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Theoretical Overview on Top Quark Physics

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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
  - Concentrate on general structure of our predictions
  - Special case *tt* ⇨ **NNLO**
  - *tt* + *X*, *X*=*H*, *γ*, *W*, *Z*, *j*, *jj*, *bb*, *tt*, *γγ*, … ⇨ **NLO**

My Goal

- Identify which effects are important *&* should be taken into account
- Few examples
- Vital for SM top quark physics studies *&* BSM searches *&* SM Higgs boson measurements ⇨ *ttH*

- *(Biased) Selection* ⇨ Only latest *2020 & 2021* results ⇨ Only LHC results

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

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

CERN webpage: LHC/ HL-LHC Plan

Unlike Other Quarks

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

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

World Combination '14
ATLAS, CDF, CMS, D0

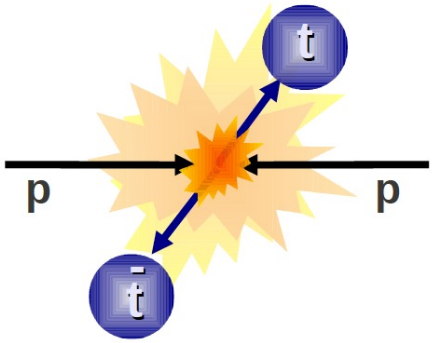
- Substantial Yukawa coupling ⇨ Special relation with SM Higgs boson

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

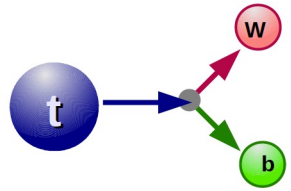
- Short lifetime ⇨ Decay before bound states can be formed
- Direct handle on top-quark properties from its decay products

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

Production



Decays



Intrinsic properties

LHC as Top Quark Factory

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

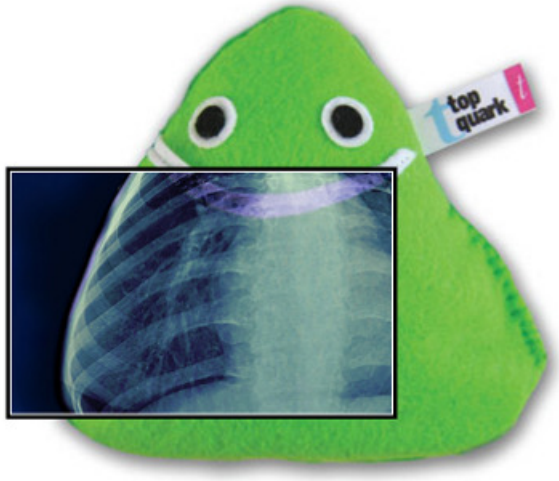
ATLAS & CMS
Statistics doubled
HL-LHC

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

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

Czakon, Mitov '14

SM & New Physics @ LHC



- Both can be Probe with Top Quark

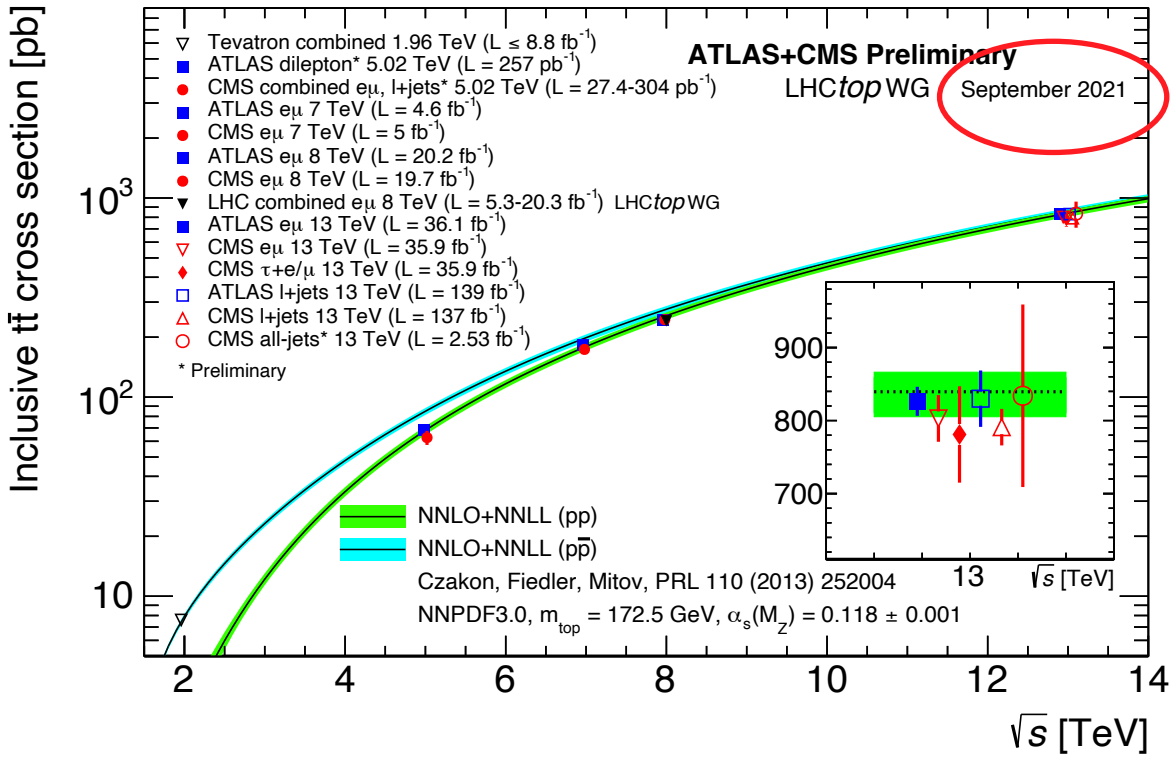
- Precision Top-Quark Physics @ LHC
  - Infrared structure of *QCD*
  - Electroweak sector of SM

- Precision Top-Quark physics & BSM Direct Searches
  - No sign of New Physics in TeV range
  - Search for new phenomena with (simplified)-models involving tops ⇨ *tt + DM*
  - *tt (+ X)* ⇨ Main backgrounds to many BSM scenarios

- Precision Top-quark physics & BSM Indirect Searches
  - Various production modes *&* decay channels *&* properties *&* rare decays *&* …
  - Extract SM parameters, constraining PDFs, verify Higgs boson couplings to top quarks *&* …
  - Study very specific infra-red safe observables as precisely as possible

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

Top-Quark Pair Production @ NNLO + NNLL



LHCTopWG

- ***LHC & Tevatron*** ⇨ σ_{tt} as function of $\sqrt{s}$
- NNLO ***QCD*** + NNLL ⇨ Top++2.0

  Czakon, Mitov '14

- Theory uncertainties due to μ_R & μ_F & ***PDF***
- Measurements & theory for $m_t = 172.5$ ***GeV***

  Czakon, Fiedler, Mitov '13

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

- NNLO ***QCD*** with all-order radiative corrections as implemented via parton-shower simulations

