

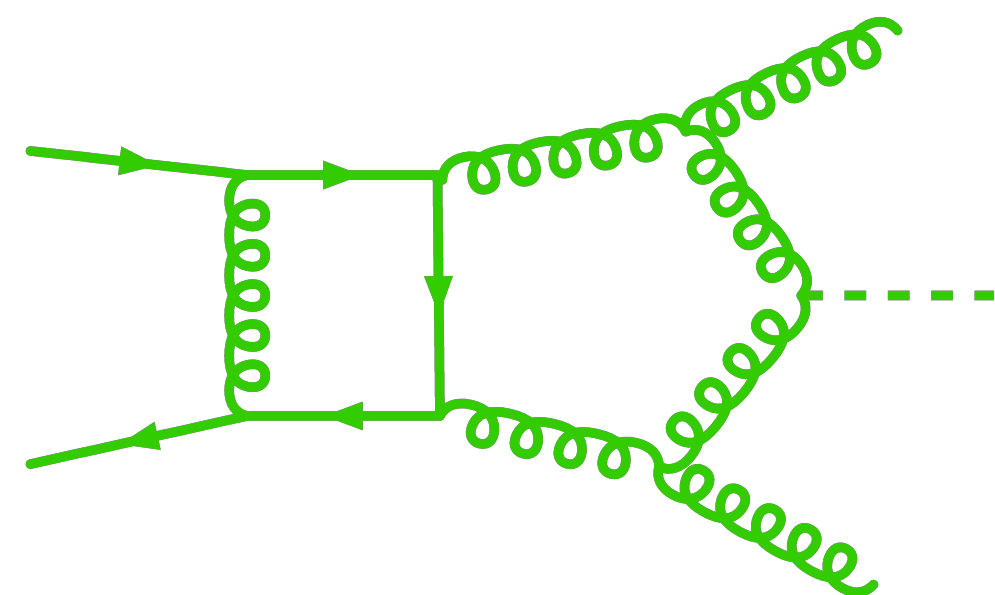
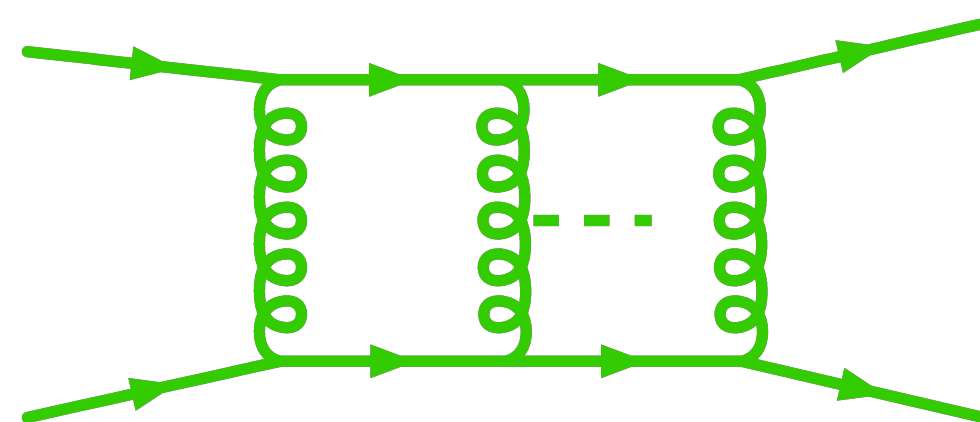
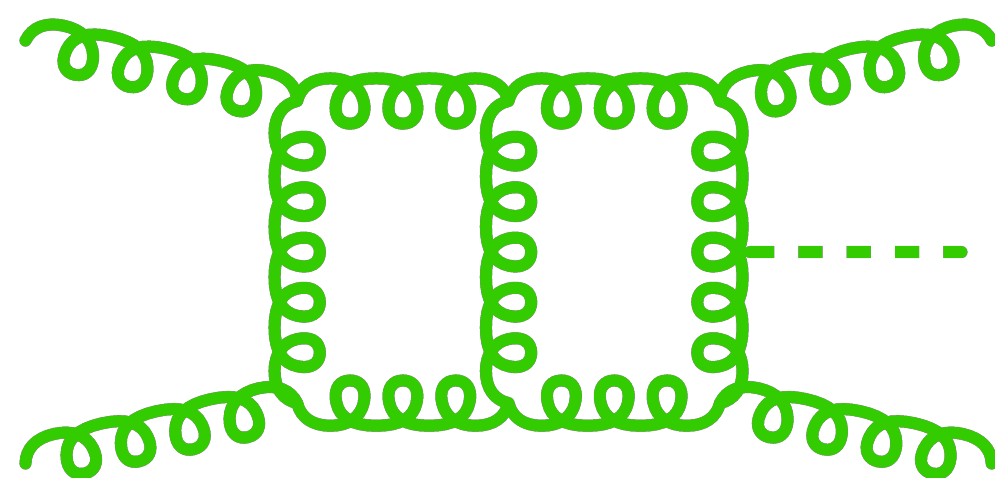
PSI

Center for Neutron and
Muon Sciences



Universität
Zürich^{UZH}

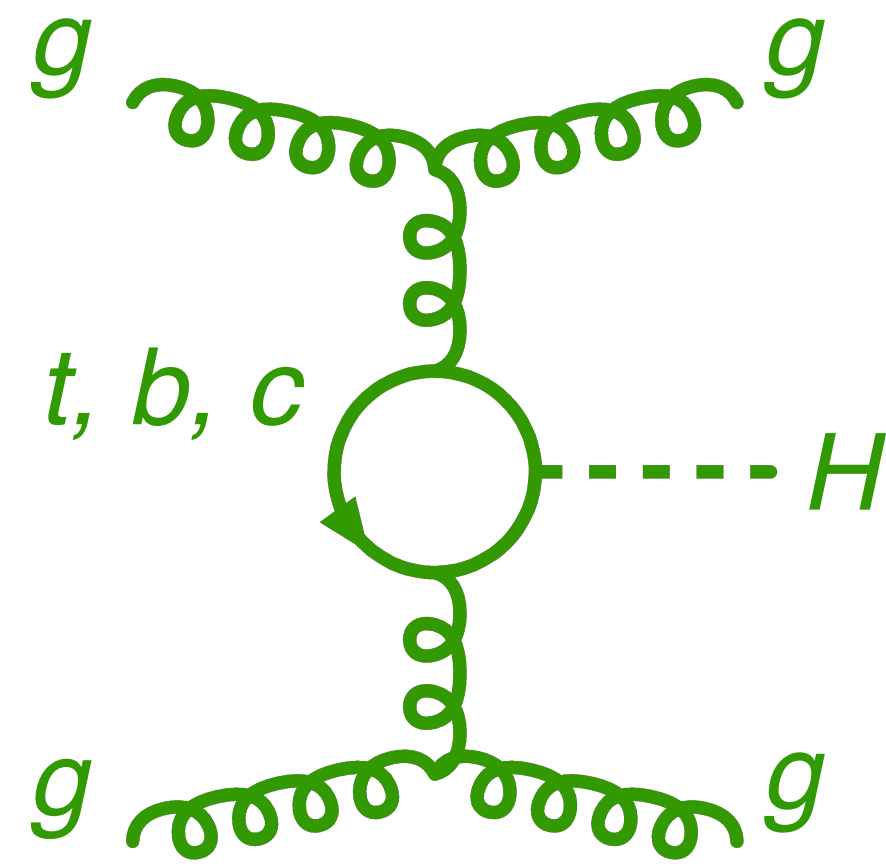
2-loop QCD corrections for H + 2-jet production through gluon fusion



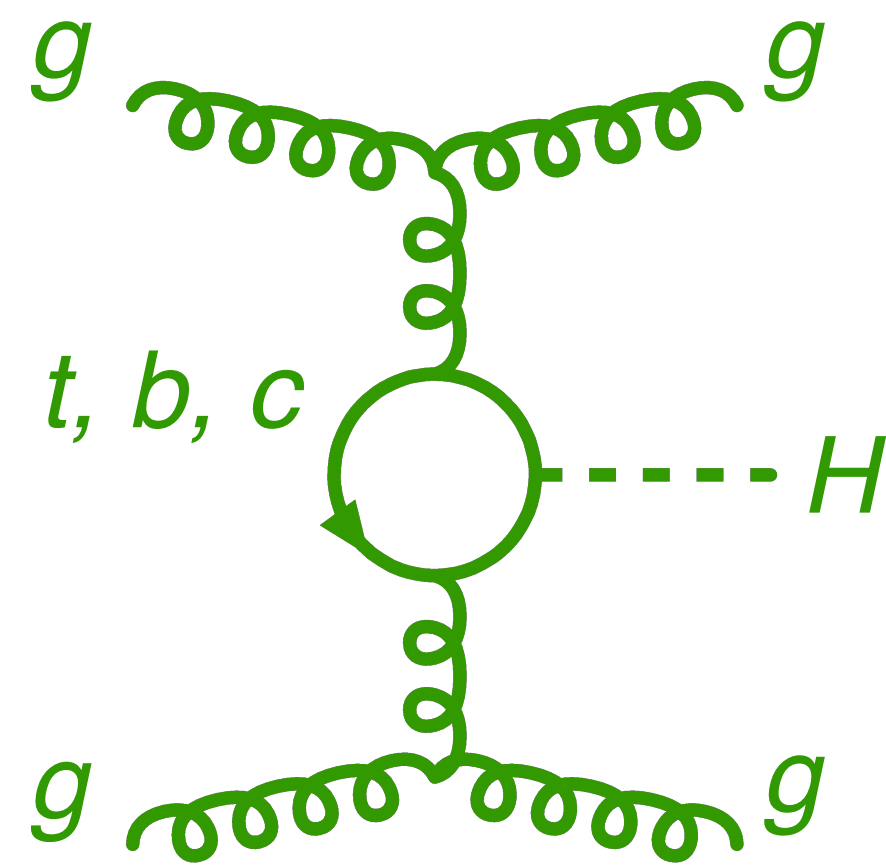
Based on [2605.04009] in collaboration with
Giuseppe De Laurentis, Harald Ita, V.K.,
Michael Ruf, Vasily Sotnikov

