TOWARDS MORE PRECISE PREDICTIONS FOR TTH AND TTZ PRODUCTION AT THE LHC

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OUTLINE

1. Motivations
2. Experimental Status
3. Higher Order Corrections
4. Preliminary Results on TTH and TTZ
5. Conclusions

MOTIVATIONS: WHY TTH AND TTZ?

- Top quark: Heaviest elementary particle known so far
  $m_t \simeq 173$ GeV (Gold Atom Mass ~ 197 u ~183.21 GeV).
  Strong coupling with the Higgs Boson

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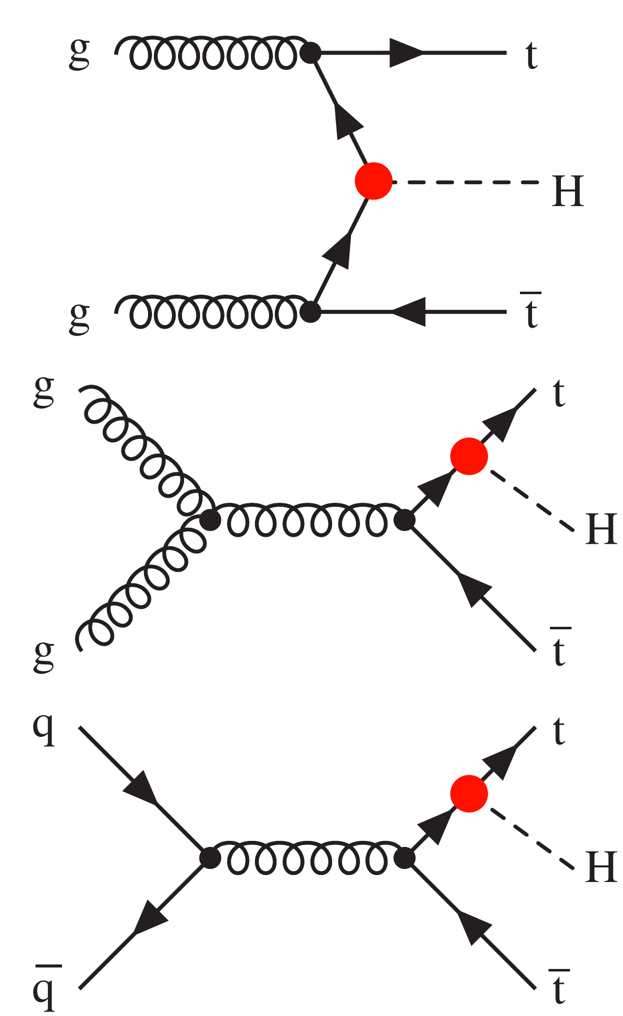

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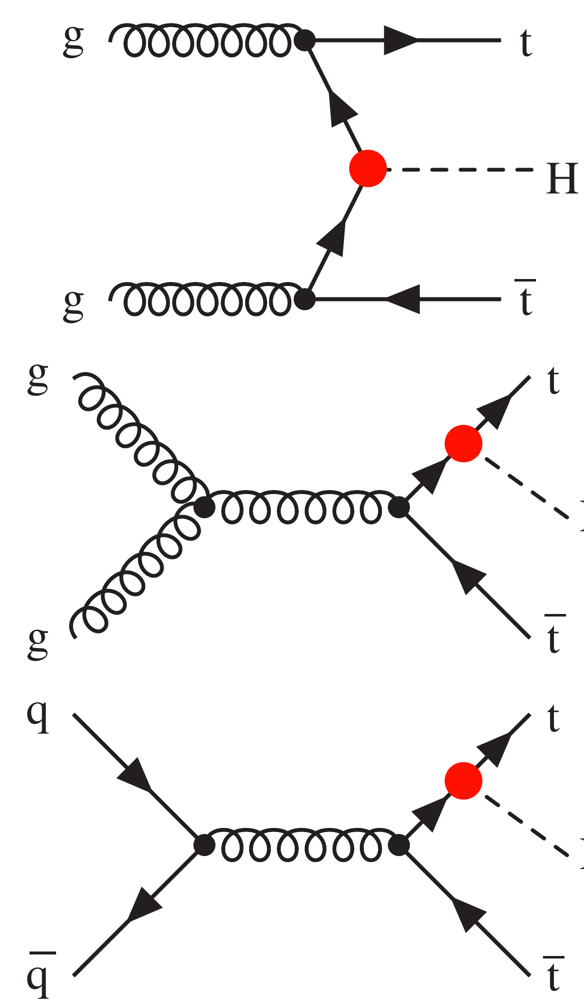

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- *tth* provides a tree level sensitivity to the top Yukawa coupling y_t.
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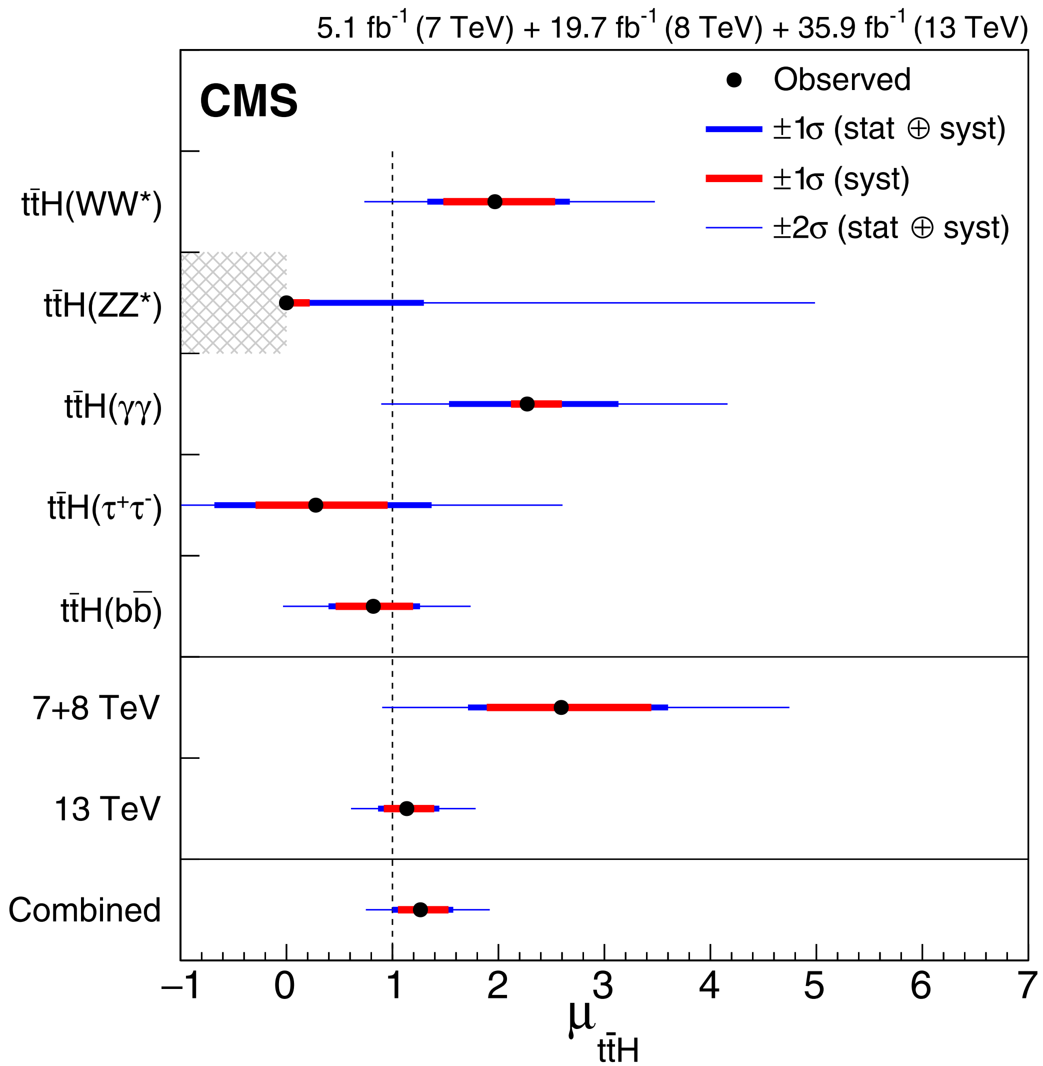
- *ttZ* is an important background in *tth* searches, in the decay channels $H \rightarrow (b\bar{b}, WW^{*}\ \tau\bar{\tau})$