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

Top-Quark Pair Production & Decay @ NNLO

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

- Predictions in NWA

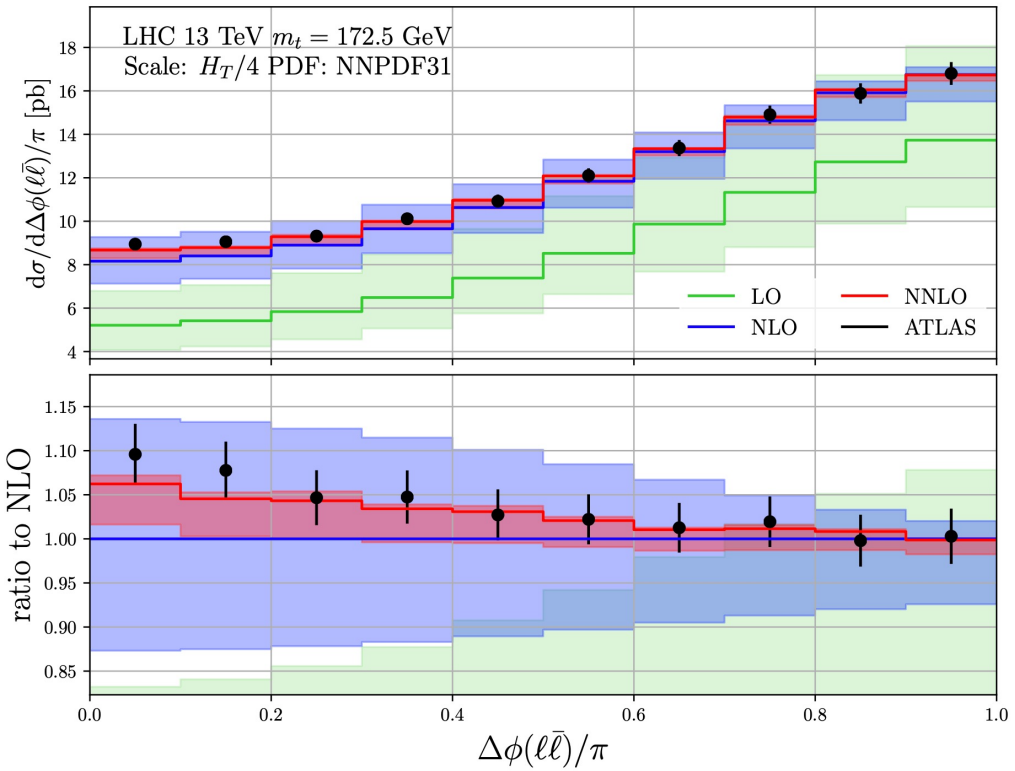
$$\mathrm{d}\sigma^{\mathrm{LO}} = \sigma^{\mathrm{LOxLO}},$$

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

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

Di-lepton

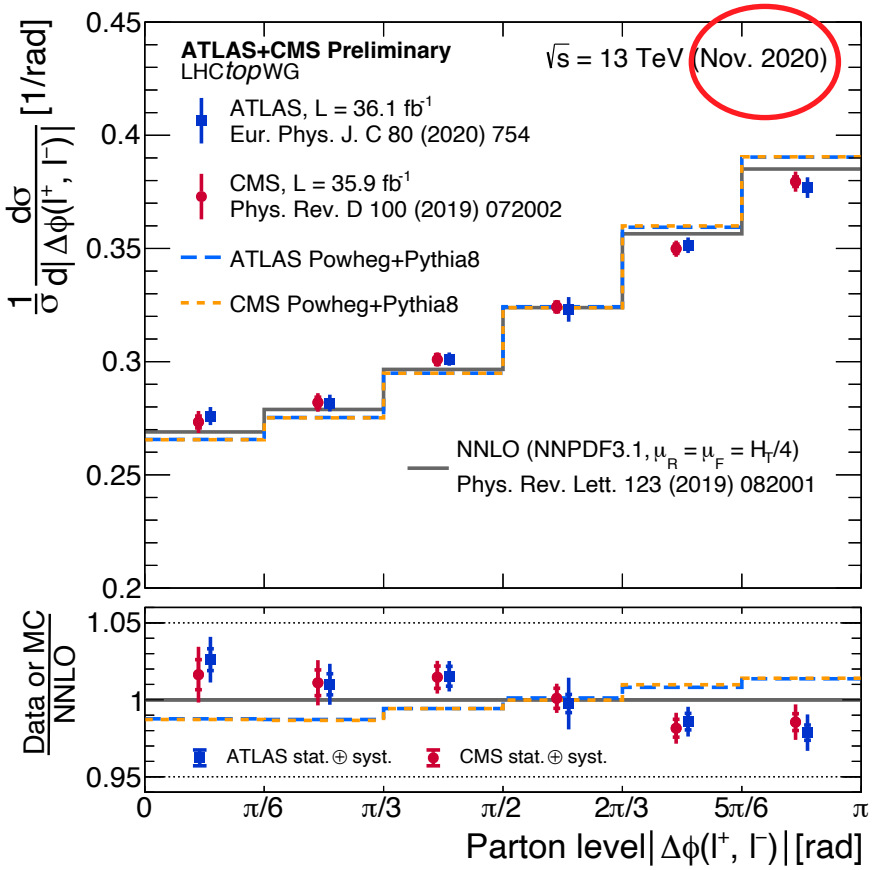
Czakon, Mitov, Poncelet '19



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

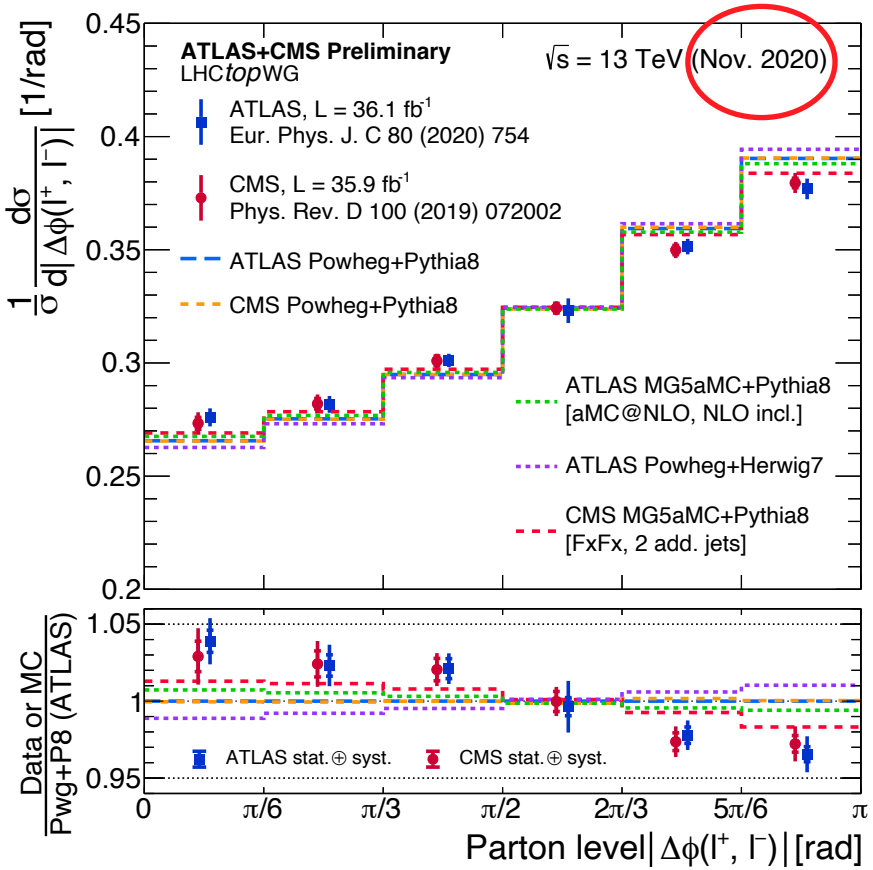
Top-Quark Pair Production & Decay @ NNLO

