Top-quark studies at the HL/HE LHC

Marco Zaro

with material and input from

Matteo Cacciari, Fabrizio Caola, Alexander Mitov, Davide Pagani, Andew Papanastasiou, Emanuele Re, Ioannis Tsinikos…

Disclaimer: Everything is preliminary!

Nikhef

NWO
Netherlands Organisation
for Scientific Research

Top-pair production

Total cross-section

✓ At a 27 TeV HE-LHC the top-pair production cross-section is very large:

σ_{tot} [27 TEV, m_{top}=173.3 GeV] = 3727 $^{+\,119\,(3.2\%)}_{-\,179\,(4.8\%)}$ [pb]   (in NNLO QCD)

✓ This is 4x larger than at LHC 14 TeV

✓ Composition of the initial state at 27 TeV:

- ✓ gg = 92% , qqbar = 6% , qg = 2%

✓ Approximately the same composition of the initial state as at 14 TeV:

- ✓ gg = 90% , qqbar = 9% , qg = 1%

Slide by Alex Mitov

Notes on differential production

- ✓ Emphasis will be on kinematic reach for both 14 TeV and 27 TEV

- ✓ At 14 TeV (HL-LHC):

  - ✓ Top quark results for 1-dim and 2-dim distributions
  - ✓ Lepton distributions (within fiducial volume from CMS)
  - ✓ Predictions for LHCb. There is non-trivial overlap with the other experiments – will try to emphasise that.

- ✓ At 27 TeV (HE-LHC):

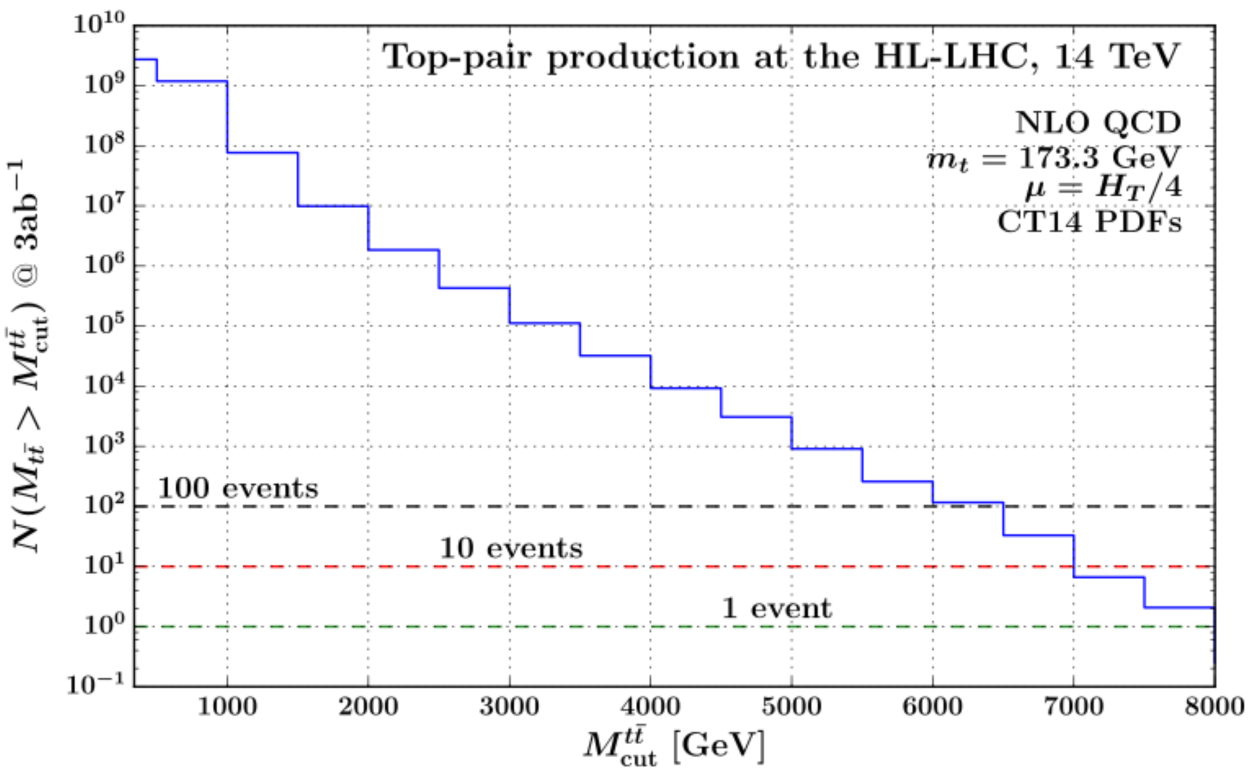
  - ✓ No experimental input.
  - ✓ The interest is in what one can do with top quarks. Therefore, only top-quark distributions will be discussed (no decays)
  - ✓ 1dim and 2-dim distributions shown.

  - ✓ FO-NLL predictions to be compared with fixed order ones.

