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Non-factorisable contribution to t-channel single-top production

Based on arXiv:2204.05770 with Christian Brønnum-Hansen, Kirill Melnikov, Chiara Signorile-Signorile & Chen-Yu Wang

Jérémie Quarroz | 27 Apr 2022 | Loops and Legs

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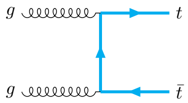
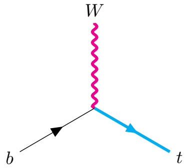
Motivation



- Top quark is the heaviest particle of the Standard Model.
  - ➥ Better understanding of electroweak symmetry breaking.
  - ➥ Hopefully, hints for physics beyond the Standard Model.

- Primarily produced in pairs. However, **single-top** production also occurs frequently

$$\sigma_{t,\text{single}} \approx \frac{1}{4}\sigma_{t\bar{t}}$$

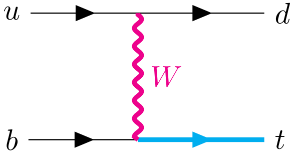


- tWb interaction is interesting due to:
  - ➥ determination of the CKM matrix element V_{bt}
  - ➥ indirect determination of Γ_t and the top-quark mass m_t
  - ➥ constrains on bottom-quark PDF $f_b(x_1)$

Single-top production

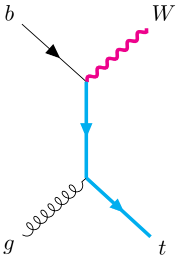
There are three single-top production modes

t channel: $qb \to q'\,t$



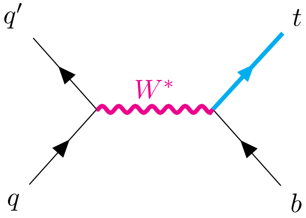
$\mathcal{O}\,(70\%)$

associated production:
$gb \to Wt$



$\mathcal{O}\,(25\%)$

s channel: $q\bar{q}' \to W^* \to t\bar{b}$



$\mathcal{O}\,(5\%)$

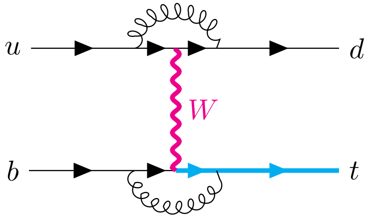
The main production mode is the t-channel.

NNLO QCD corrections to t-channel single-top production

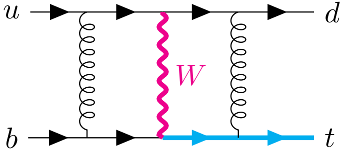
Higher order corrections are known up to an advanced stage.

- NLO QCD and electroweak corrections are known since a while. *Harris et al. 2002; Campbell, Ellis, et al. 2004; Sullivan 2004; Cao and Yuan 2005; Sullivan 2005; Beccaria et al. 2006; Schwienhorst et al. 2011*
- NNLO QCD corrections are known **except for non-factorisable corrections**. *Brucherseifer, Caola and Melnikov 2014; Berger, Edmond, Gao, Yuan, Zhu 2016; Campbell, Neumann and Sullivan 2021*

Factorisable

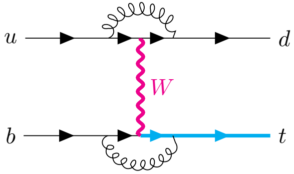


Non-factorisable

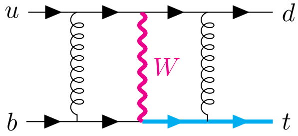


Factorisable approximation

These *non-factorisable* corrections are **colour-suppressed** and, therefore, are expected to be **negligible**.



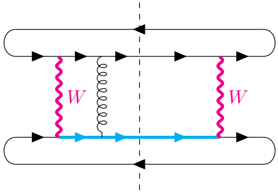
$$\text{tr}\left(t^a t^a\right)\text{tr}\left(t^b t^b\right) = \frac{1}{4}(N_c^2 - 1)^2$$



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

Non-factorisable corrections **vanish** at NLO because of colour.

→ **No indication from NLO.**



$$\propto \text{Tr}[t^a] = 0$$

Non-factorisable contributions

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But it is not obvious that *non-factorisable* corrections are in fact negligible.

- Factorisable NNLO QCD corrections are **small** (few %).
- **Possible π^2 enhancement** due to the *Glauber phase*.
  - ➥ **Virtual effect** that, in principle, does not require a scattering to occur. $p_\perp^t \to 0$

$$\sigma = \underbrace{\sigma_0}_{\pi^2} + \overbrace{\frac{p_\perp^t}{\sqrt{s}}\sigma_1 + \mathcal{O}\left(\left(p_\perp^t/\sqrt{s}\right)^2\right)}^{\text{real emission}}$$

(virtual correction: $\sigma_0 + \frac{p_\perp^t}{\sqrt{s}}\sigma_1 + \mathcal{O}\left(\left(p_\perp^t/\sqrt{s}\right)^2\right)$)

$p_\perp^t \sim 40\,\mathrm{GeV} \qquad \sqrt{s} \sim 300\,\mathrm{GeV}$

  - ➥ Explicitely proved for the non-factorisable corrections to the Higgs production in weak boson fusion in the eikonal approximation. *Liu, Melnikov, et al. 2019* → See Alexander Penin's talk

This factor $\pi^2 \sim 10$ could **compensate** the factor 8 from colour suppression.

A better understanding of **non-factorisable** corrections to single-top production at LHC would be **beneficial**.

