
iTHEMS
RIKEN Center for Interdisciplinary
Theoretical and Mathematical Sciences
RIKEN's
Programs for
Junior Scientists

Chiral gauge theories

$$S = \int_x \frac{1}{4} F^a_{\mu\nu} F^a_{\mu\nu} + \psi^\dagger \bar{\sigma}^\mu D_\mu \psi + \chi^\dagger \bar{\sigma}^\mu D_\mu \chi$$

Chiral: Weyl fermions, only left (right)-handed

- Phenomenology:
  - SM and BSM physics (GUTs, preon models, …)

Georgi,Glashow'74 Raby,Dimopoulos,Susskind '79 Bars,Yankielowitz'81 … Bolognesi,Konishi,Orso[2605.10416] Cacciapaglia,Sannino,Wagner [2605.08294]

- Theory:
  - understand QFT
  - conjectured **rich** and **unexplored** dynamics, a challenge
    - ★Exotic condensates
    - ★Tumbling: several patterns of SB
    - ★Symmetric Mass Generation

Wang,You[2204.14271] Karasik,Önder,Tong[2208.07842] Tong[2104.03997]

	$SU(N_c)$	$SU(N_c-4)$	$U(1)$
ψ	$\overline{\square}$	$\square$	$-(N_c-2)$
χ	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$	1	N_c-4

Bars-Yankielowitz (BY)

	$SU(N_c)$	$SU(N_c+4)$	$U(1)$
ψ	$\overline{\square}$	$\square$	$-(N_c-2)$
χ	$\square\square$	1	N_c+4

What do we know?

Method	Major challenges	Results
Monte Carlo Lattice simulations Nielsen,Ninomiya'80'81Eichten,Preskill'86	Doubler and sign problems	
Most Attractive Channel Raby,Dimopoulos,Susskind '79 Dimopoulos,Raby,Susskind '80 Eichten,Feinberg '82	Too naive	*Color-flavor-locked* IR with $\langle\chi\psi\rangle$
Large N Eichten,Peccei,Preskill,Zeppenfeld'86 Karasik,Önder,Tong[2208.07842]	Finite N	If confinement, no dSB
Anomaly mediated SUSY breaking Csáki,Murayama,Telem[2105.03444]	Non-SUSY limit	Conformal theories for few N<13 and for larger, $\langle\chi\psi\rangle$ and $\langle\chi\chi\rangle$
Anomaly matching, discrete symmetries and higher forms 't Hooft '80 Bolognesi,Konishi,Luzio[2101.02601] Bars,Yankielowitz'81	Not sufficiently constraining	Massless $\mathcal{B}\sim\langle\chi\psi\psi\rangle$ baryons with no dSB, or *color-flavor-locked* phase

What do we know?

Method	Major challenges	Results
Monte Carlo Lattice simulations Nielsen,Ninomiya'80'81Eichten,Preskill'86		
Most Attractive Channel Raby,Dimopoulos,Susskind '79 Dimopoulos,Raby,Susskind '80 Eichten,Feinberg '8		*lavor-locked* IR with $\langle\chi\psi\rangle$
Large N Eichten,Peccei,Preskill,Zeppenfeld'86 Karasik,Önder,Tong[2208.07842]	Finite N	If confinement, no dSB
Anomaly mediated SUSY breaking Csáki,Murayama,Telem[2105.03444]	Non-SUSY limit	Conformal theories for few N<13 and for larger, $\langle\chi\psi\rangle$ and $\langle\chi\chi\rangle$
Anomaly matching, discrete symmetries and higher forms 't Hooft '80 Bolognesi,Konishi,Luzio[2101.02601] Bars,Yankielowitz'81	Not sufficiently constraining	Massless $\mathcal{B}\sim\langle\chi\psi\psi\rangle$ baryons with no dSB, or *color-flavor-locked* phase

In conclusion:

no good understanding of the IR

What do we know?

Method	Major challenges	Results
Monte Carlo Lattice simulations Nielsen,Ninomiya'80'81Eichten,Preskill'86		
Most Attractive Channel Raby,Dimopoulos,Susskind '79 Dimopoulos,Raby,Susskind '80 Eichten,Feinberg '8		*lavor-locked* IR with $\langle\chi\psi\rangle$
Large N Eichten,Peccei,Preskill,Zeppenfeld'86 Karasik,Önder,To	Finite N	If confinement, no dSB
Anomaly m Csáki,Murayama,		<13 and
Anomaly matching, discrete symmetries and higher forms 't Hooft '80 Bolognesi,Konishi,Luzio[2101.02601] Bars,Yankielowitz'81	Not sufficiently constraining	Massless $\mathcal{B} \sim \langle\chi\psi\psi\rangle$ baryons with no dSB, or *color-flavor-locked* phase

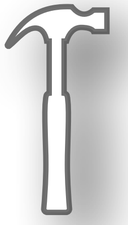
In conclusion:

no good understanding of the IR

A new path:

Functional methods

Functional Renormalisation Group



- Progressive integration of momentum shells:

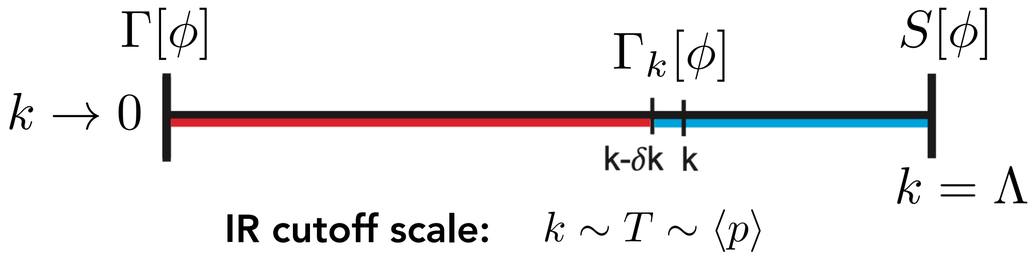
$$\int [\mathcal{D}\phi]_{p>k} = \int \mathcal{D}\phi \, \exp(-\Delta S_k[\phi]) \qquad \Delta S_k[\phi] = \int_p \phi(p) \, R_k(p) \, \phi(-p)$$

- **Effective average action**:

$$\Gamma_k[\phi] = \int_x J(x)\phi(x) - \mathcal{W}_k[J] - \Delta S_k[\phi] \qquad \text{Wetterich '89}$$

- Average action of fields over a k^{-d} space-time volume

- Kadanoff's block-spinning idea in the continuum limit



IR cutoff scale: $k \sim T \sim \langle p \rangle$

➡ Pedagogical introduction: Gies [0611146] ➡ Review: Dupuis,et.al [2006.04853]

Functional Renormalisation Group

- Progressive integration of momentum shells:

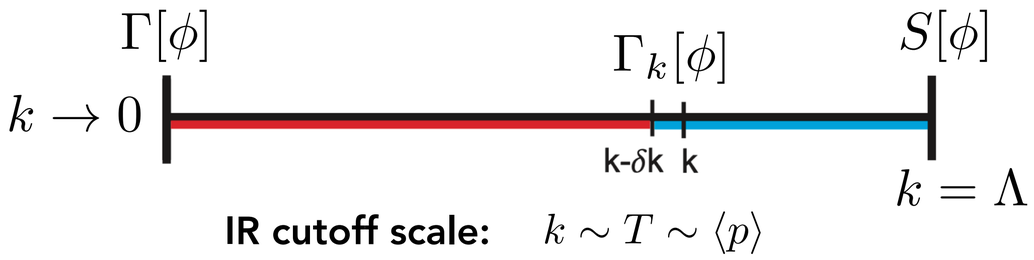
$$\int [\mathcal{D}\phi]_{p>k} = \int \mathcal{D}\phi \, \exp(-\Delta S_k[\phi]) \qquad \Delta S_k[\phi] = \int_p \phi(p)\, R_k(p)\, \phi(-p)$$

- **Effective average action**:

$$\Gamma_k[\phi] = \int_x J(x)\phi(x) - \mathcal{W}_k[J] - \Delta S_k[\phi] \qquad \text{Wetterich '89}$$

- Average action of fields over a k^{-d} space-time volume

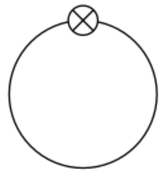
- Kadanoff's block-spinning idea in the continuum limit



IR cutoff scale: $k \sim T \sim \langle p \rangle$

Flow equation:

$$\partial_t \Gamma_k[\phi] = \frac{1}{2}\mathrm{Tr}\left[\frac{1}{\Gamma_k^{(2)} + R_k}\partial_t R_k\right] = \frac{1}{2}$$



$\partial_t \equiv k\,\partial_k$ Wetterich '93

- Exact
- Non-perturbative
- One loop
- Analytic regulators
- Versatile
- UV-IR finite
- Systematic truncation schemes
- Chiral regulators

$$R_{\psi/\chi,\,k}(p^2) = \mathrm{i}\, Z_{\psi/\chi}\, \bar{\sigma}_\mu p_\mu\, r_{\psi/\chi}(x)$$

$$r_{\psi/\chi}(x) = (1/\sqrt{x} - 1)\,\theta\,(1-x)$$

…

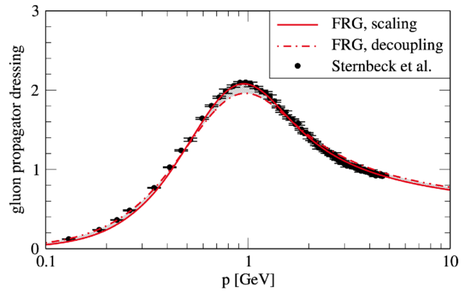
➡ Pedagogical introduction: Gies [0611146] ➡ Review: Dupuis,et.al [2006.04853]

Some results in gauge-fermion theories

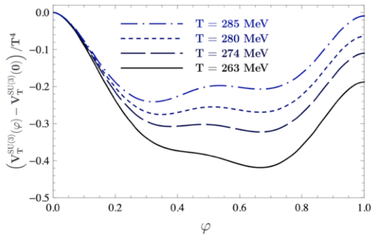
a.k.a. QCD

Colour confinement

Cyrol,Fister,Mitter,Pawlowski [1605.01856]

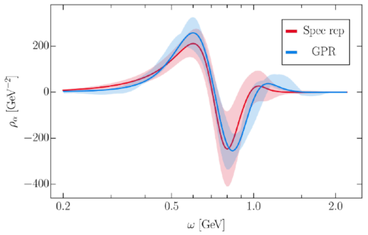


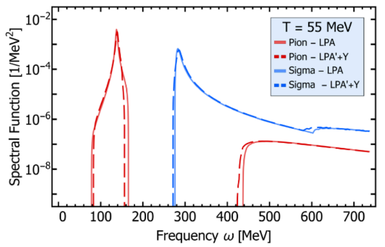
Fister,Pawlowski [1301.4163]



Real time properties

Horak,Pawlowski,Turnwald,Urban,Wink, Zafeiropoulos[1711.07444]

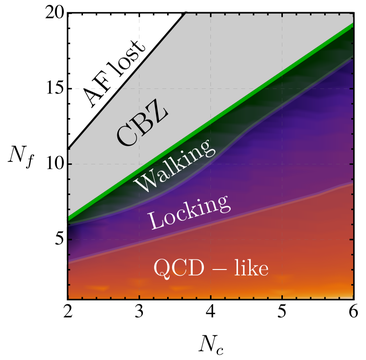




Pawlowski,Wink,Strodthoff[1711.07444]

