EFT

Brian Henning
Yale

with Xiaochuan Lu, Tom Melia, Hitoshi Murayama

1706.08520, 1512.03433(, 1507.07240)

+ some ongoing with Lukáš Gráf; Tom Melia; Jed Thompson

Higgs Couplings 2017, Heidelberg

EFT
from the bottom

Brian Henning
Yale

with Xiaochuan Lu, Tom Melia, Hitoshi Murayama

1706.08520, 1512.03433(, 1507.07240)

+ some ongoing with Lukáš Gráf; Tom Melia; Jed Thompson

Higgs Couplings 2017, Heidelberg

*spoken disclaimers

EFT
from the bottom

Brian Henning
Yale

with Xiaochuan Lu, Tom Melia, Hitoshi Murayama

1706.08520, 1512.03433(, 1507.07240)

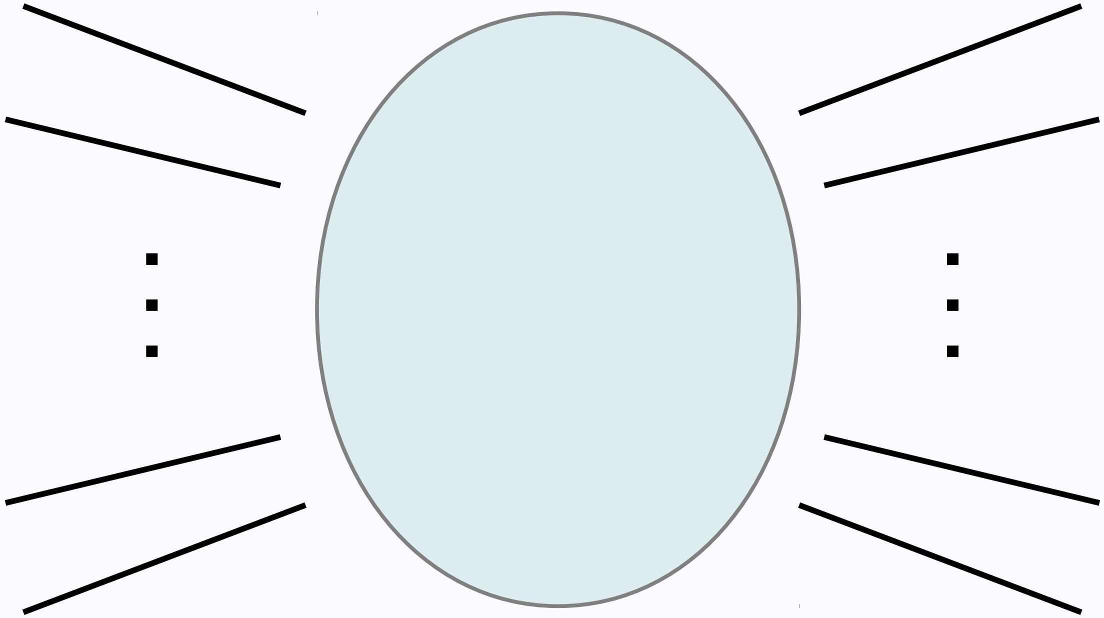
+ some ongoing with Lukáš Gráf; Tom Melia; Jed Thompson

Higgs Couplings 2017, Heidelberg

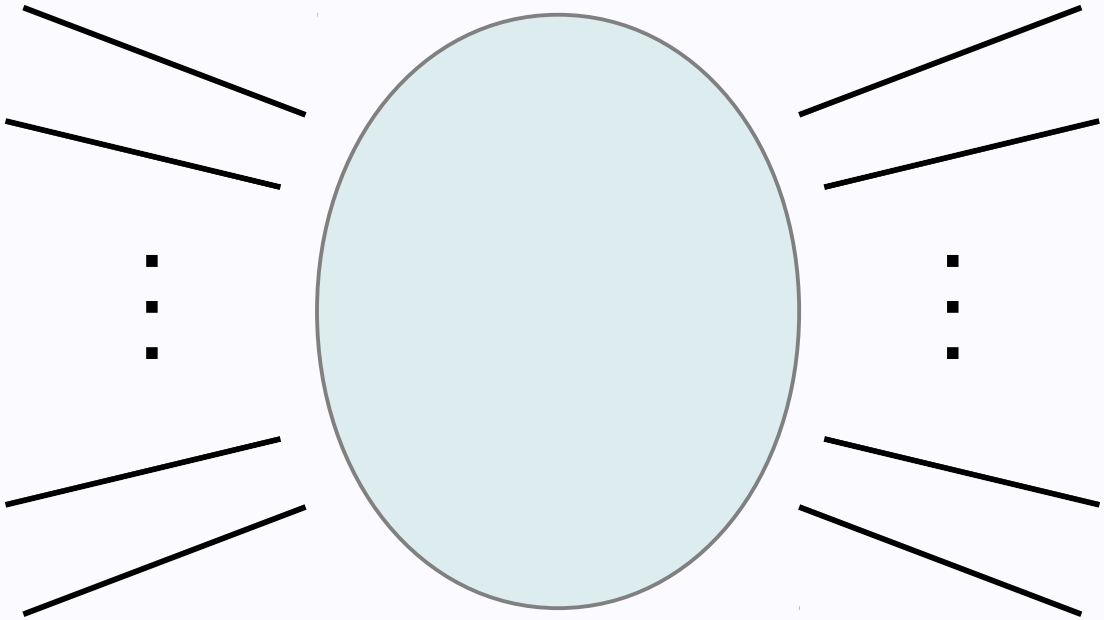
EFT is essentially an experimentalist's way of thinking

roughly:
given what I have, what can I see?

what can we measure in principle?



