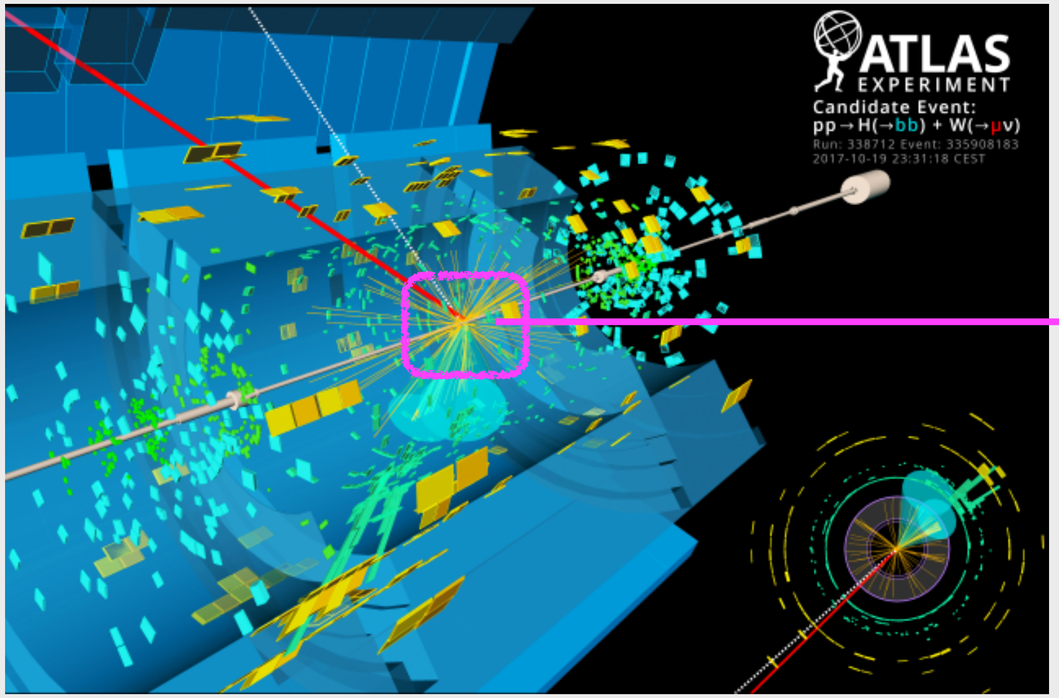
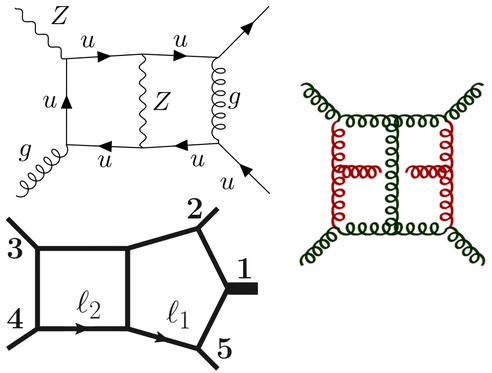


The "simple", high-energy core process

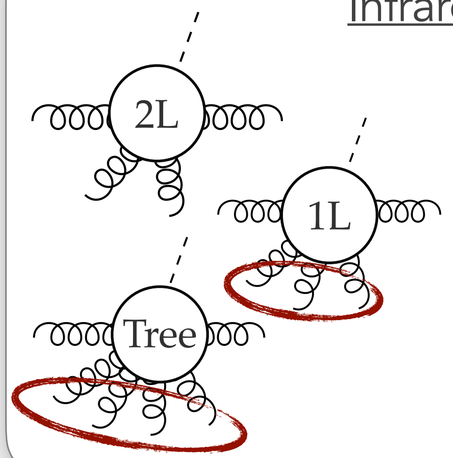
or fixed, higher-order corrections

Multi-loop scattering amplitudes



- Semi-numerical approaches → Xiao
- Analytic calculations, structures → Federica, Giulio

