Electroweak corrections to top associated production

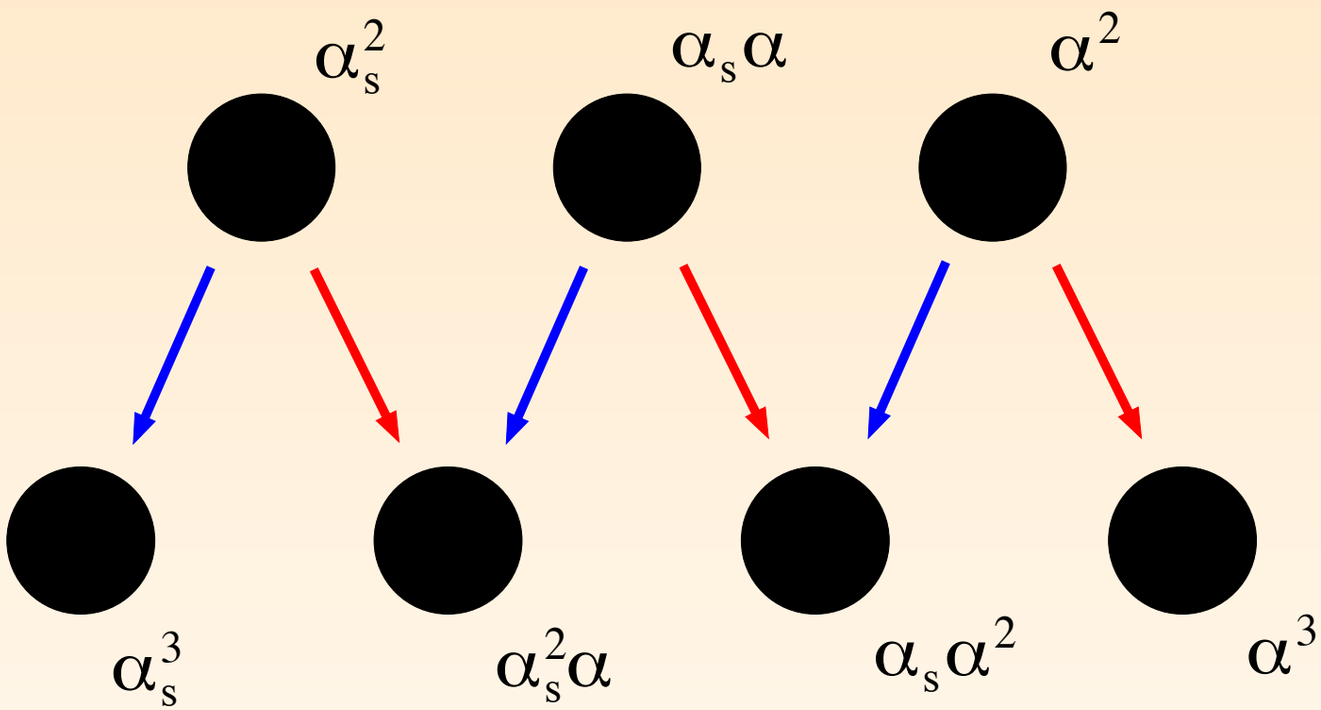
Rikkert Frederix
Technische Universität München

In collaboration with
Davide **Pagani** and Marco **Zaro** arXiv:1711.02116
and
Stefano **Frixione**, Valentin **Hirschi**, Davide **Pagani**, Hua-Sheng **Shao** & Marco **Zaro** arXiv:1804.10017

High Precision for Hard Processes (HP2 2018), Freiburg, Germany, Oct. 1-3, 2018

Anatomy at NLO

- For example: consider di-jet production



- "NLO EW" is a bit of a misnomer:
  NLO_2 and NLO_3 part of a "mixed" expansion

- "**Complete-NLO**" takes all the LO and NLO contributions in the mixed coupling expansion into account

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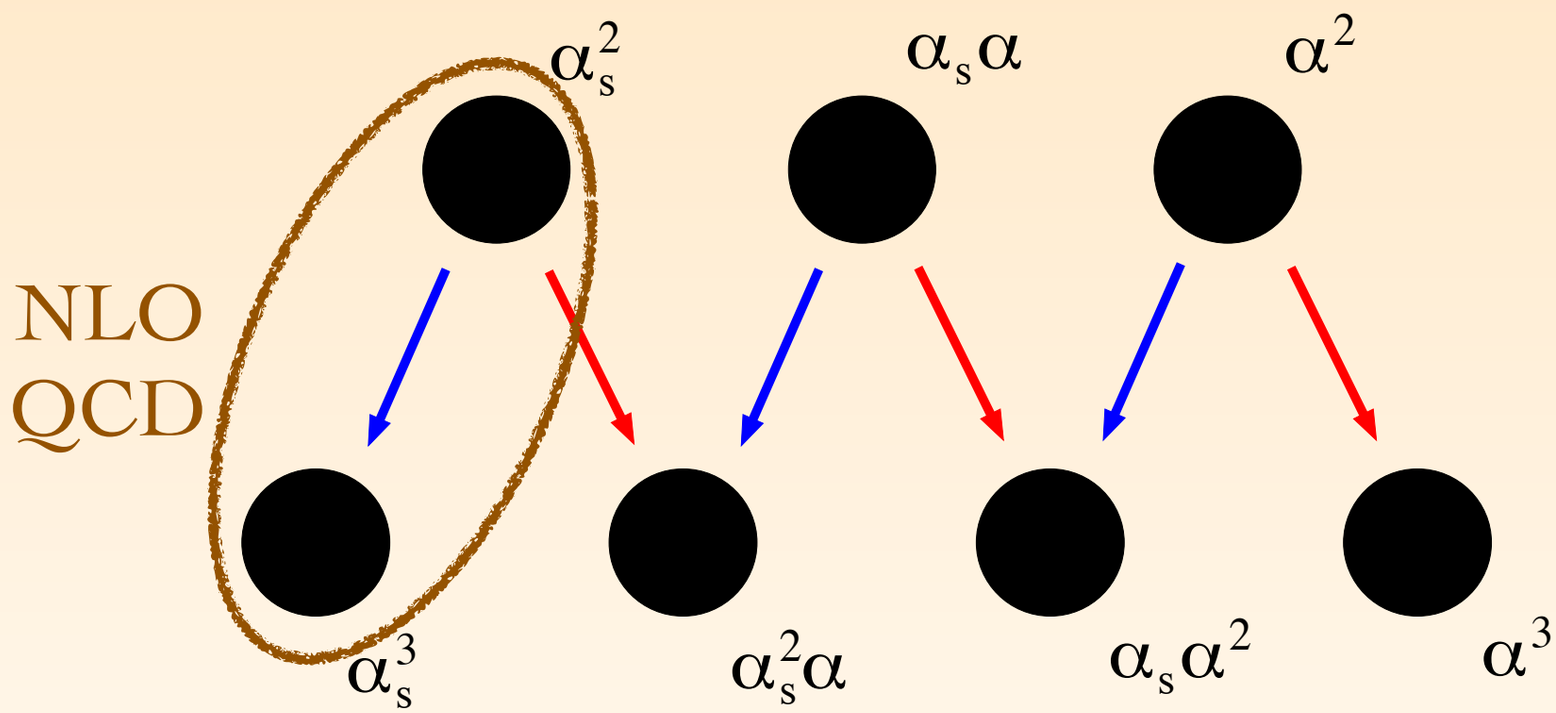

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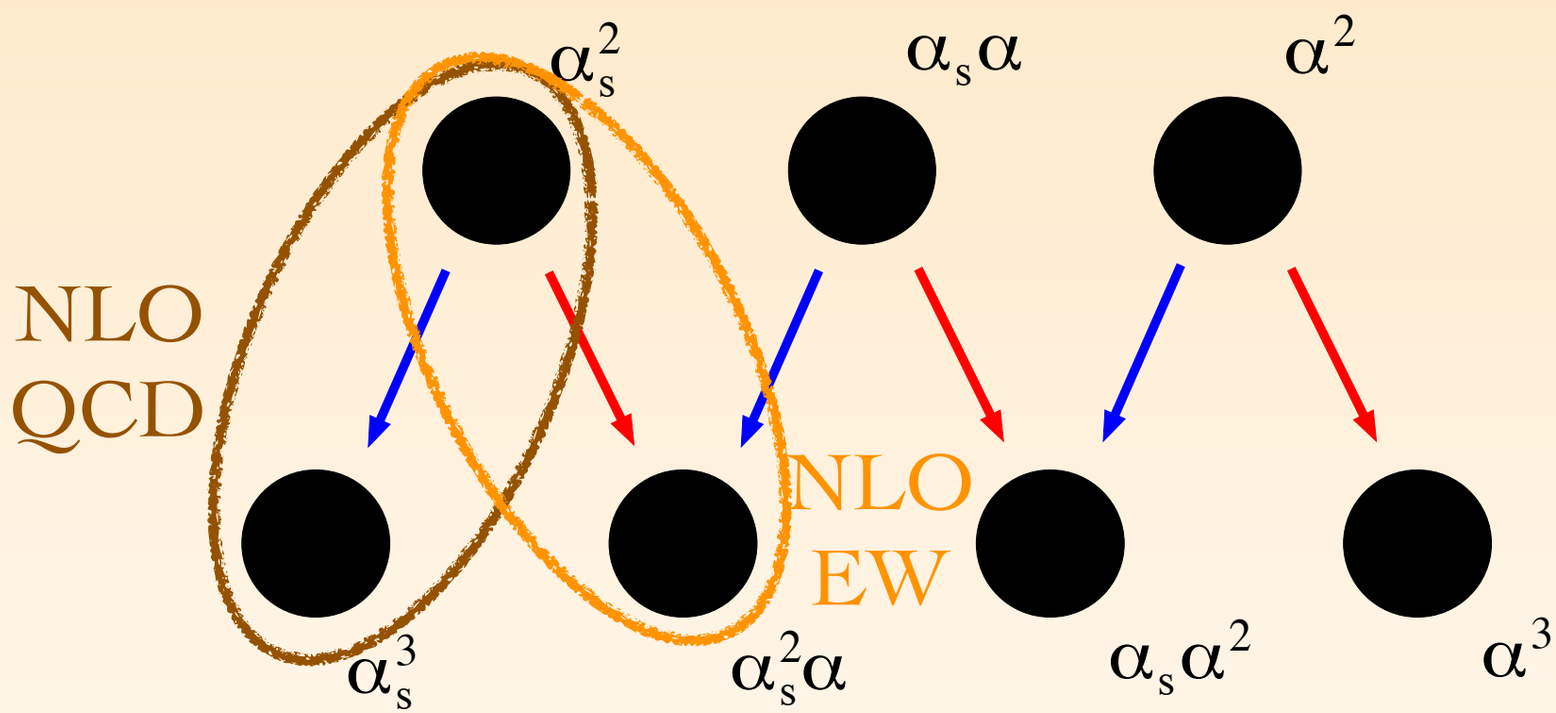

