Funded by
DFG Deutsche Forschungsgemeinschaft
German Research Foundation

Theoretical Aspects of Top-Quark Physics

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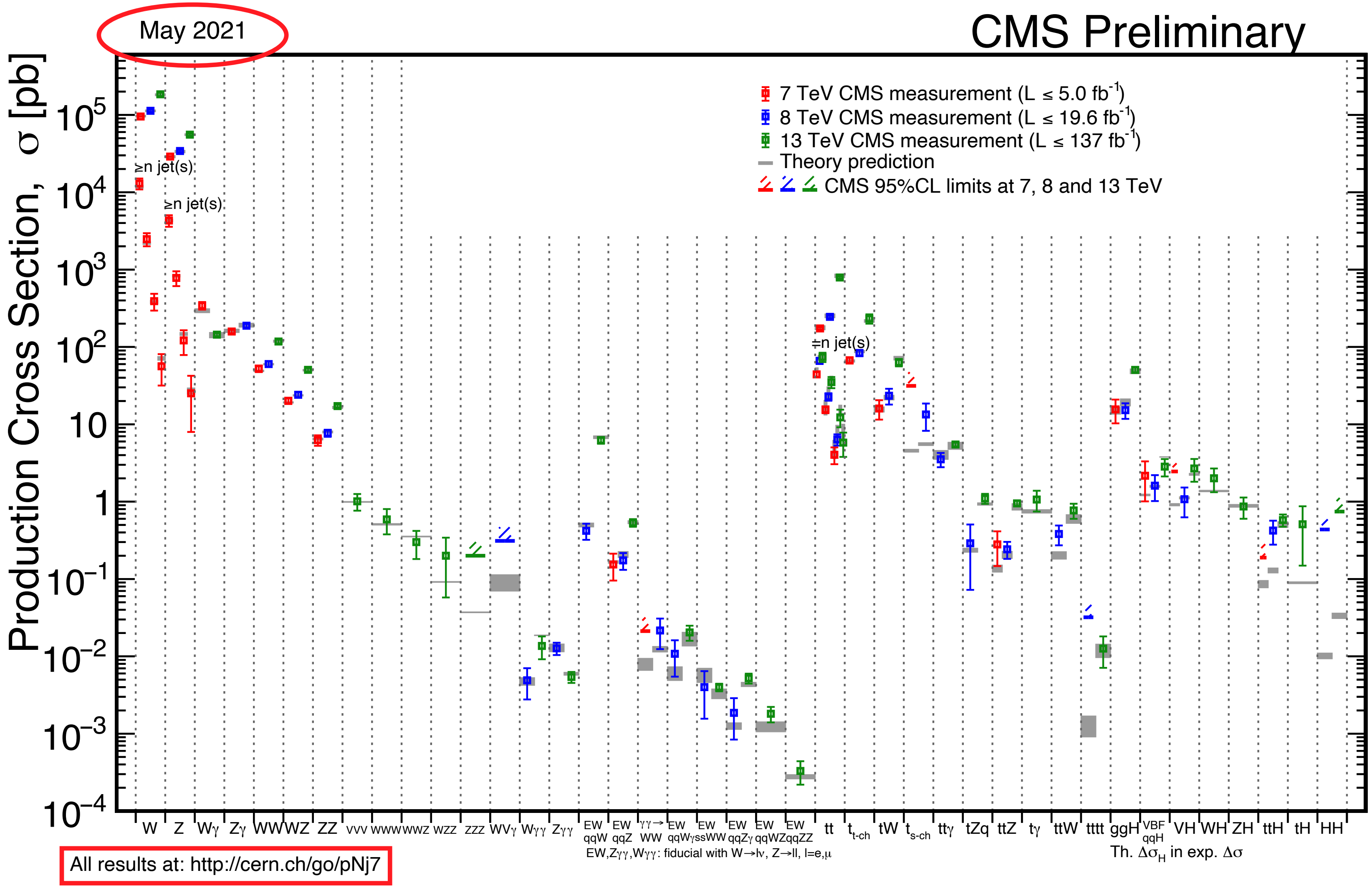
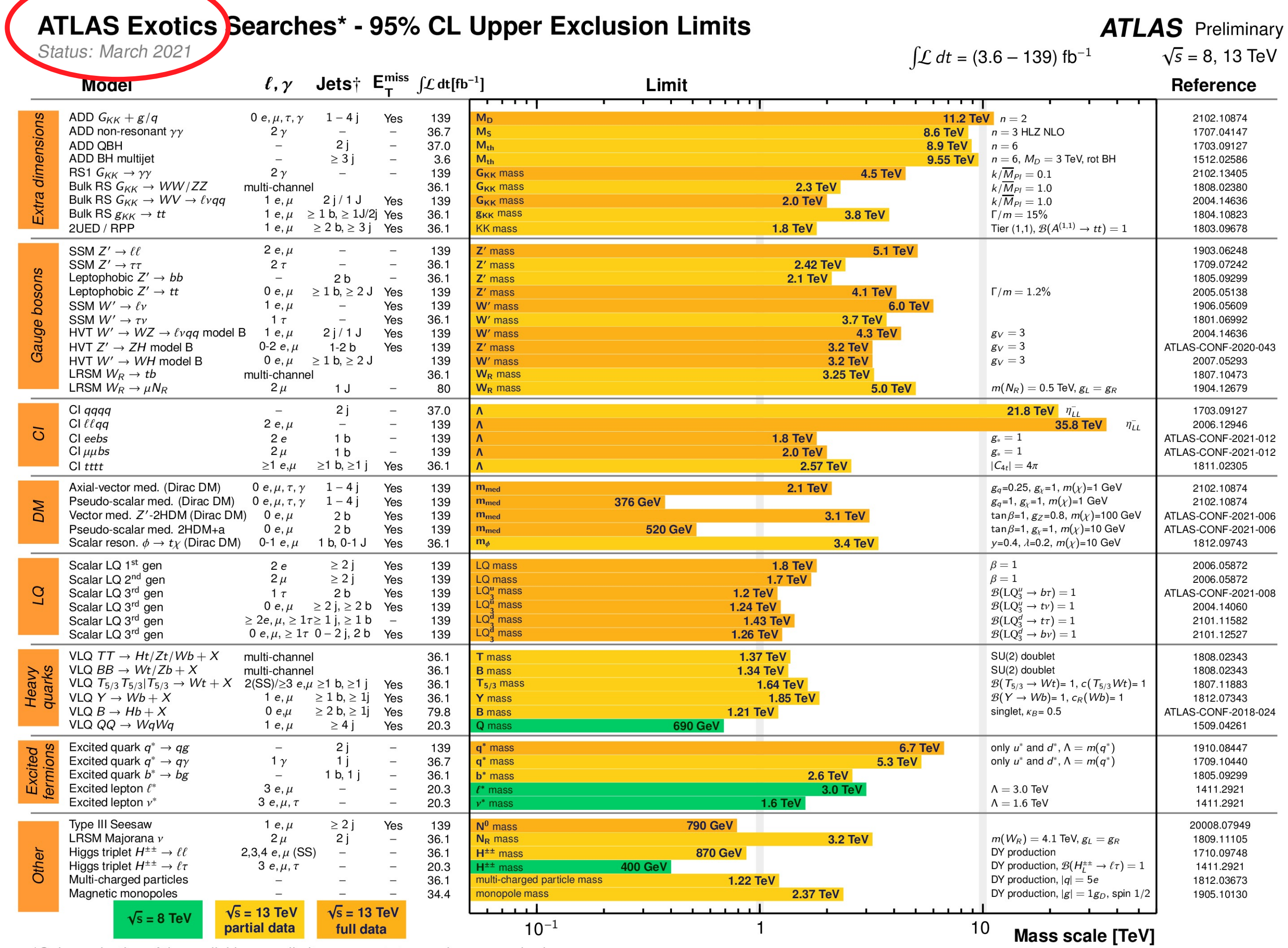
LHC continues to confirm Standard Model



SM has been extremely successful in describing experimental data accumulated so far ...

No sign of New Physics in TeV range



*Only a selection of the available mass limits on new states or phenomena is shown.
†Small-radius (large-radius) jets are denoted by the letter j (J).

ATL-PHYS-PUB-2021-009

- Significant number of open questions remains
- Search for new phenomena key aspect of physics programme of LHC

Instead of Introduction

- SM ⇰ Extremely fun & exciting & enjoyable time for people working on *QCD + EW*

- BSM Direct Searches
  - Many proposals for New Physics
  - No model of New Physics really stands out ⇰ No obvious Candidates to look for @ LHC

- BSM Indirect Searches
  - New Physics can be seen as small corrections to SM reactions
  - Precision SM measurements @ LHC ⇰ BSM Physics ⇰ High Luminosity LHC
  - Fully exploit experimental program ⇰ High Precision Theoretical Predictions ⇰ Top Quark

CERN webpage: LHC/ HL-LHC Plan (last update January 2021)

Unlike Other Quarks

- *Top Quark* ⇨ Discovered at TeVatron in 1995
- Heaviest observed particle

$$m_t = (173.34 \pm 0.76)\ \text{GeV}$$

World Combination '14
ATLAS, CDF, CMS, D0

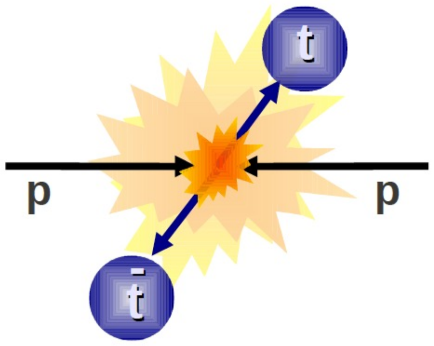
- Substantial Yukawa coupling ⇨ Special relation with SM Higgs boson

$$Y_t = \sqrt{2}\,\frac{m_t}{v} \approx 1$$

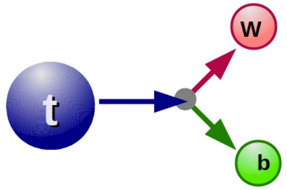
- Short lifetime ⇨ Decay before bound states can be formed
- Direct handle on top-quark properties from its decay products

$$b-jets, p_T^{miss}, \ell^{\pm}\ \&\ light-jets$$

Production



Decays

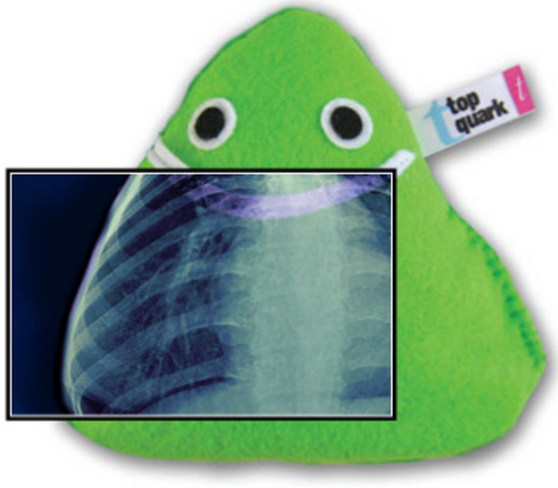


Intrinsic properties

Why top quark is special

- **Precision Top-Quark Physics**
  - Infrared structure of *QCD*
  - Electroweak sector of SM

  } Perturbative calculations



- **Precision Top-Quark physics & BSM Direct Searches**
  - *tt & tt + jets & tt + V* ⇨ Main backgrounds to many BSM scenarios

- **Precision Top-quark physics & BSM Indirect Searches**
  - Various production modes & decay channels & properties & rare decays & …
  - Extract SM parameters
  - Constraining PDFs
  - Verify Higgs boson couplings to top quark & top quark to gauge bosons
  - Study specific infra-red safe observables
  - Cross section ratios
  - Various asymmetries

- **Discrepancies between Precise measurements & Precise Theory**
  - Find hints of new physics in LHC data

LHC as Top Quark Factory

	Collider	σ_{tt} [pb]	L [fb^{-1}]	N_{event}
LHC Run 1	$LHC_{7\ TeV}$	180	5.0	9×10^5
	$LHC_{8\ TeV}$	256	19.7	5×10^6
LHC Run 2	$LHC_{13\ TeV}$	835	139	1×10^8
High Luminosity	$HL\text{-}LHC_{14\ TeV}$	987	3000	3×10^9
High Energy	$HE\text{-}LHC_{27\ TeV}$	3840	15000	6×10^{10}

ATLAS & CMS
Statistics doubled
HL-LHC

Top quark pair production @ NNLO QCD with *TOP++*
CT14nnlo PDF & m_t = 173.2 GeV
$\mu_R = \mu_F = \frac{1}{2} m_t$

Theoretical uncertainties:
NNLO QCD: *5% - 6%*
NNLO QCD + NNLL: *3% - 4%*

Czakon, Mitov arXiv:1112.5675 [hep-ph]

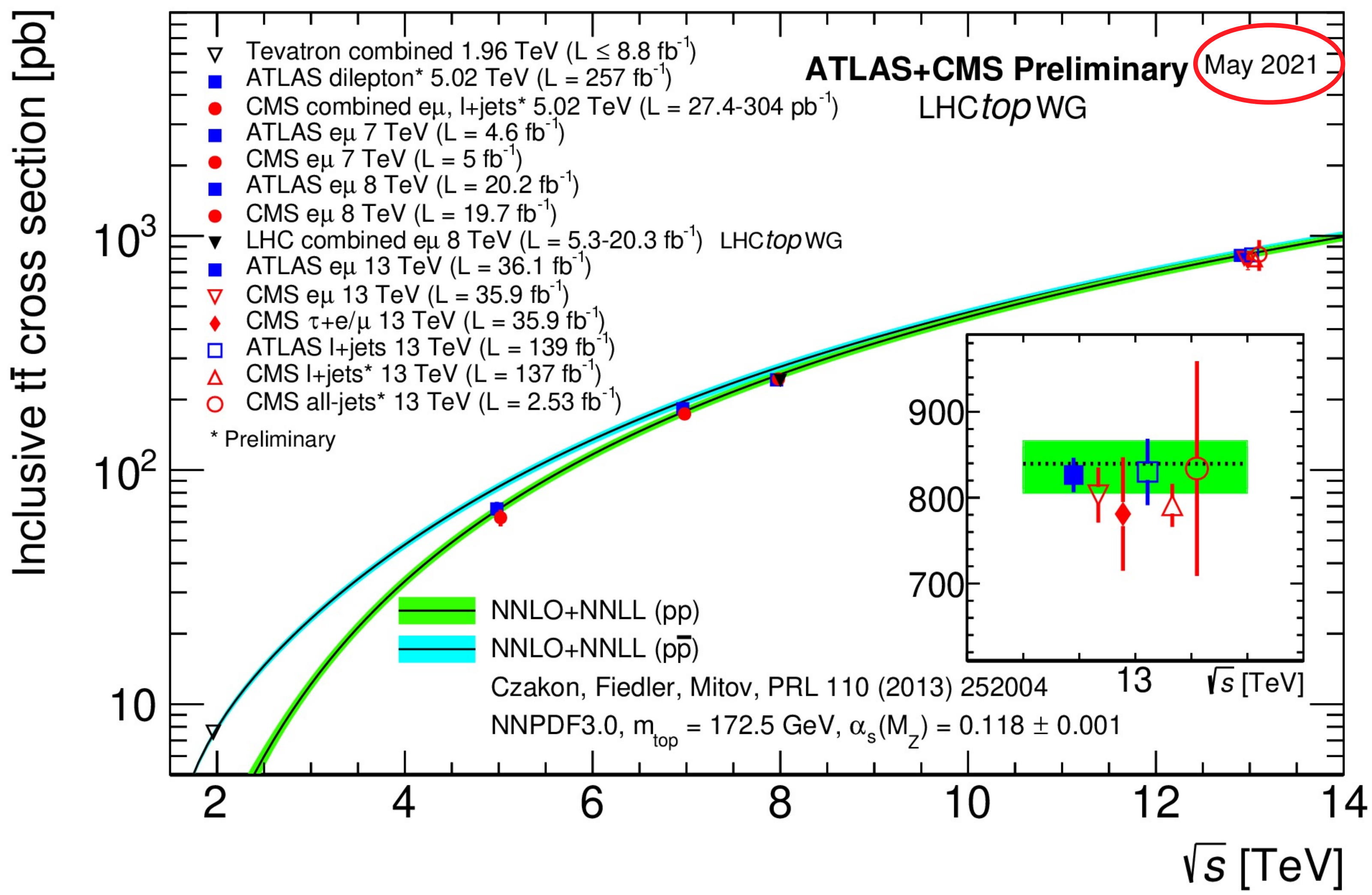
Disclaimer

- Many new & interesting results
- (Biased) Selection ⇨ Only latest ***2020 & 2021*** results
- Only state-of-the-art results
- Only fixed order ***NNLO & NLO*** results
- Only ***QCD***
- Only Standard Model

