New Physics in Drell-Yan at the Z-pole and in High-Mass Tails: Inherent Uncertainties in the 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…

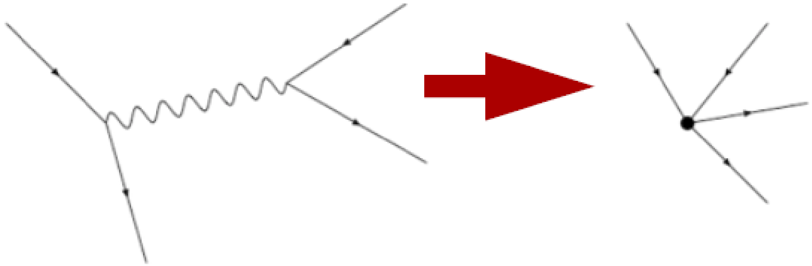
- 1611.09879 with Christine Hartmann and Michael Trott
- 1711.07484, 1812.07575 with Stefan Alte and Matthias König

Introduction: EFT

- Effective Field Theory is a toolset that is used in a variety of ways
  - Organize contributions by importance
    - SCET, Flavor Physics, χPT, EFT for LSS…
  - Parametrize ignorance about new effects
- General approach is to identify the symmetries of a system and then consider everything allowed by them
  - Requires a robust power counting rule to determine relative importance of distinct terms

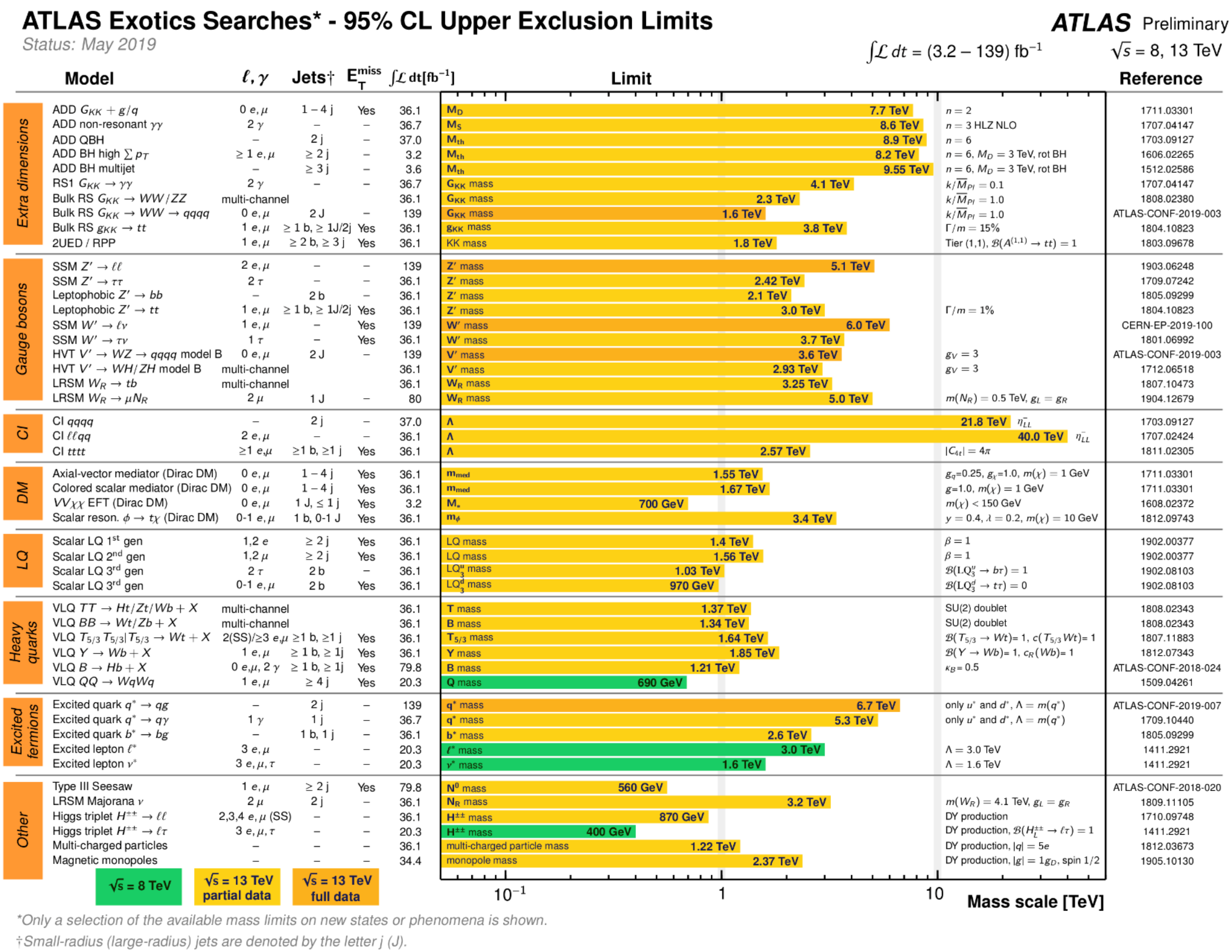
Introduction: EFT

- 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

Why EFT and not <my favorite model>?



SMEFT

- Applying EFT techniques to integrate out new physics already requires assumptions
- The main open question is the nature of the Higgs-like boson discovered at the LHC
  - Without knowing anything, one can expand in powers of $\frac{h}{v}$ and $\frac{D}{\Lambda}$ to get the HEFT approach
  - If this scalar is embedded in the doublet which breaks SU(2) one can insist on the full SM gauge group, leading to the SMEFT

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}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$
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}	$H^\dagger \tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$

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

7 : $\psi^2 H^2 D$	
$Q_{Hl}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^I H)(\bar{l}_p \tau^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
$Q_{Hq}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
$Q_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^I H)(\bar{q}_p \tau^I \gamma^\mu q_r)$
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}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

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

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

Why Loops?

- Electroweak observables have been measured with amazing precision
  - Theory calculations have to match this precision to get full value out of the data

Observable	Experimental Value	Ref.	SM Theoretical Value	Ref.
$\hat{m}_Z$[GeV]	91.1875 ± 0.0021	[38]	-	-
$\hat{m}_W$[GeV]	80.385 ± 0.015	[39]	80.365 ± 0.004	[40]
σ_h^0 [nb]	41.540 ± 0.037	[38]	41.488 ± 0.006	[41]
Γ_Z[GeV]	2.4952 ± 0.0023	[38]	2.4942 ± 0.0005	[41]
R_ℓ^0	20.767 ± 0.025	[38]	20.751 ± 0.005	[41]
R_b^0	0.21629 ± 0.00066	[38]	0.21580 ± 0.00015	[41]
R_c^0	0.1721 ± 0.0030	[38]	0.17223 ± 0.00005	[41]
A_{FB}^ℓ	0.0171 ± 0.0010	[38]	0.01616 ± 0.00008	[42]
A_{FB}^c	0.0707 ± 0.0035	[38]	0.0735 ± 0.0002	[42]
A_{FB}^b	0.0992 ± 0.0016	[38]	0.1029 ± 0.0003	[42]

Why Loops?

