NLO EFT in Drell-Yan:
Theory Errors and their Impact

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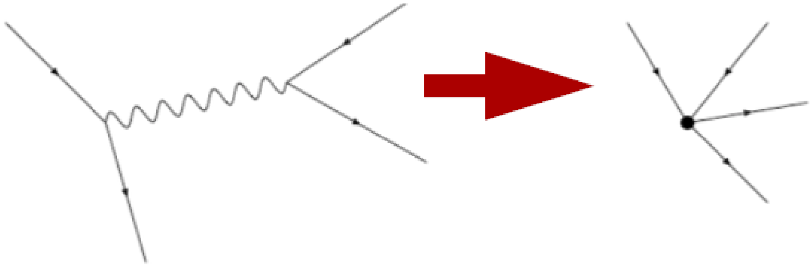
Based on…

- 1611.09879 with Christine Hartmann and Michael Trott

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	$(H^\dagger H)^3$

$3: H^4D^2$

$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$\left(H^\dagger D_\mu H\right)^*\left(H^\dagger D_\mu H\right)$

$5: \psi^2H^3 + \text{h.c.}$

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}	$(H^\dagger H)(\bar{q}_p d_r H)$

$4: X^2H^2$

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

$6: \psi^2XH + \text{h.c.}$

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}	$(\bar{q}_p\sigma^{\mu\nu}d_r)H\, B_{\mu\nu}$

$7: \psi^2H^2D$

$Q_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p\gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{l}_p\tau^I\gamma^\mu l_r)$
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} + 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?

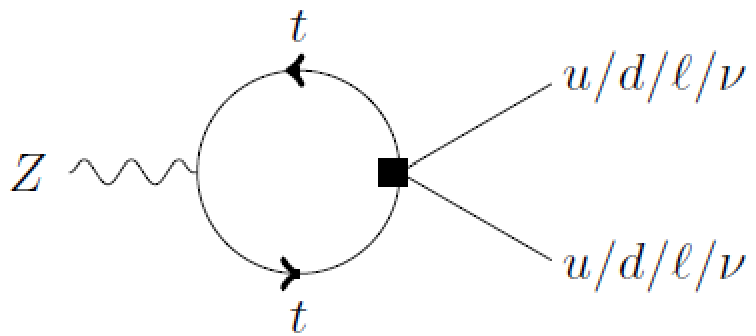
- What is the theory error on a tree-level prediction for EFT effects?
  - Standard loop factor is $\frac{1}{16\pi^2} \sim 1\%$
  - $\frac{v^2}{\Lambda^2} \sim 1\%$ as well
  - Numerical coefficients not known a priori
- SMEFT renormalization known, RG improvement will capture logs
  - For LHC-scale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

Large y_t, λ limit

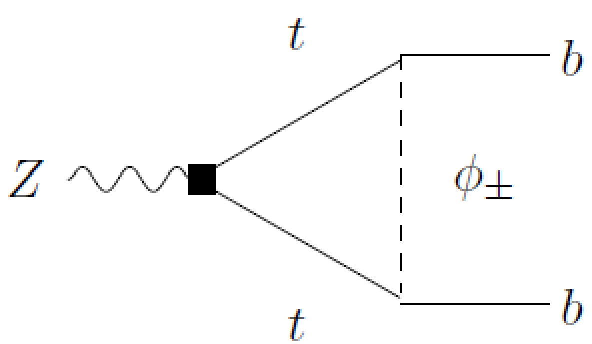
- These two couplings are known to be sizeable
  - Only QCD coupling compares
- Calculations are simpler in vanishing gauge coupling limit
  - Gauge fixing in the presence of D=6 operators leads to additional subtleties
  - Gauge independence assured here
- A good first step toward a full NLO treatment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

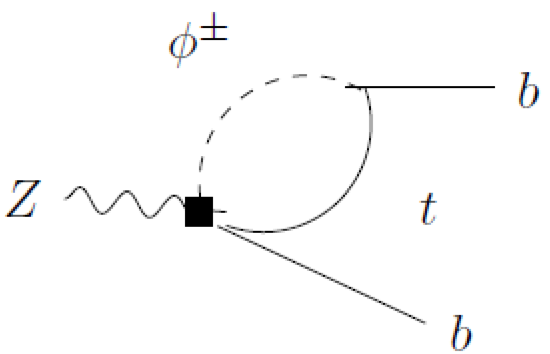
Contributing Operators

- 4-fermion operators:



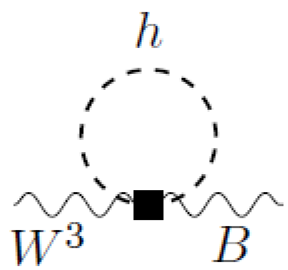
- Scalar-fermionic current operators:



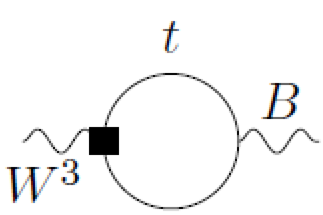


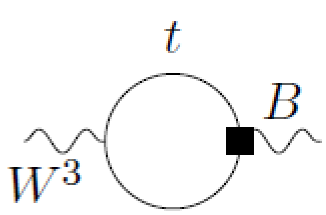
Contributing Operators

- 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

Numerics

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

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

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

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

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

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

Phenomenology

- Counting is all that's needed for the most important point
- NLO corrections have introduced dependence on (neglecting flavor indices):
  - 3 Higgs-gauge WCs
  - 2 Dipole WCs
  - 7 Higgs-fermion current WCs
  - 9 four-fermion WCs
- 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

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…

- 1812.07575 with Stefan Alte and Matthias König
- 2006.xxxxx with Alyssa Horne, Jordan Pittman, Marcus Snedeker, and Joel Walker

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
  - EFT is a new perturbation series; need to estimate size of neglected contributions at next order as theory error

Dileptons from SMEFT

- Two types of contributions to dileptons from SMEFT
  - Z couplings can be shifted by SMEFT operator contributions
  - Direct four-fermion operators give amplitudes growing with energy

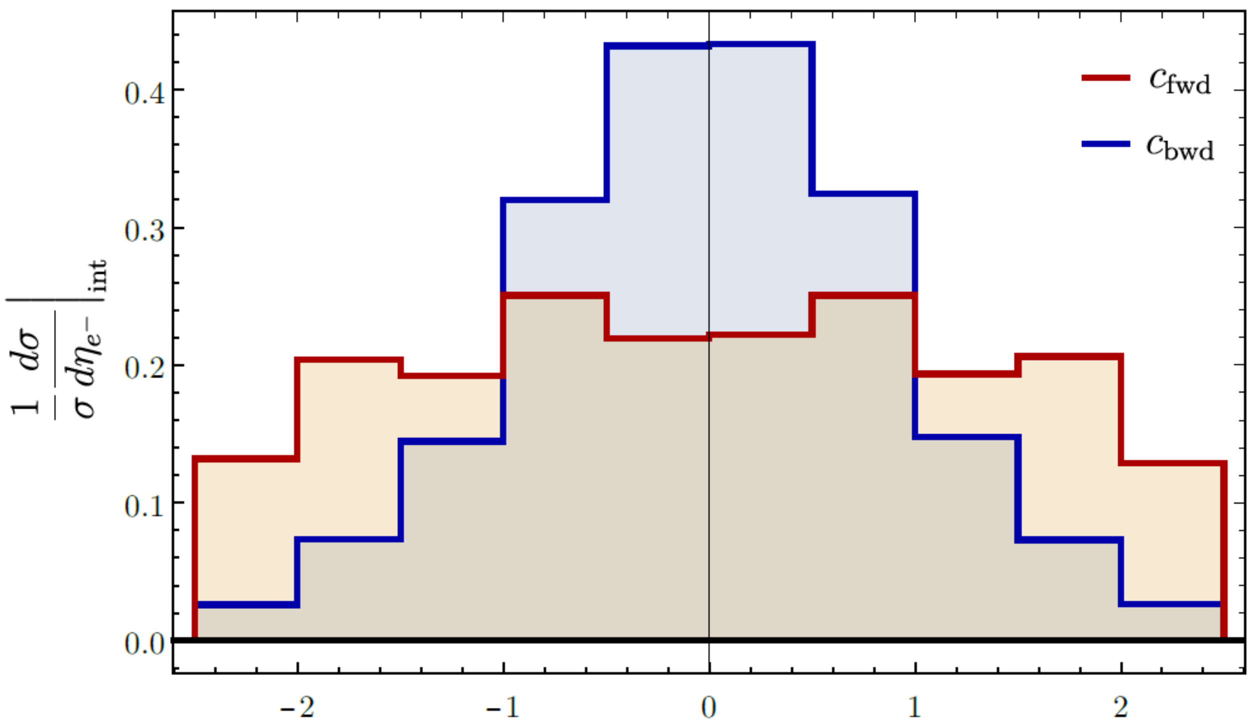
Shift Operators	Direct Forward Operators	Direct Backward Operators
$Q_{HWB} \equiv H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$	$Q^{(1)}_{lq} \equiv (\bar{l}_p \gamma_\mu l_p)\,(\bar{q}_s \gamma^\mu q_s)$	$Q_{lu} \equiv (\bar{l}_p \gamma_\mu l_p)\,(\bar{u}_s \gamma^\mu u_s)$
$Q'_{ll} \equiv (\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$	$Q^{(3)}_{lq} \equiv (\bar{l}_p \gamma_\mu \tau^I l_p)\,(\bar{q}_s \gamma^\mu \tau^I q_s)$	$Q_{ld} \equiv (\bar{l}_p \gamma_\mu l_p)\,(\bar{d}_s \gamma^\mu d_s)$
$Q_{Hd} \equiv (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$	$Q_{eu} \equiv (\bar{e}_p \gamma_\mu e_p)\,(\bar{u}_s \gamma^\mu u_s)$	$Q_{qe} \equiv (\bar{q}_p \gamma_\mu q_p)\,(\bar{e}_s \gamma^\mu e_s)$
$Q_{Hu} \equiv (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$	$Q_{ed} \equiv (\bar{e}_p \gamma_\mu e_p)\,(\bar{d}_s \gamma^\mu d_s)$	
$Q_{He} \equiv (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$		
$Q^{(1)}_{Hl} \equiv (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$		
$Q^{(3)}_{Hl} \equiv (H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$		
$Q^{(1)}_{Hq} \equiv (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$		
$Q^{(3)}_{Hq} \equiv (H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$		
$Q_{HD} \equiv (H^\dagger D_\mu H)^* (H^\dagger D_\mu H)$		