Goal

- Identify which effects are important & should be taken into account ⇨ Few examples ⇨ Important for Higgs boson studies in ***ttH***

Top-Quark Pair Production @ NNLO + NNLL



- *LHC & Tevatron* measurements of σ_{tt} as function of $\sqrt{s}$
- Compared to NNLO *QCD* calculation complemented with NNLL resummation (top++2.0)
- Theory band represents uncertainties due to μ_R & μ_F & *PDF*
- Measurements and theory calculation for m_t=172.5 GeV

Top-Quark Pair Production & Decay @ NNLO

$$\mathrm{d}\sigma = \mathrm{d}\sigma^{\mathrm{LO}} + \alpha_s \mathrm{d}\sigma^{\mathrm{NLO}} + {\alpha_s}^2 \mathrm{d}\sigma^{\mathrm{NNLO}}$$

- Predictions in NWA

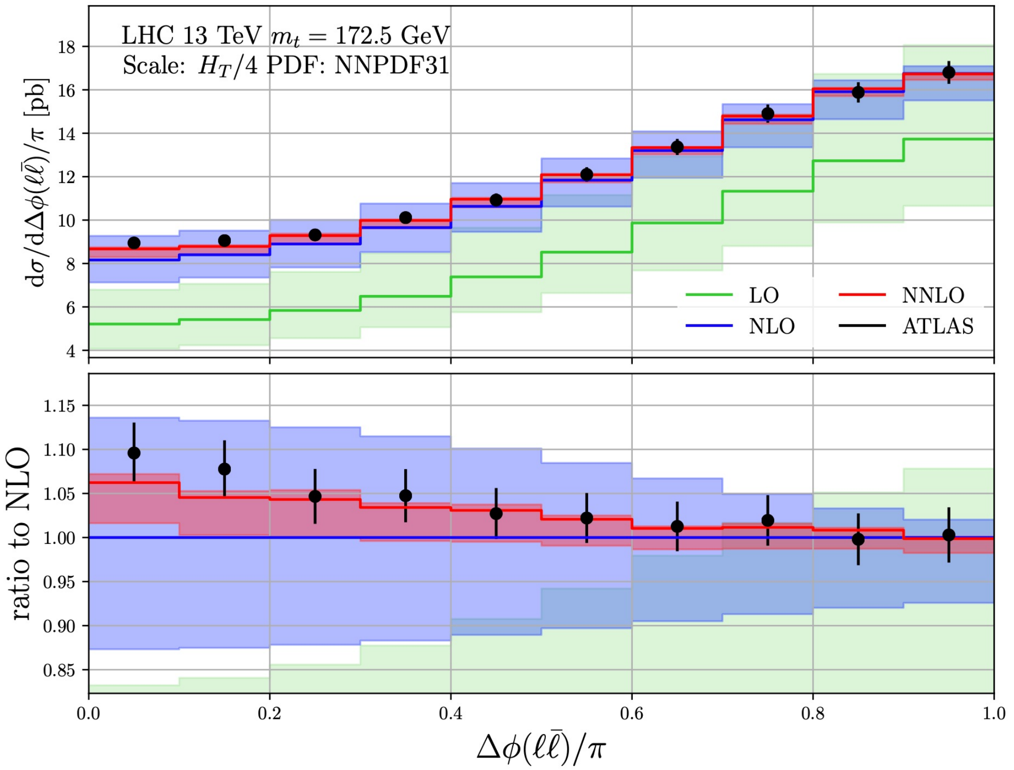
$$\mathrm{d}\sigma^{\mathrm{LO}} = \sigma^{\mathrm{LOxLO}},$$

$$\mathrm{d}\sigma^{\mathrm{NLO}} = \mathrm{d}\sigma^{\mathrm{NLOxLO}} + \mathrm{d}\sigma^{\mathrm{LOxNLO}} - \frac{2\Gamma_t^{(1)}}{\Gamma_t^{(0)}}\mathrm{d}\sigma^{\mathrm{LO}},$$

$$\mathrm{d}\sigma^{\mathrm{NNLO}} = \mathrm{d}\sigma^{\mathrm{NNLOxLO}} + \mathrm{d}\sigma^{\mathrm{NLOxNLO}} + \mathrm{d}\sigma^{\mathrm{LOxNNLO}} - \frac{2\Gamma_t^{(1)}}{\Gamma_t^{(0)}}\mathrm{d}\sigma^{\mathrm{NLO}} + \left(\frac{3\Gamma_t^{(1)2}}{\Gamma_t^{(0)2}} - \frac{2\Gamma_t^{(0)}\Gamma_t^{(2)}}{\Gamma_t^{(0)2}}\right)\mathrm{d}\sigma^{\mathrm{LO}}$$

Di-lepton

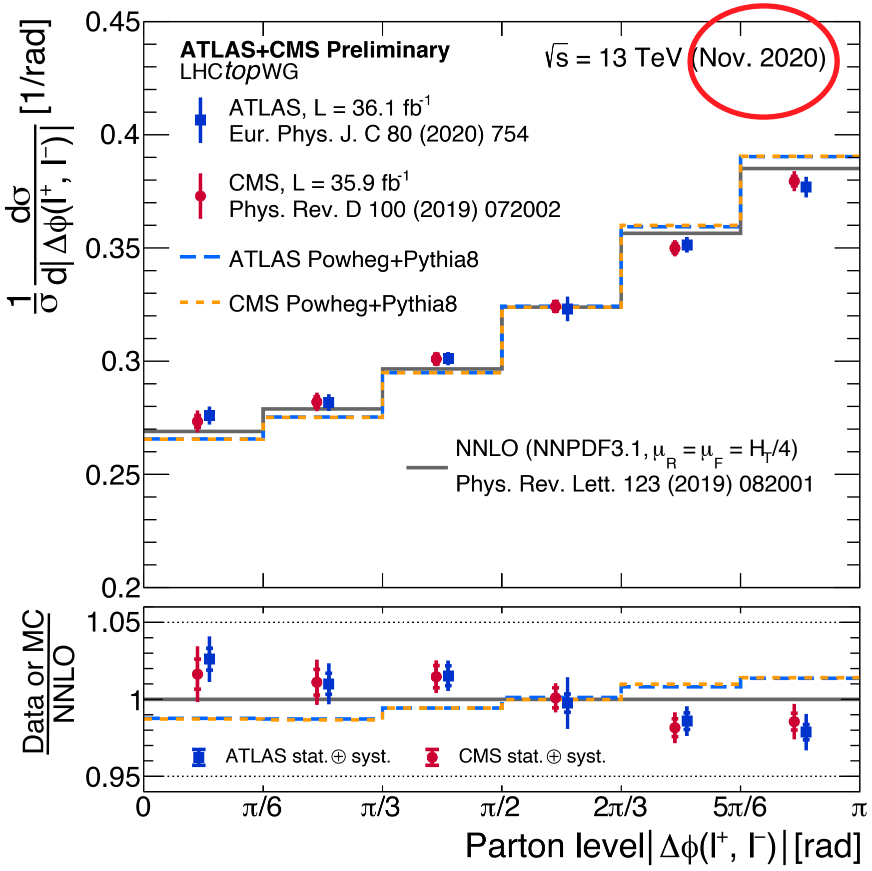
Czakon, Mitov, Poncelet arXiv:2008.11133 [hep-ph]



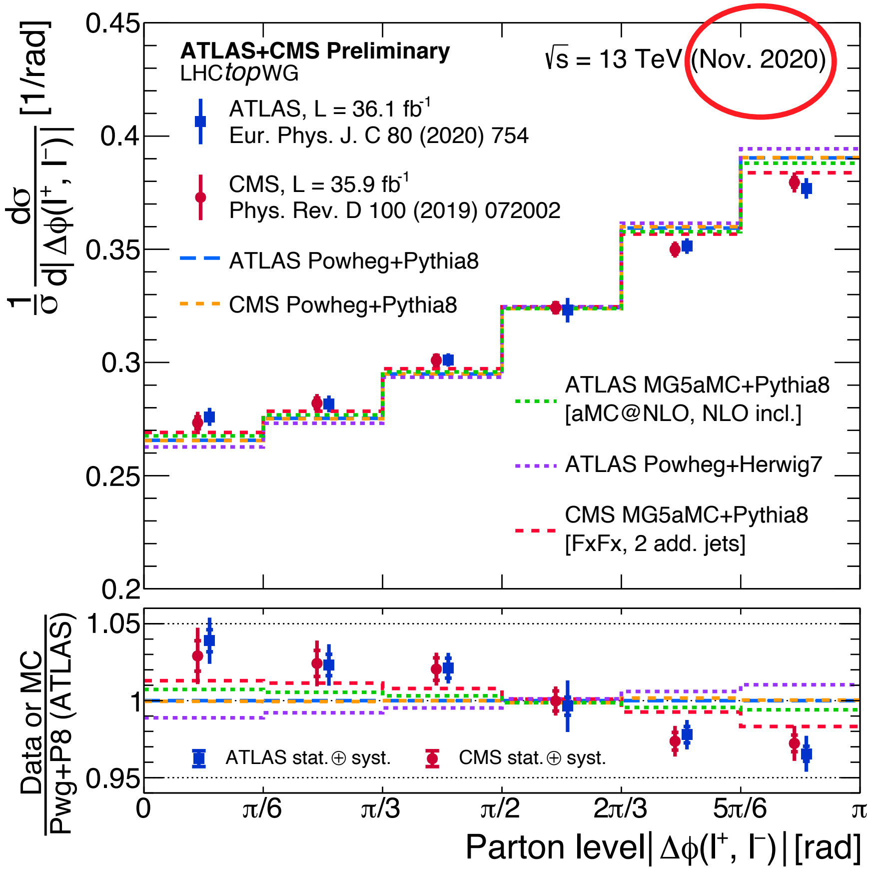
$$pp \to t\bar{t} + X \to W^+W^-b\bar{b} + X \to \ell^+\nu_\ell\,\ell^-\bar{\nu}_\ell\,b\bar{b} + X$$

Top-Quark Pair Production & Decay @ NNLO

LHCTopWG



Di-lepton



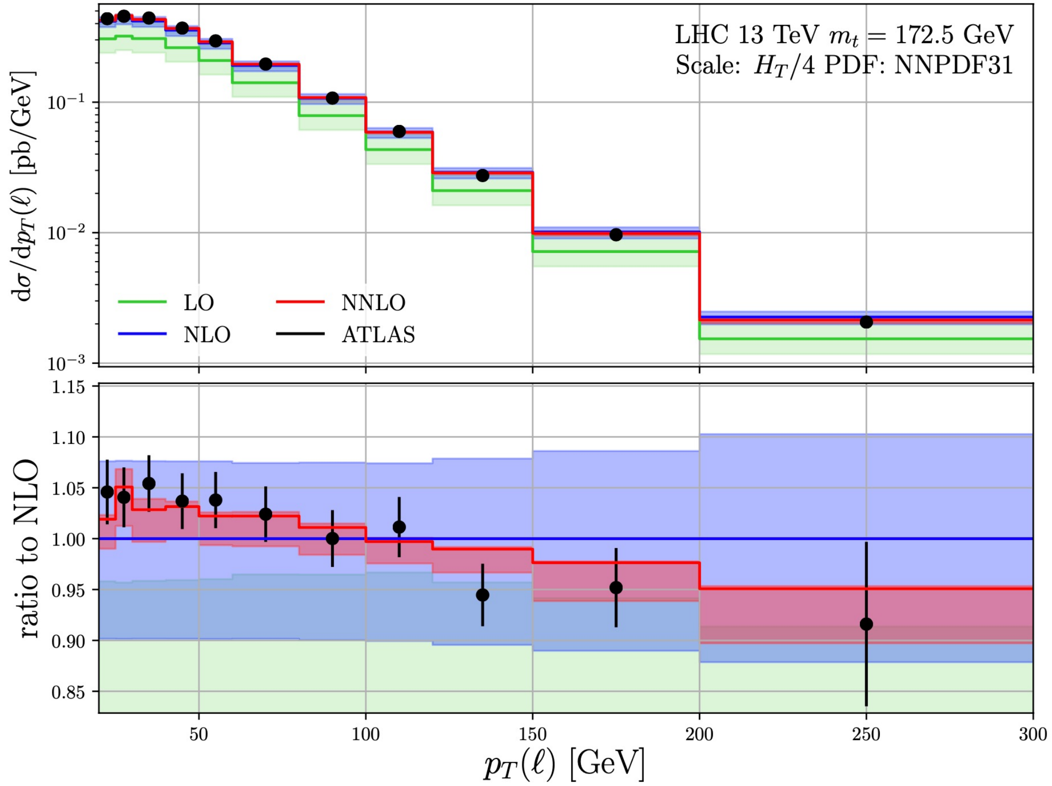
- ATLAS & CMS data
- Compared to Powheg-Box+Pythia8
- Also to calculations @ NNLO *QCD*

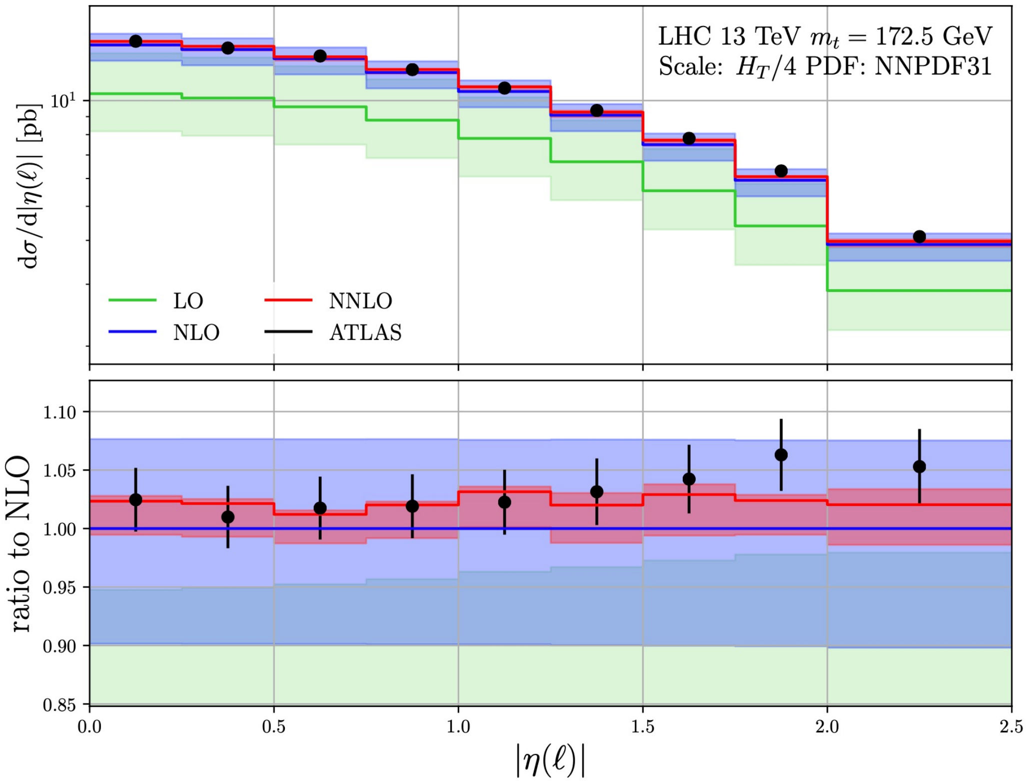
- ATLAS & CMS data
- Compared to MC Simulation
- Ratio to Powheg-Box+Pythia8