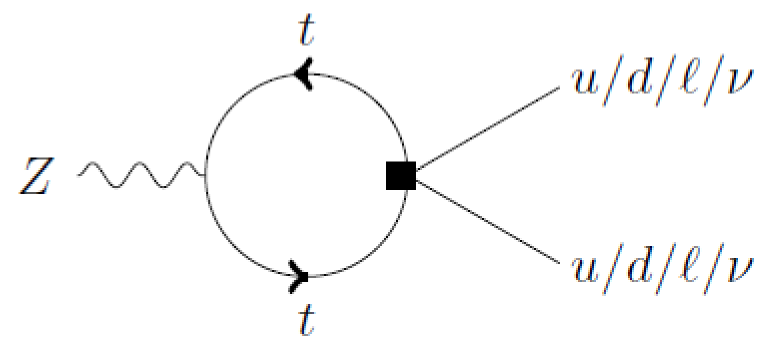
- What is the theory error on a tree-level prediction for EFT effects?
  - Standard loop factor is $\frac{1}{16\pi^2} \sim 1\%$
  - $\frac{v^2}{\Lambda^2} \sim 1\%$ as well (we hope)
  - Numerical coefficients not known a priori
- SMEFT renormalization known, RG improvement will capture logs
  - For LHC-scale physics logs aren't so large
  - Pure-finite effects can be of comparable size

Large y_t, λ limit

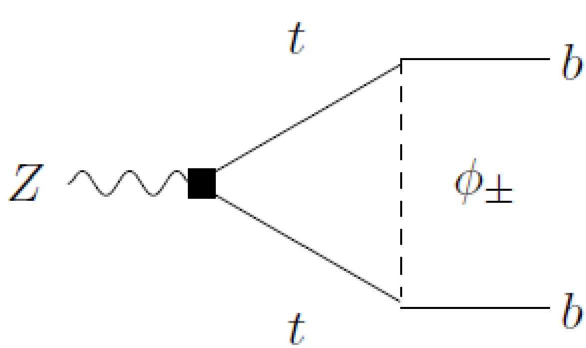
- These two couplings are known to be sizeable
  - Only QCD coupling compares
- Calculations are simpler in vanishing gauge coupling limit
  - Gauge fixing in the presence of D=6 operators leads to additional subtleties
  - Gauge independence assured here
- A good first step toward a full NLO treatment of the problem

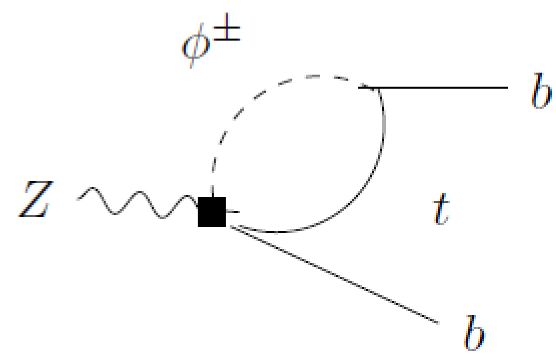
Contributing Operators

- 4-fermion operators:



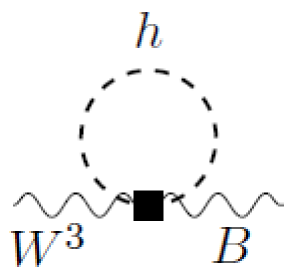
- Scalar-fermionic current operators:



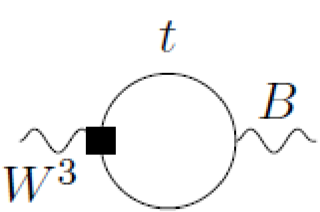


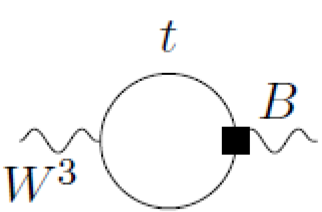
Contributing Operators

- Gauge-Higgs operators:



- Dipole operators:





Input Parameters

- Any calculation depends on the inputs used to set the theory parameters
- We use a canonical set of inputs for the SM
  - $\alpha_{EM}, G_F, M_Z, M_t, M_h$
- EFT gives corrections to the extraction of each
- We treat the Wilson coefficients in $\overline{MS}$ at the NP scale as EFT input parameters to be measured and/or constrained

Sample Results

$$\begin{aligned}
\Delta(g_L^d)_{rr} &= \Delta\bar{g}_Z (g_L^d)_{rr}^{SM} + \frac{N_c \hat{m}_t^2}{16\pi^2} \log\left[\frac{\Lambda^2}{\hat{m}_t^2}\right] \left[C^{(1)}_{\substack{qq\\33rr}} + C^{(1)}_{\substack{qq\\rr33}} - C^{(3)}_{\substack{qq\\33rr}} - C^{(3)}_{\substack{qq\\rr33}} - C^{(1)}_{\substack{qu\\rr33}}\right], \\
&- \frac{1}{2}\left(\frac{\Delta G_F}{\hat{G}_F} + \Delta V^2\right)\left(C^{(1)}_{\substack{Hq\\rr}} + C^{(3)}_{\substack{Hq\\rr}}\right) + \delta_{br}\frac{\hat{m}_t^2}{4\,\pi^2}\left[C^{(3)}_{\substack{qq\\3333}}\left(-1 + \log\left[\frac{\Lambda^2}{\hat{m}_t^2}\right]\right)\right] - \frac{1}{3}\Delta s_\theta^2, \\
&- \delta_{br}\,\frac{\hat{m}_t^2}{16\,\pi^2}\left[\left(\frac{1}{4} - \frac{1}{2}\log\left[\frac{\Lambda^2}{\hat{m}_t^2}\right]\right) C_{Hu} + C^{(1)}_{Hq}\right] - \delta_{br}\,\Delta R_b^L\,\left((g_L^d)_{rr}^{SM} + \delta(g_L^d)_{rr}\right), \\
&- \delta_{br}\,\frac{\hat{m}_t^2}{16\,\pi^2}\, C^{(3)}_{Hq}\left[\frac{1}{2} - \mathcal{Q}_b\, s_{\hat{\theta}}^2 + (3 - 2\,\mathcal{Q}_b\, s_{\hat{\theta}}^2)\log\left[\frac{\Lambda^2}{\hat{m}_t^2}\right]\right], \\
&- \delta_{br}\,\frac{\hat{m}_t^2}{4\,\pi}\,\tilde{\alpha}\,(c_{\hat{\theta}}^2 - s_{\hat{\theta}}^2)\, C_{HWB}\,(\mathcal{Q}_u - 1)\left[\frac{3}{2} + \log\left[\frac{\Lambda^2}{\hat{m}_t^2}\right]\right],
\end{aligned}$$

$$\begin{aligned}
\Delta\Gamma_{Z\to Had} &= 2\,\Delta\Gamma_{Z\bar{u}u} + 2\,\Delta\Gamma_{Z\bar{d}d} + \Delta\Gamma_{Z\bar{b}b}, \\
&= \frac{\sqrt{2}\,\hat{G}_F \hat{m}_Z^3}{6\,\pi}\left[4\,(g_R^u + \delta g_R^u)\,\Delta g_R^u + 4\,(g_L^u + \delta g_L^u)\,\Delta g_L^u + 4\,(g_R^d + \delta g_R^d)\,\Delta g_R^d\right] \\
&+ \frac{\sqrt{2}\,\hat{G}_F \hat{m}_Z^3}{6\,\pi}\left[4\,(g_L^d + \delta g_L^d)\,\Delta g_L^d + 2\,(g_R^b + \delta g_R^b)\,\Delta g_R^b + 2\,(g_L^b + \delta g_L^b)\,\Delta g_L^b\right]
\end{aligned}$$

Numerics

The δ correction to $\bar{R}^b_\ell$ is given by

$$\frac{\delta R_b^0}{10^{-2}} = -0.192\, C_{Hd} + 0.039\, C_{HD} + 0.158\, C_{H\ell}^{(3)} + 2.13\, C_{Hq}^{(1)} - 0.055\, C_{Hq}^{(3)}, \\ -0.494\, C_{Hu} + 0.043\, C_{HWB} - 0.079\, C_{\ell\ell}. \tag{7.35}$$