Forward/Backward production

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

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

$1200\,\mathrm{GeV} \le m_{ll} < 1800\,\mathrm{GeV}$



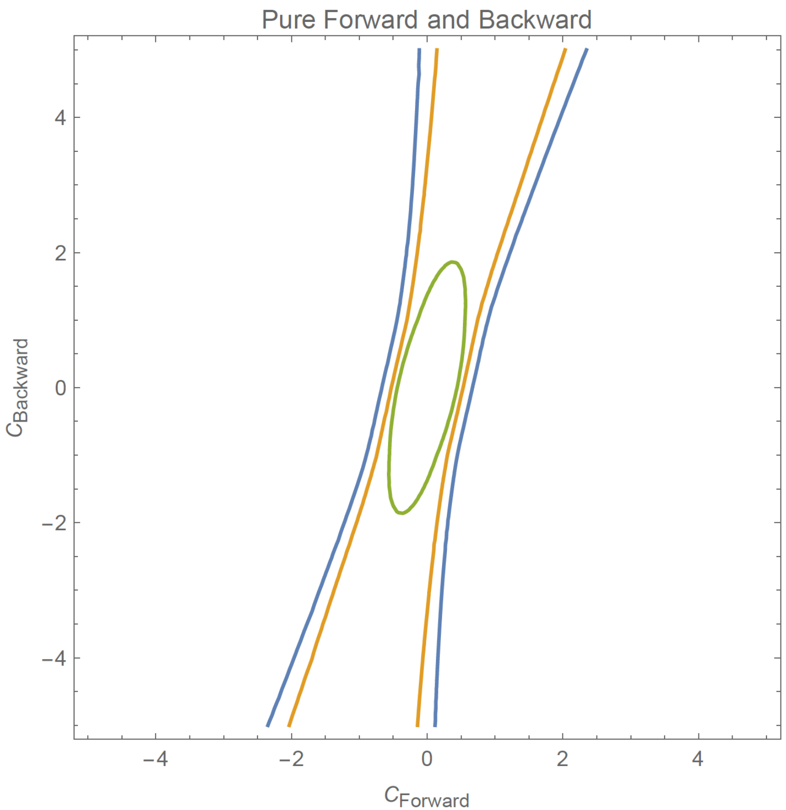
$$c_{\rm fwd}^{\rm (shift)} = -.014C_{Hd} - .12C_{HD} - .047C_{He} + .19C_{Hl}^{(1)} - .29C_{Hl}^{(3)} - .058C_{Hq}^{(1)} + .14C_{Hq}^{(3)} + .062C_{Hu} - .28C_{HWB} + .24C'_{ll}$$

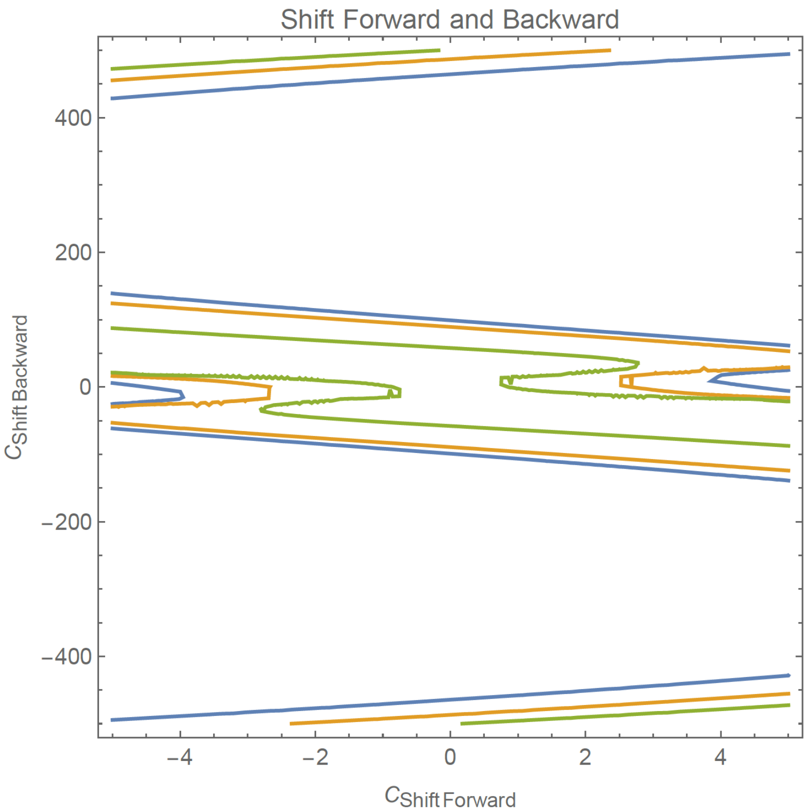
$$c_{\rm bwd}^{\rm (shift)} = .006C_{Hd} + .012C_{HD} + .008C_{He} - .029C_{Hl}^{(1)} + .016C_{Hl}^{(3)} + .042C_{Hq}^{(1)} - .013C_{Hq}^{(3)} - .038C_{Hu} + .009C_{HWB} - .021C'_{ll}$$

Theory Error Treatment

- Dim-8 effects are order $\frac{1}{\Lambda^4}$, signal is $\frac{1}{\Lambda^2}$
  - Dim-6-squared is also order $\frac{1}{\Lambda^4}$, can use that as a mock-up of total term of that order
- Model theory error as $\left(c_6^2 + g_w^2 c_8 \sqrt{N_8}\right) \sigma_{d6^2}$
  - Uncorrelated between bins
  - Insist $c_8 \gtrsim 1, c_6$
- Sum in quadrature with other error sources

LHC Sensitivity





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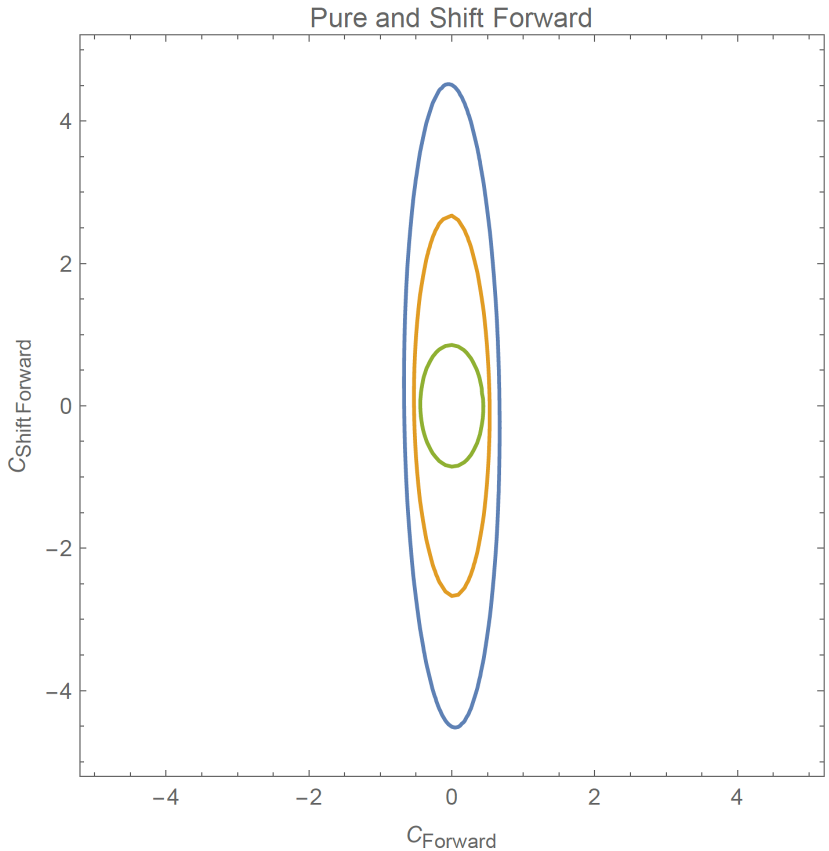
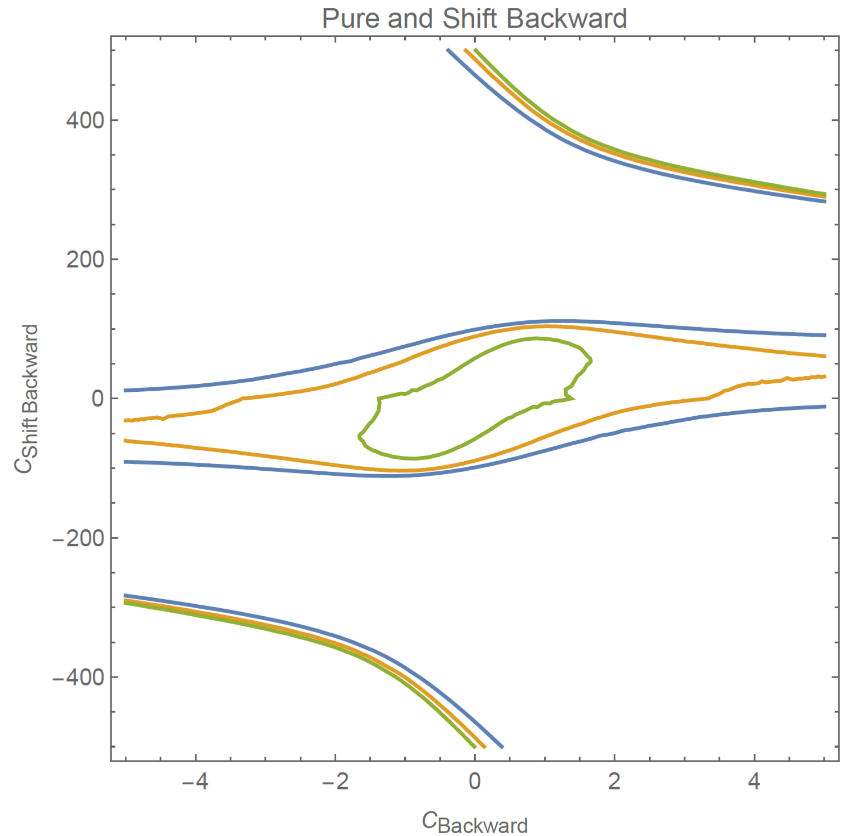




Conclusions

- 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
  - Loops in Z-pole data make this completely unavoidable
- A truly global analysis will be needed to properly constrain the EFT without UV assumptions
  - Developing more off-shell 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!

