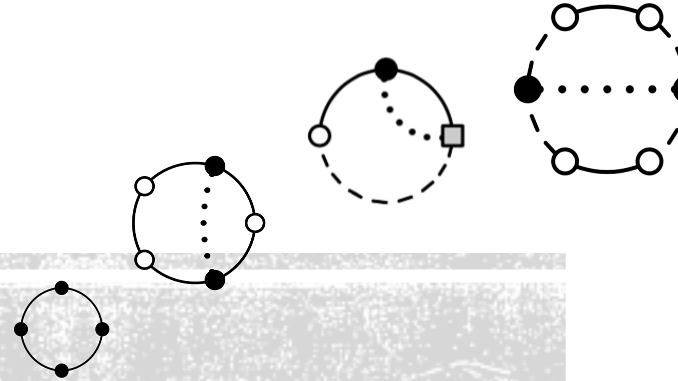

Covariant diagrams for one-loop matching

and applications in trans-TeV SUSY

Zhengkang (Kevin) Zhang (University of Michigan)

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Based on:

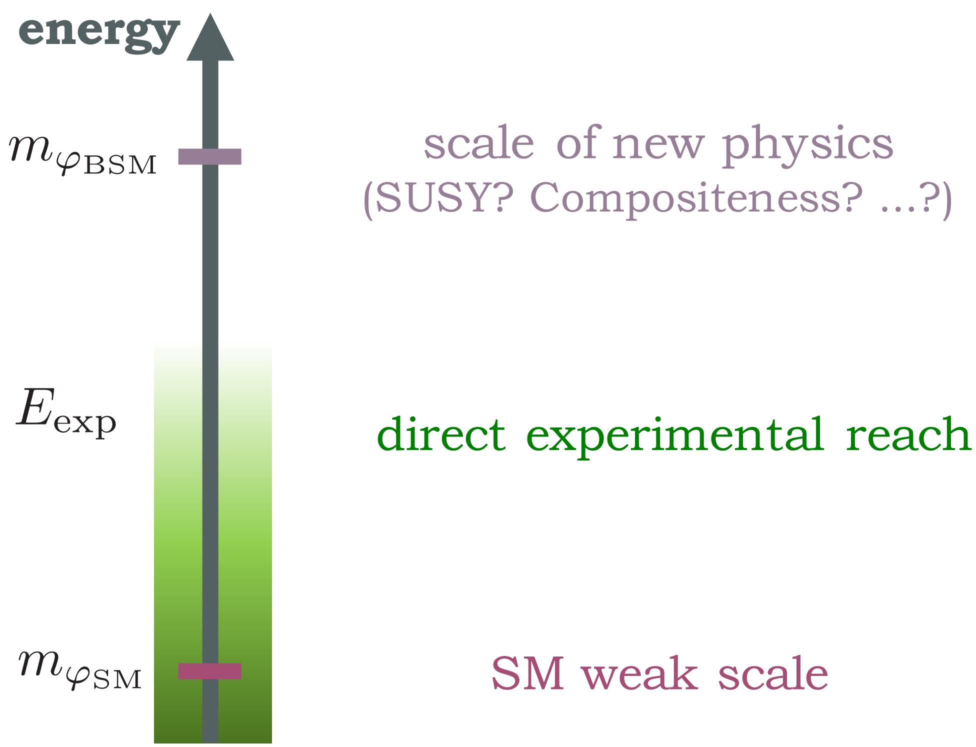
- ***ZZ [1610.00710]*** *"Covariant diagrams for one-loop matching"*
- ***J. Wells, ZZ [1711.04774]*** *"EFT approach to trans-TeV SUSY"*

See also:

- ***S. Ellis, J. Quevillon, T. You, ZZ [1604.02445, 1706.07765]***

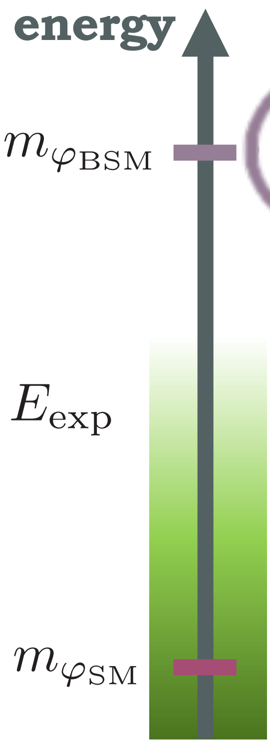
Intro: EFT matching

- New physics may be somewhat decoupled from weak scale.



Intro: EFT matching

- **Appropriate** and **convenient** framework: EFT.



this talk

$$\mathcal{L}_{\rm UV}[\varphi_{\rm BSM}, \varphi_{\rm SM}]$$

⇩ ***match*** *(UV ←→ EFT dictionary)*

$$\mathcal{L}_{\rm EFT}[\varphi_{\rm SM}] = \mathcal{L}_{\rm SM} + \sum_i c_i\, \mathcal{O}_i\ (\mu \sim m_{\varphi_H})$$

⇩ ***run*** *(resum large logs)*

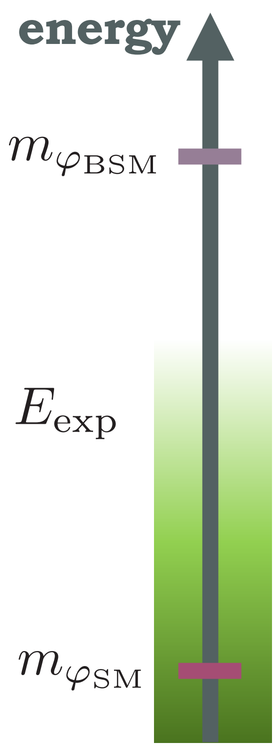
$$\mathcal{L}_{\rm EFT}[\varphi_{\rm SM}] = \mathcal{L}_{\rm SM} + \sum_i c_i\, \mathcal{O}_i\ (\mu \sim E_{\rm exp})$$

⇩ ***calculate*** *(model-independent)*

observables (cross sections, etc.)

Intro: EFT matching

- Conventional approach to matching —



$\mathcal{L}_\mathrm{UV}[\varphi_\mathrm{BSM}, \varphi_\mathrm{SM}]$ — *Feynman diagrams* → $\langle \varphi_L \varphi_L \dots \varphi_L \rangle$

$$\mathcal{L}_\mathrm{EFT}[\varphi_\mathrm{SM}] = \mathcal{L}_\mathrm{SM} + \sum_i c_i\, \mathcal{O}_i \; (\mu \sim m_{\varphi_H})$$

run *(resum large logs)*

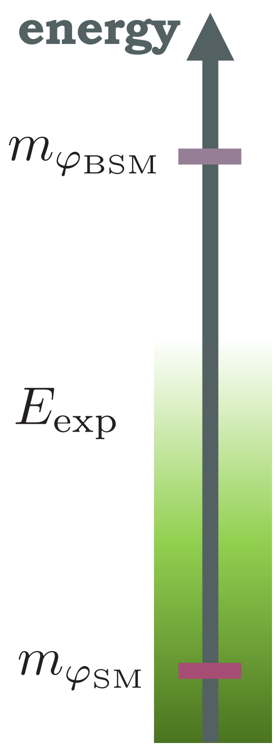
$$\mathcal{L}_\mathrm{EFT}[\varphi_\mathrm{SM}] = \mathcal{L}_\mathrm{SM} + \sum_i c_i\, \mathcal{O}_i \; (\mu \sim E_\mathrm{exp})$$

calculate *(model-independent)*

observables (cross sections, etc.)

Intro: EFT matching

- I will introduce a more **direct** and elegant approach.



$$\mathcal{L}_{\rm UV}[\varphi_{\rm BSM}, \varphi_{\rm SM}]$$

Feynman diagrams → $\langle \varphi_L \varphi_L \cdots \varphi_L \rangle$

covariant diagrams

$$\mathcal{L}_{\rm EFT}[\varphi_{\rm SM}] = \mathcal{L}_{\rm SM} + \sum_i c_i\, \mathcal{O}_i\, (\mu \sim m_{\varphi_H})$$

run *(resum large logs)*

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calculate *(model-independent)*