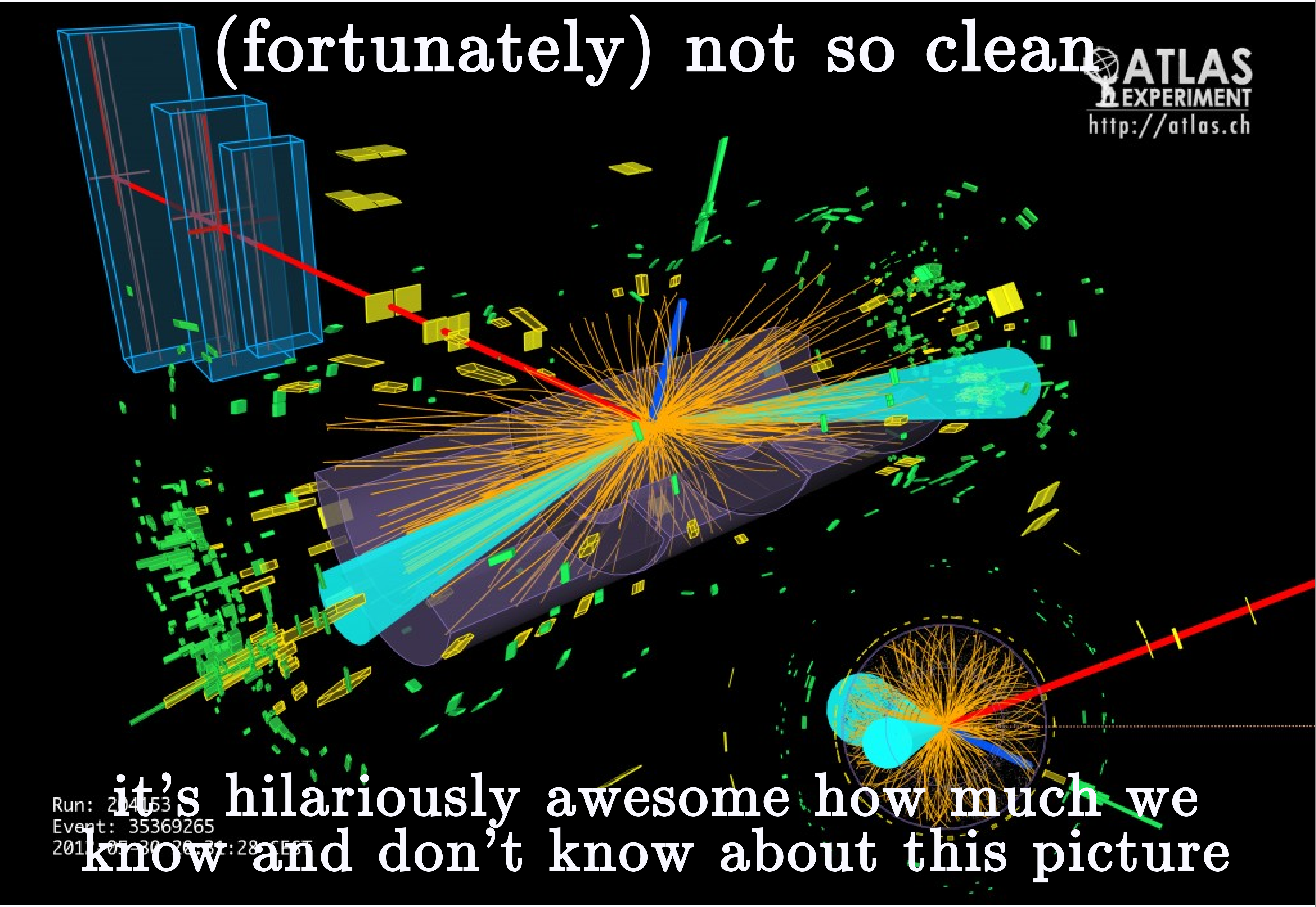
what can we measure in principle?



given a set of particles we have asymptotic access to,
what are the kinematically allowed scattering events?

recurring theme: spacetime symmetry principles
a.k.a. Poincare and its unitary representations

(fortunately) not so clean



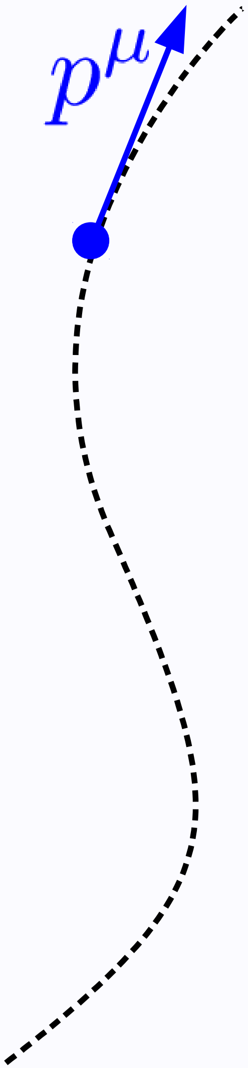
it's hilariously awesome how much we know and don't know about this picture particles,

fields,

& multi-particle/field theory

what are particles?

got a momentum

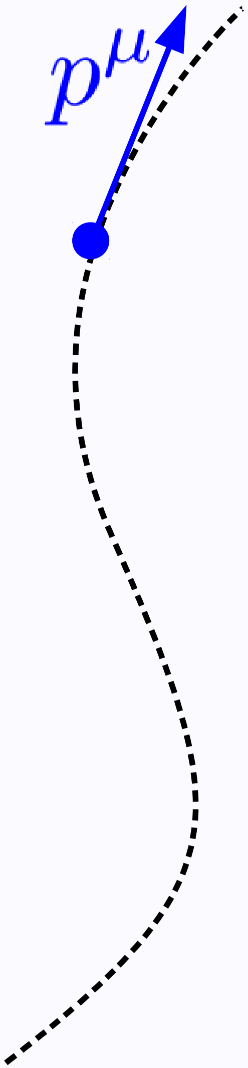


what are particles?

got a momentum

let's boost to some configuration, e.g.

$$p^\mu = \begin{pmatrix} m \\ 0 \\ 0 \\ 0 \end{pmatrix}$$



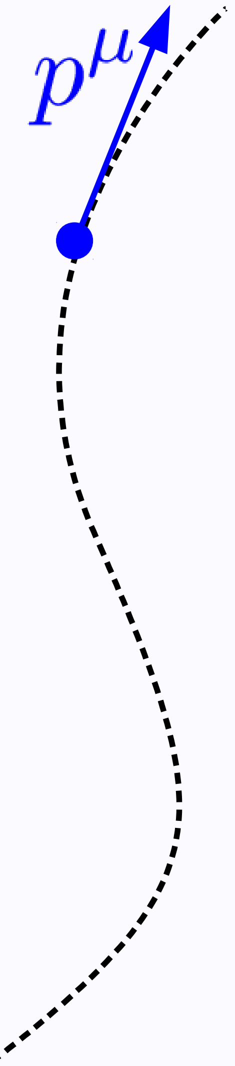
what are particles?

got a momentum

let's boost to some configuration, e.g.

$$p^\mu = \begin{pmatrix} m \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

what can we do in these directions?



what are particles?

got a momentum

let's boost to some configuration, e.g.

$$p^\mu = \begin{pmatrix} m \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

