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Catching Four-Fermions SMEFT Operators in the Drell-Yan Process

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Strengths and Limitations of the Standard Model

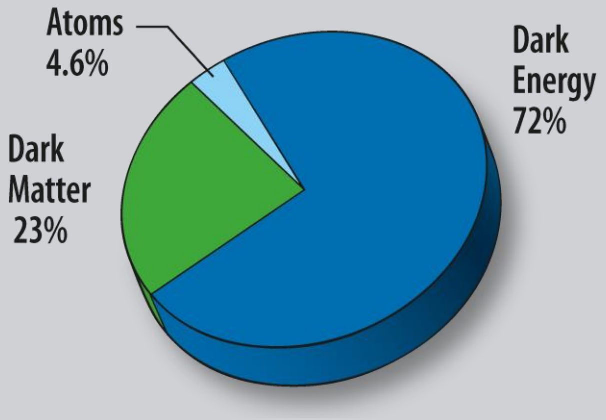
The most successful theory in particle physics

- It is both renormalizable and mathematically self-consistent
- It predicted the Higgs boson
- Allowed the most precise measurement in physics: *Electron Anomalous Magnetic Momentum*

However, it cannot explain several observed phenomena

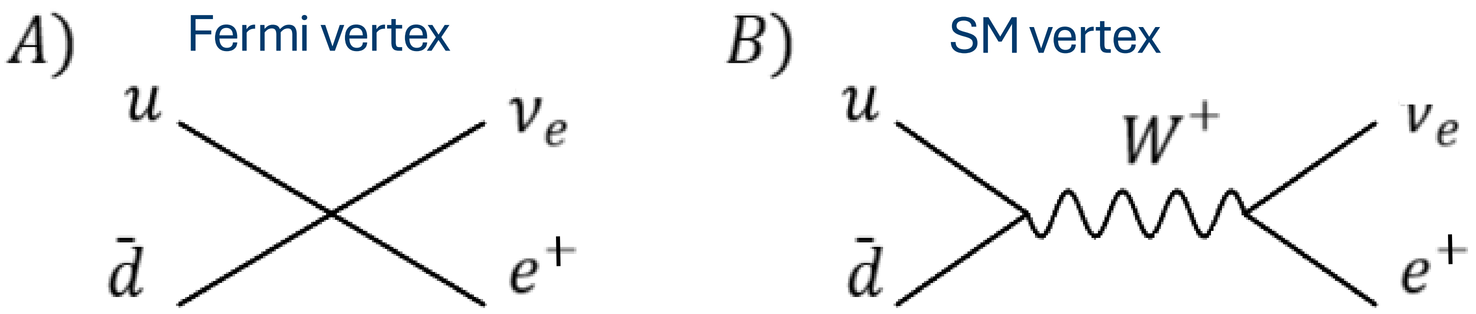
- Matter-Antimatter asymmetry
- Neutrino Oscillations
- Gravity
- Dark Matter
- Dark Energy

Ultimately, it describes only around 5% of the energy in the universe



Effective Field Theory (EFT)

- Search for new physics through "*bump-hunting*" at the LHC have so far been unsuccessful
- We need to look for ***indirect signs*** of new physics, particularly in scenarios where the mass of the new particles lies well above the collider energy
- In this context, an EFT can help
- A classical example of EFT is the ***Fermi interaction***, the *low-energy effective field theory* of weak interactions

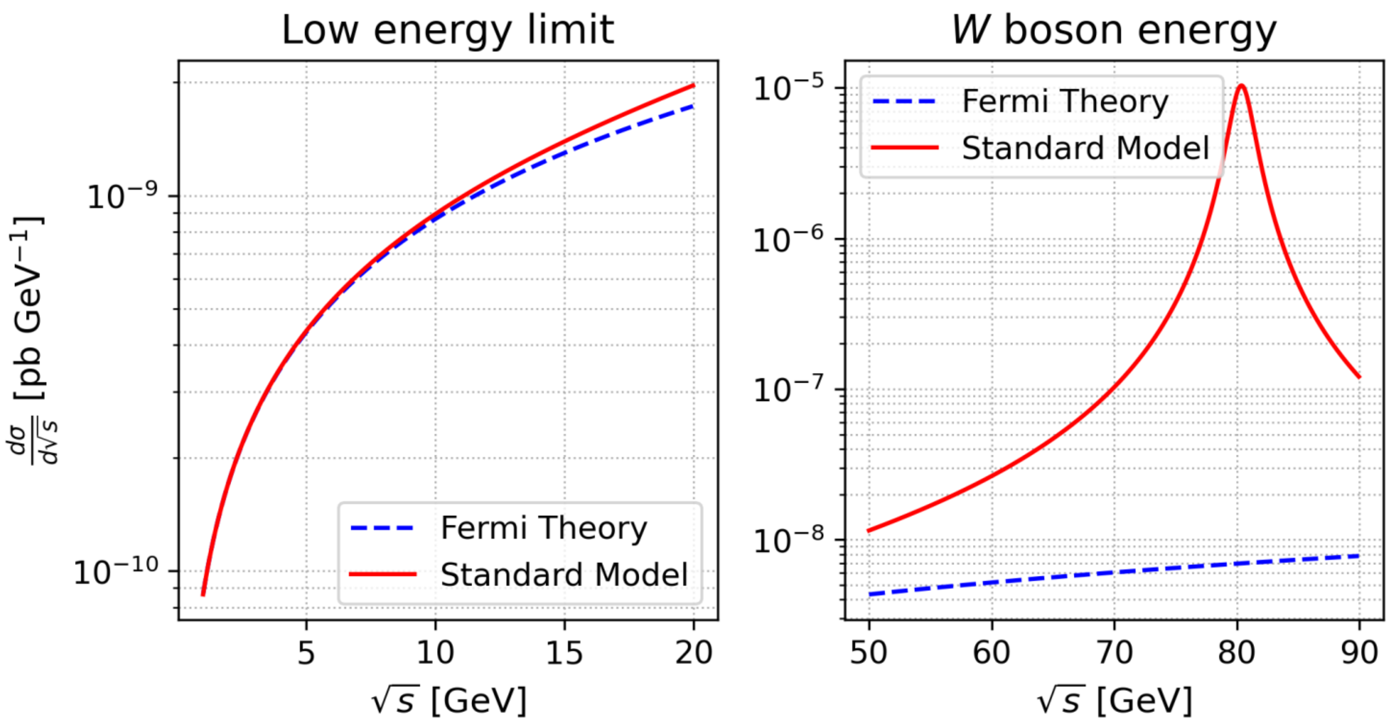


Fermi Theory as an EFT

We can look at the differential cross section predictions of SM and Fermi theory

1. At low energy, the two theories give the same result
2. At slightly higher energy, deviations from the Fermi prediction would become visible
3. Around W boson energy, the Fermi theory becomes completely inapplicable

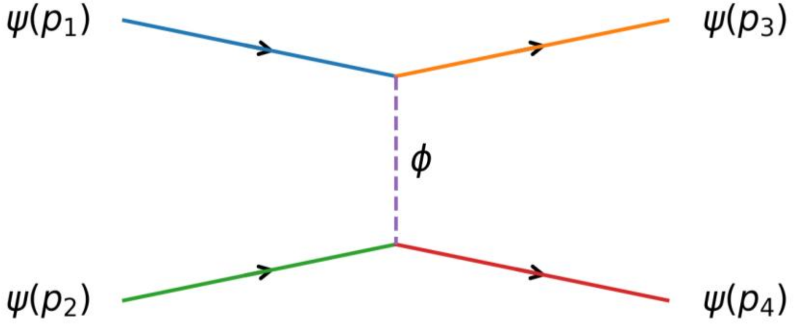
$\frac{d\sigma}{d\sqrt{s}}$ for $\nu d \to \ell^- u$



A Toy Effective Field Theory[+]

Let's consider this toy model:

$$S = \int d^4x \left\{ -\frac{1}{2}(\partial_\mu\phi)(\partial^\mu\phi) - \frac{1}{2}M^2\phi^2 + \bar{\Psi}\,(i\gamma^\mu\partial_\mu - m)\Psi + iy\,\phi\,\bar{\Psi}\gamma^5\Psi - \frac{1}{4!}\,\lambda\phi^4 \right\}$$



- Ψ is a fermionic field with small mass
- Φ is a scalar field with high mass m << M
- *y*, λ << 1 so that we can work in perturbation theory

The matrix element for an elastic scattering of two fermions is:

$$i\mathcal{M} = (-y)^2 \left\{ \bar{u}_{\lambda_3,p_3}\gamma^5\,u_{\lambda_1,p_1}\,\frac{-i}{(p_3-p_1)^2+M^2}\,\bar{u}_{\lambda_4,p_4}\gamma^5\,u_{\lambda_2,p_2} - (3 \leftrightarrow 4) \right\}$$

[+]*An Introduction to Effective Field Theories - arXiv:2006.16285v1*

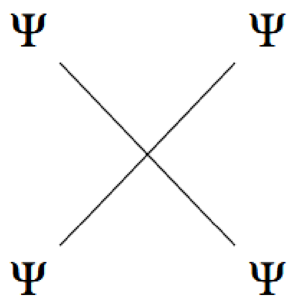
A Toy Effective Field Theory

The scalar propagator can be expanded in powers of momenta (considering $m^2 \ll p^2 \ll M^2$).
The first term is:

$$i\mathcal{M} \simeq -\frac{i\,y^2}{M^2}\left[\bar{u}_{\lambda_3,p_3}\gamma^5 u_{\lambda_1,p_1}\,\bar{u}_{\lambda_4,p_4}\gamma^5 u_{\lambda_2,p_2} - (3 \leftrightarrow 4)\right] + \mathcal{O}\left(\frac{E^2}{M^2}\right)$$