LHCTopWG



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

Di-lepton



- Higher order corrections in production & decay important

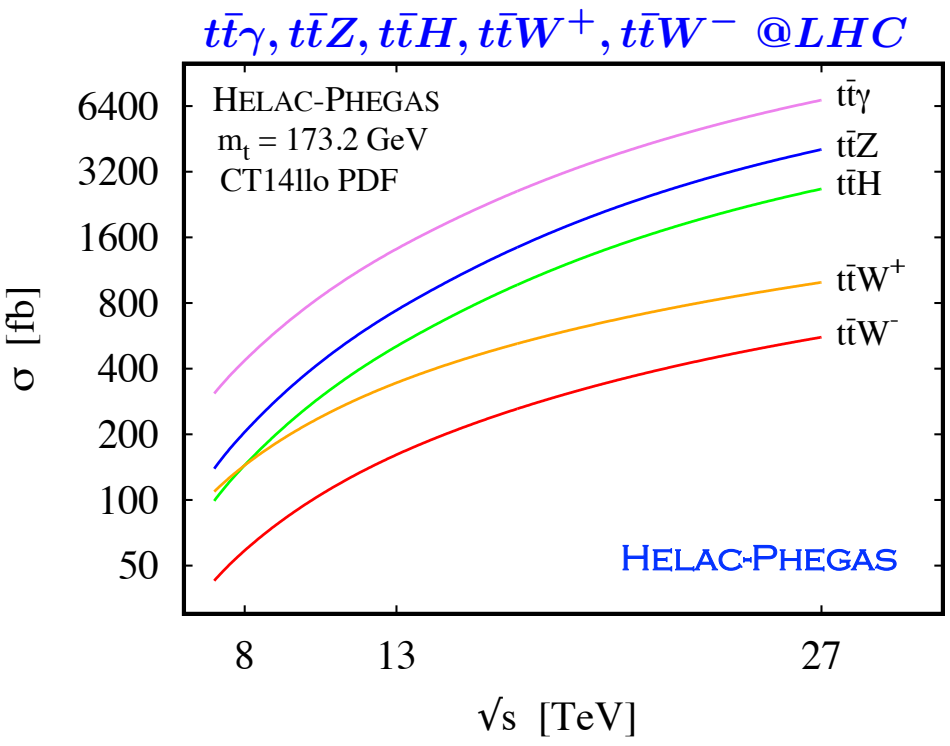
TT+X Production & Decay @ NLO

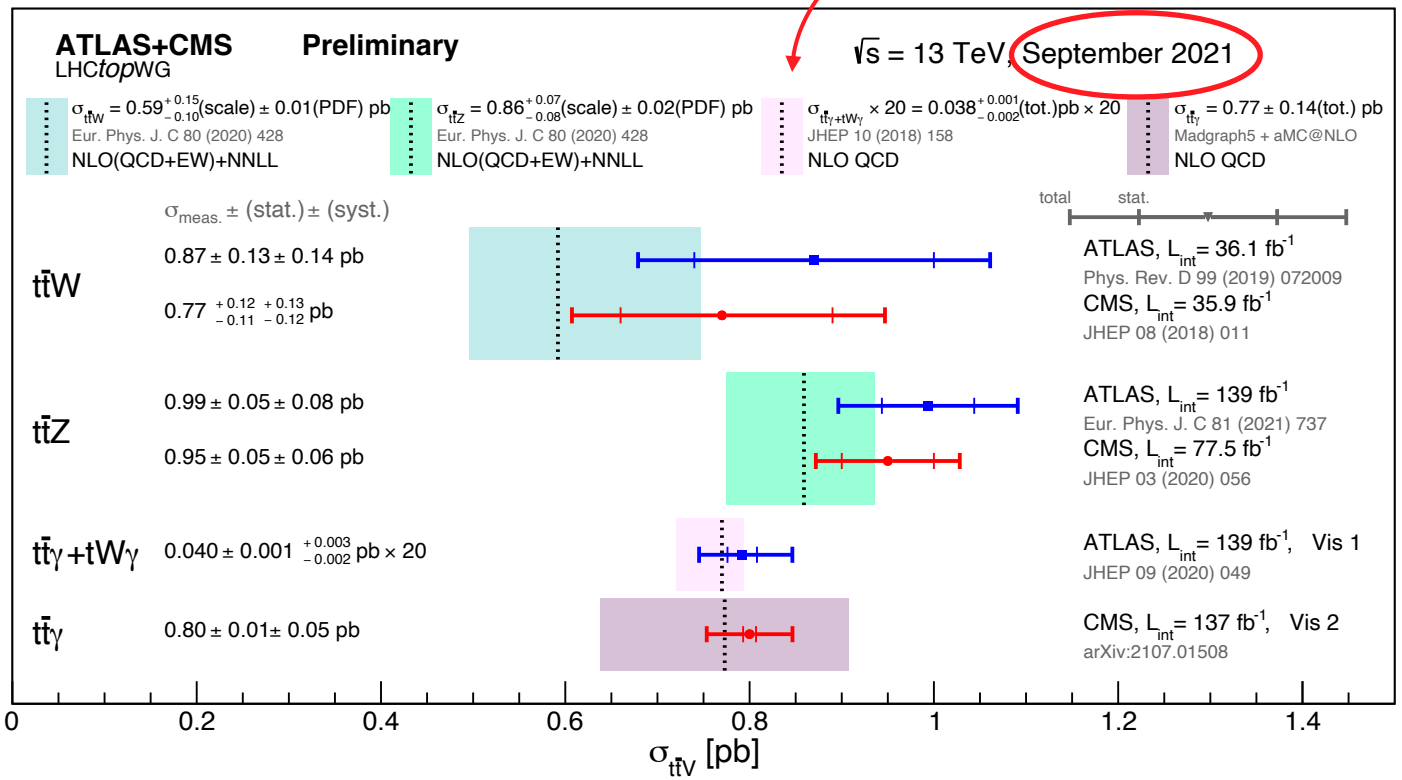
- *NNLO QCD* theoretical predictions only for *tt*
- More exclusive final states produced @ LHC