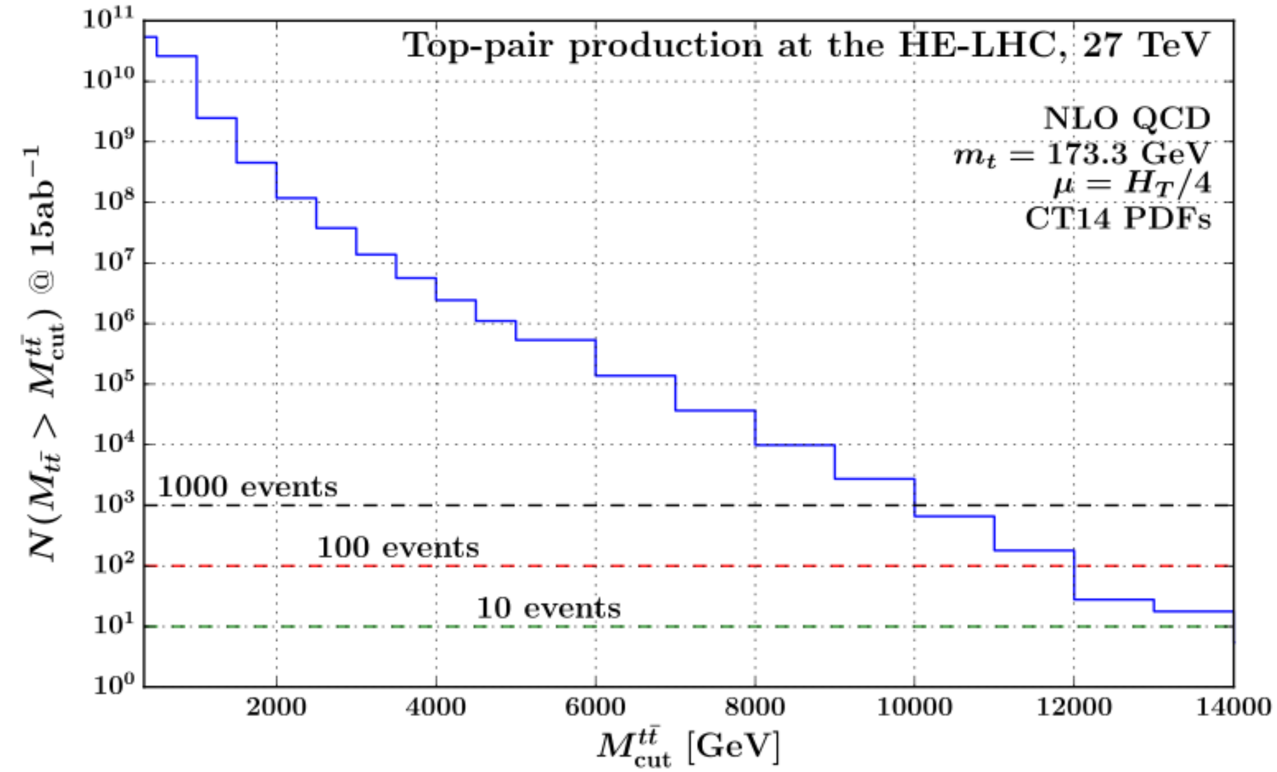
Slide by Alex Mitov

Cumulative in M_{tt}

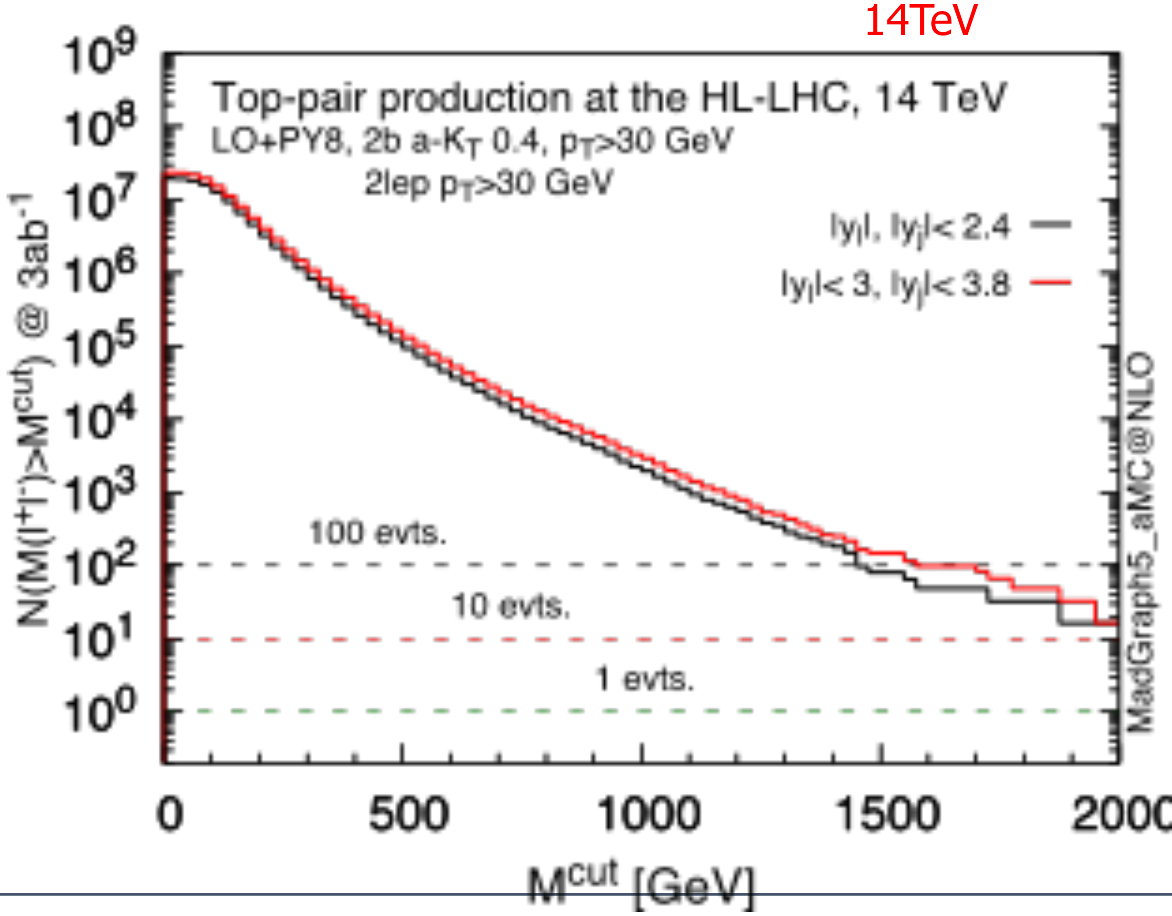
14TeV



27TeV



14TeV



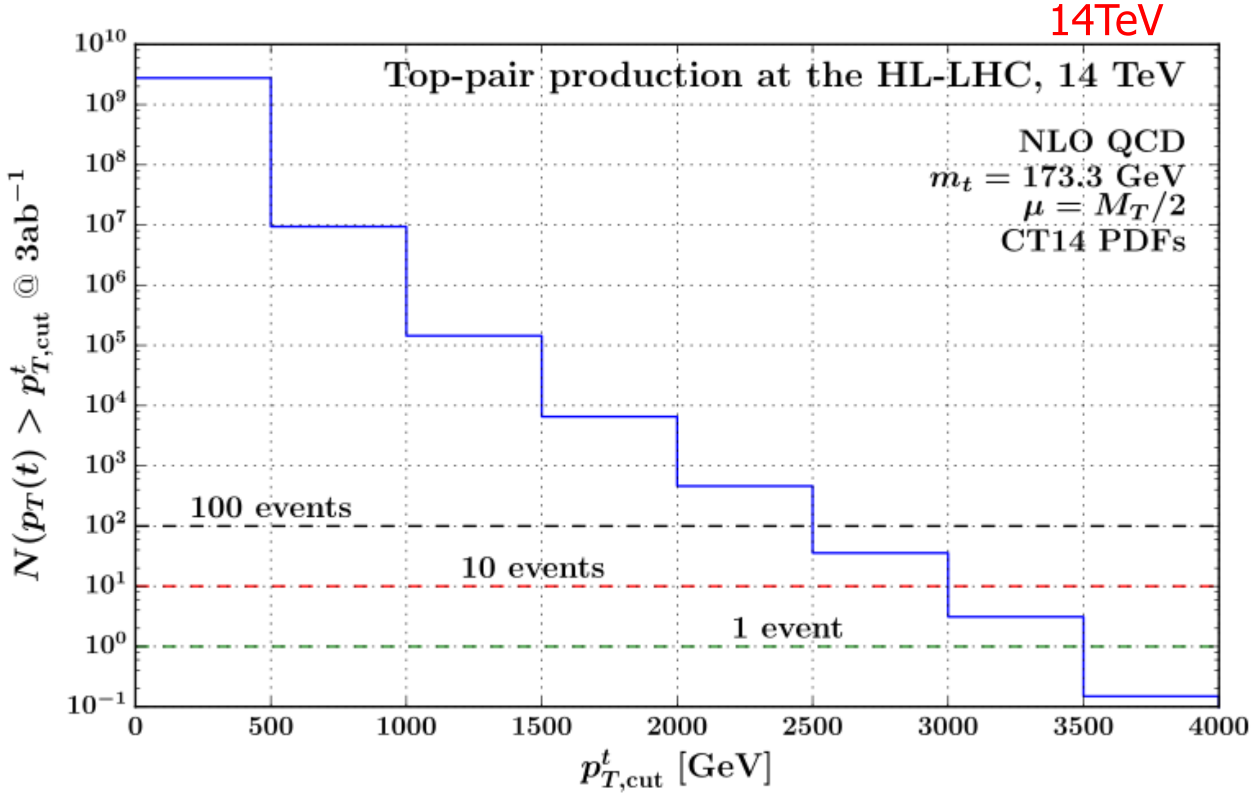
- ✓ All at NLO QCD.
- ✓ Shown is: cumulative times max luminosity

- ✓ For tops: to add EW (and possibly NNLO?)
- ✓ Decay: if feasible, may add some NNLO corrections
- ✓ Assess the advantage of calorimeter upgrade (extended lepton tracking/b-tagging)