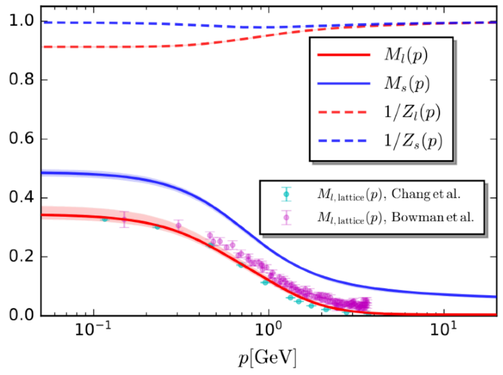
Many flavour and colours

Gies,Jaeckel[hep-ph/0507171]
Braun,Gies[0912.4168]
Braun,Fischer,Gies[1012.4279]
Goertz,APG,Pawlowski[2412.12254]

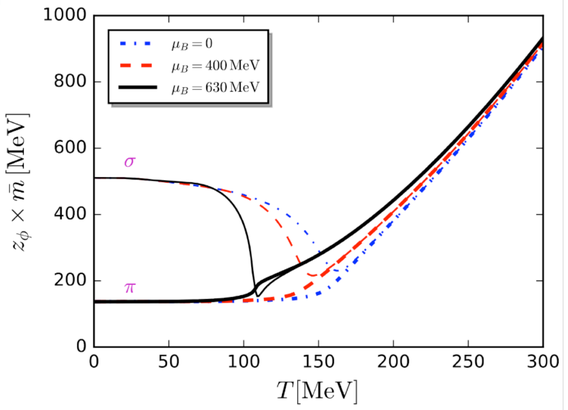


Dynamical chiral symmetry and bound states

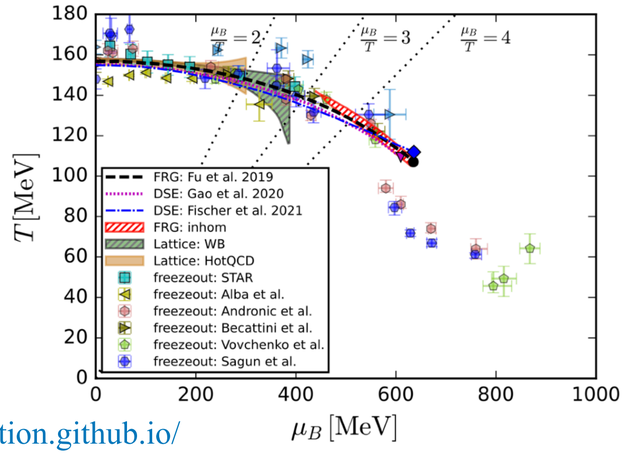
Fu,Huang,Pawlowski,Tan,Zhou[2502.14388]



Fu,Pawlowski,Rennecke [1909.02991]



Finite temperature and chemical potential



https://fqcd-collaboration.github.io/

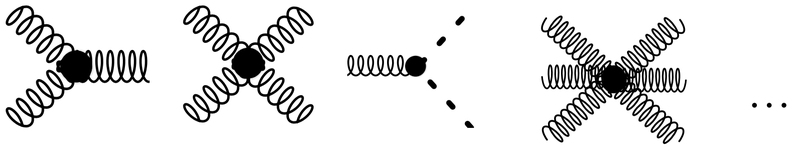
Effective action for gauge-fermion theories

$$\Gamma[A_\mu, \bar{c}, c, \chi^\dagger, \chi, \psi^\dagger, \psi]$$

Effective action for gauge-fermion theories

$$\Gamma[A_\mu, \bar{c}, c, \chi^\dagger, \chi, \psi^\dagger, \psi]$$

$$\Gamma_{\text{gauge}}[A_\mu, \bar{c}, c]$$

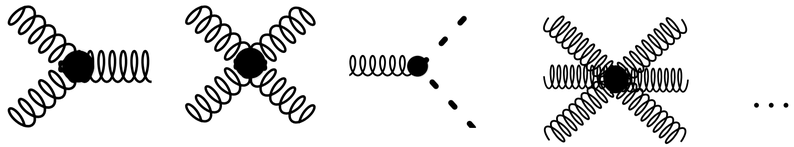


Asymptotic freedom and colour confinement

Effective action for gauge-fermion theories

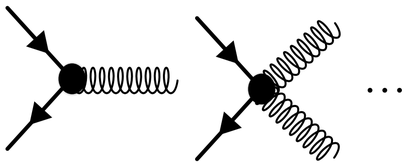
$$\Gamma[A_\mu, \bar{c}, c, \chi^\dagger, \chi, \psi^\dagger, \psi]$$

$$\Gamma_{\text{gauge}}[A_\mu, \bar{c}, c]$$



Asymptotic freedom and colour confinement

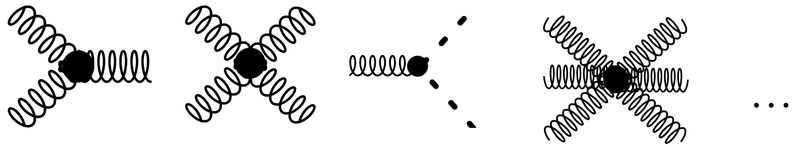
$$\Gamma_{\text{gauge-fermion}}[A_\mu, \chi^\dagger, \chi, \psi^\dagger, \psi]$$



Effective action for gauge-fermion theories

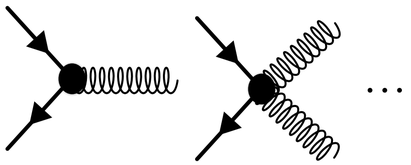
$$\Gamma[A_\mu, \bar{c}, c, \chi^\dagger, \chi, \psi^\dagger, \psi]$$

$$\Gamma_{\text{gauge}}[A_\mu, \bar{c}, c]$$

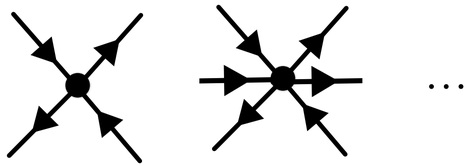


Asymptotic freedom and colour confinement

$$\Gamma_{\text{gauge-fermion}}[A_\mu, \chi^\dagger, \chi, \psi^\dagger, \psi]$$



$$\Gamma_{\text{fermion}}[\chi^\dagger, \chi, \psi^\dagger, \psi]$$



Emergence of a condensate, fermionic bound states …

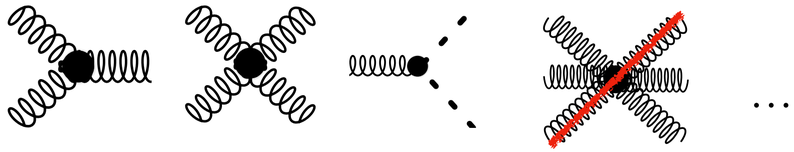
Effective action for gauge-fermion theories

Truncation of the effective action here:

- Keep canonically (marginal) relevant operators and four-fermion interactions
- Minimal setup to describe dSB and confinement

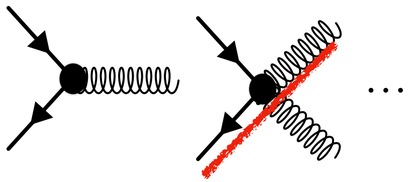
$$\Gamma[A_\mu, \bar{c}, c, \chi^\dagger, \chi, \psi^\dagger, \psi]$$

$$\Gamma_{\text{gauge}}[A_\mu, \bar{c}, c]$$

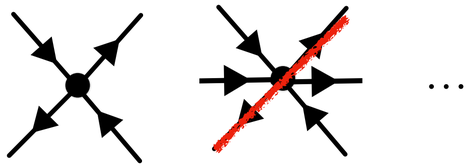


Asymptotic freedom and colour confinement

$$\Gamma_{\text{gauge-fermion}}[A_\mu, \chi^\dagger, \chi, \psi^\dagger, \psi]$$



$$\Gamma_{\text{fermion}}[\chi^\dagger, \chi, \psi^\dagger, \psi]$$



Emergence of a condensate, fermionic bound states …

Signatures of colour confinement and the gluon mass gap

Alkofer,von Smekal'96'00 Pawlowski,Litim,Nedelko,von Smekal[hep-th/0312324] Fischer, Maas, Pawlowski[0810.1987] Cyrol,Fister,Mitter,Pawlowski [1605.01856]…

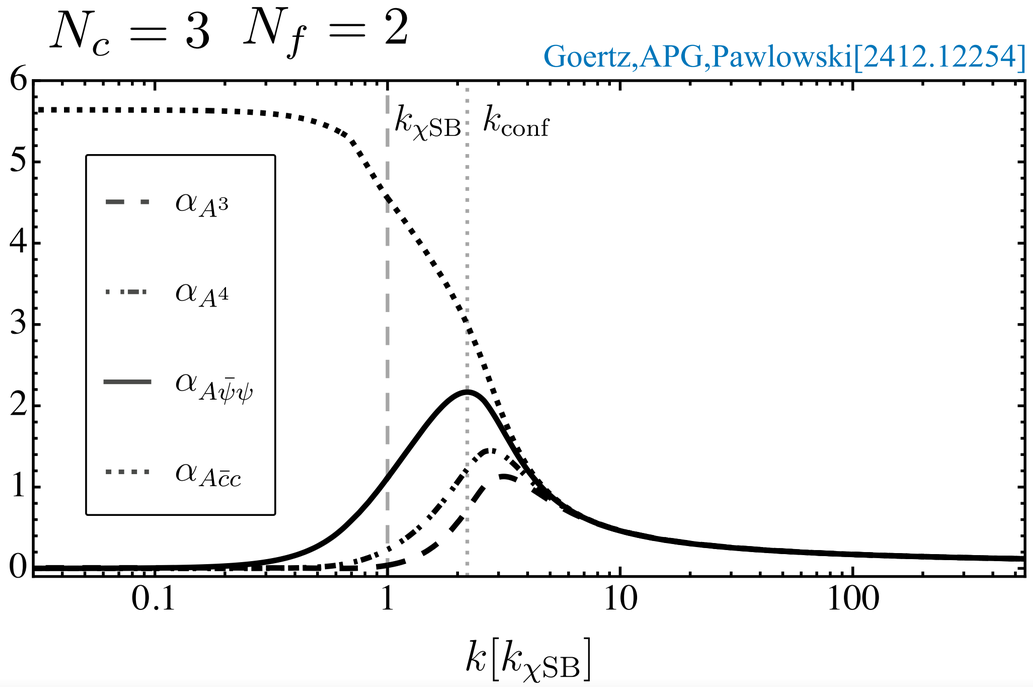
- **Gluon mass gap** generated by **quantum fluctuations**

