Electroweak corrections in the SMEFT: four-fermion operators at high energies

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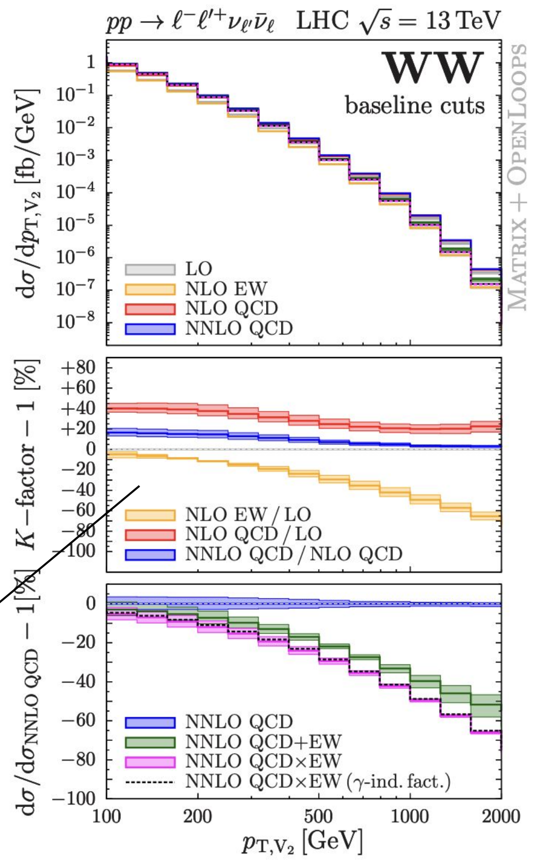
SM at the LHC, April 2025, Durham

Introduction

At high energies, EW corrections are not necessarily negligible compared to QCD ones

→ at high energies, Sudakov logarithms can make EW corrections significant; domination of negative and large Sudakov logs.



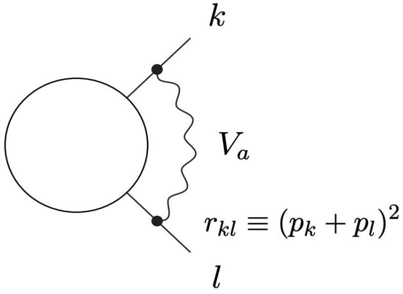
Grazzini et al, 1912.0068; see talk by Pozzorini

EW Sudakov Logarithms (EWSL): physical origin

EWSLs arise from potential divergences regulated by the finite masses of the EW bosons

→ soft divergences: low energy emission of gauge bosons

→ collinear divergences: emission nearly parallel to an external particle



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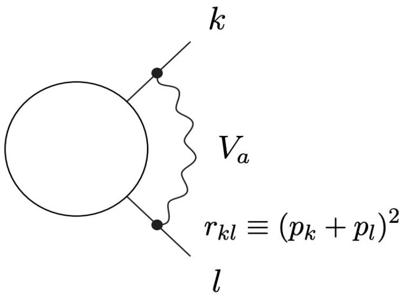


→ soft divergences: low energy emission of gauge bosons

→ collinear divergences: emission nearly parallel to an external particle

Double logarithms (DL): $L(|r_{kl}|, M^2) \equiv \frac{\alpha}{4\pi} \log^2 \frac{|r_{kl}|}{M^2}$ **soft and collinear regions**

Single logarithms (SL): $l(|r_{kl}|, M^2) \equiv \frac{\alpha}{4\pi} \log \frac{|r_{kl}|}{M^2}$ **soft/collinear region**

EWSL: universality at high energies

At high energies, EWSL are universal; with dependence on:

→ quantum numbers of external particles

→ and the energy scale relative to the EW scale

$$\mathcal{A}(s) = \mathcal{A}_{\text{hard}} \cdot \mathcal{F}_{\text{soft+collinear}}$$

The factorisation enables precision calculations → the hard amplitude can be computed separately, with Sudakov logarithms included as a multiplicative correction

EWSL: why bother if we have the exact NLO EW?

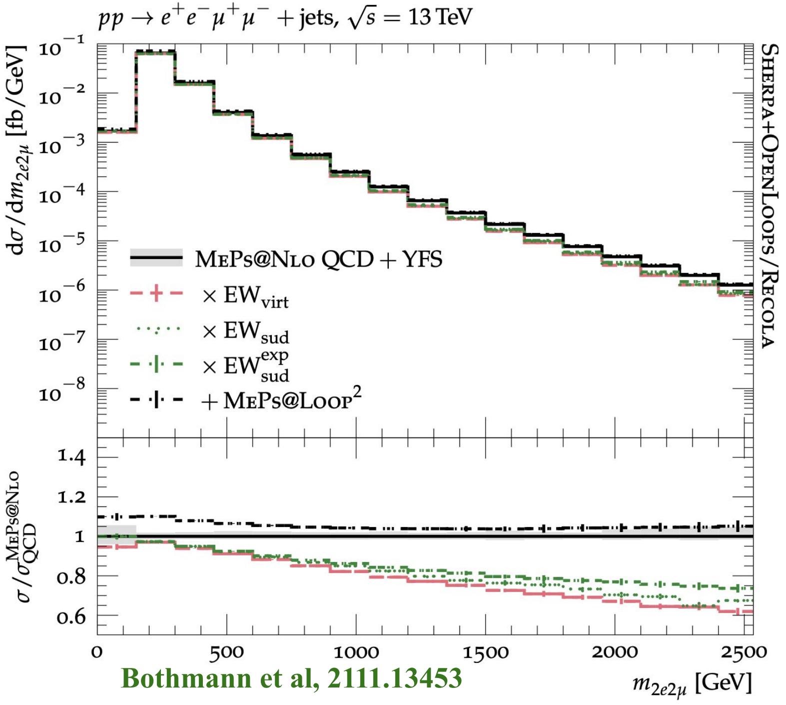
EWSL have recently garnered renewed interest Sherpa, Bothmann et al, 2006.14635; OpenLoops, Lindert et al, 2312.07927