October 1st
QCD @ LHC 2026
Viktor Kuschke

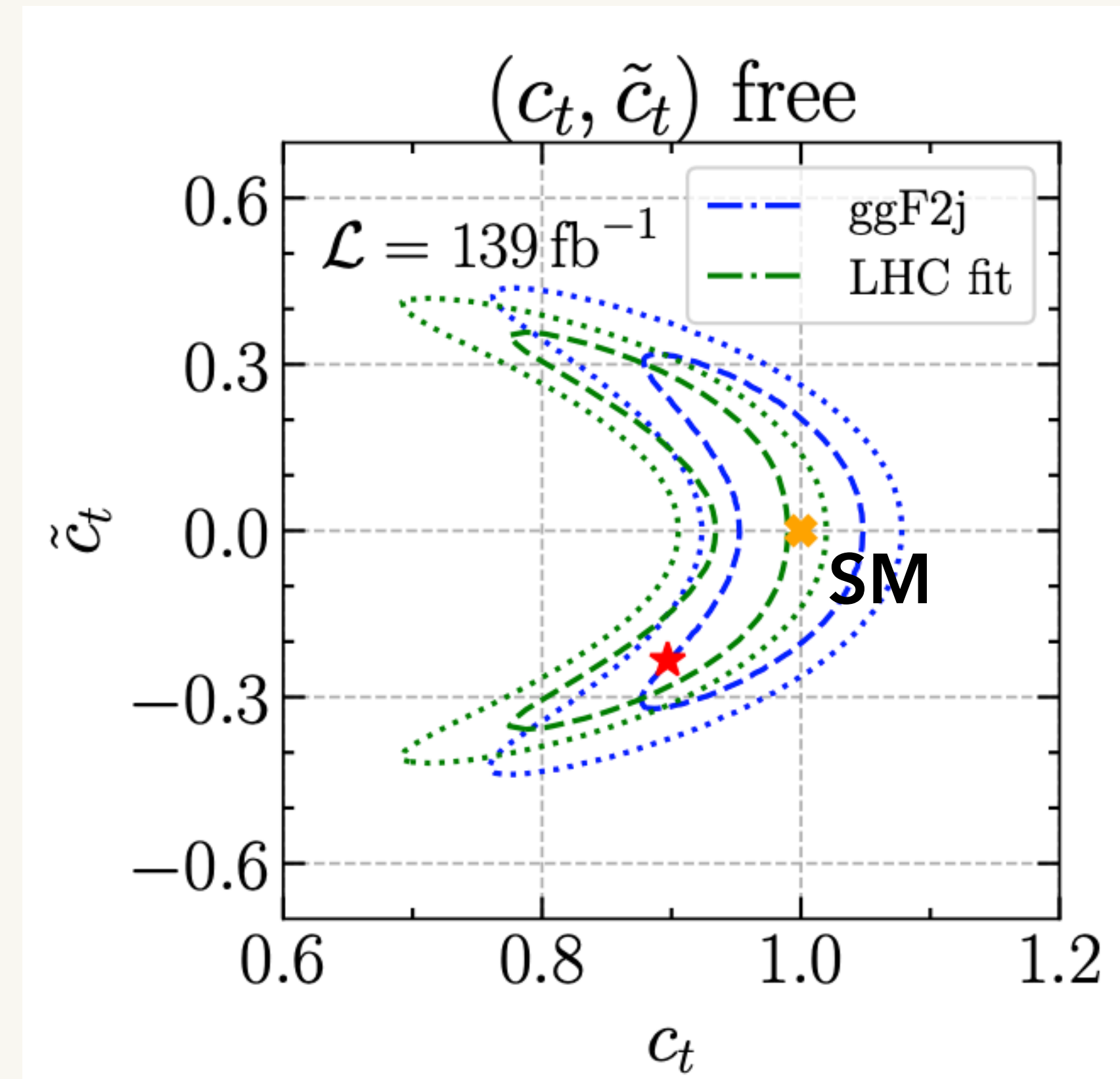
Why study $H+2$ jets from gluon fusion?



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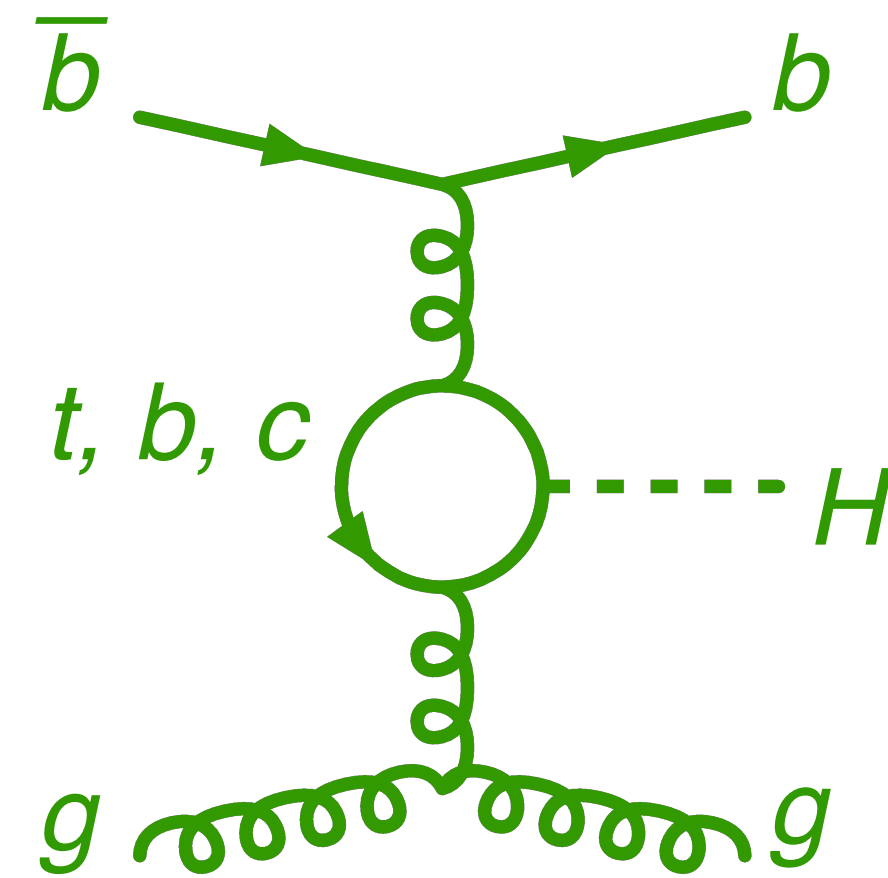
- CP nature of the top Yukawa coupling
[Klmke, Zeppenfeld '07; Dolan, Harris, Jankowiak, Spannowsky '14; Demartin, Maltoni, Mawarti, Page, Zaro '14]



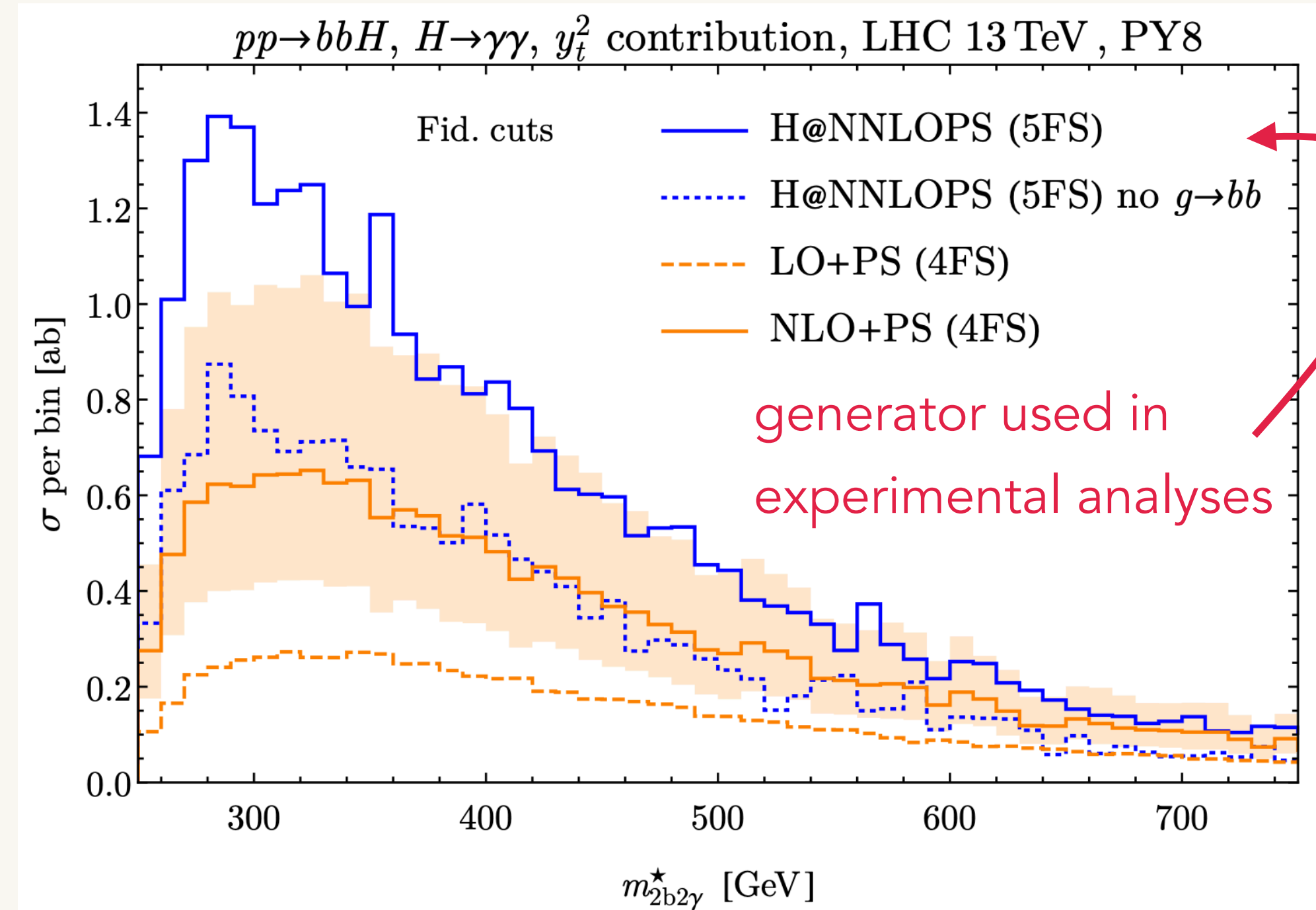
[Bahl, Fuchs, Hannig, Menen '23]

$$\mathcal{L}_{\text{top-Yuk}} = -\frac{y_t^{\text{SM}}}{\sqrt{2}} \bar{t} \left(\underset{\text{even}}{c_t} + i\gamma_5 \underset{\text{odd}}{\tilde{c}_t} \right) t H$$

Why study H+2 jets from gluon fusion?

