A Generalised, Manifestly Gauge Invariant Exact Renormalisation Group for $SU(N)$ Yang-Mills

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Outline

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Motivation

Why the ERG?

- Renormalisation is built in
- Huge freedom in the construction
  - manifest gauge invariance
    - the gauge field need not renormalise
    - simple, strong constraints on vertices
    - Gribov copies entirely avoided
  - universal, diagrammatic computation
  - straightforward renormalisation to all loops

Status of the Manifestly Gauge Invariant ERG

β_2 Computed (OJR, 2004)

- consistency confirmed
- ready for (non)-perturbative computation

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- scalar field, φ
- Euclidean dimension, D

Integrating Out

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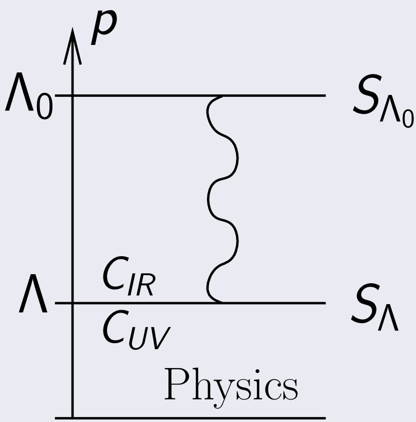

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Definitions

- Bare
- Effective
- IR cutoff function
- UV cutoff function
  - $C_{UV}(z) \to 0$ as $z \to \infty$
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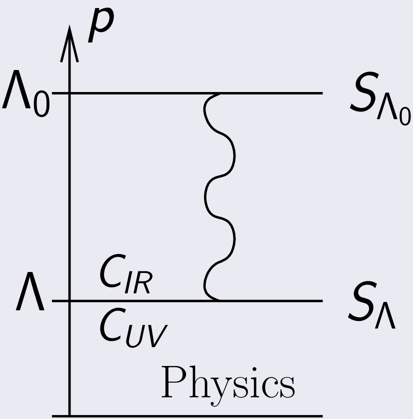

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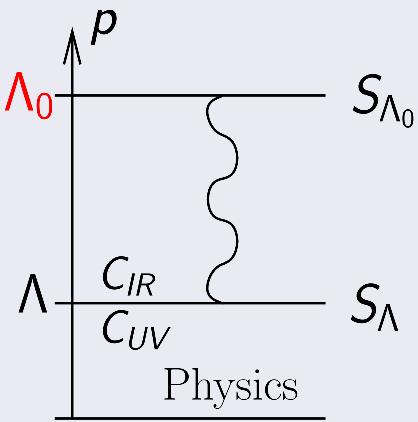

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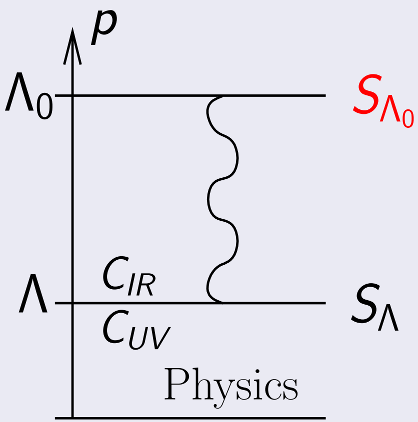

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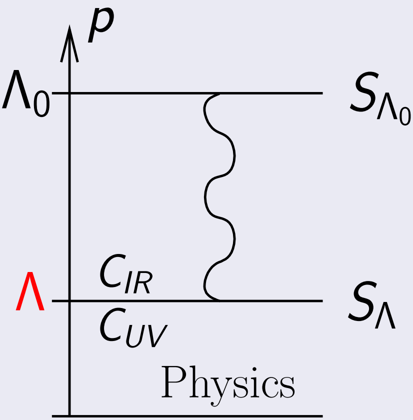

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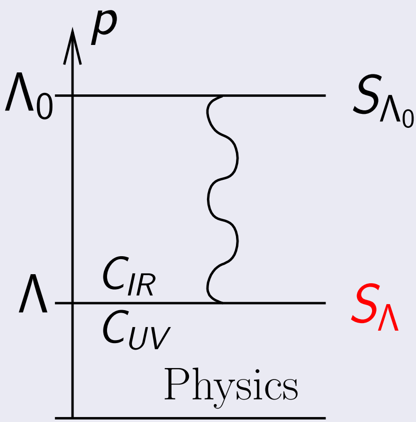

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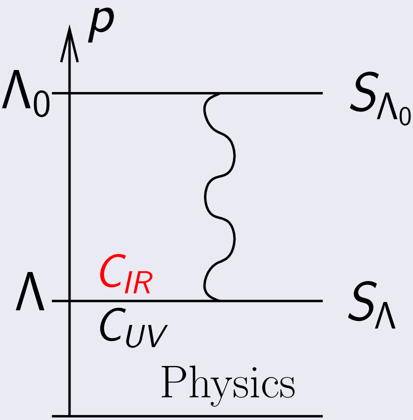

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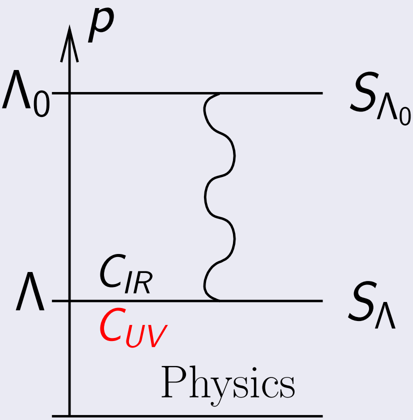

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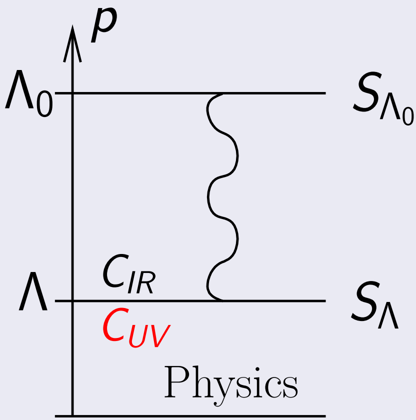

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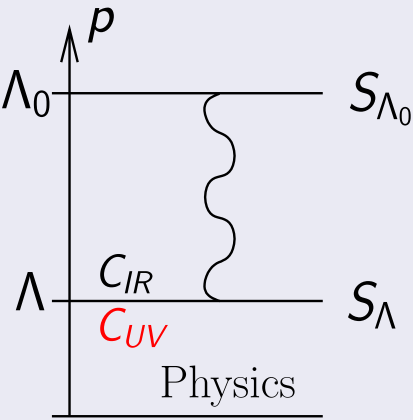

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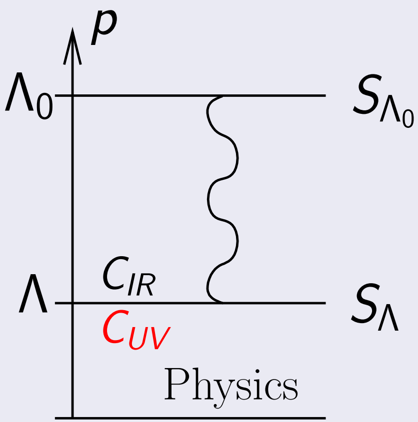

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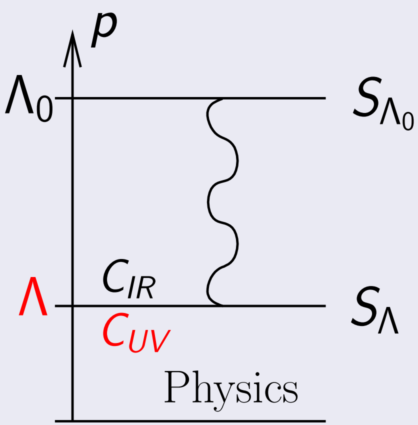

A Generalised ERG

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- Choice of $\Psi \Rightarrow$ ERG

A Scalar Flow Equation

Example

$$\Psi_x = \frac{1}{2} \int_y \dot{\Delta}_{xy} \frac{\delta \Sigma_1}{\delta \varphi(y)}$$

- $\dot{\Delta}$ is an ERG Kernel
- $\Sigma_1 = S - 2\hat{S}$

$$\begin{aligned} -\Lambda \partial_\Lambda S &= a_0[S, \Sigma_1] - a_1[\Sigma_1] \\ &= \frac{1}{2} \frac{\delta S}{\delta \varphi} \cdot \dot{\Delta} \cdot \frac{\delta \Sigma_1}{\delta \varphi} - \frac{1}{2} \frac{\delta}{\delta \varphi} \cdot \dot{\Delta} \cdot \frac{\delta \Sigma_1}{\delta \varphi} \end{aligned}$$

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What is it?

- A non-universal input which controls the flow
- Same structure and symmetries as S

Example

- $\hat{S}$ has just regularised kinetic term, $\frac{1}{2}\varphi \cdot \Delta^{-1} \cdot \varphi$
- flow equation is Polchinski's equation (up to discarded vacuum energy)

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The Seed Action

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Universal quantities cannot depend on non-universal details

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Isn't a General $\hat{S}$ just Scaffolding?

