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Top Physics - Precision for Discoveries

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Instead of Introduction

- Latest theoretical results for $t\bar{t}$ & $t\bar{t}+X$ where $X = H, \gamma, W^{\pm}, Z, j, b\bar{b}, \ldots$
  - Not only are they impressive, but there are plenty of them
- Tell story, hopefully interesting one
  - *Full processes* ➪ *Phenomenological results* ➪ *Compared to LHC data*
  - Various results for $pp \to t\bar{t}$ & $pp \to t\bar{t}+X$
  - NNLO QCD & NLO QCD

My Goal

- Identify which effects are important & should be taken into account
- Give a few examples for NLO QCD $pp \to t\bar{t}+X$ results
- Vital for SM top quark physics studies & BSM searches & SM Higgs boson measurements ➪ $pp \to t\bar{t}H$
- *(Biased) Selection* ➪ Only fixed order calculations ➪ LHC

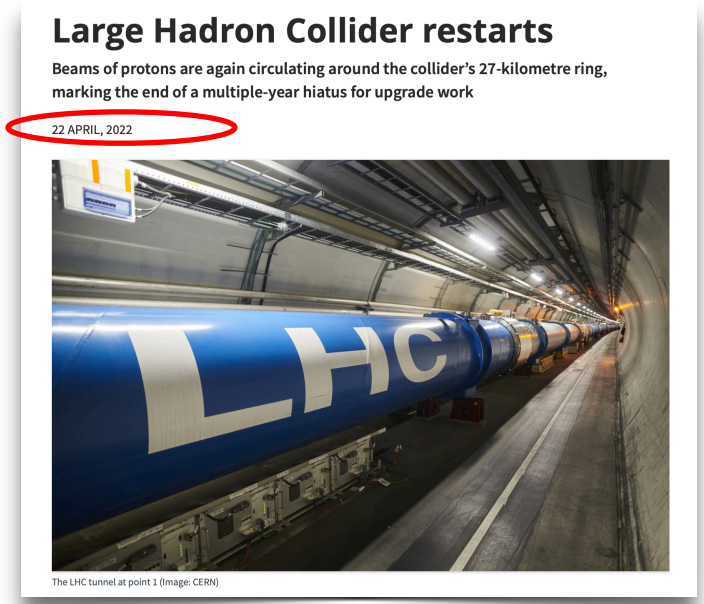
Instead of Introduction

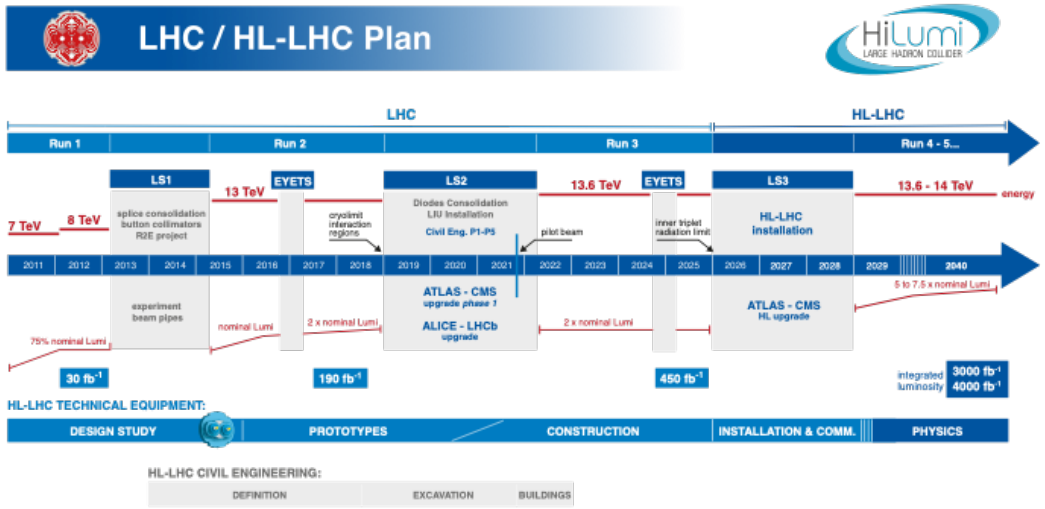
- SM ➪ Extremely fun & exciting & enjoyable time for people working on SM Physics ➪ QCD + EW

- 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
  - $t\bar{t}, t\bar{t} + jets, t\bar{t}V$ ➪ Important backgrounds for BSM

- BSM Indirect Searches
  - New Physics as small corrections to SM reactions
  - *Precision SM measurements @ LHC*
    ➪ High Luminosity LHC
  - *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

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

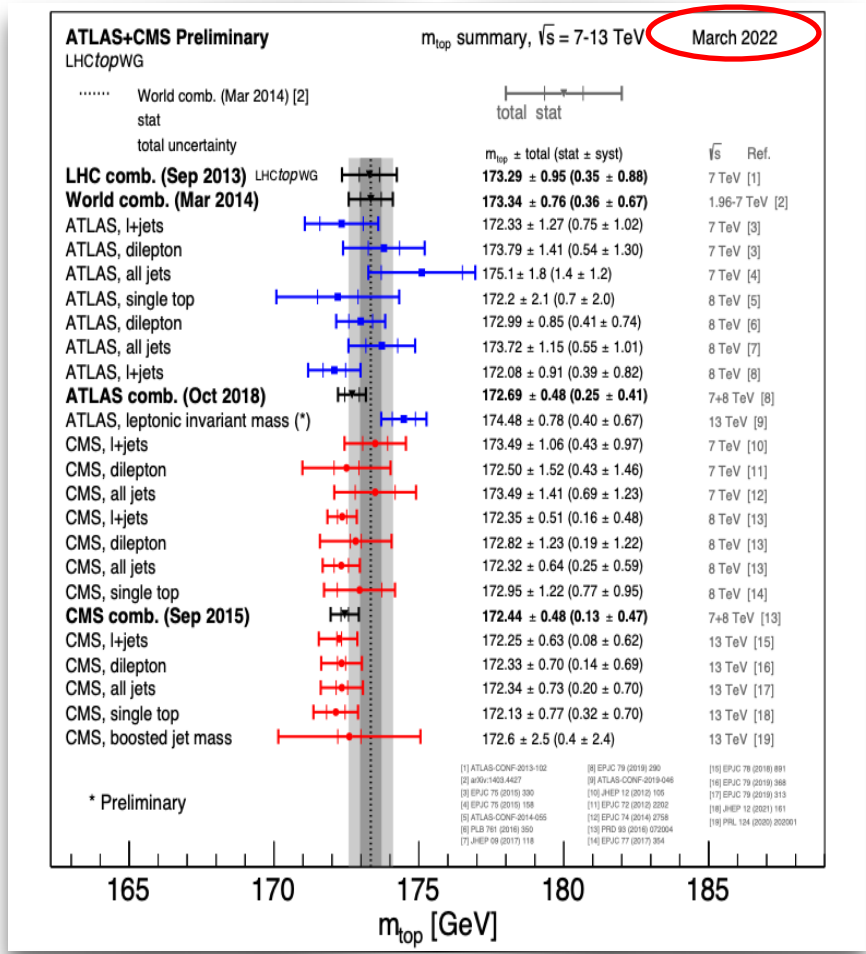
World Combination '14
ATLAS, CDF, CMS, D0

- 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

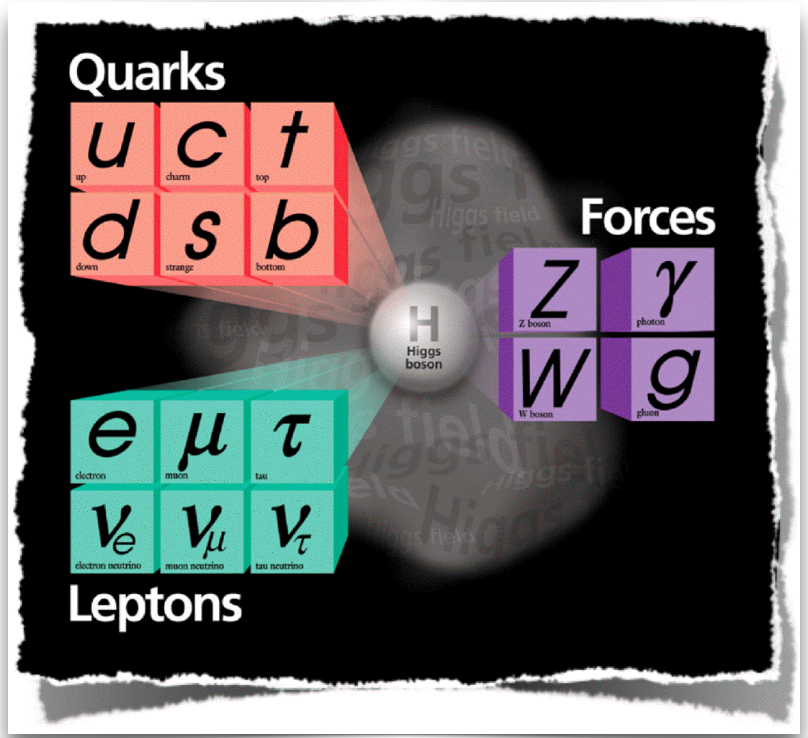
$$j_b\,, p_T^{miss}\,, \ell^{\pm}\ \&\ jets$$



$$m_t = (171.77 \pm 0.38)\ \text{GeV}$$

CMS Collaboration '22

Precision Top Quark Physics

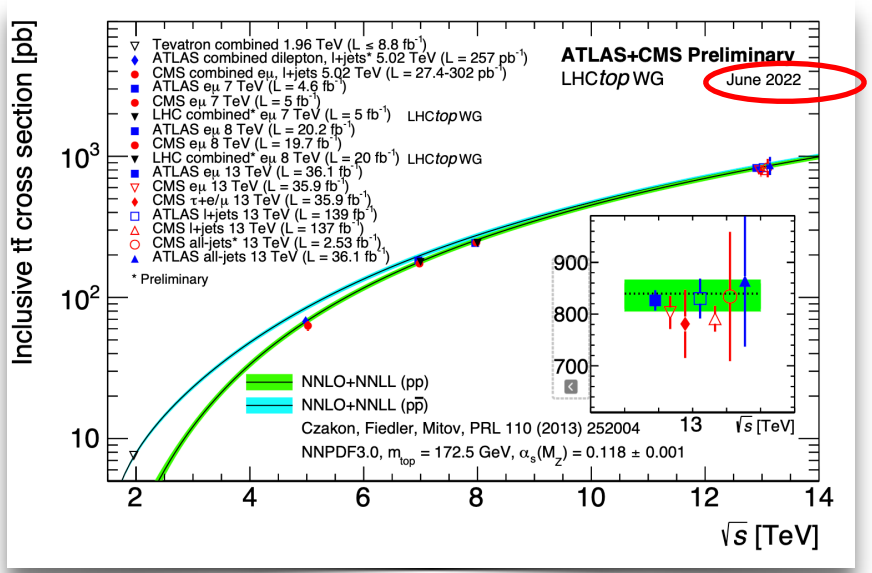


- Infrared Structure of QCD
  - Extract SM parameters as precisely as possible ➪ α_s & m_t
  - Constraining gluon PDFs
  - Verify couplings to other particles ➪ $\gamma, H, Z, W^{\pm}$
- Various IR-Safe Observables
  - Integrated & differential (fiducial) cross sections
  - Cross section ratios
    - More stable against radiative corrections
    - Reduced scale dependence ➪ Various uncertainties cancel in ratio
    - Enhanced predictive power ➪ Interesting to probe new physics @ LHC
  - Top quark charge asymmetry
  - Differential & cumulative top quark charge asymmetries ➪ Lepton charge asymmetry, …

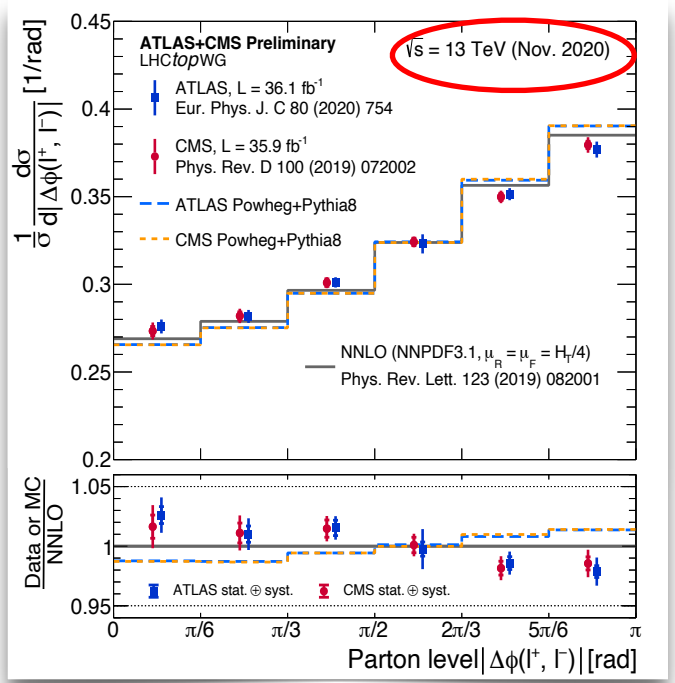
Top Quark Pair Production

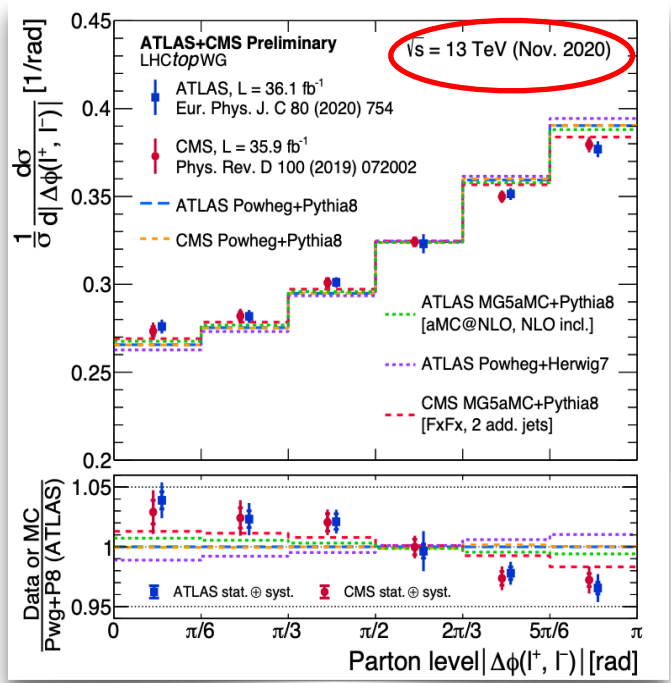
- NNLO + NNLL predictions for tt
- NNLO Production & Decays
  - Narrow-width-approximation
  - di-lepton top quark decay channel
- NNLO Production + LO decays + PS
  - $\text{MiNNLO}_{\text{PS}}$

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



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



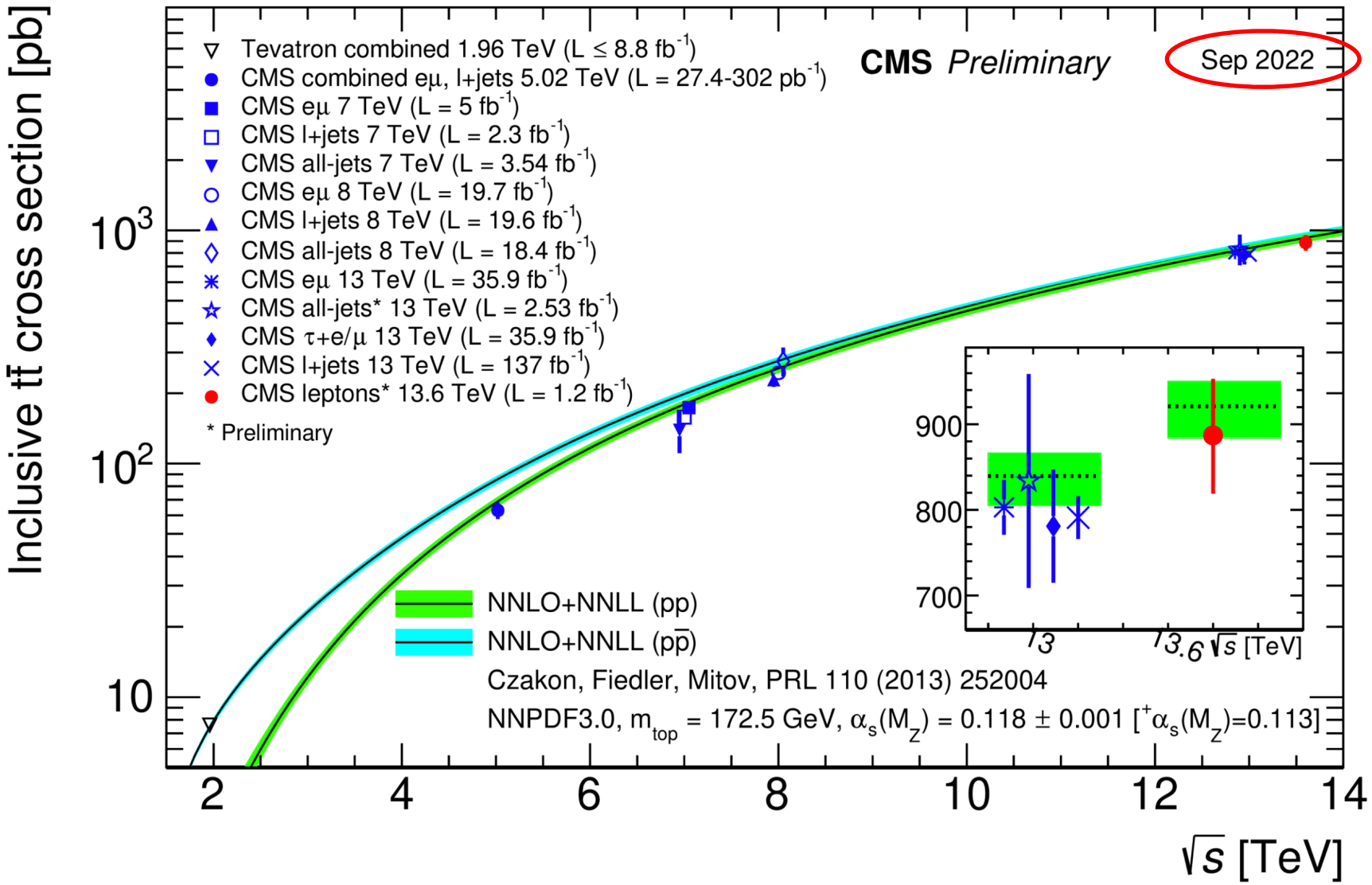


Czakon, Fiedler, Mitov '13
Czakon, Heymes, Mitov '16 '17
Behring, Czakon, Mitov, Papanastasiou, Poncelet '19
Czakon, Mitov, Poncelet '21

