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Production & decay of a (heavy) boson in association with top quarks

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Loops and Legs in Quantum Field Theory, 25–30 April 2022, Ettal

Instead of Introduction

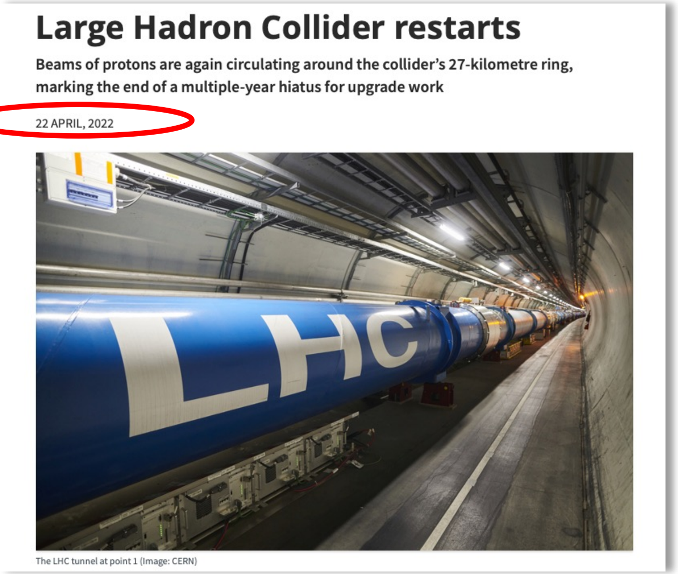
- Simply list, page-by-page, latest theoretical results
  - Not only are they impressive, but there are plenty of them
- Tell story, hopefully interesting one
  - Based on many years of work & development of Helac-Nlo
  - *Instead of partial results* ⇨ *Full processes* ⇨ *Phenomenological applications* ⇨ *Compared to LHC data*
  - Various results for $pp \to tt + X$ where $X = H, \gamma, W, Z, j, bb$
  - **NLO QCD**
    - $2 \to 5$ *processes* ⇨ $pp \to WWbbX$ where $X = H, \gamma, W, Z, j$
    - $2 \to 6$ *process* ⇨ $pp \to WWbbbb$

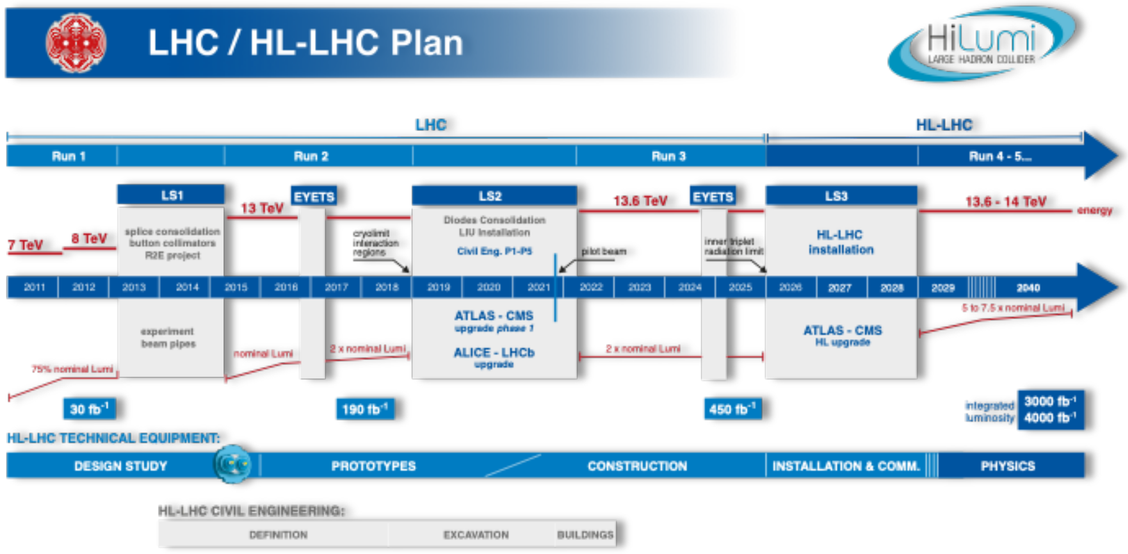
My Goal

- Identify which effects are important & should be taken into account
- Give a few examples for **NLO QCD** $pp \to tt + X$ results
- Vital for SM top quark-physics studies & BSM searches & SM Higgs boson measurements ⇨ $pp \to ttH$
- *(Biased) Selection* ⇨ Only **NLO QCD** with off-shell effects ⇨ Only latest results *2020-2022* ⇨ Only LHC

Instead of Introduction

- SM ⇨ Extremely fun & exciting & enjoyable time for people working on **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*
    - *BSM Physics* ⇨ *High Luminosity LHC*
  - Fully exploit experimental program
    - *High Precision Theoretical Predictions* ⇨ *Top Quark*





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

WHY TOP QUARK IS SO SPECIAL

- TOP QUARK ⇨ Discovered at TeVatron in 1995
- Heaviest observed particle

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

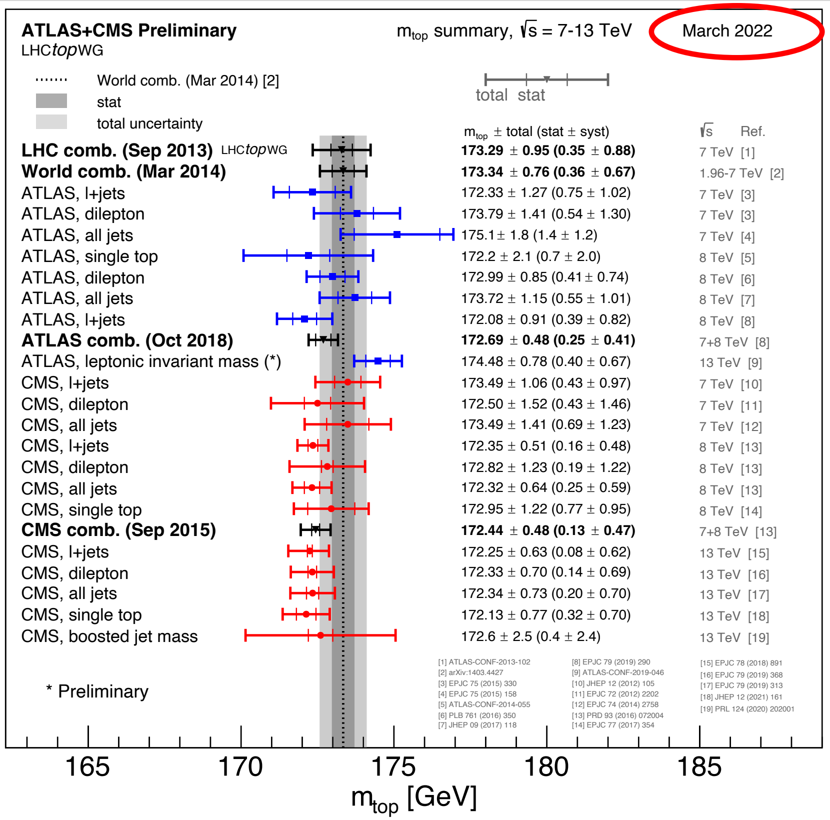
World Combination '14
ATLAS, CDF, CMS, D0

- Substantial Yukawa coupling

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

- 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

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

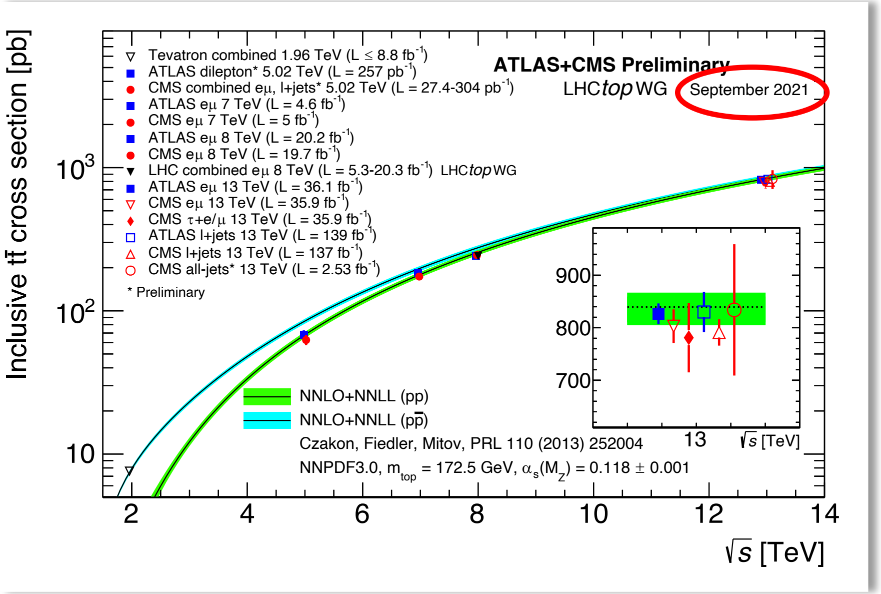


- PRECISION TOP-QUARK PHYSICS
  - Extracting SM parameters
  - Constraining PDFs
  - Examining (anomalous) couplings
  - Studying various IR safe observables