Purposes of this work

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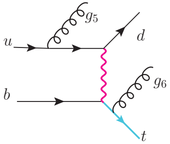
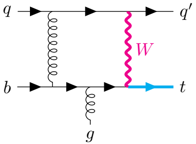
$\mathcal{A}_6^{(0)} =$



$\mathcal{A}_5^{(1)} =$

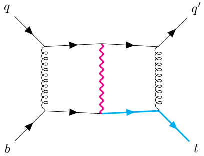


To calculate the non-factorisable corrections to single-top production.

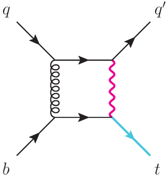
$$d\hat{\sigma}_{\text{n.f.}}^{\text{NNLO}} = \underbrace{d\hat{\sigma}_{\text{RR}}}_{\mathcal{A}_6^{(0)}} + \underbrace{d\hat{\sigma}_{\text{RV}}}_{\mathcal{A}_5^{(1)},\,\mathcal{A}_5^{(0)}} + \underbrace{d\hat{\sigma}_{\text{VV}}}_{\mathcal{A}_4^{(2)},\,\mathcal{A}_4^{(1)},\,\mathcal{A}_4^{(0)}}$$

- We keep the **exact dependence** on kinematic invariants, m_t and m_W.
- Master two-loop integrals are computed using the **auxiliary mass flow method**. *Liu, Ma, and Wang 2018* ⟶ See Christian's talk

$\mathcal{A}_4^{(2)} =$



$\mathcal{A}_4^{(1)} =$

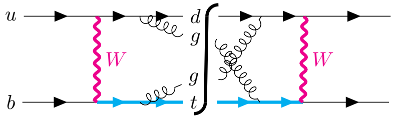


Non-factorisable contributions at NNLO

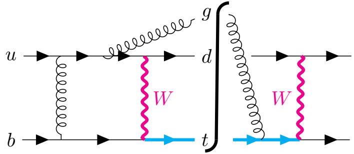
- What is needed to compute non-factorisable contribution at NNLO ?

$$d\hat{\sigma}^{\text{NNLO}}_{\text{n.f.}} = \underbrace{d\hat{\sigma}_{\text{RR}}}_{\mathcal{A}_6^{(0)}} + \underbrace{d\hat{\sigma}_{\text{RV}}}_{\mathcal{A}_5^{(1)},\, \mathcal{A}_5^{(0)}} + \underbrace{d\hat{\sigma}_{\text{VV}}}_{\mathcal{A}_4^{(2)},\, \mathcal{A}_4^{(1)},\, \mathcal{A}_4^{(0)}}$$

$$d\hat{\sigma}_{\text{RR}} : \mathcal{A}_6^{(0)} \otimes \mathcal{A}_6^{(0)} =$$



$$d\hat{\sigma}_{\text{RV}} : \mathcal{A}_5^{(1)} \otimes \mathcal{A}_5^{(0)} =$$



Properties of the process

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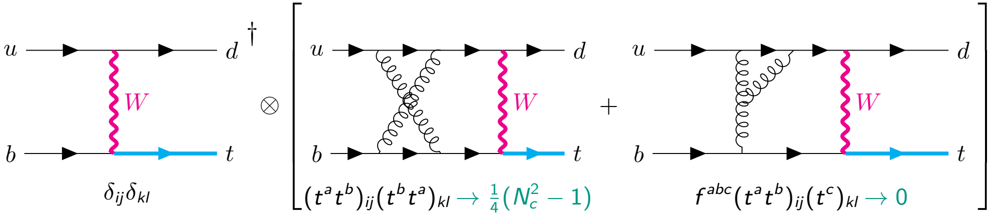
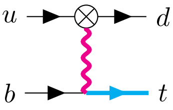


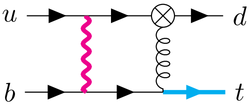
Upon interference, the non-Abelian part of the amplitude disappears and the amplitude is, effectively, **Abelian**.

UV and IR singularities

- Non-factorisable contributions are **UV-finite** at NNLO.

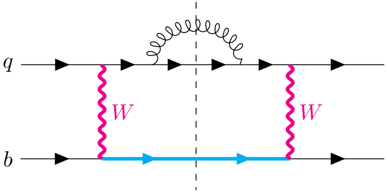


$\delta_{ij}\delta_{kl}$



$t^a_{ij} t^a_{kl}$

- **No collinear singularities** appear in non-factorisable contributions



$\in$ factorisable corrections

All singularities are from soft origin.

How to extract the soft singularity from loop amplitudes?

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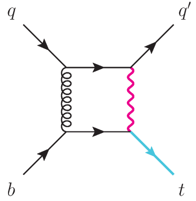
It is standard to project out loop amplitudes on **colour space vectors** $|c\rangle$ to extract their singularities *Catani 1998*

$$\langle c|\mathcal{A}_4^{(1)}(1_q, 2_b, 3_{q'}, 4_t)\rangle = \frac{\alpha_s}{2\pi}\left(\cdots + t^a_{c_3 c_1} t^a_{c_4 c_2} B_1(1_q, 2_b, 3_{q'}, 4_t)\right) .$$



The **pole structure** of the one-loop amplitude reads

$$B_1(1_q, 2_b, 3_{q'}, 4_t) = I_1(\epsilon)\, A_0(1_q, 2_b, 3_{q'}, 4_t) + B_{1,\mathrm{fin}}(1_q, 2_b, 3_{q'}, 4_t) ,$$

where

$$I_1(\epsilon) \equiv \frac{1}{\epsilon}\left[\ln\left(\frac{p_1 \cdot p_4\; p_2 \cdot p_3}{p_1 \cdot p_2\; p_3 \cdot p_4}\right) + 2\pi i\right] .$$

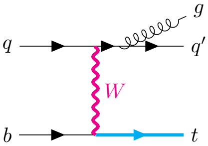
The **Abelian nature** of the *non-factorisable* corrections leads to a simple pole structure of the two-loop amplitude

$$B_2(1_q, 2_b, 3_{q'}, 4_t) = -\frac{I_1^2(\epsilon)}{2}\, A_0(1_q, 2_b, 3_{q'}, 4_t) + I_1(\epsilon)\, B_1(1_q, 2_b, 3_{q'}, 4_t) + B_{2,\mathrm{fin}}(1_q, 2_b, 3_{q'}, 4_t) .$$

How to extract the soft singularity from real emission?