Please visit with me in the coffee break!

https://shsu.zoom.us/j/97927003584

Password: same as this room

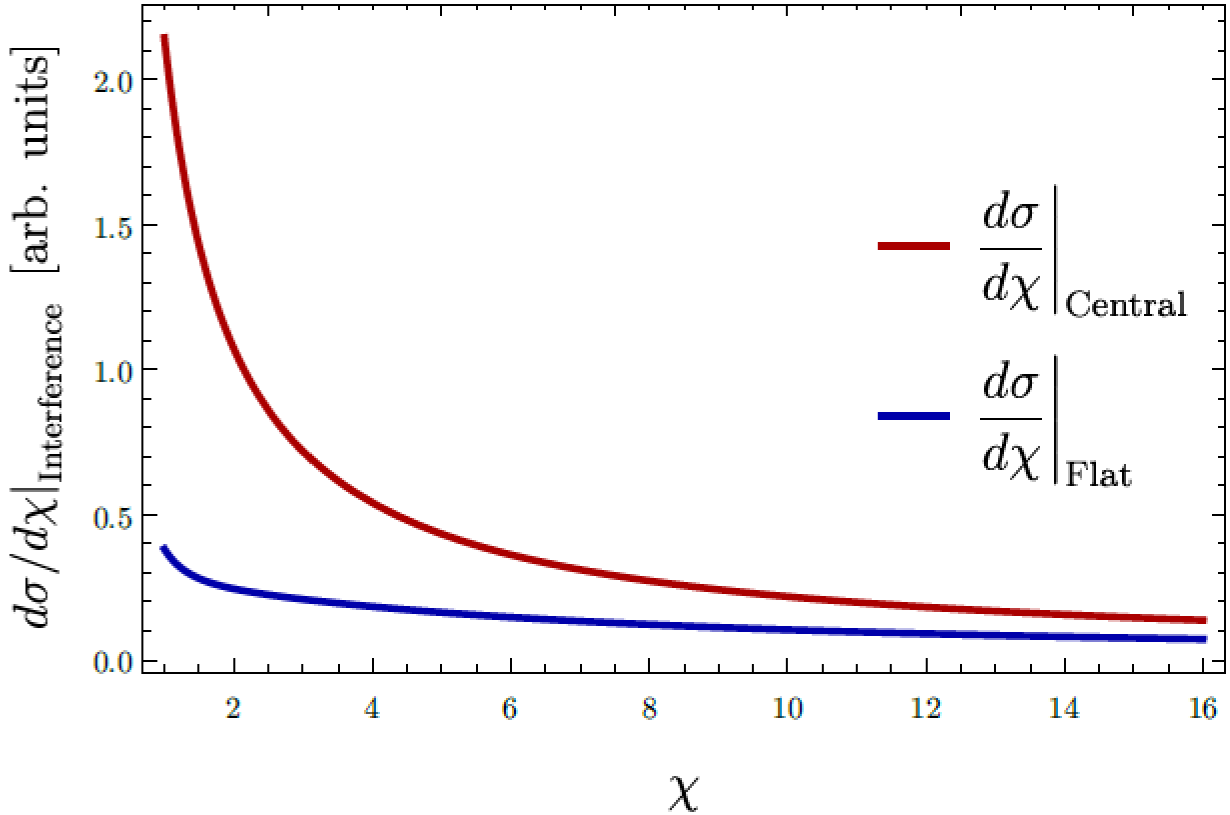
Backup: Dijets

Based on…

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

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

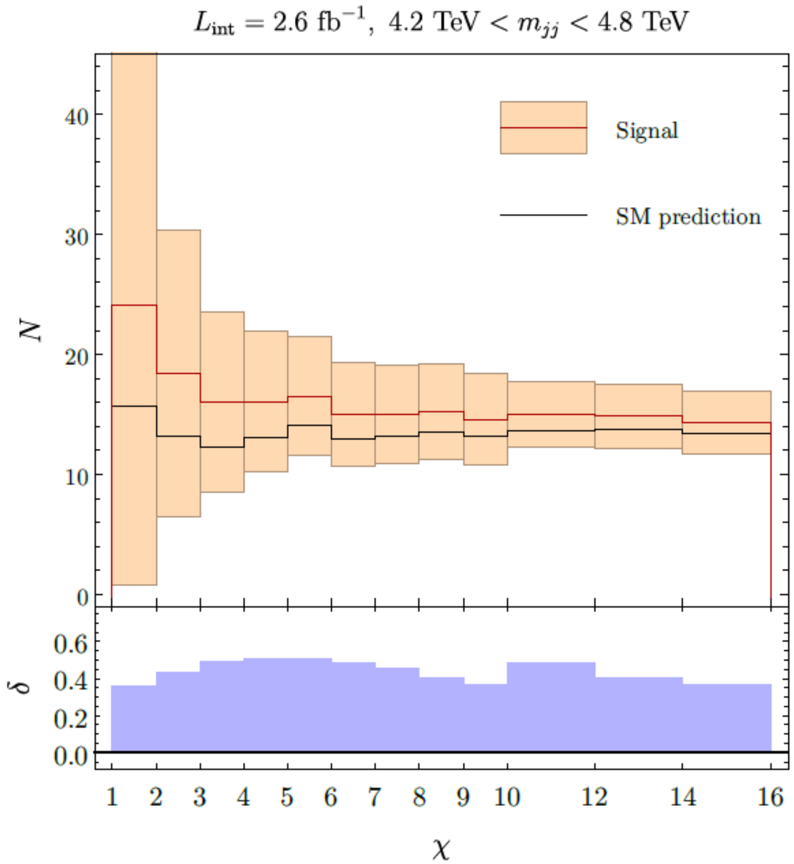
- The quark compositeness search has kept all terms naively predicted by the dimension 6 operator $Q_{qq}^{(1)}$, including squared term
- This is strongly centrally peaked, as the interference is central and the squared term even more so
- Thus, a search in angular variables is a natural technique to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

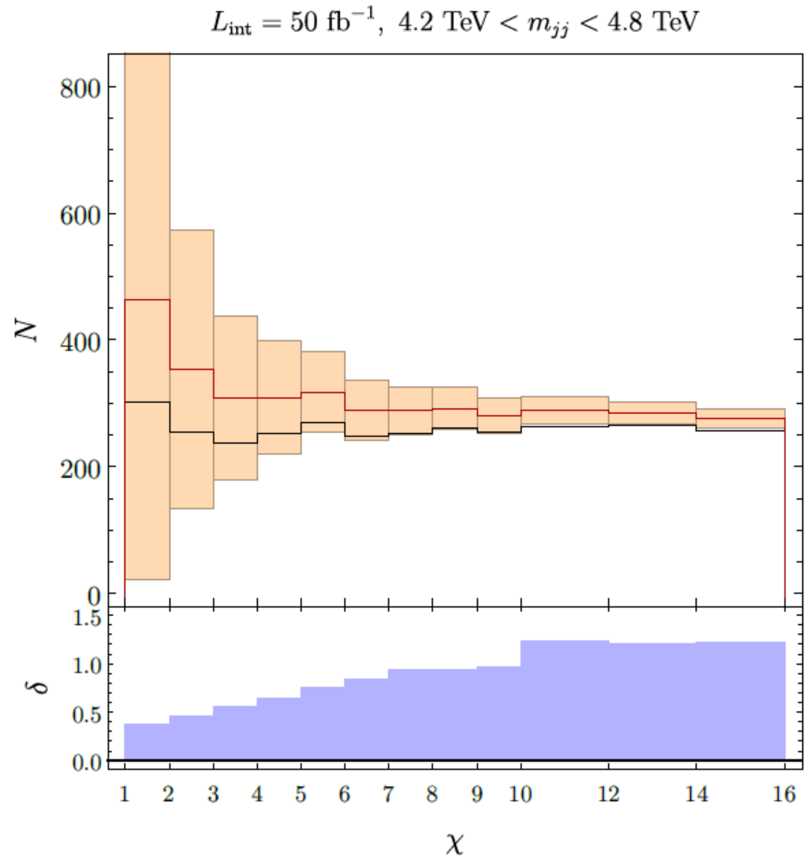
Search in Un-Normalized Distributions

- 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



Search in Un-Normalized Distributions

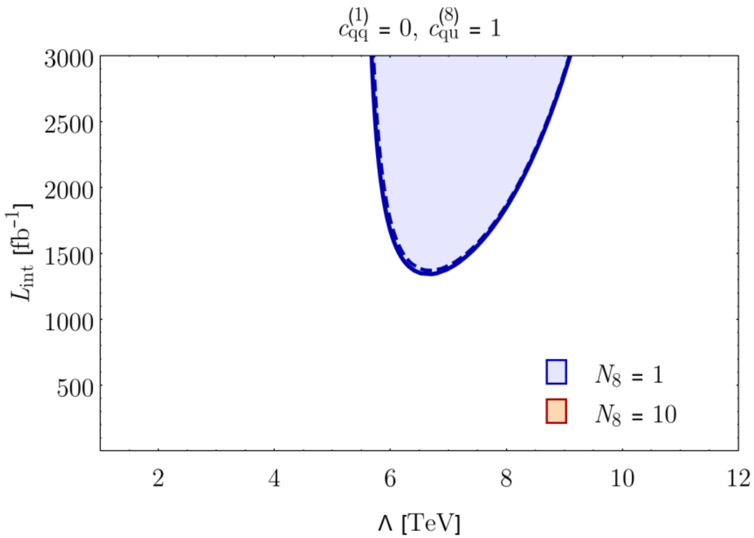
- There can be large systematic differences between signal and background if we don't discard total cross-section information
- These analyses are bounded by EFT error at low χ, but statistics are important elsewhere

