Karlsruher Institut für Technologie

CARLSBERG FOUNDATION

Non-factorisable contributions to Higgs production in Weak Boson Fusion

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based on work with
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presented in 2305.08016 and 23xx.xxxxx

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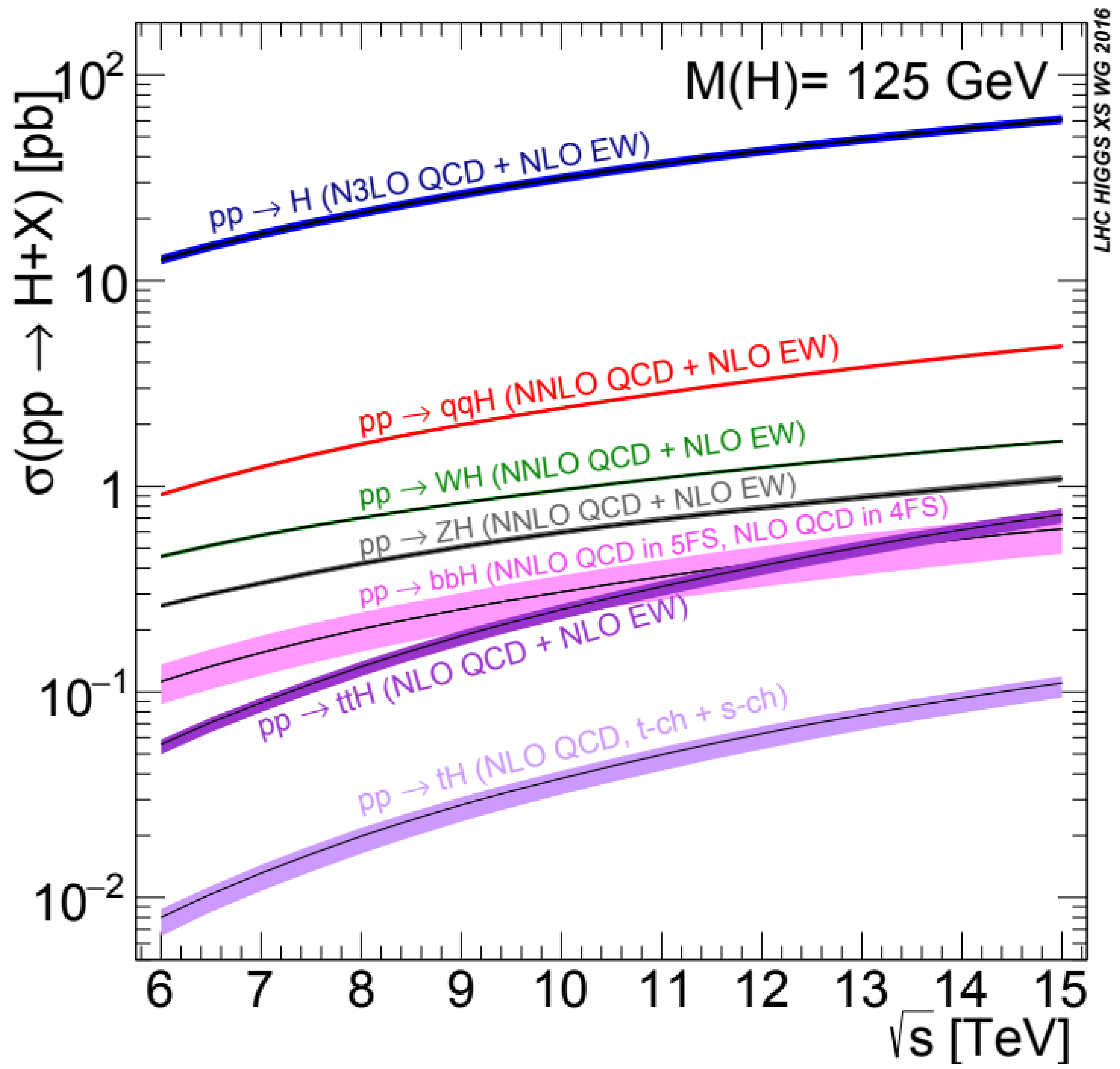
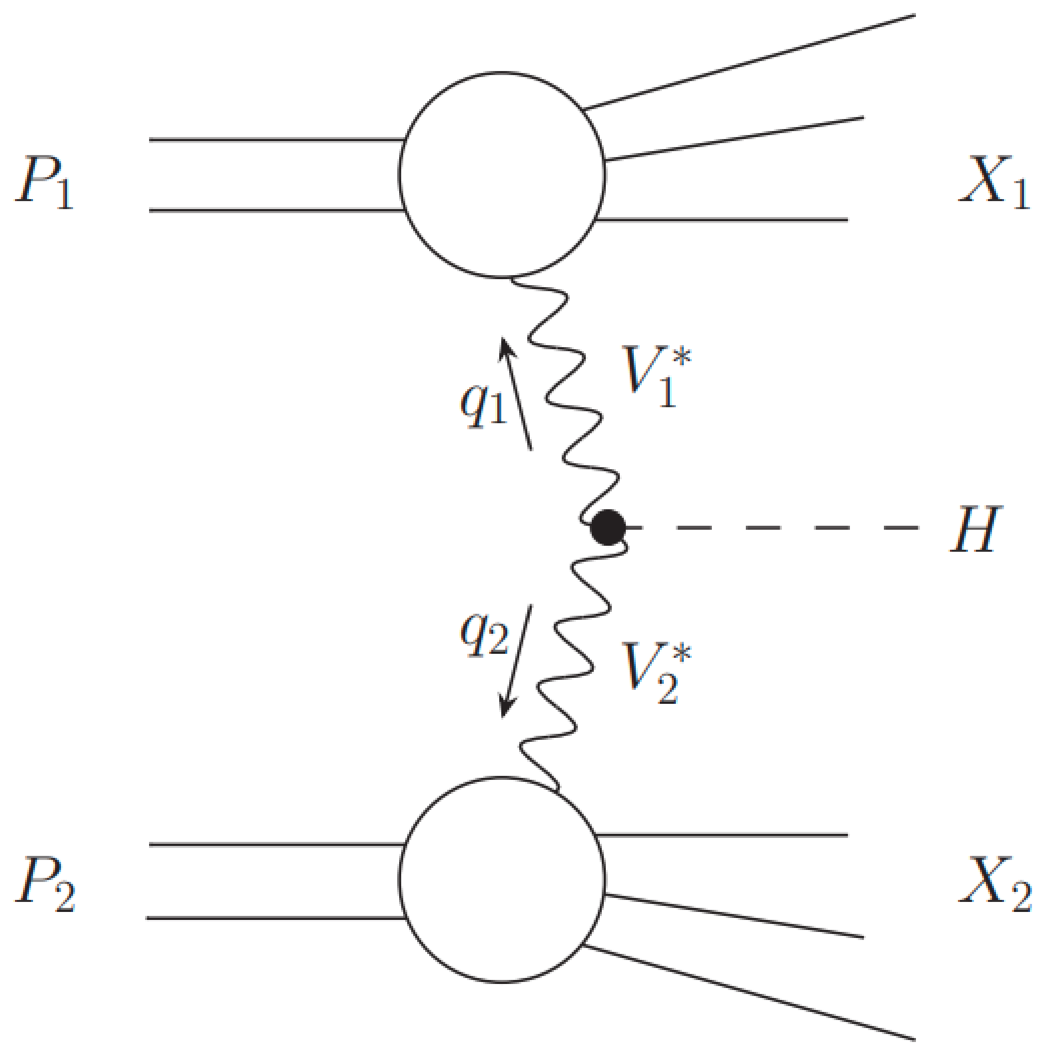
Motivation

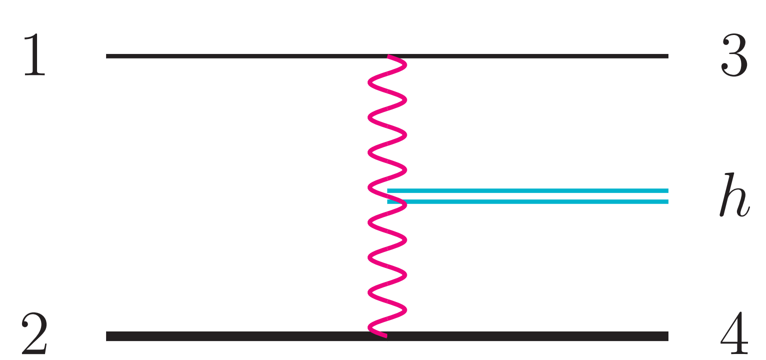
- colourless exchange in the t-channel involving weak gauge bosons
- clear kinematic signature
- study of electroweak parameters and vertex structures
- large (but subdominant) cross section

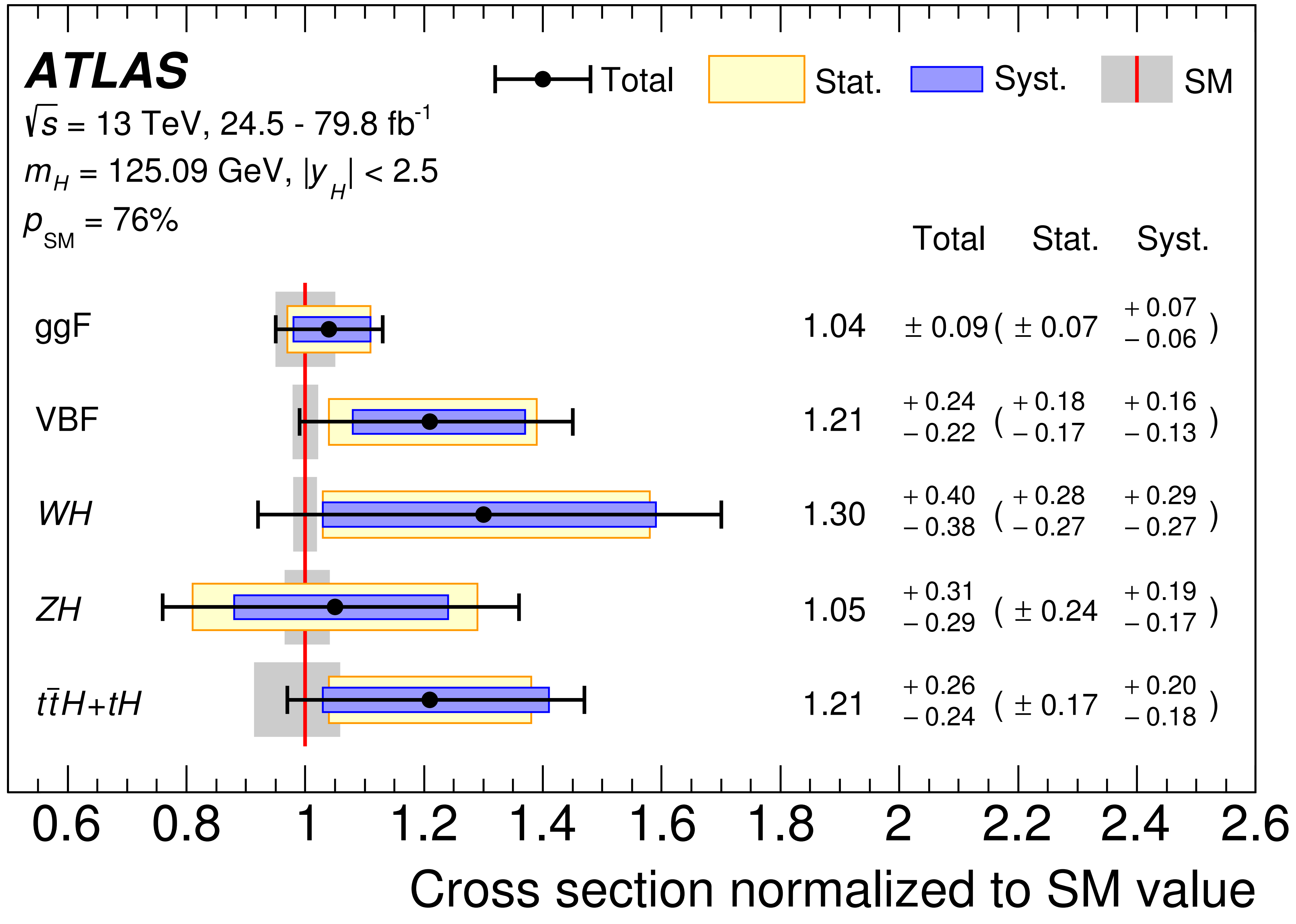




[Bolzoni, Maltoni, Moch, Zaro 2015]

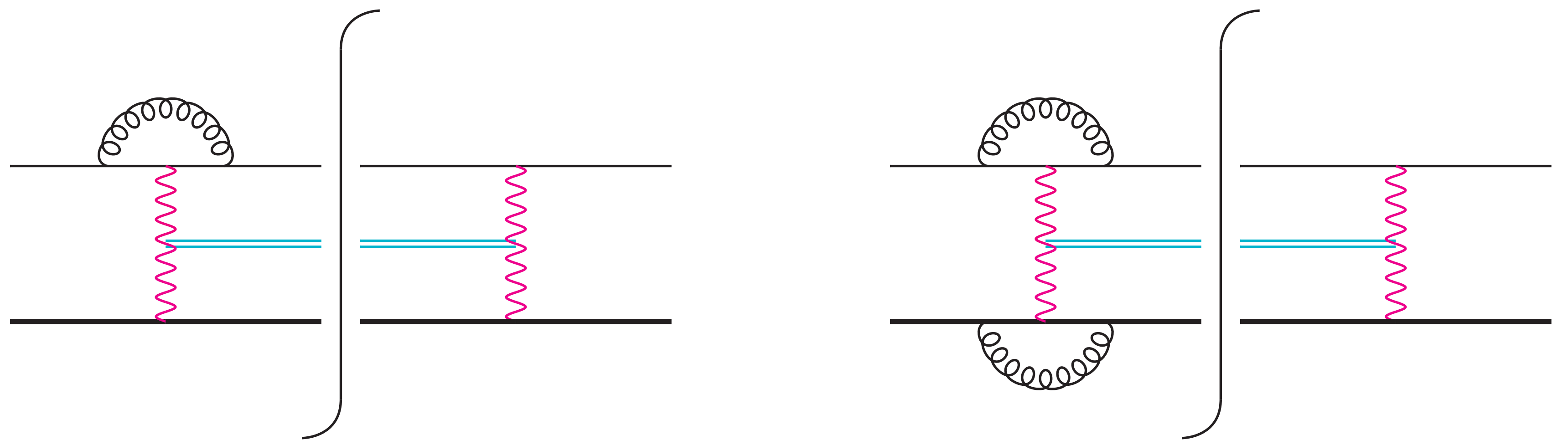
$$q\,Q \to q'\,Q' + H$$





Motivation – theoretical developments

- advanced theoretical predictions in **factorisable** approximation



$$q\,Q \to q'\,Q' + H$$

	$\sigma^{(\text{no cuts})}$ [pb]	$\sigma^{(\text{VBF cuts})}$ [pb]
LO	$4.032\,^{+0.057}_{-0.069}$	$0.957\,^{+0.066}_{-0.059}$
NLO	$3.929\,^{+0.024}_{-0.023}$	$0.876\,^{+0.008}_{-0.018}$
NNLO	$3.888\,^{+0.016}_{-0.012}$	$0.844\,^{+0.008}_{-0.008}$

TABLE I: Cross sections at LO, NLO and NNLO for VBF Higgs production, fully inclusively and with VBF cuts. The quoted uncertainties correspond to scale dependence, while statistical errors at NNLO are about 0.1% with VBF cuts and much smaller without.