We consider one gluon emission amplitude and extract the **color structure**

$$\langle c|\mathcal{A}_5^{(0)}(1_q,2_b,3_{q'},4_t,5_g)\rangle = g_s\left(t^{c_5}_{c_3c_1}\delta_{c_4c_2}\,A_0^L(1_q,2_b,3_{q'},4_t;5_g)+\delta_{c_3c_1}t^{c_5}_{c_4c_2}\,A_0^H(1_q,2_b,3_{q'},4_t;5_g)\right),$$



The amplitude **factorises** in the limit where the gluon energy $E_5 \to 0$

$$S_5 A_0^L = J(3,1;5,\epsilon_5)A_0(1_q,2_b,3_{q'},4_t) \quad \text{with} \quad J(i,j;k,\epsilon) = \epsilon_\mu\left(\frac{p_i^\mu}{p_i\cdot p_k}-\frac{p_j^\mu}{p_j\cdot p_k}\right)$$

We need the **interference** between emission from the **light line** A_0^L and the one with emission from **heavy line** A_0^H

$$S_5\left\{2\mathrm{Re}[A_0^{L*}A_0^H]\right\} = \sum_\lambda J(3,1,5,\epsilon_5)J(4,2,5,\epsilon_5)|A_0(1_q,2_b,3_{q'},4_t)| = \mathrm{Eik}_{nf}(1_q,2_b,3_{q'},4_t,5_g)|A_0(1_q,2_b,3_{q'},4_t)|$$

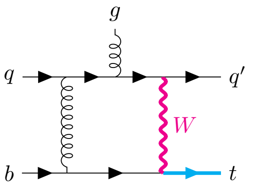
After integration over the gluon phase space

$$g_s^2\int[dk]\,\mathrm{Eik}_{\mathrm{nf}}(1_q,2_b,3_{q'},4_t;k_g) \equiv \frac{\alpha_s}{2\pi}\left(\frac{2E_{\max}}{\mu}\right)^{-2\epsilon}\left[\frac{1}{\epsilon}\ \ln\left(\frac{p_1\cdot p_4\ p_2\cdot p_3}{p_1\cdot p_2\ p_3\cdot p_4}\right)+\mathcal{O}(\epsilon^0)\right].$$

Real-virtual contribution

We need the one-loop five-point amplitude $\mathcal{A}_5^{(1)}(1_q, 2_b, 2_{q'}, 4_t, 5_g)$.

- Turn out to be **non-trivial** due to the presence of **multiple mass scales**!
- 24 diagrams generated with `QGRAF` and `FORM` - 8 pentagons and 16 boxes



7 mass scales

Spinor structure - How to extract ϵ dependence?

External momenta lives in $d = 4$, internal momenta in $d = 4-2\epsilon$: $\gamma^\mu = \gamma^{\bar{\mu}} + \gamma^{\tilde{\mu}}$

$$\overline{u}_t(p_4)\gamma^\mu\gamma^\nu u_b(p_2) = \overline{u}_t(p_4)\gamma^{\bar{\mu}}\gamma^{\bar{\nu}} u_b(p_2) + g^{\tilde{\mu}\tilde{\nu}}\,\overline{u}_t(p_4)u_b(p_2)\,.$$

W boson **forces light quark to be left-handed** and we decompose the massive momentum into 2 massless momenta

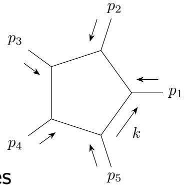
$$P_L u(p_4) = |4^\flat] + \frac{m_t}{\langle 4^\flat 1_q\rangle}|1_q\rangle, \qquad P_R u(p_4) = |4^\flat\rangle + \frac{m_t}{[4^\flat 1_q]}|1_q]$$

We are left with 2 spinor structures per helicity configuration

E.g. Left-handed gluon and left-handed top: $\langle 4^\flat 5_g\rangle^2 \langle 1_q 3_{q'}\rangle [4^\flat 1_q][1_q 2_b]$, $\quad \langle 4^\flat 5_g\rangle \langle 3_{q'} 5_g\rangle [1_q 2_b]$

Form factors

Reduction of pentagons of rank r, $r \leq 3$



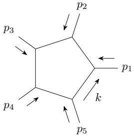
$$\int \frac{d^d k}{(2\pi)^d} \frac{k^{\mu_1} \dots k^{\mu_r}}{\prod_{i=1}^{5} \left[(k+q_i)^2 - m_i^2\right]} \quad \text{where } q_i = \sum_{j=1}^{i} p_j$$

We introduce the **van Neerven-Vermaseren basis** $v_i \cdot p_j = \delta_{ij}$ and the loop momentum becomes

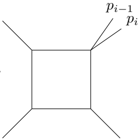
$$k^\mu = \sum_{i=1}^{4} (k \cdot p_i) v_i$$

and rewrite
$$k \cdot p_i = \underbrace{\frac{1}{2}\left[(k+q_i)^2 - m_i^2\right] - \frac{1}{2}\left[(k+q_{i-1})^2 - m_{i-1}^2\right]}_{\text{Boxes of rank } r-1 \quad \to \text{Passarino-Veltman}} + \underbrace{\frac{1}{2}\left[m_i^2 - m_{i-1}^2 - p_i^2 - 2p_i \cdot q_{i-1}\right]}_{\text{Pentagon of rank } r-1 \quad \to \text{Repeat}}$$

