STATE-OF-THE-ART PREDICTIONS FOR TT+H/TT+W/(TT+Z)

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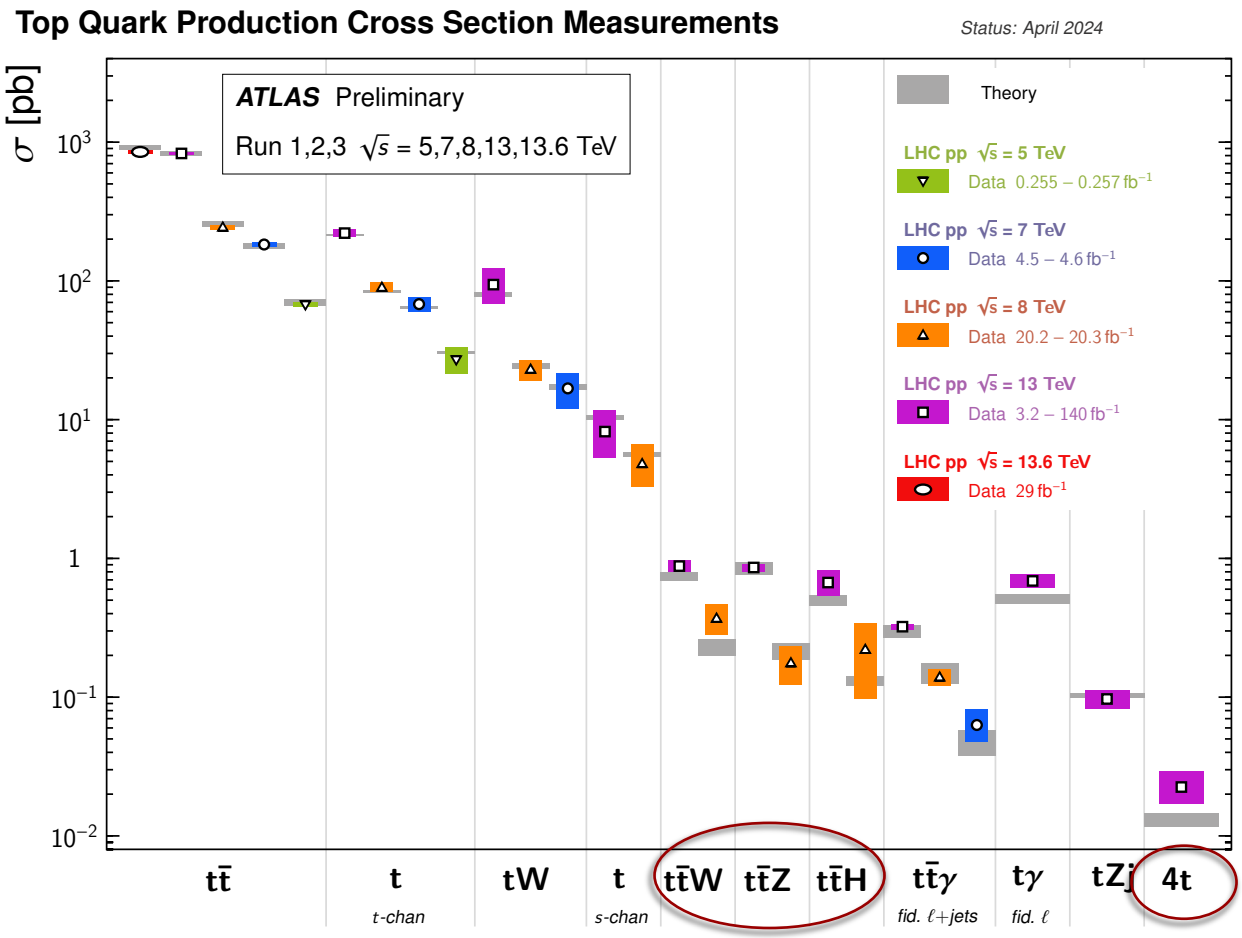
DFG Deutsche Forschungsgemeinschaft

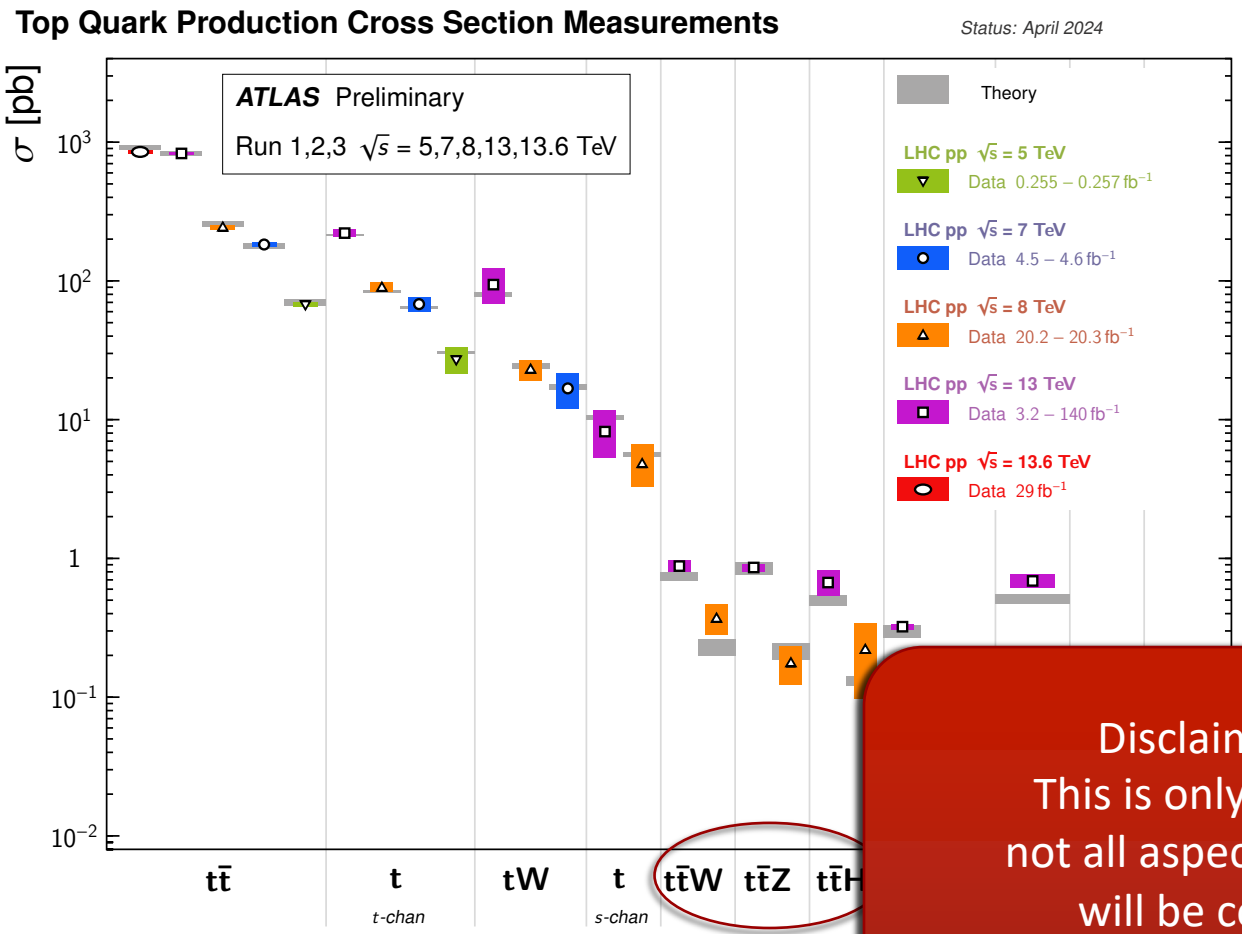
STANDARD MODEL AT THE LHC, 08.05.2024, ROME

Associated ttbar production



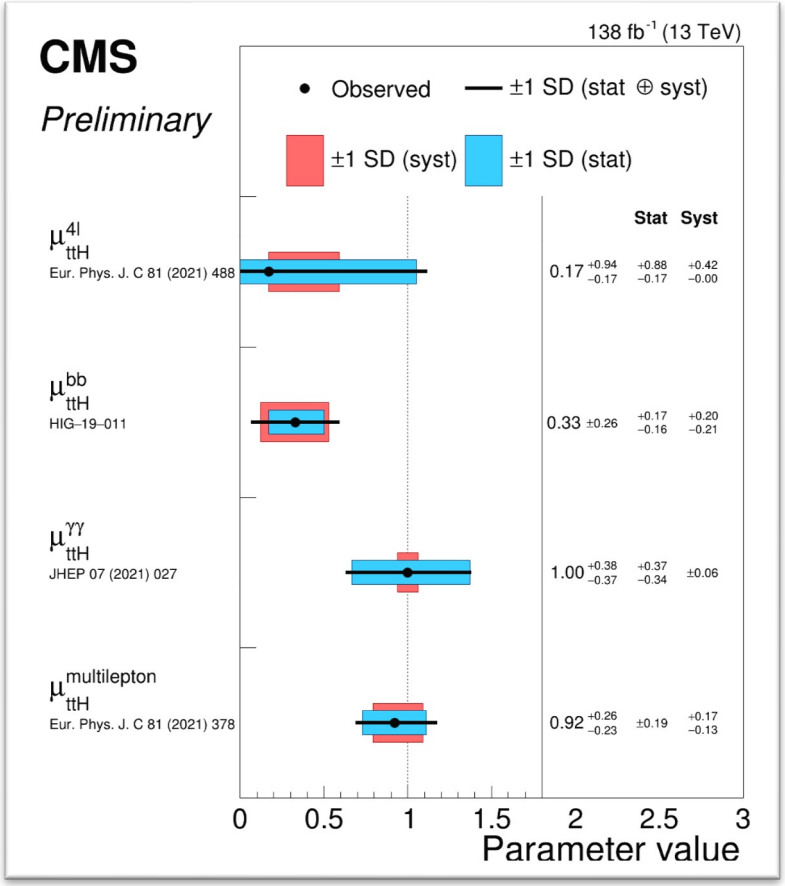
Some of the heaviest signatures measured at the LHC!

