Theory Status of Top Production

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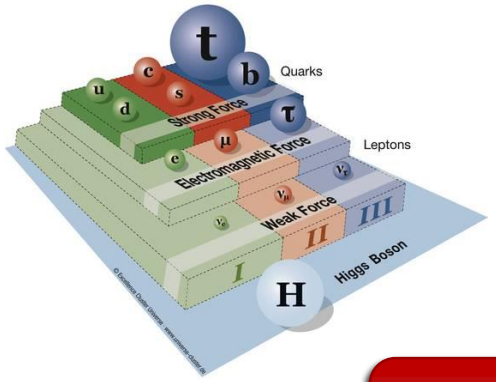
DFG Deutsche Forschungsgemeinschaft

9th Edition of the Large Hadron Collider Physics Conference

Top Role



(from fnal.gov)

Precision physics at the LHC

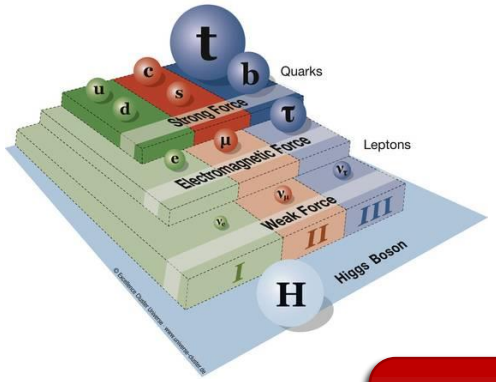
TOP QUARK

SM tests

BSM searches

- A unique particle: heaviest of all, does not hadronize, has large coupling to the Higgs boson, probes EWSB, determines stability of the Universe through it's mass, ...
- Plays a central role in QCD, EW and flavour physics: an extremely versatile and useful tool!
- Physics programme at the LHC requires precise determination of top properties as well as studies of production and decay mechanisms

Top Role



Precision physics at the LHC

SM tests

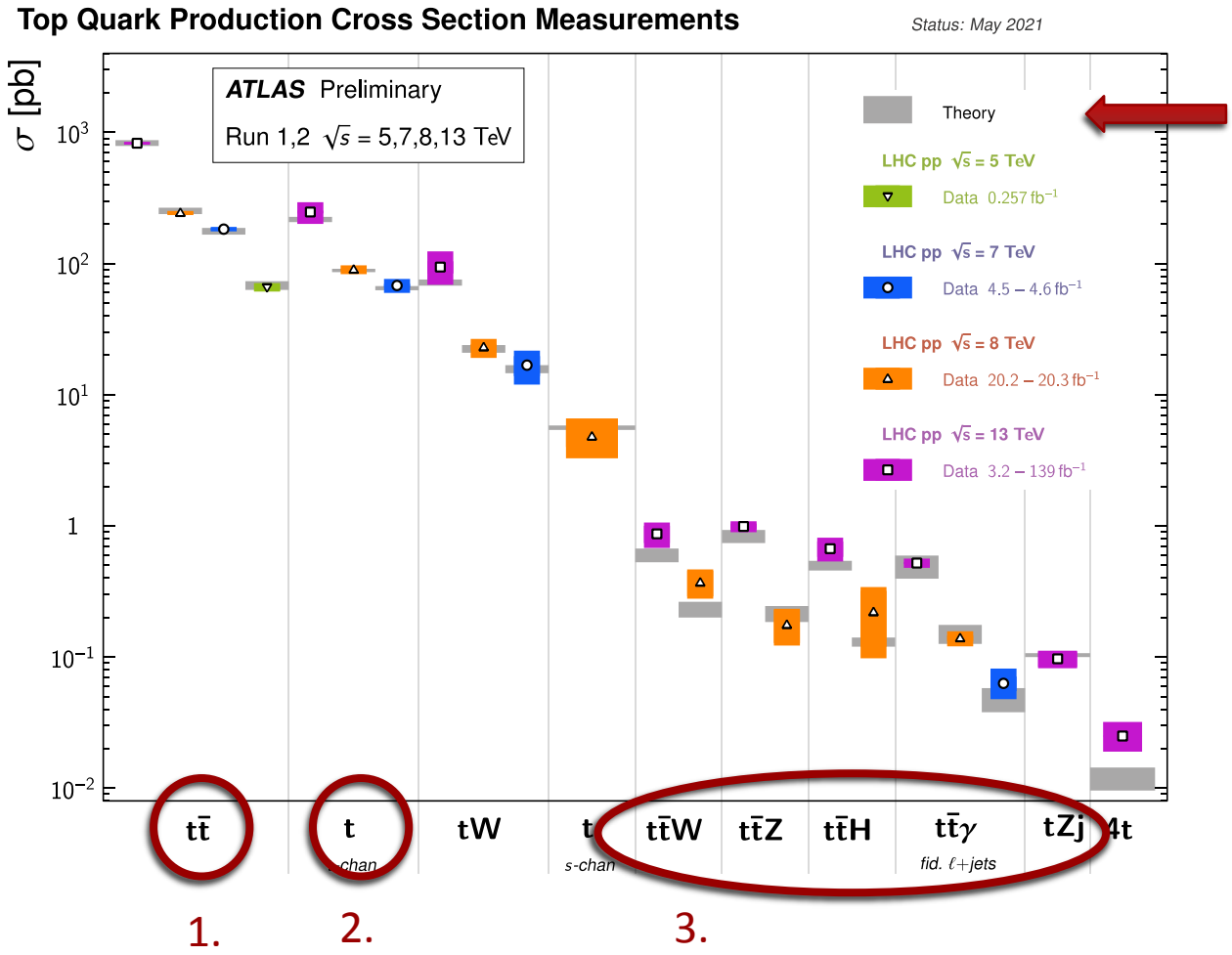
Other related theory talks:

- M. Worek, plenary Tuesday
- A. Mitov, theory status of top properties, parallel Thursday
- A. Ferroglia, tt+X calculations and modelling, parallel Tuesday
- E. Vryonidou, theory aspects in global analyses, parallel Wednesday

- A unique particle: heaviest of all, does not
  EWSB, determines stability of the Univers
- Plays a vital role in QCD, EW and flavour p
- Physics programme at the LHC requires pr
  of production and decay mechanisms