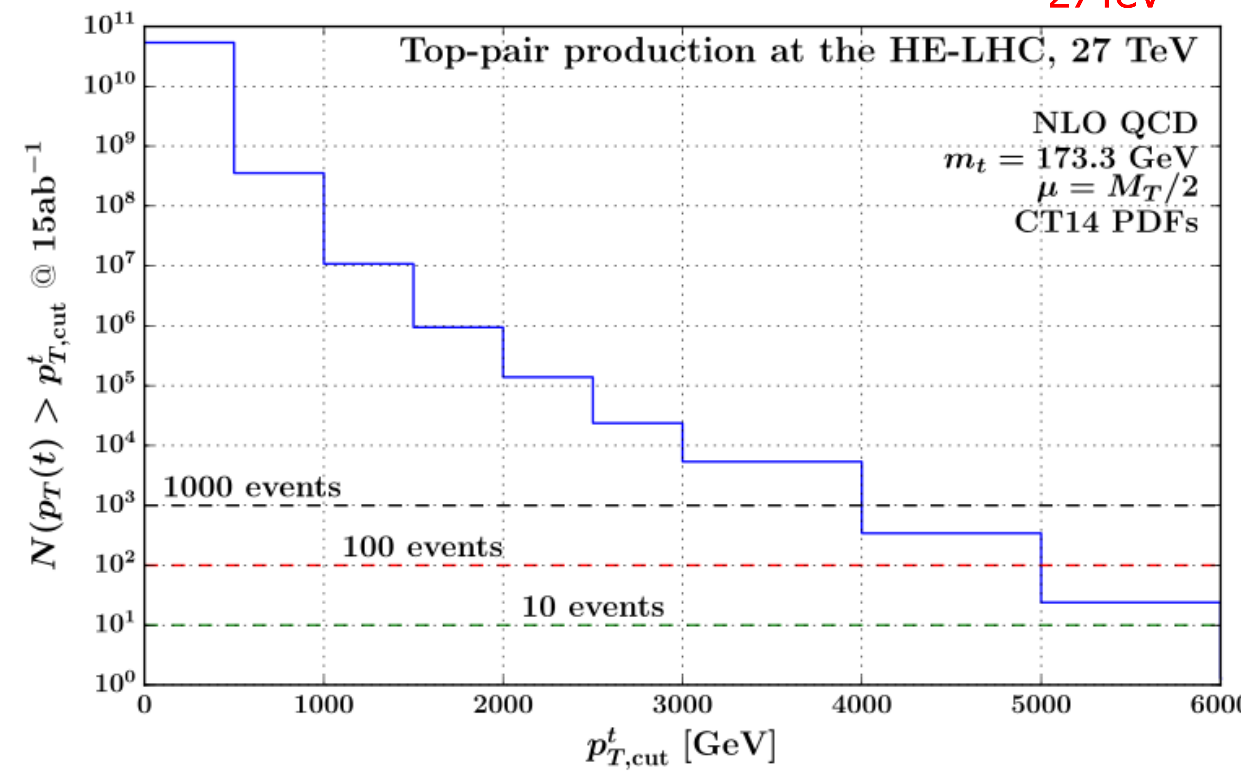
Slide by Alex Mitov

Cumulative in P_T

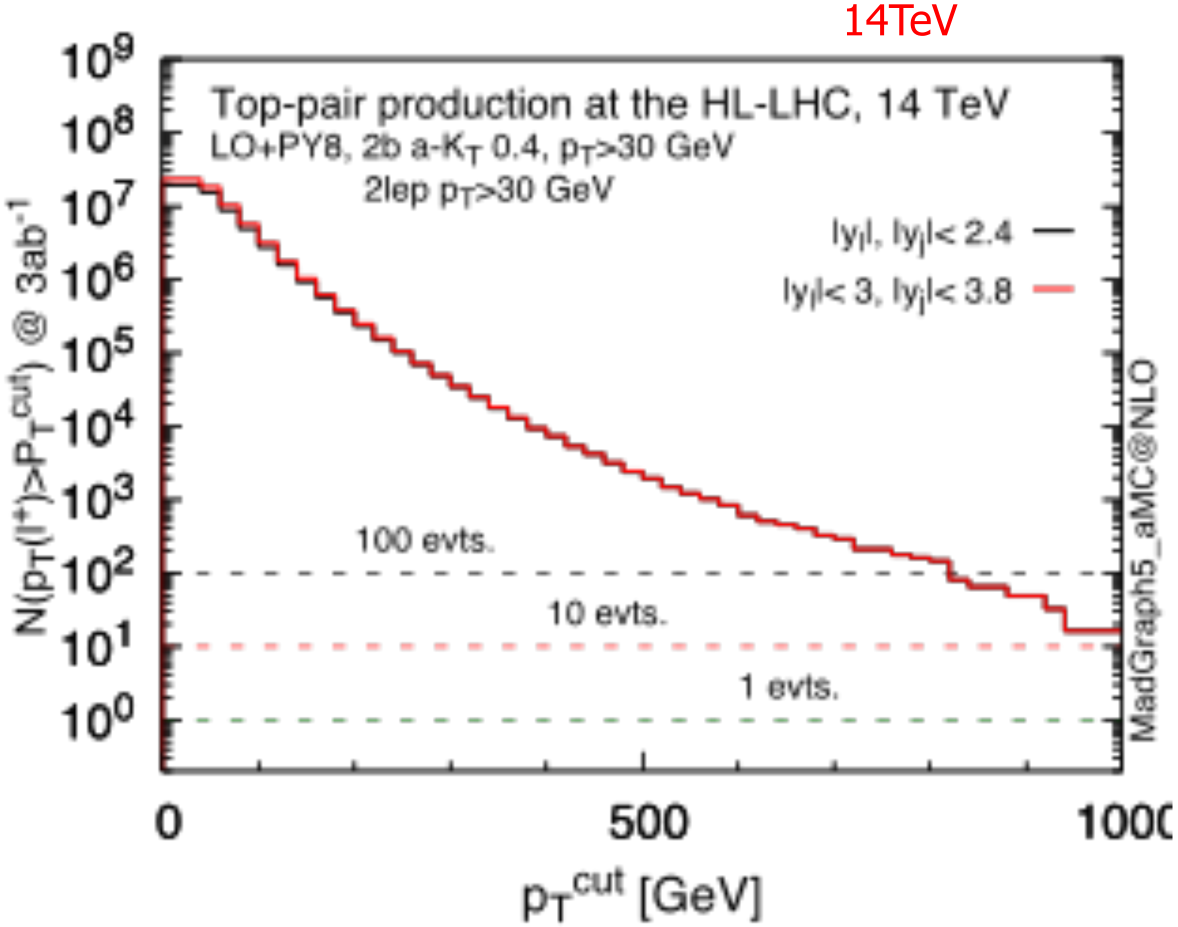
14TeV



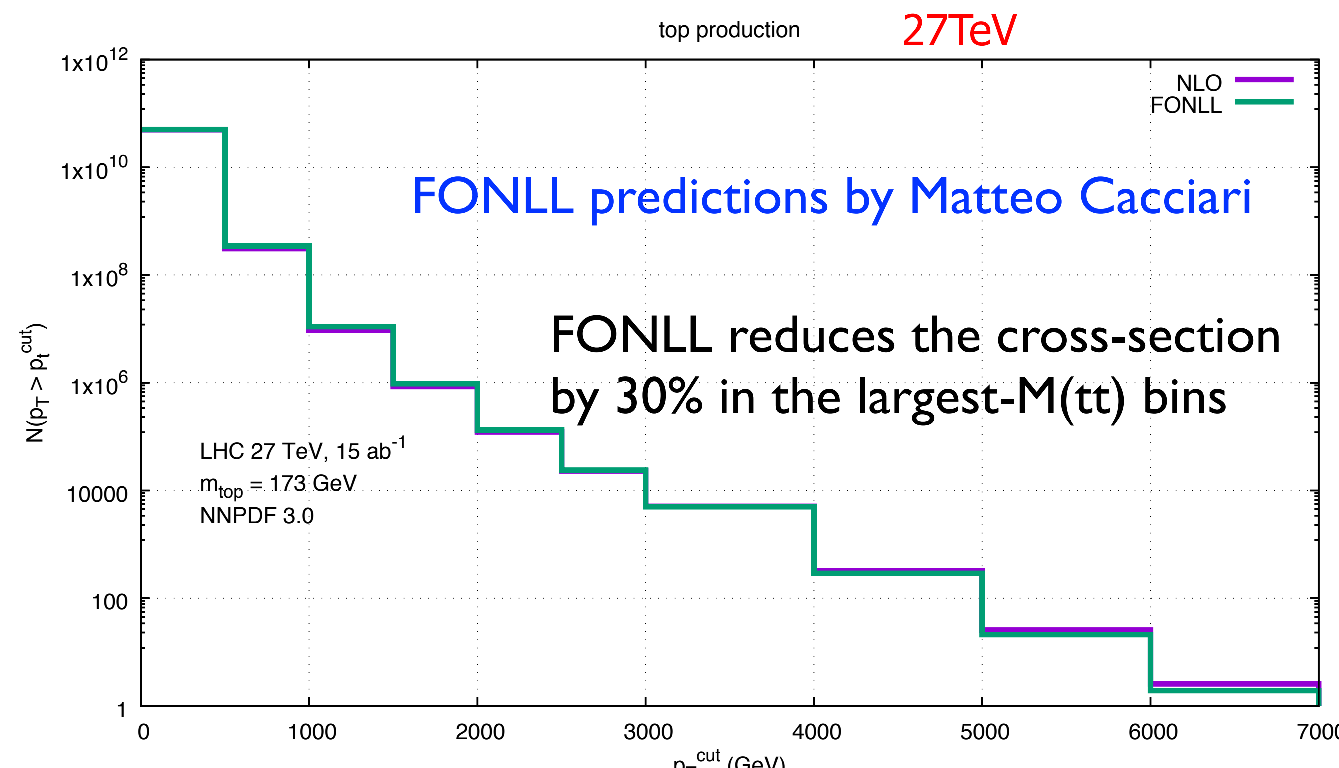
27TeV



14TeV



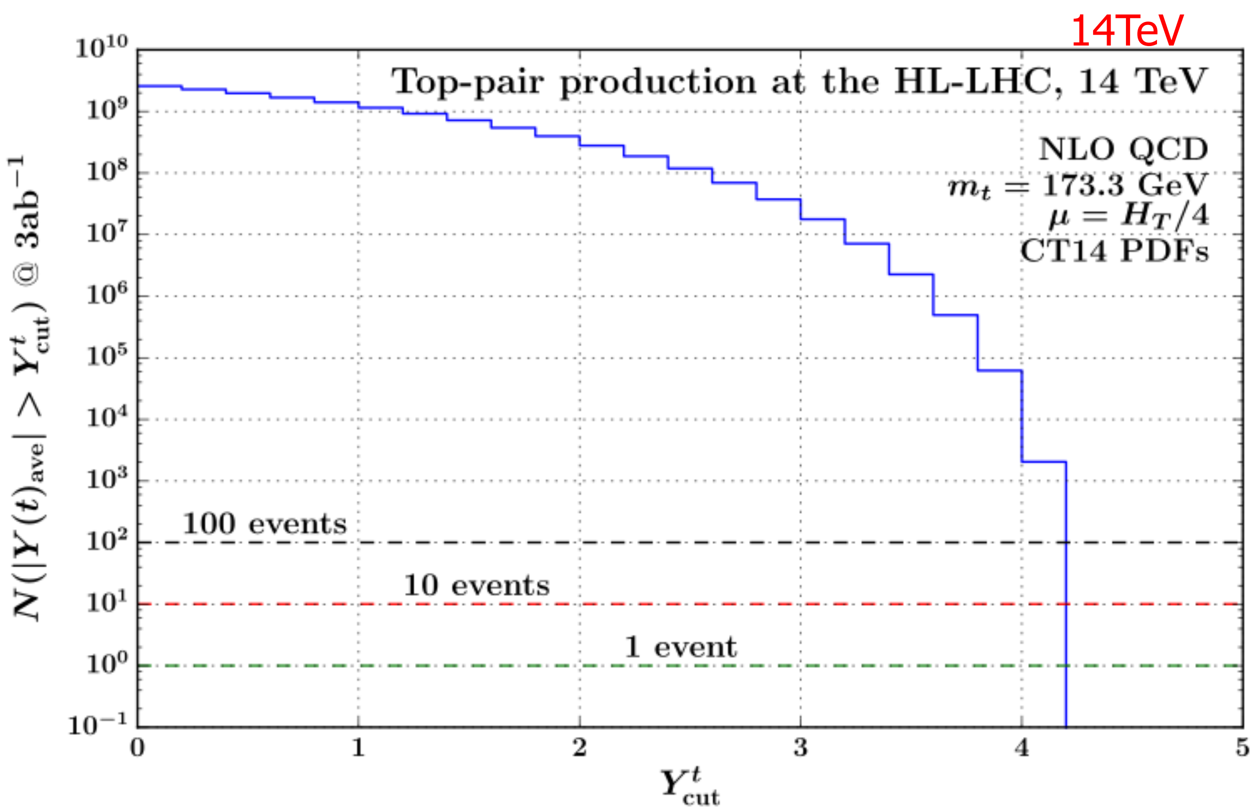
