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The quark chromomagnetic dipole operators in the gradient-flow scheme at NNLO

Robert Harlander

RWTH Aachen University

based on work with
Janosch Borgulat, Andrea Shindler, Matthew Rizik

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Goal: compute its effect on the neutron EDM → requires lattice QCD

The challenge

$$\mathcal{O}_{\mathrm{CE}} = \bar{\psi}(x)\,\sigma_{\mu\nu}\gamma_5\,t^a\,\psi(x)G^{a,\mu\nu}$$

mass dimension 5

mixes with

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Alternative approach: gradient flow

The gradient flow

flowed gauge field:

$$\frac{\partial}{\partial t} B_\mu(t,x) = \mathcal{D}_\nu G_{\nu\mu}(t,x)$$
$$B_\mu(t=0,x) = A_\mu(x)$$

flowed quark field:

$$\frac{\partial}{\partial t} \chi(t,x) = \mathcal{D}^2 \chi(t,x)$$
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Lüscher '10, '13

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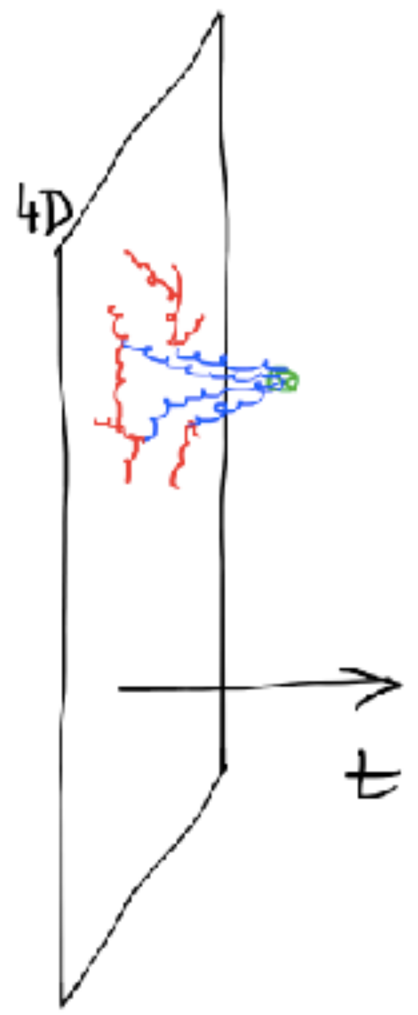

$$B_\mu(t,p) \sim e^{-tp^2} A_\mu(p)$$

5-dimensional field theory

Lüscher, Weisz ‘11

- gluon propagator:

$$s, \nu, b \;\overset{p}{\sim\!\sim\!\sim}\; t, \mu, a \;=\; \delta^{ab}\frac{1}{p^2}\left(\left(\delta_{\mu\nu}-\frac{p_\mu p_\nu}{p^2}\right)e^{-(t+s)p^2} + \xi\frac{p_\mu p_\nu}{p^2}e^{-\kappa(t+s)p^2}\right)$$

- (anti)quark propagator:

$$s, \beta, j \;\overset{p}{\longrightarrow}\; t, \alpha, i \;=\; \delta_{ij}\frac{(-i\not{p}+m)_{\alpha\beta}}{p^2+m^2}\,e^{-(t+s)p^2}$$

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Artz, RH, Lange, Neumann, Prausa ‘19

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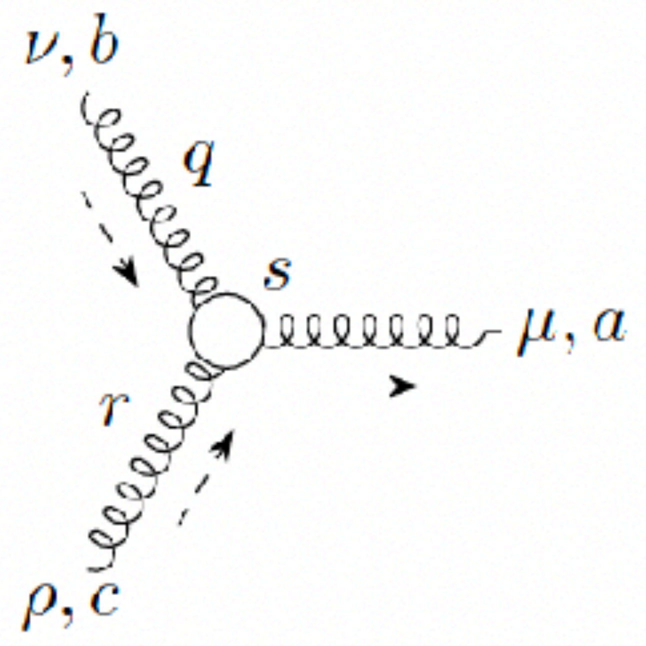
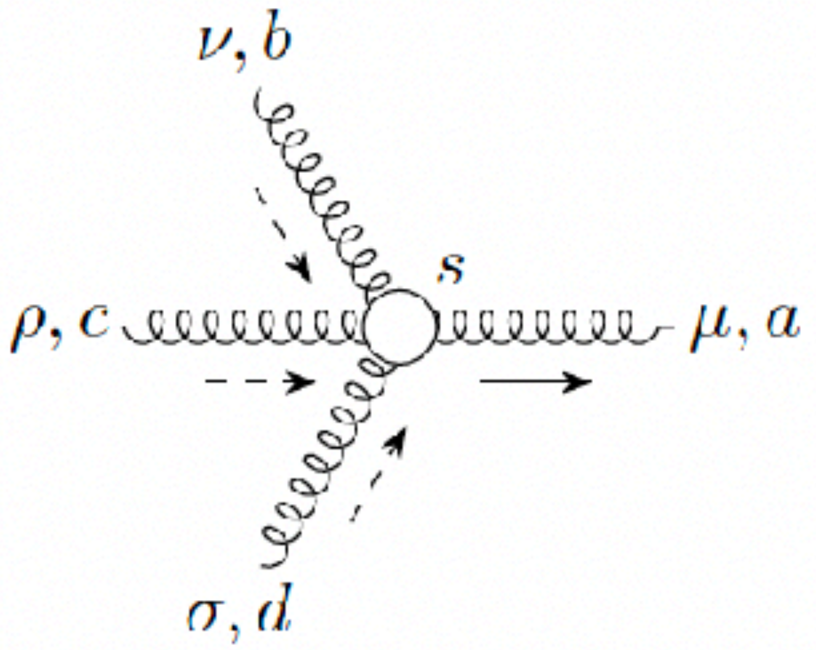
- two-plus-one gluon flow vertex:



$$= -\mathrm{i}g f^{abc} \int_0^\infty \mathrm{d}s \, \big(\delta_{\nu\rho}(r-q)_\mu + 2\delta_{\mu\nu} q_\rho - 2\delta_{\mu\rho} r_\nu + (\kappa-1)(\delta_{\mu\rho} q_\nu - \delta_{\mu\nu} r_\rho)\big)$$

- three-plus-one gluon flow vertex:



$$= -g^2 \int_0^\infty \mathrm{d}s \, \big(f^{abe} f^{cde}(\delta_{\mu\rho}\delta_{\nu\sigma} - \delta_{\mu\sigma}\delta_{\nu\rho}) + f^{ace} f^{bde}(\delta_{\mu\nu}\delta_{\rho\sigma} - \delta_{\mu\sigma}\delta_{\nu\rho}) + f^{ade} f^{bce}(\delta_{\mu\nu}\delta_{\rho\sigma} - \delta_{\mu\rho}\delta_{\nu\sigma})\big)$$

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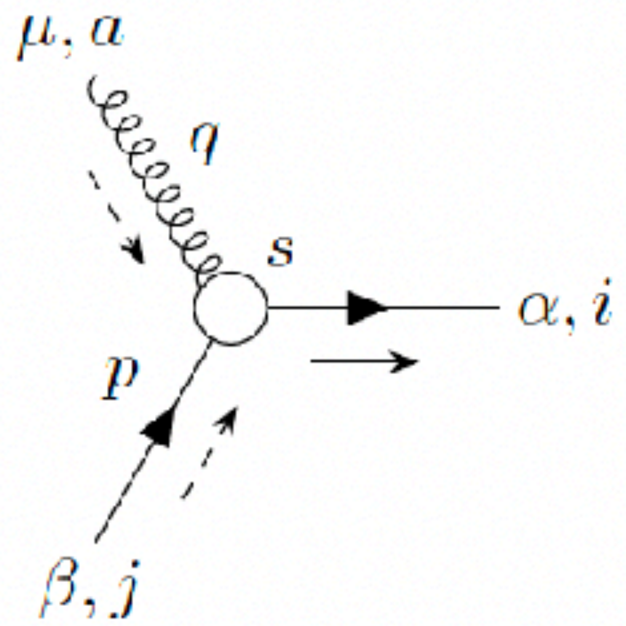

$$= \mathrm{i}g \, \delta_{\alpha\beta} (T^a)_{ij} \int_0^\infty \mathrm{d}s \, \big(2p_\mu + (1-\kappa) q_\mu\big)$$

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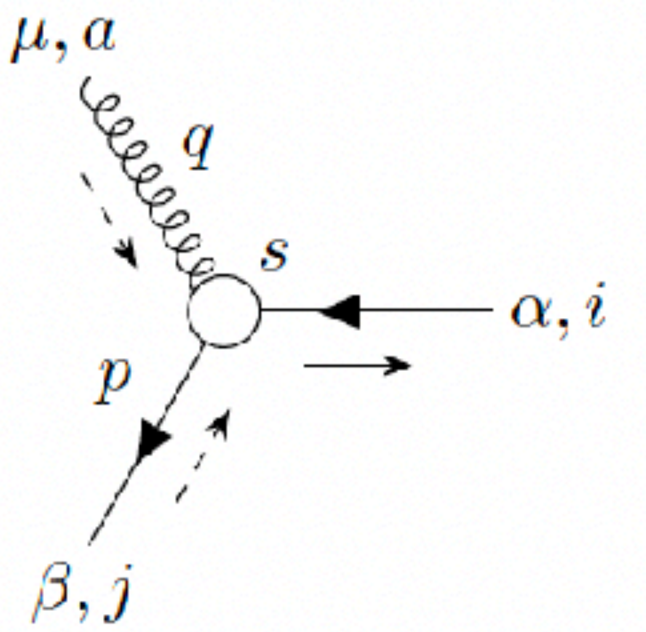

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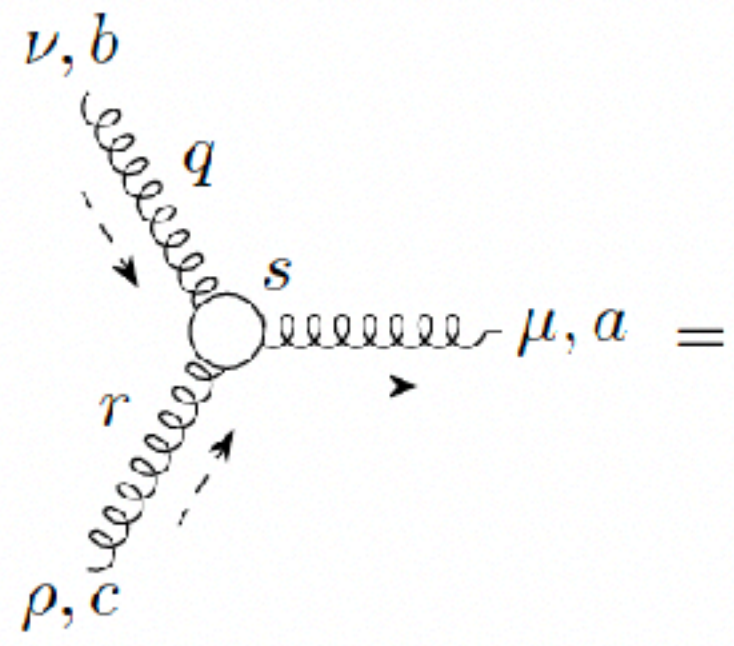

