Operators, amplitudes, states, and all that

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Some past and current collaborators:
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Francesco Riva, Jed Thompson, Matthew Walters

HEFT 2020

Same, same. But different.

EFT operators

$$\int dx\, \mathcal{O}(x)$$

Amplitude contact terms

$$\mathcal{A} \supset \langle ij \rangle^{\#} [kl]^{\#}$$

States in Hilbert space

$$|\psi\rangle \in \mathcal{H}$$

Form factors

$$F_{\mathcal{O}}(q; p_1, \ldots, p_N)$$

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I will elaborate on this piece of the story today.

Hopefully we'll gain further insight into the rest of this diagram

EFT operators

The “traditional” working definition of EFTs

$$S = \int d^d x \sum_i c_i \mathcal{O}_i(x)$$

Basic question: what is a basis of operators?

*See talks by J. Serra, J.C. Criado

- # of operators? → counting
- What are the operators? → constructing

Important question: what physics do these ops give?

*See talks by most people here

*See talks by C. Machado, Y. Shadmi, ...

Amplitudes

$$\langle \alpha | \beta \rangle |_{\text{poly,tree}} \sim \sum_{n,m} c_{n,m} s^n t^m \qquad s + t + u = 0$$

Amplitudes can have "contact" terms, which exhibit polynomial growth in energy

---

What is the connection to EFT operators?

consider Dyson's formula...

$$S = Te^{i\int d^dx \mathcal{H}} = 1 + \sum_{n=1}^{\infty} \frac{i^n}{n!} \int d^dx_1 \cdots d^dx_n \, T\{\mathcal{H}(x_1) \cdots \mathcal{H}(x_n)\}$$

...in the leading approximation:

$$\langle \alpha | S | \beta \rangle = \delta_{\alpha\beta} + i \int d^dx \sum_i c_i \, \langle \alpha | \mathcal{O}_i(x) | \beta \rangle + \cdots$$

→ For every contact term there exists a corresponding local operator!

Form factors

$$F_{\mathcal{O}}(q; p_1, \ldots, p_N) = \int d^d x \, e^{iq\cdot x} \, \langle \Omega | \mathcal{O}(x) | p_1 \ldots p_N \rangle$$

- Form factors have well-studied connection with EFTs
- Currently, not particularly in vogue for the SMEFT/HEFT communities (however, see talk by M. Riembau)
- I will not say anything more about them in this talk

Hilbert space states

By considering operators acting on the vacuum, we can generate states

$$|\mathcal{O}(P)\rangle = \int d^d x \, e^{-iP\cdot x} \mathcal{O}(x) \, |0\rangle$$
$$= \int d\Pi \, \delta^d(P - p_1 - \cdots - p_N) f_{\mathcal{O}}(p_i) \, |p_1 \ldots p_N\rangle$$

I will elaborate much more on this picture shortly

Recent years have seen tremendous progress on enumeration and construction of ops/amplitudes

I defer to the aforementioned talks for details

However, I would like to mention two very challenging issues concerning $N > 4$ point amplitudes

Group relations in kinematics

a.k.a. Gram conditions/Schouten identities

$$p_i^\mu = \begin{pmatrix} p_1^\mu & \cdots & p_N^\mu \end{pmatrix} = \begin{pmatrix} p_1^0 & \cdots & p_N^0 \\ \vdots & & \vdots \\ p_1^3 & \cdots & p_N^3 \end{pmatrix} \quad \Leftarrow \quad 4 \times N \text{ matrix}$$

$$\text{for } N \geq 4, \ \text{rank}(p_i^\mu) \leq 4$$

$$s_{ij} = p_i \cdot p_j = \begin{pmatrix} s_{11} & \cdots & s_{1N} \\ \vdots & & \vdots \\ s_{N1} & \cdots & s_{NN} \end{pmatrix} \quad \Leftarrow \quad N \times N \text{ matrix}$$

$$\text{rank}(p) \leq 4 \ \Rightarrow \ \text{rank}(s) \leq 4 \ \Rightarrow \ \text{Gram conditions (vanishing minors)}$$

Group relations in kinematics

a.k.a. Gram conditions/Schouten identities

$$\lambda_a^i = \begin{pmatrix} \lambda_1^1 & \cdots & \lambda_1^N \\ \lambda_2^1 & \cdots & \lambda_2^N \end{pmatrix} \;\Leftarrow\; 2 \times N \text{ matrix}$$

$$\langle ij \rangle \equiv \epsilon^{ab} \lambda_a^i \lambda_b^j \;\Leftarrow\; N \times N \text{ matrix}$$

$$\text{rank}(\lambda) \leq 2 \;\Rightarrow\; \text{rank}(\langle ij \rangle) \leq 2 \;\Rightarrow\; \text{Schouten identities}$$

$$\epsilon^{i_1 i_2 \ldots i_N} \langle i_1 i_2 \rangle \langle i_3 i_4 \rangle = 0$$

Bonus difficulty: The constraints aren't all independent!

