
  - NP does not generate the operators

Operator correlation shedding/hiding light on NP

--the LHC inverse problem in SMEFT



- If $(mC_1 + nC_2)/\Lambda^2 \neq 0$

  $\delta\sigma^{obs1} = (aC_1 - bC_2)/\Lambda^2 = 0$

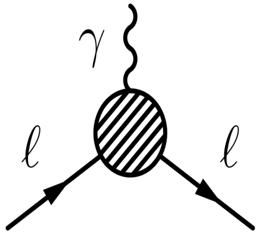
  $\delta\sigma^{obs2} = (mC_1 + nC_2)/\Lambda^2 \neq 0$

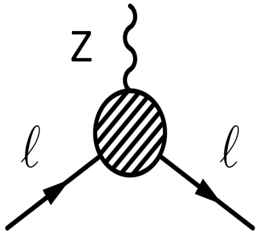
  NP along direction of $\frac{C_1}{C_2} = \frac{b}{a}$

Operator correlation: magnetic moment operator

Q. H. Cao, H. R. Jiang, B. Li, **YL**, G. J. Zeng, Chin.Phys.C 45 (2021) 9, 093108

- Magnetic dipole moments: probing the internal structures of particles
  - Electron: $g/2 = 1.001159\cdots$
  - Proton: $g/2 = 2.7928444\cdots$
- Magnetic dipole and weak magnetic dipole moment





$$O_{d_iW} = (\bar{Q}_i\sigma^{\mu\nu}\tau^I d_i)\phi W^I_{\mu\nu}$$

$$O_{d_iB} = (\bar{Q}_i\sigma^{\mu\nu} d_i)\phi B_{\mu\nu}$$

Operator correlation: magnetic moment operator

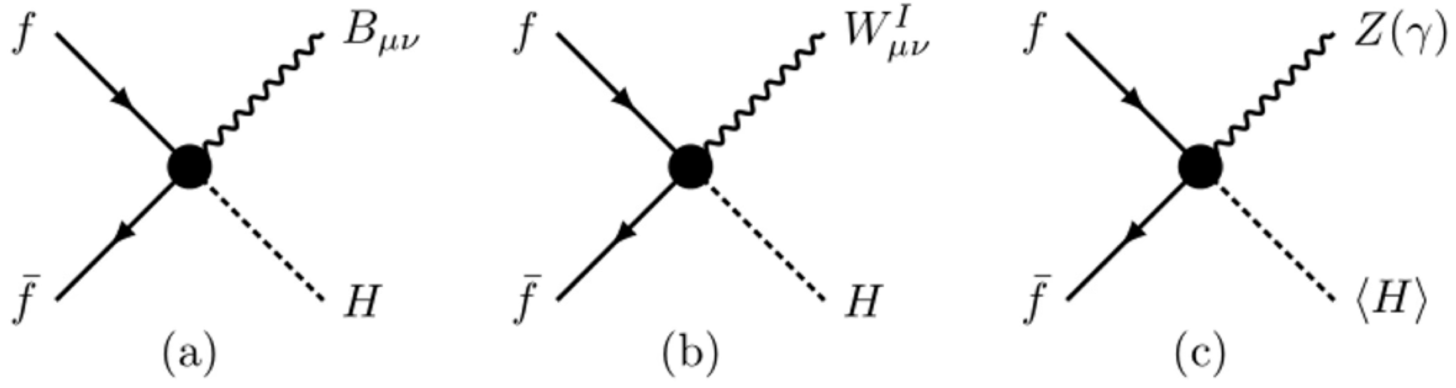
Q. H. Cao, H. R. Jiang, B. Li, **YL**, G. J. Zeng, Chin.Phys.C 45 (2021) 9, 093108