27TeV

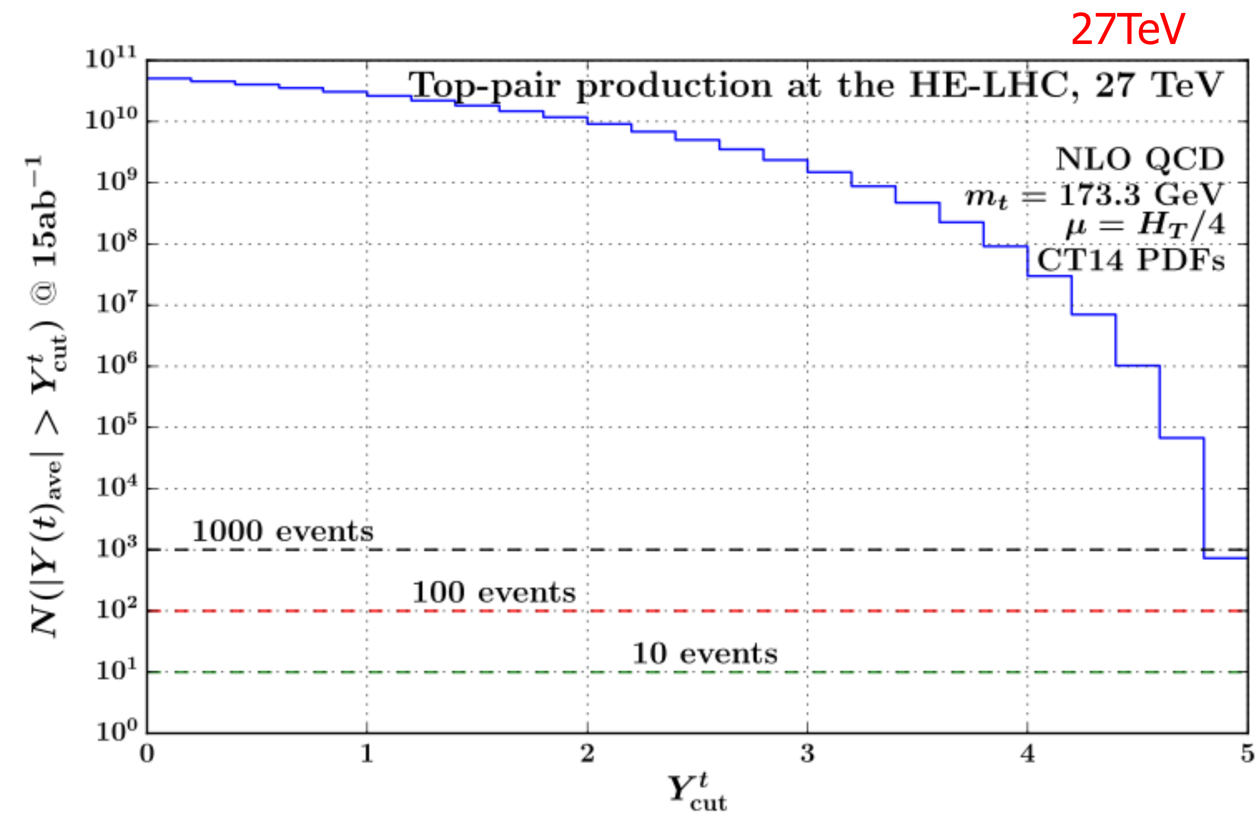


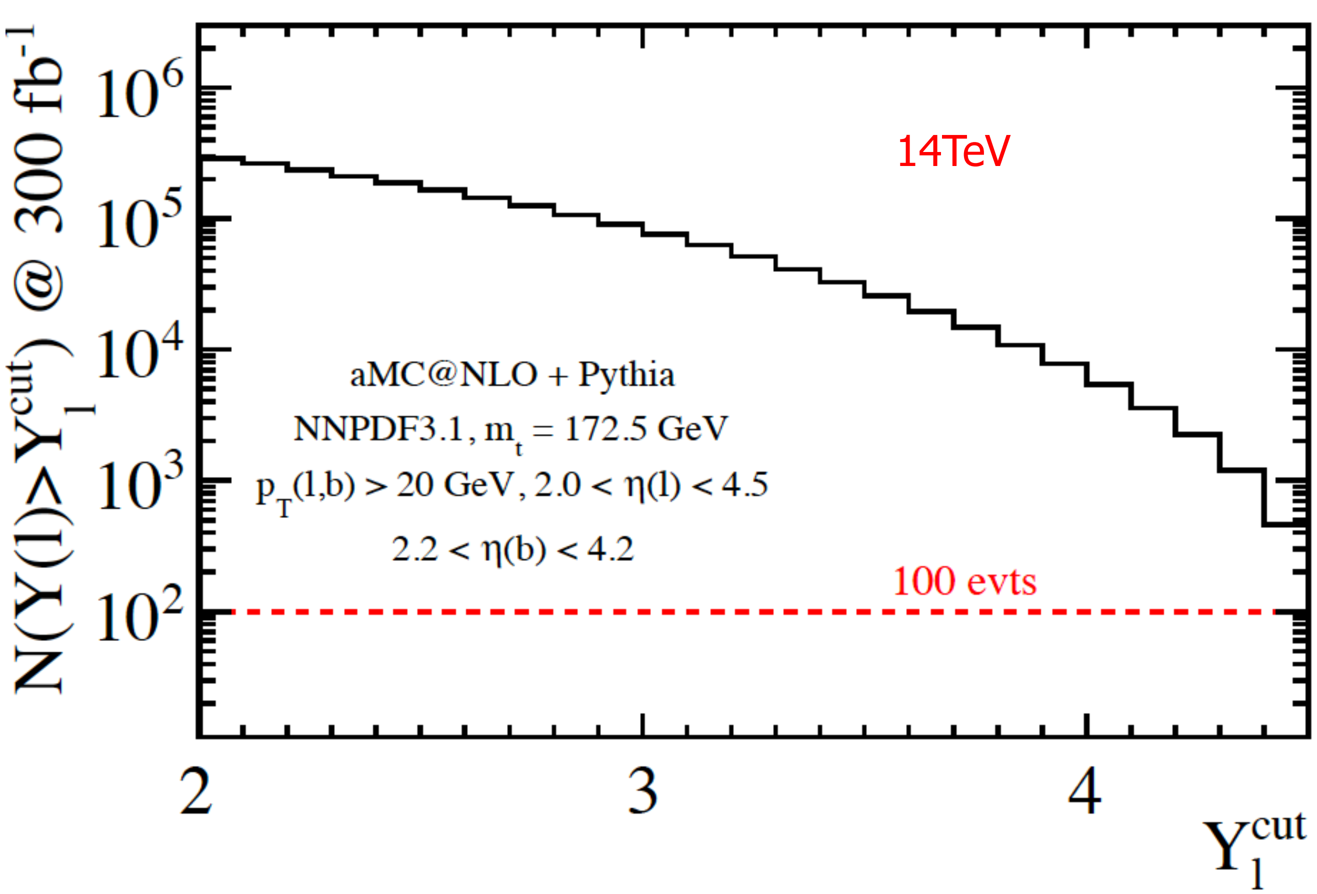
- ✓ For tops: to add EW (and possibly NNLO?)
- ✓ Decay: if feasible, may add some NNLO corrections

