The future via the past: Effective Field Theory searches for new physics at JADE, LHC, and future colliders

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Baylor University

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Baylor University

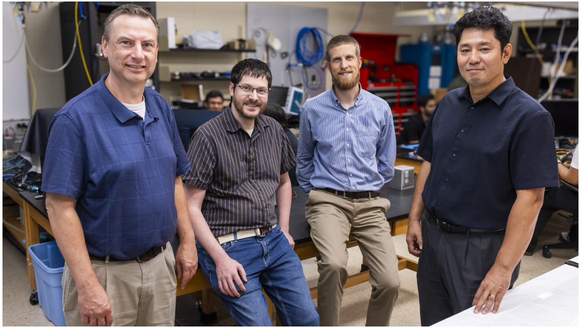
- Medium-sized private R1 university
- Affiliated with the Baptist Church
- Central Texas, between Dallas and Austin
- Chartered in 1845 by the Republic of Texas – oldest university in the state

2024 total eclipse passed right across Baylor

Department of Physics and Astronomy

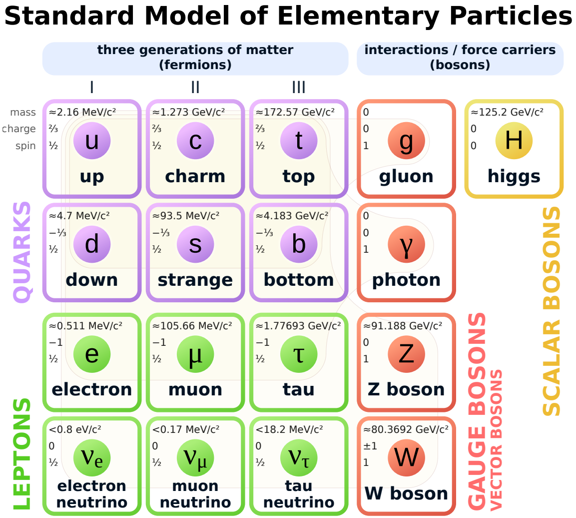
- 20 faculty, ∼50 majors, ∼50 grad students
- Broad range of research:
  - Astrophysics: observational cosmology, stellar evolution
  - Space physics: dusty plasmas, hypervelocity impacts
  - Cosmology, strings, gravity
  - Ultrafast spectroscopy & nonlinear optics
  - Surface physics and Raman spectroscopy
  - Quantum dots, nanoscale fabrication, structure-property relationship
  - Nonlinear dynamics
  - Particle theory and lattice QCD
  - Experimental particle physics

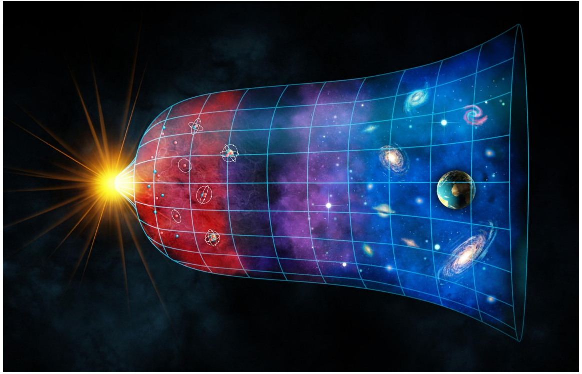
- Experimental HEP group at Baylor
- Established 2003 (CDF experiment)
- Four faculty, 3 postdocs, 6 grad students, $\sim$5 undergrads
- Working primarily on the CMS experiment
- Studying Higgs boson, top quark, SUSY, exotica, Effective Field Theory
- Trigger, data-quality monitoring, reconstruction, hadron calorimeter upgrade and operations, endcap calorimeter upgrade
- Developing advanced calorimeters for future colliders (CalVision)

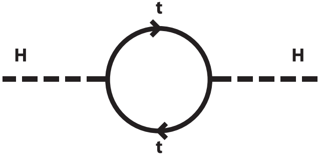


(left to right) Jay Dittmann, JSW, Andrew Brinkerhoff, and Kenichi Hatakeyama

- The standard model of particle physics is the most successful scientific theory yet
  - Explains (almost) all phenomena across a huge range of scales
  - Includes all known fundamental particles
    - Final predicted particle, the Higgs boson, discovered in 2012
  - All known interactions except gravity
  - Has withstood vast array of extremely precise measurements for half a century
  - Only 19 free parameters



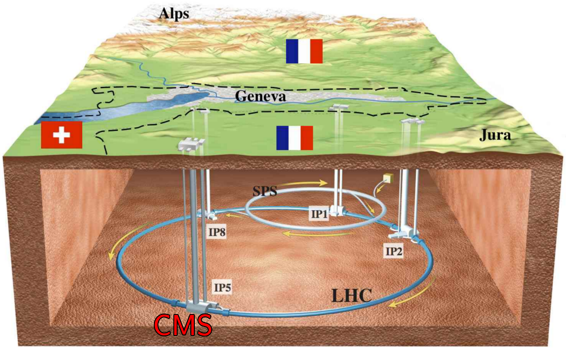


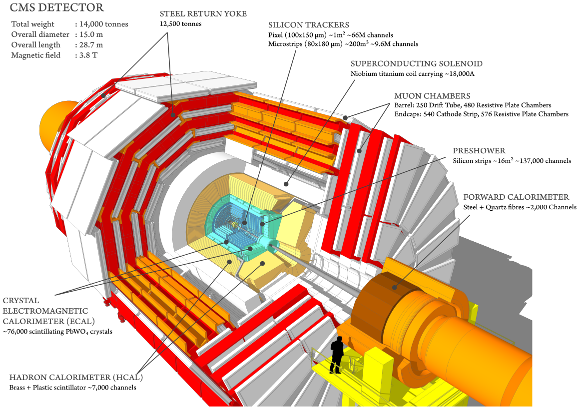


$$\Delta M_{H^2} = -\frac{3y_t^2}{8\pi^2}\Lambda^2$$

- The SM cannot explain:
  - Gravity
  - Cosmic inflation
  - Dark energy
  - Dark matter
  - Fine-tuning of the Higgs boson mass
  - Strong CP problem
  - Neutrino masses
- We know that there is undiscovered physics out there
- New particles and interactions
- Why haven't we found them yet?
- Either large masses or small couplings

