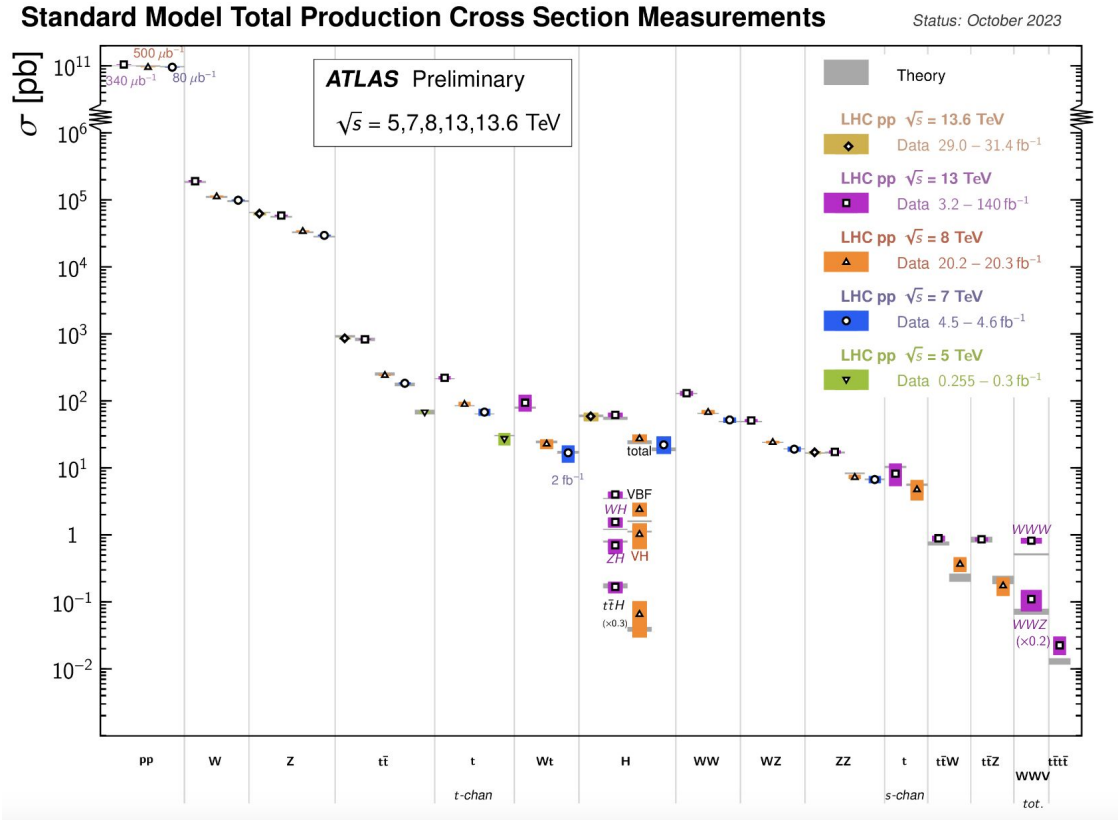
3- vs 4-Top Quark Production at c-NLO

Based on WIP with *G. Durieux, R. Frederix, D. Pagani and M. Zaro*

Hesham El Faham
The University of Manchester

LHC TOP WG, April 2024, CERN

Status



- Top quark plays a special role in SM and beyond
- So far, no direct signs of beyond the SM physics
- Keep measuring rare processes

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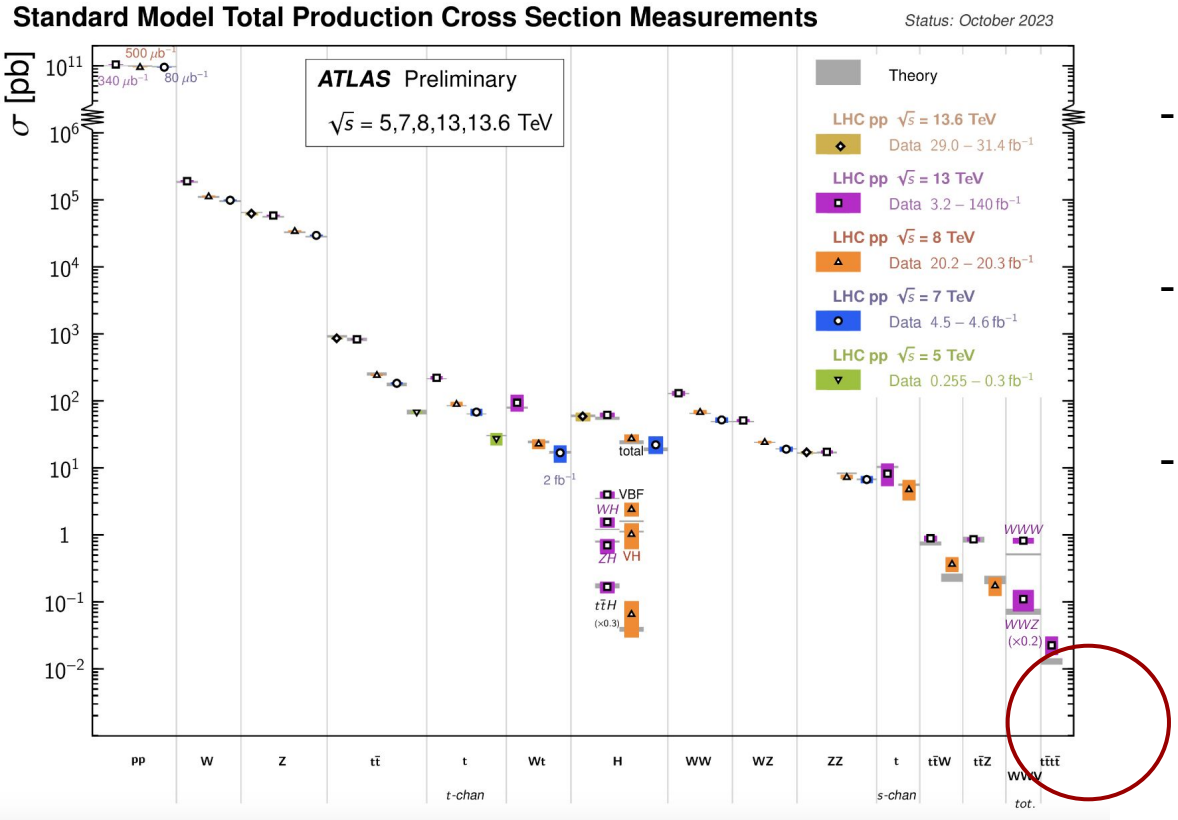