Associated ttbar production



Disclaimer and apology:
This is only a limited selection;
not all aspects/publications/work
will be covered in this talk

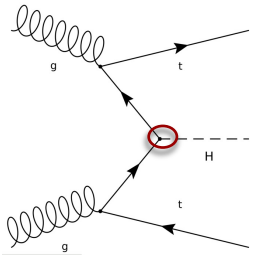
ttH

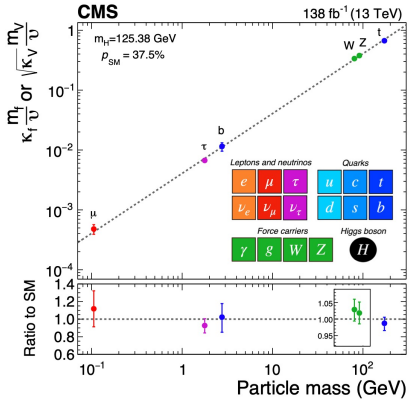


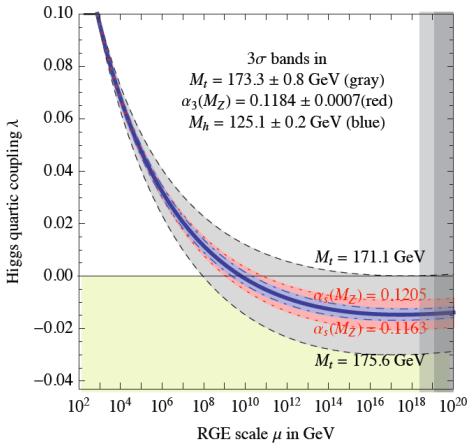
see also talks by
M. Schröder,
M. Grazzini and T. Vitos

Associated Higgs Production with Top Quarks

- Direct probe of the strength of the top-Yukawa coupling without making any assumptions regarding its nature
- Yukawa coupling proportional to mass -> top-Higgs is the strongest interaction of the Yukawa type between fundamental SM particles
- Far-reaching consequences: stability of our Universe
- HL-LHC: expected 3-4% precision for the top-quark Yukawa coupling determination





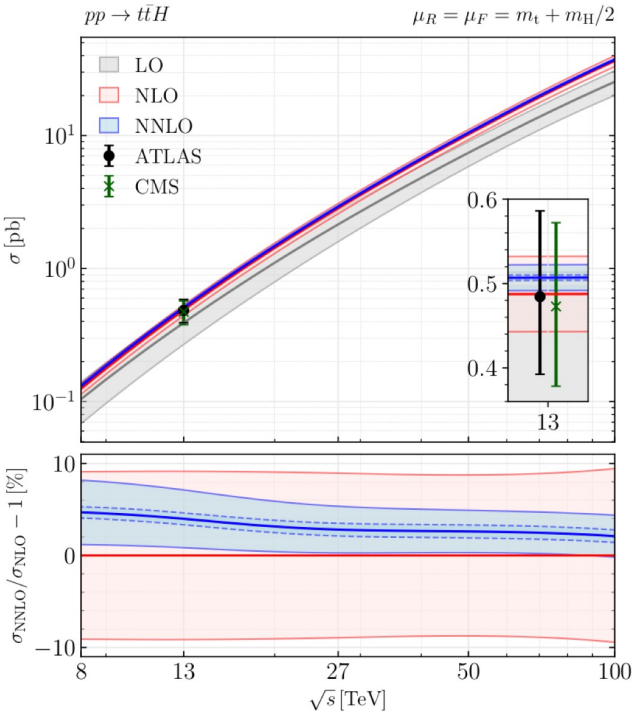


A Brief History of ttH Theory

- NLO QCD available > 20 years *[Beenakker, Dittmaier, Krämer, Plumper, Spira, Zerwas '01-'02][Reina, Dawson'01][Reina, Dawson, Wackeroth'02][Dawson,Orr,Reina,Wackeroth'03] [Dawson, Jackson, Orr, Reina, Wackeroth'03]*
- NLO matched with parton showers *[Garzelli, Kardos,Papadopoulos,Trocsanyi'11] [Frederix, Frixione, Hirschi, Maltoni, Pittau, Torrielli'11] [Hartanto, Jäger,Reina, Wackeroth'15][Maltoni, Pagani, Tsinikos'15] [Pagani, Vitos, Zaro'23]*
- QCD and EW@NLO *[Frixione, Hirschi, Pagani,Shao,Zaro'14-'15][Zhang, Ma, Zhang, Chen, Guo'14][Biedermann, Bräuer, Denner, Pellen, Schumann, Thompson'17]*
- Off-shell effects at NLO QCD *[Denner, Feger'15] [Stremmer, Worek'21]* and EW *[Denner,Lang, Pellen, Uccirati'16]*
- NNLL+NLO resummation in direct QCD *[AK, Motyka, Stebel, Theeuwes'15], [AK, Motyka, Stebel, Theeuwes'17] [AK, Motyka, Schwartländer, Stebel, Theeuwes'20] [Ju and Yang'19]* and in SCET *[Broggio, Ferroglia, Pecjak, Signer, Yang'15] [Broggio, Ferroglia, Pecjak, Yang'16] [Broggio, Ferroglia, Frederix, Pagani, Pecjak, Tsinikos'19]*

NNLO ADVANCES: TTH

- Off-diagonal partonic channels *[Catani, Fabre, Grazzini, Kallweit'21]*
- Coefficients of the two-loop infrared singularities *[Chen, Ma,Wang,Yang,Ye'22]*
- Soft Higgs approximation *[Catani, Devoto, Grazzini, Kallweit, Mazzitelli, Savoini'22]*



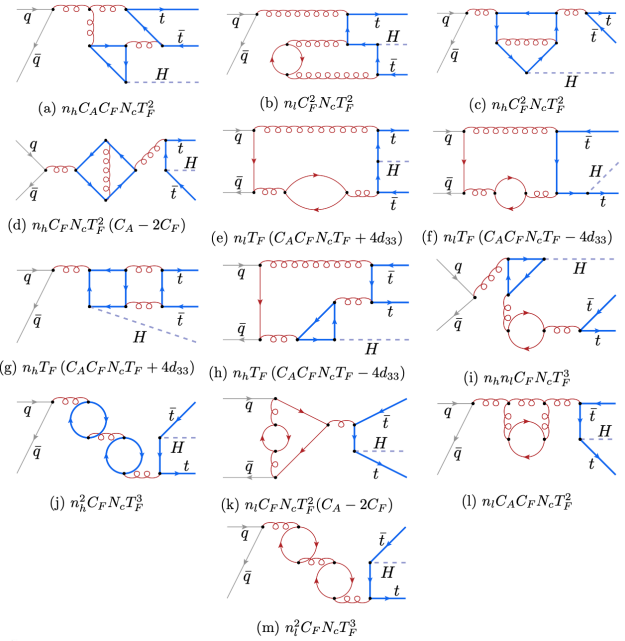
- Full computation using the q_T subtraction framework, apart from the two-loop amplitude
- Two-loop contribution estimated using the soft Higgs approximation: in the limit $p_H \to 0$, $m_H \ll m_t$, Higgs emission is factorized out, in analogy to soft gluon emission
- Two-loop contributions provide ~1% of the NNLO cross section, introducing O(+/- 0.6%) systematic error on NNLO
- 4% correction from NNLO QCD at 13 TeV + reduction of scale uncertainties