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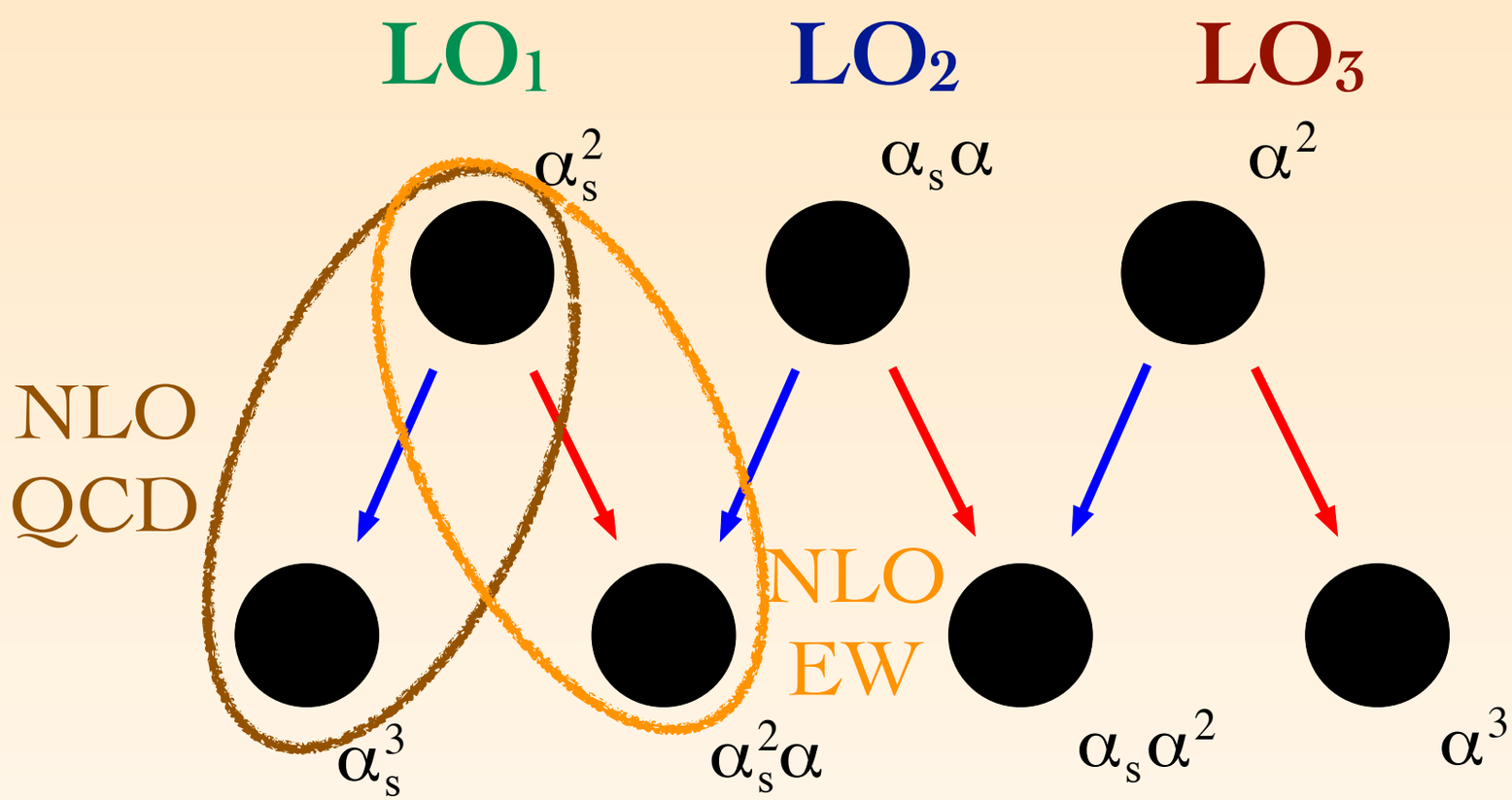

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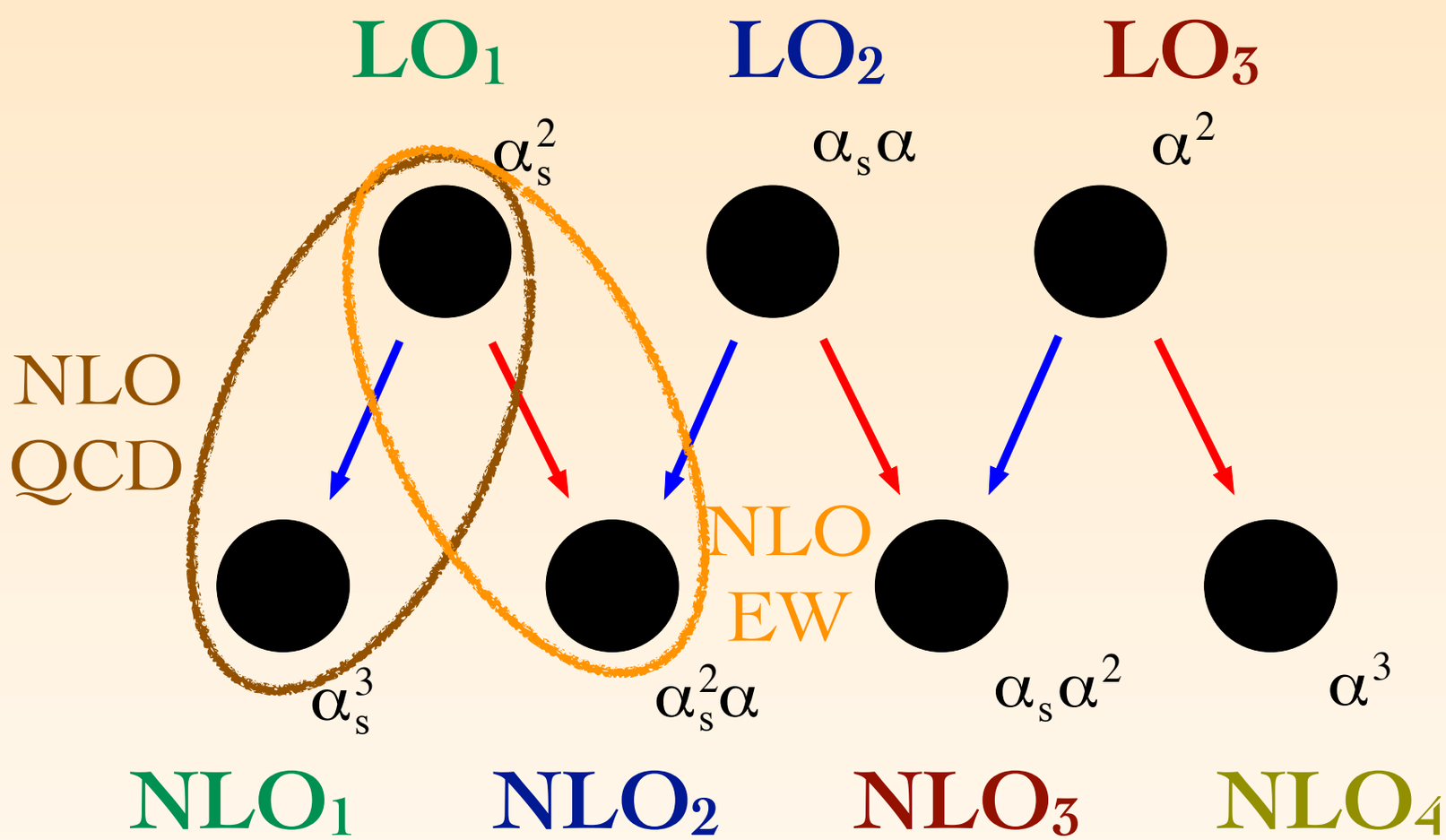

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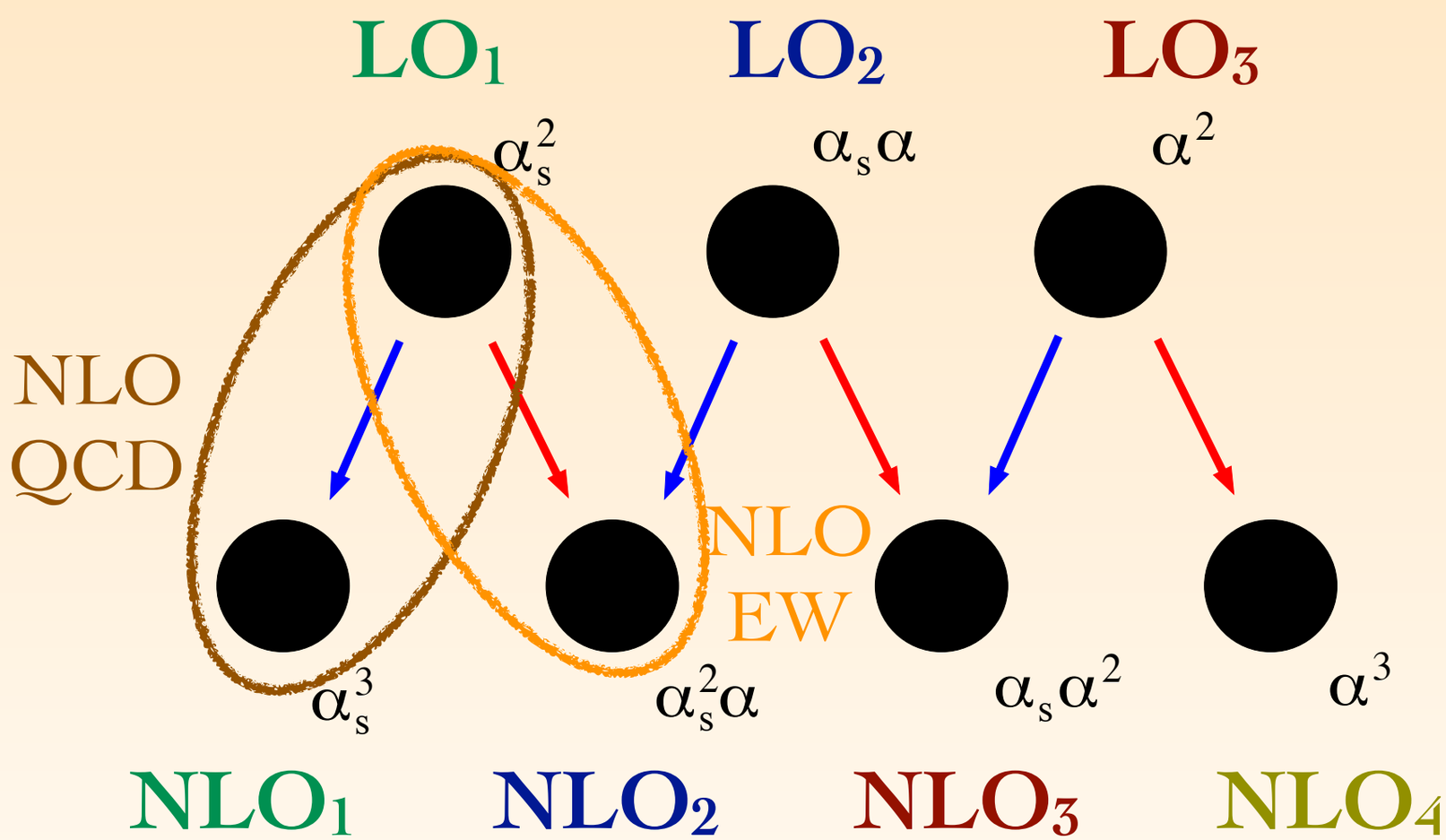

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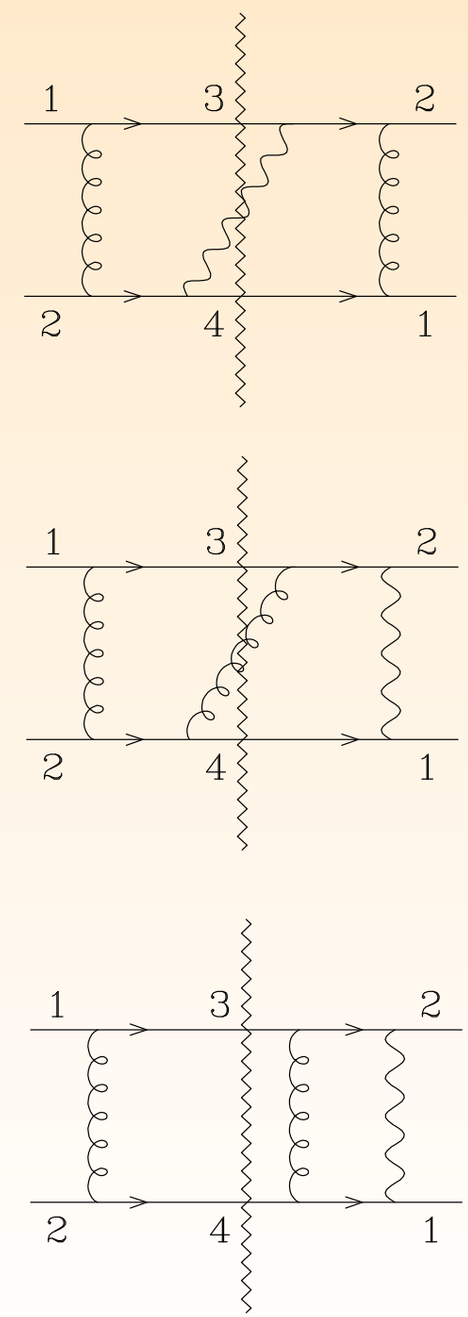
For example: NLO_2 has both "QCD" and "EW" contributions



MadGraph5_aMC@NLO

[RF, Frixione, Hirschi, Pagani, Shao, Zaro, 2018]