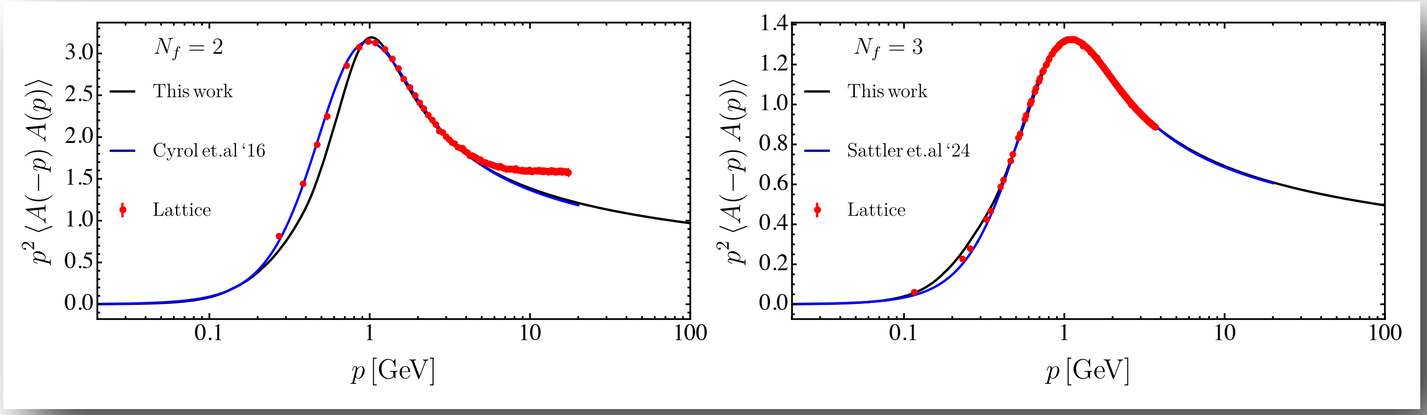
$$\Gamma_k^{(AA)}(p^2) = Z_{A,k}(p)(p^2 + m^2_{\text{gap},k}) = \hat{Z}_{A,k}(p)\, p^2$$

- How we know its confinement?
  - **Kugo-Ojima criterion satisfied** Kugo, Ojima'79 Nakanishi,Ojima'90
    - Sufficient conditions: **Massive spectrum** of **physical states** in the **Hilbert space** and a **global BRST** transformation
    - **Unique** IR scaling of correlation functions

$$\lim_{p\to 0} Z_A(p^2) \propto (p^2)^{-2\kappa} \qquad \lim_{p\to 0} Z_c(p^2) \propto (p^2)^{\kappa}$$

Kugo[hep-th/9511033]





Dynamical symmetry breaking in the effective action

a chiral QCD example

$$S = \int_x \frac{1}{4} F^a_{\mu\nu} F^a_{\mu\nu} + \mathcal{L}_{\text{gf}} + \mathcal{L}_{\text{gh}} + \bar{\psi} \gamma_\mu D_\mu \psi$$

Dynamical symmetry breaking in the effective action

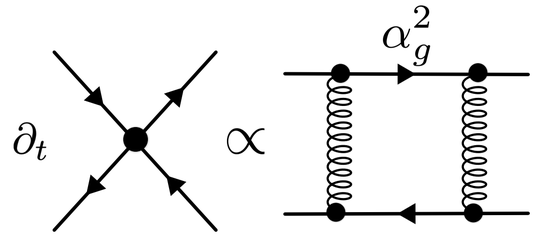
a chiral QCD example

$$\Gamma = \int_x \frac{1}{4} F^a_{\mu\nu} F^a_{\mu\nu} + \mathcal{L}_{\mathrm{gf}} + \mathcal{L}_{\mathrm{gh}} + \lambda_i \left(\bar{\psi} \mathcal{T}_i \psi\right)^2 + \kappa_i \left(\bar{\psi} \mathcal{T}_i \psi\right)^3 + \dots$$

Dynamical symmetry breaking in the effective action

a chiral QCD example

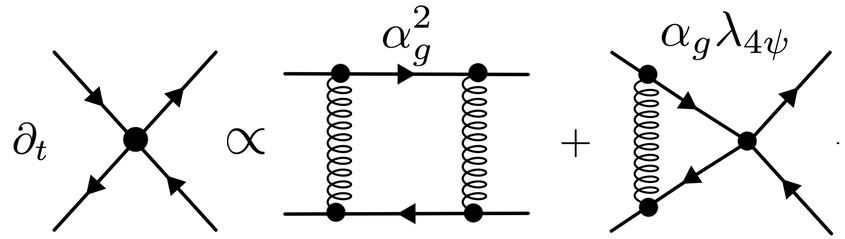
$$\Gamma = \int_x \frac{1}{4} F^a_{\mu\nu} F^a_{\mu\nu} + \mathcal{L}_{\mathrm{gf}} + \mathcal{L}_{\mathrm{gh}} + \lambda_i \left(\bar{\psi} \mathcal{T}_i \psi\right)^2 + \kappa_i \left(\bar{\psi} \mathcal{T}_i \psi\right)^3 + \dots$$



Dynamical symmetry breaking in the effective action

a chiral QCD example

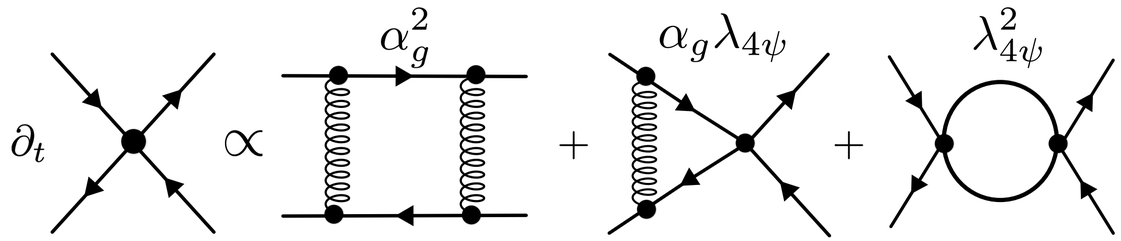
$$\Gamma = \int_x \frac{1}{4} F^a_{\mu\nu} F^a_{\mu\nu} + \mathcal{L}_{\rm gf} + \mathcal{L}_{\rm gh} + \lambda_i \left(\bar{\psi} \mathcal{T}_i \psi\right)^2 + \kappa_i \left(\bar{\psi} \mathcal{T}_i \psi\right)^3 + \dots$$



Dynamical symmetry breaking in the effective action

a chiral QCD example

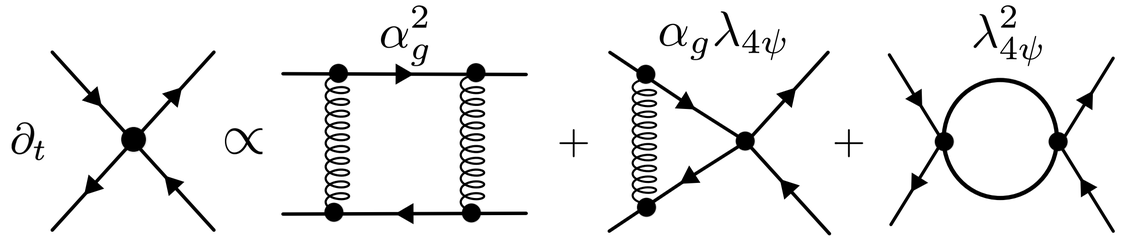
$$\Gamma = \int_x \frac{1}{4} F^a_{\mu\nu} F^a_{\mu\nu} + \mathcal{L}_{\mathrm{gf}} + \mathcal{L}_{\mathrm{gh}} + \lambda_i \left(\bar{\psi} \mathcal{T}_i \psi\right)^2 + \kappa_i \left(\bar{\psi} \mathcal{T}_i \psi\right)^3 + \dots$$

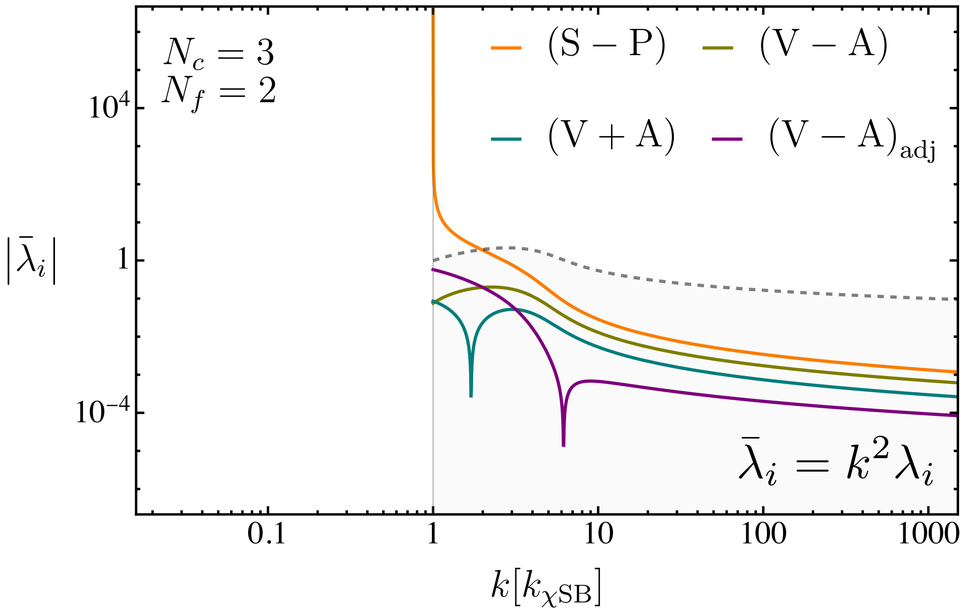


Dynamical symmetry breaking in the effective action

a chiral QCD example

$$\Gamma = \int_x \frac{1}{4} F^a_{\mu\nu} F^a_{\mu\nu} + \mathcal{L}_{\rm gf} + \mathcal{L}_{\rm gh} + \lambda_i \left(\bar{\psi} \mathcal{T}_i \psi\right)^2 + \kappa_i \left(\bar{\psi} \mathcal{T}_i \psi\right)^3 + \dots$$