- New particles with small couplings require extremely high precision experiments, e.g.
  - Muon g-2
  - Mu2e
  - LZ, LDMX
  - DUNE, NOνA
- New particles with large masses require high energy colliders
  - LHC: highest energy collider in the world
  - At CERN, on Swiss-French border
  - Collides two beams of protons at a center of mass energy of 13.6 TeV
  - Began operations in 2009
  - Four experiments: ATLAS, ALICE, Compact Muon Solenoid (CMS), and LHCb

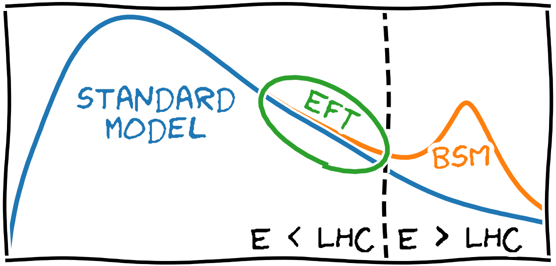




- CMS is a general-purpose particle detector
- Total mass 14000 tonnes
- Position and momentum measured with tracking system, inside 3.8 T solenoid
- Energy measured with calorimeter (electromagnetic and hadronic)
- Muons identified by dedicated muon detectors, interspersed with magnet return yoke
- Sees 40 million events per second
  - Each event includes tens of proton-proton interactions
  - Trigger system picks out about 1000 "interesting" events per second

- So what do we do with this data?
- Both direct and indirect searches
- Direct searches look for new particles with mass less than the center-of-mass energy
  - Require detailed simulation of specific models – computationally expensive
  - Could miss something if we don't try the right model
  - If you see something, gain detailed knowledge of the new physics
  - Like a magnifying glass, to examine things you can reach
- Indirect searches can stretch to higher masses
  - Generic description of new physics – Effective Field Theory
  - Only gain generic knowledge from indirect observation
  - Like binoculars, to spot things you can't get to yet
- Crucial to do both!

- Effective Field Theory (EFT) is a model-independent approach to physics beyond the standard model
- Assume that new physics exists at some scale Λ beyond the current reach of experiments
- Enumerate all terms in the Lagrangian, ordered by their mass dimension
- Multiply terms up to some maximum mass dimension by Wilson coefficients
  - SM corresponds to all coefficients at zero
  - Small coefficients = small perturbation on SM = low-energy tail of new physics
- Perfect tool for indirect searches
- Just measure Wilson coefficients



The EFT Langrangian

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_{d=5}^{\infty} \sum_{i} \frac{1}{\Lambda^{d-4}} c_i^{(d)} \mathcal{O}_i^{(d)}$$

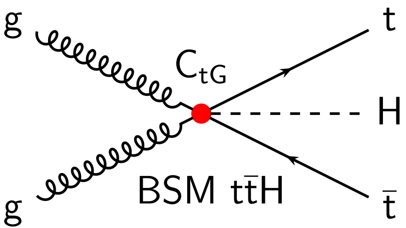
where d is the mass dimension, $c_i^{(d)}$ is a Wilson coefficient, and $\mathcal{O}_i^{(d)}$ is a dimension d operator

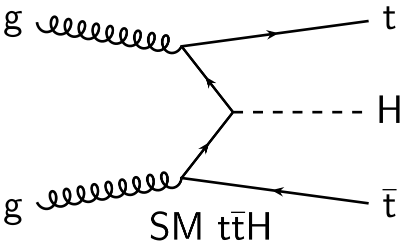
- This is the standard model EFT or "SMEFT"
  - Provides a common language across measurements, experiments
  - Facillitates comparison and combination of results
- Some EFTs other than SMEFT also used in particle physics
  - Low energy effective field theory used in studies of bottom and charm quarks

Historical / other EFTs include

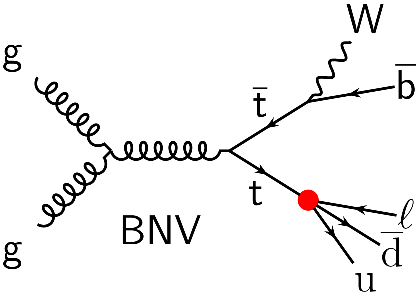
- Fermi's theory of beta decay
- BCS theory of superconductivity
- many others, especially in condensed matter physics

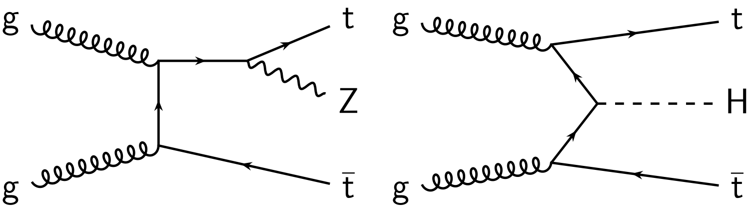
- Usually look at dimension 6 operators
  - SM already covers dim 2 and 4
  - Dim 5 only does neutrino mixing
  - The fun stuff starts at dim 6
  - Higher dimensions more suppressed by Λ
- In total, SMEFT has 2499 dim 6 operators
- Driven by quark- and lepton-flavor combinatorics
- Simple assumptions about flavor universality leave us with $O(100)$ operators
- Most processes only affected by a few dozen at most