Infrared radiation patterns → Federica



- A "good" NNLO subtraction scheme?
- How to generalise to higher orders?
- Theoretical obstructions (factorisation breaking…)
- IR radiation at NLP, non-perturbative insight

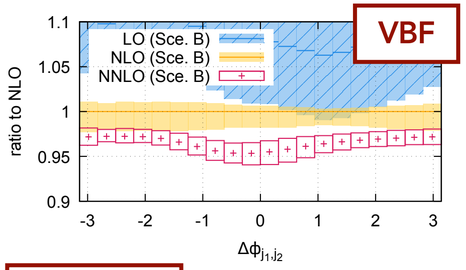
Fabrizio Caola

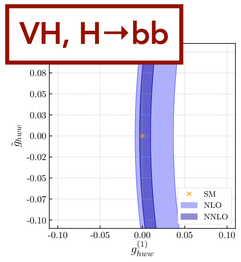
Rudolf Peierls Centre for Theoretical Physics & Wadham College, University of Oxford

A snapshot of some recent results

+ slides from Xiao, Giulio & Federica

NNLO Higgs pheno, SM(EFT)

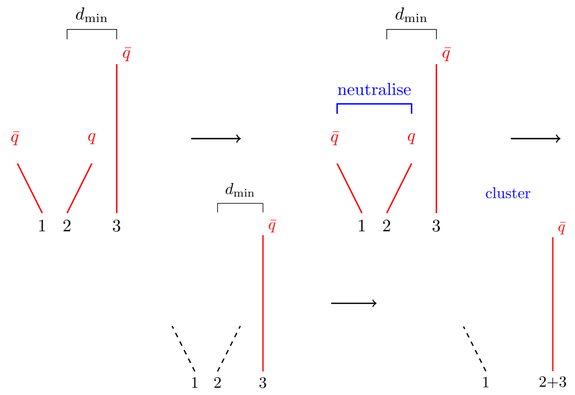




NNLO vs anomalous couplings in realistic setup

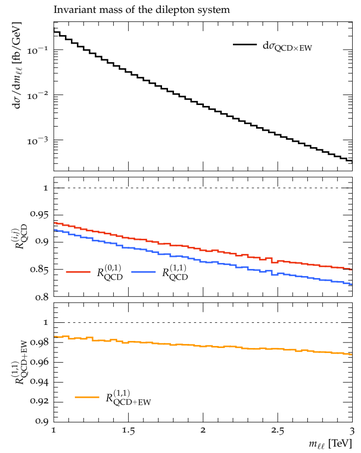
w. Kirill Melnikov, R. Röntsch, K. Asteriadis, W. Bizon…

Jet flavour



w. Gavin, Radek Grabarczyk, Max Hutt, Ludo Scyboz & Jesse Thaler

Mixed NNLO QCD-EW



Di-lepton invariant mass spectrum, NLO QCD, EW vs NNLO QCDxEW

w. Federica, Kirill, F. Buccioni, H. Chawdhry, M. Heller, A. von Manteuffel, Raoul, C. Signorile-Signorile

+ work in progress with Xiao, Herschel, P. Bargiela

Towards a rigorous understanding of NP corrections

$$\mathrm{d}\sigma = \int \mathrm{d}x_1 \mathrm{d}x_2 f(x_1) f(x_2) \mathrm{d}\hat{\sigma}(x_1, x_2) F_J (1 + \mathcal{O}(\Lambda^n_{\mathrm{QCD}}/Q^n))$$

w. Kirill, P. Nason, Giovanni Limatola, Silvia Ferrario, Ravasio, Melih Ozcelik,

Fabrizio Caola

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Xiao Liu

Postdoctoral research assistant

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Perturbative QFT, scattering amplitudes, Feynman integrals