HELAC-NLO

Bevilacqua, Hartanto, Kraus, Weber, Worek '18

LHCTopWG

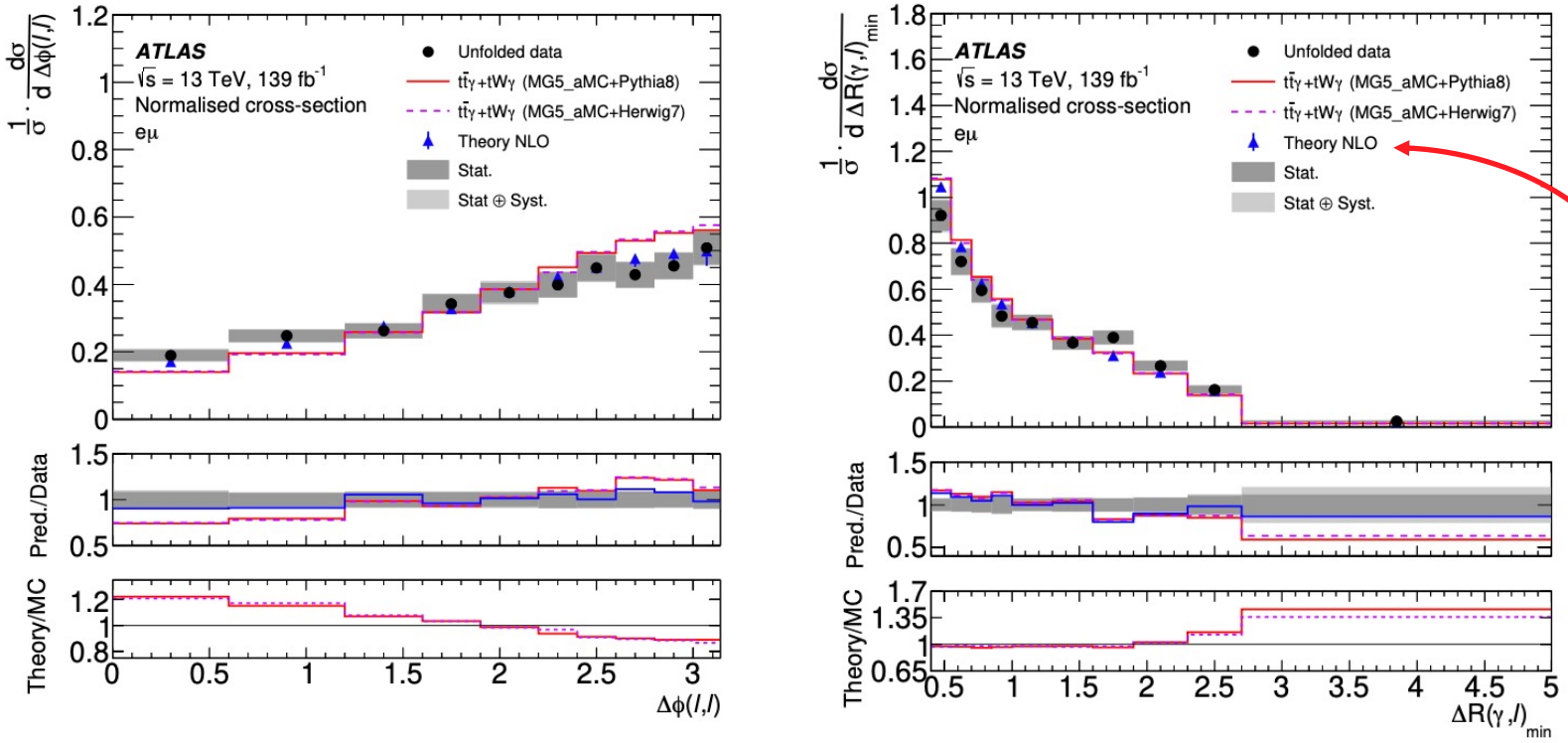




Cafarella, Papadopoulos, Worek '09

$t\bar{t}\gamma$ Production & Decay @ NLO

Di-lepton



ATLAS Collaboration '20

HELAC-NLO

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

- Higher order corrections to production & decays important

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

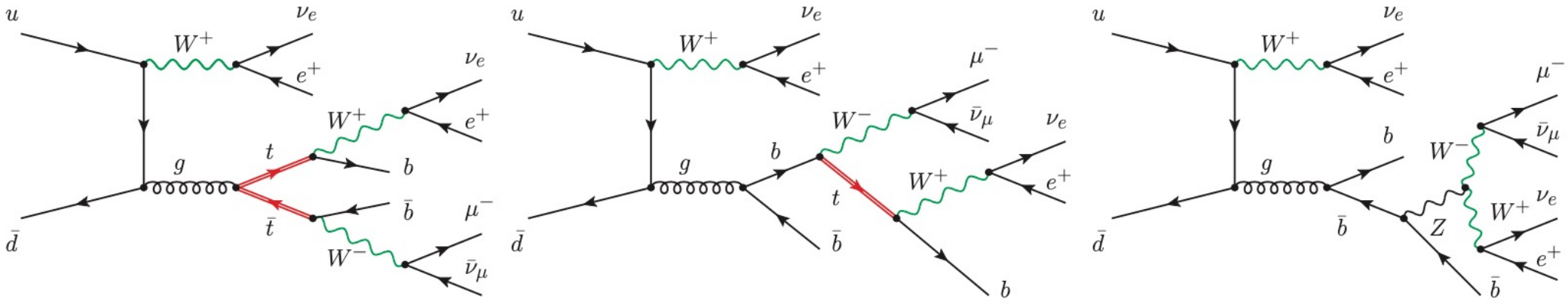
Theoretical Predictions for TT + X

- NLO corrections for stable top quarks
  - General idea about size of NLO corrections.
  - Can not provide reliable description of top quark decay products and radiation pattern
  - NLO QCD
  - NLO Electro-Weak
- For more realistic studies decays are needed:
  - NLO QCD for TT+X + PS
  - NLO QCD for TT+X + LO Decays + PS
  - NLO QCD in NWA
  - NLO QCD Complete Off-shell Effects

Definition with TTW

- Full/Complete Off-shell Effects

Bevilacqua, Bi, Hartanto, Kraus, Worek '20 '21



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

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

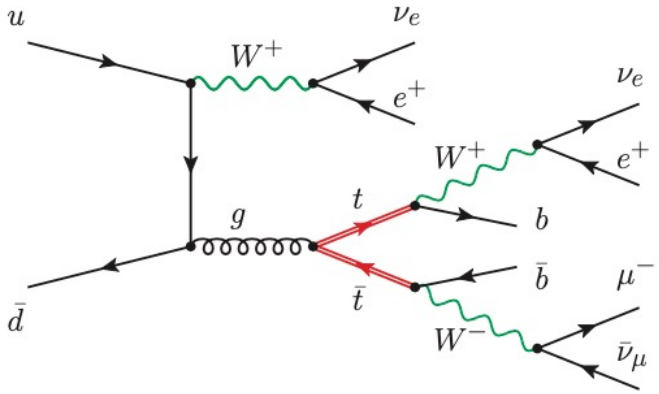
$$pp \to e^-\bar{\nu}_e\,\mu^+\,\nu_\mu\,e^-\bar{\nu}_e\,b\bar{b} + X$$

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

Definition with TTW

- Narrow Width Approximation (NWA)

Bevilacqua, Bi, Hartanto, Kraus, Worek '20 '21



- NWA:
  - Works in the limit ⇨ $\Gamma_t/m_t \to 0$
  - Incorporates only double resonant contributions
  - Restricts unstable t & W to on-shell states

- NWA with LO Decays ($\text{NWA}_{\text{LODEC}}$)
  - Without NLO QCD corrections to top decays
  - LO spin correlations