We would have obtained the same result with the effective theory:

$$S_{\text{eff}} = \int d^4x \left\{\bar{\Psi}(i\,\partial\!\!\!/ - m)\Psi \;-\; \frac{y^2}{2M^2}\left(\bar{\Psi}\gamma^5\Psi\right)^2\right\}$$



- At low energy ($E \ll M$) the two theories are *indistinguishable*
- The effective theory does **not** postulate a scalar boson

Standard Model as an EFT (SMEFT)

- Just like Fermi theory is an EFT for the SM, we can consider the SM to be an EFT of some bigger underlying theory
- SMEFT extends the SM in a model-independent way, capturing possible effects of high-energy new physics from lower-energy data

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

- Λ is the energy scale of new physics (here fixed at 1 TeV)
- C_i are the so-called ***Wilson coefficients***
- Any relevant operator that is compatible with the symmetries of the system should in principle be included
- $O_i^{(5)}$ and $O_i^{(7)}$ are not considered because they violate either leptonic or baryonic number[+]

[+] arXiv:1604.05726

SMEFT Operators in the Amplitude

The matrix element will then be:

$$\mathcal{M} = \mathcal{M}_{\rm SM} + \mathcal{M}^{(6)}_{\rm SMEFT} + \mathcal{M}^{(8)}_{\rm SMEFT}$$

And the cross section will be proportional to:

$$|\mathcal{M}|^2 = |\mathcal{M}_{\rm SM}|^2 + 2\,{\rm Re}\left(\mathcal{M}^*_{\rm SM}\mathcal{M}^{(6)}_{\rm SMEFT}\right) + |\mathcal{M}^{(6)}_{\rm SMEFT}|^2 + 2\,{\rm Re}\left(\mathcal{M}^*_{\rm SM}\mathcal{M}^{(8)}_{\rm SMEFT}\right) + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

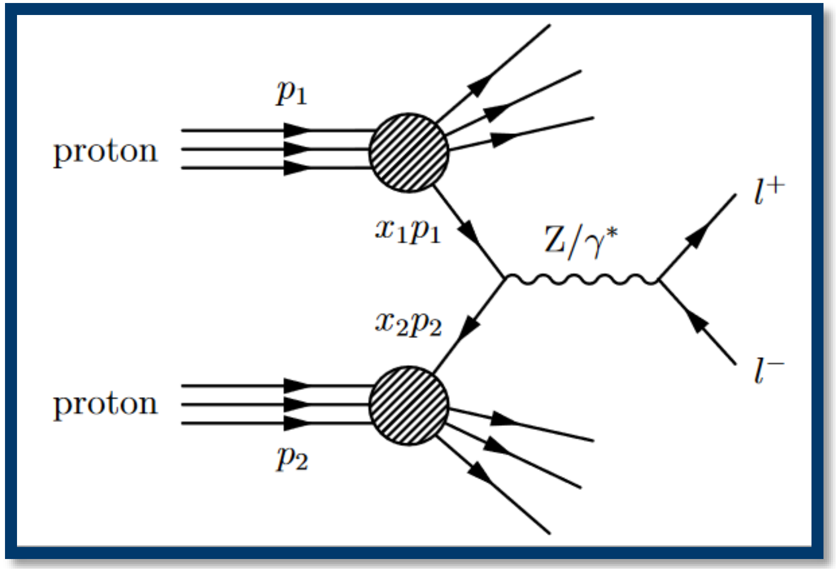
- The second term is the **interference** between SMEFT and SM (~$1/\Lambda^2$) and is a linear combination of the Wilson coefficients
- The third term is the pure SMEFT contribution (~$1/\Lambda^4$), sometimes referred to as the **squared term**, and it is a quadratic combination of the Wilson coefficients
- The interference between SM and dim-8 SMEFT operators also contributes to ~$1/\Lambda^4$

The Drell-Yan (DY) Process

The Drell–Yan process consists of a quark from one hadron and an antiquark from another hadron annihilating to produce a virtual photon or Z boson, which subsequently decays into a pair of oppositely charged leptons

➢Why choose DY?

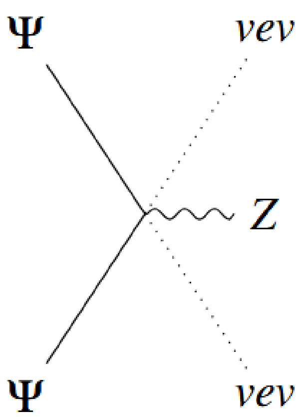
- With **2499** dimension-6 operators in the SMEFT, we must target specific processes where only a subset contributes significantly
- DY has a simple final state
- Many measurements of DY have already been performed at colliders



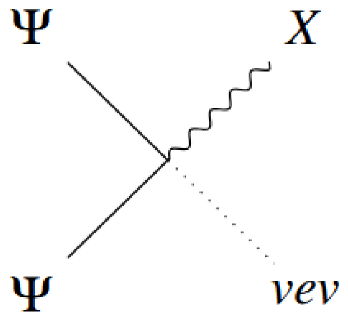
Dim-6 SMEFT Operators in DY

There are three classes of dim-6 operators for DY:

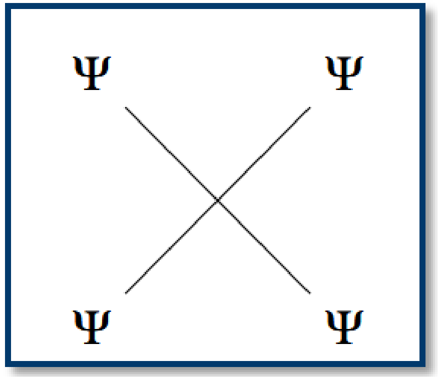
- $\Psi^2\phi^2 D$: these operators include a single derivative, a Higgs doublet and two fermions
  - They shift the SM coupling of the fermions to gauge bosons
  - *They have already been constrained at LEP*



- $\Psi^2 X\phi$: two fermions coupled to a gauge boson ($X = B_{\mu\nu}$, $G_{\mu\nu}$, $W_{\mu\nu}$) and a Higgs.
  - *They don't interfere with the SM*



- **Ψ^4: four-fermion operators**
  - **10 different operators (7 interfere with the SM)**
  - **They grow with E^2/Λ^2**



SMEFT Operators in DY

The relevant 4-fermion operators are:[+]

Operators $(LL)(LL)$

$$Q_{\ell q}^{(1)} = (\bar{\ell}_p \gamma_\mu \ell_r)(\bar{q}_s \gamma^\mu q_t)$$

$$Q_{\ell q}^{(3)} = (\bar{\ell}_p \gamma_\mu \tau^I \ell_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$$

Operators $(RR)(RR)$

$$Q_{eu} = (\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$$

$$Q_{ed} = (\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$$

Operators $(LL)(RR)$

$$Q_{\ell u} = (\bar{\ell}_p \gamma_\mu \ell_r)(\bar{u}_s \gamma^\mu u_t)$$

$$Q_{\ell d} = (\bar{\ell}_p \gamma_\mu \ell_r)(\bar{d}_s \gamma^\mu d_t)$$

$$Q_{qe} = (\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$$

Operators $(LR)(LR)$ and $(LR)(RL)$

$$^{*}Q_{ledq} = (\bar{\ell}_p^j e_r)(\bar{d}_s q_t^j)$$

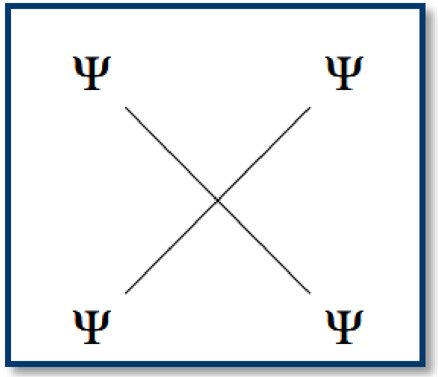
$$Q_{lequ}^{(1)} = (\bar{\ell}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$$

