The Impact of Theoretical Errors in the SMEFT

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In Search of New Physics Using SMEFT
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Why should we care about uncertainties in signals?

- Neglecting or downplaying signal-function theory errors is very common in the pheno community
  - Idea being that you can clean up the calculations once we find something, but signatures won't change drastically
- Neglecting errors is never correct in precision measurements or calculations, though, and that's the business we're in

A Quote from a Model Builder

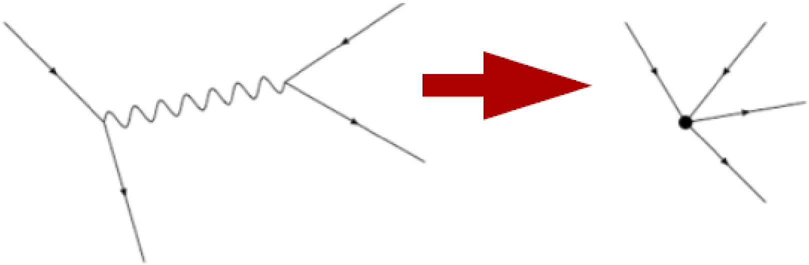
- “Whatever bound you get from your EFT, I can always write down a model that passes the test against data and violates the bound you claim to have.” – Bhaskar Dutta

Based on…

- 1711.07484, 1812.07575 with Stefan Alte and Matthias König
- 1907.13160 with Eduard Keilmann

Introduction: EFT

- The canonical example of an EFT is Fermi's theory of weak decay
  - A real limit of the SM



- We still use this today!
- Captures physics in a particular energy regime
  - Count in powers of E/Mw
- Ability to systematically improve theory predictions is the key virtue of EFTs

Warsaw Basis

$1 : X^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$Q_{\widetilde{W}}$	$\epsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

$2 : H^6$	
Q_H	$(H^\dagger H)^3$

$3 : H^4 D^2$	
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$

$5 : \psi^2 H^3 + \text{h.c.}$	
Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$

$4 : X^2 H^2$	
Q_{HG}	$H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}^A_{\mu\nu} G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}^I_{\mu\nu} W^{I\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$
Q_{HWB}	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}^I_{\mu\nu} B^{\mu\nu}$

$6 : \psi^2 X H + \text{h.c.}$	
Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I H W^I_{\mu\nu}$
Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \widetilde{H}\, G^A_{\mu\nu}$
Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \widetilde{H}\, W^I_{\mu\nu}$
Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \widetilde{H}\, B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H\, G^A_{\mu\nu}$
Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I H\, W^I_{\mu\nu}$
Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

$7 : \psi^2 H^2 D$	
$Q_{Hl}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
$Q_{Hq}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
$Q_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$
Q_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
Q_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
$Q_{Hud} + \text{h.c.}$	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$

Warsaw Basis: 4-fermion

$8:(\bar{L}L)(\bar{L}L)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$

$8:(\bar{R}R)(\bar{R}R)$	
Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$
Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$
Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$8:(\bar{L}L)(\bar{R}R)$	
Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$8:(\bar{L}R)(\bar{R}L)+\mathrm{h.c.}$	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$

$8:(\bar{L}R)(\bar{L}R)+\mathrm{h.c.}$	
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\epsilon_{jk}(\bar{q}_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\epsilon_{jk}(\bar{q}_s^k T^A d_t)$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu} u_t)$

How to build a collider search

- Canonical search design boils down to plugging a new physics model into Monte Carlo tools and constraining what comes out
  - Many nice tools exist for this purpose now, e.g. SMEFTsim
- Greatest challenge to such a search is the concern about EFT consistency; this description breaks down when the new particles are light enough
  - Ensuring EFT internal consistency is the best model-independent way of addressing this concern

Ideal EFT Search

- Ideally, we want to be able to treat the theory errors as measurable nuisance parameters
  - Often possible for systematics, occasionally used for e.g. normalizations of EW corrections
- Since we aren’t calculating the full dim-8 effect anytime soon, we must rely on the EFT structure to do this
- Power series in inverse cutoff scale is the only robust prediction of the EFT

Ideal EFT Search

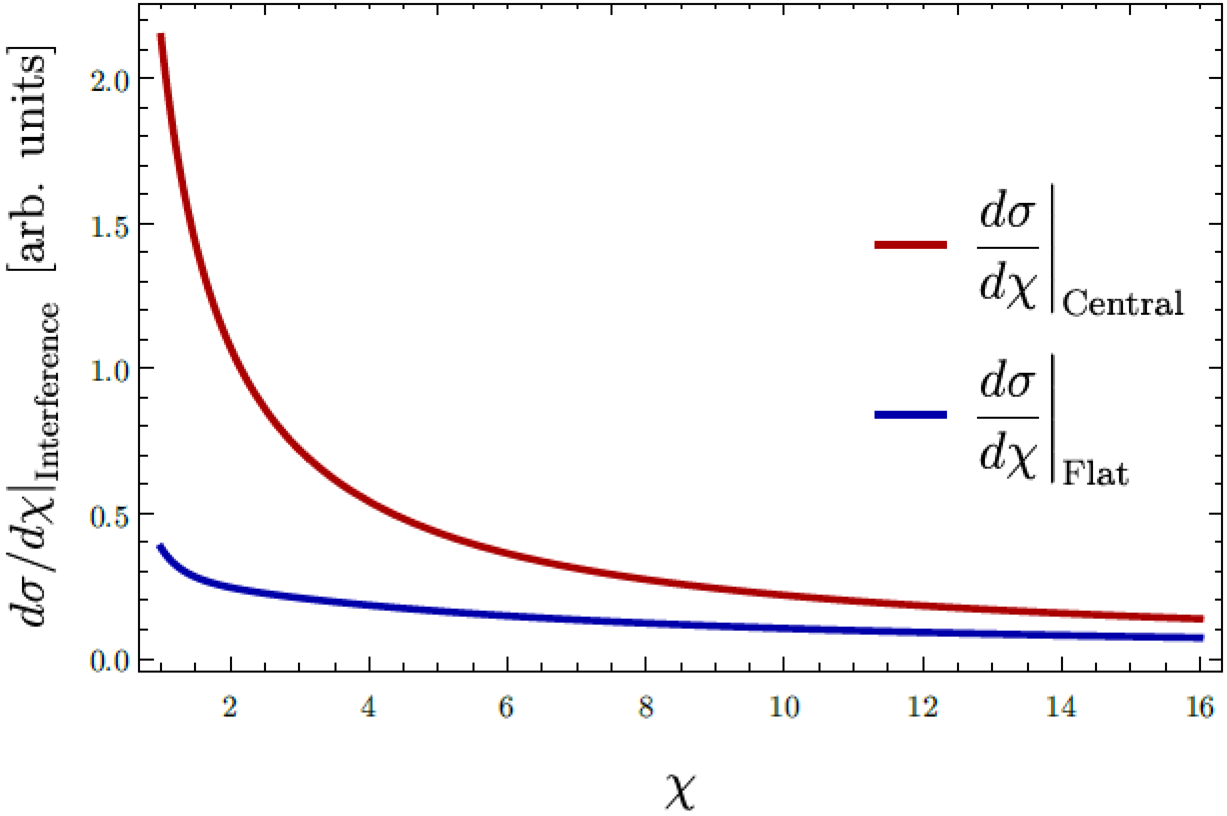
- The best way to utilize this feature is to fit the data in event energy scale
- $\sigma = \sigma_{SM}(1 + \sum_1^\infty c_n \frac{\hat{s}^{2n}}{\Lambda^{2n}})$
  - ‘Signal’ is linear term, predicted in terms of dim-6 operator Wilson coefficients
- Theory error now probed by sensitivity to series truncation

Real-World Problems

- $\sigma \neq \sigma_{SM}(1 + \sum_1^\infty c_n \frac{\hat{s}^{2n}}{\Lambda^{2n}})$
  - Different PDF contributions to different order contributions to cross section
  - Indicates that errors cannot be fit away cleanly for unknown higher-order effects
- A combination of signal shape fitting with error estimation is the best we can do
- I'll focus here on dijet and dilepton signals

Dijets from EFT

$$\left.\frac{d\sigma}{d\chi}\right|_{\text{Central}} \propto -\left(c_{qq}^{(1)} + 0.61\,c_{qq}^{(3)} + 0.85\,c_{uu} + 0.15\,c_{dd} + 0.20\,c_{ud}^{(8)}\right) \qquad \left.\frac{d\sigma}{d\chi}\right|_{\text{Flat}} \propto -\left(c_{qu}^{(8)} + 0.45 c_{qd}^{(8)}\right)$$