[Cacciari, Dreyer, Karlberg, Salam, Zanderighi 2015]

NLO QCD [Figy, Oleari, Zeppenfeld 2003] [Berger, Campbell 2004] [Figy, Zeppenfeld 2004] [Andersen, Binoth, Heinrich, Smillie 2007]

NLO EW [Ciccolini, Denner, Dittmaier 2007 & 2008] [Figy, Palmer, Weiglein 2012]

NNLO QCD [Bolzoni, Maltoni, Moch, Zaro 2010 & 2012] [Cacciari, Dreyer, Karlberg, Salam, Zanderighi 2015] [Cruz-Martinez, Gehrmann, Glover, Huss 2018] [Asteriadis, Caola, Melnikov, Röntsch 2022 & 2023]

NNNLO QCD [Dreyer, Karlberg 2016]

TABLE I. Inclusive cross sections at LO, NLO, NNLO, and N^{3}LO for VBF Higgs production. The quoted uncertainties correspond to scale variations $Q/2 < \mu_R, \mu_F < 2Q$, while statistical uncertainties are at the level of 0.2‰.

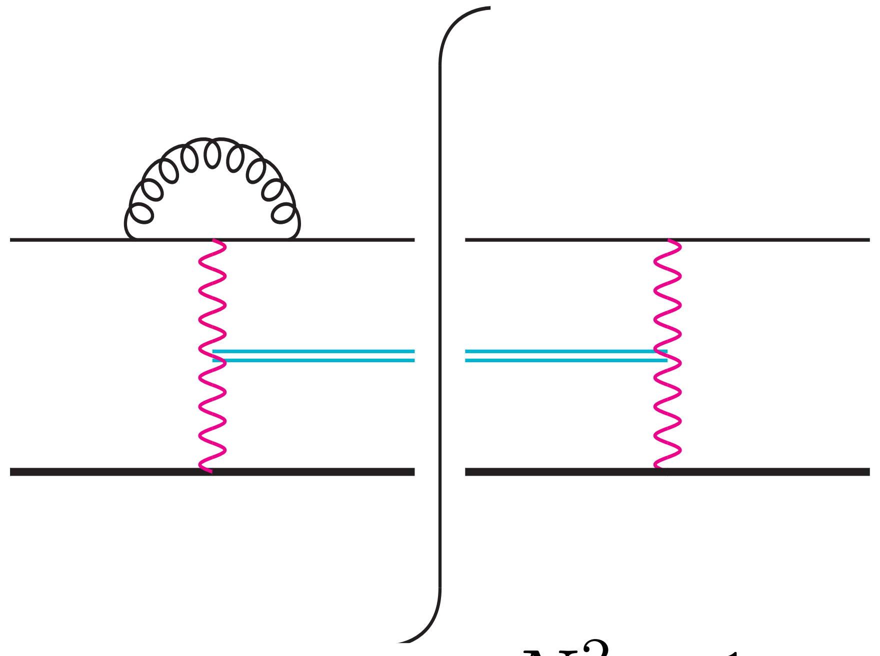
	$\sigma^{(13\,\text{TeV})}$ (pb)	$\sigma^{(14\,\text{TeV})}$ (pb)	$\sigma^{(100\,\text{TeV})}$ (pb)
LO	$4.099^{+0.051}_{-0.067}$	$4.647^{+0.037}_{-0.058}$	$77.17^{+6.45}_{-7.29}$
NLO	$3.970^{+0.025}_{-0.023}$	$4.497^{+0.032}_{-0.027}$	$73.90^{+1.73}_{-1.94}$
NNLO	$3.932^{+0.015}_{-0.010}$	$4.452^{+0.018}_{-0.012}$	$72.44^{+0.53}_{-0.40}$
N^{3}LO	$3.928^{+0.005}_{-0.001}$	$4.448^{+0.006}_{-0.001}$	$72.34^{+0.11}_{-0.02}$

[Dreyer, Karlberg 2016]

Motivation – Non-factorisable contribution (I)

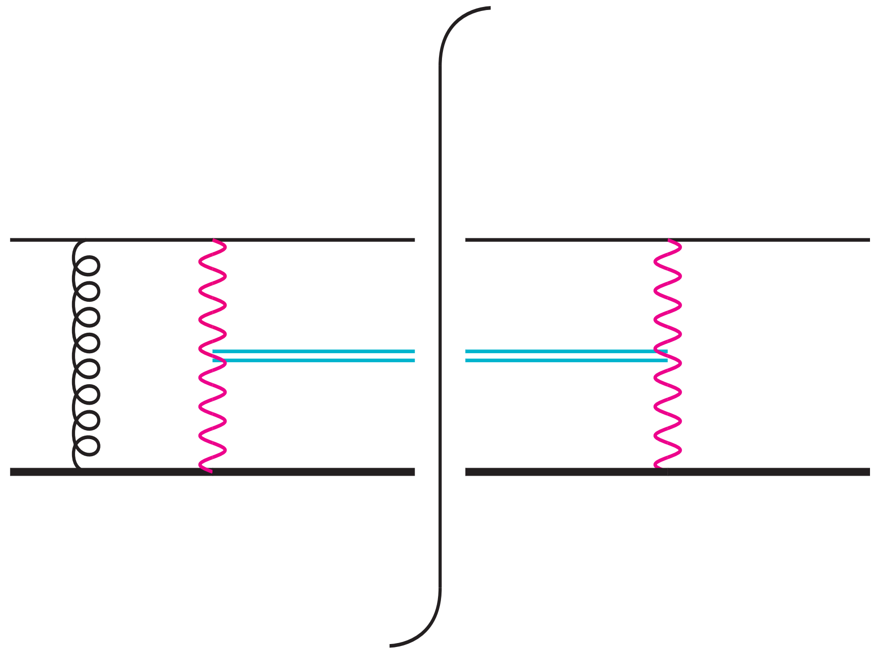
NLO

Factorisable contributions



$$\mathrm{tr}\,(t^a t^a) = \frac{N_c^2 - 1}{2}$$

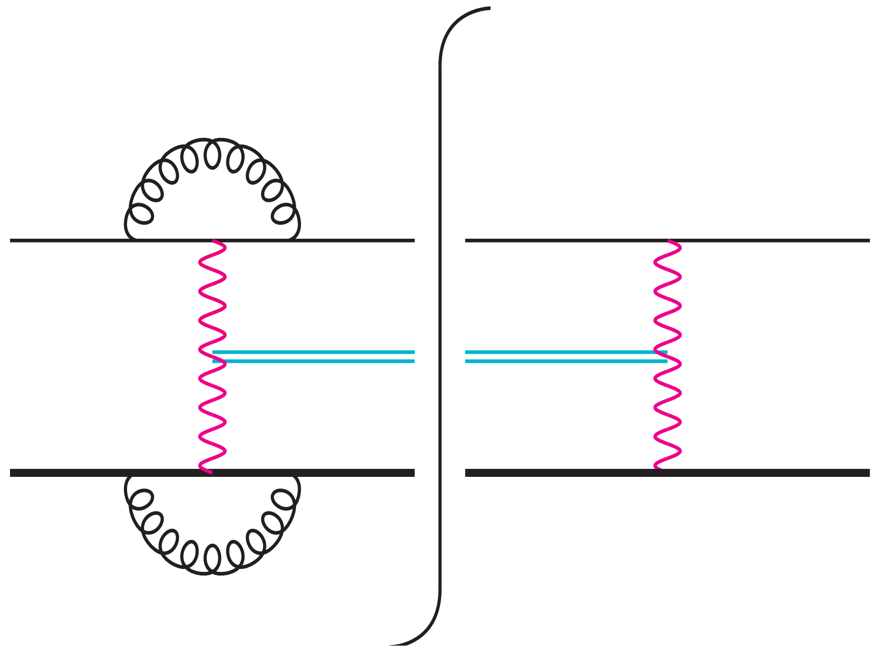
Non-factorisable contributions



$$\mathrm{tr}\,(t^a)\mathrm{tr}\,(t^a) = 0$$

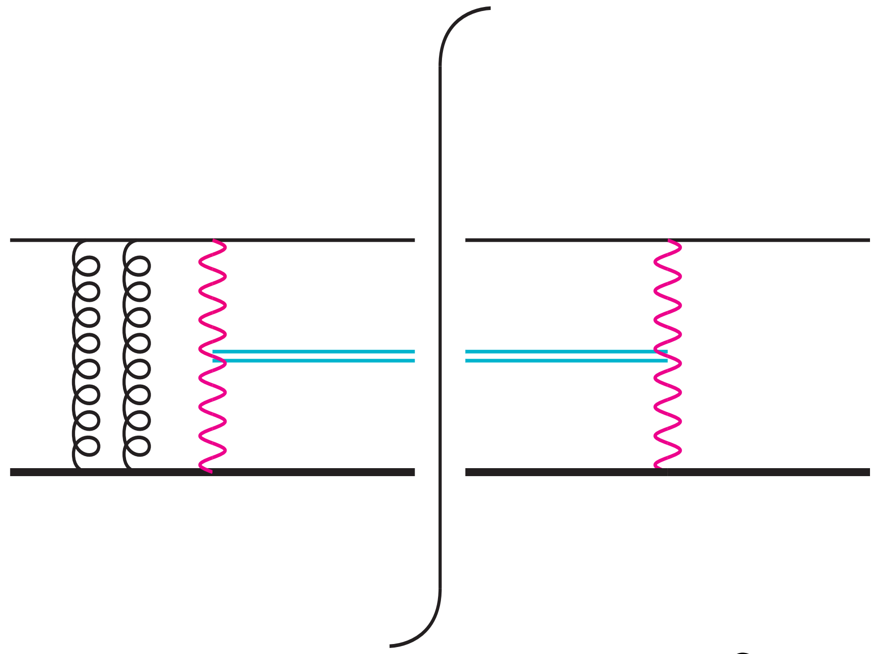
NNLO

Factorisable contributions:



$$\mathrm{tr}\,(t^a t^a)\,\mathrm{tr}\,\left(t^b t^b\right) = \frac{\left(N_c^2 - 1\right)^2}{4}$$

Non-factorisable contributions:



$$\mathrm{tr}\,\left(t^a t^b\right)\,\mathrm{tr}\,\left(t^a t^b\right) = \frac{N_c^2 - 1}{4}$$

- Non-factorisable contributions vanish at NLO due to their colour structure, and are suppressed by a factor $N_c^2 - 1 = 8$ at NNLO
- Factorisable predictions are already small, at or below % level
- The actual size of NNLO non-factorisable corrections **cannot be inferred from NLO contributions**

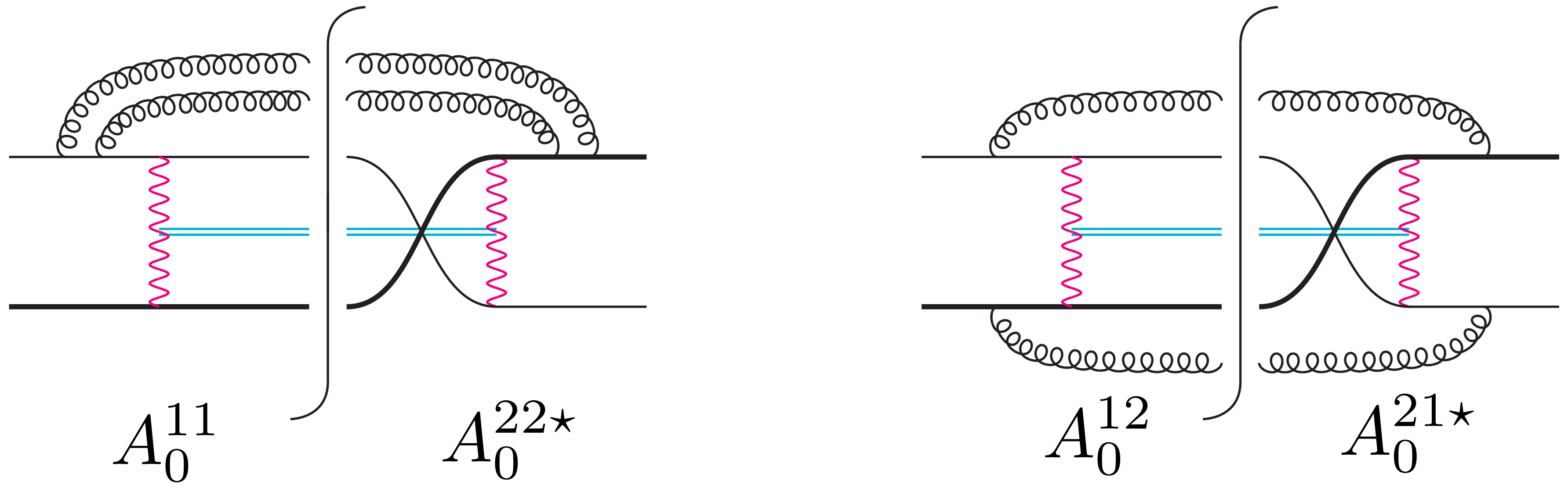
Non-factorisable contribution – ingredients of the calculation (I)

