TOWARDS A GENERAL NESTED SOFT-COLLINEAR SUBTRACTION METHOD FOR NNLO CALCULATIONS

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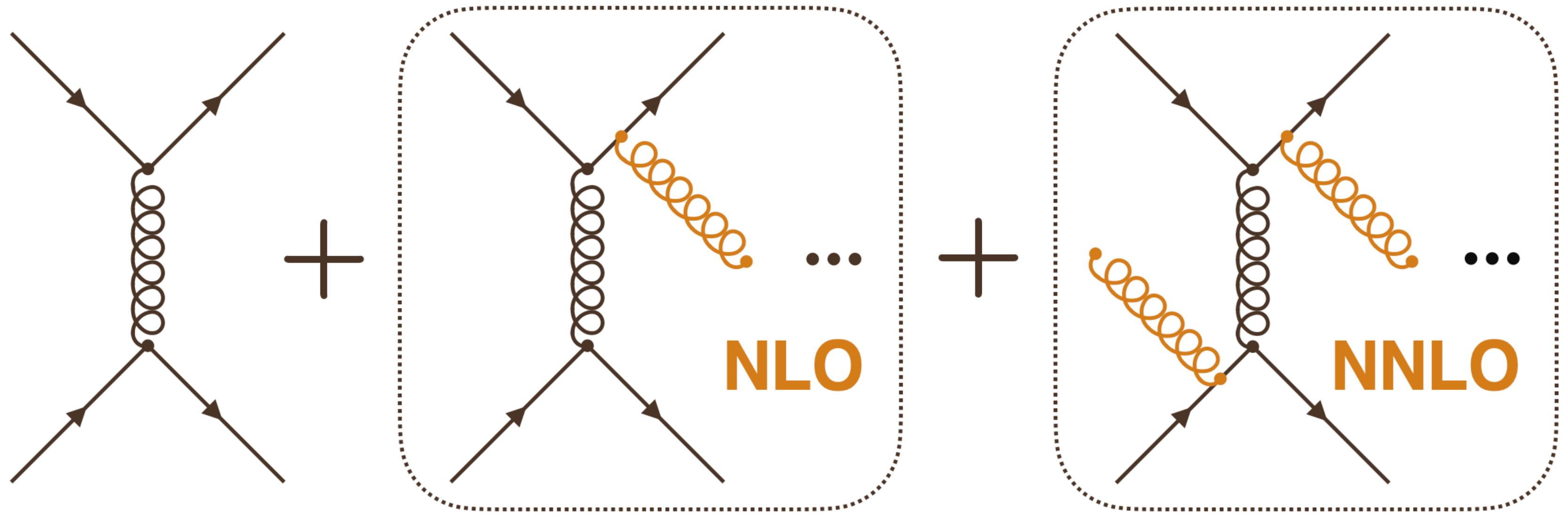
WHAT IS THE STATUS?

- Any collider process is characterized by its differential partonic cross section which is often computed in **fixed-order perturbation theory**

- The orders in the perturbative expansion are referred to as **LO**, **NLO**, **NNLO** and so on