→ EWSL are computationally faster and more stable than exact NLO EW corrections

→ EWSL can be resummed e.g. Denner, Rode, 2402.10503

→ Born-like kinematics; simplified PS merging/matching Chiesa et al, 1305.6837; Bothmann et al, 2111.13453; Pagani et al, 2309.00452

→ EWSL are universal at high energies



Bothmann et al, 2111.13453

EWSL: algorithm by Denner and Pozzorini hep-ph/0010201 & hep-ph/0104127

One-loop leading logarithms in electroweak radiative corrections I. Results

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Abstract:

We present results for the complete one-loop electroweak logarithmic corrections for general processes at high energies and fixed angles. Our results are applicable to arbitrary matrix elements that are not mass-suppressed. We give explicit results for 4-fermion processes and gauge-boson-pair production in e^+e^- annihilation.

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In LA the corrections assume the form

$$\delta\mathcal{M}^{i_1\ldots i_n}(p_1,\ldots,p_n) = \mathcal{M}_0^{i'_1\ldots i'_n}(p_1,\ldots,p_n)\delta_{i'_1 i_1\ldots i'_n i_n}, \tag{2.11}$$

i.e. they factorize as a matrix, and are split into various contributions according to their origin:

$$\delta = \delta^{\mathrm{LSC}} + \delta^{\mathrm{SSC}} + \delta^{\mathrm{C}} + \delta^{\mathrm{PR}}. \tag{2.12}$$

The leading and subleading soft–collinear logarithms are denoted by δ^{LSC} and δ^{SSC}, respectively, the collinear logarithms by δ^{C}, and the logarithms resulting from parameter renormalization, which can be determined by the running of the couplings, by δ^{PR}.

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- at least one-helicity configuration *is not mass suppressed*
- split the EW logarithmic corrections into various contributions
- EWSL computed helicity-by-helicity

EWSL: numerical SM implementation Pagani and Zaro, hep-ph/2110.03714

Building upon the DP algorithm:

→ automate the computation of EWSL for any process in MG5_aMC **Alwall et al, 1405.0301 & Frixione et al, 1804.10017**

→ Introduce some additional features, e.g. angular dependence in logarithmic contributions

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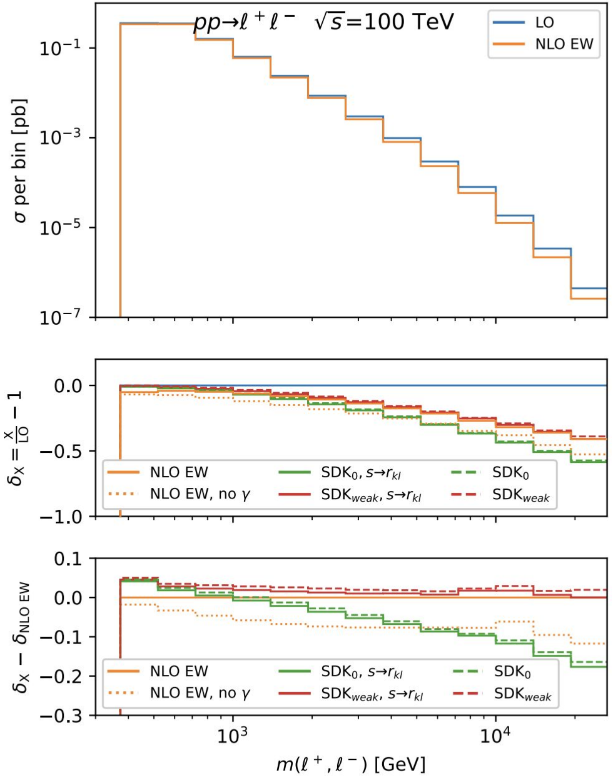
→ approximate physical cross-section, i.e, virtual + real emissions; SDK_{weak}



SMEFT and EW corrections

→ BSM effects are expected to manifest in the tails of distributions, i.e. at high energies

→ SMEFT simulation as it stands, does not include EW corrections

→ EW corrections in SMEFT are challenging, only available for few simple processes

μ decay: Pruna et al, 1408.3565;

H decay: Hartmann et al, 1505.02646 & 1507.03568; Ghezzi et al, 1505.03706; Gauld et al, 1512.02508; Dawson et al, 1801.01136 & 1807.11504; Dedes et al, 1805.00302 & 1903.12046; Cullen et al, 1904.06358 & 2007.15238;

Z/W pole obs.: Hartmann et al, 1611.09879; Dawson et al, 1808.05948 & 1909.02000;

Drell-Yan: Dawson et al, 2105.05852

.. and so the question is, can we make use of EWSL in SMEFT?