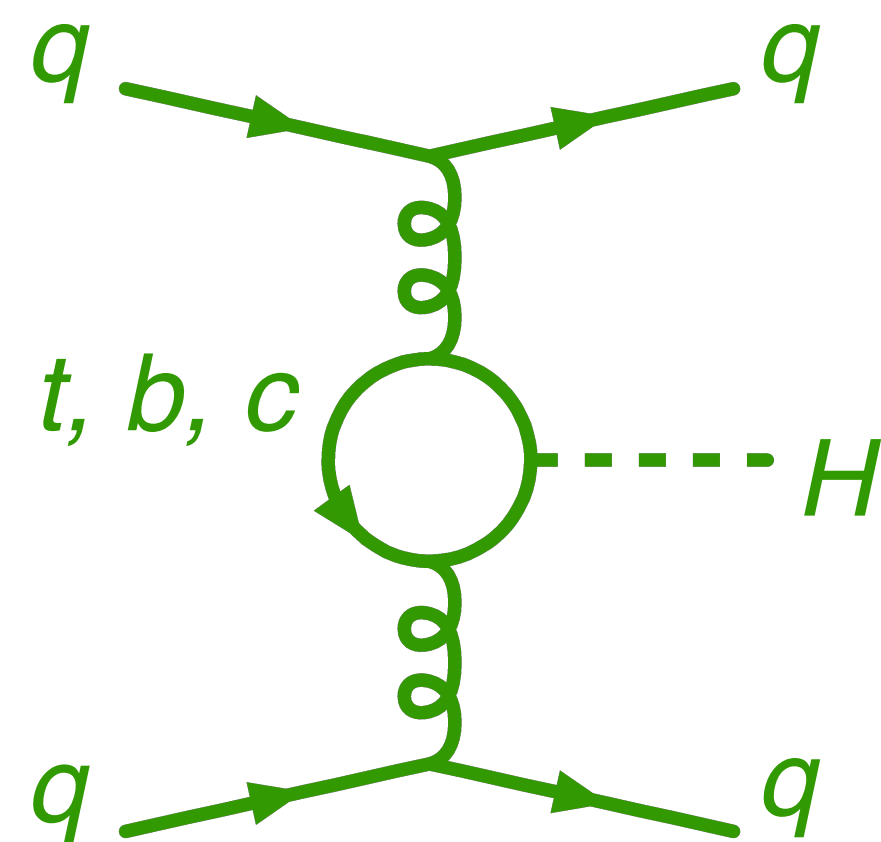


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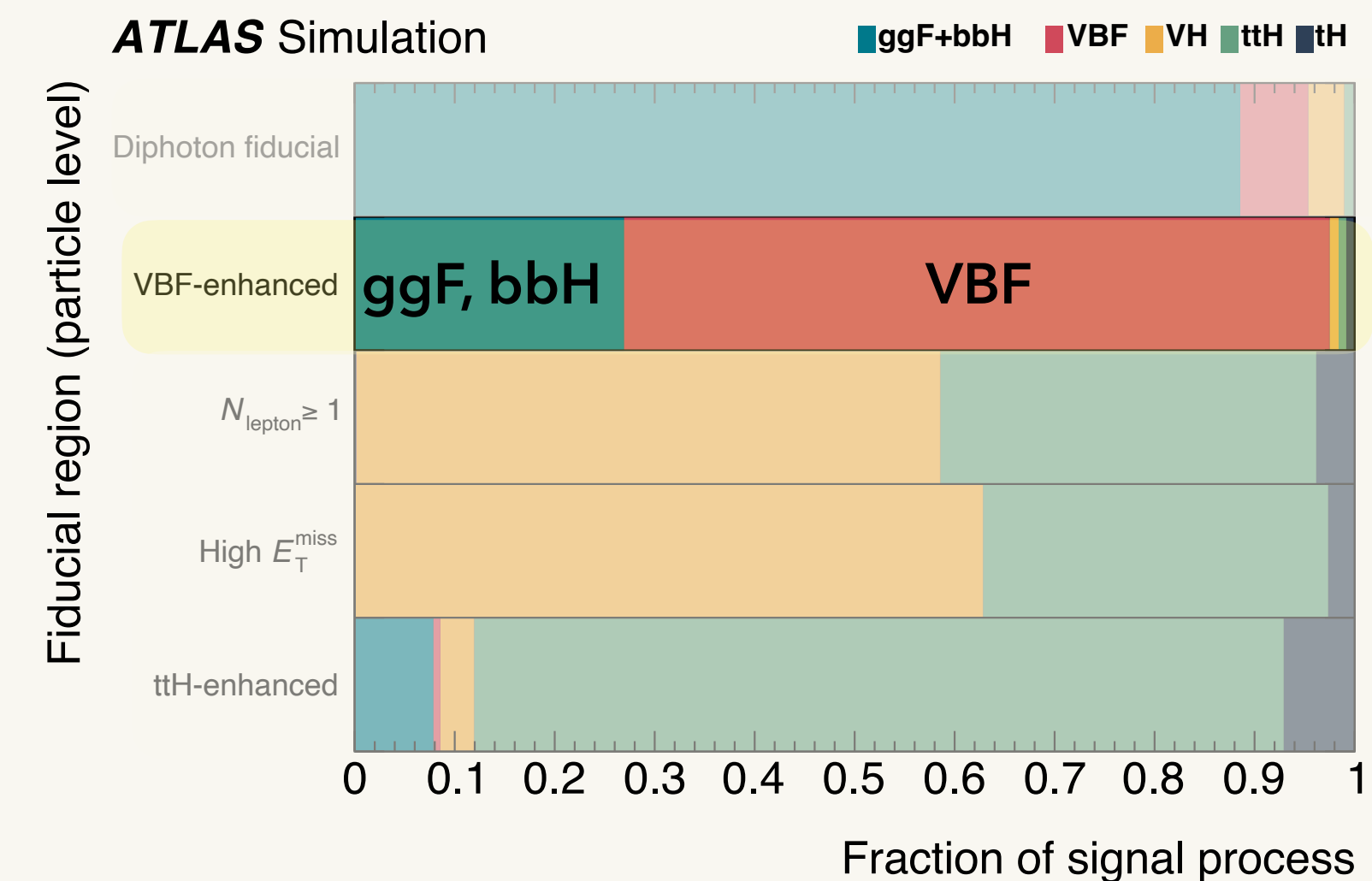
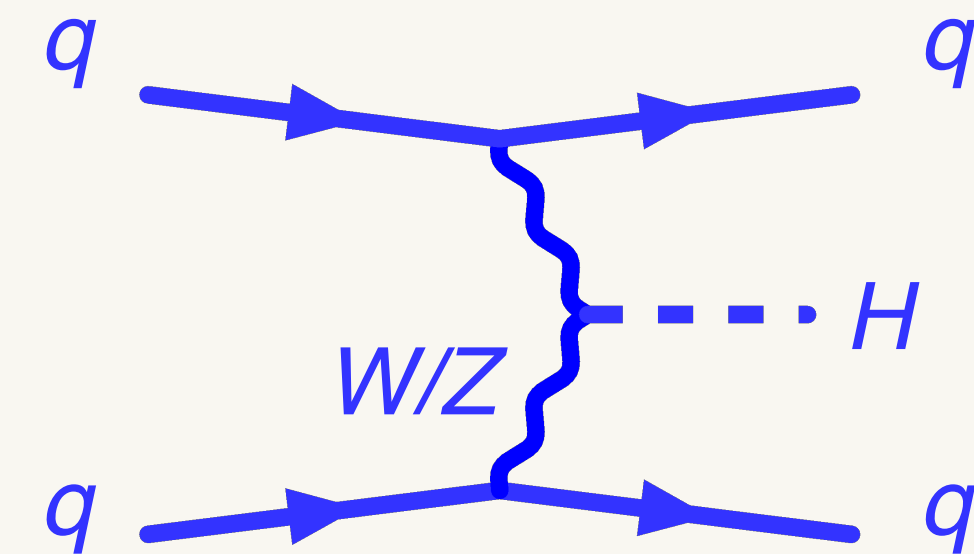


[arXiv:2307.09992]

Why study H+2 jets from gluon fusion?



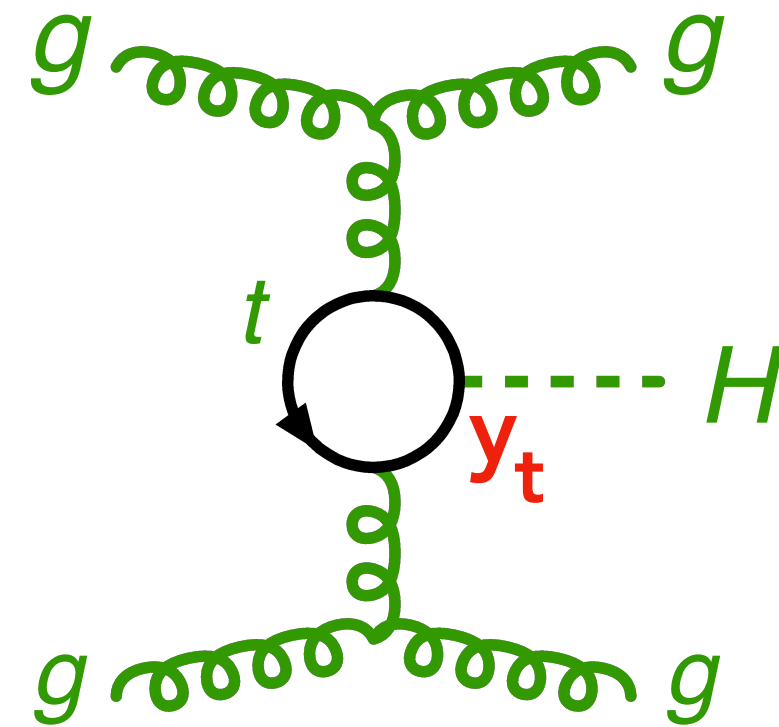
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- Background Vector boson fusion



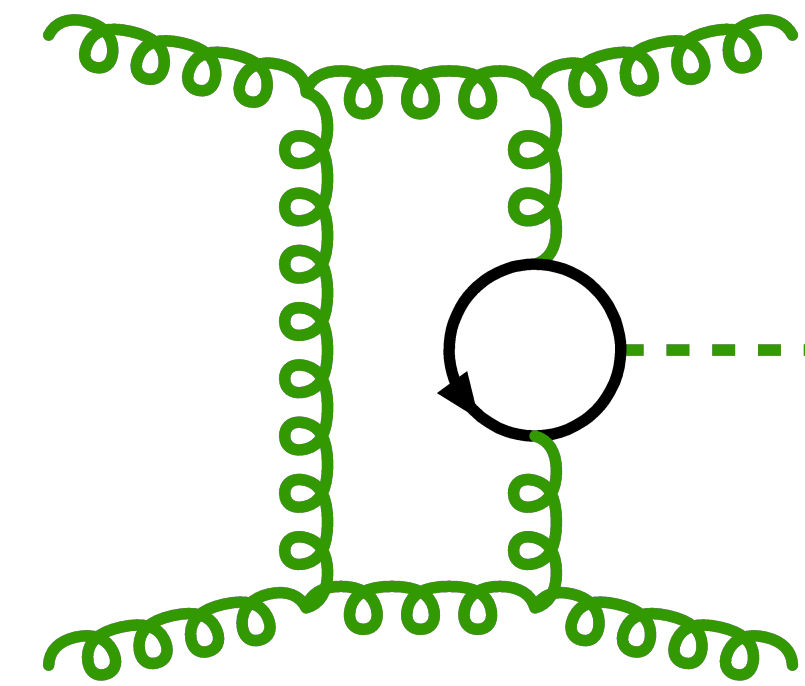
[ATLAS '22]