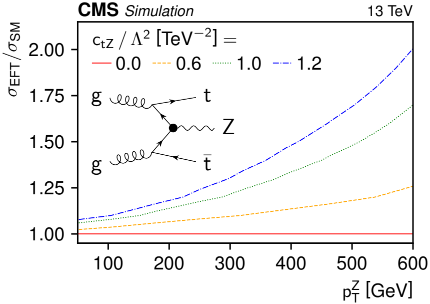


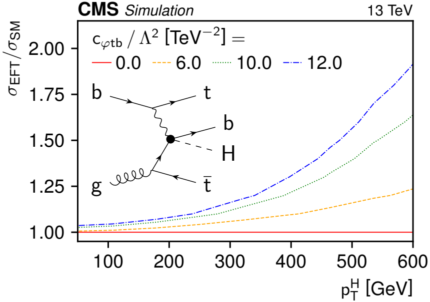


- Operators may alter rates/spectra for SM processes directly or via interference (diagrams on left)
- Or allow SM-forbidden processes (below)
- Make precision measurements and perform searches to constrain Wilson coefficients
- I'll give an overview of one precision measurement involving top quarks and a Higgs or Z boson



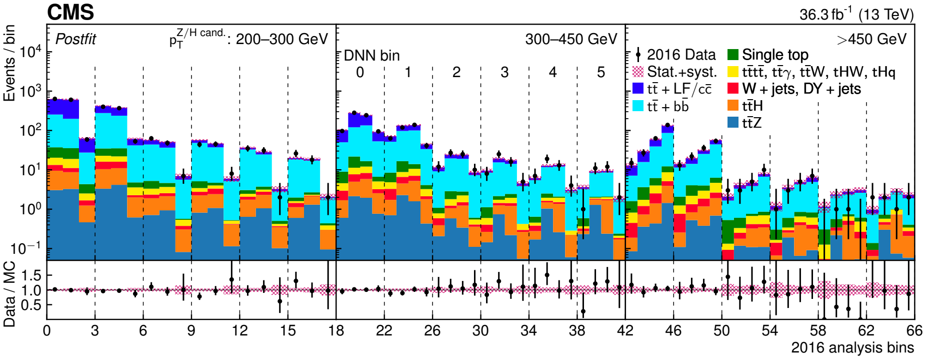






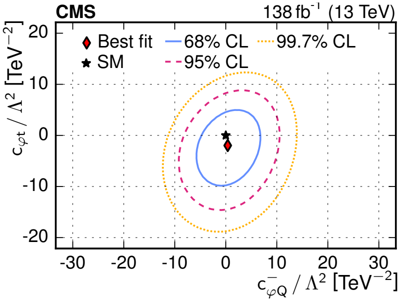
- Measure $t\bar{t}Z/t\bar{t}H$ when $p_T(Z/H)$ is large
- EFT effects more pronounced at high $p_T(Z/H)$
- Select events with one charged lepton, missing p_T, and jets
- Measure 8 WCs: $c_{t\varphi}$, $c^{-}_{\varphi Q}$, $c^{3}_{\varphi Q}$, $c_{\varphi t}$, $c_{\varphi tb}$, c_{tW}, c_{bW}, c_{tZ}

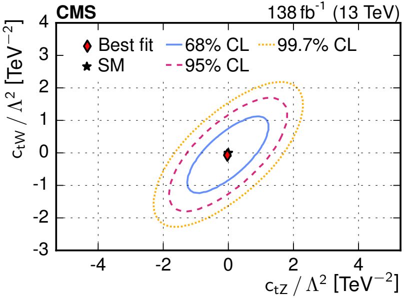
- 3 large groups $p_{\mathrm{T}}(Z/H)$ bins
- 6 medium subgroups are NN bins
- Individual bins are Z/H mass bins
- No significant deviation from SM expectation
- Use this to constrain WCs

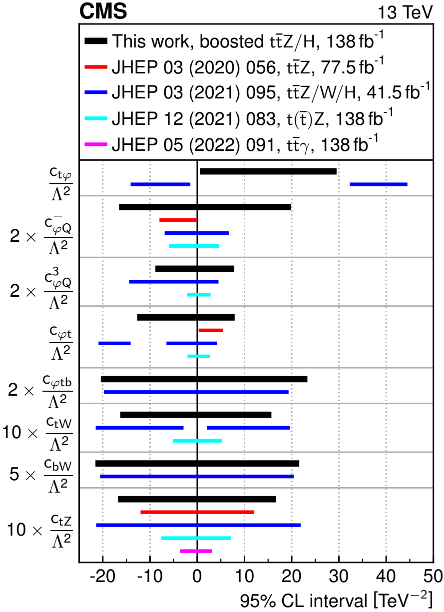


- $p_{\mathrm{T}}(Z/H)$ provides EFT sensitivity
- Neural network (NN) trained to distinguish signals from backgrounds
- NN score and Z/H mass help control backgrounds
- Major backgrounds are $t\bar{t}+b\bar{b}$ and $t\bar{t}+$jets

- Vary the $t\bar{t}Z/H$ signal and $t\bar{t}+b\bar{b}$ background as functions of the WCs
- Perform 1-D and 2-D likelihood scans for each WC and pair of WCs
- Consistent with SM (all WCs zero) at 95% CL
- Comparable sensitivity to other measurements
- Unique phase space with high-momentum Z/H makes this complementary to other measurements