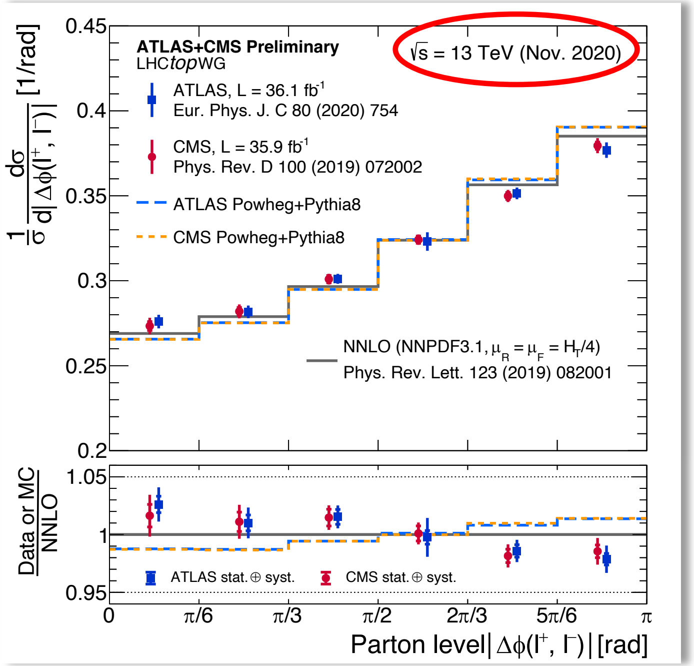
Top Quark Pair Production

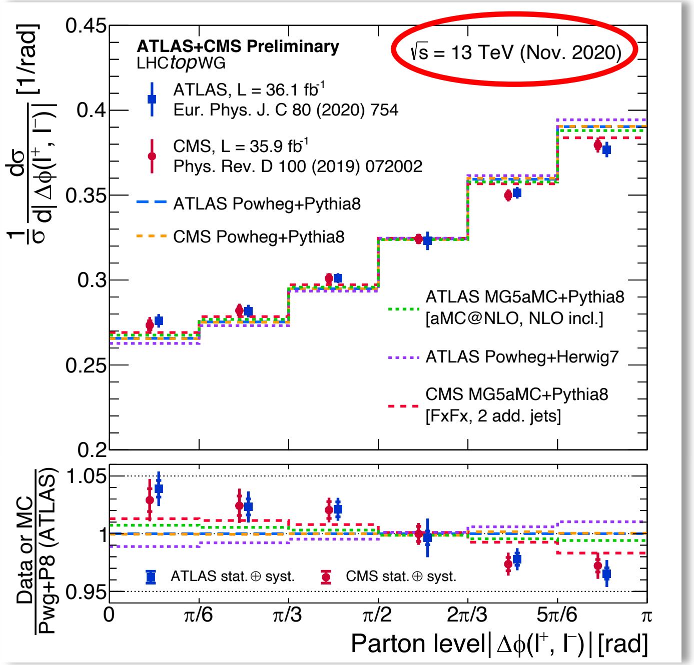
- NNLO + NNLL predictions for $t\bar{t}$
- NNLO Production & Decays
  - Narrow-width-approximation
  - di-lepton top-quark decay channel
- NNLO Production + LO decays + PS
  - MiNNLO$_{PS}$

$$pp \to t\bar{t} + X$$



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





Czakon, Fiedler, Mitov '13
Czakon, Heymes, Mitov '16 '17
Behring, Czakon, Mitov, Papanastasiou, Poncelet '19
Czakon, Mitov, Poncelet '21

Catani, Devoto, Grazzini, Kallweit, Mazzitelli, Sargsyan '19
Catani, Devoto, Grazzini, Kallweit, Mazzitelli '19

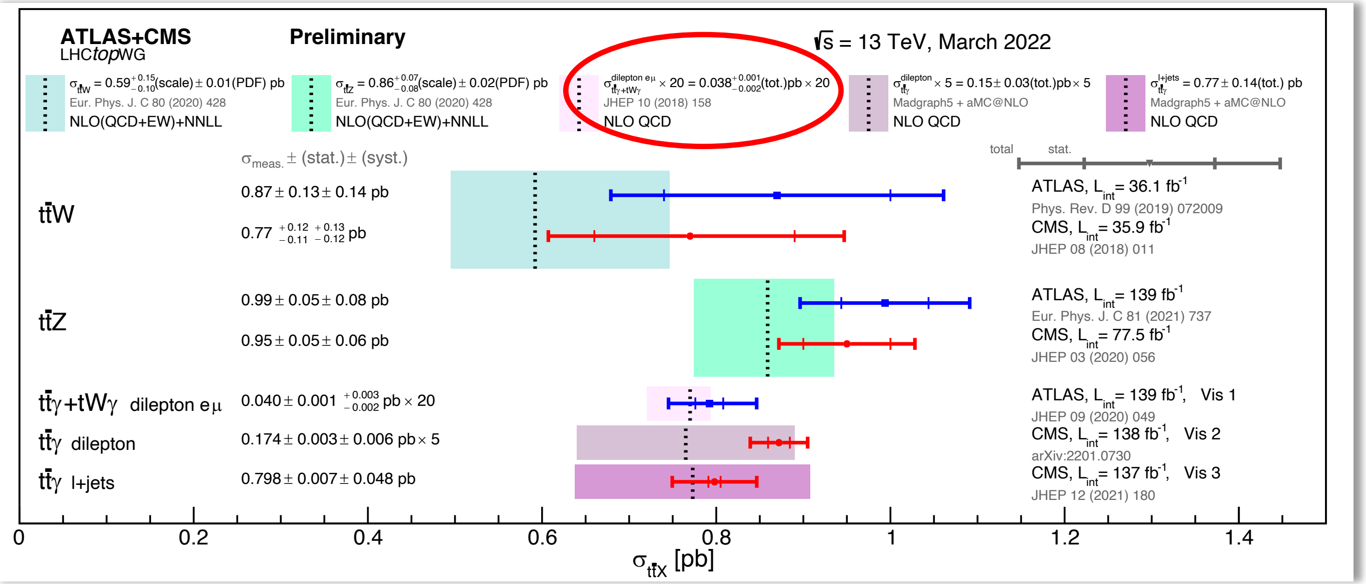
Mazzitelli, Monni, Nason, Re, Wiesemann, Zanderighi '21 '22

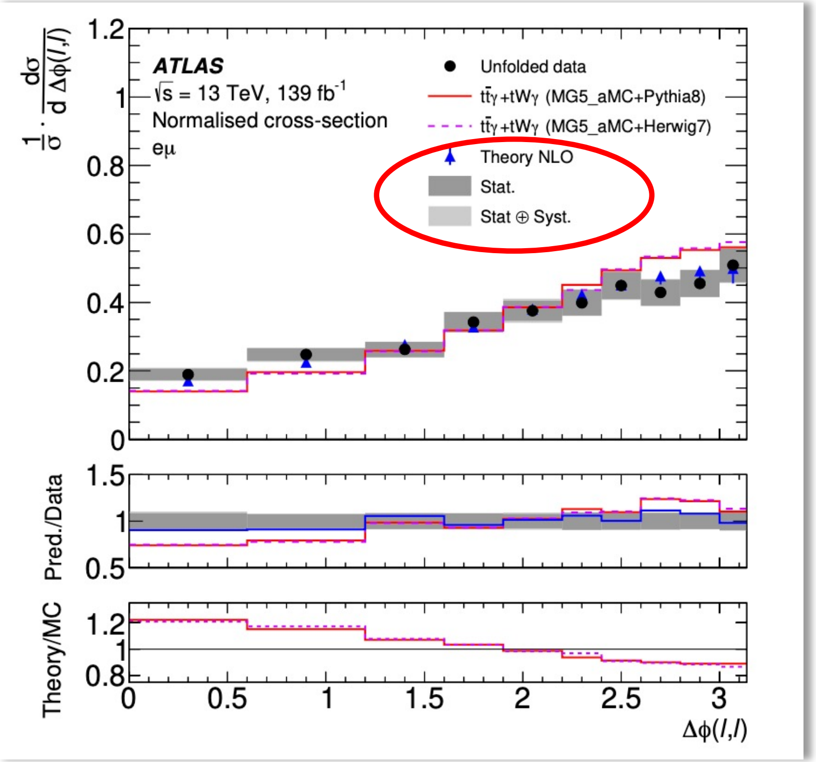
Associated TT Production

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

- More exclusive final states are produced @ LHC

$$pp \to t\bar{t} + X \, , X = \gamma, W^{\pm}, Z$$





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 $tt\gamma$
  - Di-lepton channel

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

Full Off-Shell Effects

NLO ttW

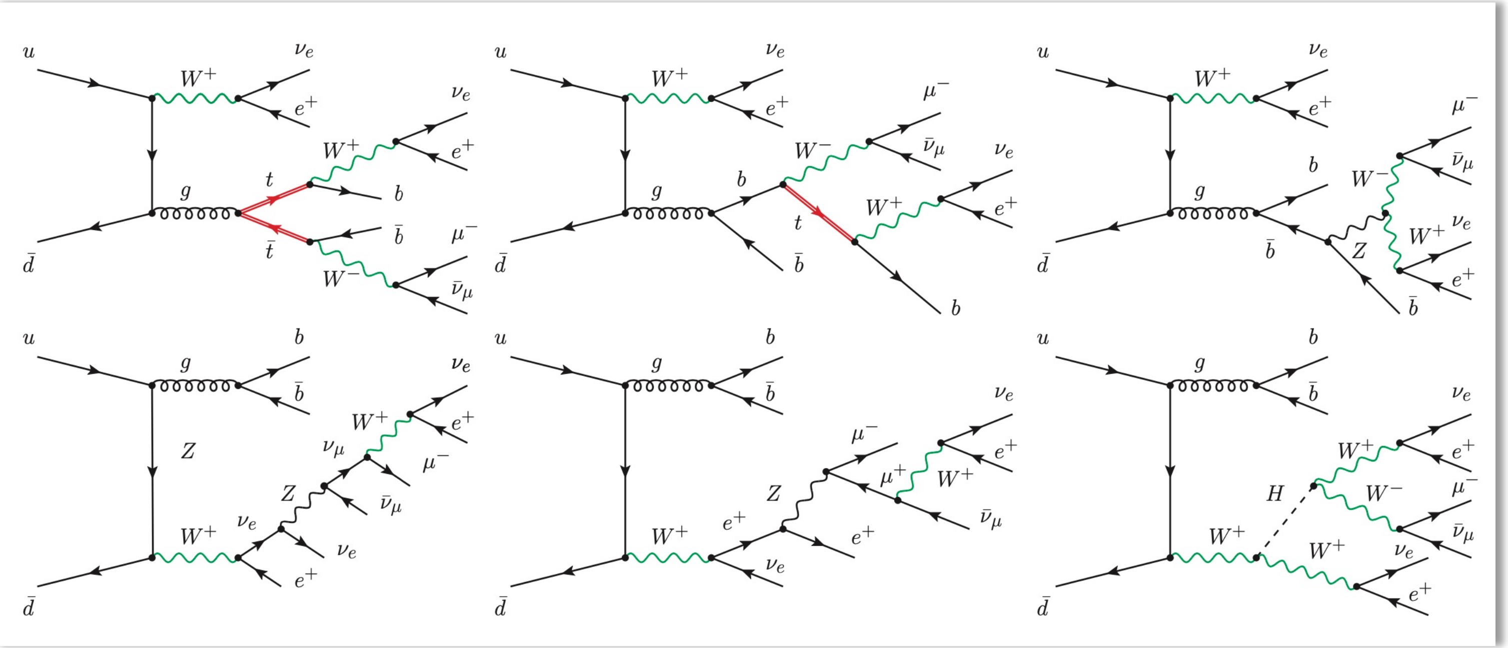
- *Off-shell top quarks & W described by Breit-Wigner propagators*
- *Double-, single- & non-resonant top-quark & W contributions included*
- *All interference effects incorporated at matrix element level*