Higgs + 2 jet amplitudes

○ **LO:**



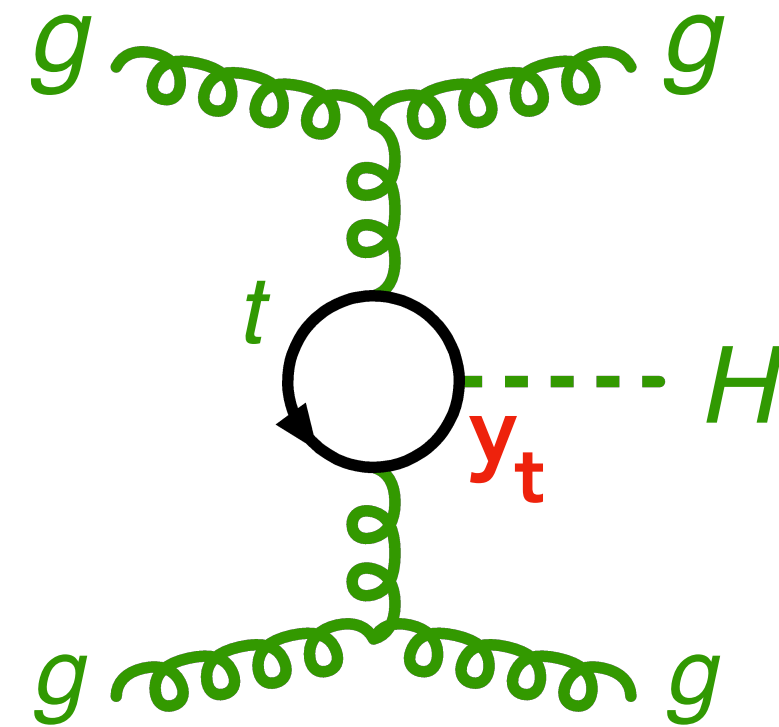
○ **NLO:** missing 2L integrals



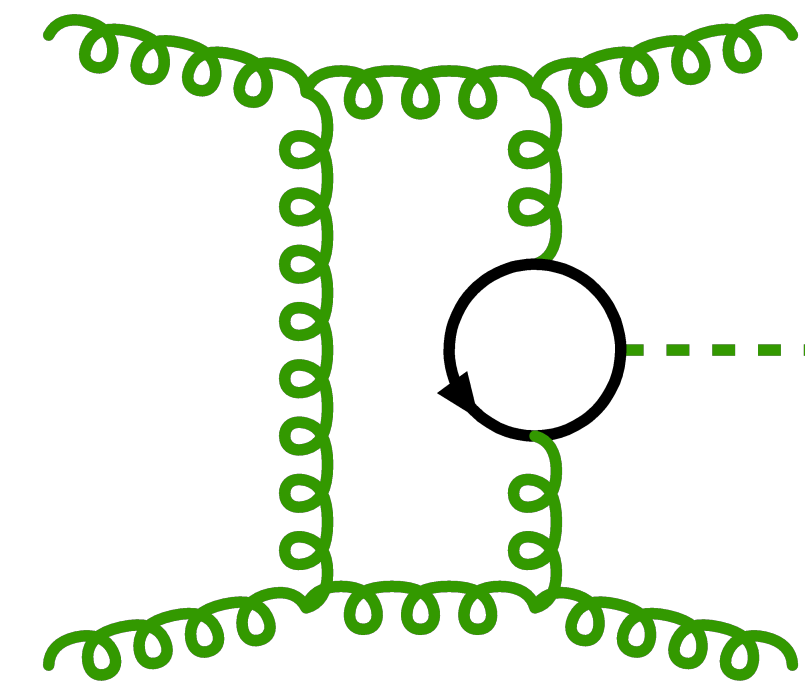
→ approximation top-quark loop
[Ellis, Giele, Zanderighi '05]

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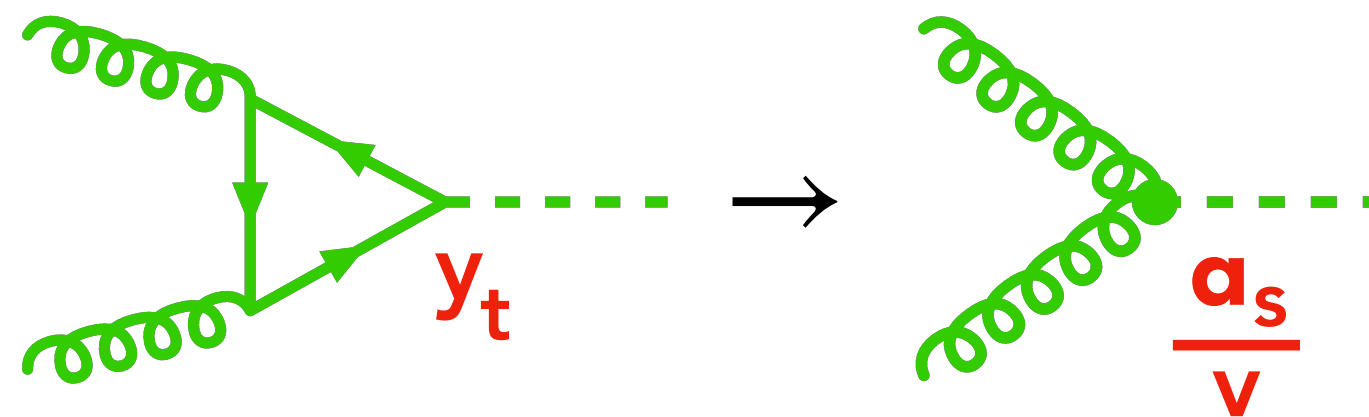


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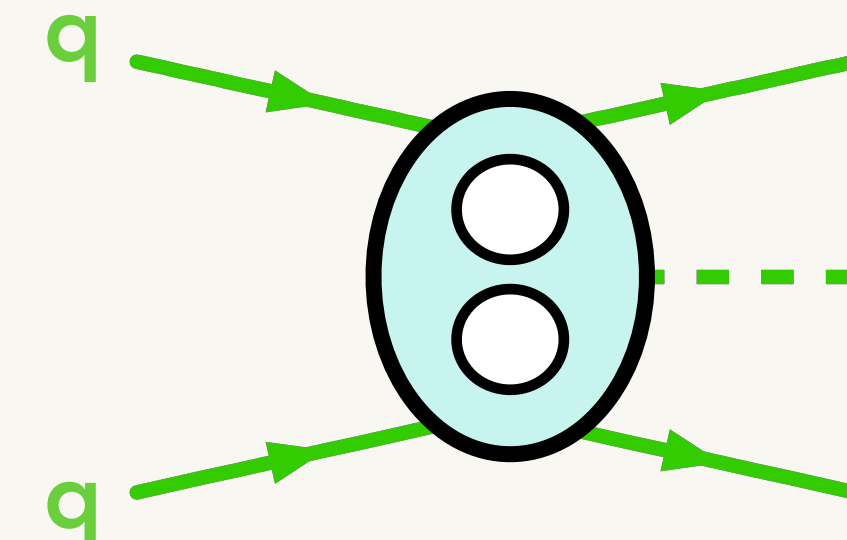
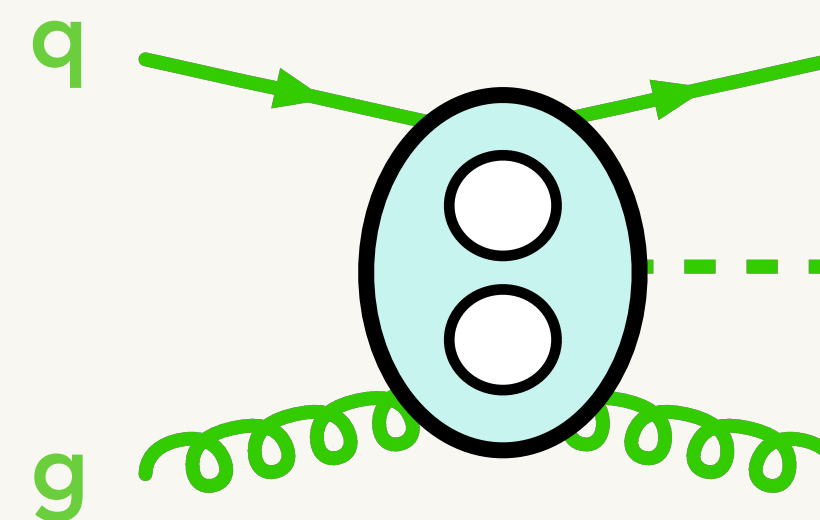
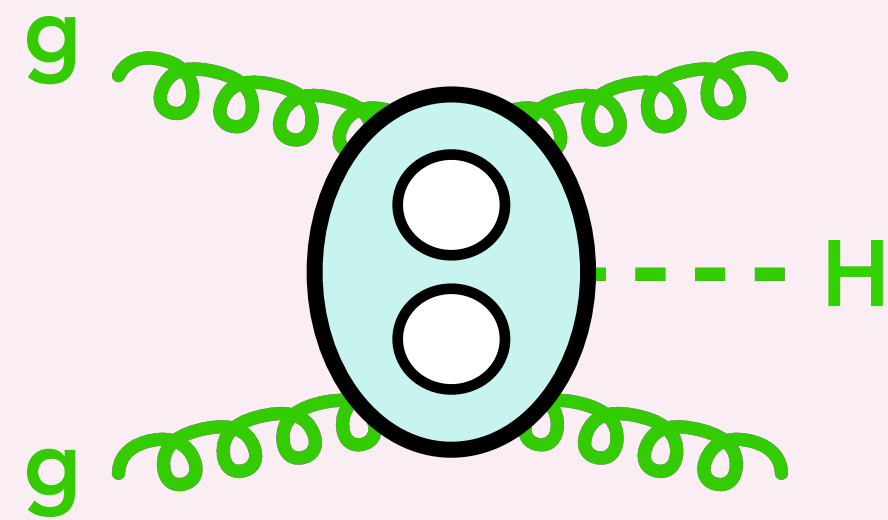
- **heavy top-mass limit** (HTL) $m_t \rightarrow \infty$ & rescaling by LO mass-effects



- e.g. for H+j cross section @ NLO: $\sim 1\%$ (FTapprox) effect vs. $\sim 15\%$ NLO uncertainty
[Chen, Huss, Jones, Kerner, Lang, Lindert, Zhang '21]