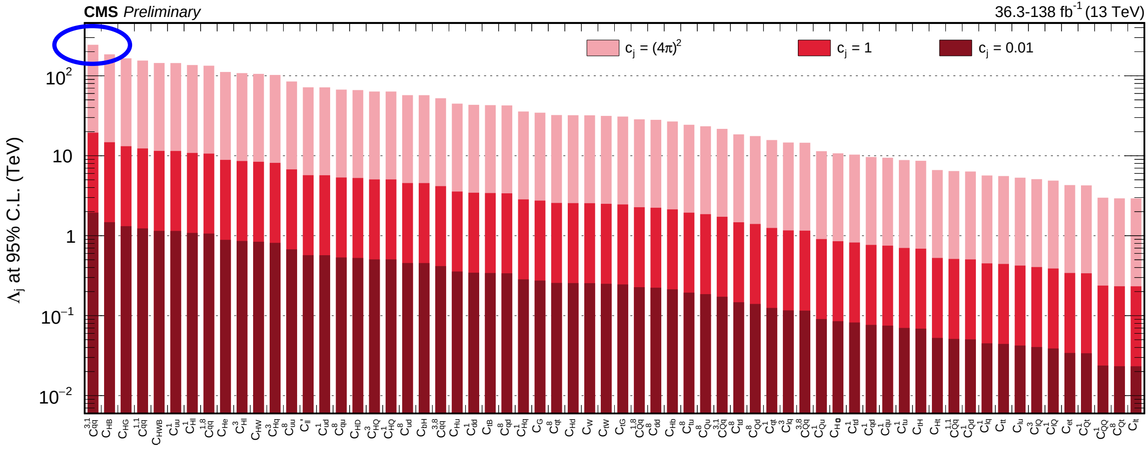




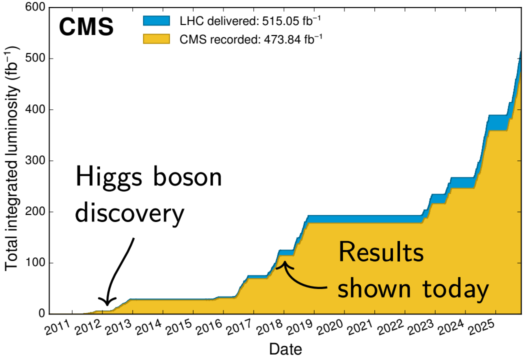
- Statistical combinations of results are a central promise of EFT
- Work on combinations only just getting off the ground
  - First, combinations of top-related measurements, Higgs-related, etc.
  - Then move to CMS-global combination
  - Finally combine with other experiments
- Some pilot efforts in all three of these categories already exist
- First broad EFT combination from CMS involves 7 CMS measurements, plus electroweak precision observables from the Large Electron Positron collider [CMS-PAS-SMP-24-003]
  - One Higgs boson
  - Three with W or Z bosons
  - Two with top quarks
  - One with generic jets
- Constrains 64 Wilson coefficients

EFT Combination

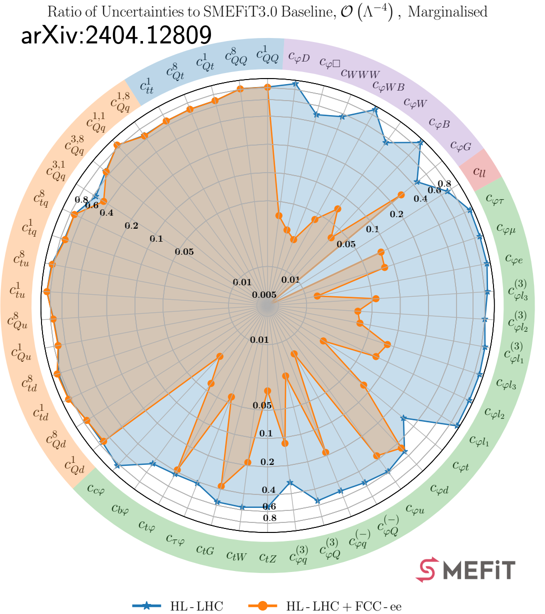
- We always set limits on C/Λ^2, not C
- Assume value of C, interpret as limits on new physics scale Λ
- Best case: for $C_{qq}^{1,3} = (4\pi)^2$, $\Lambda >$ 229 TeV
- $\sim 17\times$ the LHC center-of-mass energy
- Demonstrates reach of indirect searches



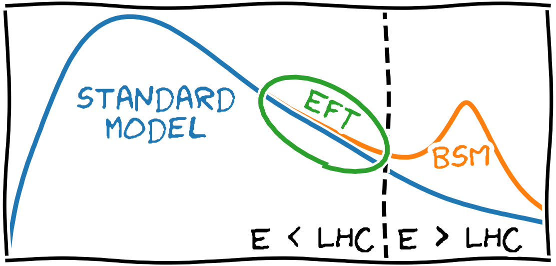
- Need more data—most EFT results today limited by data set size
- Already have $> 3.5\times$ as much data
- Current run will go into July 2026
- Long shutdown to upgrade LHC, CMS
- Start High-Luminosity LHC June 2030
- HL-LHC to run through 2041
- Will deliver $\sim 10\times$ more data than before
- Plausible to push Λ sensitivity into PeV scale!

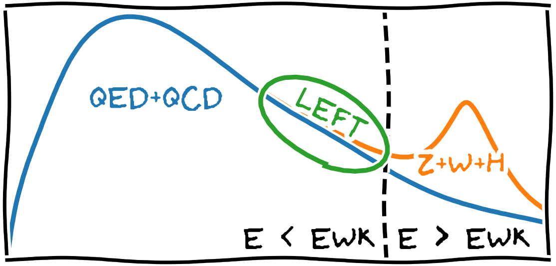


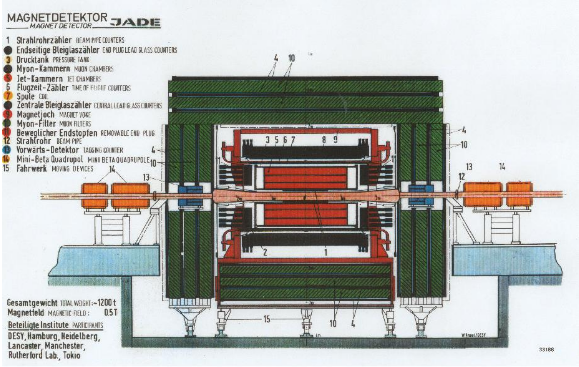
- FCC-ee: Future Circular Collider e^+e^- is a proposed collider, will run in a new 100 km tunnel at CERN
- Projected impact on Wilson coefficients (SMEFiT collaboration)
  - Outer edge shows current SMEFiT bounds
  - Closer to the center is stronger constraint
- HL-LHC: substantial improvement over now
- FCC-ee: massive improvement, except 4-quark operators
- Will be wonderful to exclude all this phase space for new physics
- But…we really want to discover something
- What would it look like to make a discovery via EFT?