Three terms contribute to the non-factorisable cross section at NNLO

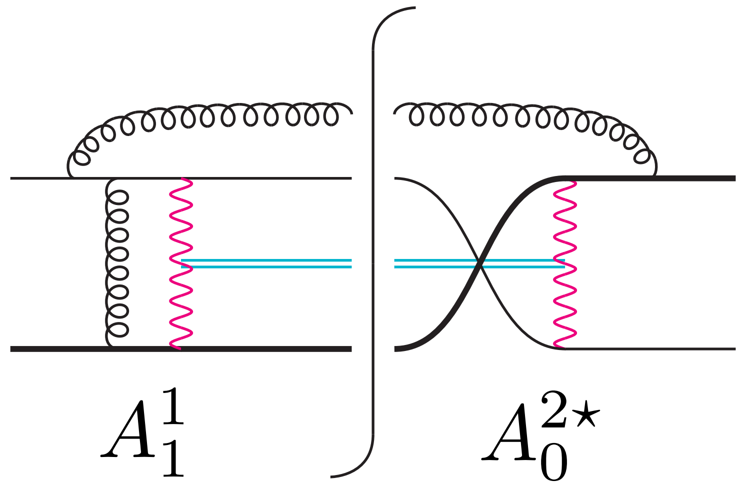
$$\mathrm{d}\sigma^{\mathrm{nf}}_{pp\to X+H} = \sum_{i,j} \int \mathrm{d}x_1 \mathrm{d}x_2\, f_i(x_1,\mu_F) f_j(x_2,\mu_F)\, \mathrm{d}\hat{\sigma}^{\mathrm{nf}}_{ij\to X+H}(x_1,x_2)$$

$$\mathrm{d}\hat{\sigma}^{\mathrm{nf}}_{\mathrm{nnlo}} = \mathrm{d}\hat{\sigma}^{\mathrm{nf}}_{\mathrm{RR}} + \mathrm{d}\hat{\sigma}^{\mathrm{nf}}_{\mathrm{RV}} + \mathrm{d}\hat{\sigma}^{\mathrm{nf}}_{\mathrm{VV}}$$

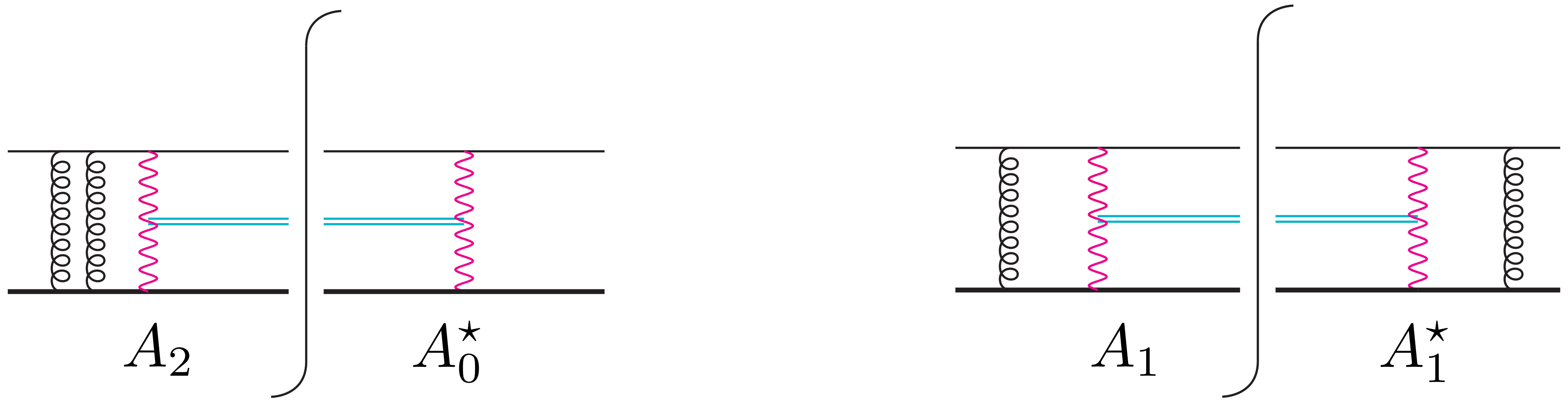
$\mathrm{d}\hat{\sigma}^{\mathrm{nf}}_{\mathrm{RR}}$



$\mathrm{d}\hat{\sigma}^{\mathrm{nf}}_{\mathrm{RV}}$



$\mathrm{d}\hat{\sigma}^{\mathrm{nf}}_{\mathrm{VV}}$

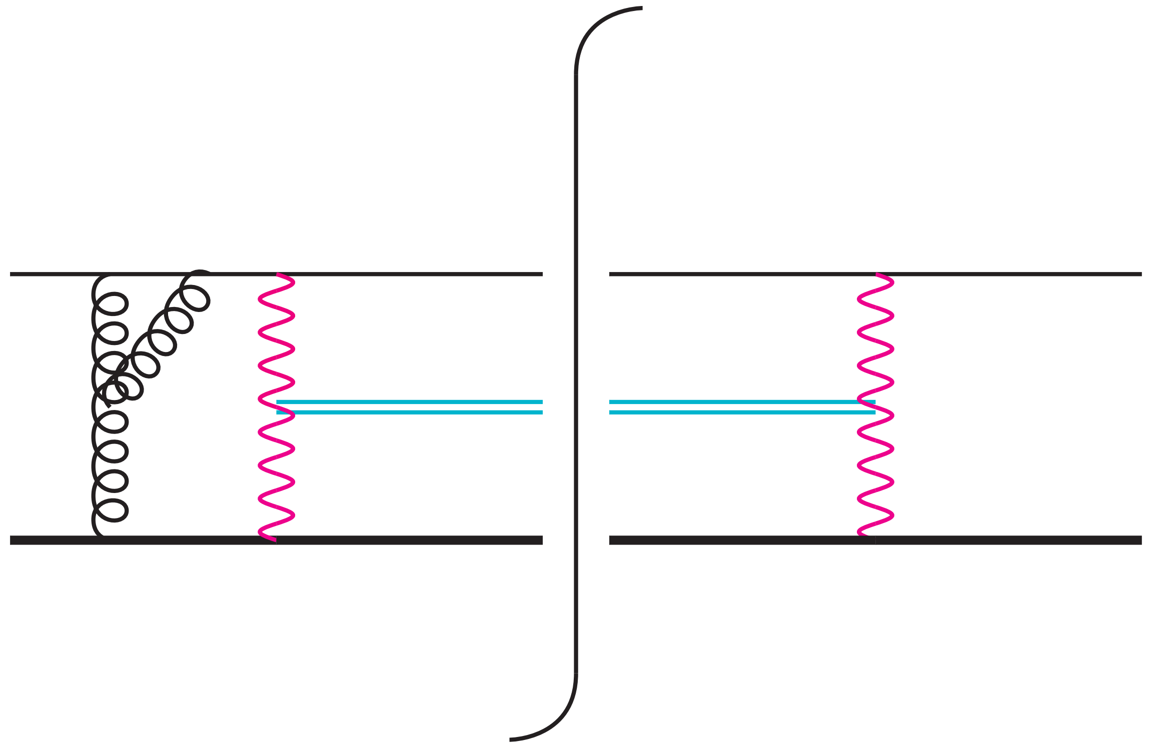


Each ingredient requires **individual treatment** with different challenges:

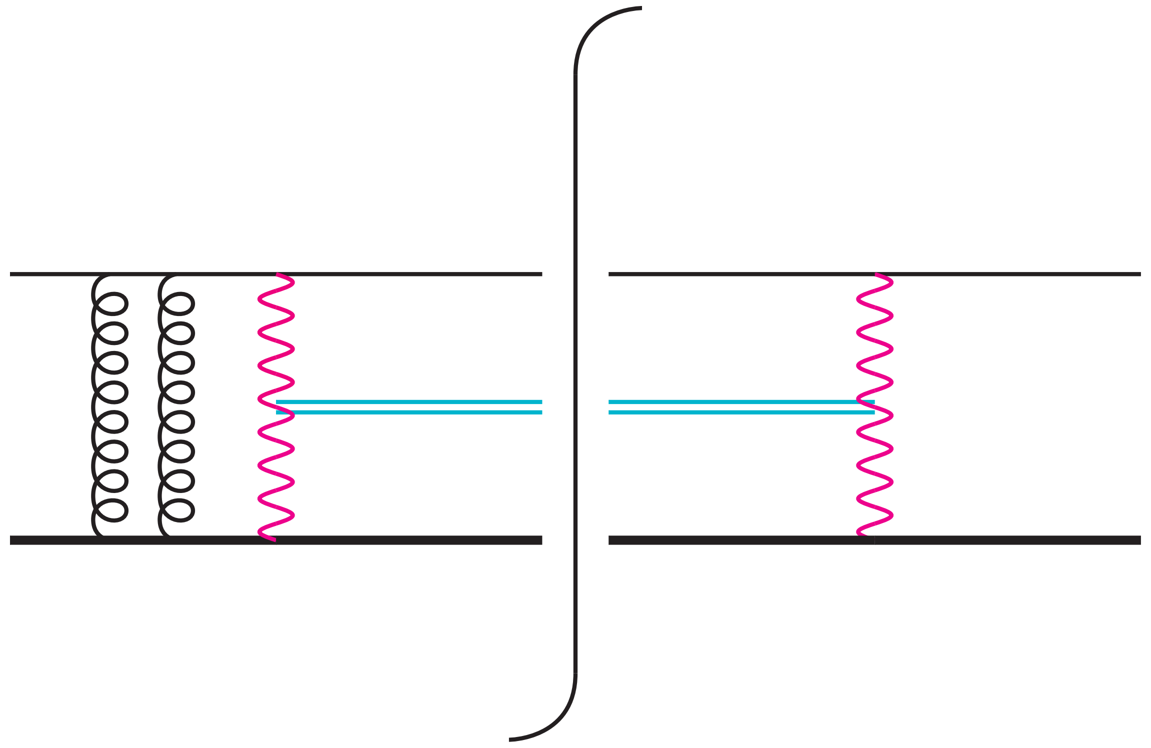
- Pole cancellation
- Loop amplitudes

Non-factorisable contribution – ingredients of the calculation (II)

Non-factorisable contributions have to **connect upper and lower quark lines** and are effectively **Abelian**



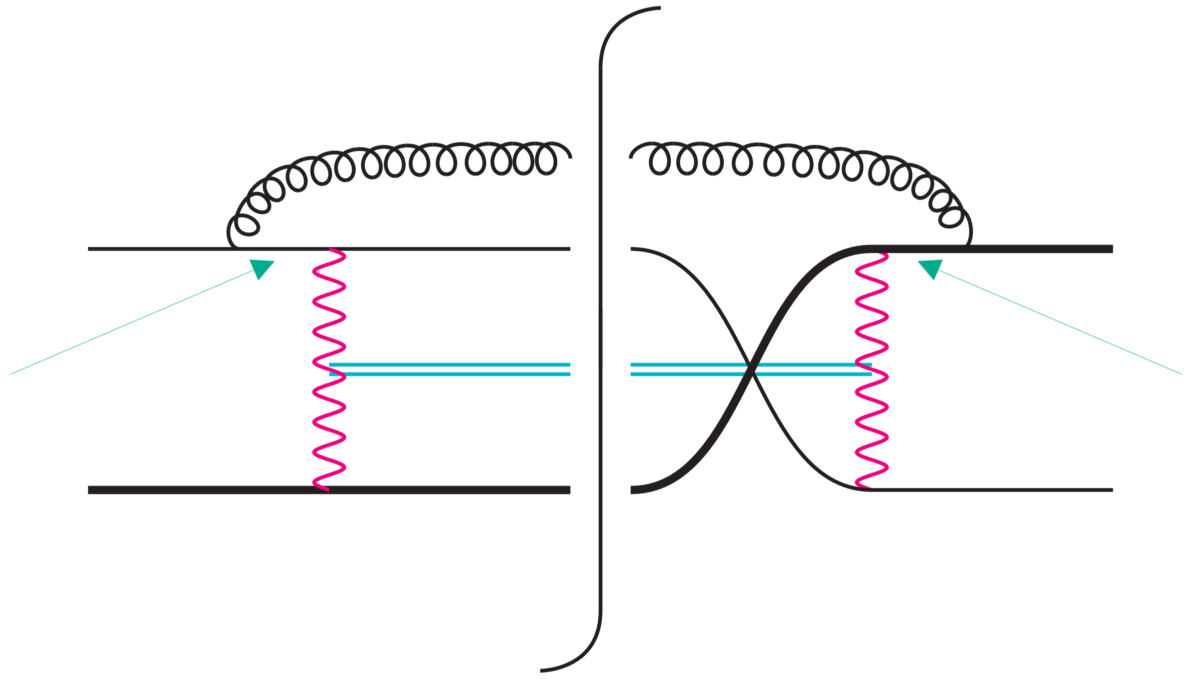
$$f^{abc}\,\mathrm{tr}\left(t^a\right)\mathrm{tr}\left(t^b t^c\right) = 0$$



$$\mathrm{tr}\left(t^a t^b\right)\mathrm{tr}\left(t^a t^b\right) = \frac{N_c^2 - 1}{4}$$