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This talk is on 3- and 4-tops

3- and 4-tops: A brief motivation

Both processes

- are extremely rare under the SM assumptions [e.g. 2107.07529]
- can probe four-fermion operators within a SMEFT framework [e.g. 2011.15060]
- can be affected through top-philic new physics scenarios [see 2404.14482]

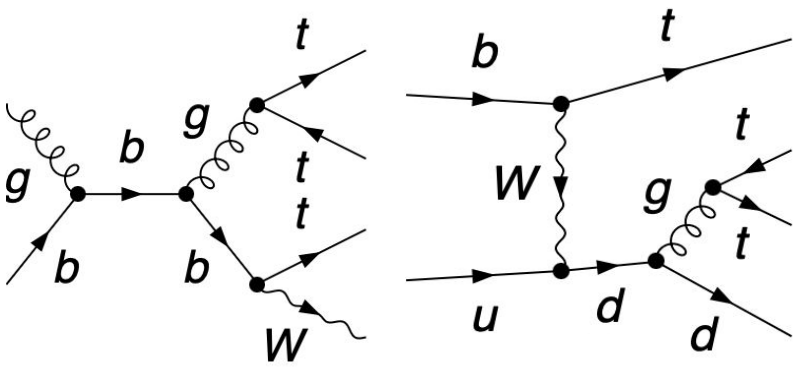
3-tops

is unique as a NP searching program, can be a crucial signature of flavour-violating neutral Interactions [e.g. 1901.04643]

4-tops

is sensitive to many new physics scenarios, such as composite Higgs models and supersymmetry [e.g. 2104.09512]

3-tops: Components



3-tops (tttW) > 3-tops (tttj)

~2x total rate

At NLO QCD in the 5FS

tttt with one ***t*** decaying is ***tttW*** with real radiation emission

Overlap removal is necessary!

All computations are via MadGraph where Diagram Removal (DR) scheme is used for the overlap treatment

3- vs 4-tops: Basics

	4-tops	**3-tops**
Cross-section [fb]	~20	~1
Experimental signature	Multi-lepton	Multi-lepton
Measured?	Yes (with 3-tops set to SM) [2303.15061, 2305.13439]	No
Computed?	c-NLO [1711.02116]	LO in QCD [2107.07629]

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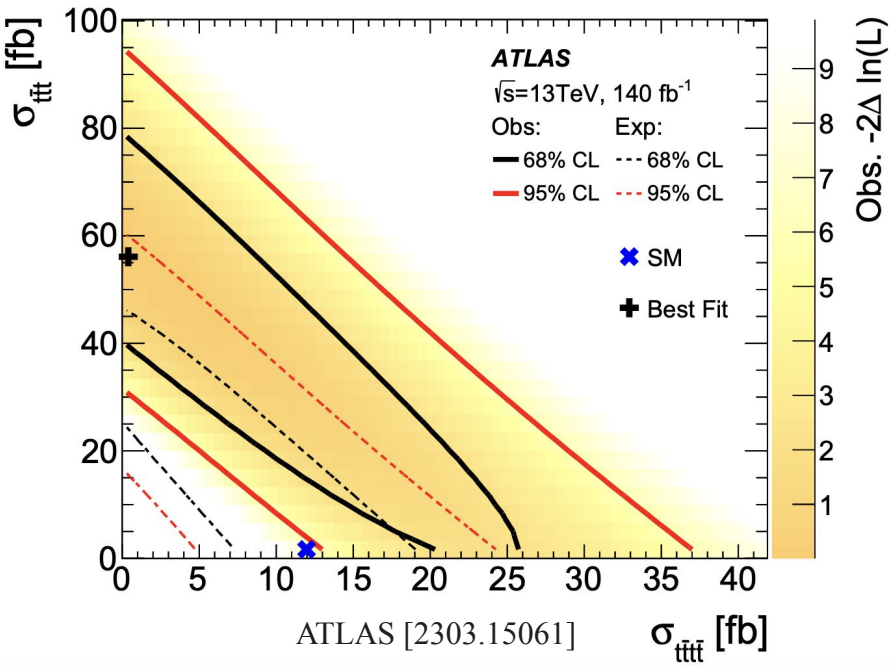
3-tops at NLO QCD was made (~ 1 year) available by Gauthier on https://github.com/gdurieux/triple-top-nlo

3- and 4-tops: Striking similarities?

Strong anti-correlation observed..



ATLAS [2303.15061]

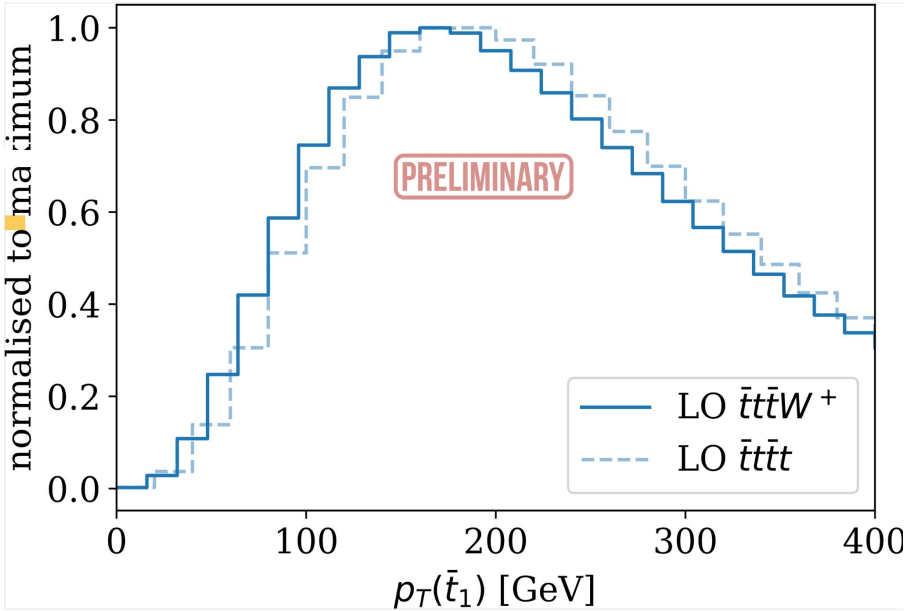
Lack of discrimination power between very similar processes