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

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

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

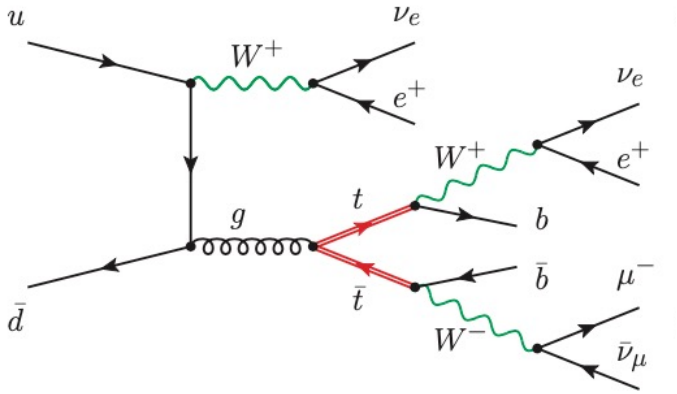
- NLO QCD correction separately to production & separately to decays
- NLO QCD nonfactorizable corrections missing ⇨ No cross-talk between production & decays
- NLO spin correlations

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

Definition with TTW

Cordero, Kraus, Reina '21
Frederix, Tsinikos '20

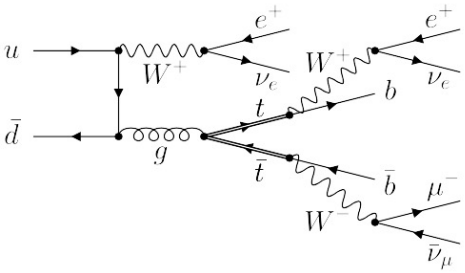
- NLO + PS



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

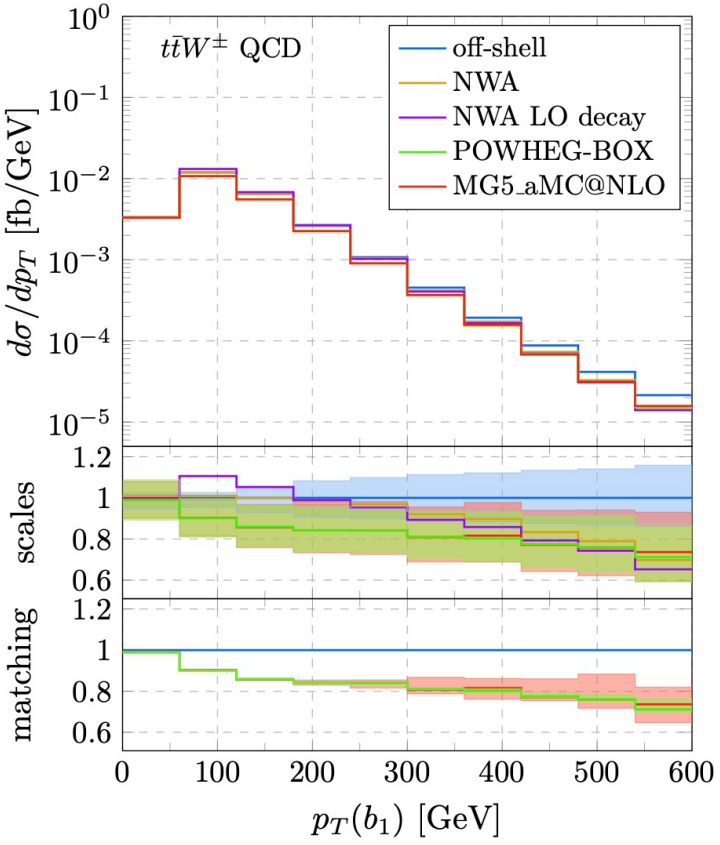
- NLO QCD corrections to stable *t & W* matched to parton shower programs
  - Without NLO QCD corrections to decays
- Decays via parton shower ⇨ Without spin correlations
- Decays using LO matrix element
  - Double resonant contributions only
  - Breit-Wigner propagators for *t & W* with some cut-off
  - LO spin correlations
  - Single & non-resonant contributions for *t & W* are still missing