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

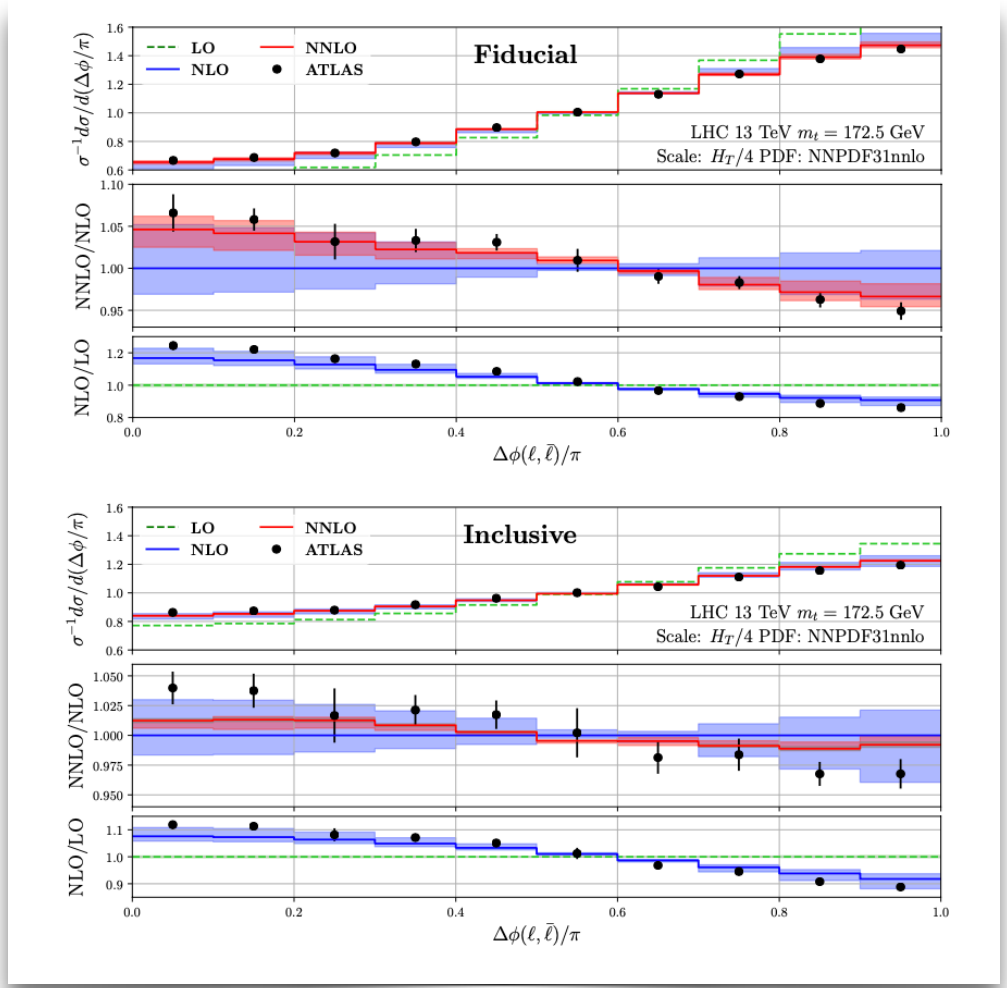
Mazzitelli, Monni, Nason, Re, Wiesemann, Zanderighi '21 '22

First Results for Run-3 in CMS



Top Quark Pair Production & Decays

Agreement



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

- Normalised differential $t\bar{t}$ cross section @ NNLO QCD
- NWA ➪ Di-lepton channel
- Azimuthal opening angle between two leptons

- Inclusive ➪ Does not assume any selection cuts
- Fiducial ➪ Based on the ATLAS selection cuts

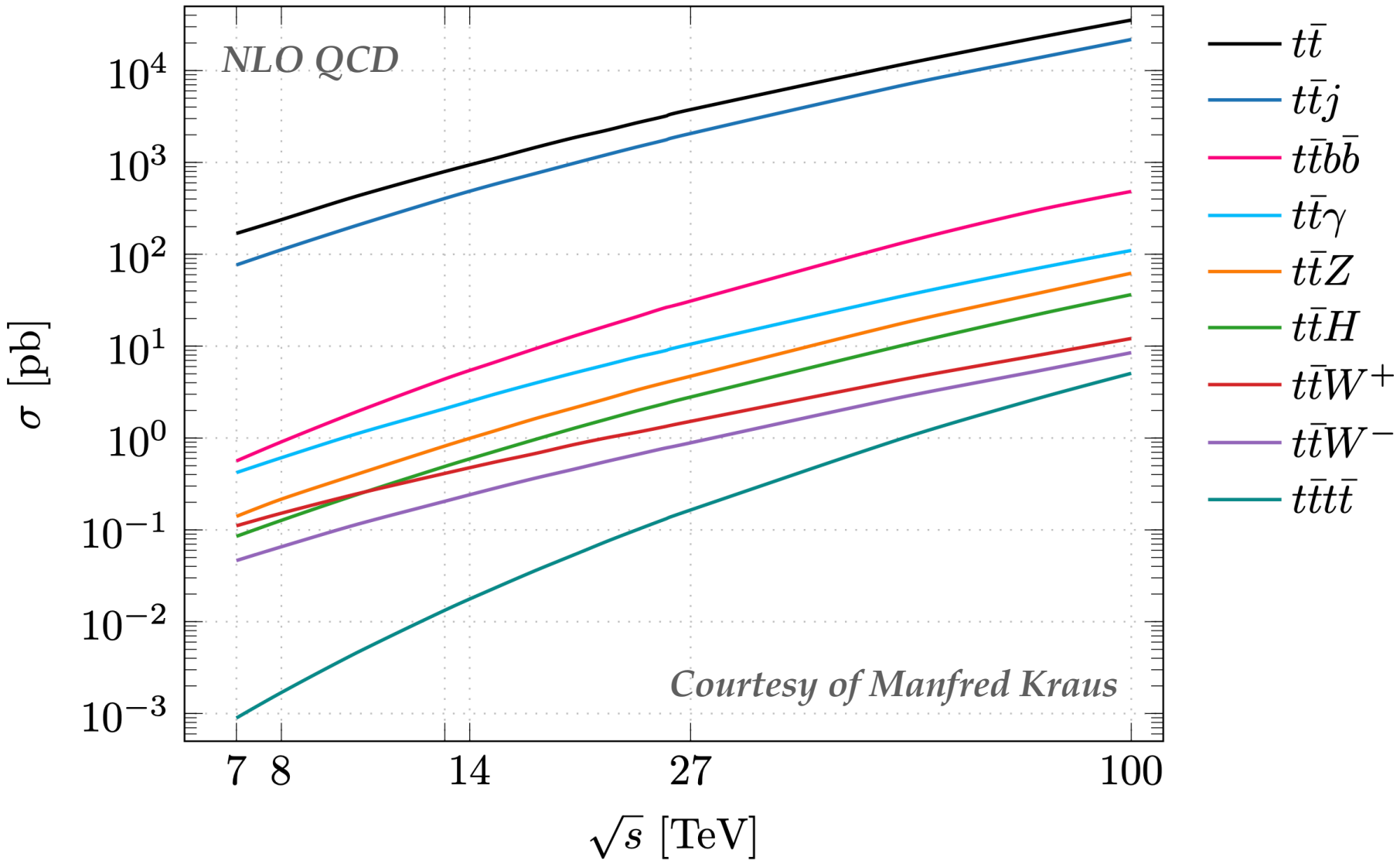
Behring, Czakon, Mitov, Papanastasiou, Poncelet '19
Czakon, Mitov, Poncelet '20

Proper modeling of top-quark production & decay essential

Tension

Associated TT Production

- More exclusive final states are produced @ LHC

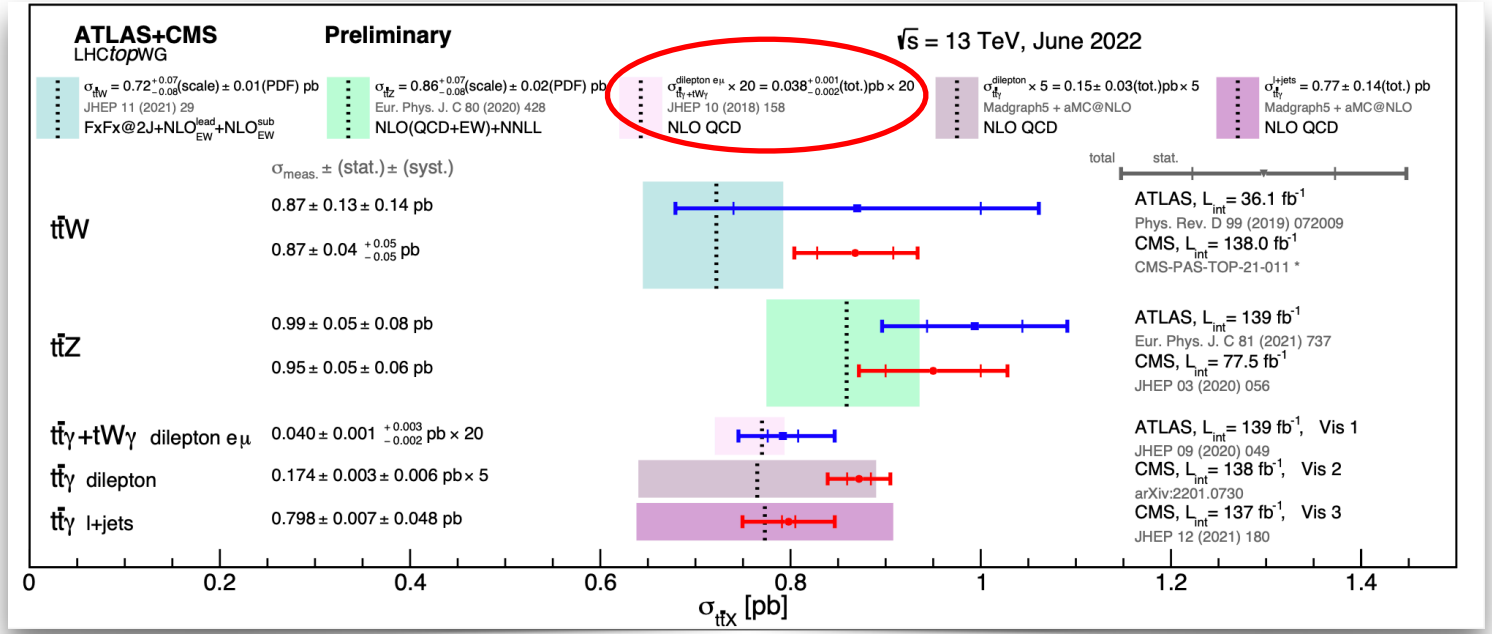


Associated TT Production

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

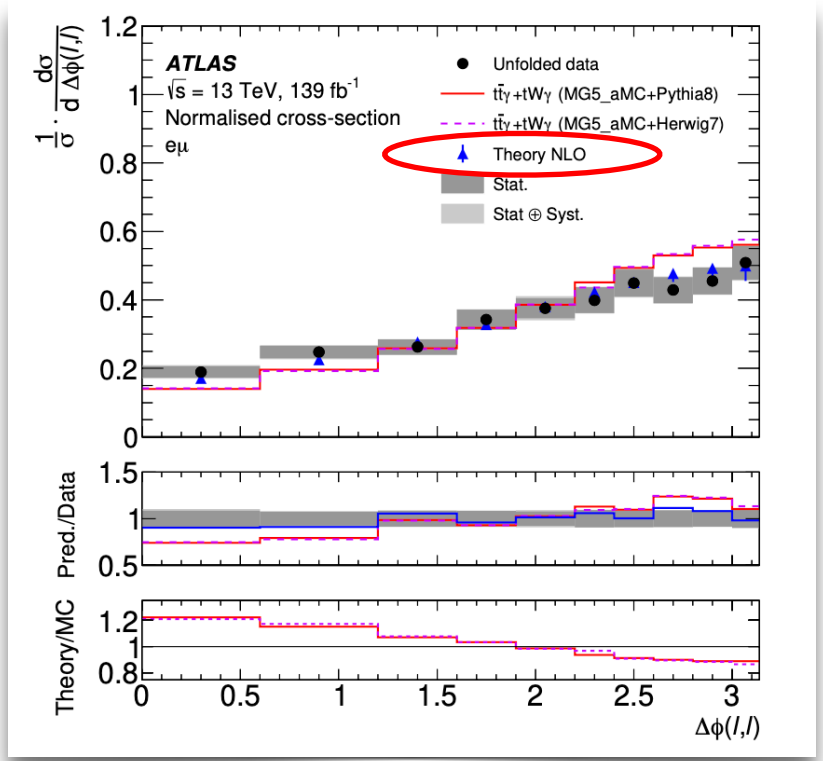
- More exclusive final states are produced @ LHC

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



Predictions	$p_T(\gamma)$ χ^2/ndf	p-value	$\lvert\eta(\gamma)\rvert$ χ^2/ndf	p-value	$\Delta R(\gamma,\ell)_{\min}$ χ^2/ndf	p-value	$\Delta\phi(\ell,\ell)$ χ^2/ndf	p-value	$\lvert\Delta\eta(\ell,\ell)\rvert$ χ^2/ndf	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 $t\bar{t}\gamma$
  - Di-lepton channel

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

Full Off-Shell Effects

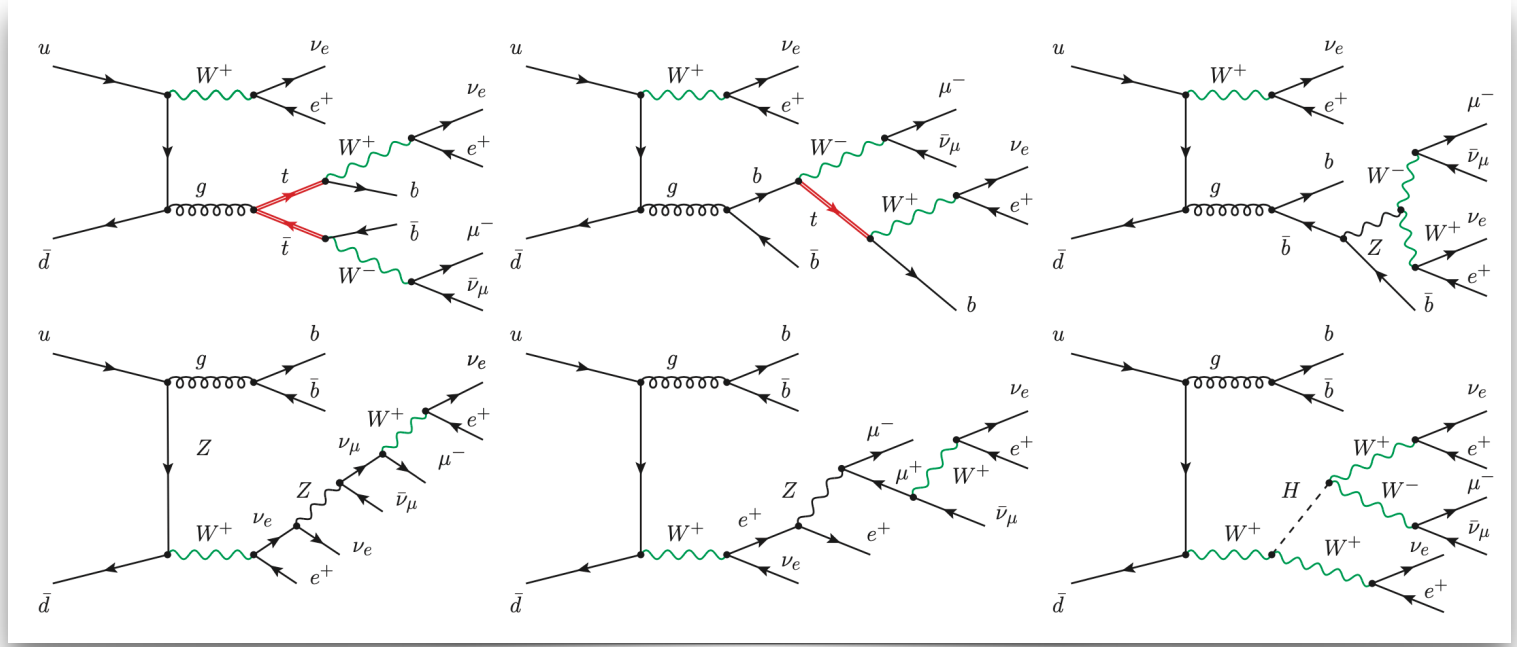
NLO *ttW*

- *Off-shell t & $W^{\pm}$ described by Breit-Wigner propagators*
- *Double-, single- & non-resonant t & $W^{\pm}$ contributions included*
- *All interference effects incorporated at matrix element level*