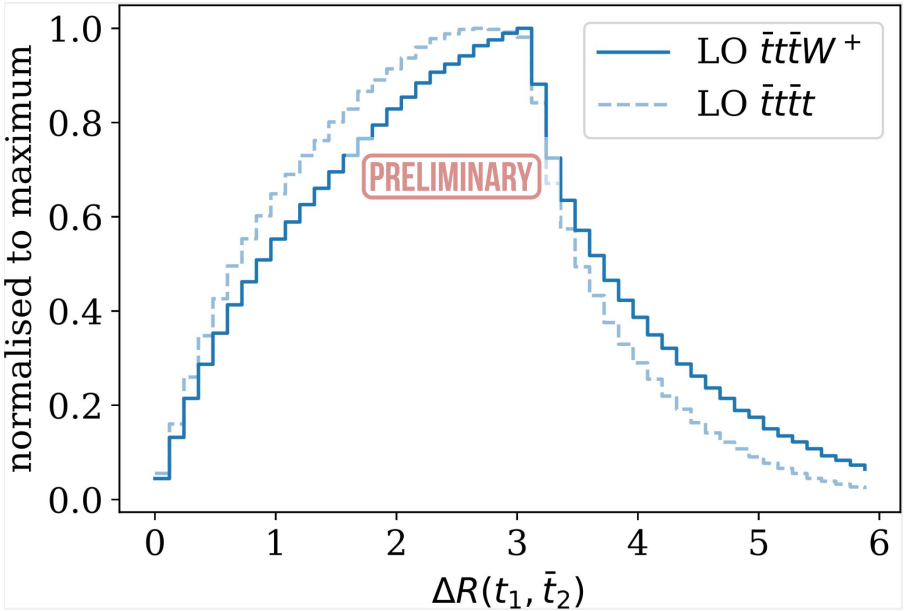
Need for precise total rates and differential predictions for SM 3-tops

i.e. theoretical understanding is key

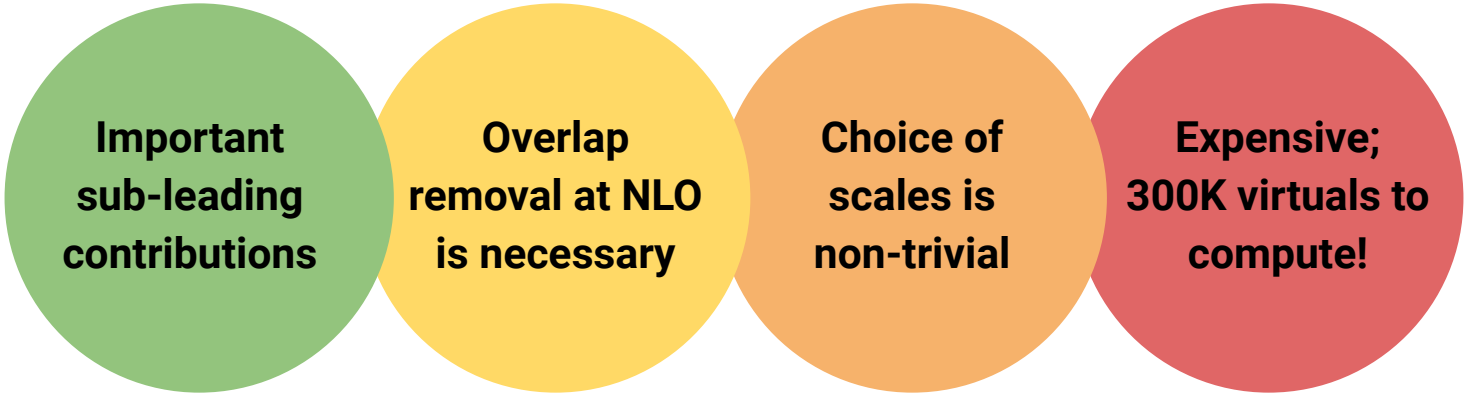
3- vs 4-tops: Differentially at LO

Kinematic similarities manifest differentially





3-tops: Theoretical challenges



3-tops: Theoretical challenges

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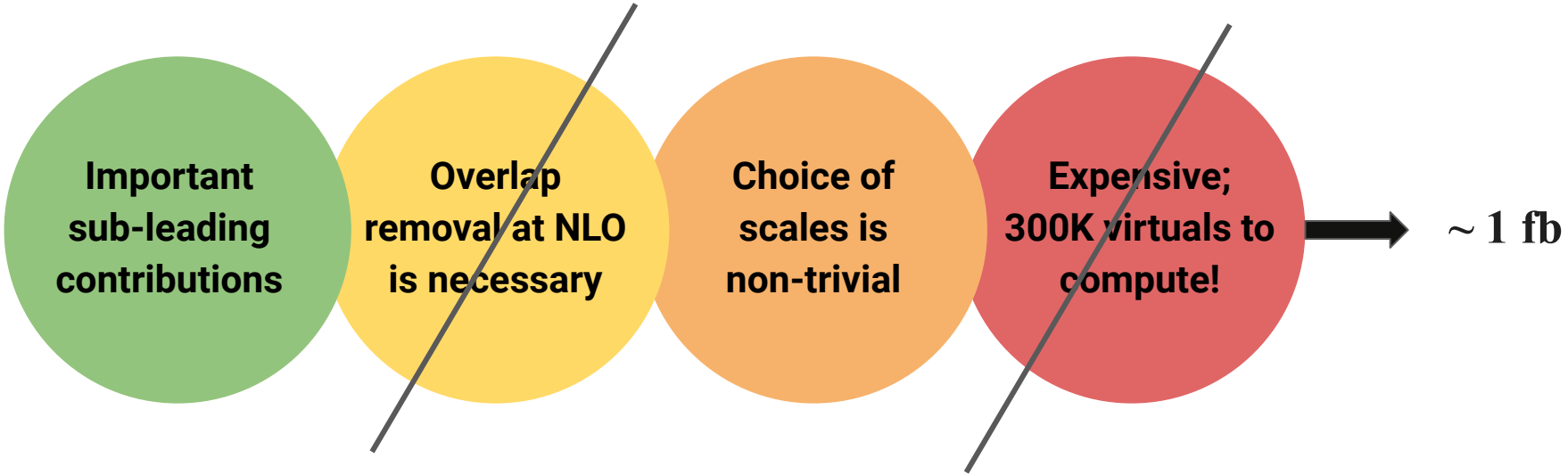


So far, all challenges have been overcome, some are more technical in nature than others;
will focus here on the more physics-oriented ones

