

Off-shell $t\bar{t}b\bar{b}$ @ LHC with HELAC-NLO

MALGORZATA WOREK



JHEP 08 (2021) 008 [arXiv:2105.08404 [hep-ph]]

OUTLINE

INTRODUCTION

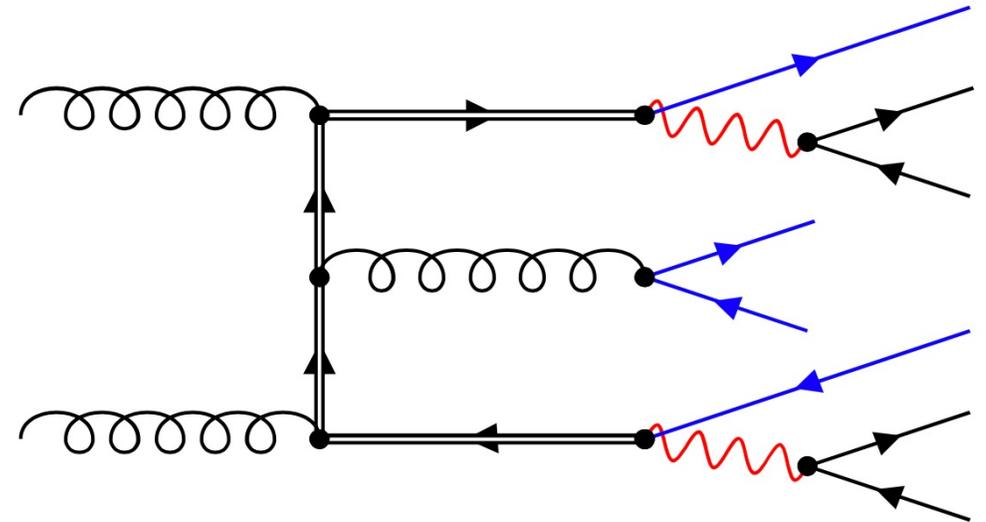
- Motivations for $ttbb$ @ LHC
- State-of-the-art
- Need for precision

OFF-SHELL TTBB AT NLO QCD

- Dominant theory uncertainties
- Size of QCD corrections
- Impact of b -initiated subprocesses

SUMMARY & OUTLOOK

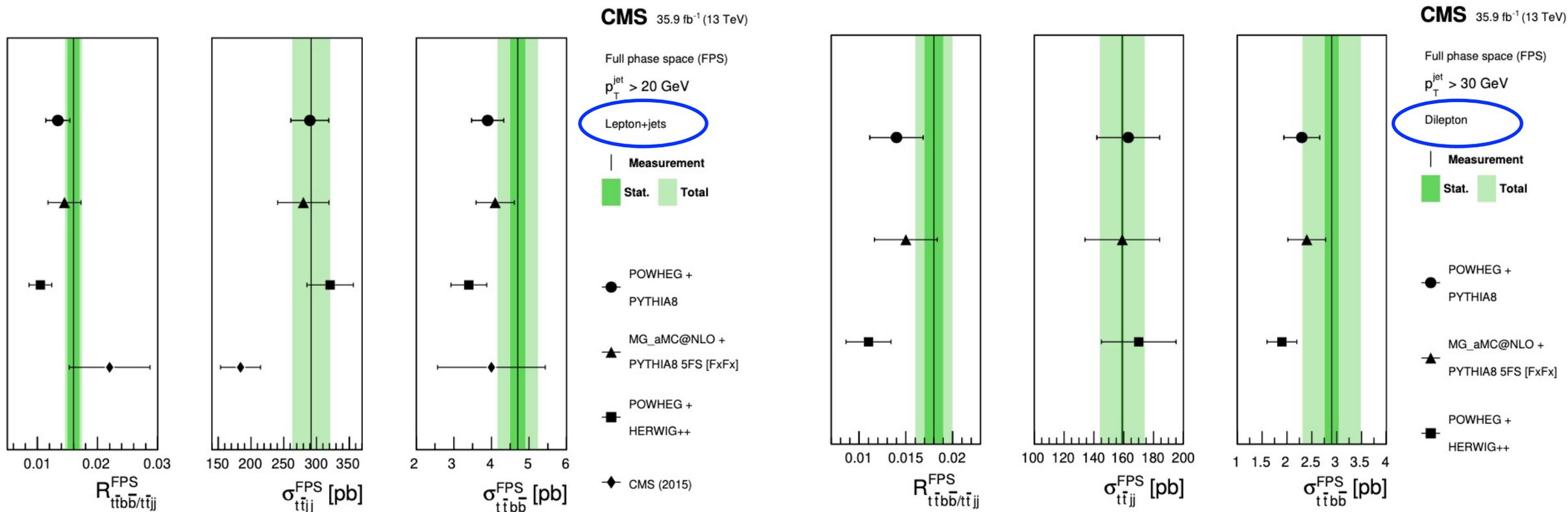
$$pp \rightarrow e^+ \nu_e \mu^- \bar{\nu}_\mu b\bar{b} b\bar{b} + X$$