EXPERIMENTAL STATUS: TTH

PRL 120, 231801 (2018)



$$\mu_{t\bar{t}H} = 1.26^{+0.31}_{-0.26}$$

Parameter	Best fit	Uncertainty: Statistical	Uncertainty: Experimental	Uncertainty: Background theory	Uncertainty: Signal theory
$\mu^{WW^*}_{t\bar{t}H}$	$1.97^{+0.71}_{-0.64}$	$^{+0.42}_{-0.41}$	$^{+0.46}_{-0.42}$	$^{+0.21}_{-0.21}$	$^{+0.25}_{-0.12}$
	$\left(^{+0.57}_{-0.54}\right)$	$\left(^{+0.39}_{-0.38}\right)$	$\left(^{+0.36}_{-0.34}\right)$	$\left(^{+0.17}_{-0.17}\right)$	$\left(^{+0.12}_{-0.03}\right)$
$\mu^{ZZ^*}_{t\bar{t}H}$	$0.00^{+1.30}_{-0.00}$	$^{+1.28}_{-0.00}$	$^{+0.20}_{-0.00}$	$^{+0.04}_{-0.00}$	$^{+0.09}_{-0.00}$
	$\left(^{+2.89}_{-0.99}\right)$	$\left(^{+2.82}_{-0.99}\right)$	$\left(^{+0.51}_{-0.00}\right)$	$\left(^{+0.15}_{-0.00}\right)$	$\left(^{+0.27}_{-0.00}\right)$
$\mu^{\gamma\gamma}_{t\bar{t}H}$	$2.27^{+0.86}_{-0.74}$	$^{+0.80}_{-0.72}$	$^{+0.15}_{-0.09}$	$^{+0.02}_{-0.01}$	$^{+0.29}_{-0.13}$
	$\left(^{+0.73}_{-0.64}\right)$	$\left(^{+0.71}_{-0.64}\right)$	$\left(^{+0.09}_{-0.04}\right)$	$\left(^{+0.01}_{-0.00}\right)$	$\left(^{+0.13}_{-0.05}\right)$
$\mu^{\tau^+\tau^-}_{t\bar{t}H}$	$0.28^{+1.09}_{-0.96}$	$^{+0.86}_{-0.77}$	$^{+0.64}_{-0.53}$	$^{+0.10}_{-0.09}$	$^{+0.20}_{-0.19}$
	$\left(^{+1.00}_{-0.89}\right)$	$\left(^{+0.83}_{-0.76}\right)$	$\left(^{+0.54}_{-0.47}\right)$	$\left(^{+0.09}_{-0.08}\right)$	$\left(^{+0.14}_{-0.01}\right)$
$\mu^{b\bar{b}}_{t\bar{t}H}$	$0.82^{+0.44}_{-0.42}$	$^{+0.23}_{-0.23}$	$^{+0.24}_{-0.23}$	$^{+0.27}_{-0.27}$	$^{+0.11}_{-0.03}$
	$\left(^{+0.44}_{-0.42}\right)$	$\left(^{+0.23}_{-0.22}\right)$	$\left(^{+0.24}_{-0.23}\right)$	$\left(^{+0.26}_{-0.27}\right)$	$\left(^{+0.11}_{-0.04}\right)$
$\mu^{7+8\ \mathrm{TeV}}_{t\bar{t}H}$	$2.59^{+1.01}_{-0.88}$	$^{+0.54}_{-0.53}$	$^{+0.53}_{-0.49}$	$^{+0.55}_{-0.49}$	$^{+0.37}_{-0.13}$
	$\left(^{+0.87}_{-0.79}\right)$	$\left(^{+0.51}_{-0.49}\right)$	$\left(^{+0.48}_{-0.44}\right)$	$\left(^{+0.50}_{-0.44}\right)$	$\left(^{+0.14}_{-0.02}\right)$
$\mu^{13\ \mathrm{TeV}}_{t\bar{t}H}$	$1.14^{+0.31}_{-0.27}$	$^{+0.17}_{-0.16}$	$^{+0.17}_{-0.17}$	$^{+0.13}_{-0.12}$	$^{+0.14}_{-0.06}$
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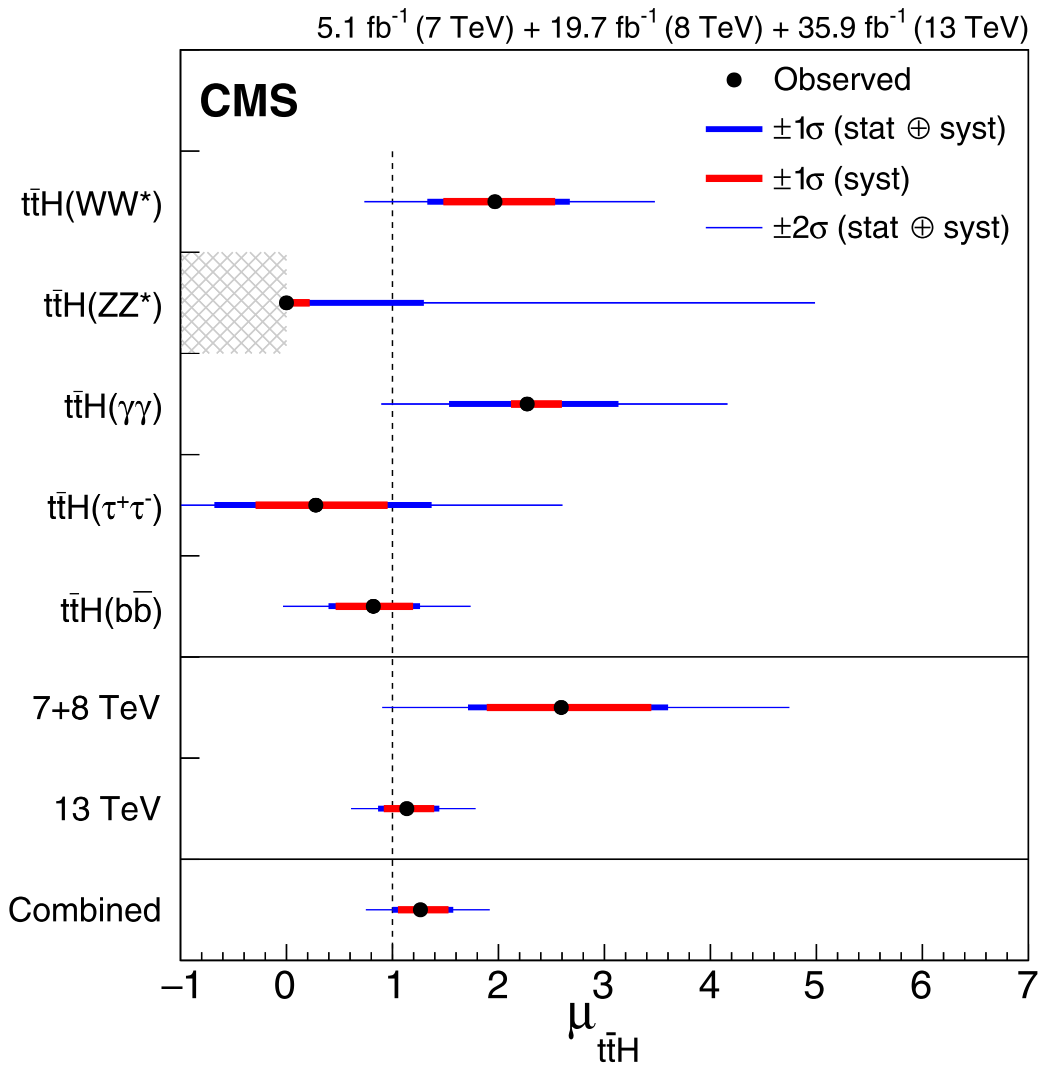

