FACTORISATION AND SUBTRACTION BEYOND NLO

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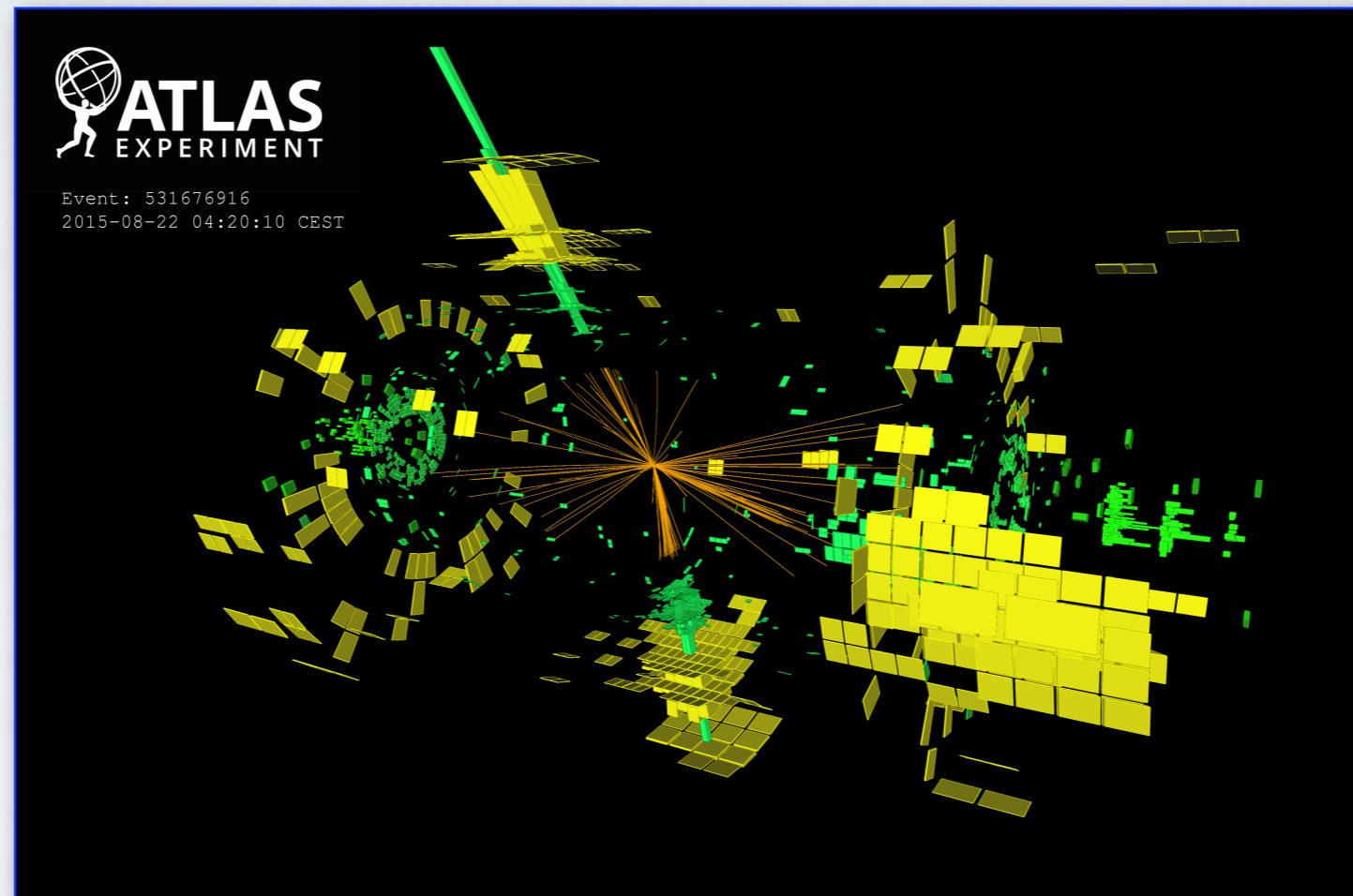Cavendish-DAMTP seminar - Cambridge - 17/01/19

Outline

- Introduction

- Algorithms

- Factorisation

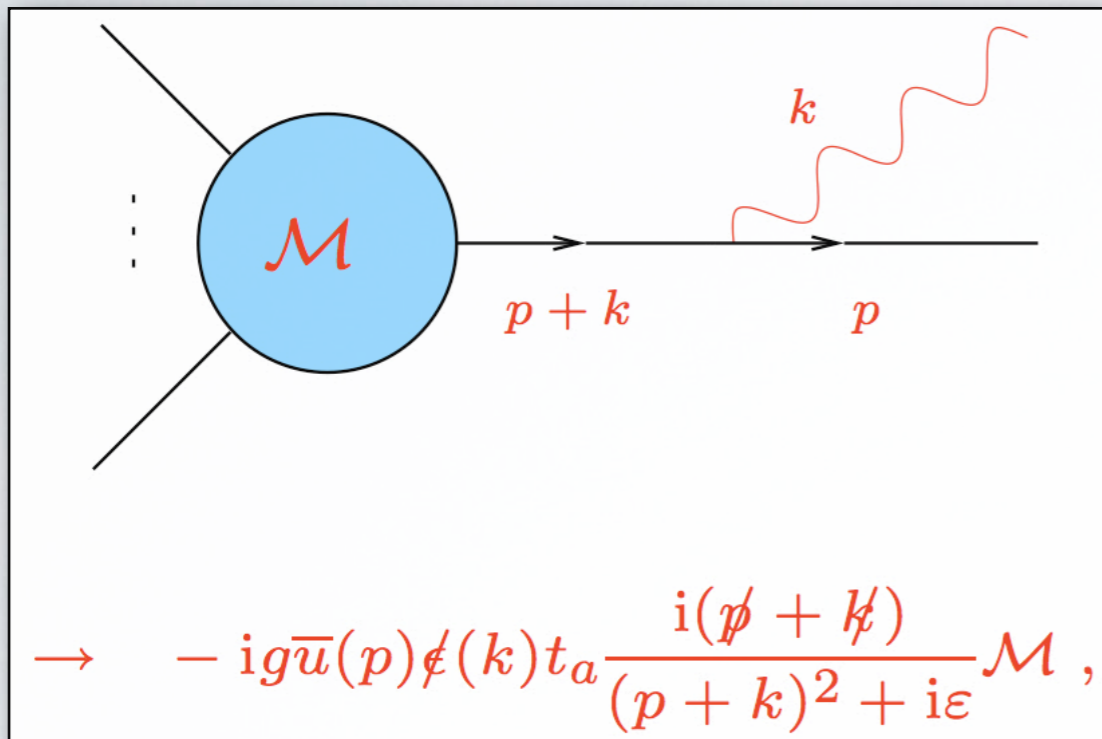- Counterterms

- Outlook

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- Algorithms

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- Counterterms

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In collaboration with
Ezio Maina,
Giovanni Pelliccioli
Chiara Signorile-Signorile
Paolo Torrielli
Sandro Uccirati

INTRODUCTION

Textbook infrared

$$\rightarrow \quad -\,\mathrm{i}g\overline{u}(p)\,\slashed{\epsilon}(k)\,t_a\frac{\mathrm{i}(\slashed{p}+\slashed{k})}{(p+k)^2+\mathrm{i}\varepsilon}\mathcal{M}\,,$$

Singularities arise only when propagators go on shell

$$2p\cdot k = 2p_0 k_0(1-\cos\theta_{pk}) = 0\,,$$
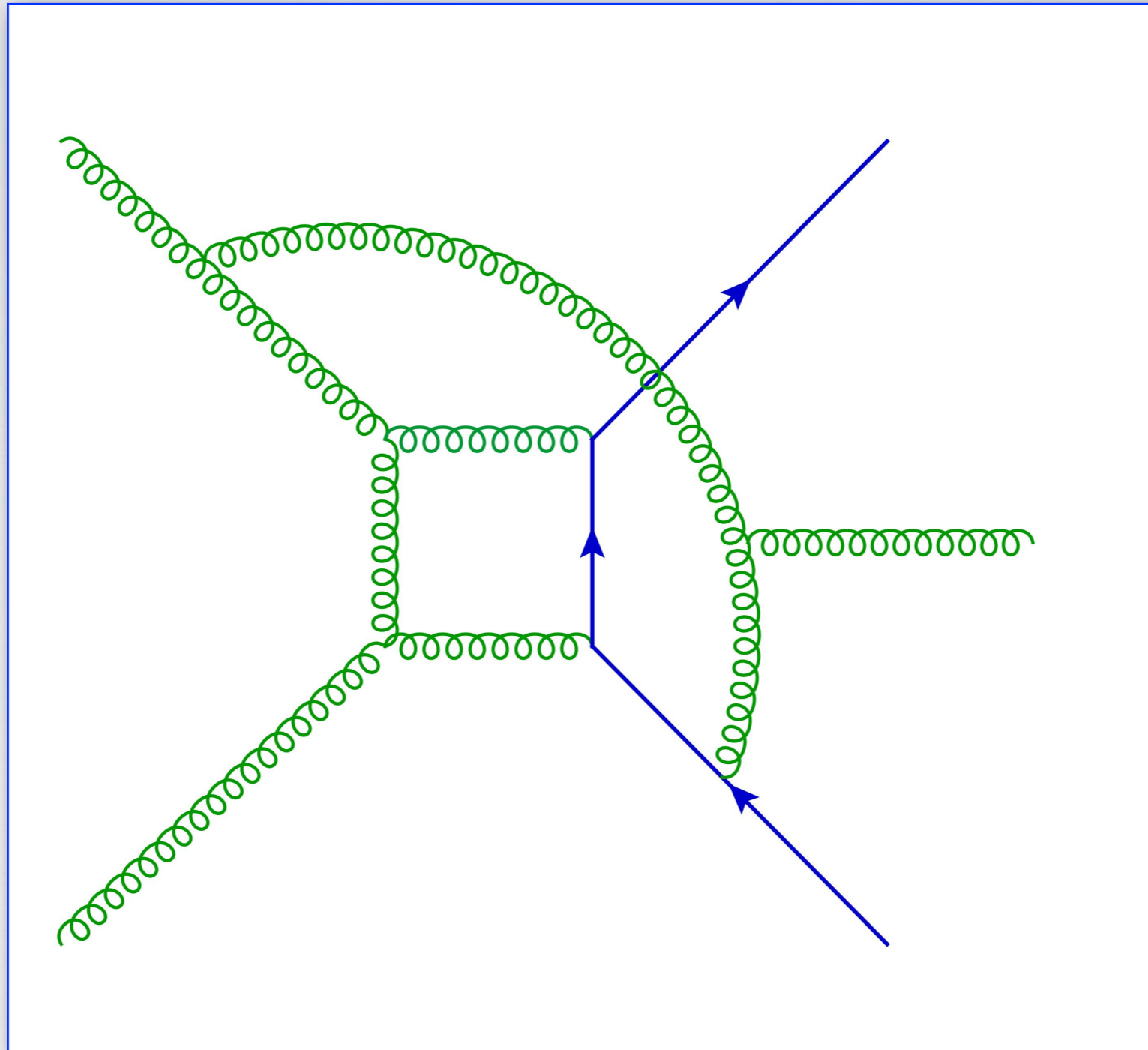$$\rightarrow k_0 = 0\ (IR);\quad \cos\theta_{pk}=1\,.$$

➡ Emission is not suppressed at long distances

➡ Isolated charged particles are not true asymptotic states of unbroken gauge theories

📌 A serious problem: the S matrix does not exist in the usual Fock space

📌 Possible solutions: construct finite transition probabilities (KLN theorem)
construct better asymptotic states (coherent states)

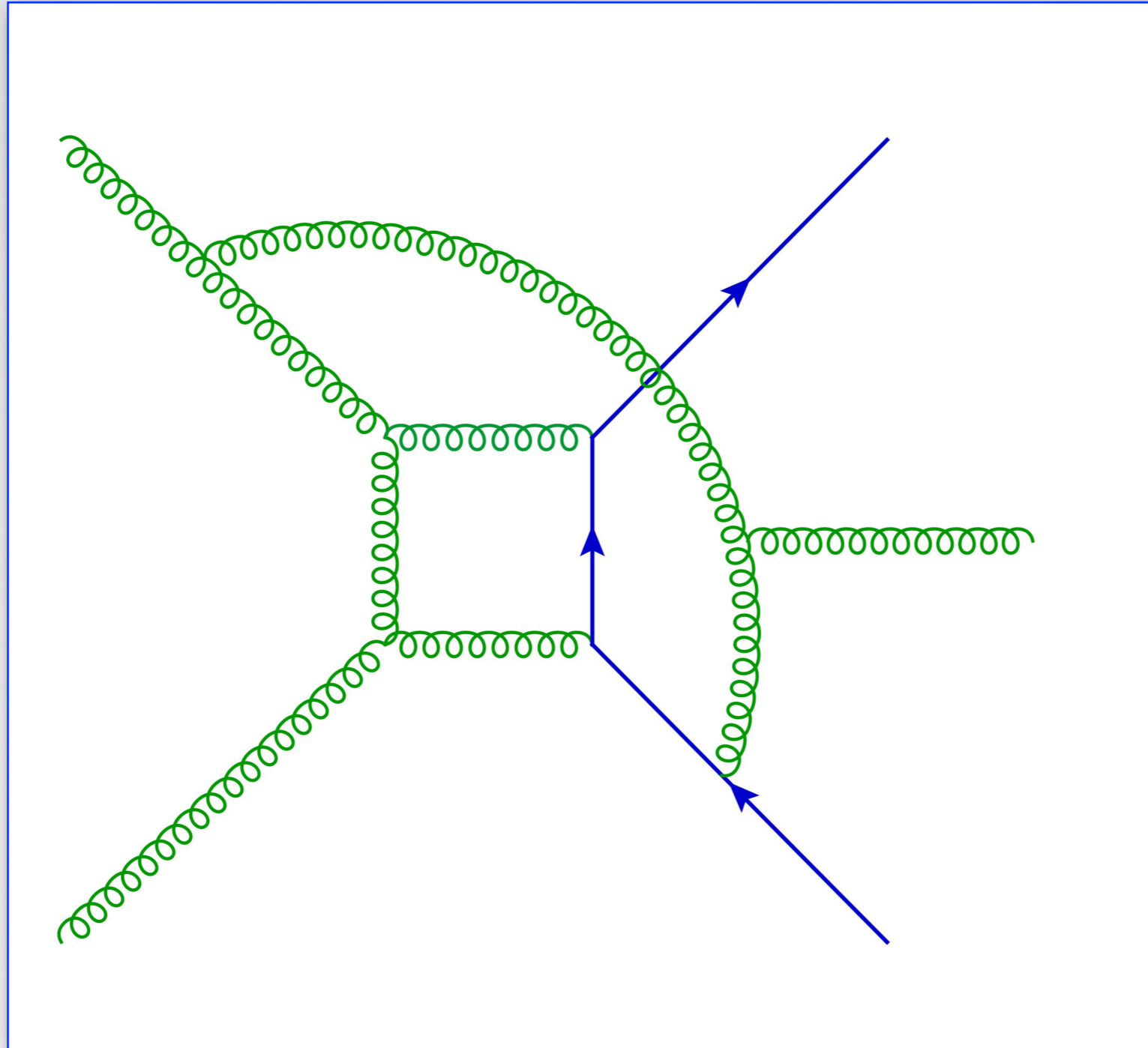📌 Long-distance singularities obey a pattern of exponentiation

$$\mathcal{M} = \mathcal{M}_0\left[1 - \kappa\,\frac{\alpha}{\pi}\frac{1}{\epsilon} + \ldots\right]\ \Rightarrow\ \mathcal{M} = \mathcal{M}_0\exp\left[-\kappa\,\frac{\alpha}{\pi}\frac{1}{\epsilon} + \ldots\right]$$

