D>6

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based on 1503.07537, 1510.00372 L.Lehman, AM
also Henning et al 1512.03433, 1507.07240

HEFT, Oct 27th, 2016 Neils Bohr Institute

SM is a poster child EFT: SMEFT

degrees of freedom are: Q, u^c, d^c, L, e^c, H, gauge fields

symmetry is: Lorentz ⊗ SU(3)c⊗SU(2)w⊗ U(1)Y

write down all operators, lowest mass dimension terms dominate in the IR

$$\mathcal{L} = \int \sum_i c_i \, \mathcal{O}_i(Q, u^c, d^c, L, e^c, H, F, W, G)$$

low-dimension operators are easy, but quickly gets more complicated higher dimension operators are complicated because there are more fields = number ways to contract indices grows rapidly. Also IBP and EOM redundancies

dim ≤ 4: Standard Model

dim 5: 1 operator (neutrino mass) [Weinberg '79]

dim 6: 63 terms (neglecting flavor) [Büchmuller, Wyler '86, Grzadkowski et al '10]

dim 7: 20 terms [Lehman '14]

dim 8^{+}: as of Oct. 2015, no complete set known

Main message: For EFTs with fields in linear irreps:

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now a

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1503.07537

Hilbert Series for Constructing Lagrangians: expanding the phenomenologist's toolbox

Landon Lehman and Adam Martin

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2, 84, 30, 993, 560, 15456, 11962, 261485,...: Higher dimension operators in the SM EFT

Brian Henning,[a] Xiaochuan Lu,[b] Tom Melia[c,d] and Hitoshi Murayama[c,d,e]

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Specifically:

know **number** and **form** (field content) of SMEFT operators to arbitrary mass dimension, correctly incorporating EOM and IBP redundancies

How? Using an algebraic technique known as **Hilbert series**

Focus on SMEFT, but technique applies to other EFTs

subset of dim-8:

$(d_c^\dagger d_c)(e_c^\dagger e_c)F^L$	$(u_c^\dagger u_c)(e_c^\dagger e_c)F^L$	$2\,(d_c^\dagger d_c)(u_c^\dagger u_c)F^L$	$(d_c^\dagger d_c)(L^\dagger L)F^L$
$(u_c^\dagger u_c)(L^\dagger L)F^L$	$(e_c^\dagger e_c)(L^\dagger L)F^L$	$(e_c^\dagger e_c)(Q^\dagger Q)F^L$	$(d_c Q)(e_c^\dagger L^\dagger)F^L$
$(d_c Q)(e_c^\dagger L^\dagger)F^R$	$2\,(L^\dagger L)(Q^\dagger Q)F^L$	$2\,(d_c^\dagger d_c)(Q^\dagger Q)F^L$	$2\,(u_c^\dagger u_c)(Q^\dagger Q)F^L$
$3\,(e_c L)(u_c Q)F^L$	$3\,(u_c d_c)\,Q^2\,F^L$	$(d_c^\dagger d_c)(L^\dagger L)W^L$	$(e_c^\dagger e_c)(L^\dagger L)W^L$
$(e_c^\dagger e_c)(Q^\dagger Q)W^L$	$(u_c^\dagger u_c)(L^\dagger L)W^L$	$(L^\dagger L)^2 W^L$	$(e_c^\dagger L^\dagger)(d_c Q)W^L$
$(e_c L)(d_c^\dagger Q^\dagger)W^L$	$2\,(d_c^\dagger d_c)(Q^\dagger Q)W^L$	$2\,(u_c^\dagger u_c)(Q^\dagger Q)W^L$	$3\,(L^\dagger L)(Q^\dagger Q)W^L$
$2\,(Q^\dagger Q)^2 W^L$	$3\,(e_c L)(u_c Q)W^L$	$3\,(u_c d_c)\,Q^2\,W^L$	$(d_c^\dagger)^2\,d_c^2\,G^L$
$(u_c^\dagger)^2\,u_c^2\,G^L$	$(d_c^\dagger d_c)(e_c^\dagger e_c)\,G^L$	$(u_c^\dagger u_c)(e_c^\dagger e_c)\,G^L$	$4\,(d_c^\dagger d_c)(u_c^\dagger u_c)\,G^L$
$(Q^\dagger Q)(e_c^\dagger e_c)\,G^L$	$(d_c^\dagger d_c)(L^\dagger L)\,G^L$	$(u_c^\dagger u_c)(L^\dagger L)\,G^L$	$2\,(Q^\dagger Q)(L^\dagger L)\,G^L$
$4\,(d_c^\dagger d_c)(Q^\dagger Q)\,G^L$	$4\,(u_c^\dagger u_c)(Q^\dagger Q)\,G^L$	$2\,(Q^\dagger)^2\,Q^2 G^L$	$(d_c Q)(e_c^\dagger L^\dagger)\,G^L$
$(d_c Q)(e_c^\dagger L^\dagger)\,G^R$	$3\,(e_c L)(u_c Q)\,G^L$	$6\,(d_c u_c)\,Q^2\,G^L$	