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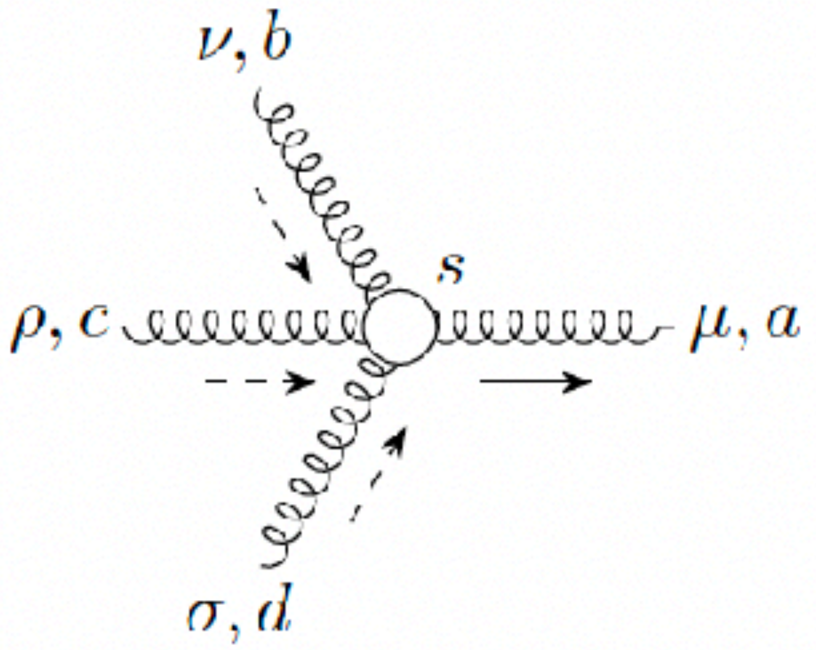

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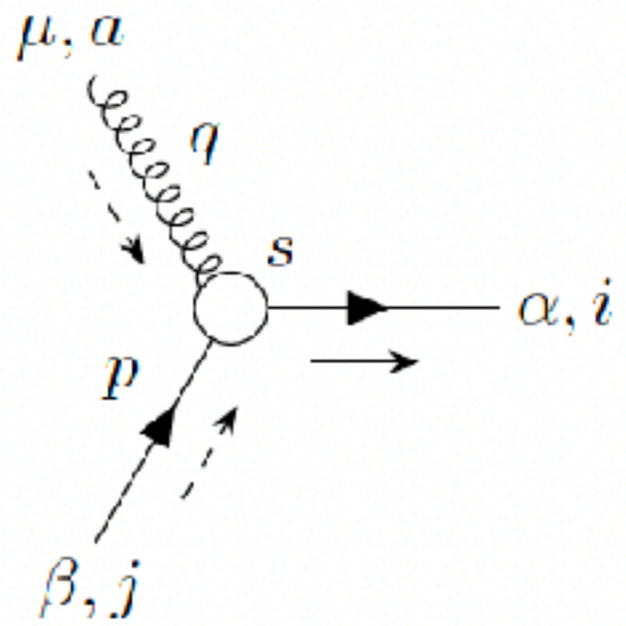

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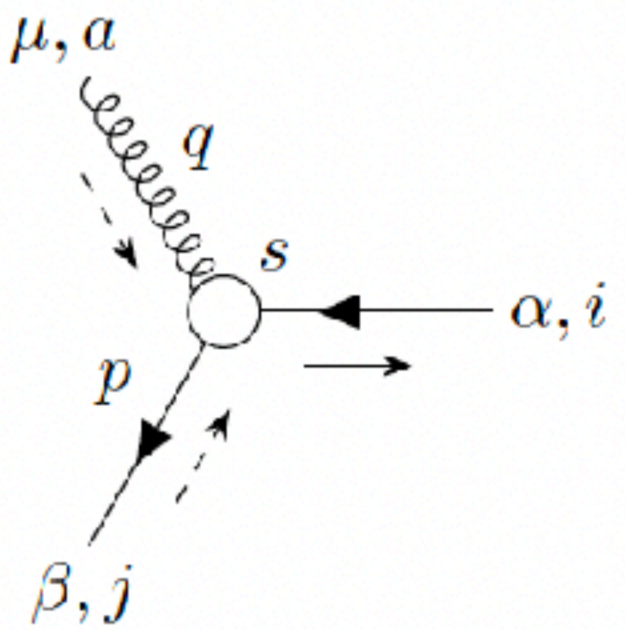

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$$\mathcal{O}_{\rm CE} = \bar{\psi}(x)\,\sigma_{\mu\nu}\gamma_5\,t^a\,\psi(x)G^{a,\mu\nu}$$

mass dimension 5

mixes with

$$\mathcal{O}_{\rm P} = \bar{\psi}(x)\,\gamma_5\,\psi(x)$$

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$$\langle \mathcal{O}^R_{\rm CE} \rangle = Z_1 \langle \mathcal{O}_{\rm CE} \rangle + \frac{1}{a^2} Z_2 \langle \mathcal{O}_{\rm P} \rangle + \cdots$$

Alternative approach: gradient flow

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How? Compute suitable correlation functions and take $t \to 0$

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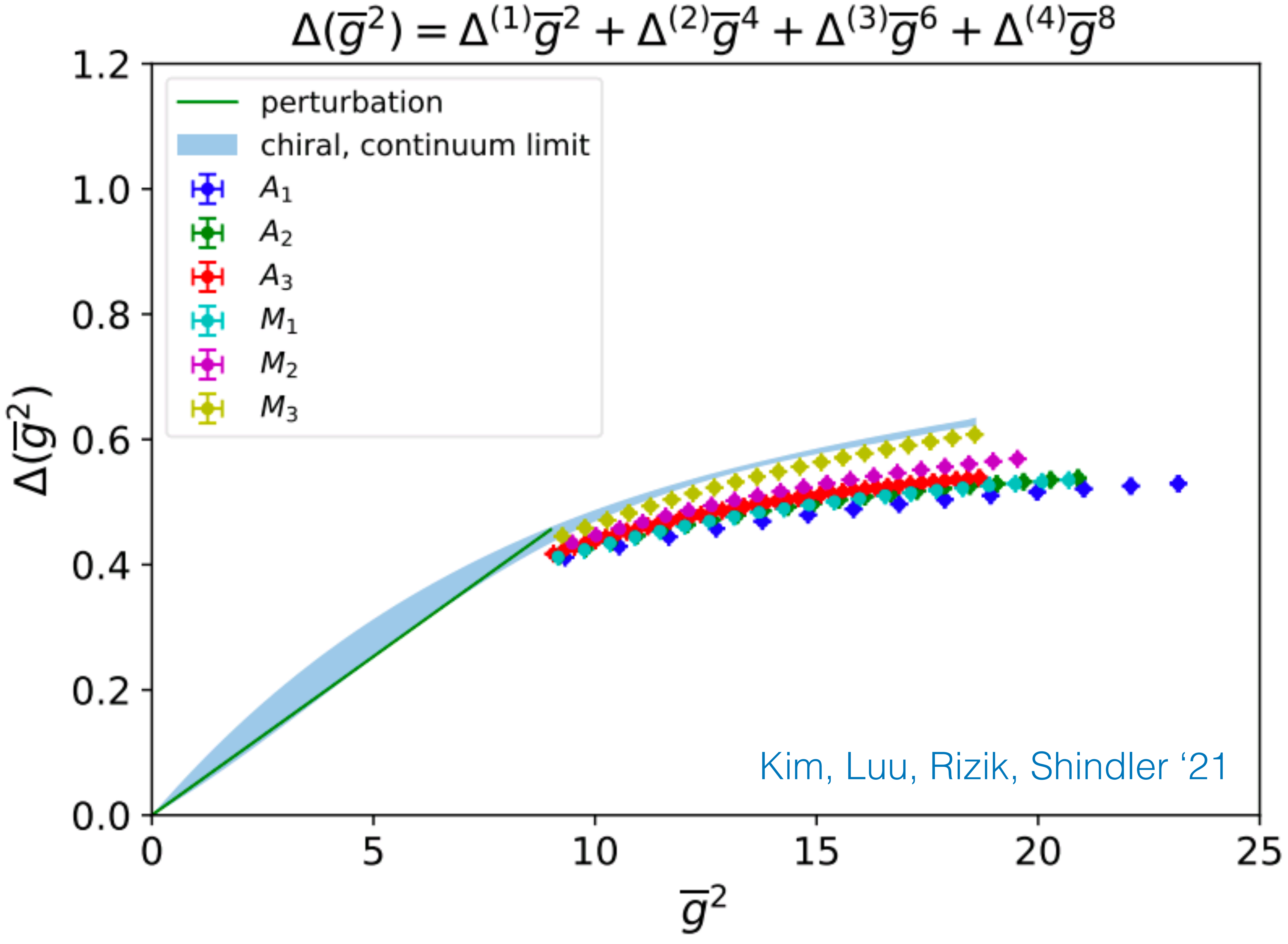
Lattice results

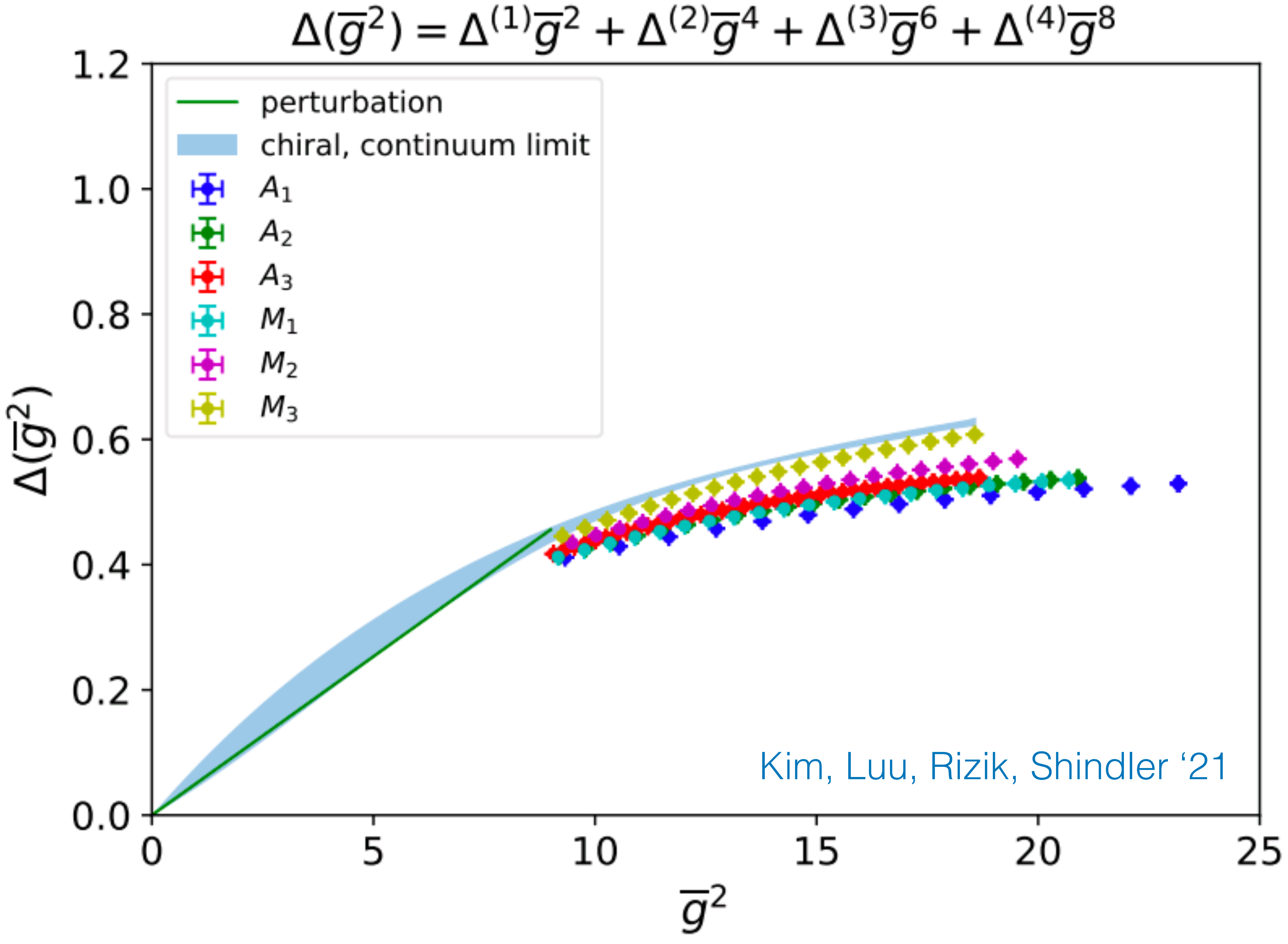


Perturbative result: NLO

Rizik, Monahan, Shindler '20
Mereghetti, Monahan, Rizik, Shindler, Stoffer '21

$$c_{\mathrm{P}}(t) = 2\frac{\alpha_s(\mu)}{\pi}$$

Lattice results



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$$c_P(t) = 2\frac{\alpha_s(\mu)}{\pi} + \left(\frac{\alpha_s(\mu)}{\pi}\right)^2 \left[x_0 + x_1 \ln \mu^2 t\right]$$