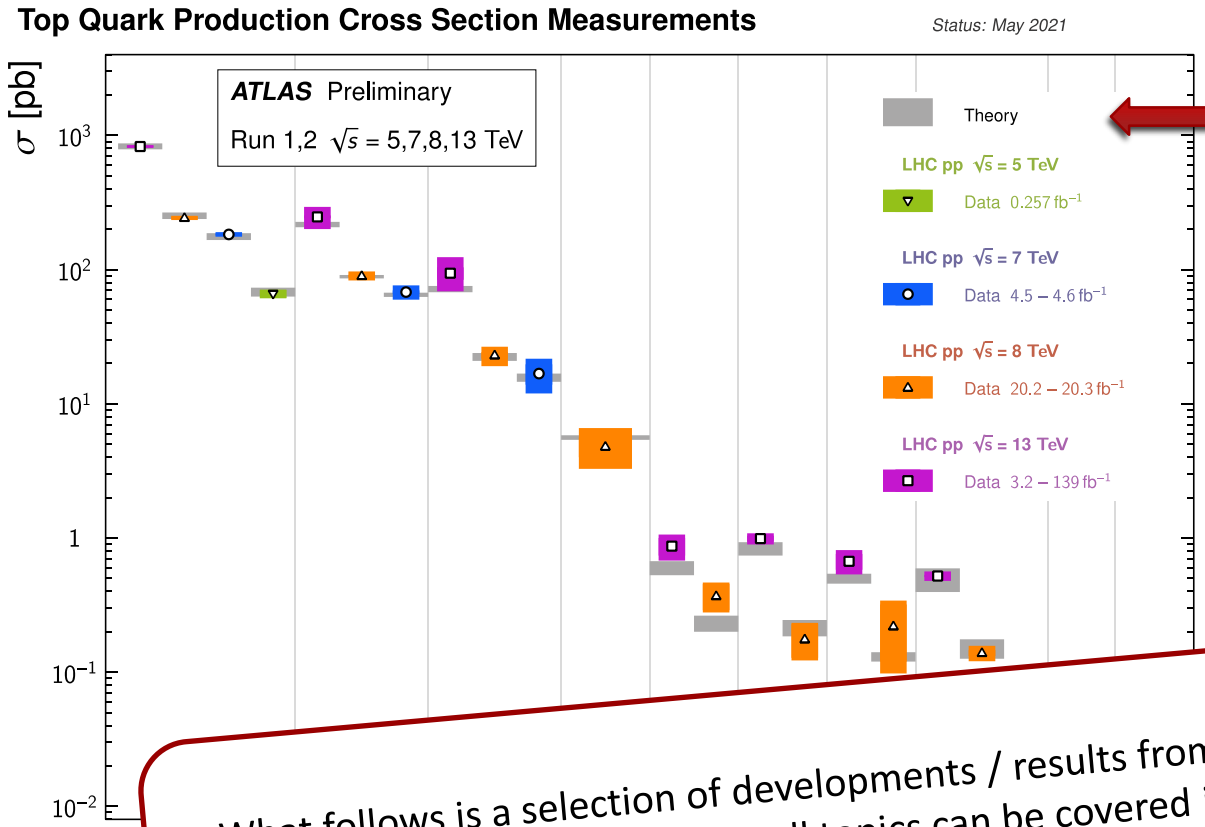
this talk: top production in the SM

Outline of the Talk



Recent developments in theory

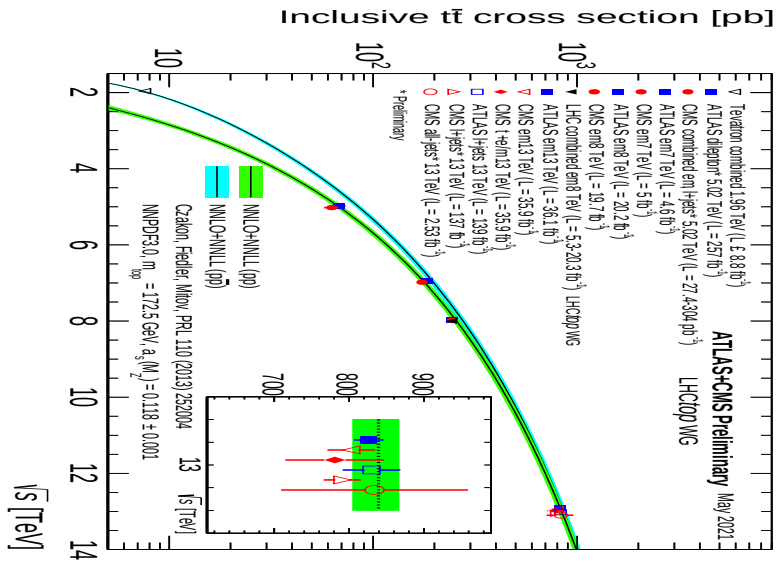
Outline of the Talk



Recent developments in theory

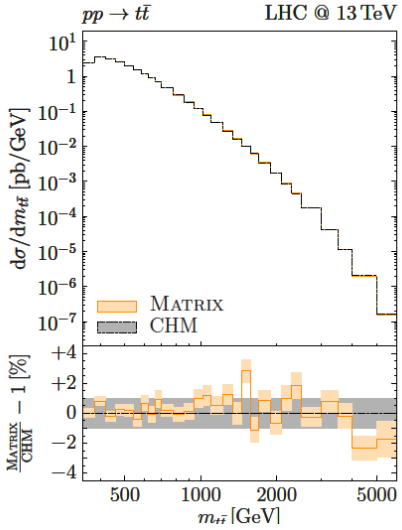
What follows is a selection of developments / results from the last 1-2 years Not all topics can be covered in this talk, apologies for all omissions

1. TOP PAIRS


Inclusive tt̄ cross section [pb]
ATLAS+CMS Preliminary
LHCtop WG
May 2021
Tevatron combined 1.96 TeV (L = 8.8 fb⁻¹)
ATLAS dilepton* 5.02 TeV (L = 257 fb⁻¹)
CMS combined e/m l+jets* 5.02 TeV (L = 27.4-304 pb⁻¹)
ATLAS e/m* 7 TeV (L = 4.6 fb⁻¹)
CMS e/m* 7 TeV (L = 5 fb⁻¹)
ATLAS e/m 8 TeV (L = 20.2 fb⁻¹)
CMS e/m 8 TeV (L = 19.7 fb⁻¹)
LHC combined e/m 8 TeV (L = 5,3-20.3 fb⁻¹) LHCtop WG
ATLAS e/m 13 TeV (L = 36.1 fb⁻¹)
CMS e/m 13 TeV (L = 35.9 fb⁻¹)
CMS l+e/m 13 TeV (L = 35.9 fb⁻¹)
ATLAS l+jets 13 TeV (L = 139 fb⁻¹)
CMS l+jets* 13 TeV (L = 137 fb⁻¹)
CMS all-jets* 13 TeV (L = 2.53 fb⁻¹)
* Preliminary
NNLO+NNLL (pp)
NNLO+NNLL (pp̄)
Czakon, Fiedler, Mitov, PRL 110 (2013) 252004
NNPDF3.0, m_top = 172.5 GeV, α_s(M_Z) = 0.118 ± 0.001
√s [TeV]