$$O_{d_iW} = (\bar{Q}_i\sigma^{\mu\nu}\tau^I d_i)\phi W^I_{\mu\nu}$$

$$O_{d_iB} = (\bar{Q}_i\sigma^{\mu\nu} d_i)\phi B_{\mu\nu}$$

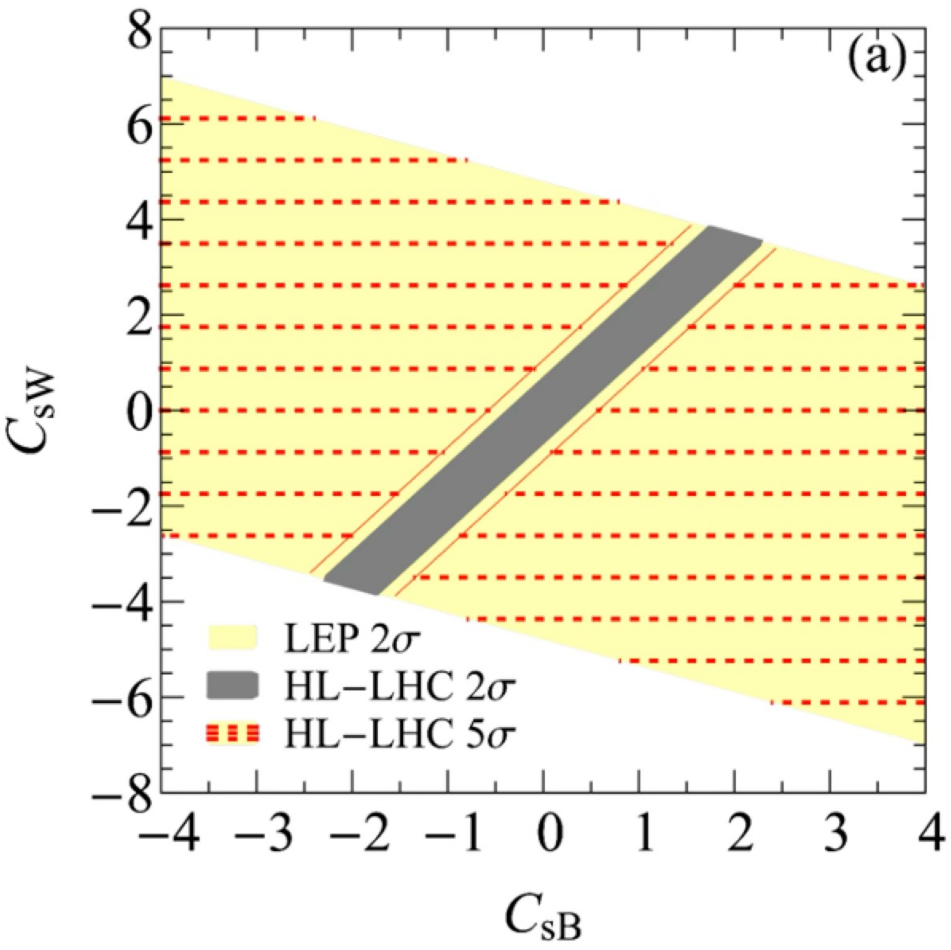
$$\delta a^s_\gamma = -2\sqrt{2}\frac{m_s v}{\Lambda^2}\frac{1}{eQ_f}\left(c_W C_{fB} - s_W C_{fW}\right)$$

$$\delta a^s_W = +2\sqrt{2}\frac{m_s v}{\Lambda^2}\frac{1}{eQ_f}\left(s_W C_{fB} + c_W C_{fW}\right)$$



Operator correlation: magnetic moment operator

Q. H. Cao, H. R. Jiang, B. Li, **YL**, G. J. Zeng, Chin.Phys.C 45 (2021) 9, 093108



LEP constraint on the weak magnetic moment:

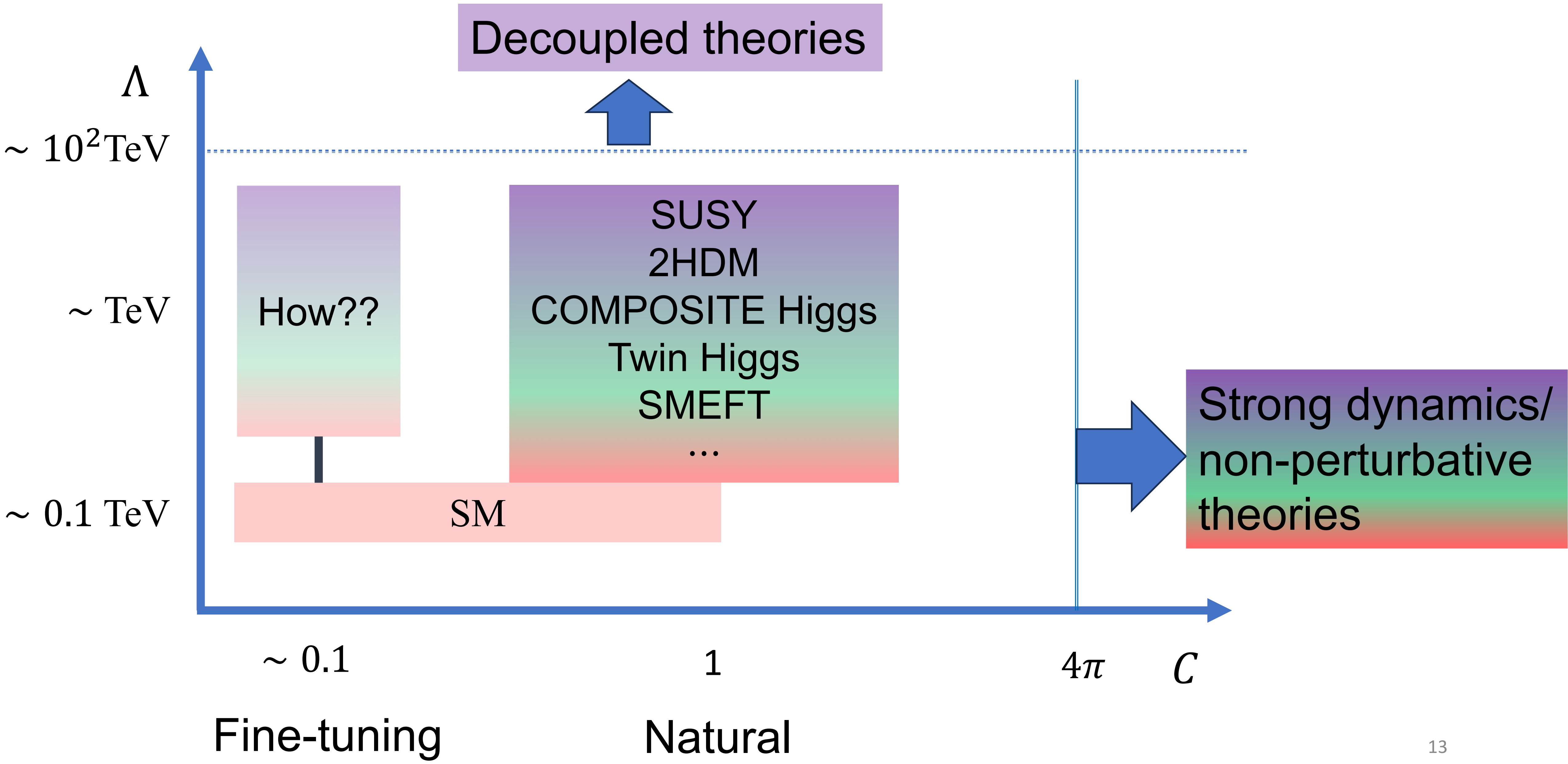
$$|s_W C_{sB} + c_W C_{sW}| \left(\frac{1\ \text{TeV}}{\Lambda}\right)^2 \leq 4.2$$

