Precision Phenomenology and New Physics Probes at Future Colliders

Dissertation Talk

Kaan Şimşek

Committee members:
John Joseph M. Carrasco
André Luiz de Gouvêa
Francis John Petriello

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Image credit Maurice Leloir (1894)

Prelude

Position at the time

Particle physics at a crossroads in the quest to uncover physics beyond the Standard Model.

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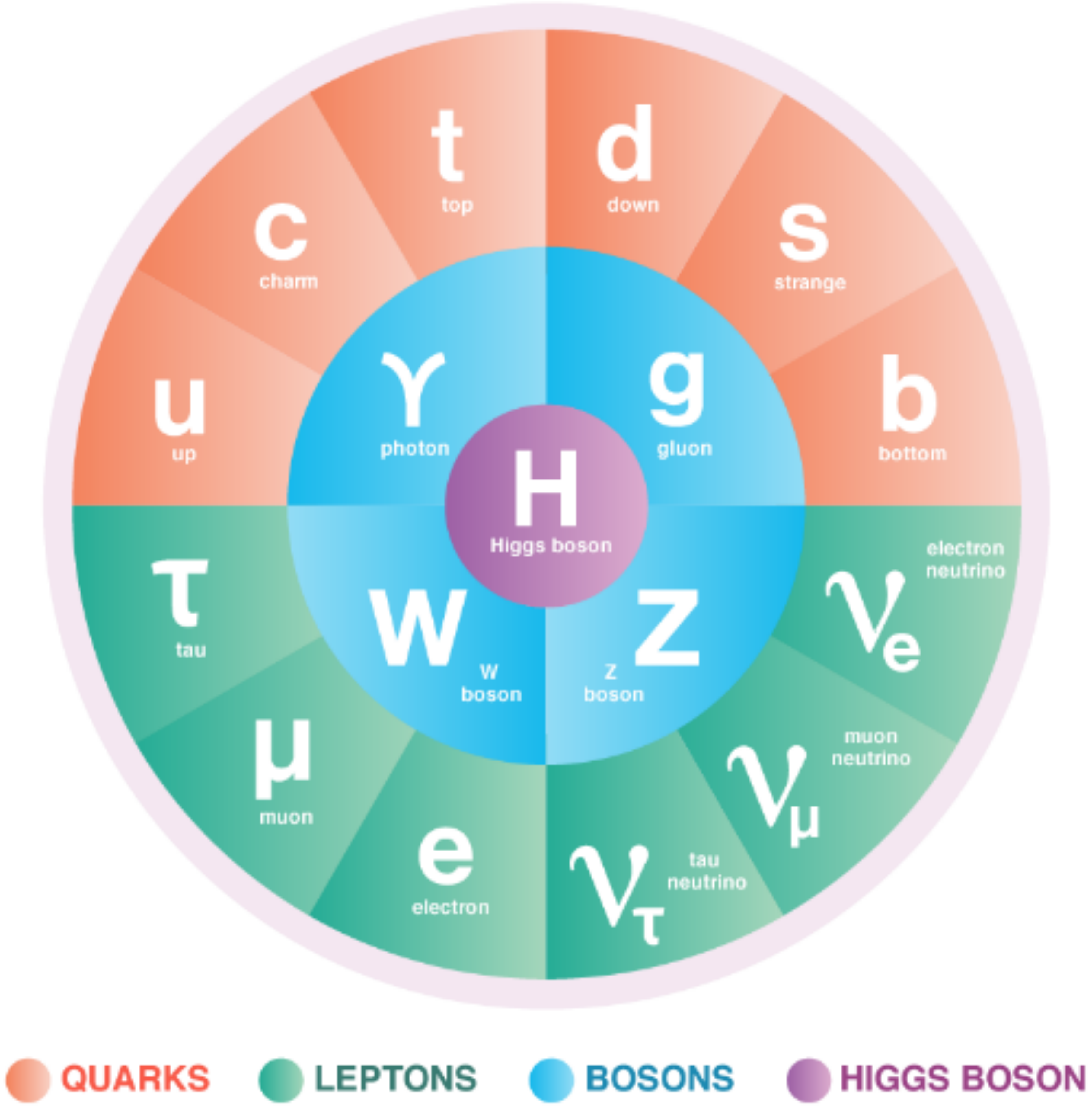
Particle physics at a crossroads in the quest to uncover physics beyond the Standard Model.

Standard Model:

- Successfully describing known particles and their interactions
- Complete spectrum with the discovery of Higgs in 2012
- No conclusive evidence for new particles



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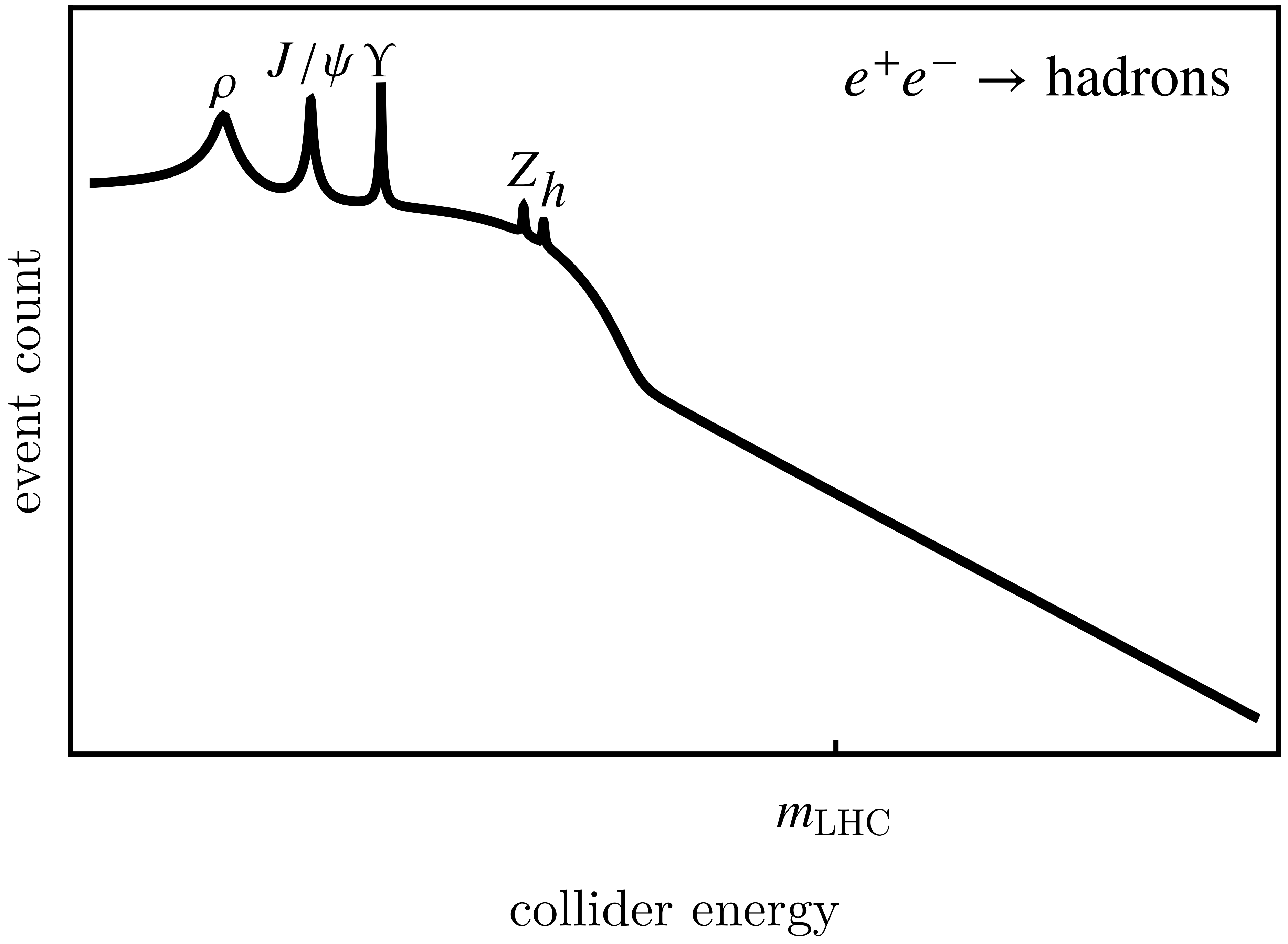
Position at the time

No clear new signals



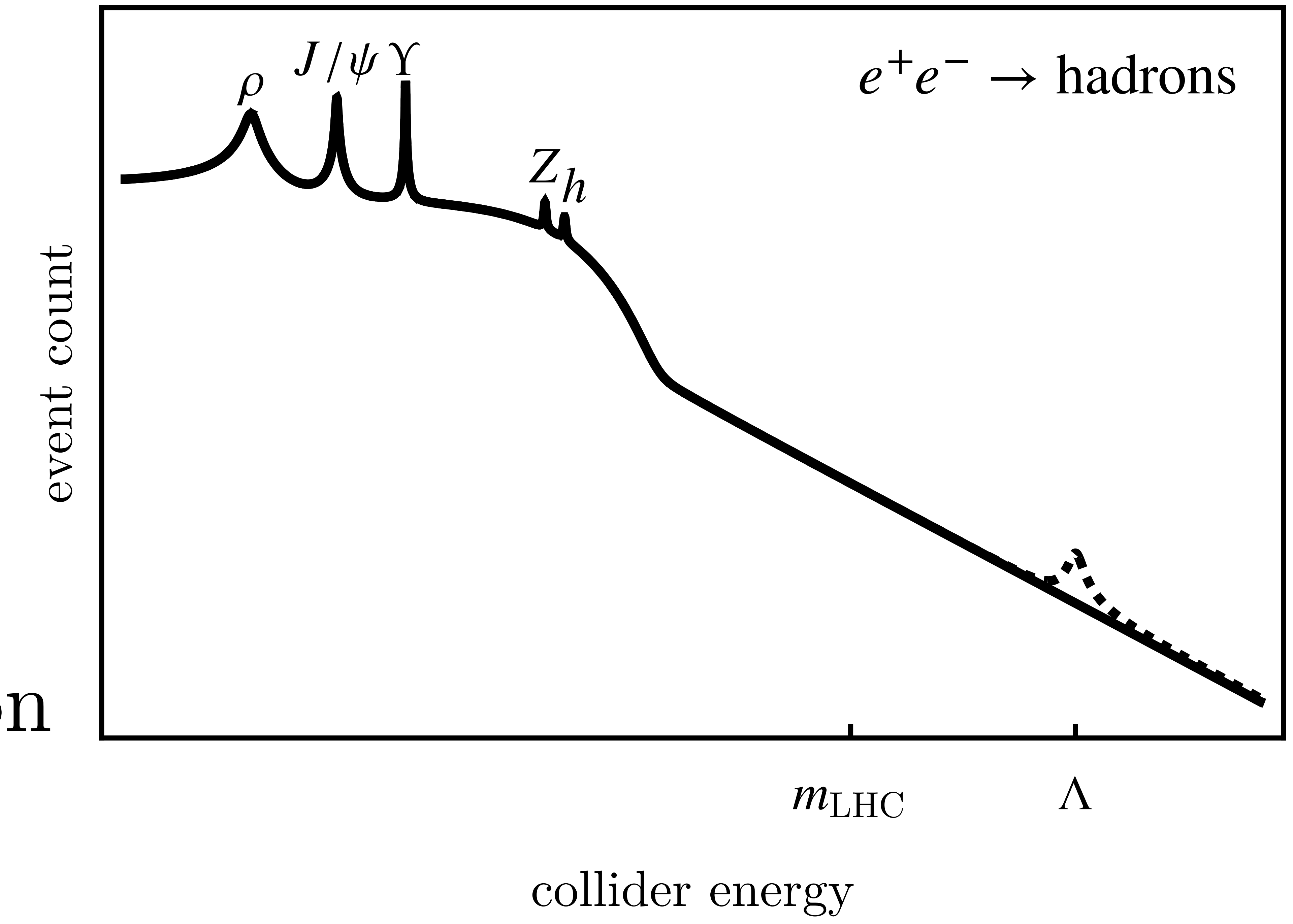
Position at the time

No clear new signals

⇒ new physics must be heavy, $\Lambda > m_{\mathrm{LHC}}$, or weakly coupled, hiding subtly within precise measurements

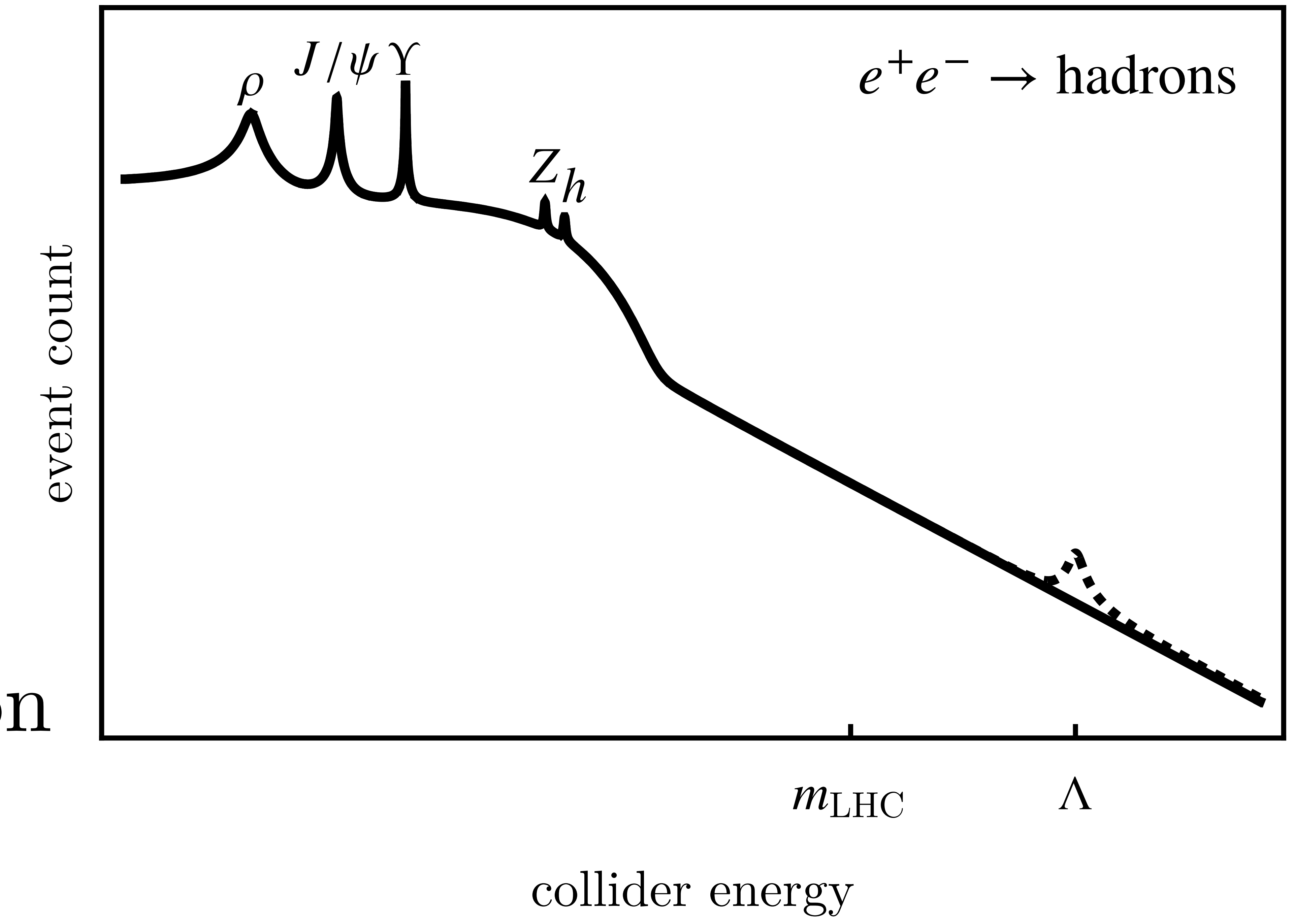
⇒ precision pheno is a powerful approach to indirectly probe new physics

⇒ need for bigger machines with utmost precision



Position at the time

No clear new signals
$\Rightarrow$ new physics must be heavy, $\Lambda > m_{\text{LHC}}$, or weakly coupled, hiding subtly within precise measurements
$\Rightarrow$ precision pheno is a powerful approach to indirectly probe new physics
$\Rightarrow$ need for bigger machines with utmost precision



Precision in what?

Three key processes for precision physics

Three key processes for precision physics

Deep inelastic scattering (DIS)

Lepton-hadron collisions: clean QED probe of nucleon structure

Kinematics reconstructable from scattered lepton

Access to PDFs, spin structure, and EW couplings

Historically: HERA ($e^{-}p$, 1991-2007)

Future: EIC, LHeC, FCC-eh

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Drell-Yan (DY)

Hadron-hadron collisions producing lepton pairs via virtual γ/Z

Simple final state with high precision in dilepton invariant mass

Clean probe of EW interactions at very high energies

Backbone of precision measurements at LHC and HL-LHC

Sensitive to small deviations in kinematic distributions

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We consider DY+jet (DYj)!

$$pp \to j\gamma/Z* \to je^-e^+$$

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e^+e^- annihilation

Point-like initial state with tunable energy and beam polarization

No hadronic initial-state uncertainties

Precision measurements of Z, W, Higgs, and top properties

Legacy: LEP, SLD

Future: FCC-ee

Ideal environment for ultra-clean EW physics

Electron-Ion Collider

- At Brookhaven National Lab (BNL), NY
- First ever dedicated e^-A collider in the USA
- Collides polarized e^- with protons and light/heavy ions: ^{1}H, ^{2}H, ^{3}He, ^{4}He, ^{197}Au, ^{238}U
- Both beams polarized:
  - Electrons: 85% at the source, 70% in the ring
  - Ions: up to 70% for light nuclei
- Approved by DOE in 2020
- Construction starting at the end of 2025
- First collisions expected in early 2030s

Electron-Ion Collider

- Electron beam: up to 18 GeV
- Proton beam: up to 275 GeV, heavier ions $\leq$ 137 GeV
- $\sqrt{s}$ = 20 to 140 GeV
- Luminosity: 100 fb^{-1}/yr (~1000× HERA)
- Reuses RHIC tunnel (3.9 km); new electron ring added
- Physics goals:
  - $3D$ imaging of nucleon structure
  - Gluon saturation, small-x dynamics
  - Precision electroweak observables in polarized DIS
  - Strong constraints on PDFs ⇒ improves precision at all colliders