→Relations among relations (syzygies)

Group relations in kinematics

a.k.a. Gram conditions/Schouten identities

*See also talk by T. Melia at HEFT 2019

I want to point out that the results of 1902.06754 automatically account for these relations

Comments on symmeterization

(I’m going to speak a very technical comment)

Building a Hilbert space

Single particle states

$$|\mathbf{p}, \sigma\rangle$$

on-shell

spin/helicity state

$$E = \sqrt{\mathbf{p}^2 + m^2} > 0$$

we'll take m=0
(valid for SMEFT)

States are normalized as

$$\langle \mathbf{p}'\sigma'|\mathbf{p}\sigma\rangle = 2E_{\mathbf{p}}\delta^3(\mathbf{p}-\mathbf{p}')\delta_{\sigma\sigma'}$$

δ-fxn norm ↔ distribution
(blah blah blah...wavepackets...blah blah blah)

Single particle states

We introduce creation/annihilation operators...

$$|\mathbf{p},\sigma\rangle = a^\dagger_{\mathbf{p},\sigma}|0\rangle$$

...and then construct interpolating fields*

*fields are constrained (EoM, Bianchi identities) → allows a covariant transformation rule which correctly reproduces transformation of single particle states

for example:

$$\phi(x) = \int \overbrace{d^4p\, \underbrace{\delta(p^2-m^2)\Theta(p^0)}_{\text{on-shell, positive energy}}}^{\text{Integrating over } p^0 \;\to\; \frac{d^3\mathbf{p}}{2E_{\mathbf{p}}}} \left(e^{-ip\cdot x}a_{\mathbf{p}} + e^{ip\cdot x}a^\dagger_{\mathbf{p}}\right)$$

on-shell, positive energy

Integrating over p^0

↓

$$\frac{d^3\mathbf{p}}{2E_{\mathbf{p}}}$$

Massless? Use spinors!

$$\int d^4p\, \underbrace{\delta(p^2 - m^2)\Theta(p^0)}\Big(\;\cdots\; \Big)$$

massless

$$\int d^4p\, \overbrace{\delta(p^2)\Theta(p^0)}\Big(\;\cdots\; \Big)$$

switch to spinors

$$\int d\lambda \left(e^{\frac{i}{2}\langle\lambda\widetilde{\lambda}x\rangle} a^\dagger_\lambda \;\cdots\; \right)$$

$p_{a\dot{a}} = \lambda_a \widetilde{\lambda}_{\dot{a}}$ $(p = \lambda\lambda^\dagger)$

$\widetilde{\lambda} = +(\lambda)^*$

note the matrix notation

$$\langle\lambda\widetilde{\lambda}x\rangle \equiv \lambda_a \widetilde{\lambda}_{\dot{a}} x^{\dot{a}a} = \lambda^\dagger x \lambda = \mathrm{tr}\big(\lambda\lambda^\dagger x\big)$$

will label the momentum state with λ:

$$|\mathbf{p}\rangle \to |\lambda\rangle$$

$$|\lambda\rangle = a^\dagger_\lambda |0\rangle$$

examples

–helicity 0

$$\phi(x)\,|0\rangle = \int d\lambda\, e^{\frac{i}{2}\langle\lambda\lambda^\dagger x\rangle}\,|\lambda\rangle$$

–helicity +1

$$F_{ab}(x)\,|0\rangle = \int d\lambda\, e^{\frac{i}{2}\langle\lambda\lambda^\dagger x\rangle}\lambda_a\lambda_b\,|\lambda\rangle$$

$$\left(i.e.\;\; \langle\mathbf{p},\sigma=+1|F_{ab}(x)|0\rangle = e^{\frac{i}{2}\langle\lambda\lambda^\dagger x\rangle}\lambda_a\lambda_b\right)$$

–spinors capture helicity info (no need for polarization tensors)

–for general helicity h:

$$h \geq 0 : \quad (\lambda)^{2h}$$

$$h < 0 : \quad (\widetilde{\lambda})^{2|h|}$$

having constructed the single particle Hilbert space, we can build the multi-particle Hilbert space as a tensor product

$$\mathcal{H}_N \subseteq \mathcal{H}_1^{\otimes N} \quad \Leftrightarrow \quad a^\dagger_\lambda \otimes \cdots \otimes a^\dagger_\lambda$$

intuitively, this implies the existence of interpolating operators which are polynomials in the fields and their derivatives

$$:\mathcal{O}^{(N)}(x): \;\sim\; :\big(\Phi_1 \cdots \Phi_N \partial^{\#}\big)(x):$$

we will formulate this more precisely over the coming slides

Multi-particle states/operators

Define an N-particle operator via

$$|\lambda\rangle = |\lambda_a^1 \cdots \lambda_a^N\rangle$$

$$: \mathcal{O}^{(N)}(x) : |0\rangle = \int d\lambda \, e^{\frac{i}{2}\langle \lambda\lambda^\dagger x\rangle} \, f_{\mathcal{O}}(\lambda) \, |\lambda\rangle$$

tensor product of creation ops

$$\lambda = \begin{pmatrix} \lambda_1^1 & \cdots & \lambda_1^N \\ \lambda_2^1 & \cdots & \lambda_2^N \end{pmatrix}$$

$$(\lambda\lambda^\dagger)_{a\dot{a}} = \sum_{i=1}^{N} \lambda_a^i \widetilde{\lambda}_{\dot{a}i}$$

we're coming in HOT with the matrix notation...best to think of λ as a 2xN matrix!

