Karlsruher Institut für Technologie

LHCPhysics
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Non-factorisable contributions to *t*-channel single-top production

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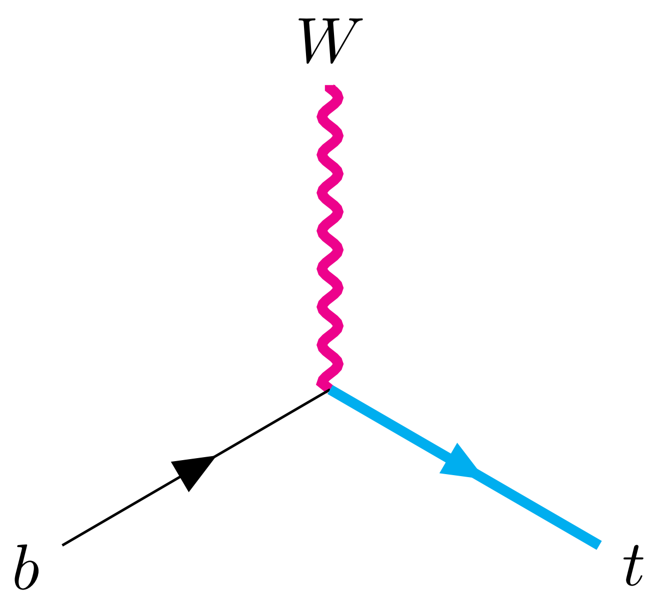
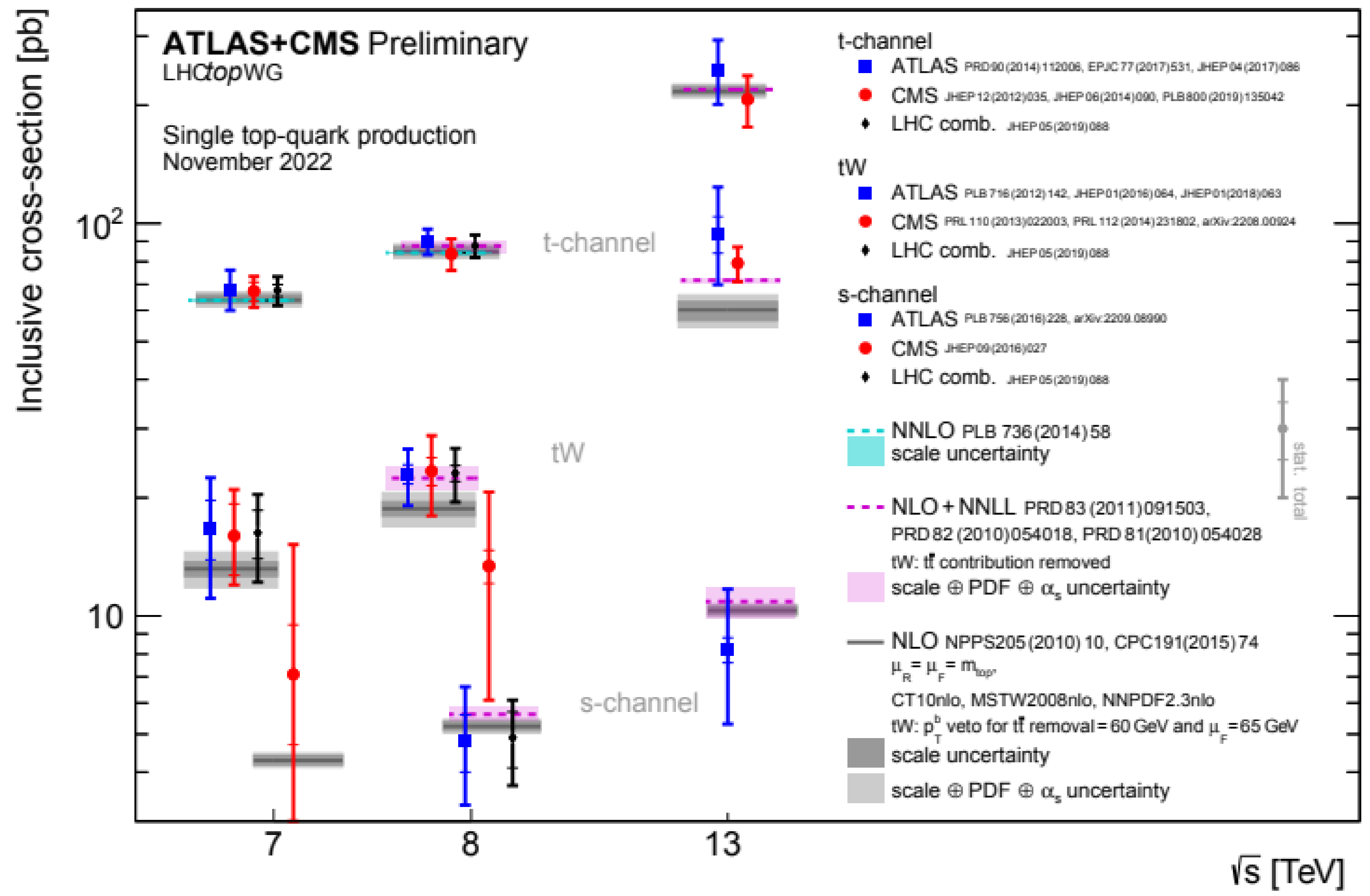
In collaboration with: Kirill Melnikov, Jérémie Quarroz, Chiara Signorile-Signorile, and Chen-Yu Wang
Based on 2108.09222 and 2204.05770

Single-top production: 3 channels

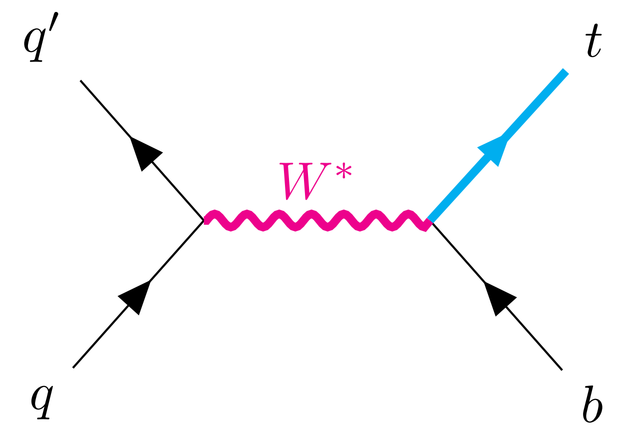
- Electroweak mediated



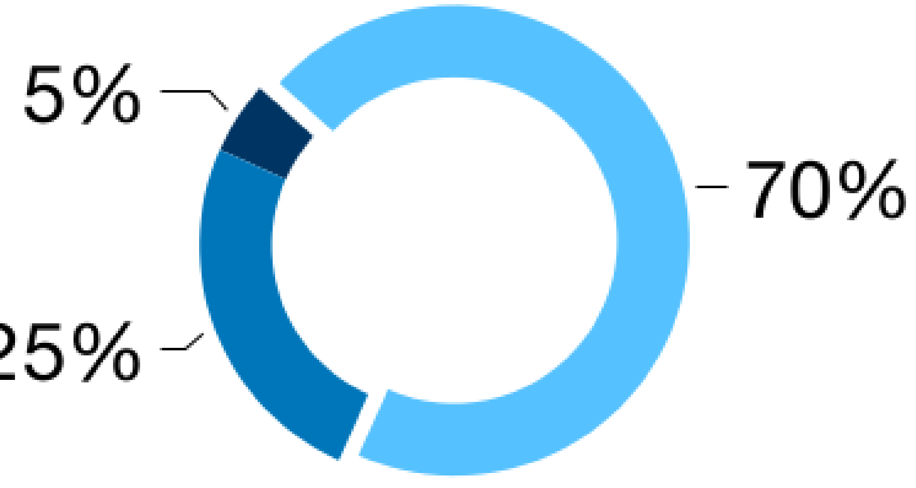
Determination of the **CKM matrix element**
Anomalous couplings
Indirect determination of top **width** and **mass**
Provides constraints on **PDF**

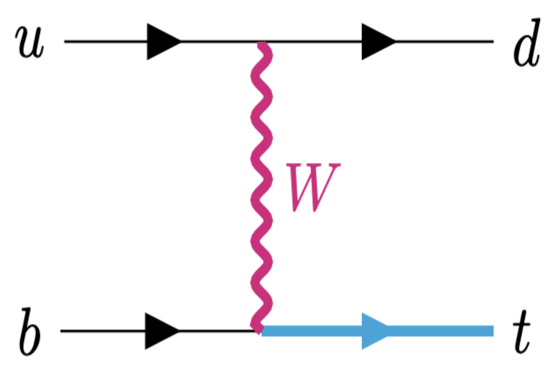


- Production rate at the LHC of comparable of magnitude to top pair: $\sigma_t \sim 0.2\,\sigma_{t\bar{t}}$