This talk

$\mathcal{O}_{\mathrm{CE}} = \bar{\psi}(x)\,\sigma_{\mu\nu}\gamma_5\,t^a\,\psi(x)G^{a,\mu\nu}$ mixes with $\mathcal{O}_{\mathrm{P}} = \bar{\psi}(x)\,\gamma_5\,\psi(x)$

This talk

$\mathcal{O}_{\mathrm{CM}} = \bar{\psi}(x)\,\sigma_{\mu\nu}\,t^a\,\psi(x)G^{a,\mu\nu}$ mixes with $\mathcal{O}_{\mathrm{S}} = \bar{\psi}(x)\,\psi(x)$

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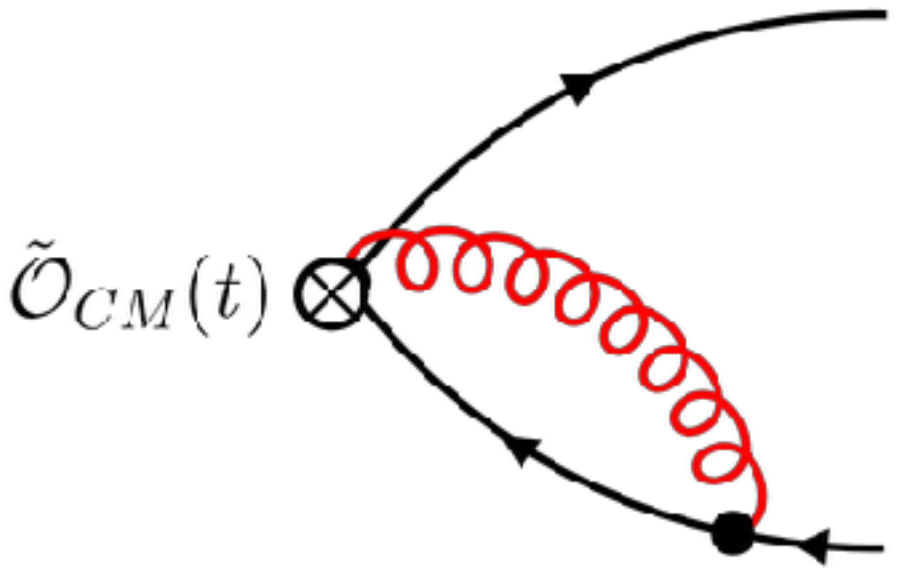
$c_{\rm S}(t) \sim \langle 0 \,|\, \tilde{O}_{\rm CM}(t) \,|\, \bar{\psi}\psi \rangle$



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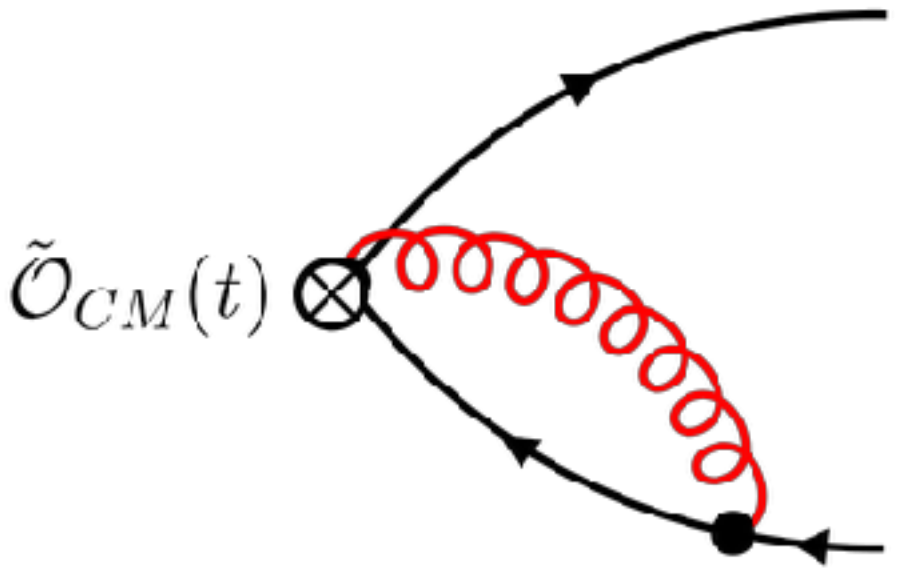

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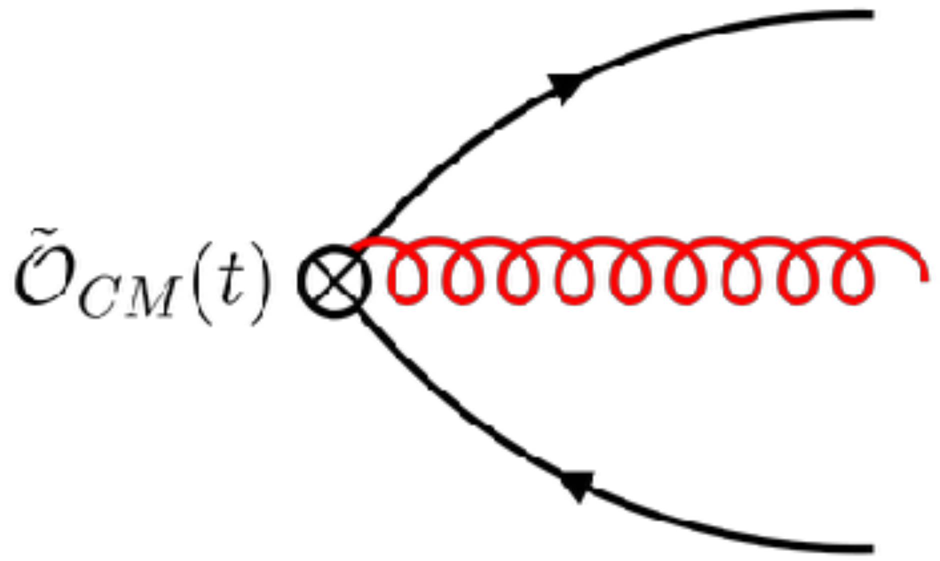

Next-to-next-to-leading order

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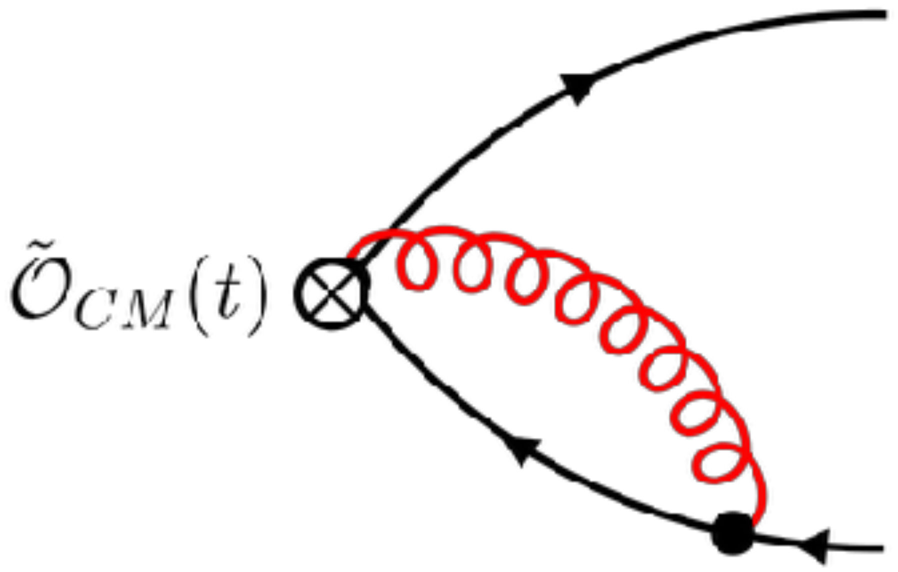

5 diagrams

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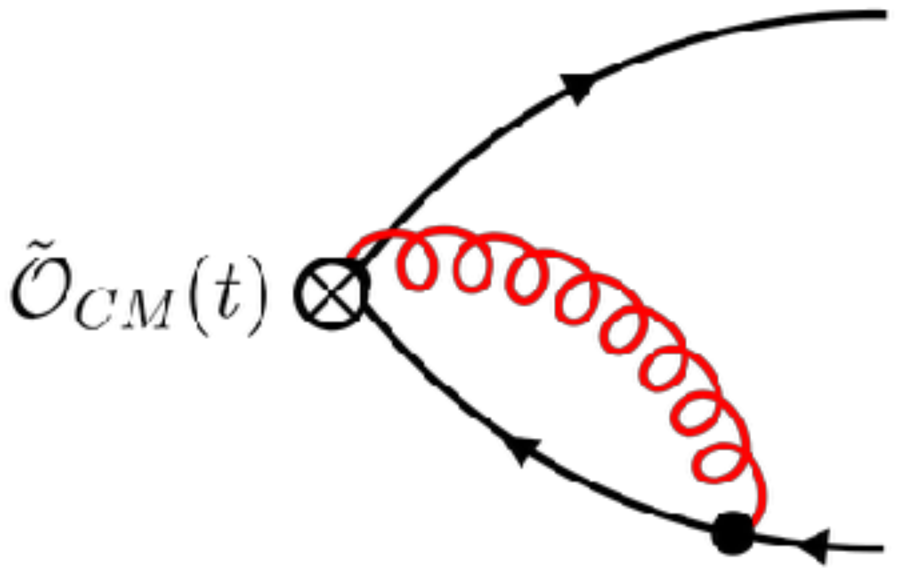

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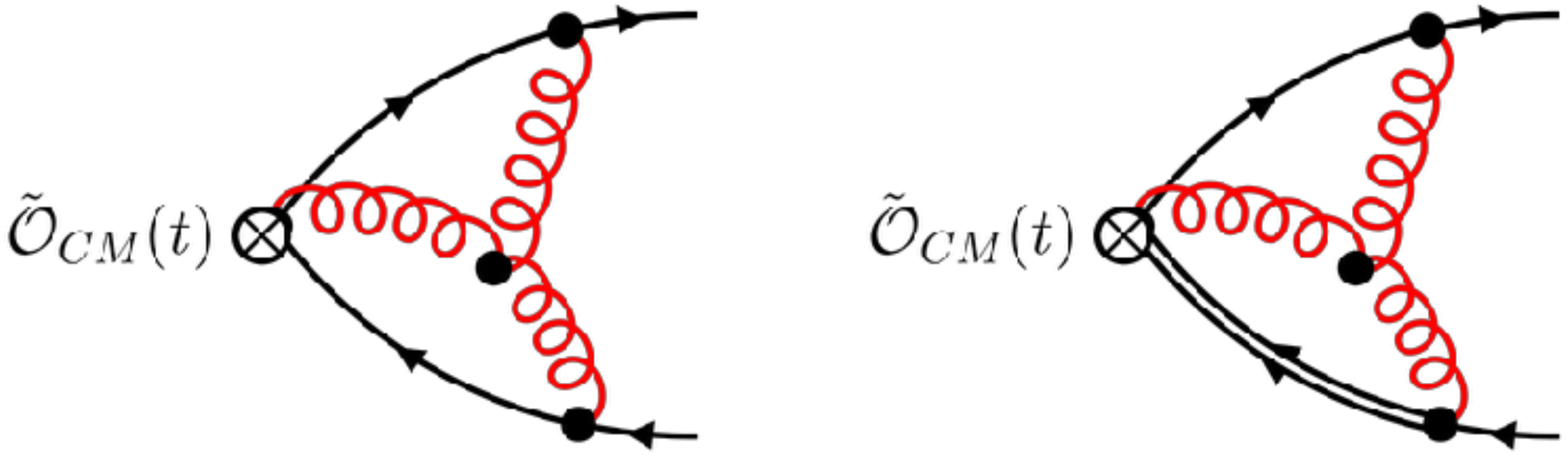