Top-Quark Pair Production & Decay @ NNLO

Di-lepton

Czakon, Mitov, Poncelet arXiv:2008.11133 [hep-ph]





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

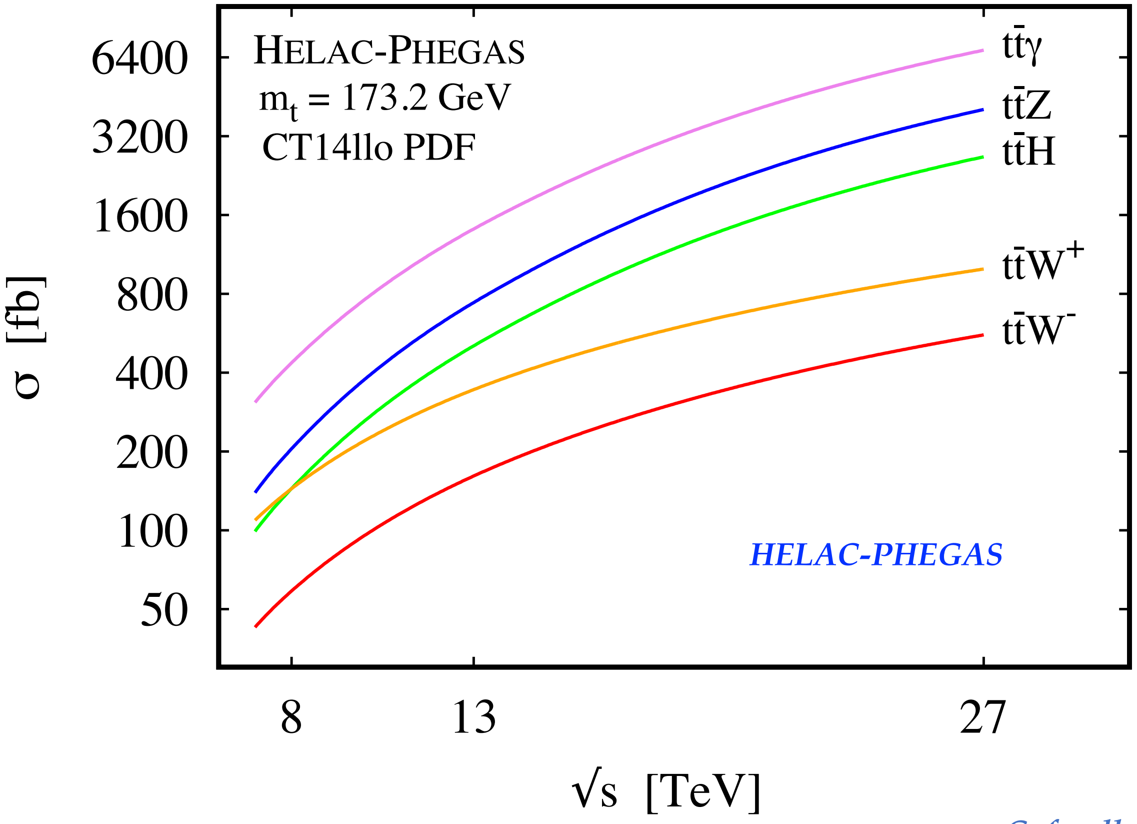
TT+X Production & Decay @ NLO

- *NNLO QCD* theoretical predictions only for *tt*
  - di-lepton channel

Stable top quarks

- More exclusive final states produced @ LHC

$t\bar{t}\gamma, t\bar{t}Z, t\bar{t}H, t\bar{t}W^+, t\bar{t}W^-$ @LHC



Cafarella, Papadopoulos, Worek arXiv:0710.2427 [hep-ph]

TT+X Production & Decay @ NLO

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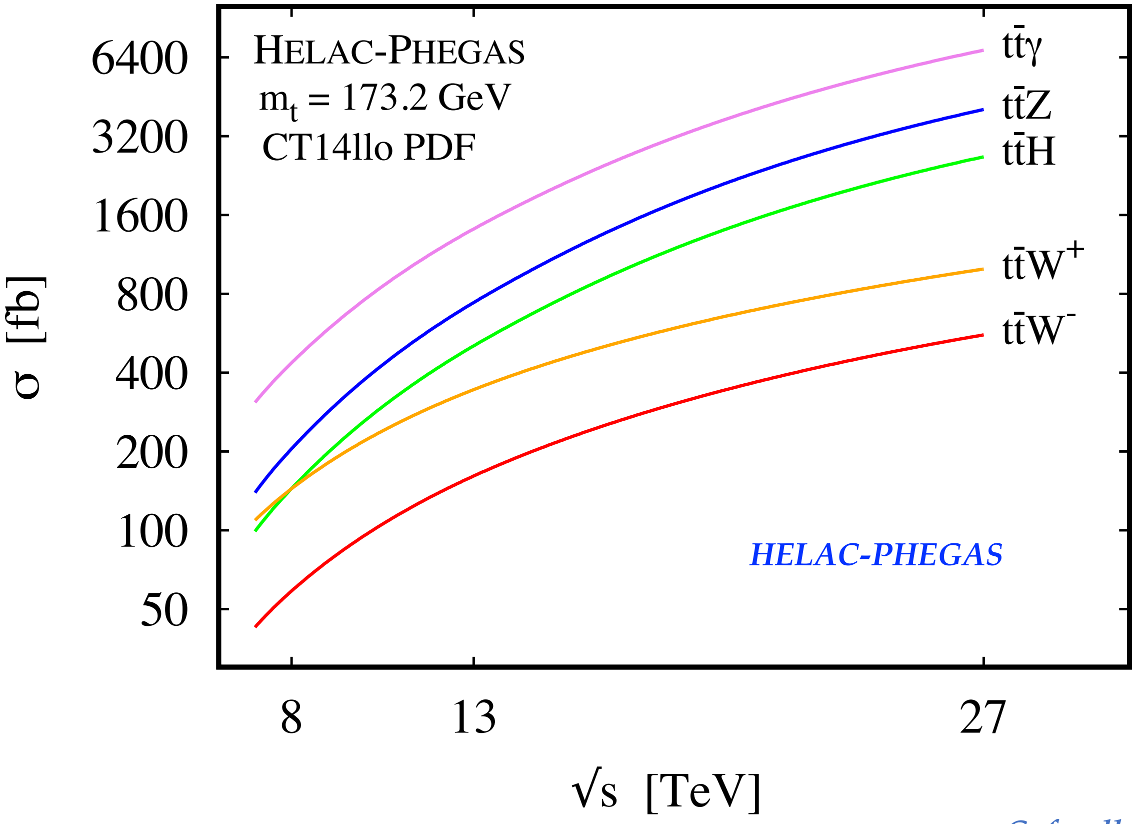
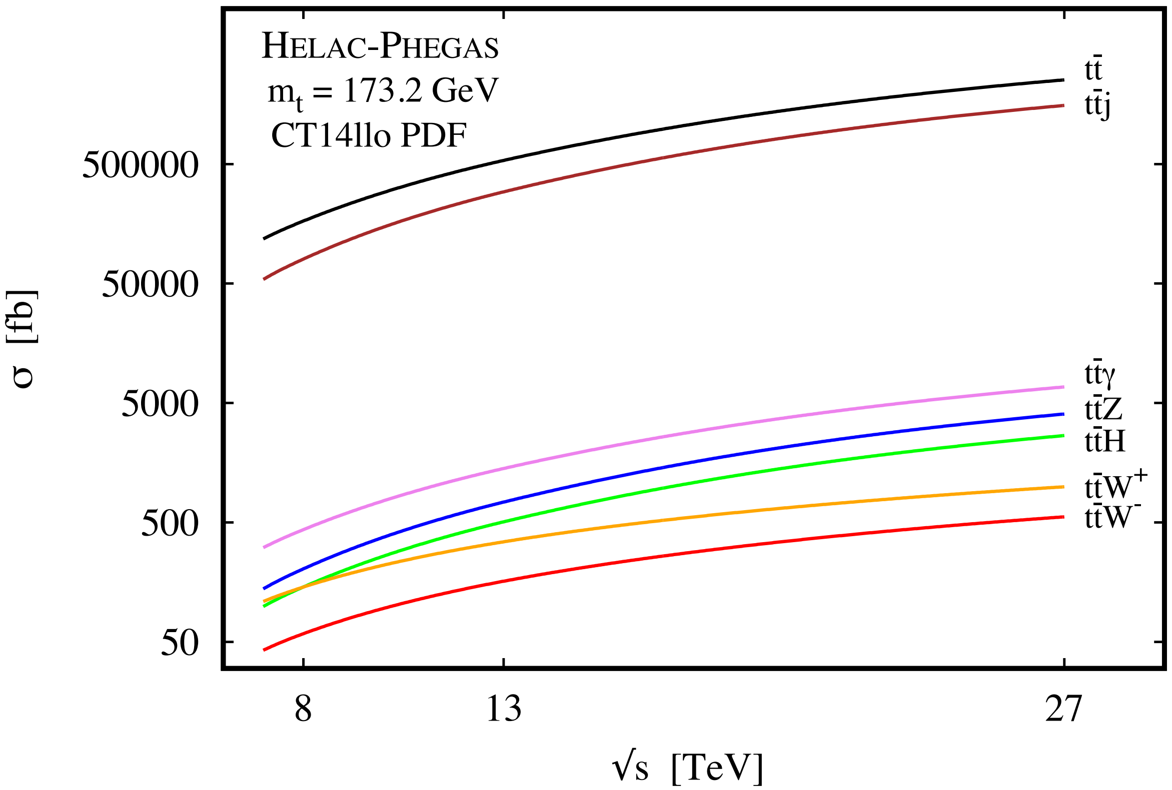
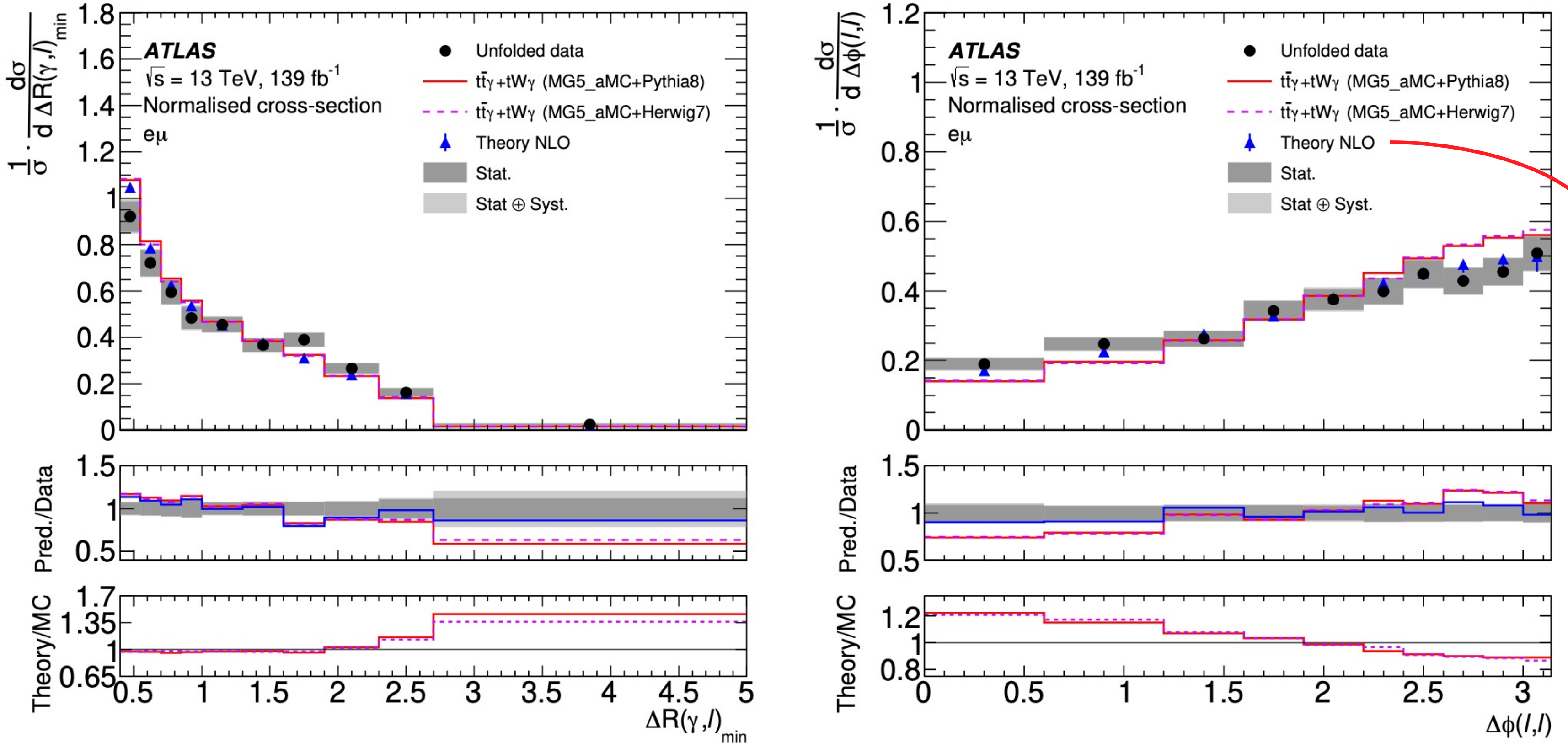


tt, ttj, ttγ, ttZ, ttH, ttW+, ttW- @ LHC



Cafarella, Papadopoulos, Worek arXiv:0710.2427 [hep-ph]

TTγ Production & Decay @ NLO



Di-lepton

ATLAS Collaboration
arXiv:2007.06946 [hep-ex]

HELAC-NLO

Bevilacqua, Hartanto, Kraus, Weber, Worek
arXiv:1803.09916 [hep-ph]
arXiv:1809.08562 [hep-ph]
arXiv:1912.09999 [hep-ph]

χ^2/ndf and p-values between measured normalised cross-sections & MC simulation & NLO QCD calculation

Predictions	$p_T(\gamma)$ χ^2/ndf	$p_T(\gamma)$ p-value	$\|\eta(\gamma)\|$ χ^2/ndf	$\|\eta(\gamma)\|$ p-value	$\Delta R(\gamma,\ell)_{min}$ χ^2/ndf	$\Delta R(\gamma,\ell)_{min}$ p-value	$\Delta\phi(\ell,\ell)$ χ^2/ndf	$\Delta\phi(\ell,\ell)$ p-value	$\|\Delta\eta(\ell,\ell)\|$ χ^2/ndf	$\|\Delta\eta(\ell,\ell)\|$ p-value
$t\bar{t}\gamma + tW\gamma$ (MG5_aMC+Pythia8)	6.3/10	0.79	7.3/7	0.40	20.1/9	0.02	30.8/9	<0.01	6.5/7	0.48
$t\bar{t}\gamma + tW\gamma$ (MG5_aMC+Herwig7)	5.3/10	0.87	7.7/7	0.36	18.9/9	0.03	31.6/9	<0.01	6.8/7	0.45
Theory NLO	6.0/10	0.82	4.5/7	0.72	13.5/9	0.14	5.8/9	0.76	5.6/7	0.59

TTW Production & Decay @ NLO

- NNLO *QCD* theoretical predictions only for *tt*
  - di-lepton channel
- More exclusive final states produced @ LHC