EWSL in SMEFT: introduction to our work

Leveraging previous works, we

→ apply the DP algorithm to SMEFT; identify the domain of applicability

→ study top-quark pair and Drell-Yan production at the LHC with 4F insertions

→ assess the significance of those corrections in SMEFT and their phenomenological implications

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Four-fermion (4F) dim-6 contact interactions are *not* mass-suppressed

→ utilise to compute Sudakov EW corrections at dim-6

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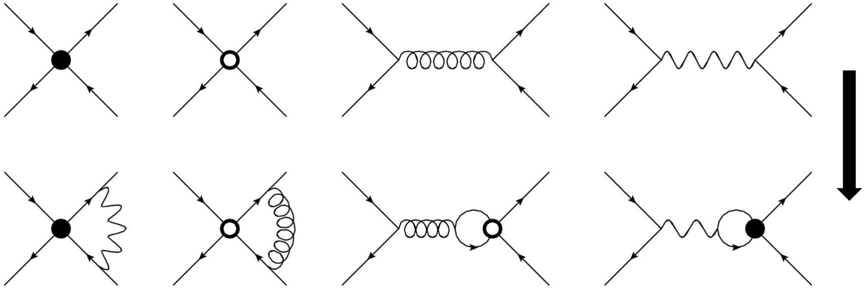

one-loop perturbation on 2→2 scattering

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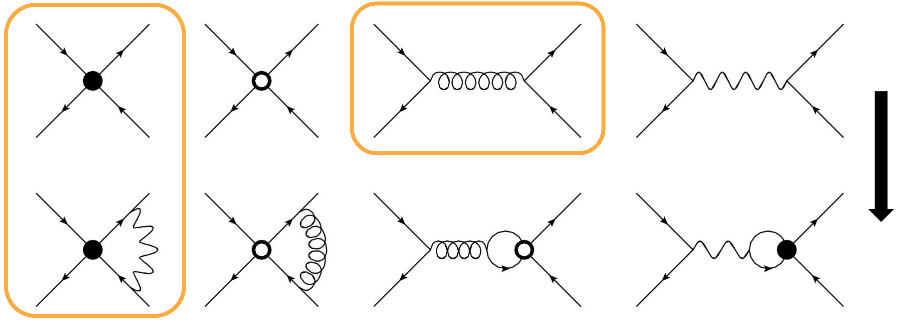

one-loop perturbation on 2→2 scattering

$pp \to t\bar{t}$ with color-octet 4F

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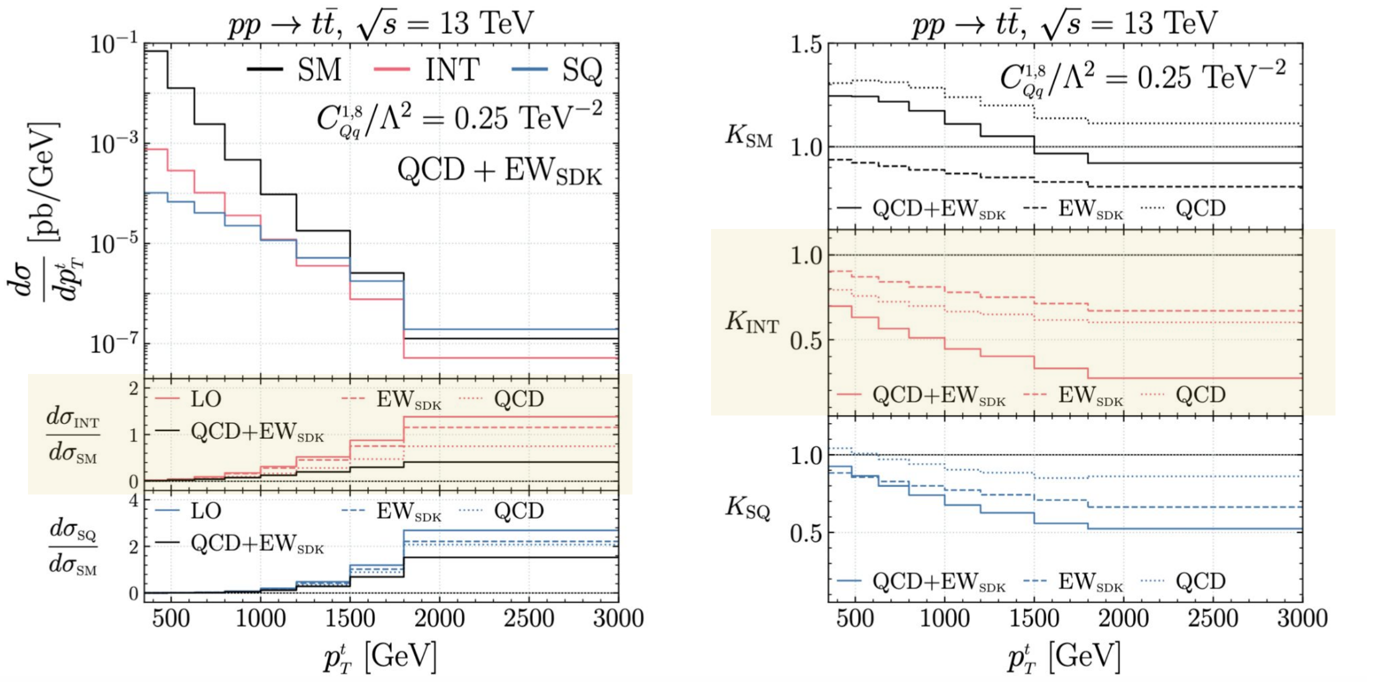
- **Utilise the EWSL implementation in MG5_aMC** **Pagani and Zaro, 2110.03714**
- **UFO model for SMEFT based on SMEFTatNLO** **Degrande et al, 2008.11743**