226 diagrams

Next-to-next-to-leading order

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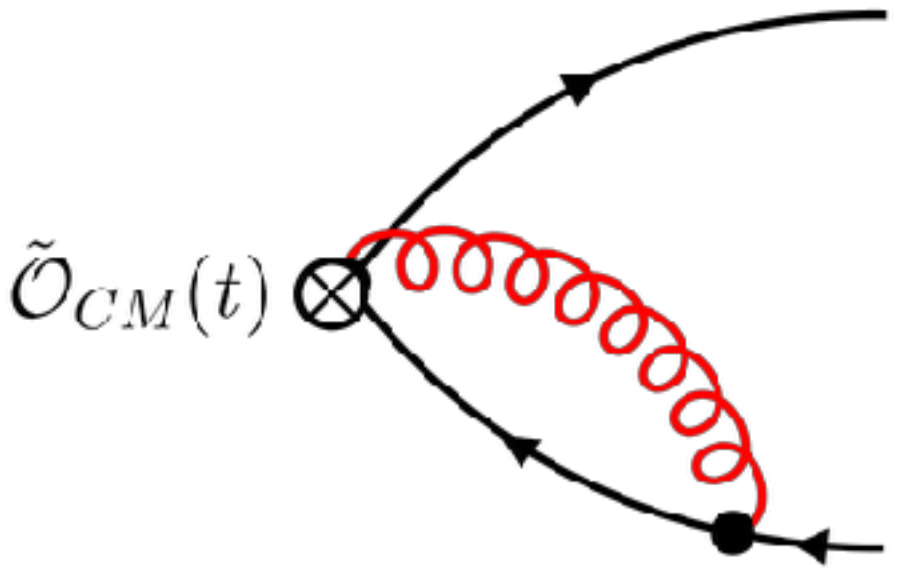

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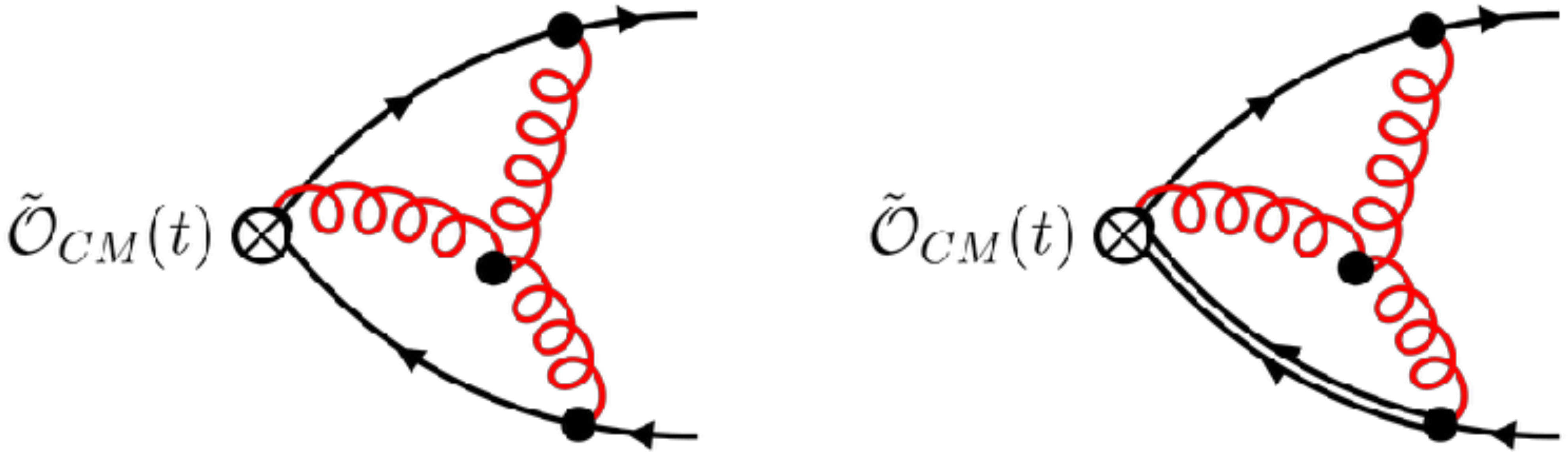

226 diagrams

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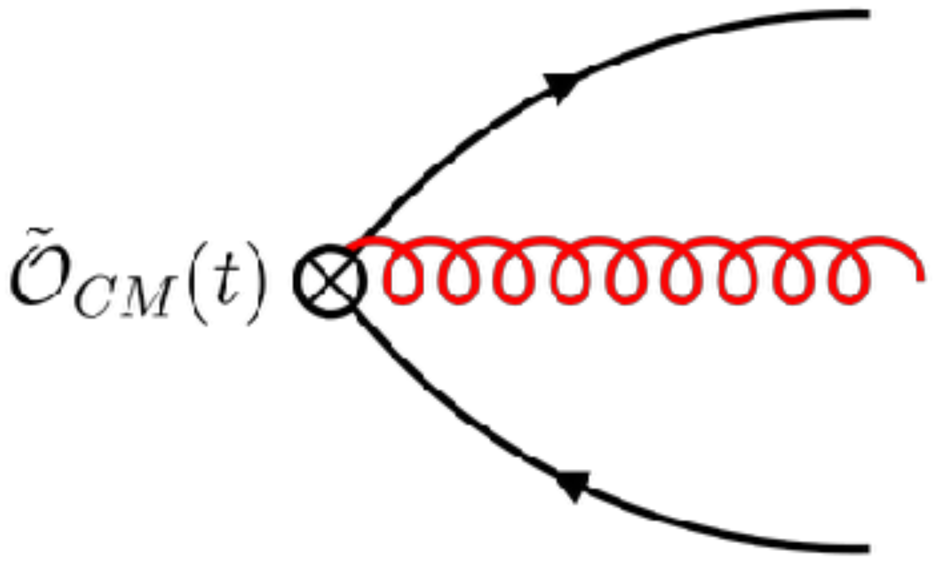

1 diagram

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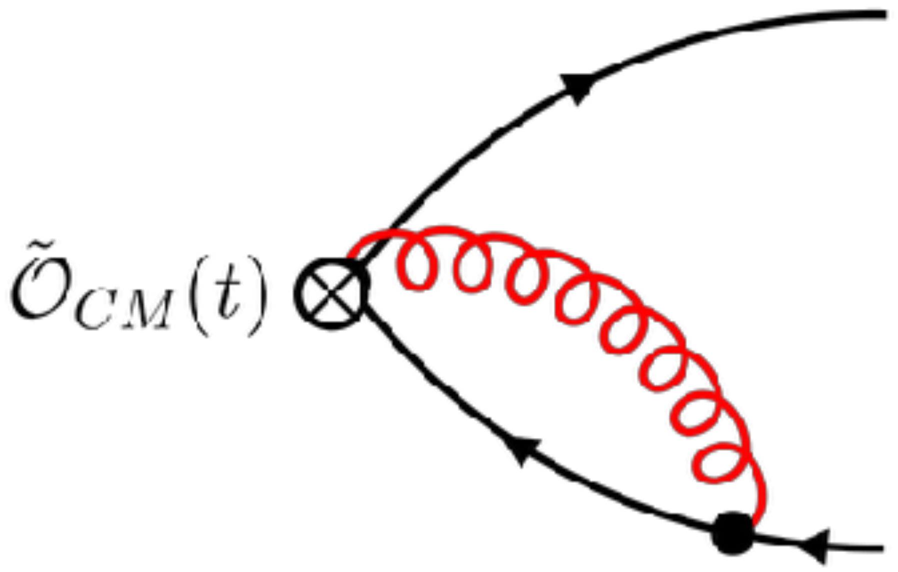

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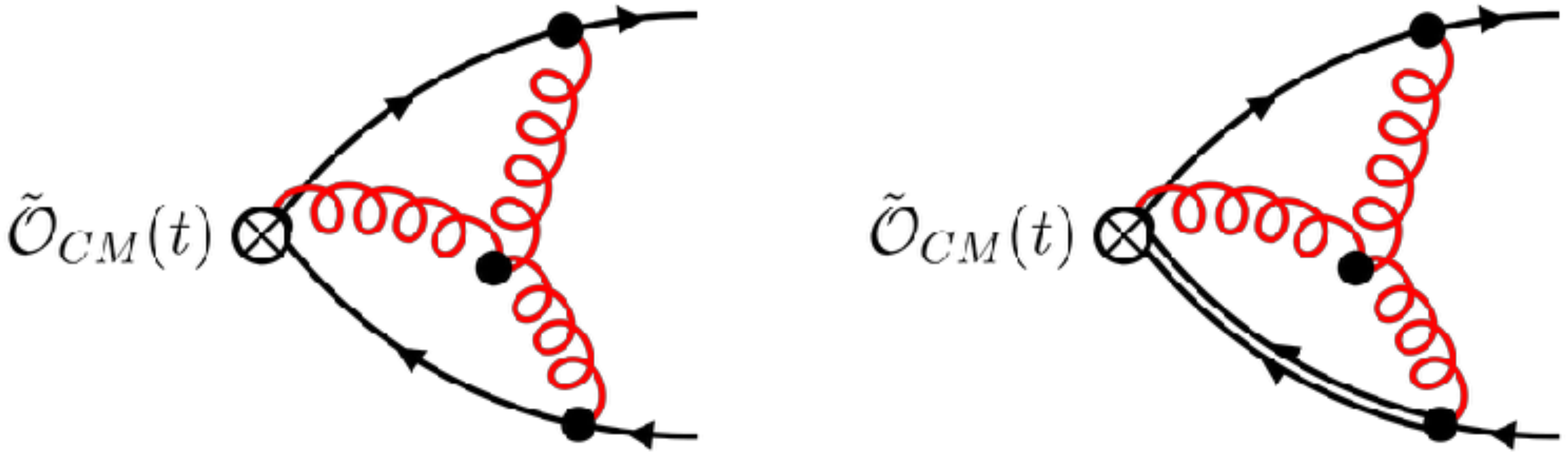
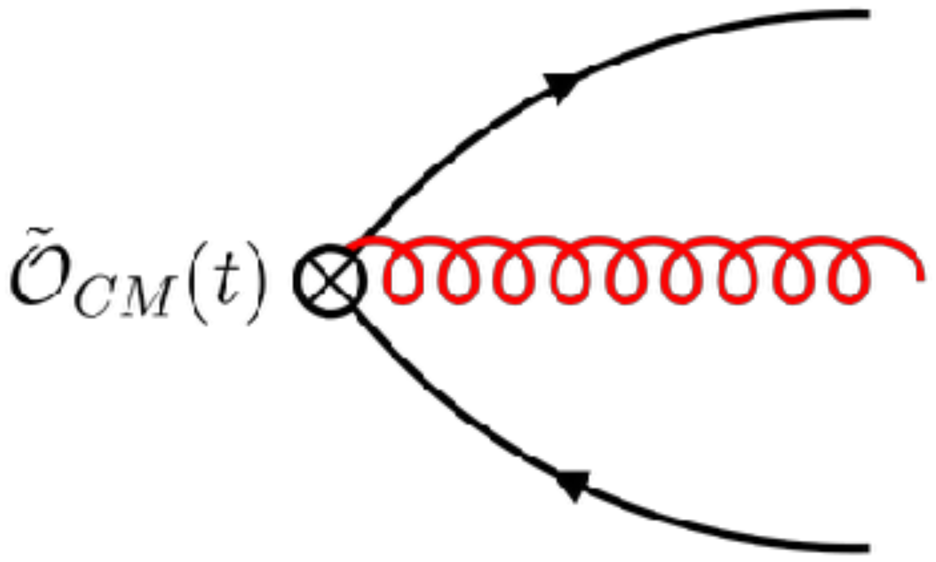
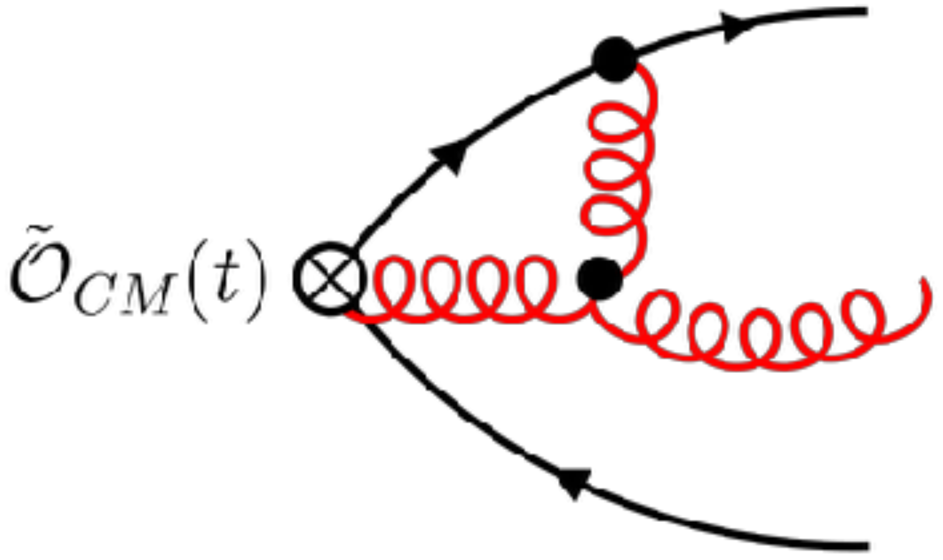