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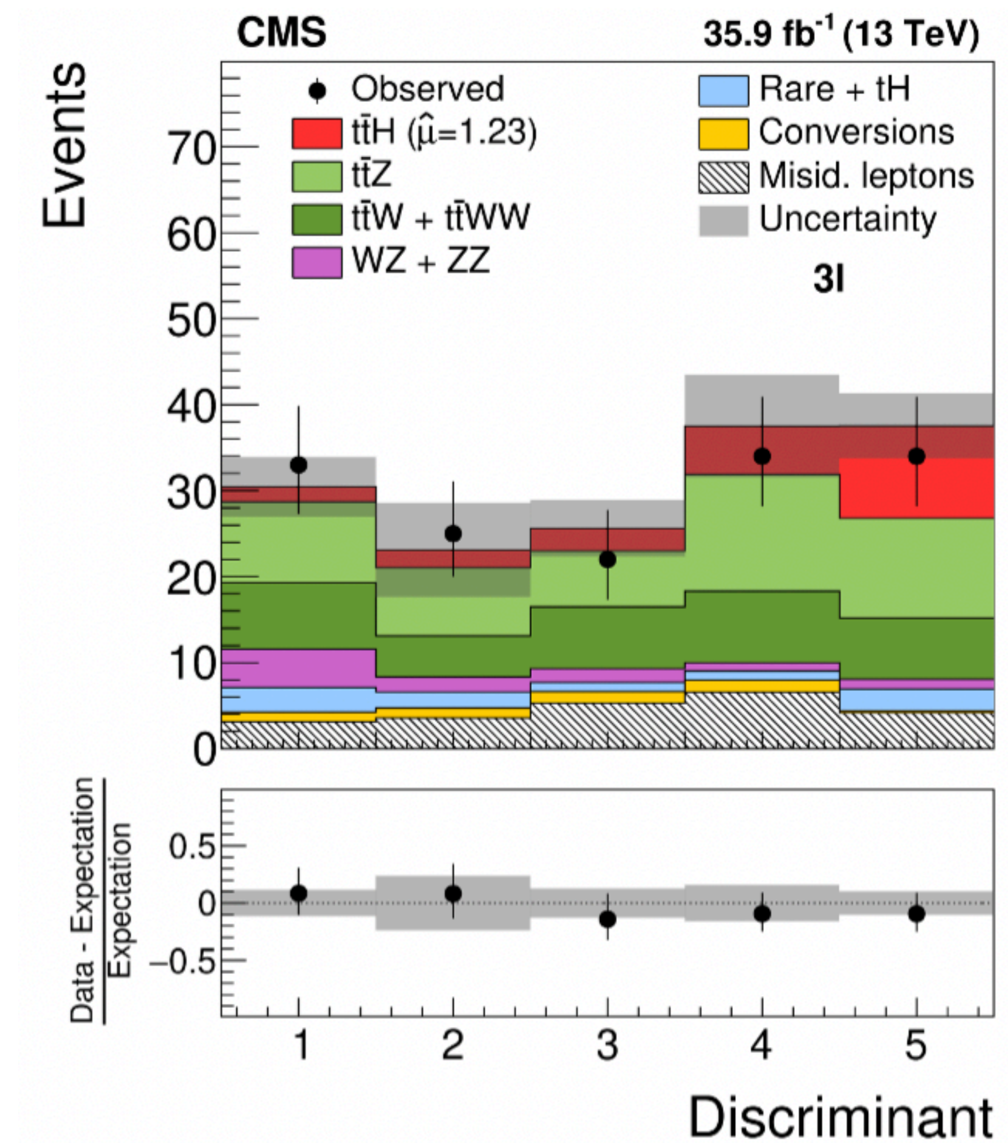
$\sim 13\,\%$ (22 % combined) $\sim 12\,\%$

➡ Experimental uncertainty challenges the theory prediction.

EXPERIMENTAL STATUS: TTZ

Important Background for tth!

PRL 120(2018)231801



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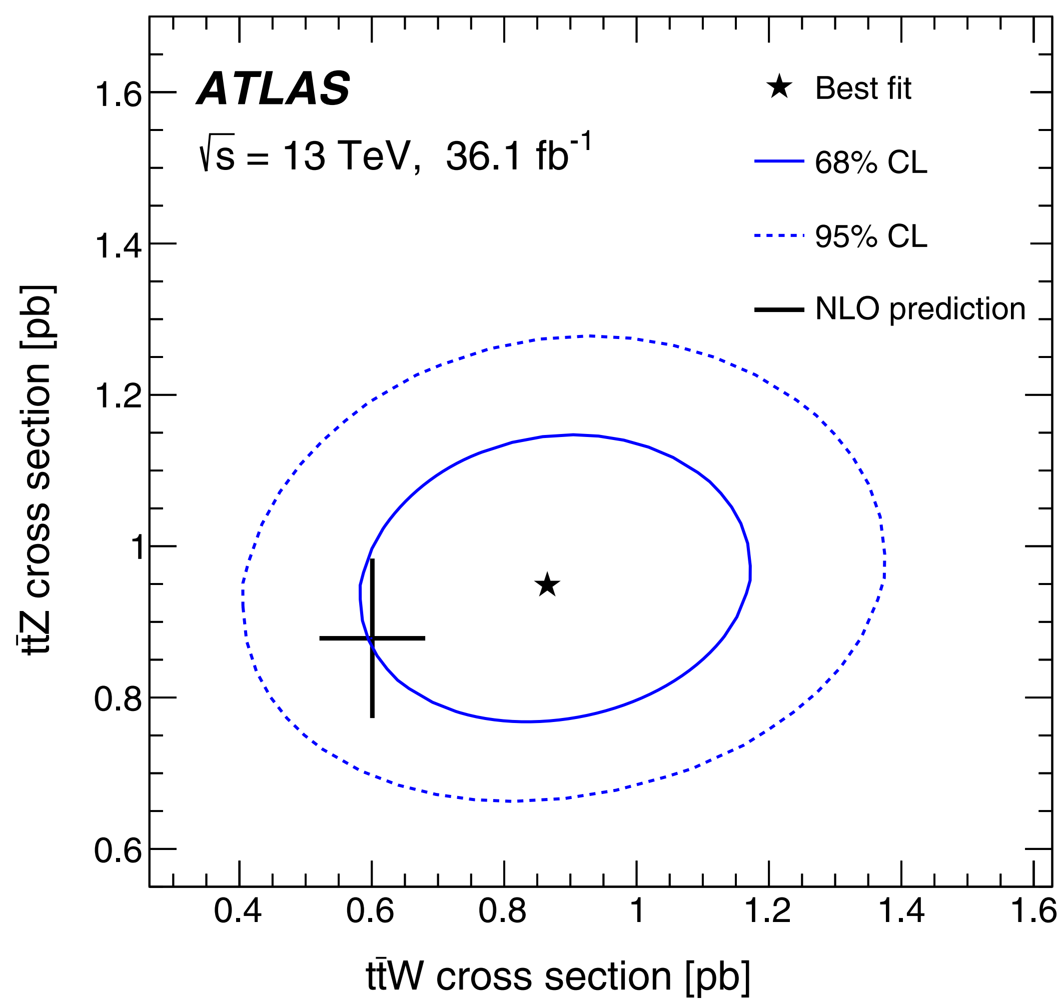
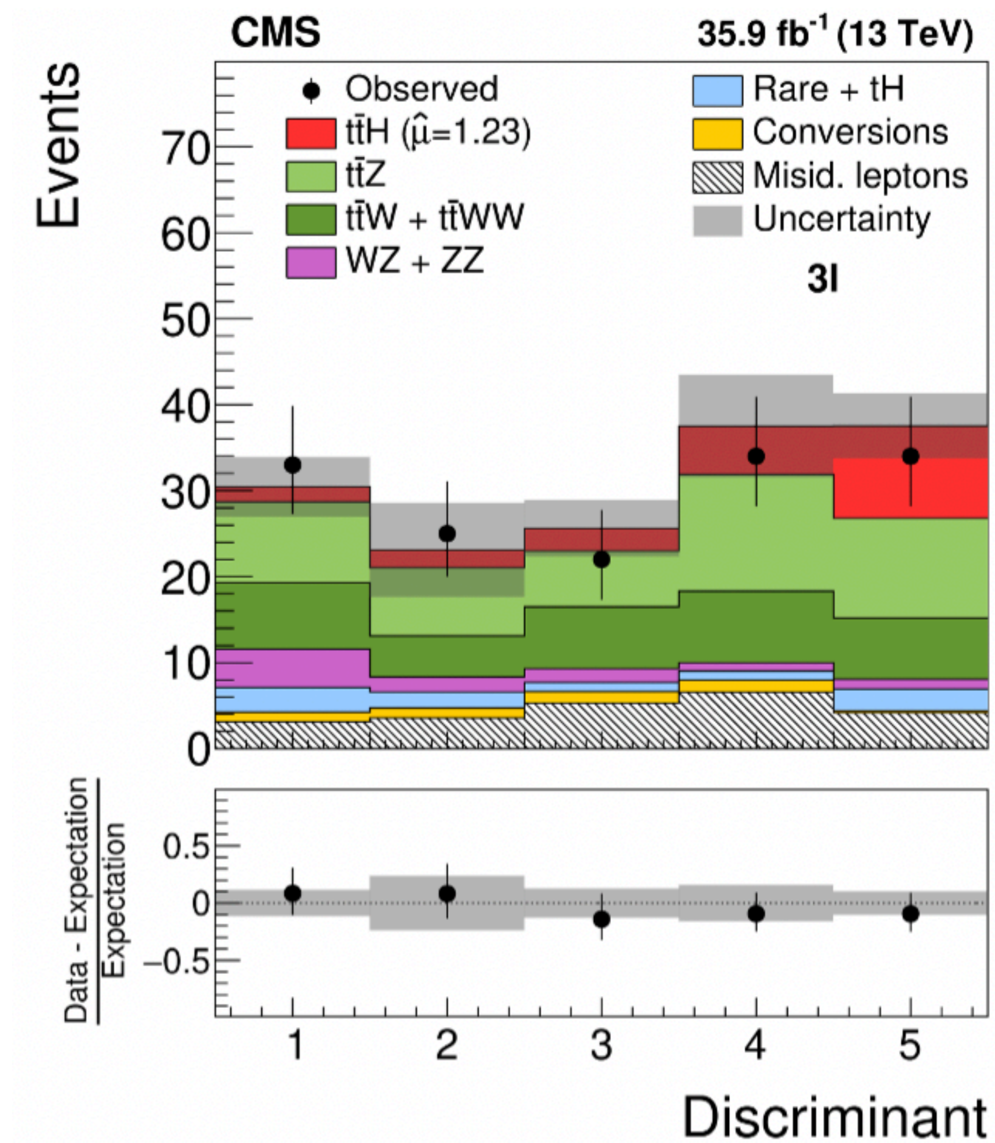