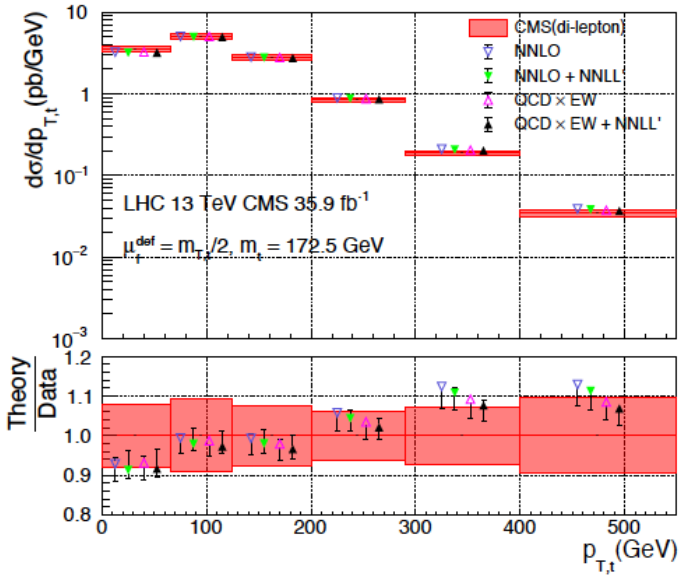
Stable Tops

- NNLO for total cross sections *[Czakon, Fiedler, Mitov'13] [Catani, Devoto, Grazzini, Kallweit, Mazzitelli, Sargsyan'19]* and differential distributions *[Czakon, Heymes, Mitov'16] [Catani, Devoto, Grazzini, Kallweit, Mazzitelli'19]*



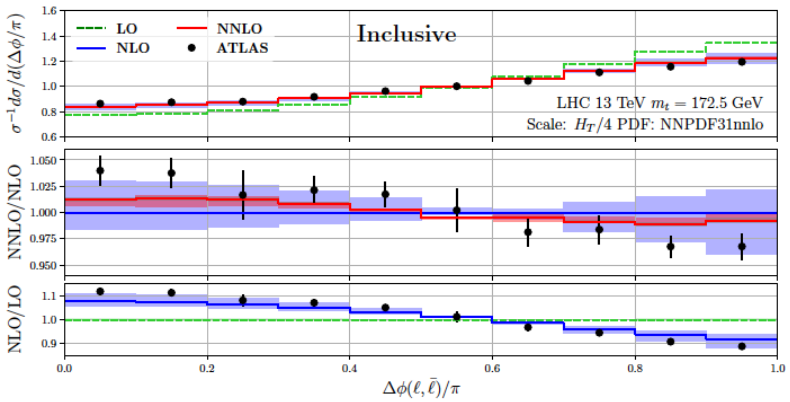
σ_{NNLO} [pb]	q_T subtraction	TOP++
8 TeV	$238.5(2)^{+3.9\%}_{-6.3\%}$	$238.6^{+4.0\%}_{-6.3\%}$
13 TeV	$793.4(6)^{+3.5\%}_{-5.7\%}$	$794.0^{+3.5\%}_{-5.7\%}$

- NNLO combined with NNLL resummation and EW corrections *[Czakon, Ferroglia, Mitov, Pagani, Papanastasiou, Pecjak, Scott, Tsinikos, Wang, Yang, Zaro'19]*



NNLO for Dilepton Final States

- QCD NNLO production with NNLO decay $t \to bW(\to l\nu)$ in the narrow width approximation *[Behring, Czakon, Mitov, Papanastasiou, Poncelet'19] [Czakon, Mitov, Poncelet'20]*
- In general good perturbative convergence, small NNLO/NLO K-factors, strongly reduced scale dependedence
- Spin correlations: azimuthal difference between charged leptons



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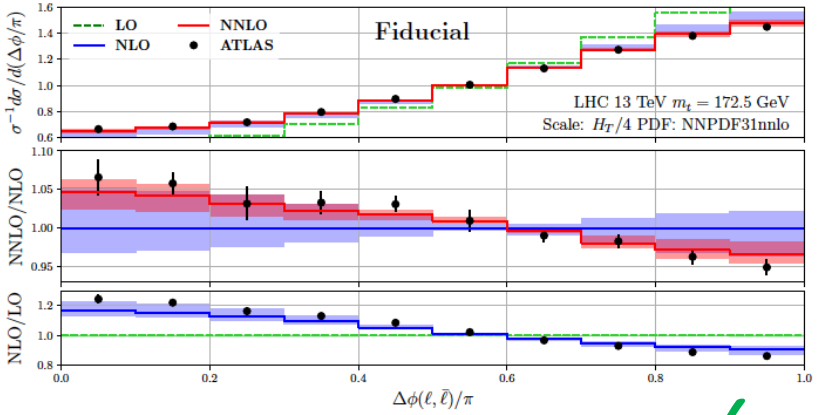

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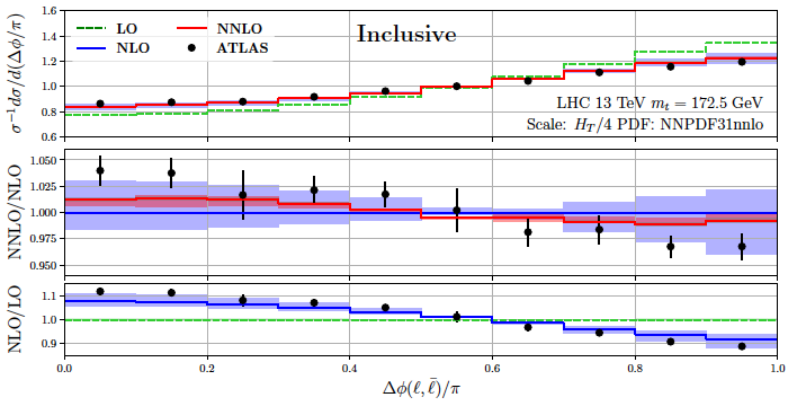
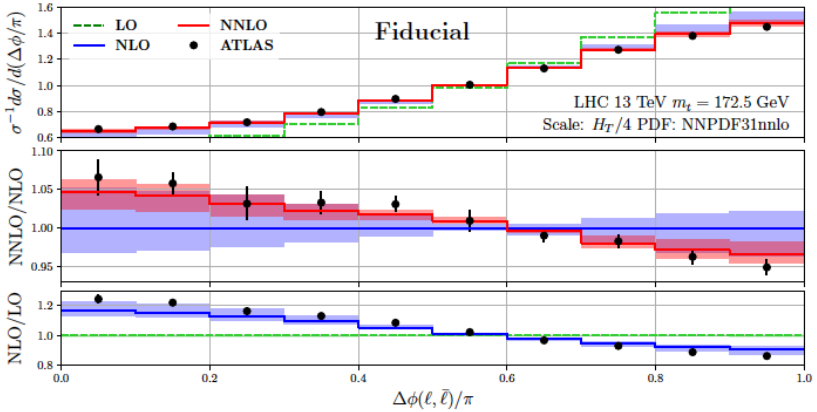
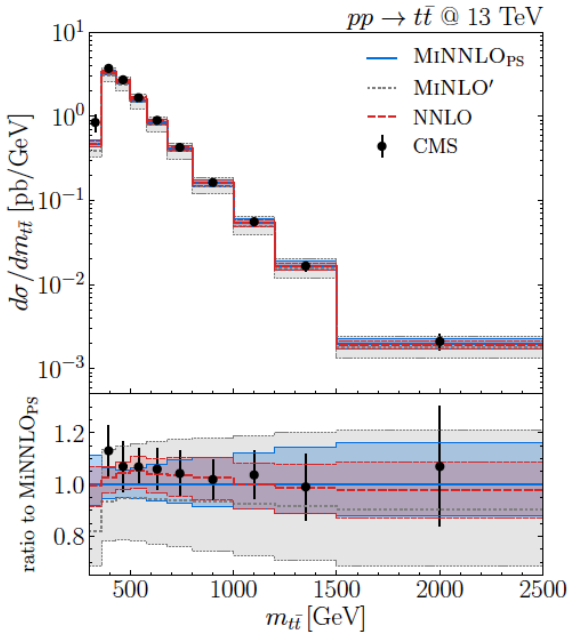