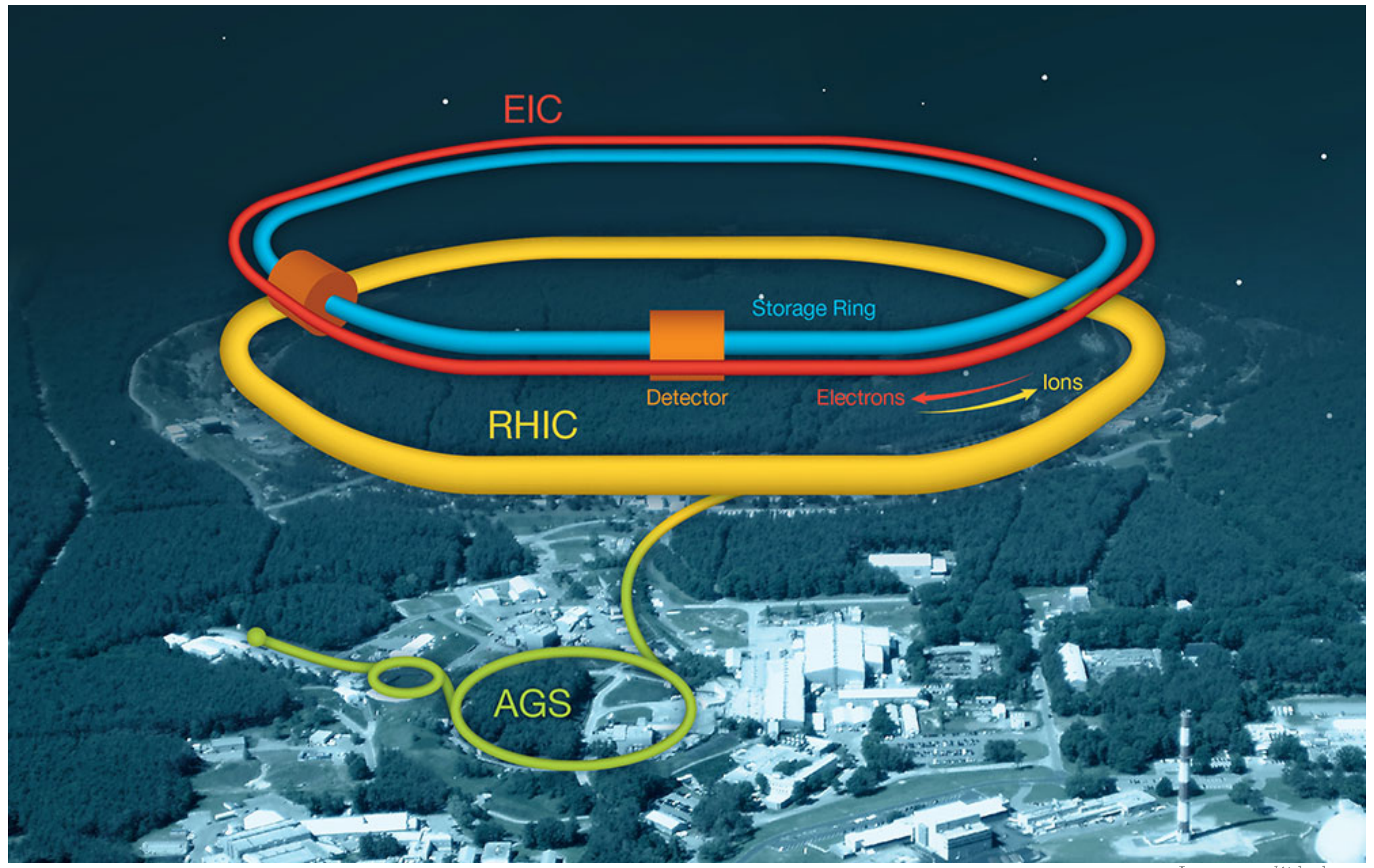


Image credit bnl.gov

Large Hadron-electron Collider

- Proposed upgrade to LHC
- Adds a 60-GeV e^- beam in a new energy recovery linac
- Uses existing LHC 7-TeV proton beam
- First discussed in 1984 (LEP-LHC); LHeC study launched in 2007
- Conceptual design completed in 2011
- Awaiting approval; timeline tied to LHC Long Shutdown 3
- If approved, installation during 2026-2027
- Potential operation along side HL-LHC (Run 4) around 2027-2030

Large Hadron-electron Collider

- Electron beam: 60 GeV
- Proton beam: 7 TeV
- $\sqrt{s} = 1.3$ TeV
- Luminosity: 10 $\mathbf{fb}^{-1}$/yr
- Polarization: Electron beam only, 80%
- Physics goals:
  - Extend PDFs to high x and high Q
  - Precision Higgs, W, and top studies in clean environment
  - Explore electroweak structure at high energies via DIS
  - Strong complement to LHC measurements, especially for BSM effects in leptonic channels

Future Circular Collider

- CERN-led long-term project for post-LHC colliders
- 91 km tunnel near Geneva; staged operation plan
- Feasibility report published May 2025
- Approval decision expected around 2027-2028
- FCC-ee: starts around 2045, runs for 15 years
- FCC-hh: follows in 2070s, 100 TeV pp collider
- FCC-eh: operates concurrently with FCC-ee
- Shared infrastructure between e^+e^-, pp, and e^-p modes

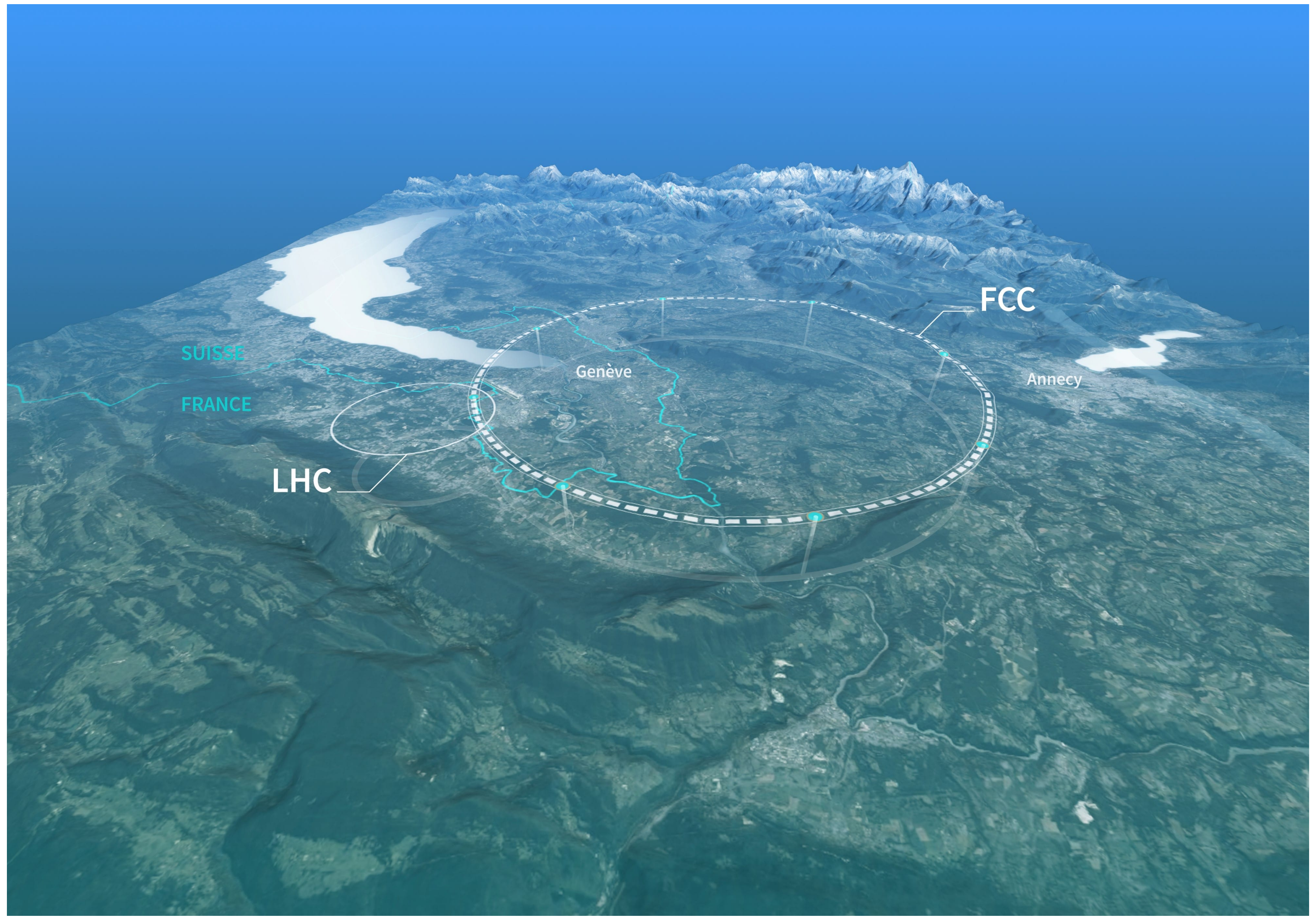


Image credit cern.ch

Future Circular Collider

FCC-ee (lepton mode):

- e^+e^- collisions at Z pole (91 GeV), WW threshold (160 GeV), Higgsstrahlung peak (240 GeV), $t\bar{t}$ threshold (365 GeV)
- Luminosity: 10 ab^{-1}/stage
- Transverse beam polarization at low energies; longitudinal optional ($\geq$ 40%)
- Goals: ultra-precise Z, W, Higgs, and top studies

FCC-eh (lepton-proton mode):

- 60 GeV $\times$ 50 TeV e^-p collisions, $\sqrt{s} = 3.5$ TeV
- Luminosity: 100 fb^{-1}/yr
- Electron beam polarized (80%); proton beam unpolarized
- Goals: PDFs at extreme x and Q, electroweak couplings

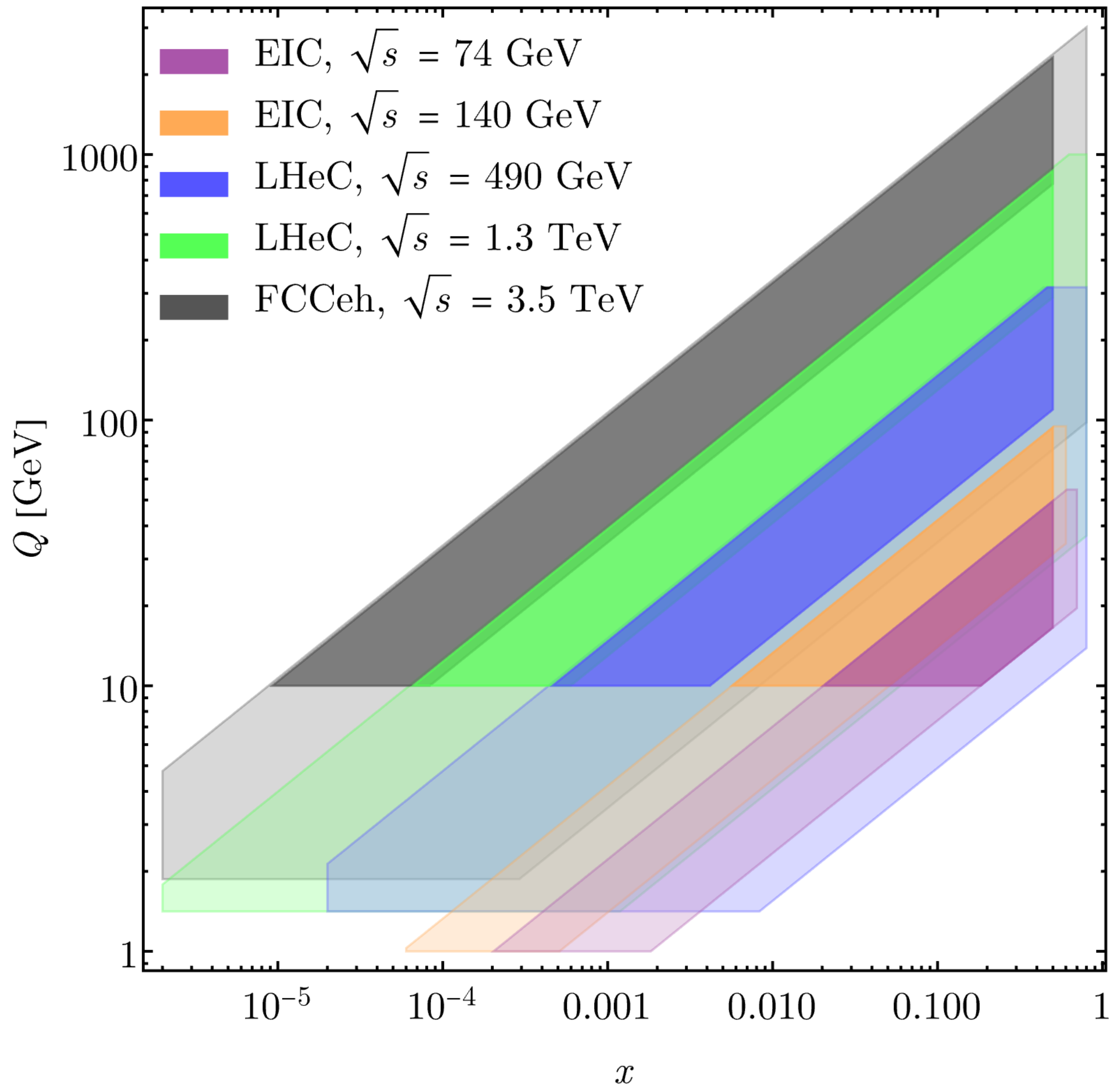
High-Luminosity LHC

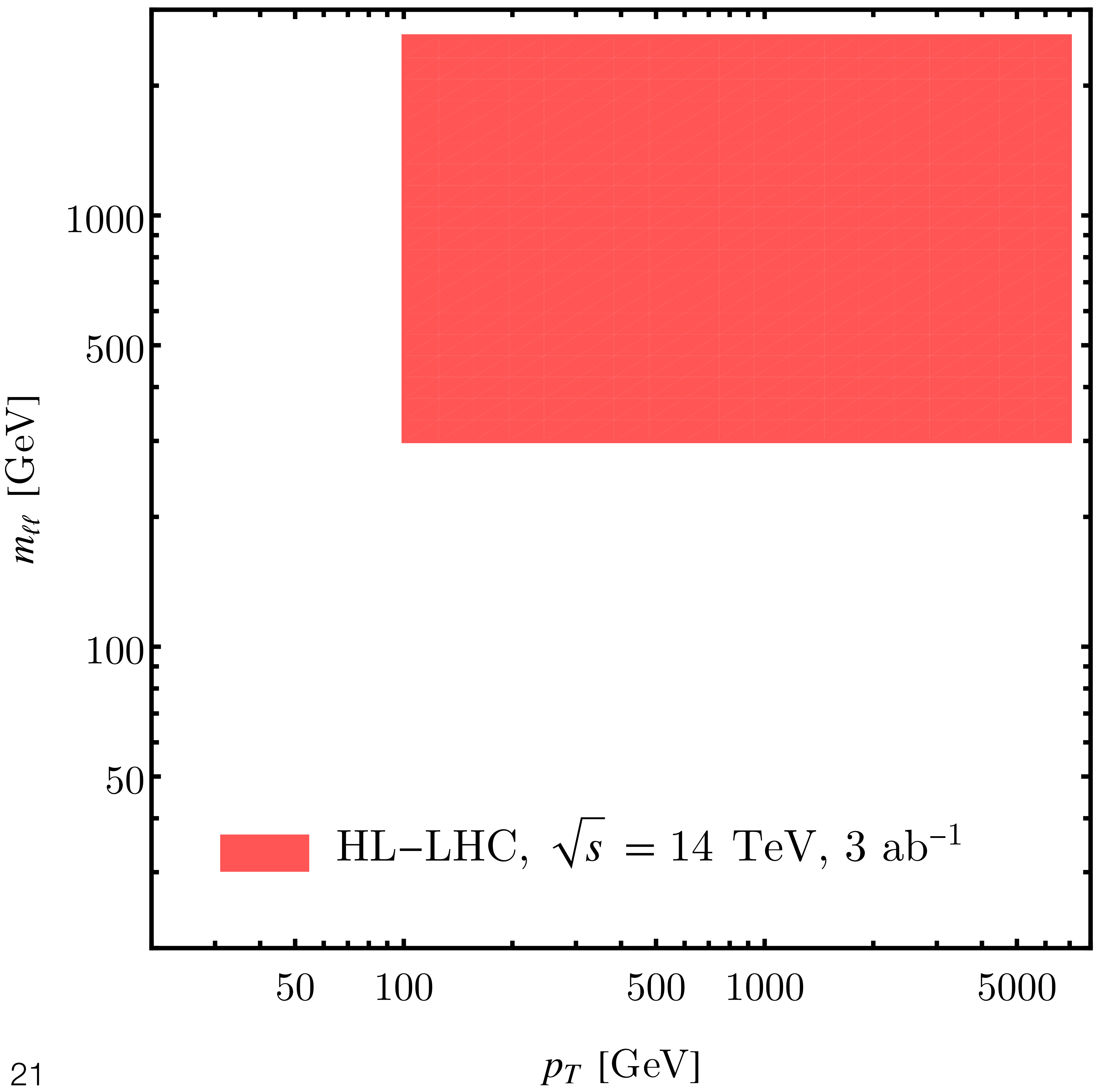
- Next-phase pp program at CERN
- Builds on current LHC, extending to around 2039
- Designed for 10× integrated luminosity: 3 ab^{-1} at 14 TeV
- Detector upgrades, improved pileup mitigation
- Focus on rare SM processes, precision, and discovery
- Major input for global fits and new physics searches

High-Luminosity LHC

- $\sqrt{s} = 14$ TeV
- Luminosity: 3 $\mathbf{ab}^{-1}$ (total)
- Unpolarized pp beams
- Physics goals:
  - Precision measurements in high-mass Drell-Yan ($m_{\ell\ell} \gg m_Z$)
  - Constraints on vector boson scattering, contact interactions
  - High-statistics studies of Higgs, top, Z/W
  - Direct searches and indirect probes via tail distributions

Kinematic coverage





Toolbox

Standard Model Effective Field Theory

Model-independent extension of the SM Lagrangian with higher-dimensional operators $O_k^{(n)}$ built up of SM fields at an energy scale Λ heavier than all SM fields and beyond accessible collider energy, introducing Wilson coefficients $C_k^{(n)}$ as effective couplings:

$$\mathscr{L} = \mathscr{L}_{\mathrm{SM}} + \sum_{n>4} \frac{1}{\Lambda^{n-4}} \sum_k C_k^{(n)} O_k^{(n)}$$

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Focus on $n = 6$ for DIS ➡ Operators with two leptons, two quarks

➡ First leading contribution at dimension 6

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Focus on $n = 6$ for DIS and $n = 8$ for DYj ➡ Operators with two leptons, two quarks, one gluon

➡ We want $p_T(\ell\ell) = p_T(V) = p_T(g)$ bins

➡ gluon field strength ∴ dimension 8

Standard Model Effective Field Theory

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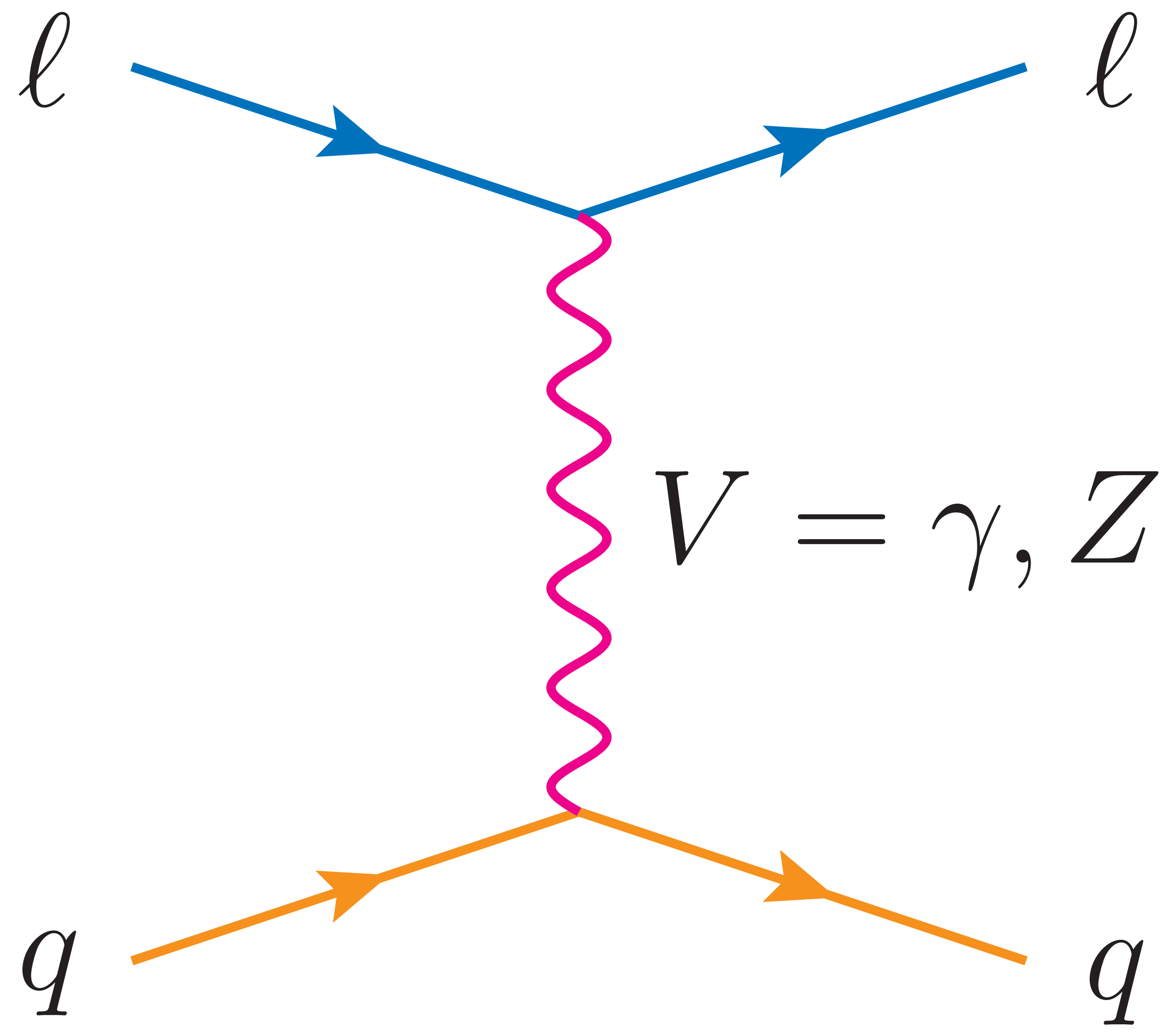
Focus on $n = 6$ for DIS and $n = 8$ for DYj. Restrict to leading order SMEFT.