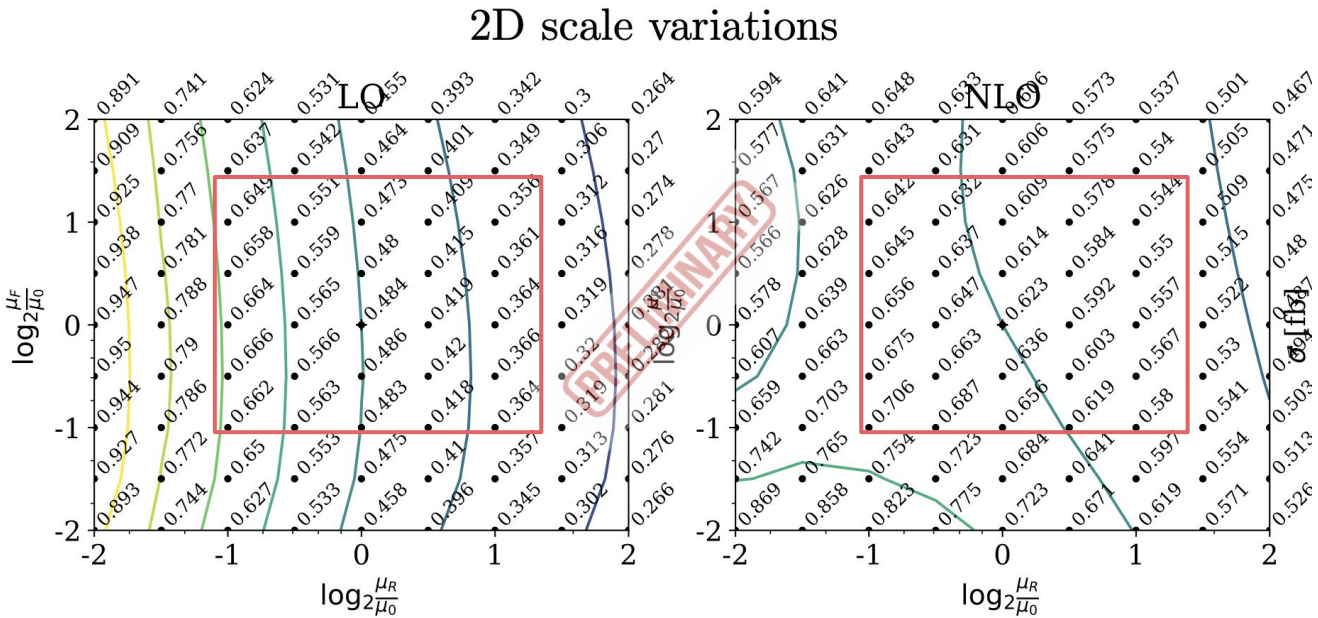
Set the stage

In the upcoming slides, I refer to LO QCD and NLO QCD as just “LO” and “NLO” **until otherwise mentioned**

3-tops: Scale choice at the inclusive-level

Choice of scales is non-trivial

Lower scales feature higher scale variations uncertainties

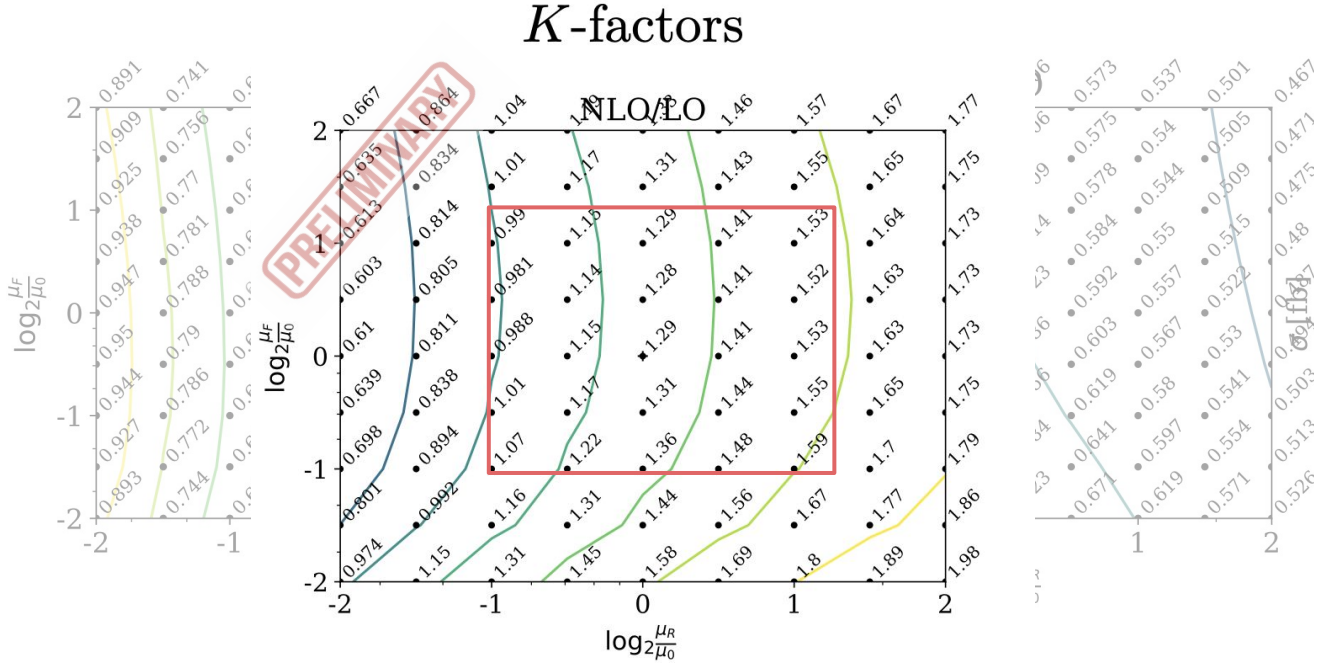


Scale variation is close to minimal at *HT/8*

3-tops: Scale choice at the inclusive-level

Choice of scales is non-trivial

Higher scales hints to worse convergence; higher k-factors

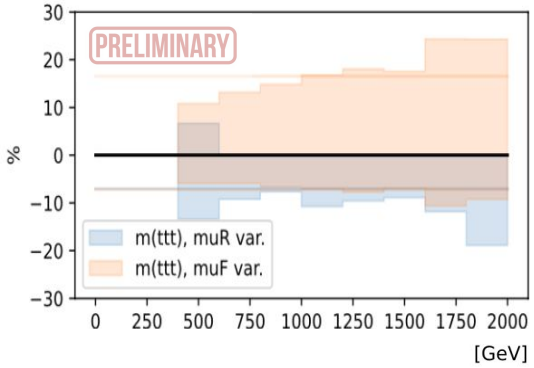


K*-factor is close to minimal at *HT/8

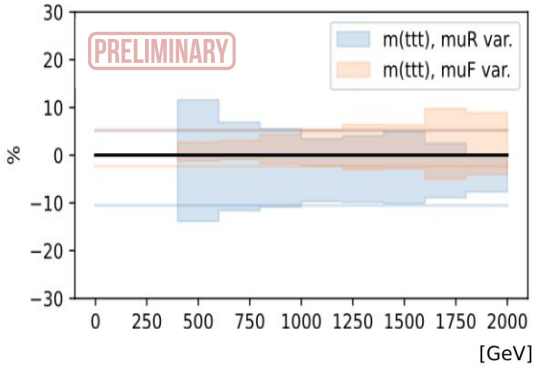
3-tops: Scale choice at the differential-level

