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QCD @ LHC - Precision for Discoveries

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Instead of Introduction

- Latest NLO & NNLO QCD results for $2 \to 3$ & $2 \to 5, 6 \ldots$ processes in SM
  - Not only are they impressive, but there are plenty of them

- Tell story, hopefully interesting one about precision in top-quark physics

  - A few results for SM top-quark associated processes
    - ✓ $pp \to tt + \gamma$
    - ✓ $pp \to tt + Z\ (Z \to \nu\nu)$
    - ✓ $pp \to tt + H$

Selection !

  - Top-quark results in the context of BSM physics
    - ✓ $pp \to tt$ + *Dark Matter*
    - ✓ $pp \to tt + H$ ⇨ *CP* structure of top-quark Yukawa interaction

- **My Goal:**
  - Identify which effects are important & should be taken into account
  - Top-quark production and decays with complete off-shell effects included @ NLO QCD
  - Helac-Nlo & Fixed order calculations @ LHC 13 TeV

Bevilacqua, Czakon, Garzelli, Hameren, Kardos, Papadopoulos, Pittau, Worek '13

Instead of Introduction

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

- BSM ⇰ Significant number of open questions remains
  Search for new phenomena key aspect of LHC

- BSM Direct Searches
  - Many proposals for New Physics
  - No model of New Physics really stands out
  - No obvious candidates to look for @ LHC
  - *tt, tt + jets, tt +V* ⇰ Important backgrounds for BSM

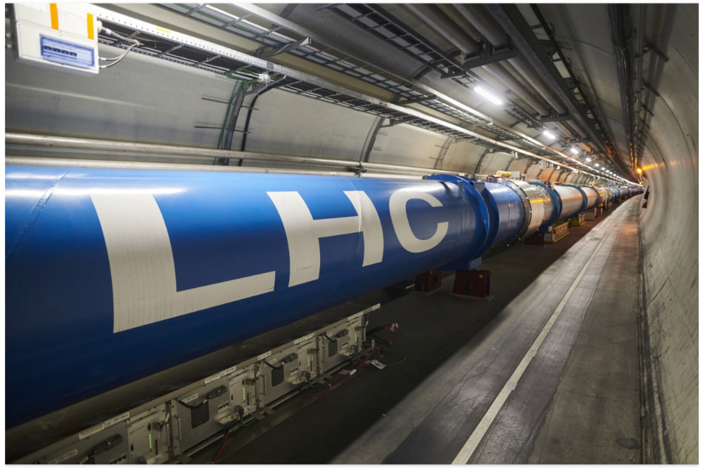
- BSM Indirect Searches
  - New Physics as small corrections to SM reactions

  - *Precision SM measurements @ LHC*
    - ✓ Run 3 & High Luminosity LHC, …
  - *High Precision Theoretical Predictions for SM Processes*
    - ✓ Top Quark

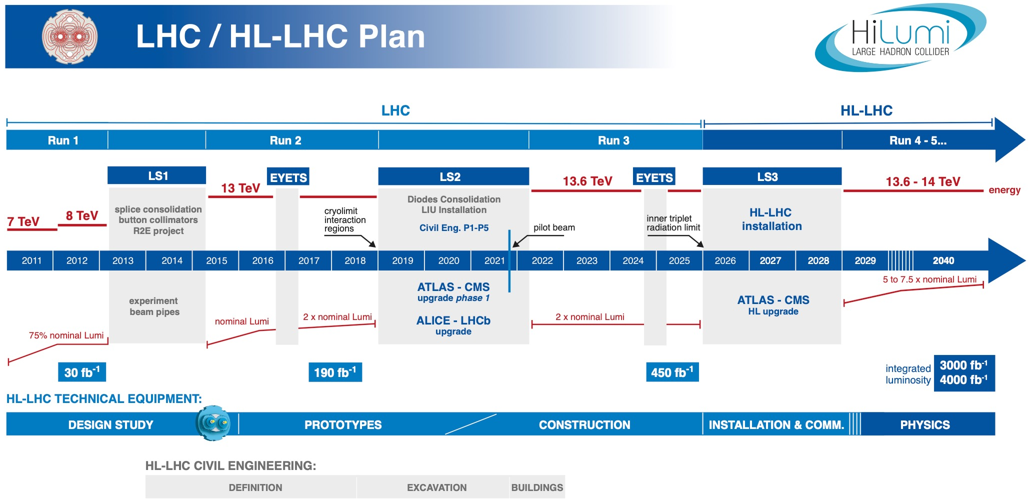
Large Hadron Collider restarts

Beams of protons are again circulating around the collider's 27-kilometre ring, marking the end of a multiple-year hiatus for upgrade work

22 APRIL, 2022



The LHC tunnel at point 1 (Image: CERN)



CERN: LHC/ HL-LHC Plan (last update February 2022)

Why Top Quark is so Special

- Heaviest observed particle

$$m_t = (173.34 \pm 0.76)\ GeV$$

World Combination '14
ATLAS, CDF, CMS, D0

- Substantial Yukawa coupling

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

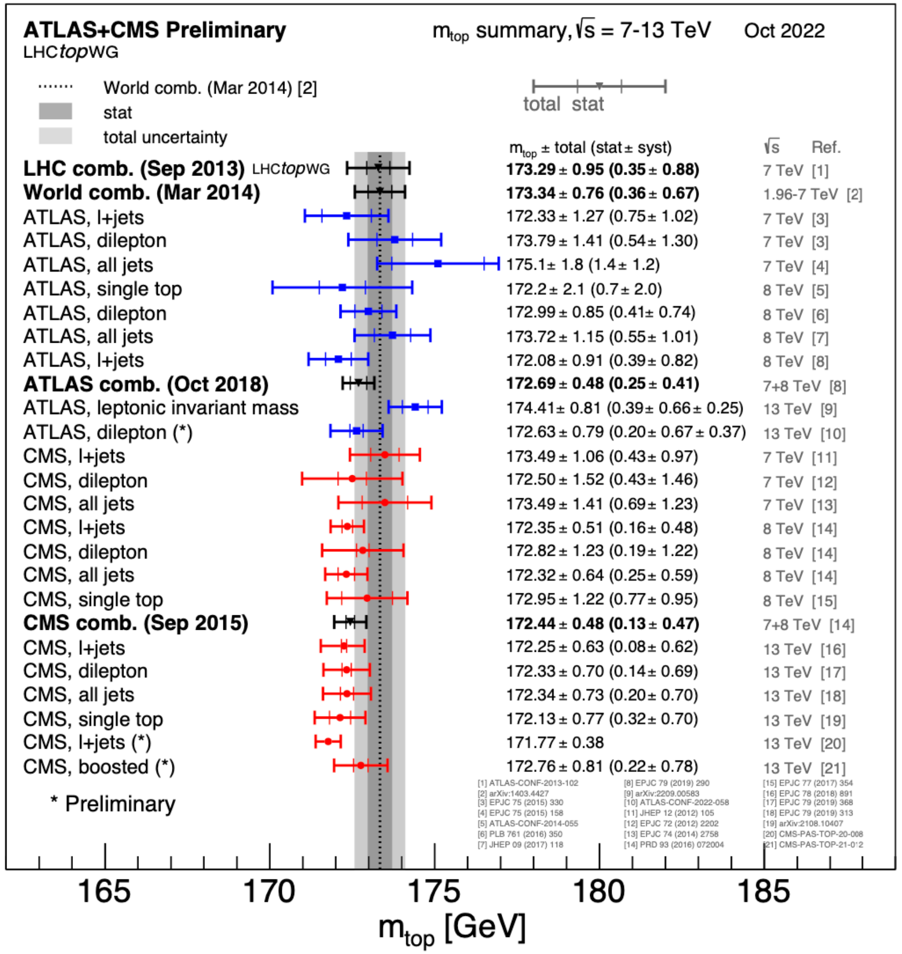
- Special relation with SM Higgs boson

- Short lifetime ⇨ Decay before bound states can be formed

- Direct handle on top-quark properties from its decay products

$$b\text{-jets, light jets, } l^{\pm},\ p_T^{miss}$$

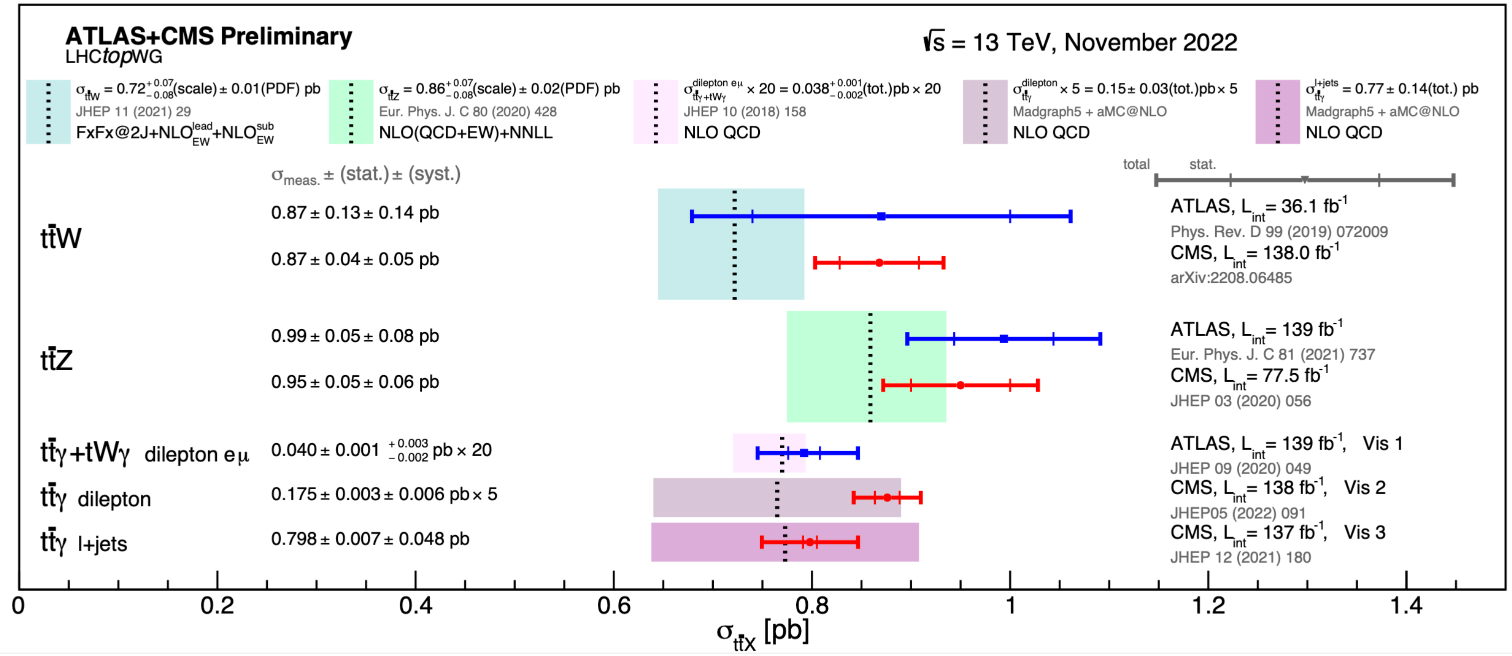
- Final states that are present in almost all BSM scenarios



$$m_t = (171.77 \pm 0.38)\ GeV$$

CMS Collaboration '22

Associated tt Production

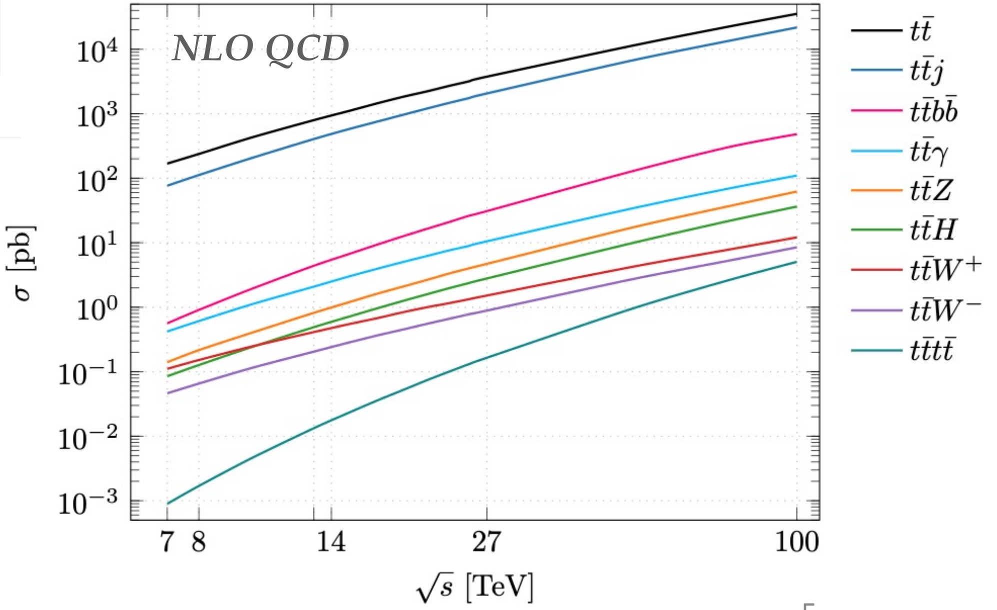


Summary of ATLAS and CMS measurements of $pp \to tt + X,\ X = \gamma, Z, W$ cross sections at 13 TeV

More exclusive final states are produced @ LHC

Report of the Topical Group on Top quark physics and heavy flavor production for Snowmass 2021
e-Print: 2209.11267 [hep-ph]

Total cross sections for various $pp \to tt + X$ processes as function of center-of-mass energy
Also shown is $pp \to tt$



