Precise predictions for ttbar, ttV, ttH, ...

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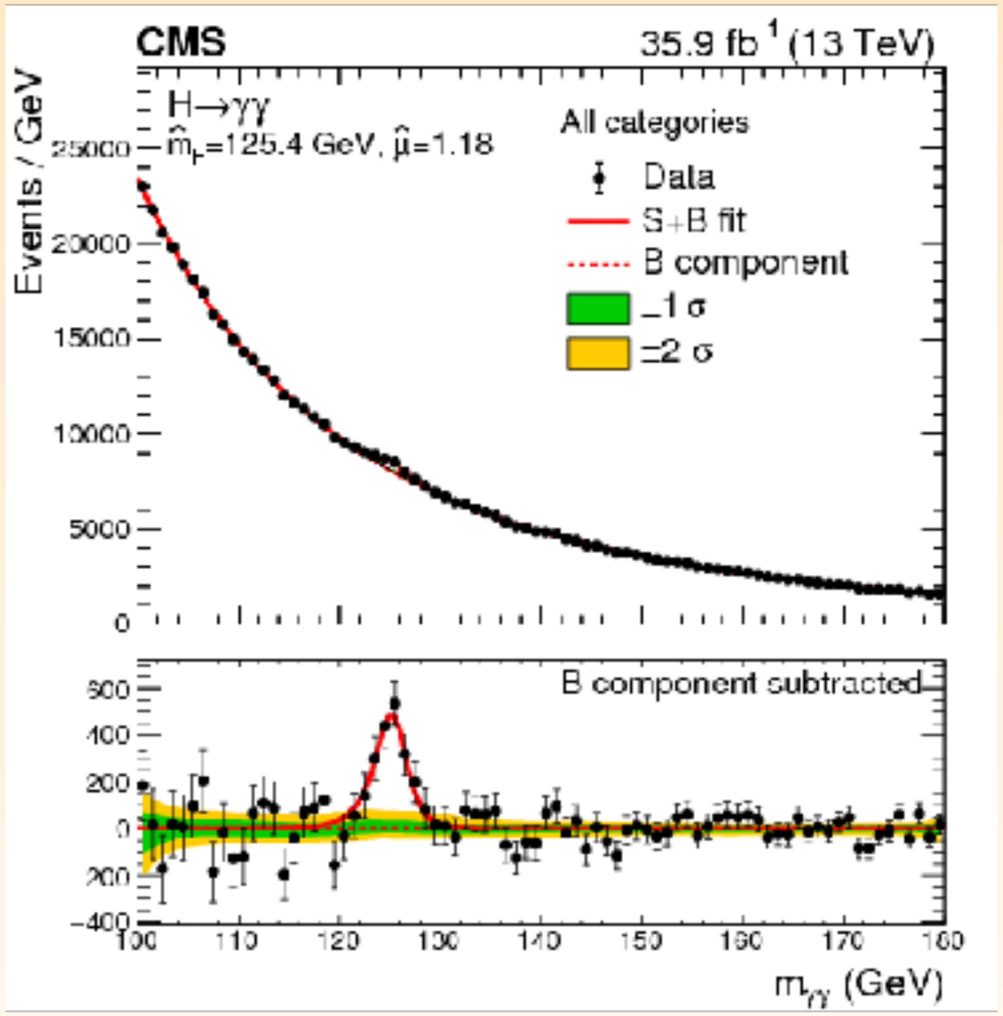
Technische Universität München

Top LHC France 2018, Paris, France, May 23-25 2018

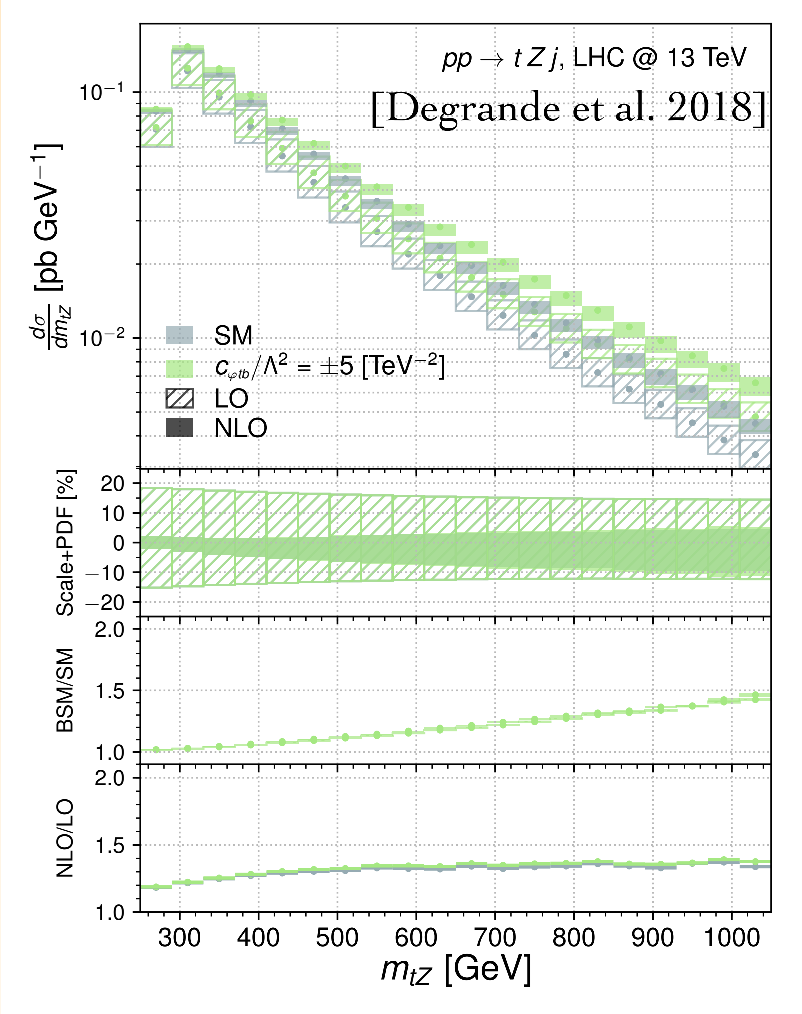
SEARCH FOR NEW PHYSICS

Invariant mass peak: "easy"



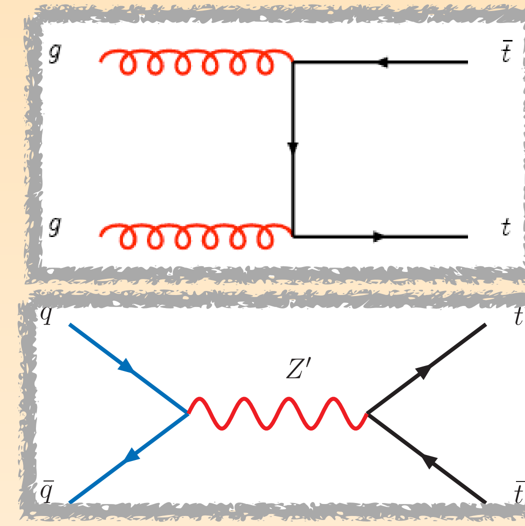
- ✦ Theory predictions not important for finding a resonance peak
- ✦ However, they do play a role in measuring its properties…

Shape variation: "hard"

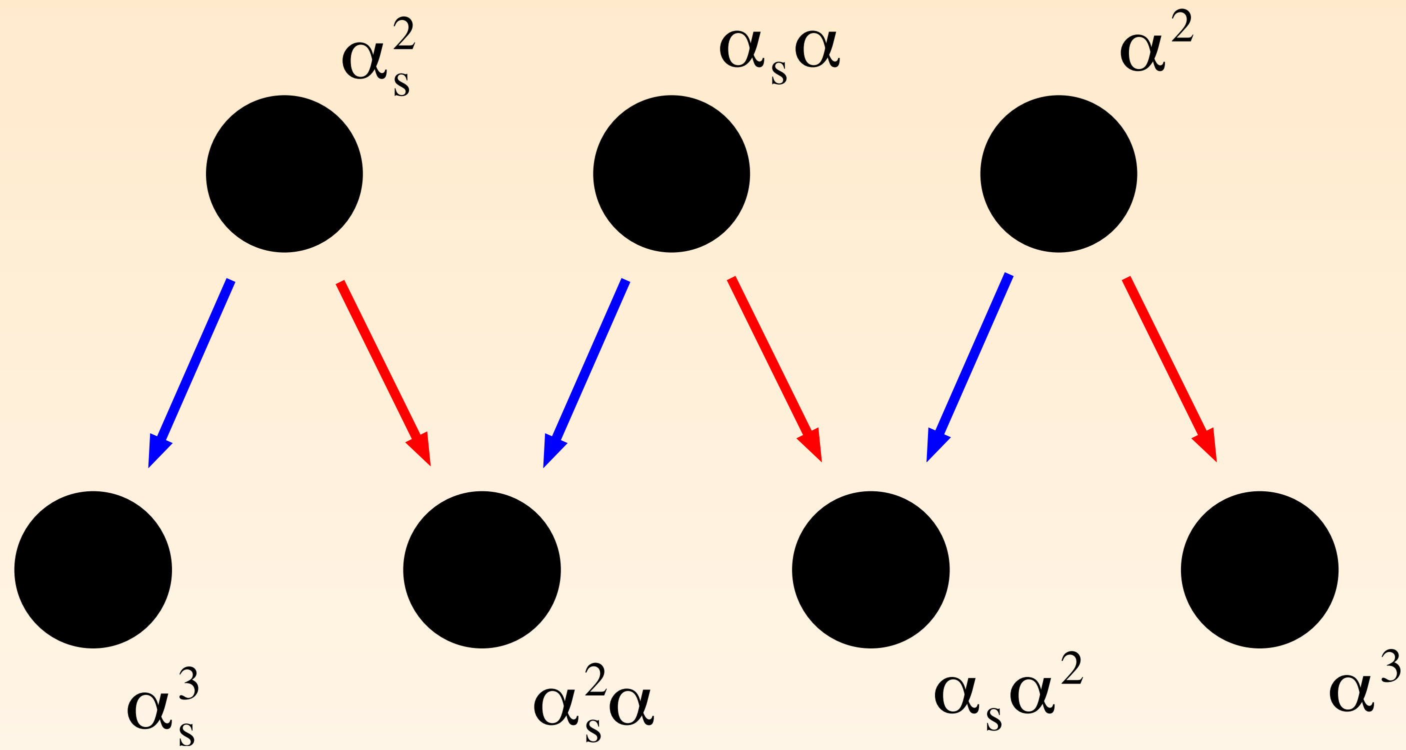


- ✦ Theory predictions fundamental in extraction of signal
- ✦ Need accuracy, including realistic theory estimates: **at least NLO**

NLO DISSECTION



- For example: consider top-pair 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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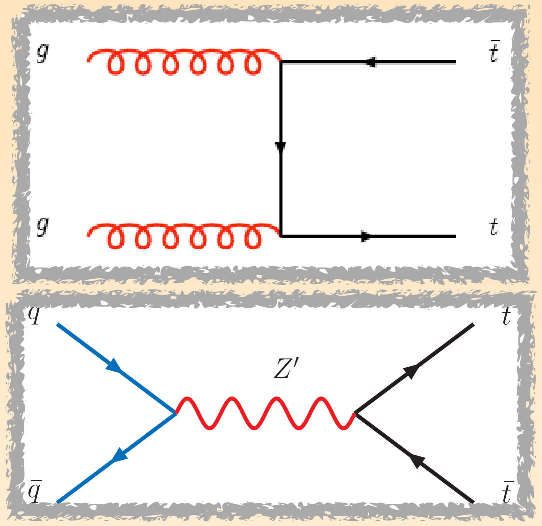

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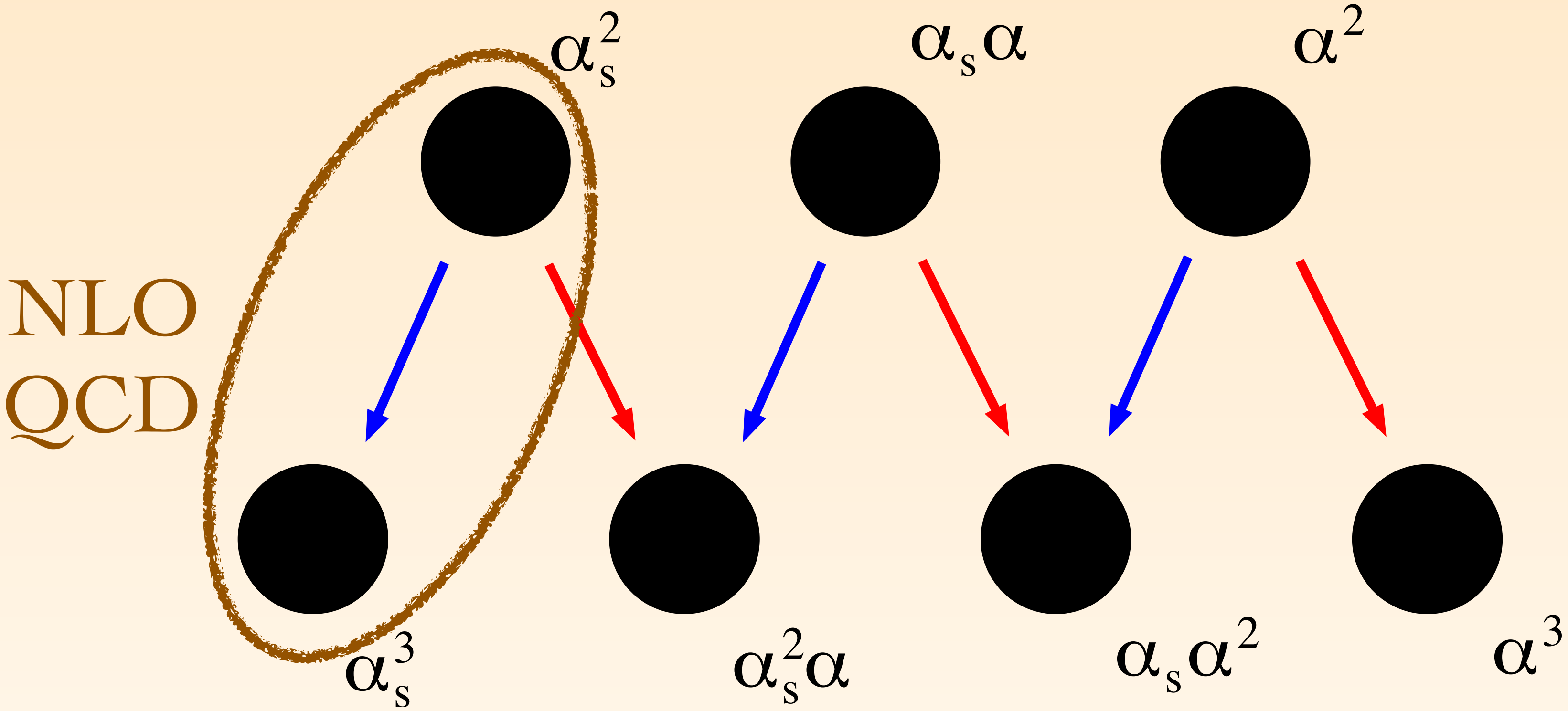

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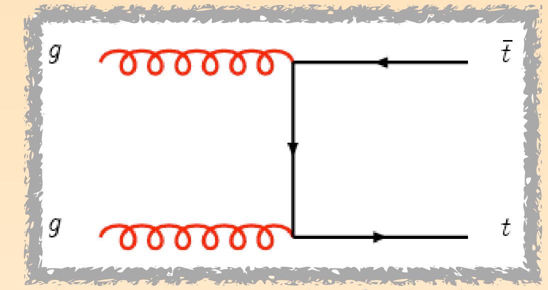