Slide by Alex Mitov

Cumulative in Y_t





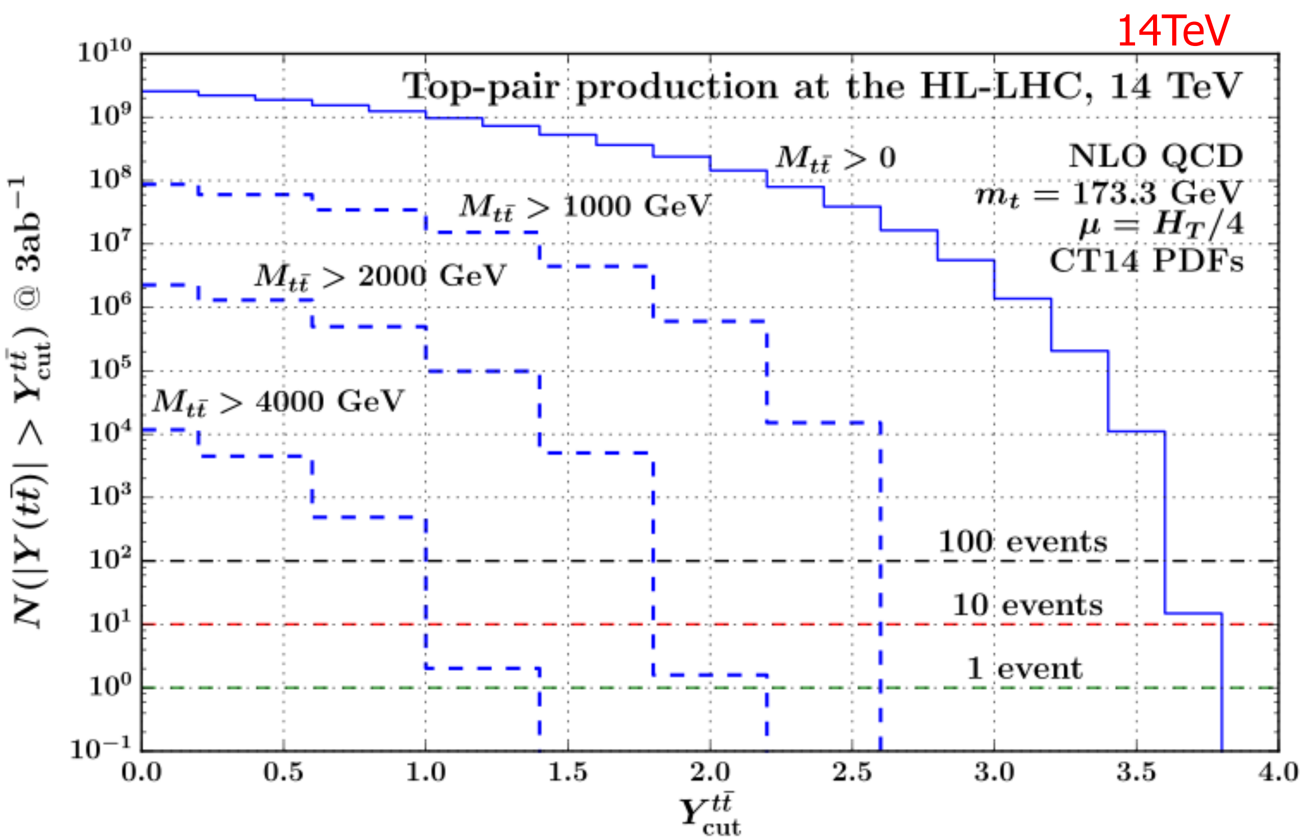


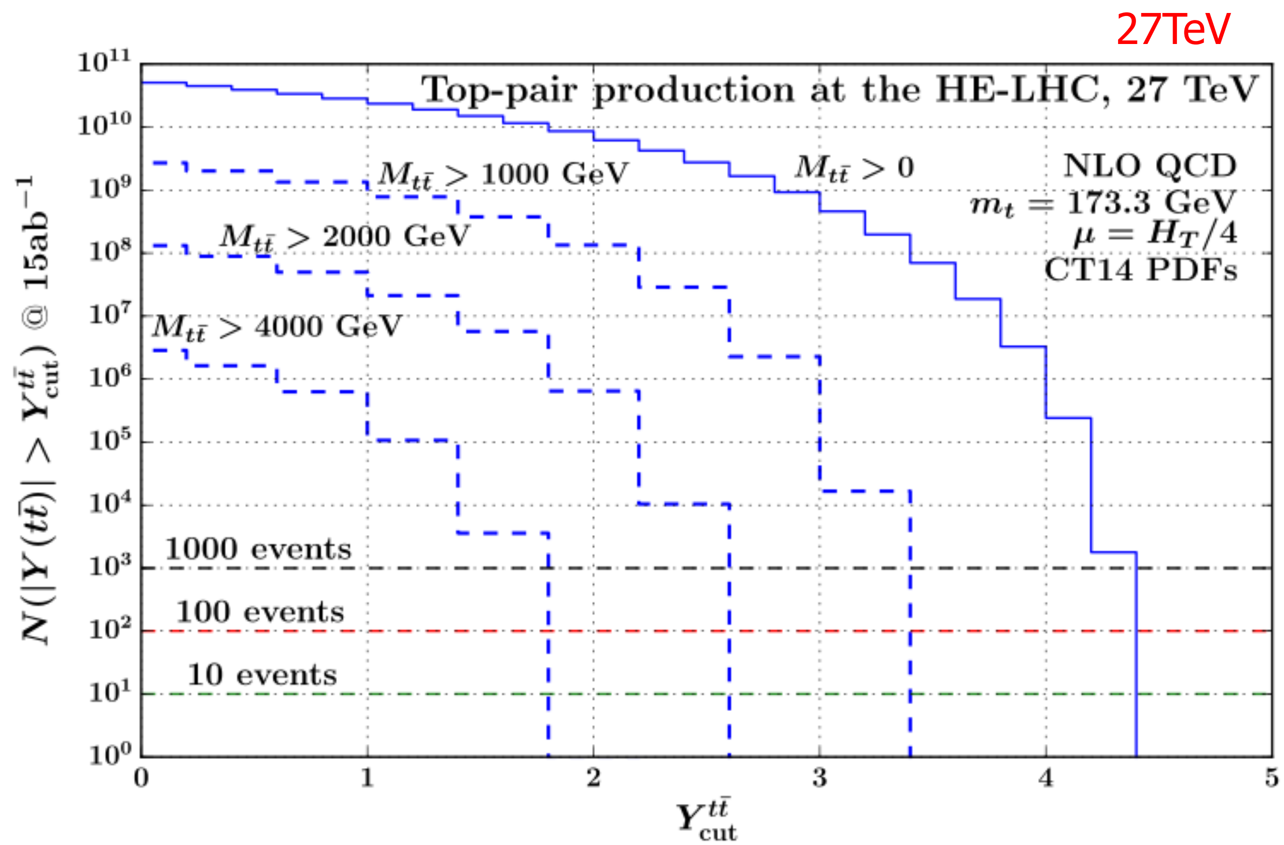
LHCb

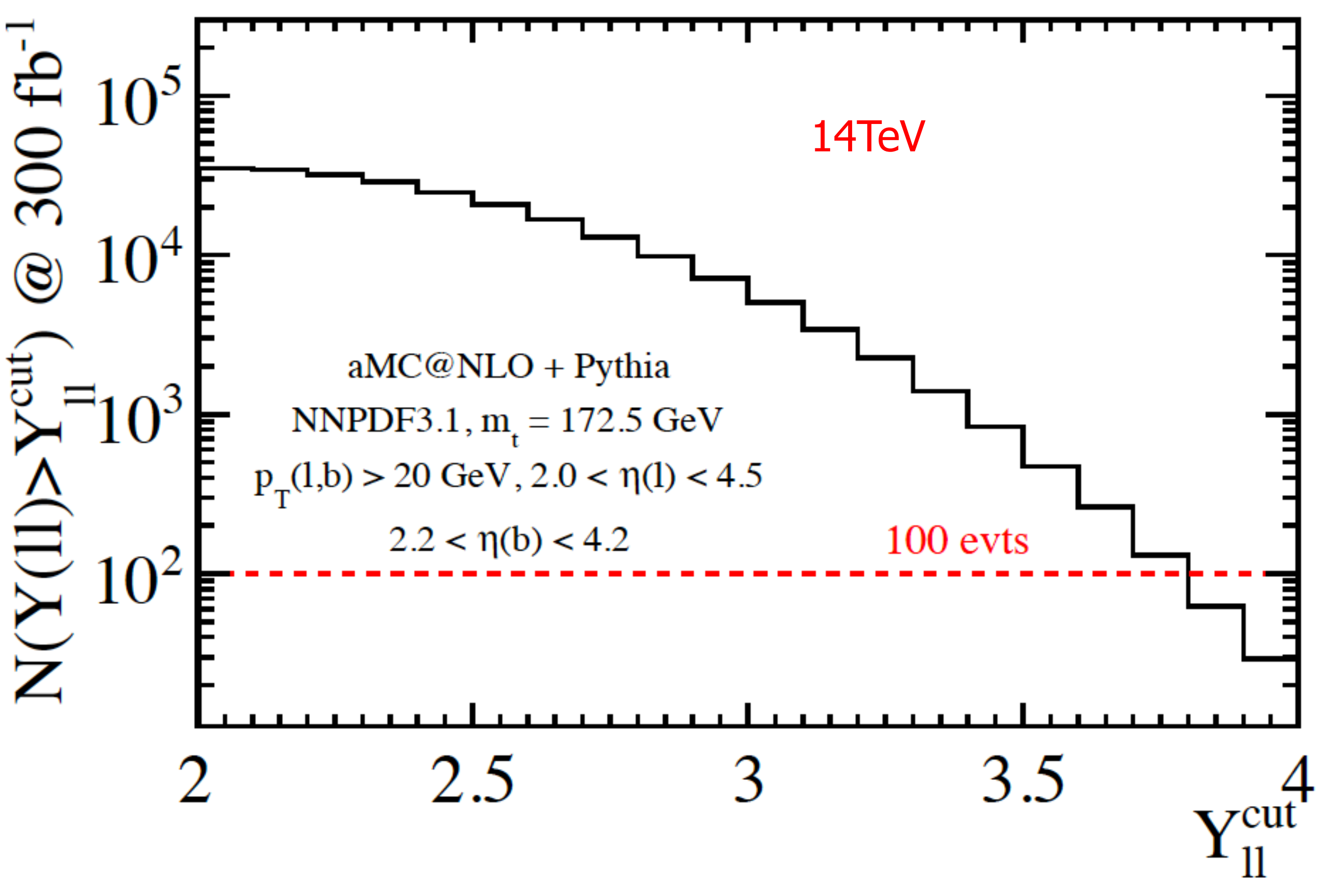
- ✓ For tops: to add EW (and possibly NNLO?)

Slide by Alex Mitov

Cumulative in Y_{tt} (both 1d and 2d for extracting PDFs)







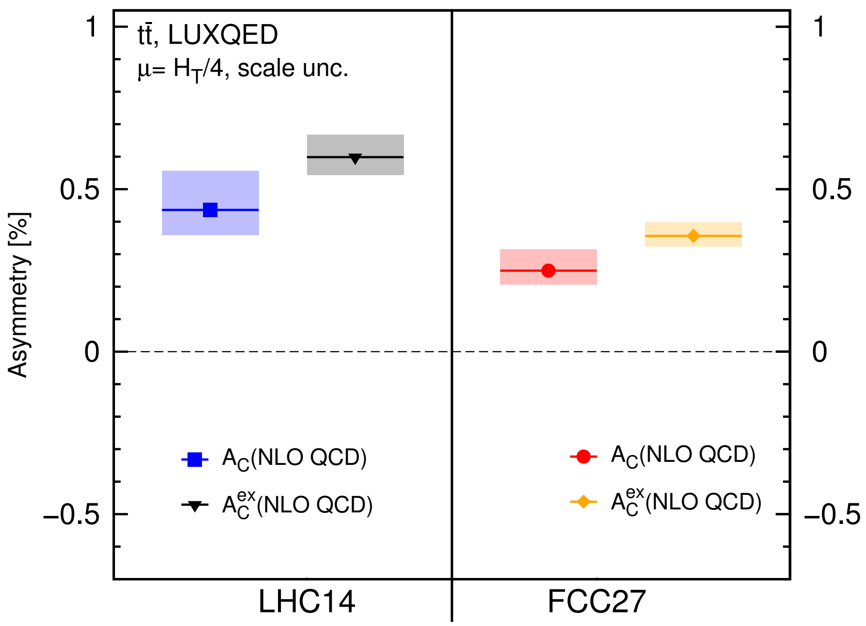
- ✓ For tops: to add EW (and possibly NNLO?)