The **infrared structure is simplified**: **no collinear singularities**

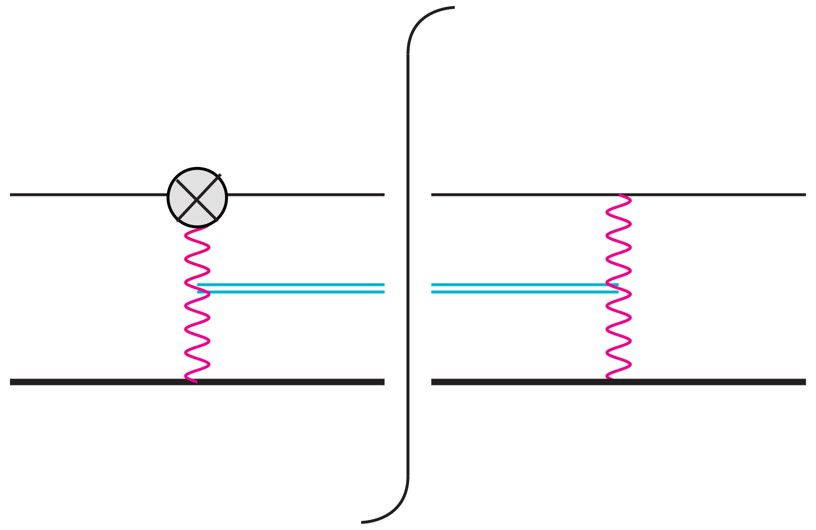
$$\frac{1}{E_g E_q(1-\cos\theta_{gq})}$$

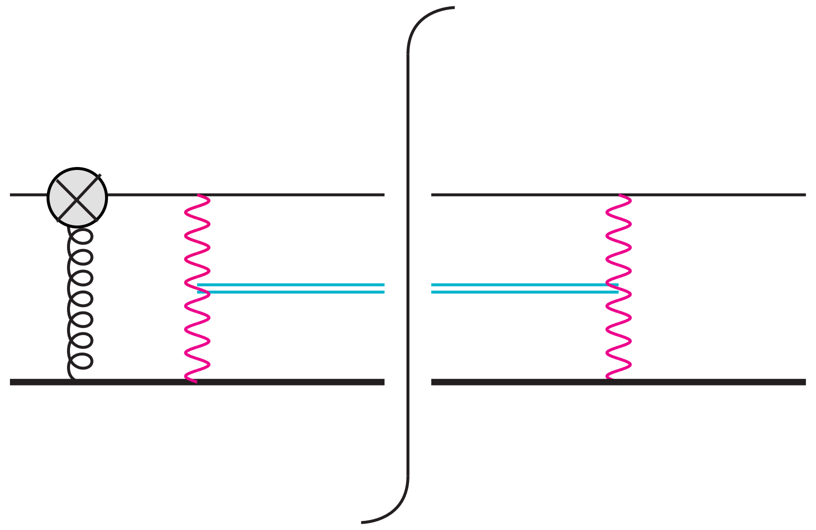


$$\frac{1}{E_g E_Q(1-\cos\theta_{gQ})}$$

All IR singularities are of **soft origin.**

Non-factorisable contributions are **UV finite**





Renormalisation simply consists of $\alpha_s^{\mathrm{bare}} = \alpha_s \mu^{2\epsilon} S_\epsilon$

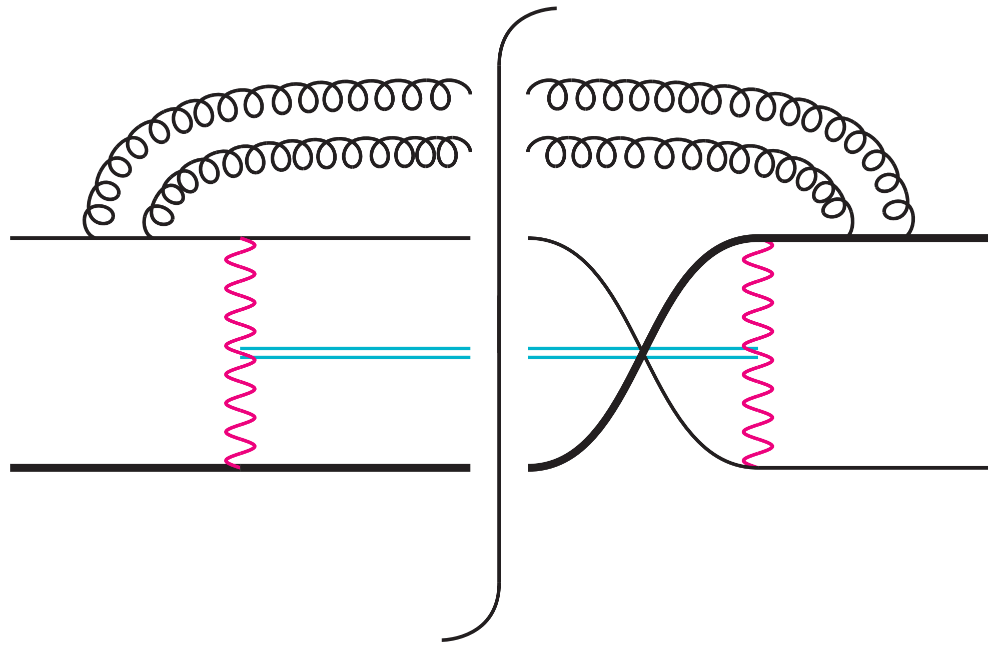
Double-real emission (I)

Main issue of the **double-real contribution: extract IR singularities** while preserving the fully-differential nature of the calculation

→ **simplified nested soft-collinear subtraction scheme** [Caola, Melnikov, Röntsch 2017]

- fully factorised emissions due to Abelian nature
- abscence of collinear singularities

see Davide's talk



$$F_{\rm LM}^{\rm nf}\left(1_q,2_Q,3_{q'},4_{Q'}|5_g,6_g\right) = \mathcal{N}\int {\rm dLips}_{34H}\,(2\pi)^d\,\delta^{(d)}\Big(p_1+p_2-p_H-\sum_{i=3}^{6}p_i\Big)\times\; 2{\rm Re}\left[A_0^{11}A_0^{22*}+A_0^{12}A_0^{21*}\right]$$

$$2s\cdot\hat{\sigma}_{\rm RR}^{\rm nf} = \frac{1}{2!}\int[{\rm d}p_5]\,[{\rm d}p_6]\,F_{\rm LM}^{\rm nf}\left(1_q,2_Q,3_{q'},4_{Q'}|5_g,6_g\right)\equiv\left\langle F_{\rm LM}^{\rm nf}\left(1_q,2_Q,3_{q'},4_{Q'}|5_g,6_g\right)\right\rangle$$

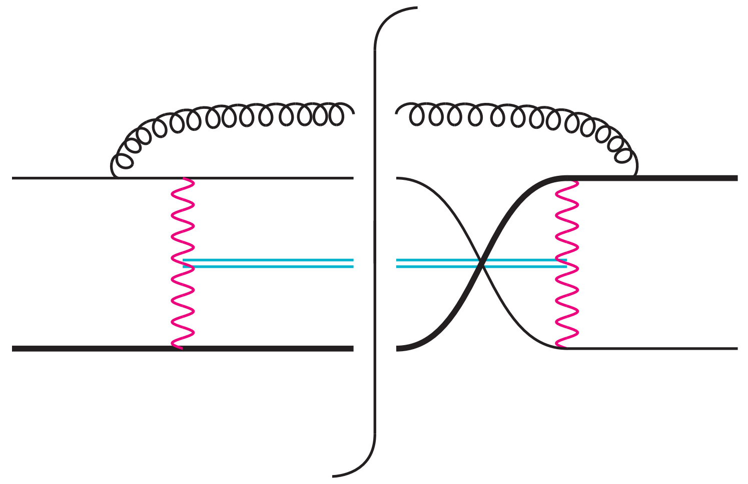
integration over potentially unresolved phase space

$$[{\rm d}p] = \frac{{\rm d}^{d-1}p}{(2\pi)^{d-1}2E_p}\,\theta\big(E_{\rm max}-E_p\big)$$

Separate the **soft-finite contribution** from the **soft-divergent part**

$$\left\langle F_{\rm LM}^{\rm nf}\left(1_q,2_b,3_{q'},4_t;5_g,6_g\right)\right\rangle = \left\langle (I-S_6)\,F_{\rm LM}^{\rm nf}\left(1_q,2_b,3_{q'},4_t;5_g,6_g\right)\right\rangle + \left\langle S_6\,F_{\rm LM}^{\rm nf}\left(1_q,2_b,3_{q'},4_t;5_g,6_g\right)\right\rangle$$

Double-real emission (II)



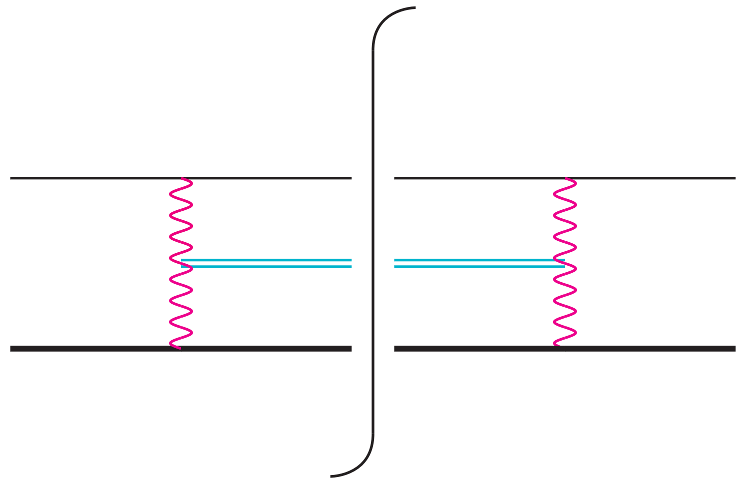
$$S_6 F^{\rm nf}_{\rm LM}(1_q,2_b,3_{q'},4_t;5_g,6_g) = -2\, g_{s,b}^2\, \kappa_{qQ} \int [{\rm d}p_6]\theta(E_5-E_6)\, {\rm Eik}_{\rm nf}(1_q,2_Q,3_{q'},4_{Q'}\,|\,6_g)\, F^{\rm nf}_{\rm LM}(1_q,2_b,3_{q'},4_t;5_g)$$

Integrate the eikonal factor over the radiation phase space

$${\rm Eik}_{\rm nf}(1_q,2_Q,3_{q'},4_{Q'};k_g) = \sum_{\substack{i\in[1,3]\\ j\in[2,4]}} \frac{\lambda_{ij}\; p_i\cdot p_j}{(p_i\cdot p_k)(p_j\cdot p_k)}$$

$$g_{s,b}^2 \int [{\rm d}p_k]\, {\rm Eik}_{\rm nf}(1_q,2_Q,3_{q'},4_{Q'};k_g) \equiv \frac{\alpha_s}{2\pi}\left(\frac{2E_5}{\mu}\right)^{-2\epsilon} K_{\rm nf}(1_q,2_Q,3_{q'},4_{Q'};\epsilon) = \frac{\alpha_s}{2\pi}\left(\frac{2E_5}{\mu}\right)^{-2\epsilon} \frac{1}{\epsilon}\left[\log\left(\frac{p_1\cdot p_4\; p_2\cdot p_3}{p_1\cdot p_2\; p_3\cdot p_4}\right) + \mathcal{O}(\epsilon^0)\right]$$

One more soft limit to consider in the single-gluon emission amplitude



$$S_5 (2E_5)^{-2\epsilon} F^{\rm nf}_{\rm LM}(1_q,2_Q,3_{q'},4_{Q'};5_g) = -2\, g_{s,b}^2\, \kappa_{qQ}\, (2E_5)^{-2\epsilon} {\rm Eik}_{\rm nf}(1_q,2_Q,3_{q'},4_{Q'}\,|\,5_g) F_{\rm LM}(1_q,2_Q,3_{q'},4_{Q'})$$

Double-real at **cross-section level** results in a remarkably simple object

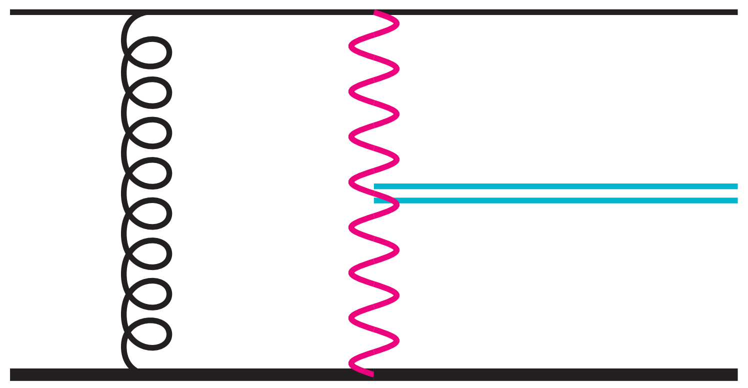
$$\left\langle F^{\rm nf}_{\rm LM}(1_q,2_Q,3_{q'},4_{Q'}|5_g,6_g)\right\rangle = \left\langle [I-S_6]\left\langle F^{\rm nf}_{\rm LM}(1_q,2_b,3_{q'},4_t;5_g,6_g)\right\rangle - 2\left(\frac{\alpha_s}{2\pi}\right)\kappa_{qQ}\left\langle [I-S_5]\left(\frac{2E_5}{\mu}\right)^{-2\epsilon} K_{\rm nf}\, F^{\rm nf}_{\rm LM}(1_q,2_b,3_{q'},4_t;5_g)\right\rangle\right.$$

$$+\, 2\left(\frac{\alpha_s}{2\pi}\right)^2\left(\frac{2E_{\rm max}}{\mu}\right)^{-4\epsilon}\left\langle K^2_{\rm nf}\, F_{\rm LM}(1_q,2_Q,3_{q'},4_{Q'})\right\rangle$$

Virtual corrections

Extract IR singularities from virtual amplitudes and compute finite contributions.