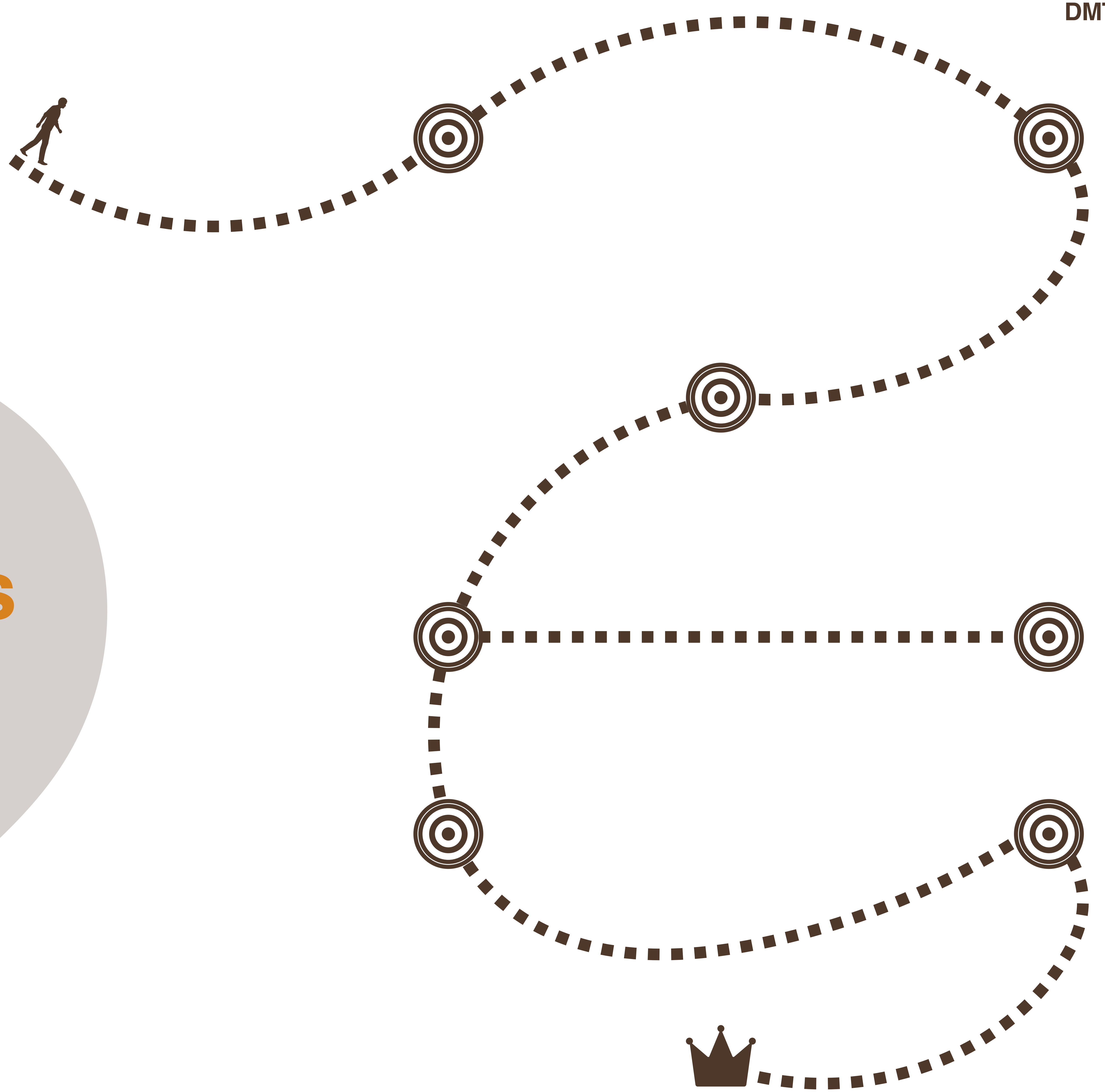


- **NLO**: solved in full generality almost a decade ago
  NNLO: noteworthy results have been achieved up to now
  N^{3}LO: some results are already available

- Two main difficulties: **IR singularities**, arising from real radiation, and **multi-loop amplitude** calculations

- *About IR singularities*: they are unphysical and require specific methods to arrive at a finite physical result. Such methods are referred to as **SUBTRACTION SCHEMES**

WHY WE STUDY
$P + P \to X + N$ gluons
AT NNLO



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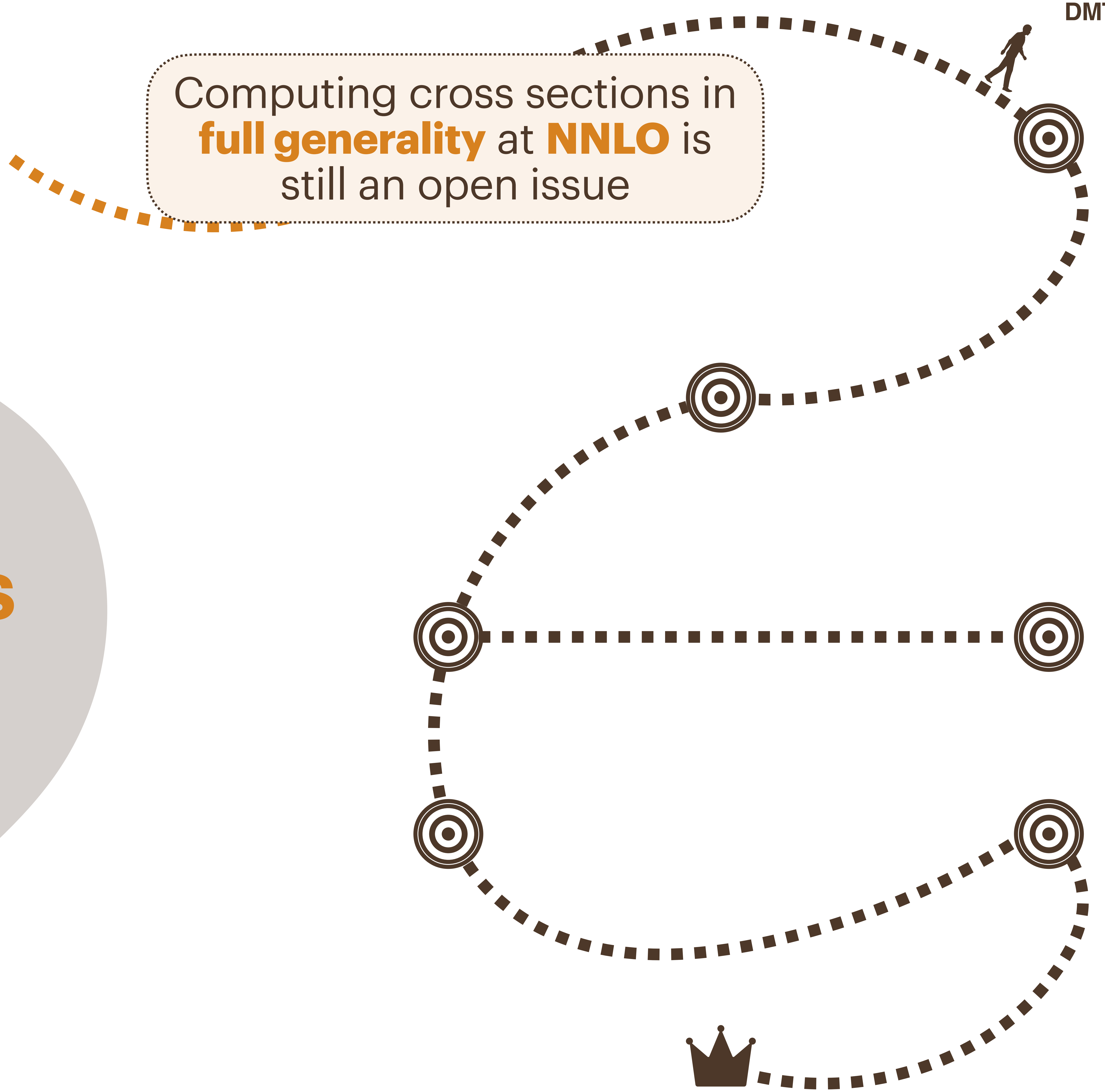