At HL-LHC, $H\gamma$ production involve the magnetic moment:

$$|c_W C_{sB} - s_W C_{sW}| \left(\frac{1\ \text{TeV}}{\Lambda}\right)^2 \leq 0.32 \text{ at } 2\sigma$$

$$|c_W C_{sB} - s_W C_{sW}| \left(\frac{1\ \text{TeV}}{\Lambda}\right)^2 \geq 0.51 \text{ at } 5\sigma$$

New Physics beyond Standard Model

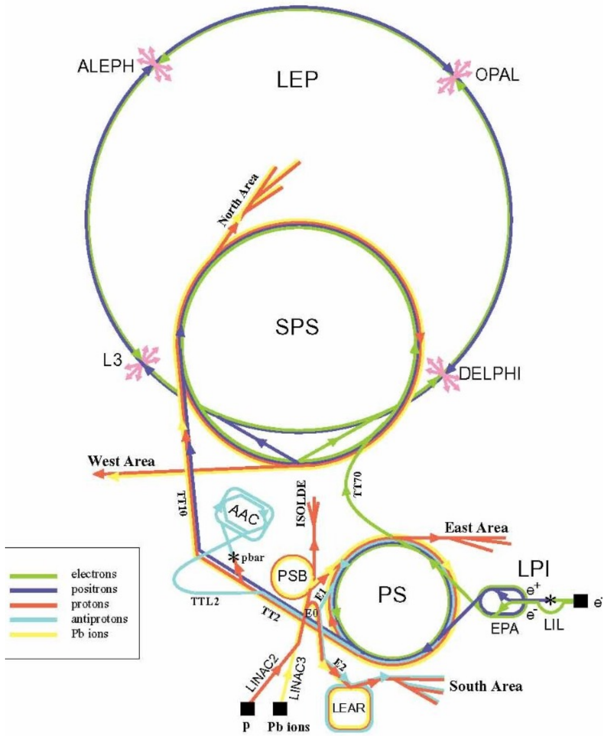


Muon Collider: Discovery and Precision Machine

Lepton Colliders:
precision machines

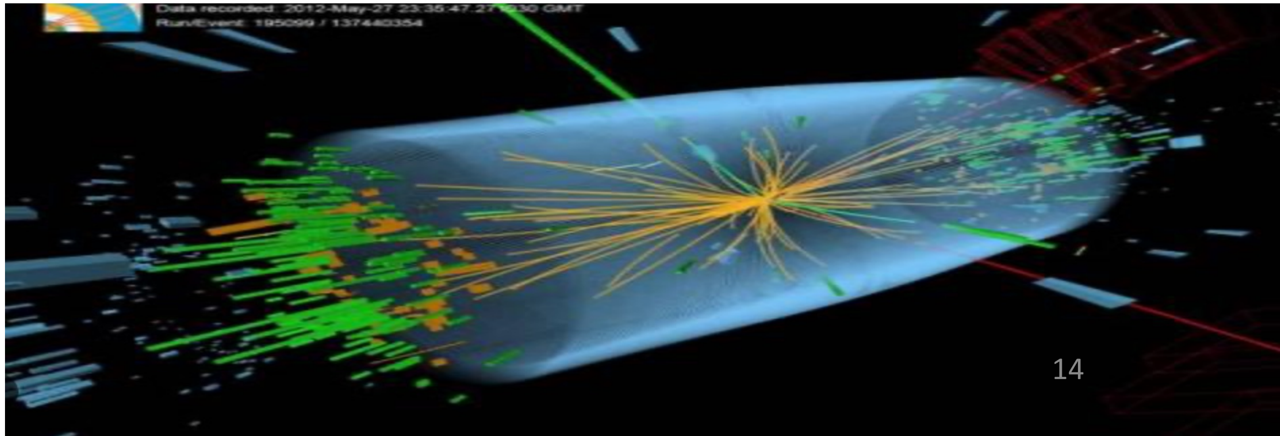
- ❑Well-defined initial states
- ❑Clean final states
- ❑Indirect sensitivity to new physics