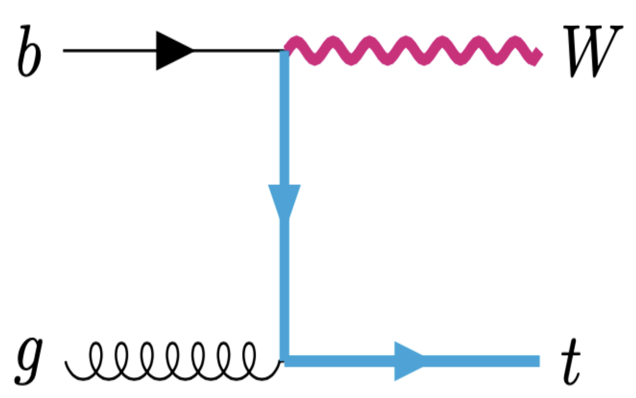


s-channel
$q\,q' \to b\,t$





t-channel
$q\,b \to q'\,t$



associated production
$g\,b \to W\,t$
not observed until 2014

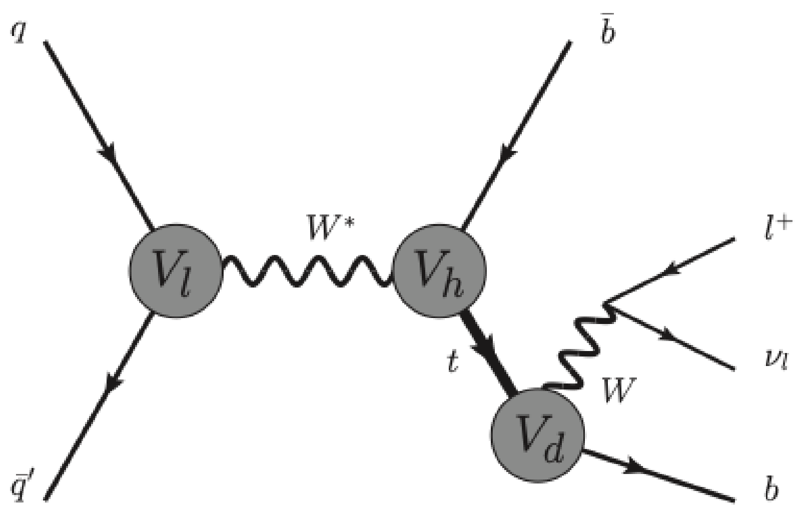
Single-top production: theory status, *s*- and *tW-channel*

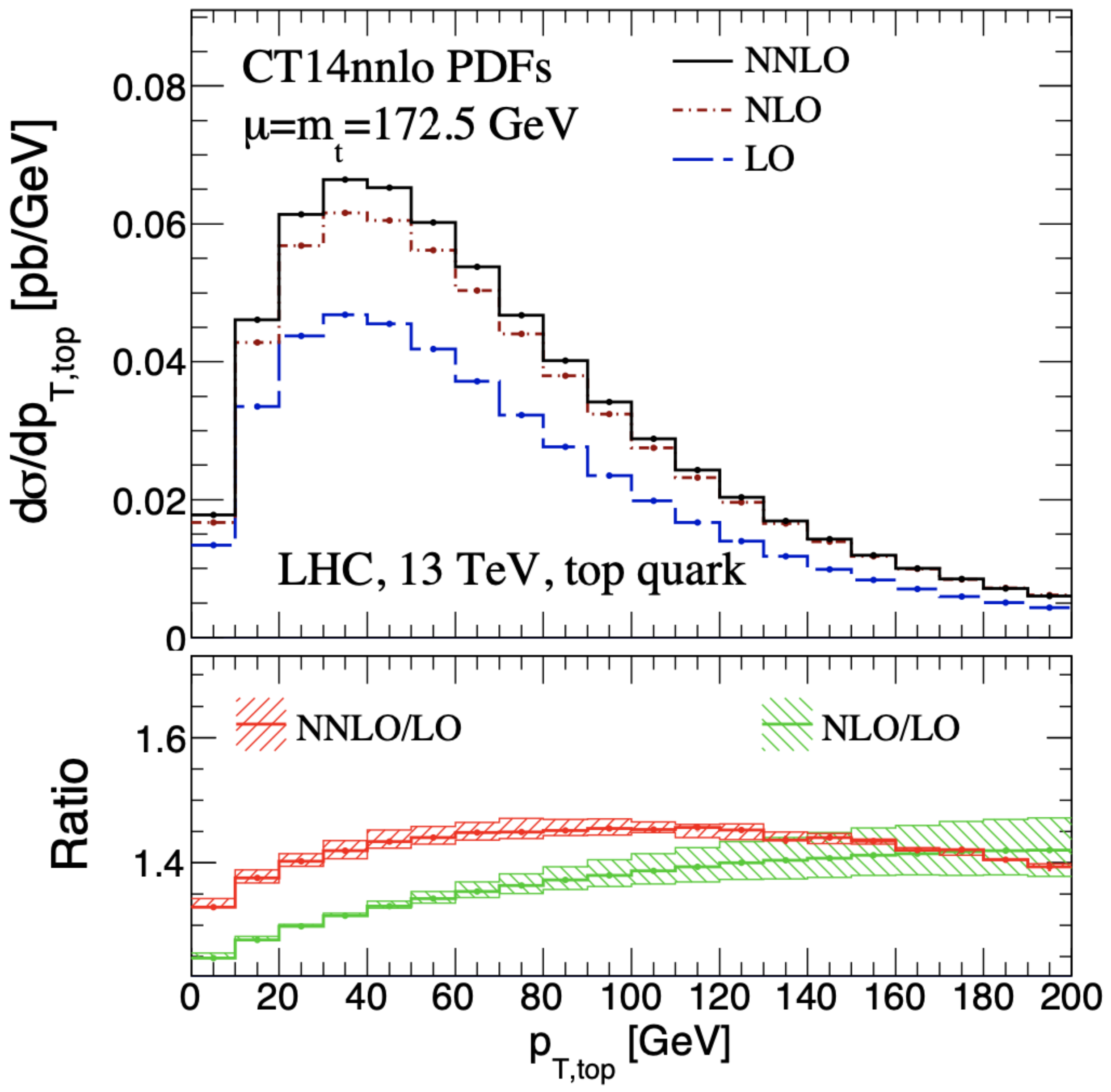
s-channel:

NNLO QCD corrections in production and decay *[Liu, Gao '18]*
Inclusive corrections are ~5 % w.r.t. NLO

In low $p_\perp$ region, NNLO corrections can reach 10 %

No overlap of NLO and NNLO bands in most regions: NNLO corrections underestimated.