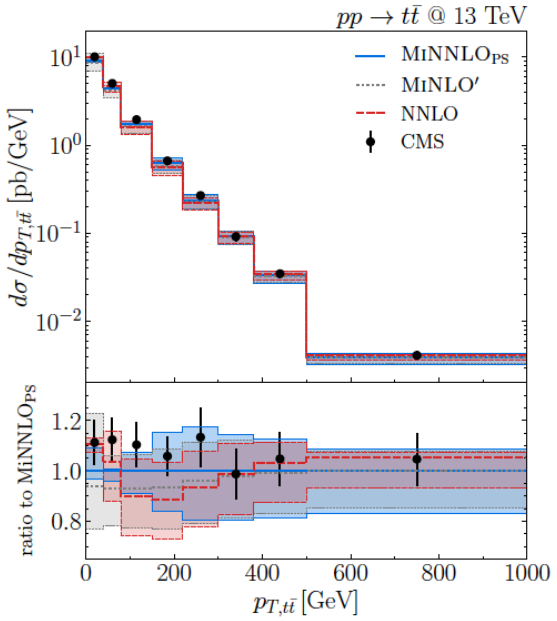


- Well described by NNLO in the fiducial volume, tensions at the inclusive level: confirmed in *[Czakon, Mitov, Poncelet'20] ->* effects of modelling?
- Complete NLO EW+QCD in NWA *[Frederix, Tsinikos, Vitos'21]*

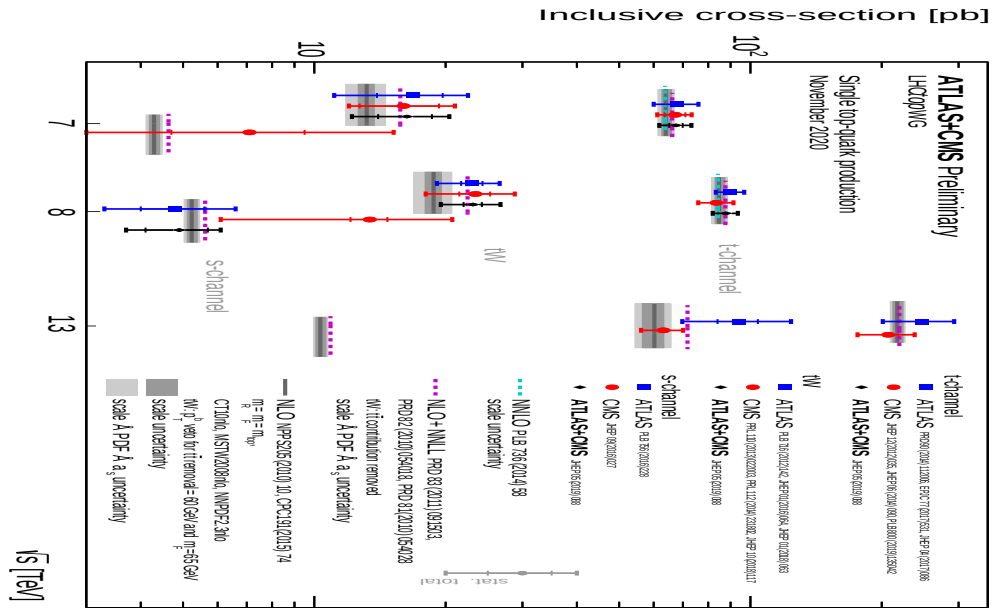
NNLO+PS

- Combination of NNLO calculations with parton showe (PS) in a consistent manner
  - NNLO accuracy for inclusive observables
  - Corresponding fixed-order accuracy for observables with hard jets: NLO for +1 jet, LO for +2 jets
  - Resummation at the PS accuracy
- First application to coloured system: MiNNLO$_{PS}$ *[Mazzitelli,Monni, Nason, Re, Wiesemann, Zanderighi'20]*





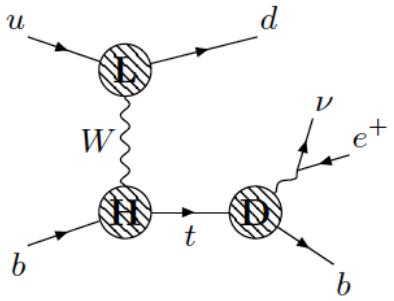
2. SINGLE TOP

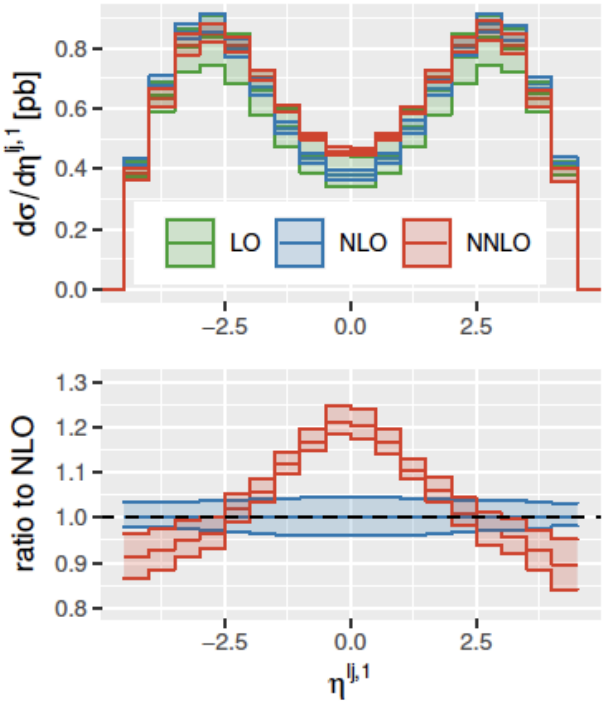

ATLAS+CMS Preliminary
LHCtopWG
Single top-quark production
November 2020
Inclusive cross-section [pb]
t-channel
ATLAS
CMS
ATLAS+CMS
tW
ATLAS
CMS
ATLAS+CMS
s-channel
ATLAS
CMS
ATLAS+CMS
NNLO
scale uncertainty
NLO+NNLL
scale uncertainty
stat.
total
NLO MSTW2008nlo, NNPDF2.3nlo
CT10nlo, MSTW2008nlo, NNPDF2.3nlo
tW: p_T^b veto for ttbar/tW = 60 GeV and m_t=mt GeV
Scale uncertainty
Scale ⊕ PDF ⊕ α_s uncertainty
t-channel
S-channel
tW
$\sqrt{s}$ [TeV]