Muon Colliders

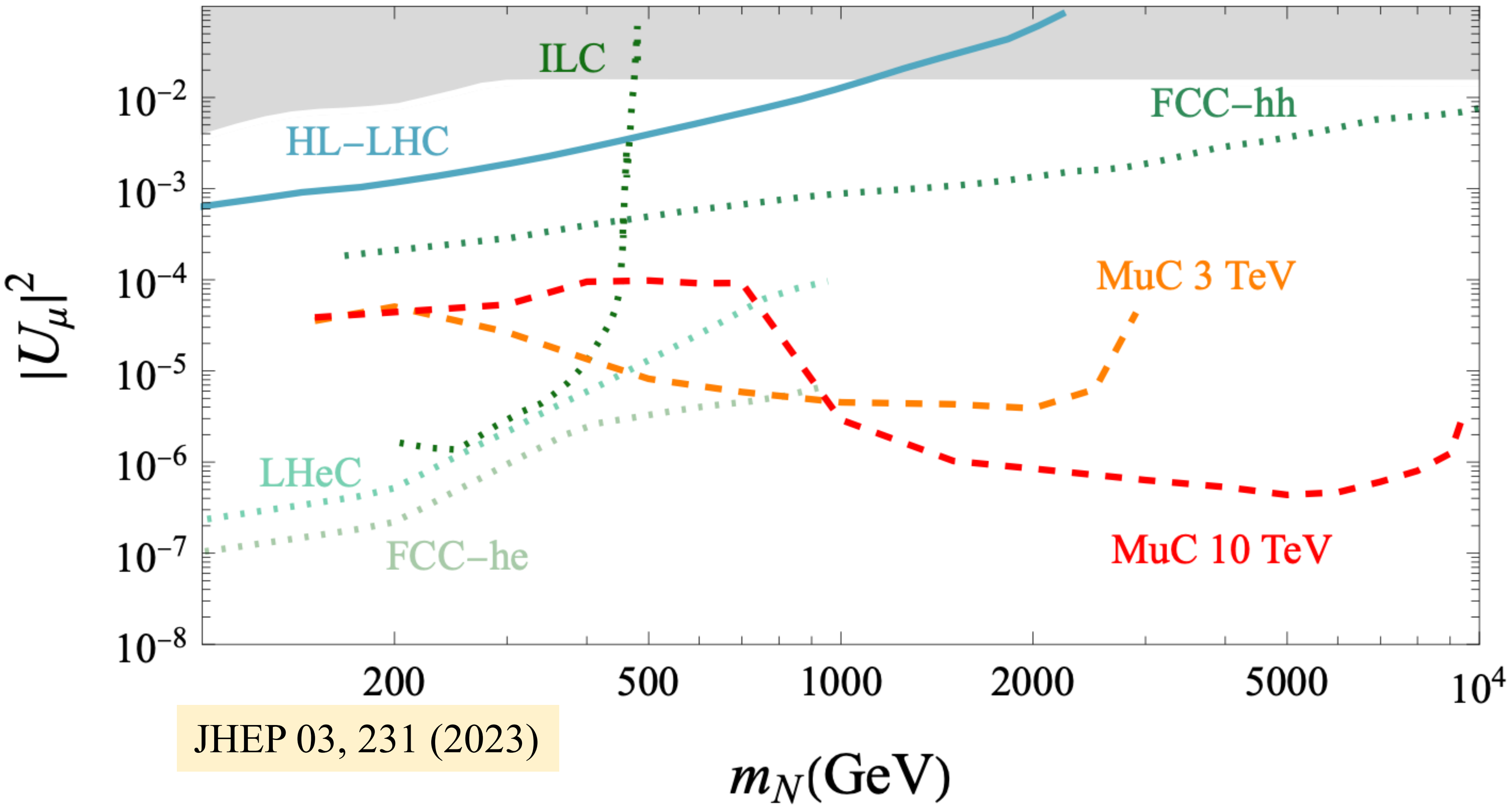


- Broad energy reach
- Sensitive to new heavy resonances
- ~~Messy environment~~

Hadron Colliders: discovery machines



Sterile Neutrino at Muon Colliders



JHEP 03, 231 (2023)

I. Chakraborty, H. Roy, and T. Srivastava, (2022), 10.1140/ep jc/s10052-023-11406-0; T. Li, C.-Y. Yao, and M. Yuan, JHEP 09, 131 (2023); T. H. Kwok, L. Li, T. Liu, and A. Rock, (2023), arXiv:2301.05177; P. Li, Z. Liu, and K.-F. Lyu, JHEP 03, 231 (2023), arXiv:2301.07117; R.-Y. He, J.-Q. Huang, J.-Y. Xu, F.-X. Yang, Z.-L. Han, and F.-L. Shao, (2024), arXiv:2401.14687

How can we do better?

