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QCD @ LHC - Precision for Discoveries

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Institute for Theoretical Particle Physics and Cosmology | RWTH AACHEN UNIVERSITY

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Collaborative Research Center TRR 257
P3H
Particle Physics Phenomenology after the Higgs Discovery

Theory Seminar at the Max-Planck Institute in Munich, 09.11.2023

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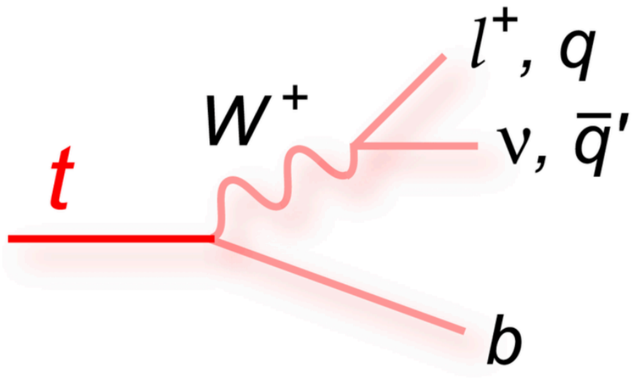
TOP @ LHC - Precision for Discoveries



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Instead of Introduction

- Latest theoretical results for $t\bar{t}$ & $t\bar{t}+X$ where $X = H, \gamma, W^{\pm}, Z, j, b\bar{b}, \gamma\gamma, jj, W^{\pm}j, \ldots$
  - 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

- *Precision & Accuracy* ➪ 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* ➪ (Almost) Only fixed order calculations ➪ LHC

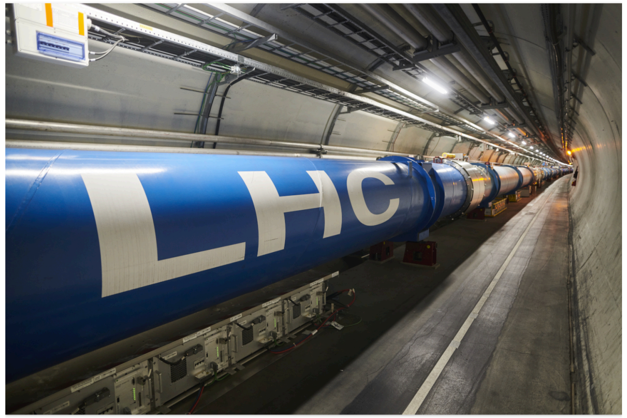
Instead of Introduction

- 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

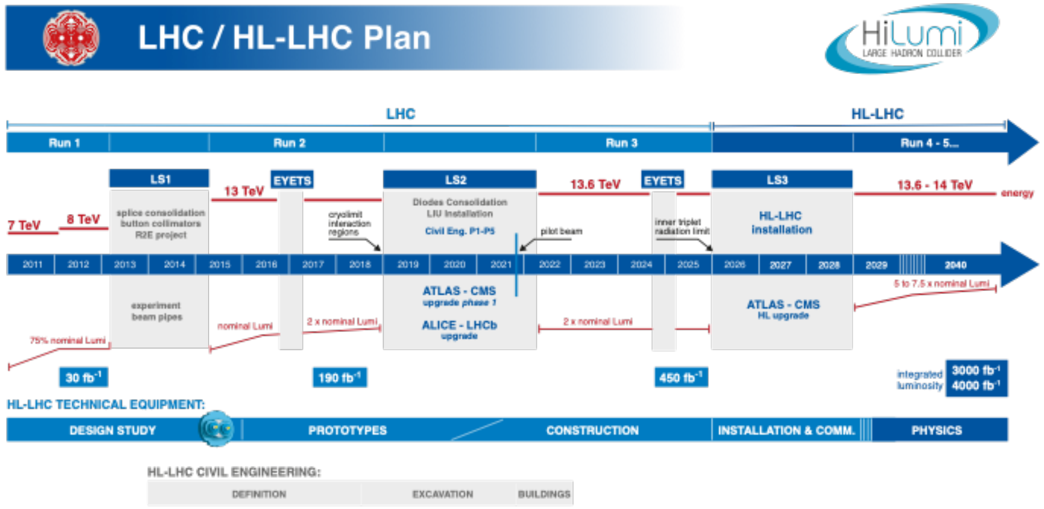
Large Hadron Collider restarts

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

- 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

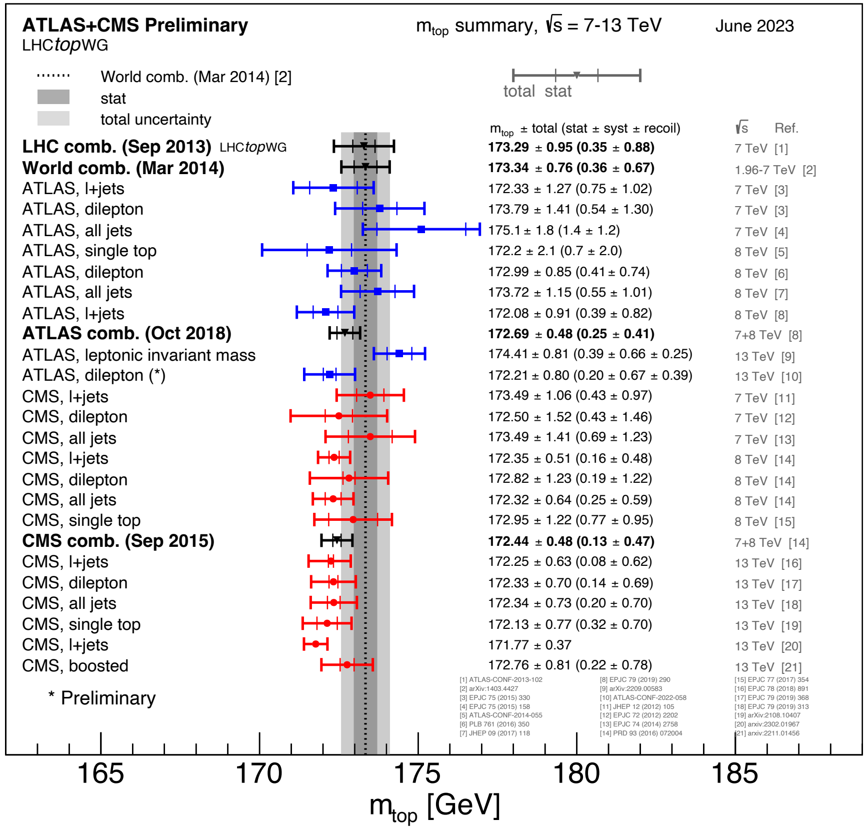
$$Y_t = \sqrt{2}\,\frac{m_t}{v} \approx 1$$

- 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

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



$$m_t = (171.77 \pm 0.37)\ \text{GeV}$$

CMS Collaboration '22

LHC as Top Quark Factory

ATLAS & CMS

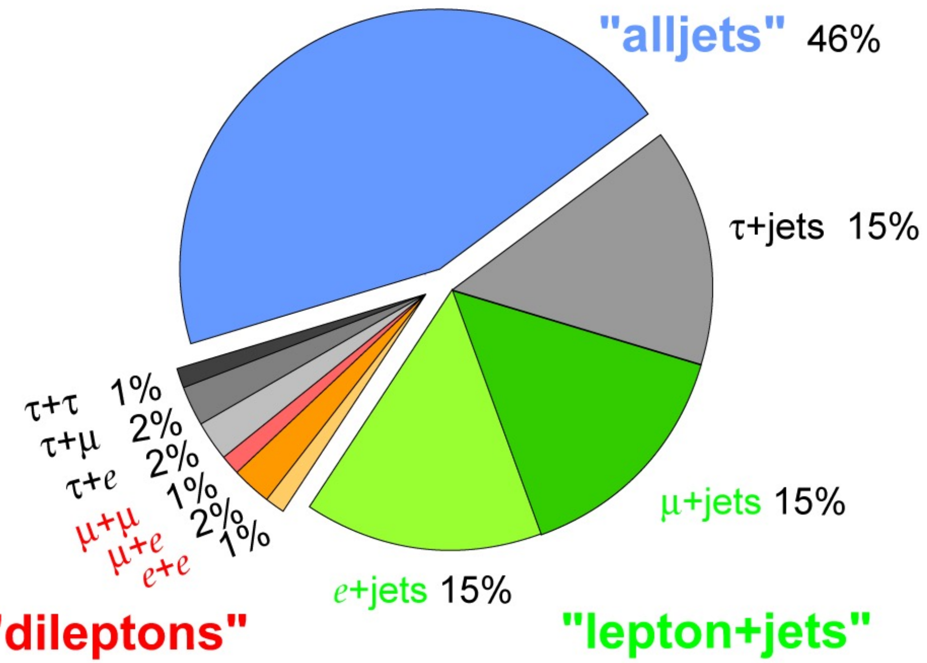
Collider	σ_{tt} [pb]	L [fb^{-1}]	Nevent
LHC7 TeV	180	5.0	9×10^5
LHC8 TeV	256	19.7	5×10^6
LHC13 TeV	835	139	1×10^8
HL-LHC14 TeV	987	3000	3×10^9
HE-LHC27 TeV	3840	15000	6×10^{10}

Czakon, Mitov '14

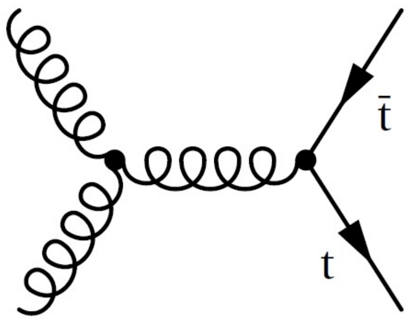
Top quark pair production @ NNLO QCD with *TOP++*
CT14nnlo PDF & $m_t = 173.2$ GeV
$\mu_R = \mu_F = ½\, m_t$

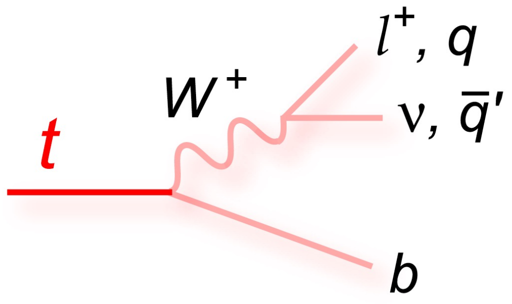
Theoretical uncertainties: NNLO QCD: *5% - 6%*
NNLO QCD + NNLL: *3% - 4%*

Top Pair Branching Fractions



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



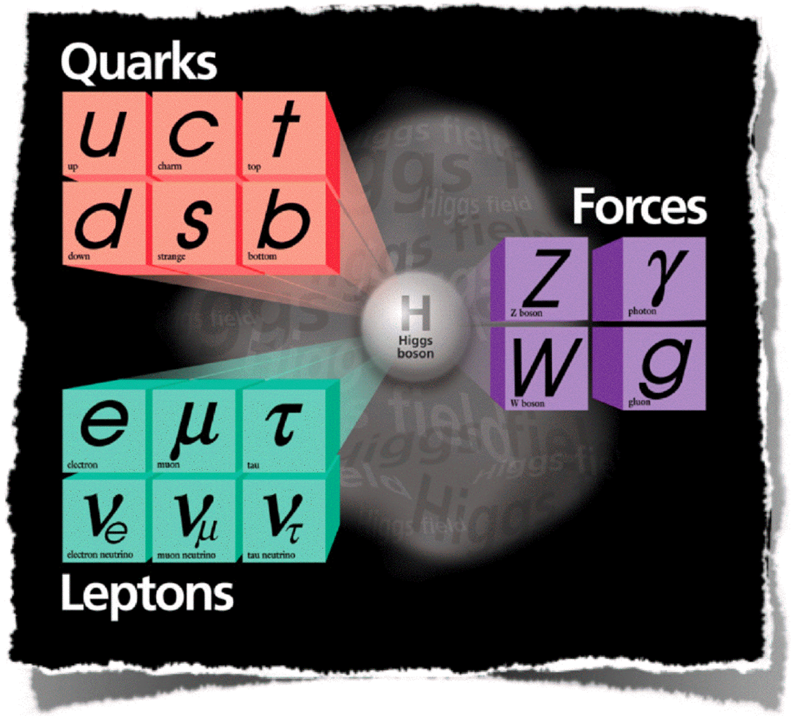


- Top quark produced via QCD interaction & Decay through weak interaction
- Producing W-boson and a down-type quark (down, strange, or bottom)

$$\mathcal{BR}(t \to Wb) = \frac{\Gamma(t \to Wb)}{\Gamma(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2} \approx 0.99$$

$$\text{SM}: \quad t \to Wb \approx 100\%$$

Precision Top Quark Physics

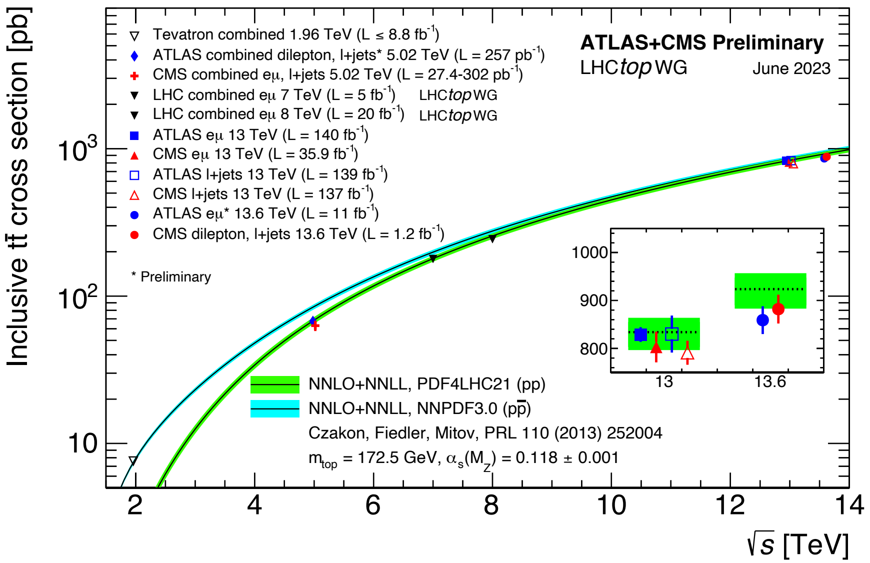


- Infrared Structure of QCD
  - Extract SM parameters as precisely as possible ➪ α_s & m_t
  - Constraining gluon PDFs
  - Verify couplings to other particles ➪ $\gamma, H, Z, W^{\pm}$
- Various IR-Safe Observables
  - Integrated & differential (fiducial) cross sections
  - Cross section ratios
    - 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, …

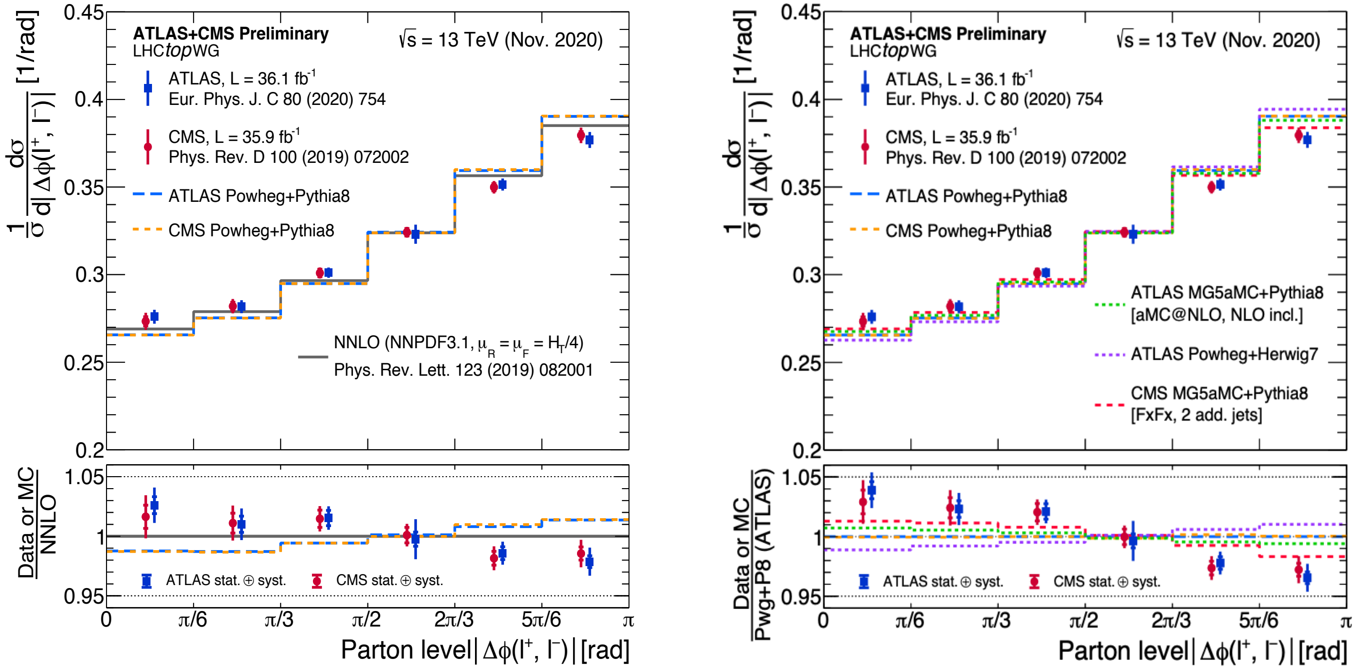
Top Quark Pair Production

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

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



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



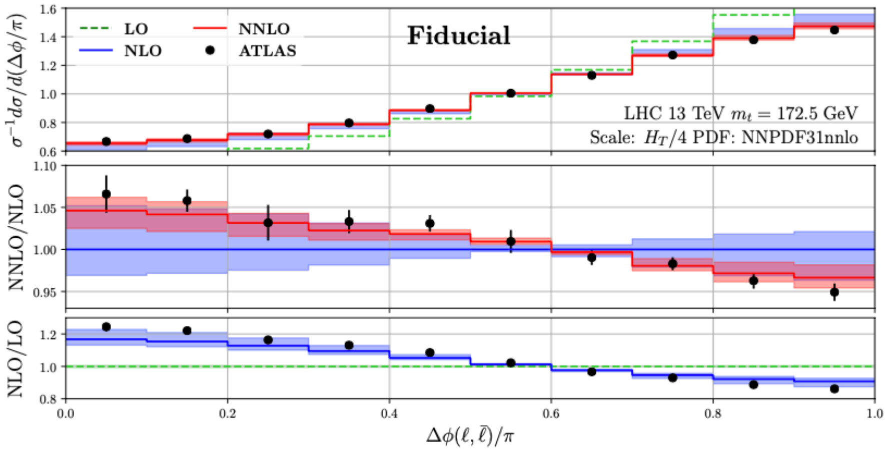
Czakon, Fiedler, Mitov '13
Czakon, Heymes, Mitov '16 '17
Behring, Czakon, Mitov, Papanastasiou, Poncelet '19
Czakon, Mitov, Poncelet '21

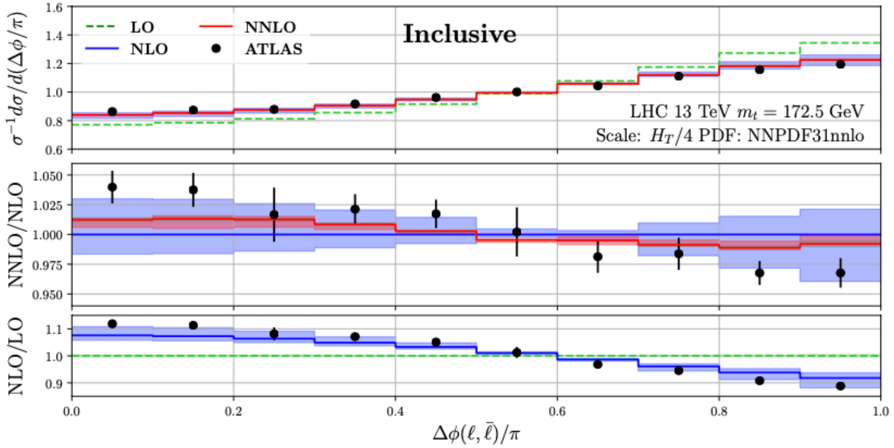
Catani, Devoto, Grazzini, Kallweit, Mazzitelli, Sargsyan '19
Catani, Devoto, Grazzini, Kallweit, Mazzitelli '19