Full Off-Shell Effects

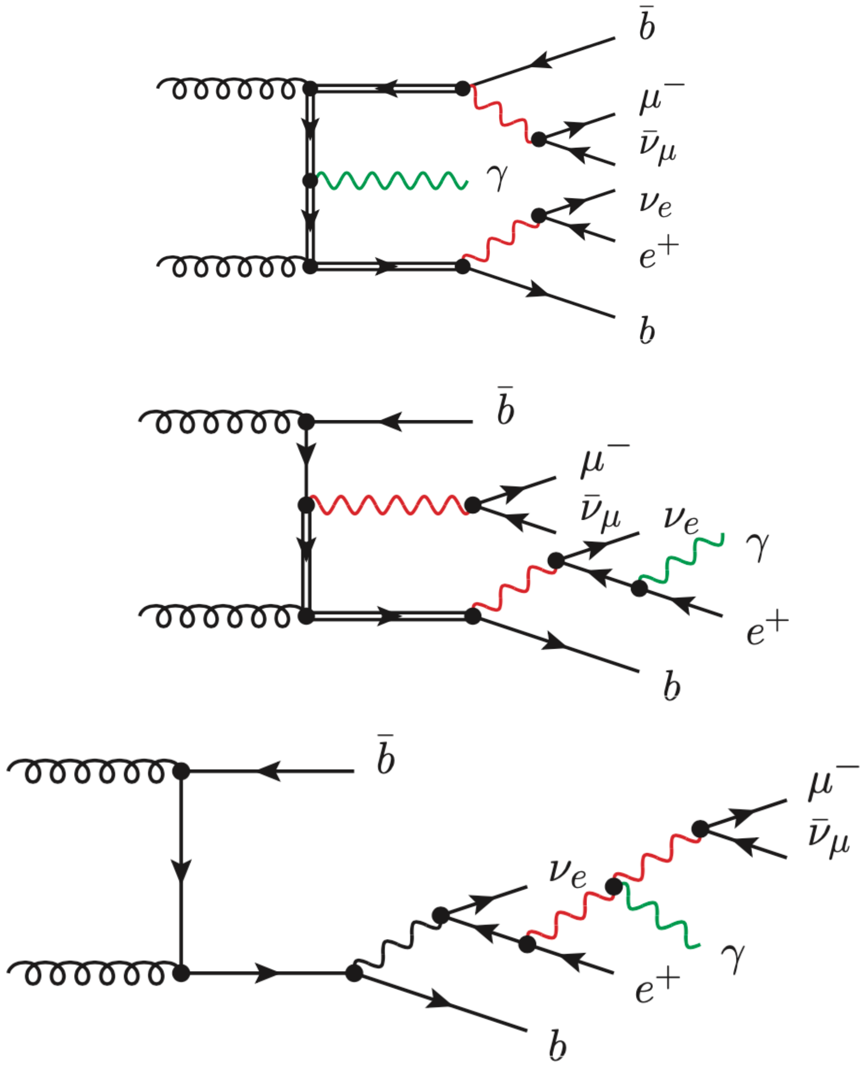
NLO $t\bar{t}\gamma$

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

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

- NLO QCD corrections to *$t\bar{t}\gamma$* production & top-quark decays
- Nonfactorizable NLO QCD corrections included
- Cross-talk between production & both top-quark decays
- Photon emission in production & top-quark decays
- NLO spin correlations

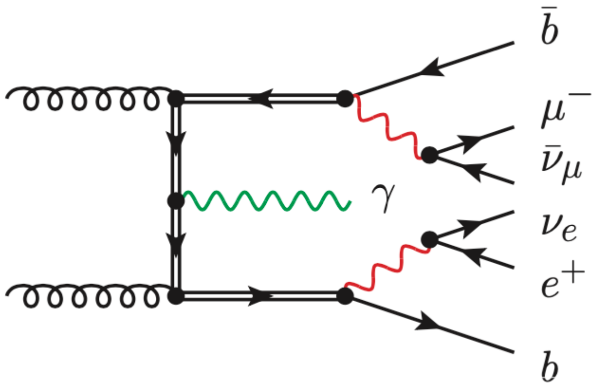
Bevilacqua, Hartanto, Kraus, Weber, Worek '18 '19 '20



Narrow Width Approximation

NLO $t\bar{t}\gamma$

- Full NWA ⇨ $\mathrm{NWA_{Full}}$



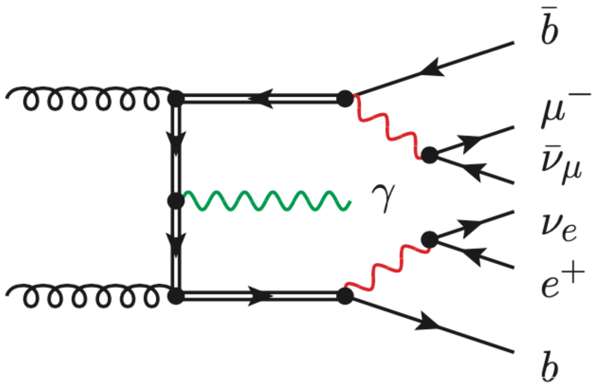
- *Works in the limit* ⇨ $\Gamma/m \rightarrow 0$
- *Incorporates only double resonant contributions*
- *Restricts unstable tops & W to on-shell states*

- NLO QCD correction separately to $t\bar{t}\gamma$ production & separately to both top-quark decays
- NLO QCD nonfactorizable corrections missing
- No cross-talk between production & both top-quark decays
- NLO spin correlations

Narrow Width Approximation

NLO $t\bar{t}\gamma$

- Full NWA ⇨ NWA_{Full}



- *Works in the limit ⇨ $\Gamma/m \to 0$*
- *Incorporates only double resonant contributions*
- *Restricts unstable tops & W to on-shell states*
- NLO QCD correction separately to $t\bar{t}\gamma$ production & both top-quark decays
- NLO QCD nonfactorizable corrections missing
- No cross-talk between production & both top-quark decays
- NLO spin correlations

- NWA with LO Decays ⇨ $\text{NWA}_{\text{LOdec}}$
  - *Without NLO QCD corrections to top-quark decays*
  - *Photons only in production*
  - LO spin correlations

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

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

$$\frac{\Gamma_W}{m_W} > \frac{\Gamma_t}{m_t} \gg \frac{\Gamma_H}{m_H},$$

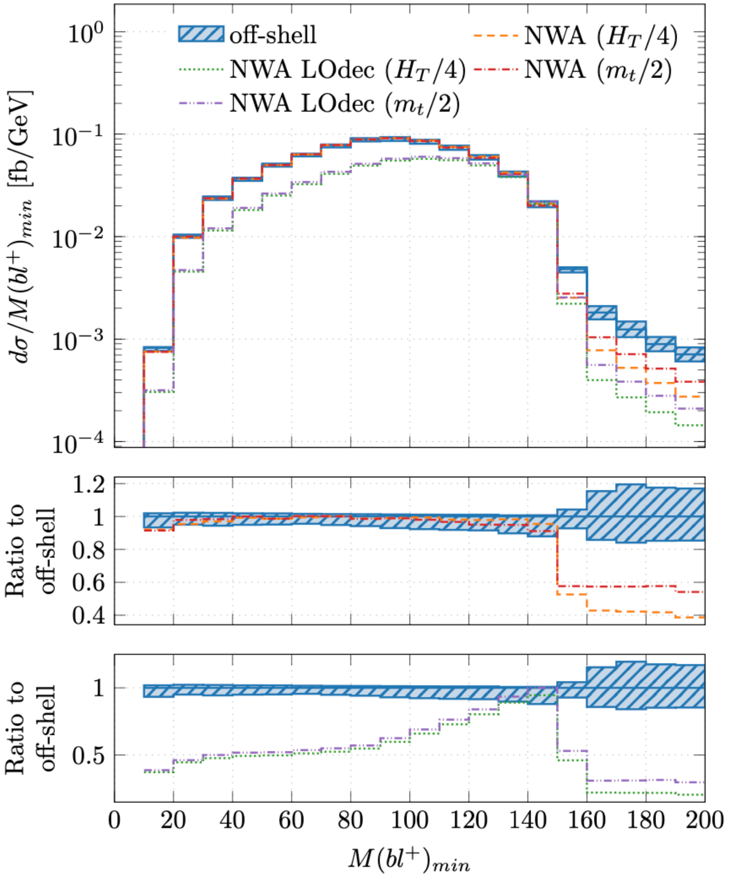
$$2.6\% > 0.8\% \gg 0.003\%\,.$$

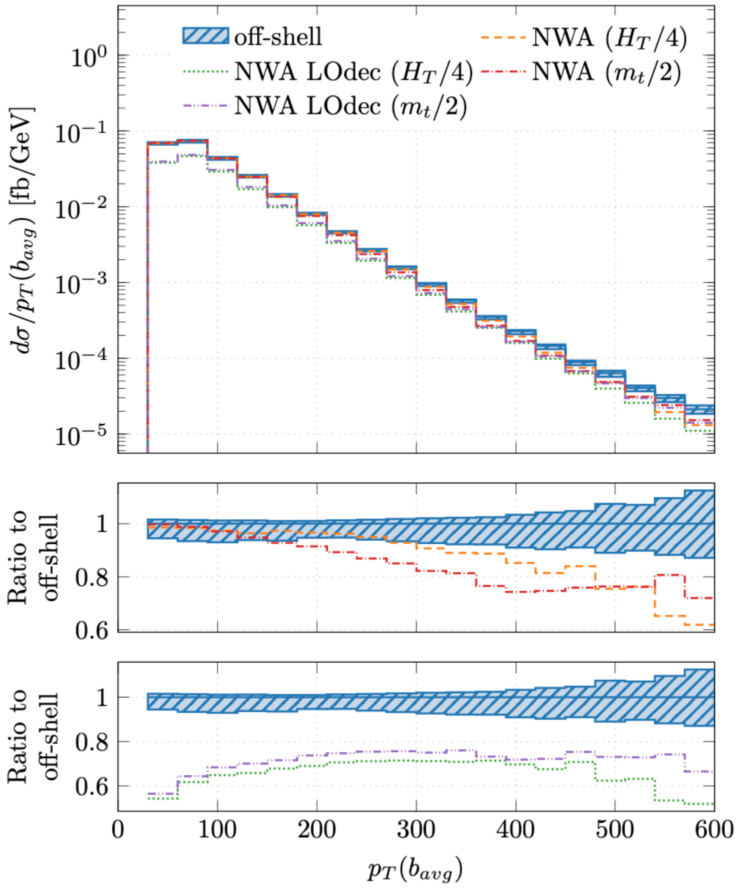
How Good is NWA

NLO $t\bar{t}\gamma$

Bevilacqua, Hartanto, Kraus, Weber, Worek '18 '19 '20

$M(be^+) = \sqrt{m_t^2 - m_W^2} \approx 153\,\text{GeV}$





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

Dimensionful observables

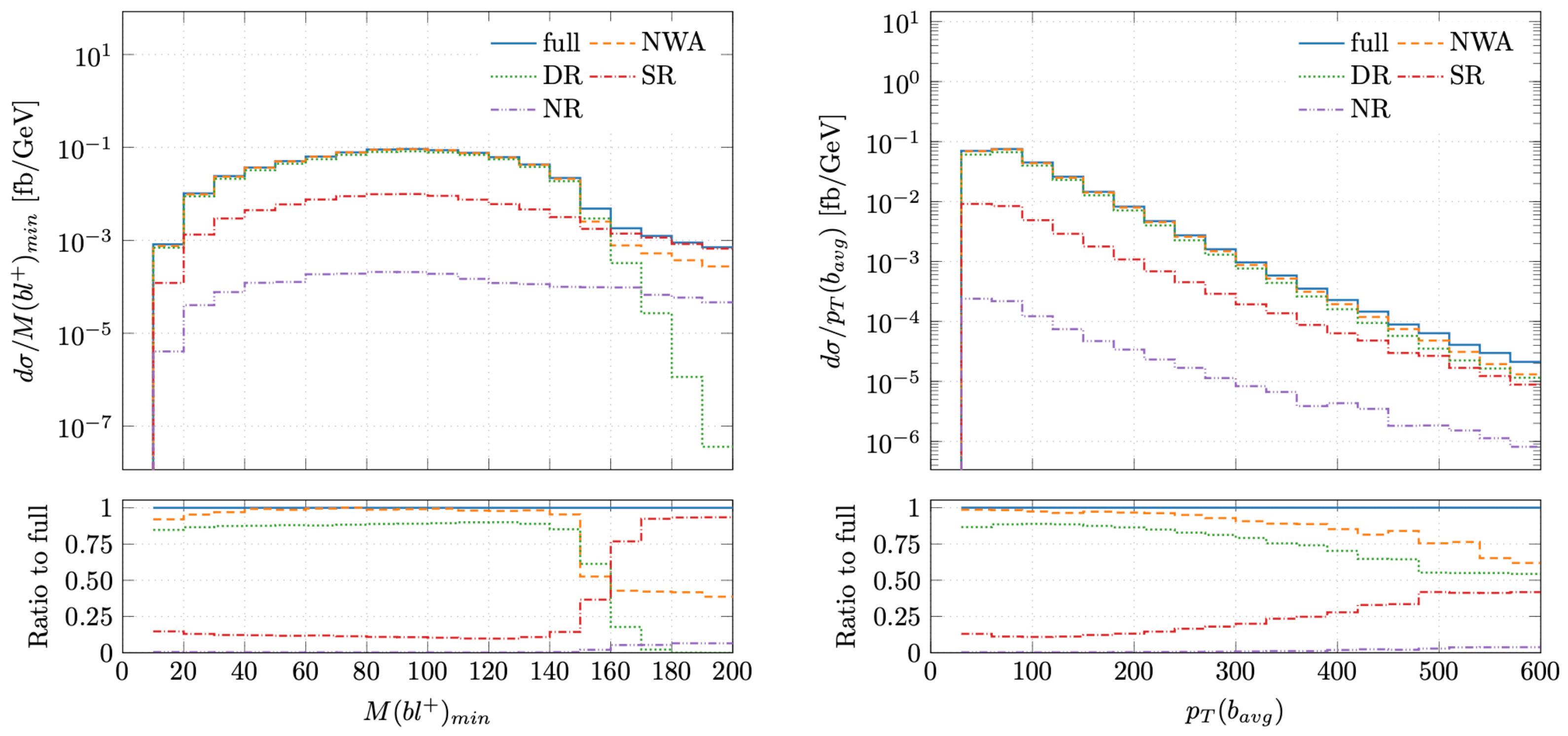
- Sensitive to non-factorizable top quark corrections *50% − 60%*
- Sensitive phase-space regions
  - *Kinematical edges*
  - *High p_T regions*
- NLO QCD corrections to top-quark decays *12% - 17%*

Normalisation & shape differences due to not adequate renormalisation & factorisation scale setting

Various Phase-Space Regions

NLO $tt\gamma$

Bevilacqua, Hartanto, Kraus, Weber, Worek '18 '19 '20



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

Dimensionful observables

- Sensitive to non-factorizable top quark corrections
- Effects up to *50% − 60%*
- Sensitive phase-space regions
  - *Kinematical edges*
  - *High p_T regions*

Normalisation & shape differences due to large single top-quark contributions and interreference effects