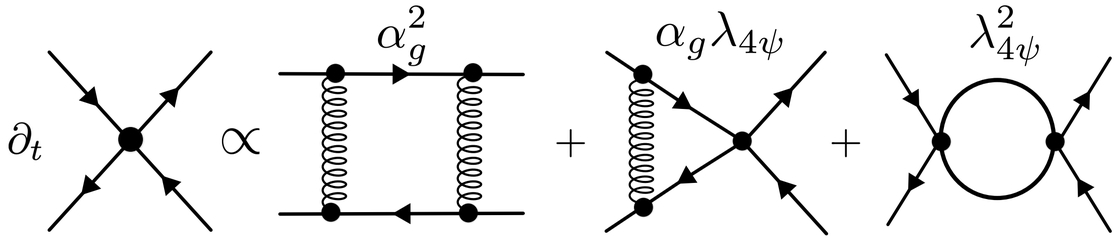


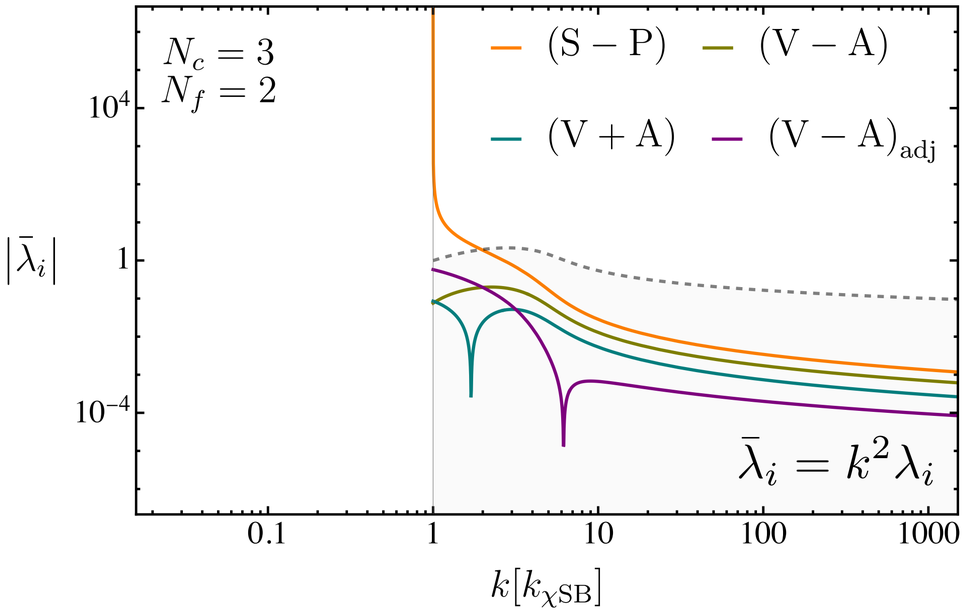


Dynamical symmetry breaking in the effective action

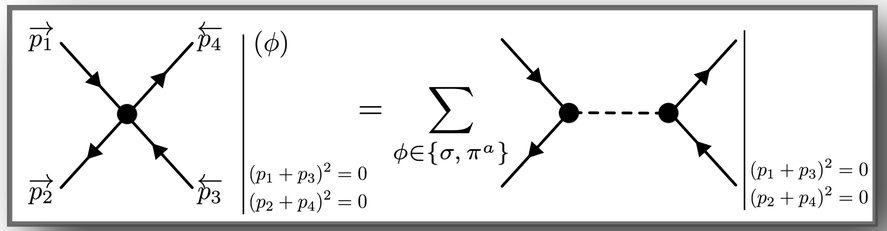
a chiral QCD example

$$\Gamma = \int_x \frac{1}{4} F^a_{\mu\nu} F^a_{\mu\nu} + \mathcal{L}_{\rm gf} + \mathcal{L}_{\rm gh} + \lambda_i \left(\bar{\psi} \mathcal{T}_i \psi\right)^2 + \kappa_i \left(\bar{\psi} \mathcal{T}_i \psi\right)^3 + \dots$$





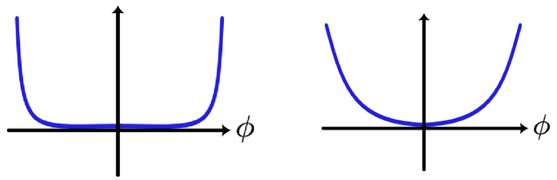
Stratonovich'57 Hubbard'59

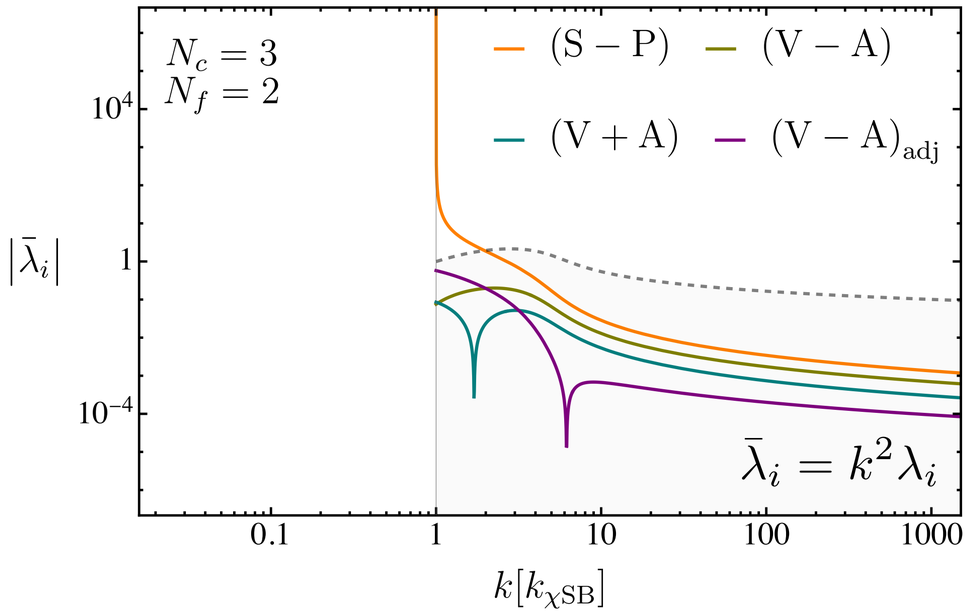


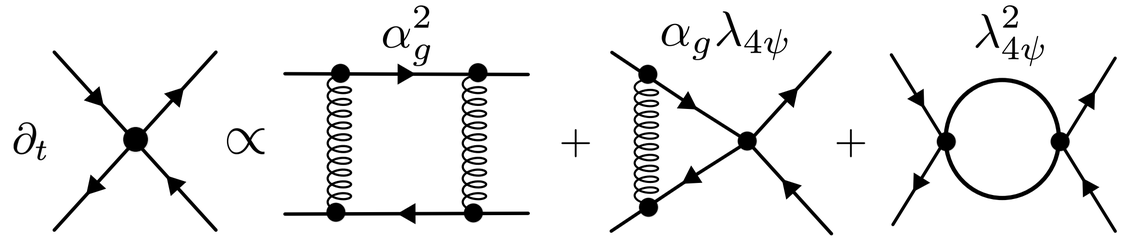
Dynamical symmetry breaking in the effective action

a chiral QCD example

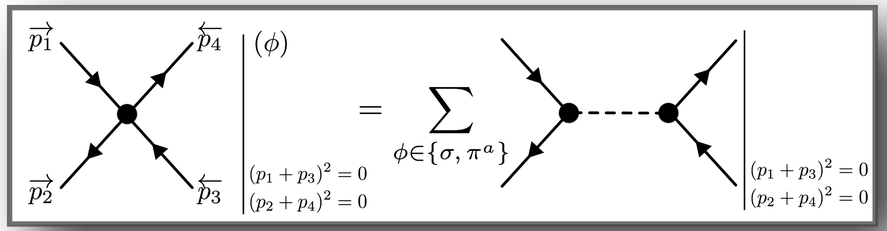
$$\Gamma = \int_x \frac{1}{4} F^a_{\mu\nu} F^a_{\mu\nu} + \mathcal{L}_{\rm gf} + \mathcal{L}_{\rm gh} + \lambda_i \left(\bar{\psi} \mathcal{T}_i \psi\right)^2 + \kappa_i \left(\bar{\psi} \mathcal{T}_i \psi\right)^3 + \dots$$







Stratonovich'57 Hubbard'59



$$\lambda_i \propto 1/m^2_{\phi_i}$$

$$m^2_{\phi_i} = \partial^2_{\phi_i} V(\phi_i)$$

Infinite correlation length:

$$\xi \to \infty$$

$$\lambda_i \to \infty \qquad m^2_{\phi_i} = 0$$

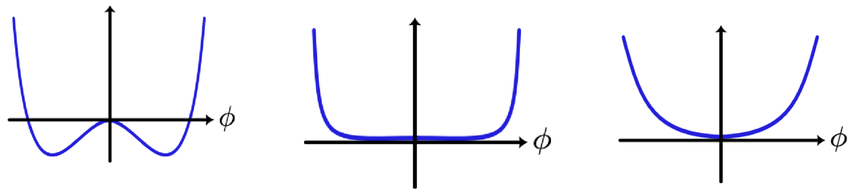
Phase transition

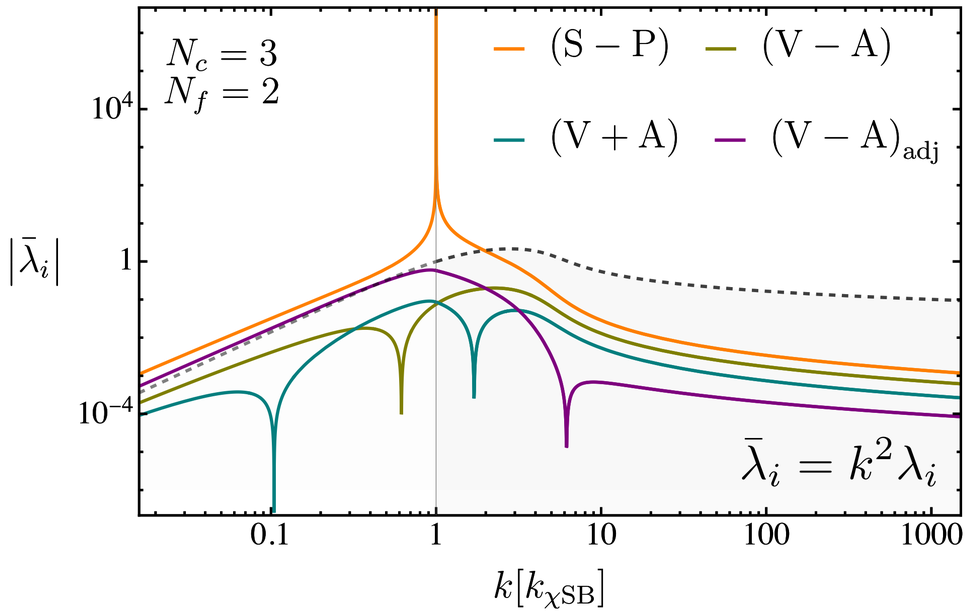
Nambu,Jona-Lasinio'60'61

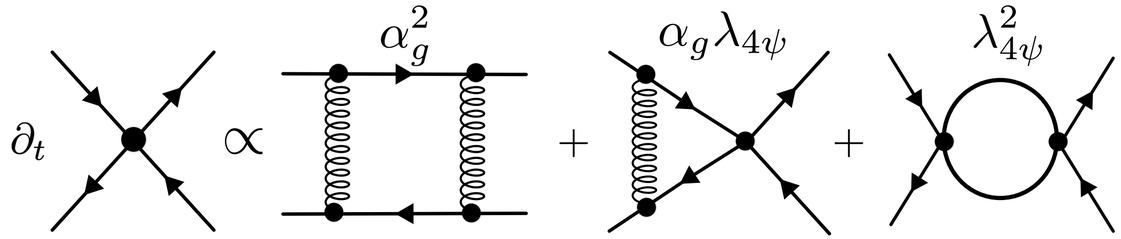
Dynamical symmetry breaking in the effective action

a chiral QCD example

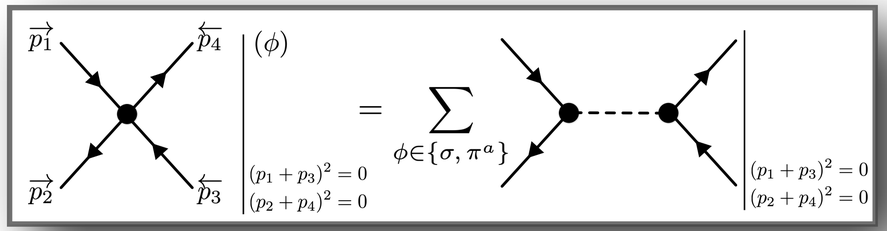
$$\Gamma = \int_x \frac{1}{4} F^a_{\mu\nu} F^a_{\mu\nu} + \mathcal{L}_{\rm gf} + \mathcal{L}_{\rm gh} + \lambda_i \left(\bar{\psi} \mathcal{T}_i \psi\right)^2 + \kappa_i \left(\bar{\psi} \mathcal{T}_i \psi\right)^3 + \dots$$