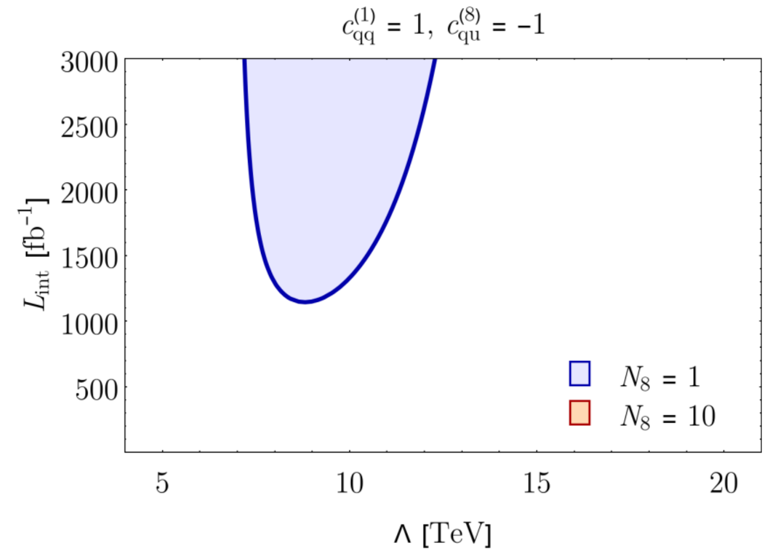


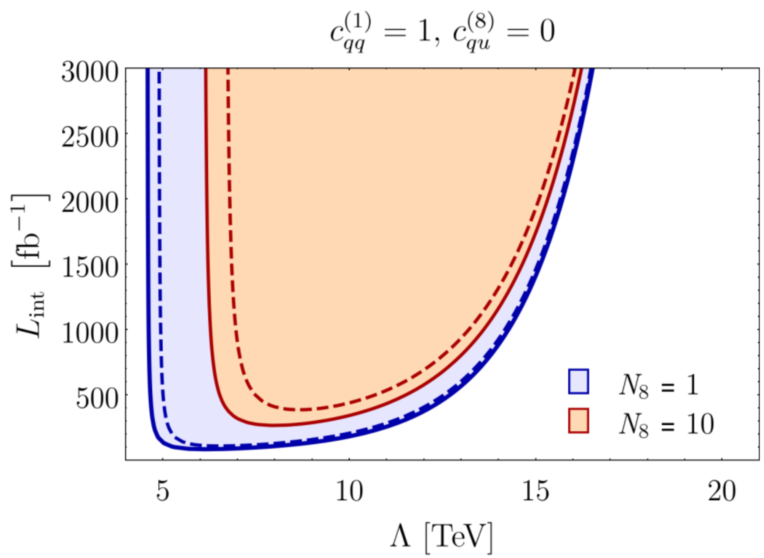
Interpretation of EFT Bounds

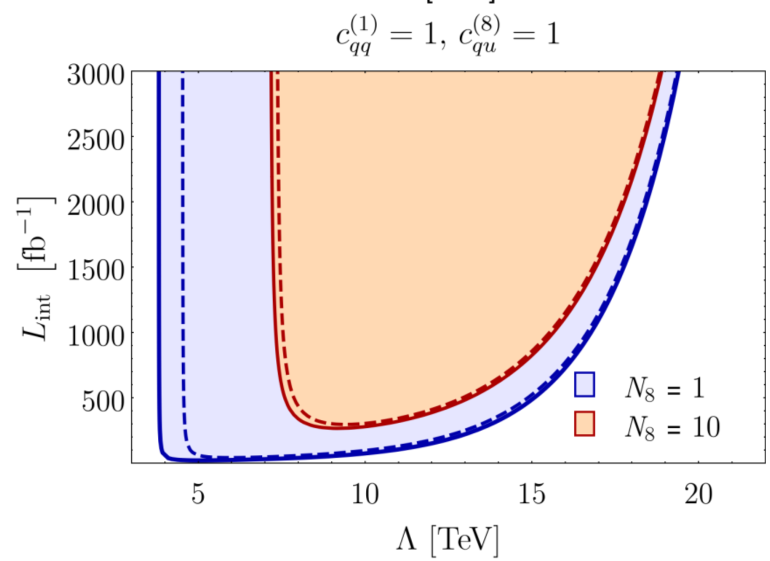
- EFT signal size is only sensitive to the combination ${c_i}/{\Lambda^2}$, cannot distinguish the two
  - Broken weakly by RG effects
- This leaves us two ways to interpret the bounds coming from any EFT search
  - If we fix the new physics scale, searches bound Wilson coefficients
  - Fixed coefficients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