The functions f(λ) are the objects of interest

→Unitarity (requiring finite norms) will imply the f's are polynomial functions

→In turn, this implies ops are polys in fields and their derivatives

→Along the way, a natural basis will present itself :)

Multi-particle states/operators

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→Unitarity (requiring finite norms) will imply the f's are polynomial functions
→In turn, this implies ops are polys in fields and their derivatives

$$|\widetilde{\mathcal{O}}(P)\rangle \equiv \int d^4x\, e^{-\frac{i}{2}\langle Px\rangle}\ :\mathcal{O}(x):|0\rangle$$
$$= \int d\lambda\, \delta^4\left(P - \lambda\lambda^\dagger\right) f_{\mathcal{O}}(\lambda)\ |\lambda\rangle$$

Multi-particle states/operators

Define an N-particle operator via

$$: \mathcal{O}^{(N)}(x) : |0\rangle = \int d\lambda \, e^{\frac{i}{2}\langle \lambda\lambda^\dagger x\rangle} f_{\mathcal{O}}(\lambda) \, |\lambda\rangle$$

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$$\lambda = \begin{pmatrix} \lambda_1^1 & \cdots & \lambda_1^N \\ \lambda_2^1 & \cdots & \lambda_2^N \end{pmatrix}$$

$$(\lambda\lambda^\dagger)_{a\dot{a}} = \sum_{i=1}^{N} \lambda_a^i \widetilde{\lambda}_{\dot{a}i}$$

We assume the fourier transform to exist, and choose to work in momentum space.

That is, we define states as

$$|\widetilde{\mathcal{O}}(P)\rangle \equiv \int d^4x \, e^{-\frac{i}{2}\langle Px\rangle} \; : \mathcal{O}(x) : |0\rangle$$

$$= \int d\lambda \, \delta^4\!\left(P - \lambda\lambda^\dagger\right) f_{\mathcal{O}}(\lambda) \; |\lambda\rangle$$

Inner product

$$|\widetilde{\mathcal{O}}(P)\rangle = \int d\lambda\, \delta^4\big(P - \lambda\lambda^\dagger\big)\, f_{\mathcal{O}}(\lambda)\ |\lambda\rangle$$

The creation/annihilation ops endow a natural inner product on these states

$$\langle\widetilde{\mathcal{O}}_1(p_1)|\widetilde{\mathcal{O}}_2(p_2)\rangle = \int d\lambda\, \delta^4\big(p_1 - \lambda\lambda^\dagger\big) \int d\eta\, \delta^4\big(p_2 - \eta\eta^\dagger\big)\, f_1^*(\lambda) f_2(\eta)\, \overbrace{\langle\lambda|\eta\rangle}^{\delta(\lambda-\eta)}$$

$$= \delta^4(p_1 - p_2) \int d\lambda\, \delta^4\big(p_1 - \lambda\lambda^\dagger\big)\, f_1^*(\lambda) f_2(\lambda)$$

From translational invariance.
Reflects distributional
character of these states

This inner product amounts to

$$\langle\!\langle\widetilde{\mathcal{O}}(P)|\widetilde{\mathcal{O}}(P)\rangle\!\rangle = \int d\lambda\, \delta^4\big(P - \lambda\lambda^\dagger\big)\ |f_{\mathcal{O}}(\lambda)|^2$$

To be a Hilbert space, this needs to be positive definite and finite. What does this imply about f?

Radial coords

$$\langle\!\langle \widetilde{\mathcal{O}}(P) | \widetilde{\mathcal{O}}(P) \rangle\!\rangle = \int d\lambda\, \delta^4\big(P - \lambda\lambda^\dagger\big)\ |f_{\mathcal{O}}(\lambda)|^2$$

$$\lambda\lambda^\dagger = 2 \times 2 \text{ positive definite, hermitian matrix}$$

Implies P is in the forward lightcone (timelike, positive energy)

Can pass to "radial" coordinates

$$\lambda = Q^{1/2}\hat{\lambda} \ \text{ with } \ \hat{\lambda}\hat{\lambda}^\dagger = \mathbf{1}_{2\times 2}$$

$$\Big(\text{matrix analog of } \vec{x} = \sqrt{r^2}\hat{n} \ \text{ with } \ \hat{n}\hat{n}^T = 1\Big)$$

Under this change of variables:

$$\delta^4(P - \lambda\lambda^\dagger) \to \delta^4(P - Q)$$

$$d\lambda \propto dQ\big(\det Q\big)^{\#}\, d\hat{\lambda}$$

Jacobian factor follows by Lorentz invariance (with exponent fixed by dim analysis)

Back to inner product...

$\lambda = Q^{1/2}\hat{\lambda}$ with $\hat{\lambda}\hat{\lambda}^\dagger = \mathbf{1}_{2\times 2}$

$$
\begin{aligned}
\langle\!\langle \widetilde{\mathcal{O}}(P) | \widetilde{\mathcal{O}}(P) \rangle\!\rangle &= \int d\lambda\, \delta^4\big(P - \lambda\lambda^\dagger\big)\ |f_{\mathcal{O}}(\lambda)|^2 \\
&= \int dQ\, \delta^4(P - Q)\, (\det Q)^{\#} \int d\hat{\lambda}\, \Big| f_{\mathcal{O}}(Q^{1/2}\hat{\lambda}) \Big|^2 \\
&= (\det P)^{\#} \int d\hat{\lambda} \Big| f_{\mathcal{O}}(P^{1/2}\hat{\lambda}) \Big|^2
\end{aligned}
$$

$\hat{\lambda}\hat{\lambda}^\dagger = \mathbf{1}_{2\times 2}$

compact manifold!

Hilbert space = square integrable functions on this manifold!

