Theoretical status of SINGLE TOP and TOP ASSOCIATED predictions

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NLO+RESUMMATION FOR TOP ASSOCIATED PRODUCTION

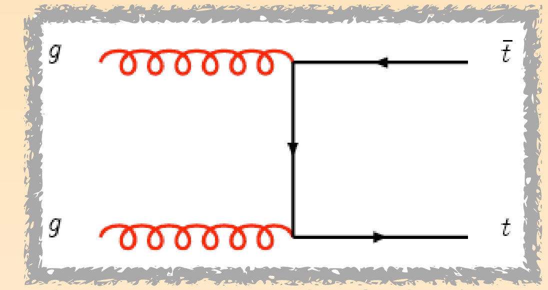
[A. Broggio et al., 2016-2017]

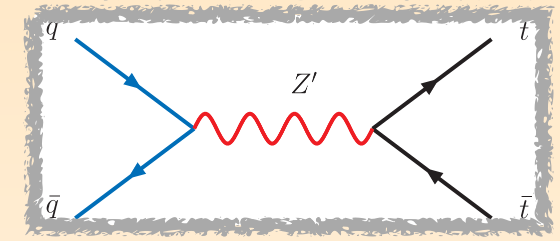
- Scale dependence for NLO top pair associated production is of the order of 10-15%
- NNLO is beyond what is currently possible
- The resummation of threshold logarithms in the limit $z \to 1$ with $z \equiv M^2/\hat{s}$ captures effects beyond the NLO
- This reduces the scale dependence by 30-50%, and leads to the most-accurate theoretical predictions
- Also differential distributions
- What about EW corrections?

13 TeV

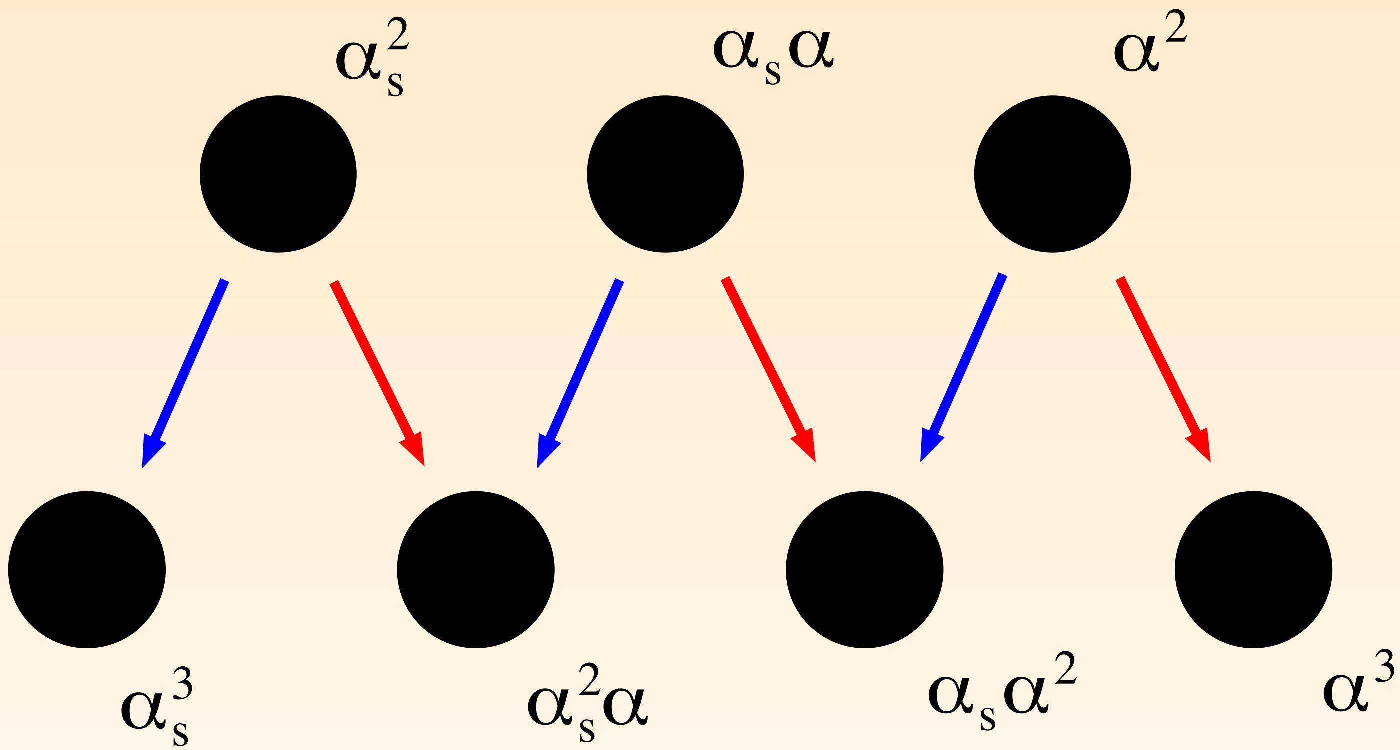
pert. order	process	PDF order	σ [fb]
NLO	$t\bar{t}H$	NLO	$474.8^{+47.2}_{-51.9}$
NLO+NNLL	$t\bar{t}H$	NNLO	$486.4^{+29.9}_{-24.5}$
NLO	$t\bar{t}W^+$	NLO	$356.3^{+43.7}_{-39.5}$
NLO+NNLL	$t\bar{t}W^+$	NNLO	$341.0^{+23.1}_{-13.6}$
NLO	$t\bar{t}W^-$	NLO	$182.2^{+23.1}_{-20.4}$
NLO+NNLL	$t\bar{t}W^-$	NNLO	$177.1^{+12.0}_{-6.9}$
NLO	$t\bar{t}Z$	NLO	$728.3^{+93.8}_{-90.3}$
NLO+NNLL	$t\bar{t}Z$	NNLO	$777.8^{+61.3}_{-65.2}$

NLO DISSECTION





✦ For example: consider top-pair production



✦ "NLO EW" is a bit of a misnomer:
NLO2 and NLO3 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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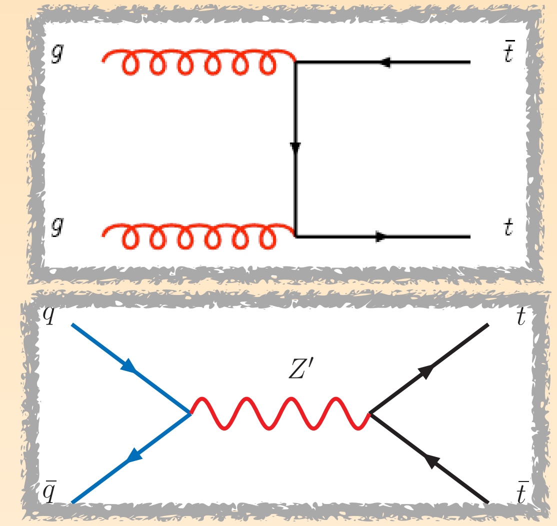

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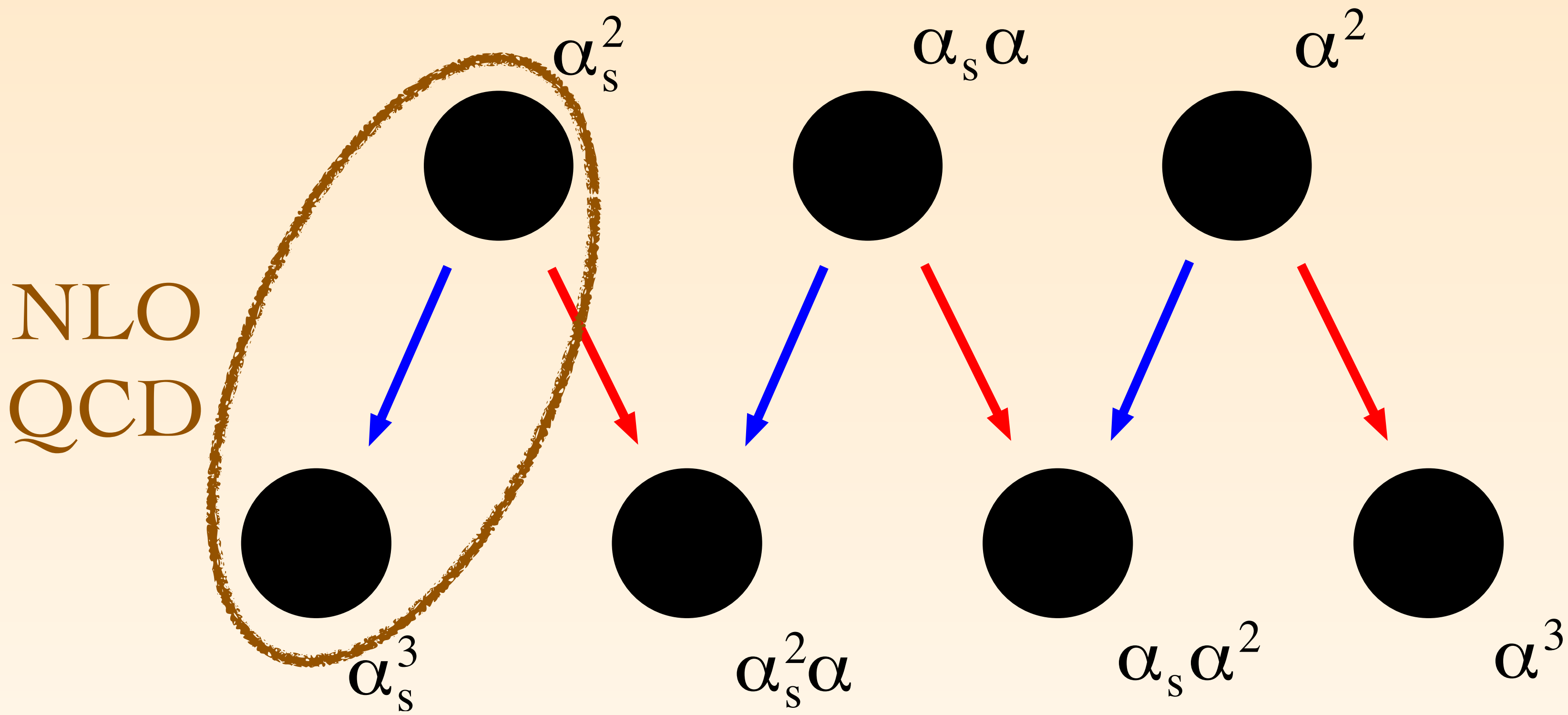

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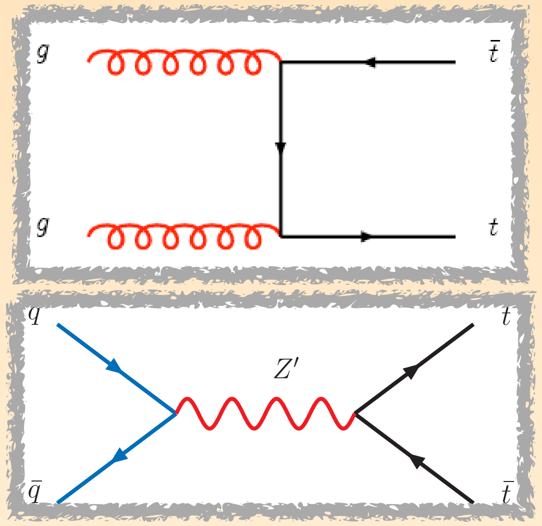

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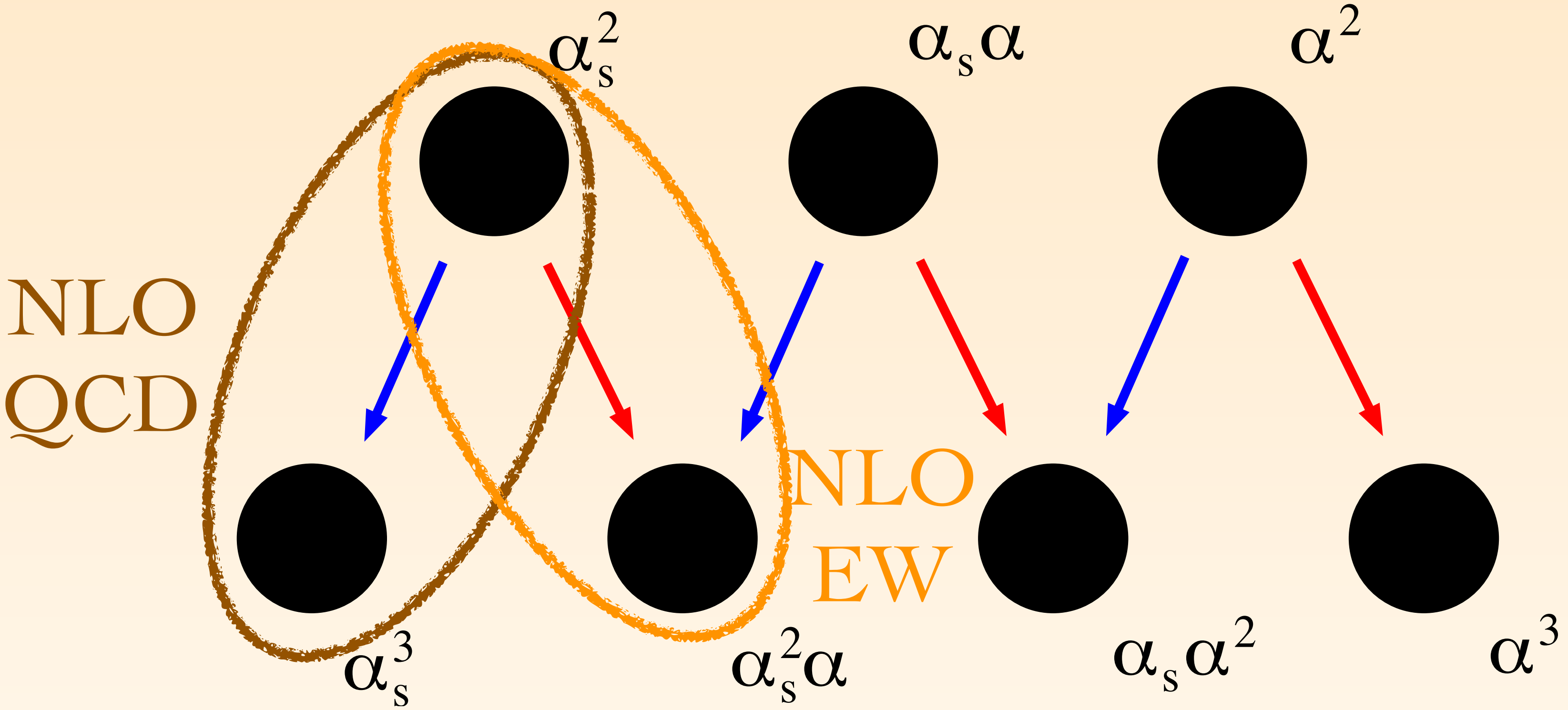