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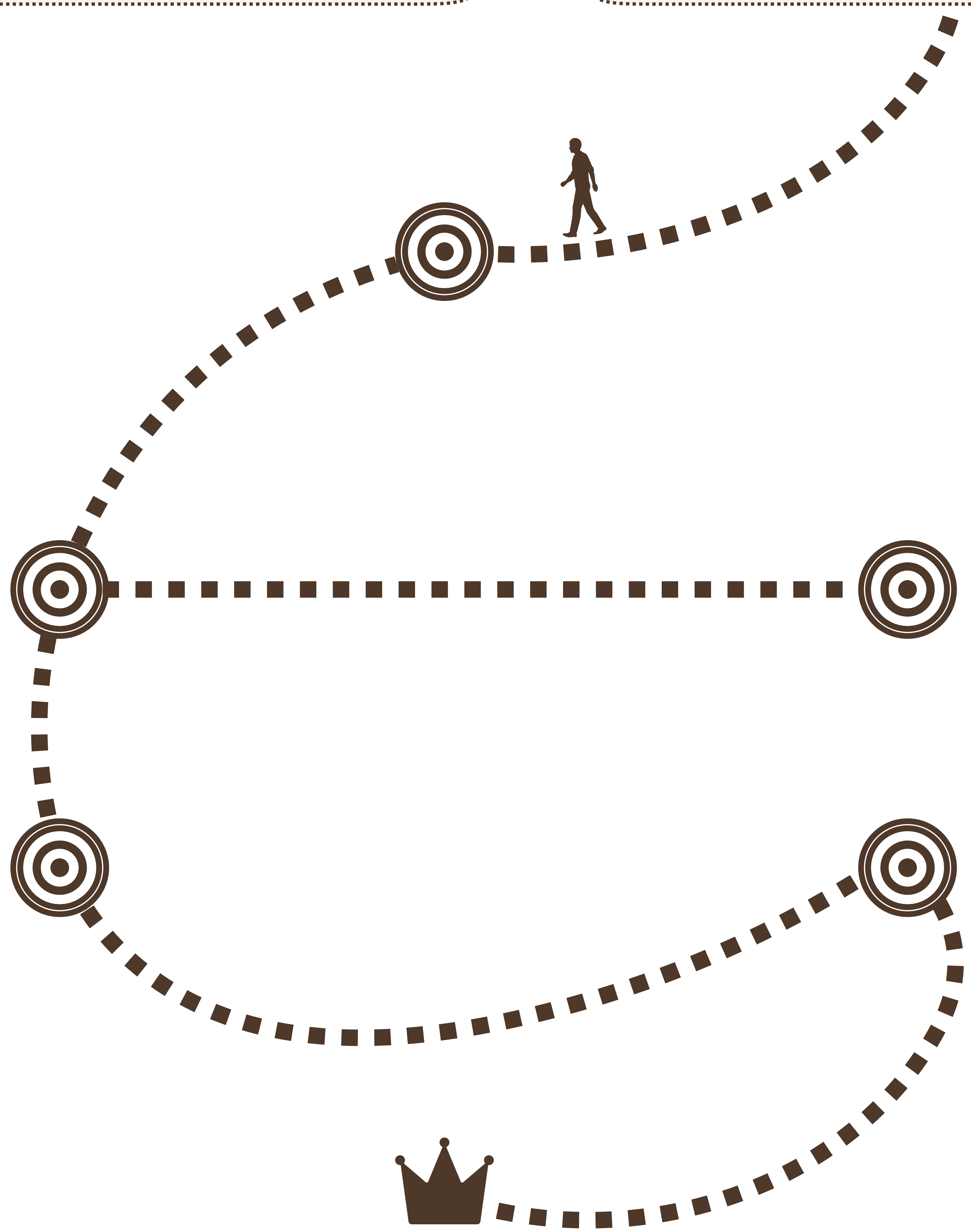
Computing cross sections in **full generality** at **NNLO** is still an open issue