Basis on compact manifold

$\hat{\lambda}\hat{\lambda}^\dagger = \mathbf{1}_{2\times 2}$

square integrable functions on a compact manifold

↓

can be expanded in polynomials

$$f(\lambda) \sim \sum_{n,m} c^{j_1\ldots j_m}_{i_1\ldots i_n} (\lambda^i)^n (\widetilde{\lambda}_j)^m = \sum_{n=0}^{\infty} \sum_{k=0}^{n} d^{j_1\ldots j_k}_{i_1\ldots i_{n-k}} (\lambda^i)^{n-k} (\widetilde{\lambda}_j)^k$$

Upshot: A natural basis is supplied by the "spherical harmonics" on the manifold (which correspond to certain homogeneous polys in the spinors)

Naming the manifold

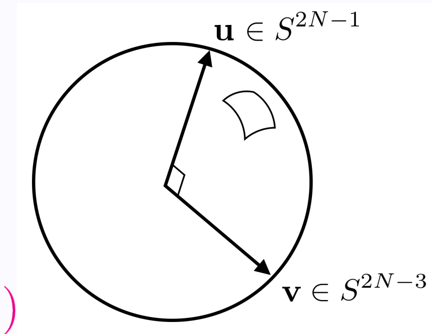
Similar to how $\hat{n}\hat{n}^T = 1$ defines a sphere

$\hat{\lambda}\hat{\lambda}^\dagger = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$ basically defines 2 (complex) spheres

Called a Stiefel manifold: $V_{N,2}(\mathbb{C}^N)$

Can be viewed as a homogeneous space

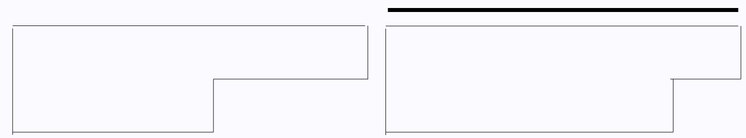
$$\hat{\lambda}\hat{\lambda}^\dagger = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \xrightarrow{U(N) \text{ rotation}} \hat{\lambda} = \underbrace{\begin{pmatrix} 1 & & & \\ & 1 & & \end{pmatrix}}_{\text{preserves } U(N-2)}$$



$$V_{N,2}(\mathbb{C}^N) = U(N) \big/ U(N-2)$$

upshot on Stiefel harmonics

harmonics labeled by Young diagrams
(with at most two rows)



these dictate specific polynomials in the spinors

comments:

1) each shape corresponds to operators

2) multiple operators belong to same shape

   a) these involve particles with different spin

3) these operators are conformal primaries

Lorentz invariant operators: Grassmannian harmonics

$$\langle\!\langle \widetilde{\mathcal{O}}(P) | \widetilde{\mathcal{O}}(P) \rangle\!\rangle = \int d\lambda\, \delta^4\big(P - \lambda\lambda^\dagger\big)\ |f_{\mathcal{O}}(\lambda)|^2$$

$$= \int dQ\, \delta^4(P - Q)\, (\det Q)^{\#} \int d\hat{\lambda}\, \left| f_{\mathcal{O}}(Q^{1/2}\hat{\lambda}) \right|^2$$

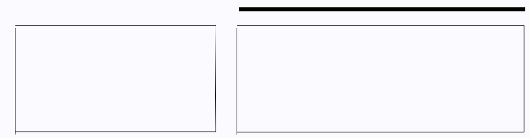
$$= (\det P)^{\#} \int d\hat{\lambda}\, \left| f_{\mathcal{O}}(P^{1/2}\hat{\lambda}) \right|^2$$

For Lorentz invariant polynomials, can further mod out by a factor of U(2)

Grassmannian

$$G_{N,2}(\mathbb{C}^N) = U(N) \big/ U(N-2) \times U(2)$$

Young diagrams for Grassmann harmonics



Constructing other terms in the operator

We've identified the "all $a^\dagger$" term in the operator.

Rest of the terms constructed by continuation from positive to negative energy

$$\mathcal{O}^{(N)}(x) = \int d\lambda \Big[(a_\lambda^\dagger)^N e^{\frac{i}{2}(\lambda_1 \widetilde{\lambda}^1 + \cdots + \lambda_N \widetilde{\lambda}^N)x} f(\ldots, \lambda_i, \ldots; \ldots, \widetilde{\lambda}^i, \ldots)$$

$$+ (a_\lambda^\dagger)^{N-1} a_\lambda \, e^{\frac{i}{2}(\cdots - \lambda_i \widetilde{\lambda}^i + \cdots)x} f(\ldots, \lambda_i, \ldots; \ldots, -\widetilde{\lambda}^i, \ldots) + \cdots \Big]$$

$$\lambda \lambda^\dagger = \lambda \eta^{(N,0)} \lambda^\dagger = \lambda^1 \widetilde{\lambda}_1 + \cdots + \lambda^N \widetilde{\lambda}_N$$

$$\lambda \eta^{(N-1,1)} \lambda^\dagger = \lambda^1 \widetilde{\lambda}_1 + \cdots + \lambda^{N-1} \widetilde{\lambda}_{N-1} - \lambda^N \widetilde{\lambda}_N$$

These pieces can contribute to matrix elements,

$$\langle \widetilde{\mathcal{O}}_f(p_f) | \mathcal{O}(x) | \widetilde{\mathcal{O}}_i(p_i) \rangle$$