112 at $O(D^0)$

$3\,D\,(d_c^\dagger d_c)(L\,H\,e_c)$	$D\,(e_c^\dagger e_c)(L\,H\,e_c)$	$3\,D\,(L^\dagger L)(L\,H\,e_c)$	$3\,D\,(d_c^\dagger d_c)(Q\,H\,d_c)$
$3\,D\,(e_c^\dagger e_c)(Q\,H\,d_c)$	$6\,D\,(L^\dagger L)(Q\,H\,d_c)$	$6\,D\,(Q^\dagger Q)(L\,H\,e_c)$	$6\,D\,(Q^\dagger Q)(Q\,H\,d_c)$
$3\,D\,(d_c^\dagger u_c)(L\,H^\dagger\,e_c)$	$6\,D\,(d_c^\dagger d_c)(Q\,H^\dagger\,u_c)$	$3\,D\,(e_c^\dagger e_c)(Q\,H^\dagger\,u_c)$	$6\,D\,(L^\dagger L)(Q\,H^\dagger\,u_c)$
$6\,D\,(Q^\dagger Q)(Q\,H^\dagger\,u_c)$	$3\,D\,(u_c^\dagger u_c)(L\,H\,e_c)$	$6\,D\,(u_c^\dagger u_c)(Q\,H\,d_c)$	$3\,D\,(u_c^\dagger u_c)(Q\,H^\dagger\,u_c)$

181 at $O(D)$

...

This talk:

Motivation for D > 6 and existing work

Basics of Hilbert series: no derivatives

Derivatives & conformal picture: **Henning**

Formal aspects of Hilbert Series: **Melia**

Why D > 6?

precision: LHC, HL-LHC, etc. will soon test SM to unprecedented precision = sensitivity to effects from even higher dimension

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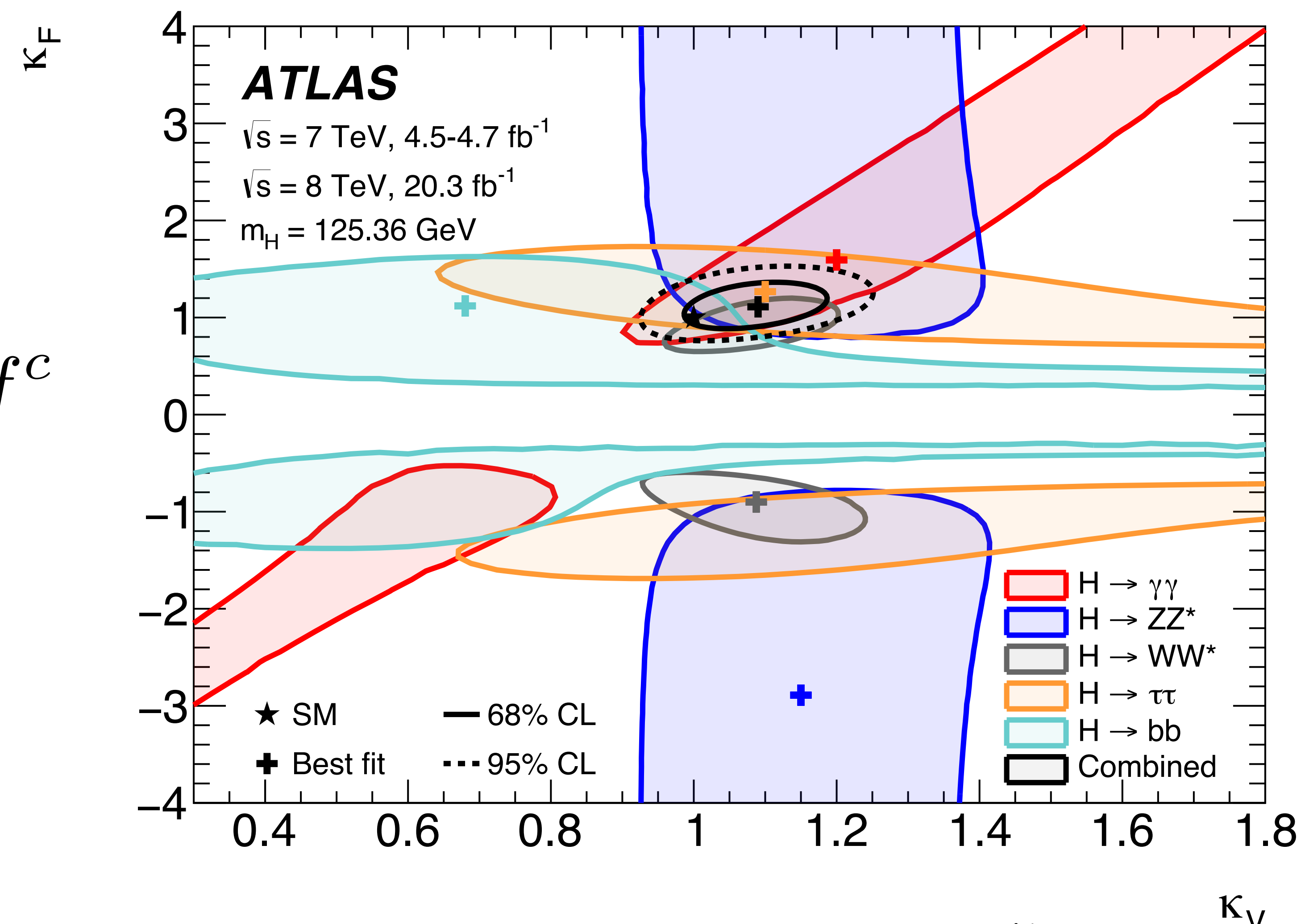