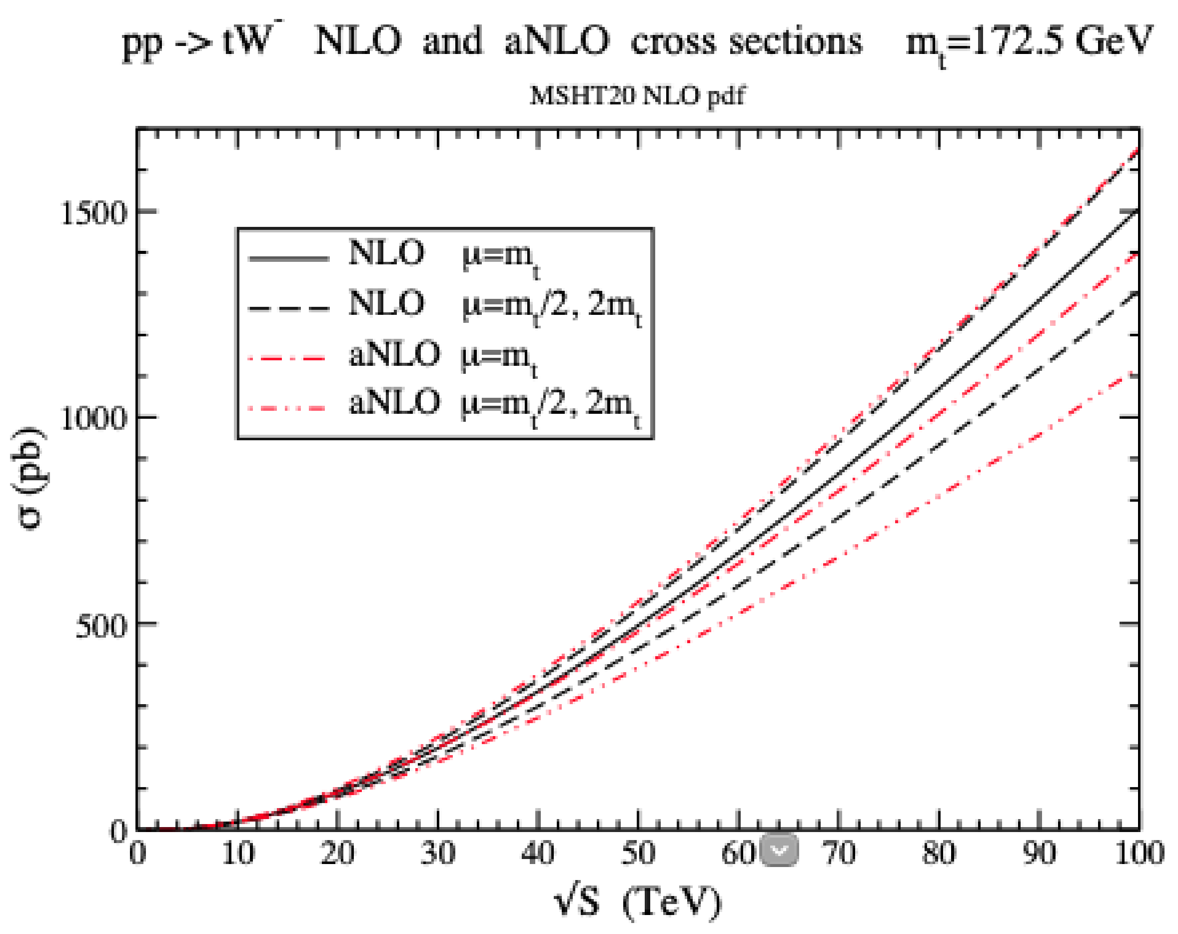


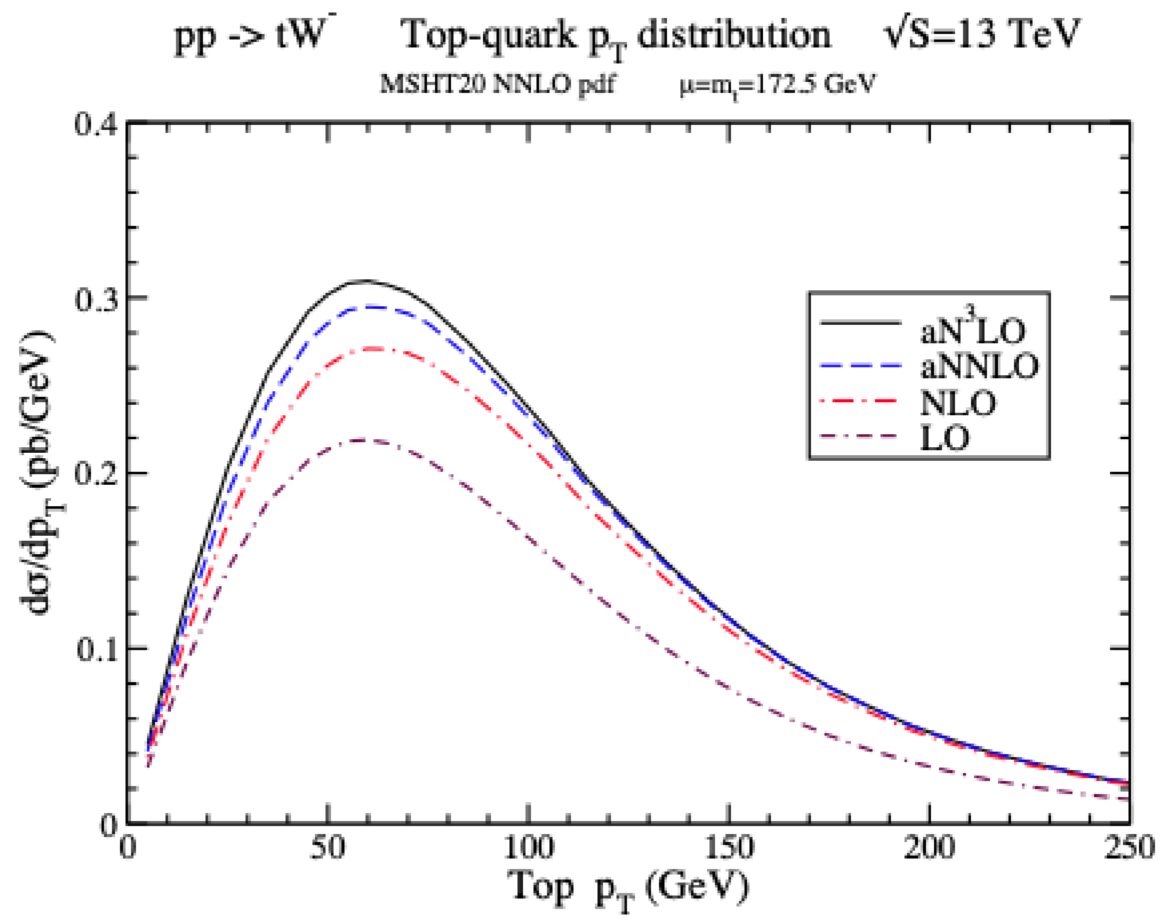
inclusive		LO	NLO	NNLO
8 TeV	$\sigma(t)$ [pb]	$2.498^{+0.17\%}_{-0.74\%}$	$3.382^{+2.36\%}_{-1.81\%}$	$3.566^{+0.95\%}_{-0.78\%}$
	$\sigma(\bar{t})$ [pb]	$1.418^{+0.12\%}_{-0.73\%}$	$1.922^{+2.37\%}_{-1.81\%}$	$2.029^{+1.07\%}_{-0.83\%}$
	$\sigma(t+\bar{t})$ [pb]	$3.916^{+0.15\%}_{-0.73\%}$	$5.304^{+2.36\%}_{-1.81\%}$	$5.595^{+0.99\%}_{-0.80\%}$
	$\sigma(t)/\sigma(\bar{t})$	$1.762^{+0.04\%}_{-0.01\%}$	$1.760^{+0.00\%}_{-0.02\%}$	$1.757^{+0.05\%}_{-0.12\%}$
13 TeV	$\sigma(t)$ [pb]	$4.775^{+2.69\%}_{-3.50\%}$	$6.447^{+1.39\%}_{-0.91\%}$	$6.778^{+0.76\%}_{-0.53\%}$
	$\sigma(\bar{t})$ [pb]	$2.998^{+2.69\%}_{-3.55\%}$	$4.043^{+1.33\%}_{-0.94\%}$	$4.249^{+0.69\%}_{-0.48\%}$
	$\sigma(t+\bar{t})$ [pb]	$7.772^{+2.69\%}_{-3.52\%}$	$10.49^{+1.36\%}_{-0.92\%}$	$11.03^{+0.74\%}_{-0.51\%}$
	$\sigma(t)/\sigma(\bar{t})$	$1.593^{+0.05\%}_{-0.01\%}$	$1.595^{+0.06\%}_{0.03\%}$	$1.595^{+0.07\%}_{-0.05\%}$

tW-channel:

Approximate approaches used to infer higher-order corrections *[Kidonakis, Yamanaka '21]*

NNLO QCD corrections not known yet (analytic 2-loop amplitudes known *[Chen, Dong, Li, Li, Wang, Wang '22]*)

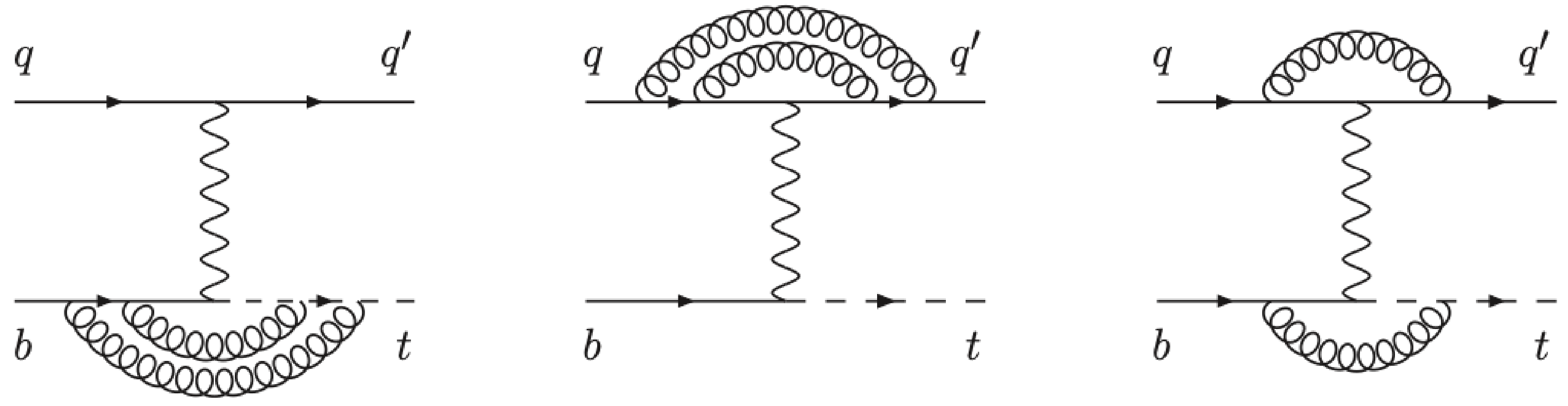




Single-top production: theory status, *t*-channel (I)

Two types of topologies contribute to the *t*-channel, single-top production:

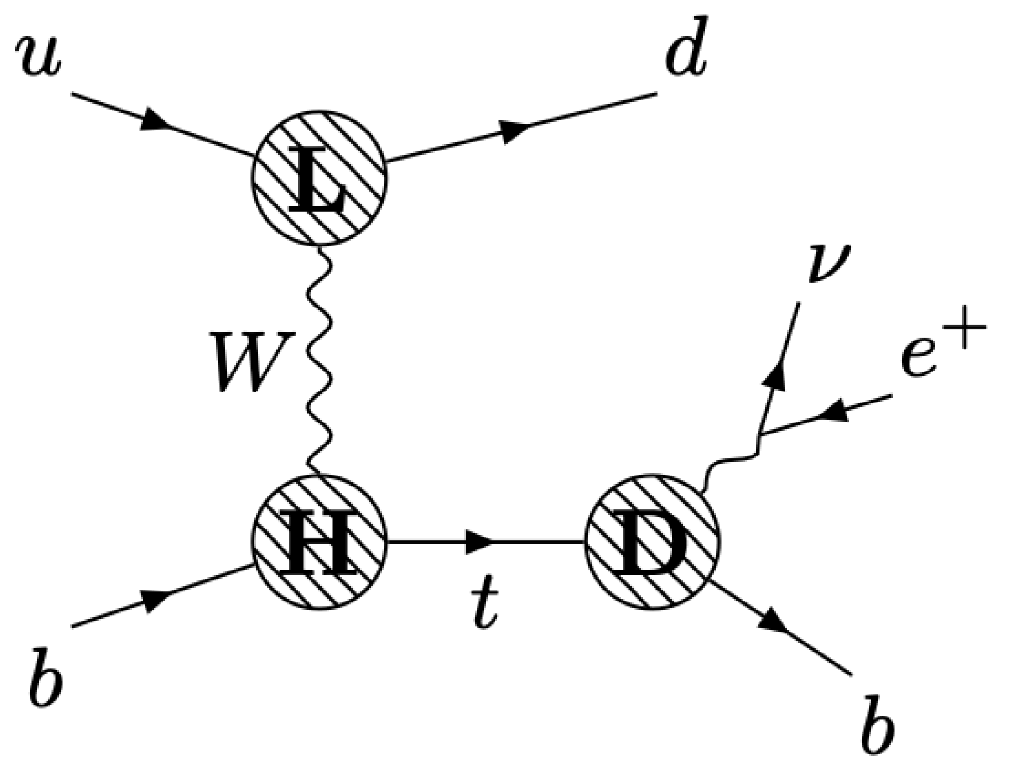
- **Factorisable contributions**
  - **Structure function approximation** → crosstalk between quark lines neglected due to colour suppression
  - **NLO QCD** *[Bordes, van Eijk '95] [Campbell, Ellis, Tramontano '04] [Cao, Yuan '05] [Cao, Schwienhorst, Benitez, Brock, Yuan '05] [Harris, Laenen, Phaf, Sullivan, Weinzierl '02] [Schwienhorst, Yuan, Mueller, Cao '11]*
  - **NNLO QCD**
  - First calculated for a **stable top quark** *[Brucherseifer, Caola, Melnikov '14]*
  - **Small effects** on inclusive cross-section and on cross-section with $p_{\perp,t}$ cuts



MSTW2008, lo, nlo, nnlo PDF, $\mu_R = \mu_F = m_t = 173$ GeV @ 8 TeV

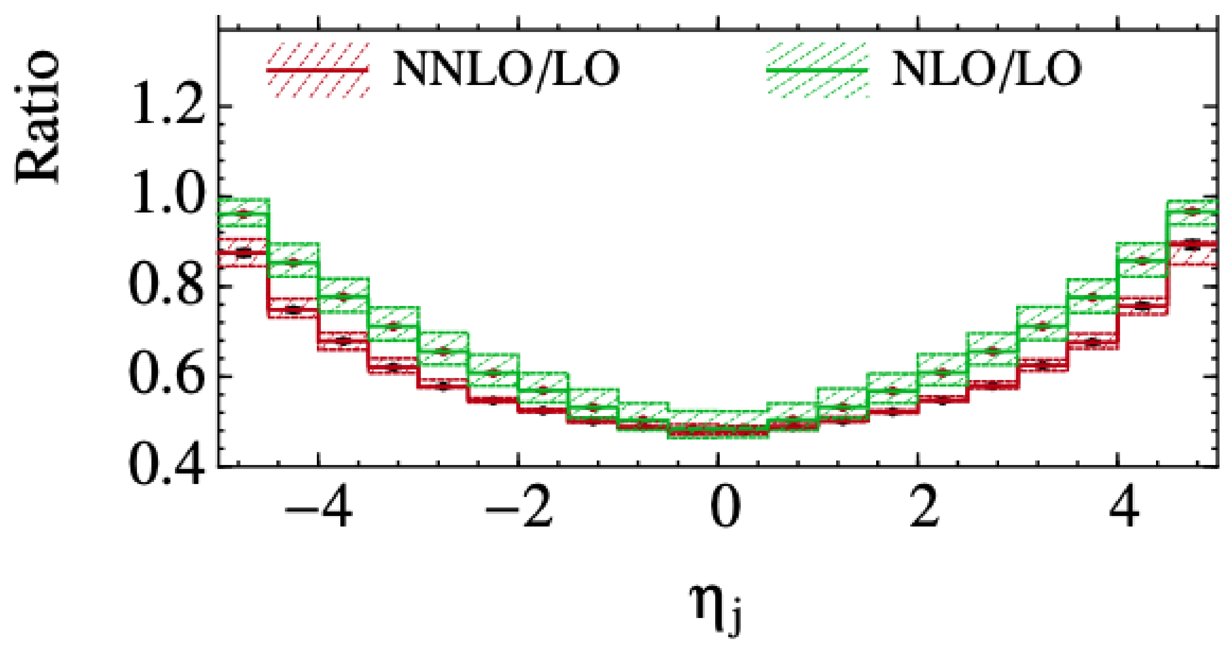
$p_\perp$	$\sigma_{\rm LO}$, pb	$\sigma_{\rm NLO}$, pb	$\delta_{\rm NLO}$	$\sigma_{\rm NNLO}$, pb	$\delta_{\rm NNLO}$
0 GeV	$53.8^{+3.0}_{-4.3}$	$55.1^{+1.6}_{-0.9}$	+2.4%	$54.2^{+0.5}_{-0.2}$	−1.6%
20 GeV	$46.6^{+2.5}_{-3.7}$	$48.9^{+1.2}_{-0.5}$	+4.9%	$48.3^{+0.3}_{-0.02}$	−1.2%
40 GeV	$33.4^{+1.7}_{-2.5}$	$36.5^{+0.6}_{-0.03}$	+9.3%	$36.5^{+0.1}_{+0.1}$	−0.1%
60 GeV	$22.0^{+1.0}_{-1.5}$	$25.0^{+0.2}_{+0.3}$	+13.6%	$25.4^{-0.1}_{+0.2}$	+1.6%

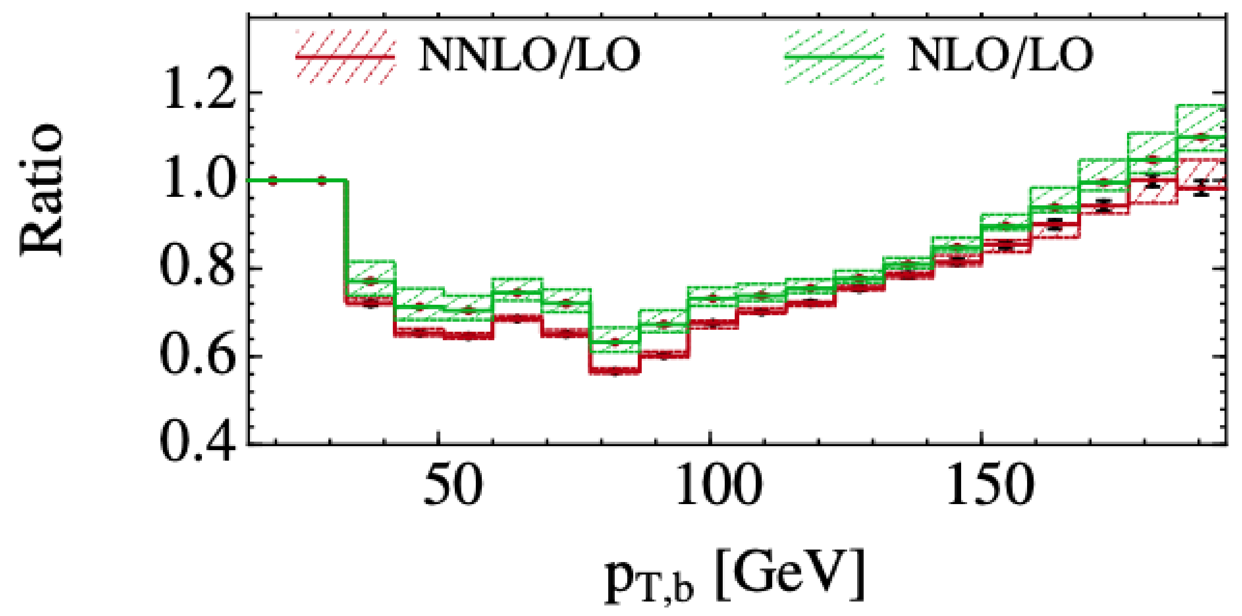
Single-top production: theory status, *t*-channel (II)



NNLO QCD

- Extension to **top-quark decay in the NW approximation**, including also NNLO in decay
- (computed using SCET/jettiness + projection to Born) *[Berger, Gao, Yuan, Zhu '16, '17]*
- Large corrections for some distributions





- Disagreement with earlier calculation of inclusive cross-section

- Independent calculation based on SCET approach *[Campbell, Neumann, Sullivan '21]*

$$\text{CT14, lo, nlo, nnlo PDF, } \mu_R = \mu_F = m_t = 172.5\,\text{GeV} @ 14\,\text{TeV}$$