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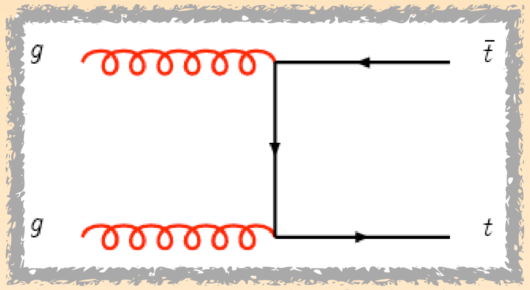

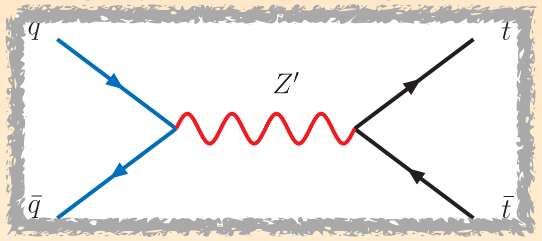

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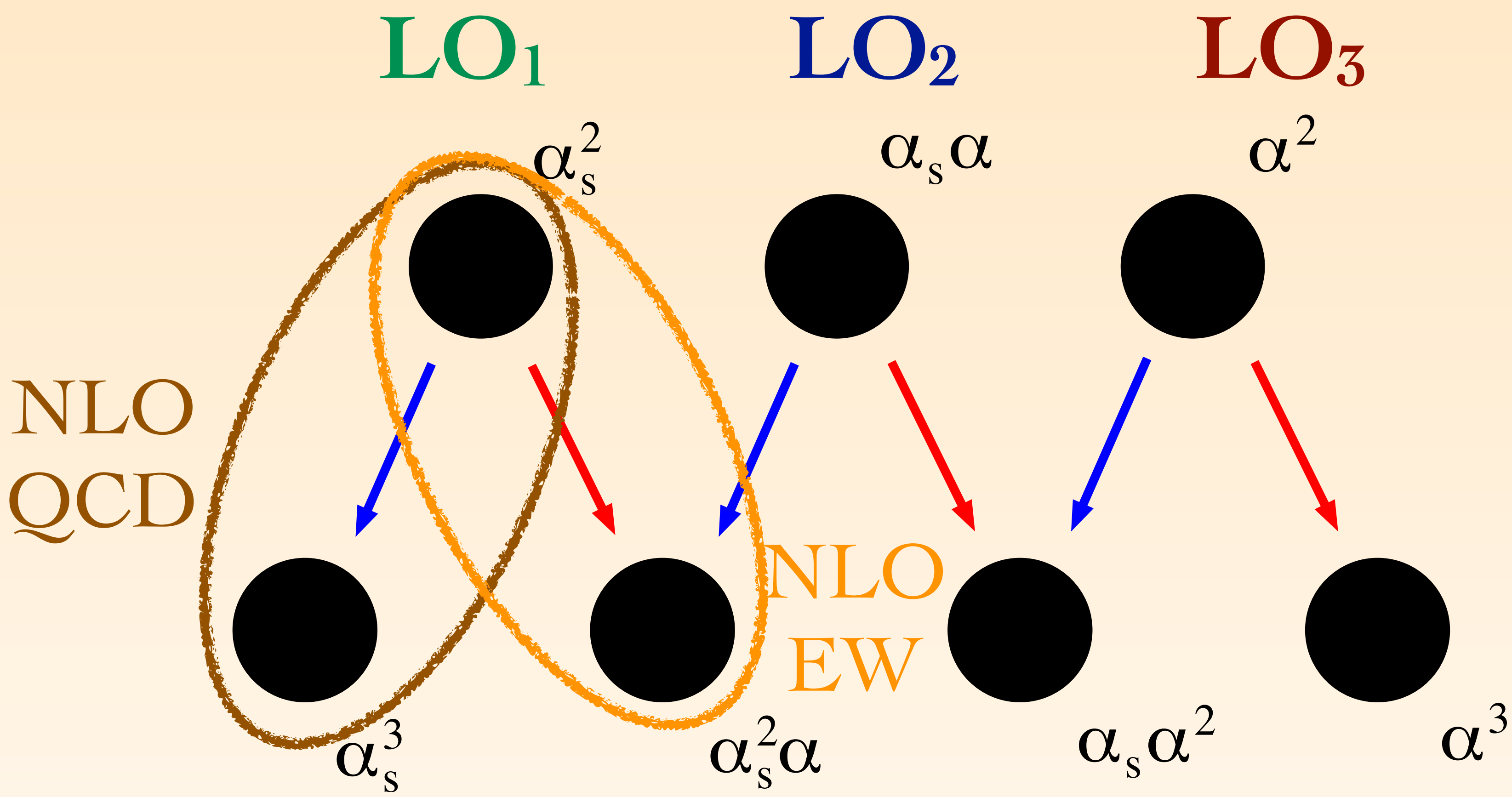

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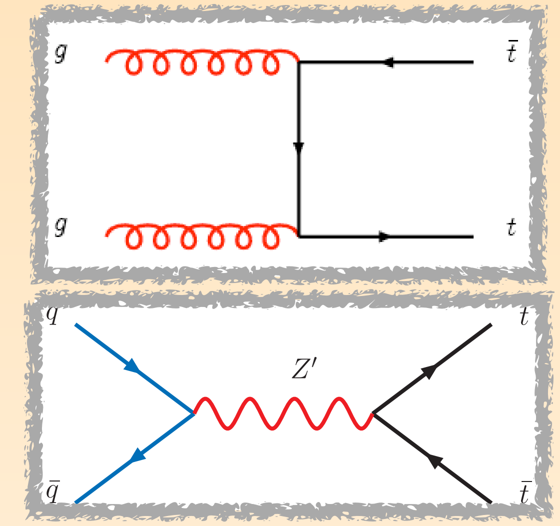

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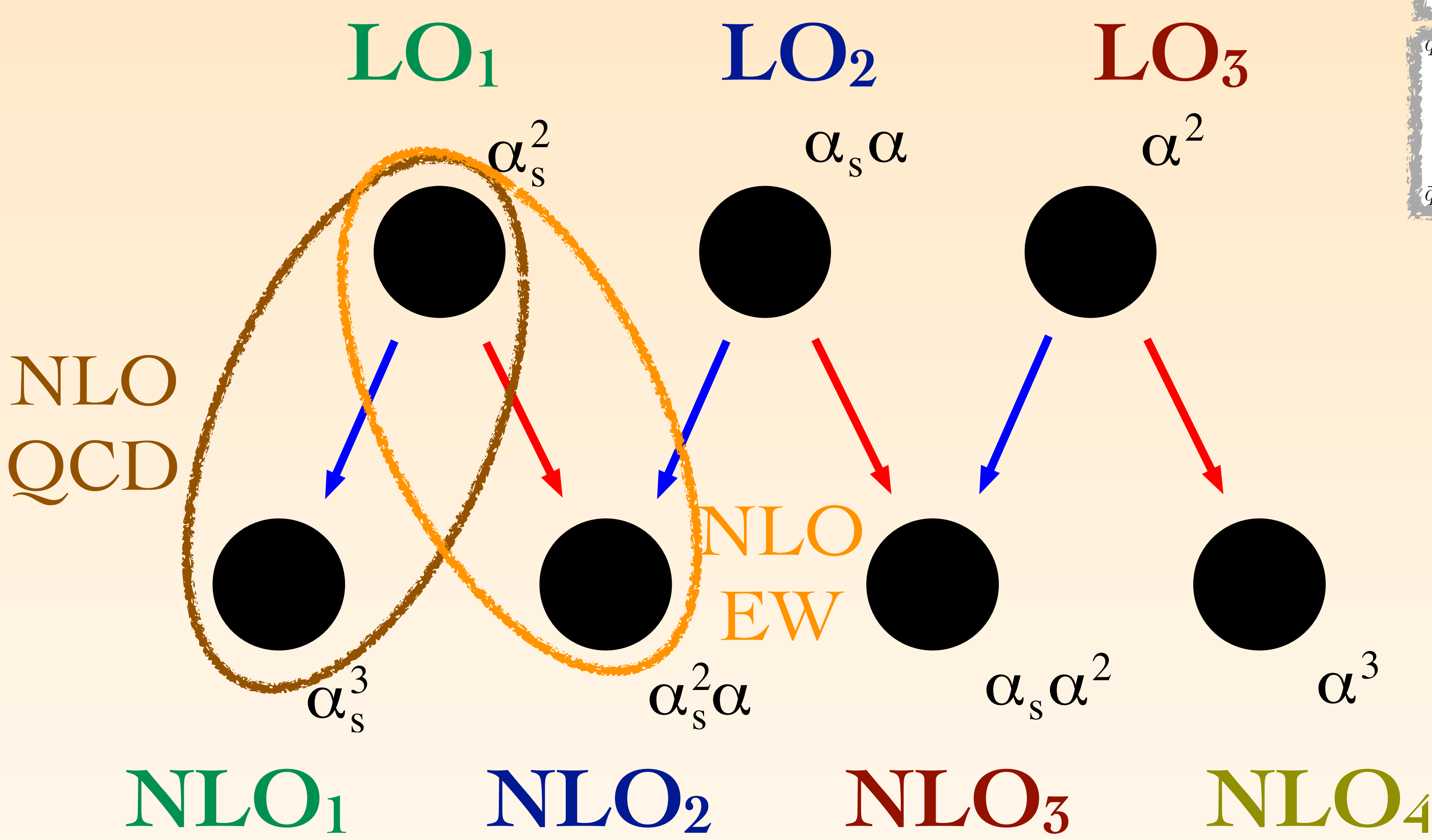

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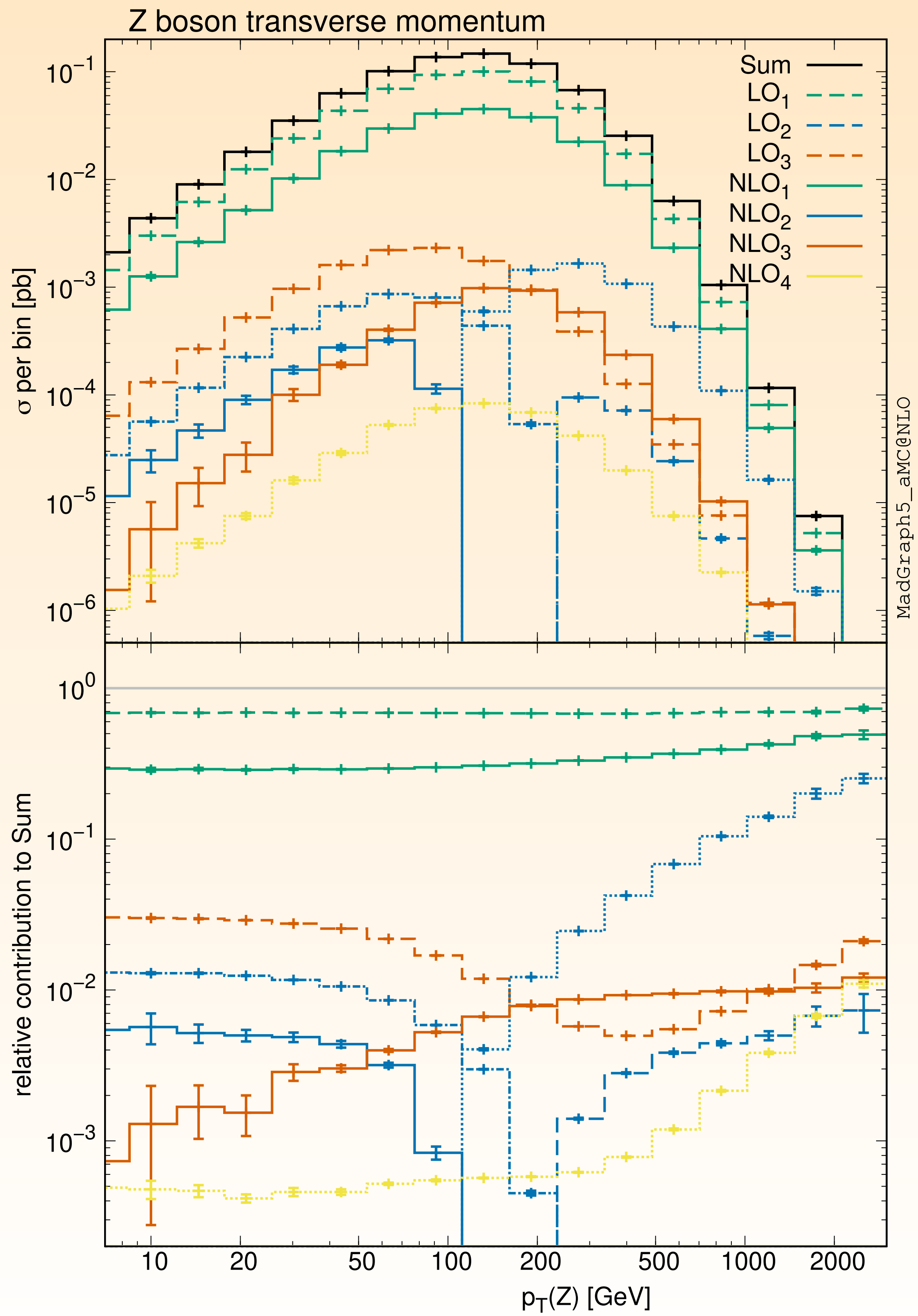
Complete-NLO ttbar+Z