Standard Model Effective Field Theory

SMEFT contributions to DIS:



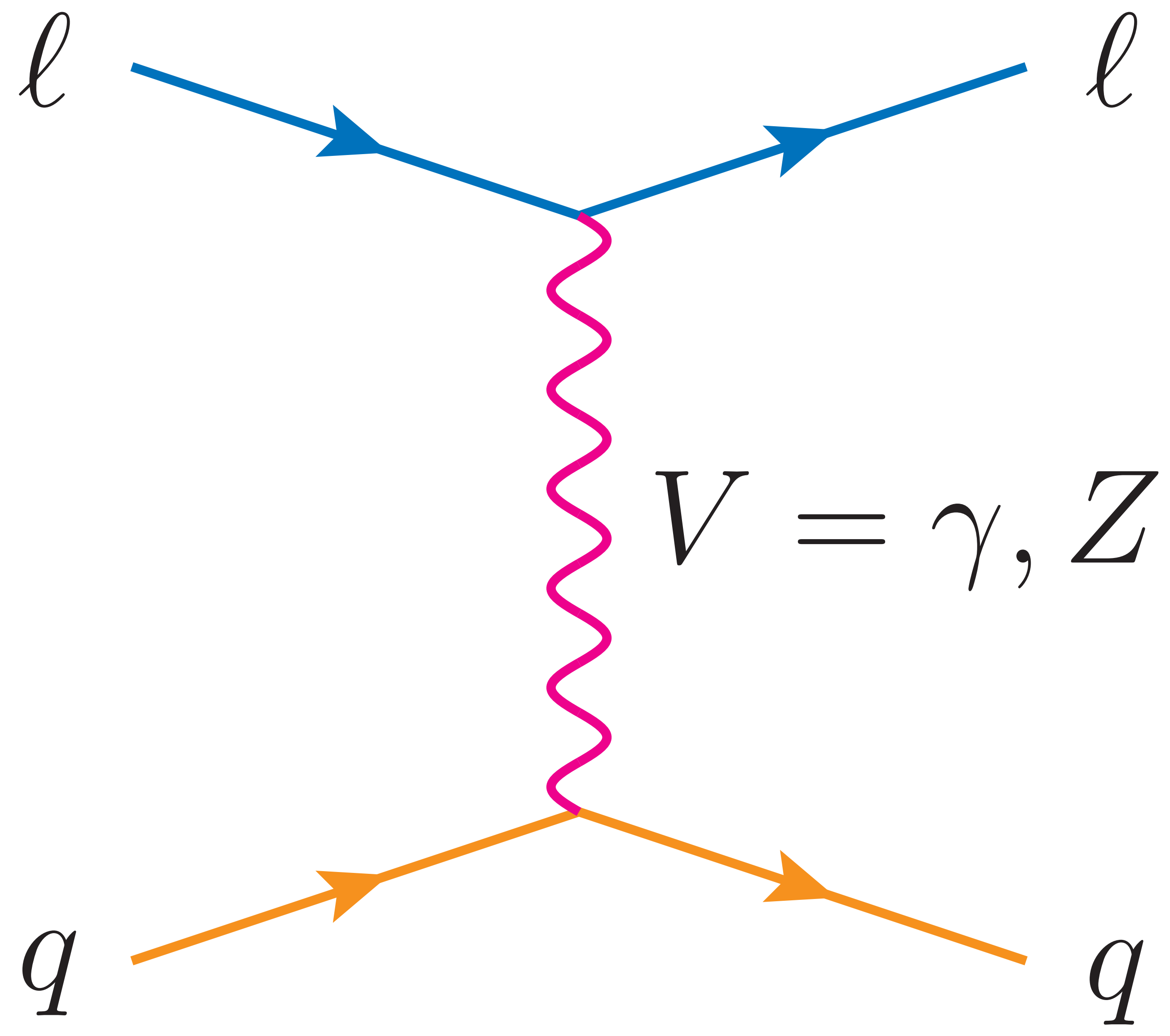
Semi-leptonic four-fermion operators:

$$O_{XY} = [\bar{\ell}\gamma^{\mu}P_X\ell][\bar{q}\gamma_{\mu}P_Y q]$$

For nontrivial SM-SMEFT interference, we need helicity-preserving currents.

Standard Model Effective Field Theory

SMEFT contributions to DIS:



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For nontrivial SM-SMEFT interference, we need helicity-preserving currents.

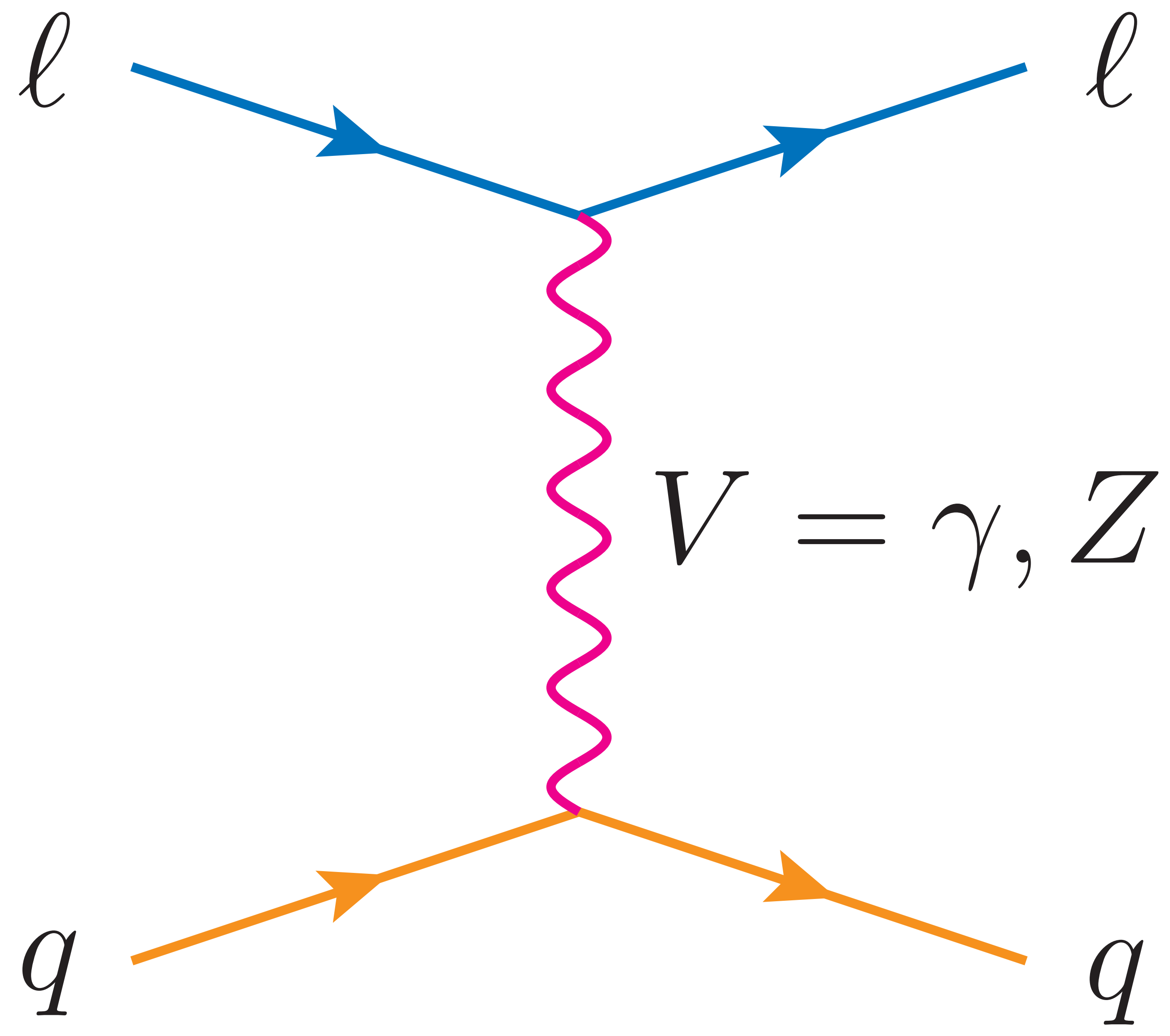
Corrections to ffV vertices:

$$V^{\mu} = V^{\mu}_{\mathrm{SM}}\left(1 + \sum_k C_k V_k\right)$$

SM vertices are shifted in a gauge-invariant manner.

Standard Model Effective Field Theory

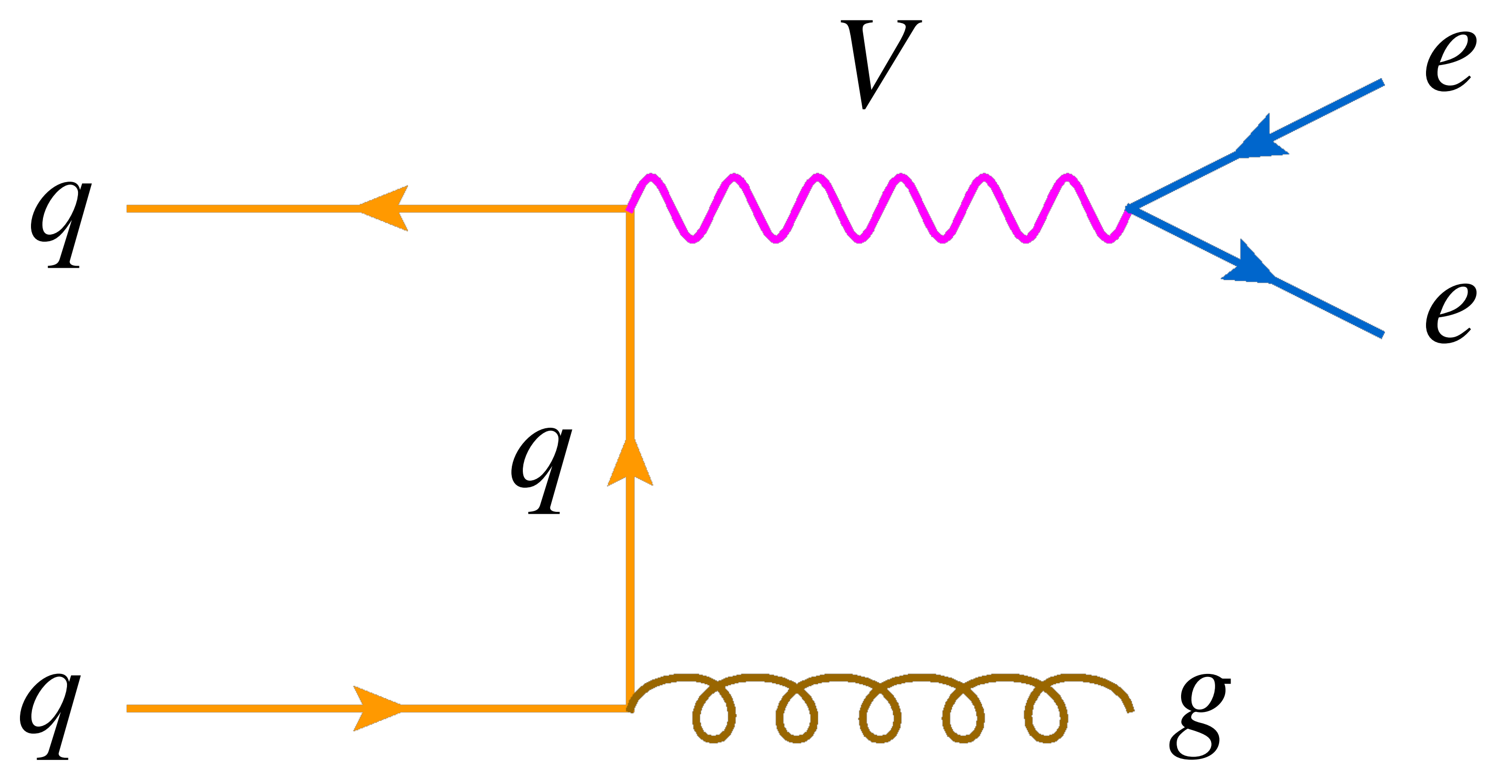
SMEFT contributions to DIS:

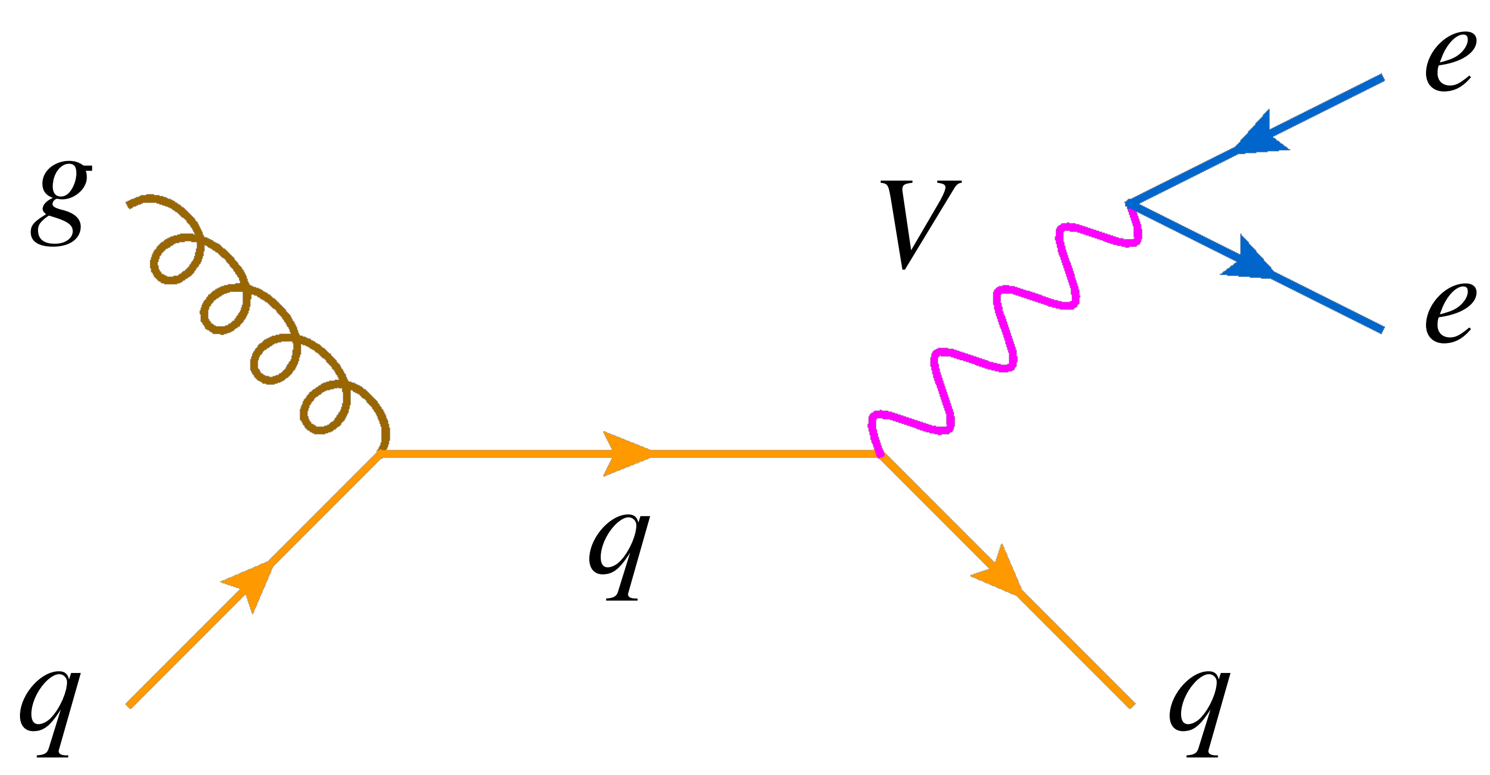


ffV	semi-leptonic four-fermion
$O_{\varphi WB} = (\varphi^\dagger \tau^I \varphi) W^I_{\mu\nu} B^{\mu\nu}$	$O^{(1)}_{\ell q} = (\bar\ell \gamma^\mu \ell)(\bar q \gamma_\mu q)$
$O_{\varphi D} = (\varphi^\dagger D^\mu \varphi)^* (\varphi^\dagger D_\mu \varphi)$	$O^{(1)}_{\ell q} = (\bar\ell \gamma^\mu \tau^I \ell)(\bar q \gamma_\mu \tau^i q)$
$O^{(1)}_{\varphi\ell} = (\varphi^\dagger i \overleftrightarrow{D}^\mu \varphi)(\bar\ell \gamma_\mu \ell)$	$O_{eu} = (\bar e \gamma^\mu e)(\bar u \gamma_\mu u)$
$O^{(3)}_{\varphi\ell} = (\varphi^\dagger i \overleftrightarrow{D}^\mu \tau^I \varphi)(\bar\ell \gamma_\mu \tau^I \ell)$	$O_{ed} = (\bar e \gamma^\mu e)(\bar d \gamma_\mu d)$
$O_{\varphi e} = (\varphi^\dagger i \overleftrightarrow{D}^\mu \varphi)(\bar e \gamma_\mu e)$	$O_{\ell u} = (\bar\ell \gamma^\mu \ell)(\bar u \gamma_\mu u)$
$O^{(1)}_{\varphi q} = (\varphi^\dagger i \overleftrightarrow{D}^\mu \varphi)(\bar q \gamma_\mu q)$	$O_{\ell d} = (\bar\ell \gamma^\mu \ell)(\bar d \gamma_\mu d)$
$O^{(3)}_{\varphi q} = (\varphi^\dagger i \overleftrightarrow{D}^\mu \tau^I \varphi)(\bar q \gamma_\mu \tau^I q)$	$O_{qe} = (\bar e \gamma^\mu e)(\bar q \gamma_\mu q)$
$O_{\varphi u} = (\varphi^\dagger i \overleftrightarrow{D}^\mu \varphi)(\bar u \gamma_\mu u)$	
$O_{\varphi d} = (\varphi^\dagger i \overleftrightarrow{D}^\mu \varphi)(\bar d \gamma_\mu d)$	
$O_{\ell\ell} = (\bar\ell \gamma^\mu \ell)(\bar\ell \gamma_\mu \ell)$	