Reach: Fixed Wilson Coefficient

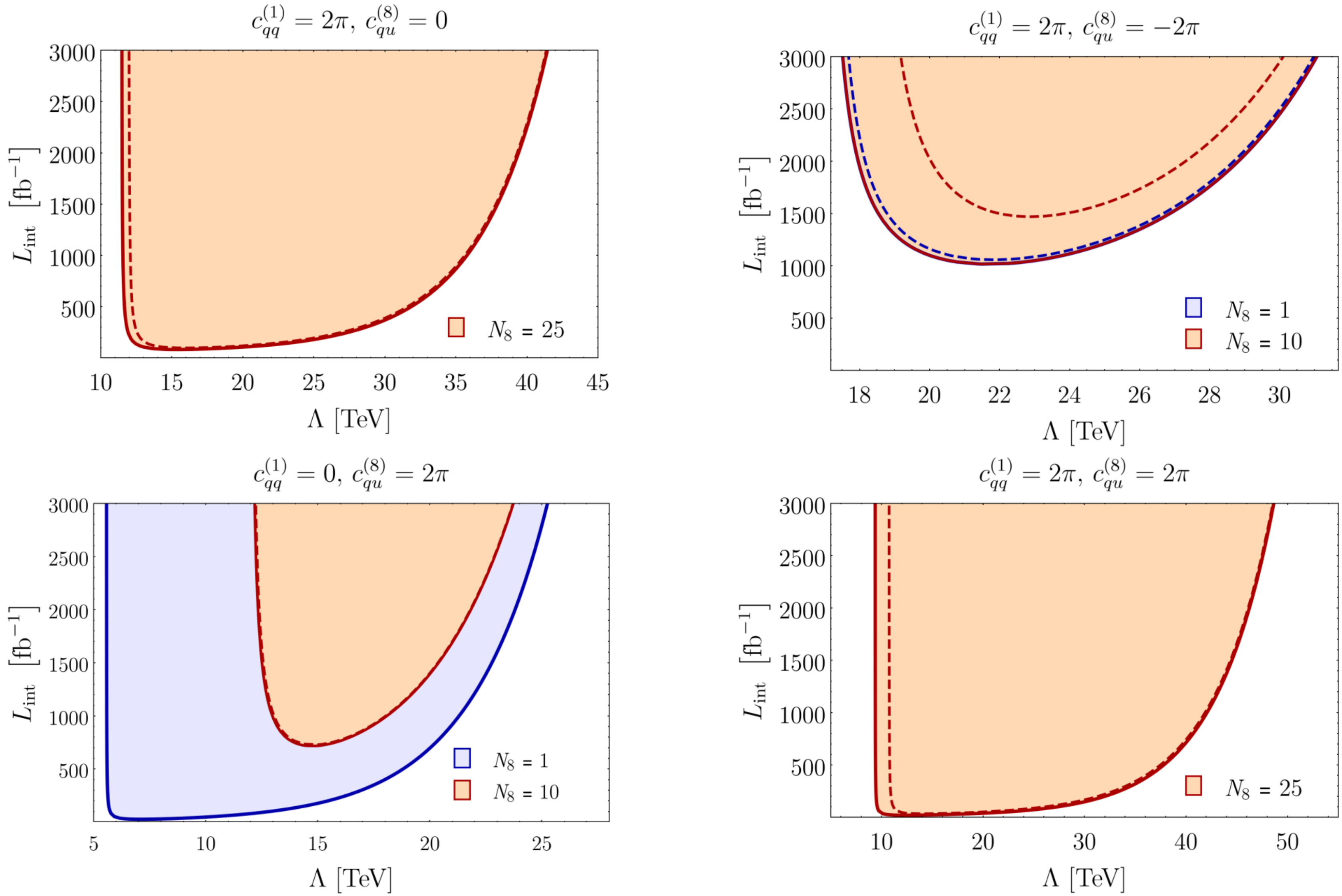






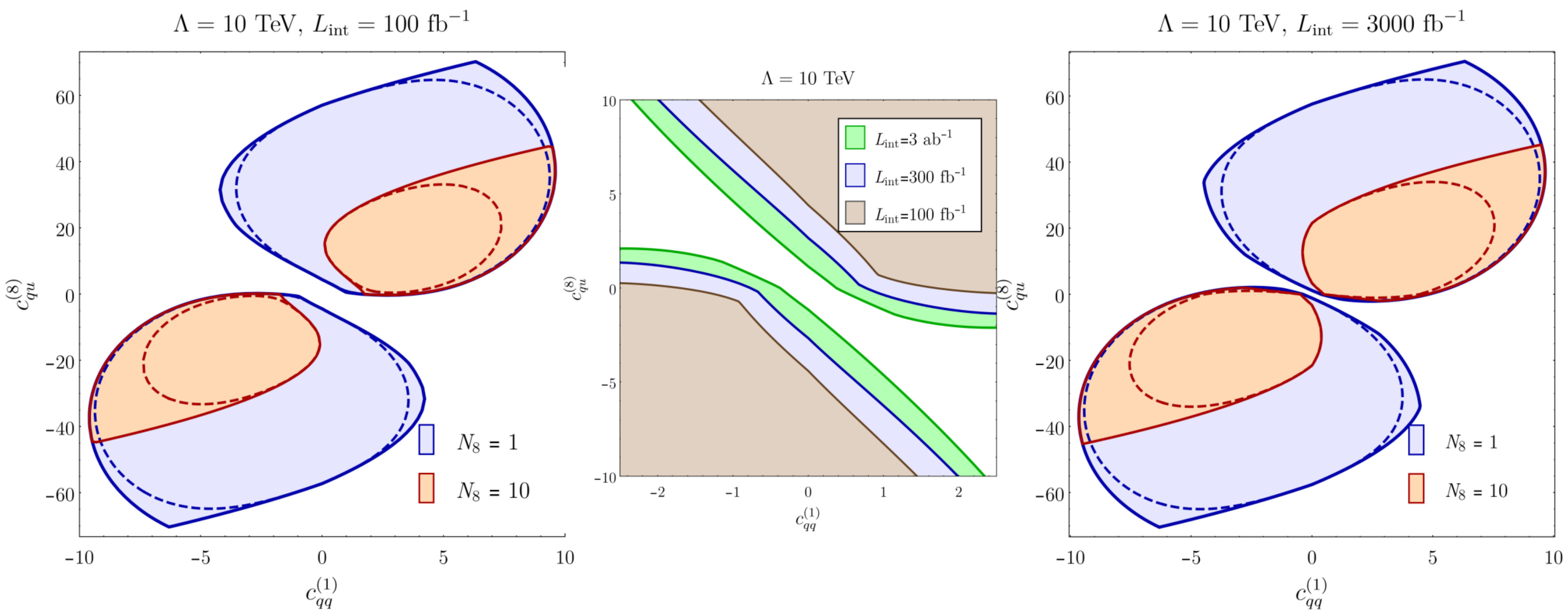


Reach: Fixed Wilson Coefficient



Reach: Fixed NP Scale

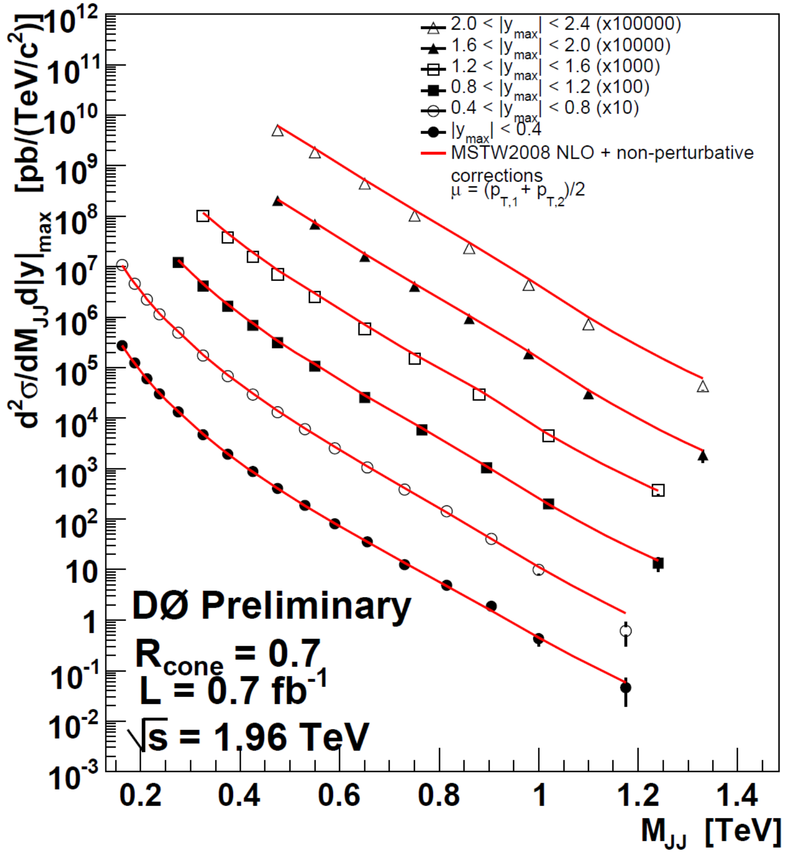
- For large N8, only a narrow angle in coupling space can be constrained