$\sigma_{t\bar{t}Z} = 0.95 \pm 0.08\textbf{(stat)} \pm 0.10\textbf{(syst)}\ \textbf{pb}$
$\sigma_{t\bar{t}W} = 0.87 \pm 0.13\textbf{(stat)} \pm 0.14\textbf{(syst)}\ \textbf{pb}$

13%

22%

PRD 99(2019)072009

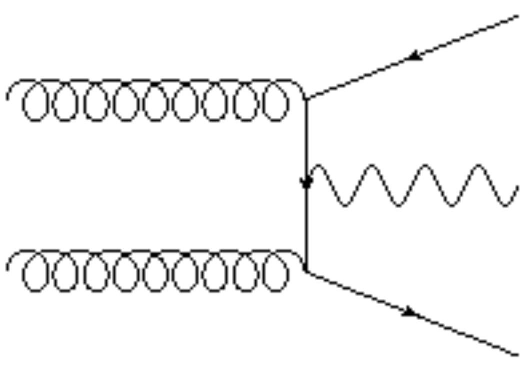
Theory Prediction:

$\sigma^{NLO}_{t\bar{t}Z} = 0.88^{+0.09}_{-0.11}\ \textbf{pb}$ $\qquad$ $\sigma^{NLO}_{t\bar{t}W} = 0.6^{+0.08}_{-0.07}\ \textbf{pb}$ **13%**

➡ Need to go to higher theory precision: NNLO

HIGHER ORDER CORRECTIONS

LO:



Born

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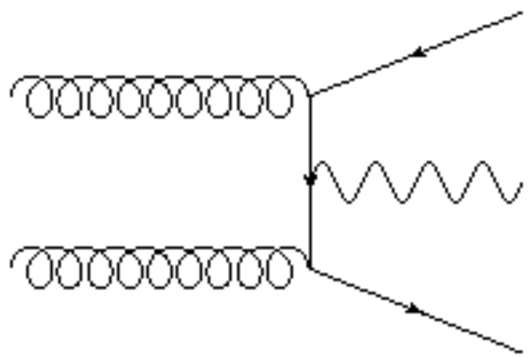

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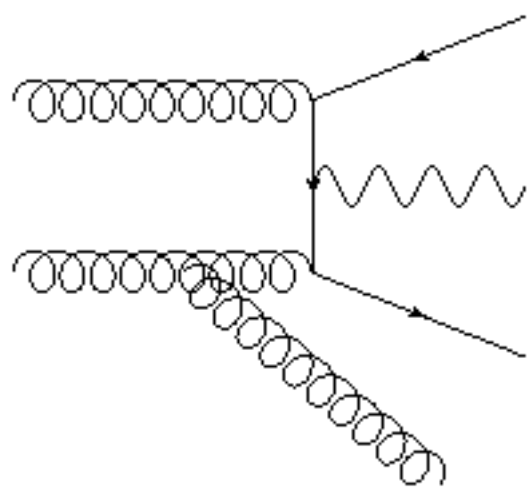
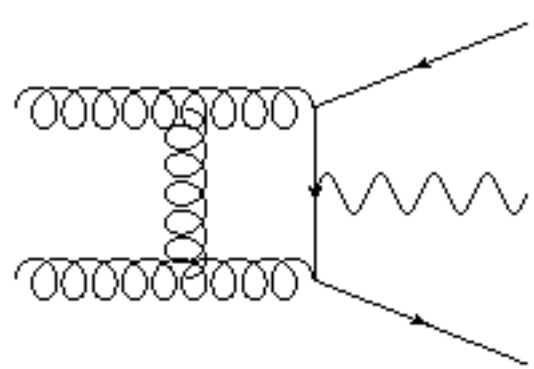


Real emission radiation

Loop



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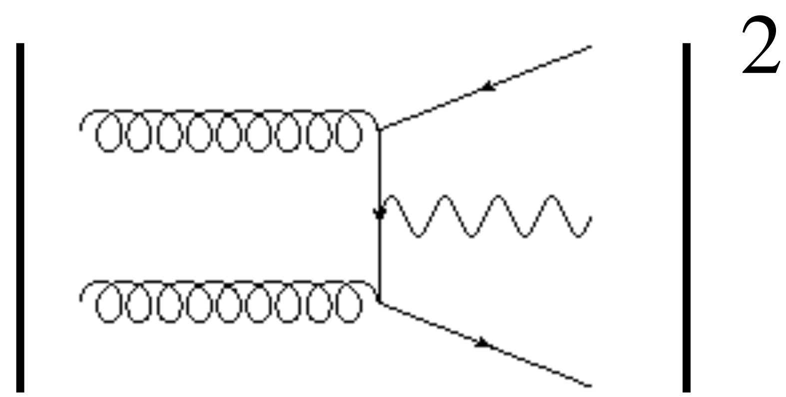

← Born

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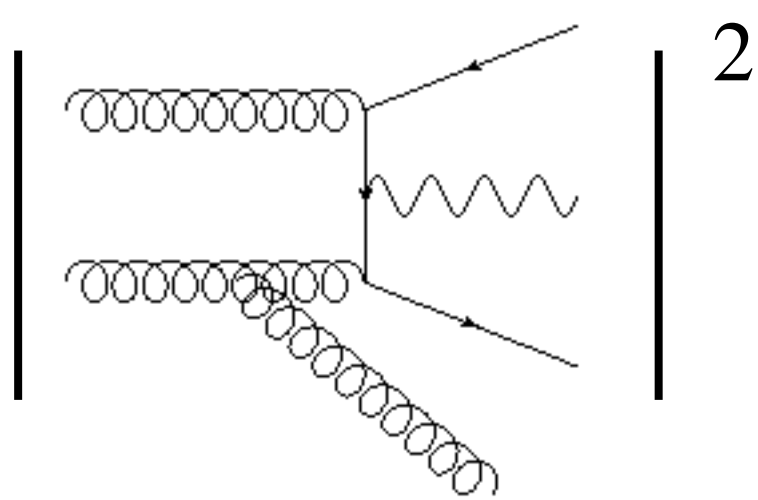
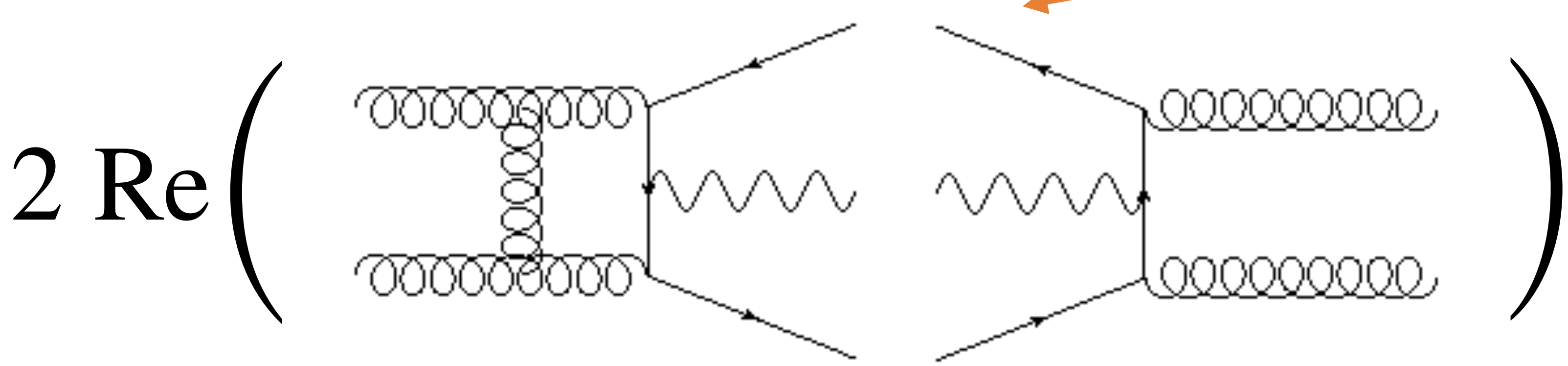