Sterile neutrino: N Discrimination of Dirac or Majorana nature.

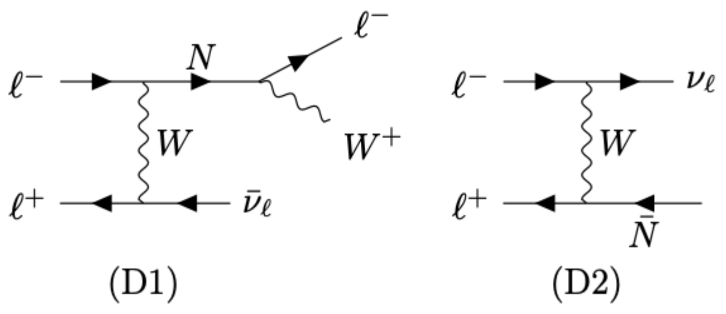
Whether the Majorana fermion exists?

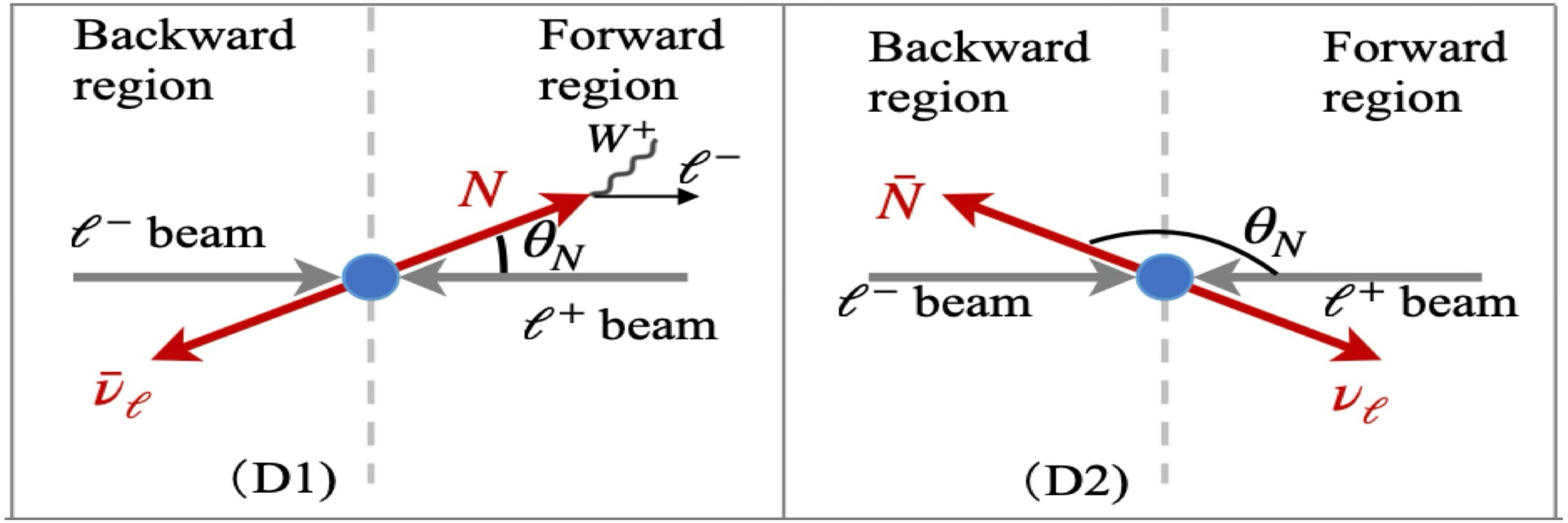
Revisiting Kinematic Variables: Rapidity

Q. H. Cao, K. Cheng, **YL**, **Phys.Rev.Lett.** 134 (2025) 2, 021801

Sterile neutrino: N

Dirac or Majorana?





For Dirac N, $N \to l^- W^+$, $\bar{N} \to l^+ W^-$

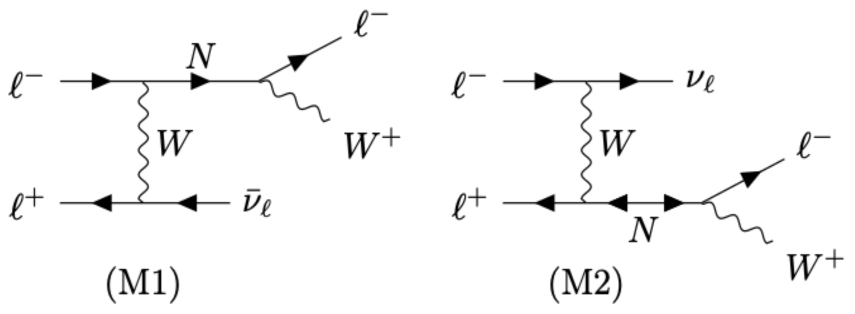
Decay products $l^- W^+$ from N fly in the forward region