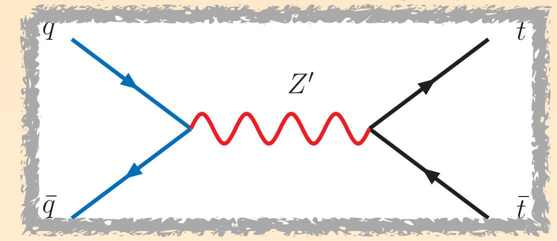

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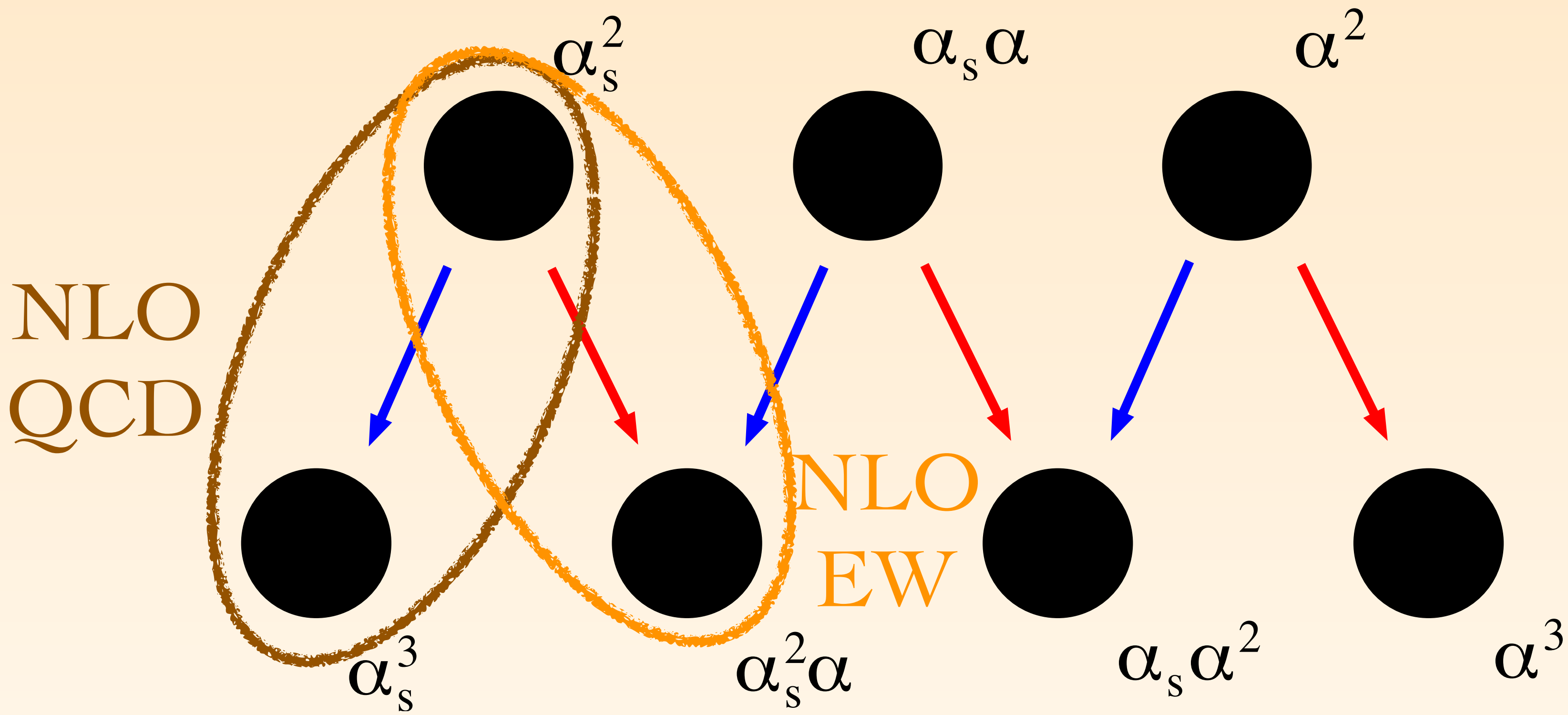

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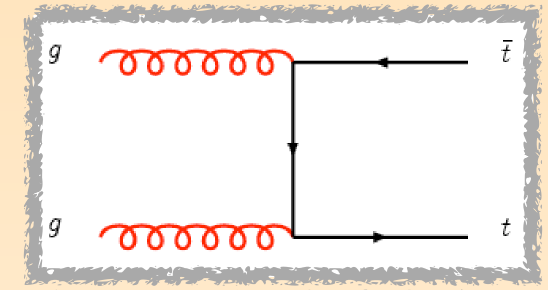

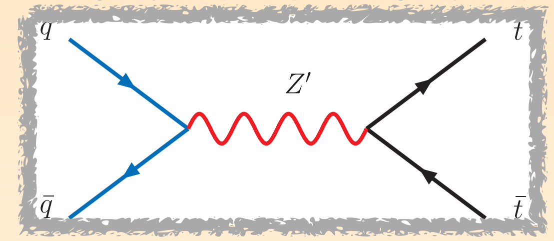

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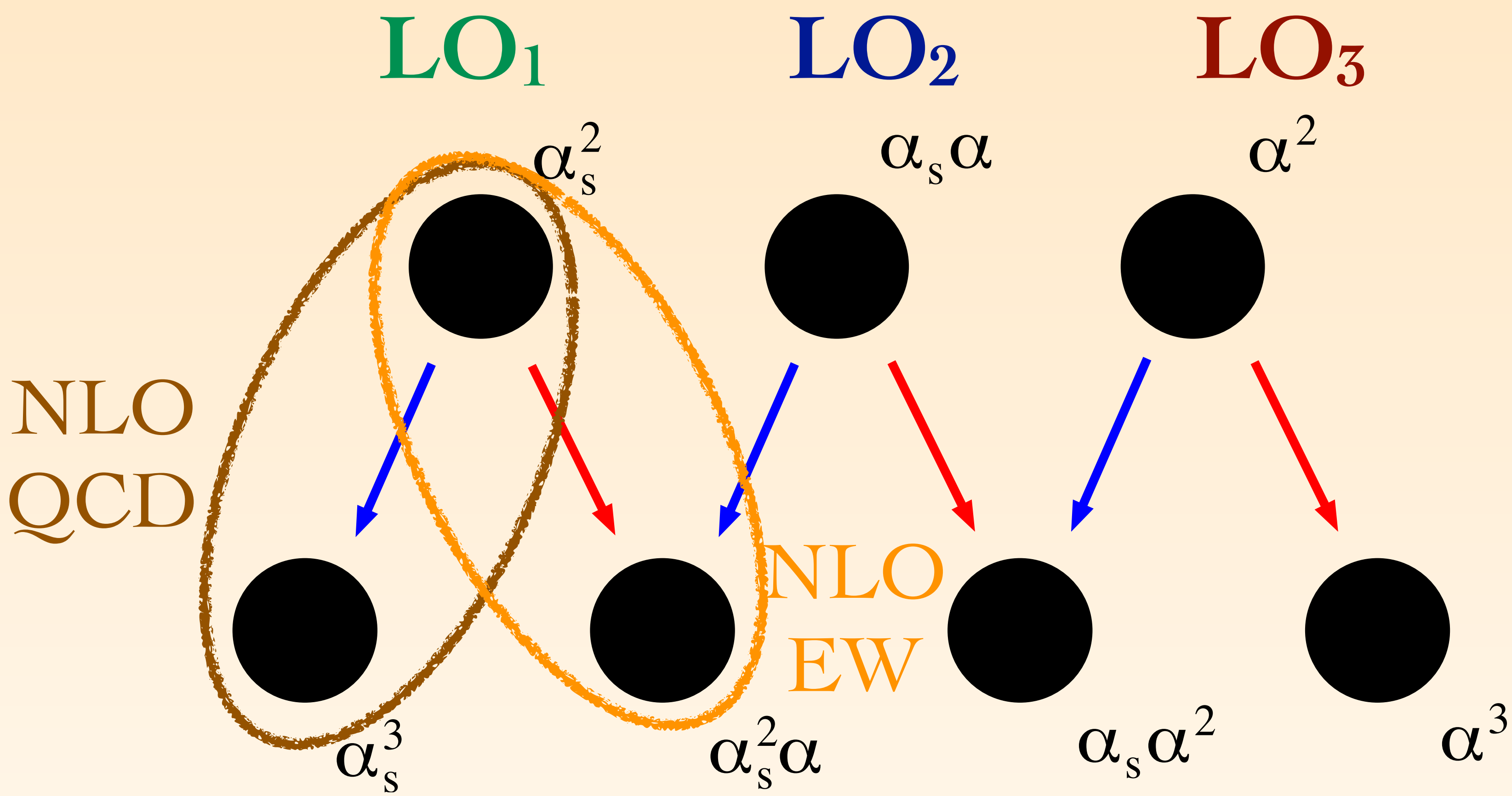

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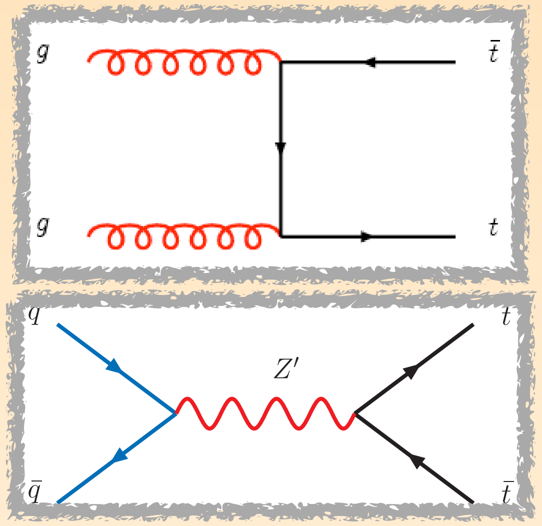

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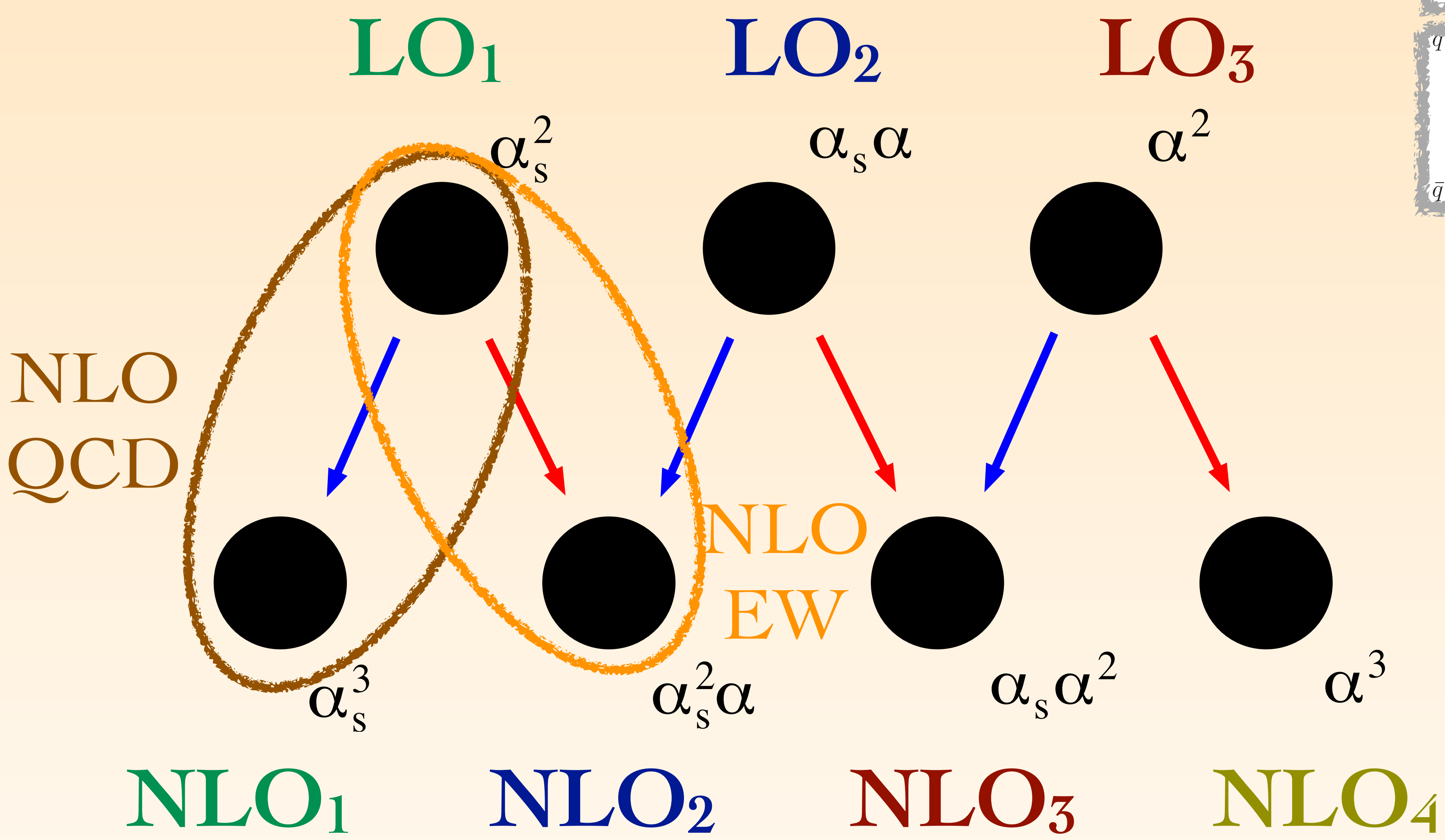

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Complete-NLO for top pair production

- MadGraph5_aMC@NLO v. 3 beta recently released: complete-NLO computations possible out-of-the-box [RF, S. Frixione, V. Hirschi, D. Pagani, H.-S. Shao, M. Zaro, 2018]
    - Only fixed-order NLO, i.e., not yet with matching to parton shower

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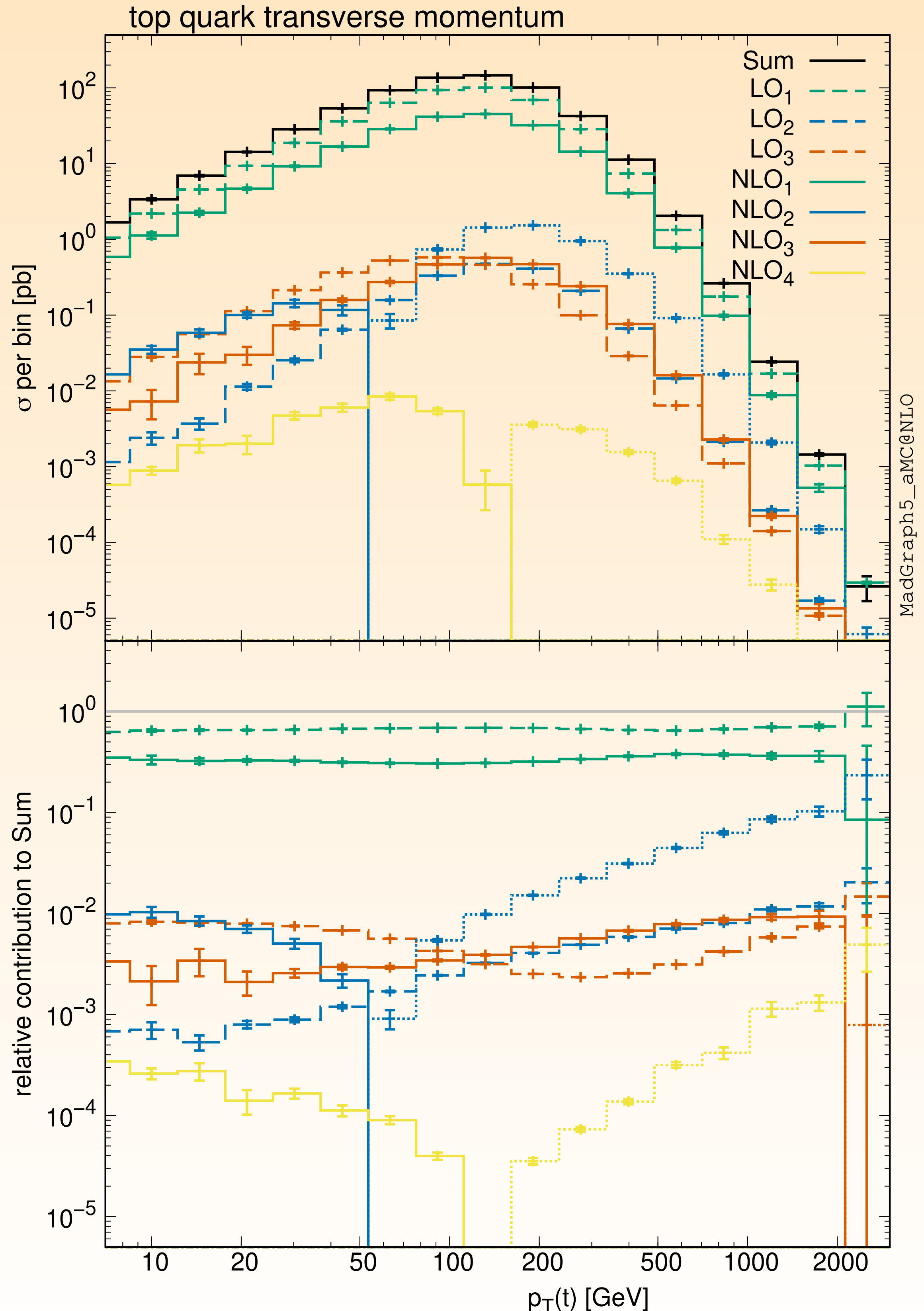
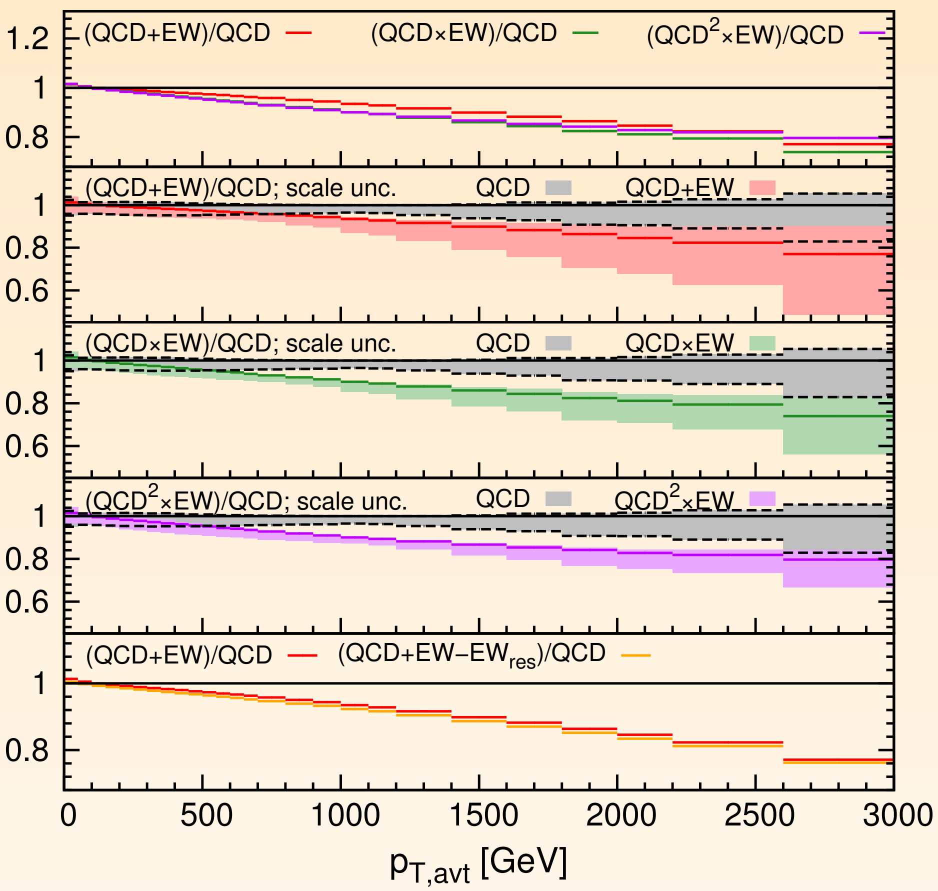
  - Only fixed-order NLO, i.e., not yet with matching to parton shower
- Top quark transverse momentum
- NLO2 (= NLO EW) non-negligible at large p_T's, reaching -10% at p_T=1TeV
- (N)LO3 and NLO4 are negligible for this observable for this process