Quark Compositeness

- Searches originally proposed by Eichten, Lane, and Peskin in 1983, they posit some contact interaction between quarks
- This is not an EFT treatment, nor is it meant to be; it's a specific UV model
- To do a proper EFT expansion requires care
  - Consider the errors arising from unknown (or neglected) operators
  - Investigate the effects of all operators at a given power-counting order on the given observable

Compositeness Search Signal

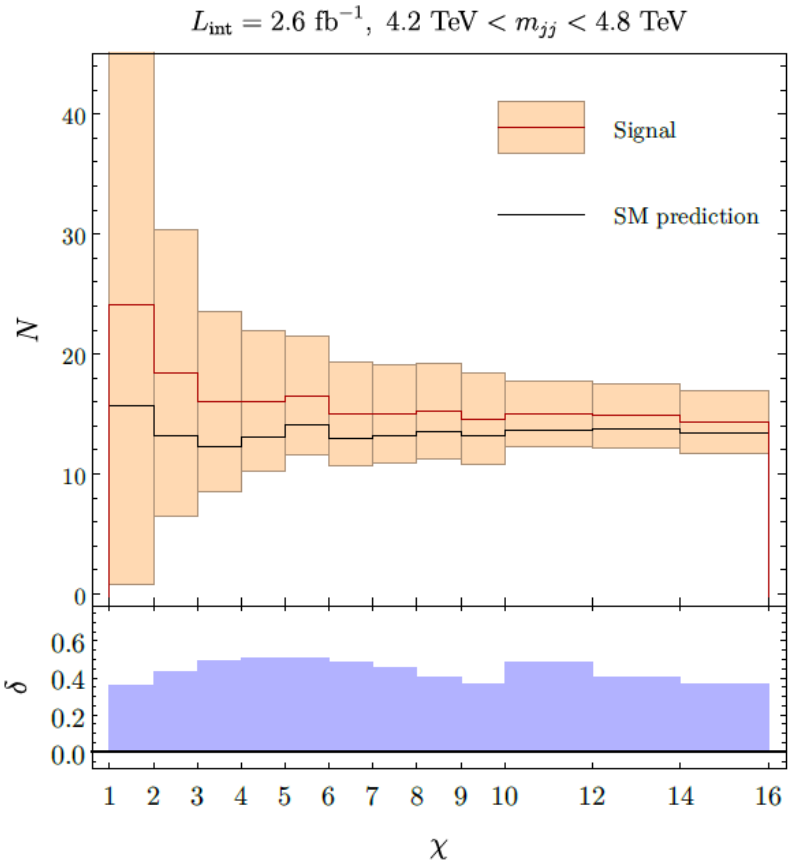
- The quark compositeness search has kept all terms naively predicted by the dimension 6 operator $Q_{qq}^{(1)}$, including squared term
- This is strongly centrally peaked, as the interference is central and the squared term even more so
- Thus, a search in angular variables is a natural technique to distinguish it from the SM

EFT error treatment

- The consistent EFT treatment is to expand the observable in a power series
  - Cross section, not amplitude
- Must include the full set of contributing operators at dim-6
  - Surprisingly, only two independent angular distributions contribute strongly
  - Remaining small differences arise from PDF evolution
- As we only have the full dim-6 contribution, everything else ought to be discarded
- The dim-6 squared piece is a proxy for the size of the unknown total dim-8 contribution
  - Note that additional operators needn't give correlated angular distribution

Search in Un-Normalized Distributions

- There can be large systematic differences between signal and background if we don't discard total cross-section information
- These analyses are bounded by EFT error at low χ, but statistics are important elsewhere



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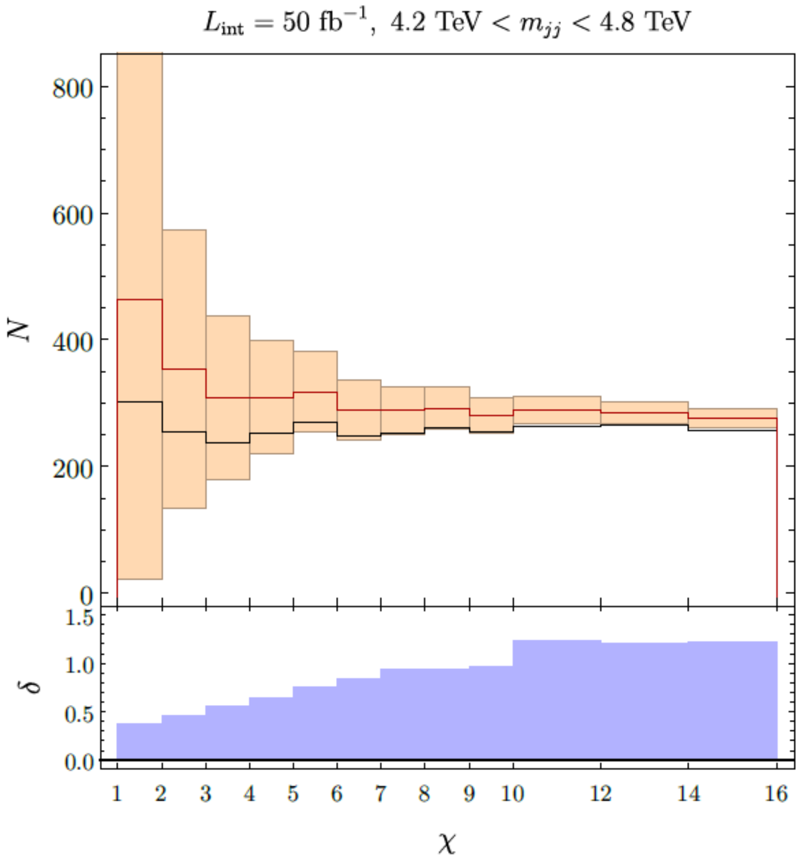
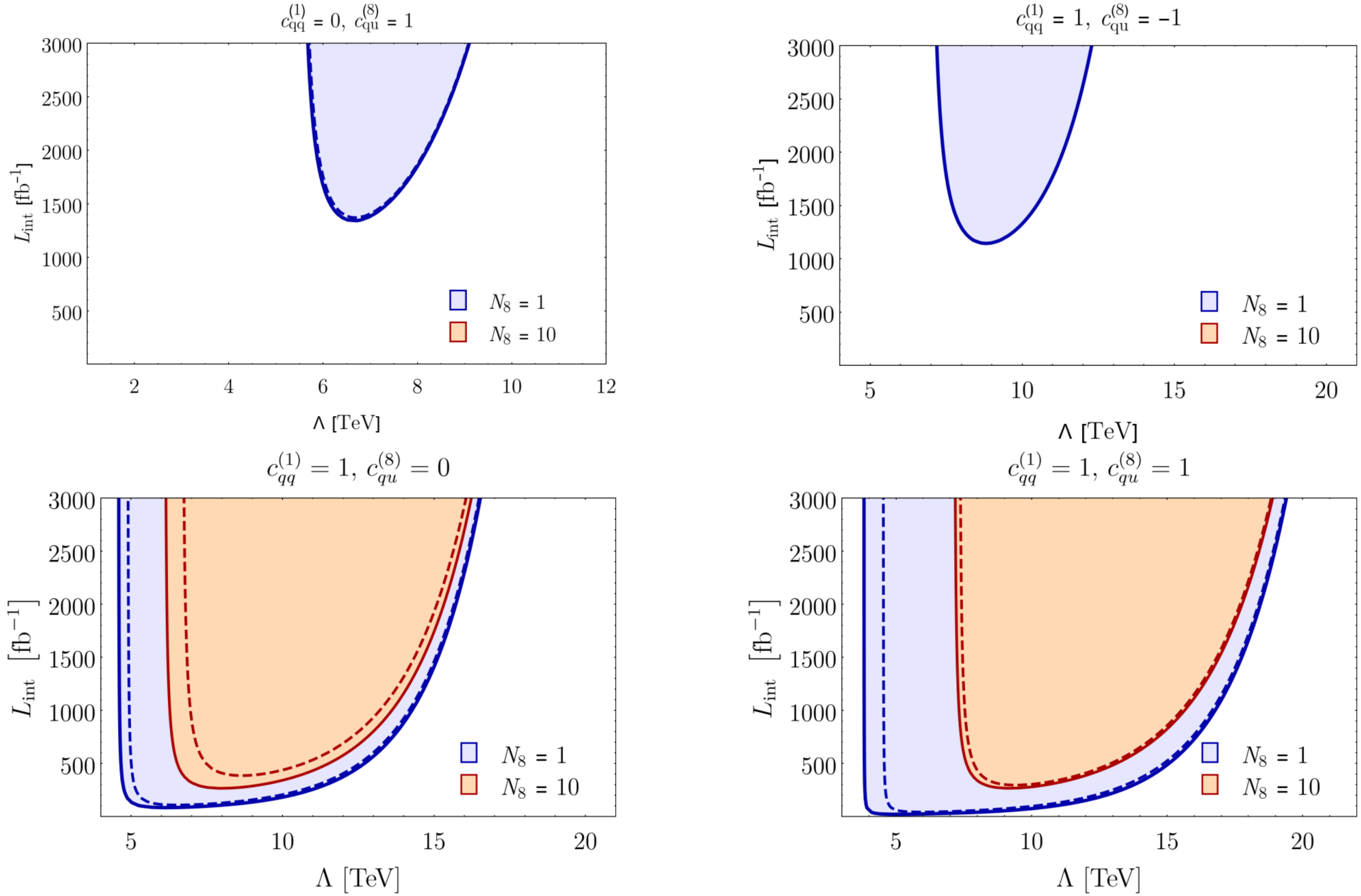