Up to now **NSC** has only been applied to **simple** processes



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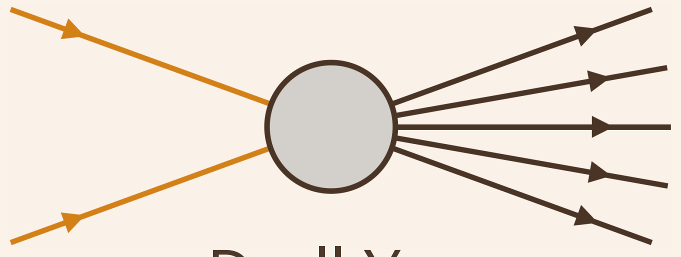

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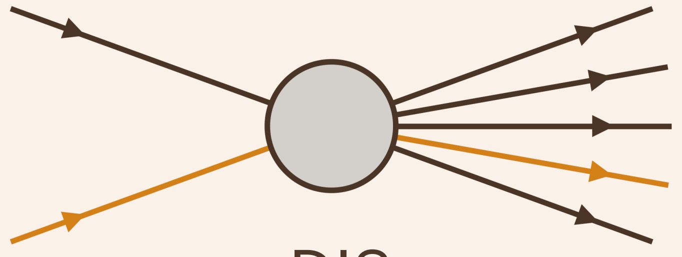
[Caola, Melnikov, Röntsch '19]



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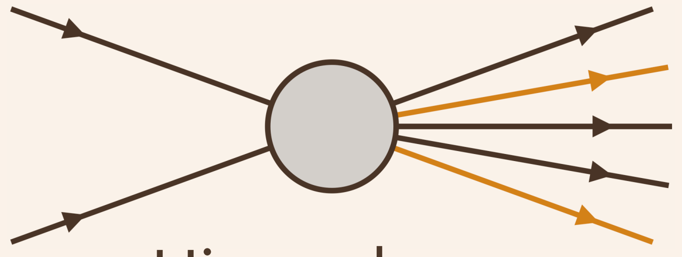

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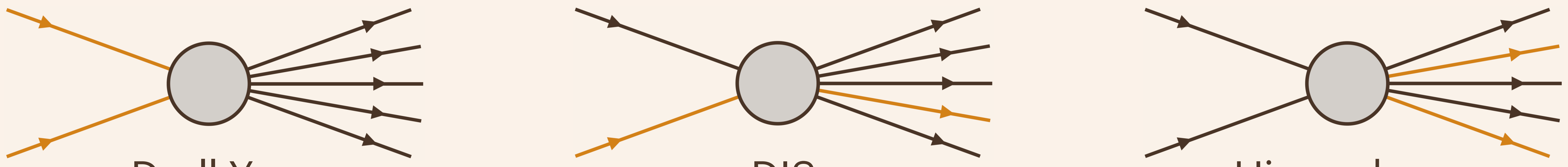

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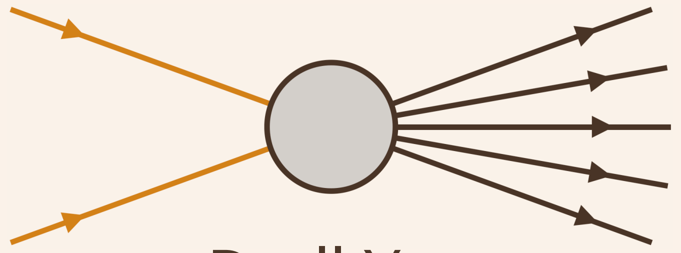

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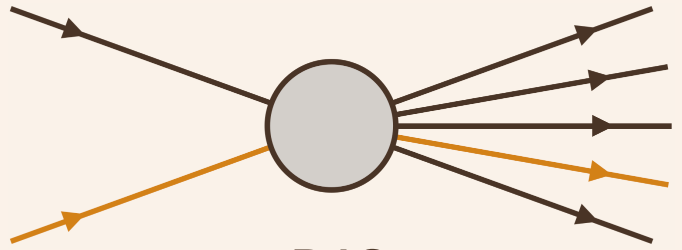