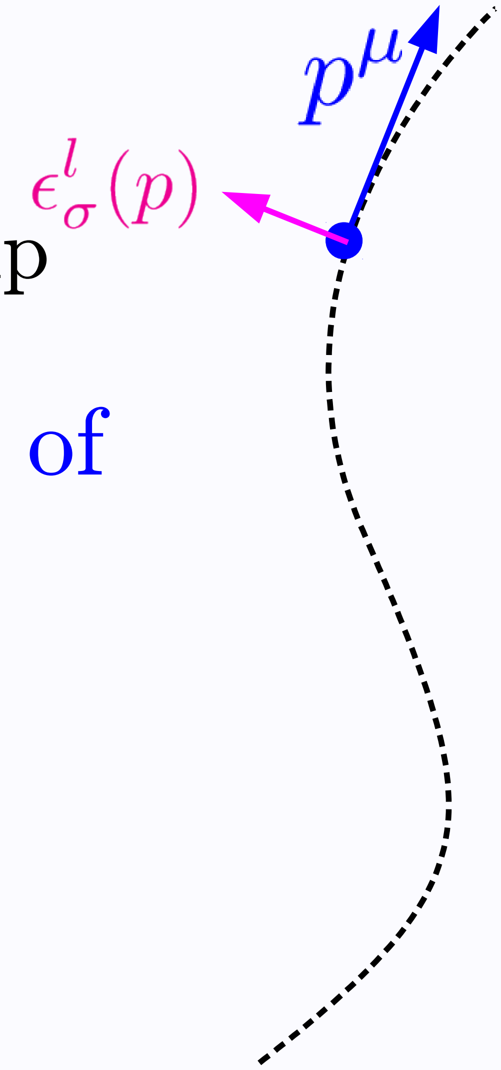
what can we do in these directions?

assign some spin (= polarization states)

what are particles?

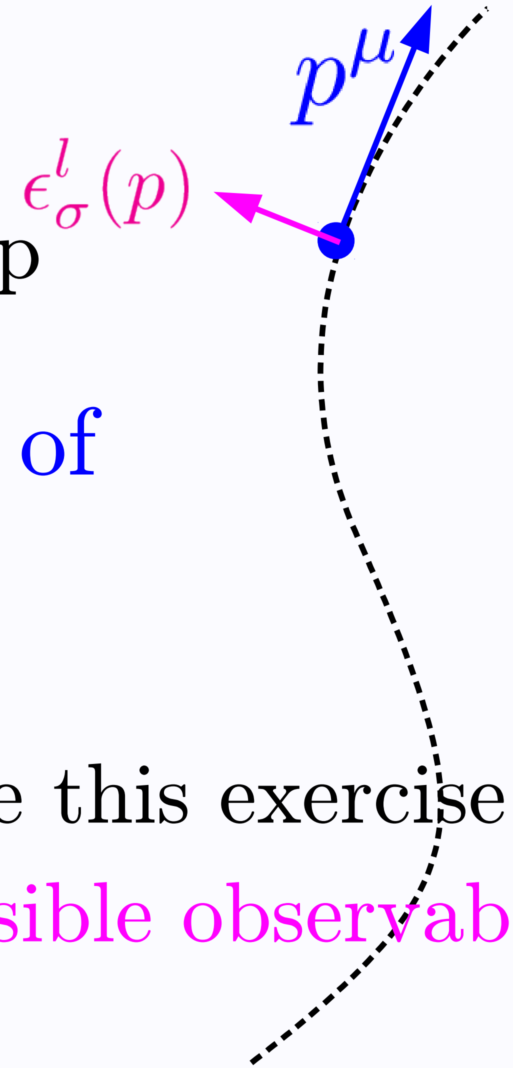
congrats, you just induced a
representation of the Poincare group

i.e. particles are representations of
spacetime symmetry group



what are particles?

congrats, you just induced a representation of the Poincare group



i.e. particles are representations of spacetime symmetry group

for later purposes, I want to rephrase this exercise as:

given a momentum, what other possible observables are there?

answer (in this case): helicity/spin states

what are fields?

Fields are realizations of the spacetime representations

$$\langle 0|\phi_l(x)|\mathbf{p}\,\sigma\rangle \sim \epsilon_{l\sigma}(p)e^{ip\cdot x}$$

transformation properties of the physical states dictate equations of motion

what are fields?

Fields are realizations of the spacetime representations

$$\langle 0|\phi_l(x)|\mathbf{p}\,\sigma\rangle \sim \epsilon_{l\sigma}(p)e^{ip\cdot x}$$

transformation properties of the physical states dictate equations of motion

for example

- scalar $\sigma = 0$

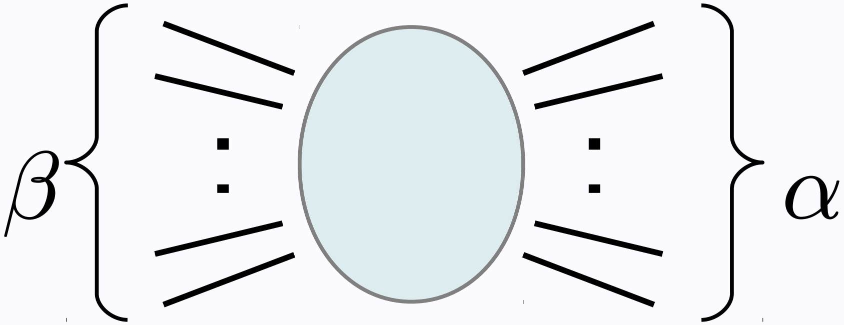
$$\langle 0|\phi(x)|\mathbf{p}\rangle \sim e^{ip\cdot x} \longrightarrow (\partial^2 + m^2)\phi = 0$$

- massless vector

$$\langle 0|F_{\mu\nu}(x)|\mathbf{p}\,\sigma\rangle \sim p_{[\mu}\epsilon^\sigma_{\nu]}(p)e^{ip\cdot x} \longrightarrow \begin{cases} \partial_\mu F^{\mu\nu} = 0 \\ \partial_\mu \widetilde{F}^{\mu\nu} = 0 \end{cases}$$

what is quantum field theory?

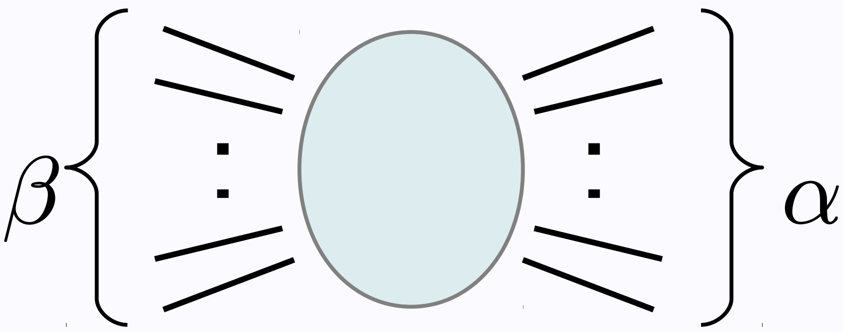
The study of multi-particle systems



$$|\alpha\rangle = |\mathbf{p}_1\,\sigma_1\rangle \otimes \cdots \otimes |\mathbf{p}_n\,\sigma_n\rangle$$

what is quantum field theory?