- Having discovered diagrammatics why not use simplest $\hat{S}$?
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Gauge Theory

$U(1)$ Gauge Theory

- Simply replace φ with A_μ
- $-\Lambda\partial_\Lambda S = \frac{1}{2}\frac{\delta S}{\delta A_\mu}\cdot\dot{\Delta}\cdot\frac{\delta\Sigma_1}{\delta A_\mu} - \frac{1}{2}\frac{\delta}{\delta A_\mu}\cdot\dot{\Delta}\cdot\frac{\delta\Sigma_1}{\delta A_\mu}$
  - $\delta/\delta A_\mu$ is gauge invariant
  - Flow equation is manifestly gauge invariant

$SU(N)$ Yang-Mills

- $\delta/\delta A_\mu$ transforms homogeneously under adjoint representation
- Choose $\Psi = \frac{1}{2}\{\dot{\Delta}\}\frac{\delta\Sigma_g}{\delta A_\mu}$
  - $\{\dot{\Delta}\}$ is a covariantisation of the kernel, $\dot{\Delta}$
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- Regularisation fails at one loop

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$SU(N|N)$ Regularisation

Covariantisation + Pauli-Villars = Regularisation

- Embed physical $SU(N)$ in spontaneously broken $SU(N|N)$
- Heavy fields act as Pauli-Villars!
- Defining rep.: $\mathcal{A}_\mu = \begin{pmatrix} A^1_\mu & B_\mu \\ \bar{B}_\mu & A^2_\mu \end{pmatrix} + \mathcal{A}^0_\mu \mathbb{1}$
  - a supergauge field valued in $SU(N|N)$
    - Hermitian
    - supertraceless: $\mathrm{str}\mathcal{A}_\mu = \mathrm{tr}A^1_\mu - \mathrm{tr}A^2_\mu$
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  - the physical gauge field
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Symmetries

local invariance

$\delta \mathcal{A}_\mu = [\nabla_\mu, \Omega(x)] + \lambda_\mu(x)\mathbb{1}$

- local $SU(N|N)$ invariance
- 'no-$\mathcal{A}^0$ symmetry'

Symmetry Breaking: $SU(N|N) \to SU(N) \times SU(N) \times U(1)$

- Superscalar $\mathcal{C} = \begin{pmatrix} C^1 & D \\ \bar{D} & C^2 \end{pmatrix}$
- Mass of B tracks Λ if
  - $\mathcal{C}$ dimensionless
  - Effective Potential of $\hat{S}$ has min. at $< \mathcal{C} > = \sigma := \begin{pmatrix} \mathbb{1} & 0 \\ 0 & -\mathbb{1} \end{pmatrix}$
- S has min. at σ

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  - Effective Potential of $\hat{S}$ has min. at $< \mathcal{C} > = \sigma := \begin{pmatrix} \mathbb{1} & 0 \\ 0 & -\mathbb{1} \end{pmatrix}$
- S has min. at σ

Symmetries

local invariance

$$\delta\mathcal{A}_\mu = [\nabla_\mu, \Omega(x)] + \lambda_\mu(x)\mathbb{1}$$

- local $SU(N|N)$ invariance
- 'no-$\mathcal{A}^0$ symmetry'

Symmetry Breaking: $SU(N|N) \to SU(N) \times SU(N) \times U(1)$

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local invariance

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  - Effective Potential of $\hat{S}$ has min. at $< \mathcal{C} > = \sigma := \begin{pmatrix} \mathbb{1} & 0 \\ 0 & -\mathbb{1} \end{pmatrix}$
- S has min. at σ automatically at classical level

Symmetries

local invariance

$$\delta \mathcal{A}_\mu = [\nabla_\mu, \Omega(x)] + \lambda_\mu(x)\mathbb{1}$$

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- S has min. at σ imposed at quantum level

The Broken Phase

Particle Content

- Massive Higgs fields C^1 and C^2
- Composite field $F_R = (B_\mu, D)$
  - five index
  - B and D gauge transform into each other
  - B eats D in unitarity gauge
- Massless fields A^1 and A^2
- Ignore $\mathcal{A}^0 \Rightarrow$ convenient diagrammatic prescription

Decoupling in the limit $\Lambda \to \infty$

- A^1 and A^2 communicate via massive fields
- Theory renormalisable in $D \leq 4$
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A Manifestly Gauge Invariant, Regularised Flow Equation

Requirements

- $SU(N|N)$ Invariance at high energies
- No-$\mathcal{A}^0$ Invariance
- Treats A^1 and A^2 asymmetrically

Construction

$$-\Lambda\partial_\Lambda S = a_0[S, \Sigma_g] - a_1[\Sigma_g],$$

- $a_0[S, \Sigma_g] = \frac{1}{2}\frac{\delta S}{\delta \mathcal{A}_\mu}\{\dot{\Delta}^{\mathcal{A}\mathcal{A}}\}\frac{\delta \Sigma_g}{\delta \mathcal{A}_\mu} + \frac{1}{2}\frac{\delta S}{\delta \mathcal{C}}\{\dot{\Delta}^{\mathcal{C}\mathcal{C}}\}\frac{\delta \Sigma_g}{\delta \mathcal{C}}$
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Diagrammatics for the Action

$$
\begin{aligned}
S \;=\;& \frac{1}{2}S^{\mathcal{A}\mathcal{A}}\mathrm{str}\mathcal{A}\mathcal{A} + \frac{1}{3}S^{\mathcal{A}\mathcal{A}\mathcal{A}}\mathrm{str}\mathcal{A}\mathcal{A}\mathcal{A} + \frac{1}{4}S^{\mathcal{A}\mathcal{A}\mathcal{A}\mathcal{A}}\mathrm{str}\mathcal{A}\mathcal{A}\mathcal{A}\mathcal{A} \\
&+ \frac{1}{8}S^{\mathcal{A}\mathcal{A},\mathcal{A}\mathcal{A}}\mathrm{str}\mathcal{A}\mathcal{A}\,\mathrm{str}\mathcal{A}\mathcal{A} + \frac{1}{2}S^{\mathcal{C}\mathcal{C}}\mathrm{str}\mathcal{C}\mathcal{C} + \frac{1}{2}S^{\mathcal{C},\mathcal{C}}\mathrm{str}\mathcal{C}\,\mathrm{str}\mathcal{C} \\
&+ \frac{1}{3}S^{\mathcal{A}\mathcal{C}\mathcal{C}}\mathrm{str}\mathcal{A}\mathcal{C}\mathcal{C}
\end{aligned}
$$

Diagrammatics for the Action

$$
\begin{aligned}
S \;=\;& \frac{1}{2} S^{\mathcal{A}\mathcal{A}} \mathrm{str}\mathcal{A}\mathcal{A} + \frac{1}{3} S^{\mathcal{A}\mathcal{A}\mathcal{A}} \mathrm{str}\mathcal{A}\mathcal{A}\mathcal{A} + \frac{1}{4} S^{\mathcal{A}\mathcal{A}\mathcal{A}\mathcal{A}} \mathrm{str}\mathcal{A}\mathcal{A}\mathcal{A}\mathcal{A} \\
& + \frac{1}{8} S^{\mathcal{A}\mathcal{A},\mathcal{A}\mathcal{A}} \mathrm{str}\mathcal{A}\mathcal{A}\, \mathrm{str}\mathcal{A}\mathcal{A} + \frac{1}{2} S^{\mathcal{C}\mathcal{C}} \mathrm{str}\mathcal{C}\mathcal{C} + \frac{1}{2} S^{\mathcal{C},\mathcal{C}} \mathrm{str}\mathcal{C}\, \mathrm{str}\mathcal{C} \\
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\end{aligned}
$$

Diagrammatics for the Action

$$S = \frac{1}{2} S^{\mathcal{A}\mathcal{A}} \mathrm{str} \mathcal{A}\mathcal{A} + \frac{1}{3} S^{\mathcal{A}\mathcal{A}\mathcal{A}} \mathrm{str} \mathcal{A}\mathcal{A}\mathcal{A} + \frac{1}{4} S^{\mathcal{A}\mathcal{A}\mathcal{A}\mathcal{A}} \mathrm{str} \mathcal{A}\mathcal{A}\mathcal{A}\mathcal{A}$$
$$+ \frac{1}{8} S^{\mathcal{A}\mathcal{A},\mathcal{A}\mathcal{A}} \mathrm{str} \mathcal{A}\mathcal{A} \, \mathrm{str} \mathcal{A}\mathcal{A} + \frac{1}{2} S^{\mathcal{C}\mathcal{C}} \mathrm{str} \mathcal{C}\mathcal{C} + \frac{1}{2} S^{\mathcal{C},\mathcal{C}} \mathrm{str} \mathcal{C} \, \mathrm{str} \mathcal{C}$$
$$+ \frac{1}{3} S^{\mathcal{A}\mathcal{C}\mathcal{C}} \mathrm{str} \mathcal{A}\mathcal{C}\mathcal{C}$$