T-CHANNEL AT NNLO

- Re-calculation of production and decay *[Campbell, Neumann, Sullivan'21]*
- Previously calculated at NNLO in *[Brucherseifer, Caola, Melnikov'14]* for stable tops and in *[Berger, Gao, Yuan, Zhu'16]* for production and decay

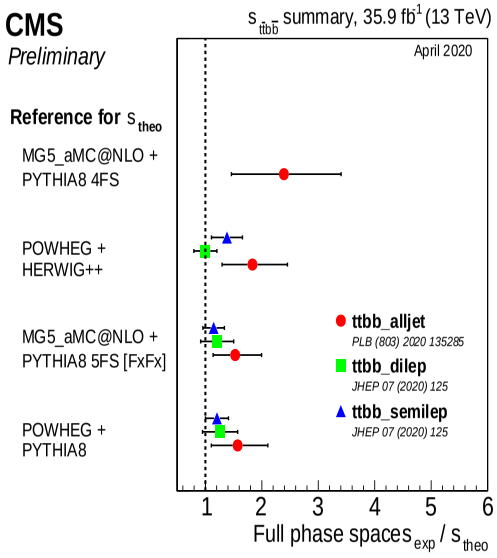
structure function approximation

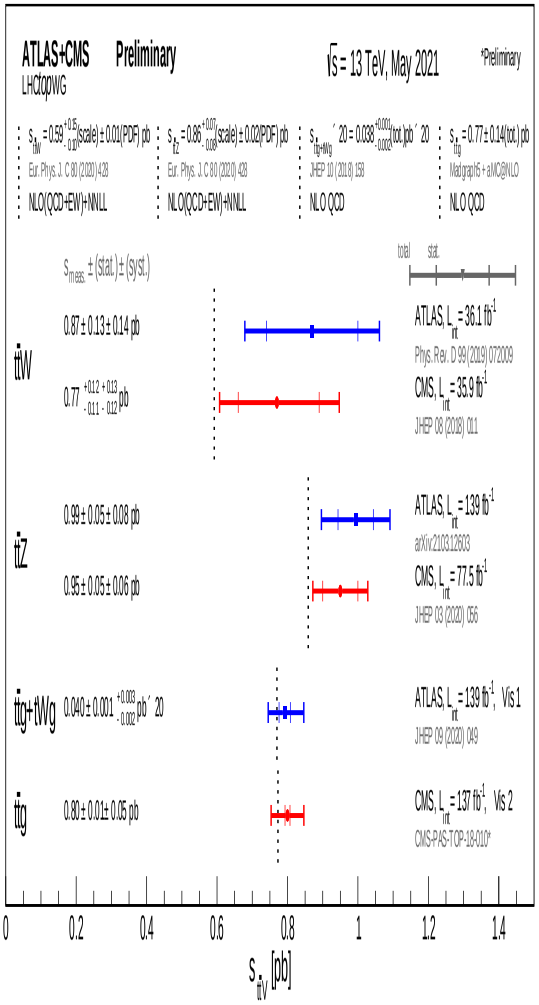




- Results in agreement with *[Berger, Gao, Yuan, Zhu]*
- NNLO in 5FS in good agreement with NLO in 4FS for shapes of kinematical distributions of the top quark *[Berger, Gao'20]*

3. ASSOCIATED TOP PRODUCTION

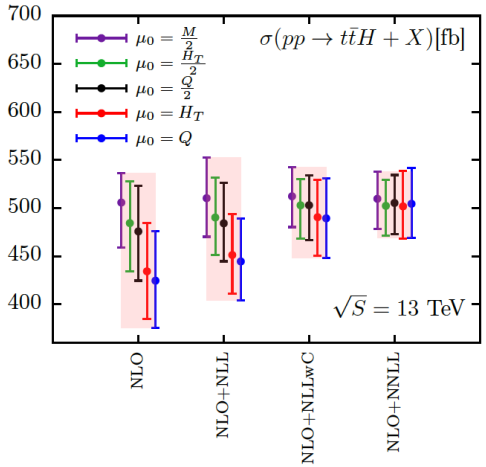


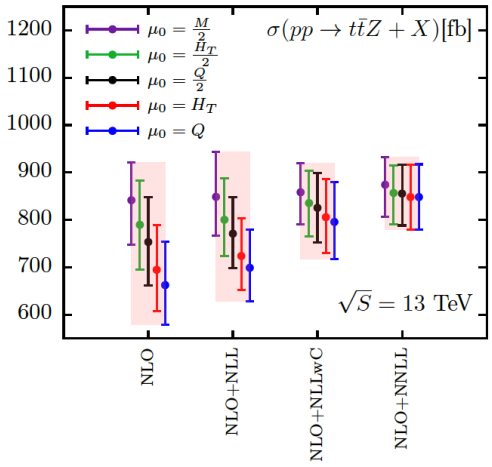


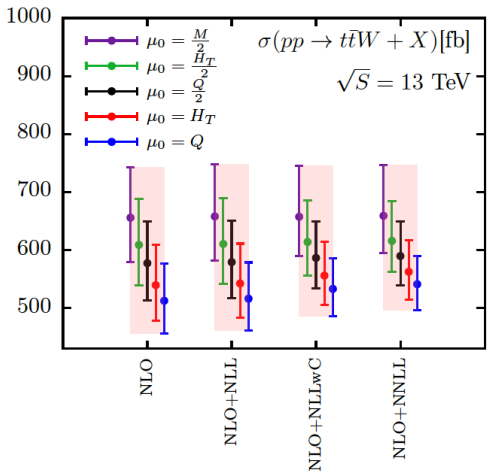
TTBAR+X (X=H,W,Z) AT NLO+NNLL

- The most precise predictions rely on NNLL resummation *[AK, Motyka, Stebel, Schwartländer, Theeuwes'17-20]* matched to NLO(QCD+EW) *[Frederix, Frixione, Hirschi,Pagani,Zaro'18] for* total and differential cross section (stable tops)

[AK, Motyka, Stebel, Schwartländer, Theeuwes'20]







- ttZ: accuracy of theoretical prediction comparable with experimental precision thanks to NNLL

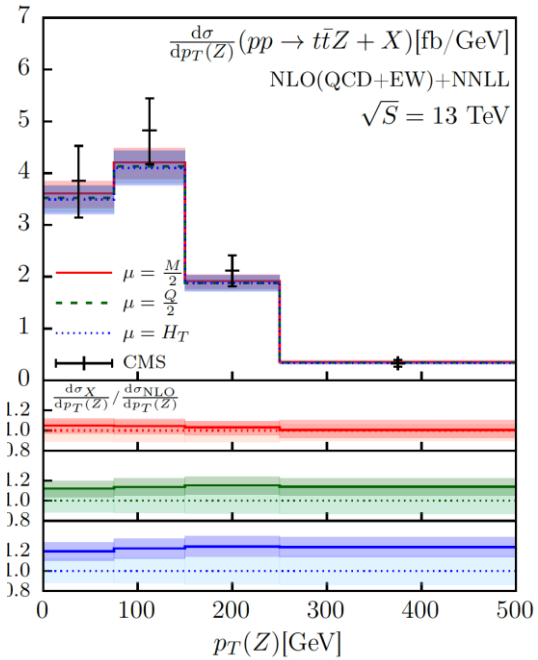
$$\sigma^{t\bar{t}Z}_{\text{NLO+NNLL}} = 863^{+8.5\%+3.2\%}_{-9.9\%-3.2\%}\ \text{fb} = 0.863^{+0.073+0.028}_{-0.085-0.028}\ \text{pb}$$