TTW Various Results

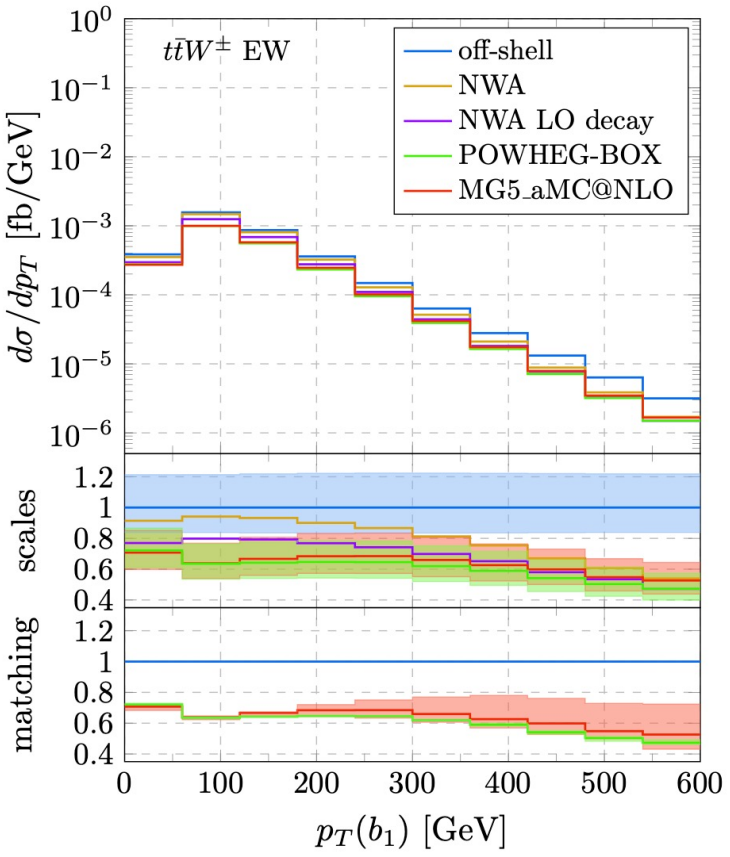


Multi-lepton

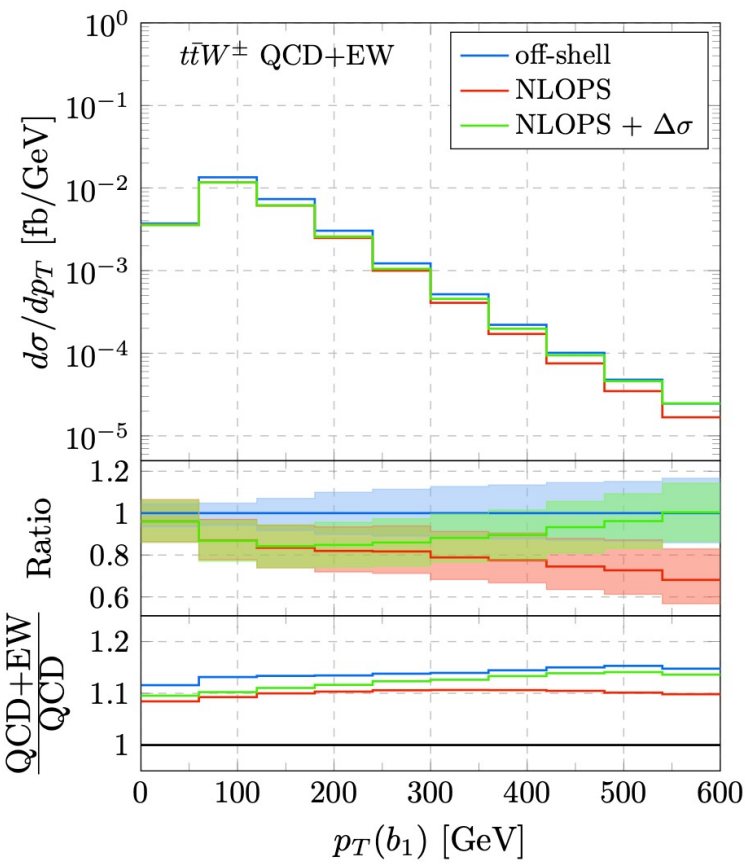
QCD



EW



Combined



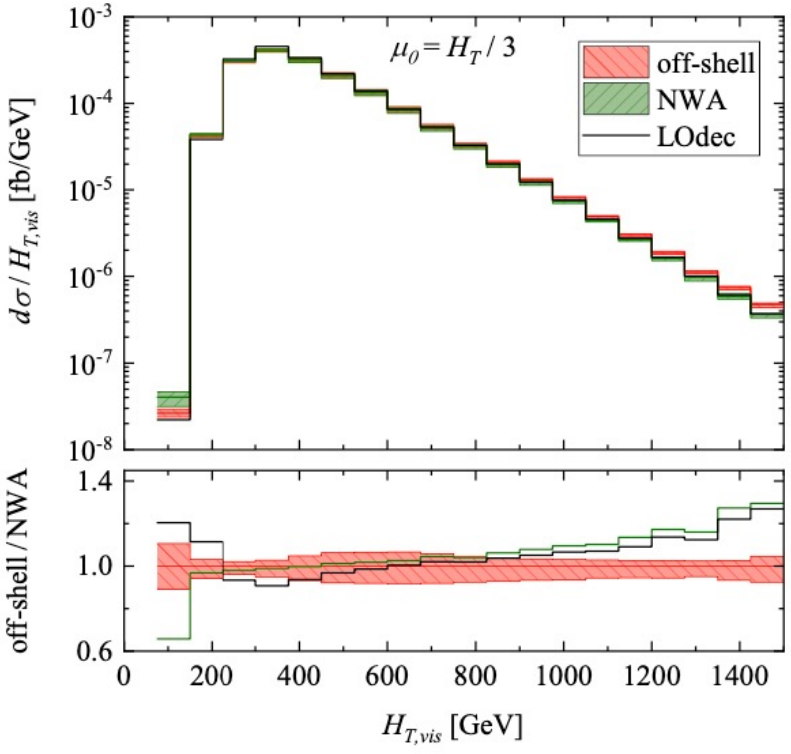
Bevilacqua, Bi, Cordero, Hartanto, Kraus, Nasufi, Reina, Worek ' 21

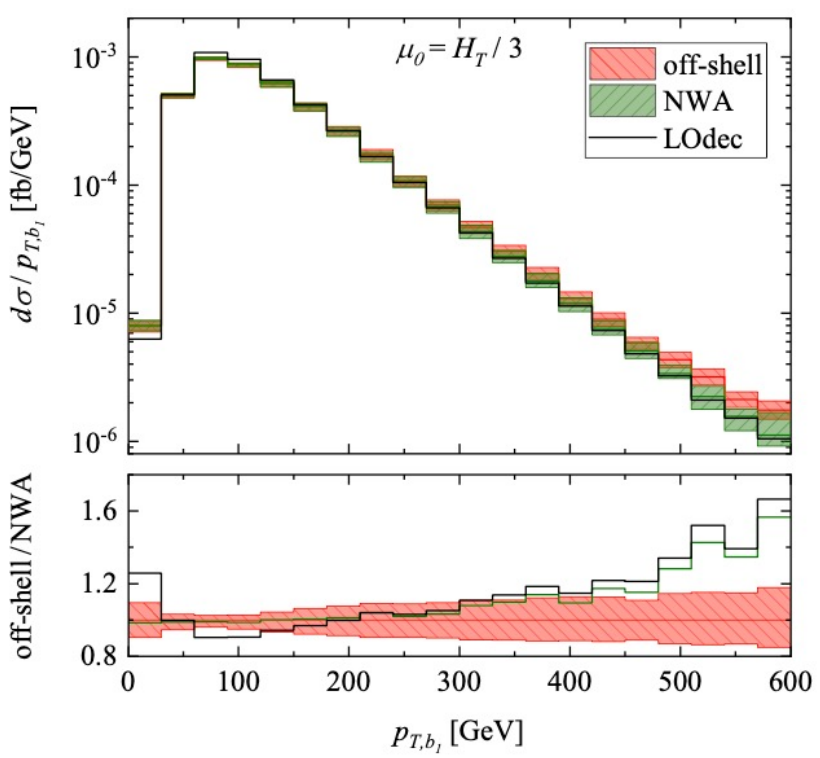
TTW How Good Is the NWA ?

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

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

Di-lepton





Bevilacqua, Bi, Hartanto, Kraus, Worek '20

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

Differential level:

- Off-shell up to ***60% - 70%***
- Substantial differences between NWA & $NWA_{LOdecay}$

Integrated level:

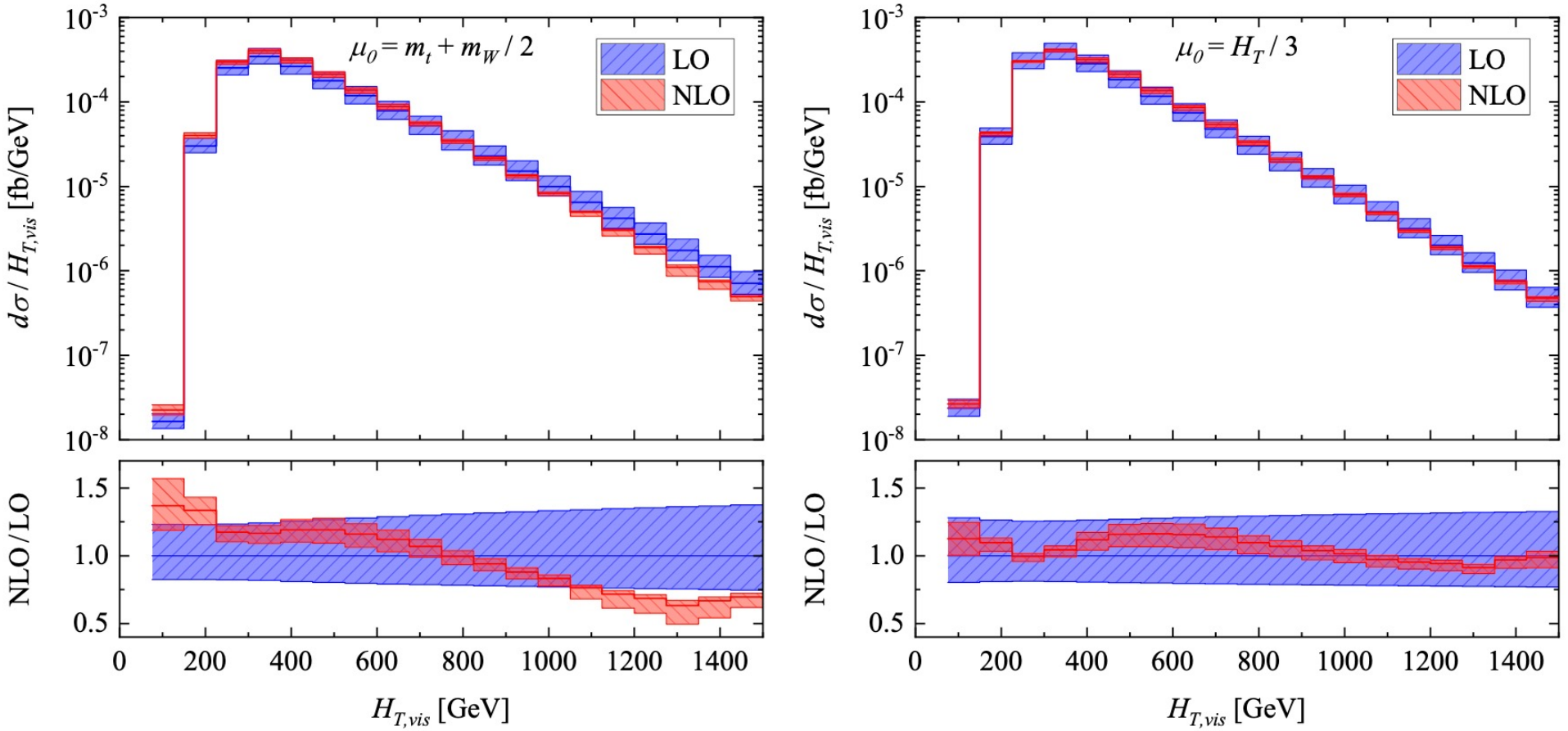
- Complete top-quark off-shell effects ***0.2%***
- NLO ***QCD*** corrections to decays ***3%-5%***