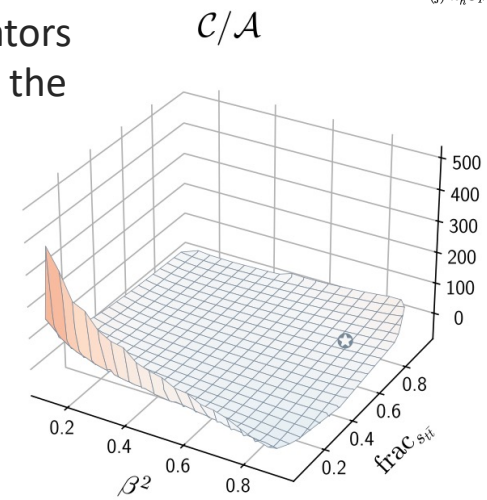
NNLO ADVANCES: TTH

- Off-diagonal partonic channels *[Catani, Fabre, Grazzini, Kallweit'21]*
- Coefficients of the two-loop infrared singularities *[Chen, Ma,Wang,Yang,Ye'22]*
- Soft Higgs approximation *[Catani, Devoto, Grazzini, Kallweit, Mazzitelli, Savoini'22]*
- Analytic results for two-loop master integrals with a light-quark loop in the leading colour approximation *[Febres Cordero, Figueiredo, Kraus, Page, Reina '23]*
- Semi-numerical calculation of the $gg \to ttH$ one-loop amplitude to to $O(\varepsilon^2)$ *[Buccioni, Kreer, Liu, Tancredi '23]*
- Two-loop amplitudes in the high-energy (boosted) limit, $|s_{ij}| \gg m_t^2$ *[Wang, Xia, Yang,Ye'24]*
- Numerical results for the N_f part of the two-loop $qqbar \to ttH$ virtual amplitude *[Agarwal, Heinrich, Jones, Kerner, Klein, Lang, Magerya, Olsson'24]*

2-Loop for ttH Frontier

- N_f part of the two-loop $qq \to ttH$ virtual amplitude *[Agarwal, Heinrich, Jones, Kerner, Klein, Lang, Magerya, Olsson'24]*
  - Numerical reduction to master integrals for individual phase-space points, as well as master integral evaluation
  - Proof of concept for calculation of two-loop pentagon amplitudes with internal massive propagators and three massive particles in the final state



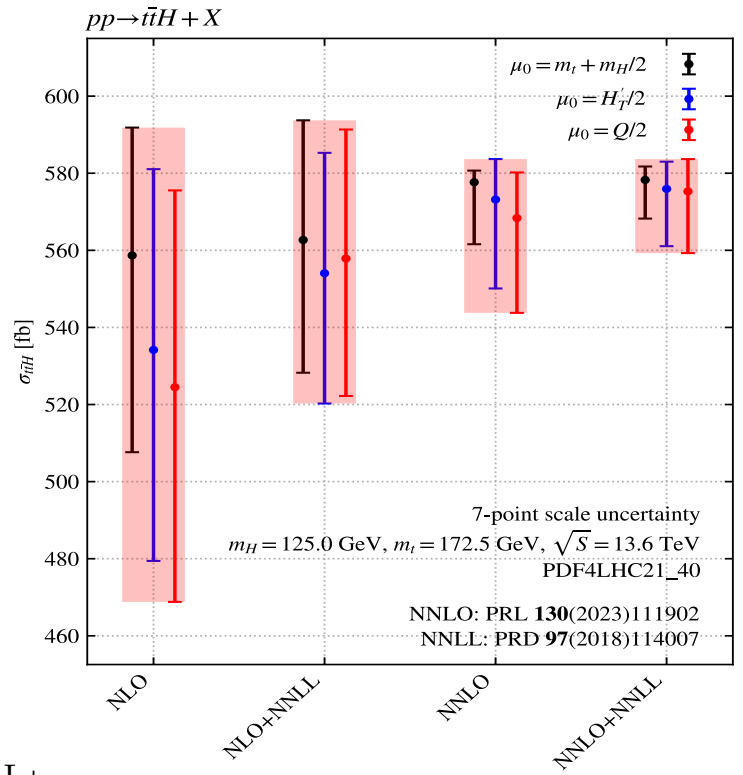


ttH@NNLO+NNLL

[Balsach, AK, Motyka, Stebel]

- The precision of the fixed-order predictions can be further improved by matching the NNLO cross section *[Catani, Devoto, Grazzini, Kallweit, Mazzitelli, Savoini'22]* with NNLL soft gluon resummation *[AK, Motyka, Stebel, Theeuwes'17]*

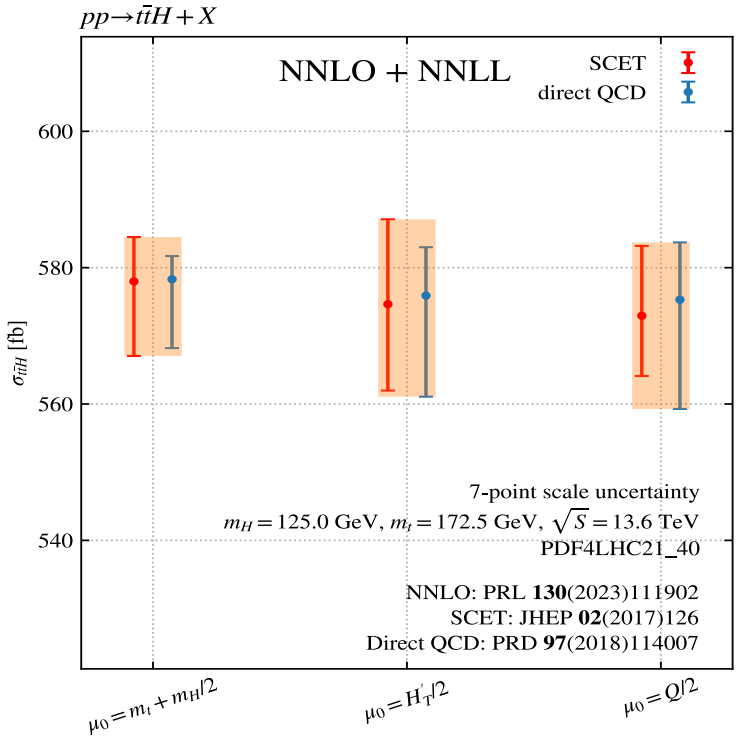
- In addition to NNLO, logarithmic terms of the form $\alpha_s^n \left(\frac{\log^m(1-\hat{\rho})}{1-\hat{\rho}}\right)_+ \; ; \; \hat{\rho} = Q^2/\hat{s}$ are accounted for



$$d\sigma^{\mathrm{N(N)LO+NNLL}} = d\sigma^{\mathrm{N(N)LO}} + d\sigma^{\mathrm{NNLL}} - d\sigma^{\mathrm{NNLL}}|_{\mathrm{N(N)LO}}$$

ttH@NNLO+NNLL

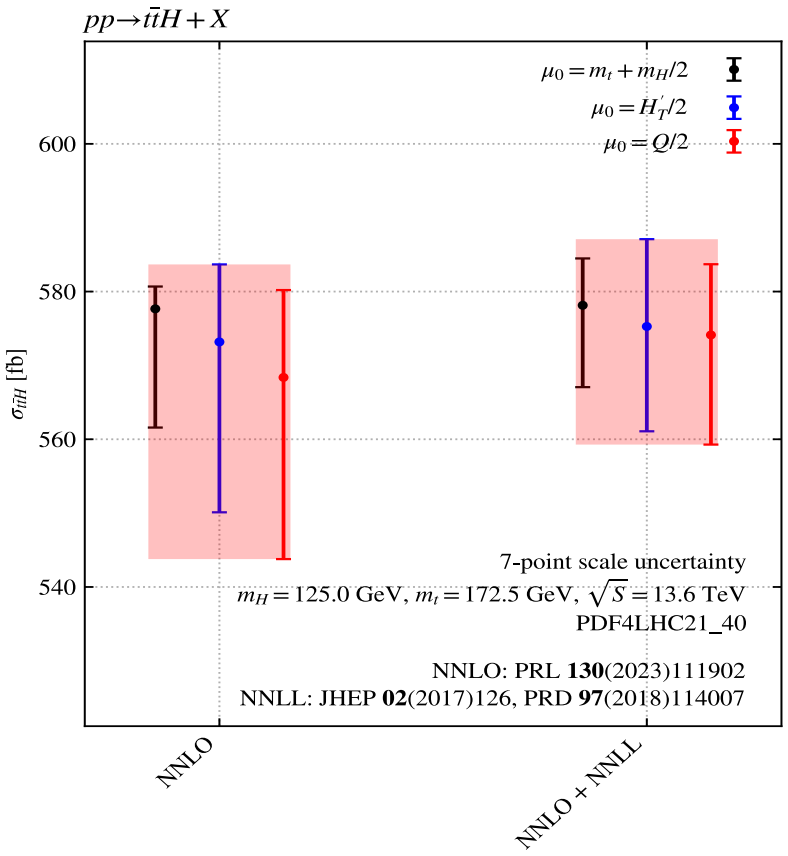
- Comparison with the NNLL+NNLO result based on SCET *[Broggio, Ferroglia, Pecjak, Yang'16]* within the framework of the ttH LHCHWG subgroup



- Two **very different frameworks**: perturbative "full" theory (QCD) vs effective theory (SCET)
- Analytical formulas agree at NNLL
- Different subsets of subleading terms are included beyond NNLL → small numerical differences
- Results for central scale choices agree within a few permille

[NNLL dQCD: Balsach, AK, Motyka, Stebel] [NNLL SCET: Broggio, Ferroglia, Pecjak] [NNLO: Devoto, Grazzini, Kallweit, Mazzitelli, Savoini]