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

Bevilacqua, Bi, Hartanto, Kraus, Worek '20

- NLO QCD corrections to production & decays
- Non-factorisable NLO QCD corrections included ➪ Cross-talk between production & decays
- NLO spin correlations



- Simply putting $\Gamma \neq 0$ 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

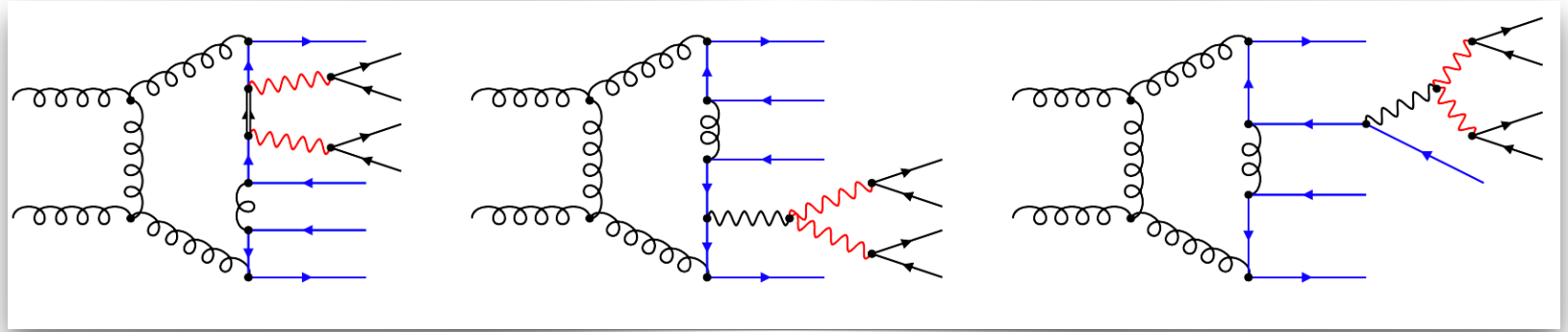
- Scalar integrals with complex masses ➪ **ONELOOP**

  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

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

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

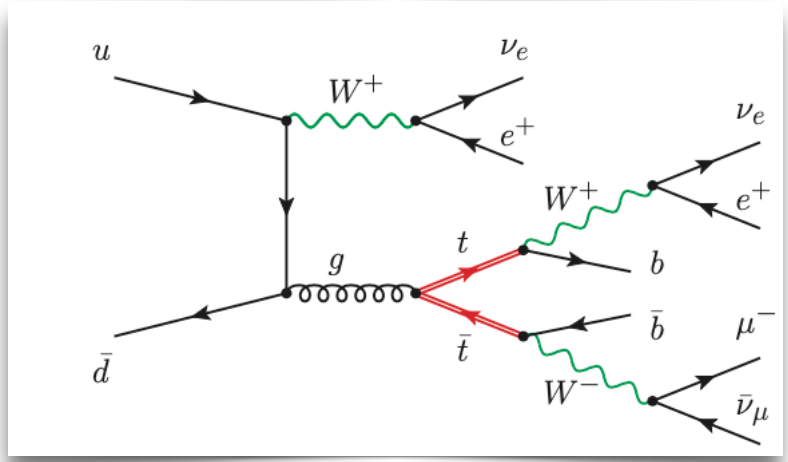
Partonic Subprocess	Number of Feynman diagrams	Number of CS Dipoles	Number of NS Subtractions
$gg \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}\,b\bar{b}\,g$	41364	90	18
$q\bar{q} \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}\,b\bar{b}\,g$	9576	50	10
$gq \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}\,b\bar{b}\,q$	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 ➪ NWA_{LODEC}
  - *Without NLO QCD corrections to top quark decays*
  - LO spin correlations

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

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

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

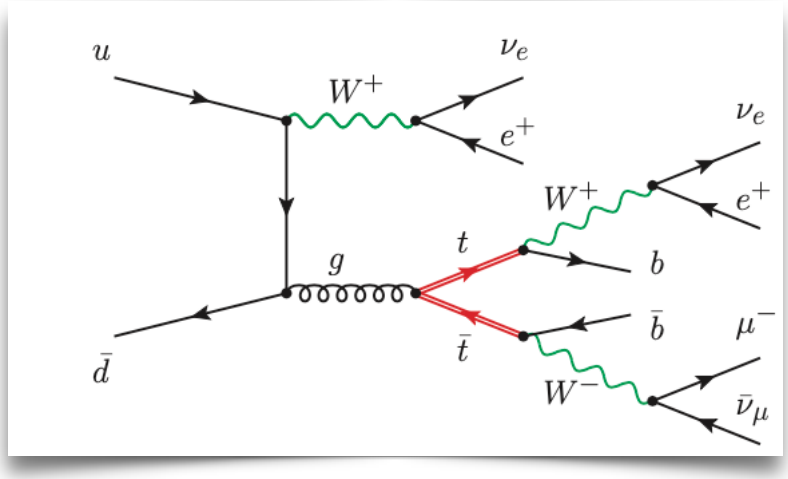
$$2.6\% > 0.8\% \gg 0.003\%.$$

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

NLO + PS

- NLO QCD corrections to stable t & $W^{\pm}$ matched to Parton Shower programs



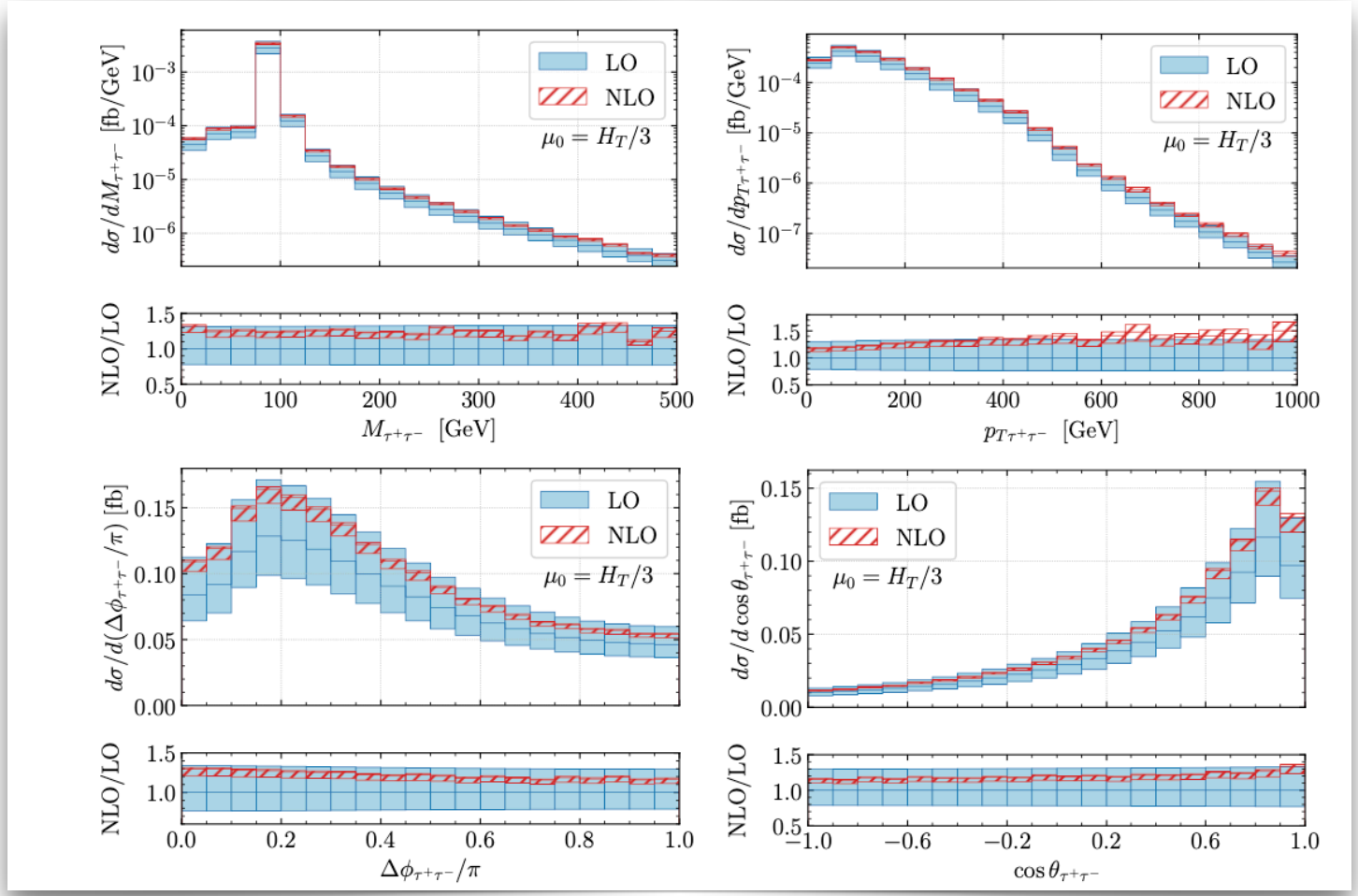
Powheg-Box MG5_aMC@NLO
Powheg-Box + LO Decays MG5_aMC@NLO + MadSpin

- Decays via parton shower ➪ Without spin correlations

- Decays using LO matrix element
  - *Double resonant contributions only*
  - *Breit-Wigner propagators for t & $W^{\pm}$ with some cut-off*
  - *LO spin correlations*
  - *Single & non-resonant contributions for t & $W^{\pm}$ are still missing as well as their interference effects*

NLO QCD Corrections

NLO *ttZ*



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

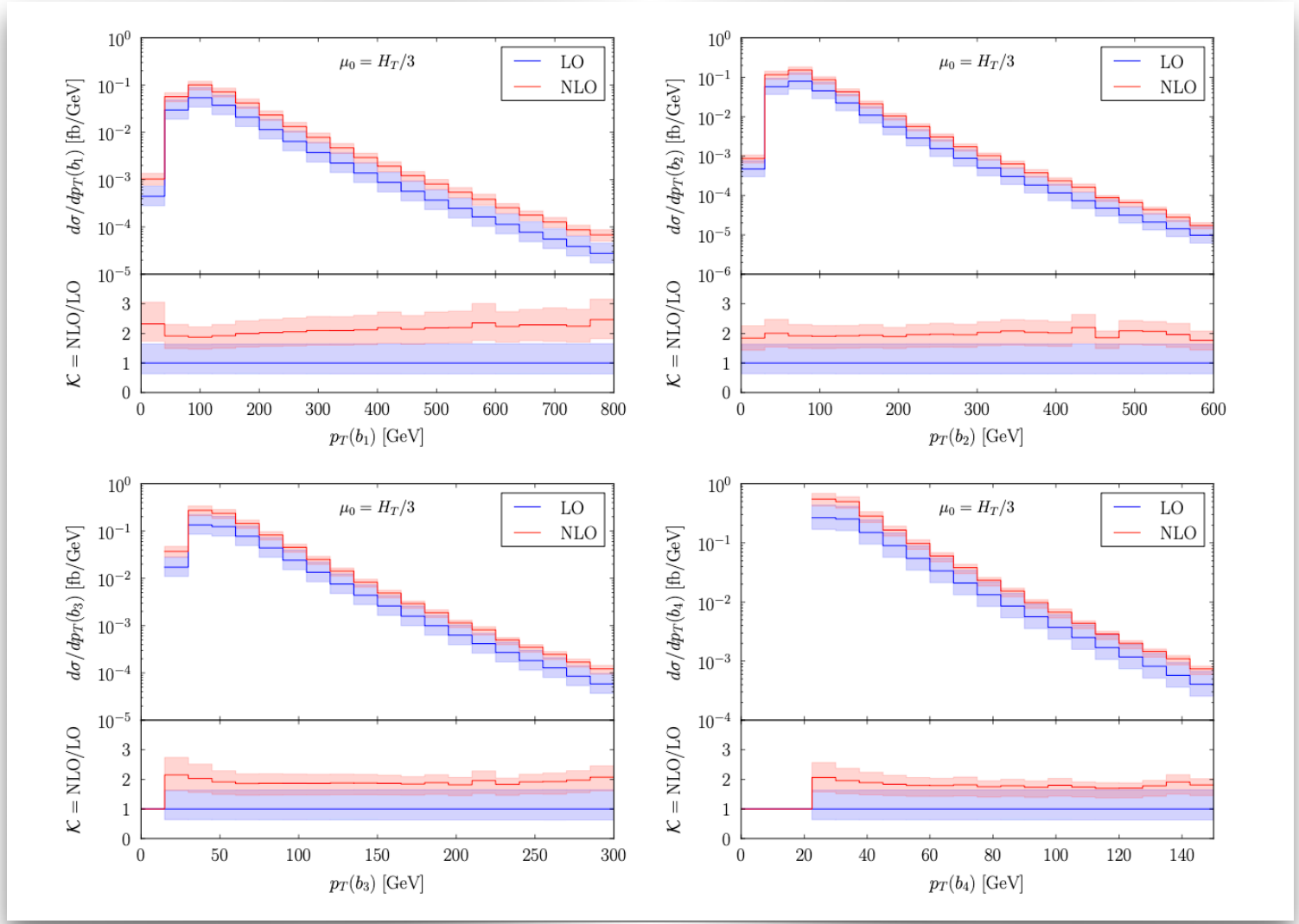
Bevilacqua, Hartanto, Kraus, Nasufi, Worek '22

- NLO QCD Corrections Mandatory
  - Affect shape of various distributions
  - Impact theoretical uncertainties
  - NLO QCD corrections ➪ *10% – 50%*
  - Scale dependence reduced
    - *30%* @ LO
    - *10%* @ NLO
    - *For dynamical scale setting*

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

NLO QCD Corrections

NLO *ttbb*



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

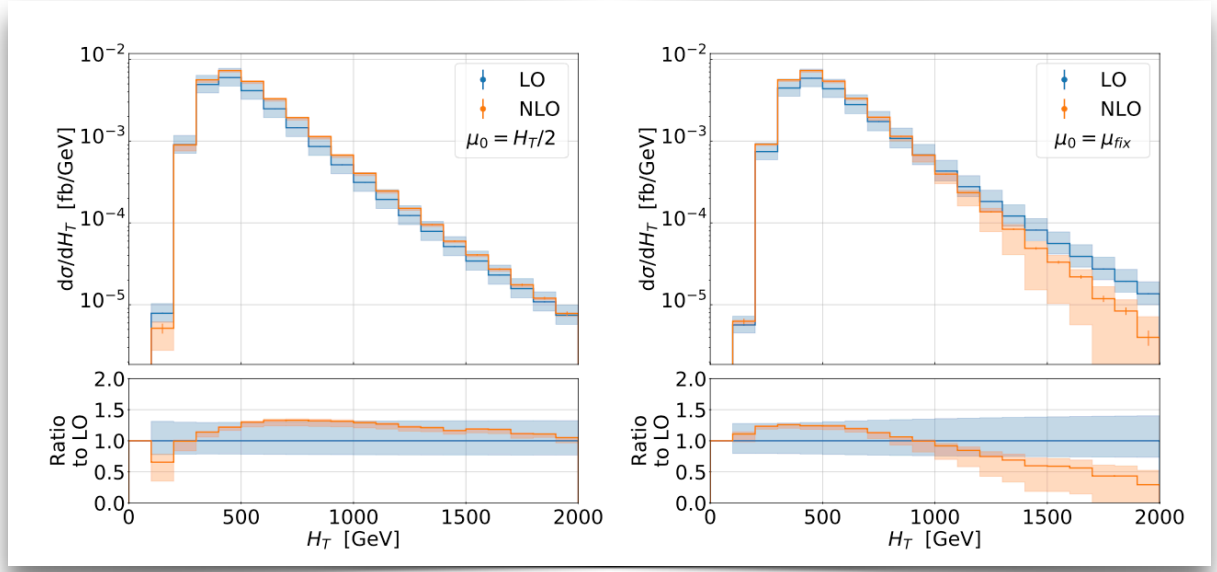
- Integrated fiducial cross sections plagued by large NLO QCD effects
- Large NLO QCD corrections also @ differential level
- NLO QCD corrections ➪ *70% - 135%*
- Uncertainties ➪ *10% - 25%*