TTW NLO Corrections

Off-shell ttW⁺

Bevilacqua, Bi, Hartanto, Kraus, Worek '20

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



Di-lepton

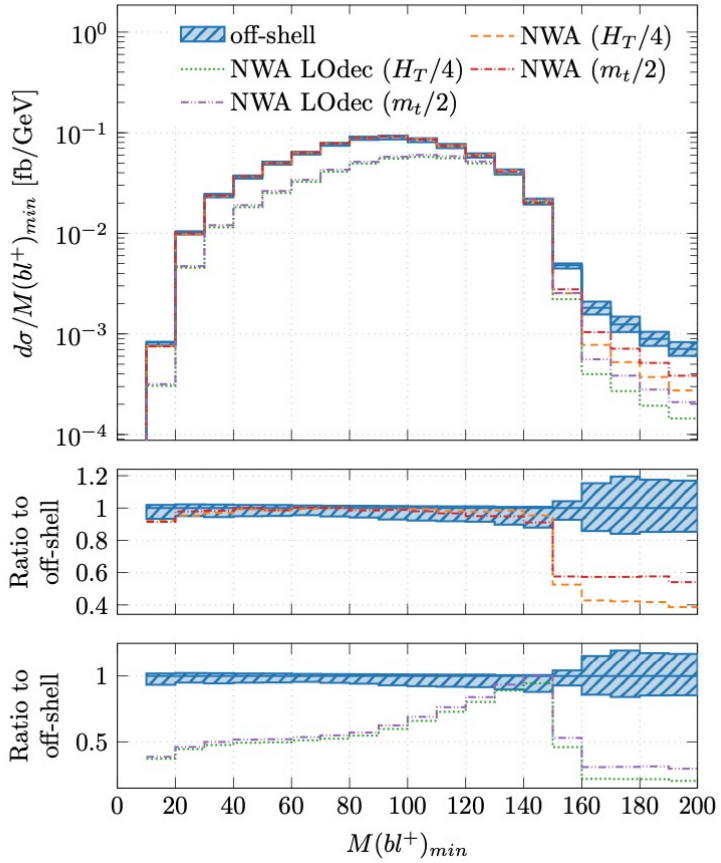
- *K-factor not flat*

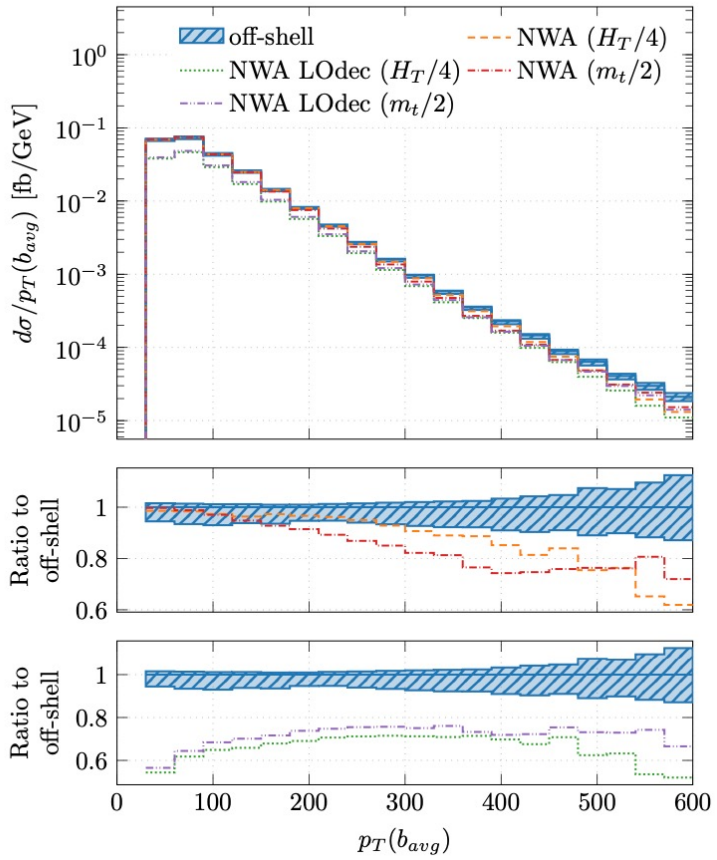
- ***Fixed scale choice*** ⇨ Leads to perturbative instabilities in TeV region of differential cross & Large distortions
- ***Dynamical scale choice*** ⇨ Stabilises tails & keeps NLO uncertainties bands within LO ones

TTγ How Good Is the NWA ?