Pictorial infrared

A diagram contributing a double-virtual NNLO correction to t-tbar-jet production
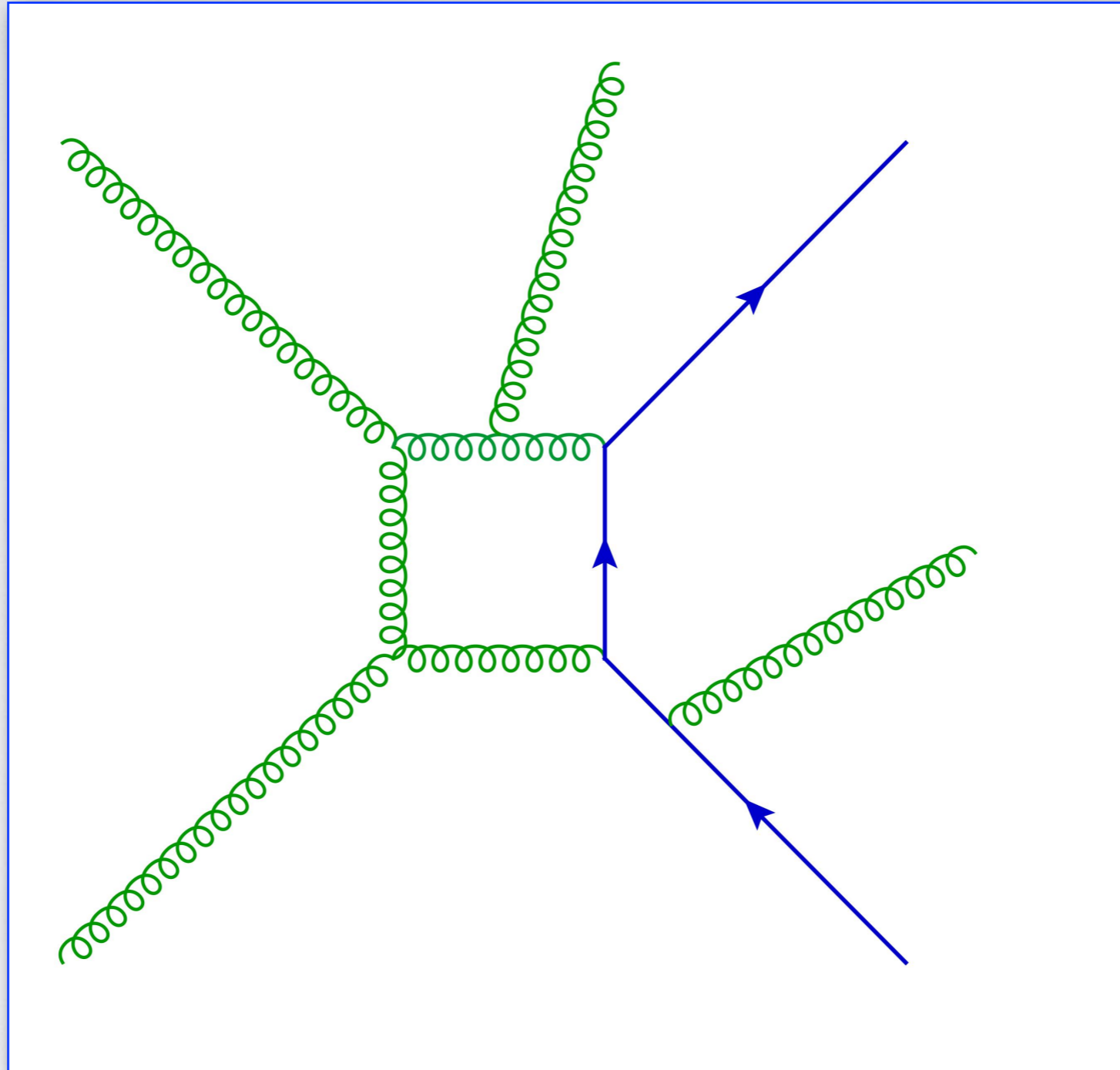
Pictorial infrared

$$\frac{1}{\epsilon^4}$$

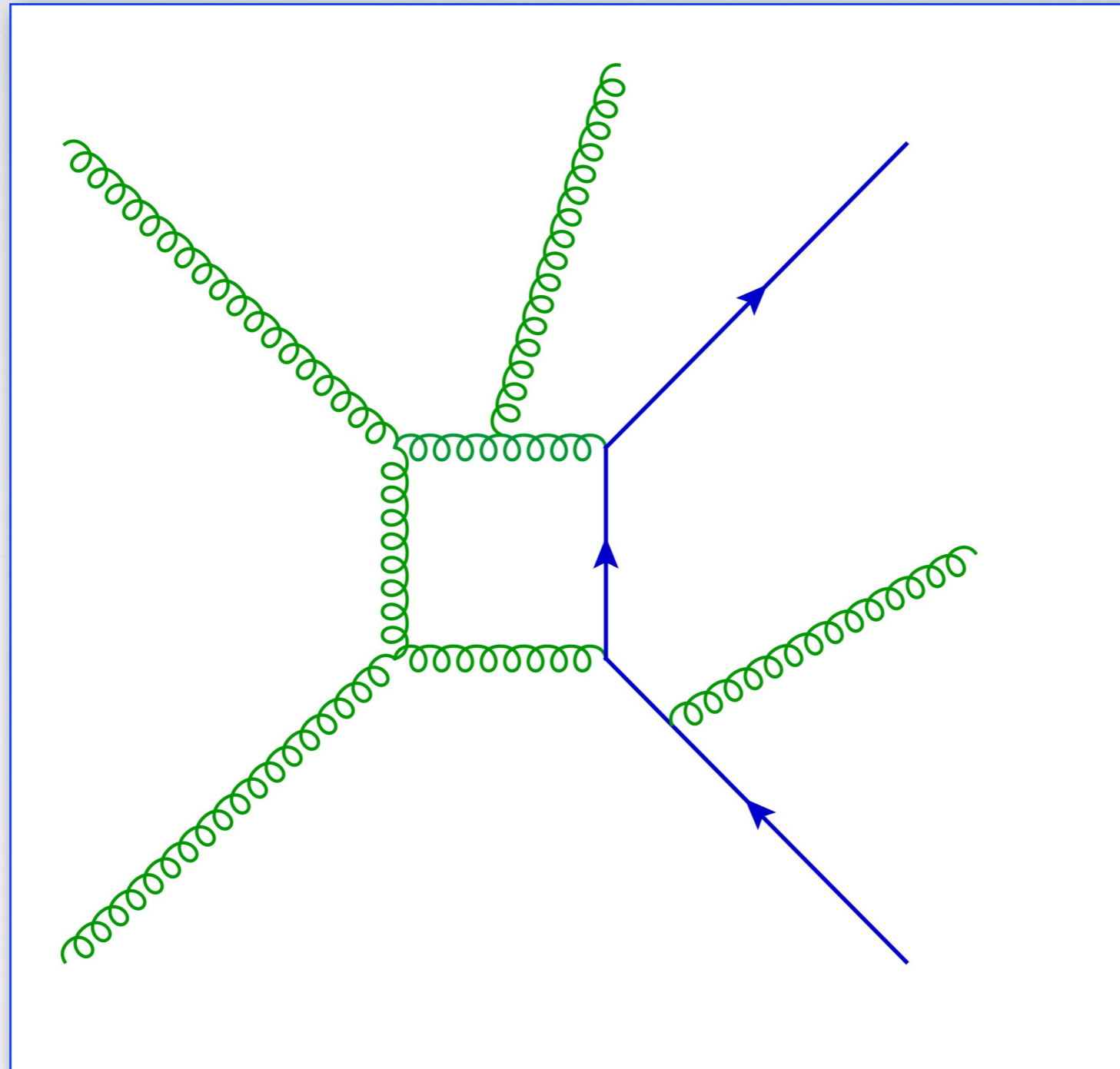A diagram contributing a double-virtual NNLO correction to t-tbar-jet production

Pictorial infrared

A diagram contributing a real-virtual NNLO correction to t-tbar-jet production

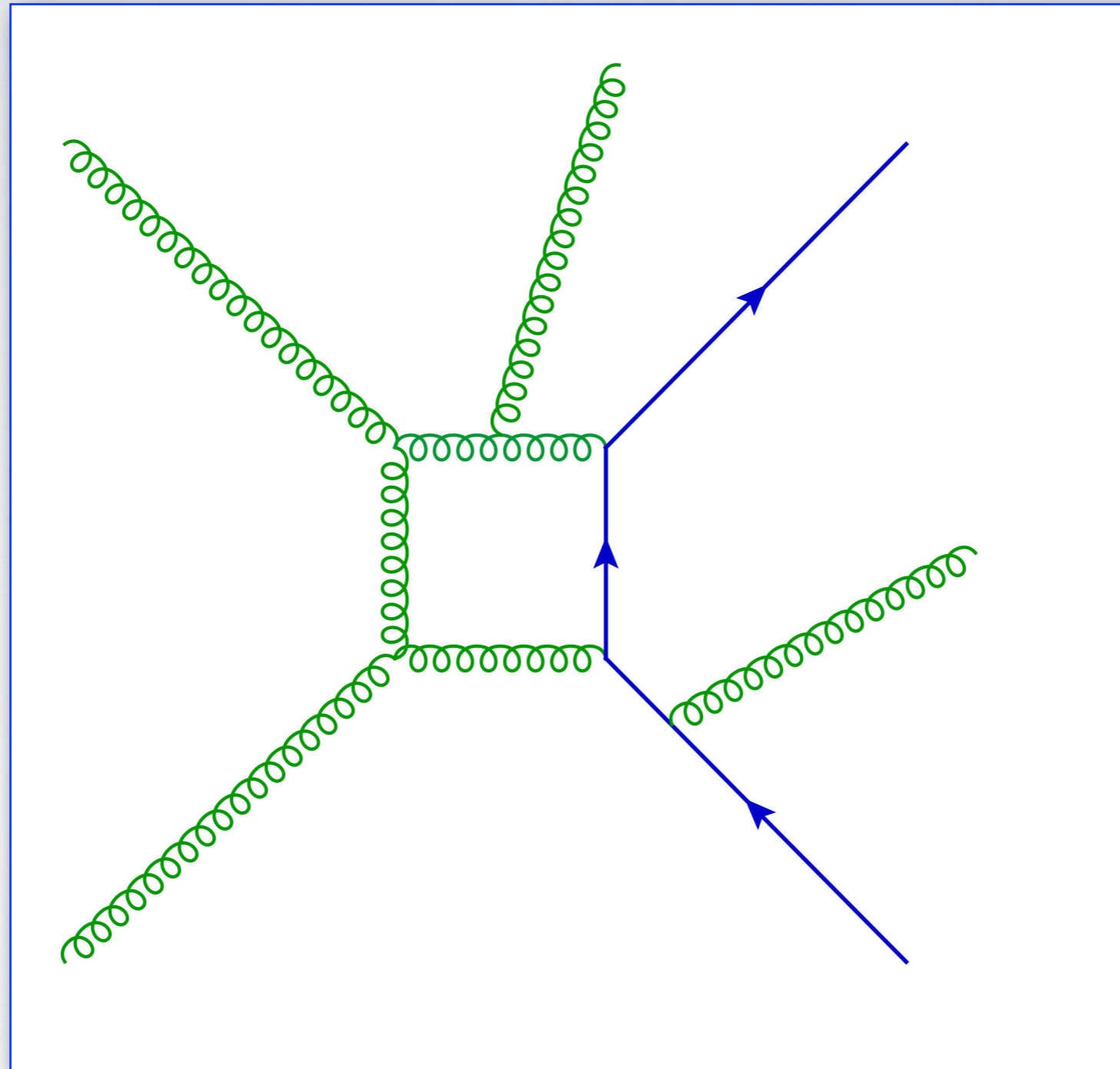# Pictorial infrared

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$$\frac{dE}{E}\,\frac{dk_\perp}{k_\perp}$$

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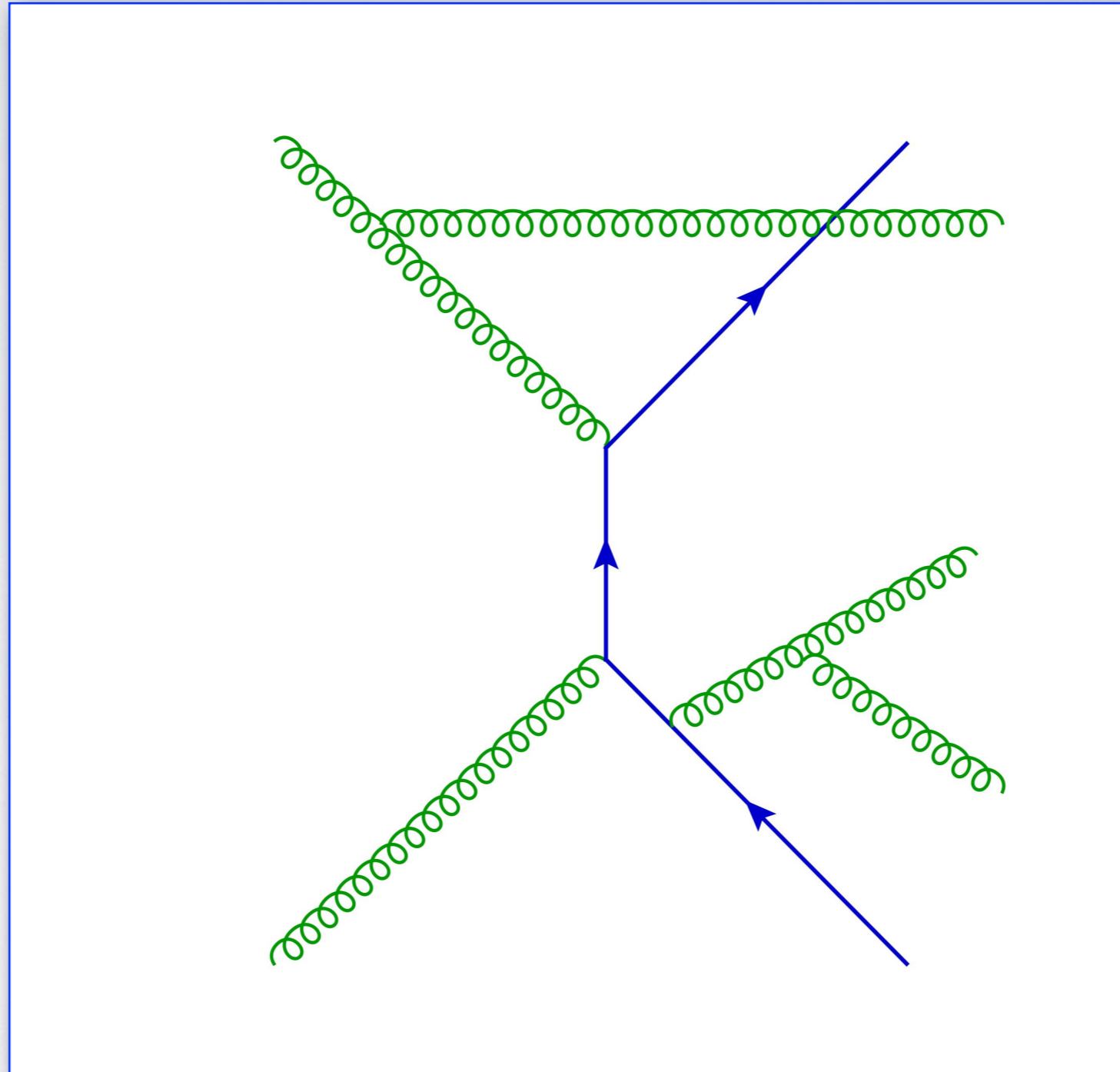
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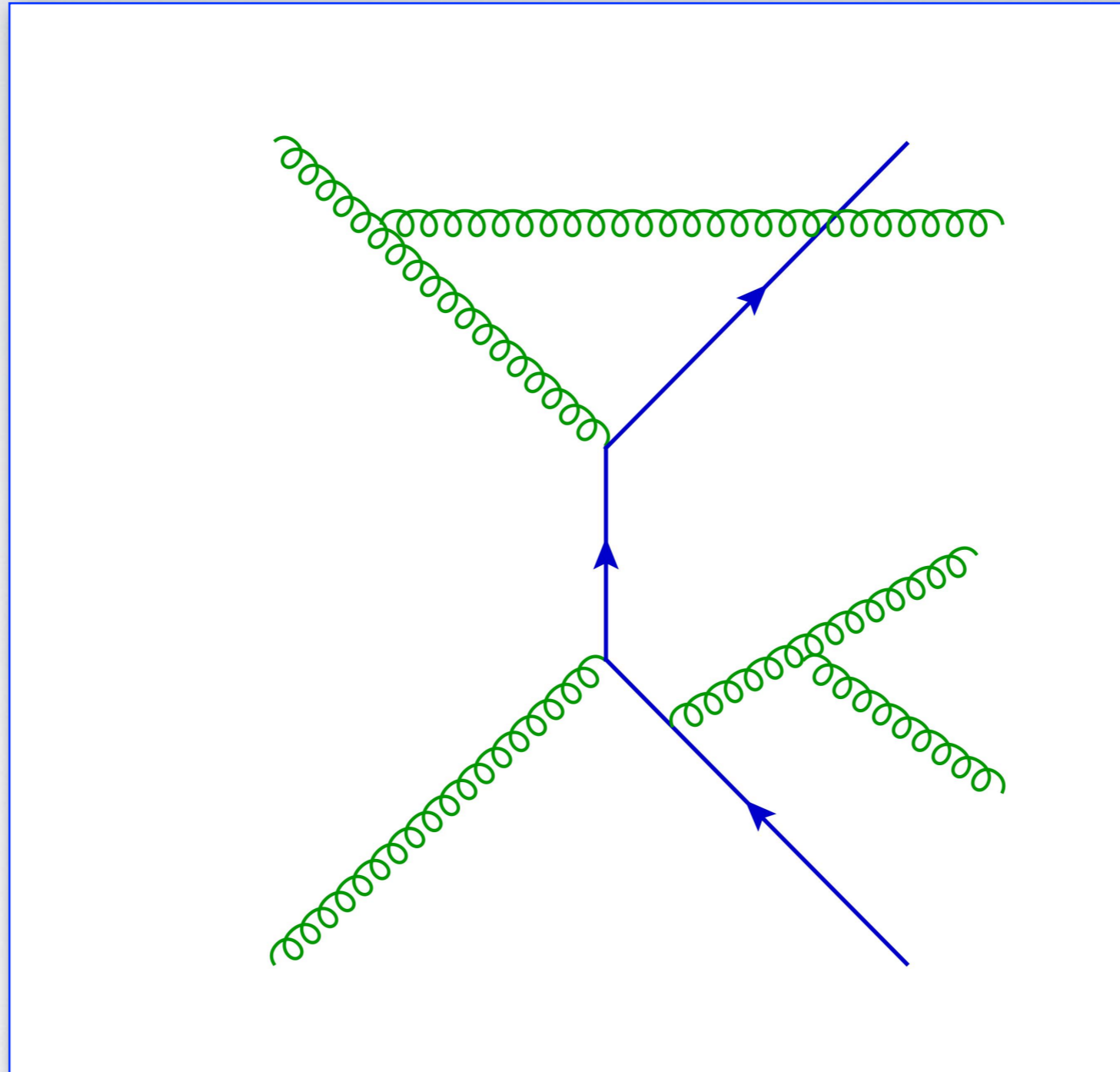
$$\left(\frac{dE}{E} \, \frac{dk_\perp}{k_\perp} \right)^2$$

A diagram contributing a double-real NNLO correction to t-tbar-jet production

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- Can one use the structure of virtual singularities as an organising principle for subtraction?

- Can the simplifying features of virtual corrections be exported to real radiation?

The subtraction problem at NLO is completely solved, with efficient algorithms applicable to any process for which matrix elements are known.

At NNLO after fifteen years of efforts several groups have working algorithms, successfully applied to `simple' process with up to four legs. Heavy computational costs.

- Antenna Subtraction.

- Stripper

- Nested Soft-Collinear Subtractions.

- ColourfulNNLO.

- N-Jettiness Slicing.

- Q_T Slicing.

- Projection to Born.

- Unsubtraction.

- Geometric Slicing.

- Finite Subtraction …

ALGORITHMS

The computation of a generic IRC-safe observable at NLO requires the combination

$$\langle O \rangle_{\mathrm{NLO}} = \lim_{d \to 4} \left\{ \int d\Phi_n \left[B_n + V_n \right] O_n + \int d\Phi_{n+1} R_{n+1} O_{n+1} \right\}$$

The necessary numerical integrations require finite ingredients in d=4. Define counterterms

$$\langle O \rangle_{\mathrm{ct}} = \int d\Phi_n \, d\hat{\Phi}_1 \, K_{n+1} O_n \,.$$

$$I_n = \int d\hat{\Phi}_1 \, K_{n+1} \,,$$

Add and subtract the same quantity to the observable: each contribution is now finite.

$$\langle O \rangle_{\mathrm{NLO}} = \int d\Phi_n \left[B_n^{(4)} + (V_n + I_n)^{(4)} \right] O_n + \int d\Phi_n \left[\int d\Phi_1^{(4)} R_{n+1}^{(4)} O_{n+1} - \int d\hat{\Phi}_1^{(4)} K_{n+1}^{(4)} O_n \right]$$

Search for the simplest fully local integrand K_{n+1} with the correct singular limits.