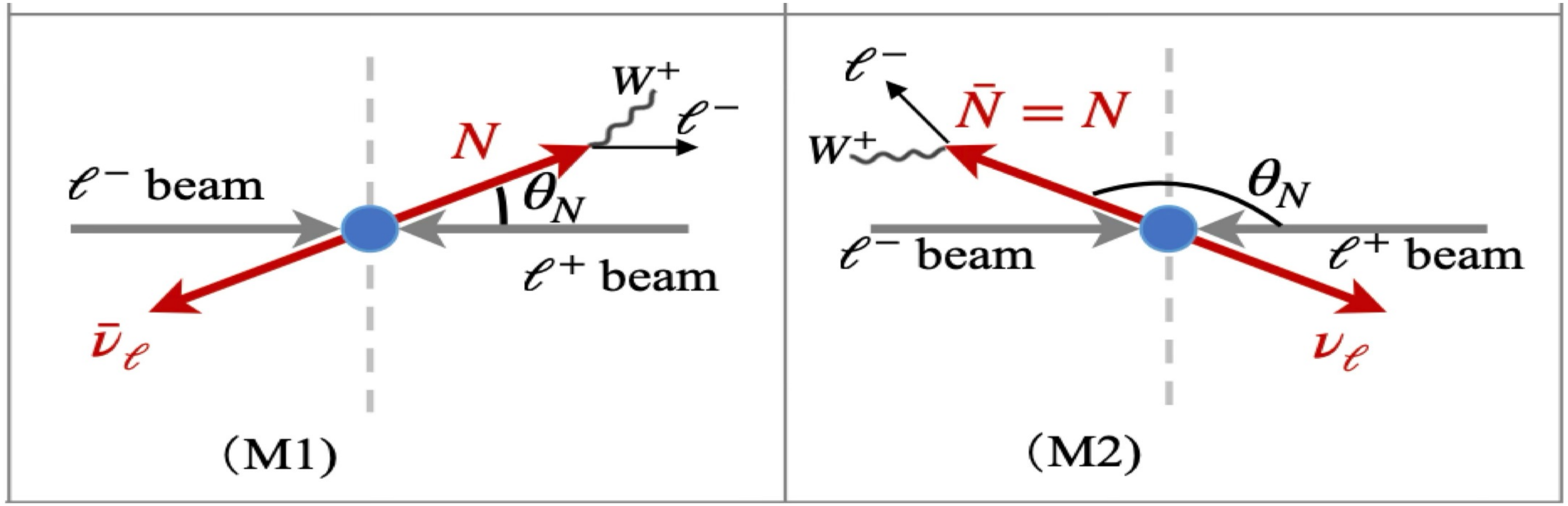
Revisiting Kinematic Variables: Rapidity

Q. H. Cao, K. Cheng, **YL**, **Phys.Rev.Lett.** 134 (2025) 2, 021801

Sterile neutrino: N

Dirac or Majorana?