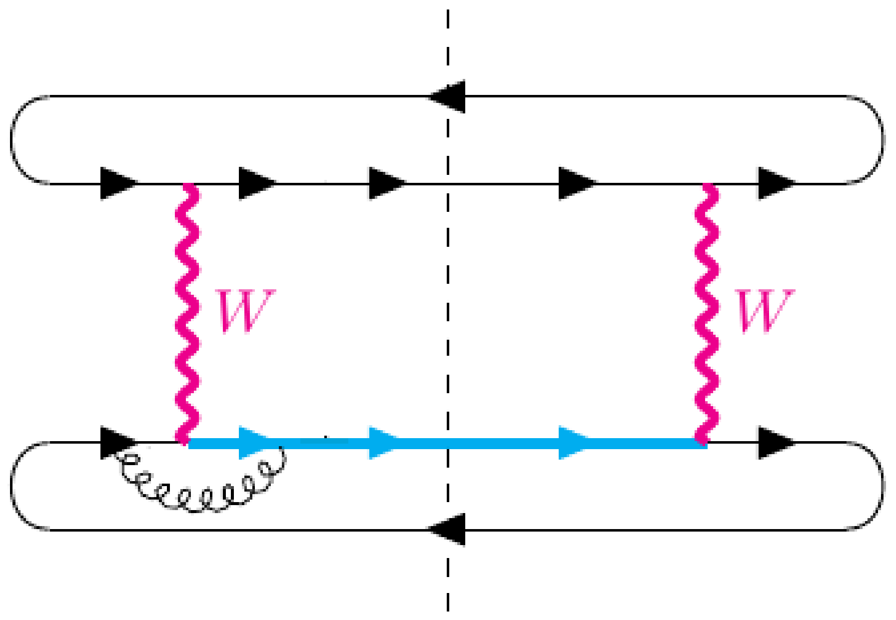
$$\delta\sigma^{\text{NNLO}} \sim -0.7\,\%\,\sigma^{\text{NLO}}$$

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

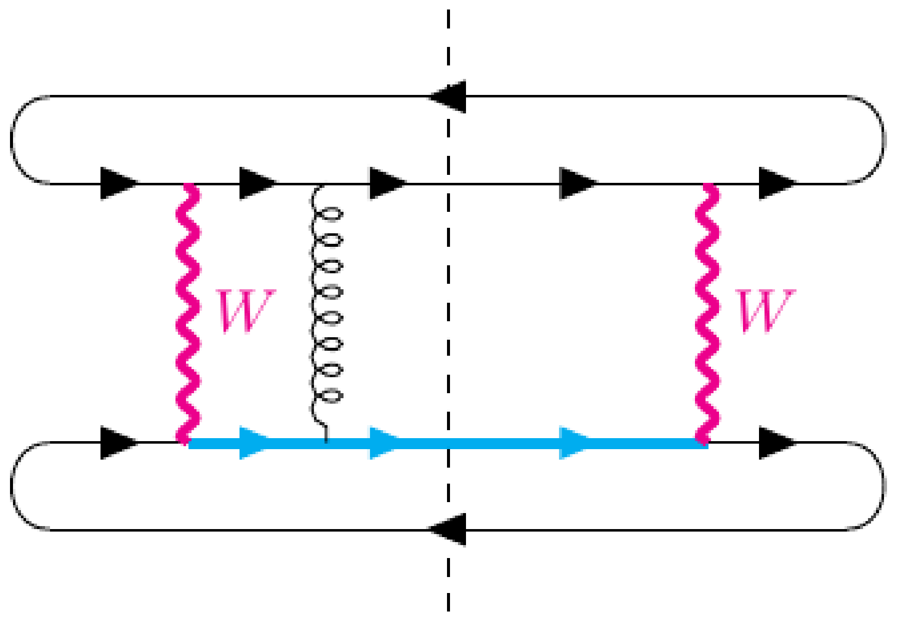
Non-factorisable corrections: why? (I)

Factorisable contributions | **Non-factorisable contributions**

NLO

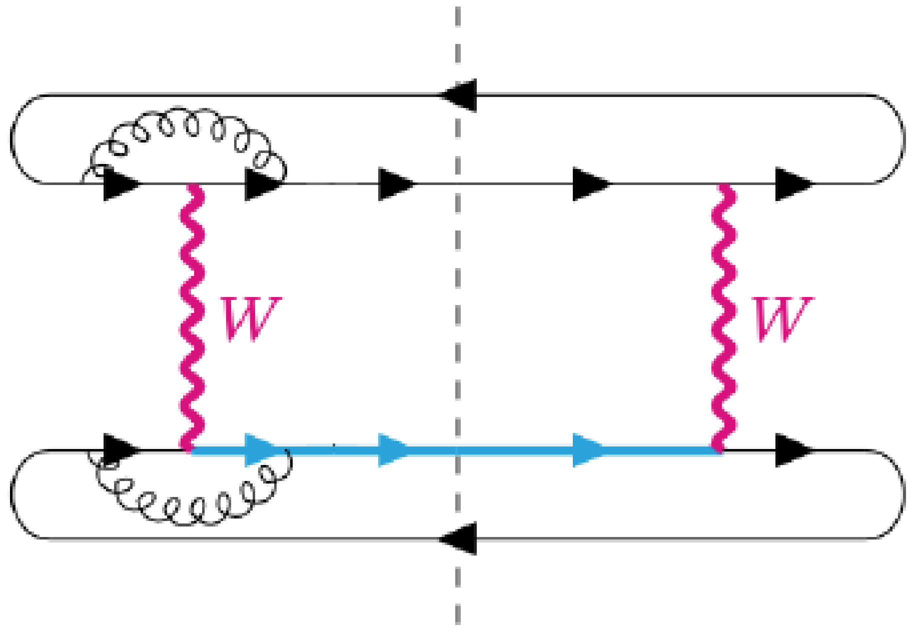


$$\mathrm{tr}\left(t^a t^a\right) = \frac{N_c^2 - 1}{2}$$

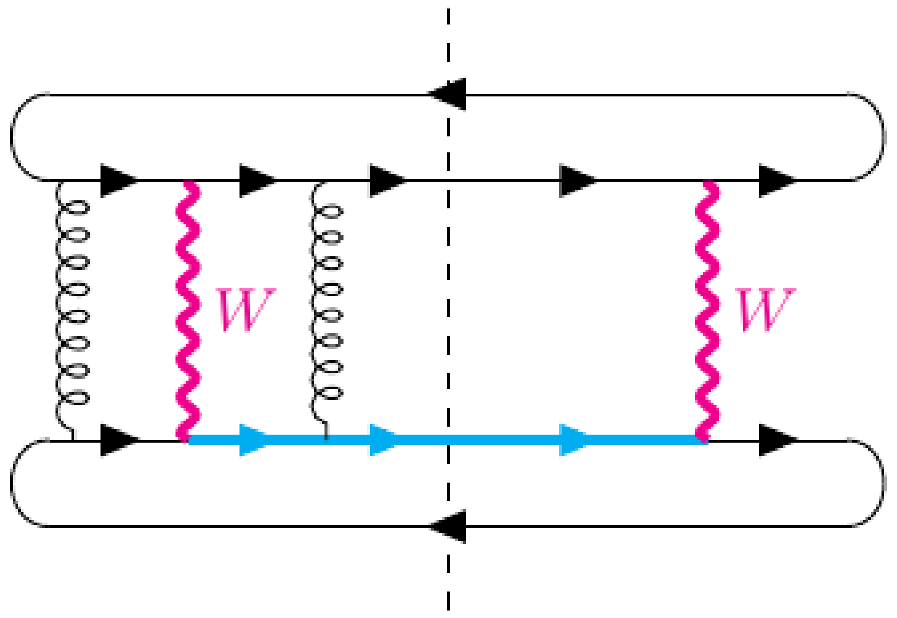


$$\mathrm{tr}\left(t^a\right) = 0$$

NNLO



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



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

Non-factorisable corrections: why? (II)

Non-factorisable contributions vanish at NLO due to their colour structure, and are suppressed by a factor $N_c^2 - 1 = 8$ at NNLO.

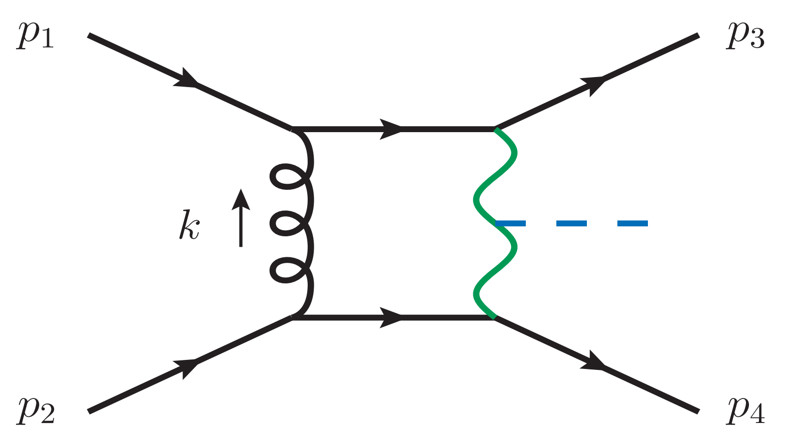
However:

Factorisable predictions are already small, about a few percent

The actual size of NNLO non-factorisable corrections **cannot be inferred from NLO contributions**

Non-factorisable corrections could be enhanced by a factor $\pi^2 \simeq 10$ related to a Glauber phase

- shown for Higgs production in weak boson fusion in the eikonal approximation *[Liu, Melnikov, Penin '19]*
- loop effect that, in principle, does not require a scattering to occur

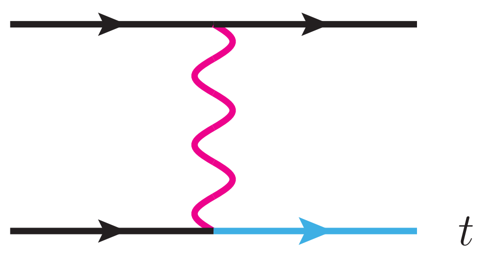


π^2

real contribution

$$\sigma = \sigma_0 + \left(\frac{p_\perp}{\sqrt{s}}\right)^2 \sigma_1 + \ldots$$