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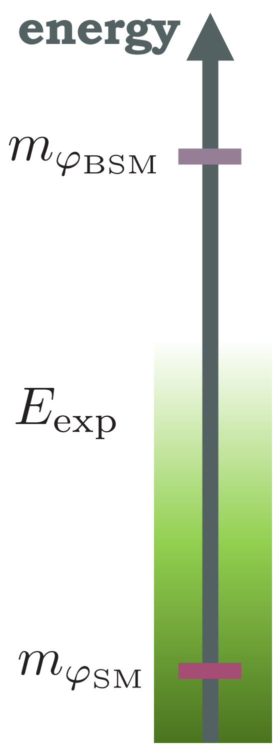

$$\mathcal{L}_{\rm UV}[\varphi_{\rm BSM}, \varphi_{\rm SM}]$$

covariant diagrams

Bonus: preserve gauge covariance

$$\mathcal{L}_{\rm EFT}[\varphi_{\rm SM}] = \mathcal{L}_{\rm SM} + \sum_i c_i\, \mathcal{O}_i\, (\mu \sim m_{\varphi_H})$$

run *(resum large logs)*

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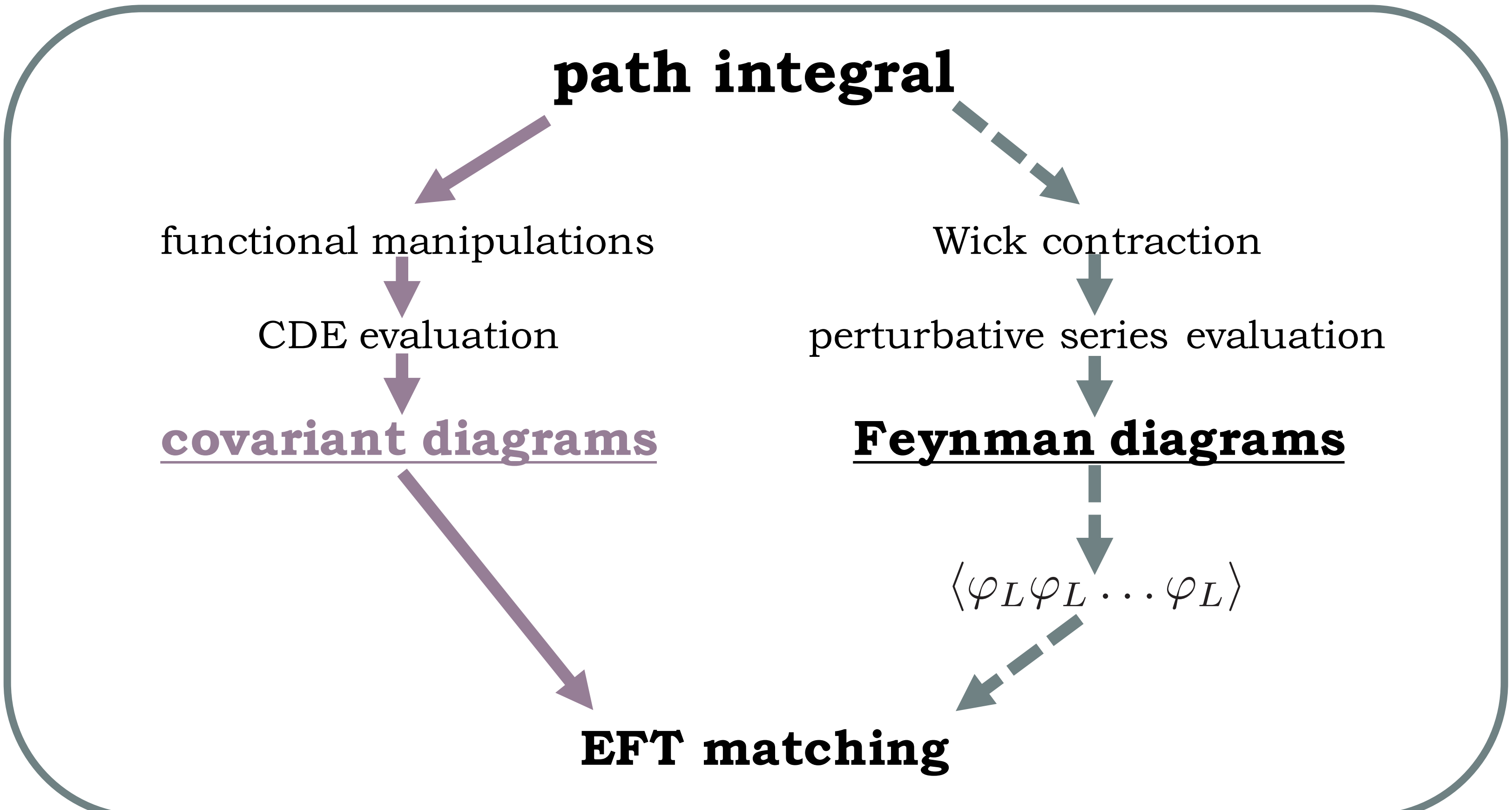
calculate *(model-independent)*

observables (cross sections, etc.)

Previous literature on correlation-function-free matching that covariant diagrams build upon

- *Gaillard [Nucl.Phys.B268,669 (1986)];* — early studies
- *Chan [Phys.Rev.Lett.57,1199 (1986)];* — early studies
- *Cheyette [Nucl.Phys.B297,183 (1988)].* — early studies
- ***Henning, Lu, Murayama [1412.1837];*** ← ***revival***
- *Chiang, Huo [1505.06334];* — application
- *Huo [1506.00840, 1509.05942];* — application
- ***Drozd, Ellis, Quevillon, You [1512.03003].*** ← *generalization*
- *Del Aguila, Kunszt, Santiago [1602.00126];* — criticism
- *Boggia, Gomez-Ambrosio, Passarino [1603.03660];* — criticism
- ***Henning, Lu, Murayama [1604.01019];*** — ***partial resolution***
- ***Ellis, Quevillon, You, ZZ [1604.02445];*** — ***partial resolution***
- ***Fuentes-Martin, Portoles, Ruiz-Femenia [1607.02142].*** ← ***simplification***

Previous literature on correlation-function-free matching that covariant diagrams build upon



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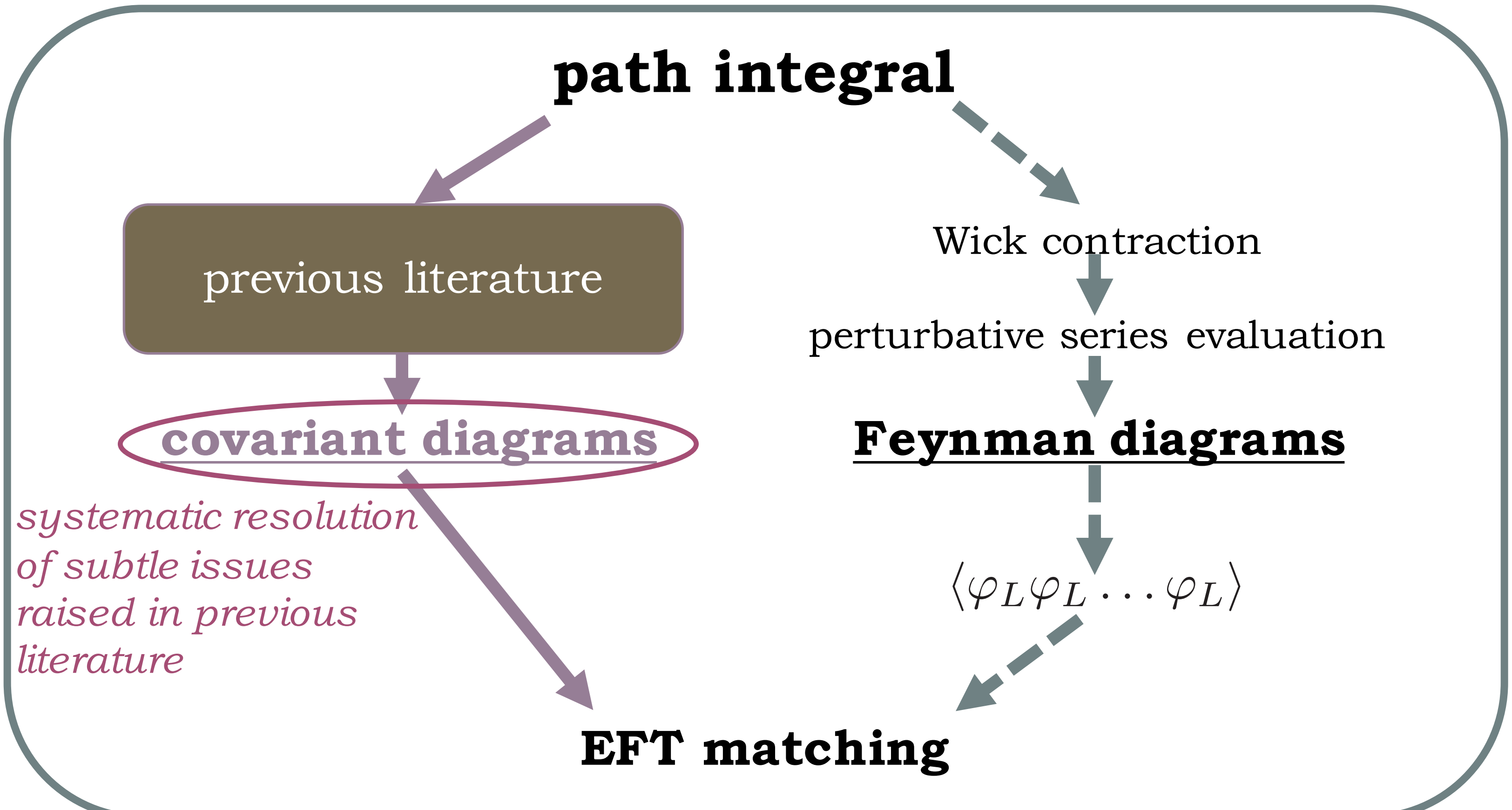
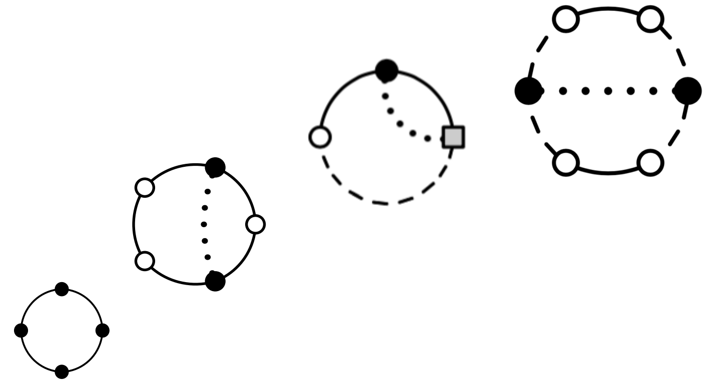