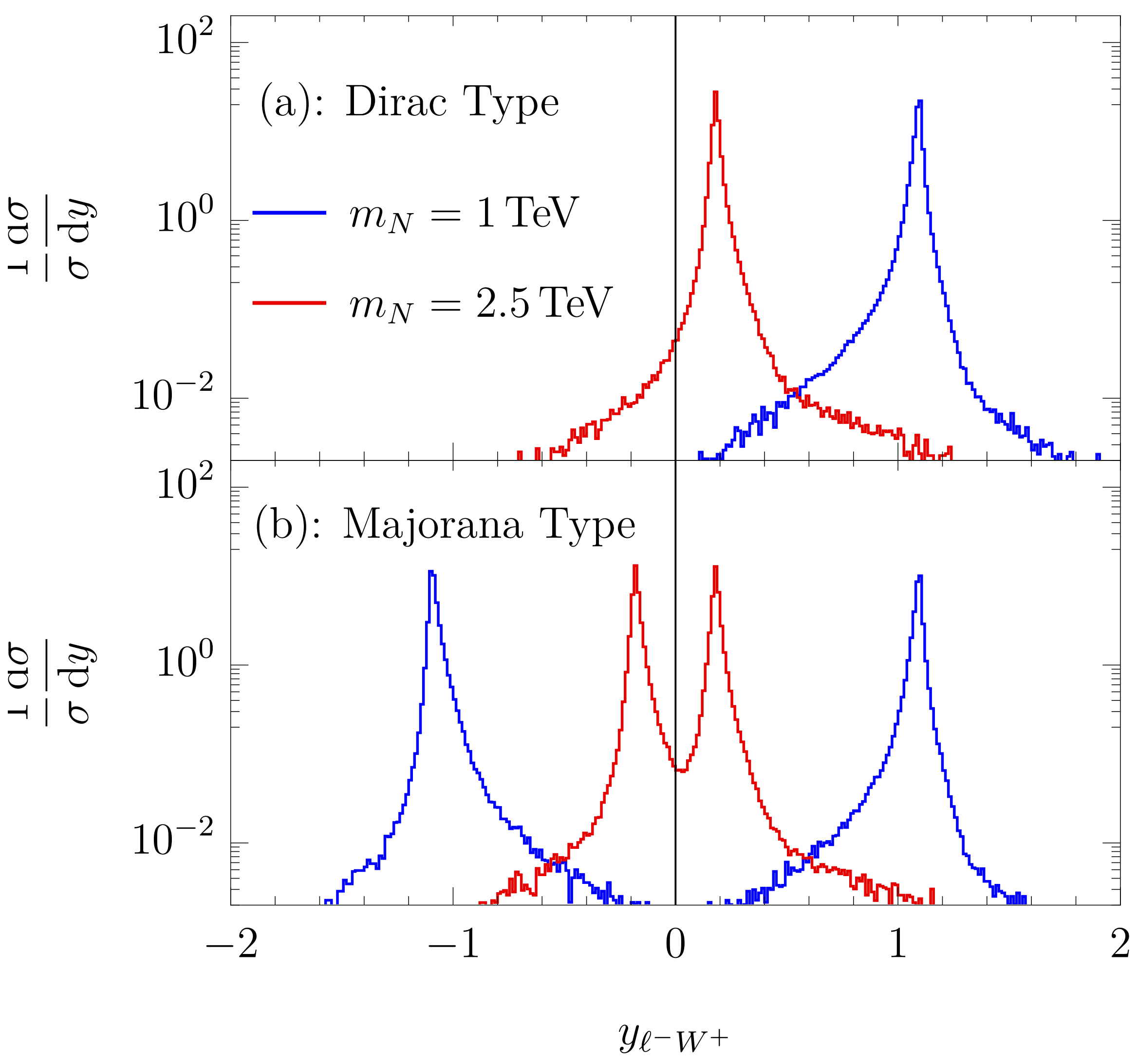




For Majorana N, $N \to l^- W^+$, $\bar{N} \to l^- W^+$

Decay products $l^- W^+$ from $N(\bar{N})$ fly equivalently in the forward region and backward region