Similarly, the $\delta\,\Delta$ correction to $\bar{R}^0_b$ has the contributions

$$\frac{\delta\Delta R_b^0}{10^{-3}} = \Big[(0.036\,\Delta\bar{v}_T + 0.083)\, C_{Hd} + (0.011\,\Delta\bar{v}_T + 0.013)\, C_{HD} + (0.084\,\Delta\bar{v}_T - 0.014)\, C_{H\ell}^{(3)}, \\ -(0.085\,\Delta\bar{v}_T + 0.152)\, C_{Hq}^{(1)} - (0.016\,\Delta\bar{v}_T + 0.019)\, C_{Hq}^{(3)} + (0.099\,\Delta\bar{v}_T + 0.208)\, C_{Hu}, \\ -(0.042\,\Delta\bar{v}_T - 0.007)\, C_{\ell\ell} + (0.013\,\Delta\bar{v}_T + 0.009)\, C_{HWB} - 0.015\, C_{\ell q}^{(3)}, \\ +0.597\, C_{qq}^{(3)} + 0.047\, C_{uH} - 0.006\,(C_{HB} + C_{HW}) - 0.106\,\Delta v\Big], \tag{7.36}$$

and the $\delta\,\Delta$ correction to R^0_b also has the logarithmic terms

$$\frac{\delta\Delta R_b^0}{10^{-3}} = \Big[0.129\, C_{Hd} + 0.025\, C_{HD} + 0.067\, C_{H\ell}^{(3)} - 0.559\, C_{Hq}^{(1)} + 0.383\, C_{Hq}^{(3)} + 0.240\, C_{Hu}, \\ +0.023\, C_{HWB} - 0.049\, C_{\ell\ell} + 0.030\, C_{\ell q}^{(3)} + 0.036\left(C_{qd}^{(1)} - C_{ud}^{(1)}\right) - 0.618\, C_{qq}^{(3)}, \\ -0.803\, C_{qq}^{(1)} + 0.494\, C_{qu}^{(1)} - 0.002\, C_{uB} + 0.032\, C_{uH} - 0.004\, C_{uW} - 0.186\, C_{uu}\Big] \log\left[\frac{\Lambda^2}{\hat{m}_t^2}\right] \\ + \Big[-8.94\times 10^{-7}\, C_{HD} + \Big(0.313\, C_{Hd} - 3.49\, C_{Hq}^{(1)} + 0.090\, C_{Hq}^{(3)} - 0.258\, C_{H\ell}^{(3)}, \\ +0.808\, C_{Hu} + 0.129\, C_{\ell\ell} - 0.020\, C_{HWB}\Big)10^{-2}\Big] \log\left[\frac{\Lambda^2}{\hat{m}_h^2}\right]. \tag{7.37}$$

Phenomenology

- Counting is all that's needed for the most important point
- NLO corrections have introduced dependence on (neglecting flavor indices):
  - 3 Higgs-gauge Cs
  - 2 Dipole Cs
  - 7 Higgs-fermion current Cs
  - 9 four-fermion Cs
- At this level of precision, we can measure only 5 Z pole observables (A_{FB} goes beyond NWA)

Phenomenology

- Recall that at tree level there were flat directions in Z pole observables
  - Lifted by TGC measurements
- With this increase in relevant parameters, all of EWPD not enough to constrain the EFT
- The lesson: loop corrections cannot be constrained by EWPD alone, thus EWPD bounds (at tree level) can never be more precise than a loop factor on WCs

Where else can we look?

- There is a huge body of data outside of LEP precision measurements; how can we exploit this to constrain this framework?
- Canonical choice is to plug EFT interactions into Monte Carlo tools and constrain what comes out
- 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 have to 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 dijet mass, integrated over angles
  - Removes angular uncertainties
- $\sigma = \sigma_{SM}(1 + \sum_1^\infty c_n \frac{m_{jj}^{2n}}{\Lambda^{2n}})$
  - 'Signal' is linear term, predicted in terms of dim-6 operator Wilson coefficients
- Theory error now probed by sensitivity to series truncation

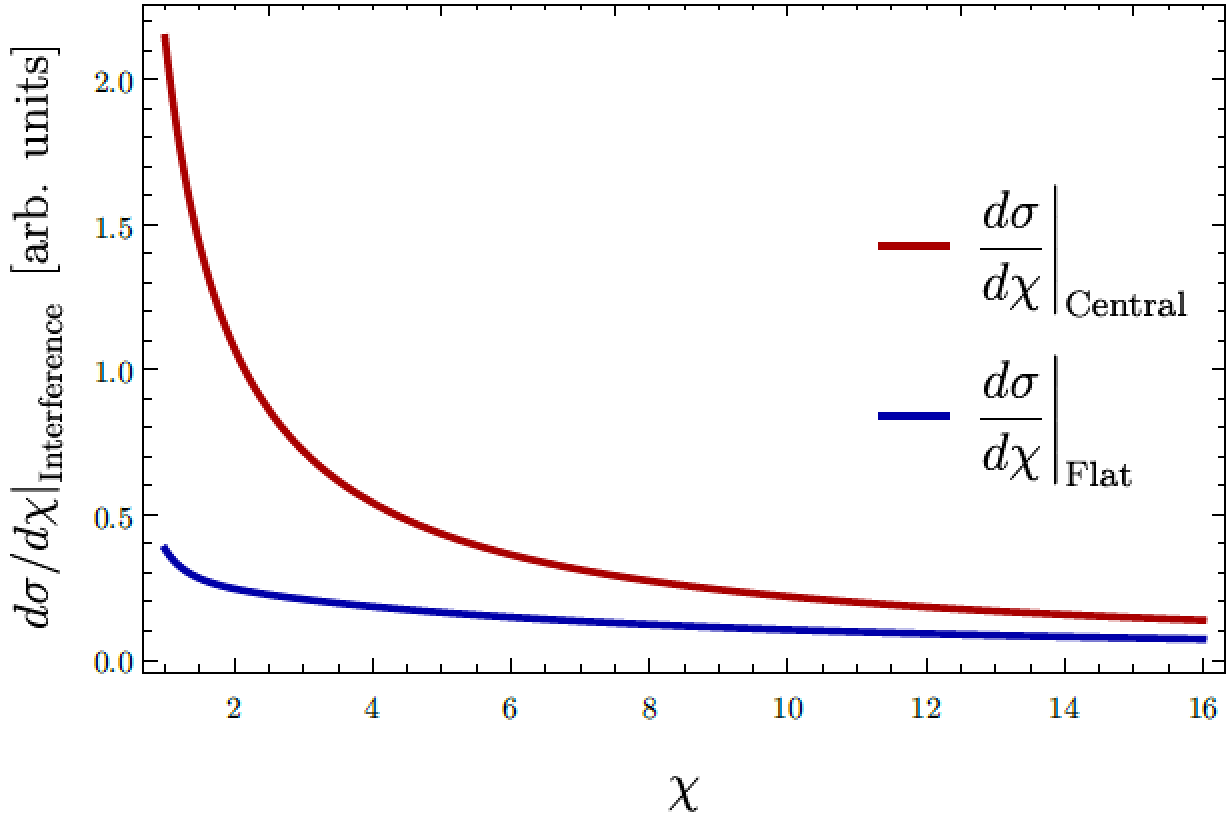
Real-World Problems

- $\sigma \neq \sigma_{SM}(1 + \sum_1^\infty c_n \frac{m_{jj}^{2n}}{\Lambda^{2n}})$
  - 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

Dijets from EFT

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

$$\left.\frac{d\sigma}{d\chi}\right|_{\text{Flat}} \propto -\left(c_{qu}^{(8)} + 0.45 c_{qd}^{(8)}\right)$$