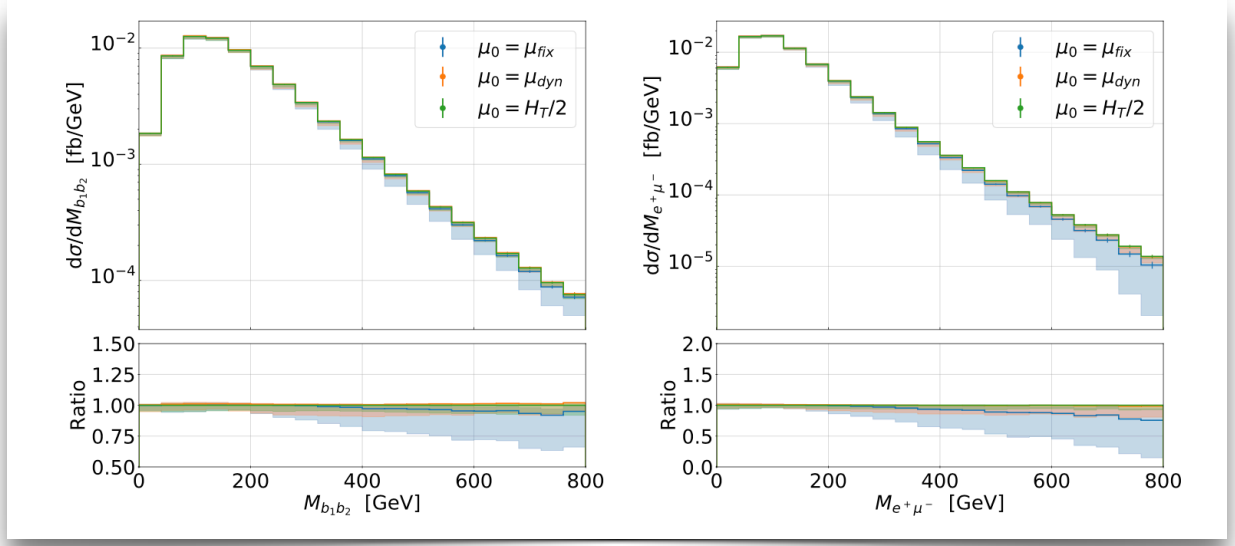
Bevilacqua, Bi, Hartanto, Kraus, Lupattelli, Worek '21

NLO QCD Corrections & Scale Setting

NLO *ttH*

Stremmer, Worek '22





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

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

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

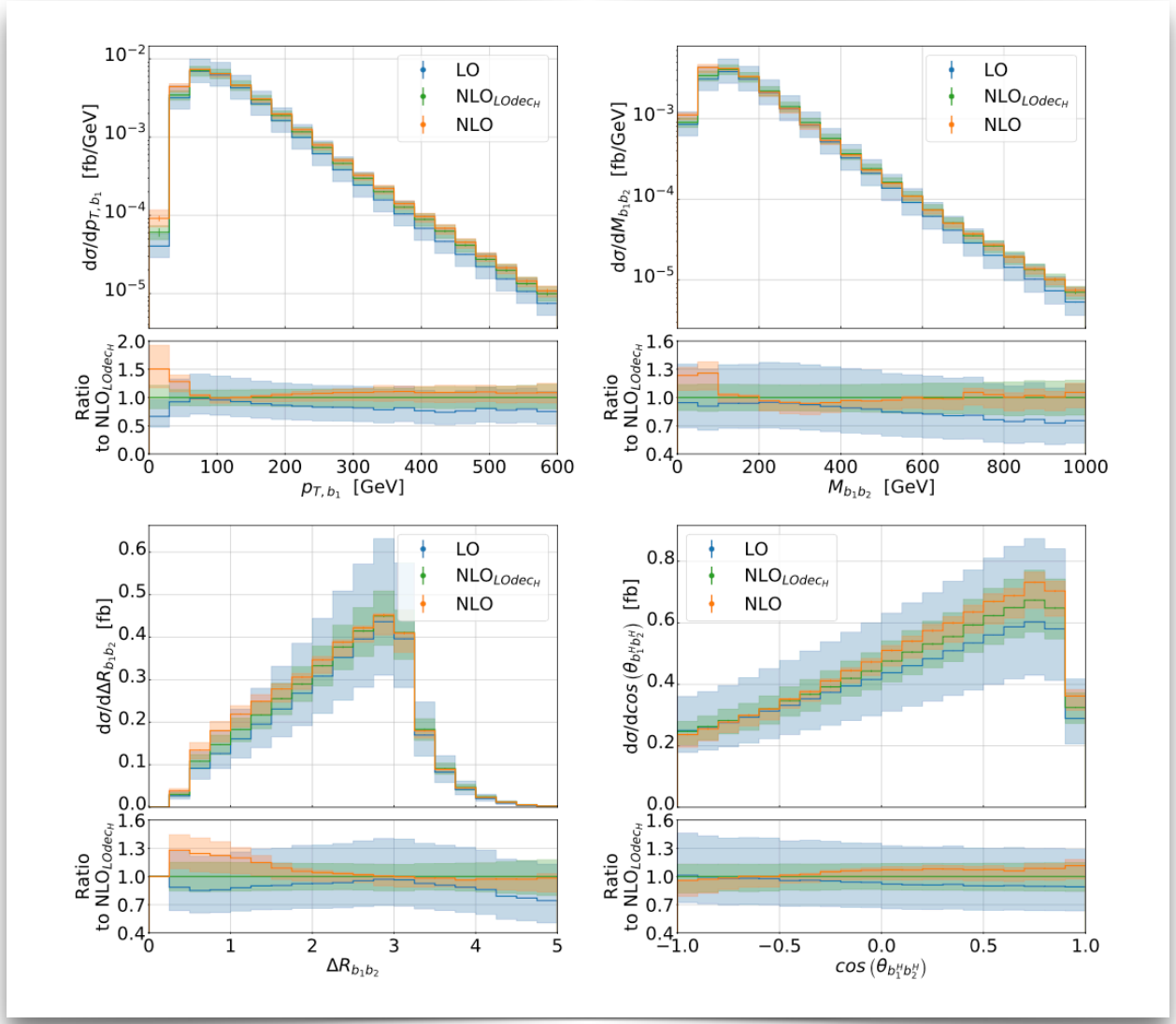
$$\mu_{dyn} = \left(m_{T,t}\, m_{T,\bar{t}}\, m_{T,H}\right)^{\frac{1}{3}} \qquad m_T = \sqrt{m^2 + p_T^2}.$$

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

NLO QCD Corrections & Higgs decays

NLO *ttH*

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



Stremmer, Worek '22

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

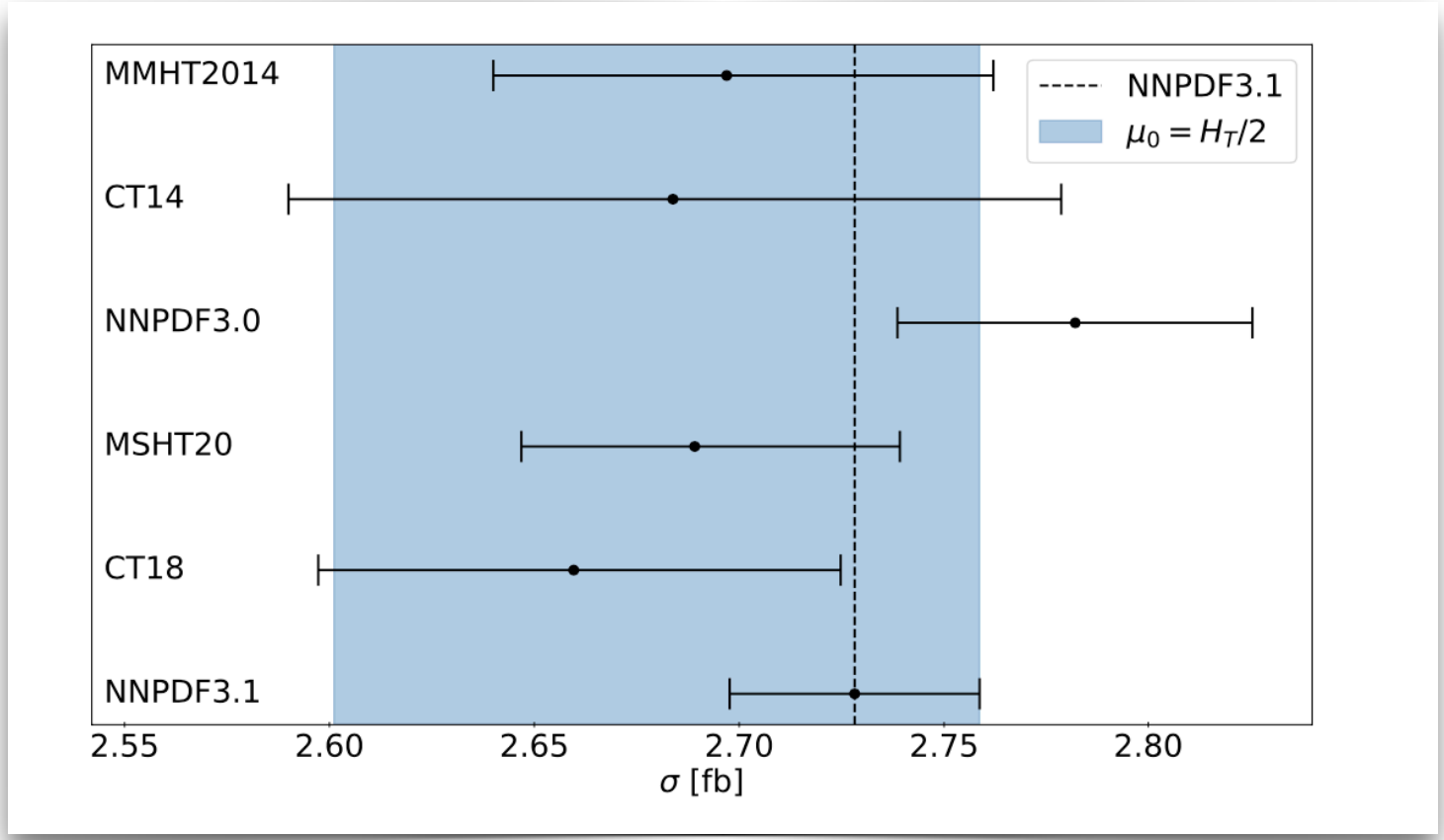
- Full off-shell effects for t & $W^\pm$
- Higgs boson decays in NWA

	$\sigma_{\rm LO}$ [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. ⇨ 6%
- 4 b-jets ⇨ $\mathcal{Q}_{ij} = |M_{b_ib_j} - m_H|$