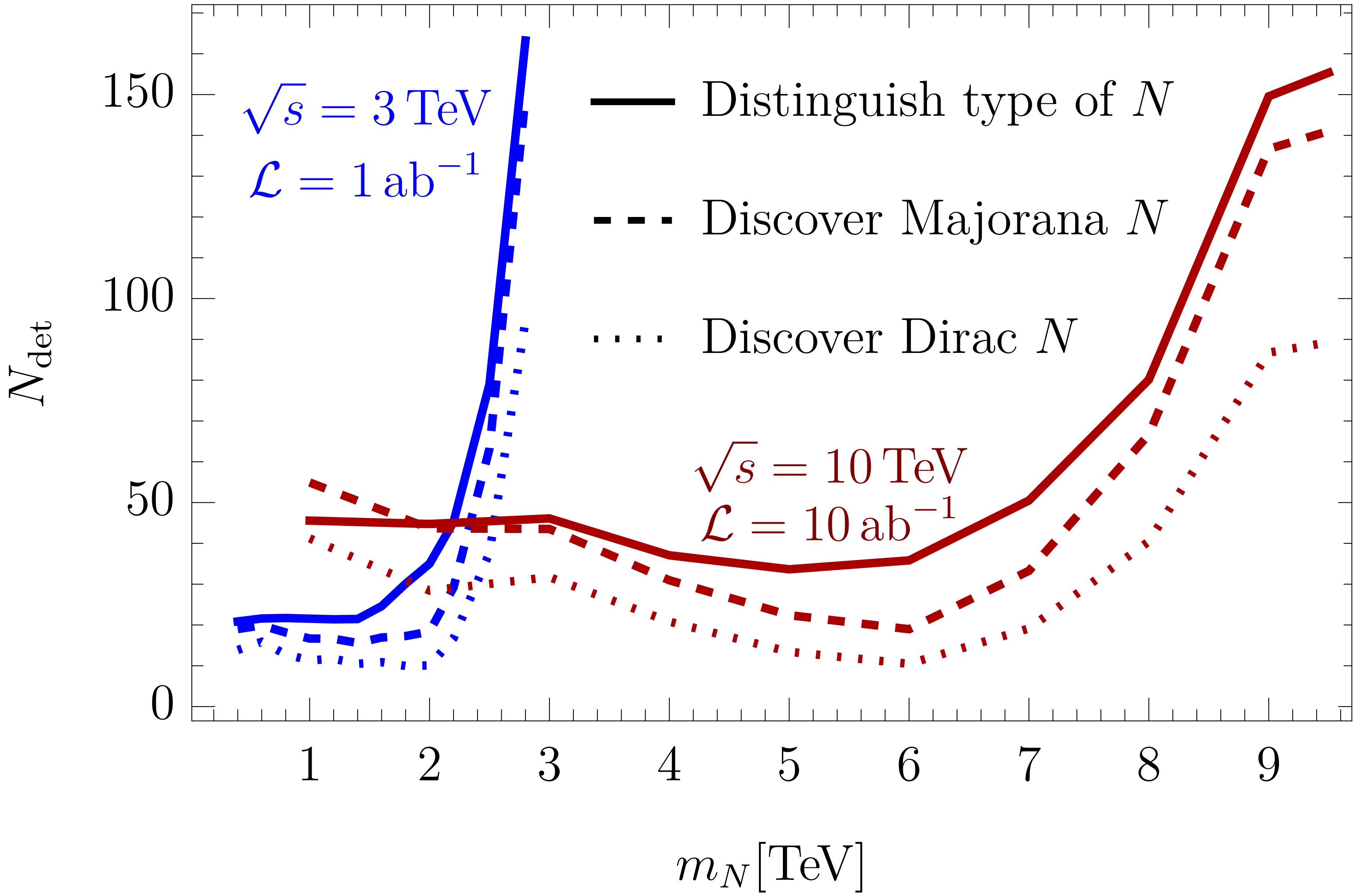
Rapidity Distribution at Muon Colliders



Dirac case: asymmetric distribution

Majorana case: symmetric distribution

Discovery and Discrimination Reach at Muon Colliders



Summary and Outlook

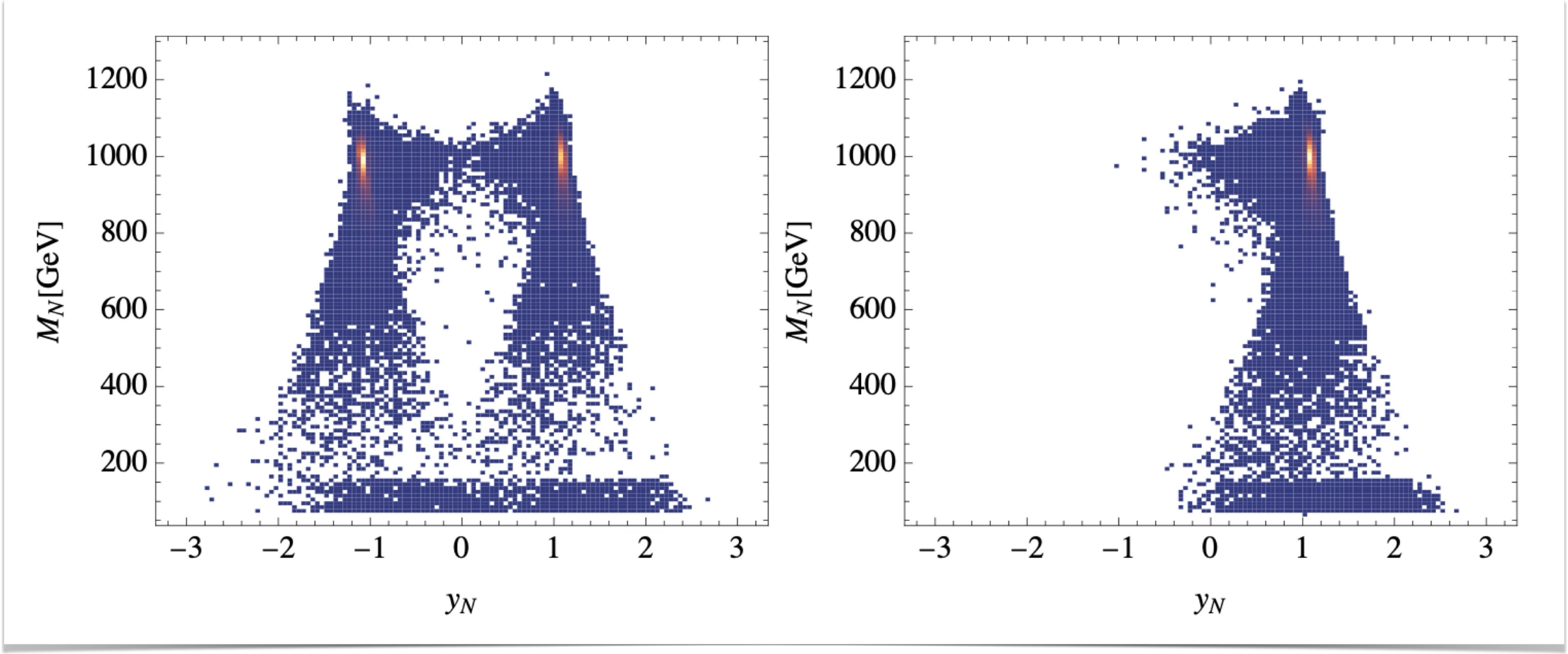
- The Standard Model remains remarkably successful, yet many fundamental questions strongly motivate NP.
- No clear NP signal has emerged at colliders, indicating that we may not be missing energy — we may be missing the strategy, such as operator correlations and degenerate resonances.
- Revisiting kinematica observables and transversely polarized beams may help.
- Quantum information inspired ideas (e.g., quantum entanglement observables) may open an entirely new window to probe NP.

Thanks!!!

Advance of Rapidity: Correlation with Mass

$$y_N = \frac{1}{2}\log\frac{E + p_N \ \cos\theta_N}{E - p_N \ \cos\theta_N}$$

$$\mathrm{v}_N^Z = tanh\, y_N$$



Advance of Rapidity: Signal Discrimination