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

Top Quark Pair Production & Decays

Agreement





Tension

Precision

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

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

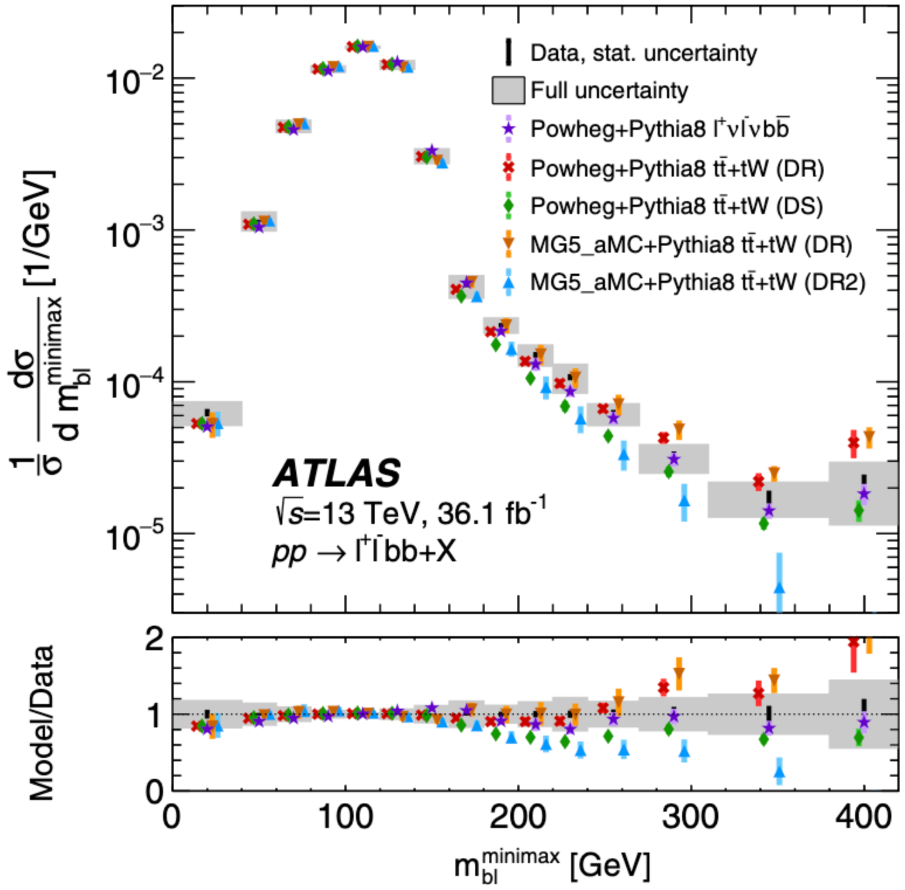
- Inclusive ➪ Does not assume any selection cuts
- Fiducial ➪ Based on the ATLAS selection cuts

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

Proper modeling of top-quark production & decay essential

TT & TWB

ATLAS '18
ATL-PHYS-PUB-2021-042



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

Accuracy

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

- Normalised differential $t\bar{t}$ cross section @ NLO QCD + PS
- Full off-shell versus $t\bar{t} + tW(b)$ ➪ 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*

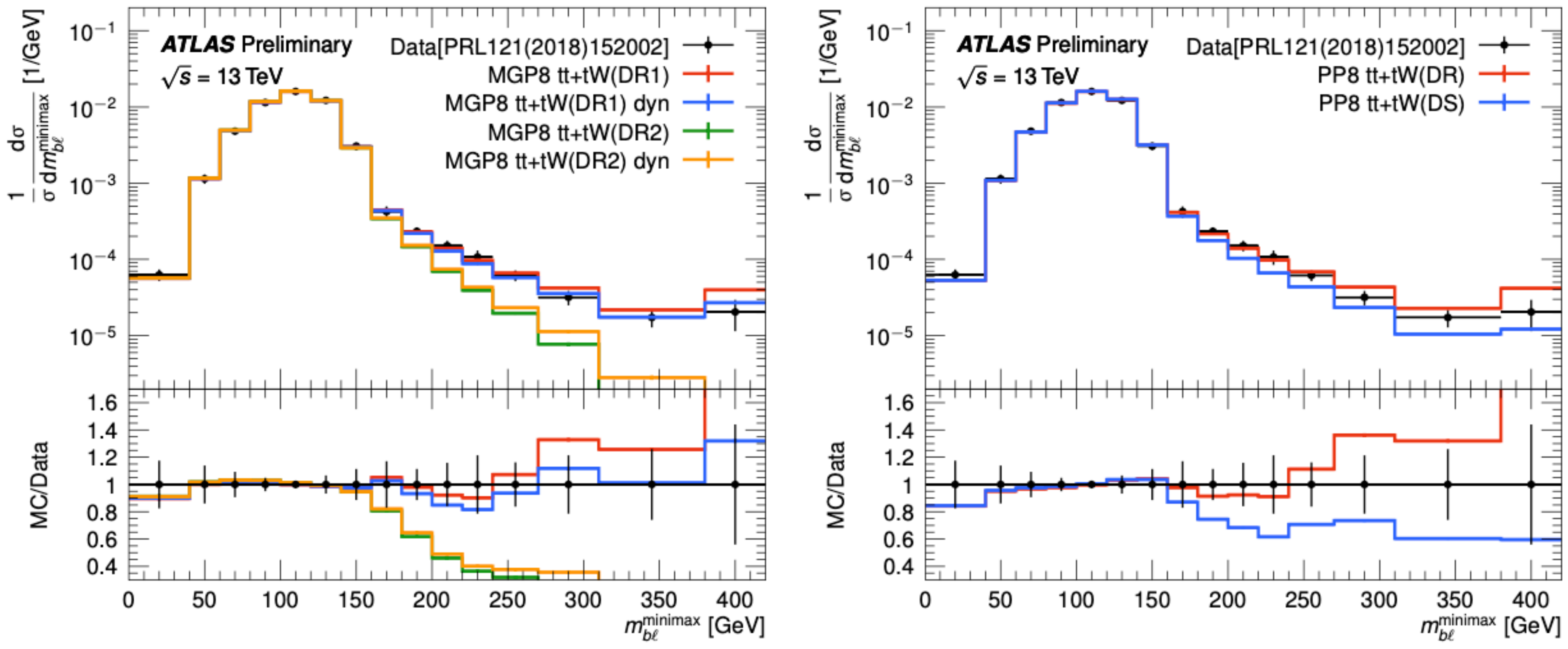
p values comparing data & various MC predictions

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)

ATLAS '18
ATL-PHYS-PUB-2021-042



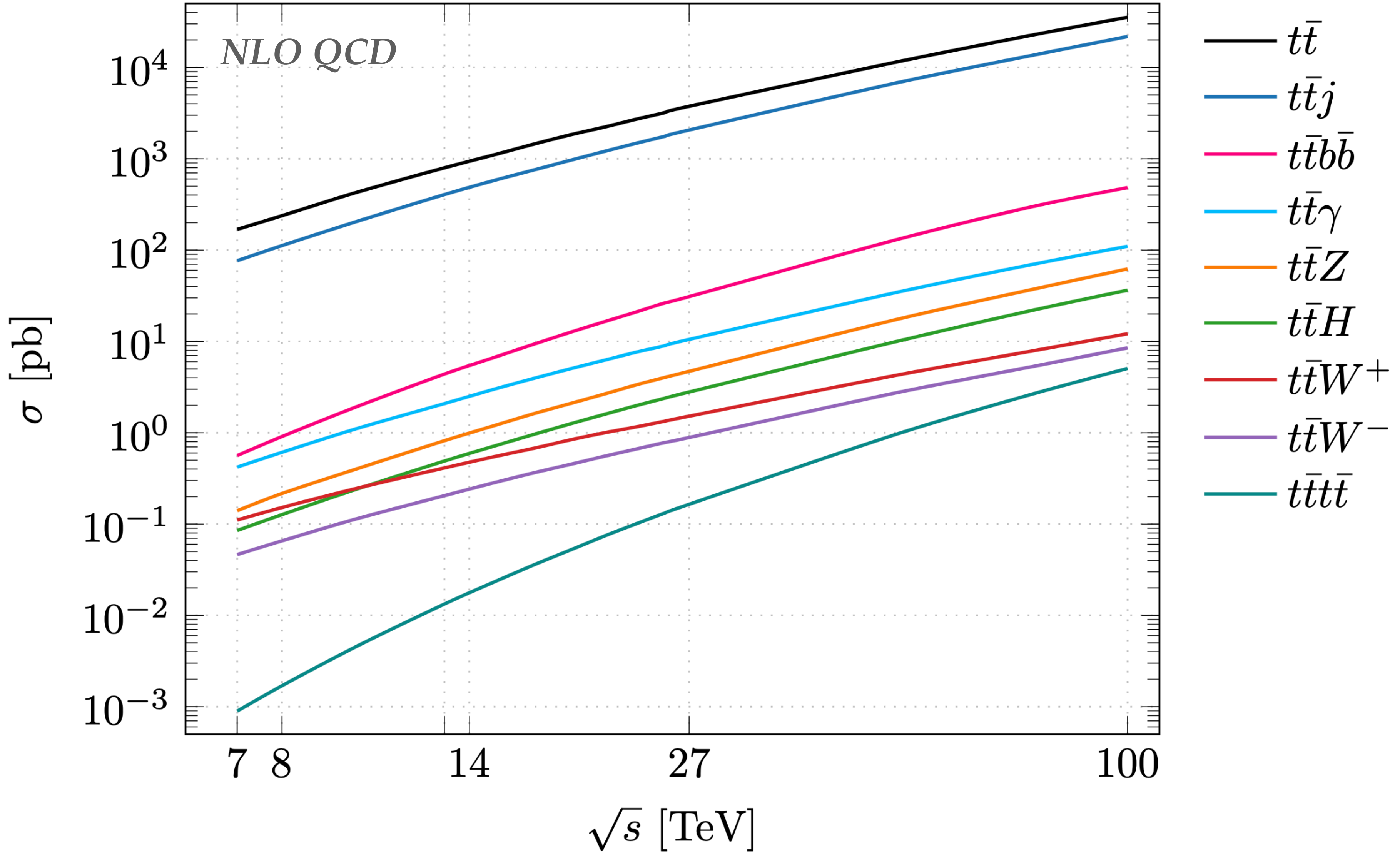
Accuracy *Important for proper modelling & tuning*

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

Associated TT Production

Top quark physics and heavy flavor production
Snowmass 2021

- More exclusive final states are produced @ LHC

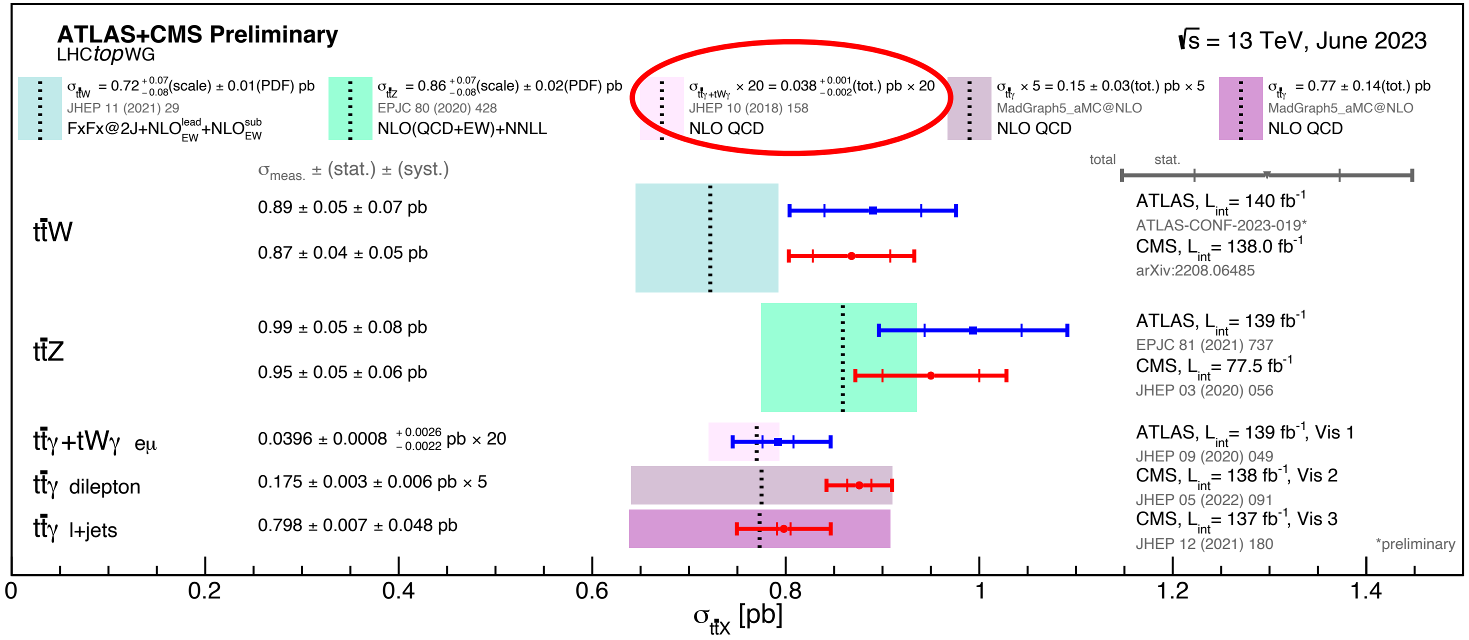


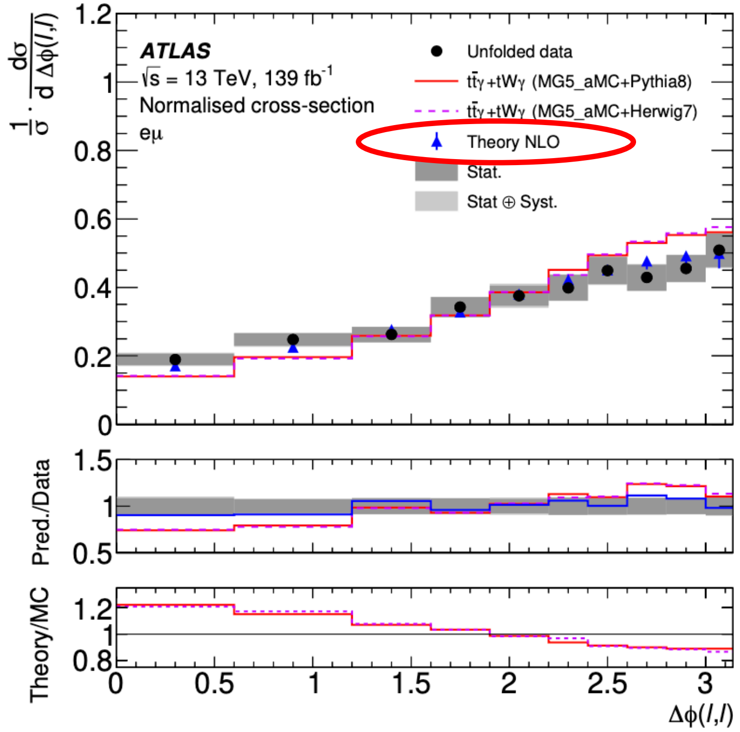
Associated TT Production

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

- 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	$p_T(\gamma)$ 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

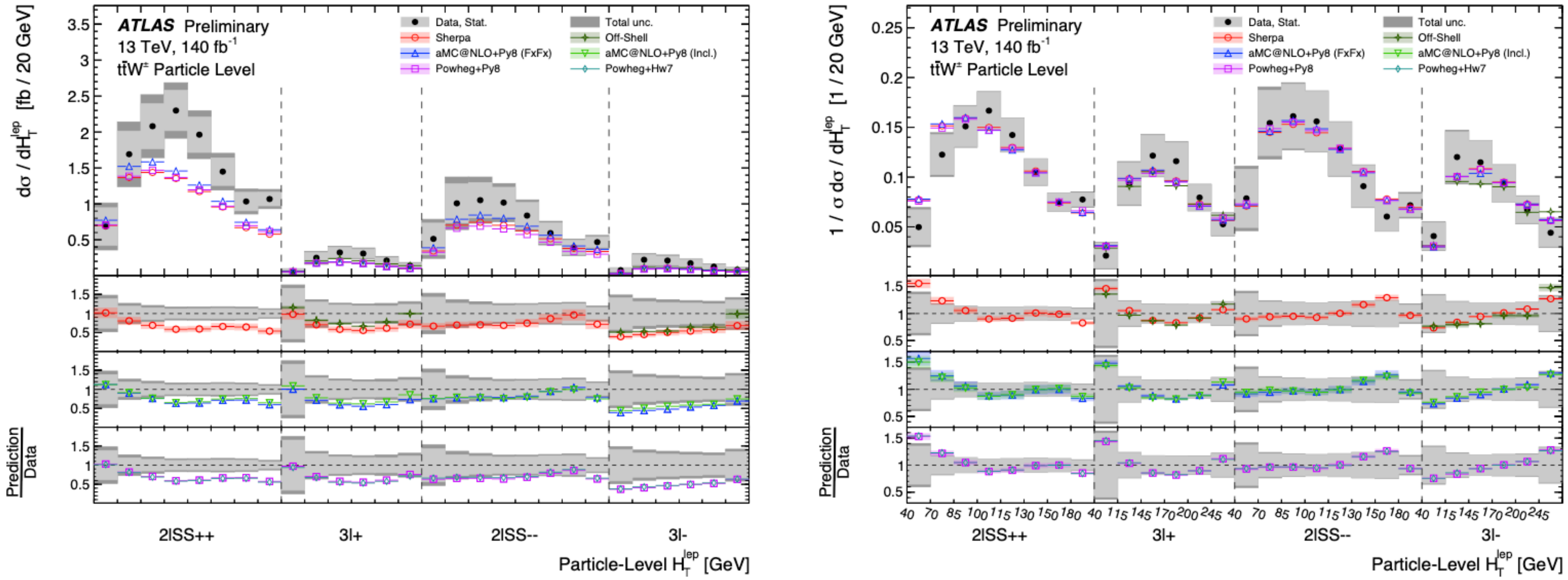
- NLO QCD full off-shell predictions for $t\bar{t}\gamma$
  - Di-lepton channel

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

Associated TT Production

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

- More exclusive final states are produced @ LHC



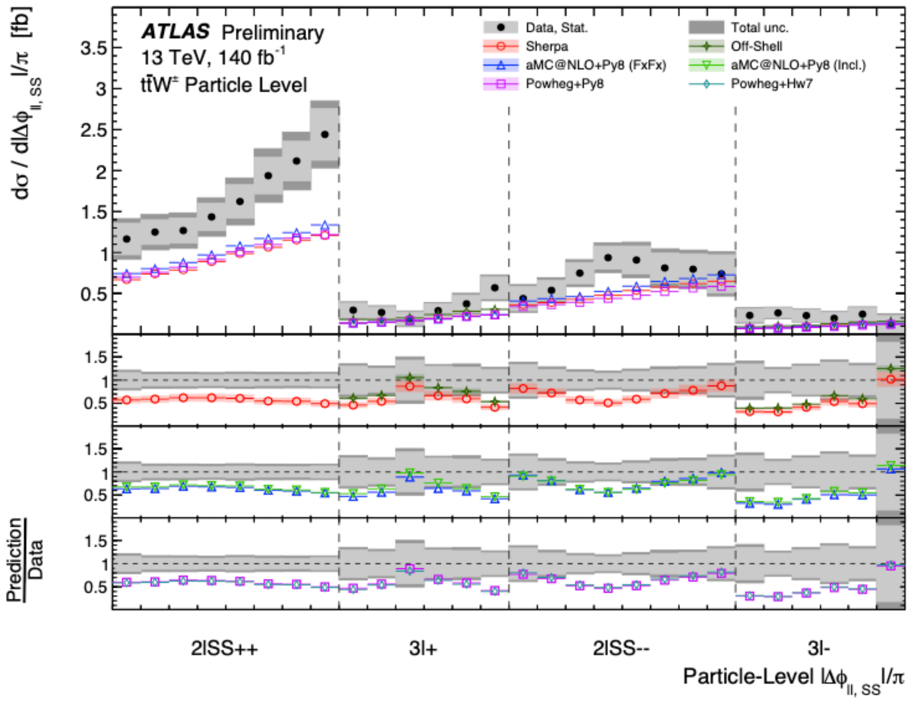
- Absolute and normalised cross-sections as function of $H_T^{lep} = p_T^{\ell^+} + p_T^{\ell^-} + p_T^{\ell^\pm}$
- *Off-shell results:* Parton-level corrected to particle-level through bin-by-bin scaling factors that account for non-perturbative effects, such as multi-parton interactions and hadronisation