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

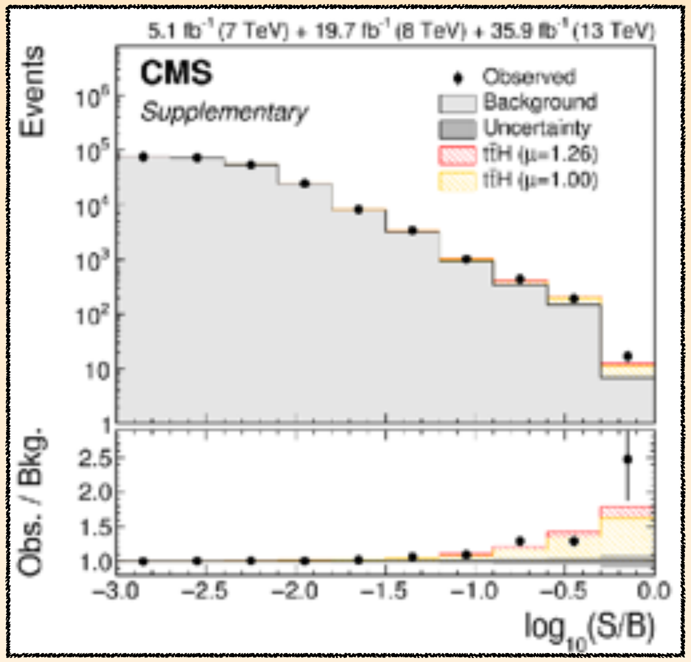


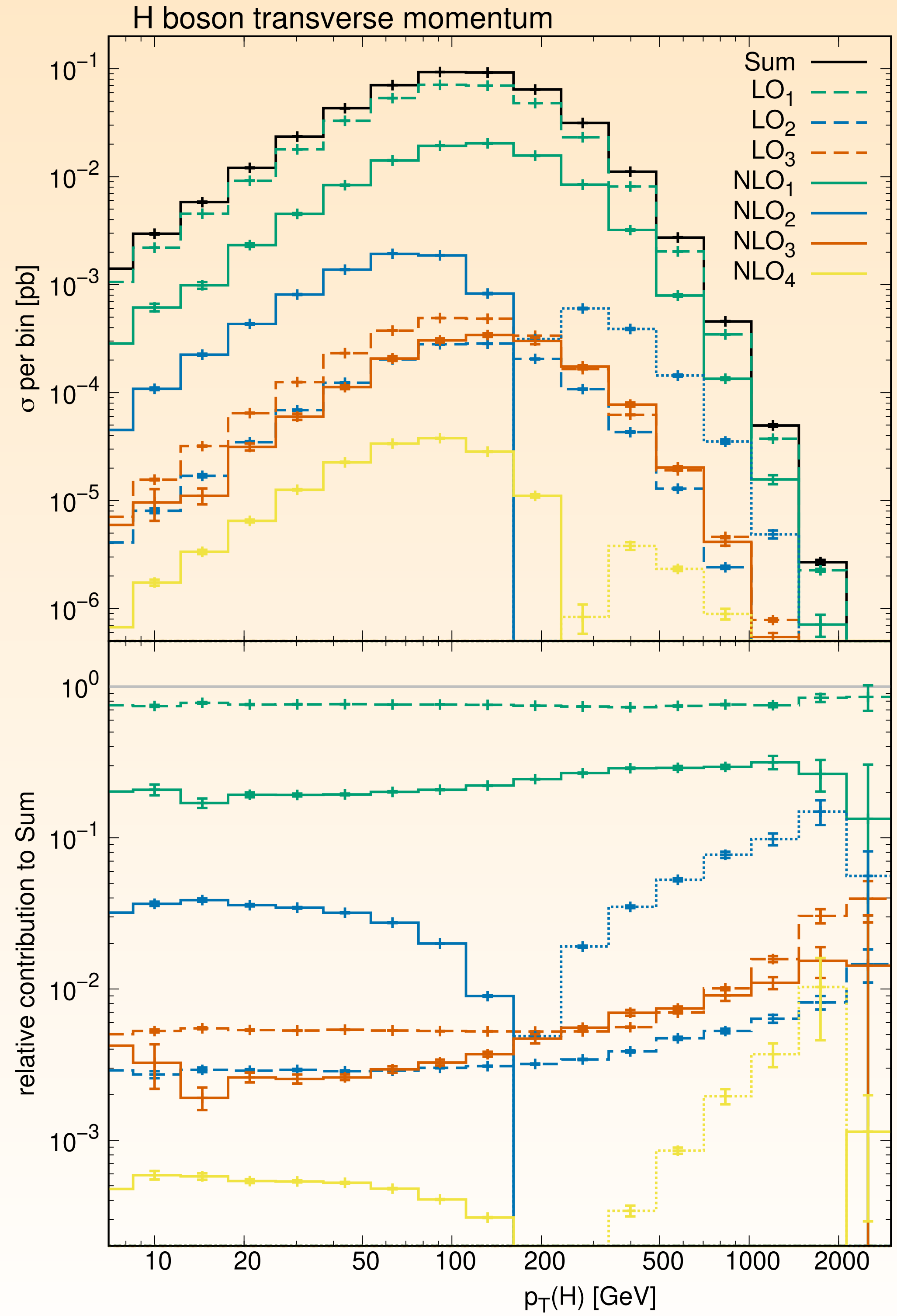
- Top pair production in association with a Z-boson
  - Transverse momentum of the vector boson
- Significant EW corrections (NLO_2) at very large p_Ts, where they can reach ~-25% of the total rate
  - Partly canceling the QCD corrections (NLO_1), which grow with increasing p_T
- (N)LO_3 and NLO_4 typically 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 with a top-quark pair now observed by both CMS and ATLAS



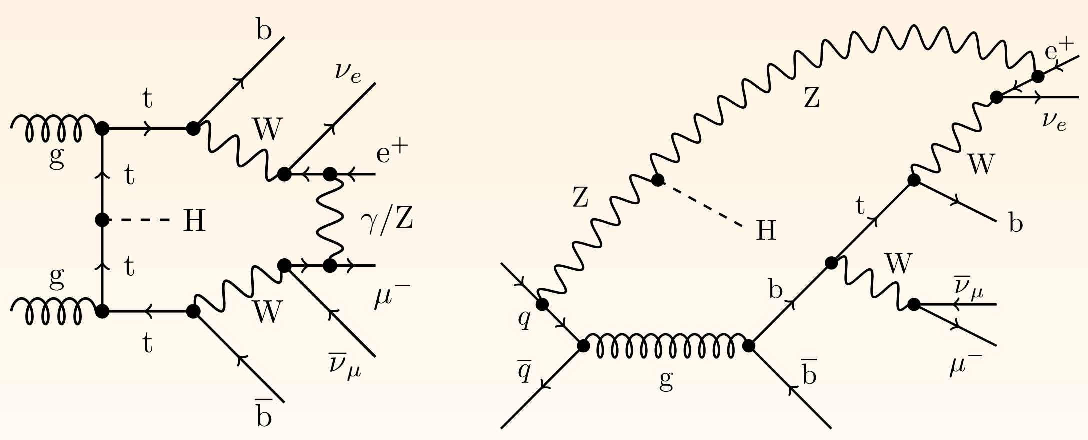


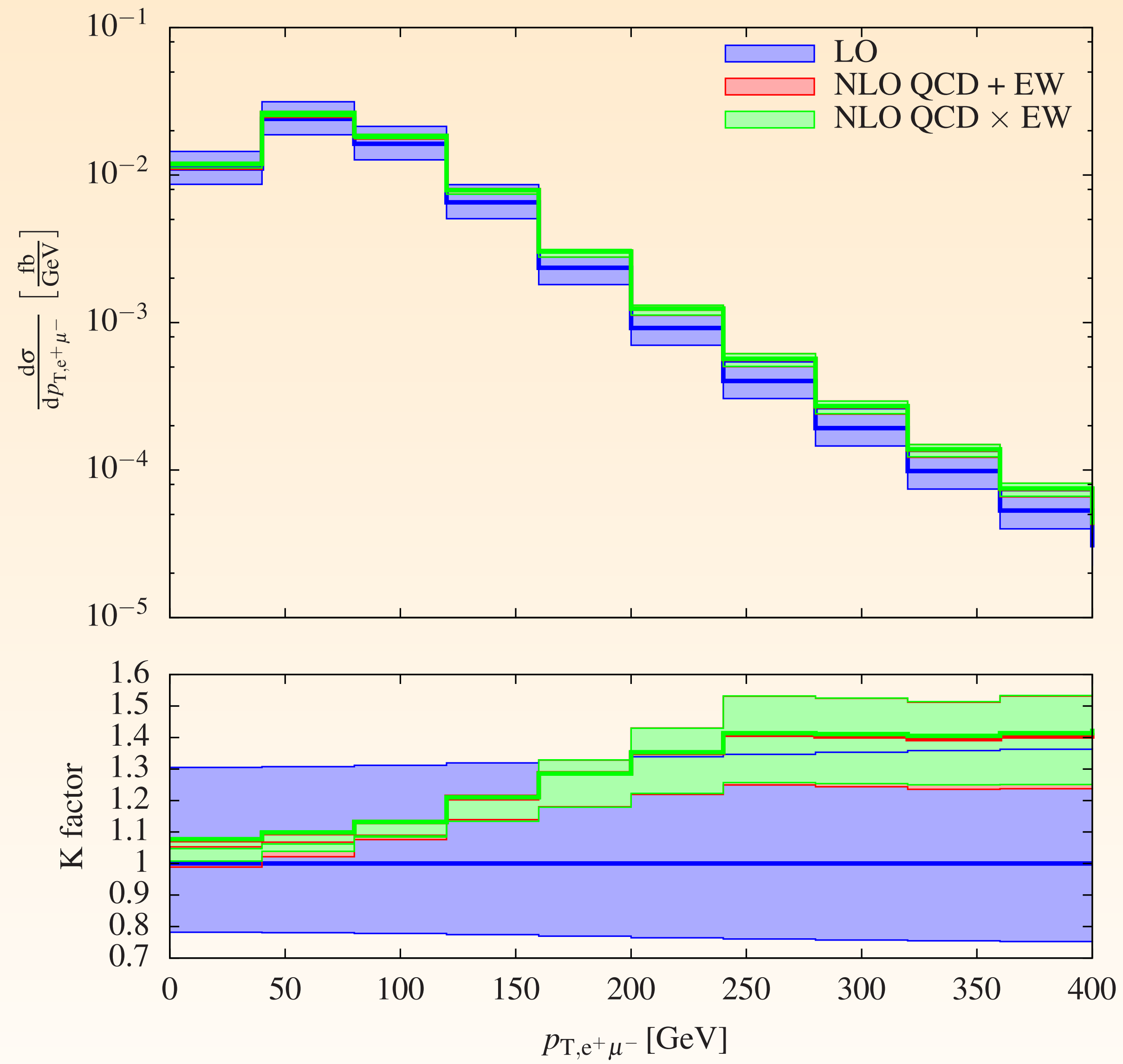
- Corrections (slightly) smaller than for ttbar+Z
  - NLO_2 at the percent-level, apart from the far tail, where its effect is slightly larger
  - $(N)LO_3$ and NLO_4 negligibly small

NLO QCD+EW for ttH with off-shell tops

[Denner, Lang, Pellen, Uccirati, 2016]

- NLO QCD+EW corrections to ttH with off-shell top quarks
- Amazingly complicated calculation
  - "octagons" and even "nonagons"