The **pattern** of cancellations is more **intricate** at **higher orders**

$$\langle O \rangle_{\text{NNLO}} = \lim_{d \to 4} \left\{ \int d\Phi_n \left[B_n + V_n + VV_n \right] O_n + \int d\Phi_{n+1} \left[R_{n+1} + RV_{n+1} \right] O_{n+1} \right.$$

$$\left. + \int d\Phi_{n+2} \, RR_{n+2} \, O_{n+2} \right\} .$$

More counterterm **functions** need to be **defined**

$$I_{n+1}^{(1)} = \int d\hat{\Phi}_1' \, K_{n+2}^{(1)} ,$$

$$I_n^{(2)} = \int d\hat{\Phi}_2 \, K_{n+2}^{(2)} = \int d\hat{\Phi}_1 \, d\hat{\Phi}_1' \, K_{n+2}^{(2)} ,$$

$$I_n^{(\mathbf{RV})} = \int d\hat{\Phi}_1 \, K_{n+1}^{(\mathbf{RV})} .$$

A **finite expression** for the observable in **d=4** must combine **several ingredients**

$$\langle O \rangle_{\text{NNLO}} = \int d\Phi_n \left[B_n^{(4)} + (V_n + I_n)^{(4)} + \left(VV_n + I_n^{(2)} + I_n^{(\mathbf{RV})} \right)^{(4)} \right] O_n$$

$$+ \int d\Phi_n \left[\int d\Phi_1^{(4)} \, R_{n+1}^{(4)} \, O_{n+1} - \int d\hat{\Phi}_1^{(4)} \, K_{n+1}^{(4)} \, O_n \right.$$

$$+ \int d\Phi_1^{(4)} \left(RV_{n+1} + I_{n+1}^{(1)} \right)^{(4)} O_{n+1} - \int d\hat{\Phi}_1^{(4)} \, K_{n+1}^{(\mathbf{RV})(4)} \, O_n \right]$$

$$+ \int d\Phi_n \left[\int d\Phi_2^{(4)} \, RR_{n+2}^{(4)} \, O_{n+2} - \int d\Phi_1^{(4)} d\hat{\Phi}_1'^{(4)} \, K_{n+2}^{(1)(4)} \, O_{n+1} - \int d\hat{\Phi}_2^{(4)} \, K_{n+2}^{(2)(4)} \, O_n \right]$$

NNLO Subtraction

The pattern of cancellations is more intricate at higher orders

$$
\langle O \rangle_{\mathrm{NNLO}} = \lim_{d \to 4} \left\{ \int d\Phi_n \left[B_n + V_n + VV_n \right] O_n + \int d\Phi_{n+1} \left[R_{n+1} + RV_{n+1} \right] O_{n+1} \right.
$$
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$$
\frac{d\sigma_{\mathrm{NNLO}}}{dX} = \int d\Phi_n \left(VV + I^{(2)} + I^{(\mathbf{RV})} \right) \delta_n
$$
$$
+ \int \left[\left(d\Phi_{n+1} \, RV + d\hat{\Phi}_{n+1} \, I^{(1)} \right) \delta_{n+1} - d\hat{\Phi}_{n+1} \left(\overline{K}^{(\mathbf{RV})} - I^{(12)} \right) \delta_n \right]
$$
$$
+ \int \left[d\Phi_{n+2} \, RR \, \delta_{n+2|} - d\hat{\Phi}_{n+2} \, \overline{K}^{(1)} \, \delta_{n+1} - d\hat{\Phi}_{n+2} \left(\overline{K}^{(2)} + \overline{K}^{(12)} \right) \delta_n \right] .
$$

NLO Sectors

Minimize complexity: split phase space in sectors with sector function $\mathcal{W}_{ij}$ in order to have at most one soft and one collinear singularity in each sector (FKS).

- Sector functions must form a partition of unity.

- In order not to appear in analytic integrations, sector functions must obey sum rules. Denoting with $\mathbf{S}_i$ the soft limit for parton i and $\mathbf{C}_{ij}$ the collinear limit for the ij pair,

$$\mathbf{S}_i \sum_{k \neq i} \mathcal{W}_{ik} = 1 \,, \qquad \mathbf{C}_{ij} \sum_{ab \,\in\, \mathrm{perm}(ij)} \mathcal{W}_{ab} = 1 \,, \qquad \longleftarrow \quad \mathrm{sum\ rules}$$

- Sector functions are defined in terms of Lorentz invariants before choosing an explicit parametrisation of phase space. A possible choice is

$$\mathcal{W}_{ij} = \frac{\sigma_{ij}}{\displaystyle\sum_{k,\,l \neq k} \sigma_{kl}} \,, \qquad \mathrm{with} \qquad \sigma_{ij} = \frac{1}{e_i \, w_{ij}} \,, \qquad e_i = \frac{s_{qi}}{s} \,, \qquad w_{ij} = \frac{s \, s_{ij}}{s_{qi} \, s_{qj}} \,.$$

- In each sector one can now define a candidate counterterm

$$K_{ij} = (\mathbf{S}_i + \mathbf{C}_{ij} - \mathbf{S}_i \, \mathbf{C}_{ij}) R \, \mathcal{W}_{ij}$$

In order to factorise a Born matrix element B_n with n on-shell particles conserving momentum, we need a mapping from the (n+1)-particle to the Born phase spaces. We use (CS)

$$\bar{k}_i^{(abc)} = k_i, \quad \text{if } i \neq a, b, c,$$

$$\bar{k}_b^{(abc)} = k_a + k_b - \frac{s_{ab}}{s_{ac} + s_{bc}} k_c, \qquad \bar{k}_c^{(abc)} = \frac{s_{abc}}{s_{ac} + s_{bc}} k_c,$$

We can now redefine soft and collinear limits to include the re-parametrisation. Explicitly

$$\bar{\mathbf{S}}_i R(\{k\}) = -\mathcal{N}_1 \sum_{l,m} \delta_{f_i g} \frac{s_{lm}}{s_{il} s_{im}} B_{lm}\left(\{\bar{k}\}^{(ilm)}\right),$$

$$\overline{\mathbf{C}}_{ij} R(k) = \frac{\mathcal{N}_1}{s_{ij}} \left[P_{ij} B\left(\{\bar{k}\}^{(ijr)}\right) + Q_{ij}^{\mu\nu} B_{\mu\nu}\left(\{\bar{k}\}^{(ijr)}\right) \right],$$

$$\bar{\mathbf{S}}_i \overline{\mathbf{C}}_{ij} R(\{k\}) = 2\mathcal{N}_1 C_{f_j} \delta_{f_i g} \frac{s_{jr}}{s_{ij} s_{ir}} B\left(\{\bar{k}\}^{(ijr)}\right),$$

Note that we have assigned parametrisation triplets differently in different terms. Then

$$\overline{K} = \sum_{i,j \neq i} \overline{K}_{ij}, \qquad \overline{K}_{ij} \equiv \left(\bar{\mathbf{S}}_i + \overline{\mathbf{C}}_{ij} - \bar{\mathbf{S}}_i \overline{\mathbf{C}}_{ij} \right) R \mathcal{W}_{ij},$$
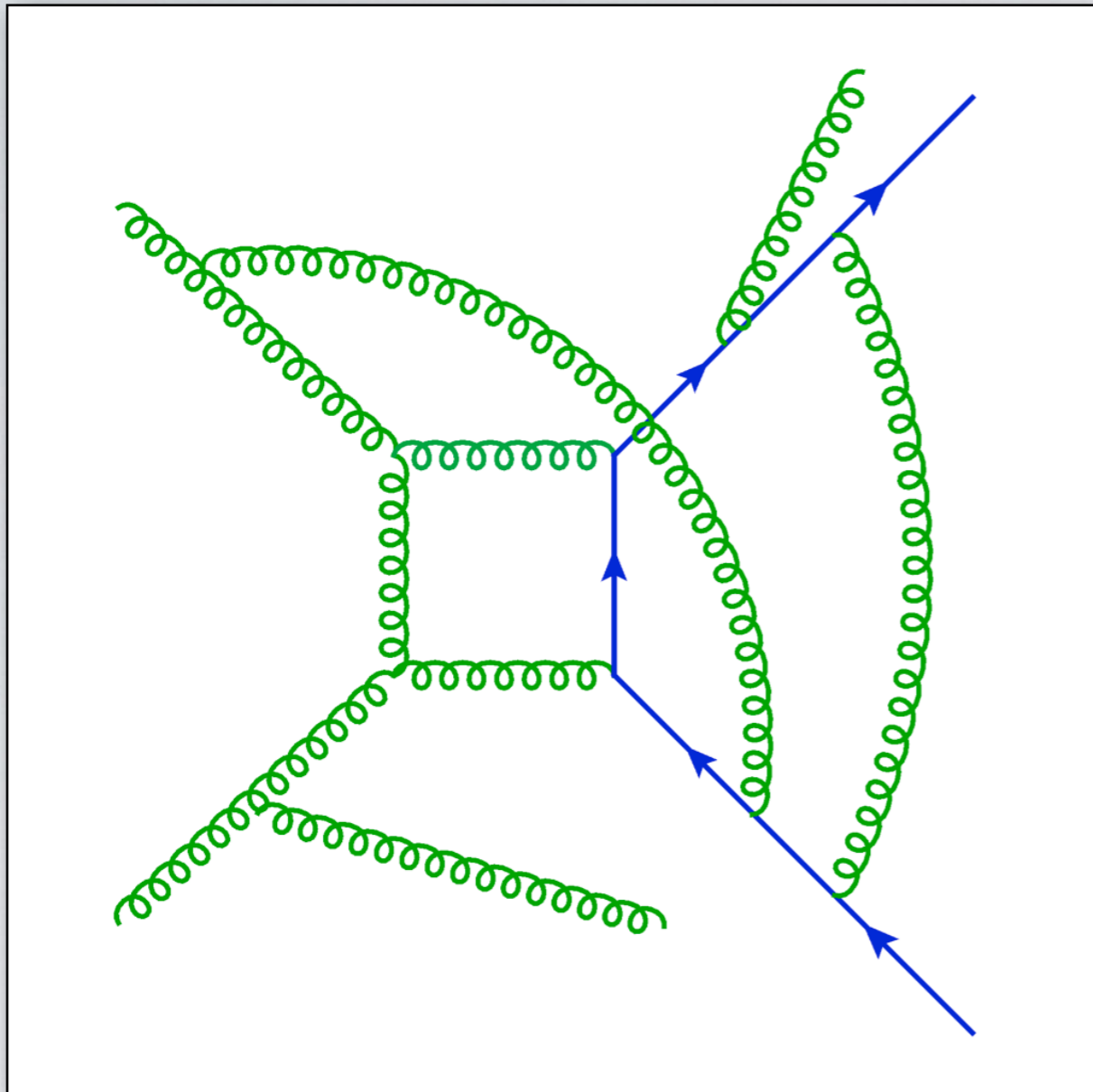
NNLO status

- So far we have applied the formalism to massless final state radiation.

- For this case, at NLO we have a full-fledged subtraction formalism, and simple integrals.

- A simple proof-of-concept case (double-quark-pair production) has been completed.

- A complete set of NNLO sector functions with the desired sum rules is available.

- Flexible phase space mappings for single and double unresolved limits exist.

- Checks that phase-space mappings do not misalign nested limits are near completion.

- All integrals for final state radiation are done/doable, possibly without IBP techniques.

- The development of a differential code for NNLO subtraction is under way.

- Generalisation to initial state radiation requires (hard) work but no new concepts.

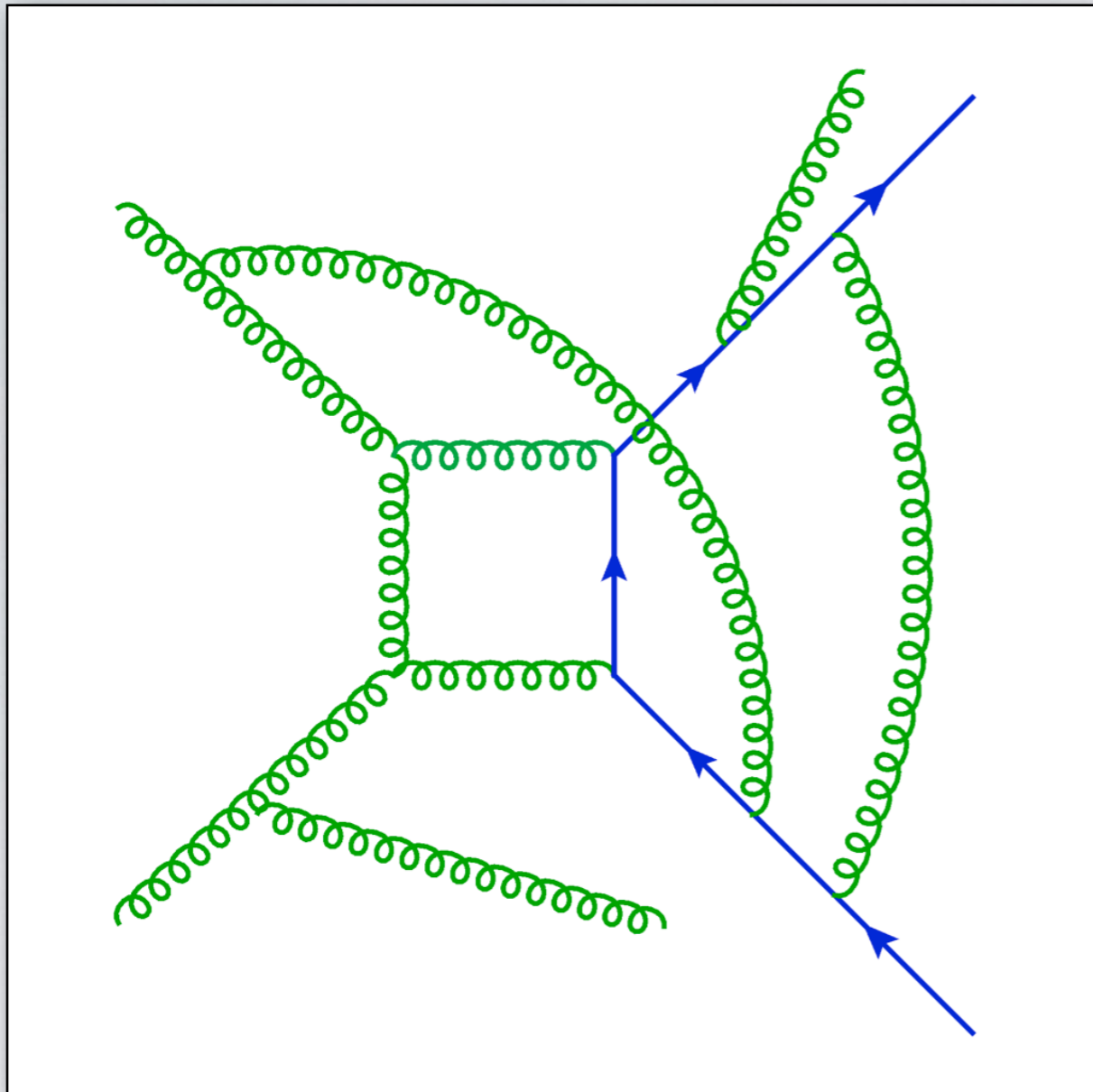- More `interesting' integrals may arise with massive partons.

FACTORISATION

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"long distance love"
by:

A gauge theory Feynman diagram with
potential soft and collinear enhancements

Soft-collinear factorisation

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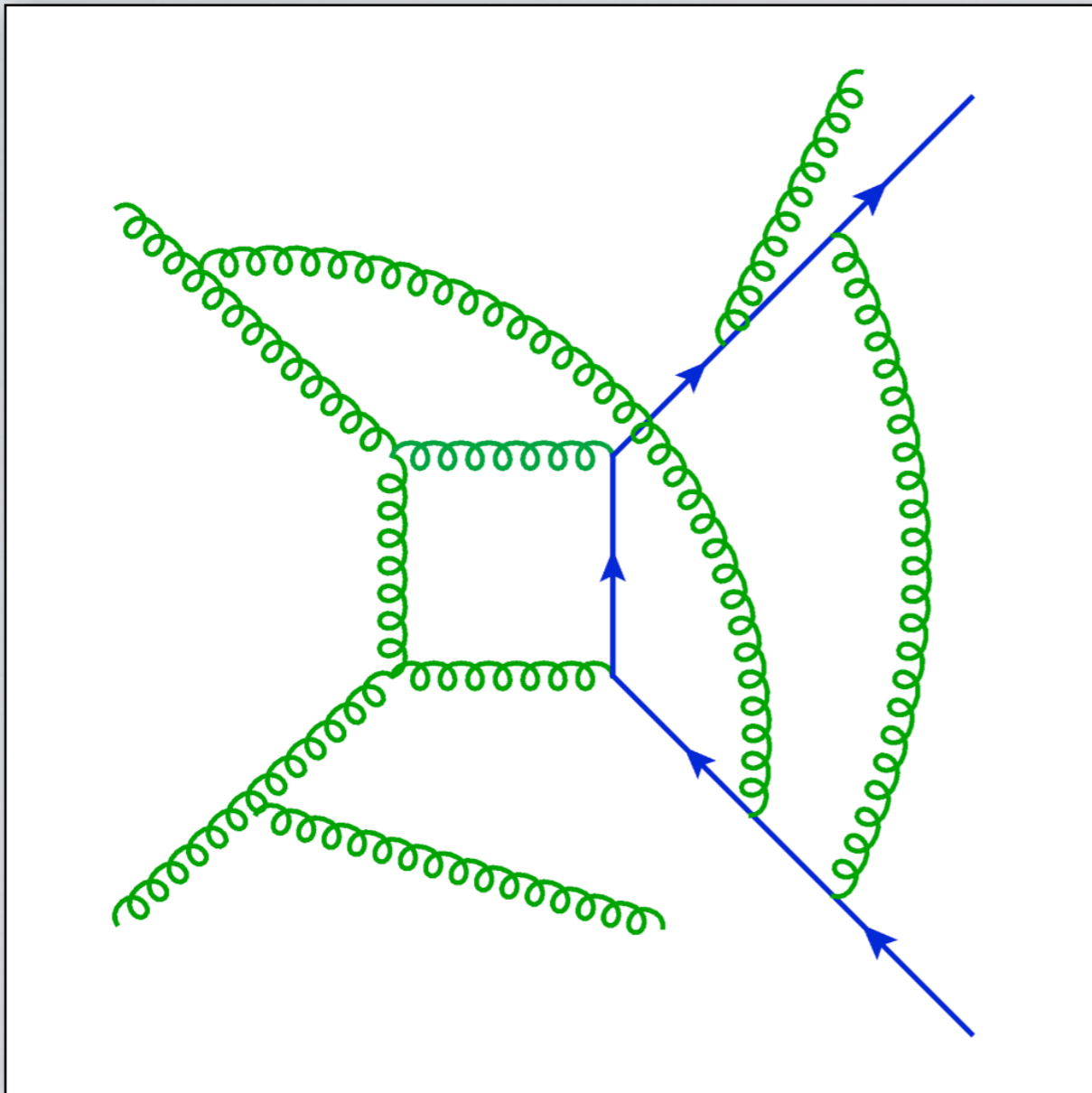
📌 Divergences arise in scattering amplitudes from leading regions in loop momentum space.