CMS, 1907.11270: $\sigma(\text{pp} \to \text{t}\bar{\text{t}}\text{Z}) = 0.95 \pm 0.05\,(\text{stat}) \pm 0.06\,(\text{syst})\,\text{pb}$

Associated Top-Pair Production with Z @ NLO+NNLL

[AK, Motyka, Stebel, Schwartländer, Theeuwes'20]

CMS, 1907.11270



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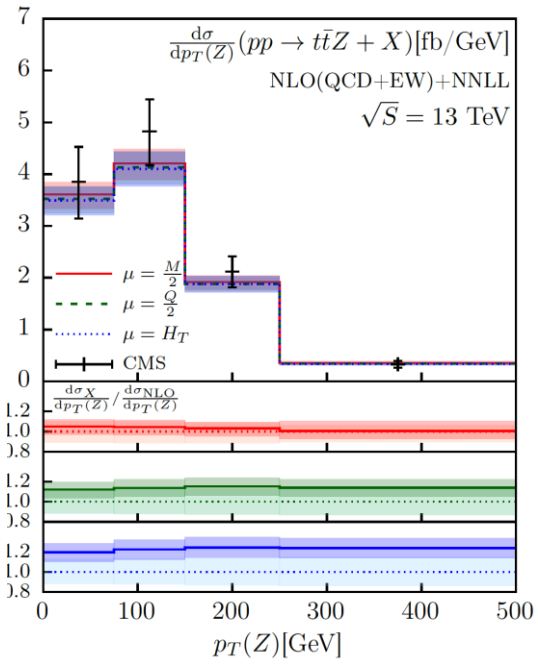
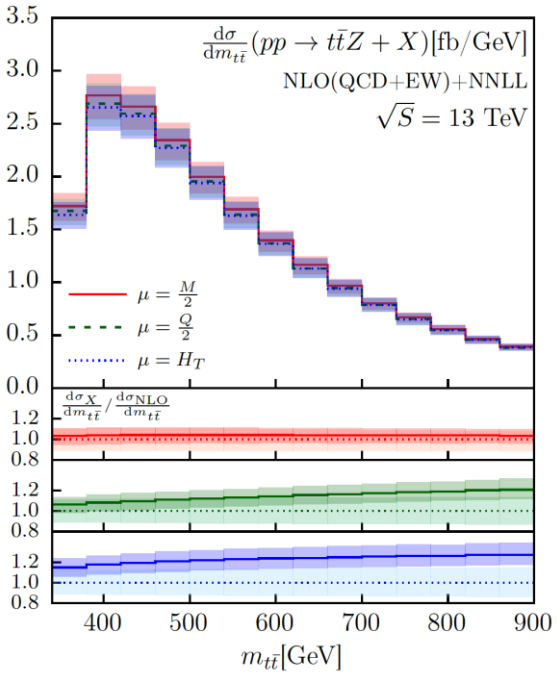
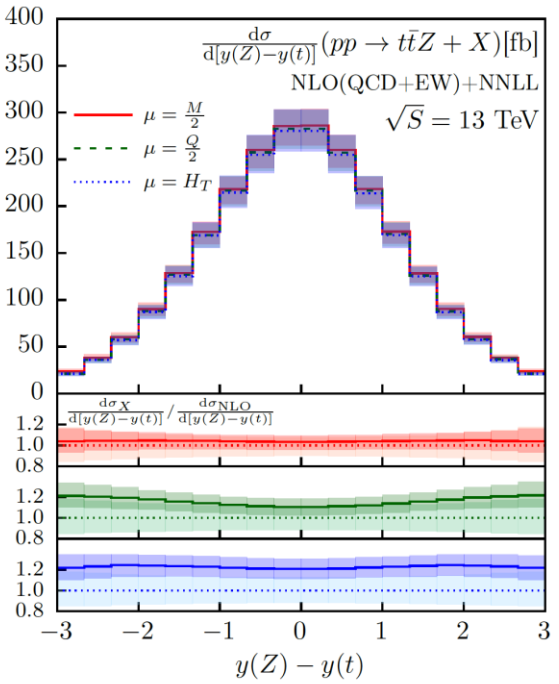




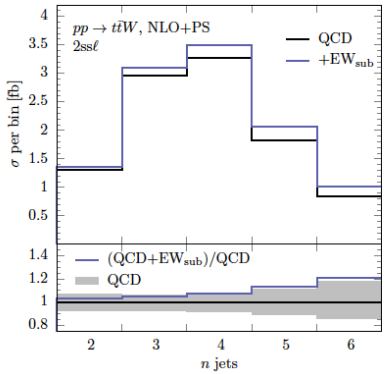


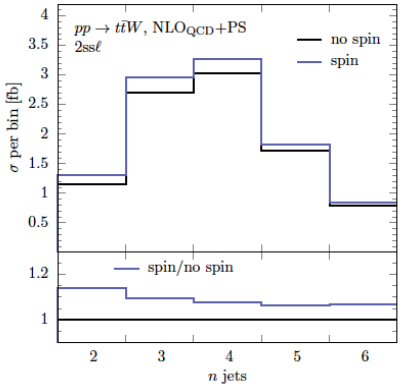
- Results in the SCET framework also available *[Broggio, Ferroglia, Frederix, Pagani, Pecjak, Tsinikos'19]*

TTW @NLO +PS WITH DECAYS

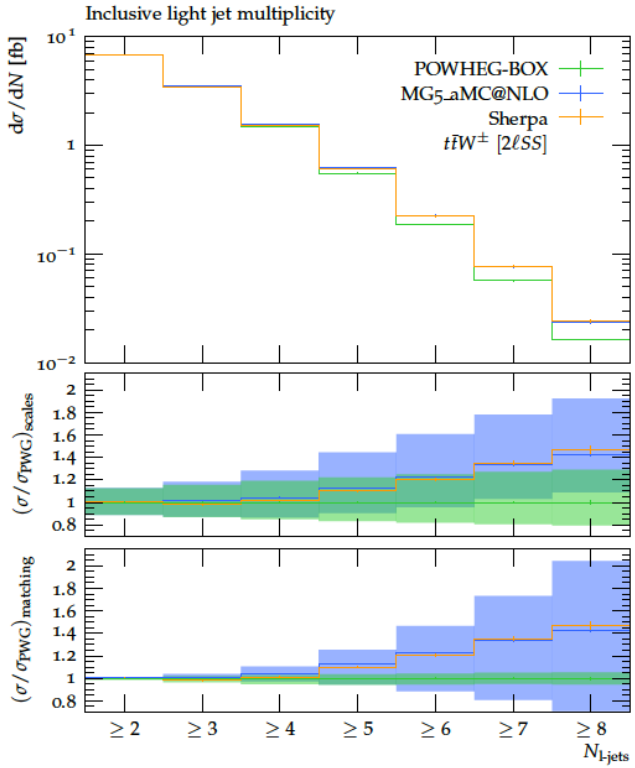
ttW: Apart from $O(\alpha_s^3\,\alpha)$ QCD correction to QCD LO, substantial EW contributions of $O(\alpha_s\,\alpha^3)$ due to the *qg* channel opening at NLO QCD (QCD correction to LO EW), consistently matched to PS in