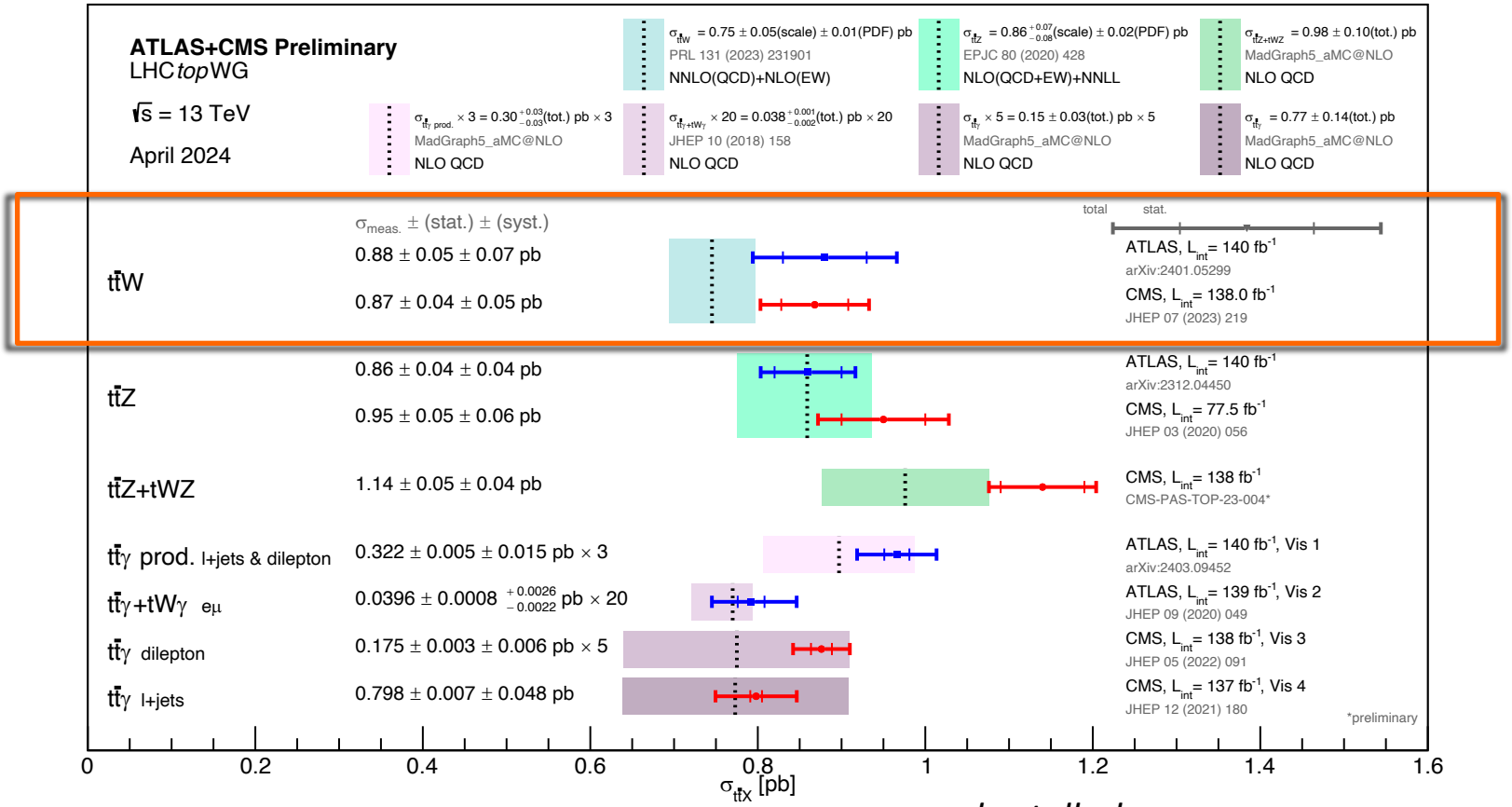
ttH@NNLO+NNLL



- Combination of the (NNLO+)NNLL results obtained in direct QCD and in SCET
  - Central value taken as average of the central values in the two approaches
  - Uncertainties determined from the envelope over the dQCD and SCET scale variation error bands
  - In this way, the uncertainties do not only account for scale variation, but also for O(N^3LL) intrinsic differences between the two formalisms

[NNLL dQCD: Balsach, AK, Motyka, Stebel] [NNLL SCET: Broggio, Ferroglia, Pecjak] [NNLO: Devoto, Grazzini, Kallweit, Mazzitelli, Savoini]

TTW

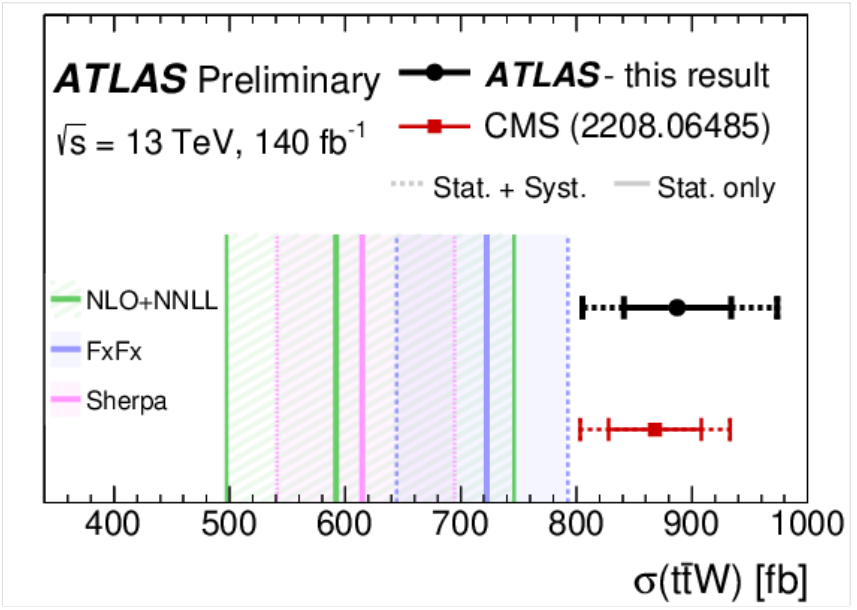


see also talks by
J. Jamieson, M. Schröder
and M. Grazzini

TTW

- Probe of top-quark couplings to EW bosons
- Sensitive to BSM contributions (SUSY, BSM Higgs, vector-like quarks, heavy top quark partners, extra dimensions, ..)
- Dominant backgrounds to searches and SM precision measurements (*ttH* included)
- Additional handle on the top charge asymmetry at the LHC *[Maltoni, Mangano, Tsinikos, Zaro,'14]*
- A lot of interest due to tension between theory and data, both in direct and indirect (ttH, 4t) measurements

ATLAS-CONF-2023-019



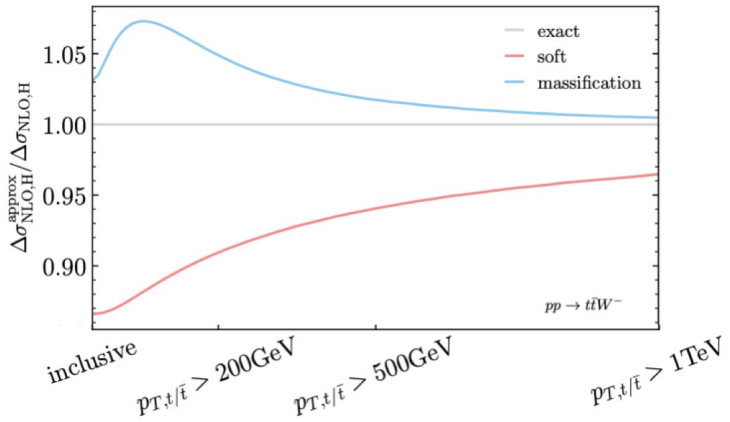
THEORY FOR ttW OVER THE YEARS

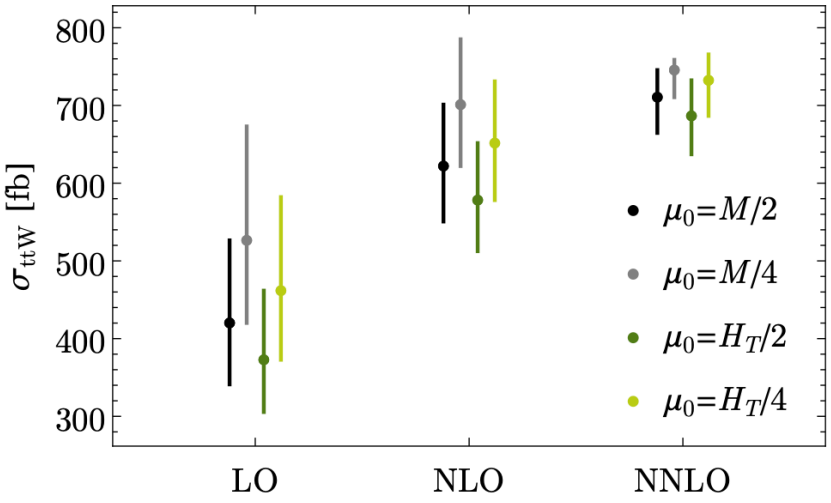
- NLO QCD production and decay *[Campbell, Ellis'12]*
- NLO interfaced to parton showers *[Garzelli, Kardos,Papadopoulos,Trocsanyi'12][Alwall, Frederix, Frixione, Hirschi, Maltoni, Mattalaer, Shao Stelzer, Torrieli, Zaro,'14] [Maltoni, Mangano, Tsinikos, Zaro'14] [Maltoni, Pagani, Tsinikos'15]*
- EW corrections *[Frixione, Hirschi, Pagani, Shao, Zaro'14-15][Dror, Farina, Salvioni, Serra'16][Frederix, Pagani, Zaro'18],* with matching to parton showers *[Frederix, Tsinikos'20] [Febres Cordero, Kraus, Reina'21]* and jet merging *[von Buddenbrock, Ruiz, Mellado'20][Frederix, Tsinikos'21]*
- NNLL+NLO resummation *[Li, Li, Li'14], [Broggio, Ferroglia, Ossola, Pecjak'16] [AK, Motyka, Schwartländer, Stebel, Theeuwes'18] [Broggio, Ferroglia, Frederix, Pagani, Pecjak, Tsinikos'19] [AK, Motyka, Schwartländer, Stebel, Theeuwes'20]*
- Off-shell effects at NLO QCD *[Bevilacqua, Bi, Hartanto, Kraus, Worek'20][Bevilacqua, Bi, Hartanto, Kraus, Nasufi, Worek'21] [Denner, Pelliccioli'20] [Bevilacqua, Bi, Febres Cordero, Hartanto, Kraus, Nasufi, Reina, Worek'22]* and together with NLO EW *[Denner, Pelliccioli'21]*