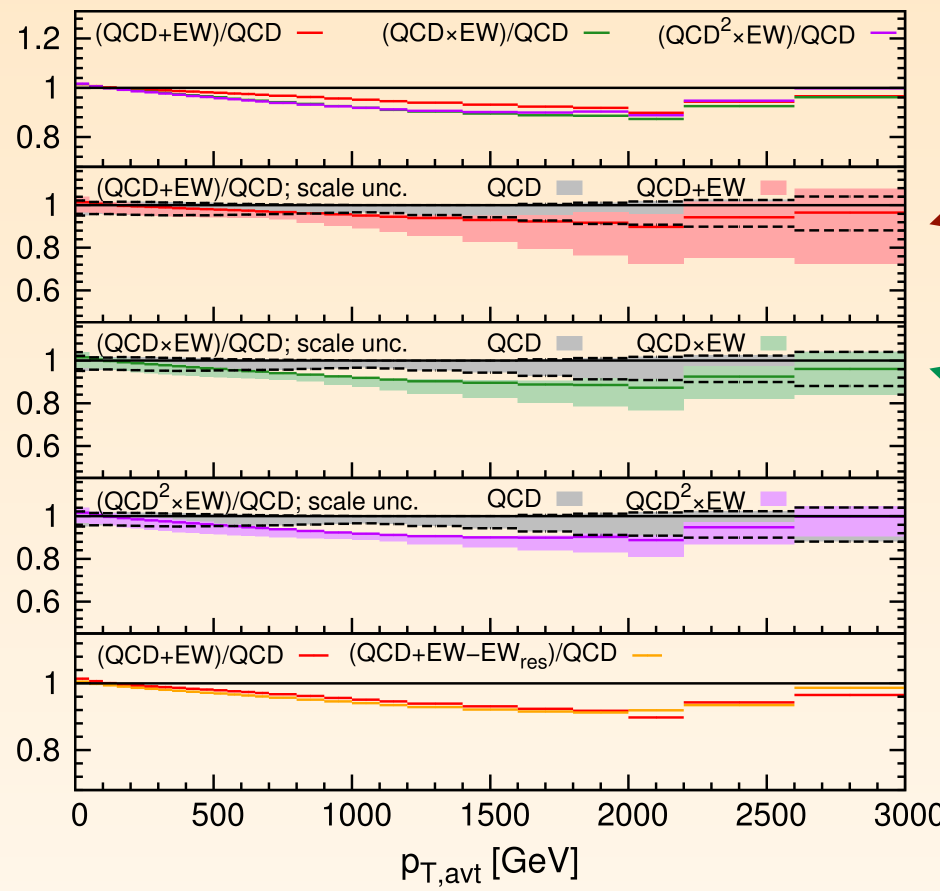
COMPLETE-NLO COMBINED WITH NNLO QCD

[Czakon, Heymes, Mitov, Pagani, Tsinikos, 2017]

LUXQED



NNPDF3.0



Additive

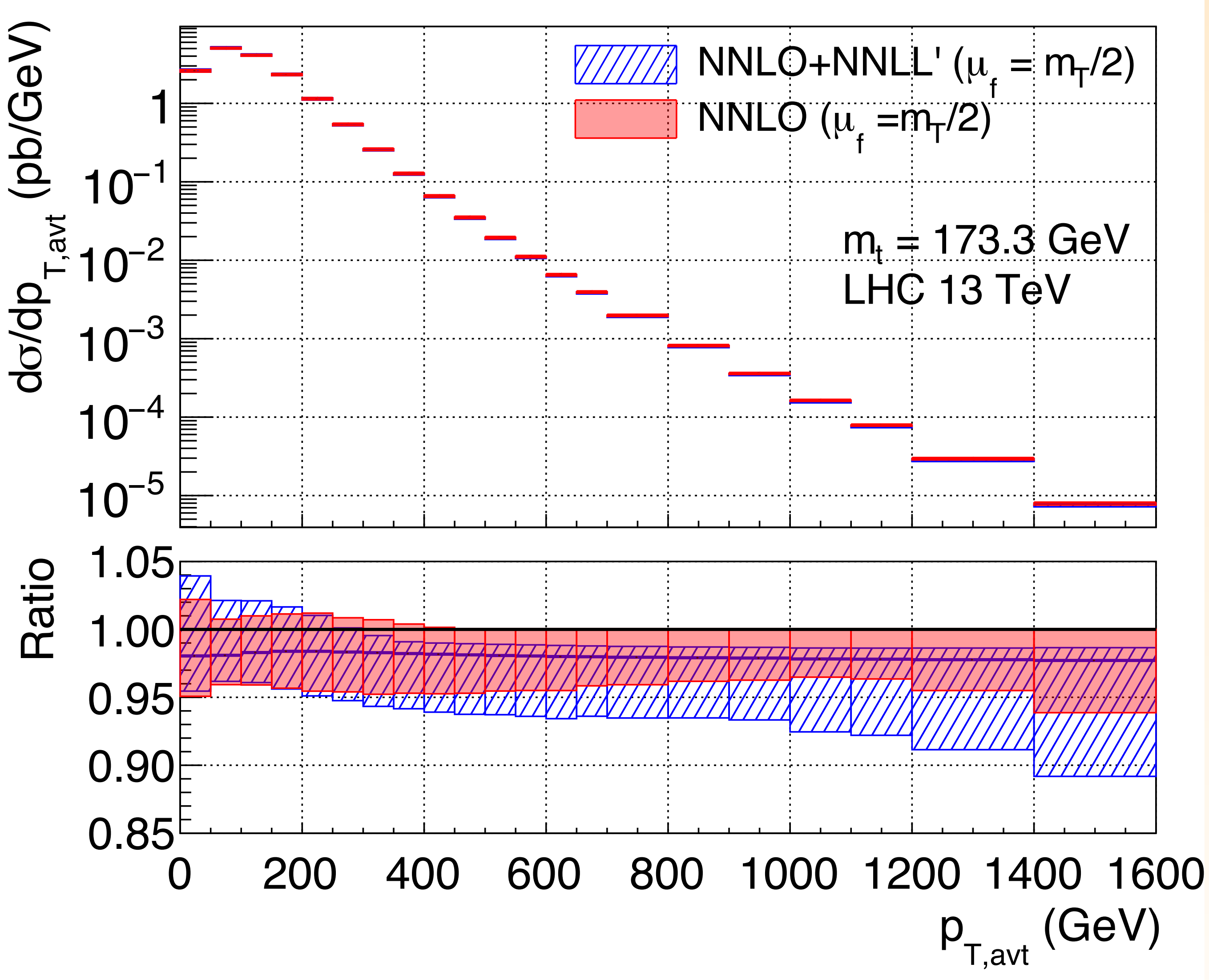
Multiplicative

- Top transverse momentum at LHC 13TeV
- Difference between LUXQED and NNPDF mainly due to superior treatment of the photon luminosity in LUXQED [Newer versions of NNPDF include the LUXQED photon treatment]
- Multiplicative approach results in smaller scale dependence at large p_T's (assumes factorisation of QCD and EW NLO corrections)

NNLO+NNLL'

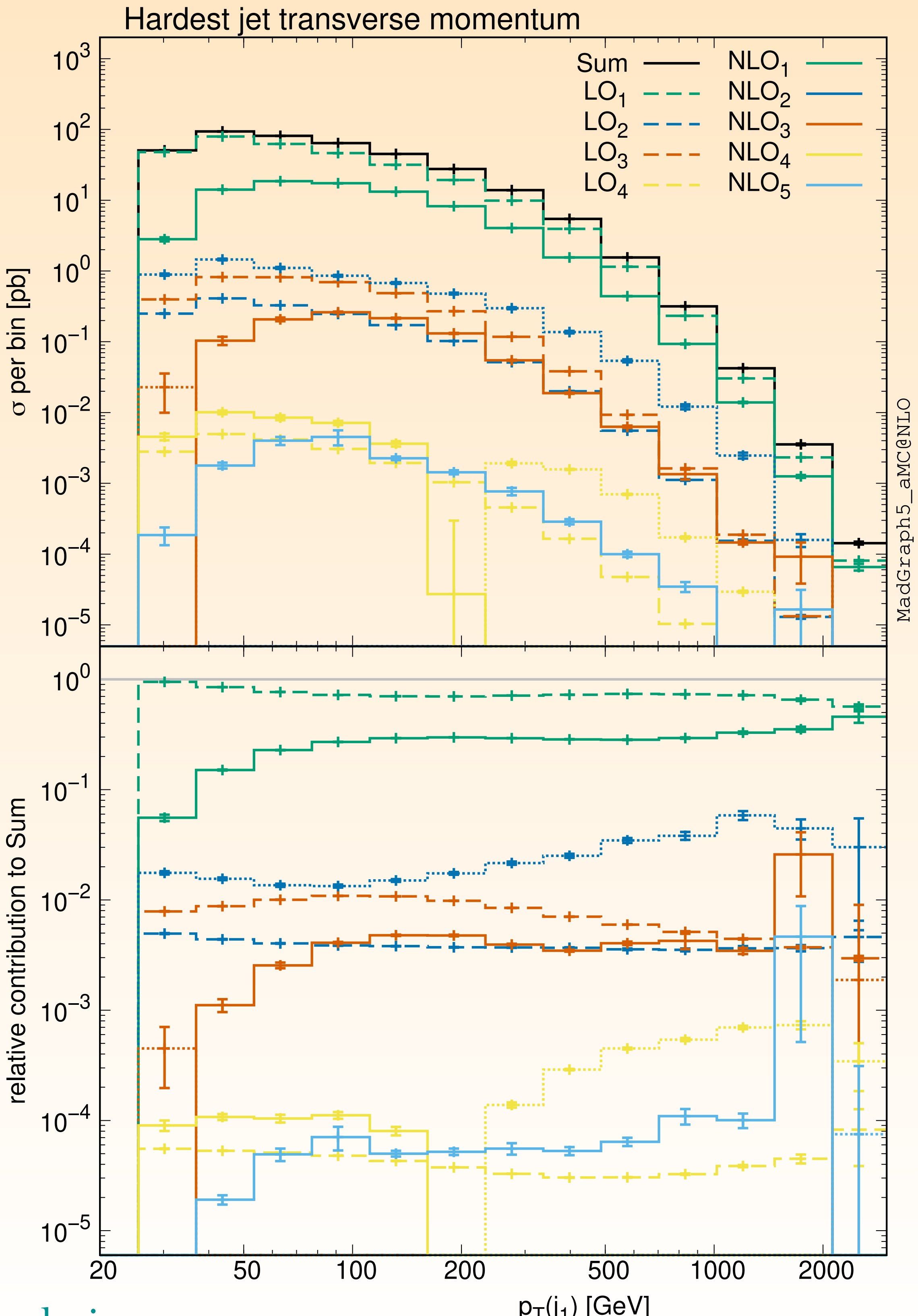
- ✦ Combines fixed order with soft gluon resummation
- ✦ Effect small on top transverse momentum (similarly small for top pair invariant mass)
  - Slight increase in scale dependence at large p_T's
  - Underestimation of theory uncertainties at NNLO for differential distributions?
  - Effect smaller than the EW corrections (which have not been included here)

[Czakon, et al. 2018]



Complete-NLO ttbar+jet

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

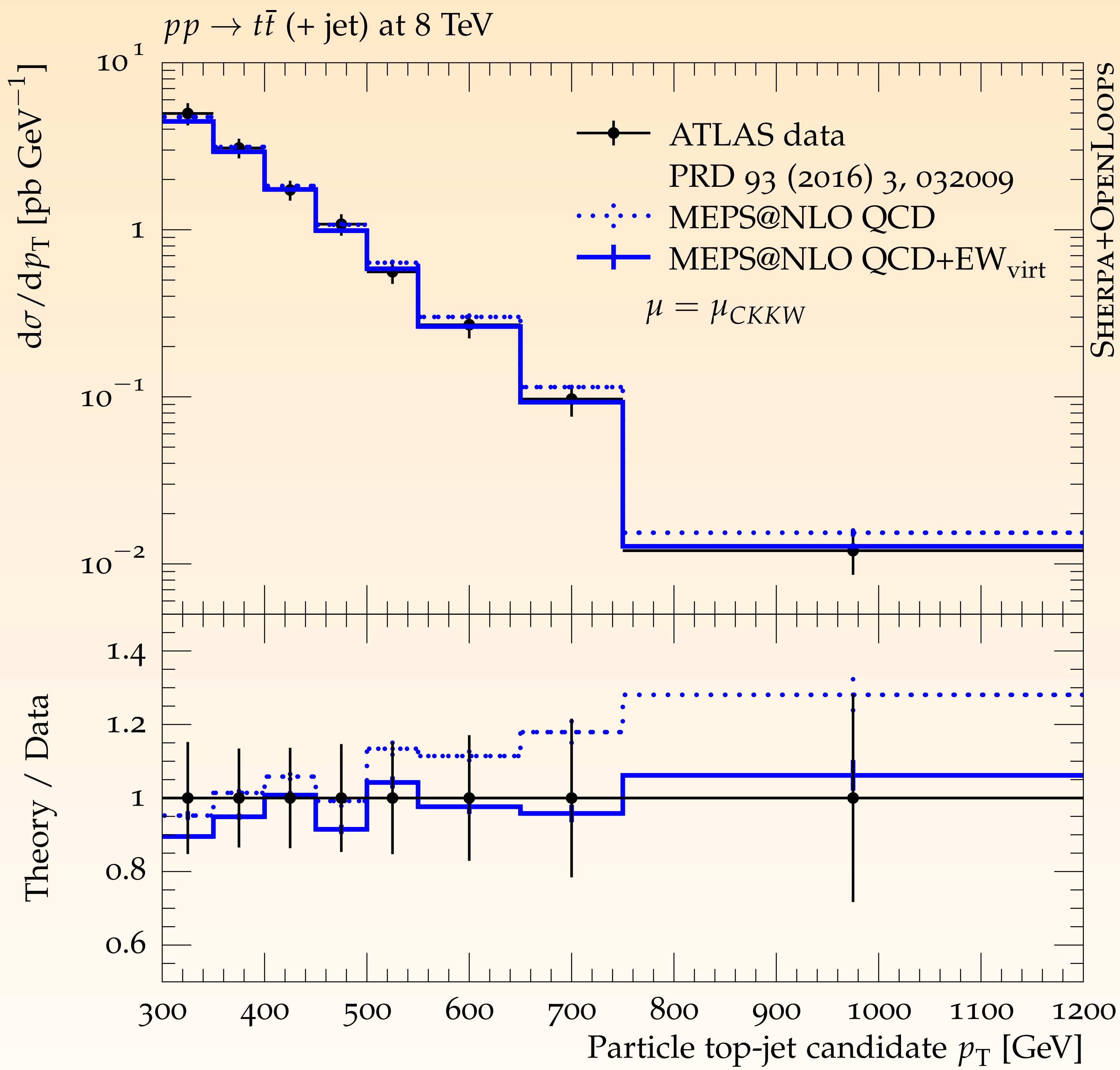


- ✦ Transverse momentum of the leading jet (no top quark decays)
- ✦ Dominated by QCD contributions (LO_1+NLO_1)
  - Even at large p_Ts, the EW corrections (NLO_2) remain small
  - Also true for $(N)LO_3$, $(N)LO_4$ and NLO_5