Higgs + 2 jet amplitudes in HTL @ 2 loops

Goal: virtual NNLO QCD corrections in HTL

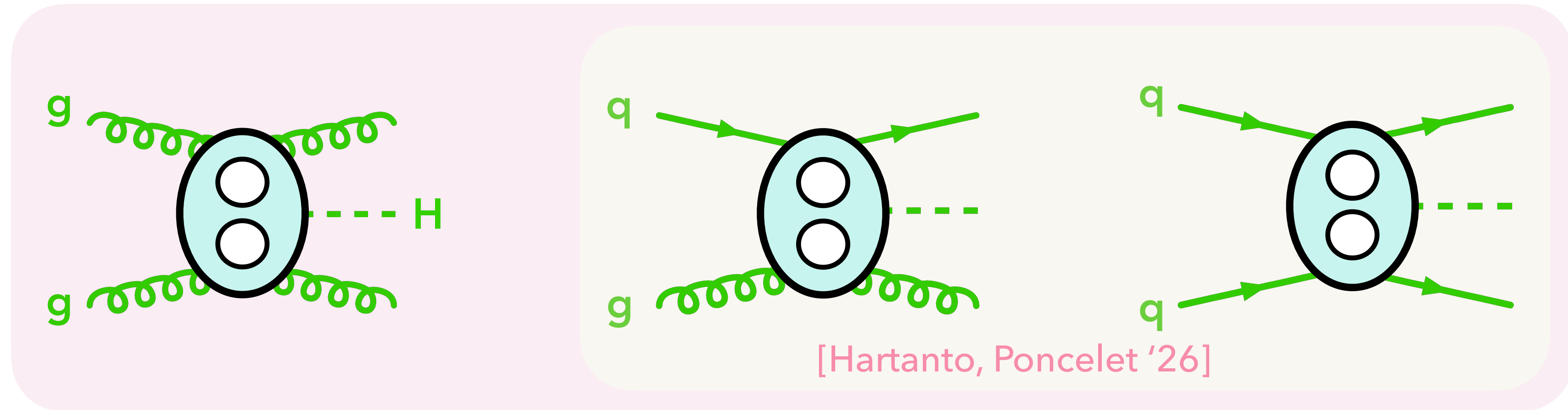


[Hartanto, Poncelet '26]

[De Laurentis, Ita, V.K., Ruf, Sotnikov '26]

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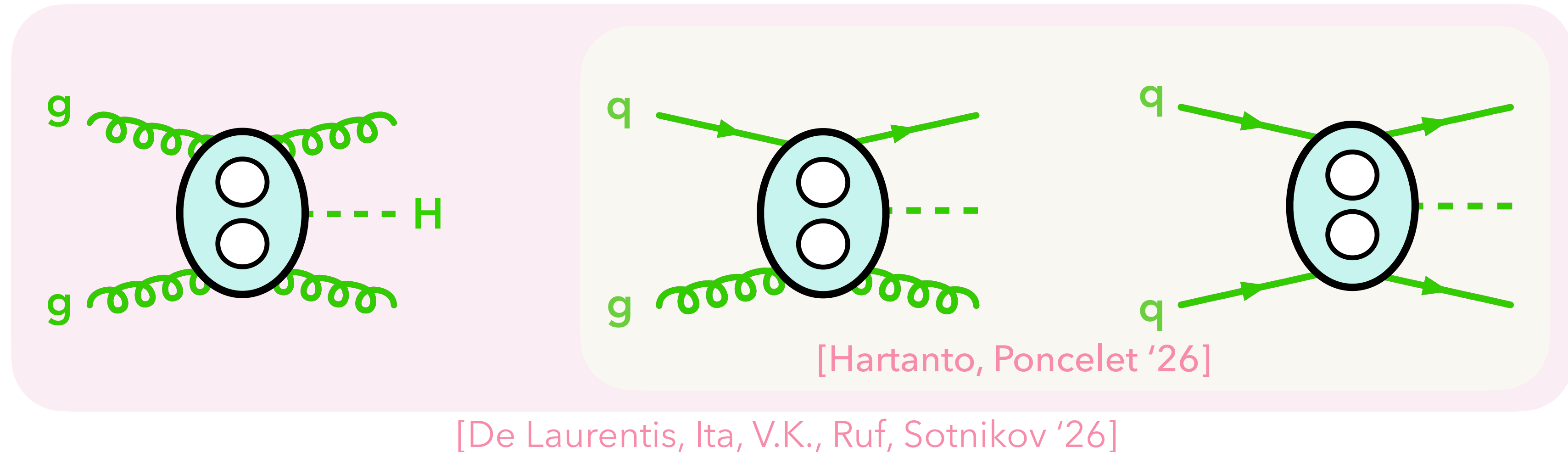
[De Laurentis, Ita, V.K., Ruf, Sotnikov '26]

Challenges:

- ▶ Scale: # (color-factors x helicities x crossings x Feynman diagrams)
- ▶ Complexity: 6 scales, non-planar integrals, higher rank integrands

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Challenges:

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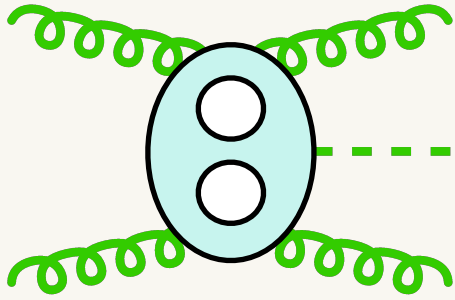
→ **Strategy:**

- ▶ **leading color** approximation: $N_c, N_f \rightarrow \infty$
- ▶ **amplitude reduction** & **evaluation** in **finite fields** $\mathbb{F}_p = \mathbb{Z}/p\mathbb{Z}$
[von Manteuffel, Schabinger '15], [Peraro '16]
- ▶ Analytic **reconstruction** from numeric samples

new ideas

Numerical amplitude reduction

Amplitude decomposition


$$= \sum_i c_i \mathcal{I}_i$$

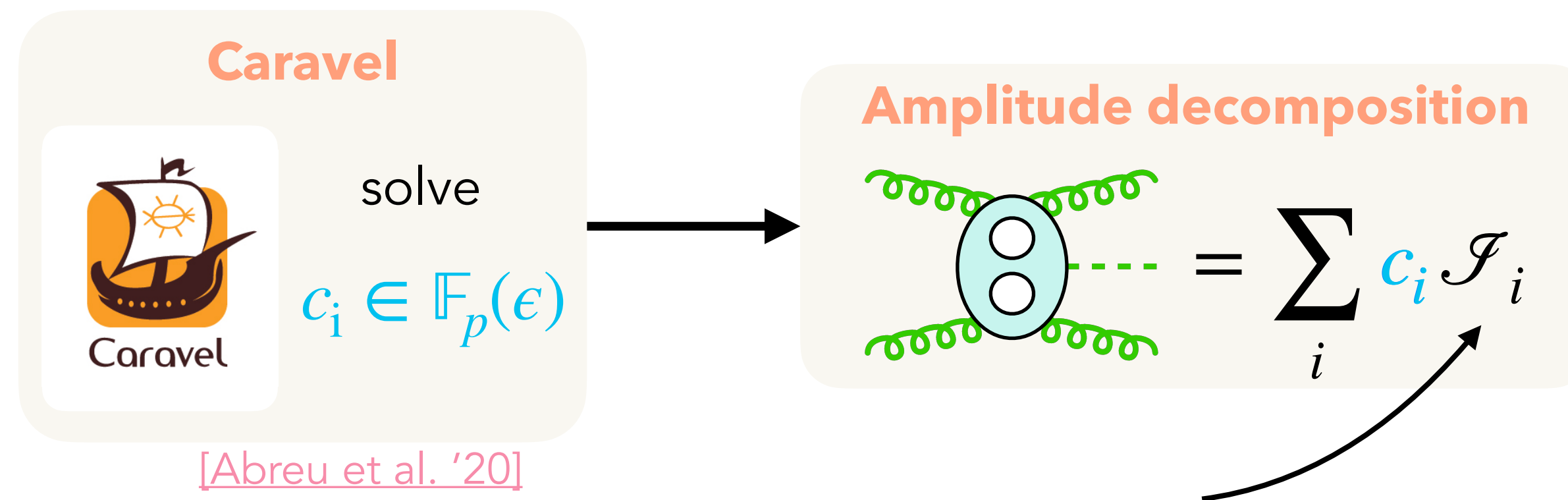
Master Integrals

[Abreu, Chicherin, Ita, Page,
Sotnikov, Tschernow, Zoia '23]

[Abreu, Ita, Moriello, Page, Tschernow '20]

[Papadopoulos, Tommasini, Wever '15 & '19]

Numerical amplitude reduction



Master Integrals

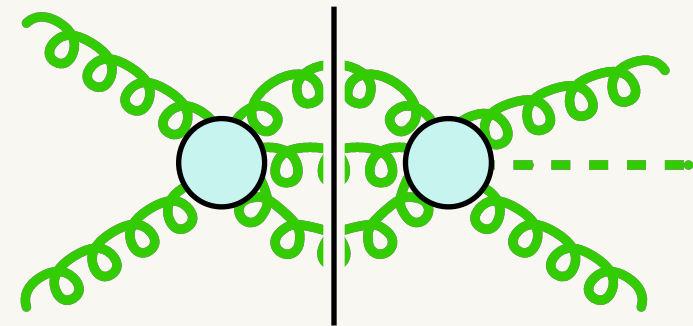
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Numerical amplitude reduction

Unitarity cuts



[Bern, Dixon, Dunbar, Kosower, '94],
 [Britto, Cachazo, Feng '04],
 [Ossola, Papadopoulos, Pittau '06]
 [Giele, Kunszt, Melnikov '08; + Zanderighi '08;
 + Ellis '09],
 [Abreu, Febres Cordero, Ita, Jaquier, Page '17;
 + Zeng '17]

Caravel



solve

$$c_i \in \mathbb{F}_p(\epsilon)$$

[Abreu et al. '20]