Choice of scales is non-trivial

Strong scale dependence manifest differentially



$H_T/16$



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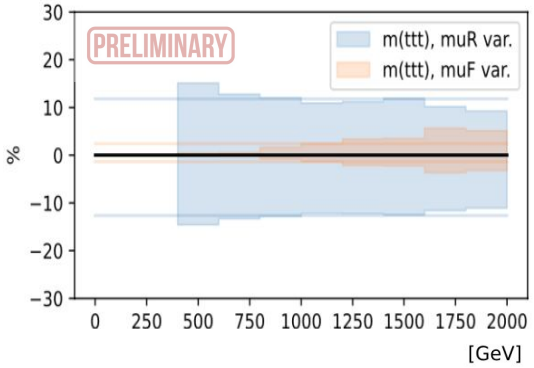
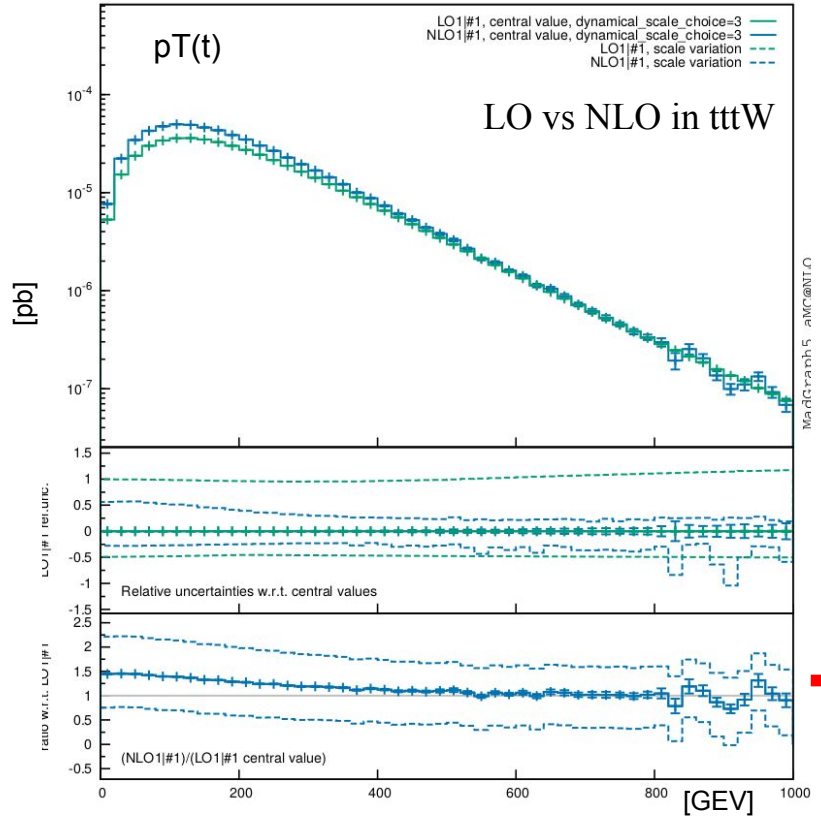


$H_T/4$

~ similar muR and muF variations

3-tops: NLO differential *k*-factors



→ **~ flat differential *k*-factors with significant variation within scales band**

N(LO) EW corrections

3-tops:

LO → 1,2,3,4 → LO1 = LO QCD

NLO → 1,2,3,4,5 → NLO1 = NLO QCD

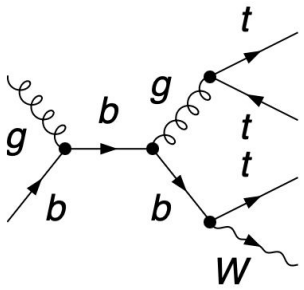
4-tops:

LO → 1,2,3,4,5 → LO1 = LO QCD

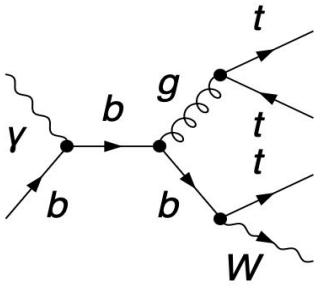
NLO → 1,2,3,4,5,6 → NLO1 = NLO QCD

In the upcoming slides, I will be mentioning LO and NLO with their indices, i.e. 1, 2, etc.

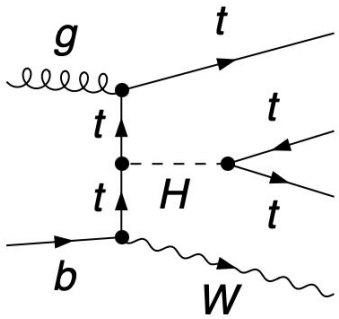
3- and 4-tops: Mechanism



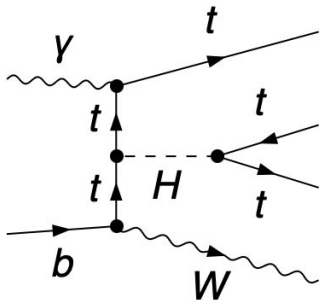
LO1



LO2

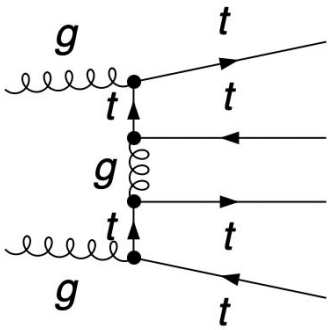


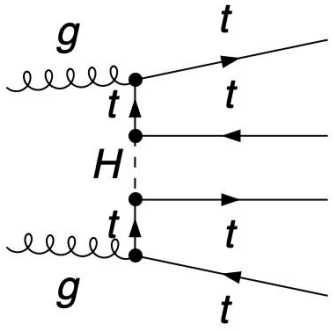
LO3



LO4

3-tops (tttW)