MOTIVATIONS FOR TTBB @ LHC



CMS Collaboration, JHEP 07 (2020) 125

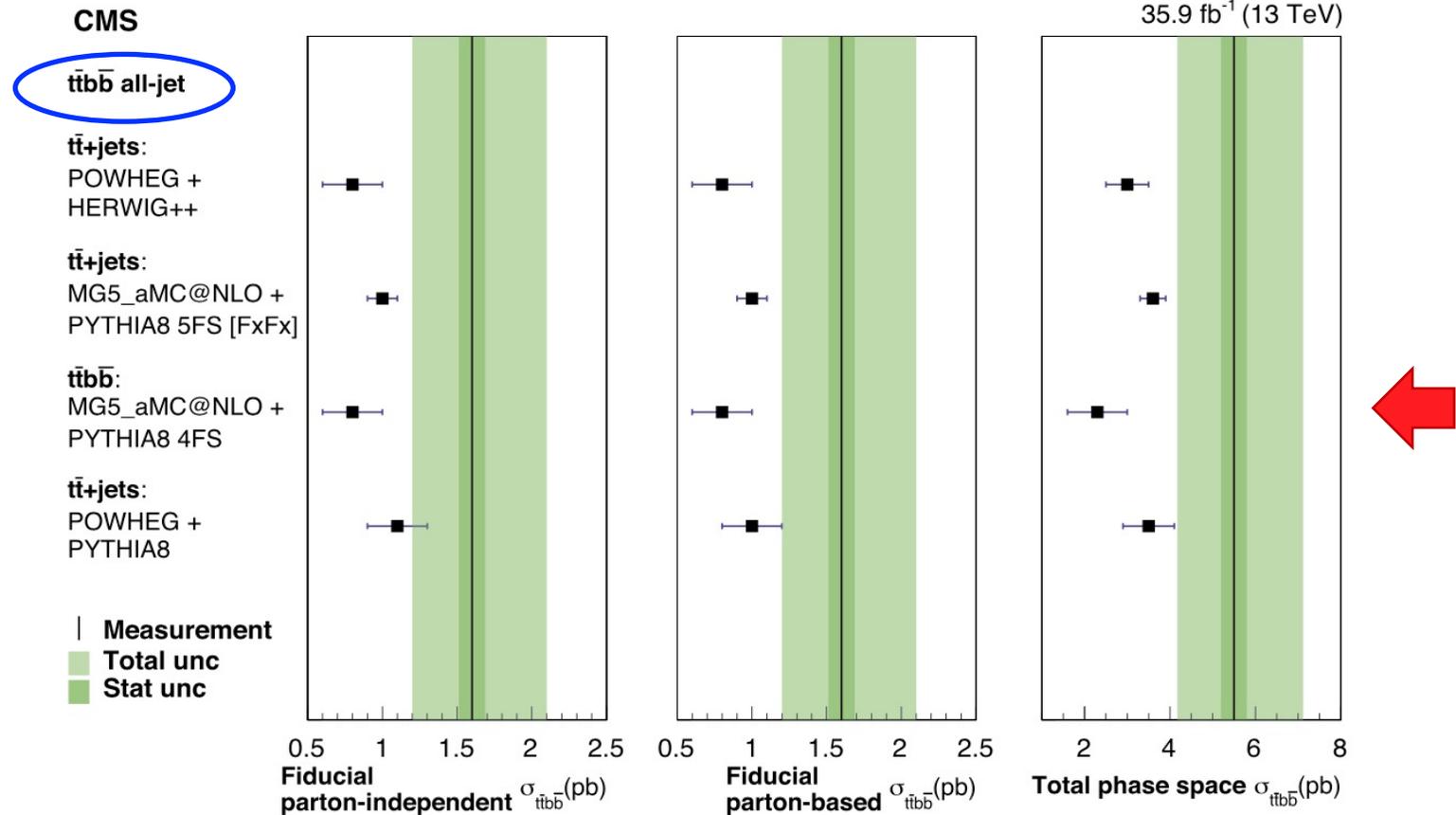


MEASURED TTBB CROSS SECTION HIGHER THAN MONTE CARLO PREDICTIONS
 DILEPTON & LEPTON+JET

MOTIVATIONS FOR TTBB @ LHC



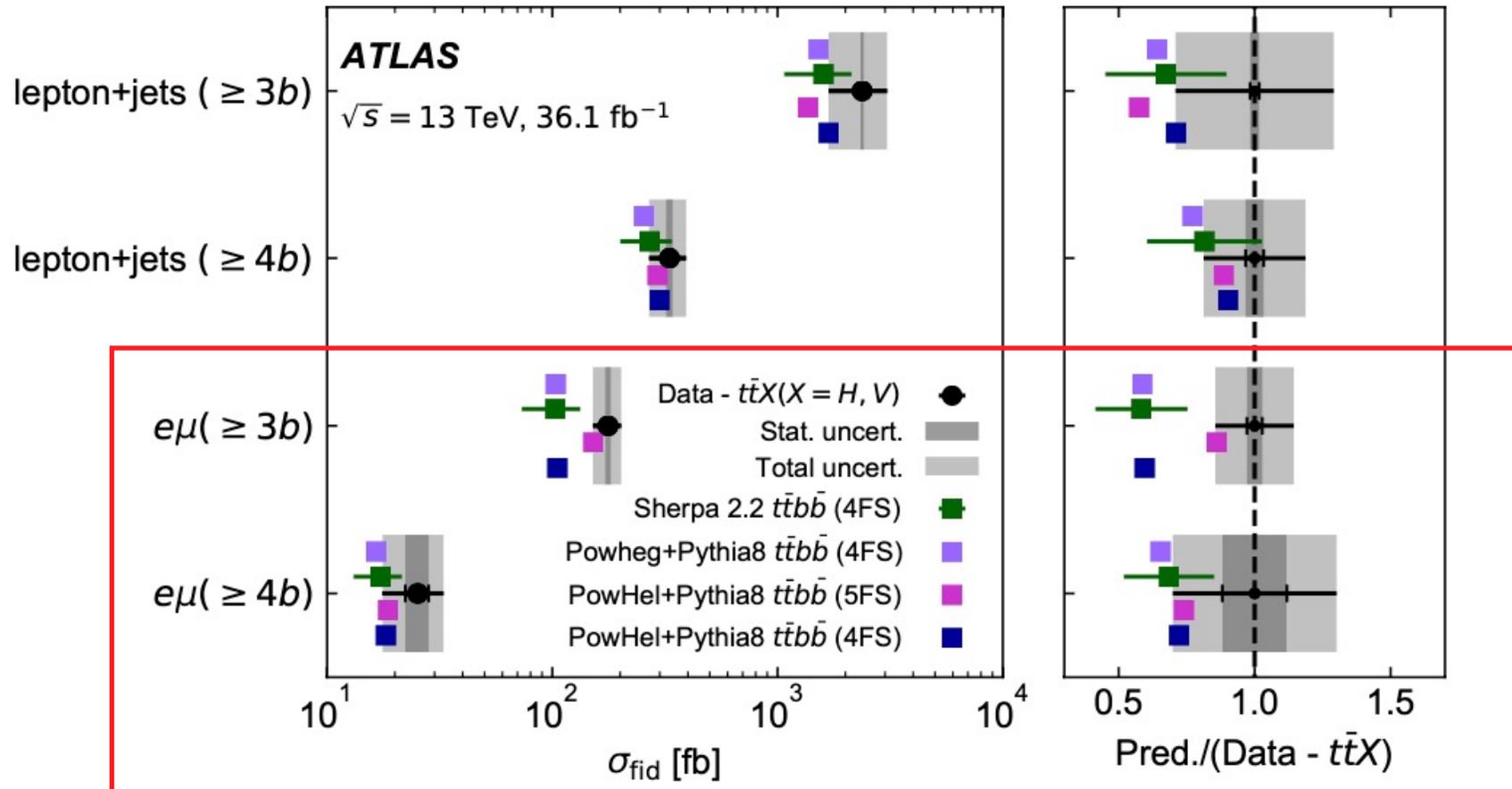
CMS Collaboration, Physics Letters B 803 (2020) 135285