ttW@NNLO

[Buonocore, Devoto, Grazzini, Kallweit, Mazzitelli, Rottoli, Savoini'23]

- Full computation in the q_T subtraction framework, apart from the two-loop amplitude
- Two approximations used to estimate the two-loop contributions:
  - soft W approximation (p_W small , $m_W \ll m_t$), two-loop ttbar as input
  - massification procedure ($m_t \ll Q_{ttW}$), two-loop W+4 parton as input
- Two-loop contributions provide 6-7% of the NNLO cross section, translating into O(+/- 2%) systematic error on NNLO
- 15% correction from NNLO QCD
- Additional 5% correction from NLO EW





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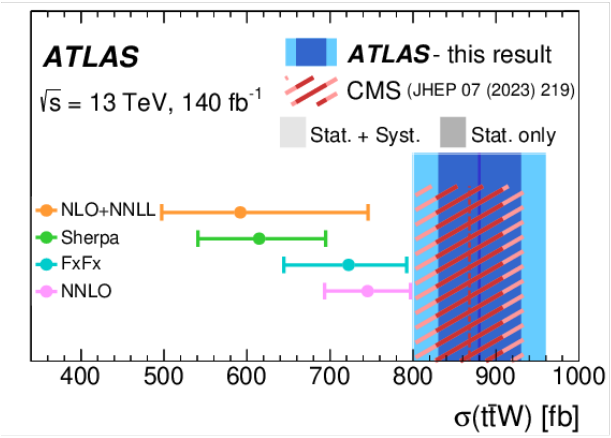
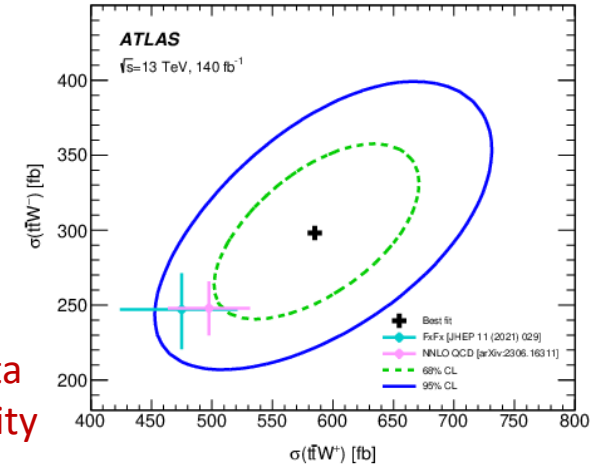




Theory-data compatibility at 1.4 σ

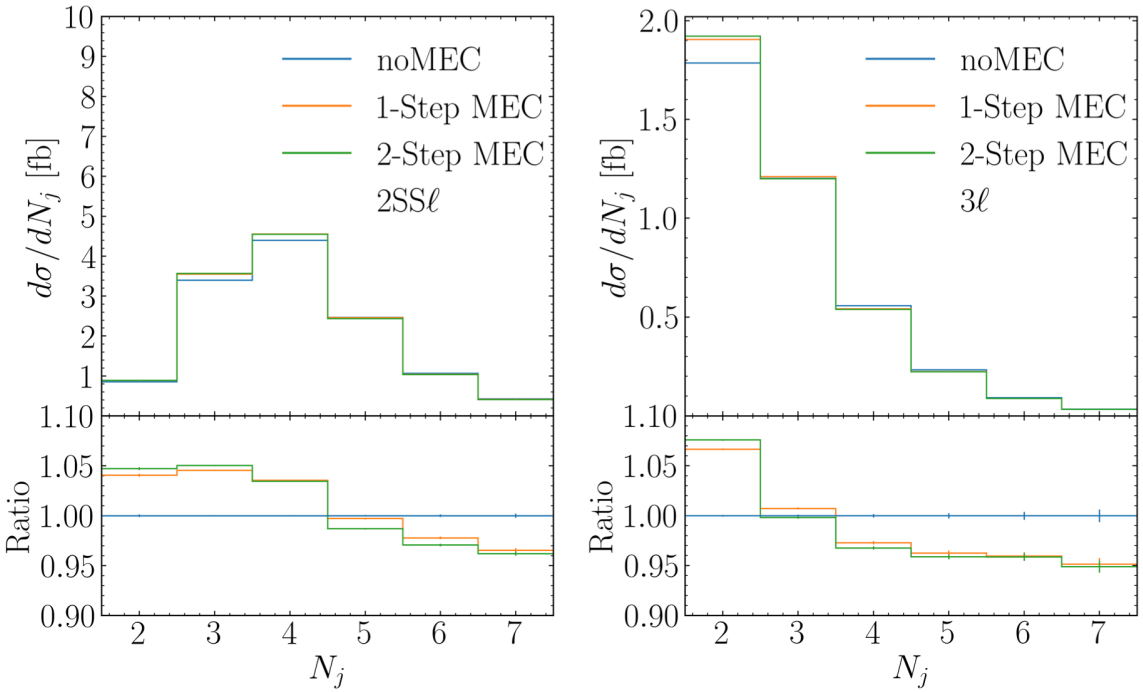
Top decays in ttW

[Frederix, Gellersen, Nasufi'24]

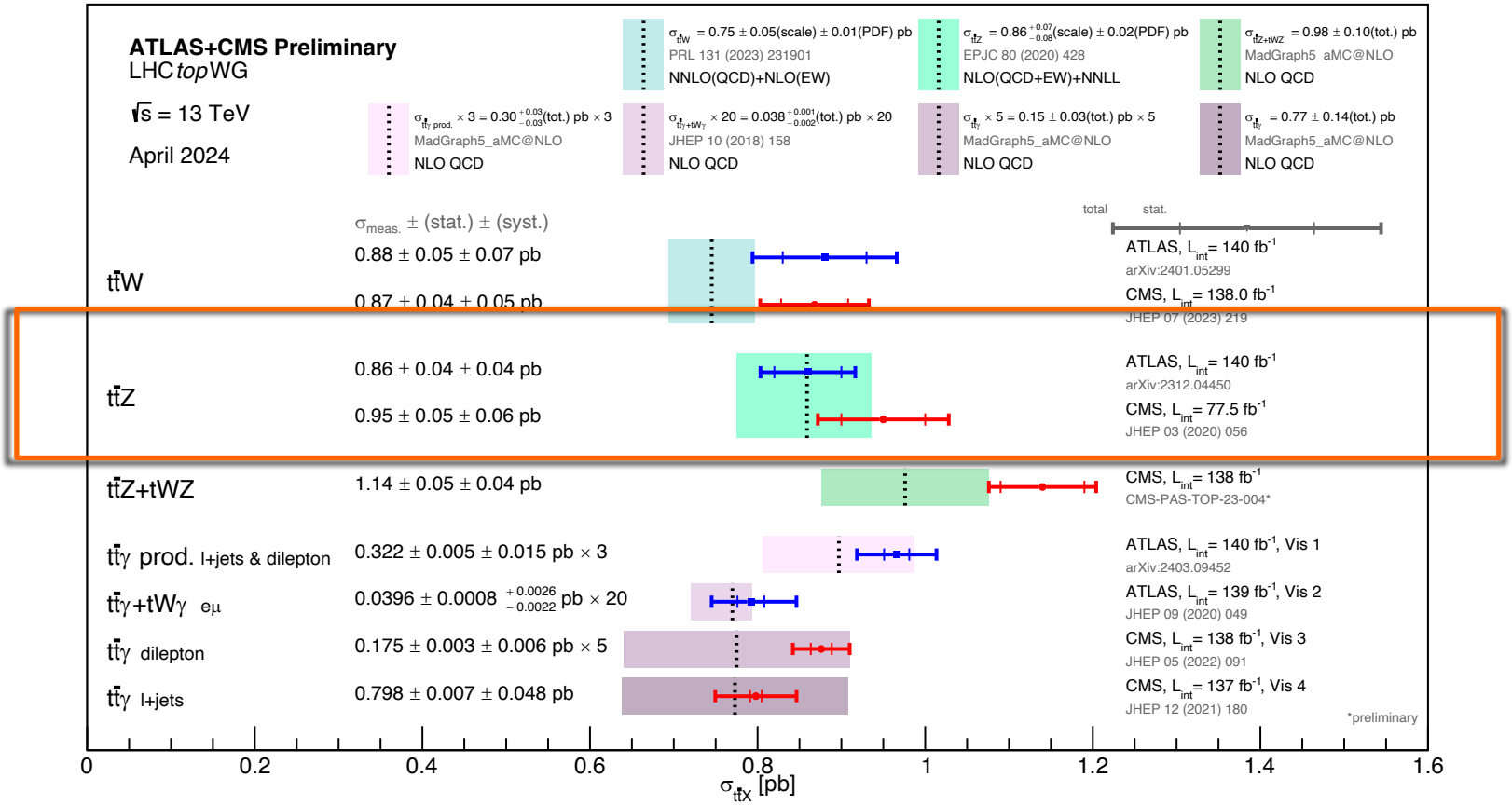
- Resolving incompatibility between matrix element corrections (MEC) in PYTHIA8 and aMC@NLO-style matching enables to account, through MEC, for decay of tops at NLO in the PYTHIA shower