- The complete-NLO predictions are now automated in MadGraph5_aMC@NLO
  similar efforts in OpenLoops, Recola & Sherpa

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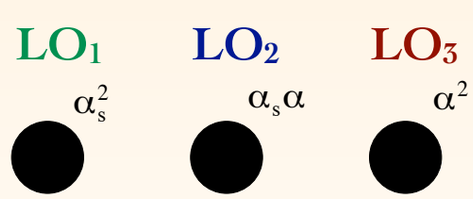

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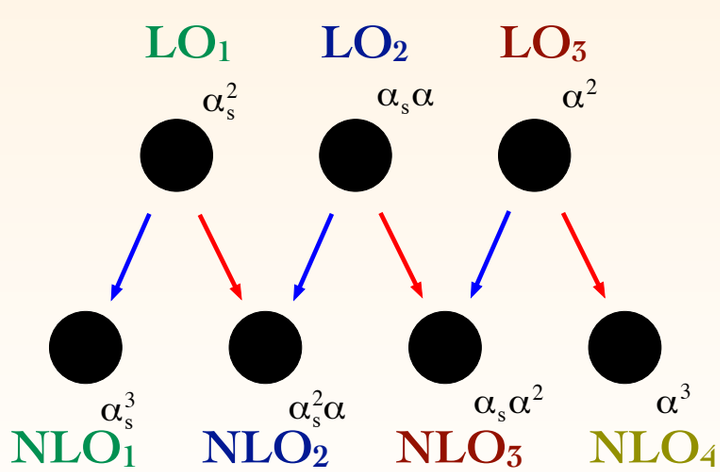

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MG5_aMC> launch
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Complete-NLO for top pairs + friends

[RF, Frixione, Hirschi, Pagani, Shao, Zaro, 2018]

	$pp \to t\bar{t}$	$pp \to t\bar{t}Z$	$pp \to t\bar{t}W^+$	$pp \to t\bar{t}H$	$pp \to t\bar{t}j$
LO_1	$4.3803 \pm 0.0005 \cdot 10^2$ pb	$5.0463 \pm 0.0003 \cdot 10^{-1}$ pb	$2.4116 \pm 0.0001 \cdot 10^{-1}$ pb	$3.4483 \pm 0.0003 \cdot 10^{-1}$ pb	$3.0278 \pm 0.0003 \cdot 10^2$ pb
LO_2	$+0.405 \pm 0.001$ %	-0.691 ± 0.001 %	$+0.000 \pm 0.000$ %	$+0.406 \pm 0.001$ %	$+0.525 \pm 0.001$ %
LO_3	$+0.630 \pm 0.001$ %	$+2.259 \pm 0.001$ %	$+0.962 \pm 0.000$ %	$+0.702 \pm 0.001$ %	$+1.208 \pm 0.001$ %
LO_4					$+0.006 \pm 0.000$ %
NLO_1	$+46.164 \pm 0.022$ %	$+44.809 \pm 0.028$ %	$+49.504 \pm 0.015$ %	$+28.847 \pm 0.020$ %	$+26.571 \pm 0.063$ %
NLO_2	-1.075 ± 0.003 %	-0.846 ± 0.004 %	-4.541 ± 0.003 %	$+1.794 \pm 0.005$ %	-1.971 ± 0.022 %
NLO_3	$+0.552 \pm 0.002$ %	$+0.845 \pm 0.003$ %	$+12.242 \pm 0.014$ %	$+0.483 \pm 0.008$ %	$+0.292 \pm 0.007$ %
NLO_4	$+0.005 \pm 0.000$ %	-0.082 ± 0.000 %	$+0.017 \pm 0.003$ %	$+0.044 \pm 0.000$ %	$+0.009 \pm 0.000$ %
NLO_5					$+0.005 \pm 0.000$ %

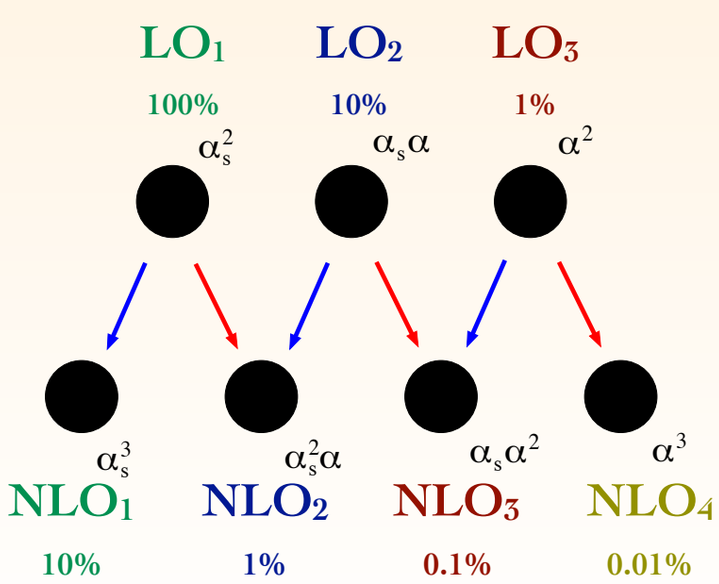
8 TeV

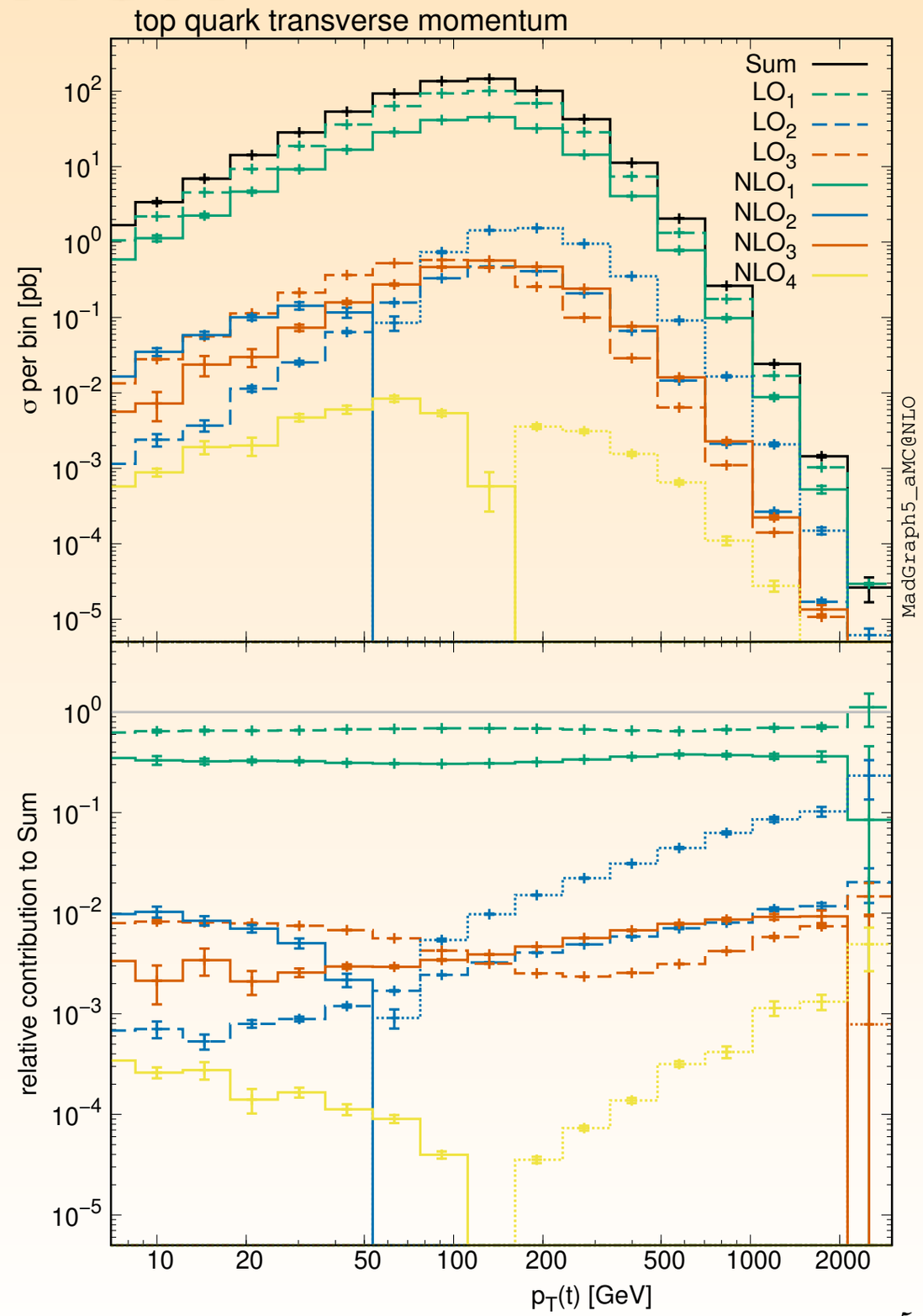
- Typically: size of the corrections follows what one expects from the coupling hierarchy, with the exceptions
  - LO_2 is smaller than expected. No surprise: pure interference term, which requires initial state b-quarks to be non-zero
  - NLO_3 for ttW is much larger than expected!

complete-NLO for tops first computed in:
pp->tt [Czakon et al.]; pp->ttW [RF, Pagani et al.]; pp->ttj [Gütschow et al.]

Complete-NLO for top pair production

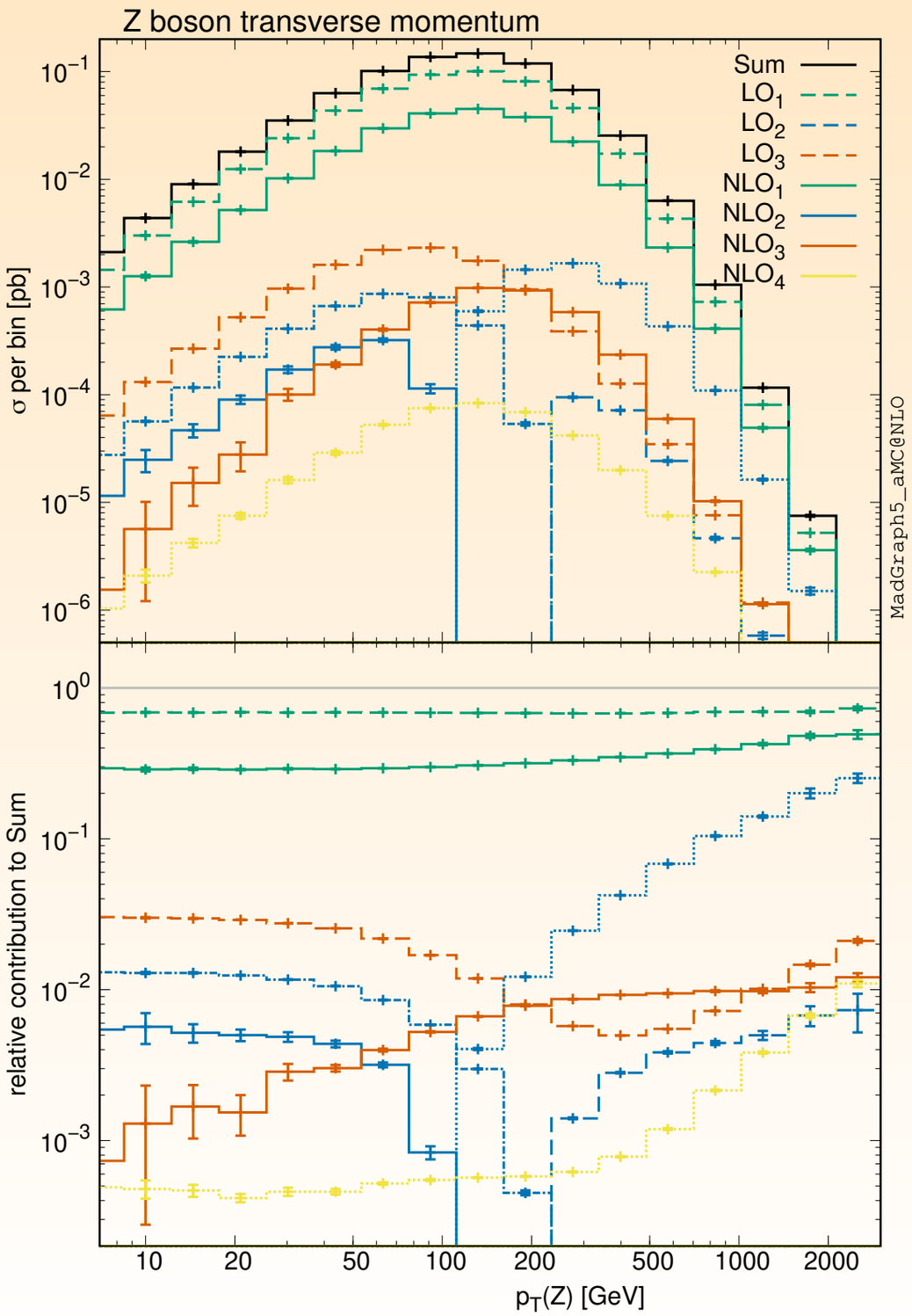
- Top quark transverse momentum
- NLO_2 = NLO EW non-negligible at large p_T's, reaching -10% at p_T=1TeV
- $(N)LO_3$ and NLO_4 are negligible for this observable for this process