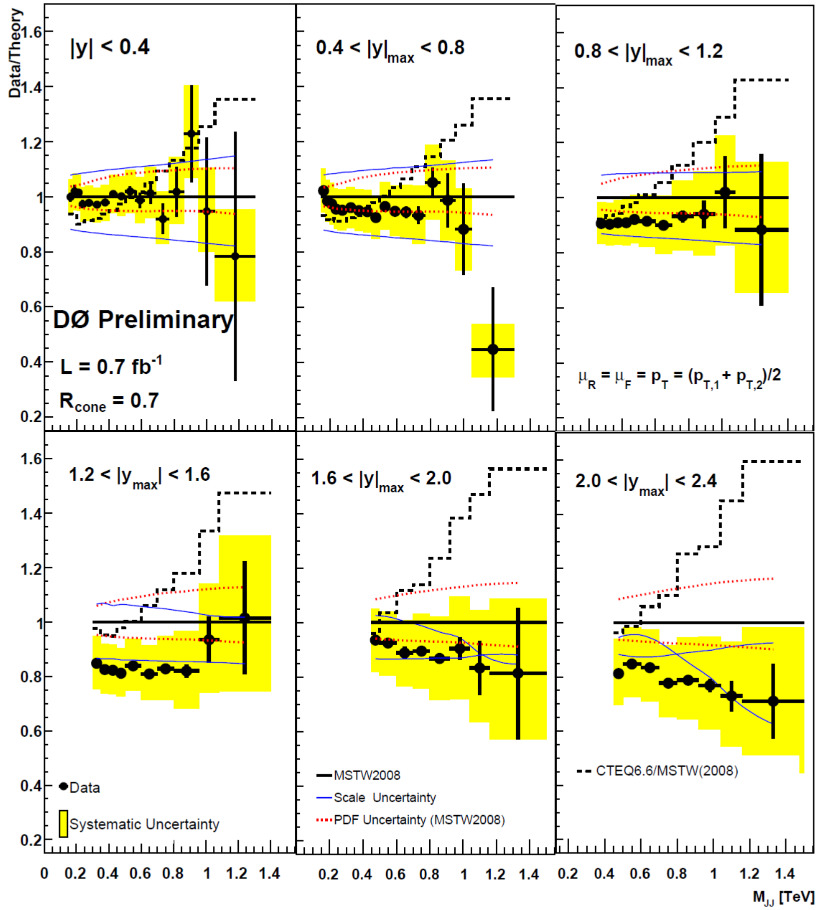
Low Lambda Dijets

- 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

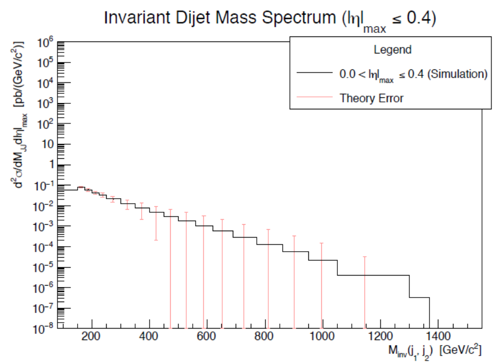
Tevatron Dijet Cross Section

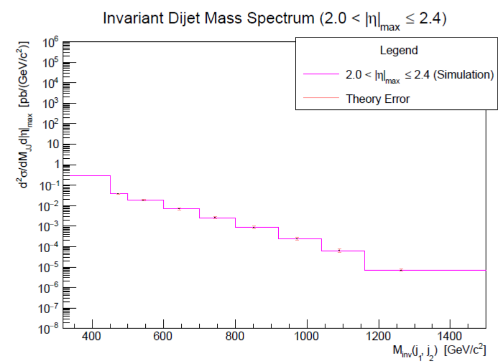


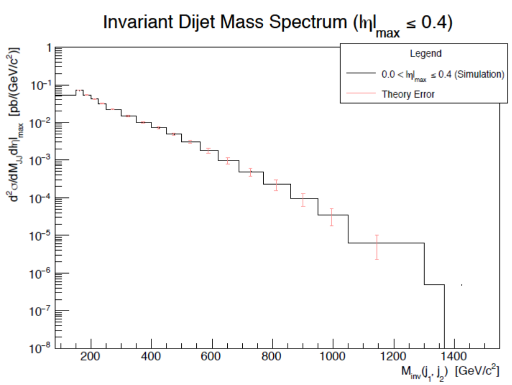
Tevatron Dijet Cross Section

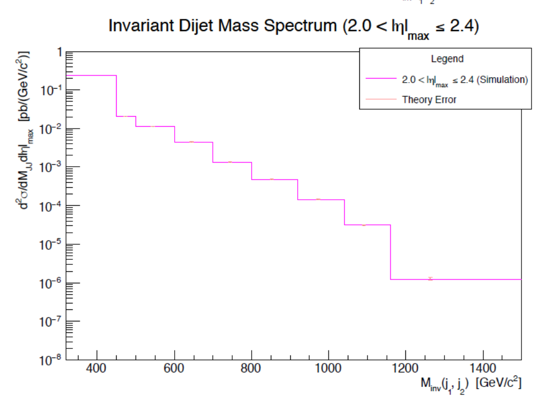


SMEFT Dijets at Tevatron

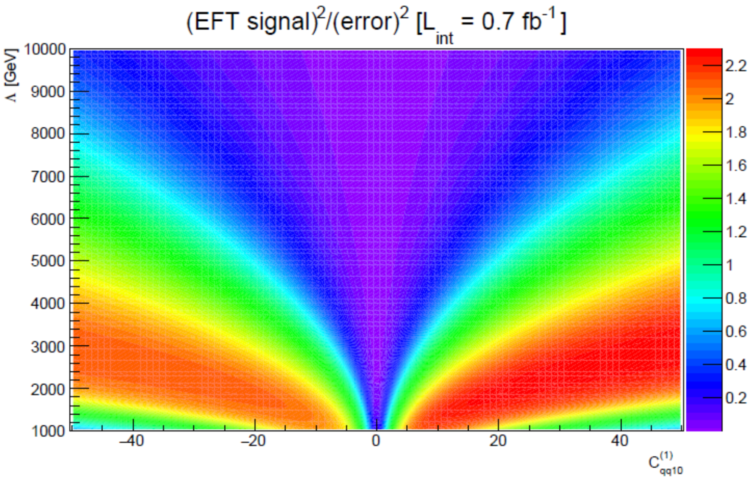


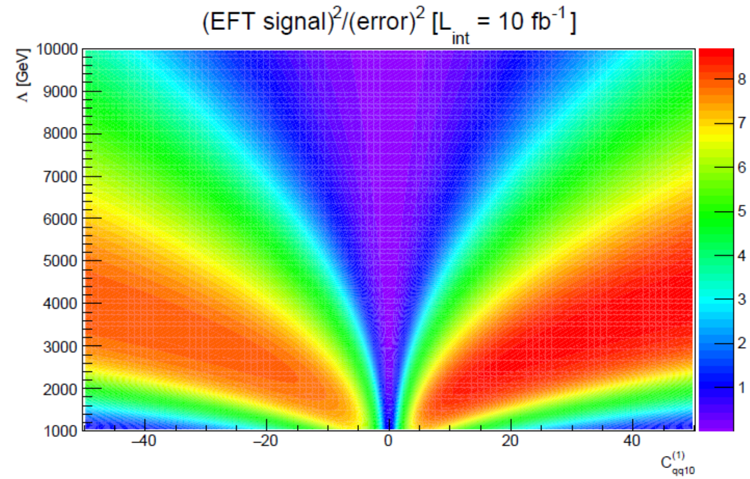






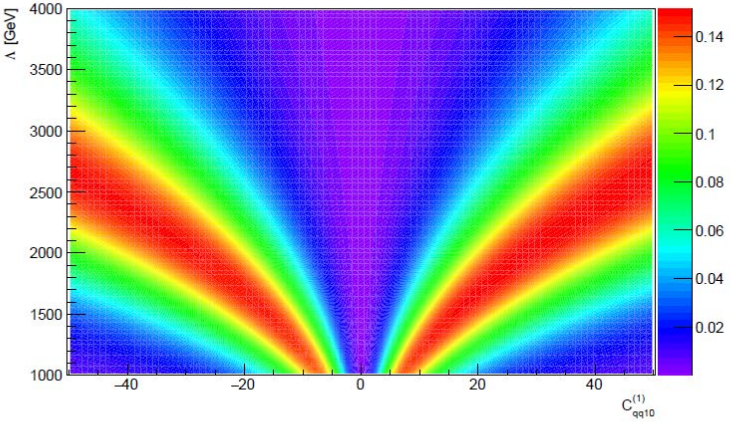
Full-spectrum fits to Tevatron

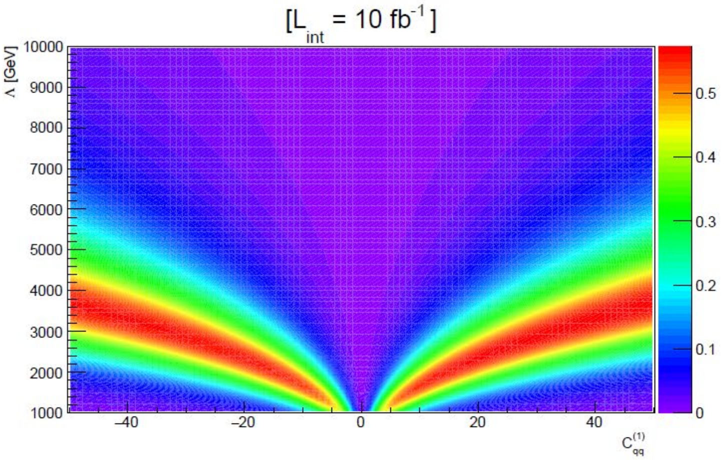




- Fits to Tevatron data for the reported and full experimental luminosity
  - Note that this is fit over a large number of bins (71), so these test statistic values are not significant
  - Also, the full lumi fit assumes that systematics scale like statistics, which is aggressive

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

Backup: Flavor Matching

Based on…

- 1903.00500 with Tobias Hurth and Sophie Renner
- 2003.05432 with Rafael Aoude, Tobias Hurth, and Sophie Renner

MFV and the SMEFT

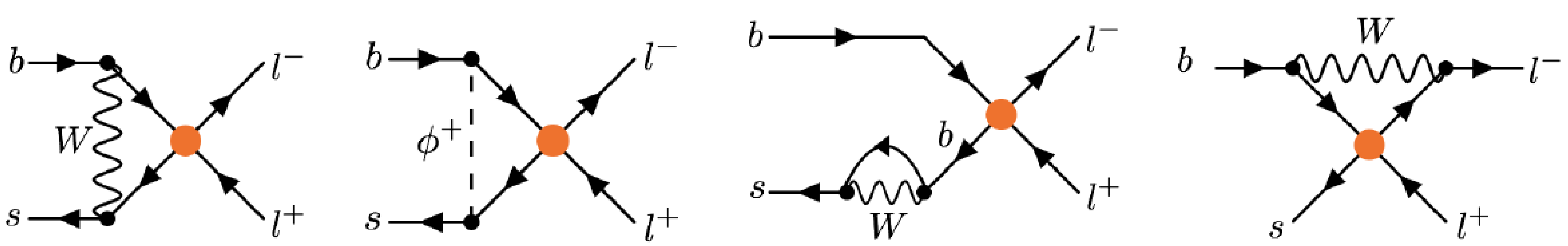
- We can insist that all flavor violation is given by powers of Yukawa matrices
  - Allowing arbitrary powers returns back to the full flavor-violation basis, with an approximate $U(2)^2$
- Allowing no CP or flavor violation leaves only 16+20 parameters, linear flavor violation permits an additional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

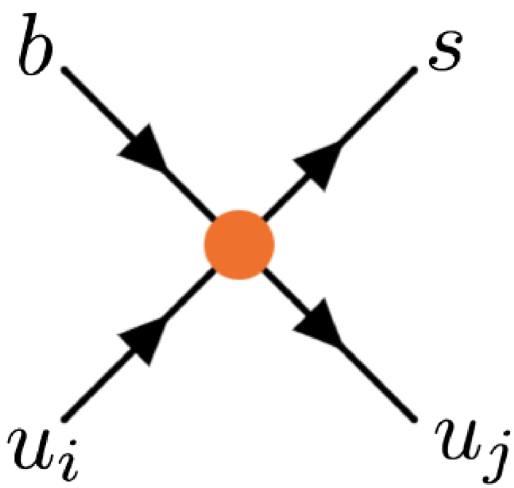
4-fermi operators

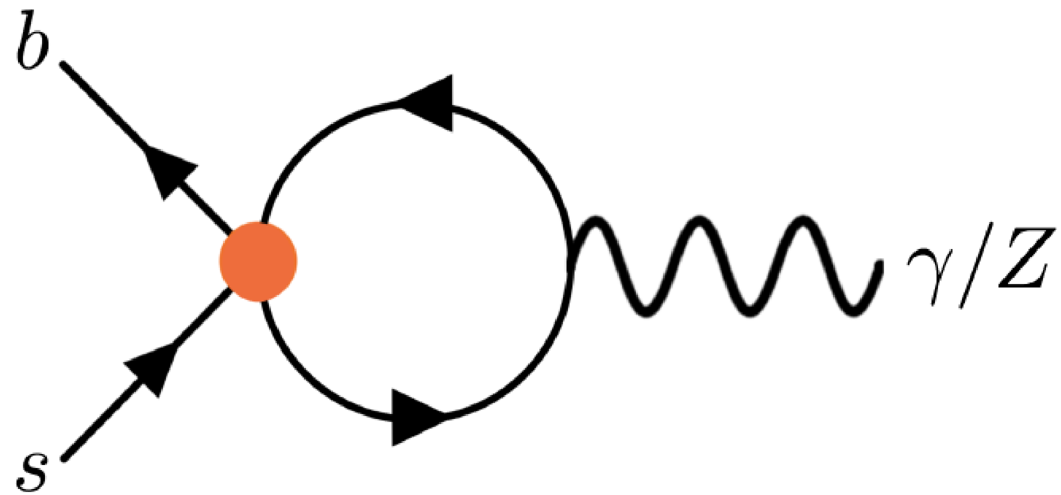
- Most 4-fermion operators that contribute are mixed quark-lepton operators
- SM charged-current loop then gives access to flavor changing effects
  - Non-top effects cancel mass-independent terms by GIM



4-fermi operators – tree level FCNCs

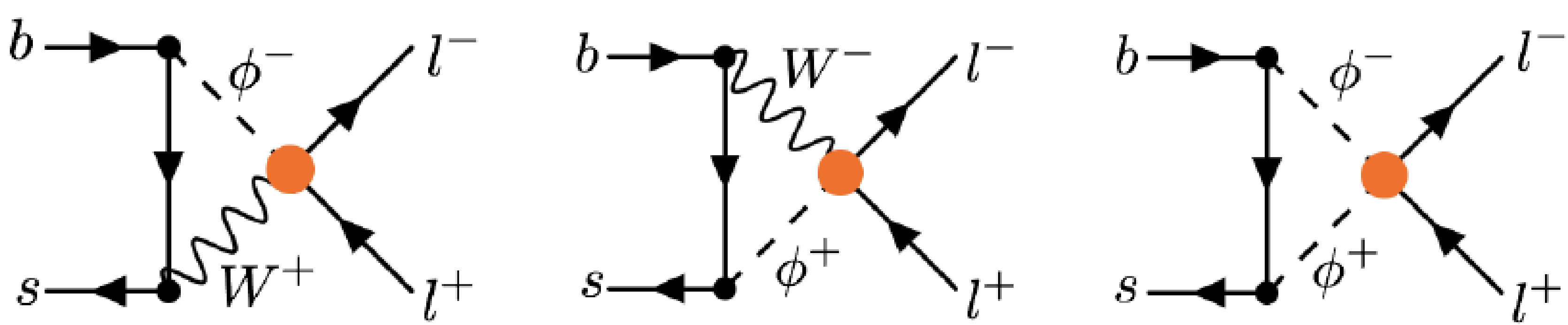
- 4-doublet operators can yield tree-level flavor changes due to CKM effects
- These will run into observable operators either with explicit matching or WET running