MEASURED TTBB CROSS SECTION HIGHER THAN MONTE CARLO PREDICTIONS
DILEPTON & LEPTON+JET

MOTIVATIONS FOR TTBB @ LHC

ATLAS Collaboration, JHEP 04 (2019) 046



MEASURED TTBB CROSS SECTION HIGHER THAN MONTE CARLO PREDICTIONS
 DILEPTON & LEPTON+JET

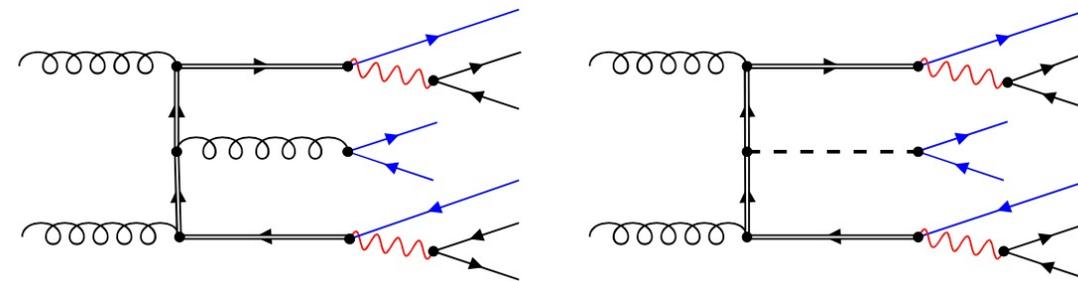
FULL OFF-SHELL TTBB

- Irreducible background for Higgs boson studied
- ttH \Leftrightarrow Observation in 2018
- Top-Yukawa coupling Y_t \Leftrightarrow Probed directly
- ATLAS & CMS reported measurements for $ttH(H \rightarrow bb)$ decay channel of Higgs boson

EXPERIMENTAL CHALLENGES

- Identification of candidates for Higgs decay
- Combinatorial background
- Misidentification of light jets with b -jets
- b -jet tagging
- SM backgrounds

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



$$pp \rightarrow t\bar{t}b\bar{b} \quad \& \quad pp \rightarrow t\bar{t}H \rightarrow t\bar{t}b\bar{b}$$

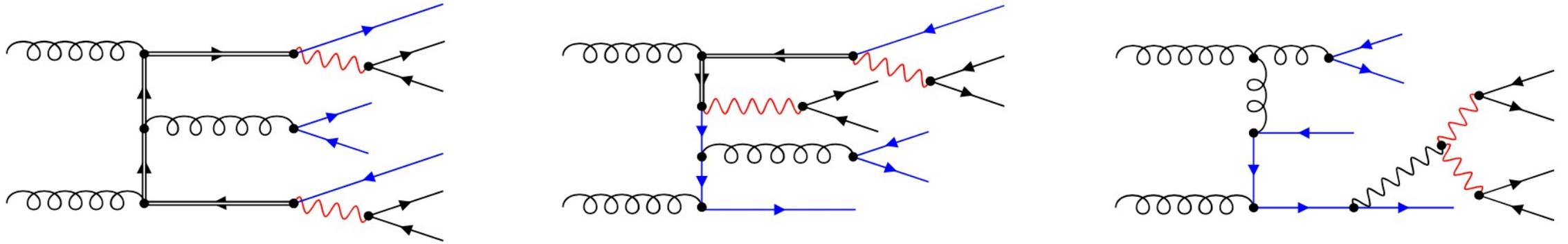
THEORY CHALLENGES

- Two very different & distinctive scales
- m_t \Leftrightarrow tt production & top-quark decays
- $p_T(b)$ \Leftrightarrow Describes b -jets from $g \rightarrow bb$ splitting
- Second calculation for off-shell $ttbb$ in di-lepton channel \Leftrightarrow Agreement with first calculations

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

Denner, Lang, Pellen *arXiv:2008.00918 [hep-ph]*
 Bevilacqua, Bi, Hartanto, Kraus, Lupattelli, Worek *arXiv:2105.08404 [hep-ph]*

FULL OFF-SHELL TTBB



COMPLETE OFF-SHELL EFFECTS:

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

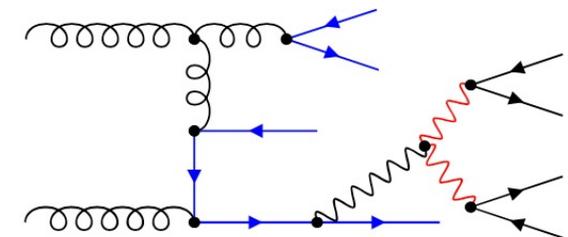
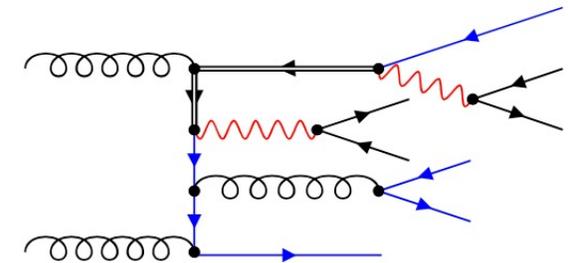
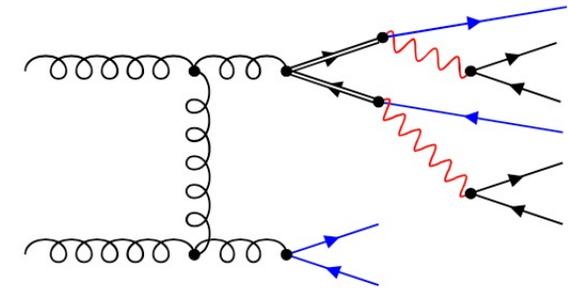
- NLO QCD corrections to production & decays
- Nonfactorizable NLO QCD corrections included \Leftrightarrow Cross-talk between production & decays
- NLO spin correlations

INTEGRATED FIDUCIAL CROSS SECTIONS FOR TTBB

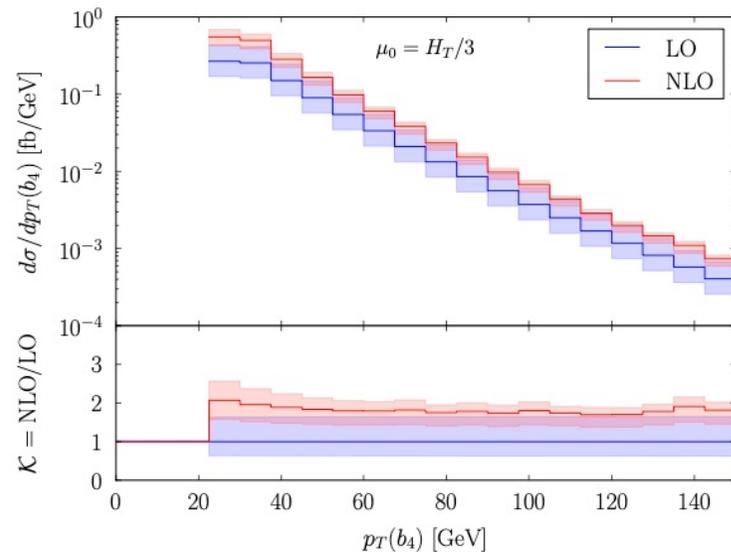
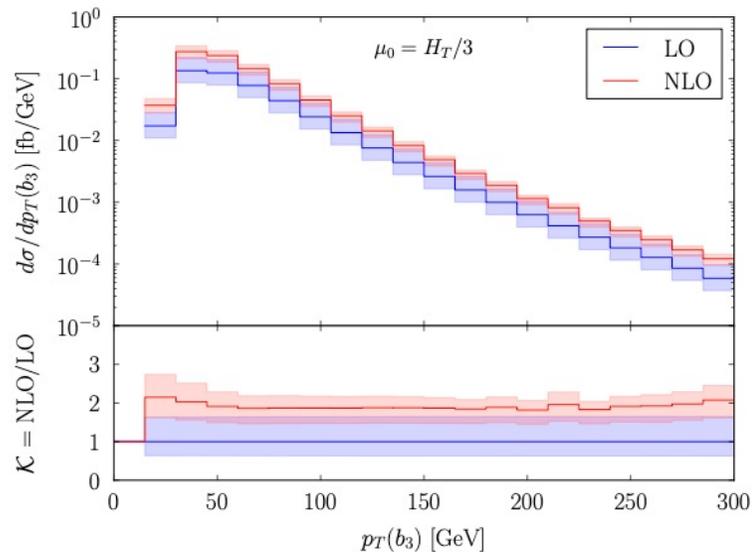
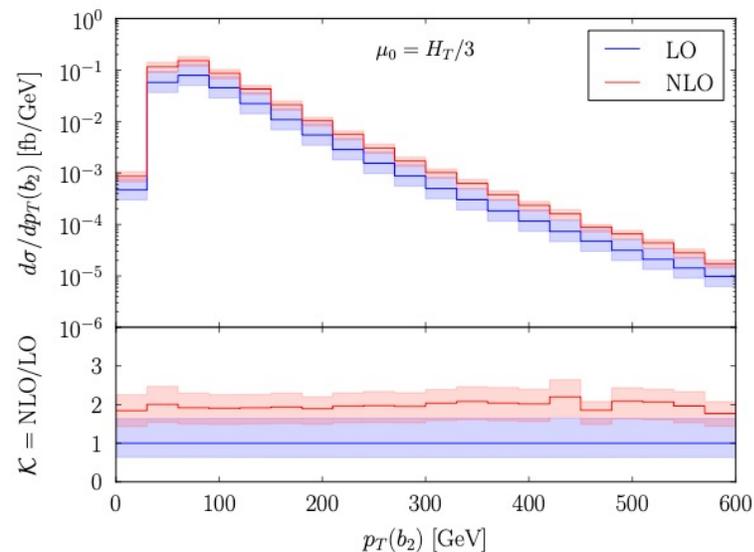
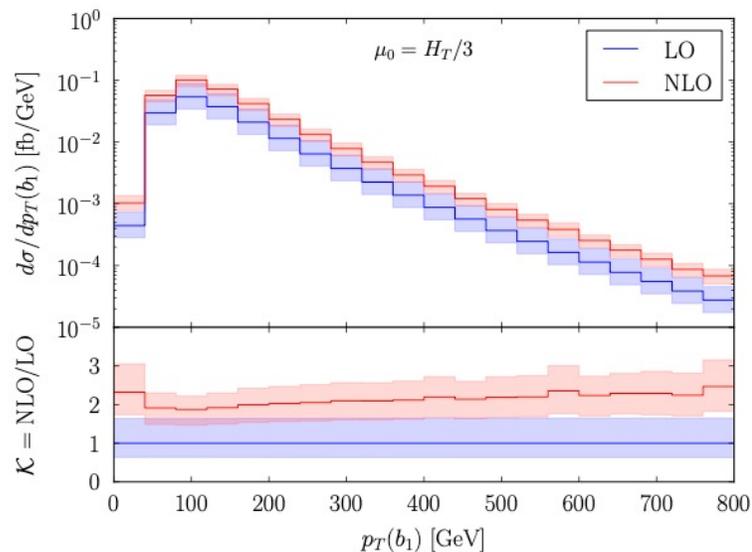
Bevilacqua, Bi, Hartanto, Kraus, Lupattelli, Worek
arXiv:2105.08404 [hep-ph]