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

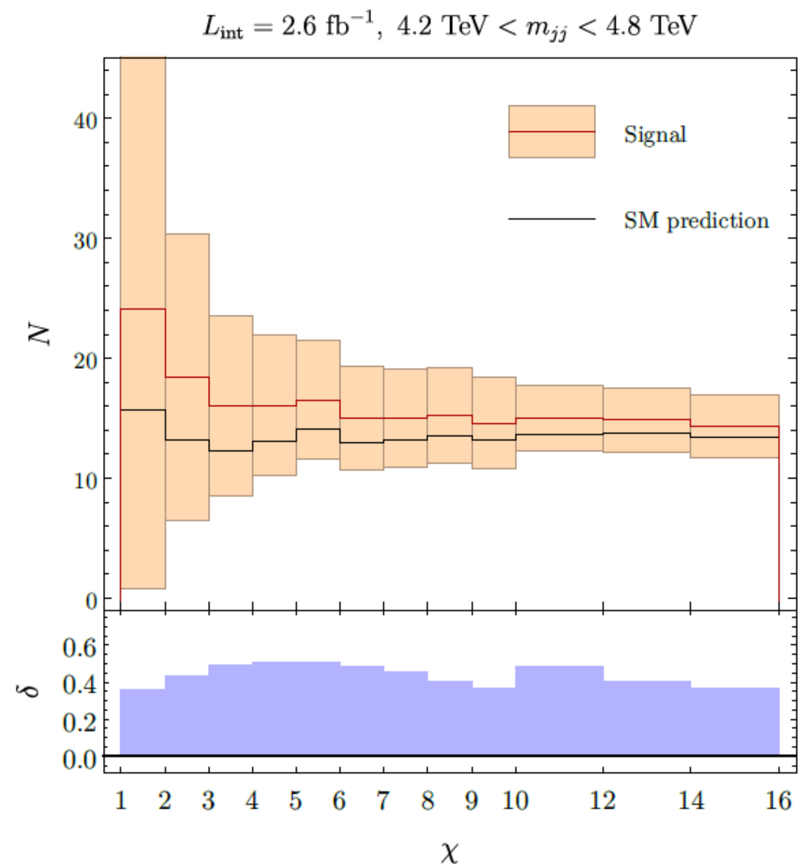
- The quark compositeness search has kept all terms naively predicted by the dimension 6 operator $Q_{qq}^{(1)}$, including squared term
- This is strongly centrally peaked, as the interference is central and the squared term even more so
- Thus, a search in angular variables is a natural technique to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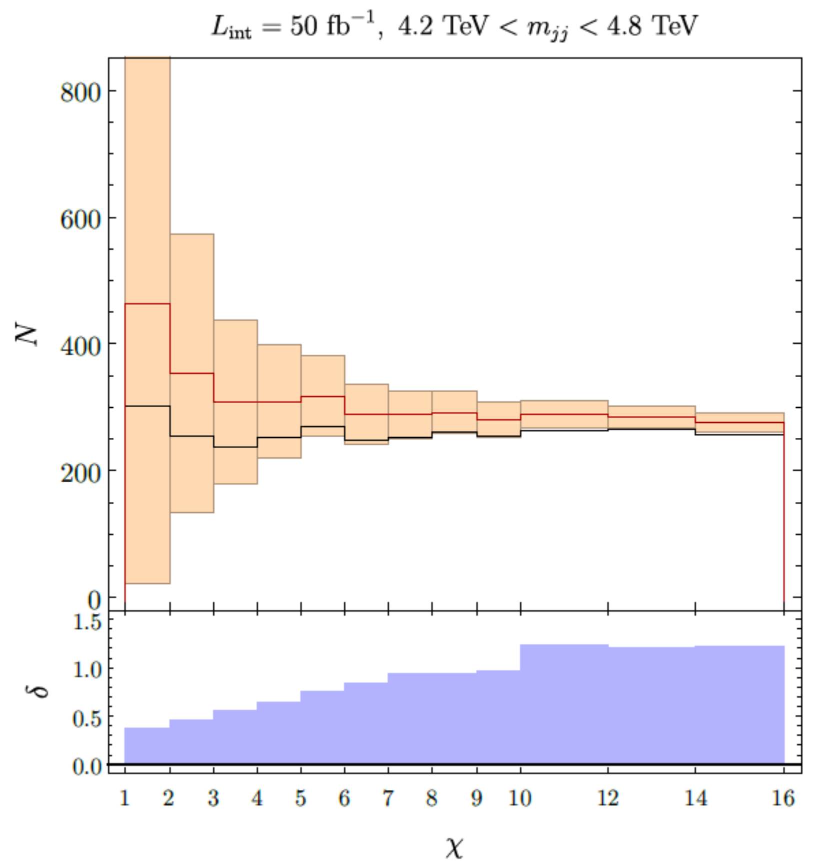
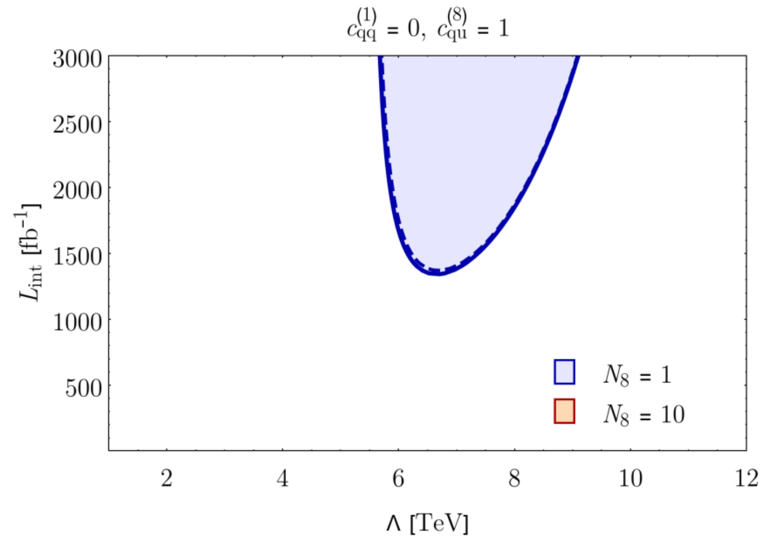
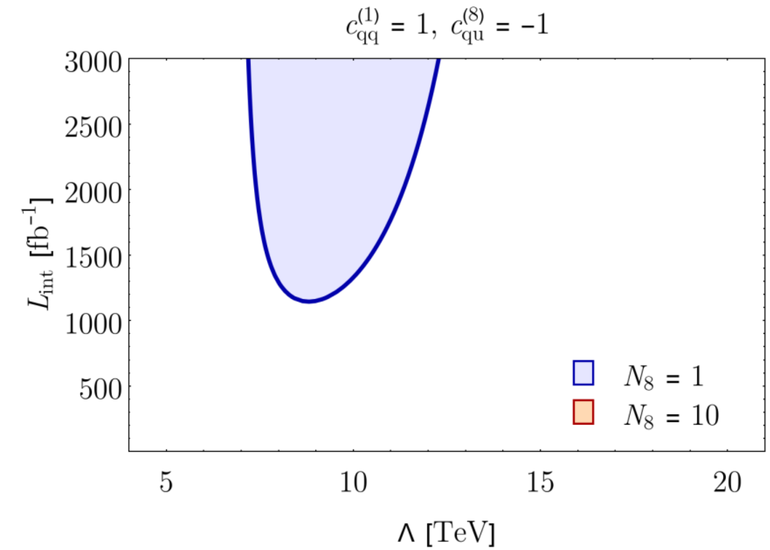