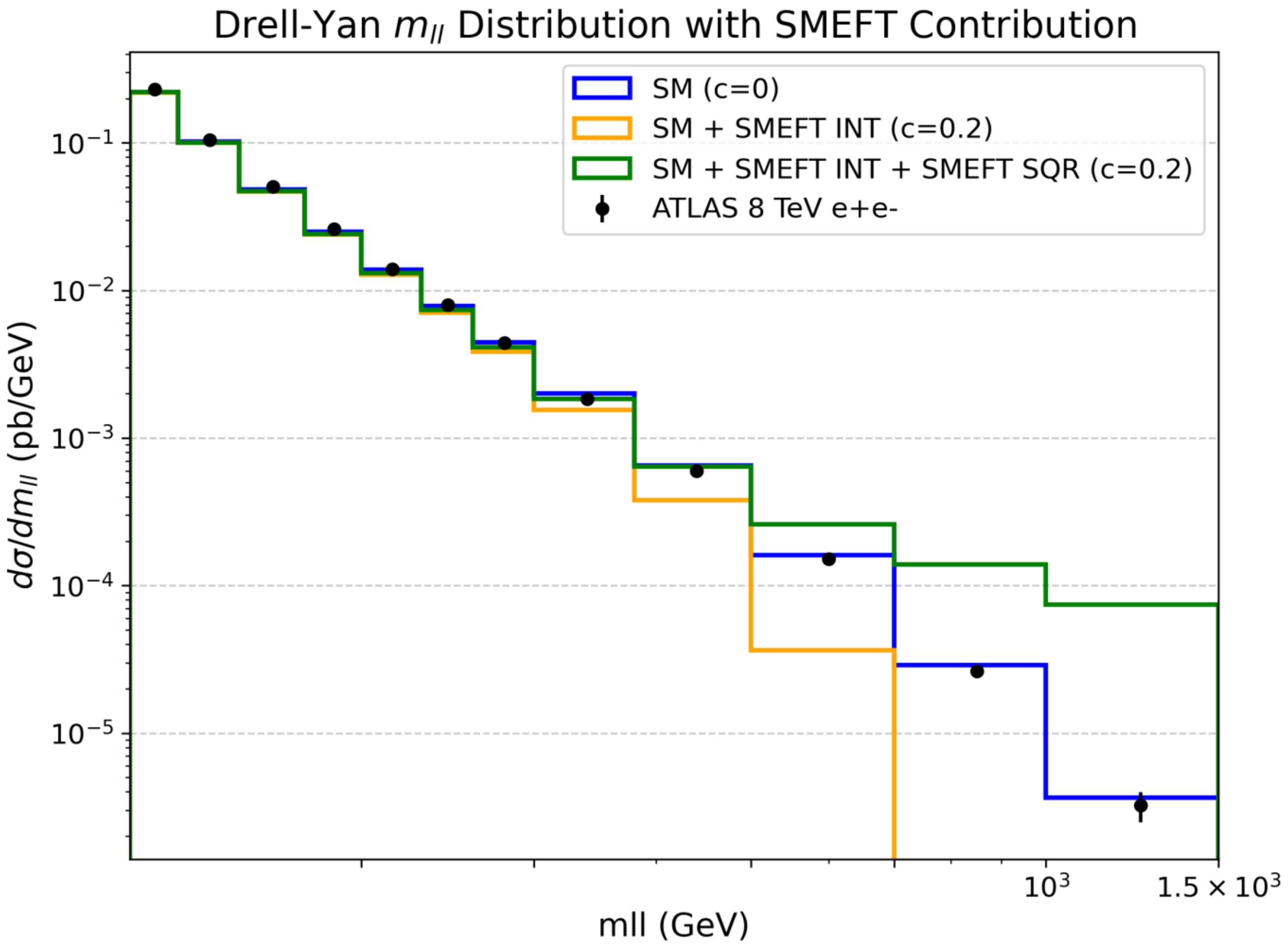
$$Q_{lequ}^{(3)} = (\bar{\ell}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$$

*In the code: c_{dls}, c_{uls}, c_{ult}

[+] *Dimension-Six Terms in the Standard Model Lagrangian - arXiv:1008.4884v3*

Including SMEFT Terms





- At higher energies, data are more sensitive to 4-fermion SMEFT operators
- We can vary *c* to fit the data

Fitting strategy

- For the fit, we use the signal strenght μ: $$\mu \equiv \frac{\sigma_{\exp}}{\sigma_{\mathrm{SM}}}$$
- And minimize the χ^2:

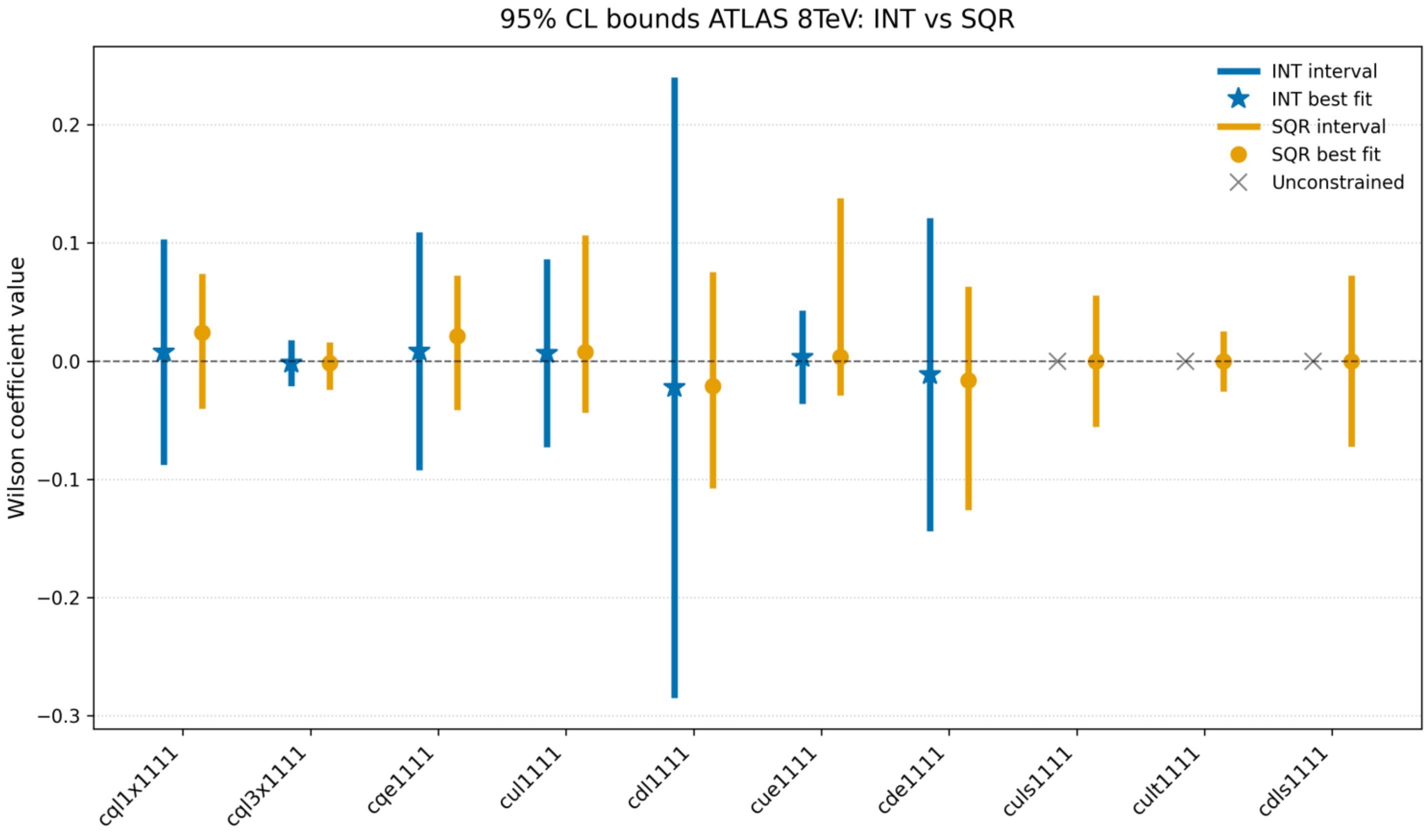
$$\chi^2(\vec{C}) = \left(\vec{\mu}_{\mathrm{data}} - \vec{\mu}_{\mathrm{th}}(\vec{C})\right)^T \mathbf{V}^{-1} \left(\vec{\mu}_{\mathrm{data}} - \vec{\mu}_{\mathrm{th}}(\vec{C})\right)$$

- Where:
  - C is a vector of the Wilson coefficients
  - V is the full covariance matrix
  - μ_{th} is defined as:

$$\mu_{\mathrm{th}}(\vec{C}) = 1 + \sum_i C_i\, \mu_i^{\mathrm{INT}} + \sum_{i \leq j} C_i C_j\, \mu_{ij}^{\mathrm{SQR}}$$

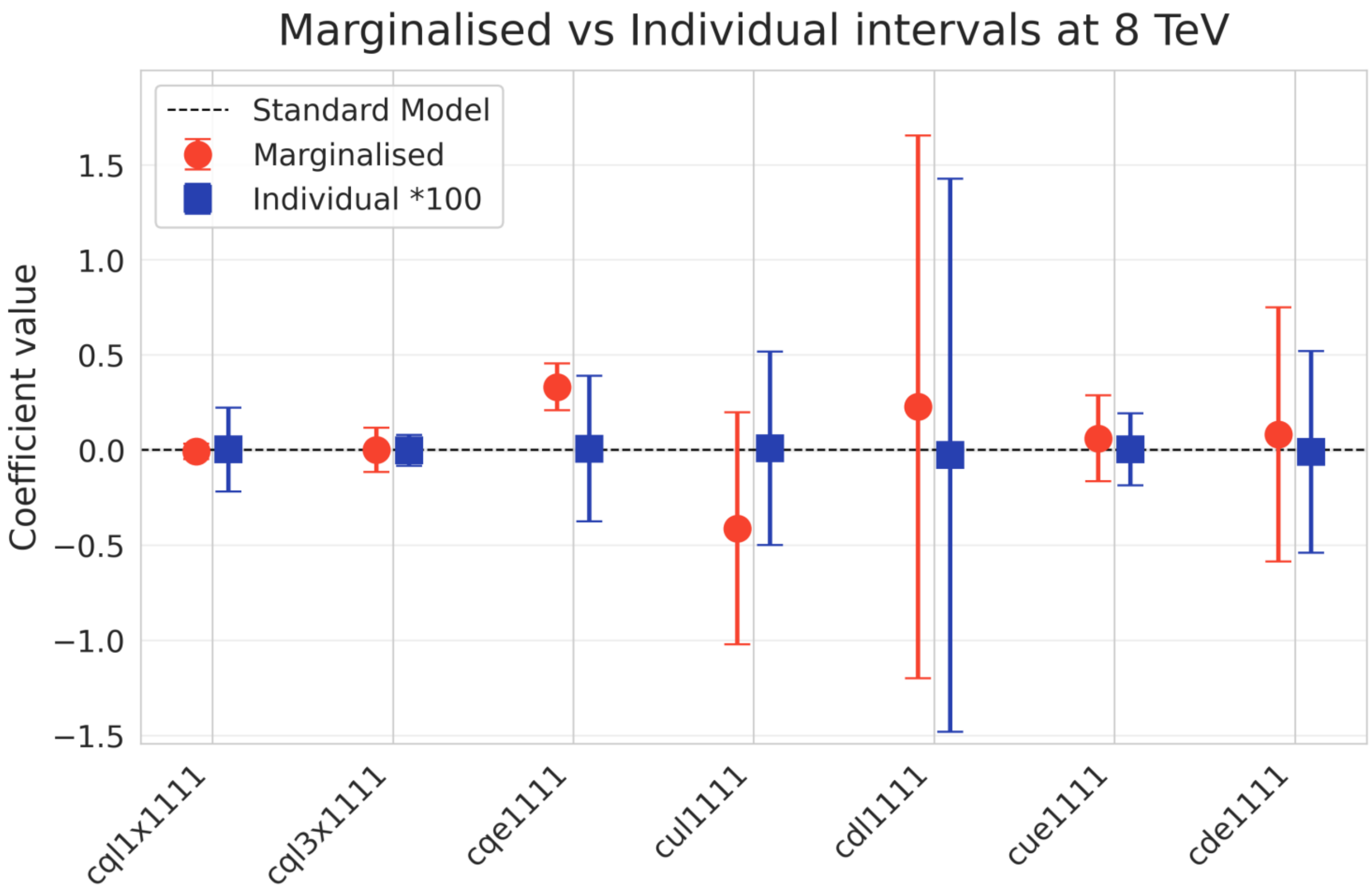
Preliminary SMEFT constraints from Drell–Yan