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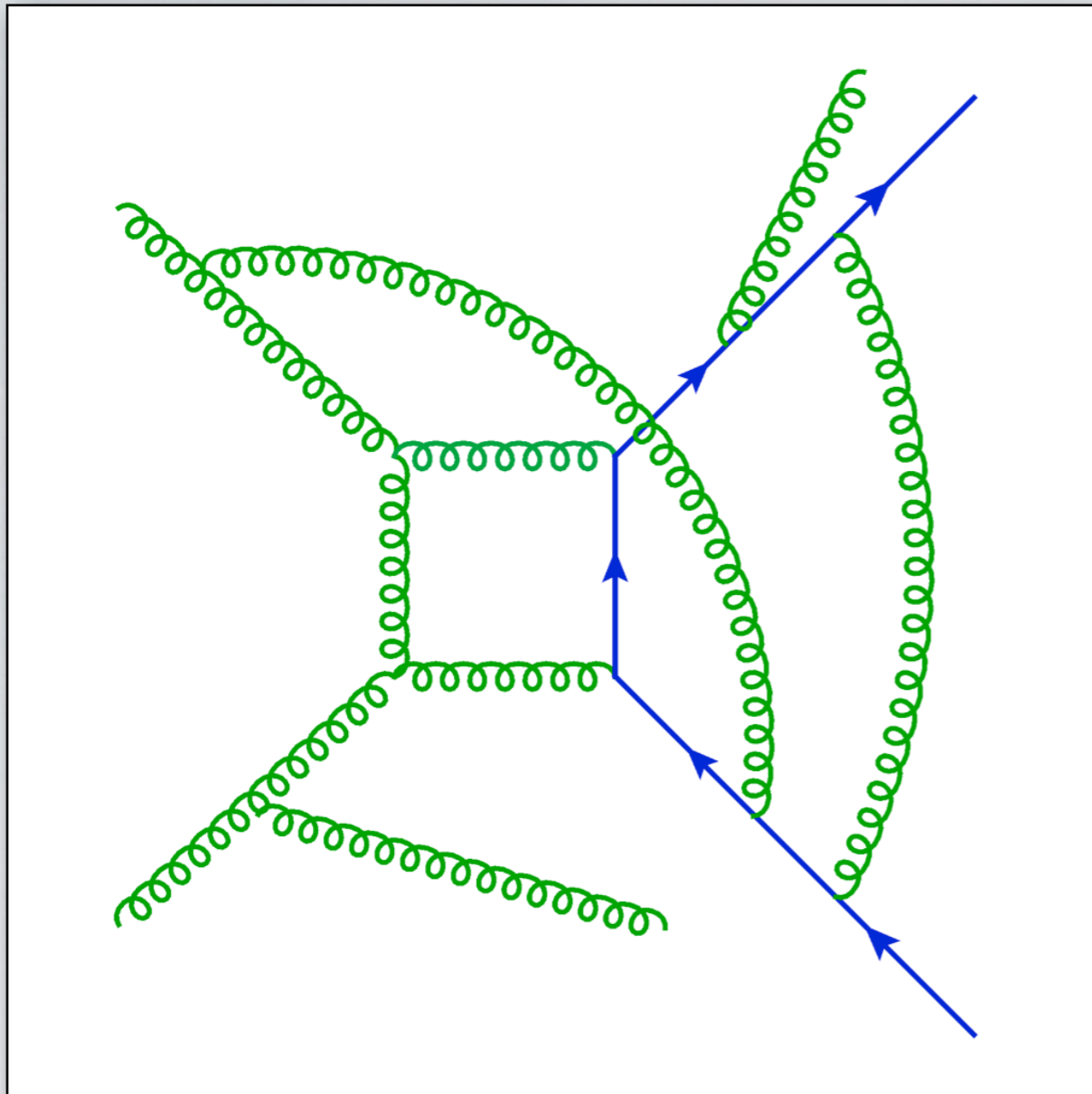
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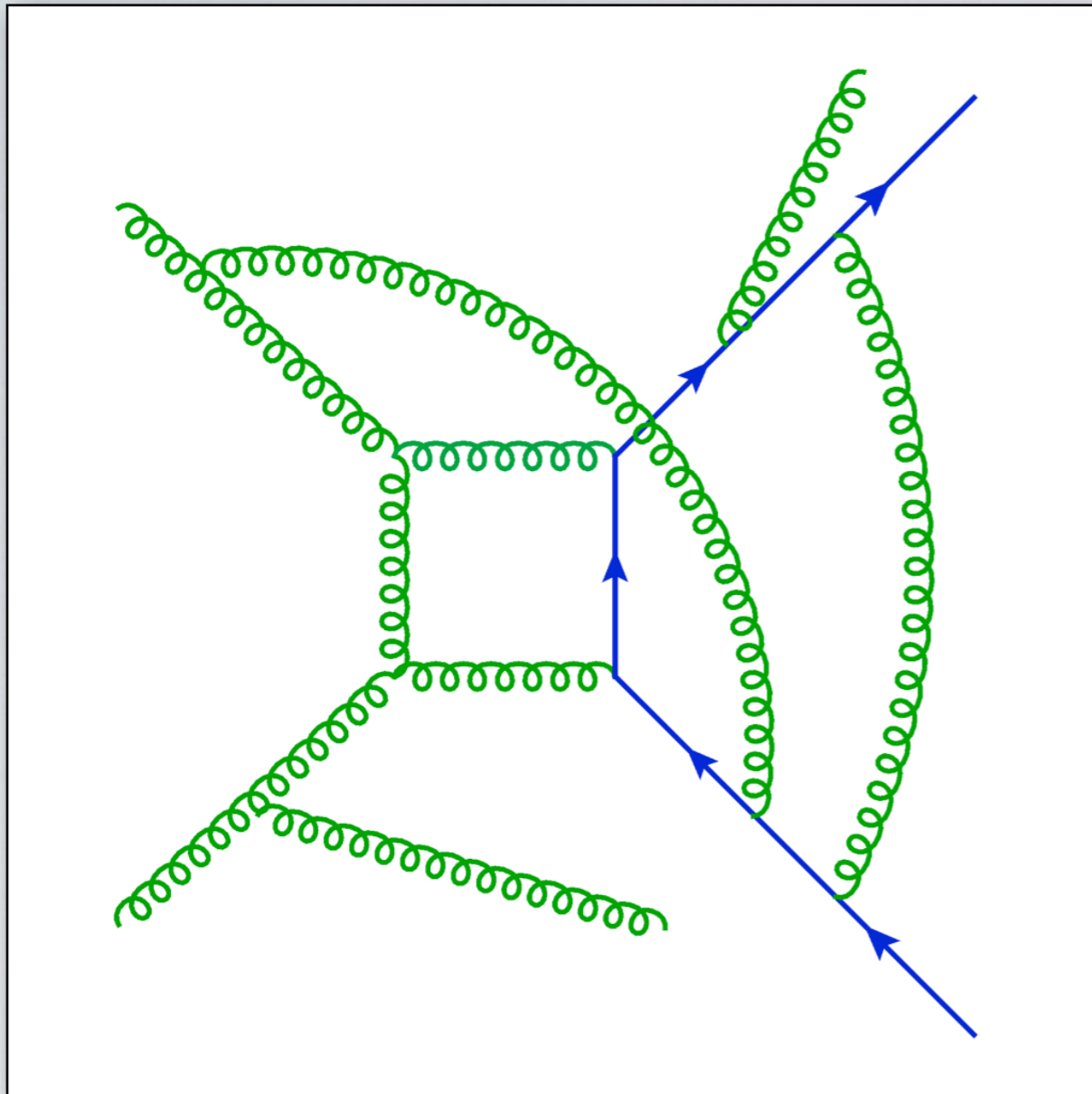- Potential singularities can be located using Landau equations.

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- **Divergences** arise in scattering amplitudes from **leading regions** in loop momentum space.