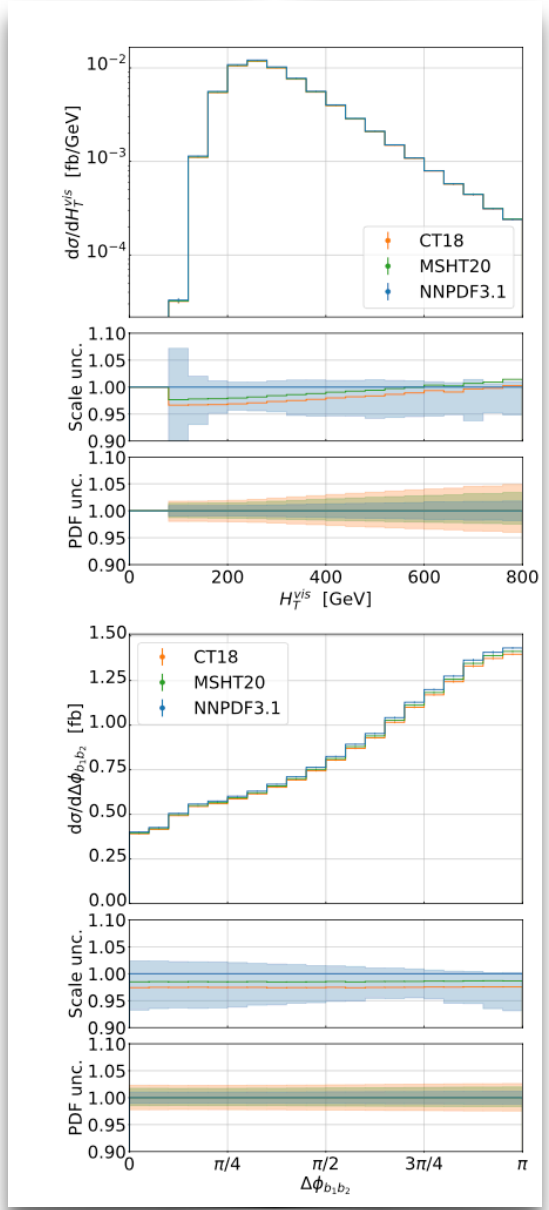
PDF Uncertainties

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



Integrated level

Stremmer, Worek '22



NLO *ttH*

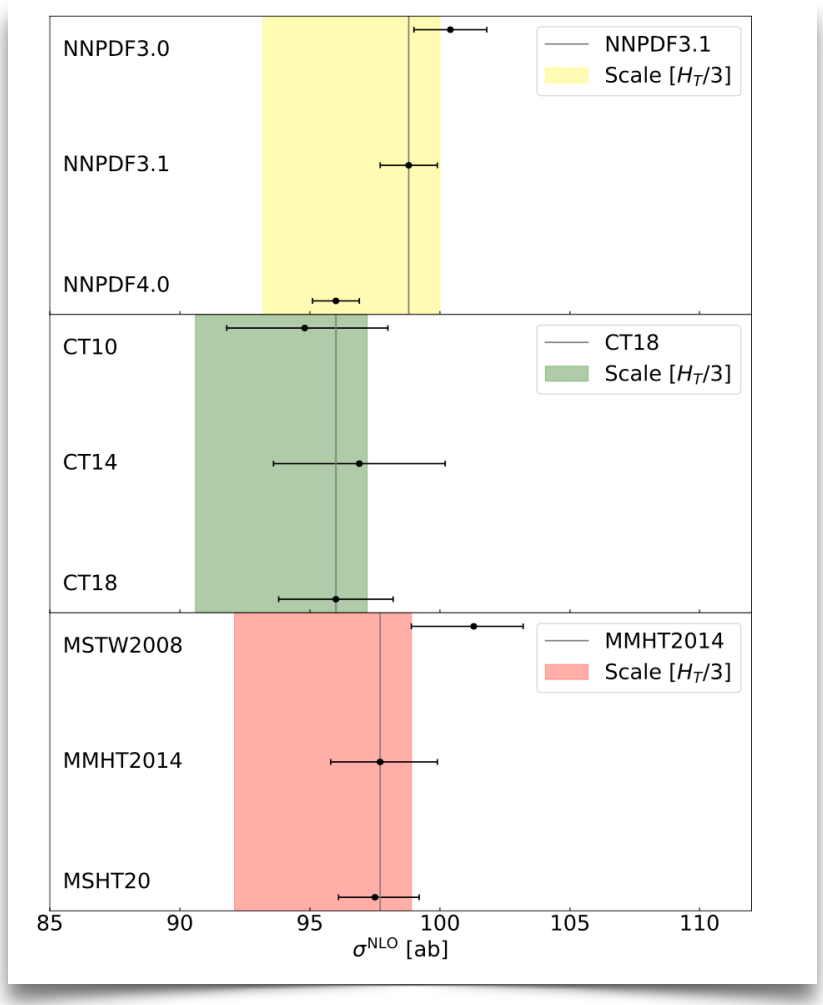
Differential level

PDF Uncertainties

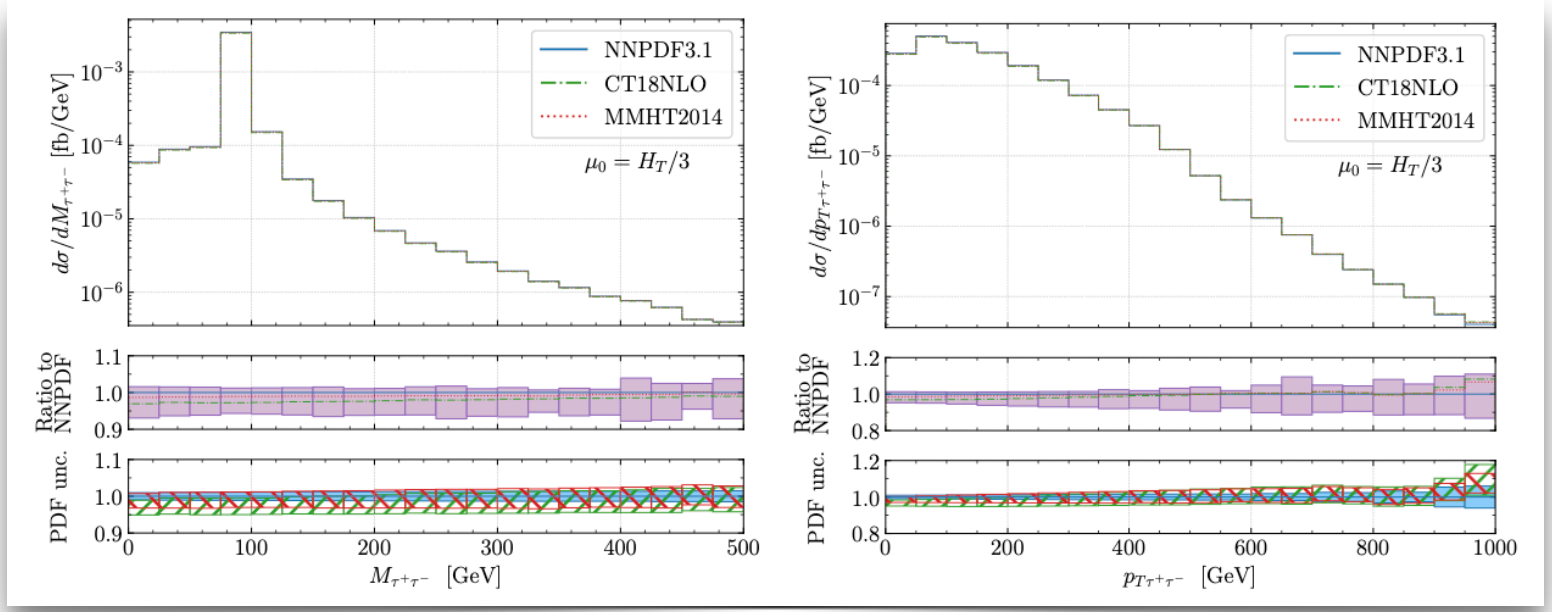
NLO *ttZ*

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

Bevilacqua, Hartanto, Kraus, Nasufi, Worek '22



Integrated level



Differential level

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

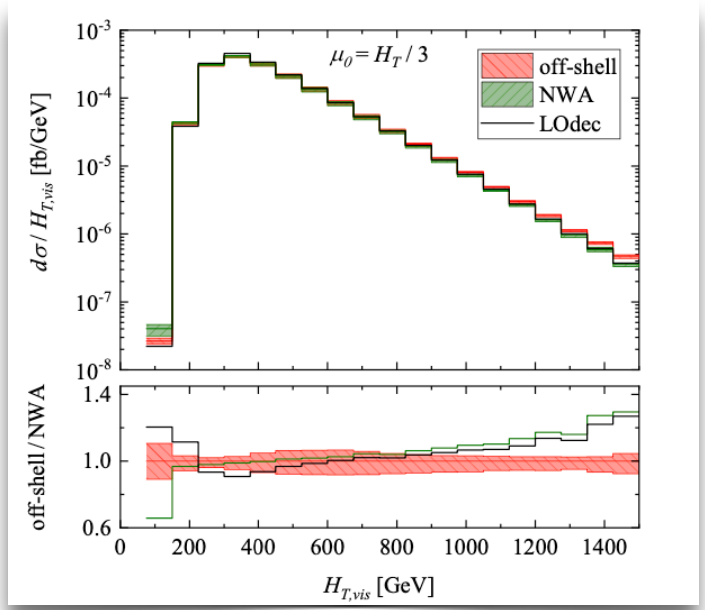
How Good is NWA

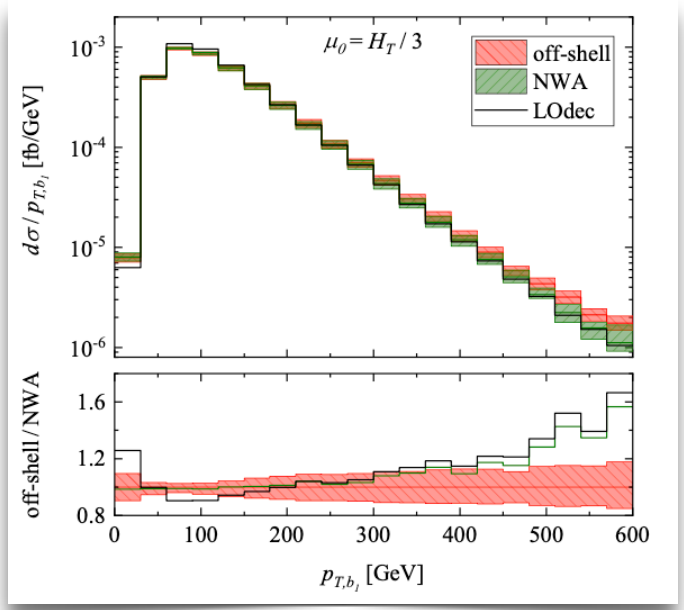
NLO *ttW*

Bevilacqua, Bi, Hartanto, Kraus, Worek '20

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

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 ($\mu_0 = H_T/3$)	$115.1^{+30.4\,(26\%)}_{-22.4\,(19\%)}$	$124.2^{+4.1\,(3\%)}_{-7.7\,(6\%)}$
$\text{NWA}_{\text{LOdecay}}$ ($\mu_0 = m_t + m_W/2$)		$127.0^{+14.2\,(11\%)}_{-13.3\,(10\%)}$
$\text{NWA}_{\text{LOdecay}}$ ($\mu_0 = H_T/3$)		$130.7^{+13.6\,(10\%)}_{-13.2\,(10\%)}$





Integrated level

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

Differential level

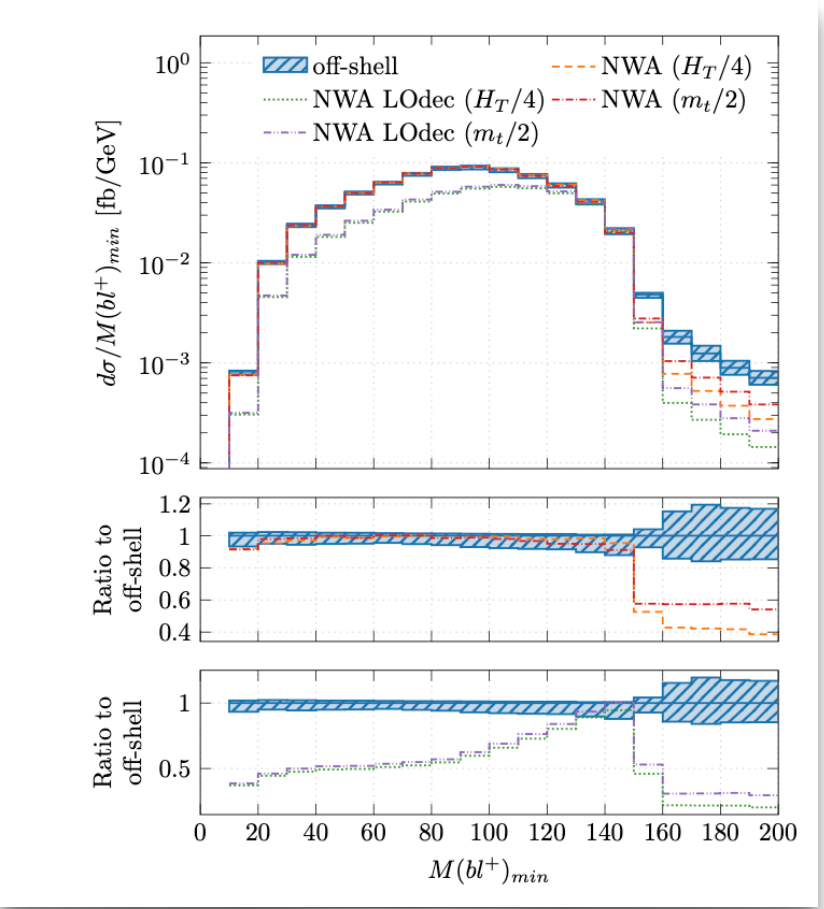
- Off-shell effects up to *60% - 70%*
- Substantial differences between NWA & $\text{NWA}_{\text{LODECAY}}$

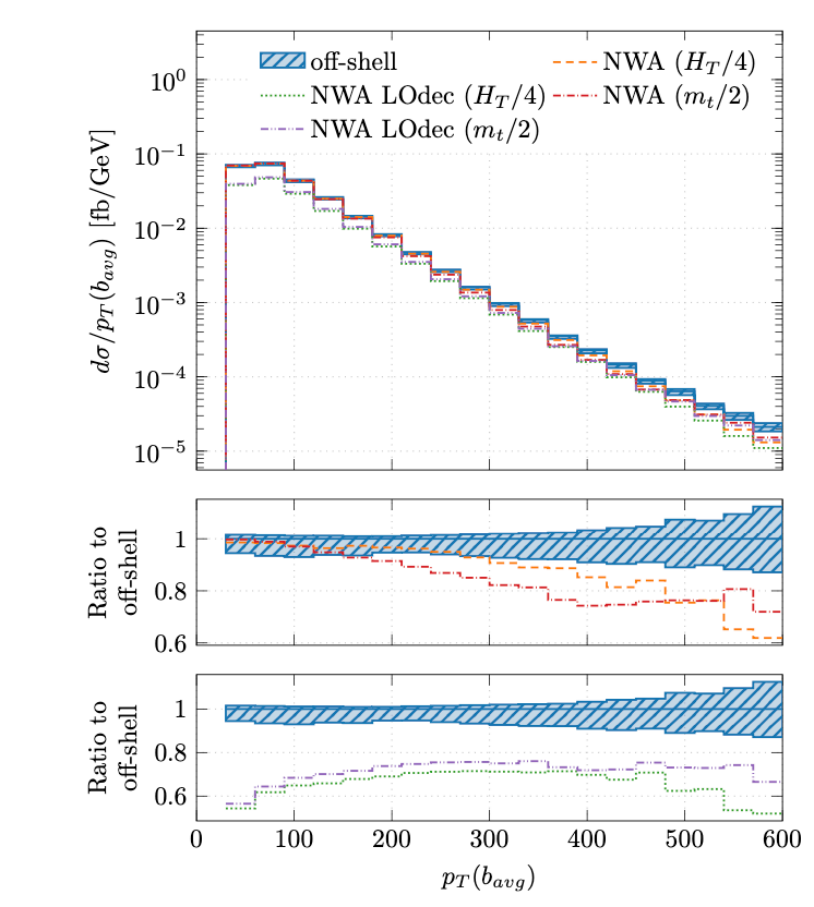
How Good is NWA

NLO $tt\gamma$

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

Bevilacqua, Hartanto, Kraus, Weber, Worek '20





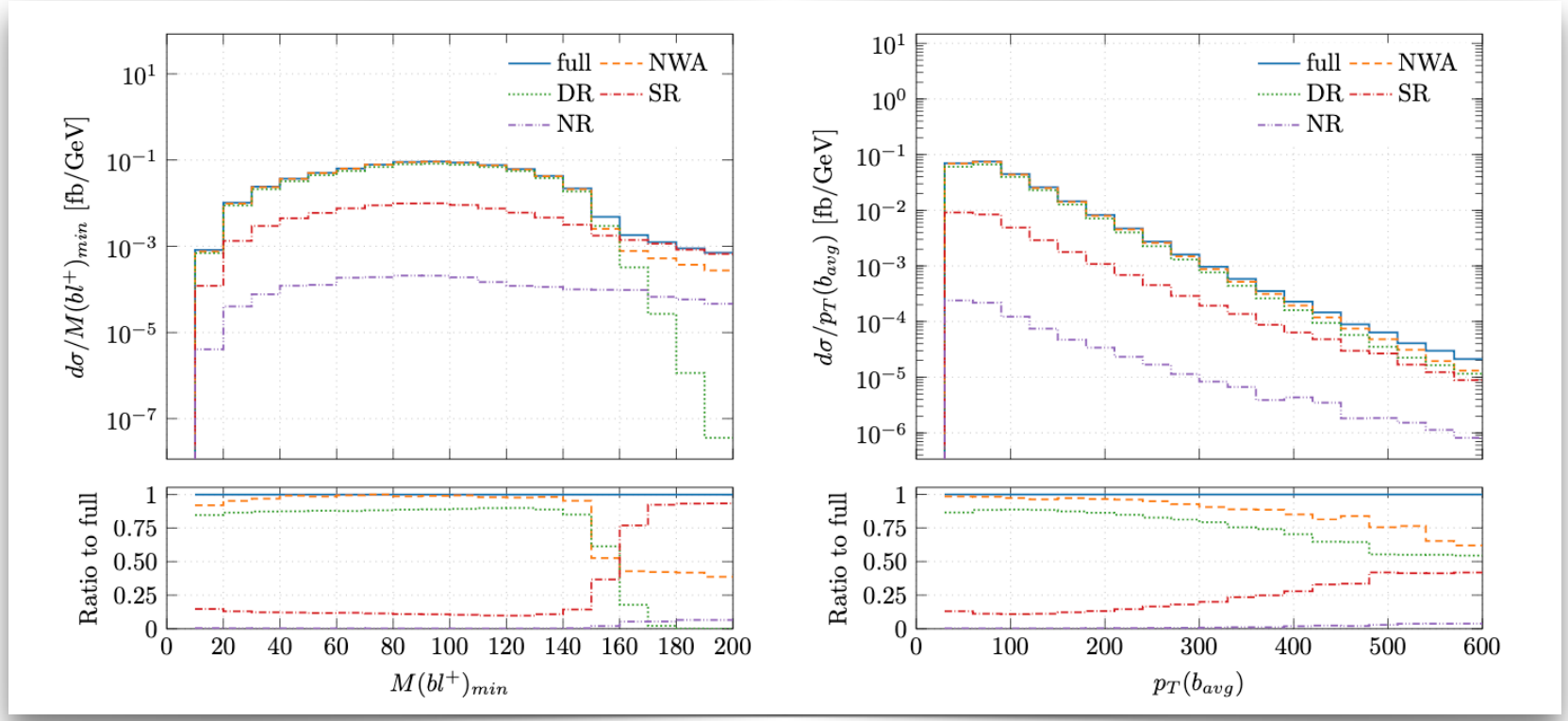
Dimensionful observables

- 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



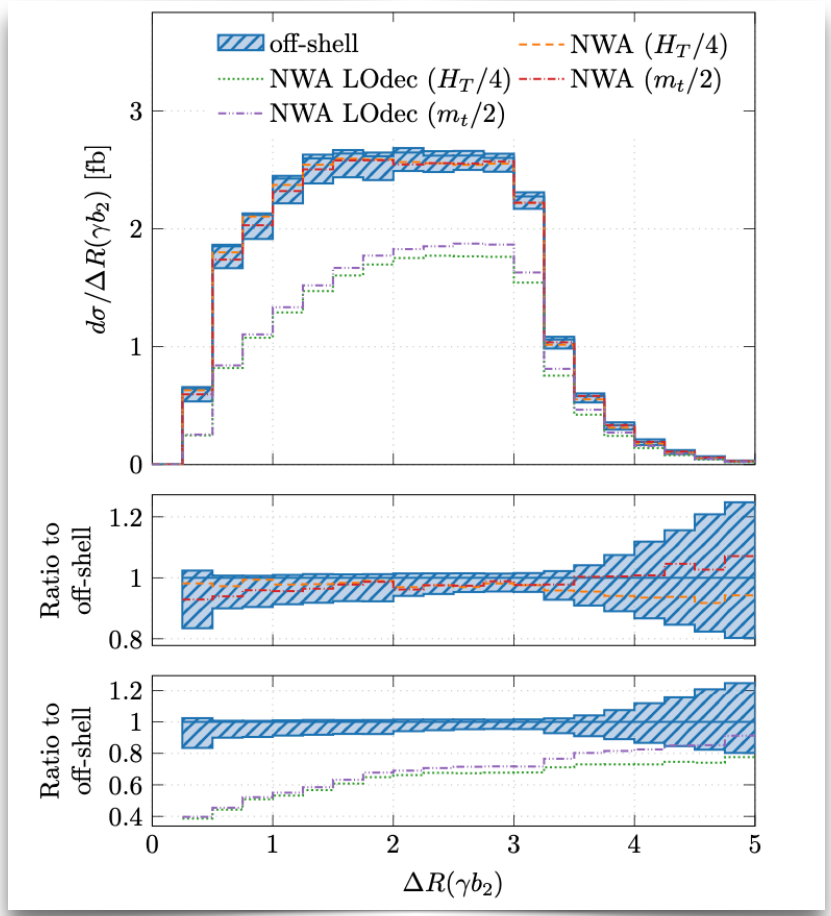
$$pp \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}\,\gamma$$

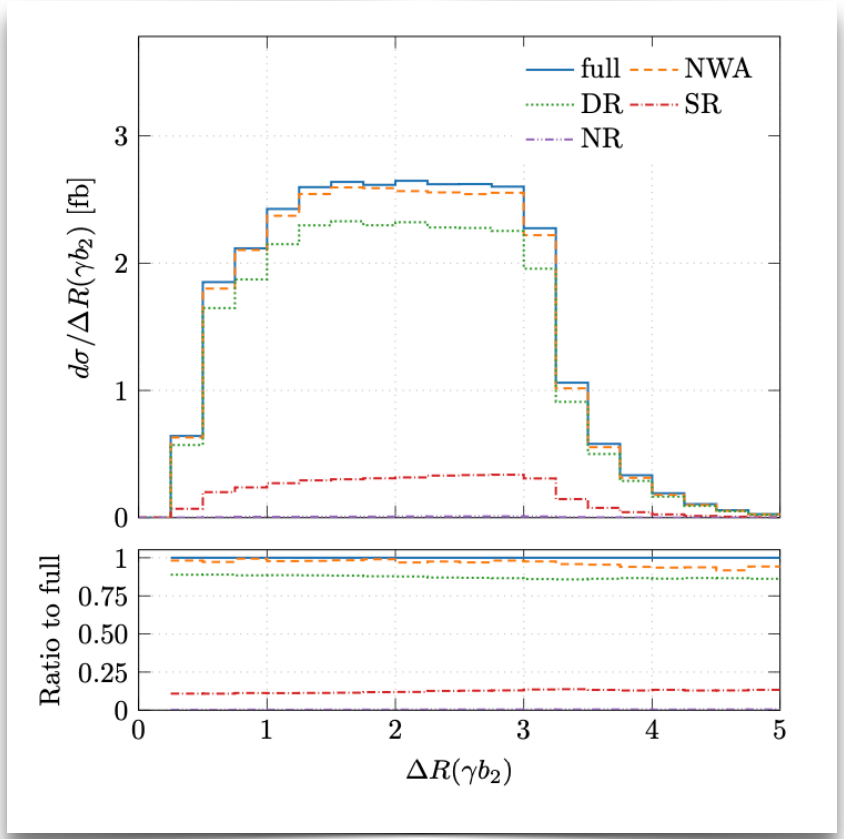
Dimensionful observables

- 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 $tt\gamma$





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

- Observables sensitive to off-shell effects ➪ Substantial contributions from single top quark process
- *Dimensionless observables rather insensitive to top quark off-shell effects*