- symmetry factor
- vertex coefficient function
- supertrace over fields

Diagrammatics for the Action

$$S = \frac{1}{2} S^{\mathcal{A}\mathcal{A}} \mathrm{str} \mathcal{A}\mathcal{A} + \frac{1}{3} S^{\mathcal{A}\mathcal{A}\mathcal{A}} \mathrm{str} \mathcal{A}\mathcal{A}\mathcal{A} + \frac{1}{4} S^{\mathcal{A}\mathcal{A}\mathcal{A}\mathcal{A}} \mathrm{str} \mathcal{A}\mathcal{A}\mathcal{A}\mathcal{A}$$
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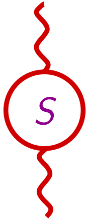
$$
\begin{aligned}
S \quad = \quad & \frac{1}{2} S^{\mathcal{A}\mathcal{A}} \mathrm{str}\mathcal{A}\mathcal{A} + \frac{1}{3} S^{\mathcal{A}\mathcal{A}\mathcal{A}} \mathrm{str}\mathcal{A}\mathcal{A}\mathcal{A} + \frac{1}{4} S^{\mathcal{A}\mathcal{A}\mathcal{A}\mathcal{A}} \mathrm{str}\mathcal{A}\mathcal{A}\mathcal{A}\mathcal{A} \\
& + \frac{1}{8} S^{\mathcal{A}\mathcal{A},\mathcal{A}\mathcal{A}} \mathrm{str}\mathcal{A}\mathcal{A}\, \mathrm{str}\mathcal{A}\mathcal{A} + \frac{1}{2} S^{\mathcal{C}\mathcal{C}} \mathrm{str}\mathcal{C}\mathcal{C} + \frac{1}{2} S^{\mathcal{C},\mathcal{C}} \mathrm{str}\mathcal{C}\, \mathrm{str}\mathcal{C} \\
& + \frac{1}{3} S^{\mathcal{A}\mathcal{C}\mathcal{C}} \mathrm{str}\mathcal{A}\mathcal{C}\mathcal{C}
\end{aligned}
$$

Diagrammatics for the Action

$$S = \frac{1}{2}S^{\mathcal{A}\mathcal{A}}\mathrm{str}\mathcal{A}\mathcal{A} + \frac{1}{3}S^{\mathcal{A}\mathcal{A}\mathcal{A}}\mathrm{str}\mathcal{A}\mathcal{A}\mathcal{A} + \frac{1}{4}S^{\mathcal{A}\mathcal{A}\mathcal{A}\mathcal{A}}\mathrm{str}\mathcal{A}\mathcal{A}\mathcal{A}\mathcal{A} + \frac{1}{8}S^{\mathcal{A}\mathcal{A},\mathcal{A}\mathcal{A}}\mathrm{str}\mathcal{A}\mathcal{A}\,\mathrm{str}\mathcal{A}\mathcal{A} + \frac{1}{2}S^{\mathcal{C}\mathcal{C}}\mathrm{str}\mathcal{C}\mathcal{C} + \frac{1}{2}S^{\mathcal{C},\mathcal{C}}\mathrm{str}\mathcal{C}\,\mathrm{str}\mathcal{C} + \frac{1}{3}S^{\mathcal{A}\mathcal{C}\mathcal{C}}\mathrm{str}\mathcal{A}\mathcal{C}\mathcal{C}$$

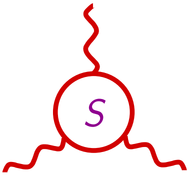


Diagrammatics for the Action

$$
\begin{aligned}
S \;=\; & \frac{1}{2} S^{\mathcal{A}\mathcal{A}} \mathrm{str}\mathcal{A}\mathcal{A} + \frac{1}{3} S^{\mathcal{A}\mathcal{A}\mathcal{A}} \mathrm{str}\mathcal{A}\mathcal{A}\mathcal{A} + \frac{1}{4} S^{\mathcal{A}\mathcal{A}\mathcal{A}\mathcal{A}} \mathrm{str}\mathcal{A}\mathcal{A}\mathcal{A}\mathcal{A} \\
& + \frac{1}{8} S^{\mathcal{A}\mathcal{A},\mathcal{A}\mathcal{A}} \mathrm{str}\mathcal{A}\mathcal{A}\,\mathrm{str}\mathcal{A}\mathcal{A} + \frac{1}{2} S^{\mathcal{C}\mathcal{C}} \mathrm{str}\mathcal{C}\mathcal{C} + \frac{1}{2} S^{\mathcal{C},\mathcal{C}} \mathrm{str}\mathcal{C}\,\mathrm{str}\mathcal{C} \\
& + \frac{1}{3} S^{\mathcal{A}\mathcal{C}\mathcal{C}} \mathrm{str}\mathcal{A}\mathcal{C}\mathcal{C}
\end{aligned}
$$

Diagrammatics for the Action

$$S = \frac{1}{2}S^{\mathcal{A}\mathcal{A}}\mathrm{str}\mathcal{A}\mathcal{A} + \frac{1}{3}S^{\mathcal{A}\mathcal{A}\mathcal{A}}\mathrm{str}\mathcal{A}\mathcal{A}\mathcal{A} + \frac{1}{4}S^{\mathcal{A}\mathcal{A}\mathcal{A}\mathcal{A}}\mathrm{str}\mathcal{A}\mathcal{A}\mathcal{A}\mathcal{A}$$
$$+\frac{1}{8}S^{\mathcal{A}\mathcal{A},\mathcal{A}\mathcal{A}}\mathrm{str}\mathcal{A}\mathcal{A}\,\mathrm{str}\mathcal{A}\mathcal{A} + \frac{1}{2}S^{\mathcal{C}\mathcal{C}}\mathrm{str}\mathcal{C}\mathcal{C} + \frac{1}{2}S^{\mathcal{C},\mathcal{C}}\mathrm{str}\mathcal{C}\,\mathrm{str}\mathcal{C}$$
$$+\frac{1}{3}S^{\mathcal{A}\mathcal{C}\mathcal{C}}\mathrm{str}\mathcal{A}\mathcal{C}\mathcal{C}$$



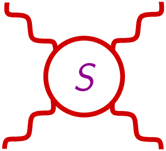
Diagrammatics for the Action

$$S = \frac{1}{2}S^{\mathcal{A}\mathcal{A}}\mathrm{str}\mathcal{A}\mathcal{A} + \frac{1}{3}S^{\mathcal{A}\mathcal{A}\mathcal{A}}\mathrm{str}\mathcal{A}\mathcal{A}\mathcal{A} + \frac{1}{4}S^{\mathcal{A}\mathcal{A}\mathcal{A}\mathcal{A}}\mathrm{str}\mathcal{A}\mathcal{A}\mathcal{A}\mathcal{A}$$
$$+\frac{1}{8}S^{\mathcal{A}\mathcal{A},\mathcal{A}\mathcal{A}}\mathrm{str}\mathcal{A}\mathcal{A}\,\mathrm{str}\mathcal{A}\mathcal{A} + \frac{1}{2}S^{\mathcal{C}\mathcal{C}}\mathrm{str}\mathcal{C}\mathcal{C} + \frac{1}{2}S^{\mathcal{C},\mathcal{C}}\mathrm{str}\mathcal{C}\,\mathrm{str}\mathcal{C}$$
$$+\frac{1}{3}S^{\mathcal{A}\mathcal{C}\mathcal{C}}\mathrm{str}\mathcal{A}\mathcal{C}\mathcal{C}$$

- $\mathrm{str}\mathcal{A} = 0$
- $S^{\mathcal{A}\mathcal{C}} = 0$ (charge conjugation)

Diagrammatics for the Action

$$S = \frac{1}{2}S^{\mathcal{A}\mathcal{A}}\mathrm{str}\mathcal{A}\mathcal{A} + \frac{1}{3}S^{\mathcal{A}\mathcal{A}\mathcal{A}}\mathrm{str}\mathcal{A}\mathcal{A}\mathcal{A} + \frac{1}{4}S^{\mathcal{A}\mathcal{A}\mathcal{A}\mathcal{A}}\mathrm{str}\mathcal{A}\mathcal{A}\mathcal{A}\mathcal{A} + \frac{1}{8}S^{\mathcal{A}\mathcal{A},\mathcal{A}\mathcal{A}}\mathrm{str}\mathcal{A}\mathcal{A}\,\mathrm{str}\mathcal{A}\mathcal{A} + \frac{1}{2}S^{\mathcal{C}\mathcal{C}}\mathrm{str}\mathcal{C}\mathcal{C} + \frac{1}{2}S^{\mathcal{C},\mathcal{C}}\mathrm{str}\mathcal{C}\,\mathrm{str}\mathcal{C} + \frac{1}{3}S^{\mathcal{A}\mathcal{C}\mathcal{C}}\mathrm{str}\mathcal{A}\mathcal{C}\mathcal{C}$$



- $\mathrm{str}\mathcal{A} = 0$
- $S^{\mathcal{A}\mathcal{C}} = 0$ (charge conjugation)

Diagrammatics for the Action

$$
\begin{aligned}
S = & \frac{1}{2}S^{\mathcal{A}\mathcal{A}}\mathrm{str}\mathcal{A}\mathcal{A} + \frac{1}{3}S^{\mathcal{A}\mathcal{A}\mathcal{A}}\mathrm{str}\mathcal{A}\mathcal{A}\mathcal{A} + \frac{1}{4}S^{\mathcal{A}\mathcal{A}\mathcal{A}\mathcal{A}}\mathrm{str}\mathcal{A}\mathcal{A}\mathcal{A}\mathcal{A} \\
& + \frac{1}{8}S^{\mathcal{A}\mathcal{A},\mathcal{A}\mathcal{A}}\mathrm{str}\mathcal{A}\mathcal{A}\,\mathrm{str}\mathcal{A}\mathcal{A} + \frac{1}{2}S^{\mathcal{C}\mathcal{C}}\mathrm{str}\mathcal{C}\mathcal{C} + \frac{1}{2}S^{\mathcal{C},\mathcal{C}}\mathrm{str}\mathcal{C}\,\mathrm{str}\mathcal{C} \\
& + \frac{1}{3}S^{\mathcal{A}\mathcal{C}\mathcal{C}}\mathrm{str}\mathcal{A}\mathcal{C}\mathcal{C}
\end{aligned}
$$