Outline



- **Preliminaries.**
  - **Path integral** at tree and one-loop levels.
- **Core techniques.**
  - **Expansion** by regions.
  - Covariant Derivative **Expansion** (CDE).
- **Covariant diagrams** (to systematically keep track of expansion)**.**
  - Basic rules with a simple example.
- **Application.**
  - Matching the MSSM onto the SMEFT.

Preliminary: path integral at tree level

$$\int [D\varphi_H][D\varphi_L]\, e^{i\int d^dx\, \mathcal{L}_{\text{UV}}[\varphi_H,\varphi_L]} = \int [D\varphi_L]\, e^{i\int d^dx\, \mathcal{L}_{\text{EFT}}[\varphi_L]}$$

- **Tree level = stationary point approximation.**
  - Solve classical equations of motion:

$$\left.\frac{\delta\mathcal{L}_{\text{UV}}}{\delta\varphi_H}\right|_{\varphi_H=\varphi_{H,\text{c}}} = 0$$

$$\Rightarrow \quad \mathcal{L}_{\text{EFT}}^{\text{tree}}[\varphi_L] = \mathcal{L}_{\text{UV}}\big[\varphi_{H,\text{c}}[\varphi_L], \varphi_L\big]$$

Preliminary: path integral at one-loop level

$$\int [D\varphi_H][D\varphi_L]\, e^{i\int d^dx\,\mathcal{L}_{\rm UV}[\varphi_H,\varphi_L]} = \int [D\varphi_L]\, e^{i\int d^dx\,\mathcal{L}_{\rm EFT}[\varphi_L]}$$

- **One-loop level = Gaussian approximation.**
  - Background field method:

$$\varphi_H = \varphi_{H,\rm b} + \varphi'_H\,,\qquad \varphi_L = \varphi_{L,\rm b} + \varphi'_L$$

$$\Rightarrow\quad \mathcal{L}_{\rm UV}[\varphi_H,\varphi_L] + J_L\varphi_L \;=\; \mathcal{L}_{\rm UV}\big[\varphi_{H,\rm c}[\varphi_{L,\rm b}],\varphi_{L,\rm b}\big] + J_L\varphi_{L,\rm b}$$

*terms **quadratic** in quantum fluctuations* →

$$-\frac{1}{2}\begin{pmatrix}\varphi_H'^T & \varphi_L'^T\end{pmatrix} \mathcal{Q}_{\rm UV}\big[\varphi_{H,\rm c}[\varphi_{L,\rm b}],\varphi_{L,\rm b}\big]\begin{pmatrix}\varphi'_H\\ \varphi'_L\end{pmatrix} + \mathcal{O}(\varphi'^3)$$

  - Path integral is *Gaussian* at this order
    => functional determinant of the **quadratic operator** $\mathcal{Q}_{\rm UV}$.

1LPI effective action vs. EFT Lagrangian

- This is what we would do if we were to compute the **1LPI effective action** (Legendre transform of the path integral):

$$\Gamma^{\text{1-loop}}_{\text{L,UV}}[\varphi_{L,\text{b}}] = i\, c_s\, \log\det \mathcal{Q}_{\text{UV}}\big[\varphi_{H,\text{c}}[\varphi_{L,\text{b}}], \varphi_{L,\text{b}}\big]$$

$$= i\, c_s\, \text{Tr} \log \mathcal{Q}_{\text{UV}} = i\, c_s \int d^d x \int \frac{d^d q}{(2\pi)^d}\, \text{tr} \log \mathcal{Q}_{\text{UV}}\big|_{P_\mu \to P_\mu - q_\mu}$$

  - c_s is spin factor (= +1/2 for real scalar, -1/2 for Weyl fermion).
  - Notation: $P_\mu \equiv i D_\mu$ ("kinetic momentum operator," hermitian).

- But we are interested in a **different** quantity:

$$\int d^d x\, \mathcal{L}^{\text{1-loop}}_{\text{EFT}}[\varphi_L] \quad \neq \quad \Gamma^{\text{1-loop}}_{\text{L,UV}}[\varphi_L]$$

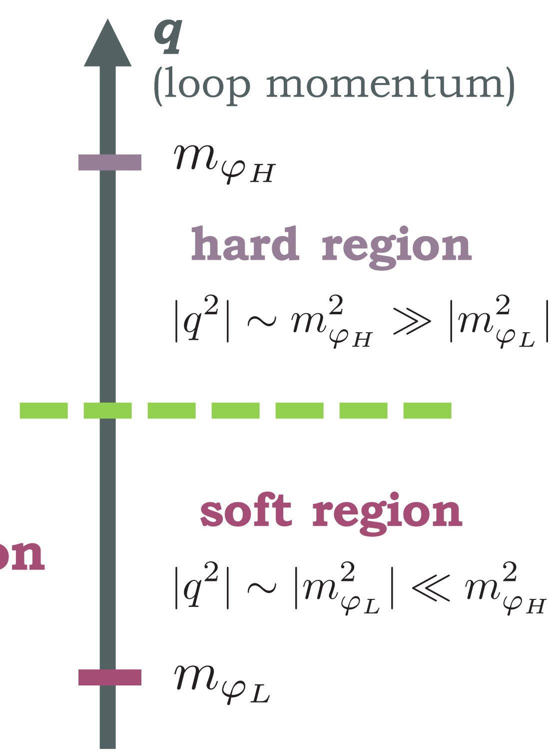
Core technique #1: expansion by regions

- After careful functional manipulations, we can show *(ZZ [1610.00710])*:

$$\int d^dx\, \mathcal{L}^{\text{1-loop}}_{\text{EFT}}[\varphi_L] = \Gamma^{\text{1-loop}}_{\text{L,UV}}[\varphi_L]\Big|_{\text{hard}}$$

  - Previously argued in *Fuentes-Martin, Portoles, Ruiz-Femenia [1607.02142]*.

- Expand integrand before integrating.
- **Full integral = hard region + soft region** contributions.
  - See e.g. *Beneke, Smirnov, hep-ph/9711391; Jantzen, 1111.2589*.



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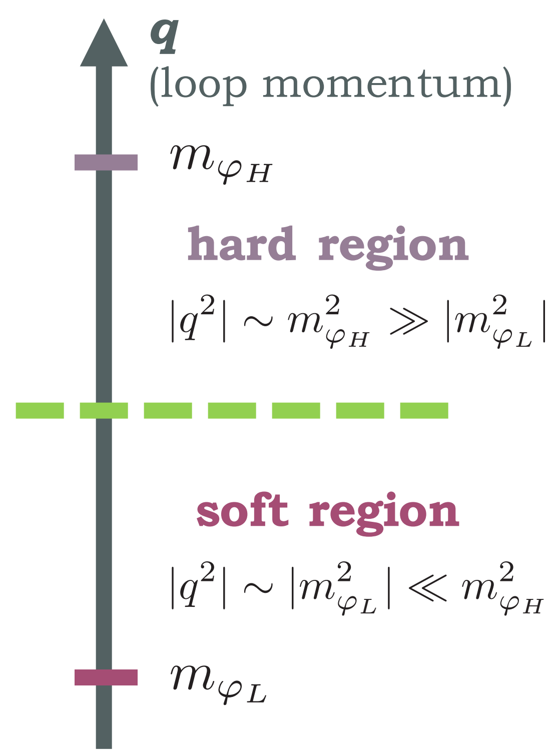
- Intuition:
  - **1PI effective actions** encode quantum fluctuations at **all scales**.
  - Extract **short-distance** fluctuations => **local** operators in **EFT Lagrangian**.