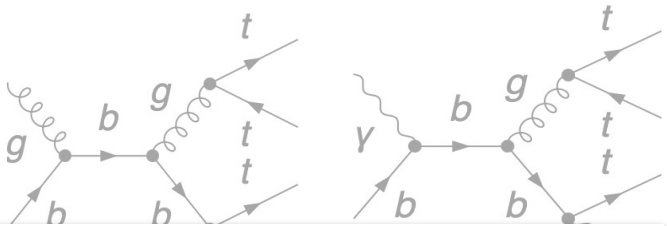




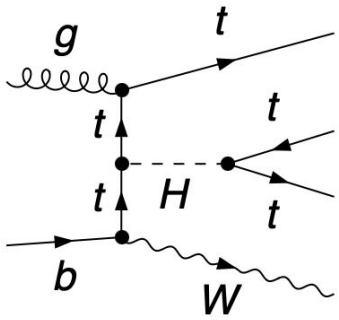
4-tops

~ 90% of 4-tops cross-section is via gg

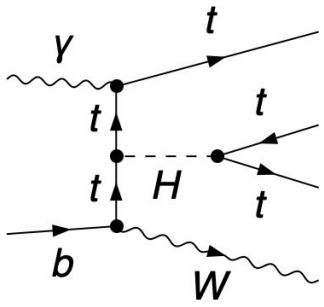
3- and 4-tops: Mechanism



Both processes feature EW scattering between tops



LO3



LO4

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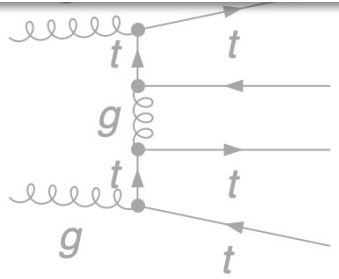

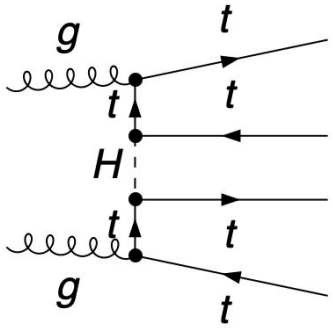

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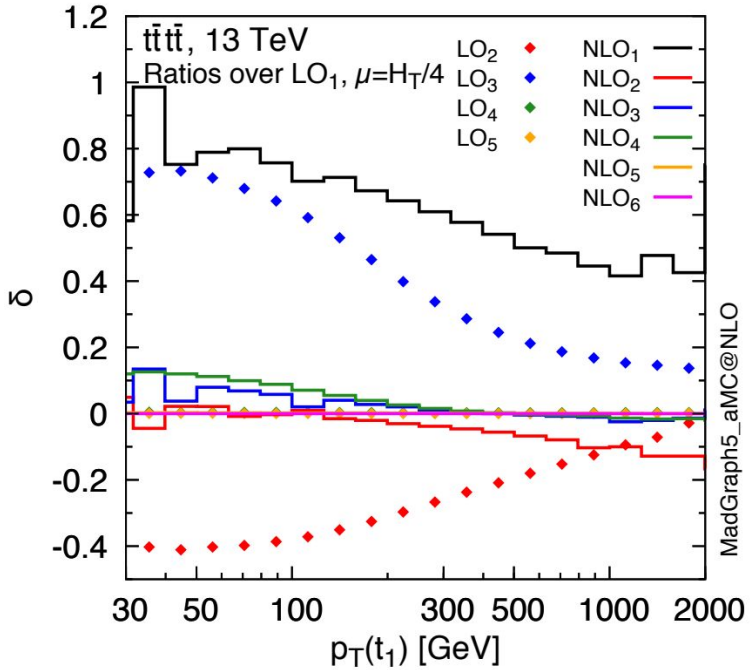
4-tops: Sub-leading orders

Important sub-leading contributions

The computation of [1711.02116]; *Frederix, Pagani and Zaro*

$\delta[\%]$	$\mu = H_T/8$	$\mu = H_T/4$	$\mu = H_T/2$
LO_2	-26.0	-28.3	-30.5
LO_3	32.6	39.0	45.9
LO_4	0.2	0.3	0.4
LO_5	0.02	0.03	0.05
NLO_1	14.0	62.7	103.5
NLO_2	8.6	-3.3	-15.1
NLO_3	-10.3	1.8	16.1
NLO_4	2.3	2.8	3.6
NLO_5	0.12	0.16	0.19
NLO_6	< 0.01	< 0.01	< 0.01
$NLO_2 + NLO_3$	-1.7	-1.6	0.9