- $\mathrm{str}\mathcal{A} = 0$
- $S^{\mathcal{A}\mathcal{C}} = 0$ (charge conjugation)

Diagrammatics for the Action

$$S = \frac{1}{2}S^{\mathcal{A}\mathcal{A}}\mathrm{str}\mathcal{A}\mathcal{A} + \frac{1}{3}S^{\mathcal{A}\mathcal{A}\mathcal{A}}\mathrm{str}\mathcal{A}\mathcal{A}\mathcal{A} + \frac{1}{4}S^{\mathcal{A}\mathcal{A}\mathcal{A}\mathcal{A}}\mathrm{str}\mathcal{A}\mathcal{A}\mathcal{A}\mathcal{A} + \frac{1}{8}S^{\mathcal{A}\mathcal{A},\mathcal{A}\mathcal{A}}\mathrm{str}\mathcal{A}\mathcal{A}\,\mathrm{str}\mathcal{A}\mathcal{A} + \frac{1}{2}S^{\mathcal{C}\mathcal{C}}\mathrm{str}\mathcal{C}\mathcal{C} + \frac{1}{2}S^{\mathcal{C},\mathcal{C}}\mathrm{str}\mathcal{C}\,\mathrm{str}\mathcal{C} + \frac{1}{3}S^{\mathcal{A}\mathcal{C}\mathcal{C}}\mathrm{str}\mathcal{A}\mathcal{C}\mathcal{C}$$

- $\mathrm{str}\mathcal{A} = 0$
- $S^{\mathcal{A}\mathcal{C}} = 0$ (charge conjugation)

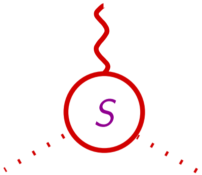
Diagrammatics for the Action

$$
\begin{aligned}
S = \; & \frac{1}{2} S^{\mathcal{A}\mathcal{A}} \mathrm{str} \mathcal{A}\mathcal{A} + \frac{1}{3} S^{\mathcal{A}\mathcal{A}\mathcal{A}} \mathrm{str} \mathcal{A}\mathcal{A}\mathcal{A} + \frac{1}{4} S^{\mathcal{A}\mathcal{A}\mathcal{A}\mathcal{A}} \mathrm{str} \mathcal{A}\mathcal{A}\mathcal{A}\mathcal{A} \\
& + \frac{1}{8} S^{\mathcal{A}\mathcal{A},\mathcal{A}\mathcal{A}} \mathrm{str} \mathcal{A}\mathcal{A} \, \mathrm{str} \mathcal{A}\mathcal{A} + \frac{1}{2} S^{\mathcal{C}\mathcal{C}} \mathrm{str} \mathcal{C}\mathcal{C} + \frac{1}{2} S^{\mathcal{C},\mathcal{C}} \mathrm{str} \mathcal{C} \, \mathrm{str} \mathcal{C} \\
& + \frac{1}{3} S^{\mathcal{A}\mathcal{C}\mathcal{C}} \mathrm{str} \mathcal{A}\mathcal{C}\mathcal{C}
\end{aligned}
$$

- $\mathrm{str} \mathcal{A} = 0$
- $S^{\mathcal{A}\mathcal{C}} = 0$ (charge conjugation)

Diagrammatics for the Action

$$S = \frac{1}{2}S^{\mathcal{A}\mathcal{A}}\mathrm{str}\mathcal{A}\mathcal{A} + \frac{1}{3}S^{\mathcal{A}\mathcal{A}\mathcal{A}}\mathrm{str}\mathcal{A}\mathcal{A}\mathcal{A} + \frac{1}{4}S^{\mathcal{A}\mathcal{A}\mathcal{A}\mathcal{A}}\mathrm{str}\mathcal{A}\mathcal{A}\mathcal{A}\mathcal{A}$$
$$+ \frac{1}{8}S^{\mathcal{A}\mathcal{A},\mathcal{A}\mathcal{A}}\mathrm{str}\mathcal{A}\mathcal{A}\,\mathrm{str}\mathcal{A}\mathcal{A} + \frac{1}{2}S^{\mathcal{C}\mathcal{C}}\mathrm{str}\mathcal{C}\mathcal{C} + \frac{1}{2}S^{\mathcal{C},\mathcal{C}}\mathrm{str}\mathcal{C}\,\mathrm{str}\mathcal{C}$$
$$+ \frac{1}{3}S^{\mathcal{A}\mathcal{C}\mathcal{C}}\mathrm{str}\mathcal{A}\mathcal{C}\mathcal{C}$$



- $\mathrm{str}\mathcal{A} = 0$
- $S^{\mathcal{A}\mathcal{C}} = 0$ (charge conjugation)

Symmetric Phase Diagrammatics Flow Equation

The Classical Term

$$-\Lambda\partial_\Lambda S = \frac{1}{2}\frac{\delta S}{\delta \mathcal{A}_\mu}\{\dot{\Delta}^{\mathcal{A}\mathcal{A}}\}\frac{\delta \Sigma_g}{\delta \mathcal{A}_\mu} + \frac{1}{2}\frac{\delta S}{\delta \mathcal{C}}\{\dot{\Delta}^{\mathcal{C}\mathcal{C}}\}\frac{\delta \Sigma_g}{\delta \mathcal{C}} - a_1[\Sigma_g]$$

Symmetric Phase Diagrammatics Flow Equation

The Classical Term

$$-\Lambda\partial_\Lambda S = \frac{1}{2}\frac{\delta S}{\delta \mathcal{A}_\mu}\{\dot{\Delta}^{\mathcal{A}\mathcal{A}}\}\frac{\delta \Sigma_g}{\delta \mathcal{A}_\mu} + \frac{1}{2}\frac{\delta S}{\delta \mathcal{C}}\{\dot{\Delta}^{\mathcal{C}\mathcal{C}}\}\frac{\delta \Sigma_g}{\delta \mathcal{C}} - a_1[\Sigma_g]$$

- S and Σ_g are composed of supertraces

Symmetric Phase Diagrammatics Flow Equation

The Classical Term

$$-\Lambda\partial_\Lambda S = \frac{1}{2}\frac{\delta S}{\delta \mathcal{A}_\mu}\{\dot{\Delta}^{\mathcal{A}\mathcal{A}}\}\frac{\delta \Sigma_g}{\delta \mathcal{A}_\mu} + \frac{1}{2}\frac{\delta S}{\delta \mathcal{C}}\{\dot{\Delta}^{\mathcal{C}\mathcal{C}}\}\frac{\delta \Sigma_g}{\delta \mathcal{C}} - a_1[\Sigma_g]$$

- S and Σ_g are composed of supertraces
- $\frac{\delta}{\delta \mathcal{A}_\mu}$, $\frac{\delta}{\delta \mathcal{C}}$ break open a supertrace

Symmetric Phase Diagrammatics Flow Equation

The Classical Term

$$-\Lambda\partial_\Lambda S = \frac{1}{2}\frac{\delta S}{\delta \mathcal{A}_\mu}\{\dot{\Delta}^{\mathcal{A}\mathcal{A}}\}\frac{\delta \Sigma_g}{\delta \mathcal{A}_\mu} + \frac{1}{2}\frac{\delta S}{\delta \mathcal{C}}\{\dot{\Delta}^{\mathcal{C}\mathcal{C}}\}\frac{\delta \Sigma_g}{\delta \mathcal{C}} - a_1[\Sigma_g]$$

- S and Σ_g are composed of supertraces
- $\frac{\delta}{\delta \mathcal{A}_\mu}$, $\frac{\delta}{\delta \mathcal{C}}$ break open a supertrace
- The covariantisation glues everything back together

Symmetric Phase Diagrammatics Flow Equation

The Classical Term

$$-\Lambda\partial_\Lambda S = \frac{1}{2}\frac{\delta S}{\delta \mathcal{A}_\mu}\{\dot{\Delta}^{\mathcal{A}\mathcal{A}}\}\frac{\delta \Sigma_g}{\delta \mathcal{A}_\mu}$$

Symmetric Phase Diagrammatics Flow Equation

The Classical Term

$$-\Lambda\partial_\Lambda S = \frac{1}{2}\frac{\delta S}{\delta \mathcal{A}_\mu}\{\dot{\Delta}^{\mathcal{A}\mathcal{A}}\}\frac{\delta \Sigma_g}{\delta \mathcal{A}_\mu}$$

$-\Lambda\partial_\Lambda \Big[\frac{1}{2}$  $\mathrm{str}\mathcal{A}\mathcal{A} \Big] =$