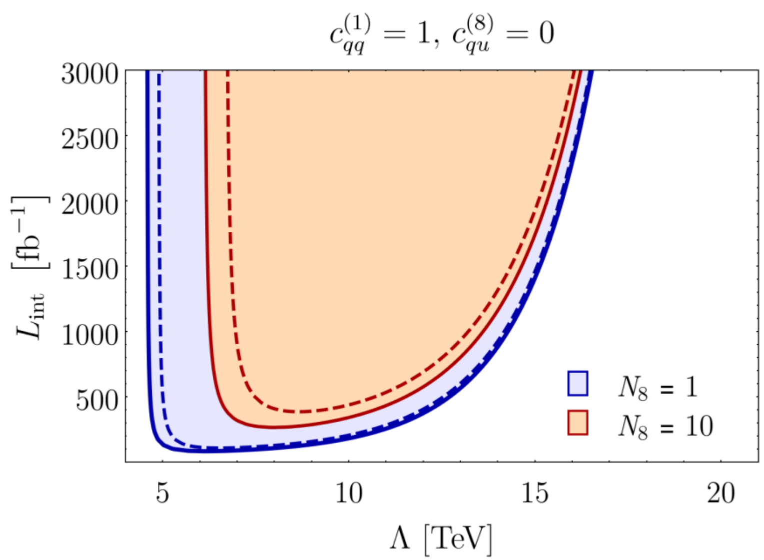
Interpretation of EFT Bounds

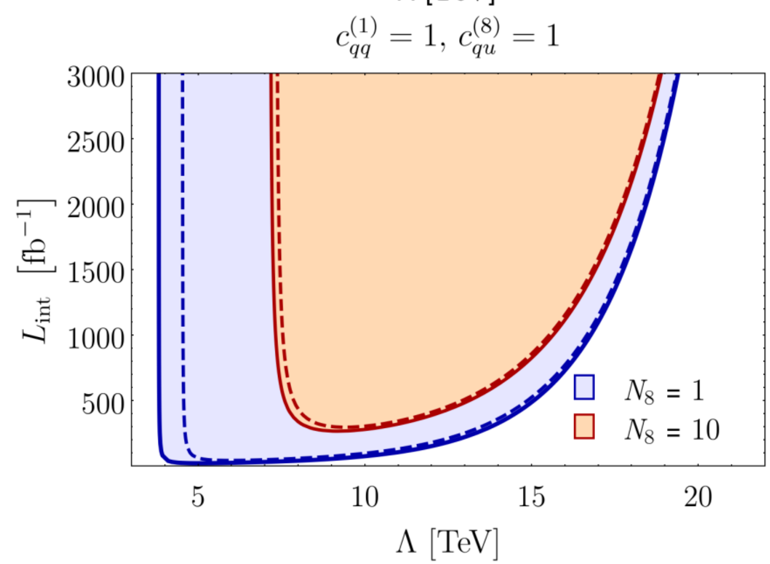
- EFT signal size is only sensitive to the combination c_i / Λ^2, cannot distinguish the two
  - Broken weakly by RG effects
- This leaves us two ways to interpret the bounds coming from any EFT search
  - If we fix the new physics scale, searches bound Wilson coefficients
  - Fixed coefficients lead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