- Effective Field Theory gives us a way to describe the effects of high-scale physics on low-scale experiments
- Can be hard to visualize generic BSM
- Let's treat part of the SM that we're very familiar with as "new" physics
- Look at data below electroweak scale – look to the past to understand the future
- Integrate out W, Z, and Higgs bosons (and top quark)
  - Low-energy Effective Field Theory (LEFT) [JHEP 03 (2018) 016]

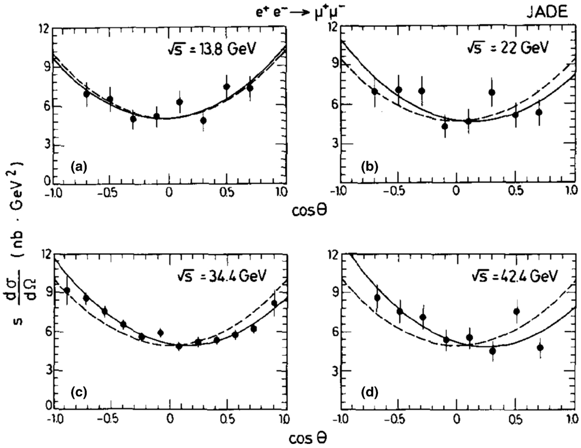


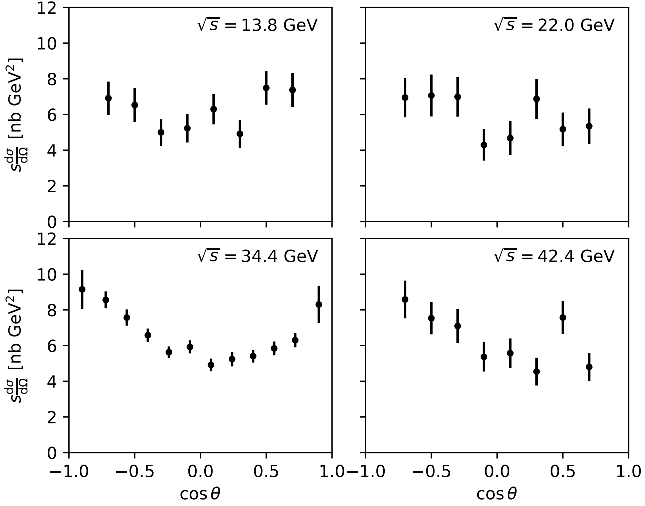




- JADE was an experiment at the PETRA e^+e^- collider at DESY
- Discovered the gluon by observing 3 jet events from e^+e^-
- 1979 – 1986
- Partly before UA1 and UA2 discovered W and Z
- Center of mass energies below electroweak scale: roughly 10 to 45 GeV

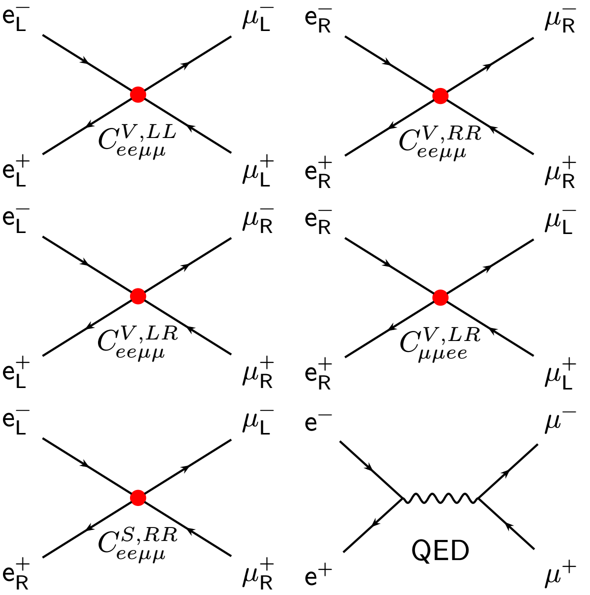
- JADE also measured $e^+e^- \to \mu^+\mu^-$
- Z.Phys.C 26 (1985) 507
- Muon asymmetry at 4 energies
- Dashed line QED, solid line EWK
- Let's apply LEFT to this data and see what we can learn
- An ahistorical case study
  - Pretend this is the only data we have:
    - No UA1/UA2
    - No neutrino data
    - Don't even know G_F
  - What can LEFT tell us about physics beyond QED from JADE alone?





- First, we need to digitize the JADE data
- I used WebPlotDigitizer, but other plot digitizers would work
- Also need to understand binning and normalization
- At 13.8, 22, and 42.4 GeV, 8 bins span $|\cos\theta| < 0.8$: bin size 0.2
- At 34.4, ten bins span $|\cos\theta| < 0.8$: bin size 0.16, plus one bin at each end covering $0.8 < |\cos\theta| < 1.0$
- Plot contains $s\,d\sigma/d\Omega$, in nb GeV^2
- Bin width divided out

- Now we need to understand what LEFT predicts for this data
- Relevant operators (excluding CLFV, CPV, and dipole operators):
  - $C^{V,LL}_{ee\mu\mu}$: $(\bar{\psi}_{eL}\gamma_\mu\psi_{eL})(\bar{\psi}_{\mu L}\gamma^\mu\psi_{\mu L})$
  - $C^{V,RR}_{ee\mu\mu}$: $(\bar{\psi}_{eR}\gamma_\mu\psi_{eR})(\bar{\psi}_{\mu R}\gamma^\mu\psi_{\mu R})$
  - $C^{V,LR}_{ee\mu\mu}$: $(\bar{\psi}_{eL}\gamma_\mu\psi_{eL})(\bar{\psi}_{\mu R}\gamma^\mu\psi_{\mu R})$
  - $C^{V,LR}_{\mu\mu ee}$: $(\bar{\psi}_{\mu L}\gamma_\mu\psi_{\mu L})(\bar{\psi}_{eR}\gamma^\mu\psi_{eR})$
  - $C^{S,RR}_{ee\mu\mu}$: $(\bar{\psi}_{eL}\psi_{eR})(\bar{\psi}_{\mu L}\psi_{\mu R})$
- Four vector operators, one scalar
- Vector: like integrating out the Z boson
- Scalar: like integrating out the Higgs boson
- Also include QED!