EWSL in SMEFT: top-quark pair production with 4F



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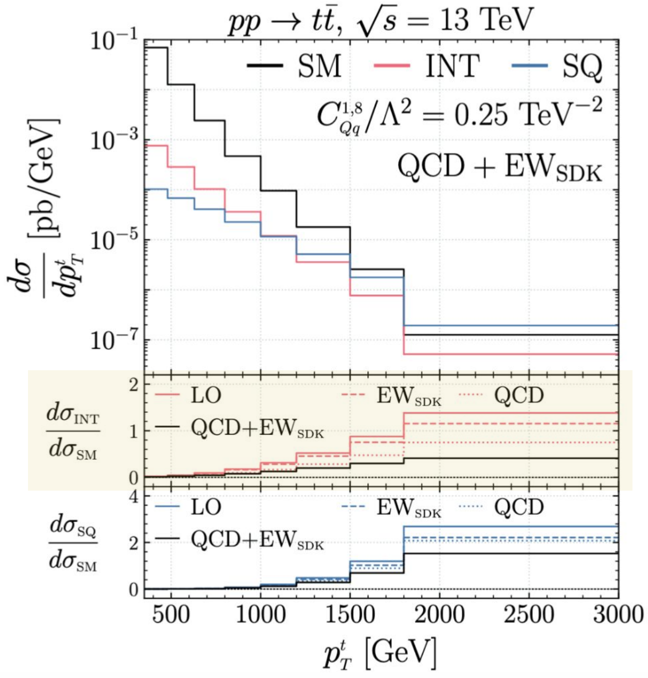