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

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

Bevilacqua, Bi, Hartanto, Kraus, Worek '20

- NLO QCD corrections to production & decays
- Nonfactorizable NLO QCD corrections included ⇨ Cross-talk between production & decays
- NLO spin correlations



- Simply putting *Γ ≠ 0* violates gauge invariance
- *Complex Mass Scheme* ⇨ Gauge-invariant scheme for calculation of higher-order corrections with unstable particles

Denner, Dittmaier, Roth, Wackeroth '99
Denner, Dittmaier, Roth, Wieders '05

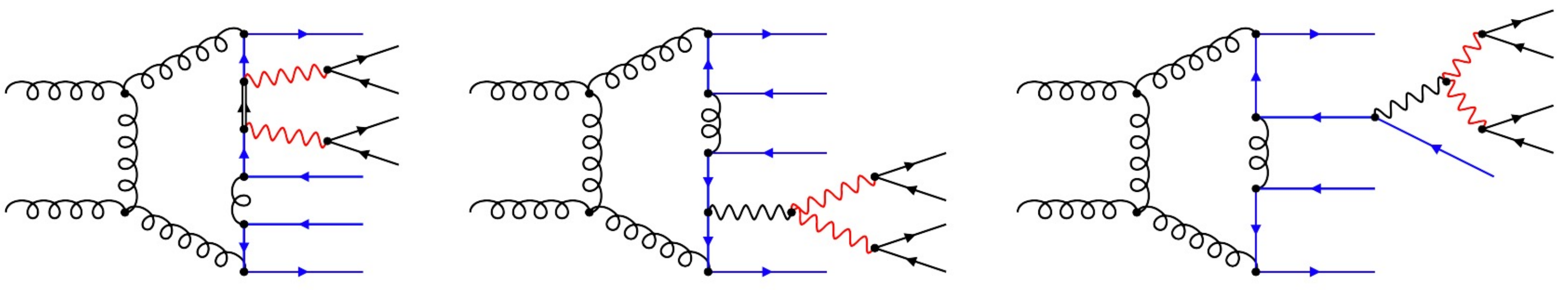
- Scalar integrals with complex masses ⇨ **ONELOOP**

van Hameren '11

Complexity for TTBB

NLO *ttbb*

Examples of octagon-, heptagon- & hexagon-type of one-loop diagrams



One-loop correction type	Number of Feynman diagrams
Self-energy	93452
Vertex	88164
Box-type	49000
Pentagon-type	25876
Hexagon-type	11372
Heptagon-type	3328
Octagon-type	336
Total number	271528

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

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

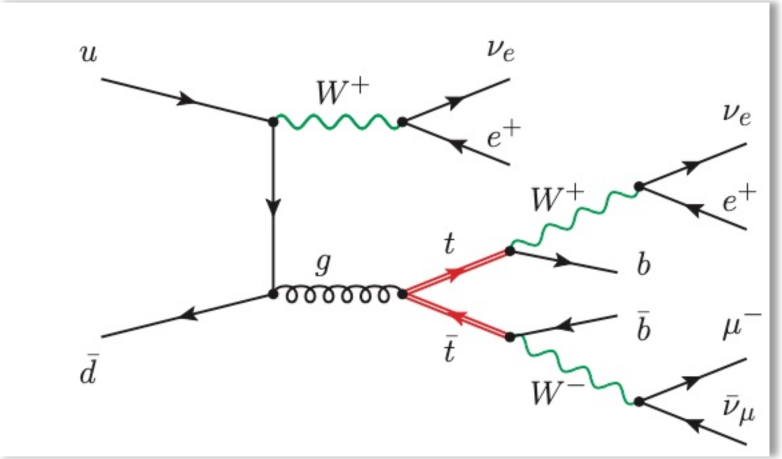
Partonic Subprocess	Number of Feynman diagrams	Number of CS Dipoles	Number of NS Subtractions
$gg \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}\,b\bar{b}\,g$	41364	90	18
$q\bar{q} \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}\,b\bar{b}\,g$	9576	50	10
$gq \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}\,b\bar{b}\,q$	9576	50	10
$g\bar{q} \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}\,b\bar{b}\,\bar{q}$	9576	50	10

Bevilacqua, Bi, Hartanto, Kraus, Lupattelli, Worek '21 '22

Narrow Width Approximation

NLO ttW

- 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*

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

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

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

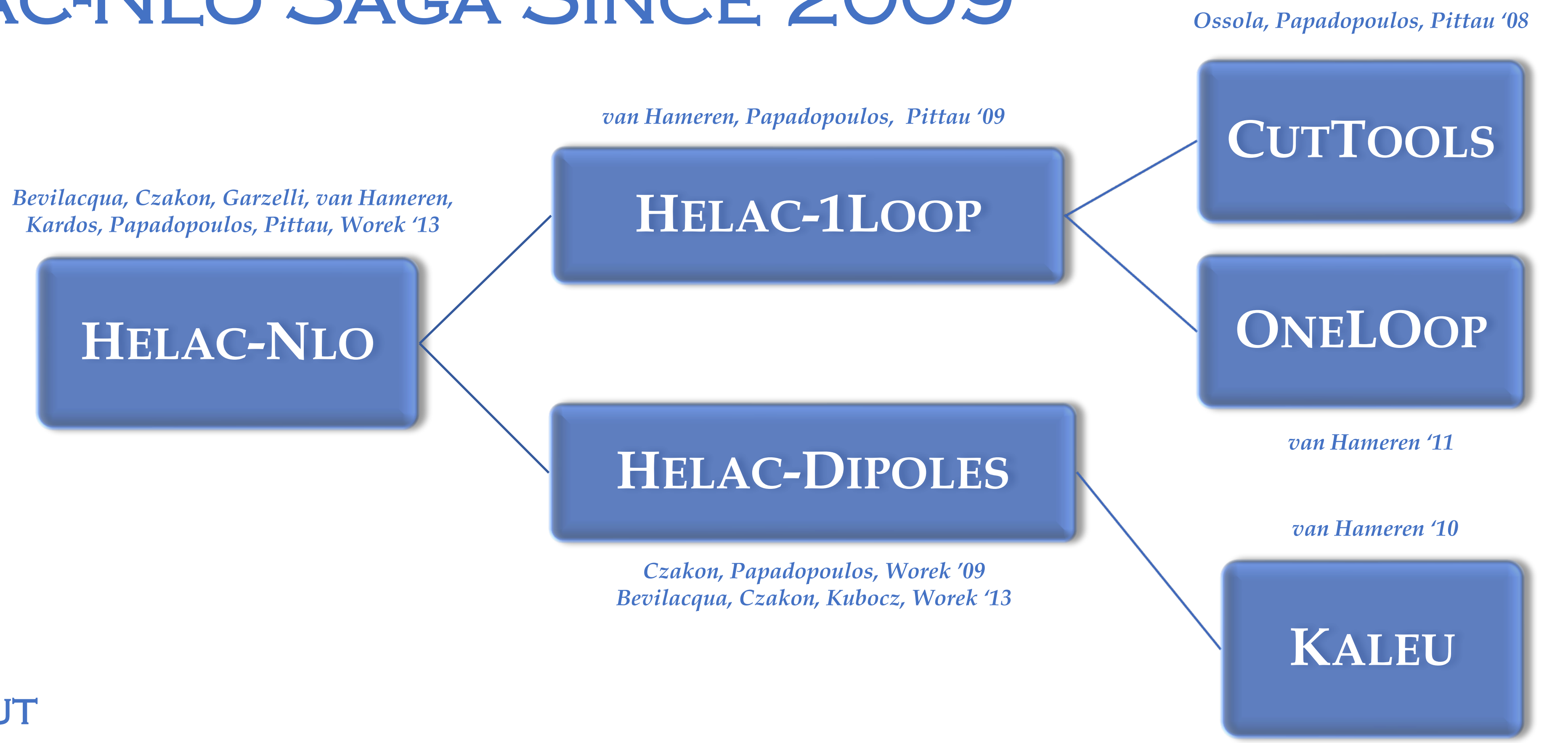
$$\frac{\Gamma_W}{m_W} > \frac{\Gamma_t}{m_t} \gg \frac{\Gamma_H}{m_H},$$

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

Bevilacqua, Bi, Hartanto, Kraus, Worek '20

- NLO QCD correction separately to production & separately to top-quark decays
- NLO QCD nonfactorizable corrections missing ⇨ No cross-talk between production & decays
- NLO spin correlations

Helac-Nlo Saga Since 2009



- Output
  - Theoretical predictions are stored ⇨ *Ntuples Files* & modified *Les Houches & ROOT Files*
  - Each "event" provided with supplementary matrix element & PDF information
  - Results for different scale settings & PDF choices by can be obtained by reweighting
  - Different observables and/or binning can be provided + more exclusive cuts ⇨ With caveat