The study of multi-particle systems



$$|\alpha\rangle = |\mathbf{p}_1\,\sigma_1\rangle \otimes \cdots \otimes |\mathbf{p}_n\,\sigma_n\rangle$$

couple the momenta together to some

total momentum

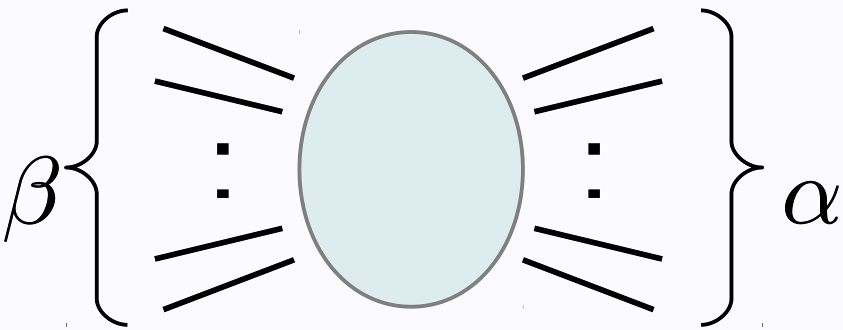
$$P^\mu = p_1^\mu + \cdots + p_n^\mu$$

and, in complete analogy with single particles, ask

besides P^μ, what else can we observe?

what is quantum field theory?*

The study of multi-particle systems



$$|\alpha\rangle = |\mathbf{p}_1\,\sigma_1\rangle \otimes \cdots \otimes |\mathbf{p}_n\,\sigma_n\rangle$$

couple the momenta together to some

total momentum

$$P^\mu = p_1^\mu + \cdots + p_n^\mu$$

and, in complete analogy with single particles, ask

besides P^μ, what else can we observe?

*S-matrix theory made practical – Weinberg

building blocks

$$\phi \qquad\qquad 1$$

$$\partial_\mu \phi \qquad\qquad p_\mu$$

$$\partial_{\{\mu_1}\partial_{\mu_2\}}\phi \qquad\qquad p_{\{\mu_1}p_{\mu_2\}}$$

$$\partial_{\{\mu_1}\partial_{\mu_2}\partial_{\mu_3\}}\phi \qquad\qquad p_{\{\mu_1}p_{\mu_2}p_{\mu_3\}}$$

$$\vdots \qquad\qquad \vdots$$

"generators" for all local operators

no ∂^2 terms

i.e. no EOM

"generators" for all Feynman rules

no p^2 terms

now have conceptual framework to build operator bases

- Specify particle states available at experiment and possible symmetries*
  - SMEFT: massless gluon, W, B
  - HEFT: massless gluon & photon, massive W & Z

- Local composite operators = multi-particle states
  - Built from single particle states and decomposed back into Poincare reps

- Operator basis = scattering states
  - Vanishing total spin and momentum (vacuum quantum numbers)
  - Operator version of partial wave decomposition

*at state level, symmetries enter in the true sense of the word: globally

counting

enumeration with Hilbert series

"Hilbert series"

$$H \equiv \mathrm{Tr}_{\mathcal{K}}\, \widehat{w} = \sum_{\mathcal{O}\in\mathcal{K}} \widehat{w}(\mathcal{O})$$

$\mathcal{K}$ = operator basis

$\widehat{w}(\mathcal{O})$ = weighting fxn for operator

Hilbert series is a partition fxn,weighted by field content

SMEFT Hilbert at dim-6

$$\begin{aligned}
H^{\text{SM}}_{\text{dim-6}} = {} & HH^\dagger B_L^2 + HH^\dagger B_R^2 \\
& + W_L^3 + W_R^3 \\
& + 2H^2 H^{\dagger\,2} \mathcal{D}^2 \\
& + H^3 H^{\dagger\,3} + Q^3 L \\
& + \cdots
\end{aligned}$$

counting
according to field
content

SMEFT Hilbert at dim-6

$$\begin{aligned} H^{\mathrm{SM}}_{\text{dim-6}} = \underbrace{\begin{aligned} & H H^\dagger B_L^2 + H H^\dagger B_R^2 \\ & + W_L^3 + W_R^3 \\ & + 2 H^2 H^{\dagger\,2} \mathcal{D}^2 \\ & + H^3 H^{\dagger\,3} + Q^3 L \\ & + \cdots \end{aligned}}_{\text{counting according to field content}} \end{aligned}$$

readily interpret as actual operators

$$\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$$

$$\left(\partial_\mu \left|H\right|^2\right)^2$$

SMEFT Hilbert at dim-6

$$\underbrace{\begin{aligned} H^{\text{SM}}_{\text{dim-6}} = {} & HH^\dagger B_L^2 + HH^\dagger B_R^2 \\ & + W_L^3 + W_R^3 \\ & + 2H^2 H^{\dagger\,2} \mathcal{D}^2 \\ & + H^3 H^{\dagger\,3} + Q^3 L \\ & + \cdots \end{aligned}}$$