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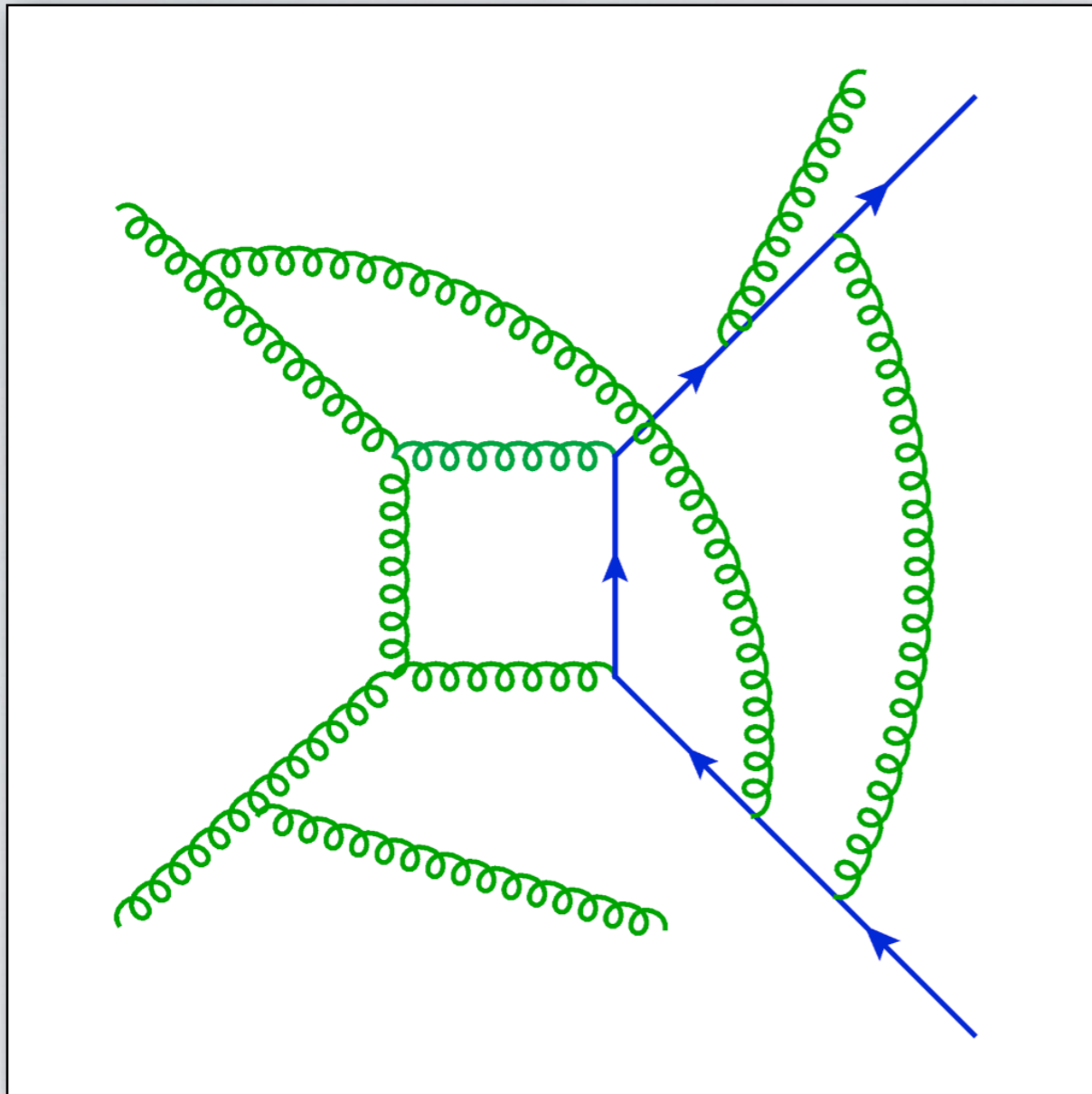
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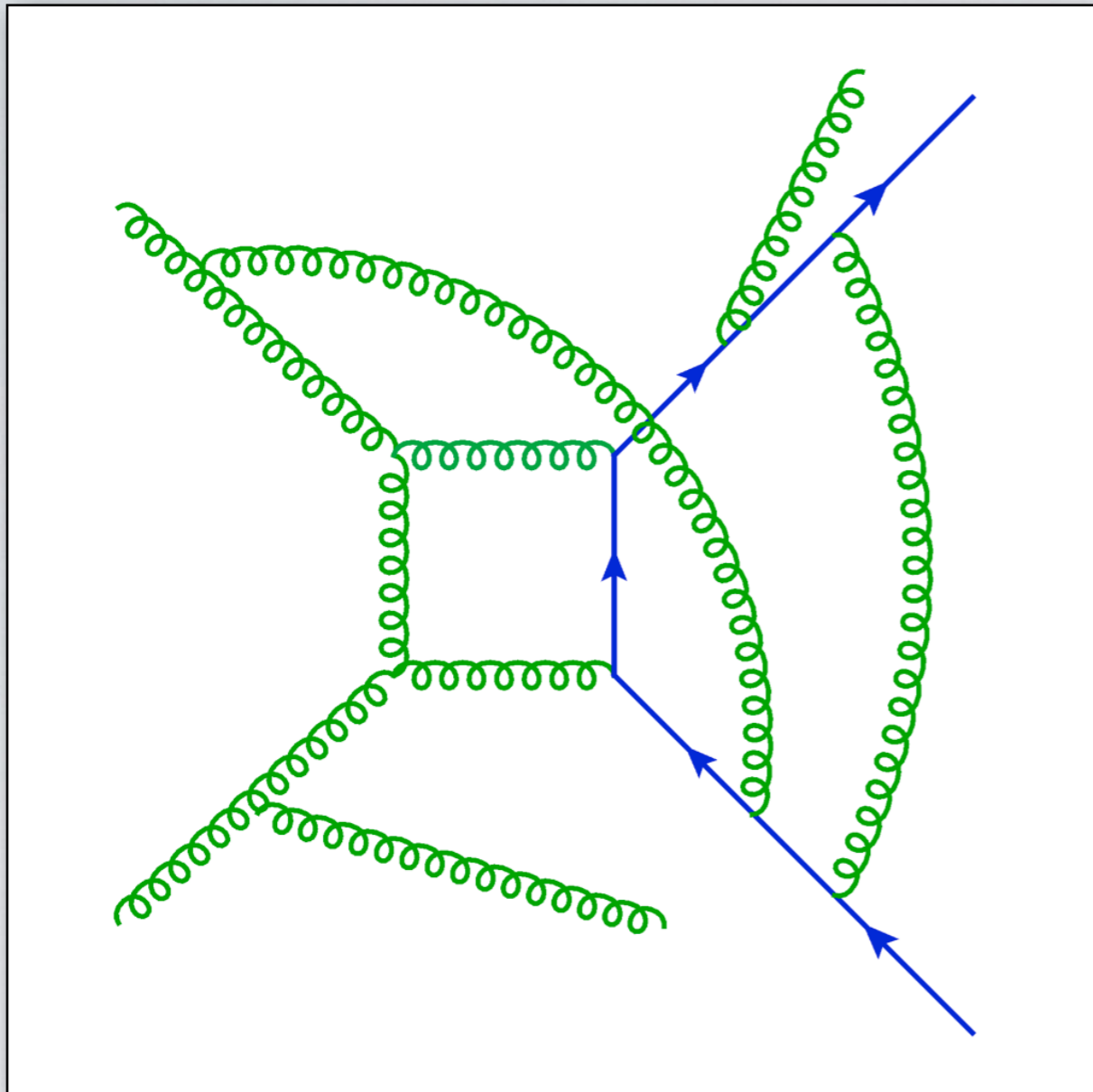
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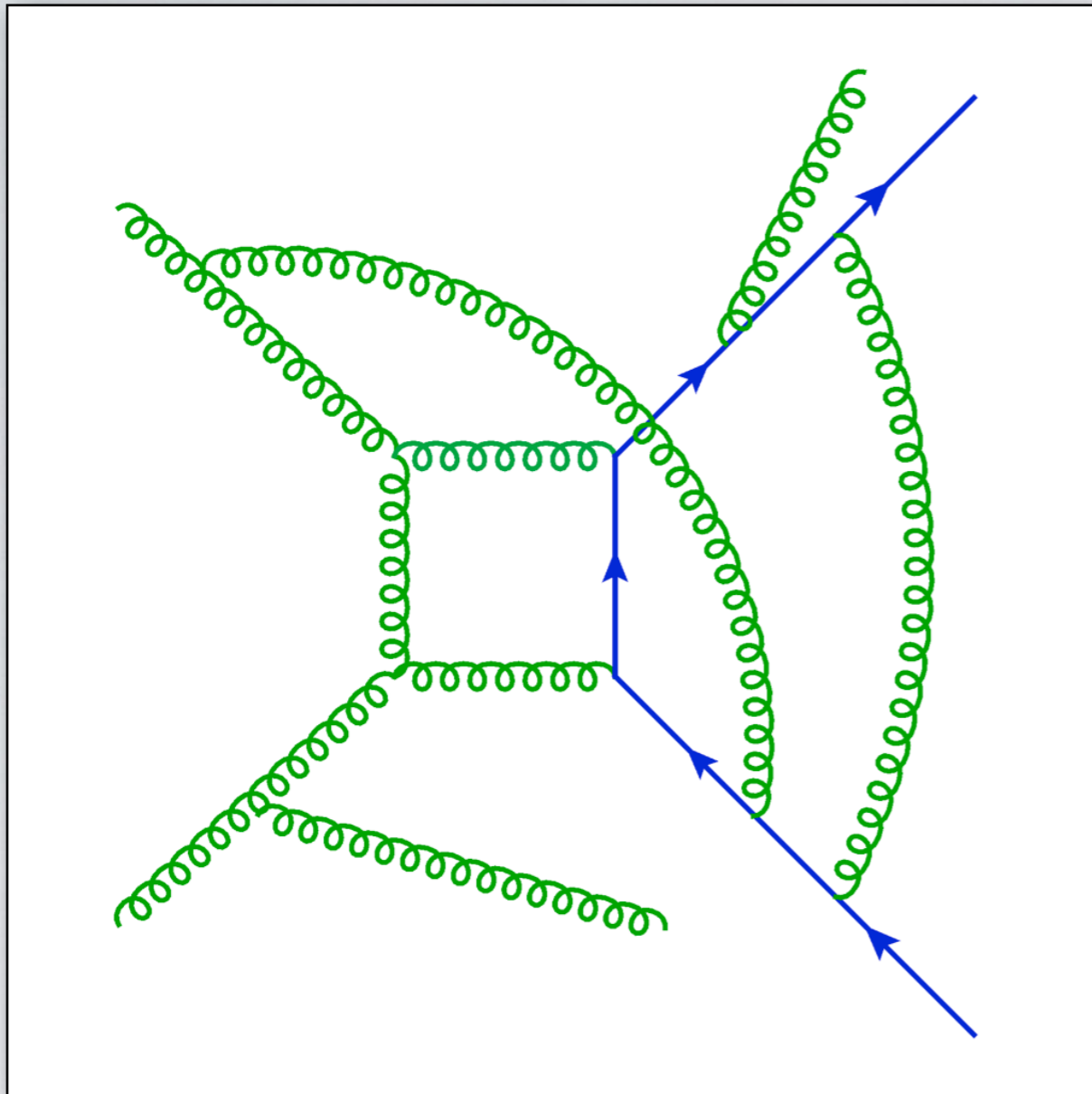
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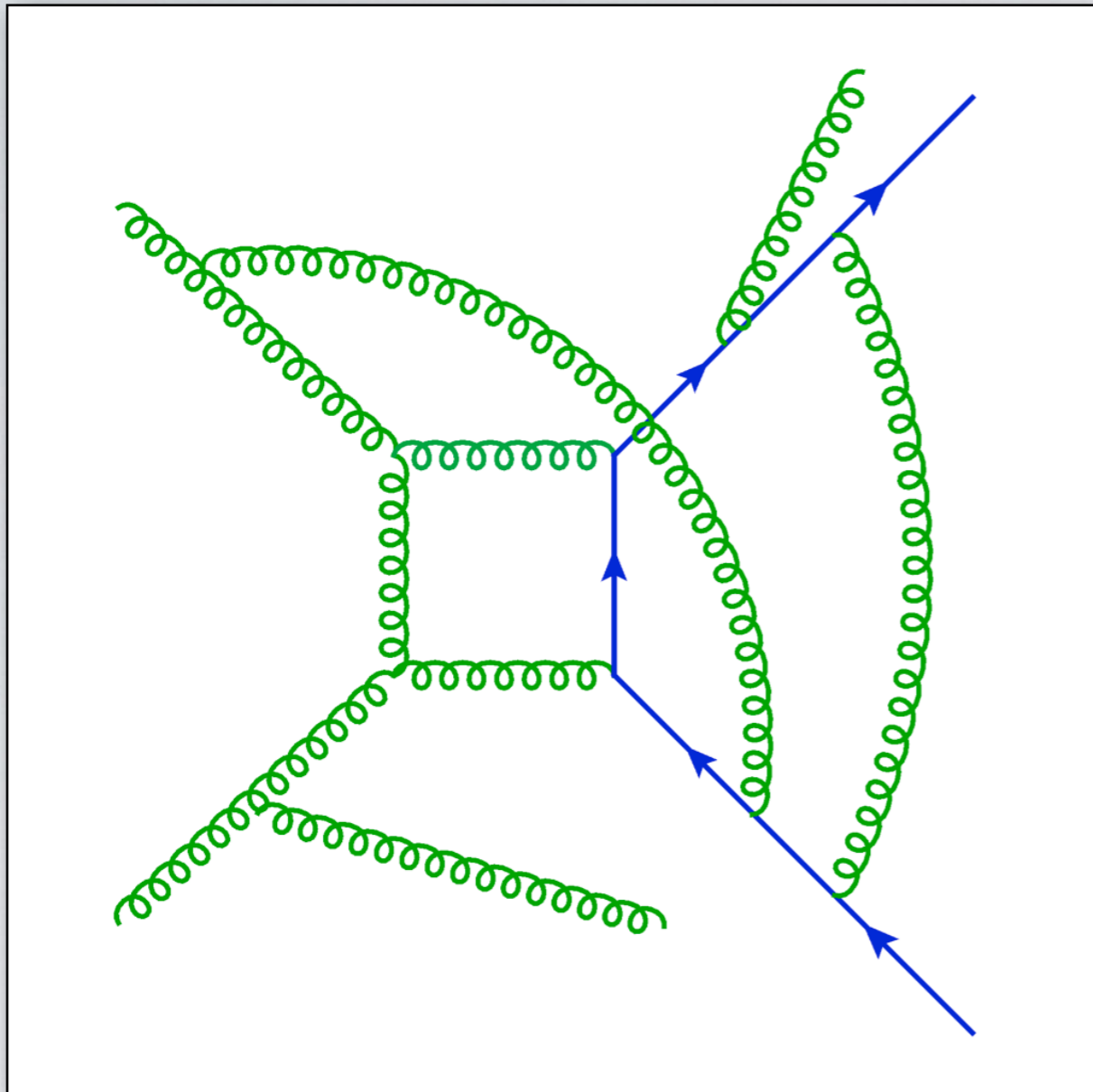
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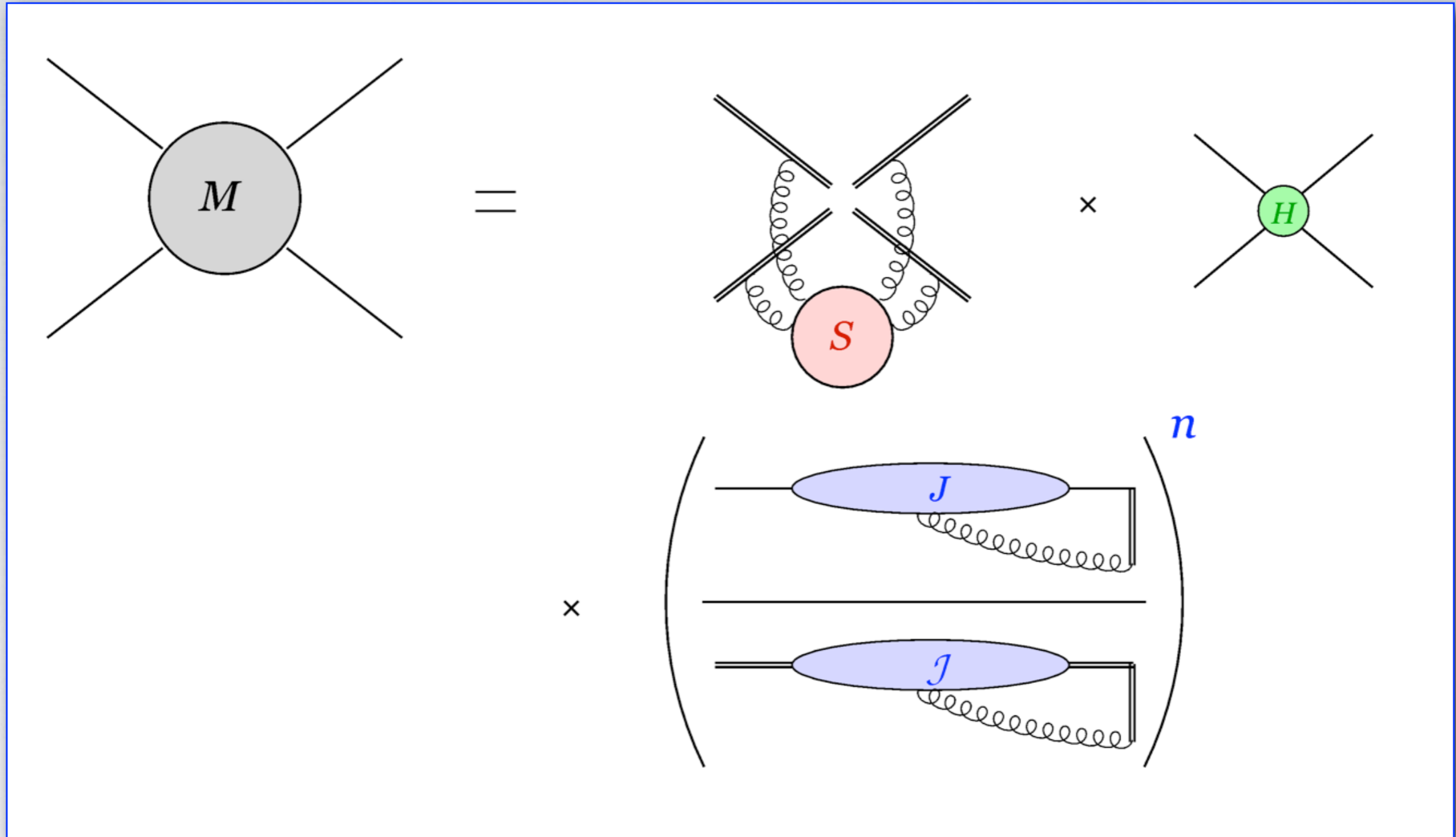
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- **Similar** factorisation theorems hold for **inclusive** (soft and collinear safe) **cross sections**.

A pictorial representation of soft-collinear factorisation for fixed-angle scattering amplitudes
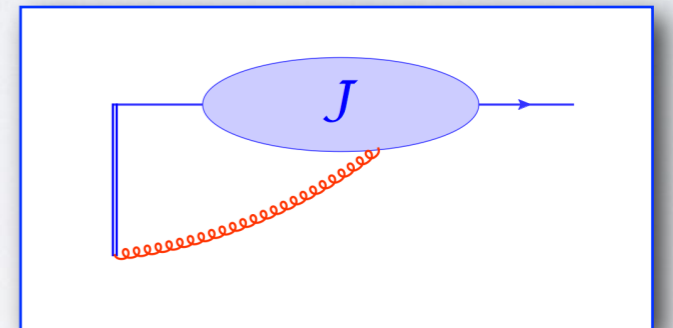
The precise **functional form** of this graphical factorisation is

$$
\mathcal{A}_n\left(\frac{p_i}{\mu}\right) = \prod_{i=1}^{n} \left[\frac{\mathcal{J}_i\left((p_i \cdot n_i)^2/(n_i^2 \mu^2)\right)}{\mathcal{J}_{E,i}\left((\beta_i \cdot n_i)^2/n_i^2\right)} \right] \mathcal{S}_n\left(\beta_i \cdot \beta_j\right) \, \mathcal{H}_n\left(\frac{p_i \cdot p_j}{\mu^2}, \frac{(p_i \cdot n_i)^2}{n_i^2 \mu^2}\right)
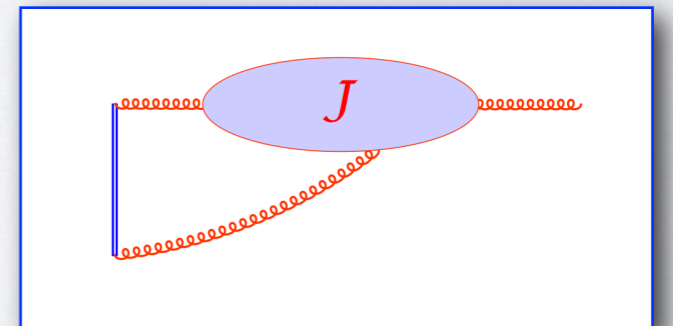$$

Here we introduced dimensionless **four-velocities** $\beta_i = p_i/Q$, and **factorisation vectors** n_i^{μ}, $n_i^2 \neq 0$ to define the jets in a **gauge-invariant** way. For **outgoing quarks**

$$
\overline{u}_s(p)\, \mathcal{J}_q\left(\frac{(p \cdot n)^2}{n^2 \mu^2}\right) = \langle p, s \,|\, \overline{\psi}(0)\, \Phi_n(0, \infty)\,|0\rangle
$$

where Φ_n is the **Wilson line** operator along the direction n. For **outgoing gluons**

$$
g_s\, \varepsilon_{\mu}^{*(\lambda)}(k)\, \mathcal{J}_g^{\mu\nu}\left(\frac{(k \cdot n)^2}{n^2 \mu^2}\right) \equiv \langle k, \lambda|\, \left[\Phi_n(\infty, 0)\, iD^{\nu}\, \Phi_n(0, \infty)\right]|0\rangle \,,
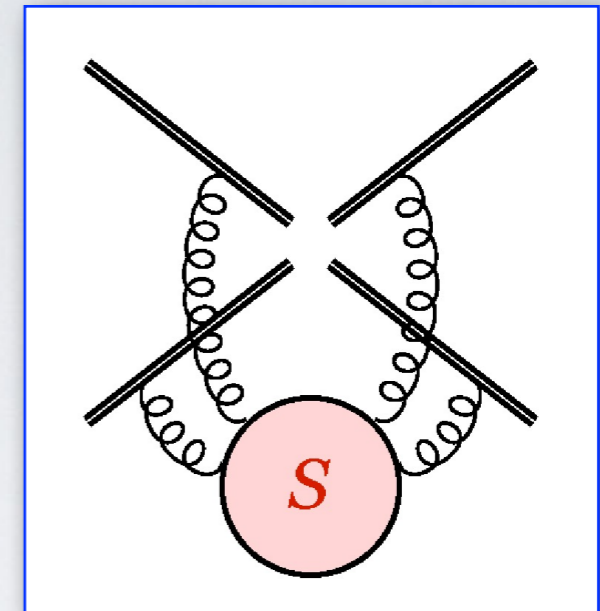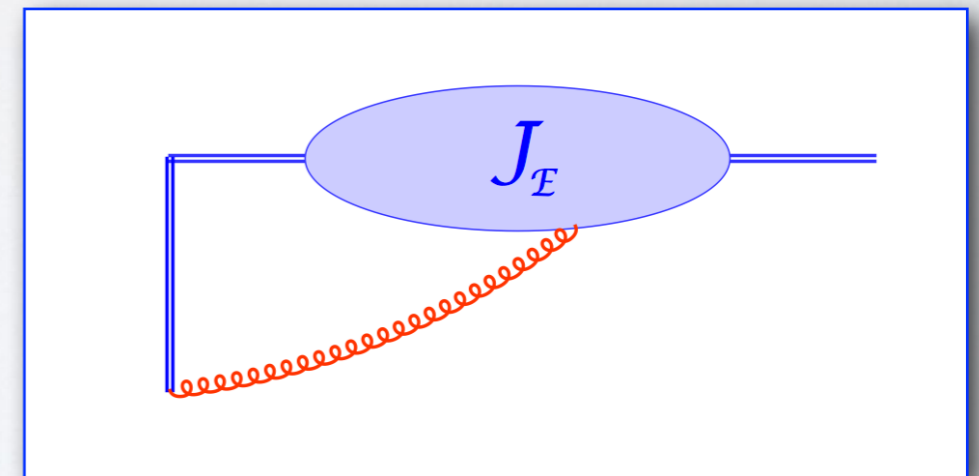$$

Wilson line correlators

The soft function S is a color operator, mixing the available color tensors. It is defined by a correlator of Wilson lines.

$$\mathcal{S}_n \left(\beta_i \cdot \beta_j\right) = \langle 0| \prod_{k=1}^{n} \Phi_{\beta_k}(\infty, 0) |0\rangle$$
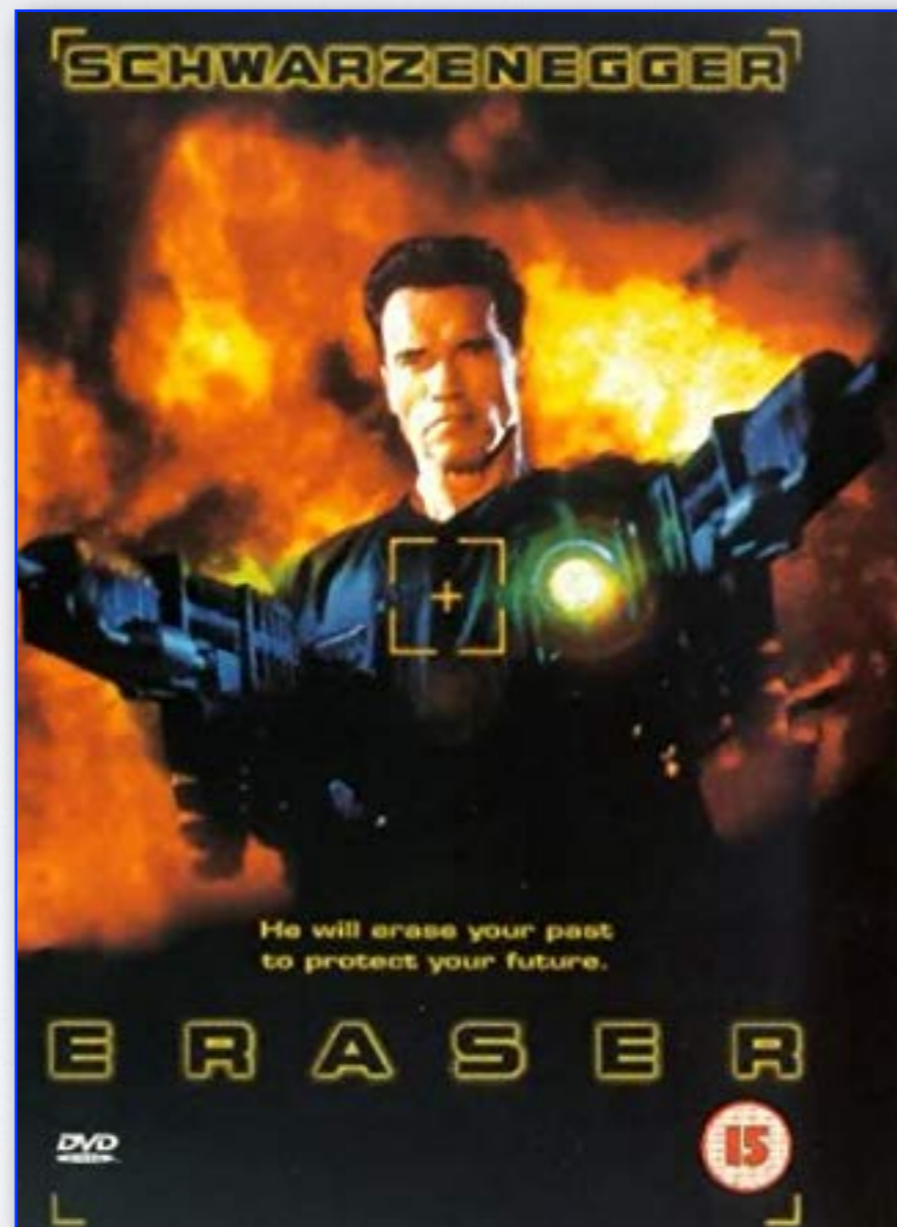

The soft jet function $J_{\mathcal{E}}$ contains soft-collinear poles: it is defined by replacing the field in the ordinary jet J with a Wilson line in the appropriate color representation.

$$\mathcal{J}_{\mathrm{E}} \left(\frac{(\beta \cdot n)^2}{n^2}\right) = \langle 0| \Phi_{\beta}(\infty, 0) \Phi_n(0, \infty) |0\rangle$$

Wilson-line matrix elements exponentiate non-trivially and have tightly constrained functional dependence on their arguments. They are known to three loops.