Stratonovich'57 Hubbard'59



$$\lambda_i \propto 1/m^2_{\phi_i}$$

$$m^2_{\phi_i} = \partial^2_{\phi_i} V(\phi_i)$$

Infinite correlation length:

$$\xi \to \infty$$

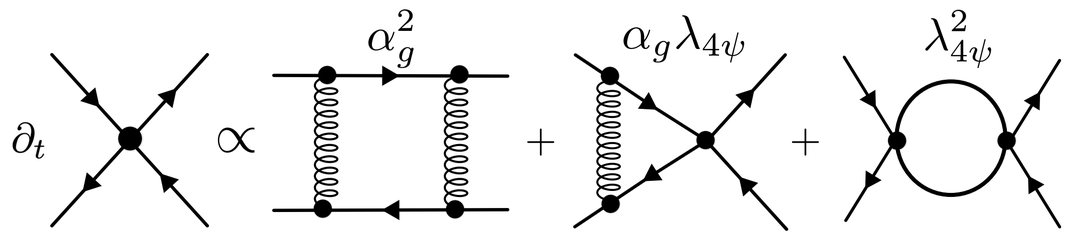
$$\lambda_i \to \infty \qquad m^2_{\phi_i} = 0$$

Phase transition

Nambu,Jona-Lasinio'60'61

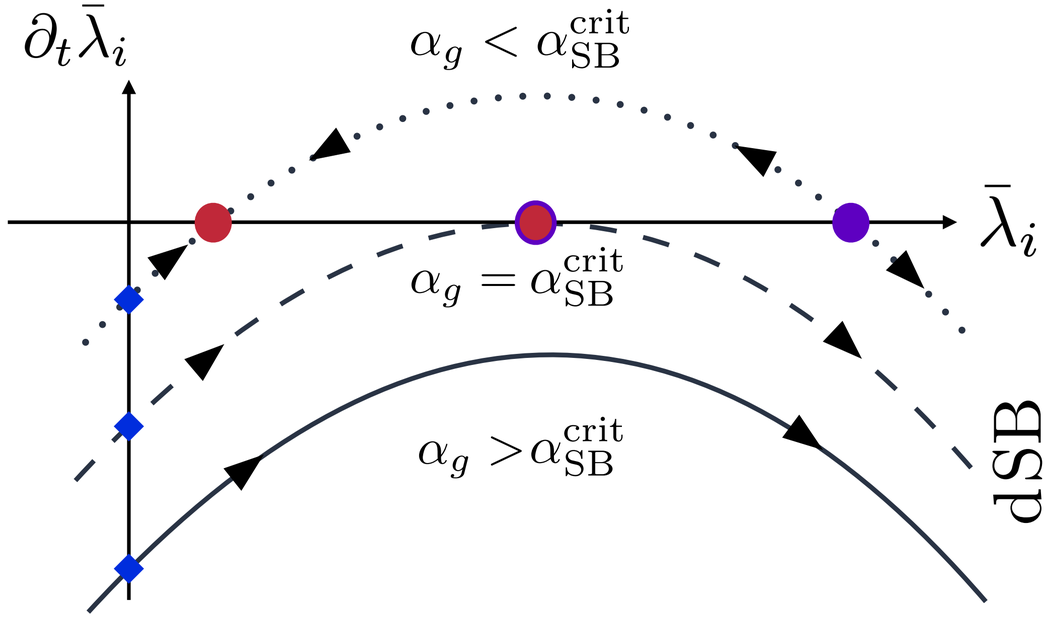
Mechanism underlying dSB

Nambu,Jona-Lasinio'60'61 Kosterlitz'74 Miransky'85 Jungnickel,Wetterich[hep-ph/9505267] Gies,Jaeckel[hep-ph/0507171] B.Kaplan,Lee,T.Son,Stephanov[0905.4752] Braun[1108.4449]



$$\partial_t \bar{\lambda}_i \propto 2\,\bar{\lambda}_i + \boldsymbol{c}_{\mathrm{A},i} \cdot \alpha_g^2 + \boldsymbol{c}_{\mathrm{B},ij} \cdot \alpha_g\,\bar{\lambda}_j + \boldsymbol{c}_{\mathrm{C},ijk} \cdot \bar{\lambda}_j \bar{\lambda}_k + \ldots$$

Critical strength of gauge dynamics $\alpha_g > \alpha_{\mathrm{SB}}^{\mathrm{crit}}$

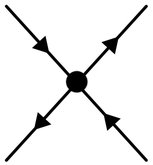


$$\alpha_{\mathrm{SB}}^{\mathrm{crit}} = \inf\left\{\alpha_g \,\middle|\, \exists\, i: \;\; \left(\partial_t \bar{\lambda}_i \leq 0 \quad \forall\, \bar{\lambda}_j\right)\right\}$$

Goertz,APG,Pawlowski[2412.12254]
Li,APG,Vatani,Xu[2507.21208]

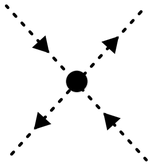
Fierz-complete four-fermion basis in chiral gauge theories

$$\Gamma_{\text{fermion},k}[\chi^\dagger,\chi,\psi^\dagger,\psi] = -\int_x \underbrace{Z_\psi^2 \sum_{i=1}^{2} \lambda_i \mathcal{O}_i^\psi}_{} + \underbrace{Z_\chi^2 \sum_{i=4}^{5} \lambda_i \mathcal{O}_i^\chi}_{} + \underbrace{Z_\psi Z_\chi \sum_{i=6}^{7} \lambda_i \mathcal{O}_i^{\chi\psi}}_{}$$



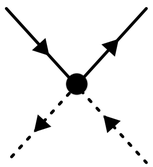
$$\mathcal{O}_1^\psi = (\psi^\dagger \bar{\sigma}^\mu \psi)(\psi^\dagger \bar{\sigma}^\mu \psi)$$

$$\mathcal{O}_2^\psi = (\psi^{\dagger f_1} \bar{\sigma}^\mu \psi_{f_2})(\psi^{\dagger f_2} \bar{\sigma}^\mu \psi_{f_1})$$



$$\mathcal{O}_4^\chi = (\chi^\dagger \bar{\sigma}^\mu \chi)(\chi^\dagger \bar{\sigma}^\mu \chi)$$

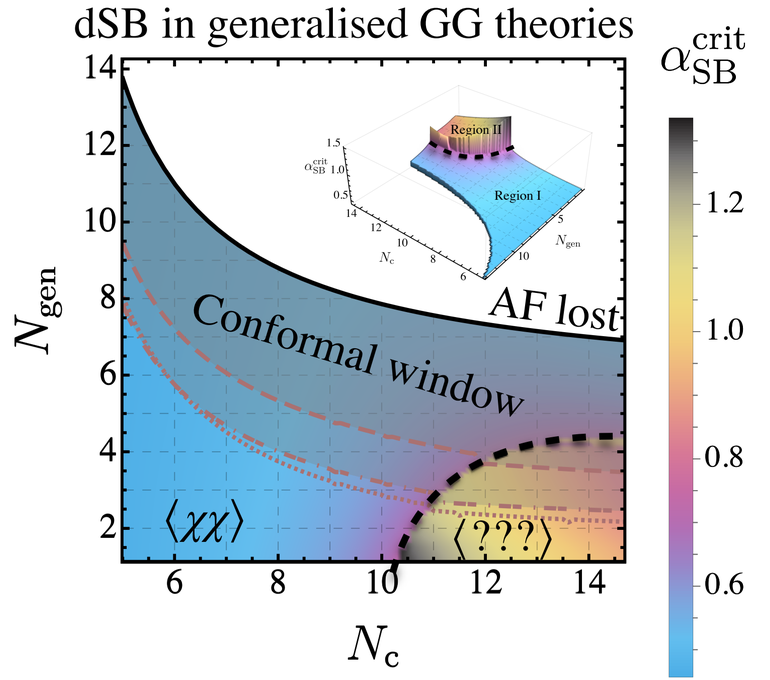
$$\mathcal{O}_5^\chi = (\chi^\dagger \bar{\sigma}^\mu T_{\text{sym}} \chi)(\chi^\dagger \bar{\sigma}^\mu T_{\text{sym}} \chi)$$



$$\mathcal{O}_6^{\chi\psi} = (\psi^\dagger \bar{\sigma}^\mu \psi)(\chi^\dagger \bar{\sigma}^\mu \chi)$$

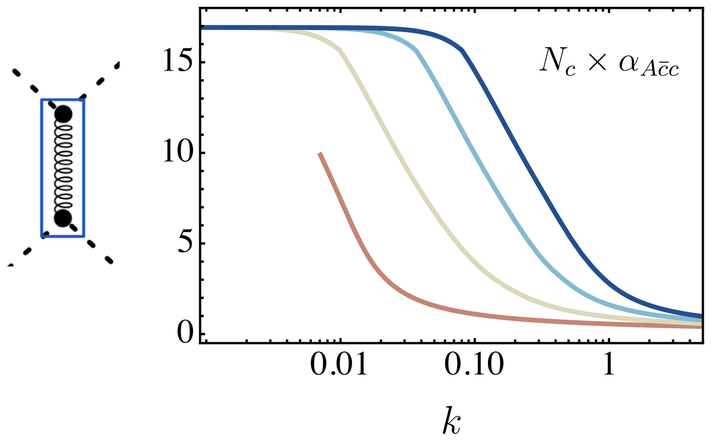
$$\mathcal{O}_7^{\chi\psi} = (\psi^\dagger \bar{\sigma}^\mu T_{\text{anti}} \psi)(\chi^\dagger \bar{\sigma}^\mu T_{\text{sym}} \chi)$$

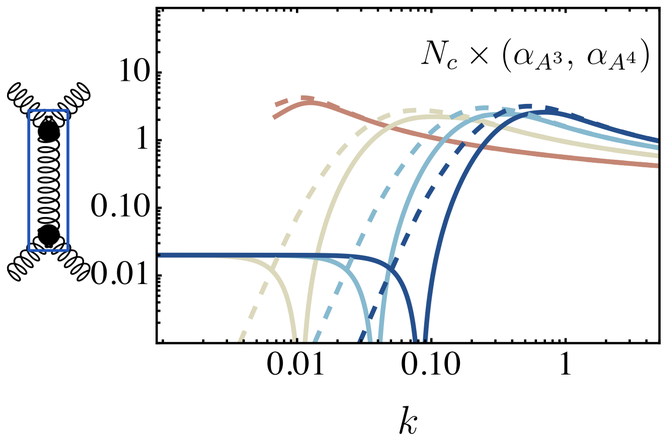
Li,APG,Vatani,Xu[2507.21208]