Symmetric Phase Diagrammatics Flow Equation

The Classical Term

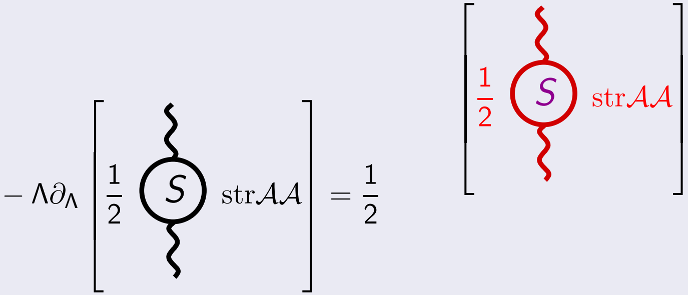
$$-\Lambda\partial_\Lambda S = \frac{1}{2}\frac{\delta S}{\delta \mathcal{A}_\mu}\{\dot{\Delta}^{\mathcal{A}\mathcal{A}}\}\frac{\delta \Sigma_g}{\delta \mathcal{A}_\mu}$$

$-\Lambda\partial_\Lambda \left[\frac{1}{2} \right.$  $\left. \mathrm{str}\mathcal{A}\mathcal{A} \right] = \frac{1}{2}$

Symmetric Phase Diagrammatics Flow Equation

The Classical Term

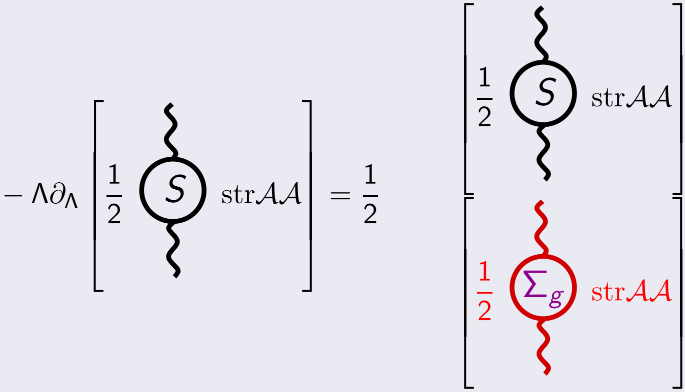
$$-\Lambda\partial_\Lambda S = \frac{1}{2}\frac{\delta S}{\delta \mathcal{A}_\mu}\{\dot{\Delta}^{\mathcal{A}\mathcal{A}}\}\frac{\delta \Sigma_g}{\delta \mathcal{A}_\mu}$$



Symmetric Phase Diagrammatics Flow Equation

The Classical Term

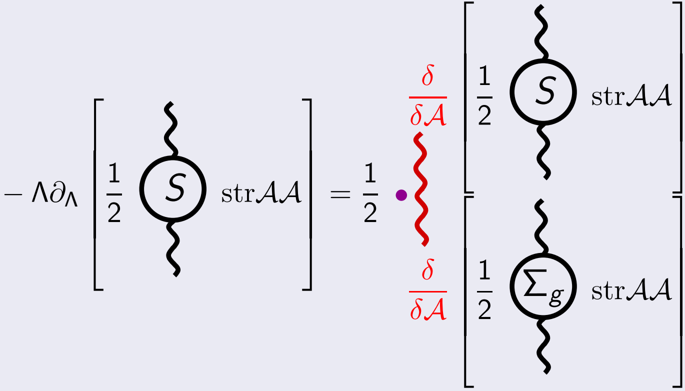
$$-\Lambda\partial_\Lambda S = \frac{1}{2}\frac{\delta S}{\delta \mathcal{A}_\mu}\{\dot{\Delta}^{\mathcal{A}\mathcal{A}}\}\frac{\delta \Sigma_g}{\delta \mathcal{A}_\mu}$$



Symmetric Phase Diagrammatics Flow Equation

The Classical Term

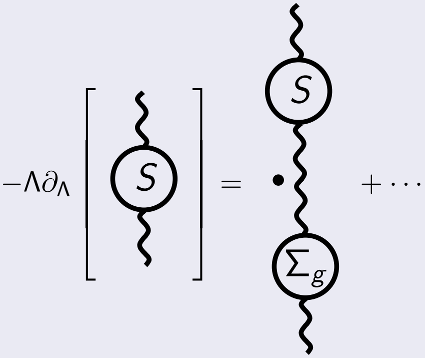
$$-\Lambda\partial_\Lambda S = \frac{1}{2}\frac{\delta S}{\delta \mathcal{A}_\mu}\{\dot{\Delta}^{\mathcal{A}\mathcal{A}}\}\frac{\delta \Sigma_g}{\delta \mathcal{A}_\mu}$$



Symmetric Phase Diagrammatics Flow Equation

The Classical Term

$$-\Lambda\partial_\Lambda S = \frac{1}{2}\frac{\delta S}{\delta \mathcal{A}_\mu}\{\dot{\Delta}^{\mathcal{A}\mathcal{A}}\}\frac{\delta \Sigma_g}{\delta \mathcal{A}_\mu}$$



Symmetric Phase Diagrammatics Flow Equation

The Quantum Term

$$-\Lambda\partial_\Lambda S = a_0[S,\Sigma_g] - \frac{1}{2}\frac{\delta}{\delta\mathcal{A}_\mu}\{\dot{\Delta}^{\mathcal{A}\mathcal{A}}\}\frac{\delta\Sigma_g}{\delta\mathcal{A}_\mu} - \frac{1}{2}\frac{\delta}{\delta\mathcal{C}}\{\dot{\Delta}^{\mathcal{C}\mathcal{C}}\}\frac{\delta\Sigma_g}{\delta\mathcal{C}}$$

Symmetric Phase Diagrammatics Flow Equation

The Quantum Term

$$-\Lambda\partial_\Lambda S = a_0[S,\Sigma_g] - \frac{1}{2}\frac{\delta}{\delta\mathcal{A}_\mu}\{\dot{\Delta}^{\mathcal{A}\mathcal{A}}\}\frac{\delta\Sigma_g}{\delta\mathcal{A}_\mu} - \frac{1}{2}\frac{\delta}{\delta\mathcal{C}}\{\dot{\Delta}^{\mathcal{C}\mathcal{C}}\}\frac{\delta\Sigma_g}{\delta\mathcal{C}}$$

- For Consistency take
  - $\frac{\delta}{\delta\mathcal{A}_\mu}\{\dot{\Delta}^{\mathcal{A}\mathcal{A}}\} = 0$
  - $\frac{\delta}{\delta\mathcal{C}}\{\dot{\Delta}^{\mathcal{C}\mathcal{C}}\} = 0$

Symmetric Phase Diagrammatics Flow Equation

The Quantum Term

$$-\Lambda\partial_\Lambda S = a_0[S, \Sigma_g] - \frac{1}{2}\frac{\delta}{\delta \mathcal{A}_\mu}\{\dot{\Delta}^{\mathcal{A}\mathcal{A}}\}\frac{\delta \Sigma_g}{\delta \mathcal{A}_\mu} - \frac{1}{2}\frac{\delta}{\delta \mathcal{C}}\{\dot{\Delta}^{\mathcal{C}\mathcal{C}}\}\frac{\delta \Sigma_g}{\delta \mathcal{C}}$$

- For Consistency take
  - $\frac{\delta}{\delta \mathcal{A}_\mu}\{\dot{\Delta}^{\mathcal{A}\mathcal{A}}\} = 0$
  - $\frac{\delta}{\delta \mathcal{C}}\{\dot{\Delta}^{\mathcal{C}\mathcal{C}}\} = 0$
- The pairs of derivatives

Symmetric Phase Diagrammatics Flow Equation

The Quantum Term

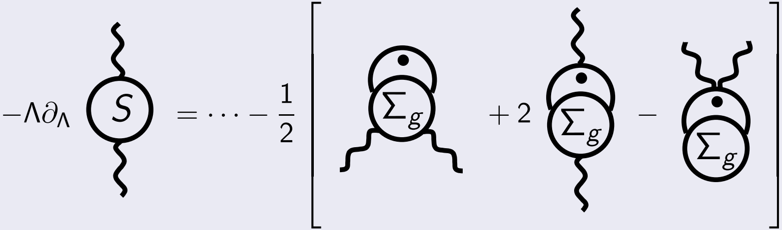
$$-\Lambda\partial_\Lambda S = a_0[S,\Sigma_g] - \frac{1}{2}\frac{\delta}{\delta\mathcal{A}_\mu}\{\dot{\Delta}^{\mathcal{A}\mathcal{A}}\}\frac{\delta\Sigma_g}{\delta\mathcal{A}_\mu} - \frac{1}{2}\frac{\delta}{\delta\mathcal{C}}\{\dot{\Delta}^{\mathcal{C}\mathcal{C}}\}\frac{\delta\Sigma_g}{\delta\mathcal{C}}$$

- For Consistency take
  - $\dfrac{\delta}{\delta\mathcal{A}_\mu}\{\dot{\Delta}^{\mathcal{A}\mathcal{A}}\} = 0$
  - $\dfrac{\delta}{\delta\mathcal{C}}\{\dot{\Delta}^{\mathcal{C}\mathcal{C}}\} = 0$
- The pairs of derivatives knock two fields out of Σ_g