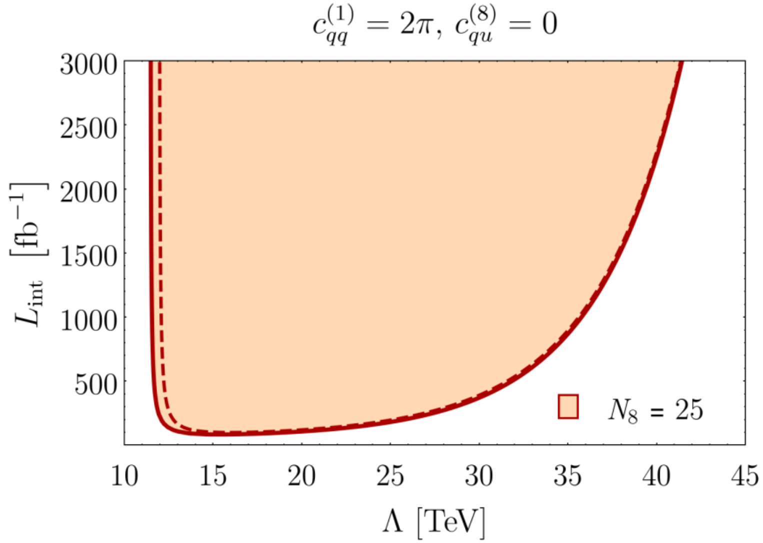
Interpretation of EFT Bounds

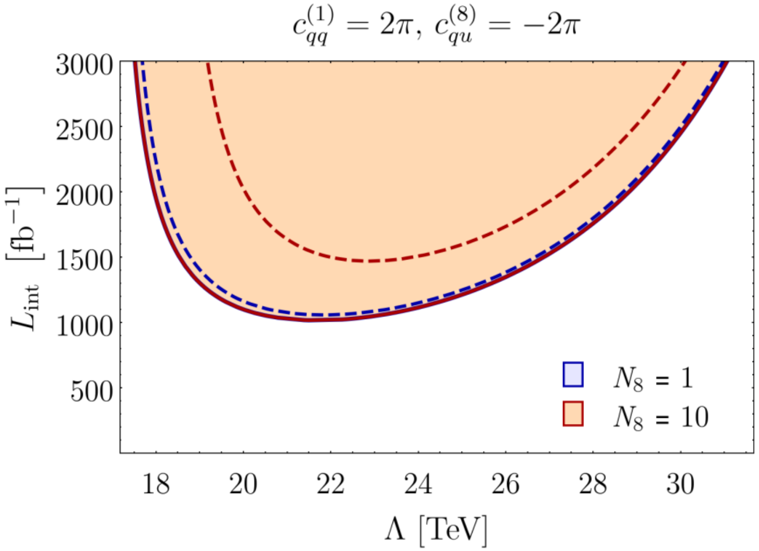
- EFT signal size is only sensitive to the combination ${}^{c_i}/_{\Lambda^2}$, cannot distinguish the two
  - Broken weakly by RG effects
- This leaves us two ways to interpret the bounds coming from any EFT search
  - If we fix the new physics scale, searches bound Wilson coefficients
  - Fixed coefficients lead to bounds on mass scale