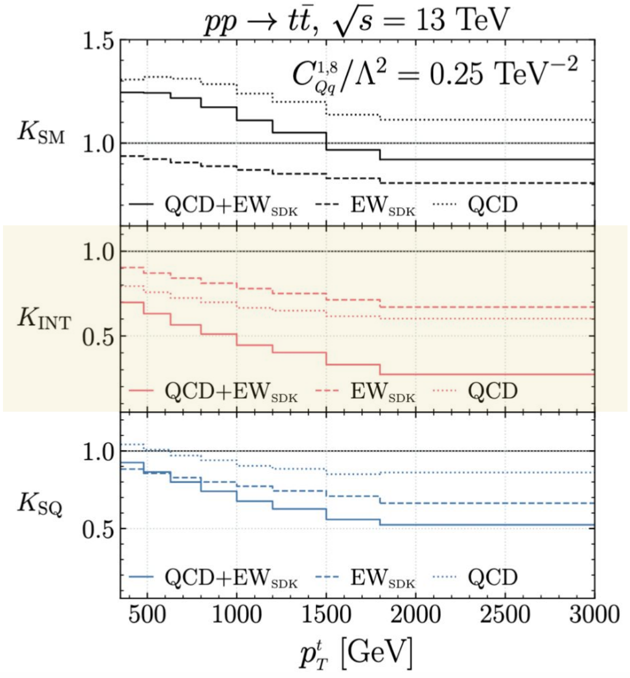

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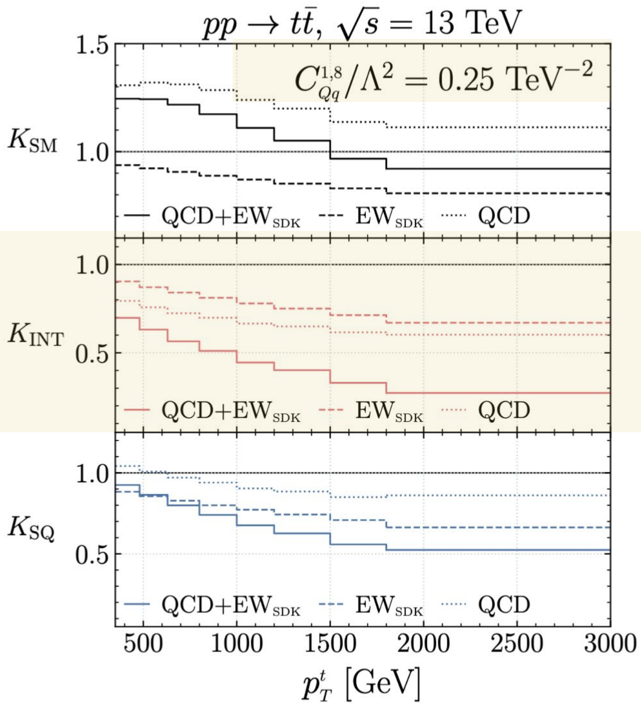
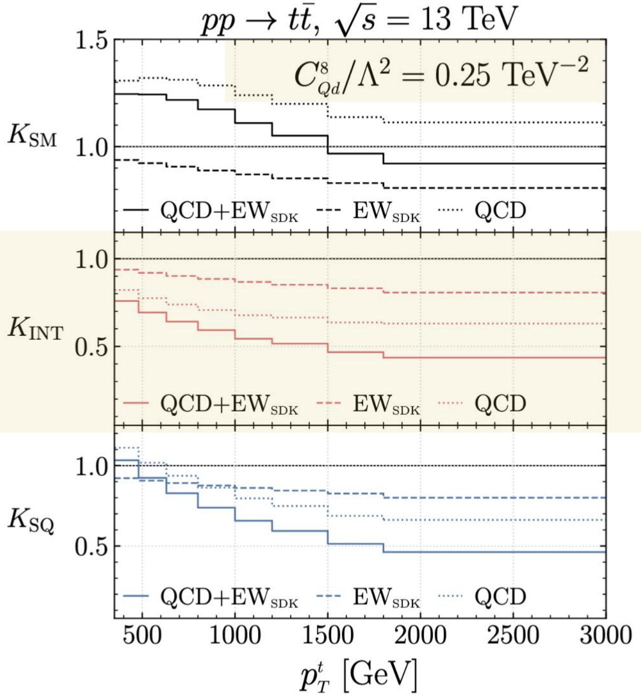
In the high-energy region, EW corrections can be important, in the SM and SMEFT

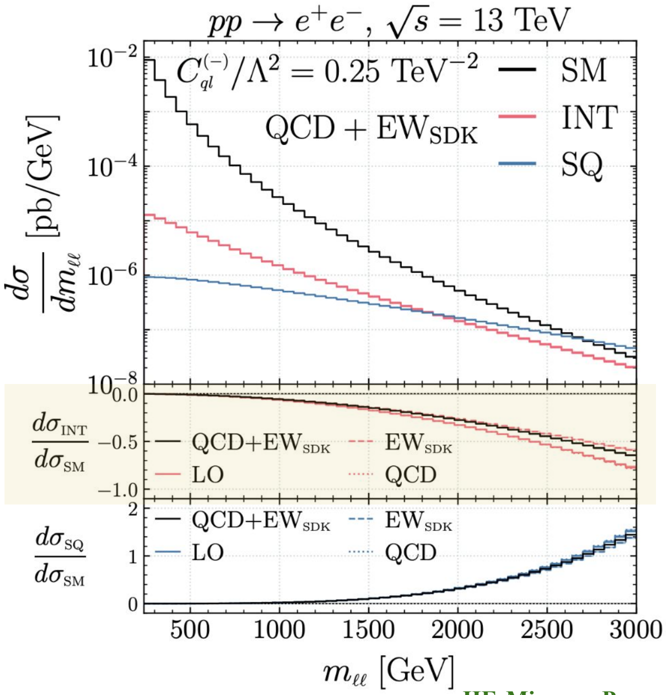
EWSL in SMEFT: top-quark pair production with 4F