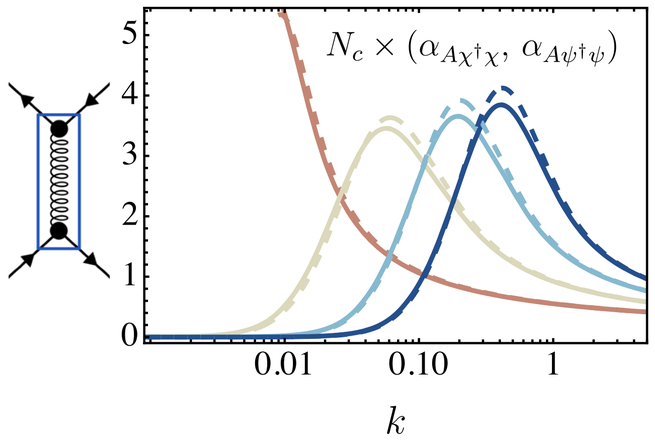


Colour-confinement and dSB in BY

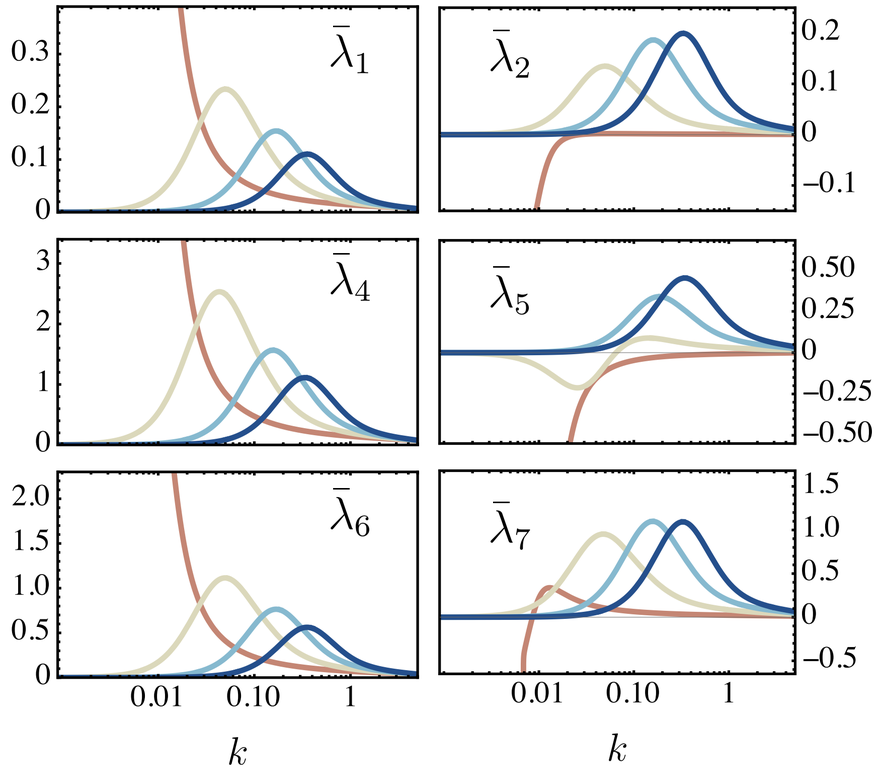
Li,APG,Vatani[2603.19355]





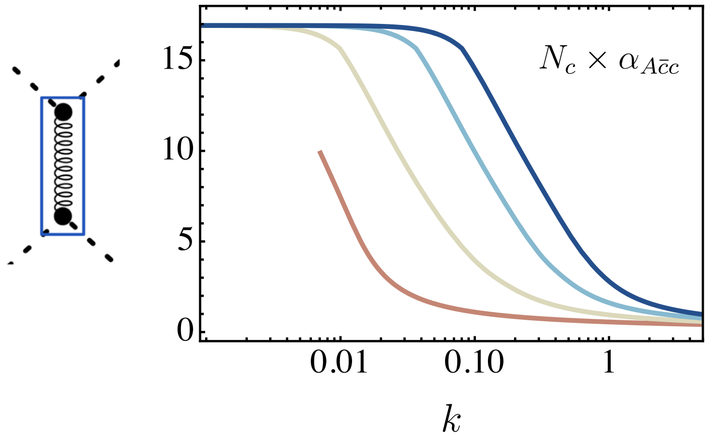


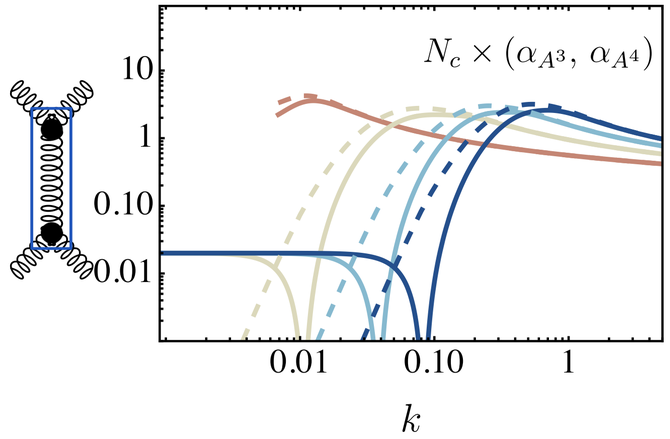
N_c : 3 4 5 6

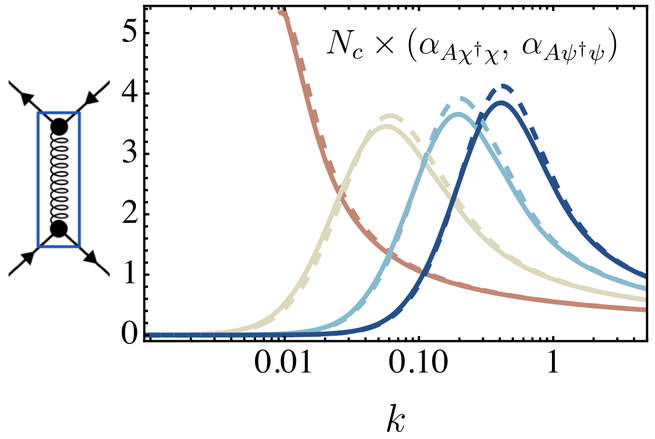


Colour-confinement and dSB in BY

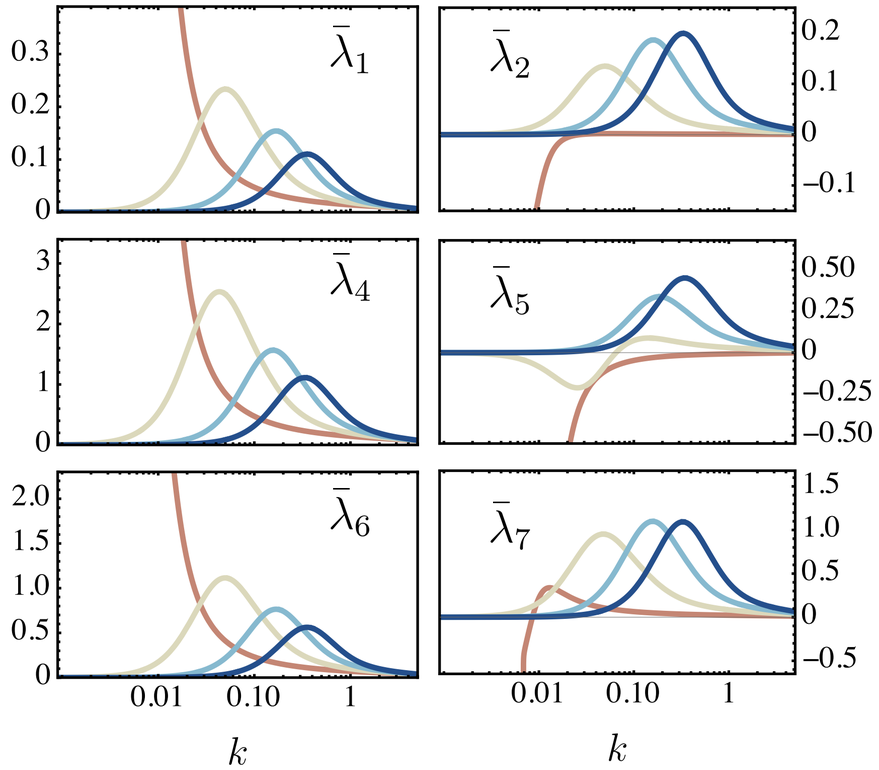
Li,APG,Vatani[2603.19355]







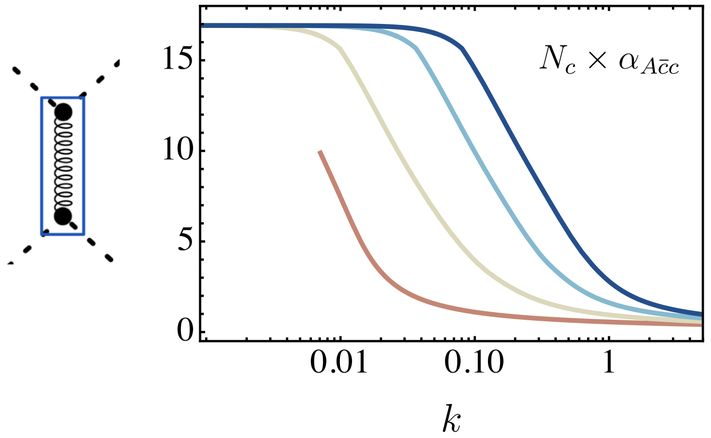
N_c : 3 4 5 6

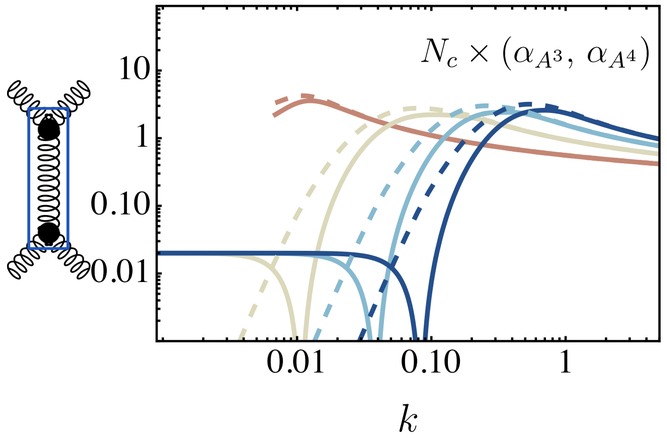


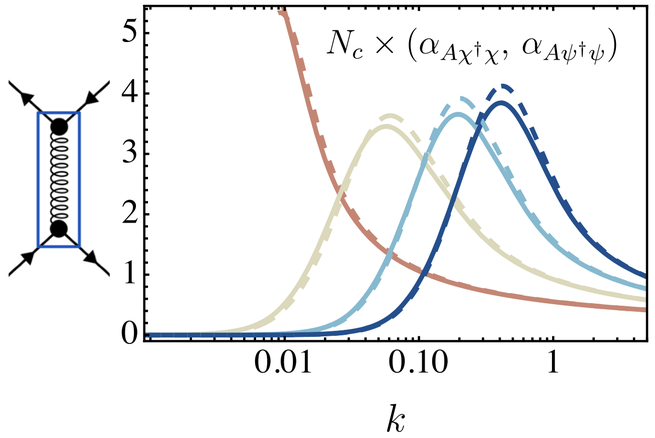
Signatures of confinement in the Landau gauge

Colour-confinement and dSB in BY

Li,APG,Vatani[2603.19355]