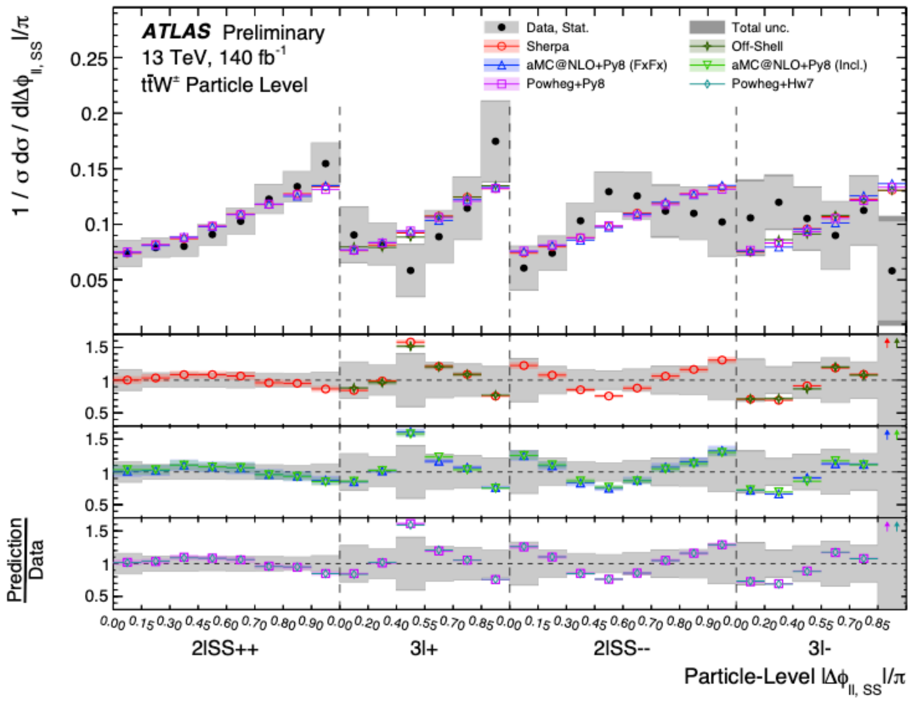
Bevilacqua, Bi, Hartanto, Kraus, Worek '20 '21 '22
ATLAS Collaboration '23

Associated TT Production

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

- More exclusive final states are produced @ LHC





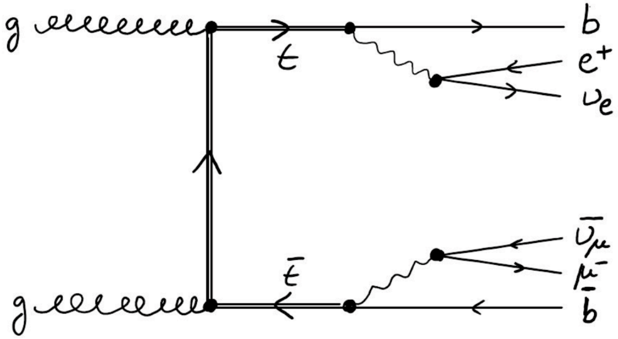
- Absolute and normalised cross-sections as function of $\Delta\phi_{\ell\ell}$
- *Off-shell results:* Parton-level corrected to particle-level through bin-by-bin scaling factors that account for non-perturbative effects, such as multi-parton interactions and hadronisation

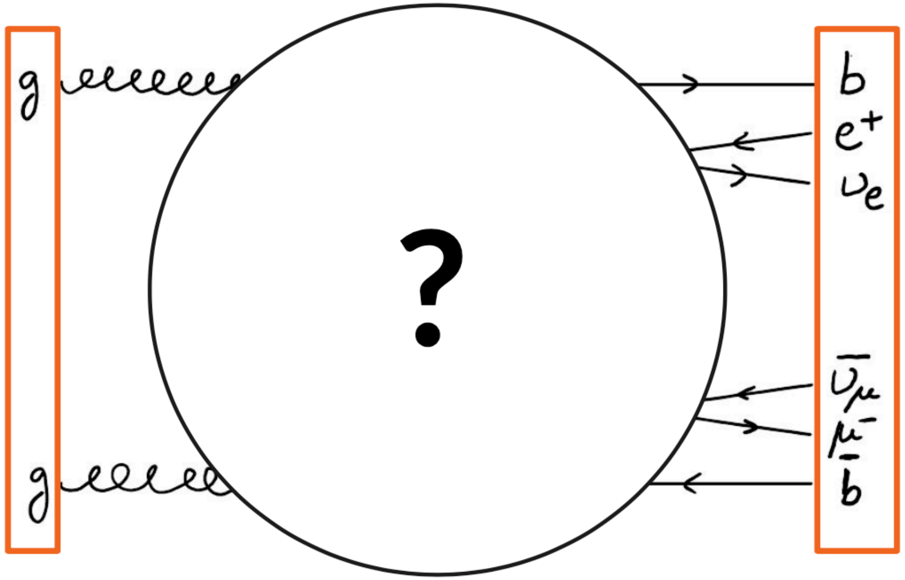
Bevilacqua, Bi, Hartanto, Kraus, Worek '20 '21 '22
ATLAS Collaboration '23

Precision & Accuracy

- Modelling of unstable particles

$$pp \to b\bar{b}e^+\mu^-\nu_e\bar{\nu}_\mu \text{ at } \mathcal{O}(\alpha_s^2\alpha^4)$$





Precision & Accuracy

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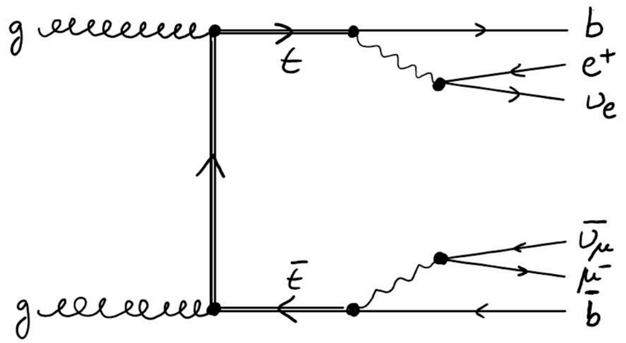
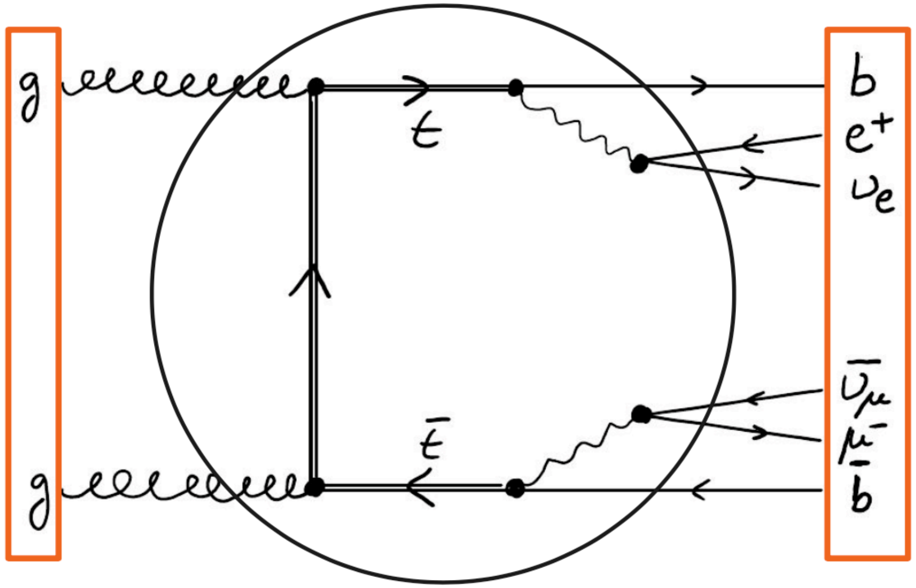


Double-resonant diagram



Precision & Accuracy

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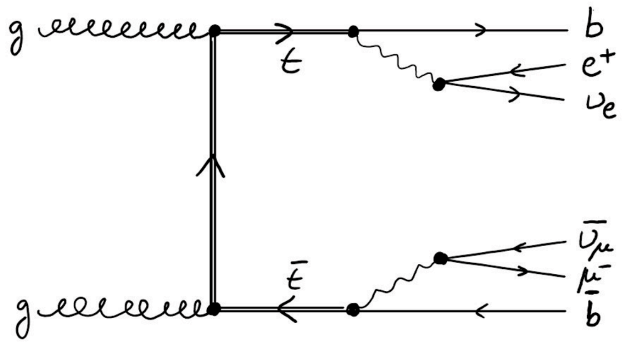
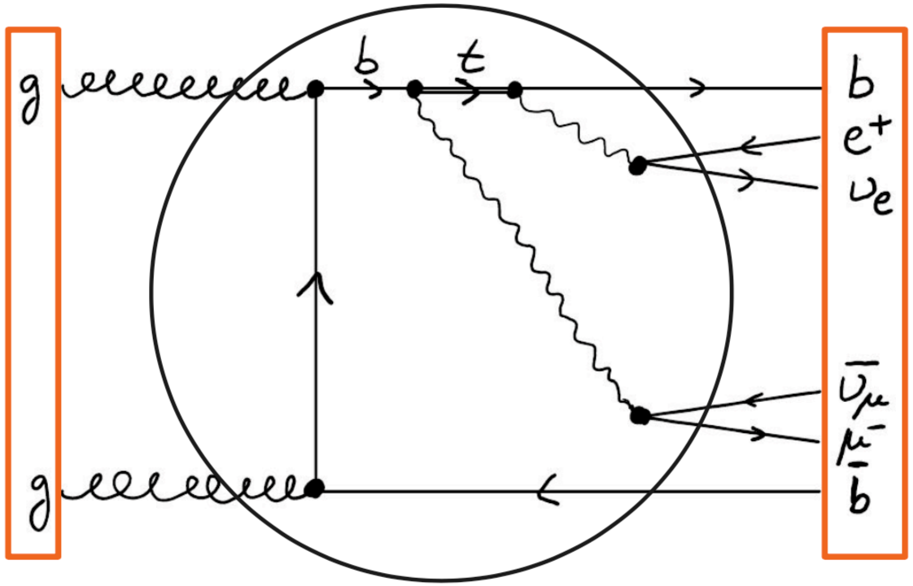


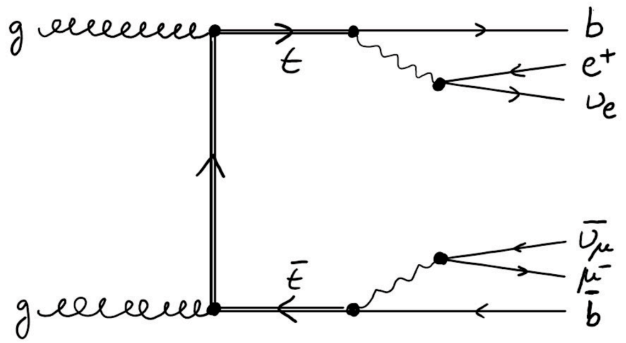


Single-resonant diagram

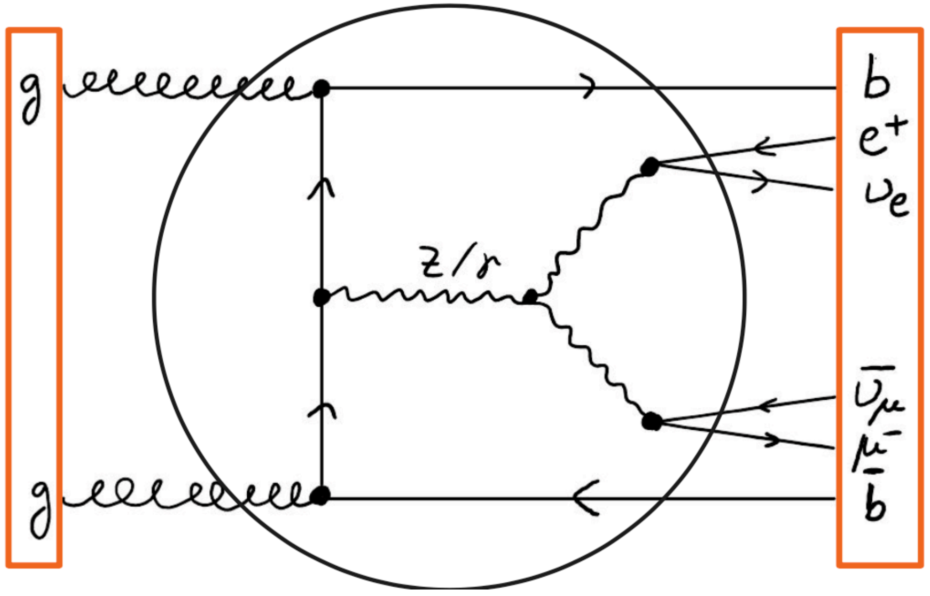
Precision & Accuracy

- Modelling of unstable particles

$$pp \to b\bar{b}e^+\mu^-\nu_e\bar{\nu}_\mu \text{ at } \mathcal{O}(\alpha_s^2\alpha^4)$$



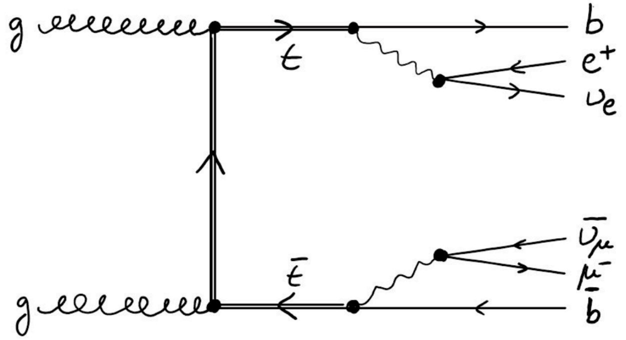
Non-resonant diagram



Precision & Accuracy

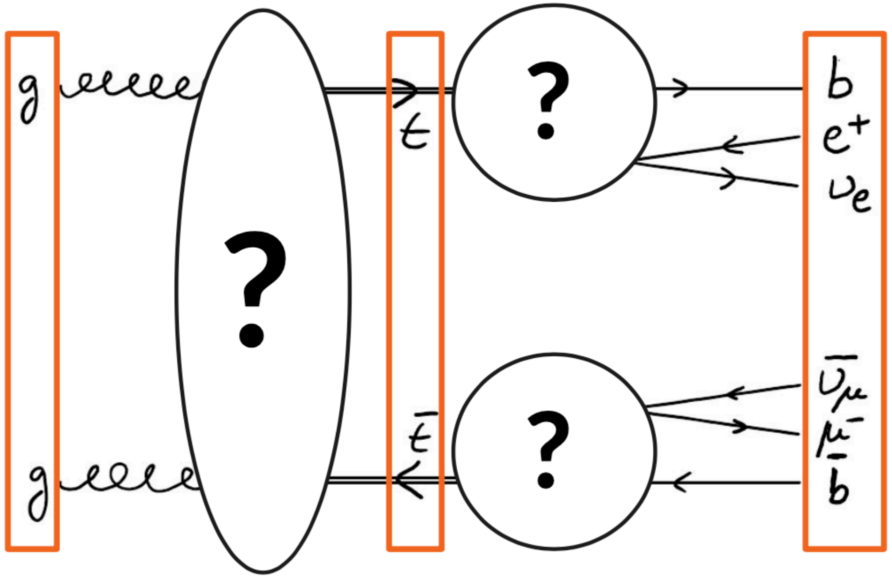
- Modelling of unstable particles

$$pp \to b\bar{b}e^{+}\mu^{-}\nu_e\bar{\nu}_\mu \quad \text{at } \mathcal{O}(\alpha_s^2\alpha^4)$$



Narrow-width approximation (NWA)
→ Fix intermediate state to be on-shell

$$\frac{\Gamma}{m} \to 0$$



Precision & Accuracy

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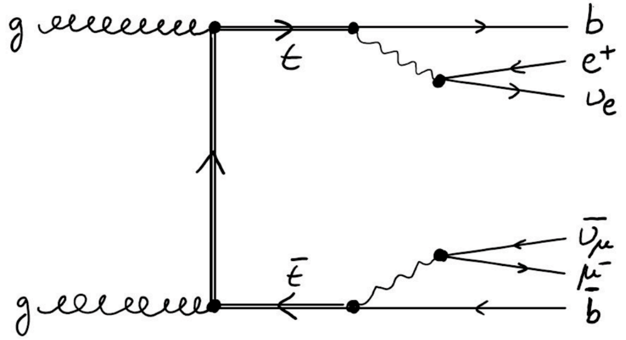
$$pp \to b\bar{b}e^+\mu^-\nu_e\bar{\nu}_\mu \quad \text{at } \mathcal{O}(\alpha_s^2\alpha^4)$$

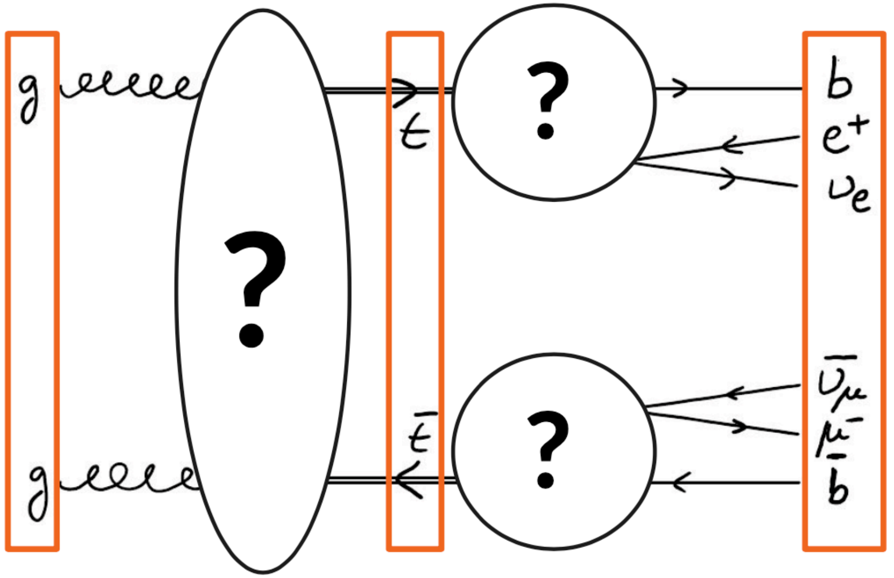


$$\frac{\Gamma_W}{m_W} > \frac{\Gamma_t}{m_t} \gg \frac{\Gamma_H}{m_H},$$

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

Narrow-width approximation (NWA)
→ Fix intermediate state to be on-shell

$$\frac{\Gamma}{m} \to 0$$

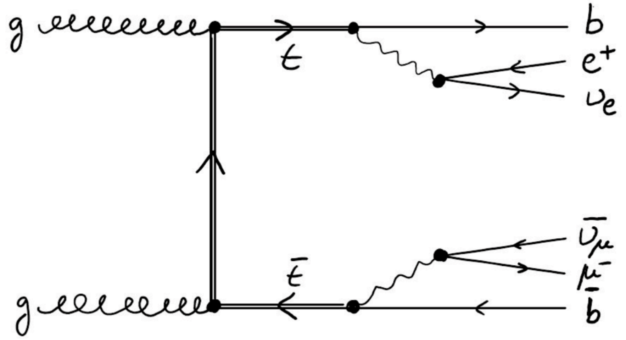


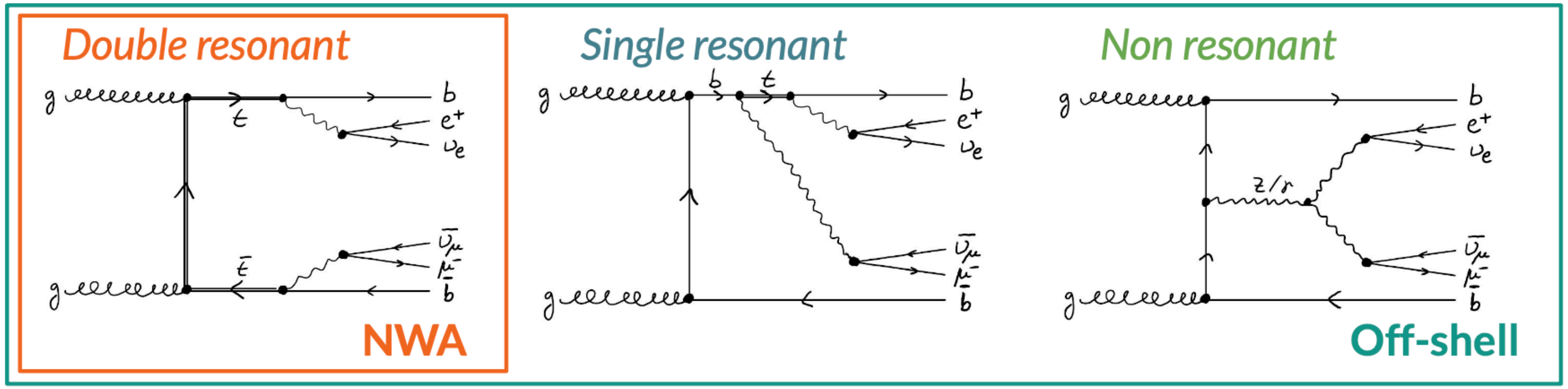
- NLO QCD correction separately to production & separately to top quark decays
- NLO QCD nonfactorizable corrections missing
- No cross-talk between production & decays & between 2 top-quark decays
- NLO spin correlations

Precision & Accuracy

- Modelling of unstable particles

$$pp \to b\bar{b}e^+\mu^-\nu_e\bar{\nu}_\mu \quad \text{at } \mathcal{O}(\alpha_s^2\alpha^4)$$