counting according to field content

readily interpret as actual operators

$$|H|^2 B_{L,\mu\nu} B_L^{\mu\nu}$$

$$|H|^2 B_{R,\mu\nu} B_R^{\mu\nu}$$

note the chirality

$$B_{L/R} = B \pm i\widetilde{B}$$

$$|H|^2 B_{\mu\nu} B^{\mu\nu}$$

$$|H|^2 B_{\mu\nu} \widetilde{B}^{\mu\nu}$$

SMEFT Hilbert at dim-6

$$
\begin{aligned}
H^{\rm SM}_{\text{dim-6}} =& H^3 H^{\dagger\,3} + u^\dagger Q^\dagger H H^{\dagger\,2} + 2Q^2 Q^{\dagger\,2} + Q^{\dagger\,3} L^\dagger + Q^3 L + 2QQ^\dagger LL^\dagger + L^2 L^{\dagger\,2} + uQH^2H^\dagger \\
&+ 2uu^\dagger QQ^\dagger + uu^\dagger LL^\dagger + u^2 u^{\dagger\,2} + e^\dagger u^\dagger Q^2 + e^\dagger L^\dagger H^2 H^\dagger + 2e^\dagger u^\dagger Q^\dagger L^\dagger + eLHH^{\dagger\,2} + euQ^{\dagger\,2} \\
&+ 2euQL + ee^\dagger QQ^\dagger + ee^\dagger LL^\dagger + ee^\dagger uu^\dagger + e^2 e^{\dagger\,2} + d^\dagger Q^\dagger H^2 H^\dagger + 2d^\dagger u^\dagger Q^{\dagger\,2} + d^\dagger u^\dagger QL \\
&+ d^\dagger e^\dagger u^{\dagger\,2} + d^\dagger e Q^\dagger L + dQHH^{\dagger\,2} + 2duQ^2 + duQ^\dagger L^\dagger + de^\dagger QL^\dagger + deu^2 + 2dd^\dagger QQ^\dagger + dd^\dagger LL^\dagger \\
&+ 2dd^\dagger uu^\dagger + dd^\dagger ee^\dagger + d^2 d^{\dagger\,2} + u^\dagger Q^\dagger H^\dagger G_R + d^\dagger Q^\dagger H G_R + HH^\dagger G_R^2 + G_R^3 + uQHG_L \\
&+ dQH^\dagger G_L + HH^\dagger G_L^2 + G_L^3 + u^\dagger Q^\dagger H^\dagger W_R + e^\dagger L^\dagger H W_R + d^\dagger Q^\dagger H W_R + HH^\dagger W_R^2 + W_R^3 \\
&+ uQHW_L + eLH^\dagger W_L + dQH^\dagger W_L + HH^\dagger W_L^2 + W_L^3 + u^\dagger Q^\dagger H^\dagger B_R + e^\dagger L^\dagger H B_R \\
&+ d^\dagger Q^\dagger H B_R + HH^\dagger B_R W_R + HH^\dagger B_R^2 + uQHB_L + eLH^\dagger B_L + dQH^\dagger B_L + HH^\dagger B_L W_L \\
&+ HH^\dagger B_L^2 + 2QQ^\dagger HH^\dagger \mathcal{D} + 2LL^\dagger HH^\dagger \mathcal{D} + uu^\dagger HH^\dagger \mathcal{D} + ee^\dagger HH^\dagger \mathcal{D} + d^\dagger u H^2 \mathcal{D} + du^\dagger H^{\dagger\,2} \mathcal{D} \\
&+ dd^\dagger HH^\dagger \mathcal{D} + 2H^2 H^{\dagger\,2} \mathcal{D}^2
\end{aligned}
$$

Hilbert series incredibly useful for constructing operators

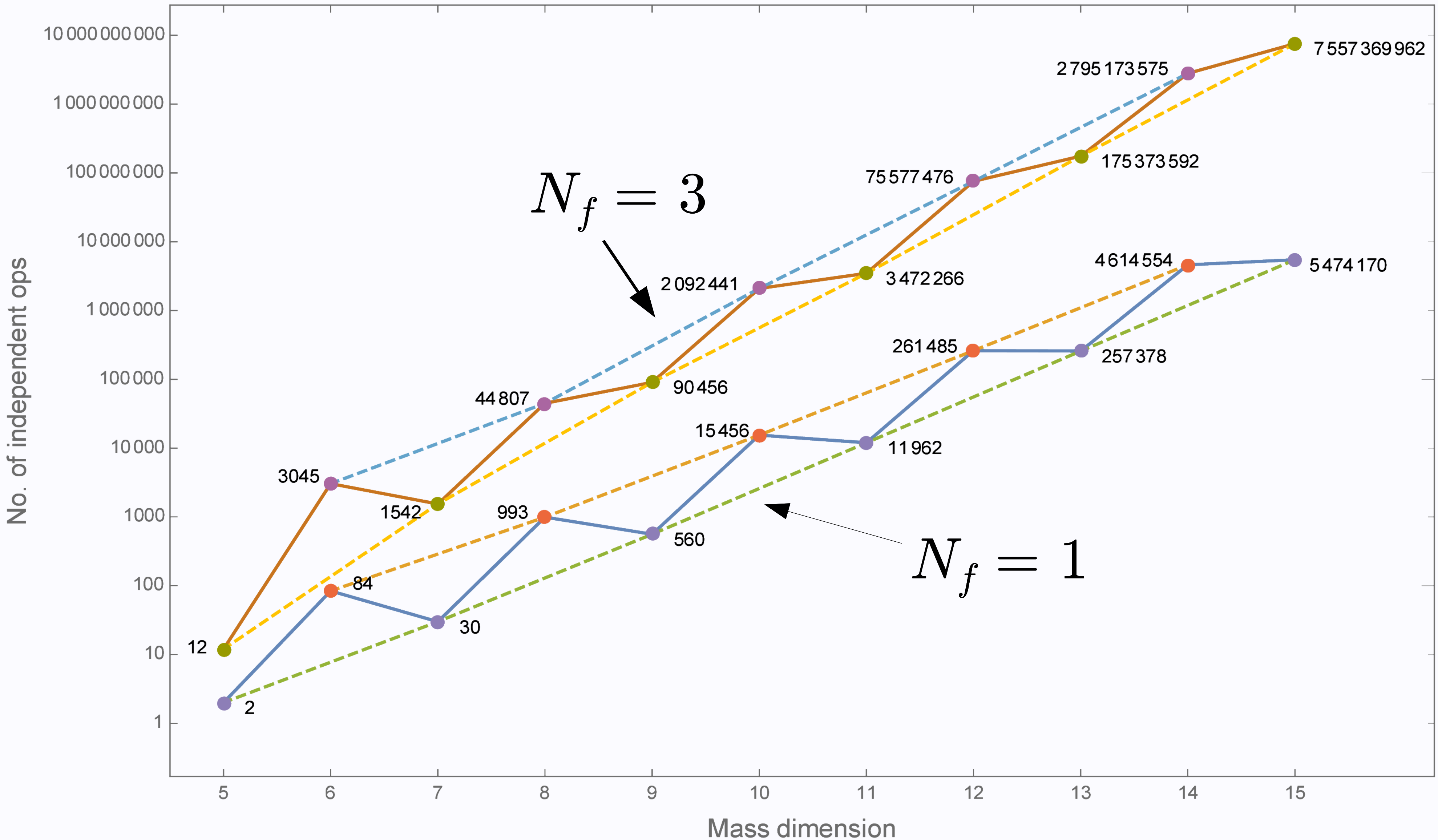
Summary of dim-8 Hilbert series

Note: classes can be further refined to find how many dim-8 ops contain, e.g., $Z\psi\psi$ terms