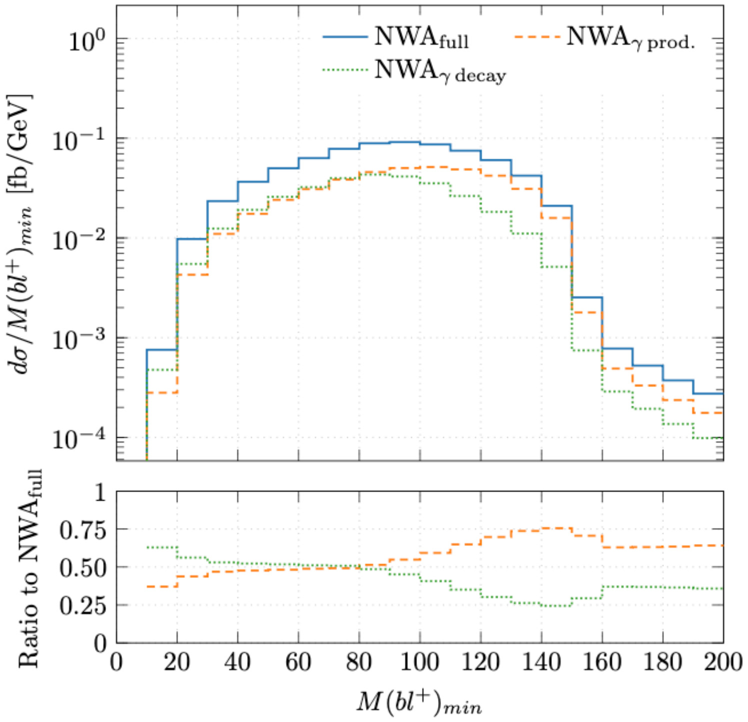
Not due to new physics effects

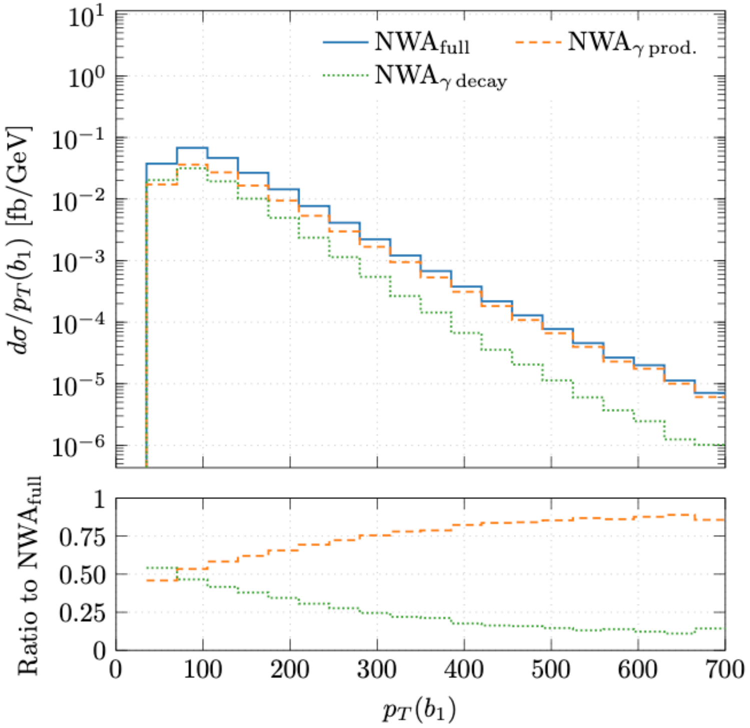
γ in Top-Quark Production & Decays

NLO $tt\gamma$

Bevilacqua, Hartanto, Kraus, Weber, Worek '18 '19 '20

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





Normalisation & shape differences due to large γ emission contributions in top-quark decays

Not due to new physics effects

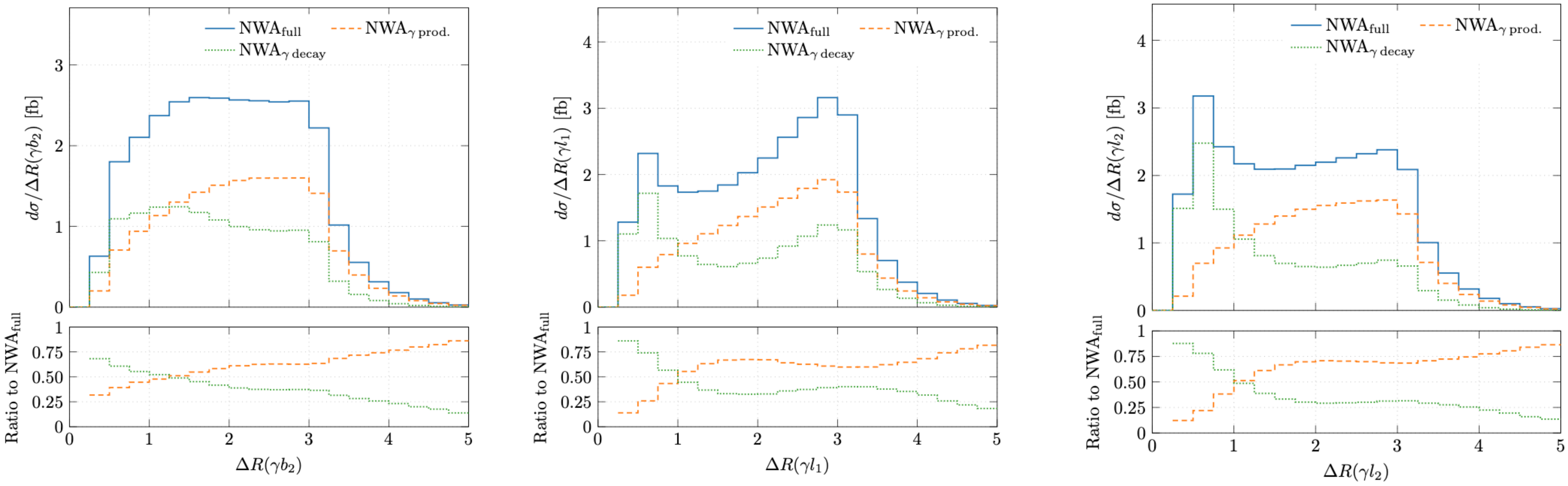
- For $p_{T,b}$ > 40 GeV
  - 57% ⇨ γ in production
  - 43% ⇨ γ in top-quark decays
- For $p_{T,b}$ > 25 GeV
  - γ in top-quark decays increases up to almost 50%
- Photon radiation is distributed evenly between $tt\gamma$ production & top-quark decays

γ in Top-Quark Production & Decays

NLO $tt\gamma$

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

Bevilacqua, Hartanto, Kraus, Weber, Worek '18 '19 '20



Normalisation & shape differences due to γ emission contributions in top-quark decays

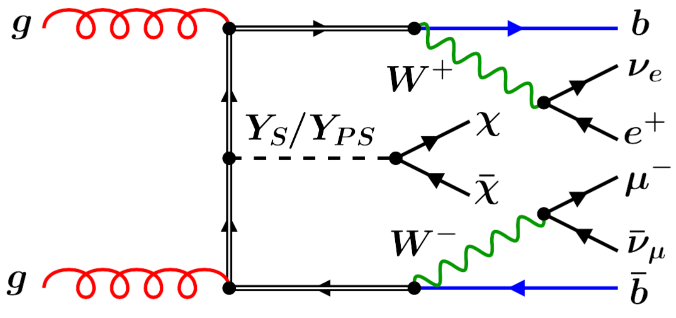
Not due to new physics effects

Associated tt + Dark Matter Production

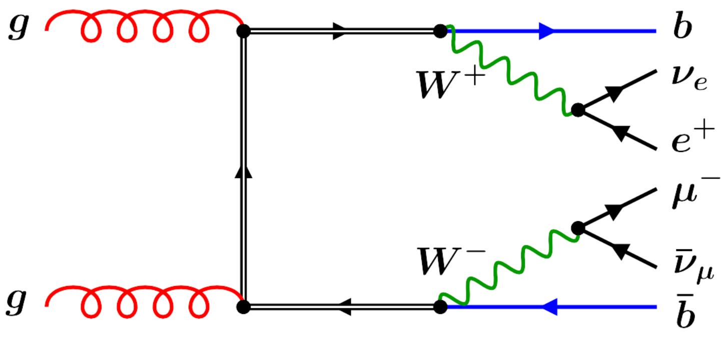
- *tt + DM* ⇨ Top-quark backgrounds: *tt & ttZ*

Haisch, Pani, Polesello '17

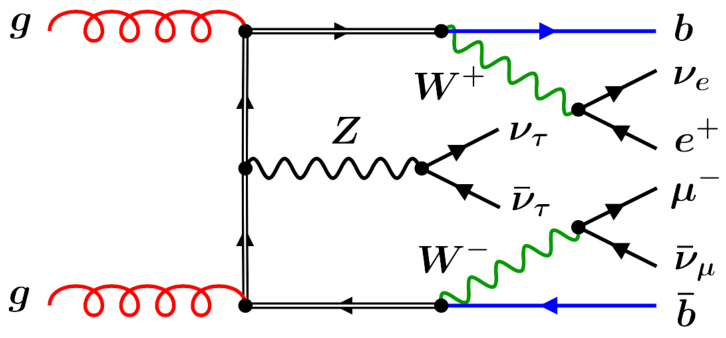
$$pp \to t\bar{t} + Y_{S/PS} \to W^+W^-b\bar{b} + Y_{S/PS} \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b} + \chi\chi$$



SIGNAL



LARGEST BACKGROUND



IRREDUCIBLE BACKGROUND

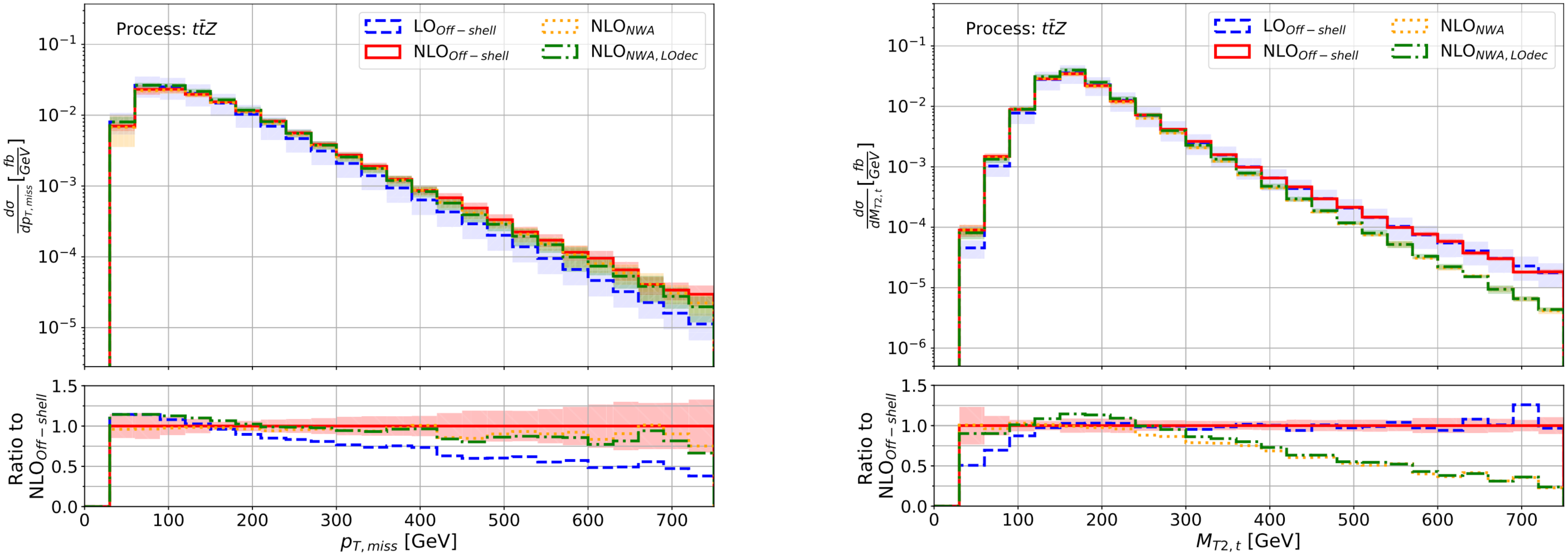
- SIMPLIFIED SPIN-0 S-CHANNEL MEDIATOR MODEL ⇨ Fermionic DM particle χ & mediator Y that can either be a scalar Y_S or pseudoscalar Y_{PS}
- FINAL STATES ⇨ *$2l^\pm$, 2b-jets, large p_T^{miss}*
- OBSERVABLE ⇨ *$M_{T2,W}$ & $M_{T2,t}$ & p_T^{miss}* ⇨ Observables with kinematical edges & high p_T regions

Associated tt + Z Production

NLO *ttZ*

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

Hermann, Worek '21



Comparison of differential distributions for *ttZ* background process for different modelling approaches

tt & tt + Z Production After Exclusive Cuts

Hermann, Worek '21

Process	Order	Scale	σ_{uncut} [fb]	σ_{cut} [fb]	$\sigma_{\text{cut}}/\sigma_{\text{uncut}}$ (%)	Events for $L = 300\text{ fb}^{-1}$
$t\bar{t}$ NWA	LO	$H_T/4$	1061	0	0.0	0
	LO	$E_T/4$	984	0	0.0	0
	LO	m_t	854	0	0.0	0
	NLO	$H_T/4$	1097	0	0.0	0
	NLO, LO dec	$H_T/4$	1271	0	0.0	0
$t\bar{t}Z$ NWA	LO	$H_T/3$	0.1223	0.0130	11	47
	LO	$E_T/3$	0.1052	0.0116	11	42
	LO	$m_t + m_Z/2$	0.1094	0.0134	12	48
	NLO	$H_T/3$	0.1226	0.0130	11	47
	NLO, LO dec	$H_T/3$	0.1364	0.0140	10	50
$t\bar{t}$ Off-shell	LO	$H_T/4$	1067	0.0144	0.0013	17
	LO	$E_T/4$	989	0.0131	0.0013	16
	LO	m_t	861	0.0150	0.0017	18
	NLO	$H_T/4$	1101	0.0156	0.0014	19
$t\bar{t}Z$ Off-shell	LO	$H_T/3$	0.1262	0.0135	11	49
	LO	$E_T/3$	0.1042	0.0115	11	41
	LO	$m_t + m_Z/2$	0.1135	0.0140	12	50
	NLO	$H_T/3$	0.1269	0.0134	11	48

Comparison of LO and NLO integrated cross sections for two background processes in NWA and including full off-shell effects before and after applying additional cuts