COUNTERTERMS

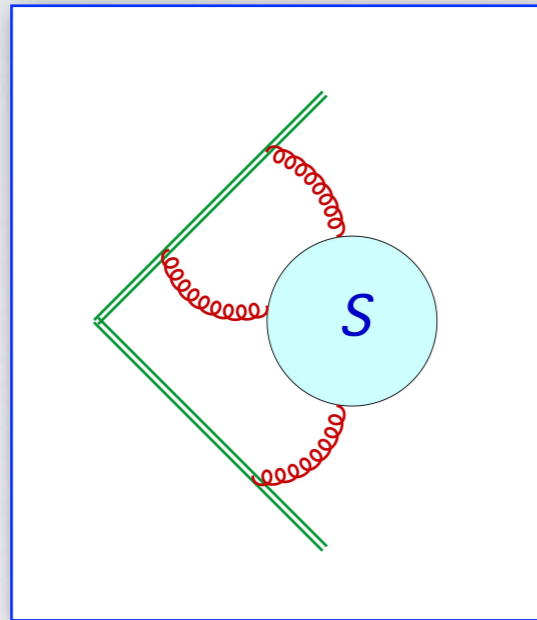Consider first the (academic) case of purely soft final state divergences.

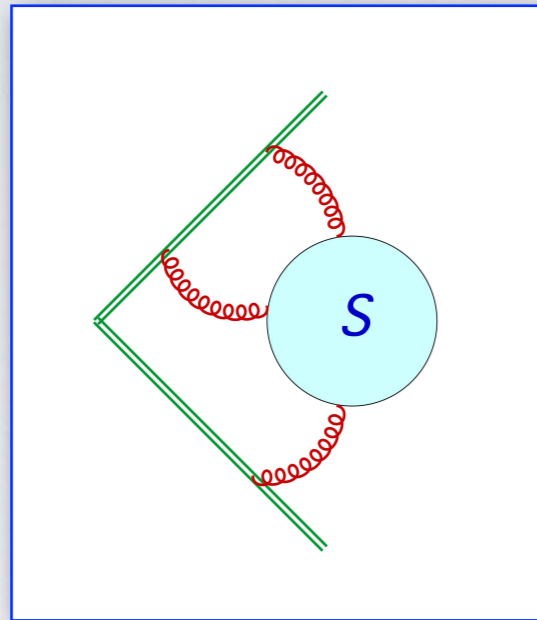Consider first the (academic) case of purely soft final state divergences.

At amplitude level poles factorise and exponentiate.

Soft cross sections: pictorial

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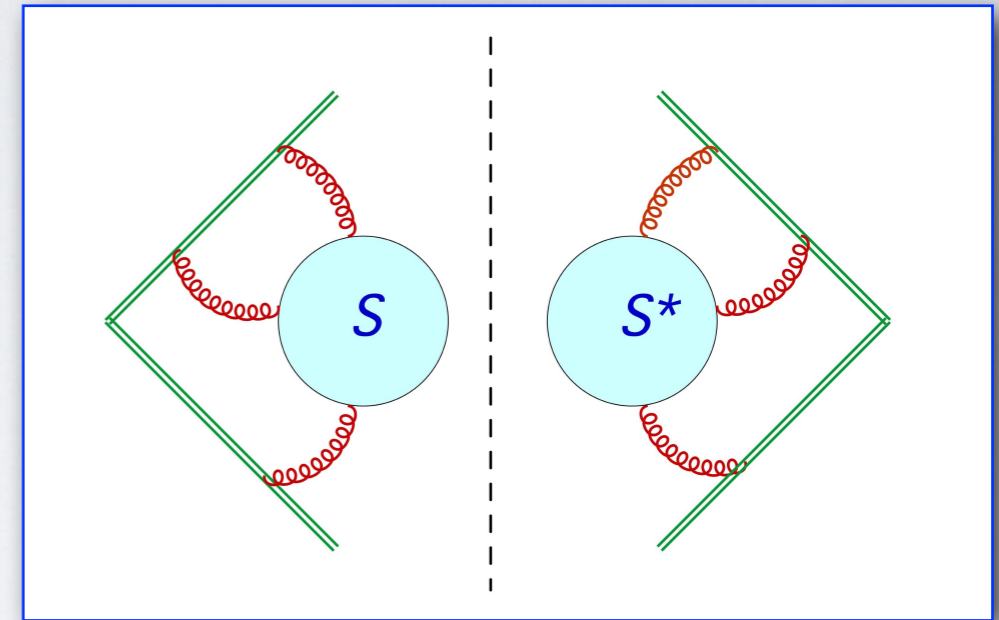

We need to build **cross-section level** quantities.

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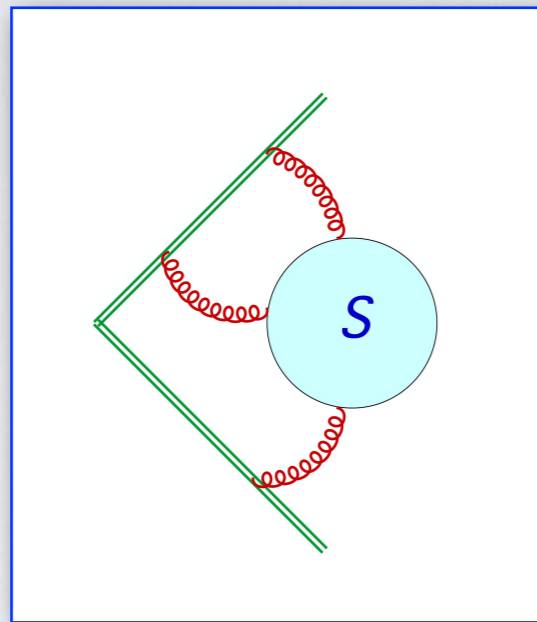
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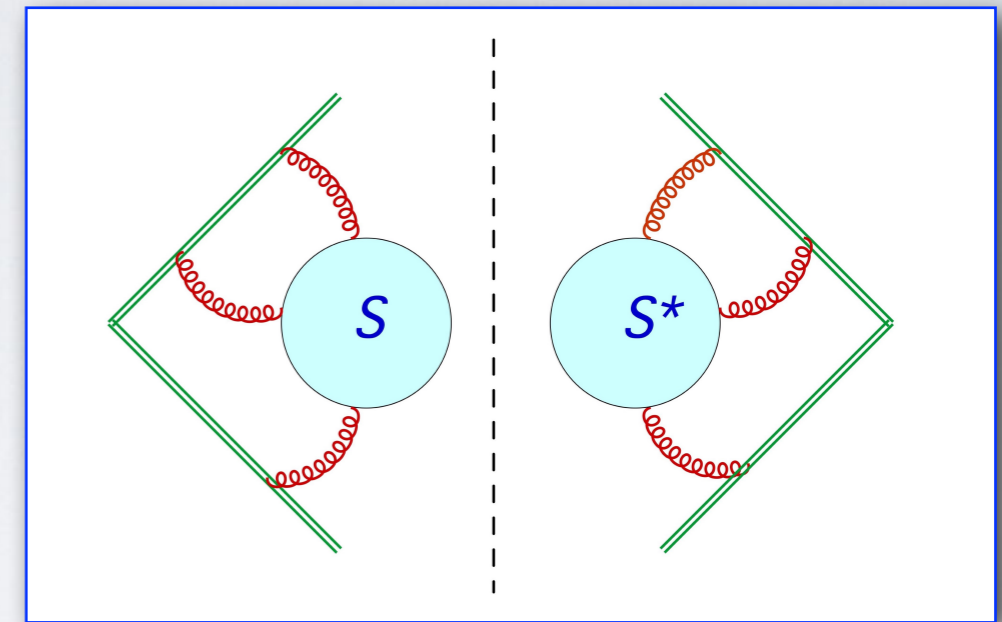
- Inclusive eikonal cross sections are finite.
- They are building blocks for threshold and Q_T resummations.
- They are defined by gauge-invariant operator matrix elements.
- Fixing the quantum numbers of particles crossing the cut one obtains local IR counterterms.
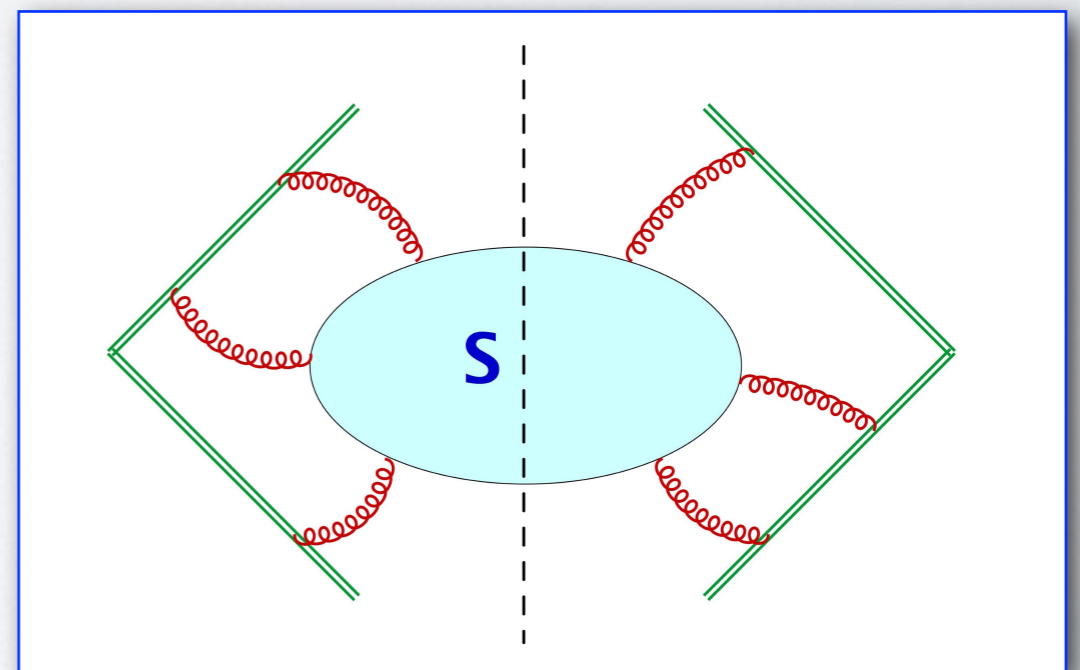
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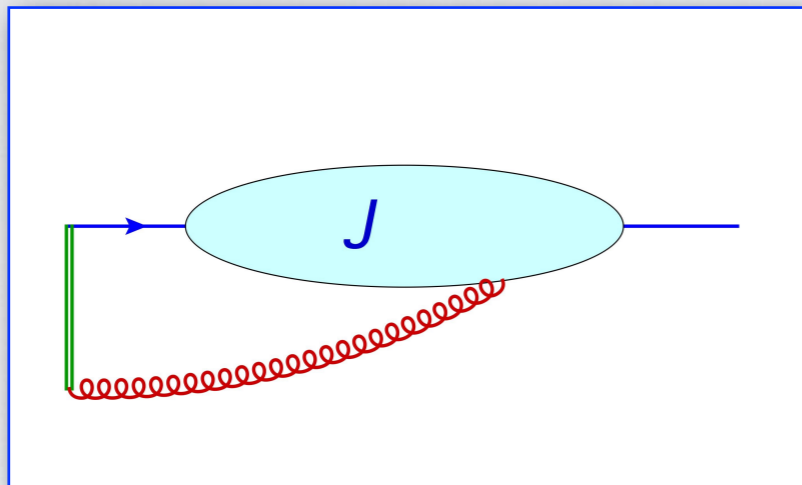
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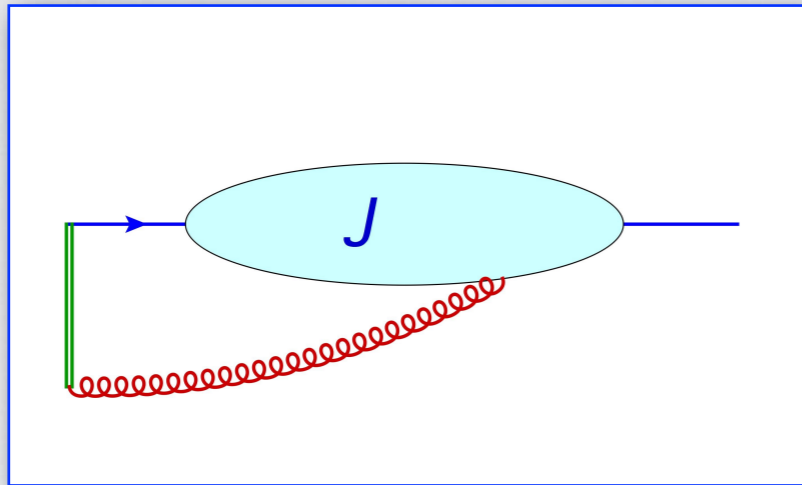
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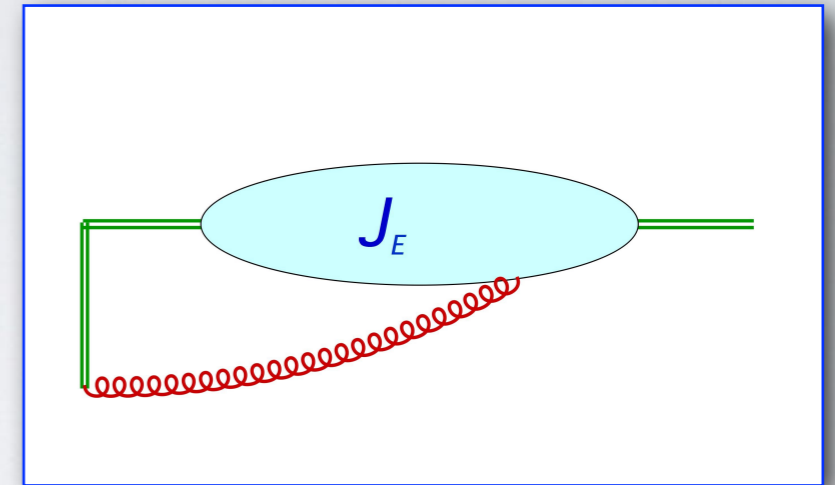
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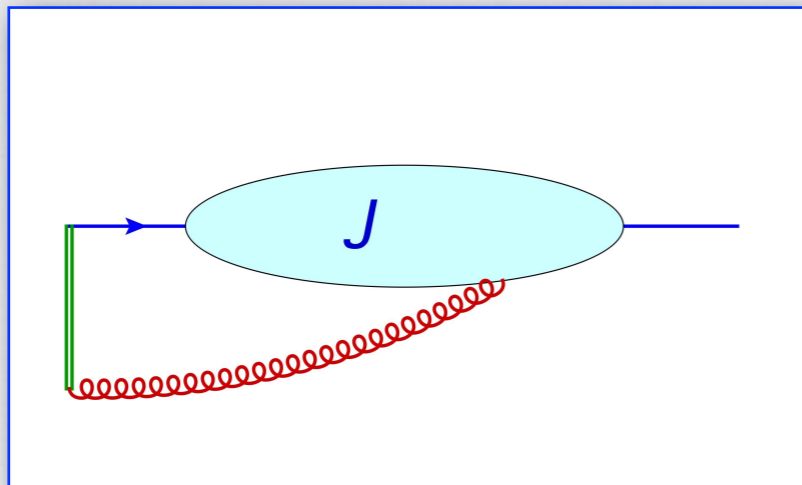
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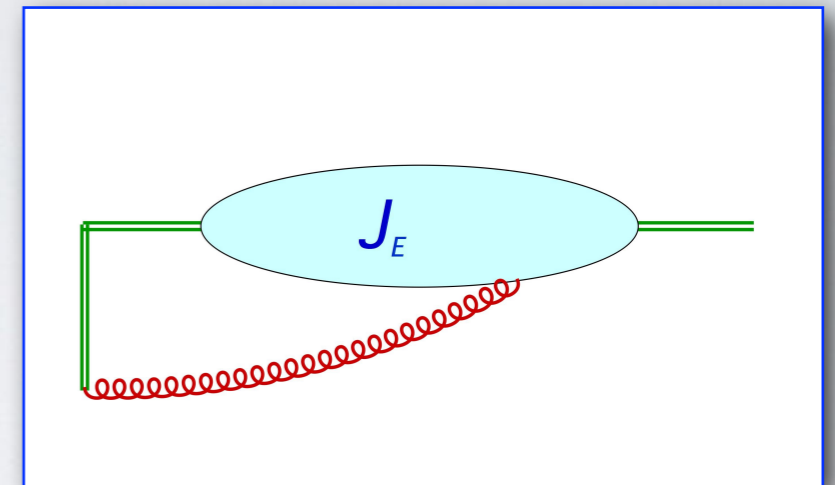
- Inclusive jet cross sections are finite.
- They are building blocks for threshold and Q_T resummations.
- They are defined by gauge-invariant operator matrix elements.
- Fixing the quantum numbers of particles crossing the cut one obtains local collinear counterterms.
- Eikonal jet cross sections subtract the soft-collinear double counting.
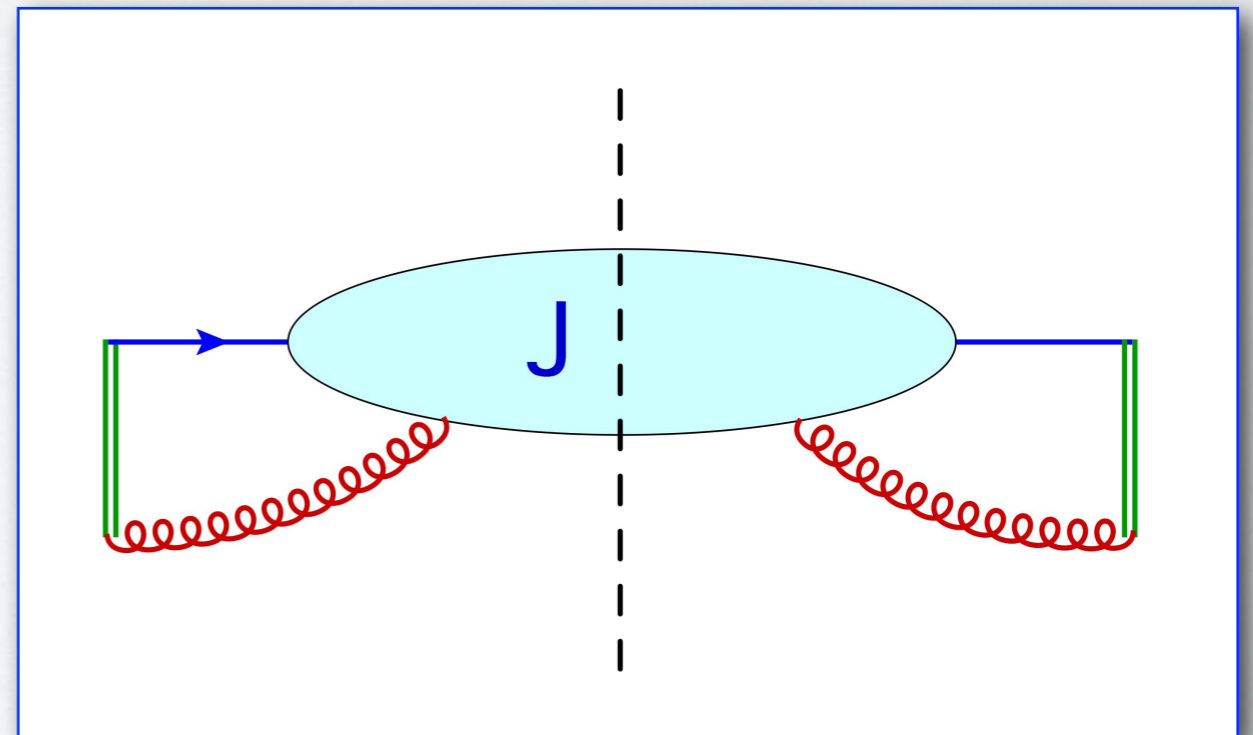
Introduce **eikonal form factors** for the emission of **m** **soft** partons from **n** **hard** ones.