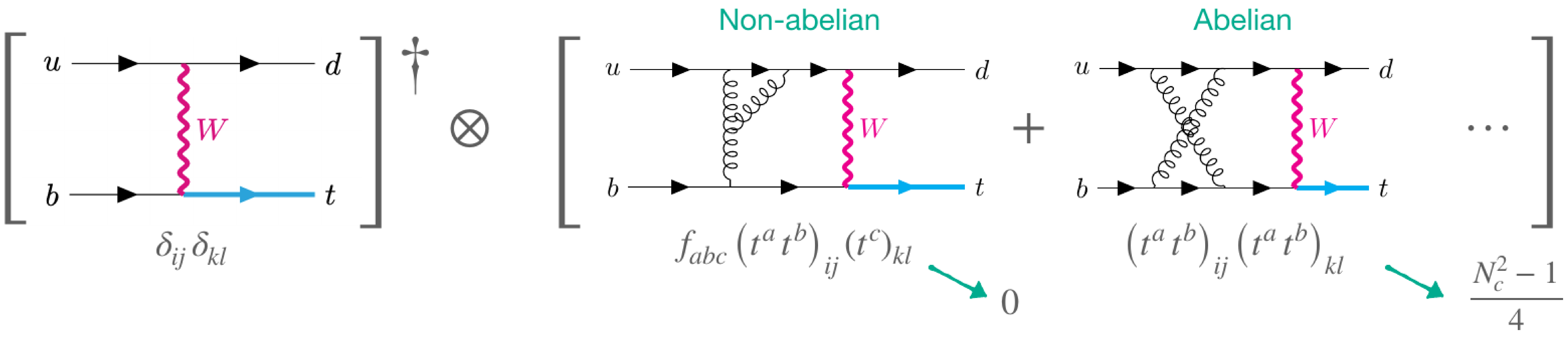
virtual contribution



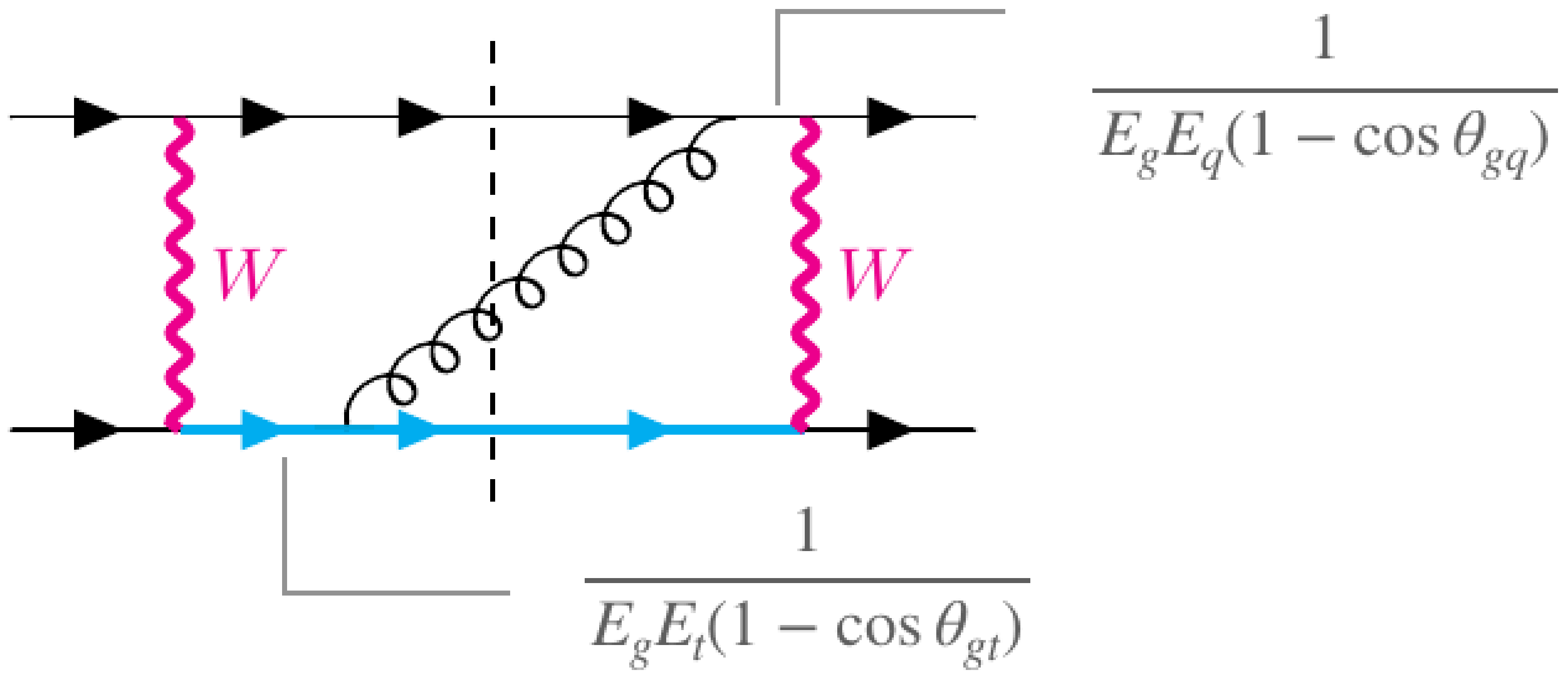
$p_\perp^t \sim 40\,\mathrm{GeV}$ $\qquad$ $\sqrt{s} \sim 300\,\mathrm{GeV}$

Non-factorisable corrections: ingredients of the calculation (II)

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

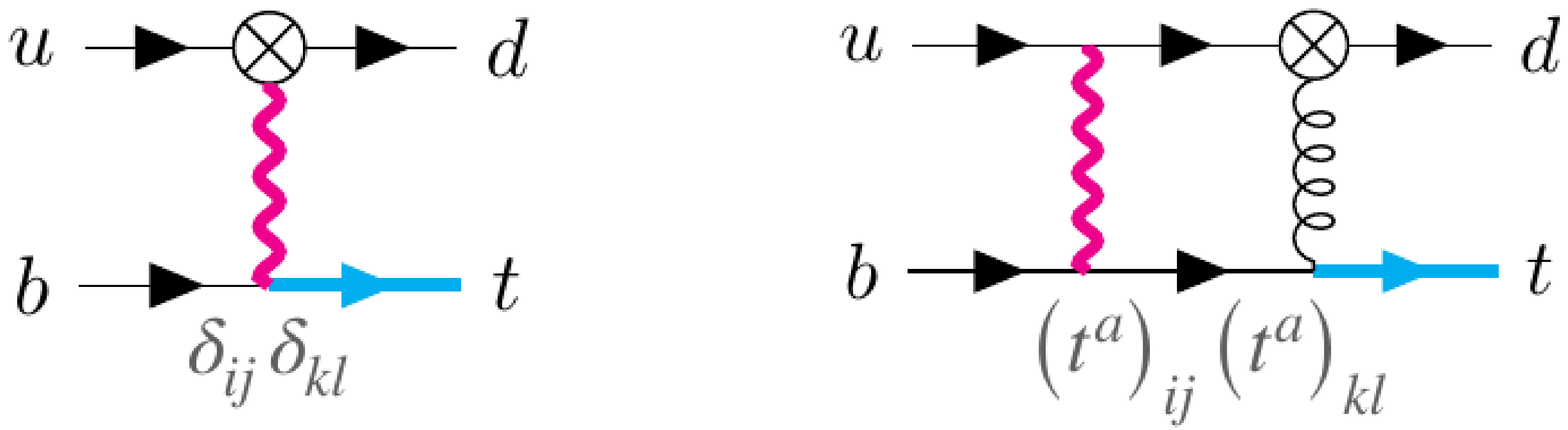


The **infrared structure is simplified**: **no collinear singularities**



All IR singularities are of soft origin.

Non-factorisable contributions are **UV finite**



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

Single top production: Results at 13 TeV (I)

Differential cross section:

pp collision: $\sqrt{s} = 13\,\mathrm{TeV}$, PDFs: CT14_lo@LO, CT14_nnlo@NNLO $m_W = 80.379\,\mathrm{GeV},\ m_t = 173.0\,\mathrm{GeV}, \alpha_S(m_t) = 0.108,\ \mu_F = m_t$