Lepton flavour factors are included: *4 for tt & 12 for ttZ*

tt & ttZ

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

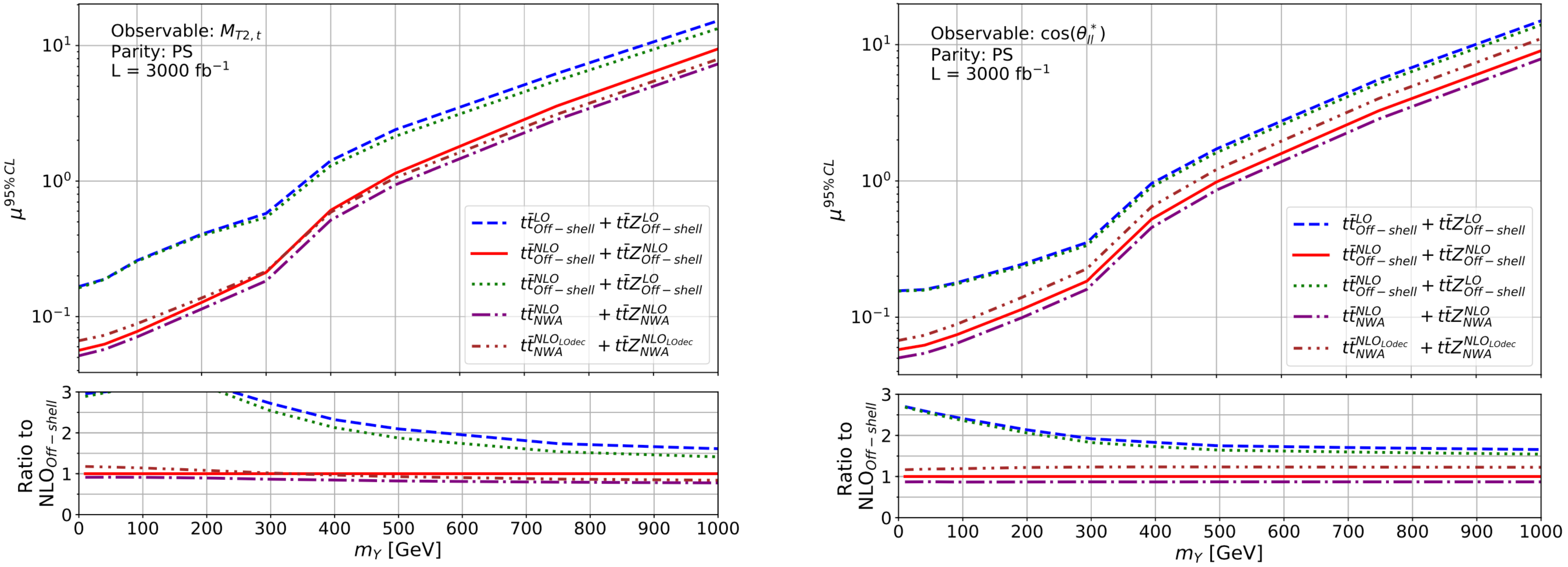
Before & after applying additional cuts

- After cuts *25%* of events come from *tt*
- NLO smaller uncertainties w.r.t LO, NLO + LO decays

BSM Exclusion Limits

Hermann, Worek '21

Comparison of signal strength exclusion limits computed with different background predictions for pseudoscalar mediator scenario



$$M^2_{T2,t} = \min_{\substack{\mathbf{p}_T^{\nu_1}+\mathbf{p}_T^{\nu_2} \\ =\mathbf{p}_{T,\text{miss}}}} [\max\{M_T^2\left(\mathbf{p}_T^{(lb)_1}, \mathbf{p}_T^{\nu_1}\right), M_T^2\left(\mathbf{p}_T^{(lb)_2}, \mathbf{p}_T^{\nu_2}\right)\}]$$

$$\cos(\theta^*_{ll}) = \tanh(|\eta_{l_1} - \eta_{l_2}|/2)$$

$$M_T^2\left(\mathbf{p}_T^{(lb)_i}, \mathbf{p}_T^{\nu_i}\right) = M^2_{(lb)_i} + 2\left(E_T^{(lb)_i} E_T^{\nu_i} - \mathbf{p}_T^{(lb)_i} \cdot \mathbf{p}_T^{\nu_i}\right)$$

Associated tt + H Production

- Allows for direct probe of Yukawa interaction and it's ***CP*** nature at tree level ⇨ In SM Higgs is ***CP* even**

- Higgs ***CP*** studies in *ttH* are ongoing

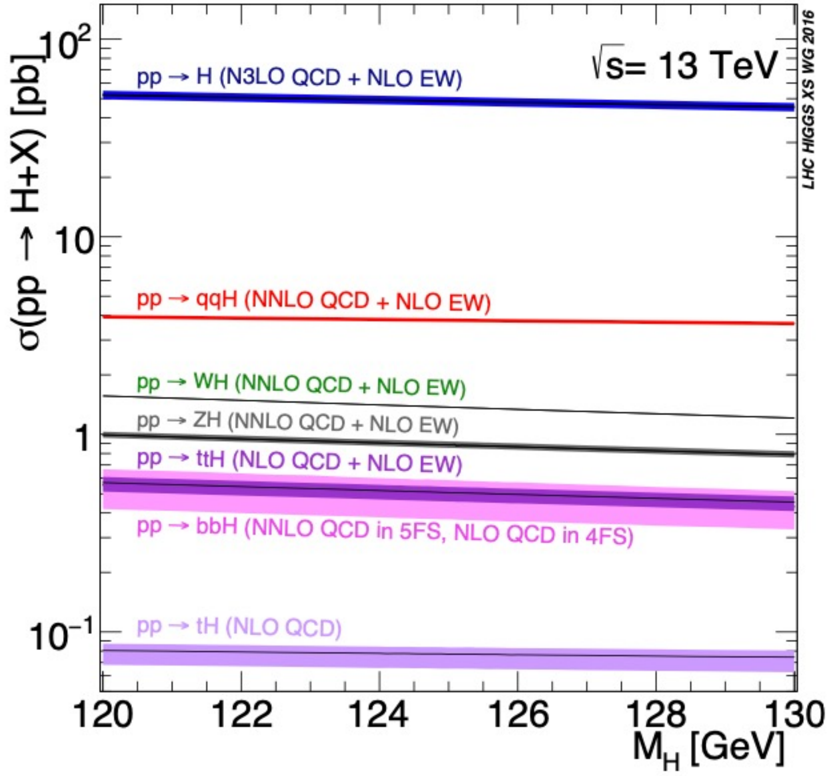
- ATLAS *ATLAS Collaboration arXiv:2004.04545 [hep-ex]*
  - Purely ***CP*-odd** hypothesis excluded **3.9σ**
  - ***CP*-mixing** angle $|\alpha_{CP}| > 43°$ excluded at 95% CL

- CMS *CMS Collaboration arXiv:2208.02686 [hep-ex]*
  - Purely ***CP*-odd** hypothesis $|f^{Htt}_{CP}| = 1$ excluded **3.7σ**
  - ***CP*-mixing** angle $|f^{Htt}_{CP}| < 0.55$ at 68 % CL

- Weak constrains exist on possible admixture between ***CP*-even** & ***CP*-odd** component

- DEVIATION FROM SM VALUE WOULD INDICATE NEW PHYSICS EFFECTS

SM Higgs boson production cross section at 13 TeV



$pp \rightarrow ttH$ only **1%** of total $pp \rightarrow H + X$

Report of the LHC Higgs Cross Section Working Group arXiv:1610.07922 [hep-ph]

Associated tt + H Production

- *CP*-even, *CP*-odd & *CP*-mixed Higgs boson in Higgs characterisation framework

Mixing angle

$$\mathcal{L}_{t\bar{t}H} = -\bar{\psi}_t \frac{Y_t}{\sqrt{2}} \left(\kappa_{Ht\bar{t}} \cos(\alpha_{\mathrm{CP}}) + i\kappa_{At\bar{t}} \sin(\alpha_{\mathrm{CP}})\gamma_5 \right) \psi_t H$$

CP-even   *CP*-odd

$$\mathcal{L}_{HVV} = \kappa_{HVV} \left(\frac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W^+_\mu W^{-\mu} \right) H$$

Scenario	α
Purely CP-even	0° or 180°
Purely CP-odd	90°
Mixed	$\neq 0°, \neq 90°, \neq 180°$

Recover SM results for any value of α_{CP} & ensure consistency with bounds from GF and VBF

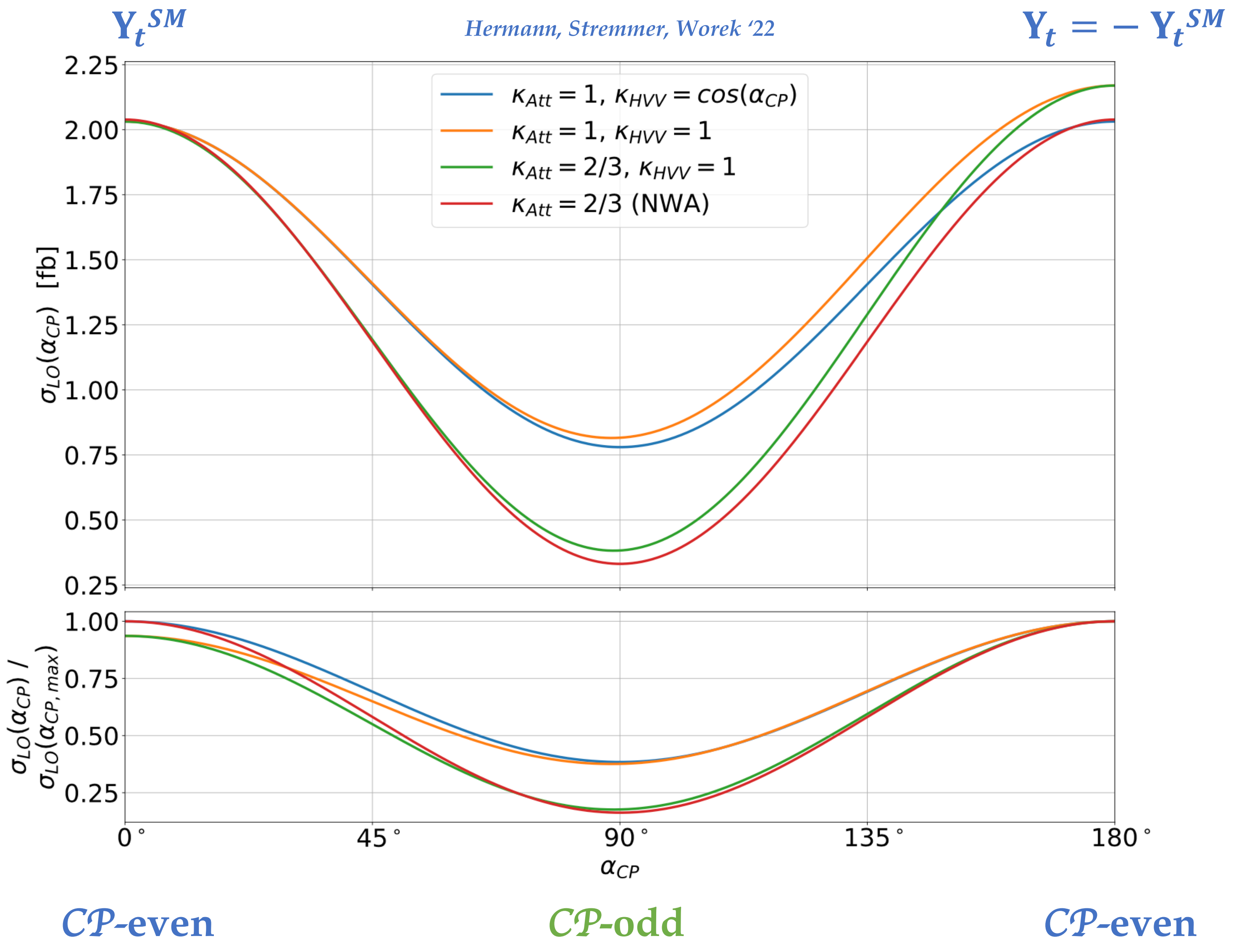
$$\kappa_{At\bar{t}} = 2/3 \text{ and } \kappa_{Ht\bar{t}} = 1$$

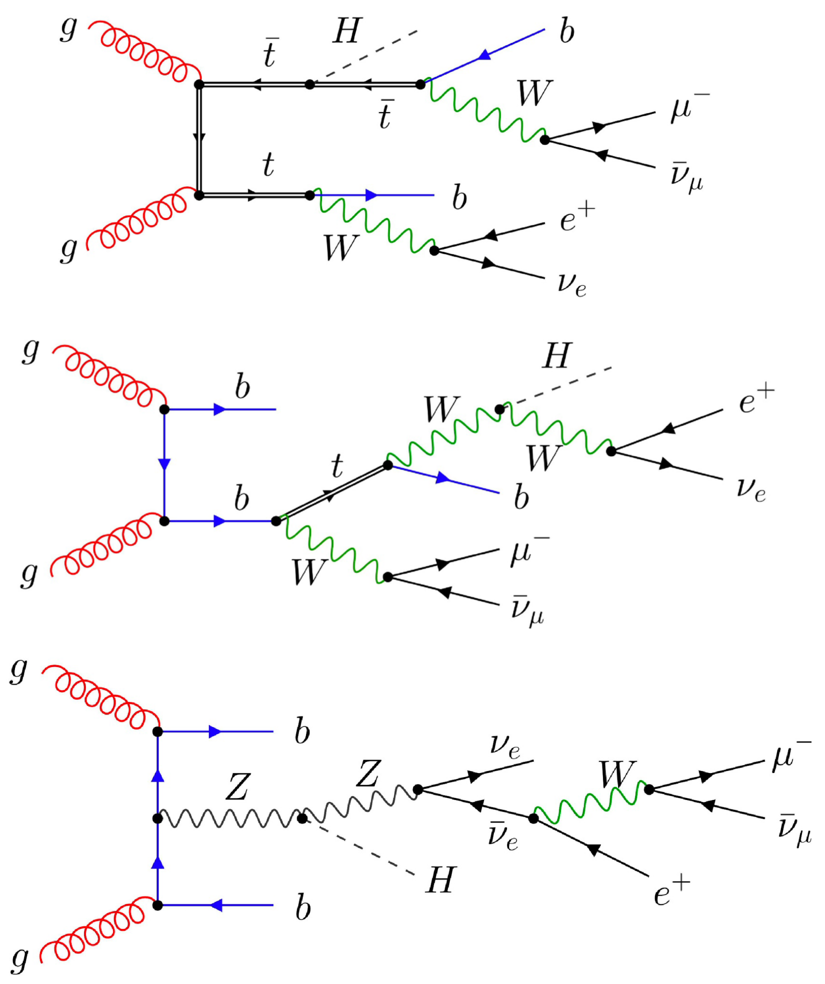
$$\kappa_{HVV} = 1$$

Artoisenet, Aquino, Demartin, Frederix, Frixione, Maltoni, Mandal, Mathews, Mawatari, Ravindran, Seth, Torrielli, Zaro '13
Maltoni, Mawatari, Zaro '14
Demartin, Maltoni, Mawatari, Page, Zaro '14
Demartin, Maltoni, Mawatari, Zaro '15
Demartin, Maier, Maltoni, Mawatari, Zaro '17