$\#\, H\, f_L\, f^c$

$\#\, H\, V_\mu\, V^\mu$

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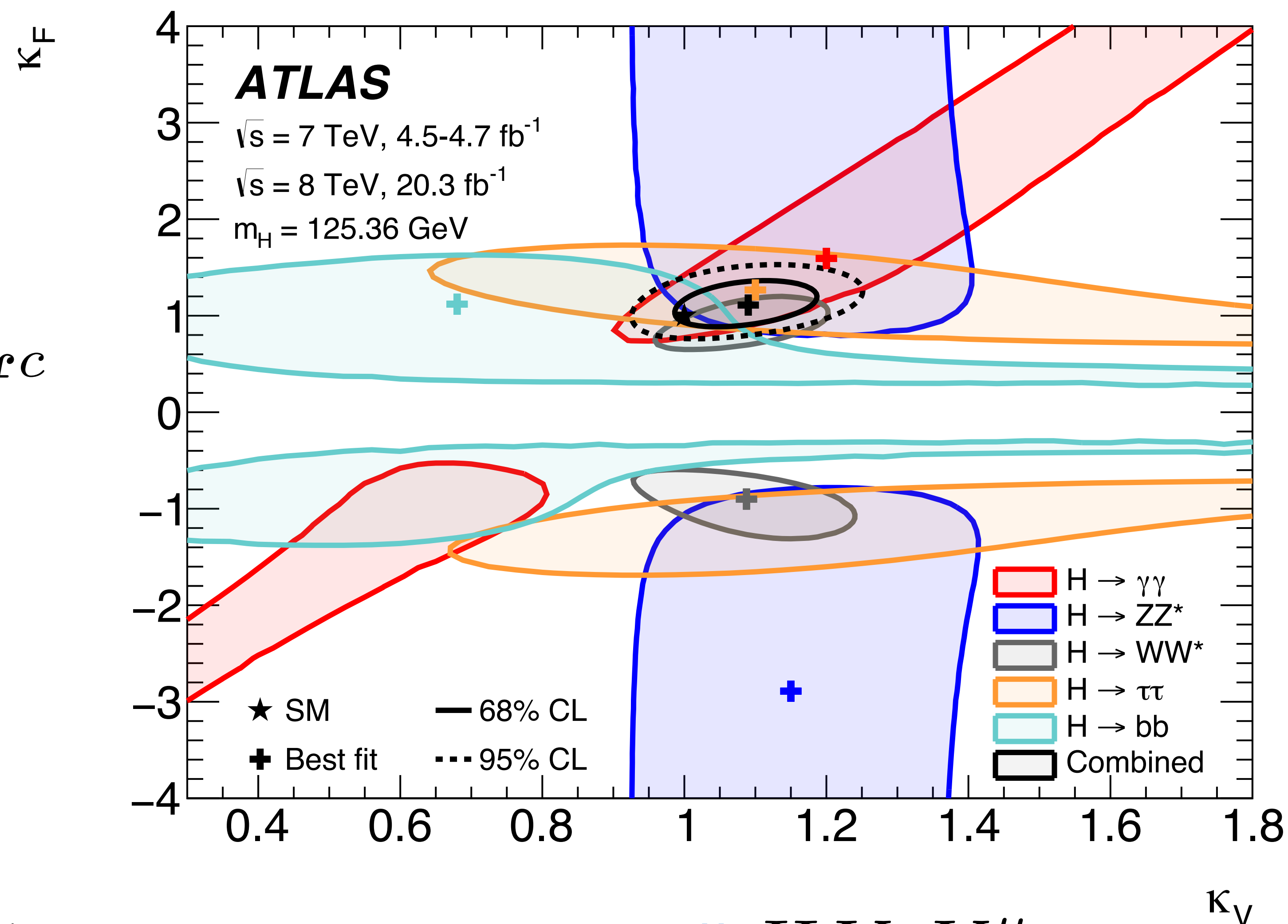