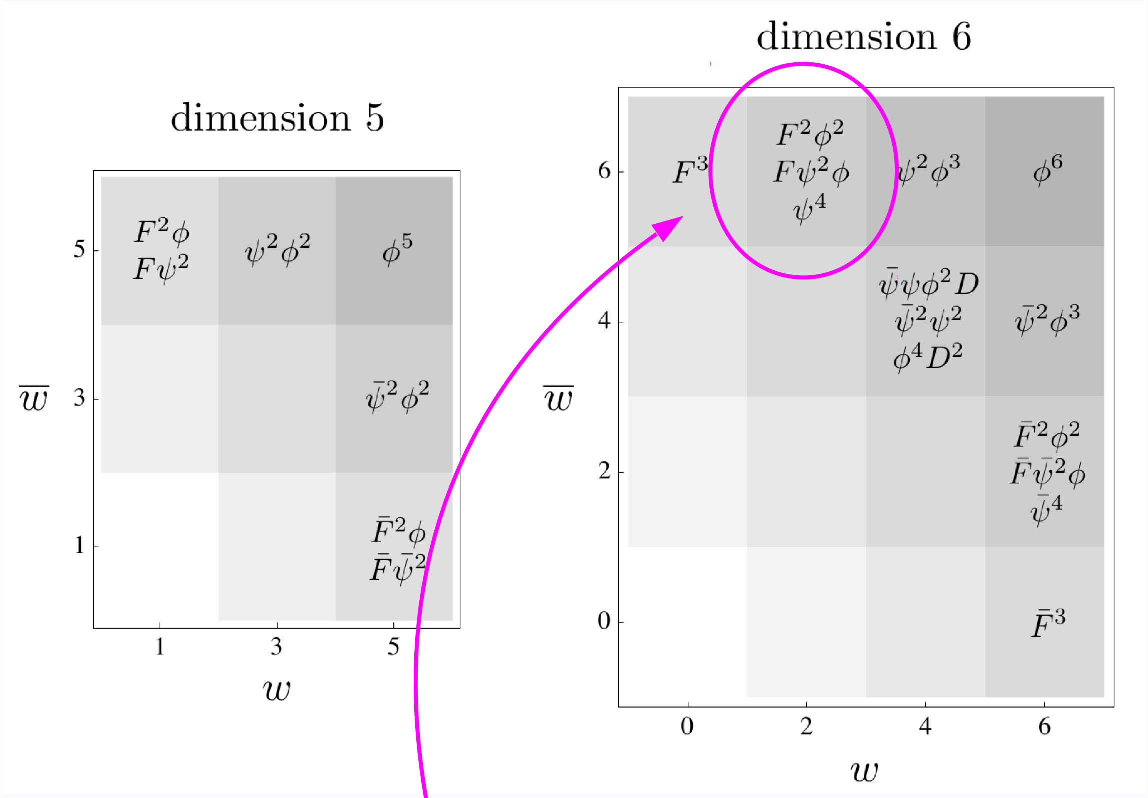
and can have non-compact behavior [e.g. U(N) → U(N-1,1)?]

→Much to study/explore

Applications

EFT non-renormalization

Alonso et. al. 1409.0868; Elias-Miró et. al. 1412.7151;
Cheung & Shen 1505.01844, Bern et. al. 1910.05831



*See also talk by M. Riembau

$$\frac{d}{d\log\mu}c_i = \frac{1}{(4\pi)^2}\sum_j \gamma_{ij}c_j$$

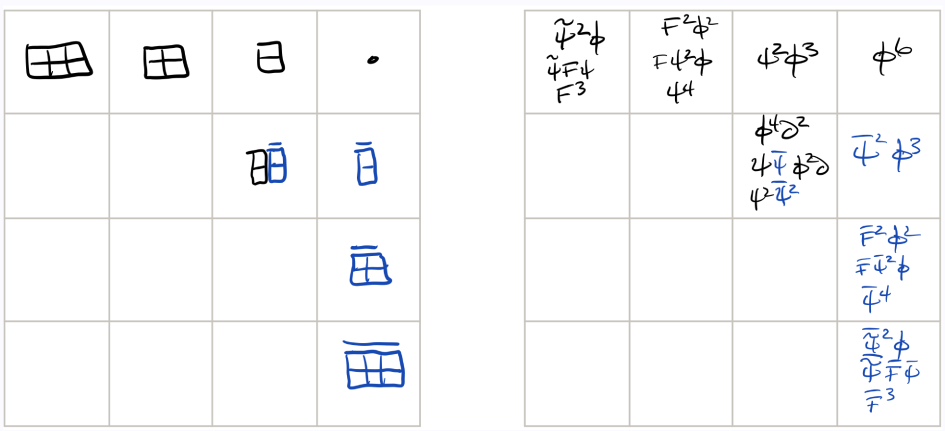
$$w(\mathcal{O}) = N(\mathcal{O}) - h(\mathcal{O})$$