- Extended Higgs sector: $\kappa_{At\bar{t}} = 1 \qquad \kappa_{HVV} = \cos(\alpha_{\mathrm{CP}})$
  - Same coupling for scalar and pseudoscalar Higgs
  - Relevant for SM extensions like 2HDM

Associated tt + H Production





Integrated fiducial cross-section dependence on $\boldsymbol{\alpha_{CP}}$

- NWA is symmetric $\alpha_{CP} \rightarrow \pi - \alpha_{CP}$
- *Off-shell contributions break symmetry*
- Full result is only symmetric for

$$\kappa_{HVV} = \cos(\alpha_{CP})$$

Associated $tt + H$ Production

NLO ttH

Hermann, Stremmer, Worek '22

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

	α_{CP}		Off-shell	NWA	Off-shell effects
CP-even	0 (SM)	σ_{LO} [fb]	$2.0313(2)^{+0.6275\,(31\%)}_{-0.4471\,(22\%)}$	$2.0388(2)^{+0.6290\,(31\%)}_{-0.4483\,(22\%)}$	-0.37%
		σ_{NLO} [fb]	$2.466(2)^{+0.027\,(1.1\%)}_{-0.112\,(4.5\%)}$	$2.475(1)^{+0.027\,(1.1\%)}_{-0.113\,(4.6\%)}$	-0.36%
		$\sigma_{NLO_{LOdec}}$ [fb]	—	$2.592(1)^{+0.161\,(6.2\%)}_{-0.242\,(9.3\%)}$	
		$\mathcal{K} = \sigma_{NLO}/\sigma_{LO}$	1.21	1.21 (LOdec: 1.27)	
CP-mixed	$\pi/4$	σ_{LO} [fb]	$1.1930(2)^{+0.3742\,(31\%)}_{-0.2656\,(22\%)}$	$1.1851(1)^{+0.3707\,(31\%)}_{-0.2633\,(22\%)}$	0.66%
		σ_{NLO} [fb]	$1.465(2)^{+0.016\,(1.1\%)}_{-0.071\,(4.8\%)}$	$1.452(1)^{+0.015\,(1.0\%)}_{-0.069\,(4.8\%)}$	0.89%
		$\sigma_{NLO_{LOdec}}$ [fb]	—	$1.517(1)^{+0.097\,(6.4\%)}_{-0.144\,(9.5\%)}$	
		$\mathcal{K} = \sigma_{NLO}/\sigma_{LO}$	1.23	1.23 (LOdec: 1.28)	
CP-odd	$\pi/2$	σ_{LO} [fb]	$0.38277(6)^{+0.13123\,(34\%)}_{-0.09121\,(24\%)}$	$0.33148(3)^{+0.11240\,(34\%)}_{-0.07835\,(24\%)}$	13.4%
		σ_{NLO} [fb]	$0.5018(3)^{+0.0083\,(1.2\%)}_{-0.0337\,(6.7\%)}$	$0.4301(2)^{+0.0035\,(0.8\%)}_{-0.0264\,(6.1\%)}$	14.3%
		$\sigma_{NLO_{LOdec}}$ [fb]	—	$0.4433(2)^{+0.0323\,(7.3\%)}_{-0.0470\,(11\%)}$	
		$\mathcal{K} = \sigma_{NLO}/\sigma_{LO}$	1.31	1.30 (LOdec: 1.34)	

Comparison of LO and NLO QCD integrated fiducial cross-sections as calculated in NWA, NWA with LO top-quark decays and full off-shell approach

NLO corrections:

- **21% - 31%** corrections
- Increase with mixing angle
- Reduced scale uncertainties
- NLO with LO decays overestimates NLO results by few percent

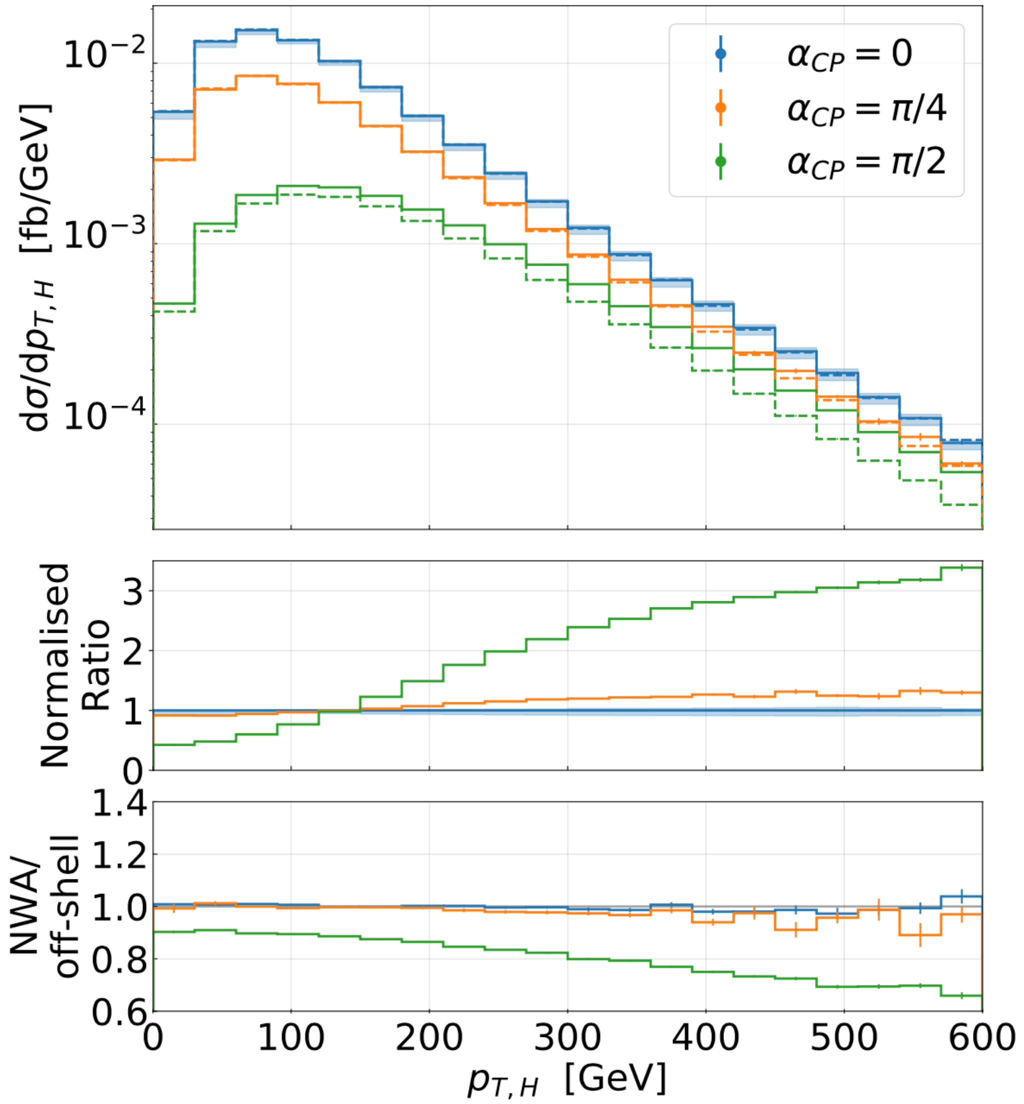
Off-shell effects:

- Small for *CP*-even and *CP*-mixed Higgs boson
- Large effects for *CP*-odd Higgs boson

Associated $t\bar{t} + H$ Production

NLO ttH

Hermann, Stremmer, Worek '22



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

Shape comparison:

- ***CP*-even** and ***CP*-mixed** similar, small difference in tails
- Tails much more pronounced in ***CP*-odd** case even up to **200%**

Off-shell effects:

- Large effects on size and shape for ***CP*-odd** Higgs boson
- Up to **35%** effects driven by single-resonant top-quark contributions
- Only **a few %** effects for ***CP*-even** and ***CP*-mixed**

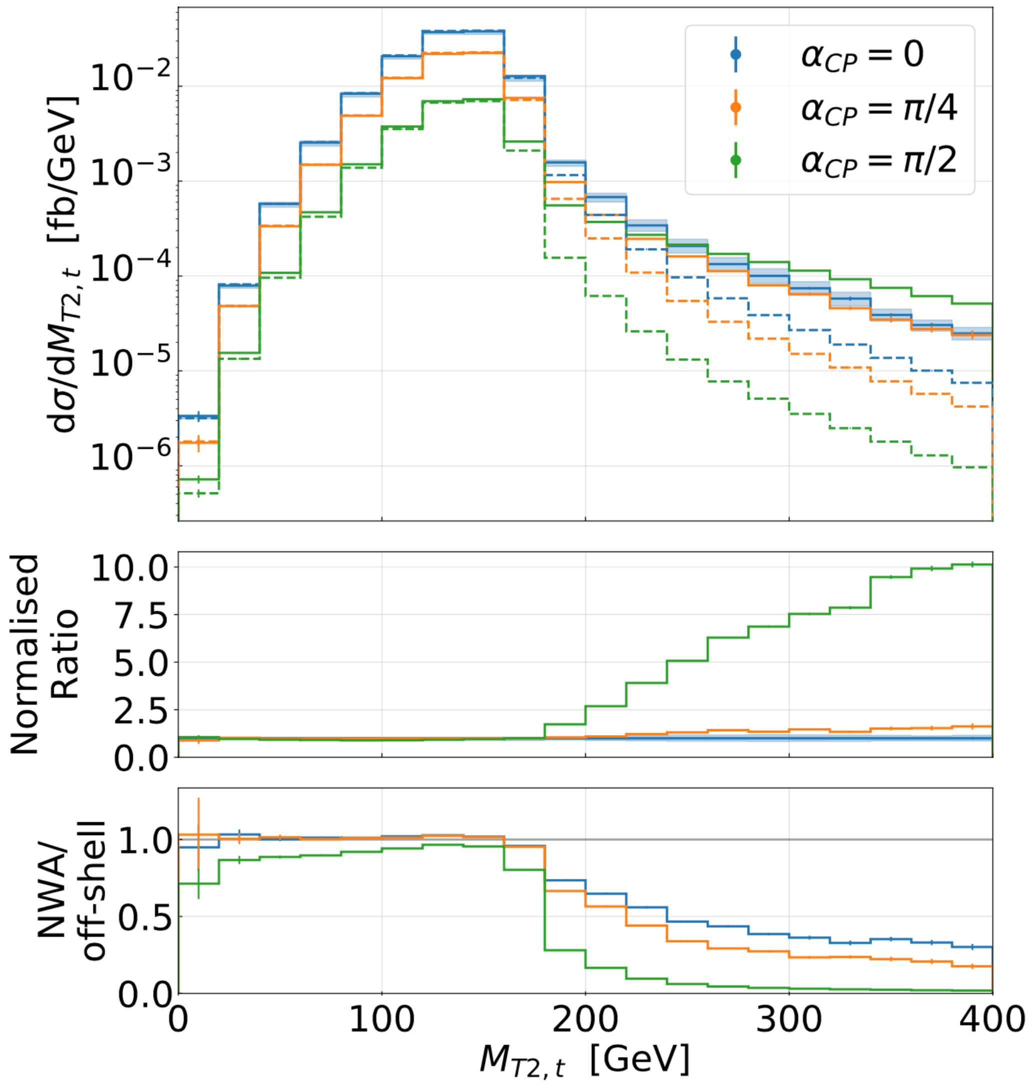
Off-shell Results: Solid line
NWA Results: Dashed line

Associated tt + H Production

NLO *ttH*

Hermann, Stremmer, Worek '22

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



Shape comparison:

- ***CP*-even** and ***CP*-mixed** rather similar for small values
- Large difference above kinematic edges $M_{T2,t} > m_t$
- Can reach factor of **10**
-
- For ***CP*-odd** case cross-section is actually the largest

Off-shell effects:

- Large effects **70% - 99%** for all ***CP*-states** for $M_{T2,t} > m_t$
- Driven by single-resonant top-quark contributions
- Largest effects for ***CP*-odd** Higgs boson

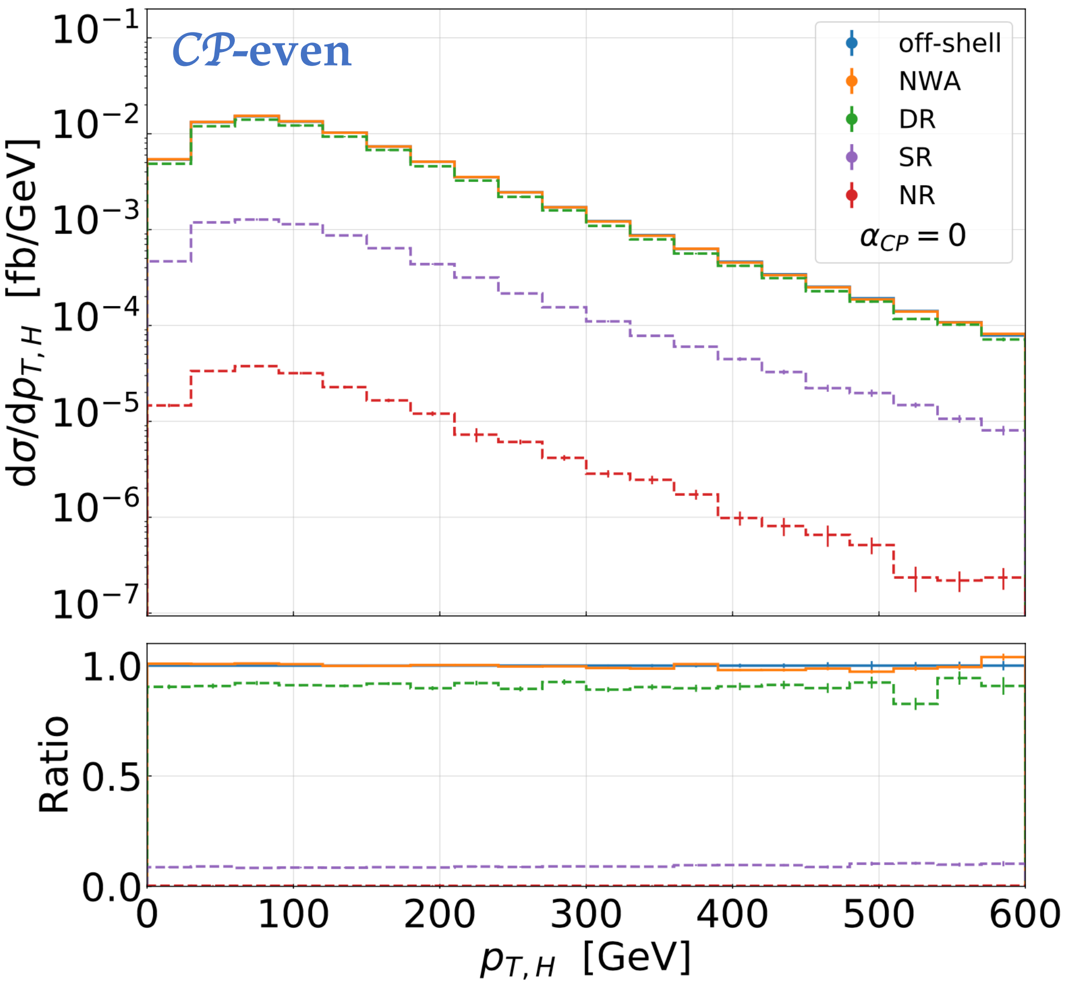
Off-shell Results: Solid line
NWA Results: Dashed line