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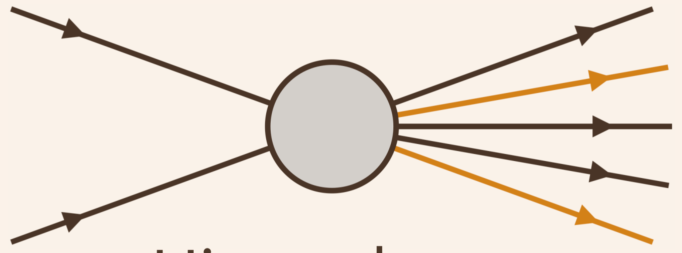

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$N \to 3$
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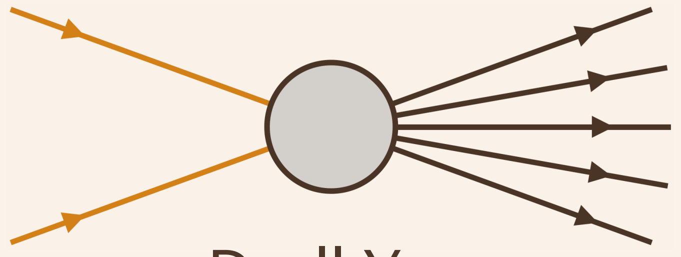

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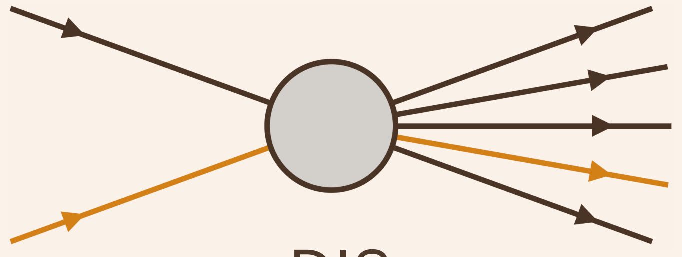

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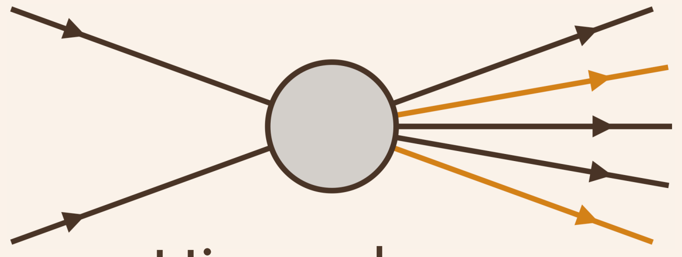

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What is a good prototype of the problem?
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This talk!
[Devoto, Melnikov, Röntsch, Signorile-Signorile, **D.M.T.**, to appear]

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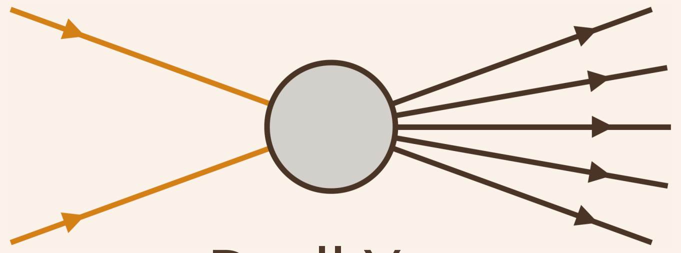

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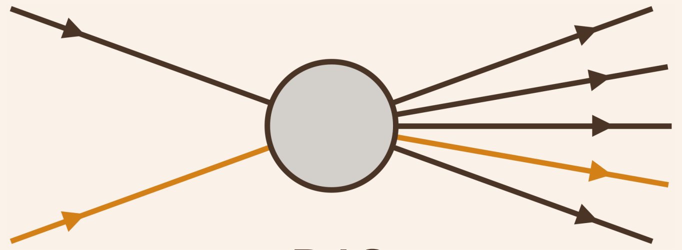

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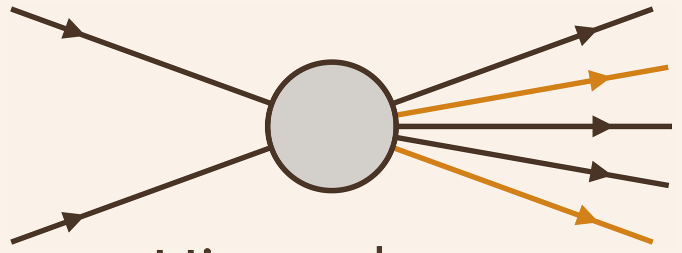

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double-loop amplitudes

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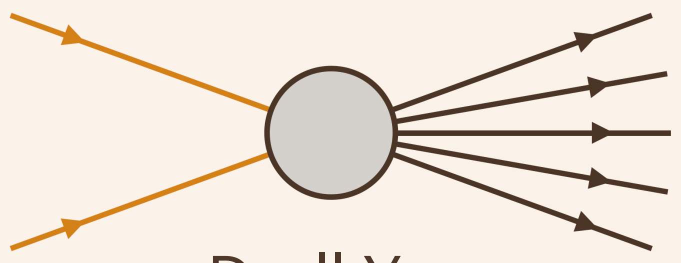