Standard Model Effective Field Theory

SMEFT contributions to DYj:





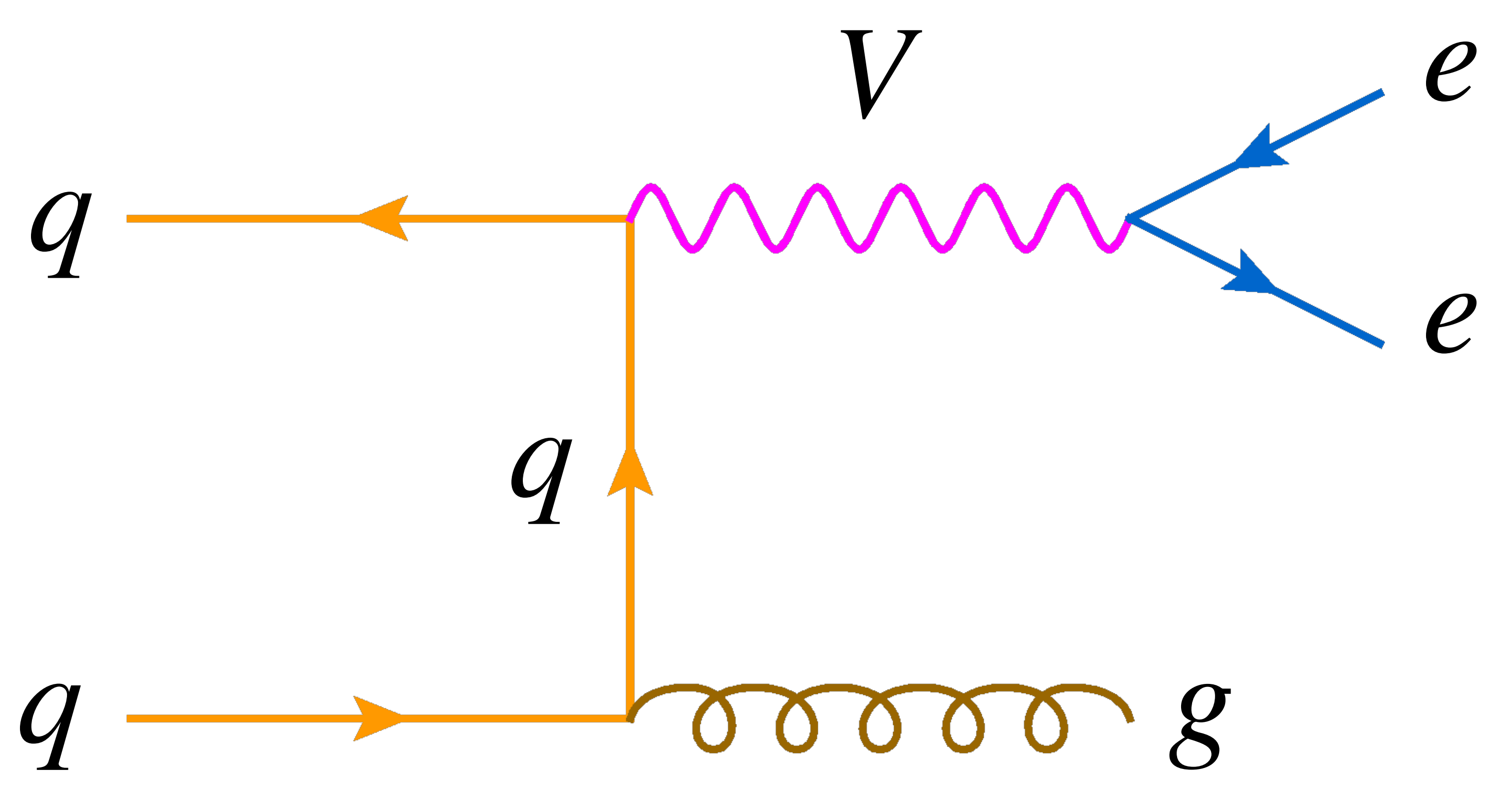
Semi-leptonic four-fermion operators coupled to gluon field strength tensor:

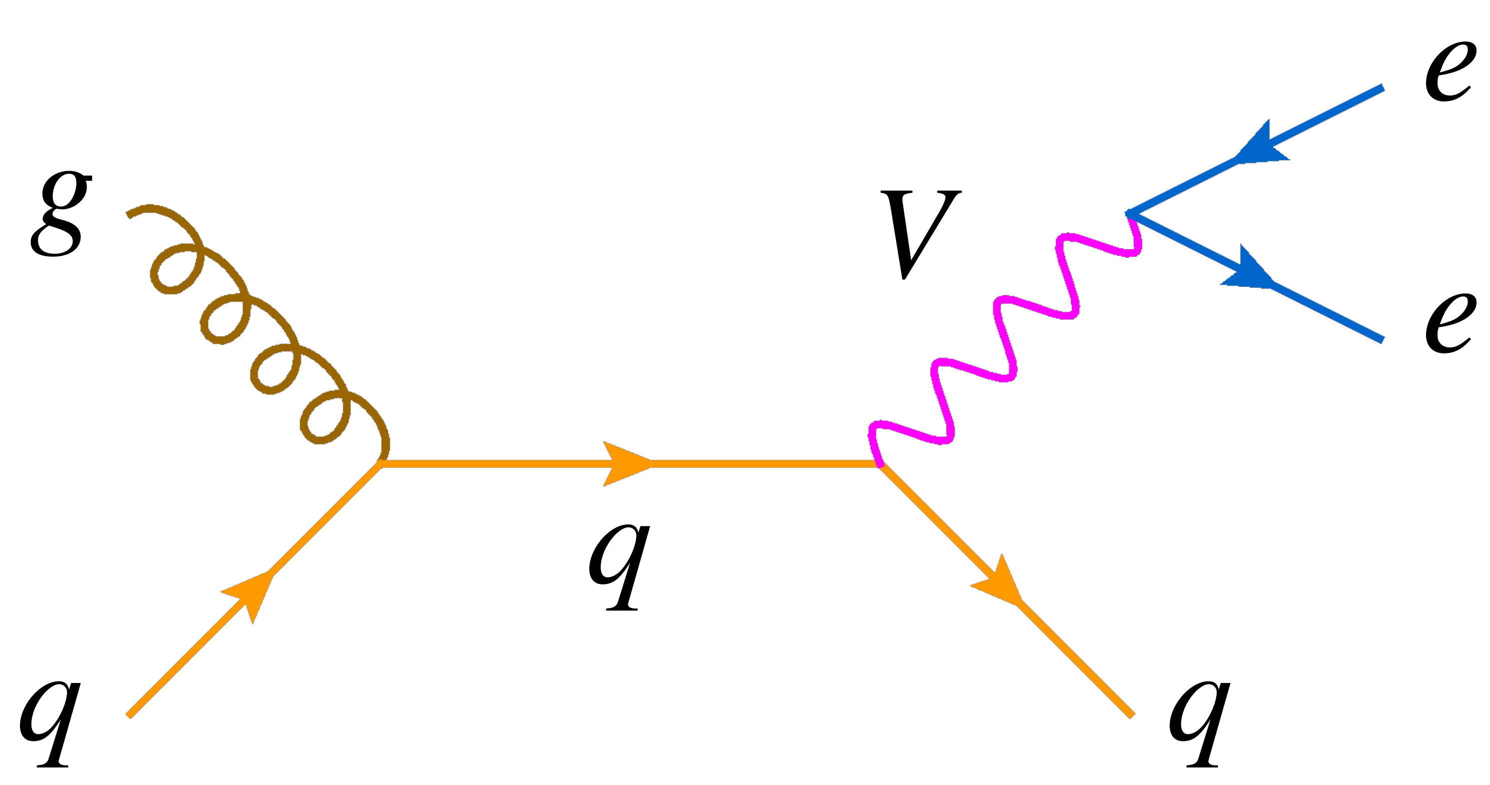
$$O_{XYg} = [\bar{\ell}\gamma^{\mu}P_X\ell][\bar{q}\gamma^{\nu}P_Y T^A q]G^A_{\mu\nu}$$

$$\tilde{O}_{XYg} = [\bar{\ell}\gamma^{\mu}P_X\ell][\bar{q}\gamma^{\nu}P_Y T^A q]\tilde{G}^A_{\mu\nu}$$

Standard Model Effective Field Theory

SMEFT contributions to DYj:





CP-even		CP-odd	
$\widetilde{O}^{(1)}_{\ell^2 q^2 g}$	$(\bar{\ell}\gamma^\mu \ell)(\bar{q}\gamma^\nu T^a q)\widetilde{G}^a_{\mu\nu}$	$O^{(1)}_{\ell^2 q^2 g}$	$(\bar{\ell}\gamma^\mu \ell)(\bar{q}\gamma^\nu T^a q)G^a_{\mu\nu}$
$\widetilde{O}^{(3)}_{\ell^2 q^2 g}$	$(\bar{\ell}\tau^i\gamma^\mu \ell)(\bar{q}\tau^i\gamma^\nu T^a q)\widetilde{G}^a_{\mu\nu}$	$O^{(3)}_{\ell^2 q^2 g}$	$(\bar{\ell}\tau^i\gamma^\mu \ell)(\bar{q}\tau^i\gamma^\nu T^a q)G^a_{\mu\nu}$
$\widetilde{O}_{e^2 u^2 g}$	$(\bar{e}\gamma^\mu e)(\bar{u}\gamma^\nu T^a u)\widetilde{G}^a_{\mu\nu}$	$O_{e^2 u^2 g}$	$(\bar{e}\gamma^\mu e)(\bar{u}\gamma^\nu T^a u)G^a_{\mu\nu}$
$\widetilde{O}_{e^2 d^2 g}$	$(\bar{e}\gamma^\mu e)(\bar{d}\gamma^\nu T^a d)\widetilde{G}^a_{\mu\nu}$	$O_{e^2 d^2 g}$	$(\bar{e}\gamma^\mu e)(\bar{d}\gamma^\nu T^a d)G^a_{\mu\nu}$
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$\widetilde{O}_{q^2 e^2 g}$	$(\bar{e}\gamma^\mu e)(\bar{q}\gamma^\nu T^a q)\widetilde{G}^a_{\mu\nu}$	$O_{q^2 e^2 g}$	$(\bar{e}\gamma^\mu e)(\bar{q}\gamma^\nu T^a q)G^a_{\mu\nu}$

Standard Model Effective Field Theory

All SMEFT observables $\mathcal{O}$ are linearized in SMEFT parameters.

XSection:

$$\sigma = F \int |\mathcal{A}|^2 \, \mathrm{dLIPS} = \sigma_{\mathrm{SM}} + \sum_k C_k \sigma_k$$

Asymmetry:

$$A = \text{ratio of polarized to unpolarized xsection} = A_{\mathrm{SM}} + \sum_k C_k A_k$$

Statistical analysis

A standard χ^2 test function:

$$\chi^2 = \sum_{bb'} (\mathcal{O} - \mathcal{O}^{(p)})_b \mathcal{H}_{bb'} (\mathcal{O} - \mathcal{O}^{(p)})_{b'}$$

$\mathcal{O}$: SMEFT observable/model, $\mathcal{O}^{(p)}$: pseudodata, $\mathcal{H}$: inverse uncertainty matrix

$$\mathcal{O}_b^{(p)} = \mathcal{O}_b^{\mathrm{SM}} + r_b\, \delta\mathcal{O}_b^{\mathrm{uncorr}} + \sum_j r'_j\, \delta\mathcal{O}_b^{\mathrm{corr}_j}, \quad r_b, r'_j \sim \mathcal{N}(0,1)$$

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Various experimental uncertainty components:

EIC: statistical; uncorrelated systematic; fully correlated beam polarization or luminosity

LHeC/FCC-eh: statistical; global efficiency; fully correlated systematic (lepton energy and polar angle; hadron energy; radiative corrections; photoproduction background; calorimetry noise; luminosity)

HL-LHC: statistical

Statistical analysis

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Best-fit values:

$$\nabla\chi^2(\hat{\mathbf{C}}) = 0$$

Fisher information matrix:

$$\mathcal{F} = \frac{1}{2} \nabla\nabla\chi^2(\hat{\mathbf{C}})$$

Works

Previously...

- Neutral-current parity-violating DIS asymmetries at EIC:

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  - Semi-leptonic four-fermion operators $O_{XY} = [\bar{\ell}\gamma^{\mu}P_X\ell][\bar{q}\gamma_{\mu}P_Y q]$

Previously...

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  - Simultaneous fits with beam polarization and luminosity difference parameters

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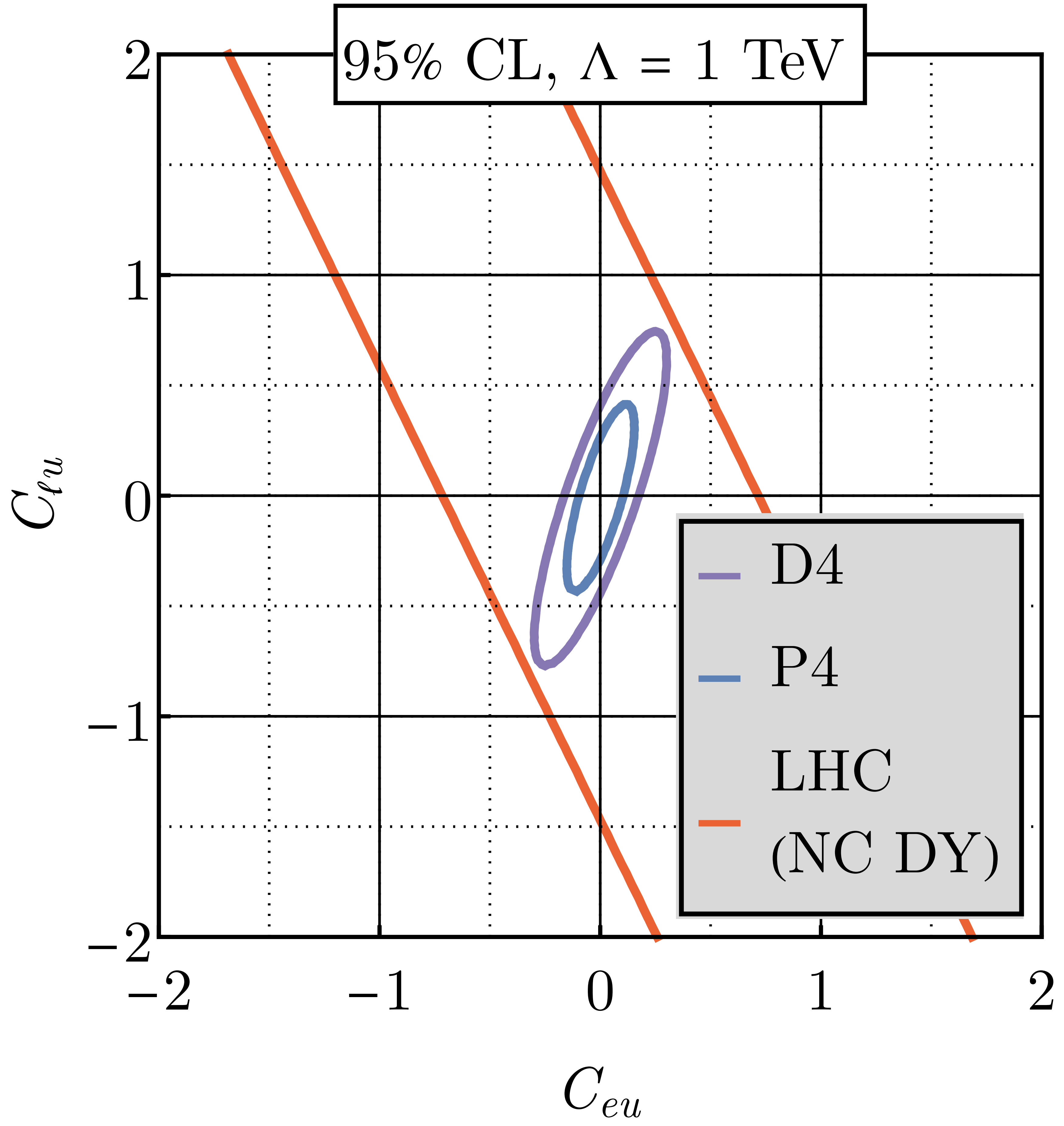
  - Simultaneous fits with beam polarization and luminosity difference parameters
  - Resolve flat directions in neutral-current DY at the LHC

Previously...

- Neutral-current parity-violating DIS asymmetries at EIC:



D4: 10 GeV $\times$ 137 GeV $e^- D$, 100 fb^{-1}

P4: 10 GeV $\times$ 275 GeV $e^- p$, 100 fb^{-1}

LHC: 8 TeV, 20 fb^{-1}, not 13 TeV and HL, adapted from Boughezal+[2104.03979]

Previously...

- Neutral-current parity-violating DIS asymmetries at EIC:
  - Semi-leptonic four-fermion operators $O_{XY} = [\bar{\ell}\gamma^{\mu}\ell][\bar{q}\gamma_{\mu}q]$
  - Simultaneous fits with beam polarization and luminosity difference parameters
  - Resolve flat directions in neutral-current DY at the LHC
  - Effective UV scales 1 to 4 TeV in single Wilson coefficient fits

Previously...