- **Two SMEFT fits**
  - one retaining only interference (INT) terms
  - one including also quadratic (SQR) contributions
- **Input observable**
  - Single-differential Drell–Yan cross section $d\sigma/dm$ from arXiv:1606.01736
- **Fit setup**
  - One Wilson coefficient at a time, all others set to zero



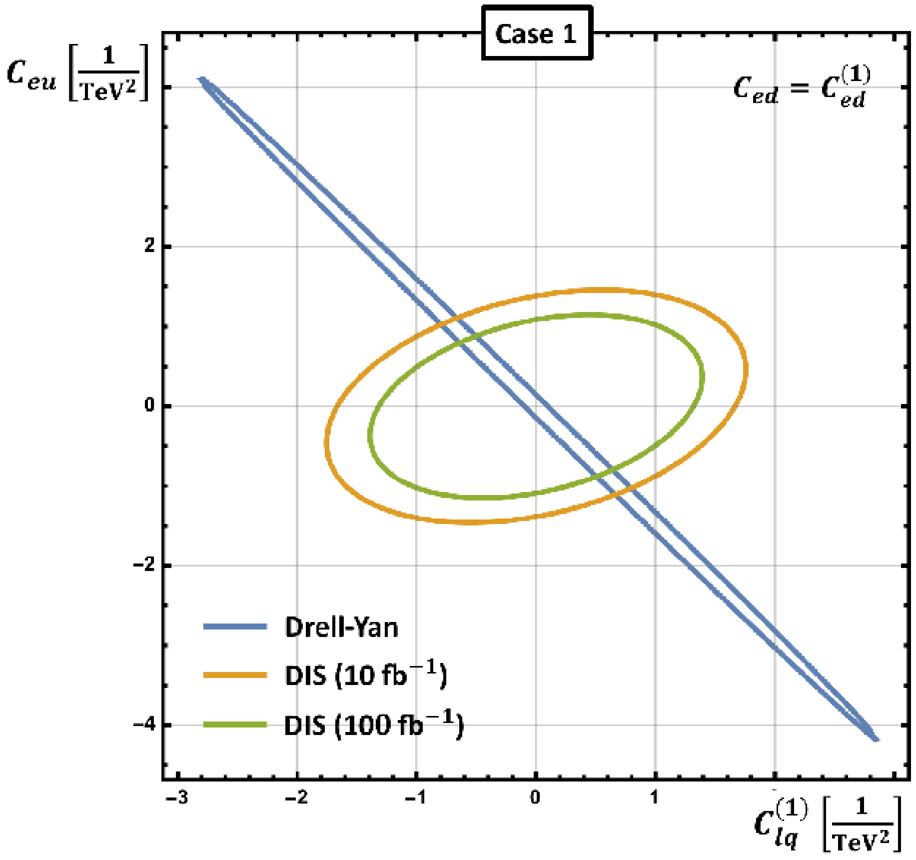
Preliminary SMEFT constraints from Drell–Yan

- **Input observable**
  - Double-differential Drell–Yan cross sections (from arXiv:1606.01736)
- **Fit setup**
  - Interference terms only (INT)
- **Treatment of Wilson coefficients**
  - individual fits: one coefficient at a time
  - marginalised fit: all coefficients varied simultaneously



Flat Directions

- **A common issue in Drell–Yan SMEFT fits**
  - Flat directions in the Wilson coefficient parameter space
- **Origin of flat directions**
  - One coefficient, or a linear combination of coefficients, remains unconstrained or weakly constrained by the data
- **Strategies to resolve flat directions**
  - Additional observables (e.g. forward–backward asymmetry, angular coefficients)
  - Increased differential information (double- or fully-differential distributions)
  - Complementary processes (e.g. charged Drell–Yan, low-energy measurements



Boughezal et al arXiv:2004.00748

Conclusions and Outlook

Conclusions

- Presented first results from a SMEFT fit to **ATLAS 8 TeV double-differential Drell–Yan data**
- Compared individual and marginalised constraints at **interference level**
- Highlighted the role of flat directions in DY-only fits

Outlook

- Implement a fitting framework based on **analytic EFT predictions**
- Address flat directions by including:
  - Low-energy observables[+]
  - Charged Drell–Yan measurements[*]

[+] arXiv:1706.03783
[*]arXiv:2502.12250v1

Thank you for your attention!

Matching Amplitudes

In order to understand the procedure it is useful to look at the generating function:

$$Z[J=0,\bar{\eta},\eta] = \int D\bar{\Psi}\, D\Psi\, e^{\frac{i}{\hbar}\int(\bar{\eta}\Psi+\bar{\Psi}\eta)} \int D\phi\, e^{\frac{i}{\hbar}S[\phi,\Psi]} = \int D\bar{\Psi}\, D\Psi\, e^{\frac{i}{\hbar}\int(\bar{\eta}\Psi+\bar{\Psi}\eta)} e^{\frac{i}{\hbar}S_{\text{eff}}[\Psi]}$$

$$S_{\text{eff}} = S_{\text{eff}}^{(0)} + \hbar S_{\text{eff}}^{(1)} + \mathcal{O}(\hbar^2),$$

Recalling that it is possible to evaluate the amplitude from Z through the LSZ formulae:

$$Z[J] \xrightarrow{\delta/\delta J} \langle 0|T\phi(x_1)\dots\phi(x_n)|0\rangle \xrightarrow{\text{LSZ}} \boxed{\mathcal{M}_{fi}}$$

- $S_{eff}^{(0)}$ describes an EFT that reproduces all tree-level amplitudes of fermions in the full theory
- $S_{eff}^{(1)}$ describes all 1-loop corrections
- And so on…

Matching Amplitudes

Let's focus on the tree-level effective action $S_{eff}^{(0)}$ and assume:

$$e^{iS_{\text{eff}}^{(0)}[\Psi]/\hbar} = e^{iS[\hat{\phi},\Psi]/\hbar}, \qquad \text{with } \hat{\phi}[\Psi] \text{ a solution of } \quad \frac{\delta S[\hat{\phi},\Psi]}{\delta\hat{\phi}} = 0.$$

The Lagrangian equation of the full theory with respect to Φ will be:

$$(\Box - M^2)\phi + yJ - \frac{\lambda}{3!}\phi^3 = 0 \qquad \text{with } J \equiv i\bar{\Psi}\gamma^5\Psi$$

We can solve this equation using a perturbative expansion:

$$\hat{\phi} = \sum_{n=0}^{\infty} \frac{1}{M^{2n+2}}\phi^{(n)}$$

And obtain:

$$\hat{\phi} = \frac{y}{M^2}\left(1 + \frac{\Box}{M^2} + \frac{\Box^2}{M^4} + \frac{\Box^3}{M^6}\right) J - \frac{\lambda y^3}{6M^8} J^3 + \cdots$$

Matching Amplitudes

We can now use this result in the starting generating functional to obtain the complete effective action at tree level:

$$S^{(0)}_{\text{eff}} = \int d^4x \left\{ \bar{\Psi}(i\gamma^\mu \partial_\mu - m)\Psi + \frac{y^2}{2M^2}\mathcal{J}\left(1 + \frac{\Box}{M^2} + \frac{\Box^2}{M^4} + \frac{\Box^3}{M^6}\right)\mathcal{J} - \frac{\lambda y^4}{4!M^8}\mathcal{J}^4 + \cdots \right\}$$

- The first dim-6 term is the same as the one obtained from the 4-fermions elastic scattering
- The other terms capture all possible tree-level amplitudes
- The EFT contains an infinite number of *non-renormalizable* interactions
- The ***coefficients*** before each operator are a specific function of the full theory parameters
- Here, a complete matching procedure was possible because we knew the full theory