- Pure QED prediction at tree level:

$$\frac{d\sigma}{d\cos\theta} = \frac{\pi\alpha^2}{2s}\left(1+\cos^2\theta\right)$$

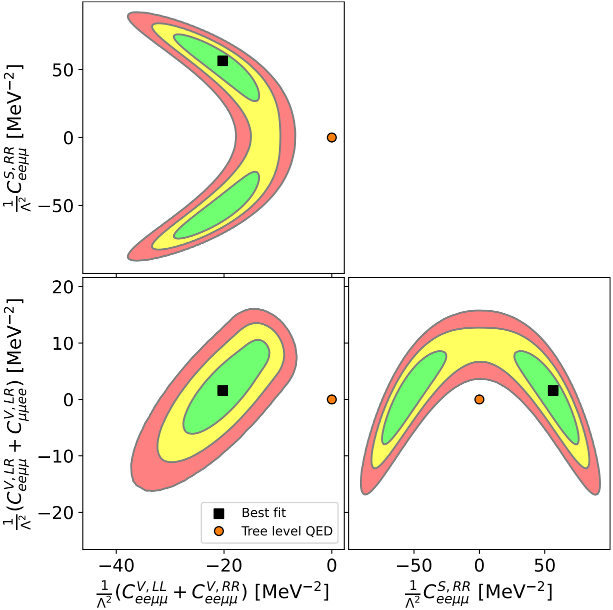
- Tree-level LEFT prediction, up to leading order in EFT:

$$\begin{aligned}\frac{d\sigma}{d\cos\theta} = &\left[\frac{\alpha}{16}\frac{1}{\Lambda^2}\Re\left(C^{V,LL}_{ee\mu\mu}+C^{V,RR}_{ee\mu\mu}+C^{V,LR}_{ee\mu\mu}+C^{V,LR}_{\mu\mu ee}\right)+\frac{\pi\alpha^2}{2s}\right]\left(1+\cos^2\theta\right)\\ &+\left[\frac{\alpha}{16}\frac{1}{\Lambda^2}\Re\left(C^{V,LL}_{ee\mu\mu}+C^{V,RR}_{ee\mu\mu}-C^{V,LR}_{ee\mu\mu}-C^{V,LR}_{\mu\mu ee}\right)\right]2\cos\theta\\ &+\frac{1}{128\pi}\frac{s}{\Lambda^4}\left|C^{S,RR}_{ee\mu\mu}\right|^2\end{aligned}$$

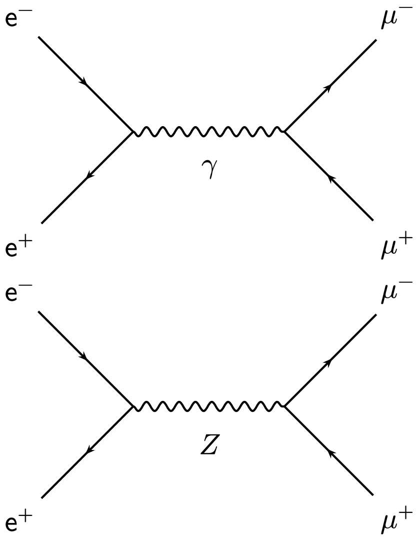
- Now have components $1+\cos^2\theta$, $2\cos\theta$, and flat
- Only sensitive to some linear combinations of Wilson coefficients:

- $\Re\left(C^{V,LL}_{ee\mu\mu}+C^{V,RR}_{ee\mu\mu}\right)/\Lambda^2$
- $\Re\left(C^{V,LR}_{ee\mu\mu}+C^{V,LR}_{\mu\mu ee}\right)/\Lambda^2$
- $\left|C^{S,RR}_{ee\mu\mu}\right|^2/\Lambda^4$

- Flat priors for the WCs
- Integrate cross section in each bin
- Data Gaussian around cross section, width=data error bar
- Use MCMC (`pymc5`) to sample from posterior
- Plot 68.27, 95.45, and 99.73% credible regions
- Banana-shaped region in 3D
- Very far from QED-only prediction
- We have used EFT to discover “new” physics!



- Great, now what?
- EFT alone doesn't tell much detail about new physics
- Talk to model builders
- Take a specific model, compare to WCs
  - Don't need to re-analyze data to compare to other models
  - No model-specific Monte Carlo
- What do WCs tell about model parameters?
- Obvious model: electroweak theory
  - Two relevant parameters: M_W and M_Z
  - Equivalent: G_F and $\sin^2\theta_W$
- Two diagrams: γ and Z



- Tree level prediction of the electroweak theory:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta} = \frac{\pi\alpha^2}{2s}\left(1+\cos^2\theta\right) + \frac{G_F^2 M_Z^4}{\pi}\frac{s}{\left(s-M_Z^2\right)^2+M_Z^2\Gamma_Z^2}\left[\left(g_V^2+g_A^2\right)^2\left(1+\cos^2\theta\right)+8g_V^2 g_A^2\cos\theta\right] + \sqrt{2}\alpha G_F M_Z^2 \frac{s-M_Z^2}{\left(s-M_Z^2\right)^2+M_Z^2\Gamma_Z^2}\left[g_V^2\left(1+\cos^2\theta\right)+2g_A^2\cos\theta\right]$$