Bevilacqua, Hartanto, Kraus, Weber, Worek '20

Photon in Top-Quark Decays

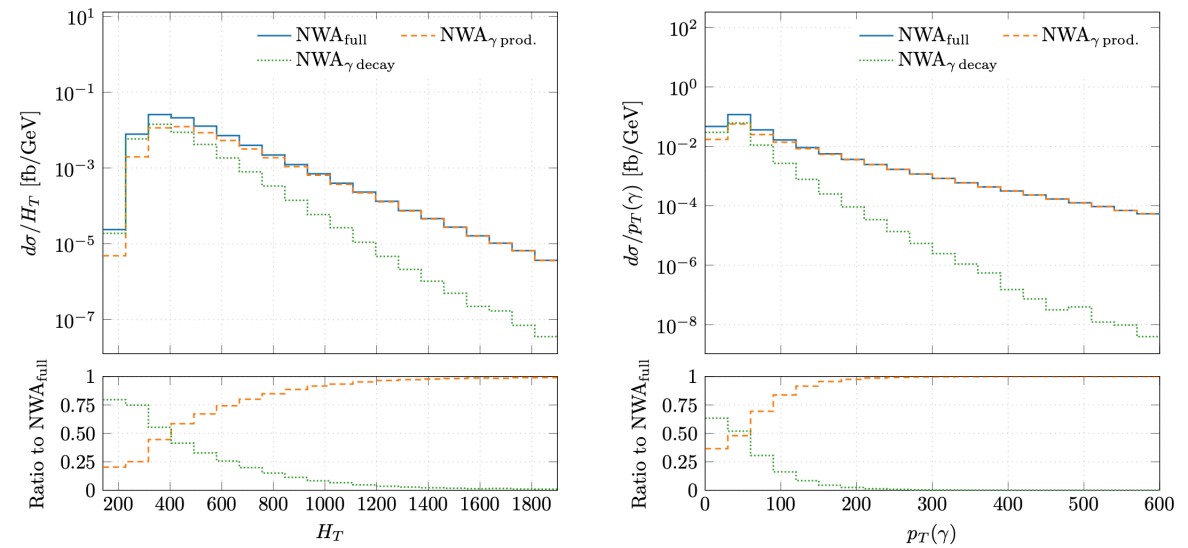
NLO $tt\gamma$

Bevilacqua, Hartanto, Kraus, Weber, Worek '20

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

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

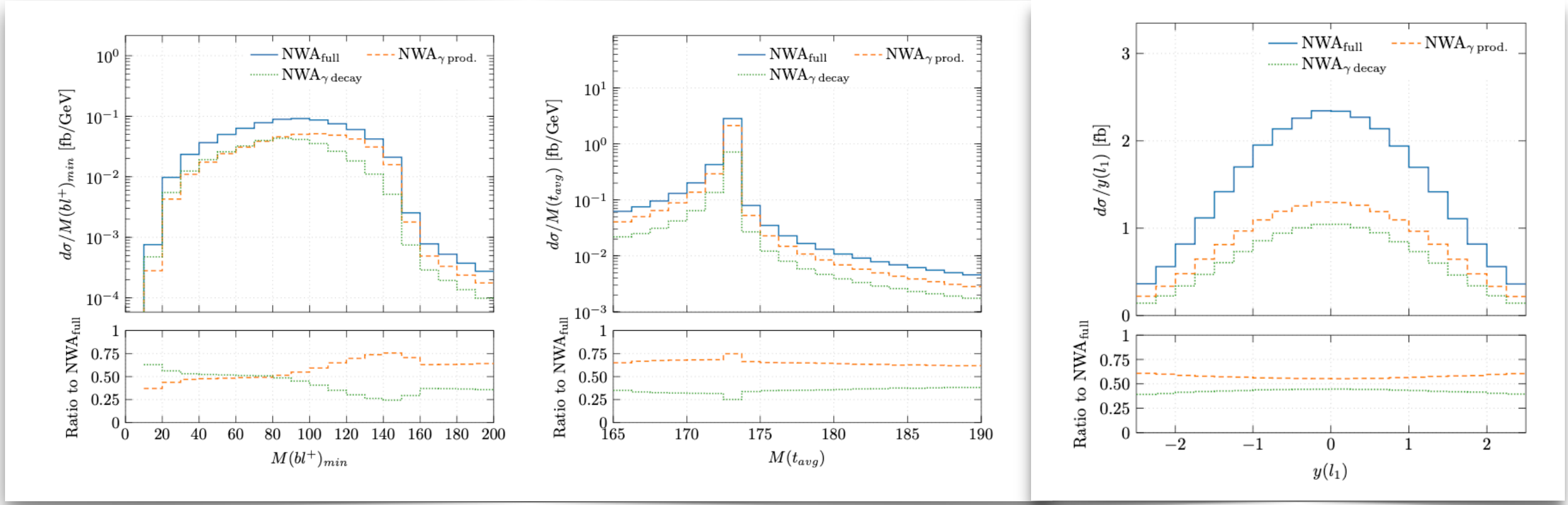
- For $p_{T,b} > 40$ GeV
  - *57%* ➪ γ emitted in production
  - *43%* ➪ γ emitted in decay stage
- NLO QCD corrections to top quark decays
  - *12% - 17%*



Photon in Top-Quark Decays

NLO $tt\gamma$

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



Bevilacqua, Hartanto, Kraus, Weber, Worek '20

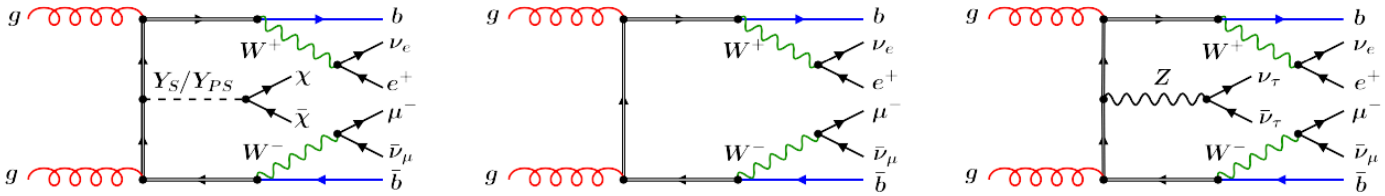
Diverse picture

Application: BSM Exclusion Limits

NLO ttZ

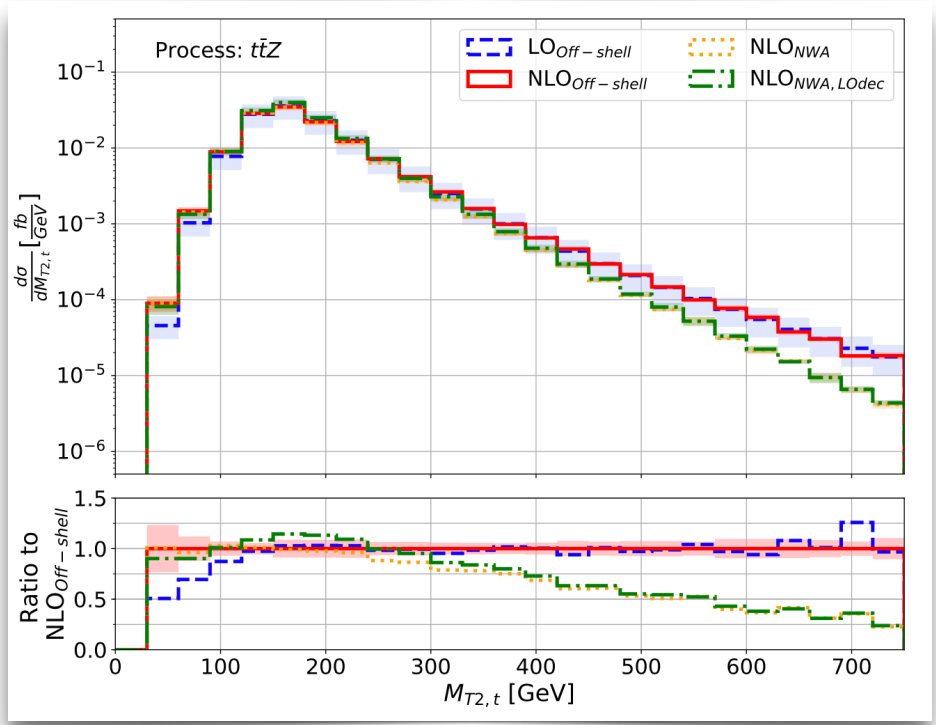
- BSM ➪ Kinematical edges & high p_T regions
- $t\bar{t} + DM$ ➪ Top quark backgrounds: $t\bar{t}$ & $t\bar{t}Z$
- Observable ➪ $M_{T2,W}$ & $M_{T2,t}$ & p_T^{miss}

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



Before & after applying additional cuts

Process	Order	Scale	$\sigma_{\rm uncut}$ [fb]	$\sigma_{\rm cut}$ [fb]	$\sigma_{\rm cut}/\sigma_{\rm uncut}$	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 $t\bar{t}$
- NLO smaller uncertainties w.r.t LO, NLO + LO decays

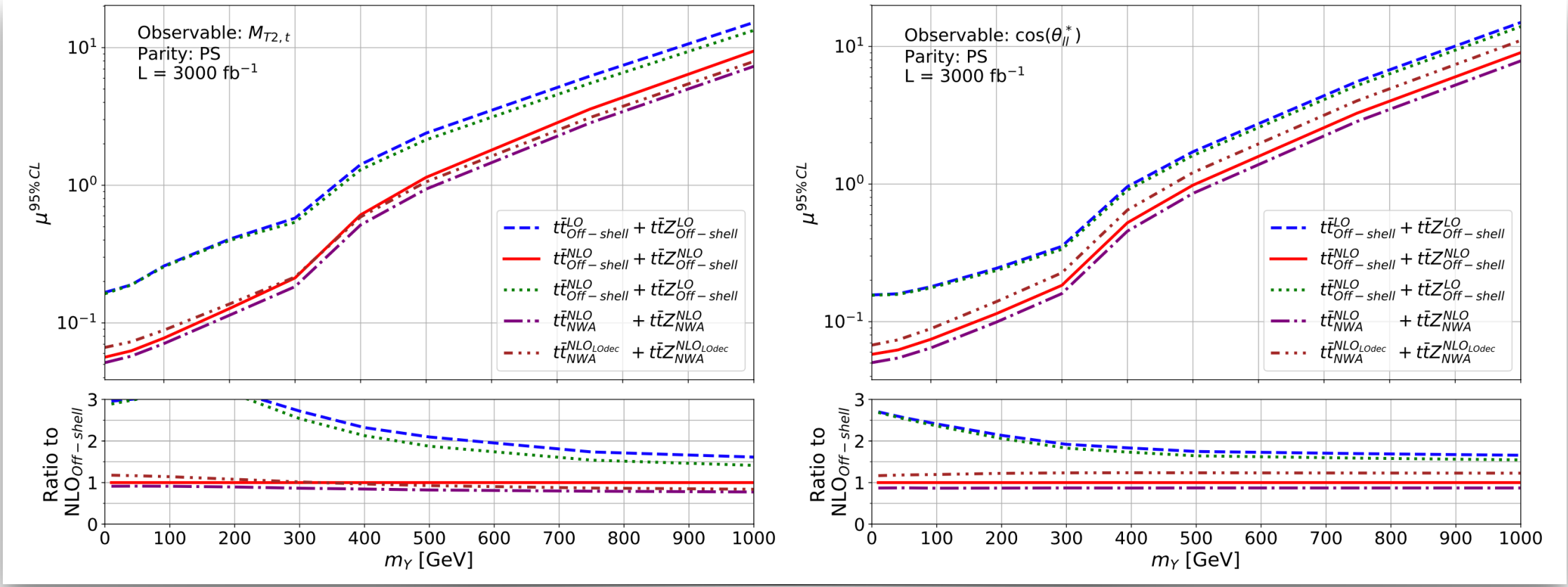
Hermann, Worek '21

Application: BSM Exclusion Limits

NLO *ttZ*

Comparison of signal strength exclusion limits

Hermann, Worek '21



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

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

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

Summary

- Proper Modelling of Top-Quark production & decay essential
  - Already now in presence of inclusive cuts:

- NNLO QCD for $t\bar{t}$ in di-lepton channel

- NLO QCD corrections to $pp \to t\bar{t}$ & $t\bar{t} + X$
  - $X = H, \gamma, W^{\pm}, Z, j, b\bar{b}$

- Important
  - Corrections to production & decays important ➪ NNLO & NLO $t\bar{t}$ spin correlations
  - Possibility of using kinematic dependent μ_R & μ_F scales important
  - 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

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 $pp \to t\bar{t}W^{\pm}$ & $pp \to t\bar{t}j$

- 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

Backup Slides

Various Phase – Space Regions

NLO $tt\gamma$

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

(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	$\bar{t} = W^-(\to \mu^-\bar{\nu}_\mu)\, \bar{b}\gamma$

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

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)

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

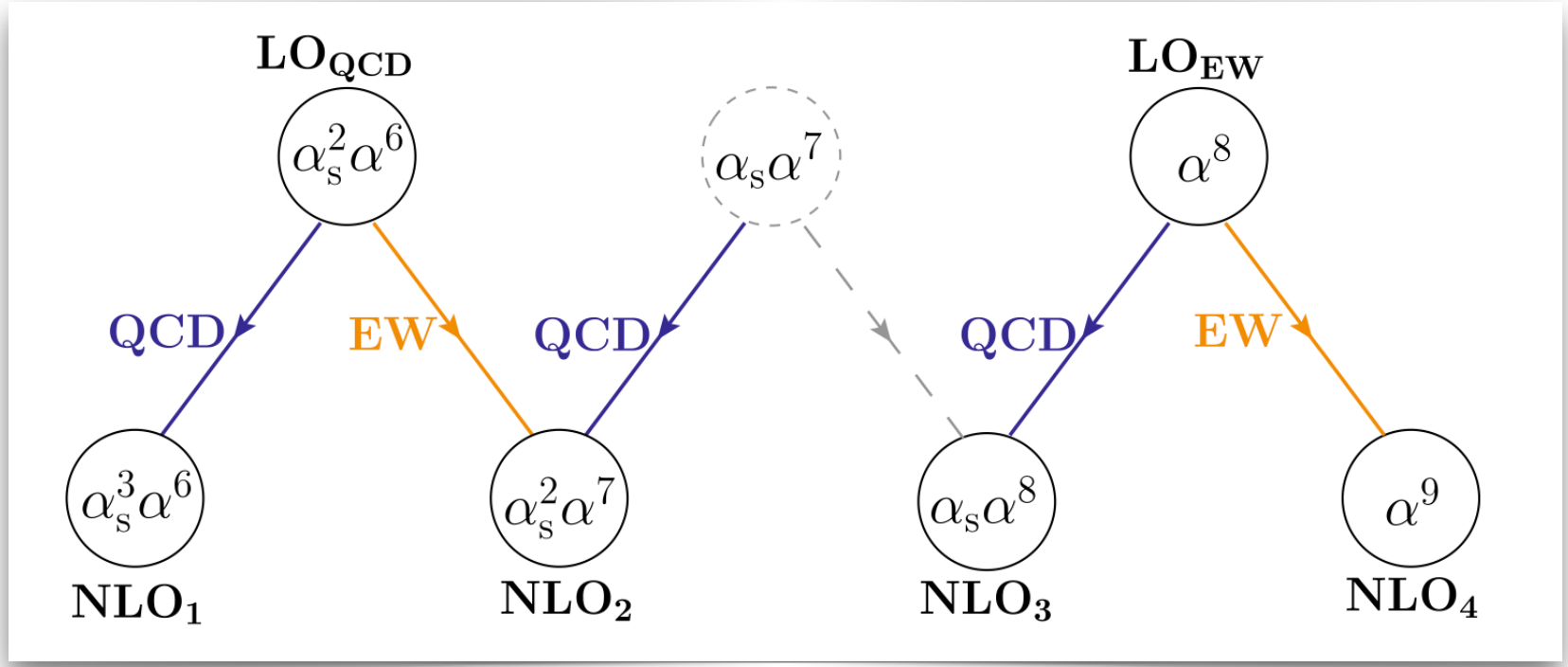
- Boundary parameter
  - Determines size of resonant region for each reconstructed top quark
  - *n = 5, 10, 15*
  - For n = 15