Summary of the SMEFT approach

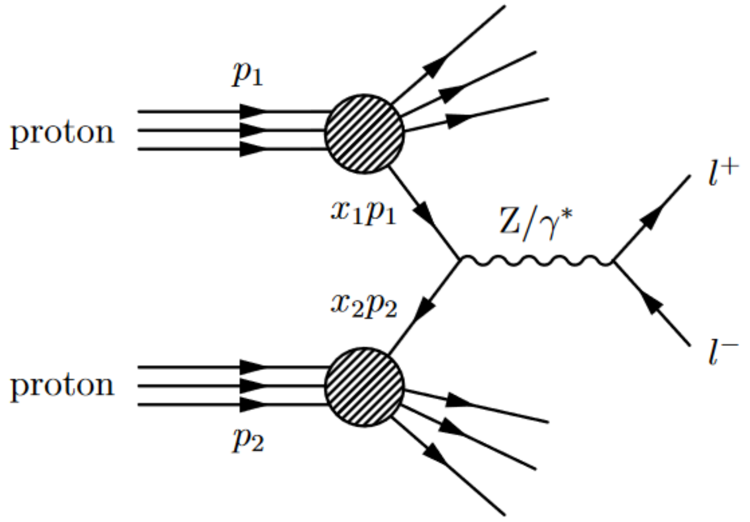
- Contrary to the toy model, we don't know the full theory
- A matching procedure for the Wilson coefficients is not possible
- All dim-6 and dim-8 SMEFT operators have been categorized[+]
- We can include them in our calculations and try to constrain the Wilson coefficients
- A non-zero W*ilson coefficient* would suggest new physics
- The SMEFT is *not* a final theory, but a framework that may offer hints about the underlying one
- At new physics energy, it will break and a new theory will be needed

[+]*DOI: 10.1016/0550-3213(86)90262-2 , arXiv:1008.4884v3, DOI: 10.1007/JHEP10(2020)174, DOI: 10.1103/PhysRevD.104.015026*

Differential Cross Section in DY

The hadronic differential cross section in cosθ is obtained by integrating over PDFs:

$$\frac{d\sigma}{d\cos\theta} = \sum_q \int dx_1 dx_2\, f_q(x_1)\, f_{\bar{q}}(x_2)\, \frac{d\hat{\sigma}}{d\cos\theta}(\hat{s}), \quad \hat{s} = x_1 x_2 s$$



To express σ in terms of the invariant mass, we perform a change of variables:

$$\sigma = \sum_q \int_0^1 dx_1 \int_0^1 dx_2 \left(f_q(x_1,Q^2) f_{\bar{q}}(x_2,Q^2) + q \leftrightarrow \bar{q}\right) \hat{\sigma}(x_1 x_2 s)$$

$$\left(x_1 x_2 \equiv \tau,\ y \equiv \frac{1}{2}\ln\frac{x_1}{x_2},\ x_{1,2} = \sqrt{\tau} e^{\pm y}\right)$$

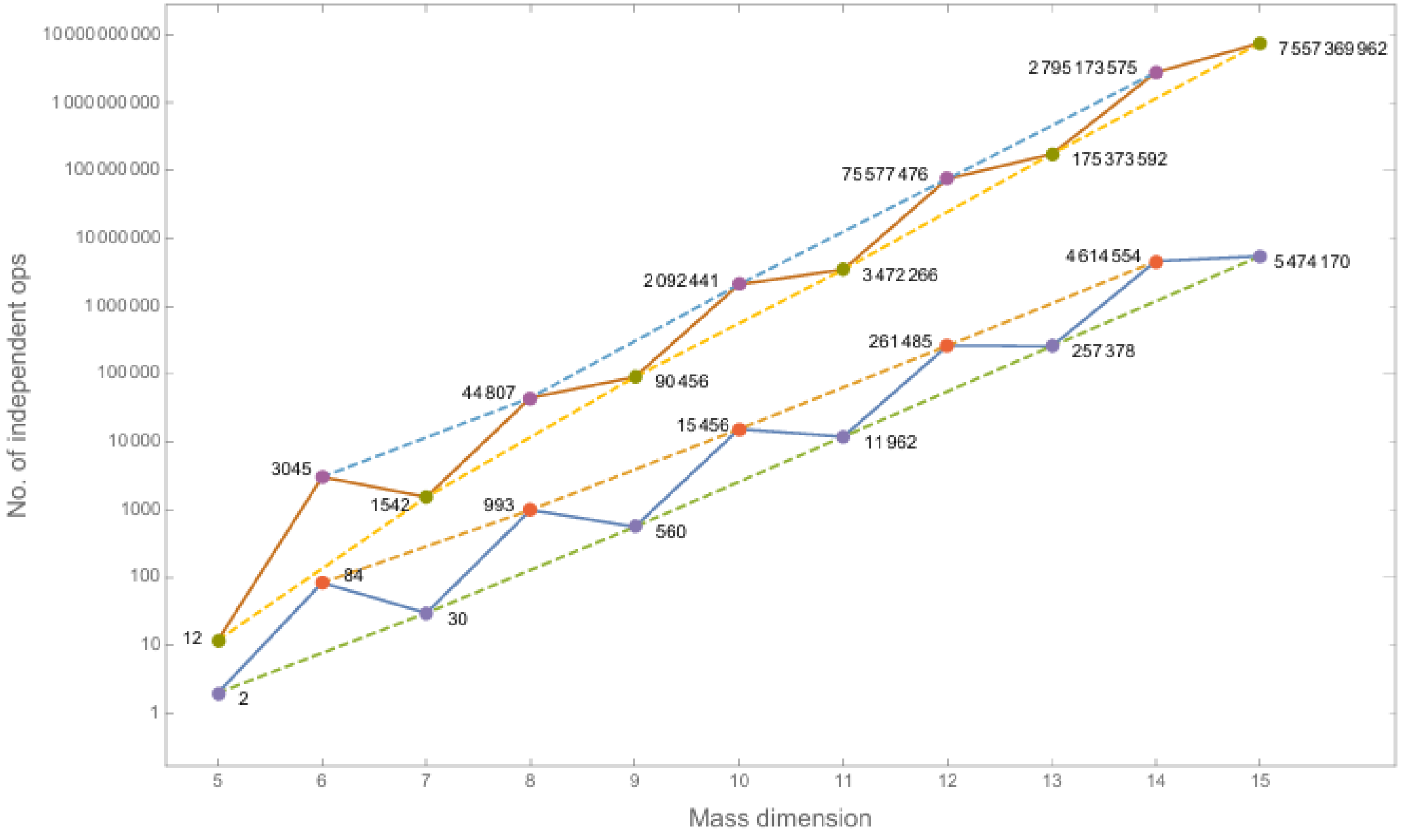
$$= \sum_q \int_0^1 d\tau \int_{-\frac{1}{2}\ln\tau}^{\frac{1}{2}\ln\tau} dy \left(f_q(\sqrt{\tau}e^{+y},Q^2) f_{\bar{q}}(\sqrt{\tau}e^{-y},Q^2) + q \leftrightarrow \bar{q}\right) \hat{\sigma}(\tau s)$$

$$\frac{d\sigma}{d\hat{s}} = \frac{1}{s} \int_{-\frac{1}{2}\ln\frac{\hat{s}}{s}}^{\frac{1}{2}\ln\frac{\hat{s}}{s}} dy \left(f_q(\sqrt{\frac{\hat{s}}{s}}e^{+y},Q^2) f_{\bar{q}}(\sqrt{\frac{\hat{s}}{s}}e^{-y},Q^2) + q \leftrightarrow \bar{q}\right) \hat{\sigma}(\hat{s})$$

We obtain this result for the single differential cross section:

$$\frac{d\sigma}{dM} = \frac{2M}{s} \int_{-\frac{1}{2}\ln\frac{M^2}{s}}^{\frac{1}{2}\ln\frac{M^2}{s}} dy \left(f_q(\sqrt{\frac{M^2}{s}}e^{+y},Q^2) f_{\bar{q}}(\sqrt{\frac{M^2}{s}}e^{-y},Q^2) + q \leftrightarrow \bar{q}\right) \hat{\sigma}(M^2)$$

How many SMEFT operators?



Growth of the number of independent operators in the SM EFT up to mass dimension 15. Points joined by the lower solid line are for one fermion generation; those joined by the upper solid line are for three generations. Dashed lines are to guide the eye to the growth of the even and odd mass dimension operators in both cases.

Ref: arXiv:1512.03433v2

Helicity Amplitudes

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

$$\{\bar{R}L\bar{L}L\}, \{\bar{R}L\bar{R}R\}, \{\bar{L}L\bar{L}R\}, \{\bar{R}R\bar{R}L\}, \quad 0$$

$$\{\bar{L}R\bar{R}R\}, \{\bar{L}R\bar{L}L\}, \{\bar{R}R\bar{L}R\}, \{\bar{L}L\bar{R}L\}, \quad 0$$

$$\{\bar{R}L\bar{R}L\}, \{\bar{L}R\bar{L}R\}, \quad 0$$

$$\{\bar{R}L\bar{L}R\} \quad -\frac{4ic_{ulS}^{1111}\,s\,\delta_{\mathrm{Col1,Col2}}}{\Lambda^2}$$

$$\{\bar{L}L\bar{L}L\} \quad \frac{is(c_{Ql1x}^{1111}-c_{Ql3x}^{1111})(1+\cos\theta)\,\delta_{\mathrm{Col1,Col2}}}{\Lambda^2}+\frac{ie^2\,(1+\cos\theta)\,\delta_{\mathrm{Col1,Col2}}(3c_w^4 s+4c_w^2 s_w^2(s-2M_Z^2)+ss_w^4)}{12c_w^2 s_w^2(M_Z^2-s)}$$

$$\{\bar{L}L\bar{R}R\} \quad \frac{ie^2\,(1-\cos\theta)\,\delta_{\mathrm{Col1,Col2}}(c_w^2(4M_Z^2-s)-ss_w^2)}{6c_w^2(M_Z^2-s)}-\frac{2ic_{Qe}^{1111}s\,(1-\cos\theta)\,\delta_{\mathrm{Col1,Col2}}}{\Lambda^2}$$

$$\{\bar{R}R\bar{L}L\} \quad \frac{ie^2\,(1-\cos\theta)\,\delta_{\mathrm{Col1,Col2}}(c_w^2(2M_Z^2-s)-ss_w^2)}{3c_w^2(M_Z^2-s)}-\frac{ic_{ul}^{1111}s\,(1-\cos\theta)\,\delta_{\mathrm{Col1,Col2}}}{\Lambda^2}$$

$$\{\bar{R}R\bar{R}R\} \quad \frac{2ie^2\,(1+\cos\theta)\,\delta_{\mathrm{Col1,Col2}}(c_w^2(M_Z^2-s)-ss_w^2)}{3c_w^2(M_Z^2-s)}-\frac{ic_{ue}^{1111}s\,(1+\cos\theta)\,\delta_{\mathrm{Col1,Col2}}}{\Lambda^2}$$

$$\{\bar{L}R\bar{R}L\} \quad \frac{4ic_{ulS}^{1111}\,s\,\delta_{\mathrm{Col1,Col2}}}{\Lambda^2}$$