Complete-NLO ttbar+Z

[RF, S. Frixione, V. Hirschi, D. Pagani, H.-S. Shao, M. Zaro, 2018]

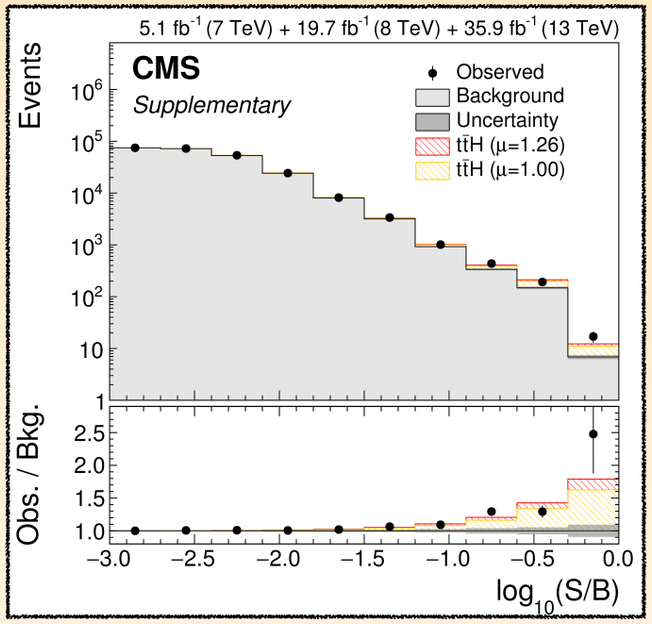


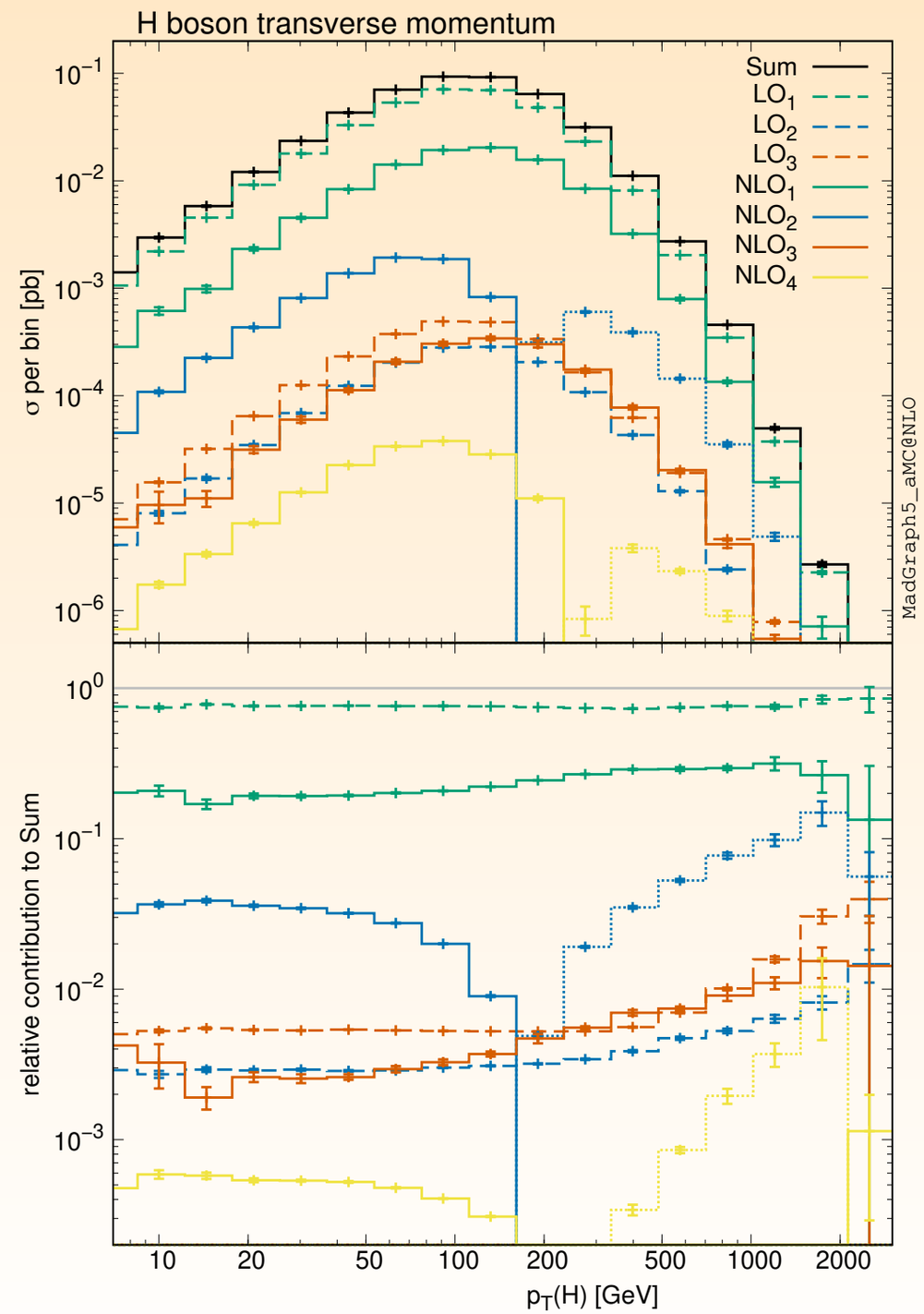
- Top pair production in association with a Z-boson
  - Transverse momentum of the vector boson
- Significant EW corrections (NLO_2) at very large p_Ts, where they can reach ~-25% of the total rate
  - Partly canceling the QCD corrections (NLO_1), which grow with increasing p_T
- (N)LO_3 and NLO_4 typically small and negligible for most practical purposes

Complete-NLO ttbar+H

[RF, S. Frixione, V. Hirschi, D. Pagani, H.-S. Shao, M. Zaro, 2018]

- Higgs production in association of a top-quark pair recently observed at the LHC
- Corrections smaller than for ttbar+Z
  - NLO_2 at the percent-level, apart from the far tail, where its effect is slightly larger
  - $(N)LO_3$ and NLO_4 negligibly small





Complete-NLO ttbar+W

- Top pair production in association with a W-boson
  - Transverse momentum of the boson
- Known: NLO_1 dominant at large p_T (larger than LO_1); would be even more pronounced for $p_T(tt)$ observable
  - can be avoided with a jet veto
- Surprise! **NLO_3 is the largest subleading NLO correction**; being close to 10% of the complete-NLO at small and medium transverse momenta
  - due to opening of t-W scattering
- Significant EW corrections (NLO_2) at very large p_Ts, where they can reach ~-25% of the total rate
  - LO_2 are exactly zero

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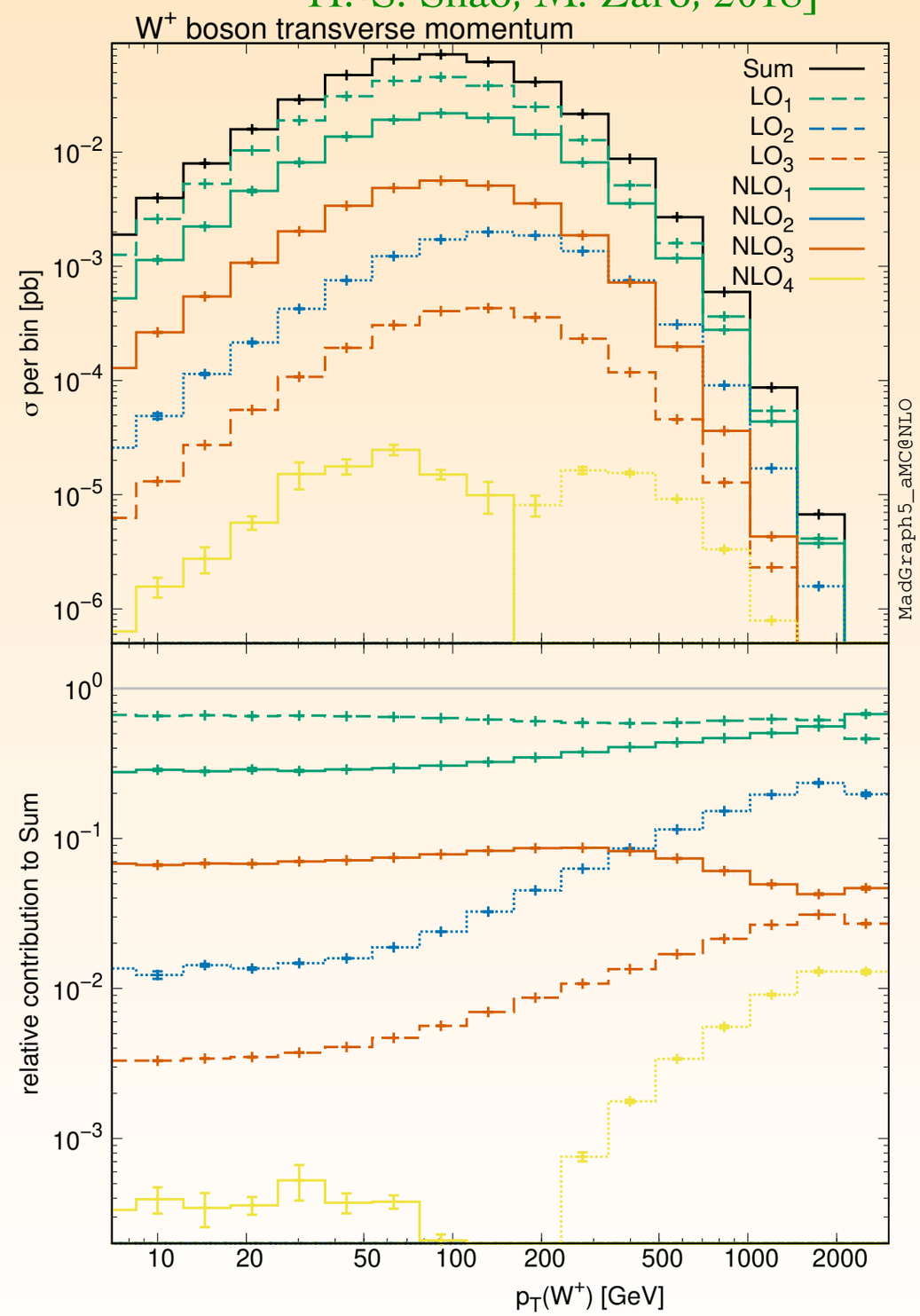