Scalar pentagon can be expressed as a combination of boxes up to $\mathcal{O}(\epsilon)$



$$= \sum_{i=1}^{5} \mathcal{C}_i$$



$$+ \mathcal{O}(\epsilon)$$

Numerical stability

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- The real-virtual amplitude can be written in terms of **109** scalar box,triangle and bubble integrals.
- By switching to a basis with **finite box integrals**, the complexity of the integral coefficient **reduces drastically**.

$$\text{e.g.} \qquad I_{4,1} = \int \frac{\mathrm{d}^d k}{(2\pi)^d} \frac{1}{k^2(k-p_1)^2(k-p_1-p_2)^2(k-p_1-p_2+p_5)^2} \, .$$

This integral is **infrared-divergent** when one of the propagator goes on-shell. We can **regulate** these divergences through numerator insertion

$$\begin{aligned}\mathrm{tr}\left((-\not{p}_1)(\not{k}-\not{p}_1)(\not{k}-\not{p}_1-\not{p}_2)(\not{p}_5)\right) = &- s_{12}\left(s_{12}+s_{15}-s_{34}\right) + \left(s_{12}+s_{15}-s_{34}\right) k^2 \\ &- \left(s_{12}-s_{34}\right)\left(k-p_1\right)^2 + \left(s_{12}+s_{15}\right)\left(k-p_1-p_2\right)^2 \\ &- s_{12}\left(k-p_1-p_2+p_5\right)^2 \, .\end{aligned}$$

After this change of basis:

- The **complicated coefficients** in front of the box integrals can be evaluated with $\epsilon \to 0$.
- The coefficients of the triangle integrals either become independent of $d = 4 - 2\epsilon$ or simply **vanish**.

Double-virtual contribution

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- Reduction performed **analytically** with `KIRA` 2.0: *Klappert, Lange, et al. 2020* → See Johann Usovitsch's talk and `FireFly` *Klappert and Lange 2020; Klappert, Klein, et al. 2021*:

$$\langle A^{(0)} | A^{(2)}_{\text{nf}} \rangle = \sum_{i=1}^{428} c_i(d, s, t, m_t, m_W) I_i$$

- Analytic reduction is possible with four scales $(s,\ t,\ m_t,\ m_W)$: $\mathcal{O}(1)$ day

- 428 master integrals I_i in 18 families

- All **428** master integrals evaluated numerically using **the auxiliary mass flow method** to 20 digits in ~ 30 minutes on a single core. → See Christian's talk

Double-virtual contribution

- Comparison of poles at a typical phase space point $s \approx 104.337$ GeV^2 and $t \approx -5179.68$ GeV^2.

	ϵ^{-2}	ϵ^{-1}
$\langle \mathcal{A}^{(0)} \vert \mathcal{A}_{\mathrm{nf}}^{(2)} \rangle$	$-229.0940408654660 - 8.978163333241640i$	$-301.180298894476 4 - 264.1773596529505i$
IR poles	$-229.0940408654665 - 8.978163333241973i$	$-301.1802988944791 - 264.1773596529535i$

- The cross-section is evaluated with a **Vegas integrator**.

- 10 sets of 10^5 points extracted from a grid prepared **on the Born squared amplitude.**

- The 10 different sets give an estimation of the error on σ_{VV}: $\mathcal{O}(2\%)$ *Brønnum-Hansen et al. 2021*

Results

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- The non-factorisable correction to the leading-order cross section at 13 TeV and $\mu_F = m_t$

$$\frac{\sigma_{pp\to X+t}}{1\,\mathrm{pb}} = 117.96 \pm 0.26 \left(\frac{\alpha_s(\mu_R)}{0.108}\right)^2$$

- *Non-factorisable* correction is about **0.2%** for $\boldsymbol{\mu_R = m_t}$.
- *Non-factorisable* corrections **appear for the first time** at NNLO ; for this reason, they are **independent** of LO, NLO, and NNLO *factorisable* contribution. $\rightarrow$ No indication of a good scale choice.
- At $\mu_R = 40$ GeV, typical transverse momentum of the top quark, corrections become **close to 0.35%.**
- In comparison, NNLO **factorisable correction** to NLO cross section are about **0.7%** *Campbell, Neumann, et al. 2021*

Top-quark transverse momentum distribution

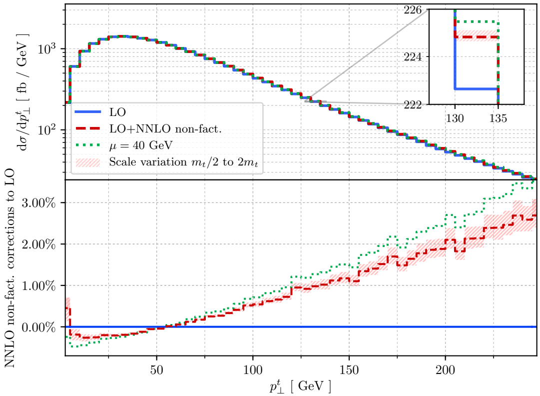

Figure: The top quark transverse momentum distribution.

- There is a **significant** $p_\perp^t$-dependence of the non-factorisable corrections.
- The behaviour of the corrections at small $p_\perp^t$ is the same as the one for the double-virtual cross-section.
- Non-factorisable corrections vanish around 50 GeV. The factorisable corrections vanish around 30 GeV. *Campbell, Neumann, et al. 2021*
- In some part of the phase space at low $p_\perp^t$, at the peak of the distribution, non-factorisable corrections are **dominant** compare to non-factorisable corrections.

Conclusion

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- We computed **the missing part** of NNLO QCD corrections to the t-channel single-top production: **the non-factorisable corrections**.