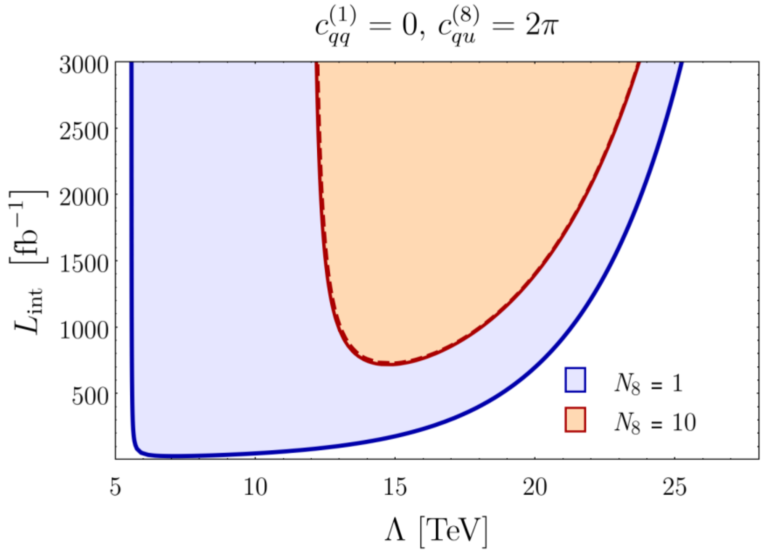
Reach: Fixed Wilson Coefficient

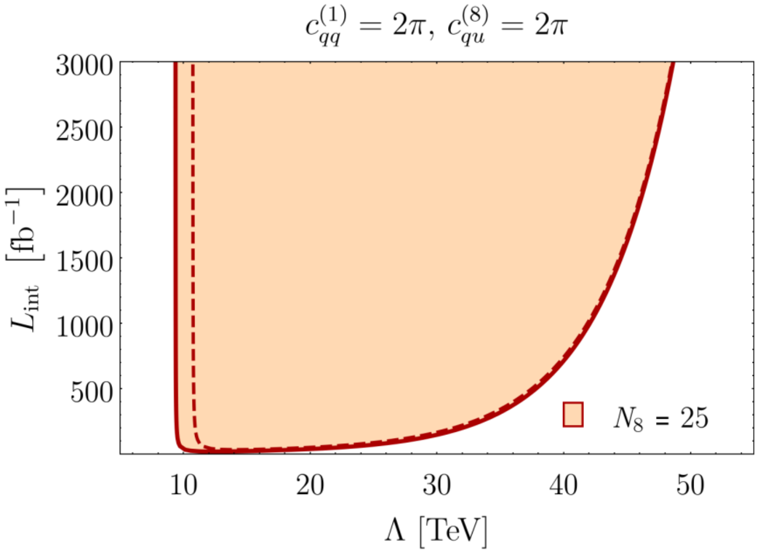


Reach: Fixed Wilson Coefficient


$c_{qq}^{(1)} = 2\pi,\ c_{qu}^{(8)} = 0$

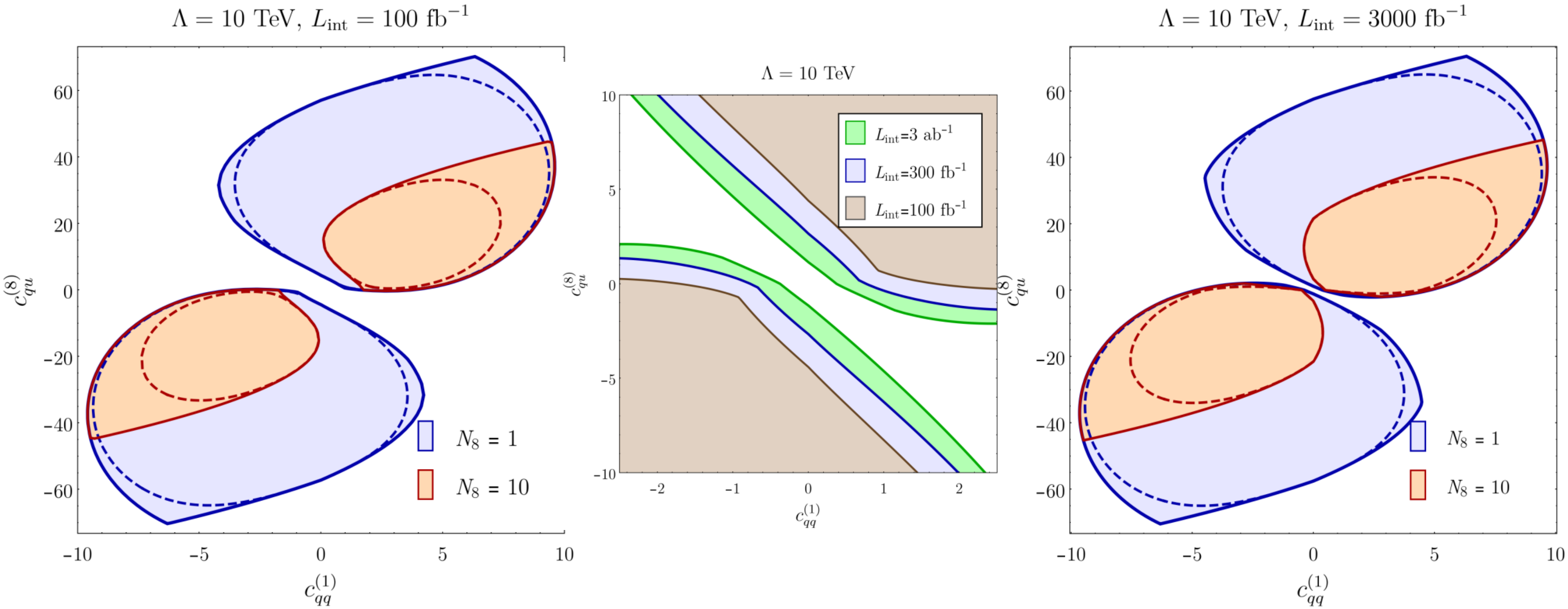

$c_{qq}^{(1)} = 2\pi,\ c_{qu}^{(8)} = -2\pi$


$c_{qq}^{(1)} = 0,\ c_{qu}^{(8)} = 2\pi$


$c_{qq}^{(1)} = 2\pi,\ c_{qu}^{(8)} = 2\pi$

Reach: Fixed NP Scale

- For large N8, only a narrow angle in coupling space can be constrained

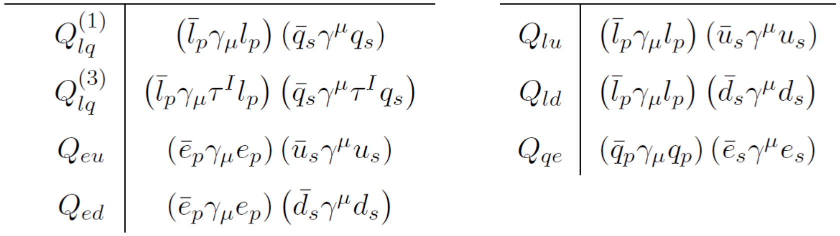

$\Lambda = 10$ TeV, $L_{\rm int} = 100$ fb^{-1}

$\Lambda = 10$ TeV

$\Lambda = 10$ TeV, $L_{\rm int} = 3000$ fb^{-1}

Dileptons from SMEFT

- Additional effects arise in dilepton production compared to dijets
  - Z couplings can be reefined by SMEFT operator contributions
- In this process, however, only four-fermion operators give amplitudes growing with energy



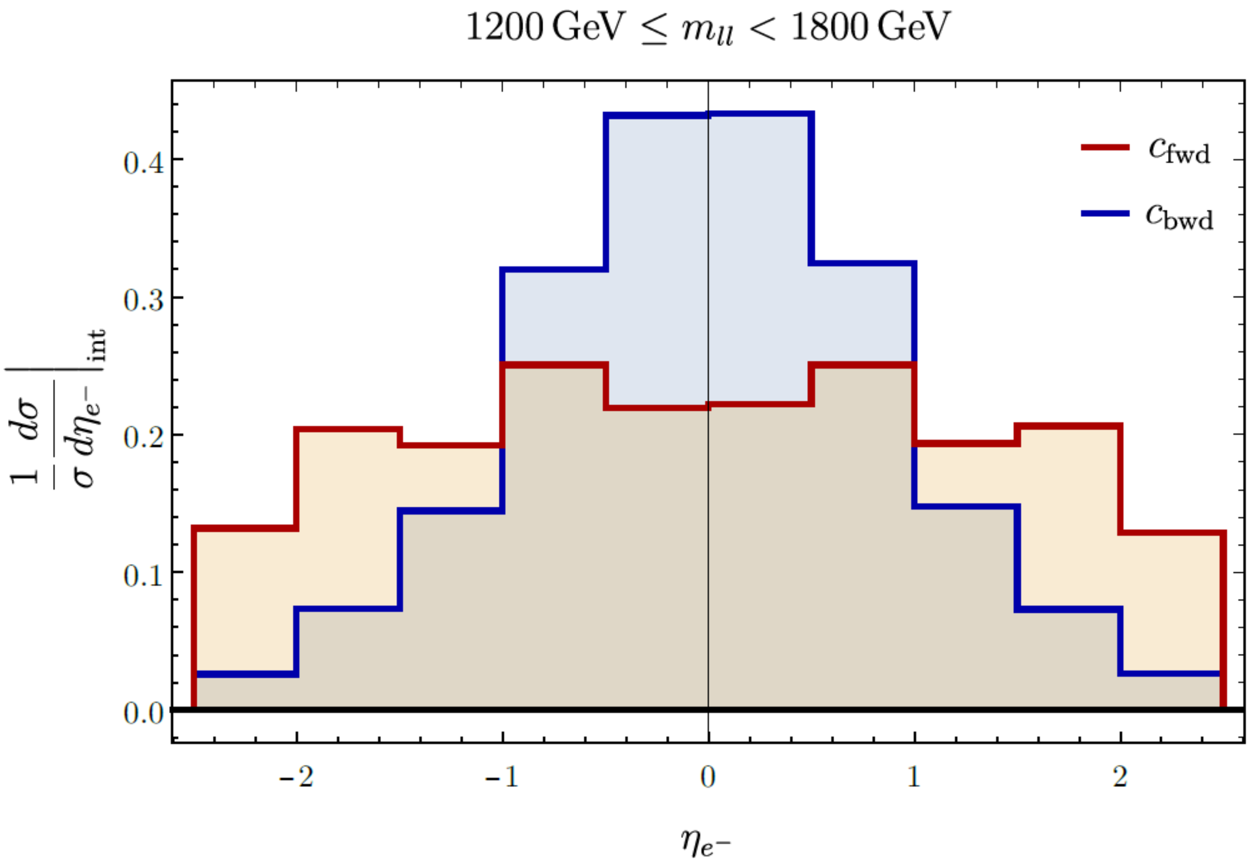
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_p)\,(\bar{q}_s\gamma^\mu q_s)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_p)\,(\bar{q}_s\gamma^\mu\tau^I q_s)$
Q_{eu}	$(\bar{e}_p\gamma_\mu e_p)\,(\bar{u}_s\gamma^\mu u_s)$
Q_{ed}	$(\bar{e}_p\gamma_\mu e_p)\,(\bar{d}_s\gamma^\mu d_s)$

Q_{lu}	$(\bar{l}_p\gamma_\mu l_p)\,(\bar{u}_s\gamma^\mu u_s)$
Q_{ld}	$(\bar{l}_p\gamma_\mu l_p)\,(\bar{d}_s\gamma^\mu d_s)$
Q_{qe}	$(\bar{q}_p\gamma_\mu q_p)\,(\bar{e}_s\gamma^\mu e_s)$