$H\, f_L\, f^c$

$\frac{(H^\dagger H)}{\Lambda^2}\, H f_L f^c$

$\frac{(H^\dagger H)}{\Lambda^2}\, D_\mu H^\dagger\, D^\mu H$

$H\, V_\mu\, V^\mu$

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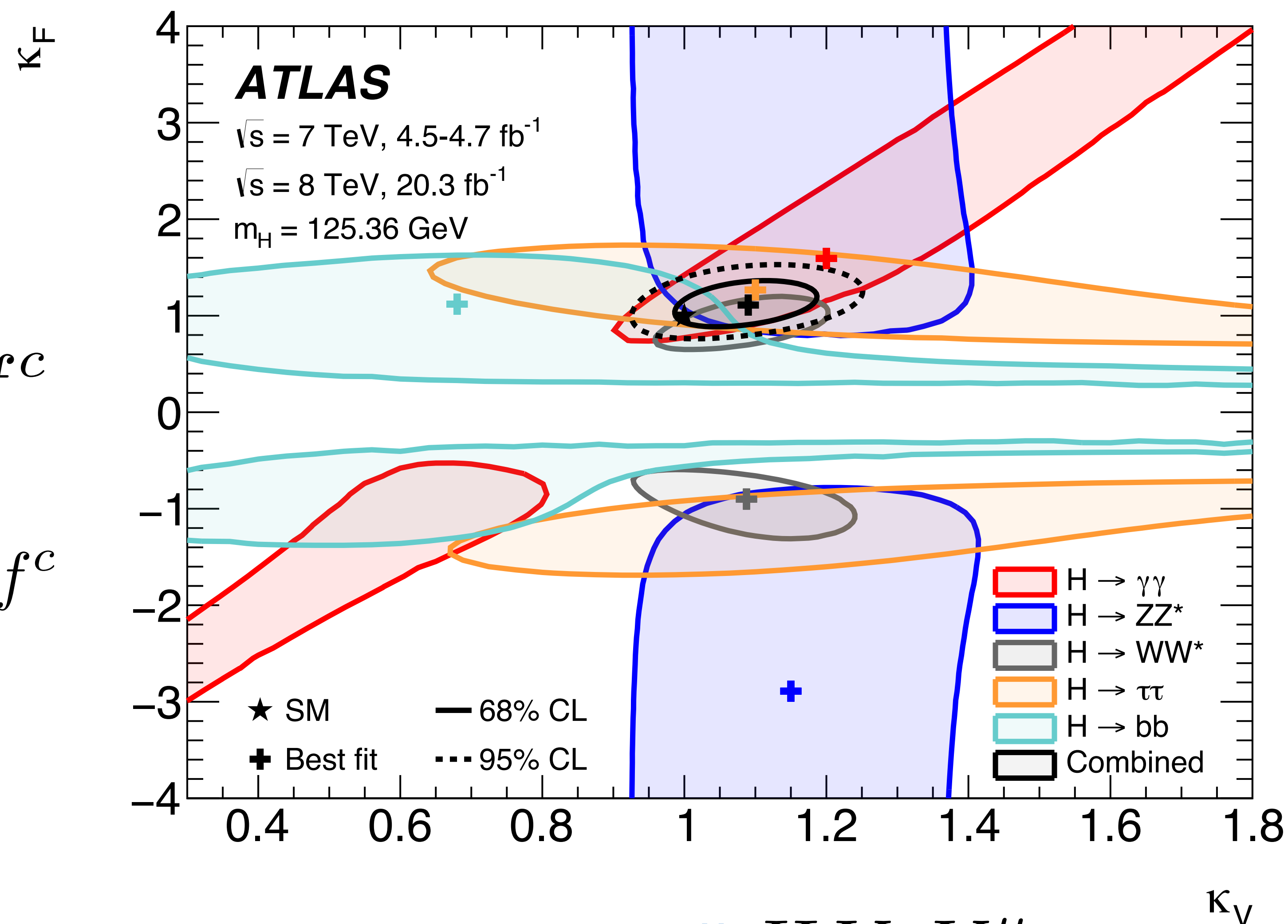