- **The auxiliary mass flow method** has been used for integrals evaluation. It is sufficiently **robust** to produce results relevant for phenomenology.

- Due to **multiple mass scales** appearing in one-loop amplitude, its reduction to master integral and its **stable and efficient numerical evaluation** turns out to be **non-trivial.**

- Non-factorisable corrections are smaller than, but **quite comparable** to, the factorisable ones.

- If a percent precision in single-top studies can be reached, **the non-factorisable effect will have to be taken into account.**

Thank you for your attention !

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Leading jet rapidity distribution

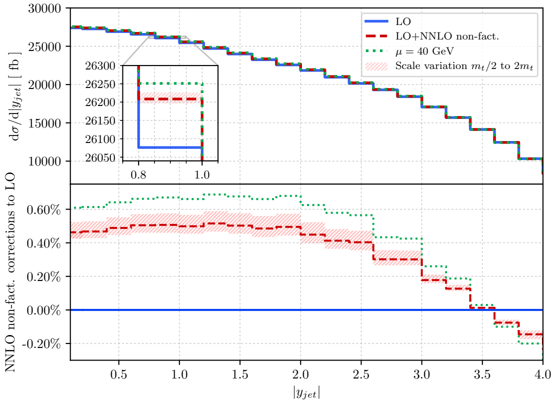

Figure: Rapidity of the leading jet distribution.

- k_t jet algorithm - $p_\perp^{jet} = 30\,\mathrm{GeV}$ and $R_{jet} = 0.4$
- Constant correction of $\mathcal{O}(0.5\%)$ from $|y_{jet}| < 2$.
- Corrections change sign at $|y_{jet}| \sim 3.5$.

Table for factorisable corrections

	7 TeV pp		14 TeV pp		1.96 TeV $\bar{p}p$
	top	anti-top	top	anti-top	$t+\bar{t}$
$\sigma_{\text{LO}}^{\mu=m_t}$	$37.1^{+7.1\%}_{-9.5\%}$	$19.1^{+7.3\%}_{-9.7\%}$	$134.6^{+10.0\%}_{-12.1\%}$	$78.9^{+10.4\%}_{-12.6\%}$	$2.09^{+0.8\%}_{-3.1\%}$
$\sigma_{\text{LO}}^{\text{DDIS}}$	$39.5^{+6.4\%}_{-8.6\%}$	$19.9^{+7.0\%}_{-9.3\%}$	$140.9^{+9.4\%}_{-11.4\%}$	$80.7^{+10.2\%}_{-12.3\%}$	$2.31^{-0.3\%}_{-1.8\%}$
$\sigma_{\text{NLO}}^{\mu=m_t}$	$41.4^{+3.0\%}_{-2.0\%}$	$21.5^{+3.1\%}_{-2.0\%}$	$154.3^{+3.1\%}_{-2.3\%}$	$91.4^{+3.1\%}_{-2.2\%}$	$1.96^{+3.1\%}_{-2.3\%}$
$\sigma_{\text{NLO}}^{\text{DDIS}}$	$41.8^{+3.3\%}_{-2.0\%}$	$21.5^{+3.4\%}_{-1.6\%}$	$154.4^{+3.7\%}_{-1.4\%}$	$91.2^{+3.1\%}_{-1.8\%}$	$2.00^{+3.6\%}_{-3.4\%}$
	PDF $^{+1.7\%}_{-1.4\%}$	PDF $^{+2.2\%}_{-1.5\%}$	PDF $^{+1.7\%}_{-1.1\%}$	PDF $^{+1.9\%}_{-0.9\%}$	PDF $^{+4.3\%}_{-5.3\%}$
$\sigma_{\text{NNLO}}^{\mu=m_t}$	$41.9^{+1.2\%}_{-0.7\%}$	$21.9^{+1.2\%}_{-0.7\%}$	$153.3(2)^{+1.0\%}_{-0.6\%}$	$91.5(2)^{+1.1\%}_{-0.9\%}$	$2.08^{+2.0\%}_{-1.3\%}$
$\sigma_{\text{NNLO}}^{\text{DDIS}}$	$41.9^{+1.3\%}_{-0.8\%}$	$21.8^{+1.3\%}_{-0.7\%}$	$153.4(2)^{+1.1\%}_{-0.7\%}$	$91.2(2)^{+1.1\%}_{-0.9\%}$	$2.07^{+1.7\%}_{-1.1\%}$
	PDF $^{+1.3\%}_{-1.1\%}$	PDF $^{+1.4\%}_{-1.3\%}$	PDF $^{+1.2\%}_{-1.0\%}$	PDF $^{+1.0\%}_{-1.0\%}$	PDF $^{+3.7\%}_{-5.0\%}$

Figure: Fully inclusive in pb for pp at 7 TeV and 14 TeV (LHC), as well as $p\bar{p}$ at 1.96 TeV (Tevatron) with scales $\mu_R = \mu_F = m_t$ and DDIS scales and using CT14 PDFs. *Campbell, Neumann, et al. 2021*

Results for the virtual contribution

- Comparison of poles at a typical phase space point $s \approx 104.337$ GeV^2 and $t \approx -5179.68$ GeV^2.

	ϵ^{-2}	ϵ^{-1}
$\langle \mathcal{A}^{(0)} \vert \mathcal{A}^{(2)}_{\rm nf} \rangle$	$-229.0940408654660 - 8.978163333241640i$	$-301.1802988944764 - 264.1773596529505i$
IR poles	$-229.0940408654665 - 8.978163333241973i$	$-301.1802988944791 - 264.1773596529535i$

- Double-virtual cross-section calculation from fixed grid of 100k points

$$\sigma^{ub}_{pp\to dt} = \left(90.3 + 0.3\left(\frac{\alpha_s(\mu_{\rm nf})}{0.108}\right)^2\right)\ \mathrm{pb}$$

- Correction of about 0.3% for $\mu_{\rm nf} = 173$ GeV

- **Typical transverse momentum**: $\mu_{nf} = 40 - 60$ GeV. The magnitude of the non-factorisable corrections will **increase** by a factor $\mathcal{O}(1.5)$ and become close to **half a percent**.