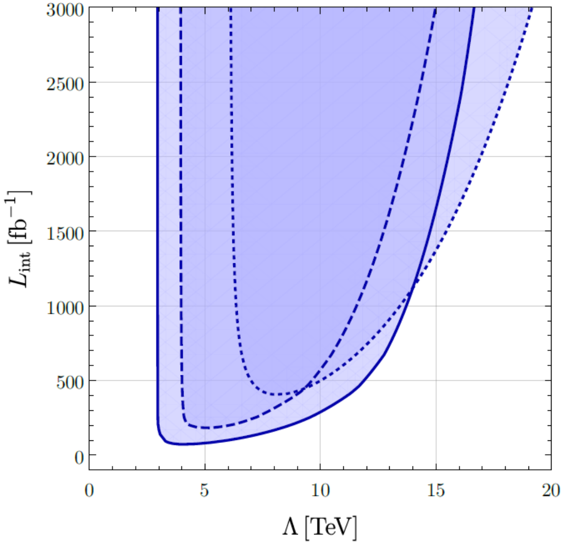
Forward/Backward production

$c_{\text{fwd}} = C_{lq}^{(3)} - 0.48\, C_{eu} - 0.33\, C_{lq}^{(1)} + 0.15\, C_{ed}$

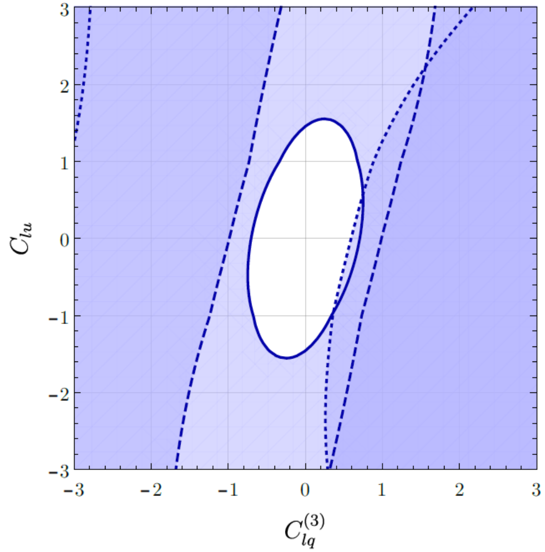
$c_{\text{bwd}} = C_{lu} + 0.81\, C_{qe} - 0.33\, C_{ld}$



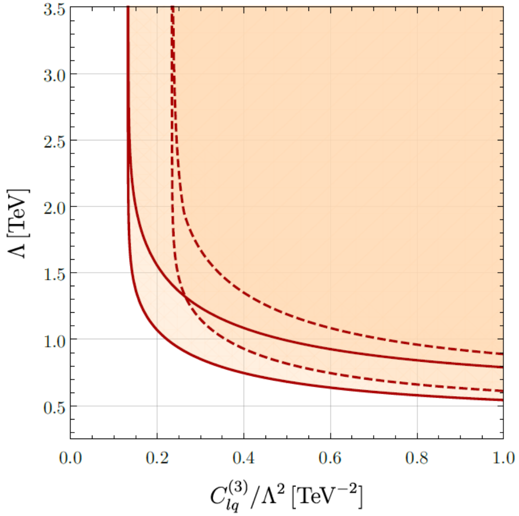
LHC and Tevatron Sensitivity



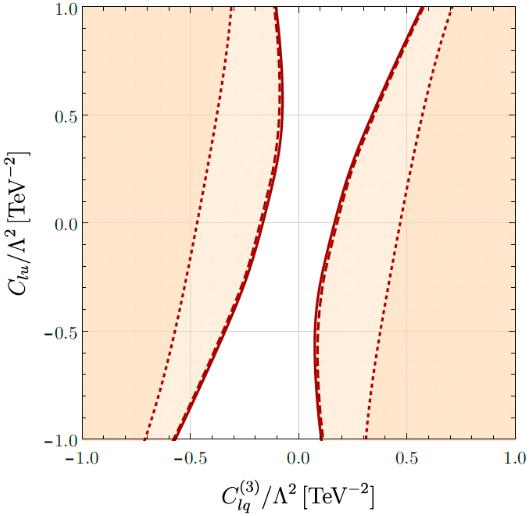
$(C_{lq}^{(3)}, C_{lu}) = (1,0),\ (1,1),\ (0,3),\ N_8 = 20$



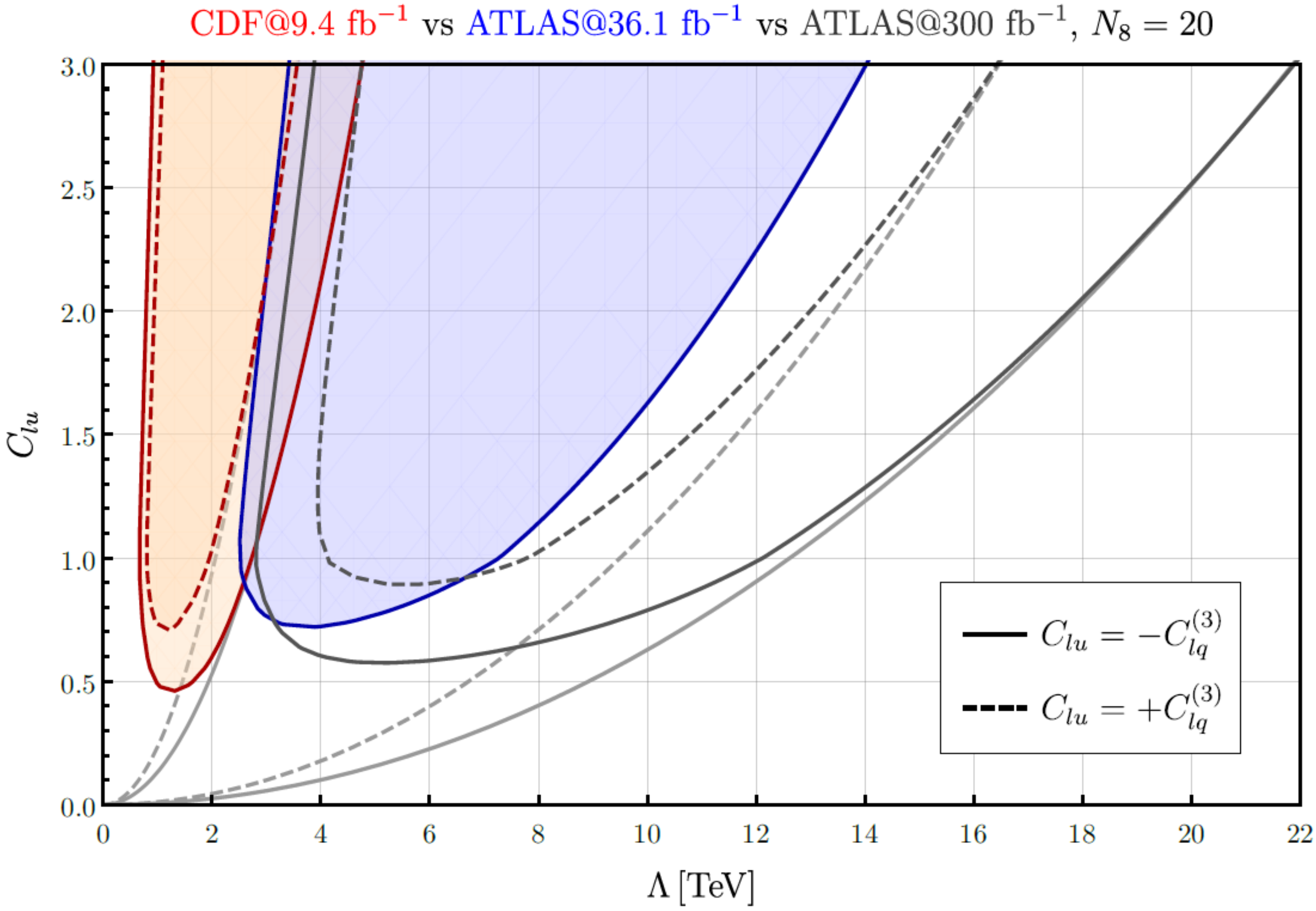
$\Lambda = 10\,{\rm TeV},\ L_{\rm int} = 36.1,\ 300,\ 3000\ {\rm fb}^{-1},\ N_8 = 20$