$p_T(b)$	σ^{LO} [fb]	δ_{scale}	σ^{NLO} [fb]	δ_{scale}	δ_{PDF}	$\mathcal{K} = \sigma^{\text{NLO}}/\sigma^{\text{LO}}$
$\mu_R = \mu_F = \mu_0 = m_t$						
25	6.998	+4.525 (65%) -2.569 (37%)	13.24	+2.33 (18%) -2.89 (22%)	+0.19 (1%) -0.19 (1%)	1.89
30	5.113	+3.343 (65%) -1.889 (37%)	9.25	+1.32 (14%) -1.93 (21%)	+0.14 (2%) -0.14 (2%)	1.81
35	3.775	+2.498 (66%) -1.401 (37%)	6.57	+0.79 (12%) -1.32 (20%)	+0.10 (2%) -0.10 (2%)	1.74
40	2.805	+1.867 (67%) -1.051 (37%)	4.70	+0.46 (10%) -0.91 (19%)	+0.08 (2%) -0.08 (2%)	1.68
$\mu_R = \mu_F = \mu_0 = H_T/3$						
25	6.813	+4.338 (64%) -2.481 (36%)	13.22	+2.66 (20%) -2.95 (22%)	+0.19 (1%) -0.19 (1%)	1.94
30	4.809	+3.062 (64%) -1.756 (37%)	9.09	+1.66 (18%) -1.98 (22%)	+0.16 (2%) -0.16 (2%)	1.89
35	3.431	+2.191 (64%) -1.256 (37%)	6.37	+1.07 (17%) -1.36 (21%)	+0.11 (2%) -0.11 (2%)	1.86
40	2.464	+1.582 (64%) -0.901 (37%)	4.51	+0.72 (16%) -0.95 (21%)	+0.09 (2%) -0.09 (2%)	1.83

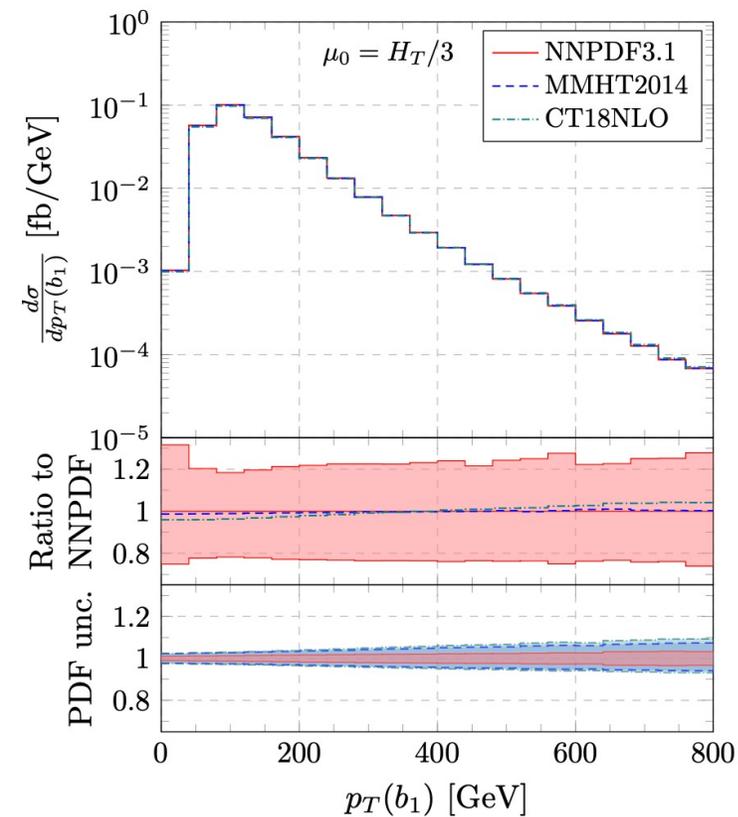
- Results for NNPDF3.1 LO & NLO with $\alpha_s(m_Z) = 0.118$
- LO NNPDF3.1 PDF set with $\alpha_s(m_Z) = 0.130 \Leftrightarrow \mathcal{K} = 1.45$
- Other PDF sets give \mathcal{K} -factor $\in (1.81 \ \& \ 1.37 \ \& \ 1.23)$
- With jet veto of 50 GeV $\mathcal{K} = 1.11 \ \& \ K = 1.23$