226 diagrams

$c_{CM}(t) \sim \langle 0 | \tilde{O}_{CM}(t) | \bar{\psi}\psi g \rangle$



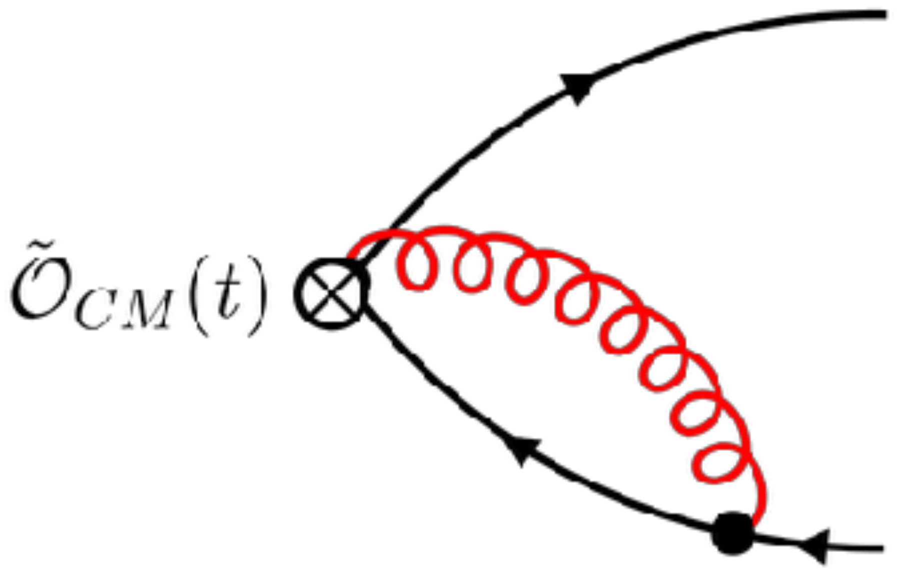
1 diagram



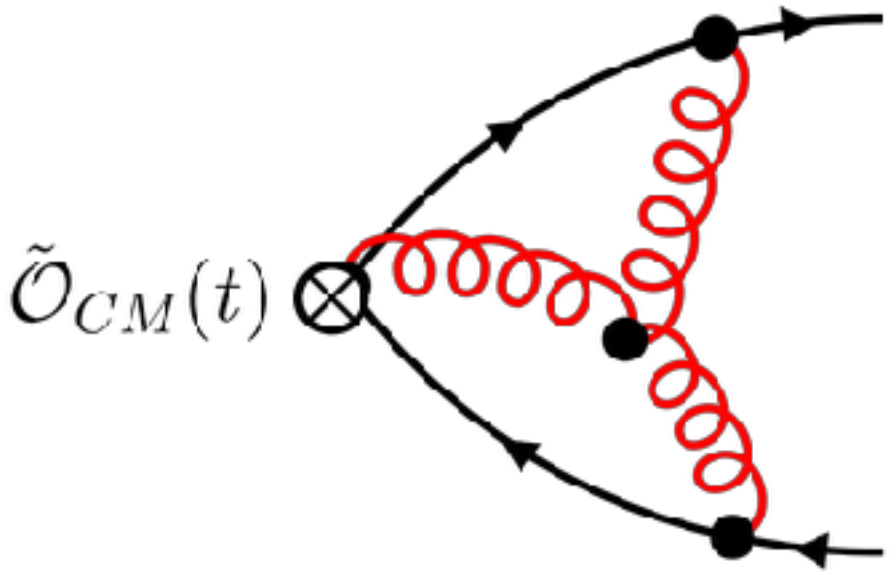
45 diagrams

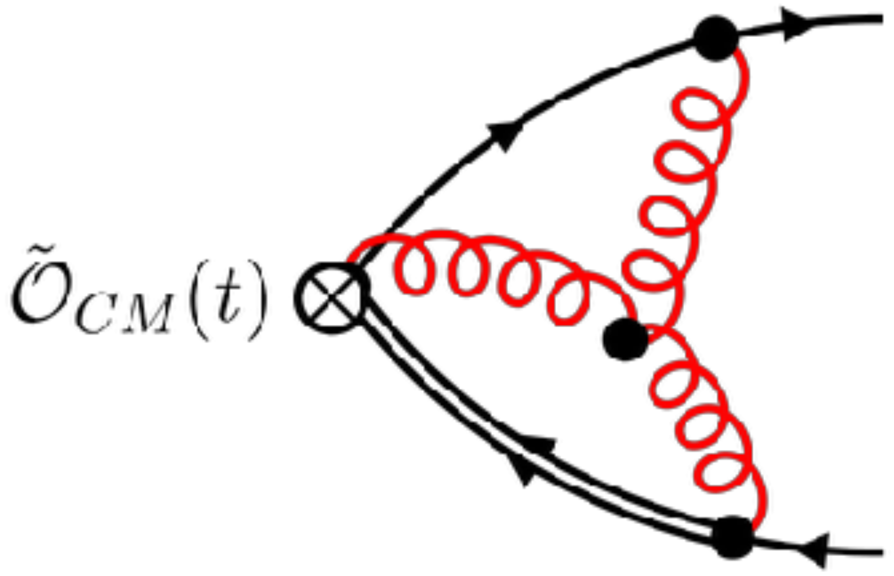
Next-to-next-to-leading order

$c_{\mathrm{S}}(t) \sim \langle 0 | \tilde{O}_{\mathrm{CM}}(t) | \bar{\psi}\psi \rangle$



5 diagrams





226 diagrams

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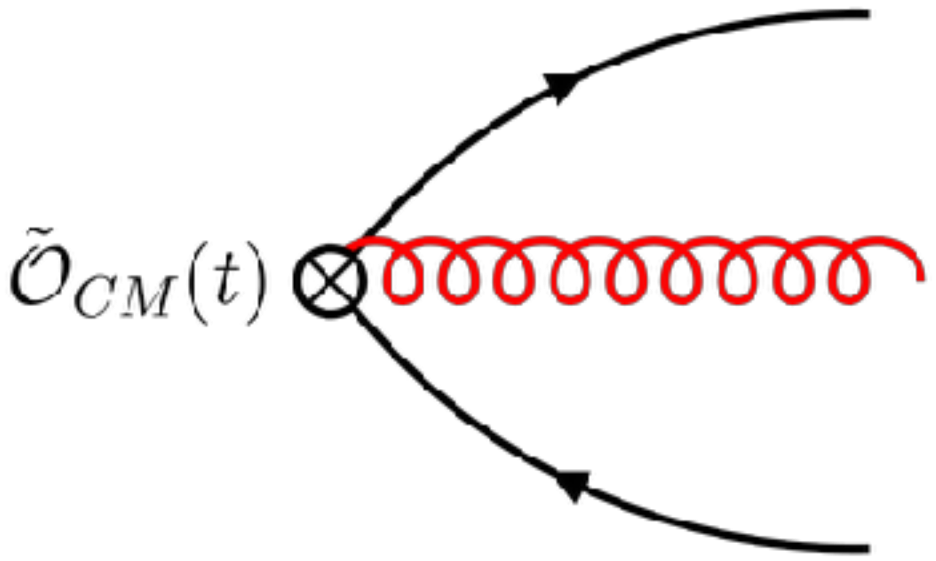

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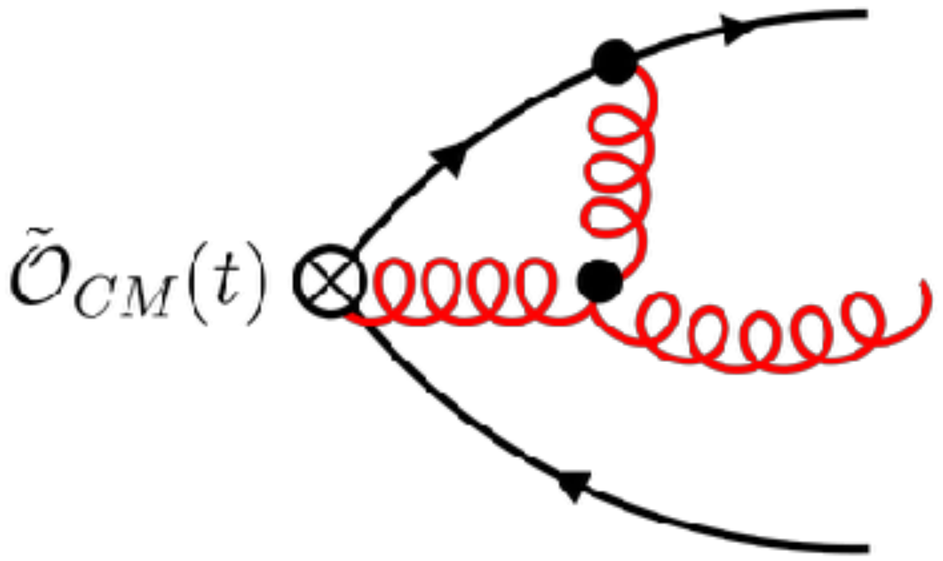

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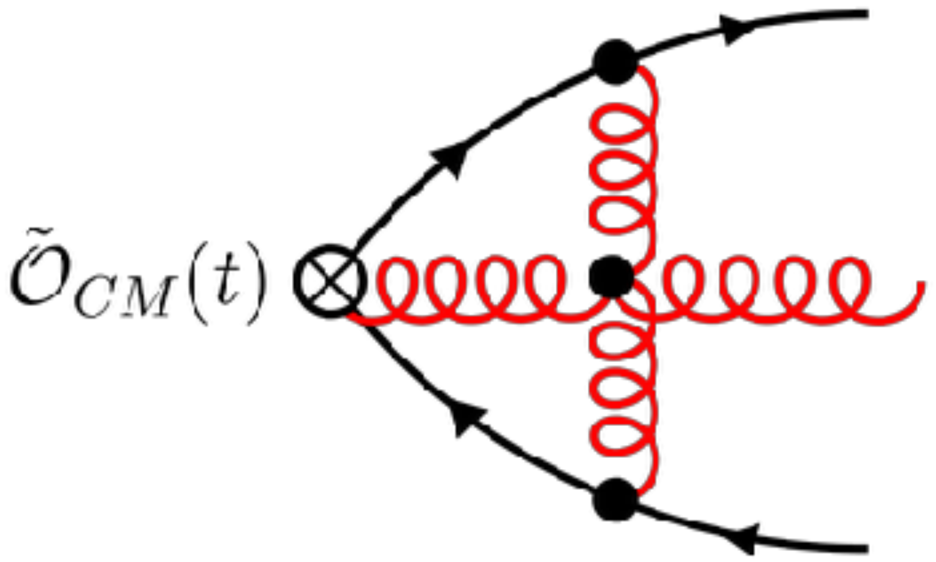

3375 diagrams

Next-to-next-to-leading order

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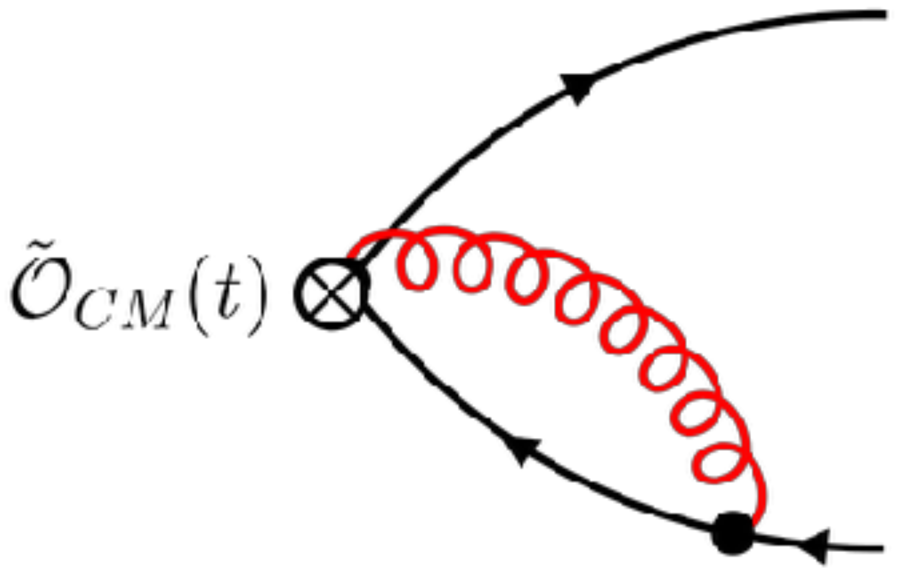