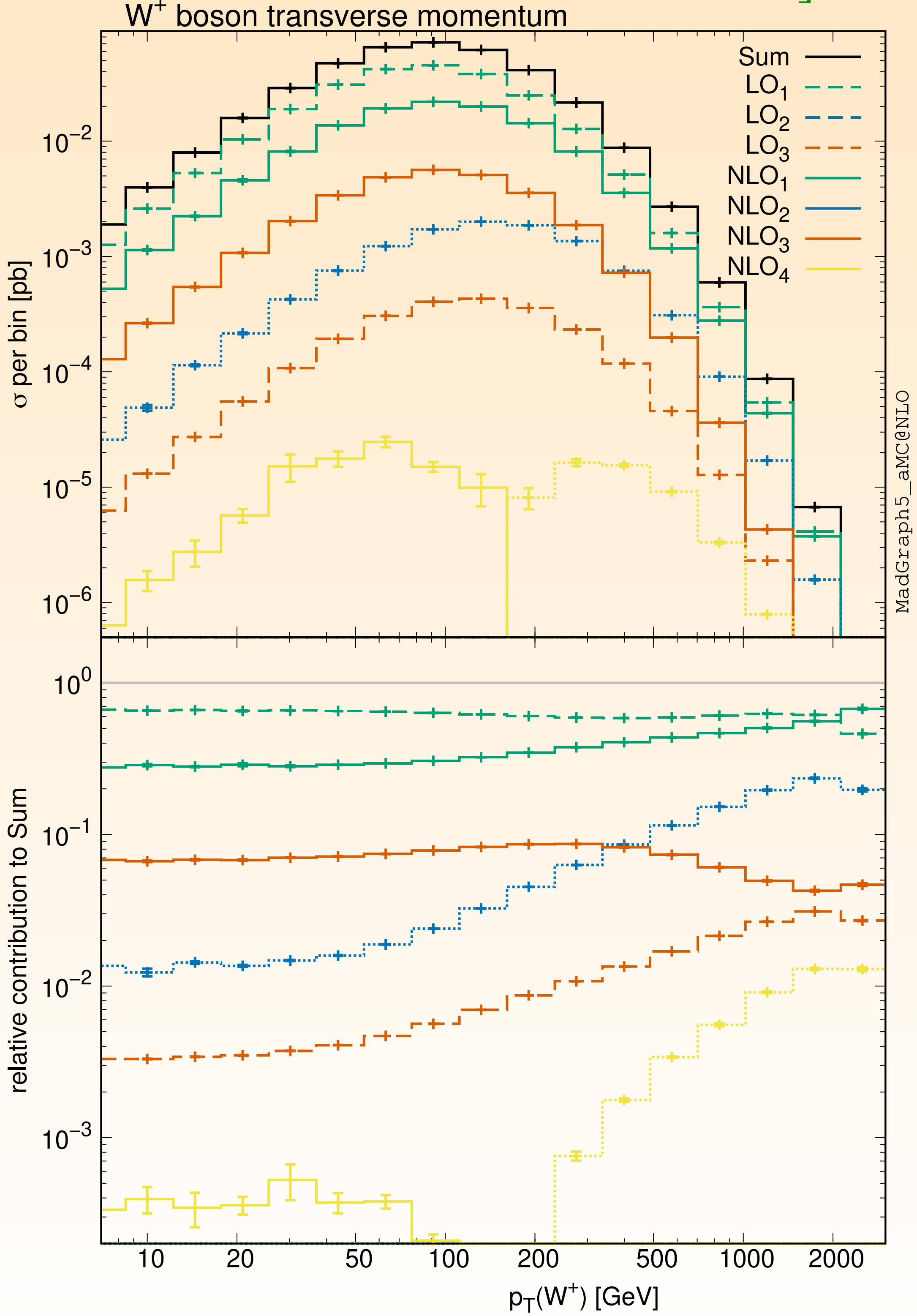




Complete-NLO ttbar+W

- 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**; begin close to 10% of the complete-NLO at small and medium transverse momenta
- Significant EW corrections (NLO_2) at very large p_Ts, where they can reach ~-25% of the total rate
  - LO_2 are exactly zero

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



Complete-NLO ttbar+W

[RF, Pagani, Zaro, 2017]

Slightly different normalisation as compared to ratio plot $\delta_{(N)LO_i}(\mu) = \frac{\Sigma_{(N)LO_i}(\mu)}{\Sigma_{LO_{QCD}}(\mu)}$

Naive expectation	$\delta[\%]$	$\mu = H_T/4$	$\mu = H_T/2$	$\mu = H_T$
10%	LO_2	-	-	-
1%	LO_3	0.8	0.9	1.1
10%	NLO_1	34.8 (7.0)	50.0 (25.7)	63.4 (42.0)
1%	NLO_2	−4.4 (−4.8)	−4.2 (−4.6)	−4.0 (−4.4)
0.1%	NLO_3	11.9 (8.9)	12.2 (9.1)	12.5 (9.3)
0.01%	NLO_4	0.02 (−0.02)	0.04 (−0.02)	0.05 (−0.01)

- Numbers in brackets correspond to a 100 GeV jet-veto
  - This reduces the NLO_1 enormously
  - large scale dependence in NLO_1 to compensate scale dependence in LO_1
  - But does not affect the large NLO_3
- NLO_3 contribution due to t-W scattering

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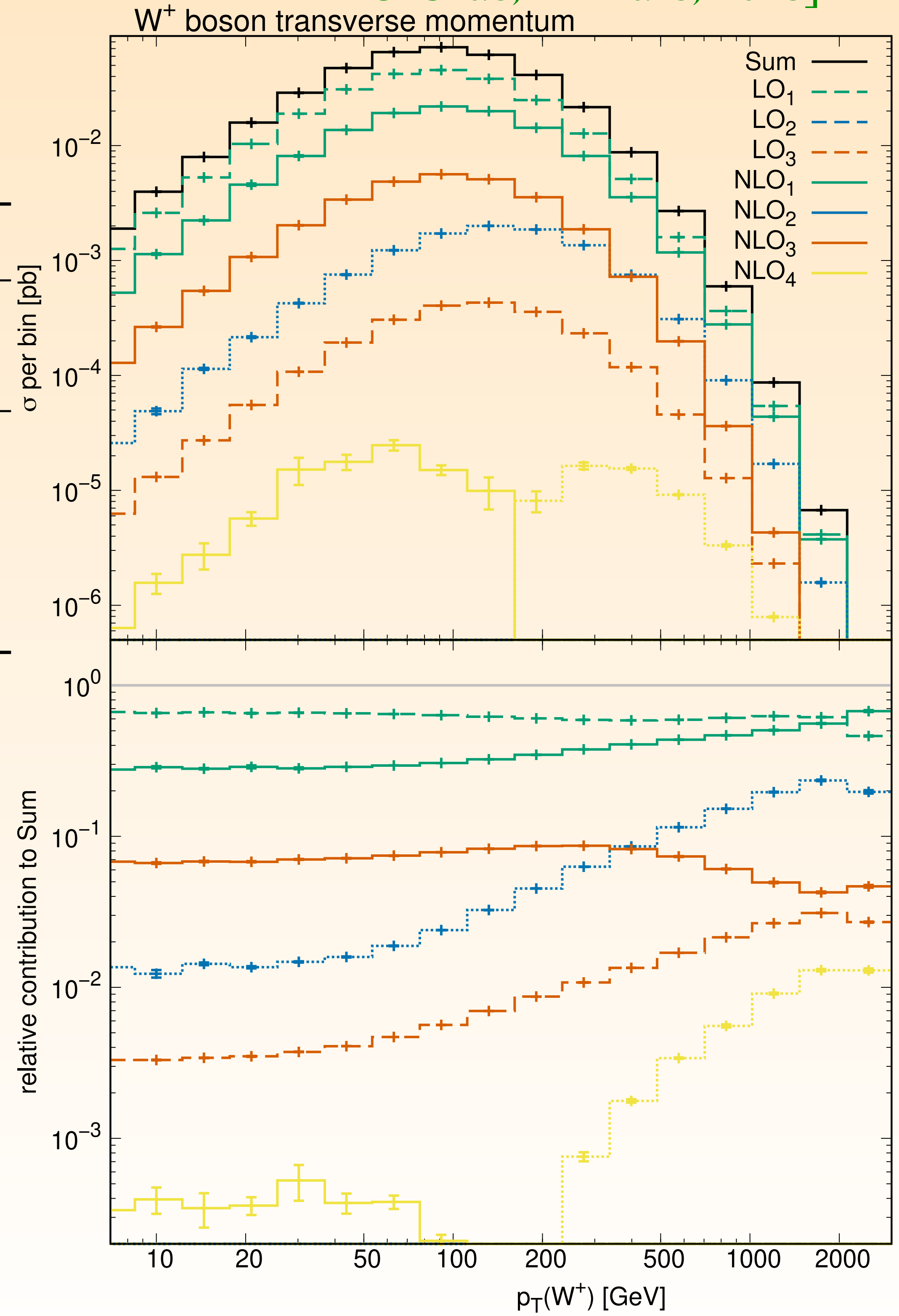

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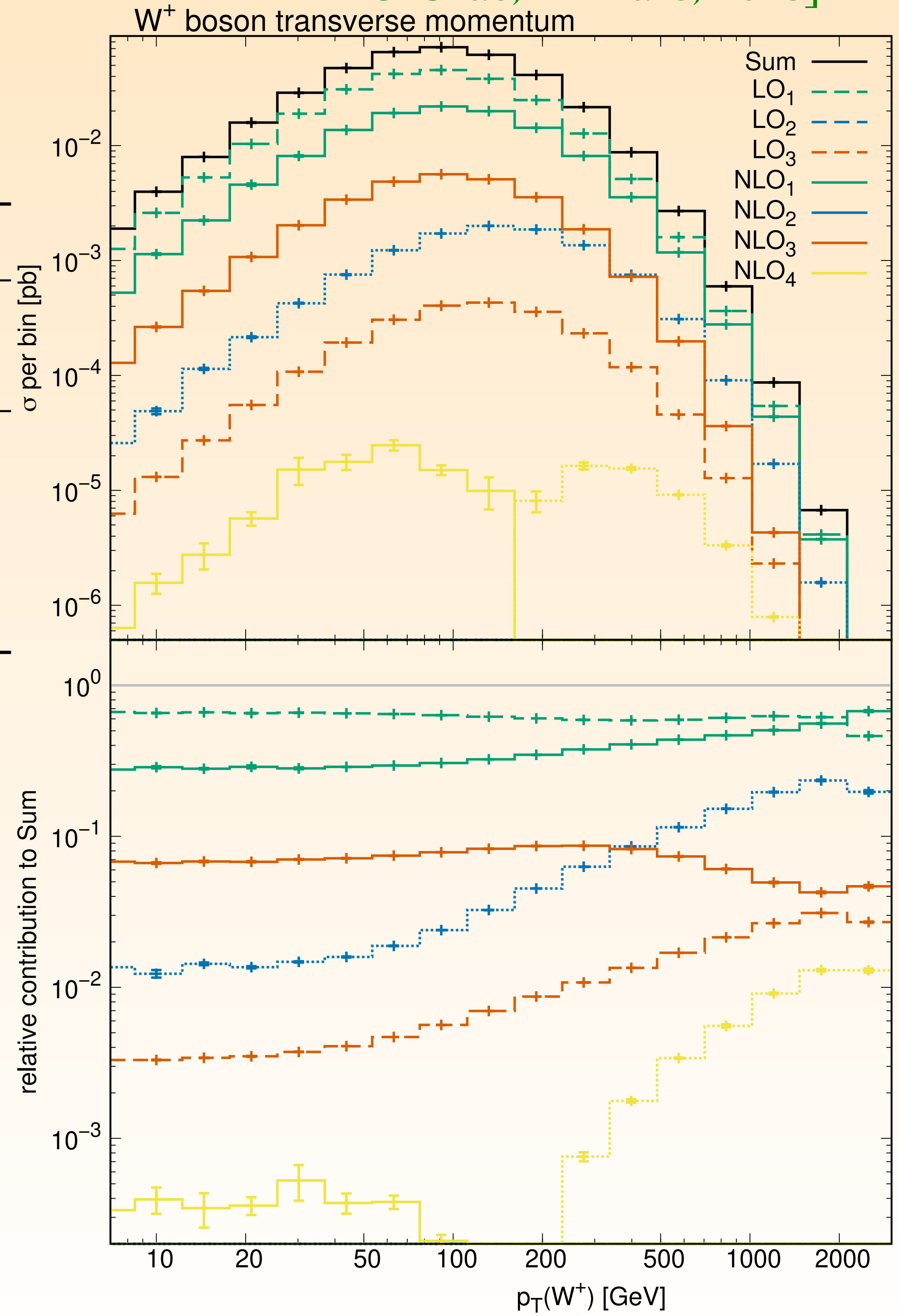

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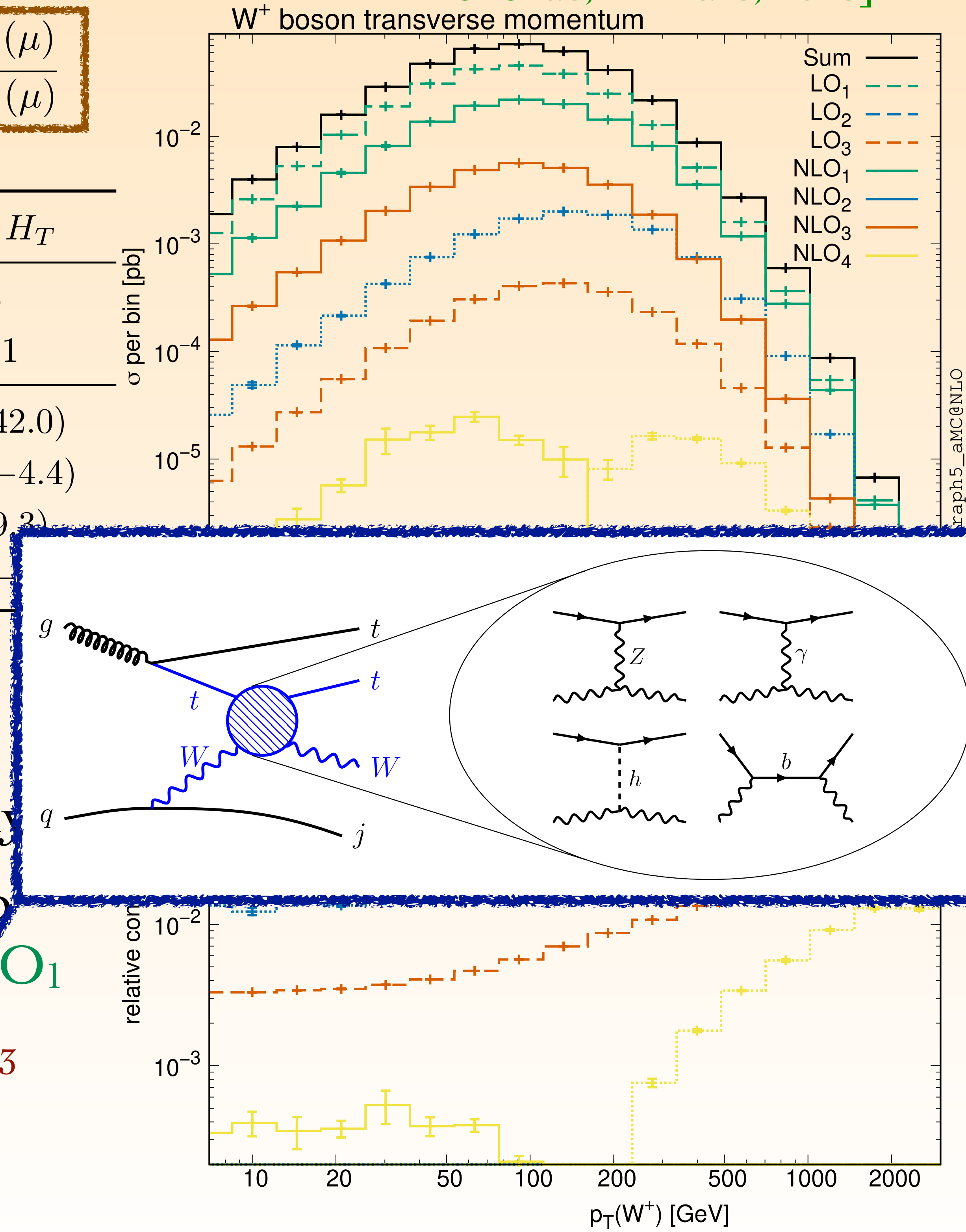