- One-loop correction to the colour-stripped 5-point amplitude



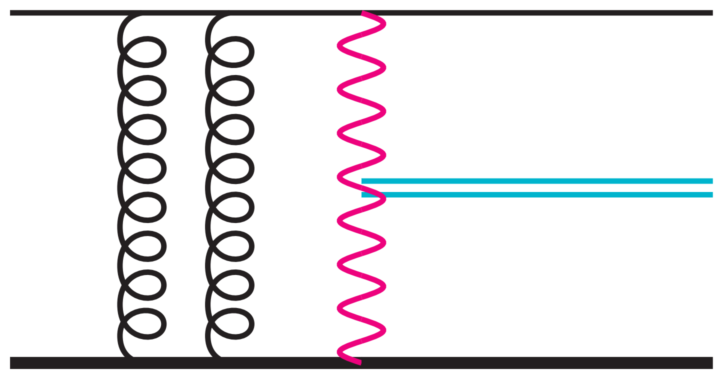
$$\mathrm{F}_{\mathrm{LV}}^{\mathrm{nf}}\left(1_q, 2_Q, 3_{q'}, 4_{Q'}\right) = \mathcal{N} \int \mathrm{dLips}_{34H}\,(2\pi)^d\,\delta^{(d)}\Big(p_1{+}p_2{-}p_H{-}\textstyle\sum_{i=3}^4 p_i\Big)\; 2\mathrm{Re}\left[A_0 A_1^*\right]$$

The amplitudes are UV-finite, but IR-divergent:

$$F_{\mathrm{LV}}^{\mathrm{nf}}\left(1_q, 2_Q, 3_{q'}, 4_{Q'}\right) = \frac{\alpha_s}{2\pi}\,2\,\kappa_{qQ}\,I_1(\epsilon)\,F_{\mathrm{LM}}\left(1_q, 2_Q, 3_{q'}, 4_{Q'}\right) + F_{\mathrm{LV,fin}}^{\mathrm{nf}}\left(1_q, 2_Q, 3_{q'}, 4_{Q'}\right)$$

$$I_1(\epsilon) \equiv \frac{1}{\epsilon}\log\left(\frac{p_1\cdot p_4\; p_2\cdot p_3}{p_1\cdot p_2\; p_3\cdot p_4}\right)$$

- Two-loop correction, the Abelian nature of the correction leads to the simple pole structure



$$\left\langle F_{\mathrm{LVV}}\left(1_q, 2_Q, 3_{q'}, 4_{Q'}\right)\right\rangle = \left(\frac{\alpha_s}{2\pi}\right)^2 \left\langle 2\,I_1(\epsilon)^2 F_{\mathrm{LM}}\left(1_q, 2_Q, 3_{q'}, 4_{Q'}\right)\right\rangle + \frac{\alpha_s}{2\pi}\,\kappa_{qQ}\left\langle 2\,I_1(\epsilon)\,F_{\mathrm{LV,fin}}^{\mathrm{nf}}\left(1_q, 2_Q, 3_{q'}, 4_{Q'}\right)\right\rangle + \left\langle F_{\mathrm{LVV,fin}}^{\mathrm{nf}}\left(1_q, 2_Q, 3_{q'}, 4_{Q'}\right)\right\rangle$$

Pole cancellation

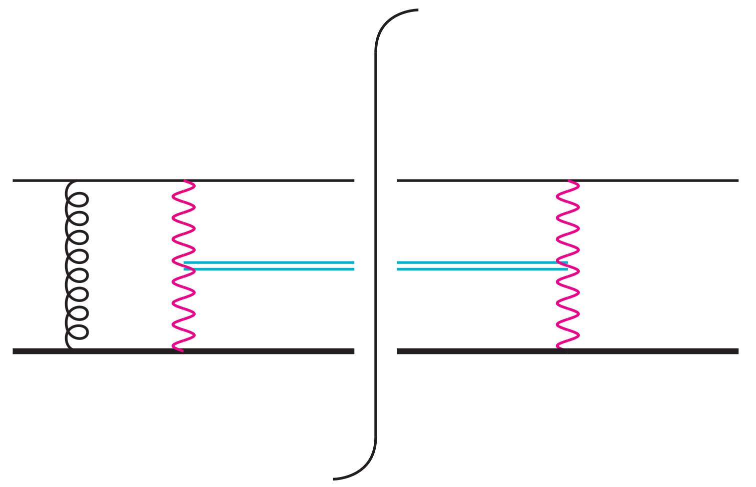
We introduce a finite combination of two the divergent functions

$$\mathcal{W}(E;(1_q,2_Q,3_{q'},4_{Q'}) = \left(\frac{2E^{-2\epsilon}}{\mu}\right) K_{\rm nf}(\epsilon) - I_1(\epsilon) = \mathcal{O}(\epsilon^0)$$

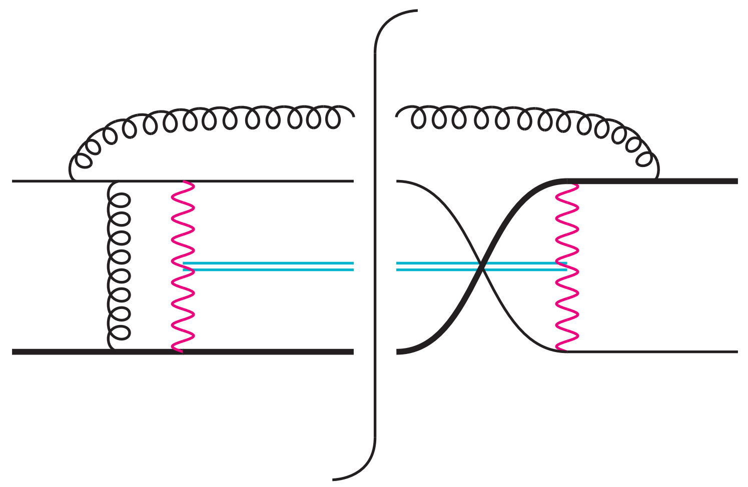
$$\begin{aligned}
{\rm d}\hat{\sigma}^{\rm nf}_{\rm nnlo} &= \frac{T_R^2(N_c^2-1)}{2s}\Big[\big\langle F^{\rm nf}_{\rm LM}(1_q,2_Q,3_{q'},4_{Q'}|5_g,6_g) + \big\langle F^{\rm nf}_{\rm LM}(1_q,2_Q,3_{q'},4_{Q'}|5_g)\big\rangle + \big\langle F^{\rm nf}_{\rm LVV}(1_q,2_Q,3_{q'},4_{Q'})\big\rangle\Big] \\
&= \frac{T_R^2(N_c^2-1)}{2s}\Big[\big\langle [I-S_6] F^{\rm nf}_{\rm LM}(1_q,2_Q,3_{q'},4_{Q'}|5_g,6_g)\big\rangle - 2\left(\frac{\alpha_s}{2\pi}\right)\big\langle [I-S_5]\,\mathcal{W}(E_5;1_q,2_Q,3_{q'},4_{Q'})\,F_{\rm LM}(1_q,2_Q,3_{q'},4_{Q'}|5_g)\big\rangle \\
&\quad + 2\left(\frac{\alpha_s}{2\pi}\right)^2 \big\langle \mathcal{W}(E_{\rm max};(1_q,2_Q,3_{q'},4_{Q'})^2 F_{\rm LM}(1_q,2_Q,3_{q'},4_{Q'})\big\rangle + \big\langle [I-S_5] F^{\rm nf}_{\rm LV,fin}(1_q,2_Q,3_{q'},4_{Q'}|5_g\big\rangle \\
&\quad - 2\big\langle \mathcal{W}(E_{\rm max};1_q,2_Q,3_{q'},4_{Q'})\,F^{\rm nf}_{\rm LV,fin}(1_q,2_Q,3_{q'},4_{Q'})\big\rangle + \big\langle F^{\rm nf}_{\rm LVV,fin}((1_q,2_Q,3_{q'},4_{Q'})\big\rangle\Big]
\end{aligned}$$

Achievement: **local pole cancellation** and simple form due to **abelian nature of non-factorisable contribution**

Virtual contributions



$$q\,Q \to q'\,Q' + H$$



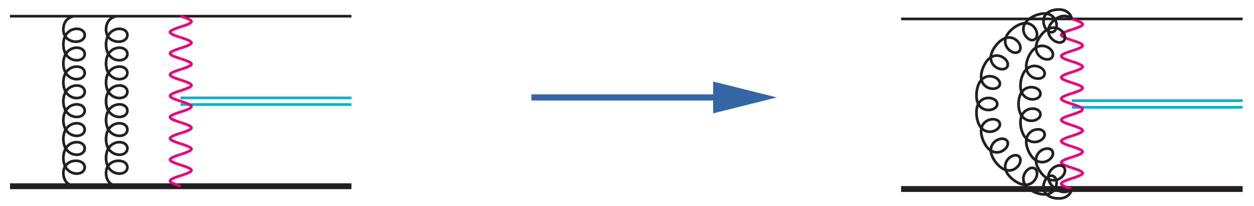
$$q\,Q \to q'\,Q' + H + g$$

calculated previously [Campanario, Figy, Plätzer, Sjödahl 2013]

computationally expensive due to multiplicity and large cancellations in the soft limit

$$E_g \to 0$$

pole prediction and soft limit checked



$$q\,Q \to q'\,Q' + H$$

7 scales: $s_{12}, s_{23}, s_{34}, s_{45}, s_{51}, m_W, m_t$

eikonal approximation [Liu, Melnikov, Penin 2019] [Dreyer, Karlberg, Tancredi 2020] [Gates 2023]

sub-eikonal approximation [Long, Melnikov, Quarroz 2023]

validity ensured by kinematic signature and WBF cuts

anti-k_t	2 jets, $R = 0.4$
jet transverse momentum	$p_{\perp,j} > 25$ GeV
jet rapidity	$\lvert y_j \rvert < 4.5$
jet separation	$\lvert y_{j_1} - y_{j_2} \rvert > 4.5$
invariant mass of jets	$M_{jj} > 600$ GeV
separate hemispheres	$y_{j_1} y_{j_2} < 0$

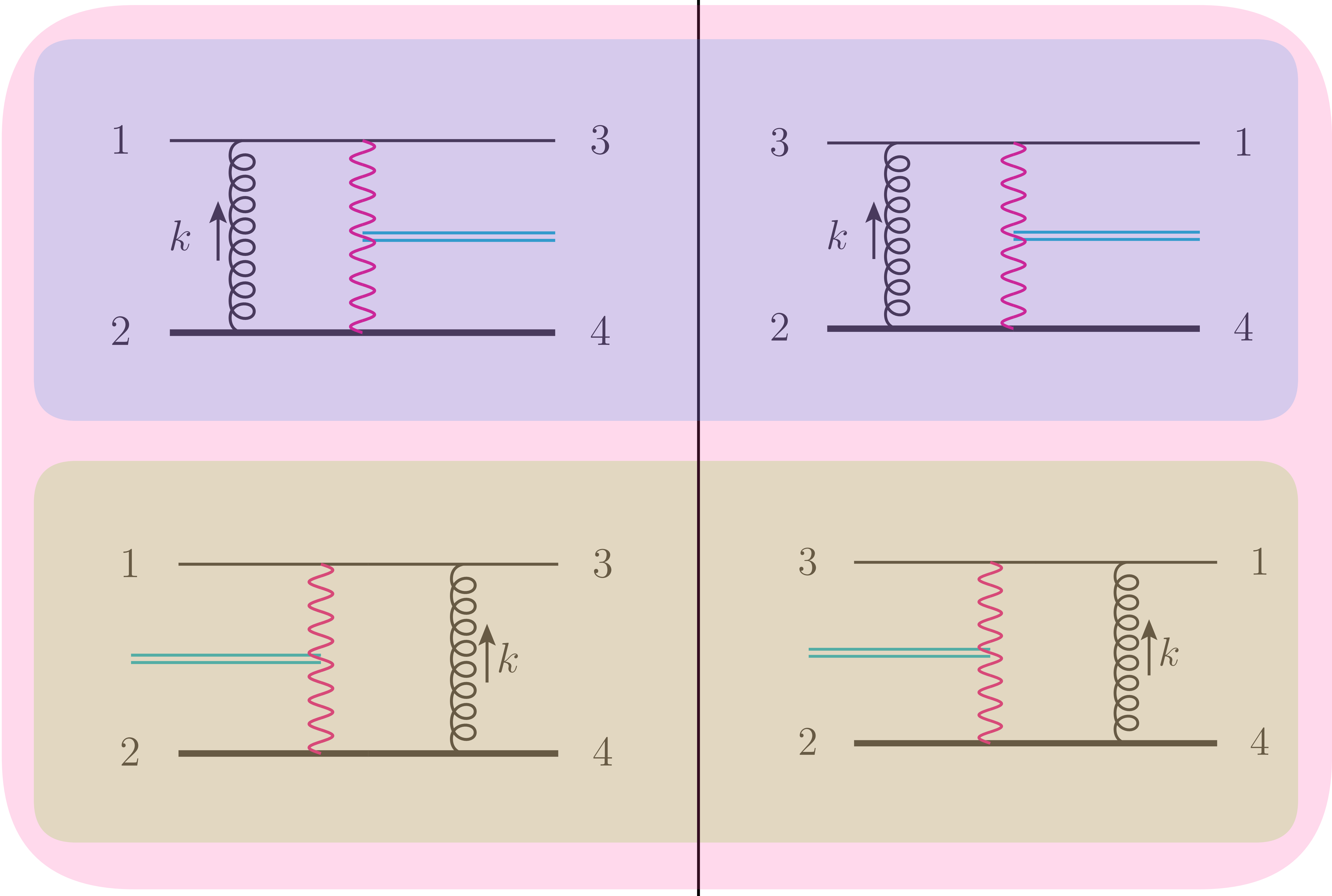
Eikonal approximation

$$\sqrt{s} \gtrsim 600 \text{ GeV}$$
$$p_{j,\perp} \sim 100 \text{ GeV}$$
$$k_\perp \sim m_h \ll \sqrt{s}/2$$