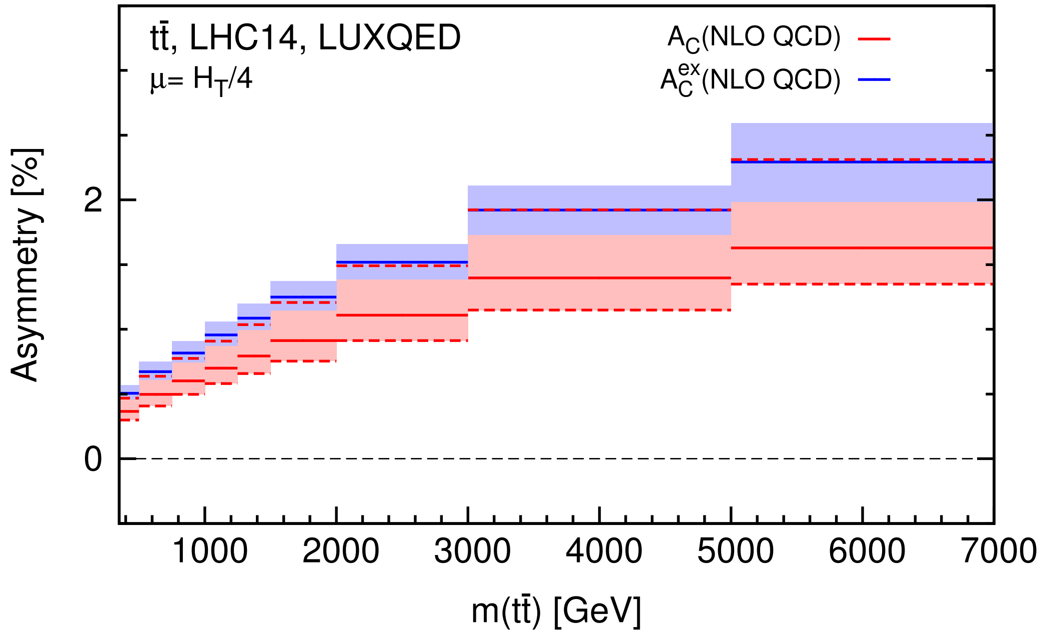
LHCb

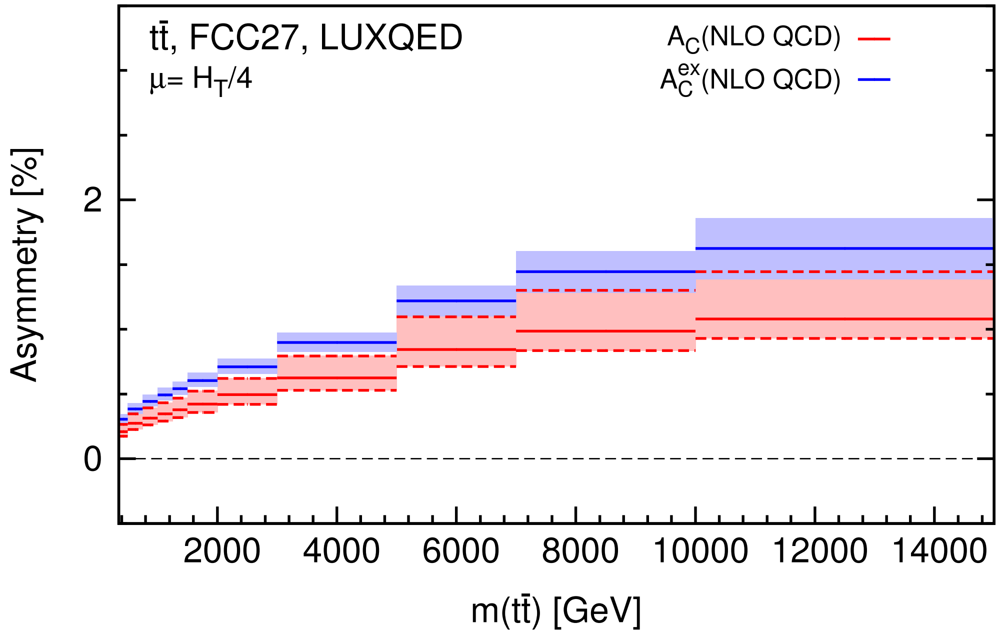
Slide by Alex Mitov

Asymmetry

- Preliminary studies @NLO QCD, to be upgraded at NNLO QCD+NLOEW accuracy
- Experimental proposal for differential binning
  {350, 500, 750, 1000, 1250, 1500, 2000, 3000, 5000, 7000, 10000, 15000}







Plots by Ioannis Tsinikos

Single-top production

Predictions for rates at 14 and 27 TeV

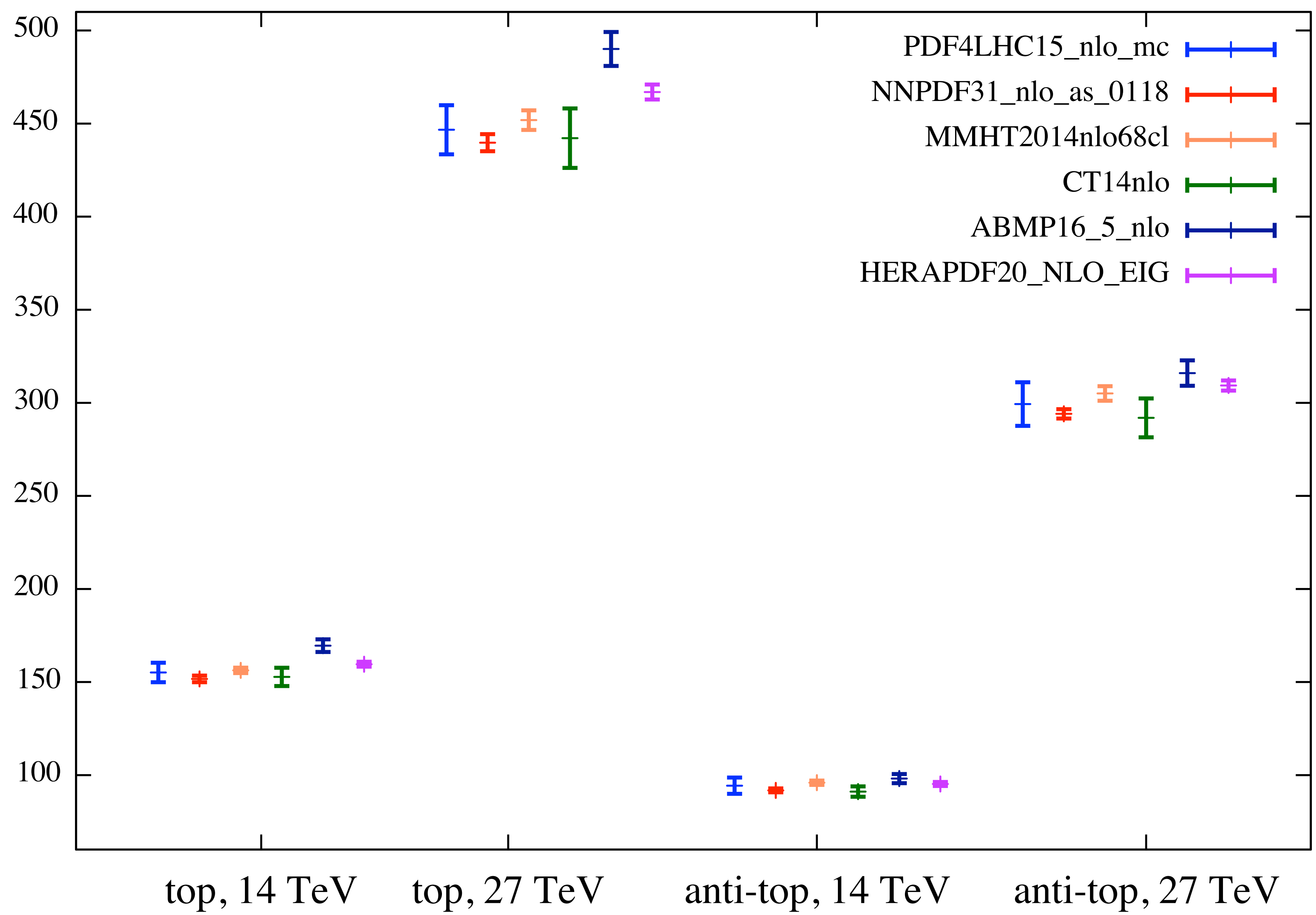
	14 TeV			27 TeV		
	σ [pb]	$\Delta_7^{\mu_r,\mu_f}$	Δ_{PDF}	σ [pb]	$\Delta_7^{\mu_r,\mu_f}$	Δ_{PDF}
$\sigma_{\text{NLO, t-ch,}}\ t$	**156**	+3% -2.2%	2,3 %	**447**	+3% -2.6%	2 %
$\sigma_{\text{NLO, t-ch,}}\ \bar{t}$	**94**	+3.1% - 2.1%	3,1 %	**299**	+3.1% -2.5%	2,6 %
$\sigma_{\text{NLO, Wt}} = \sigma_{\text{NLO, W}\bar{t}}$ $\mu_{r,f} = p_{\perp,b,\text{veto}}$ = 50 GeV	**36**	+2.9% -4.4%	5 %	**137**	+3.8% -6.1%	4 %
$\sigma_{\text{NLO, s-ch,}}\ t$	**6,8**	+2.7% -2.2%	1,7 %	**14,8**	+2.7% -3.2%	1,8 %
$\sigma_{\text{NLO, s-ch,}}\ \bar{t}$	**4,3**	+2.7% -2.2%	1,8 %	**10,4**	+2.7% -3.3%	1,8 %

PDF4LHC15_nlo_mc, μ_0=m_t=173.2 GeV, V_{tb}=1, 5FNS

- t-channel, NNLO: very similar central value, error reduced by ~1/2 [*results for LHC14: Berger, Gao, Zu, arXiv:1708.09405*]
- For differential distributions: error above is in many cases underestimate
- Nevertheless, good NLO → NNLO convergence