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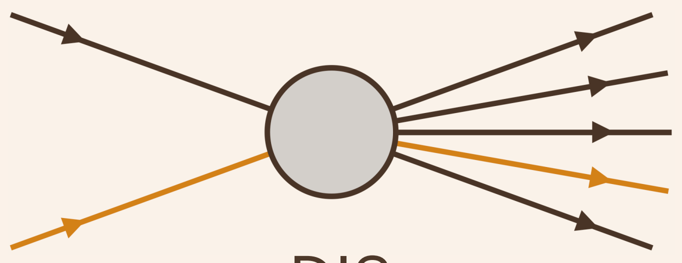

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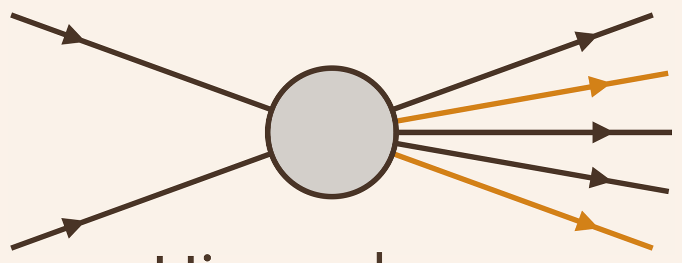

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<< If someone gives me the finite part of the double-loop amplitude of any kind of process, then I can give back the analytical expression of the whole partonic cross section. >>

FOLLOWING CATANI'S SOUL: NLO

- **Virtual corrections $\mathrm{d}\hat{\sigma}^{\mathrm{V}}$**: the IR content of virtual amplitude is known [Catani '98]. Through the operator

$$\bar{I}_1(\epsilon) = \frac{1}{2}\sum_{i\neq j}^{Np} \frac{\mathscr{V}_i^{\text{sing}}(\epsilon)}{\boldsymbol{T}_i^2}(\boldsymbol{T}_i\cdot\boldsymbol{T}_j)\left(\frac{\mu^2}{2p_i\cdot p_j}\right)^{\epsilon} e^{i\pi\lambda_{ij}\epsilon} \qquad \mathscr{V}_i^{\text{sing}}(\epsilon) = \frac{\boldsymbol{T}_i^2}{\epsilon^2} + \frac{\gamma_i}{\epsilon}, \quad N_p = N+2$$

the divergent part of $\mathrm{d}\hat{\sigma}^{\mathrm{V}}$ can be written as

$$\boldsymbol{I}_{\mathrm{V}}(\boldsymbol{\epsilon}) = \bar{I}_1(\epsilon) + \bar{I}_1^{\dagger}(\epsilon)$$

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Real corrections $\mathrm{d}\hat{\sigma}^{\mathrm{R}}$: we would like something similar

Soft emission $[S_{\mathfrak{m}}\colon E_{\mathfrak{m}}\to 0]$ — Collinear emission $[C_{i\mathfrak{m}}\colon \theta_{i\mathfrak{m}}\to 0]$

We use **NESTED SOFT-COLLINEAR SCHEME** (FKS at NLO) to regularize this divergences [Caola, Melnikov, Röntsch '17]

$$\mathrm{d}\hat{\sigma}^{\mathrm{R}} = \underbrace{\left\langle S_{\mathfrak{m}}F_{\mathrm{LM}}(\mathfrak{m})\right\rangle}_{\text{Soft term } [S_{\mathfrak{m}}:\, E_{\mathfrak{m}}\to 0]} + \sum_{i=1}^{N_p}\underbrace{\left\langle \bar{S}_{\mathfrak{m}}C_{i\mathfrak{m}}\Delta^{(\mathfrak{m})}F_{\mathrm{LM}}(\mathfrak{m})\right\rangle}_{\text{Hard-Collinear term } [C_{i\mathfrak{m}}:\, \theta_{i\mathfrak{m}}\to 0]} + \left\langle \mathcal{O}_{\mathrm{NLO}}\,\Delta^{(\mathfrak{m})}F_{\mathrm{LM}}(\mathfrak{m})\right\rangle$$

FOLLOWING CATANI'S SOUL: NLO

- It turns out that the **soft term** can be written by means of an **operator** that, at least in its soul, is very **close to $I_V(\epsilon)$**:

$$I_S(\epsilon) = -\frac{(2E_{\max}/\mu)^{-2\epsilon}}{\epsilon^2}\sum_{i\neq j}^{N_p}\eta_{ij}^{-\epsilon}K_{ij}\,(\boldsymbol{T}_i\cdot\boldsymbol{T}_j)$$

$$\eta_{ij} = (1-\cos\theta_{ij})/2$$

$$K_{ij} \sim \eta_{ij}^{1+\epsilon}\,{}_2F_1(1,1,1-\epsilon,1-\eta_{ij})$$

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Combination of $I_{\mathrm{V}}(\epsilon)+I_{\mathrm{S}}(\epsilon)$: not only does it **vanishes** the pole $\mathcal{O}(\epsilon^{-2})$, but it makes the pole $\mathcal{O}(\epsilon^{-1})$ free of **color-correlations**