Spinor structures and γ_5

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- Projection on to 11 spinor stuctures *Assadsolimani et al. 2014*

$$
\begin{aligned}
S_1 &= \bar{t}(p_4)\ b(p_2) \times \bar{q}'(p_3)\, \not{p}_4\, b(p_1) \\
S_2 &= \bar{t}(p_4)\, \not{p}_1\, b(p_2) \times \bar{q}'(p_3)\, \not{p}_4\, b(p_1) \\
S_3 &= \bar{t}(p_4)\, \gamma^{\mu_1}\, b(p_2) \times \bar{q}'(p_3)\, \gamma_{\mu_1}\, b(p_1) \\
S_4 &= \bar{t}(p_4)\, \gamma^{\mu_1} \not{p}_1\, b(p_2) \times \bar{q}'(p_3)\, \gamma_{\mu_1}\, b(p_1) \\
&\ \vdots \\
S_{11} &= \bar{t}(p_4)\, \gamma^{\mu_1}\gamma^{\mu_2}\gamma^{\mu_3}\gamma^{\mu_4}\gamma^{\mu_5}\, b(p_2) \times \bar{q}'(p_3)\, \gamma_{\mu_1}\gamma_{\mu_2}\gamma_{\mu_3}\gamma_{\mu_4}\gamma_{\mu_5}\, b(p_1)
\end{aligned}
$$

- Exploit anti-commutativity of γ_5 to move left-handed projectors to external *massless* fermions.
- Non-factorisable amplitude is expressed in terms of 11 form factors $\mathcal{A}_{nf}^{(2)} = \vec{f} \cdot \vec{S}$
- Form factors does not depend on helicities of external states.
  $\rightarrow$ **one can compute them with vector currents**.

Helicity amplitudes

- *'t Hooft-Veltman scheme*: external momenta in $d = 4$ and internal in $d = 4 - 2\epsilon$
- *At least two* matrices in $d = 4 - 2\epsilon$ are needed between two $d = 4$ spinors to have a support in -2ϵ space.

$$\bar{u}_d(p_3)\gamma_\mu\gamma_\nu \not{p}_4 u_u(p_1) \to \begin{pmatrix} \bar{u}_d(p_3) \\ 0 \end{pmatrix} \begin{pmatrix} \underbrace{\gamma_\mu \quad 0}_{d=4} \\ \underbrace{0 \quad \gamma_\mu}_{d=-2\epsilon} \end{pmatrix} \begin{pmatrix} \underbrace{\gamma_\nu \quad 0}_{d=4} \\ \underbrace{0 \quad \gamma_\nu}_{d=-2\epsilon} \end{pmatrix} \begin{pmatrix} \underbrace{\not{p}_4 \quad 0}_{d=4} \\ \underbrace{0 \quad 0}_{d=-2\epsilon} \end{pmatrix} \begin{pmatrix} \bar{u}_u(p_1) \\ 0 \end{pmatrix}$$

- ϵ dependence can be explicitly and unambigously extracted and γ_5 restored

$$\begin{cases} \mathcal{S}_{1,..,4} = \mathcal{S}^{(4)}_{1,..,4}\,, \\ \mathcal{S}_{5,6} = \mathcal{S}^{(4)}_{5,6} - 2\epsilon \mathcal{S}^{(4)}_{1,2}\,, \\ \mathcal{S}_{7,8} = \mathcal{S}^{(4)}_{7,8} - 6\epsilon \mathcal{S}^{(4)}_{3,4}\,, \\ \mathcal{S}_{9,10} = \mathcal{S}^{(4)}_{9,10} - 12\epsilon \mathcal{S}^{(4)}_{5,6} + \left(12\epsilon^2 + 4\epsilon\right) \mathcal{S}^{(4)}_{1,2}\,, \\ \mathcal{S}_{11} = \mathcal{S}^{(4)}_{11} - 20\epsilon \mathcal{S}^{(4)}_{7} + \left(60\epsilon^2 + 20\epsilon\right) \mathcal{S}^{(4)}_{3} \end{cases}$$

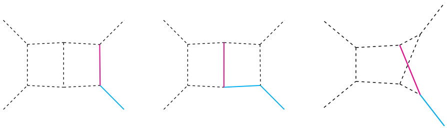
IBP reduction

- Find symmetry relations with `REDUZE` 2 *Manteuffel and Studerus 2012.*
- Reduction performed **analytically** with `KIRA` 2.0: *Klappert, Lange, et al. 2020* and `FireFly` *Klappert and Lange 2020; Klappert, Klein, et al. 2021:*

$$\langle A^{(0)} | A^{(2)}_{\mathrm{nf}} \rangle = \sum_{i=1}^{428} c_i(d, s, t, m_t, m_W) I_i$$

- Analytic reduction is possible with four scales $(s,\ t,\ m_t,\ m_W)$: $\mathcal{O}(1)$ day
- 428 master integrals I_i in 18 families
- file size of the simplified coefficients c_i: $\mathcal{O}(1)$ MB

Master integrals evaluation



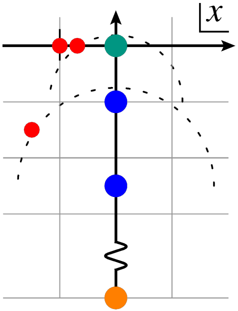
- Based on the **auxiliary mass flow method** *Liu, Ma, and Wang 2018; Liu, Ma, Tao, et al. 2020; Liu and Ma 2021*

$$m_W^2 \to m_W^2 - i\eta.$$

- Solve differential equations at each kinematic point

$$\partial_x \boldsymbol{I} = \boldsymbol{M}\boldsymbol{I}, \quad x \propto -i\eta.$$

with boundary condition $x \to -i\infty$.