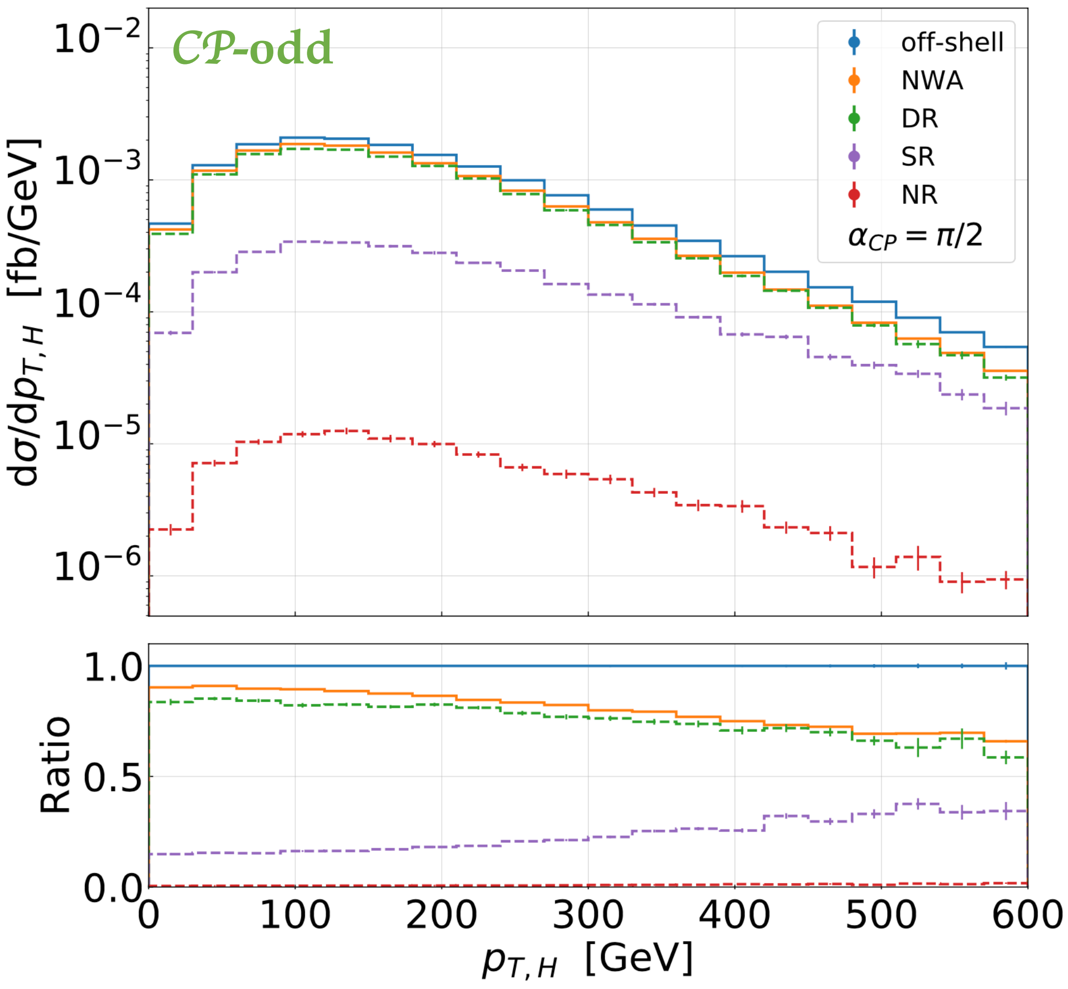
Associated tt + H Production

NLO *ttH*

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

Hermann, Stremmer, Worek '22





SR contributions $pp \to tWH(b)$ lead to larger off-shell effects in *CP*-**odd** case

Summary

- PROPER MODELING OF TOP-QUARK PRODUCTION & DECAY ESSENTIAL FOR $pp \to t\bar{t} + X, X = \gamma, Z, W^{\pm}, H$
  - Already now & already in presence of inclusive cuts

- IMPORTANT
  - Corrections to production & decays important ⇨ NLO *tt* spin correlations
  - Photon emission in production and decays
  - Possibility of using kinematic-dependent μ_R & μ_F scale settings important
  - Complete off-shell effects important ⇨ Single top-quark contributions and interference effects
    - ✓ *Kinematical edges & high* p_T *regions*
    - ✓ *Phase space regions that are relevant for BSM physics*

- EVEN MORE IMPORTANT FOR
  - Exclusive cuts & High luminosity measurements
  - New Physics searches & 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 precise theoretical predictions

Outlook

- What can be done with such state-of-the-art fixed order calculations ?

- Compare directly to LHC data in fiducial phase space regions
  - Have been done @ NNLO in QCD in NWA for $pp \to t\bar{t}$ predictions

    Czakon, Mitov, Poncelet '21
    CMS-PAS-TOP-20-006

  - Have been done @ NLO in QCD for $pp \to t\bar{t}\gamma$ $pp \to tW\gamma$ predictions with full off-shell effects included

    ATLAS '20
    CERN-EP-2020-100

  - On the way for other processes

- Provide correction to $pp \to t\bar{t}V$ predictions matched to parton showers where
  - Approximately incorporate full off-shell effects in NLO computation of on-shell $pp \to t\bar{t}V$ process
  - Have been done @ NLO in QCD for $pp \to t\bar{t}W^{\pm}$ predictions with full off-shell effects included

Bevilacqua, Bi, Cordero, Hartanto, Kraus, Nasufi, Reina, Worek '22

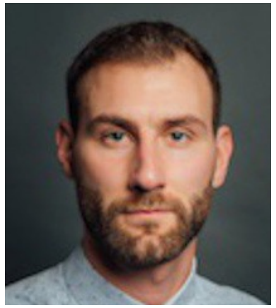
- Matching to parton shower programs using methods that allow for consistent treatment of resonances
  - Have been done @ NLO in QCD only for $pp \to t\bar{t}$ predictions with full off-shell effects included

Jezo, Lindert, Nason, Oleari, Pozzorini '16

Long Term Collaborators

- ***Giuseppe Bevilacqua*** (NCSR "Demokritos", Athens)
- ***Huan-Yu Bi*** (Peking University)
- ***Heribertus Bayu*** Hartanto (Cambridge University)
- ***Manfred Kraus*** (National Autonomous University of Mexico)
- ***Jasmina Nasufi*** (Lund University)

My Team in Aachen



Michele Lupattelli

Jonathan Hermann

Daniel Stremmer

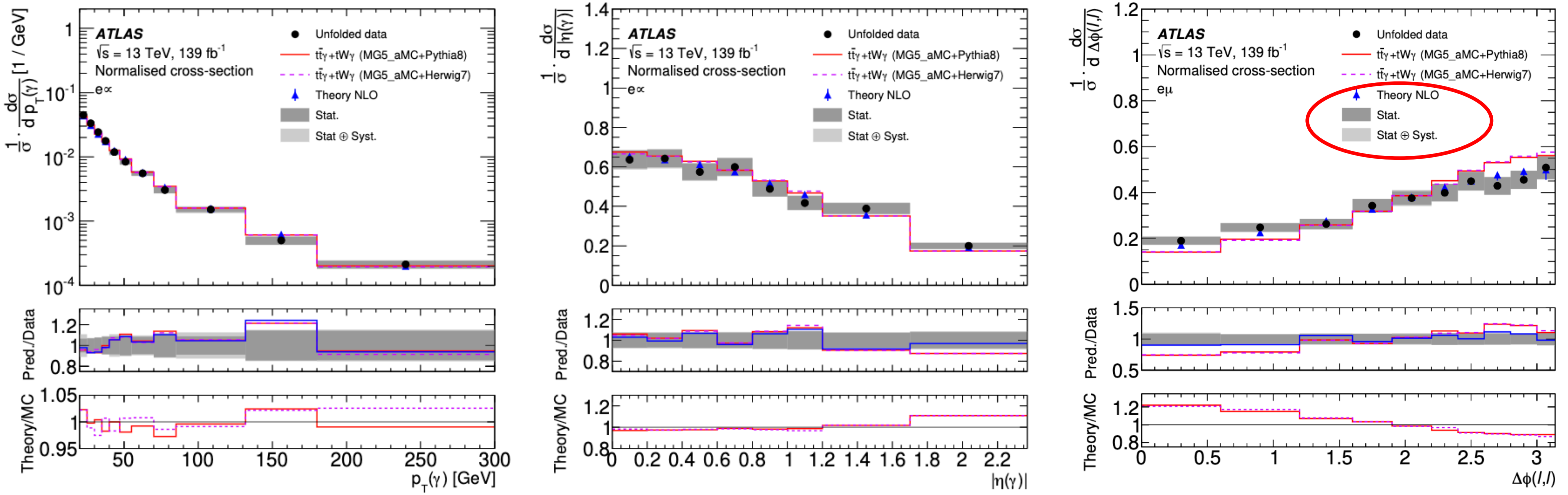
Minos Reinartz

Nikolaos Dimitrakopoulos

Backup

Associated ttγ + tWγ Production

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



Predictions	$p_T(\gamma)$ χ^2/ndf	$p_T(\gamma)$ p-value	$\lvert\eta(\gamma)\rvert$ χ^2/ndf	$\lvert\eta(\gamma)\rvert$ 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	$\lvert\Delta\eta(\ell,\ell)\rvert$ χ^2/ndf	$\lvert\Delta\eta(\ell,\ell)\rvert$ 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

χ^2/ndf and p-values between measured normalised cross-sections and various predictions from MC simulations and NLO calculation

- NLO QCD full off-shell predictions for *ttγ*
- NLO in production & decays
- NLO spin correlations

Bevilacqua, Hartanto, Kraus, Weber, Worek '18 '19 '20
ATLAS Collaboration JHEP 09 (2020) 049

Results with Full Off-Shell Effects @ LHC

• *tt* (di-lepton)	Denner, Dittmaier, Kallweit, Pozzorini '11 '12 Bevilacqua, Czakon, van Hameren, Papadopoulos, Worek '11 Frederix '14 Heinrich, Maier, Nisius, Schlenk, Winter '14 Denner, Pellen '16 (EW+QCD) Jezo, Lindert, Nason, Oleari, Pozzorini '16 (PS)
• *tt* (lepton+jets)	Denner, Pellen '18
• *ttH* (di-lepton) • *ttH* $(H \to bb, \tau^+\tau^-, \gamma\gamma$ & $e^+e^-e^+e^-)$	Denner, Feger '15 Denner, Lang, Pellen, Uccirati '17 (EW+QCD) Hermann,Stremmer, Worek '22 Stremmer, Worek '22
• *ttj* (di-lepton)	Bevilacqua, Hartanto, Kraus, Worek '16 '16 Bevilacqua, Hartanto, Kraus, Worek Schulze '18
• $tt\gamma$ (di-lepton)	Bevilacqua, Hartanto, Kraus, Weber, Worek '18 '19 '20
• *ttZ* & $Z \to \nu_l\nu_l$ (di-lepton)	Bevilacqua, Hartanto, Kraus, Weber, Worek '19 Hermann, Worek '21
• *ttZ* & $Z \to ll$ (tetra-lepton)	Bevilacqua, Hartanto, Kraus, Nasufi, Worek '22
• *ttW* (three-lepton)	Bevilacqua, Bi, Hartanto, Kraus, Worek '20 Denner, Pelliccioli '20 Bevilacqua, Bi, Hartanto, Kraus, Nasufi, Worek '21 Denner, Pelliccioli '21 (EW+QCD) Bevilacqua, Bi, Cordero, Hartanto, Kraus, Nasufi, Reina, Worek '22
• *ttbb* (di-lepton)	Denner, Lang, Pellen '21 Bevilacqua, Bi, Hartanto, Kraus, Lupattelli, Worek '21 '22

Various Phase Space Regions

NLO $t\bar{t}\gamma$

- 3 different resonance histories ⇨ Resolved jet at NLO gives 9 in total

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

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

Bevilacqua, Hartanto, Kraus, Weber, Worek '20

- Compute for each history Q and pick one that minimises Q

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

- **Double-resonant (DR)**

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

- **Two single-resonant regions (SR)**

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

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

- **Non-resonant region (NR)**

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

- **Boundary parameter**
  - Determines size of resonant region for each reconstructed top quark
  - *n = 5, 10, 15*
  - For n = 15