Eikonal approximation of virtual contribution to WBF Higgs [Liu, Melnikov, Penin 2019]

$$\frac{\gamma_\mu\left(k^\mu + p^\mu_{1,2}\right)}{\left(k+p_{1,2}\right)^2 + i\varepsilon} \approx \frac{\gamma_\mu p^\mu_{1,2}}{2k\cdot p_{1,2} + i\varepsilon} = \frac{\gamma^\mp}{2k^\mp + i\varepsilon}$$

$$\frac{\gamma_\mu\left(k^\mu - p^\mu_{1,2}\right)}{\left(k-p_{1,2}\right)^2 + i\varepsilon} \approx \frac{-\gamma_\mu p^\mu_{1,2}}{-2k\cdot p_{1,2} + i\varepsilon} = \frac{\gamma^\mp}{2k^\mp - i\varepsilon}$$



$$\frac{1}{2k^- + i\varepsilon} - \frac{1}{2k^- - i\varepsilon} \to -i\pi\delta\left(k^-\right)$$

$$\int \frac{d^dk}{(2\pi)^d}\frac{-i\pi\delta(k^-)}{k^2(2k^+ - i\varepsilon)[(k+p_1-p_3)^2 - m_W^2][(k-p_2+p_4-m_W^2)]}$$

$$\int \frac{d^dk}{(2\pi)^d}\frac{+i\pi\delta(k^-)}{k^2(2k^+ + i\varepsilon)[(k+p_1-p_3)^2 - m_W^2][(k-p_2+p_4-m_W^2)]}$$

$$\frac{1}{2k^+ + i\varepsilon} - \frac{1}{2k^+ - i\varepsilon} \to -i\pi\delta\left(k^+\right)$$

$$\int \frac{d^dk}{(2\pi)^d}\frac{\pi^2\delta(k^-)\delta(k^+)}{k^2[(k+p_1-p_3)^2 - m_W^2][(k-p_2+p_4-m_W^2)]}$$

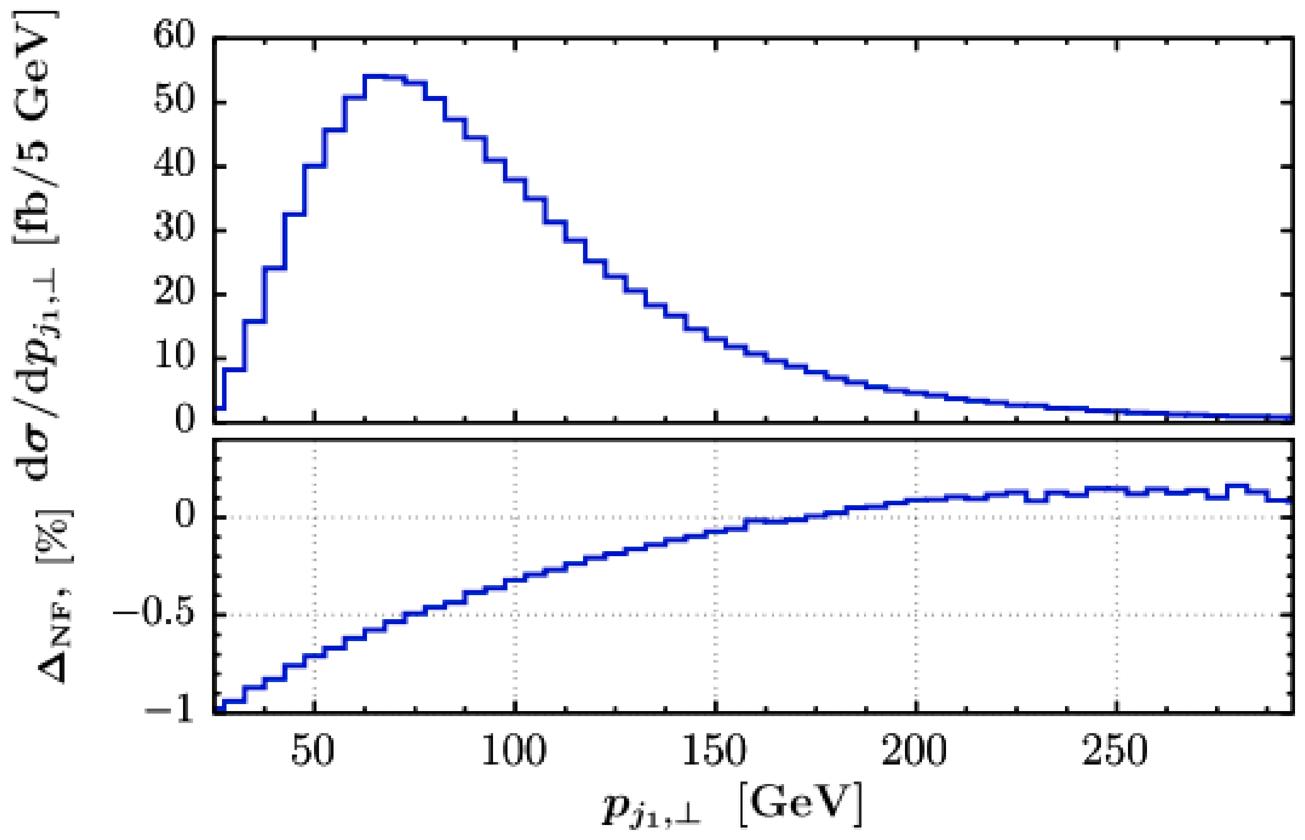
WBF Higgs production: Results at 13 TeV (I)

pp collision: $\sqrt{s} = 13\,\text{TeV}$, PDFs: NNPDF31-nnlo-as-118

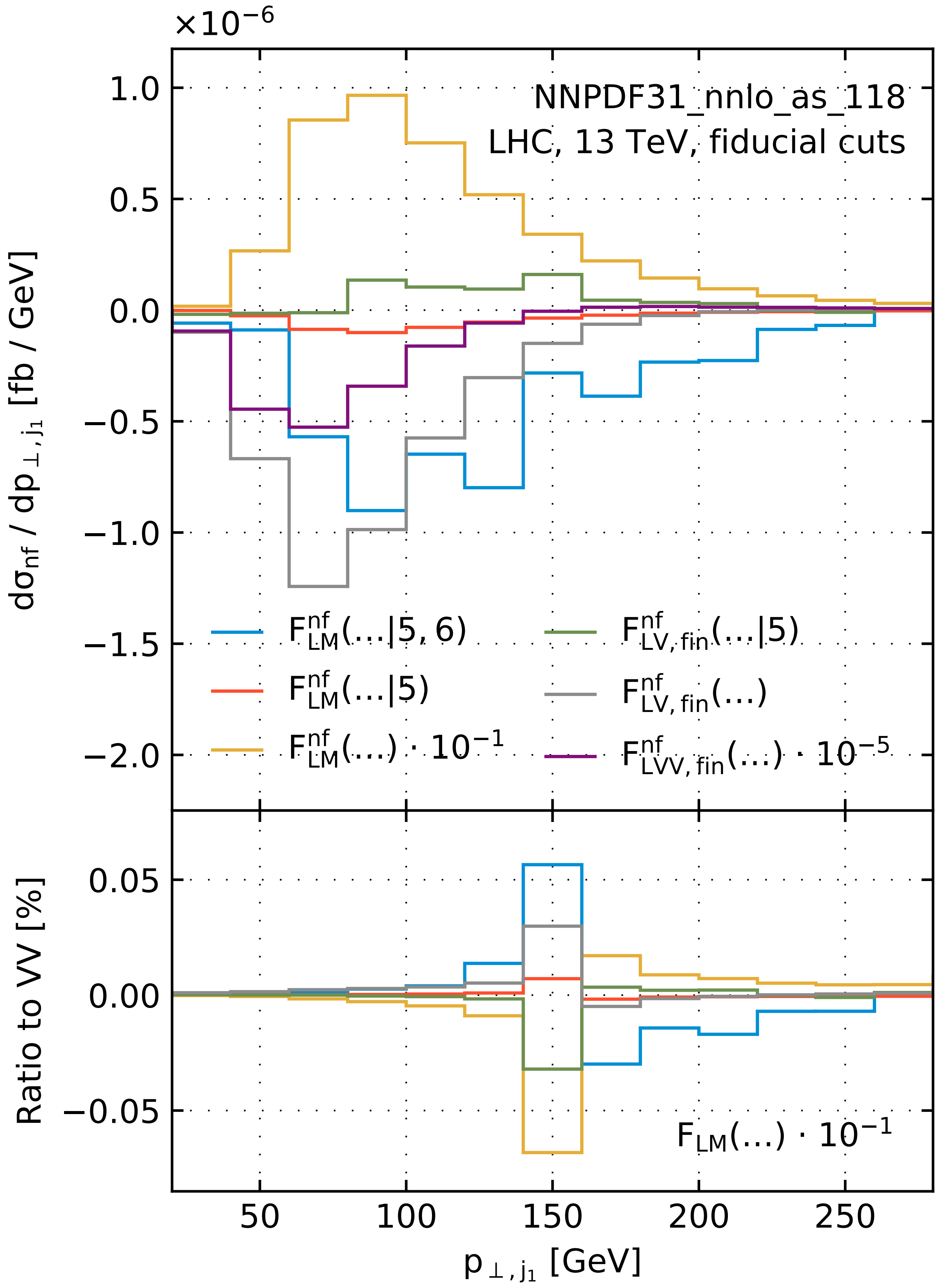
$$\sigma_{\text{nf}} = -3.1\,\text{fb} \qquad \mu_R = \mu_F = \sqrt{\frac{m_H}{2}\sqrt{\frac{m_H^2}{4} + p_{\perp,H}^2}}$$

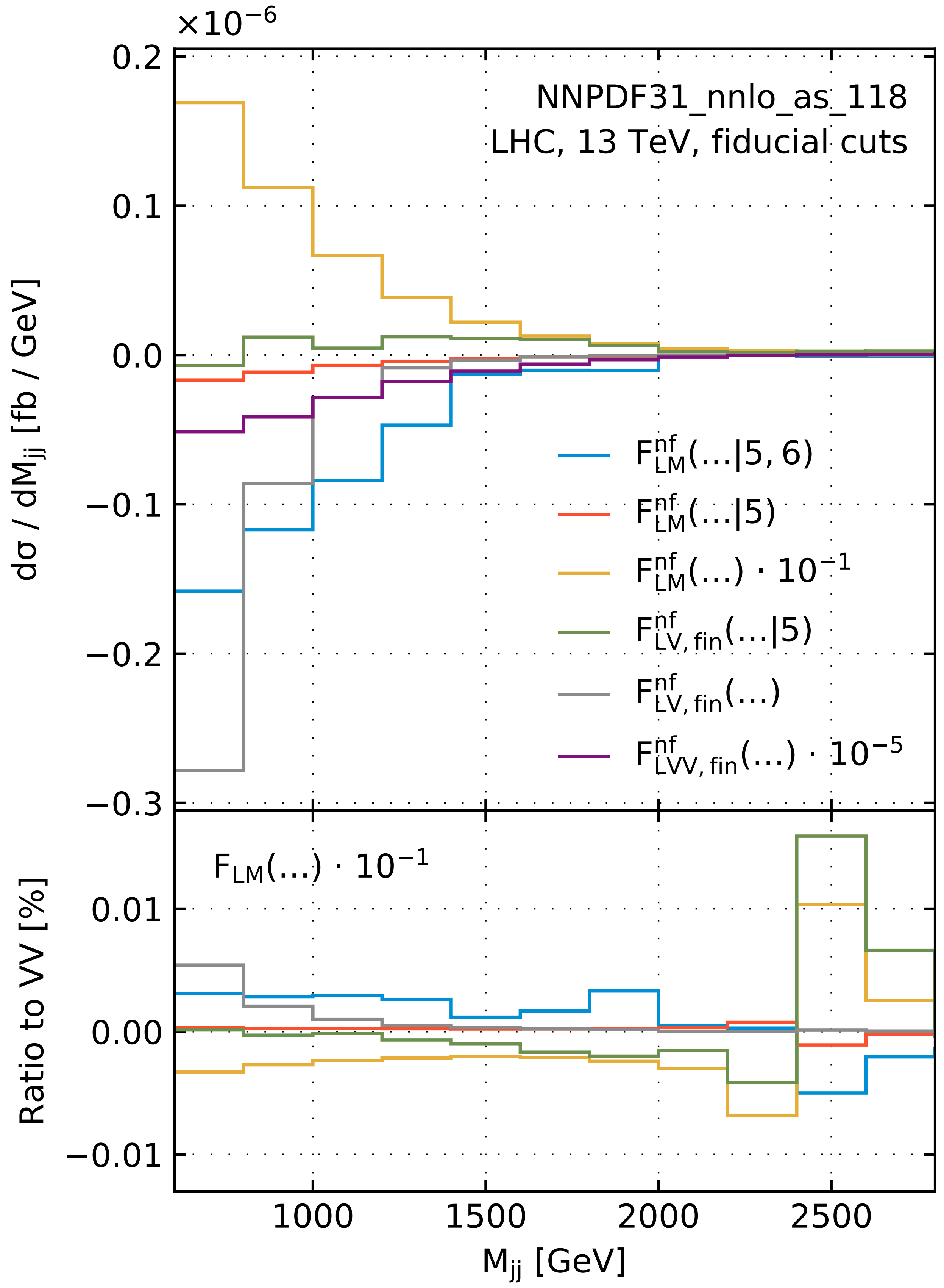
$$m_H = 125.0\,\text{GeV},\, m_W = 80.398\,\text{GeV},\, m_Z = 91.1876\,\text{GeV},\, \alpha_S(m_Z) = 0.118$$

- Non-factorisable corrections are $0.5\,\%$ of factorisable through NNLO
- Double-virtual accounts for $99.99\,\%$
- For $\mu_R = \mu_F$ scale variation is $\mathcal{O}(40)\,\%$



[Liu, Melnikov, Penin 2019]

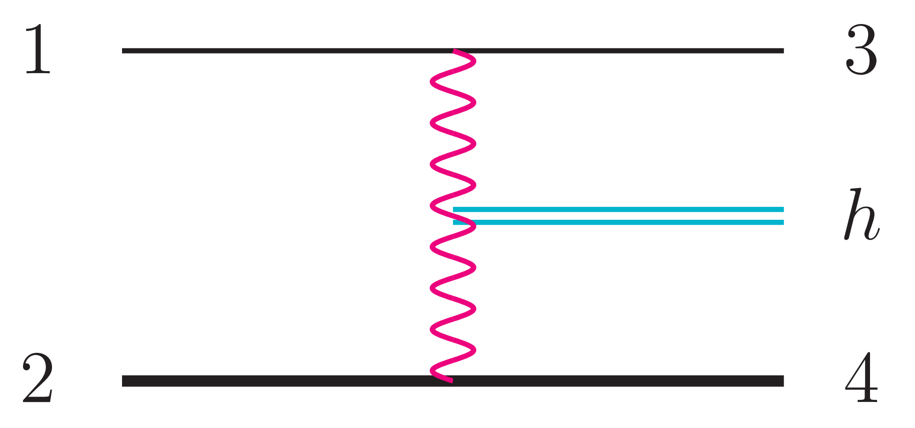




[Asteriadis, **Brønnum-Hansen**, Melnikov 2305.08016]