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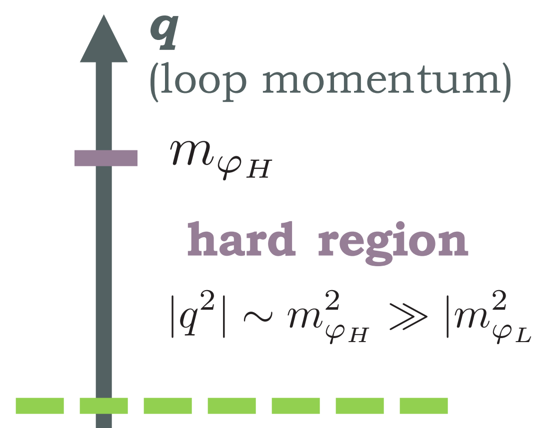

$$\mathcal{L}_{\text{EFT}}^{\text{1-loop}}[\varphi_L] = i\, c_s\, \text{tr} \int \frac{d^dq}{(2\pi)^d} \left[\log \mathcal{Q}_{\text{UV}}\big|_{P_\mu \to P_\mu - q_\mu}\right]_{\text{expand for } |q^2| \sim m_{\varphi_H}^2 \gg |m_{\varphi_L}^2|}$$

➢ Covariant diagrams keep track of this series expansion.

Core technique #2: Covariant Derivative Expansion

- CDE = expansion where derivatives are **covariant**.
  - We never separate D_μ into ∂_μ and $-igA_\mu$.

$$\mathcal{L}_{\text{EFT}}^{\text{1-loop}}[\varphi_L] = i\, c_s \,\text{tr} \int \frac{d^d q}{(2\pi)^d} \left[\log \mathcal{Q}_{\text{UV}}|_{P_\mu \to P_\mu - q_\mu} \right]_{\text{expand for } |q^2| \sim m_{\varphi_H}^2 \gg |m_{\varphi_L}^2|}$$

- General form of quadratic operator Q_{UV}:

$$\mathcal{Q}_{\text{UV}}[\varphi\,,\, P_\mu = iD_\mu\,;\, m_{\varphi_H}\,,\, m_{\varphi_L}]$$

$$= \begin{Bmatrix} -P^2 + \mathbf{M}^2 & \text{(boson)} \\ -\not{P} + \mathbf{M} & \text{(fermion)} \end{Bmatrix} + \mathbf{U}[\varphi] + P_\mu\, \mathbf{Z}^\mu[\varphi] + \mathbf{Z}^{\dagger\mu}[\varphi]\, P_\mu + \dots$$

  - Recall: $\varphi_H = \varphi_{H,\text{b}} + \varphi'_H\,, \quad \varphi_L = \varphi_{L,\text{b}} + \varphi'_L$

$$\Rightarrow \quad \mathcal{L}_{\text{UV}}^{\text{quadratic}} = -\frac{1}{2} \begin{pmatrix} \varphi'^T_H & \varphi'^T_L \end{pmatrix} \mathcal{Q}_{\text{UV}}\left[\varphi_{H,\text{c}}[\varphi_{L,\text{b}}], \varphi_{L,\text{b}}\right] \begin{pmatrix} \varphi'_H \\ \varphi'_L \end{pmatrix}$$

Core technique #2:
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$$\mathcal{L}_{\text{EFT}}^{\text{1-loop}}[\varphi_L] = i\, c_s \,\text{tr} \int \frac{d^d q}{(2\pi)^d} \Big[\log \ldots \quad {}_{H} \gg |m^2_{\varphi_L}|$$

Example: real singlet scalar S coupling to SM Higgs H

$$\mathbf{U} = \begin{pmatrix} U_{SS} & U_{SH} & \cdots \\ U_{HS} & U_{HH} & \cdots \\ \cdots & \cdots & \cdots \end{pmatrix}$$

- General form of quadrati

$$\mathcal{Q}_{\text{UV}}[\varphi\,,\, P_\mu = iD_\mu\,;\, m_{\varphi_H}\,,\, m_{\varphi_L}]$$

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$$\mathcal{L}_{\text{EFT}}^{\text{1-loop}}[\varphi_L] = i\, c_s \,\text{tr} \int \frac{d^d q}{(2\pi)^d} \left[\log \mathcal{Q}_{\text{UV}}|_{P_\mu \to P_\mu - q_\mu} \right]_{\text{expand for } |q^2| \sim m_{\varphi_H}^2 \gg |m_{\varphi_L}^2|}$$

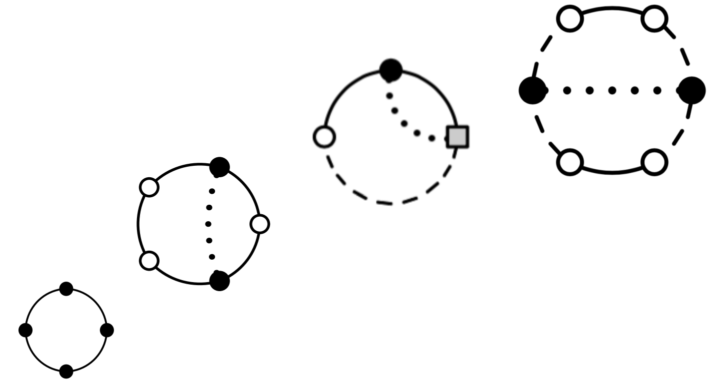
- General form of quadratic operator Q_{UV}:

$$\mathcal{Q}_{\text{UV}}[\varphi, P_\mu = iD_\mu; m_{\varphi_H}, m_{\varphi_L}] = \begin{cases} -P^2 + \mathbf{M}^2 & \text{(boson)} \\ -\not{P} + \mathbf{M} & \text{(fermion)} \end{cases} + \mathbf{U}[\varphi] + P_\mu \mathbf{Z}^\mu[\varphi] + \mathbf{Z}^{\dagger\mu}[\varphi] P_\mu + \dots$$

- Result of expansion: **operators** made of fields φ and **covariant** derivatives $P_\mu \equiv iD_\mu$ (rather than correlation functions)

  => automatically **gauge-invariant**!

Covariant diagrams
(to keep track of CDE)



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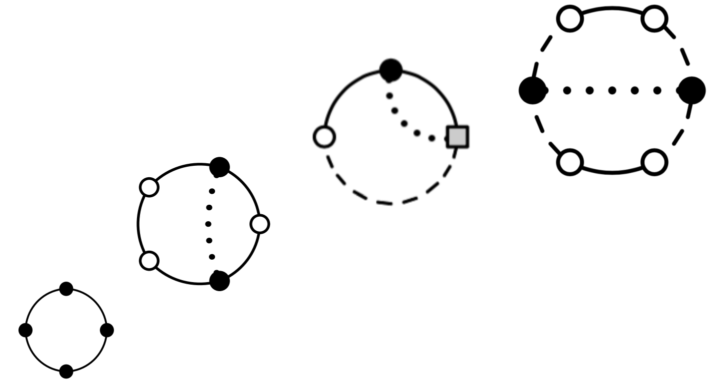
- Collect identical terms, and encode in diagrams.
- Enumerate diagrams ➔ recover the full expansion.
- Rules can be derived from the general form of Q_{UV} (UV model-independent).

Covariant diagrams
(to keep track of CDE)



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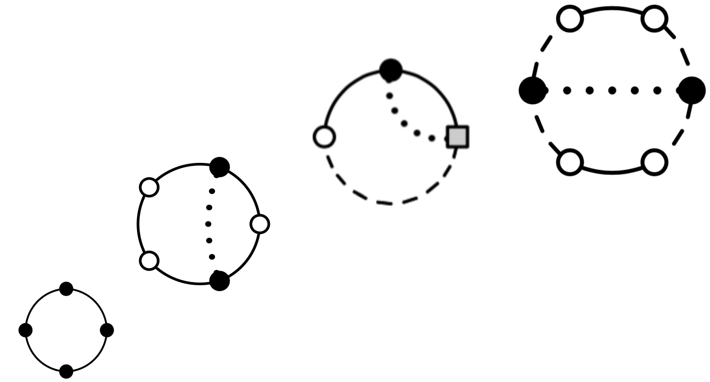
Building blocks	Bosonic	Fermionic
Propagators	i $= 1$	i $= \begin{cases} M_i & \text{(heavy)} \\ 0 & \text{(light)} \end{cases}$ i $= -\gamma_\mu$
P insertions	i i $= 2P_\mu$	i i $= -\not{P}$
U insertions	i j , i j , i j , i j $= U_{ij}[\varphi]$	
Contractions	μ ...... ν $= g^{\mu\nu}$	

Analogously, there are also Z insertions

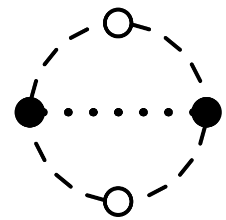
Covariant diagrams
(to keep track of CDE)



- Example: real singlet scalar

  Recall $\mathcal{L}_{\text{UV}} \supset -\frac{1}{2}\lambda_{HS}|H|^2 S^2$

  $\Rightarrow \quad U_{SS} \supset \lambda_{HS}|H|^2$



$\propto \operatorname{tr}(2P^\mu \cdot U_{SS} \cdot 2P_\mu \cdot U_{SS})$

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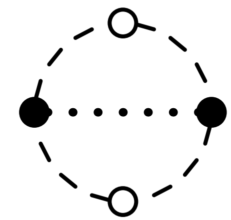