$I_{\mathrm{V,S}}(\epsilon) \sim \boldsymbol{T}_i\cdot\boldsymbol{T}_j$ $\quad$ $\boldsymbol{T}_i =$ matrices in color space

$$N_p < 4 \Rightarrow \mathrm{d}\hat{\sigma}^{\mathrm{NLO}} \sim \frac{C_{A,F}}{\epsilon}\boxed{\langle M_0|M_0\rangle}$$

NO color-correlations

$$N_p \geq 4 \Rightarrow \mathrm{d}\hat{\sigma}^{\mathrm{NLO}} \sim \frac{1}{\epsilon}\boxed{\langle M_0|\boldsymbol{T}_i\cdot\boldsymbol{T}_j|M_0\rangle}$$

YES color-correlations

This result for $I_{\mathrm{V}}(\epsilon)+I_{\mathrm{S}}(\epsilon)$ is trivially **dependent** on the **number of gluons** in the final state

FOLLOWING CATANI'S SOUL: NLO

What about the **hard-collinear term**? Some parts vanish against the DGLAP contribution, the remaining part **can be collected** within the following **Catani-like operator**

$$I_C(\epsilon) = \sum_{i=1}^{N_p} \frac{\Gamma_{i,f_i}}{\epsilon}$$

$$\Gamma_{a,f_a} = \left[\left(\frac{2E_a}{\mu}\right)^{-2\epsilon} \frac{\Gamma^2(1-\epsilon)}{\Gamma(1-2\epsilon)}\right]\left[\gamma_{f_a} + C_{f_a}\frac{1-e^{-2\epsilon L_a}}{\epsilon}\right], \quad a = 1,2$$

$$\Gamma_{i,f_i} = \left[\left(\frac{2E_i}{\mu}\right)^{-2\epsilon} \frac{\Gamma^2(1-\epsilon)}{\Gamma(1-2\epsilon)}\right]\gamma^{22}_{z,g\to gg}(\epsilon, L_i), \qquad i \in [3,N_p]$$

Once more the definition **depends** in a trivial way on N_p

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$I_{\mathrm{C}}(\epsilon)$ cancels perfectly the pole $\mathcal{O}(\epsilon^{-1})$ left by $I_{\mathrm{V}}(\epsilon) + I_{\mathrm{S}}(\epsilon)$. It is thus natural to introduce the **total operator**

$$I_{\mathrm{T}}(\epsilon) = I_{\mathrm{V}}(\epsilon) + I_{\mathrm{S}}(\epsilon) + I_{\mathrm{C}}(\epsilon)$$

- pole free
- fully general w.r.t. N_p

In this way the final result for the NLO fits in a line:

$$\mathrm{d}\hat{\sigma}^{\mathrm{NLO}} = [\alpha_s]\left\langle I_{\mathrm{T}}(\epsilon)\cdot F_{\mathrm{LM}}\right\rangle + [\alpha_s]\left[\left\langle P^{\mathrm{NLO}}_{aa}\otimes F_{\mathrm{LM}}\right\rangle + \left\langle F_{\mathrm{LM}}\otimes P^{\mathrm{NLO}}_{aa}\right\rangle\right] + \left\langle F^{\mathrm{fin}}_{\mathrm{LV}}\right\rangle + \left\langle \mathcal{O}_{\mathrm{NLO}}\,\Delta^{(\mathfrak{m})}F_{\mathrm{LM}}(\mathfrak{m})\right\rangle$$

WHAT HAPPENS AT NNLO?

$$\mathrm{d}\hat{\sigma}^{\mathrm{NNLO}} = \underbrace{\mathrm{d}\hat{\sigma}^{\mathrm{VV}}}_{\text{Double-Virtual}} + \underbrace{\mathrm{d}\hat{\sigma}^{\mathrm{RV}}}_{\text{Real-Virtual}} + \underbrace{\mathrm{d}\hat{\sigma}^{\mathrm{RR}}}_{\text{Double-Real}} + \underbrace{\mathrm{d}\hat{\sigma}^{\mathrm{pdf}}}_{\text{PDFs Renor.}}$$

Consider for instance $\mathrm{d}\hat{\sigma}^{\mathrm{VV}}$ $\Rightarrow$ it depends **quadratically** on $\bar{I}_1(\epsilon)$ and $\bar{I}_1^\dagger(\epsilon)$

$$\Rightarrow \bar{I}_1, \bar{I}_1^\dagger \sim \boldsymbol{T}_i \cdot \boldsymbol{T}_j$$

$$\Rightarrow \mathrm{d}\hat{\sigma}^{\mathrm{VV}} \sim \boxed{(\boldsymbol{T}_i \cdot \boldsymbol{T}_j) \cdot (\boldsymbol{T}_k \cdot \boldsymbol{T}_l)}$$ double color-correlations