- Neutral-current parity-violating DIS asymmetries at EIC + polarized xsection at LHeC and FCC-eh with NLO QCD corrections:

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  - Operators modifying ffV vertices

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  - Operators modifying ffV vertices
  - Resolve flat directions in global EWPO fits

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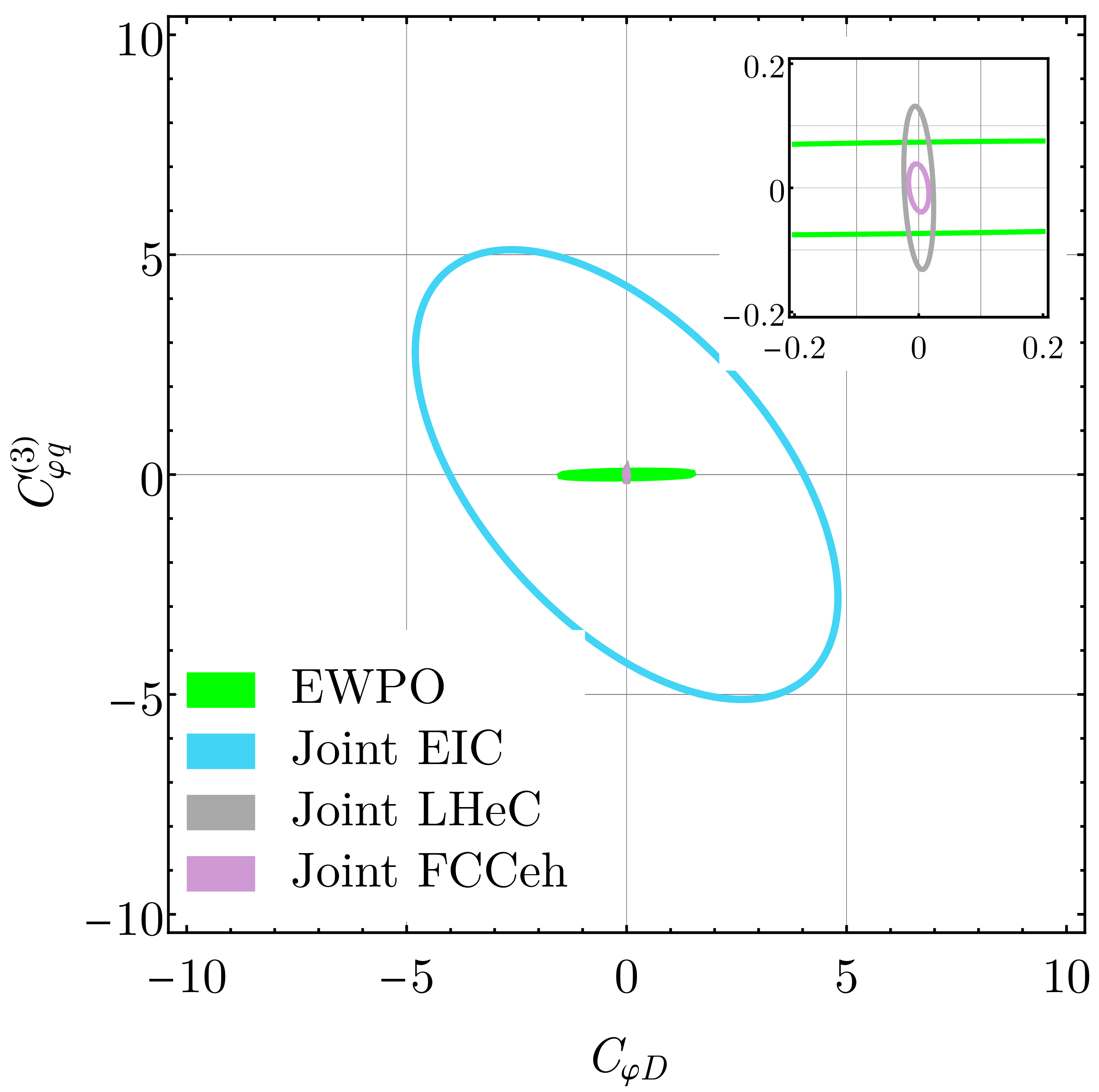
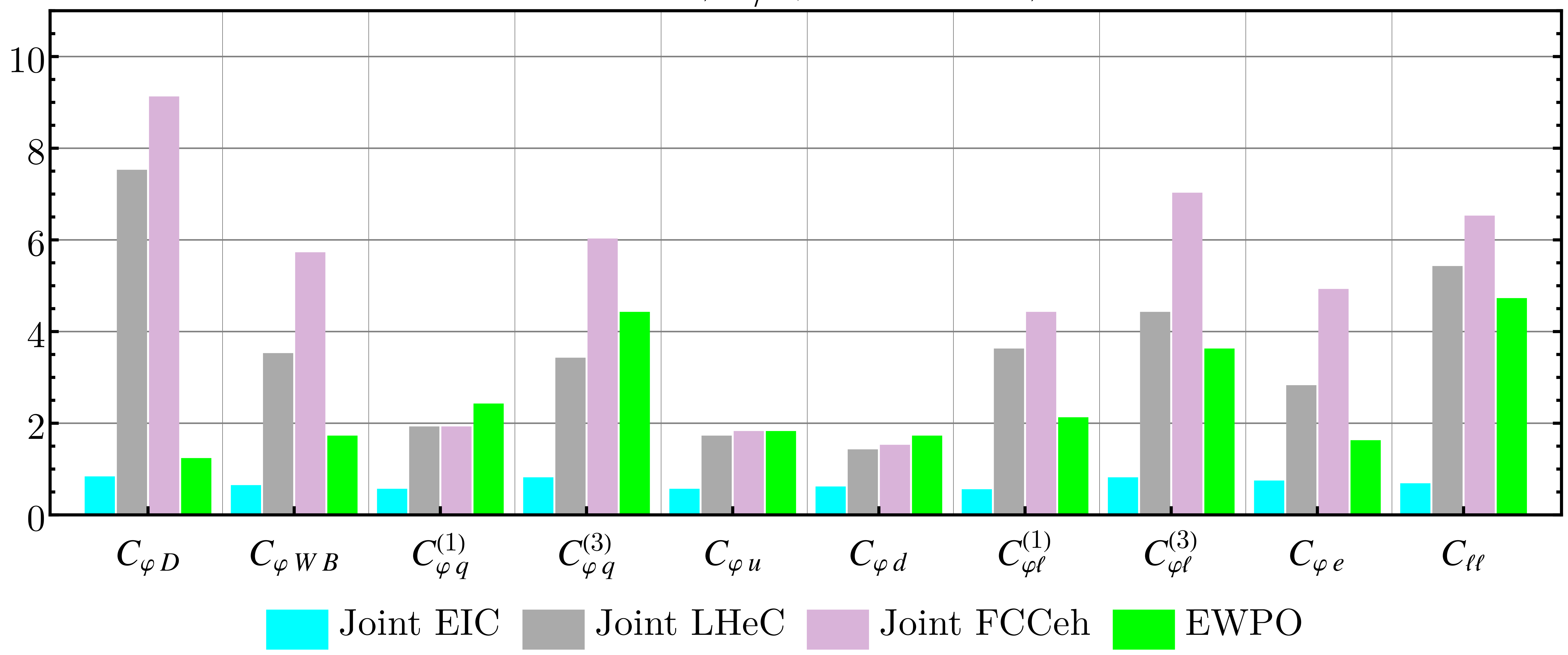




EWPO: 34d fit using Higgs, diboson, top data adapted from Ellis+[2012.02779]

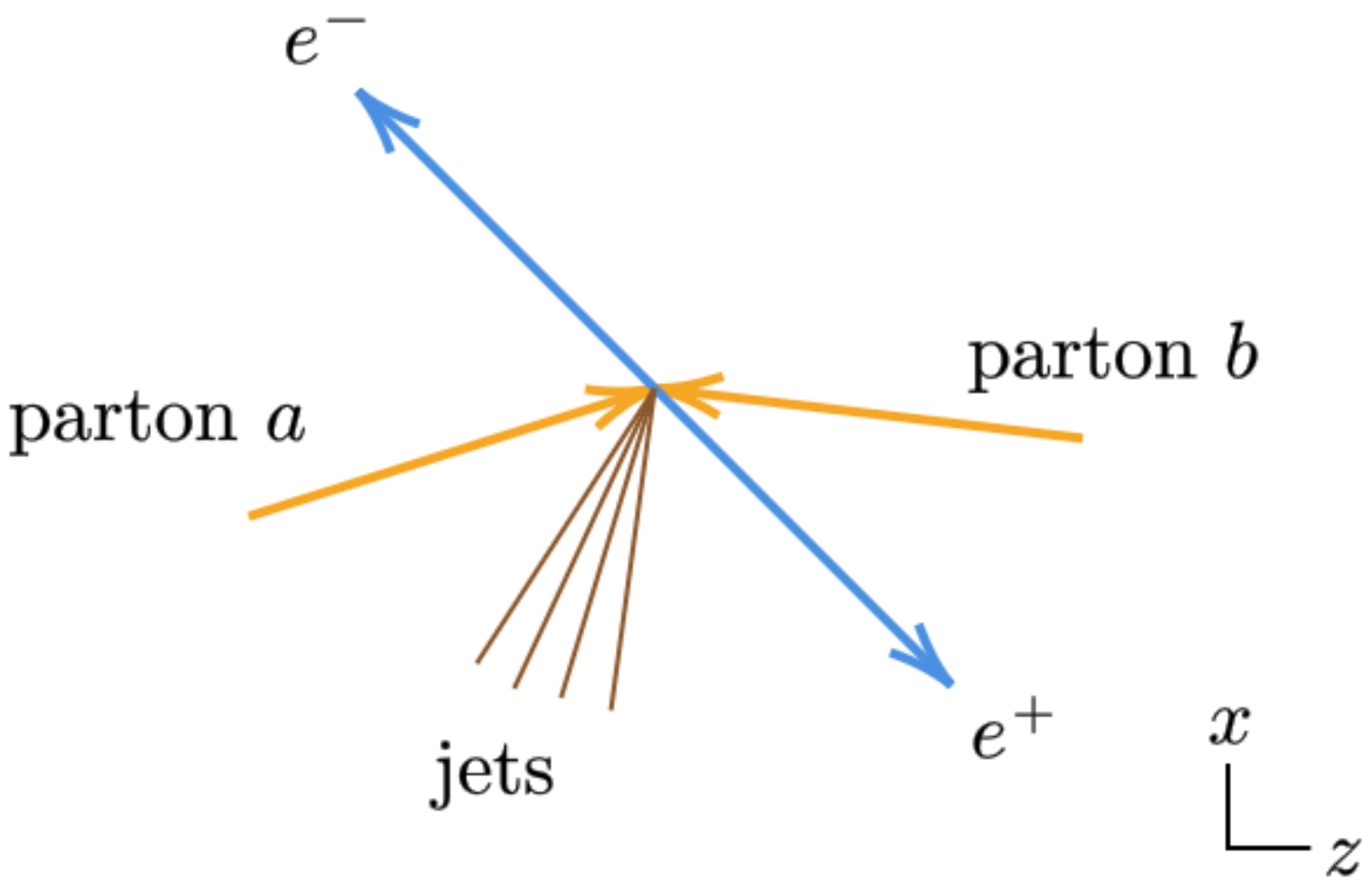
Probing CP-odd dimension-8 SMEFT with DYj at HL-LHC

Probing CP-odd dimension-8 SMEFT with DYj at HL-LHC

- Angular distribution of $pp \to je^- e^+$ encodes rich structure when written in Collins-Soper (CS) basis.
- The moments A_6 and A_7 are naive T-odd.
  - Vanish at tree level in SM
  - Activated at $O(\alpha_s^2)$, or with two or more jets at tree level
- SMEFT introduces operators that can generate CP-violating observables.
- No one has looked at this sector at HL-LHC; studies focus on inclusive DY.
- Goal: Use the clean null prediction for A_6 and A_7 in SM to probe new physics with high statistics.

Probing CP-odd dimension-8 SMEFT with DYj at HL-LHC

- Process of interest: $pp \to j\gamma/Z^* \to je^-e^+$
- Jet enables construction of CS frame



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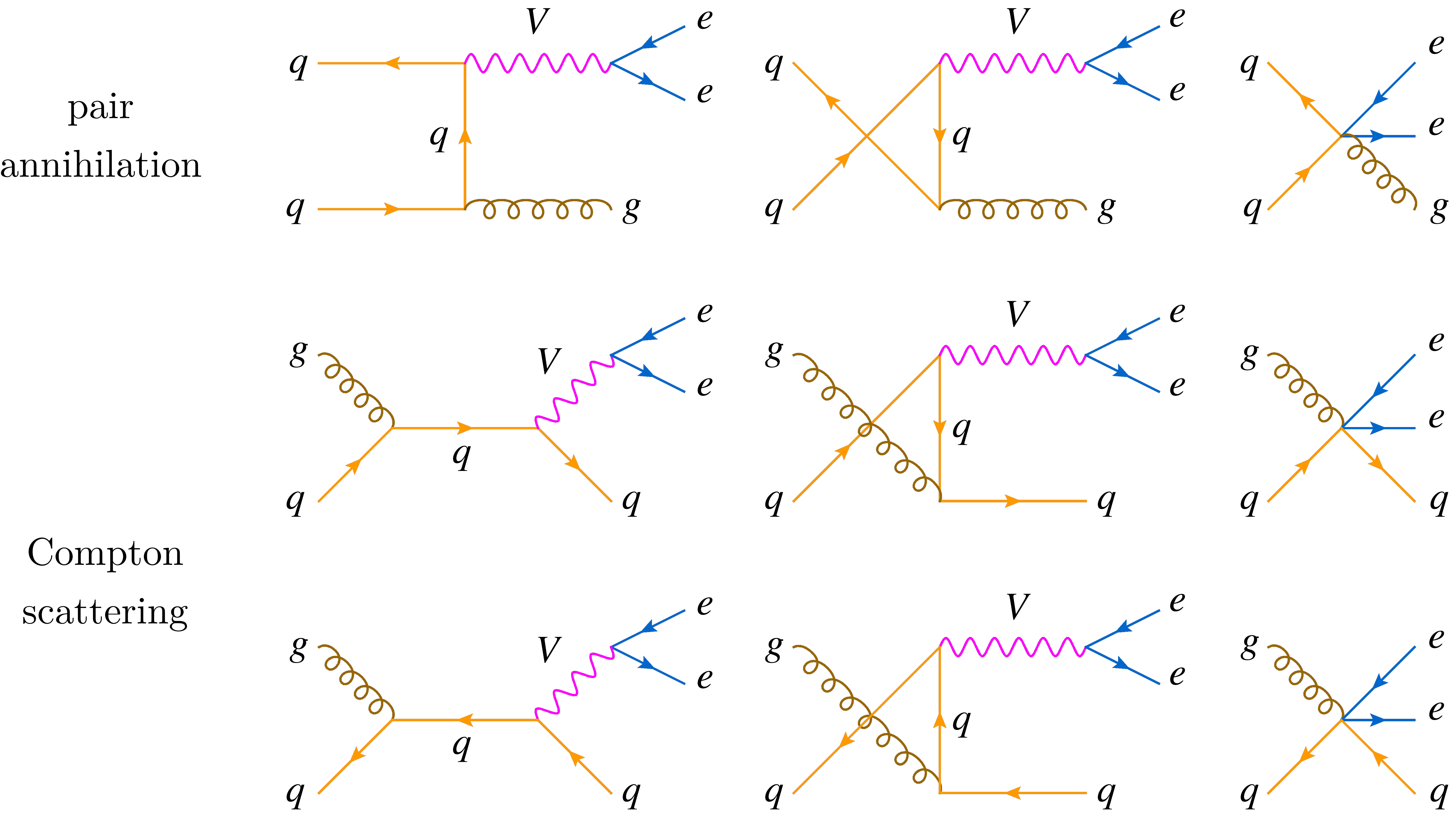

Semi-leptonic four-fermion operators coupled to gluon field strength tensor:

$$O_{XYg} = [\bar{\ell}\gamma^\mu P_X \ell][\bar{q}\gamma^\nu P_Y T^A q] G^A_{\mu\nu}$$

$$\tilde{O}_{XYg} = [\bar{\ell}\gamma^\mu P_X \ell][\bar{q}\gamma^\nu P_Y T^A q] \tilde{G}^A_{\mu\nu}$$

Probing CP-odd dimension-8 SMEFT with DYj at HL-LHC

XSection in terms of CS moments:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega^\star} = \frac{3\sigma}{16\pi}\left[1 + c_{\theta^\star}^2 + \sum_{m=0}^{7} A_m Y_m(\Omega^\star)\right]$$

Angular structures:

$$Y_0 = \frac{1}{2}(1 - 3c_{\theta^\star}^2),\ Y_1 = s_{2\theta^\star}c_{\varphi^\star},\ Y_2 = \frac{1}{2}s_{\theta^\star}^2 c_{2\varphi^\star},\ Y_3 = s_{\theta^\star}c_{\varphi^\star},\ Y_4 = c_{\theta^\star},$$

$$Y_5 = s_{\theta^\star}^2 s_{2\varphi^\star},\ Y_6 = s_{2\theta^\star}s_{\varphi^\star},\ Y_7 = s_{\theta^\star}s_{\varphi^\star}$$

CS moments:

$$A_0 = \frac{20}{3}\langle Y_0\rangle + \frac{2}{3},\ A_1 = 5\langle Y_1\rangle,\ A_2 = 20\langle Y_2\rangle,\ A_3 = 4\langle Y_3\rangle,\ A_4 = 4\langle Y_4\rangle,$$

$$A_5 = 5\langle Y_5\rangle,\ A_6 = 5\langle Y_6\rangle,\ A_7 = 4\langle Y_7\rangle$$

$Y_4 \propto Y_1^0$

$Y_7 \propto Y_1^1 + Y_1^{-1}$

$Y_3 \propto Y_1^1 - Y_1^{-1}$

$Y_0 \propto Y_2^0$

$Y_6 \propto Y_2^1 + Y_2^{-1}$

$Y_1 \propto Y_2^1 - Y_2^{-1}$

$Y_2 \propto Y_2^2 + Y_2^{-2}$

$Y_5 \propto Y_2^2 - Y_2^{-2}$

$$\langle Y_m\rangle = \frac{\int Y_m\,\mathrm{d}\sigma}{\sigma}$$

Probing CP-odd dimension-8 SMEFT with DYj at HL-LHC

$\{\tilde{O}_{XYg}\}$: studied with inclusive xsection (Boughezal+ [2207.01703]).

Focus on $\{O_{XYg}\}$.