Bern, Dixon, Febres Cordero, Hoeche, Ita, Kosower, Maitre '14

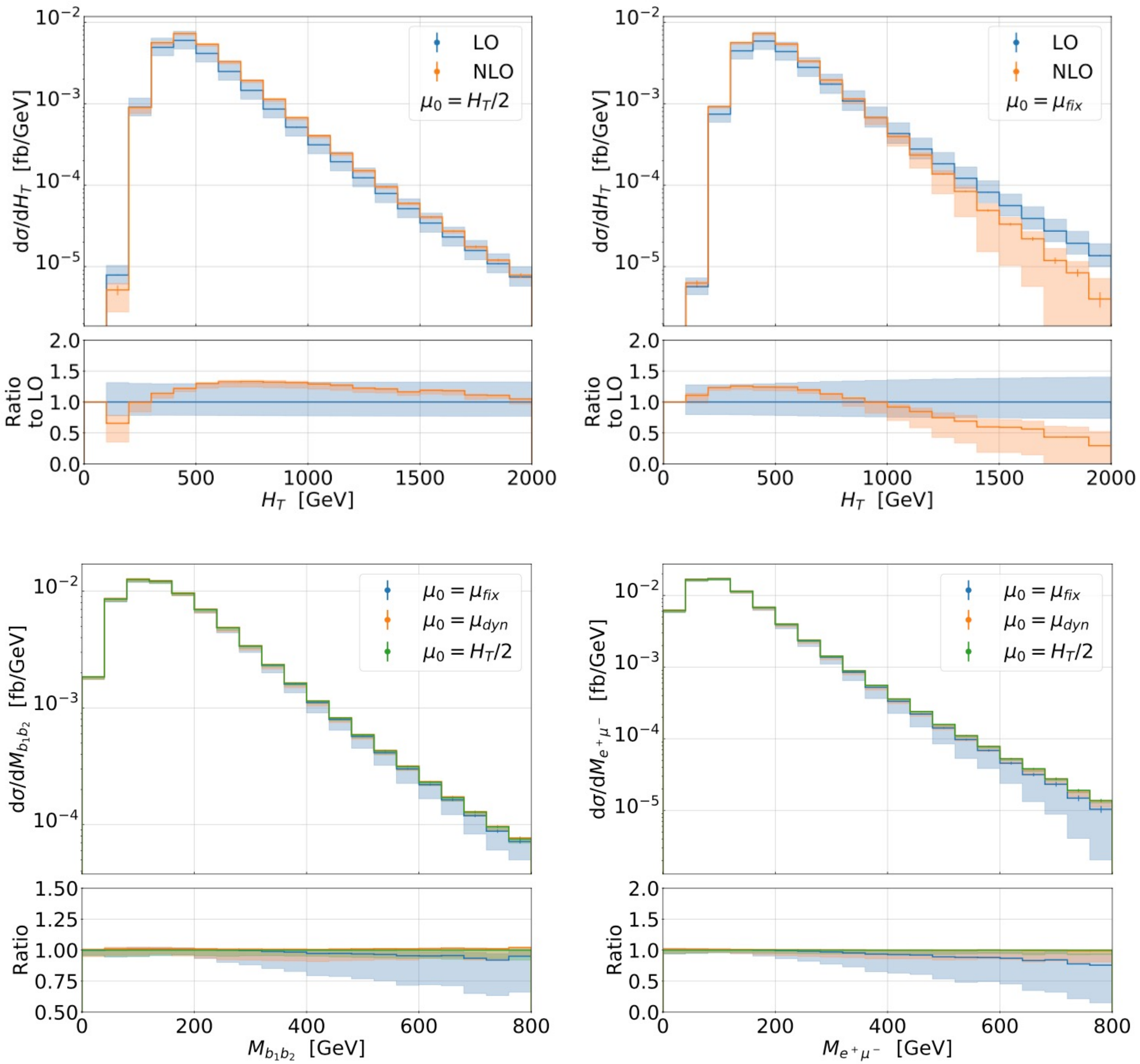
Results with Full Off-Shell Effects

• *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)* *Stremmer, Worek '22*
• *ttj* (di-lepton)	*Bevilacqua, Hartanto, Kraus, Worek '16 '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*

NLO QCD Corrections & Scale Setting

NLO ttH

Stremmer, Worek '22



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

- **Fixed scale choice**
  - Perturbative instabilities in ~ TeV regions
  - LO & NLO uncertainties band do not overlap
  - Scale uncertainties at NLO larger than for LO
  - For some scale choices NLO results negative
- **Dynamical scale choice**
  - Stabilises tails
  - NLO uncertainties bands within LO ones

$$H_T = p_{T,\,b_1} + p_{T,\,b_2} + p_{T,\,e^+} + p_{T,\,\mu^-} + p_{T,\,miss} + p_{T,\,H}$$

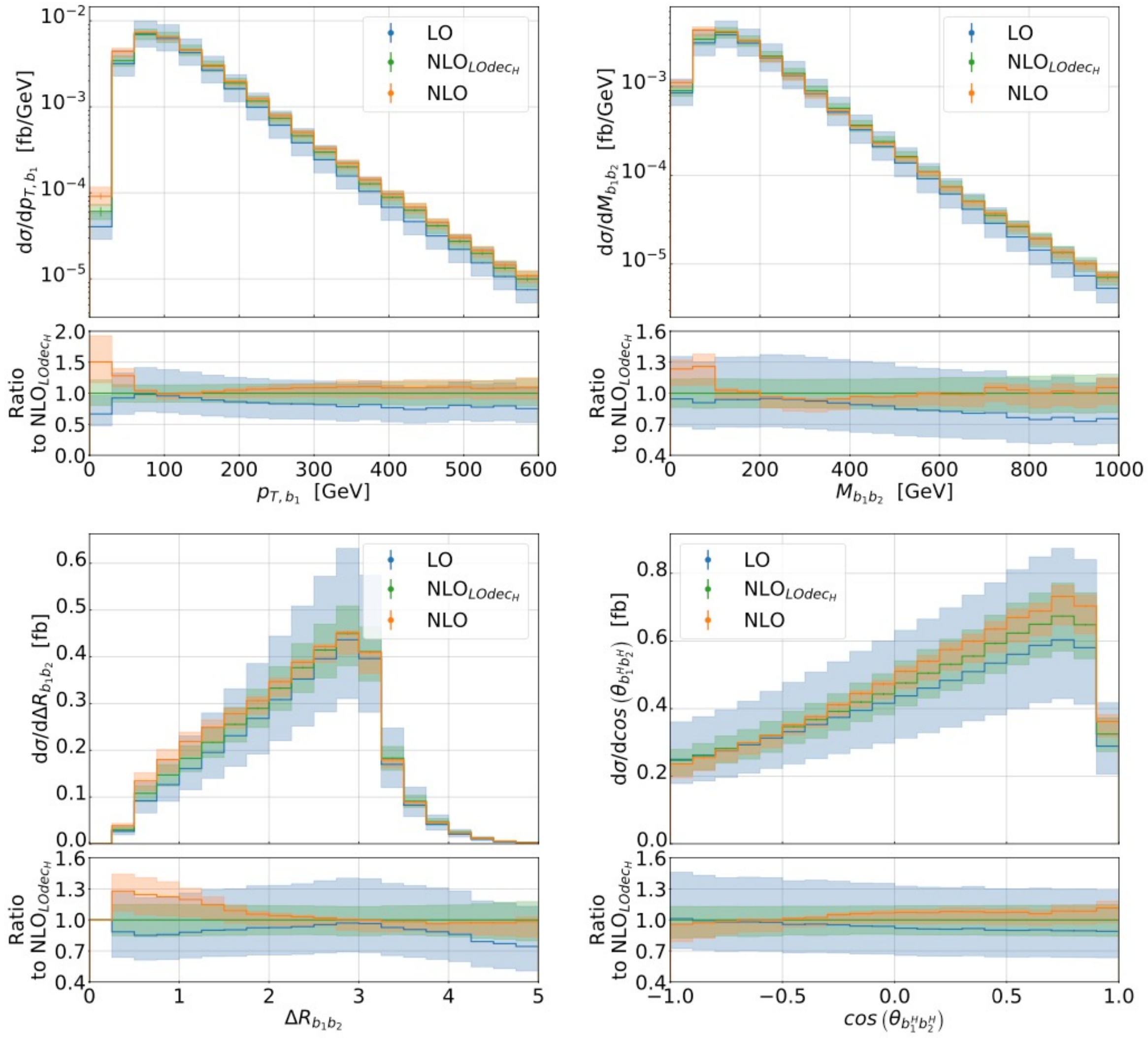
$$\mu_{dyn} = \left(m_{T,\,t}\,m_{T,\,\bar{t}}\,m_{T,\,H}\right)^{\frac{1}{3}} \qquad m_T = \sqrt{m^2 + p_T^2}.$$

$$\mu_{fix} = m_t + \frac{m_H}{2} = 236 \text{ GeV}$$

NLO QCD Corrections & Higgs decays

NLO ttH

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



Stremmer, Worek '22

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

- Full off-shell effects for t & W
- Higgs boson decays in NWA

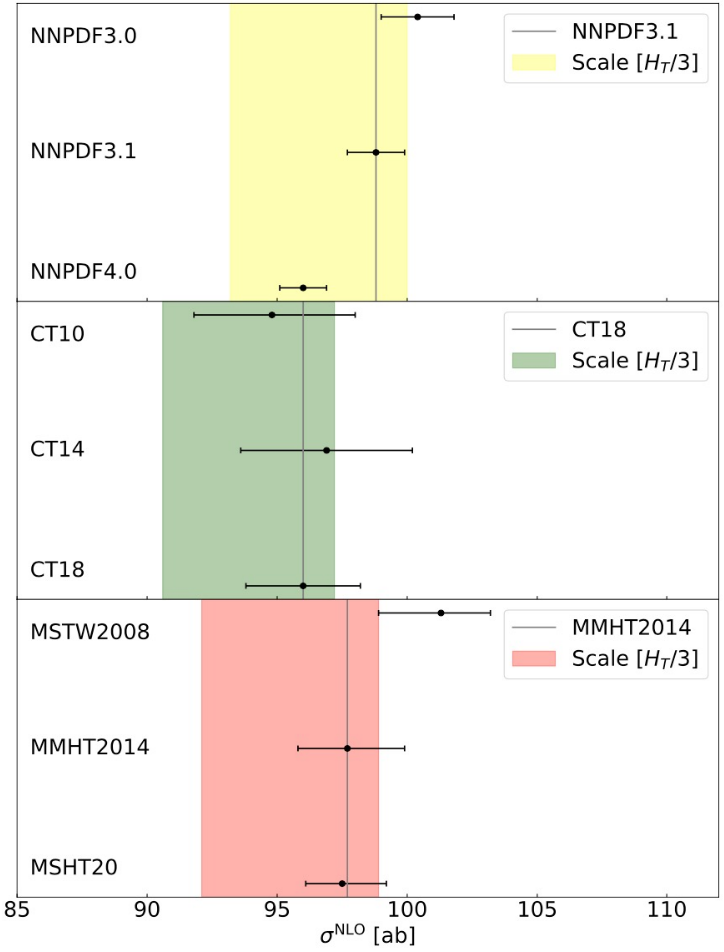
	$\sigma_{\rm LO}$ [fb]	$\sigma_{\rm NLO}$ [fb]	$\mathcal{K}$
Stable Higgs	$2.2130(2)^{+30.1\%}_{-21.6\%}$	$2.728(2)^{+1.1\%}_{-4.7\%}$	1.23
$H \to b\bar{b}$	$0.8304(2)^{+44.4\%}_{-28.7\%}$	$0.9456(8)^{+2.5\%}_{-9.5\%}$	1.14
$H \to \tau^+\tau^-$	$0.11426(2)^{+30.0\%}_{-21.6\%}$	$0.1418(1)^{+1.2\%}_{-4.8\%}$	1.24
$H \to \gamma\gamma$	$0.0037754(8)^{+30.0\%}_{-21.6\%}$	$0.004552(4)^{+0.9\%}_{-4.1\%}$	1.21
$H \to e^+e^-e^+e^-$	$1.0083(7)\cdot 10^{-5}{}^{+30.2\%}_{-21.6\%}$	$1.313(4)\cdot 10^{-5}{}^{+1.8\%}_{-6.2\%}$	1.30