- G_F: Fermi constant
- M_Z: Z boson mass
- Γ_Z: Z boson width
- α: Fine-structure constant
- g_V: vector coupling of muon/electron to Z, $-\frac{1}{4}+\sin^2\theta_W$
- g_A: axial-vector coupling of muon/electron to Z, $-\frac{1}{4}$
- $\sin^2\theta_W$: Weinberg angle

- If we compare the electroweak and LEFT cross sections, we can find electroweak predictions for the WCs
- LEFT cross section is already leading-order expansion in s/Λ^2, so take leading-order expansion of electroweak cross section (i.e., just set $s \to 0$):

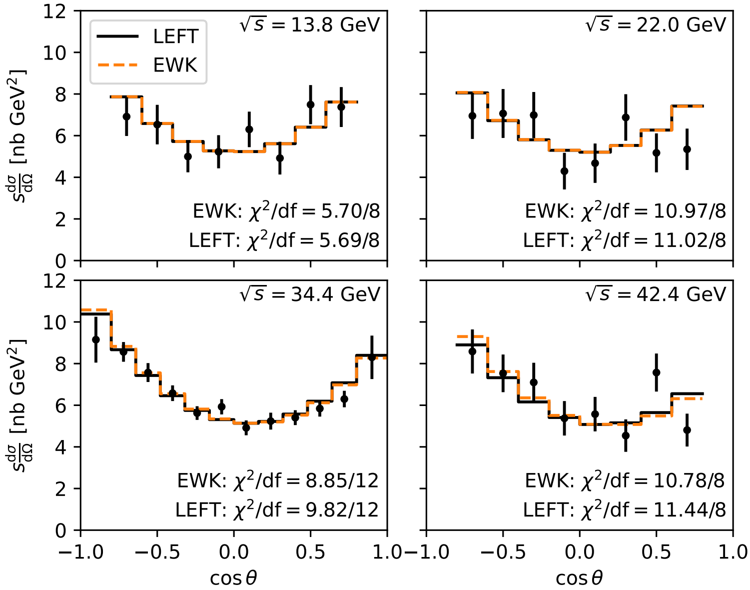
$$\Re\left(C^{V,LL}_{ee\mu\mu} + C^{V,RR}_{ee\mu\mu}\right)/\Lambda^2 = -8\sqrt{2}G_F \frac{M_Z^2}{M_Z^2 + \Gamma_Z^2}(g_V^2 + g_A^2) \tag{1}$$

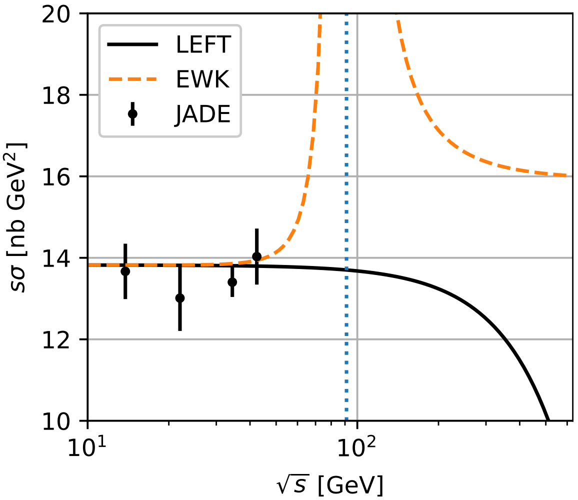
$$\Re\left(C^{V,LR}_{ee\mu\mu} + C^{V,LR}_{\mu\mu ee}\right)/\Lambda^2 = -8\sqrt{2}G_F \frac{M_Z^2}{M_Z^2 + \Gamma_Z^2}(g_V^2 - g_A^2) \tag{2}$$

$$C^{S,RR}_{ee\mu\mu} = 0 \tag{3}$$

- We can let $\Gamma_Z \to 0$ to very good approximation
- Then these are just in terms of G_F and $\sin^2\theta_W$ (via g_V)

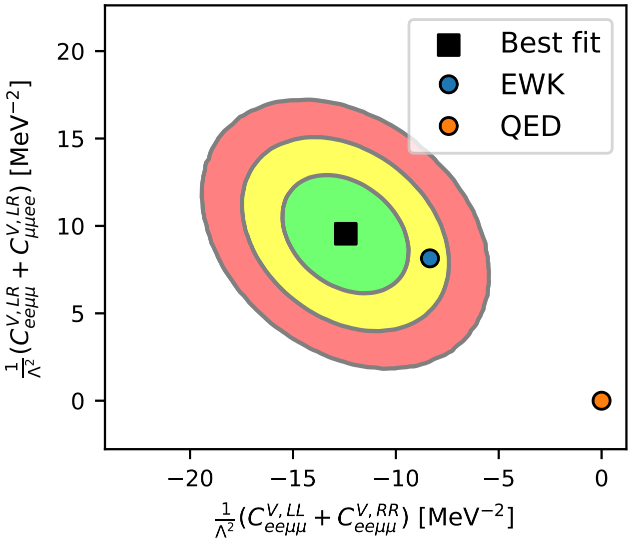
- Compare data to electroweak and LEFT predictions (WCs matched to EWK)
- Generally good description of data
- Electroweak and LEFT predictions very similar, not identical