$H\, f_L\, f^c$

$\dfrac{(H^\dagger H)^2}{\Lambda^4} H\, f_L\, f^c$

$\dfrac{(H^\dagger H)^2}{\Lambda^4}(D_\mu H^\dagger\, D^\mu H)$

$H\, V_\mu\, V^\mu$

more specifically

- dim-8 vs. dim-6 @ NLO

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- dim-8 vs. dim-6 @ NLO
- dim-8 ~$\mathcal{O}(\frac{1}{\Lambda^4})$ same order as |dim-6|^2

naively always small compared to (SM x dim-6) ~ $\mathcal{O}(\frac{1}{\Lambda^2})$

however, when helicity structure of SM ≠ helicity structure of dim-6, no interference

[1607.05236 Azatov et al]

A_4	$\lvert h(A_4^{\mathrm{SM}})\rvert$	$\lvert h(A_4^{\mathrm{BSM}})\rvert$
$VVVV$	0	4,2
$VV\phi\phi$	0	2
$VV\psi\psi$	0	2
$V\psi\psi\phi$	0	2
$\psi\psi\psi\psi$	2,0	2,0
$\psi\psi\phi\phi$	0	0
$\phi\phi\phi\phi$	0	0

see talk by Riva

Why D > 6?

new effects: lower dim. operators have accidental symmetries (i.e. baryon #, lepton #). Higher dim. operators are the first place violation of these symmetries occurs

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Can be studied systematically, i.e.1604.05772 Kobach

from hypercharge conservation & Lorentz Invariance

$$\frac{\Delta B - \Delta L}{2}$$ even for d = even

$$\frac{\Delta B - \Delta L}{2}$$ odd for d = odd

How? Basic ingredient

A generating function that generates all possible products of its arguments

Ex:

$$\frac{1}{(1-x)(1-y)} = (1 + x + x^2 + x^3 \cdots)(1 + y + y^2 + y^3 + \cdots)$$

generates all x^n y^m

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generates all $x^n\, y^m$

We'd like something similar, but forming (group theoretic) products of Q, u^c, d^c, e^c, L, F, W, G. And we'd like to count the number of times a particular product appears (i.e. 2 $Q^\dagger Q L^\dagger L$)

How? Basic ingredient

A generating function that generates all possible products of its arguments

for us: Plethystic exponential

$$PE[\phi] = \exp\left(\sum_{r=1}^{\infty} \frac{1}{r} \sum_i \phi_i^r \chi_\phi^r\right)$$

"fields" in the theory → here just complex #, mod <= 1

character of field under symmetry groups

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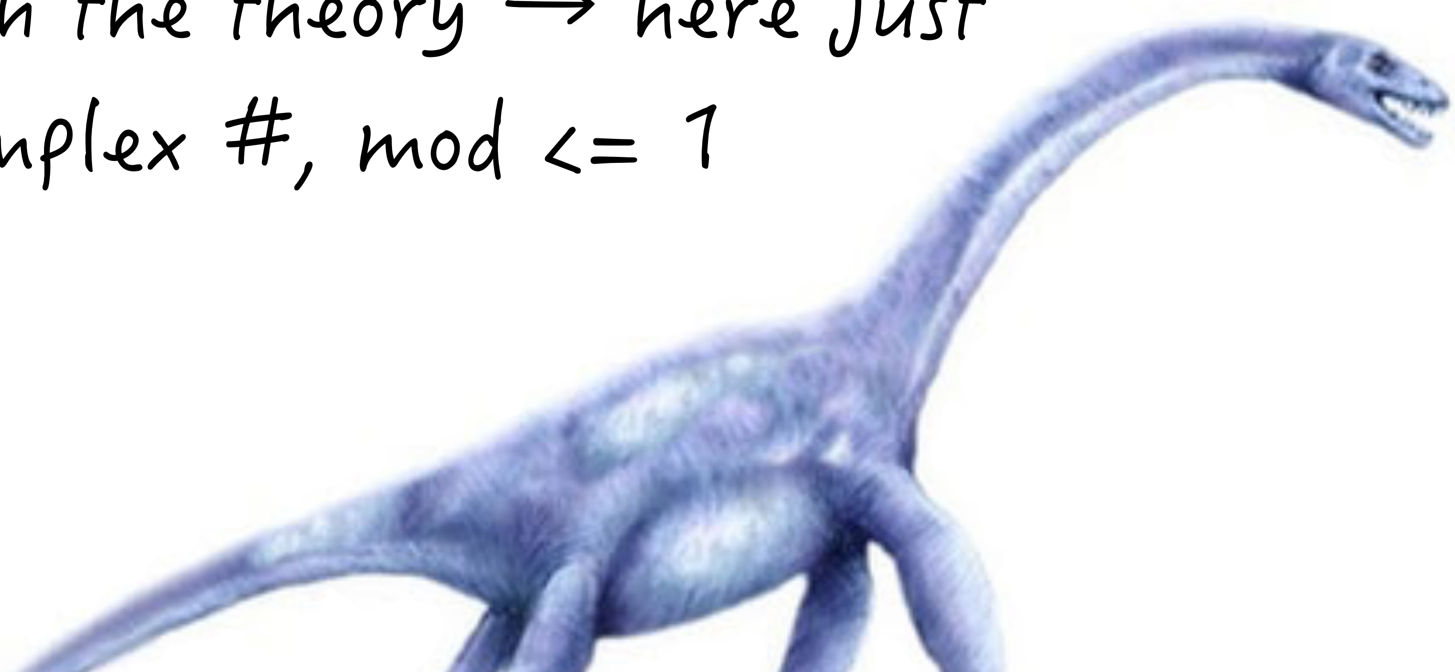