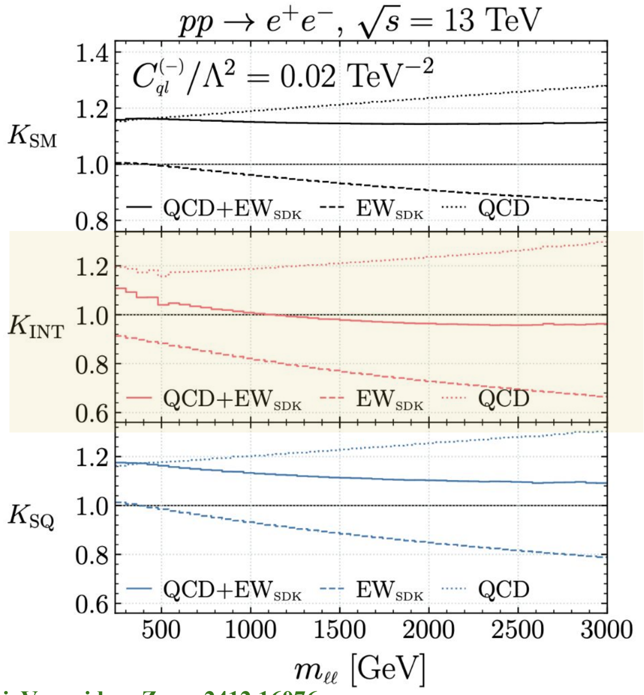




SMEFT K-factors are different among different 4F operators and from the SM

EWSL in SMEFT: Drell-Yan production with 4F





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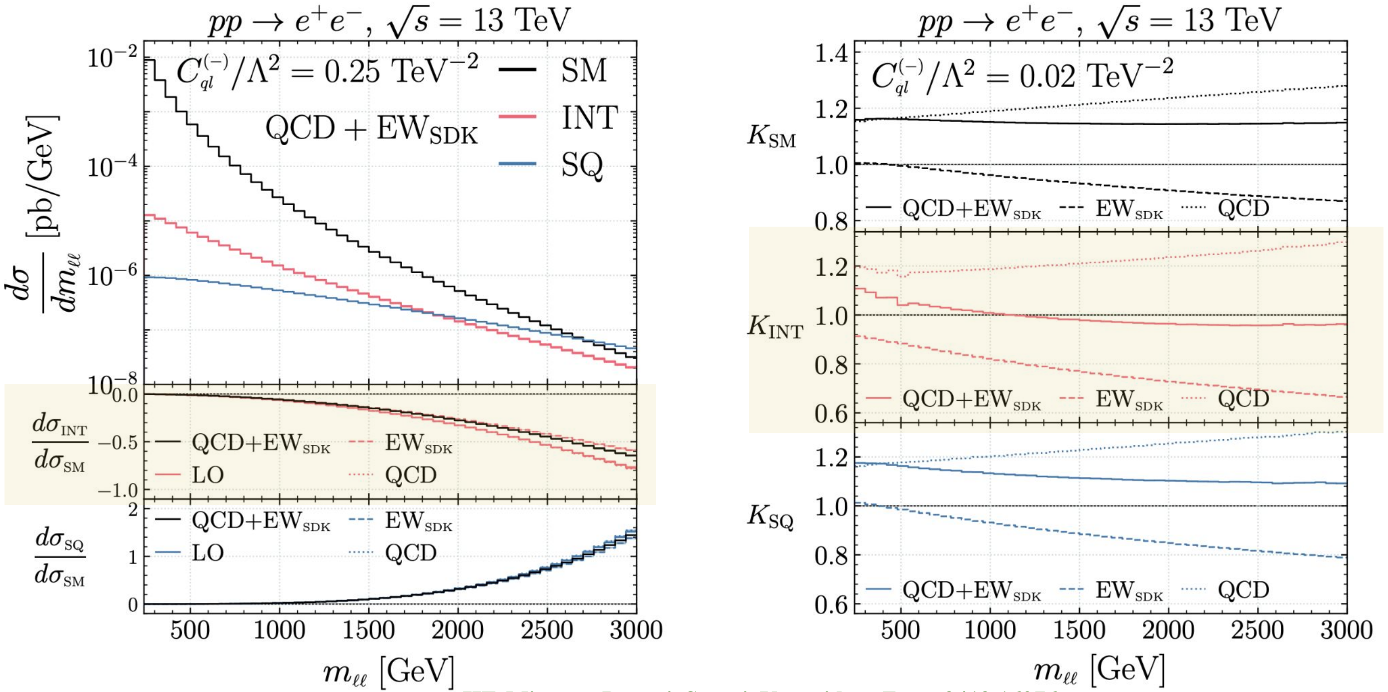

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QCD and EW corrections may feature strong, almost exact, cancellations in the EFT

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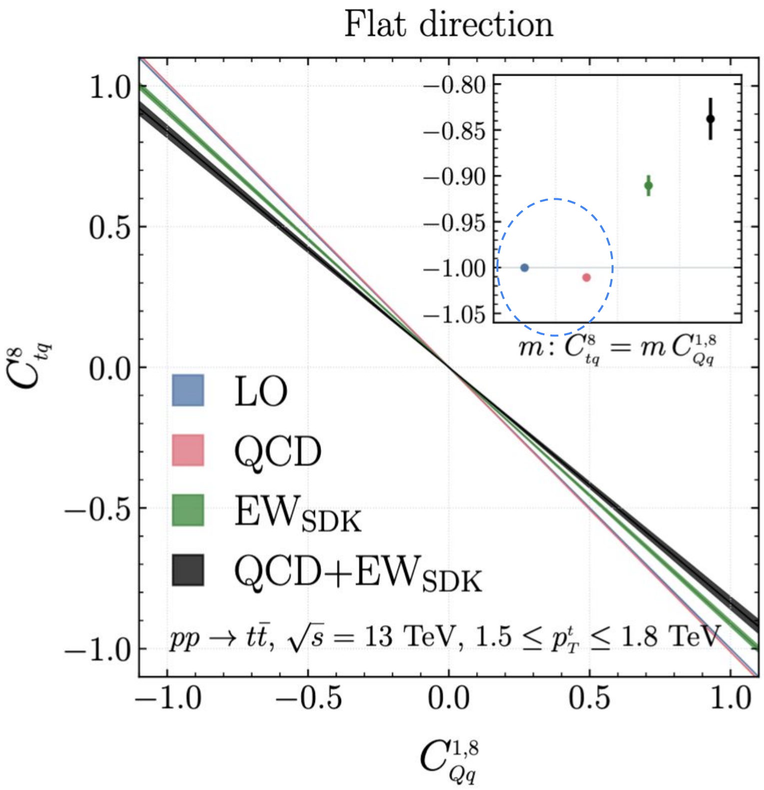
EWSL: SMEFT flat directions in top-quark pair production