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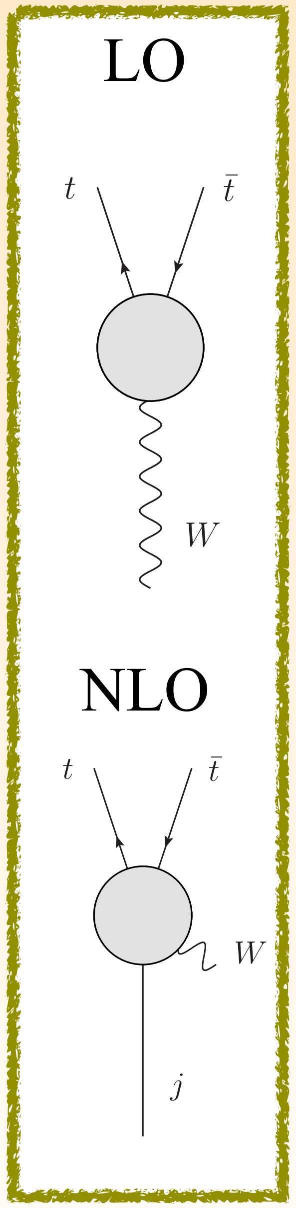
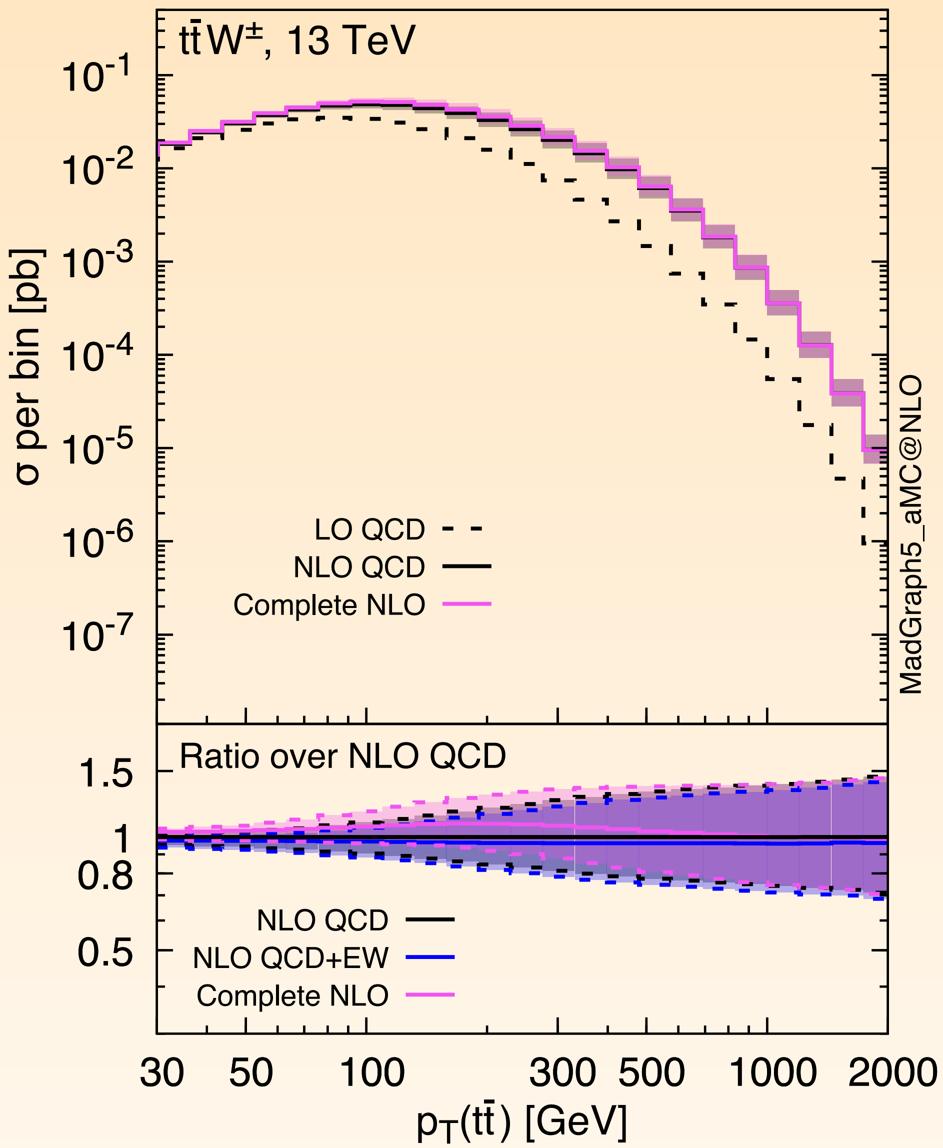
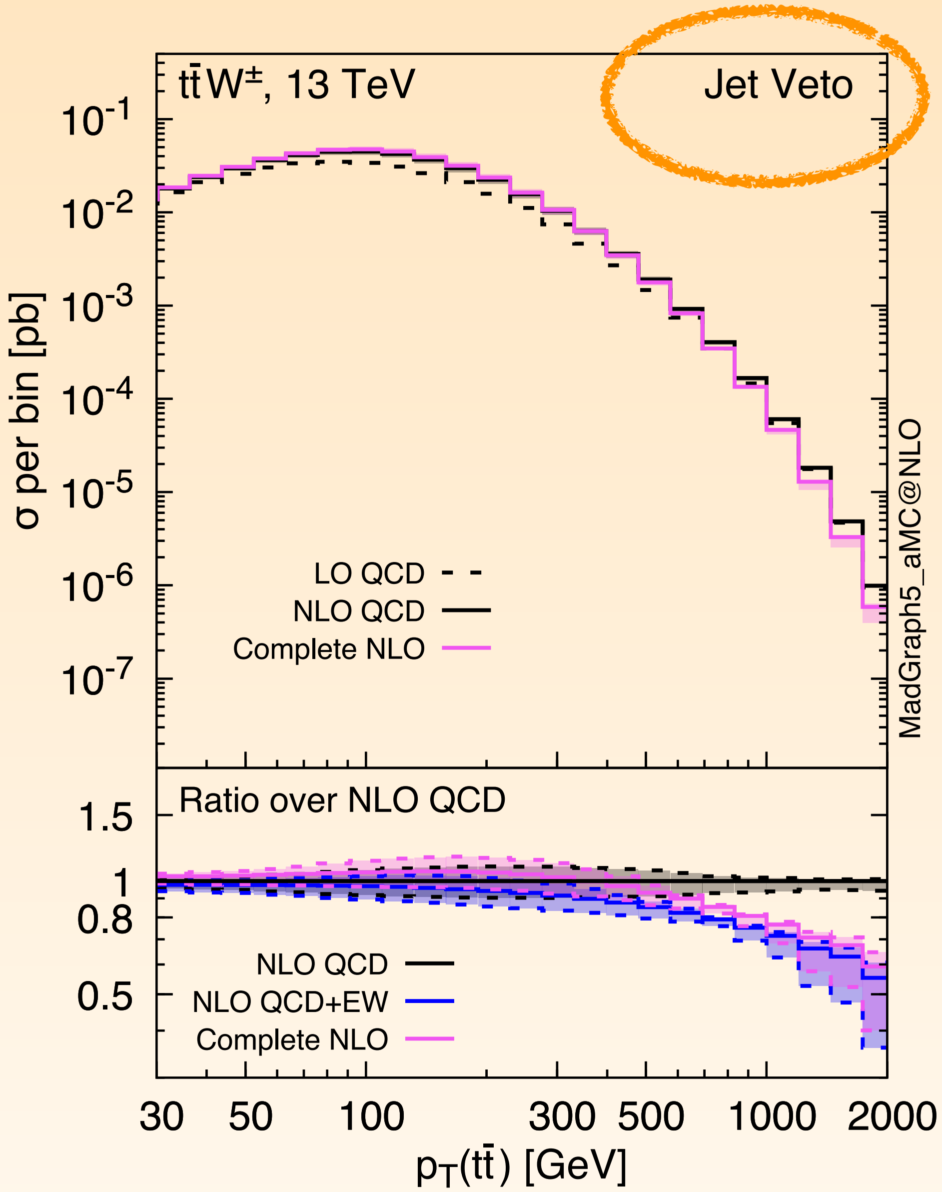




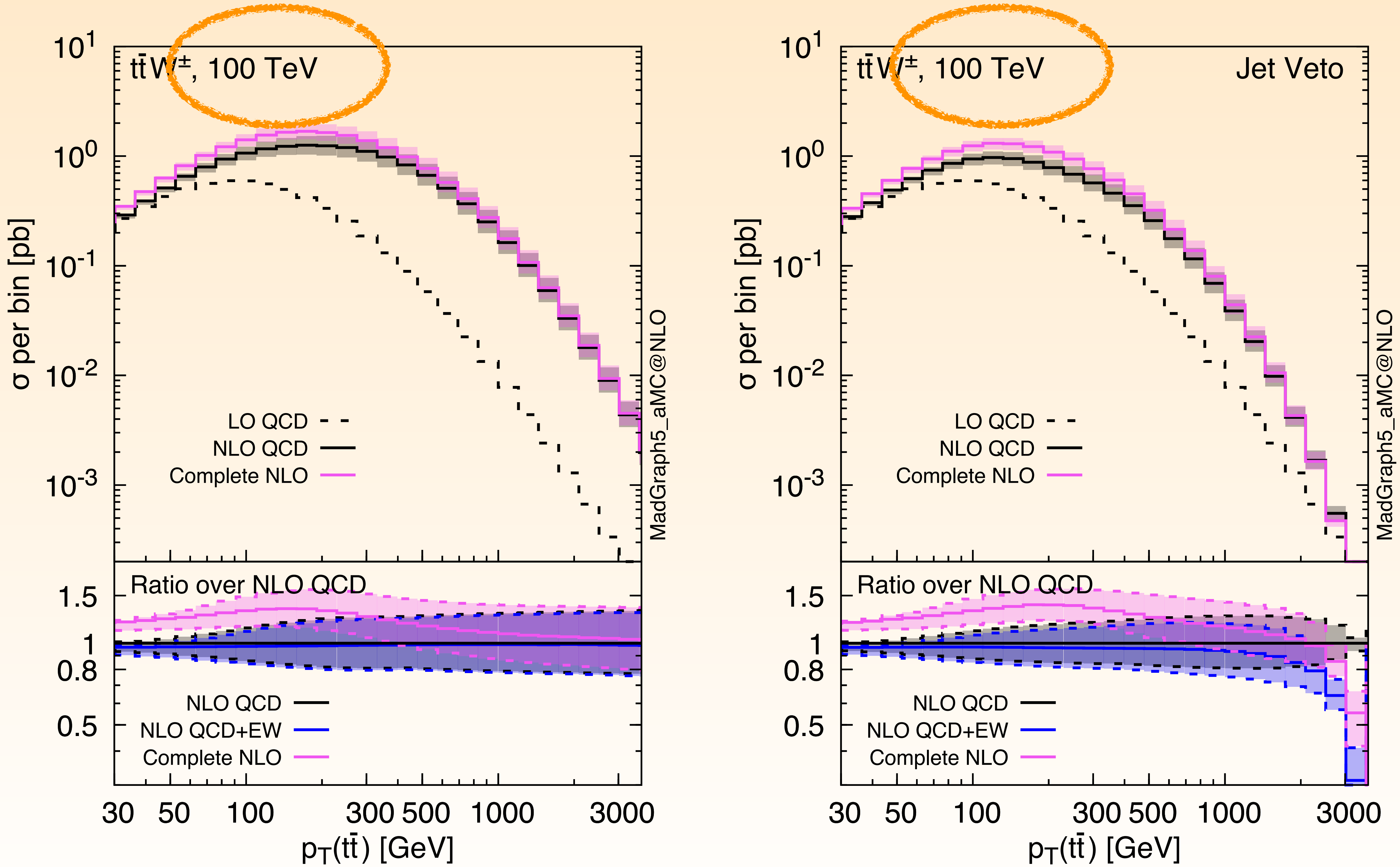


- ✦ Large NLO corrections, and large scale dependence without the jet veto
  - ttbar recoiling predominantly against jet (instead of W-boson) at NLO
- ✦ EW corrections are large when the results are not dominated by NLO_1
- ✦ Subleading corrections (NLO_3) are larger than expected, but uncertainty bands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

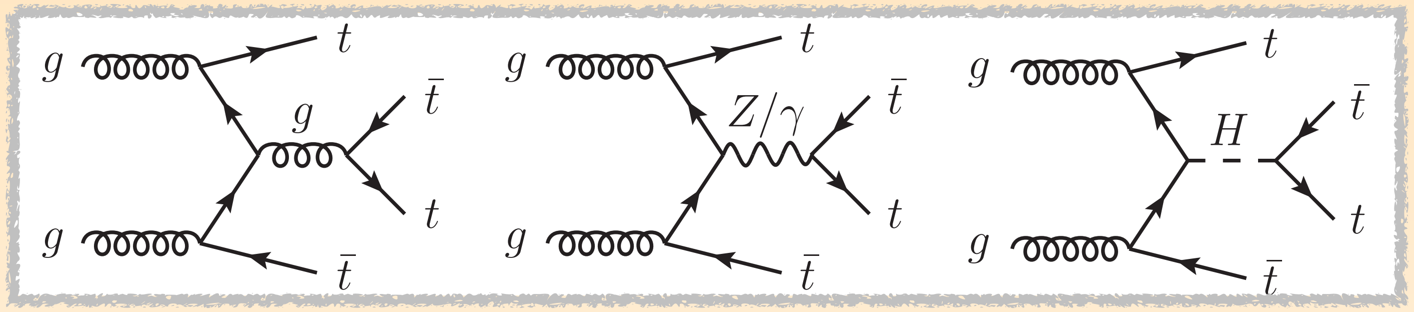
Complete-NLO ttbar+W

[RF, Pagani, Zaro, 2017]

✦ Effects much more extreme at 100 TeV!