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

Photon in Top-Quark Production & Decays

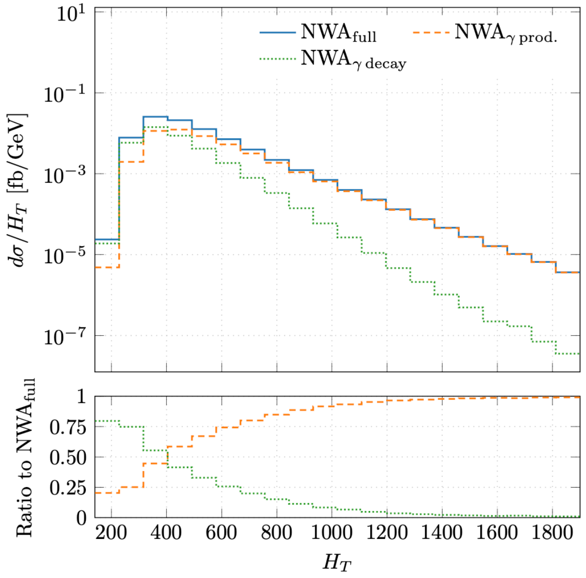
NLO $tt\gamma$

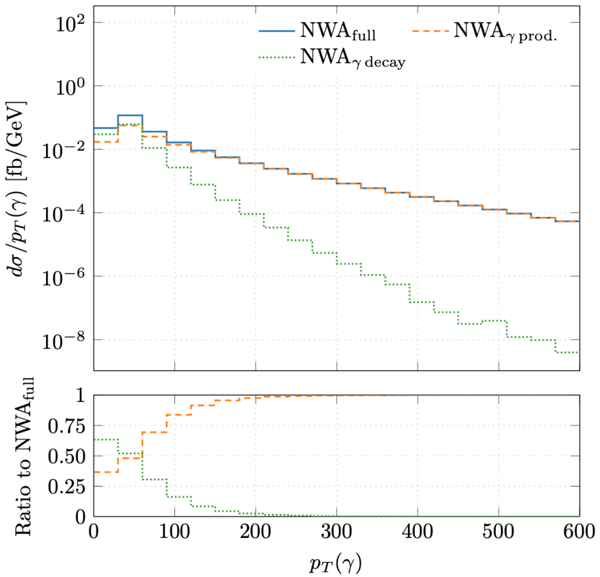
Bevilacqua, Hartanto, Kraus, Weber, Worek '18 '19 '20

Modelling Approach	$\sigma^{\rm LO}$ [fb]	$\sigma^{\rm NLO}$ [fb]
full off-shell ($\mu_0 = H_T/4$)	$7.32^{+2.45\,(33\%)}_{-1.71\,(23\%)}$	$7.50^{+0.11\,(1\%)}_{-0.45\,(6\%)}$
NWA ($\mu_0 = m_t/2$)	$8.08^{+2.84\,(35\%)}_{-1.96\,(24\%)}$	$7.28^{-0.99\,(13\%)}_{-0.03\,(0.4\%)}$
NWA ($\mu_0 = H_T/4$)	$7.18^{+2.39\,(33\%)}_{-1.68\,(23\%)}$	$7.33^{-0.43\,(5.9\%)}_{-0.24\,(3.3\%)}$
$\mathrm{NWA}_{\gamma-\mathrm{prod}}$ ($\mu_0 = m_t/2$)	$4.52^{+1.63\,(36\%)}_{-1.11\,(24\%)}$	$4.13^{-0.53\,(13\%)}_{-0.05\,(1.2\%)}$
$\mathrm{NWA}_{\gamma-\mathrm{prod}}$ ($\mu_0 = H_T/4$)	$3.85^{+1.29\,(33\%)}_{-0.90\,(23\%)}$	$4.15^{-0.12\,(2.3\%)}_{-0.21\,(5.1\%)}$
$\mathrm{NWA}_{\gamma-\mathrm{decay}}$ ($\mu_0 = m_t/2$)	$3.56^{+1.20\,(34\%)}_{-0.85\,(24\%)}$	$3.15^{-0.46\,(15\%)}_{+0.03\,(0.9\%)}$
$\mathrm{NWA}_{\gamma-\mathrm{decay}}$ ($\mu_0 = H_T/4$)	$3.33^{+1.10\,(33\%)}_{-0.77\,(23\%)}$	$3.18^{-0.31\,(9.7\%)}_{-0.03\,(0.9\%)}$
$\mathrm{NWA}_{\mathrm{LOdecay}}$ ($\mu_0 = m_t/2$)		$4.85^{+0.26\,(5.4\%)}_{-0.48\,(9.9\%)}$
$\mathrm{NWA}_{\mathrm{LOdecay}}$ ($\mu_0 = H_T/4$)		$4.63^{+0.44\,(9.5\%)}_{-0.52\,(11\%)}$

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

- For $p_{T,b} > 40$ GeV
  - 57% ⇨ γ emitted in production
  - 43% ⇨ γ emitted in decay stage
- NLO QCD corrections to top-quark decays
  - 12% - 17%

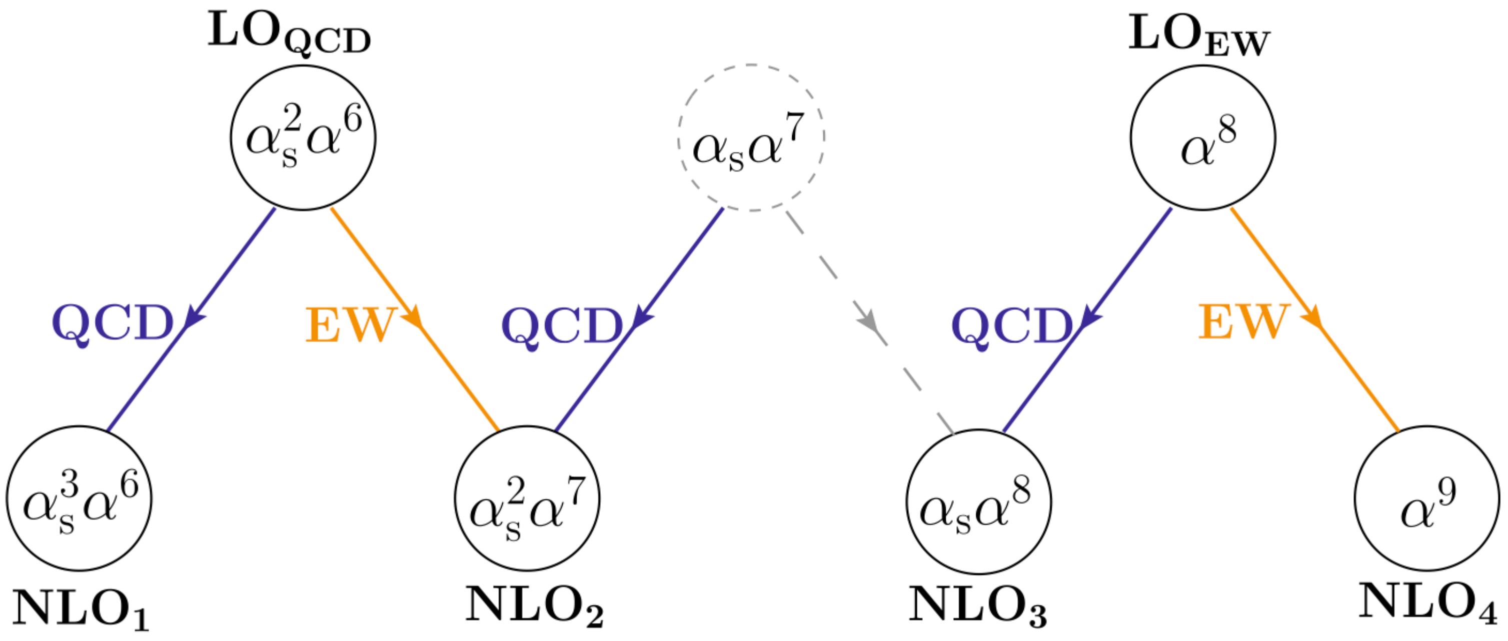


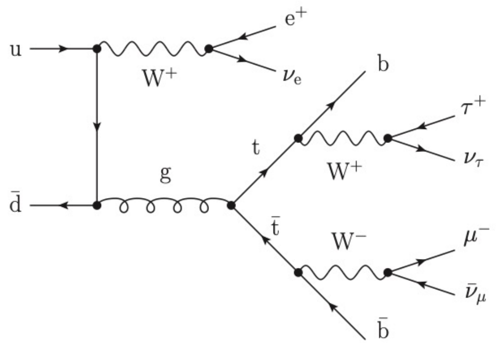


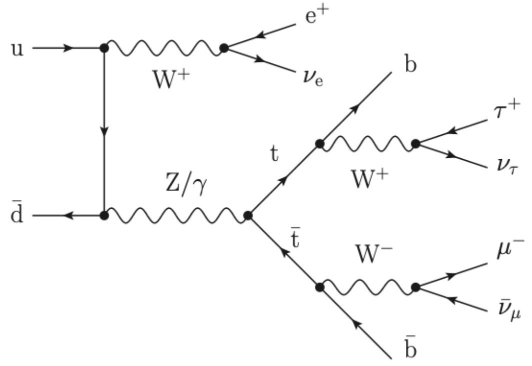
ttW & Parton Shower

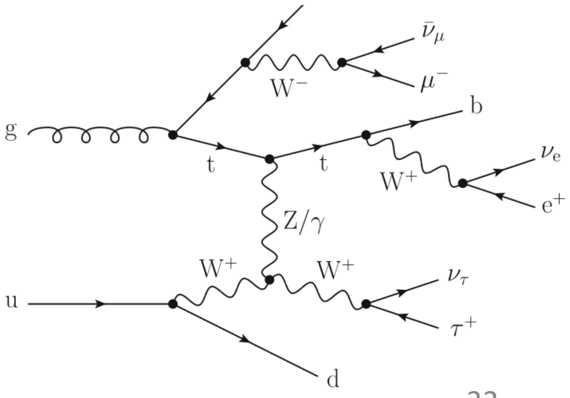
NLO ttW

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









$\alpha_s\alpha^8$ contribution larger than $\alpha_s^2\alpha^7$

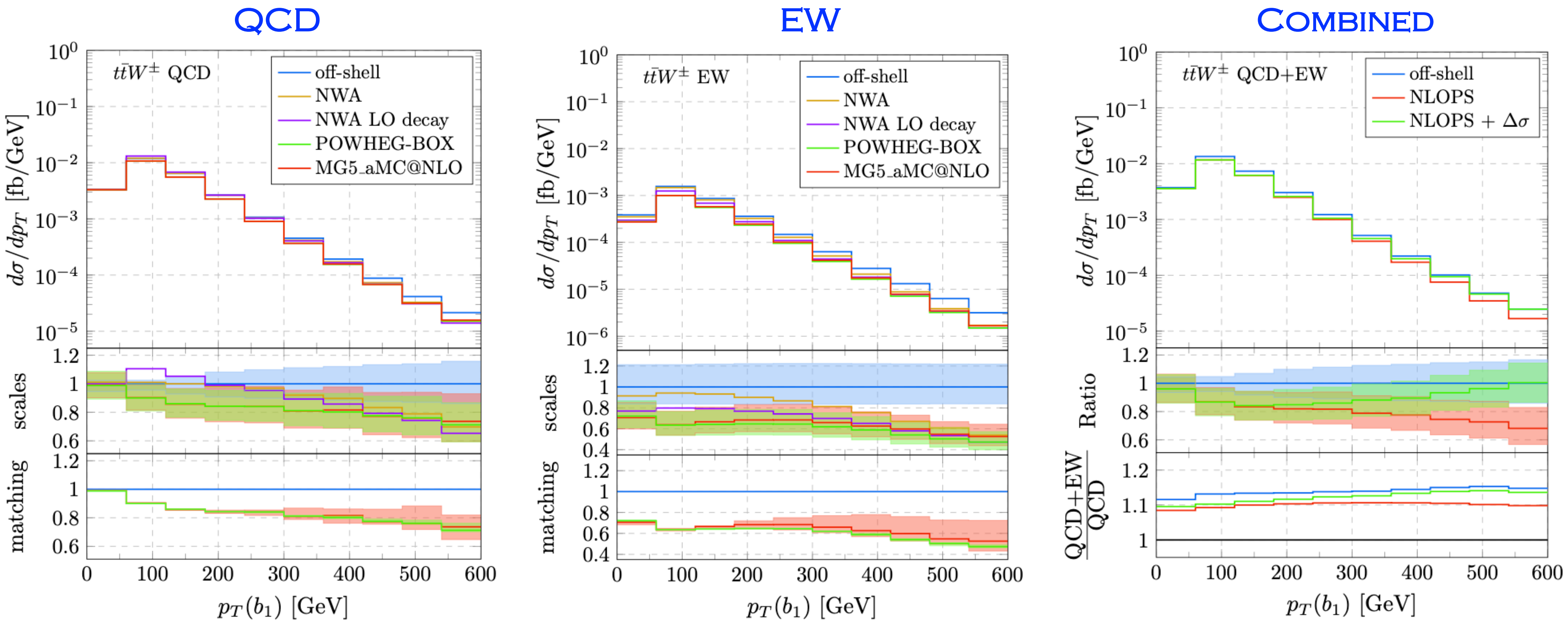
t-channel $tW \to tW$ scattering in the qg channels opens up @ NLO

Frederix, Pagani, Zaro '18, Frederix, Tsinikos '20, Denner, Pellicciolli '21

ttW & Parton Shower

NLO *ttW*

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



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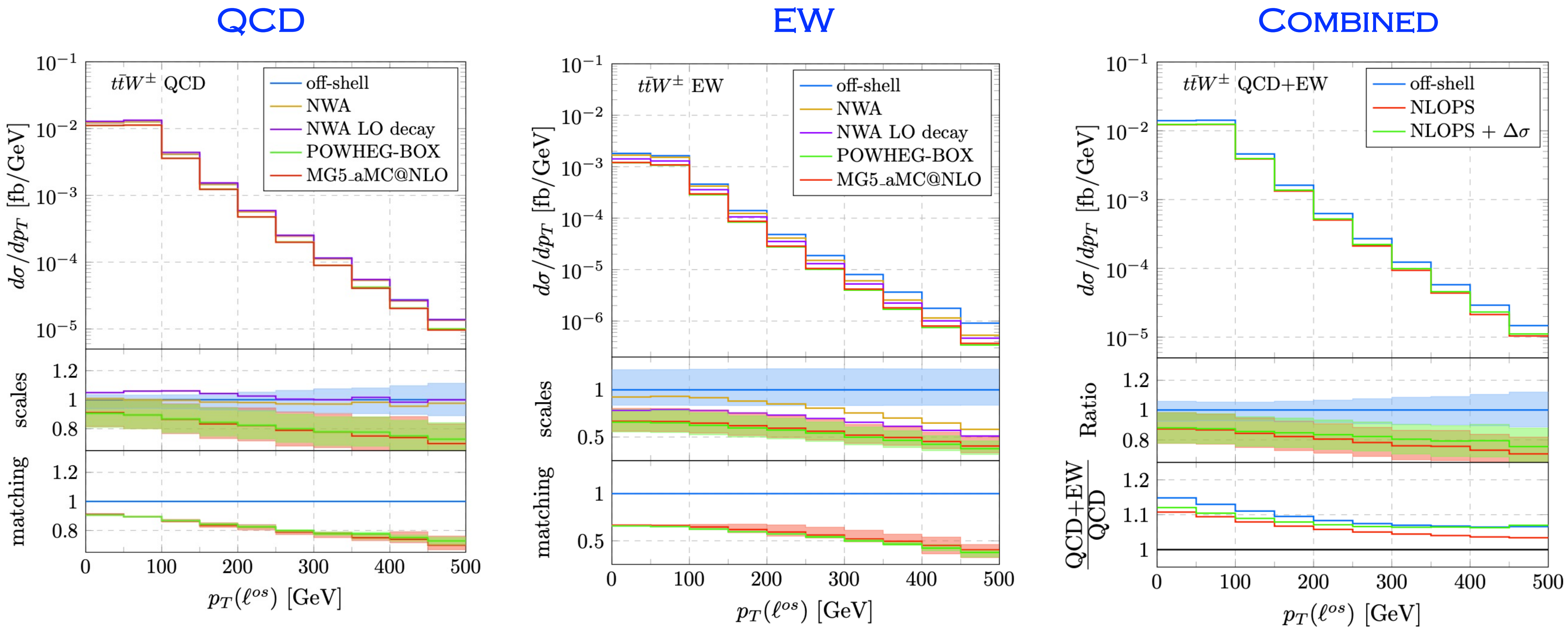
ttW & Parton Shower