FULL OFF-SHELL TTBB



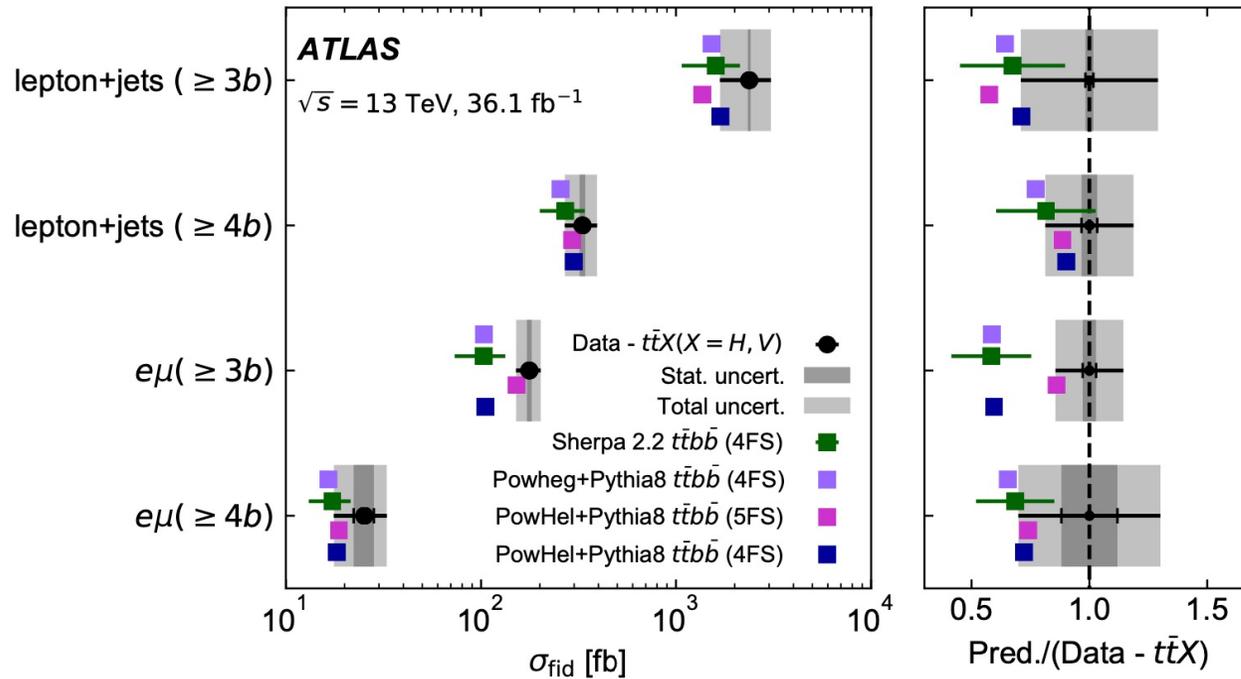
- Large but rather stable NLO corrections @ differential level
- Dynamical scales important
- PDF uncertainties small



TTBB @ NLO

Bevilacqua, Bi, Hartanto, Kraus, Lupattelli, Worek *arXiv:2105.08404 [hep-ph]*

ATLAS Collaboration, *JHEP 04 (2019) 046*



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

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

$$\sigma_{e\mu+4b}^{\text{HELAC-NLO}} = (20.0 \pm 4.3) \text{ fb}$$

- Comparison to ATLAS results
- $e\mu$ channel @ 13 TeV
- Agreements within theoretical uncertainties

- Higher with leptonic τ decays into l
- For similar scale choice HELAC-NLO result is even higher $\sim 21 \text{ fb}$

INITIAL STATE BOTTOM QUARKS

- 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

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

CHARGE AWARE B-TAGGING

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

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

- Jets clustered with *anti- k_T* algorithm with $R = 0.4$
- Two b -jet tagging variants are IR-safe @ NLO
- Beyond NLO
 - *flavor k_T*

Banfi, Salam, Zanderighi e-Print: hep-ph/0601139 [hep-ph]