Mathematica file with SM Hilbert series available at arXiv:1512.03433

Class		N_f	1	3
X^4		43	43	43
X^3H^2		6	6	6
X^2H^4		10	10	10
H^8		1	1	1
$X^2H\psi^2$		$96N_f^2$	96	864
$XH^3\psi^2$		$22N_f^2$	22	198
$H^5\psi^2$		$6N_f^2$	6	54
$X\psi^4$	(B)	$4N_f^2(40N_f^2-1)$	156	12924
	$(\not{B})$	$2N_f^3(21N_f+1)$	44	3456
$H^2\psi^4$	(B)	$N_f^2(67N_f^2+N_f+7)$	75	5517
	$(\not{B})$	$\frac{1}{3}N_f^2(43N_f^2-9N_f+2)$	12	1086
$X^2\psi^2\mathcal{D}$		$57N_f^2$	57	513
$XH^2\psi^2\mathcal{D}$		$92N_f^2$	92	828
$H^4\psi^2\mathcal{D}$		$13N_f^2$	13	117
$H\psi^4\mathcal{D}$	(B)	$N_f^3(135N_f-1)$	134	10908
	$(\not{B})$	$N_f^3(29N_f+3)$	32	2430
$X^2H^2\mathcal{D}^2$		18	18	18
$XH^4\mathcal{D}^2$		6	6	6
$H^6\mathcal{D}^2$		2	2	2
$XH\psi^2\mathcal{D}^2$		$48N_f^2$	48	432
$H^3\psi^2\mathcal{D}^2$		$36N_f^2$	36	324
$\psi^4\mathcal{D}^2$	(B)	$\frac{11}{2}N_f^2(9N_f^2+1)$	55	4059
	$(\not{B})$	$N_f^3(11N_f-1)$	10	864
$H^2\psi^2\mathcal{D}^3$		$16N_f^2$	16	144
$H^4\mathcal{D}^4$		3	3	3
Total	(B)	$\frac{823}{2}N_f^4+\frac{789}{2}N_f^2+89$	895	36971
	$(\not{B})$	$\frac{289}{3}N_f^4+N_f^3+\frac{2}{3}N_f^2$	98	7836

hopefully experiments don't get too precise



Number of indep ops in SM EFT up to dim 15

HEFT

ongoing with Lukáš Gráf

this “non-linear” realization is basically saying
we have E&M with some massive vectors

take massive vector representations of Poincare

HEFT

ongoing with Lukáš Gráf

this “non-linear” realization is basically saying we have E&M with some massive vectors

take massive vector representations of Poincare

consists of transverse and longitudinal polarizations (shocking)

$$\begin{matrix} F_{\mu\nu} & & u_\mu \\ D_{\{\mu_1}F_{\mu_2\}\nu} & + & D_{\{\mu_1}u_{\mu_2\}} \\ D_{\{\mu_1}D_{\mu_2}F_{\mu_3\}\nu} & & D_{\{\mu_1}D_{\mu_2}u_{\mu_3\}} \\ \vdots & & \vdots \end{matrix}$$

HEFT

ongoing with Lukáš Gráf

this "non-linear" realization is basically saying we have E&M with some massive vectors

take massive vector representations of Poincare

consists of transverse and longitudinal polarizations (shocking)

$$\begin{array}{ccc} F_{\mu\nu} & & u_\mu \\ D_{\{\mu_1} F_{\mu_2\}\nu} & + & D_{\{\mu_1} u_{\mu_2\}} \\ D_{\{\mu_1} D_{\mu_2} F_{\mu_3\}\nu} & & D_{\{\mu_1} D_{\mu_2} u_{\mu_3\}} \\ \vdots & & \vdots \end{array}$$

Similar longitudinal structure for genuine massless goldstones...related to soft limits

constructing

an obvious question from HC2017:
do we need dim-8 operators?

an obvious question from me:
do these free field operators have further use?

I want to <u>suggest</u> that these states <u>potentially</u> have value for addressing difficult dynamics

Large QCD effects and many small corrections

From Kirill's talk

Current estimates of the gluon fusion cross section include large number of subtle effects and require careful evaluation of the residual uncertainty.

$$\sigma = 48.58\ \text{pb}^{+2.22\ \text{pb}(+4.56\%)}_{-3.27\ \text{pb}(-6.72\%)}\,(\text{theory}) \pm 1.56\ \text{pb}\ (3.20\%)(\text{PDF}+\alpha_s)$$

$$\begin{aligned}
48.58\,\text{pb} = \; & 16.00\,\text{pb} & (+32.9\%) & \quad (\text{LO, rEFT}) \\
& + 20.84\,\text{pb} & (+42.9\%) & \quad (\text{NLO, rEFT}) \\
& - \;\; 2.05\,\text{pb} & (-4.2\%) & \quad ((t,b,c),\ \text{exact NLO}) \\
& + \;\; 9.56\,\text{pb} & (+19.7\%) & \quad (\text{NNLO, rEFT}) \\
& + \;\; 0.34\,\text{pb} & (+0.7\%) & \quad (\text{NNLO}, 1/m_t) \\
& + \;\; 2.40\,\text{pb} & (+4.9\%) & \quad (\text{EW, QCD-EW}) \\
& + \;\; 1.49\,\text{pb} & (+3.1\%) & \quad (\text{N}^3\text{LO, rEFT}) \\
& \;\; \ldots\ldots
\end{aligned}$$

$\delta(\text{scale})$	$\delta(\text{trunc})$	$\delta(\text{PDF-TH})$	$\delta(\text{EW})$	$\delta(t,b,c)$	$\delta(1/m_t)$
$^{+0.10\ \text{pb}}_{-1.15\ \text{pb}}$	± 0.18 pb	± 0.56 pb	± 0.49 pb	± 0.40 pb	± 0.49 pb
$^{+0.21\%}_{-2.37\%}$	$\pm 0.37\%$	$\pm 1.16\%$	$\pm 1\%$	$\pm 0.83\%$	$\pm 1\%$

Anastasiou, Duhr, Dulat, Furlan, Gehrmann, Herzog, Lazopoulos, Mistlberger

Large QCD effects and many small corrections

From Kirill's talk

Current estimates of the gluon fusion cross section include large number of subtle effects and require careful evaluation of the residual uncertainty.

"to push down, likely need N^{4}LO...that won't happen in my lifetime" - K.M.

$$\sigma = 48.58\ \text{pb}^{+2.22\ \text{pb}(+4.56\%)}_{-3.27\ \text{pb}(-6.72\%)}\ (\text{theory}) \pm 1.56\ \text{pb}\ (3.20\%)(\text{PDF} + \alpha_s)$$

16.00 pb		(+32.9%)	(LO, rEFT)
+	20.84 pb	(+42.9%)	(NLO, rEFT)
−	2.05 pb	(−4.2%)	((t, b, c), exact NLO)
+	9.56 pb	(+19.7%)	(NNLO, rEFT)
+	0.34 pb	(+0.7%)	(NNLO, $1/m_t$)
+	2.40 pb	(+4.9%)	(EW, QCD-EW)
+	1.49 pb	(+3.1%)	(N^{3}LO, rEFT)

....