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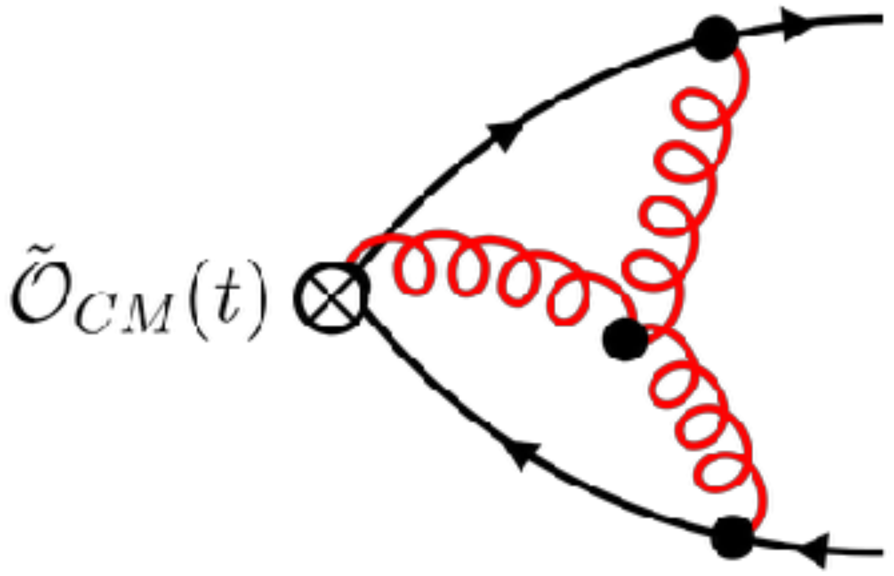

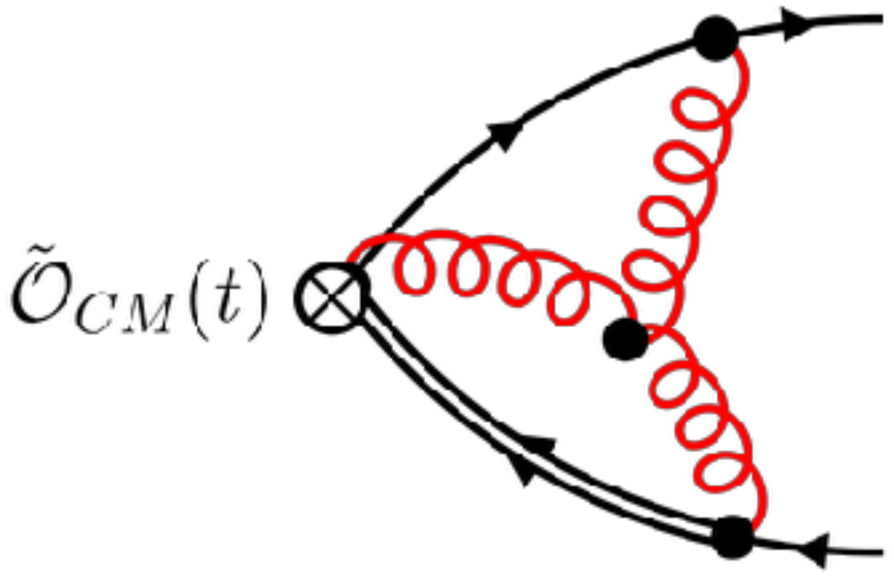

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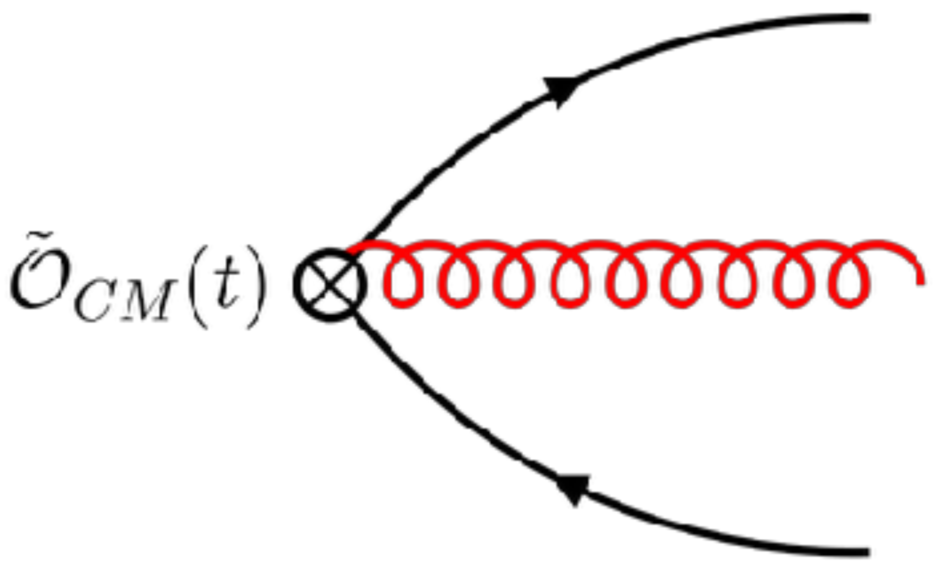

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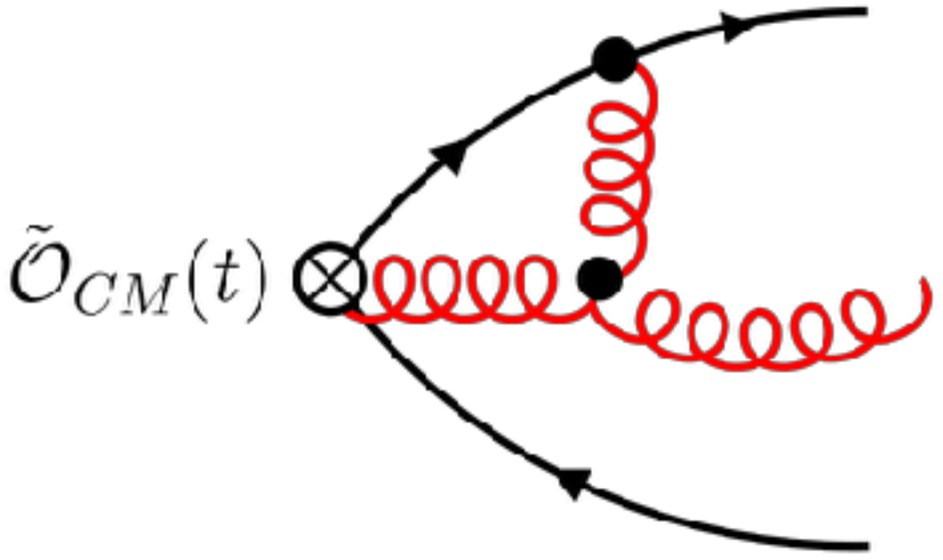

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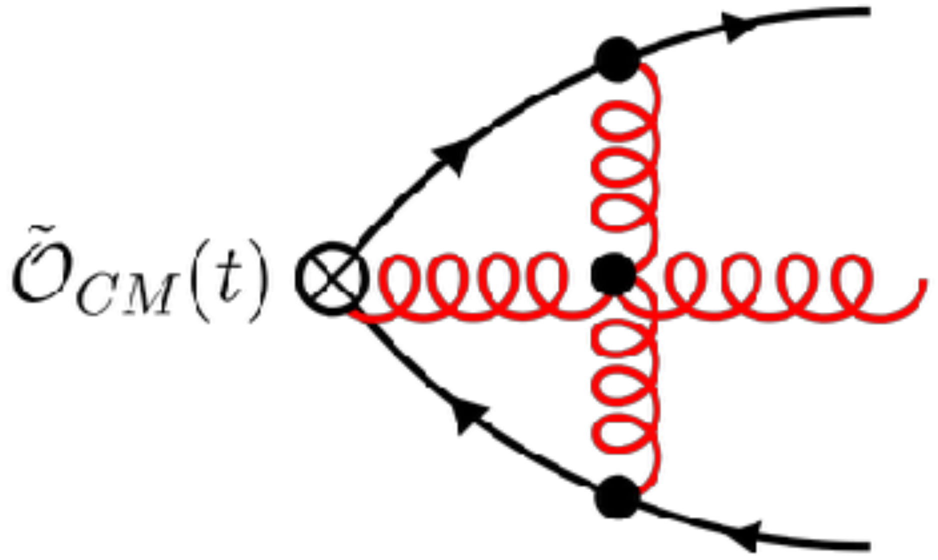
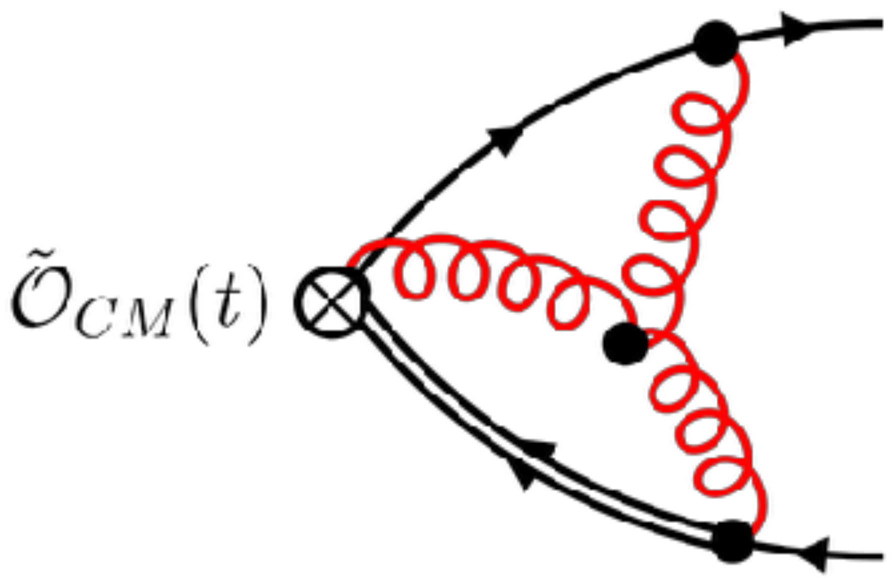


3375 diagrams

diagrams drawn with FeynGame

Method of projectors

$c_S(t) \sim \langle 0 | \tilde{O}_{CM}(t) | \bar{\psi}\psi \rangle$



$c_S(t)$ is independent of momenta and masses ⇒ set them = 0.