Character?

if under G $\phi_i \to D^R_{ij}(g)\phi_j$, character $\chi_R = \mathrm{tr}(D^R_{ij})$

Ex: SU(2)

doublet irrep: $D^{1/2}_{ij} = \exp(i\theta^a\,\tau_a)$

$$\chi_{1/2} = \mathrm{tr}(D^{1/2}_{ij}) = e^{-i\theta/2} + e^{i\theta/2} \quad , \quad \theta = (\sum_a \theta_a^2)^{1/2}$$

defining $e^{i\theta/2} = z$, $\mathrm{tr}(D^{1/2}_{ij}) = z + \dfrac{1}{z}$

Character?

if under G $\phi_i \to D^R_{ij}(g)\phi_j$, character $\chi_R = \mathrm{tr}(D^R_{ij})$

Ex: SU(2)

triplet irrep: $D^1_{ij} = \exp(i\theta^a\, J_a)$

$$\ldots \quad \chi_1 = z^2 + \frac{1}{z^2} + 1$$

Generally: $\chi_R(z_i)$

function of **j** complex variables, **j** = rank of group

(1 for U(1), SU(2), 2 for SU(3), etc.)

Character?

if under G $\phi_i \to D^R_{ij}(g)\phi_j$, character $\chi_R = \mathrm{tr}(D^R_{ij})$

Ex: U(1), charge Q, $\chi_Q = u^Q$

Ex: SU(3) triplet, $\chi_3 = w_1 + \frac{w_2}{w_1} + \frac{1}{w_2}$

Generally: $\chi_R(z_i)$

function of **j** complex variables, **j** = rank of group

(1 for U(1), SU(2), 2 for SU(3), etc.)

Okay…

lets stick with one complex field ϕ charged as a doublet under an SU(2)

$$PE[\phi](z) = \exp\Big(\sum_{r=1}^{\infty}\frac{1}{r}(\phi^r\chi_\phi^r(z) + \phi^{r\dagger}\chi_\phi^*(z)\Big)$$

expanded out, will give all possible products of ϕ and ϕ*, i.e.

$$c_0(z)\phi^*\phi + c_1(z)\phi(\phi^*\phi) + \cdots + c_2(z)\phi^2(\phi^*\phi)^3 + \cdots$$

each term weighted with z-dependent coefficient

Okay…

lets stick with one complex field ϕ charged as a doublet under an SU(2)

$$PE[\phi,\phi^*] = \exp\Big(\sum_{r=1}^{\infty}\frac{1}{r}(\phi^r+\phi^{*r})(z^r+\frac{1}{z^r})\Big)$$

$$= \frac{z^2}{(z-\phi)(z-\phi^*)(z\,\phi-1)(z\,\phi^*-1)}$$

$$= (2+z^2+\frac{1}{z^2})\phi\phi^* + (z^3+\frac{1}{z^3}+2\,z+\frac{2}{z})\phi(\phi^*\phi)+\cdots$$

$$+(z^8+\frac{1}{z^8}+2\,z^6+\frac{2}{z^6}+3\,z^4+\frac{3}{z^4}+4\,z^2+\frac{4}{z^2}+4)\phi^2(\phi^*\phi)^3$$

Key concept: Peter-Weyl theorem

characters of compact Lie groups form an orthonormal basis set for functions of the j complex variables