$\propto \text{tr}(2P^\mu \cdot U_{SS} \cdot 2P_\mu \cdot U_{SS})$

- **Prefactor rule:** $-ic_s \cdot \frac{1}{S} \cdot \mathcal{I}[q^{2n_c}]^{n_i n_j \dots}_{ij\dots}$

Spin factor c_s	1/2 for each real scalar/vector, -1/2 for each Weyl fermion
Symmetry factor *1/S*	if diagram has Z_S symmetry
Master integral $\mathcal{I}[q^{2n_c}]^{n_i n_j \dots}_{ij\dots}$	n_i propagators with mass M_i n_c Lorentz contractions

$c_s = 1/2$

$S = 2$

$n_i = 4$

$n_c = 1$

Covariant diagrams

(to keep track of CDE)

- Examp
  Reca

Defined by $\int \frac{d^dq}{(2\pi)^d} \frac{q^{\mu_1}\cdots q^{\mu_{2n_c}}}{(q^2-M_i^2)^{n_i}(q^2-M_j^2)^{n_j}\cdots} \equiv g^{\mu_1\ldots\mu_{2n_c}}\,\mathcal{I}[q^{2n_c}]^{n_in_j\ldots}_{ij\ldots}$

$\tilde{\mathcal{I}}[q^{2n_c}]^{n_i}_i$	$n_c=0$	$n_c=1$	$n_c=2$	$n_c=3$
$n_i=1$	$M_i^2\left(1-\log\frac{M_i^2}{\mu^2}\right)$	$\frac{M_i^4}{4}\left(\frac{3}{2}-\log\frac{M_i^2}{\mu^2}\right)$	$\frac{M_i^6}{24}\left(\frac{11}{6}-\log\frac{M_i^2}{\mu^2}\right)$	$\frac{M_i^8}{192}\left(\frac{25}{12}-\log\frac{M_i^2}{\mu^2}\right)$
$n_i=2$	$-\log\frac{M_i^2}{\mu^2}$	$\frac{M_i^2}{2}\left(1-\log\frac{M_i^2}{\mu^2}\right)$	$\frac{M_i^4}{8}\left(\frac{3}{2}-\log\frac{M_i^2}{\mu^2}\right)$	$\frac{M_i^6}{48}\left(\frac{11}{6}-\log\frac{M_i^2}{\mu^2}\right)$
$n_i=3$	$-\frac{1}{2M_i^2}$	$-\frac{1}{4}\log\frac{M_i^2}{\mu^2}$	$\frac{M_i^2}{8}\left(1-\log\frac{M_i^2}{\mu^2}\right)$	$\frac{M_i^4}{32}\left(\frac{3}{2}-\log\frac{M_i^2}{\mu^2}\right)$
$n_i=4$	$\frac{1}{6M_i^4}$	$-\frac{1}{12M_i^2}$	$-\frac{1}{24}\log\frac{M_i^2}{\mu^2}$	$\frac{M_i^2}{48}\left(1-\log\frac{M_i^2}{\mu^2}\right)$
$n_i=5$	$-\frac{1}{12M_i^6}$	$\frac{1}{48M_i^4}$	$-\frac{1}{96M_i^2}$	$-\frac{1}{192}\log\frac{M_i^2}{\mu^2}$
$n_i=6$	$\frac{1}{20M_i^8}$	$-\frac{1}{120M_i^6}$	$\frac{1}{480M_i^4}$	$-\frac{1}{960M_i^2}$

Table 7. Commonly-used degenerate master integrals $\tilde{\mathcal{I}}[q^{2n_c}]^{n_i}_i \equiv \mathcal{I}[q^{2n_c}]^{n_i}_i/\frac{i}{16\pi^2}$, with $\frac{2}{\bar\epsilon}=\frac{2}{\epsilon}-\gamma+\log 4\pi$ dropped. All nondegenerate (including mixed heavy-light) master integrals can be reduced to degenerate master integrals by Eq. (A.2).

- **Prefacto**

Spin fact	
Symmetry	
Master integral $\mathcal{I}[q^{2n_c}]^{n_in_j\ldots}_{ij\ldots}$	n_i propagators with mass M_i n_c Lorentz contractions

$n_i = 4$
$n_c = 1$

Covariant diagrams
(to keep track of CDE)

➢ Examp

Reca

- **Prefacto**

Defined by $\int \frac{d^dq}{(2\pi)^d} \frac{q^{\mu_1}\cdots q^{\mu_{2n_c}}}{(q^2-M_i^2)^{n_i}(q^2-M_j^2)^{n_j}\cdots} \equiv g^{\mu_1\cdots\mu_{2n_c}}\,\mathcal{I}[q^{2n_c}]_{ij\ldots}^{n_in_j\ldots}$

$\tilde{\mathcal{I}}[q^{2n_c}]_i^{n_i}$	$n_c=0$	$n_c=1$	$n_c=2$	$n_c=3$
$n_i=1$	$M_i^2\left(1-\log\frac{M_i^2}{\mu^2}\right)$	$\frac{M_i^4}{4}\left(\frac{3}{2}-\log\frac{M_i^2}{\mu^2}\right)$	$\frac{M_i^6}{24}\left(\frac{11}{6}-\log\frac{M_i^2}{\mu^2}\right)$	$\frac{M_i^8}{192}\left(\frac{25}{12}-\log\frac{M_i^2}{\mu^2}\right)$
$n_i=2$	$-\log\frac{M_i^2}{\mu^2}$	$\frac{M_i^2}{2}\left(1-\log\frac{M_i^2}{\mu^2}\right)$	$\frac{M_i^4}{8}\left(\frac{3}{2}-\log\frac{M_i^2}{\mu^2}\right)$	$\frac{M_i^6}{48}\left(\frac{11}{6}-\log\frac{M_i^2}{\mu^2}\right)$
$n_i=3$	$-\frac{1}{2M_i^2}$	$-\frac{1}{4}\log\frac{M_i^2}{\mu^2}$	$\frac{M_i^2}{8}\left(1-\log\frac{M_i^2}{\mu^2}\right)$	$\frac{M_i^4}{32}\left(\frac{3}{2}-\log\frac{M_i^2}{\mu^2}\right)$
$n_i=4$	$\frac{1}{6M_i^4}$	$-\frac{1}{12M_i^2}$	$-\frac{1}{24}\log\frac{M_i^2}{\mu^2}$	$\frac{M_i^2}{48}\left(1-\log\frac{M_i^2}{\mu^2}\right)$
$n_i=5$	$-\frac{1}{12M_i^6}$	$\frac{1}{48M_i^4}$	$-\frac{1}{96M_i^2}$	$-\frac{1}{192}\log\frac{M_i^2}{\mu^2}$
$n_i=6$	$\frac{1}{20M_i^8}$	$-\frac{1}{120M_i^6}$	$\frac{1}{480M_i^4}$	$-\frac{1}{960M_i^2}$

Table 7. Commonly-used degenerate master integrals $\tilde{\mathcal{I}}[q^{2n_c}]_i^{n_i} \equiv \mathcal{I}[q^{2n_c}]_i^{n_i}/\frac{i}{16\pi^2}$, with $\frac{2}{\bar\epsilon} = \frac{2}{\epsilon} - \gamma + \log 4\pi$ dropped. All nondegenerate (including mixed heavy-light) master integrals can be reduced to degenerate master integrals by Eq. (A.2).

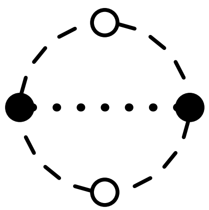
Spin fact	
Symmetry	
Master integral $\mathcal{I}[q^{2n_c}]_{ij\ldots}^{n_in_j\ldots}$	n_i propagators with mass M_i n_c Lorentz contractions

$n_i = 4$

$n_c = 1$

Covariant diagrams
(to keep track of CDE)

- Now let's put the pieces together —



$$= -\frac{i}{2}\cdot\frac{1}{2}\cdot\mathcal{I}[q^2]_i^4\cdot\mathrm{tr}(2P^\mu\cdot U_{SS}\cdot 2P_\mu\cdot U_{SS}) = -\frac{\lambda_{HS}^2}{192\pi^2 M_S^2}\,\mathrm{tr}(P^\mu|H|^2 P_\mu|H|^2)$$

- This is part of

$$\begin{aligned}(\partial_\mu|H|^2)^2 &= [D^\mu,|H|^2][D_\mu,|H|^2] = -[P^\mu,|H|^2][P_\mu,|H|^2]\\ &= 2\,\mathrm{tr}(P^2|H|^4) - 2\,\mathrm{tr}(P^\mu|H|^2P_\mu|H|^2)\end{aligned}$$

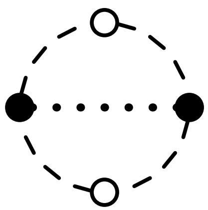
- In fact, this is the only $\mathcal{O}(\lambda_{HS}^2)$ contribution to the 2nd term.

$$\Rightarrow \boxed{\mathcal{L}_{\text{eff}} \supset \frac{\lambda_{HS}^2}{384\pi^2 M_S^2}(\partial_\mu|H|^2)^2}$$

(a one-loop-generated dim-6 operator that modifies Higgs couplings)

Covariant diagrams
(to keep track of CDE)

- Now let's put the pieces together —



$$= -\frac{i}{2}\cdot\frac{1}{2}\cdot\mathcal{I}[q^2]_i^4\cdot \mathrm{tr}(2P^\mu\cdot U_{SS}\cdot 2P_\mu\cdot U_{SS}) = -\frac{\lambda_{HS}^2}{192\pi^2 M_S^2}\,\mathrm{tr}(P^\mu|H|^2P_\mu|H|^2)$$

- This is part of

$$\begin{aligned}(\partial_\mu|H|^2)^2 &= [D^\mu,|H|^2][D_\mu,|H|^2] = -[P^\mu,|H|^2][P_\mu,|H|^2]\\ &= 2\,\mathrm{tr}(P^2|H|^4) - 2\,\mathrm{tr}(P^\mu|H|^2P_\mu|H|^2)\end{aligned}$$

Aside: 1$^{\text{st}}$ term comes from other terms in the CDE.