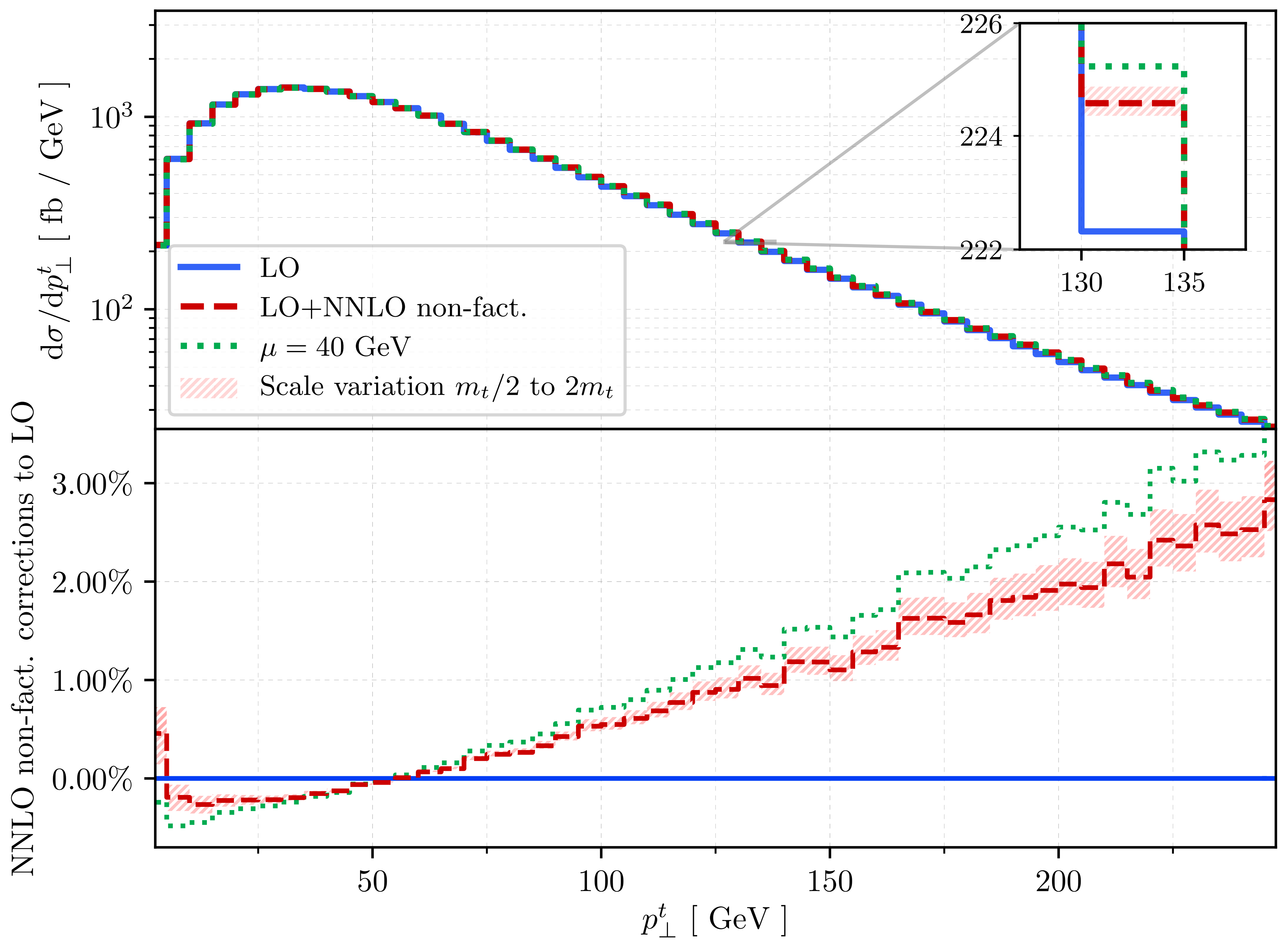
$$\frac{\sigma_{pp\to X+t}}{1\ \mathrm{pb}} = 117.96 + 0.26\left(\frac{\alpha_s(\mu_R)}{0.108}\right)^2$$

- Non-factorisable corrections are $0.22^{-0.04}_{+0.05}\,\%$ LO for $\mu_R = m_t$.
- **Theoretical uncertainties** are estimated through **scale variation**: $\mu_R \in [m_t/2,\ 2m_t]$.
- **Unclear optimal scale choice**: non-factorisable corrections appear for the first time at NNLO → no indication from lower orders.
- For $\mu_R = 40$ GeV (typical **momentum transfer scale** of top quark) non-factorisable corrections are $0.35\,\%$ LO.
- In comparison, **NNLO factorisable** corrections to **NLO cross section** are around $0.7\,\%$.

Single top production: Results at 13 TeV (II)

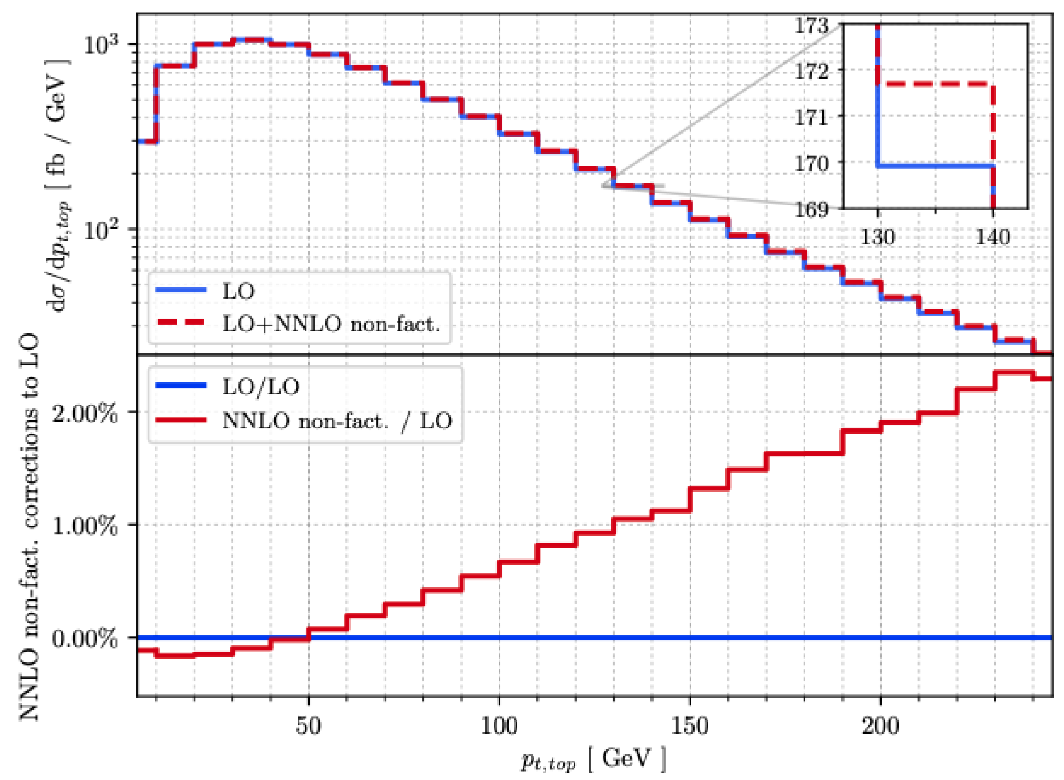
Differential cross section:

pp collision: $\sqrt{s} = 13\,\text{TeV}$, PDFs: CT14_lo@LO, CT14_nnlo@NNLO $m_W = 80.379\,\text{GeV},\ m_t = 173.0\,\text{GeV}, \alpha_S(m_t) = 0.108,\ \mu_F = m_t$



[Brønnum-Hansen, Melnikov, Quarroz, Signorile-Signorile, Wang '22]

- Non-factorisable corrections are $p_\perp^t$ dependent.
- Non-factorisable corrections are small and negative at low values of $p_\perp^t$
- They vanish at $p_\perp^t \sim 50\,\text{GeV}$ (in agreement with results for virtual corrections)
- **Factorisable corrections** vanish around $p_\perp^t \sim 30 - 40\,\text{GeV}$
- Factorisable and non-factorisable corrections are comparable in the region around the maximum of the $p_\perp^t$ distribution.



[Brønnum-Hansen, Melnikov, Quarroz, Wang '21]

Results at 100 TeV

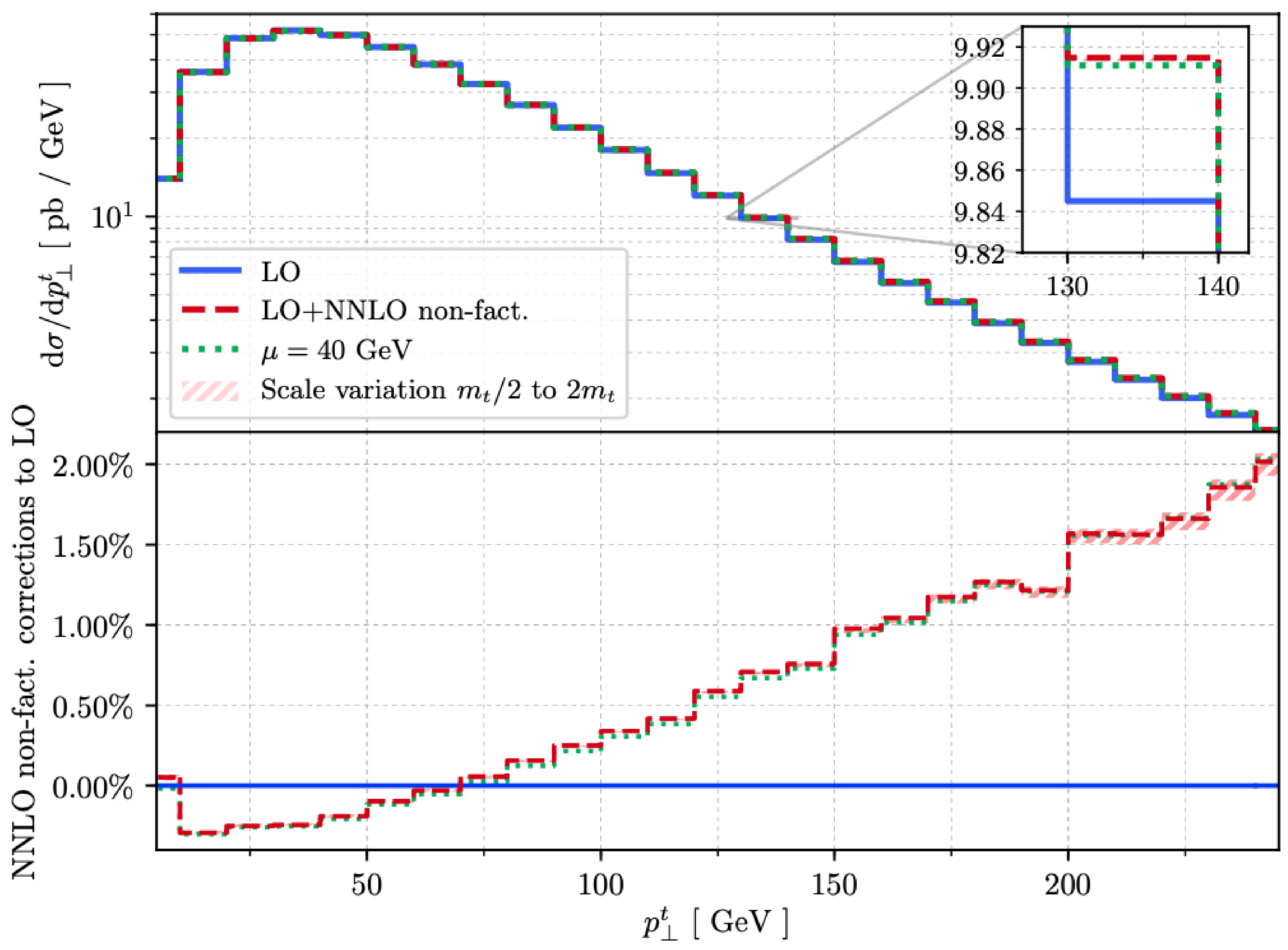
Differential cross section:

pp collision: $\sqrt{s} = 100\,\text{TeV}$ PDFs: CT14_lo@LO, CT14_nnlo@NNLO $m_W = 80.379\,\text{GeV},\ m_t = 173.0\,\text{GeV}, \alpha_S(m_t) = 0.108,\ \mu_F = m_t$

$$\frac{\sigma_{pp\to X+t}}{1\,\text{pb}} = 2367.0 + 3.8\left(\frac{\alpha_s(\mu_R)}{0.108}\right)^2$$

- Non-factorisable corrections are $0.16\,\%$ LO for $\mu_R = m_t$.
- $p_\perp^t$ peaks around 40 GeV, changes sign around 70 GeV.
- For $\mu_R = 40$ GeV non-factorisable corrections are $0.25\,\%$ LO.

		$\mu_R = m_t$		$\mu_R = 40$ GeV	
$p_\perp^{t,\text{cut}}$	σ_{LO} (pb)	$\sigma^{\text{nf}}_{\text{NNLO}}$ (pb)	δ_{NNLO} [%]	$\sigma^{\text{nf}}_{\text{NNLO}}$ (pb)	δ_{NNLO} [%]
0 GeV	2367.02	$3.79^{-0.63}_{0.84}$	$0.16^{-0.03}_{0.04}$	5.95	0.25
20 GeV	2317.03	$3.89^{-0.64}_{0.86}$	$0.17^{-0.03}_{0.04}$	6.11	0.26
40 GeV	2216.61	$4.14^{-0.69}_{0.92}$	$0.19^{-0.03}_{0.04}$	6.50	0.29
60 GeV	2121.88	$4.28^{-0.71}_{0.95}$	$0.20^{-0.03}_{0.04}$	6.71	0.32



Recent work on non-factorisable VBF Higgs production

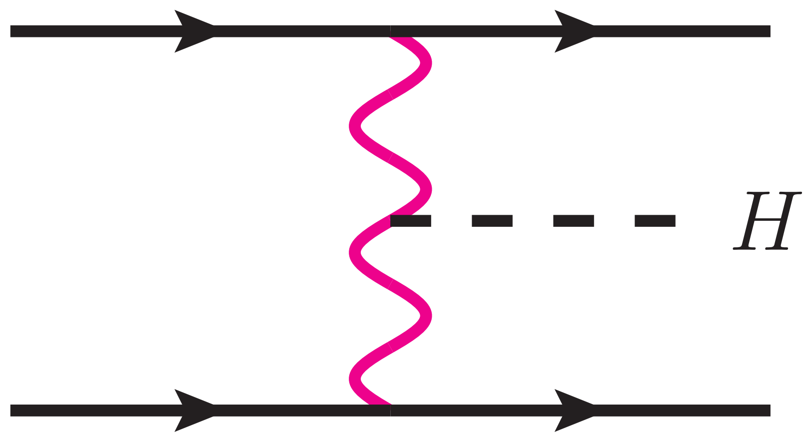
presented in arXiv:2305.08016

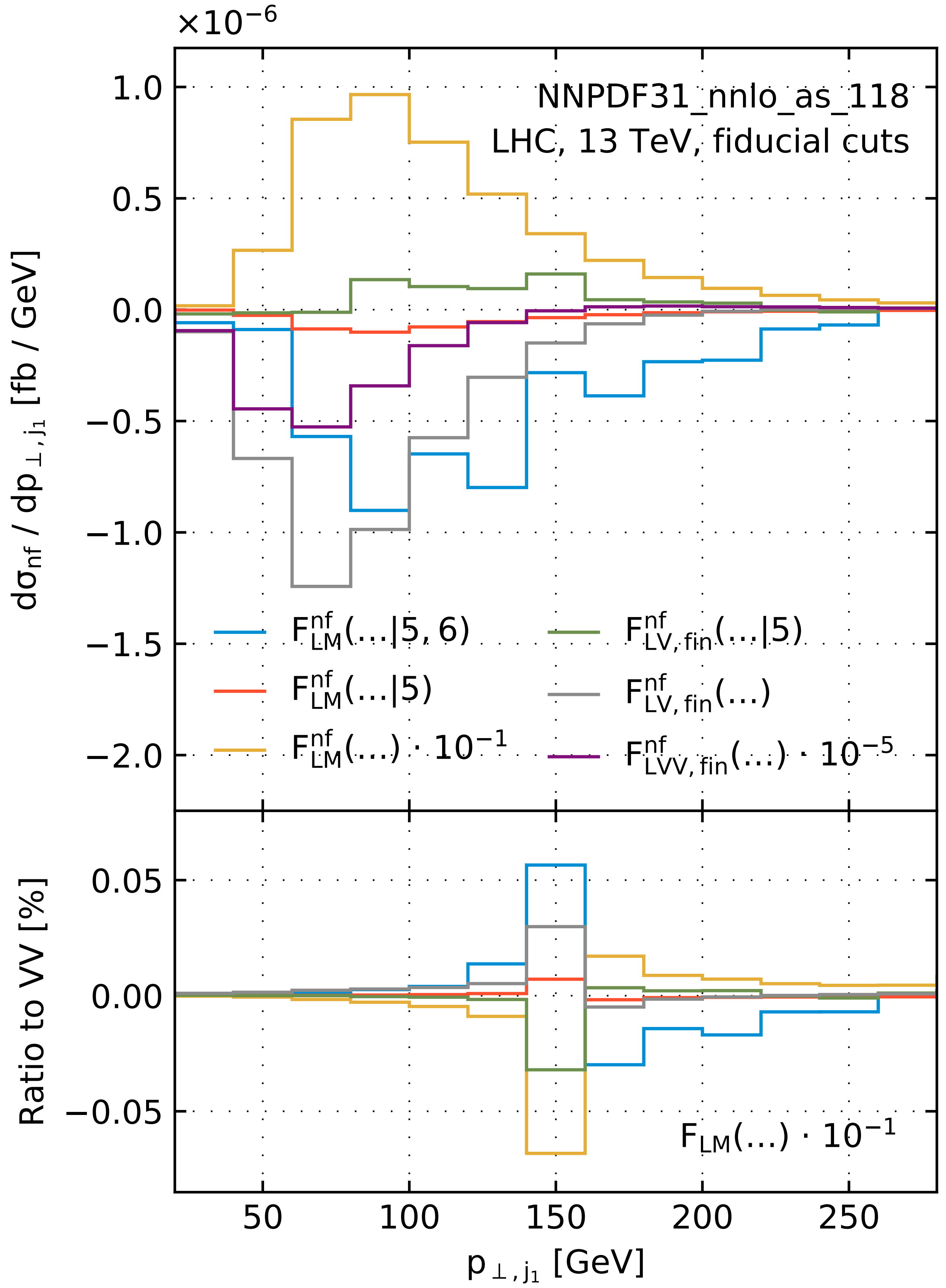
Differential cross section:

pp collision: $\sqrt{s} = 13\,\mathrm{TeV}$, PDFs: NNPDF31-nnlo-as-118 $\quad m_H = 125.0\,\mathrm{GeV},\, m_W = 80.398\,\mathrm{GeV},\, m_Z = 91.1876\,\mathrm{GeV}, \alpha_S(m_Z) = 0.118$

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

- Non-factorisable corrections are $0.5\,\%$ of factorisable through NNLO
- Double-virtual accounts for $99.99\,\%$ due to strong suppression of other contributions within fiducial volume
- For $\mu_R{=}\mu_F$ scale variation is $\mathcal{O}(40)\,\%$





[Asteriadis, Brønnum-Hansen, Melnikov '23]

Thank you for your attention!