Amplitude decomposition

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Master Integrals

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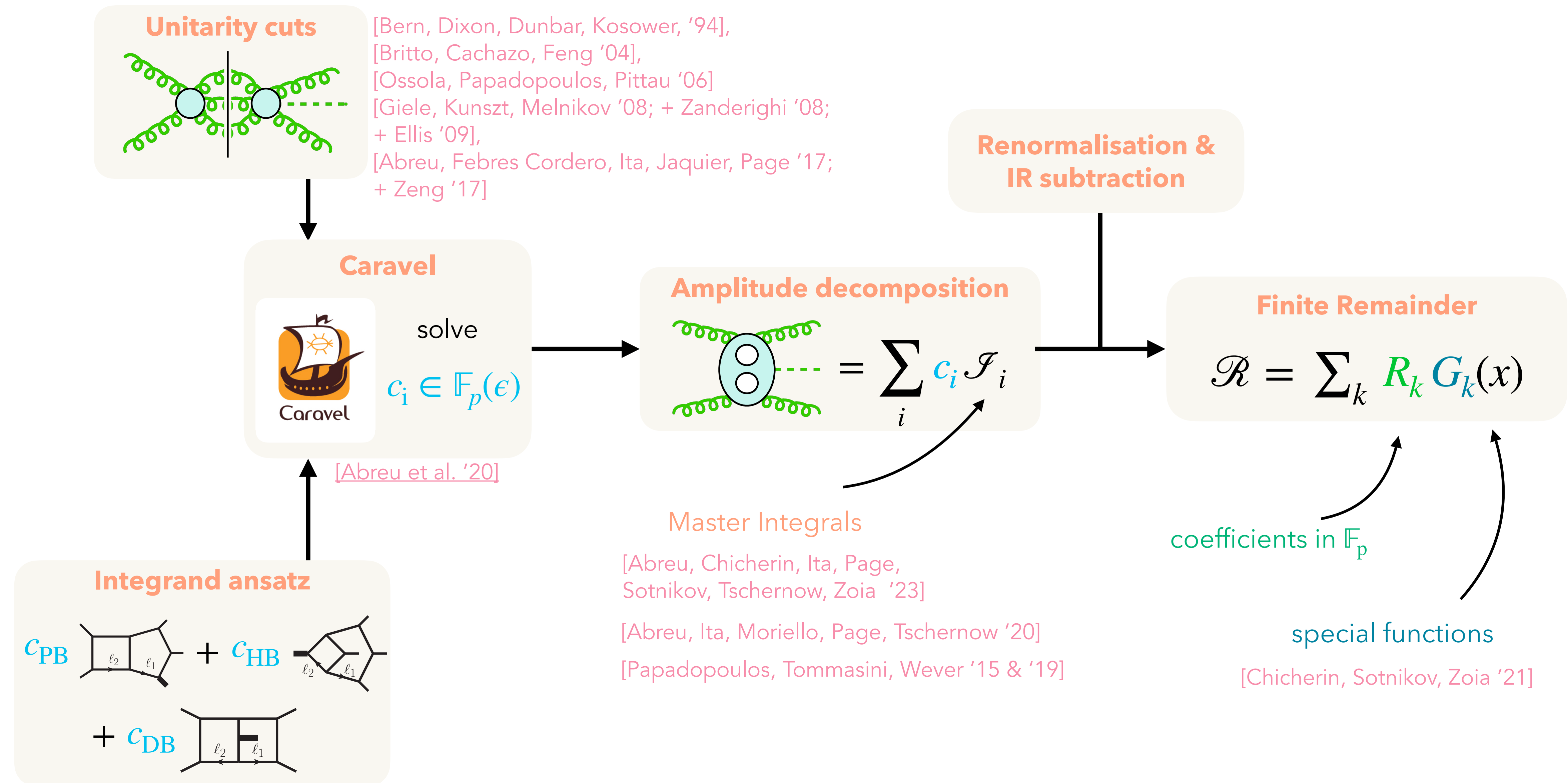
[Abreu, Ita, Moriello, Page, Tschernow '20]

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Integrand ansatz

$$c_{\text{PB}} \text{ (pentagon diagram)} + c_{\text{HB}} \text{ (hexagon diagram)} + c_{\text{DB}} \text{ (box diagram)}$$

Numerical amplitude reduction



Coefficient reconstruction

Numeric Coefficient

$$R_k \in \mathbb{F}_p$$



Rational Function

$$R_k(x) = \frac{N(x)}{D(x)}$$

$$\begin{array}{c} \swarrow \\ \searrow \end{array} \in \mathbb{Q}[x]$$

- spinor-helicity variables $\rightarrow$ homogeneous little group transformation and mass-dimensions

$$x \in \{ \langle ij \rangle, [ij], s_{i5}, \langle i | 5 | i \rangle, \langle i | j + k | i \rangle, \dots \}$$

- multivariate rational reconstruction: $R_k(x)$ recoverable from enough samples
[Peraro '16], [Klappert, Lange '19], [Magerya '22], [Belitsky, Smirnov, Yakovlev '23], [Liu '26]

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- **Simplification:** $R_k(x)$ have denominator structure
[Abreu, Dormans, Febres Cordero, Ita, Page '18]

$$D(x) = \omega_1^a \cdot \dots \cdot \omega_n^z$$

letters from symbol alphabet
of integrals



Coefficient reconstruction

Numeric Coefficient

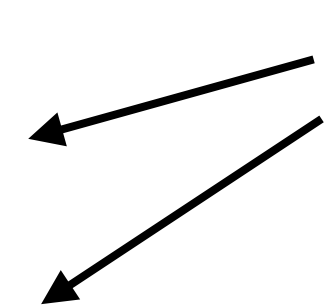
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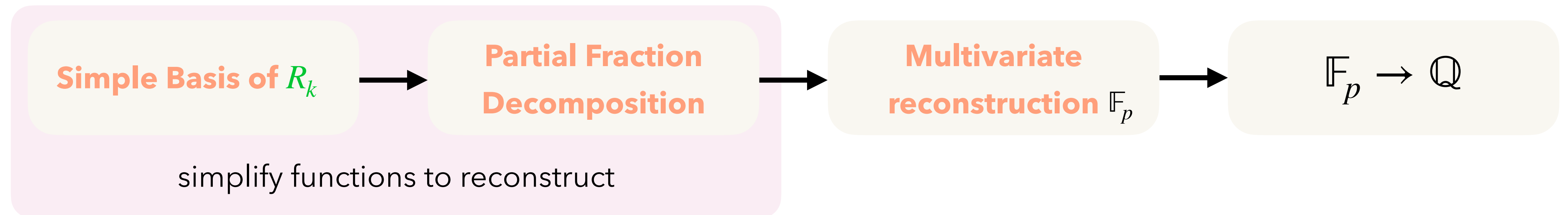
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- **Bottleneck:** numerators $N(x)$
 - numerator power up to 168 $\rightarrow 8 \times 10^7$ free parameters
 - evaluation time per kinematic point $O(2h)$

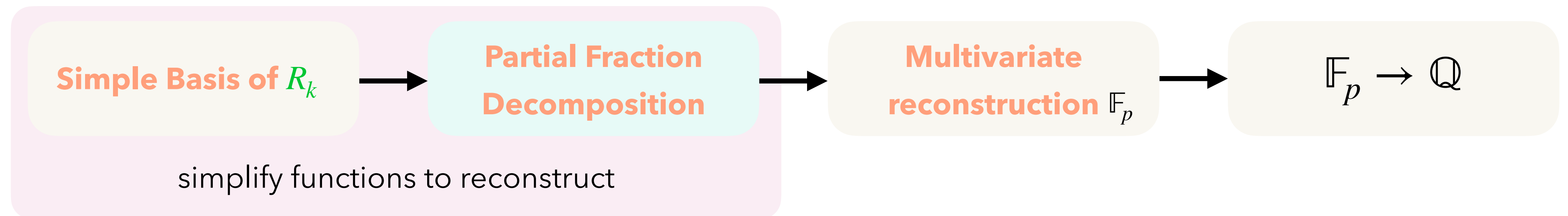
Improved reconstruction strategy

- steps in reconstruction:



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- PFD from excluded pairings of denominator factors

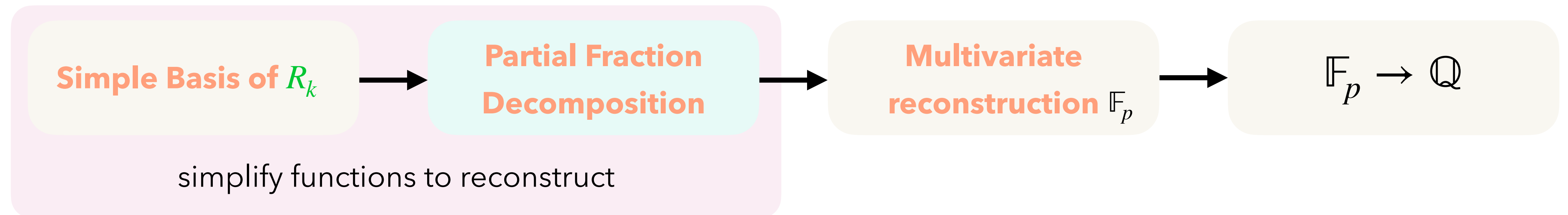
$$R = \frac{N}{\omega_1 \omega_2 \omega_3^2}$$

example: no $\omega_1 \omega_2$ and no $\omega_1 \omega_3^2$ denominators

$$\rightarrow \frac{N}{\omega_1 \omega_2 \omega_3^2} = \frac{N_1}{\omega_1} + \frac{N_2}{\omega_2 \omega_3^2}$$

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[De Laurentis, Page '22], [Abreu et al. '23],
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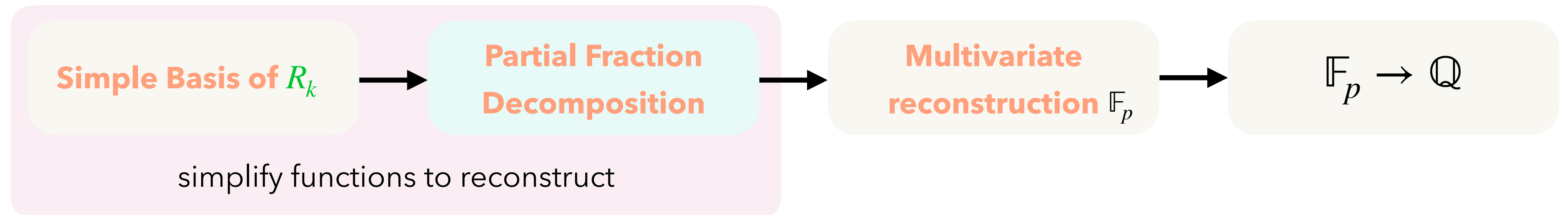
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- PFD from excluded pairings of denominator factors
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[De Laurentis, Page '22], [Abreu et al. '23],
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- **new strategy**: probe exclusion of pairs on two-dimensional subspaces
- **improvement**: $8 \times 10^7 \rightarrow 1 \times 10^4$ free parameters for worst function

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Results for H + 2 jet amplitudes

- Physically relevant theory input: **hard function**

$$\mathcal{H}^{(2)} = \text{Diagram 1} + \text{Diagram 2}$$

The equation shows the hard function $\mathcal{H}^{(2)}$ as a sum of two terms. Each term consists of a light blue oval with a black outline, connected to four external black lines (two on the left, two on the right). A vertical red line separates the two diagrams in each term. In the first term, the left oval contains two small white circles, and the right oval is empty. In the second term, the left oval contains one small white circle, and the right oval contains one small white circle. Dashed lines connect the right side of the left oval to the left side of the right oval in both terms.