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

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





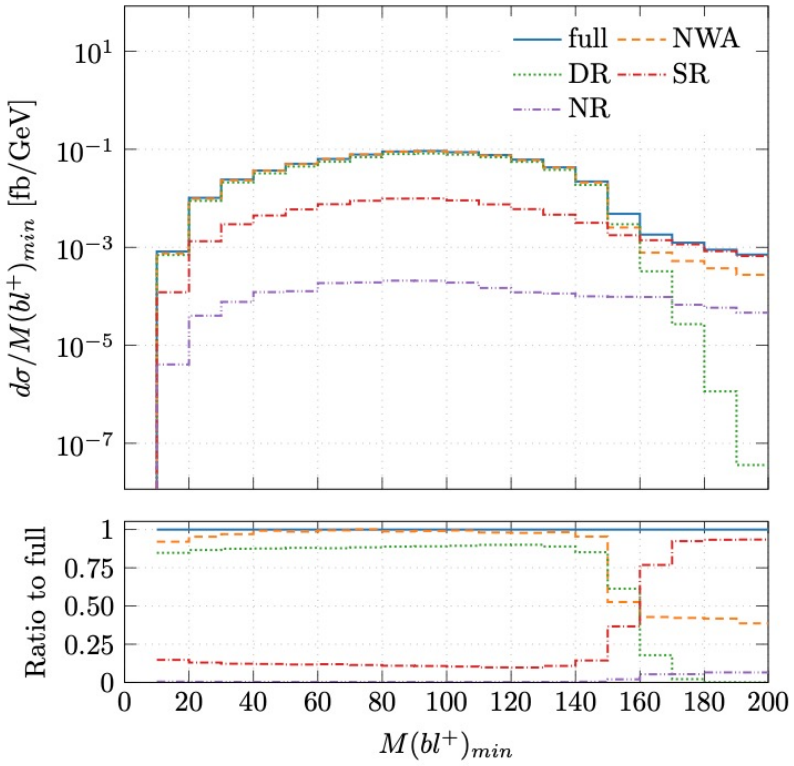
Dimensionful observables

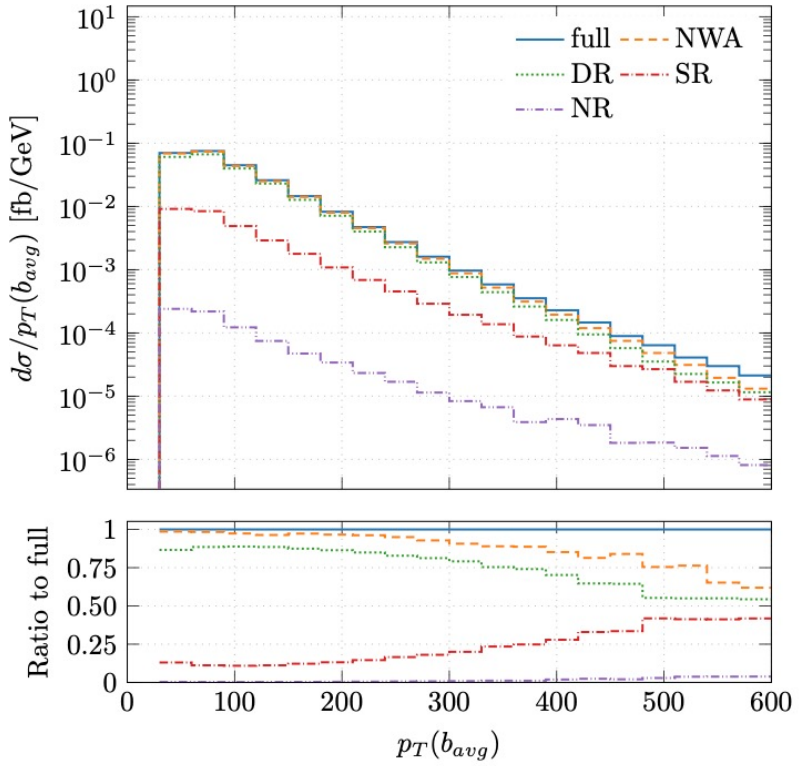
- Sensitive to non-factorizable top quark corrections
- *Tens of per cent* in specific phase-space regions
- *Kinematical edges & high p_T regions*

Bevilacqua, Hartanto, Kraus, Weber, Worek '20

TTγ Various Phase-space Regions

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





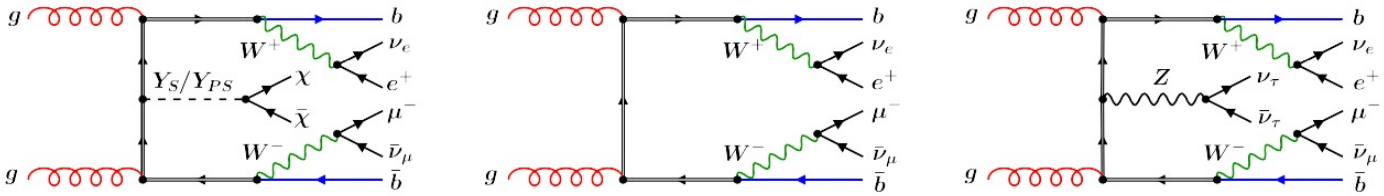
- Full Off-shell Effects:
  - High p_T region of various dimensionful observables
  - Vicinity of kinematical edges
  - Effects up to ***50% – 60%***

Bevilacqua, Hartanto, Kraus, Weber, Worek '20

Dark Matter Searches @ LHC

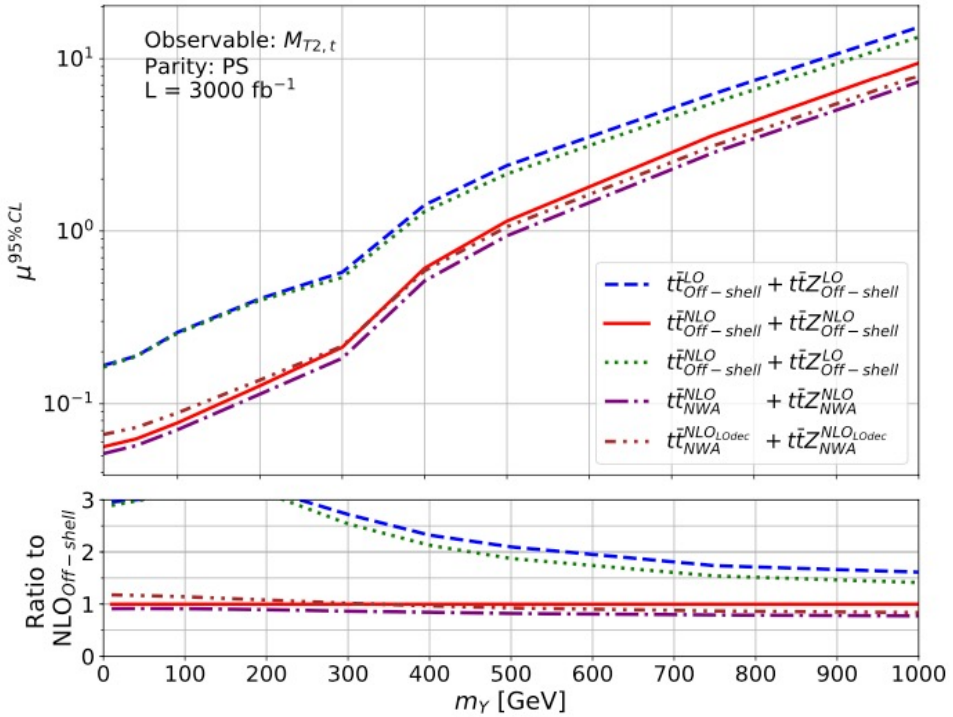
- **BSM:** Kinematical edges & high p_T regions
- ***tt + DM*** ⇨ QCD backgrounds: ***tt & ttZ***
- **Observable** ⇨ $M_{T2,W}$ & $M_{T2,t}$ & p_{Tmiss}

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



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 + PS & NLO + LO decays

Hermann, Worek '21

SUMMARY

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

- NLO QCD corrections to ***tt+X***
  1. Corrections to production & decays important ⇨ NLO ***tt*** spin correlations
  2. Possibility of using kinematic-dependent μ_R & μ_F scales important
  3. Complete off-shell effects important

- *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 state-of-the-art theoretical predictions*

- Full off-shell results for ***tt, ttj, ttγ, ttZ, ttW$^{\pm}$, ttbb & ttH (+ H decays in NWA)*** with HELAC-NLO
  - Stored ⇨ ***Ntuples Files*** ⇨ ***Les Houches & ROOT Files***
  - Can be used by ATLAS & CMS
  - Should be matched to parton shower program