- *flavor anti- k_T*

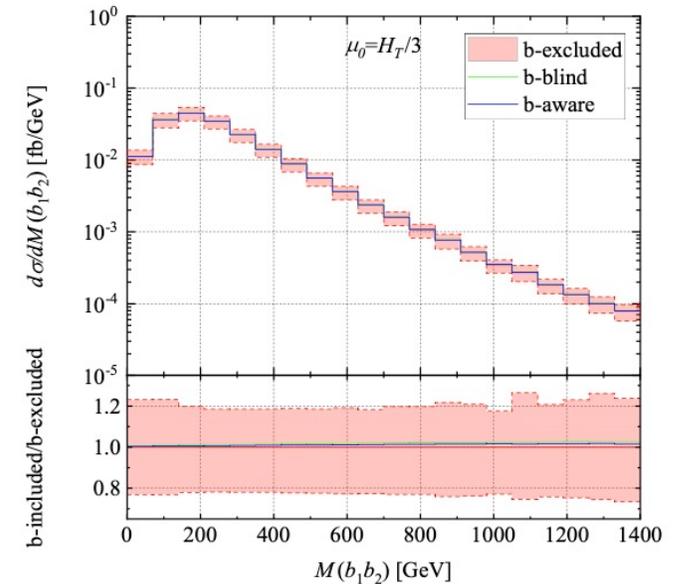
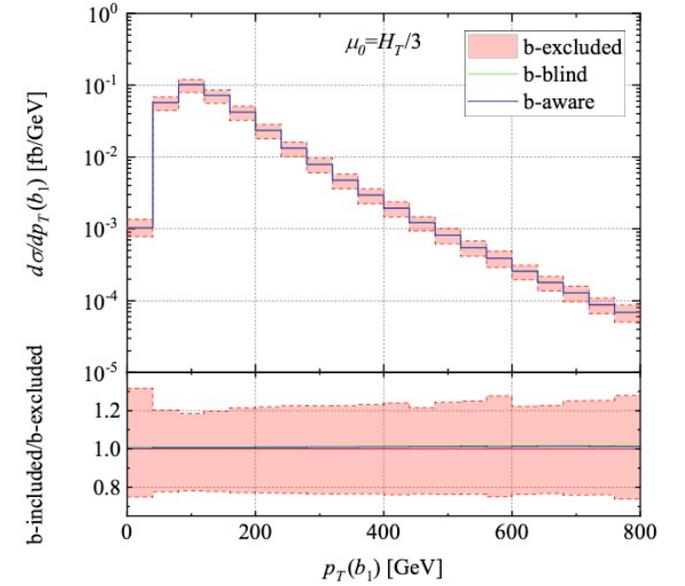
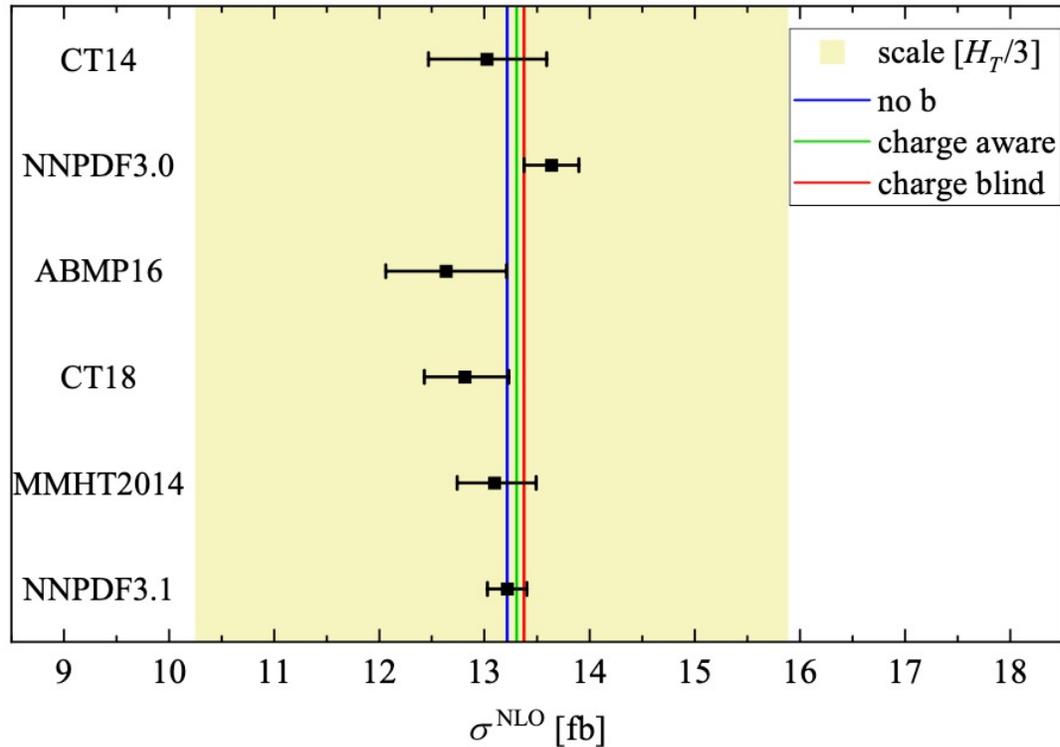
Czakon TOP2021

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

INITIAL STATE BOTTOM QUARKS

NEGLIGIBLE CONTRIBUTION

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



SUMMARY

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

NLO QCD CORRECTIONS

- Corrections to production & decays
- NLO tt spin correlations
- Kinematic-dependent μ_R & μ_F scales
- Complete off-shell effects for top quarks

COMPARISONS

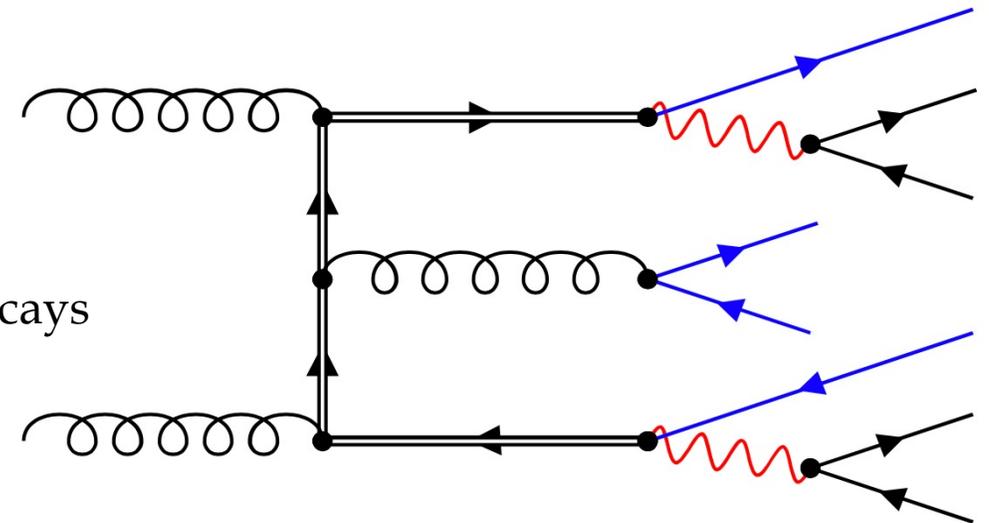
- NWA results \Leftrightarrow Size of off-shell effects
- $\text{NWA}_{\text{LOdec}}$ \Leftrightarrow Size of NLO QCD corrections to top decays
- Parton shower programs \Leftrightarrow Modeling of top decays