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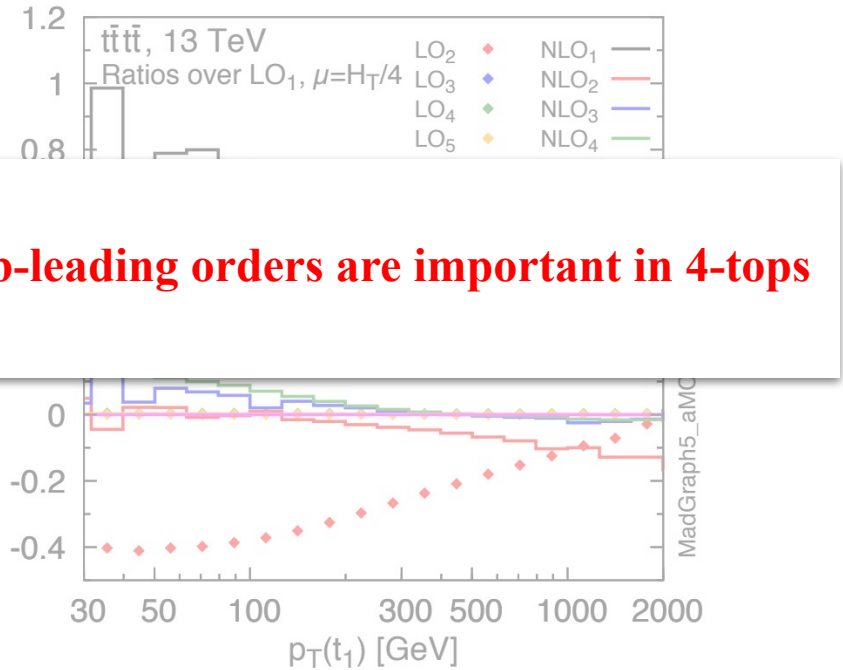
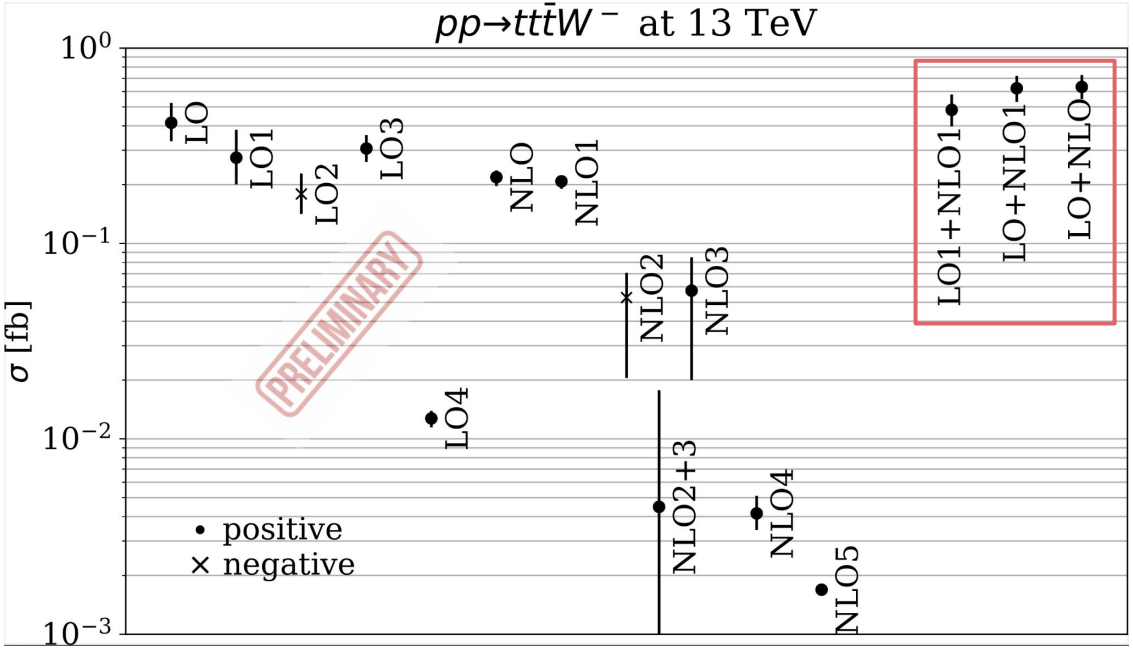


Sub-leading orders are important in 4-tops

3-tops: Hierarchy of LO and NLO

Important sub-leading contributions

At the inclusive-level, it is an *"all-or-not-at-all"* situation



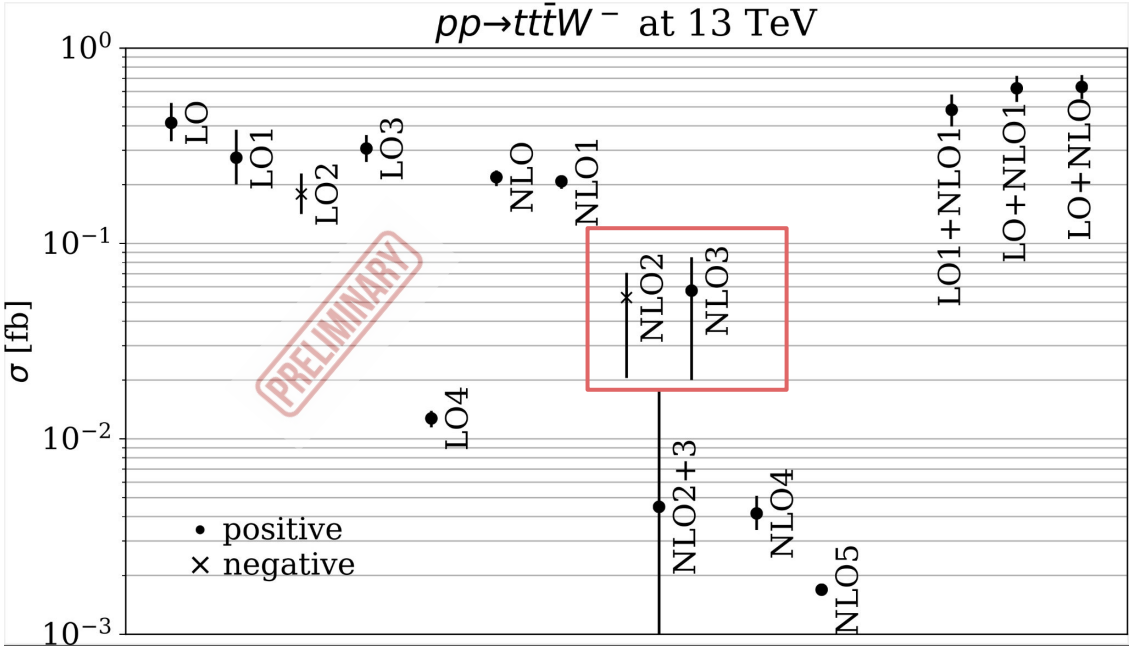
LO	0.41 fb	−20%	+20%	(±0.3%)
LO1	0.27 fb	−30%	+40%	(±0.2%)
LO2	−0.18 fb	+30%	−20%	(±0.1%)
LO3	0.31 fb	−10%	+20%	(±0.2%)
LO4	0.013 fb	−9%	+8%	(±0.3%)
NLO	0.22 fb	−8%	+7%	(±1%)
NLO1	0.21 fb	−7%	+2%	(±0.8%)
NLO2	−0.053 fb	+30%	−60%	(±1%)
NLO3	0.057 fb	−60%	+50%	(±1%)
NLO4	0.0042 fb	−20%	+20%	(±7%)
NLO5	0.0017 fb	−4%	+5%	(±1%)