New techniques

Auxiliary mass flow [2017~2022]

$$\frac{\partial}{\partial\eta}\vec{I}(\epsilon,\eta) = A(\epsilon,\eta)\cdot\vec{I}(\epsilon,\eta)$$

$$\vec{I} \overset{\eta\to\infty}{\sim} \text{vacuum integrals}$$

Block triangular relations [2018~]

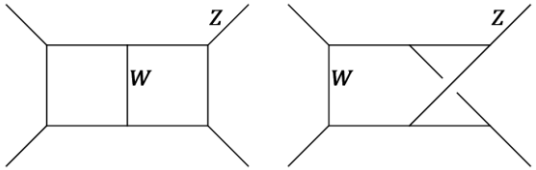
$$B(\vec{s})\cdot\vec{J}(\vec{s}) = 0 \overset{\text{samples}}{\Longrightarrow} \tilde{B}(\vec{s})\cdot\vec{J}(\vec{s}) = 0$$

Rational functions reconstruction [2023~]

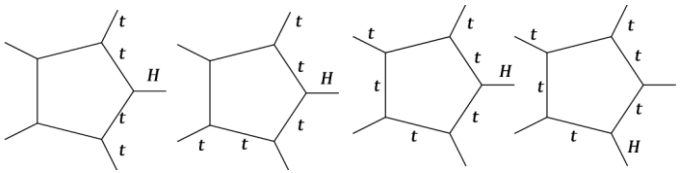
$$C(\vec{x})\cdot\vec{R}(\vec{x}) = 0$$

Applications

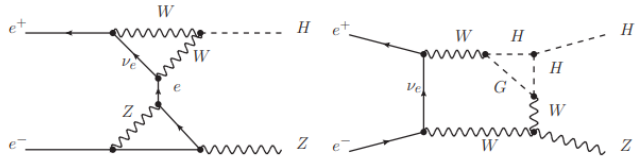
$pp \to Zj$@2Loop mixed QCD-Electroweak



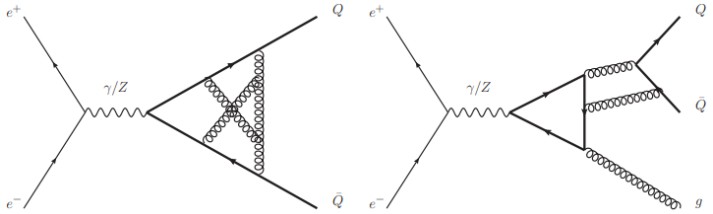
$pp \to t\bar{t}H$@1Loop QCD $O(\epsilon^2)$