NLO *ttW*

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



Bevilacqua, Bi, Cordero, Hartanto, Kraus, Nasufi, Reina, Worek '22

ttW & Parton Shower

NLO ttW

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

Type	QCD [fb]	EW [fb]	QCD+EW [fb]	(QCD+EW)/QCD
full off-shell	$1.58^{+0.05\ (3\%)}_{-0.10\ (6\%)}$	$0.206^{+0.045\ (22\%)}_{-0.034\ (16\%)}$	$1.79^{+0.10\ (6\%)}_{-0.13\ (7\%)}$	1.13
NLOPS	$1.40^{+0.16\ (11\%)}_{-0.15\ (11\%)}$	$0.133^{+0.028\ (21\%)}_{-0.021\ (16\%)}$	$1.53^{+0.19\ (12\%)}_{-0.17\ (11\%)}$	1.10
NLOPS+$\Delta\sigma$	$1.41^{+0.16\ (11\%)}_{-0.16\ (11\%)}$	$0.149^{+0.028\ (19\%)}_{-0.028\ (19\%)}$	$1.56^{+0.21\ (13\%)}_{-0.21\ (13\%)}$	1.11

$$\frac{d\sigma^{\rm th}}{dX} = \frac{d\sigma^{\rm NLO+PS}}{dX} + \frac{d\Delta\sigma_{\rm off\text{-}shell}}{dX}\,, \quad \text{with} \quad \frac{d\Delta\sigma_{\rm off\text{-}shell}}{dX} = \frac{d\sigma^{\rm NLO}_{\rm off\text{-}shell}}{dX} - \frac{d\sigma^{\rm NLO}_{\rm NWA}}{dX}$$

$$\delta^{\rm th} = \sqrt{\left(\delta^{\rm NLO+PS}_{\rm scale}\right)^2 + \left(\delta^{\rm NLO+PS}_{\rm matching}\right)^2 + \left(\delta^{\Delta\sigma}_{\rm scale}\right)^2}$$

Bevilacqua, Bi, Cordero, Hartanto, Kraus, Nasufi, Reina, Worek '22

Ntuple Files

NLO *ttj*

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

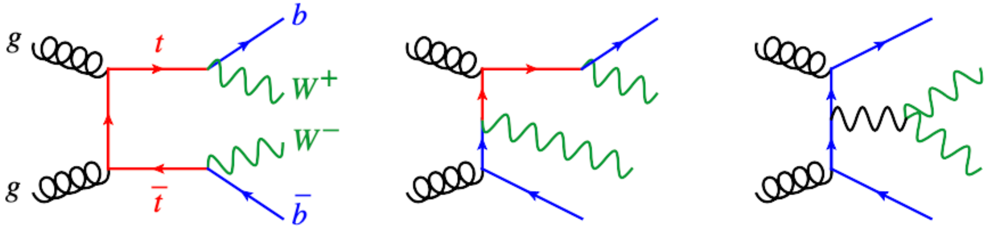
Bevilacqua, Hartanto, Kraus, Worek '16

Number of events, number of files & averaged number of events per file as well as total size per contribution for different NTUPLE samples

Contribution	Nr. of Events	Nr. of files	(avg) events/file	Size
Born	21×10^6	60	350×10^3	38 GB
Born + Virtual	33×10^6	380	87×10^3	72 GB
Integrated dipoles	80×10^6	450	178×10^3	160 GB
Real + Sub. Real	626×10^6	18000	35×10^3	1250 GB
Total:	760×10^6	18890	40×10^3	1520 GB

tW(b)

Demartin, Maier, Maltoni, Mawatari, Zaro '17

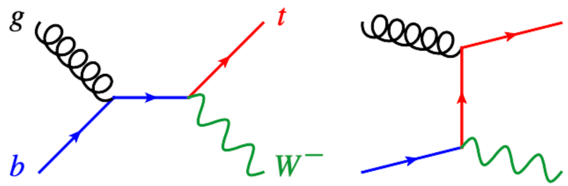


$(\mathcal{A}_{2t})$ $(\mathcal{A}_{1t})$ $(\mathcal{A}_{0t})$

- *DS (diagram subtraction):*

$$|\mathcal{A}_{tWb}|^2_{\mathrm{DS}} = |\mathcal{A}_{1t} + \mathcal{A}_{2t}|^2 - \mathcal{C}_{2t},$$

- Local subtraction term C_{2t} by definition must
- cancel exactly the resonant matrix element $|\mathcal{A}_{2t}|^2$ when the kinematics is exactly on top of the resonant pole
- Be gauge invariant
- Decrease quickly away from the resonant region



- Squared matrix element for producing $tW^-\overline{b}$

$$|\mathcal{A}_{tWb}|^2 = |\mathcal{A}_{1t} + \mathcal{A}_{2t}|^2$$
$$= |\mathcal{A}_{1t}|^2 + 2\mathrm{Re}(\mathcal{A}_{1t}\mathcal{A}^*_{2t}) + |\mathcal{A}_{2t}|^2,$$

- *DR1 (without interference):*

$$|\mathcal{A}_{tWb}|^2_{\mathrm{DR1}} = |\mathcal{A}_{1t}|^2.$$

- *DR2 (with interference):*

$$|\mathcal{A}_{tWb}|^2_{\mathrm{DR2}} = |\mathcal{A}_{1t}|^2 + 2\mathrm{Re}(\mathcal{A}_{1t}\mathcal{A}^*_{2t}).$$

- DR schemes based on removing contributions all over the phase space

- They are not gauge invariant

tt & tWb

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

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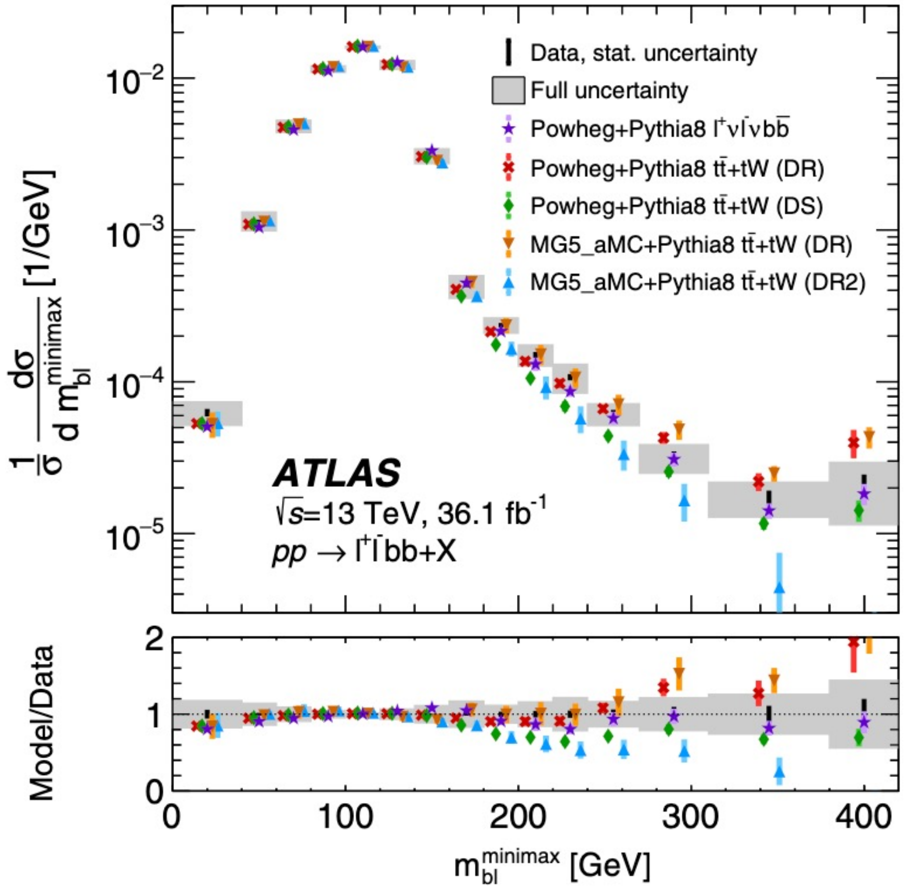
ATL-PHYS-PUB-2021-042



$$m_{b\ell}^{\text{minimax}} \equiv \min\{\max(m_{b_1\ell_1}, m_{b_2\ell_2}), \max(m_{b_1\ell_2}, m_{b_2\ell_1})\}$$

- Normalized differential $t\bar{t}$ cross section @ NLO QCD + PS
- Full off-shell versus $t\bar{t} + tWb$ ⇨ Di-lepton channel
- Regions sensitive to interference between doubly & singly resonant top-quark pair production
- Full off-shell prediction $\ell^+\nu_\ell\ell^-\bar{\nu}_\ell b\bar{b}$ models well all regions
- Beyond top-quark mass traditional models of interference diverge

p values comparing data & various MC predictions

Model	All bins	$m_{b\ell}^{\text{minimax}} > 160$ GeV
POWHEG-BOX $t\bar{t} + tW$ (DR)	0.71	0.40
POWHEG-BOX $t\bar{t} + tW$ (DS)	0.77	0.56
MG5_aMC $t\bar{t} + tW$ (DR)	0.14	0.17
MG5_aMC $t\bar{t} + tW$ (DR2)	0.02	0.08
POWHEG-BOX $\ell^+\nu\ell^-\nu bb$	0.92	0.95

tt & tWb

MadGraph5_aMC@NLO+Pythia 8 (left)
Powheg+Pythia 8 (right)

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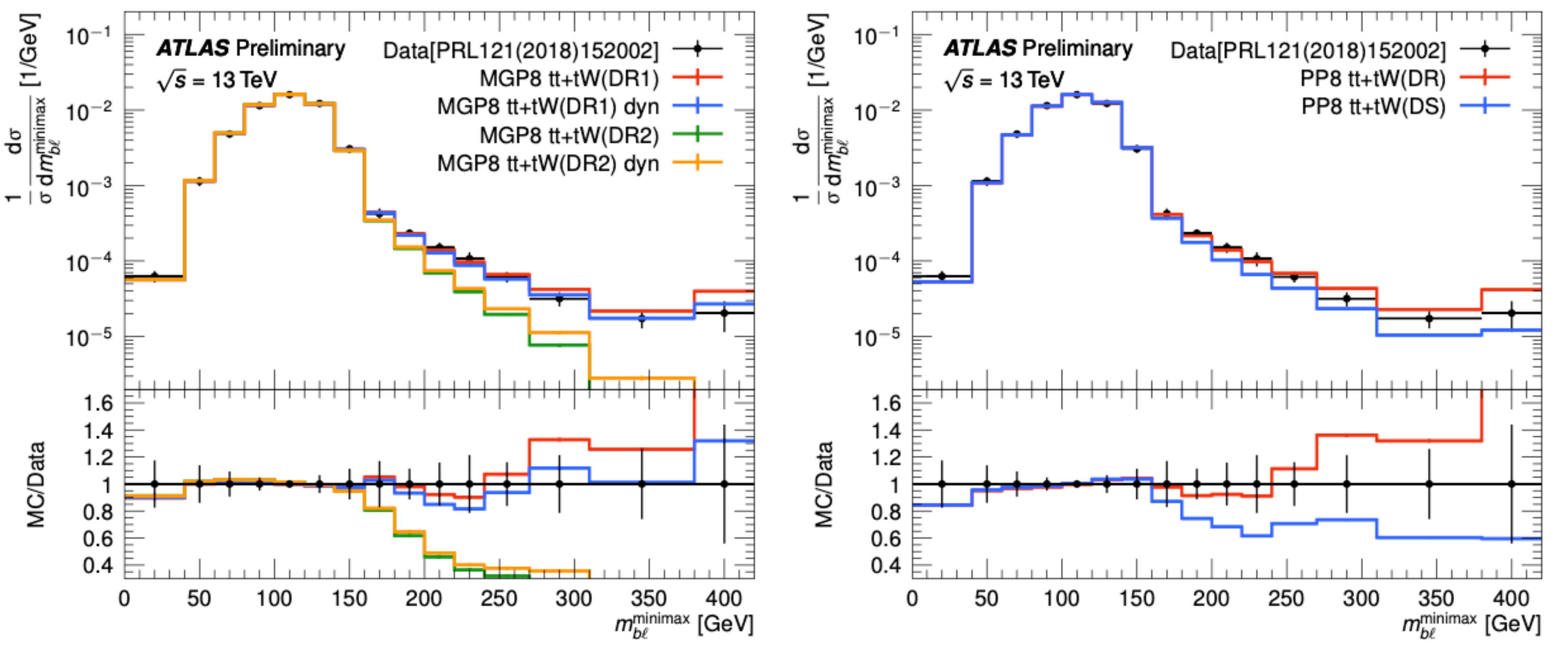

Important for proper modelling & tuning

$$m_{b\ell}^{\mathrm{minimax}} \equiv \min\{\max(m_{b_1\ell_1}, m_{b_2\ell_2}), \max(m_{b_1\ell_2}, m_{b_2\ell_1})\}$$