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

$$\{\bar{R}L\bar{L}L\}, \{\bar{R}L\bar{R}R\}, \{\bar{L}L\bar{L}R\}, \{\bar{R}R\bar{R}L\}, \quad 0$$

$$\{\bar{L}R\bar{R}R\}, \{\bar{L}R\bar{L}L\}, \{\bar{R}R\bar{L}R\}, \{\bar{L}L\bar{R}L\}, \quad 0$$

$$\{\bar{R}L\bar{L}R\}, \{\bar{L}R\bar{R}L\}, \quad 0$$

$$\{\bar{R}L\bar{R}L\} \quad \frac{-4ic_{dls}^{1111}\,s\,\delta_{\mathrm{Col1,Col2}}}{\Lambda^2}$$

$$\{\bar{L}L\bar{L}L\} \quad \frac{is(c_{Ql1x}^{1111}+c_{Ql3x}^{1111})(\cos\theta+1)\,\delta_{\mathrm{Col1,Col2}}}{\Lambda^2}-\frac{ie^2\left(\frac{1+\cos\theta}{2}\right)\delta_{\mathrm{Col1,Col2}}\left(3c_w^4 s+2c_w^2 s_w^2(s-2M_Z^2)-ss_w^4\right)}{6c_w^2 s_w^2(M_Z^2-s)}$$

$$\{\bar{L}L\bar{R}R\} \quad \frac{ic_{Qe}^{1111}s(\cos\theta-1)\,\delta_{\mathrm{Col1,Col2}}}{\Lambda^2}+\frac{ie^2(\cos\theta-1)\,\delta_{\mathrm{Col1,Col2}}\left(c_w^2(2M_Z^2+s)+ss_w^2\right)}{6c_w^2(M_Z^2-s)}$$

$$\{\bar{R}R\bar{L}L\} \quad \frac{i\,(1-\cos\theta)\,\delta_{\mathrm{Col1,Col2}}\,c_{dl}^{1111}s}{\Lambda^2}-\frac{i\,(1-\cos\theta)\,\delta_{\mathrm{Col1,Col2}}\,EL^2\left(cw^2(s-2MZ^2)+s\,sw^2\right)}{6\,cw^2(MZ^2-s)}$$

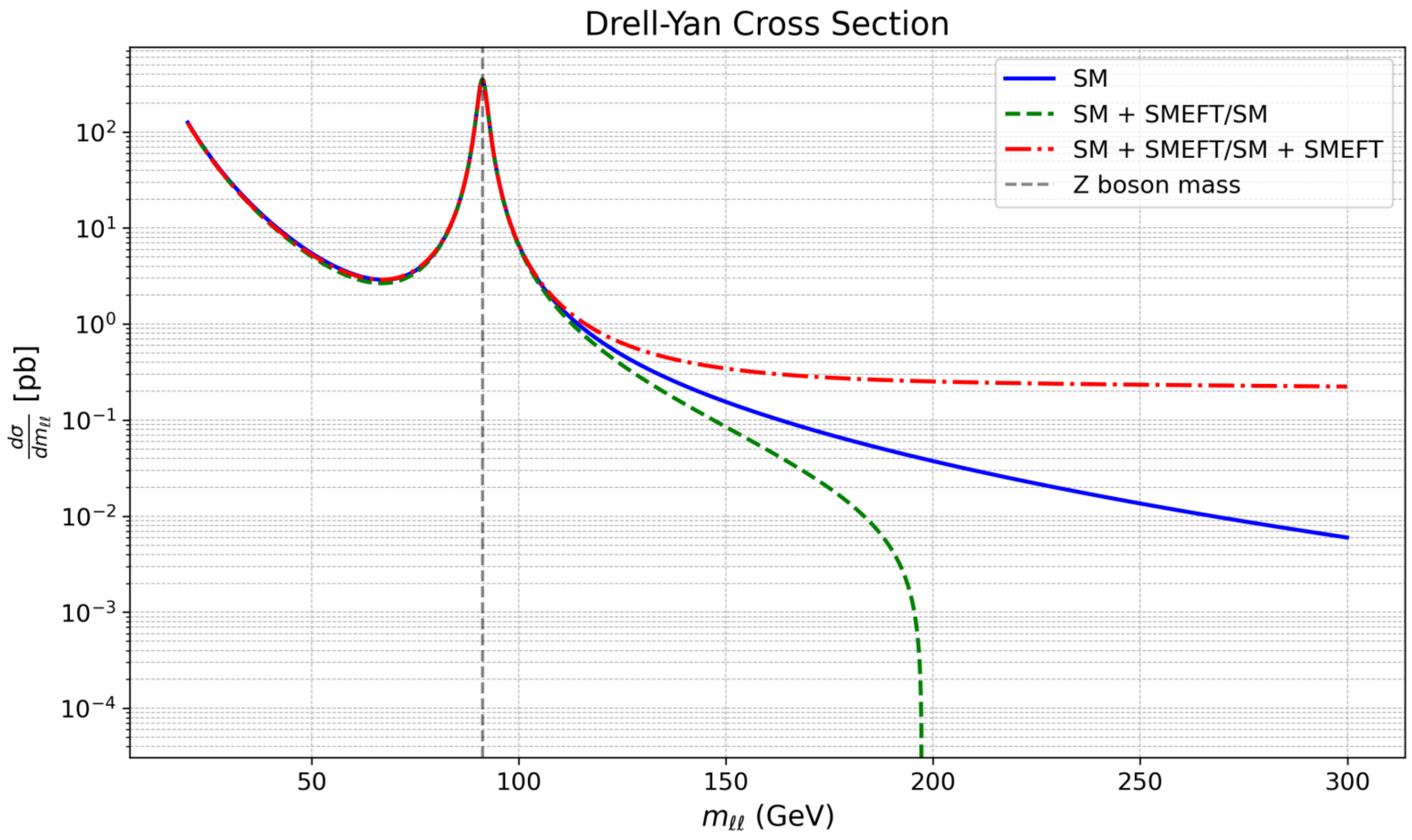
$$\{\bar{R}R\bar{R}R\} \quad \frac{2}{3}ie^2\left(\frac{1+\cos\theta}{2}\right)\delta_{\mathrm{Col1,Col2}}\left(\frac{ss_w^2}{c_w^2(M_Z^2-s)}-1\right)-\frac{2ic_{de}^{1111}s\left(\frac{1+\cos\theta}{2}\right)\delta_{\mathrm{Col1,Col2}}}{\Lambda^2}$$

$$\{\bar{L}R\bar{L}R\} \quad \frac{4ic_{dls}^{1111}\,s\,\delta_{\mathrm{Col1,Col2}}}{\Lambda^2}$$

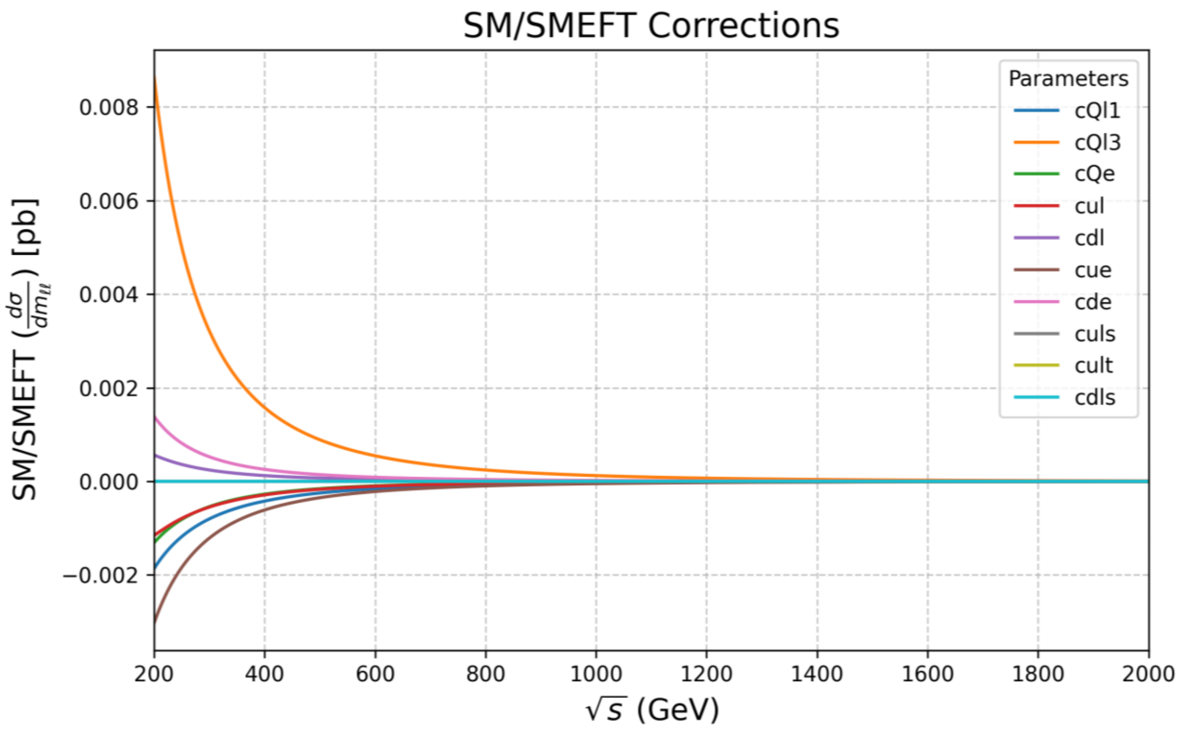
These are the subprocesses helicity amplitudes at order *~1/Λ²*
(SM is marked in *black*, interference terms are in *red*)