Complete-NLO ttbar+W

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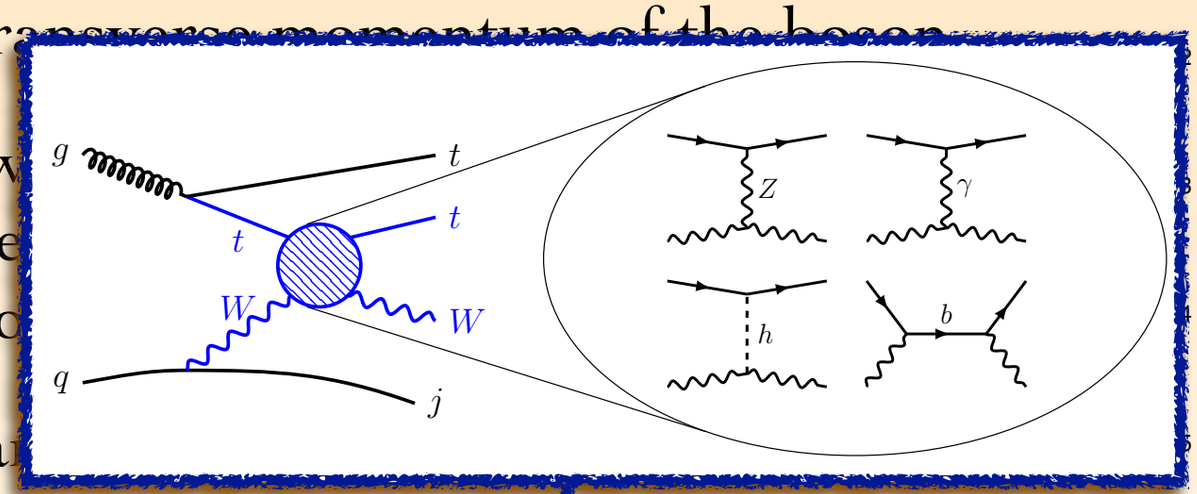

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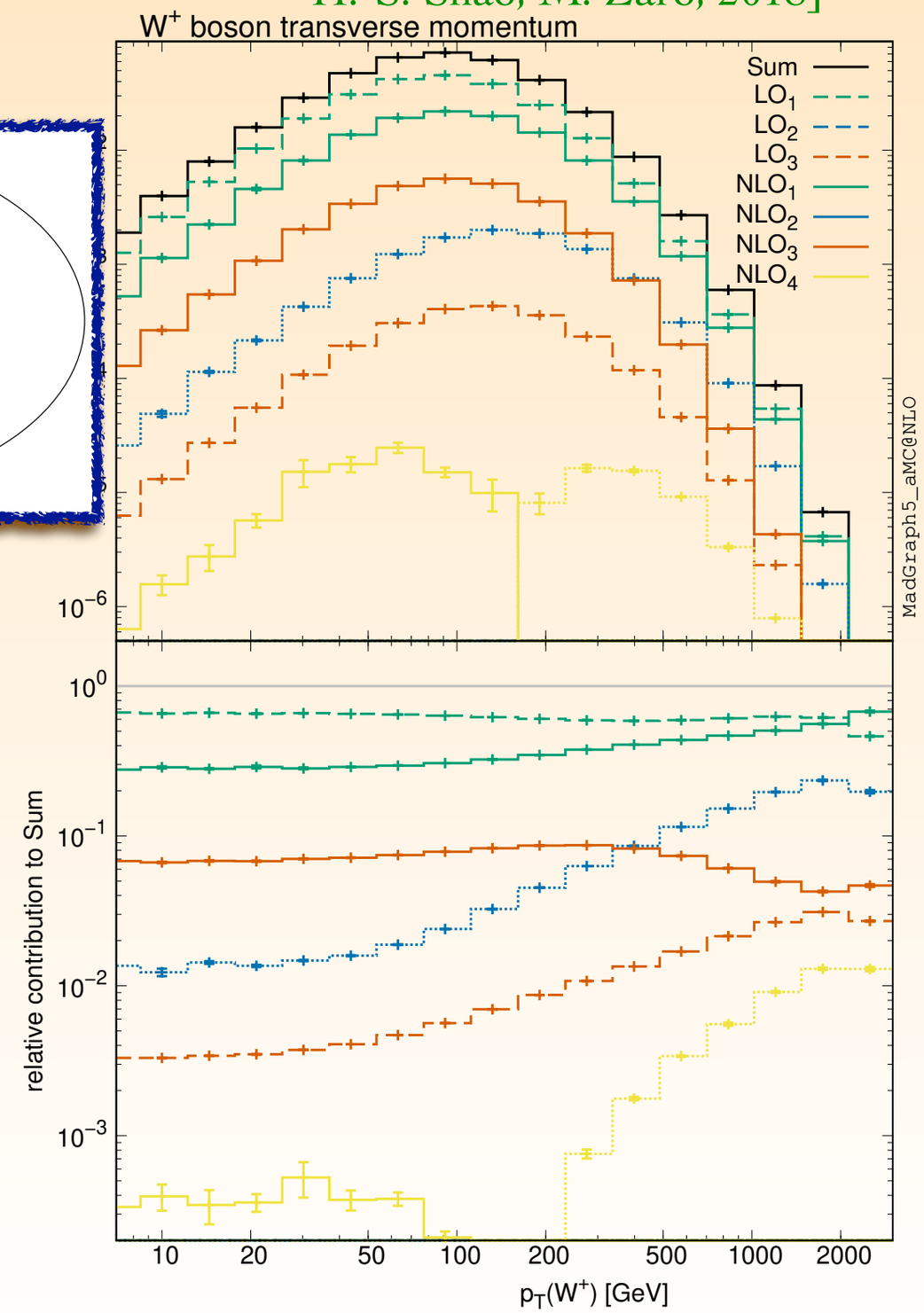

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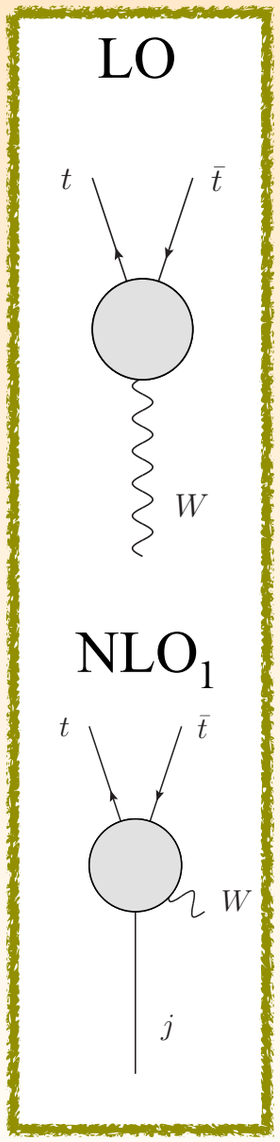
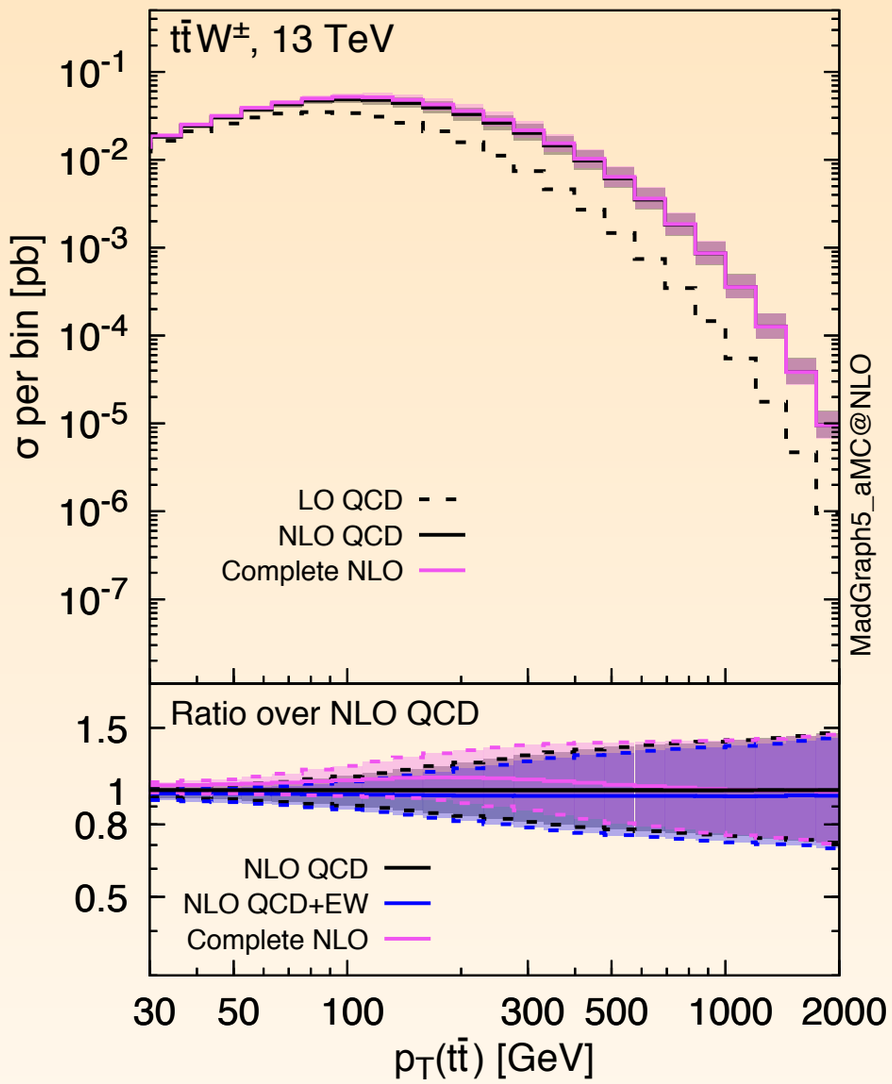
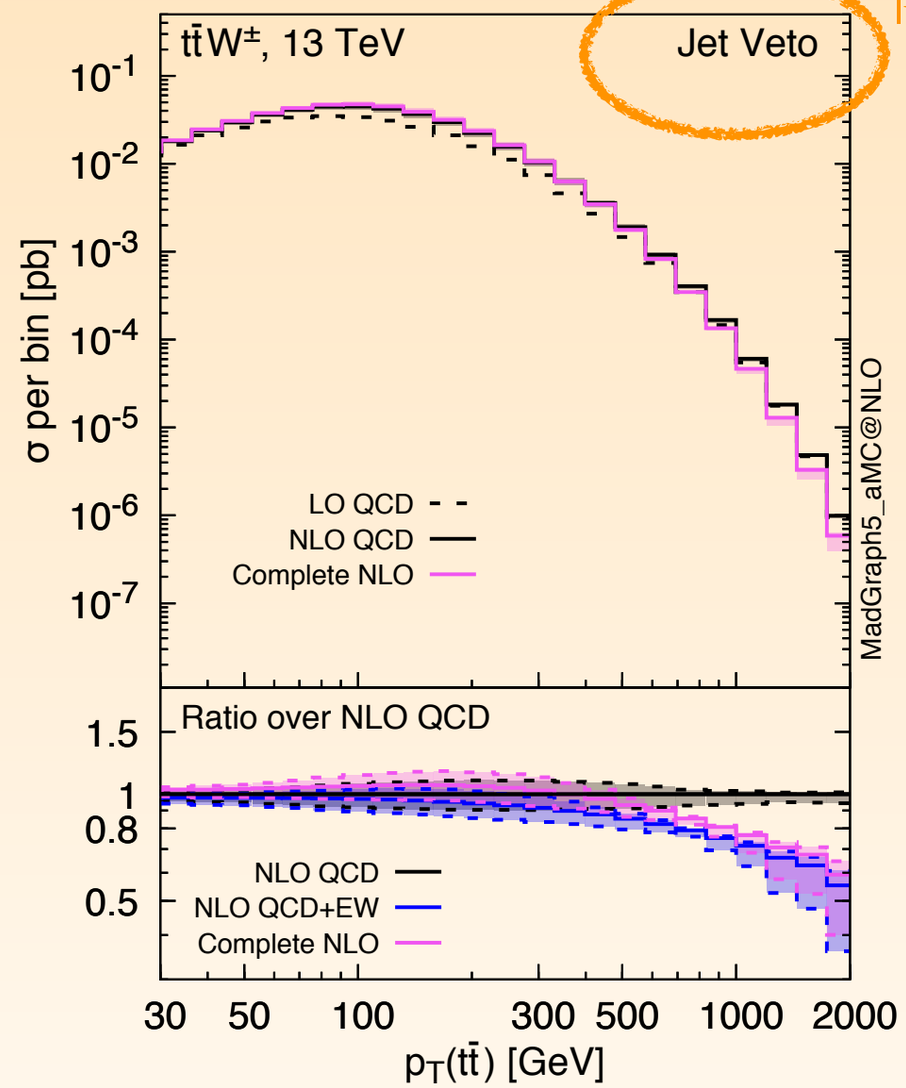
[RF, Pagani, Zaro, 2017]