← Real emission radiation

+

Loop



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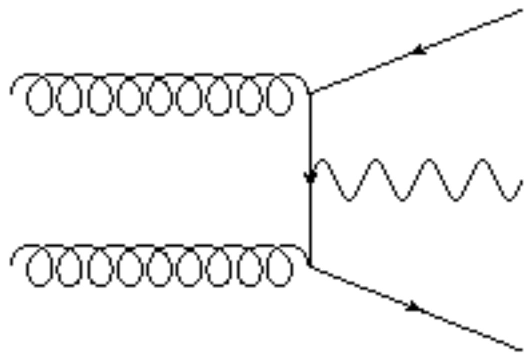
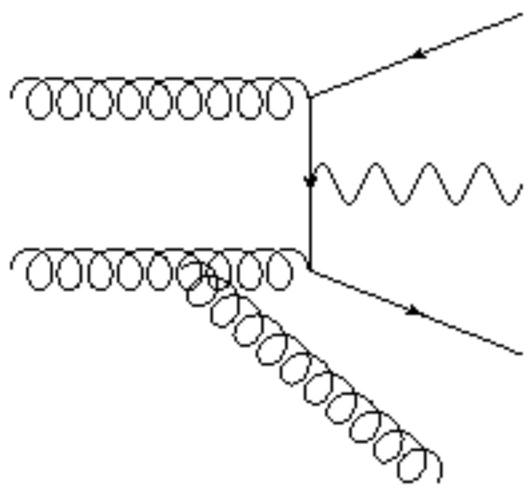
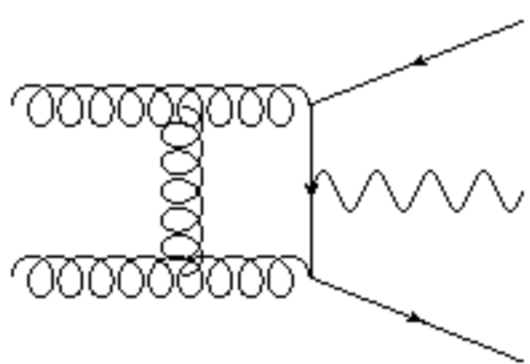
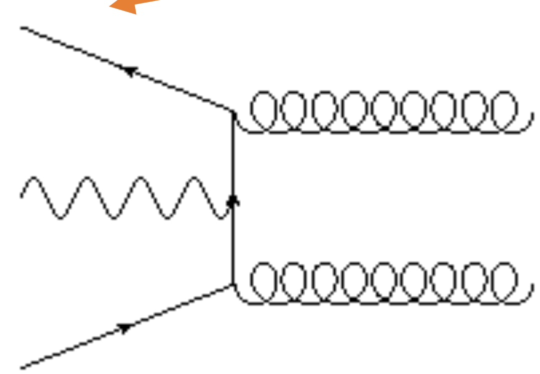
$\int \mathrm{dPS}_F \Big|$  $\Big|^2$ ← Born

NLO:

$\int \mathrm{dPS}_{F+j} \Big|$  $\Big|^2$ ← Real emission radiation

$+$

Loop

$\int \mathrm{dPS}_F \; 2\,\mathrm{Re} \Big($   $\Big)$

COMPLICATIONS: SINGULARITIES

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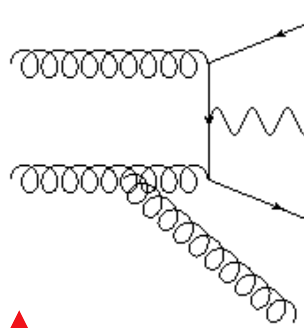
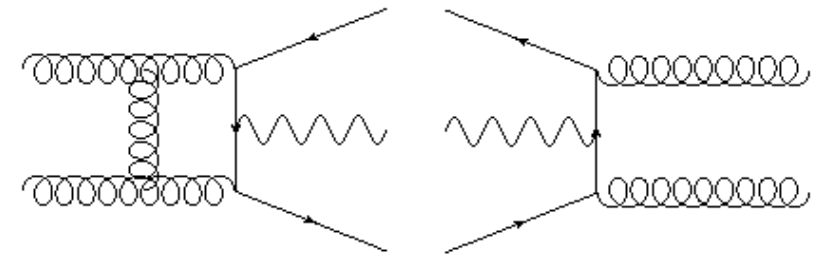
- "*Technical complication*":
  After steps 1 and 2, Loop and Real emission radiation contributions are still separately singular, but the sum of them is finite for *well defined* observables (i.e. *Infrared Safe*).
  - Extra ingredient needed: A "*Recipe*" for combining contributions numerically.

SUBTRACTION METHODS

$\int_{F+j}$ $\Bigg|$  $\Bigg|^2$ $+ \int_F 2\,\mathrm{Re}\Bigg($  $\Bigg)$

Divergent

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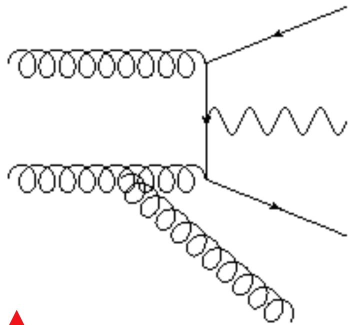
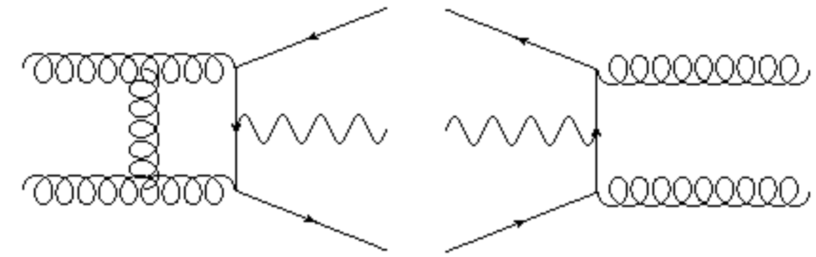
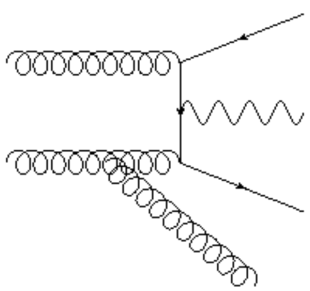
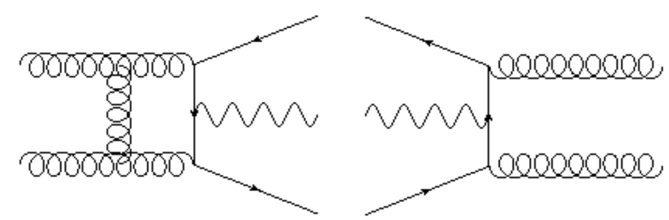
$\int_{F+j} \Big|$  $\Big|^2 + \int_F 2\,\mathrm{Re}\Big($  $\Big)$

Divergent **Divergent**

$\int_{F+j} \Big[\Big|$  $\Big|^2 - CT \Big] + \int_F \Big[2\,\mathrm{Re}\Big($  $\Big) + \int_j CT \Big]$

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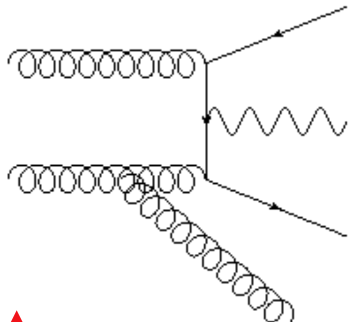
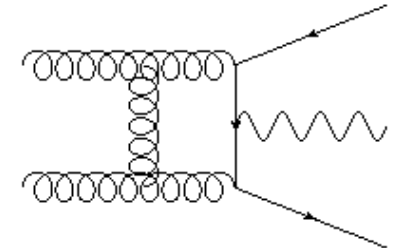
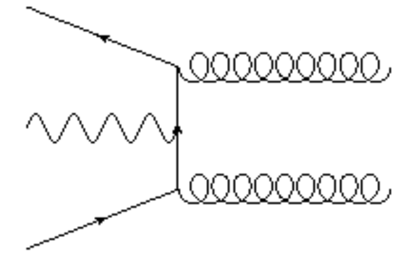
$\int_{F+j} \Big|$  $\Big|^2 + \int_F 2\,\mathrm{Re}\Big($   $\Big)$