Gorishnii, Larin, Tkachov '83

⇒ all integrals of type

$$\int d^D k \int d^D p \int_0^t ds_1 \int_0^{s_1} ds_2 \int_0^{s_2} ds_3 \, \frac{e^{-s_1 p^2 - s_2 k^2 - s_3 (k-p)^2}}{k^\alpha p^\beta (k-p)^\gamma}$$

or simpler

The perturbative toolbox

[For details, see: Artz, RH, Lange, Neumann, Prausa]

Diagram generation:	`qgraf`	Nogueira
Diagram analyzation:	`q2e/exp`	RH, Seidensticker, Steinhauser
Algebraic manipulations:	`FORM`	Vermaseren
Reduction to masters:	`Kira` ⊗ `FireFly`	
Chetyrkin, Tkachov Laporta	Usovitsch, Uwer, Maierhöfer ⊗ Klappert, Klein, Lange	

Sector Decomposition:

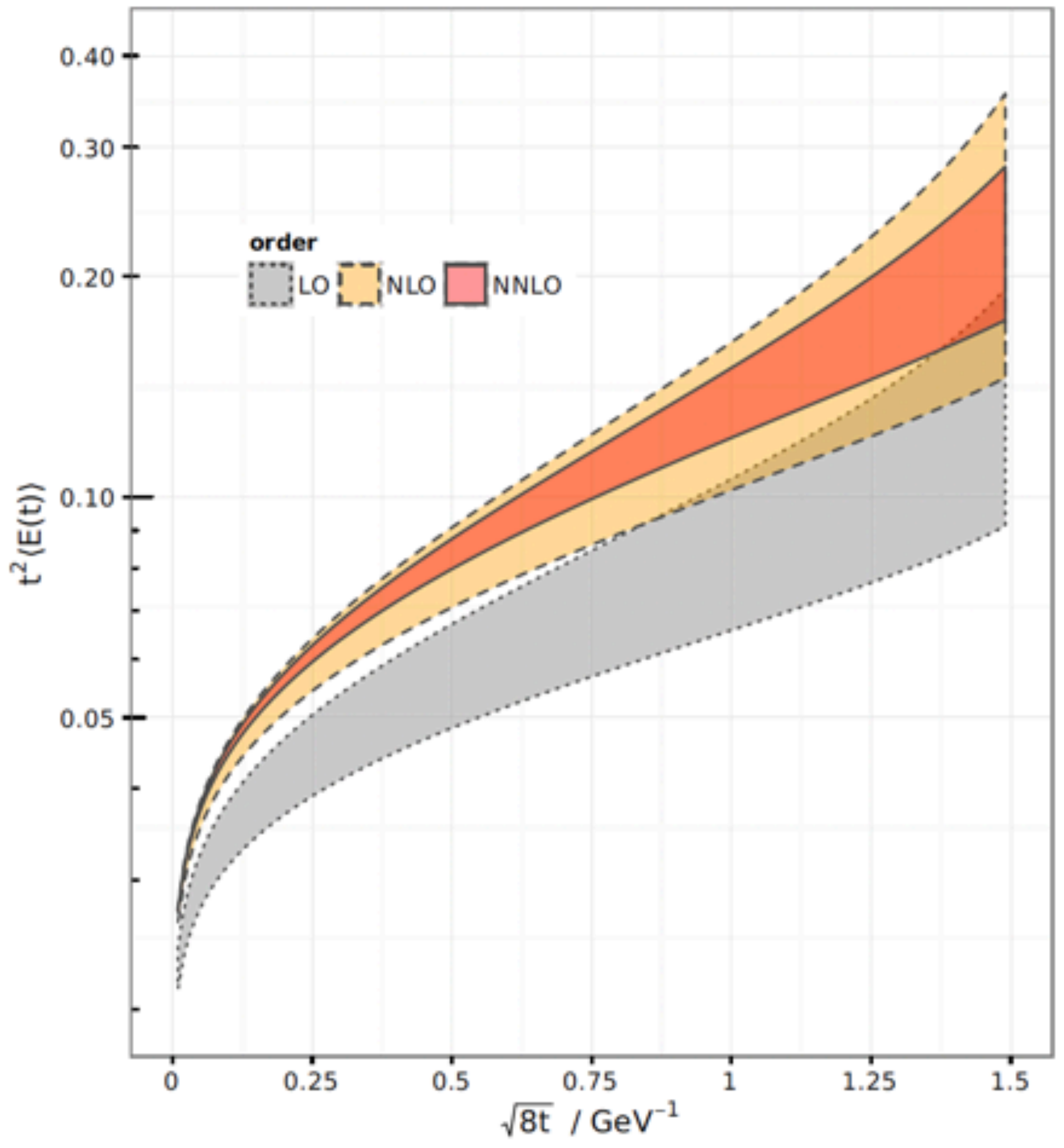
Binoth, Heinrich

$$\int d^Dk \int d^Dp \int_0^t ds \frac{e^{-tp^2-s(k-p)^2}}{k^2p^2(k-p^2)} = \frac{A}{\epsilon^2} + \frac{B}{\epsilon} + C + \ldots$$

Examples

$$E(t) = \langle G_{\mu\nu}(t) G_{\mu\nu}(t) \rangle$$

RH, Neumann '16



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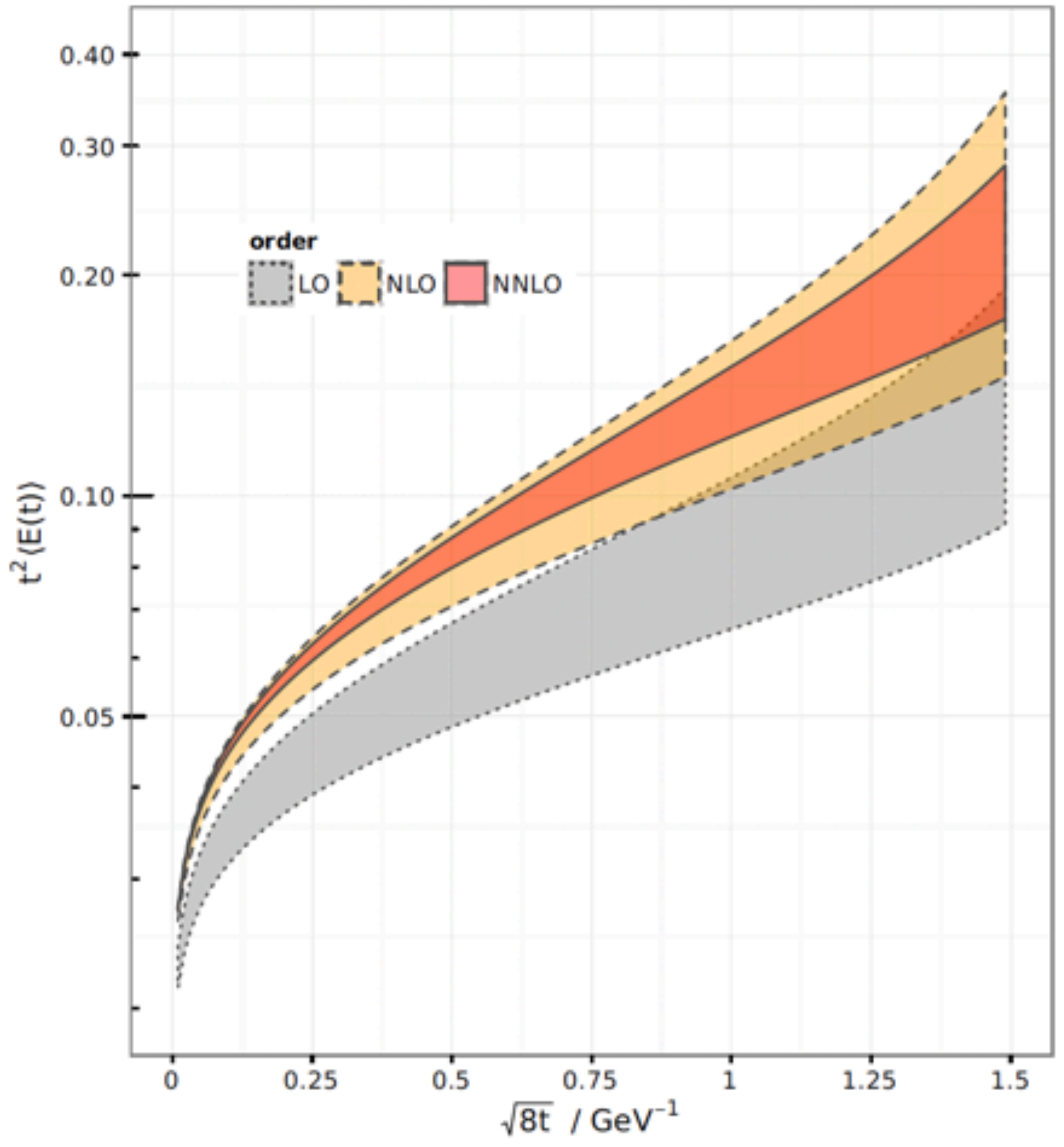
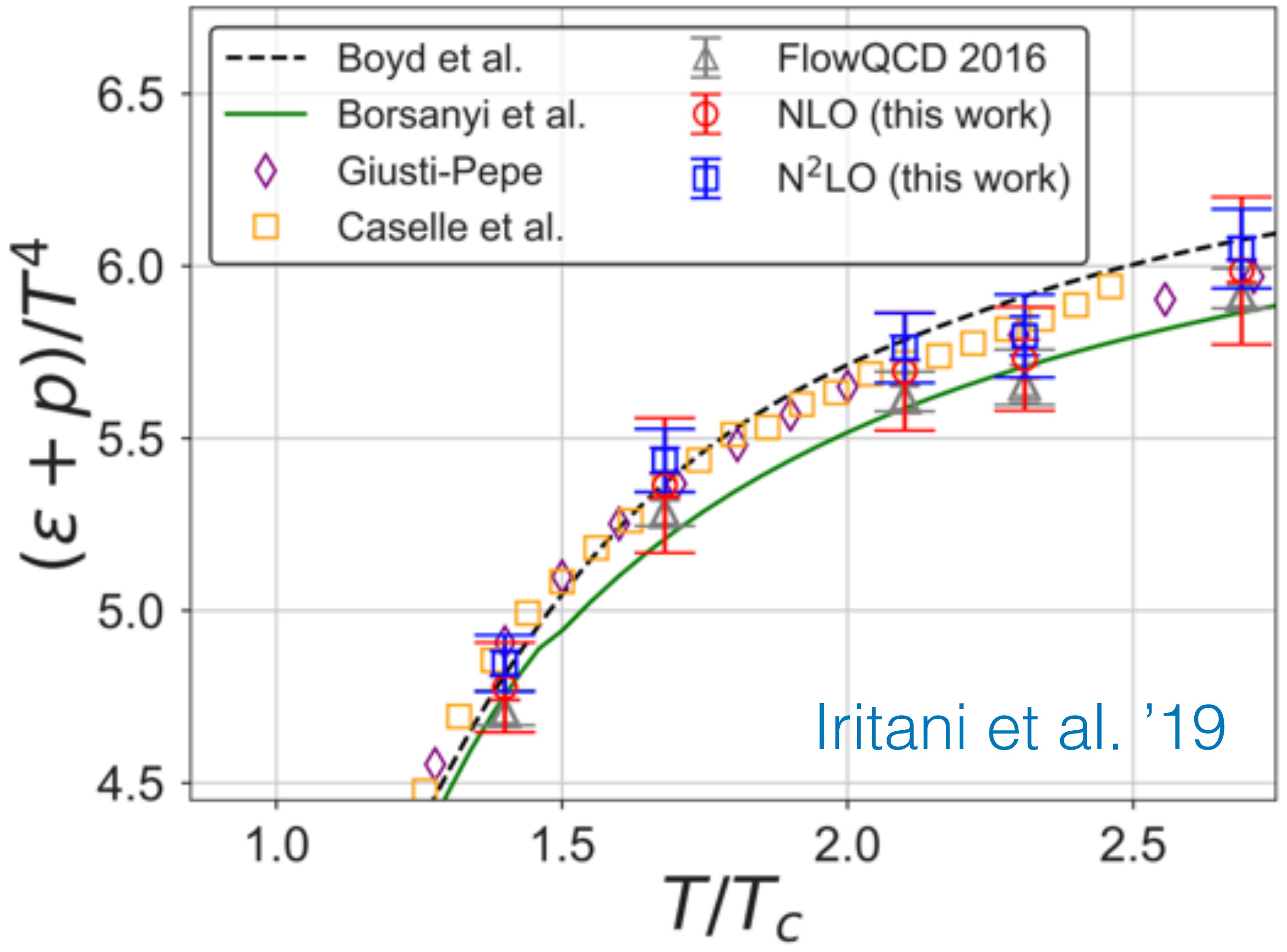