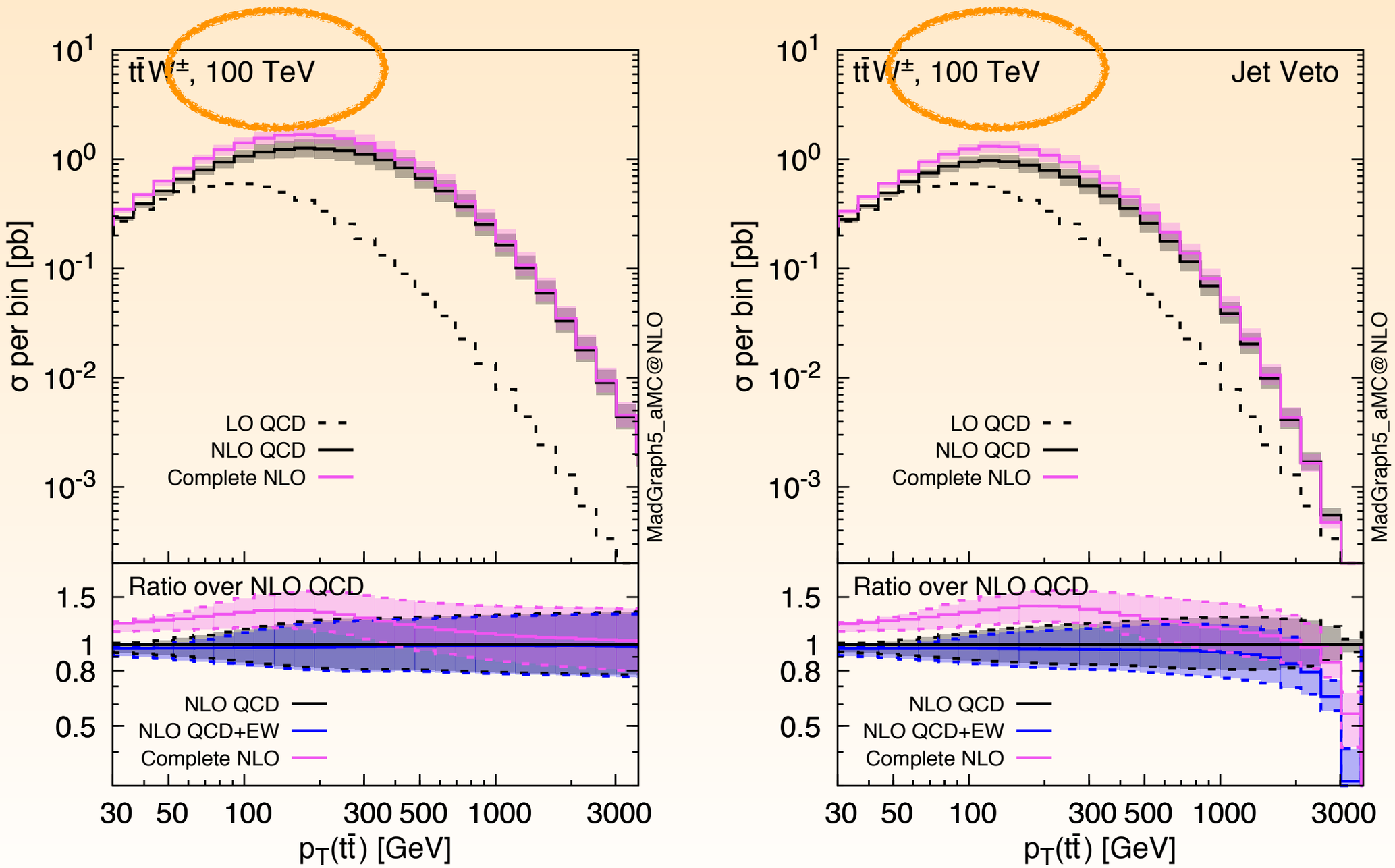
$p_T(j) > 100$ GeV
$|\eta(j)| < 2.5$

- Large NLO corrections, and large scale dependence without the jet veto
- ttbar recoiling predominantly against jet (instead of W-boson) at NLO
- EW corrections are large when the results are not dominated by NLO_1
- Subleading corrections (NLO_3) are larger than expected, but uncertainty bands overlap

Complete-NLO ttbar+W

[RF, Pagani, Zaro, 2017]

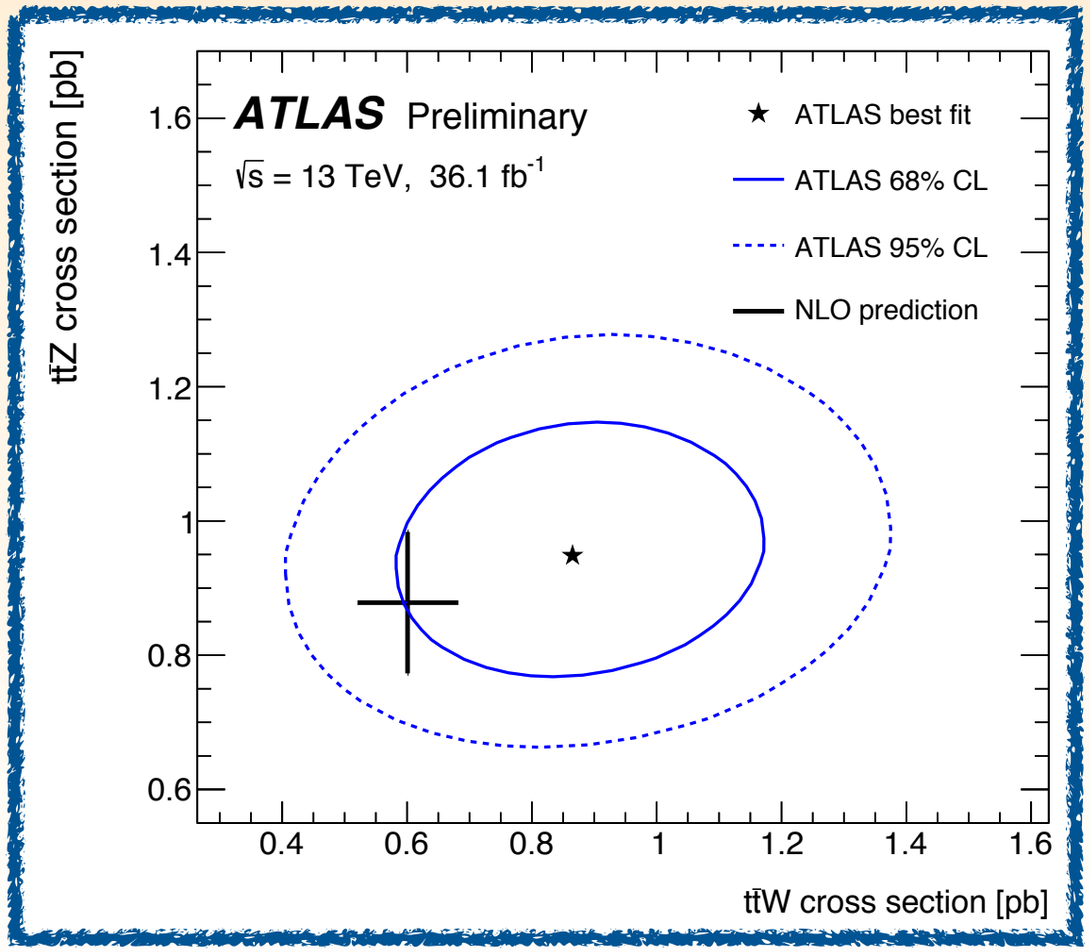
✦ Effects much more extreme at 100 TeV!



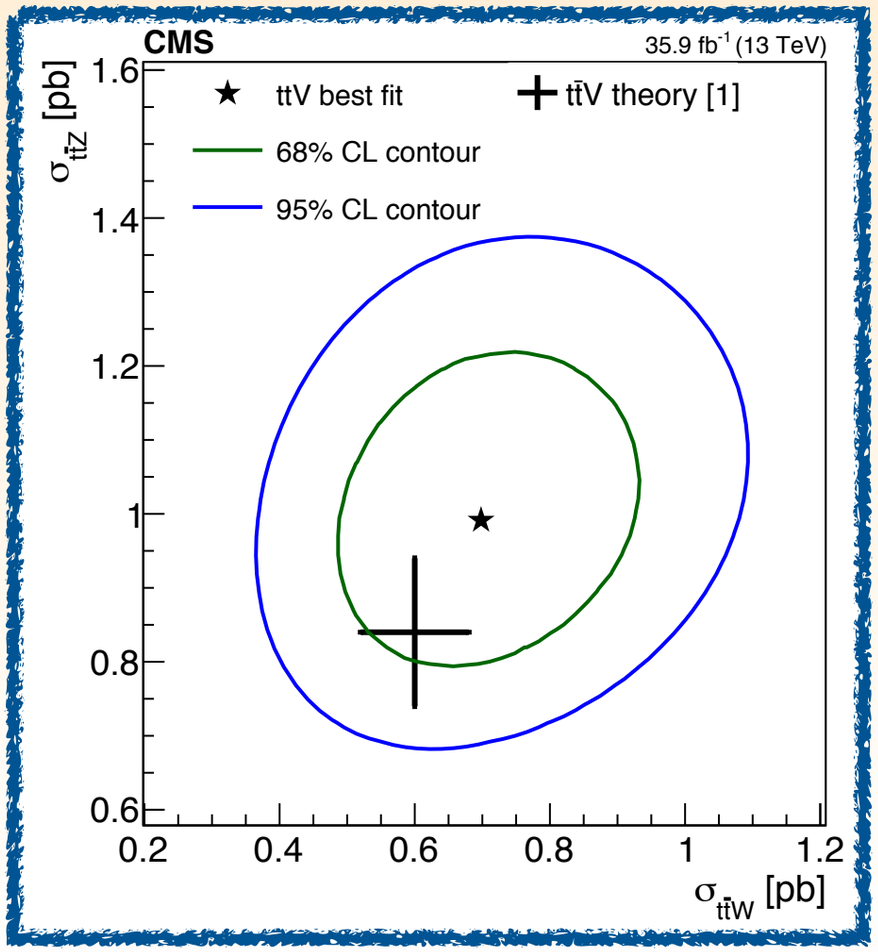
ttW at the LHC

- ttW (together with ttZ) have already been measured at the LHC
- Multi-lepton+jets signature (of which some b-tagged)
- Measurements is in agreement with SM prediction, but still has sizeable uncertainties (which are dominated by statistics)

ATLAS-CONF-2018-047



arXiv:1711.02547

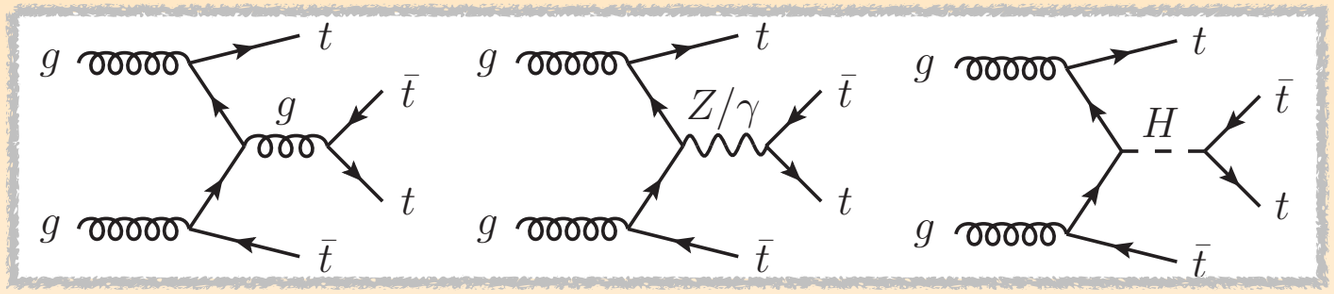


Scattering of heavy particles

- Large corrections due to the opening of t-W scattering
- Yesterday, in parallel session A, Christopher Schwan showed large EW corrections in W-Z scattering
- Also large corrections for same-sign W-W scattering [Biedermann et al.]
- What about t-t scattering?