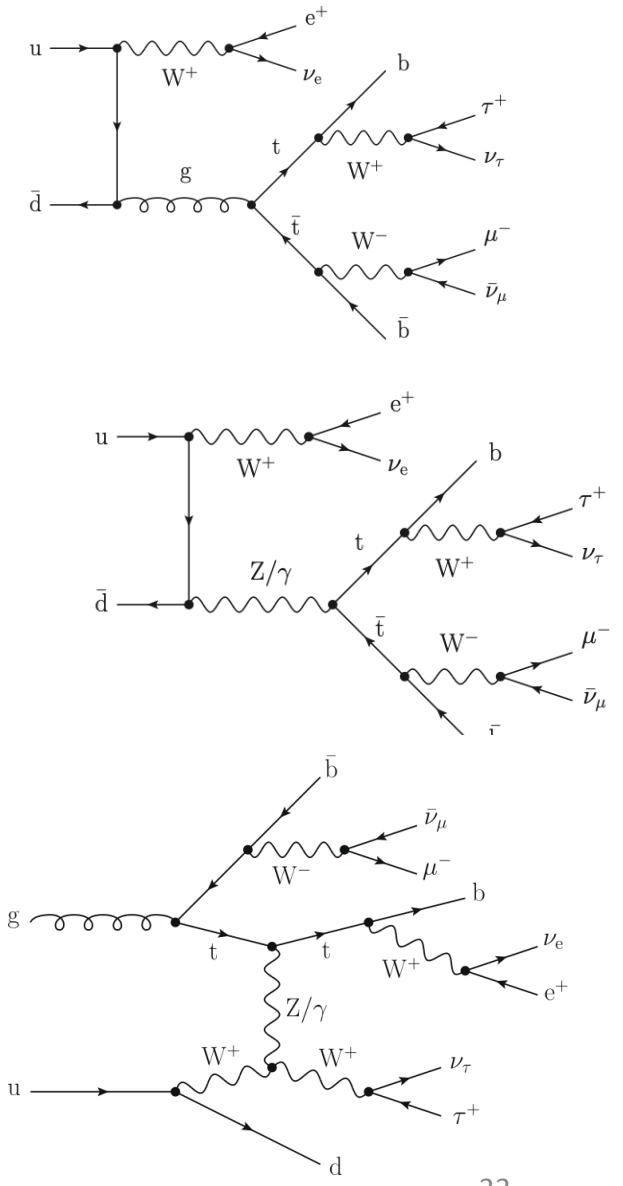
$$M(t) \in (152.9, 193.5)\ \text{GeV}$$

Application II: 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

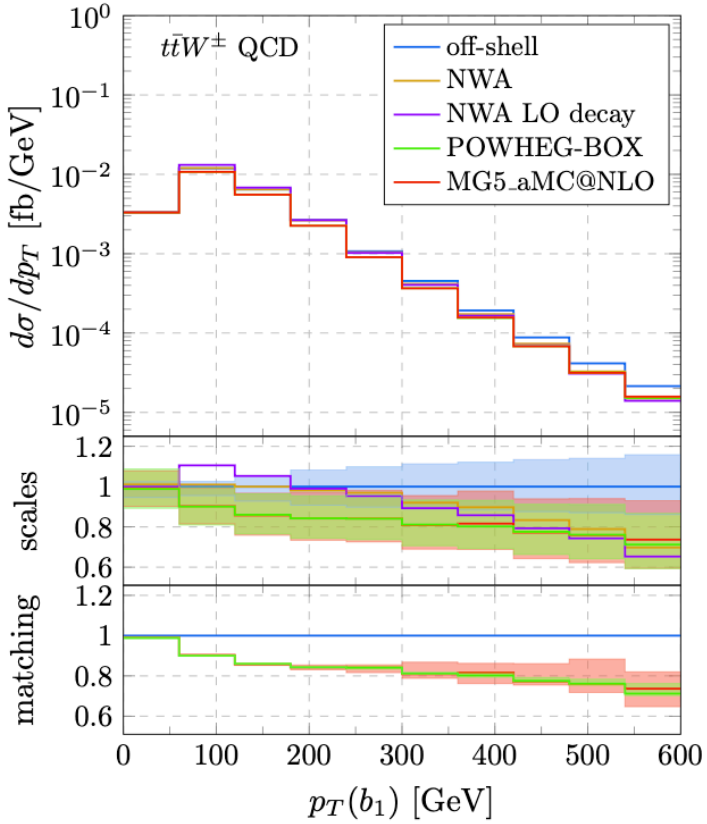
Frederix, Pagani, Zaro '18, Frederix, Tsinikos '20, Denner, Pelliccioli '21

Application II: Parton Shower

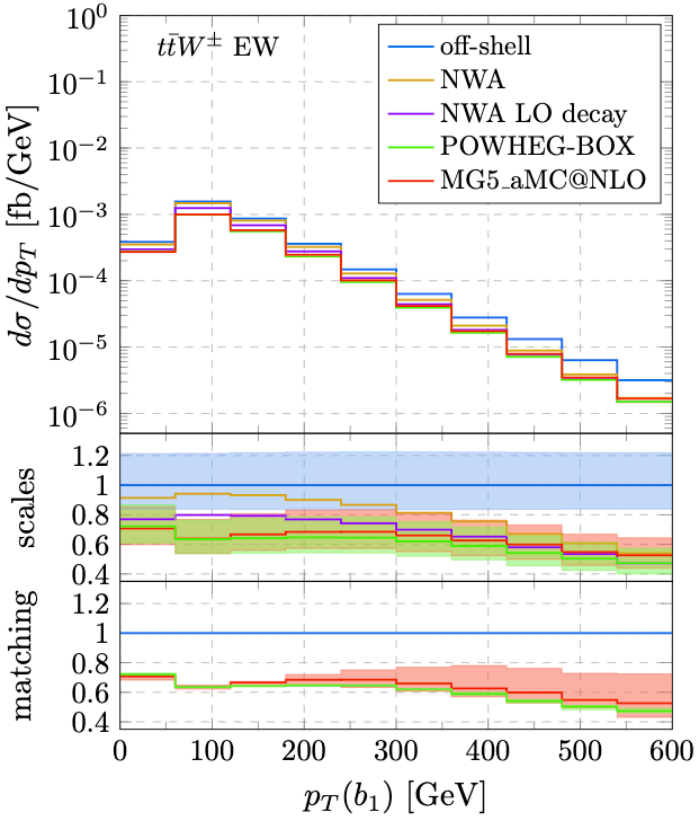
NLO *ttW*

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

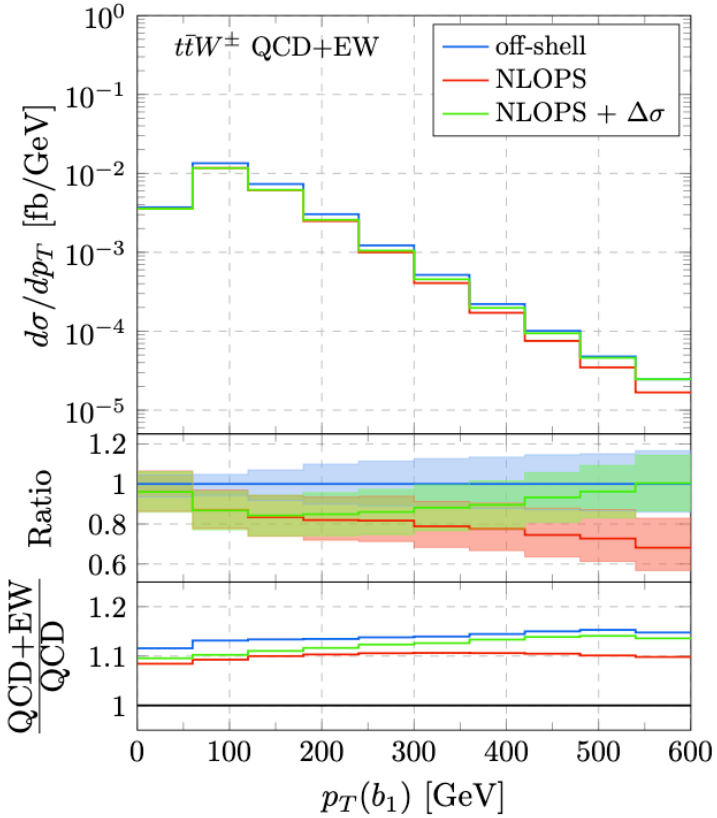
QCD



EW



Combined



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

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

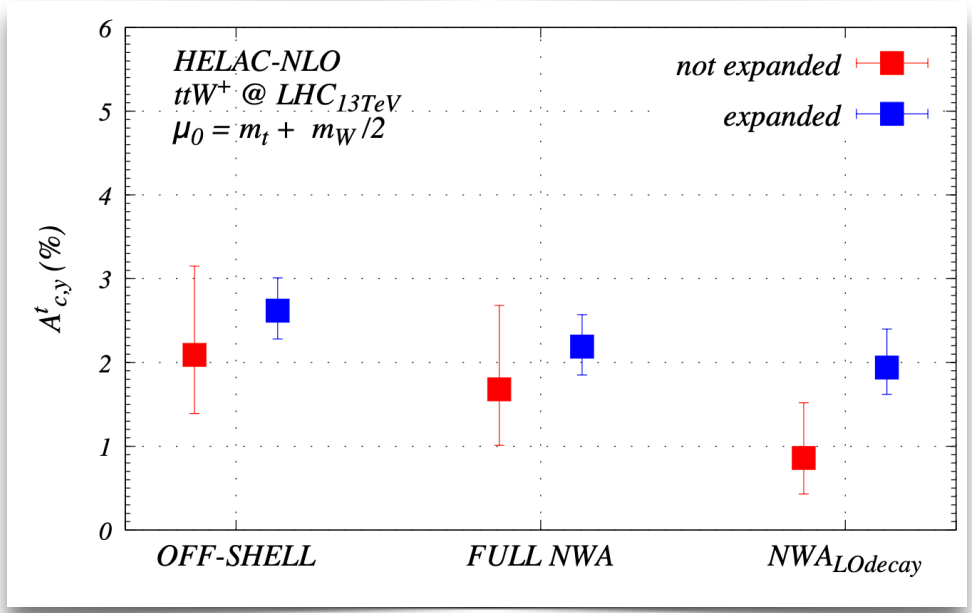
Application III: Top Charge Asymmetry

NLO ttW

Searching for more precise observables

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

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



- A_c^t charge asymmetry @ NLO for $pp \to t\bar{t}W^+$

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

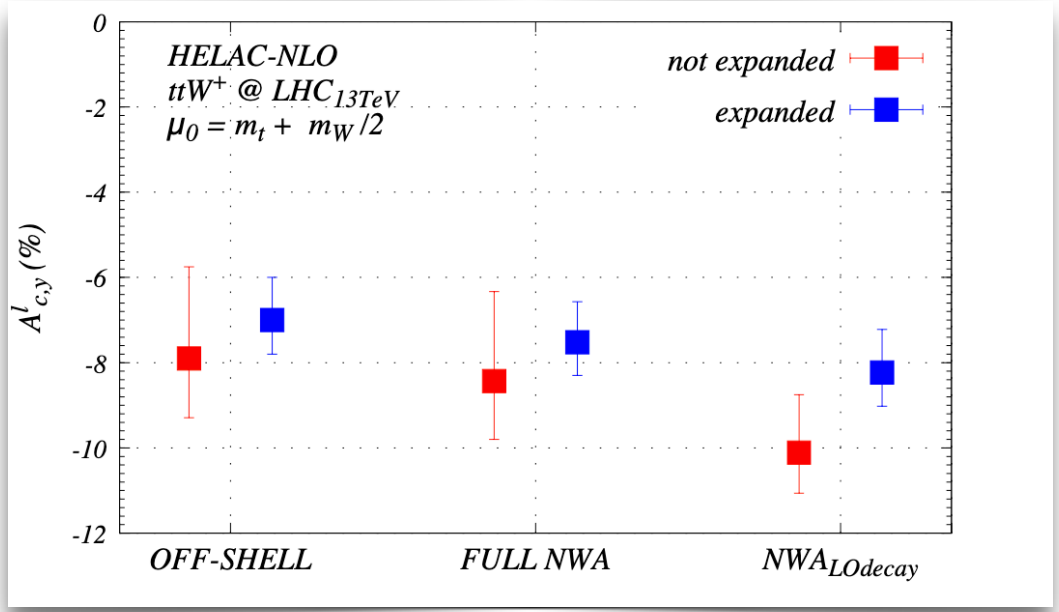
- Asymmetry larger than for $pp \to t\bar{t}$
- Top quark momenta must be reconstructed
- Scale setting not important ➪ Fixed & dynamical scale choice gives similar results
- Top-quark modelling important

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

Application III: Top Charge Asymmetry

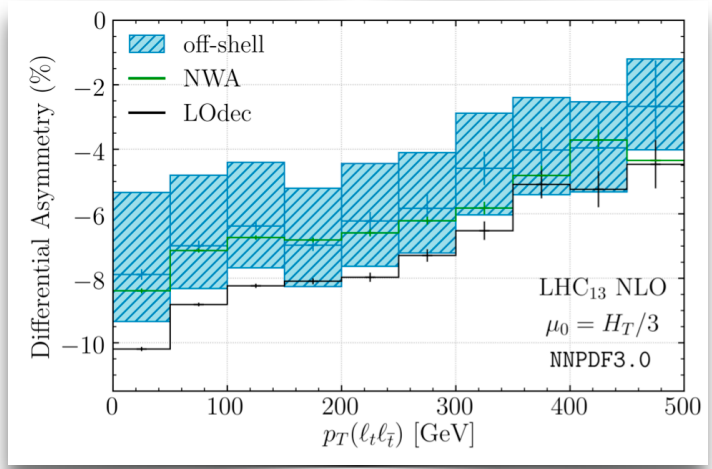
NLO *ttW*

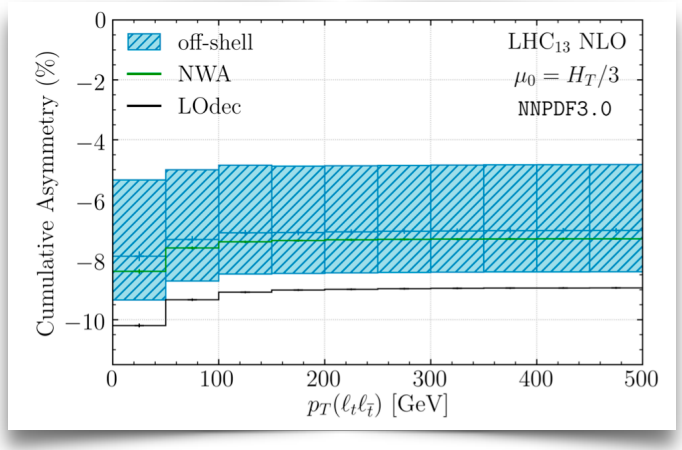
Bevilacqua, Bi, Hartanto, Kraus, Nasufi, Worek '21



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

Differential & Cumulative A^ℓ_c



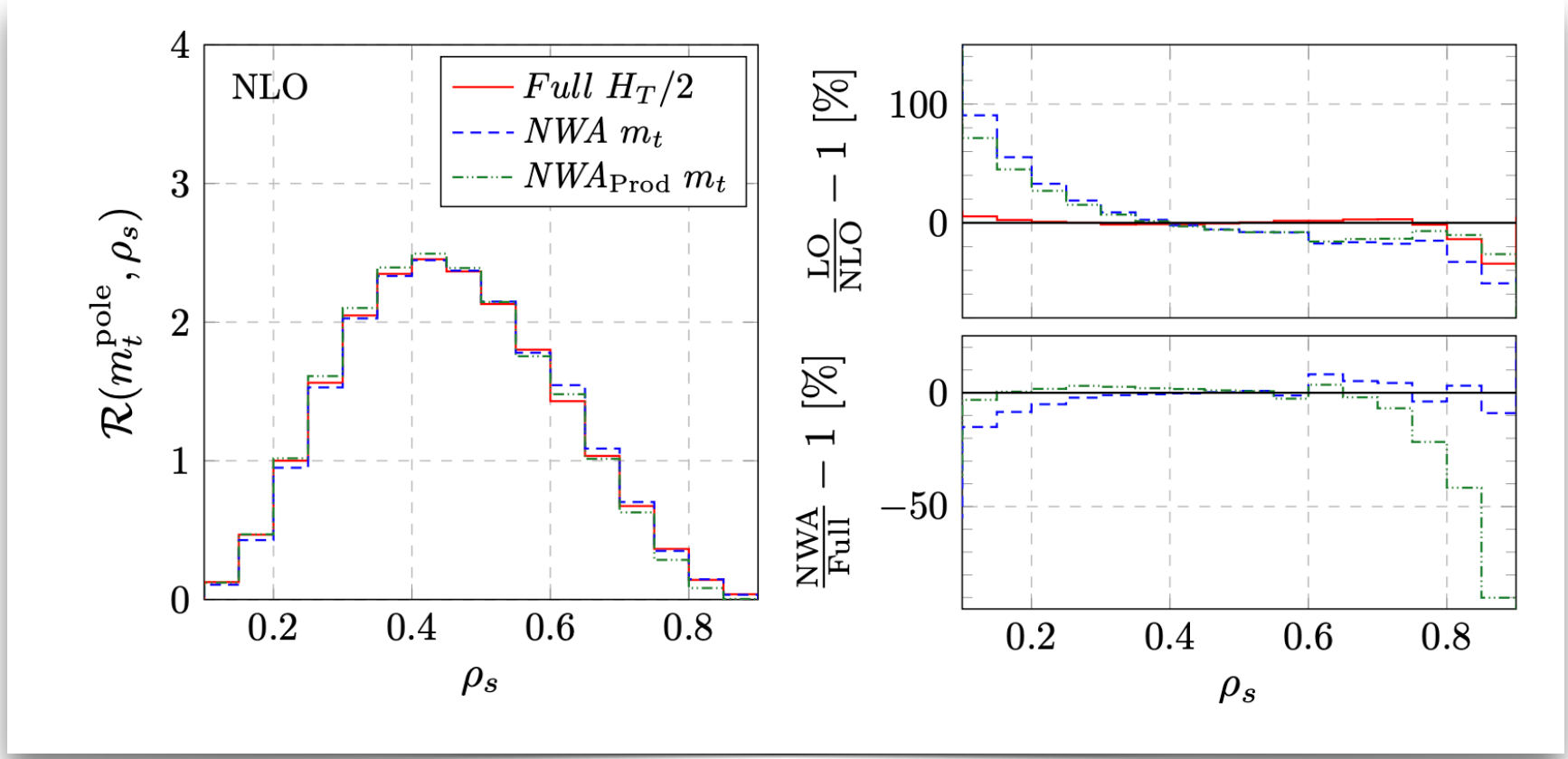


- A^ℓ_c charge asymmetry @ NLO for $pp \to t\bar{t}W^+$
- Directly measurable ➪ No need for top quark reconstruction