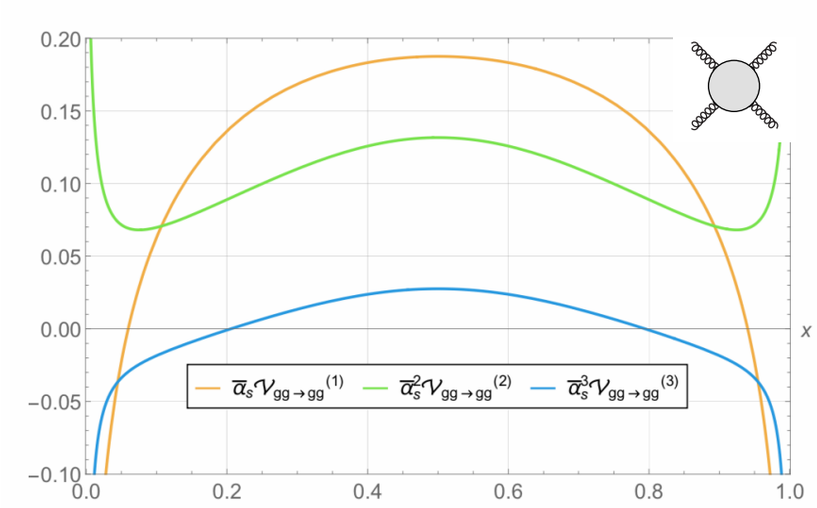
$e^+e^- \to HZ$@2Loop Electroweak

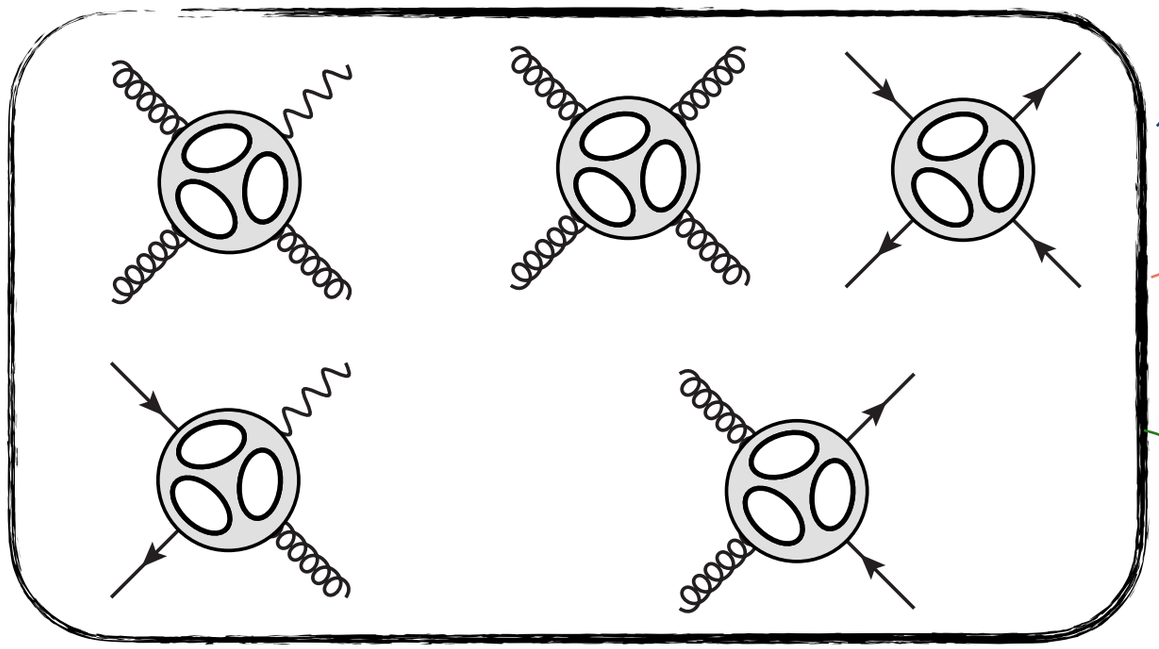


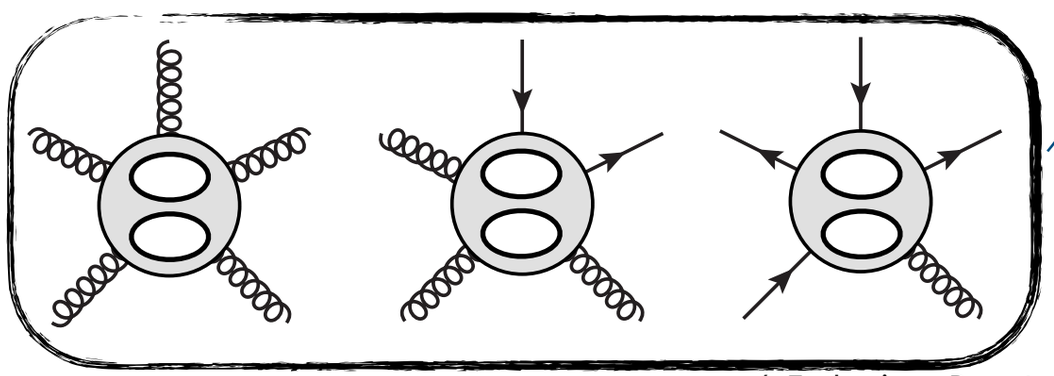
$e^+e^- \to t\bar{t}$@NNNLO QCD



QCD Amplitudes







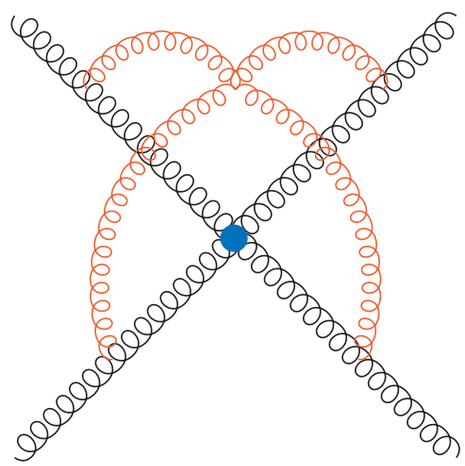
w/ Federica Devoto

Input for pheno