Stepping from the boundary at $x \to -i\infty$, via regular points, to the physical mass. Step size is limited by singularities of the equation.

Master integral evaluation

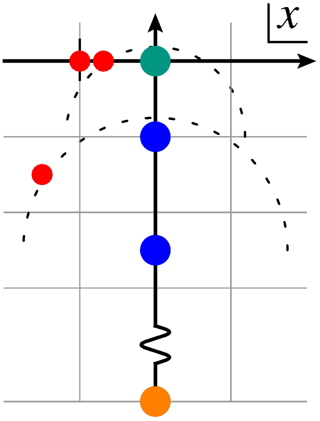
- Expand $\boldsymbol{I}$ around **boundary** in variable $y = x^{-1} = 0$:

$$\boldsymbol{I} = \sum_{j}^{M} \epsilon^{j} \sum_{k}^{N} \sum_{l} \boldsymbol{c}_{jkl} y^{k} \ln^{l} y + \dots$$

- Evaluate and expand around **regular points**:

$$\boldsymbol{I} = \sum_{j}^{M} \epsilon^{j} \sum_{k=0}^{N} \boldsymbol{c}_{jk} x'^{k} + \dots$$

- Evaluate at the **physical point.** $x = 0 \leftarrow$ **regular point**
- **Path** is fixed by **singularities** and desired precision.



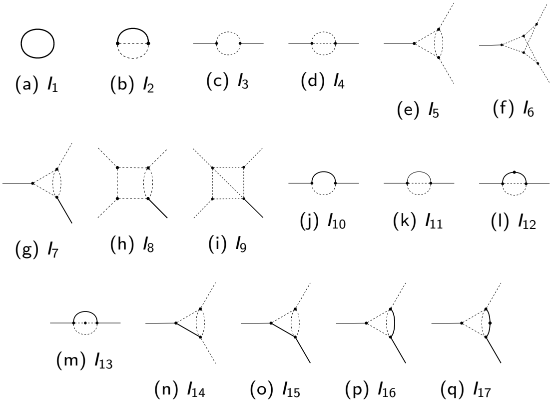
$m_W^2 \to m_W^2(1+x)$

References

Boundary conditions

- Most of the integrals needed can be found in the literature.
- Some of them are not available or are not known to sufficiently high ϵ order.
- All **428** master integrals evaluated numerically to 20 digits in ~ 30 minutes on a single core.

Master integrals for the boundary conditions



massive leg/propagator
massless leg/propagator

Master integral evaluation

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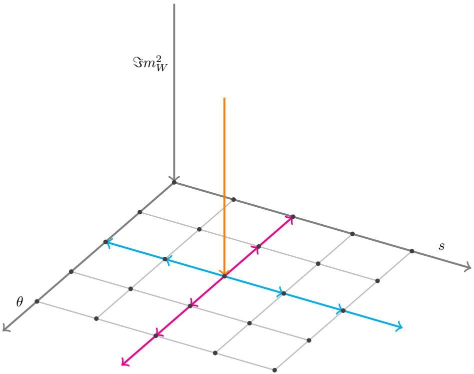
- We can use the differential equation w.r.t s and t to generate phase space points.
- Solving differential equation in each direction:

$$(s_1, t_1) \xrightarrow{s} (s_2, t_1) \xrightarrow{t} (s_2, t_2)$$

- This also serves as a consistency check.



Evaluation of the cross-section

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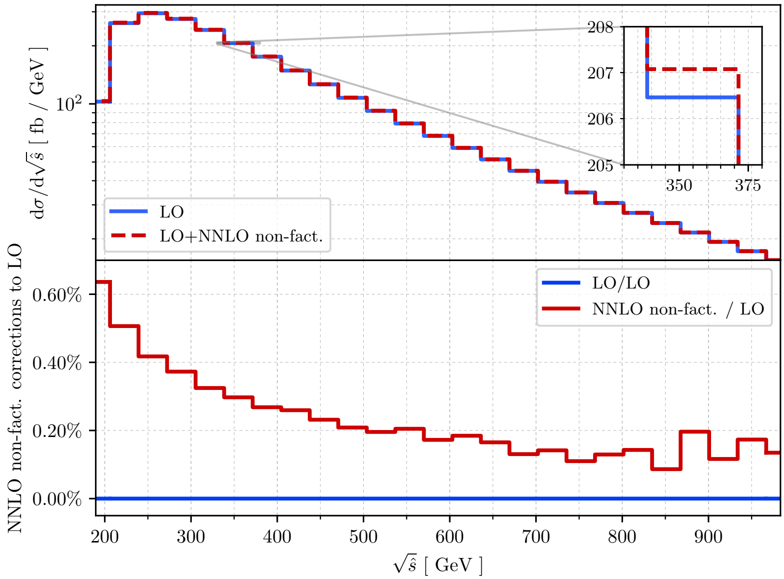
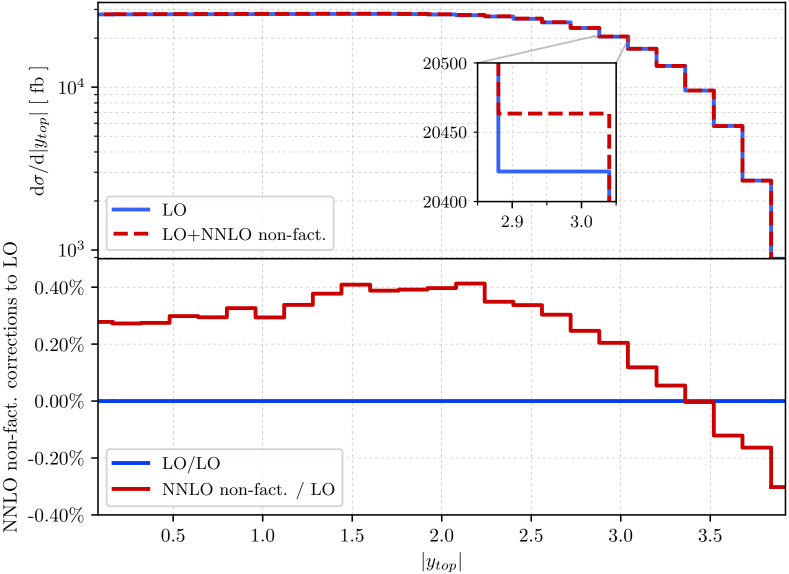
- The cross-section is evaluated with the help of a **Vegas integrator**.
- 10 grids of 10^4 points are prepared **on the Born squared amplitude**.
- $\mathcal{A}_{nf}^{(1)} \otimes \mathcal{A}_{nf}^{(1)}$ and $\mathcal{A}^{(0)} \otimes \mathcal{A}_{nf}^{(2)}$ are evaluated for each of the 10^5 points. ($\approx \mathcal{O}(1 \text{ day})$)
- The 10 different set of points give an estimation of the error of the total cross-section. (2%)