$C_{lq}^{(3)} = \pm C_{lu},\ N_8 = 1,\ 20$



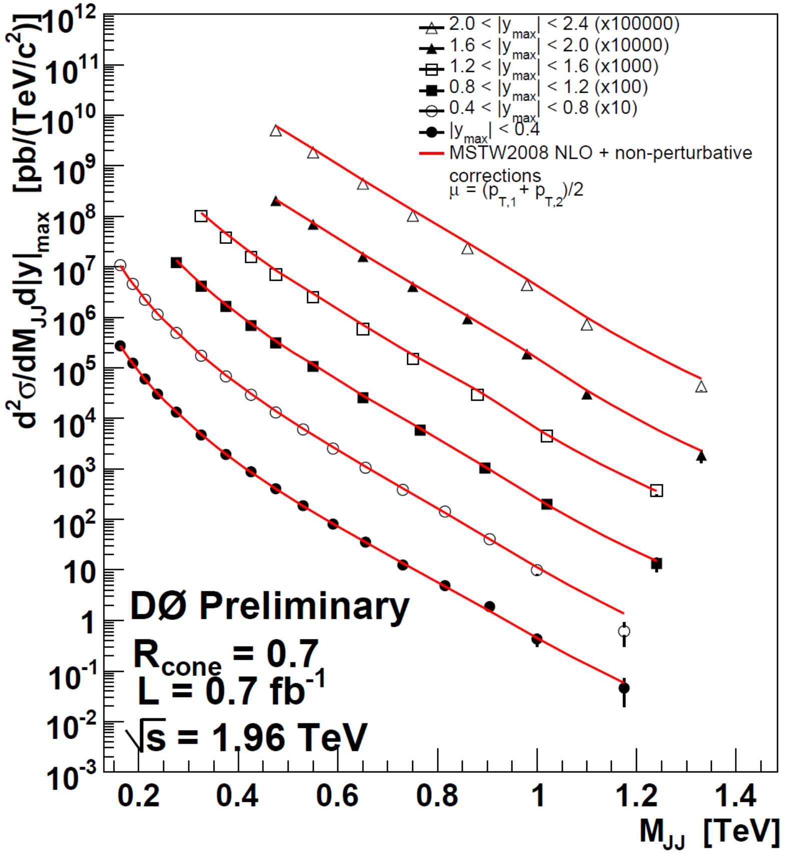
$\Lambda = 1, 2, 5\,{\rm TeV},\ N_8 = 10$


CDF@9.4 fb^{-1} vs ATLAS@36.1 fb^{-1} vs ATLAS@300 fb^{-1}, $N_8 = 20$
C_{lu}
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
2
4
6
8
10
12
14
16
18
20
22
Λ [TeV]
$C_{lu} = -C_{lq}^{(3)}$
$C_{lu} = +C_{lq}^{(3)}$

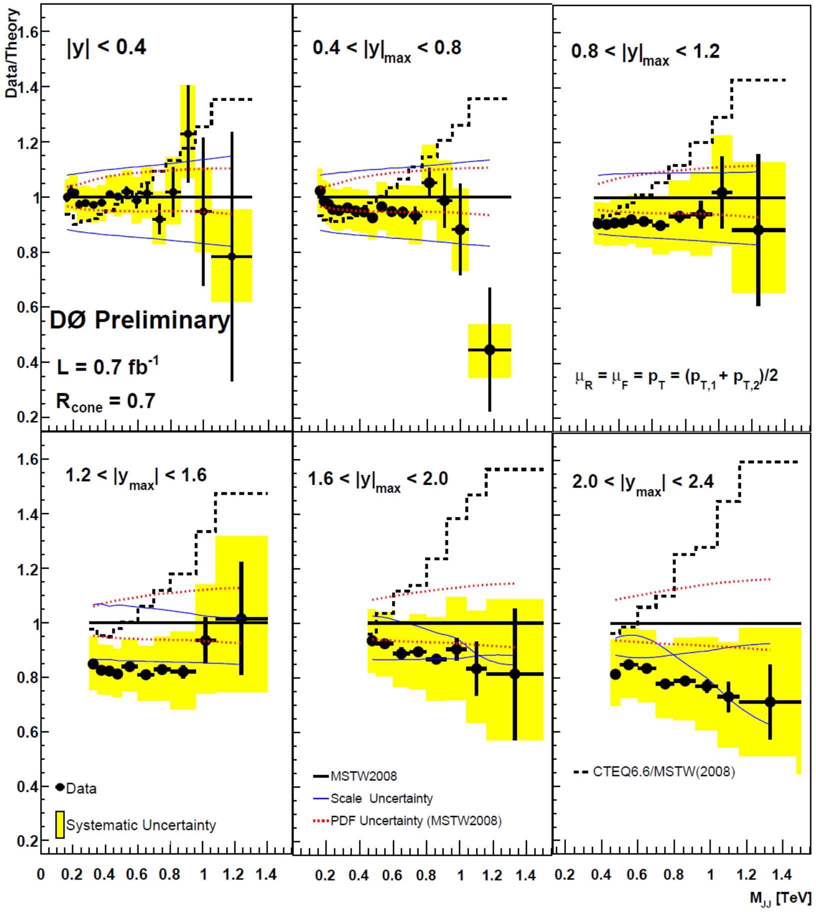
Low Lambda Dijets

- Can Tevatron data fill in the low-lambda region from the dijet study earlier?
  - Recall, dijet bounds lost sensitivity below 5 TeV or even higher
- Luckily, dijet cross section was measured at Tevatron as well

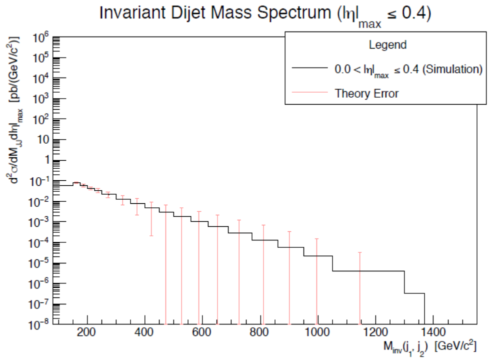
Tevatron Dijet Cross Section

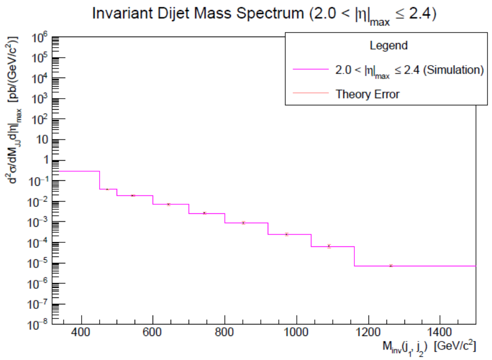


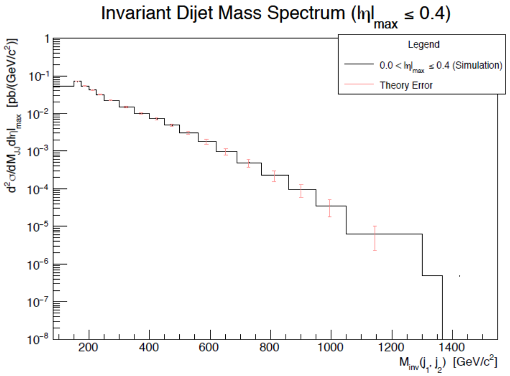
Tevatron Dijet Cross Section



SMEFT Dijets at Tevatron


Invariant Dijet Mass Spectrum ($|\eta|_{max} \leq 0.4$)