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- A_5 doesn't require Γ_Z but shows strong cancellations due to kinematics

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Observables are linearized:

$$A = N\langle Y\rangle = N\frac{\int Y\,\mathrm{d}\sigma}{\sigma} = \frac{N_{\mathrm{SM}} + \sum_k C_k N_k}{D_{\mathrm{SM}} + \sum_k C_k D_k} = A_{\mathrm{SM}} + \sum_k C_k A_k$$

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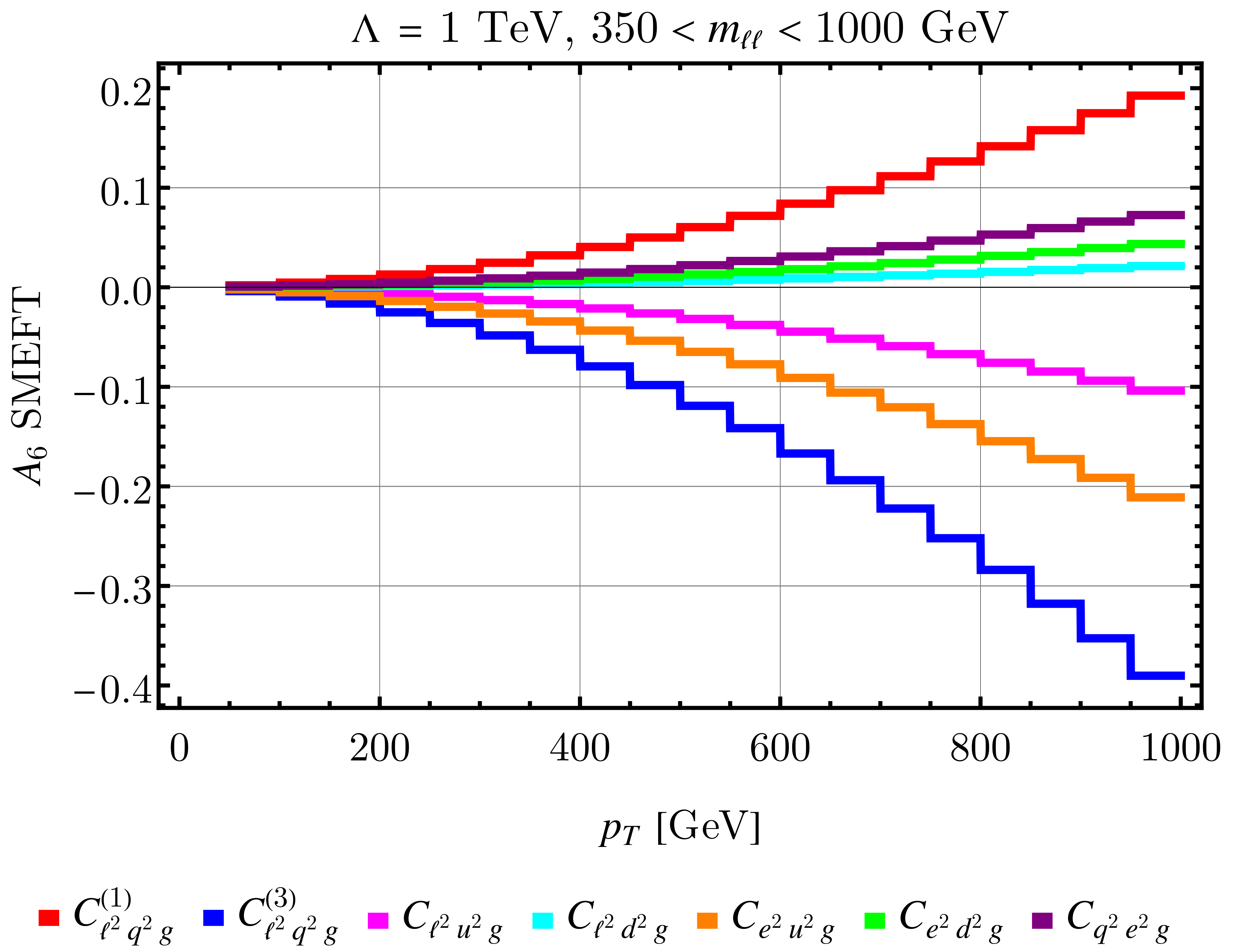
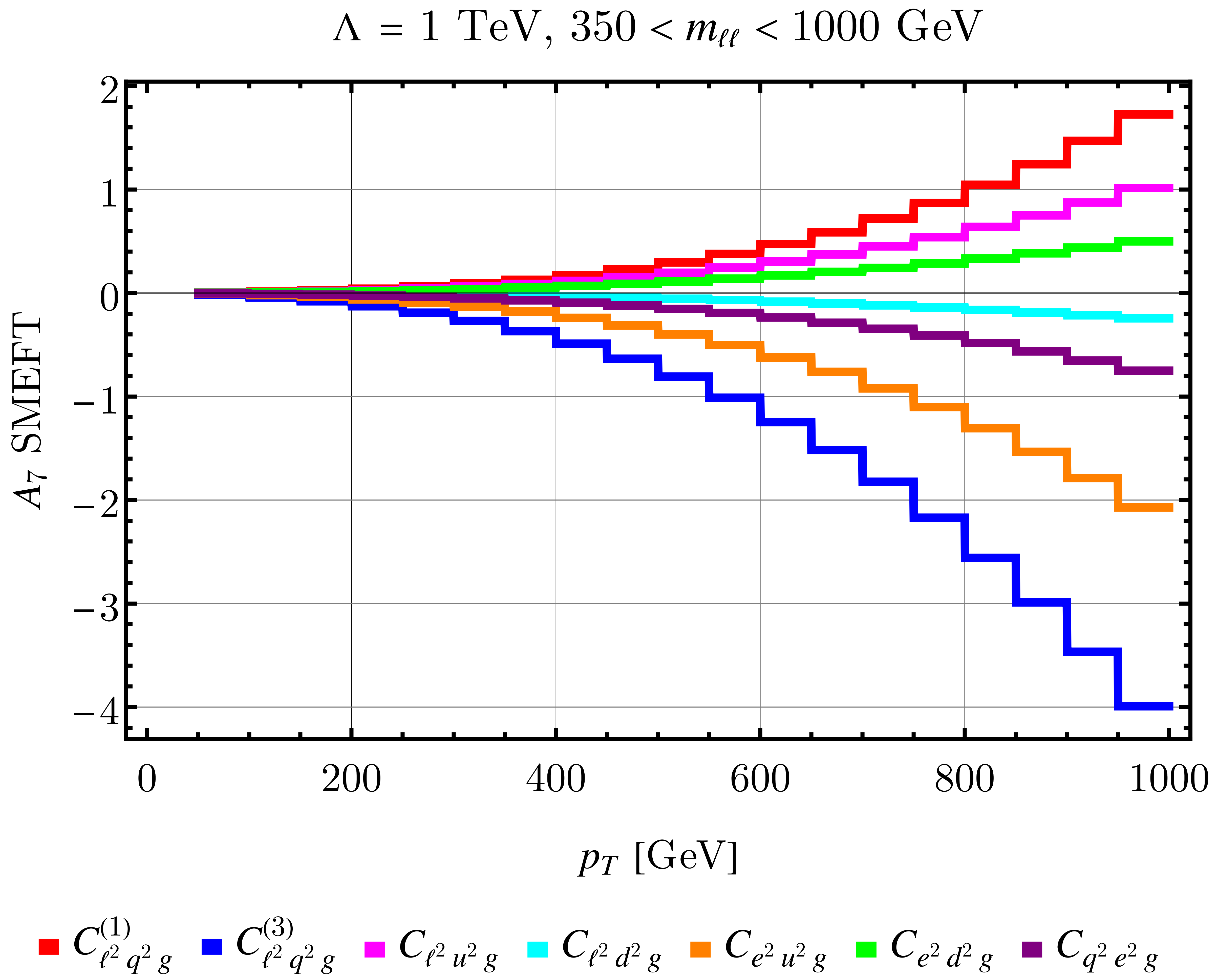
Probing CP-odd dimension-8 SMEFT with DYj at HL-LHC





Probing CP-odd dimension-8 SMEFT with DYj at HL-LHC

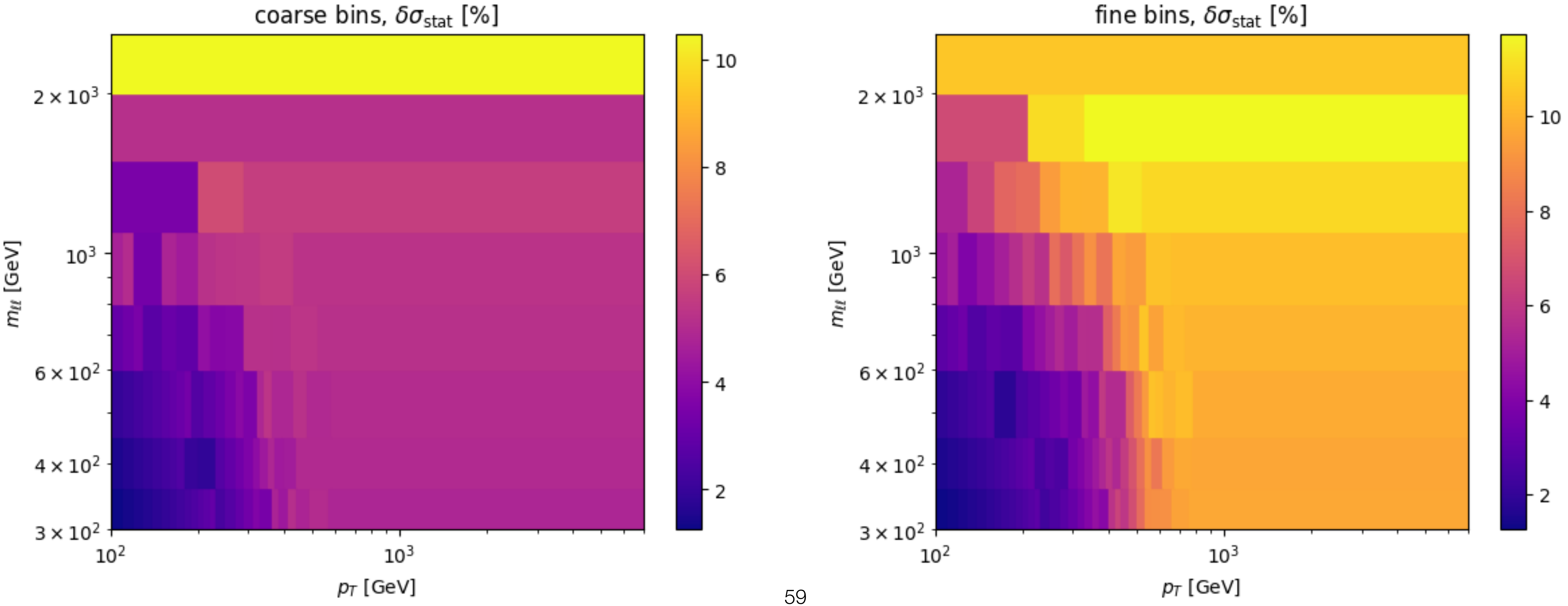
HL-LHC simulation: $\sqrt{s} = 14$ TeV, $L = 3$ ab^{-1}

Detector cuts:

- Leading electron: $p_T > 25$ GeV, subleading electron $p_T > 20$ GeV
- Both electrons: $|\eta| < 2.4$
- Jet: $p_T > 30$ GeV, $|y| > 2.4$
- Jet-electron separation: $\Delta R_{je} > 0.4$ for all jet-electron pairs
- Dilepton system: $p_T > 100$ GeV, $|y| < 2.4$

Probing CP-odd dimension-8 SMEFT with DYj at HL-LHC

Coarse and fine bins: $300 < m_{\ell\ell} < 2600$ GeV, $100 < p_T < 7000$ GeV



Probing CP-odd dimension-8 SMEFT with DYj at HL-LHC

Experimental uncertainties:

- Statistical uncertainties: $\delta A_m = \dfrac{N_m}{\sqrt{N}}\sqrt{\langle Y_m^2 \rangle}$, $N = \sigma L$, $\langle Y_m^2 \rangle = \dfrac{\int Y_m^2 \, \mathrm{d}\sigma}{\sigma}$, $m = 6{,}7$

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Probing *CP*-odd dimension-8 SMEFT with DYj at HL-LHC

Experimental uncertainties:

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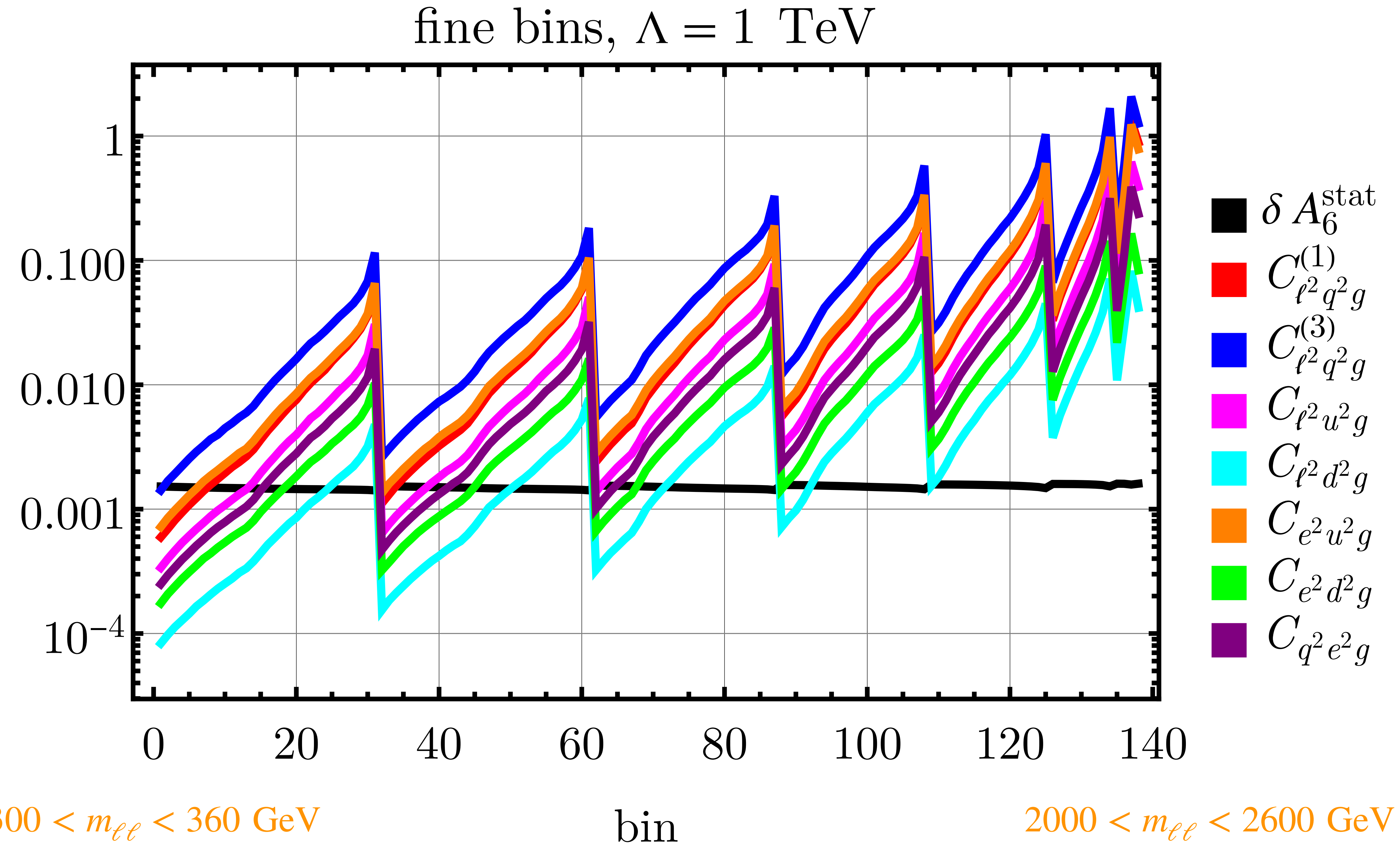
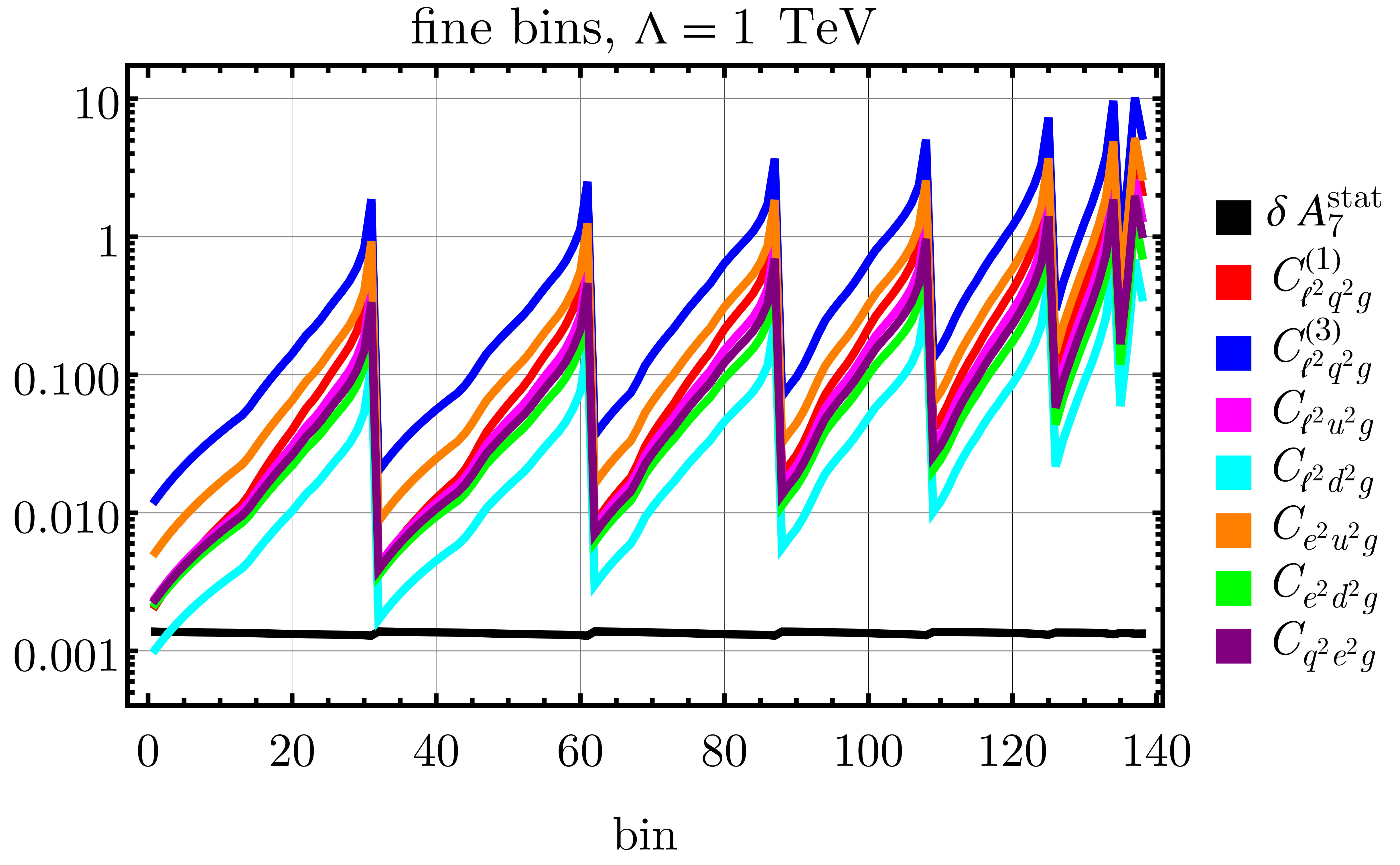
$\therefore$ We have only statistical uncertainties.