no MEC	$\sigma^{t\bar{t}W^{\pm}}_{2SS\ell} = 12.84$ fb	$\sigma^{t\bar{t}W^{\pm}}_{3\ell} = 3.92$ fb
with MEC	$\sigma^{t\bar{t}W^{\pm}}_{2SS\ell} = 13.12$ fb	$\sigma^{t\bar{t}W^{\pm}}_{3\ell} = 4.02$ fb

2-3% correction to the integrated fiducial cross section



TTZ


ATLAS+CMS Preliminary
LHC top WG
√s = 13 TeV
April 2024
σ_ttW = 0.75 ± 0.05(scale) ± 0.01(PDF) pb
PRL 131 (2023) 231901
NNLO(QCD)+NLO(EW)
σ_ttZ = 0.86 +0.07 −0.08 (scale) ± 0.02(PDF) pb
EPJC 80 (2020) 428
NLO(QCD+EW)+NNLL
σ_tZ+WZ = 0.98 ± 0.10(tot.) pb
MadGraph5_aMC@NLO
NLO QCD
σ_ttγ prod. × 3 = 0.30 +0.03 −0.03 (tot.) pb × 3
MadGraph5_aMC@NLO
NLO QCD
σ_ttγ+tWγ × 20 = 0.038 +0.001 −0.002 (tot.) pb × 20
JHEP 10 (2018) 158
NLO QCD
σ_ttγ × 5 = 0.15 ± 0.03(tot.) pb × 5
MadGraph5_aMC@NLO
NLO QCD
σ_ttγ = 0.77 ± 0.14(tot.) pb
MadGraph5_aMC@NLO
NLO QCD
σ_meas. ± (stat.) ± (syst.)
total
stat.
ttW
0.88 ± 0.05 ± 0.07 pb
ATLAS, L_int = 140 fb^-1
arXiv:2401.05299
0.87 ± 0.04 ± 0.05 pb
CMS, L_int = 138.0 fb^-1
JHEP 07 (2023) 219
ttZ
0.86 ± 0.04 ± 0.04 pb
ATLAS, L_int = 140 fb^-1
arXiv:2312.04450
0.95 ± 0.05 ± 0.06 pb
CMS, L_int = 77.5 fb^-1
JHEP 03 (2020) 056
ttZ+tWZ
1.14 ± 0.05 ± 0.04 pb
CMS, L_int = 138 fb^-1
CMS-PAS-TOP-23-004*
ttγ prod. l+jets & dilepton
0.322 ± 0.005 ± 0.015 pb × 3
ATLAS, L_int = 140 fb^-1, Vis 1
arXiv:2403.09452
ttγ+tWγ eμ
0.0396 ± 0.0008 +0.0026 −0.0022 pb × 20
ATLAS, L_int = 139 fb^-1, Vis 2
JHEP 09 (2020) 049
ttγ dilepton
0.175 ± 0.003 ± 0.006 pb × 5
CMS, L_int = 138 fb^-1, Vis 3
JHEP 05 (2022) 091
ttγ l+jets
0.798 ± 0.007 ± 0.048 pb
CMS, L_int = 137 fb^-1, Vis 4
JHEP 12 (2021) 180
*preliminary
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
σ_ttX [pb]

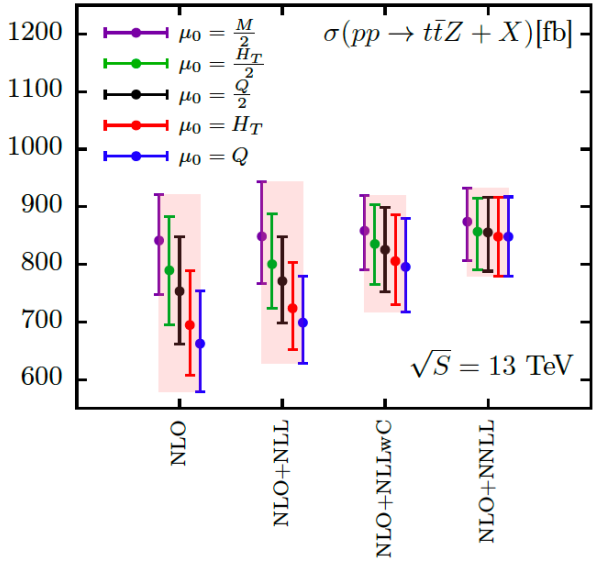
ttZ

- NLO QCD *[Lazopoulos, Melnikov, Petriello'07] [Lazopoulos, McElmurry, Melnikov, Petriello'08] [Kardos, Trocsanyi, Papadopoulos'12]* with decays at NLO *[Roentsch, Schulze'14-'15]*
- NLO interfaced to parton showers *[Alwall, Frederix, Frixione, Hirschi, Maltoni, Mattalaer, Shao Stelzer, Torrieli, Zaro,'14] [Maltoni, Pagani, Tsinikos'15] [Garzelli, Kardos,Papadopoulos,Trocsanyi'11-12][Ghezzi, Jaeger, Chavez,Reina, Wackeroth'15]*
- EW corrections *[Frixione, Hirschi, Pagani,Shao,Zaro'15][Frederix, Frixione, Hirschi, Pagani, Shao, Zaro'18]*
- NNLL resummation *[AK, Motyka, Schwartländer, Stebel, Theeuwes'18-'20]][Broggio, Ferroglia, Ossola, Pecjak, Samoshima'17]*
- Off-shell effects at NLO QCD *[Bevilacqua, Hartanto, Kraus, Weber, Worek'19][Bevilacqua, Bi, Hartanto, Kraus, Nasufi, Worek'22]* and NLO EW *[Denner, Lombardi, Pelliccioli'23]*

ttZ on Shell

[AK, Motyka, Schwartländer, Stebel, Theeuwes'18-'20]