Complete-NLO ttbar+0,1jet merged

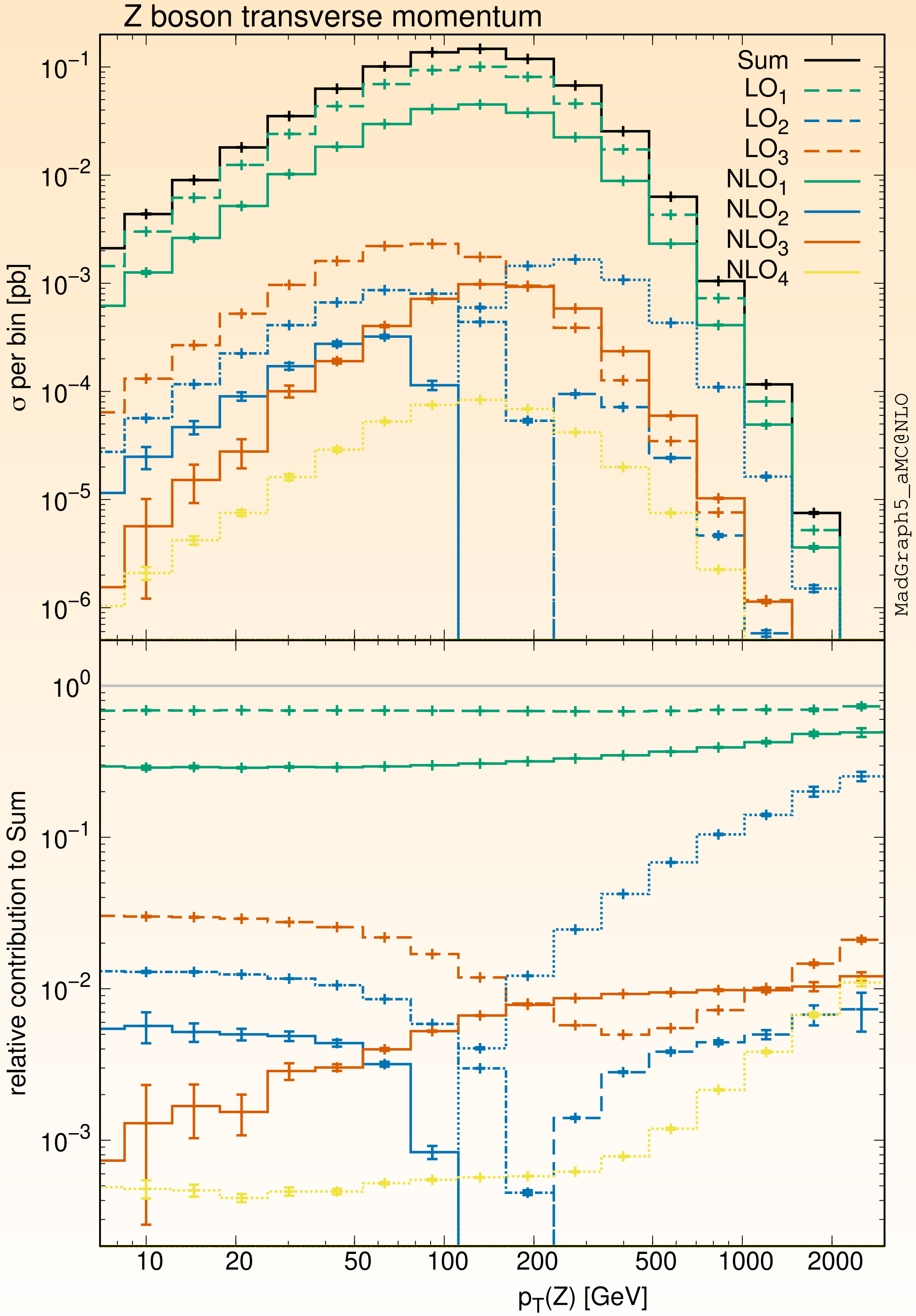
[Gütschow, Lindert, Schönherr, 2018]

- Includes an *approximate* matching to the parton shower, together with multi-jet merging for ttbar+ 0,1 jets
- Including EW corrections greatly improves agreement with data for the candidate top quark transverse momentum
    - Jet-substructure analysis to find the (hadronically-decaying) top quark at high p_T.



Complete-NLO ttbar+Z

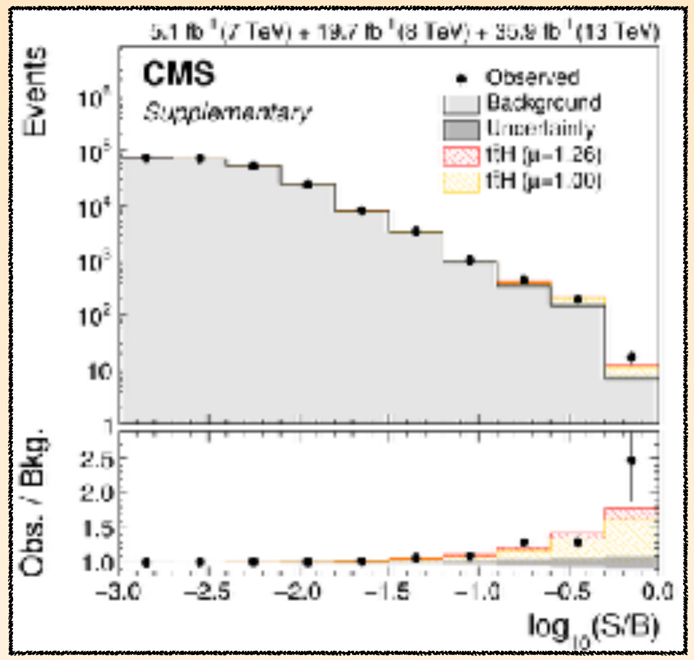
[RF, S. Frixione, V. Hirschi, D. Pagani, H.-S. Shao, M. Zaro, 2018]

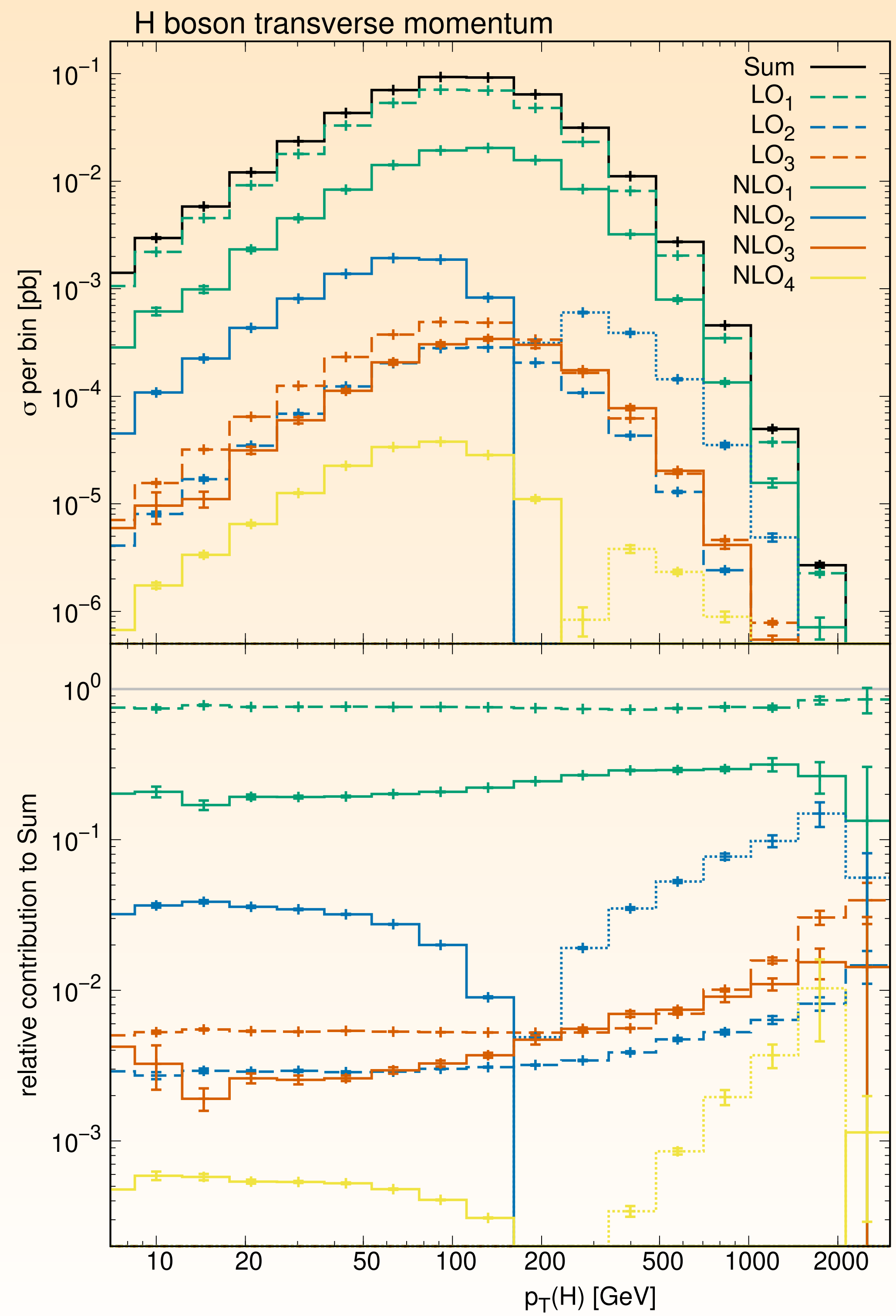


- Top pair production in association with a Z-boson
  - Transverse momentum of the vector boson
- Significant EW corrections (NLO2) at very large pTs, where they can reach ~-25% of the total rate
  - Partly canceling the QCD corrections (NLO1), which grow with increasing pT
- (N)LO3 and NLO4 typically small and negligible for most practical purposes

Complete-NLO ttbar+H

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



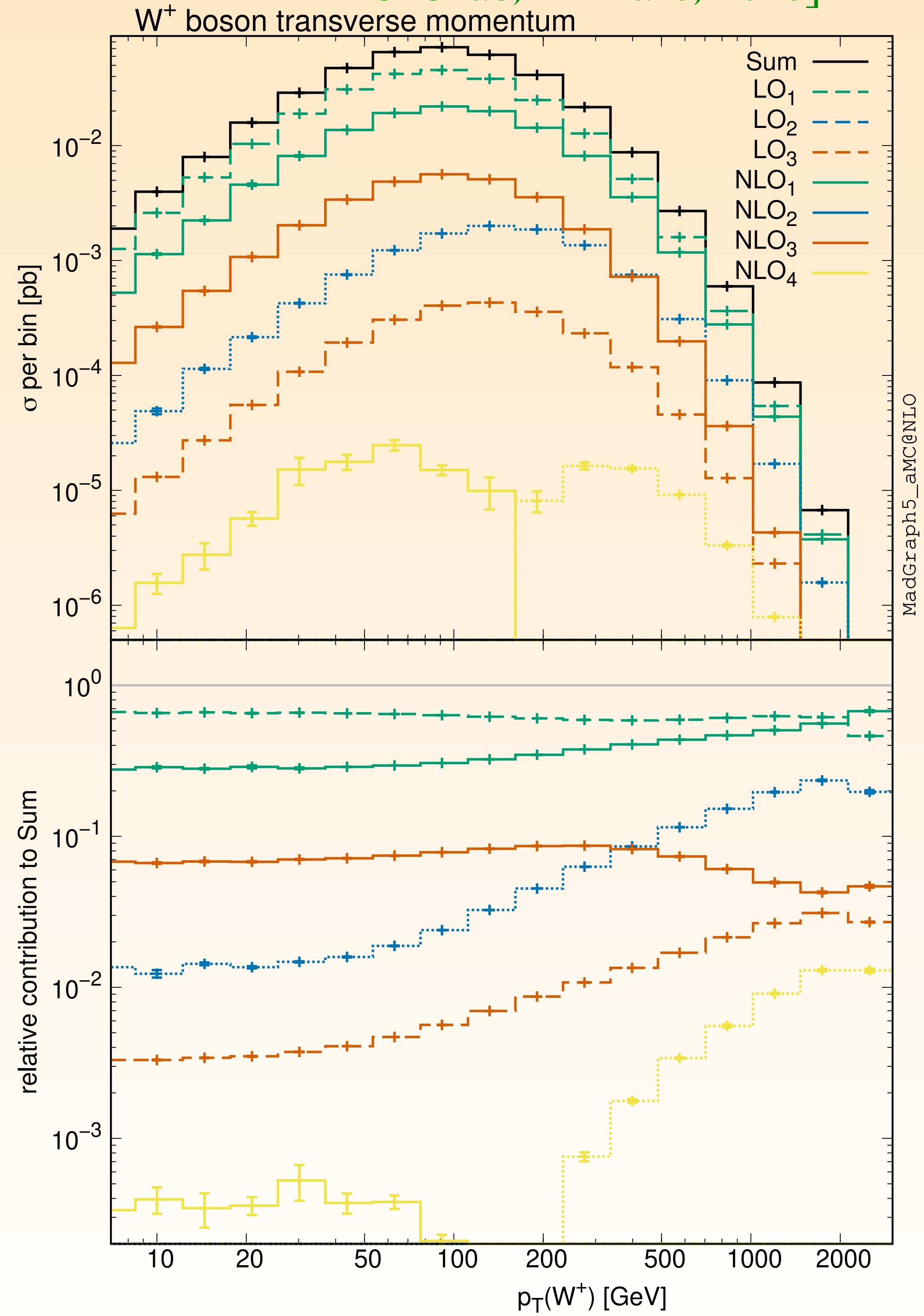


- ✦ Higgs production in association of a top-quark pair recently observed at the LHC
- ✦ Corrections smaller than for ttbar+Z
  - NLO$_2$ at the percent-level, apart from the far tail, where its effect is slightly larger
  - (N)LO$_3$ and NLO$_4$ negligibly small

Complete-NLO ttbar+W

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

- 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



Complete-NLO ttbar+W

[RF, Pagani, Zaro, 2017]

Slightly different normalisation as compared to ratio plot $\delta_{(\mathrm{N})\mathrm{LO}_i}(\mu) = \frac{\Sigma_{(\mathrm{N})\mathrm{LO}_i}(\mu)}{\Sigma_{\mathrm{LO}_{\mathrm{QCD}}}(\mu)}$

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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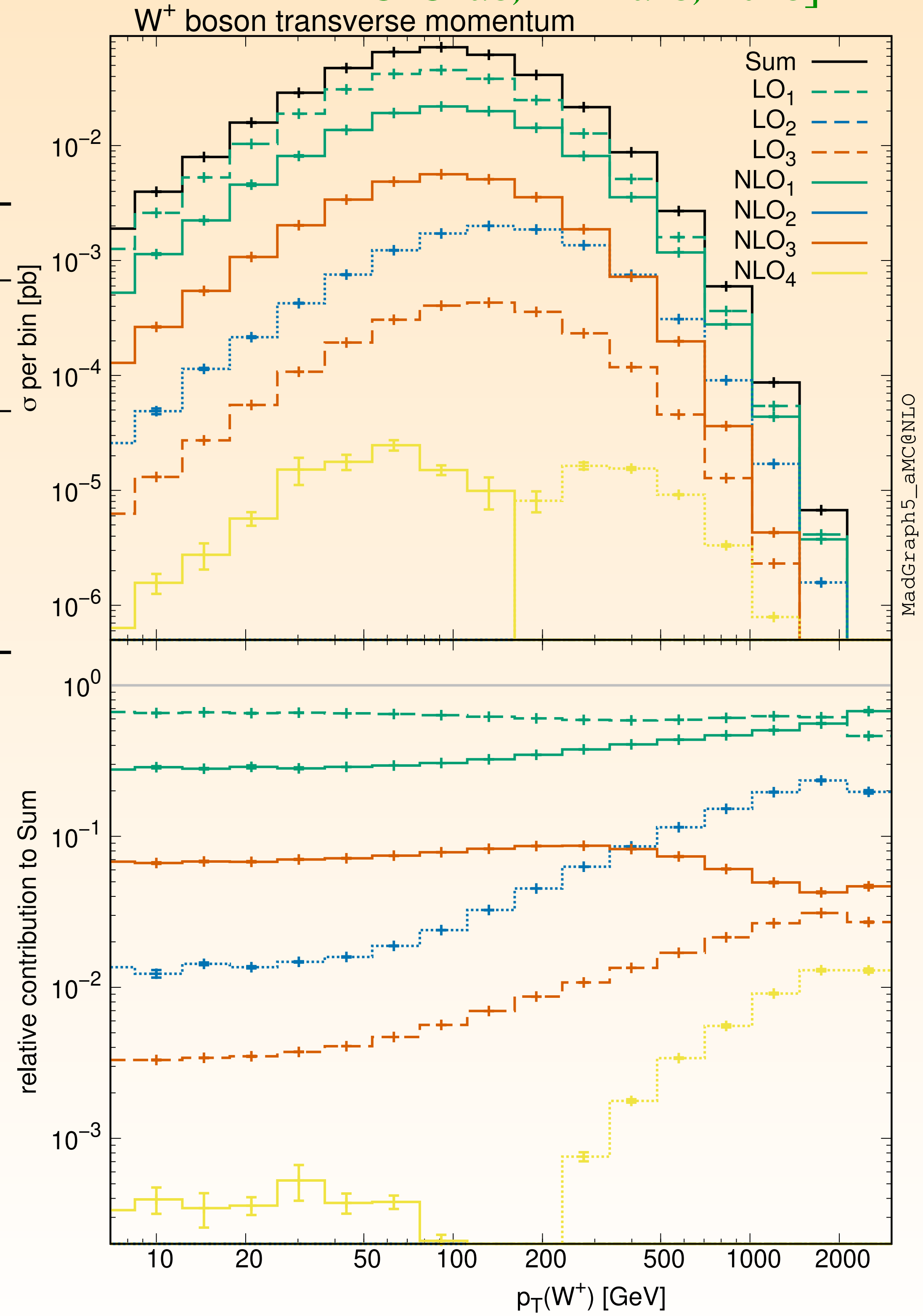