Invariant Dijet Mass Spectrum ($2.0 < |\eta|_{max} \leq 2.4$)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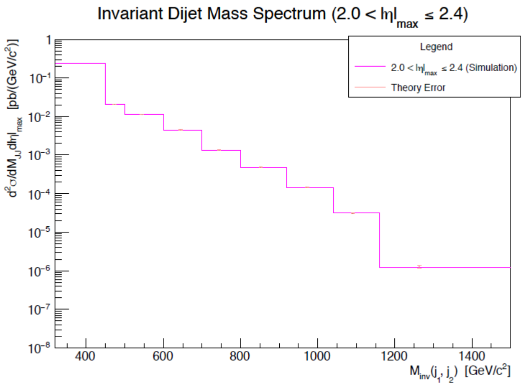
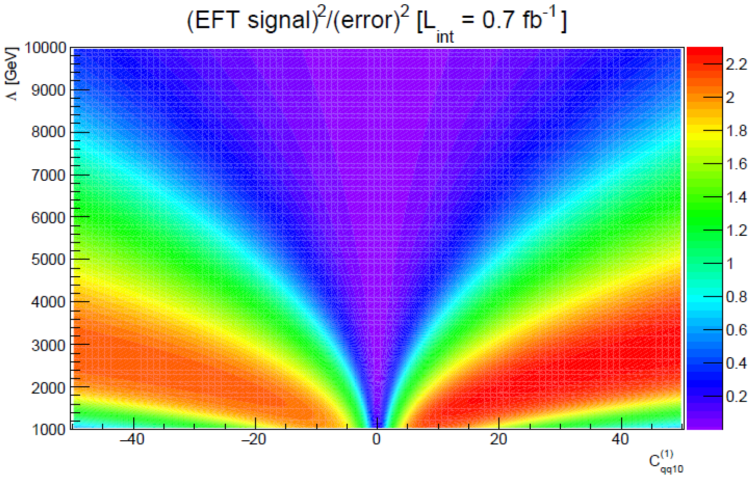
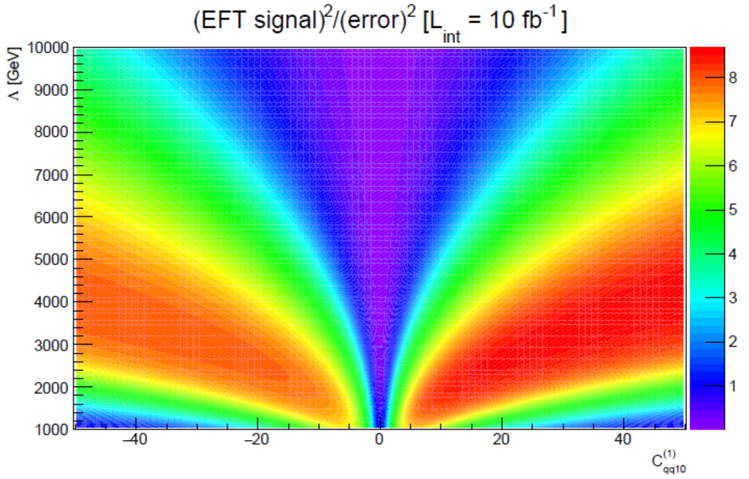

Invariant Dijet Mass Spectrum ($2.0 < |\eta|_{max} \leq 2.4$)

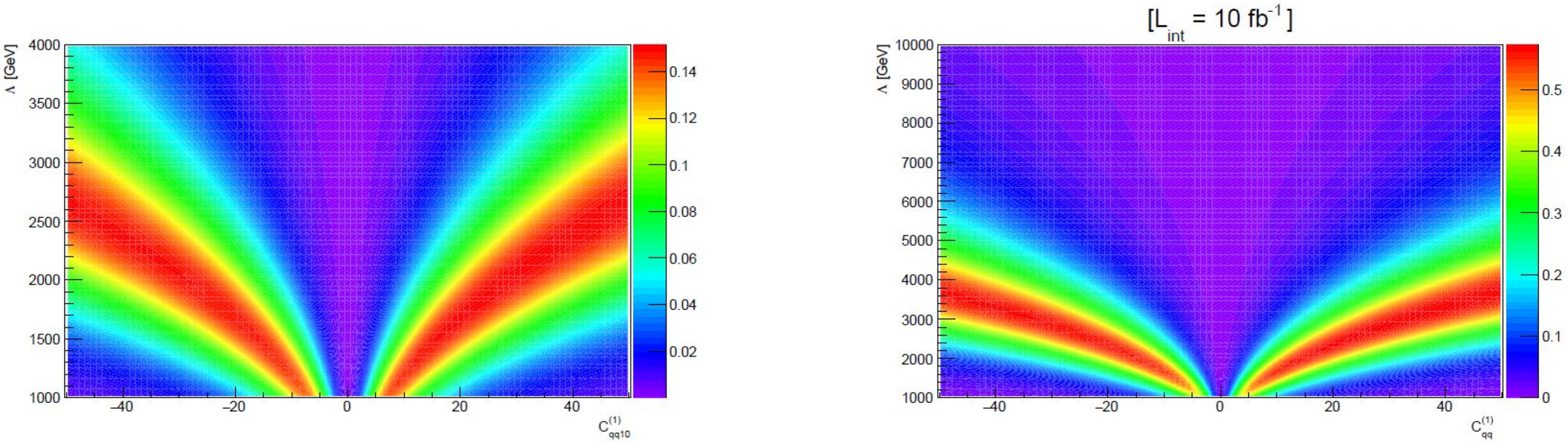
Full-spectrum fits to Tevatron





- Fits to Tevatron data for the reported and full experimental luminosity
  - Note that this is fit over a large number of bins (71), so these test statistic values are not significant
  - Also, the full lumi fit assumes that systematics scale like statistics, which is aggressive

Optimized cut-and-count Tevatron



- Cutting out optimal region isn’t much better
- Single-bin analysis with best sensitivity shown above, note we never reach 1sigma here

Tevatron can’t constrain SMEFT dijets

- The dataset is simply too small for such a messy final state
  - An excellent argument for the high-lumi phase of the LHC
- This isn’t necessarily disastrous; new interactions of colored particles at few TeV (we hope) would be directly probed as resonances at the LHC

Conclusions

- We have excellent data available, and must have enough respect for that to understand our new physics predictions at comparable precision
- In the most model-independent formulation of heavy new physics, the SMEFT parameter space is under-constrained by low energy data
- A truly global analysis will be needed to properly constrain the EFT without UV assumptions
  - Developing more observables that can be consistently constrained is an important future path for this field
  - Dijets and dileptons are a first step toward this global analysis goal; other directions ongoing, but much still to do

The Take-Away

- Setting shifts in EW observables to zero for the purposes of further searches does not give model-independent results
- Neglecting theory errors gets our analyses ignored by model-builders, who should be our biggest customers, so definitely stop doing that!
  - Produce results that they can’t evade by utilizing an honest error estimate
  - ‘New and improved’ sales pitch needed to bring them back
  - Push back against any claim that a model can always be built to evade our EFT results

We need to make Bhaskar wrong about this!

- “Whatever bound you get from your EFT, I can always write down a model that passes the test against data and violates the bound you claim to have.” – Bhaskar Dutta

Thank You!

Backup: Flavor Matching

MFV and the SMEFT

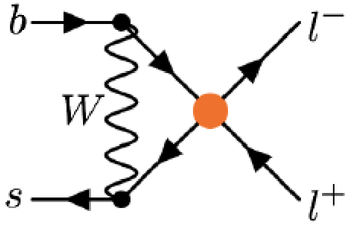
- We can insist that all flavor violation is given by powers of Yukawa matrices
  - Allowing arbitrary powers returns back to the full flavor-violation basis, with an approximate $U(2)^2$
- Allowing no CP or flavor violation leaves only 16+20 parameters, linear flavor violation permits an additional 11 operators
- SM loops still generate obligatory FV effects which involve these new physics interactions

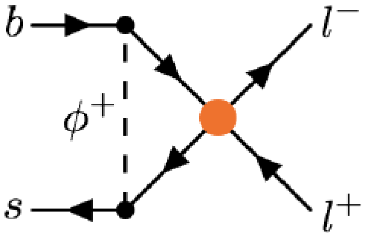
Matching SMEFT to WET

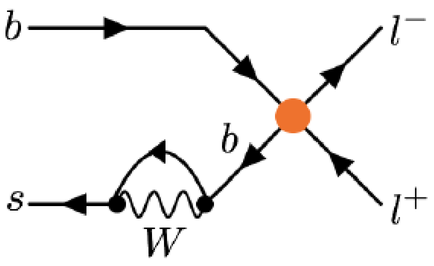
- Given loop-origin of FV in this ansatz, focus on down-type neutral transitions
  - Grants access to large top-Yukawa effects
  - SM process also at loop level
- WET operators of interest are dipoles and 4-fermi interactions
  - Standard basis for b-physics labels these as O1-10
  - For cleaner observables involving photons or leptons, O7-10 are most relevant

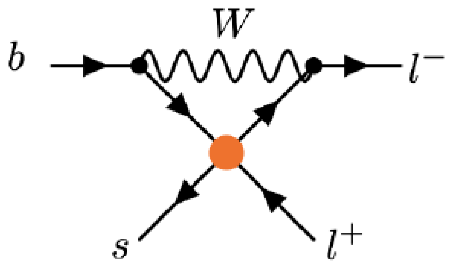
4-fermi operators

- Most 4-fermion operators that contribute are mixed quark-lepton operators
- SM charged-current loop then gives access to flavor changing effects
  - Non-top effects cancel mass-independent terms by GIM