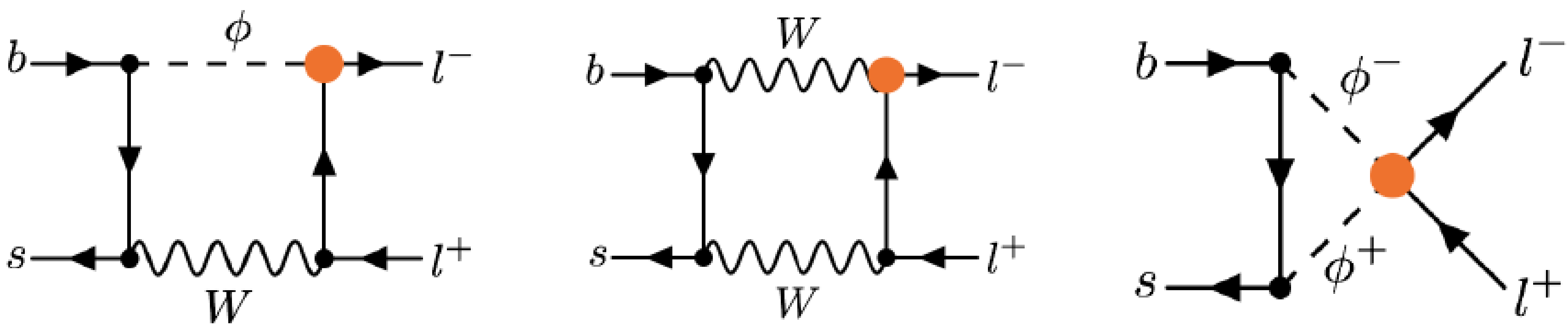
Higgs-leptonic current operators

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



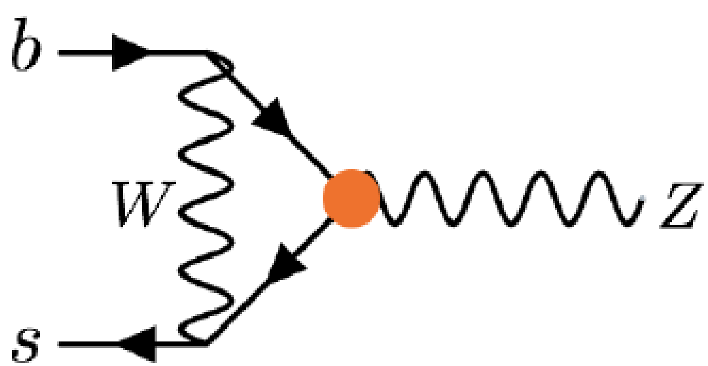
Higgs-leptonic current operators

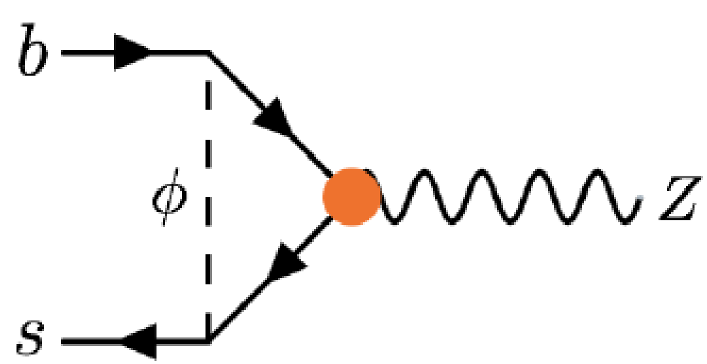
- Triplet operators give corrections to W and Z couplings to leptons
- Again also generate new diagrams important for gauge invariance



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

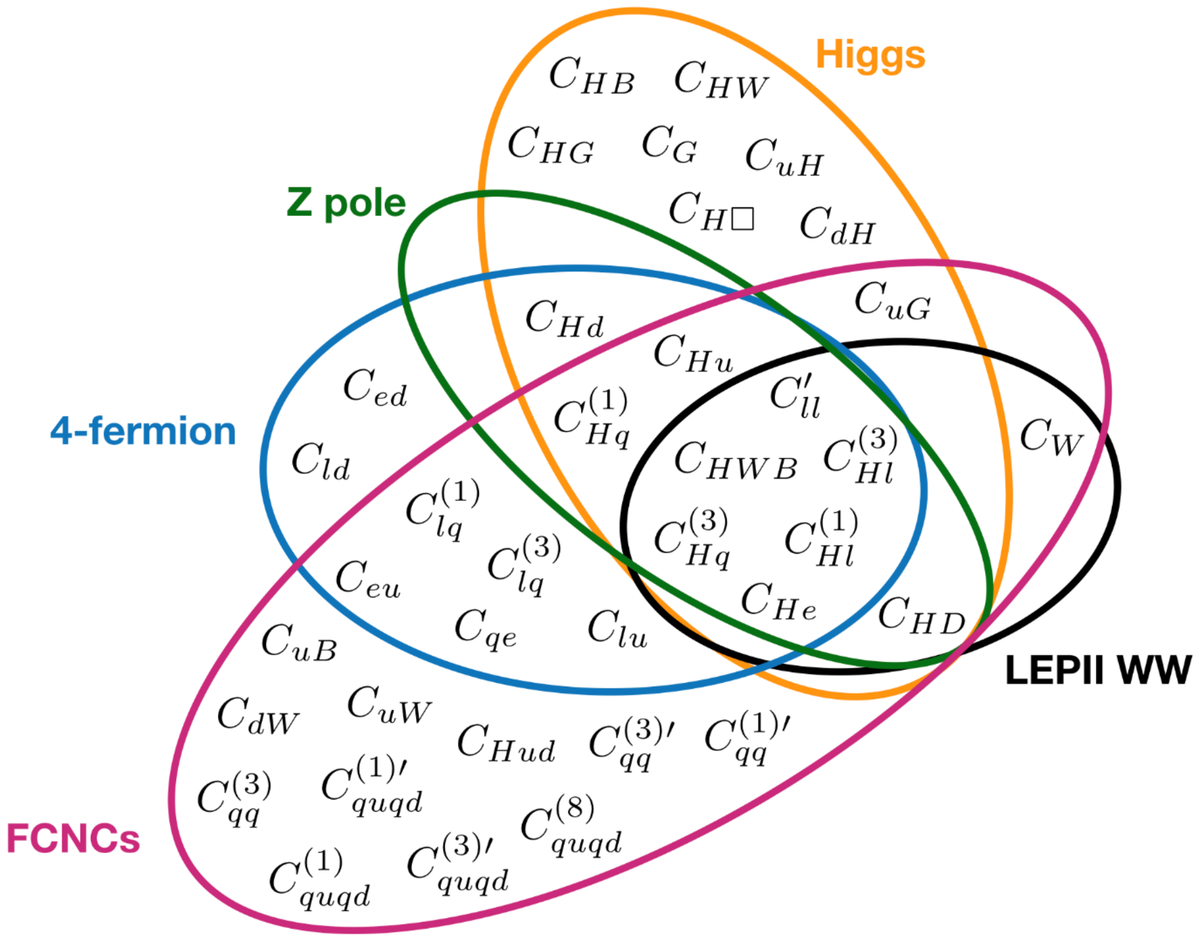
So what can we learn from flavor?

- Clearly flavor-bland models still contribute to flavor observables
- How big are these effects, and how can we best understand them?
- Could quote bounds on each operator we turn on, one at a time, but that's definitely wrong
  - Gives very strong constraints that don't hold when additional directions in parameter space explored

Global Fitting

- Really need to explore all directions at once
- Consider a set of interesting observables, and all the operators that affect them
- Develop a region of parameter space that is allowed and one that is excluded
- For illustration, we'll look at FCNC flavor effects, Higgs rates, low-E and Z-pole scattering, and LEP WW production

Relevant Operators



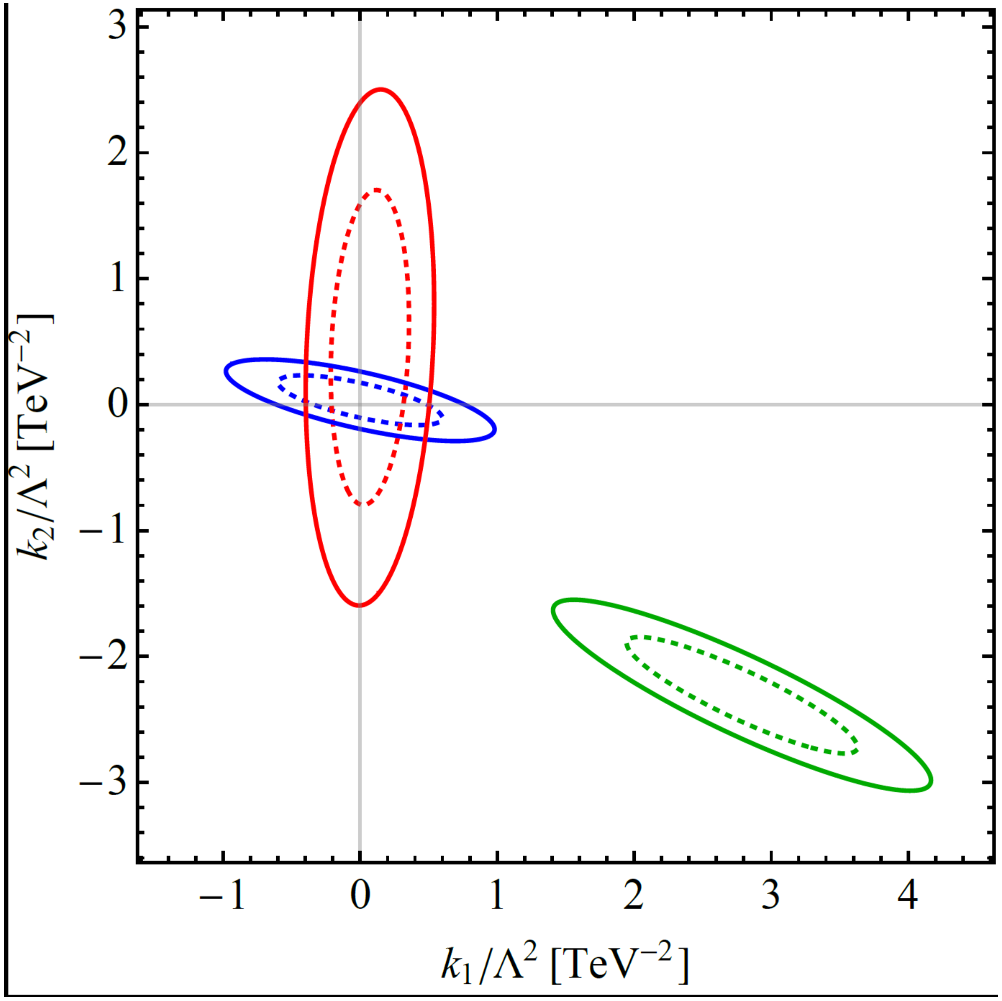
Illustrative Example

- Imagine, for no good reason, that only operators that contribute to Z-pole observables are active.

$$\{C_{HWB}, C_{HD}, C_{Hl}^{(1)}, C_{Hl}^{(3)}, C_{Hq}^{(1)}, C_{Hq}^{(3)}, C_{Hu}, C_{Hd}, C_{He}, C'_{ll}\}$$

- Famously, there are two unconstrained directions when considering this data alone; traditionally this is constrained by adding LEP WW production data.
  - Higgs and flavor also make contact with these unconstrained directions in parameter space