Probing CP-odd dimension-8 SMEFT with DYj at HL-LHC

Error budget:



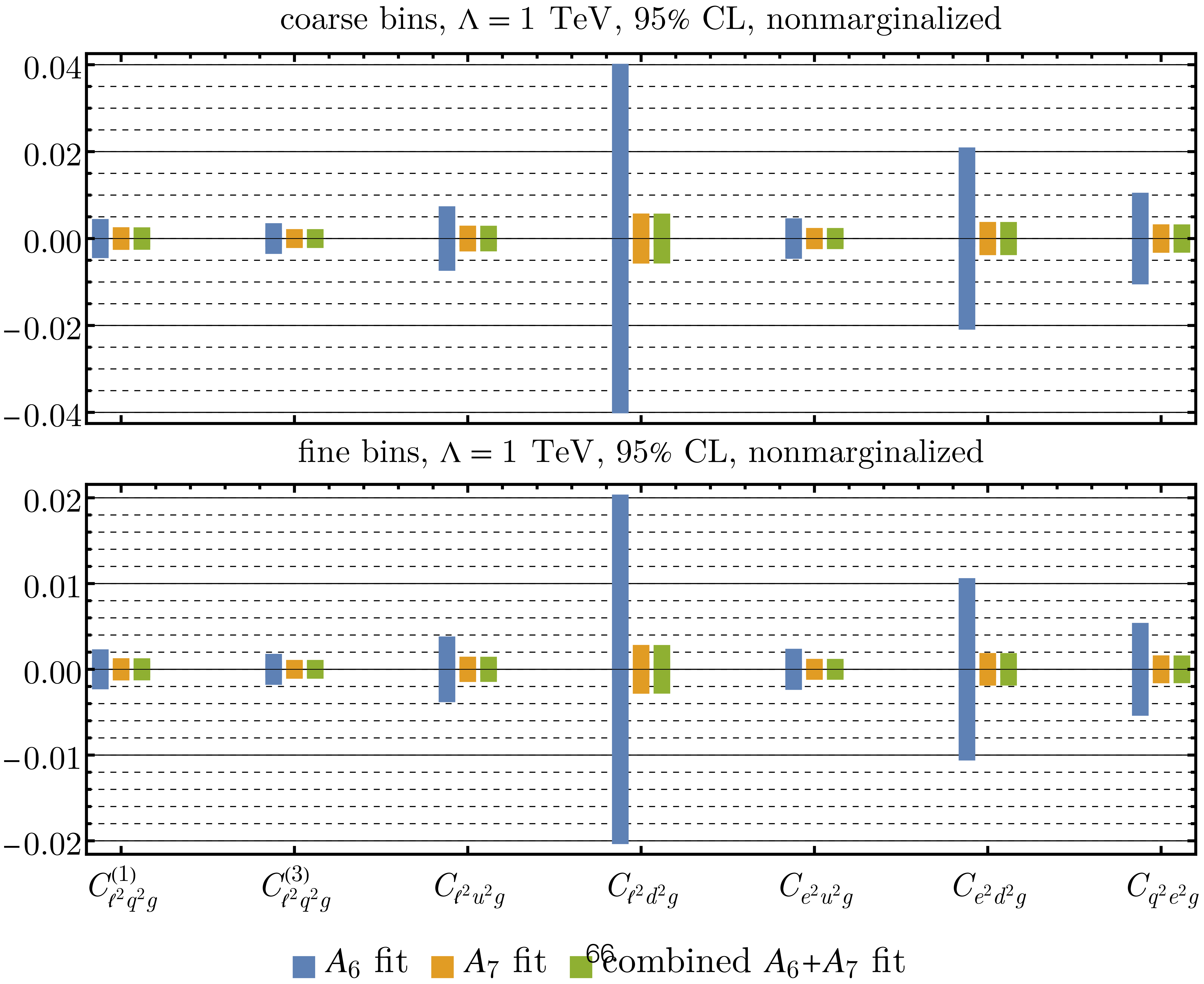


$300 < m_{\ell\ell} < 360$ GeV
$100 < p_T < 110$ GeV

$2000 < m_{\ell\ell} < 2600$ GeV
$100 < p_T < 7000$ GeV

Bins are sorted by $m_{\ell\ell}$ first and then by p_T.

Probing *CP*-odd dimension-8 SMEFT with DYj at HL-LHC



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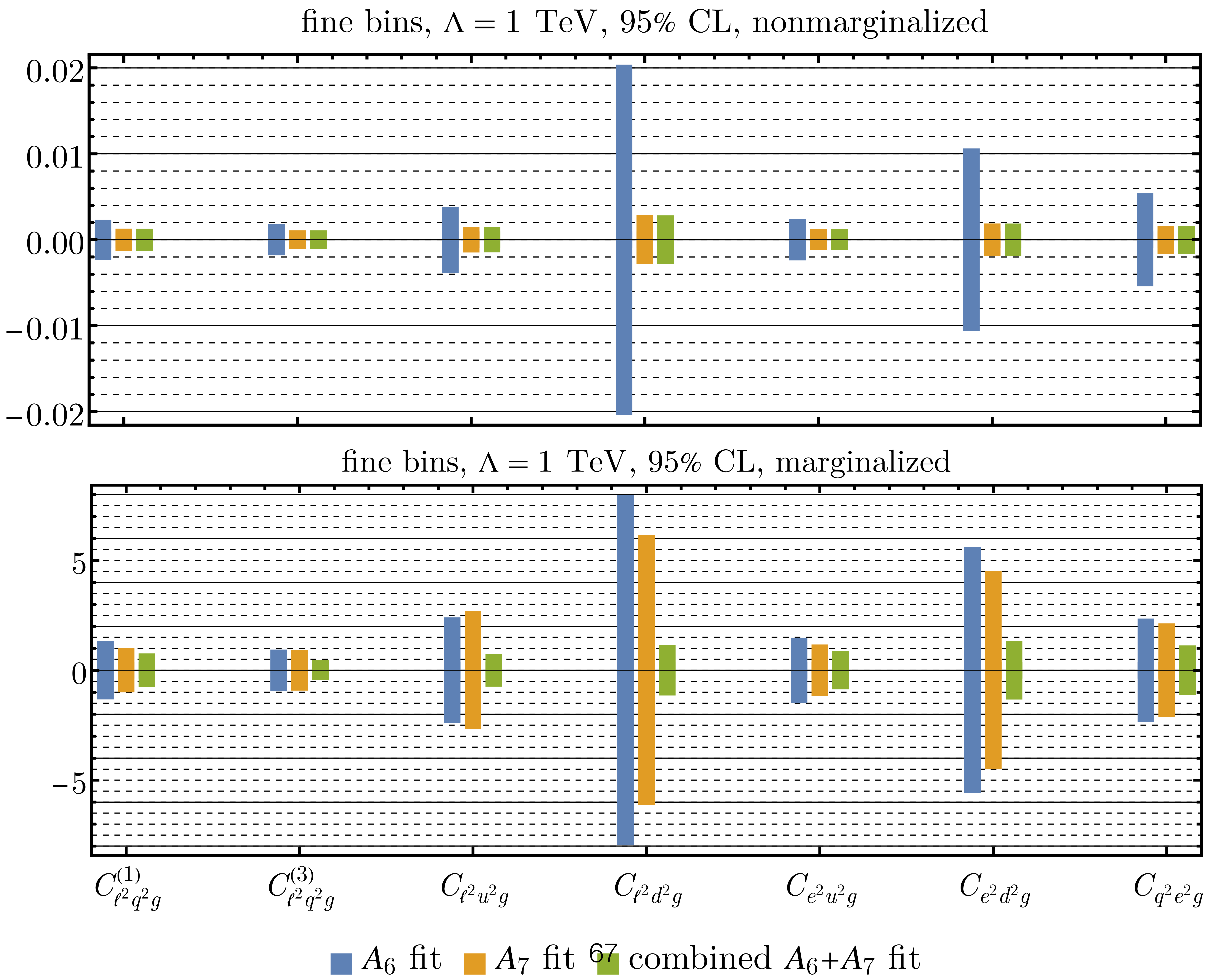

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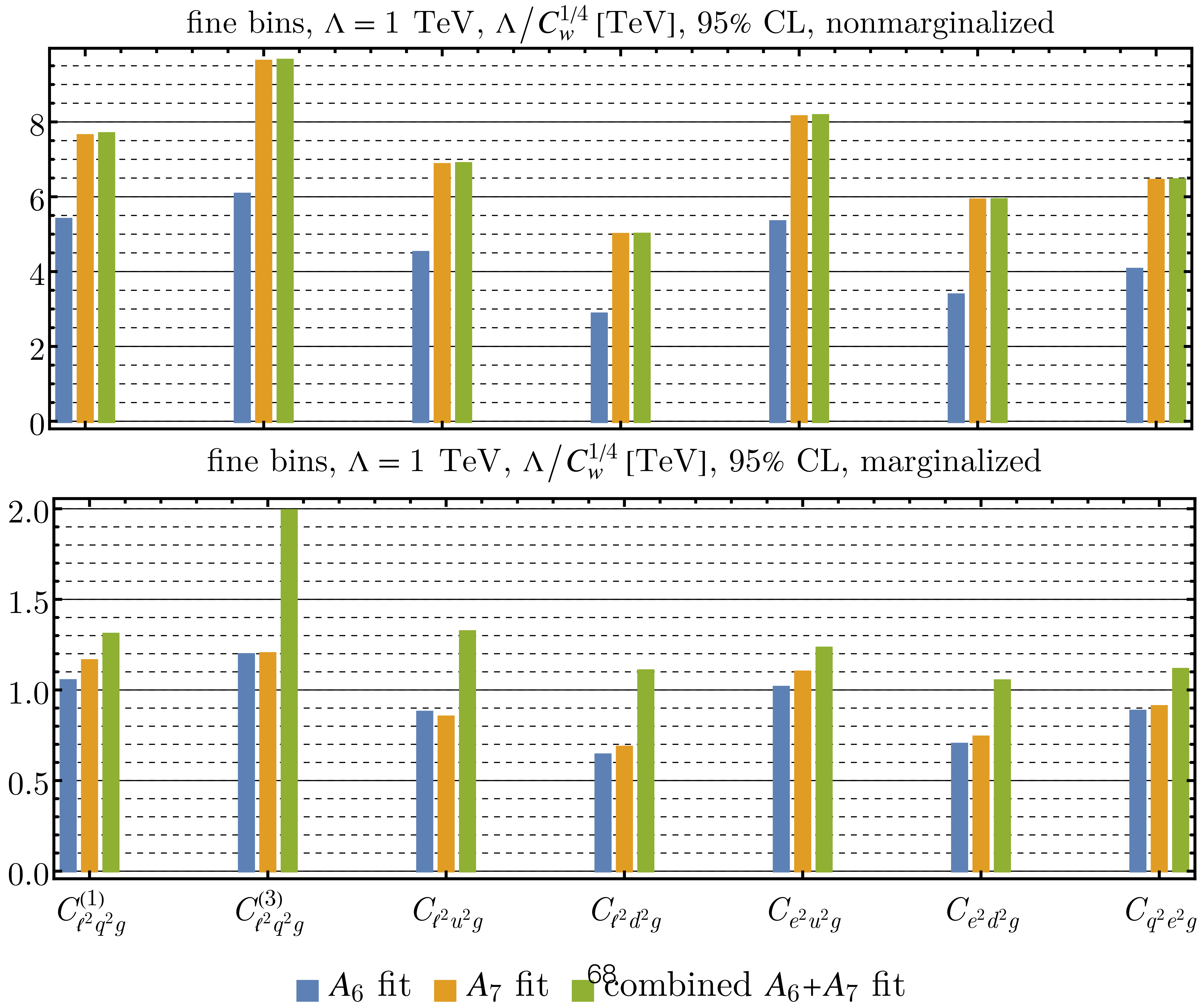

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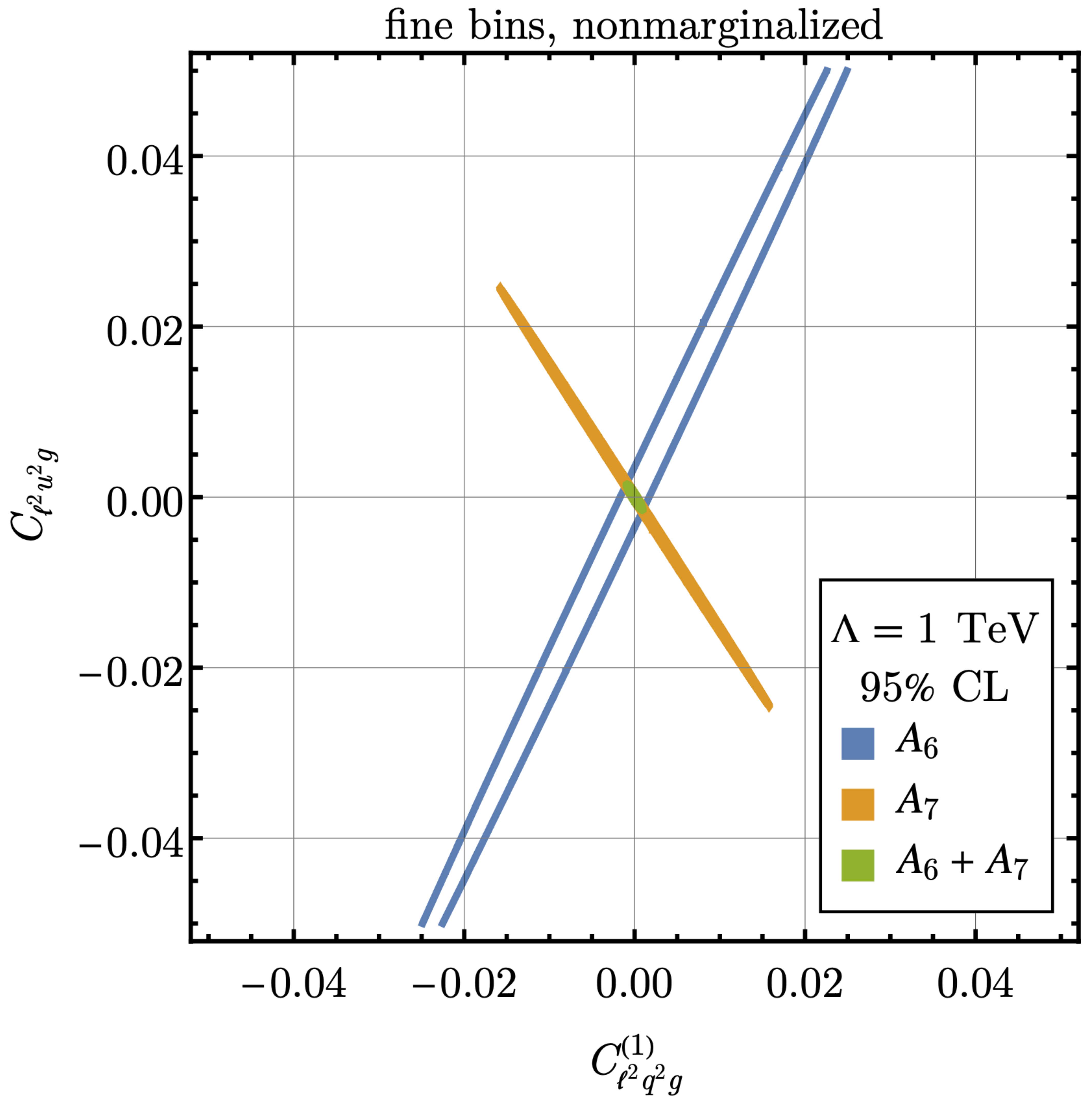

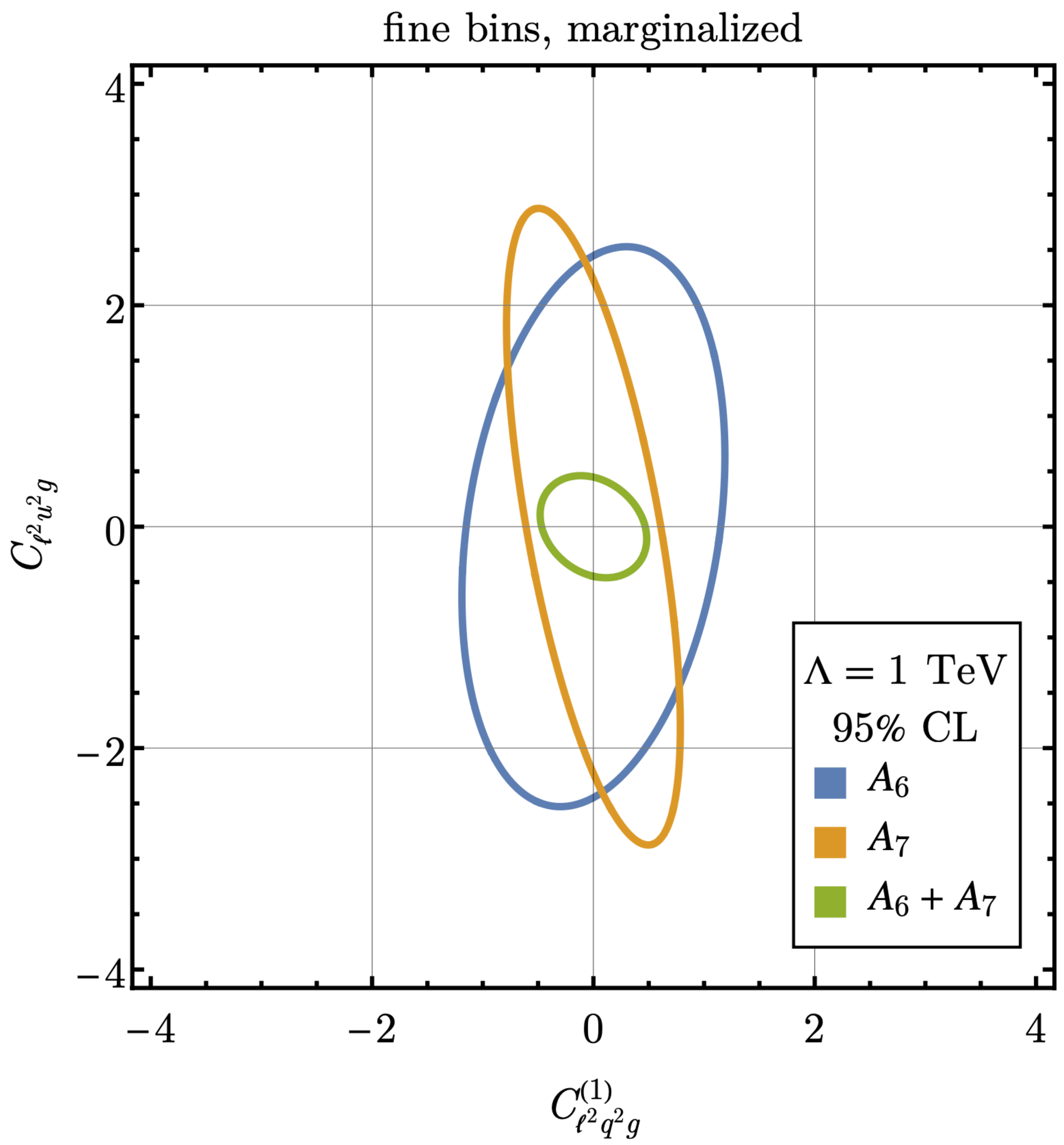

Probing CP-odd dimension-8 SMEFT with DYj at HL-LHC

Previously unexplored sector of dimension-8 SMEFT:

- Tight bounds ⇒ $\Lambda_{\text{eff}} \sim 9$ TeV in single-parameter fits
- Bounds weakened by two orders ⇒ strong correlations

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Future plans for this work:

- UV matching
- New operators

Probing y_e via transverse spin asymmetries at the FCC-ee

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- Electron Yukawa coupling, $y_e^{\mathrm{SM}} = \dfrac{\sqrt{2} m_e}{v} \approx 2.9 \times 10^{-9}$, the tiniest in SM
- Measuring this = one of the most precise tests

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- Bounds from DY at LHC: $|y_e| \leq 260 |y_e^{\rm SM}|$ at 2-σ
- Projected bounds from HL-LHC: $|y_e| \geq 120 |y_e^{\rm SM}|$
- Challenging because xsection $\propto y_e^2$

Probing y_e via transverse spin asymmetries at the FCC-ee

- More direct access at FCC-ee near Higgs resonance, $\sqrt{s} = 125$ GeV
- Most complete analysis of inclusive xsection: $|y_e| \leq 1.6\,|y_e^{\mathrm{SM}}|$ (d'Enterria+ [2107.02686])

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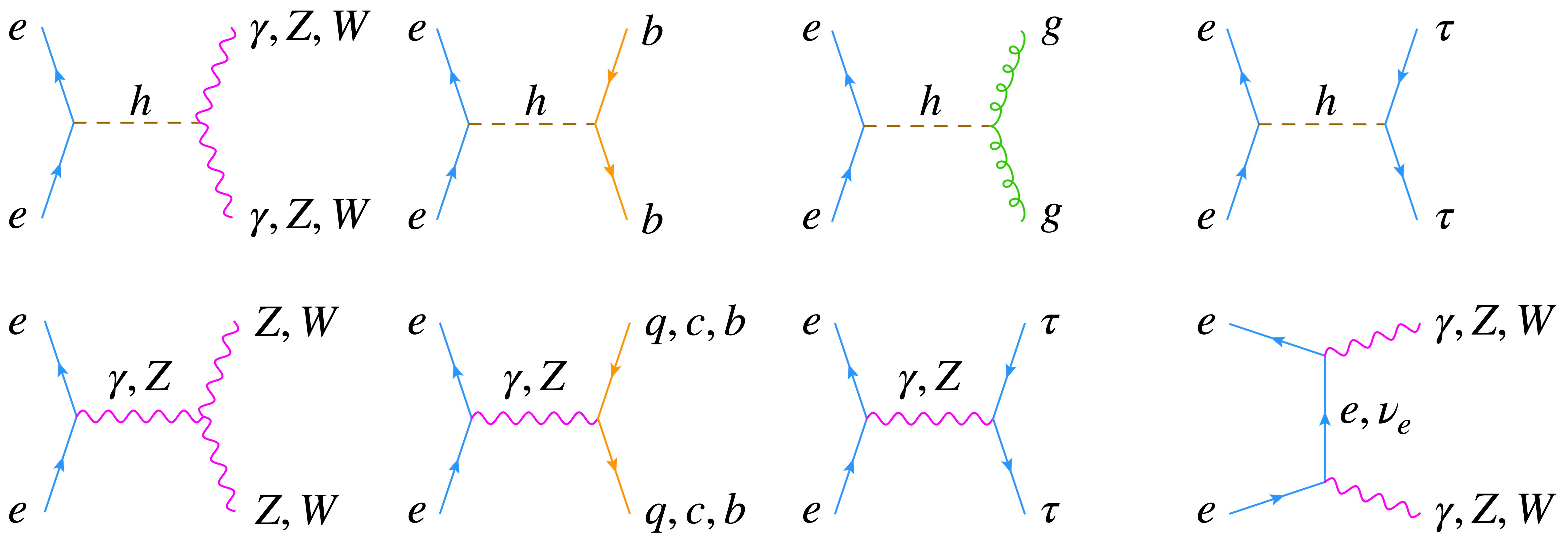
large EW continuum background!