- **Additional rule:** we only need to compute covariant diagrams where no Lorentz contraction is between adjacent P's — those are sufficient to fix all independent EFT operator coefficients.

Application: MSSM → SMEFT

- Weak-scale SUSY, a leading solution to the hierarchy problem, is falling out of favor due to:
  - Lack of superpartner discovery at the LHC
  - Measurement of m_h=125GeV
- However, dismissing traditional naturalness concerns, **trans-TeV SUSY** still has attractive features:
  - Gauge coupling unification
  - Yukawa coupling unification
  - Dark matter candidate
- EFT treatment is warranted.

Application: MSSM → SMEFT

d≤4 operators & threshold corrections

- SM couplings (gauge, Yukawa, ...) are numerically different above and below SUSY threshold.

$$\int [D\varphi_{\rm BSM}][D\varphi_{\rm SM}]\, e^{i\int d^dx\, \mathcal{L}[\varphi_{\rm BSM},\varphi_{\rm SM}]} = \int [D\varphi_{\rm SM}]\, e^{i\int d^dx\, \mathcal{L}_{\rm SMEFT}[\varphi_{\rm SM}]}$$

$$\begin{aligned}\mathcal{L}_{\rm SMEFT} \;=\; & \mathcal{L}_{\rm SM} + \delta Z_\phi |D_\mu\phi|^2 + \sum_{f=q,u,d,l,e} \bar{f}\,\boldsymbol{\delta Z_f}\, i\not{D} f - \frac{1}{4}\delta Z_G G^A_{\mu\nu}G^{A\mu\nu} - \frac{1}{4}\delta Z_W W^I_{\mu\nu}W^{I\mu\nu} - \frac{1}{4}\delta Z_B B_{\mu\nu}B^{\mu\nu} \\ & + \delta m^2 |\phi|^2 + \delta\lambda |\phi|^4 + \left(\bar{u}\,\boldsymbol{\delta y_u}\, q\cdot\epsilon\cdot\phi + \bar{d}\,\boldsymbol{\delta y_d}\, q\cdot\phi^* + \bar{e}\,\boldsymbol{\delta y_e}\, l\cdot\phi^* + \text{h.c.}\right) + \text{dimension 6} \ldots\end{aligned}$$

$$g_3 - g_3^{\rm eff} = \frac{1}{2}\, g_3\, \delta Z_G, \quad g_2 - g_2^{\rm eff} = \frac{1}{2}\, g_2\, \delta Z_W, \quad g_1 - g_1^{\rm eff} = \frac{1}{2}\, g_1\, \delta Z_B,$$

$$m^2 - m^2_{\rm eff} = \delta m^2 + m^2\, \delta Z_\phi, \quad \lambda - \lambda_{\rm eff} = \delta\lambda + 2\,\lambda\, \delta Z_\phi,$$

$$\boldsymbol{y_u} - \boldsymbol{y_u}^{\rm eff} = \boldsymbol{\delta y_u} + \frac{1}{2}\left(\boldsymbol{y_u}\,\boldsymbol{\delta Z_q} + \boldsymbol{\delta Z_u}\,\boldsymbol{y_u} + \boldsymbol{y_u}\,\delta Z_\phi\right),$$

$$\boldsymbol{y_d} - \boldsymbol{y_d}^{\rm eff} = \boldsymbol{\delta y_d} + \frac{1}{2}\left(\boldsymbol{y_d}\,\boldsymbol{\delta Z_q} + \boldsymbol{\delta Z_d}\,\boldsymbol{y_d} + \boldsymbol{y_d}\,\delta Z_\phi\right),$$

$$\boldsymbol{y_e} - \boldsymbol{y_e}^{\rm eff} = \boldsymbol{\delta y_e} + \frac{1}{2}\left(\boldsymbol{y_e}\,\boldsymbol{\delta Z_l} + \boldsymbol{\delta Z_e}\,\boldsymbol{y_e} + \boldsymbol{y_e}\,\delta Z_\phi\right).$$

Application: MSSM → SMEFT

d≤4 operators & threshold corrections

- SM couplings (gauge, Yukawa, ...) are numerically different above and below SUSY threshold.

- SUSY threshold corrections are important for —
  - Consistent matching of the Higgs quartic
  - Bottom-tau Yukawa unification

$$g_3 - g_3^{\text{eff}} = \frac{1}{2}\, g_3\, \delta Z_G, \quad g_2 - g_2^{\text{eff}} = \frac{1}{2}\, g_2\, \delta Z_W, \quad g_1 - g_1^{\text{eff}} = \frac{1}{2}\, g_1\, \delta Z_B,$$

$$m^2 - m_{\text{eff}}^2 = \delta m^2 + m^2\, \delta Z_\phi, \quad \lambda - \lambda_{\text{eff}} = \delta\lambda + 2\,\lambda\, \delta Z_\phi,$$

$$\boldsymbol{y_u} - \boldsymbol{y_u^{\text{eff}}} = \boldsymbol{\delta y_u} + \frac{1}{2}\left(\boldsymbol{y_u}\, \boldsymbol{\delta Z_q} + \boldsymbol{\delta Z_u}\, \boldsymbol{y_u} + \boldsymbol{y_u}\, \delta Z_\phi\right),$$

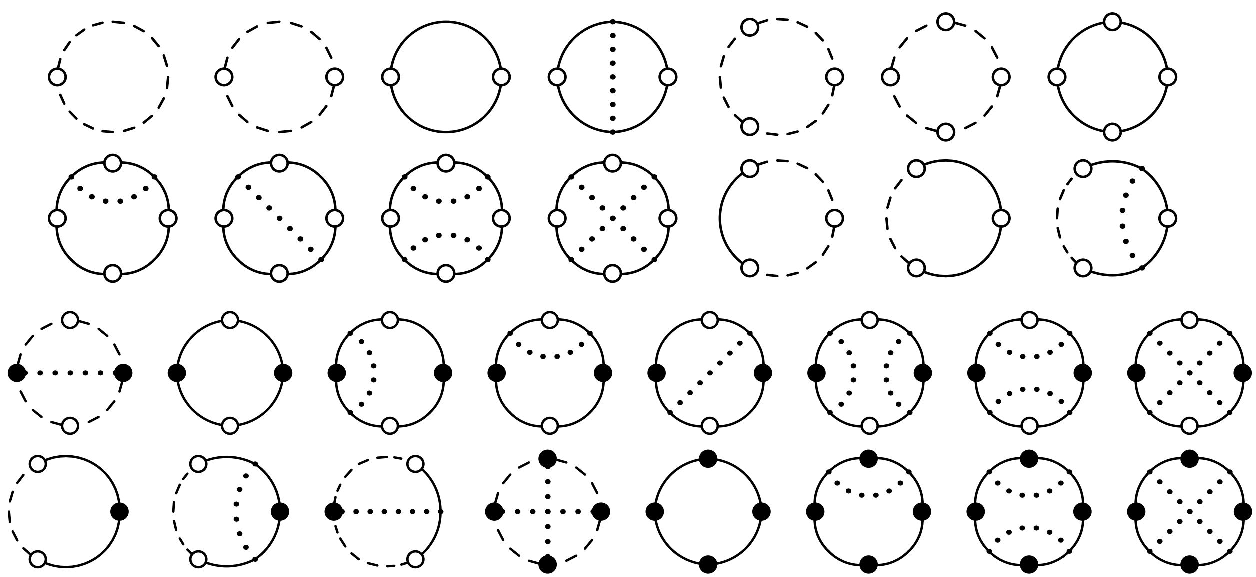
$$\boldsymbol{y_d} - \boldsymbol{y_d^{\text{eff}}} = \boldsymbol{\delta y_d} + \frac{1}{2}\left(\boldsymbol{y_d}\, \boldsymbol{\delta Z_q} + \boldsymbol{\delta Z_d}\, \boldsymbol{y_d} + \boldsymbol{y_d}\, \delta Z_\phi\right),$$

$$\boldsymbol{y_e} - \boldsymbol{y_e^{\text{eff}}} = \boldsymbol{\delta y_e} + \frac{1}{2}\left(\boldsymbol{y_e}\, \boldsymbol{\delta Z_l} + \boldsymbol{\delta Z_e}\, \boldsymbol{y_e} + \boldsymbol{y_e}\, \delta Z_\phi\right).$$

Application: MSSM → SMEFT

d≤4 operators & threshold corrections

- **Just 30** covariant diagrams => full 1-loop SUSY threshold corrections in the MSSM.
  - Full agreement with (much more involved) Feynman diagram calculation in *Bagger, Matchev, Pierce, Zhang [hep-ph/9606211]*.