δ(scale)	δ(trunc)	δ(PDF-TH)	δ(EW)	$\delta(t,b,c)$	$\delta(1/m_t)$
+0.10 pb −1.15 pb	±0.18 pb	±0.56 pb	±0.49 pb	±0.40 pb	±0.49 pb
+0.21% −2.37%	±0.37%	±1.16%	±1%	±0.83%	±1%

Anastasiou, Duhr, Dulat, Furlan, Gehrmann, Herzog, Lazopoulos, Mistlberger

Large QCD effects and many small corrections

From Kirill's talk

Current estimates of the gluon fusion cross section include large number of subtle effects and require careful evaluation of the residual uncertainty.

"to push down, likely need N^4LO…that won't happen in my lifetime" - K.M.

$$\sigma = 48.58\ \mathrm{pb}^{+2.22\ \mathrm{pb}\,(+4.56\%)}_{-3.27\ \mathrm{pb}\,(-6.72\%)}\ (\mathrm{theory}) \pm 1.56\ \mathrm{pb}\ (3.20\%)(\mathrm{PDF}+\alpha_s)$$

$$
\begin{aligned}
48.58\ \mathrm{pb} =\ & 16.00\ \mathrm{pb} && (+32.9\%) && (\mathrm{LO,\ rEFT})\\
& + 20.84\ \mathrm{pb} && (+42.9\%) && (\mathrm{NLO,\ rEFT})\\
& -\ 2.05\ \mathrm{pb} && (-4.2\%) && ((t,b,c),\ \mathrm{exact\ NLO})\\
& +\ 9.56\ \mathrm{pb} && (+19.7\%) && (\mathrm{NNLO,\ rEFT})\\
& +\ 0.34\ \mathrm{pb} && (+0.7\%) && (\mathrm{NNLO},\ 1/m_t)\\
& +\ 2.40\ \mathrm{pb} && (+4.9\%) && (\mathrm{EW,\ QCD\text{-}EW})\\
& +\ 1.49\ \mathrm{pb} && (+3.1\%) && (\mathrm{N^3LO,\ rEFT})\\
& \ldots
\end{aligned}
$$

any other ways of computing?

first principles, non-perturbative?

lattice MC? ... prob not ... SM is chiral

δ(scale)	δ(trunc)	δ(PDF-TH)	δ(EW)	$\delta(t,b,c)$	$\delta(1/m_t)$
$^{+0.10\ \mathrm{pb}}_{-1.15\ \mathrm{pb}}$	±0.18 pb	±0.56 pb	±0.49 pb	±0.40 pb	±0.49 pb
$^{+0.21\%}_{-2.37\%}$	$\pm0.37\%$	$\pm1.16\%$	$\pm1\%$	$\pm0.83\%$	$\pm1\%$

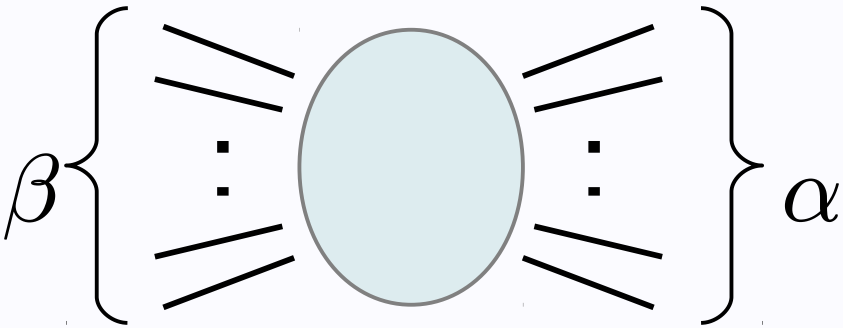
Anastasiou, Duhr, Dulat, Furlan, Gehrmann, Herzog, Lazopoulos, Mistlberger

constructing operators with spinors

ongoing with Tom Melia

New for Higgs Couplings 2017!

recall multi-particle states



$$|\alpha\rangle = |\mathbf{p}_1\,\sigma_1\rangle \otimes \cdots \otimes |\mathbf{p}_n\,\sigma_n\rangle$$

couple the momenta together to some total momentum

$$P^\mu = p_1^\mu + \cdots + p_n^\mu$$

besides P^μ, what else can we observe?

geometry of kinematics

single massless particle

keeps
on-shell

$$\delta(p^2)\delta^4(P^\mu - p^\mu)$$

constrained to the cone $\quad p_0 = \sqrt{\mathbf{p}^2}$

geometry of kinematics

single massless particle

keeps
on-shell

$$\delta(p^2)\delta^4(P^\mu - p^\mu)$$

constrained to the cone $\quad p_0 = \sqrt{\mathbf{p}^2}$

multiple massless particles

$$\underbrace{\delta(p_1^2)\cdots\delta(p_n^2)}_{\text{cones}} \times \underbrace{\delta^4\big(P^\mu - (p_1^\mu + \cdots + p_n^\mu)\big)}_{\text{simplex}}\delta(P^2 - M^2)$$

complicated geometry!

coupled momentum
is massive

kinematics with spinors

$$p_{\alpha\dot{\alpha}} = \begin{pmatrix} p_0 + p_3 & p_1 - ip_2 \\ p_1 + ip_2 & p_0 - p_3 \end{pmatrix}$$

$$p^2 = 0 \Rightarrow p_{\alpha\dot{\alpha}} = \lambda_\alpha \widetilde{\lambda}_{\dot{\alpha}}$$

trivializes $\delta(p^2)$

so that

$$\delta(p_1^2) \cdots \delta(p_n^2) \times \delta^4\Big(P^\mu - (p_1^\mu + \cdots + p_n^\mu)\Big)$$

$$\downarrow$$

$$\delta^4\Big(P_{\alpha\dot{\alpha}} - (\lambda^1 \widetilde{\lambda}^1 + \cdots + \lambda^n \widetilde{\lambda}^n)_{\alpha\dot{\alpha}}\Big)$$

kinematics with spinors

$$\delta^4\Big(P_{\alpha\dot\alpha} - (\lambda^1\widetilde{\lambda}^1 + \cdots + \lambda^n\widetilde{\lambda}^n)_{\alpha\dot\alpha}\Big)$$

in c.o.m. frame

$$p_{\alpha\dot\alpha} = \begin{pmatrix} p_0 + p_3 & p_1 - ip_2 \\ p_1 + ip_2 & p_0 - p_3 \end{pmatrix}$$

$$P_{\alpha\dot\alpha} = \begin{pmatrix} M & 0 \\ 0 & M \end{pmatrix} = \begin{pmatrix} \left|\vec{\lambda}_1\right|^2 & \vec{\lambda}_1 \cdot \vec{\lambda}_2^* \\ \vec{\lambda}_2 \cdot \vec{\lambda}_1^* & \left|\vec{\lambda}_2\right|^2 \end{pmatrix}$$