energy-momentum tensor

Suzuki, Makino '14
RH, Kluth, Lange '18

$$T_{\mu\nu} = \sum_n c_n(t)\, \tilde{\mathcal{O}}_{\mu\nu}(t)$$



Examples

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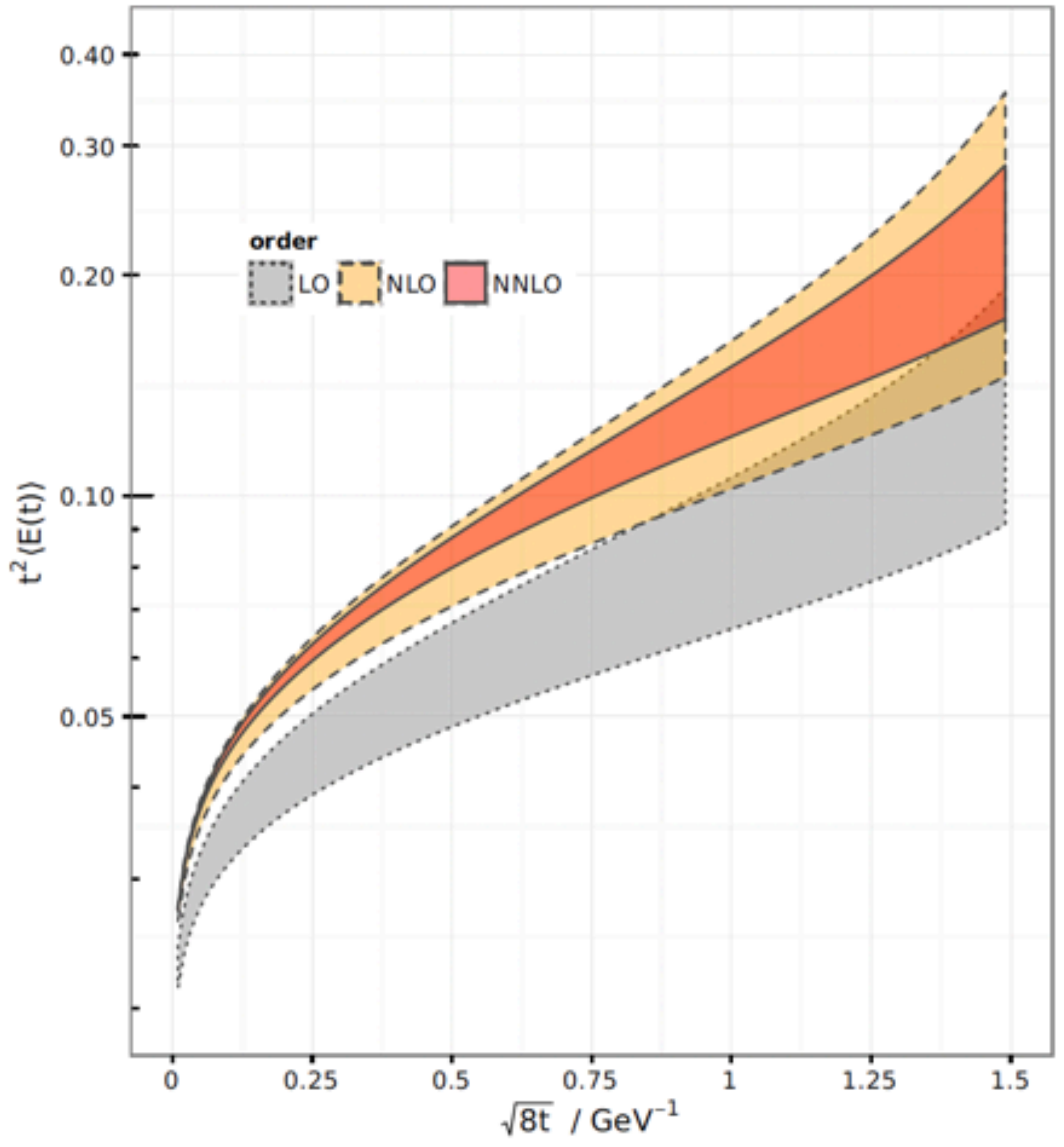
RH, Neumann '16



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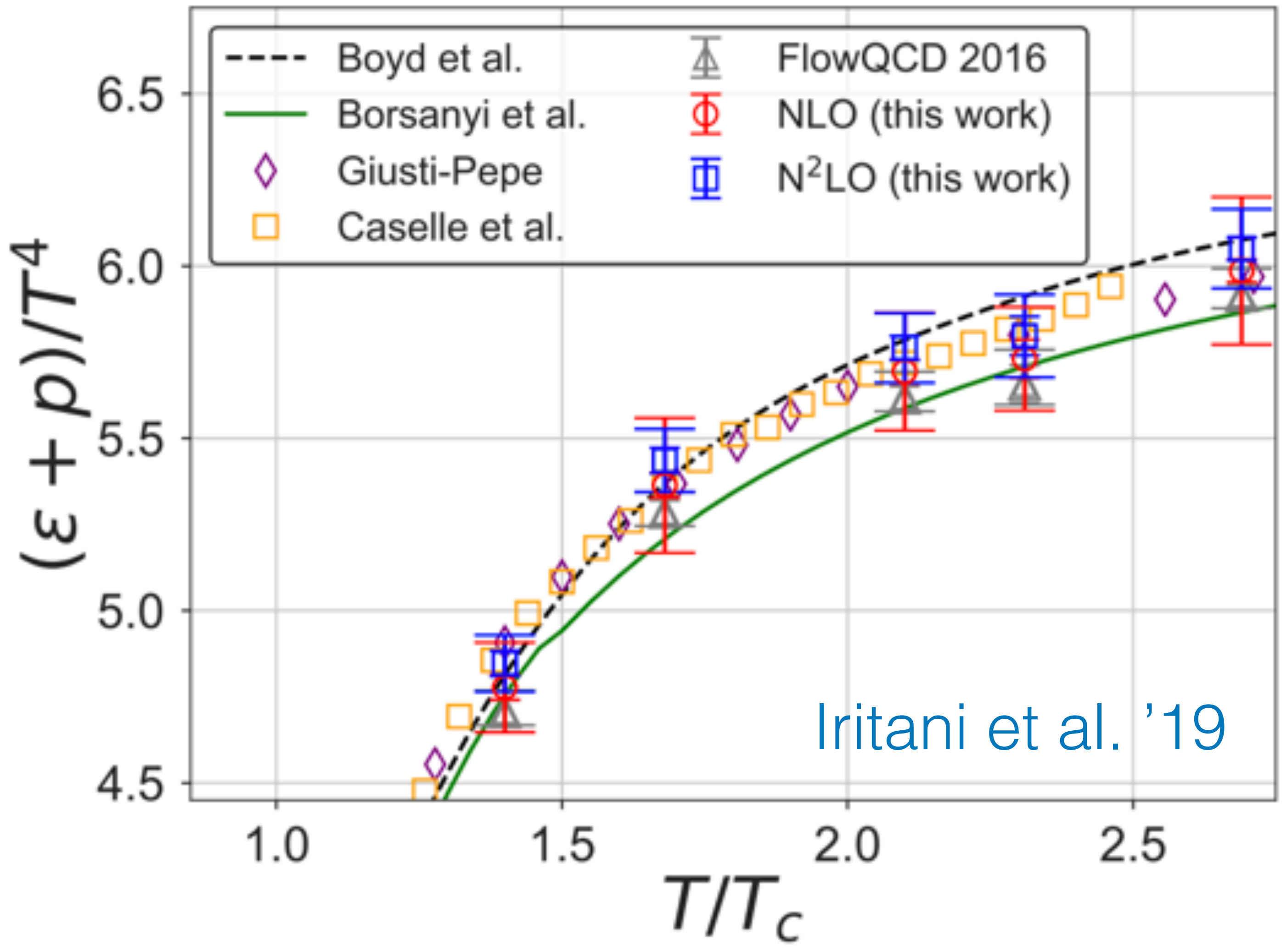
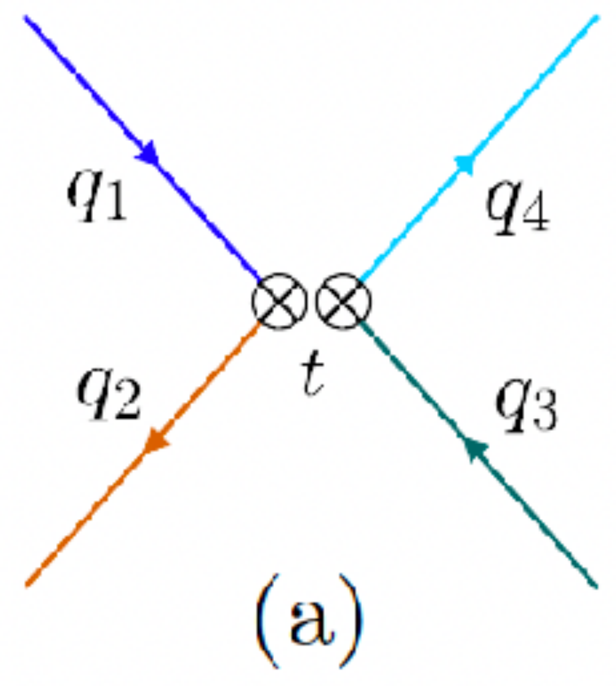


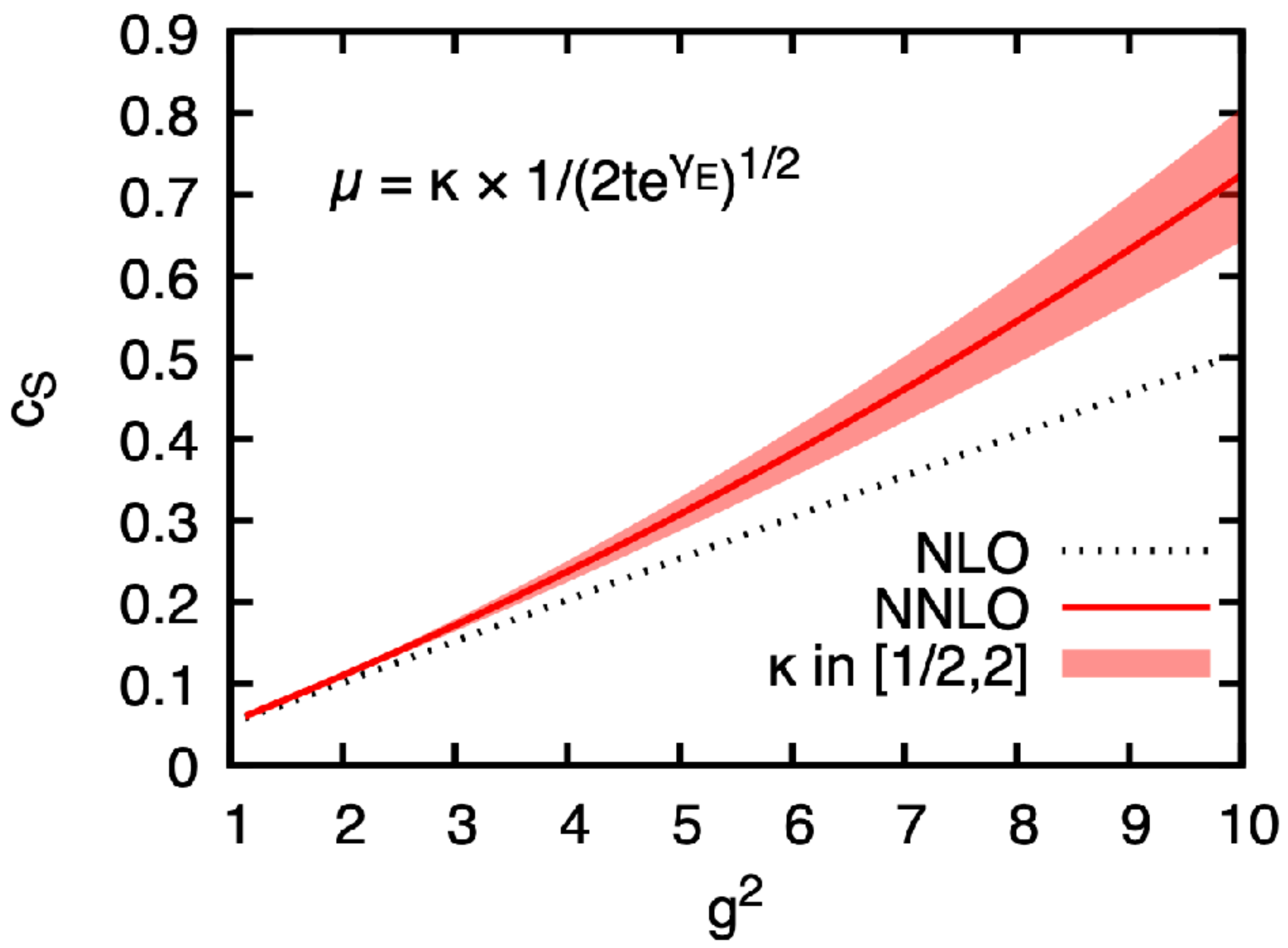
EW Hamiltonian

Suzuki et al., '20
RH, Lange, '22



see also Fabian Lange's talk at this conference

Result (preliminary)



$$c_{\mathrm{P}}(t) = 2\frac{\alpha_s(\mu)}{\pi} + \left(\frac{\alpha_s(\mu)}{\pi}\right)^2 \left[x_0 + x_1 \ln \mu^2 t\right]$$

Conclusions and Outlook

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Institute for Theoretical Particle Physics and Cosmology | RWTH AACHEN UNIVERSITY

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Conclusions and Outlook

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- requires non-perturbative calculation
- gradient flow offers viable approach
- here: perturbative determination of small-flow-time coefficients (CMDM)
- outlook: EDM (γ_5), quark mass effects, gluon CEDM, …
- side message: do not re-invent the wheel — perturbative toolbox is very powerful!