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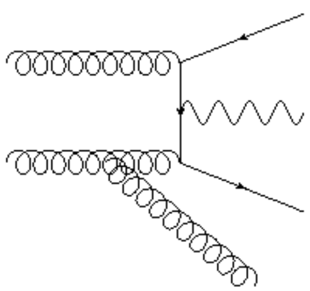
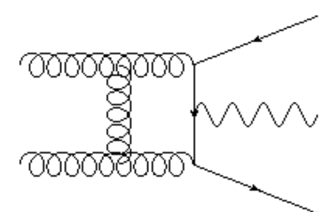
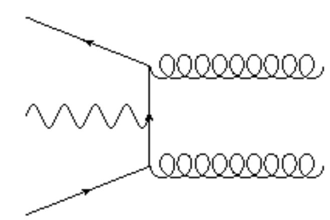
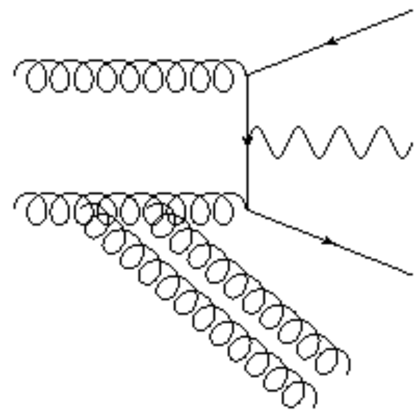
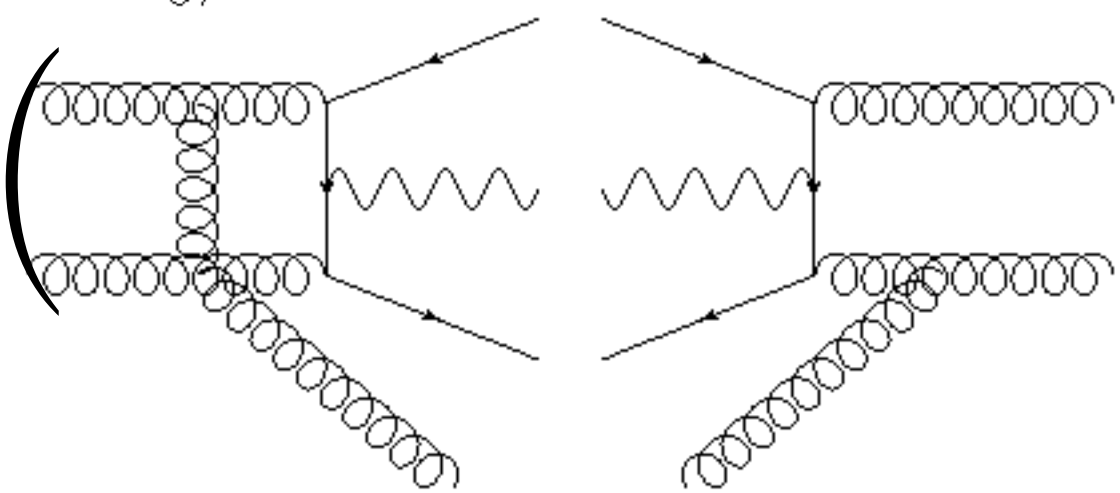
$\int_{F+j} \Big[\Big|$  $\Big|^2 - CT \Big] + \int_F \Big[2\,\mathrm{Re}\Big($   $\Big) + \int_j CT \Big]$

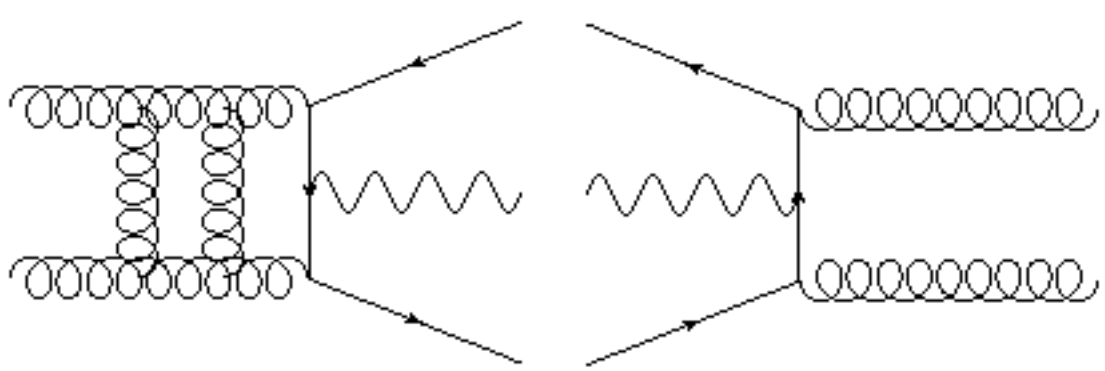
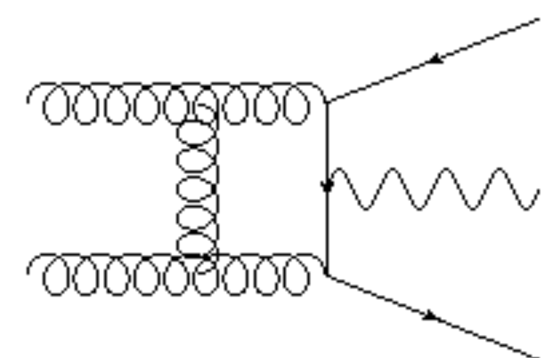
Finite **Finite**

HIGHER ORDER CORRECTIONS

NNLO:

$\int \mathrm{dPS}_{F+jj} \, \Big|$  $\Big|^2 +$

$\int \mathrm{dPS}_{F+j} \; 2\,\mathrm{Re}\Big($  $\Big)$

$\int \mathrm{dPS}_{F} \; 2\,\mathrm{Re}\Big($  $\Big) + \Big|$  $\Big|^2$

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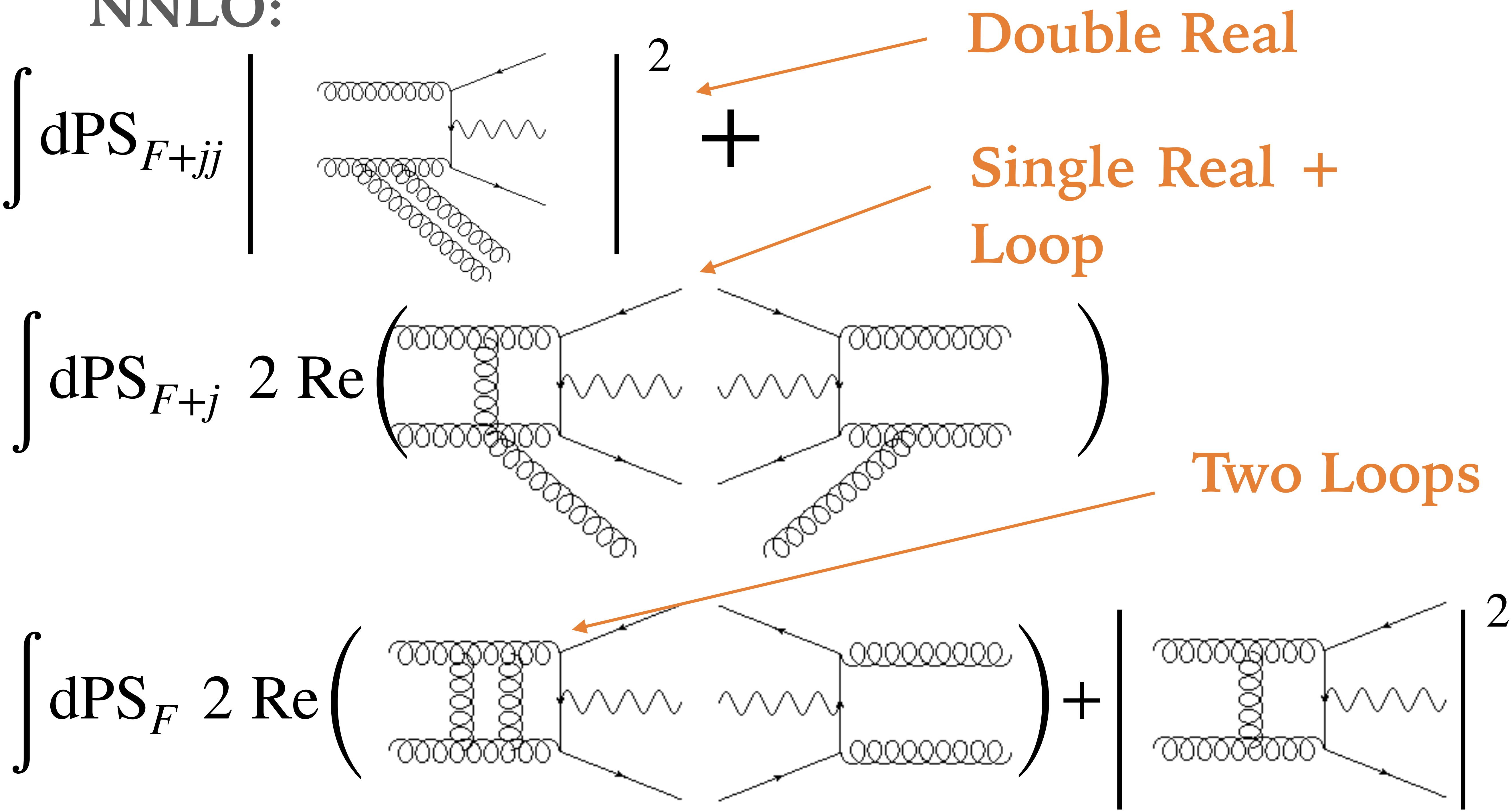


➡ Infrared Singularities consequently more involved.