$$\overline{w}(\mathcal{O}) = N(\mathcal{O}) + h(\mathcal{O})$$

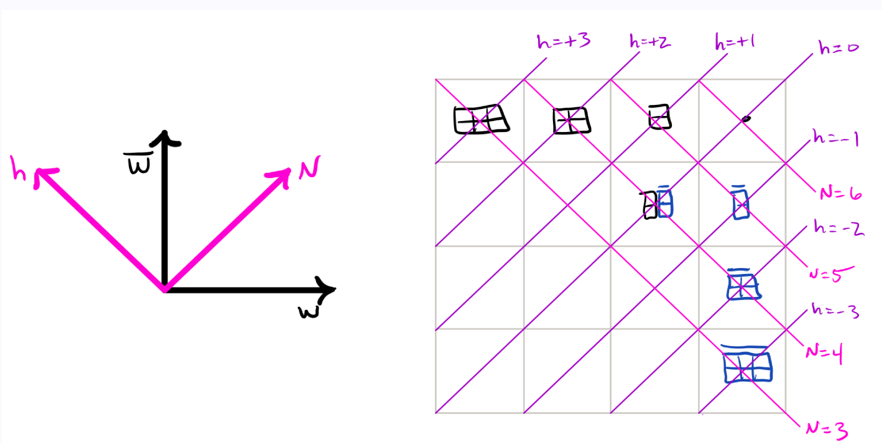
$$\gamma_{ij} = 0 \;\text{ if }\; w_i < w_j \;\text{ or }\; \overline{w}_i < \overline{w}_j$$

Families of operators belong to a given weight

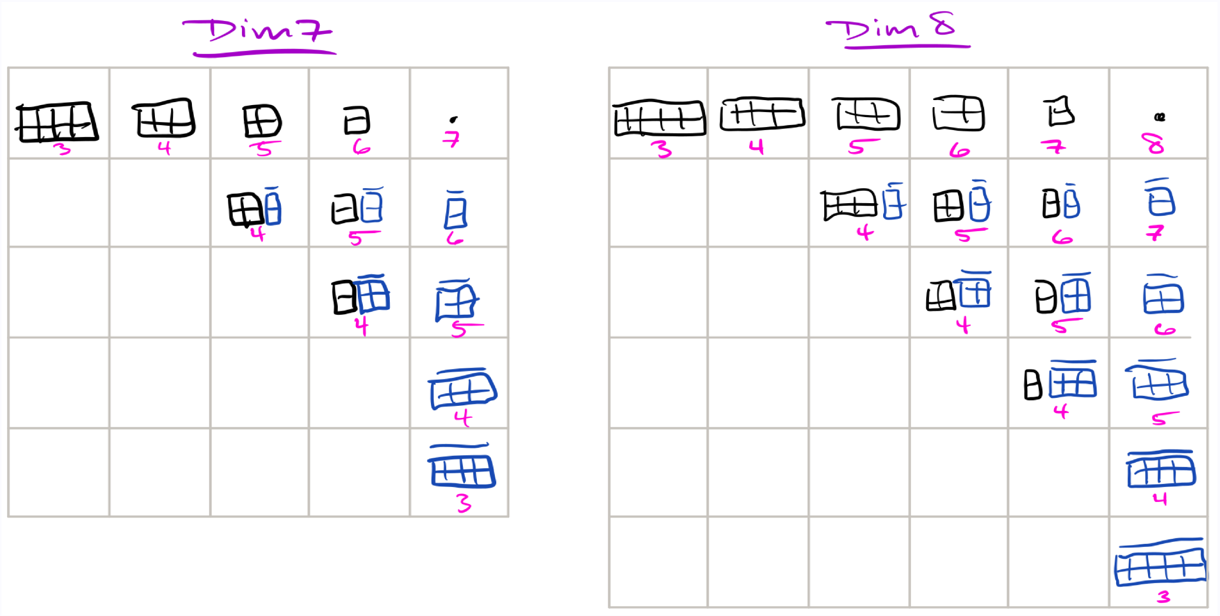
EFT non-renormalization



The families of operators belong to the same Grassmann harmonic!



EFT non-renormalization



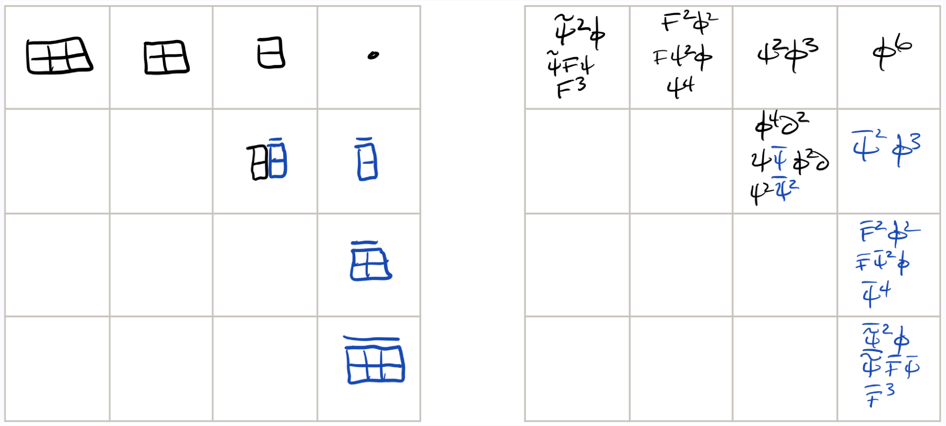
Easy to generalize to
higher mass dimension