✓ Full off-shell = DR + SR + NR + interferences + Breit-Wigner propagators

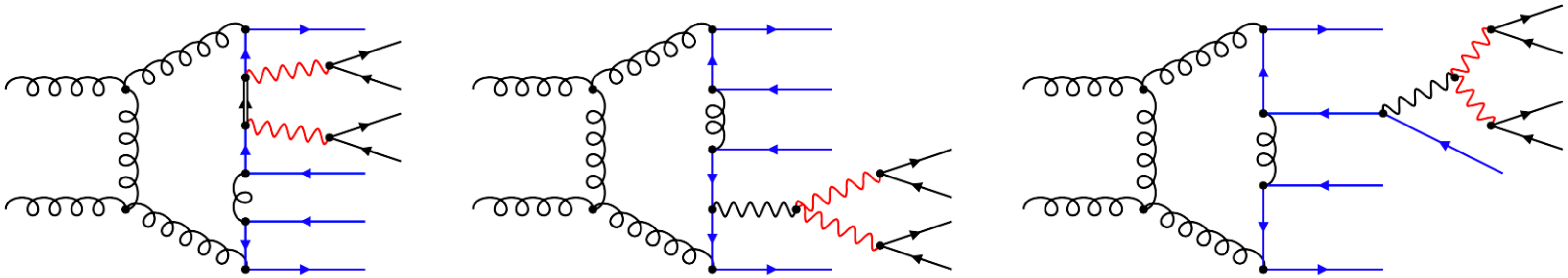
✓ NWA = DR restricts unstable t & W to on-shell states

Complexity for TTBB

NLO $ttbb$

Examples of Octagon-, Heptagon- & Hexagon-Type of one-loop diagrams

HELAC-NLO



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

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

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

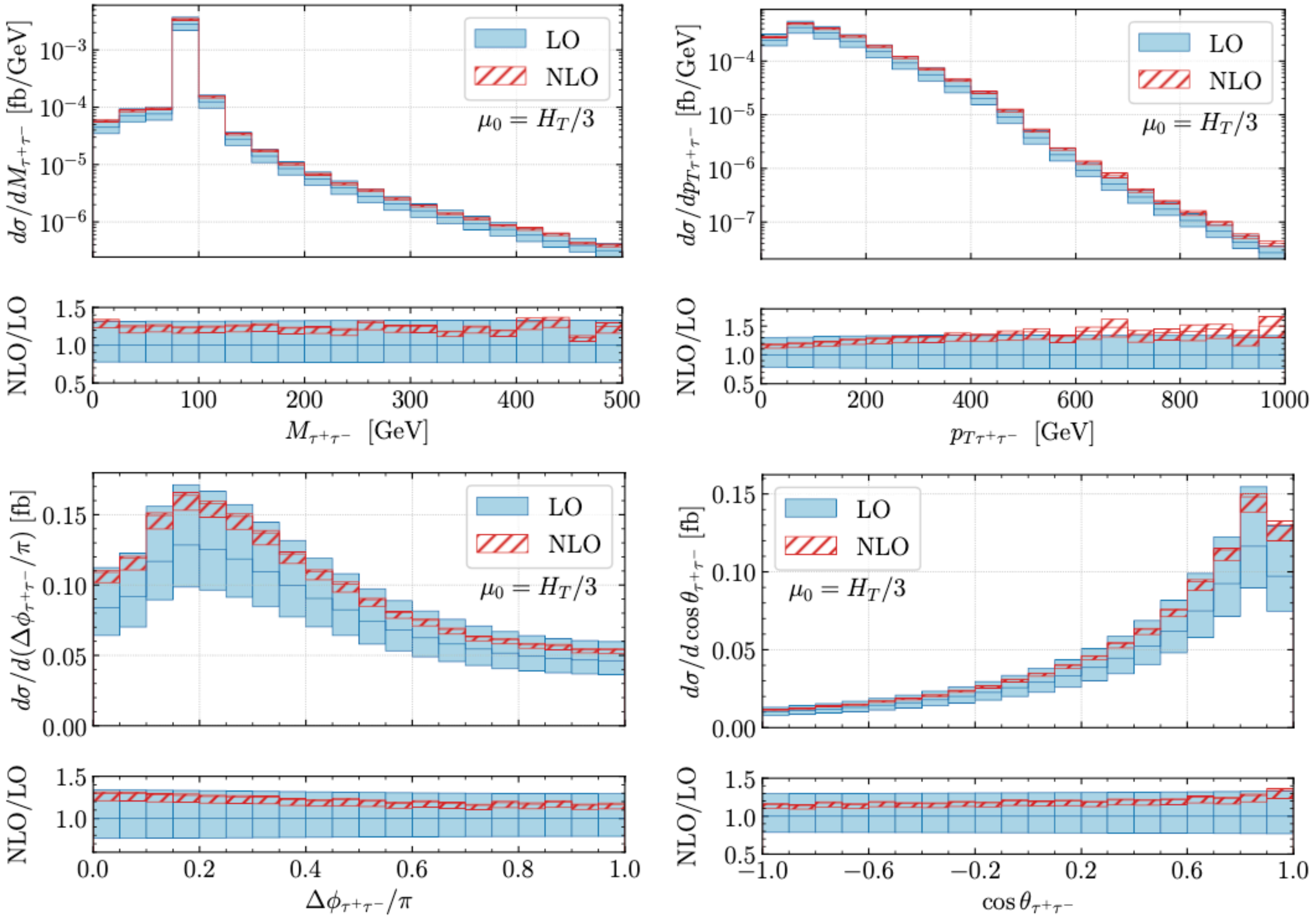
Partonic Subprocess	Number of Feynman diagrams	Number of CS Dipoles	Number of NS Subtractions
$gg \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}\,b\bar{b}\,g$	41364	90	18
$q\bar{q} \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}\,b\bar{b}\,g$	9576	50	10
$gq \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}\,b\bar{b}\,q$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

NLO QCD Corrections

NLO ttZ

Bevilacqua, Hartanto, Kraus, Nasufi, Worek '22



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

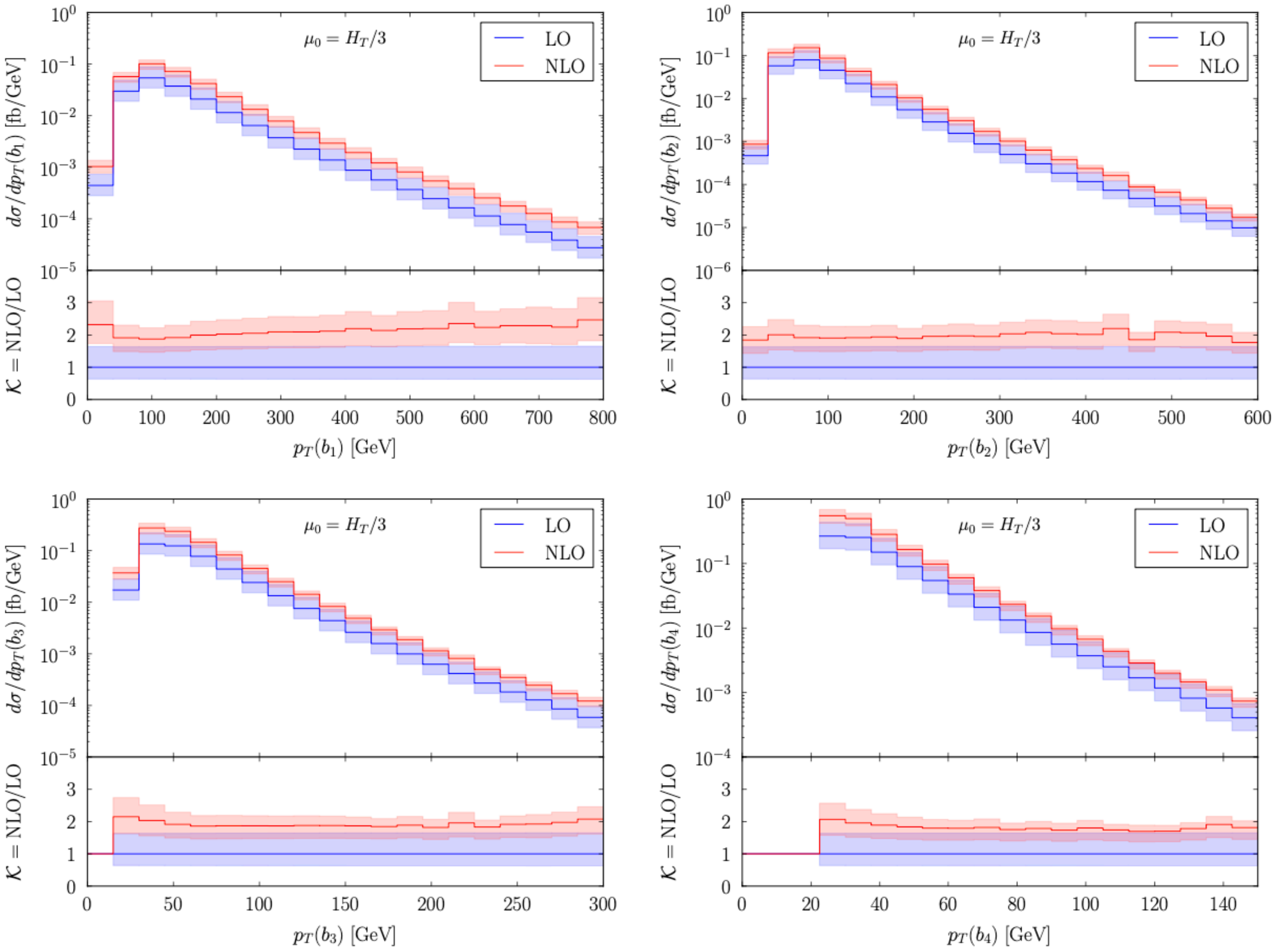
$$pp \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}\,\tau^+\tau^-$$

- 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*

NLO QCD Corrections

NLO *ttbb*

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



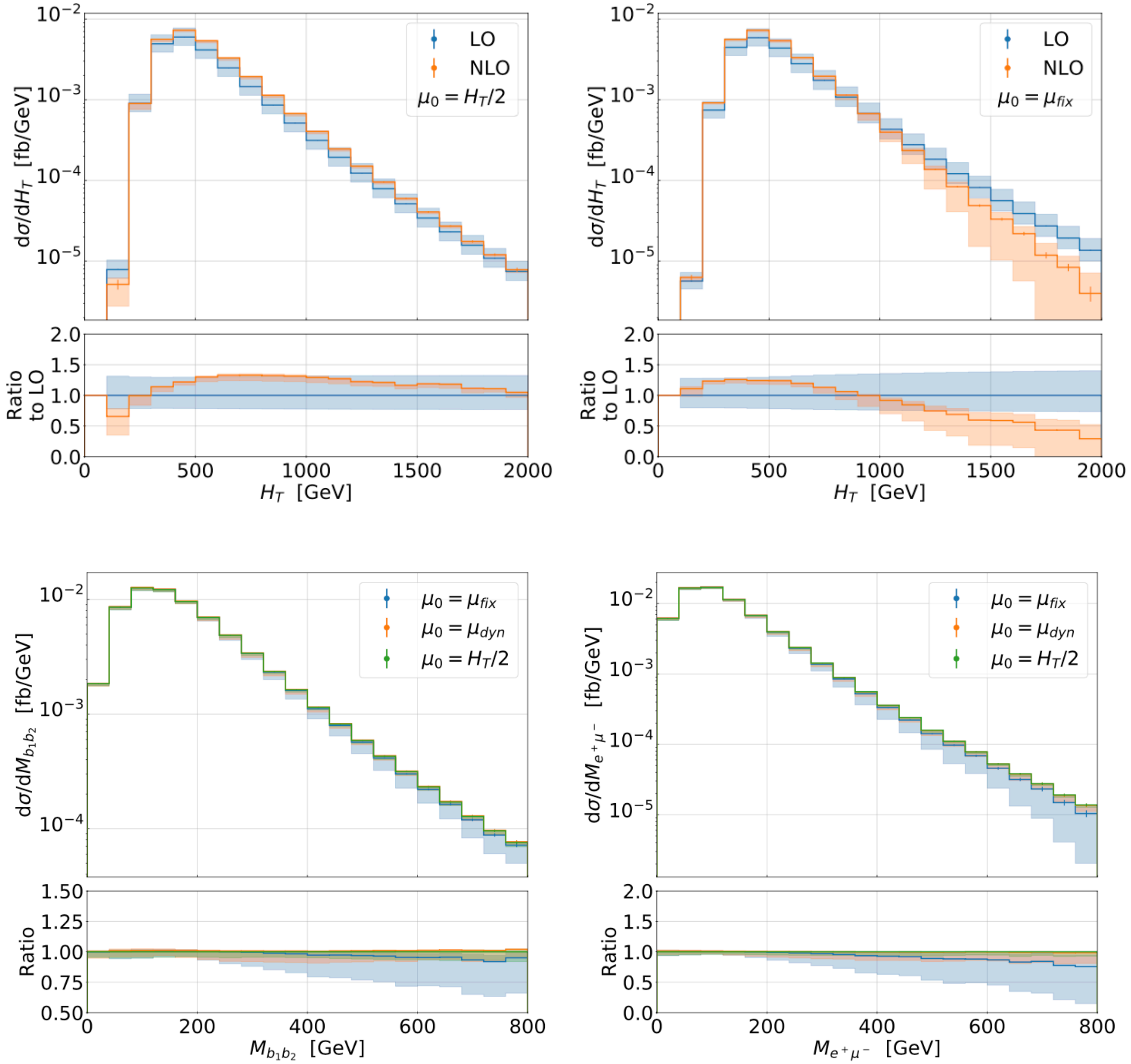
$$pp \to e^+\nu_e\, \mu^-\bar{\nu}_\mu\, b\bar{b}b\bar{b}$$

- 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%*

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

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

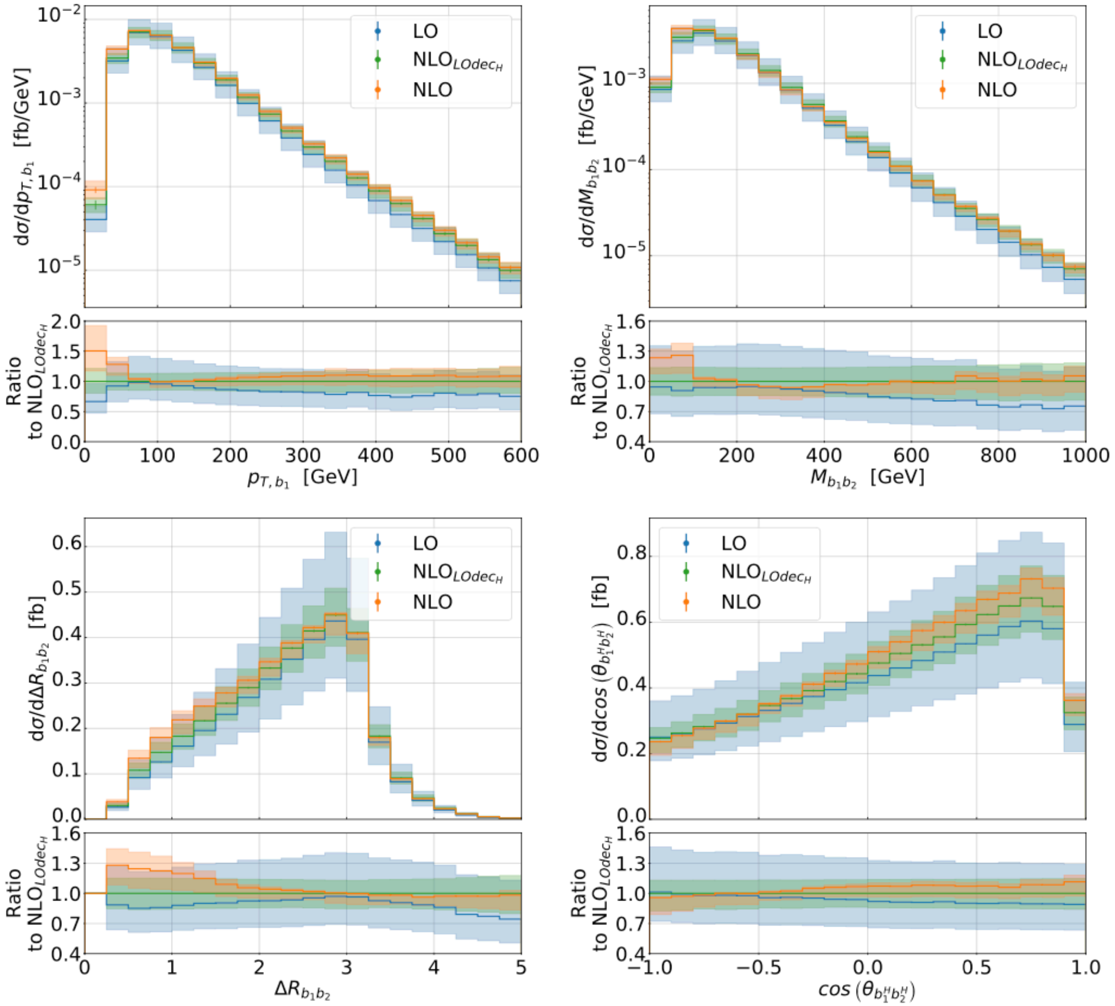
$$\mu_{dyn} = \left(m_{T,t}\, m_{T,\bar{t}}\, m_{T,H}\right)^{\frac{1}{3}} \qquad m_T = \sqrt{m^2 + p_T^2}.$$

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

NLO QCD Corrections & Higgs decays

NLO ttH

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



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

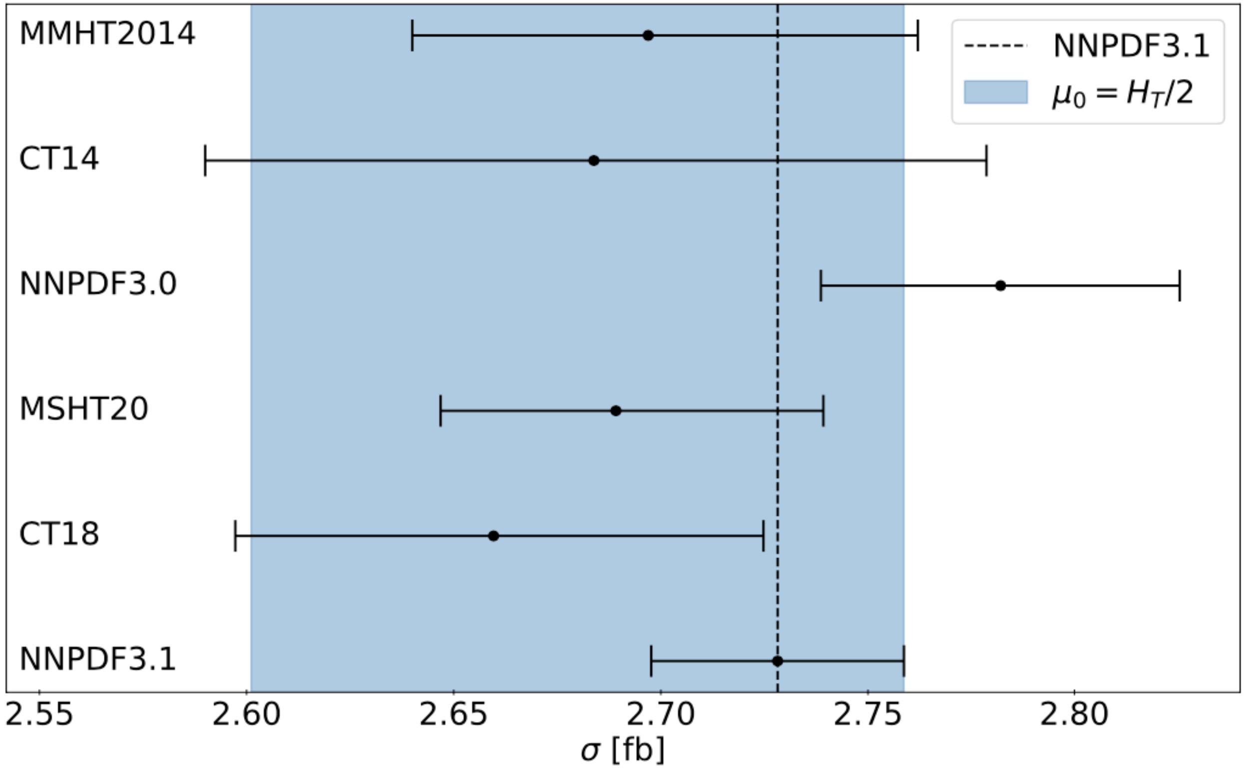
- Full off-shell effects for t & $W^{\pm}$
- Higgs boson decays in NWA