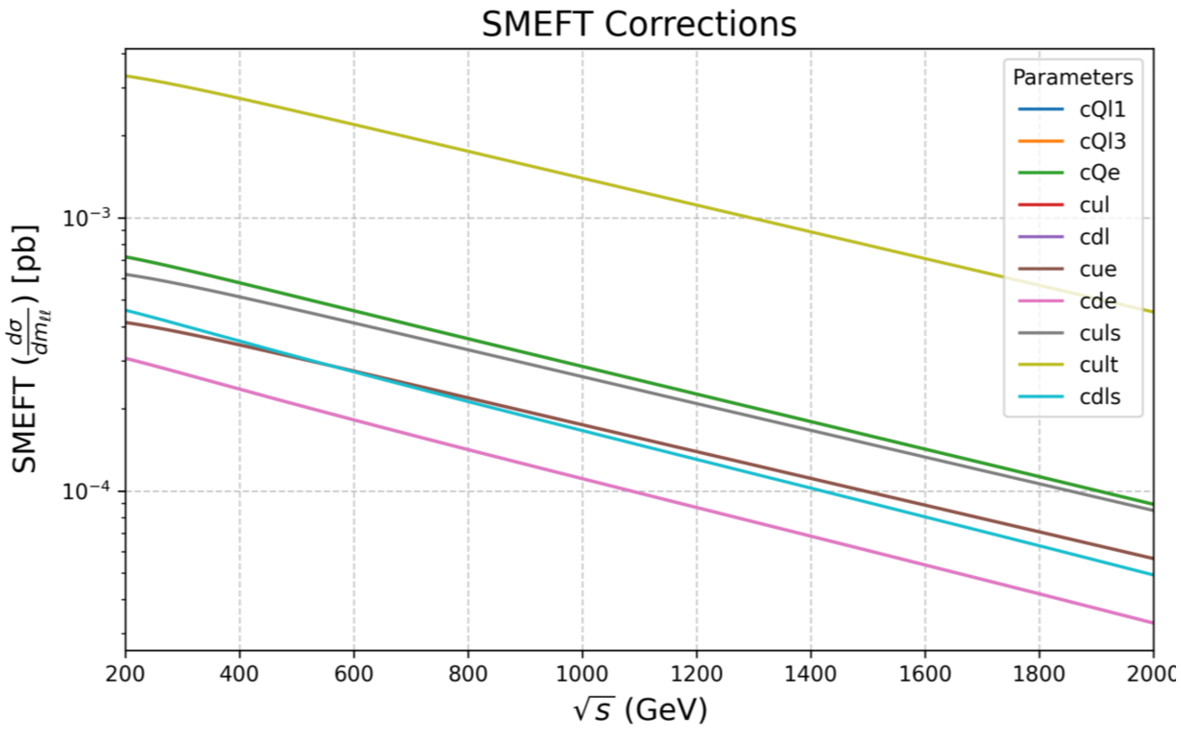
Differential Cross Section: p p → e^+e^-

- In this plot Λ = *1TeV*, $c_{Ql(1)}^{1111} = 10$
- Effects from the SMEFT operators are relevant at high m_{ll}
- Results up to $1/\Lambda^2$ are negative at high m_{ll} for the chosen *Wilson coefficient*



SMEFT Contributions: p p ⟶ e^+e^-

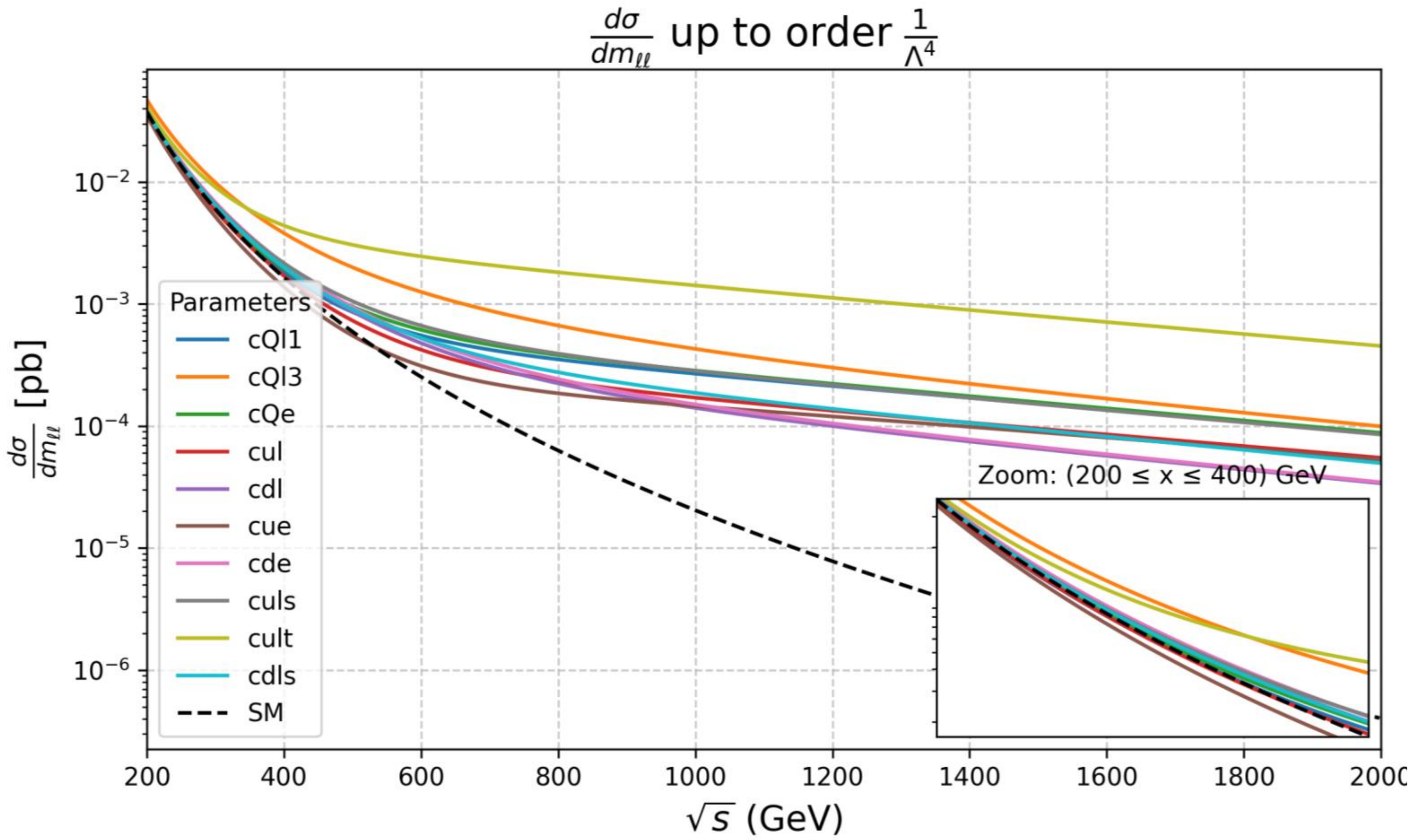




- Each class of operators is tested by setting its coefficient to *0.5*, while the others are set to zero
- Some interference terms are identically zero
- Both the interference and the squared contributions go to zero at high energy due to PDFs

Differential Cross Section: p p → e^+e^-

Summing these contributions to the SM, we obtain:



Relative impact of the SMEFT contributions

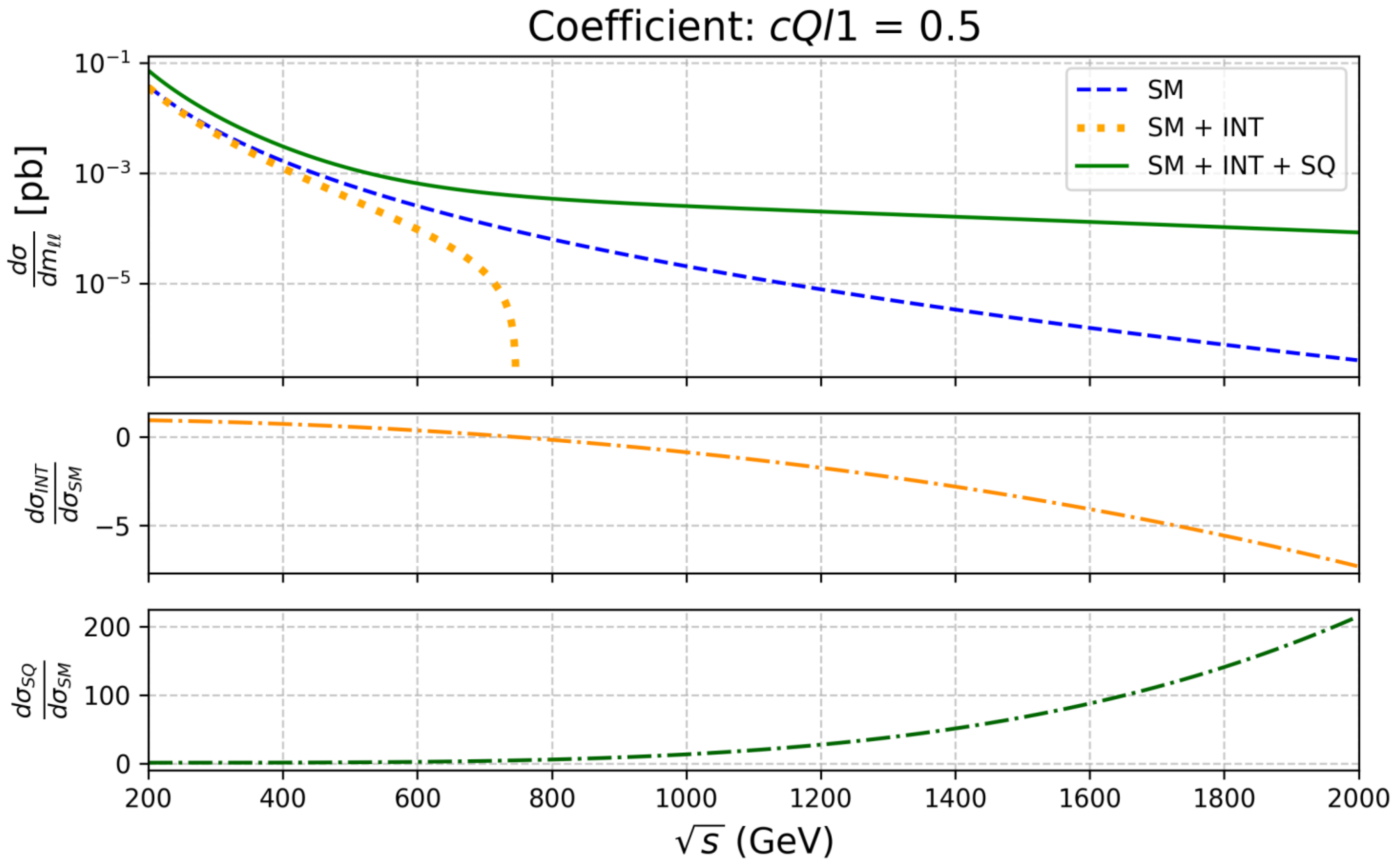
- In this plot $\Lambda = 1TeV$, $c_{Ql(1)} = 0.5$
- The second panel displays the ratio:

$$\frac{d\sigma_{\text{SM}} + d\sigma_{\text{INT}}}{d\sigma_{\text{SM}}}$$

- The third panel displays the ratio:

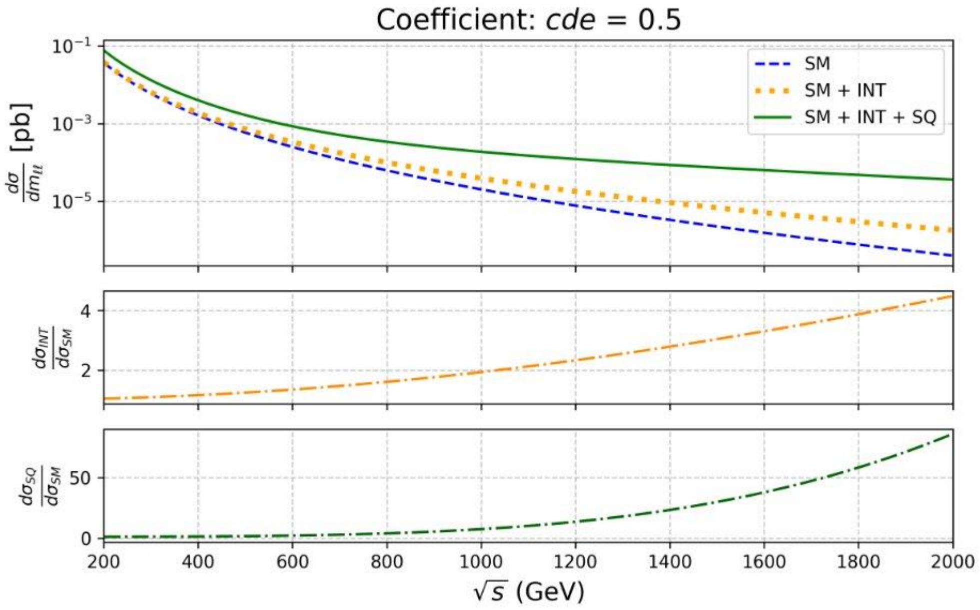
$$\frac{d\sigma_{\text{SM}} + d\sigma_{\text{INT}} + d\sigma_{\text{SQ}}}{d\sigma_{\text{SM}}}$$

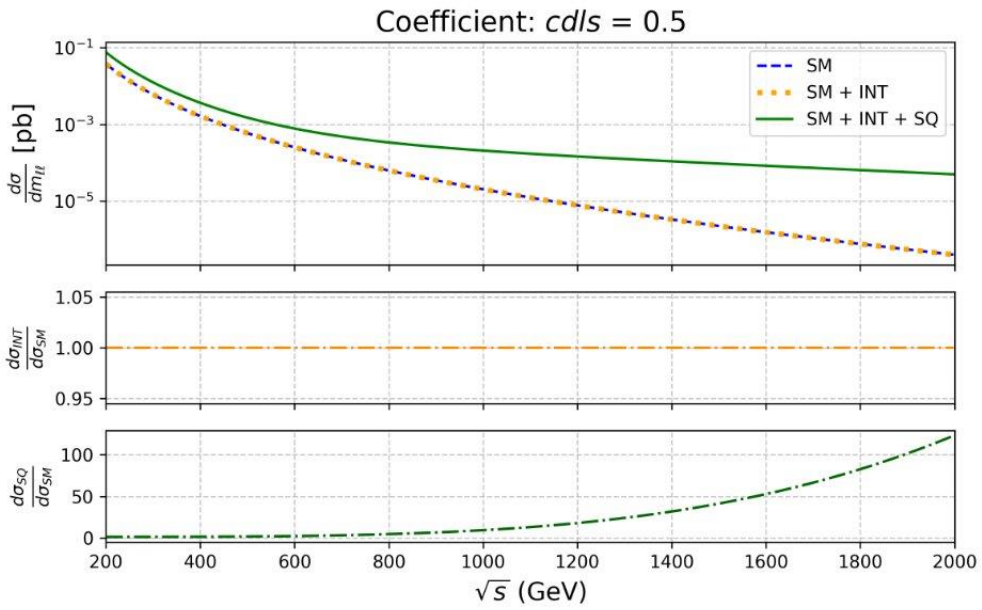
- In both cases the absolute value of the ratio increases at high energy
- This makes these operators of particular interest



Relative impact of the SMEFT contributions

The same plot can be replicated for all operators:



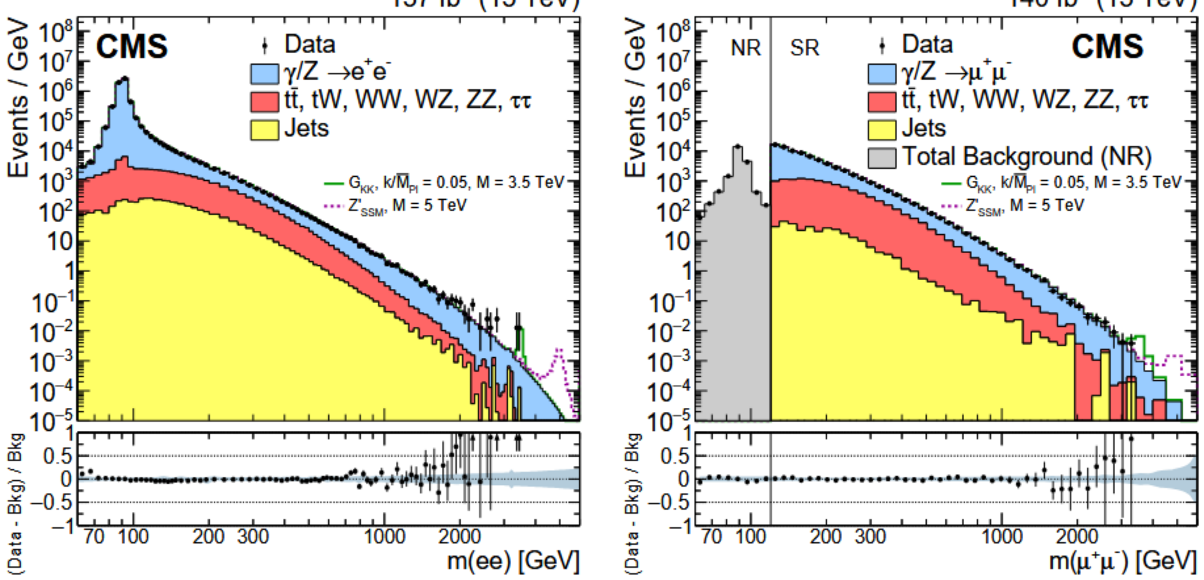


- The operators shown here yield, respectively, positive and zero interference terms
- This, once again, shows a ratio that increases with energy

Conclusions

- I have shown analytic calculations of helicity amplitudes for different subprocesses
- I used these results to compute a single differential cross section, which allows for future predictions at collider energies
- The results have been validated with MadGraph5 aMC@NLO [+] and require less computational resources than a Monte Carlo simulation to be produces

arXiv:2103.02708v2



[+] *arXiv:1405.0301*