Application IV: Top-Quark Mass

NLO *ttj*

$$\mathcal{R}(m_t^{pole}, \rho_s) = \frac{1}{\sigma_{t\bar{t}j}} \frac{d\sigma_{t\bar{t}j}}{d\rho_s}(m_t^{pole}, \rho_s)\,, \qquad \text{with} \qquad \rho_s = \frac{2m_0}{M_{t\bar{t}j}}$$



- Introduced in 2013

Alioli, Fernandez, Fuster, Irles, Moch, Uwer, Vos '13

- Used by ATLAS & CMS
  - ATLAS @ 8 TeV

    $m_t = 171.1^{+1.2}_{-1.0}$ GeV

    ATLAS collaboration '19

  - CMS @ 13 TeV

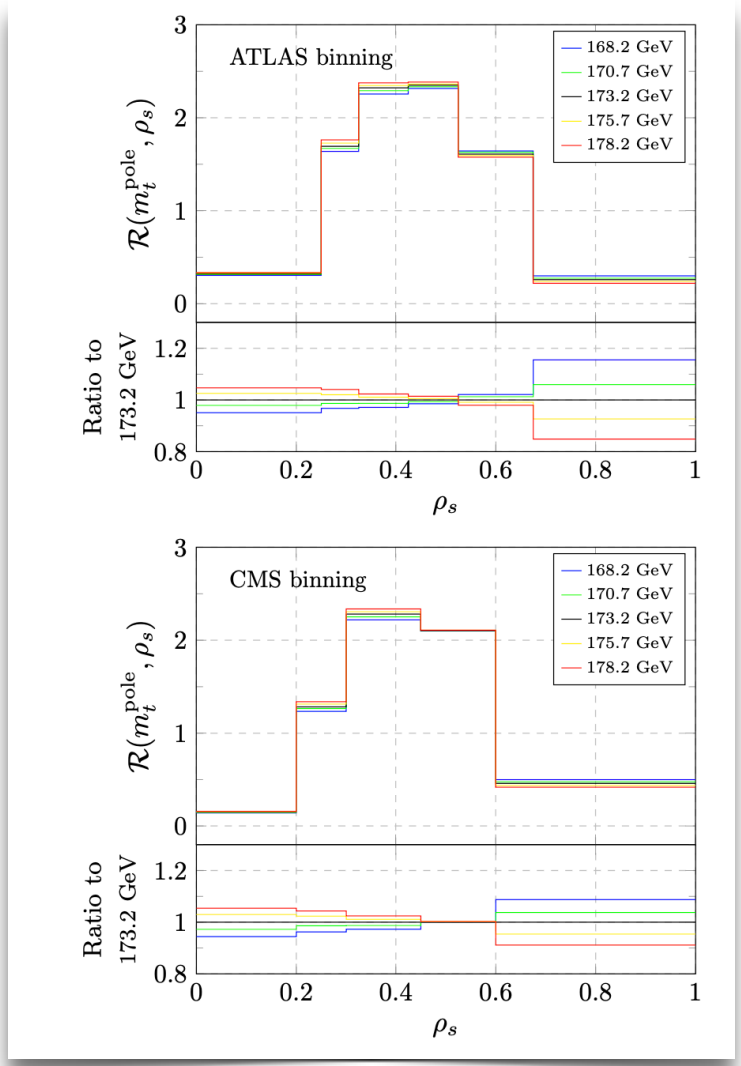
    $m_t = 172.94 \pm 1.37$ GeV

    CMS Collaboration '22

Bevilacqua, Hartanto, Kraus, Schulze, Worek '18

Application IV: Top-Quark Mass

NLO *ttj*



Theory, NLO QCD CT14 PDF	$m_t^{out} \pm \delta m_t^{out}$ [GeV]	Averaged χ^2/d.o.f.	Probability *p-value*	$m_t^{in} - m_t^{out}$ [GeV]
	31 bins			
Full, $\mu_0 = H_T/2$	173.09 ± 0.42	1.04	0.41 (0.8σ)	+0.11
Full, $\mu_0 = E_T/2$	172.45 ± 0.39	1.12	0.30 (1.0σ)	+0.75
Full, $\mu_0 = m_t$	173.76 ± 0.40	1.87	0.003 (3.0σ)	−0.56
NWA, $\mu_0 = m_t$	175.65 ± 0.31	2.99	$7 \cdot 10^{-8}$ (5.4σ)	−2.45
$NWA_{Prod.}$, $\mu_0 = m_t$	169.59 ± 0.30	3.10	$2 \cdot 10^{-8}$ (5.6σ)	+3.61
	5 bins			
Full, $\mu_0 = H_T/2$	173.08 ± 0.40	0.94	0.44 (0.8σ)	+0.12
Full, $\mu_0 = E_T/2$	172.48 ± 0.38	1.58	0.18 (1.3σ)	+0.72
Full, $\mu_0 = m_t$	173.75 ± 0.40	6.76	$2 \cdot 10^{-5}$ (4.3σ)	−0.55
NWA, $\mu_0 = m_t$	175.49 ± 0.30	5.31	$2 \cdot 10^{-4}$ (3.7σ)	−2.29
$NWA_{Prod.}$, $\mu_0 = m_t$	169.39 ± 0.47	3.42	$8 \cdot 10^{-3}$ (2.6σ)	+3.81
	ATLAS binning			
Full, $\mu_0 = H_T/2$	173.06 ± 0.44	0.97	0.44 (0.8σ)	+0.14
Full, $\mu_0 = E_T/2$	172.36 ± 0.44	1.38	0.23 (1.2σ)	+0.84
Full, $\mu_0 = m_t$	173.84 ± 0.42	5.12	$1 \cdot 10^{-4}$ (3.9σ)	−0.64
NWA, $\mu_0 = m_t$	175.23 ± 0.37	5.28	$7 \cdot 10^{-5}$ (4.0σ)	−2.03
$NWA_{Prod.}$, $\mu_0 = m_t$	169.43 ± 0.50	2.61	0.02 (2.3σ)	+3.77
	CMS binning			
Full, $\mu_0 = H_T/2$	173.09 ± 0.50	0.96	0.43 (0.8σ)	+0.11
Full, $\mu_0 = E_T/2$	172.22 ± 0.48	1.32	0.26 (1.1σ)	+0.98
Full, $\mu_0 = m_t$	174.02 ± 0.46	6.57	$3 \cdot 10^{-5}$ (4.2σ)	−0.82
NWA, $\mu_0 = m_t$	175.74 ± 0.34	6.00	$8 \cdot 10^{-5}$ (3.9σ)	−2.54
$NWA_{Prod.}$, $\mu_0 = m_t$	170.22 ± 0.53	2.19	0.07 (1.8σ)	+2.98

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

- Sensitivity to scaler setting and top quark modelling

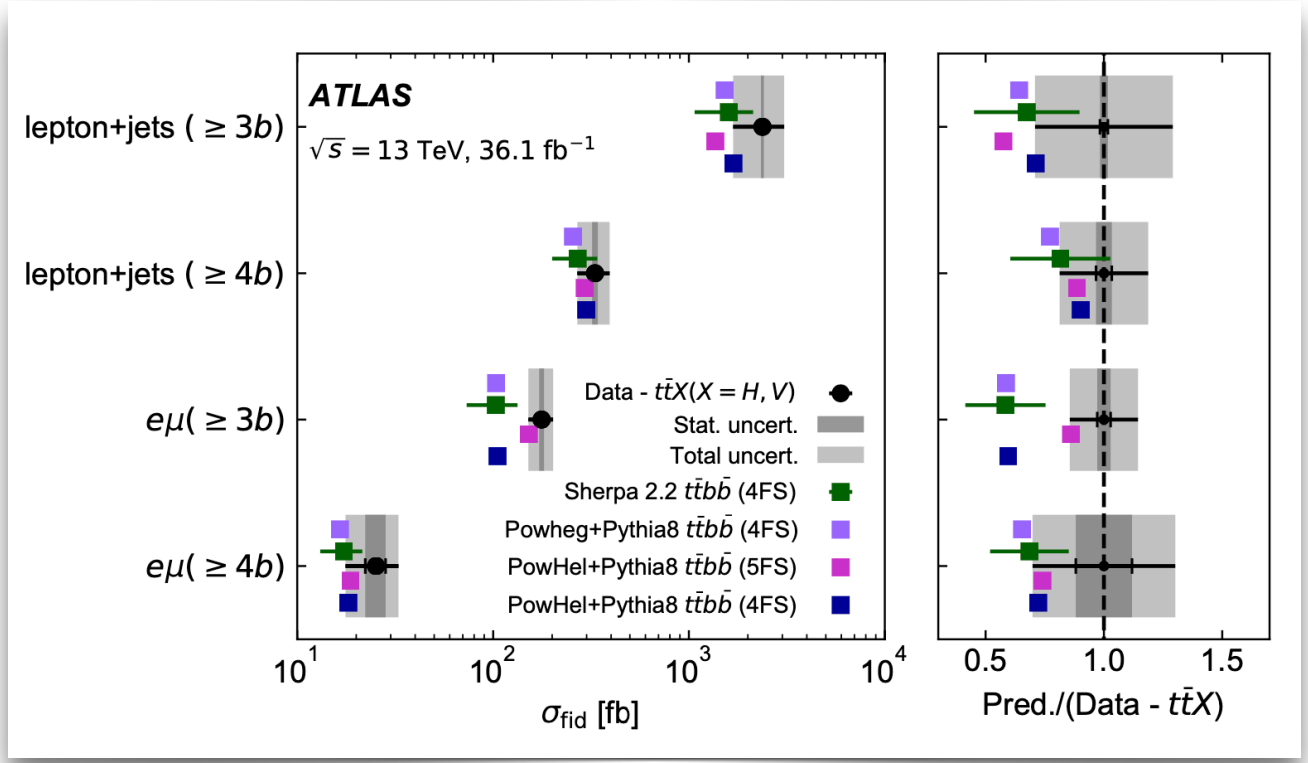
Bevilacqua, Hartanto, Kraus, Schulze, Worek '18

TTBB @ NLO

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

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

ATLAS Collaboration '19



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 $\tau^\pm$ decays into $\ell^\pm$
- For similar scale choice HELAC-NLO result is even higher ~ *21 fb*

Initial State Bottom Quarks

Charge aware and charge blind schemes for b-jet tagging

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

Charge blind b-tagging

- Sensitive to *absolute flavour of b-jet*
- Cannot distinguish between b & $\bar{b}$ jets
- Recombination rules

$$bg \to b, \bar{b}g \to \bar{b}, b\bar{b} \to g, bb \to g, \bar{b}\bar{b} \to g$$

Charge aware b-tagging

- Sensitive to *charge of b-jet*
- Can distinguish between b & $\bar{b}$ jets
- Recombination rules

$$bg \to b, \bar{b}g \to \bar{b}, b\bar{b} \to g, bb \to b, \bar{b}\bar{b} \to \bar{b}$$

- Jets clustered with *anti-k_T* algorithm with $R = 0.4$
- 5 flavour scheme with massless b quarks
- Two b-jet tagging variants are IR-safe @ NLO
- Beyond NLO
  - *flavor k_T* *Banfi, Salam, Zanderighi '06*
  - *flavor anti-k_T* *Czakon, Mitov, Poncelet '22*

LO	NLO
$\sigma^{\rm LO}_{\rm no\,b} = 6.813(3)$ fb	$\sigma^{\rm NLO}_{\rm no\,b} = 13.22(3)$ fb
$\sigma^{\rm LO}_{\rm aware} = 6.822(3)$ fb	$\sigma^{\rm NLO}_{\rm aware} = 13.31(3)$ fb
$\sigma^{\rm LO}_{\rm blind} = 6.828(3)$ fb	$\sigma^{\rm NLO}_{\rm blind} = 13.38(3)$ fb
impact: ~0.2%	impact: ~1%

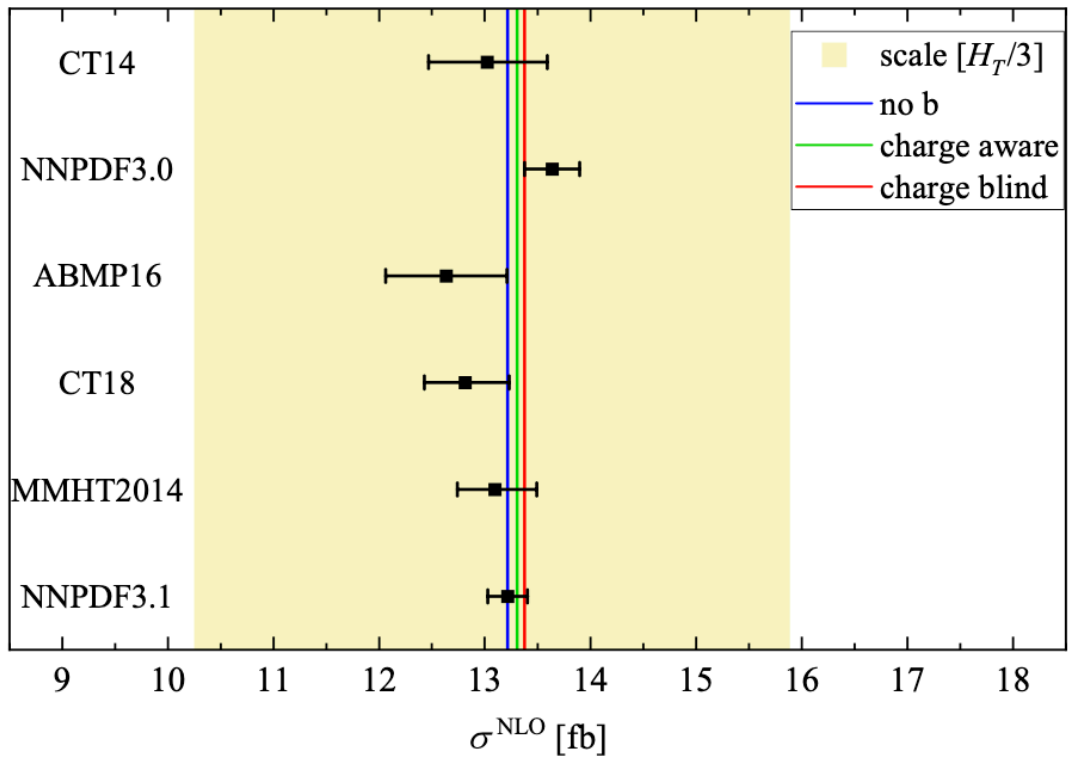
Bevilacqua, Bi, Hartanto, Kraus, Lupattelli, Worek '21

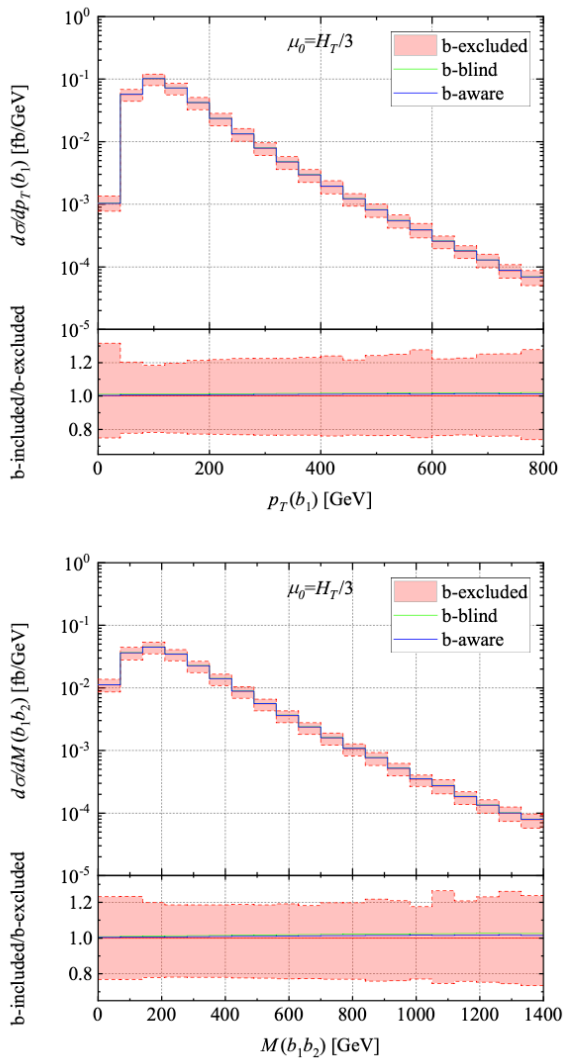
Initial State Bottom Quarks

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

Negligible contribution

- Contributions induced by initial state can be safely neglected even in extreme phase space regions





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