- aMC@NLO *[Frederix, Tsinikos'20]*





- POWHEG-BOX *[Febres Cordero, Kraus, Reina'21]*



10% flat EW correction for most observables

TT+X Off-Shell

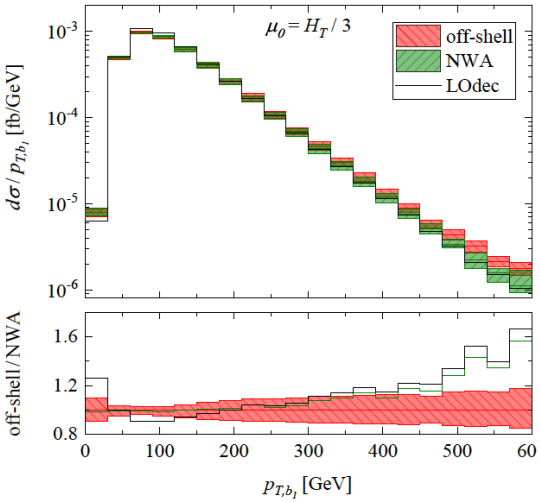
ttH	pp→ ttH → W^+W^-bbH →$e^+\nu_e\ \mu^-\nu_\mu$ bb H	NLO QCD	[Denner,Feger'15]
		NLO QCD+EW	[Denner,Lang, Pellen, Uccirati'17]
ttγ	$pp \to e^+\nu_e\mu^-\,\bar{\nu}_\mu\, b\bar{b}\gamma$	NLO QCD	[Bevilacqua, Hartanto, Kraus, Weber, Worek'18-19]
ttZ	$pp \to e^+\nu_e\mu^-\,\bar{\nu}_\mu\, b\bar{b}\nu_l\bar{\nu}_l$	NLO QCD	[Bevilacqua, Hartanto, Kraus, Weber, Worek'19]
ttW	$pp \to e^+\nu_e\mu^-\,\bar{\nu}_\mu\, e^+\nu_e b\bar{b}$	NLO QCD	Bevilacqua, Bi, Hartanto, Kraus, Worek'20][Bevilacqua, Bi, Hartanto, Kraus, Nasufi, Worek'21]
	$pp \to e^+\nu_e\tau^+\nu_\tau\mu^-\,\bar{\nu}_\mu\, e^+\nu_e b\bar{b}$	NLO QCD	[Denner, Pelliccioli'20]
		NLO QCD+EW	[Denner, Pelliccioli'21]
ttbb	$pp \to e^+\nu_e\mu^-\,\bar{\nu}_\mu\, b\bar{b}b\bar{b}$	NLO QCD	[Denner,Lang, Pellen'20] [Bevilacqua, Bi, Hartanto, Kraus, Lupatelli, Worek'21]

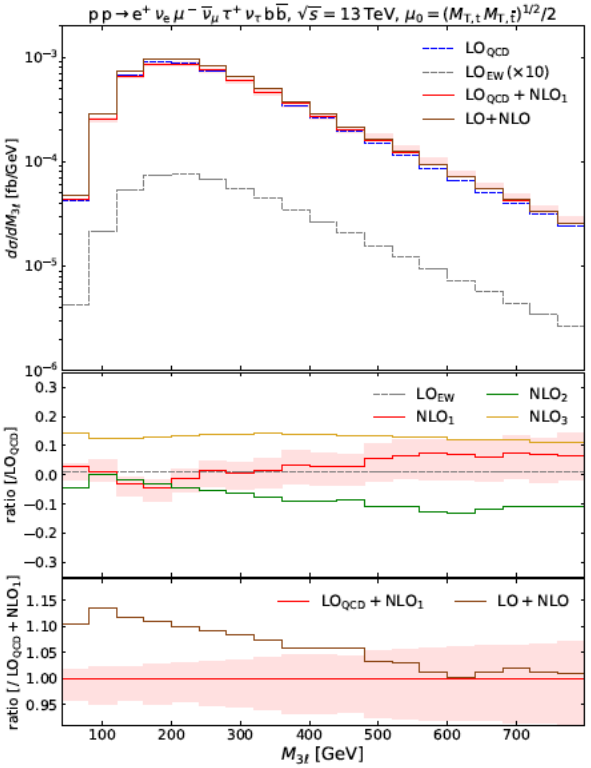
TTW Off-Shell

[Denner, Pelliccioli'21]

[Bevilacqua, Bi, Hartanto, Kraus, Worek'20]

Modelling Approach	σ^{LO} [ab]	σ^{NLO} [ab]
full off-shell ($\mu_0 = m_t + m_W/2$)	$106.9^{+27.7\,(26\%)}_{-20.5\,(19\%)}$	$123.2^{+6.3\,(5\%)}_{-8.7\,(7\%)}$
full off-shell ($\mu_0 = H_T/3$)	$115.1^{+30.5\,(26\%)}_{-22.5\,(20\%)}$	$124.4^{+4.3\,(3\%)}_{-7.7\,(6\%)}$
NWA ($\mu_0 = m_t + m_W/2$)	$106.4^{+27.5\,(26\%)}_{-20.3\,(19\%)}$	$123.0^{+6.3\,(5\%)}_{-8.7\,(7\%)}$
NWA ($\mu_0 = H_T/3$)	$115.1^{+30.4\,(26\%)}_{-22.4\,(19\%)}$	$124.2^{+4.1\,(3\%)}_{-7.7\,(6\%)}$
$\text{NWA}_{\text{LOdecay}}$ ($\mu_0 = m_t + m_W/2$)		$127.0^{+14.2\,(11\%)}_{-13.3\,(10\%)}$
$\text{NWA}_{\text{LOdecay}}$ ($\mu_0 = H_T/3$)		$130.7^{+13.6\,(10\%)}_{-13.2\,(10\%)}$