WBF Higgs production: Results at 13 TeV (II)

To **estimate the real emission contributions** to the cross section, we consider the quantity



$$L(1,2,3,4) = \ln\left(\frac{p_1\cdot p_4\; p_3\cdot p_2}{p_1\cdot p_2\; p_3\cdot p_4}\right)$$

WBF kinematics is **characterised by two hard jets** that are nearly collinear to the beam axis

$$p_3 = \alpha_3\, p_1 + \beta_3\, p_2 + p_{3,\perp}$$
$$p_4 = \alpha_4\, p_1 + \beta_4\, p_2 + p_{4,\perp}$$

$$\alpha_3, \beta_4 \sim 1$$

$$\beta_3 \sim \frac{p_{3,\perp}^2}{s} \ll 1\,, \quad \alpha_4 \sim \frac{p_{4,\perp}^2}{s} \ll 1$$

With this approximation, we get

$$L(1,2,3,4) = -\ln\left(1 + \frac{\beta_3\,\alpha_4}{\alpha_3\,\beta_4} - \frac{2\,\vec{p}_{3,\perp}\cdot\vec{p}_{4,\perp}}{s\,\alpha_3\,\beta_4}\right)$$
$$\approx \frac{2\vec{p}_{3,\perp}\cdot\vec{p}_{4,\perp}}{s} \approx 10^{-2}$$

typical values

$$|\vec{p}_{i,\perp}| \sim 60\,\text{GeV}$$
$$\sqrt{s} \sim 600\,\text{GeV}$$

and we **estimate the contribution from two soft gluons** and compare to the π^2 -enhanced double-virtual

$$\sigma_{RR} \sim N_c^2 \langle L^2(1,2,3,4) F_{\text{LM}}^{\text{nf}}(1_q, 2_q, 3_q, 4_q)\rangle$$
$$\sim 10^{-4}\,\sigma_{\text{LO}}\,,$$

$$\sigma_{VV} \sim N_c^2 \langle\, \chi_{\text{nf}}(1,2,3,4)\; F_{\text{LM}}^{\text{nf}}(1,2,3,4)\rangle$$
$$\approx 10\,\sigma_{\text{LO}}$$

π^2

Beyond the eikonal approximation

Going beyond the eikonal approximation of virtual contribution to WBF Higgs [Long, Melnikov, Quarroz 2023]

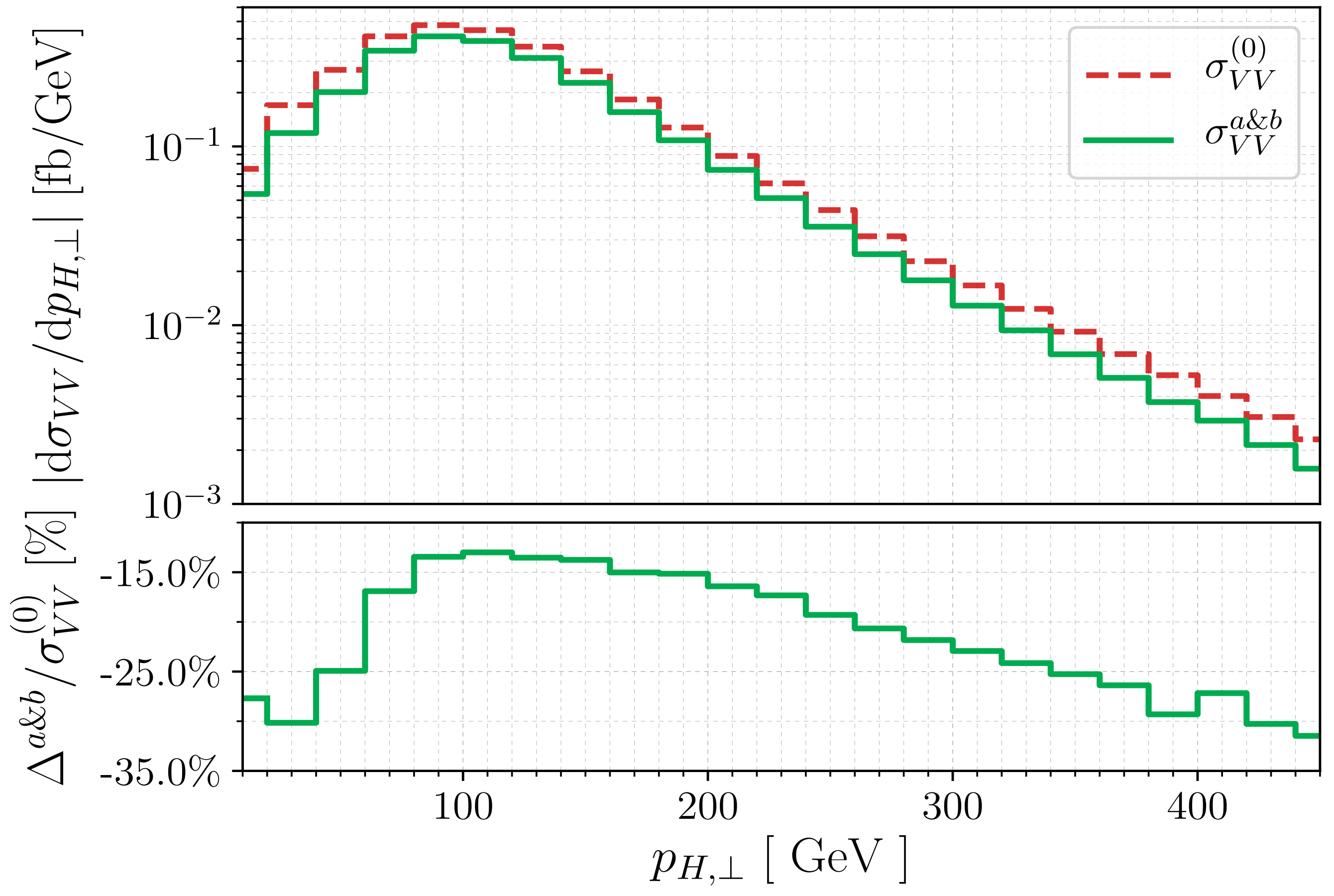
$1-\delta_3$

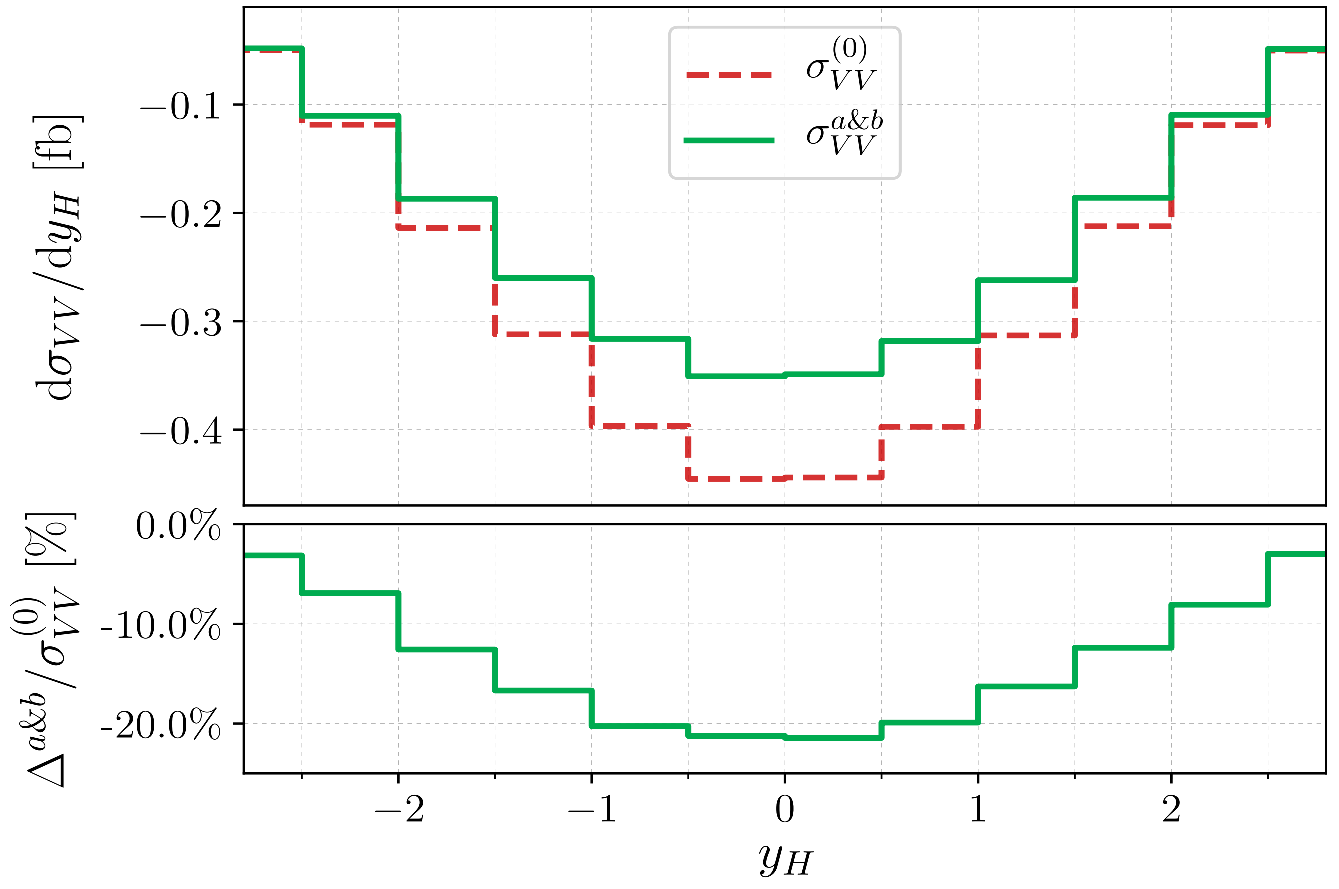
$$k_i = \alpha_i\, p_1 + \beta_i\, p_2 + k_{i,\perp}$$
$$p_3 = \alpha_3\, p_1 + \beta_3\, p_2 + p_{3,\perp}$$
$$p_4 = \alpha_4\, p_1 + \beta_4\, p_2 + p_{4,\perp}$$

$1-\delta_4$

Calculation using method of regions:

$$\delta_3 \sim \delta_4 \sim \sqrt{\lambda} \sim \sqrt{\frac{p_{3,\perp}^2}{s}} \sim \sqrt{\frac{p_{4,\perp}^2}{s}}$$





Correction to total cross section of around 20% :

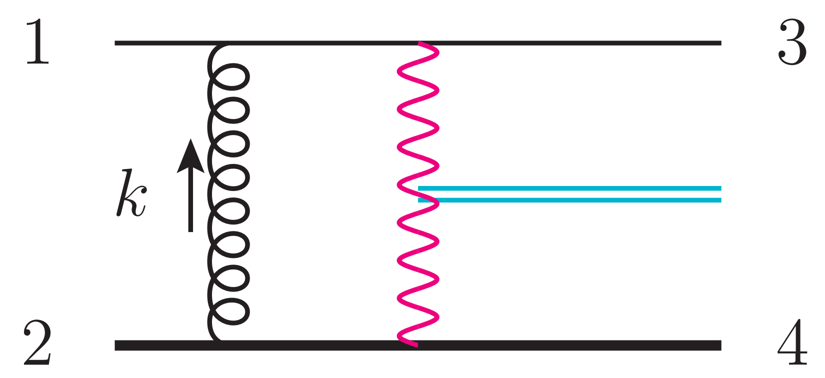
$$\sigma_{VV}^{\rm nf} = (-3.1 + 0.53)\ \text{fb} \quad \text{(WBF cuts)}$$

with WBF cuts and without cuts :