Motivation ⇨ *ttW production @ LHC*

- Background for *ttH* ⇨ *2lSS & 3l*
  - Higher normalization for *ttW* compared to SM predictions from multipurpose MC generators *30%−70%*
  - Problems with modeling of final states in phase space regions dominated by *ttW*

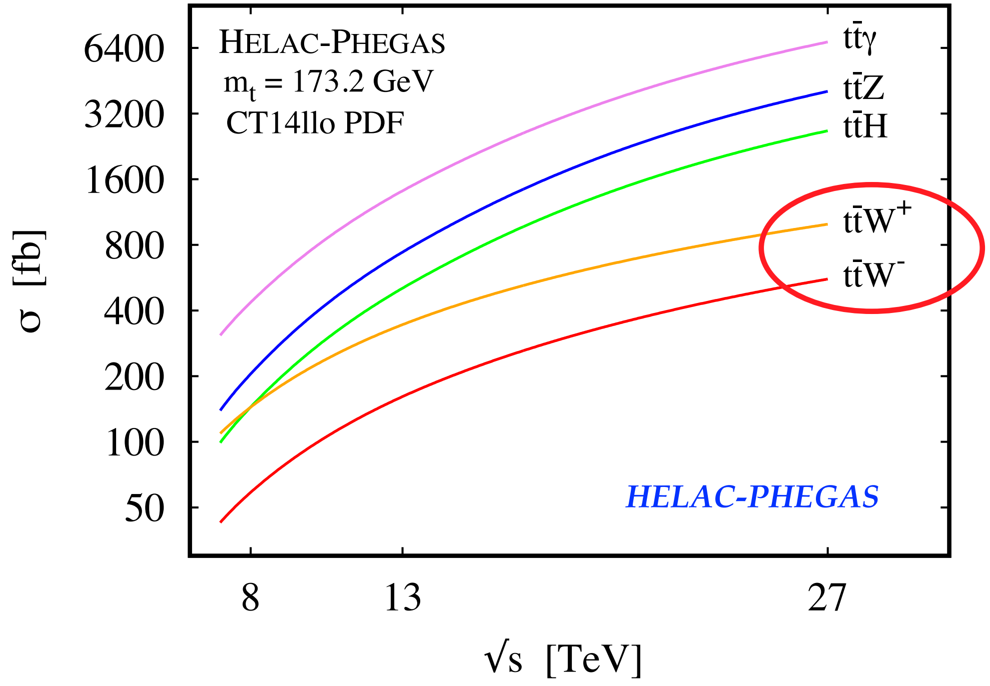
ATLAS-CONF-2019-045

- Improved description of *ttW* background needed to reach greater precision in future
- First calculations for off-shell *ttW* confirmed by second group ⇨ *di-lepton channel*

Bevilacqua, Bi, Hartanto, Kraus, Worek arXiv:2005.09427 [hep-ph]
Denner, Pellicciol arXiv:2007.12089 [hep-ph]

Stable top quarks

$t\bar{t}\gamma, t\bar{t}Z, t\bar{t}H, t\bar{t}W^+, t\bar{t}W^-$ @LHC



Cafarella, Papadopoulos, Worek arXiv:0710.2427 [hep-ph]

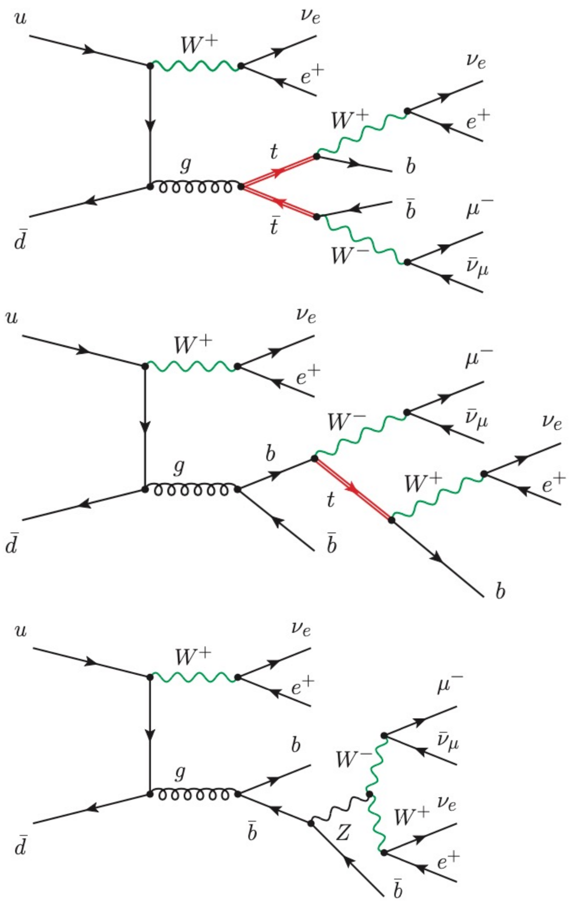
TTW Production & Decay @ NLO

Di-lepton

Bevilacqua, Bi, Hartanto, Kraus, Worek
arXiv:2005.09427 [hep-ph]

- **Complete off-shell effects:**
  - Off-shell top quarks described by Breit-Wigner propagators
  - Double-, single- & non-resonant top-quark contributions included
  - All interference effects incorporated at matrix element level

$pp \to e^+\nu_e\,\mu^-\,\bar{\nu}_\mu\,e^+\nu_e\,b\bar{b} + X$
$pp \to e^-\bar{\nu}_e\,\mu^+\,\nu_\mu\,e^-\bar{\nu}_e\,b\bar{b} + X$



- **NWA:**
  - Works in the limit ⇨ $\Gamma_t/m_t \to 0$

$$\Gamma_t = 1.35159\ \text{GeV},\ m_t = 173.2\,\text{GeV},\ \Gamma_t/m_t \approx 0.008$$

  - Incorporates only double resonant contributions
  - Restricts unstable top quarks & W gauge bosons to on-shell states

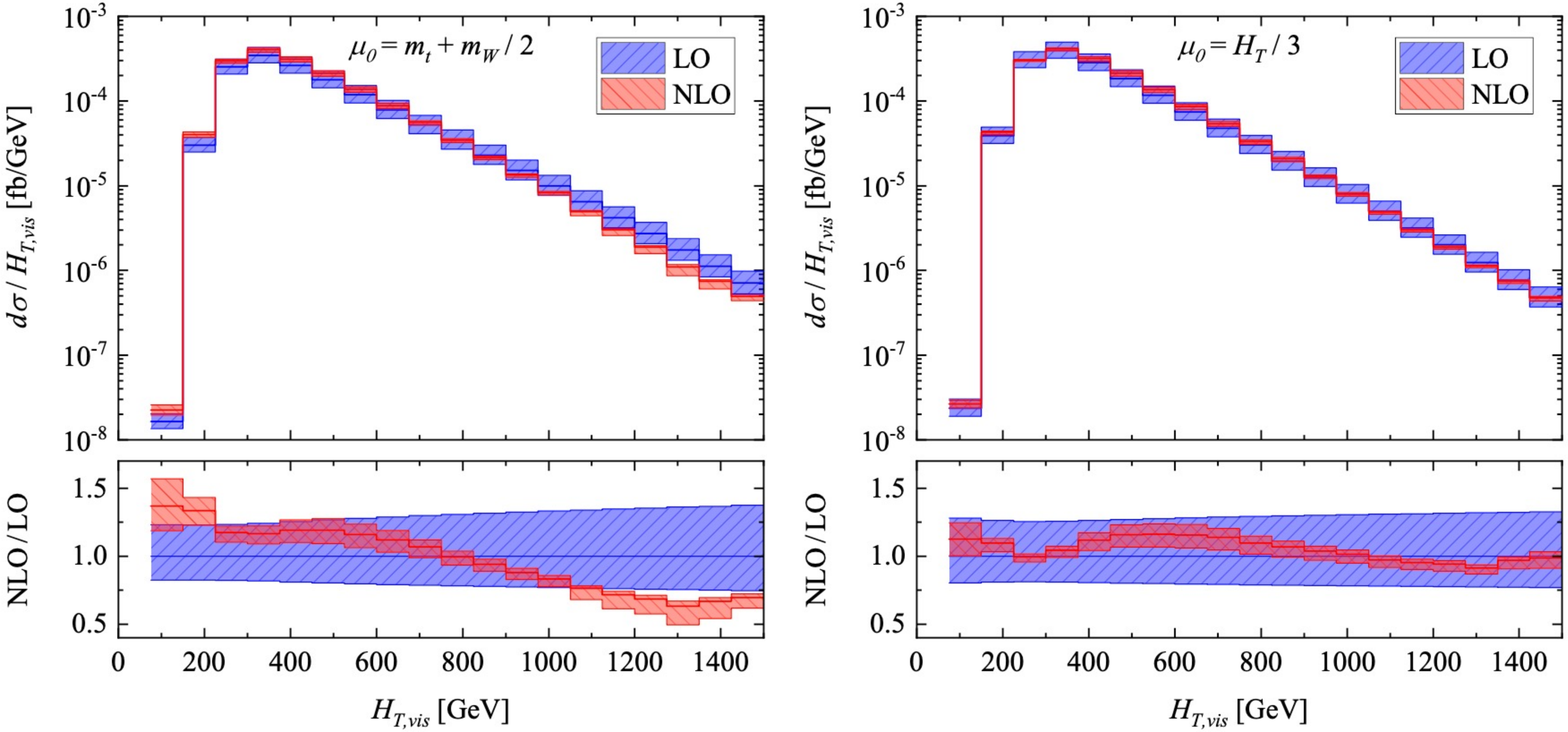
$$pp \to t\bar{t}W^+ + X \to W^+W^+W^-\,b\bar{b} + X \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,e^+\nu_e\,b\bar{b}$$

TTW Production & Decay @ NLO

Off-shell ttW⁺

Bevilacqua, Bi, Hartanto, Kraus, Worek
arXiv:2005.09427 [hep-ph]

$$H_T^{vis} = p_T(\mu^-) + p_T(\ell_1) + p_T(\ell_2) + p_T(j_{b_1}) + p_T(j_{b_2})$$



Di-lepton

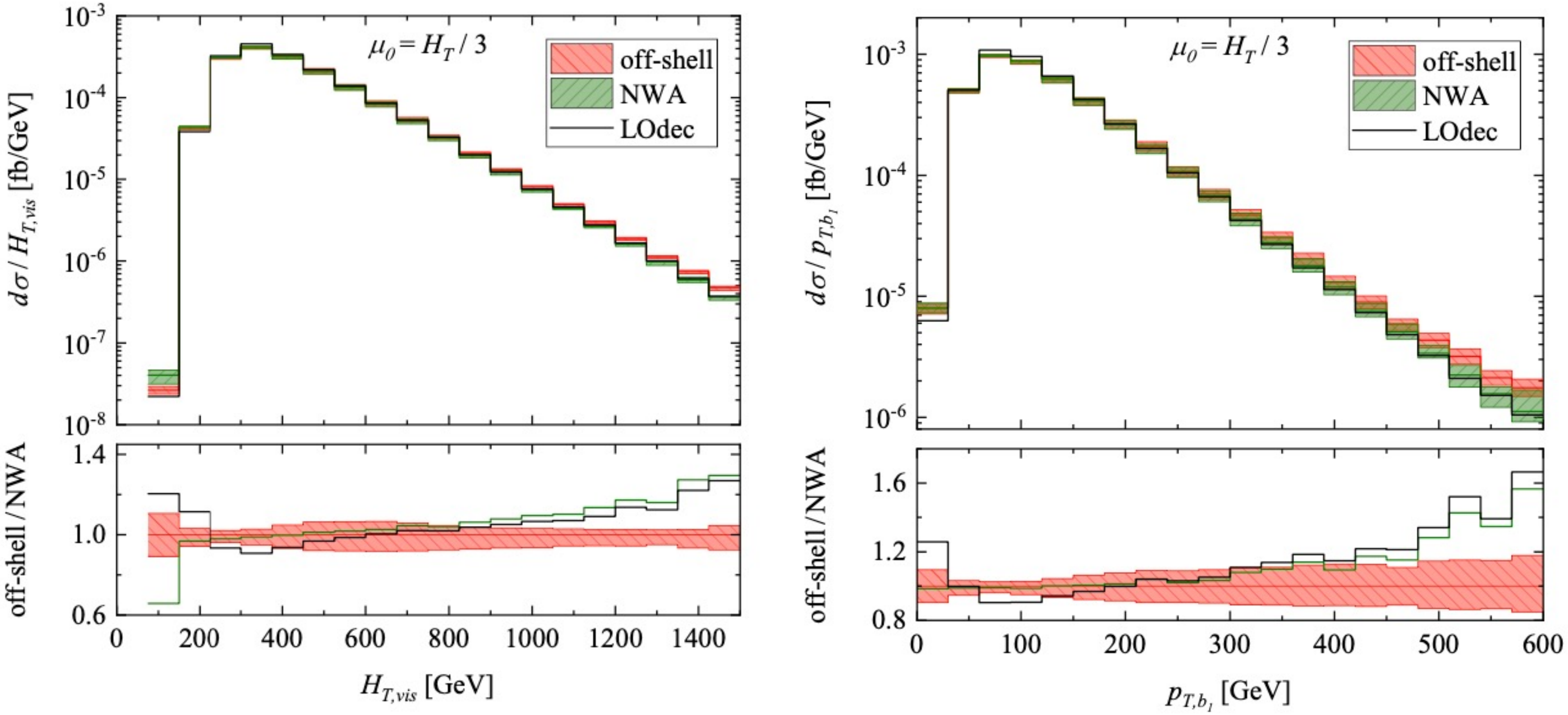
- *Fixed scale choice* ⇨ Leads to perturbative instabilities in TeV region of differential cross & Large distortions
- *Dynamical scale choice* ⇨ Stabilises tails & keeps NLO uncertainties bands within LO ones

TTW Production & Decay @ NLO

Off-shell & NWA & $NWA_{LOdecay}$

$H_T^{vis} = p_T(\mu^-) + p_T(\ell_1) + p_T(\ell_2) + p_T(j_{b_1}) + p_T(j_{b_2})$

Di-lepton



Bevilacqua, Bi, Hartanto, Kraus, Worek
arXiv:2005.09427 [hep-ph]

$$pp \to e^+\nu_e\, \mu^-\bar{\nu}_\mu\, e^+\nu_e\, b\bar{b} + X$$

Differential level:

- Off-shell up to *60% - 70%*
- NLO *QCD 10% - 20%*
- PDF up to *10%*
- Scales *10% - 20%*
- For central value of scale substantial differences between NWA & $NWA_{LOdecay}$

- *Similar effects for ttW^-*

Integrated level:

- Complete top-quark off-shell effects *0.2%*
- NLO *QCD* around *10%* & Theoretical uncertenties: Scales *6%-7%* ⇨ PDF *2%*
- NLO *QCD* corrections to decays *3%-5%*

TTW$^+$ / TTW$^-$ @ NLO

Bevilacqua, Bi, Hartanto, Kraus, Nasufi, Worek
arXiv:2012.01363 [hep-ph]