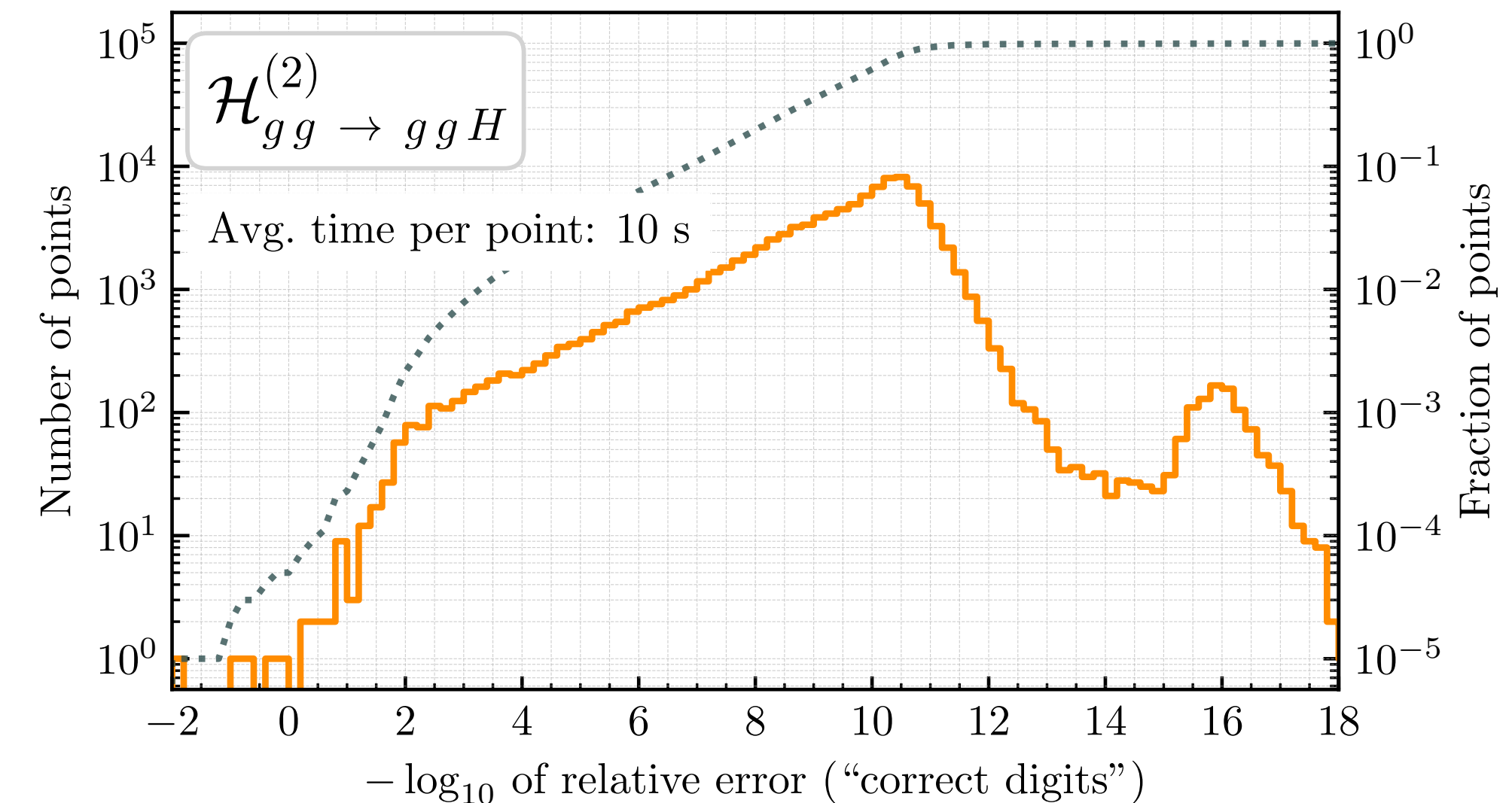
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- **Compact expressions:** [FivePointAmplitudes-cpp.git](https://github.com/FivePointAmplitudes/cpp.git)
 - ▶ **24MB** disk space in total
 - ▶ evaluation times: ~ **10s** gluons, **3s** quarks

numerical precision @ 10^5 PS points



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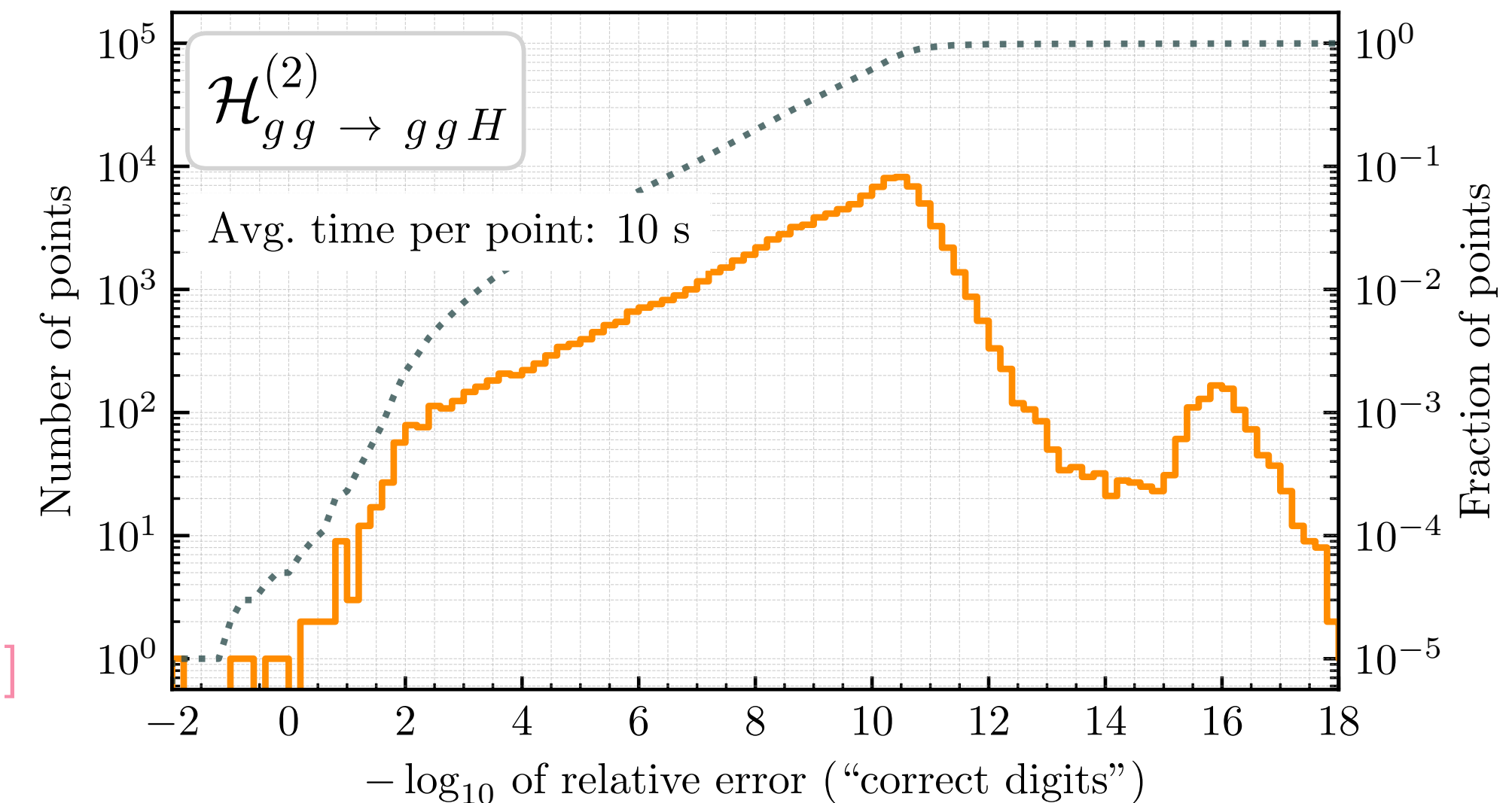
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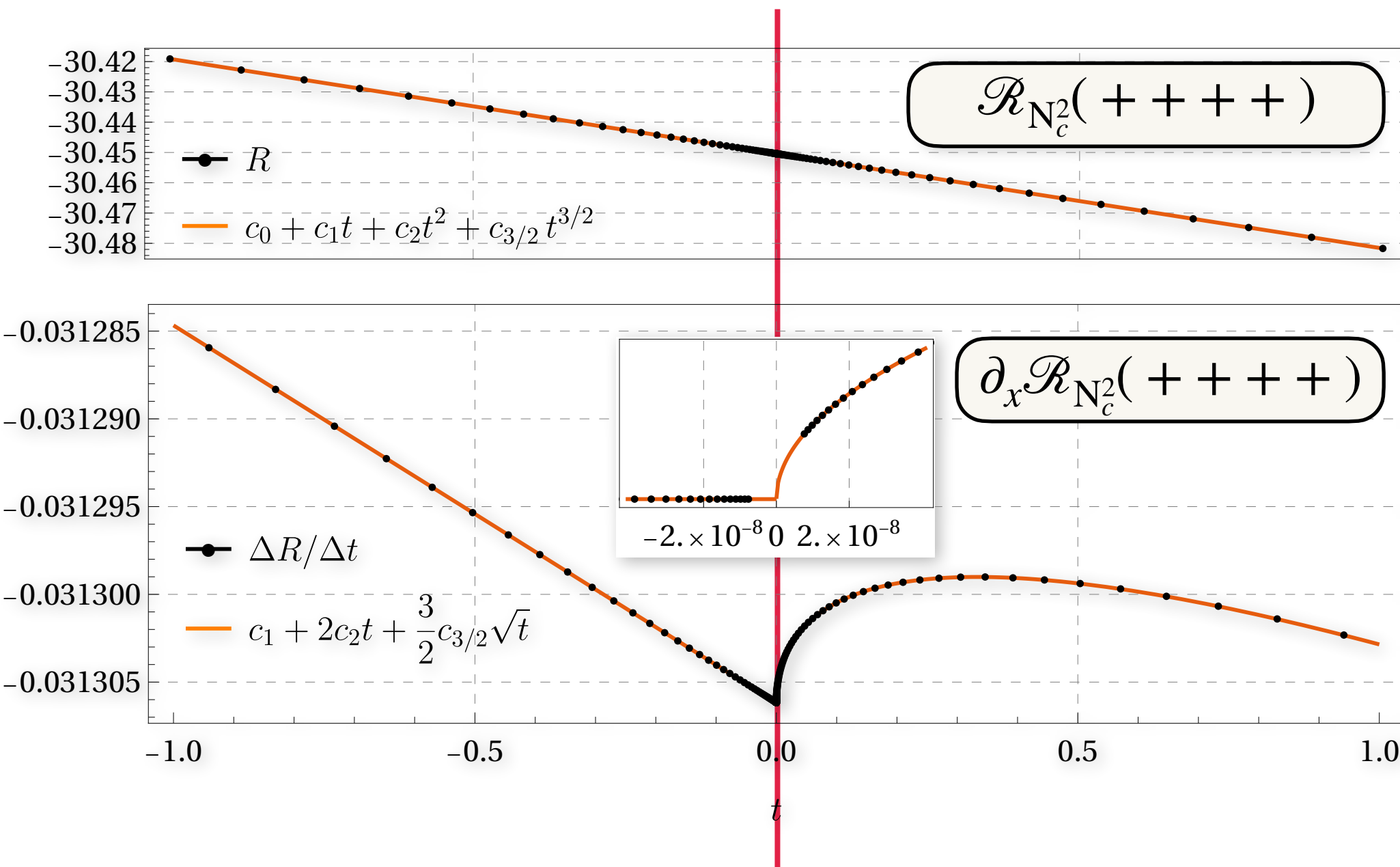
- **Validation:**

- ▶ Scale variation & UV and IR pole structure
- ▶ Correct scaling behavior in collinear limits
- ▶ Quark channels agree with [\[Hartanto, Poncelet '26\]](#)

numerical precision @ 10^5 PS points



Analytic structure: anomalous threshold?