- $H \to bb$ ⇰ $\sigma_{\rm NLO_{LOdec_H}} = 0.8956(8)^{+13.8\%}_{-14.2\%}$ fb. ⇰ 5%
- 4 b-jets ⇰ $Q_{i,j} = |M_{b_ib_j} - m_H|$

PDF Uncertainties

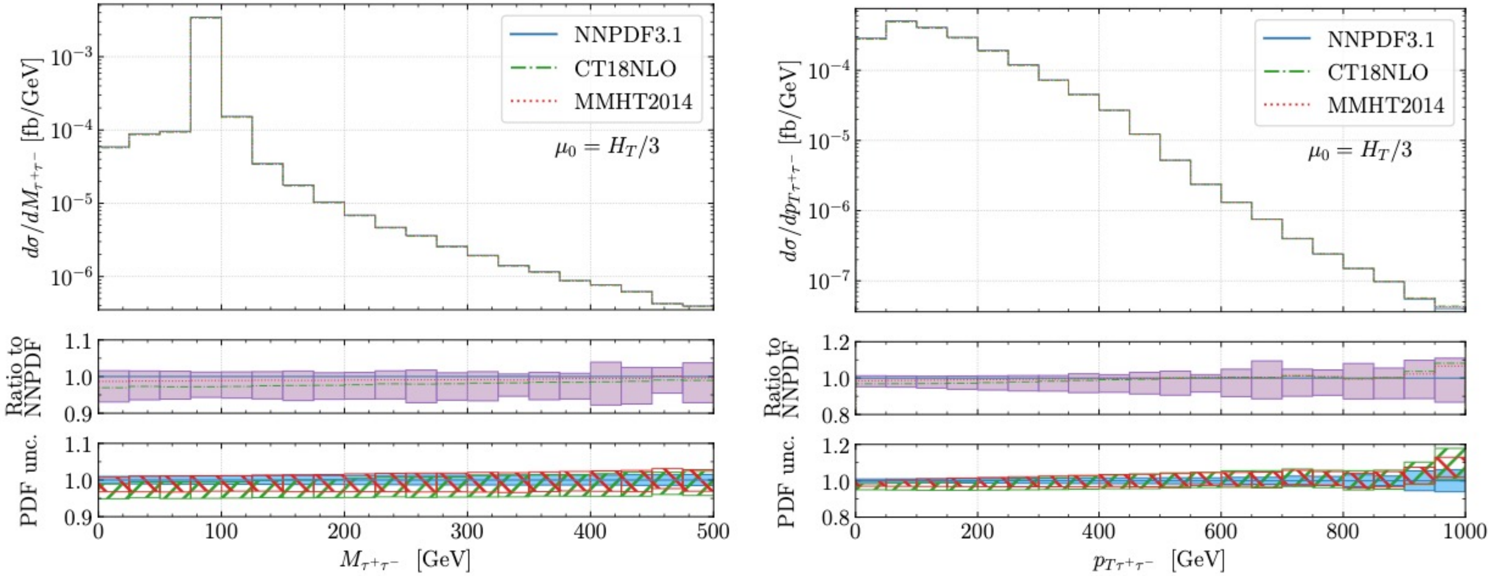
NLO ttZ

Bevilacqua, Hartanto, Kraus, Nasufi, Worek '22



Integrated level

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



Differential level

- PDF uncertainties for CT18 & MMHT14 similar
- Factor of 2 larger than PDF uncertainties for NNPDF3.1
- *PDF uncertainties smaller than scale variation*

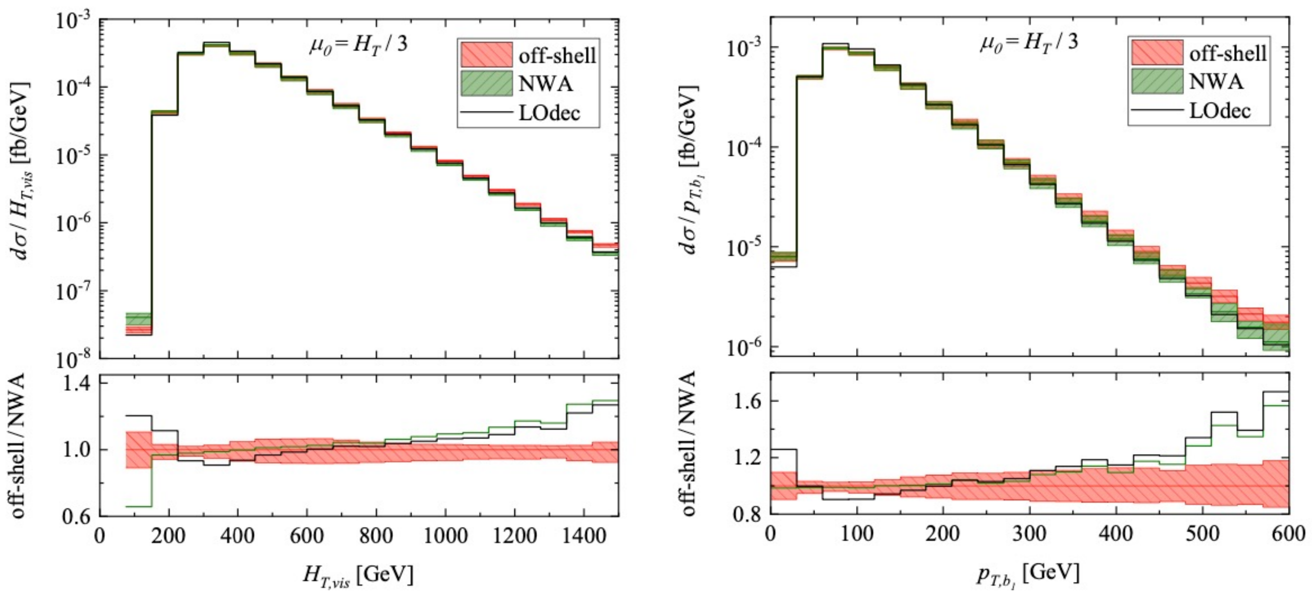
How Good is NWA

NLO ttW

Bevilacqua, Bi, Hartanto, Kraus, Worek '20

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

Modelling Approach	$\sigma^{\rm LO}$ [ab]	$\sigma^{\rm NLO}$ [ab]
full off-shell ($\mu_0 = m_t + m_W/2$)	$106.9^{+27.7\,(26\%)}_{-20.5\,(19\%)}$	$123.2^{+6.3\,(5\%)}_{-8.7\,(7\%)}$
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 ($\mu_0 = H_T/3$)	$115.1^{+30.4\,(26\%)}_{-22.4\,(19\%)}$	$124.2^{+4.1\,(3\%)}_{-7.7\,(6\%)}$
$\mathrm{NWA_{LOdecay}}$ ($\mu_0 = m_t + m_W/2$)		$127.0^{+14.2\,(11\%)}_{-13.3\,(10\%)}$
$\mathrm{NWA_{LOdecay}}$ ($\mu_0 = H_T/3$)		$130.7^{+13.6\,(10\%)}_{-13.2\,(10\%)}$



Integrated level

- Full off-shell effects *0.2%*
- NLO QCD corrections to decays *3%-5%*

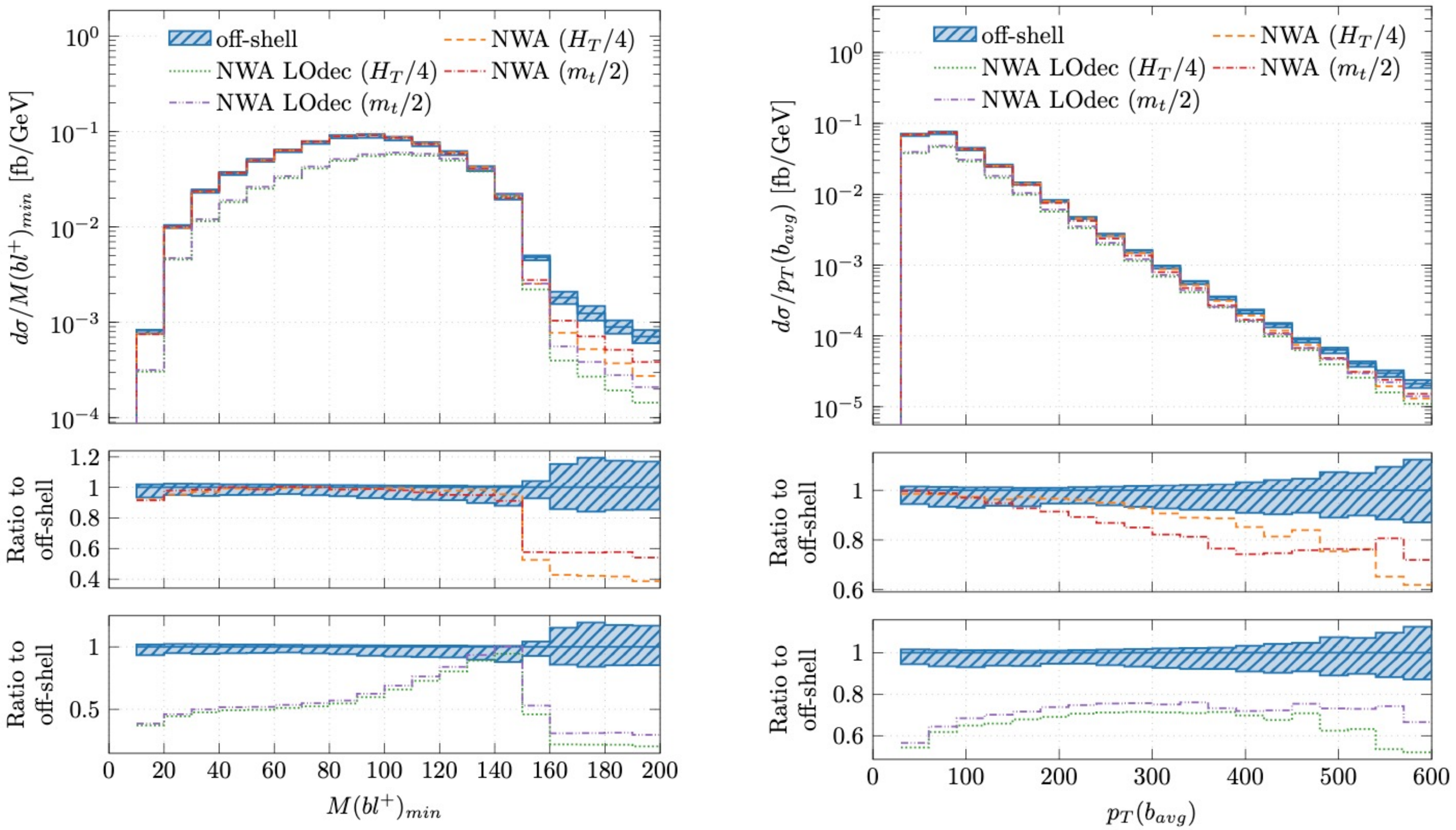
Differential level

- Off-shell effects up to *60% - 70%*
- Substantial differences between NWA & $\mathrm{NWA_{LODECAY}}$