Searching for more precise observables

$\mu_0 = m_t + m_W/2$ NNPDF3.0	$\sigma^{\rm NLO}_{t\bar{t}W^+} \pm \delta_{\rm scale} \pm \delta_{\rm PDF}$ [ab]	$\sigma^{\rm NLO}_{t\bar{t}W^-} \pm \delta_{\rm scale} \pm \delta_{\rm PDF}$ [ab]	$\sigma^{\rm NLO}_{t\bar{t}W^+}/\sigma^{\rm NLO}_{t\bar{t}W^-}$ $\mathcal{R}$
$p_{T,\,b} > 25$ GeV	$123.2^{+6.3\,(5\%)}_{-8.7\,(7\%)}{}^{+2.1\,(2\%)}_{-2.1\,(2\%)}$	$68.0^{+4.8\,(7\%)}_{-5.5\,(8\%)}{}^{+1.2\,(2\%)}_{-1.2\,(2\%)}$	$1.81 \pm 0.03\,(2\%)$
$p_{T,\,b} > 30$ GeV	$113.1^{+5.4\,(5\%)}_{-7.8\,(7\%)}{}^{+1.9\,(2\%)}_{-1.9\,(2\%)}$	$62.3^{+4.2\,(7\%)}_{-4.9\,(8\%)}{}^{+1.1\,(2\%)}_{-1.1\,(2\%)}$	$1.81 \pm 0.03\,(2\%)$
$p_{T,\,b} > 35$ GeV	$102.6^{+4.7\,(5\%)}_{-6.8\,(7\%)}{}^{+1.7\,(2\%)}_{-1.7\,(2\%)}$	$56.3^{+3.7\,(7\%)}_{-4.4\,(8\%)}{}^{+1.0\,(2\%)}_{-1.0\,(2\%)}$	$1.82 \pm 0.03\,(2\%)$
$p_{T,\,b} > 40$ GeV	$92.0^{+4.0\,(4\%)}_{-6.1\,(7\%)}{}^{+1.6\,(2\%)}_{-1.6\,(2\%)}$	$50.3^{+3.3\,(6\%)}_{-3.9\,(8\%)}{}^{+0.9\,(2\%)}_{-0.9\,(2\%)}$	$1.83 \pm 0.04\,(2\%)$

Off-shell ttW$^{\pm}$

Di-lepton

NLO QCD integrated fiducial cross sections & cross section ratios

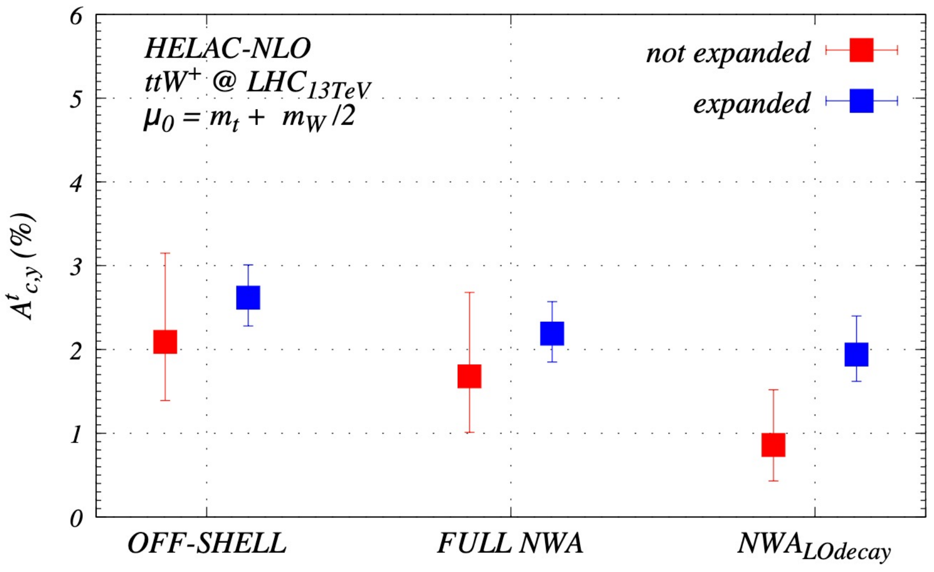
- *ttW$^+$ & ttW$^-$* similar from NLO *QCD* point of view ⇨ Integrated & differential level
- Scale uncertainties can be taken correlated
- Cross section ratios stable with respect to $p_T(b)$
- Insensitive to details of modelling of top quark production & decays ⇨ Off-shell/NWA/NWA$_{\rm LOdecay}$
- Insensitive to scale choice ⇨ $\mu_0 = m_t + m_W/2$ versus $\mu_0 = H_T/3$

Top Quark Charge Asymmetry @ NLO

Searching for more precise observables

$$A_c^t = \frac{\sigma^+_{\rm bin} - \sigma^-_{\rm bin}}{\sigma^+_{\rm bin} + \sigma^-_{\rm bin}}, \qquad \sigma^\pm_{\rm bin} = \int \theta(\pm\Delta|y|)\,\theta_{\rm bin}\, d\sigma$$

$$\Delta|y| = |y_t| - |y_{\bar{t}}|$$



- $A^t{}_c$ charge asymmetry @ NLO for $pp \to ttW^+$

Off-shell ttW^+

Bevilacqua, Bi, Hartanto, Kraus, Nasufi, Worek
arXiv:2012.01363 [hep-ph]

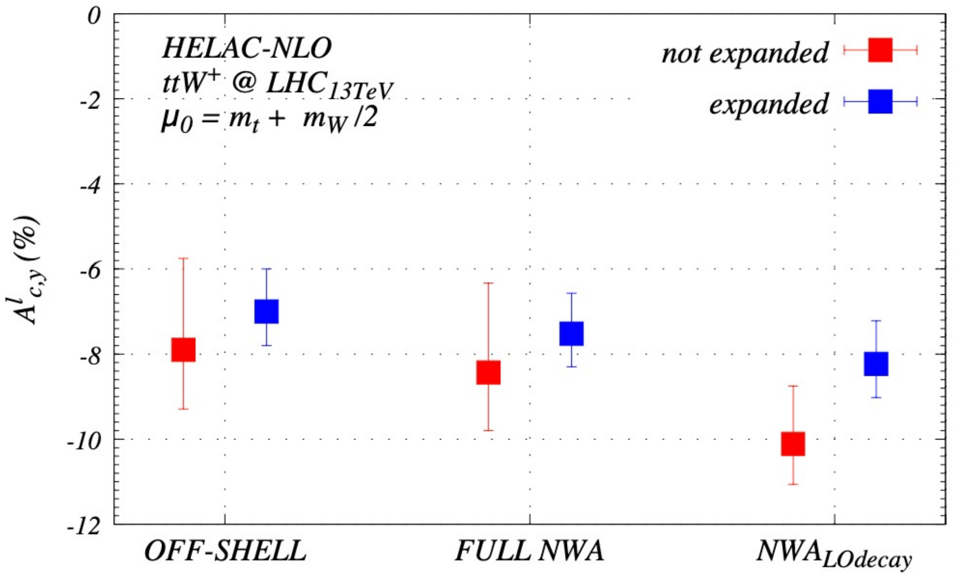
- Asymmetry larger than for $pp \to tt$
- Top quark momenta must be reconstructed
- Scales no important
- Modelling important

$t\bar{t}W^+$, $\mu_0 = H_T/3$	Off-shell	Full NWA	NWA$_{\rm LOdecay}$
$A^t_{c,y}$ [%]	$2.36(8)^{+1.19\,(50\%)}_{-0.77\,(33\%)}$	$1.93(5)^{+1.23\,(64\%)}_{-0.72\,(37\%)}$	$1.11(3)^{+0.55\,(49\%)}_{-0.53\,(48\%)}$
$A^t_{c,exp,y}$ [%]	$2.66(10)^{+0.38\,(14\%)}_{-0.34\,(13\%)}$	$2.20(5)^{+0.45(20\%)}_{-0.31(14\%)}$	$2.08(5)^{+0.24\,(11\%)}_{-0.40\,(19\%)}$
$t\bar{t}W^+$, $\mu_0 = m_t + m_W/2$	Off-shell	Full NWA	NWA$_{\rm LOdecay}$
$A^t_{c,y}$ [%]	$2.09(8)^{+1.06\,(51\%)}_{-0.70\,(33\%)}$	$1.68(4)^{+1.00(60\%)}_{-0.67(40\%)}$	$0.86(3)^{+0.66\,(77\%)}_{-0.43\,(50\%)}$
$A^t_{c,exp,y}$ [%]	$2.62(10)^{+0.39\,(15\%)}_{-0.34\,(13\%)}$	$2.19(4)^{+0.38(17\%)}_{-0.34(16\%)}$	$1.94(5)^{+0.46\,(24\%)}_{-0.32\,(16\%)}$

Lepton Charge Asymmetry @ NLO

Off-shell $ttW^{\pm}$

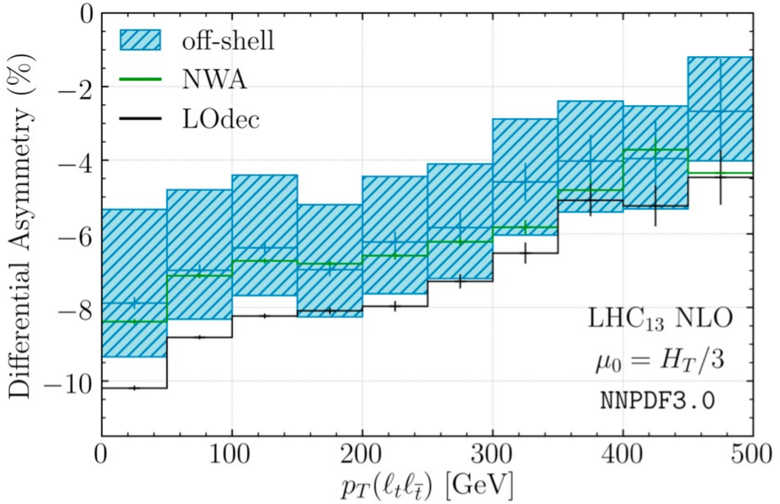
Bevilacqua, Bi, Hartanto, Kraus, Nasufi, Worek arXiv:2012.01363 [hep-ph]

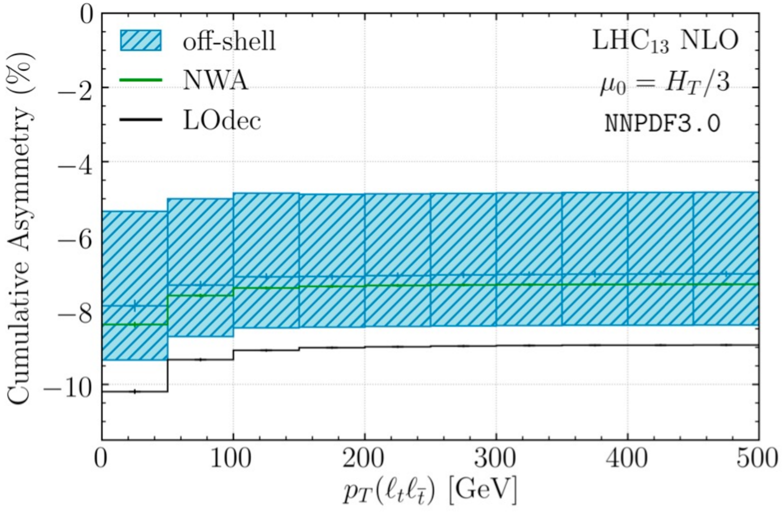


$t\bar{t}W^+$ $\mu_0 = H_T/3$	Off-shell	Full NWA	NWA$_{\mathrm{LOdecay}}$
$A^{\ell}_{c,y}$ [%]	$-7.46(11)^{+2.46\,(33\%)}_{-1.55\,(21\%)}$	$-7.94(4)^{+2.45(31\%)}_{-1.54(19\%)}$	$-9.81(4)^{+1.46\,(15\%)}_{-1.03\,(10\%)}$
$A^{\ell}_{c,exp,y}$ [%]	$-6.93(13)^{+1.01\,(14\%)}_{-0.81\,(12\%)}$	$-7.43(5)^{+0.99(13\%)}_{-0.79(11\%)}$	$-8.14(5)^{+1.00\,(12\%)}_{-0.81\,(10\%)}$

Differential & Cumulative A^l_c

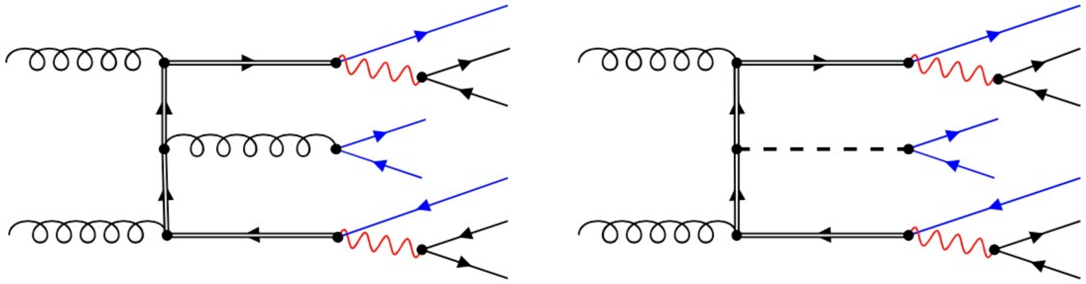
NLO QCD for $pp \to ttW^{\pm}$





- A^l_c charge asymmetry @ NLO for $pp \to ttW^+$
- Directly measurable ⇨ Top quark reconstruction not needed

Off-Shell TTBB @ NLO



$pp \to t\bar{t}b\bar{b}$ & $pp \to t\bar{t}H \to t\bar{t}b\bar{b}$

Motivation ⇨ *ttbb production @ LHC*

- Irreducible background for Higgs boson studied
- *ttH* ⇨ $H \to bb$
- Top-Yukawa coupling Y_t ⇨ Probed directly
- ATLAS & CMS reported measurements for $ttH(H \to bb)$ decay channel of Higgs boson

Experimental Challenges

- Identification of candidates for Higgs decay
- Combinatorial background
- Misidentification of light jets with *b*-jets
- *b*-jet tagging
- SM backgrounds

$$pp \to t\bar{t}H \to t\bar{t}b\bar{b} \to W^+W^-b\bar{b}b\bar{b}$$

Theory Challenges

- Two very different & distinctive scales
- m_t ⇨ *tt* production & top-quark decays
- $p_T(b)$ ⇨ Describes *b*-jets from $g \to bb$ splitting

- Second calculation for off-shell *ttbb* in ***di-lepton*** channel ⇨ Agreement with first calculations

$$pp \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}\,b\bar{b} + X$$

Denner, Lang, Pellen arXiv:2008.00918 [hep-ph]
Bevilacqua, Bi, Hartanto, Kraus, Lupattelli, Worek arXiv:2105.08404 [hep-ph]

OFF-SHELL TTBB @ NLO

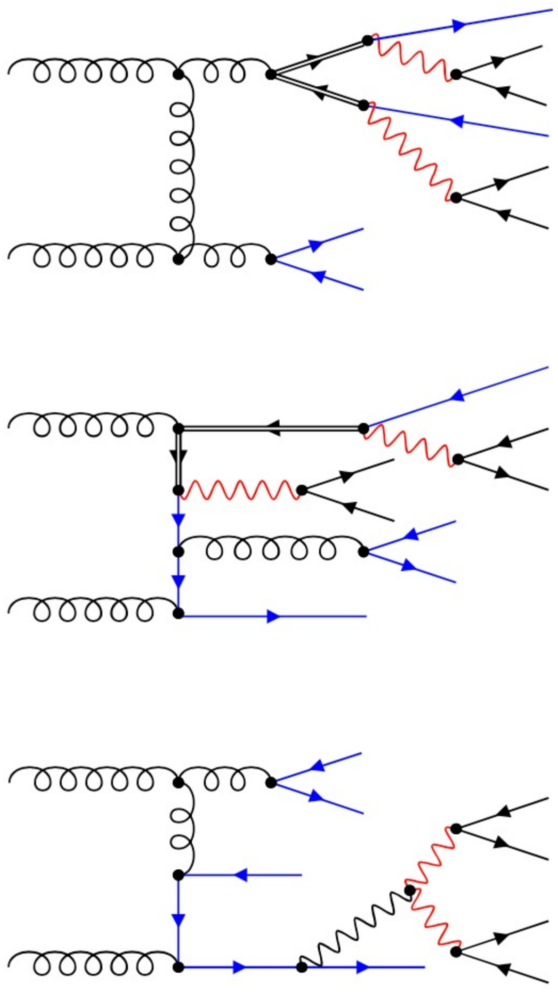
Integrated fiducial cross sections for ttbb