$$\mathcal{S}_{n,m}(k_1, \ldots, k_m; \beta_i) \equiv \langle k_1, \lambda_1; \ldots; k_m, \lambda_m | \prod_{i=1}^{n} \Phi_{\beta_i}(\infty, 0) | 0 \rangle$$

$$\equiv \epsilon^{*(\lambda_1)}_{\mu_1}(k_1) \ldots \epsilon^{*(\lambda_m)}_{\mu_m}(k_m) \, J_{\mathcal{S}}^{\mu_1 \ldots \mu_m}(k_1, \ldots, k_m; \beta_i)$$

$$\equiv \sum_{p=0}^{\infty} \mathcal{S}_{n,m}^{(p)}(k_1, \ldots, k_m; \beta_i)$$

These matrix elements **define** soft gluon **multiple emission currents.** They are **gauge invariant** and they contain **loop corrections** to all orders.

Existing finite order **calculations** and all-order **arguments** are **consistent** with the **factorisation**

$$\mathcal{A}_{n,m}(k_1, \ldots, k_m; p_i) = \mathcal{S}_{n,m}(k_1, \ldots, k_m; \beta_i) \, \mathcal{H}_n(p_i) + \mathcal{R}_{n,m}(k_1, \ldots, k_m; p_i)$$

with **corrections** that are **finite** in dimensional regularisation, and **integrable** in the soft gluon phase space. It is a **working assumption**: a formal all-order proof is still **lacking**.

Soft counterterms: all orders

The factorisation is reflected at cross-section level, for fixed final state quantum numbers.

$$\sum_{\lambda_i} \left| \mathcal{A}_{n,m}\left(k_1, \ldots, k_m; p_i\right) \right|^2 \simeq \mathcal{H}_n^\dagger(p_i)\, S_{n,m}\left(k_1, \ldots, k_m; \beta_i\right) \mathcal{H}_n(p_i)$$

The cross-section level "radiative soft functions" are Wilson-line squared matrix elements

$$S_{n,m}\left(k_1, \ldots, k_m; \beta_i\right) \equiv \sum_{p=0}^{\infty} S_{n,m}^{(p)}\left(k_1, \ldots, k_m; \beta_i\right)$$

$$\equiv \sum_{\lambda_i} \langle 0 | \prod_{i=1}^{n} \Phi_{\beta_i}(0, \infty) | k_1, \lambda_1; \ldots; k_m, \lambda_m \rangle \langle k_1, \lambda_1; \ldots; k_m, \lambda_m | \prod_{i=1}^{n} \Phi_{\beta_i}(\infty, 0) | 0 \rangle \, .$$

These functions provide a complete list of local soft subtraction counterterms, to all orders. Indeed, summing over particle numbers and integrating over the soft phase space one finds

$$\sum_{m=0}^{\infty} \int d\Phi_m\, S_{n,m}\left(k_1, \ldots, k_m; \beta_i\right) = \langle 0 | \prod_{i=1}^{n} \Phi_{\beta_i}(0, \infty) \prod_{i=1}^{n} \Phi_{\beta_i}(\infty, 0) | 0 \rangle$$

This is a finite fully inclusive soft cross section, order by order in perturbation theory.

Soft current at tree level

At NLO, only the tree-level single-emission current is required, simply defined by

$$\epsilon^{*\,(\lambda)}(k) \cdot J_{\mathcal{S}}^{(0)}(k, \beta_i) = \mathcal{S}_{n,1}^{(0)}(k; \beta_i) = \langle k, \lambda| \prod_{i=1}^{n} \Phi_{\beta_i}(\infty, 0) \, |0\rangle \bigg|_{\text{tree}}$$

One obviously recovers all the well-known results for the leading-order soft gluon current

$$\mathcal{A}_{n,1}^{(0)}(k, p_i) = \epsilon^{*\,(\lambda)}(k) \cdot J_{\mathcal{S}}^{(0)}(k, \beta_i) \, \mathcal{H}_n^{(0)}(p_i) + \mathcal{O}(k^0)$$

$$J_{\mathcal{S}}^{\mu\,(0)}(k, \beta_i) = g \sum_{i=1}^{n} \frac{\beta_i^{\mu}}{\beta_i \cdot k} \, \mathbf{T}_i \cdot$$

For the cross-section, the tree-level single-radiation soft function acts as a local counterterm.

$$\sum_{\lambda} \left| \mathcal{A}_{n,1}^{(0)}(k, p_i) \right|^2 \simeq \mathcal{H}^{(0)\,\dagger}(p_i) \, S_{n,1}^{(0)}(k; \beta_i) \, \mathcal{H}_n^{(0)}(p_i)$$

$$= -4\pi\alpha_s \sum_{i,j=1}^{n} \frac{\beta_i \cdot \beta_j}{\beta_i \cdot k \, \beta_j \cdot k} \, \mathcal{A}_n^{(0)\dagger}(p_i) \, \mathbf{T}_i \cdot \mathbf{T}_j \, \mathcal{A}_n^{(0)}(p_i)$$

- The single-radiative soft function acts as a color operator on the color-correlated Born.
- Beyond NLO, tree-level multiple gluon emission currents also follow from this definition.

At one loop, for single radiation, our definition of the soft currents gives

$$\mathcal{A}_{n,\,1}\,(k;p_i) \simeq \mathcal{S}_{n,\,1}\,(k;\beta_i)\,\mathcal{H}_n(p_i)$$
$$= \mathcal{S}_{n,\,1}^{(0)}\,(k;\beta_i)\,\mathcal{H}_n^{(1)}(p_i) \,+\, \mathcal{S}_{n,\,1}^{(1)}\,(k;\beta_i)\,\mathcal{H}_n^{(0)}(p_i)$$

The factorisation proposed in the classic work by Catani-Grazzini appears different

$$\mathcal{A}_{n,\,1}\,(k;p_i) \simeq \epsilon^{*\,(\lambda)}(k) \cdot J_{\mathrm{CG}}\,(k,\beta_i)\,\mathcal{A}_n(p_i)$$

but it is easily matched using the factorisation of the non-radiative amplitude

$$\mathcal{A}_n\,(p_i) \simeq \mathcal{S}_n\,(\beta_i)\,\mathcal{H}_n(p_i) \quad \longrightarrow \quad \mathcal{H}_n^{(1)}(p_i) = \mathcal{A}_n^{(1)}\,(p_i) - \mathcal{S}_n^{(1)}\,(\beta_i)\,\mathcal{A}_n^{(0)}(p_i)$$

Recombining, we get an explicit eikonal expression for the CG one-loop soft current

$$\epsilon^{*\,(\lambda)}(k) \cdot J_{\mathrm{CG}}^{(1)}(k,\beta_i) \;=\; \mathcal{S}_{n,\,1}^{(1)}\,(k;\beta_i) - \mathcal{S}_{n,\,1}^{(0)}\,(k;\beta_i)\,\mathcal{S}_n^{(1)}\,(\beta_i)$$

The two calculations are easily matched: same diagrammatic content, cancellations and result.

The procedure is easily generalised to generic higher orders. At two loops one finds

$$
\mathcal{A}_{n,1}^{(2)}(k; p_i) \simeq \mathcal{S}_{n,1}^{(0)}(k; \beta_i)\, \mathcal{H}_n^{(2)}(p_i) + \mathcal{S}_{n,1}^{(1)}(k; \beta_i)\, \mathcal{H}_n^{(1)}(p_i) + \mathcal{S}_{n,1}^{(2)}(k; \beta_i)\, \mathcal{H}_n^{(0)}(p_i)
$$

To map to the CG definition, express the two-loop hard part in terms of the amplitude

$$
\mathcal{H}_n^{(2)}(p_i) = \mathcal{A}_n^{(2)}(p_i) - \mathcal{S}_n^{(1)}(\beta_i)\, \mathcal{A}_n^{(1)}(p_i) + \left[\mathcal{S}_n^{(1)}(\beta_i)\right]^2 \mathcal{A}_n^{(0)}(p_i) - \mathcal{S}_n^{(2)}(\beta_i)\, \mathcal{A}_n^{(0)}(p_i)
$$

Recombining, we get an explicit eikonal expression for the two-loop single-gluon soft current

$$
\epsilon^{*(\lambda)}(k) \cdot J_{\mathrm{CG}}^{(2)}(k, \beta_i) = \mathcal{S}_{n,1}^{(2)}(k; \beta_i) - \mathcal{S}_{n,1}^{(1)}(k; \beta_i)\, \mathcal{S}_n^{(1)}(\beta_i) - \mathcal{S}_{n,1}^{(0)}(k; \beta_i)\left[\mathcal{S}_n^{(2)}(\beta_i) - \left(\mathcal{S}_n^{(1)}(\beta_i)\right)^2\right]
$$

For the two-leg case, this was computed in (Badger, Glover 2004) to $O(\epsilon^0)$ and by (Duhr, Gehrmann 2013) to $O(\epsilon^2)$, by taking soft limits of full matrix elements. This definition allows to extend the calculation to the general case.

A similar definition emerges for the double-gluon soft current at one and two loops. Based on eikonal Feynman rules, one can begin the process of systematising these calculations.

Collinear counterterms: all orders

For collinear poles, introduce jet matrix elements for the emission of m partons. For quarks

$$\overline{u}_s(p)\,\mathcal{J}_{q,m}\left(k_1,\ldots,k_m;p,n\right)\,\equiv\,\langle p,s;k_1,\lambda_1;\ldots;k_m,\lambda_m|\,\overline{\psi}(0)\,\Phi_n(0,\infty)\,|0\rangle$$

At cross-section level, "radiative jet functions" can be defined as Fourier transforms of squared matrix elements, to account for the non-trivial momentum flow. We propose

$$J_{q,m}\left(k_1,\ldots k_m;l,p,n\right)\,\equiv\,\sum_{p=0}^{\infty}J_{q,m}^{(p)}\left(k_1,\ldots k_m;l,p,n\right)$$

$$\equiv\,\int d^dx\,\mathrm{e}^{\mathrm{i}l\cdot x}\sum_{\{\lambda_j\}}\langle 0|\,\Phi_n(\infty,x)\,\psi(x)\,|p,s;k_j,\lambda_j\rangle\,\langle p,s;k_j,\lambda_j|\,\overline{\psi}(0)\,\Phi_n(0,\infty)\,|0\rangle$$

These functions provide a complete list of local collinear counterterms, to all orders. Summing over particle numbers and integrating over the collinear phase space one finds

$$\sum_{m=0}^{\infty}\int d\Phi_{m+1}\,J_{q,m}\left(k_1,\ldots,k_m;l,p,n\right)\,=\,\mathrm{Disc}\left[\int d^dx\,\mathrm{e}^{\mathrm{i}l\cdot x}\,\langle 0|\,\Phi_n(\infty,x)\psi(x)\overline{\psi}(0)\Phi_n(0,\infty)\,|0\rangle\right]$$

A "two-point function", finite order by order in perturbation theory. Note however

- The collinear limit must still be taken (as $l^2\rightarrow 0$), unlike the case of radiative soft functions.
- Working with $n^2\neq 0$ eliminates spurious collinear poles, but is cumbersome in practice.

Collinear counterterms: NLO

At NLO, only tree-level single-emission contributes, resulting (for quarks) in three diagrams
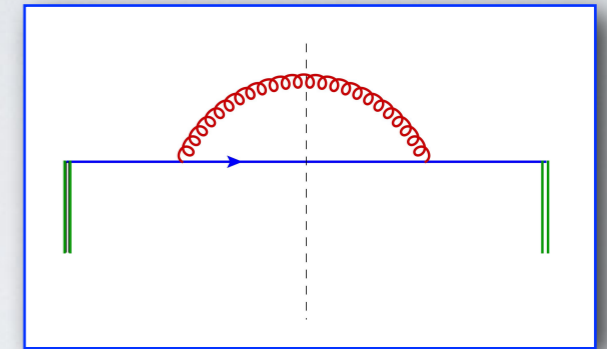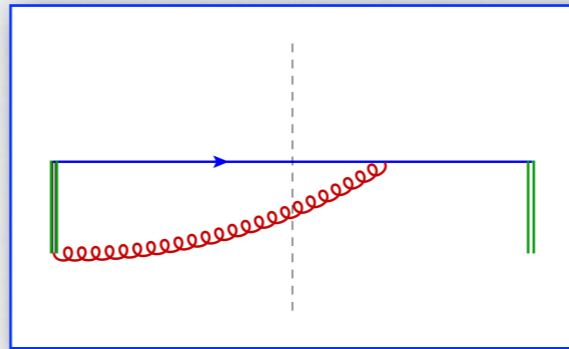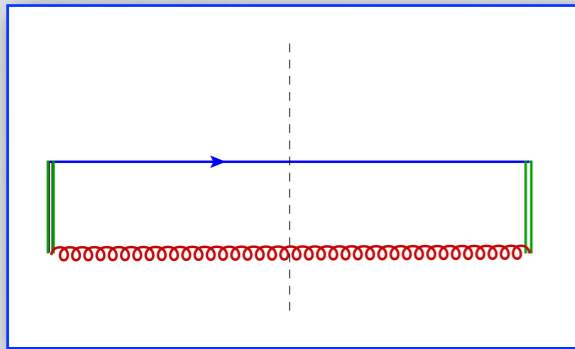
Summing over helicities, and taking the $n^2 \to 0$ limit, one finds a spin-dependent kernel

$$\sum_s J_{q,1}(k;l,p,n) = \frac{4\pi\alpha_s C_F}{l^2}(2\pi)^d \delta^d(l-p-k)\left[-\not{l}\gamma_\mu\not{p}\gamma^\mu\not{l} + \frac{1}{k\cdot n}\left(\not{l}\not{n}\not{p} + \not{p}\not{n}\not{l}\right)\right]$$

With a Sudakov decomposition

$$p^\mu = zl^\mu + \mathcal{O}(l_\perp), \qquad k^\mu = (1-z)l^\mu + \mathcal{O}(l_\perp), \qquad n^2 = 0$$

and taking $l_\perp \to 0$, one recovers the full unpolarised DGLAP LO splitting kernel.

$$\sum_s J_{q,1}(k;l,p,n) = \frac{8\pi\alpha_s C_F}{l^2}(2\pi)^d \delta^d(l-p-k)\left[\frac{1+z^2}{1-z} - \epsilon(1-z) + \mathcal{O}(l_\perp)\right]$$

- The three diagrams map precisely to the axial gauge calculation by Catani, Grazzini.
- All LO DGLAP kernels are easily reproduced, triple collinear limits are under way.