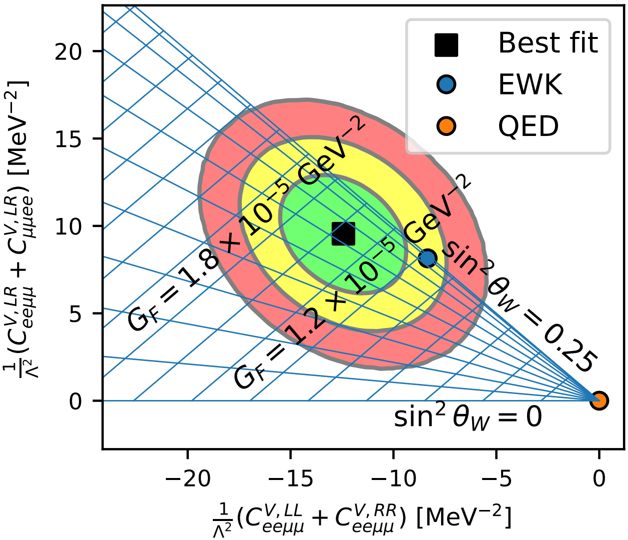


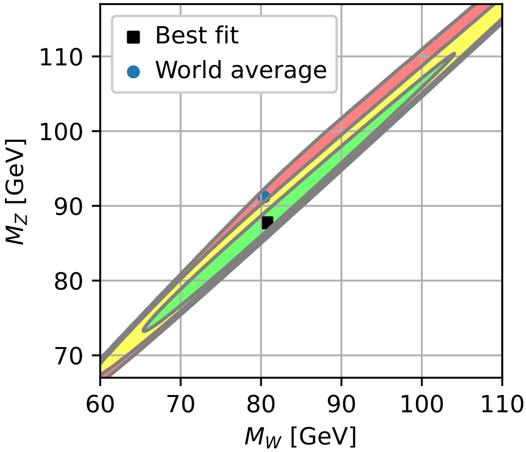
- Sum data over bins after correcting for bin width, then correct for fiducial region, to get total cross section
- Compare to electroweak prediction and to LEFT (matched WCs)
- For JADE energies, LEFT good approximation to electroweak
- Diverge rapidly closer to Z pole
- Above Z pole, LEFT will not converge, even with inclusion of arbitrarily high dimension operators

- What can we say about electroweak parameters from LEFT WCs?
- First, redo fit with $C^{S,RR}_{ee\mu\mu} = 0$
  - Equivalent to taking slice through posterior at $C^{S,RR}_{ee\mu\mu} = 0$
- Plot 2D posterior as function of remaining WCs
- QED-only still strongly excluded
- EWK expectation for WCs within 95.45% credible region



- Overlay contours of constant G_F and $\sin^2\theta_W$
- $G_F = 0$ recovers QED (= infinite M_W, M_Z)
- $\sin^2\theta_W = 0$ is horizontal
- $\sin^2\theta_W = 0.25$ is diagonal
- For larger $\sin^2\theta_W$, turns around and goes back down
  - $\sin^2\theta_W = 0.5$ is horizontal
  - $\sin^2\theta_W = 1$ opposite diagonal
  - Posterior is double covered
  - Upper right region impossible (at electroweak tree level)
- Calculate $M_{W,Z}$ from G_F, $\sin^2\theta_W$
- We can measure M_W and M_Z!



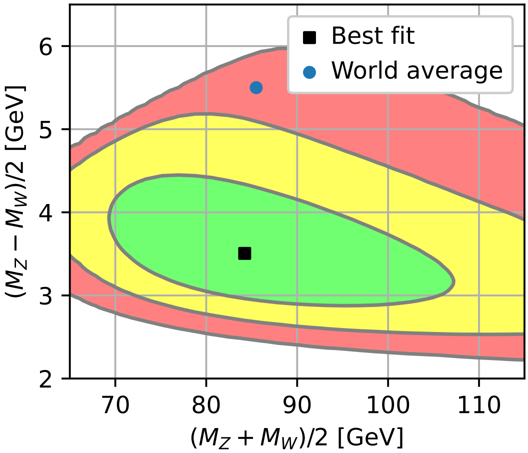


- For each posterior point in allowed region, compute G_F, $\sin^2\theta_W$ from WCs
  - Forbidden region removed, posterior rescaled to total probability of 1
  - For double-covered region, use $\sin^2\theta_W < 0.25$
- Then compute

$$M_W^2 = \frac{\pi\alpha}{\sqrt{2}G_F \sin^2\theta_W}$$

$$M_Z^2 = \frac{\pi\alpha}{\sqrt{2}G_F\left(1-\sin^2\theta_W\right)\sin^2\theta_W}$$

- Plot posterior as function of M_W, M_Z
- Looks pretty decent!
- Let's look more closely



- Plotting sum vs. diff makes it easier to see
- Real M_W, M_Z fall outside 95.45% region, inside 99.73% region
- Lots of room for improvement:
  - Calculations beyond LO
    - Radiative corrections to QED
    - Top-quark loop affects $M_W - M_Z$
    - Running couplings, esp. α
  - Better treatment of data uncertainties
- But still, remarkable that we could get W and Z boson masses from this data through the EFT lens!
- Would have been enough to guide construction of $Sp\bar{p}S$ or LEP, even without other electroweak constraints available at the time

- The point is *not* to measure the W and Z masses; we already know those
- The point *is* that EFT gave us a crude measurement of the "new particle" masses
- It's very hard to get funding to build a new, higher-energy collider
  - Especially when we don't even know whether there's anything for it to find
- But if we had something of this caliber, a $\sim 20\,\%$ measurement of new particle masses, the (funding) world would be very different

In fairness, none of that was my goal in starting this case study

- I wanted to develop intuition about the relationship between BSM physics and SMEFT operators
- Also to better understand how "matching" works
- But the end result was so much better than the starting plan
- If we find new physics via EFT, we will learn enough to guide the future of the field towards on-shell discovery
- "EFT at JADE: a case study", arXiv:2407.03468.

BACKUP

- Important note for correct normalization of cross sections: $\mathrm{d}\Omega = \mathrm{d}\varphi \mathrm{d}\cos\theta$
- Because the cross sections do not depend on φ, $\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta} = \int_0^{2\pi} d\varphi \frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = 2\pi \frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}$
- The JADE data plots show $\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}$, while the analytic tree level cross sections in the slides are given as $\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta}$.
- Also, to recover physical units nb GeV^2 from natural units, one has to multiply by $(\hbar c)^2 = 3.893\,793\,72 \times 10^5$ nb GeV^2