	$\sigma_{\rm LO}$ [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

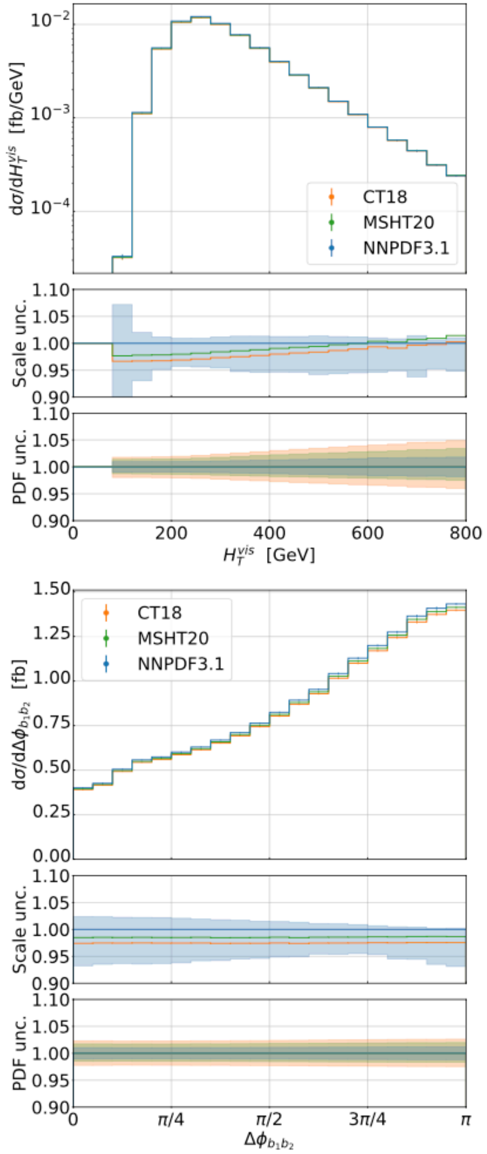
$$pp \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}H$$



Integrated level

Stremmer, Worek '22

NLO ttH



Differential level

PDF Uncertainties

NLO $t\bar{t}Z$

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

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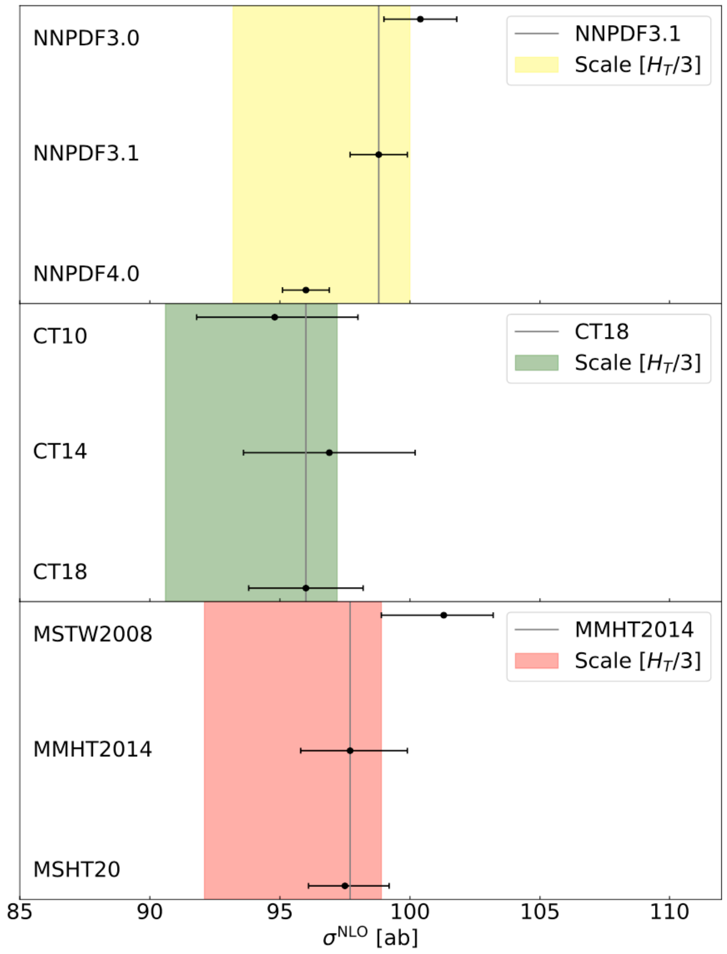
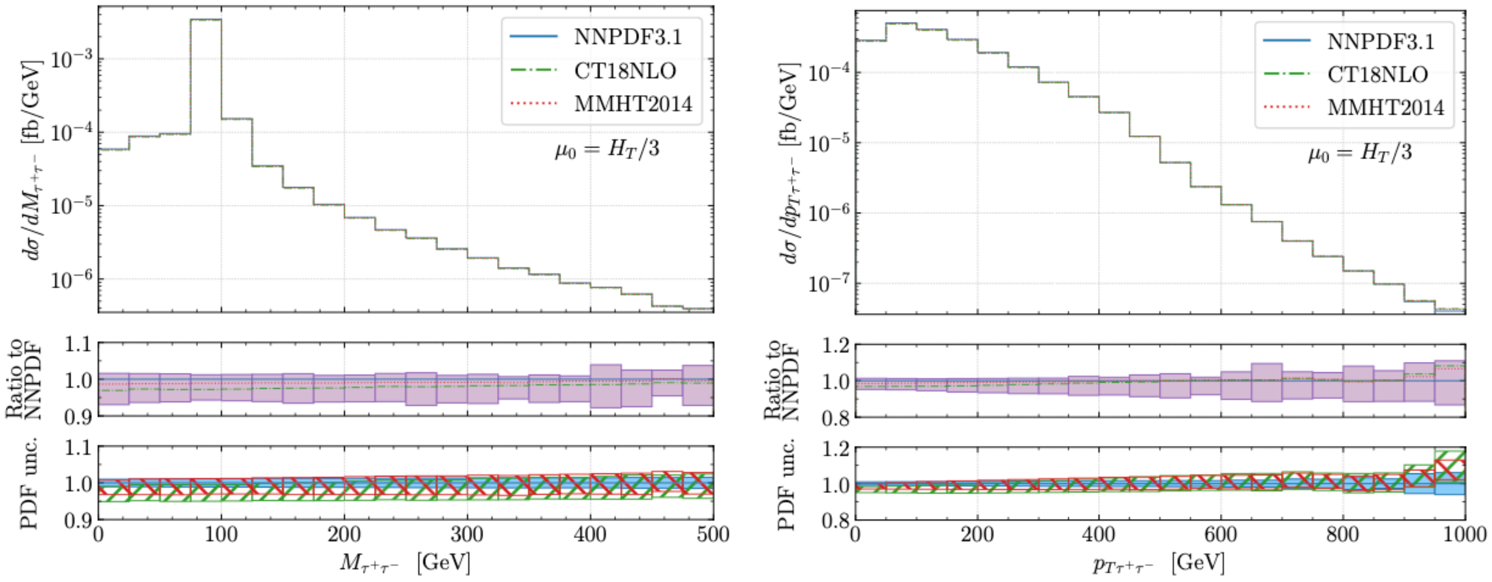


Integrated level



Differential level

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

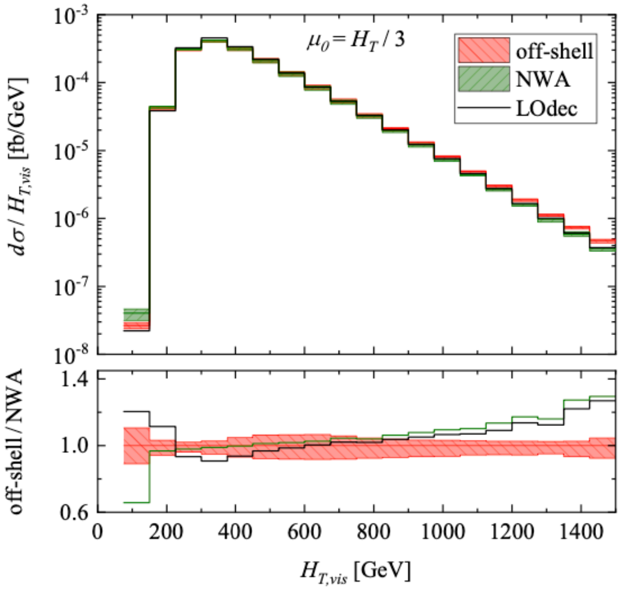
How Good is NWA

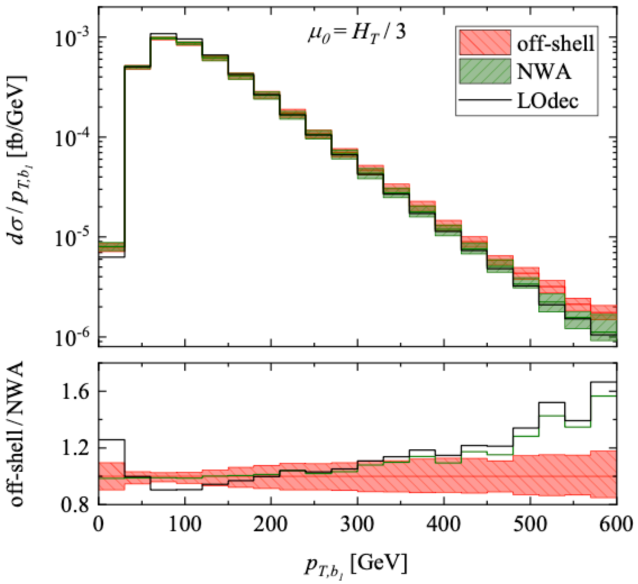
NLO ttW

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

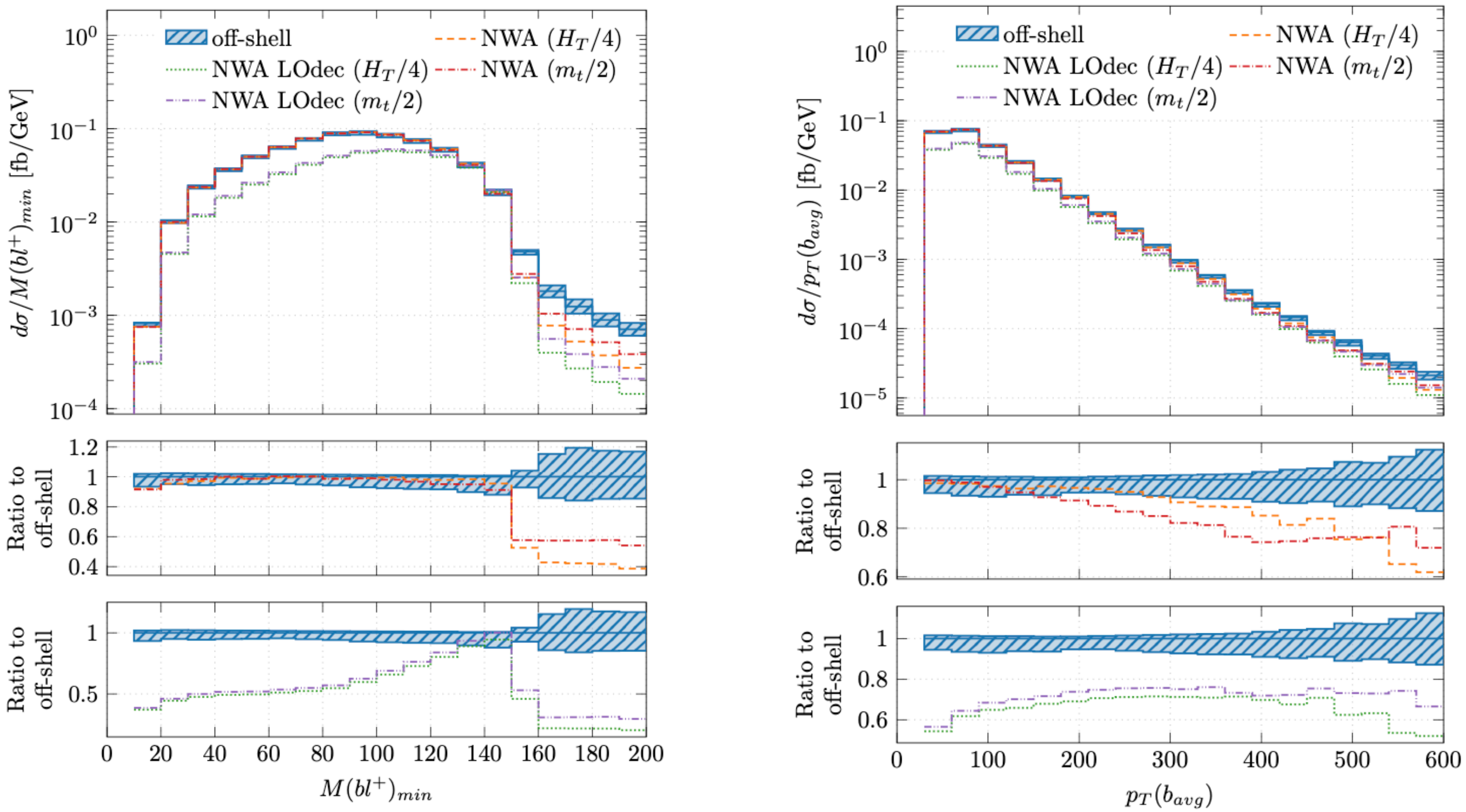
- Off-shell effects up to *60% - 70%*
- Substantial differences between NWA & $\text{NWA}_{\text{LODECAY}}$

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



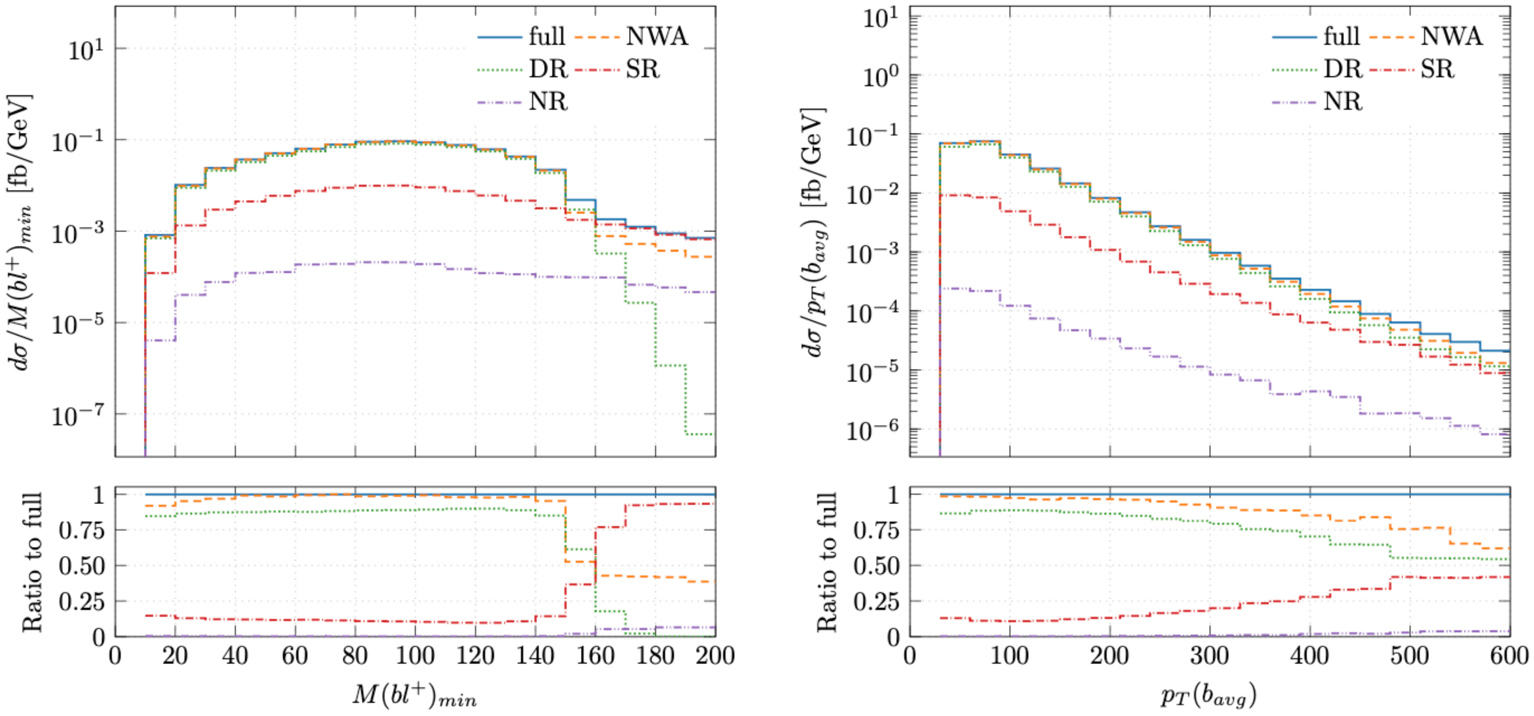
Dimensionful observables

- 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



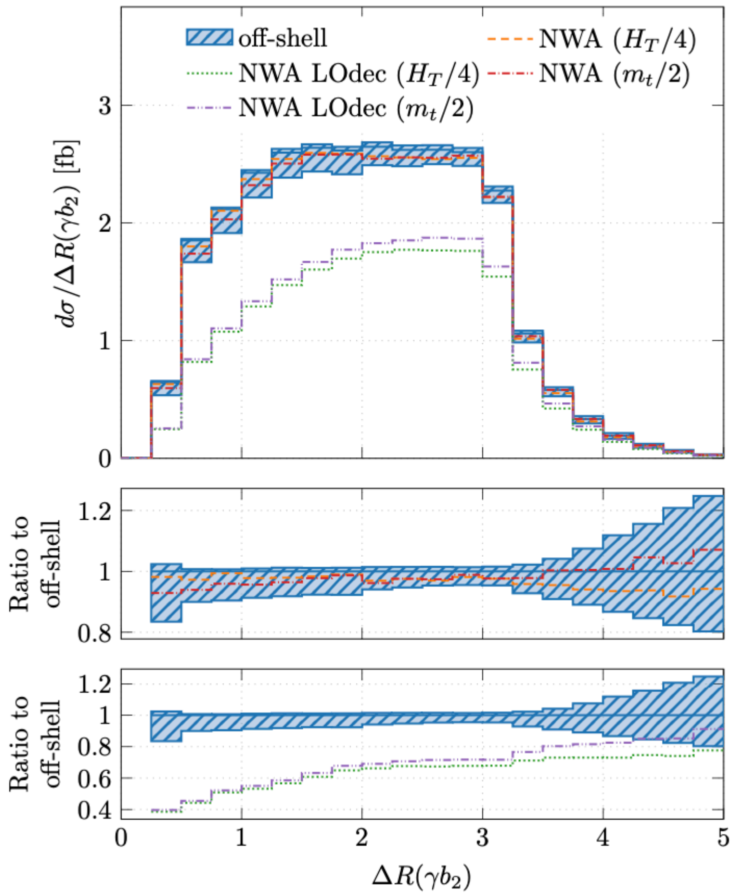
$$pp \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}\,\gamma$$