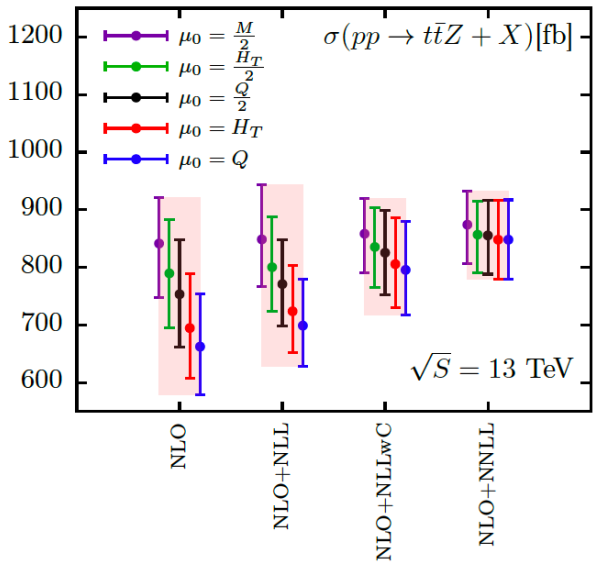
- NLO(QCD+EW) +NNLL resummation

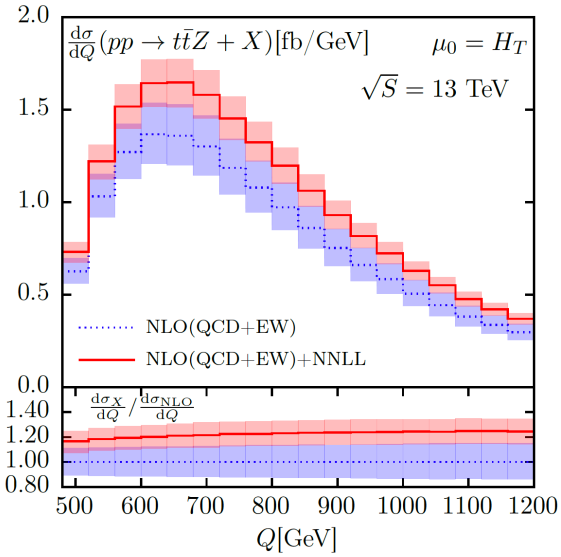


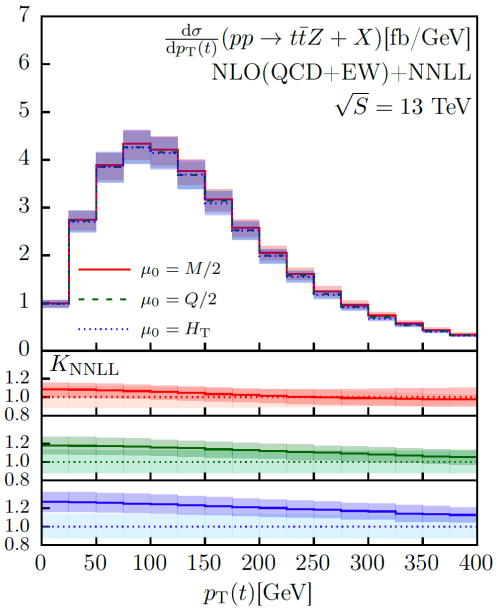
ttZ on Shell

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

- NLO(QCD+EW) +NNLL resummation, also for differential distributions



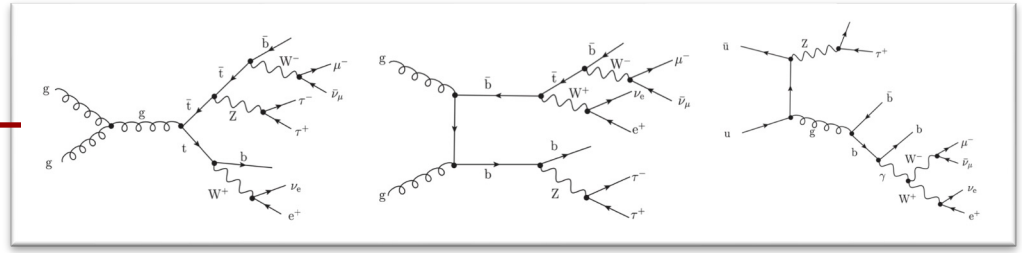


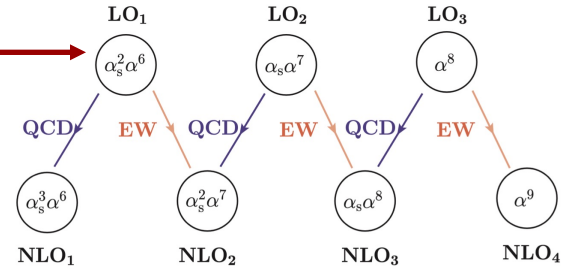


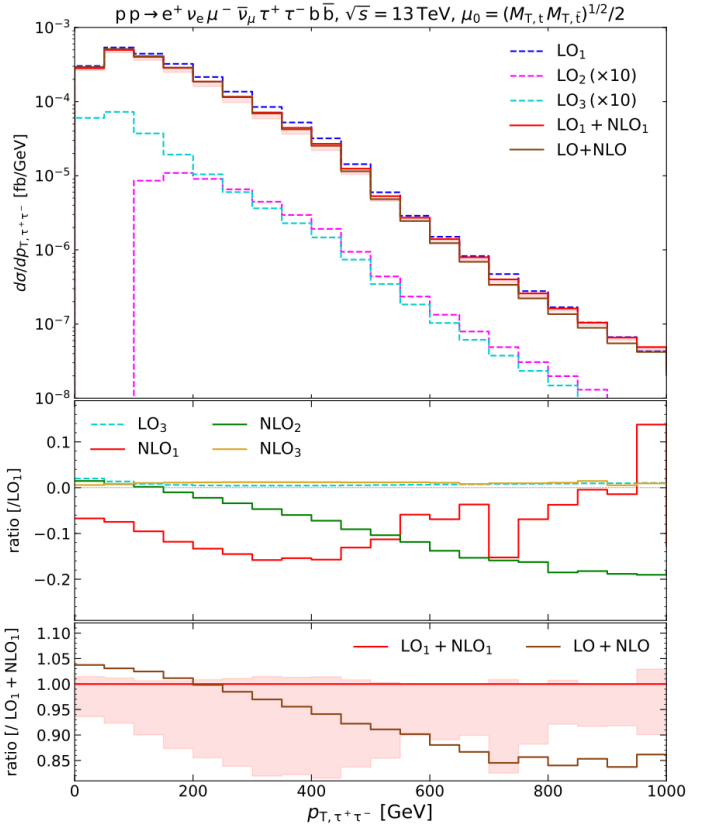
ttZ Off-shell

[Denner, Lombardi, Pelliccioli'23]

- First calculation of the off-shell production of a top–antitop pair in association with a Z boson in the multilepton decay channel accurate both at NLO QCD and NLO EW (full matrix elements)

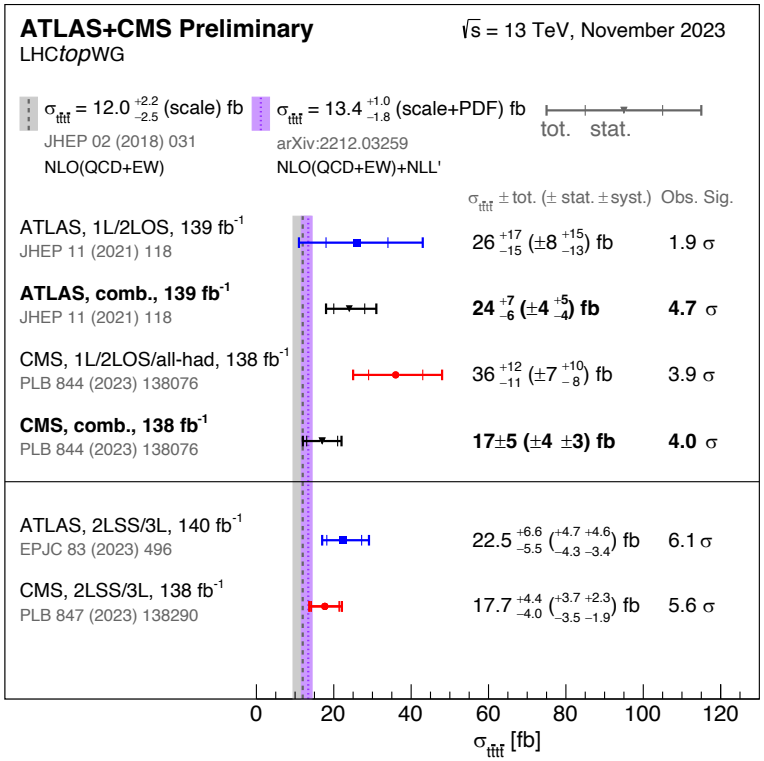






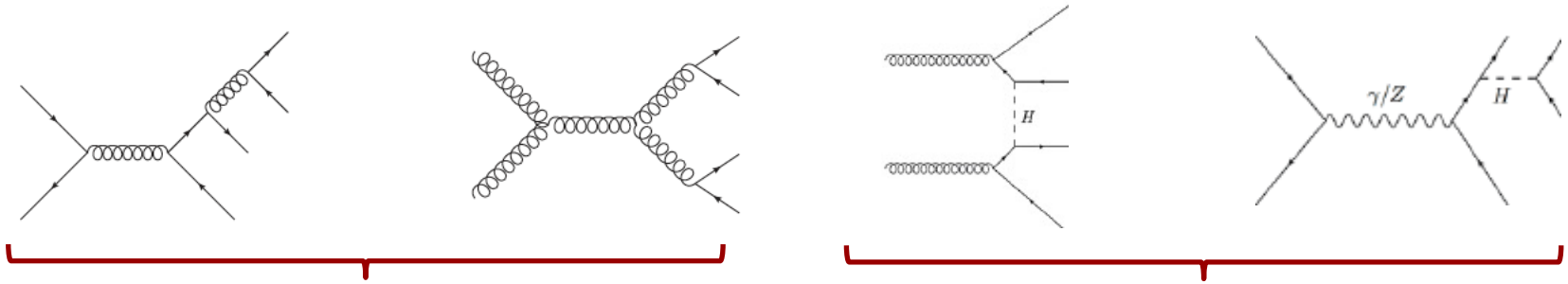
- At the inclusive level, subleading LO and NLO corrections amount to less than 1%

4 TOPS



see also talk by Tae Jeong Kim

4 Tops Theory



- First calculations of NLO QCD corrections in *[Bevilacqua, Worek'12]*
- Matched with parton shower and studied in aMC@NLO *[Alwall et al. '14][Maltoni, Pagani, Tsinikos'15]*
- Full set of EW corrections added in *[Frederix, Pagani, Zaro'17]*
- Spin correlations in LO top quark decays within the framework of Powheg Box *[Jezo, Krauss'21]*

ATLAS, 2303.15061:

$$\sigma_{t\bar{t}t\bar{t}} = 22.5^{+6.6}_{-5.5}\ \text{fb}$$

CMS , 2305.13439:

$$\sigma(t\bar{t}t\bar{t}) = 17.7^{+4.4}_{-4.0}\ \text{fb}$$

4 TOPS

- On-shell production:

$\sqrt{s}$ (TeV)	NLO
13	$11.00(2)^{+25.2\%}_{-24.5\%}$ fb
$\sqrt{s}$ (TeV)	NLO(QCD+EW)
13	$11.64(2)^{+23.2\%}_{-22.8\%}$ fb

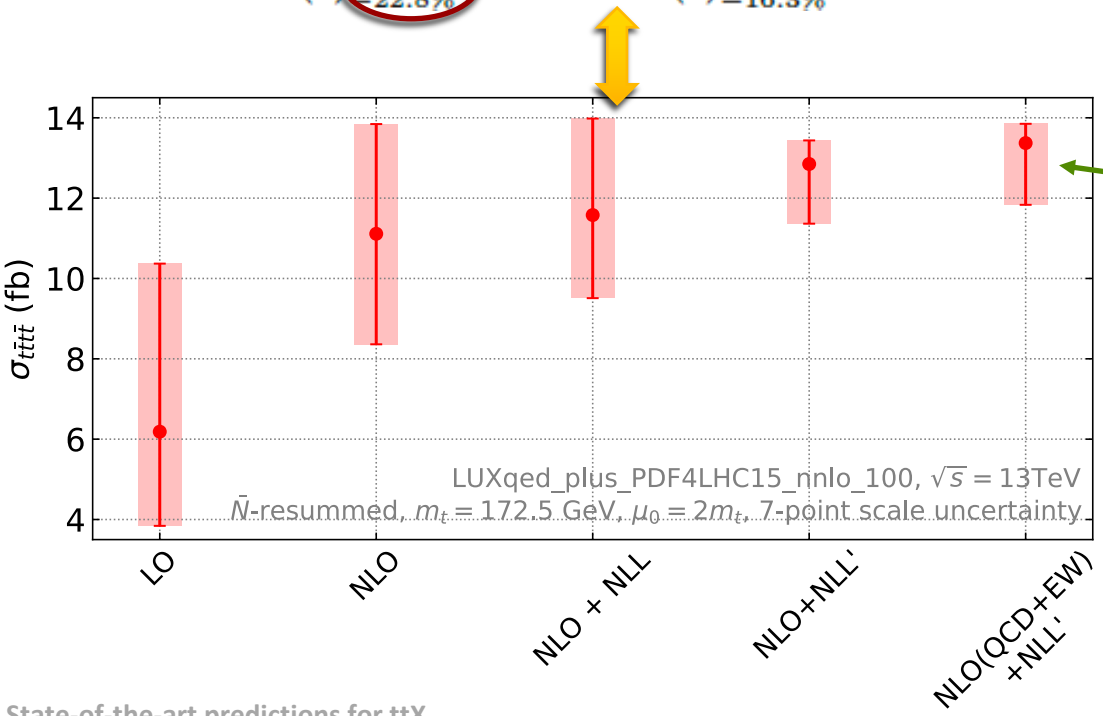
4 TOPS

[van Beekveld, AK, Moreno Valero'22]

- On-shell production:

QCD only

$\sqrt{s}$ (TeV)	NLO	NLO+NLL	NLO+NLL′	$K_{NLL'}$
13	$11.00(2)^{+25.2\%}_{-24.5\%}$ fb	$11.46(2)^{+21.3\%}_{-17.7\%}$ fb	$12.73(2)^{+4.1\%}_{-11.8\%}$ fb	1.16
$\sqrt{s}$ (TeV)	NLO(QCD+EW)	NLO(QCD+EW)+NLL	NLO(QCD+EW)+NLL′	$K_{NLL'}$
13	$11.64(2)^{+23.2\%}_{-22.8\%}$ fb	$12.10(2)^{+19.5\%}_{-16.3\%}$ fb	$13.37(2)^{+3.6\%}_{-11.4\%}$ fb	1.15



- **Reduction** of the scale error by **more than a factor of 2**
- 15 % correction to the NLO (QCD+EW) prediction due to NLL' resummation

Top Decay@NLO; 4 tops

[Dimitrakopoulos, Worek'24]

NLO QCD corrections to 4t production and decay in the 4 lepton channel in the NWA

$$pp \to t\bar{t}t\bar{t} + X \to W^+W^-W^+W^- b\bar{b}b\bar{b} + X \to \ell^+\nu_\ell\,\ell^-\bar{\nu}_\ell\;\ell^+\nu_\ell\,\ell^-\bar{\nu}_\ell\,b\bar{b}b\bar{b} + X$$

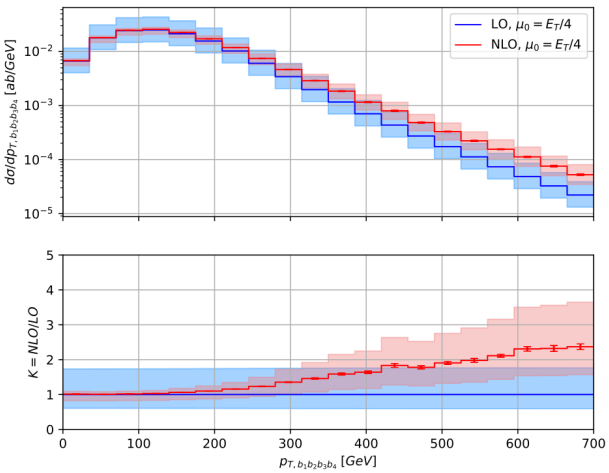
- Integrated fiducial cross sections

Decay treatment	$\sigma_i^{\rm NLO}$ [ab]	$+\delta_{scale}$ [ab]	$-\delta_{scale}$ [ab]
	$\mu_R = \mu_F = \mu_0 = 2m_t$		
full	5.462(3)	+0.156 (3%)	−0.853 (16%)
$\rm LO_{dec}$	5.295(3)	+1.123 (21%)	−1.224 (23%)
exp	4.895(2)	+0.624 (13%)	−1.002 (20%)

- NLO corrections to top decay impact both the size of the cross section and their scale uncertainties

- Differentially, for the majority of observables, stable and moderate corrections, similar to the integrated ones

- Apart from observables sensitive to additional jet radiation



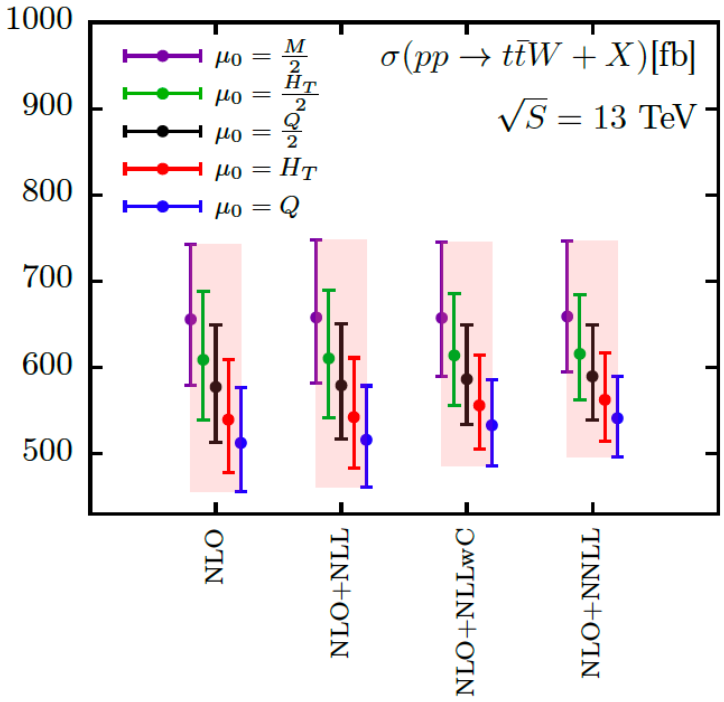
Summary

- Ongoing progress on increasing accuracy of the fixed-order predictions to NNLO -> two-loop virtual contributions; proof-of-concept calculations emerging
- ttH, ttW cross-sections (amplitudes) for on-shell production available at NNLO in the soft Higgs/soft W+massification approximations
- ttH: further improvement of theoretical precision achieved with NNLL resummation, very good agreement at NNLO+NNLL between two independent calculations; NNLL (+NLO) results for ttZ also available
- ttH, ttW, ttZ: off-shell effects calculated at NLO, including EW effects

BACKUP

NNLL FOR TTW

[AK, Motyka, Schwartländer, Stebel, Theeuwes'18-20']



- NNLL resummation provides only a moderate correction: only $q\bar{q}$ initial channel at LO

	μ_0	NLO[fb]	NLO+NNLL[fb]	K_{NNLL}
$t\bar{t}W$	Q	$512^{+12.5\%}_{-11.1\%}$	$541^{+8.9\%}_{-8.4\%}$	1.06
	H_T	$539^{+13.0\%}_{-11.3\%}$	$562^{+9.6\%}_{-8.5\%}$	1.04
	$Q/2$	$577^{+12.5\%}_{-11.1\%}$	$590^{+10.0\%}_{-8.5\%}$	1.02
	$H_T/2$	$609^{+13.0\%}_{-11.5\%}$	$616^{+11.2\%}_{-8.8\%}$	1.01
	$M/2$	$656^{+13.2\%}_{-11.7\%}$	$659^{+13.3\%}_{-9.8\%}$	1.00