Reach: Fixed Wilson Coefficient

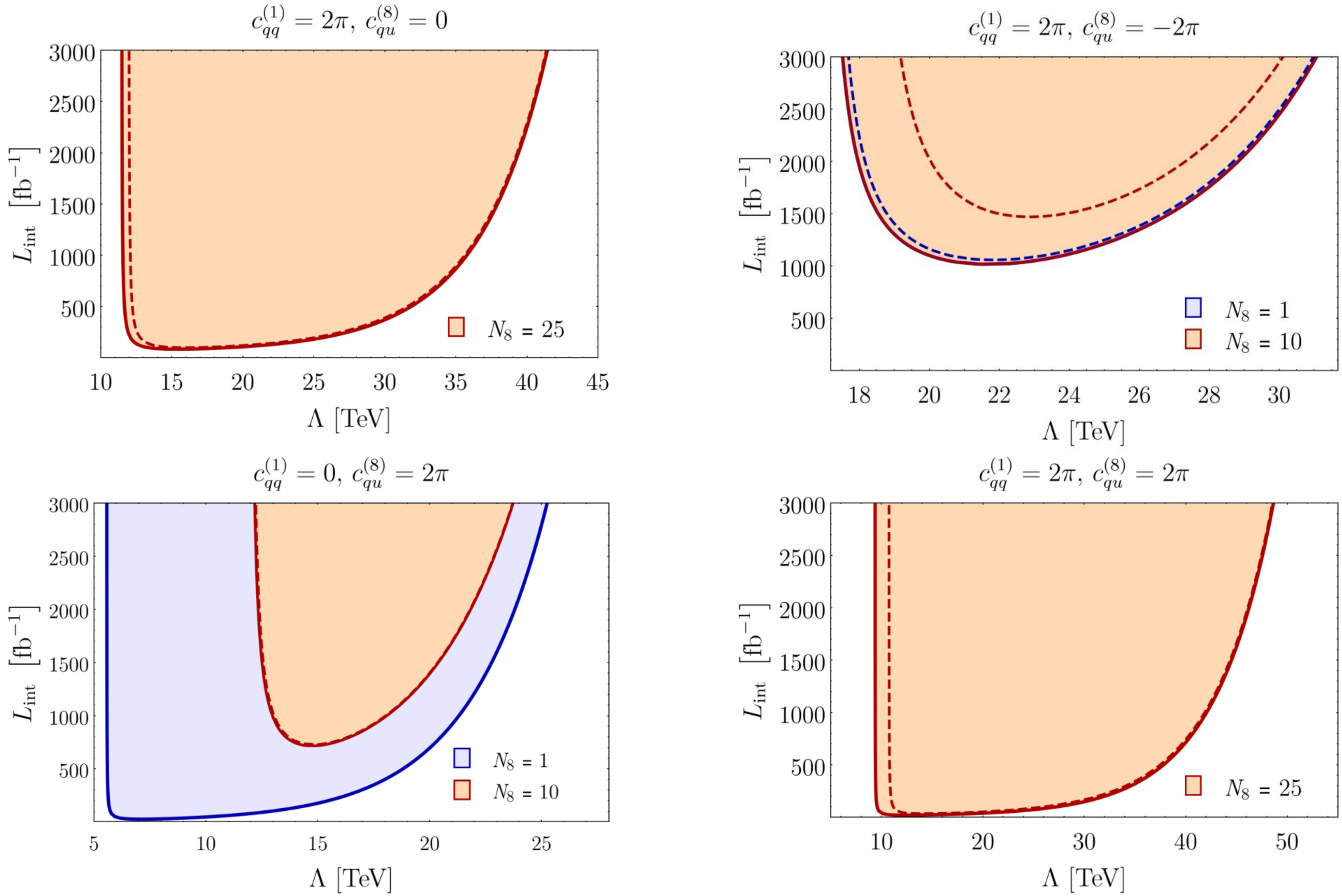






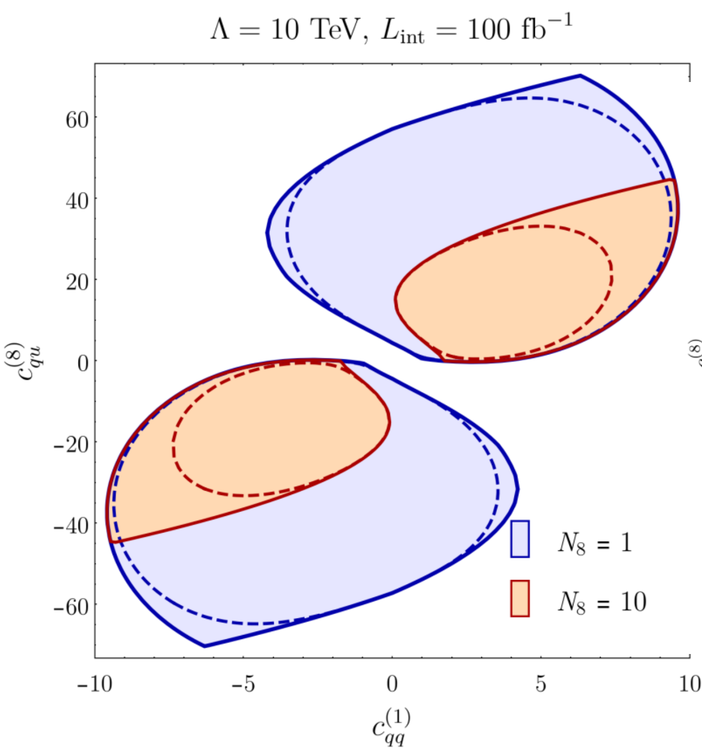


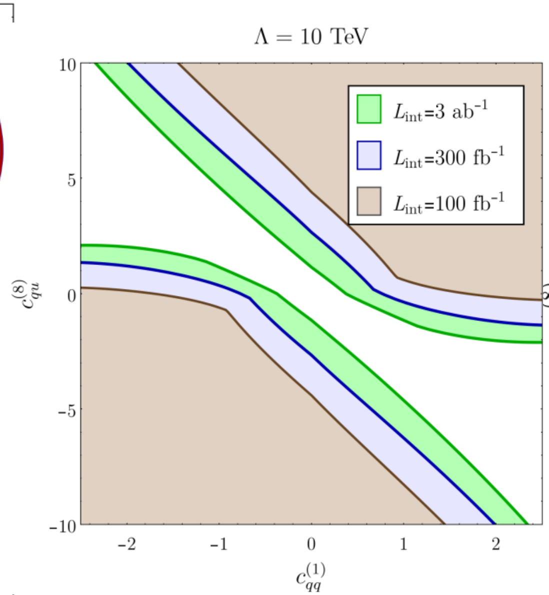
Reach: Fixed Wilson Coefficient

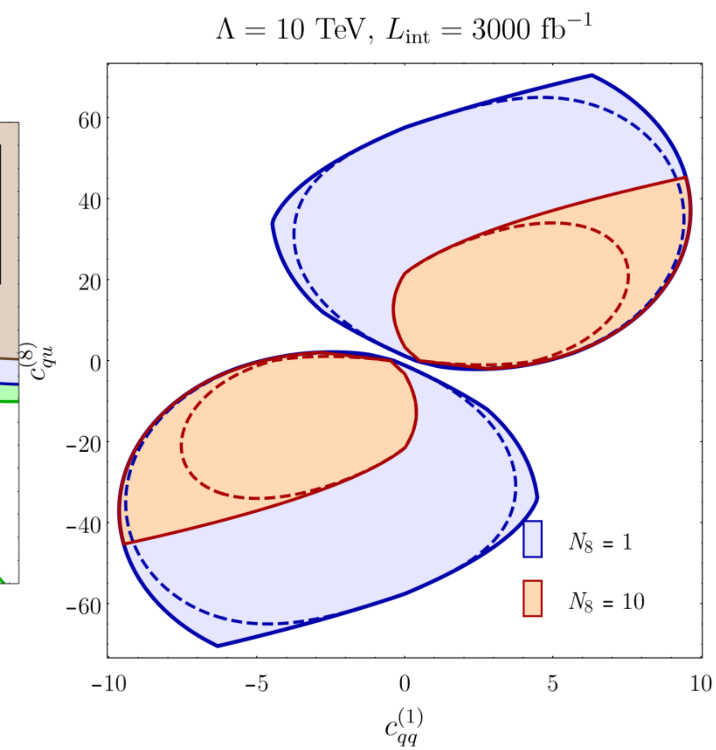


Reach: Fixed NP Scale

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







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

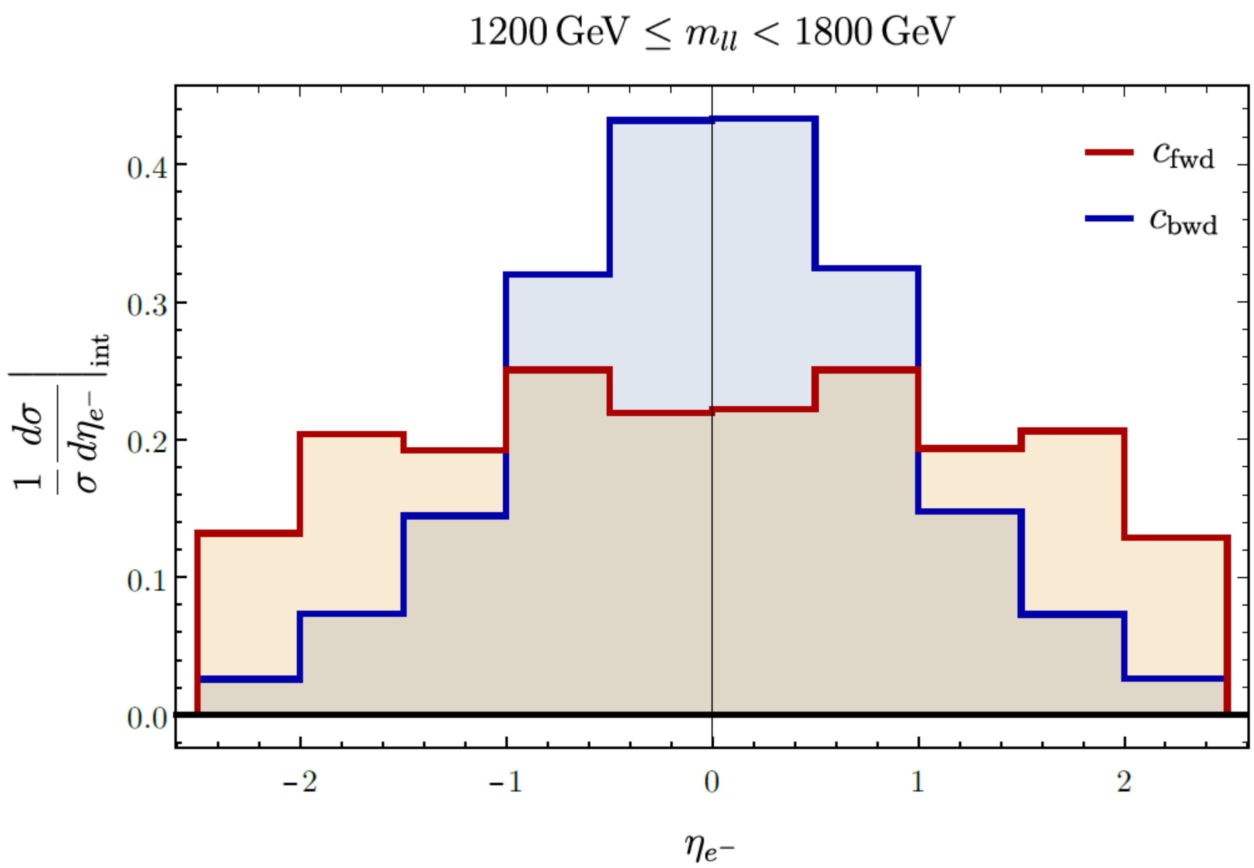
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_p)(\bar{q}_s \gamma^\mu q_s)$
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_p)(\bar{q}_s \gamma^\mu \tau^I q_s)$
Q_{eu}	$(\bar{e}_p \gamma_\mu e_p)(\bar{u}_s \gamma^\mu u_s)$
Q_{ed}	$(\bar{e}_p \gamma_\mu e_p)(\bar{d}_s \gamma^\mu d_s)$