→ flat direction at LO and ~ NLO QCD

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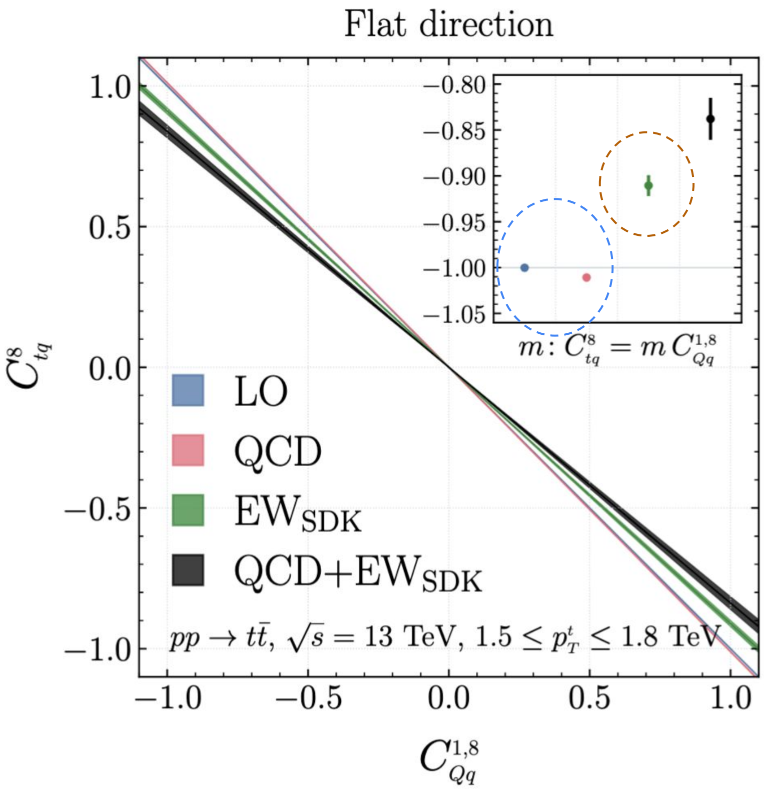

→ flat direction at LO and ~ NLO QCD

→ EW corrections lift the flat direction

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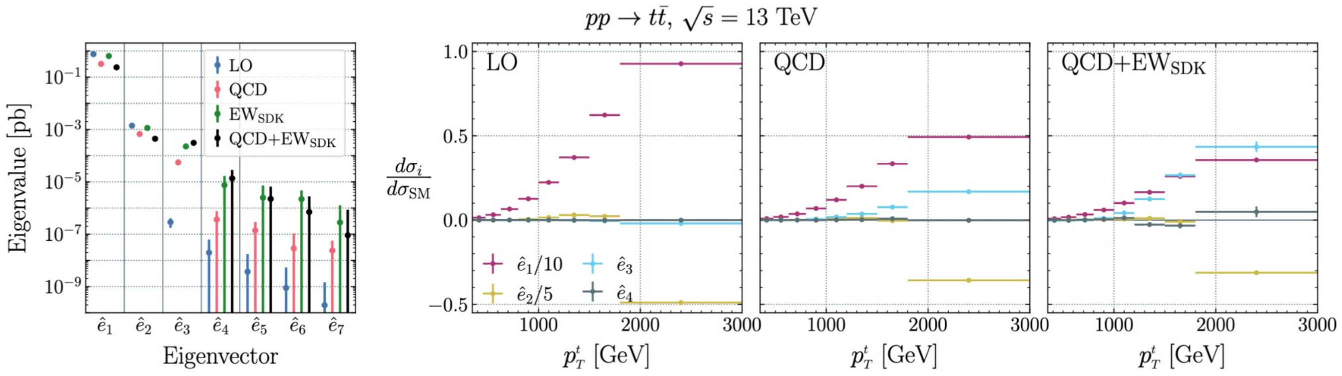
EWSL: SMEFT flat directions Fisher information



Fisher Information: quantifies the sensitivity of the data to a given direction in the parameter space

large eigenvalues → well-constrained directions; **zero eigenvalues** → flat directions