STATUS OF HIGHER ORDER CORRECTIONS

NLO:

- Tree-level Amplitudes: (Born, real emission radiation) Fully automatised.
- One-Loop Amplitudes: Fully automatised.
- Subtraction methods: Well established and fully automatised.

  ➡ Fully automatic NLO computations.

STATUS OF HIGHER ORDER CORRECTIONS

NNLO:

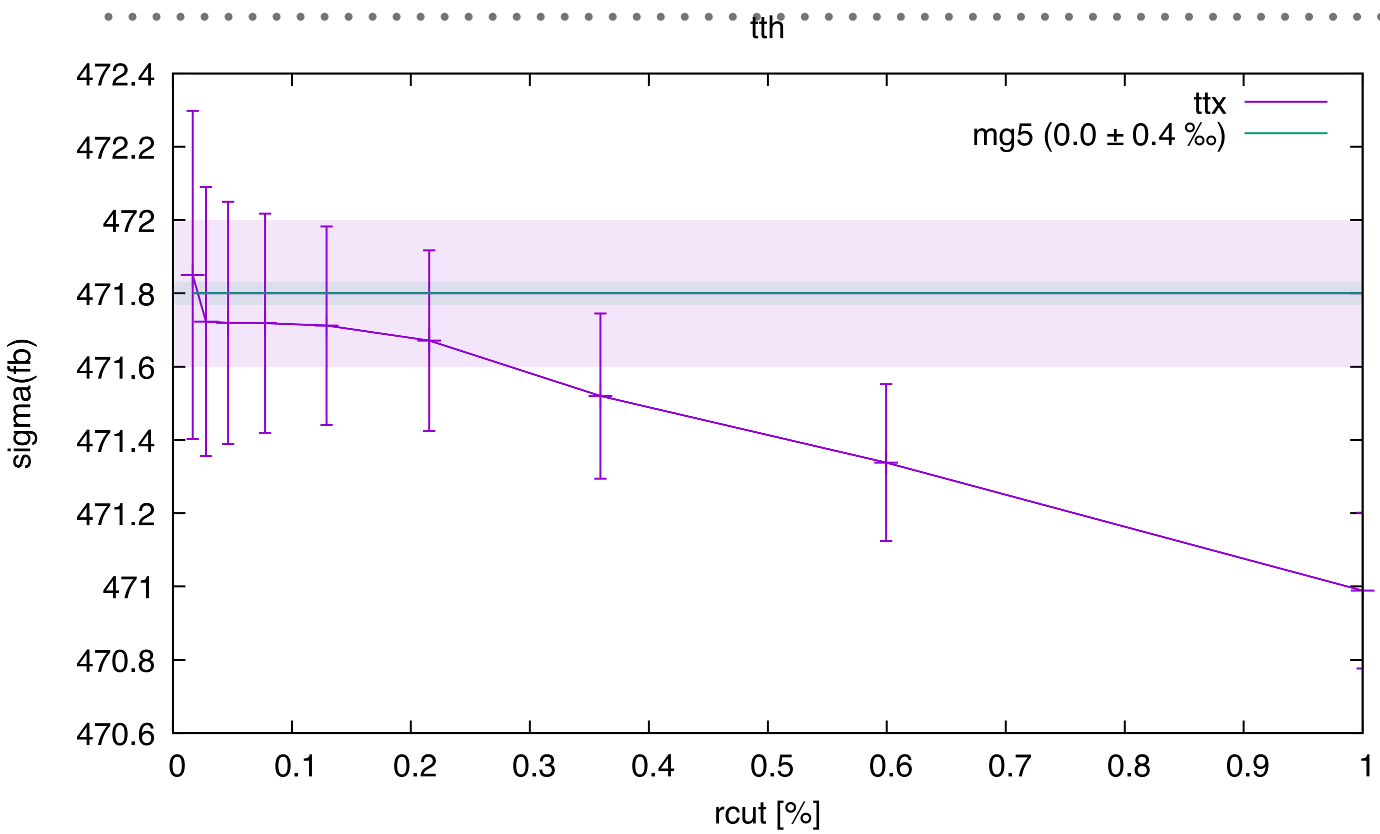
- Tree-level Amplitudes: (Born, real emission radiation) Fully automatised.
- One-Loop Amplitudes: Fully automatised.
- Two-Loops Amplitudes: Generically not known (case by case calculation).
- Subtraction methods: Different proposals (e.g. QT-subtraction).
  - ➡ NNLO results available only for certain processes.

STATUS OF HIGHER ORDER CORRECTIONS

TTH and TTZ:

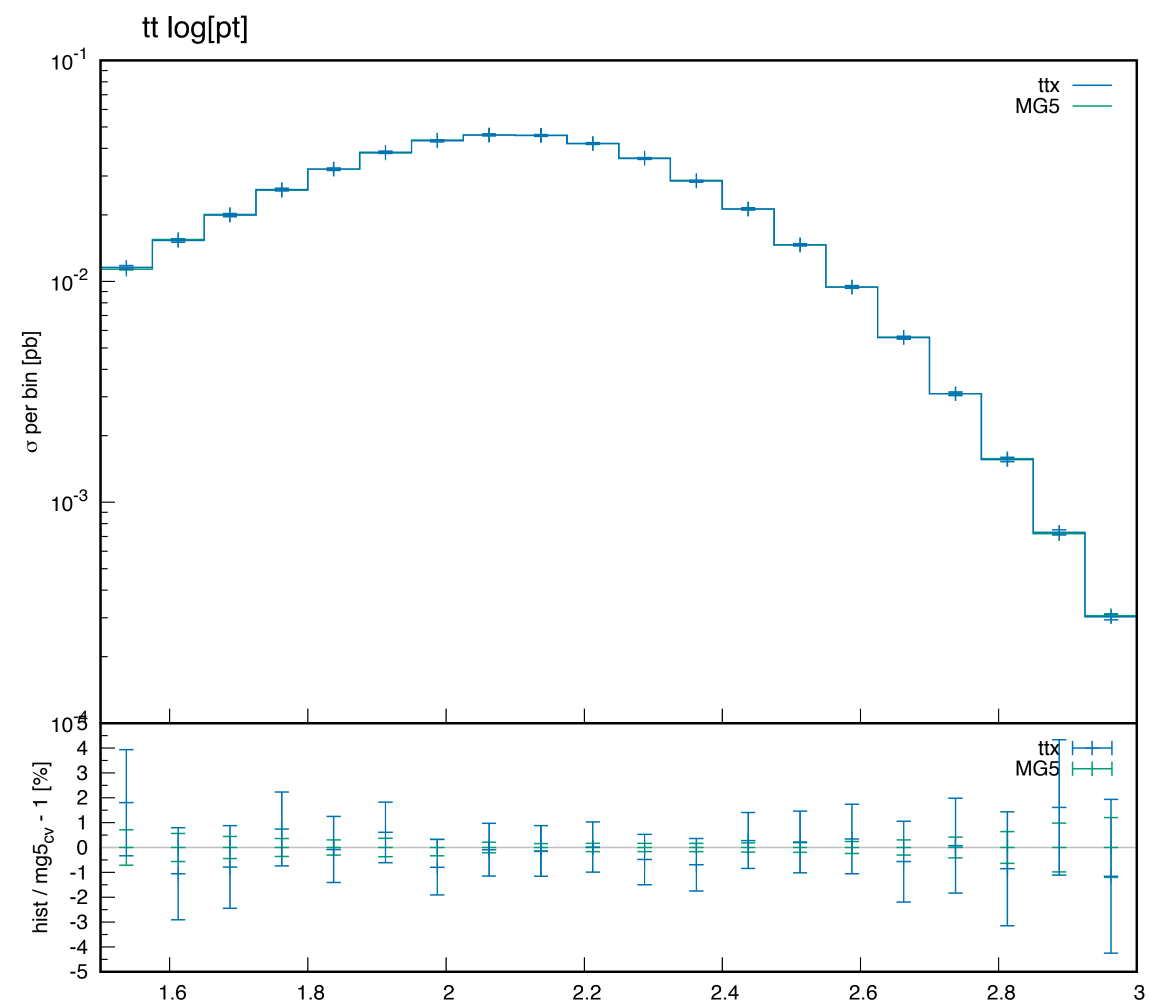
- Tree and One-loop amplitudes available (in our implementation thanks to *OpenLoops*).
- Two Loop amplitudes not known at the moment.
- Handling of infrared singularities:
  - Extension of the QT-subtraction method to tt+colorless currently under work: NLO validation completed and NNLO on the way.