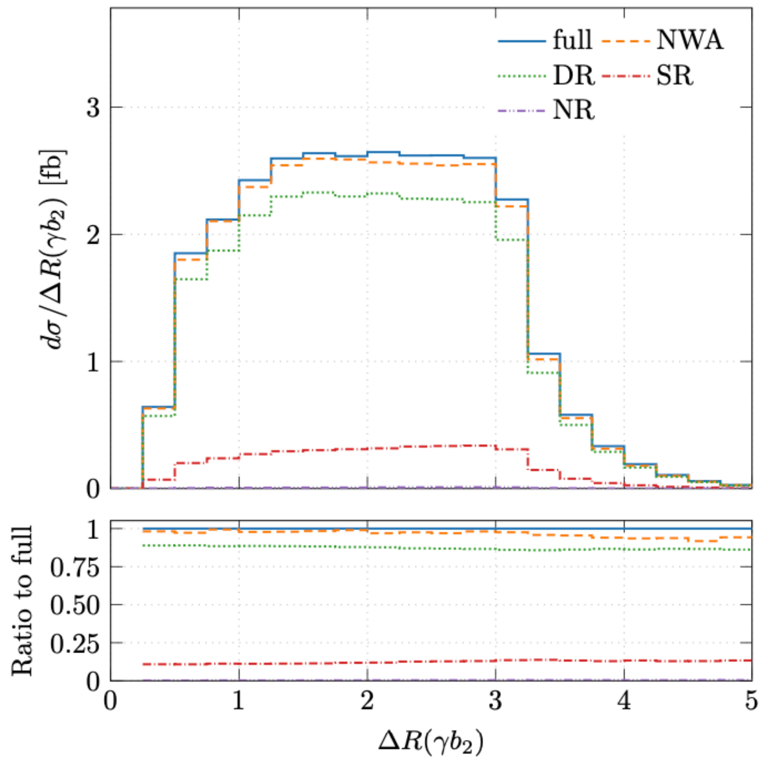
Dimensionful observables

- 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 Production & Decays

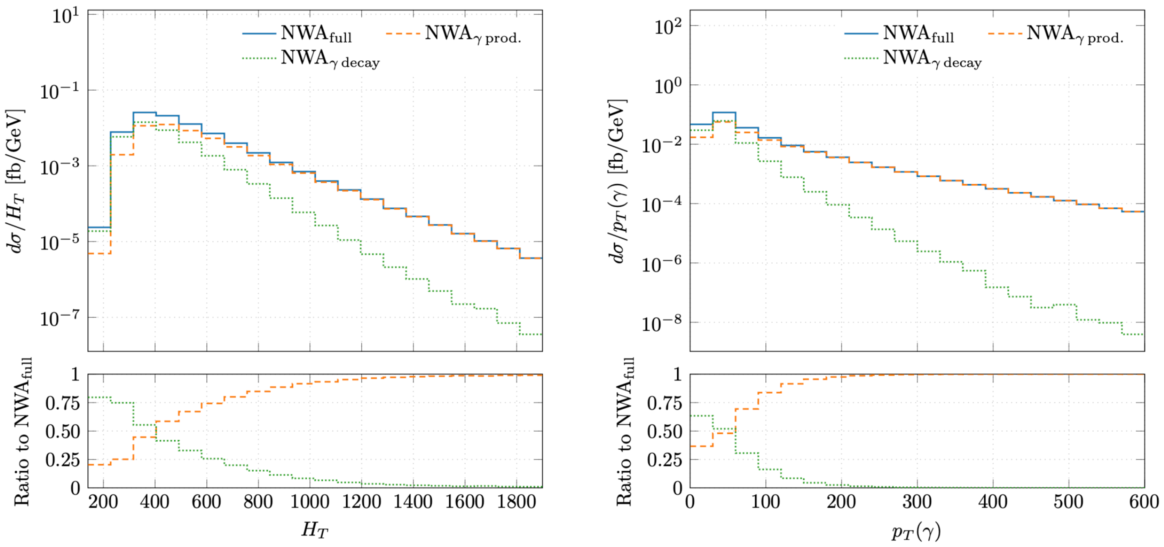
NLO $tt\gamma$

Bevilacqua, Hartanto, Kraus, Weber, Worek '20

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

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

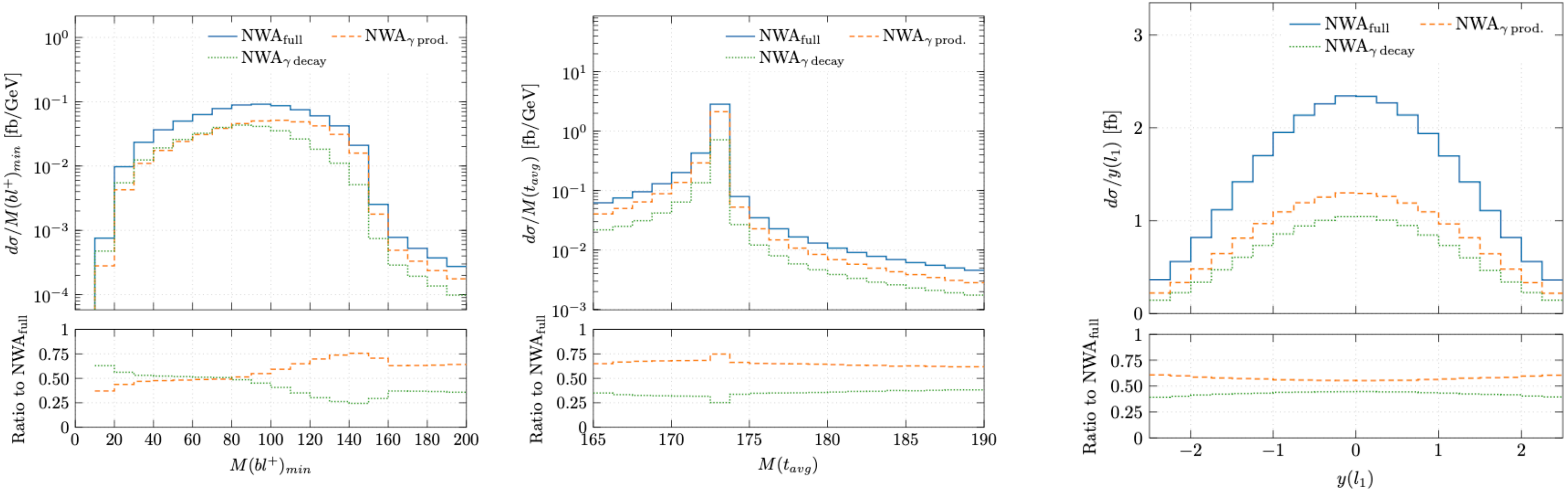
- For $p_{T,b} > 40$ GeV
  - *57%* ➪ γ emitted in production
  - *43%* ➪ γ emitted in decay stage
- NLO QCD corrections to top quark decays
  - *12% - 17%*



Photon in Production & Decays

NLO $tt\gamma$

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



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Diverse picture

Photons in Production & Decays

NLO $t t\gamma\gamma$

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

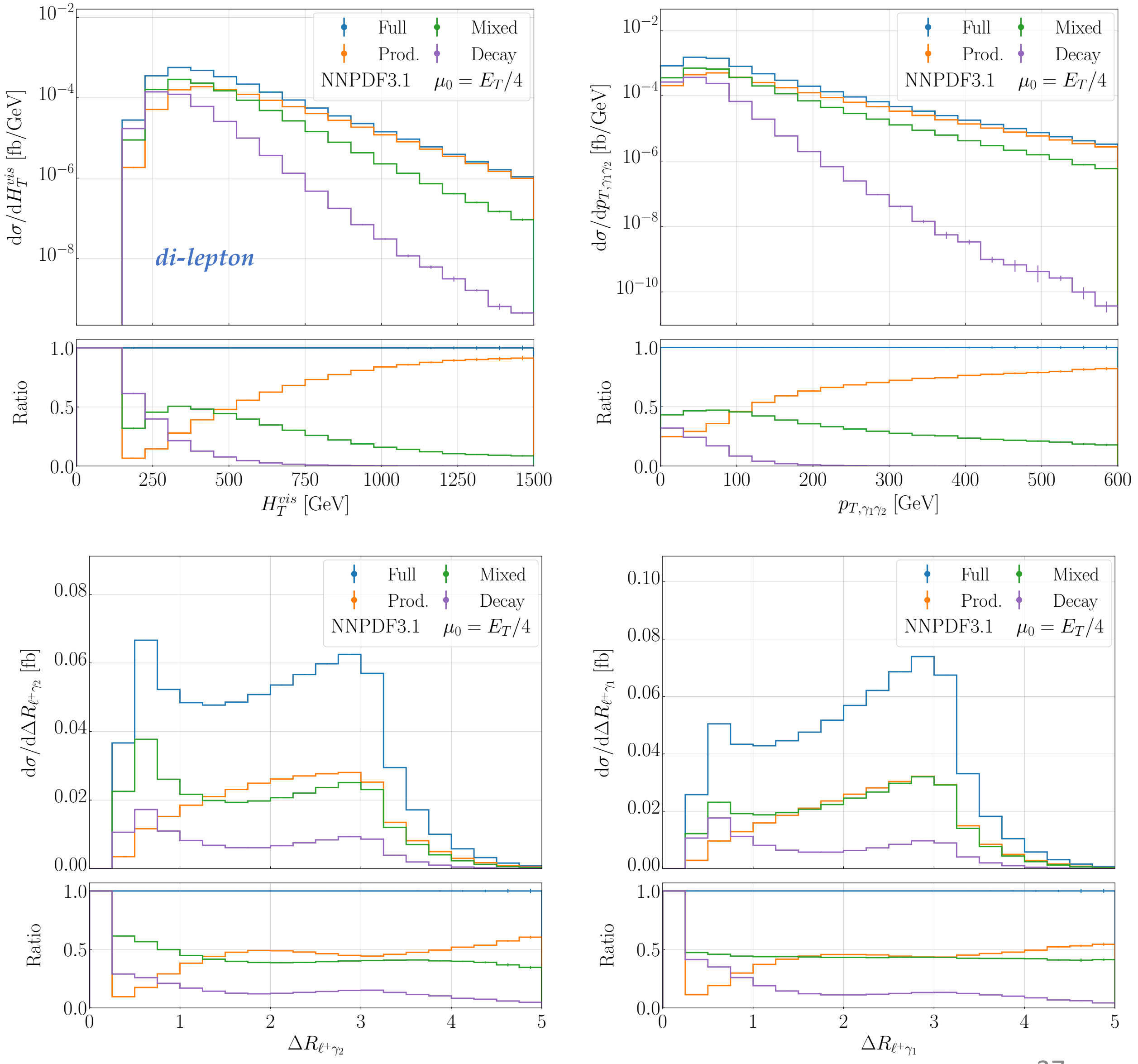
$$d\sigma_{\rm Full} = \overbrace{d\sigma_{t\bar{t}\gamma\gamma} \times \frac{d\Gamma_t}{\Gamma_t} \times \frac{d\Gamma_{\bar{t}}}{\Gamma_t}}^{\sigma_{\rm Prod.}} + \overbrace{d\sigma_{t\bar{t}\gamma} \times \left(\frac{d\Gamma_{t\gamma}}{\Gamma_t} \times \frac{d\Gamma_{\bar{t}}}{\Gamma_t} + \frac{d\Gamma_t}{\Gamma_t} \times \frac{d\Gamma_{\bar{t}\gamma}}{\Gamma_t} \right)}^{\sigma_{\rm Mixed}}$$
$$\underbrace{+ \, d\sigma_{t\bar{t}} \times \left(\frac{d\Gamma_{t\gamma\gamma}}{\Gamma_t} \times \frac{d\Gamma_{\bar{t}}}{\Gamma_t} + \frac{d\Gamma_t}{\Gamma_t} \times \frac{d\Gamma_{\bar{t}\gamma\gamma}}{\Gamma_t} + \frac{d\Gamma_{t\gamma}}{\Gamma_t} \times \frac{d\Gamma_{\bar{t}\gamma}}{\Gamma_t} \right)}_{\sigma_{\rm Decay}} .$$

- Integrated fiducial cross-section level

  $p_{T,b} > 25$ GeV, $p_{T,\gamma} > 25$ GeV:

  - *Mixed contribution* at the level of *44%*
  - *Prod. contribution* at the level of *40%*
  - *Decay contribution* is about half the size *16%*
- Differential fiducial cross-section level
  - Various phase-space regions with various effects

Stremmer, Worek '23



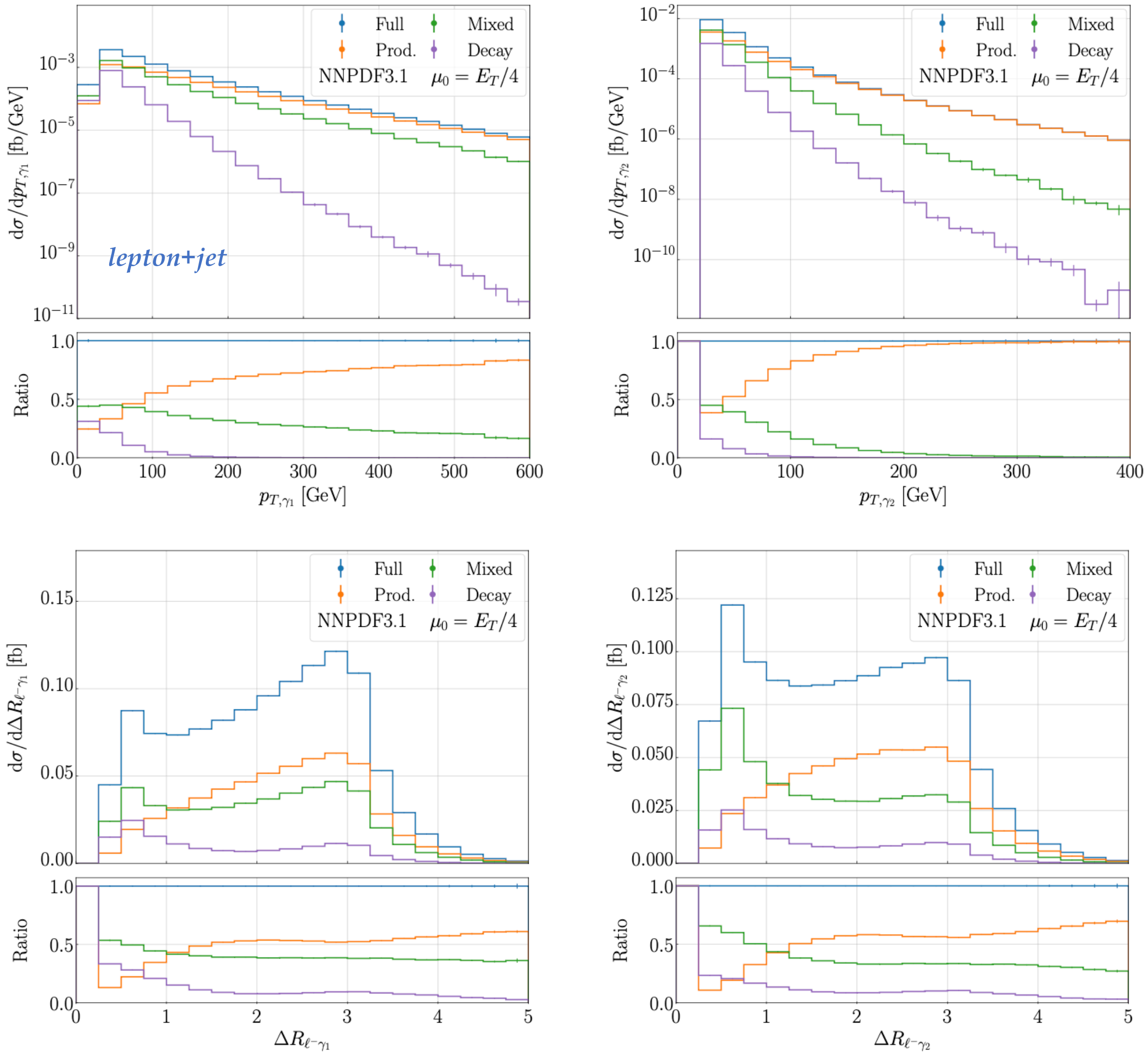
Photons in Production & Decays

NLO $tt\gamma\gamma$

$$pp \to \ell^- \bar{\nu}_\ell \, jj \, b\bar{b} \, \gamma\gamma$$

$$d\sigma_{\rm Full} = \overbrace{d\sigma_{t\bar{t}\gamma\gamma} \times \frac{d\Gamma_t}{\Gamma_t} \times \frac{d\Gamma_{\bar{t}}}{\Gamma_t}}^{\sigma_{\rm Prod.}} + \overbrace{d\sigma_{t\bar{t}\gamma} \times \left(\frac{d\Gamma_{t\gamma}}{\Gamma_t} \times \frac{d\Gamma_{\bar{t}}}{\Gamma_t} + \frac{d\Gamma_t}{\Gamma_t} \times \frac{d\Gamma_{\bar{t}\gamma}}{\Gamma_t} \right)}^{\sigma_{\rm Mixed}}$$
$$+ \underbrace{d\sigma_{t\bar{t}} \times \left(\frac{d\Gamma_{t\gamma\gamma}}{\Gamma_t} \times \frac{d\Gamma_{\bar{t}}}{\Gamma_t} + \frac{d\Gamma_t}{\Gamma_t} \times \frac{d\Gamma_{\bar{t}\gamma\gamma}}{\Gamma_t} + \frac{d\Gamma_{t\gamma}}{\Gamma_t} \times \frac{d\Gamma_{\bar{t}\gamma}}{\Gamma_t} \right)}_{\sigma_{\rm Decay}} .$$

- Integrated fiducial cross-section level with and without $|m_W - M_{jj}| < Q_{\rm cut} = 15$ GeV $p_{T,b} > 25$ GeV, $p_{T,j} > 25$ GeV, $p_{T,\gamma} > 25$ GeV:
  - *Prod. contribution* at the level of *48%* ⇨ *40%*
  - *Mixed contribution* at the level of *40%* ⇨ *43%*
  - *Decay contribution* is about half the size *12%* ⇨ *17%*



Stremmer, Worek '23

Initial State Bottom Quarks

NLO $t\bar{t}b\bar{b}$

Charge aware and charge blind schemes for b-jet tagging

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

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

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

- 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 '23*

LO

$\sigma^{\rm LO}_{\rm no\,b} = 6.813(3)$ fb

$\sigma^{\rm LO}_{\rm aware} = 6.822(3)$ fb

$\sigma^{\rm LO}_{\rm blind} = 6.828(3)$ fb

impact: ~0.2%

NLO

$\sigma^{\rm NLO}_{\rm no\,b} = 13.22(3)$ fb

$\sigma^{\rm NLO}_{\rm aware} = 13.31(3)$ fb

$\sigma^{\rm NLO}_{\rm blind} = 13.38(3)$ fb

impact: ~1%

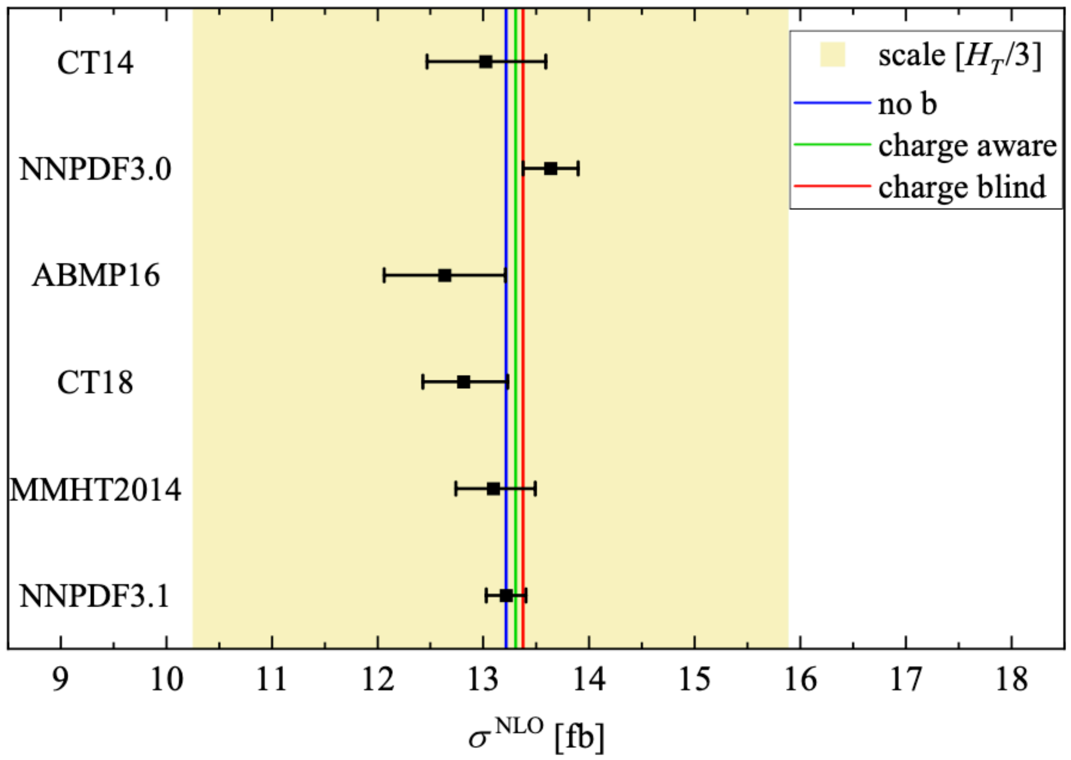
Bevilacqua, Bi, Hartanto, Kraus, Lupattelli, Worek '21

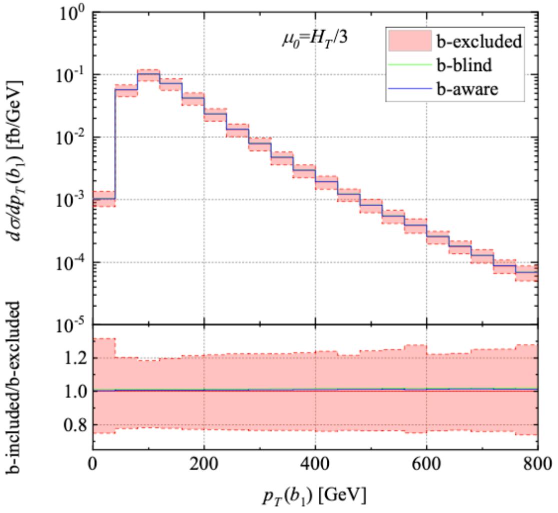
Initial State Bottom Quarks

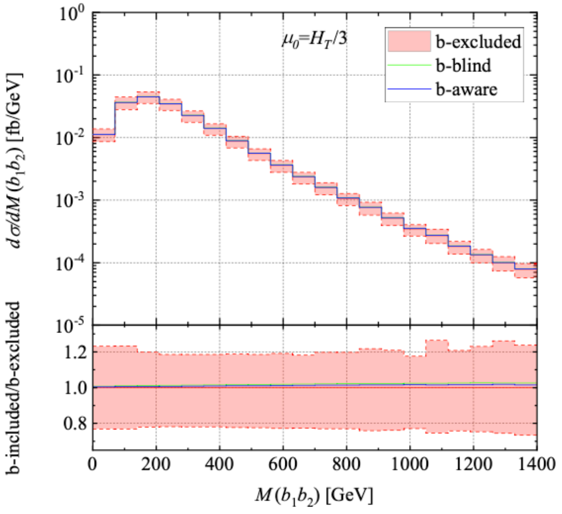
$$pp \to e^+\nu_e\, \mu^-\bar{\nu}_\mu\, b\bar{b}\, b\bar{b}$$