Probing y_e via transverse spin asymmetries at the FCC-ee

- A new avenue: transverse spin asymmetries
  - Chiral mass suppression: still an obstacle
  - Arise from Higgs-background interference $\therefore$ linear y_e suppression
  - With a proper weight $\Rightarrow$ can isolate signal from background

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$$e^+e^- \to b\bar{b}$$

$$e^+e^- \to WW \to \ell\nu jj$$

highest branching ratios
in $e^+e^- \to h$

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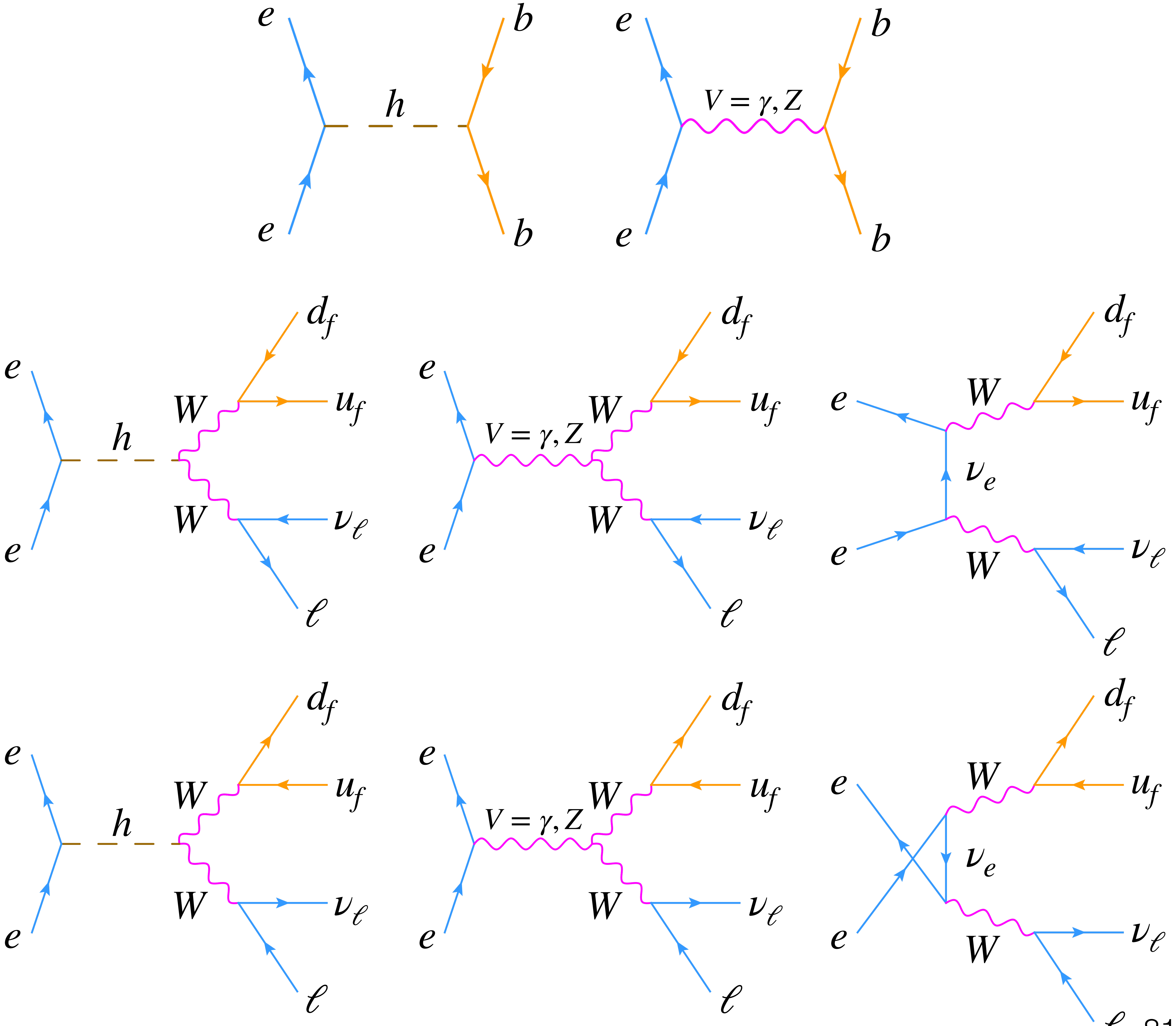
- Construct asymmetry observables and assess statistical significance.
- Realistic experimental effects: beam energy spread, initial state radiation, optimized kinematic cuts

Probing y_e via transverse spin asymmetries at the FCC-ee



$$\sigma^{\lambda\bar{\lambda}} = F \int |\mathscr{A}^{\lambda\bar{\lambda}}|^2 \, \text{dLIPS}$$

electron: transverse polarization

positron: longitudinal polarization

$$u_\lambda \bar{u}_\lambda = (\gamma \cdot p + m)\mathbb{P}^+_\lambda(S_T)$$
$$v_\lambda \bar{v}_\lambda = (\gamma \cdot p - m)\mathbb{P}^-_\lambda(S_L)$$

$$\mathbb{P}^\pm_\lambda(S^\mu) = \frac{1 \pm \lambda\gamma_5\gamma \cdot S}{2}$$

$$S^\mu_T = (0, \cos(\varphi), \sin(\varphi), 0)$$

$$S^\mu_L = \frac{1}{m}(|\vec{p}\,|, E\hat{p})$$

Probing y_e via transverse spin asymmetries at the FCC-ee

Asymmetry observables: $A = \dfrac{N}{D}$

$N = \dfrac{1}{4}(\sigma^{++} - \sigma^{+-} - \sigma^{-+} + \sigma^{--})$: double polarization (DP)

$N = \dfrac{1}{2}(\sigma^{+0} - \sigma^{-0})$: single polarization with unpolarized positron (SP^0)

$N = \dfrac{1}{2}(\sigma^{++} - \sigma^{-+})$: single polarization with LH positron (SP^+)

$N = \dfrac{1}{2}(\sigma^{+-} - \sigma^{--})$: single polarization with RH positron (SP^-)

D: same as N with all the contributions added

Probing y_e via transverse spin asymmetries at the FCC-ee

Asymmetry observables: $A = \dfrac{N}{D}$

$$N = \sum_c F \int w N^c \,\mathrm{dLIPS},$$

c: channels $(h, \gamma, Z, \nu, h\gamma, hZ, h\nu, \gamma Z, \gamma\nu, Z\nu)$

w: angular weight to eliminate interference channels, isolate y_e

Probing y_e via transverse spin asymmetries at the FCC-ee

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w: angular weight to eliminate interference channels, isolate y_e

Best angular weight:

$$w = \sin(\varphi)$$

φ: azimuthal angle of b or $W(\ell\nu)$ in the c.m. frame of e^+e^-

Completely isolates y_e in $b\bar{b}$, maximally isolates in WW in hZ interference.

Probing y_e via transverse spin asymmetries at the FCC-ee

Dilution of the signal:

$$\sigma(E_{\text{coll}}) = \int_{-\infty}^{\infty} \mathrm{d}\hat{E}\ \frac{\mathrm{d}L(E_{\text{coll}}, \hat{E}, \delta)}{\mathrm{d}\hat{E}} \int_0^1 \mathrm{d}x\ f(x, \hat{E})\ \sigma(\sqrt{x}\hat{E})$$

$$E_{\text{coll}} = m_h$$

$$\delta = \Gamma_h$$

$$\frac{\mathrm{d}L(E_{\text{coll}}, \hat{E}, \delta)}{\mathrm{d}\hat{E}} = \frac{1}{\sqrt{2\pi\delta^2}} \exp\left[-\frac{(\hat{E} - E_{\text{coll}})^2}{2\delta^2}\right]$$

$f(x, \hat{E})$: JWW ISR function

Probing y_e via transverse spin asymmetries at the FCC-ee

Sensitivity estimates:

$$A^{\text{exp}} = \frac{1}{P_{e^-}P_{e^+}}\frac{N_N}{N_D}\text{: experimental reconstruction of asymmetry}$$

$$N_N = \eta L N, \quad N_D = \eta L D\text{: event counts}$$

$$\delta A^{\text{exp}} = \frac{\delta P_{e^-}}{P_{e^-}} A^{\text{exp}} \oplus \frac{\delta P_{e^+}}{P_{e^+}} A^{\text{exp}} \oplus \frac{1}{P_{e^-}P_{e^+}}\frac{1}{\sqrt{N_D}}$$

$P_{e^-} = 80\,\%$, $P_{e^+} = 30\,\%$, 3% relative uncertainties,

$L = 10\ \text{ab}^{-1}, \quad \eta = 80\,\%$ (100%) for $b\bar{b}$ (WW)

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$$\delta A^{\exp} = \frac{\delta P_{e^-}}{P_{e^-}} A^{\exp} \oplus \frac{\delta P_{e^+}}{P_{e^+}} A^{\exp} \oplus \frac{1}{P_{e^-}P_{e^+}} \frac{1}{\sqrt{N_D}}$$

$$\mathcal{S} = \frac{A^{\exp}}{\delta A^{\exp}}$$

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Probing y_e via transverse spin asymmetries at the FCC-ee

Realistic experimental cuts:

$5^\circ < \theta < 175^\circ$ for $b\bar{b}$

$E_{j_1,j_2} < 52,\ 45$ GeV, $E_\ell > 10$ GeV, $E_{\text{miss}} > 20$ GeV, $m_{\ell\nu} > 12$ GeV for WW

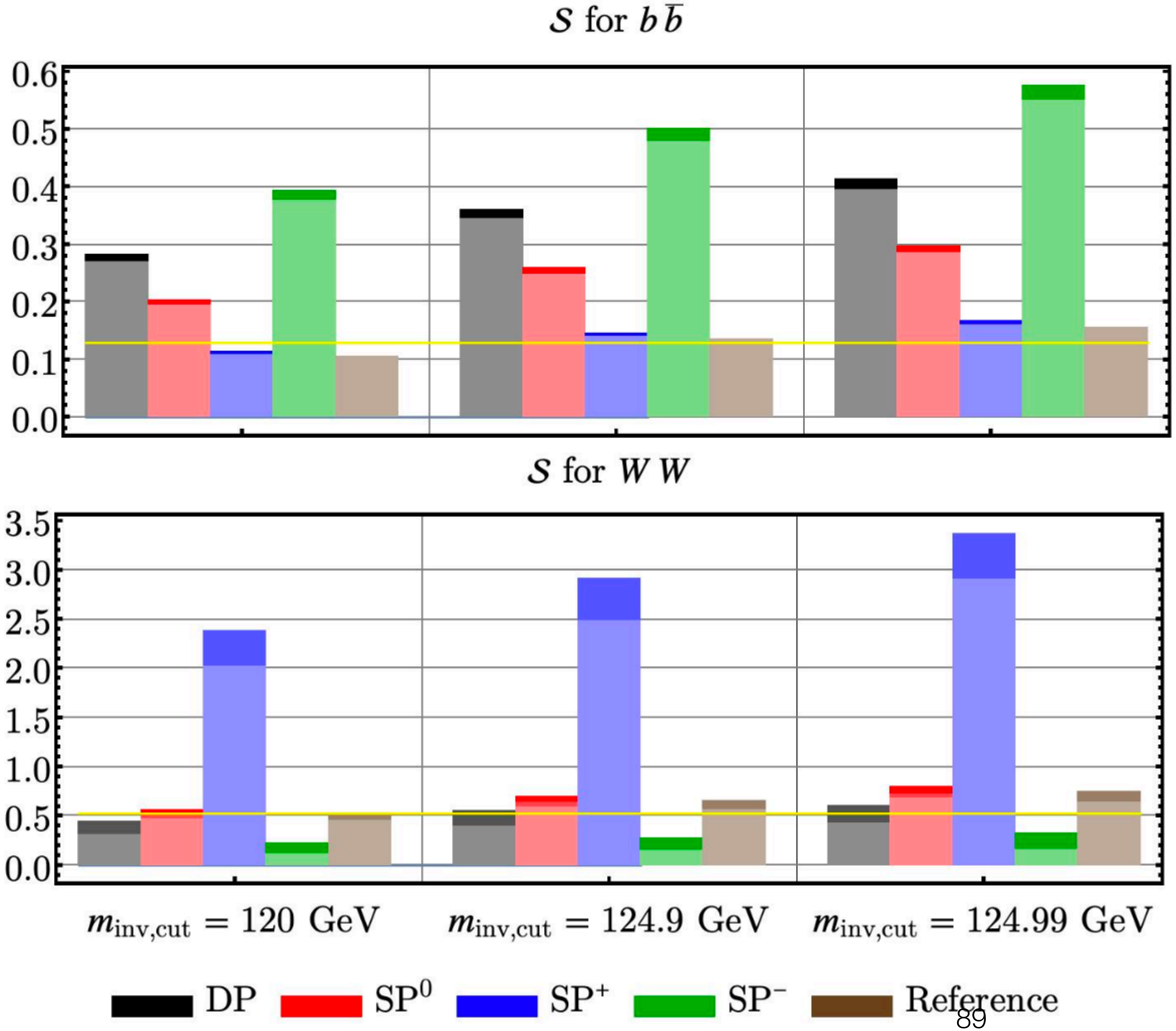
Optimization cuts:

$m_{\text{inv}} > m_h - x\Gamma_h$

39% symmetric cut on $\theta \in [0, 180^\circ]$ for b

28% symmetric cut on $\theta \in [0, 180^\circ]$ for $W(\ell\nu)$

Probing y_e via transverse spin asymmetries at the FCC-ee



dark: optimization cuts

light: no optimization cuts

$$\text{Reference} = \frac{\text{signal}}{\sqrt{\text{background}}}$$

using inclusive xsection

Yellow line: from inclusive xsection using boosted decision tree analysis to remove background, from d'Enterria+ [2107.02686]

Coda

Summary

- Motivation: Can future colliders, via precision observables, reveal or constrain BSM physics?
- Collider diversity = different tools needed for different bolts: Each collider targets a different direction in SMEFT parameter space. Together, they close gaps no single machine can.
- DIS (EIC, LHeC, and FCC-eh): Covers distinct kinematic regimes. When combined, they lift flat directions in global fits and set powerful bounds on new interactions.
- DY (HL-LHC): Pushes high invariant mass tails ($m_{\ell\ell} \gg m_Z$) with enormous statistics, testing SMEFT directions beyond the reach of LEP or low-energy DIS.
- e^+e^- (FCC-ee): Precision machine par excellence. Clean initial state. Sensitive to subtle couplings like the electron Yukawa.

Summary

What's the point of constraining SMEFT parameters?

- *We haven't found new particles yet*: New physics must be either too heavy to produce or too weakly coupled to resolve.
- *But new physics still leaves footprints*: Even if we can't see the particles, we can detect their effect as tiny deviations in precision observables.
- *SMEFT is our translator*: It tells us how unknown heavy physics would subtly deform SM predictions:
  - Deviations are encoded in Wilson coefficients.
  - Constraining these coefficients = testing every possible UV completion, all at once.

Contributions

Papers:

- R. Boughezal, A. Emmert, T. Kutz, S. Mantry, M. Nycz, F. Petriello, K. Şimşek, D. Wiegand, X. Zheng, *Neutral-current electroweak physics and SMEFT studies at the EIC*, Phys. Rev. D **106** (2022) 016006, arXiv:2204.07557
- C. Bissolotti, R. Boughezal, K. Şimşek, *SMEFT probes in future precision DIS experiments,* Phys. Rev. D **108** (2023) 075007, arXiv:2306.05564
- R. Boughezal, F. Petriello, K. Şimşek, *Transverse spin asymmetries and the electron Yukawa coupling at an FCC-ee,* Phys. Rev. D **110** (2024) 075026, arXiv:2407.12975
- DY+jet project: in progress

Other publications:

- R. Abdul Khalek *et al., Snowmass 2021 White Paper: Electron Ion Collider for high energy physics,* arXiv:2203.13199
- C. Bissolotti, R. Boughezal, K. Şimşek, *SMEFT analysis with LHeC, FCC-eh, and EIC DIS pseudodata,* DIS2023 Proceedings, arXiv:2307.09459

Outlook and future directions

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top physics • NLO FCNC top decays and single top production • BSM within extra dimensional models

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numerical methods
statistical analysis
machine learning
more packages

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Outlook and future directions

top physics • NLO FCNC top decays and single top production • BSM within extra dimensional models

QCD/EW precision pheno • collider physics • BSM within SMEFT

top physics • single top, top pair, associated top-h/Z production • NNLO/ aN3LO + resummation • next-gen CTEQ fits • PDF-SMEFT combined fits

universal packages

numerical methods
statistical analysis
machine learning
more packages

hadron physics • QCD light-cone sum rules • formfactors and strong couplings

Thank you.