$p_T(b)$	$\sigma^{\rm LO}$ [fb]	$\delta_{\rm scale}$	$\sigma^{\rm NLO}$ [fb]	$\delta_{\rm scale}$	$\delta_{\rm PDF}$	$\mathcal{K} = \sigma^{\rm NLO}/\sigma^{\rm LO}$
$\mu_R = \mu_F = \mu_0 = m_t$						
25	6.998	$^{+4.525\ (65\%)}_{-2.569\ (37\%)}$	13.24	$^{+2.33\ (18\%)}_{-2.89\ (22\%)}$	$^{+0.19\ (1\%)}_{-0.19\ (1\%)}$	1.89
30	5.113	$^{+3.343\ (65\%)}_{-1.889\ (37\%)}$	9.25	$^{+1.32\ (14\%)}_{-1.93\ (21\%)}$	$^{+0.14\ (2\%)}_{-0.14\ (2\%)}$	1.81
35	3.775	$^{+2.498\ (66\%)}_{-1.401\ (37\%)}$	6.57	$^{+0.79\ (12\%)}_{-1.32\ (20\%)}$	$^{+0.10\ (2\%)}_{-0.10\ (2\%)}$	1.74
40	2.805	$^{+1.867\ (67\%)}_{-1.051\ (37\%)}$	4.70	$^{+0.46\ (10\%)}_{-0.91\ (19\%)}$	$^{+0.08\ (2\%)}_{-0.08\ (2\%)}$	1.68
$\mu_R = \mu_F = \mu_0 = H_T/3$						
25	6.813	$^{+4.338\ (64\%)}_{-2.481\ (36\%)}$	13.22	$^{+2.66\ (20\%)}_{-2.95\ (22\%)}$	$^{+0.19\ (1\%)}_{-0.19\ (1\%)}$	1.94
30	4.809	$^{+3.062\ (64\%)}_{-1.756\ (37\%)}$	9.09	$^{+1.66\ (18\%)}_{-1.98\ (22\%)}$	$^{+0.16\ (2\%)}_{-0.16\ (2\%)}$	1.89
35	3.431	$^{+2.191\ (64\%)}_{-1.256\ (37\%)}$	6.37	$^{+1.07\ (17\%)}_{-1.36\ (21\%)}$	$^{+0.11\ (2\%)}_{-0.11\ (2\%)}$	1.86
40	2.464	$^{+1.582\ (64\%)}_{-0.901\ (37\%)}$	4.51	$^{+0.72\ (16\%)}_{-0.95\ (21\%)}$	$^{+0.09\ (2\%)}_{-0.09\ (2\%)}$	1.83

- Results for NNPDF3.1 LO & NLO with ***$\alpha_s(m_Z)$ = 0.118***
- LO NNPDF3.1 PDF set with ***$\alpha_s(m_Z)$ = 0.130*** ⇨ ***K = 1.45***
- Other PDF sets give K-factor ***∈ (1.81 & 1.37 & 1.23)***
- With jet veto of 50 GeV ***K = 1.11 & K = 1.23***

Bevilacqua, Bi, Hartanto, Kraus, Lupattelli, Worek arXiv:2105.08404 [hep-ph]

Off-shell ttbb

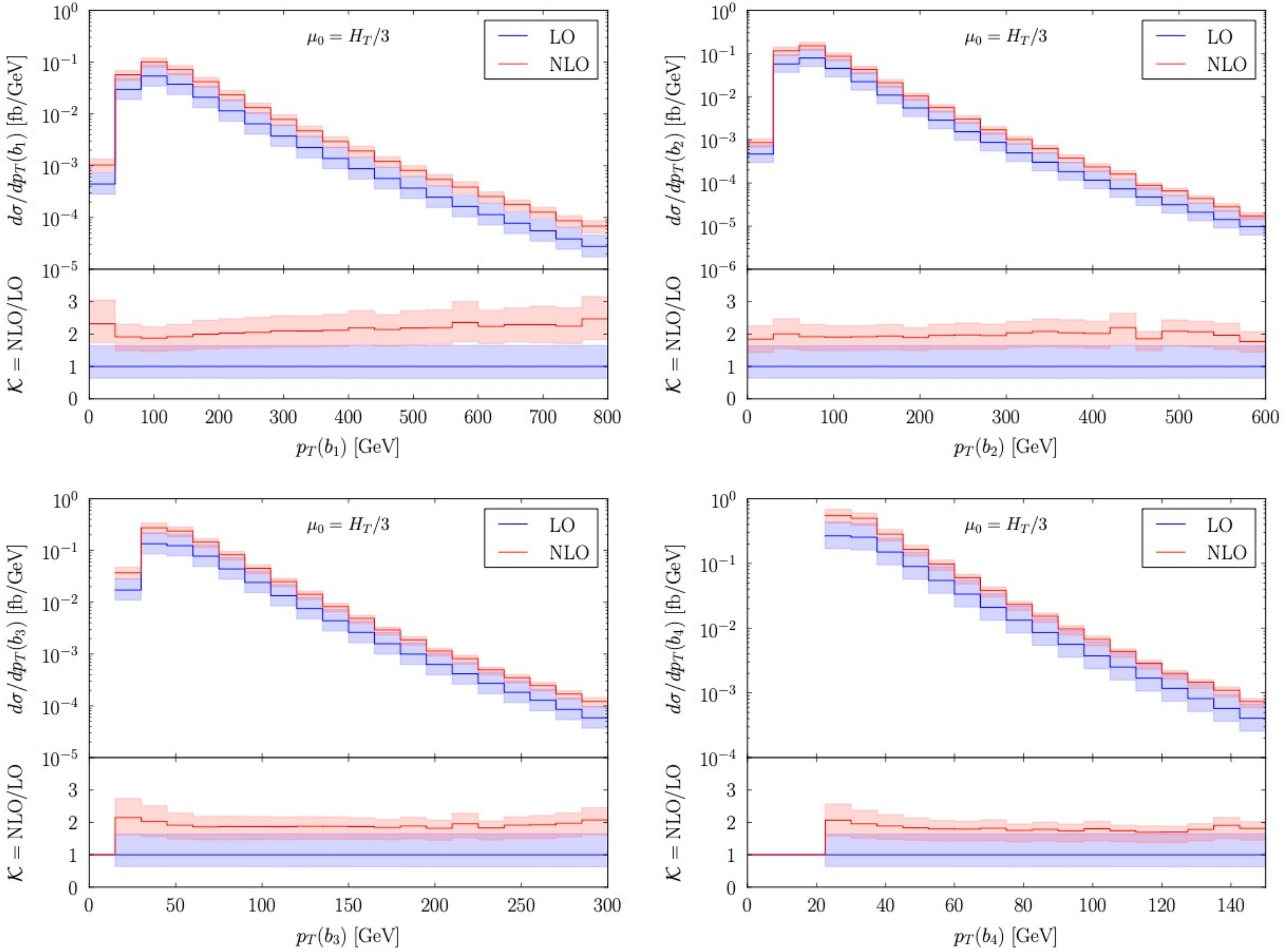


Di-lepton

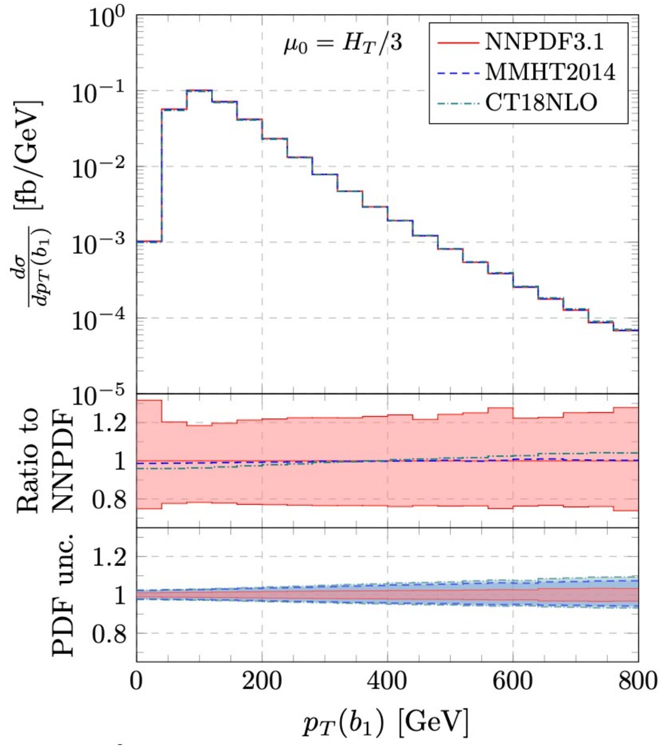
Off-Shell TTBB @ NLO

Off-shell ttbb

Bevilacqua, Bi, Hartanto, Kraus, Lupattelli, Worek
arXiv:2105.08404 [hep-ph]



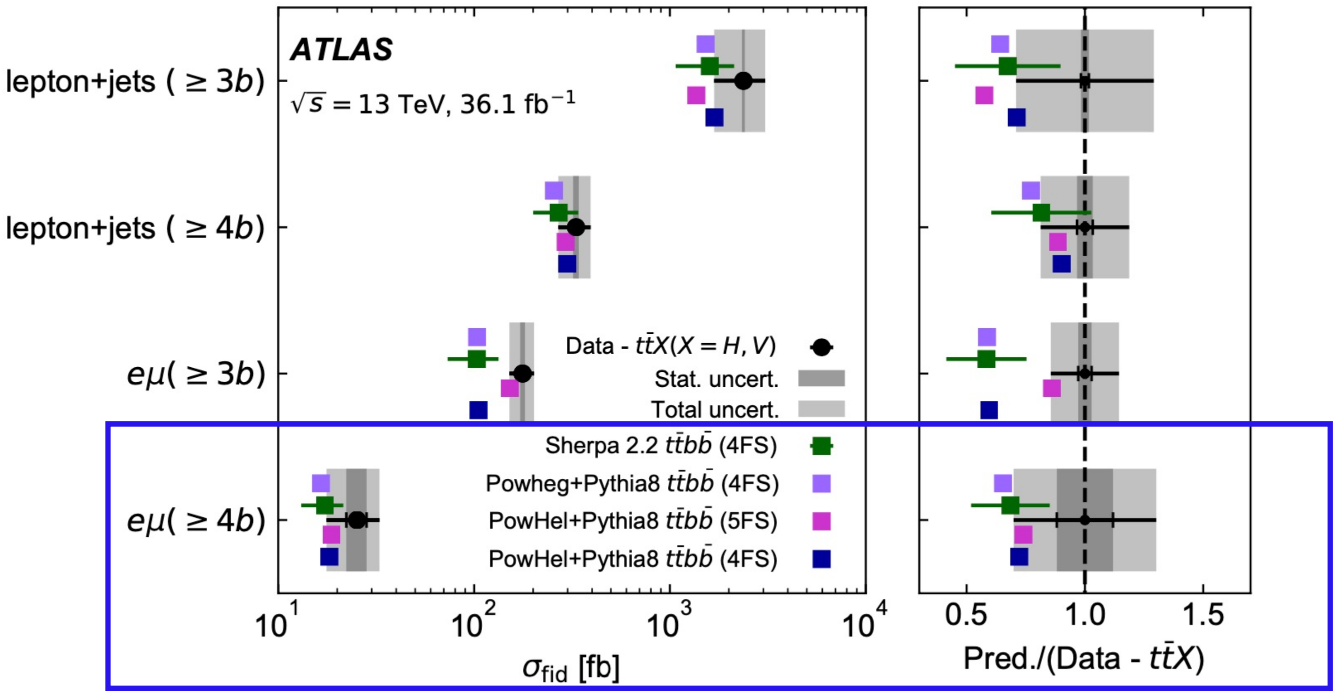
- Large but rather stable NLO corrections @ differential level
- Dynamical scales important
- PDF uncertainties small



OFF-SHELL TTBB @ NLO

Bevilacqua, Bi, Hartanto, Kraus, Lupattelli, Worek
arXiv:2105.08404 [hep-ph]

ATLAS arXiv:1811.12113 [hep-ex]



Theoretical predictions	$\sigma_{e\mu+4b}$ [fb]
SHERPA+OPENLOOPS (4FS)	17.2 ± 4.2
POWHEG-BOX+PYTHIA 8 (4FS)	16.5
POWHEL+PYTHIA 8 (5FS)	18.7
POWHEL+PYTHIA 8 (4FS)	18.2
HELAC-NLO (5FS)	19.4 ± 4.2

$$\sigma^{\text{ATLAS}}_{e\mu+4b} = (25 \pm 6.5)\ \text{fb}$$

$$\sigma^{\text{HELAC-NLO}}_{e\mu+4b} = (20.0 \pm 4.3)\ \text{fb}$$

- Comparison to ATLAS results
- ***eμ channel @ 13 TeV***
- Agreements within theoretical uncertainties

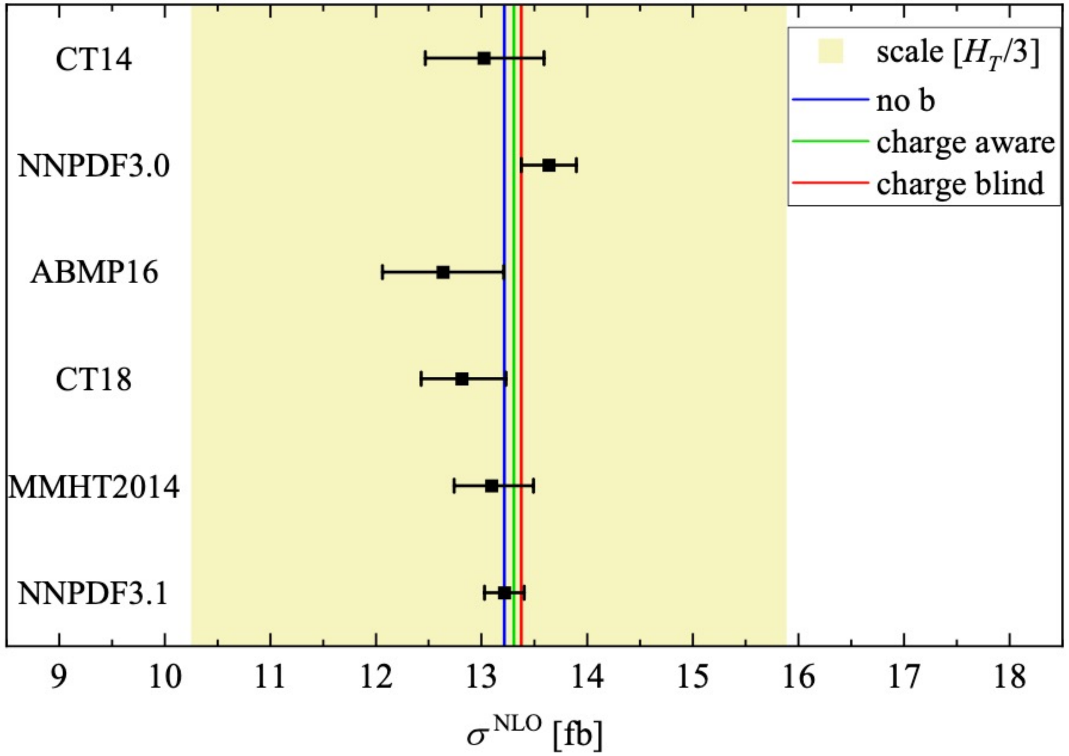
- Higher with leptonic ***τ*** decays into ***l***
- For similar scale choice ***HELAC-NLO*** result is even higher ***~ 21 fb***