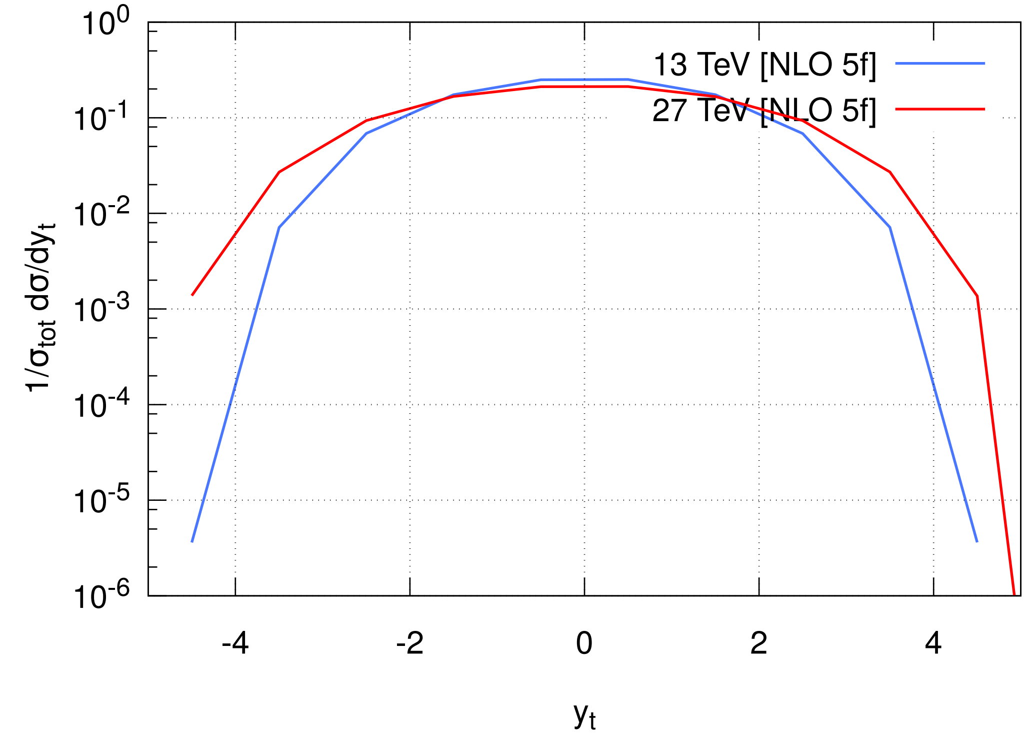
Slide by Fabrizio Caola

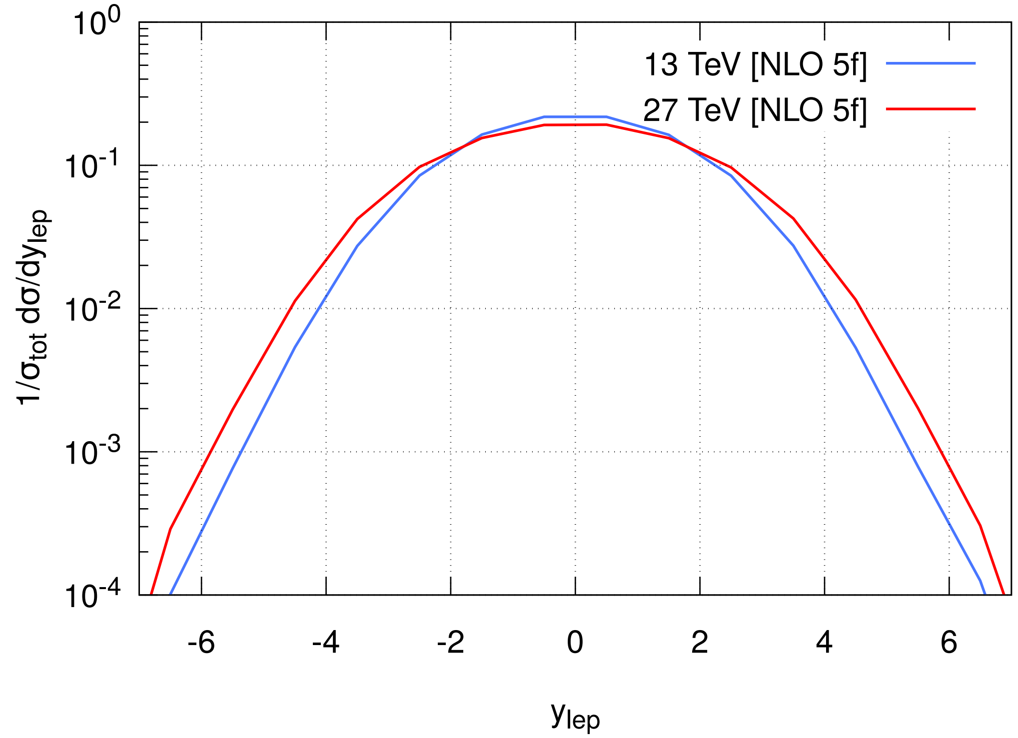
Total t-channel cross section

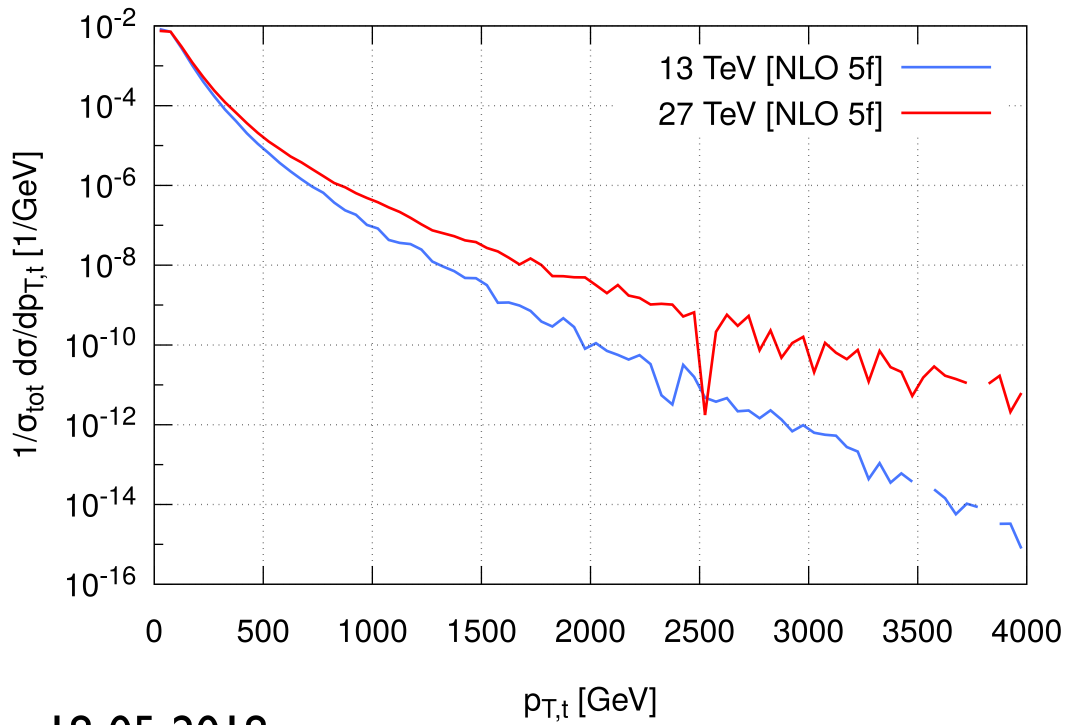


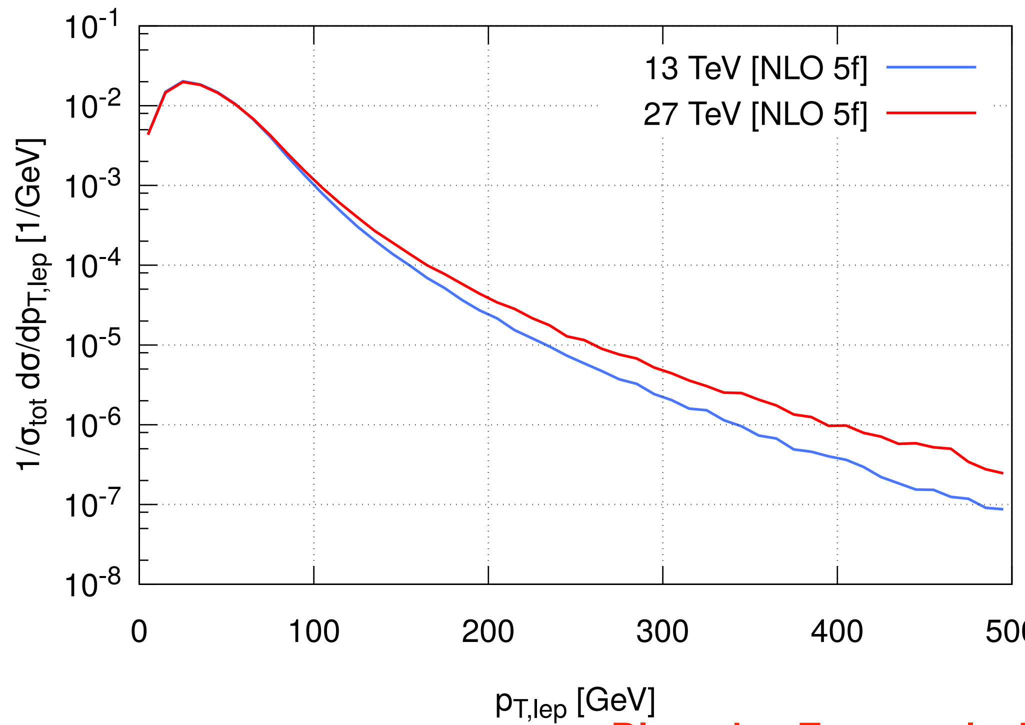
Slide by Fabrizio Caola

Distributions (unit-normalised)









Plots by Emanuele Re

Distributions (unit-normalised)

- Smaller effects for jet multiplicity and $\cos\theta_{jet,lep}$
- Any other useful distribution?

V_{tX}

- Constrain V_{tX} with measurements of single-top production
  see e.g. Alwall et al, hep-ph/0607115, Lacker et al, arXiv:1202.4694
- NLO cross-sections (in pb), computed assuming V_{tX}=1 are listed below
- Differential studies can also be performed

√s [TeV]	V_{tb}=1			V_{ts}=1			V_{td}=1		
	$t+\bar{t}$	t	$\bar{t}$	$t+\bar{t}$	t	$\bar{t}$	$t+\bar{t}$	t	$\bar{t}$
13	260	155	105	546	331	215	1230	921	308
14	291	175	116	608	371	237	1357	1008	348
27	910	529	381	1697	995	702	3250	2262	988

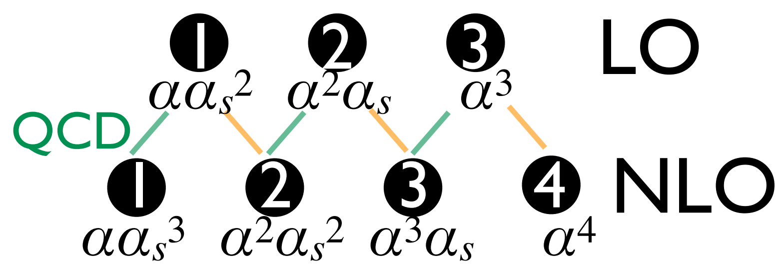
Top-pair production in association with a vector boson

Predictions at complete-NLO accuracy for ttW

Frederix, Pagani, MZ, arXiv:1711.02116

13 TeV

$\delta[\%]$	$\mu = H_T/2$
LO_2	-
LO_3	0.9
NLO_1	50.0 (25.7)
NLO_2	-4.2 (-4.6)
NLO_3	12.2 (9.1)
NLO_4	0.04 (-0.02)



$\delta[\%]$	$\mu = H_T/2$
LO_2	-
LO_3	1.1
NLO_1	149.5 (71.1)
NLO_2	-5.6 (-6.2)
NLO_3	68.8 (56.6)
NLO_4	0.2 (0.2)

100 TeV

- Subleading contributions to $t\bar{t}W$ exist beyond NLO QCD and EW. An estimate based on coupling-constants suggest them to be negligible.
- This is not the case:
  - Relative contributions /LO_1 (number in parentheses are for a 100 GeV jet-veto)
  - $LO_{2,3}$ are completely negligible (LO_2 is identically zero)
  - Because of the t-W scattering, NLO_3 is positive and (much) larger than NLO_2
  - The jet veto greatly reduces the NLO_1 (QCD corrections), which is dominated by hard radiation, and only mildly affects the other contributions

Cross-sections for $t\bar{t}W$

Predictions at complete-NLO accuracy

14

σ[fb]	$\mathrm{LO_{QCD}}$	$\mathrm{LO_{QCD}+NLO_{QCD}}$	LO	LO + NLO	$\frac{\mathrm{LO+NLO}}{\mathrm{LO_{QCD}+NLO_{QCD}}}$
$\mu = H_T/2$	$414^{+23\%}_{-18\%}$	$628^{+11\%}_{-11\%}$ $(521^{+5\%}_{-7\%})$	$418^{+23\%}_{-17\%}$	$670^{+12\%}_{-11\%}$ $(548^{+6\%}_{-7\%})$	1.07 (1.05)