The outlines of a subtraction procedure emerge. Begin by expanding the virtual matrix element

$$
\mathcal{A}_n(p_i) = \left[\mathcal{S}_n^{(0)}(\beta_i)\mathcal{H}_n^{(0)}(p_i) + \mathcal{S}_n^{(1)}(\beta_i)\mathcal{H}_n^{(0)}(p_i) + \mathcal{S}_n^{(0)}(\beta_i)\mathcal{H}_n^{(1)}(p_i) \right.
$$

$$
\left. + \sum_{i=1}^{n} \left(\mathcal{J}_i^{(1)}(p_i) - \mathcal{J}_{\mathrm{E},i}^{(1)}(\beta_i) \right) \mathcal{S}_n^{(0)}(\beta_i)\, \mathcal{H}_n^{(0)}(p_i) \right] \left(1 + \mathcal{O}\left(\alpha_s^2 \right) \right)
$$

From the master formula, get the virtual poles of the cross section in terms of virtual kernels

$$
V_n \equiv 2\,\mathbf{Re}\left[\mathcal{A}_n^{(0)*}\mathcal{A}_n^{(1)} \right] \simeq \mathcal{H}_n^{(0)\,\dagger}(p_i)S_{n,0}^{(1)}(\beta_i)\mathcal{H}_n^{(0)}(p_i) + \sum_i \left(J_{i,0}^{(1)}(p_i) - J_{\mathrm{E},i,0}^{(1)}(\beta_i) \right) \left| \mathcal{A}_n^{(0)}(p_i) \right|^2
$$

Go through the list of proposed soft and collinear counterterms to collect the relevant ones

$$
S_{n,0}^{(1)}(\beta_i) + \int d\Phi_1\, S_{n,1}^{(0)}(k,\beta_i) = \text{finite}
$$

$$
J_{i,0}^{(1)}(l,p,n) + \int d\Phi_1\, J_{i,1}^{(0)}(k;l,p,n) = \text{finite}
$$

Construct the appropriate local functions.

$$
K_{n+1}^{\mathrm{NLO,\,s}} = \mathcal{H}_n^{(0)\,\dagger}(p_i)\, S_{n,1}^{(0)}(k,\beta_i)\, \mathcal{H}_n^{(0)}(p_i)
$$

$$
K_{n+1}^{\mathrm{NLO,\,c}} = \sum_{i=1}^{n} J_{i,1}^{(0)}(k_i;l,p_i,n_i) \left| \mathcal{A}_n^{(0)}(p_1,\ldots,p_{i-1},l,p_{i+1},\ldots,p_n) \right|^2
$$

with a similar expression for the anti-subtraction of the soft-collinear region in terms of $J_{\mathcal{E}}$.

Tracing soft and collinear at NNLO

As an example of the detailed structure of soft and collinear subtractions at high orders, consider the "jet factor" in the factorised virtual matrix element.
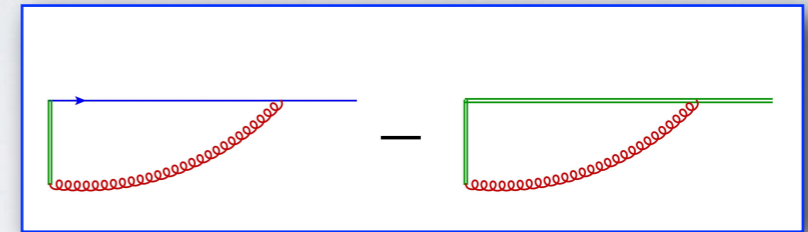
As an **example** of the **detailed structure** of soft and collinear subtractions at high orders, consider the "jet factor" in the factorised **virtual** matrix element.

$$\frac{\prod_{i=1}^{n} \mathcal{J}_0 \left(p_i \right)}{\prod_{i=1}^{n} \mathcal{J}_0^E \left(\beta_i \right)} = 1 + g^2 \sum_{i=1}^{n} \left[\mathcal{J}_0^{(1)} \left(p_i \right) - \mathcal{J}_0^{E\,(1)} \left(\beta_i \right) \right]$$

$$+ g^4 \sum_{i=1}^{n} \left[\mathcal{J}_0^{(2)} \left(p_i \right) - \mathcal{J}_0^{E\,(2)} \left(\beta_i \right) \right]$$

$$+ g^4 \sum_{i<j=1}^{n} \left[\mathcal{J}_0^{(1)} \left(p_i \right) - \mathcal{J}_0^{E\,(1)} \left(\beta_i \right) \right] \left[\mathcal{J}_0^{(1)} \left(p_j \right) - \mathcal{J}_0^{E\,(1)} \left(\beta_j \right) \right]$$

$$- g^4 \sum_{i=1}^{n} \mathcal{J}_0^{E\,(1)} \left(\beta_i \right) \left[\mathcal{J}_0^{(1)} \left(p_i \right) - \mathcal{J}_0^{E\,(1)} \left(\beta_i \right) \right]$$

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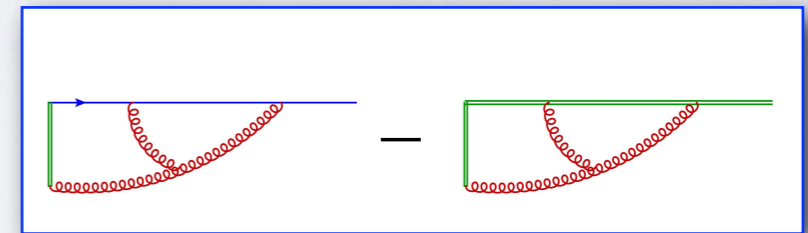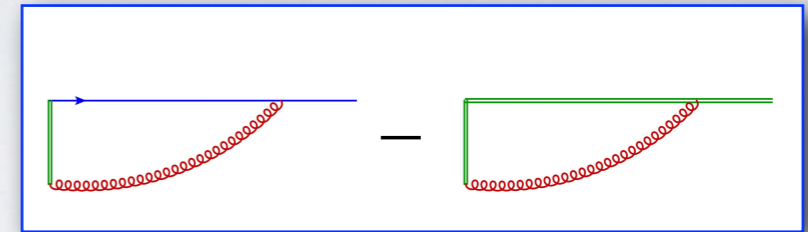
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$$+ g^4 \sum_{i=1}^{n} \left[\mathcal{J}_0^{(2)}(p_i) - \mathcal{J}_0^{E(2)}(\beta_i) \right]$$

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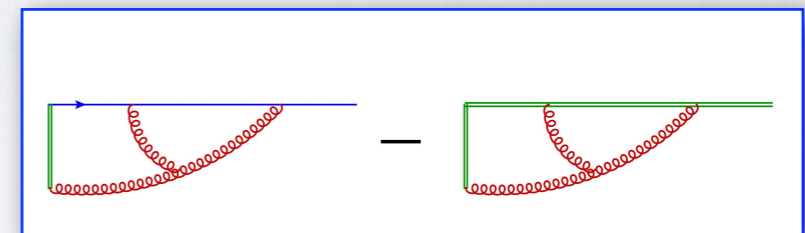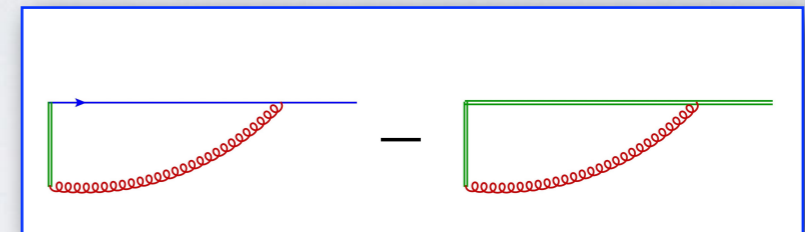
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$$+ g^4 \sum_{i<j=1}^{n} \left[\mathcal{J}_0^{(1)}\left(p_i\right) - \mathcal{J}_0^{E\,(1)}\left(\beta_i\right)\right]\left[\mathcal{J}_0^{(1)}\left(p_j\right) - \mathcal{J}_0^{E\,(1)}\left(\beta_j\right)\right]$$

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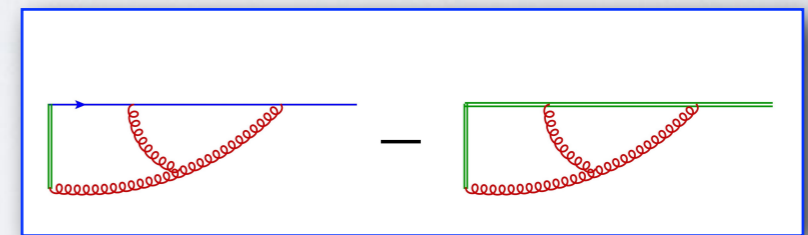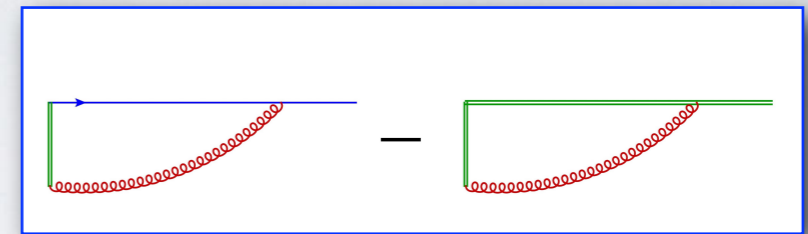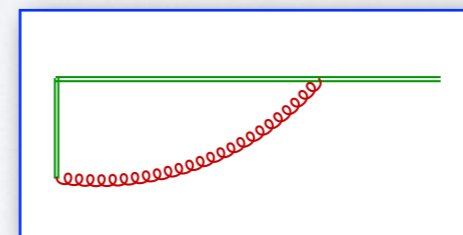

Independent hard collinear poles

Tracing soft and collinear at NNLO

As an example of the detailed structure of soft and collinear subtractions at high orders, consider the "jet factor" in the factorised virtual matrix element.

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$$+ g^4 \sum_{i=1}^{n} \left[\mathcal{J}_0^{(2)}(p_i) - \mathcal{J}_0^{E\,(2)}(\beta_i) \right]$$

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$$- g^4 \sum_{i=1}^{n} \mathcal{J}_0^{E\,(1)}(\beta_i) \left[\mathcal{J}_0^{(1)}(p_i) - \mathcal{J}_0^{E\,(1)}(\beta_i) \right]$$

Independent hard collinear poles

The contributions of a single soft gluon accompanied by a hard collinear one factor out and are automatically taken into account.

Let us follow the same procedure at NNLO. Collect the poles of the virtual amplitude

$$
\begin{aligned}
\mathcal{A}_n^{(2)}(p_i) =\ & \mathcal{S}_n^{(2)}(\beta_i)\mathcal{H}_n^{(0)}(p_i) + \mathcal{S}_n^{(0)}(\beta_i)\mathcal{H}_n^{(2)}(p_i) + \mathcal{S}_n^{(1)}(\beta_i)\mathcal{H}_n^{(1)}(p_i) \\
& + \sum_{i=1}^{n}\left[\mathcal{J}_i^{(2)}(p_i) - \mathcal{J}_{\mathrm{E},i}^{(2)}(\beta_i) - \mathcal{J}_{\mathrm{E},i}^{(1)}(\beta_i)\left(\mathcal{J}_i^{(1)}(p_i) - \mathcal{J}_{\mathrm{E},i}^{(1)}(\beta_i)\right)\right]\mathcal{A}_n^{(0)}(p_i) \\
& + \sum_{i<j=1}^{n}\left(\mathcal{J}_i^{(1)}(p_i) - \mathcal{J}_{\mathrm{E},i}^{(1)}(\beta_i)\right)\left(\mathcal{J}_j^{(1)}(p_j) - \mathcal{J}_{\mathrm{E},j}^{(1)}(\beta_j)\right)\mathcal{A}_n^{(0)}(p_i) \\
& + \sum_{i=1}^{n}\left(\mathcal{J}_i^{(1)}(p_i) - \mathcal{J}_{\mathrm{E},i}^{(1)}(\beta_i)\right)\left[\mathcal{S}_n^{(1)}(\beta_i)\mathcal{H}_n^{(0)}(p_i) + \mathcal{S}_n^{(0)}(\beta_i)\mathcal{H}_n^{(1)}(p_i)\right]
\end{aligned}
$$

Cross-section level soft and jet functions have non-trivial structure starting at NNLO

$$
S_n^{(2)} = \mathcal{S}_n^{(0)\,\dagger}\mathcal{S}_n^{(2)} + \mathcal{S}_n^{(2)\,\dagger}\mathcal{S}_n^{(0)} + \mathcal{S}_n^{(1)\,\dagger}\mathcal{S}_n^{(1)}
$$

$$
J_{q,m}^{(2)} = \int d^d x\, e^{il\cdot x} \sum_{\{\lambda_j\}}\left[\mathcal{J}_{q,m}^{(1)\,\dagger}(x)\,\slashed{p}\,\mathcal{J}_{q,m}^{(1)}(0) + \mathcal{J}_{q,m}^{(0)\,\dagger}(x)\,\slashed{p}\,\mathcal{J}_{q,m}^{(2)}(0) + \mathcal{J}_{q,m}^{(0)}(x)\,\slashed{p}\,\mathcal{J}_{q,m}^{(2)\,\dagger}(0)\right]
$$

All poles of the squared virtual amplitude can nonetheless be expressed in terms of squared jets and eikonal correlators, which leads to the identification of local NNLO counterterms.

Cross-section level **double-virtual** poles originate from **a number** of **different** configurations

$$(VV)_n \equiv (VV)_n^{(2s)} + (VV)_n^{(1s)} + \sum_{i=1}^{n} (VV)_{n,i}^{(2hc)} + \sum_{i<j=1}^{n} (VV)_{n,ij}^{(2hc)} + \sum_{i=1}^{n} (VV)_{n,i}^{(1hc,1s)} + \sum_{i=1}^{n} (VV)_{n,i}^{(1hc)}$$

Focus on **double collinear** radiation along the direction of a **selected hard particle**. One finds

$$(VV)_{n,i}^{(2hc)} = \left[J_{i,0}^{(2)} - J_{E,i,0}^{(2)} - J_{E,i,0}^{(1)} \left(J_{i,0}^{(1)} - J_{E,i,0}^{(1)} \right) \right] \left| \mathcal{A}_n^{(0)} \right|^2$$

It is easy to **identify finite combinations** of **virtual** and **real** (hard) collinear radiation

$$J_{i,0}^{(2)} + \int d\Phi_1 J_{i,1}^{(1)} + \int d\Phi_2 J_{i,2}^{(0)} = \text{finite}$$

$$\left[J_{E,i,0}^{(1)} + \int d\Phi_1 J_{E,i,1}^{(0)} \right] \left[J_{i,0}^{(1)} - J_{E,i,0}^{(1)} + \int d\Phi_1' \left(J_{i,1}^{(0)} - J_{E,i,1}^{(0)} \right) \right] = \text{finite}$$

Real radiation **naturally organises** into **single** and **double** unresolved, and **real-virtual** terms

$$K_{n+2,i}^{\text{NNLO},(\mathbf{2},\text{hc})} = \left[J_{i,2}^{(0)} - J_{E,i,2}^{(0)} - J_{E,i,1}^{(0)} \left(J_{i,1}^{(0)} - \mathcal{J}_{E,i,1}^{(0)} \right) \right] \left| \mathcal{A}_n^{(0)} \right|^2$$

$$K_{n+2,i}^{\text{NNLO},(\mathbf{1},\text{hc})} = \left(J_{i,1}^{(0)} - \mathcal{J}_{E,i,1}^{(0)} \right) \left| \mathcal{A}_{n+1}^{(0)} \right|^2$$

$$K_{n+1,i}^{\text{NNLO},(\mathbf{RV},\text{hc})} = \left[J_{i,1}^{(1)} - \mathcal{J}_{E,i,1}^{(1)} - J_{i,0}^{(1)} J_{E,i,1}^{(0)} - J_{E,i,0}^{(1)} J_{i,1}^{(0)} + 2 J_{E,i,0}^{(1)} J_{E,i,1}^{(0)} \right] \left| \mathcal{A}_n^{(0)} \right|^2 .$$

Cross-section level **double-virtual** poles originate from **a number** of **different** configurations

$$(VV)_n \equiv (VV)_n^{(2s)} + (VV)_n^{(1s)} + \sum_{i=1}^{n} (VV)_{n,i}^{(2hc)} + \sum_{i<j=1}^{n} (VV)_{n,ij}^{(2hc)} + \sum_{i=1}^{n} (VV)_{n,i}^{(1hc,1s)} + \sum_{i=1}^{n} (VV)_{n,i}^{(1hc)}$$

Focus on **double soft** and **single soft** radiation. One finds

$$(VV)_n^{(2s)} = \mathcal{H}_n^{(0)\,\dagger} S_{n,0}^{(2)} \mathcal{H}_n^{(0)}$$

$$(VV)_n^{(1s)} = \mathcal{H}_n^{(0)\,\dagger} S_{n,0}^{(1)} \mathcal{H}_n^{(1)} + \mathcal{H}_n^{(1)\,\dagger} S_{n,0}^{(1)} \mathcal{H}_n^{(0)}$$

It is easy to **identify finite combinations** of **virtual**, **real-virtual** and **double real** soft radiation

$$S_{n,0}^{(2)}(\beta_i) + \int d\Phi_1 \, S_{n,1}^{(1)}(k,\beta_i) + \int d\Phi_2 \, S_{n,2}^{(0)}(k_1,k_2,\beta_i) = \text{finite}\,.$$

Real radiation **naturally organises** into **single** and **double** unresolved, and **real-virtual** terms

$$K_{n+2}^{\text{NNLO},\,(\mathbf{2},\text{s})} = \mathcal{H}_n^{(0)\,\dagger} S_{n,2}^{(0)} \mathcal{H}_n^{(0)}$$

$$K_{n+2}^{\text{NNLO},\,(\mathbf{1},\text{s})} = \mathcal{H}_{n+1}^{(0)\,\dagger} S_{n+1,1}^{(0)} \mathcal{H}_{n+1}^{(0)}$$

$$K_{n+1}^{\text{NNLO},\,(\mathbf{RV},\text{s})} = \mathcal{H}_n^{(0)\,\dagger} S_{n,1}^{(0)} \mathcal{H}_n^{(1)} + \mathcal{H}_n^{(1)\,\dagger} S_{n,1}^{(0)} \mathcal{H}_n^{(0)} + \mathcal{H}_n^{(0)\,\dagger} S_{n,1}^{(1)} \mathcal{H}_n^{(0)}$$

OUTLOOK

Outlook

- A number of successful NNLO subtraction algorithms are available.

- They are computationally expensive, either analytically, or numerically, or both.

- Extensions to multi-leg processes or higher orders is expected to be useful but hard.

- Work on refining existing tools to find the `minimal toolbox' is necessary and under way.

- The factorisation of soft and collinear virtual amplitudes contains important information.

- A general all-order definition of soft and/or collinear counterterms has been proposed.

- Existing results at NLO and beyond are reproduced and systematised.

- Tracing the real emission counterterms starting from virtual poles is a useful strategy.

- A parallel effort to construct a detailed analytic subtraction algorithm is under way.

- What we have is promising preliminary evidence: a lot of work remains to be done.

THANK YOU !