IDENTIFICATION

- Prompt b -jets
- b -jets from top quark decays

OUR FULL OFF-SHELL RESULTS

- Stored \Leftrightarrow *Ntuples Files* \Leftrightarrow *Les Houches & ROOT Files*
- Used by ATLAS Collaboration for tty \Leftrightarrow [JHEP 09 \(2020\) 049](#)



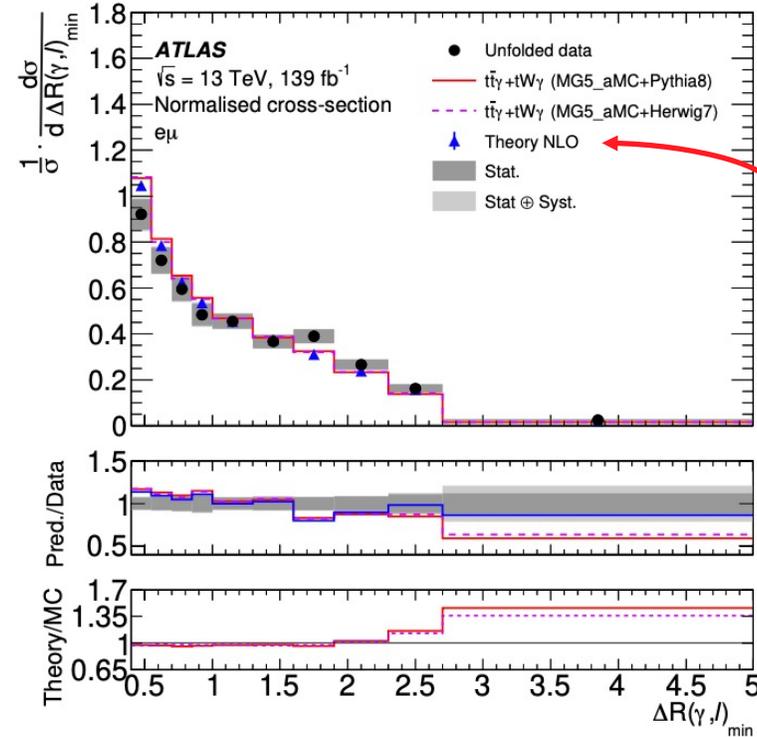
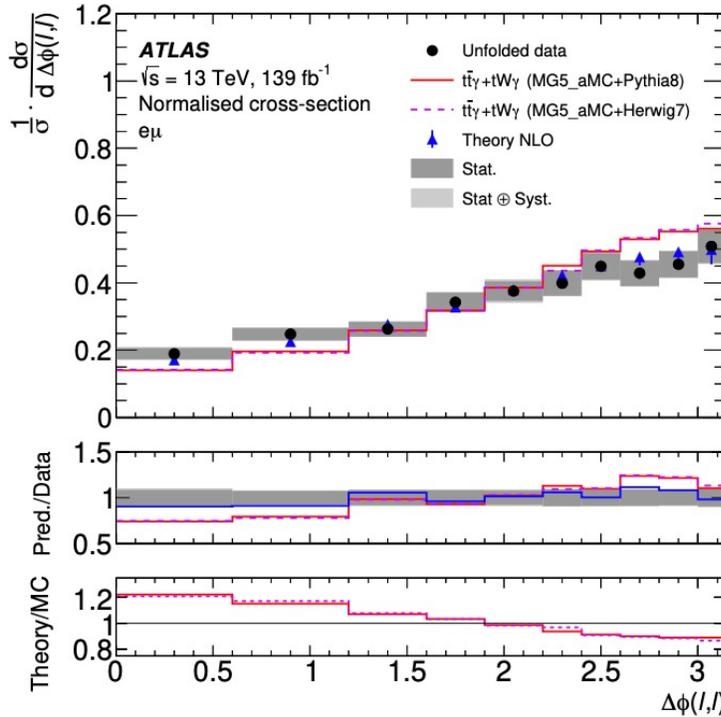
SUMMARY

ATLAS $\sigma_{\text{fid}} = 39.6 \pm 0.8$ (stat) $_{-2.2}^{+2.6}$ (syst) fb = $39.6_{-2.3}^{+2.7}$ fb.

HELAC-NLO $\sigma_{\text{fid}} = 38.50_{-2.18}^{+0.56}$ (scale) $_{-1.18}^{+1.04}$ (PDF) fb

ep channel

ATLAS Collaboration *JHEP 09 (2020) 049*



HELAC-NLO

Predictions	$p_T(\gamma)$		$ \eta(\gamma) $		$\Delta R(\gamma, \ell)_{\text{min}}$		$\Delta\phi(\ell, \ell)$		$ \Delta\eta(\ell, \ell) $	
	χ^2/ndf	p -value	χ^2/ndf	p -value	χ^2/ndf	p -value	χ^2/ndf	p -value	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

OUTLOOK

- NLO corrections for stable top quarks \Rightarrow General idea about size of NLO corrections. Can not provide reliable description of top quark decay products and radiation pattern
 - NLO QCD
 - NLO ELECTROWEAK
- For more realistic studies decays are needed:
 - **NLO QCD FOR $ttX + PS$** \Rightarrow Corrections to production & Top decays in parton shower approximation & omitting even LO tt spin correlations
 - **NLO QCD FOR $ttX + LO$ DECAYS + PS** \Rightarrow Top decays @ LO before matched to parton shower programs & Double resonant contributions only + Breit-Wigner propagators \Rightarrow LO tt spin correlations
 - **NLO QCD IN NWA** \Rightarrow NLO QCD corrections to top production & decays & NLO tt spin correlations & Double resonant contributions only & On-shell tops & W
 - **NLO QCD COMPLETE OFF-SHELL EFFECTS OF TOP QUARKS** \Rightarrow Additionally to the previous point \Rightarrow Resonant & non-resonant diagrams & Interference effects & Off-shell top quarks described by Breit-Wigner propagators