The **same** happens for $\mathrm{d}\hat{\sigma}^{\mathrm{RV}}$ and $\mathrm{d}\hat{\sigma}^{\mathrm{RR}}$. Dealing with such double-color correlated terms (**DCC**) in general makes the **structure of the poles very complicated**

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$$\Downarrow$$

The strategy: **isolate DCC** in $\mathrm{d}\hat{\sigma}^{\mathrm{VV}}$ and then **combine** them with **those** contained within $\mathrm{d}\hat{\sigma}^{\mathrm{RV}}$ and $\mathrm{d}\hat{\sigma}^{\mathrm{RR}}$

$$\Downarrow$$

The goal: **assemble** all these **DCC** into an expression that we expect being **quadratic** in $I_{\mathrm{T}}(\epsilon)$

WHAT HAPPENS AT NNLO?

Here it is what we find [Devoto, Melnikov, Röntsch, Signorile-Signorile, **D.M.T.**, to appear]

$$Y_{\rm VV} = \frac{[\alpha_s]^2}{2}\left\langle M_0 \middle| \bar{I}_1^2 + (\bar{I}_1^\dagger)^2 + 2\bar{I}_1^\dagger\,\bar{I}_1 \middle| M_0\right\rangle + \dots$$

$$Y_{\rm RR}^{(\rm ss)} = \frac{[\alpha_s]^2}{2}\langle M_0 | I_{\rm S}^2 | M_0\rangle + \dots$$

$$Y_{\rm RR}^{(\rm shc)} = [\alpha_s]^2\langle M_0 | I_{\rm S}\, I_{\rm C} | M_0\rangle + \dots$$

$$Y_{\rm RR}^{(\rm cc)} = \frac{[\alpha_s]^2}{2}\langle M_0 | I_{\rm C}^2 | M_0\rangle + \dots$$

$$Y_{\rm RV}^{(\rm s)} = \frac{[\alpha_s]^2}{2}\left\langle M_0 \middle| I_{\rm S}\,\bar{I}_1 + \bar{I}_1^\dagger\, I_{\rm S} \middle| M_0\right\rangle + \dots$$

$$Y_{\rm RV}^{(\rm shc)} = [\alpha_s]^2\left\langle M_0 \middle| (\bar{I}_1 + \bar{I}_1^\dagger)\, I_{\rm C} \middle| M_0\right\rangle + \dots$$

Once combined, these objects return

NB square of NLO

$$Y = \frac{[\alpha_s]^2}{2}\left\langle M_0 \middle| \left[I_{\rm V} + I_{\rm S} + I_{\rm C}\right]^2 \middle| M_0\right\rangle + \dots \equiv \langle M_0 | I_{\rm T}^2 | M_0\rangle + \dots$$

WHAT HAPPENS AT NNLO?

The benefits of introducing these Catani's like operators:

- the problem of **double color-correlated poles disappears**, since everything is written in terms of $\boldsymbol{I_{\mathrm{T}}^2(\epsilon)}$, which is $\boldsymbol{\mathcal{O}(\epsilon^0)}$
- the **definition** of $\boldsymbol{I_{\mathrm{T}}(\epsilon)}$ depends trivially on N_p so the result we got is **fully general w.r.t. the final state**
- We **do not explicitly calculate** the individual sub-blocks of the process. Instead, we write each of these in terms of $I_{\mathrm{V}}(\epsilon)$, $I_{\mathrm{S}}(\epsilon)$ and $I_{\mathrm{C}}(\epsilon)$, then recombine them to get $I_{\mathrm{T}}(\epsilon)$. The **cancellation of the poles** takes place **automatically**

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If $\boldsymbol{N_p \geq 4}$

$[\bar{I}_1, \bar{I}_1^\dagger] \neq 0$

$[\bar{I}_1^\dagger, \bar{I}_S] \neq 0 \quad \rightarrow \quad f_{abc} T_i^a T_j^b T_k^c$

$[\bar{I}_1, \bar{I}_S] \neq 0$

Once combined, these objects return

$$Y = \frac{[\alpha_s]^2}{2} \left\langle M_0 \middle| \left[I_{\mathrm{V}} + I_{\mathrm{S}} + I_{\mathrm{C}} \right]^2 \middle| M_0 \right\rangle + \ldots \equiv \langle M_0 | I_{\mathrm{T}}^2 | M_0 \rangle \boxed{+ \ldots}$$

CONCLUSIONS AND OUTLOOK

1. We can also **vanish the poles** $\sim f_{abc} T_i^a T_j^b T_k^c$. How this happens is non trivial

2. There are still **terms** that **do not fit** $I_{\mathrm{T}}(\epsilon)$

3. The next step is studying the process where we **add** a $q\,\bar{q}$ couple **in the final state**

4. We also intend to study the **asymmetric initial state** $g\,q$

MANY THANKS FOR YOUR ATTENTION

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