PRELIMINARY RESULTS: TTH NLO



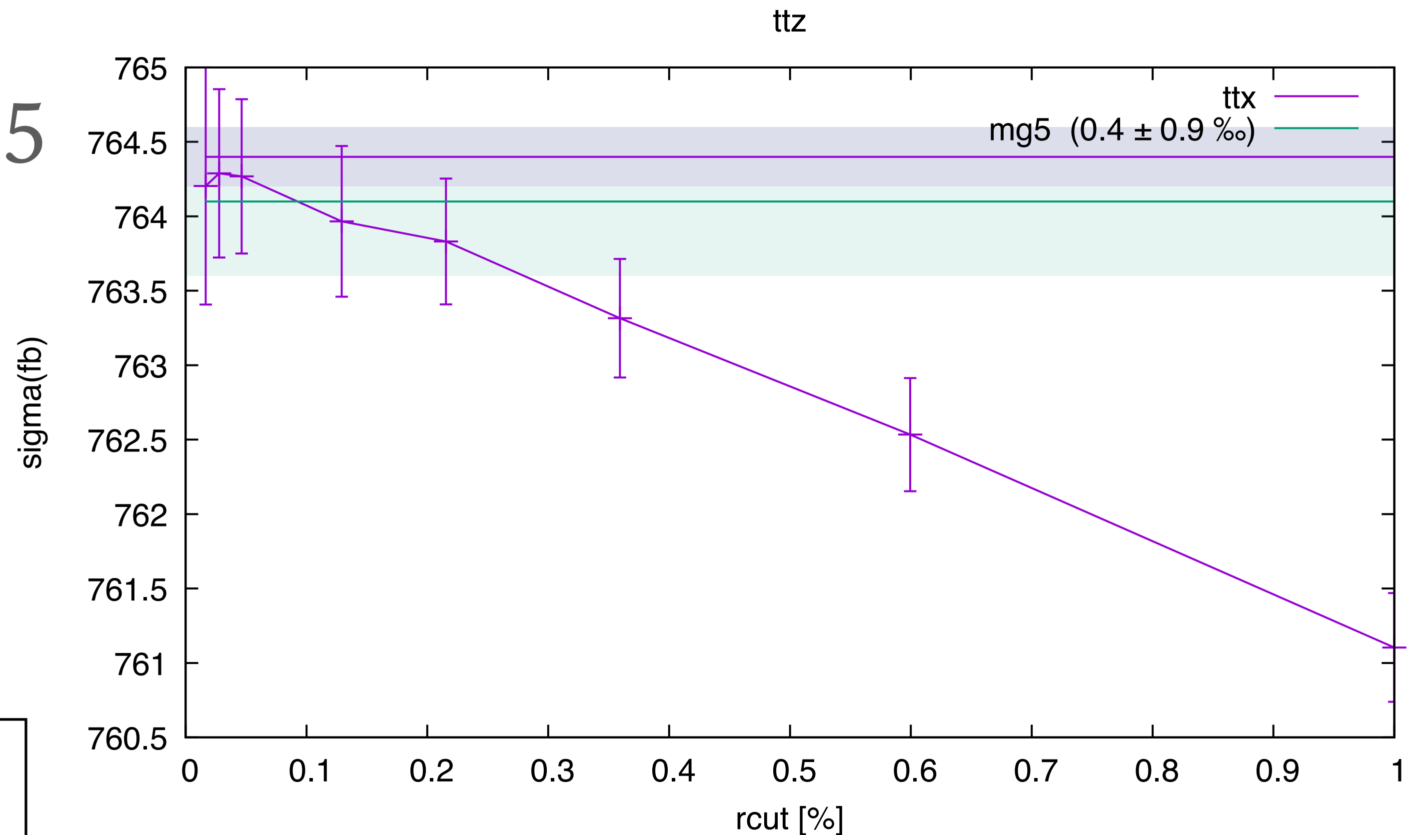
➤ Agreement with MadGaph5 within sub-permill numerical precision for the inclusive cross section.

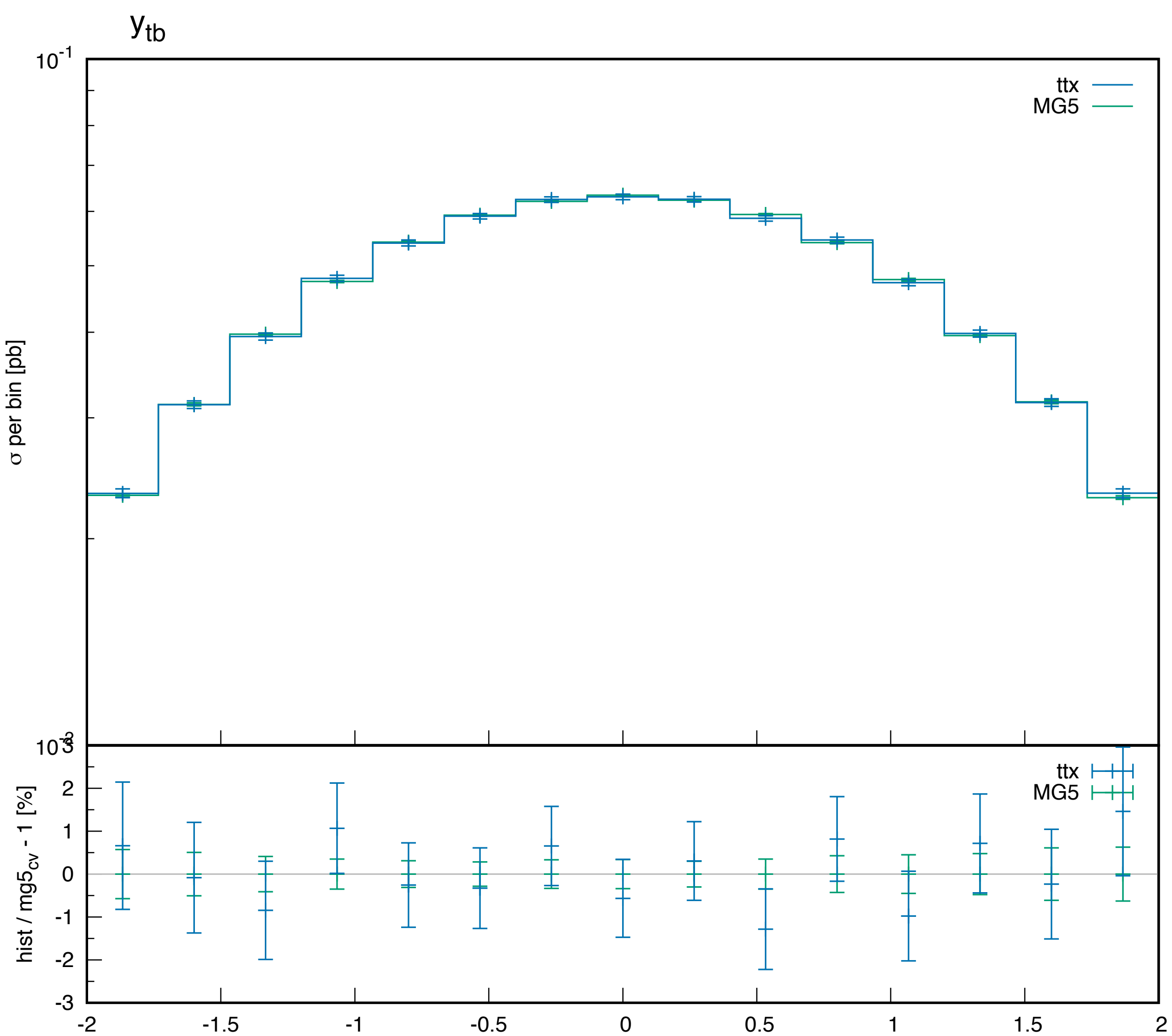
➤ Fully agreement in differential distributions within percent-level numerical precision.



PRELIMINARY RESULTS: TTZ NLO

- Agreement with MadGaph5 with a per-mill numerical precision for the inclusive cross section.





- Fully agreement in differential distributions within percent-level numerical precision (that could be lowered with more runtime of the MC).

SO FAR...

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The only missing ingredient would be the two-loop amplitudes which, thanks to recent advances in numerical techniques, we might obtain in not too far a future.

QUESTIONS