Four-top production and Top Yukawa coupling



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

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

[Cao, Chen, Liu, 2016]

- Four-top production can be used together with ttH to constrain/measure an **anomalous top Yukawa coupling**
  - kappa-framework
- Large contributions from subleading LOi, 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,
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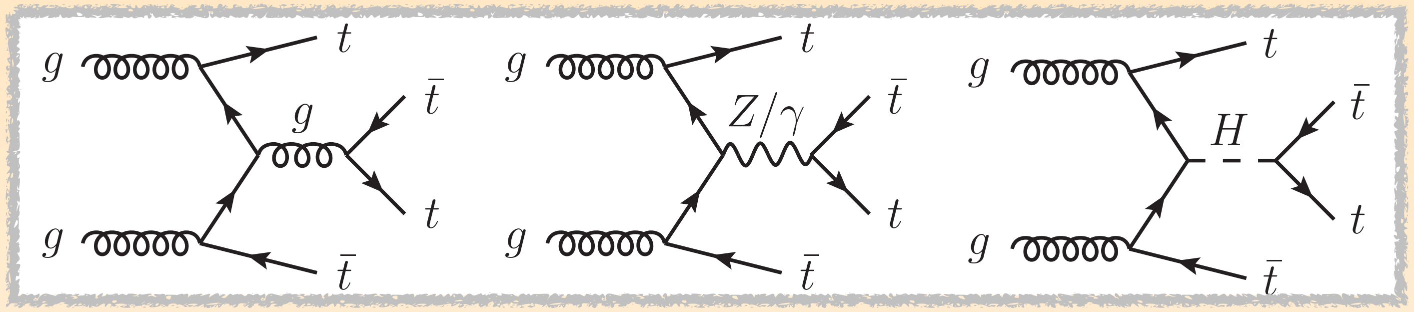

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LO_1 LO_3 LO_2 (+LO_1 and LO_3)

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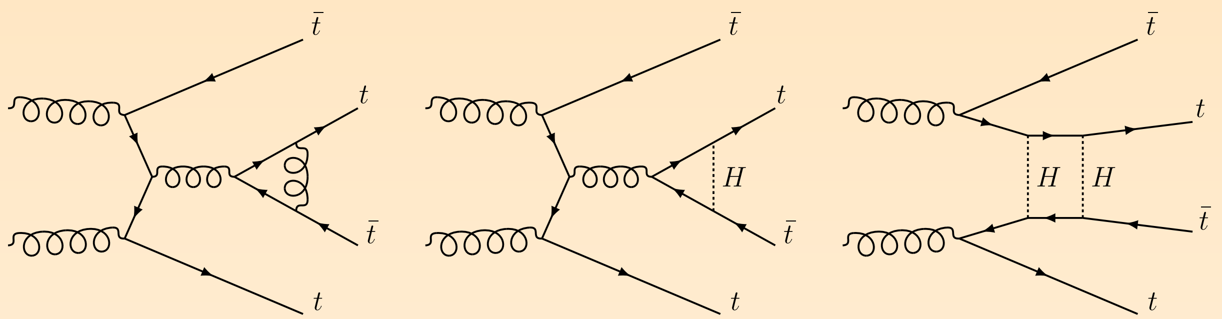
NLO KAPPA FRAMEWORK...?



- 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: through renormalisation too many operators need to be considered together
- Still, NLO four-top in the SM will tell us about possible cancelations among various contributions

NLO four-top production

[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

$\delta[\%]$	$\mu = H_T/8$	$\mu = H_T/4$	$\mu = H_T/2$	Naive expectation
LO_2	-18.7	-20.7	-22.8	10%
LO_3	26.3	31.8	37.8 ←	1%
LO_4	0.05	0.07	0.09	0.1%
LO_5	0.03	0.05	0.08	0.01%
NLO_1	33.9	68.2	98.0	10%
NLO_2	-0.3	-5.7	-11.6 ←	1%
NLO_3	-3.9	1.7	8.9 ←	0.1%
NLO_4	0.7	0.9	1.2	0.01%
NLO_5	0.12	0.14	0.16	0.001%
NLO_6	< 0.01	< 0.01	< 0.01	0.0001%
$NLO_2 + NLO_3$	-4.2	-4.0	2.7	

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

NLO FOUR-TOP PRODUCTION

[RF, Pagani, Zaro, 2017]

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NLO_5	0.12	0.14	0.16	0.001%
NLO_6	< 0.01	< 0.01	< 0.01	0.0001%
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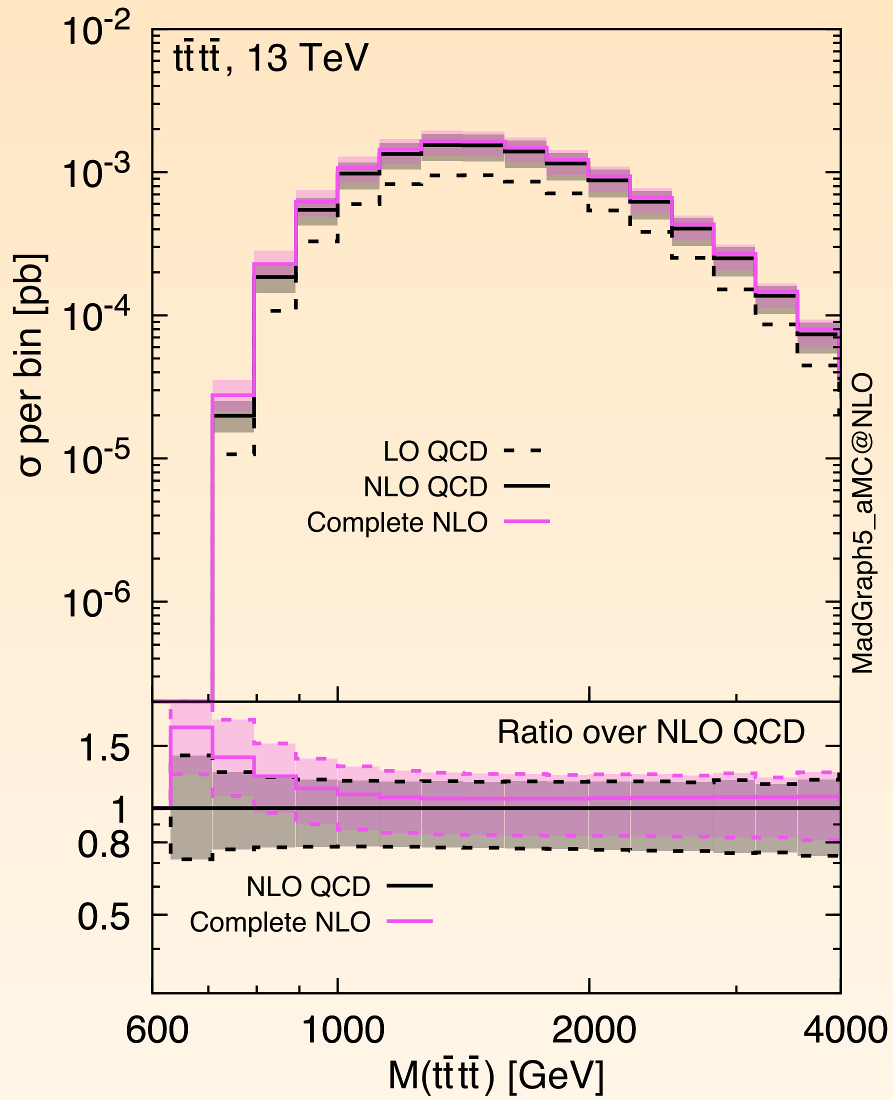
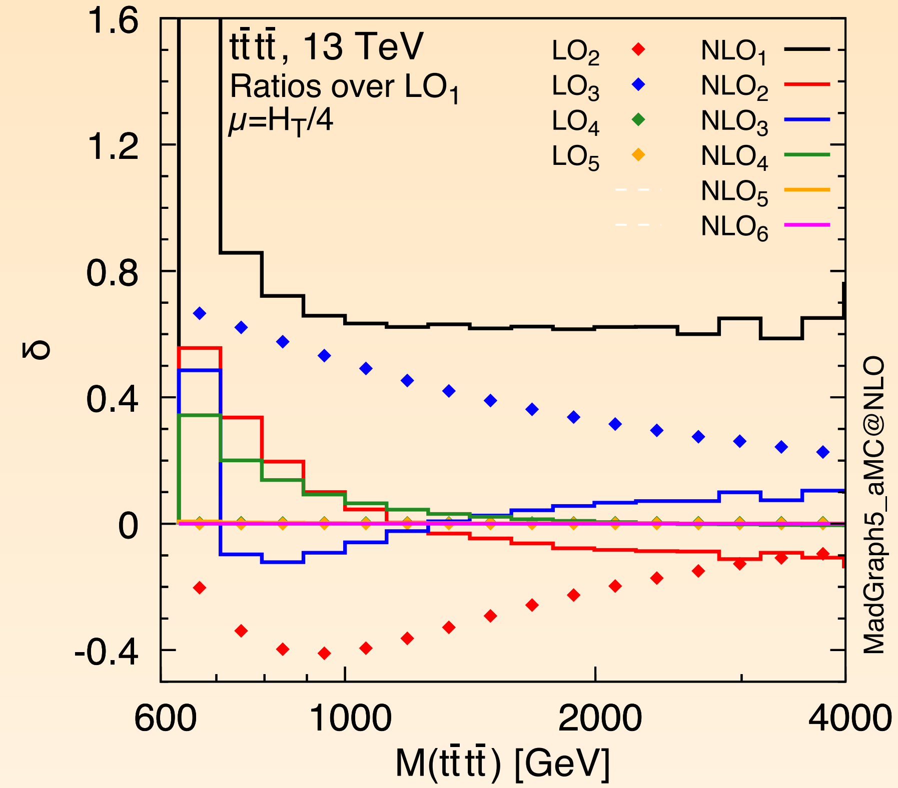
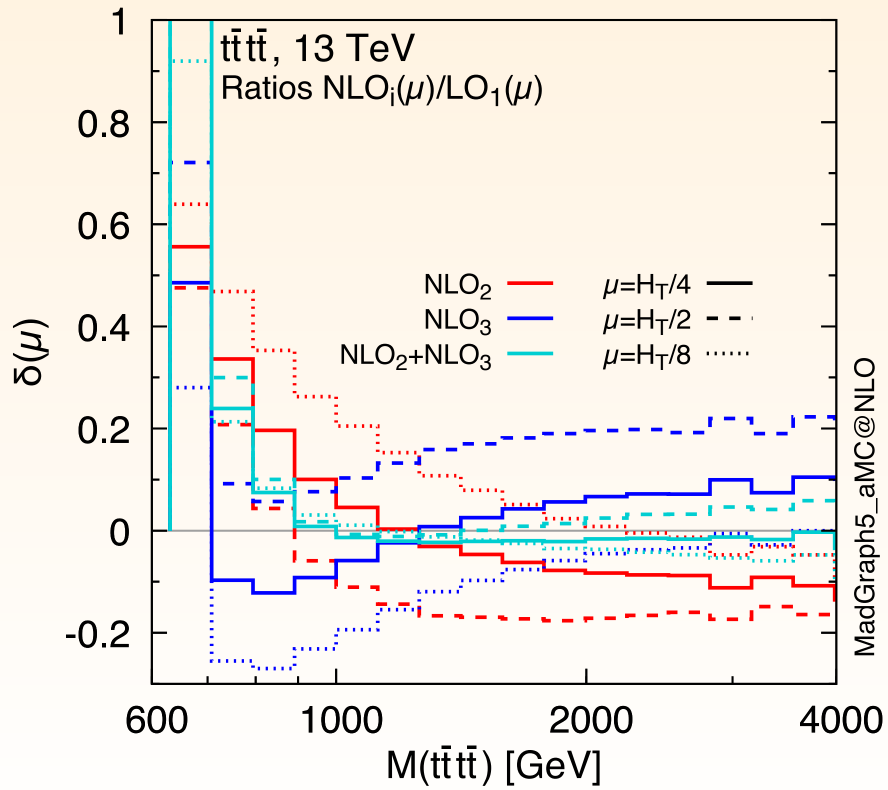
FOUR-TOP INVARIANT MASS

[RF, Pagani, Zaro, 2017]