Symmetric Phase Diagrammatics Flow Equation

The Quantum Term

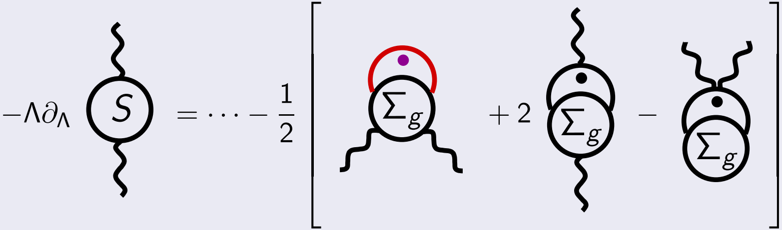
$$-\Lambda\partial_\Lambda S = a_0[S,\Sigma_g] - \frac{1}{2}\frac{\delta}{\delta \mathcal{A}_\mu}\{\dot{\Delta}^{\mathcal{A}\mathcal{A}}\}\frac{\delta \Sigma_g}{\delta \mathcal{A}_\mu} - \frac{1}{2}\frac{\delta}{\delta \mathcal{C}}\{\dot{\Delta}^{\mathcal{C}\mathcal{C}}\}\frac{\delta \Sigma_g}{\delta \mathcal{C}}$$



Symmetric Phase Diagrammatics Flow Equation

The Quantum Term

$$-\Lambda\partial_\Lambda S = a_0[S, \Sigma_g] - \frac{1}{2}\frac{\delta}{\delta\mathcal{A}_\mu}\{\dot{\Delta}^{\mathcal{A}\mathcal{A}}\}\frac{\delta\Sigma_g}{\delta\mathcal{A}_\mu} - \frac{1}{2}\frac{\delta}{\delta\mathcal{C}}\{\dot{\Delta}^{\mathcal{C}\mathcal{C}}\}\frac{\delta\Sigma_g}{\delta\mathcal{C}}$$

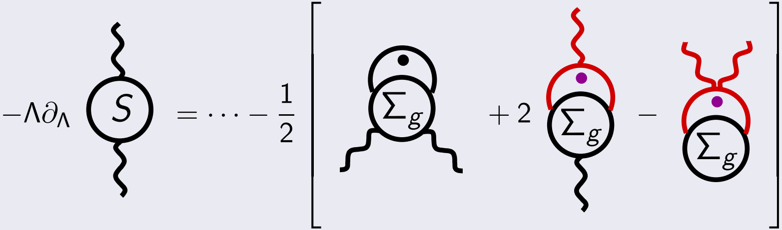


- Sum over kernels

Symmetric Phase Diagrammatics Flow Equation

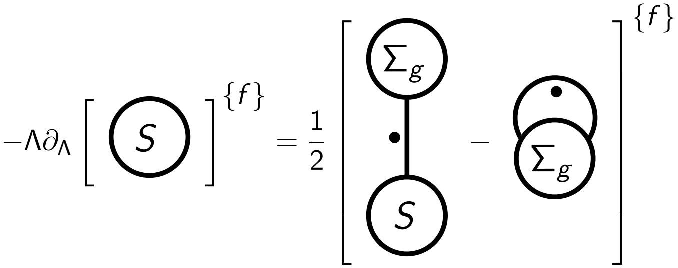
The Quantum Term

$$-\Lambda\partial_\Lambda S = a_0[S,\Sigma_g] - \frac{1}{2}\frac{\delta}{\delta\mathcal{A}_\mu}\{\dot{\Delta}^{\mathcal{A}\mathcal{A}}\}\frac{\delta\Sigma_g}{\delta\mathcal{A}_\mu} - \frac{1}{2}\frac{\delta}{\delta\mathcal{C}}\{\dot{\Delta}^{\mathcal{C}\mathcal{C}}\}\frac{\delta\Sigma_g}{\delta\mathcal{C}}$$

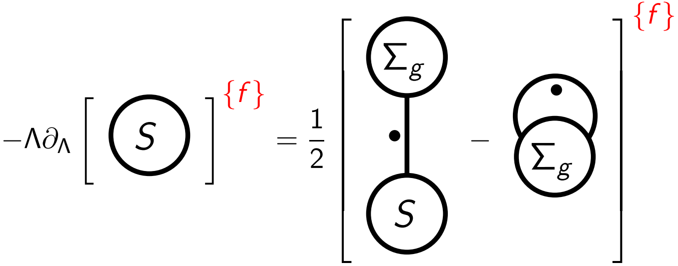


- Vertices of the covariantised kernels

Broken Phase Diagrammatic Flow Equation

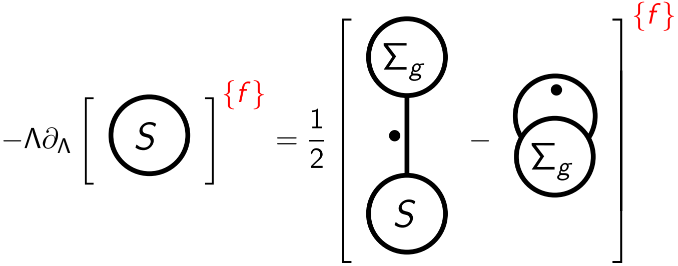


Broken Phase Diagrammatic Flow Equation



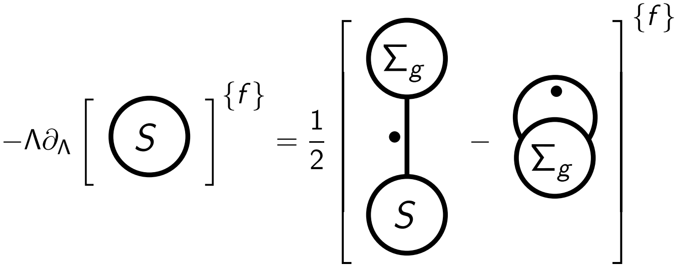
- The fields $\{f\}$
  - Any of A^1, A^2, C^1, C^2, F, $\bar{F}$

Broken Phase Diagrammatic Flow Equation



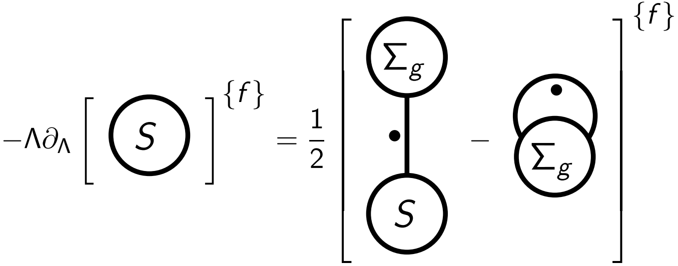
- The fields $\{f\}$
  - Any of A^1, A^2, C^1, C^2, F, $\bar{F}$
  - Distributed in all independent ways

Broken Phase Diagrammatic Flow Equation



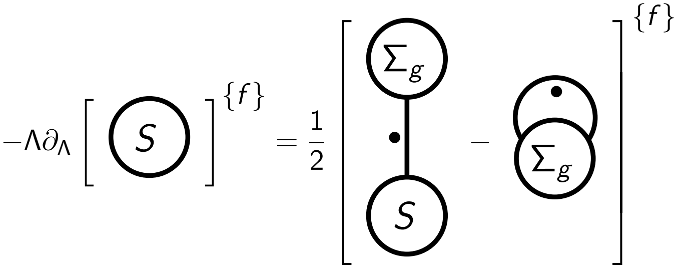
- The fields $\{f\}$
  - Any of A^1, A^2, C^1, C^2, F, $\bar{F}$
  - Distributed in all independent ways
- Prescription for evaluating group theory

Broken Phase Diagrammatic Flow Equation



- The fields $\{f\}$
  - Any of A^1, A^2, C^1, C^2, F, $\bar{F}$
  - Distributed in all independent ways
- Prescription for evaluating group theory
- Internal fields label the kernels

Broken Phase Diagrammatic Flow Equation



- The fields $\{f\}$
  - Any of A^1, A^2, C^1, C^2, F, $\bar{F}$
  - Distributed in all independent ways
- Prescription for evaluating group theory
- Internal fields label the kernels
- ERG sufficiently general to allow $\dot{\Delta}^{A^1A^1} \neq \dot{\Delta}^{A^2A^2}$

Weak Coupling Limit

Expansions

Weak Coupling Limit

Expansions

- $S = \sum_{i=0}^{\infty} \left(g^2\right)^{i-1} S_i = \frac{1}{g^2} S_0 + S_1 + \cdots$

Weak Coupling Limit

Expansions

- $S = \sum_{i=0}^{\infty} \left(g^2\right)^{i-1} S_i = \frac{1}{g^2} S_0 + S_1 + \cdots$
  - S_0: classical effective action

Weak Coupling Limit

Expansions

- $S = \sum_{i=0}^{\infty} \left(g^2\right)^{i-1} S_i = \frac{1}{g^2} S_0 + S_1 + \cdots$
  - S_0: classical effective action
  - $S_{i>0}$: ith-loop corrections

Weak Coupling Limit

Expansions

- $$S = \sum_{i=0}^{\infty} \left(g^2\right)^{i-1} S_i = \frac{1}{g^2} S_0 + S_1 + \cdots$$
  - S_0: classical effective action
  - $S_{i>0}$: ith-loop corrections
- $$\hat{S} = \sum_{i=0}^{\infty} g^{2i} \hat{S}_i$$

Weak Coupling Limit

Expansions

- $S = \sum_{i=0}^{\infty} \left(g^2\right)^{i-1} S_i = \frac{1}{g^2} S_0 + S_1 + \cdots$
  - S_0: classical effective action
  - $S_{i>0}$: ith-loop corrections
- $\hat{S} = \sum_{i=0}^{\infty} g^{2i} \hat{S}_i$
- Define $\alpha = g_2^2/g^2$