$$\sigma_{VV}^{\rm nf} = (-16.8 + 6.8)\ \text{fb} \quad \text{(no cuts)}$$

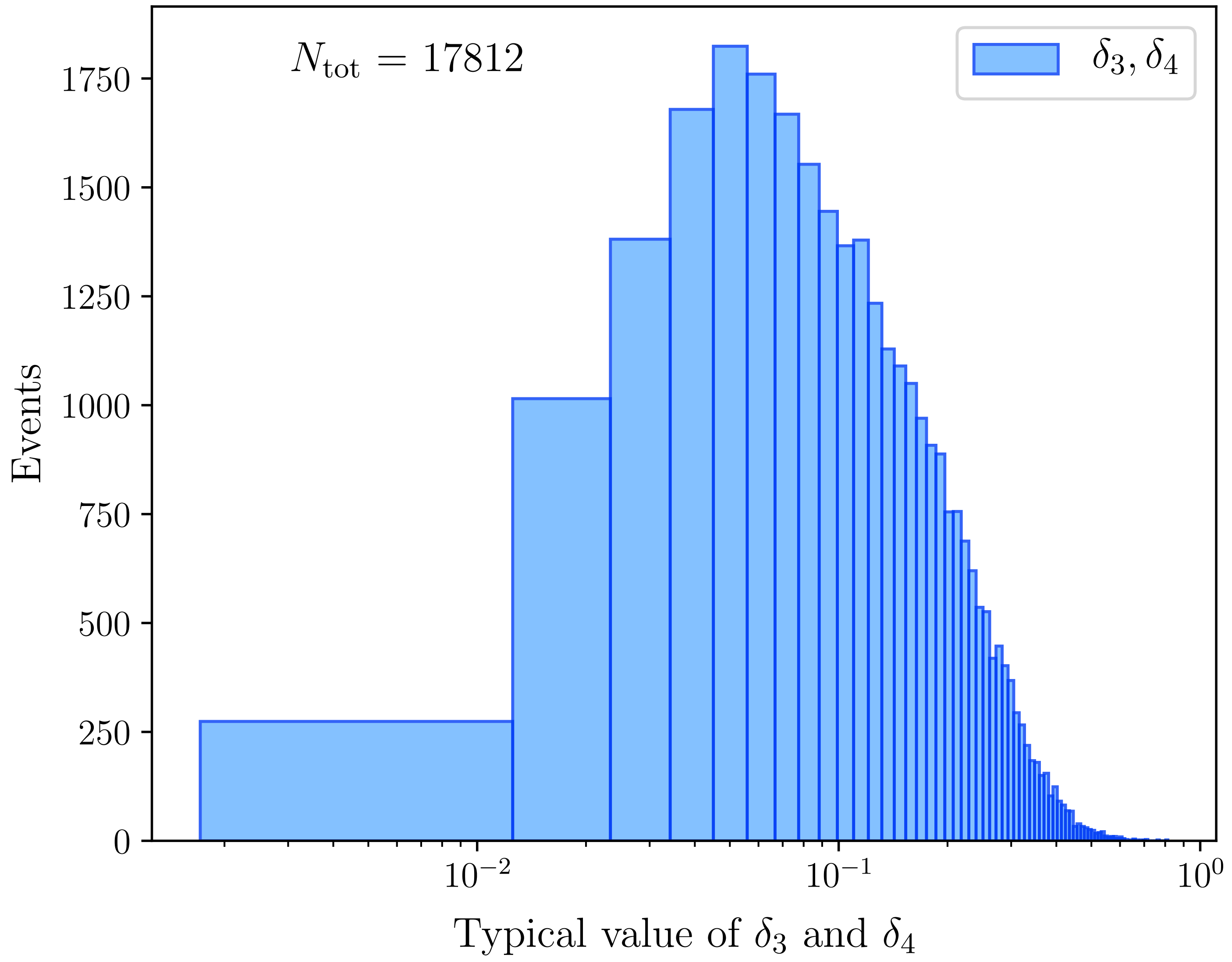
and including real contributions

$$\sigma_{\rm nnlo}^{\rm nf} = (-15.2 + 6.8)\ \text{fb} \quad \text{(no cuts)}$$

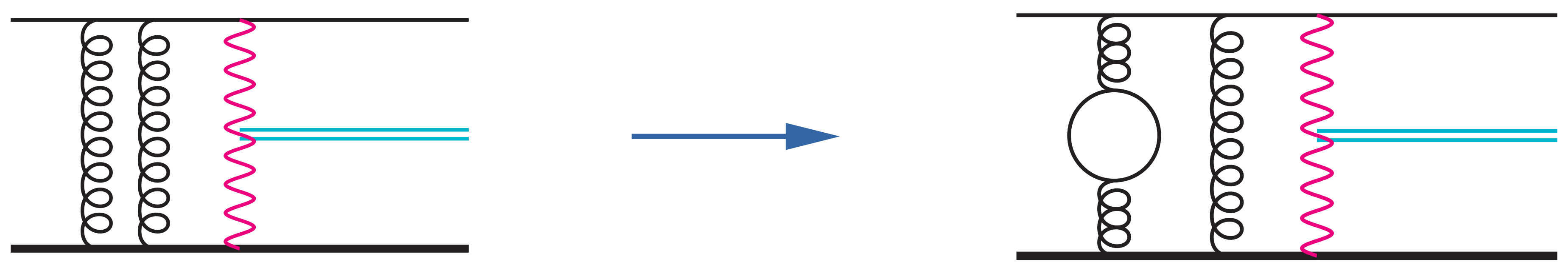


$$\sigma_{\rm nnlo}^{\rm fact.} = 3932\ \text{fb} \quad \text{(no cuts)}$$
$$\sigma_{\rm nnnlo}^{\rm fact.} = 3928\ \text{fb} \quad \text{(no cuts)}$$

[Dreyer, Karlberg 2016]



Beyond NNLO



Non-factorisable corrections can be written:

$$\mathrm{d}\sigma_{\mathrm{nnlo}}^{\mathrm{nf}} = \frac{N_c^2 - 1}{4N_c^2}\alpha_s^2 \, \mathrm{d}\sigma_{\mathrm{lo}} \, C_{\mathrm{nf}}$$

where

$$C_{\mathrm{nf}} = C_1^2 - C_2$$

and

$$C_1 = -2\int \frac{\mathrm{d}^{d-2}\mathbf{k}_1}{(2\pi)^{d-3}} \frac{\Delta_3\Delta_4}{\Delta_1\Delta_{3,i}\Delta_{4,1}},$$

$$C_2 = 4\int \frac{\mathrm{d}^{d-2}\mathbf{k}_1}{(2\pi)^{d-3}} \frac{\mathrm{d}^{d-2}\mathbf{k}_2}{(2\pi)^{d-3}} \frac{\Delta_3\Delta_4}{\Delta_1\Delta_2\Delta_{3,12}\Delta_{4,12}}$$

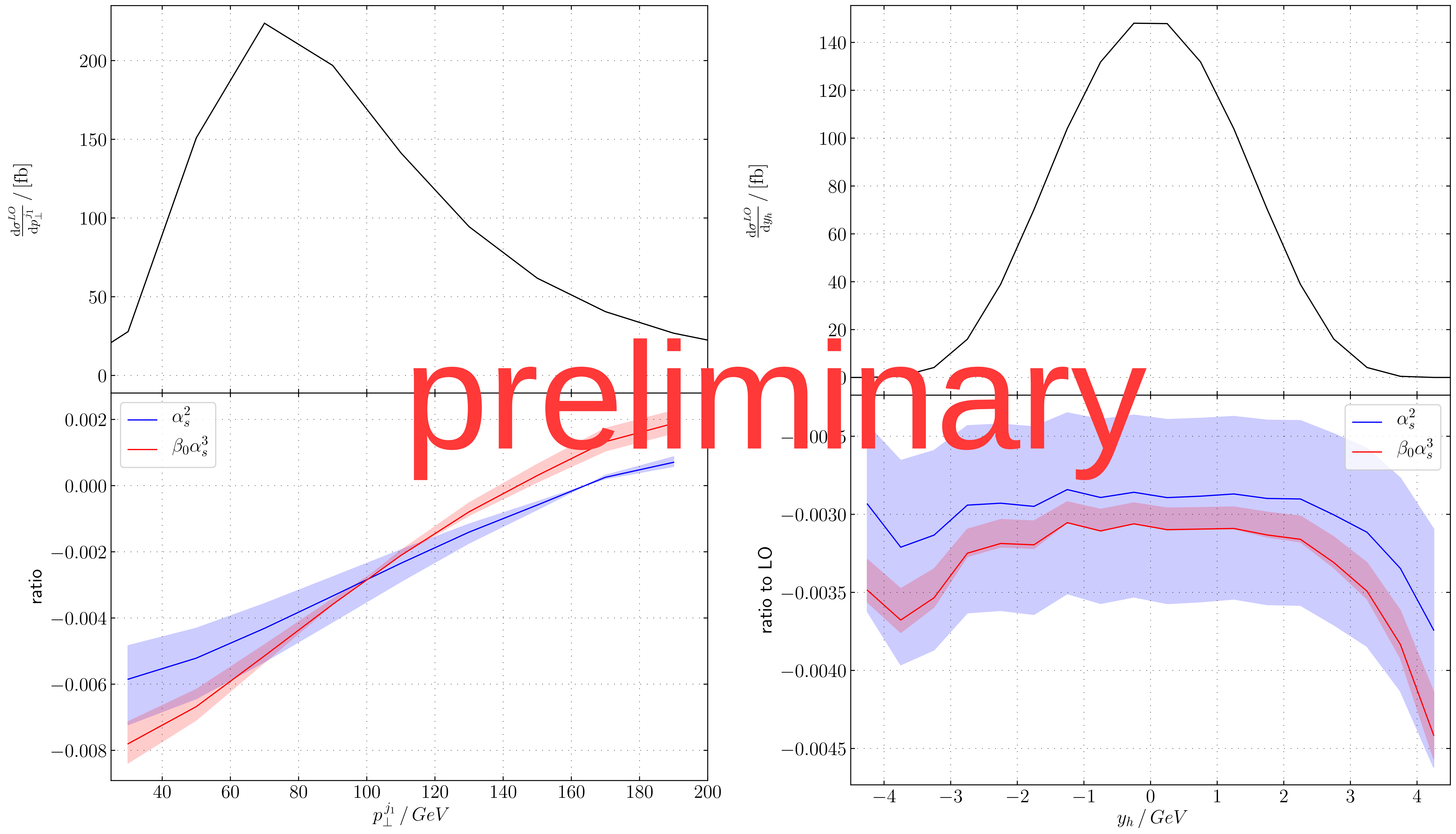
$$\Delta_i = \mathbf{k}_i^2, \quad \Delta_{3,i} = (\mathbf{k}_i - \mathbf{p}_3)^2 + m_V^2, \quad \Delta_{4,i} = (\mathbf{k}_i + \mathbf{p}_4)^2 + m_V^2$$

extracting $\beta_0\alpha_s$ contribution from n_f diagrams

$$\Delta_{1,2} \to \Delta_{1,2}\left(1 + \frac{\beta_0\alpha_s}{2\pi}\ln\frac{\mathbf{k}_i^2}{\mu^2 e^{5/3}}\right)$$

[Brodsky, Lepage, Mackenzie 1983]

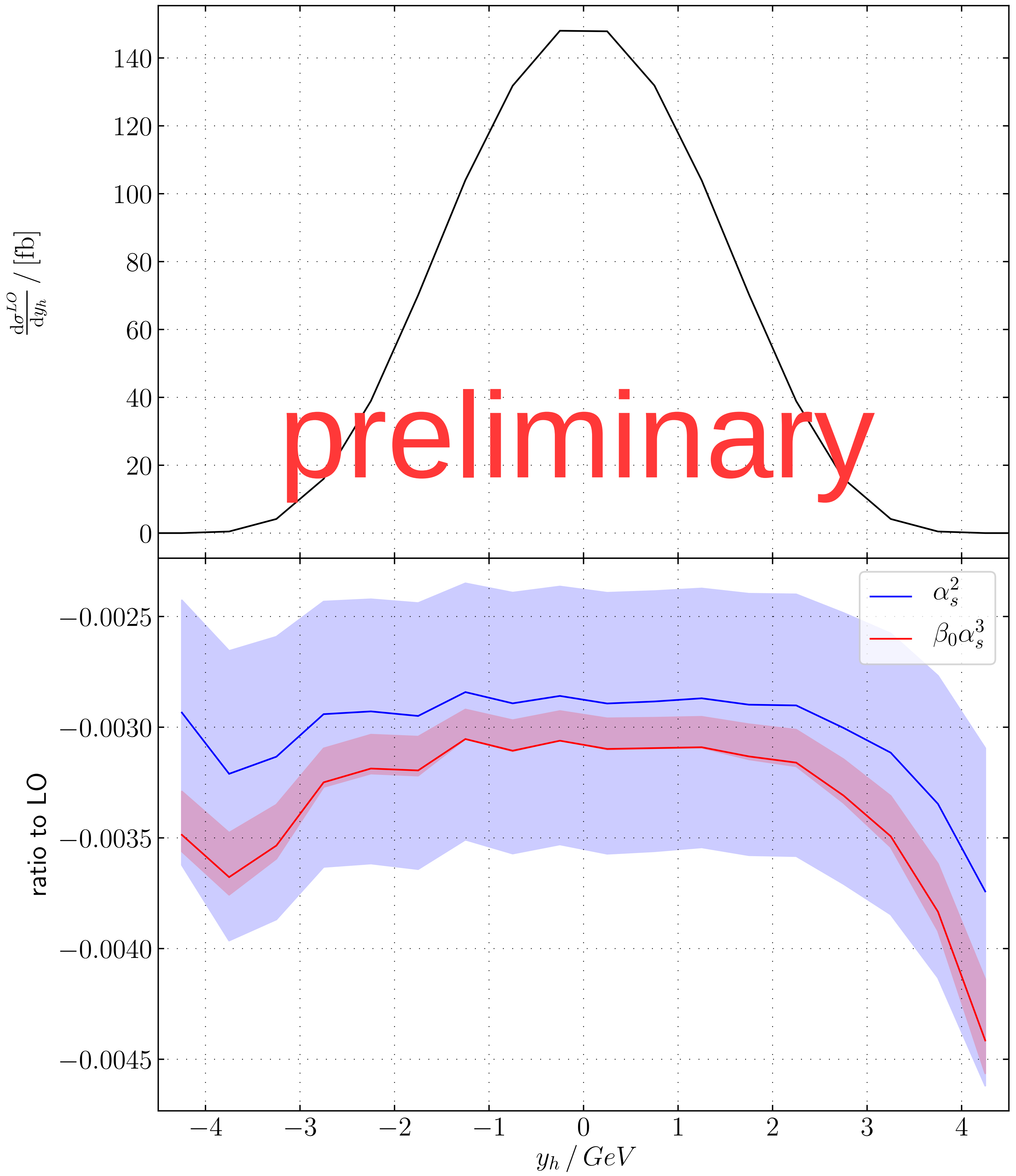
$$\sigma_{\mathrm{nnlo}}^{\mathrm{nf}} = -2.96^{-0.70}_{+0.51}\,\mathrm{fb} \qquad \sigma_{\mathrm{nnlo\,+\,bub}}^{\mathrm{nf}} = -3.19^{-0.01}_{+0.14}\,\mathrm{fb} \qquad \mu_{\mathrm{ren}} = [m_h/2; 2m_h]$$



[**Brønnum-Hansen**, Long, Melnikov 23xx.xxxxx]

Summary

- Theoretical predictions for Higgs production in WBF are at an advanced stage with **factorisable NNLO** (differential) and **NNNLO** (inclusive) known
- Significant recent progress for **non-factorisable contributions**
- Dominated by **double-virtual** which can be reliably estimated in the eikonal limit
- **Sub-percent correction** to factorisable total cross section through NNLO, but larger than NNNLO corrections
- Percent-level correction in certain regions of phase space
- **Ongoing work:** accounting for running of coupling for stable theoretical predictions



Thank you for your attention