Z-pole flat directions



LEP WW
Higgs
Flavor

Real Global Fitting

- We can write our predictions as

$$\boldsymbol{\mu}(\boldsymbol{\theta}) = \boldsymbol{\mu}_{SM} + \mathbf{H} \cdot \boldsymbol{\theta}$$

- Then $\chi^2(\boldsymbol{\theta}) = (\mathbf{y} - \boldsymbol{\mu}(\boldsymbol{\theta}))^T \mathbf{V}^{-1} (\mathbf{y} - \boldsymbol{\mu}(\boldsymbol{\theta}))$
- Which gives us the maximum likelihood point

$$\hat{\boldsymbol{\theta}} = \left(\mathbf{H}^T \mathbf{V}^{-1} \mathbf{H}\right)^{-1} \mathbf{H}^T \mathbf{V}^{-1} \mathbf{y}$$

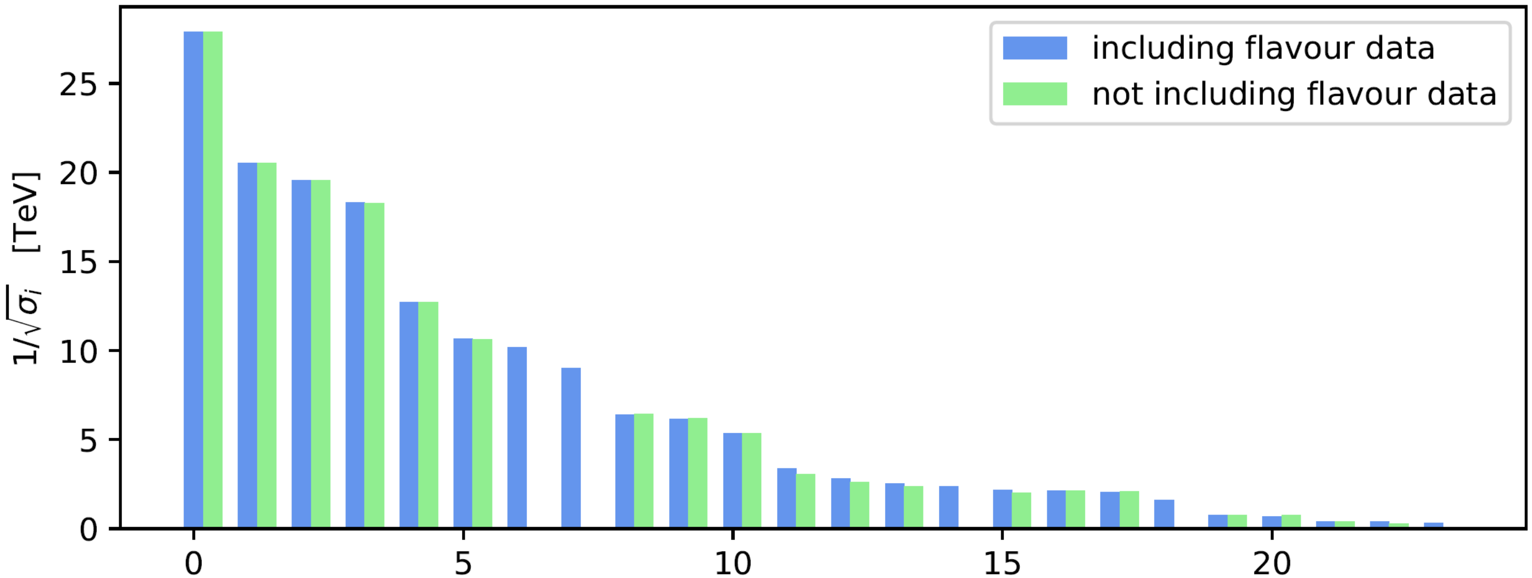
- And the correlations between Wilson coefficients are encoded in the Fisher matrix

$$\mathbf{F} = \mathbf{H}^T \mathbf{V}^{-1} \mathbf{H} = \mathbf{U}^{-1}$$

LO MFV Fit

- All 36 Wilson coefficients allowed
  - Weighted by minimum necessary set of Yukawas
- Including all relevant data, there are 7 unconstrained directions
- Dropping FCNC information, there are 12 flat directions
  - In a model built to avoid flavor constraints, 5 new constraints come from flavor!

LO MFV Fit results



$$c_1 \approx -0.61\left(C_{qq}^{(1)\prime} - C_{qq}^{(3)\prime}\right) - 0.29C_{qq}^{(3)} + 0.19C_{Hq}^{(1)} - 0.17C_{ll}^{\prime} + 0.13C_{Hl}^{(1)} + 0.12C_{Hq}^{(3)} - 0.12C_{dW} + 0.10C_{He} + \cdots ,$$

$$c_2 \approx 0.85C_{dW} + 0.32C_{uB} - 0.18C_{Hq}^{(3)} - 0.14C_{Hl}^{(3)} - 0.11\left(C_{qq}^{(1)\prime} - C_{qq}^{(3)\prime}\right) + 0.11C_{quqd}^{(1)\prime} + \cdots , \quad (4$$

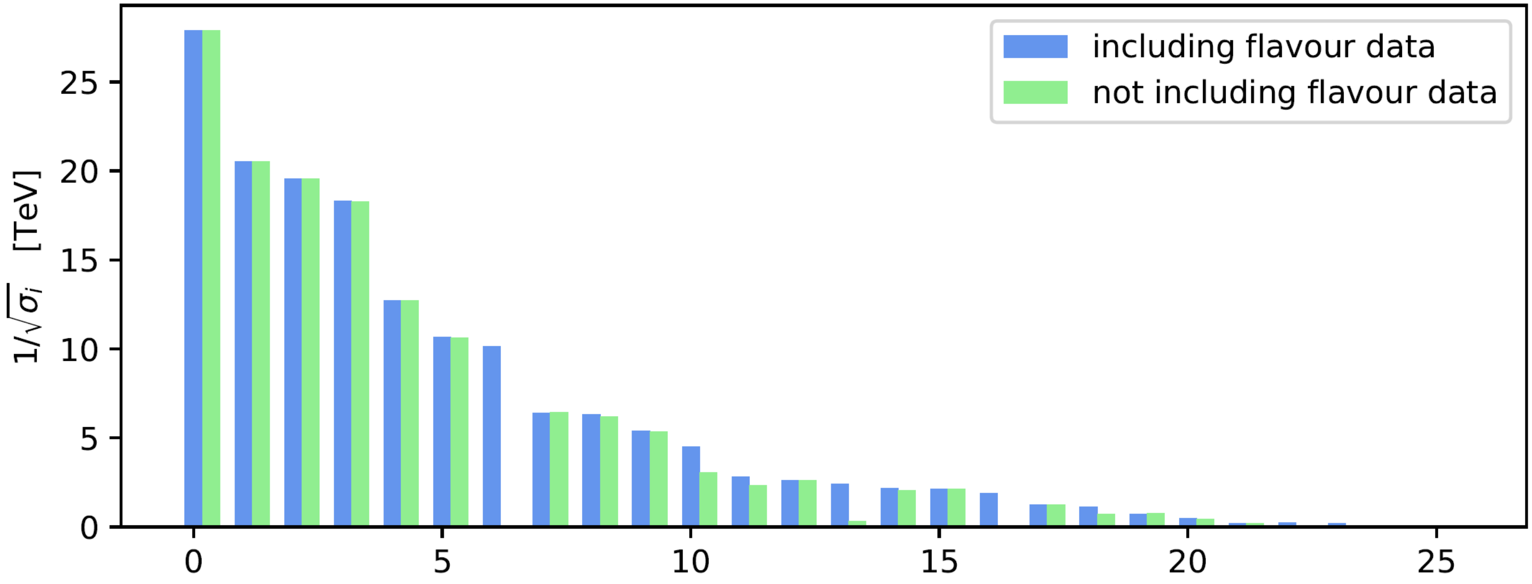
Flavor-Blind NP Fit

- Let's be even more careful to avoid flavor and turn off anything that needs a Yukawa at the scale of NP. Then, we have 26 coefficients:

$$\{C_{H\Box}, C_{HWB}, C_{HD}, C_{HW}, C_{HB}, C_{HG}, C_W, C_G, C^{(1)}_{Hl}, C^{(3)}_{Hl}, C^{(1)}_{Hq}, C^{(3)}_{Hq}, C_{Hu}, C_{Hd}, C_{He},$$
$$C'_{ll}, C^{(3)}_{lq}, C^{(1)}_{lq}, C_{qe}, C_{lu}, C_{ld}, C_{eu}, C_{ed}, C^{(1)\prime}_{qq}, C^{(3)}_{qq}, C^{(3)\prime}_{qq}\}. \quad (4.$$

- Here, including flavor data, there's only one flat direction: $f = \sqrt{2}\left(C^{(1)\prime}_{qq} + C^{(3)\prime}_{qq}\right)$
- Without flavor information, there are 3.

Flavor-Blind Fit results



$$c = -0.62\,(C_{qq}^{(1)\prime} - C_{qq}^{(3)\prime}) - 0.30\,C_{qq}^{(3)} + 0.06\,C_{lq}^{(1)} - 0.04\,C_{lq}^{(3)} + 0.02\,C_{eu} - 0.07\,C_{lu} - 0.02\,C_{qe}$$
$$- 0.01\,C_{Hu} - 0.01\,C_{Hd} + 0.19\,C_{Hq}^{(1)} + 0.11\,C_{Hq}^{(3)} + 0.10\,C_{He} + 0.13\,C_{Hl}^{(1)}$$
$$+ 0.09\,C_{Hl}^{(3)} - 0.17\,C_{ll}' - 0.04\,C_{HB} - 0.01\,C_{HW} - 0.09\,C_{HWB} + 0.01\,C_W. \quad (4.14)$$

Conclusions

- Nothing can avoid flavor data!
  - Even the blandest of models still must pass the taste test
- These constraints can be quite strong, and constitute the *least* amount of information we could imaging getting from flavor in SMEFT
  - Models built with explicit flavor structure will of course learn more from flavor than this
- These inputs to a global fit are important to successfully close a curve in parameter space
  - Limits from low-energy phenomena like this are the most robust for SMEFT – theory errors are well under control here, unlike in high-energy LHC processes, where caution is needed