Weak Coupling Limit

Expansions

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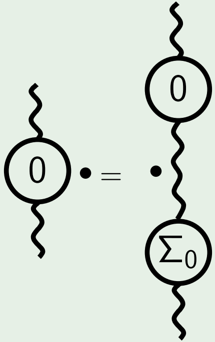
$$\beta \equiv \Lambda\partial_\Lambda g = \sum_{i=1}^{\infty} g^{2i+1}\beta_i(\alpha)$$

$$\gamma \equiv \Lambda\partial_\Lambda \alpha = \sum_{i=1}^{\infty} g^{2i}\gamma_i(\alpha).$$

The Classical Flow Equation

Example (Classical $A^1 A^1$ Vertex)



The Classical Flow Equation

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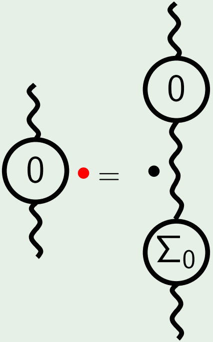

$\bullet\ \bullet = -\Lambda\partial_\Lambda|_\alpha$

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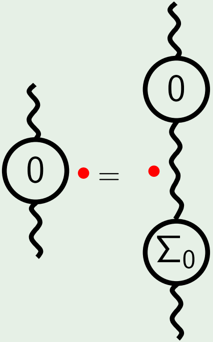

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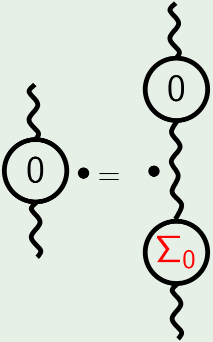

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The Classical Flow Equation

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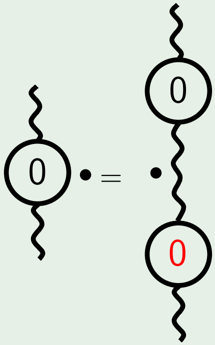

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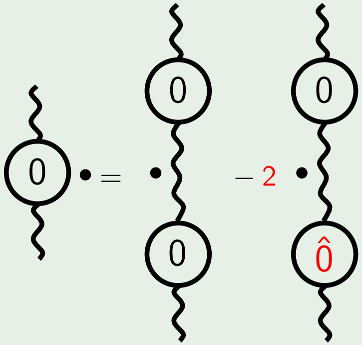

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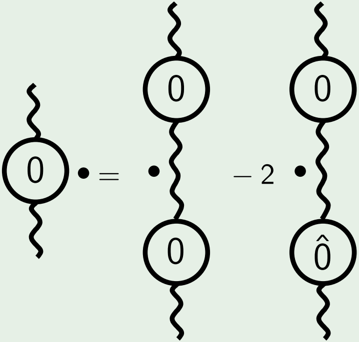
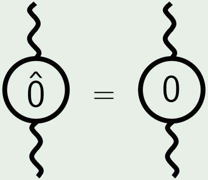


Choose



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The Classical Flow Equation

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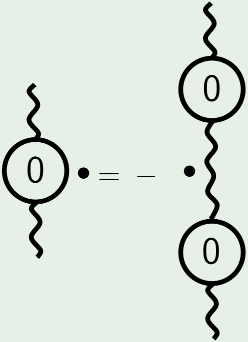
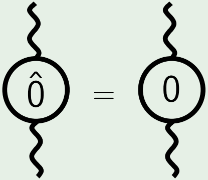


Choose



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The Classical Flow Equation

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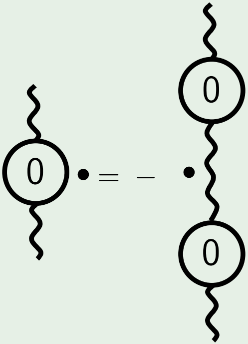

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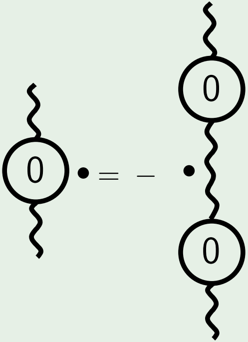
- Gauge Invariance:

The Classical Flow Equation

Example (Classical $A^1 A^1$ Vertex)



- Gauge Invariance: $p_\mu \, S^{11}_{0\mu\nu}(p) = 0$

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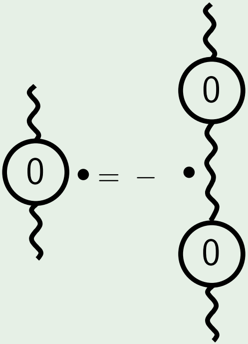
The Classical Flow Equation

Example (Classical $A^1 A^1$ Vertex)



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The Classical Flow Equation

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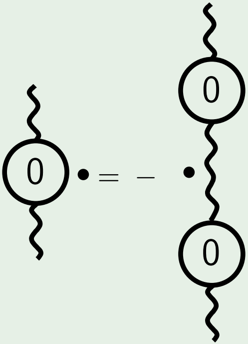

- Gauge Invariance: $p_\mu \, S^{11}_{0\mu\nu}(p) = 0$
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The Classical Flow Equation

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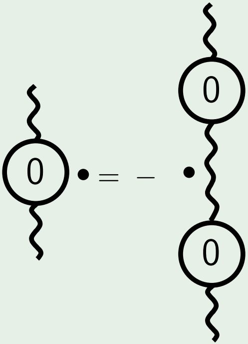

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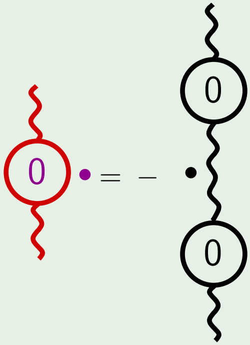

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The Classical Flow Equation

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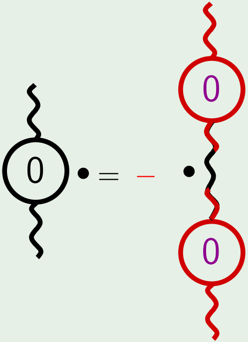

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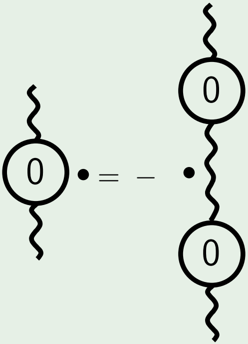

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The Classical Flow Equation

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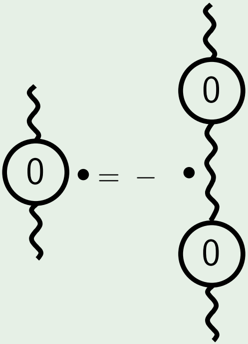

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The Classical Flow Equation

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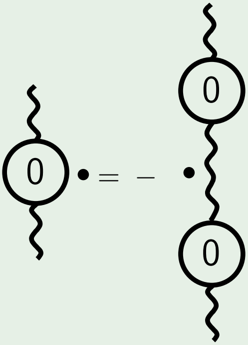

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The Classical Flow Equation

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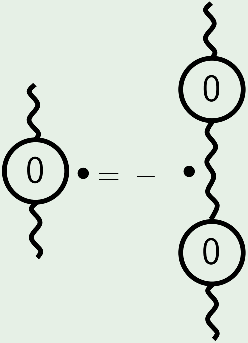

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- $A(p)\Delta^{11}(p) = \frac{1}{p^2}$
- $S^{11}_{0\mu\nu}(p)\Delta^{11}(p) = \delta_{\mu\nu} - \frac{p_\mu p_\nu}{p^2}$

$\Delta^{11}(p)$ is an Effective Propagator

$$S_{0\mu\nu}^{11}(p)\Delta^{11}(p) = \delta_{\mu\nu} - \frac{p_\mu p_\nu}{p^2}$$

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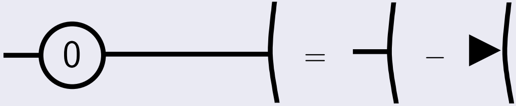
  - Relationship to $S^{11}_{0\mu\nu}(p)$ down to choice of $\hat{S}$

The Effective Propagator Relation

Diagrammatics

- The effective propagator relation works in all sectors



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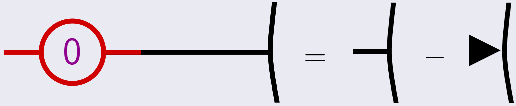

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The Effective Propagator Relation

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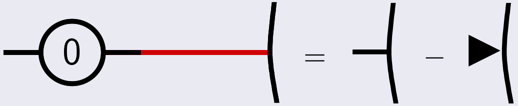

  - Two-point, classical vertex
  - Effective Propagator (always an internal line)

The Effective Propagator Relation

Diagrammatics

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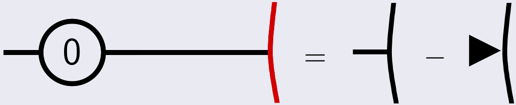

- Two-point, classical vertex
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- Arbitrary Structure

The Effective Propagator Relation

Diagrammatics

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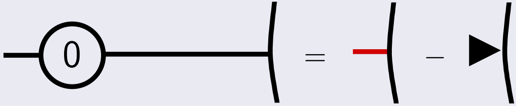

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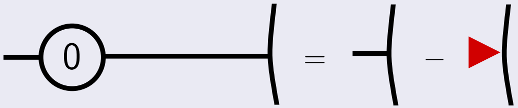

- Two-point, classical vertex
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The Effective Propagator Relation

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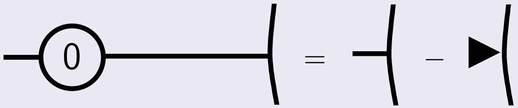

  - Two-point, classical vertex
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  - Arbitrary Structure
  - Kronecker δ part
  - Gauge Remainder (null in C sector)
- ERG sufficiently general for $\Delta^{11}(p) \neq \Delta^{22}(p)$
  - $S_{0\mu\nu}^{11}(p) \neq S_{0\mu\nu}^{22}(p)$

Universal Computation

Renormalisation Condition for g:

- $S[\mathcal{A} = A^1, \mathcal{C} = \sigma] = \frac{1}{2g^2} \operatorname{str} \int d^D x \, \left(F^1_{\mu\nu}\right)^2 + \cdots$

Universal Computation

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Universality

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  - The $\mathcal{O}(p^2)$ part of $S^{\,11}_{0\mu\nu}(p)$

Universal Computation

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Universality

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  - The $\mathcal{O}(p^2)$ part of $S^{\;11}_{0\mu\nu}(p)$
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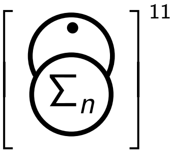
  - The A^1 gauge remainders
- All non-universal contributions cancel, diagrammatically!