Negligible contribution

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







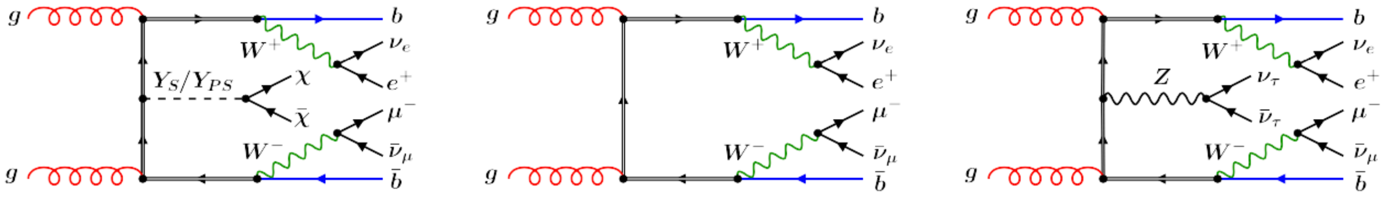
Bevilacqua, Bi, Hartanto, Kraus, Lupattelli, Worek '21

Application I: BSM Exclusion Limits

NLO $t\bar{t}Z$

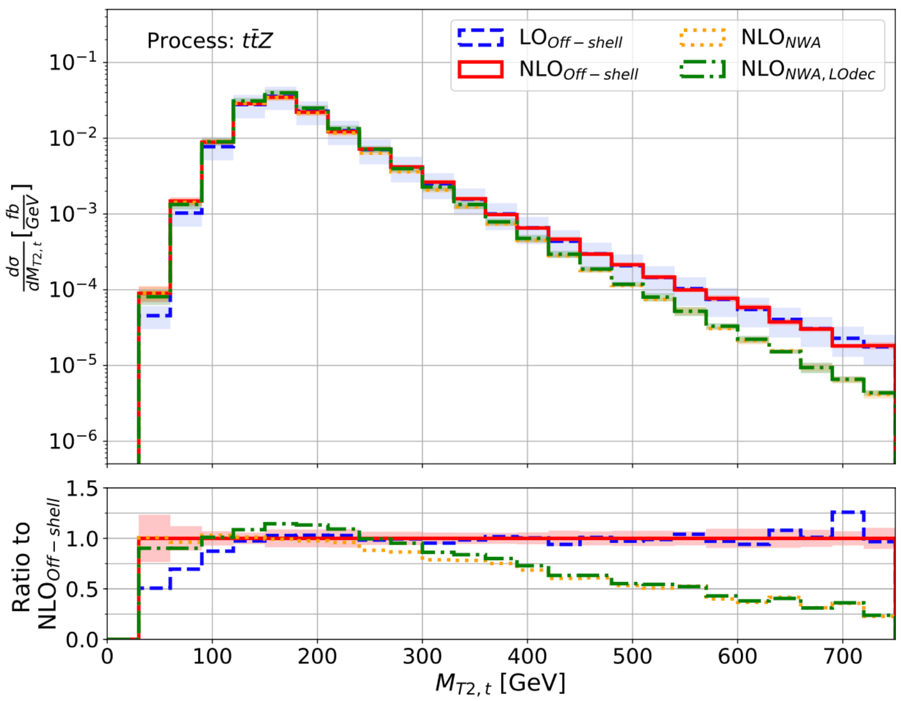
- BSM ➪ Kinematical edges & high p_T regions
- $t\bar{t} + DM$ ➪ Top quark backgrounds: $t\bar{t}$ & $t\bar{t}Z$
- Observable ➪ $M_{T2,W}$ & $M_{T2,t}$ & p_T^{miss}

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



Before & after applying additional cuts

Process	Order	Scale	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 $t\bar{t}$
- NLO smaller uncertainties w.r.t LO, NLO + LO decays

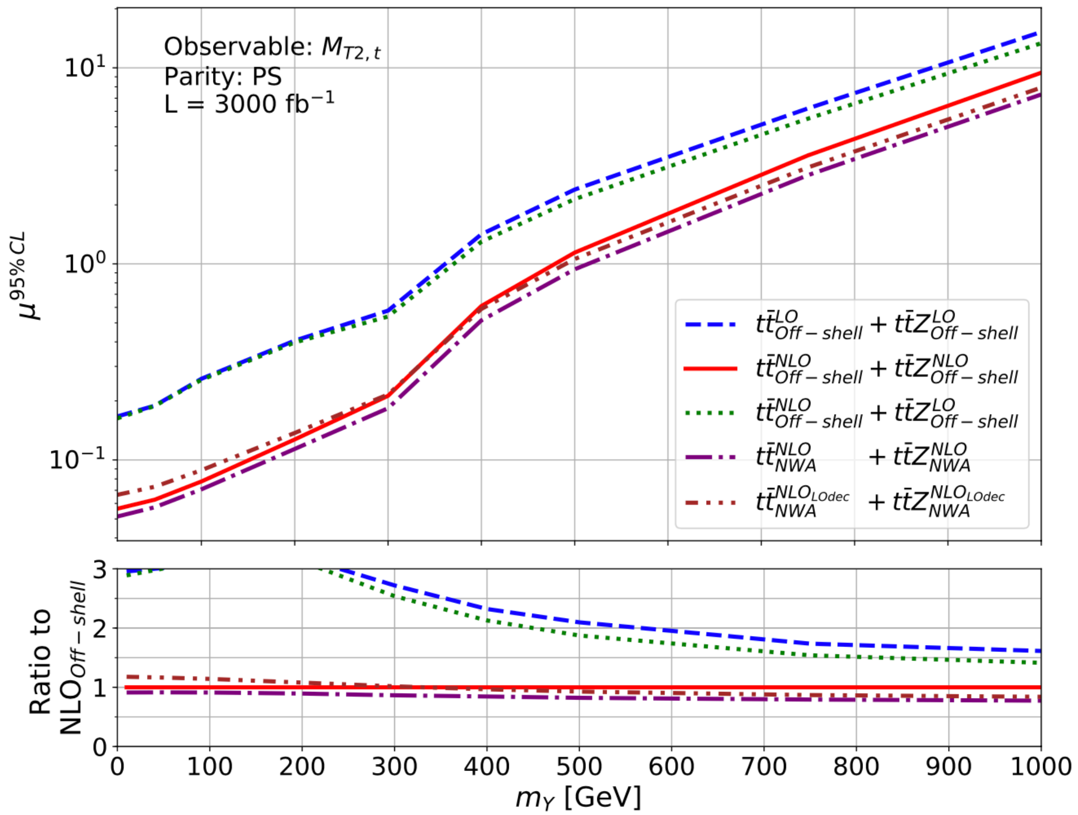
Hermann, Worek '21

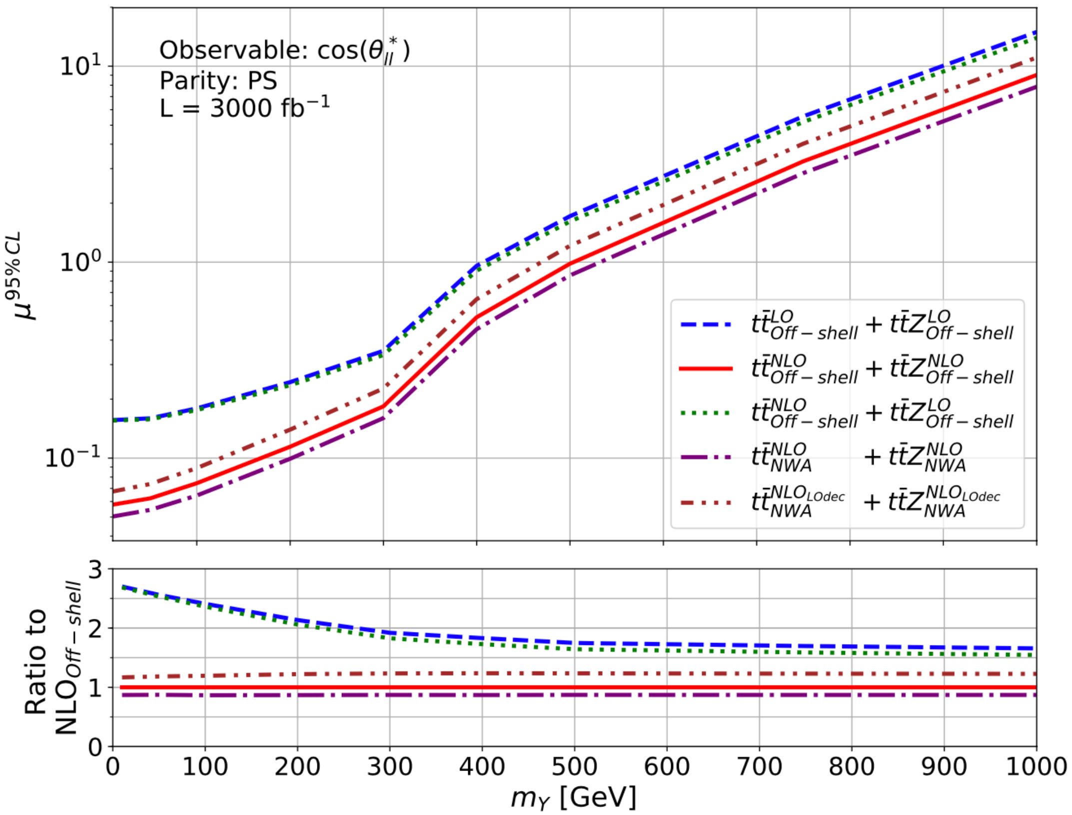
Application I: BSM Exclusion Limits

NLO ttZ

Comparison of signal strength exclusion limits

Hermann, Worek '21





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

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

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

Application II: Top Charge Asymmetry

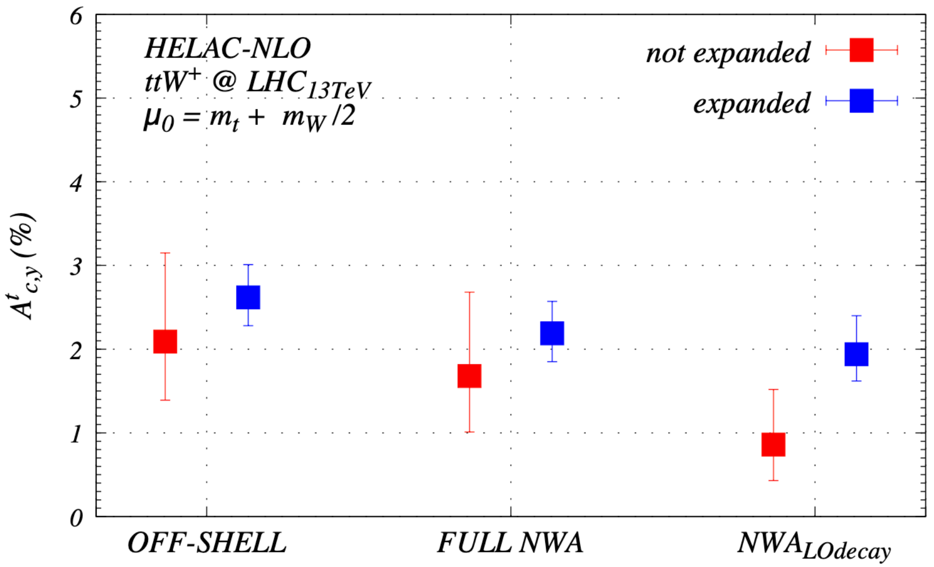
NLO ttW

Searching for more precise observables

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

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

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



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

- 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

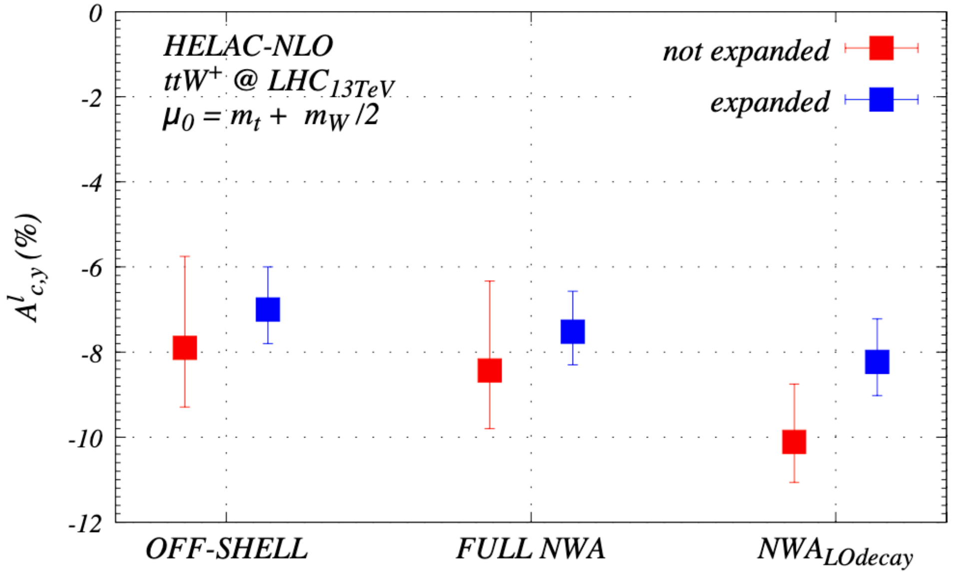
$t\bar{t}W^+$, $\mu_0 = H_T/3$	Off-shell	Full NWA	$\text{NWA}_{\text{LOdecay}}$
$A^t_{c,y}$ [%]	$2.36(8)^{+1.19\,(50\%)}_{-0.77\,(33\%)}$	$1.93(5)^{+1.23\,(64\%)}_{-0.72\,(37\%)}$	$1.11(3)^{+0.55\,(49\%)}_{-0.53\,(48\%)}$
$A^t_{c,exp,y}$ [%]	$2.66(10)^{+0.38\,(14\%)}_{-0.34\,(13\%)}$	$2.20(5)^{+0.45(20\%)}_{-0.31(14\%)}$	$2.08(5)^{+0.24\,(11\%)}_{-0.40\,(19\%)}$

$t\bar{t}W^+$, $\mu_0 = m_t + m_W/2$	Off-shell	Full NWA	$\text{NWA}_{\text{LOdecay}}$
$A^t_{c,y}$ [%]	$2.09(8)^{+1.06\,(51\%)}_{-0.70\,(33\%)}$	$1.68(4)^{+1.00(60\%)}_{-0.67(40\%)}$	$0.86(3)^{+0.66\,(77\%)}_{-0.43\,(50\%)}$
$A^t_{c,exp,y}$ [%]	$2.62(10)^{+0.39\,(15\%)}_{-0.34\,(13\%)}$	$2.19(4)^{+0.38(17\%)}_{-0.34(16\%)}$	$1.94(5)^{+0.46\,(24\%)}_{-0.32\,(16\%)}$

Application II: Top Charge Asymmetry

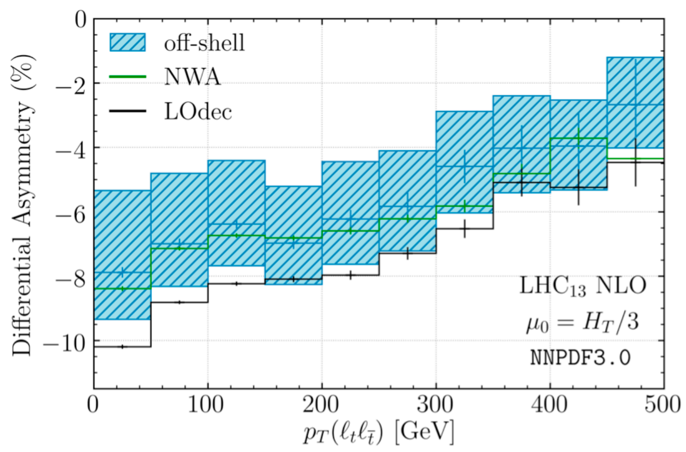
NLO ttW

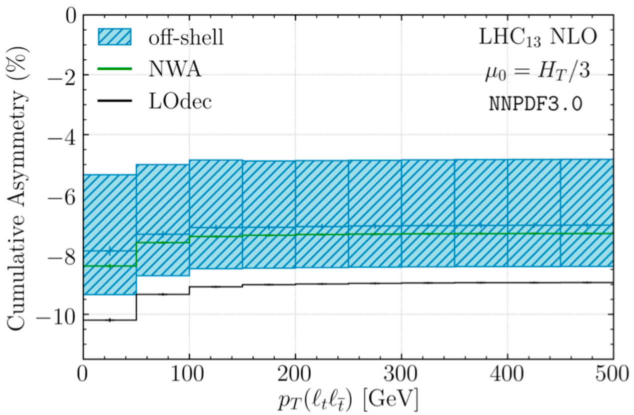
Bevilacqua, Bi, Hartanto, Kraus, Nasufi, Worek '21



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

Differential & Cumulative A^ℓ_c





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

Application III: Yukawa Coupling

NLO ttH

α_{CP}		Off-shell	NWA	Off-shell effects
0 (SM) *CP-even*	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)	
$\pi/4$ *CP-mixed*	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)	
$\pi/2$ *CP-odd*	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)	

- Off-shell effects @ integrated fiducial level:
  - Small for *CP-even* and *CP-mixed* Higgs boson
  - Large effects for *CP-odd* Higgs boson

Hermann, Stremmer, Worek '22

- Higgs characterisation framework

Mixing angle

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

CP-even *CP-odd*

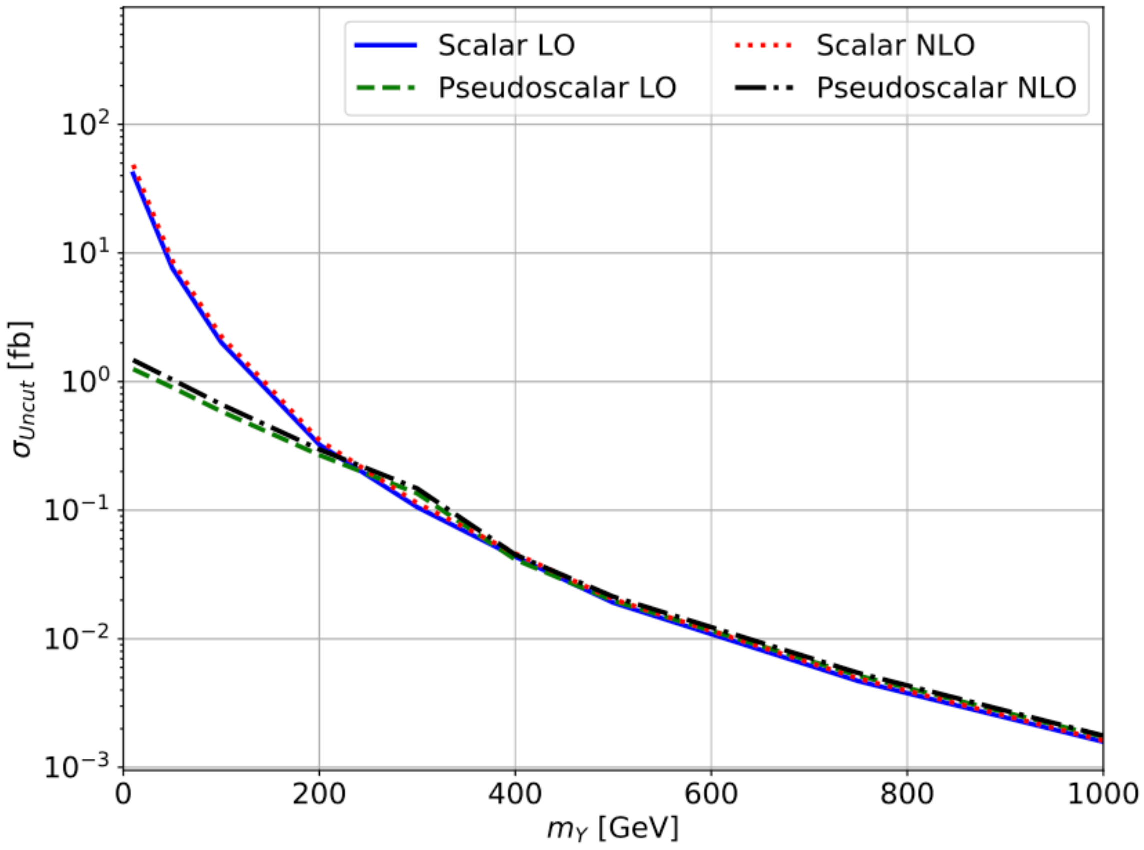
$$\mathcal{L}_{HVV} = \kappa_{HVV} \left(\frac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W_\mu^+ W^{-\mu}\right) H,$$