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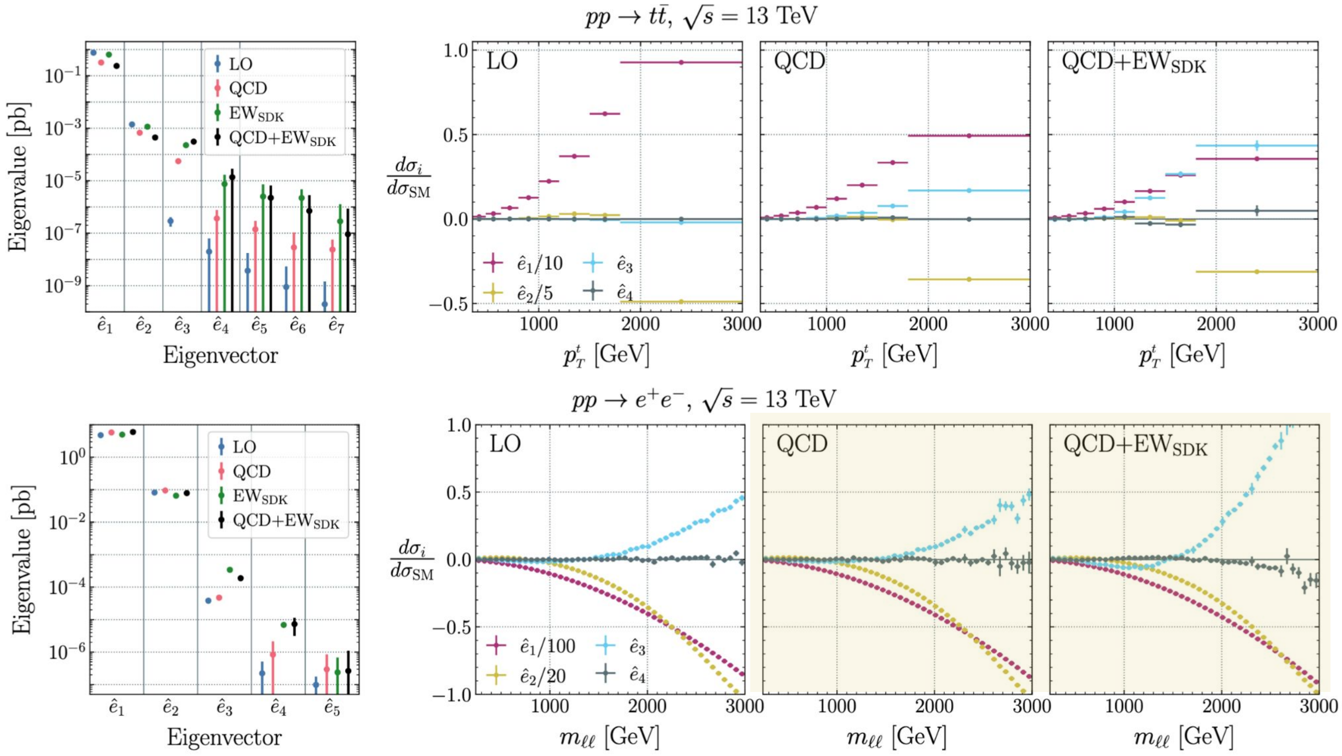
EWSL: SMEFT flat directions Fisher information



EW corrections lift some of the SMEFT flat directions existent at LO and NLO QCD

Summary and outlook

→ Computed EWSL for two illustrative processes with the insertion of four-fermion operators

→ The DP algorithm **can't be generally applied to the SMEFT**

→ EWSL can lead to significant enhancements in the SM and EFT

→ The K-factors in EFT and the SM are discrepant, as are the K-factors for different EFT operators, **making a simplistic K-factor approach to account for EW corrections inadvisable**

→ EW corrections seem capable of lifting some flat directions in the SMEFT parameter space

Backup

What do we actually compute?

$$\lim_{M_W^2/s\to 0} \mathrm{NLO}_2^{(6)} \propto 2\Re\left[\mathcal{M}_0^{\mathrm{NP}} \left(\mathcal{M}_0^{\mathrm{SM}} \delta_{\mathrm{EW}}^{\mathrm{SM}} \Big|_{\mathrm{SDK_{weak}}} \right)^* + \mathcal{M}_0^{\mathrm{SM}} \left(\mathcal{M}_0^{\mathrm{NP}} \delta_{\mathrm{EW}}^{\mathrm{SM}} \Big|_{\mathrm{SDK_{weak}}} \right)^* \right], \tag{2.43}$$

$$\lim_{M_W^2/s\to 0} \mathrm{NLO}_2^{(8)} \propto 2\Re\left[\mathcal{M}_0^{\mathrm{NP}} \left(\mathcal{M}_0^{\mathrm{NP}} \delta_{\mathrm{EW}}^{\mathrm{SM}} \Big|_{\mathrm{SDK_{weak}}} \right)^* \right]. \tag{2.44}$$

EWSL: amplitudes suppression

Sudakov corrections can be included as multiplicative factor to scattering amplitude,

$$\mathcal{A}(s) \sim \mathcal{A}_{\text{tree}} \cdot \exp\left[-\frac{\alpha}{4\pi}\sum_i C_i \log^2\left(\frac{s}{M_W^2}\right)\right]$$

At asymptotically high energies, the exponential suppression is significant

→ .. and EWSLs enhancements dominate over constant and power suppressed radiative corrections