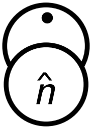
β_{n+1} Diagrammatics

$$-8\beta_{n+1}\Box_{\mu\nu}(p) + \cdots =$$



β_{n+1} Diagrammatics

$$-8\beta_{n+1}\Box_{\mu\nu}(p) + \cdots = \Bigg[-2$$



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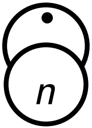
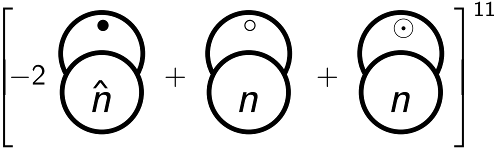


$$\Bigg]^{11}$$

β_{n+1} Diagrammatics

$$-8\beta_{n+1}\Box_{\mu\nu}(p) + \cdots =$$



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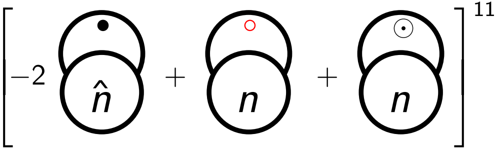

- Must be decorated

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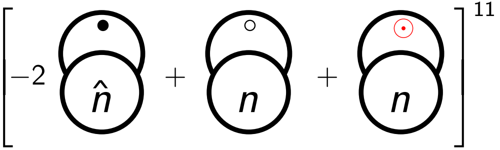

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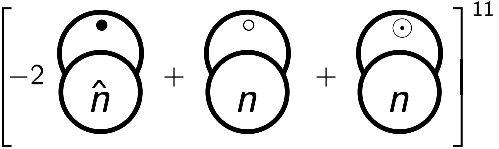
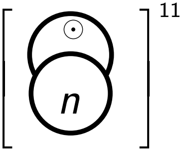
β_{n+1} Diagrammatics

$-8\beta_{n+1}\Box_{\mu\nu}(p) + \cdots =$ 



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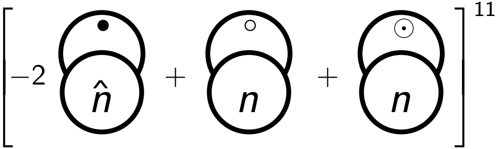

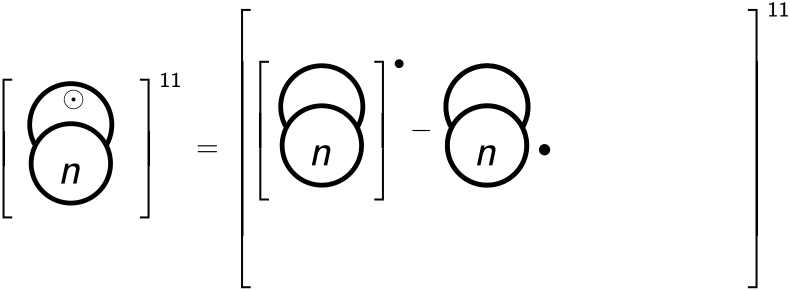

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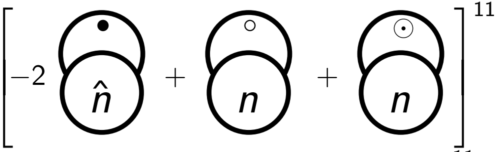

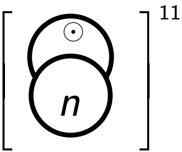

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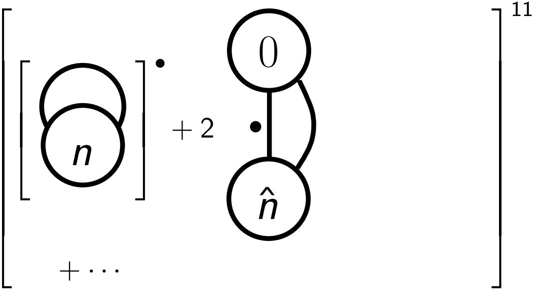

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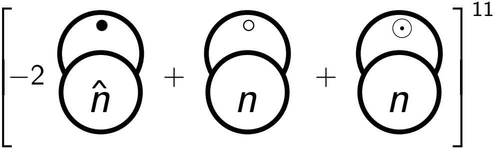

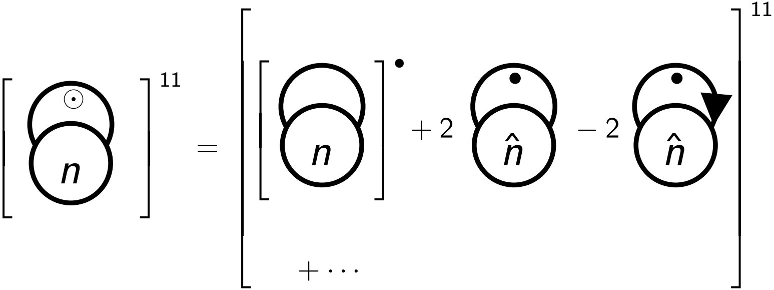

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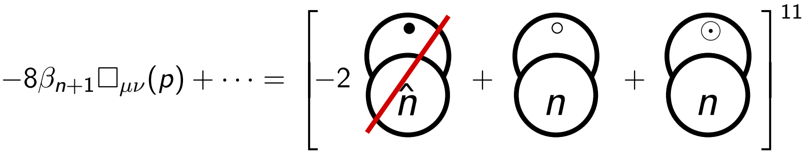

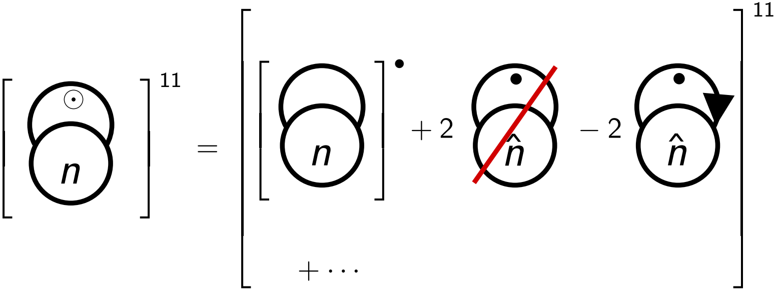

Iterating the Diagrammatic Procedure

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Cancellations to all orders

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- All explicit instances of $\hat{S}$

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Cancellations to all orders

- All explicit instances of $\hat{S}$
- All explicit details of the covariantisation

A Universal β Function?

What does β_n depend on?

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Cancellation of Remaining non-Universality

- Trivial, at one loop
- Iterative, diagrammatic procedure at two loops
- Iterative, diagrammatic procedure at n loops??
- Strong suggestion that all β_n can be arranged to depend only on the universal details of this ERG

Future Directions

Perturbative

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- Complete analysis of universality of β_n

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Evaluating the Λ-Derivative Terms

Strategy

◂ Return

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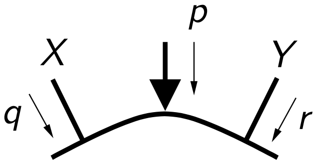
Diagrammatics for Gauge Remainders

Return



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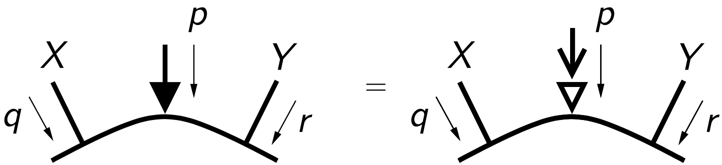

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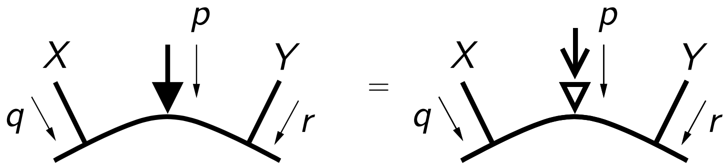

$$\triangleright = \begin{cases} p_\rho & A^i \\ p_R = (p_\rho, 2) & F \;\; \bar{F} \\ \text{null} & C^i \end{cases}$$

Diagrammatics for Gauge Remainders

Return