27

σ[fb]	$\mathrm{LO_{QCD}}$	$\mathrm{LO_{QCD}+NLO_{QCD}}$	LO	LO + NLO	$\frac{\mathrm{LO+NLO}}{\mathrm{LO_{QCD}+NLO_{QC}}}$
$\mu = H_T/2$	$1182^{+21\%}_{-16\%}$	$2066^{+14\%}_{-11\%}$ $(1561^{+7\%}_{-7\%})$	$1194^{+21\%}_{-16\%}$	$2329^{+14\%}_{-11\%}$ $(1750^{+7\%}_{-7\%})$	1.13 (1.12)

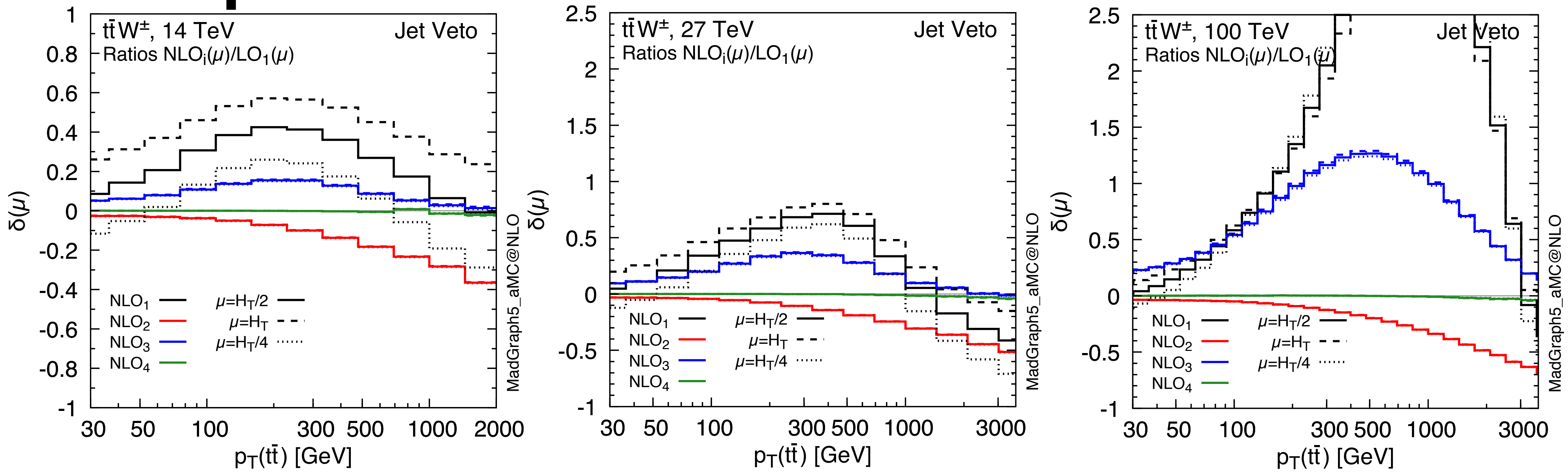
Breakdown of contributions (w.r.t. $\mathrm{LO_1}$)

δ[%]	$\mu = H_T/4$	$\mu = H_T/2$	$\mu = H_T$
$\mathrm{LO_2}$	-	-	-
$\mathrm{LO_3}$	0.8	1.0	1.1
$\mathrm{NLO_1}$	37.4 (7.7)	51.8 (25.9)	64.7 (41.9)
$\mathrm{NLO_2}$	−4.5 (−4.7)	−4.3 (−4.5)	−4.1 (−4.3)
$\mathrm{NLO_3}$	13.0 (9.7)	13.3 (9.9)	13.6 (10.1)
$\mathrm{NLO_4}$	0.02 (−0.00)	0.03 (0.00)	0.05 (0.01)

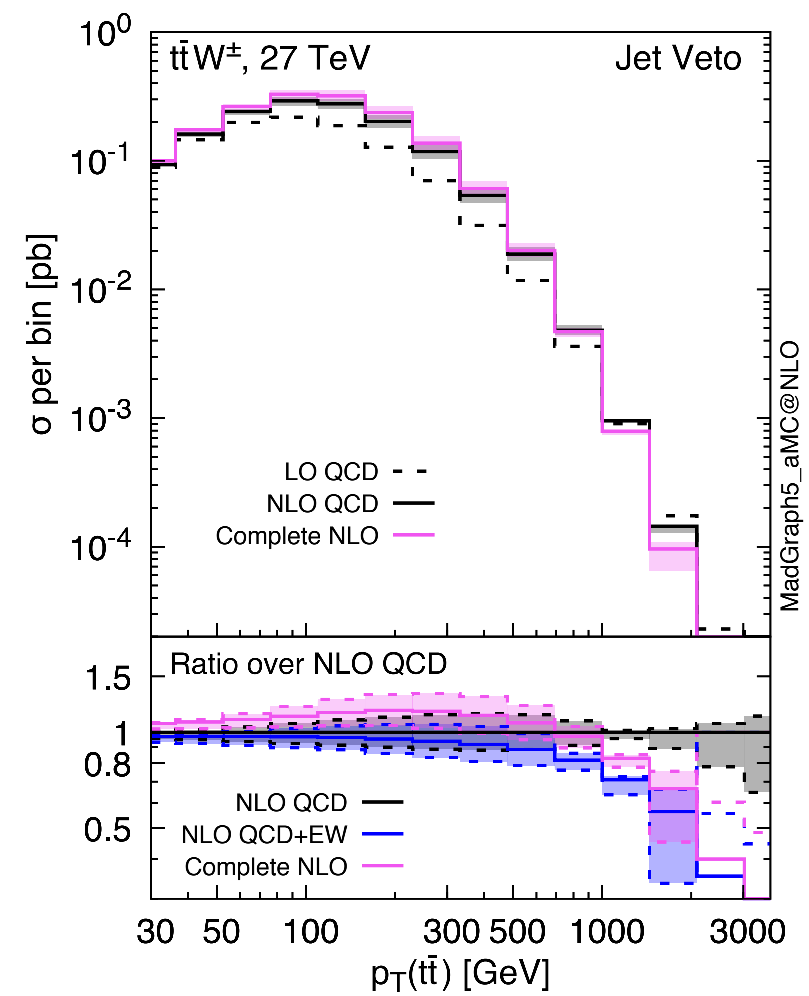
δ[%]	$\mu = H_T/4$	$\mu = H_T/2$	$\mu = H_T$
$\mathrm{LO_2}$	-	-	-
$\mathrm{LO_3}$	0.9	1.0	1.2
$\mathrm{NLO_1}$	67.4 (18.4)	74.8 (32.0)	82.0 (44.3)
$\mathrm{NLO_2}$	−5.1 (−5.4)	−5.0 (−5.2)	−4.8 (−5.1)
$\mathrm{NLO_3}$	25.5 (19.8)	26.1 (20.2)	26.6 (20.6)
$\mathrm{NLO_4}$	0.06 (0.01)	0.08 (0.02)	0.10 (0.03)

Tables and results by Davide Pagani

Complete-NLO corrections for $t\bar{t}W$



- QCD corrections to ttW are dominated by hard-jet and soft-W configurations (giant K-factors)
- A jet veto (p_T>100 GeV, |y|<2.5) disfavours these configurations, bringing more stable predictions
- NLO_3 ($\alpha_s\alpha^3$) includes t-W scattering, large and positive contribution which survives jet veto: 10/20/55% (vs NLO_1 25/30/70%) w.r.t LO_1 at 14/27/100 TeV, while EW ($\alpha_s^2\alpha^2$) corrections are ~-5%
- Complete-NLO and NLO QCD+EW bands barely overlap in large part of the phase-space



Cross-sections for $t\bar{t}Z$

Frixione, Hirschi, Pagani, Shao, MZ arXiv:1504.03446

- For ttZ, corrections beyond (N)LO_2 are negligible. Use NLO QCD+EW
- For 14 TeV, see YR4 (Table 41)

Process	$\sqrt{s}$	$\sigma^{\rm NLO}_{\rm QCD}$	$\sigma^{\rm NLO}_{\rm QCD+EW}$	$K_{\rm QCD}$	$\delta_{\rm EW}[\%]$	Scale[%]		PDF[%]		$\alpha_S[\%]$	
$t\bar{t}Z$	14	1018(2.2)	1015(2.2)	1.40	-0.3	$+9.6\%$	-11.2%	$+2.7\%$	-2.7%	$+2.8\%$	-2.8%

- Updated numbers for 27 TeV, with same setup

$\sigma_{\rm NLOQCD}$ [pb]	$\sigma_{\rm NLOQCD+EW}$ [pb]	$K_{\rm QCD}$	$\delta_{\rm EW}$ [%]	$\Delta\mu$ [%]	ΔPDF[%]	$\Delta\alpha_s$[%]
4.90	4.81	1.45	-2	+9.9 -10.4	±2.0	±2.0

Proposal for the four-top section: Theory part

More in Frederic Deliot's talk

1. Precision
   A. The complete-NLO predictions for four-top production
      Frederix, Pagani, MZ, arXiv:1711.02116
      New numbers for 14 and 27 TeV available
2. Four top as a probe of new physics
   A. Constraining qqtt operators in the EFT
      Zhang, arXiv:1708.05928
      Predictions for 14TeV/3ab^{-1} and 27 TeV/15ab^{-1} available
   B. Constraining top quark flavor violation and dipole moments through three and four-top quark productions at the LHC
      Malekhosseini, Ghominejad, Khanpour, Najafabad, (+Ebadi, Khatibi), arXiv:1804.05598
      Predictions for 14TeV/3ab^{-1} and 27 TeV/15ab^{-1} available
   C. Higgs width and top quark Yukawa coupling
      Cao, Chen, Liu, arXiv:1602.01934
      Predictions for HL-LHC and FCC available. HE-LHC in progress
3. Bonus (i.e. if time and energy allows): how to use findings of 1.A in BSM searches

Thank you for your attention
and for your feedback!