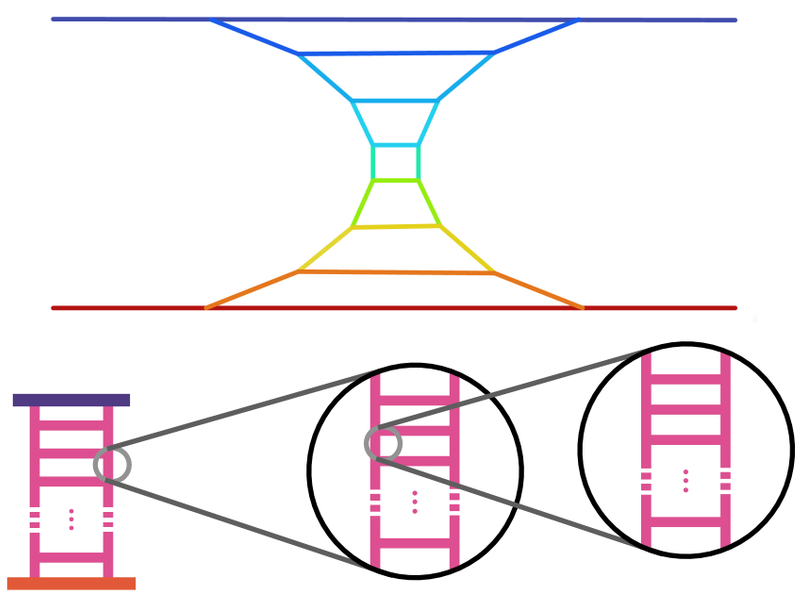
NNLO pp → j j

N³LO pp → j j j

Infrared QFT



High-Energy Limit

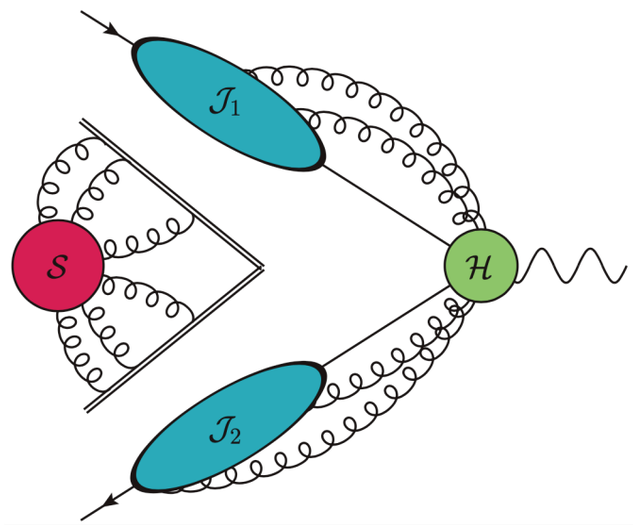


Planar $\mathcal{N}=4$ SYM → QCD

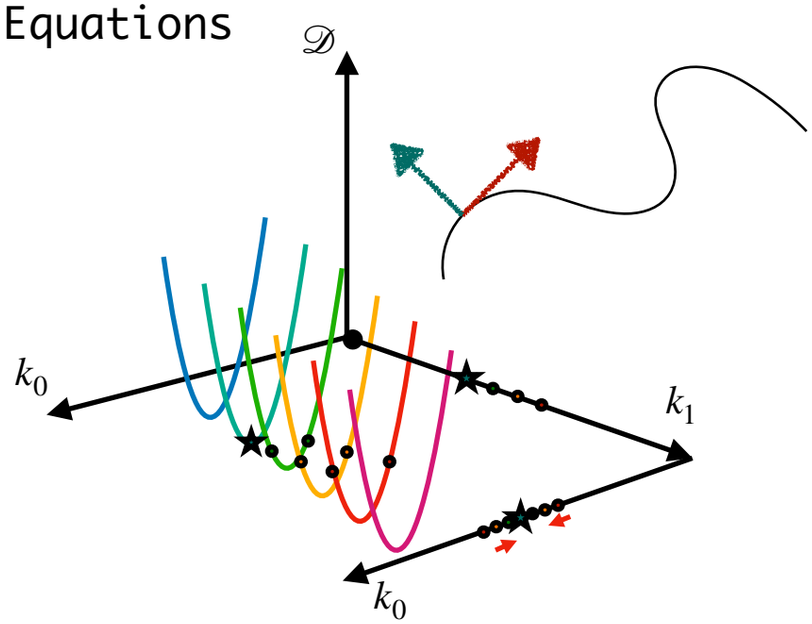
Feynman Integrals