208
207
206
205
350
375
LO
LO+NNLO non-fact.
LO/LO
NNLO non-fact. / LO
0.60%
0.40%
0.20%
0.00%
200
300
400
500
600
700
800
900
10^2
$d\sigma/d\sqrt{\hat{s}}$ [fb / GeV]
NNLO non-fact. corrections to LO
$\sqrt{\hat{s}}$ [GeV]



10^4
10^3
$d\sigma/d|y_{top}|$ [fb]
LO
LO+NNLO non-fact.
20500
20450
20400
2.9
3.0
0.40%
0.20%
0.00%
-0.20%
-0.40%
NNLO non-fact. corrections to LO
LO/LO
NNLO non-fact. / LO
0.5
1.0
1.5
2.0
2.5
3.0
3.5
$|y_{top}|$

UV and IR singularities

- **No UV divergences** if we consider only non-factorisable contributions at NNLO.
- IR divergences are predicted using colour-space operators. *Catani 1998; Becher and Neubert 2009; Czakon and Heymes 2014*

$$|\mathcal{A}_{\rm nf}\rangle = \boldsymbol{Z}_{\rm nf}|\mathcal{F}_{\rm nf}\rangle, \qquad \mu\frac{d}{d\mu}\boldsymbol{Z}_{\rm nf} = -\boldsymbol{\Gamma}_{\rm nf}\boldsymbol{Z}_{\rm nf}$$

where the anomalous dimension operator, $\boldsymbol{\Gamma}_{\rm nf}$, is limited to non-factorisable relevant contributions

$$\boldsymbol{\Gamma}_{\rm nf} = \left(\frac{\alpha_s}{4\pi}\right)\boldsymbol{\Gamma}_{0,\rm nf} = \left(\frac{\alpha_s}{4\pi}\right)4\Bigg[\boldsymbol{T}_u\cdot\boldsymbol{T}_b\ln\left(\frac{\mu^2}{-s-i\varepsilon}\right) + \boldsymbol{T}_b\cdot\boldsymbol{T}_d\ln\left(\frac{\mu^2}{-u-i\varepsilon}\right)$$
$$+\boldsymbol{T}_u\cdot\boldsymbol{T}_t\ln\left(\frac{\mu\, m_t}{m_t^2-u-i\varepsilon}\right) + \boldsymbol{T}_d\cdot\boldsymbol{T}_t\ln\left(\frac{\mu\, m_t}{m_t^2-s-i\varepsilon}\right)\Bigg]$$

- Divergences of non-factorisable amplitude starts at $1/\epsilon^2$ due to **absence of collinear contributions**.

$$\langle\mathcal{A}^{(0)}|\mathcal{A}^{(2)}_{\rm nf}\rangle = -\frac{1}{8\epsilon^2}\langle\mathcal{A}^{(0)}|\boldsymbol{\Gamma}^2_{0,\rm nf}|\mathcal{A}^{(0)}\rangle + \frac{1}{2\epsilon}\langle\mathcal{A}^{(0)}|\boldsymbol{\Gamma}_{0,\rm nf}|\mathcal{A}^{(1)}_{\rm nf}\rangle + \langle\mathcal{A}^{(0)}|\mathcal{F}^{(2)}_{\rm nf}\rangle,$$
$$\langle\mathcal{A}^{(1)}_{\rm nf}|\mathcal{A}^{(1)}_{\rm nf}\rangle = \frac{1}{4\epsilon^2}\langle\mathcal{A}^{(0)}||\boldsymbol{\Gamma}_{0,\rm nf}|^2|\mathcal{A}^{(0)}\rangle + \frac{1}{2\epsilon}\langle\mathcal{A}^{(1)}_{\rm nf}|\boldsymbol{\Gamma}_{0,\rm nf}|\mathcal{A}^{(0)}\rangle + \frac{1}{2\epsilon}\langle\mathcal{A}^{(0)}|\boldsymbol{\Gamma}^\dagger_{0,\rm nf}|\mathcal{A}^{(1)}_{\rm nf}\rangle + \langle\mathcal{F}^{(1)}_{\rm nf}|\mathcal{F}^{(1)}_{\rm nf}\rangle.$$