kinematics with spinors

$$\delta^4\Big(P_{\alpha\dot\alpha} - (\lambda^1\widetilde{\lambda}^1 + \cdots + \lambda^n\widetilde{\lambda}^n)_{\alpha\dot\alpha}\Big)$$

in c.o.m. frame

$$p_{\alpha\dot\alpha} = \begin{pmatrix} p_0 + p_3 & p_1 - ip_2 \\ p_1 + ip_2 & p_0 - p_3 \end{pmatrix}$$

$$\downarrow$$

$$P_{\alpha\dot\alpha} = \begin{pmatrix} M & 0 \\ 0 & M \end{pmatrix} = \begin{pmatrix} \left|\vec{\lambda}_1\right|^2 & \vec{\lambda}_1 \cdot \vec{\lambda}_2^* \\ \vec{\lambda}_2 \cdot \vec{\lambda}_1^* & \left|\vec{\lambda}_2\right|^2 \end{pmatrix}$$

Geometry basically complex version of two orthogonal spheres

$$r^2 = \vec{v}^2$$

$$r^2 = \vec{u}^2$$

$$0 = \vec{v} \cdot \vec{u}$$

$$G/H = U(N)\big/U(N-2)$$

space of states

What else can we have besides momentum?

"besides" = "modulo" = coset

$$U(N)\Big/U(N-2)$$

operator content of free CFTs in d=4

claim

N-particle primaries built from massless particles belong to the manifold

$$U(N) \big/ U(N-2)$$

- gives explicit construction of primaries built from arbitrary spin
- essentially computes free field OPE
- remarkable pairing between U(N) and SL(2,C) – they control each other's representations exactly
- similar games in $d = 2$ & 3

these states have use in exploring a (recently revived) technique to numerically access strongly coupled phenomena called Hamiltonian truncation

the dumbest idea which might actually work

- take free theory, where we know the states and couplings
- deform with relevant interaction
- compute Hamiltonian matrix elements
- diagonalize Hamiltonian

result ideally approximates true spectrum and states

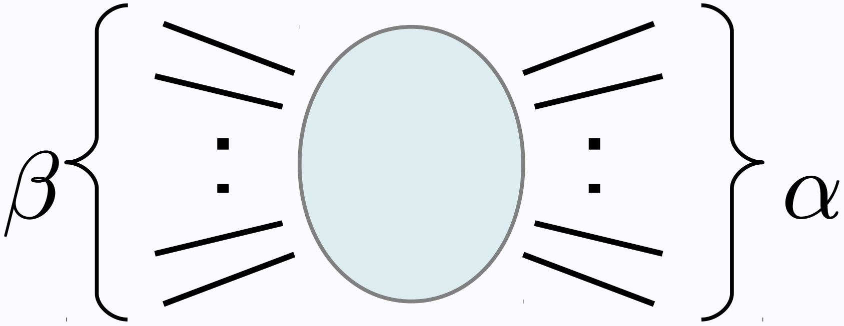
can use these states to compute correlation functions (even at strong coupling)

Hamiltonian truncation

- several d=2 success stories (works best with strongly relevant operators)
  - e.g. “parton content” of bound states d=2 QCD
- one successful study in d=3 - begs for more studies
- operator construction provides necessary starting ingredients

and one last vague thought

unitarity

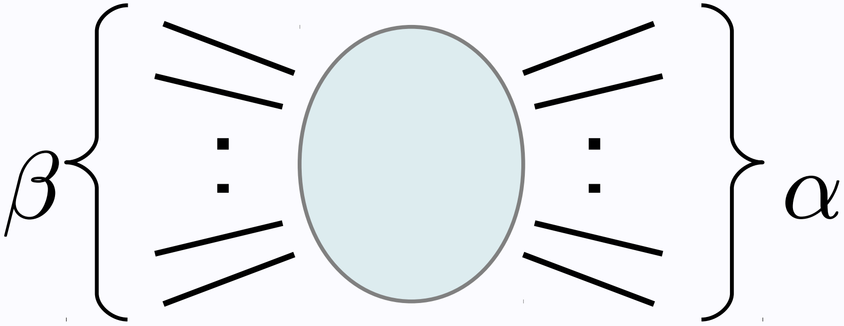


Scattering matrix:

transitions from in to out states

$$S_{\beta\alpha} = \langle \beta | S | \alpha \rangle$$

unitarity



Scattering matrix:

transitions from in to out states

$$S_{\beta\alpha} = \langle \beta | S | \alpha \rangle$$

several re-phrasings

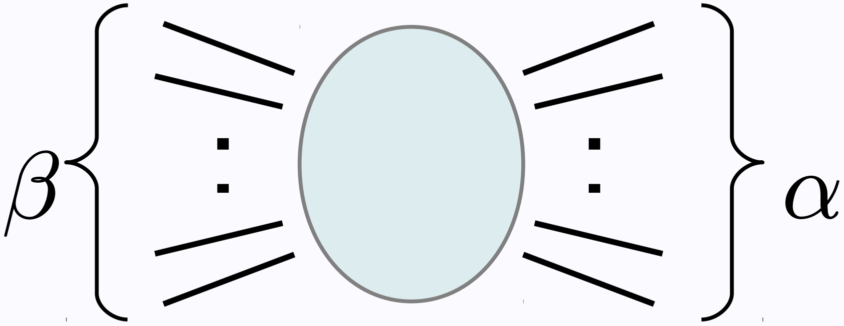
- transitions from one state to another state
- transitions from one representation to another
- intertwines representations

$$SU = US$$

$U \in$ Poincaré

$|\alpha\rangle \to D_\alpha[U]\,|\alpha\rangle$

unitarity



Scattering matrix:

transitions from in to out states

$$S_{\beta\alpha} = \langle \beta | S | \alpha \rangle$$

several re-phrasings

- transitions from one state to another state
- transitions from one representation to another
- intertwines representations

$$SU = US$$

$U \in$ Poincaré

$|\alpha\rangle \to D_\alpha[U]\,|\alpha\rangle$

constraint equation!

can this equation be made concrete?

can we connect with standard dispersion relation results?

exiting questions

exiting questions

can we bootstrap the S-matrix?

exiting questions

can we bootstrap the S-matrix?

can spacetime symmetry principles provide more nuanced frameworks useful for experimental analysis?

- Large particle multiplicity (jets, decays, ...)
- Multiple scales (indiv. PT, differential distributions,...)

once again, nature has graced us with interesting, difficult problems

an exciting feedback loop between experiment and theory once again, nature has graced us with interesting, difficult problems

an exciting feedback loop between experiment and theory

homies, it's kinda a golden era right now

smile about it