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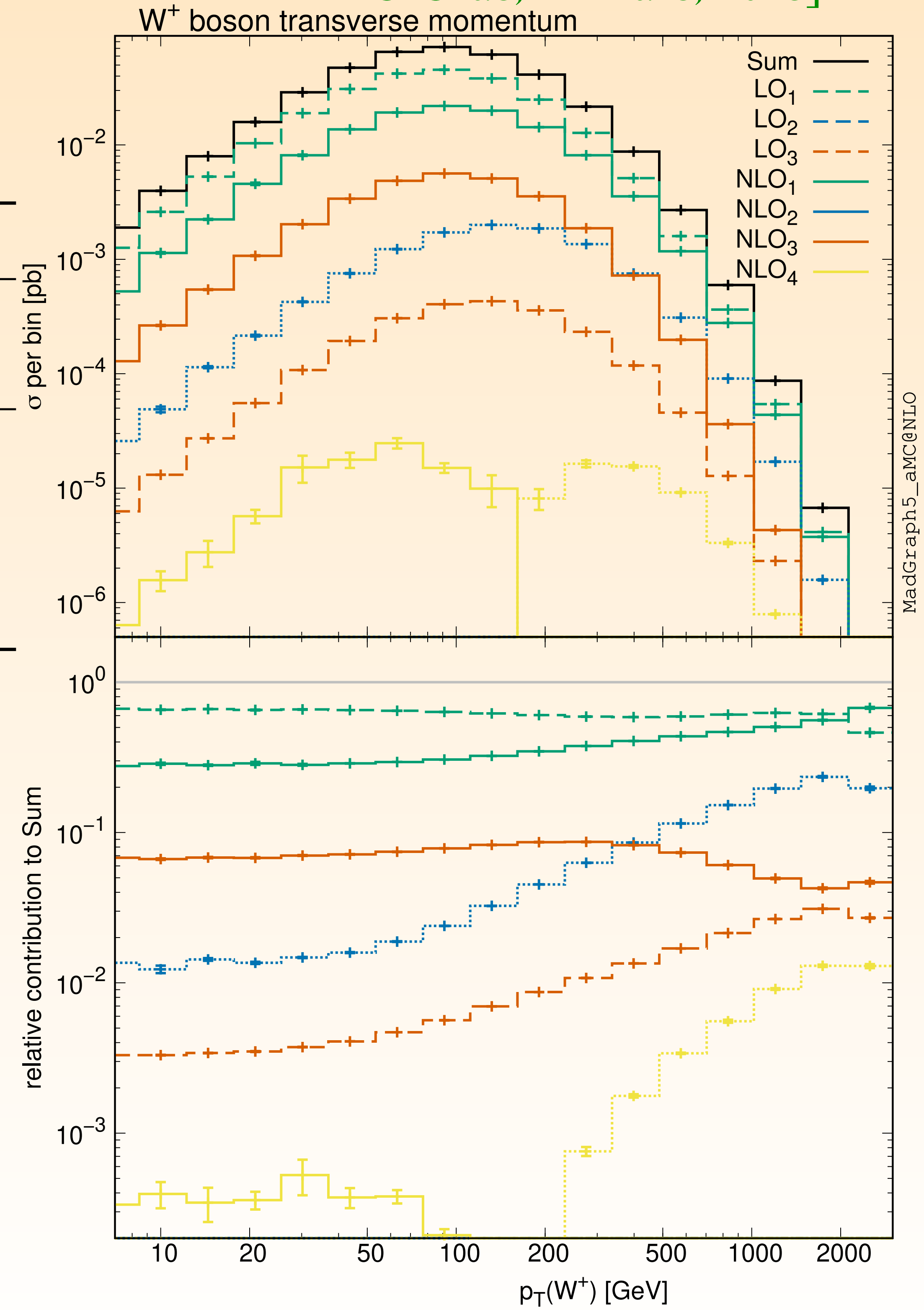

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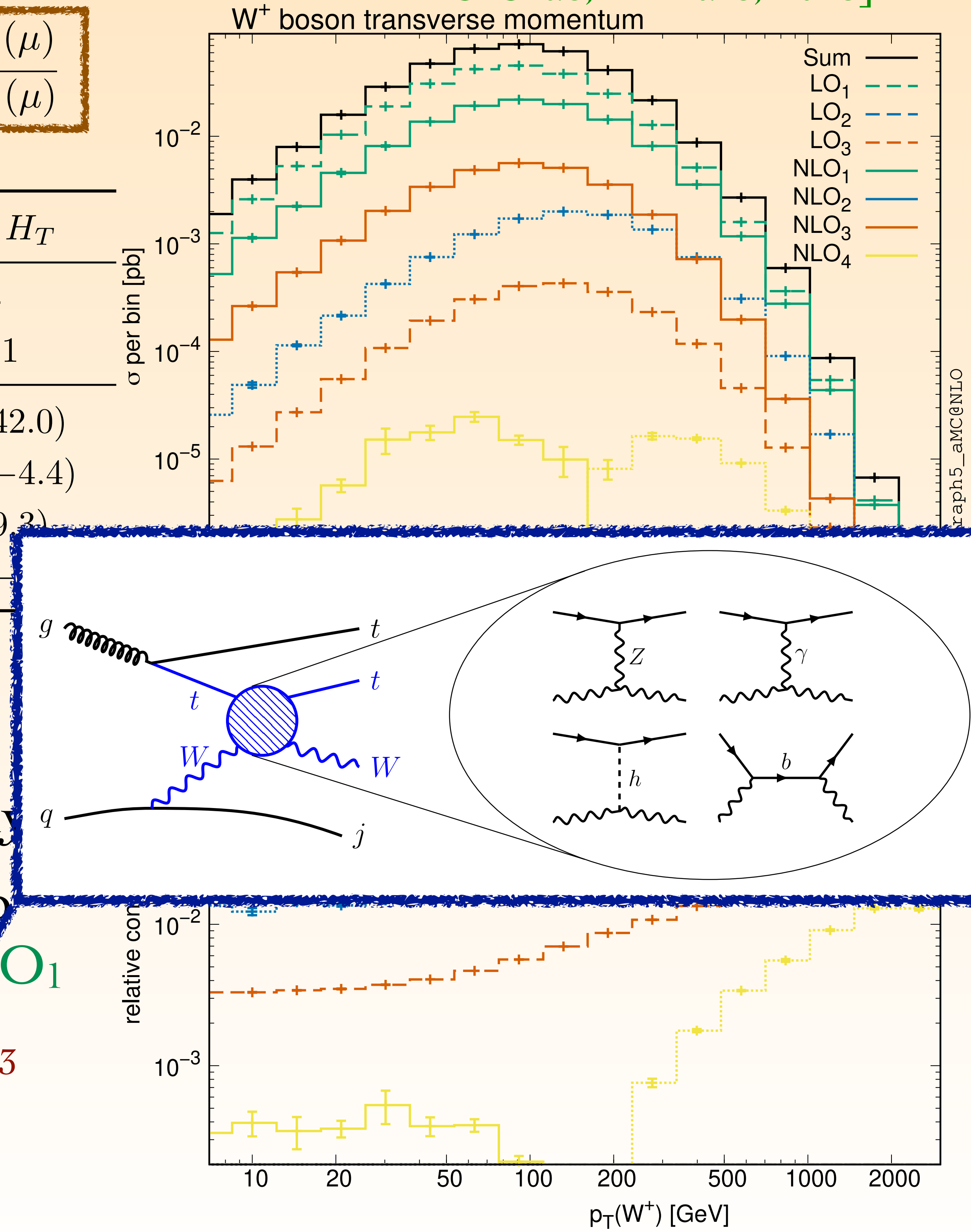

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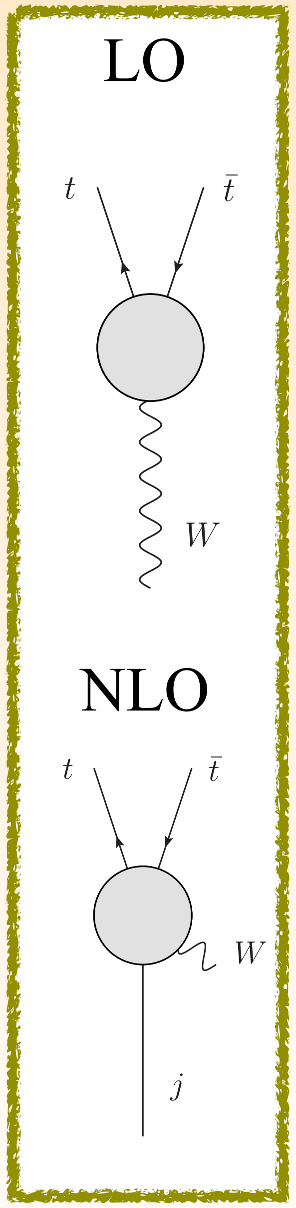
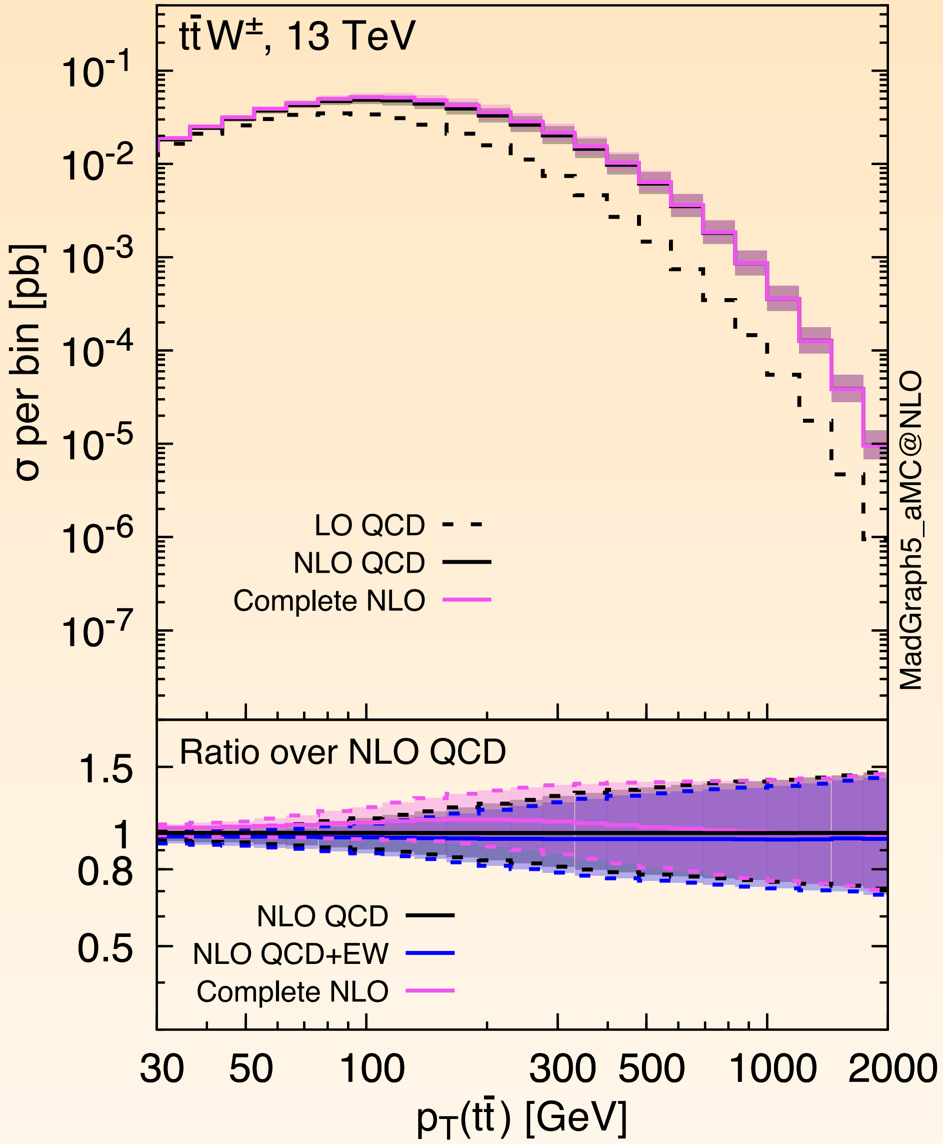
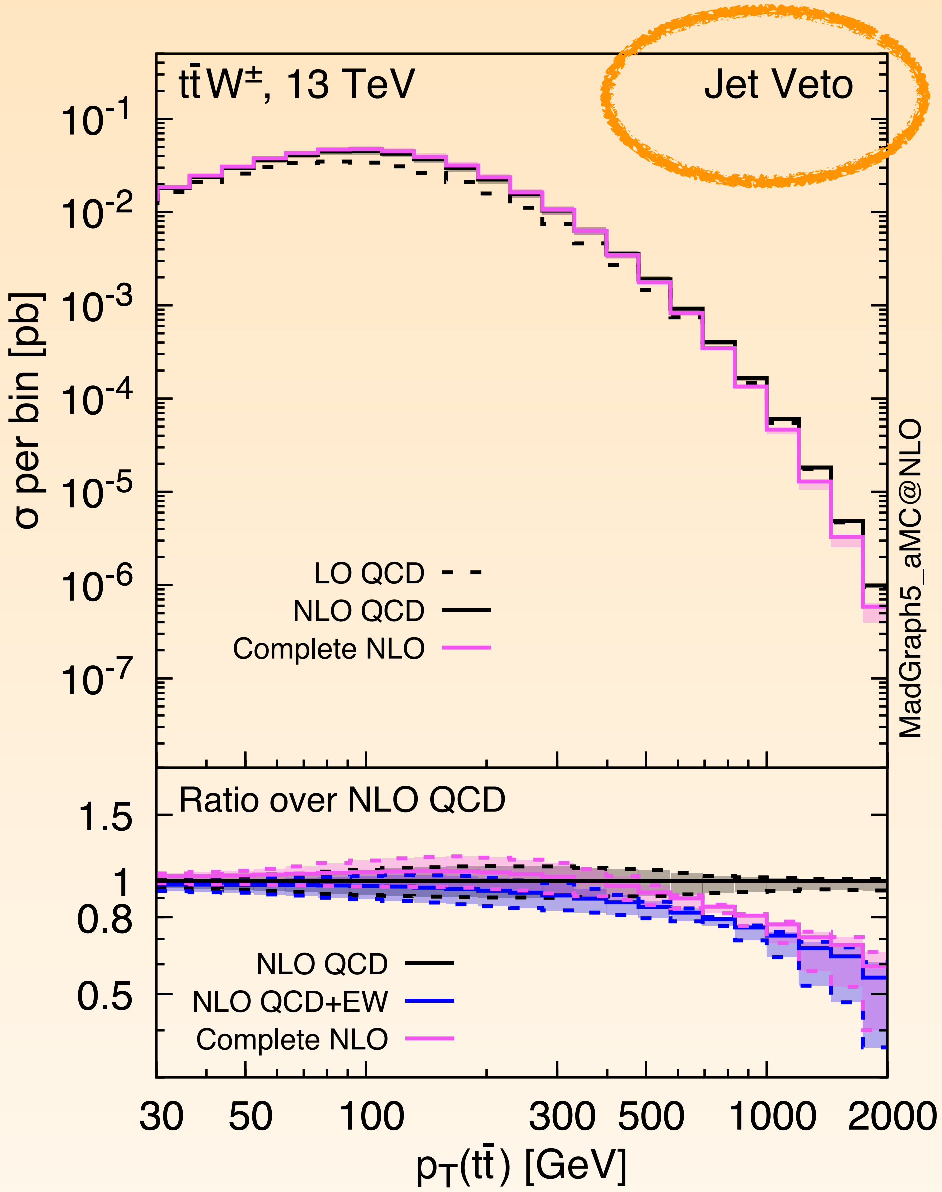