How Good is NWA

NLO $tt\gamma$

Bevilacqua, Hartanto, Kraus, Weber, Worek '20



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

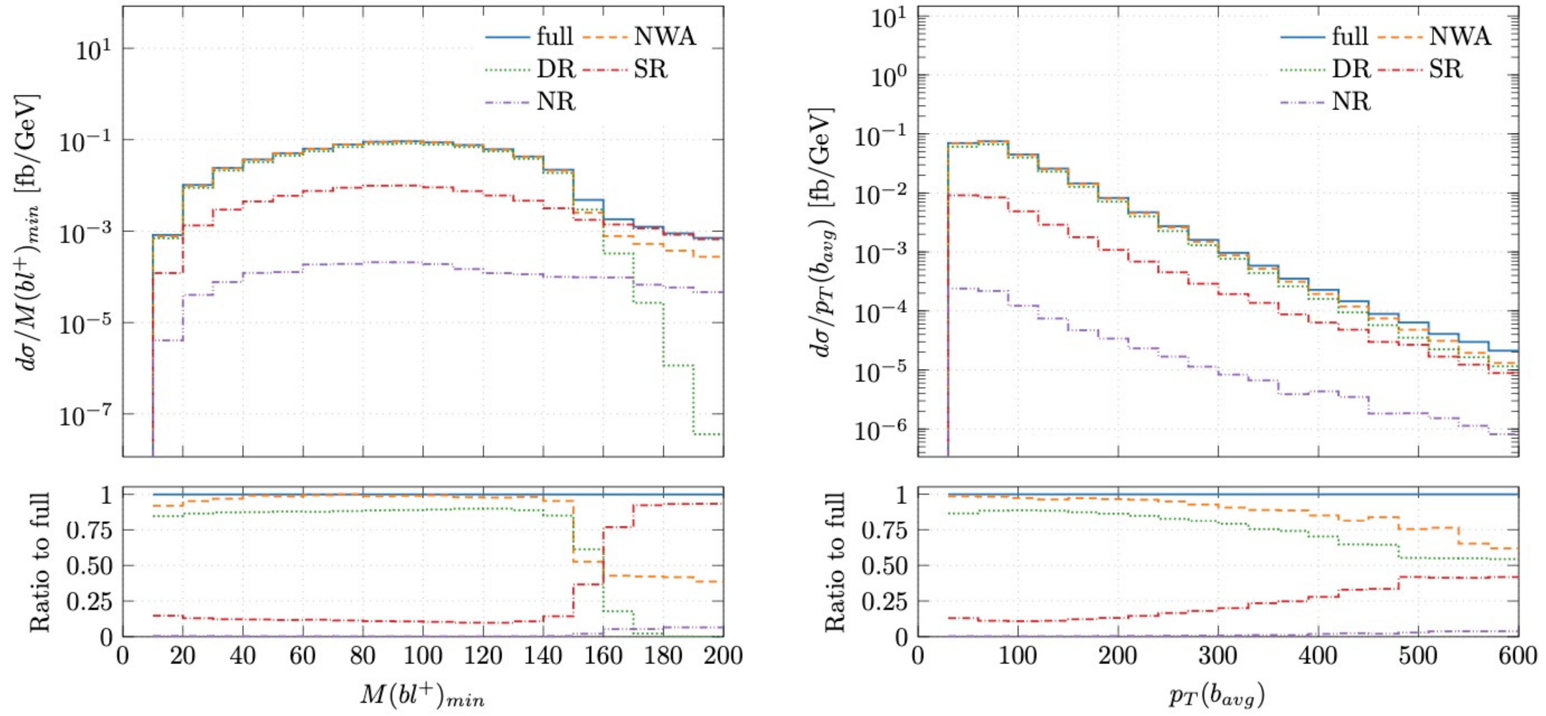
Dimensionful observables

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

Various Phase-Space Regions

NLO $tt\gamma$

Bevilacqua, Hartanto, Kraus, Weber, Worek '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%*
- Specific phase-space regions
  - *Kinematical edges*
  - *High p_T regions*

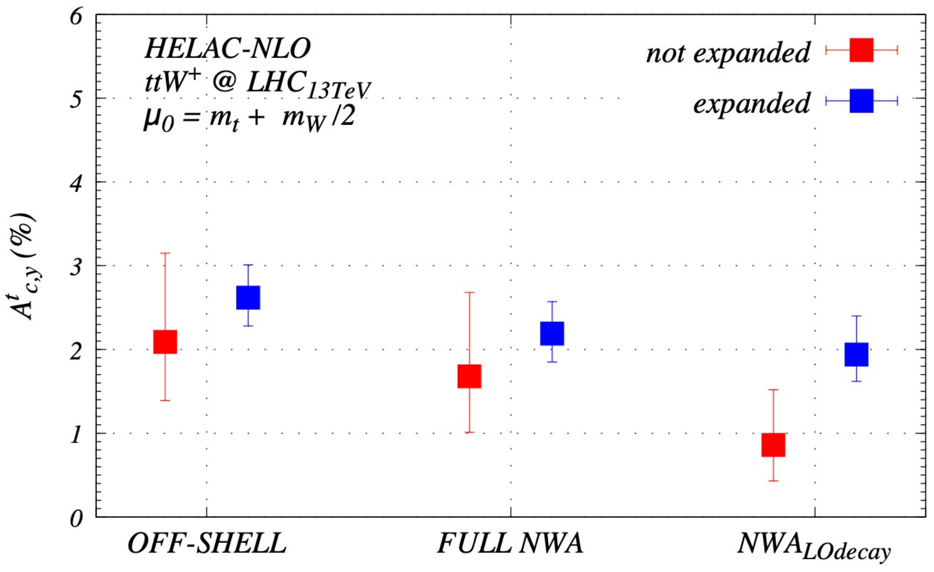
Application I: Top Charge Asymmetry

NLO ttW

Searching for more precise observables

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

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



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

Bevilacqua, Bi, Hartanto, Kraus, Nasufi, Worek '21

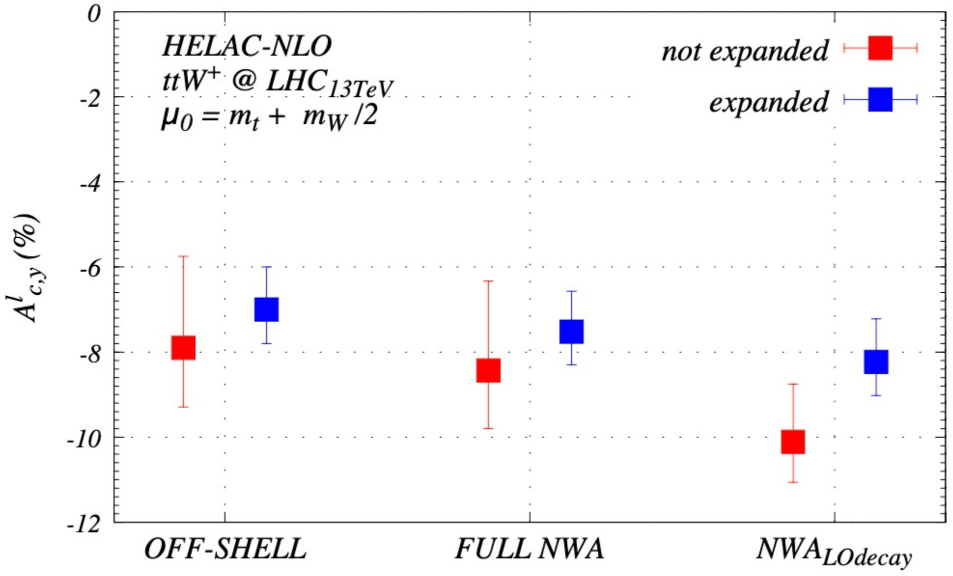
- Asymmetry larger than for $pp \to tt$
- Top quark momenta must be reconstructed
- Scale setting not important ⇨ Fixed & dynamical scale choice gives similar results
- Top-quark modelling important