EFT non-renorm & conf-hel duality

non-renorm from helicity selection rules

→ using the duality →

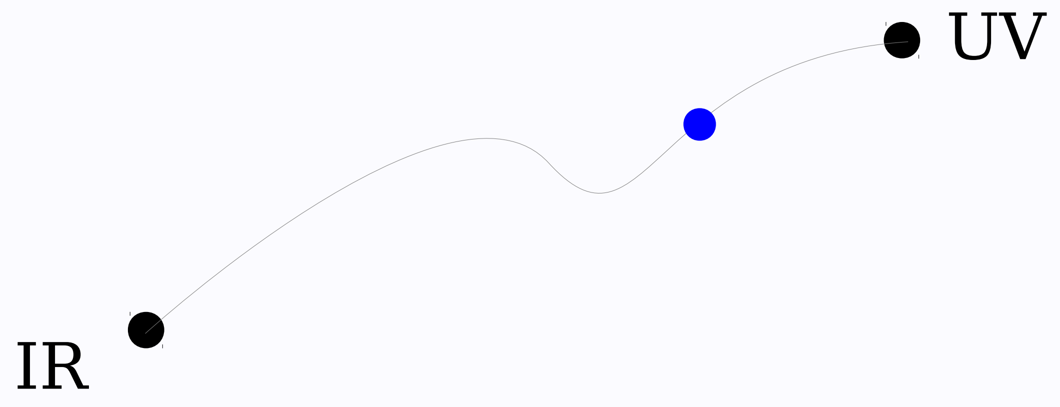
must also follow from conformal selection rules



Not just selection rules:

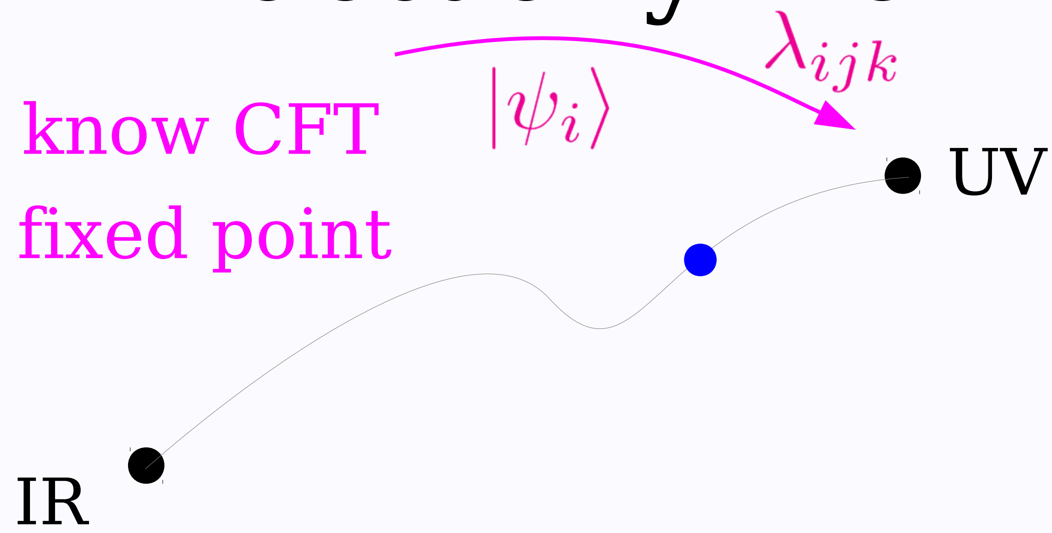
Conjecture: up to powers of marginal coupling constants, one-loop anomalous dimension matrix determined by free OPE coefficients

the dumbest idea which might actually work



the dumbest idea which might actually work

say we know CFT data at fixed point



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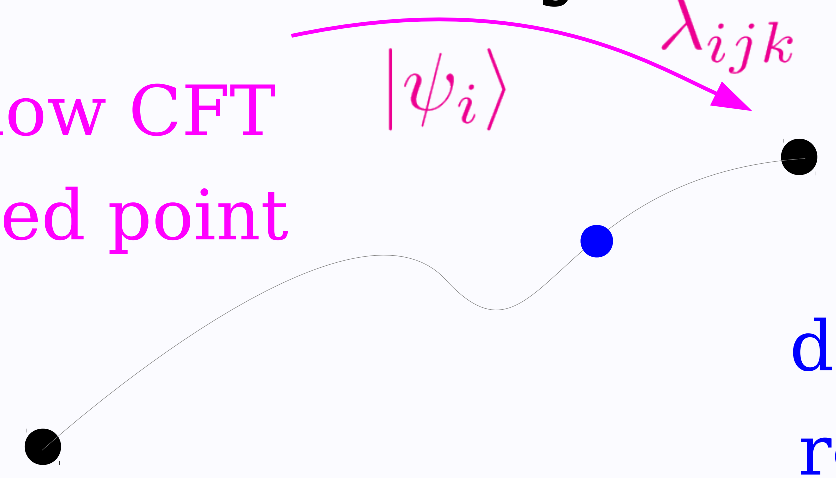
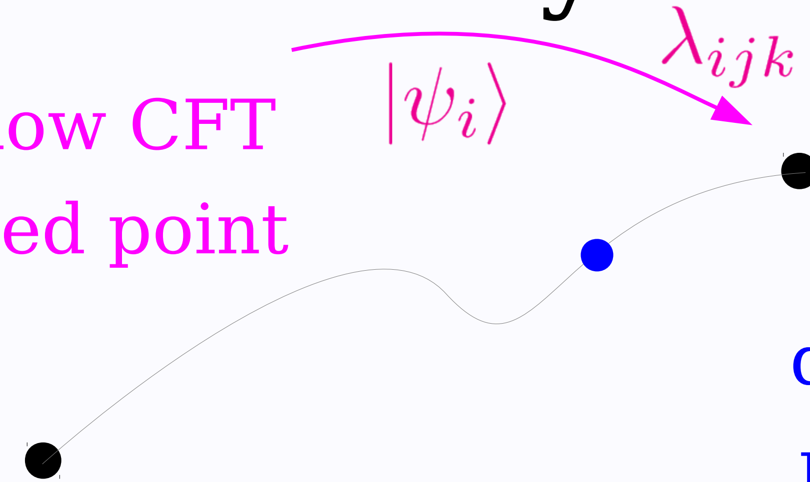