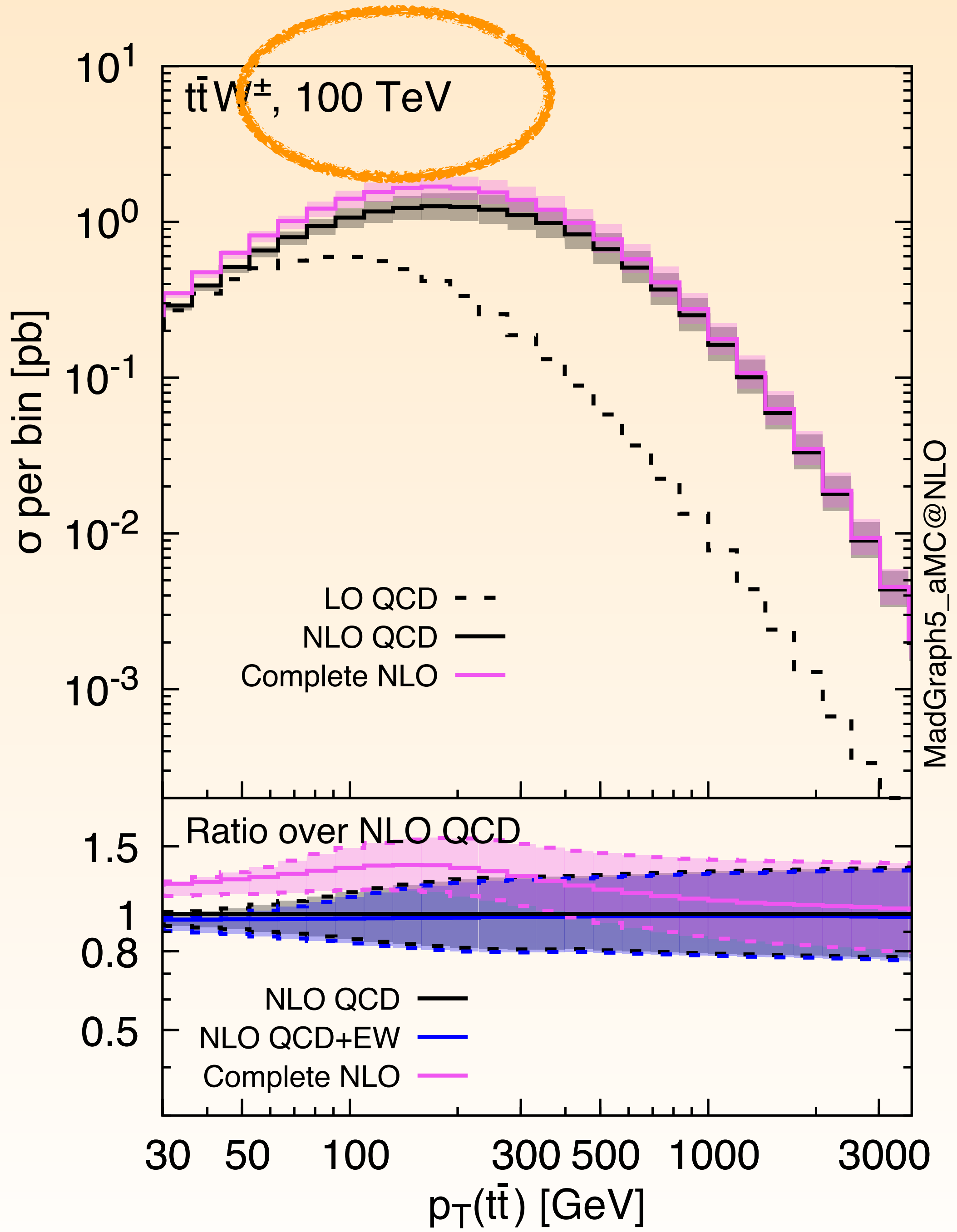


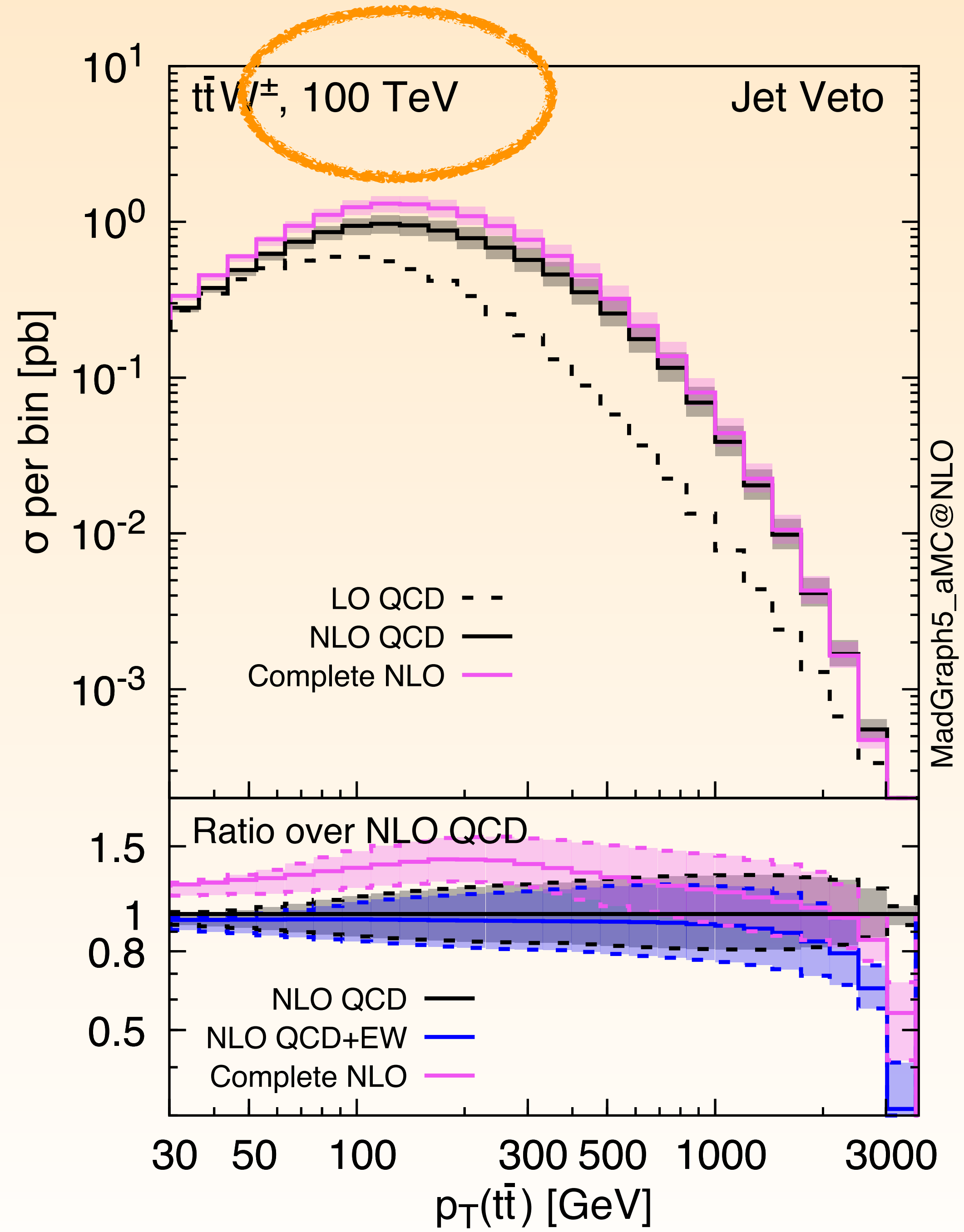
- Large NLO corrections, and large scale dependence without the jet veto
  - ttbar recoiling predominantly against jet (instead of W-boson) at NLO
- EW corrections are large when the results are not dominated by NLO_1
- Subleading corrections (NLO_3) are larger than expected, but uncertainty bands overlap

Complete-NLO ttbar+W

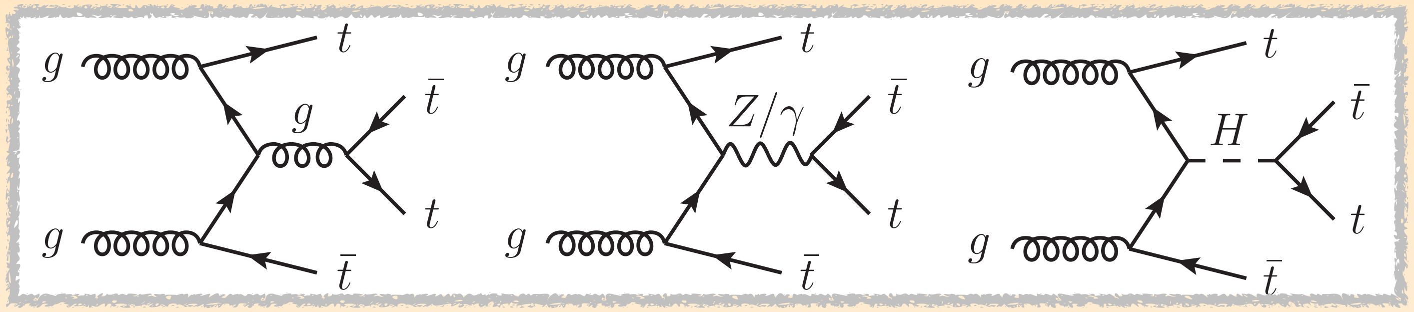
[RF, Pagani, Zaro, 2017]

✦ Effects much more extreme at 100 TeV!





Four-top production and Top Yukawa coupling



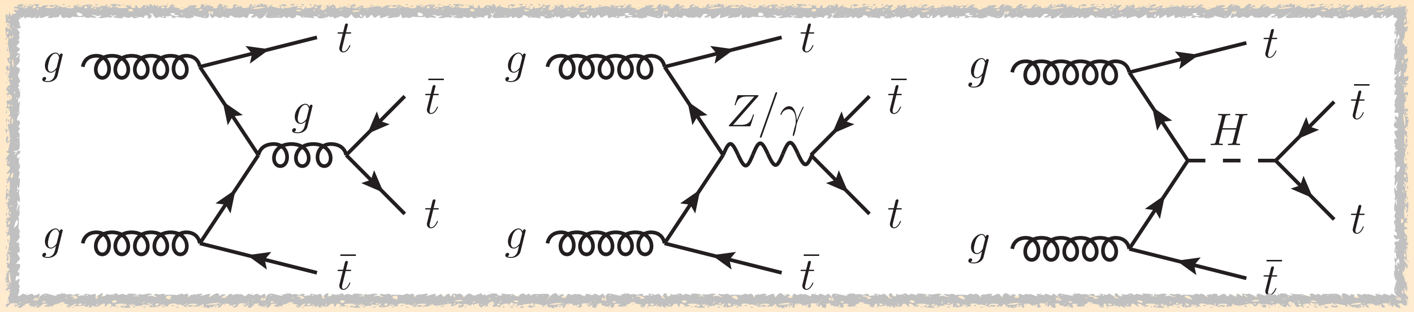
$$\sigma^{\rm SM}(t\bar{t}t\bar{t})_{g+Z/\gamma} \propto \left|\mathcal{M}_g + \mathcal{M}_{Z/\gamma}\right|^2,$$
$$\sigma^{\rm SM}(t\bar{t}t\bar{t})_{H} \propto \left|\mathcal{M}_H\right|^2,$$
$$\sigma^{\rm SM}(t\bar{t}t\bar{t})_{\rm int} \propto \mathcal{M}_{g+Z/\gamma}\mathcal{M}_H^\dagger + \mathcal{M}_{g+Z/\gamma}^\dagger\mathcal{M}_H$$

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

- Four-top production can be used together with ttH to constrain/measure a **anomalous top Yukawa coupling**
  - 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,
$\sigma^{\rm SM}(t\bar{t}t\bar{t})_{\rm int}$:	−0.229 fb,	−2.060 fb.

Four-top production and Top Yukawa coupling



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

	8 TeV	14 TeV
$\sigma^{\rm SM}(t\bar{t}t\bar{t})_{g+Z/\gamma}$:	1.193 fb,	12.390 fb,
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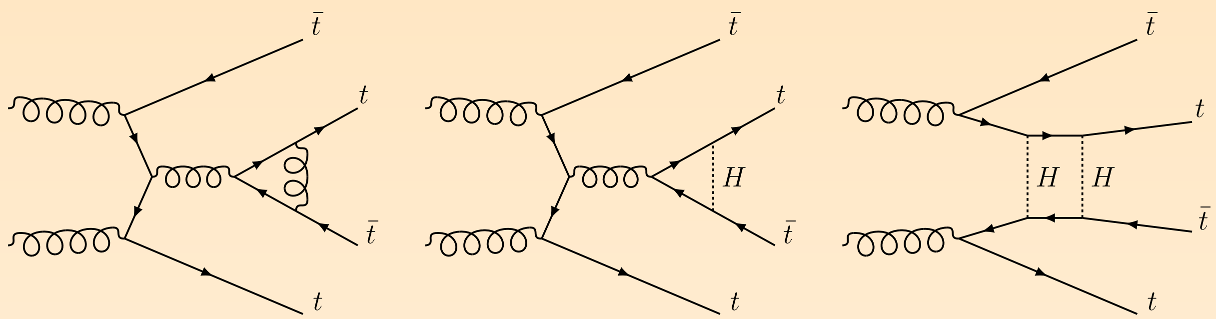
NLO KAPPA FRAMEWORK...?



- 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 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 ←	0.1%
NLO_3	-3.9	1.7	8.9 ←	0.01%
NLO_4	0.7	0.9	1.2	0.001%
NLO_5	0.12	0.14	0.16	0.0001%
NLO_6	< 0.01	< 0.01	< 0.01	0.00001%
$NLO_2 + NLO_3$	-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]

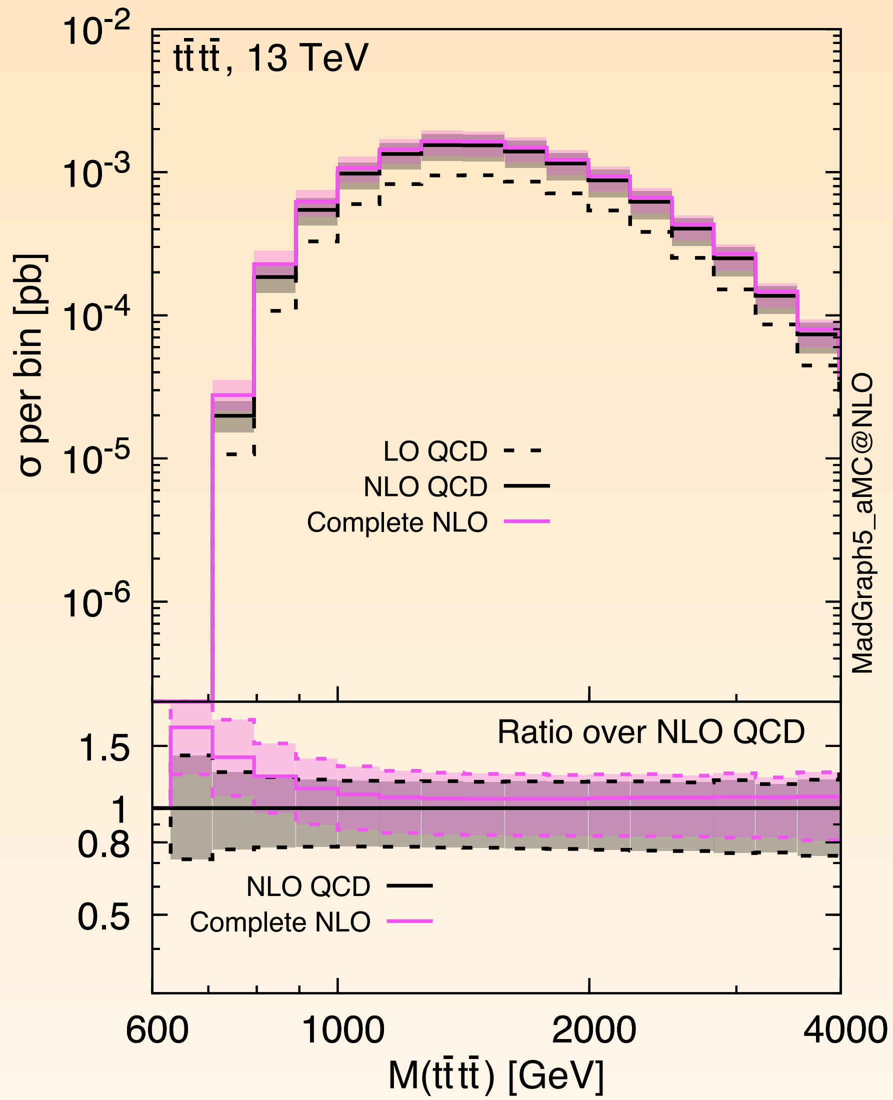
- ✦ LO_2 and LO_3 have large cancelations
- ✦ NLO_2 and NLO_3 mainly given by QCD corrections on top of them
  - large and strongly dependent on the scale choice
- ✦ However, the sum of NLO_2+NLO_3 very stable and small
- ✦ Different scale choices have even more extreme cancelations between NLO_2 and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