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

Application I: Top Charge Asymmetry

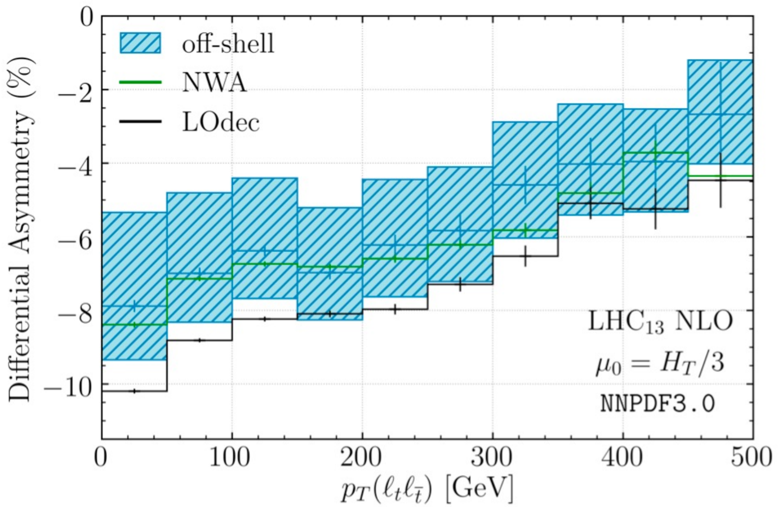
NLO ttW

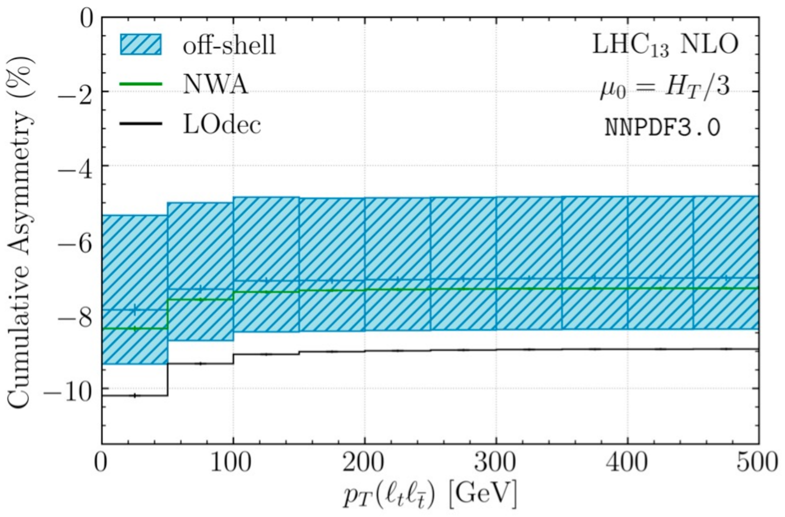
Bevilacqua, Bi, Hartanto, Kraus, Nasufi, Worek '21



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

Differential & Cumulative A^l_c





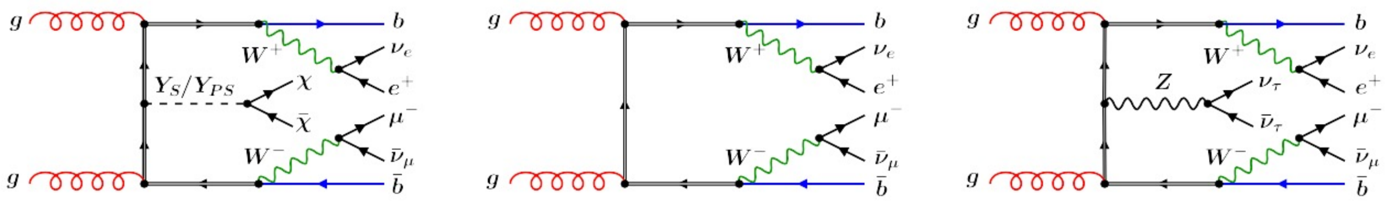
- A^l_c charge asymmetry @ NLO for $pp \to ttW^+$
- Directly measurable ⇨ No need for top-quark reconstruction

Application II: BSM Exclusion Limits

NLO ttZ

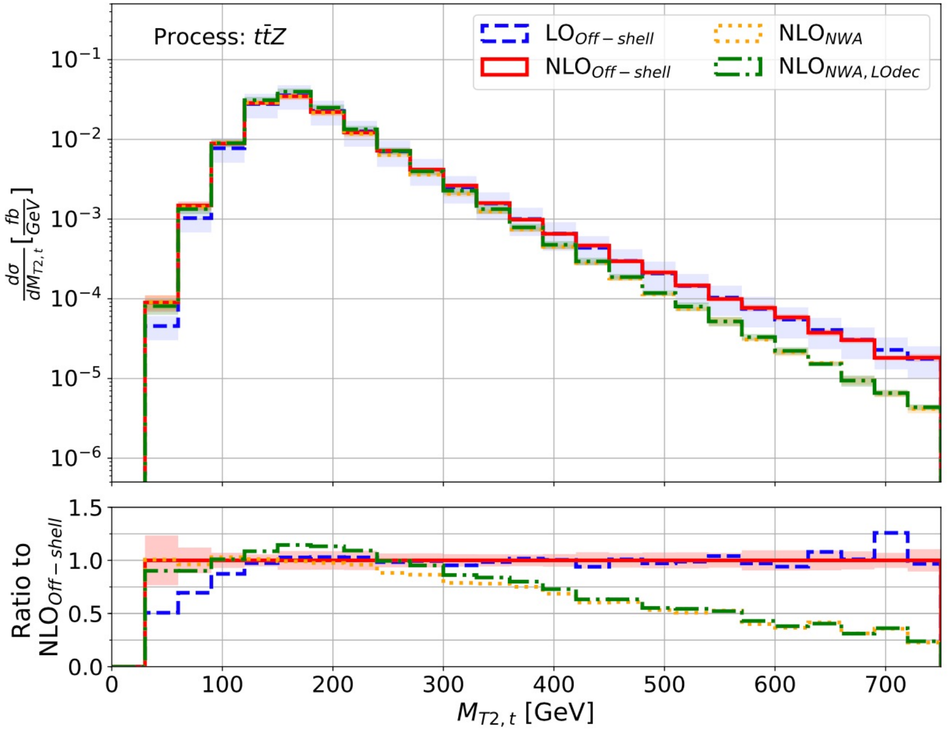
- **BSM** ⇨ Kinematical edges & high p_T regions
- *tt + DM* ⇨ Top-quark backgrounds: *tt & ttZ*
- **Observable** ⇨ $M_{T2,W}$ & $M_{T2,t}$ & p_{Tmiss}

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



Before & after applying additional cuts

Process	Order	Scale	σ_{uncut} [fb]	σ_{cut} [fb]	$\sigma_{\text{cut}}/\sigma_{\text{uncut}}$	Events for $L = 300$ 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



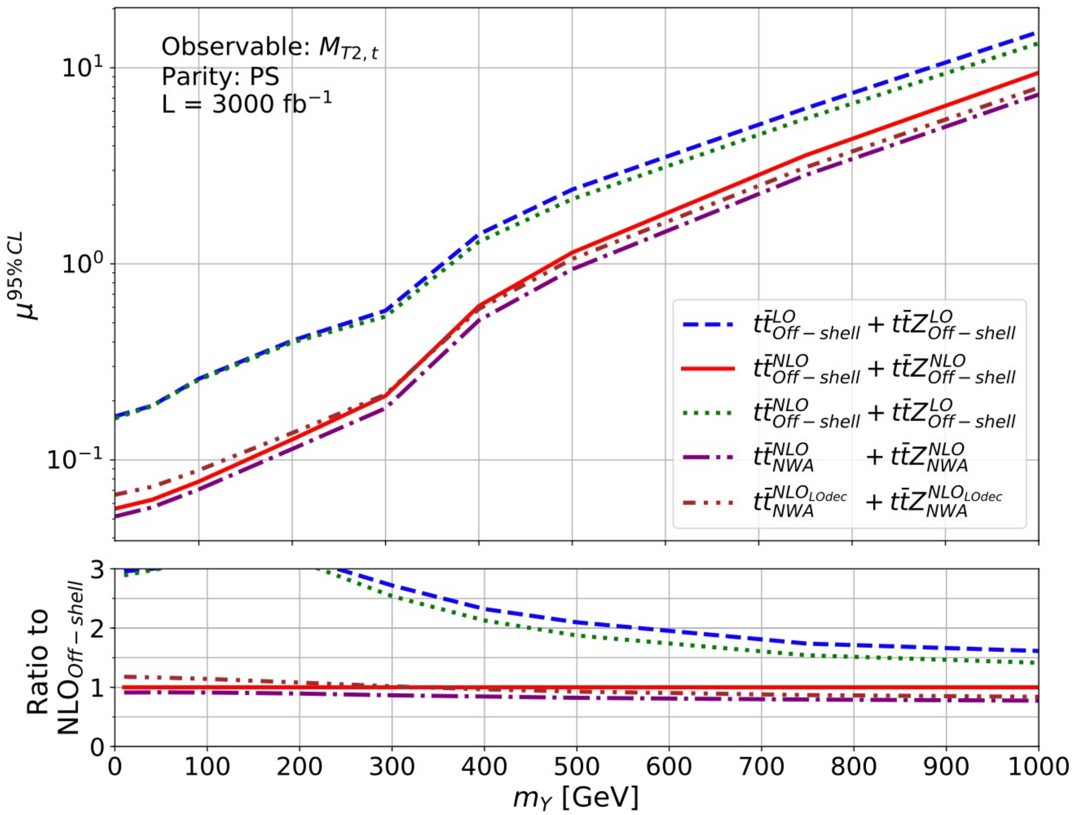
- After cuts *25%* of events come from *tt*
- NLO smaller uncertainties w.r.t LO, NLO + LO decays

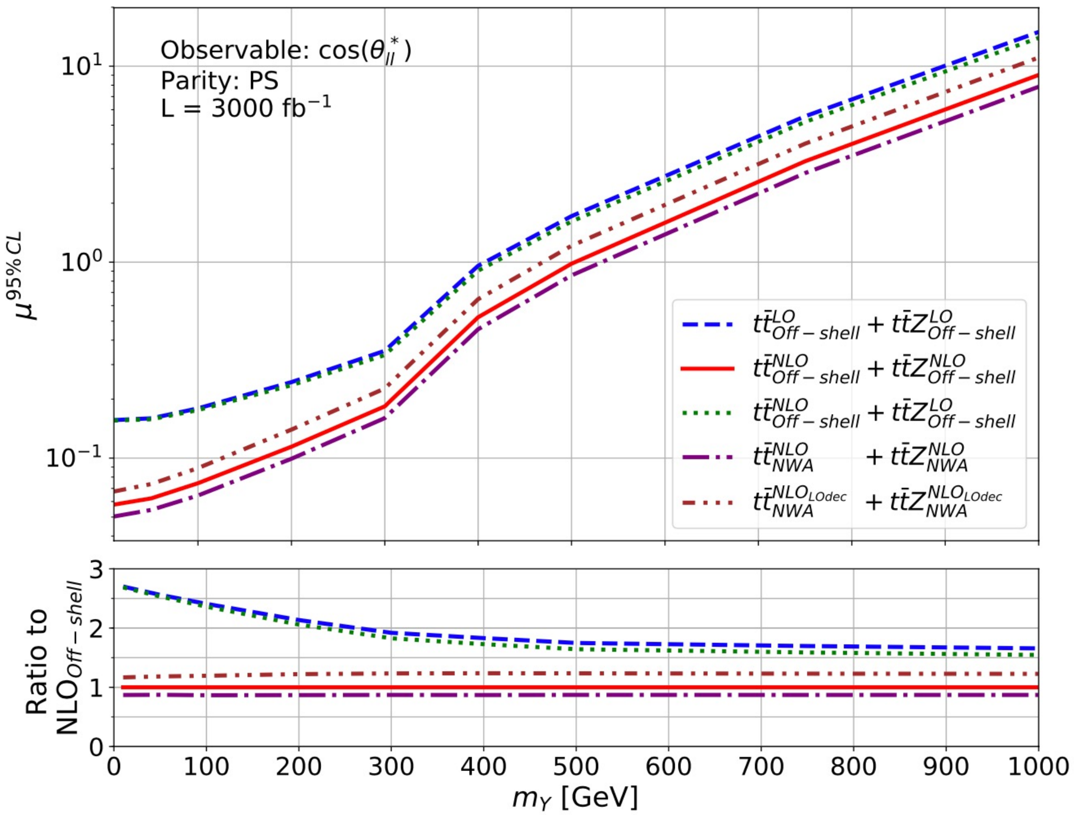
Hermann, Worek '21

Application II: BSM Exclusion Limits

NLO ttZ

Hermann, Worek '21





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

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

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

SUMMARY

- *Proper modeling of top quark production & decay essential already now in presence of inclusive cuts:*