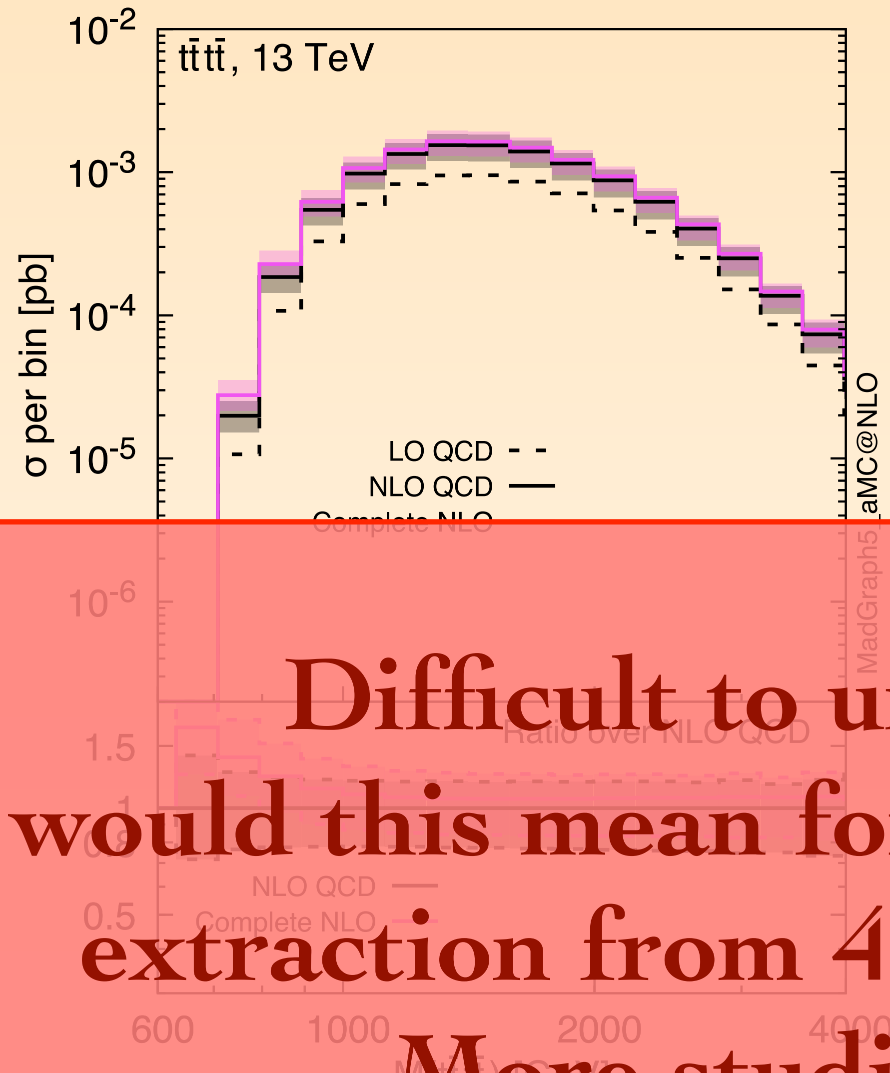


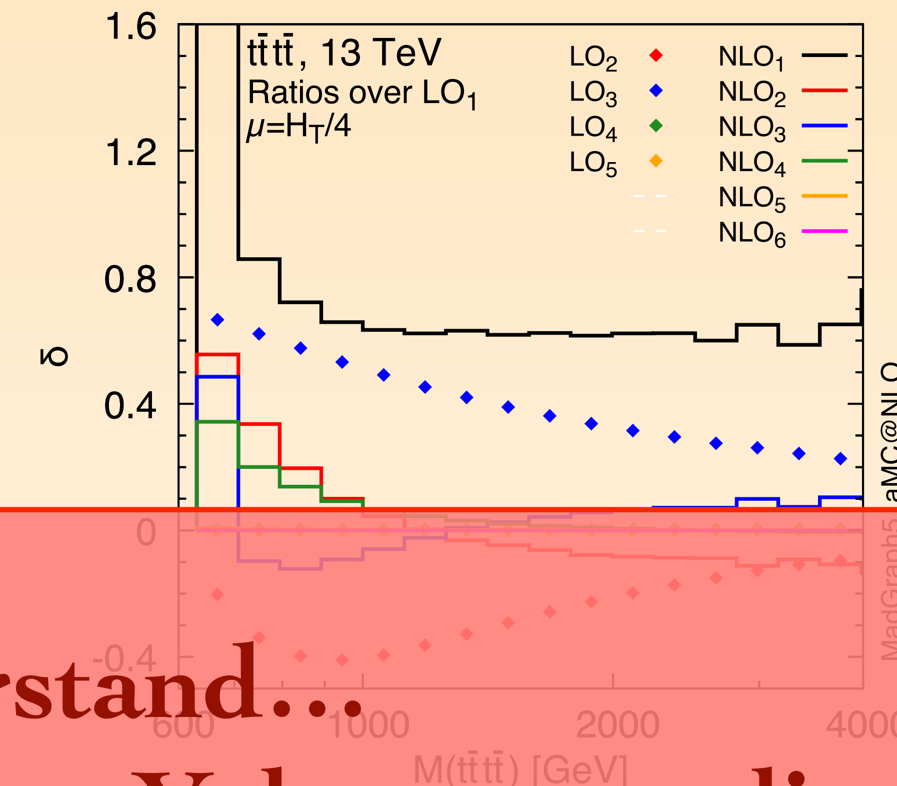


- ✦ Large cancelations between NLO_2 and NLO_3 also at the differential level
- ✦ NLO_4 large at threshold

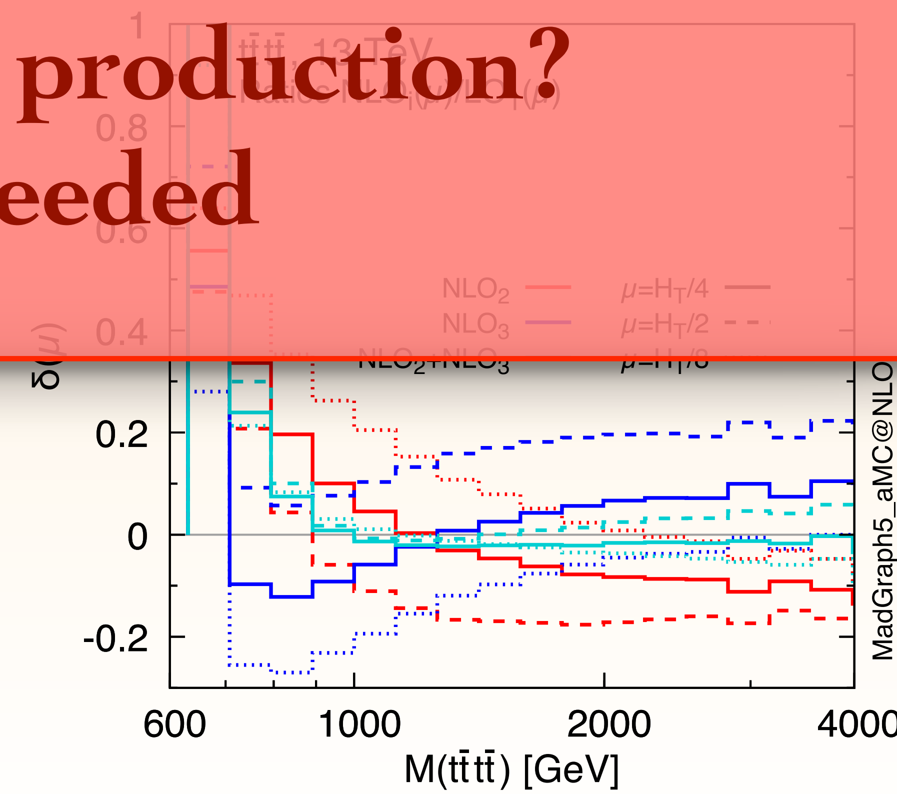
FOUR-TOP INVARIANT MASS

[RF, Pagani, Zaro, 2017]





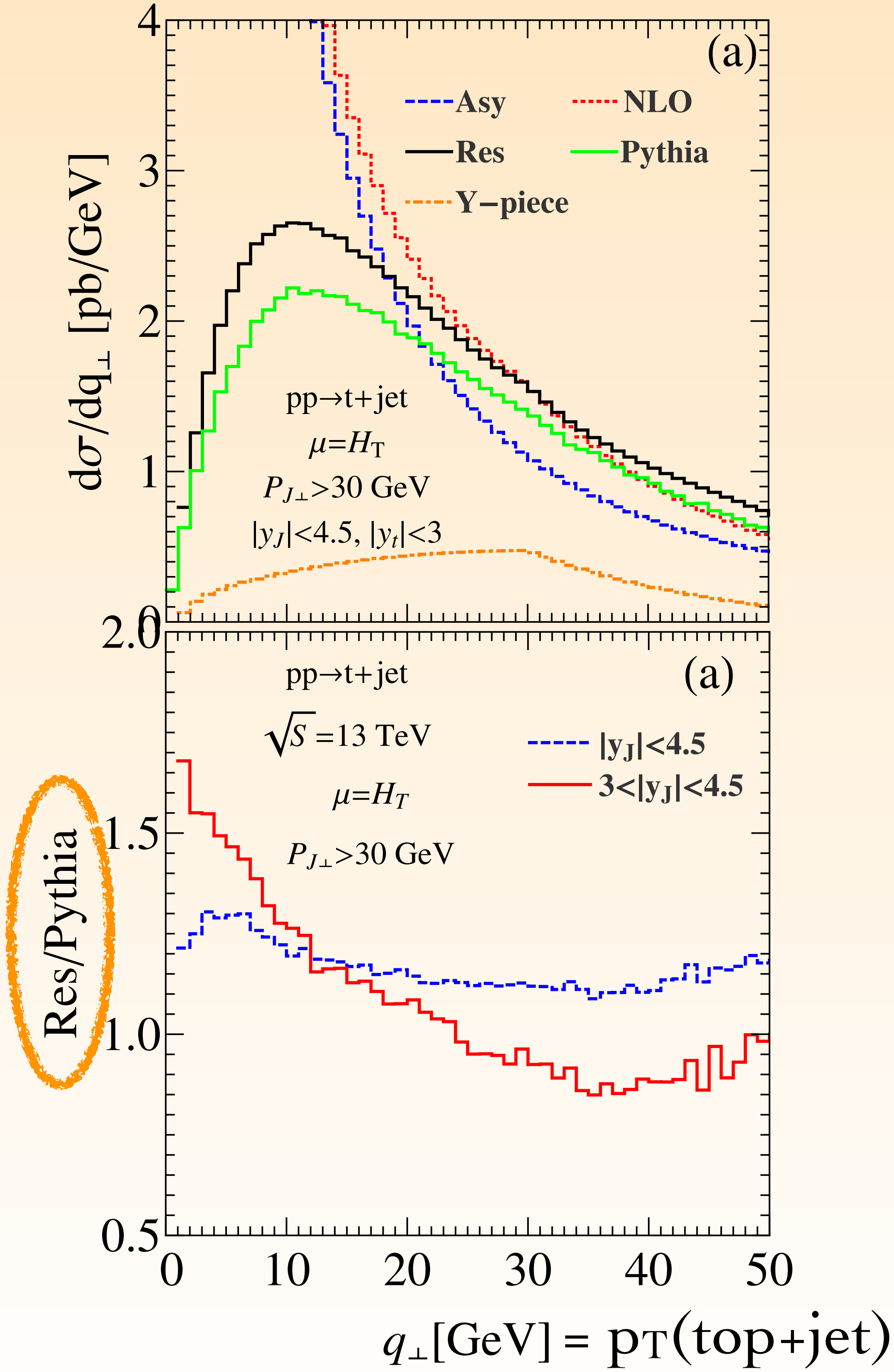
Difficult to understand…
What would this mean for a top Yukawa coupling extraction from 4-top production?
More studies needed



- ✦ Large cancelations between NLO$_2$ and NLO$_3$ also at the differential level
- ✦ NLO$_4$ large at threshold

SINGLE-TOP

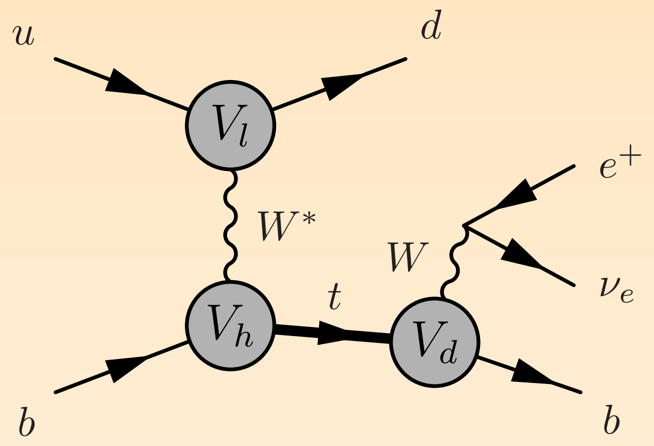
Transverse momentum resummation



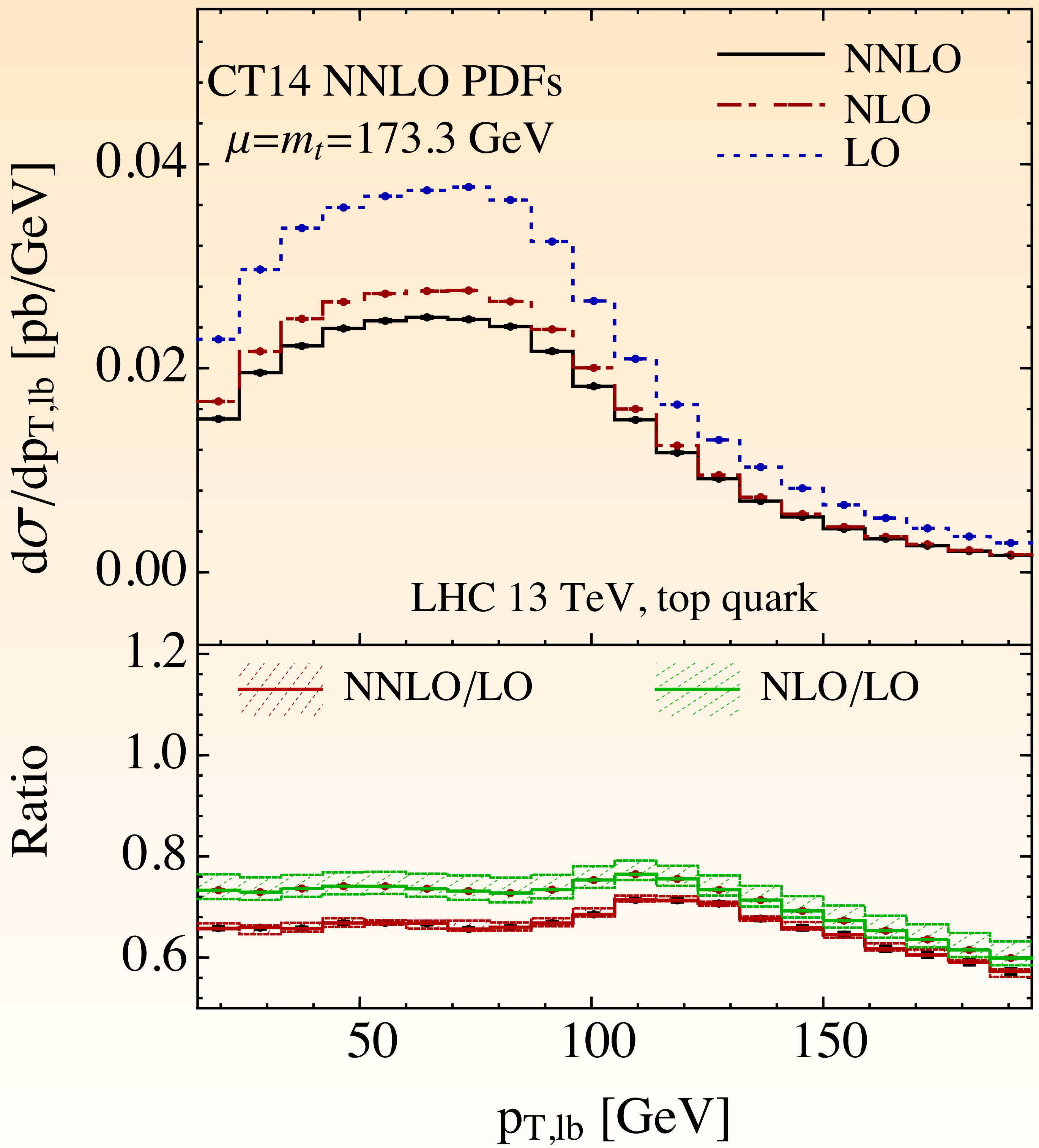
[Cao, Sun, Yan, Yuan, Yuan, 2018]