$$I[\mathcal{N}(\ell_i)] = \int \prod_{i=1}^{\mathrm{L}} \mathrm{d}^D \ell_i \, \frac{\mathcal{N}(\ell_i)}{\mathcal{D}_1 \cdots \mathcal{D}_{\mathrm{E}}}$$

Infrared Factorisation & Renormalisability



Landau Equations



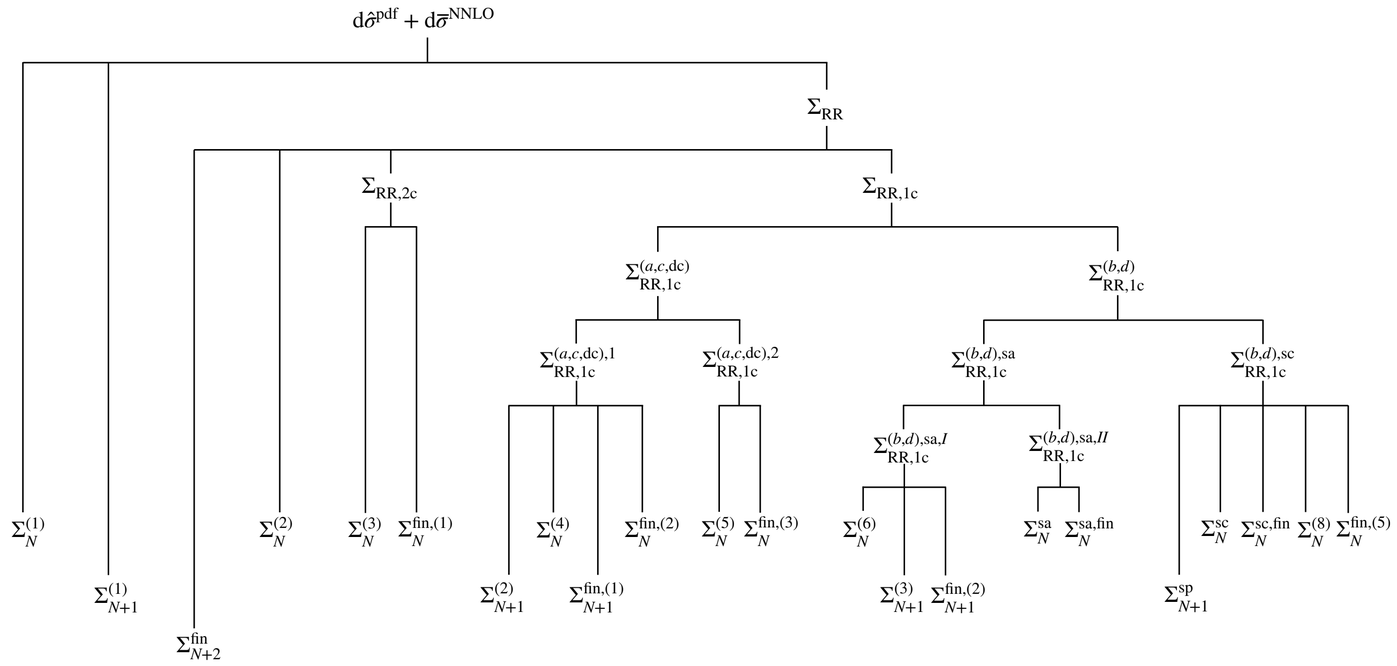
developing new ways of computing real-world Amplitudes