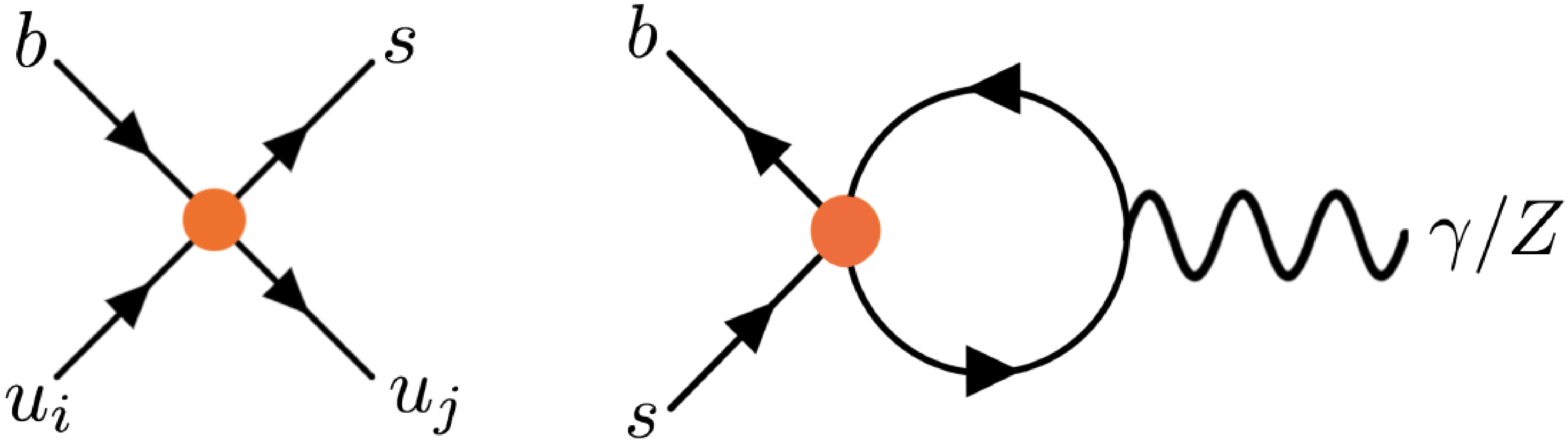






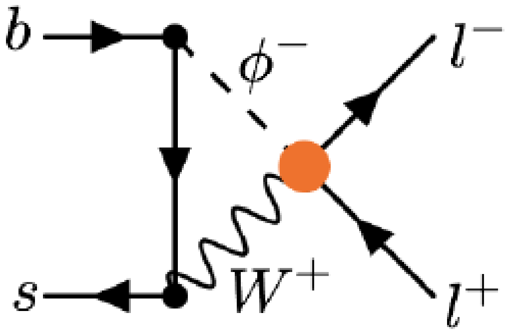
4-fermi operators – tree level FCNCs

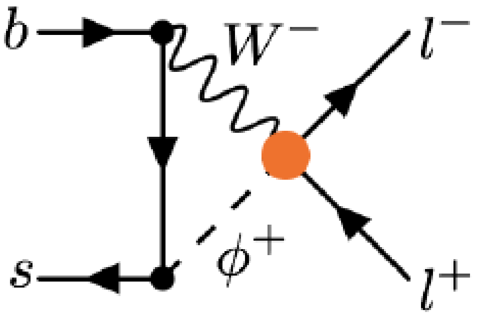
- 4-doublet operators can yield tree-level flavor changes due to CKM effects
- These will run into observable operators either with explicit matching or WET running

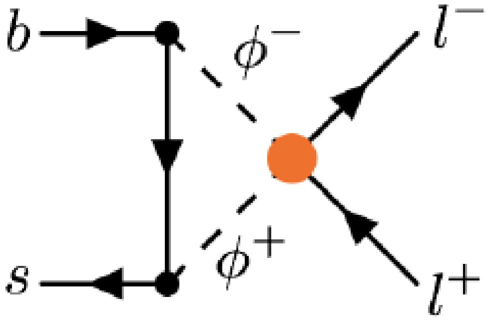


Higgs-leptonic current operators

- Correct Z coupling to leptons
  - Tree-level effect in Z-pole data
- Also give new graphs
  - Necessary to achieve gauge invariant final answer

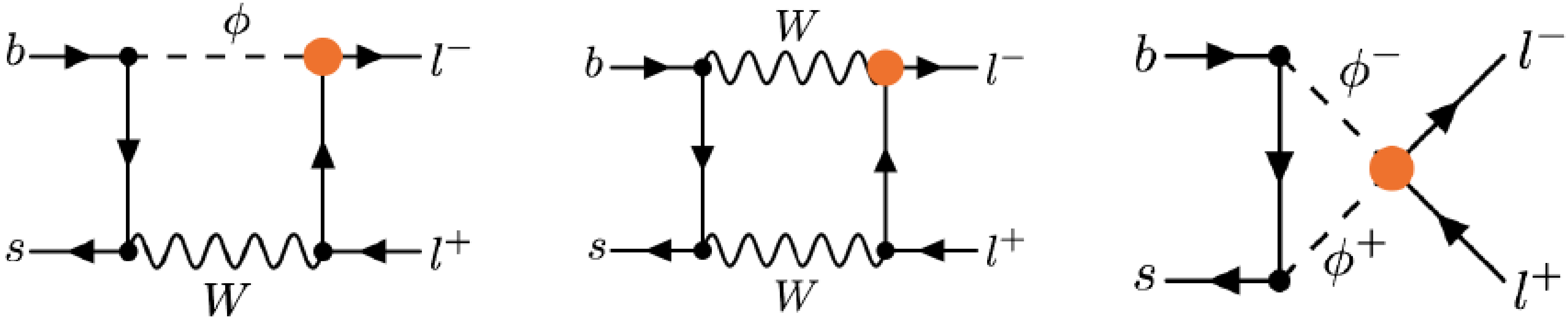






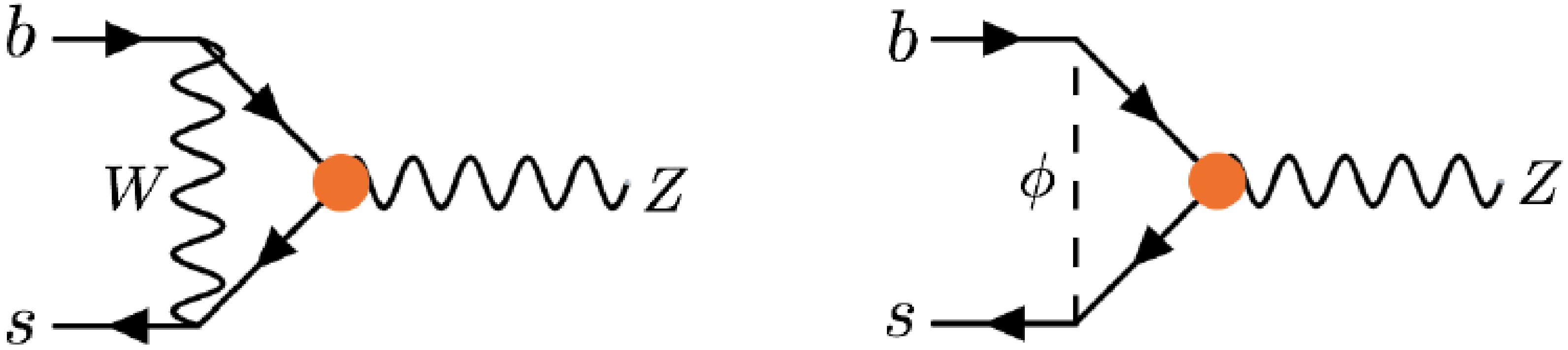
Higgs-leptonic current operators

- Triplet operators give corrections to W and Z couplings to leptons
- Again also generate new diagrams important for gauge invariance



Higgs-quark current operators

- Correct couplings of Z to quarks
  - Triplet operator also corrects coupling of W
- Yield new bubble-type graphs with 4-point interaction



Input parameter effects

- Importantly, input parameter shifts also play a role in this process
- Gives sensitivity to e.g. four-lepton operator
- Unavoidable consequence of QFT
  - Lagrangian parameters are not observables
  - Must calculate all observables in same theory
- These contributions have been neglected in the flavor literature thus far

Flavor Conclusions

- In the flavor sector we will have access to about 8 new constraints in the SMEFT parameter space from B, K decays and mixings
- A phenomenological analysis of these constraints (and how they play together with Precision EW) is underway – stay tuned.