Application: MSSM → SMEFT

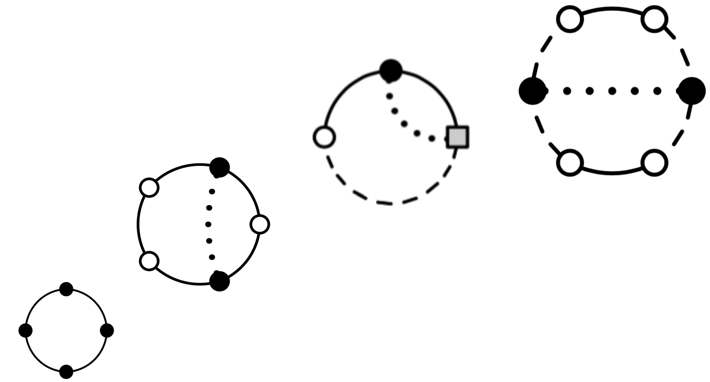
d=6 operators & Higgs couplings

- The matching calculation can be extended to dim-6.
- d>4 operators lead to observable deviations from the SM.
  - Generically small for one-loop generated operators, but there can be parametric enhancement.
  - Example: *hbb* coupling shift due to $\mathcal{L}_{(d=6)} \supset |\phi|^2 \, (\bar{\psi}_q \, \boldsymbol{C_{d\phi}} \, \psi_d) \cdot \phi$

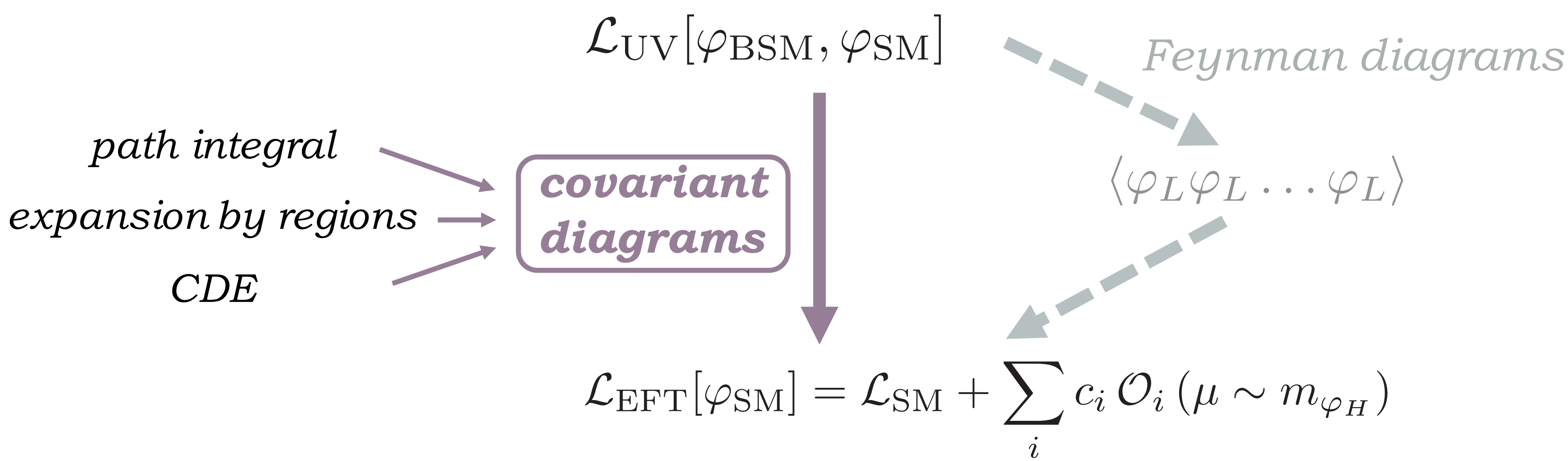
$$C_{b\phi} \simeq -\frac{y_b}{2M_\Phi^2}\left[(g^2+g'^2) - \frac{\tan\beta}{16\pi^2}\, y_t^4 \left(\frac{\mu}{M_s}\right) x_t(x_t^2-6)\right]$$

  - One-loop matching contribution can be enhanced for large tanβ, and can dominate over tree-level contribution.
- Heavy sfermions and gauginos out of reach of direct search can lead to sizable *hbb* coupling deviation.

Summary

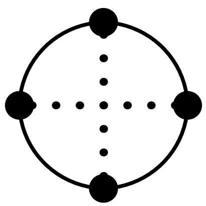


- Covariant diagrams: a systematic diagrammatic representation of functional approaches to one-loop matching, which
  - avoids the detour of computing correlation functions;
  - preserves gauge covariance;
  - can make EFT matching calculations easier.



Backup

- Another example —



$$= -i \cdot \frac{1}{4} \cdot \mathcal{I}[q^4]_i^4 \cdot \mathrm{tr}(2P^\mu \cdot 2P^\nu \cdot 2P_\mu \cdot 2P_\nu)$$

$$= -\frac{1}{96\pi^2} \log \frac{M_i^2}{\mu^2} \boxed{\mathrm{tr}(P^\mu P^\nu P_\mu P_\nu)}$$

- This is part of

$$\begin{aligned} g^2\, \mathrm{tr}(G^{\mu\nu}G_{\mu\nu}) &= -\mathrm{tr}([D^\mu, D^\nu][D_\mu, D_\nu]) = -\mathrm{tr}([P^\mu, P^\nu][P_\mu, P_\nu]) \\ &= 2\,\mathrm{tr}(P^2 P^2) - 2\boxed{\mathrm{tr}(P^\mu P^\nu P_\mu P_\nu)} \end{aligned}$$

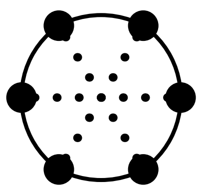
- In fact, this is the only possible contribution to the 2nd term.

$$\Rightarrow \boxed{\mathcal{L}_{\text{eff}} \supset -\frac{g^2}{48\pi^2} \log \frac{M_i^2}{\mu^2} \left[-\frac{1}{4}\mathrm{tr}(G^{\mu\nu}G_{\mu\nu})\right]} \quad \Rightarrow \quad \frac{g_{\text{eff}}^2(\mu)}{g^2(\mu)} = 1 + \frac{g^2}{48\pi^2} T(R_i) \log \frac{M_i^2}{\mu^2}$$

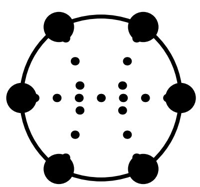
Dynkin index

Backup

- Similarly, we can compute **dim-6 pure-gauge operators**.
  - Need covariant diagrams with **6 *P* insertions**.
  - 2 ways of Lorentz contraction => **2 independent operators**.



$$= -i\,\frac{1}{6}\,\mathcal{I}[q^6]_i^6 \cdot 2^6\,\mathrm{tr}(P^\mu P^\nu P^\rho P_\mu P_\nu P_\rho)$$



$$= -i\,\frac{1}{2}\,\mathcal{I}[q^6]_i^6 \cdot 2^6\,\mathrm{tr}(P^\mu P^\nu P^\rho P_\nu P_\mu P_\rho)$$

$$\Rightarrow \boxed{\mathcal{L}_{\text{eff}} \supset \frac{g^2}{480\pi^2}\frac{T(R_i)}{M_i^2}\left[-\frac{1}{2}\left(D^\mu G^a_{\mu\nu}\right)^2 + \frac{g}{3!} f^{abc} G^{a\nu}_{\mu} G^{b\rho}_{\nu} G^{c\mu}_{\rho}\right]}$$

Backup

- The MSSM **U** matrix (schematic, assuming R-parity):