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

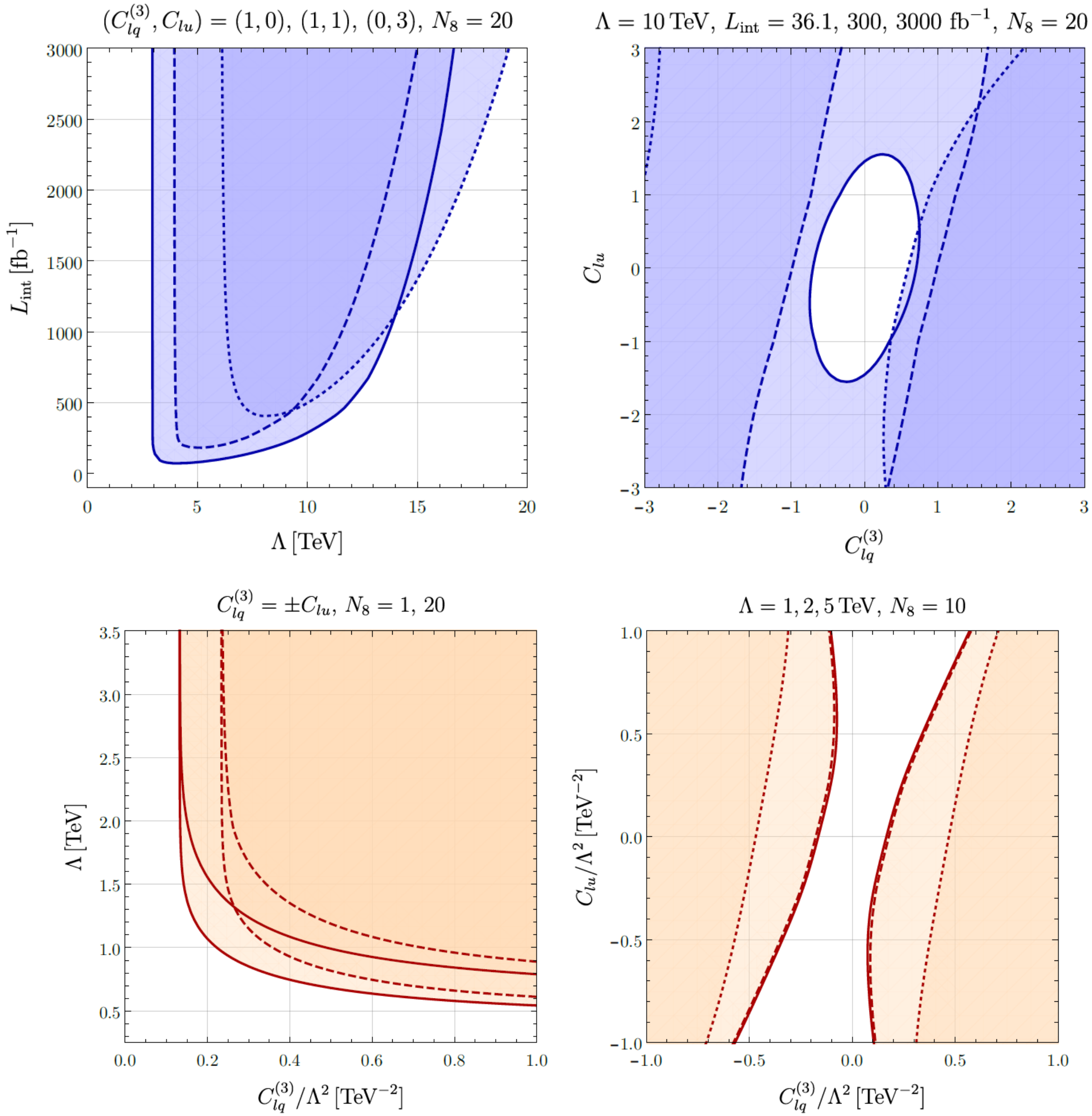
$c_{\text{fwd}} = C_{lq}^{(3)} - 0.48\, C_{eu} - 0.33\, C_{lq}^{(1)} + 0.15\, C_{ed}$

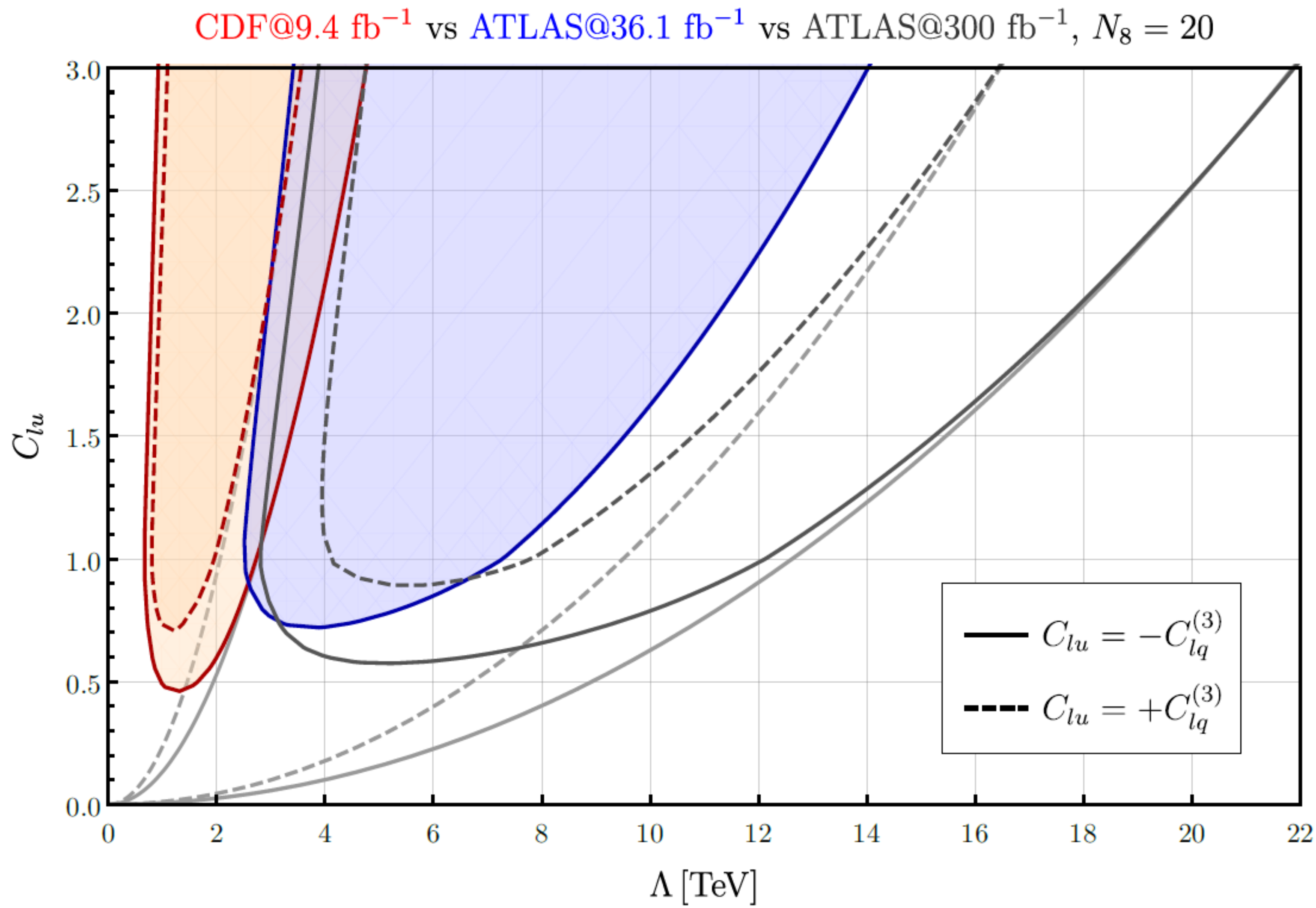
$c_{\text{bwd}} = C_{lu} + 0.81\, C_{qe} - 0.33\, C_{ld}$



William Shepherd, SHSU

LHC and Tevatron Sensitivity





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

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 NLO predictions are under-constrained by low energy data
  - LO fits should include an honest appraisal of NLO corrections, not make overly-strong claims
- 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

Thank You!

Backup: Flavor Matching

MFV and the SMEFT

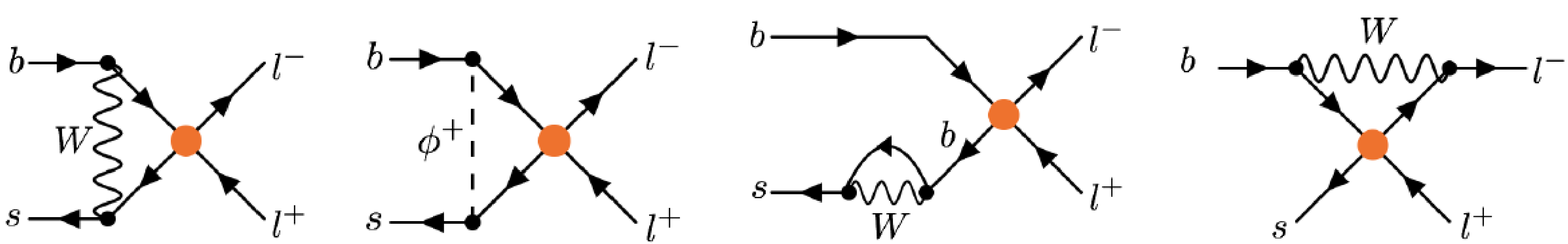
- We can insist that all flavor violation is given by powers of Yukawa matrices
  - Allowing arbitrary powers returns back to the full flavor-violation basis, with an approximate $U(2)^2$
- Allowing no CP or flavor violation leaves only 16+20 parameters, linear flavor violation permits an additional 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