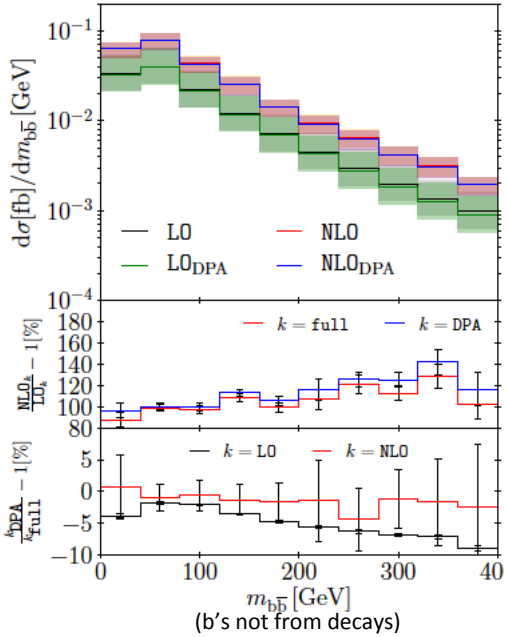


- Spin-correlated production ⊗ decay a good approximation for inclusive observables
- Off-shell effects important in the tails of distributions
- Combined NLO predictions can exceed the scale uncertainties of QCD predictions

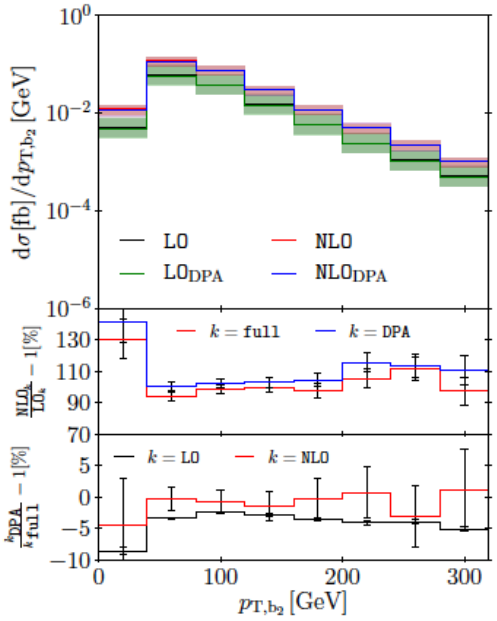
TTBB Off-Shell

- Tour de force calculations: 2->8 with 6 external strongly-interacting legs

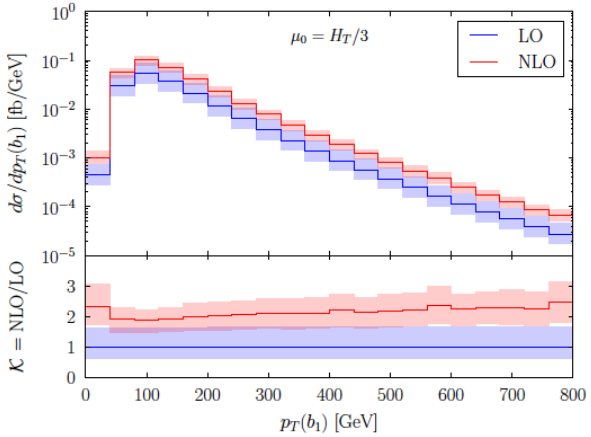
[Denner,Lang, Pellen'20]



(b's not from decays)



[Bevilacqua, Bi, Hartanto, Kraus, Lupatelli, Worek'21]

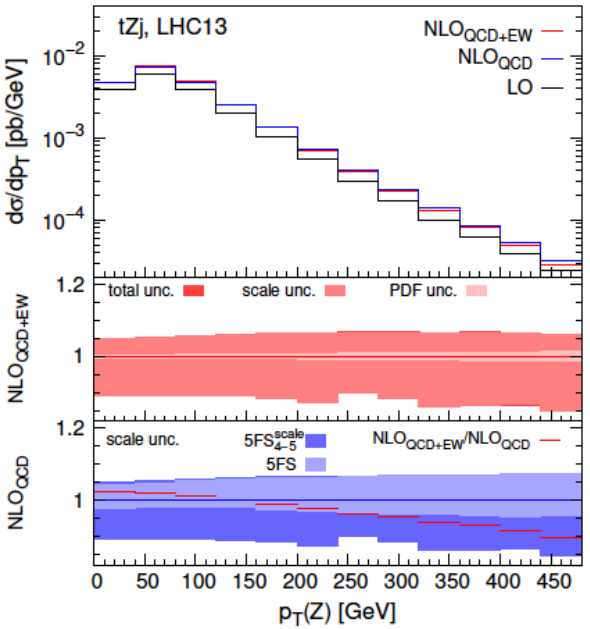


- Large NLO QCD corrections ~ 100%, significant shape modifications of tens of %
- Full calculations provide ~a few % in relevant phase-space regions compared to only resonant structures, qualitative differences in the shape of corrections compared to on-shell calculations

THJ, TZJ @NLO QCD+EW

- $O(\alpha_s \alpha^3)$ QCD and $O(\alpha^4)$ EW correction to the $O(\alpha^3)$ LO *tZj* and *tHj* production calculated within the aMC@NLO framework *[Pagani, Tsinikos, Vryonidou'20]*
- At this level of accuracy, no separation between t-, s- and Wt-channels
- Flavour-scheme (4FS vs 5FS) dependence considered as part of the theory uncertainty

Accuracy	Channel	FS	tHj	tZj
NLO_{QCD}	t-ch., s-ch., tW_h	5FS	$85.1(2)^{+5.4(+6.4\%)}_{-2.3(-2.7\%)}\ ^{+0.5(+0.6\%)}_{-0.5(-0.6\%)}$	$895(2)^{+46(+5.1\%)}_{-16(-1.8\%)}\ ^{+4(+0.4\%)}_{-4(-0.4\%)}$
		$5\text{FS}^{\text{scale}}_{4-5}$	$85.1(2)^{+6.2(+7.2\%)}_{-9.2(-10.9\%)}\ ^{+0.5(+0.6\%)}_{-0.5(-0.6\%)}$	$895(2)^{+50(+5.5\%)}_{-99(-11.1\%)}\ ^{+4(+0.4\%)}_{-4(-0.4\%)}$
$\text{NLO}_{\text{QCD+EW}}$	t-ch., s-ch., tW_h	5FS	$82.2(2)^{+5.6(+6.8\%)}_{-2.4(-2.9\%)}\ ^{+0.5(+0.6\%)}_{-0.5(-0.6\%)}$	$904(2)^{+42(+4.7\%)}_{-19(-2.1\%)}\ ^{+4(+0.4\%)}_{-4(-0.4\%)}$
		$5\text{FS}^{\text{scale}}_{4-5}$	$82.2(2)^{+5.9(+7.2\%)}_{-8.9(-10.9\%)}\ ^{+0.5(+0.6\%)}_{-0.5(-0.6\%)}$	$904(2)^{+50(+5.5\%)}_{-100(-11.1\%)}\ ^{+4(+0.4\%)}_{-4(-0.4\%)}$



- In general, EW corrections smaller than the QCD scale+flavour uncertainties

Summary

Great recent progress, pandemic notwithstanding!

- Top-pairs and single tops: NNLO QCD for production and decay
- First results for matching NNLO to PS for coloured final states
- Associated top-pair production with a heavy boson: NLO (QCD+EW) +NNLL
- Complete NLO available (full set of QCD, EW and mixed NLO contributions)
- Many new off-shell calculations at NLO (QCD, QCD+EW), specifically for associated production