PRELIMINARY

3-tops: Hierarchy of LO and NLO

Important sub-leading contributions

(N)LO2 and N(LO)3 are significant albeit with strong cancellations occuring



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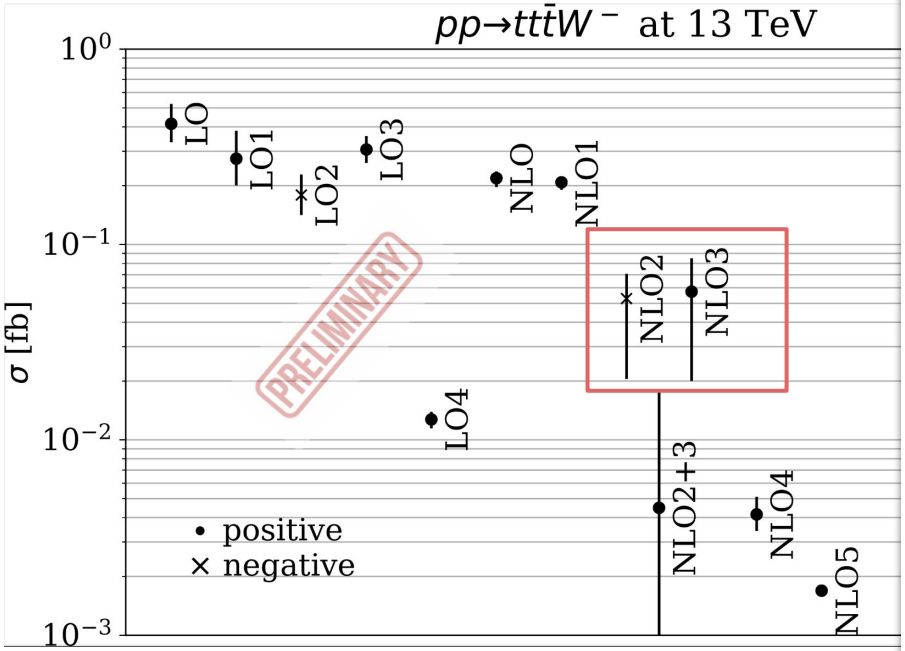
PRELIMINARY

3-tops: Hierarchy of LO and NLO

Important sub-leading contributions

..similar cancellations have been observed for 4-tops at c-NLO



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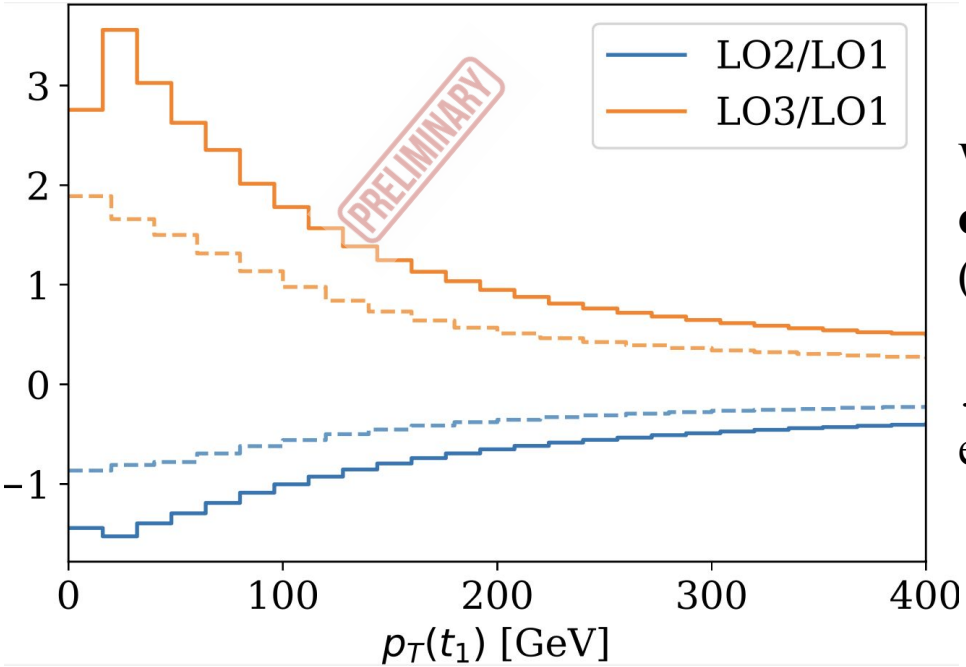
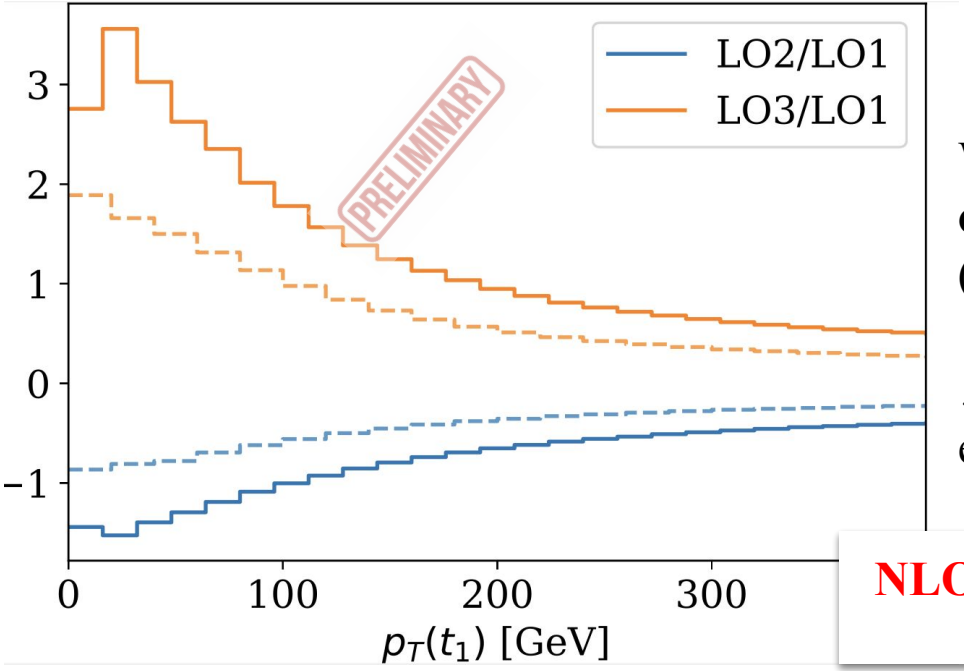
3-tops vs 4-tops: Differential LO Hierarchy



We observe **slightly larger subleading orders in 3-tops** (solid) compared to 4-tops (dashed)

… particularly at threshold → Sommerfeld enhancement

3-tops vs 4-tops: Differential LO Hierarchy



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… particularly at threshold → Sommerfeld enhancement

NLO EW differential results are on the way!

Summary and Conclusions

- 3-tops and 4-tops are rare processes with strong motivations for a good theoretical and experimental control
- 3-tops is ~ 10 times smaller than 4-tops; albeit with kinematic similarities which require reliable differential and total rate predictions
- Complete NLO predictions are necessary for both processes; while this is available for 4-tops, **here we presented the our WIP on c-NLO predictions for 3-tops**
- c-NLO 3-tops is challenging due to several factors like: scale choices, overlap treatment, expensive MC simulations, etc.
- NLO QCD and EW LOs are indispensable; NLO EW orders cancel strongly at the inclusive-level → **We are investigating the differential impacts..**