IR DIVERGENCES: NESTED SOFT-COLLINEAR SUBTRACTION

Goal: analytic understanding of cancellation pattern of IR divergences in high multiplicity processes at NNLO QCD

Key idea: try to iterate NLO-like structures as much as possible

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



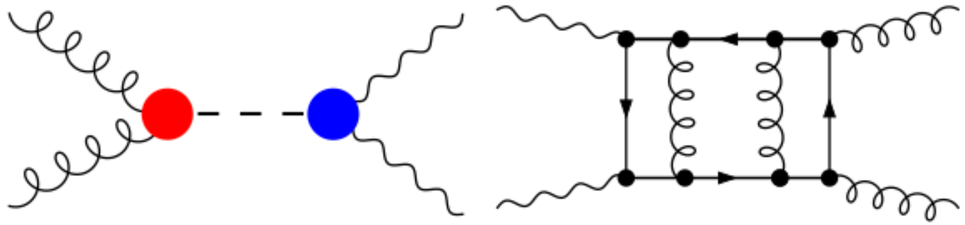
Compact, analytic final formula for integrated subtracion terms

$$\begin{aligned} 2s\, d\hat{\sigma}^{\rm NNLO}_{\rm el} = {} & \left[\frac{\alpha_s(\mu)}{2\pi}\right]^2 \Bigg\{ \left\langle \left[I^{\rm fin}_{\rm cc} + I^{\rm fin}_{\rm tri} + I^{\rm fin}_{\rm unc}\right] \cdot F_{\rm LM} \right\rangle \\ & + \sum_{i=1}^{N_p} \left\langle \left[\gamma^{\mathcal{W}}(L_i)\,\theta_{i2}\,\mathcal{W}_i^{i\|\mathfrak{n},\rm fin} + \delta_g^{(0)}\,\mathcal{W}_i^{\mathfrak{m}\|\mathfrak{n},\rm fin} + \delta_g^{\perp}\mathcal{W}_r^{(i)}\right] \cdot F_{\rm LM} \right\rangle \Bigg\} \\ & + \left[\frac{\alpha_s(\mu)}{2\pi}\right] \left\langle I_{\rm T}^{(0)} \cdot F^{\rm fin}_{\rm LV} \right\rangle + \left\langle S_{\mathfrak{mn}} \Theta_{\mathfrak{mn}} F_{\rm LM}(\mathfrak{m},\mathfrak{n}) \right\rangle^{\rm fin}_{T^2} + \left\langle F^{\rm fin}_{\rm LV^2} \right\rangle + \left\langle F^{\rm fin}_{\rm VV} \right\rangle \end{aligned}$$

AMPLITUDES & SUBTRACTION: THE PHENO PERSPECTIVE

Can we **observe** effects coming from more loops & more legs? **Sometimes, YES!**

$H \to \gamma\gamma$ interference: bounding the Higgs width



Destructive interference @ NNLOsv ~ -1.7 % of signal NNLO cross section