Haar measure: volume of group

$$\int_G d\mu\, \chi_M(z_i)\, \chi_N^*(z_i) = \delta_{MN}$$

therefore we can expand any function of z as a linear combination of $\chi_R(z)$

$$f(z) = \sum_R A_R\, \chi_R(z)$$

z-independent

and can project out any A_M using orthonormality

$$A_M = \int d\mu(z)\, f(z)\, \chi_M^*(z)$$

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Haar measure: volume of group

$$\int_G d\mu \, \chi_M(z_i) \, \chi_N^*(z_i) = \delta_{MN}$$

In particular:

$$\int d\mu(z) \, f(z) \, \mathbf{1} = A_0$$

projects out the **singlet** = group invariant part of f(z) exactly like Fourier series:

$$f(\theta) = \sum_{n=-\infty}^{\infty} A_n \, e^{i\,n\,\theta}$$

$$= A_0 + \sum_n \tilde{A}_n \, \cos(n\theta) + \sum_n \tilde{B}_n \sin(n\theta)$$

project out individual coefficient

$$\frac{1}{2\pi} \int_{-\pi}^{\pi} d\theta \, f(\theta) = A_0$$

exactly like Fourier series:

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project out individual coefficient

$$\frac{1}{2\pi} \int_{-\pi}^{\pi} d\theta \, f(\theta) = A_0$$

in fact: set $x = e^{i\theta}$ $d\theta/(2\pi) \rightarrow dx/(2\pi\, i\, x)$

Fourier series = character orthonormality for U(1)

putting pieces together

1.) $$PE[\phi](z) = \exp\Big(\sum_{r=1}^{\infty}\frac{1}{r}(\phi^r\chi_\phi^r(z) + \phi^{r\dagger}\chi_\phi^*(z))\Big)$$

all products of ϕ,ϕ*

2.) integration: $$\int d\mu_{SU(2)}\, PE[\phi](z)\,\mathbf{1}$$

projects out only the invariant (i.e. singlet) pieces in PE

$$1 + (\phi^*\phi) + (\phi^*\phi)^2 + (\phi^*\phi)^3 + \cdots$$

coefficient = number of invariants at that order

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$$\frac{1}{2\pi i}\oint dz\,\frac{(1-z^2)}{z}\,\frac{z^2}{(z-\phi)(z-\phi^*)(z\,\phi-1)(z\,\phi^*-1)}$$

$$= \frac{1}{1-\phi^*\phi}$$

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Getting more general:

multiple groups: character → product of characters under individual groups

$$\chi_\phi(z) \to \prod_G \chi_{G,\phi}(z_i)$$

integrate over volume of all groups

$$\int d\mu \to \int \prod_G d\mu_G$$

multiple fields: add each field into PE, accompanied by character

Getting more general:

fermions: anti-commuting, non-trivial Lorentz properties

PE for all fermionic fields

[Hanany '14]

$$PEF[\psi] = \exp\left\{\sum_{r=1}^{\infty} \frac{(-1)^{r+1}}{r} (\psi\, \chi(z_i))^r\right\}$$

$\therefore$ total PE = PE[ϕ_i]$\times$ PE[ψ_i]

Lorentz group: $SO(3,1) \cong SU(2)_L \otimes SU(2)_R$

just two more symmetry groups

use LH fermions only for simplicity: Q, u^c, d^c, etc ~ (0, 1/2)

$Q^\dagger$, $u^{\dagger c}$, $d^{\dagger c}$, etc ~ (1/2, 0)

Field strengths:

$$X^{\pm}_{\mu\nu} = X_{\mu\nu} \pm i\tilde{X}_{\mu\nu}$$ in (1,0) or (0,1) irrep.

put the pieces together:

$$\mathcal{H}_{0,SM} = \int \prod_G d\mu_{Gi}\, PE[H, F^+, W^+, G^+ + c.c.] \times PEF[Q, u^c, d^c, L, e^c + c.c]$$

$$[SU(2)_L \times SU(2)_R] \times SU(3)_c \times SU(2)_W \times U(1)_Y$$

generates **all** invariants (with one flavor of QUDLE) with no derivatives example: QQQL operators, $N_f = 3$

$$PEF[3\,Q(0,1/2;3,2,1/6)+3\,L(0,1/2;1,2,-1/2)]$$

x, y for $SU(2)_R \times SU(2)_L$; (w_1, w_2) for $SU(3)$, z for $SU(2)_W$, u for $U(1)_Y$

$$PEF[3\,Q\Big(y+\frac{1}{y}\Big)\Big(z+\frac{1}{z}\Big)\Big(w_1+\frac{w_2}{w_1}+\frac{1}{w_2}\Big)\,u^{1/6} \\ +3\,L\Big(y+\frac{1}{y}\Big)\Big(z+\frac{1}{z}\Big)\,u^{-1/2}]$$

$$\int d\mu_{\mathrm{Lorentz}}(x,y)\,d\mu_{SU(3)}(w_1,w_2)d\mu_{SU(2)}(z)d\mu_{U(1)}(u)\;PEF[3Q,3L]$$

$$1+57\,LQ^3+4818\,L^2\,Q^6+162774\,L^3\,Q^9+\cdots$$

A first step towards derivatives:

$\partial_\mu \sim (1/2, 1/2)$ of Lorentz group… add it in to PE like other fields

PE[ϕ, $\partial_\mu\phi$] will contain all products of ϕ, $\partial_\mu\phi$

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repeat for higher derivatives? even at ∂^2 there are two possibilities:

$$\partial_{\{\mu,\nu\}}\phi, \quad \Box\phi$$

$$(1,1), \quad (0,0)$$

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$$\begin{array}{cc} \partial_{\{\mu,\nu\}}\phi, & \cancel{\Box\phi} \\ (1,1), & \cancel{(0,0)} \end{array}$$

always reduces by EOM.. so omit from PE

from where? still doesn't account for IBP redundancy

— see next talks!

Now what?

Useful subsets of operators, formats?

HS output

$$
\begin{array}{cc}
3\,D\,(d_c^\dagger\, d_c)(L\,H\,e_c) & D\,(e_c^\dagger\, e_c)(L\,H\,e_c) \\
3\,D\,(e_c^\dagger\, e_c)(Q\,H\,d_c) & 6\,D\,(L^\dagger\, L)(Q\,H\,d_c) \\
3\,D\,(d_c^\dagger\, u_c)(L\,H^\dagger\, e_c) & 6\,D\,(d_c^\dagger\, d_c)(Q\,H^\dagger\, u_c) \\
6\,D\,(Q^\dagger\, Q)(Q\,H^\dagger\, u_c) & 3\,D\,(u_c^\dagger\, u_c)(L\,H\,e_c)
\end{array}
$$

$$\cdots$$

normal human output

$$
\begin{gathered}
(H^\dagger H)^2 (D_\mu H^\dagger D_\mu H) \\
\delta_{IJ}\,(H^\dagger H)(H^\dagger \tau^I H)(D_\mu H^\dagger \tau^J D_\mu H) \\
(D_\mu H^\dagger\, D_\nu H)\, B^L_{\rho(\mu} B^R_{\nu)\rho} \\
\delta_{AB}\,(D_\mu H^\dagger\, D_\nu H)\, G^{L,A}_{\rho(\mu} G^{R,B}_{\nu)\rho} \\
\delta_{IJ}\,(D_\mu H^\dagger\, D_\nu H)\, W^{L,I}_{\rho(\mu} W^{R,J}_{\nu)\rho} \\
\epsilon_{IJK}\,(D_\mu H^\dagger \tau^I\, D_\nu H)\, W^{L,J}_{\rho(\mu} W^{R,K}_{\nu)\rho} \\
(D_\mu H^\dagger\, D_\mu H)\, B^L_{\rho\sigma} B^L_{\rho\sigma} + \text{h.c.} \\
\delta_{AB}\,(D_\mu H^\dagger\, D_\mu H)\, G^{L,A}_{\rho\sigma} G^{L,B}_{\rho\sigma} + \text{h.c.} \\
\delta_{IJ}\,(D_\mu H^\dagger\, D_\mu H) W^{L,I}_{\rho\sigma} W^{L,J}_{\rho\sigma} + \text{h.c.} \\
\epsilon_{IJK}\,(D_\mu H^\dagger \tau^I D_\nu H) W^{L,J}_{\rho\{\mu} W^{L,K}_{\nu\}\rho} + \text{h.c.} \\
\delta_{IJ}\,(D_\mu H^\dagger \tau^I\, D_\mu H)\, B^L_{\rho\sigma} W^{L,J}_{\rho\sigma} + \text{h.c.} \\
\delta_{IJ}\,(D_\mu H^\dagger \tau^I D_\nu H) B^L_{\rho\{\mu} W^{L,J}_{\nu\}\rho} + \text{h.c.}
\end{gathered}
$$

$$\cdots$$

translation ~done for bosonic dim-8
(FeynRules UFO too)

conclusions:

given symmetry group **G**, fields **ϕ_i, ψ_i, $X_i^{L,R}$** $\xrightarrow{\text{Hilbert series}}$ # and form of **all** invariant (Lorentz & gauge) operators,

- generates all possible combinations of operators, uses character orthonormality to pick out invariants
- derivatives tricky, but issues recently overcome: **see next two talks for details!**

lots of interesting directions to explore!

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Thank You!