Four-top production and Top Yukawa coupling

[Cao, Chen & Liu, 2016]



$$\sigma^{\rm SM}(t\bar{t}t\bar{t})_{g+Z/\gamma} \propto \left|\mathcal{M}_g + \mathcal{M}_{Z/\gamma}\right|^2,$$
$$\sigma^{\rm SM}(t\bar{t}t\bar{t})_{H} \propto \left|\mathcal{M}_H\right|^2,$$
$$\sigma^{\rm SM}(t\bar{t}t\bar{t})_{\rm int} \propto \mathcal{M}_{g+Z/\gamma}\mathcal{M}_H^\dagger + \mathcal{M}_{g+Z/\gamma}^\dagger\mathcal{M}_H$$

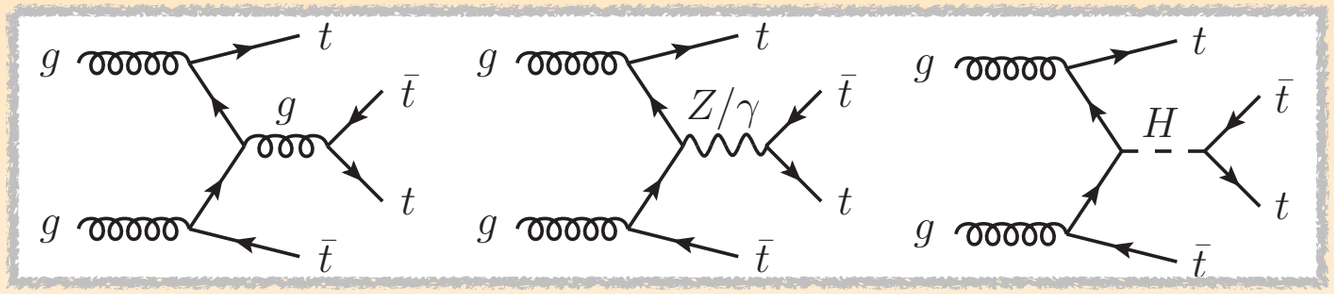
$$\sigma(t\bar{t}t\bar{t}) = \sigma^{\rm SM}(t\bar{t}t\bar{t})_{g+Z/\gamma} + \kappa_t^2\sigma^{\rm SM}_{\rm int} + \kappa_t^4\sigma^{\rm SM}(t\bar{t}t\bar{t})_H$$

- Four-top production can be used together with ttH to constrain/measure a **anomalous top Yukawa coupling** independently from the top width
  - kappa-framework
- Large contributions from subleading **LO$_i$**, with large cancelations
  - How do NLO corrections affect these?

	8 TeV	14 TeV
$\sigma^{\rm SM}(t\bar{t}t\bar{t})_{g+Z/\gamma}$:	1.193 fb,	12.390 fb,
$\sigma^{\rm SM}(t\bar{t}t\bar{t})_{H}$:	0.166 fb,	1.477 fb,
$\sigma^{\rm SM}(t\bar{t}t\bar{t})_{\rm int}$:	−0.229 fb,	−2.060 fb.

Four-top production and Top Yukawa coupling

[Cao, Chen & Liu, 2016]



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LO$_1$ LO$_3$ LO$_2$ (+LO$_1$ and LO$_3$)

	8 TeV	14 TeV
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$\sigma^{\rm SM}(t\bar{t}t\bar{t})_{\rm int}$:	−0.229 fb,	−2.060 fb.

Top Yukawa from 4-top

- Limits have been set on the Top Yukawa coupling from this process
- Constraint to be less than 2.1 times the SM value (or 2.4, if uncertainty in the predictions are taken into account)
- However, based on LO cross sections, with a global 1.27 K-factor

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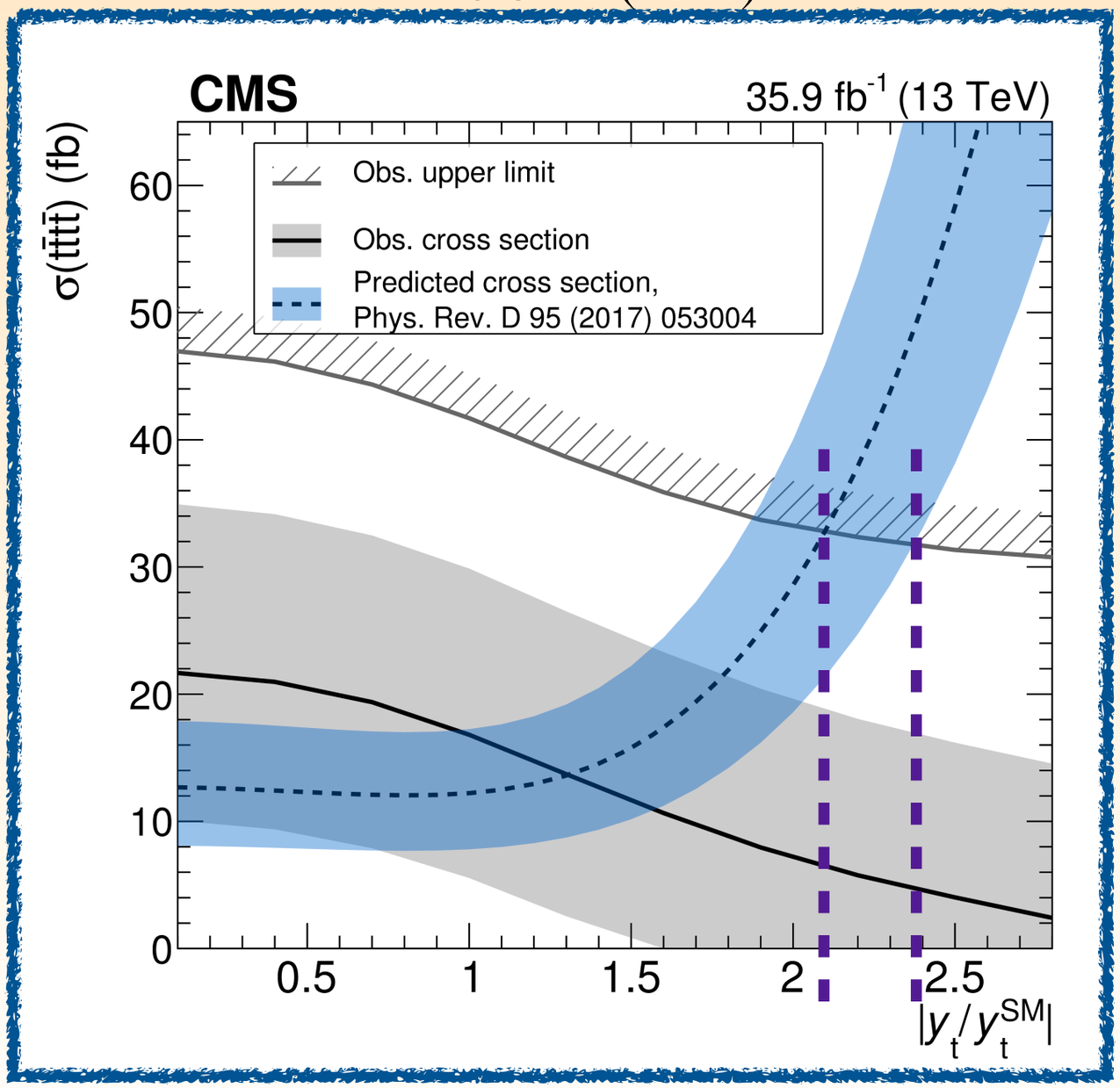
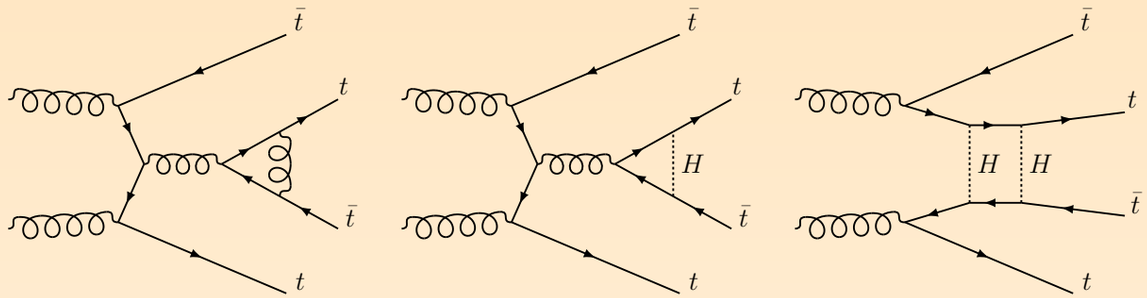


NLO kappa framework...?



- Kappa-framework: replace all SM Higgs couplings $y_{sm,i}$ with "anomalous" couplings, with strength $y_i = \kappa_i \times y_{sm,i}$
- When computing NLO_i (with i>1) corrections, e.g. NLO EW, top Yukawa coupling and top mass are not independent parameters
  - Cannot use kappa-framework
- Need complete Effective Field Theory framework
  - Currently beyond capabilities for four-top production
- Still, NLO four-top in the SM will tell us about possible cancelations among various contributions

NLO 4-top production in the SM

[RF, Pagani, Zaro, 2017]

- LO_2 and LO_3 have large cancelations
- NLO_2 and NLO_3 mainly given by QCD corrections on top of them
  - large and strongly dependent on the scale choice
- However, the sum of NLO_2+NLO_3 very stable and small
- Different scale choices have even more extreme cancelations between NLO_2 and NLO_3

σ[fb]	LO_{QCD}
$\mu = H_T/4$	$6.83^{+70\%}_{-38\%}$

$$\delta_{(N)LO_i}(\mu) = \frac{\Sigma_{(N)LO_i}(\mu)}{\Sigma_{LO_{QCD}}(\mu)}$$

δ[%]	$\mu = H_T/8$	$\mu = H_T/4$	$\mu = H_T/2$	Naive expectation
LO_2	−26.0	−28.3	−30.5	10%
LO_3	32.6	39.0	45.9	1%
LO_4	0.2	0.3	0.4	0.1%
LO_5	0.02	0.03	0.05	0.01%
NLO_1	14.0	62.7	103.5	10%
NLO_2	8.6	−3.3	−15.1	1%
NLO_3	−10.3	1.8	16.1	0.1%
NLO_4	2.3	2.8	3.6	0.01%
NLO_5	0.12	0.16	0.19	0.001%
NLO_6	< 0.01	< 0.01	< 0.01	0.0001%
$NLO_2 + NLO_3$	−1.7	−1.6	0.9	