- ✦ When the top+jet system has small transverse momentum, large logs appear: $\log[Q/q_T]$
  - These can be resummed to all orders in perturbation theory [Collins, Soper, Sterman, 1985]
- ✦ Resummed results similar to parton shower (Pythia8), except when jet is forward
  - However, default Pythia8 suboptimal for DIS like configurations; improved dipole recoil scheme is currently being considered [Cabouat & Sjöstrand, 2018]
  - Might have an effect on these conclusions?

NNLO for t-channel single top



[Berger, Gao, Zhu, 2017, 2018]

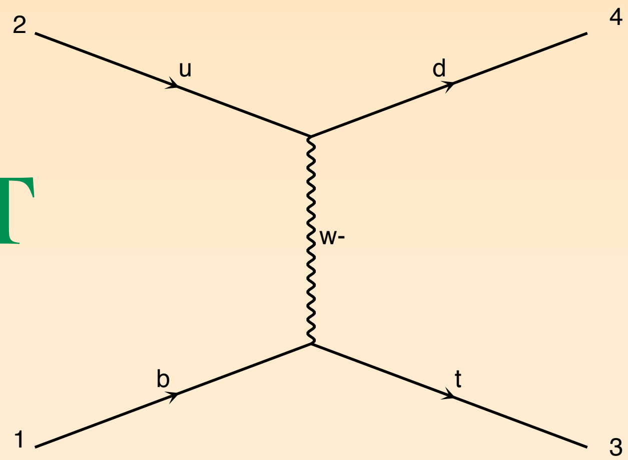


- NNLO corrections to factorised approach
- Fiducial region: requiring exactly 2 jets, of which one is b-tagged
- Effects larger than expected; outside of theoretical uncertainty bands
  - Origin is not obvious
  - Might the parton shower capture a part of these effects?
    … more investigation needed

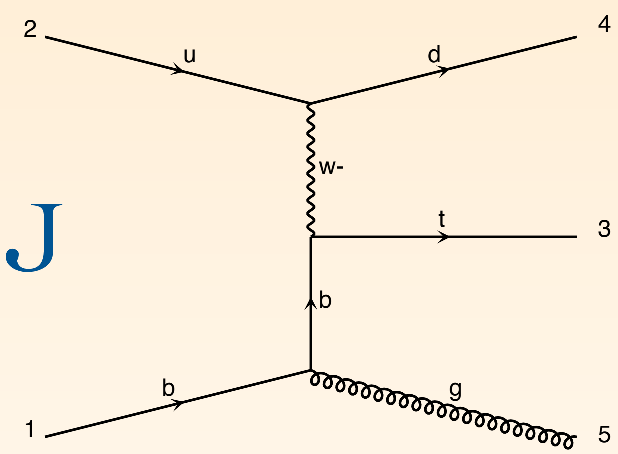
Single top MINLO

[Carazza, RF, Hamilton, Zanderighi, 2018]

ST



STJ

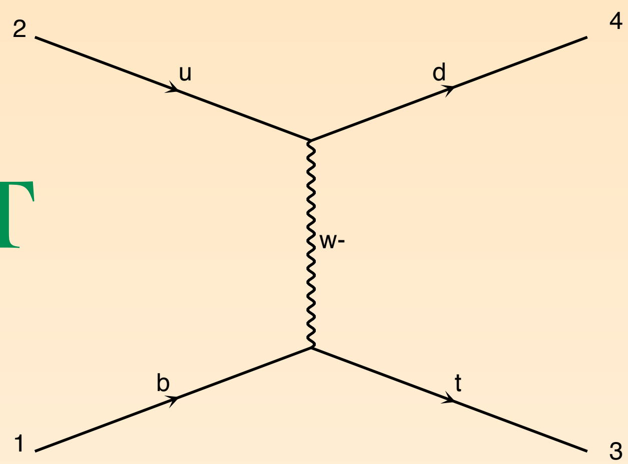


- t-channel single top MiNLO′ merging, within POWHEG framework
- Start from NLO STJ, apply MiNLO algorithm to get LO correct in ST
- Use novel Artificial Neural Network techniques to reweight the MiNLO STJ to **NLO** ST for inclusive observables
- Hence:
  - STJ★ NLO correct in both the ST and STJ phase-spaces
  - No merging scale. Negligible merging ambiguities/uncertainties

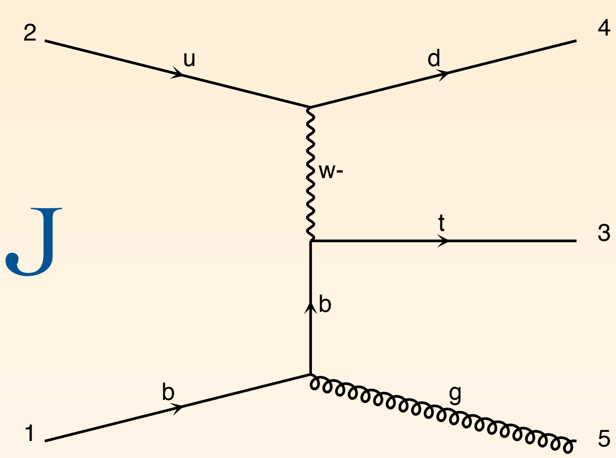
Single top MINLO

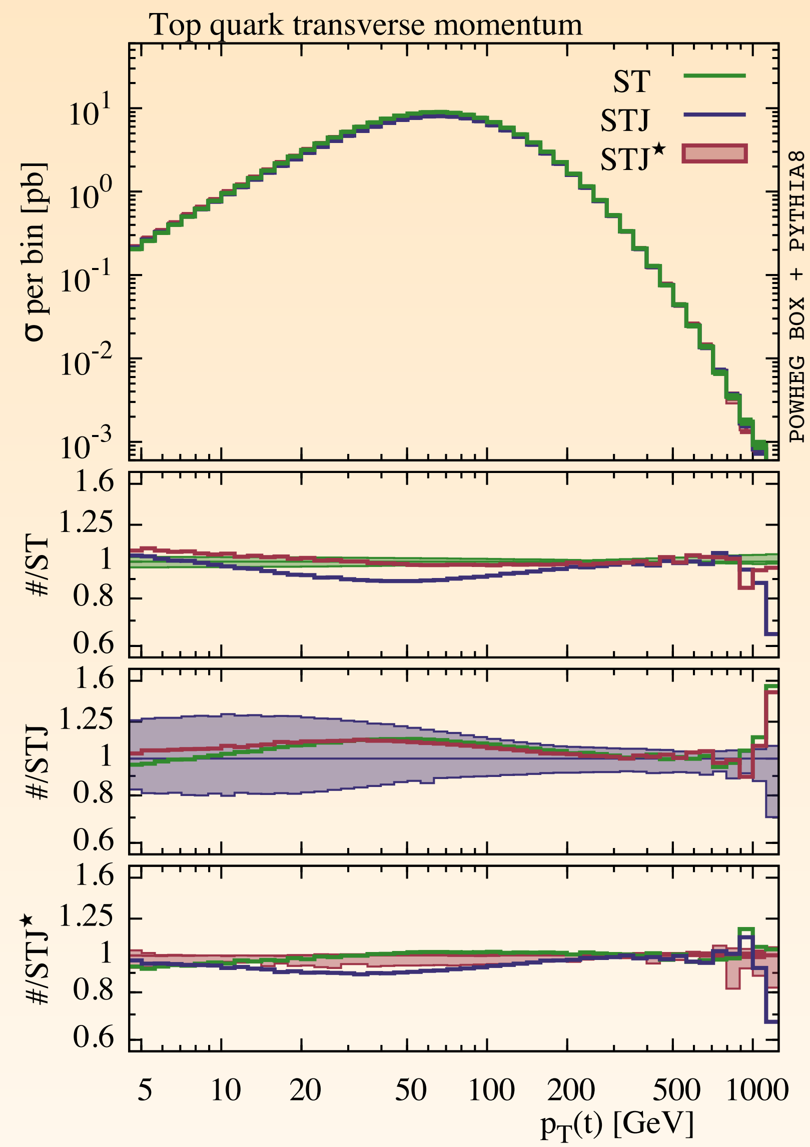
[Carazza, RF, Hamilton, Zanderighi, 2018]

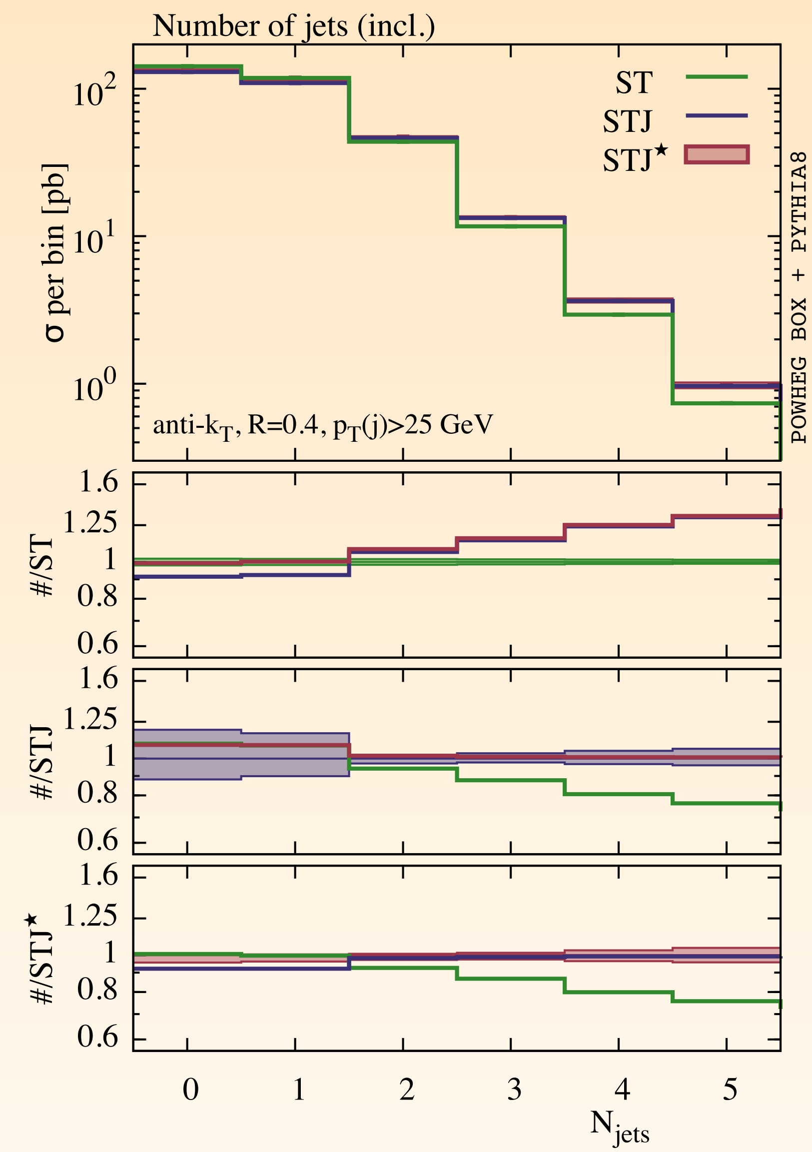
ST



STJ







- STJ★ is NLO correct in both the ST and STJ phase-space
- Top transverse momentum: ST is NLO, STJ is LO, STJ★ NLO
- 0,1-jet bins: ST is NLO; 2-jet bin STJ is NLO; STJ★ is NLO in 0,1,2-jet bins

Top is kept stable; no hadronisation/ underlying event

Conclusions

- NLO+NNLL resummation available for ttbar+heavy boson production. Uncertainties from QCD scale dependence well below 10%
- Complete-NLO available for ttbar+X production processes
  - Some surprises: in particular for ttW and 4-top where NLO_3 effects are much larger than expected
- NNLO for single-top production+decay in the NWA: large effects for fiducial cross sections (jet veto). Missing logarithms?
- MiNLO' merging for single-top production within POWHEG
  - STJ★ NLO correct in both the ST and STJ phase-space. No merging scale!
  - Opens a road to include NNLO corrections