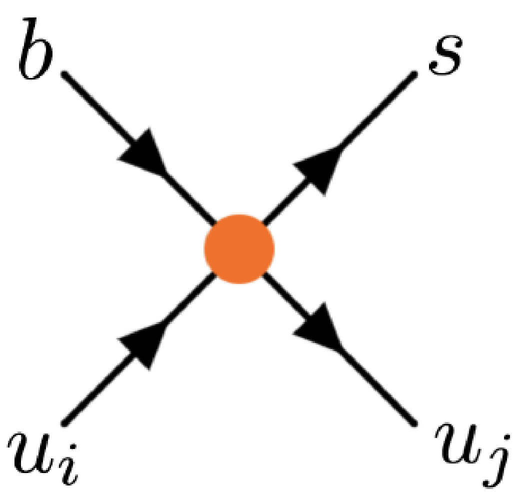
4-fermi operators

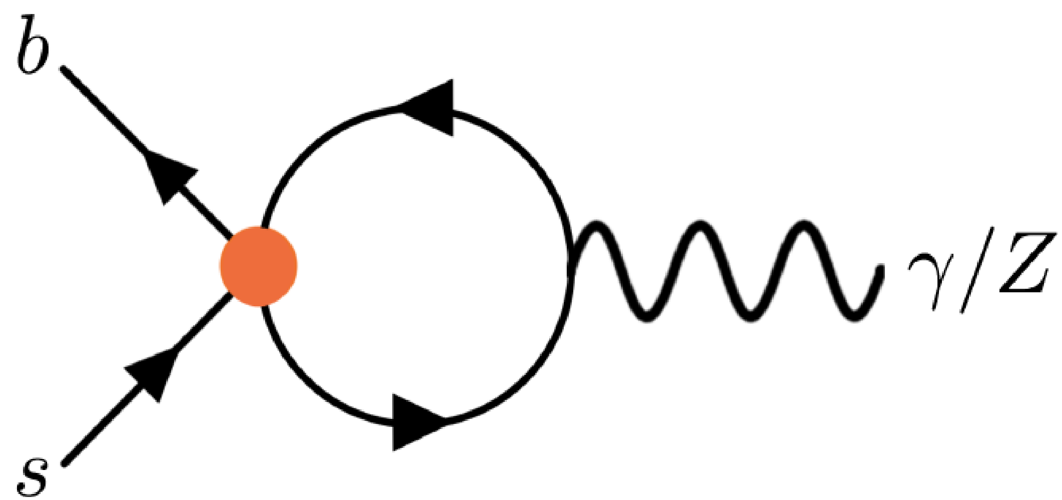
- Most 4-fermion operators that contribute are mixed quark-lepton operators
- SM charged-current loop then gives access to flavor changing effects
  - Non-top effects cancel mass-independent terms by GIM



4-fermi operators – tree level FCNCs

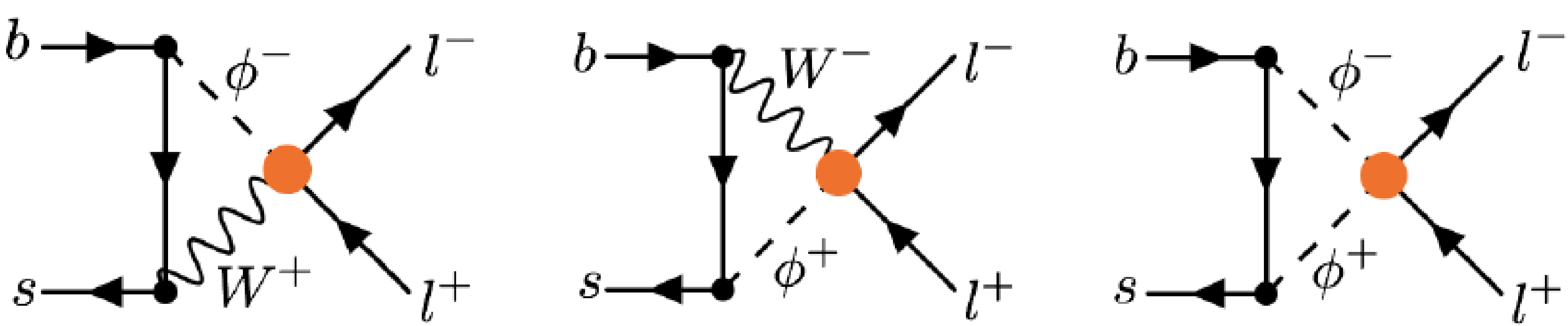
- 4-doublet operators can yield tree-level flavor changes due to CKM effects
- These will run into observable operators either with explicit matching or WET running





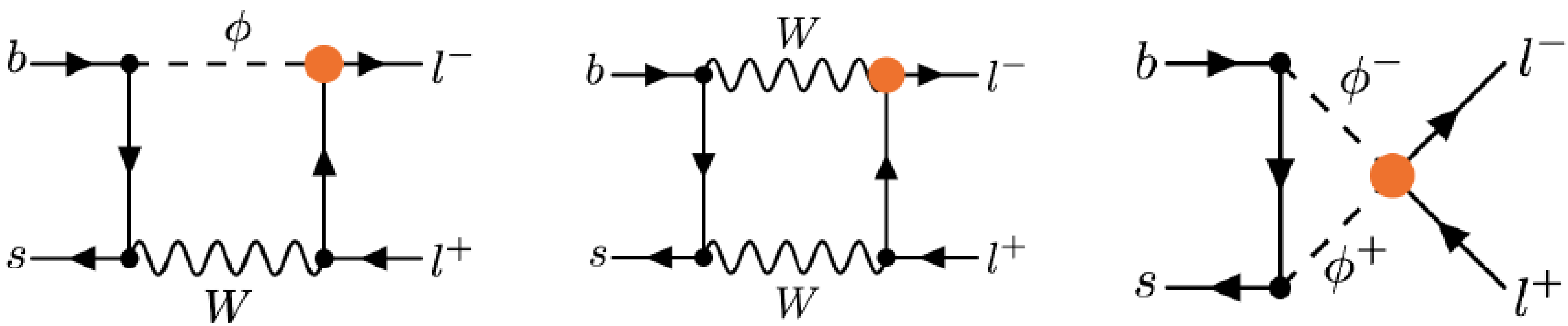
Higgs-leptonic current operators

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



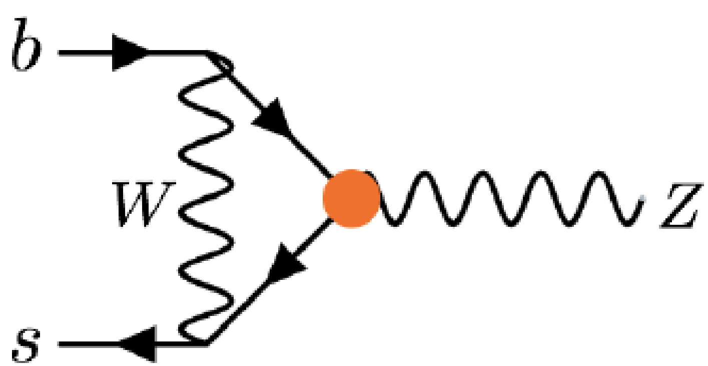
Higgs-leptonic current operators

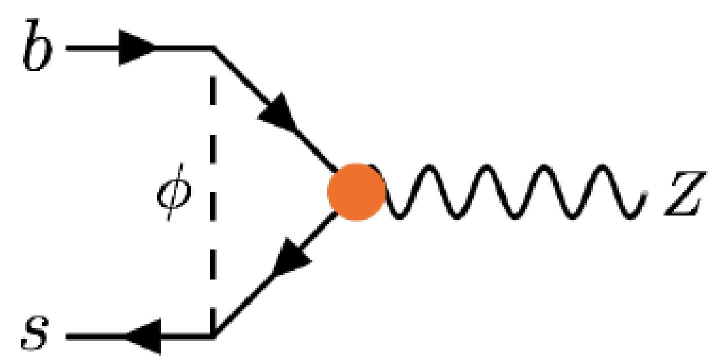
- Triplet operators give corrections to W and Z couplings to leptons
- Again also generate new diagrams important for gauge invariance



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.