13 TeV

- LO_4, $(N)LO_5$ and NLO_6 only qqbar initial state. Hence, very small

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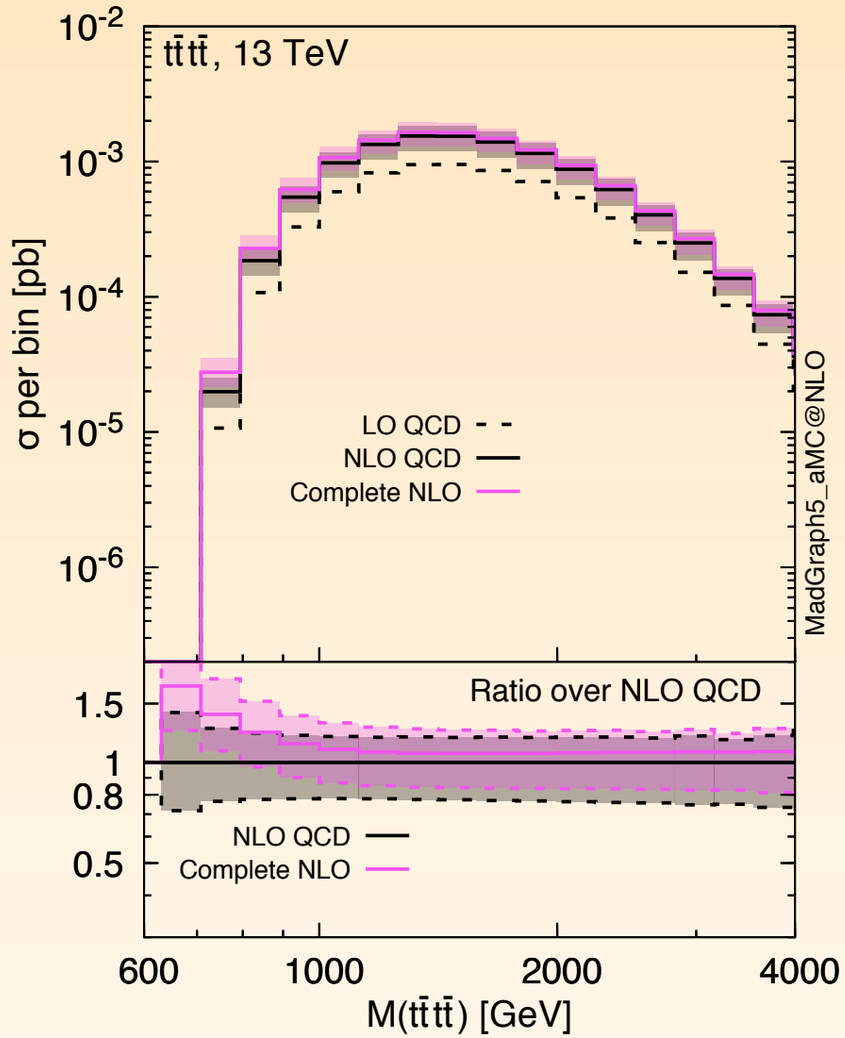
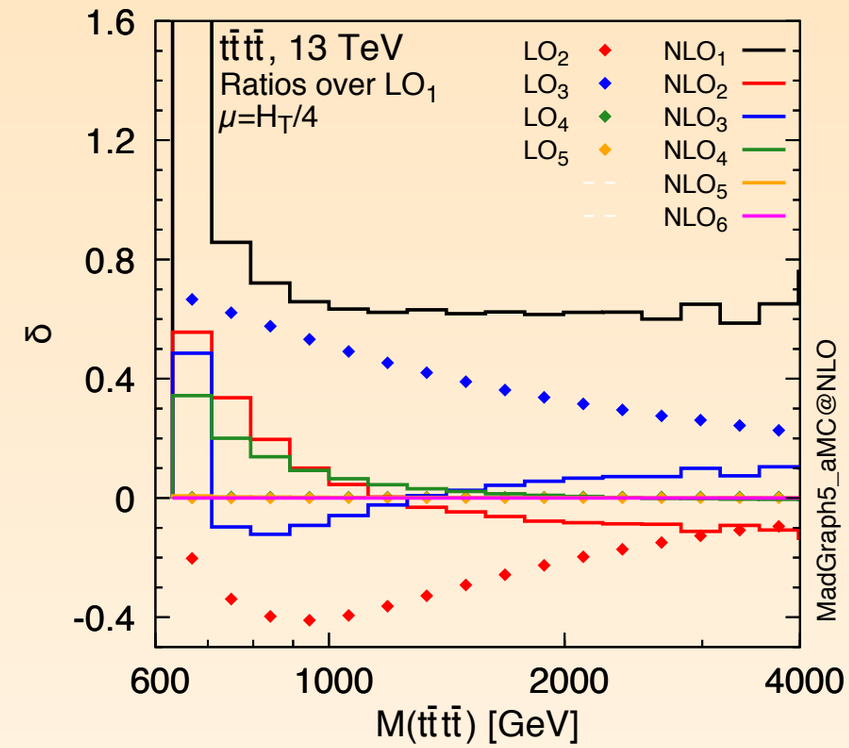
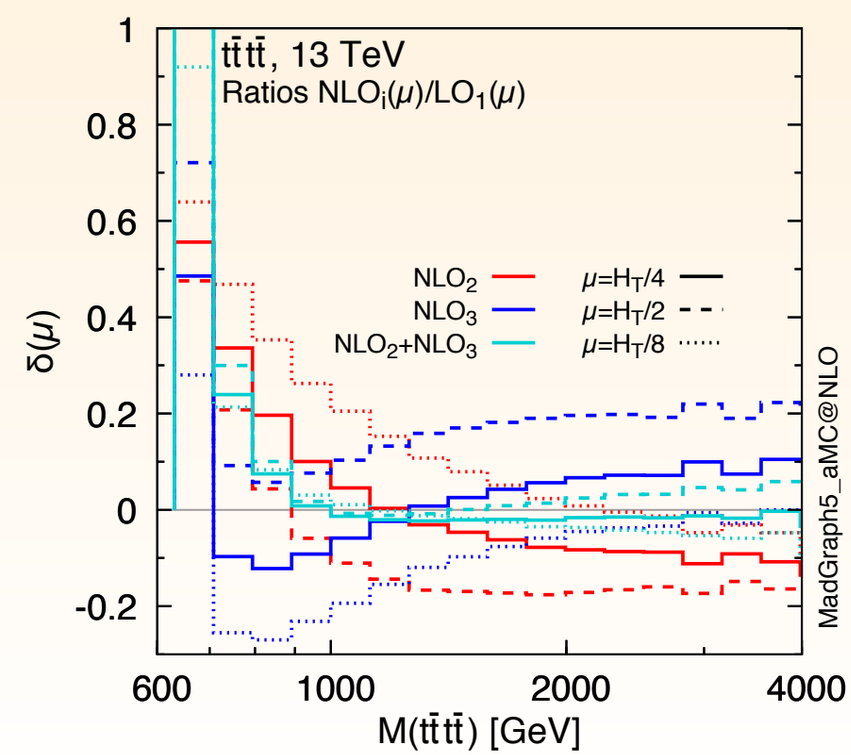
FOUR-TOP INVARIANT MASS

[RF, Pagani, Zaro, 2017]



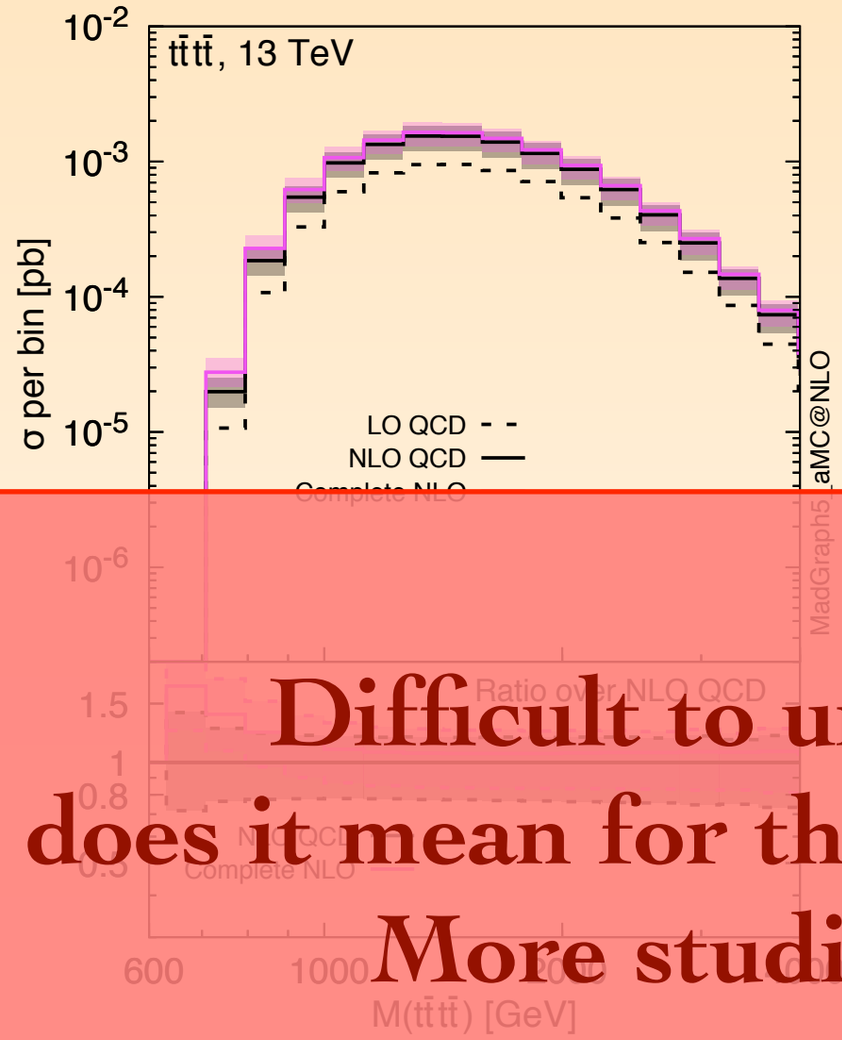


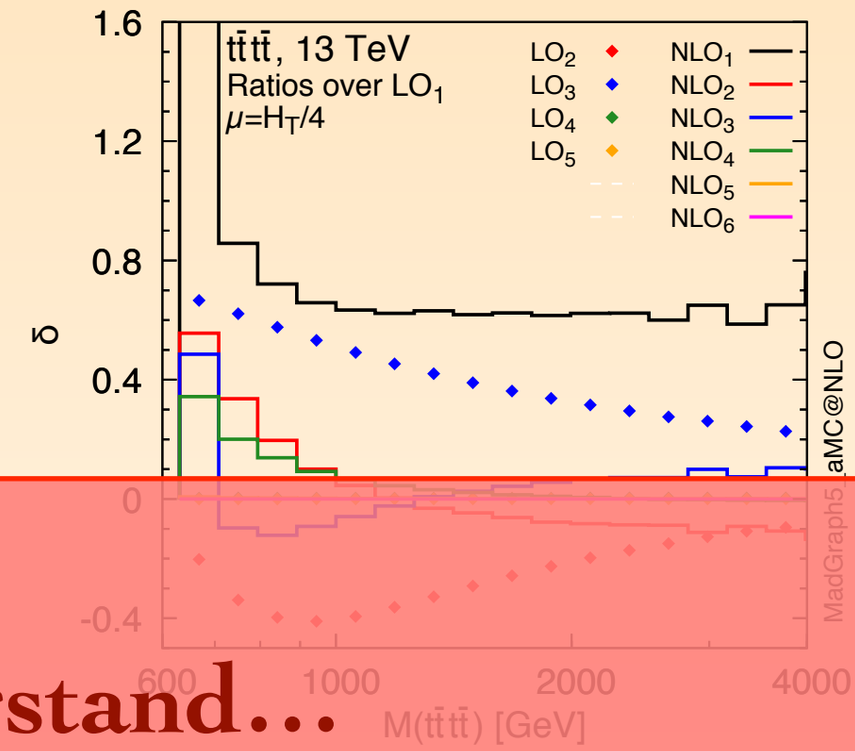


- Large cancelations between NLO_2 and NLO_3 also at the differential level
- NLO_4 large at threshold

FOUR-TOP INVARIANT MASS

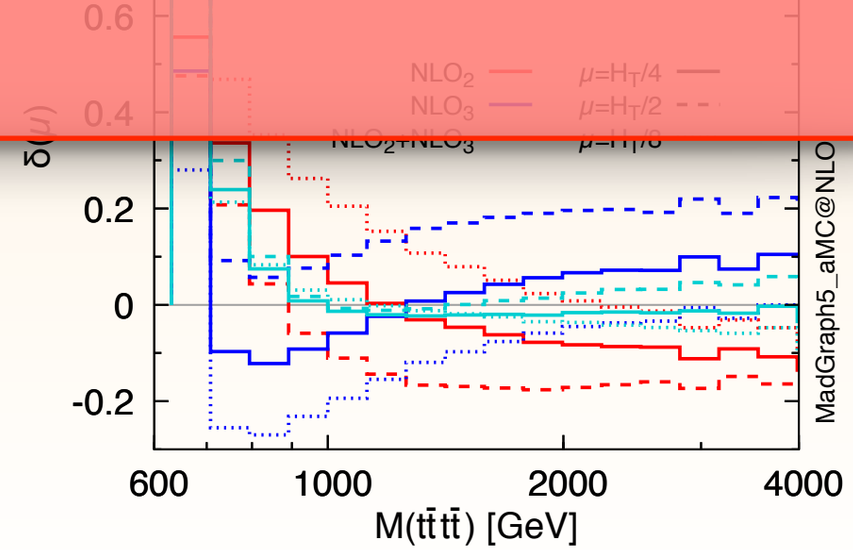
[RF, Pagani, Zaro, 2017]





Difficult to understand…
What does it mean for the top Yukawa coupling?
More studies needed

- Large cancelations between NLO_2 and NLO_3 also at the differential level
- NLO_4 large at threshold



Conclusions

- No "easy" new physics at the LHC. There is a need for more accurate predictions for background process to uncover small signals
  - This talk focussed on the NLO EW corrections and beyond
- Automation of mixed-coupling expansion available in MadGraph5_aMC@NLO v3-beta
  - Allows for **complete-NLO** for all* relevant SM processes
- Complete-NLO predictions for ttbar+X production processes
  - Some surprises: in particular for
    - ttW has NLO_3 effects which are much larger than expected
    - 4-top has large cancelations among NLOi terms; reason not fully understood, but relevant for independent top Yukawa extraction