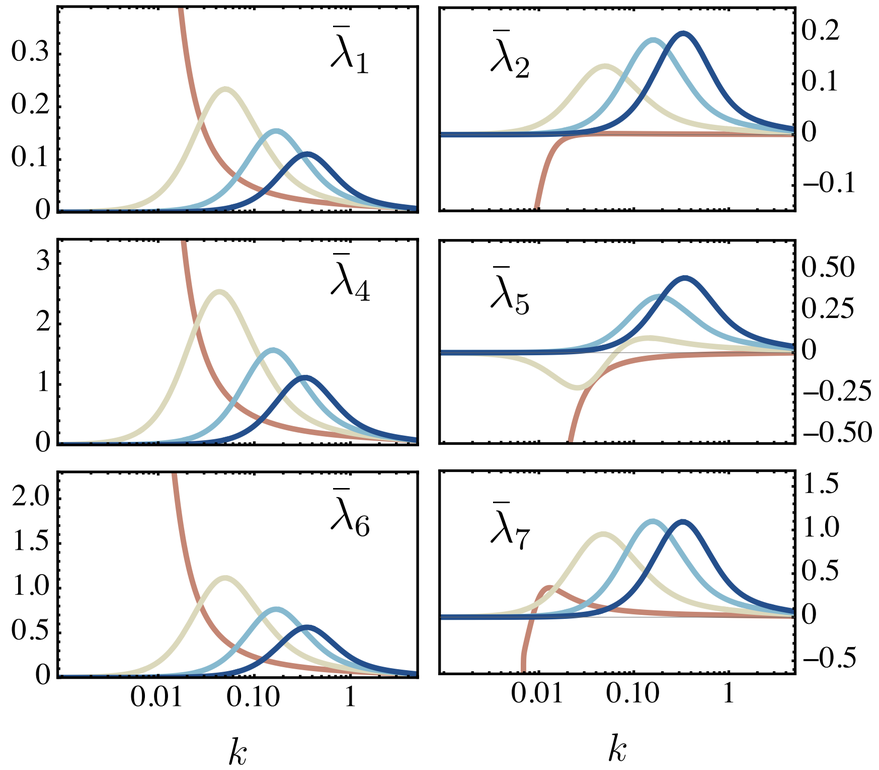


N_c : 3 | 4 5 6

Divergence → dSB

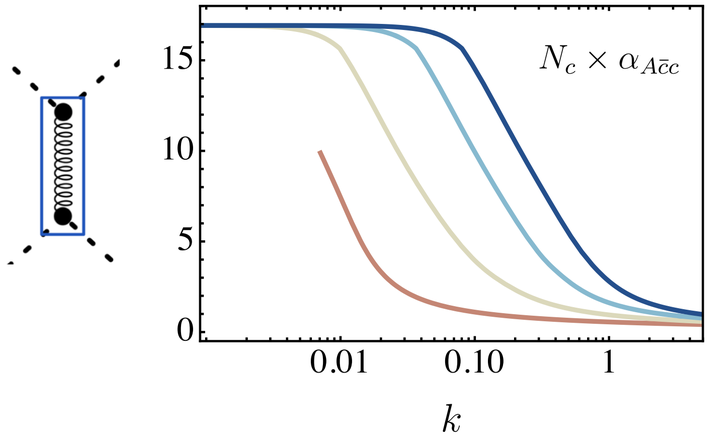
No divergence → no dSB

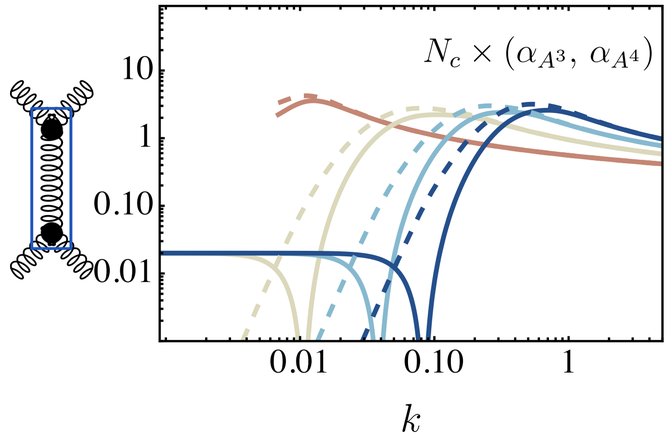
Signatures of confinement in the Landau gauge

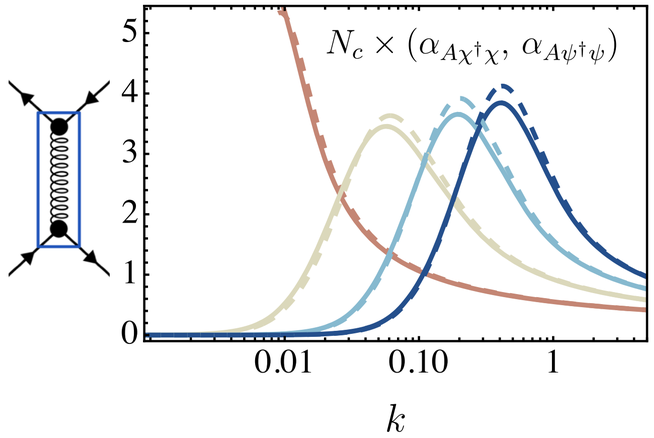


Colour-confinement and dSB in BY

Li,APG,Vatani[2603.19355]



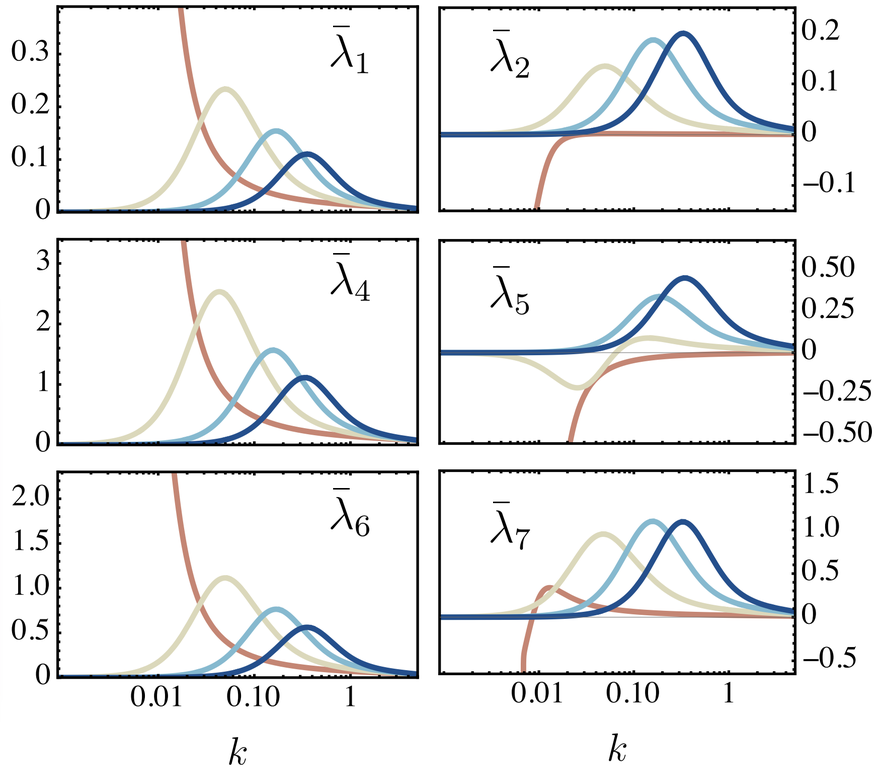




N_c : 3 | 4 5 6

Divergence → dSB

No divergence → no dSB



Signatures of confinement in the Landau gauge

Dominant four-fermion operators:

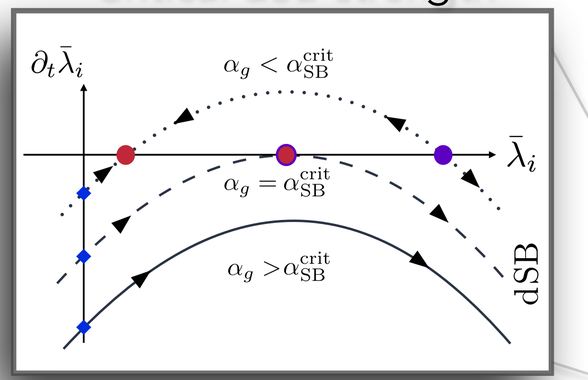
$$\mathcal{O}_4^\chi = (\chi^\dagger \bar{\sigma}^\mu \chi)(\chi^\dagger \bar{\sigma}^\mu \chi)$$

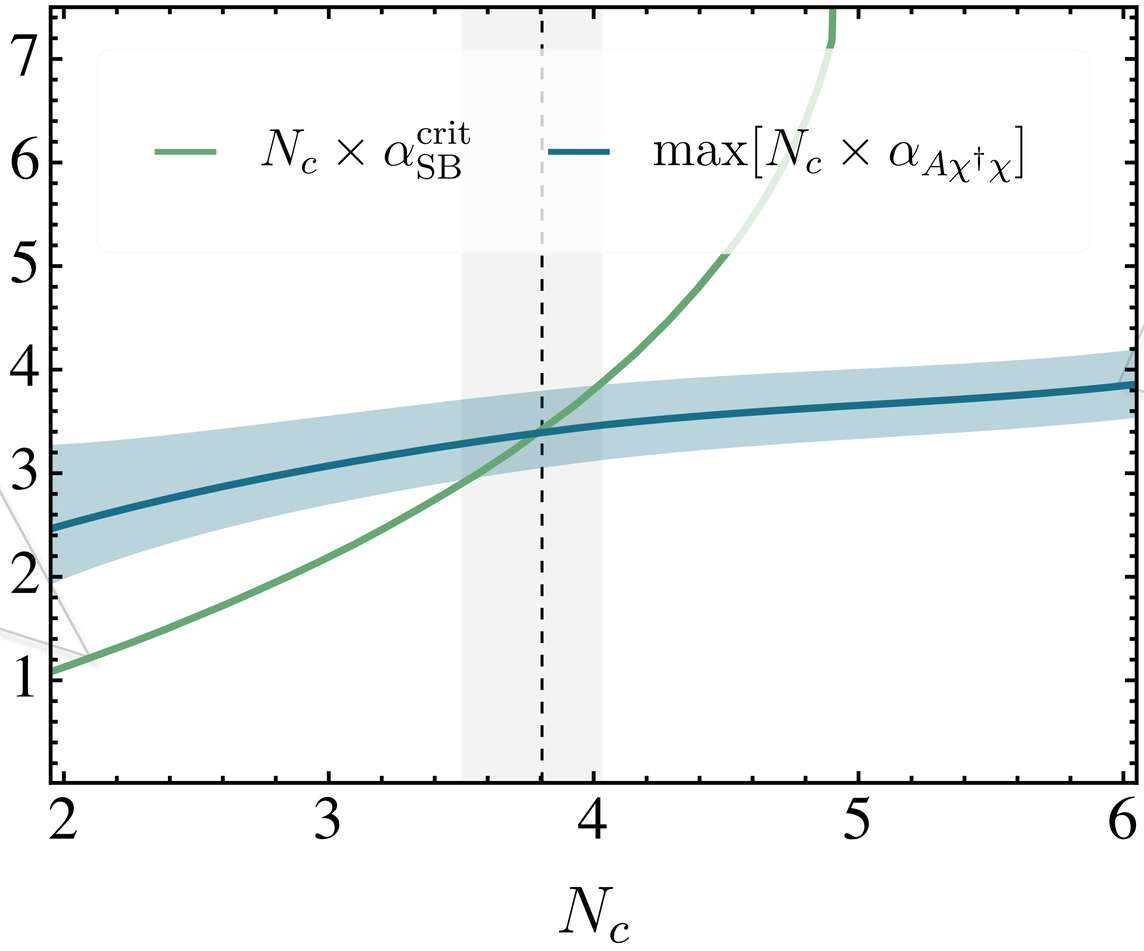
$$\mathcal{O}_5^\chi = (\chi^\dagger \bar{\sigma}^\mu T_{\rm sym} \chi)(\chi^\dagger \bar{\sigma}^\mu T_{\rm sym} \chi)$$