deform with some relevant operator

$$\delta H = \int d^{d-1}x \, \mathcal{O}_r(x)$$

the dumbest idea which might actually work

say we know CFT data at fixed point



deform with some relevant operator

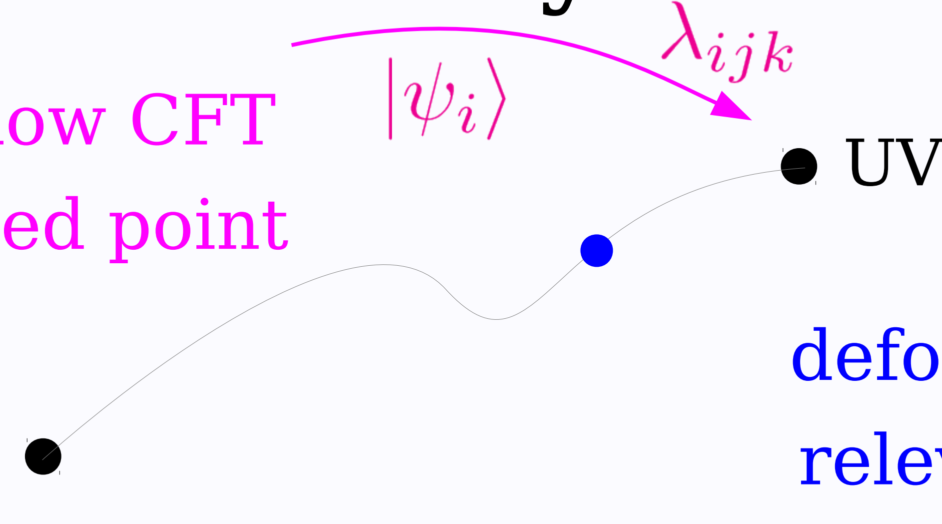
$$\delta H = \int d^{d-1}x\, \mathcal{O}_r(x)$$

$$\langle i|H_0 + \delta H|j\rangle$$

compute matrix elements

the dumbest idea which might actually work

say we know CFT data at fixed point



deform with some relevant operator

$$\delta H = \int d^{d-1}x \, \mathcal{O}_r(x)$$

$$\langle i | H_0 + \delta H | j \rangle$$

compute matrix elements

diagonalize

result approximates true spectrum

"Hamiltonian truncation"

See, e.g., Katz, Khandker, Walters arXiv:1604.01766

HT ingredients

$$\text{states } |i\rangle \quad \Rightarrow \quad |\widetilde{\mathcal{O}}(P)\rangle$$

$$\text{matrix elements } \int d^{d-1}x \, \langle i|\mathcal{O}(x)|j\rangle \quad \Rightarrow \quad \int d^{d-1}x \, \langle\widetilde{\mathcal{O}}_f(p_f)|\mathcal{O}(x)|\widetilde{\mathcal{O}}_i(p_i)\rangle$$

Many of the same ingredients that we discuss in EFT also enter in HT

Perhaps some of you, like me, could enjoy playing around with this promising, non-perturbative technique for studying quantum field theories (in Lorentzian signature, at infinite-volume)

HT…something to think about

We firmly believe HT would benefit/ needs the input of phenomenologists

The barrier of entry is a bit high, but we expect this to be significantly lowered in about 1 year

Proposal for a
Symposium Latsis EPFL 2021
on *Nonperturbative Methods in Quantum Field Theory*

Main organizer	Prof. João Penedones (FSL, EPFL)
Co-organizers	Dr. Brian Henning (UniGe) Dr. Matthew Walters (FSL, EPFL)

Inclusivity A novel aspect of our proposal is a call for, and action towards, inclusivity and diversity. The interdisciplinary nature of this topic naturally lends itself to larger scale collaboration. Coupled with the emerging status of the field, this provides an interesting opportunity to try and exploit the diversity inherent to the topic in order to increase diversity in its practitioners. A general stumbling block for engaging and bringing in new communities, however, is the universal difficulty of learning a new topic and entering a new field.

With this in mind, our plan is to provide funding for 10 participants, specifically encouraging young researchers—at any stage of familiarity with the topic—who are eager to join this research program. We will hold an application, supported by an active advertising campaign to ensure we reach a broad audience, especially underrepresented communities. The symposium format—the structured discussions, in particular—will encourage the participation of these new researchers as well as benefit from their outside perspective. We hope that these measures will not only provide an exciting opportunity for these young researchers, but also foster the positive growth of this community.

**who knows if we’ll get funding, but we’re hopeful

Summary

- A basis for the Hilbert space can be put in correspondence with a basis of operators/basis of contact terms in amplitudes
- For massless particles, a simple geometric picture involving Stiefel/Grassmann manifolds arises
  - Similar constructions work in d = 2,3 dimensions as well
- Can a similar perspective be developed for massive particles?
- We’re beginning to see useful applications to dynamics – surely many more goodies to discover!

Thank you!

Stay healthy, safe, and in solidarity during these trying times

Much love

Come to Granada they said

It will be a good time of year to visit they said