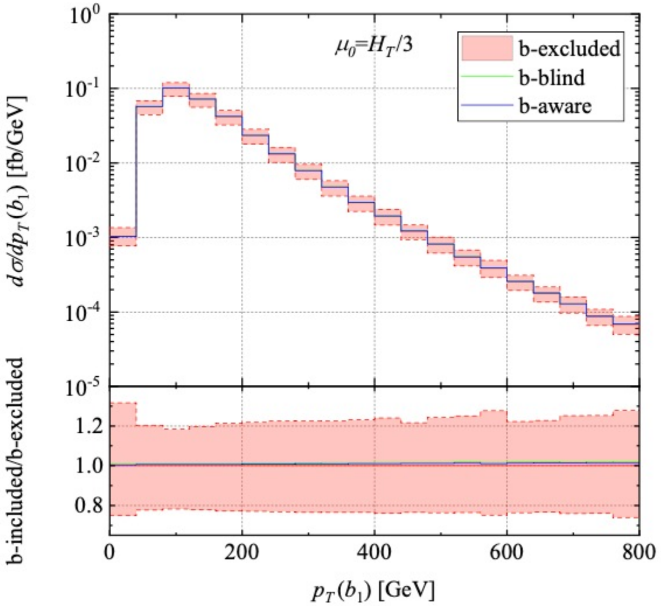
Off-Shell TTBB @ NLO

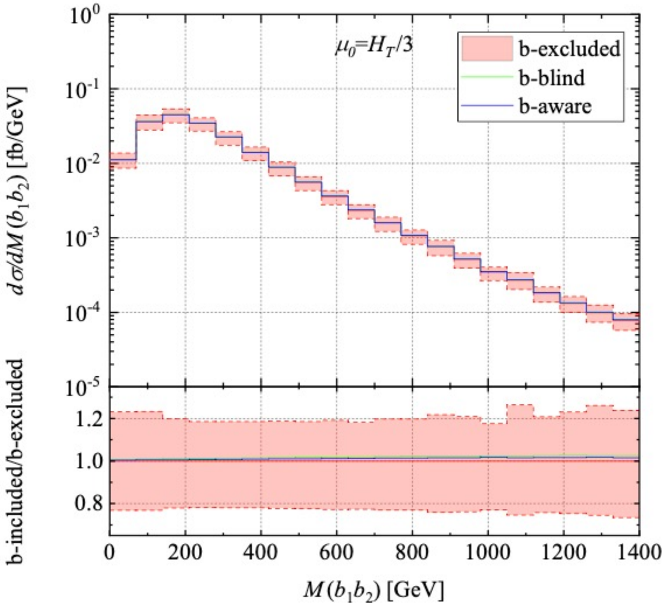
Bevilacqua, Bi, Hartanto, Kraus, Lupattelli, Worek
arXiv:2105.08404 [hep-ph]

Initial state bottom

- Charge aware and charge blind schemes for *b*-jet tagging
- ***@ LO*** initial state *b*-quark contributions ⇨ ***0.1% − 0.2%***
- ***@NLO*** ⇨ ***1%*** *&* up to ***1.5%*** with $p_T(b)$ scan *&* up to ***2%*** for jet veto of ***50 GeV*** ⇨ Negligible contribution







Take-Home Message

- *Standard:* ***tt+X @ NLO*** with stable tops or LO decays in NWA matched to PS ⇰ ***all channels***

- *State-of-the-art:*
  - ***tt @ NNLO QCD*** ⇰ ***di-lepton***
  - ***ttX, X = H & Z (→ νν) & W & γ & bb @ NLO QCD*** with full off-shell effects ⇰ ***di-lepton***

- *Proper modelling of production & decay essential already now in presence of inclusive cuts*
  - Corrections to production & decays ⇰ *At least full NWA*
  - NNLO or NLO ***tt*** spin correlations
  - Possibility of using kinematic-dependent μ_R & μ_F scales
  - Complete off-shell effects for *top quarks & W/Z* gauge bosons

- *Even more important for:*
  - Exclusive cuts & High luminosity measurements
  - New Physics searches & Might impact exclusion limits
  - SM parameter extraction

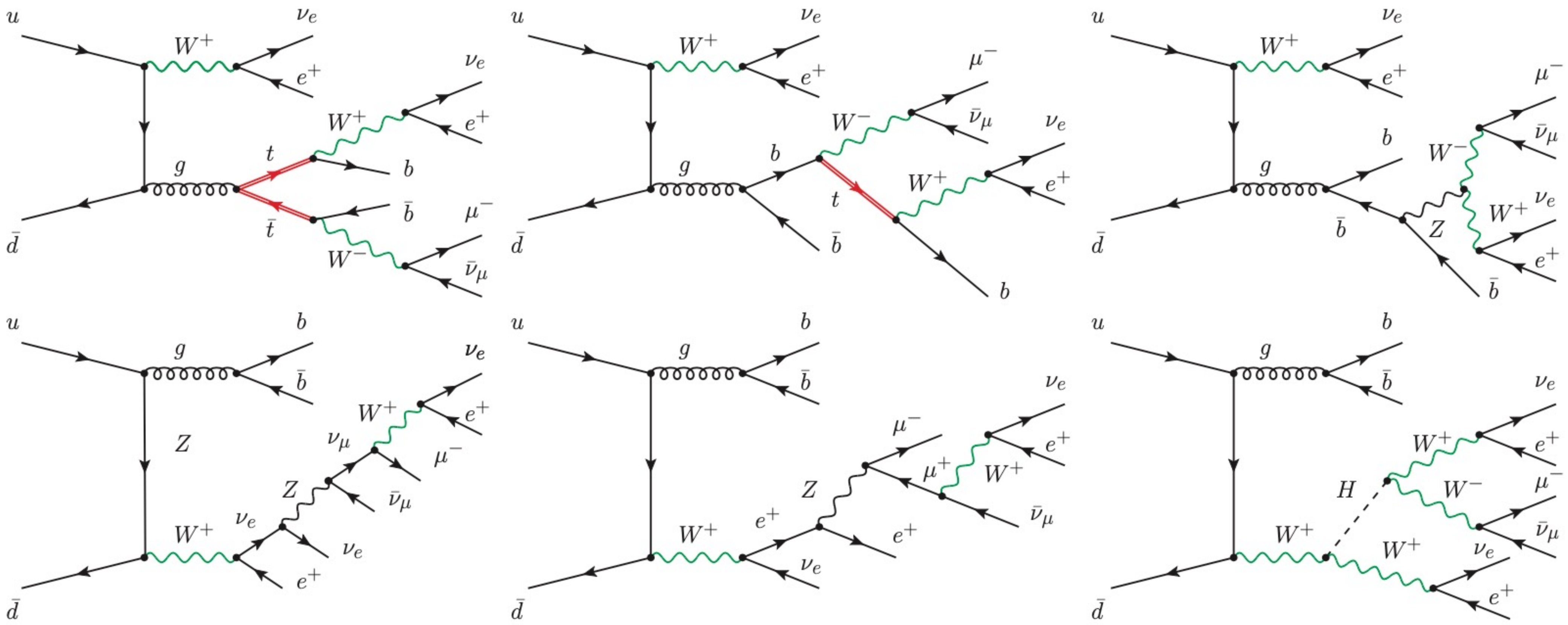
- Top quarks play important role in virtually every LHC analysis ⇰ *SM & BSM*

- *Lots of data, sophisticated analyses, precision measurements* ⇰ *Should be compared to state-of-the-art theoretical predictions*

Backup

TTW

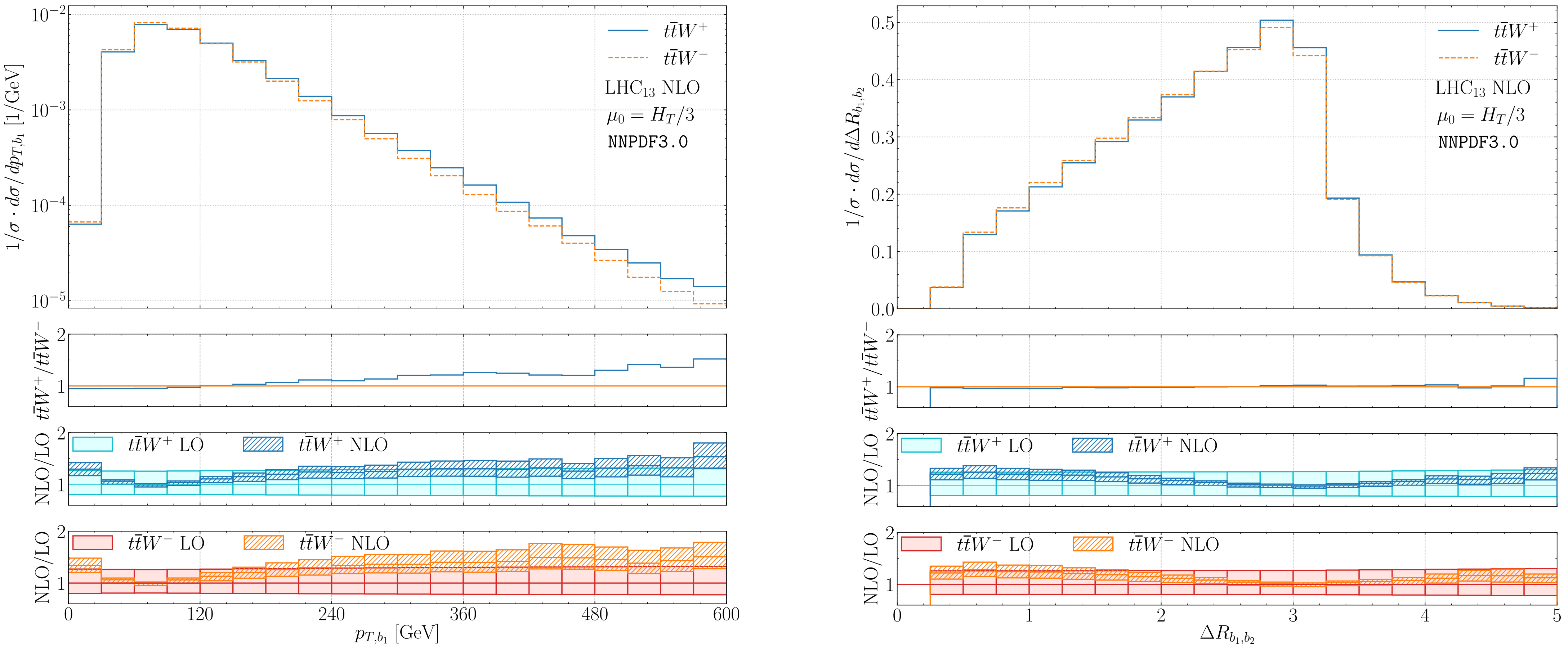
Bevilacqua, Bi, Hartanto, Kraus, Worek
arXiv:2005.09427 [hep-ph]



$$pp \to e^+\nu_e\,\mu^-\,\bar{\nu}_\mu\,e^+\nu_e\,b\bar{b} + X$$

TTW

Bevilacqua, Bi, Hartanto, Kraus, Nasufi, Worek
arXiv:2012.01363 [hep-ph]



$$pp \to e^+\nu_e\,\mu^-\,\bar{\nu}_\mu\,e^+\nu_e\,b\bar{b} + X$$
$$pp \to e^-\bar{\nu}_e\,\mu^+\,\nu_\mu\,e^-\bar{\nu}_e\,b\bar{b} + X$$

TTW

Bevilacqua, Bi, Hartanto, Kraus, Nasufi, Worek
arXiv:2012.01363 [hep-ph]

Modelling Approach	$\sigma^{\rm LO}$ [ab]	$\sigma^{\rm NLO}$ [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 ($\mu_0 = H_T/3$)	$115.1^{+30.4\,(26\%)}_{-22.4\,(19\%)}$	$124.2^{+4.1\,(3\%)}_{-7.7\,(6\%)}$
$\rm NWA_{LOdecay}$ ($\mu_0 = m_t + m_W/2$)		$127.0^{+14.2\,(11\%)}_{-13.3\,(10\%)}$
$\rm NWA_{LOdecay}$ ($\mu_0 = H_T/3$)		$130.7^{+13.6\,(10\%)}_{-13.2\,(10\%)}$

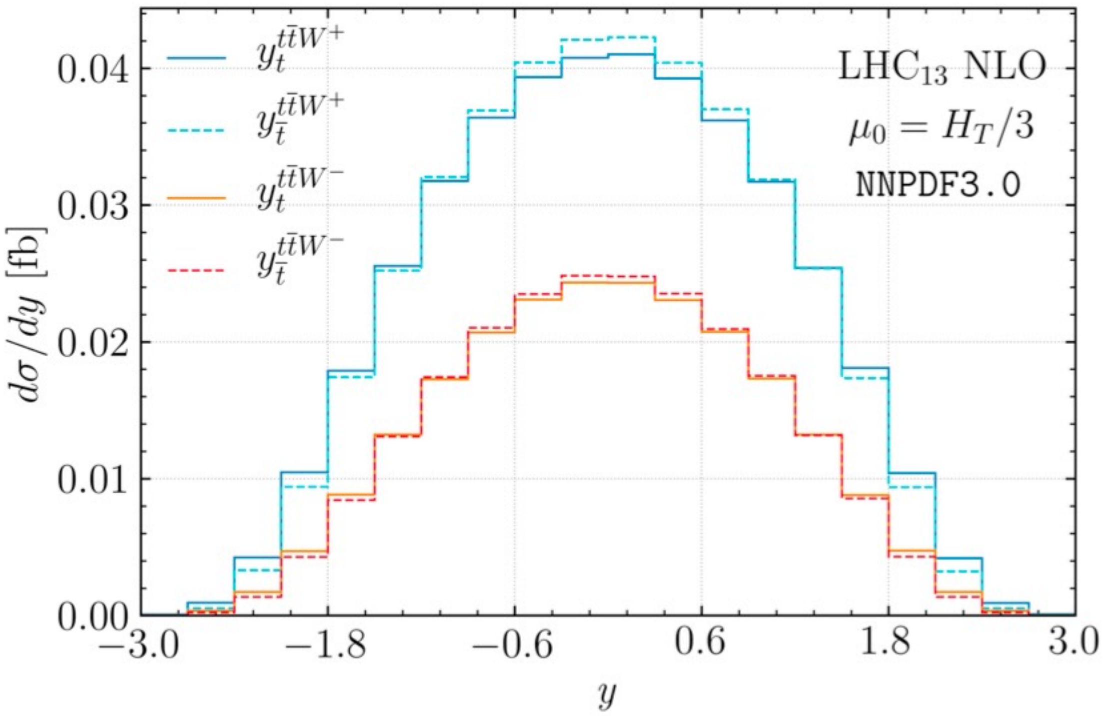
$$pp \to e^+\nu_e\,\mu^-\,\bar\nu_\mu\,e^+\nu_e\,b\bar b + X$$