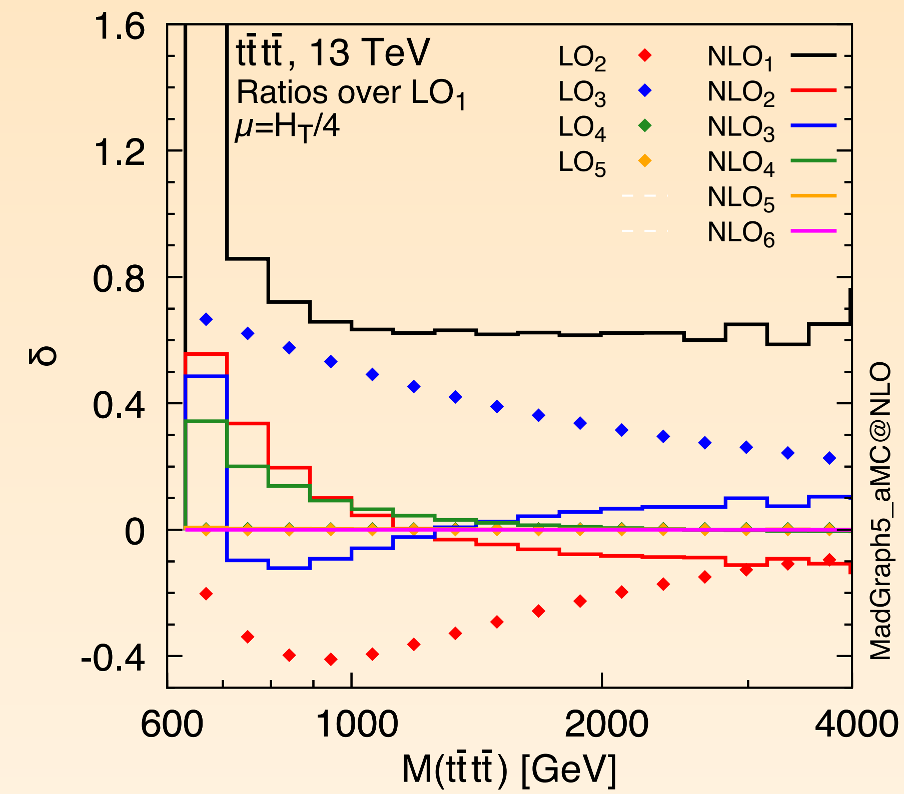
$\delta[\%]$	$\mu = H_T/8$	$\mu = H_T/4$	$\mu = H_T/2$	Naive expectation
LO_2	-18.7	-20.7	-22.8	10%
LO_3	26.3	31.8	37.8 ←	1%
LO_4	0.05	0.07	0.09	0.1%
LO_5	0.03	0.05	0.08	0.01%
NLO_1	33.9	68.2	98.0	10%
NLO_2	-0.3	-5.7	-11.6 ←	0.1%
NLO_3	-3.9	1.7	8.9 ←	0.01%
NLO_4	0.7	0.9	1.2	0.001%
NLO_5	0.12	0.14	0.16	0.0001%
NLO_6	< 0.01	< 0.01	< 0.01	0.00001%
$NLO_2 + NLO_3$	-4.2	-4.0	2.7	

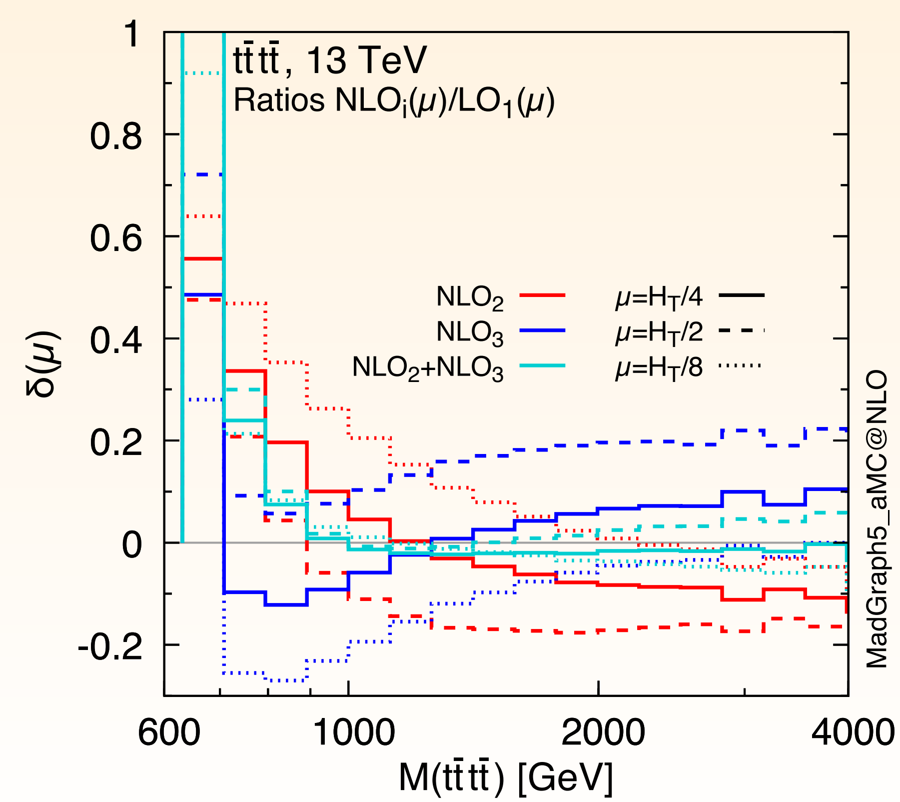
- ✦ LO_4, $(N)LO_5$ and NLO_6 only qqbar initial state. Hence, very small

FOUR-TOP INVARIANT MASS

[RF, Pagani, Zaro, 2017]



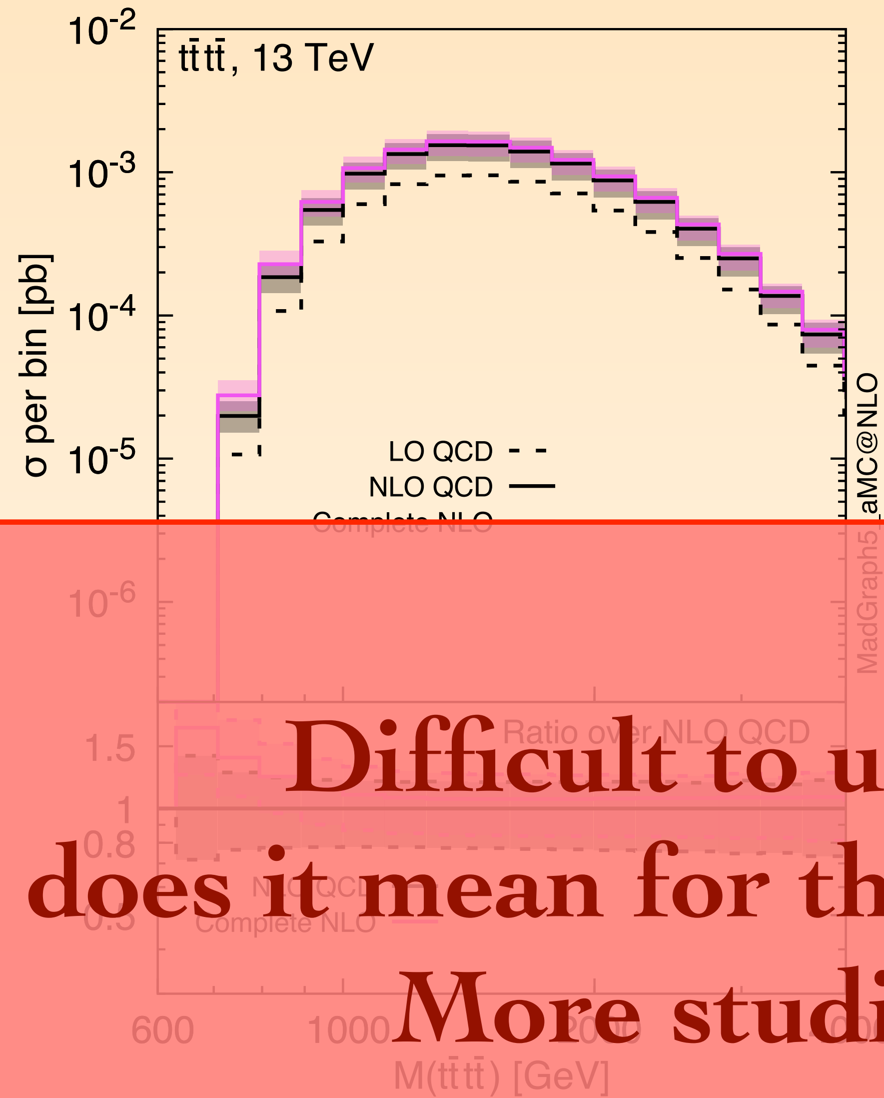


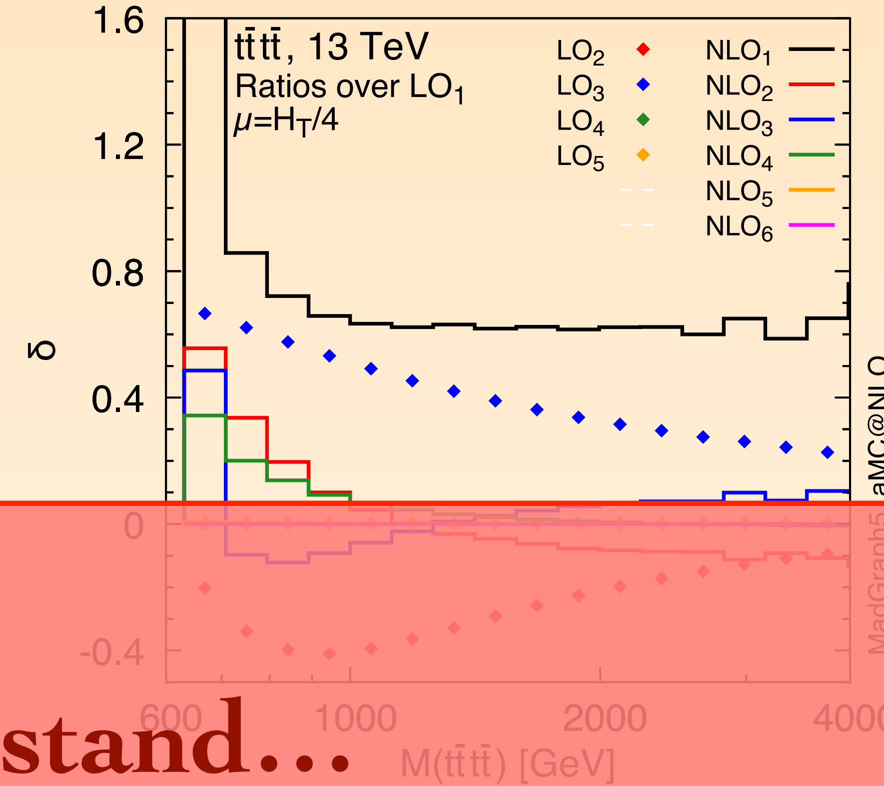


- ✦ Large cancelations between NLO_2 and NLO_3 also at the differential level
- ✦ NLO_4 large at threshold

FOUR-TOP INVARIANT MASS

[RF, Pagani, Zaro, 2017]

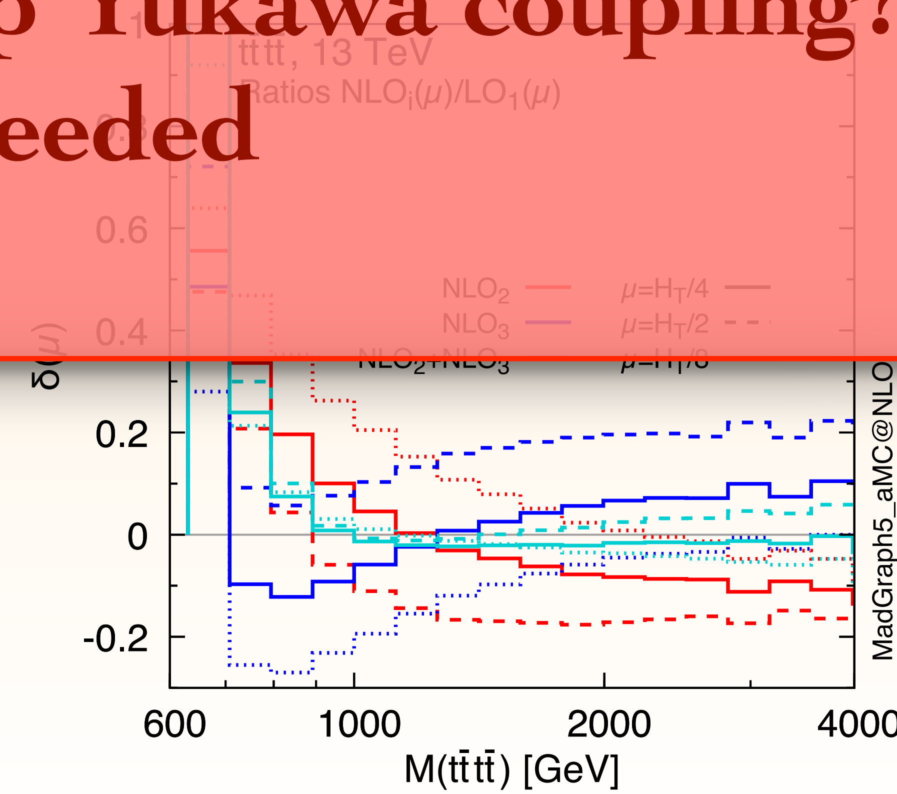




Difficult to understand…

What does it mean for the top Yukawa coupling?

More studies needed

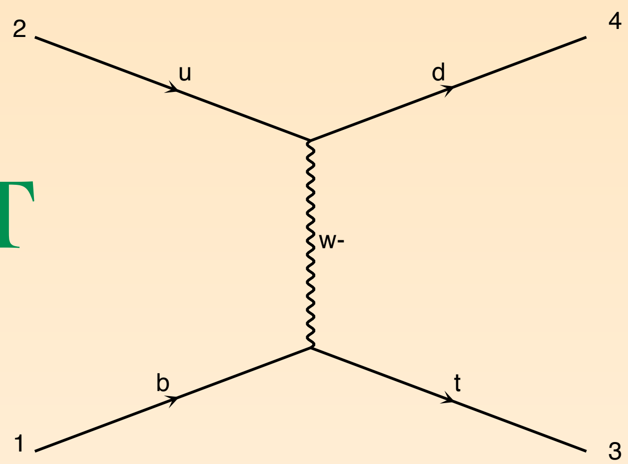


- ✦ Large cancelations between NLO$_2$ and NLO$_3$ also at the differential level
- ✦ NLO$_4$ large at threshold

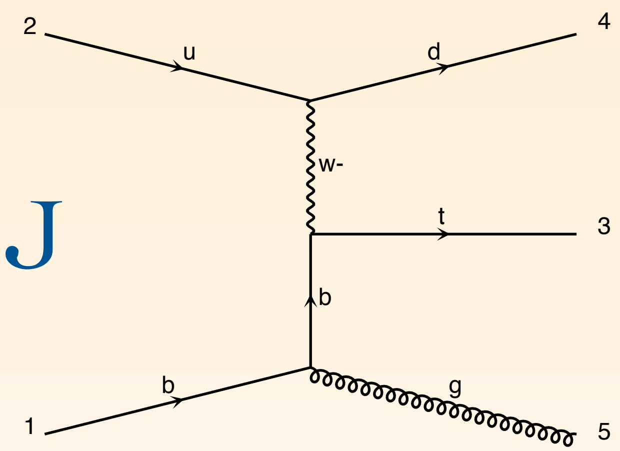
Single top MINLO

[Carazza, RF, Hamilton, Zanderighi (to appear)]

ST



STJ

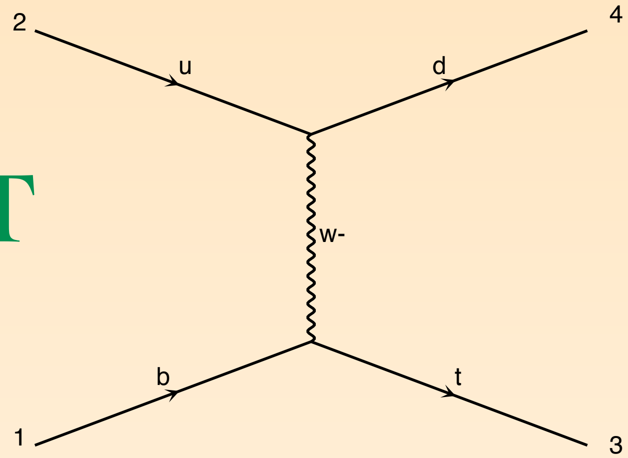


- t-channel single top MiNLO' merging, within POWHEG framework
- Start from NLO STJ, apply MiNLO algorithm to get LO correct in ST
- Use novel Artificial Neural Network techniques to reweight the MiNLO STJ to **NLO** ST for inclusive observables
- Hence:
  - STJ★ NLO correct in both the ST and STJ phase-spaces
  - No merging scale. Negligible merging ambiguities/uncertainties