	Φ	$\tilde{q}$	$\tilde{u}$	$\tilde{d}$	$\tilde{l}$	$\tilde{e}$	$\tilde{\chi}$	$\tilde{g}$	$\tilde{W}$	$\tilde{B}$	ϕ	q	u	d	l	e	G	W	B
Φ	φ^2										v^2, φ^2	u, d	q	q	e	l		$D\Phi$	$D\Phi$
$\tilde{q}$		φ^2	φ	φ			u, d	q	q	q									
$\tilde{u}$		φ	φ^2	$\Phi\phi$			q	u		u									
$\tilde{d}$		φ	$\Phi\phi$	φ^2			q	d		d									
$\tilde{l}$					φ^2	φ	e		l	l									
$\tilde{e}$					φ	φ^2	l			e									
$\tilde{\chi}$		u, d	q	q	e	l			φ	φ									
$\tilde{g}$		q	u	d															
$\tilde{W}$		q			l		φ												
$\tilde{B}$		q	u	d	l	e	φ												
ϕ	v^2, φ^2										φ^2	u, d	q	q	e	l		$D\phi$	$D\phi$
q	u, d										u, d		φ	φ			q	q	q
u	q										q	φ					u		u
d	q										q	φ					d		d
l	e										e					φ		l	l
e	l										l				φ				e
G												q	u	d			$G_{\mu\nu}$		
W	$D\Phi$										$D\phi$	q			l			$W_{\mu\nu}, \phi^2, \Phi^2$	
B	$D\Phi$										$D\phi$	q	u	d	l	e			$B_{\mu\nu}, \phi^2, \Phi^2$

heavy fields

light fields

Backup

- The MSSM **U** matrix (schematic, assuming *R*-parity):

heavy fields / *light fields*

	Φ	$\tilde{q}$	$\tilde{u}$	$\tilde{d}$	$\tilde{l}$	$\tilde{e}$	$\tilde{\chi}$	$\tilde{g}$	$\tilde{W}$	$\tilde{B}$	ϕ	q	u	d	l	e	G	W	B
Φ	φ^2										v^2, φ^2	u, d	q	q	e	l		$D\Phi$	$D\Phi$
$\tilde{q}$		φ^2	φ	φ			u, d	q	q	q									
$\tilde{u}$		φ	φ^2	$\Phi\phi$			q	u		u									
$\tilde{d}$		φ	$\Phi\phi$	φ^2			q	d											
$\tilde{l}$					φ^2	φ	e		l										
$\tilde{e}$					φ	φ^2	l												
$\tilde{\chi}$		u, d	q	q	e	l			φ										
$\tilde{g}$		q	u	d															
$\tilde{W}$		q			l		φ												
$\tilde{B}$		q	u	d	l	e	φ												
ϕ	v^2, φ^2										φ^2	u, d	q	q	e	l		$D\phi$	$D\phi$
q	u, d										u, d		φ	φ			q	q	q
u	q										q	φ					u		u
d	q										q	φ					d		d
l	e										e					φ		l	l
e	l										l				φ				e
G												q	u	d			$G_{\mu\nu}$		
W	$D\Phi$										$D\phi$	q			l			$W_{\mu\nu}, \phi^2, \Phi^2$	
B	$D\Phi$										$D\phi$	q	u	d	l	e			$B_{\mu\nu}, \phi^2, \Phi^2$

squark-gluino interaction with background quark field

$$U_{\tilde{q}\tilde{g}} = \sqrt{2}\, g_3 \begin{pmatrix} \left(T^B \bar{\psi}_q^c\right)_{i\alpha} \\ \left(\bar{\psi}_q T^B\right)^{i\alpha} \end{pmatrix}$$

Backup

- The MSSM **U** matrix (schematic, assuming *R*-parity):

heavy fields (rows Φ to $\tilde{B}$); *light fields* (rows ϕ to B)

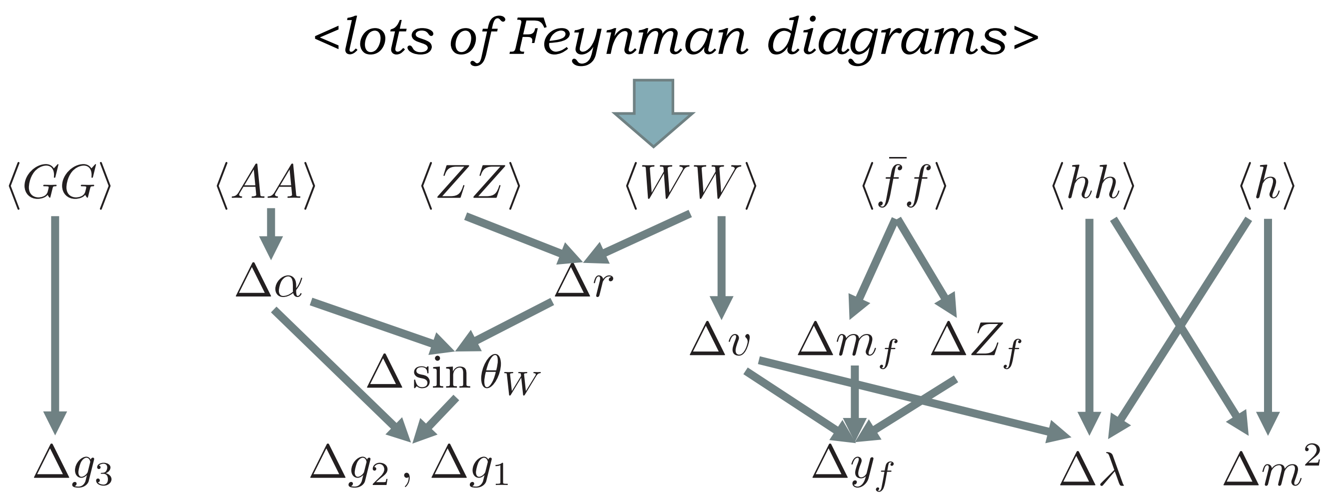
	Φ	$\tilde{q}$	$\tilde{u}$	$\tilde{d}$	$\tilde{l}$	$\tilde{e}$	$\tilde{\chi}$	$\tilde{g}$	$\tilde{W}$	$\tilde{B}$	ϕ	q	u	d	l	e	G	W	B
Φ	φ^2										v^2, φ^2	u, d	q	q	e	l		$D\Phi$	$D\Phi$
$\tilde{q}$		φ^2	φ	φ			u, d	q	q	q									
$\tilde{u}$																			
$\tilde{d}$																			
$\tilde{l}$																			
$\tilde{e}$																			
$\tilde{\chi}$																			
$\tilde{g}$																			
$\tilde{W}$																			
$\tilde{B}$																			
ϕ	v^2, φ^2										φ^2	u, d	q	q	e	l		$D\phi$	$D\phi$
q	u, d										u, d		φ	φ			q	q	q
u	q										q	φ					u		u
d	q										q	φ					d		d
l	e										e					φ		l	l
e	l										l				φ				e
G												q	u	d			$G_{\mu\nu}$		
W	$D\Phi$										$D\phi$	q			l			$W_{\mu\nu}, \phi^2, \Phi^2$	
B	$D\Phi$										$D\phi$	q	u	d	l	e			$B_{\mu\nu}, \phi^2, \Phi^2$

heavy Higgs-light quark interaction with background light quark fields

$$U_{\Phi q} = \begin{pmatrix} -\delta_\alpha^\beta\, \bar{\psi}_d^j\, \boldsymbol{y_d} \tan\beta & \epsilon_{\beta\alpha}\, \bar{\psi}_{uj}^c\, \boldsymbol{y_u^*} \cot\beta \\ \epsilon^{\beta\alpha}\, \bar{\psi}_u^j\, \boldsymbol{y_u} \cot\beta & -\delta_\beta^\alpha\, \bar{\psi}_{dj}^c\, \boldsymbol{y_d^*} \tan\beta \end{pmatrix}$$

Backup

- Old way of doing this calculation:
  - See classic paper *Bagger, Matchev, Pierce, Zhang [hep-ph/ 9606211]*.



- In the decoupling limit, we can use covariant diagrams to easily reproduce all their results.

Backup

- The matching calculation can be extended to dim-6.
- d>4 operators lead to observable deviations from the SM.
  - Example: Higgs coupling shifts

$$\mathcal{L}_{(d=6)} \supset |\phi|^2 \left(\bar{\psi}_q \, \boldsymbol{C_{d\phi}} \, \psi_d\right) \cdot \phi + |\phi|^2 \left(\bar{\psi}_l \, \boldsymbol{C_{e\phi}} \, \psi_e\right) \cdot \phi + \text{h.c.}$$

$$\delta\kappa_b = -\frac{C_{b\phi} v^2}{y_b^{\text{eff}}}, \qquad \delta\kappa_\tau = -\frac{C_{\tau\phi} v^2}{y_\tau^{\text{eff}}}$$

  - One-loop matching contributions to these operators can be parametrically enhanced for large tanβ, and can dominate over tree-level contributions.

$$C_{b\phi} \simeq -\frac{y_b}{2M_\Phi^2}\left[(g^2 + g'^2) - \frac{\tan\beta}{16\pi^2} \, y_t^4 \left(\frac{\mu}{M_s}\right) x_t (x_t^2 - 6)\right]$$

Backup

- In our numerical analysis, we require:
  - Consistent matching onto SM parameters extracted at weak scale
  - Bottom-tau Yukawa unification

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- Higgs coupling measurements can probe regions of SUSY parameter space inaccessible to direct searches!