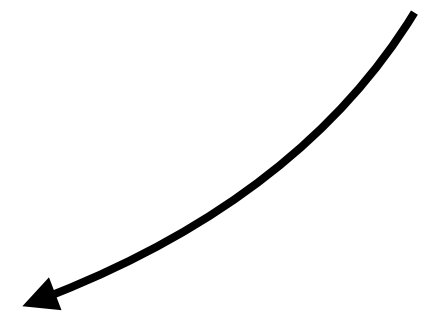


$$\Sigma_5^{(3)} = 0$$

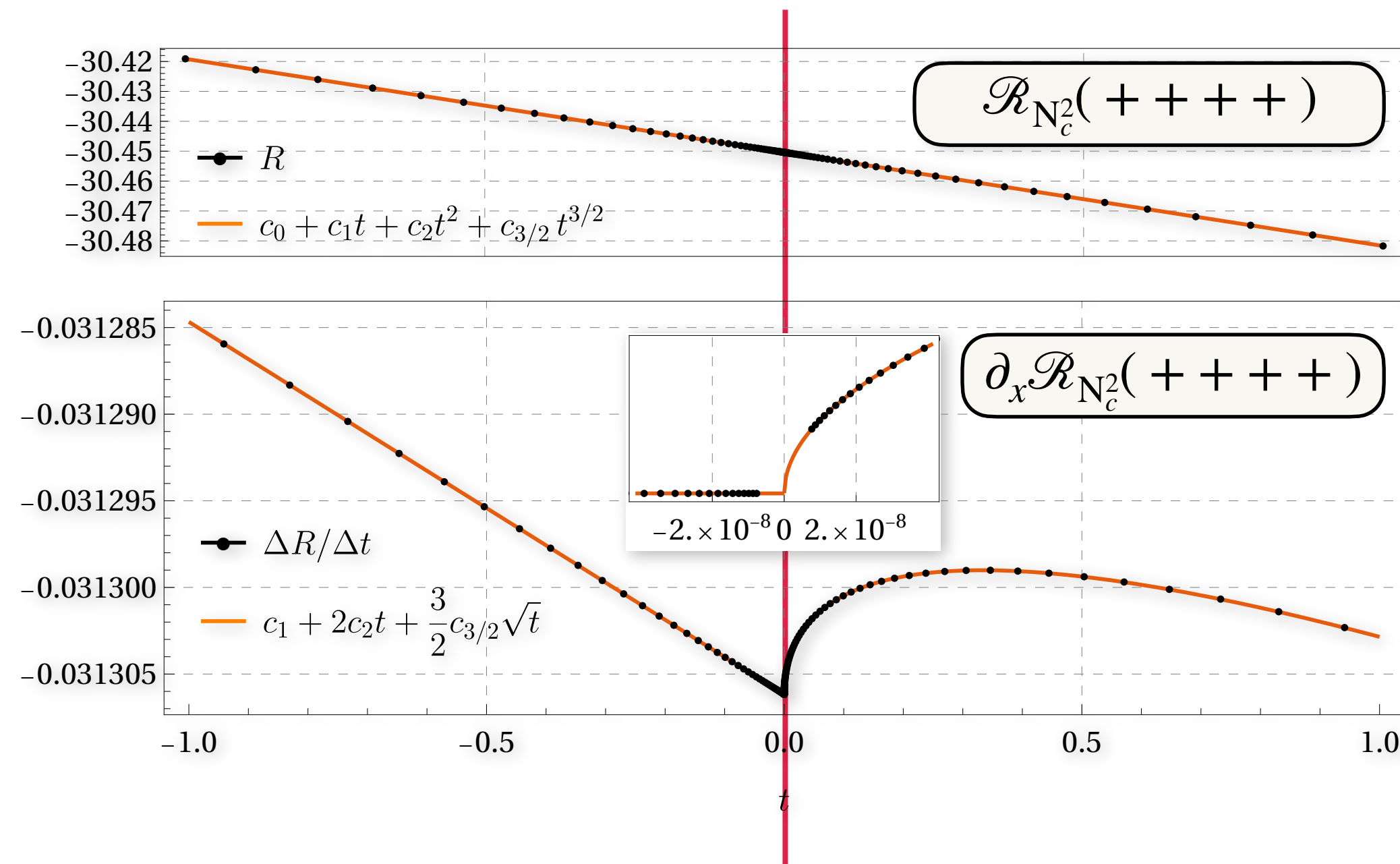
○ letter from non-planar 2L integrals

$$\Sigma_5^{(3)} = \left(s_{12}s_{24} + s_{13}(s_{14} + s_{24}) + s_{123}(s_{12} + s_{14}) \right)^2 - 4s_{13}s_{14}s_{123}s_{124}$$

not a gram determinant!



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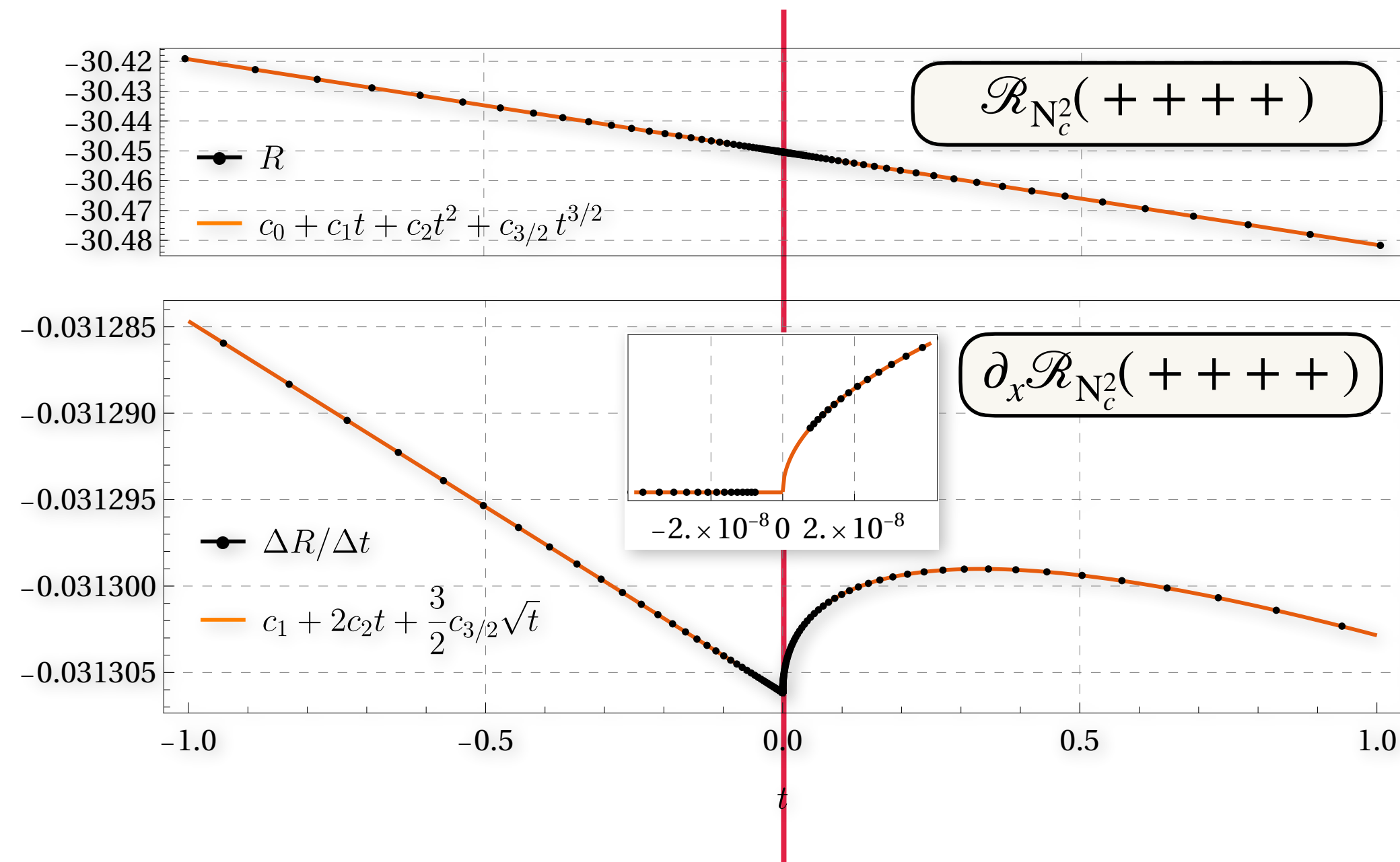
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- non-degenerate momenta in scattering region

- non-analyticity of amplitude:

- continuous** but **not regular** across $\Sigma_5^{(i)} = 0$

Outlook

- H+2j amplitudes are ready for phenomenology:

- ▶ ggF Hjj and $H \rightarrow 4j$ @ NNLO_{HTL} : all LC ingredients available
- ▶ ggF Hj @ $\text{N}^3\text{LO}_{\text{HTL}}$ with 3 loop Hj results from [Chen, Guan, Mistlberger '25]
- ▶ towards ggF H @ $\text{N}^4\text{LO}_{\text{HTL}}$ with 3loop Hj

talk earlier by Xi Guan at 14:00

previous talk by Adi Suresh at 14:20

- Future directions:

- ▶ Subleading color
→ tools and integrals available
- ▶ Study top-mass dependence H+2j
→ subleading orders in HTL or numerical analyses
- ▶ Similar processes achievable!

How much color do we really need?

Two-loop subleading-color effects in photon and jet physics

Michał Czakon,^a Rene Poncelet^b