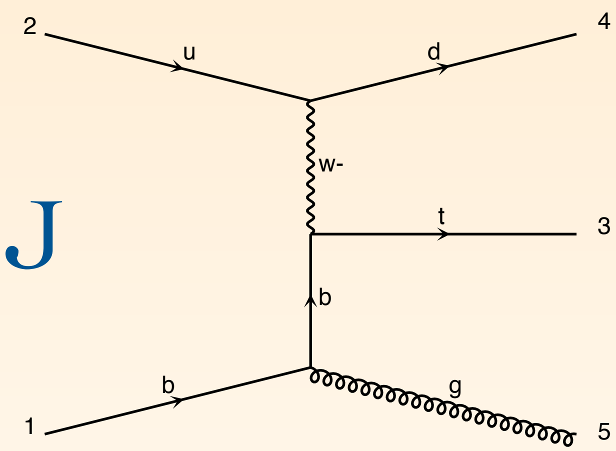
Single top MINLO

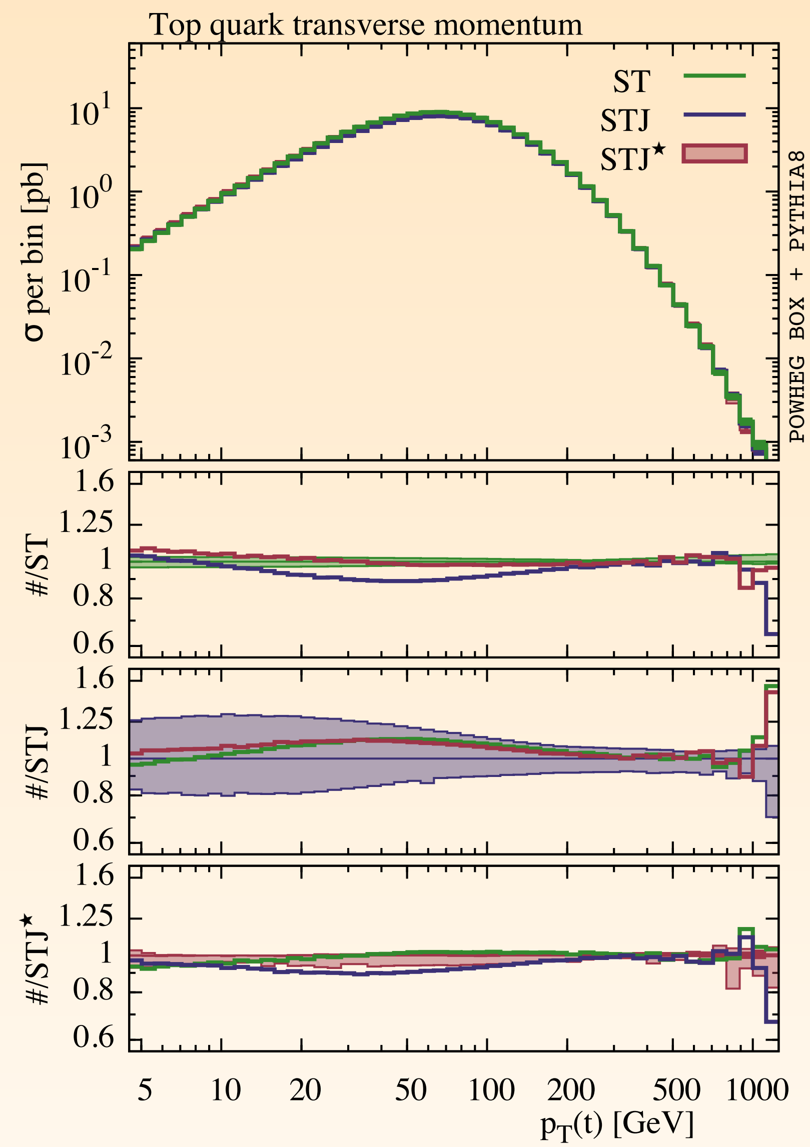
[Carazza, RF, Hamilton, Zanderighi (to appear)]

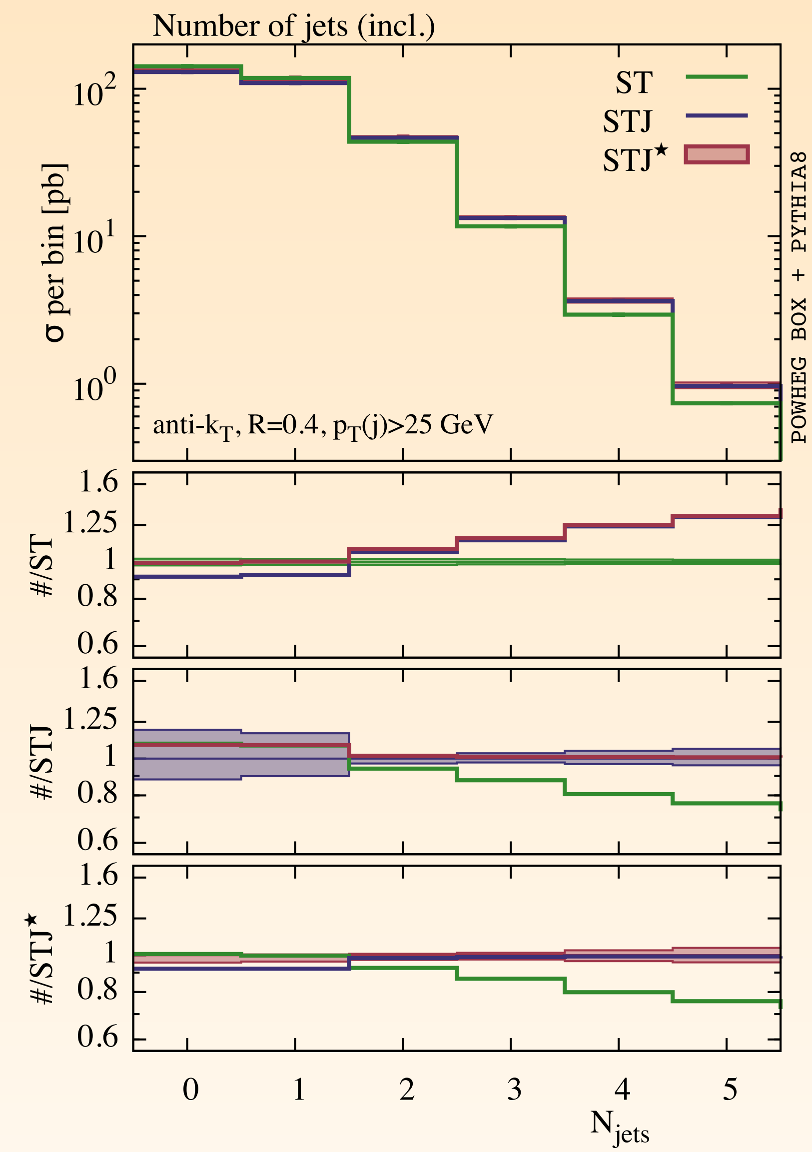
ST



STJ







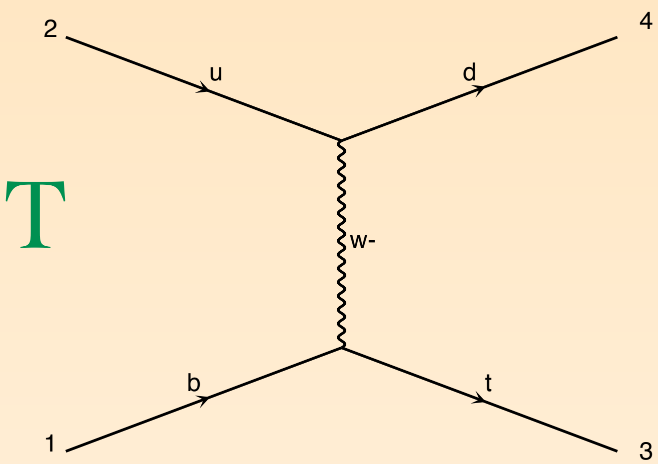
- ✦ STJ★ is NLO correct in both the ST and STJ phase-space
- ✦ Top transverse momentum: ST is NLO, STJ is LO, STJ★ NLO
- ✦ 0,1-jet bins: ST is NLO; 2-jet bin STJ is NLO; STJ★ is NLO in 0,1,2-jet bins

Top is kept stable; no hadronisation/ underlying event

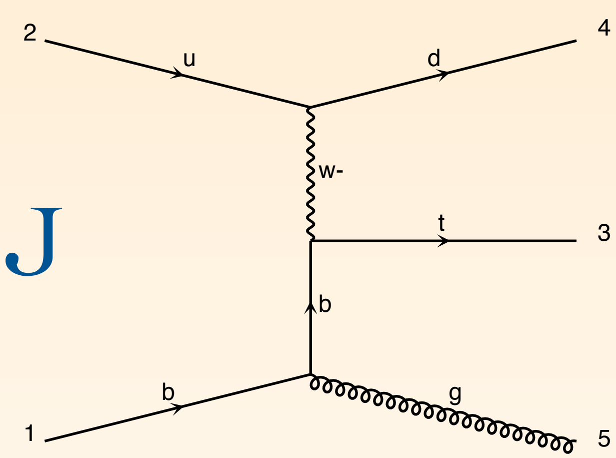
Single top MINLO

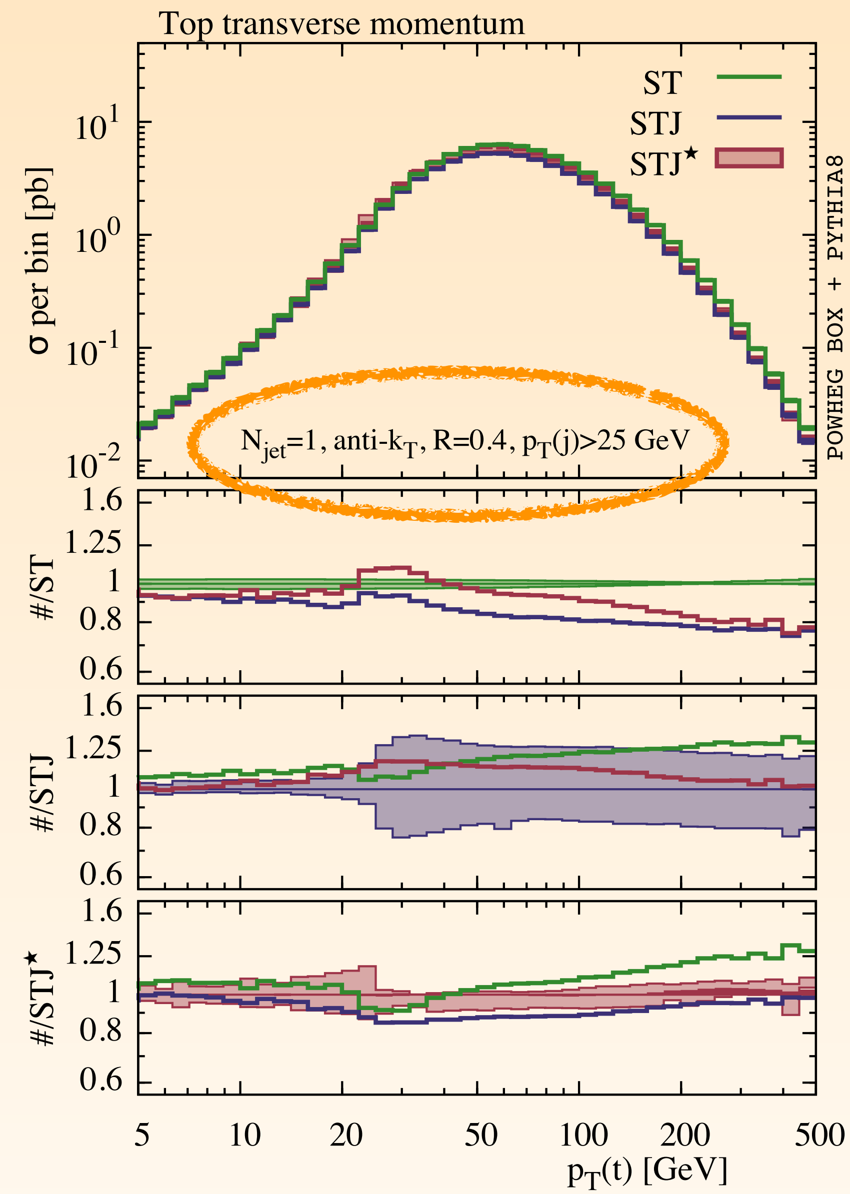
[Carazza, RF, Hamilton, Zanderighi (to appear)]

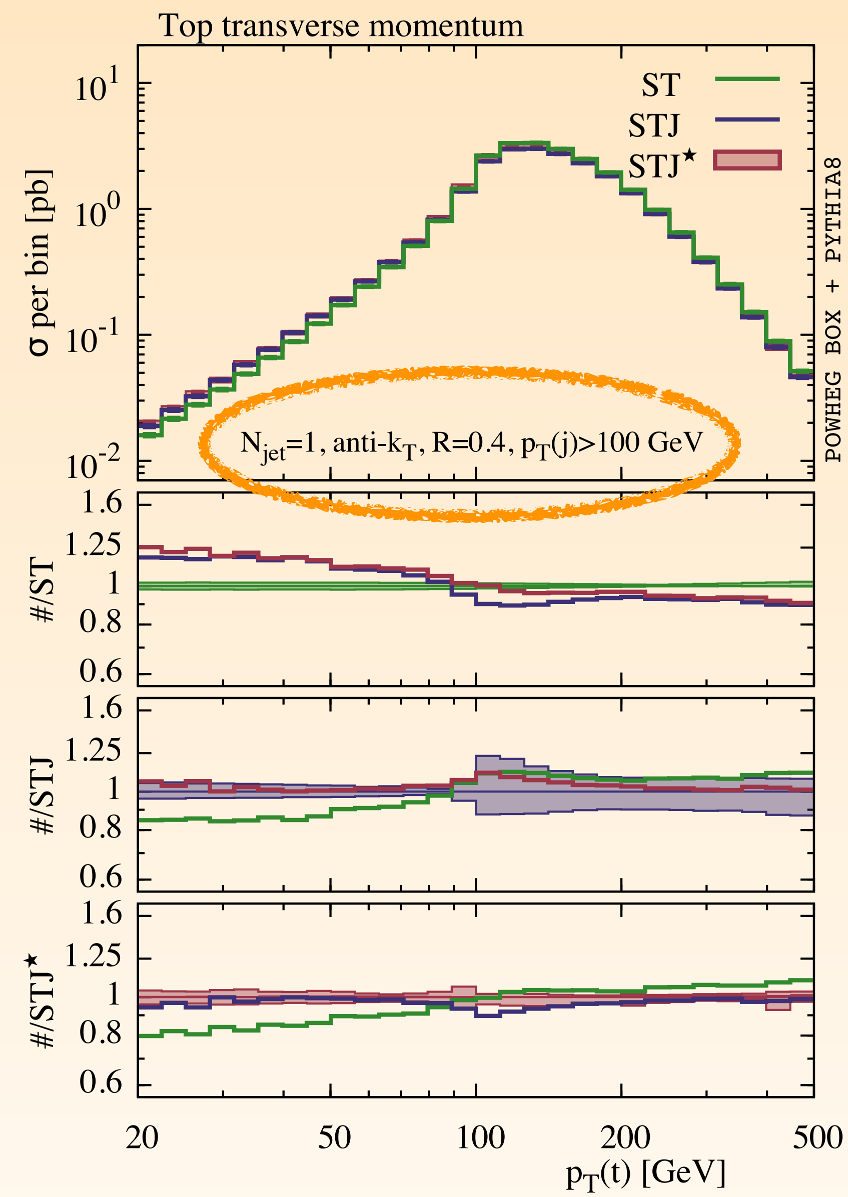
ST



STJ







- STJ★ NLO correct in both the ST and STJ phase-space
- Top quark transverse momentum with jet veto: small p_T STJ is NLO, intermediate p_T ST is NLO, large p_T STJ is NLO (but dominated by Sudakov logs) ⇒ STJ★ is NLO in whole p_T range

Top is kept stable; no hadronisation/ underlying event

Conclusions

- 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
  - Available from public MadGraph5_aMC@NLO v3 (beta)
    - although not yet with matching to a parton shower
- MiNLO' merging for Single-top within POWHEG
  - STJ_R NLO correct in both the ST and STJ phase-space. No merging scale!
  - Allows for inclusion of NNLO corrections as well