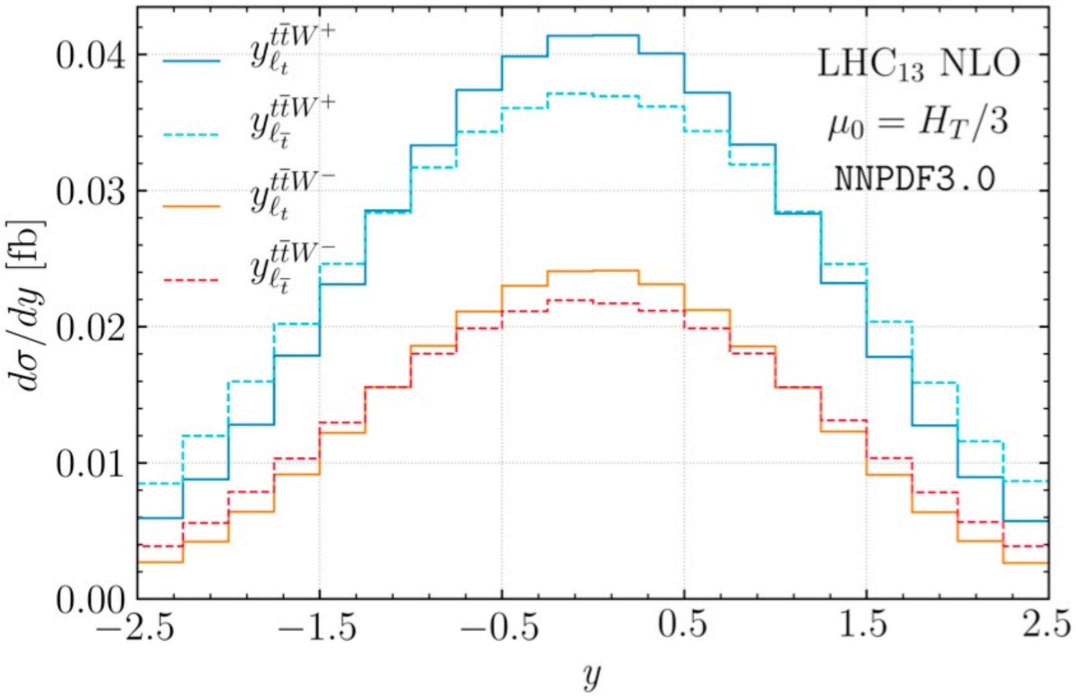
Modelling Approach	$\sigma^{\rm LO}$ [ab]	$\sigma^{\rm NLO}$ [ab]
full off-shell ($\mu_0 = m_t + m_W/2$)	$57.2^{+14.9\,(26\%)}_{-11.0\,(19\%)}$	$68.0^{+4.8\,(7\%)}_{-5.5\,(8\%)}$
full off-shell ($\mu_0 = H_T/3$)	$62.4^{+16.7\,(27\%)}_{-12.3\,(20\%)}$	$68.6^{+3.5\,(5\%)}_{-4.8\,(7\%)}$
NWA ($\mu_0 = m_t + m_W/2$)	$57.2^{+14.9\,(26\%)}_{-11.0\,(19\%)}$	$68.0^{+4.9\,(7\%)}_{-5.4\,(8\%)}$
NWA ($\mu_0 = H_T/3$)	$62.6^{+16.7\,(27\%)}_{-12.3\,(20\%)}$	$68.7^{+3.5\,(5\%)}_{-4.8\,(7\%)}$
$\rm NWA_{LOdecay}$ ($\mu_0 = m_t + m_W/2$)		$69.8^{+8.8\,(13\%)}_{-7.8\,(11\%)}$
$\rm NWA_{LOdecay}$ ($\mu_0 = H_T/3$)		$72.0^{+8.3\,(11\%)}_{-7.7\,(11\%)}$

$$pp \to e^-\bar\nu_e\,\mu^+\,\nu_\mu\,e^-\bar\nu_e\,b\bar b + X$$

TTW

Bevilacqua, Bi, Hartanto, Kraus, Nasufi, Worek
arXiv:2012.01363 [hep-ph]



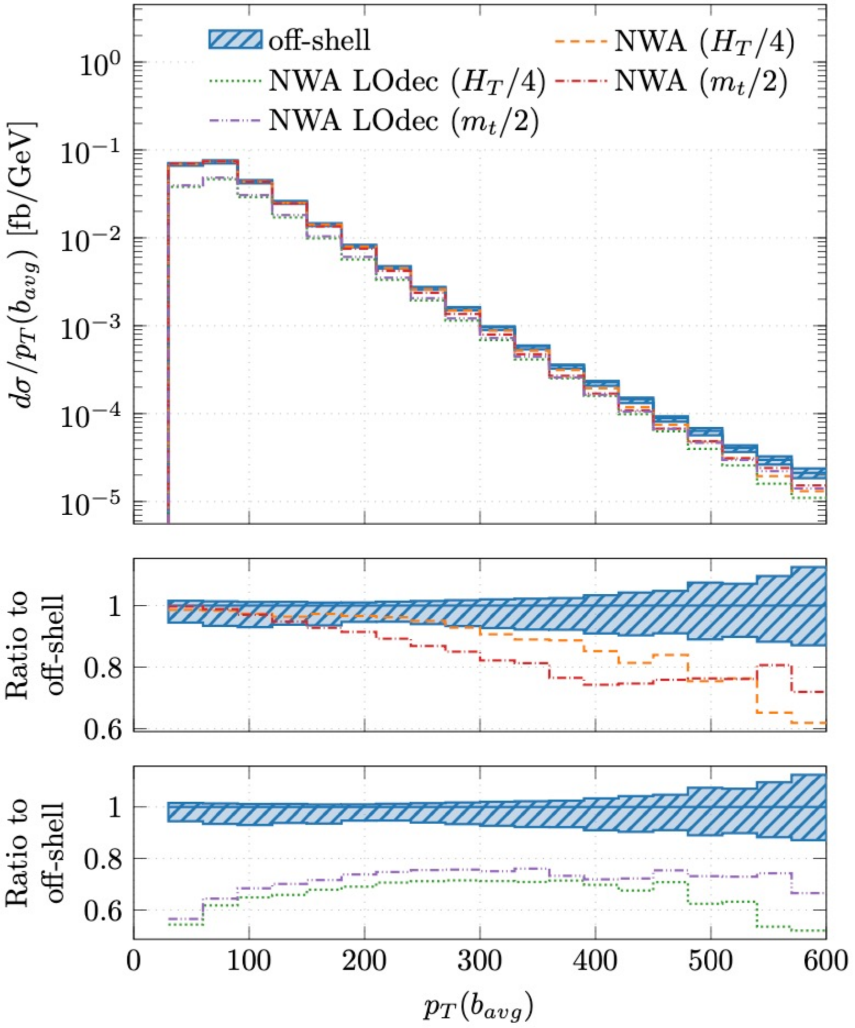


$$\Delta|y| = |y_t| - |y_{\bar{t}}|$$

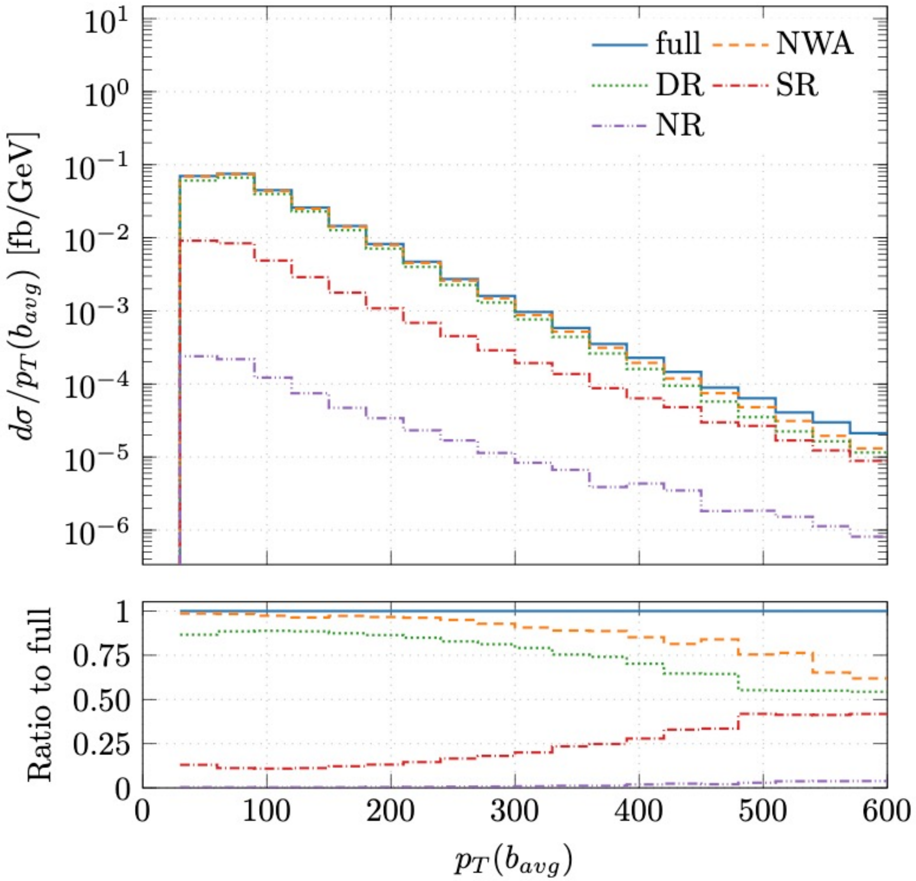
$$pp \to e^+\nu_e\,\mu^-\,\bar{\nu}_\mu\,e^+\nu_e\,b\bar{b} + X$$

TTγ

Bevilacqua, Hartanto, Kraus, Weber, Worek
arXiv:1912.09999 [hep-ph]

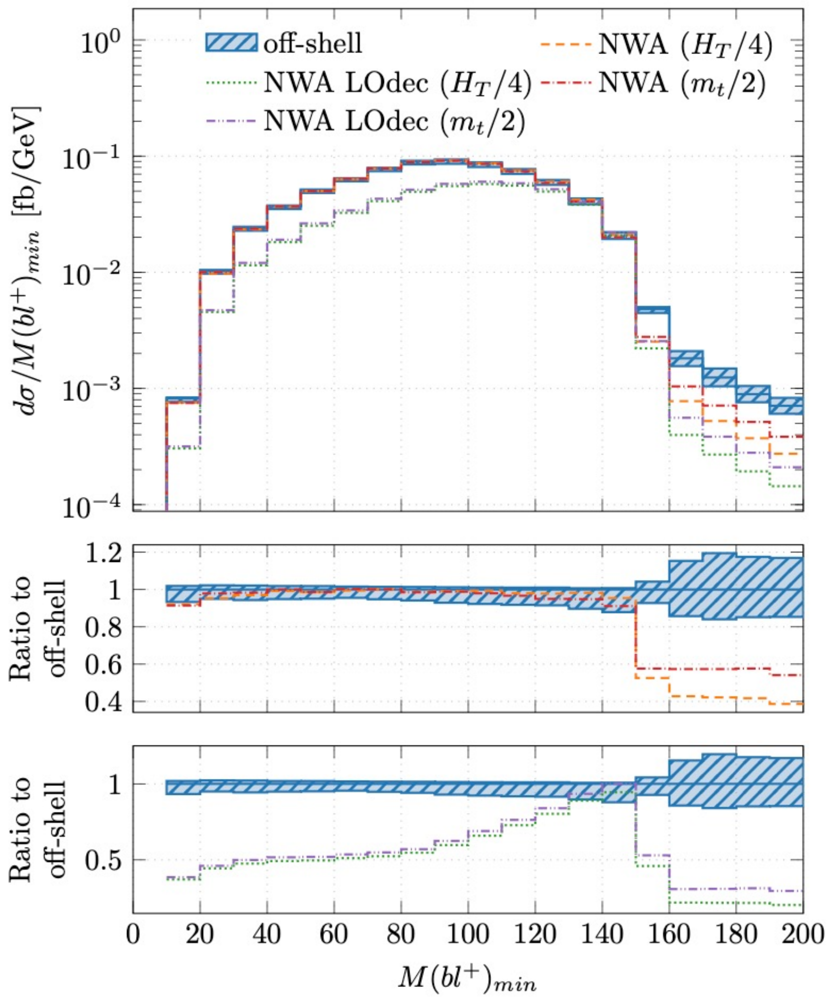


$pp \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}\,\gamma\,+X$

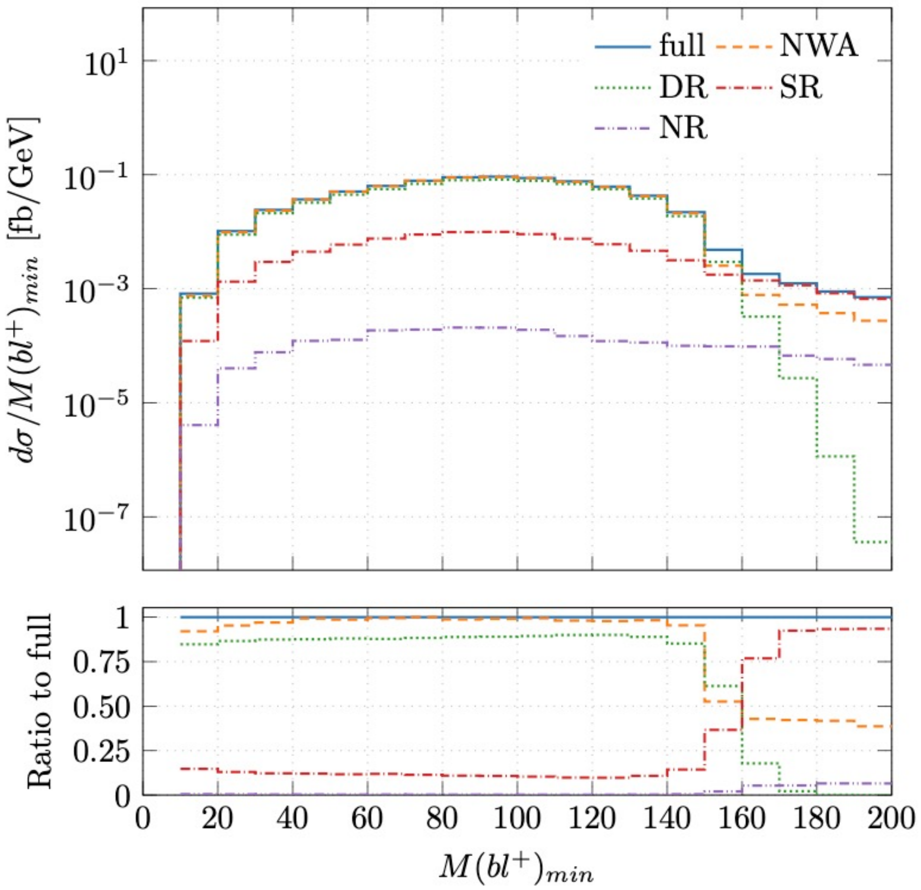


TTγ

Bevilacqua, Hartanto, Kraus, Weber, Worek
arXiv:1912.09999 [hep-ph]



$pp \to e^+\nu_e\, \mu^-\bar{\nu}_\mu\, b\bar{b}\,\gamma\, + X$



TTγ

$$pp \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}\,\gamma\,+X$$

Bevilacqua, Hartanto, Kraus, Weber, Worek
arXiv:1912.09999 [hep-ph]

3 @ LO & 9 @ NLO different possibilities

(i)	$t = W^+(\to e^+\nu_e)\,b$	and	$\bar{t} = W^-(\to \mu^-\bar{\nu}_\mu)\,\bar{b}\,,$
(ii)	$t = W^+(\to e^+\nu_e)\,b\gamma$	and	$\bar{t} = W^-(\to \mu^-\bar{\nu}_\mu)\,\bar{b}\,,$
(iii)	$t = W^+(\to e^+\nu_e)\,b$	and	$\bar{t} = W^-(\to \mu^-\bar{\nu}_\mu)\,\bar{b}\gamma$

$$Q = |M(t) - m_t| + |M(\bar{t}) - m_t|$$

Double-resonant (DR) region

$$|M(t) - m_t| < n\,\Gamma_t\,, \qquad \text{and} \qquad |M(\bar{t}) - m_t| < n\,\Gamma_t$$

Single-resonant (SR) regions

$$|M(t) - m_t| < n\,\Gamma_t\,, \qquad \text{and} \qquad |M(\bar{t}) - m_t| > n\,\Gamma_t$$

or

$$|M(t) - m_t| > n\,\Gamma_t\,, \qquad \text{and} \qquad |M(\bar{t}) - m_t| < n\,\Gamma_t$$

Non-resonant (NR) region

$$|M(t) - m_t| > n\,\Gamma_t\,, \qquad \text{and} \qquad |M(\bar{t}) - m_t| > n\,\Gamma_t$$

Boundary parameter

- n = 5, 10, 15
- For n = 15

$$M(t) \in (152.9, 193.5)\ \text{GeV}$$