Diquark-like condensate: $\sim \langle \chi\chi \rangle$

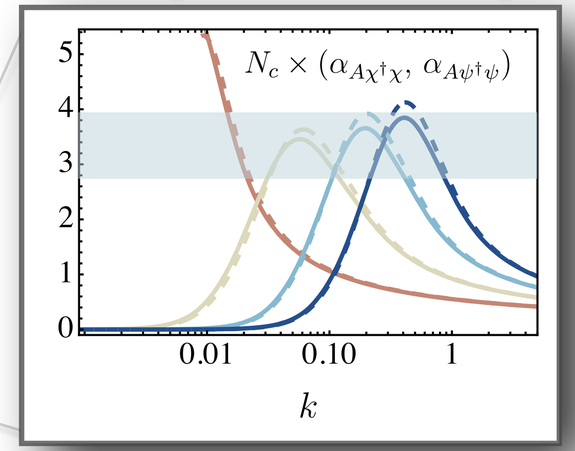
Phase diagram

Critical dSB strength



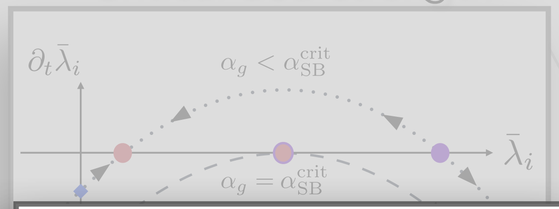


Gauge-fermion strength



Phase diagram

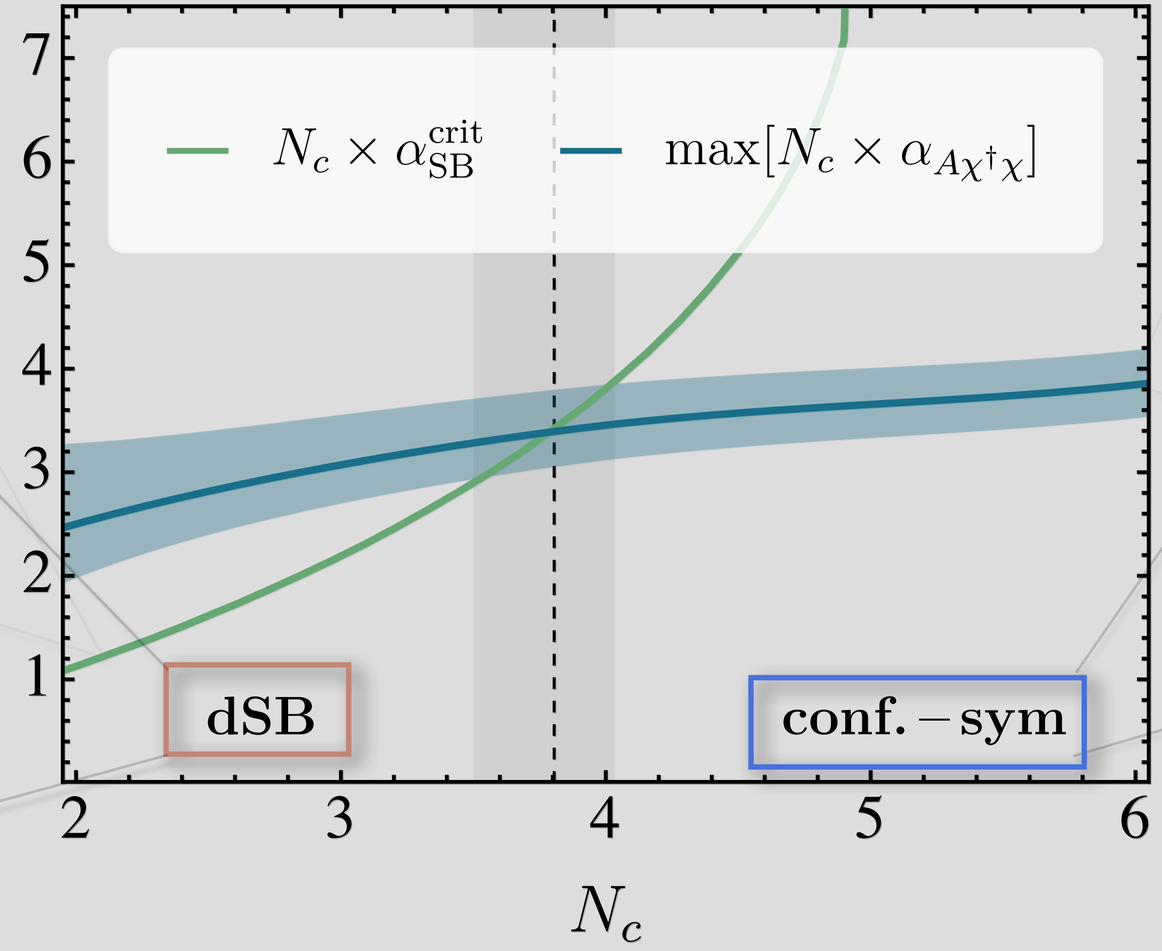
Critical dSB strength



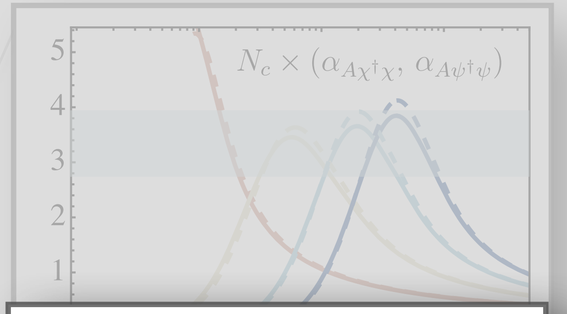
Highest condensate

Di-quark like $\sim \langle \chi\chi \rangle$

(Partial) higgsing of gluons, symmetry tumbling, … (tbd)



Gauge-fermion strength



Confinement without dSB

Bars,Yankielowitz'81

Massless baryons saturate the anomaly

Raby,Dimopoulos,Susskind '79
Eichten,Peccei,Preskill,Zeppenfeld'86

What is this dynamics? SMG?,…

Wang,You[2204.14271]
Karasik,Önder,Tong[2208.07842]

Conclusions

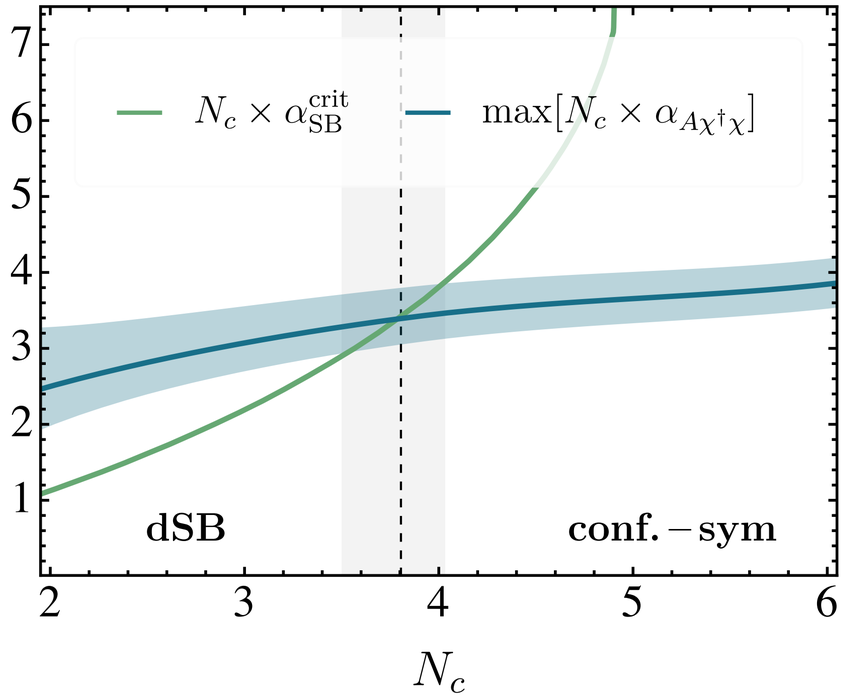
First steps: dynamical emergence of confinement and dSB in the BY class of chiral gauge theories

- fRG approach: approximate, first-principles and nonperturbative
  - Well-defined criteria for confinement (Kugo-Ojima) and dSB (FP merger)
- Phase structure:
  1. dSB, $\langle\chi\chi\rangle$ condensate, tumbling
  2. Confinement without dSB
     - ⋆ Novel dynamics and features to be explored deeper
     - ⋆ Massless hadrons, SMG, ?, …
- Promising path towards systematically studying chiral gauge theories

Raby,Dimopoulos,Susskind '79
Eichten,Peccei,Preskill,Zeppenfeld'86

Wang,You[2204.14271]
Karasik,Önder,Tong[2208.07842]

Li,APG,Vatani,Xu[2507.21208] Li,APG,Vatani[2603.19355]



Conclusions

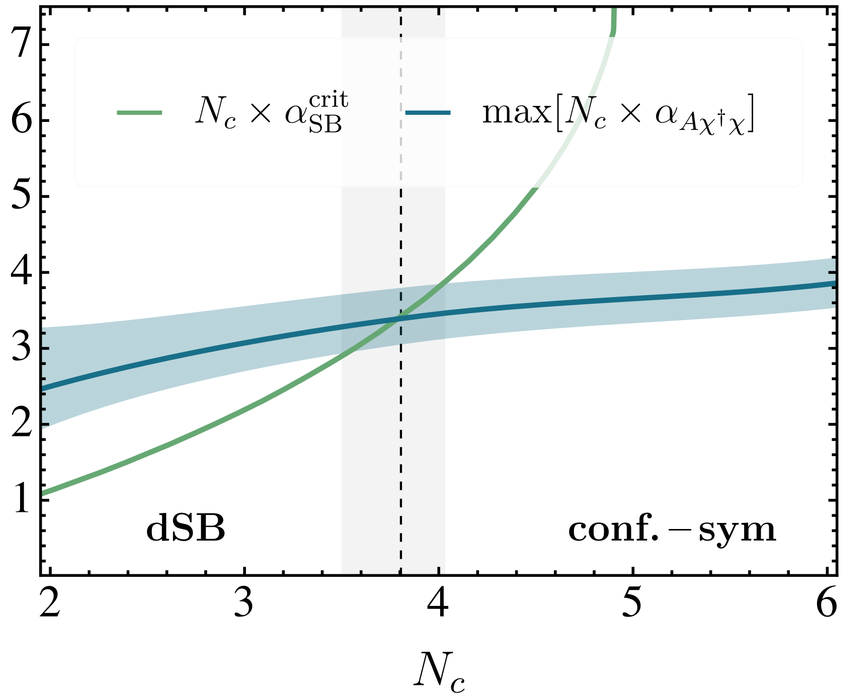
First steps: dynamical emergence of confinement and dSB in the BY class of chiral gauge theories

- fRG approach: approximate, first-principles and nonperturbative
  - Well-defined criteria for confinement (Kugo-Ojima) and dSB (FP merger)
- Phase structure:
  1. dSB, $\langle\chi\chi\rangle$ condensate, tumbling
  2. Confinement without dSB
     - ⋆ Novel dynamics and features to be explored deeper
     - ⋆ Massless hadrons, SMG, ?, …
- Promising path towards systematically studying chiral gauge theories

Raby,Dimopoulos,Susskind '79
Eichten,Peccei,Preskill,Zeppenfeld'86

Wang,You[2204.14271]
Karasik,Önder,Tong[2208.07842]

Li,APG,Vatani,Xu[2507.21208] Li,APG,Vatani[2603.19355]



Thank you for your attention!