Coupling choices: $\kappa_{At\bar{t}} = 2/3,\ \kappa_{Ht\bar{t}} = 1,\ \kappa_{HVV} = 1$
Ensure consistency with current experimental bounds (ggF, VBF)

Artoisenet et al. '13, Maltoni et al. '14, Demartin et al. '14, Demartin et al. '15

Scalar versus Pseudoscalar Production

Hermann, Worek '21



- Cross section for $pp \to b\bar{b}\, e^+\mu^-\, \nu_e\bar{\nu}_\mu\, \chi\bar{\chi}$ with scalar & pseudoscalar mediators depending on the mass m_Y

- Production of pseudoscalar in association with top quarks is suppressed compared to scalar for masses below ~ 200 GeV if the two couplings $\kappa_{Ht\bar{t}} = \kappa_{At\bar{t}} = 1$

Haisch, Pani, Polesello '17

- This difference can be understood when looking at $t \to t + H/A$ fragmentation functions

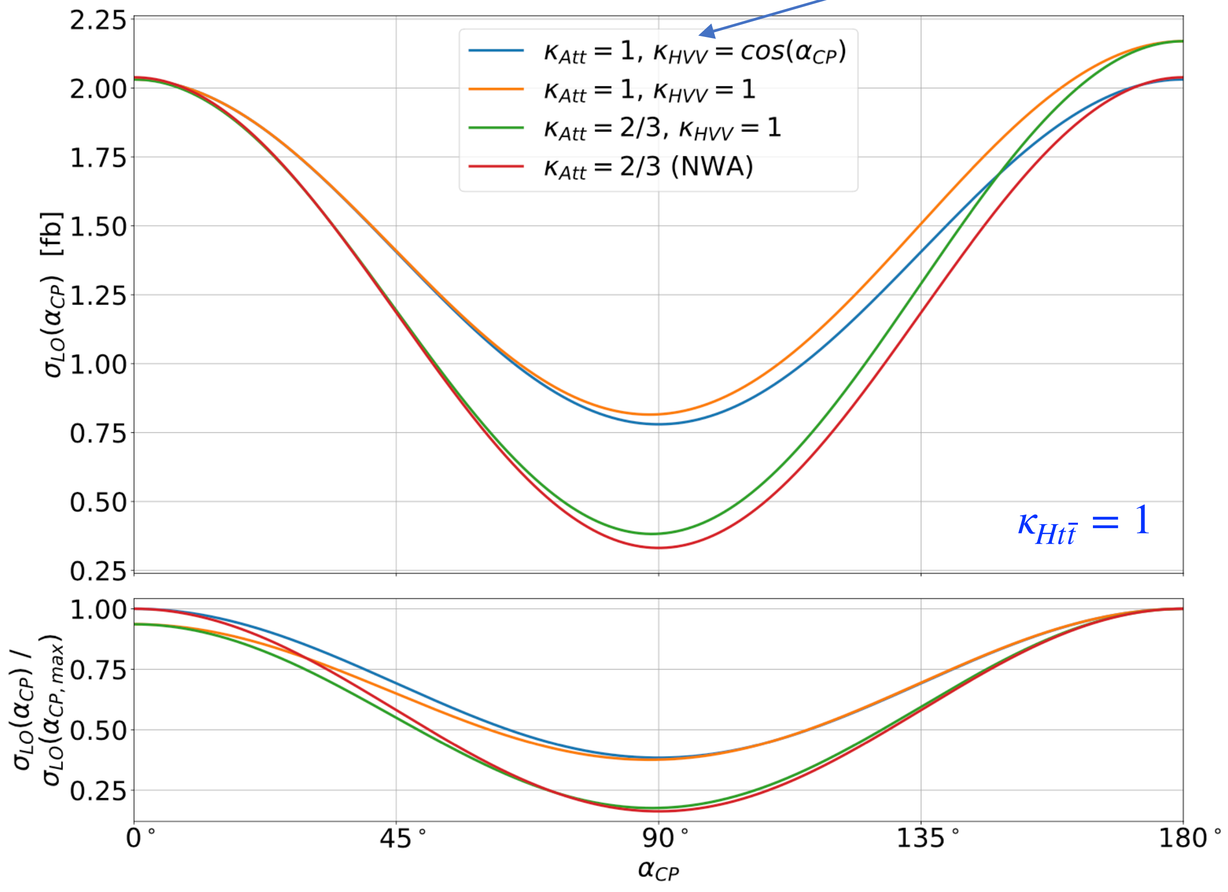
$$f_{t\to t+H}(x) = \frac{\kappa^2_{Ht\bar{t}}}{(4\pi)^2}\left[\frac{4(1-x)}{x} + x\ln\left(\frac{s}{m_t^2}\right)\right]$$
$$f_{t\to t+A}(x) = \frac{\kappa^2_{At\bar{t}}}{(4\pi)^2}\left[x\ln\left(\frac{s}{m_t^2}\right)\right],$$

Dawson, Reina '98
Dittmaier, Krämer, Liao, Spira, Zerwas '20

- x momentum fraction that Higgs boson carries
- Scalar fragmentation function has additional $1/x$
- Enhanced production of soft scalar compared to pseudoscalars

Application III: Yukawa Coupling

NLO ttH



Hermann, Stremmer, Worek '22

- Cross sections in NWA symmetric with respect to

$$\alpha_{CP} \to \pi - \alpha_{CP}$$

- Equivalent to changing sign of Y_t

- In full off-shell case symmetry is present if we set

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

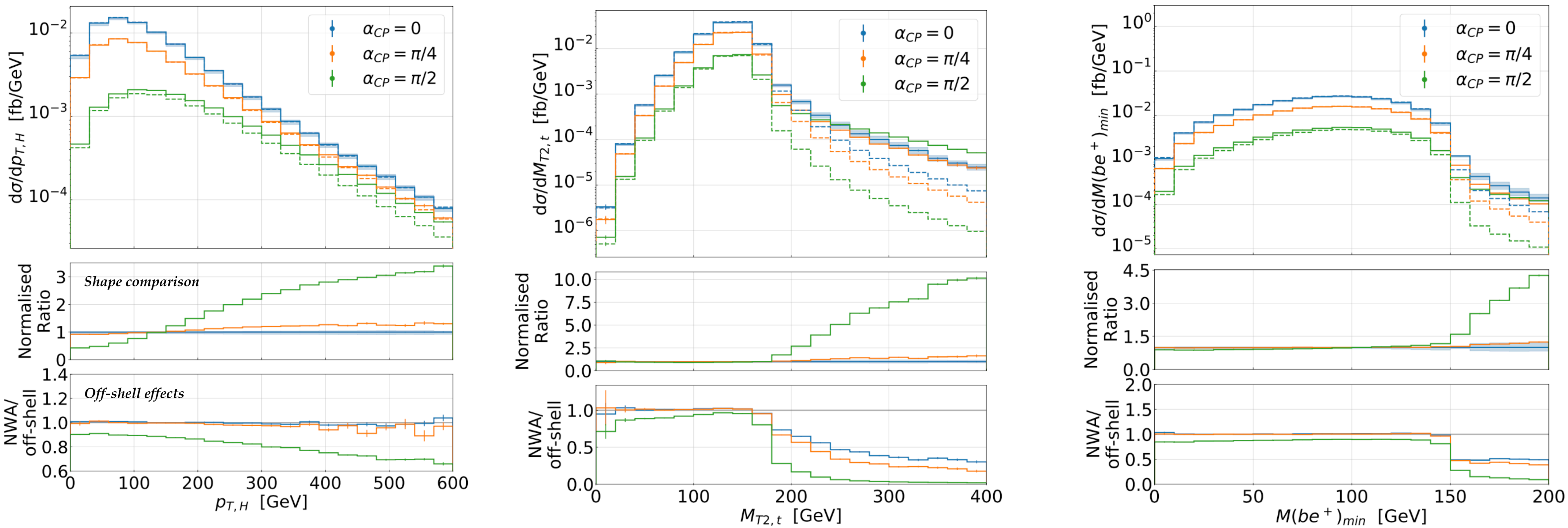
- Symmetry is broken if we take $\kappa_{HVV} = 1$

- *Interference:* Higgs boson radiated off W/Z ➪ *SR & NR* ➪ Higgs boson emitted top quarks ➪ *DR & SR*

  - *CP-even*
  - *CP-mixed*
  - *CP-odd*

Application III: Yukawa Coupling

NLO *ttH*



- *CP-even*
- *CP-mixed*
- *CP-odd*

- Off-shell effects @ differential fiducial level:
  - Large effects on size and shape for CP-odd Higgs boson
  - Only small effects for CP-even and CP-mixed
  - *Reason: SR contributions ~ tWHb production*

Hermann, Stremmer, Worek '22

Full Off-shell Effects Versus NWA

- Impact on IR-safe (integrated) cross sections ➪ Normalisation
- Impact on IR-safe (differential) cross sections ➪ Shape of distributions
- Impact on SM observables ➪ $A_c^t,\ A_c^\ell$
- Impact on SM parameter extraction ➪ m_t & Γ_t
- Impact on BSM exclusion limits ➪ $pp \to t\bar{t} + DM$ at the LHC with SM background processes $pp \to t\bar{t}$ & $t\bar{t}Z$
- Impact on New Physics ➪ Impact on signal modelling ➪ $pp \to t\bar{t}H$ with anomalous couplings
- Subtraction of $pp \to tW$ from $pp \to t\bar{t}$ and its impact on final experimental systematic uncertainties

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 $pp \to t\bar{t}$ & $t\bar{t} + X$
  - *Full-off-shell predictions:* $X = H, \gamma, W^{\pm}, Z(\to \nu_\ell \bar{\nu}_\ell), Z(\to \ell\ell), j, b\bar{b}, W^{\pm}j$
  - *NWA Results:* $X = jj, \gamma\gamma$

- 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

Backup Slides

Various Phase – Space Regions

NLO $tt\gamma$

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

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

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

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)

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

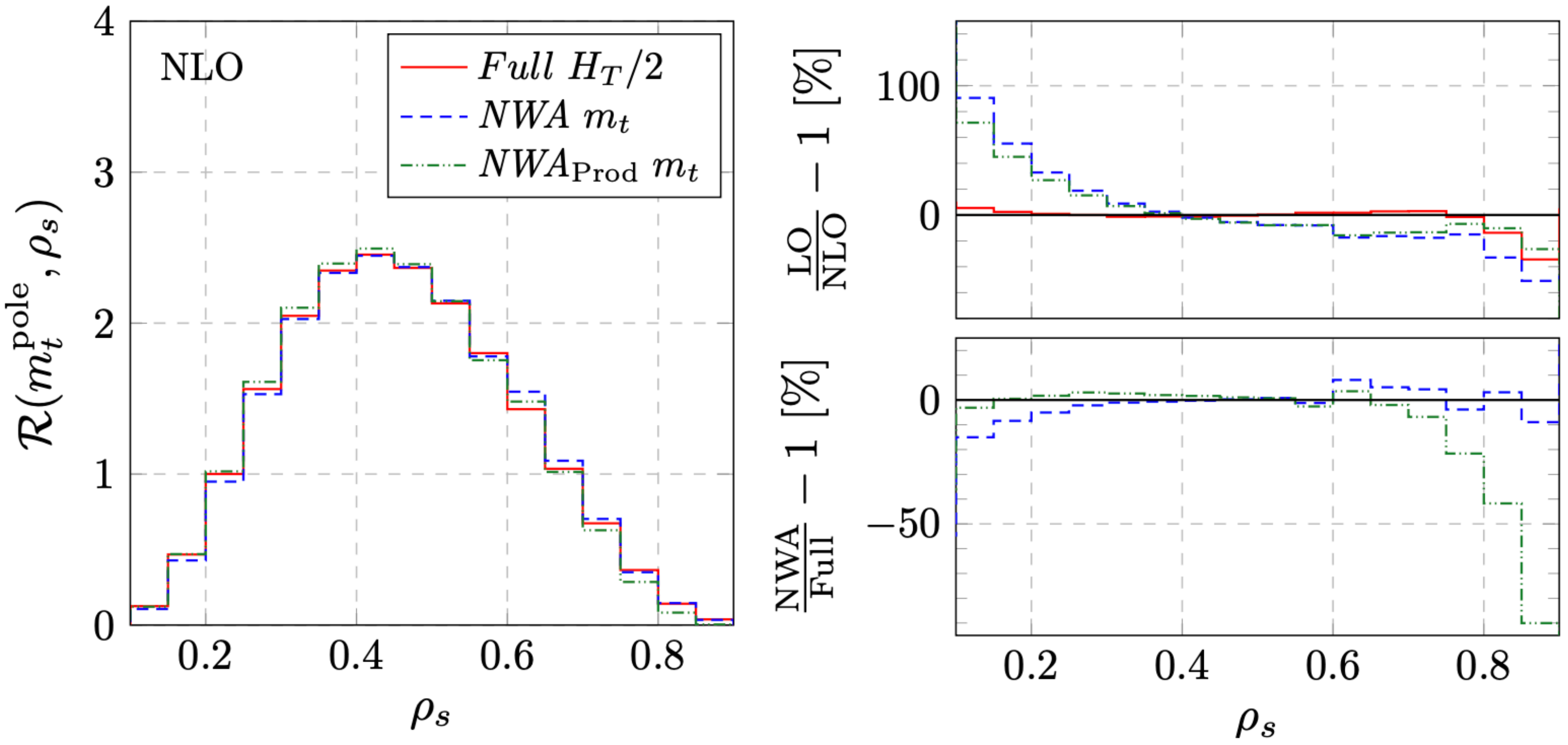
- Boundary parameter
  - Determines size of resonant region for each reconstructed top quark
  - *n = 5, 10, 15*
  - For n = 15

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

Application IV: Top-Quark Mass

NLO $t\bar{t}j$

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



Bevilacqua, Hartanto, Kraus, Schulze, Worek '18

- 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

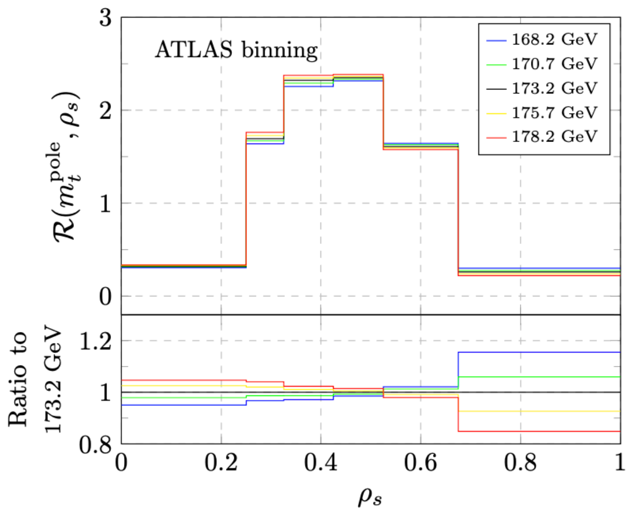
  - CMS @ 13 TeV

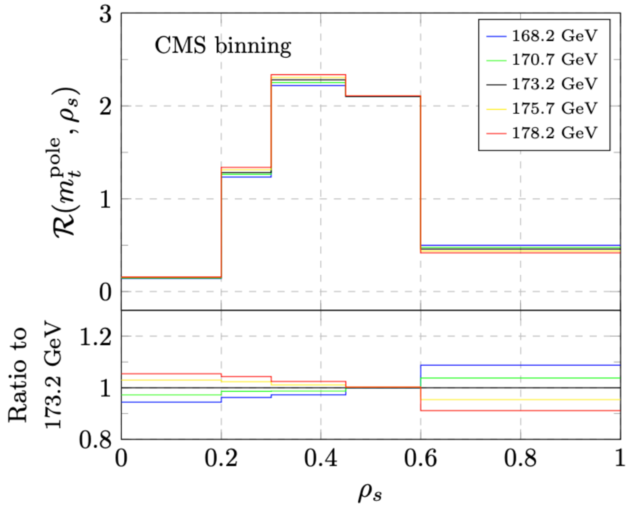
    $m_t = 172.94 \pm 1.37$ GeV

    CMS Collaboration '22

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

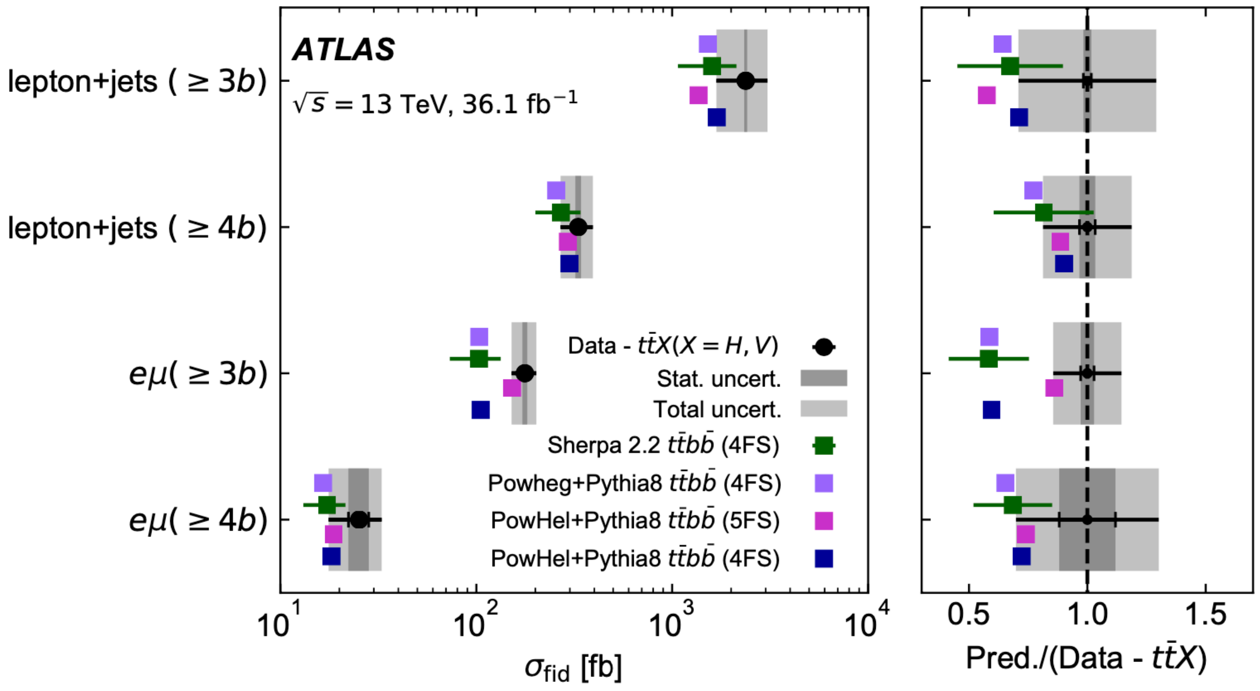
$$pp \to e^+\nu_e \mu^- \bar{\nu}_\mu b\bar{b} j$$

- Sensitivity to scaler setting and top quark modelling

Bevilacqua, Hartanto, Kraus, Schulze, Worek '18

TTBB @ NLO

ATLAS Collaboration '19



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

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

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

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

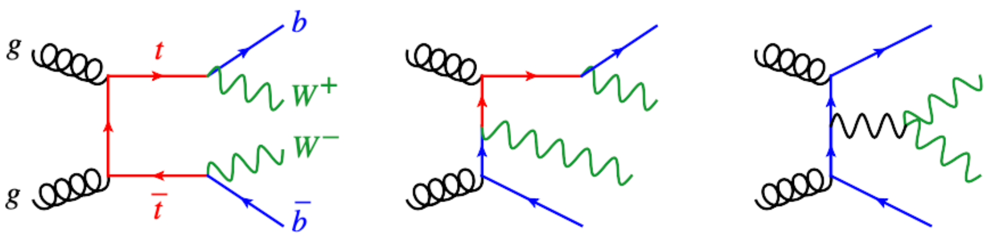
$$\sigma^{\text{ATLAS}}_{e\mu+4b} = (25 \pm 6.5)\ \text{fb}$$

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

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

TWB

Demartin, Maier, Maltoni, Mawatari, Zaro '17

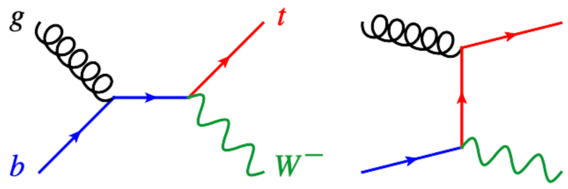


$(\mathcal{A}_{2t})$ $(\mathcal{A}_{1t})$ $(\mathcal{A}_{0t})$

- *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 $|\mathscr{A}_{2t}|^2$ 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 $tW^-\bar{b}$

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

- *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