- NLO QCD corrections to $t\bar{t} + X$ where $X = H$ (+ *H decays in NWA*), γ, W, Z ($Z \to \nu\nu$ & $Z \to ll$), j, $b\bar{b}$
  1. Corrections to production & decays important ⇨ NLO $t\bar{t}$ spin correlations
  2. Possibility of using kinematic-dependent μ_R & μ_F scales important
  3. Complete off-shell effects important ⇨ *kinematical edges & high* p_T *regions*

- *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*

- Full off-shell results & NWA & $\text{NWA}_{\text{LODEC}}$
- HELAC – NLO ⇨ Stored Events ⇨ *Ntuples Files* ⇨ *Les Houches & ROOT Files*
- Our goal is to provide state-of-the-art NLO QCD + EW results ⇨ $t\bar{t} + X$ where $X = \gamma\gamma, jj, t\bar{t}, \ldots$
- Compare to LHC data

Backup

Various Phase – Space Regions

NLO $t\bar{t}\gamma$

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

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

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

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)

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

Photon in Top-Quark Decays

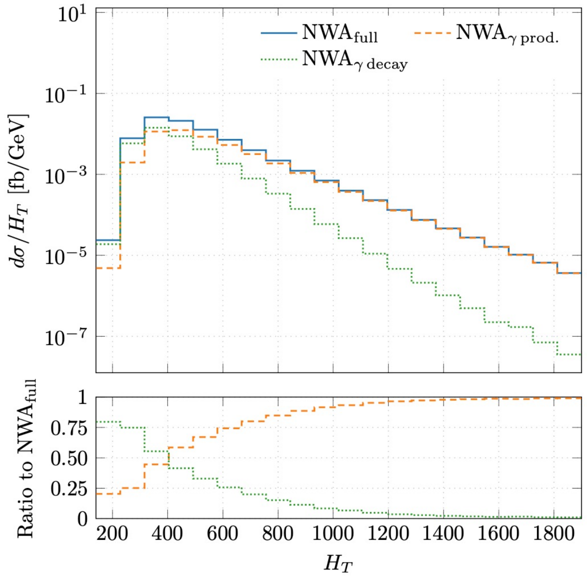
NLO $tt\gamma$

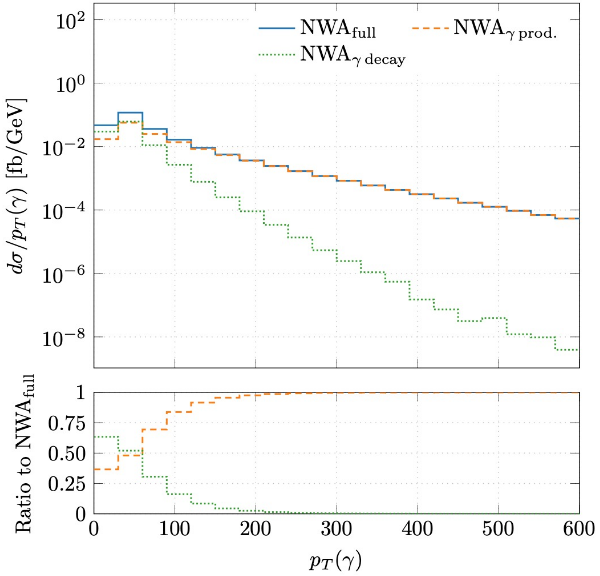
Bevilacqua, Hartanto, Kraus, Weber, Worek '20

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

Modelling Approach	σ^{LO} [fb]	σ^{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 ($\mu_0 = H_T/4$)	$7.18^{+2.39\,(33\%)}_{-1.68\,(23\%)}$	$7.33^{-0.43\,(5.9\%)}_{-0.24\,(3.3\%)}$
$\text{NWA}_{\gamma-\text{prod}}$ ($\mu_0 = m_t/2$)	$4.52^{+1.63\,(36\%)}_{-1.11\,(24\%)}$	$4.13^{-0.53\,(13\%)}_{-0.05\,(1.2\%)}$
$\text{NWA}_{\gamma-\text{prod}}$ ($\mu_0 = H_T/4$)	$3.85^{+1.29\,(33\%)}_{-0.90\,(23\%)}$	$4.15^{-0.12\,(2.3\%)}_{-0.21\,(5.1\%)}$
$\text{NWA}_{\gamma-\text{decay}}$ ($\mu_0 = m_t/2$)	$3.56^{+1.20\,(34\%)}_{-0.85\,(24\%)}$	$3.15^{-0.46\,(15\%)}_{+0.03\,(0.9\%)}$
$\text{NWA}_{\gamma-\text{decay}}$ ($\mu_0 = H_T/4$)	$3.33^{+1.10\,(33\%)}_{-0.77\,(23\%)}$	$3.18^{-0.31\,(9.7\%)}_{-0.03\,(0.9\%)}$
$\text{NWA}_{\text{LOdecay}}$ ($\mu_0 = m_t/2$)		$4.85^{+0.26\,(5.4\%)}_{-0.48\,(9.9\%)}$
$\text{NWA}_{\text{LOdecay}}$ ($\mu_0 = H_T/4$)		$4.63^{+0.44\,(9.5\%)}_{-0.52\,(11\%)}$

- 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%





Diverse picture

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

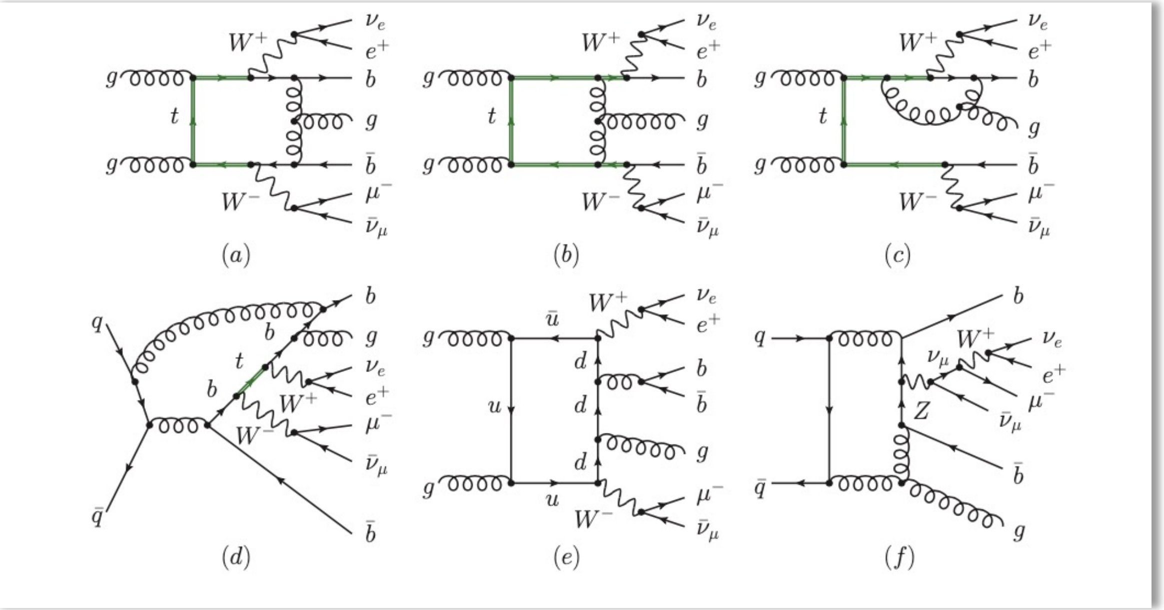
Complexity for TTJ

NLO ttj

Partonic Subprocess	Number Of Feynman Diagrams	Number Of CS Dipoles	Number Of NS Subtractions
$gg \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}gg$	4447	56	14
$gg \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}q\bar{q}$	1952	40	10
$gq \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}gq$	1952	40	10
$g\bar{q} \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}g\bar{q}$	1952	40	10
$q\bar{q} \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}gg$	1952	40	10
$qq \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}qq$	930	20	5
$q\bar{q} \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}q\bar{q}$	930	16	4
$\bar{q}\bar{q} \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\bar{q}\bar{q}$	930	20	5
$qq' \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}qq'$	501	12	3
$q\bar{q} \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}q'\bar{q}'$	501	8	2
$q\bar{q}' \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}q\bar{q}'$	501	12	3
$\bar{q}\bar{q}' \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\bar{q}\bar{q}'$	501	12	3
$qQ \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}qQ$	465	12	3
$q\bar{q} \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}Q\overline{Q}$	465	8	2
$q\overline{Q} \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}q\overline{Q}$	465	12	3
$\bar{q}\overline{Q} \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\bar{q}\overline{Q}$	465	12	3
$qQ \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}q'Q'$	36	4	1
$q\overline{Q} \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}q'\overline{Q}'$	36	4	1
$q\bar{q}' \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}Q\overline{Q}'$	36	4	1
$\bar{q}\overline{Q} \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\bar{q}'\overline{Q}'$	36	4	1
$gg \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}b\bar{b}$	3904	48	12
$q\bar{q} \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}b\bar{b}$	930	16	4

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

Bevilacqua, Hartanto, Kraus, Worek '16



- *gg* channel *39180* one-loop diagrams
- *120* Heptagons
- *1155* Hexagons
- Tensor integrals up to rank six